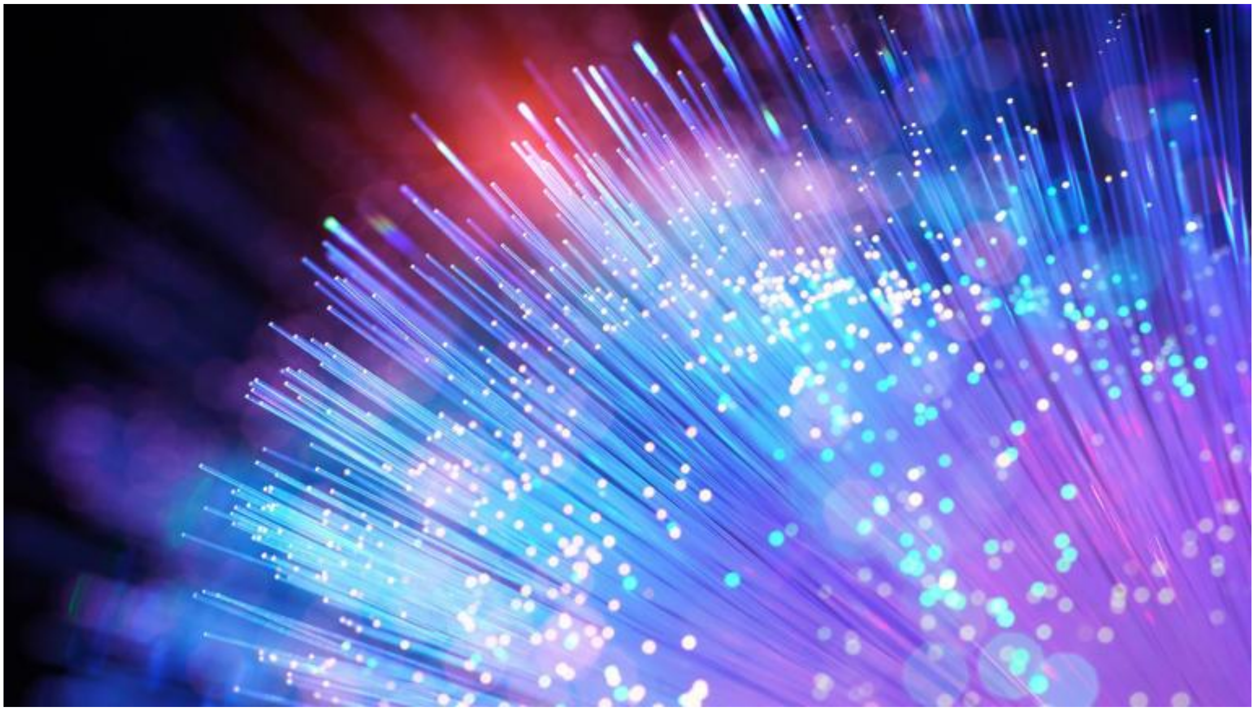
GENERAL PHYSICS TO ASTRO PHYSICS VOL 2

Engineers enable quantum communication over existing fiber optic cables — new research shows data transmission using quantum teleportation is possible in parallel with a classical network at specific wavelengths



Engineers at Northwestern University have successfully achieved quantum communication in parallel with classical channels by identifying specific wavelengths with minimal interference from classical signals (Source: northwestern.edu). This breakthrough lays the groundwork for quantum communication by leveraging existing infrastructure and sending quantum data alongside classical data. The researchers managed quantum teleportation over a 30.2km fiber optic cable carrying 400 Gbps of classical traffic.

Quantum computing seems to be all the hype these days. Google claims its new quantum chip can solve problems swiftly, which classical computers would otherwise take, and I quote 10 billion years to do; that's 10, followed by 24 zeroes. Quantum entanglement is a phenomenon wherein two particles are linked so that their quantum states (spin, polarization, energy levels, etc.) are connected, regardless of the physical distance. When measuring the state of one particle, the entanglement collapses, revealing the correlated state of the other particle. However, this does not allow for FTL (Faster Than Light) communication in line with the no communication theorem.

Enter Quantum teleportation. This concept combines entanglement with a classical channel, such as the Internet, and is the backbone of this research. It transfers one particle's quantum state to another located elsewhere.

Jordan Thomas, one of the research paper's authors, underlined the essence of quantum teleportation; “By performing a destructive measurement on two photons — one carrying a quantum state and one entangled with another photon — the quantum state is transferred onto the remaining photon, which can be very far away.” A key point to understand here is that the photons aren't transmitted physically. Instead, information encoded within their quantum states is what is sent.

The primary concern with a worldwide network employing quantum teleportation is compatibility; will quantum communication work over classical channels? The likelihood of interference is exceptionally high among the billions of photons being sent concurrently in a fiber optic cable. The research discovered specific wavelengths where the density of classical photons was lower, making such wavelengths suitable for the photons in quantum teleportation. Bell state measurement, or simply state measurement, is performed at the mid-point of the cable. Coupled with other methods to reduce noise and interference, this method can potentially support multiple TB/s of classical data alongside quantum communication.

While it may take years or decades before quantum communication goes mainstream, Prem Kumar, the head of the research team, has high hopes for the future. Based on the current roadmap, the next major milestones are using two pairs of entangled photons instead of one and scaling this experiment to real-world optical fiber networks.

Quantum teleportation has begun to change the world

Researchers have uncovered novel ways to transmit information instantly across vast distances, with potential to revolutionize computing, communications, and cryptography. CREDIT: CC BY-SA 4.0)© The Brighter Side of News

Quantum teleportation, once confined to the pages of science fiction, is steadily becoming a tangible scientific achievement. Advances in quantum mechanics over the last decade have transformed teleportation from a theoretical concept into an experimental reality.

These breakthroughs have revealed innovative methods for transmitting information instantaneously over vast distances, offering transformative possibilities for computing, communication, and cryptography. Scientists are now closer than ever to bridging the gap between imagination and reality in this cutting-edge field.

The Science of Quantum Teleportation

At its core, teleportation in the quantum world isn't about physically transporting objects or people, as popularized by franchises like *Star Trek*. Instead, it involves transmitting quantum states—essentially the fundamental properties of particles like electrons or photons—without physical movement of the particles themselves.

Star Trek teleportation. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

This is made possible through quantum entanglement, a phenomenon where two or more particles become so interconnected that the state of one directly influences the other, no matter how far apart they are.

In April 2022, a groundbreaking study led by Dr. Jian-Wei Pan, a physicist at the University of Science and Technology of China, reported a new record in quantum teleportation distance. Using entangled photons, Pan and his team successfully transmitted quantum information over 1,200 kilometers via satellite.

Published in Physical Review Letters, the study marks a significant leap from earlier experiments that were limited to tens or hundreds of kilometers.

“We’ve demonstrated that quantum entanglement can be preserved over incredibly long distances using satellite-based links,” said Dr. Pan. “This paves the way for global-scale quantum communication networks.”

Entanglement at the Edge of Possibility

The key to the experiment’s success lies in the use of Micius, a Chinese satellite launched in 2016 specifically for quantum experiments. Micius creates pairs of entangled photons and transmits one photon to a ground station while the other remains aboard the satellite. When the photon on Earth is manipulated, its twin in space instantly reflects the same change, proving that entanglement holds even over immense distances.

In a complementary study published in Nature, researchers at Delft University of Technology in the Netherlands achieved high-fidelity teleportation of quantum states between two network nodes without losing information. Using nitrogen-vacancy centers in diamonds to create and store quantum bits (qubits), they demonstrated a teleportation accuracy rate of 90%, a record for terrestrial quantum networks.

“Achieving such a high level of accuracy shows that practical quantum networks are feasible,” said Dr. Ronald Hanson, the project’s lead scientist. “This brings us closer to building a quantum internet capable of unhackable communication.”

Overcoming Noise in Quantum Teleportation

A major hurdle in quantum teleportation is noise—unwanted disturbances that can disrupt the transmission of quantum information. In May 2024, researchers from the University of Turku in Finland and the University of Science and Technology of China in Hefei made a groundbreaking discovery: certain types of noise can actually enhance the quality of quantum teleportation.

By utilizing multipartite hybrid entanglement, which involves entangling different physical properties of particles, they achieved near-perfect teleportation even in noisy environments. Professor Chuan-Feng Li from the University of Science and Technology of China stated, "This is a significant proof-of-principle experiment in the context of one of the most important quantum protocols."

Building on this, in June 2024, the team led by Academician Guangcan Guo, achieved a teleportation fidelity of nearly 90% despite environmental noise. They employed a novel method involving hybrid entanglement between photons' polarization and frequency, effectively countering noise interference. This advancement is a significant step toward practical quantum communication systems capable of operating in real-world conditions.

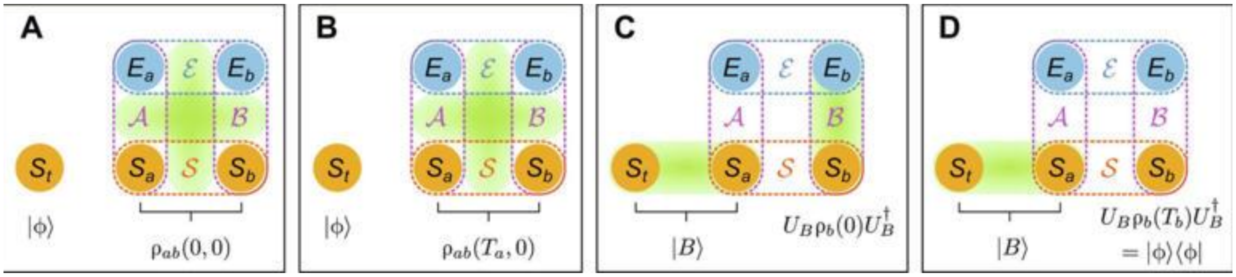
Optimal Quantum Teleportation Fidelity in Arbitrary Dimensions

In November 2024, researchers from the Beijing University of Posts and Telecommunications and the University of Science and Technology of China published a study in Physical Review Applied detailing a general approach for achieving optimal quantum teleportation fidelity across various dimensions.

They experimentally verified their method using three-dimensional quantum teleportation, demonstrating its validity and paving the way for more complex quantum communication protocols.

Quantum Routing with Teleportation

Another notable development in September 2024 involved quantum routing using teleportation. Researchers from the University of Maryland and the University of Cambridge published a study in Physical Review Research exploring the implementation of arbitrary permutations of qubits under interaction constraints.

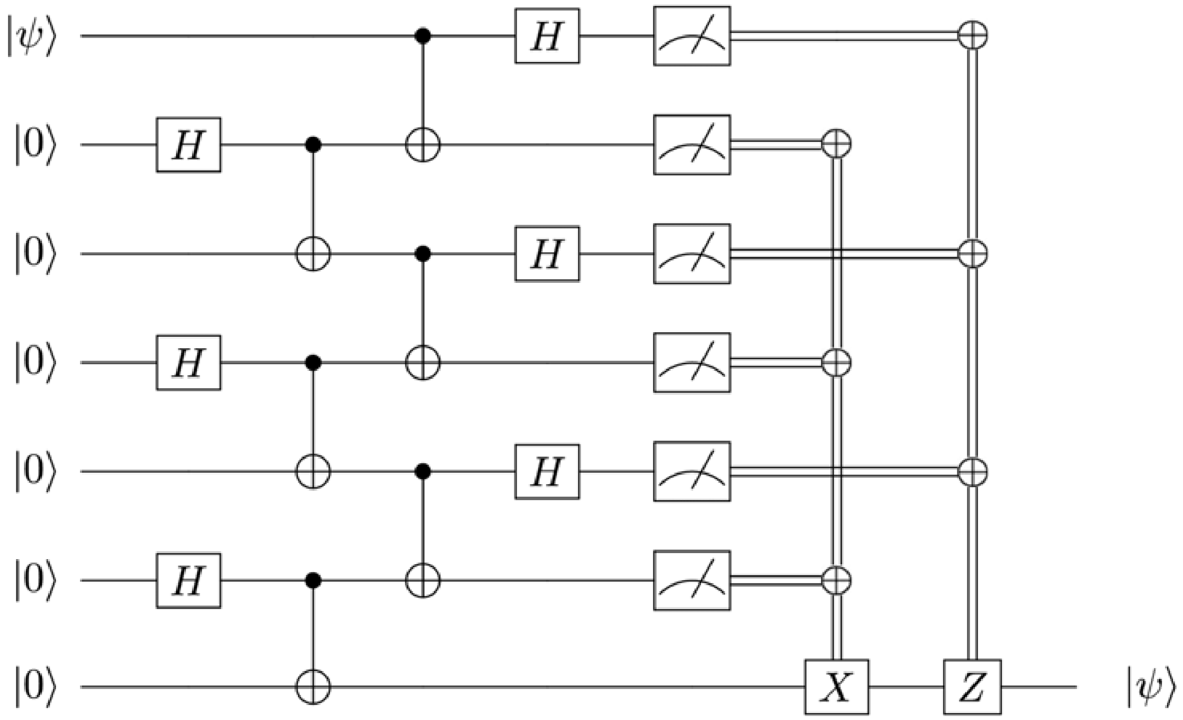


Stages of noisy quantum teleportation. (CREDIT: Science)© The Brighter Side of News

They demonstrated that by distributing entanglement and using local operations and classical communication (LOCC) to perform quantum teleportation, it's possible to achieve speedups over traditional swap-based routing methods. This finding has significant implications for the efficiency of quantum computing networks.

Real-World Implications: From Security to Computing

The implications of these advances are profound. Quantum teleportation could lead to the development of quantum networks that transmit data with unparalleled security. Traditional encryption methods rely on complex algorithms that can, in theory, be cracked by sufficiently advanced computers. Quantum communication, however, uses entangled particles to detect any eavesdropping, as any interference disrupts the entangled state and alerts the sender and receiver. For governments and industries reliant on secure communication—such as banking, healthcare, and national defense—this could mean an unprecedented level of data protection. Already, the European Union’s Quantum Internet Alliance is investing millions into building a continent-wide quantum communication network by 2030.



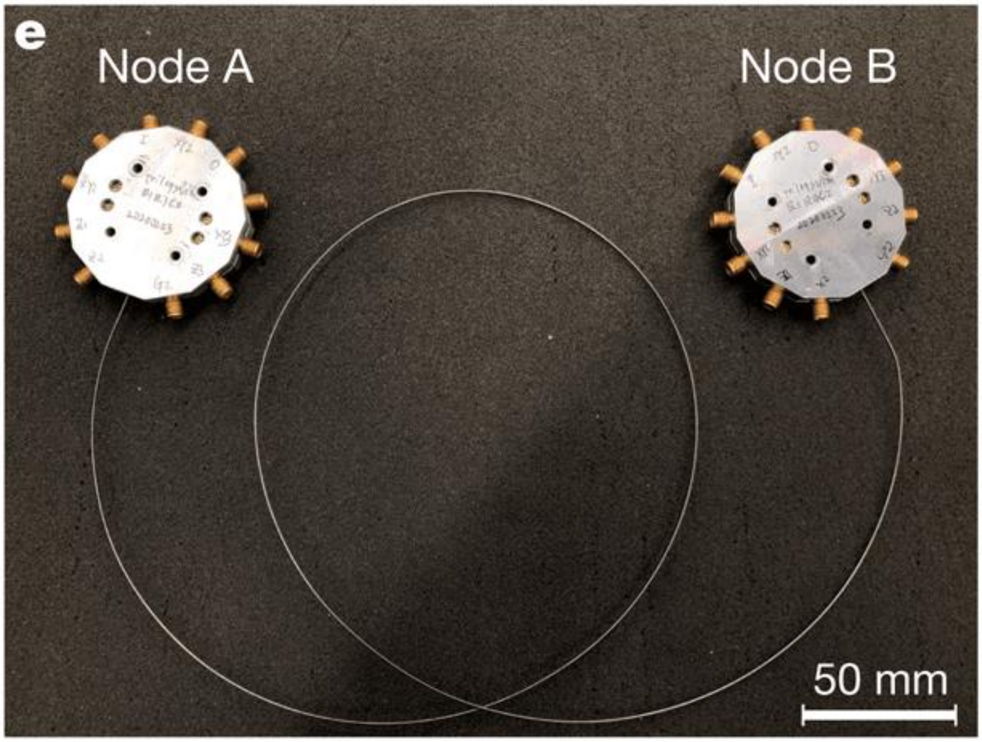
Constant-depth long-range teleportation protocol on a path of seven qubits. (CREDIT: Physical Review Research)© The Brighter Side of News

Beyond security, quantum teleportation could supercharge quantum computing, where information is processed exponentially faster than in classical computing.

A study from the University of Chicago, led by physicist Dr. David Schuster, revealed that teleportation can efficiently link quantum processors across distances. Published in Nature Communications, the research outlines a method for scaling up quantum computers by connecting processors via entangled photons. This overcomes the limitations of physical wiring, enabling more powerful and interconnected systems. “The teleportation of quantum states between processors is a major step toward creating a scalable quantum computer,” said Dr. Schuster. “This technology could revolutionize industries from drug discovery to artificial intelligence.”

Challenges on the Road Ahead

Despite these successes, quantum teleportation faces significant hurdles. One major challenge is decoherence—the loss of quantum information due to environmental factors like temperature fluctuations or electromagnetic interference. This makes maintaining entanglement over long periods a technical feat.



Quantum network comprising two superconducting quantum nodes connected by a one-metre-long superconducting coaxial cable, where each node includes three interconnected qubits. (CREDIT: Nature Communications)© The Brighter Side of News

Additionally, the infrastructure required for large-scale quantum networks remains in its infancy. For instance, transmitting photons over optical fibers leads to signal loss over distances longer than 100 kilometers, which satellites like Micius help mitigate. However, creating a global quantum network will require a hybrid approach, combining satellite links with terrestrial fiber-optic cables.

Cost is another consideration. Building and maintaining quantum infrastructure is expensive, with many projects reliant on government funding. For example, the U.S. National Quantum Initiative, launched in 2018, has allocated over $1 billion to quantum research, including teleportation. Similar investments are being made by the European Union and China.

The Bigger Picture: A Quantum Future

The long-term potential of quantum teleportation extends beyond secure communication and computing. In theoretical physics, teleportation experiments are deepening our understanding of the universe.

Recent research from the California Institute of Technology (Caltech) suggests that teleportation could provide insights into the nature of spacetime and black holes. Dr. John Preskill, a quantum physicist at Caltech, posits that quantum entanglement may hold clues to resolving the "information paradox" in black holes.

“These experiments are not just technological feats,” said Dr. Preskill. “They’re also windows into some of the deepest questions about the universe.”

Moreover, teleportation could eventually influence energy transmission. While the concept of "beaming" energy via quantum methods remains speculative, early studies indicate it may be possible to teleport energy states in specific conditions. This could open doors to energy distribution systems that are far more efficient and less wasteful than current grids.

Transforming the Possible

What does all this mean for you? Quantum teleportation is no longer a futuristic fantasy but a tangible technology that's reshaping how information—and perhaps one day energy—is transmitted. The strides made by scientists like Dr. Pan, Dr. Hanson, and Dr. Schuster are laying the foundation for a future where secure global communication, superpowered computing, and even new forms of energy transmission become the norm.

As the barriers of distance and speed continue to crumble under the weight of these discoveries, the real-world applications of teleportation are beginning to take shape. While many challenges remain, the promise of this technology is immense.

Teleportation may not yet be ready to transport people, but its potential to transform society is every bit as exciting as the science fiction dreams it once inspired.

Scientist says human consciousness comes from another dimension

A baffling new theory to explain human consciousness has suggested it comes from hidden dimensions and is not just brain activity.

A physicist claimed that we plug in to these invisible planes of the universe when making art, practicing science, pondering philosophy or dreaming, and this could explain the phenomenon that has evaded scientific understanding for centuries.

Michael Pravica, a professor of physics at the University of Nevada, Las Vegas, has based the wild idea on hyperdimensionality, the idea that the universe is made up of more dimensions than just the four we perceive: height, length width and time. But his theory is highly controversial, with one scientist saying that the cornerstone of Pravica's theory 'borders on science fiction.'


© Getty Images/Science Photo Libra

Physicist Michael Pravica believes that human consciousness transcend the physical world and move between hidden dimensions

'The sheer fact that we can conceive of higher dimensions than four within our mind, within our mathematics, is a gift... it's something that transcends biology,'

Scientists have been attempting to explain human consciousness and its origins for hundreds of years - and the theories run the gamut.

One leading theory suggests that consciousness is related to how much information is integrated between the different parts of the brain. The more information is connected and integrated, the more conscious a being is thought to be.

Another posits that conscious mental states are driven by top-down signaling in the brain. Top-down signaling refers to the process by which higher-level brain regions send information, expectations or context to lower-level brain regions.

But Pravica's theory ventures outside the realm of neuroscience and into theoretical physics.

He suggested that in moments of heightened awareness, like when we enter a dream state or use our brains for deeply creative or intellectual tasks, our consciousness could transcend our physical dimension and enter a higher plane.

In these moments, our consciousness syncs with hidden dimensions and receives a flood of inspiration, Pravica said.

To better understand the controversial theory, consider the following scenario.

Imagine you're a two-dimensional being living in a two-dimensional world, like a character in a comic book. Now, imagine that a sphere passes through your plane of view.

The sphere would look like a dot that grows into a larger and larger circle as it comes closer, then gradually shrinks until it's out of view. You would have no way of knowing that it's actually a three-dimensional shape.

Pravica sees us as a version of these 2D characters. Although we exist in a four-dimensional world, we can only perceive matter and energy that is of those four dimensions, just like how beings in a 2D world cannot perceive a 3D object.

Thus, the limitations of our world prevent us from detecting higher dimensions that could, in theory, exist all around us.

This is the foundation of hyperdimensionality - the idea that the universe is made up of many dimensions, some of which are hidden because they are beyond the reach of our physical realm.

Hyperdimensionality ties into string theory, which states that reality is made up of infinitely small vibrating strings that are smaller than atoms, electrons or quarks.

As the strings vibrate, twist and fold, they produce effects in multiple unseen dimensions that give rise to all the particles and forces that we can observe, from particle physics to gravity.

'String theory is essentially a theory of hyperdimensionality,' Pravica said. 'It's looking at how the universe is put together on a sub-quantum scale.'

Pravica believes that our brains can tap into higher dimensions when in a dream state or performing deeply creating or intellectual tasks

Although we can observe the effects that these vibrating strings have on the physics of our dimension, we can't observe the hidden dimensions that they're vibrating in.

That is - we can't physically observe them.

But our consciousness may be able to tap into them, Pravica says.

Hyperdimensionality and string theory are widely accepted by physicists, but Pravica's idea of their relationship with consciousness is more controversial - especially because it blurs the lines between science and spirituality.

As an Orthodox Christian with a Ph.D. from Harvard, Pravica has found hyperdimensionality to be a way to bridge his scientific background with his religious beliefs.

For example, he believes Jesus may be a hyperdimensional being.

'According to the Bible, Jesus ascended into heaven 40 days after being on Earth. How do you ascend into heaven if you're a four-dimensional creature?' Pravica asked.

But being hyperdimensional could, theoretically, have allowed Jesus to move between our world and heaven - which may be a world of higher or infinite dimensions, he said.

Pravica's theory is based on a 'God of the gaps' perspective, where gaps in scientific knowledge are explained by divine intervention, said Stephen Holler, associate professor of physics at Fordham University.

He believes that this type of thinking is insufficient, and hampers the scientific inquiry needed to truly understand and explain ineffable phenomena like human consciousness.

'It's a poor explanation mechanism that arguably stifles the inquisitive nature required for good science and teaches that it's not okay to say, 'I don't know,'' Holler told Popular Mechanics.

He points out that our ability to mathematically manipulate higher dimensions is not proof that they actually exist, or that our consciousness can interact with them.

What's more, exploring these higher dimensions is impossible due to the limitations of our current technological capabilities.

Not even the most powerful particle accelerator in the world - the Large Hadron Collider (LHC) at CERN - can provide real proof that these dimensions exist.

The LHC smashes particles together at incredibly high speeds - up to the speed of light.

This allows physicists to study the fundamental building blocks of matter and energy and access infinitesimally small dimensions - even smaller than a single proton.

But even the LHC isn't able to reveal the high-dimensional strings that quantum physics predicts. To get that granular, physicists would need a much more powerful collider.

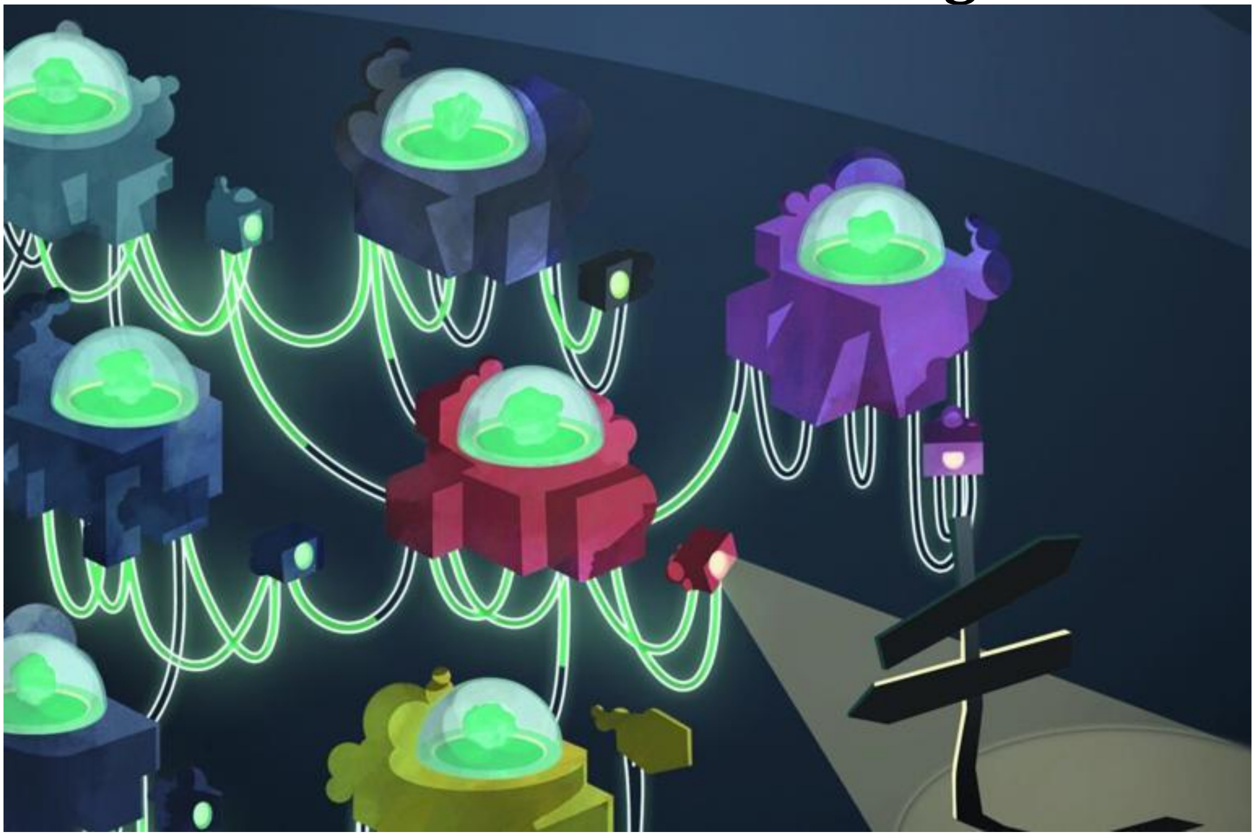
Without that concrete evidence, Holler says that hyperdimensionality 'borders on science fiction.'

But Pravica is optimistic that such technology could exist within his children's lifetime.

Until then, he will continue to support hyperdimensionality and his theory of how it relates to our consciousness.

'I see no point otherwise,' he said. 'Why study? Why live?'

Introducing perceptein, a protein-based artificial neural network in living cells



Here, each neuron is represented as spacecrafts, with their pilots in the cockpits depicted in the shape of protein 3D structures. These spacecrafts collectively process and transmit information to the final red neuron to make decisions on space navigation. The wires that connect the neurons, with the green substance inside, indicate the flow of biological information. Credit: Ehmad Chehre

Westlake University in China and the California Institute of Technology have designed a protein-based system inside living cells that can process multiple signals and make decisions based on them.

The researchers have also introduced a unique term, "perceptein," as a combination of protein and perceptron. Perceptron is a foundational artificial neural network concept, effectively solving binary classification problems by mapping input features to an output decision.

By merging concepts from neural network theory with protein engineering, "perceptein" represents a biological system capable of performing classification computations at the protein level, similar to a basic artificial neural network. This "perceptein" circuit can classify different signals and respond accordingly, such as deciding to stay alive or undergo programmed cell death.

Cells naturally process multiple classification cues, such as stress and developmental signals, to initiate cell functions with distinct outcomes. Immune cells respond to threats based on the signals they detect. The p53 signaling pathway determines whether to repair damage or self-destruct to prevent cancer.

Scientists have struggled to create artificial systems that can replicate this decision-making process inside cells. Most existing attempts rely on DNA or RNA, which can be slow and less direct. Instead of DNA-based systems, the researchers built their decision-making circuit with proteins, de novo protein heterodimers and engineered proteases.

By creating protein pairs that bind together in specific ways, the proteins arrange into the perceptein network, where some proteins activate themselves and inhibit others. This ensures that when multiple signals are present, only the strongest one triggers a reaction, ignoring weaker signals.

In the study, "A synthetic protein-level neural network in mammalian cells," published in *Science*, researchers showed that perceptein circuits could distinguish signal inputs with tunable decision boundaries, offering the possibility of controlling complex cellular responses without transcriptional regulation.

The team assembled six perceptein protein components and two input proteins necessary for a complete two-input, two-output circuit. They selected two well-known proteases, split tobacco etch virus protease and tobacco vein mottling virus protease, and fused them in a way that controls for protease cleavage and degradation.

To test the activation of the perceptein circuit, researchers engineered a stable human embryonic kidney reporter cell line. This cell line contained a construct that simultaneously expressed two fluorescent proteins: Citrine and mCherry.

Each fluorescent protein was tagged with a cleavage-activated N-degron (degradation signal) specific to one of the two input proteases in the perceptein circuit. When a corresponding protease was active, it would cleave the degron, reducing fluorescence. This setup allowed the researchers to visually and quantitatively assess activity based on fluorescence levels. The team confirmed that each protease variant specifically reduced fluorescence only from its target reporter.

Further validation steps demonstrated that input proteins correctly reconstituted their target proteases. By altering perceptein component levels, they could effectively fine-tune the decision outcomes, and performance remained strong even when input timing varied or noise was introduced.

To showcase practical application, the researchers connected the perceptein circuit's output to a caspase-3 apoptosis pathway. This linkage allowed the circuit to trigger cell death based on specific input conditions, transforming fluorescence-based outputs into life-or-death decisions for the cells.

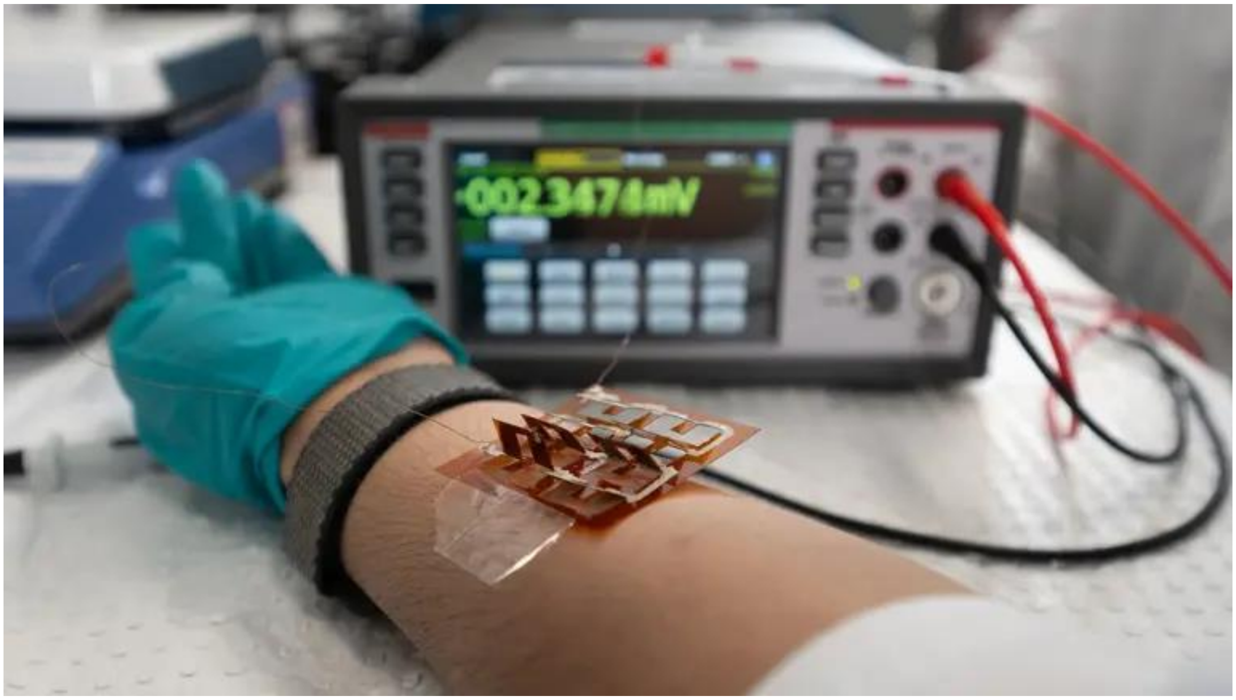
The study demonstrates the feasibility of constructing artificial neural network-inspired circuits in mammalian cells using synthetic proteins to perform complex signal classifications. These circuits have potential applications in programmable therapies, where cells could respond to disease-specific signals with tailored outputs, such as selective apoptosis or other cellular responses.

There are also obvious implications for constructing complex computational systems out of interacting proteins as a form of biology-based artificial intelligence, though such considerations are outside the scope of the current research effort.

More information: Zibo Chen et al, A synthetic protein-level neural network in mammalian cells, *Science* (2024). DOI: 10.1126/science.add8468

Katie Galloway et al, Bringing neural networks to life, *Science* (2024). DOI: 10.1126/science.adu1327

Body Heat Could Power Next Generation of Wearable Devices, Marking New Battery Era



Body Heat Could Power Next Generation of Wearable Devices, Marking New Battery Era

Why it matters: Scientists have developed flexible thermoelectric devices that convert body heat into electricity, potentially eliminating the need for traditional batteries in wearable technology. As reported by PopSci, this breakthrough comes as the global battery industry undergoes massive transformation to meet growing energy storage demands.

The Big Picture: According to The Hustle, researchers at Queensland University of Technology and the University of Washington have created innovative materials that harness body heat:

- Uses nanobinder crystals and bismuth telluride sheets
- Generates enough power to run LED lights
- Enables battery-free medical devices
- Creates self-powered smart clothing

Healthcare Applications: The technology could revolutionize medical devices:

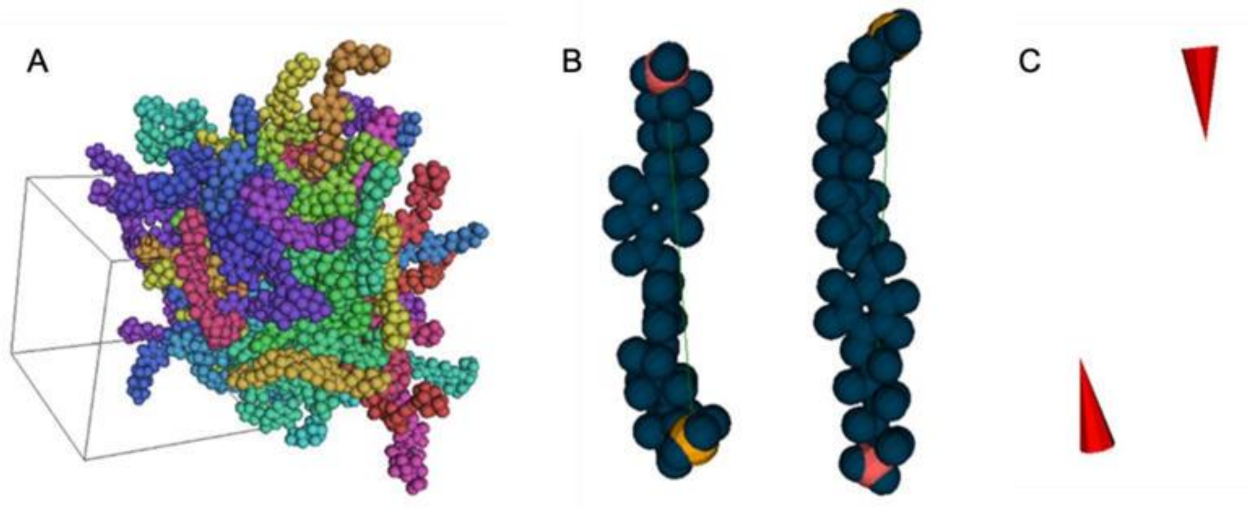
- Continuous glucose monitoring without battery changes
- Self-powered pacemakers
- Uninterrupted health tracking
- Enhanced patient comfort and safety

Broader Energy Transition: This development coincides with massive growth in battery technology:

- Lead-acid battery market projected to reach $59 billion by 2032
- Electric car registrations hit 14 million globally in 2023
- Lithium-ion battery demand growing at 15.5% annually
- Battery costs declining through economies of scale

Looking Forward: The technology could expand beyond wearables to cool data centers and power virtual reality systems, marking a significant step toward sustainable electronics like the best smart watches and reduced environmental impact.

Shape-changing polymer resembles animal movements with temperature shifts



Mesogen representation in MD simulations. (A) An all-atom representation of the initial system with mesogens randomly placed in a simulation box of ~40Å side length. (B) Two isolated LCE end-on mesogens depicted with the yellow carbon atom representing the carbon atom in the CH_2 of the reactive acrylate group, and the peach red carbon atom corresponding to the carbon atom of the terminal CH_3 group of the unreactive alkyl chain. (C) Conic representation of the mesogens shown in (B), where each cone is centered at the carbon atom of the reactive acrylate group [yellow carbon atom in (B)] and directed towards the terminal methyl group [peach red carbon atom in (B)]. This simplified representation facilitates the observation of specific mesogen packing in different phases. Credit: Science (2024). DOI: 10.1126/science.adq6434

A team of scientists has created a new shape-changing polymer that could transform how future soft materials are constructed. Made using a material called a liquid crystalline elastomer (LCE), a soft rubber-like material that can be stimulated by external forces like light or heat, the polymer is so versatile that it can move in several directions.

Its behavior, which resembles the movements of animals in nature, includes being able to twist, tilt left and right, shrink and expand, said Xiaoguang Wang, co-author of the study and an assistant professor in chemical and biomolecular engineering at The Ohio State University.

"Liquid crystals are materials that have very unique characteristics and properties that other materials cannot normally achieve," said Wang. "They're fascinating to work with."

This new polymer's ability to change shapes could make it useful for creating soft robots or artificial muscles, among other high-tech devices in medicine and other fields.

Today, liquid crystals are most often used in TVs and cell phone displays, but these materials often degrade over time. But with the expansion of LEDs, many researchers are focused on developing new applications for liquid crystals.

Unlike conventional materials that can only bend in one direction or require multiple components to create intricate shapes, this team's polymer is a single component that can twist in two directions. This property is tied to how the material is exposed to temperature changes to control the molecular phases of the polymer, said Wang.

"Liquid crystals have orientational order, meaning they can self-align," he said. "When we heat the LCE, they transition into different phases causing a shift in their structure and properties."

This means that molecules, tiny building blocks of matter, that were once fixed in place can be directed to rearrange in ways that allow for greater flexibility. This aspect may also make the material easier to manufacture, said Wang.

The study was recently published in the journal *Science*.

If scaled up, the polymer in this study could potentially advance several scientific fields and technologies, including controlled drug delivery systems, biosensor devices and as an aid in complex locomotion maneuvers for next-generation soft robots.

One of the study's most important findings reveals the three phases that the material goes through as its temperature changes, said Alan Weible, co-author of the study and a graduate fellow in chemical and biomolecular engineering at Ohio State. Throughout these phases, molecules shift and self-assemble into different configurations.

"These phases are one of the key factors we optimized to allow the material ambidirectional shape deformability," he said. In terms of size, the study further suggests that the material can be scaled up or down to adapt to nearly any need.

"Our paper opens a new direction for people to start synthesizing other multiphase materials," said Wang.

Researchers note that with future computational advances, their polymer could eventually be a useful tool for dealing with delicate situations, like those that require the precise design of artificial muscles and joints or upgrading soft nanorobots needed for complex surgeries.

"In the next few years, we plan to develop new applications and hopefully break into the biomedical field," said Weible. "There's a lot more we can explore based on these results."

Other co-authors include Yuxing Yao, Shucong Li, Atalaya Milan Wilborn, Friedrich Stricker, Joanna Aizenberg, Baptiste Lemaire, Robert K. A. Bennett, Tung Chun Cheung and Alison Grinthal from Harvard University; Foteini Trigka and Michael M. Lerch from the University of Groningen; Guillaume Freychet, Mikhail Zhernenkov and Patryk Wasik from Brookhaven National Laboratory; and Boris Kozinsky from Bosch Research.

More information: Yuxing Yao et al, Programming liquid crystal elastomers for multistep ambidirectional deformability, *Science* (2024). DOI: 10.1126/science.adq6434

Provided by The Ohio State University

Astronomers discover what may have existed before the Big Bang

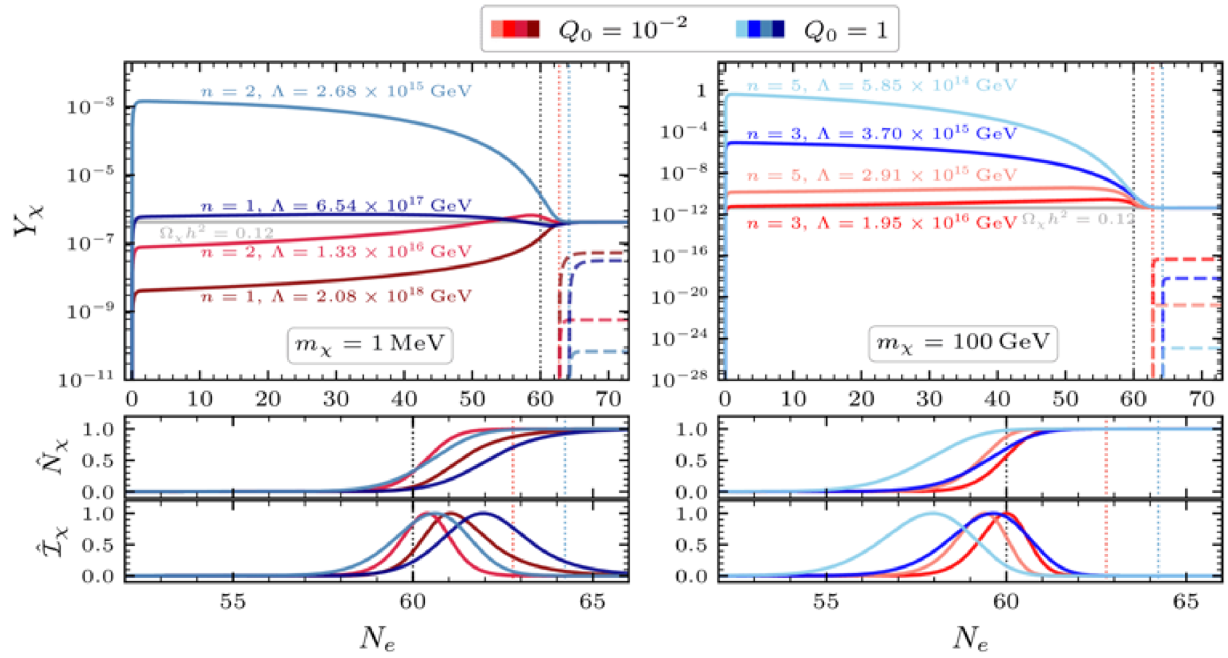
Approximately 85% of the universe's matter is undetectable by even the most advanced scientific tools to date. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

Dark matter has puzzled physicists for nearly a century, remaining one of modern science's greatest mysteries. Although invisible, its gravitational effects are crucial to explaining the structure and dynamics of galaxies.

Approximately 85% of the universe's matter is undetectable by even the most advanced tools. This unseen mass, known as dark matter, may have predated the Big Bang.

Dark matter was first proposed in the 1930s to explain discrepancies between galactic motions and their visible mass. Later, observations of the cosmic microwave background (CMB)—the faint afterglow of the Big Bang—solidified its role in cosmology.

According to the 2018 Planck Collaboration, dark matter accounts for 27% of the universe's total energy, far surpassing the 5% comprised of ordinary matter.



The DM yield Y χ as a function of the number of e-folds (solid lines), assuming vanishing initial DM abundance. (CREDIT: Physical Review Letters)© The Brighter Side of News

Since its discovery, researchers have sought to uncover dark matter's nature. Supersymmetry (SUSY), an extension of the Standard Model of particle physics, offers one of the most promising frameworks by proposing partner particles for every known particle.

Within this framework, weakly interacting massive particles (WIMPs) emerged as prime candidates for dark matter. WIMPs, if they exist, would interact weakly with ordinary matter and could be produced in particle accelerators like the Large Hadron Collider (LHC) or detected directly through underground experiments.

However, the search for WIMPs has so far come up empty. Experiments like DAMA, which reported an annual modulation signal potentially linked to dark matter, remain contentious. Efforts to reproduce such signals through projects like COSINE-100 have yet to yield conclusive results.

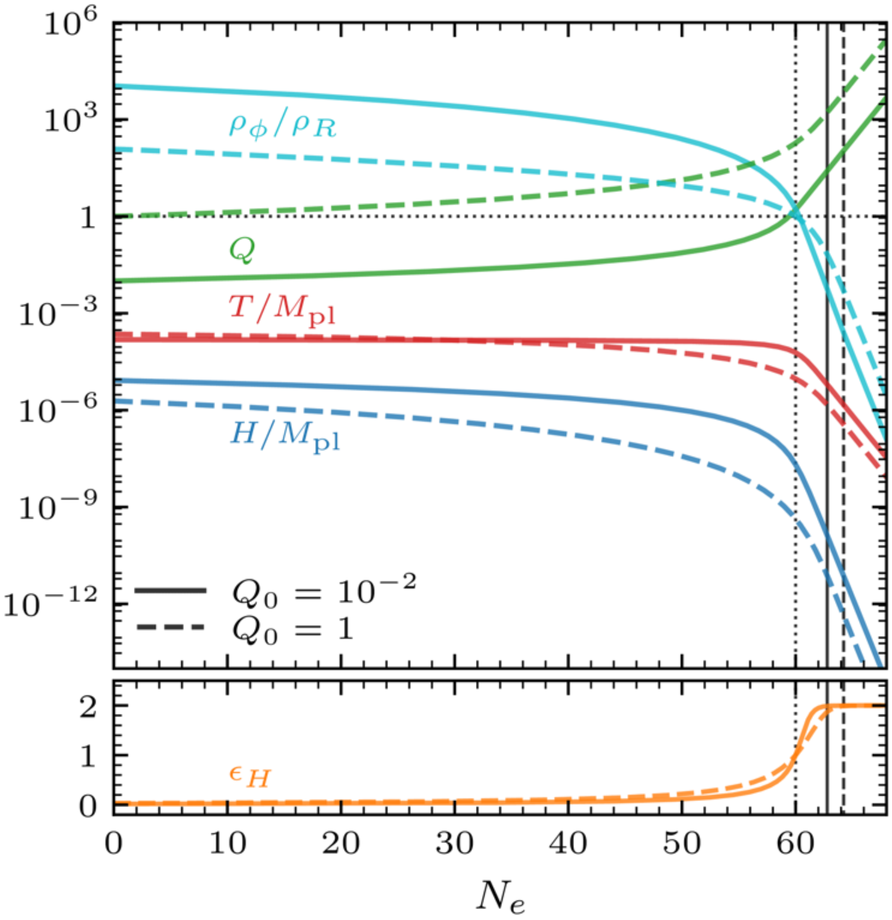
Similarly, the LHC has failed to detect any SUSY particles, casting doubt on the simplest WIMP models. As a result, scientists have begun to explore more exotic possibilities for dark matter's origin and behavior.

One such groundbreaking idea is the "Dark Big Bang" (DBB) theory, proposed in 2023 by Katherine Freese and Martin Winkler from the University of Texas at

Austin. Unlike the conventional Big Bang, which explains the birth of ordinary matter, the DBB suggests that dark matter arose from a separate event.

This second Big Bang, occurring sometime after the first, would have generated dark matter through the decay of a quantum field trapped in a false vacuum state. In this model, the early universe consisted of two sectors: the visible sector, filled with the familiar particles and forces, and a dark sector, which remained cold and decoupled. Eventually, the dark sector underwent its own phase transition, analogous to the visible sector's hot Big Bang.

This transition produced a thermal bath of dark particles, governed by a unique set of physical laws. The DBB model is particularly versatile, as it can accommodate a wide range of dark matter particle masses, from as light as a few keV to as heavy as 101210^{12}1012 GeV.



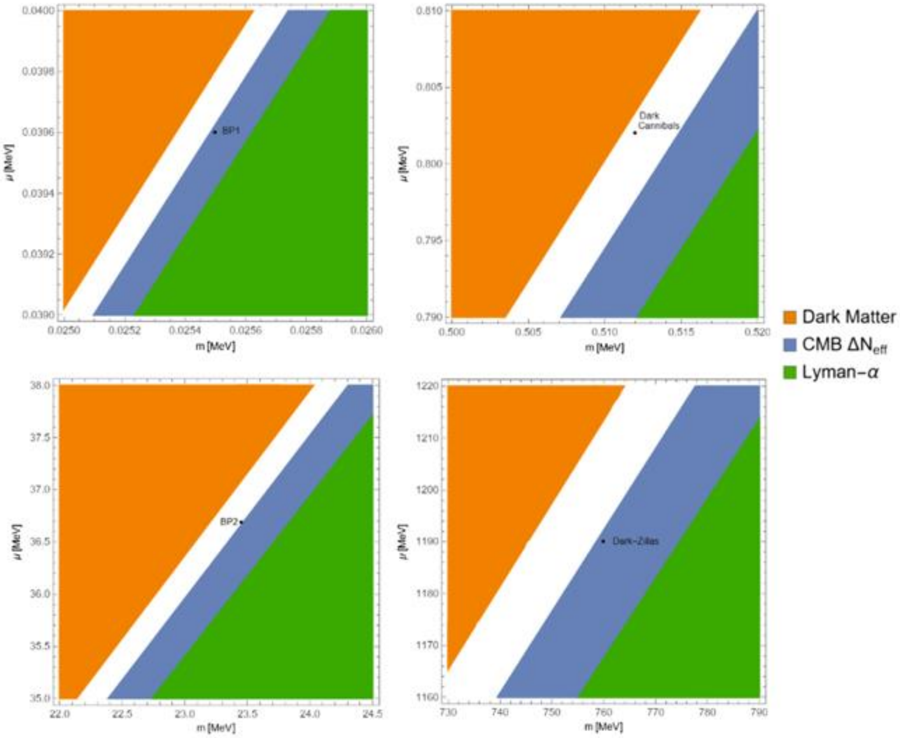
The evolution of various quantities for the case of WI with V (ϕ)=λ ϕ4 as a function of the number of e-folds after the onset of inflation, for two initial values of the dissipation strength Q≡Υ/(3H), namely 10−2 (solid lines) and (dashed lines). (CREDIT: Physical Review Letters)© The Brighter Side of News

What sets the DBB model apart is its potential to leave observable traces. The phase transition in the dark sector could generate gravitational waves (GWs), ripples in the fabric of spacetime. These GWs would be distinct from those produced by black hole mergers or neutron star collisions and could be detected by next-generation observatories.

In particular, low-frequency GWs detectable by pulsar timing arrays (PTAs) such as the International Pulsar Timing Array (IPTA) and the Square Kilometer Array (SKA) could provide crucial evidence for the DBB.

Recent work by Cosmin Ilie, an Assistant Professor of Physics and Astronomy at Colgate University, and Richard Casey, a senior physics student, has further refined the DBB theory. Their study explores new parameter spaces for the dark sector's tunneling field, identifying scenarios that align with existing cosmological observations.

These scenarios predict not only the correct abundance of dark matter but also GW signals that could soon be within reach of PTA experiments.



