GENERAL PHYSICS TO ASTROPHYSICS VOL 3

How Many Dimensions Are There? 11-Dimensional World and String Theory

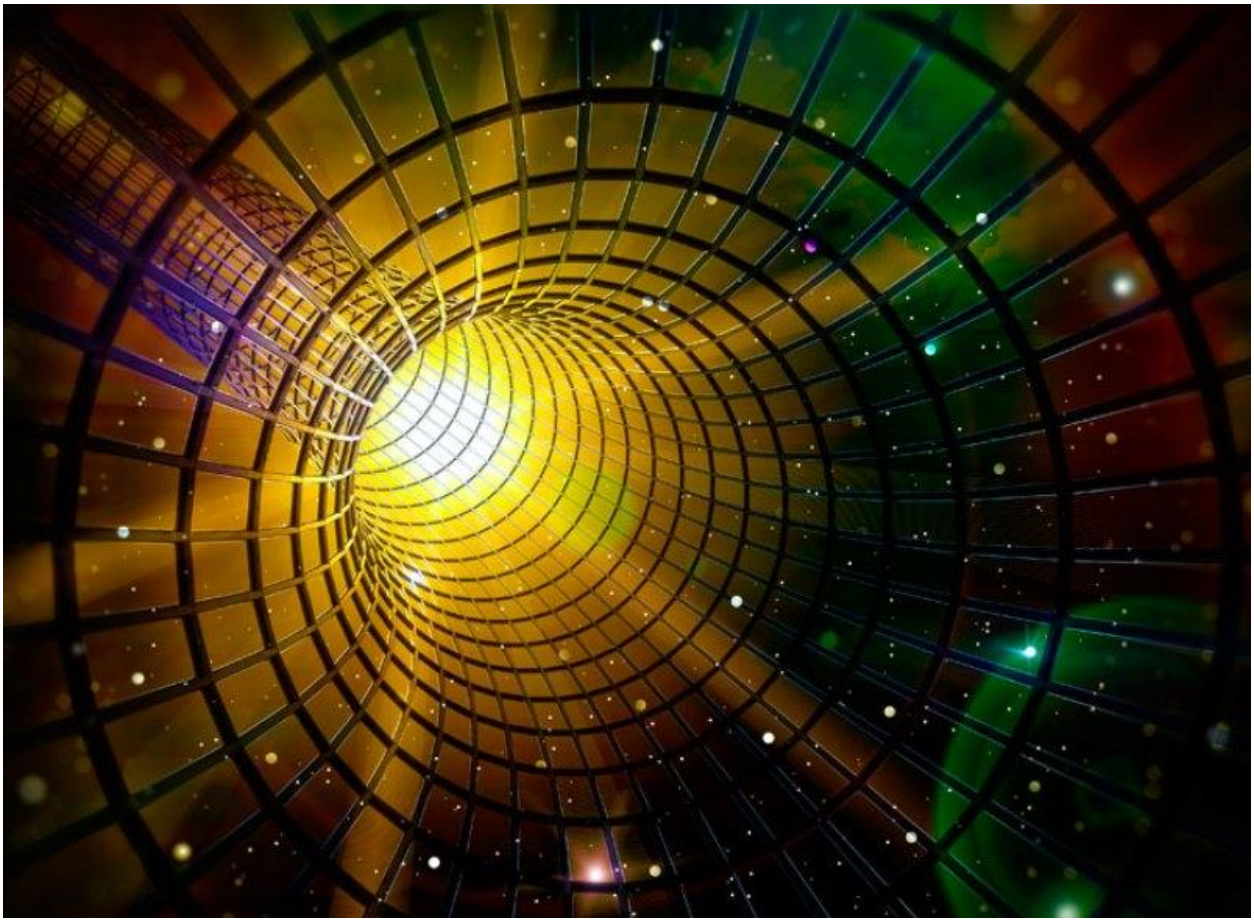
What if there are more than three dimensions in our universe? String theory suggests there are 11 of them. Let's explore this intriguing theory and its possible applications.

Since ancient days, humans have been familiar with the sense of 3-dimensionality of space. This idea was better understood after the **theory of classical mechanics by Isaac Newton** was presented about 380 years ago.

This concept is now clear to everyone that space has three dimensions, meaning that for every position, there correspond three numbers with regards to a reference point that can direct one to the right location. In other words, one can define sequences of positions in three independent ways.

This fact has its trace not only in physics but in other aspects of our life such as the biology of every living creature. For example, the inner ear of almost all vertebrates is composed of exactly three semicircular canals that sense the position of the body in the three dimensions of space. The eye of every human too has three pairs of muscles by which the eye is moved to every direction.

Einstein's special theory of relativity further developed this concept through its revolutionary idea that time should also be regarded as a 4th dimension. This notion was a must for the theory to resolves inconsistencies of Newtonian mechanics with classical electromagnetism.
Once a strange concept, after more than a century of its presentation, it is now a widely accepted concept in physics and astronomy. But still, one of the greatest mysteries and challenges of our era is **the origin of the three dimensions of space, the origin of time as well as details of big bang why does space have three dimensions and not more?**



The possibility of **the existence of even higher dimensional space** came about on the pure theoretical work of physicists who were trying to find a consistent and unified theory capable of explaining gravity within the framework of quantum mechanics.

Einstein's general theory of relativity is a classical theory since it is valid only at large distances. It is capable of making its successful predictions such as retrogression movement of the planet mercury, bending of light beams passing by massive objects, black holes, and many similar phenomena at large distances.

However, it cannot be used at the quantum level since there is no quantum theory capable of explaining gravitational force.

Unification of fundamental interactions

It is known that there are **four types of interactions in nature:** strong and weak nuclear forces, electromagnetism, and gravity. The relative strength of these forces differs with the gravitational field being the weakest force in nature.
During the past 100 years, physicists have long dreamed of unifying all fundamental fields and units of matter into a single self-consistent model. In the late 1960s, **Steven Weinberg** and **Abdus Salam** managed to unify two of these fields, i.e., weak interactions and electromagnetic field in a genuine theory named ***electroweak.***

The theory was later confirmed by its predictions. However, despite enormous efforts by physicists all over the world, there has been a little success for the unification of all four interactions into a single theory, with gravity being the most difficult one.

String theory and multidimensional space

In conventional quantum physics, elementary particles, such as electrons, quarks, etc., are regarded as mathematical points. This notion has been a long source of heated debate by physicist especially because of its deficiencies in dealing with gravity.

The general theory of relativity is incompatible with quantum field theory and numerous attempts to use a point-like particle model of quantum theory have failed to offer a consistent explanation of the gravitational field.

This was the time that ***string theory*** attracted a lot of attention aimed at finding a sound quantum theory for gravity. The way that string theory resolves the problem is by giving up the assumption that

elementary particles are mathematical points and developing a quantum model of one-dimensional extended bodies named ***string.***

This theory reconciles quantum theory and gravity. The theory once regarded as a purely theoretical conjecture is new regarded as one of the most consistent theories of quantum physics, promising a unified quantum theory of fundamental forces including gravity.