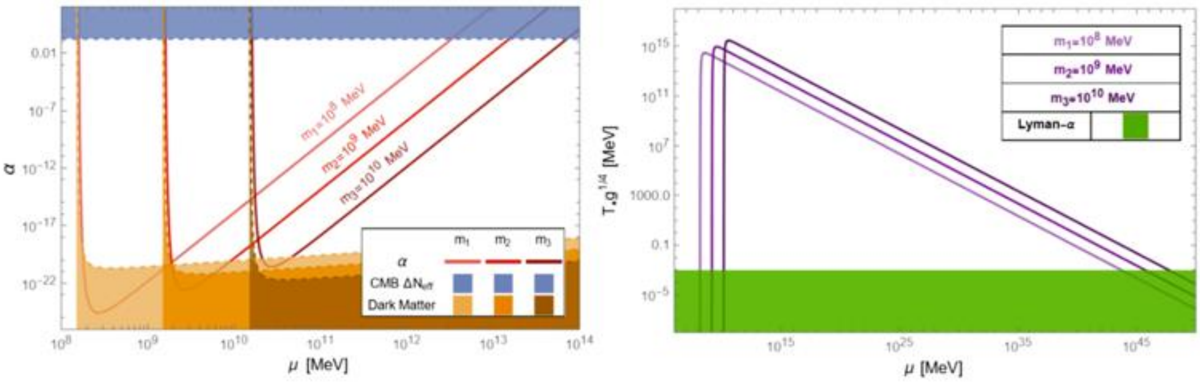
The choices of parameters for BP1 (panel 1) and Dark-Zillas (panel 4) slightly violate the upper bound on α. These discrepancies do not significantly impact the results of [18], as the parameters can be adjusted slightly to produce the same phase transition characteristics used in their analysis. (CREDIT: Phys.Rev.D)© The Brighter Side of News

“Detecting gravitational waves generated by the Dark Big Bang could provide crucial evidence for this new theory of dark matter,” says Ilie. Such detection would be groundbreaking, offering the first direct evidence of dark matter's distinct origin.

The 2023 detection of background GWs by the NANOGrav collaboration, a part of IPTA, adds an intriguing dimension to this research. While the exact source of these waves remains uncertain, they could potentially align with the DBB model’s predictions.

Beyond its implications for dark matter, the DBB theory offers a fresh perspective on the early universe. Traditionally, cosmology has operated under the assumption that all matter, dark or otherwise, emerged from the same event.

The idea of a dual-origin universe challenges this notion, suggesting a more complex interplay of forces and fields in the universe's infancy. If confirmed, the DBB model could reshape our understanding of cosmic evolution, from the formation of the first galaxies to the large-scale structure of the universe.



Left: values of α for fixed m. As before, α is bounded above by the CMB ΔNeff (blue) bound and below by the dark matter (orange) bounds. Right: temperature of the visible sector at the time of the DBB as a function of μ. (CREDIT: Phys.Rev.D)© The Brighter Side of News

The search for dark matter is a central pillar of modern physics, driving advancements in technology and theory. Direct detection experiments, such as those conducted deep underground, continue to push the boundaries of sensitivity, aiming to capture fleeting interactions between dark matter particles and ordinary matter.

Meanwhile, astrophysical observations, from the CMB to galactic rotation curves, provide indirect but compelling evidence for dark matter’s gravitational influence. The DBB model, with its unique predictions and testable consequences, adds a powerful new tool to this arsenal.

As observational capabilities advance, the prospect of detecting GWs from a DBB becomes increasingly plausible. Projects like SKA, expected to come online in the next decade, promise unprecedented sensitivity to low-frequency GWs. These efforts could finally lift the veil on dark matter's mysterious origins, answering questions that have puzzled scientists for generations.

In the broader context, understanding dark matter is not just a scientific pursuit but a quest to comprehend the fundamental nature of the universe. Whether through traditional particle physics or novel cosmological theories like the DBB, each discovery brings us closer to unveiling the full tapestry of existence.

Understanding a mysterious subject: Dark matter

What is dark matter?

What is dark matter? Have you ever heard of it before? Over the years scientists have learned a lot about it but there is still much mystery surrounding dark matter.

Dark matter: the invisible majority

Dark matter is like the hidden scaffolding of the universe, unseen but essential, according to astronomists. In a standard theory, the mass-energy content of the universe is just 5% ordinary matter, 27% dark matter and 68% dark energy, according to NASA.

A centuries-old mystery

The concept of dark matter dates back to the 19th century. Lord Kelvin first suggested that a majority of stars may be "dark bodies." Decades later, Dutch astronomer Jacobus Kapteyn and Swiss astrophysicist Fritz Zwicky proposed the idea when they observed that galaxies didn’t have enough visible mass to account for their gravitational effects.

But understanding this hypothetical form of matter is like piecing together an invisible puzzle. "It's something we know is there," theoretical physicist from Harvard Lisa Randall said on the Lex Fridman podcast. "We deduce the existence of something that we don't directly see."

Gravitational fingerprints

Dark matter's presence is felt through its gravitational pull, which is what clues scientists to its existence. Although gravity is relatively a weak force, since there is so much dark matter in the universe, it combines to do some big things... like driving galaxy formation.

The unseen workers of the universe

Randall compares dark matter to the unseen workers behind a building. "It’s like when we think about a building, we think about the architect, we think about the high level, but we forget about all the workers that did all the grunt work. In fact, dark matter was really important in the formation of our universe, and we forget that sometimes," said Randall.

Energy dominance

Dark matter even theoretically carries more energy than visible matter. "Five times the amount of energy as the matter," says Randall, underscoring its significant role in the universe's energy balance.

It does not interact with light

Unlike ordinary matter, dark matter doesn't interact with light, as far as scientists know. That's why we can't see it. It does not absorb, reflect or emit any light. As Randall put it: "It interacts gravitationally... but it doesn't experience electromagnetism," making it fundamentally different.

Dark halos

Dark matter is thought to form a roughly spherical halo around galaxies. According to the European Organization for Nuclear Research (CERN), this is predicted because galaxies are rotating so quickly that without dark matter, they would have been torn apart long ago. Why? Because the gravity of the "ordinary matter" isn't enough to hold it together. It also explains why galaxies like the Milky Way are shaped like discs.

A vast web-like structure

While we don't know what, scientists have an idea of its structure. "Scientists today think dark matter exists in a vast, web-like structure that winds through the whole universe – a gravitational scaffold that attracts most of the cosmos' normal matter," says NASA.

What is dark matter? The elusive candidates

Weakly Interacting Massive Particles (WIMPs) are a popular dark matter candidate. Despite extensive searches, they remain elusive, but researchers continue to seek these particles. Another particle candidate is the axion.

Primordial black holes?

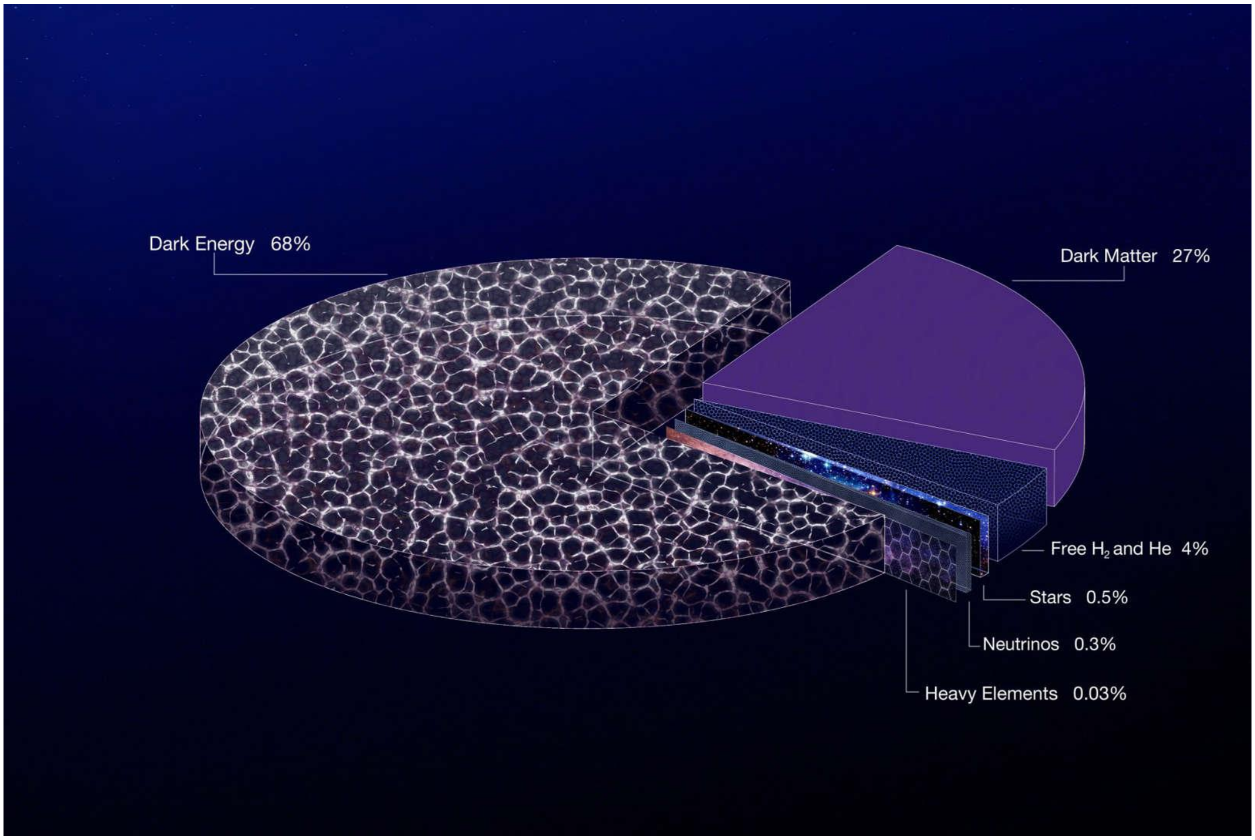
Primordial black holes (PBHs), possibly formed from density fluctuations shortly after the Big Bang, are a compelling candidate for dark matter. They vary significantly in mass and could mimic dark matter by exerting gravitational forces that affect galaxy formation and movement. Don't confuse these with the black holes formed from the collapse of stars!

Hidden valleys

The "hidden valleys" theory visualizes a parallel world made of dark matter that has little in common with the matter we know. These valleys contain unique particles that don't interact with our familiar matter except through gravity. This theory is intriguing because it proposes entirely new kinds of matter and interactions, potentially solving some dark matter mysteries.

The Large Hadron Collider

Psychics and projects like the Large Hadron Collider (LHC) aim to uncover dark matter's secrets. In fact, the search for WIMPs was one of its main goals... which is still elusive. However, Randall said that new underground xenon detectors are a promising new technology.



What about dark energy?

According to the CERN, dark energy, which makes up the majority of the universe, appears to be associated with the vacuum in space. It is distributed evenly through space... and time. Said differently, it is not diluted as the energy expands and does not have local gravity effects. NASA adds that it may be responsible for the expanding universe, pushing it apart instead of pulling it back together.

Why do scientists care?

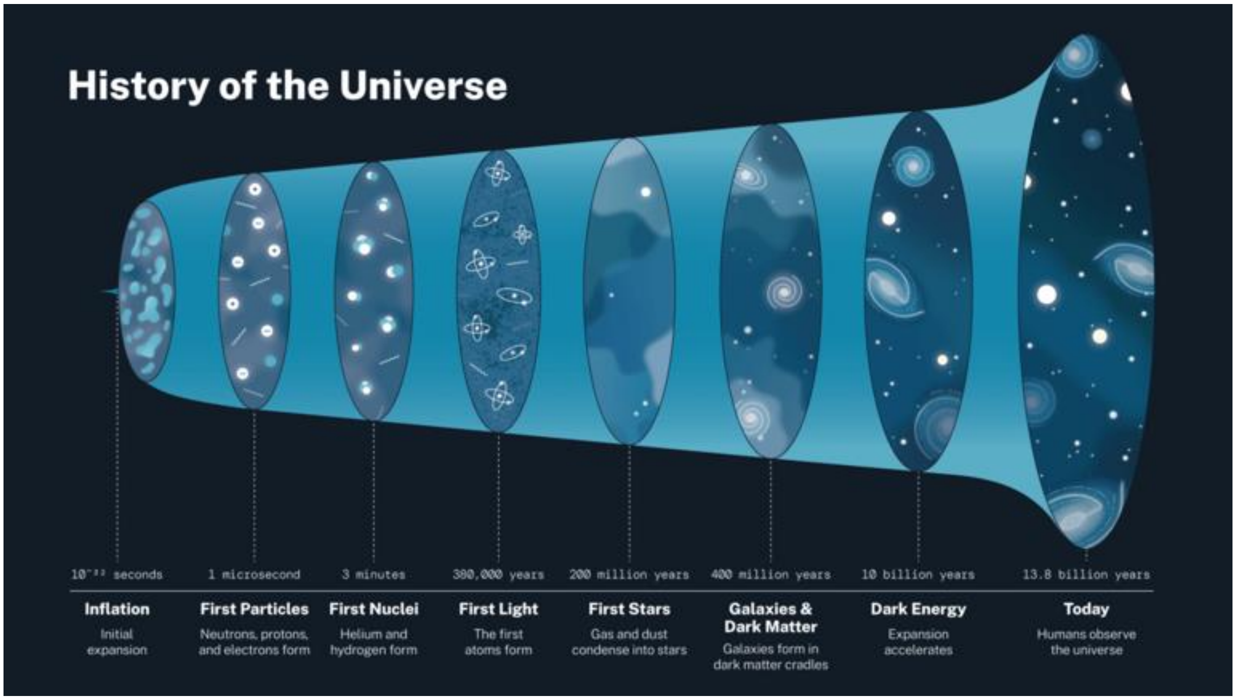
Of course, dark matter sounds cool, but what could cracking its invisible puzzle really solve? According to CERN, "it could help scientists gain a better understanding of the composition of our universe and, in particular, how galaxies hold together."

Dark energy doesn't exist? Scientists propose radical rethink of cosmic expansion

CHRISTCHURCH, New Zealand — Dark energy has been modern physics' most successful placeholder, a theoretical force invented to explain why galaxies seem to be racing away from each other at ever-increasing speeds. Now, after analyzing light from over 1,500 exploding stars, researchers have reached a startling conclusion: this mysterious force might not exist at all. Instead, the answer may lie in how time itself flows differently across the cosmic landscape.

While not definitively disproving the existence of dark energy, the research presents compelling evidence for an alternative explanation that could reshape fundamental cosmology.

The concept of dark energy can be traced all the way back to the early 20th century. In 1917, Albert Einstein added a term called the "cosmological constant" to his equations of general relativity, essentially proposing a force that would prevent the universe from collapsing under its own gravity. When Edwin Hubble discovered in the late 1920s that the universe was actually expanding, Einstein abandoned this idea, which he reportedly later called his “biggest blunder.”



This graphic offers a glimpse of the history of the Universe, as we currently understand it. The cosmos began expanding with the Big Bang but then around 10 billion years later it strangely began to accelerate thanks to a theoretical phenomenon termed dark energy. Click to expand. (Credit: NASA)

But in 1998, two independent teams of astronomers made a shocking discovery while studying distant supernovae. They found that very remote galaxies appeared to be moving away from us faster than predicted by the known laws of physics, suggesting the universe’s expansion was mysteriously accelerating rather than slowing down as expected.

To explain this puzzling observation, physicists revived Einstein’s cosmological constant in a new form — dark energy, a hypothetical force that works against gravity, pushing the cosmos apart. This mysterious energy was calculated to make up roughly 68% of the universe’s total energy content, dwarfing the contributions of normal matter (5%) and dark matter (27%).

The scientists who discovered this apparent acceleration, Saul Perlmutter, Brian Schmidt, and Adam Riess, were awarded the 2011 Nobel Prize in Physics for their work — even though the fundamental nature of dark energy remained, and still remains, unknown. In an ironic turn of scientific history, the cosmological constant that Einstein had rejected became a cornerstone of modern cosmology.

In this latest study, a team of researchers from the University of Canterbury in New Zealand propose an alternative explanation that might eliminate the need for dark energy entirely.

Their theory, known as "timescape cosmology," suggests that what we perceive as cosmic acceleration might actually result from how we measure and interpret cosmic distances. This new perspective takes into account something the standard model largely ignores: the universe isn't smooth like soup, but rather "lumpy," with galaxies clustered together and separated by vast empty voids.

The research, published in *Monthly Notices of the Royal Astronomical Society*, analyzed data from the Pantheon+ catalogue containing 1,690 supernova observations, representing 1,535 unique stellar explosions. These supernovae serve as cosmic "standard candles," allowing astronomers to measure vast distances across space. The team developed new statistical methods specifically designed to avoid assumptions tied to traditional cosmological models.

Modern cosmology rests heavily on Einstein's theory of general relativity and assumes that space is uniformly distributed on large scales. However, anyone who has looked at pictures from powerful telescopes knows that matter in our universe is actually clumped together in a cosmic web of galaxies and voids. The timescape theory takes this inherent lumpiness into account, proposing that these structural variations affect how we perceive cosmic distances and time itself.

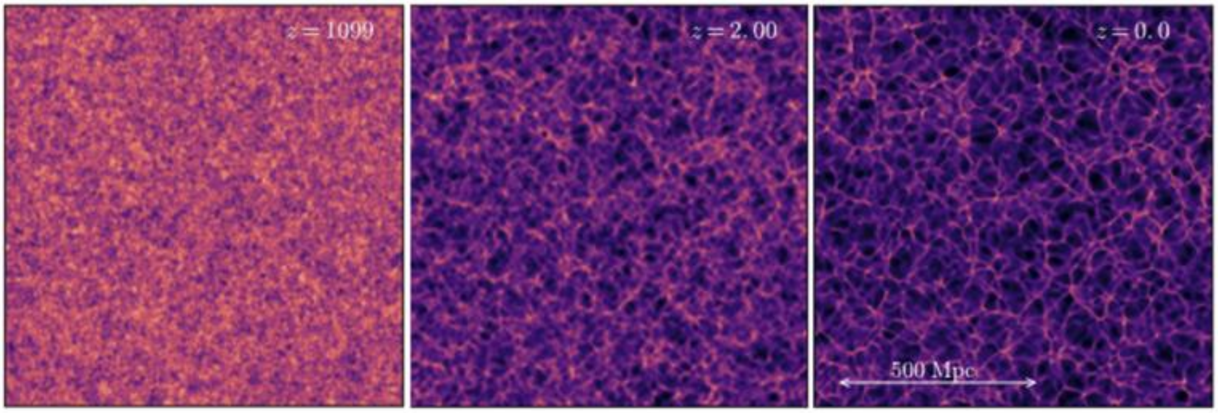
Instead of assuming uniform expansion throughout space, timescape cosmology suggests that different regions of the universe expand at different rates. Imagine a cosmic landscape where galaxy-rich regions experience time and space differently than the vast empty voids between them. This varying expansion rate could create an illusion of acceleration when viewed from our particular vantage point in the cosmos.

By analyzing the light from distant supernovae using a sophisticated statistical approach, the researchers found evidence supporting this alternative view. Their analysis revealed patterns in the data that align better with timescape predictions than with the standard model, particularly at certain cosmic distances.

Most intriguingly, the study identified a specific scale — roughly equivalent to 75% of the way to cosmic structures like the "Great Attractor" — where the universe begins to show signs of statistical homogeneity. This scale, larger than previously thought, might represent a fundamental transition point in how cosmic structure influences our measurements.

What makes this research particularly timely is its potential to resolve the "Hubble tension" – a significant discrepancy between different methods of measuring the universe's expansion rate. Recent observations from the Dark Energy Spectroscopic Instrument (DESI) have revealed that the standard cosmological model doesn't fit observations as well as previously thought, particularly when considering how dark energy might evolve over time.

The implications of timescape cosmology are profound. According to the research team, a clock placed in our Milky Way would tick approximately 35% slower than an identical clock positioned in the vast cosmic voids between galaxies. Over billions of years, this time difference would allow for greater expansion of space in void regions, creating what appears to us as accelerating expansion when these enormous empty regions come to dominate the universe's volume.



This graphic shows the emergence of a cosmic web in a cosmological simulation using general relativity. From left, 300,000 years after the Big Bang to right, a Universe similar to ours today. The dark regions are void of matter, where an ideal clock would run faster and allow more time for the expansion of space. The lighter purple regions are denser so clocks would run slower, meaning under the "timescape" model of cosmology that acceleration of the Universe's expansion is not uniform. (Credit: Hayley Macpherson, Daniel Price, Paul Lasky / Physical Review D 99 (2019) 063522)

"Our findings show that we do not need dark energy to explain why the universe appears to expand at an accelerating rate. Dark energy is a misidentification of variations in the kinetic energy of expansion, which is not uniform in a universe as lumpy as the one we actually live in," explains Professor David Wiltshire, who led the study, in a statement.

"The research provides compelling evidence that may resolve some of the key questions around the quirks of our expanding cosmos," continues Wiltshire. "With new data, the universe's biggest mystery could be settled by the end of the decade."

Looking ahead, several major astronomical projects, including the Euclid space telescope and the Vera C. Rubin Observatory, will provide unprecedented amounts of data to further test these ideas. These observations could definitively determine whether timescape cosmology truly offers a better description of our universe than the standard model.

The European Space Agency's Euclid satellite, launched in July 2023, and the upcoming Nancy Grace Roman Space Telescope will be crucial in gathering new data. According to Professor Wiltshire, "With new data, the Universe's biggest mystery could be settled by the end of the decade." However, testing these competing theories will require at least 1,000 high-quality supernova observations.

While this research doesn't definitively resolve all questions about cosmic expansion, it offers a compelling alternative to dark energy that aligns with both Einstein's general relativity and our observations of the universe's structure. As more data becomes available from new telescopes and surveys, we may find that the greatest mystery in modern cosmology isn't why the universe's expansion is accelerating, but rather how our perception of time and space across cosmic scales affects our measurements of that expansion.

Paper Summary

Methodology

The research team analyzed the Pantheon+ catalogue, which contains 1,690 supernova observations representing 1,535 unique supernovae. They developed a new statistical framework that specifically avoided assumptions tied to the standard Lambda Cold Dark Matter (ΛCDM) model. A key innovation was their treatment of the data covariance matrix – they reconstructed it to be as independent as possible from cosmological model assumptions, particularly those related to peculiar velocities. This allowed for a fairer comparison between timescape cosmology and the standard model. The team also introduced new statistical methods to refine Type Ia supernova light-curve analysis, focusing particularly on parameters that influence brightness measurements.

Key Results

The analysis revealed several key findings. The team identified a “scale of statistical homogeneity” at a redshift of 0.075, significantly larger than previous estimates. In analyzing the Bayesian evidence, they found that timescape cosmology provided a better overall fit to the data than ΛCDM for certain subsamples of the data. Importantly, when examining data beyond this homogeneity scale, the results showed consistent patterns that aligned with timescape predictions. The study found varying levels of statistical support for timescape depending on which subset of the data was analyzed, with some subsets showing strong evidence in favor of timescape while others showed more modest support.

Study Limitations

First, the analysis couldn’t include certain bias corrections typically used in supernova studies, as these corrections assume a standard ΛCDM framework. The team also had to exclude 15 supernovae from their analysis due to statistical constraints. Additionally, the study noted that their findings with the full sample showed different results from smaller subsamples, suggesting possible selection effects that need further investigation. The research also acknowledges that while their results challenge the need for dark energy, they don’t definitively rule it out.

Discussion & Takeaways

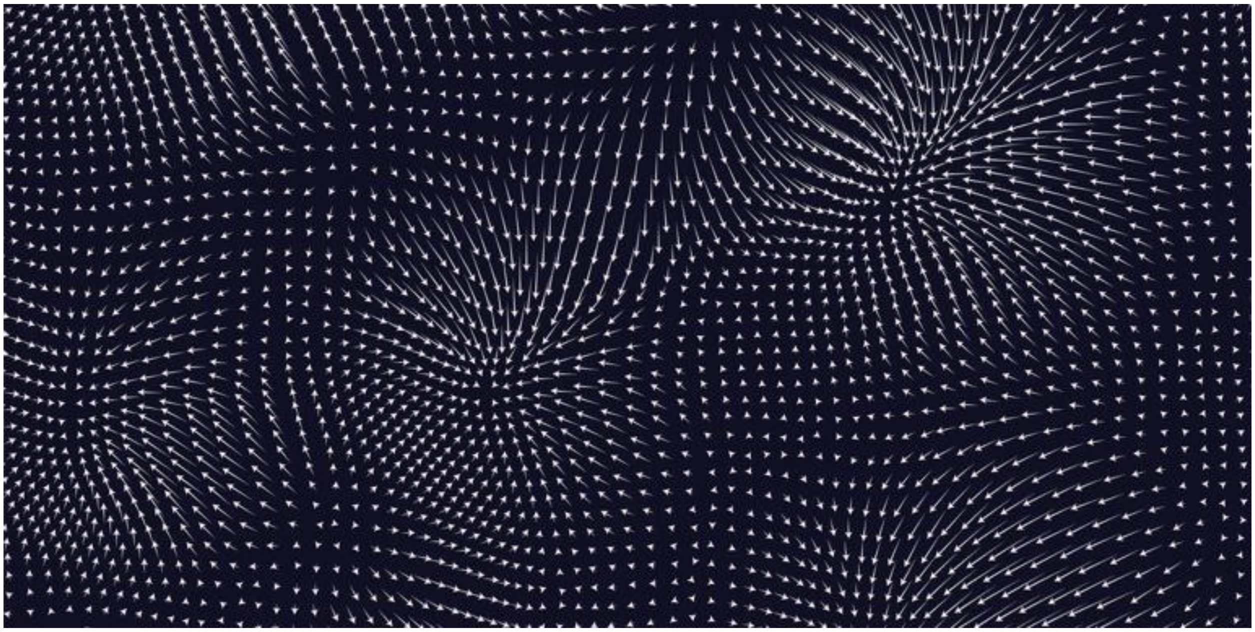
The study suggests a potential paradigm shift in how we understand cosmic expansion. Rather than requiring mysterious dark energy, observed acceleration might result from how we measure cosmic distances and time across vastly different regions of space. The research provides a possible resolution to the

Hubble tension and other cosmological puzzles. However, the team emphasizes that definitive confirmation will require additional data from upcoming surveys. Their work also highlights the importance of examining fundamental assumptions in cosmological models, particularly regarding how we average over cosmic structures.

Funding & Disclosures

The research was supported by the Marsden Fund administered by the Royal Society of New Zealand, Te Aparangi, under grants M1271 and M1255. Additional support came from the Rutherford Foundation Postdoctoral Fellowship and the German Academic Exchange Service. The researchers declared no competing interests. The study benefited from collaboration with the Pantheon+ team, who provided essential data and feedback on implementation details.

A Sixth Sense For Magnetic Fields May Be Surprisingly Common In Animals



The model organism Drosophila has the capacity to detect magnetic fields, and the way their cells can do this indicates it could be common across animals. - Image Credit: GarryKillian/Shutterstock.com© IFL Science

Many migratory species use the Earth's magnetic field to keep their journeys on track. Now a study of a very non-migratory animal, the *Drosophila* fruit fly, shows the same capacity exists in some unexpected places. Perhaps humans are the rare ones because we don't have this capability; if so, why?

In the quest for survival, access to information about the world, particularly information your rivals lack, is exceptionally valuable. So it is not surprising animals have developed an astonishing array of ways to observe the world around them. Magnetic fields are one of these, but before humanity's invention of powerful electromagnets these were generally very weak. The effort required to detect them was much greater than for light or sound.

Consequently, biologists thought that only those animals that really needed to know their place on Earth – migratory pigeons or turtles for example – had exploited magnetoreception. However, a paper in Nature calls this into question.

The possibility that *Drosophila* are capable of magnetoreception was raised in 2015 with the identification of a MagR protein produced by the flies that orientates itself to align with magnetic fields.

A recently published paper goes past this, revealing two methods by which the flies' cells appear able to detect fields. The previous work identified photoreceptor proteins known as cryptochromes as being the sensors used by *Drosophila* to detect fields, with the capacity apparently failing in flies engineered not to produce cryptochromes leaving them magnetically blind.

The authors of the paper point to work showing cryptochromes do this by harnessing the powers of quantum super-positioning. However, the team also question the need for cryptochromes, showing their role may be substituted by a molecule that occurs in all living cells, humans included.

Dr Alex Jones (no, not that one) of the National Physics Laboratory said in a statement, "The absorption of light by the cryptochrome results in movement of an electron within the protein which, due to quantum physics, can generate an active form of cryptochrome that occupies one of two states. The presence of a magnetic field impacts the relative populations of the two states, which in turn influences the 'active-lifetime' of this protein."

The authors showed the molecule flavin adenine dinucleotide (FAD) binds to the cryptochromes to create their sensitivity to magnetism. However, they also found the cryptochromes may be an amplifier of FAD’s capacity, not essential to it.

Even without cryptochromes, fly cells engineered to express extra FAD were able to respond to the presence of magnetic fields, as well as being highly sensitive to blue light in the presence of these fields. The magnetoreception required nothing more complex than an electron transfer to a side chain. The authors think cryptochromes may have evolved to take advantage of this.

"This study may ultimately allow us to better appreciate the effects that magnetic field exposure might potentially have on humans,” said co-lead author Professor Ezio Rosato of the University of Leicester.

Migratory animals not only detect fields, but can feel their direction, using the fact fields point at different angles depending on location. Whether the flies still get a benefit, or if this is a trait left over from some migratory ancestor, is not known.

The paper is published open access in Nature.

Scientists develop game-changing method to grow crops using 'built-in' fertilizer: 'We're learning what genes ... are needed'

Reducing pollution from fertilizer further benefits human health.

In a win for crucial cereal crops, researchers have developed a way to allow the plants to convert nitrogen gas from the air to fertilizer to help them grow, as reported by Interesting Engineering.

The method, which aims to place a series of a minimum of seven genes into the crops' mitochondria and chloroplasts, allows cereal crops, such as corn and rice, to achieve nitrogen fixation through sunlight without applying fertilizer.

Nearly 100 years ago, the Haber-Bosch process led to an enormous increase in global food production by revolutionizing the conversion of nitrogen in the atmosphere to a form that allowed for the production of fertilizer on an industrial scale.

However, despite the mass production of the product, IE explained that many areas, like sub-Saharan Africa, are still unable to get it due to a lack of infrastructure. This area, and others like it, have high food scarcity, an issue that is growing as extreme weather further threatens the crops they can grow.

Ironically, while the Haber-Bosch process has prevented mass starvation, it also has a large carbon footprint. While it allows crops to be mass produced, it also contributes to Earth's overheating, the effects of which are threatening staple products.

Utah State University biochemist Lance Seefeldt told the publication that almost 2% of the world's well of dirty energy is used to produce fertilizer. Not only does this harm the environment, but the fertilizer itself is also damaging, with toxic runoff wreaking havoc on water ecosystems.

To help highly struggling areas and the overall global food supply, which is at risk due to the effects of rising global temperatures, Seefeldt and USU Senior Scientist Zhi-Yong Yang have collaborated on a project with colleagues in Spain and the United States for the past five years to reengineer the biology of cereal crops.

At first, they narrowed the number of genes needed for nitrogen fixation to nine but were later surprised to find they could eliminate some they initially considered critical.

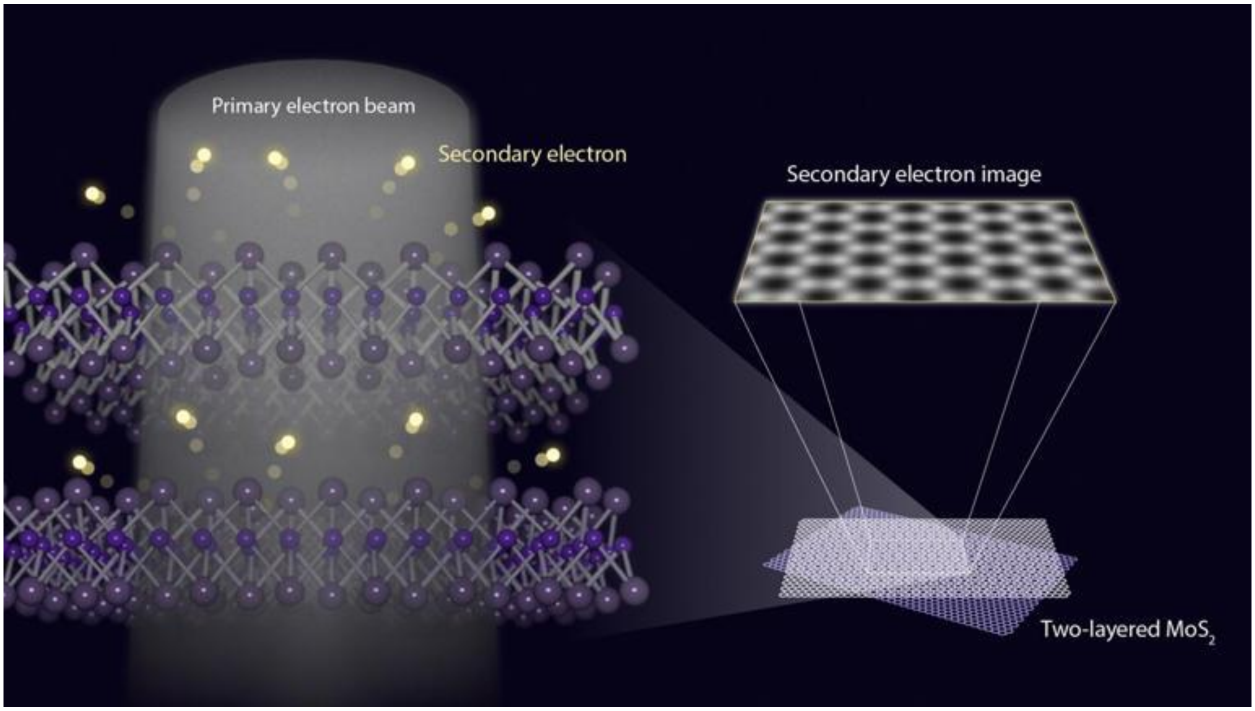
"The goal is to place genes into the crops' mitochondria and chloroplasts, enabling them to generate sufficient energy to drive nitrogen fixation," Yang told IE. "This is a pretty cool piece of evidence. Essentially, these staple caloric crops — rice, corn, and potatoes — could have built-in fertilizer."

"Piece by piece, we're learning what genes and what combination of genes are needed to achieve nitrogen fixation in different cells," Seefeldt said. "Instead of just one horn playing, we're trying to get the whole orchestra to play together."

Aside from providing a solution to end food scarcity in less-developed and less-accessible areas, by eliminating the need for toxic fertilizer for a large subset of crops, the process plays a major role in helping to clean up the food and agriculture industries. Reducing pollution from fertilizer further benefits human health.

The process brings out-of-this-world benefits, too. IE reported that Seefeldt and USU colleague Bruce Bugbee have collaborated on NASA-funded efforts to investigate how to sustain human life on long-duration space missions, including trips to Mars.

Electron imaging reveals the vibrant colors of the outermost electron layer



Secondary electrons (SEs) emitted from the surface layer are detected by the SE microscopy whereas the SEs from the bottom layer are absorbed or scattered by the surface layer. Credit: Reiko Matsushita

Surfaces play a key role in numerous chemical reactions, including catalysis and corrosion. Understanding the atomic structure of the surface of a functional material is essential for both engineers and chemists. Researchers at Nagoya University in Japan used atomic-resolution secondary electron (SE) imaging to capture the atomic structure of the very top layer of materials to better understand the differences from its lower layers. The researchers published their findings in the journal *Microscopy*.

Some materials exhibit "surface reconstruction," where the surface atoms are organized differently from the interior atoms. To observe this, especially at the atomic level, surface-sensitive techniques are needed.

Traditionally, scanning electron microscopy (SEM) has been an effective tool to examine nanoscale structures. SEM works by scanning a sample with a focused electron beam and capturing the SEs emitted from the surface. SEs are typically emitted from a shallow depth below the surface, making it difficult to observe phenomena like surface reconstruction, especially if only a single atomic layer is involved.

The Nagoya University research team tackled this issue using the simplest workable system, a two-layered molybdenum disulfide (MoS_2) sample, to measure how much information SE imaging can extract from the surface and subsurface layers. By stacking two layers of MoS_2, they distinguished the surface layer from the second layer using the technique.

The researchers found that atomic resolution SE imaging is effective in identifying surface atomic arrangements with extremely high surface sensitivity. Their findings revealed that the intensity of SE images from the surface layer was about three times higher than from the second layer, providing strong evidence of the method's sensitivity.

Atomic-resolution SE images of a single-layer MoS_2 sample revealed stunning honeycomb-like structures composed of molybdenum and sulfur atoms. Beyond its visual appeal, SE imaging revealed overlapping patterns, indicating distinct atomic arrangements in the surface and second layers.

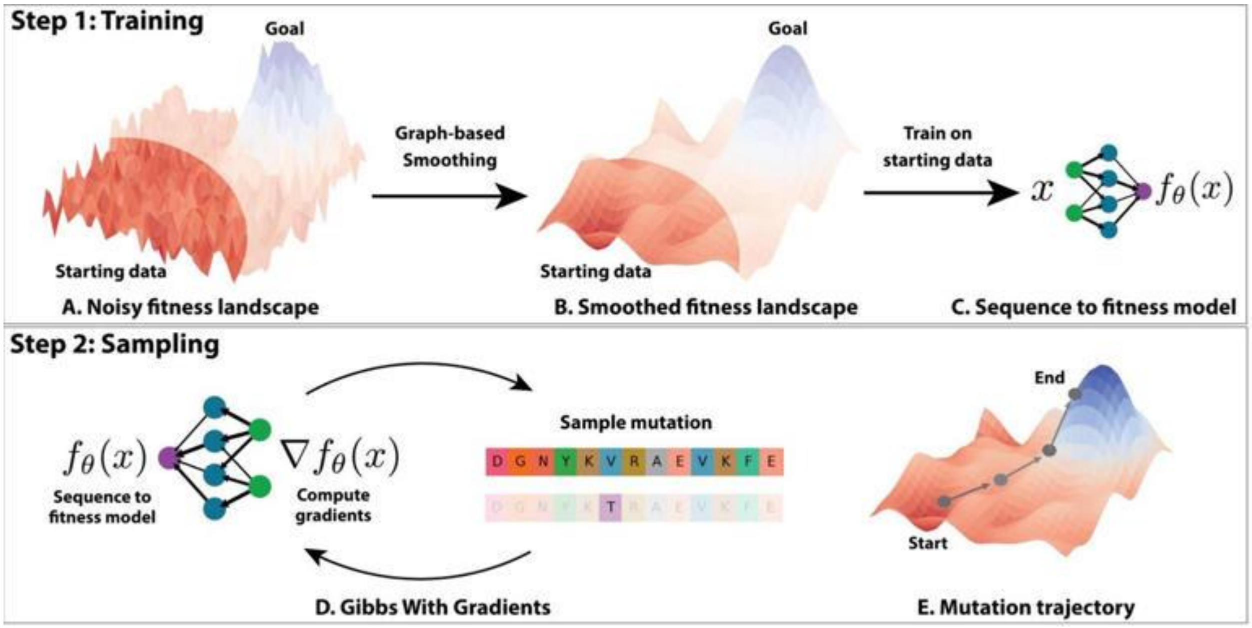
"Most notably, the SE yield from the surface layer was about three times greater than from the second layer," Koh Saitoh, lead author and researcher at Nagoya University's Institute of Materials and Systems Sustainability (IMASS), explained. "This result suggests that the surface layer absorbs or scatters SEs from the second layer. This absorption contributes to the method's depth sensitivity."

The aim of the group is to use atomic resolution SE imaging to reveal the surface structure at the atomic level, including surface reconstruction and other unique structures formed on surfaces. To control the growth, fabrication, and electronic and mechanical properties of nanomaterials, understanding these processes is essential.

More information: Koh Saitoh et al, Surface sensitivity of atomic-resolution secondary electron imaging, *Microscopy* (2024). DOI: 10.1093/jmicro/dfae041

Provided by Nagoya University

A new computational technique could make it easier to engineer useful proteins



Overview. (A) Protein optimization is challenging due to a noisy fitness landscape where the starting dataset (unblurred) is a fraction of the landscape with the highest fitness sequences hidden (blurred). (B) We develop Graph-based Smoothing (GS) to estimate a smoothed fitness landscape from the starting data. (C) A model is trained on the smoothed fitness landscape to infer the rest of the landscape. (D) Gradients from the model are used in Gibbs With Gradients (GWG) where on each step a new mutation is proposed. (E) The goal of sampling is for each trajectory to gradually head towards higher fitness. Credit: arXiv (2023). DOI: 10.48550/arxiv.2307.00494© Provided by Phys.org

To engineer proteins with useful functions, researchers usually begin with a natural protein that has a desirable function, such as emitting fluorescent light, and put it through many rounds of random mutation that eventually generate an optimized version of the protein.

This process has yielded optimized versions of many important proteins, including green fluorescent protein (GFP). However, for other proteins, it has proven difficult to generate an optimized version. MIT researchers have now developed a computational approach that makes it easier to predict mutations that will lead to better proteins, based on a relatively small amount of data.

Using this model, the researchers generated proteins with mutations that were predicted to lead to improved versions of GFP and a protein from adeno-associated virus (AAV), which is used to deliver DNA for gene therapy. They hope it could also be used to develop additional tools for neuroscience research and medical applications.

"Protein design is a hard problem because the mapping from DNA sequence to protein structure and function is really complex. There might be a great protein 10 changes away in the sequence, but each intermediate change might correspond to a totally nonfunctional protein.

"It's like trying to find your way to the river basin in a mountain range, when there are craggy peaks along the way that block your view. The current work tries to make the riverbed easier to find," says Ila Fiete, a professor of brain and cognitive sciences at MIT, a member of MIT's McGovern Institute for Brain Research, director of the K. Lisa Yang Integrative Computational Neuroscience Center, and one of the senior authors of the study.

Regina Barzilay, the School of Engineering Distinguished Professor for AI and Health at MIT, and Tommi Jaakkola, the Thomas Siebel Professor of Electrical Engineering and Computer Science at MIT, are also senior authors of an open-access paper on the work, which will be presented at the International Conference on Learning Representations (ICLR 2024) in May. It is available on the *arXiv* preprint server.

MIT graduate students Andrew Kirjner and Jason Yim are the lead authors of the study. Other authors include Shahar Bracha, an MIT postdoc, and Raman Samusevich, a graduate student at Czech Technical University.

Optimizing proteins

Many naturally occurring proteins have functions that could make them useful for research or medical applications, but they need a little extra engineering to optimize them. In this study, the researchers were originally interested in developing proteins that could be used in living cells as voltage indicators.

These proteins, produced by some bacteria and algae, emit fluorescent light when an electric potential is detected. If engineered for use in mammalian cells, such proteins could allow researchers to measure neuron activity without using electrodes.

While decades of research have gone into engineering these proteins to produce a stronger fluorescent signal, on a faster timescale, they haven't become effective enough for widespread use. Bracha, who works in Edward Boyden's lab at the McGovern Institute, reached out to Fiete's lab to see if they could work together on a computational approach that might help speed up the process of optimizing the proteins.

"This work exemplifies the human serendipity that characterizes so much science discovery," Fiete says. "It grew out of the Yang Tan Collective retreat, a scientific meeting of researchers from multiple centers at MIT with distinct missions unified by the shared support of K. Lisa Yang. We learned that some of our interests and tools in modeling how brains learn and optimize could be applied in the totally different domain of protein design, as being practiced in the Boyden lab."

For any given protein that researchers might want to optimize, there is a nearly infinite number of possible sequences that could generated by swapping in different amino acids at each point within the sequence. With so many possible variants, it is impossible to test all of them experimentally, so researchers have turned to computational modeling to try to predict which ones will work best.

In this study, the researchers set out to overcome those challenges, using data from GFP to develop and test a computational model that could predict better versions of the protein.

They began by training a type of model known as a convolutional neural network (CNN) on experimental data consisting of GFP sequences and their brightness—the feature that they wanted to optimize.

The model was able to create a "fitness landscape"—a three-dimensional map that depicts the fitness of a given protein and how much it differs from the original sequence—based on a relatively small amount of experimental data (from about 1,000 variants of GFP).

These landscapes contain peaks that represent fitter proteins and valleys that represent less fit proteins. Predicting the path that a protein needs to follow to reach the peaks of fitness can be difficult, because often a protein will need to undergo a mutation that makes it less fit before it reaches a nearby peak of higher fitness. To overcome this problem, the researchers used an existing computational technique to "smooth" the fitness landscape.

Once these small bumps in the landscape were smoothed, the researchers retrained the CNN model and found that it was able to reach greater fitness peaks more easily. The model was able to predict optimized GFP sequences that had as many as seven different amino acids from the protein sequence they started with, and the best of these proteins were estimated to be about 2.5 times fitter than the original.

"Once we have this landscape that represents what the model thinks is nearby, we smooth it out and then we retrain the model on the smoother version of the landscape," Kirjner says. "Now there is a smooth path from your starting point to the top, which the model is now able to reach by iteratively making small improvements. The same is often impossible for unsmoothed landscapes."

Proof of concept

The researchers also showed that this approach worked well in identifying new sequences for the viral capsid of adeno-associated virus (AAV), a viral vector that is commonly used to deliver DNA. In that case, they optimized the capsid for its ability to package a DNA payload.

"We used GFP and AAV as a proof of concept to show that this is a method that works on data sets that are very well-characterized, and because of that, it should be applicable to other protein engineering problems," Bracha says.

The researchers now plan to use this computational technique on data that Bracha has been generating on voltage indicator proteins.

"Dozens of labs having been working on that for two decades, and still there isn't anything better," she says. "The hope is that now with generation of a smaller data set, we could train a model in silico and make predictions that could be better than the past two decades of manual testing."

More information: Andrew Kirjner et al, Improving Protein Optimization with Smoothed Fitness Landscapes, *arXiv* (2023). DOI: 10.48550/arxiv.2307.00494

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Provided by Massachusetts Institute of Technology

New Form Of Oxygen Observed For The First Time

Scientists have observed a never-before-seen form of oxygen, and its behavior could call into question what nuclear physics says about “magic numbers”.

Imagine, if you will, that you could see within an atom; at its core is the nucleus, containing subatomic particles called protons and neutrons. The number of protons is what defines the element. Oxygen, for example, has eight protons. However, the number of neutrons in an atom can vary, leading to different forms of elements, called isotopes.

The recently observed type of oxygen is one such isotope – oxygen-28, which has 20 neutrons. Working at the Radioactive Isotope Beam Factory (note: they do not mass produce little beams and package them up), a team of scientists successfully produced oxygen-27 and oxygen-28 for the first time.

They did this by first firing another isotopic element, calcium-48, at a ball of beryllium. This produced lighter atoms, those with fewer protons and neutrons than the original element. The scientists then isolated fluorine-29 from the lighter atoms and collided it with liquid hydrogen, which knocked off the proton necessary to make oxygen-28.

However, the scientists were taken by surprise when oxygen-28 quickly decayed into another isotope, contradicting one of nuclear physics’ assumptions about the stability of atoms.

Elements and their isotopes have “magic numbers”. This is when the number of protons or neutrons in an atom fills a quota called the nuclear shell, conferring stability to the atom. If an atom has both a magic number of protons and a magic number of neutrons, it’s considered to be “doubly magic”. A well-established example of this is oxygen-16, the most abundant type of oxygen on Earth.

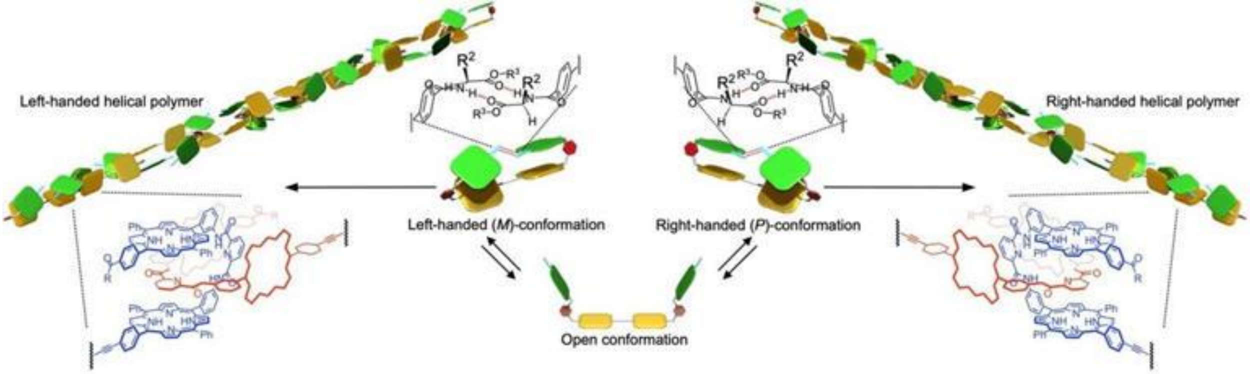
Eight is a magic number for protons and 20 for neutrons, so oxygen-28 was expected to be one of these doubly magic isotopes. Instead, its instability led scientists to conclude that the nuclear shell was not filled and therefore cast doubt on whether 20 is in fact a magic number. It could also explain why oxygen-28 has taken a long time to be successfully observed.

Oxygen-28 is not the only isotope where 20 neutrons no longer seem to be magic. In a phenomenon known as the island of inversion, isotopes of neon, sodium, and magnesium with 20 neutrons also show a lack of nuclear shell closure.

In the case of oxygen-28, the scientists involved in the study proposed that further research would require observing the atom’s nucleus in a higher-energy state. This might help to better understand why 20 might not be a magic number after all.

The study is published in Nature.

Nature inspires self-assembling helical polymer



Scientists at Hiroshima University developed brand-new helical supramolecular polymer chains from chirally twisted macrocyclic monomers. Credit: Takeharu Haino, Hiroshima University. The image is from the original paper published in Angew. Chem. Int. Ed. 2024, e202416770. 10.1002/anie.202416770

Helical structures are ubiquitous across biology, from the double-stranded helix of DNA to how heart muscle cells spiral in a band. Inspired by this twisty ladder, researchers from Hiroshima University's Graduate School of Advanced Science and Engineering have developed an artificial polymer that organizes itself into a controlled helix.

They published their results on Oct. 24 in *Angewandte Chemie*.

"Motivated by elegant biological helical structures, considerable effort has been devoted to developing artificial helical organizations with defined handedness for wide potential applications, including memory, sensing devices, chiral stationary phases, asymmetric catalysts and spin filtering," said corresponding author Takeharu Haino, professor at Hiroshima University's Graduate School of Advanced Science and Engineering.

"The helical supramolecular polymer presented here is a new type of helical polymer."

Polymers are a broad class of materials characterized by the large molecules that comprise them. They can be found in nature as proteins and more, including DNA, and in a number of industrial roles, including as synthetic components of plastics.

The molecules of a supramolecular polymer typically interact to form non-covalent bonds, which are highly directional and prompt specific behaviors depending on their arrangement.

The polymer that the Hiroshima University team developed is known as a pseudo-polycatenane, which contains mechanical bonds in addition to the non-covalent bonds. Mechanical bonds can be broken via force without disrupting the chemical structure of the non-covalent bonds—an attractive property when developing materials that require precise control.

Typically, such helical structures are categorized as "one-handed," meaning their twist turns in one direction only. As such, the way they interact with other materials is dictated by the direction of their twist. If researchers can control whether that twist is left- or right-handed, so to speak, then researchers can control how the polymer behaves when applied in different scenarios.

"Helical polymers are potentially useful for various purposes; however, the synthesis of helical polymers with preferred handedness had remained challenging," Haino said.

"Here, we present a novel synthetic method for helical polymers with preferred handedness via supramolecular polymerization controlled by complementary dimerization of the bisporphyrin cleft units."

Bisporphyrin cleft units are molecular components that can join up with other components to form molecular complexes, including polymers. By strategically inducing joining of these units—dimerization—the researchers can pre-emptively determine the handedness of the resulting polymer.

"The proposed novel strategy for controlling the handedness of supramolecular helical pseudo-polycatenane polymers paves the way for the study of supramolecular polymer materials with functions directed by controlled helicity and mechanical bonding," Haino said.

"Our goal is to apply these new helical supramolecular polymers to material separation and catalysis—or the acceleration of chemical reactions—and to create a new functional chemistry of helical supramolecular polymers."

More information: Naoka Fujii et al, Controlled Helical Organization in Supramolecular Polymers of Pseudo-Macrocyclic Tetrakisporphyrins, *Angewandte Chemie International Edition* (2024). DOI: 10.1002/anie.202416770

Provided by Hiroshima University

'We live in a universe that is just right for us': Study proposes a test for the Anthropic Principle

The Anthropic Principle—stating that the universe we live in is fine-tuned to host life—was first proposed by Brandon Carter in 1973. Since then, it has sparked significant debate.

Now, a paper published in the *Journal of Cosmology and Astroparticle Physics*, authored by Nemanja Kaloper, a physicist from the Department of Physics and Astronomy at the University of California, Davis, and Alexander Westphal, a professor at the Deutsches Elektronen-Synchrotron (DESY), describes for the first time a way to experimentally test this assumption.

The anthropic principle (AP) can be formulated in different ways. These range from a simple description of the facts—"if we are here observing it, the universe evolved with the conditions necessary for the emergence of intelligent life," known as the weak AP—to something a bit more radical: "the universe had to evolve in a way that led to our existence."

This stronger interpretation, called the strong AP, often ventures into metaphysical territory, suggesting a kind of "design" and moving beyond the realm of scientific inquiry into the universe.

The problem with the AP, according to many scientists, is that it is not particularly useful as a scientific tool because it does not generate testable, quantifiable predictions that could both expand our knowledge and subject the principle to scrutiny. Without this, it remains more of a philosophical conjecture than a scientific hypothesis.

The AP does, however, suggest that for our universe to develop as a hospitable place for carbon-based life, it must have started with a set of rather specific initial conditions. We infer this by observing, for example, the values of certain constants used in the equations that describe the universe—such as the gravitational constant, the electron charge, and Planck's constant—which must be "just right." Otherwise, we would have a very different and, most importantly, inhospitable universe.

By establishing the precise initial conditions implied by the AP and calculating, based on current physical models, how the universe would have evolved to its present state, we could compare the outcome to actual astronomical observations. Any discrepancies between theory and reality would provide a measure of the validity of the AP.

The new work by Nemanja Kaloper and Alexander Westphal offers some specific predictions that could find observational confirmation in the coming years.

To understand their proposal, some key elements in cosmological research must be outlined:

Cosmic inflation

In the earliest moments of its existence, the universe underwent a period of rapid expansion: in just 10^{-36} seconds, it grew from an infinitesimal size (almost zero) to a macroscopic scale (some theories describe it as the size of a grape or a soccer ball). After this, the expansion slowed down, continuing at rates similar to those we observe today.

The physics during this early phase was highly unusual, dominated by quantum phenomena (governing the infinitely small) that influenced the subsequent evolution, enabling the formation of structures—galaxies, stars, and so on—that we see today. Although direct evidence for cosmic inflation has not yet been found, it is a robust theory with anticipated observational confirmations in the coming years.

Dark matter

You've probably heard of it: experimental observations tell us that a significant portion of the universe—about five-sixths of its matter—is composed of something we cannot directly observe. We call it dark matter, but its true nature remains unknown. Many hypotheses have been proposed, all awaiting experimental confirmation, which is expected in the near future.

Axions

One of the candidates for dark matter is the axion. These particles—or, more likely, an entire class of particles—are extremely light (much lighter than the electron, for instance). Axions were initially proposed to explain a quantum phenomenon known as CP symmetry violation, which involves the weak nuclear interaction, one of the four fundamental forces (the others being gravity, electromagnetism, and the strong nuclear interaction).

However, researchers noticed that certain characteristics of axions—believed to have formed in great abundance during cosmic inflation—align with those expected for dark matter, such as their minimal interactions with both themselves and ordinary matter. Observations of black holes could confirm their existence in the coming years.

Testing the AP involves combining these three elements.

"It is possible that the LiteBIRD satellite discovers primordial gravity waves close to the current limits, which match high-scale inflation," explains Kaloper. "Most cosmologists would feel this confirms high-scale inflation." LiteBIRD (Lite (Light)

Satellite for the Study of B-mode Polarization) is an experiment that the Japanese Aerospace Exploration Agency (JAXA) plans to launch in 2032.

"It is also possible that we discover signs of ultralight axions by surveying supermassive black holes in the universe. The axions affect the spin-to-mass ratio of black holes, and this could be observed," Kaloper continues. Many experiments are already studying black holes, with more set to begin operating in the near future.

"Finally," adds Kaloper, "it is possible that future direct dark matter searches discover that dark matter is predominantly not made up of ultralight axions. In which case, we'd think that the anthropic principle fails."

However, this outcome is not guaranteed.

"On the other hand, if direct dark matter searches find that dark matter is, in fact, ultralight axion," Kaloper continues, "then I think we'd agree that the anthropic principle in fact passed this test; indeed, this might happen."

"I find it particularly interesting that both of these options might be experimentally tested in the not-too-distant future," Kaloper concludes.

"And that—as far as my collaborator and I know—our specific example is the first case where the anthropic principle might actually fail the test, as opposed to simply declaring that it does not apply.

"The point is, that the presence of high-scale inflation and ultralight axions with masses $m > 10^{-19}$ eV would imply that dark matter 'must' be an axion: for typical initial conditions, we'd end up with way too much dark matter, and we'd desperately need the anthropic principle to constrain it.

"To find that axion is not dark matter, we'd infer that the initial conditions were not just unlikely (which can be fixed anthropically) but extremely unlikely, which really does not even fall under the domain of anthropic reasoning."

So, we will need to wait a few more years, perhaps even longer, to gather all the necessary evidence to either falsify or confirm the anthropic principle. But what if it proves unable to pass the test?

"Without changing any of the other premises (universality of gravity, early inflation and superradiant phenomena), the failure of our simple formulation of anthropics would suggest that different rules govern the initial conditions," explains Kaloper.

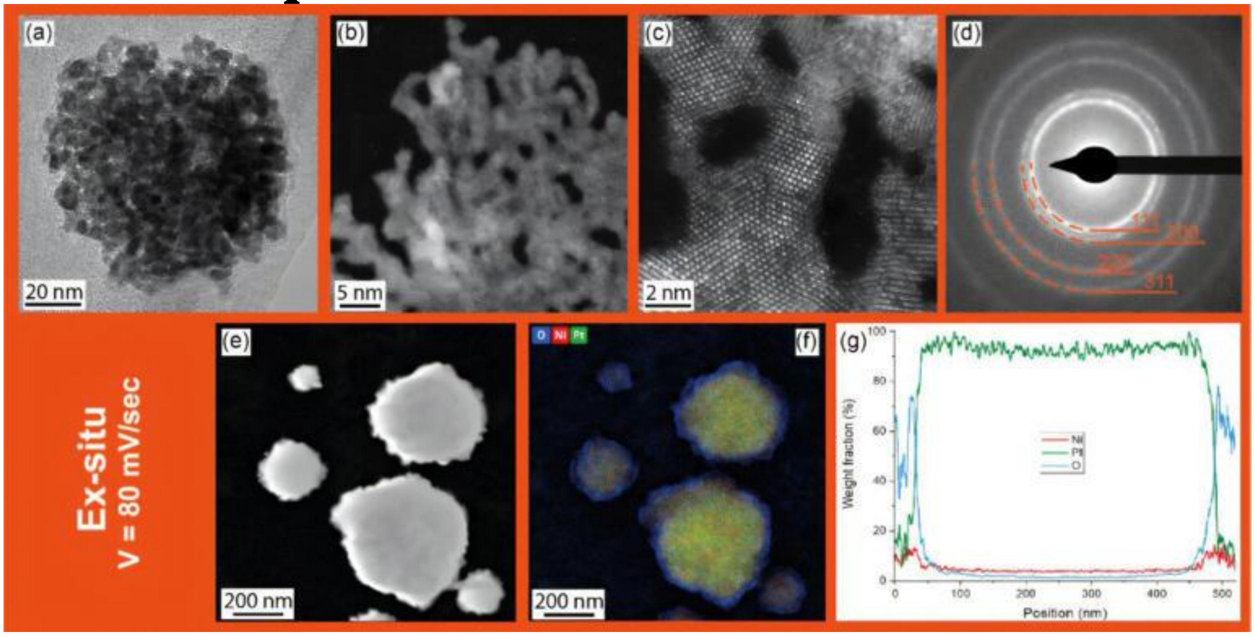
"Either different initial conditions are not equally probable, some being biased by new dynamics as yet not understood, or that some initial conditions are altogether impossible. Alternatively, the real theory of cosmology might be more complicated than we thought."

"One could also imagine more dramatic scenarios, but at least for now, to me those seem as flights of fancy," concludes Kaloper.

More information: Falsifying Anthropics, *Journal of Cosmology and Astroparticle Physics* (2024).

Provided by International School of Advanced Studies (SISSA)

How are nanostructures created? Imaging techniques unveil secrets of electrodeposition



(S)TEM and EDS analysis of the PtNi film grown ex situ on a molybdenum TEM grid with lacey carbon foil with the corresponding selected area diffraction pattern. (a) BF TEM overview image of a single nanoparticle. (b) Higher-magnification HAADF STEM image of the branched structure of the NPs. (c) HR-HAADF STEM image of the atomic structure of the branches. (d) SAED corresponding to the particle shown in panel a. (e) HAADF STEM image with (f) corresponding EDS map of the distribution of Pt, Ni and O. (g) Line scan across the bottom right particle. Credit: Nano Letters (2024). DOI: 10.1021/acs.nanolett.4c02228

Metallic nanoparticles, consisting of a few to several thousand atoms or simple molecules, are attracting significant interest. Electrodes coated with layers of nanoparticles (nanolayers) are particularly useful in areas such as energy production, serving as catalysts.

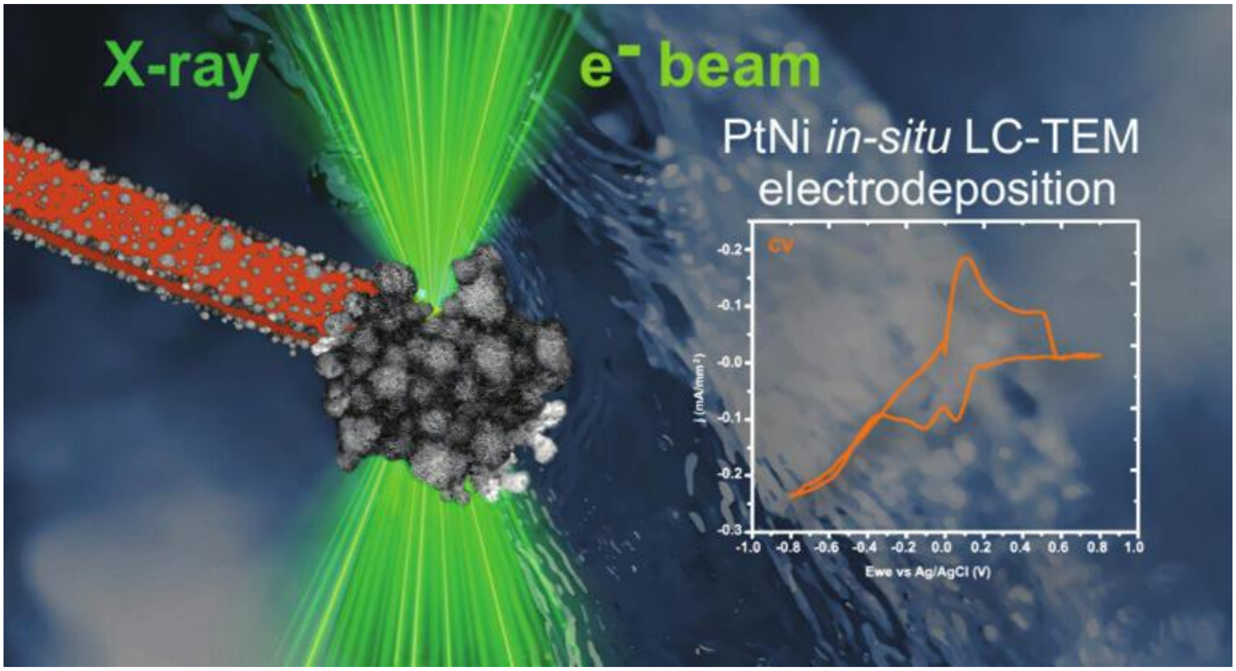
A convenient method for producing such layers on electrodes is electrodeposition, the subtle complexities of which have just been revealed by an international team of researchers led by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow. Their paper is published in the journal *Nano Letters*.

Research on nanoparticles is yielding promising results for technologies related to energy, medicine, and electronics. One of the key challenges is effectively controlling the synthesis and growth of nanostructures.

The team of scientists conducted an advanced experiment demonstrating the electrodeposition process of a platinum-nickel (PtNi) nanolayer on an electrode. Utilizing state-of-the-art imaging techniques, the researchers had a unique opportunity to observe in real-time how structures form at the atomic level, which is a significant step towards better designing materials with precisely controlled properties.

Electrodeposition is a rapid and convenient method for producing nanostructures. It involves immersing an electrode in a metal salt solution, from which the layer is to be grown, followed by applying an appropriate voltage that causes ions near the electrode surface to reduce, initiating layer growth.

To closely examine the process of electrodeposition, transmission electron microscopy (TEM) techniques are essential. TEM allows for imaging materials with sub-angstrom resolution (i.e., less than one ten-millionth of a millimeter) since it uses an electron beam with a much shorter wavelength than visible light. Ideally, it would be possible to observe, in real-time, how nucleation (the initial growth stage where nanoparticle seeds form) and layer growth occur on the electrode.



In-situ liquid-cell transmission electron microscopy electrodeposition of PtNi nanoparticle films on a carbon electrode during cyclic voltammetry. The electron beam (here in green color) illuminated the electrode (here in orange color) submerged in the platinum and nickel salt solution, enhancing the growth of the PtNi nanoparticle film (grey color) on the electrode. The film thickness increases with each cycle and by the fourth cycle reaction-rate limited growth of branched and porous structures were observed. Credit: Nano Letters (2024). DOI: 10.1021/acs.nanolett.4c02228

However, TEM imaging comes with certain limitations: the samples need to be as thin as possible and entirely dry. To overcome these challenges and enable the imaging of chemical reactions, the researchers thus utilized a special imaging technique in a liquid cell flow chamber.

"The flow cell consists of two silicon chips equipped with a 50-nanometer-thick SiN_x membrane. This membrane is electron-transparent, and an additional electrode is placed on its surface. By applying a voltage, the microscope user can observe how the layer grows on the electrode. Experiments using such a cell require a special holder for flow experiments in the TEM," explains Prof. Magdalena Parlińska-Wojtan, Ph.D.

Experiments conducted at the Silesian University of Technology using a TEM microscope confirmed that the PtNi layer indeed grows directly on the electrode, providing crucial insights into the fundamentals of the entire process. An alternative mechanism would involve nanoparticles first forming in the electrolyte and then drifting toward the electrode to attach. This effect was also observed, but only in areas illuminated by the beam, due to the fact that the electron beam interacts with water, behaving like a reducing agent.

Subsequent "dry" observations revealed that the layer is actually composed of spherical nanoparticles with diameters of several tens of nanometers. Further magnification of TEM images showed that the surface of these nanoparticles consists of densely branched, fine dendritic structures (multiple branching).

"As part of our collaboration with the Fritz Haber Institute of the Max Planck Society in Berlin, we conducted an additional experiment by extending the reaction time and reducing the rate of voltage changes. This allowed us to observe additional effects: the nucleation of individual nanoparticles, which rapidly grow and merge to form a continuous layer.

"During voltage changes in subsequent electrodeposition cycles, the nanoparticles undergo alternating growth and dissolution. However, growth is a faster process than dissolution, which ultimately results in a stable layer," explains Prof. Parlińska-Wojtan.

As part of the research, another experiment was conducted in liquid environment using a different, but also unique, apparatus: a scanning transmission X-ray microscope (STXM), available at the National Synchrotron Radiation Center

SOLARIS in Kraków. During STXM imaging, X-ray radiation is used. The resulting images do not have as high a resolution as the ones from electron microscopy, but they reveal other properties of the materials under study, such as the oxidation states of atoms in nanoparticles.

The result of electrodeposition is not always pure metal; sometimes it is a metal oxide. Depending on whether it is a metal or an oxide (and the oxidation state of the oxide), materials absorb X-ray radiation at different energies. An STXM image taken with the appropriate energy beam allows for a detailed investigation of the produced nanoparticles.

The STXM microscope at the SOLARIS center in Kraków also enabled an experiment in a liquid environment using a flow cell nearly identical to the one used in the TEM. The authors thus performed PtNi electrodeposition inside the STXM and, in real time, investigated the range of X-ray absorption by the nanoparticles. In this way, they determined that the layer actually consists of nickel(II) oxide and metallic platinum.

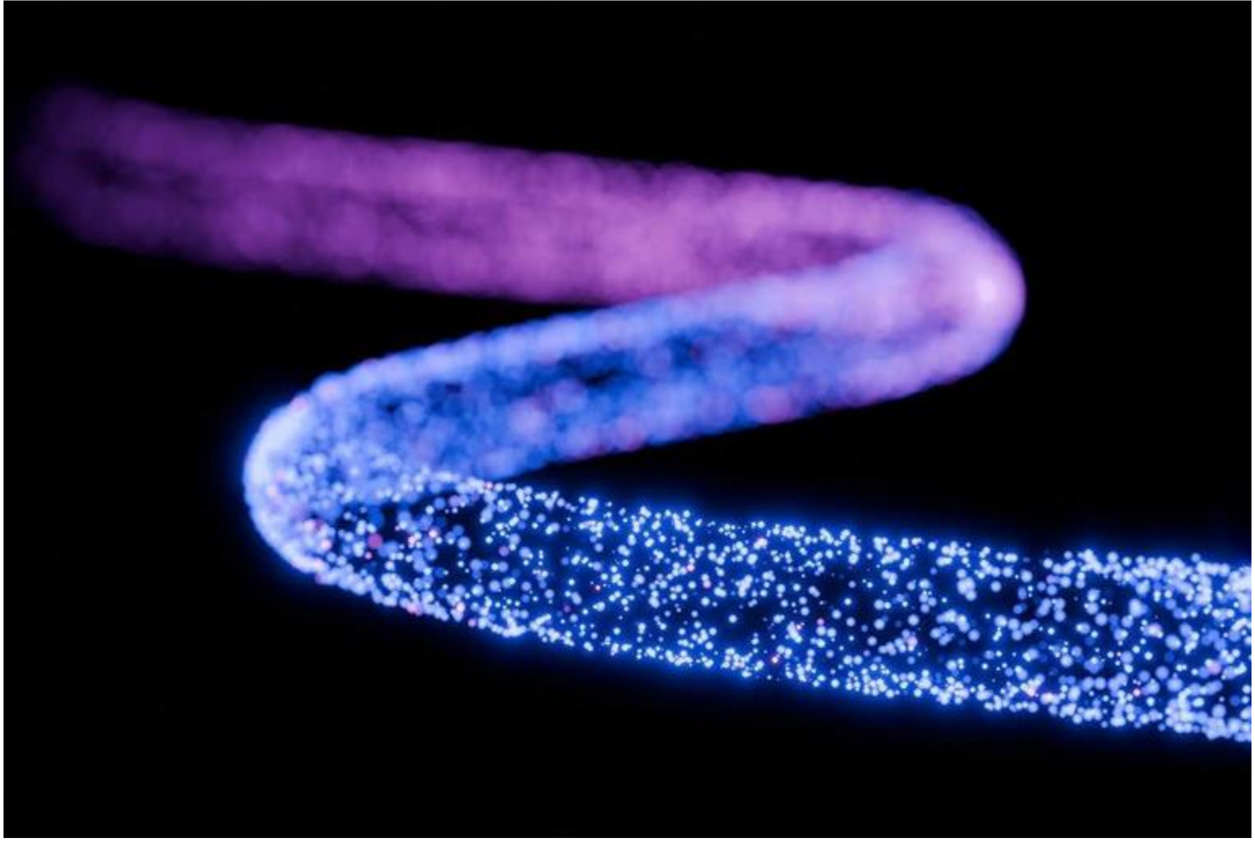
"Conducting an experiment using microscopic techniques in a liquid environment is quite a challenge. Nevertheless, our team succeeded in producing the expected PtNi layer using two different techniques, and the obtained results were complementary," says Prof. Parlińska-Wojtan.

"Such research is important for several reasons. The technical reason is that we are still exploring the capabilities and limitations of relatively new, high-end measurement tools. There was also a more important scientific reason: understanding the fundamental factors that govern the synthesis, growth, and properties of nanostructures. This knowledge may help in the future in the fabrication of nanostructured materials tailored better for applications such as fuel cells or medicine."

More information: Magdalena Parlinska-Wojtan et al, Understanding the Growth of Electrodeposited PtNi Nanoparticle Films Using Correlated In Situ Liquid Cell Transmission Electron Microscopy and Synchrotron Radiation, *Nano Letters* (2024). DOI: 10.1021/acs.nanolett.4c02228

Provided by Polish Academy of Sciences

Scientists provide first-ever demonstration of quantum teleportation over fiber-optic cables



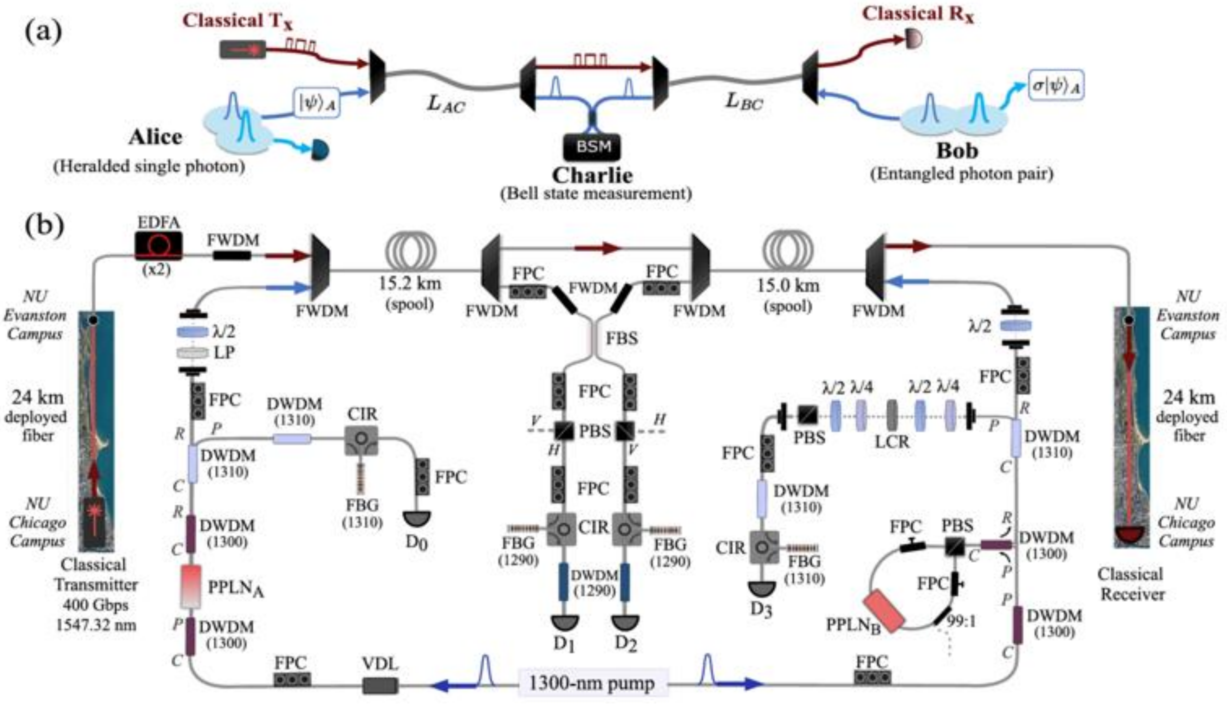
Northwestern engineers achieve quantum teleportation over fiber optics with Internet traffic, proving quantum and classical signals can coexist seamlessly. (CREDIT: Getty Images)© The Brighter Side of News

Fiber optic cables have long been the backbone of global communications, enabling the high-speed Internet that connects billions of people daily. Now, these same cables are being tested as conduits for quantum communication, a cutting-edge technology poised to revolutionize computing, cryptography, and sensing.

This groundbreaking development could integrate quantum systems with existing infrastructure, reducing the need for costly new networks and opening the door to advanced applications.

Integrating Quantum and Classical Signals

Quantum communication operates fundamentally differently from traditional Internet traffic. Instead of transmitting millions of photons to encode data, quantum systems rely on single photons carrying delicate quantum states. This presents unique challenges when attempting to share optical fibers with high-power classical signals, which can generate noise and interfere with quantum data.



Conceptual diagram of the experiment. (CREDIT: Optica)© The Brighter Side of News

Noise from inelastic scattering, particularly spontaneous Raman scattering, is a significant hurdle. It produces broadband photons that can mask the faint quantum signals, creating a trade-off between classical and quantum network performance.

Researchers have spent decades studying quantum-classical coexistence, experimenting with weak coherent state sources, entangled photon pairs, and squeezed light to address the challenges. Despite these advances, most efforts have focused on directly transmitting quantum data between nodes.

Yet many emerging quantum applications—such as quantum relays, repeaters, and networked quantum computers—rely on teleporting quantum states rather than transmitting them physically.

Teleportation, a process made possible by quantum entanglement, allows a quantum state to transfer between two distant systems without direct transmission. This non-local property has the potential to enable ultra-secure, high-speed communication over vast distances. But until now, researchers hadn't demonstrated quantum teleportation over fibers also carrying classical Internet traffic.

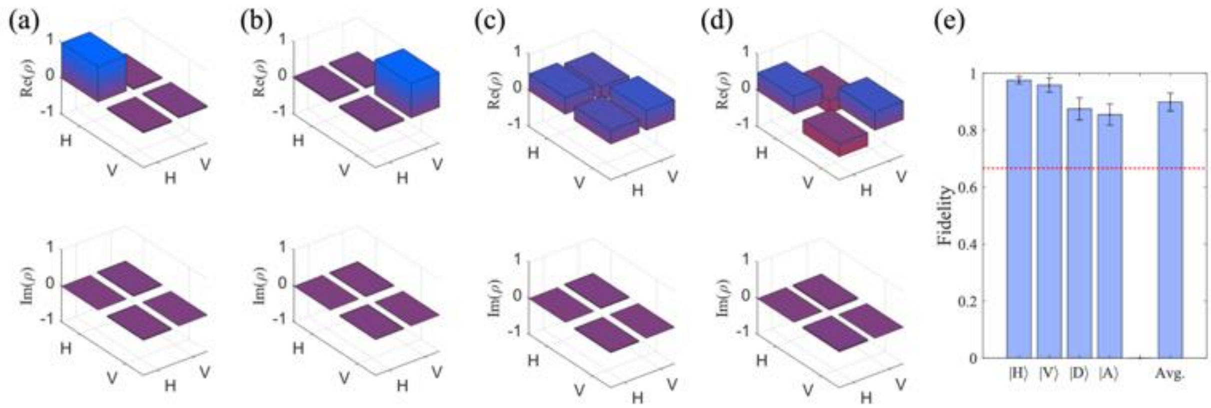
A Quantum Leap in Teleportation

In a breakthrough study published in Optica, engineers from Northwestern University have achieved the first quantum teleportation over fiber optic cables simultaneously carrying high-speed classical communications.

The experiment involved a three-node system over 30.2 kilometers of fiber, with quantum and classical signals multiplexed using different wavelengths. A joint Bell state measurement (BSM) performed on a single photon and an entangled photon pair successfully teleported the quantum state without significant degradation.

The team overcame noise challenges by strategically selecting wavelengths to minimize spontaneous Raman scattering. They placed quantum signals in the 1290-nanometer band, where scattering from high-power C-band light—used for Internet traffic—is least likely to interfere. Narrow-band filtering and coincidence detection further reduced noise, ensuring high fidelity in the quantum state transfer.

Prem Kumar, the study's lead author and a professor at Northwestern, emphasized the significance of this achievement. "This is incredibly exciting because nobody thought it was possible," he said. "Our work shows a path towards next-generation quantum and classical networks sharing a unified fiber optic infrastructure. It opens the door to pushing quantum communications to the next level."



Real and imaginary components of the density matrices obtained by single-qubit quantum state tomography on Bob’s target photon. (CREDIT: Optica)© The Brighter Side of News

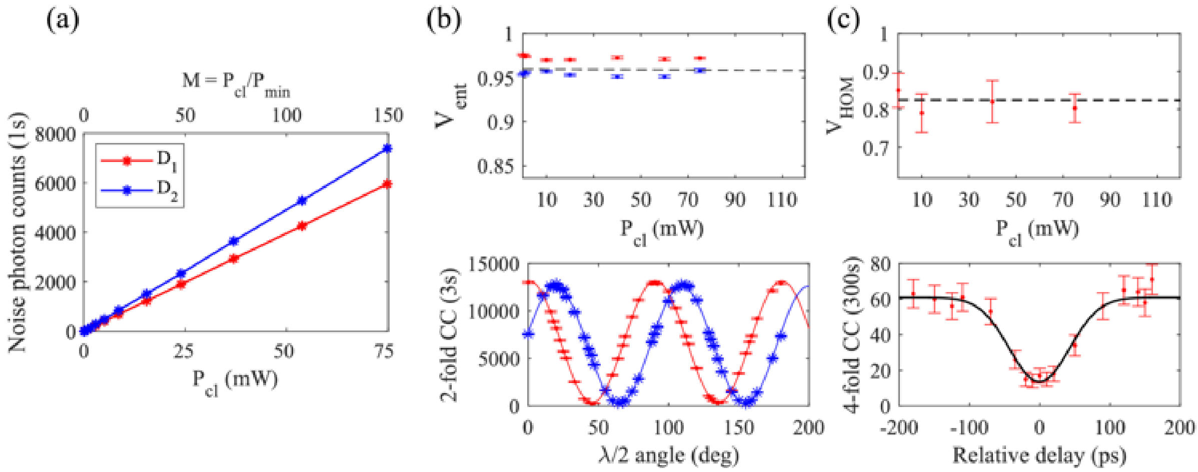
Testing the System Under Real-World Conditions

To validate their approach, the researchers simulated a real-world network environment. They transmitted quantum data and high-speed Internet traffic simultaneously through the same fiber.

At one end of the 30-kilometer cable, they placed a photon carrying a quantum state. At the other end, they stationed a photon entangled with the first. The quantum state was successfully teleported across the network, demonstrating that quantum and classical communications could coexist without interference.

Jordan Thomas, a Ph.D. candidate at Northwestern and the paper’s first author, explained the teleportation process: “By performing a destructive measurement on two photons—one carrying a quantum state and one entangled with another photon—the quantum state is transferred onto the remaining photon, which can be very far away. Teleportation allows the exchange of information over great distances without requiring the information itself to travel that distance.”

This achievement represents the culmination of years of research into quantum-classical coexistence. It also sets the stage for even more advanced applications, such as entanglement swapping and distributed quantum networks.



SpRS noise photon count rate in the Bell state measurement (BSM) detectors and as a function of the classical launch power and the ratio to the minimum power needed to operate a single 400-Gbps channel. (CREDIT: Optica)© The Brighter Side of News

Paving the Way for Future Innovations

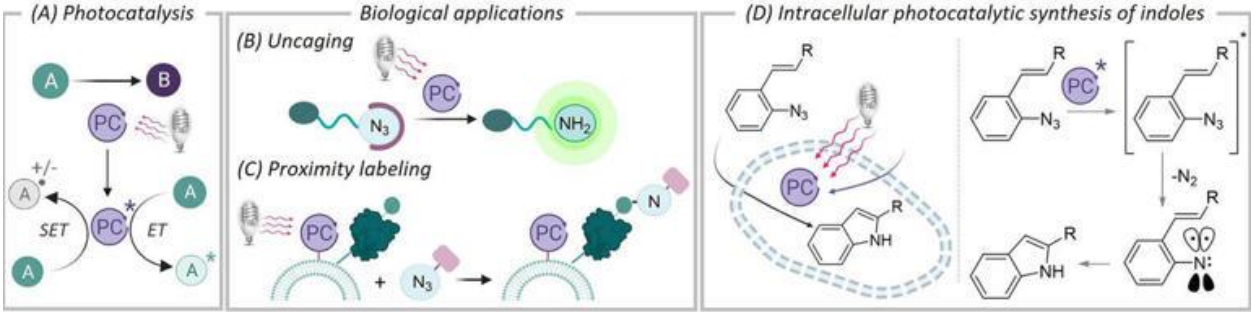
The implications of this work extend far beyond laboratory experiments. Kumar's team plans to expand their tests to longer distances and incorporate two pairs of entangled photons to demonstrate entanglement swapping, an essential step for distributed quantum applications. They also aim to transition from spooled fiber in the lab to real-world, underground optical cables, bringing the technology closer to practical implementation.

"Quantum teleportation has the ability to provide quantum connectivity securely between geographically distant nodes," Kumar said. "But many people have long assumed that nobody would build specialized infrastructure to send particles of light. If we choose the wavelengths properly, we won't have to build new infrastructure. Classical communications and quantum communications can coexist."

This coexistence could simplify the rollout of quantum technologies, leveraging existing fiber optic networks to support quantum computing, secure communications, and advanced sensing. Kumar's optimism reflects a broader vision for integrating quantum systems into everyday technologies, potentially transforming industries from finance to healthcare.

The Northwestern team's success demonstrates that the future of quantum communication doesn't require reinventing the wheel. Instead, it offers a seamless integration of cutting-edge science with the infrastructure already in place, heralding a new era of connectivity.

Researchers synthesize new compounds within living cells using light



Credit: Journal of the American Chemical Society (2024). DOI: 10.1021/jacs.3c13647© Provided by Phys.org

Plants harness chlorophyll to capture sunlight and kickstart photosynthesis, a crucial process on our planet that converts luminous energy into chemical fuel while producing oxygen. This pivotal chemical energy is subsequently utilized by plants, algae, and select bacteria to metabolize carbon dioxide and water into sugars.

Now, scientists at the Center for Research in Biological Chemistry and Molecular Materials (CiQUS) have achieved a breakthrough by integrating non-native photosensitizers into mammalian cells. This revelation showcases the capability of these substances to also absorb green or blue light, thus instigating artificial chemical reactions within cellular environments. Notably, this innovative approach has been employed for synthesizing indoles, chemical compounds boasting significant biological activities.

Such findings underscore the feasibility of leveraging light to fabricate functional molecular products, including fluorescent variants, within biological settings. Published in the *Journal of the American Chemical Society (JACS)*, this study marks the pioneering demonstration of forging synthetic chemical bonds within cells through photocatalysis.

Photocatalysis emerges as a transformative chemical technology with vast socioeconomic implications. It empowers the utilization of light as an energy source to activate catalysts and instigate chemical transformations, thereby facilitating sustainable synthetic endeavors.

"The evidence of employing these synthetic photocatalysis technologies within biological milieus, we believe, heralds a new frontier at the frontier of chemistry and biology," remarks Professor José Luis Mascareñas, co-leading the research alongside Dr. María Tomás Gamasa. "Moreover, we anticipate that in the foreseeable future, these technologies will unveil novel strategies for precisely manipulating human cells, thus fostering the development of innovative therapeutic interventions."

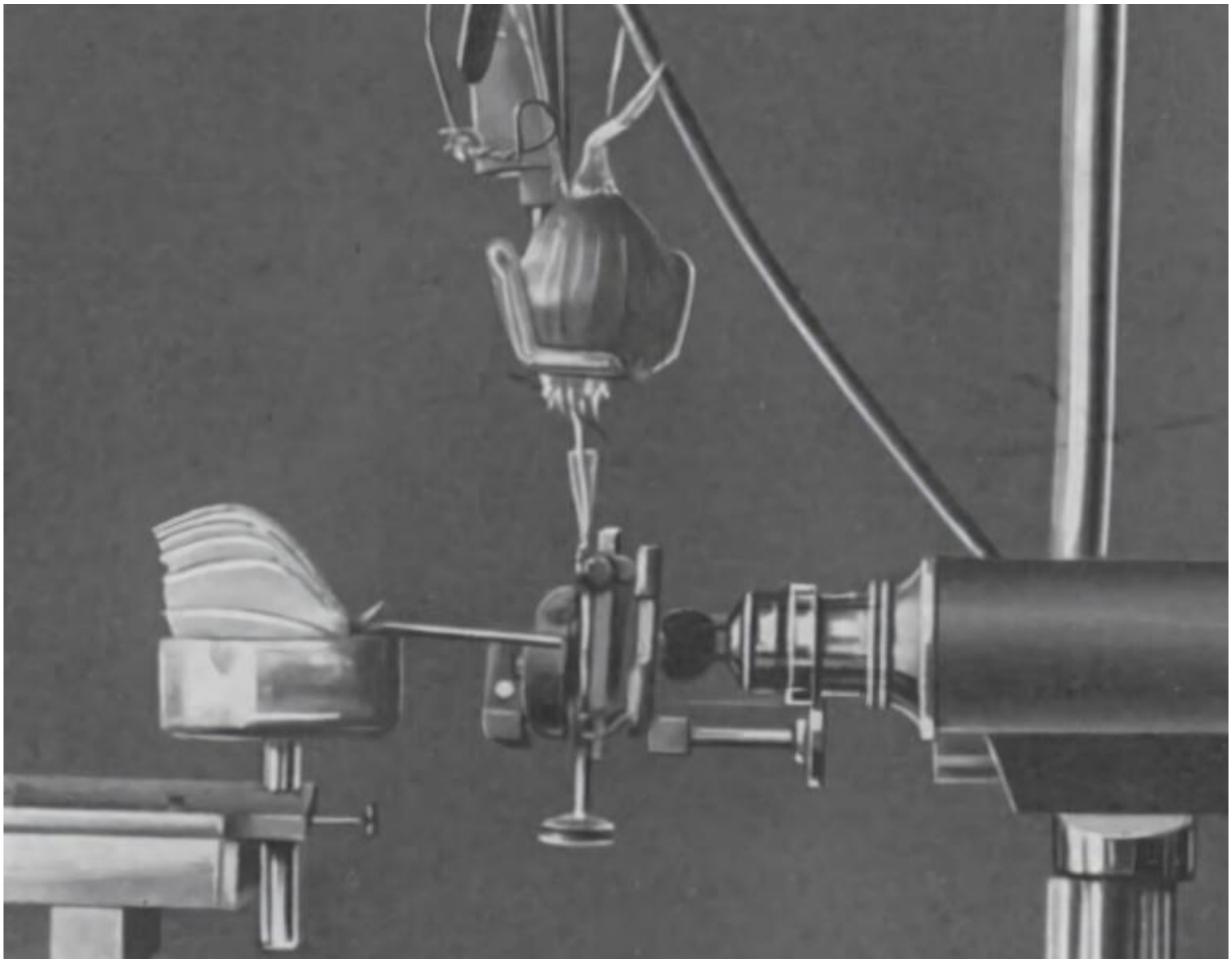
Dr. Sara Gutiérrez and Ph.D. student Cinzia D'Avino spearheaded the experimental work, conducted entirely at CiQUS.

More information: Cinzia D'Avino et al, Intracellular Synthesis of Indoles Enabled by Visible-Light Photocatalysis, *Journal of the American Chemical Society* (2024). DOI: 10.1021/jacs.3c13647

Provided by Center for Research in Biological Chemistry and Molecular Materials (CiQUS).

Quantum research sheds new light on how cells communicate

Have you ever thought that light might hold a key to life's mysteries? One hundred years ago, Alexander Gurwitsch dared to propose that living cells emit faint ultraviolet light, invisible to the naked eye, to communicate with and stimulate one another.



A photograph of Gurwitsch's onion experiment with the emitter onion held in the inductor (a bowl to hold the inducing onion bulb, left), the receiver onion (in a frame to hold the induced bulb, top), and location of mitotic induction (center). Credit: A. G. Gurwitsch, Das Problem der Zellteilung physiologisch betrachtet (1926)

It was an idea so ahead of its time that many dismissed it outright. Without a physical theory to back it up, his idea was relegated to the chronicles of history. Yet when I encountered his work, I couldn't help but ask the question: What if the UV effect is quantum mechanical? Armed with modern quantum theory, I began to uncover a new quantum dimension to life itself.

Drawings of onion root cross-sections of non-irradiated (left) and irradiated (right) roots. The line divides the irradiated root into opposite halves to show the increased number of cell divisions in the irradiated half. Credit: T. Reiter and D. Gábor, Zellteilung und Strahlung (1928)

A century-old mystery revisited

In the 1920s, Gurwitsch's experiments revealed a startling phenomenon. Placing the tip of one onion root near the side of another, he noticed that more cell divisions occurred on the side of the root facing the tip. He observed that the effect disappeared when he placed a glass slide between the roots.

Curiously, when he changed the material of the slide from glass to fine quartz, the effect reappeared.

This mysterious light, which he called "mitogenetic radiation," passed freely through air and quartz but was blocked by glass, distinguishing it from visible light and some frequencies of infrared. He concluded that faint ultraviolet light emitted by one root tip stimulated cell division in the other.

At the time, the idea that light, not hormones or other chemicals, could drive such a fundamental process seemed implausible. Skeptics dismissed his findings, and the phenomenon faded into obscurity.

Faced with this problem, I realized that the ultraviolet radiation he described might be explained using quantum resonance theory. Using resonance concepts from quantum mechanics, I've connected Gurwitsch's observations to a sophisticated framework that explains how faint ultraviolet light can spark significant biological changes.

This explanation, outlined in my new paper published in the *Computational and Structural Biotechnology Journal*, not only validates his results but also reshapes our understanding of how quantum systems interact with biological environments.

In my research, Gurwitsch's mitogenetic radiation turns out to be a prime candidate for a quantum resonance effect where specific wavelengths of light trigger responses in living cells.

Challenging conventional wisdom

Traditionally, quantum physics assumes that systems interact weakly with their environment—if at all. This misses out on the complexity of living organisms, which are nothing like isolated systems in a lab. They're dynamic, interconnected, and alive with collective interactions between photons, electrons and molecules.

For this reason, early researchers dismissed quantum effects in biology, believing cells were just too "warm, wet and noisy" for such delicate phenomena.

I took a different approach, turning to open quantum systems theory, an advanced framework that describes systems embedded in and interacting with their environments. Specifically, I employed Fano and Feshbach's model, a method originally developed for scattering phenomena in quantum mechanics.

This model is ideal for testing quantum resonance effects like those Gurwitsch proposed. By applying this framework, I've shown how biological environments could detect and amplify faint light signals, defying traditional assumptions that life is too chaotic for quantum phenomena to thrive.

Revolutionizing our understanding of life

The implications of this discovery are extraordinary. First, it predicts that light isn't just a passive byproduct of biological systems—it's an active component.

Ultraviolet ultraweak photon emissions (UPE) may provide a quantum channel for cells to communicate and coordinate activity. This adds a new layer to our understanding of cellular behavior.

Second, this work bridges biology with quantum physics in ways that seemed unimaginable last century. By applying these principles of open quantum systems theory, we can now explore processes like mitosis, photosynthesis, and enzyme catalysis through a distinctly quantum lens. This interdisciplinary approach not only advances our understanding of biology but also pushes the boundaries of quantum mechanics into a new scientific frontier.

Finally, the practical applications are immense. Cellular UPE are poised to revolutionize medical diagnostics, serving as a biomarker for cellular health, oxidative stress, or early signs of cancer. In regenerative medicine, we might harness these emissions to stimulate healing or guide tissue growth with precision light therapies.

The potential to manipulate these quantum interactions opens doors to new treatments and technologies that could reshape the life sciences, health care, and biotechnology.

Looking ahead

Rediscovering Gurwitsch's work has opened avenues for discovery that pose many new questions. How do these photon emissions integrate with other cellular processes? Could they influence immunity, aging, or even the development of complex organisms? What other hidden quantum phenomena might exist in the biological microenvironment that we can model using quantum theory?

As we dive deeper into these questions, we're not just revisiting old ideas. We're stepping into uncharted territory. Gurwitsch's intuition about the quantum nature of life was a century ahead of its time, waiting for the tools and theories of the future to unlock its potential.

Today, those tools are here, and the faint light he discovered is shining through more than ever, revealing the beginnings of a quantum blueprint for life itself.

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

More information: Nathan S. Babcock, Open quantum systems theory of ultraweak ultraviolet photon emissions: Revisiting Gurwitsch's onion experiment as a prototype for quantum biology, *Computational and Structural Biotechnology Journal* (2024). DOI: 10.1016/j.csbj.2024.11.030

Bios:

Dr. Nathan S. Babcock has over 20 years of research experience in the quantum sciences. He attended University at the two major Canadian quantum research centers, the University of Waterloo (Ontario) and the University of Calgary (Alberta).

Upon receiving his Ph.D. in Physics, Dr. Babcock deepened his understanding of the underpinnings of quantum mechanics in biology by carrying out postdoctoral research on structural biology at Simon Fraser University (British Columbia) before developing experience in spin chemistry by working on studies of radical electron pair models of avian magnetoreception while at the Living Systems Institute at the University of Exeter (UK).

He then honed his expertise on open quantum systems by investigating the quantum mechanical effect of superradiance in biological microtubules at the Quantum Biology Laboratory at Howard University in Washington, D.C.

His peer-reviewed research on quantum effects in microtubules went "viral" online, being featured on numerous news feeds, blogs, and social media websites. Dr. Babcock is currently working on the first technical monograph for the field of quantum biology, while expanding research applications of open quantum systems theory to biological systems. Dr. Babcock is counted among his colleagues as one of the pioneers of the groundbreaking new field of quantum biology.

The universe had a secret life before the Big Bang, new study hints

The universe had a secret life before the Big Bang, new study hints© ESA

The Big Bang may not have been the beginning of the universe, according to a theory of cosmology that suggests the universe can “bounce” between phases of contraction and expansion. If that theory is true, then it could have profound implications about the nature of the cosmos, including two of its most mysterious components: black holes and dark matter.

With this in mind, a recent study suggests that dark matter could be composed of black holes formed during a transition from the universe's last contraction to the current expansion phase, which occurred before the Big Bang. If this hypothesis holds, the gravitational waves generated during the black hole formation process might be detectable by future gravitational wave observatories, providing a way to confirm this dark matter generation scenario.

Observations of stellar movements in galaxies and the cosmic microwave background — an afterglow of the Big Bang — indicate that about 80% of all matter in the universe is dark matter, a substance that doesn't reflect, absorb or emit light. Despite its abundance, scientists have not yet identified what dark matter is made of.

In the new study, researchers explored a scenario where dark matter consists of primordial black holes formed from density fluctuations that occurred during the universe's last contraction phase, not long before the period of expansion that we observe now. They published their findings in June in the Journal of Cosmology and Astroparticle Physics.

The bouncing cosmos

The traditional cosmological view of the universe suggests that it started from a singularity, followed by a short period of extremely rapid expansion, called inflation. However, the authors behind the new study analyzed a more exotic theory, known as non-singular matter bouncing cosmology, which posits that the universe first underwent a contraction phase. This phase ended with a rebound due to the increasing density of matter, leading to the Big Bang and the accelerated expansion we observe today.

In this bouncing cosmology, the universe contracted to a size about 50 orders of magnitude smaller than it is today. After the rebound, photons and other particles were born, marking the Big Bang. Near the rebound, the matter density was so high that small black holes formed from quantum fluctuations in the matter’s density, making them viable candidates for dark matter.

"Small primordial black holes can be produced during the very early stages of the universe, and if they are not too small, their decay due to Hawking radiation [a hypothetical phenomenon of black holes emitting particles due to quantum effects] will not be efficient enough to get rid of them, so they would still be around now," Patrick Peter, director of research at the French National Centre for Scientific Research (CNRS), who was not involved in the study, told Live Science in an email. "Weighing more or less the mass of an asteroid, they could contribute to dark matter, or even solve this issue altogether."

The scientists' calculations show that this universe mode's properties, such as the curvature of space and the microwave background, match current observations, supporting their hypothesis.

To further test their predictions, the researchers hope to make use of next-generation gravitational wave observatories.The scientists calculated the properties of the gravitational waves produced during black hole formation in their model and found that they could be detected by upcoming gravitational observatories like the Laser Interferometer Space Antenna (LISA) and the Einstein Telescope. These detections could confirm whether primordial black holes are indeed dark matter; however, it could take more than a decade before either facility sees first light.

"This work is important in the sense that it provides a natural way of forming small yet still present black holes forming dark matter in a framework which is not the usual one based on inflation," Peter said. "Other works currently investigate the behavior of such tiny black holes around stars, potentially leading to a way of detecting them in the future."

Cracked Piece of Metal Self-Healed in Experiment That Stunned Scientists

Broken metal© Provided by ScienceAlert

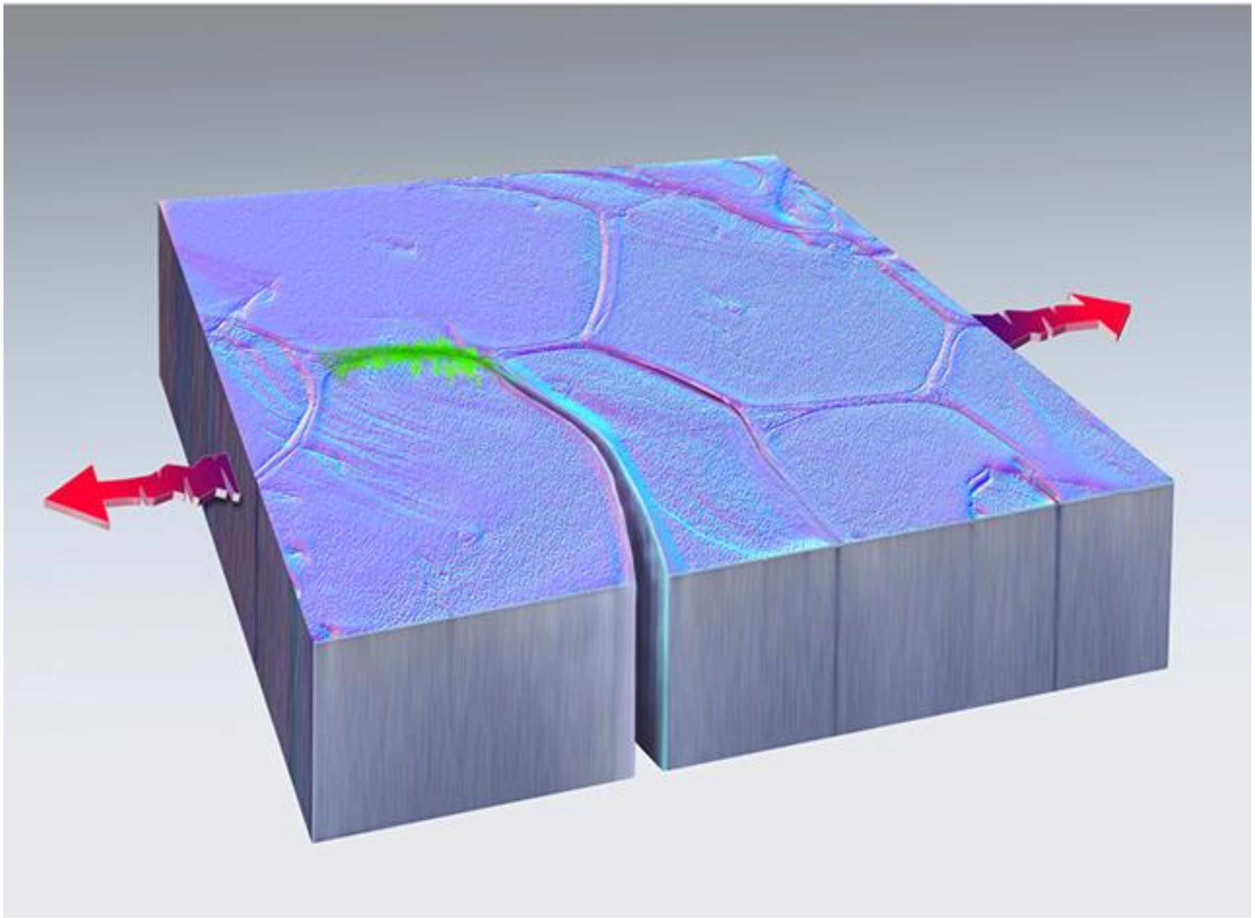
File this under 'That's not supposed to happen!'. In an experiment, scientists observed a metal healing itself. If this process can be fully understood and controlled, we could be at the start of a whole new era of engineering.

In a study published last year, a team from Sandia National Laboratories and Texas A&M University was testing the resilience of the metal, using a specialized transmission electron microscope technique to pull the ends of the metal 200 times every second.

They then observed the self-healing at ultra-small scales in a 40-nanometer-thick piece of platinum suspended in a vacuum.

Cracks caused by the kind of strain described above are known as fatigue damage: repeated stress and motion that causes microscopic breaks, eventually causing machines or structures to break.

Amazingly, after about 40 minutes of observation, the crack in the platinum started to fuse back together and mend itself before starting again in a different direction.