The theory was first suggested in the late 1960s to describe the behavior of particles called ***Hadrons*** and was later developed in the 1970s.
Since then, string theory has undergone many developments and changes. By the mid-1990s, the theory was developed in **5 different independent string theories,** but in 1995, it was realized that all versions where different aspects of the same theory named ***M-theory*** (M for "membrane" or the "mother of all string theories").
It has now become the focus of theoretical work for its success in explaining both gravity and the inside of an atom at the same time.
One of the most important aspects of the theory is that it requires the **11-dimensional space with one time coordinate and 10 other spatial coordinates.**

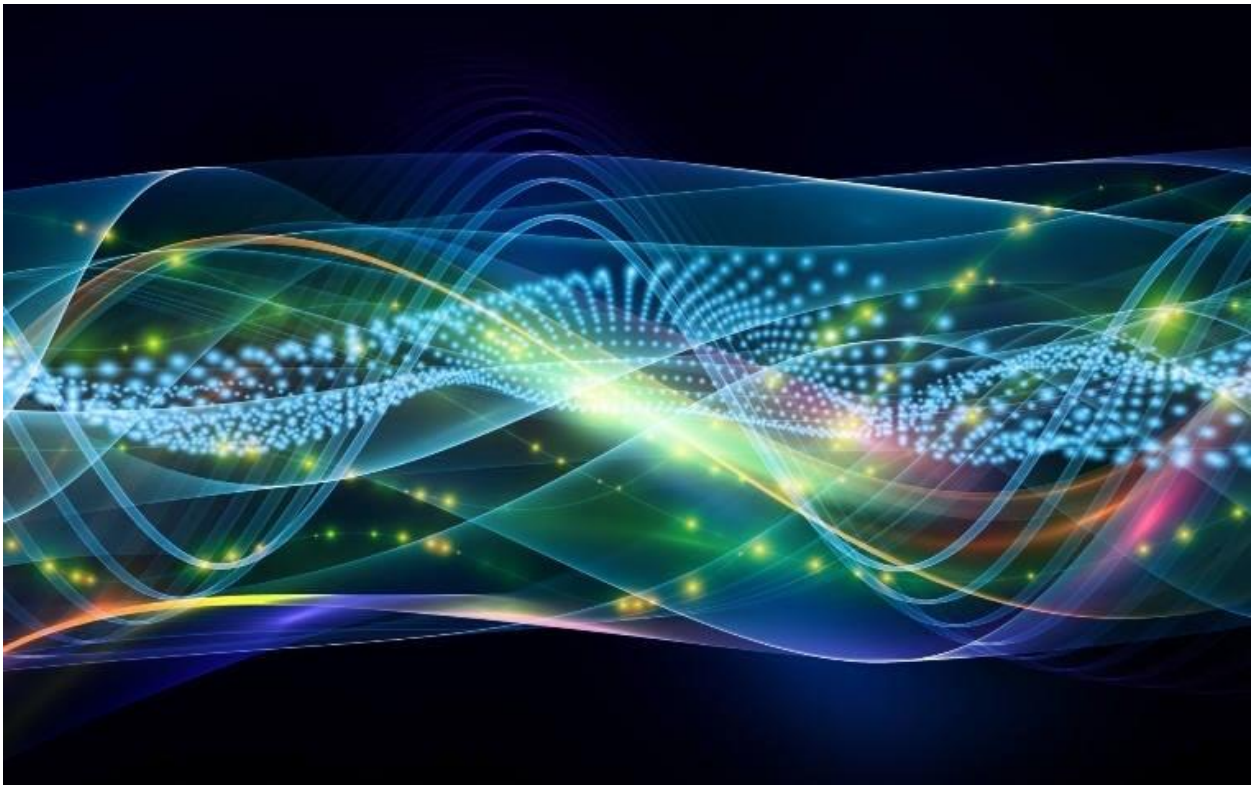
Testing and Experimental Results

The important question about M-theory is **how it can be tested.** In science fiction, extra dimensions are sometimes interpreted as alternate worlds, but these extra dimensions could simply be too small for us to feel and examine (on the order of 10^{-32} cm).
Since the M-theory is concerned about the most primitive entities of our universe, it is really a theory of Creation, and the only way to test it is to **re-create the Big Bang itself at an experimental level.** Other predictions of the theory that are to be tested include ***Super-***

symmetric particles, Extra dimensions, Microscopic black holes, and Cosmic strings.

Such an experiment needs a huge amount of input energy and speed that is beyond the present level of technology. However, it is expected that in the coming years, the new **LHC (Large Hadron Collider)** at CERN could test some of these predictions for the first time, providing more clues to the multi-dimensionality of our universe. If the attempt is successful, then **the M-theory may give answers to the following fundamental questions:**

- How did the universe begin?
- What are its fundamental constituents?
- What are the laws of Nature that govern these constituents?



As of now, there are no definite empirical results confirming M-theory and its 11-dimensional space, and the verification of the theory is a great challenge for physicists.

There is even a new theory called ***F-theory*** (F for “father”) that introduces another dimension, suggesting **a 12-dimensional space with two-time coordinates instead of one!**
The renowned physicist **John Schwartz** has even gone further by saying that **there may be no fixed dimension for the final version of M-theory**, making it independent of any dimensionality of space-time. Finding the real theory needs much more time and effort and till then the multi-dimensionality of the universe is an open case.
*As the physicist **Gregory Landsberg** said if the tests are successful, “This would be the most exciting thing since humanity discovered the Earth is not flat. It would give us a whole new reality to look at, a whole new universe.”*

Introduction to M-theory

In non-technical terms, M-theory presents an idea about the basic substance of the universe. Although a complete mathematical formulation of M-theory is not known, the general approach is the leading contender for a universal "Theory of Everything" that unifies gravity with other forces such as electromagnetism. M-theory aims to unify quantum mechanics with general relativity's gravitational force in a mathematically consistent way. In comparison, other theories such as loop quantum gravity are considered by physicists and researchers to be less elegant, because they posit gravity to be completely different from forces such as the electromagnetic force.[1][2][3]

Background

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In the early years of the 20th century, the atom – long believed to be the smallest building-block of matter – was proven to consist of even smaller components called protons, neutrons and electrons, which are known as subatomic particles. Other subatomic particles began being discovered in the 1960s. In the 1970s, it was discovered that protons and neutrons (and other hadrons) are themselves made up of smaller particles called quarks. The Standard Model is the set of rules that describes the interactions of these particles.

In the 1980s, a new mathematical model of theoretical physics, called string theory, emerged. It showed how all the different subatomic particles known to science could be constructed by hypothetical one-dimensional "strings", infinitesimal building-blocks that have only the dimension of length, but not height or width. These strings vibrate in multiple dimensions and, depending on how they vibrate, they might be seen in three-

dimensional space as matter, light or gravity. In string theory, every form of matter is said to be the result of the vibration of strings.