Pulling forces (red arrows) created a crack that healed (green) in platinum metal. (Dan Thompson/Sandia National Laboratories)

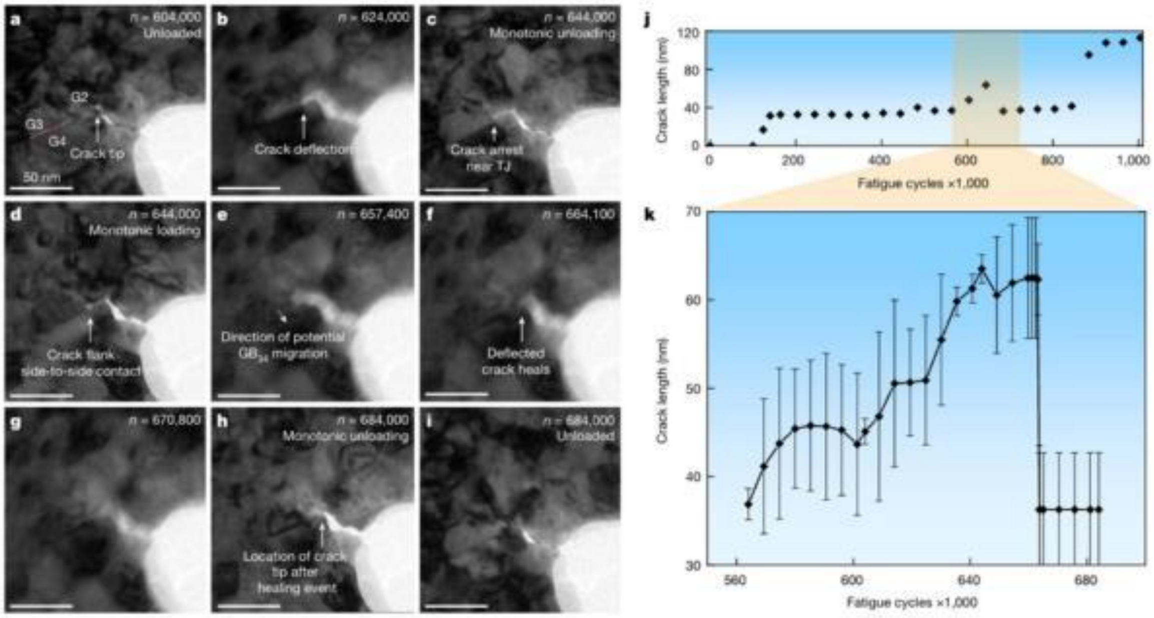
"This was absolutely stunning to watch first-hand," said materials scientist Brad Boyce from Sandia National Laboratories when the results were announced.

"We certainly weren't looking for it. What we have confirmed is that metals have their own intrinsic, natural ability to heal themselves, at least in the case of fatigue damage at the nanoscale."

These are exact conditions, and we don't know yet exactly how this is happening or how we can use it. However, if you think about the costs and effort required for repairing everything from bridges to engines to phones, there's no telling how much difference self-healing metals could make.

While the observation is unprecedented, it's not wholly unexpected. In 2013, Texas A&M University materials scientist Michael Demkowicz worked on a study predicting that this kind of nanocrack healing could happen, driven by the tiny crystalline grains inside metals essentially shifting their boundaries in response to stress.

Demkowicz also worked on this study, using updated computer models to show that his decade-old theories about metal's self-healing behavior at the nanoscale matched what was happening here.



Detailed observations of the healing process, taken from dynamic video. (Barr et al., Nature , 2023)

That the automatic mending process happened at room temperature is another promising aspect of the research. Metal usually requires lots of heat to shift its form, but the experiment was carried out in a vacuum; it remains to be seen whether the same process will happen in conventional metals in a typical environment.

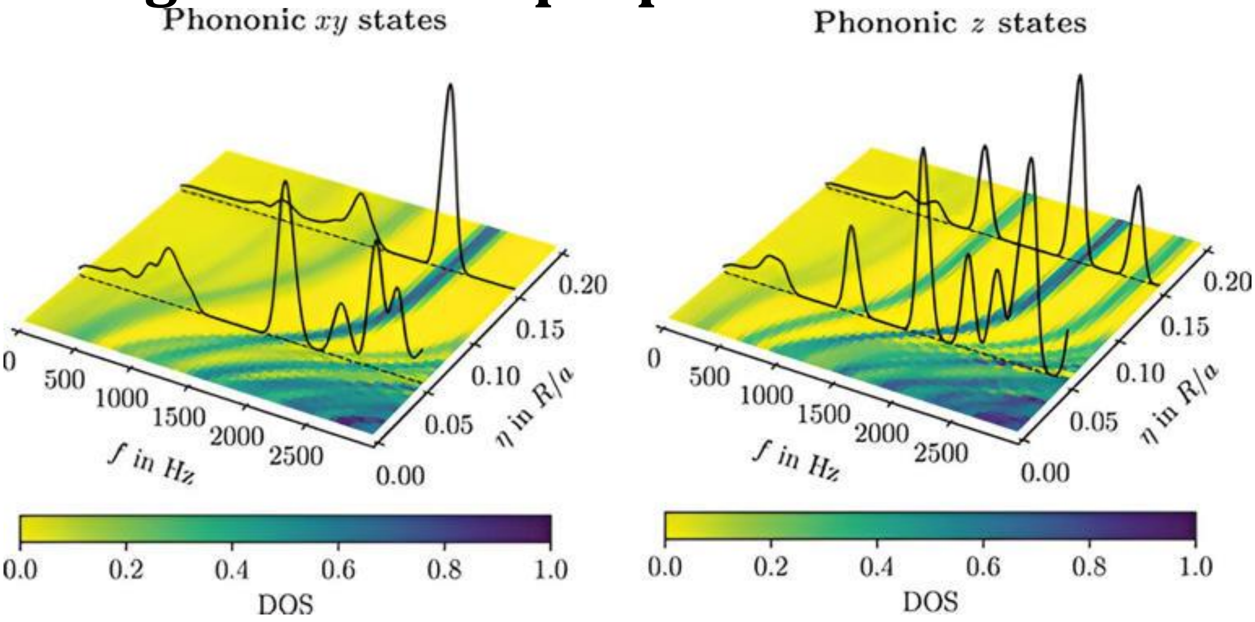
A possible explanation involves a process known as cold welding, which occurs under ambient temperatures whenever metal surfaces come close enough together for their respective atoms to tangle together.

Typically, thin layers of air or contaminants interfere with the process; in environments like the vacuum of space, pure metals can be forced close enough together to literally stick.

"My hope is that this finding will encourage materials researchers to consider that, under the right circumstances, materials can do things we never expected," said Demkowicz.

The research was published in *Nature*.

Research team proposes a novel type of acoustic crystal with smooth, continuous changes in elastic properties



Density of states of phononic crystals consisting of steel cylinders embedded in high-density polyethylene (HDPE), depicted here for σ = 50. Separate calculations were performed for two distinct cases: xy modes perpendicular (left) and z modes parallel to the scatterers (right). Notably, when broadening η softens the parameter step function, numerous new complete band gaps (vanishing DOS) appear for both modes. Credit: Europhysics Letters (2024). DOI: 10.1209/0295-5075/ad1de9© Provided by Phys.org

In dim light a cat sees much better than you do, as do dogs and nocturnal animals. That's because the structure of a cat's eye has a tapetum lucidum, a mirror-like layer immediately behind the retina. Light entering the eye that is not focused by the lens onto the retina is reflected off the tapetum lucidum, where the retina gets another chance to receive the light, process it, and send impulses to the optic nerve.

Optical scientists call this a photonic crystal. For a cat it's periodic parallel rods—it contains photonic bandgaps that are used to modify the flow of light, akin to the electron bandgaps in semiconductors, which are energy regions where no electron energy states exist. These materials have changes in their index of refraction and so modify and redirect the propagation of light.

Another example is the reflective markers on the pavement of highways that glow at night from a car's headlights. Photonic crystals, like the latter, are fabricated via layers of thin films using photolithography, hole drilling, laser writing and other techniques.

Photonic crystals prohibit light of certain frequencies in the parts of the crystalline medium that the light is traveling through. As defined by science, such crystals have periodic, distinct regions each with a periodic dielectric constant.

A dielectric is an electrically insulating material, without free electrons or atoms, opposing the flow of electrons when an electric field is applied. Instead, a dielectric material polarizes when an electric field is applied, with its molecules all pointing in the same direction. Distilled water—purified water that contains no minerals—is a dielectric material, and so is glass, porcelain, dry air, paper, and many other materials. Dielectrics are used in capacitors, liquid crystal displays, and other devices.

Extending this concept, "function photonic crystals" are materials that have a smooth, continuous change in refractive index, instead of a sharp, distinct periodicity. This enables fast electronic control of a material's properties.

The same concepts exist for phononic crystals. Phonons are quantized sound waves, just as photons are quantized light waves. A phononic crystal is a solid with continuous changes in its properties, creating a bandgap for photonic energies. Artificial structures with a periodic variation of elastic parameters can manipulate the propagation of elastic waves.

Now a team led by David Röhlig at the Technische Universität Chemnitz in Germany is proposing to create function phononic crystals, with smooth and continuous changes in elastic properties instead of strict periodic variations. The research is published in the journal *Europhysics Letters*.

The refractive index for sound would continually change inside the propagating medium, instead of step function discontinuities. In nature such substances are responsible for the long-wave propagation of sound waves in water and bent sound waves in the lower atmosphere.

Using high-performance computer simulations, the team focused on understanding the effect of a small deviation in material properties from the typical step function discontinuity on the phononic density of energy states.

Their results were surprising: even just small deviations from the ideal step function of a material could cause large, radical changes in the phononic band structure. This would lead to the emergence of many sought-after features, such as larger phonon band gaps and multiple phononic band gaps.

Because the phononic density of states can change so quickly for only small changes in the material properties, such properties would prove useful in making, for example, phononic lens in solid materials or water, or for new devices in materials science, applied physics and engineering.

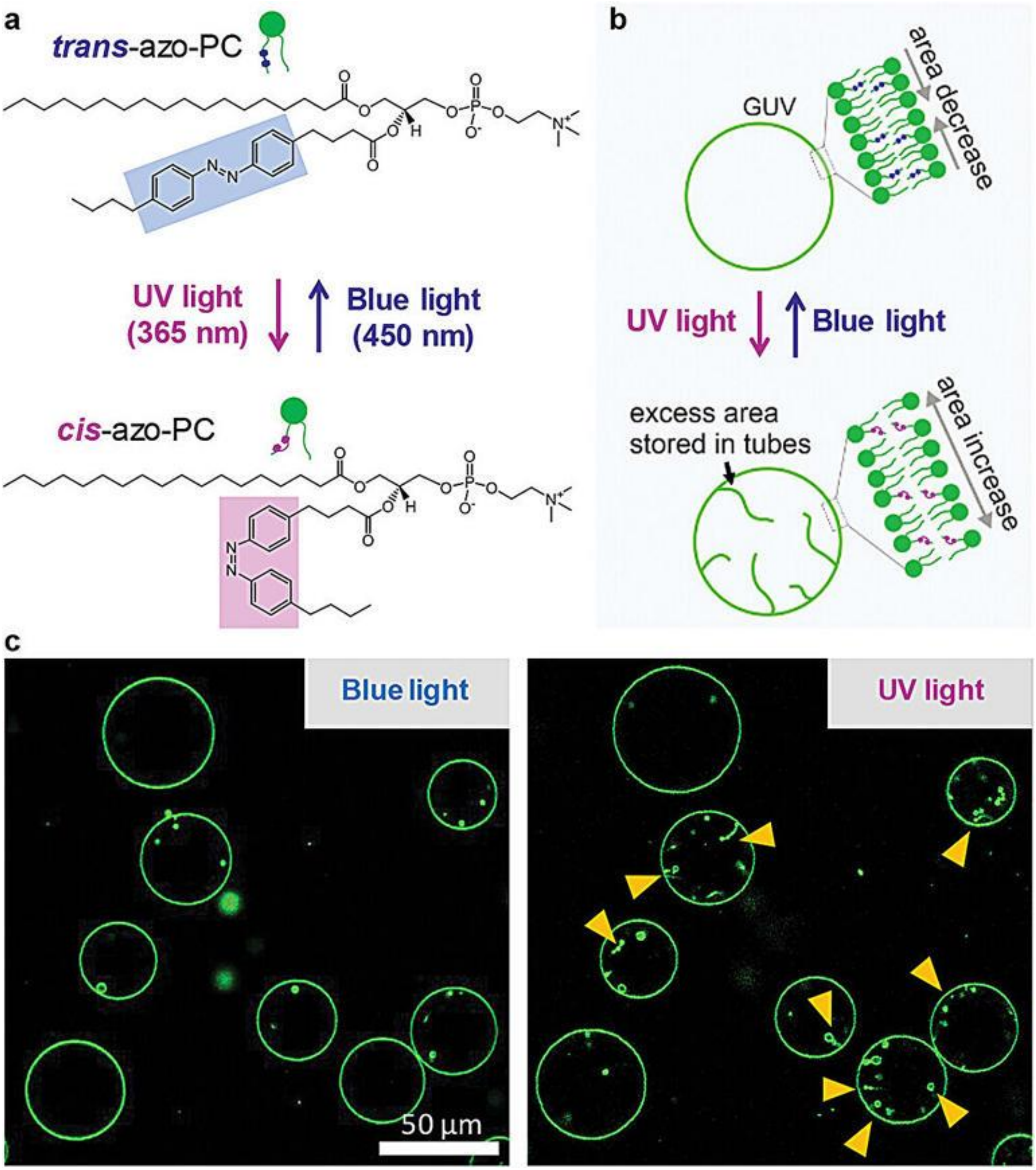
"Our findings present a novel perspective on phononic structures," said Röhlig, "offering an additional avenue to induce bandgap formation in specific geometries that lack this characteristic." Noting that the swift convergence of the density of states as the step function parameters change to be more continuous, Röhlig notes that the rapid changes would streamline potential manufacturing approaches.

"If further studies can validate our predictions experimentally, our results could find applications in microtechnology and mechatronics for the design of acousto-mechanical transducers and actuators," he said.

Even large-scale environments could be shaped, "such as arranging trees or other wooden building units, [objects] that have a known or specially designed radially continuous parameter profile regarding density and elastic properties, to enhance ambient soundproofing."

More information: David Röhlig et al, Function phononic crystals, *Europhysics Letters* (2024). DOI: 10.1209/0295-5075/ad1de9

With the flick of a switch: Shaping cells with light



Irradiation of membranes doped with photoswitchable azo-PC causes reversible area increase and morphological changes in GUVs. a) Molecular structures of cis and trans azo-PC photoswitchable isomers. b) Schematic illustration of the reversible membrane area changes in GUVs under UV and blue light. The excess area generated under UV irradiation can be stored in nanotubes. c) Confocal cross-sections showing membrane area change of POPC:azo-PC (1:1) GUVs labeled with 0.1 mol% Atto-647N-DOPE upon trans-cis photoisomerization and extensive nanotube formation in the GUV lumen (arrowheads); the right image shows the vesicle response after 1 s of UV light irradiation. Credit: Advanced Science (2024). DOI: 10.1002/advs.202309864© Provided by Phys.org

Imagine switching on a light and being able to understand and control the inner dynamics of a cell. This is what the Dimova group has achieved: by shining lights of different colors on replicates of cells, they altered the interactions between cellular elements. Controlling these complex interactions enables us to deliver specific drugs directly into the cells. And with the flick of a switch, we could adjust or even reverse this delivery, potentially revolutionizing the treatment of cells in a smart, accurate and non-invasive way.

Cells are the building blocks of our body and are organized into smaller components, each with a specialized function. Most of these components are enveloped by a protective membrane made of fats, with the exception of the biomolecular condensates. These tiny, dynamic droplets prepare the cell for rapid stress response by gathering and organizing repair molecules (among other functions).

Rumiana Dimova and her team at the Max Planck Institute of Colloids and Interfaces study the many and intricate ways in which condensates interact with membranes, and how they affect each other's shape and structure. In their latest work, published in *Advanced Science*, the researchers have focused on the process of endocytosis. This is how a cell wraps its outer membrane around nutrients or pathogens to "eat" them.

The researchers designed their own lab-made, simplified versions of cells—called giant vesicles—to simulate the cellular processes and analyze them under the microscope. They introduced fats that react to light ("photoswitchable lipids"). Dimova and her team observed how the membranes behaved when exposed to light of different colors: They changed their size and triggered various interactions with the condensates.

"When we shine ultraviolet light on a membrane, it grows and 'swallows' the condensates,"—explains Agustín Mangiarotti. "And we can also reverse the process by switching to blue light," adds Mina Aleksanyan, "so that the membrane shrinks, expelling the condensate."

The therapeutic potential of this research is immense. The combined use of giant vesicles and light could represent a non-invasive medical treatment to control cellular dynamics.

Light is inexpensive and sustainable. And because giant vesicles are synthetic (made in a lab), scientists can use them to probe several dynamics without resorting to culture cells from living organisms. Giant vesicles are also biomimetic—constructed from molecules found in the human body, such as fats and proteins. They are like tiny capsules that can carry drugs and then fuse organically with cells.

"Now we know that by modulating light we can control how vesicles shape the inner environment of a cell, which could help treat cellular disorders. It's like being able to sculpt a cell from the inside by flicking a light switch," concludes Dimova.

More information: Agustín Mangiarotti et al, Photoswitchable Endocytosis of Biomolecular Condensates in Giant Vesicles, *Advanced Science* (2024). DOI: 10.1002/advs.202309864

Provided by Max Planck Society

Computer model uncovers plant thickness growth mechanisms

Most research on plant stem cells focuses on the tips of roots and shoots, where growth occurs in height. But biologist Kirsten Ten Tusscher from Utrecht University explains that thickness growth is just as essential.

"Plants can't grow endlessly in height. They also need to grow in thickness, or they would simply fall over," she says.

The growth in thickness is what makes older trees visibly thicker and more robust over time. This growth is essential for structural strength, particularly in trees. Stem cells in the plant's cambium layer control this growth of width, producing wood to support the plant's structure. However, which genes enable these cambium stem cells to become active and how this is controlled has remained unclear until now.

Ten Tusscher and her team have developed a computer model that played a central role in an international study, which brought together scientists from Utrecht University and the University of Helsinki, Durham University, and the University of California. Her computer model provided fundamental insights, supporting lab results from the other team members as well as providing important predictions.

The work is published in the journal *Science*.

Computer model simulates wood formation

Ten Tusscher's model explores how specific genes "switch on" cambium stem cells as the plant develops, allowing for wood formation. While genes for height growth have been studied before, this is the first model to examine genes that control thickness growth and what determines where these genes are switched on.

From the model's output, Ten Tusscher's team found that thickness growth is controlled by overlapping gradients of specific chemical signals within the cambium layer. These gradients intersect to form a precise zone where stem cells are "switched on," guiding them to produce wood tissue. This interaction ensures that wood formation occurs steadily throughout the plant's life, providing the structural strength and stability needed to support height growth.

The computer model revolves around the small plant Arabidopsis, a species studied extensively by biologists worldwide to gain knowledge about plant growth in general. The model shows how cambium stem cells are activated and maintained, enabling continuous growth in thickness throughout a plant's life.

Improving forestry and CO_2 storage

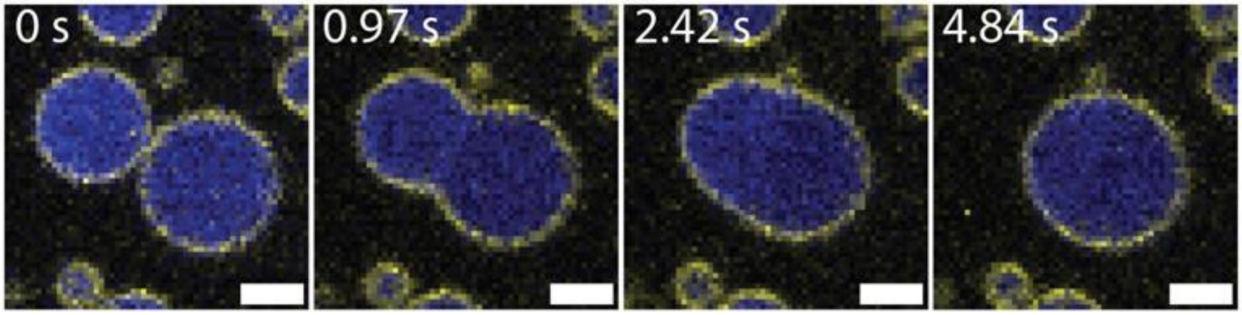
Understanding thickness growth isn't just a scientific milestone; it could lead to real-world applications in forestry and climate action. A deeper learning about plant growth is especially relevant for forestry, particularly in Finland, where forests play a major role in the economy, says Ten Tusscher.

"If you fully understand plant growth, and develop a tree that grows twice as fast in thickness, it's a great benefit for a more sustainable timber industry," says Ten Tusscher. "It's also advantageous for climate efforts, as faster-growing trees can store more CO_2. Perhaps it could even help researchers tune thickness growth in crops for better agricultural yield."

More information: Gugan Eswaran et al, Identification of cambium stem cell factors and their positioning mechanism, *Science* (2024). DOI: 10.1126/science.adj8752. www.science.org/doi/10.1126/science.adj8752

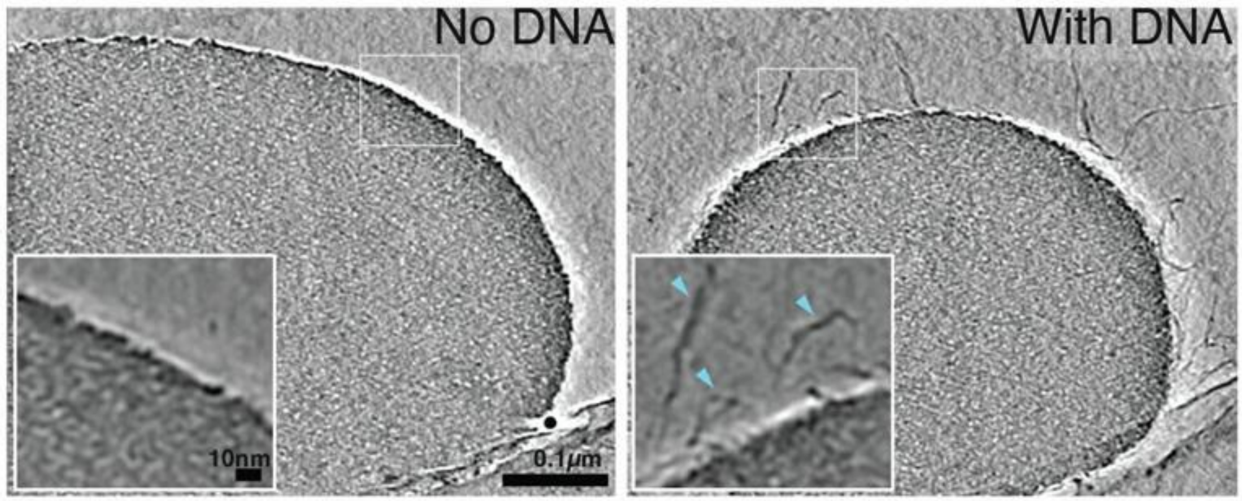
Provided by Utrecht University

Scientists discover a 'Goldilocks' zone for DNA organization, opening new doors for drug development



DNA (yellow) "shells" on the surface of polyP (blue)-magnesium ion condensates dynamically reorganize during droplet fusion. Credit: Scripps Research

In a discovery that could redefine how we understand cellular resilience and adaptability, scientists at Scripps Research have unlocked the secret interactions between a primordial inorganic polymer of phosphate known as polyphosphate (polyP), and two basic building blocks of life: DNA and the element magnesium. These components formed clusters of tiny liquid droplets–also known as condensates–with flexible and adaptable structures.

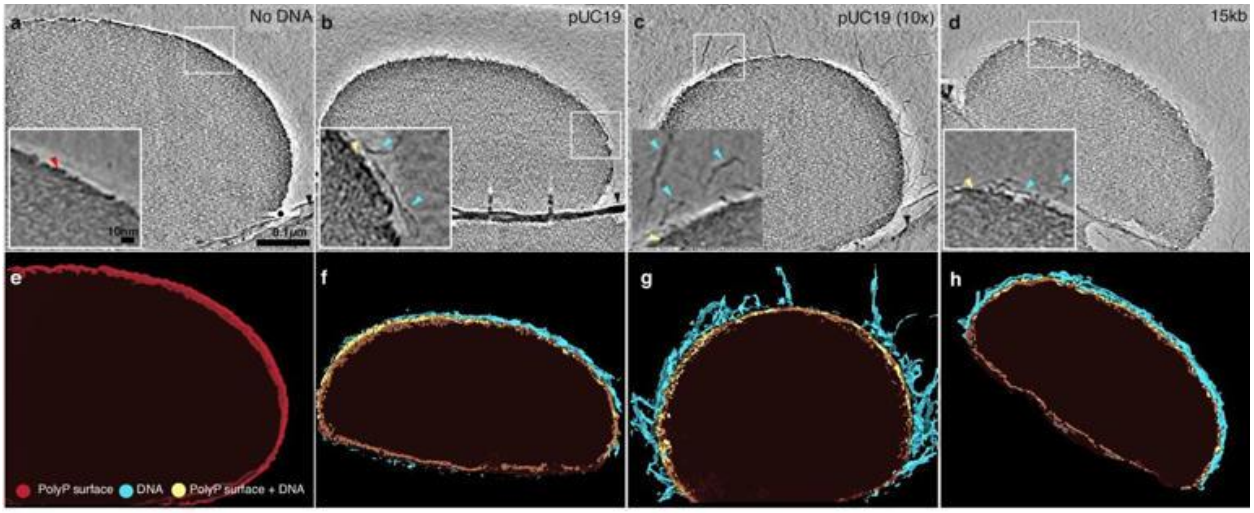


Cryo-electron tomography shows that DNA forms "hairy" filaments (cyan arrows in inset image) on the surface of polyP-magnesium ion condensates. Credit: Scripps Research

PolyP and magnesium are involved in many biological processes. Thus, the findings could lead to new methods for tuning cellular responses, which could have impactful applications in translational medicine.

The ensuing study, published in *Nature Communications* on October 26, 2024, reveals a delicate "Goldilocks" zone—a specific magnesium concentration range—where DNA wraps around polyP-magnesium ion condensates. Similar to a thin eggshell covering a liquid-like interior, this seemingly simple structure may help cells organize and protect their genetic material.

This work began as a collaboration between co-senior authors Associate Professor Lisa Racki, Ph.D., and Professor Ashok Deniz, Ph.D., both in the Department of Integrative Structural and Computational Biology at Scripps Research. Racki had been studying these structures in bacterial cells, while Deniz's next-door lab was exploring the physical chemistry of biomolecular condensates for the past decade. Collaboration, they realized, was the only way to unlock these ancient interactions.



Cryo-electron tomography shows topologies of different types of DNA on polyP condensates. Credit: Nature Communications (2024). DOI: 10.1038/s41467-024-53469-x

"We knew that DNA was in close proximity to the magnesium-rich polyP condensates in cells, but we were totally surprised by the beautiful spheres of DNA that lit up under the microscope," says Racki.

"Being molecular detectives, seeing these structures raised exciting questions for us about the physics and mathematics of the DNA shells and whether they influenced the polyP condensates," adds Deniz.

Their microscopy images revealed that DNA wraps itself around a condensate, creating a thin eggshell-like barrier. This shell could affect molecule transportation and also slow down fusion: the process where two condensates merge into one. Without DNA shells, polyP-magnesium ion condensates readily fused—like how oil drops and vinegar fuse in a salad dressing bottle when shaken.

However, careful examination showed that fusion overall slowed to varying extents, depending on DNA length. Longer DNA, the researchers suspected, caused greater entanglement on condensate surfaces—similar to how long hair tangles more than short hair.

DNA is more than 1,000 times thinner in diameter than condensates, making molecular details hard to visualize. Fortunately, infrastructure to capture such imaging has been developed by two other faculty members at Scripps Research: Assistant Professor Danielle Grotjahn, Ph.D., and Scripps Fellow Donghyun Raphael Park, Ph.D..

Teaming with Park, with help from Grotjahn, the researchers used cryo-electron tomography to closely examine the condensate surfaces. Using electrons instead of light, this technique captures three-dimensional, high-resolution images of samples that were rapidly frozen to preserve their structures. The new images revealed that DNA forms filaments protruding from condensate surfaces, resembling tangled hairs.

Another crucial discovery: DNA shell formation only occurred within a specific magnesium concentration range—too much or too little, and the shell wouldn't materialize. This "Goldilocks" effect highlights how cells can regulate condensate structure, size and function simply by tuning control parameters.

"Although we think of cellular interfaces as boundaries, they also create a new landscape by providing a surface for molecules to organize," notes Racki. "DNA may not actually be a tangled mess at the surface and is instead organized by these condensates."

In this context, Deniz and Racki are particularly interested in understanding DNA supercoiling—how DNA twists like a spring to fit inside cells.

"Cells have to manage their DNA curls," explains Racki. "Interestingly, the mathematics of DNA supercoiling results in 'action-at-a-distance' effects—like how twisting a rope can create coils far from where you're holding it."

The researchers suspect that DNA interactions with polyP condensates in cells might propagate local changes in DNA supercoiling over long distances, resulting in broader changes in gene expression and cell function. Investigating this effect is one of the team's next goals.

"We're excited by the prospects of leveraging these discoveries to develop new tools for cellular control—potentially simpler, more cost-effective approaches to manage biomatter for biomedicine," says Deniz.

In addition to Deniz, Racki, Grotjahn and Park, authors of the study, "Reentrant DNA shells tune polyphosphate condensate size," include co-first authors Ravi Chawla and Jenna K. A. Tom, and Tumara Boyd, Nicholas H. Tu and Tanxi Bai of Scripps Research.

More information: Ravi Chawla et al, Reentrant DNA shells tune polyphosphate condensate size, *Nature Communications* (2024). DOI: 10.1038/s41467-024-53469-x

Provided by The Scripps Research Institute

Can entangled particles communicate faster than light?

Entanglement is perhaps one of the most confusing aspects of quantum mechanics. On its surface, entanglement allows particles to communicate over vast distances instantly, apparently violating the speed of light. But while entangled particles are connected, they don't necessarily share information between them.

In quantum mechanics, a particle isn't really a particle. Instead of being a hard, solid, precise point, a particle is really a cloud of fuzzy probabilities, with those probabilities describing where we might find the particle when we go to actually look for it. But until we actually perform a measurement, we can't exactly know everything we'd like to know about the particle.

These fuzzy probabilities are known as quantum states. In certain circumstances, we can connect two particles in a quantum way, so that a single mathematical equation describes both sets of probabilities simultaneously. When this happens, we say that the particles are entangled.

When particles share a quantum state, then measuring the properties of one can grant us automatic knowledge of the state of the other. For example, let's look at the case of quantum spin, a property of subatomic particles. For particles like electrons, the spin can be in one of two states, either up or down. Once we entangle two electrons, their spins are correlated. We can prepare the entanglement in a certain way so that the spins are always opposite of each other.

If we measure the first particle, we might randomly find the spin pointing up. What does this tell us about the second particle? Since we carefully arranged our entangled quantum state, we now know with 100% absolute certainty that the second particle must be pointing down. Its quantum state was entangled with the first particle, and as soon as one revelation is made, both revelations are made.

But what if the second particle was on the other side of the room? Or across the galaxy? According to quantum theory, as soon as one "choice" is made, the partner particle instantly "knows" what spin to be. It appears that communication can be achieved faster than light.

The resolution to this apparent paradox comes from scrutinizing what is happening when—and more importantly, who knows what when.

Let's say I'm the one making the measurement of particle A, while you are the one responsible for particle B. Once I make my measurement, I know for sure what spin your particle should have. But you don't! You only get to know once you make your own measurement, or after I tell you. But in either case, nothing is transmitted faster than light. Either you make your own local measurement, or you wait for my signal.

While the two particles are connected, nobody gets to know anything in advance. I know what your particle is doing, but I only get to inform you at a speed slower than light—or you just figure it out for yourself.

So, while the process of entanglement happens instantaneously, the revelation of it does not. We have to use good old-fashioned no-faster-than-light communication methods to piece together the correlations that quantum entanglement demand.

Provided by Universe Today

Dark matter origins traced back to a mysterious "Dark Big Bang"

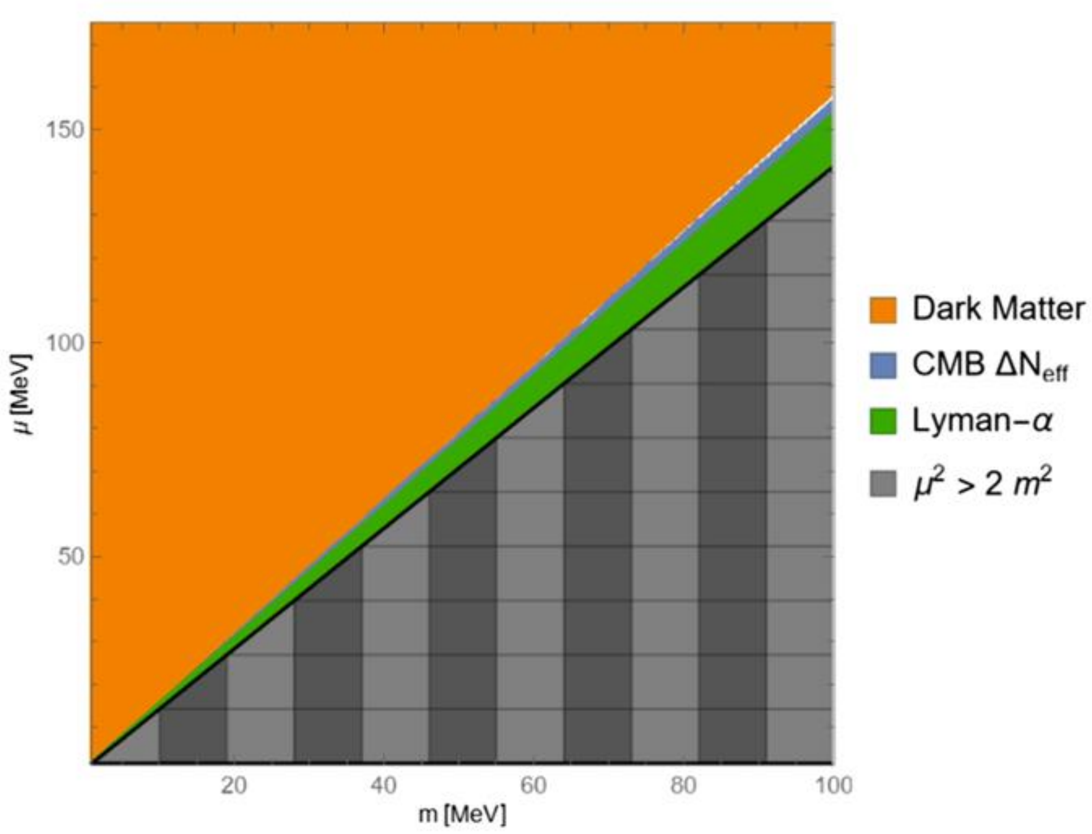
The mystery of dark matter first emerged in the 1930s, when astronomers observed discrepancies in the motions of galaxy clusters. (CREDIT: Mark Garlick)© The Brighter Side of News

Dark matter, an unseen yet influential component of the cosmos, continues to challenge physicists nearly a century after its effects were first noticed. Its gravitational influence, vital for understanding galactic structures and behaviors, is undeniable despite its elusive nature.

The mystery of dark matter first emerged in the 1930s, when astronomers observed discrepancies in the motions of galaxy clusters that could only be explained by the presence of unseen mass. Decades later, observations of the cosmic microwave background (CMB)—the faint radiation left over from the Big Bang—bolstered its significance in cosmological models.

Today, dark matter is thought to make up 27% of the universe’s total energy, according to the 2018 Planck Collaboration, dwarfing the mere 5% attributed to ordinary matter.

The quest to uncover the true nature of dark matter has driven scientists to explore various theoretical frameworks. Among the most promising is supersymmetry (SUSY), an extension of the Standard Model of particle physics that posits a partner particle for every known particle.



The available parameter space for a DBB when $\mu \gtrsim m$ (region1). (CREDIT: Phys.Rev.D)© The Brighter Side of News

Within this framework, weakly interacting massive particles (WIMPs) emerged as prime candidates for dark matter. WIMPs, if they exist, would interact weakly with ordinary matter and could be produced in particle accelerators like the Large Hadron Collider (LHC) or detected directly through underground experiments.

However, the search for WIMPs has so far come up empty. Experiments like DAMA, which reported an annual modulation signal potentially linked to dark matter, remain contentious. Efforts to reproduce such signals through projects like COSINE-100 have yet to yield conclusive results.

Similarly, the LHC has failed to detect any SUSY particles, casting doubt on the simplest WIMP models. As a result, scientists have begun to explore more exotic possibilities for dark matter's origin and behavior.

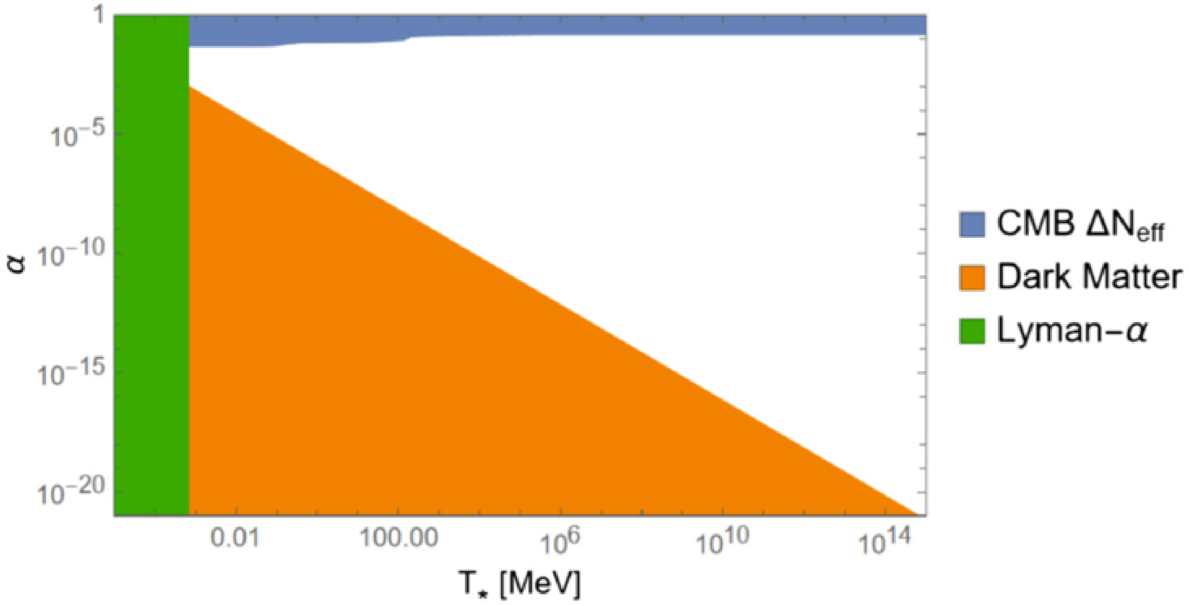
One such groundbreaking idea is the "Dark Big Bang" (DBB) theory, proposed in 2023 by Katherine Freese and Martin Winkler from the University of Texas at Austin. Unlike the conventional Big Bang, which explains the birth of ordinary matter, the DBB suggests that dark matter arose from a separate event.

This second Big Bang, occurring sometime after the first, would have generated dark matter through the decay of a quantum field trapped in a false vacuum state.

In this model, the early universe consisted of two sectors: the visible sector, filled with the familiar particles and forces, and a dark sector, which remained cold and decoupled. Eventually, the dark sector underwent its own phase transition, analogous to the visible sector’s hot Big Bang.

This transition produced a thermal bath of dark particles, governed by a unique set of physical laws. The DBB model is particularly versatile, as it can accommodate a wide range of dark matter particle masses, from as light as a few keV to as heavy as 101210^{12}1012 GeV.

What sets the DBB model apart is its potential to leave observable traces. The phase transition in the dark sector could generate gravitational waves (GWs), ripples in the fabric of spacetime. These GWs would be distinct from those produced by black hole mergers or neutron star collisions and could be detected by next-generation observatories.



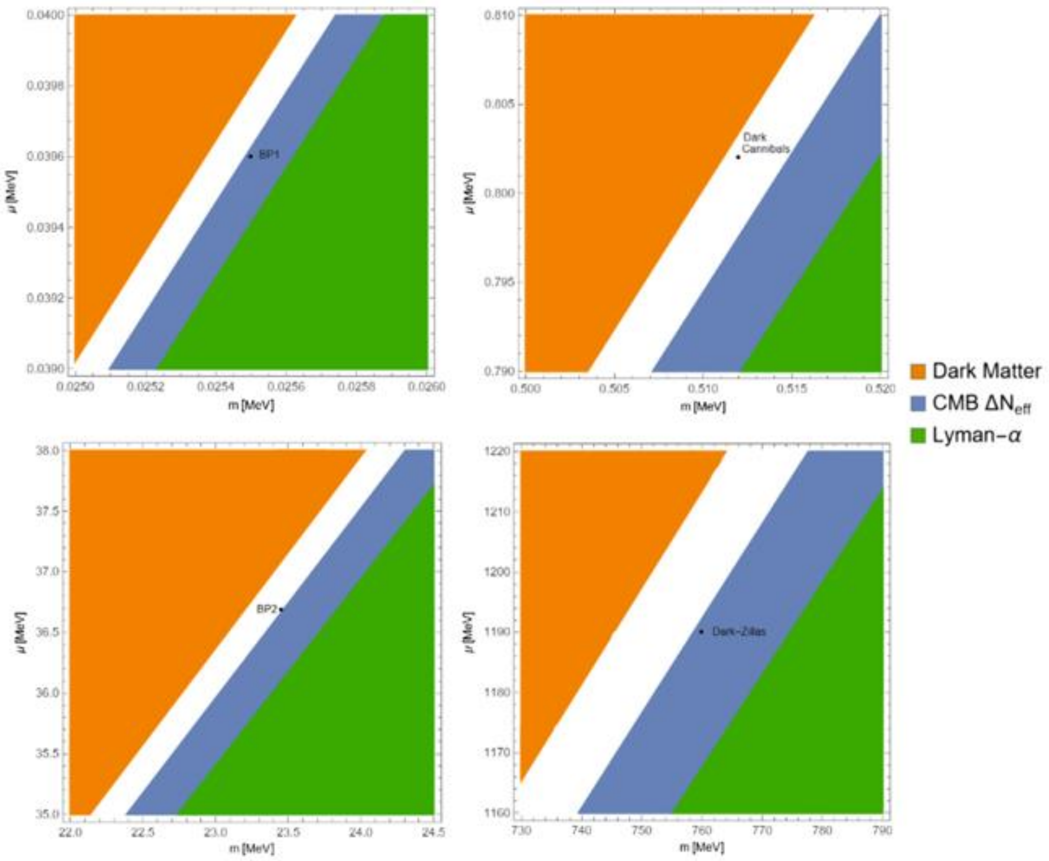
Bounds on the strength of a DBB and the latest a DBB can occur [18]. The allowed region for a DBB consistent with observations is the white space in the figure. The upper bound on α depends on the relativistic degrees of freedom in the Universe and remains constant above the mass scale of the heaviest SM particle. (CREDIT: Phys.Rev.D)© The Brighter Side of News

In particular, low-frequency GWs detectable by pulsar timing arrays (PTAs) such as the International Pulsar Timing Array (IPTA) and the Square Kilometer Array (SKA) could provide crucial evidence for the DBB.

Recent work by Cosmin Ilie, an Assistant Professor of Physics and Astronomy at Colgate University, and Richard Casey, a senior physics student, has further refined the DBB theory. Their study explores new parameter spaces for the dark sector's tunneling field, identifying scenarios that align with existing cosmological observations.

These scenarios predict not only the correct abundance of dark matter but also GW signals that could soon be within reach of PTA experiments.

“Detecting gravitational waves generated by the Dark Big Bang could provide crucial evidence for this new theory of dark matter,” says Ilie. Such detection would be groundbreaking, offering the first direct evidence of dark matter's distinct origin.



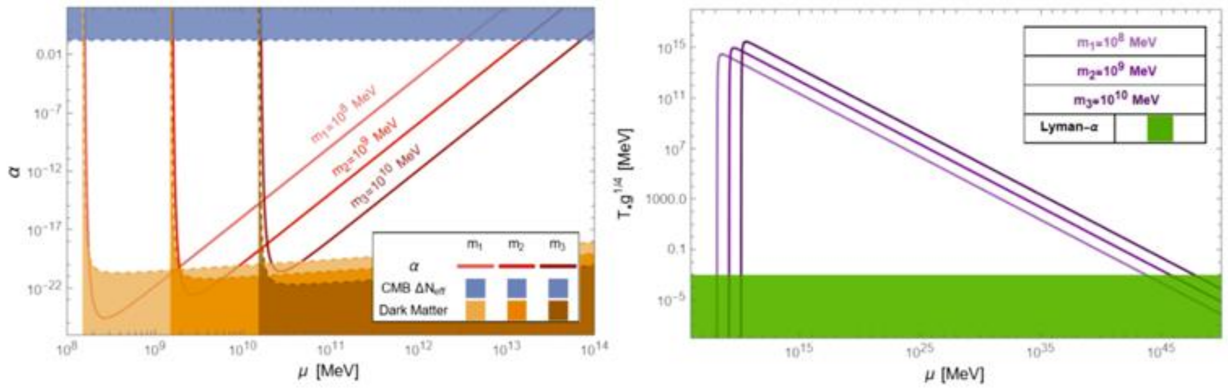
The choices of parameters for BP1 (panel 1) and Dark-Zillas (panel 4) slightly violate the upper bound on α. These discrepancies do not significantly impact the results of [18], as the parameters can be adjusted slightly to produce the same phase transition characteristics used in their analysis. (CREDIT: Phys.Rev.D)© The Brighter Side of News

The 2023 detection of background GWs by the NANOGrav collaboration, a part of IPTA, adds an intriguing dimension to this research. While the exact source of these waves remains uncertain, they could potentially align with the DBB model's predictions.

Beyond its implications for dark matter, the DBB theory offers a fresh perspective on the early universe. Traditionally, cosmology has operated under the assumption that all matter, dark or otherwise, emerged from the same event.

The idea of a dual-origin universe challenges this notion, suggesting a more complex interplay of forces and fields in the universe's infancy. If confirmed, the DBB model could reshape our understanding of cosmic evolution, from the formation of the first galaxies to the large-scale structure of the universe.

The search for dark matter is a central pillar of modern physics, driving advancements in technology and theory. Direct detection experiments, such as those conducted deep underground, continue to push the boundaries of sensitivity, aiming to capture fleeting interactions between dark matter particles and ordinary matter.



Left: values of α for fixed m. As before, α is bounded above by the CMB ΔNeff (blue) bound and below by the dark matter (orange) bounds. Right: temperature of the visible sector at the time of the DBB as a function of μ. (CREDIT: Phys.Rev.D)© The Brighter Side of News

Meanwhile, astrophysical observations, from the CMB to galactic rotation curves, provide indirect but compelling evidence for dark matter’s gravitational influence. The DBB model, with its unique predictions and testable consequences, adds a powerful new tool to this arsenal.

As observational capabilities advance, the prospect of detecting GWs from a DBB becomes increasingly plausible. Projects like SKA, expected to come online in the next decade, promise unprecedented sensitivity to low-frequency GWs. These efforts could finally lift the veil on dark matter's mysterious origins, answering questions that have puzzled scientists for generations.

In the broader context, understanding dark matter is not just a scientific pursuit but a quest to comprehend the fundamental nature of the universe. Whether through traditional particle physics or novel cosmological theories like the DBB, each discovery brings us closer to unveiling the full tapestry of existence.

Scientists make first-ever observation of 'negative time'

Researchers at the University of Toronto demonstrate the existence of “negative time© The Brighter Side of News

The interaction between light and matter has intrigued scientists for centuries. Central to this exploration is the behavior of photons—particles of light—when they travel through various media.

This journey involves complex interactions, including absorption and re-emission by atoms, that temporarily put the atoms into higher-energy states before they return to normal. These phenomena underpin groundbreaking technologies, such as quantum memories, and have opened new frontiers in nonlinear optics.

In a landmark experiment, researchers at the University of Toronto have delved into the puzzling concept of "negative time." Their findings, though not yet peer-reviewed, challenge long-held assumptions about time and energy in quantum mechanics.

Professor Aephraim Steinberg, who led the study, acknowledges the controversy their work has sparked but defends the insights as a crucial step toward understanding the peculiarities of quantum systems.

Quantum Mechanics and “Negative Time”

The notion of “negative time” arises from how photons interact with atoms in a dielectric medium. When light passes through such a material, some photons are absorbed by the atoms and later re-emitted. This interaction creates a temporary “excited” state in the atoms.

Conventional understanding assumed that photons followed a fixed timeline for absorption and re-emission. However, Steinberg’s team demonstrated that these durations can be less than zero, a result they describe as “negative time.”

To illustrate this concept, imagine cars entering a tunnel: if the average entry time for a thousand cars is noon, it might seem odd to observe the first cars exiting slightly earlier, say at 11:59 a.m. While earlier interpretations dismissed such results as artifacts of measurement, the Toronto researchers treated them as significant.

Their work suggests that these counterintuitive timings stem from quantum mechanics—a field known for its probabilistic and non-intuitive nature.

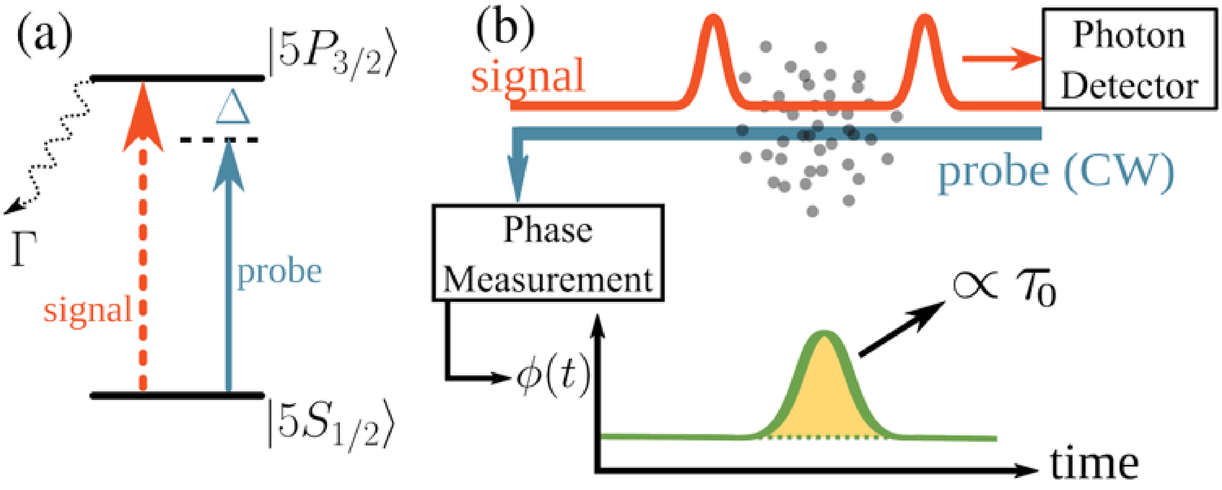
Daniela Angulo, a lead researcher on the team, played a pivotal role in measuring how long atoms remained in their excited states. Using carefully calibrated lasers in a basement laboratory filled with wires and aluminum-wrapped devices, the team optimized their experimental setup over two years.

“That time turned out to be negative,” Steinberg explained. This finding has profound implications for understanding photon behavior in dispersive media.

Negative Time and Group Delay

The group delay, a fundamental concept in light-matter interaction, refers to the time a photon seems to take to traverse a medium. This delay is influenced by the optical depth of the medium and the spectral properties of the light pulse. Steinberg’s team used quantum trajectory theory and weak-value formalism to explore how photons interact with atoms and spend time as atomic excitations.

Their calculations revealed that the time a photon spends as an atomic excitation aligns with the group delay, even when this delay becomes negative. In classical terms, such a delay would be impossible. However, quantum mechanics allows for these anomalous results, which are deeply tied to the probabilistic nature of particle interactions.