However, for string theory to be mathematically consistent, the strings must live in a universe with ten dimensions. String theory explains our perception of the universe to have four dimensions (three space dimensions and one time dimension) by imagining that the extra six dimensions are "curled up", to be so small that they can't be observed day-to-day. The technical term for this is *compactification*. These dimensions are usually made to take the shape of mathematical objects called Calabi–Yau manifolds.

Five major string theories were developed and found to be mathematically consistent with the principle of all matter being made of strings. Having five different versions of string theory was seen as a puzzle.

Speaking at the string theory conference at the University of Southern California in 1995, Edward Witten of the Institute for Advanced Study suggested that the five different versions of string theory might be describing the same thing seen from different perspectives.[4] He proposed a unifying theory called "M-theory", which brought all of the string theories together. It did this by asserting that strings are an approximation of curled-up two-dimensional membranes vibrating in an 11-dimensional spacetime. According to Witten, the *M* could stand for "magic", "mystery", or "membrane" according to taste, and the true meaning of the title should be decided when a better understanding of the theory is discovered.[5]

Status

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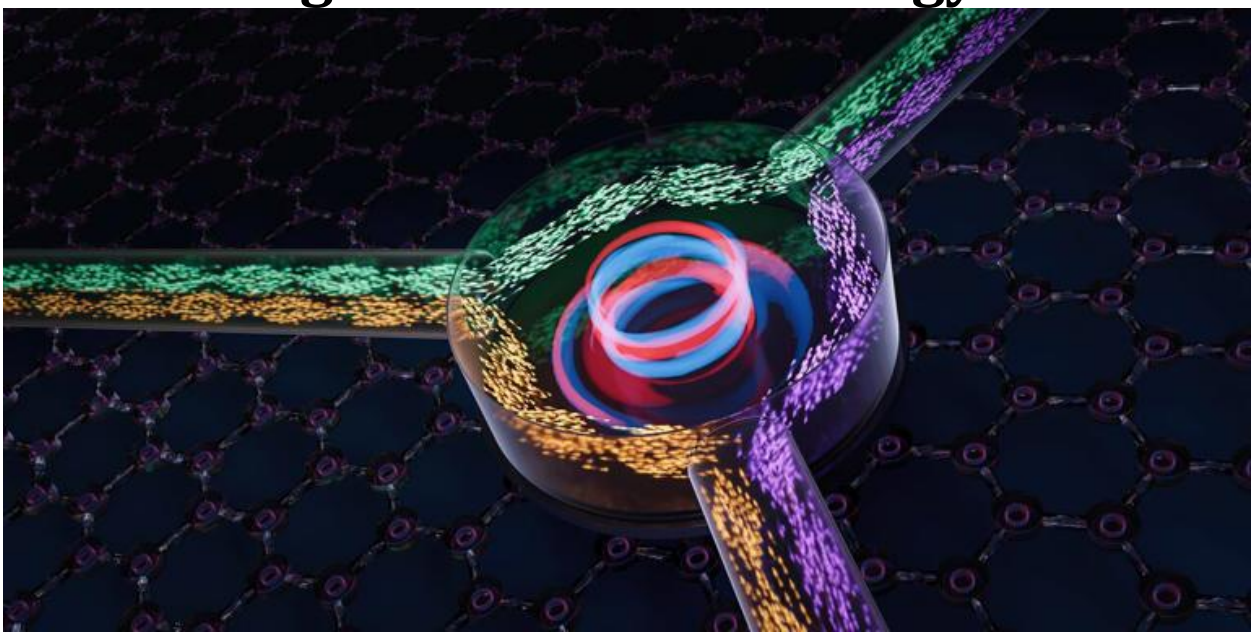
M-theory is not complete, and the mathematics of the approach are not yet well understood. M-theory is a theory of quantum gravity; and as all others it has not gained experimental evidence that would confirm its validity.[1] It also does not single out our observable universe as being special, and so does not aim to predict from first principles everything we can measure about it.

Nevertheless, some physicists are drawn to M-theory because of its degree of uniqueness and rich set of mathematical properties, triggering the hope that it may describe our world within a single framework.

One feature of M-theory that has drawn great interest is that it naturally predicts the existence of the graviton, a spin-2 particle hypothesized to mediate the gravitational force. Furthermore, M-theory naturally predicts a phenomenon that resembles black hole evaporation. Competing unification theories such as asymptotically safe gravity, E8 theory, noncommutative geometry, and causal fermion systems have not demonstrated any level of mathematical consistency.

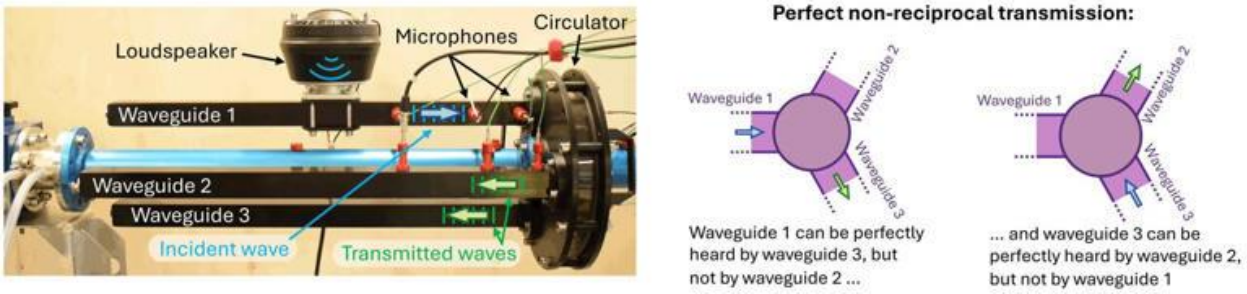
Researchers make sound waves travel in one direction only, with implications for electromagnetic wave technology



In the ETH experiment, self-oscillations (blue-red) cause sound waves (green, orange, violet) to travel through the circulator only in one direction. Credit: Xin Zou

Researchers at ETH Zurich have managed to make sound waves travel only in one direction. In the future, this method could also be used in technical applications with electromagnetic waves.

Water, light and sound waves usually propagate in the same way forward as in a backward direction. As a consequence, when we are speaking to someone standing some distance away from us, that person can hear us as well as we can hear them. This is useful when having a conversation, but in some technical applications one would prefer the waves to be able to travel only in one direction—for instance, in order to avoid unwanted reflections of light or microwaves.



Schematics of the experimental set-up (left) and wave propagation (right): Waveguide 1 can be heard perfectly by waveguide 3, but not by waveguide 2, and waveguide 3 can be heard perfectly by waveguide 2, but not by waveguide 1. As expected, the waves can only travel in one direction. Credit: Nicolas Noiray / ETH Zurich

Ten years ago, researchers succeeded in suppressing sound wave propagation in the backward direction; however, this also attenuated the waves traveling forwards.