Schematics of experimental setup. (a) Atomic level scheme. (b) Conceptual diagram of the experimental apparatus: a resonant pulsed beam (signal) and off-resonant continuous-wave beam (probe) counter-propagate through a cloud of cold 85Rb atoms, detected at opposite sides of the apparatus. (CREDIT: ARXIV)© The Brighter Side of News

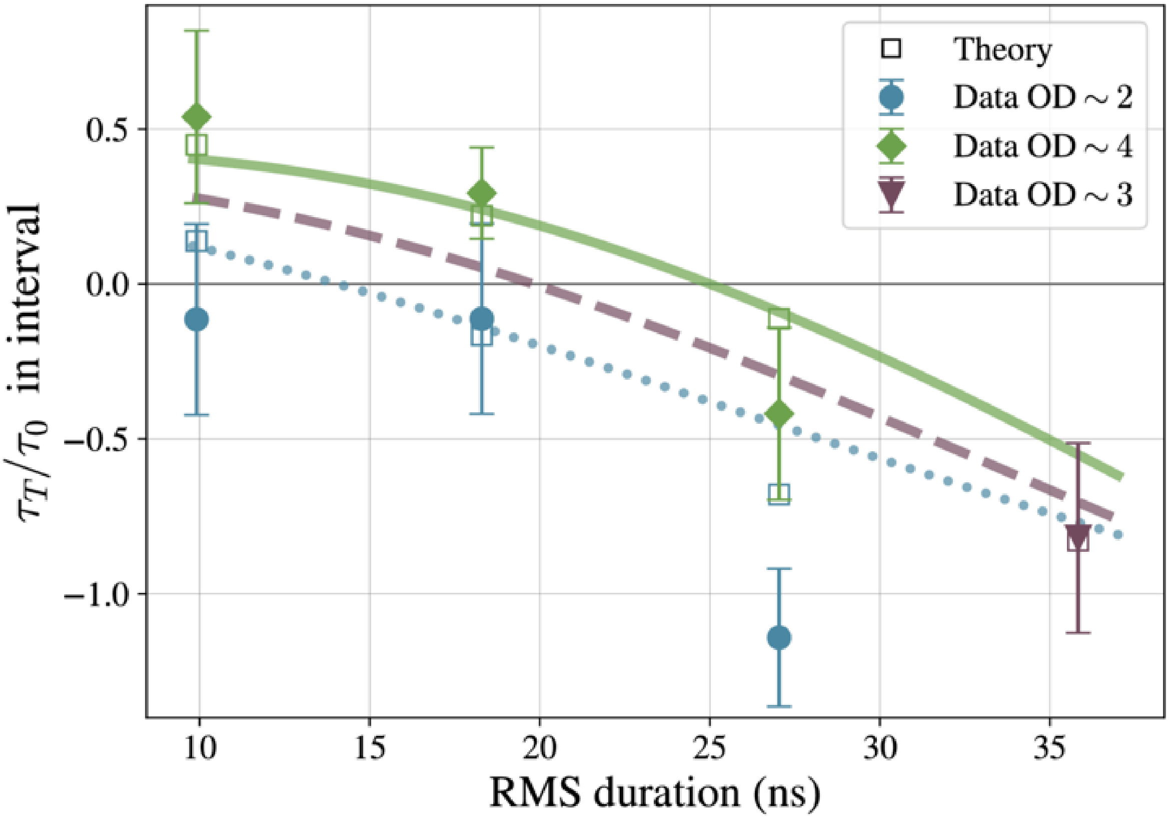
This insight was tested experimentally by observing the nonlinear phase shift imprinted on a probe beam, confirming the predictions across a range of optical parameters.

Steinberg likens this phase shift to the π phase-flip that occurs when a broadband pulse travels through an optically dense medium. This phenomenon highlights the intricate interplay between quantum coherence and material properties, challenging traditional assumptions about how light propagates.

The Toronto team’s findings underscore the nuanced behavior of photons and atoms in quantum systems. Their earlier experiments demonstrated that transmitted photons spent nearly as much time in an excited atomic state as scattered photons. These results suggested that a significant fraction of excited atoms contributed to coherent forward emission, a conclusion supported by theoretical models.

In the latest study, the researchers extended these insights, demonstrating that negative group delays are not just mathematical curiosities but observable phenomena. Their experiments also showed that photons carried no information in this process, preserving the integrity of Einstein's theory of special relativity. This ensures that no physical laws—such as the cosmic speed limit—are violated.

Steinberg emphasizes that the concept of "negative time" does not imply time travel. "We don't want to say anything traveled backward in time," he clarified. Instead, these results illuminate the complex and sometimes counterintuitive dynamics of quantum systems, where particles do not adhere to fixed timelines but operate within a spectrum of possible behaviors.



Broader Implications and Skepticism

While the findings have attracted global attention, they have also faced skepticism. German theoretical physicist Sabine Hossenfelder criticized the interpretation of "negative time" in a widely viewed YouTube video. She argued that this term misrepresents what the experiments reveal about photon behavior and phase shifts in a medium.

“The negative time in this experiment has nothing to do with the passage of time,” Hossenfelder stated. “It’s just a way to describe how photons travel through a medium and how their phases shift.”

Angulo and Steinberg, however, maintain that their work addresses critical gaps in understanding light’s interaction with matter. They argue that negative group delays provide new insights into the behavior of light in dispersive media, which could have far-reaching implications for quantum optics and photonic technologies.

The researchers also defended their choice of terminology, acknowledging that it provokes debate but also stimulates deeper discussions about the nature of quantum phenomena. “We’ve made our choice about what we think is a fruitful way to describe the results,” Steinberg said. He noted that while practical applications remain speculative, their findings lay the groundwork for exploring new aspects of quantum physics.

As the debate over “negative time” unfolds, the Toronto team’s work exemplifies the spirit of scientific inquiry. By challenging conventional wisdom and pushing the boundaries of what is measurable, they invite the scientific community to reconsider long-held assumptions about time, light, and quantum mechanics.

Their research, though still in its early stages, opens new avenues for studying light-matter interactions and the role of group delays in quantum systems. Whether or not “negative time” becomes an accepted term, the insights it represents will likely influence the trajectory of quantum physics for years to come.

World's 1st mechanical qubit uses no light or electronics. It could lead to ultra-precise gravity-sensing tech.

Scientists have created the world's first mechanical qubit: a tiny, moving system that stores quantum information using vibrations instead of electric currents or light.

Qubits are the fundamental units of quantum information. Unlike the bits you'd find in a classical computer, qubits can exist as 0, 1, or a superposition of both, thanks to the weird inner workings of quantum mechanics and entanglement.

Traditionally, these are made from superconducting circuits, charged atoms (ions), or light particles (photons). The new mechanical qubit, however, uses phonons — a type of "quasiparticle" — generated by vibrations within

A quasiparticle is a concept used to describe the behavior and interactions of a group of particles as if they were acting as a single particle. In this case, phonons represent quasiparticles that essentially serve as carriers of vibrational energy.

The breakthrough could pave the way for ultra-sensitive sensor technologies capable of detecting forces like gravity, as well as new methods for maintaining stability in quantum computers for longer periods, the scientists said. They published their study Nov. 14 in the journal Science.

Related: Will we ever have quantum laptops?

Mechanical systems have historically been considered too challenging to be used as qubits because, thanks to the principles of quantum mechanics, they are never completely still. This means there is always residual motion that needs to be accounted for and controlled in order for them to work at the quantum level.

Likewise, mechanical oscillators — devices that store and transfer energy in the form of phonons — are typically subject to harmonic vibrations at evenly spaced energy levels. This is an issue, the scientists explained, because uniform spacing makes it difficult to isolate the two energy states needed to represent the 0 and 1 of a qubit.

"[The challenge] is whether you can make the energy levels unequally spaced enough that you can address two of them without touching the others," study co-author Yiwen Chu, a physicist at ETH Zürich, told Science.

The researchers tackled this problem by creating a "hybrid" system, coupling a sapphire crystal resonator measuring 400 micrometers (0.4 mm) with a superconducting qubit, and tuning the two to interact at slightly offset frequencies. When the resonator and qubit interacted, it blended their quantum states, resulting in unevenly spaced energy levels in the resonator — a phenomenon known as "anharmonicity."

This enabled the researchers to isolate two distinct energy states, effectively turning the resonator into a mechanical qubit.

While the mechanical qubit could hold and manipulate quantum information, the system’s fidelity — a measure of how accurately it performs quantum operations — was recorded as just 60%. By comparison, state-of-the-art superconducting qubits often achieve fidelities above 99%.

Even so, mechanical qubits may offer unique advantages, the scientists said. For instance, they can interact with forces like gravity in ways that other quantum systems cannot, making them promising candidates for the development of highly sensitive quantum sensors.

Mechanical qubits may also be able to store quantum information for longer periods of time, they said. This is critical for maintaining coherence — a measure of how long a system can stay stable and perform calculations using quantum data without interference.

The researchers are now working to link multiple mechanical qubits together to perform basic calculations, which they said would mark a key step toward practical applications for the technology.

Is the universe a fractal?

For decades, cosmologists have wondered if the large-scale structure of the universe is a fractal: if it looks the same no matter the scale. And the answer is: no, not really. But in some ways, yes. Look, it's complicated.

Our universe is unimaginably vast and contains somewhere around 2 trillion galaxies. These galaxies aren't scattered around randomly, but are assembled into a series of ever-larger structures. There are the groups, containing at most a dozen galaxies or so. Then there are the clusters, which are home to a thousand galaxies and more. Above them are the superclusters, which twist and wind for millions of light-years.

Is this the end of the story?

In the mid 20th century, Benoit Mandelbrot brought the concept of fractals into the mainstream. Mandelbrot didn't invent the concept of fractals—mathematicians had been studying self-similar patterns for ages—but he did coin the word and usher in our modern study of the concept. The basic idea of a fractal is that you can use a single mathematical formula to define a structure at all scales. In other words, you can zoom in and out of a fractal and it still maintains the same shape.

Fractals appear everywhere in nature, from the branches of a tree to the edges of a snowflake. And Mandelbrot himself wondered if the universe is a fractal. If, as we zoom out, we will see the same kinds of structures appearing again and again.

And in a way, that's what we see: a hierarchy of structures at ever-larger scales in the universe. But that hierarchy does come to an end. At a certain scale, roughly 300 million lightyears across, the cosmos becomes homogenous, meaning that there are no larger structures and the universe is (at that scale) roughly the same from place to place.

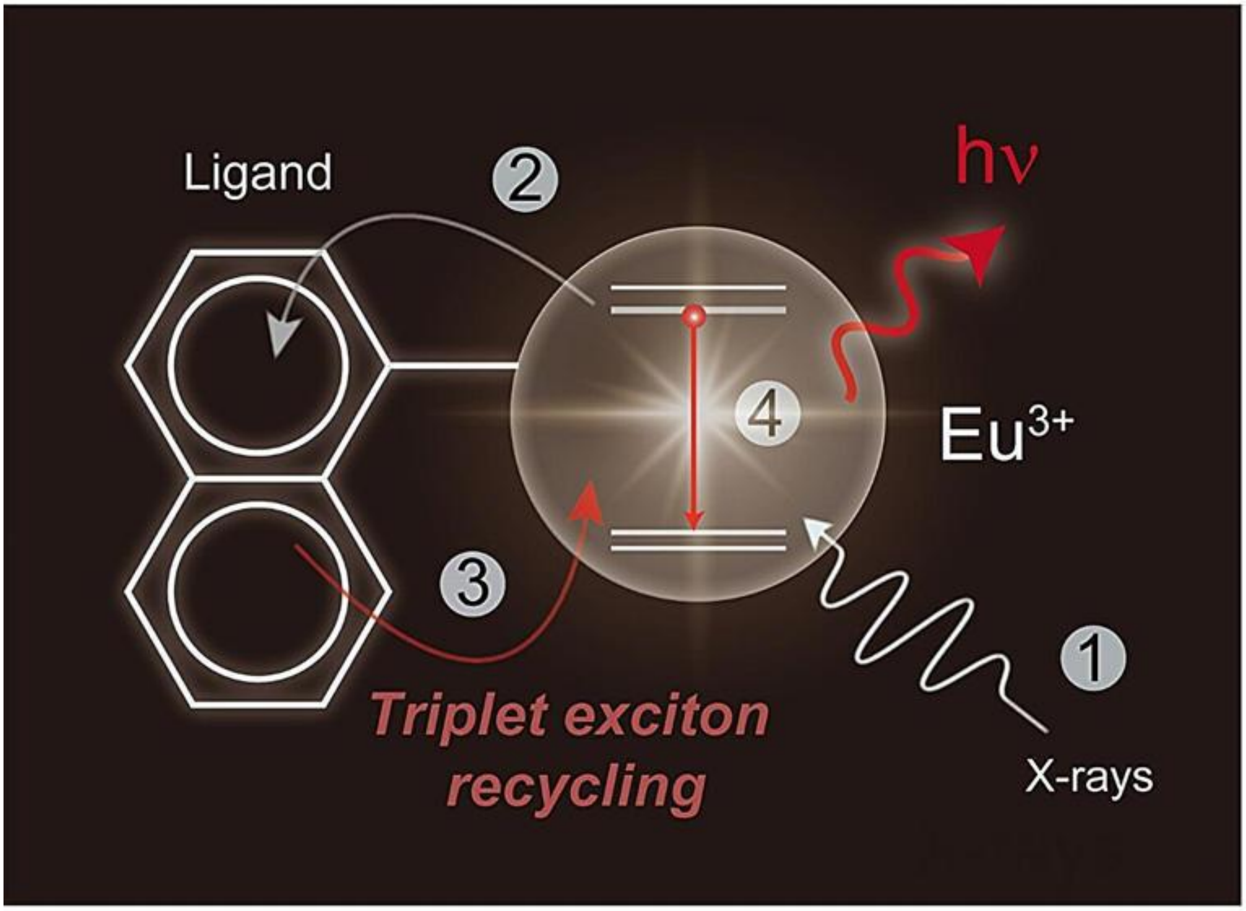
The universe is definitely not a fractal, but parts of the cosmic web still have interesting fractal-like properties. For example, clumps of dark matter called "halos," which host galaxies and their clusters, form nested structures and sub-structures, with halos holding sub-haloes, and sub-sub-halos inside those.

Conversely, the voids of our universe aren't entirely empty. They do contain a few, faint dwarf galaxies...and those few galaxies are arranged in a subtle, faint version of the cosmic web. In computer simulations, the sub-voids within that structure contain their own effervescent cosmic webs too.

So, while the universe as a whole isn't a fractal, and Mandelbrot's idea didn't hold up, we can still find fractals almost everywhere we look.

Provided by Universe Today

Novel molecular design achieves 1,300-fold increase in scintillator radioluminescence



The process of triplet exciton-mediated energy transfer from molecular antenna to lanthanide centers (Eu^{3+}). X-ray irradiation (1) triggers a cascade of secondary X-ray excitations, which are subsequently captured by organic ligands (2) after thermalization and (3) subsequently transferred back to the lanthanide centers via resonance energy transfer (4), resulting in enhanced radioluminescence (hv). Credit: Nature Photonics (2024). DOI: 10.1038/s41566-024-01586-w

Scientists from the National University of Singapore (NUS) have developed a highly effective and general molecular design that enables an enhancement in radioluminescence within organometallic scintillators by more than three orders of magnitude. This enhancement harnesses X-ray-induced triplet exciton recycling within lanthanide metal complexes.

Detection of ionizing radiation is crucial in diverse fields, such as medical radiography, environmental monitoring and astronomy. As a result, significant efforts have been dedicated to the development of luminescent materials that respond to X-rays.

However, current high-performance scintillators are almost exclusively limited to ceramic and perovskite materials, which face issues such as complex manufacturing processes, environmental toxicity, self-absorption and stability problems.

Organic phosphors present a promising alternative owing to their flexibility and cost-effectiveness. However, they are less efficient in X-ray detection because of weak X-ray absorption and limited use of molecular triplet excitons.

While halogen-doped organic phosphors and thermally activated delayed fluorescence molecules show potential, they require precise structural engineering and face absorption and reabsorption challenges, limiting their efficiency.

A research team led by Professor Liu Xiaogang from the Department of Chemistry at NUS, leveraged rare-earth X–ray absorption and ligand-mediated triplet exciton harvesting to overcome these challenges and significantly improved the performance of molecular scintillators.

The effective trapping of the energy dissipated during secondary X-ray relaxation via organic ligands led to a remarkable 1,300-fold increase in radioluminescence compared to lanthanide salts.

The study unveiled the role of triplet exciton recycling in determining scintillation efficiency, demonstrating that high photoluminescence quantum yield may not necessarily result in high scintillation efficiency.

The research was conducted in collaboration with Professor Yiming Wu from Xiamen University, China and Professor Xian Qin from Fujian Normal University, China.

The findings were published in the journal *Nature Photonics*.

Significantly, these organolanthanide compounds exhibit robust resistance to high-energy radiation and show scintillation efficiencies that surpassed those of well-known organic scintillators and inorganic LYSO:Ce crystals. Their performance was also comparable to those of CsI:Tl crystals.

By tailoring the metal centers and their coordination ligands, the researchers demonstrate the ability to achieve full-spectral X-ray scintillation from the ultraviolet to near-infrared range. Additionally, their methodology enables the fine-tuning of emission lifetimes, ranging from 50 nanoseconds to 900 microseconds.

These organolanthanide scintillators exhibit substantial Stokes shifts and offer the advantage of synthesis and processing at room temperature in solution form. Additionally, they demonstrate excellent solubility, stability, and flexibility, allowing molecular-level mixing for high-resolution radiographic imaging and potential applications in X-ray-mediated deep-tissue radiotherapy.

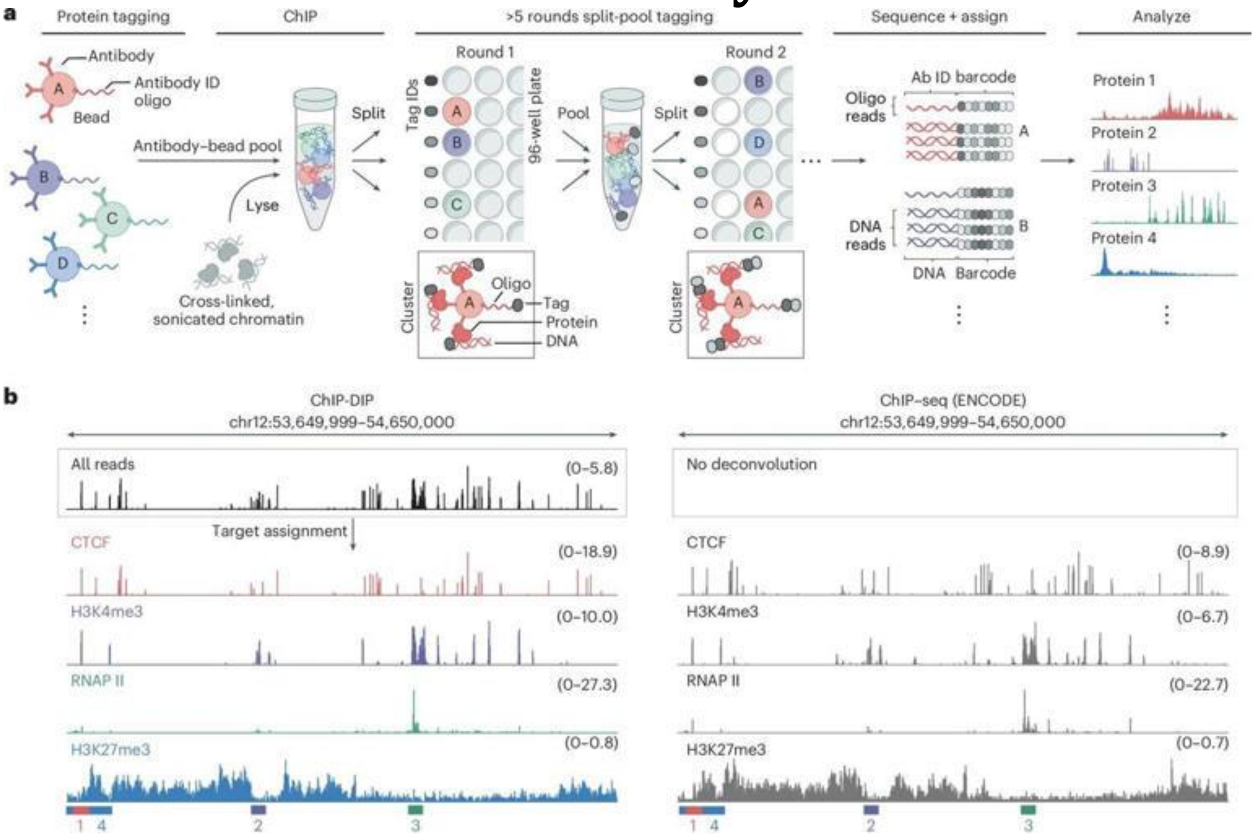
Prof Liu said, "The efficiency of triplet exciton recycling holds the key to better scintillation performance. These discoveries lend profound insights into X-ray-induced exciton migration dynamics and radioluminescence behavior, shaping the future of organic scintillators and their harnessing of high-energy X-ray quanta.

"The high stability of radioluminescence, large Stokes shift and full spectral tunability make organolanthanide molecules a promising platform for scintillation applications."

More information: Jiahui Xu et al, Ultrabright molecular scintillators enabled by lanthanide-assisted near-unity triplet exciton recycling, *Nature Photonics* (2024). DOI: 10.1038/s41566-024-01586-w

Provided by National University of Singapore

New method maps hundreds of proteins in cell nuclei simultaneously



ChIP-DIP is a highly multiplexed method for mapping proteins to genomic DNA. Credit: Nature Genetics (2024). DOI: 10.1038/s41588-024-02000-5

Caltech researchers have developed a new method to map the positions of hundreds of DNA-associated proteins within cell nuclei all at the same time. The method, called ChIP–DIP (Chromatin ImmunoPrecipitation Done In Parallel), is a versatile tool for understanding the inner workings of the nucleus during different contexts, such as disease or development.

The research was conducted in the laboratory of Mitchell Guttman, professor of biology, and is described in a paper that appears in the journal *Nature Genetics*.

Nearly all cells in the human body contain the same DNA, which encodes the blueprint for creating every cell type in the body and directing their activities. Despite having the same genetic material, different cell types express unique sets of proteins, allowing for the various cells to perform their specialized functions and to adapt to conditions within their environments. This is possible because of careful regulation within the nucleus of each cell and involves thousands of regulatory proteins that localize to precise places in the nucleus.

Because the nucleus is 50 times smaller than the width of a human hair, a cell's DNA—which measures 2 meters long when stretched out end to end—is wrapped up like spools of thread around protein structures called histones. Histones can be modified and reorganized during a cell's lifetime to reveal different sections of DNA while packing others away, allowing the cell to change the set of proteins that are expressed and, hence, its function. (As an analogy, imagine packing away your winter clothes in the back of your closet during summer and bringing them back out as it gets colder.)

Thus, though the full complement of DNA within a brain cell and a liver cell is the same, the two cells have different histone modifications and other regulatory proteins, allowing the expression of unique sets of genes in each. If this regulation goes awry, it can lead to serious diseases such as cancer, inflammatory diseases, or neurodegeneration.

Despite its importance, understanding gene regulation has been very challenging because previous methods to study regulatory proteins map them one at a time. ChIP–DIP now enables researchers to simultaneously map hundreds of DNA-associated regulatory proteins and take snapshots of how they change over time.

Isabel Goronzy (Ph.D. '24), a former graduate student in the Guttman lab and co-first author of the new paper, explains the power of the new technique, "We used ChIP–DIP to show how after an inflammatory event, cells of the immune system rapidly alter their histone proteins within a span of hours in order to activate inflammatory genes.

"We also used ChIP–DIP to identify combinations of proteins that regulate which genes are active or will become active in response to stress or during development. Previous consortium-based international projects have taken nearly a decade to conduct a few thousand experiments, but we have now done over 500 in the span of a few weeks."

The technology is exceedingly powerful for understanding gene regulation during different disease states, the researchers say. While previous techniques could only map a single type of protein at a time, ChIP–DIP can look at hundreds at once to give a comprehensive picture in rare cell types and in both healthy and disease tissue samples from patients.

"We can apply ChIP–DIP to understand the epigenetic signatures [how environmental factors influence gene expression] of diseases," says postdoctoral scholar Andrew Perez (Ph.D. '24), co-first author on the new study. "We only need one sample to map hundreds of proteins at once."

"This has been a long-standing goal of the genomics field for decades," Guttman says. "ChIP–DIP changes the paradigm of what's possible."

More information: Andrew A. Perez et al, ChIP-DIP maps binding of hundreds of proteins to DNA simultaneously and identifies diverse gene regulatory elements, *Nature Genetics* (2024). DOI: 10.1038/s41588-024-02000-5

Provided by California Institute of Technology

What is the universe expanding into if it’s already infinite?

The universe is full of stars, galaxies and planets – it's expanding every day.© NASA/JPL-Caltech/University of Wisconsin via AP

When you bake a loaf of bread or a batch of muffins, you put the dough into a pan. As the dough bakes in the oven, it expands into the baking pan. Any chocolate chips or blueberries in the muffin batter become farther away from each other as the muffin batter expands.

The expansion of the universe is, in some ways, similar. But this analogy gets one thing wrong – while the dough expands into the baking pan, the universe doesn’t have anything to expand into. It just expands into itself.

It can feel like a brain teaser, but the universe is considered everything within the universe. In the expanding universe, there is no pan. Just dough. Even if there were a pan, it would be part of the universe and therefore it would expand with the pan.

Even for me, a teaching professor in physics and astronomy who has studied the universe for years, these ideas are hard to grasp. You don't experience anything like this in your daily life. It's like asking what direction is farther north of the North Pole.

Another way to think about the universe's expansion is by thinking about how other galaxies are moving away from our galaxy, the Milky Way. Scientists know the universe is expanding because they can track other galaxies as they move away from ours. They define expansion using the rate that other galaxies move away from us. This definition allows them to imagine expansion without needing something to expand into.

The expanding universe

The universe started with the Big Bang 13.8 billion years ago. The Big Bang describes the origin of the universe as an extremely dense, hot singularity. This tiny point suddenly went through a rapid expansion called inflation, where every place in the universe expanded outward. But the name Big Bang is misleading. It wasn't a giant explosion, as the name suggests, but a time where the universe expanded rapidly.

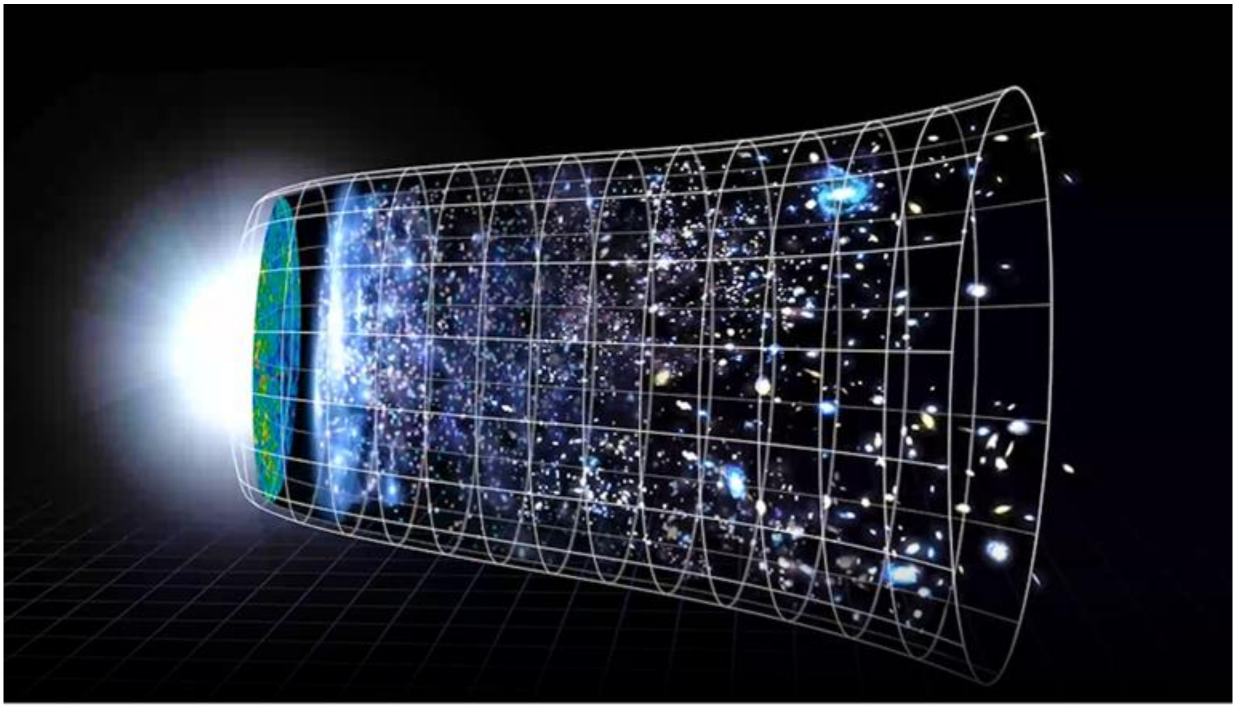
The universe then quickly condensed and cooled down, and it started making matter and light. Eventually, it evolved to what we know today as our universe.

The idea that our universe was not static and could be expanding or contracting was first published by the physicist Alexander Friedman in 1922. He confirmed mathematically that the universe is expanding.

While Friedman proved that the universe was expanding, at least in some spots, it was Edwin Hubble who looked deeper into the expansion rate. Many other scientists confirmed that other galaxies are moving away from the Milky Way, but in 1929, Hubble published his famous paper that confirmed the entire universe was expanding, and that the rate it's expanding at is increasing.

This discovery continues to puzzle astrophysicists. What phenomenon allows the universe to overcome the force of gravity keeping it together while also expanding by pulling objects in the universe apart? And on top of all that, its expansion rate is speeding up over time.

Many scientists use a visual called the expansion funnel to describe how the universe's expansion has sped up since the Big Bang. Imagine a deep funnel with a wide brim. The left side of the funnel – the narrow end – represents the beginning of the universe. As you move toward the right, you are moving forward in time. The cone widening represents the universe's expansion.



The expansion funnel visually shows how the universe's rate of expansion has increased over time. At the left of the funnel is the Big Bang, and since then, the universe has expanded at a faster and faster rate.© NASA

Scientists haven't been able to directly measure where the energy causing this accelerating expansion comes from. They haven't been able to detect it or measure it. Because they can't see or directly measure this type of energy, they call it dark energy.

According to researchers' models, dark energy must be the most common form of energy in the universe, making up about 68% of the total energy in the universe. The energy from everyday matter, which makes up the Earth, the Sun and everything we can see, accounts for only about 5% of all energy.

Outside the expansion funnel

So, what is outside the expansion funnel?

Scientists don't have evidence of anything beyond our known universe. However, some predict that there could be multiple universes. A model that includes multiple universes could fix some of the problems scientists encounter with the current models of our universe.

One major problem with our current physics is that researchers can't integrate quantum mechanics, which describes how physics works on a very small scale, and gravity, which governs large-scale physics.

The rules for how matter behaves at the small scale depend on probability and quantized, or fixed, amounts of energy. At this scale, objects can come into and pop out of existence. Matter can behave as a wave. The quantum world is very different from how we see the world.

At large scales, which physicists call classical mechanics, objects behave how we expect them to behave on a day-to-day basis. Objects are not quantized and can have continuous amounts of energy. Objects do not pop in and out of existence.

The quantum world behaves kind of like a light switch, where energy has only an on-off option. The world we see and interact with behaves like a dimmer switch, allowing for all levels of energy.

But researchers run into problems when they try to study gravity at the quantum level. At the small scale, physicists would have to assume gravity is quantized. But the research many of them have conducted doesn't support that idea.

An infinitely expanding universe lies beyond the Milky Way galaxy.© DECaPS2/DOE/FNAL/DECam/CTIO/NOIRLab/NSF/AURA, M. Zamani & D. de Martin via AP

One way to make these theories work together is the multiverse theory. There are many theories that look beyond our current universe to explain how gravity and the quantum world work together. Some of the leading theories include string theory, brane cosmology, loop quantum theory and many others.

Regardless, the universe will continue to expand, with the distance between the Milky Way and most other galaxies getting longer over time.

Concerning Findings: Microplastics in the Air Could Be Causing Cancer

Microplastics from tires and waste pollute the air, causing health problems like infertility, cancer, and lung issues. UCSF researchers call for action to limit exposure based on a comprehensive review.

A review of 3,000 studies indicates that these microscopic plastic particles in the air could be contributing to male and female infertility.

Tires and degrading garbage release tiny plastic particles into the air, contributing to air pollution that researchers at UC San Francisco believe may be linked to respiratory issues and other health problems.

A comprehensive review of approximately 3,000 studies highlights the potential dangers of these particles. They have been associated with serious health concerns such as male and female infertility, colon cancer, and impaired lung function. Additionally, these particles may trigger chronic pulmonary inflammation, which could elevate the risk of lung cancer.

“These microplastics are basically particulate matter air pollution, and we know this type of air pollution is harmful,” said Tracey J. Woodruff, PhD, MPH, a professor of obstetrics, gynecology, and reproductive sciences at UCSF.

Woodruff directs the Program on Reproductive Health & the Environment (PRHE) and is the senior author of the study, which was recently published in the journal *Environmental Science & Technology*.

Small particles, big problem

Microplastics are less than 5 millimeters – smaller than a grain of rice – and they are ubiquitous in the environment. Each year, companies around the world produce nearly 460 million metric tons of plastic. That is projected to reach 1.1 billion by 2050.

A major source of plastic in the air is driving. Friction wears down tires along with the road surface, sending plastic fragments into the air.

The paper is the first systematic review of microplastics using gold-standard methods approved by the National Academy of Sciences.

Most of the studies in the review were based on animals. But the researchers said the conclusions likely also apply to humans since they share many of the same exposures.

The study expands on a report the researchers worked on last year with the California State Policy Evidence Consortium (CalSPEC). The Consortium includes experts across the UC system and provides evidence for policymakers in the California State Legislature.

"We urge regulatory agencies and policy leaders to consider the growing evidence of health harms from microplastics, including colon and lung cancer," said Nicholas Chartres, PhD.

Chartres, the study's first author, led the science and policy team at PRHE and is now at the University of Sydney. "We hope state leaders will take immediate action to prevent further exposures."

Reference: "Effects of Microplastic Exposure on Human Digestive, Reproductive, and Respiratory Health: A Rapid Systematic Review" by Nicholas Chartres, Courtney B. Cooper, Garret Bland, Katherine E. Pelch, Sheiphali A. Gandhi, Abena BakenRa and Tracey J. Woodruff, 18 December 2024, *Environmental Science & Technology*.
DOI: 10.1021/acs.est.3c09524

The CalSPEC pilot was funded through the University of California Office of the President Major Projects and Initiatives Fund (UCOP proposal number 202110-121-AA) and a grant from the JPB Foundation (G-2022-3608).

The Unraveling of Space-Time

Somehow we have to dislodge space-time.
— Nima Arkani-Hamed, Institute for Advanced Study

I'm quite confident that space-time is emergent. It arises fairly robustly from the mutual requirements of quantum mechanics and gravity.
— Sean Carroll, Johns Hopkins University

If you drill down, space-time isn't a base layer of reality. There's something else that's there as the baseline, of which space-time is an approximation.
— Adam Brown, Stanford University

There is a consensus that it should be emergent. It's just that we don't know how it emerges.
— Josephine Suh, KAIST in South Korea

Many physicists suspect we are in for a radical reunderstanding of reality, as big as the one Albert Einstein orchestrated more than a century ago. The patent clerk, with his theory of relativity, united space and time into a single, malleable substance — space-time. In doing so, he transformed the inert nothingness behind the world into a dynamic fabric of the world, one with folds that we experience as the force of gravity.

Now it's Einstein's fabric that needs unraveling. A belief has come to dominate theoretical physics that even nothingness ought to come from something — that space-time must break up into more primitive building blocks that don't themselves inhabit space or time.

The vendetta against space-time is not new. Indeed, the classic textbook on general relativity, a 1,304-page tome called *Gravitation* published in 1973, argues in its final chapter that extreme events involving black holes and the birth of the universe point to the inevitable breakup of space-time: “One sees no alternative except to say that [space-time] geometry fails, and pregeometry has to take its place to ferry physics through the final stages of gravitational collapse and on into what happens next.”

One of the textbook’s authors, the eminent American physicist John Archibald Wheeler, worked on embryonic ideas for what a theory of reality without space-time might look like — a technical and conceptual challenge that tortured him on a spiritual level to his dying day.

What’s wrong with space-time as we know it? Physicists point to a constellation of scenarios, including ones that pit the tenets of general relativity against those of quantum theory — the other pillar of 20th-century physics, which describes matter and radiation as collections of randomly rippling waves. Einstein pioneered the use of thought experiments to sharpen his ideas about space and time. When today’s physicists imagine sufficiently fantastical procedures, they encounter conundrums that undermine their common sense notion of space-time as a fundamental fabric.

Thought experiments lead the way because the quantum substructure of gravity and space-time is too small to probe in actual experiments — the ballpark estimate is that this substructure would become apparent at a scale a trillionth of a trillionth of the size of atoms. Do thought experiments really count as evidence? It’s a question for philosophers, such as Karen Crowther at the University of Oslo in Norway, who studies the idea of emergent space-time.

In periods when we are looking for new theories, physics has always become philosophical.
— Karen Crowther, University of Oslo

What would it mean for space-time to be “emergent”? The physicist Sean Carroll proposes the following working definition: A system is emergent when you can describe it with two theories, one of which is more complete than the other. Take water. You can talk about it as a smooth fluid or as frenetically colliding molecules. Both theories can be useful, but in some situations the latter picture holds up while fluid dynamics fails. Only molecular physics can explain freezing and evaporation, for instance. Thus, the fluid description of water emerges from the more fundamental, complete physics of H_2O molecules.

Searching for the base layer underpinning space-time involves formulating equations that don’t involve space-time’s flagship properties, then showing that you can recover those properties as outputs. H_2O molecules themselves aren’t wet, for instance; that’s a property of the emergent fluid. Similarly, a more fundamental theory underlying space-time might make no reference to locality, the rule that an object can only influence objects nearby in space-time. Ultimately, this fundamental theory should reproduce familiar physics.

One starting point for understanding how physicists can describe one system using two different vocabularies is the notion of duality, a mathematical phenomenon that plays a special role in physics. One of the most tantalizing hints about what the next level down might look like came from Jacob Bekenstein and Stephen Hawking, who deduced in the 1970s that black holes have a temperature — a property normally reserved for a substance made from more primitive parts. A tea’s hotness, for instance, reflects the swift motion of its molecules. Black holes, in contrast, were thought to be nothing but smooth space-time, yet the physicists calculated a temperature nonetheless. “That means that space-time itself should consist of ‘molecules,’” said Manus Visser, a physicist at the University of Cambridge.

Bekenstein and Hawking's math contained a shocking implication: Those space-time molecules were being shuffled around on the black hole's surface, rather than filling its interior. It was as if the space-time filling the interior was emerging from the surface, much as a hologram emerges from the molecules making up a flat sticker. "This is perhaps the most profound fact that we know about quantum gravity that transcends any individual approach," said Adam Brown, a physicist at Stanford University.

That means that space-time itself should consist of 'molecules.'

— Manus Visser, University of Cambridge

Chasing that lead, physicists have spent decades exploring "holographic" theories of space-time that offer an alternative description in terms of quantum particles in a lower-dimensional space. Over the last quarter century, they've come to understand how the space-time of strangely curved toy universes can emerge holographically from their own surfaces. Much more recently, there's been a resurgence of interest in a long-overlooked form of quantum theory developed by the genius John von Neumann. His algebraic language is helping physicists plumb the depths of black holes and uncover fresh hints about how holography might work in universes resembling ours.

Other physicists are attempting to escape space-time in an entirely different way. They're developing a new way of predicting the outcomes of particle interactions with math that makes no reference to space or time — or quantum mechanics, either. Remarkably, these physicists recently managed to rewrite the quantum theories describing real elementary particles in terms of more primitive mathematical objects.

What if space-time *is* fundamental? While the eventual unraveling of space-time is widely presumed, it is not guaranteed. None of the thought experiments are ironclad. No alternative framework has produced a fully consistent, space-time-free description of our universe. And plenty of physicists, such as Latham Boyle of the University of Edinburgh, continue to pursue visions of fundamental physics that keep some version of Einstein’s fabric more or less intact.

> **Some of these ingredients we associate with traditional, continuum space-time just smell too good to be discarded. I suspect they’ll be preserved in whatever comes next.**
>
> ***— Latham Boyle, University of Edinburgh***

To be clear, the potential emergence of space-time doesn’t make it any less real. Most of our world is emergent. Tables and chairs emerge from grids of jiggling molecules. You emerge from bursts of electricity between your neurons. The discovery of cells or atoms has in no way robbed us of our reality. On the contrary, emergent descriptions are in some sense more real than fundamental ones. It’s much more convenient — and informative — to describe a cup of water as “scalding” or “ice-cold” than it is to provide a list of the velocities of all its molecules.

Dark energy: Could the mysterious force we think of as constant actually vary over cosmic time?

Globular cluster NGC 2005. Credit: ESA/Hubble & Nasa, F. Niederhofer, L. Girardi, CC BY-SA

‚As I finished my Ph.D. in 1992, the universe was full of mystery—we didn't even know exactly what it is made of. One could argue that cosmologists had made little progress in our understanding of these basic facts since the discovery of the cosmic microwave background (CMB), the afterglow of the Big Bang, in the 1960s.

I left the UK after my doctoral studies to begin a research career in the US, where I was lucky to be recruited to work on a new experiment called the Sloan Digital Sky Survey (SDSS). This new survey embraced advances in digital technologies with the ambition of measuring the "redshifts" (how light becomes more red if a source appears to move away from you) of a million galaxies.

These redshifts were then used to measure distances, and allowed cosmologists to map the three-dimensional structure of the universe.

One cosmic puzzle in the 1980s, based on the pioneering CfA Redshift Survey of Margaret Geller and John Huchra, was the significant lumpiness of galaxies, and therefore matter, in our cosmic neighborhood. Galaxies were clustered together across a wide range of scales, with evidence for coherent "superclusters" of galaxies spanning over 30 million light years in length.

It was important to know how such superclusters could have formed from the smooth CMB, as it would tell us the total amount of matter in the universe and, more intriguingly, what that matter was made of. That was assuming the only force in play was gravity.

By the end of the first phase of the SDSS, we had achieved our goal of a million redshifts. This data was used to discover many superclusters across the universe, including the amazing "Sloan Great Wall," which remains one of the largest known coherent structures in the universe, over a billion light years in length.

I am lucky to have lived through this amazing era of cosmic discovery around the turn of the century. Surveys like SDSS, combined with new observations of the CMB and searches for distant exploding stars known as Type Ia Supernovae (SNeIa), coincided to deliver an emphatic answer to the question: "What is the universe made of?"

The discovery of dark energy

From 1999 to 2004, the cosmological community came together to agree that the universe was 5% normal (baryonic) matter, 25% dark matter (unknown, invisible matter), and 70% "dark energy" (an expansive force)—essentially a cosmological constant, which was first postulated by Einstein. The discovery that the universe was dominated by this constant energy shocked everyone, especially as Einstein had called the cosmological constant his "biggest blunder."

Today, cosmologists still agree this is the most likely make-up of our universe. But observational cosmologists like me have refined our measurements of these cosmic variables significantly—reducing the errors on these quantities.

The latest numbers from the Dark Energy Survey (DES) indicate that 31.5% of the universe is matter (a combination of dark and normal), with the remainder being dark energy assuming a cosmological constant. The error on this measurement is just 3%.

Knowing these numbers to higher precision will hopefully help cosmologists understand why the universe is like this. Why would we expect to have 70% of the universe today as "dark" (can't be seen via electromagnetic radiation) and not associated with "matter" like everything else in the universe?

The origin of this dark energy remains the biggest challenge to physics, even after 20 years of intense study.

Intriguing measurements

Like me, a few cosmologists have become distracted by other problems over the last two decades. However, 2024 could be the start of a new era of discovery. This year, cosmologists published new results based on two of our best cosmological probes.

The first probe consists of exploding stars dubbed "SNeIa." As these stars have a narrow range of masses, their explosions can be well calibrated, giving cosmologists a predictable brightness that can be seen far away. By comparing the known brightness of these SNeIa to their redshifts, we can determine the expansion history of the universe. These objects were, in fact, critical for discovering that the expansion of our universe is accelerating.

The second probe works by looking at Baryon Acoustic Oscillations (BAO)—relics of predictable sound waves in the plasma (charged gas) of the early universe, before the CMB. These are now frozen into the large-scale structure of galaxies around us. Like SNeIa, their predictable size can be compared with their observed size today to measure the expansion history of the universe.

Recently, DES reported its final SNeIa results from over a decade of work, detecting and characterizing many thousands of supernova events. While these SNeIa results are consistent with the orthodox view that the universe is dominated by a cosmological constant, they do leave open the tantalizing possibility of new physics—namely, that the dark energy could be varying with cosmic time.

That said, scientists are trained to be skeptical, and there are many reasons to distrust a single experiment, single observation, or even a single set of cosmologists!

Cosmologists now go to extraordinary lengths to "blind" their results from themselves during analysis of the data, only revealing the answer at the last moment. This blinding is done to avoid unconscious human biases affecting the work, which could possibly encourage people to get the answer they believe they should see.

This is why repeatability of results is at the heart of all science. In cosmology, we cherish the need for multiple experiments, checking and challenging each other.

The second result to turn heads was the first BAO measurements from the Dark Energy Spectroscopic Instrument (DESI), successor to the SDSS. The first DESI map of the cosmos is deeper and denser than the original SDSS. Its first BAO results are intriguing—the data alone is still consistent with a cosmological constant, but with hints of a possible time-varying dark energy when combined with other data sources.

In particular, when DESI analyses the combination of its BAO results with the final DES SNeIa data, the significance of a time-varying dark energy increases to 3.9 sigma (a measure of how unusual a set of data is if a hypothesis is true)—only 0.6% chance of being a statistical fluke.

Most of us would take such odds, but scientists have been hurt before by systematic errors within their data that can mimic such statistical certainty. Particle physicists therefore demand a discovery standard of 5 sigma for any claims of new physics—or less than a one in a million chance of being wrong!

As scientists will say, "Extraordinary claims require extraordinary evidence."

Mindboggling implications

Are we entering a new era of cosmological discovery? If so, what would it mean?

The answer to my first question is probably yes. The next few years will be fun for cosmologists, with new data and results due from the European Space Agency's Euclid mission. Launched last year, it is already scanning the sky with unprecedented accuracy.

Likewise, DESI will get more and better data, while the European Southern Observatory starts its own massive redshift survey in 2025. Then you have the Rubin Observatory in Chile coming online soon. Combining these datasets should prove beyond doubt if dark energy varies with cosmic time.

If it does, it implies there is less dark energy now than in the past. This could be caused by many things but, interestingly, it could signify the end of a present, accelerated phase of the expansion of the universe.

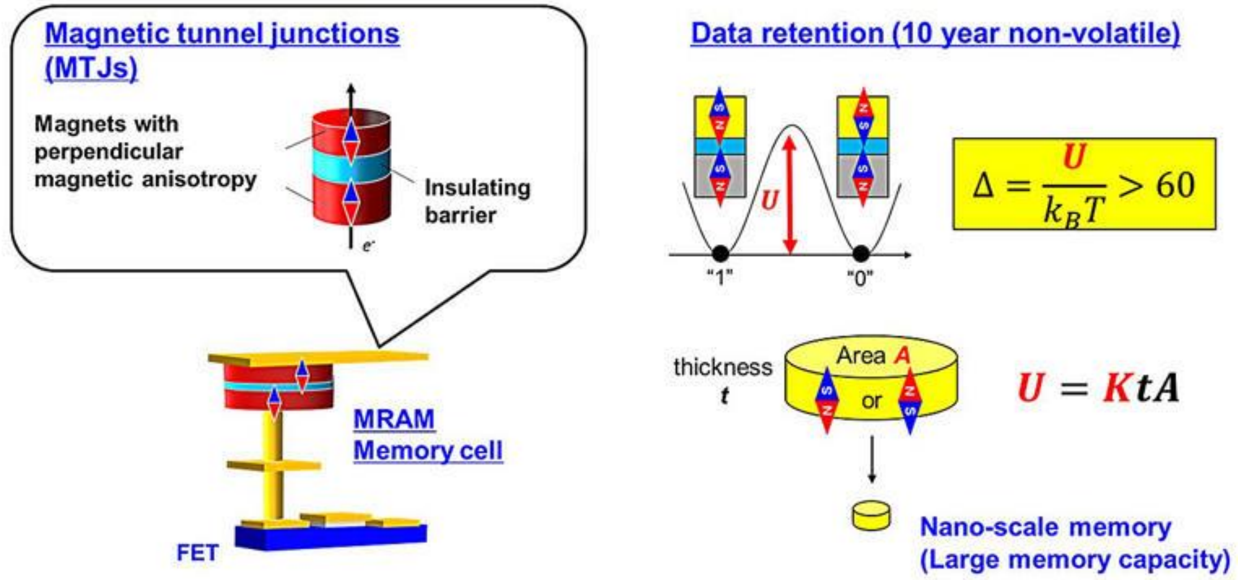
It also implies that dark energy is probably not a cosmological constant thought to be due to the background energy associated with empty space. According to quantum mechanics, empty space isn't really empty, with particles popping in and out of existence creating something we call "vacuum energy." Ironically, predictions of this vacuum energy do not agree with our cosmological observations by many orders of magnitude.

So, if we did discover that dark energy varies over time, it might explain why observations are at odds with quantum mechanics, which is an extremely well-tested theory. This would suggest the assumption in the standard model of cosmology, that dark energy is constant, needs a rethink. Such a realization may help solve other mysteries about the universe—or pose new ones.

In short, the new cosmological observations coming this decade will stimulate a new era of physical thinking. Congratulations to my younger cosmologists: it is your era to have fun.

Provided by The Conversation

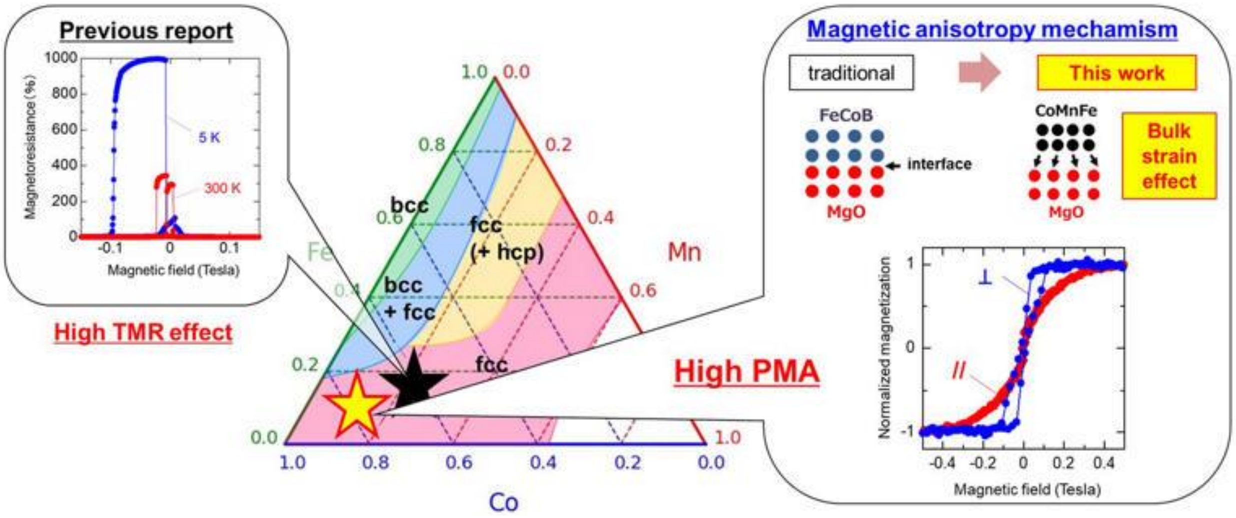
Spintronics memory innovation: A new perpendicular magnetized film



MRAM consists of semiconductor transistor (FET) and magnetic tunnel junctions with perpendicular magnetic anisotropy (Left panel). For non-volatile data retention over ten years in magnetic tunnel junction, thermal stability factor, Δ, needs to exceed 60; thus large perpendicular magnetic anisotropy K is required for nano-scale MTJs with magnetic layer with thickness t and radius D smaller than several tens nm. (right panel). Credit: S. Mizukami

Long gone are the days where all our data could fit on a two-megabyte floppy disk. In today's information-based society, the increasing volume of information being handled demands that we switch to memory options with the lowest power consumption and highest capacity possible.

Magnetoresistive Random Access Memory (MRAM) is part of the next generation of storage devices expected to meet these needs. Researchers at the Advanced Institute for Materials Research (WPI-AIMR) investigated a cobalt-manganese-iron alloy thin film that demonstrates a high perpendicular magnetic anisotropy (PMA)—key aspects for fabricating MRAM devices using spintronics.