A team of researchers at ETH Zurich led by Nicolas Noiray, professor for Combustion, Acoustics and Flow Physics, in collaboration with Romain Fleury at EPFL, has now developed a method for preventing sound waves from traveling backward without deteriorating their propagation in the forward direction.

In the future, this method, which has recently been published in *Nature Communications*, could also be applied to electromagnetic waves.

The basis of this one-way street for sound waves are self-oscillations, in which a dynamical system periodically repeats its behavior. "I've actually spent a good part of my career preventing such phenomena," says Noiray.

Among other things, he studies how self-sustaining thermo-acoustic oscillations can arise from the interplay between sound waves and flames in the combustion chamber of an aircraft engine, which can lead to dangerous vibrations. In the worst case, these vibrations can destroy the engine.

Harmless and useful self-oscillations

Noiray had the idea to use harmless self-sustaining aero-acoustic oscillations in order to allow sound waves to pass only in one direction and without any losses through a so-called circulator. In his scheme, the unavoidable attenuation of the sound waves is compensated by the self-oscillations in the circulator

synchronizing with the incoming waves, which allows them to gain energy from those oscillations.

The circulator itself was supposed to consist of a disk-shaped cavity through which swirling air is blown from one side through an opening in its center. For a specific combination of blowing speed and intensity of the swirl, a whistling sound is thus created in the cavity.

"In contrast to ordinary whistles, in which sound is created by a standing wave in the cavity, in this new whistle it results from a spinning wave," explains Tiemo Pedergnana, a former doctoral student in Noiray's group and lead author of the study.

From the idea to the experiment, it took a while. First, Noiray and his co-workers investigated the fluid mechanics of the spinning wave whistle, and then added three acoustic waveguides to it, which are arranged in a triangular shape along the edge of the circulator.

Sound waves that are fed in through the first waveguide can leave the circulator through the second waveguide. However, a wave entering through the second waveguide cannot exit "backwards" through the first waveguide, but can do so through the third waveguide.

Sound waves as a toy model

Over several years, the ETH researchers developed and theoretically modeled the various parts of the circulator; now, finally, they could experimentally demonstrate that their loss-compensation approach works. They sent a sound wave with a frequency of around 800 Hertz (roughly the high g of a soprano) through the first waveguide and measured how well it was transmitted to the second and third waveguides.

As expected, the sound wave didn't make it to the third waveguide. From the second waveguide (in the "forward" direction), however, a sound wave emerged that was even stronger than the one originally sent in.

"This concept of loss-compensated non-reciprocal wave propagation is, in our view, an important result that can also be transferred to other systems," says

Noiray. He sees his sound wave circulator mainly as a powerful toy model for the general approach of wave manipulation using synchronized self-oscillations that can, for instance, be applied to metamaterials for electromagnetic waves.

In this way, microwaves in radar systems could be guided better, and so-called topological circuits could be realized, with which signals can be routed in future communications systems.

More information: Tiemo Pedergnana et al, Loss-compensated non-reciprocal scattering based on synchronization, *Nature Communications* (2024). DOI: 10.1038/s41467-024-51373-y

Provided by ETH Zurich

How Many Dimensions Are There?

There are four dimensions in the observable universe. We live in a four-dimensional universe defined by three spatial dimensions and one time dimension.

In other words, it only takes three numbers to pinpoint your physical location at any given moment. On Earth, these coordinates break down to longitude, latitude and altitude representing the dimensions of length, width and height (or depth). Slap a time stamp on those coordinates, and you're pinpointed in time as well.

The Three Classical Dimensions

A one-dimensional world would be like a single bead on a measured thread. You can slide the bead forward and you can slide the bead backward, but you only need one number to figure out its exact location on the string: length. Where's the bead? It's at the 6-inch (15-centimeter) mark.

Now let's upgrade to a two-dimensional world. This is essentially a flat map, like the playing field in games such as Battleship or chess. You need only length and width to determine location. In Battleship, all you have to do is say "E5," and you know the location is a convergence of the horizontal "E" line and the vertical "5" line.

Now let's add one more dimension. Our world factors height (depth) into the equation. While locating a submarine's exact location in Battleship only requires two numbers, a real-life submarine would demand a third coordinate of depth. Sure, it might be charging along on the surface, but it might also be hiding 800 feet (244 meters) beneath the waves. Which will it be?

Theoretical Physics and Extra Dimensions

Could there be a fourth spatial dimension? Well, that's a tricky question because we currently can't perceive or measure anything beyond the dimensions of length, width and height. Just as three numbers are required to pinpoint a location in a three-dimensional world, a four-dimensional world would require four.

At this very moment, you're likely positioned at a particular longitude, latitude and altitude. Walk a little to your left, and you'll alter your longitude or latitude or both. Stand on a chair in the exact same spot, and you'll alter your altitude.

Here's where it gets hard: Can you move from your current location without altering your longitude, latitude or altitude? You can't, because there's not a fourth spatial dimension for us to move through.

But the fact that we can't move through a fourth spatial dimension or perceive one doesn't necessarily rule out its existence. In 1919, mathematician Theodor Kaluza theorized that a fourth spatial dimension might link general relativity and electromagnetic theory [source: Groleau].

But where would it go? Theoretical physicist Oskar Klein later revised the theory, proposing that the fourth dimension was merely curled up, while the other three spatial dimensions are extended.

In other words, the fourth dimension is there, only it's rolled up and unseen, a little like a fully retracted tape measure. Furthermore, it would mean that every point in our three-dimensional world would have an additional fourth spatial dimension rolled away inside it.

String Theory: A Theoretical Framework for Additional Dimensions

String theorists, however, need a slightly more complicated vision to empower their superstring theories about the cosmos. In fact, it's quite easy to assume they're showing off a bit in proposing 10 or 11 dimensions, including time.

Don't let that blow your mind just yet. One way of envisioning this is to imagine that each point of our 3D world contains not a retracted tape measure, but a curled-up, six-dimensional geometric shape. One such example is a Calabi-Yau shape, which looks a bit like a cross between a mollusk, an M.C. Escher drawing and a "Star Trek" holiday ornament [source: Bryant].

Think of it this way: A concrete wall looks solid and firm from a distance. Move in closer, however, and you'll see the dimples and holes that mark its surface. Move in even closer, and you'd see that it's made up of molecules and atoms.

Or consider a cable: From a distance it appears to be a single, thick strand. Get right next to it, and you'll find it's woven from countless strands. There's always greater complexity than meets the eye, and this hidden complexity may well conceal all those tiny, rolled-up dimensions.

Yet, we can only remain certain of our three spatial dimensions and one of time. If other dimensions await us, they're beyond our limited perception — for now.

Frequently Answered Questions

When given three dimensions what is the order?

The order is length, width and height.

What Is a Dimensional Space?

A dimensional space, in mathematics and physics, is a way of describing the different directions or coordinates in which objects can exist or move. It's a mathematical concept used to understand and visualize the positioning and movement of things in our world.

In our everyday world, we often use three dimensions: height (up and down), width (left and right) and depth (forward and backward) to describe the location of objects. These three dimensions create what's called 3D space.

However, in more advanced mathematics and physics, dimensional spaces can have more than three dimensions, and they help scientists and mathematicians understand complex phenomena like quantum mechanics, string theory or data analysis in higher dimensions.

These higher-dimensional spaces are harder to visualize because they go beyond our everyday experience, but they are essential for solving various problems and studying intricate systems.

Looking Beyond This Dimensional Space

In 1884, Edwin A. Abbot published a novella that depicts the problem of seeing dimensions beyond your own. In "Flatland: A Romance of Many Dimensions," Abbot describes the life of a square living in a two-dimensional world. Living in 2D means that the square is surrounded by circles, triangles and rectangles, but all the square sees are other lines. One day, the square is visited by a sphere.

On first glance, the sphere just looks like a circle to the square, and the square can't comprehend what the sphere means when he explains 3D objects. Eventually, the sphere takes the square to the 3D world, and the square understands. He sees not just lines, but entire shapes that have depth.

Emboldened, the square asks the sphere what exists beyond the 3D world; the sphere is appalled. The sphere can't comprehend a world beyond this, and in this way, stands in

for the reader. Our brains aren't trained to see anything other than our world, and it will likely take something from another dimension to make us understand.

The Fourth Dimension

But what is this other dimension? Mystics used to see it as a place where spirits lived, since they weren't bound by our earthly rules. In his theory of special relativity, Einstein referred to time as the fourth dimension, but noted that time is inseparable from space.

Science-fiction aficionados may recognize that union as space-time, and indeed, the idea of a space-time continuum has been popularized by science-fiction writers for centuries (e.g., Ray Bradbury's "The Martian Chronicles" or Joe Haldeman's "The Forever War").

Today, some physicists describe the fourth dimension as any space that's perpendicular to a cube — the problem being that most of us can't visualize something that is perpendicular to a cube [source: Duke University].

Researchers have used Einstein's ideas to determine whether we can travel through time. While we can move in any direction in our 3D world, we can only move forward in time. Thus, traveling to the past has been deemed near-impossible, though some researchers still hold out hope for finding wormholes that connect to different sections of space-time.

Beginnings of the Concept

In the early 19th century, mathematicians and thinkers began to explore the idea of a fourth spatial dimension beyond our familiar three dimensions (depth, width and height). August Ferdinand Möbius was among those who pondered the possibilities of this additional dimension. One of the intriguing aspects of the fourth dimension is that in it, a three-dimensional object could be rotated in such a way that it would appear as its own mirror image, a concept that challenges our intuitive understanding of space.

The tesseract, also known as a hypercube, is a common visual representation of 4D space. It is an extension of the concept of a cube (a 3D object) into the fourth dimension. While it's challenging to visualize in our three-dimensional world, mathematicians use diagrams and models to help convey the idea of a tesseract.

Later in the 19th century, mathematician Bernhard Riemann laid the foundations for true four-dimensional geometry, providing a mathematical framework for understanding and working with higher-dimensional spaces. This work became fundamental to later developments in mathematics and physics, particularly in the study of curved spaces and the theory of relativity.

Types of Dimensional Spaces

In mathematics and physics, we encounter various types of dimensional spaces beyond our familiar three-dimensional world.

1. **Zero-Dimensional Space (0D)**: Often referred to as a single point or a singleton, this space represents a single location or value with no spatial extent or degrees of freedom. It is the simplest and most abstract of all dimensional spaces, serving as a foundational concept in mathematics, especially in set theory and abstract algebra.
2. **One-Dimensional Space (1D)**: This is the simplest dimensional space, represented as a straight line. In a one-dimensional world, objects and entities can only move along a single axis (like a timeline), limiting their spatial freedom to one dimension.
3. **Two-Dimensional Space (2D)**: This space includes coordinates that cover a plane, like a sheet of paper. It's used for mapping and analyzing objects' positions in two directions.
4. **Three-Dimensional Space (3D)**: Our everyday space involves three dimensions: height, width and the third dimension of depth. The interaction of these dimensions allows us to describe the physical world and how objects move within it.
5. **Four-Dimensional Space (4D)**: In physics, time is often considered the fourth dimension, essential in understanding space-time in Einstein's theory of general relativity.
6. **Euclidean n-Dimensional Space (nD)**: It's a way of thinking about space that goes beyond our usual three dimensions. This space can have any number of dimensions (n), where distances and angles between points are measured in a consistent, familiar way.
7. **Vector Spaces**: These spaces can have any finite number of dimensions and are fundamental in linear algebra, which plays a vital role in physics, computer graphics and engineering.
8. **Hilbert Spaces**: Infinite-dimensional spaces are used in quantum mechanics to describe the state of quantum systems.
9. **Function Spaces**: These spaces involve functions as their elements and are used in various mathematical and scientific disciplines.
10. **Manifolds**: These spaces that look like Euclidean space near every point but may have a different overall shape.
11. **Phase Spaces**: Used in physics to describe the complete set of variables needed to predict the future behavior of a dynamic system.

Why Is It Important to Understand the Fourth Dimension?

If we can't use the fourth dimension to time travel, and if we can't even see the fourth dimension, then what's the point of knowing about it? Understanding these higher spatial dimensions is of importance to mathematicians and physicists because it helps them understand the world.

String theory, for example, relies upon at least 10 dimensions to remain viable [source: Groleau]. For these researchers, the answers to complex problems in the 3D world may be found in the next dimension — and beyond.

Applications in Math

In mathematics, particularly in geometry, comprehending higher-dimensional spaces, including the fourth dimension, is fundamental. These spaces expand problem-solving capabilities, although visualizing them challenges our conventional three-dimensional thinking. Concepts like hypercubes enable mathematicians to explore these abstract spaces.

In geometry, the fourth dimension plays a vital role in visual representation. It extends beyond our everyday experience, challenging our ability to grasp complex spatial arrangements. While we can't directly visualize four-dimensional space, math provides tools for representing and comprehending it, expanding our geometric understanding.

Applications in Physics

In physics, the fourth dimension, as time in space-time, forms the cornerstone of our comprehension of physical laws and predictions. The theories of modern physics, like Einstein's general relativity, rely on this concept. Accurate predictions about the behavior of objects and events demand the inclusion of time as the fourth dimension.

In fact, time as the fourth dimension is crucial for reshaping our understanding of gravity in the context of general relativity. It describes gravity as the curvature of space-time by massive objects, deeply intertwined with the fourth dimension. Neglecting time in this context would make explaining gravitational phenomena very challenging.

Everyday Applications

In everyday life, tasks, such as navigation and communication, heavily depend on our grasp of time as the fourth dimension. Technologies like GPS and accurate time-keeping systems rely on this foundational understanding, enhancing our daily lives.

Moreover, the concept of the fourth spatial dimension prompts profound philosophical inquiries into the nature of time and reality, challenging our perceptions and encouraging contemplation about our place within the universe.