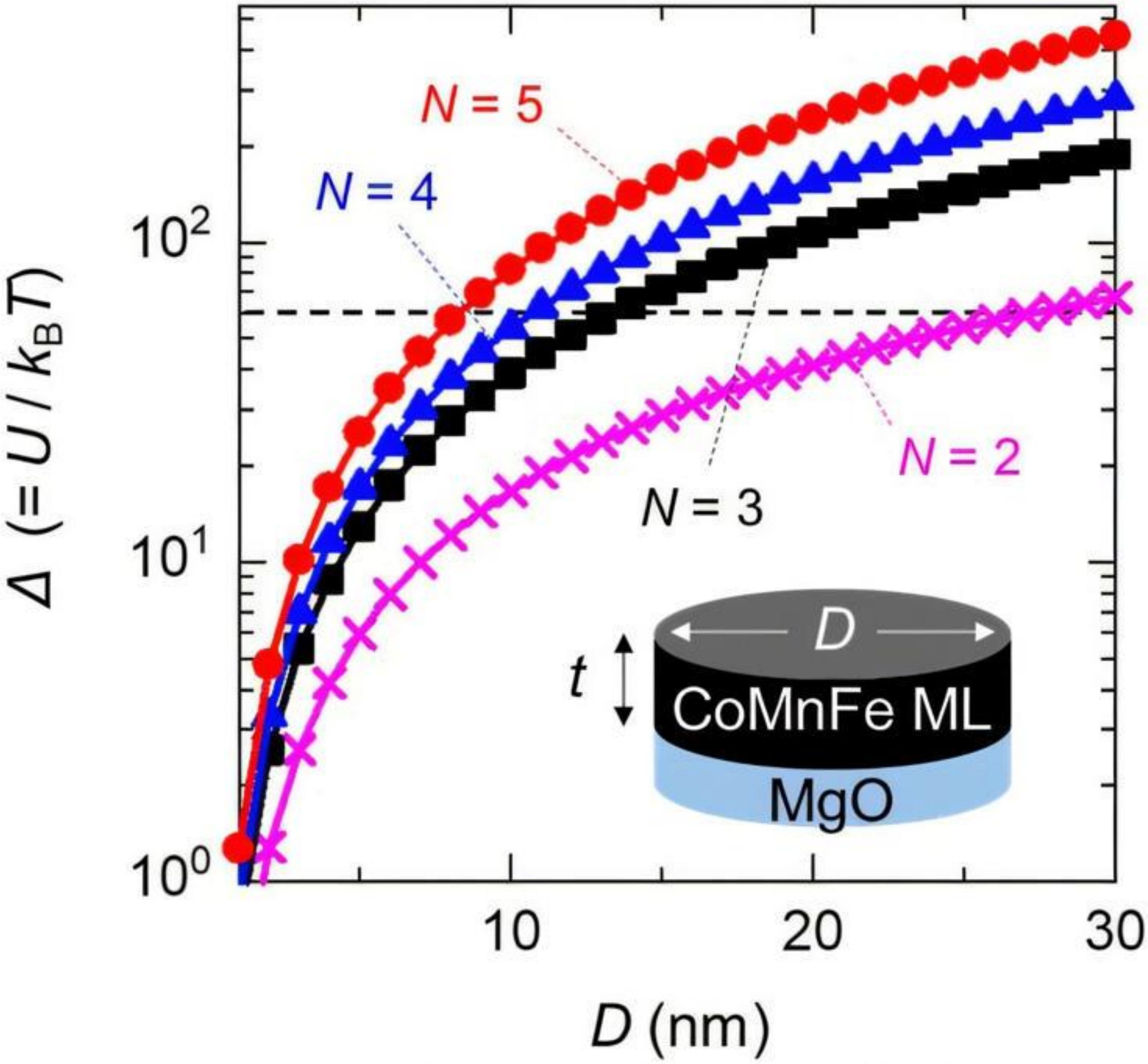


We demonstrated high TMR effect, which is prerequisite for MRAM, using novel metastable body-centered cubic (bcc) Co-Mn-Fe in a previous report [T. Ichinose et al. Journal of Alloys and Compounds 960, 170750 (2023). In this work, we demonstrated large perpendicular magnetic anisotropy (PMA) which can originate from the lattice strain. Credit: D. Kumar et al. (Part of the data is used from D. Kumar et al. Science and Technology of Advanced Materials, 25 (1), 2421746 (2024).

The findings were published in *Science and Technology of Advanced Materials* on November 13, 2024.

"This is the first time a cobalt-manganese-iron alloy has strongly shown large PMA," says Professor Shigemi Mizukami (Tohoku University),

"We previously discovered this alloy showed a high tunnel magnetoresistance (TMR) effect, but it is rare that an alloy potentially shows both together." For example, iron-cobalt-boron alloys, which are conventionally used for MRAM, possess both traits, but their PMA is not strong enough.



Numerical simulation suggested that the Co-Mn-Fe multilayer films with PMA show the large thermal stability factors delta exceeding 60 even in nano scale, which can be used for 10 nm scale MRAM. Credit: D. Kumar et al. (The data is used from D. Kumar et al. Science and Technology of Advanced Materials, 25 (1), 2421746 (2024).)

MRAM devices use magnetic storage elements instead of an electric charge to store data, which gives it several advantages such as reduced power consumption. Ideally, alloys for MRAM devices have both a high TMR and PMA, which allow them to integrate a large number of bits with high capacity and high thermal stability.

In order to find new, alternative materials to solve the issues seen with currently used alloys, researchers at Tohoku University have investigated the PMA of cobalt-manganese-iron alloy thin films, which were shown to have high TMR in their previous research.

Remarkably, the alloy they produced was found to exhibit high PMA. They also demonstrated that the PMA in their multilayer films was large enough to be capable of its intended end purpose: large memory capacity for MRAM devices using a simulation.

The results of this research will offer a new candidate for memory materials, and contribute to the continuous development of novel spintronics memory devices, with the aim of creating a more sustainable society for everyone.

More information: Deepak Kumar et al, Metastable body-centered cubic CoMnFe alloy films with perpendicular magnetic anisotropy for spintronics memory, *Science and Technology of Advanced Materials* (2024). DOI: 10.1080/14686996.2024.2421746

Provided by Tohoku University

Many physicists argue the universe is fine-tuned for life. Our findings question this idea

Physicists have long grappled with the question of why the universe was able to support the evolution of intelligent life. The values of the many forces and particles, represented by some 30 so-called fundamental constants, all seem to line up perfectly to enable it.

Take gravity. If it were much weaker, matter would struggle to clump together to form stars, planets and living beings. And if it were stronger, that would also create problems. Why are we so lucky?

Research that I recently published with my colleagues John Peacock and Lucas Lombriser now suggests that our universe may not be optimally tailored for life. In fact, we may not be inhabiting the most likely of possible universes.

We particularly studied how the emergence of intelligent life is affected by the density of "dark energy" in the universe. This manifests as a mysterious force that speeds up the expansion of the universe, but we do not know what it is.

The good news is that we can still measure it. The bad news is that the observed value is way smaller than what we would expect from theory. This puzzle is one of the biggest open questions in cosmology, and was a primary motivation for our research.

Anthropic reasoning

We tested whether "anthropic reasoning" may offer a suitable answer. Anthropic reasoning is the idea that we can infer properties of our universe from the fact that we, humans, exist. In the late 80s, physics Nobel laureate Steven Weinberg discussed a possible anthropic solution for the observed value of the dark energy density.

Weinberg reasoned that a larger dark energy density would speed up the universe's expansion. This would counteract gravity's effort to clump matter together and form galaxies. Fewer galaxies means fewer stars in the universe. Stars are essential for the emergence of life as we know it, so too much dark energy would suppress the odds of intelligent life such as humans appearing.

Weinberg then considered a "multiverse" of different possible universes, each with a different dark energy content. Such a scenario follows from some theories of cosmic inflation, a period of accelerated expansion occurring early in the universe's history.

Weinberg proposed that only a tiny fraction of the universes within the multiverse, whether real or hypothetical, would have a sufficiently small dark energy density to enable galaxies, stars and, ultimately, intelligent life, to appear. This would explain why we observe a small dark energy density—despite our theories suggesting it should be much larger—we simply could not exist otherwise.

A potential pitfall in Weinberg's reasoning is the assumption that the fraction of matter in the universe that ends up in galaxies is proportional to the number of stars formed. Some 35 years later, we know that it is not that simple. Our research then aimed at testing Weinberg's anthropic argument with a more realistic star formation model.

Counting stars

Our goal was to determine the number of stars formed over the entire history of a universe with a given dark energy density. This boils down to a counting exercise.

First, we picked a dark energy density between zero and 100,000 times the observed value. Depending on the amount, gravity can hold matter together more or less easily, determining how galaxies can form.

Next, we estimated the yearly amount of stars formed within galaxies over time. This followed from the balance between the amount of cool gas that can fuel star formation, and the opposing action of galactic outflows that heat up and push gas outside galaxies.

We then determined the fraction of ordinary matter that was converted into stars over the entire lifetime (past and future) of a certain universe model. This number expressed the efficiency of that universe at producing stars.

We then assumed that the likelihood of generating intelligent life in a universe is proportional to its star formation efficiency. As the figure above shows, this suggests that the most hospitable universe contains about one-tenth of the dark energy density observed in our universe.

Our universe is thus not too far from the most favorable possible for life. But it also isn't the most ideal.

But to validate Weinberg's anthropic reasoning, we should imagine picking a random intelligent life form in the multiverse, and ask them what dark energy density they observe.

We found that 99.5% of them would experience a larger dark energy density than observed in our universe. In other words, it looks like we inhabit a rare and unusual universe within the multiverse.

This does not contradict the fact that universes with more dark energy would suppress star formation, hence reducing the chances of forming intelligent life.

By analogy, suppose we want to sort 300 marbles into 100 boxes. Each box represents a universe, and each marble an intelligent observer. Let us put 100 marbles in box number one, four in box number two and then two marbles in all other boxes. Clearly, the first box contains the single largest number of marbles. But if we pick one marble at random from all boxes, it is more likely to come from a box other than number one.

Likewise, universes with little dark energy are individually more hospitable for life. But life, although more unlikely, can still spawn in the many possible universes with abundant dark energy too—there will still be a few stars in them. Our calculation finds that most observers among all universes will experience a higher dark energy density than is measured in our universe.

Also, we found that the most typical observer would measure a value about 500 times larger than in our universe.

Where does that leave us?

In conclusion, our results challenge the anthropic argument that our existence explains why we have such a low value of dark energy. We could have more easily found ourselves in a universe with a larger dark energy density.

Anthropic reasoning may still be salvaged if we adopt more complex multiverse models. For example, we could allow for the amount of both dark energy and ordinary matter to vary across different universes. Perhaps, the reduced spawning of intelligent life due to a higher dark energy density might be compensated by a higher density of ordinary matter.

In any case, our findings warn us against a simplistic application of anthropic arguments. This makes the dark energy problem even harder to grapple with.

What should we cosmologists do now? Roll up our sleeves and think harder. Only time will tell how we solve the puzzle. However we will do it, I am sure it will be incredibly exciting.

More information: Daniele Sorini et al, The impact of the cosmological constant on past and future star formation, *Monthly Notices of the Royal Astronomical Society* (2024). DOI: 10.1093/mnras/stae2236

Provided by The Conversation

Physicists Discover 'Quantum Embezzlement' Could Offer Infinite Source of Entanglement

Stealing from the company's bank accounts could earn you time in the big house. But embezzlement from a quantum ledger might not be against the law.

In fact, a new study finds it might be a handy way to entangle particles without messing up their mathematics.

Earlier this century, quantum computing researcher Wim van Dam and physicist Patrick Hayden described a process they called embezzling entanglement, named for the light-fingered approach some systems could potentially take to combining their numbers without leaving a trace.

Theoretical physicists Lauritz van Luijk, Alexander Stottmeister, Reinhard F. Werner, and Henrik Wilming of Leibniz University Hannover in Germany have now identified fields that could be key players in this unusual quantum heist.

Our physical Universe – where objects have very clearly defined properties like location, momentum, and energy – emerges from an unresolved version of reality consisting of maybes and likelihoods.

As uncertain as this existence is prior to being locked down by a measurement, the laws governing its operation are as strict as those of any casino. Interactions with additional particles can upset the odds as easily as an extra deck of cards could change how a game of poker is played.

Entanglement is both a handy tool and a foil for any physics card counter.

Done right, entanglement can be used as the basis of powerful algorithms combining the probabilities of hundreds or even thousands of quantum card games. In the form of random intrusions, they can turn a useful quantum state into meaningless chaos.

Mathematically speaking, it's possible to show some quantum transformations are more subtle than others. One type of change returns to a state that doesn't appear to be disturbed, for example. Described as a kind of catalyst, this reversal allows for computing operations that wouldn't have been possible in cases where end states are altered.

Where van Dam and Hayden demonstrated that catalysts could universally flip any entangled state on a whim, the researchers at Leibniz University have now algebraically demonstrated that a combination of general relativity and quantum field theory can result in a bottomless pit of catalysts.

In theory, a relativistic quantum field could serve as an infinite resource of embezzlement, entangling with particles in ways that wouldn't alter their delicate states.

"Since the bank is in the same state before and after the embezzlement, that means that no one can detect it," van Luijk explained to *New Scientist*'s Karmela Padavic-Callaghan. "It's the perfect crime."

To become a practical system, a physical equivalent of a suitable field would need to be identified. Right now, embezzling entanglement is more of a mathematical abstraction than a 'how to' guide for silently stealing from the Universe.

Yet knowing infinite levels of entanglement could naturally be occurring in absolute nothingness could point the way to a whole criminal underworld of physics, where different classes of theft occur right under our noses.

This research has been accepted for publication in *Physical Review Letters*.

A Brief Introduction To The Fascinating And Confusing Subject Of Wave-Particle Duality

The concept of wave-particle duality is one that has been at the forefront of many scientist's minds for decades. While going to university, budding physicists will spend weeks just trying to get a basic grasp of the key concepts of this topic.

While we won't attempt to cover it comprehensively, it is a fascinating subject that everyone should have at least a passing understanding of as it has a dramatic impact on how the universe around us works.

For a long time, scientists believed that light traveled as particles, which is what Isaac Newton believed, and he seems to be correct. Other scientists such as Christiaan Huygens, however, thought it behaved like waves, and he seems to be correct as well.

How can that be?

The fact light can act like particles sometimes and waves at other times is something that has long been studied, and the wave-particle duality is one basic explanation. At the quantum level, our normal understanding of things really starts to break down.

To put it simply, light can behave as both a wave and a particle, depending on how it is observed.

If you want to make things even more confusing, scientists have found that matter can behave in the same way. This was first suggested in 1924 when Louis de Brogile found that electrons, which are known to be particles, can also behave like waves in some situations.

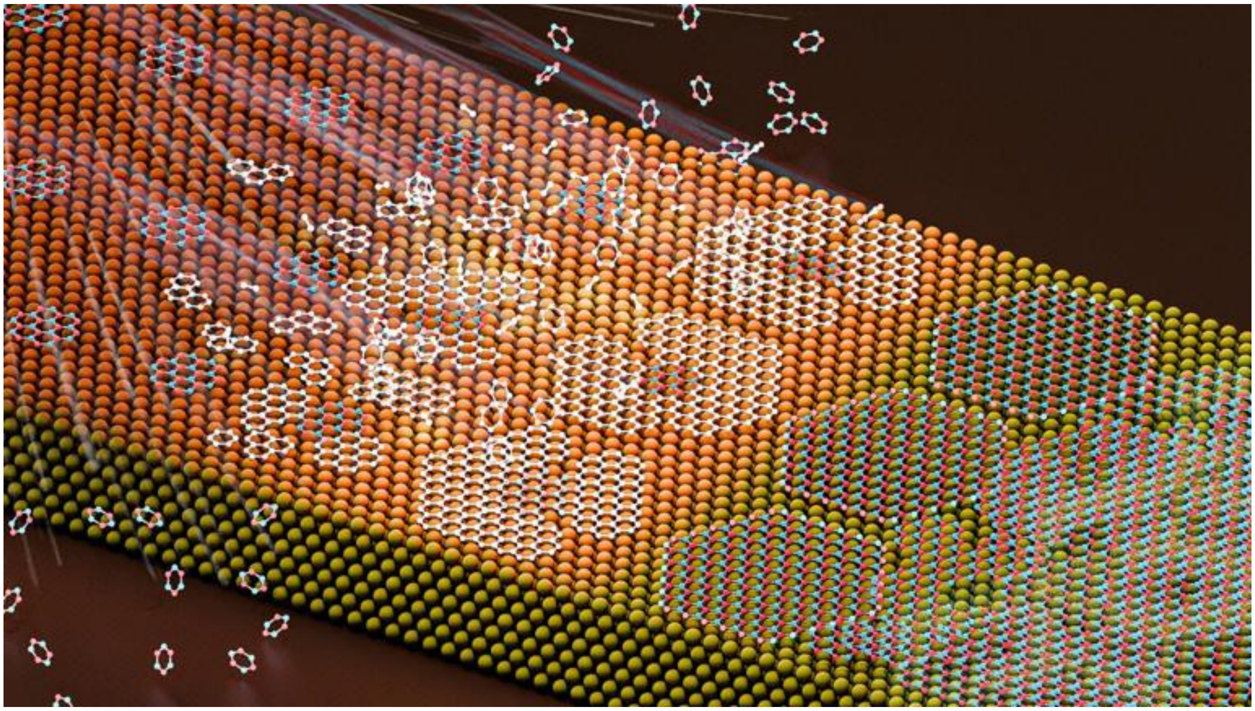
While for the average person this has very little practical impact on their day-to-day life, it is fun (or maybe a little scary) to think that the way we observe the world at a normal scale is, in some ways, entirely different than how it behaves when observed differently.

Wave-particle duality has an important impact on our lives through the use of technology. Things like lasers and some other technologies rely on this type of knowledge.

So, are you ready to take a deep dive into this concept now, or would you rather just continue to live in the comfortable ignorance about how things work?

Unlike light and matter, you can’t do both at the same time.

Hexagons of hexagonal boron nitride join up to form 2D insulator for next-gen electronic devices



Hexagonal boron nitride (hBN), an insulating material only one atom thick, is suitable for industrial-scale production. It is used in semiconductor devices and enhances the performance of other 2D materials. Credit: 2024 KAUST.

A method that can grow a useful insulating material into exceptionally high-quality films that are just one atom thick and are suitable for industrial-scale production has been developed by an international team led by Xixiang Zhang from KAUST.

The work is published in the journal *Nature Communications*.

The material, called hexagonal boron nitride (hBN), is used in semiconductor devices and can also enhance the performance of other two-dimensional (2D) materials such as graphene and transition metal dichalcogenides (TMDs).

Researchers can combine 2D materials to build tiny electronic components for quantum computing, electronic communications, and other applications. While most 2D materials conduct electricity, hBN is one of the few that is an insulator, making it an indispensable component within many of these devices.

In the laboratory, hBN flakes are often peeled from bulk samples of the material, a time-consuming and size-limiting approach that is unsuitable for mass manufacturing. Alternatively, an industrial process called chemical vapor deposition (CVD) can produce hBN by decomposing a precursor called ammonia borane.

Boron and nitrogen atoms released from the precursor then form triangular islands of hBN on a copper foil, and these islands gradually grow larger until they join together into a continuous honeycomb lattice.

The team has improved this process by growing hBN from hexagonal islands instead, producing a higher-quality film. "Hexagonal islands have fewer defects, making the final film more uniform and reliable," says Zhang. The method depends on adding a trace of oxygen during the growth process.

As hBN islands grow on copper, their edges can be zigzags of either boron or nitrogen atoms. In the triangular islands, all three edges feature nitrogen atoms. In contrast, the hexagonal islands formed by the new method have three nitrogen edges and three boron edges.

The researchers' theoretical calculations show that nitrogen edges are usually more energetically stable than boron edges, explaining why triangular islands are formed during CVD. But oxygen interacts with the islands and the copper foil in a way that gives the nitrogen and boron edges almost identical stabilities. This means the two types of edges can grow at the same rate, which generates hexagonal islands.

The researchers used techniques such as atomic force microscopy and high-resolution transmission electron microscopy to study the islands and films formed by their method. They found that it creates single-crystal films of hBN that are free of pinholes, exhibit low defect densities, have a uniform thickness, and possess excellent insulating properties.

"This makes it especially suitable for high-performance 2D-material electronic devices and offers enhanced robustness for nanodevices," says Bo Tian, who was part of the KAUST team, and is now based at Nanyang Technological University in Singapore.

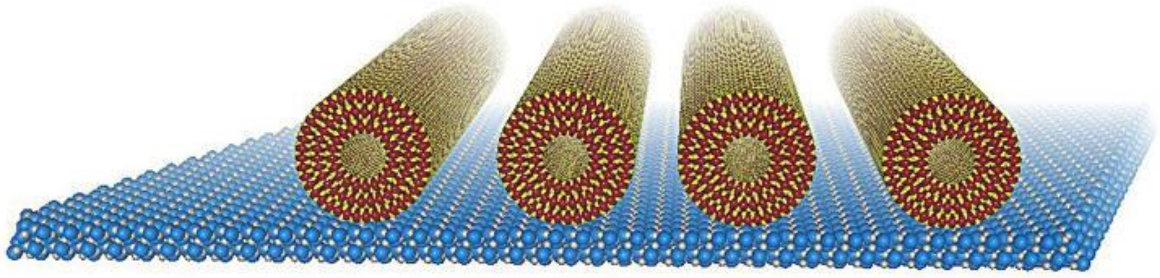
The team used the method to grow a 25 x 70 mm film of hBN, and larger areas should be possible. "The process is now limited by the CVD system or substrate size, so it is suitable for industrial production," Tian says.

The researchers are now studying the mechanism of CVD growth of hBN in more detail, to further improve the quality and increase the size of the films they can produce.

More information: Junzhu Li et al, Single-crystal hBN Monolayers from Aligned Hexagonal Islands, *Nature Communications* (2024). DOI: 10.1038/s41467-024-52944-9

Provided by King Abdullah University of Science and Technology

Scientists learn how to make nanotubes that point in one direction



The team's new synthesis protocol allows for the production of tungsten disulfide nanotubes which point in the same direction. The material they make shows the key properties of single nanotubes. Credit: Tokyo Metropolitan University

Researchers from Tokyo Metropolitan University have made tungsten disulfide nanotubes which point in the same direction when formed, for the first time. They used a sapphire surface under carefully controlled conditions to form arrayed tungsten disulfide nanotubes, each consisting of rolled nanosheets, using chemical vapor deposition.

The team's technique resolves the long-standing issue of jumbled orientations in collected amounts of nanotubes, promising real world device applications for the exotic anisotropy of single nanotubes.

The study is published in the journal *Nano Letters*.

Nanotubes consist of sheets of atoms rolled into a nanoscale tube, turning a two-dimensional sheet into a one-dimensional one. They are known to exhibit a wide range of properties which depend on the way in which the ends of the sheet meet. For example, carbon nanotubes can be either conducting or semiconducting depending on whether there is a "twist" left in the tube structure when a nanosheet is rolled up.

On the other hand, tungsten disulfide nanotubes consist of nanosheets rolled multiple times to create a Swiss-roll-like nanostructure. Interestingly, they are known to always be semiconducting regardless of how they are rolled, making them a prime candidate for application in semiconducting devices. However, for all the desirable properties of single tungsten disulfide nanotubes, real devices require collected amounts of nanotubes in the same place.

This can be achieved, but with a major proviso: they usually point in random directions. This is known to have a detrimental impact on properties like carrier mobility, which directly affects how useful it is in devices. Any unique optical properties are also masked.

No matter how interesting the direction-dependent properties of single nanotubes are, the properties of multiple nanotubes will not reflect these since it is made up of a jumbled pile.

Now, a team led by Professor Kazuhiro Yanagi of Tokyo Metropolitan University have come up with a new technique which may solve this longstanding problem. They used a sapphire substrate with a specific crystalline plane exposed to the surface, providing a template on which nanotubes can be grown.

Gases containing tungsten and sulfur were fed to the substrate at precise rates and temperatures to allow for chemical vapor deposition to form multi-walled rolled tungsten disulfide nanotubes on the surface.

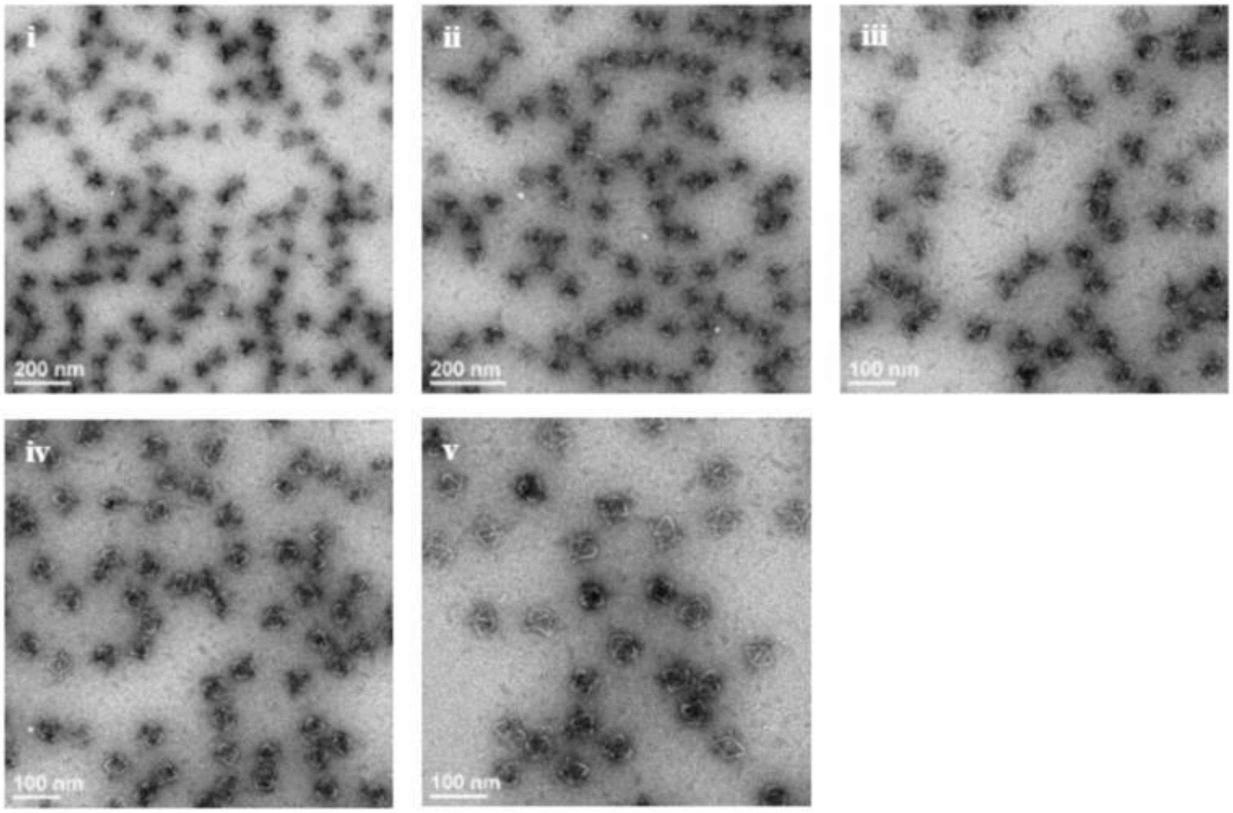
Under the right conditions, they noticed that the nanotubes all pointed along a specific crystallographic direction. This is the first time that arrayed tungsten disulfide nanotubes have been grown.

The team demonstrated that their arrays of nanotubes collectively still show the exotic, anisotropic properties of single nanotubes, specifically in how they interact with light. They believe their technique will enable the application of tungsten disulfide nanotubes to real-world devices which take full advantage of their exotic electric and optoelectronic properties.

More information: Abdul Ahad et al, Synthesis of Arrayed Tungsten Disulfide Nanotubes, *Nano Letters* (2024). DOI: 10.1021/acs.nanolett.4c03895

Provided by Tokyo Metropolitan University

Mechanical engineer figures out way to enhance sensitivity of nanopores for early detection of diseases



DNA origami octahedra under TEM at different magnification. Credit: Analytical Chemistry (2024). DOI: 10.1021/acs.analchem.4c02016

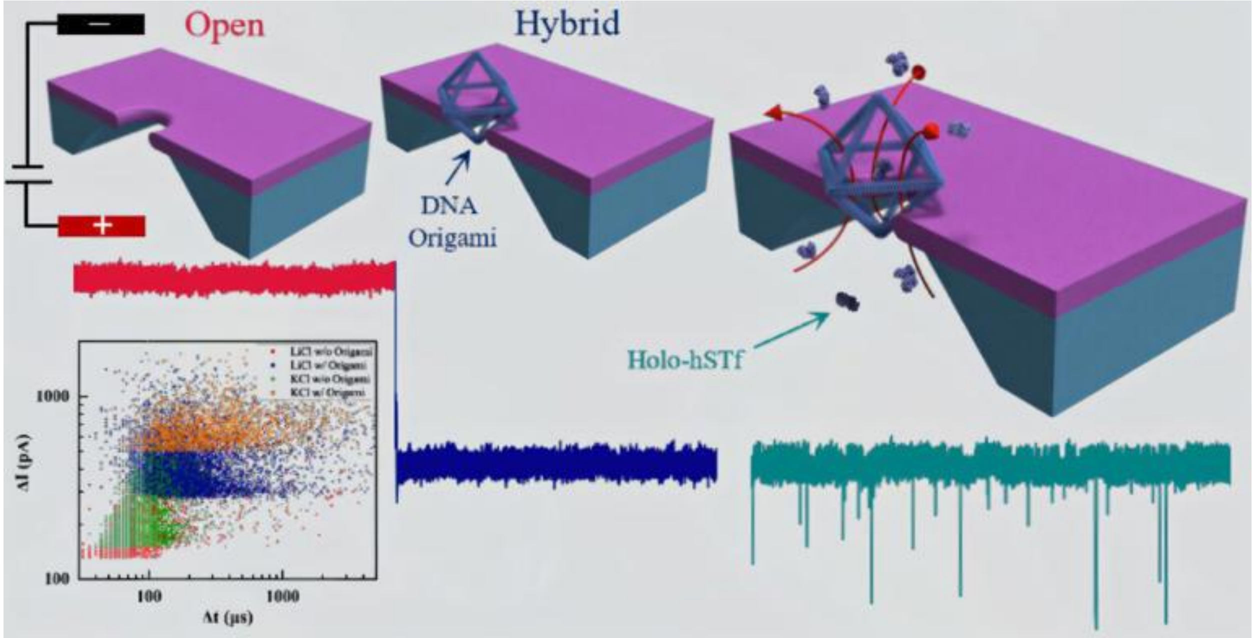
SMU Lyle mechanical engineering graduate student Kamruzzaman Joty has introduced a new technique in nanotechnology for detecting and analyzing biomolecules, potentially paving the way for new methods of early disease detection.

The study, recently featured on the cover of *Analytical Chemistry*, integrates octahedral DNA origami structures with solid-state nanopores to significantly improve the detection of proteins, especially those that are present in low concentrations.

"This work could pave the way for developing advanced biosensing technologies, with potential applications in biomedical research and diagnostic tools—especially for diseases marked by low-abundance protein biomarkers," Joty said.

Nanopores are tiny holes that can detect individual molecules as they pass through, making them ideal tools for analyzing biomolecules like DNA and proteins. However, detecting proteins at very low concentrations—such as those found in early stages of diseases—has been a challenge.

Joty and his research team determined that combining the precision of DNA origami with the robustness of solid-state nanopores could create a "hybrid nanopore" system, enabling more precise analysis. DNA origami is a method where DNA strands are folded into specific shapes, like an octahedron, to enhance the nanopore's ability to capture and sense proteins.



Credit: Analytical Chemistry (2024). DOI: 10.1021/acs.analchem.4c02016

In the study, the researchers used holo human serum transferrin as a model protein to show how the hybrid nanopore could outperform traditional nanopores in sensitivity and detection accuracy.

Many diseases, including cancer and neurodegenerative disorders, are characterized by proteins that are present in very small amounts, making them difficult to detect early. The hybrid nanopore's ability to sense these low-abundance proteins could lead to earlier diagnoses and better treatment outcomes.

"In the future, we will focus on refining the design of DNA origami structures and nanopore configurations to further enhance sensitivity and broaden the range of detectable biomolecule," Joty said. "This exciting work could lead to innovations in drug discovery, disease diagnostics, and fundamental biological research."

More information: Kamruzzaman Joty et al, DNA Origami Incorporated into Solid-State Nanopores Enables Enhanced Sensitivity for Precise Analysis of Protein Translocations, *Analytical Chemistry* (2024). DOI: 10.1021/acs.analchem.4c02016

Provided by Southern Methodist University

The Theory of Everything: Searching for the universal rules of physics

Physicists are still chasing the dream of Albert Einstein and Stephen Hawking to capture the workings of the entire universe in a single equation.

Physicists are searching for a theory that would unify quantum physics with general relativity. (Image credit: Getty Images)

The Theory of Everything is an overarching hypothetical framework that would explain the physics of the entire universe in a single equation. But unifying theories that define the large-scale cosmological structure of the universe with those that describe the minuscule quantum world of the subatomic particles has been a challenge for over a century.

Figuring out such an all-encompassing theory was the dream of two legendary physicists, Albert Einstein and Stephen Hawking. But although equations that describe the universe on the largest and smallest scales have become more precise over the decades, they still don't unite to provide a complete picture of the physical world. The situation is so exasperating that some of the greatest physicists of today concede that they might not live to see it all fall into place. Hawking himself had given up on the search for a Theory of Everything before his death in 2018.
Cambridge University astrophysicist Christopher Reynolds admits that Einstein's sense of "aesthetics for the universe" might be offended by the "complex and messy" nature of current attempts to figure out the rules of the cosmos. While the iconic German-born thinker was able to encapsulate the workings of the world on the large scale, where the rules of gravity reign supreme, in the neat E = mc^2 (a simplified form of an equation that shows energy is equal to mass times the speed of light squared), things began to crumble when physicists attempted to reconcile his theory of general relativity with quantum physics, which describes the rules that govern the world on the smallest scales.

"Standard physics right now really has two legs to it," Reynolds told Space.com. "One of them is the Standard Model of particle physics. Which is a beautiful theory that explains the properties of matter. But it doesn't explain gravity, which is the other leg."

GRAVITY VERSUS QUANTUM FIELD

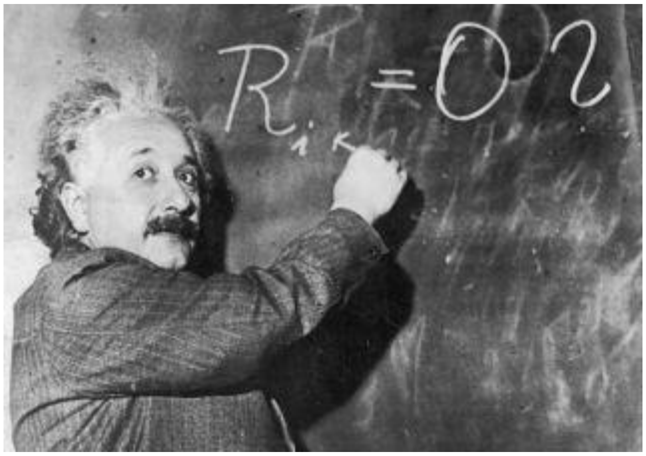
The Standard Model of particle physics is the foundation of quantum mechanics that describes the world of atoms and their constituent particles such as the quarks and gluons, that make up protons and neutrons in atomic nuclei and electrons that orbit them. The Standard Model explains three of four fundamental forces that govern the natural world: the electromagnetic force that holds atoms and molecules together through the interaction of their electrically charged components, the strong nuclear force which binds elementary particles called quarks into more complex protons, neutrons and electrons (and subsequently into atoms), and the weak nuclear force responsible for radioactive decay. These forces are a result of particle interactions, Michael Duff, an Emeritus Professor in theoretical physics at Imperial College London, told Space.com. A photon exchanged between two electrons produces the electromagnetic force, the W and Z bosons explain the strong and weak nuclear forces. But try explaining gravity by interacting particles, and you get to a point where the math goes awry, Duff said.

"According to Einstein, it's the geometry of space and time which is responsible for the gravitational force," Duff told Space.com. "You can ask yourself whether gravity perhaps could be a result of a particle called the graviton. And that works quite well to a certain degree. But when you try to make a full quantum theory of gravitons, it goes horribly wrong. Your answers, which should be finite, turned out to be infinite."
On the large cosmic scales, where the rules of Albert Einstein's general relativity match observations, quantum principles don't seem to apply. The same happens when one looks for the principles of gravity in the microworld of subatomic particles.

Duff, who has spent most of his adult life trying to reconcile the two theoretical frameworks, describes their incompatibility as "the disaster of the 21st century."

The journey to sort out this "disaster" started a hundred years ago, and Duff, now 73, admits that he may not see the day when the "rules of chess" as he calls it, are finally cracked and the Theory of Everything is complete.

"I'm not expecting it anytime soon," Duff said. "I think the key word is patience. It's going to take a long time, a lot of more research before we get there, that's my guess."



Albert Einstein attempted to unify his theory of relativity with particle physics but ultimately failed. (Image credit: Getty Images)

KALUZA-KLEIN THEORY AND THE BIRTH OF A MULTI-DIMENSIONAL UNIVERSE

Even before Albert Einstein turned his famed brain to the Theory of Everything, his contemporaries Theodor Kaluza and Oskar Klein attempted to marry his theory of general relativity with James Clerk Maxwell's theory of electromagnetism, which in the late 19th century had provided an overarching explanation for the two main forces known at that time: magnetism and the electrical force.

To make their theory work, Kaluza and Klein had to invent a world that looked very different from what we see around us. They had to add a fifth dimension to our three-dimensional space plus time. This fifth dimension, however, was curled up and microscopic, a tiny loop that we cannot see on the level of everyday life.

It was this theory that Einstein attempted to further develop into a unified field theory, which would describe all fundamental forces, including gravity, and the relationships between elementary particles in terms of a single theoretical framework without the need for quantum physics. His attempt ultimately failed. Since then things have only gotten more complicated. Electromagnetism was superseded by the more complex quantum mechanics, which Einstein, according to reports, never fully accepted as it seemed too "counterintuitive." Moreover, the number of dimensions of the universe needed for the evolving Theory of Everything (sometimes called quantum gravity) to work, has more than doubled.

Michael Duff

Emeritus Professor of Theoretical Physics at Imperial College London
Michael Duff is an Emeritus Professor of theoretical physics at Imperial College London. Duff gained his PhD in theoretical physics in 1972 at Imperial College under Nobel Laureate Abdus Salam and has spent decades researching the unifying theory of physics. He is known for his contributions to the development of quantum gravity, supergravity, string theory and M-theory. He wrote the first book devoted to M-theory, The World in Eleven Dimensions: Supergravity, Supermembranes and M-theory, which he published in 1999. He is a recipient of the 2004 Meeting Gold Medal from the El Colegio Nacional, Mexico, the

2017 Paul Dirac Gold Medal and Prize from the Institute of Physics, the U.K., and the 2018 Trotter Prize, USA.

STRING THEORY AND THE MULTIVERSE

The first big breakthrough since Kaluza and Klein's 1920s theory came in the 1980s in the form of String Theory. At that time, physicists, desperate to get rid of the infuriating infinite values produced by the theoretical colliding graviton particles (mentioned by Duff), proposed that elementary particles of the microcosmos perhaps weren't simple points in space but instead tiny loops of strings, which only appear pointlike to us.
"It looked for a moment maybe as though this was the answer to all our prayers," Duff said. "But soon we found that there were other problems."

Just like Kaluza-Klein Theory, String Theory didn't work in the ordinary four-dimensional universe. But it didn't work in Kaluza and Klein's five dimensions either. A universe of 10 and ultimately 11 dimensions emerged on physicists' blackboards, where not just one but six to seven dimensions had to be curled up in the invisible realm for the theory to work.

"It turns out that with String Theory you can do some fairly wonderful things," said Reynolds. "You can work out the vibration modes of these strings and then you figure out that the different vibration modes can take on the characteristics of different particles. An electron would be a string with one vibration mode, a quark would be a string with another vibration mode. You start to be able to describe different particles in nature as being different vibration modes of these strings."

So far, so good. The problem is that the way a string vibrates depends on how it's wrapped up. When mathematicians tried to calculate the number of possibilities of this wrapping-up, they arrived at astounding values.

"The number they often quote is 10 to the power of five hundred," Reynolds said. "That is a ten with 500 zeros after it. That's the number of different ways you can wrap the strings up."

Each of these wrapping combinations generates a possible universe in four dimensions, added Duff, a nearly endless plethora of possibilities one of which should represent the universe we inhabit.

"Some of them look like our universe, with the right numbers of quarks and electrons and so on, but some of them look nothing like our universe," Duff said. "And the problem we're faced with in String Theory is how do we pick the right one? Is there a right one? Because there seem to be billions of different possibilities."

By suggesting a multitude of different recipes for spacetime, the fabric of the universe, String Theory helped originate the multiverse concept, a theory of alternate universes alongside ours which may possess different physical laws than the universe we live in.

Christopher Reynolds

Professor of Astronomy at Cambridge University
Christopher Reynolds is a professor of astrophysics at the University of Cambridge. He is a specialist in observational and theoretical high-energy astrophysics. He studies the role of black holes in the universe and relativistic phenomena that appear in the vicinity of black holes where the rules defined by the Standard Model of particle physics break.

SUPERSYMMETRY AND SUPERGRAVITY

To make the String Theory equations work, physicists had to reconcile the behaviors of two types of particles: bosons and fermions. Quarks, the building blocks of protons and neutrons, are fermions as are electrons. This means fermions are the fundamental constituents of matter. Bosons, like photons, gluons, and W and Z bosons, on the other hand, carry the forces that hold this matter together. Both of these types of particles are characterized by their spin, which is the amount of angular momentum a particle possesses and determines which way it will travel when exposed to a magnetic field. The spin values of fermions and bosons can also exist in discrete amounts and spin is conserved for all particles, but these values are very different for these families of particles..

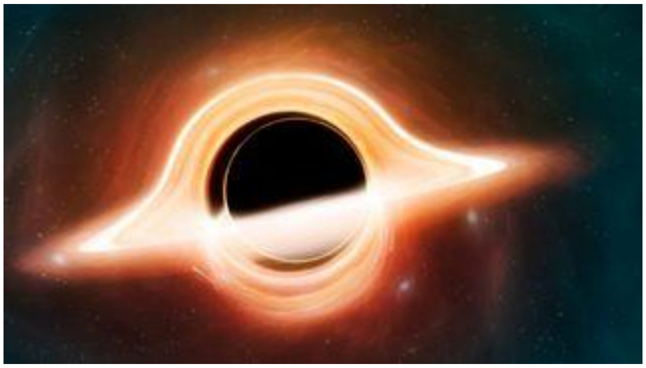
"Bosons have an intrinsic angular momentum which is a [whole number] like 0,1,2,3," Duff explained. "Fermions have spins in halves: spin half, spin three halves. So for many years, we thought these two [types of particles] were like chalk and cheese. We couldn't put them together."

Physicists solved this problem with the concept of supersymmetry, which assumes that each Standard Model particle has its "superpartner" in the other group. This means a bosonic superpartner for each fermion and a fermionic superpartner for each boson, with these superpartners possessing a spin number that differs by a half to its Standard Model counterpart.

Inserting supersymmetry into the equations helped string theorists to settle on 11 instead of 10 dimensions of the universe. This development pleased Duff, who, at that time, was a part of a group of theorists developing a theory called supergravity. The theory of supergravity didn't operate with strings but with what Duff describes as "membranes", and these membranes would only work in 11 dimensions.

"For a while, we were a splinter group looking at 11 dimensions and seeing where it took us," Duff said. "The string theorists were still looking at 10 dimensions and for a while it wasn't clear whether we were on the same page."

M THEORY



Black holes 'leak' a form of thermal radiation that is known as Hawking Radiation. (Image credit: Mark Garlick/Science Photo Library/Getty Images)

Throughout the 1980s and 1990s, competing approaches were developing side by side. Then, in 1995 came another breakthrough when American physicist Edward Witten proposed his M Theory. M Theory, according to Duff, provided an umbrella for the various String Theory variations that existed at that time.

"At first, there were six different approaches," said Duff. "And Witten showed us that they weren't really six different theories but rather six different corners of a deeper, more profound theory that he called the M Theory."

M Theory solved many problems, Duff added. It enabled physicists to perform more exact calculations and reconciled String Theory with Stephen Hawking's black hole formula and his theory that black holes 'leak' a form of thermal radiation that would come to be known as "Hawking Radiation," evaporating as they do so.

M Theory also introduced what Duff calls the holographic principle, which states that "the gravitational world in a certain number of dimensions can be described by a non-gravitational theory that lives on its boundary, which has one dimension less," said Duff, admitting that the claim, while rather "astonishing," seems to work.

Still, the Theory of Everything is far from worked out, Duff said. Most importantly, physicists still don't know how to pick out from billions of possible string-wrapping combinations the one combination that fits our universe.

"Whether M theory is the right theory or not, we don't know, but it's the most promising candidate," said Duff. "But if it is, how long it will take us to figure out all the details is anyone's guess."

THE THEORY OF EVERYTHING'S MISSING PIECES: AXIONS AND DARK MATTER

In the meantime, scientists keep looking for the missing piece of information that could plug the holes in a potential Theory of Everything. Experiments in particle accelerators such as CERN's Large Hadron Collider in Geneva, or observations of the most distant universe may one day produce the breakthrough that generations of theoretical physicists have been waiting for.

That breakthrough, Reynolds said, will most likely come from research into the nature of dark matter, the elusive invisible substance that must make up about 85% of all matter in the universe to explain the gravitational behavior of galaxies and galaxy clusters.

"There is no explanation for dark matter in the Standard Model of particle physics," Reynolds said. "There's something out there that we just have very low-fidelity data on. If we could somehow detect those dark matter particles or detect some signature of dark energy [the force driving the accelerating expansion of the universe], then that would start to really say whether the Theory of Everything is really something along the lines of String Theory or whether it's something completely different."

Astrophysicists, such as Reynolds, as well as particle physicists working with particle accelerators, have an idea of what they are looking for: a particle called axion, which is suggested as a candidate for dark matter particles and is, in fact, predicted by String Theory.

"There's a flurry of experiments right now happening that are trying to detect these axion signatures," Reynolds said.

Researchers think axions have an odd ability to convert into X-ray photons when traveling through powerful magnetic fields. X-ray observatories such as NASA's Chandra space telescope may therefore play an important role in finding out whether axions actually exist.

"We are trying to look at some of the largest magnetized systems in the universe such as galaxy clusters," said Reynolds. "You can have something like 1,000 galaxies trapped in the gravitational potential of dark matter surrounded by magnetized hot gas. And through this gas we can see X-rays generated by supermassive black holes. If axions exist, there is a probability that some of the X-ray photons will convert into axions and we will be able to see that as distortions in the light spectra that we measure."

Future missions, such as the European Space Agency's Athena mission, as well as next-generation particle colliders, may finally find the answer.

WHAT WILL HAPPEN IF WE FINALLY CRACK THE THEORY OF EVERYTHING?

What will happen when all the pieces of the puzzle finally fall into place and we understand how our world works? Will that be the end of physics? Duff disagrees. After we learn the "rules of chess", he said, we can finally "start playing the game".

Cracking the Theory of Everything will surely lead to a flurry of Nobel Prizes. But what comes next? We will have to wait and see.

The theory of everything is a theoretical framework that aims to unify all fundamental forces and particles in the universe into a single cohesive model. It seeks to explain how the four known fundamental forces—gravity, electromagnetism, the strong nuclear force, and the weak nuclear force—interact and govern the behavior of all matter and energy. Achieving this comprehensive understanding could potentially answer many profound questions about the nature of the universe.

1. The theory of everything would provide a single equation or set of equations that encapsulates all physical phenomena in the universe.
2. Currently, no complete theory of everything exists, but various approaches like string theory and loop quantum gravity are being researched.
3. The quest for a theory of everything reflects humanity's deep desire to understand the underlying principles governing reality.
4. A successful theory could lead to groundbreaking technologies and insights into the fundamental workings of nature.
5. The search for this theory emphasizes the need for collaboration across various disciplines in physics, as well as with mathematics and philosophy.
6. How does the theory of everything aim to integrate the four fundamental forces of nature?

The theory of everything aims to integrate the four fundamental forces—gravity, electromagnetism, strong nuclear force, and weak nuclear force—by providing a unified framework that explains their interactions. This integration is essential because currently, these forces are described by separate theories, such as general relativity for gravity and quantum mechanics for the other three. By unifying them, physicists hope to reveal deeper connections between these forces and provide a more complete understanding of how the universe operates.

String theory is significant because it proposes that all fundamental particles are made up of one-dimensional strings rather than point-like objects. This approach offers a pathway toward a theory of everything by suggesting that the vibrational patterns of these strings correspond to different particles and forces. If string theory is validated, it could provide a consistent framework for unifying all known forces and explaining phenomena that remain mysterious under current models, thus revolutionizing our understanding of physics.

Developing a viable theory of everything faces several challenges, including reconciling general relativity with quantum mechanics, which traditionally operate under very different principles. Another major hurdle is the mathematical complexity involved in integrating all forces into a singular framework.

Additionally, many theoretical models lack experimental evidence or predict phenomena that are difficult to test. These challenges highlight not only the limitations of our current understanding but also encourage interdisciplinary collaboration among physicists, mathematicians, and other scientists to push the boundaries of knowledge and seek innovative solutions.

Related terms

String Theory: A theoretical framework suggesting that fundamental particles are not point-like but rather one-dimensional 'strings' that vibrate at different frequencies, potentially unifying all forces and particles.

Grand Unified Theory (GUT): A model that attempts to describe the electromagnetic, weak, and strong nuclear forces as different manifestations of a single force, laying the groundwork for a complete theory of everything.

Quantum Gravity: The field of theoretical physics that seeks to describe gravity according to the principles of quantum mechanics, which is crucial for integrating gravity into a unified framework.

The Elusive Theory of Everything

A few years ago the city council of Monza, Italy, barred pet owners from keeping goldfish in curved fishbowls. The sponsors of the measure explained that it is cruel to keep a fish in a bowl because the curved sides give the fish a distorted view of reality. Aside from the measure's significance to the poor goldfish, the story raises an interesting philosophical question: How do we know that the reality we perceive is true?

The goldfish is seeing a version of reality that is different from ours, but can we be sure it is any less real? For all we know, we, too, may spend our entire lives staring out at the world through a distorting lens.

In physics, the question is not academic. Indeed, physicists and cosmologists are finding themselves in a similar predicament to the goldfish's. For decades we have strived to come up with an ultimate theory of everything—one complete and consistent set of fundamental laws of nature that explain every aspect of reality. It now appears that this quest may yield not a single theory but a family of interconnected theories, each describing its own version of reality, as if it viewed the universe through its own fishbowl.

This notion may be difficult for many people, including some working scientists, to accept. Most people believe that there is an objective reality out there and that our senses and our science directly convey information about the material world. Classical science is based on the belief that an external world exists whose properties are definite and independent of the observer who perceives them. In philosophy, that belief is called realism.

Those who remember Timothy Leary and the 1960s, however, know of another possibility: one's concept of reality can depend on the mind of the perceiver. That viewpoint, with various subtle differences, goes by names such as antirealism, instrumentalism or idealism. According to those doctrines, the world we know is constructed by the human mind employing sensory data as its raw material and is shaped by the interpretive structure of our brains. This viewpoint may be hard to accept, but it is not difficult to understand. There is no way to remove the observer—us—from our perception of the world.

The way physics has been going, realism is becoming difficult to defend. In classical physics—the physics of Newton that so accurately describes our everyday experience—the interpretation of terms such as object and position is for the most part in harmony with our commonsense, "realistic" understanding of those concepts. As measuring devices, however, we are crude instruments. Physicists have found that everyday objects and the light we see them by are made from objects—such as electrons and photons—that we do not perceive directly. These objects are governed not by classical physics but by the laws of quantum theory.

The reality of quantum theory is a radical departure from that of classical physics. In the framework of quantum theory, particles have neither definite positions nor definite velocities unless and until an observer measures those quantities. In some cases, individual objects do not even have an independent existence but rather exist only as part of an ensemble of many. Quantum physics also has important implications for our concept of the past. In classical physics, the past is assumed to exist as a definite series of events, but according to quantum physics, the past, like the future, is indefinite and exists only as a spectrum of possibilities. Even the universe as a whole has no single past or history. So quantum physics implies a different reality than that of classical physics—even though the latter is consistent with our intuition and still serves us well when we design things such as buildings and bridges.

These examples bring us to a conclusion that provides an important framework with which to interpret modern science. In our view, there is no picture- or theory-independent concept of reality. Instead we adopt a view that we call model-dependent realism: the idea that a physical theory or world picture is a model (generally of a mathematical nature) and a set of rules that connect the elements of the model to observations. According to model-dependent realism, it is pointless to ask whether a model is real, only whether it agrees with observation. If two models agree with observation, neither one can be considered more real than the other. A person can use whichever model is more convenient in the situation under consideration.