Applications in Cosmology

Lastly, in cosmology, the fourth dimension is pivotal for unveiling the history and evolution of the universe. It assists in studying significant events like the Big Bang, cosmic expansion and the formation of galaxies and stars, providing invaluable insights into the cosmos.

This article was updated in conjunction with AI technology, then fact-checked and edited by a HowStuffWorks editor.

How Many Dimensions Does Our Universe Really Have?

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Theoretical physics is a fascinating and (at times) amusing field. While most people would not claim to know much about this field of research, many of its more advanced concepts come up in popular culture all the time. In fact, words like "nuclear," "quantum," and "multiverse" are often key to the plot of our favorite TV shows and movies.

On the other hand, some of the more advanced concepts in theoretical physics (when described) sound more like philosophy and metaphysics than science. In fact, some theories even manage to blur the lines between science and religion and are generally met by either awe or dismissal (depending upon who's listening).

Consider the idea of "extra dimensions," which many people would assume refers to the existence of dimensions parallel to our own where things are slightly or vastly different — aka. "multiverse" theory. In truth, the theory of extra dimensions deals with the possible existence of extra dimensions beyond the ones we are immediately aware of.

While this kind of talk may sound like something farfetched or purely speculative, it is actually a vital part of our understanding of how our Universe works. If and when we determine how many dimensions our Universe has (and what each of them does), we will finally have a Theory of Everything (ToE) and know how it all fits together.

Dimensions 101

To break it down, the term "dimension" refers to any mathematical measurement. This can generally refer to a physical measurement (an object or space) or a temporal measurement (time). There are three dimensions that we experience daily, which define the length, width, and depth of all objects in our Universe (the x, y, and z-axis, respectively).

However, scientists maintain that to understand the laws of nature, one must include a "fourth dimension," which is time. Without this coordinate, the position, velocity, and acceleration of objects in our Universe cannot be properly measured. It's not enough to know where an object is in terms of three spatial coordinates. You also need to know *when* the object was where.

Beyond these four dimensions, theoretical physicists have ventured that there may be more at play. The number of dimensions varies, but the purpose behind extra dimensions is to find ways of unifying the known laws of the Universe, which theoretical physicists have been trying to do for about a century.

The reason has to do with two very interesting fields of study: Quantum Mechanics (QM) and General Relativity (GR). These fields emerged during the early 20th century and were almost concurrent with each other. Whereas QM has many forebears (Planck, Heisenberg, Schrodinger, et al.), GR owes its existence, at least initially, to Albert Einstein — though many of his ideas were refinements on earlier theories.

For the record, Einstein also contributed to the development of QM through his research on the behavior of light. In any case, whereas Quantum Mechanics (QM) describes how energy and matter behave at the atomic and subatomic levels, General Relativity (GR) describes how matter, energy, and spacetime behave on larger scales in the presence of gravity.

The funny thing is, our greatest scientific minds have been trying to figure out how these two fields fit together for almost a century. Both appear to work just fine on their own, but where they come together into a single coherent system, that remains largely a mystery.

Four fundamental forces

After thousands of years of research into nature and the laws that govern it, scientists have determined that four fundamental forces govern all matter-energy interactions. These forces, and the fundamental particles that make up all matter (quarks, leptons, gauge bosons, and scalar bosons), are part of The Standard Model of particle physics. These forces are:

- *Electromagnetism*
- *Weak Nuclear Force*
- *Strong Nuclear Force*
- *Gravitation*

The first three forces are all described by the field of Quantum Mechanics and are associated with specific subatomic particles. Electromagnetism is associated with electrons (a lepton), which are responsible for electricity, magnetism, and all forms of

electromagnetic radiation. That includes visible light (color), heat, microwaves, radio waves, ultraviolet radiation, and gamma rays.

The weak nuclear force deals with interactions between subatomic particles responsible for the radioactive decay of atoms and is associated with particles smaller than a proton (bosons). At higher energies, this force merges with electromagnetism, which has given rise to the unified term "electroweak force."

The strong nuclear force governs particles that are the size of protons and neutrons (hadrons) and is so-named because it is approximately 137 times as strong as electromagnetism, millions of times stronger than the weak nuclear force, and 10^{38} times as strong as gravitation. It causes quarks to come together to form larger protons and neutrons and binds them to create atomic nuclei.

Finally, there is gravitation, which is the weakest of the four forces and deals with interactions between massive objects (asteroids, planets, stars, galaxies, and the large-scale structure of the Universe.) Unlike the other three forces, there is no known subatomic particle that describes gravitation or gravitational interactions.

This is why scientists are forced to study physics in terms of QM or GR (depending on the scales involved), but generally not both combined. Because of this, scientists have been trying to come up with a theoretical framework for unifying gravity with the other forces. Attempts to do so generally fall under the heading of "quantum gravity" or a Theory of Everything (ToE).

How many dimensions are there?

Attempts to create a unified field theory of gravitation and electromagnetism can be traced to German physicist Theodor Kaluza (1885–1954). In 1921, he published a paper where he presented an extended interpretation of Einstein's Field Equations. This theory was built on the idea of a 5D Universe, which included a dimension beyond the common 4D of space and time.

In 1926, Swedish theoretical physicist Oskar Klein offered a quantum interpretation of Kaluza's 5D theory. In Klein's extension, the fifth dimension was curled up, microscopic, and could take the form of a circle that had a 10^{-30} cm radius. In the 1930s, work was undertaken on the Kaluza field theory by Einstein and his colleagues at Princeton. By the 1940s, the theory was formally completed and given the name Kaluza-Klein theory.

The work of Kaluza and Klein predicted the emergence of String Theory (ST), which was first proposed during the 1960s. By the 1990s, multiple interpretations emerged, including Superstring Theory, Loop-Quantum Gravity, M-theory, and Supergravity. Each of these theories entails the existence of "extra dimensions," "hyperspace," or something similar.

To summarize, ST states that the point-like particles of particle physics are actually one-dimensional objects called "strings." Over distances larger than the string scale, they resemble ordinary particles, though their mass, charge, and other properties are determined by the string's vibrational state. In one state, the string corresponds to the graviton, which is what causes gravitation.

However, scientists maintain that to understand the laws of nature, one must include a "fourth dimension," which is time. Without this coordinate, the position, velocity, and acceleration of objects in our Universe cannot be properly measured. It's not enough to know where an object is in terms of three spatial coordinates. You also need to know *when* the object was where.

Beyond these four dimensions, theoretical physicists have ventured that there may be more at play. The number of dimensions varies, but the purpose behind extra dimensions is to find ways of unifying the known laws of the Universe, which theoretical physicists have been trying to do for about a century.

The reason has to do with two very interesting fields of study: Quantum Mechanics (QM) and General Relativity (GR). These fields emerged during the early 20th century and were almost concurrent with each other. Whereas QM has many forebears (Planck, Heisenberg, Schrodinger, et al.), GR owes its existence, at least initially, to Albert Einstein — though many of his ideas were refinements on earlier theories.

For the record, Einstein also contributed to the development of QM through his research on the behavior of light. In any case, whereas Quantum Mechanics (QM) describes how energy and matter behave at the atomic and subatomic levels, General Relativity (GR) describes how matter, energy, and spacetime behave on larger scales in the presence of gravity.

The funny thing is, our greatest scientific minds have been trying to figure out how these two fields fit together for almost a century. Both appear to work just fine on their own, but where they come together into a single coherent system, that remains largely a mystery.

Four fundamental forces

After thousands of years of research into nature and the laws that govern it, scientists have determined that four fundamental forces govern all matter-energy interactions. These forces, and the fundamental particles that make up all matter (quarks, leptons, gauge bosons, and scalar bosons), are part of The Standard Model of particle physics. These forces are:

- *Electromagnetism*
- *Weak Nuclear Force*
- *Strong Nuclear Force*
- *Gravitation*

The first three forces are all described by the field of Quantum Mechanics and are associated with specific subatomic particles. Electromagnetism is associated with electrons (a lepton), which are responsible for electricity, magnetism, and all forms of electromagnetic radiation. That includes visible light (color), heat, microwaves, radio waves, ultraviolet radiation, and gamma rays.

The weak nuclear force deals with interactions between subatomic particles responsible for the radioactive decay of atoms and is associated with particles smaller than a proton (bosons). At higher energies, this force merges with electromagnetism, which has given rise to the unified term "electroweak force."

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Superstring theory, a variation on ST, requires the existence of **10 spacetime dimensions**. These include the four dimensions immediately apparent to us (length, width, depth, time) and six more that are not.

These extra six dimensions are curled up into a compact space. On order the string scale (10^{-33} cm) we wouldn't be able to detect the presence of these extra dimensions directly because they're just too small.

According to the theory, the fifth and sixth dimensions deal with possible worlds that began with the same initial conditions.

The **fifth dimension** encompasses worlds with slightly different outcomes than ours, while the **sixth** is where a plane of possible worlds would be visible. The **seventh dimension** is where one could see possible worlds that started with different initial conditions and then branched out infinitely — hence why the term "infinity" is used to describe them.

The **eighth dimension** would similarly give us a plane of these "infinities," while in the **ninth dimension**, all possible Universes and laws of physics could be seen. In the **tenth dimension**, anything and everything possible in terms of cosmic evolution are accessible. Beyond that, nothing can be seen by living creatures that are part of the spacetime continuum.

M-theory, which combines five distinct superstring theories, posits the existence of **11 dimensions** — ten spatial and one time. This variation on superstring theory is considered attractive because of the phenomena it predicts. For one, M-theory predicts the existence of the graviton, which is consistent with string theory as a whole and offers an explanation for quantum gravity.

It also predicts a phenomenon similar to black hole evaporation, where black holes emit "Hawking radiation" and lose mass over time. Some variations of superstring theory also predict the existence of Einstein-Rosen bridges — aka. "wormholes." Another approach, Loop Quantum Gravity (LQG), posits that gravity is completely different from the other fundamental forces and that space-time itself is made of quantized, discrete bits, in the form of tiny, one-dimensional loops.

Some versions of supergravity theory also promote an 11-D model of spacetime, with 4 common dimensions and 7 hyperspace dimensions. There's also "brane theory," which

posits that the Universe is made up of multidimensional vibrating "membranes" that have mass and a charge and can propagate through spacetime.

To date, there is no experimental evidence for the existence of "extra dimensions," "hyperspace," or anything beyond the four dimensions we can perceive.

Why can't we see them?

Alas, the question remains. If additional dimensions are required for the laws of physics to make sense, why can't we confirm their existence? There are two possibilities: one, what we think we know about physics is wrong, or two, the dimensions of spacetime beyond the 4D we experience are so subtle or tiny that they are invisible to our current experiments.

On its face, the first possibility seems highly unlikely. After all, ongoing particle experiments — like those conducted with the Large Hadron Collider (LHC) — have confirmed that the Standard Model of particle physics is correct. Similarly, General Relativity has been confirmed many times over since Einstein formally proposed it in 1915.

That leaves us with the second possibility: that extra dimensions cannot be measured or characterized using current methods and experiments. A well-studied possibility is that dimensions are "curled up" at tiny scales, which means their properties and influence on spacetime could only be measured at subatomic levels.

Another possibility is "compactification," where certain dimensions are finite or temporal in nature. In short, this theory posits that curled-up dimensions become very small or close in on themselves to form circles. If this is true, then the six extra dimensions would likely take the form of a Calabi–Yau manifold (these are shapes that satisfy the requirement needed for the six "unseen" spatial dimensions of string theory).

For astrophysicists and theoretical physicists, compactification and the idea that extra dimensions are tiny explains why the Universe still exists billions of years after its emergence. If these dimensions were larger, they would accommodate enough matter to trigger gravitational collapses and the formation of black holes (which would consume the rest of the Universe).

The fact that the cosmos still exists after 13.8 billion years, and shows no sign of being torn apart, would suggest that this theory is sound. Alternatively, the laws of physics may operate differently in these extra dimensions. Either way, there's still the unanswered question of how we might observe and study them.

How do we find them?

So if the Universe really does have extra dimensions that are imperceptible to us, how are we going to find evidence of their existence and determine their properties? One possibility

is to look for them through particle physics experiments, like those conducted by the European Organization for Nuclear Research (CERN) — the operators of the LHC — and other particle accelerator labs.

At CERN, scientists boost particles to high energies before smashing them together and measuring the resulting cascade of subatomic particles. Detectors gather clues about the particles, such as their speed, mass, and charge, which can be used to work out their identity.

Theories involving extra dimensions predict that there must be heavier versions of standard particles recurring at higher and higher energies as they navigate smaller dimensions. These would have exactly the same properties as standard particles (and so be visible to detectors like those at CERN) but at a greater mass. If evidence of these were to be found, this might suggest the presence of extra dimensions.

Another way is to look back through time towards the period known as "Cosmic Dawn," roughly 100 to 500 million years after the Big Bang, when the first stars and galaxies formed. Even if extra dimensions are imperceptible to detection today, they would have influenced the evolution of the Universe from the very beginning.

To date, astronomers have been unable to see this far back in time since no telescopes have been sensitive enough. This will change in the near future, thanks to next-generation instruments like the *James Webb Space Telescope* (JWST), the *Nancy Grace Roman Space Telescope* (RST), the Extremely Large Telescope (ELT), and the Giant Magellan Telescope (GMT).

This coincides nicely with existing Dark Matter and Dark Energy surveys that are observing early comic history in the hopes of measuring their influence on cosmic evolution. Since some theorists venture that the existence of extra dimensions could help explain the "Dark Universe," these observations could address several mysteries at once.

This dual approach is not unlike our current understanding of the Universe, which scientists can only understand in one of two ways — the largest (GR) and tiniest of scales (QM). By observing the Universe with a very wide and very tight-angle lense, we may be able to account for all the forces governing it.