Do Not Attempt to Adjust the Picture

The idea of alternative realities is a mainstay of today's popular culture. For example, in the science-fiction film *The Matrix* the human race is unknowingly living in a simulated virtual reality created by intelligent computers to keep them pacified and content while the computers suck their bioelectrical energy (whatever that is). How do we know we are not just computer-generated characters living in a Matrix-like world? If we lived in a synthetic, imaginary world, events would not necessarily have any logic or consistency or obey any laws. The aliens in control might find it more interesting or amusing to see our reactions, for example, if everyone in the world suddenly decided that chocolate was repulsive or that war was not an option, but that has never happened. If the aliens did enforce consistent laws, we would have no way to tell that another reality stood behind the simulated one. It is easy to call the world the aliens live in the "real" one and the computer-generated world a false one. But if—like us—the beings in the simulated world could not gaze into their universe from the outside, they would have no reason to doubt their own pictures of reality.

The goldfish are in a similar situation. Their view is not the same as ours from outside their curved bowl, but they could still formulate scientific laws governing the motion of the objects they observe on the outside. For instance, because light bends as it travels from air to water, a freely moving object that we would observe to move in a straight line would be observed by the goldfish to move along a curved path. The goldfish could formulate scientific laws from their distorted frame of reference that would always hold true and that would enable them to make predictions about the future motion of objects outside the bowl. Their laws would be more complicated than the laws in our frame, but simplicity is a matter of taste. If the goldfish formulated such a theory, we would have to admit the goldfish's view as a valid picture of reality.

A famous real-world example of different pictures of reality is the contrast between Ptolemy's Earth-centered model of the cosmos and Copernicus's sun-centered model. Although it is not uncommon for people to say that Copernicus proved Ptolemy wrong, that is not true. As in the case of our view versus that of the goldfish, one can use either picture as a model of the universe, because we can explain our observations of the heavens by assuming either Earth or the sun to be at rest. Despite its role in philosophical debates over the nature of our universe, the real advantage of the Copernican system is that the equations of motion are much simpler in the frame of reference in which the sun is at rest.

Model-dependent realism applies not only to scientific models but also to the conscious and subconscious mental models we all create to interpret and understand the everyday world. For example, the human brain processes crude data from the optic nerve, combining input from both eyes, enhancing the resolution and filling in gaps such as the one in the retina's blind spot. Moreover, it creates the impression of three-dimensional space from the retina's two-dimensional data. When you see a chair, you have merely used the light scattered by the chair to build a mental image or model of the chair. The brain is so good at model-building that if people are fitted with glasses that turn the images in their eyes upside down, their brains change the model so that they again see things the right way up—hopefully before they try to sit down.

Glimpses of the Deep Theory

In the quest to discover the ultimate laws of physics, no approach has raised higher hopes—or more controversy—than string theory. String theory was first proposed in the 1970s as an attempt to unify all the forces of nature into one coherent framework and, in particular, to bring the force of gravity into the domain of quantum physics. By the early 1990s, however, physicists discovered that string theory suffers from an awkward issue: there are five different string theories. For those advocating that string theory was the unique theory of everything, this was quite an embarrassment. In the mid-1990s researchers started discovering that these different theories—and yet another theory called supergravity—actually describe the same phenomena, giving them some hope that they would amount eventually to a unified theory. The theories are indeed related by what physicists call dualities, which are a kind of mathematical dictionaries for translating concepts back and forth. But, alas, each theory is a good description of phenomena only under a certain range of conditions—for example, at low energies. None can describe every aspect of the universe.

String theorists are now convinced that the five different string theories are just different approximations to a more fundamental theory called M-theory. (No one seems to know what the "M" stands for. It may be "master," "miracle" or "mystery," or all three.) People are still trying to decipher the nature of M-theory, but it seems that the traditional expectation of a single theory of nature may be untenable and that to describe the universe we must employ different theories in different situations. Thus, M-theory is not a theory in the usual sense but a network of theories. It is a bit like a map. To faithfully represent the entire Earth on a flat surface, one has to use a collection of maps, each of which covers a limited region. The maps overlap one another, and where they do, they show the same landscape. Similarly, the different theories in the M-theory family may look very different, but they can all be regarded as versions of the same underlying theory, and they all predict the same phenomena where they overlap, but none works well in all situations.

Whenever we develop a model of the world and find it to be successful, we tend to attribute to the model the quality of reality or absolute truth. But M-theory, like the goldfish example, shows that the same physical situation can be modeled in different ways, each employing different fundamental elements and concepts. It might be that to describe the universe we have to employ different theories in different situations. Each theory may have its own version of reality, but according to model-dependent realism, that diversity is acceptable, and none of the versions can be said to be more real than any other. It is not the physicist's traditional expectation for a theory of nature, nor does it correspond to our everyday idea of reality. But it might be the way of the universe.

Theories of Everything, Mapped

Explore the deepest mysteries at the frontier of fundamental physics, and the most promising ideas put forth to solve them.

"Ever since the dawn of civilization," Stephen Hawking wrote in his international bestseller *A Brief History of Time*, "people have not been content to see events as unconnected and inexplicable. They have craved an understanding of the underlying order in the world."

In the quest for a unified, coherent description of all of nature — a "theory of everything" — physicists have unearthed the taproots linking ever more disparate phenomena. With the law of universal gravitation, Isaac Newton wedded the fall of an apple to the orbits of the planets. Albert Einstein, in his theory of relativity, wove space and time into a single fabric, and showed how apples and planets fall along the fabric's curves. And today, all known elementary particles plug neatly into a mathematical structure called the Standard Model. But our physical theories remain riddled with disunions, holes and inconsistencies. These are the deep questions that must be answered in pursuit of the theory of everything.

Our map of the frontier of fundamental physics, built by the interactive developer Emily Fuhrman, weights questions roughly according to their importance in advancing the field. It seemed natural to give greatest weight to the quest for a theory of quantum gravity, which would encompass general relativity and quantum mechanics in a single framework. In their day-to-day work, though, many physicists focus more on rooting out dark matter, solving the Standard Model's hierarchy problem, and pondering the goings-on in black holes, those mysterious swallowers of space and time. For each question, the map presents several proposed solutions. Relationships between these proposals form a network of ideas.

The map provides concise descriptions of highly complex theories; learn more by exploring the links to dozens of articles and videos, and vote for the ideas you find most elegant or promising. Finally, the map is extensive, but hardly exhaustive; proposed additions are welcome below.

2024 IN REVIEW

The Year in Physics

Physicists discovered strange supersolids, constructed new kinds of superconductors, and continued to make the case that the cosmos is far weirder than anyone suspected.

By Natalie Wolchover

Senior Editor

December 17, 2024

Will 2024 be remembered as a banner year in the quest to understand the universe, or just an average one? That depends on whether a result from this spring turns out to be real.

In April, physicists detected a hint of a signal suggesting that dark energy, the mysterious energy of space itself, may be weakening. “Hint” is the preferred term because the sign in the heavens isn’t quite robust enough to be called “evidence,” to say nothing of “discovery.” Astrophysicists used the Dark Energy Spectroscopic Instrument (DESI) to map millions of galaxies at different distances in space and time, and from this map they inferred how the universe has expanded over its history. The data confirmed — as we’ve known since 1998 — that the cosmos’s expansion is accelerating, driven by what we call dark energy. But DESI’s data hints that the rate of acceleration has been dropping.

If dark energy is an energy source that can get diluted, it would upend and deepen physicists’ understanding of the fundamental laws of the universe. “If true, it would be the first real clue we have gotten about the nature of dark energy in 25 years,” Adam Riess, one of the Nobel Prize–winning discoverers of dark energy, told *Quanta*. Theoretical physicists are busy trying to explain why dark energy might change, while DESI logs more data for a more definitive assessment in the coming years.

Dark Matter Is Dead, Long Live Dark Matter

In the search for the invisible components of the universe, dark matter reached a discouraging milestone. (Fuzzy on the difference between dark energy and dark matter? Read our *Fundamentals* newsletter() from May.) Experimenters hunting for hypothesized dark matter particles known as WIMPs — heavy, inert particles that were long considered the top candidate for the nonreflective stuff floating in and around galaxies — hit a limit. Detectors have become so sensitive that they're now picking up the glow of neutrinos from the sun(), which blinds them to any subtler signals. "So that's kind of the end of the WIMP detection era," the Stanford University physicist Natalia Toro told us.

She and other dark matter hunters have switched gears and now seek new dark matter candidates, especially lightweight but abundant particles that would come in multiple species. "The most common hypothesis is that this is somehow simple. Why on Earth should we expect that?" said Philip Schuster, also a Stanford physicist, voicing an increasingly common sentiment among specialists.

Lest you suspect that dark matter is the Ptolemaic epicycle() of the 21st century — a long-believed but convoluted and ultimately erroneous model of the universe — astronomers discovered a new reason to think it's really out there. The finding, an object called MACS J0018.5(), has proved so compelling that people are referring to it as the new Bullet Cluster(). In the original Bullet Cluster — long considered one of the single most persuasive pieces of evidence for dark matter's existence — we see two enormous clusters of galaxies crashing together. The colliding gas glows brightly in the center of the crash site, but most of the matter has sailed right through, forming heavy, light-distorting blobs on either side. That's how dark matter particles would behave, because they don't (or barely) interact.

MACS J0018.5 is similar, except the galaxy clusters are merging along our line of sight. Researchers effectively pointed a radar gun at them and found that their visible gas has slowed as it collides while the majority of the mass moves faster, unimpeded by the collision.

These merging clusters are hard to explain without invoking the kind of invisible particles we're looking for.

Astronomical Discoveries

The night sky holds many secrets. The flagship of modern astronomy, the James Webb Space Telescope, beamed down a few more this year, particularly in its observations of faraway objects from the universe's first billion years. Banana-shaped galaxies, little red dots, grape-like clusters, shockingly big young black holes: Astrophysicists are reveling in the "beautiful confusion" of that formative epoch of cosmic history.

The Webb telescope also enabled a precise new measurement of the universe's expansion rate, deepening a puzzle known as the Hubble tension. Meanwhile, other telescopes revealed the largest magnetic fields in the universe, hidden organic molecules and the clumpiness of the cosmos itself.

Happy Days in the Lab

Moving from the largest stage to the very smallest one, physicists who manipulate atoms, molecules and crystals in the lab have also spent 2024 in the throes of discovery, having achieved astonishing levels of precision and control over their quantum quarries. A team in Innsbruck created a long-predicted exotic state of matter called a supersolid, and even imaged the hallmark "quantum tornadoes" that formed when they stirred an otherwise rigid crystal of dysprosium atoms. Astrophysicists suspect that this supersolid phase might arise inside incredibly dense, fast-spinning stars called pulsars.

Meanwhile, condensed matter physicists studying two-dimensional materials — that is, crystalline sheets of atoms — discovered three new kinds of superconductivity this year, while also mulling over a strange quantum phase of matter in which emergent particles possessing fractions of charge flow around the crystal's edge. No telling yet whether these phases will prove technologically useful, but that's always the dream.

Other labs made progress in encoding and manipulating information in arrays of atoms. Once an underdog approach to quantum computing, these so-called neutral-atom quantum computers seem to have suddenly shot to the front of the pack. The ascendant devices yielded a landmark result in November, achieving a noise-resistant, or "fault-tolerant," logical computation().

Moreover, for decades, physicists have sought to pinpoint the energy of a special nuclear transition in thorium, knowing it could serve as a tool to probe the fundamental forces that bind the universe. This year, three different groups finally succeeded in measuring this "nuclear clock" transition, which they plan to monitor to look for variations in the strength of those fundamental forces.

A Peek Beneath Space-Time

Theoretical physicists have made progress of a more abstract kind. They've developed a new geometric language for predicting the outcomes of particle interactions. Traditionally, they use equations that describe these interactions as dynamical events playing out in space and time according to quantum rules. Using the new method, answers seem to flow from sets of curves on surfaces. These breakthrough insights are part of an effort to discover the fundamental underpinnings of space and time themselves — the subject of "The Unraveling of Space-Time," a nine-part special issue we published in September.

For another deep dive into a deliciously profound subject, check out our multimedia exploration of entropy, which examines how the evolving understanding of this quantity has reframed the purpose of science and our role in the universe.

All Riled Up

Physics-related discussions on X (formerly known as Twitter) are pale shadows of what they used to be, but lively chatter did ensue from one bit of physics news, when *Scientific American* reported that a quantum physics experiment had detected evidence of "negative time."() What, exactly, is that supposed to mean? Had something really taken less than no time at all? Not exactly. In the quantum world, words often fail.

What happened was that physicists at the University of Toronto shot photons toward a cloud of rubidium atoms. Each photon might excite an atom in the cloud, or go straight through without interacting, or both. These quantum possibilities interfered like two waves. Then the researchers could determine that some photons went through the atom cloud faster when they got absorbed and reemitted than when they didn't, implying a "negative dwell time," as if these photons excited the atoms for a negative amount of time — but again, these are just words. "We are measuring a duration, not something finishing before it starts," one of the researchers involved tried to explain on X().

Eyebrows also shot up in October when the 2024 Nobel Prize in Physics went to pioneers of artificial intelligence() — a technology that seems, on its face, unrelated to the laws of nature. "I'm flabbergasted," one of the recipients, the computer scientist Geoffrey Hinton, told *Science*. Yet in the 1980s, he and the other winner, John Hopfield, closely modeled() their rudimentary artificial neural networks on systems in statistical physics.

Some statistical physicists were pleased by the attention given to their obscure research on the behavior of systems of many parts. "For us, it's super-great," Aurélien Decelle told *Science*(). "It's recognition at the broader level that what we're doing matters a lot."

ASTROPHYSICS

The 'Beautiful Confusion' of the First Billion Years Comes Into View

Astronomers are reveling in the James Webb Space Telescope's discoveries about the formative epoch of cosmic history.

October 9, 2024

astronomyastrophysicsblack holescosmologygalaxiesphysicstelescopesAll topics

The galaxies were never supposed to be so bright. They were never supposed to be so big. And yet there they are — oddly large, luminous objects that keep appearing in images taken by the James Webb Space Telescope (JWST).

Kevin Hainline() is part of a team that uses the JWST to find these galaxies, whose brightness, apparent mass, and sheer existence a virtual eyeblink after the Big Bang are among the biggest surprises from the three-year-old mission. And these findings have raised a lot of questions. In August, Hainline and other researchers came together at the Kavli Institute for Theoretical Physics (KITP) in Santa Barbara, California, to hash them all out.

"People were saying, 'Well, Kevin, it can't be *that*,'" he told me. "And the observers are like, 'Well, this is what we see,' and then theorists can go figure it out and mess around."

After the first morning of the conference, I found Hainline in the courtyard. The new discoveries I had been hearing about seemed revolutionary, perhaps even paradigm-shifting. I wanted to check my reaction with one of the people doing the actual work. Were these results as extraordinary as I, a reporter, thought they were?

"We are knocking on the door of history," Hainline assured me. "Astronomers need to be better about celebrating discoveries."

In Santa Barbara, they did. Over star-studded slide decks and rounds of Pacifico beer, 100 or so astrophysicists exulted in the new findings about the universe's first billion years, an epoch that JWST is revealing in exquisite detail for the first time. They shared surprising observations of "little red dots," which abound in JWST data and whose nature remains elusive, as well as images of other early galaxies that look extremely blue. They marveled at odd galactic shapes, including bright objects that resolve into tight clusters, like bunches of grapes, and others resembling bananas. People argued over the enormous black holes spotted at those early times and the circumstances of their formation.

The yellowish blob on the right is JADES-GS-Z14-0, a galaxy spotted in JWST data this year. The universe's earliest known galaxy, it is seen as it appeared 300 million years after the Big Bang.
Courtesy of Jakob Helton/University of Arizona; Image processing by: Ben Johnson/CfA, Sandro Tacchella/ Cambridge, and Phill Cargile/CfA

Susan Kassin(), an astronomer at the Space Telescope Science Institute, showed images from previous observatories compared to JWST's. It was like having the optometrist flip a lens so that the last lines on an eye chart come into focus. "Thank you, Webb — it's a $10 billion difference," she said. People chuckled and nodded.

JWST is singular in its ability to see the young cosmos, which has drifted far away from us in both space and time. Its infrared sensors, its ultracold location in space, and its sunshield — which blocks the light of the sun, moon and Earth — are uniquely suited to resolve the first galaxies and their stars. These objects are too faint and at the wrong wavelengths to be seen by previous observatories, like the Hubble Space Telescope.

For astronomers, the vibe is collegial. Many presentations at the KITP conference included pleas for collaborators and partners in brainstorming.

Caitlin Casey, an astrophysicist who specializes in galaxy formation and evolution at the University of Texas, Austin, is trying to understand how galaxies grew so bright so early in cosmic history.
Courtesy of Caitlin Casey

"It was crazy competitive when the first data dropped. Now it is about coming up with ideas," said Caitlin Casey() of the University of Texas, Austin. "There is a firehose of data, and everyone has enough."

The astrophysicist Rachel Somerville(), who co-organized the meeting, said the community is scrambling to absorb both JWST's data and its implications. Observers see things that are not explained in current theories about the evolution of the young cosmos.

"Many presentations showed that there is a tension between theory and observation," said Fabio Pacucci() of Harvard University, in one example of a cosmic understatement. To punctuate the confusion astronomers feel about this once-in-a-lifetime telescope upending what we know of the young universe, he flashed up a tongue-in-cheek slide: a cartoon of a dog sitting at a table sipping coffee while its house is in flames, captioned "This is fine."

The Biggest and the Brightest

Astronomers kept referring to one of the most consequential galaxies seen so far, an unexpectedly bright smear of light called, dryly, JADES-GS-z14-0. Hainline, at the University of Arizona, is part of the team that discovered it with JWST and confirmed its distance() in May 2024. It is the earliest known galaxy, knocking down the previous record holder, which was found() by the same team in 2023.

At the time the galaxy shone forth, sound waves from the tremendous clap that started the universe were still ringing through the void. The first stars had been born in a cataclysmic baby boom, and some had already died. The dark hearts of black holes lurked, too — regions of space where gravity is so strong that not even light can escape. And there was this cluster of stars, resolved as a fuzzy scorpion shape in JWST filters. Two instruments on JWST were able to distinguish JADES-GS-z14-0's brightness and its distance from Earth. Because of the accelerating expansion of the universe, objects at great distances are very far back in time. Astronomers can tell their ages based on the stretching of their light into longer wavelengths, known as redshift. Based on the most recent measurements, the galaxy was determined to lie at a redshift of 14.18, which means we see it as it appeared 300 million years after the Big Bang — when the universe was about 2% of its current age.

Kevin Hainline of the University of Arizona is part of a team that uses the James Webb Space Telescope to find and characterize galaxies at high redshifts.
Lara Ruggles

Initially, astronomers speculated that such huge, bright things so early in the universe were at odds with the prevailing theoretical model of the cosmos. But people have softened on that claim. Our best model of the universe — a set of equations describing the evolution of matter and radiation along with dark energy and dark matter — is not dead yet.

“There was a lot of sensationalism” in JWST’s early days, said Alice Shapley() of the University of California, Los Angeles. “There is no need for that. The data are so beautiful; let’s just study the universe we have.”

Astrophysicists are coalescing around three star-based theories for how galaxies grew so bright so fast. One holds that stars during the cosmic dawn were very different from stars today. The stars in JADES-GS-z14-0, for instance, might be ultrabright but not actually very massive. While this seems plausible, it is also tricky for theoretical modelers to deal with. The correlation between a star’s brightness and its mass is a key value entered into computer simulations. If this value — known as the initial mass function, or IMF — was different in the early universe, then researchers would have to rewrite their simulations to be able to accommodate an IMF that changes over time.

But nature doesn’t care about our computing issues, and a changing IMF is, in principle, one of the most logical ways to make sense of what we see. “The IMF is truly the house of cards on which we build everything. There are many reasons to believe it is quite different at very high redshift,” Casey said.

Another theory holds that the extra-bright early galaxies happened to be undergoing furious bursts of star formation. Over 10 million or 100 million years, galactic brightness could vary by a factor of 100 as star formation ramped up and down. That’s like a candle turning into a floodlight in the span of a few seconds. Relatedly, during these busy spells, supernova explosions might have made things look brighter than they would otherwise appear.

Erica Nelson, an astrophysicist at the University of Colorado, Boulder, is part of the JADES team, which has used JWST to spot bright, massive galaxies that existed unexpectedly early in cosmic history.
Shannon Curry

The third theory suggests that star formation was way more efficient then than now. In a typical galaxy today, a small fraction of the gas is forged into stars;

the Milky Way builds between two and six sun-size stars a year. But maybe the smallness and compactness of the early universe made it a better stellar factory. Some calculations suggest an almost 100% rate of conversion from gas to star, meaning fast and furious stellar birth, said Pratika Dayal() of the University of Groningen in the Netherlands.

All these alterations to existing theory come with side effects, like changes in how much dust there should be and puzzles about how stellar baby booms settled down. And they're not even the only ideas out there. Andrea Ferrara(), a cosmologist at the Scuola Normale Superiore in Pisa, Italy, showed his colleagues in Santa Barbara a new model that tries to explain the bright early galaxies by changing the amount of dust within them, which would typically block starlight. His model assumes that more dust used to be blown away by stellar winds. "Reducing dust attenuation is my favorite hypothesis, even though I am totally open to having the other two," he told attendees. But, he acknowledged, his calculations might not hold up at a redshift of 14, meaning they might not work for galaxies like JADES-GS-z14-0.

"So please don't discover other galaxies," he concluded, to laughter.

Big Black Holes

Star-related theories are not the only ideas. Some astrophysicists point to active supermassive black holes, which they say might heat surrounding gas and cause galaxies like JADES-GS-z14-0 to appear extremely bright.

In a series of papers published in May, the JADES team argues that the galaxy is starry, and that its brightness cannot be explained by black holes. But other galaxies do have such dark hearts. We know supermassive black holes weighing hundreds of millions or billions of suns anchor the centers of modern galaxies. And JWST is seeing smeared light from many early galaxies, indicating() that their gas, too, is being slung around by a central supermassive black hole. How, then, did the big black holes get there?

Since black holes were first predicted as a consequence of Albert Einstein's theory of gravity, astrophysicists have imagined how they might form from the inward gravitational collapse of dying stars. They now know that the cosmos is filled with black holes formed in this way. But cosmologists have struggled to understand supermassive black holes. These black holes somehow grew large enough, and fast enough, to shape the galaxies that formed around them. If they began as collapsed stars, they would have had to grow at staggering rates that defy physical explanation.

Observations by JWST and the Chandra X-Ray Observatory reveal a supermassive black hole that existed in a galaxy dubbed UHZ1 a mere 470 million years after the Big Bang. Some astrophysicists argue that the black hole, which already had an estimated mass of tens or hundreds of millions of suns, must have formed from the direct collapse of an enormous gas cloud, rather than from the death of an individual star.
X-ray: NASA/CXC/SAO/Ákos Bogdán; Infrared: NASA/ESA/CSA/STScI; Image Processing: NASA/CXC/SAO/L. Frattare & K. Arcand

Some cosmologists have begun to favor an alternative theory for supermassive black hole seeds: that the black holes formed directly from the collapse of enormous clouds of gas in the young universe. This process could produce gargantuan black holes contemporaneous with galaxies like JADES-GS-z14-0.

Again, there are problems. Some of the early galaxies that seem to host supermassive black holes do not produce X-rays, which is typically a hallmark of black holes. Maybe those black holes produce X-rays that are too faint or too heavily obscured, so we don’t see them.

Some supermassive black holes do come with copious X-rays. In 2023, combined observations from JWST and the Chandra X-ray telescope unveiled a supermassive black hole() in place just 470 million years after the Big Bang, in a galaxy labeled UHZ1. Could it have formed directly from the collapse of massive gas clouds, or from the implosion of a first-generation gargantuan star? “You either need modest growth of heavy initial seeds, versus accelerated growth of light seeds,” explained Priyamvada Natarajan() of Yale University, who helped develop the “heavy seed” theory.

Priyamvada Natarajan, an astrophysicist at Yale University, thinks JWST’s observations of supermassive black holes in the early universe support an alternative theory of their formation.
Sasha Maslov for *Quanta Magazine*

Modelers are still working out possibilities, but the early black hole in UHZ1 is a huge beacon, in terms of its energy across the electromagnetic spectrum, she said. That comment sparked pushback from Joseph Hennawi() of the University of California, Santa Barbara, who questioned whether the object’s energy output really represents its mass.

“In my opinion, a lot of the claims and possibly some of the confusion is coming from the fact that we don’t have a handle on the bolometric power,” he said, referring to an object’s total power output. “I don’t think we need to believe the numbers that people are arguing.”

Natarajan countered that the measurements of the black hole’s energy density are the best we have so far, and that they come from two independent detection methods.

“It’s still very much open season, I think, for theorists, but evidence for heavy seeds is mounting,” she added.

Little Red Dots

JWST has unveiled a new class of cosmic objects. They are colloquially called little red dots — a familiar and friendly term for something in the early universe that we have never seen before or since.

The LRDs seem to be small, red-tinted galaxies that ignited about 600 million years after the Big Bang and blazed for a billion years. There is no trace of them in today’s universe. They are actually red, not just redshifted, which might suggest that they either emit ample red light or are full of dust that blocks blue wavelengths and leaves the object looking ruddy. The little red dots are tiny, some of them about 100 times smaller than today’s Milky Way. And this is pretty much all astronomers know about them, Pacucci said.

Andrey Kravtsov() of the University of Chicago said that little red dots are the biggest discovery of JWST so far. As a theorist, he said, he had not heard much about them before the meeting. He said it reminded him of the discovery of quasars in the 1950s, mysterious ultra-luminous objects that turned out to be active supermassive black holes.

A sampling of the poorly understood little red dots that JWST has spotted in the early universe.
Courtesy of Jorryt Matthee(). Data from the EIGER() / FRESCO() surveys

“This feels a lot like that — there are ideas flying around, and people can argue,” he said. “In a few years, it will be figured out. But right now it’s exciting to be in this process of discovery.”

As Kravtsov and I chatted, our table mates started talking about why little red dots are so unusual. The objects are spinning super fast, Dale Kocevsk) of Colby College told me — gas in the clouds is being flung around at 3,000 kilometers per hour. Typical gas flow is about 300 kilometers per hour. Only something huge can accelerate gas to those speeds, so some people argue the LRDs contain spinning supermassive black holes.

“But there are ways out of it,” countered Erica Nelson() of the University of Colorado, Boulder. Her presentation described how, if LRDs are really tight, compact balls of gas, the gas might actually spin around that quickly. She and Kocevski continued explaining the theories and their weak points to me.

“So now you see the beautiful confusion,” Kravtsov said.

Cosmic Grapes

A dim young galaxy dubbed Cosmic Grapes, seen as it appeared 930 million years after the Big Bang.

Courtesy of Seiji Fujimoto

Certain discoveries seemed to stick with people, and it was almost as though you could see ideas forming as people incorporated their colleagues’ findings into their own talks. One such presentation came from Seiji Fujimoto() of the University of Texas, Austin, who showed new work demonstrating that bright massive galaxies might contain more than meets the eyepiece. He and collaborators studied a bright galaxy that JWST had imaged as it appeared 930 million years after the Big Bang. Using gravitational lensing, he was able to discern that it is not just one object, but a grapelike cluster of at least 15 individual star-forming clumps.

Astronomers buzzed about Fujimoto’s findings for the next two days. Somerville wondered whether all high-redshift galaxies are made of dense clumps like those grapes, and why computer simulations of galaxy formation are not reproducing those structures. Dense clumps could produce stars efficiently and quickly, and would shine brightly, so gobs of cosmic grapes could explain a lot about how galaxies got off the ground, she noted. “We need to think about this harder,” she said, in another phrase that came to characterize the gathering.

Viraj Pandya() of Columbia University showed that even small early galaxies have weird characteristics. They are oddly elongated, with stars aligned in such a way as to give the galaxies a cigar or pickle shape. Pandya described them as “galaxies going bananas.” This new class of galaxies in the early universe has no counterpart in the universe today.

JWST has cataloged many oddly elongated galaxies in the early universe.

Courtesy of Viraj Pandya

Another way to put it is that everything was weird during the universe’s first billion years. Galaxy size, brightness, mass and shape from that period are all weird. Black holes are weird. The efficiency of star formation is weird; the correlation between brightness, astronomical power and an object’s mass — essential for theoretical models — are not as astrophysicists expected. The presence of little red dots and chains of elongated galaxies: weird. Aren’t people baffled by all this weirdness?

Kocevski smiled as I kept saying things like this. No one feels baffled, he said. Being unsure, and thinking about what comes next, is the point of an innovative observatory like JWST. “That’s science,” he said.

More to Come

The firehose is not even all the way open. JWST is streaming new data every day, and the intensely competitive fight for time on the telescope is determining which discoveries will happen first. But that’s saying nothing of the coming generation of ground-based telescopes and new orbital telescopes.

Astronomers are buzzing about a new paper by Seiji Fujimoto, a galaxy and black hole specialist at the University of Texas, Austin, who used gravitational lensing to magnify an early galaxy and revealed it to be a grapelike cluster of at least 15 individual star-forming clumps.

Courtesy of Seiji Fujimoto

Several people looked forward to being able to combine JWST measurements with ones from the Nancy Grace Roman Space Telescope, which like JWST will observe infrared light from the early universe to tackle cosmological questions. Roman will beam down a terabyte of data per day. Euclid, a European telescope that launched last year, will determine galactic redshifts, enabling useful comparisons with JWST findings. And people were buzzing about the forthcoming Vera Rubin Observatory, set for first light in April or May 2025.

The Rubin Observatory will photograph the entire heavens every three days and will totally transform short-timescale astronomy, showing how stars evolve day to day. It is an incredibly rich time to study the stars.

Earlier in the summer, I talked with Julian Muñoz() at the University of Texas, Austin, who has proposed some new theories for bursty star formation that could explain the early massive galaxies. “There are more good questions than time,” Muñoz said.

Under the auspices of a research program dedicated to the cosmic dawn, Muñoz and several other astronomers spent much of the summer at KITP before and after I joined them at the four-day conference. Visiting scholars live in apartments provided by the institute and share dinners and evening walks to talk about their ideas. The Santa Ynez mountains to the northeast, the Pacific to the west, and the Mediterranean-like charm of Santa Barbara add to the communal experience. During one of the breaks, I made myself leave the darkened lecture room to take in the surroundings.

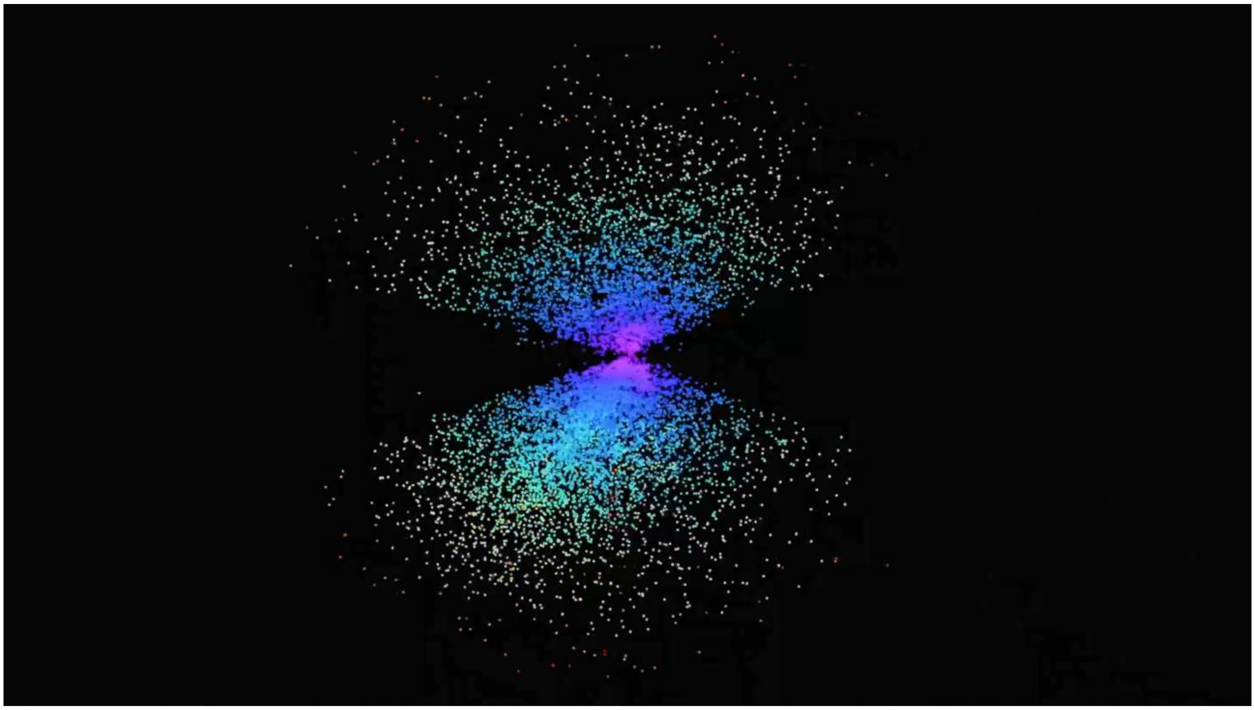
I walked toward Santa Barbara’s sun-bleached coast. Kravtsov, who also spent all summer here, had told me where to find a snowy plover habitat, a 20-minute walk along the beach. I walked down bluffs blanketed in invasive ice plant, a succulent ground cover that overtook the headlands when it was introduced in the 1950s. Yellow and pink flowers popped up randomly through the tangles. “Beautiful confusion,” Kravtsov had said. Thoughts of time started to overwhelm me.

Eighty-three years ago, during World War II, the U.S. Army Corps of Engineers built the nearby Santa Barbara airport using land dredged from Mescalitan Island, site of a Chumash Indian settlement. Indigenous peoples had lived there for at least 11,000 years.

Some 340 million years earlier, the lunar tide periodically stranded backboned fish on a beach just like this one. Over millennia, those fish began to walk on land.

About 4 billion years before that, a passing star or supernova material stirred the gaseous remains of a star some astronomers call Coatlicue, and the gas collapsed, igniting our sun.

Nearly 9 billion years earlier, light from the galaxy now called JADES-GS-z14-0 shone forth. Kevin Hainline was the first person to see it, when he downloaded a batch of JWST data in January of this year. He stood up from his chair in surprise.



COSMOLOGY

Fresh X-Rays Reveal a Universe as Clumpy as Cosmology Predicts

By mapping the largest structures in the universe, cosmologists have found that a cosmic anomaly appears to be fading away.

The eRosita X-ray telescope spotted thousands of galaxy clusters across a vast swath of the cosmos, colored in this animation according to their distance from the telescope’s location at the center. Light from the farthest clusters was emitted 9 billion years ago.

MPE, A. Liu for the eROSITA Consortium

Introduction

March 4, 2024

Clusters of hundreds or thousands of galaxies sit at the intersections of giant, crisscrossing filaments of matter that form the tapestry of the cosmos. As gravity pulls everything in each galaxy cluster toward its center, the gas that fills the space between the galaxies gets compressed, causing it to heat up and glow in X-rays.

The eRosita X-ray telescope, lofted into space in 2019, spent more than two years collecting pings of high-energy light from all over the sky. The data has allowed scientists to map the locations and sizes of thousands of galaxy clusters, two-thirds of them previously unknown. In a slew of papers() posted online on February 14 that will appear in the journal *Astronomy & Astrophysics*, the scientists used their initial catalog of clusters to weigh in on several of cosmology's big questions.

The results include new estimates of the clumpiness of the cosmos — a much-discussed characteristic of late, as other recent measurements have found it to be unexpectedly smooth — and of the masses of ghostlike particles called neutrinos and of a key property of dark energy, the mysterious repulsive energy that's speeding up the universe's expansion.

Cosmologists' reigning model of the universe identifies dark energy as the energy of space itself and pegs it at 70% of the universe's contents. A further one-quarter of the universe is invisible dark matter, and 5% is ordinary matter and radiation. All of it is evolving under the force of gravity. But some observations from the past decade defy this "standard model" of cosmology, raising the possibility that the model is missing ingredients or effects that could usher in a deeper understanding.

The eRosita observations, by contrast, bolster the existing picture on all counts. "It's a remarkable confirmation of the standard model," said Dragan Huterer(), a cosmologist at the University of Michigan who was not involved in the work.

X-Raying the Cosmos

After the Big Bang, subtle density variations in the newborn universe gradually became more pronounced as matter particles glommed onto each other. The denser clumps pulled in more material and grew larger. Today, galaxy clusters are the largest gravitationally bound structures in the cosmos. Determining their sizes and distribution lets cosmologists test their model of how the universe evolved.

To find clusters, the eRosita team trained a computer algorithm to scour for "really fluffy" X-ray sources as opposed to pointlike objects, said Esra Bulbul() of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, who led eRosita's cluster observations. They whittled a list of candidates down to an "extremely pure sample," she said, of 5,259 galaxy clusters, out of the nearly 1 million sources of X-rays the telescope detected.

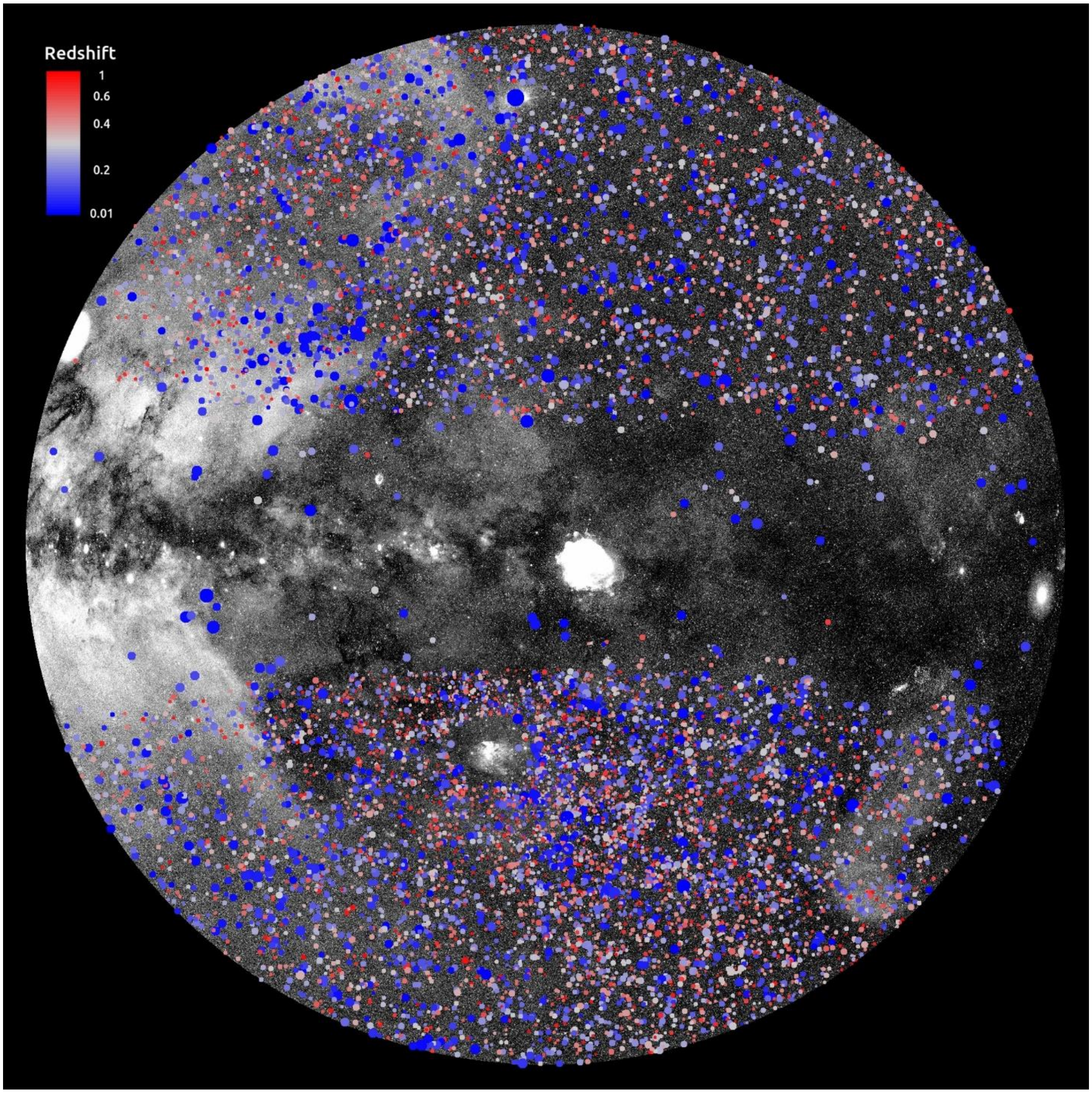
They then had to figure out how heavy these clusters are. Massive objects bend the fabric of space-time, changing the direction of passing light and making the source of the light appear distorted — a phenomenon called gravitational lensing. The eRosita scientists could calculate the masses of some of their 5,259 clusters based on the lensing of more distant galaxies sitting behind them. While only a third of their clusters had known background galaxies lined up in this way, the scientists found that the cluster mass correlated strongly with the brightness of their X-rays. Because of this strong correlation, they could use brightness to estimate the masses of the remaining clusters.

They then fed the mass information into computer simulations of the evolving cosmos to infer the values of cosmic parameters.

Gauging Clumpiness

One number of interest is the "clumpiness factor" of the universe, S_8.
An S_8 value of zero would represent a vast cosmic nothingness, akin to a flat plain with nary a rock in sight. An S_8 value closer to 1 corresponds to steep mountains looming over deep valleys. Scientists have estimated S_8 based on measurements of the cosmic microwave background (CMB) — ancient light coming from the early universe. Extrapolating from the cosmos's initial density variations, researchers expect the current S_8 value to be 0.83.

But recent studies looking at galaxies today have measured values 8% to 10% lower, implying that the universe is unexpectedly smooth. That discrepancy has intrigued cosmologists, potentially pointing to cracks in the standard cosmological model.



The eRosita catalog of galaxy clusters is plotted here on a map of the half-sky. The colors indicate the distance of the clusters and the sizes of the circles indicate the apparent X-ray brightness of each source.
MPE, J. Sanders for the eROSITA Consortium

The eRosita team, however, found no such discrepancy. “Our result was basically in line with the prediction from the very early time, from the CMB,” said Vittorio Ghirardini(), who led the analysis. He and his colleagues calculated an S_8 of 0.85.

Some team members were disappointed, Ghirardini said, since hinting at missing ingredients was a more exciting prospect than matching the known theory.

The S_8 value sitting a tad higher than the CMB estimate will likely trigger more analysis from other teams, said Gerrit Schellenberger(), an astrophysicist who studies galaxy clusters at the Harvard-Smithsonian Center for Astrophysics. “I believe it’s probably not the last paper we have seen on that topic.”

Weighing Neutrinos

Copious neutrinos formed in the early universe — nearly as many as photons (particles of light), said Marilena Loverde(), a cosmologist at the University of Washington. But physicists know that neutrinos, unlike photons, must have tiny masses because of how they oscillate between three types. The particles don’t acquire mass through the same mechanism as other elementary particles, so their mass is a much-studied mystery. And the first question is how massive they actually are.

The nature of dark energy is “the biggest question that cosmology has.”

Sebastian Grandis

Cosmologists can estimate the mass of neutrinos by studying their effects on the structure of the cosmos. Neutrinos zip around at nearly the speed of light and pass right through other matter rather than glomming onto it. So their presence in the cosmos has attenuated its clumpiness. “The more mass you put on neutrinos, the more of the mass that is smooth on those [large] scales,” Loverde said.

Combining their galaxy cluster measurements with CMB measurements, the eRosita team estimated that the sum of the masses of the three types of neutrinos is no more than 0.11 electron volts (eV), or less than a millionth of the mass of an electron. Other neutrino experiments have established a lower bound(), showing that the three neutrino masses must add up to at least 0.06 eV (for one possible ordering of the three mass values) or 0.1 eV (for the inverted order). As the distance shrinks between the upper and lower bounds, scientists are getting closer to pinpointing the value of the neutrino mass. “We are actually at the brink of making a breakthrough," Bulbul said. In subsequent data releases, the eRosita team could push down the upper bound enough to rule out the inverted-order neutrino mass models.

Caution is warranted. Any other speedy, lightweight particles that might exist — such as axions, hypothetical particles proposed as candidates for dark matter — would have the same effects on structure formation. And they would introduce errors into the neutrino mass measurement.

Tracking Dark Energy

Galaxy cluster measurements can reveal not just how structures grew, but also how their growth was impeded by dark energy — the thin glaze of repulsive energy that permeates space, accelerating space's expansion and thereby separating matter.

If dark energy is the energy of space itself, as the standard model of cosmology assumes, then it will have a constant density throughout space and time (that's why it's sometimes referred to as the cosmological constant). But if its density is instead dropping over time, then it's something else entirely. "That's the biggest question that cosmology has," said Sebastian Grandis, an eRosita team member at the University of Innsbruck in Austria.

From their map of thousands of clusters, the researchers found that dark energy matches the profile of a cosmological constant, although their measurement has a 10% uncertainty, so an ever-so-slightly varying dark energy density remains possible.

Originally, eRosita, which sits aboard a Russian spacecraft, was to conduct eight full-sky surveys, but in February 2022, weeks after the telescope began its fifth survey, Russia invaded Ukraine. In response, the German side of the collaboration, which operates and runs eRosita, put the telescope into safe mode, ceasing all scientific observations.

These initial papers draw from just the first six months of data. The German group expects to find about four times as many galaxy clusters in the additional 1.5 years of observations, which will allow all these cosmological parameters to be pinpointed with more accuracy. "Cluster cosmology could be the most sensitive probe of cosmology other than the CMB," said Anja von de), an astrophysicist at Stony Brook University.

Their initial results demonstrate the power of a relatively untapped information source. "We're kind of the new kid on the block," Grandis said.

ASTROPHYSICS

Standard Model of Cosmology Survives a Telescope's Surprising Finds

Reports that the James Webb Space Telescope killed the reigning cosmological model turn out to have been exaggerated. But astronomers still have much to learn from distant galaxies glimpsed by Webb.

The Webb telescope has spotted galaxies surprisingly far away in space and deep in the past. These four, studied by a team called JADES, are all seen as they appeared less than 500 million years after the Big Bang.

Samuel Velasco/Quanta Magazine; source: NASA

Introduction

January 20, 2023

The cracks in cosmology were supposed to take a while to appear. But when the James Webb Space Telescope (JWST) opened its lens last spring, extremely distant yet very bright galaxies immediately shone into the telescope's field of view. "They were just so stupidly bright, and they just stood out," said Rohan Naidu(), an astronomer at the Massachusetts Institute of Technology.

The galaxies' apparent distances from Earth suggested that they formed much earlier in the history of the universe than anyone anticipated. (The farther away something is, the longer ago its light flared forth.) Doubts swirled, but in December, astronomers confirmed that some of the galaxies are indeed as distant, and therefore as primordial, as they seem. The earliest of those confirmed galaxies shed its light 330 million years after the Big Bang, making it the new record-holder for the earliest known structure in the universe. That galaxy was rather dim, but other candidates loosely pegged to the same time period were already shining bright, meaning they were potentially humongous.

How could stars ignite inside superheated clouds of gas so soon after the Big Bang? How could they hastily weave themselves into such huge gravitationally bound structures? Finding such big, bright, early galaxies seems akin to finding a fossilized rabbit in Precambrian strata. “There are no big things at early times. It takes a while to get to big things,” said Mike Boylan-Kolchin(), a theoretical physicist at the University of Texas, Austin.

Astronomers began asking whether the profusion of early big things defies the current understanding of the cosmos. Some researchers and media outlets claimed that the telescope’s observations were breaking the standard model of cosmology — a well-tested set of equations called the lambda cold dark matter, or ΛCDM, model — thrillingly pointing to new cosmic ingredients or governing laws. It has since become clear, however, that the ΛCDM model is resilient. Instead of forcing researchers to rewrite the rules of cosmology, the JWST findings have astronomers rethinking how galaxies are made, especially in the cosmic beginning. The telescope has not yet broken cosmology, but that doesn’t mean the case of the too-early galaxies will turn out to be anything but epochal.

Simpler Times

To see why the detection of very early, bright galaxies is surprising, it helps to understand what cosmologists know — or think they know — about the universe.

After the Big Bang, the infant universe began cooling off. Within a few million years, the roiling plasma that filled space settled down, and electrons, protons and neutrons combined into atoms, mostly neutral hydrogen. Things were quiet and dark for a period of uncertain duration known as the cosmic dark ages. Then something happened.

Most of the material that flew apart after the Big Bang is made of something we can’t see, called dark matter. It has exerted a powerful influence over the cosmos, especially at first. In the standard picture, cold dark matter (a term that means invisible, slow-moving particles) was flung about the cosmos indiscriminately. In some areas its distribution was denser, and in these regions it began collapsing into clumps. Visible matter, meaning atoms, clustered around the clumps of dark matter. As the atoms cooled off as well, they eventually condensed, and the first stars were born. These new sources of radiation recharged the neutral hydrogen that filled the universe during the so-called epoch of reionization. Through gravity, larger and more complex structures grew, building a vast cosmic web of galaxies.

Astronomers with the CEERS survey, who are using the James Webb Space Telescope to study the early universe, look at a mosaic of images from the telescope in a visualization lab at the University of Texas, Austin.

Nolan Zunk/University of Texas at Austin

Meanwhile, everything kept flying apart. The astronomer Edwin Hubble figured out in the 1920s that the universe is expanding, and in the late 1990s, his namesake, the Hubble Space Telescope, found evidence that the expansion is accelerating. Think of the universe as a loaf of raisin bread. It starts as a mixture of flour, water, yeast and raisins. When you combine these ingredients, the yeast begins respiring and the loaf begins to rise. The raisins within it — stand-ins for galaxies — stretch further apart from one another as the loaf expands.

The Hubble telescope saw that the loaf is rising ever faster. The raisins are flying apart at a rate that defies their gravitational attraction. This acceleration appears to be driven by the repulsive energy of space itself — so-called dark energy, which is represented by the Greek letter Λ (pronounced “lambda”). Plug values for Λ, cold dark matter, and regular matter and radiation into the equations of Albert Einstein’s general theory of relativity, and you get a model of how the universe evolves. This “lambda cold dark matter” (ΛCDM) model matches almost all observations of the cosmos.

One way to test this picture is by looking at very distant galaxies — equivalent to looking back in time to the first few hundred million years after the tremendous clap that started it all. The cosmos was simpler then, its evolution easier to compare against predictions.

Astronomers first tried to see the earliest structures of the universe using the Hubble telescope in 1995. Over 10 days, Hubble captured 342 exposures of an empty-looking patch of space in the Big Dipper. Astronomers were astonished by the abundance hiding in the inky dark: Hubble could see thousands of galaxies at different distances and stages of development, stretching back to much earlier times than anyone expected. Hubble would go on to find some exceedingly distant galaxies — in 2016, astronomers found its most distant one(), called GN-z11, a faint smudge that they dated to 400 million years after the Big Bang.

That was surprisingly early for a galaxy, but it did not cast doubt on the ΛCDM model in part because the galaxy is tiny, with just 1% of the Milky Way's mass, and in part because it stood alone. Astronomers needed a more powerful telescope to see whether GN-z11 was an oddball or part of a larger population of puzzlingly early galaxies, which could help determine whether we are missing a crucial piece of the ΛCDM recipe.

Unaccountably Distant

That next-generation space telescope, named for former NASA leader James Webb, launched on Christmas Day 2021. As soon as JWST was calibrated, light from early galaxies dripped into its sensitive electronics. Astronomers published a flood of papers describing what they saw.

The James Webb Space Telescope, a joint venture of space agencies in the United States, Europe and Canada that took decades to design, build and test, was launched into space on December 25, 2021.
Northrop Grumman

Researchers use a version of the Doppler effect to gauge the distances of objects. This is similar to figuring out the location of an ambulance based on its siren: The siren sounds higher in pitch as it approaches and then lower as it recedes. The farther away a galaxy is, the faster it moves away from us, and so its light stretches to longer wavelengths and appears redder. The magnitude of this "redshift" is expressed as z, where a given value for z tells you how long an object's light must have traveled to reach us.

One of the first papers() on JWST data came from Naidu, the MIT astronomer, and his colleagues, whose search algorithm flagged a galaxy that seemed inexplicably bright and unaccountably distant. Naidu dubbed it GLASS-z13, indicating its apparent distance at a redshift of 13 — further away than anything seen before. (The galaxy's redshift was later revised down to 12.4, and it was renamed GLASS-z12.) Other astronomers working on the various sets of JWST observations were reporting redshift values from 11 to 20,

including one galaxy called CEERS-1749() or CR2-z17-1, whose light appears to have left it 13.7 billion years ago, just 220 million years after the Big Bang — barely an eyeblink after the beginning of cosmic time.
These putative detections suggested that the neat story known as ΛCDM might be incomplete. Somehow, galaxies grew huge right away. “In the early universe, you don’t expect to see massive galaxies. They haven’t had time to form that many stars, and they haven’t merged together,” said Chris Lovell(), an astrophysicist at the University of Portsmouth in England. Indeed, in a study() published in November, researchers analyzed computer simulations of universes governed by the ΛCDM model and found that JWST’s early, bright galaxies were an order of magnitude heavier than the ones that formed concurrently in the simulations.

Rohan Naidu, an astronomer at the Massachusetts Institute of Technology, was among the first scientists to spot a surprisingly bright early galaxy in JWST images.
Michelle L. Peters

Some astronomers and media outlets claimed that JWST was breaking cosmology, but not everyone was convinced. One problem is that ΛCDM’s predictions aren’t always clear-cut. While dark matter and dark energy are simple, visible matter has complex interactions and behaviors, and nobody knows exactly what went down in the first years after the Big Bang; those frenetic early times must be approximated in computer simulations. The other problem is that it’s hard to tell exactly how far away galaxies are.

In the months since the first papers, the ages of some of the alleged high-redshift galaxies have been reconsidered. Some were demoted) to later stages of cosmic evolution because of updated telescope calibrations. CEERS-1749 is found in a region of the sky containing a cluster of galaxies whose light was emitted 12.4 billion years ago, and Naidu says it’s possible the galaxy is actually part of this cluster — a nearer interloper that might be filled with dust that makes it appear more redshifted than it is. According to Naidu, CEERS-1749 is weird no matter how far away it is. “It would be a new type of galaxy that we did not know of: a very low-mass, tiny galaxy that has somehow built up a lot of dust in it, which is something we traditionally do not expect,” he said. “There might just be these new types of objects that are confounding our searches for the very distant galaxies.”

The Lyman Break

Everyone knew that the most definitive distance estimates would require JWST’s most powerful capability.

JWST not only observes starlight through photometry, or measuring brightness, but also through spectroscopy, or measuring the light’s wavelengths. If a photometric observation is like a picture of a face in a crowd, then a spectroscopic observation is like a DNA test that can tell an individual’s family history. Naidu and others who found large early galaxies measured redshift using brightness-derived measurements — essentially looking at faces in the crowd using a really good camera. That method is far from airtight. (At a January meeting of the American Astronomical Society, astronomers quipped that maybe half of the early galaxies observed with photometry alone will turn out to be accurately measured.)

But in early December, cosmologists announced() that they had combined both methods for four galaxies. The JWST Advanced Deep Extragalactic Survey (JADES) team searched for galaxies whose infrared light spectrum abruptly cuts off at a critical wavelength known as the Lyman break. This break occurs because hydrogen floating in the space between galaxies absorbs light. Because of the continuing expansion of the universe — the ever-rising raisin loaf — the light of distant galaxies is shifted, so the wavelength of that abrupt break shifts too. When a galaxy’s light appears to drop off at longer wavelengths, it is more distant. JADES identified spectra with redshifts up to 13.2, meaning the galaxy’s light was emitted 13.4 billion years ago.

Merrill Sherman/Quanta Magazine

As soon as the data was downlinked, JADES researchers began “freaking out” in a shared Slack group, according to Kevin Hainline(), an astronomer at the University of Arizona. “It was like, ‘Oh my God, oh my God, we did it we did it we did it!’” he said. “These spectra are just the beginning of what I think is going to be astronomy-changing science.”
Brant Robertson(), a JADES astronomer at the University of California, Santa Cruz, says the findings show that the early universe changed rapidly in its first billion years, with galaxies evolving 10 times quicker than they do today. It’s similar to how “a hummingbird is a small creature,” he said, “but its heart beats so quickly that it is living kind of a different life than other creatures. The heartbeat of these galaxies is happening on a much more rapid timescale than something the size of the Milky Way.”

But were their hearts beating too fast for ΛCDM to explain?

Theoretical Possibilities

As astronomers and the public gaped at JWST images, researchers started working behind the scenes to determine whether the galaxies blinking into our view really upend ΛCDM or just help nail down the numbers we should plug into its equations.

One important yet poorly understood number concerns the masses of the earliest galaxies. Cosmologists try to determine their masses in order to tell whether they match ΛCDM's predicted timeline of galaxy growth.

A galaxy's mass is derived from its brightness. But Megan Donahue(), an astrophysicist at Michigan State University, says that at best, the relationship between mass and brightness is an educated guess, based on assumptions gleaned from known stars and well-studied galaxies.

One key assumption is that stars always form within a certain statistical range of masses, called the initial mass function (IMF). This IMF parameter is crucial for gleaning a galaxy's mass from measurements of its brightness, because hot, blue, heavy stars produce more light, while the majority of a galaxy's mass is typically locked up in cool, red, small stars.

But it's possible that the IMF was different in the early universe. If so, JWST's early galaxies might not be as heavy as their brightness suggests; they might be bright but light. This possibility causes headaches, because changing this basic input to the ΛCDM model could give you almost any answer you want. Lovell says some astronomers consider fiddling with the IMF "the domain of the wicked."

Wendy Freedman at the University of Chicago is exploring how JWST observations can be squared with the standard cosmological model.

Nancy Wong

"If we don't understand the initial mass function, then understanding galaxies at high redshift is really a challenge," said Wendy Freedman(), an astrophysicist at the University of Chicago. Her team is working on observations and computer simulations that will help pin down the IMF in different environments.

Over the course of the fall, many experts came to suspect that tweaks to the IMF and other factors could be enough to square the very ancient galaxies lighting upon JWST's instruments with ΛCDM. "I think it's actually more likely that we can accommodate these observations within the standard paradigm," said Rachel Somerville(), an astrophysicist at the Flatiron Institute (which, like *Quanta Magazine*, is funded by the Simons Foundation). In that case, she said, "what we learn is: How fast can [dark matter] halos collect the gas? How fast can we make the gas cool off and get dense, and make stars? Maybe that happens faster in the early universe; maybe the gas is denser; maybe somehow it is flowing in faster. I think we're still learning about those processes." Somerville also studies the possibility that black holes interfered with the baby cosmos. Astronomers have noticed() a few glowing supermassive black holes at a redshift of 6 or 7, about a billion years after the Big Bang. It is hard to conceive of how, by that time, stars could have formed, died and then collapsed into black holes that ate everything surrounding them and began spewing radiation.

But if there are black holes inside the putative early galaxies, that could explain why the galaxies seem so bright, even if they're not actually very massive, Somerville said.

Benjamin Keller, an astronomer at the University of Memphis, showed that supercomputer simulations of the cosmos could produce early galaxies like the four that have been spectroscopically analyzed by JWST.
Wendy Adams/University of Memphis

Confirmation that ΛCDM can accommodate at least some of JWST's early galaxies arrived the day before Christmas. Astronomers led by Benjamin Keller) at the University of Memphis checked() a handful of major supercomputer simulations of ΛCDM universes and found that the simulations could produce galaxies as heavy as the four that were spectroscopically studied by the JADES team. (These four are, notably, smaller and dimmer than other purported early galaxies such as GLASS-z12.) In the team's analysis, all the simulations yielded galaxies the size of the JADES findings at a redshift of 10. One simulation could create such galaxies at a redshift of 13, the same as what JADES saw, and two others could build the galaxies at an even higher redshift. None of the JADES galaxies was in tension with the current ΛCDM paradigm, Keller and colleagues reported on the preprint server arxiv.org on December 24.

Though they lack the heft to break the prevailing cosmological model, the JADES galaxies have other special characteristics. Hainline said their stars seem unpolluted by metals from previously exploded stars. This could mean they are Population III stars — the avidly sought first generation of stars to ever ignite — and that they may be contributing to the reionization of the universe. If this is true, then JWST has already peered back to the mysterious period when the universe was set on its present course.

Extraordinary Evidence

Spectroscopic confirmation of additional early galaxies could come this spring, depending on how JWST's time allocation committee divvies things up. An observing campaign called WDEEP will specifically search for galaxies from less than 300 million years after the Big Bang. As researchers confirm more galaxies' distances and get better at estimating their masses, they'll help settle ΛCDM's fate.

Many other observations are already underway that could change the picture for ΛCDM. Freedman, who is studying the initial mass function, was up at 1 a.m. one night downloading JWST data on variable stars that she uses as "standard candles" for measuring distances and ages. Those measurements could help shake out another potential problem with ΛCDM, known as the Hubble tension. The problem is that the universe currently seems to be expanding faster than ΛCDM predicts for a 13.8-billion-year-old universe. Cosmologists have plenty of possible explanations. Perhaps, some cosmologists speculate, the density of the dark energy that's accelerating the expansion of the universe is not constant, as in ΛCDM, but changes over time. Changing the expansion history of the universe might not only resolve the Hubble tension but also revise calculations of the age of the universe at a given redshift. JWST might be seeing an early galaxy as it appeared, say, 500 million years after the Big Bang rather than 300 million. Then even the heaviest putative early galaxies in JWST's mirrors would have had plenty of time to coalesce, says Somerville.

Astronomers run out of superlatives when they talk about JWST's early galaxy results. They pepper their conversations with laughter, expletives and exclamations, even as they remind themselves of Carl Sagan's adage, however overused, that extraordinary claims require extraordinary evidence. They can't wait to get their hands on more images and spectra, which will help them hone or tweak their models. “Those are the best problems,” said Boylan-Kolchin, “because no matter what you get, the answer is interesting.”

COSMOLOGY

Asymmetry Detected in the Distribution of Galaxies

Two new studies suggest that certain tetrahedral arrangements of galaxies outnumber their mirror images, potentially reflecting details of the universe’s birth. But confirmation is needed.

When researchers counted tetrahedra whose side-lengths increase in the clockwise and counterclockwise directions, they found a surprising imbalance.

Myriam Wares for Quanta Magazine

Introduction

Physicists believe they have detected a striking asymmetry in the arrangements of galaxies in the sky. If confirmed, the finding would point to features of the unknown fundamental laws that operated during the Big Bang.

“If this result is real, someone’s going to get a Nobel Prize,” said Marc Kamionkowski(), a physicist at Johns Hopkins University who was not involved in the analysis.

As if playing a cosmic game of Connect the Dots, the researchers drew lines between sets of four galaxies, constructing four-cornered shapes called tetrahedra. When they had built every possible tetrahedron from a catalog of 1 million galaxies, they found that tetrahedra oriented one way outnumber their mirror images.

A hint of the imbalance between tetrahedra and their mirror images was reported() by Oliver Philcox(), an astrophysicist at Columbia University in New York, in a paper published in *Physical Review D* in September. In an independent analysis conducted simultaneously that’s now undergoing peer review, Jiamin Hou() and Zachary Slepian() of the University of Florida and Robert Cahn(opens a new tab) of Lawrence Berkeley National

Laboratory detected() the asymmetry with a level of statistical certainty that physicists usually consider definitive.

But with such a blockbuster finding — and one that's still under review — experts say caution is warranted.

"There's no obvious reason that they've made a mistake," said Shaun Hotchkiss(), a cosmologist at the University of Auckland. "That doesn't mean that there isn't a mistake."

The putative imbalance violates a symmetry called "parity," an equivalence of left and right. If the observation withstands scrutiny, physicists think it must reflect an unknown, parity-violating ingredient in the primordial process that sowed the seeds of all the structure that developed in our universe.

"It's an incredible result — really impressive," Kamionkowski said. "Do I believe it? I'm going to wait to really celebrate."

Left-Handed Universe

Parity was once a cherished symmetry of physics. But then, in 1957, the Chinese American physicist Chien-Shiung Wu's nuclear decay experiments revealed() that our universe indeed has a slight handedness to it: Subatomic particles involved in the weak nuclear force, which causes nuclear decay, are always magnetically oriented in the opposite direction from the one they move in, so that they spiral like the threads of a left-handed screw. The mirror-image particles — the ones like right-handed screws — don't feel the weak force.

The physicist Chien-Shiung Wu led a nuclear decay experiment that established that parity is violated in nature.
Smithsonian Image Archives

Wu's revelation was shocking. "We are all rather shaken by the death of our well-beloved friend, parity," the physicist John Blatt wrote in a letter to Wolfgang Pauli.

The left-handedness of the weak force has subtle effects that couldn't have influenced the cosmos on galactic scales. But ever since Wu's discovery, physicists have sought other ways in which the universe differs from its mirror image.

If, for instance, some primordial parity violation was in effect when the universe was in its infancy, it might have imprinted a twist onto the structure of the cosmos.

At or near the time of the universe’s birth, a field known as the inflaton is thought to have permeated space. A roiling, boiling medium where inflaton particles continuously bubbled up and disappeared, the inflaton field was also repulsive; for the brief time it may have existed, it would have caused our universe to rapidly expand to 100 trillion trillion times its original size. All of those quantum fluctuations of particles in the inflaton field were flung outward and frozen into the cosmos, becoming variations in the density of matter. The denser pockets continued to gravitationally coalesce to produce the galaxies and large-scale structure we see today.

In 1999, researchers including Kamionkowski considered) what would happen if more than one field was present before this explosion. The inflaton field could have interacted with another field that could produce right-handed and left-handed particles. If the inflaton treated right-handed particles differently than the left-handed ones, then it could have preferentially created particles of one handedness over the other. This so-called Chern-Simons coupling would have imbued the early quantum fluctuations with a preferred handedness, which would have evolved into an imbalance of left-handed and right-handed tetrahedral arrangements of galaxies.

As for what the additional field might be, one possibility is the gravitational field. In this scenario, a parity-violating Chern-Simons interaction would occur between inflaton particles and gravitons — the quantum units of gravity — which would have popped up in the gravitational field during inflation. Such an interaction would have created a handedness in the density variations of the early universe and, consequently, in today’s large-scale structure.

Each dot in this picture, which covers about one-twentieth of the sky, represents the location of a galaxy mapped by the Sloan Digital Sky Survey and its Baryon Oscillation Spectroscopic Survey. A statistical analysis of 1 million galaxies in the survey has found evidence of parity violation.
Daniel Eisenstein/SDSS-III collaboration

In 2006, Stephon Alexander(), a physicist now at Brown University, suggested() that Chern-Simons gravity could also potentially solve one of the biggest mysteries in cosmology: why our universe contains more matter than antimatter. He surmised that the Chern-Simons interaction could have yielded a relative abundance of left-handed gravitons, which would in turn preferentially create left-handed matter over right-handed antimatter.

Alexander's idea remained relatively obscure for years. When he heard about the new findings, he said, "that was a big surprise."

Tetrahedra in the Sky

Cahn thought the possibility of solving the matter-antimatter asymmetry puzzle with parity violation in the early universe was "speculative, but also provocative." In 2019, he decided to look for parity violation in a catalog of galaxies in the Sloan Digital Sky Survey. He didn't expect to find anything but thought it would be worth a check.

To test whether the galaxy distribution respects or violates parity, he and his collaborators knew they needed to study tetrahedral arrangements of four galaxies. This is because the tetrahedron is the simplest three-dimensional shape, and only 3D objects have a chance at violating parity. To understand this, consider your hands. Because hands are 3D, there's no way to rotate a left one to make it look like a right one. Flip your left hand over so that the thumbs of both hands are on the left, and your hands still look different — the palms face opposite ways. By contrast, if you trace a left hand on a sheet of paper and cut out the 2D image, flipping the cutout over makes it look like a right hand. The cutout and its mirror image are indistinguishable.

In 2020, Slepian and Cahn came up with a way of defining the "handedness" of a tetrahedral arrangement of galaxies in order to compare the number of left-handed and right-handed ones in the sky. First they took a galaxy and looked at the distances to three other galaxies. If the distances increased in the clockwise direction like a right-handed screw, they called the tetrahedron right-handed. If the distances increased going counterclockwise, it was left-handed.

The tetrahedron is the simplest shape that has parity, or handedness. It looks different when reflected in a mirror.
Merrill Sherman/Quanta Magazine

To determine whether the universe as a whole has a preferred handedness, they had to repeat the analysis for all tetrahedra constructed from their database of 1 million galaxies. There are nearly 1 trillion trillion such tetrahedra — an intractable list to handle one at a time. But a factoring trick developed in earlier work() on a different problem allowed the researchers to look at the parity of tetrahedra more holistically: Rather than assembling one tetrahedron at a time and determining its parity, they could take each galaxy in turn and group all other galaxies according to their distances from that galaxy, creating layers like the layers of an onion. By expressing the relative positions of galaxies in each layer in terms of mathematical functions of angles called spherical harmonics, they could systematically combine sets of three layers to make collective tetrahedra.

The researchers then compared the results to their expectations based on parity-preserving laws of physics. Hou led this step, analyzing fake catalogs of galaxies that had been generated by simulating the evolution of the universe starting from tiny, parity-preserving density variations. From these mock catalogs, Hou and her colleagues could determine how the tally of left- and right-handed tetrahedra randomly varies, even in a mirror-symmetric world.

The team found a “seven-sigma” level of parity violation in the real data, meaning that the imbalance between left- and right-handed tetrahedra was seven times as large as could be expected from random chance and other conceivable sources of error.

Kamionkowski called it “incredible that they were able to do that,” adding that “technically, it’s absolutely astounding. It’s a really, really, really complicated analysis.”

Philcox used similar methods (and had co-authored some earlier papers proposing such an analysis with Hou, Slepian and Cahn), but he made some different choices — for example, grouping the galaxies into fewer layers than Hou and colleagues, and omitting some problematic tetrahedra from the analysis — and therefore found a more modest 2.9-sigma violation of parity. The researchers are now studying the differences between their analyses. Even after extensive efforts to understand the data, all parties remain cautious.

Corroborating Evidence

The surprising finding hints at new physics that could potentially answer long-standing questions about the universe. But the work has only just begun.

First physicists need to verify (or falsify) the observation. New, ambitious galaxy surveys on which to repeat the analysis are already underway. The ongoing Dark Energy Spectroscopic Instrument survey, for instance, has logged 14 million galaxies so far and will contain more than 30 million when it's completed. "That'll give us an opportunity to look at this in much greater detail with much better statistics," said Cahn.

A tetrahedral arrangement of galaxies known as Robert's Quartet.
ESO

Moreover, if the parity-violating signal is real, it could show up in data other than the distribution of galaxies. The oldest light in the sky, for example — a bath of radiation known as the cosmic microwave background, left over from the early universe — provides our earliest snapshot of spatial variations in the cosmos. The dappled pattern of this light should contain the same parity-violating correlations as the galaxies that formed later. Physicists say it should be possible to find such a signal in the light.

Another place to look will be the pattern of gravitational waves that may have been generated during inflation, called the stochastic gravitational wave background. These corkscrew-like ripples in the space-time fabric can be right-handed or left-handed, and in a parity-preserving world, they would contain equal amounts of each. So if physicists manage to measure this background and find that one handedness is favored, this would be an unambiguous, independent check of parity-violating physics in the early universe.

As the search for corroborating evidence begins, theorists will study models of inflation that could have produced the signal. With Giovanni Cabass(), a theoretical physicist at the Institute for Advanced Study in Princeton, New Jersey, Philcox recently used his measurement to test a slew of parity-violating models(opens a new tab) of inflation, including those of the Chern-Simons type. (They can't yet say with certainty which model, if any, is correct.)

Alexander has also refocused his efforts on understanding Chern-Simons gravity. With collaborators including Kamionkowski and Cyril Creque-Sarbinowski() of the Flatiron Institute's Center for Computational Astrophysics, Alexander has begun working out subtle details about how Chern-Simons gravity in the early universe would influence the distribution of today's galaxies.

"I was kind of like the lone soldier pushing this stuff for a while," he said. "It's good to see people taking an interest."

Theory of everything (philosophy)

In philosophy, a **theory of everything** (**ToE**) is an ultimate, all-encompassing explanation or description of nature or reality.[1][2][3] Adopting the term from physics, where the search for a theory of everything is ongoing, philosophers have discussed the viability of the concept and analyzed its properties and implications.[1][2][3] Among the questions to be addressed by a philosophical theory of everything are: "Why is reality understandable?" – "Why are the laws of nature as they are?" – "Why is there anything at all?"[1]

A philosophical theory of everything, would need to, as much as is possible or makes sense, unify analytic and continental philosophy. Questions such as "Why is there anything at all?" are arguably metaphysics questions and not so much related to a philosophical ToE.

Comprehensive philosophical systems

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The "system building" style of metaphysics attempts to answer *all* the important questions in a coherent way, providing a complete picture of the world. The philosophies of Plato and Aristotle could be said to be early examples of comprehensive systems. In the early modern period (17th and 18th centuries), the system-building *scope* of philosophy is often linked to the rationalist *method* of philosophy, that is the technique of deducing the nature of the world by pure *a priori* reason. Examples from the early modern period include Leibniz's monadology, Descartes's dualism, and Spinoza's monism. Hegel's absolute idealism and Whitehead's process philosophy were later systems. At present, work is underway on the **structural-systematic philosophy** (**SSP**), to which the following books are devoted: Lorenz B. Puntel, *Structure and Being* (2008; translation of *Struktur und Sein*, 2006) and *Being and God* (2011; translation of *Sein und Gott*, 2010) and Alan White, *Toward a Philosophical Theory of Everything* (2014). The SSP makes no claims to finality; it aims to be the best systematic philosophy currently available.

Other philosophers do not believe philosophy should aim so high. Some scientists think a more mathematical approach than philosophy is needed for a ToE, for instance Stephen Hawking wrote in *A Brief History of Time* that even if we had a ToE, it would necessarily be a set of equations. He wrote, "What is it that breathes fire into the equations and makes a universe for them to describe?"[4]

Nicholas Rescher

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Properties and impasse of self-substantiation

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In "The Price of an Ultimate Theory",[2] originally published in 2000, Nicholas Rescher specifies what he sees as the principal properties of a Theory of Everything and describes an apparent impasse on the road to such a theory.

Properties

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Principle of sufficient reason

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First, he takes as a presupposition the principle of sufficient reason, which in his formulation states that every fact t has an explanation t':

where E predicates explanation, so that t' E t denotes "t' explains t".

Comprehensiveness

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Next, he asserts that the most direct and natural construction of a Theory of Everything T^* would confer upon it two crucial features: comprehensiveness and finality. Comprehensiveness says that wherever there is a fact t, T^* affords its explanation:

Finality

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Finality says that as an "ultimate theory", T^* has no deeper explanation:

so that the only conceivable explanation of T^* is T^* itself.

Noncircularity

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Rescher notes that it is obviously problematic to deploy a theory for its own explanation; at the heart of the traditional conception of explanatory adequacy, he says, is a principle of noncircularity stating that no fact can explain itself:

Impasse

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The impasse is then that the two critical aspects of a Theory of Everything, comprehensiveness and finality, conflict with the fundamental principle of noncircularity. A comprehensive theory which explains everything must explain itself, and a final theory which has no deeper explanation must, by the principle of sufficient reason, have *some* explanation; consequently it too must be self-explanatory. Rescher concludes that any Theorist of Everything committed to comprehensiveness and finality is bound to regard noncircularity as "something that has to be jettisoned". But how, he asks, can a theory adequately substantiate itself?

Ways forward

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Rescher's proposal in "The Price of an Ultimate Theory" is to dualize the concept of explanation so that a fact can be explained either *derivationally*, by the premises which lead to it, or *systemically*, by the consequences which follow from it. With derivational explanation, a fact *t* is explained when it is subsumed by some prior, more fundamental fact *t'*. With systemic explanation, *t* is explained when it is a "best fit" for its consequences, where fitness is measured by uniformity, simplicity, connectedness, and other criteria conducive to systemic integration. Rescher concludes that while a theory of everything cannot be explained derivationally (since no deeper explanation can subsume it), it can be explained systemically by its capacity to integrate its consequences.

In his 1996 book *The Conscious Mind*,[5] David Chalmers argues that a theory of everything must explain consciousness, that consciousness does not logically supervene on the physical, and that therefore a fundamental theory in physics would not be a theory of everything. A truly final theory, he argues, needs not just physical properties and laws, but phenomenal or protophenomenal properties and psychophysical laws explaining the relationship between physical processes and conscious experience. He concludes that "[o]nce we have a fundamental theory of consciousness to accompany a fundamental theory in physics, we may truly have a theory of everything." Developing such a theory will not be straightforward, he says, but "it ought to be possible in principle."

In "Prolegomena to Any Future Philosophy",[3] a 2002 essay in the *Journal of Evolution and Technology*, Mark Alan Walker discusses modern responses to the question of how to reconcile "the apparent finitude of humans" with what he calls "the traditional telos of philosophy—the attempt to unite thought and Being, to arrive at absolute knowledge, at a final theory of everything." He contrasts two ways of closing this "gap between the ambitions of philosophy, and the abilities of human philosophers": a "deflationary" approach in which philosophy is "scaled down into something more human" and the attempt to achieve a theory of everything is abandoned, and an "inflationary", transhumanist approach in which philosophers are "scaled up" by advanced technology into "super-intelligent beings" better able to pursue such a theory.

Criticism

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In "Holistic Explanation and the Idea of a Grand Unified Theory",[1] originally presented as a lecture in 1998, Rescher identifies two negative reactions to the idea of a unified, overarching theory: reductionism and rejectionism. Reductionism holds that large-scale philosophical issues can be meaningfully addressed only when divided into lesser components, while rejectionism holds that questions about such issues are illegitimate and unanswerable. Against reductionism, Rescher argues that explaining individual parts does not explain the coordinating structure of the whole, so that a collectivized approach is required. Against rejectionism, he argues that the question of the "reason" – the "why" – behind existence is pressing, important, and not obviously meaningless.

Theory of everything

A **theory of everything** (**TOE**), **final theory**, **ultimate theory**, **unified field theory**, or **master theory** is a singular, all-encompassing, coherent theoretical framework of physics that fully explains and links together all aspects of the universe.[1]:6 Finding a theory of everything is one of the major unsolved problems in physics.[2][3]

Over the past few centuries, two theoretical frameworks have been developed that, together, most closely resemble a theory of everything. These two theories upon which all modern physics rests are general relativity and quantum mechanics. General relativity is a theoretical framework that only focuses on gravity for understanding the universe in regions of both large scale and high mass: planets, stars, galaxies, clusters of galaxies, etc. On the other hand, quantum mechanics is a theoretical framework that focuses primarily on three non-gravitational forces for understanding the universe in regions of both very small scale and low mass: subatomic particles, atoms, and molecules. Quantum mechanics successfully implemented the Standard Model that describes the three non-gravitational forces: strong nuclear, weak nuclear, and electromagnetic force – as well as all observed elementary particles.[4]:122

General relativity and quantum mechanics have been repeatedly validated in their separate fields of relevance. Since the usual domains of applicability of general relativity and quantum mechanics are so different, most situations require that only one of the two theories be used.[5][6][7]:842–844 The two theories are considered incompatible in regions of extremely small scale – the Planck scale – such as those that exist within a black hole or during the beginning stages of the universe (i.e., the moment immediately following the Big Bang). To resolve the incompatibility, a theoretical framework revealing a deeper underlying reality, unifying gravity with the other three interactions, must be discovered to harmoniously integrate the realms of general relativity and quantum mechanics into a seamless whole: a theory of everything may be defined as a comprehensive theory that, in principle, would be capable of describing all physical phenomena in the universe.

In pursuit of this goal, quantum gravity has become one area of active research.[8][9] One example is string theory, which evolved into a candidate for the theory of everything, but not without drawbacks (most notably, its apparent lack of currently testable predictions) and controversy. String theory posits that at the beginning of the universe (up to 10^{-43} seconds after the Big Bang), the four fundamental forces were once a single fundamental force. According to string theory, every particle in the universe, at its most ultramicroscopic level (Planck length), consists of varying combinations of vibrating strings (or strands) with preferred patterns of vibration. String theory further claims that it is through these specific oscillatory patterns of strings that a particle of unique mass and force charge is created (that is to say, the electron is a type of string that vibrates one way, while the up quark is a type of string vibrating another way, and so forth). String theory/M-theory proposes six or seven dimensions of spacetime in addition to the four common dimensions for a ten- or eleven-dimensional spacetime.

Name

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Initially, the term *theory of everything* was used with an ironic reference to various overgeneralized theories. For example, a grandfather of Ijon Tichy – a character from a cycle of Stanisław Lem's science fiction stories of the 1960s – was known to work on the "General Theory of Everything". Physicist Harald Fritzsch used the term in his 1977 lectures in Varenna.[10] Physicist John Ellis claims[11] to have introduced the acronym "TOE" into the technical literature in an article in *Nature* in 1986.[12] Over time, the term stuck in popularizations of theoretical physics research.

Historical antecedents

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Antiquity to 19th century

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Many ancient cultures such as Babylonian astronomers and Indian astronomy studied the pattern of the *Seven Sacred Luminaires*/Classical Planets against the background of stars, with their interest being to relate celestial movement to human events (astrology), and the goal being to predict events by recording events against a time measure and then look for recurrent patterns. The debate between the universe having either a beginning or eternal cycles can be traced to ancient Babylonia.[13] Hindu cosmology posits that time is infinite with a *cyclic universe*, where the current universe was preceded and will be followed by an infinite number of universes.[14][15] Time scales mentioned in Hindu cosmology correspond to those of modern scientific cosmology. Its cycles run from our ordinary day and night to a day and night of Brahma, 8.64 billion years long.[16]

The natural philosophy of atomism appeared in several ancient traditions. In ancient Greek philosophy, the pre-Socratic philosophers speculated that the apparent diversity of observed phenomena was due to a single type of interaction, namely the motions and collisions of atoms. The concept of 'atom' proposed by Democritus was an early philosophical attempt to unify phenomena observed in nature. The concept of 'atom' also appeared in the Nyaya-Vaisheshika school of ancient Indian philosophy.

Archimedes was possibly the first philosopher to have described nature with axioms (or principles) and then deduce new results from them. Any "theory of everything" is similarly expected to be based on axioms and to deduce all observable phenomena from them.[17]:340

Following earlier atomistic thought, the mechanical philosophy of the 17th century posited that all forces could be ultimately reduced to contact forces between the atoms, then imagined as tiny solid particles.[18]:184[19]

In the late 17th century, Isaac Newton's description of the long-distance force of gravity implied that not all forces in nature result from things coming into contact. Newton's work in his *Mathematical Principles of Natural Philosophy* dealt with this in a further example of unification, in this case unifying Galileo's work on terrestrial gravity, Kepler's laws of planetary motion and the phenomenon of tides by explaining these apparent actions at a distance under one single law: the law of universal gravitation.[20] Newton achieved the first great unification in physics, and he further is credited with laying the foundations of future endeavors for a grand unified theory.

In 1814, building on these results, Laplace famously suggested that a sufficiently powerful intellect could, if it knew the position and velocity of every particle at a given time, along with the laws of nature, calculate the position of any particle at any other time:[21]:ch 7

> An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.
>
> —*Essai philosophique sur les probabilités, Introduction. 1814*

Laplace thus envisaged a combination of gravitation and mechanics as a theory of everything. Modern quantum mechanics implies that uncertainty is inescapable, and thus that Laplace's vision has to be amended: a theory of everything must include gravitation and quantum mechanics. Even ignoring quantum mechanics, chaos theory is sufficient to guarantee that the future of any sufficiently complex mechanical or astronomical system is unpredictable.

In 1820, Hans Christian Ørsted discovered a connection between electricity and magnetism, triggering decades of work that culminated in 1865, in James Clerk Maxwell's theory of electromagnetism, which achieved the second great unification in physics. During the 19th and early 20th centuries, it gradually became apparent that many common examples of forces – contact forces, elasticity, viscosity, friction, and pressure – result from electrical interactions between the smallest particles of matter.

In his experiments of 1849–1850, Michael Faraday was the first to search for a unification of gravity with electricity and magnetism.[22] However, he found no connection.

In 1900, David Hilbert published a famous list of mathematical problems. In Hilbert's sixth problem, he challenged researchers to find an axiomatic basis to all of physics. In this problem he thus asked for what today would be called a theory of everything.[23]

Early 20th century

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In the late 1920s, the then new quantum mechanics showed that the chemical bonds between atoms were examples of (quantum) electrical forces, justifying Dirac's boast that "the underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known".[24]

After 1915, when Albert Einstein published the theory of gravity (general relativity), the search for a unified field theory combining gravity with electromagnetism began with a renewed interest. In Einstein's day, the strong and the weak forces had not yet been discovered, yet he found the potential existence of two other distinct forces, gravity and electromagnetism, far more alluring. This launched his 40-year voyage in search of the so-called *"unified field theory"* that he hoped would show that these two forces are really manifestations of one grand, underlying principle. During the last few decades of his life, this ambition alienated Einstein from the rest of mainstream of physics, as the mainstream was instead far more excited about the emerging framework of quantum mechanics. Einstein wrote to a friend in the early 1940s, "I have become a lonely old chap who is mainly known because he doesn't wear socks and who is exhibited as a curiosity on special occasions." Prominent contributors were Gunnar Nordström, Hermann Weyl, Arthur Eddington, David Hilbert,[25] Theodor Kaluza, Oskar Klein (see Kaluza–Klein theory), and most notably, Albert Einstein and his collaborators. Einstein searched in earnest for, but ultimately failed to find, a unifying theory[26]:ch 17 (see Einstein–Maxwell–Dirac equations).

Late 20th century and the nuclear interactions

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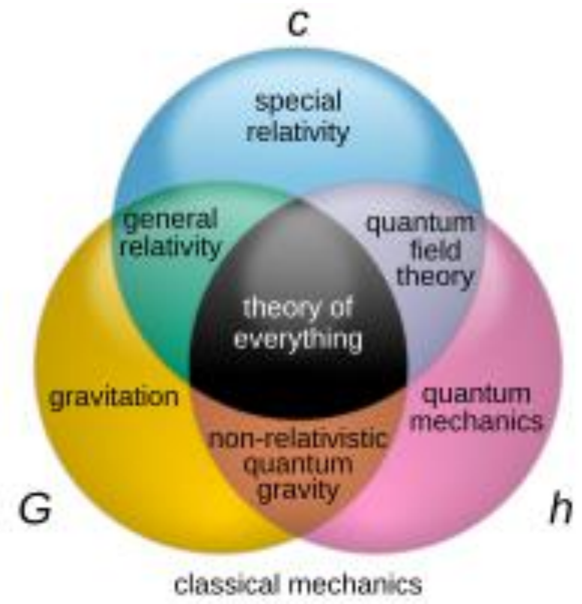
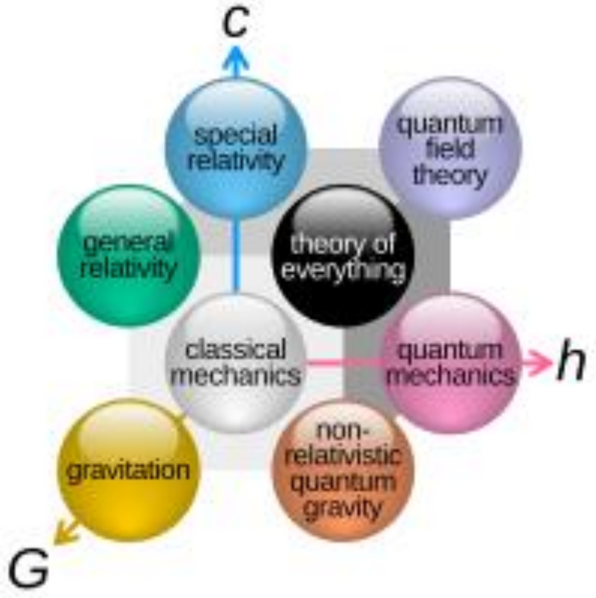
In the 20th century, the search for a unifying theory was interrupted by the discovery of the strong and weak nuclear forces, which differ both from gravity and from electromagnetism. A further hurdle was the acceptance that in a theory of everything, quantum mechanics had to be incorporated from the outset, rather than emerging as a consequence of a deterministic unified theory, as Einstein had hoped.

Gravity and electromagnetism are able to coexist as entries in a list of classical forces, but for many years it seemed that gravity could not be incorporated into the quantum framework, let alone unified with the other fundamental forces. For this reason, work on unification, for much of the 20th century, focused on understanding the three forces described by quantum mechanics: electromagnetism and the weak and strong forces. The first two were combined in 1967–1968 by Sheldon Glashow, Steven Weinberg, and Abdus Salam into the electroweak force.[27] Electroweak unification is a broken symmetry: the electromagnetic and weak forces appear distinct at low energies because the particles carrying the weak force, the W and Z bosons, have non-zero masses (80.4 GeV/c^2 and 91.2 GeV/c^2, respectively), whereas the photon, which carries the electromagnetic force, is massless. At higher energies W bosons and Z bosons can be created easily and the unified nature of the force becomes apparent.

While the strong and electroweak forces coexist under the Standard Model of particle physics, they remain distinct. Thus, the pursuit of a theory of everything remained unsuccessful: neither a unification of the strong and electroweak forces – which Laplace would have called 'contact forces' – nor a unification of these forces with gravitation had been achieve.





Modern physics

Conventional sequence of theories

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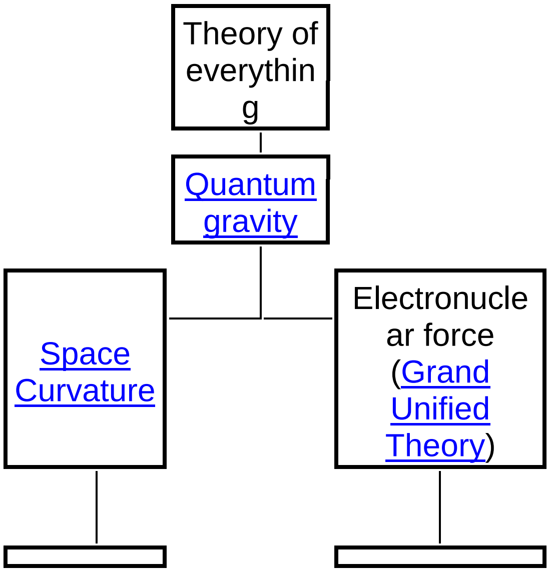
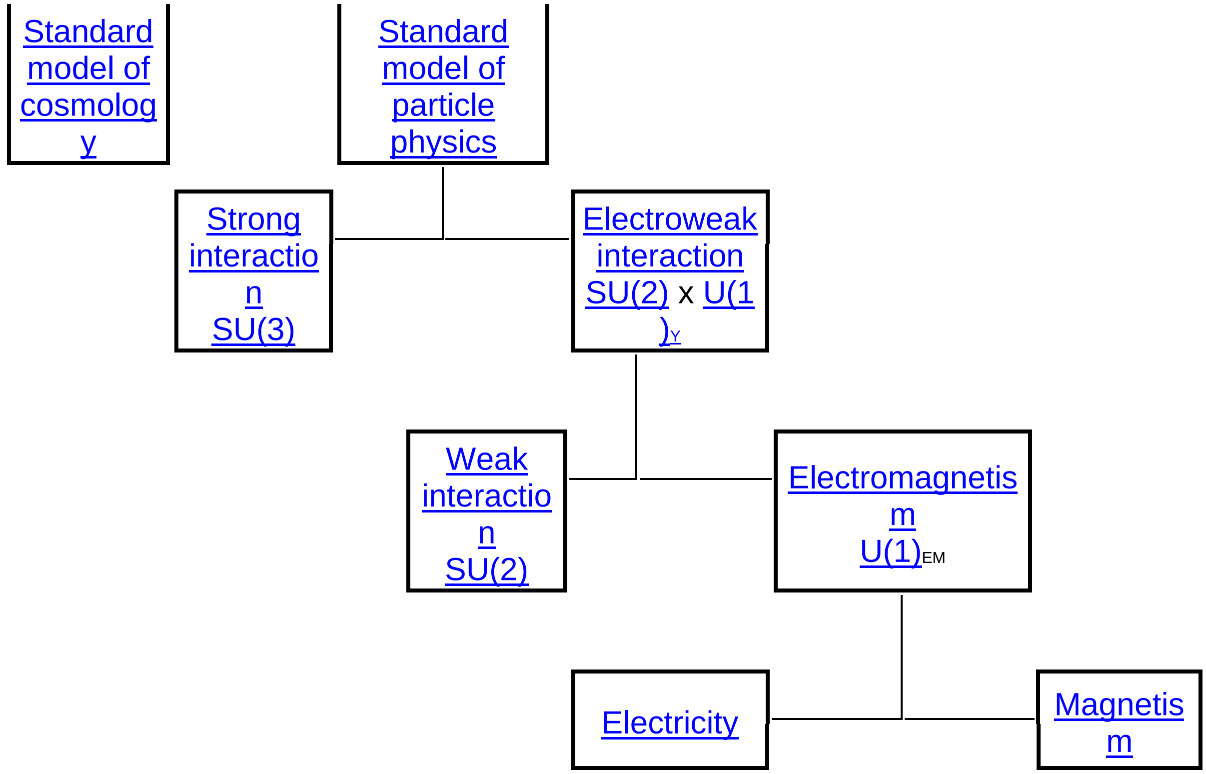
A theory of everything would unify all the fundamental interactions of nature: gravitation, the strong interaction, the weak interaction, and electromagnetism. Because the weak interaction can transform elementary particles from one kind into another, the theory of everything should also predict all the different kinds of particles possible. The usual assumed path of theories is given in the following graph, where each unification step leads one level up on the graph.





In this graph, electroweak unification occurs at around 100 GeV, grand unification is predicted to occur at 10^{16} GeV, and unification of the GUT force with gravity is expected at the Planck energy, roughly 10^{19} GeV.

Several Grand Unified Theories (GUTs) have been proposed to unify electromagnetism and the weak and strong forces. Grand unification would imply the existence of an electronuclear force; it is expected to set in at energies of the order of 10^{16} GeV, far greater than could be reached by any currently feasible particle accelerator. Although the simplest grand unified theories have been experimentally ruled out, the idea of a grand unified theory, especially when linked with supersymmetry, remains a favorite candidate in the theoretical physics community. Supersymmetric grand unified theories seem plausible not only for their theoretical "beauty", but because they naturally produce large quantities of dark matter, and because the inflationary force may be related to grand unified theory physics (although it does not seem to form an inevitable part of the theory). Yet grand unified theories are clearly not the final answer; both the current standard model and all proposed GUTs are quantum field theories which require the problematic technique of renormalization to yield sensible answers. This is usually regarded as a sign that these are only effective field theories, omitting crucial phenomena relevant only at very high energies.[6]

The final step in the graph requires resolving the separation between quantum mechanics and gravitation, often equated with general relativity. Numerous researchers concentrate their efforts on this specific step; nevertheless, no accepted theory of quantum gravity, and thus no accepted theory of everything, has emerged with observational evidence. It is usually assumed that the theory of everything will also solve the remaining problems of grand unified theories.

In addition to explaining the forces listed in the graph, a theory of everything may also explain the status of at least two candidate forces suggested by modern cosmology: an inflationary force and dark energy. Furthermore, cosmological experiments also suggest the existence of dark matter, supposedly composed of fundamental particles outside the scheme of the standard model. However, the existence of these forces and particles has not been proven.

String theory and M-theory

[edit]

Unsolved problem in physics:

Is string theory, superstring theory, or M-theory, or some other variant on this theme, a step on the road to a "theory of everything", or just a blind alley?

(more unsolved problems in physics)

Since the 1990s, some physicists such as Edward Witten believe that 11-dimensional M-theory, which is described in some limits by one of the five perturbative superstring theories, and in another by the maximally-supersymmetric eleven-dimensional supergravity, is the theory of everything. There is no widespread consensus on this issue.

One remarkable property of string/M-theory is that seven extra dimensions are required for the theory's consistency, on top of the four dimensions in our universe. In this regard, string theory can be seen as building on the insights of the Kaluza–Klein theory, in which it was realized that applying general relativity to a 5-dimensional universe, with one space dimension small and curled up, looks from the 4-dimensional perspective like the usual general relativity together with Maxwell's electrodynamics. This lent credence to the idea of unifying gauge and gravity interactions, and to extra dimensions, but did not address the detailed experimental requirements. Another important property of string theory is its supersymmetry, which together with extra dimensions are the two main proposals for resolving the hierarchy problem of the standard model, which is (roughly) the question of why gravity is so much weaker than any other force. The extra-dimensional solution involves allowing gravity to propagate into the other dimensions while keeping other forces confined to a 4-dimensional spacetime, an idea that has been realized with explicit stringy mechanisms.[28]

Research into string theory has been encouraged by a variety of theoretical and experimental factors. On the experimental side, the particle content of the standard model supplemented with neutrino masses fits into a spinor representation of SO(10), a subgroup of E8 that routinely emerges in string theory, such as in heterotic string theory[29] or (sometimes equivalently) in F-theory.[30][31] String theory has mechanisms that may explain why fermions come in three hierarchical generations, and explain the mixing rates between quark generations.[32] On the theoretical side, it has begun to address some of the key questions in quantum gravity, such as resolving the black hole information paradox, counting the correct entropy of black holes[33][34] and allowing for topology-changing processes.[35][36][37] It has also led to many insights in pure mathematics and in ordinary, strongly-coupled gauge theory due to the Gauge/String duality.

In the late 1990s, it was noted that one major hurdle in this endeavor is that the number of possible 4-dimensional universes is incredibly large. The small, "curled up" extra dimensions can be compactified in an enormous number of different ways (one estimate is 10^{500}) each of which leads to different properties for the low-energy particles and forces. This array of models is known as the string theory landscape.[17]:347

One proposed solution is that many or all of these possibilities are realized in one or another of a huge number of universes, but that only a small number of them are habitable. Hence what we normally conceive as the fundamental constants of the universe are ultimately the result of the anthropic principle rather than dictated by theory. This has led to criticism of string theory,[38] arguing that it cannot make useful (i.e., original, falsifiable, and verifiable) predictions and regarding it as a pseudoscience/philosophy. Others disagree,[39] and string theory remains an active topic of investigation in theoretical physics.[40]

Loop quantum gravity

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Current research on loop quantum gravity may eventually play a fundamental role in a theory of everything, but that is not its primary aim.[41] Loop quantum gravity also introduces a lower bound on the possible length scales.

There have been recent claims that loop quantum gravity may be able to reproduce features resembling the Standard Model. So far only the first generation of fermions (leptons and quarks) with correct parity properties have been modelled by Sundance Bilson-Thompson using preons constituted of braids of spacetime as the building blocks.[42] However, there is no derivation of the Lagrangian that would describe the interactions of such particles, nor is it possible to show that such particles are fermions, nor that the gauge groups or interactions of the Standard Model are realised. Use of quantum computing concepts made it possible to demonstrate that the particles are able to survive quantum fluctuations.[43]

This model leads to an interpretation of electric and color charge as topological quantities (electric as number and chirality of twists carried on the individual ribbons and colour as variants of such twisting for fixed electric charge).

Bilson-Thompson's original paper suggested that the higher-generation fermions could be represented by more complicated braidings, although explicit constructions of these structures were not given. The electric charge, color, and parity properties of such fermions would arise in the same way as for the first generation. The model was expressly generalized for an infinite number of generations and for the weak force bosons (but not for photons or gluons) in a 2008 paper by Bilson-Thompson, Hackett, Kauffman and Smolin.[44]

Other attempts

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Among other attempts to develop a theory of everything is the theory of causal fermion systems,[45] giving the two current physical theories (general relativity and quantum field theory) as limiting cases.

Another theory is called Causal Sets. As some of the approaches mentioned above, its direct goal isn't necessarily to achieve a theory of everything but primarily a working theory of quantum gravity, which might eventually include the standard model and become a candidate for a theory of everything. Its founding principle is that spacetime is fundamentally discrete and that the spacetime events are related by a partial order. This partial order has the physical meaning of the causality relations between relative past and future distinguishing spacetime events.

Causal dynamical triangulation does not assume any pre-existing arena (dimensional space), but rather attempts to show how the spacetime fabric itself evolves.

Another attempt may be related to ER=EPR, a conjecture in physics stating that entangled particles are connected by a wormhole (or Einstein–Rosen bridge).[46]

Present status

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At present, there is no candidate theory of everything that includes the standard model of particle physics and general relativity and that, at the same time, is able to calculate the fine-structure constant or the mass of the electron.[2] Most particle physicists expect that the outcome of ongoing experiments – the search for new particles at the large particle accelerators and for dark matter – are needed in order to provide further input for a theory of everything.

Arguments against

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In parallel to the intense search for a theory of everything, various scholars have debated the possibility of its discovery.

Gödel's incompleteness theorem

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A number of scholars claim that Gödel's incompleteness theorem suggests that attempts to construct a theory of everything are bound to fail. Gödel's theorem, informally stated, asserts that any formal theory sufficient to express elementary arithmetical facts and strong enough for them to be proved is either inconsistent (both a statement and its denial can be derived from its axioms) or incomplete, in the sense that there is a true statement that can't be derived in the formal theory.

Stanley Jaki, in his 1966 book *The Relevance of Physics*, pointed out that, because a "theory of everything" will certainly be a consistent non-trivial mathematical theory, it must be incomplete. He claims that this dooms searches for a deterministic theory of everything.[47]

Freeman Dyson has stated that "Gödel's theorem implies that pure mathematics is inexhaustible. No matter how many problems we solve, there will always be other problems that cannot be solved within the existing rules. […] Because of Gödel's theorem, physics is inexhaustible too. The laws of physics are a finite set of rules, and include the rules for doing mathematics, so that Gödel's theorem applies to them."[48]

Stephen Hawking was originally a believer in the Theory of Everything, but after considering Gödel's Theorem, he concluded that one was not obtainable. "Some people will be very disappointed if there is not an ultimate theory that can be formulated as a finite number of principles. I used to belong to that camp, but I have changed my mind."[49]

Jürgen Schmidhuber (1997) has argued against this view; he asserts that Gödel's theorems are irrelevant for computable physics.[50] In 2000, Schmidhuber explicitly constructed limit-computable, deterministic universes whose pseudo-randomness based on undecidable, Gödel-like halting problems is extremely hard to detect but does not prevent formal theories of everything describable by very few bits of information.[51]

Related critique was offered by Solomon Feferman[52] and others. Douglas S. Robertson offers Conway's game of life as an example:[53] The underlying rules are simple and complete, but there are formally undecidable questions about the game's behaviors. Analogously, it may (or may not) be possible to completely state the underlying rules of physics with a finite number of well-defined laws, but there is little doubt that there are questions about the behavior of physical systems which are formally undecidable on the basis of those underlying laws.

Since most physicists would consider the statement of the underlying rules to suffice as the definition of a "theory of everything", most physicists argue that Gödel's Theorem does *not* mean that a theory of everything cannot exist.[*citation needed*] On the other hand, the scholars invoking Gödel's Theorem appear, at least in some cases, to be referring not to the underlying rules, but to the understandability of the behavior of all physical systems, as when Hawking mentions arranging blocks into rectangles, turning the computation of prime numbers into a physical question.[54] This definitional discrepancy may explain some of the disagreement among researchers.

Fundamental limits in accuracy

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No physical theory to date is believed to be precisely accurate. Instead, physics has proceeded by a series of "successive approximations" allowing more and more accurate predictions over a wider and wider range of phenomena. Some physicists believe that it is therefore a mistake to confuse theoretical models with the true nature of reality, and hold that the series of approximations will never terminate in the "truth".[55] Einstein himself expressed this view on occasions.[56]

Definition of fundamental laws

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There is a philosophical debate within the physics community as to whether a theory of everything deserves to be called *the* fundamental law of the universe.[57] One view is the hard reductionist position that the theory of everything is the fundamental law and that all other theories that apply within the universe are a consequence of the theory of everything. Another view is that emergent laws, which govern the behavior of complex systems, should be seen as equally fundamental. Examples of emergent laws are the second law of thermodynamics and the theory of natural selection. The advocates of emergence argue that emergent laws, especially those describing complex or living systems are independent of the low-level, microscopic laws. In this view, emergent laws are as fundamental as a theory of everything.

The debates do not make the point at issue clear. Possibly the only issue at stake is the right to apply the high-status term "fundamental" to the respective subjects of research. A well-known debate over this took place between Steven Weinberg and Philip Anderson.[58]

Impossibility of calculation

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Weinberg[59] points out that calculating the precise motion of an actual projectile in the Earth's atmosphere is impossible. So how can we know we have an adequate theory for describing the motion of projectiles? Weinberg suggests that we know *principles* (Newton's laws of motion and gravitation) that work "well enough" for simple examples, like the motion of planets in empty space. These principles have worked so well on simple examples that we can be reasonably confident they will work for more complex examples. For example, although general relativity includes equations that do not have exact solutions, it is widely accepted as a valid theory because all of its equations with exact solutions have been experimentally verified. Likewise, a theory of everything must work for a wide range of simple examples in such a way that we can be reasonably confident it will work for every situation in physics. Difficulties in creating a theory of everything often begin to appear when combining quantum mechanics with the theory of general relativity, as the equations of quantum mechanics begin to falter when the force of gravity is applied to them.