ABOUT THE EDITOR

Matthew S. Williams Matthew S Williams is an author, a writer for Universe Today, and the curator of their Guide to Space section. His works include sci-fi/mystery The Cronian Incident and his articles have been featured in Phys.org, HeroX, Popular Mechanics, Business Insider, Gizmodo, and IO9, ScienceAlert, Knowridge Science Report, and Real Clear Science, with topics ranging from astronomy and Earth sciences to technological innovation and environmental issues. He is also a former educator and a 5th degree Black Belt Tae Kwon Do instructor. He lives on Vancouver Island with his wife and family.

Jason Lotay *explains how mathematicians studying special geometries are collaborating with physicists to explore M-theory, an 11-dimensional description of the world that unifies the various string theories*

I am a mathematician at University College London with a key interest in seven-dimensional geometry. This sounds pretty far away from the real world of physics, so why am I writing an article in *Physics World*? I hope to convince you that this type of geometry not only is an exciting area of research being pursued by some of the world's top mathematicians, but may also play a crucial role in enabling us to formulate a unified theory of physics.

I have been fascinated by both maths and physics ever since my school days – a combined interest that has fundamentally shaped my academic career. Quantum theory and gravity in particular captured my imagination and I wanted to learn more. During my maths degree, I did very little geometry and instead took every physics option I could. It was only when I wanted to study Albert Einstein's general theory of relativity that I realized it would be useful for me to know some more sophisticated aspects of geometry. Once I took my first geometry class, I was hooked, and when I found out that the connections between geometry and physics went much further than I thought, I knew that it was the research topic for me.

Luckily, I managed to do a PhD in this area and ended up studying it for a living. Along the way, I have found that it is possible to interpret many ideas in physics using geometry and, conversely, to use physics as a motivation in geometry to spectacular effect. The links between geometry and physics go back a long way and perhaps the most prominent player in the interaction is gravity.

Dimensions of gravity

When observing the everyday effects of gravity such as objects falling to the ground, one might intuitively think of gravity as a force of attraction between objects. This was the point of view Isaac Newton took, and although it was certainly very useful, it led to an incomplete theory.

Einstein's fundamental idea in general relativity is to replace the notion of gravity as a force with, instead, gravity as an effect of the curvature of the universe. Describing gravity in this way shows that general relativity is inherently geometric. Einstein's theory has concrete physical implications that have stood up to all experimental data so far, even those at extremely high precision: it enables us to use GPS; it correctly describes the behaviour of Mercury's orbit; and it predicted gravitational waves, which were detected in 2015 by the Laser Interferometer Gravitational-Wave Observatory in one of the most exciting recent developments in physics.

Geometry is an invaluable (and arguably indispensable) tool in understanding gravity

Since Einstein's pioneering work, it has been clear that geometry is an invaluable (and arguably indispensable) tool in understanding gravity. Additionally, we must consider geometry in more than our usual three dimensions, since general relativity is formulated in terms of space–time: a four-dimensional view of our universe where the three dimensions of space and one dimension of time can interact.

Most of us perceive the world in the familiar three spatial dimensions, so it can be challenging to conceptualize additional dimensions, which are not necessarily spatial. Let me illustrate with an example. Suppose you want to buy a piece of furniture, say a wardrobe. The size of a wardrobe is obviously important, since it has to fit in your home, so you need to know its height, width and depth – the three dimensions we know very well. However, there are many other factors involved in choosing the wardrobe, including its weight (if you have to get it up some stairs) and its cost. These are properties of the wardrobe that we can measure on a scale, just like height. Colour is another

characteristic that can be assigned a number on a scale, using wavelength. In fact we can measure all sorts of aspects of the wardrobe, all of which can be thought of as dimensions.

In this way, we can have as many dimensions as we like, and we should not be worried by the idea of adding in more dimensions; they are just ways of talking about additional properties of an object. Of course, it becomes hard to picture what higher dimensions look like. This is where I and other mathematicians come in, since we have the tools to deal with geometry in any dimensions, not just describing it but solving problems there too.

In relativity, the idea of adding a fourth dimension, time, should now not be a concern. In fact, having time as another dimension is a very old idea in physics, but the key observation of Einstein is that the universe should *curve* in the time dimension; this is why clocks run more slowly when gravity is stronger.

For mathematicians, even though adding another dimension is easy, the geometries in three and four dimensions are very different, so the number of dimensions in the theory is very important. In fact, some of the most celebrated works in mathematics involve these geometries. In three dimensions we have the famous Poincaré conjecture, a Millennium Prize Problem worth $1m, which was solved by Grigori Perelman (though he refused both the prize and the Fields Medal – the top award in mathematics). On the other hand, Simon Donaldson was awarded the Fields Medal primarily for his work using inspiration from physics (specifically Yang–Mills theory, which forms the basis for the Standard Model of particle physics) to understand 4D geometry.

Clarifying M-theory Jason Lotay performs science stand-up explaining the concept of multiple dimensions using a toy lightsaber

Despite the successes of Newton and Einstein’s theories, our understanding of gravity is still incomplete. The most well-known shortcoming is that we have no theory that unifies gravity with quantum theory, which explains the behaviour of elementary particles. The struggle for this unified theory plagued Einstein and still remains an open problem.

There are also three gravitational phenomena that general relativity struggles to explain. The first is the “missing mass” known as dark matter, which various clues point to, including a mismatch between the speeds at which stars are predicted to move around their galactic centres, and those observed. The second is that, using the cosmic microwave background, the universe appears to “look the same” in all directions, which is most easily explained using the idea of inflation: that the universe underwent a period of rapid expansion after the Big Bang. The mechanism of inflation, however, is not readily compatible with general relativity. Finally, there is the problem that not only is the universe expanding, but that the rate of expansion is increasing; this is typically explained by so-called dark energy. General relativity can account for the rate of expansion, but only by introducing a cosmological constant, as Einstein himself did. However, the observed value of the constant does not match with any currently consistent theoretical prediction.

Taking a jump

In an attempt to unify gravity with quantum theory, physicists introduced string theory. The key idea of this theory is that rather than modelling particles by points or little round balls, as one does in quantum theory or from an intuitive perspective, we should instead view particles as being little “strings”: one-dimensional objects that can either be closed loops or open pieces with free ends. These strings can vibrate just like the strings on a guitar or in a piano, and understanding these vibrations then allows us (or at least string theorists) to describe and understand the particles.

This relatively simple idea has important physical consequences in that it can potentially provide a unified theory. It also adds geometry, and in particular curvature, into the game in a fundamental way. Unlike a point or round ball, a string can be curved and how it is curved can be influenced by the world around it. For example, if we lay a string flat on the table in a straight line it is not curved at all, but if we push it flush against a sphere, say a globe, then it will be curved since the sphere is curved.

Although string theory seems like a pretty simple idea, it has a complicated consequence. In order for the theory to make sense one needs to take a major jump: we have to add extra dimensions to the universe beyond the four we know. For a mathematician this is easy, but for a typical physicist this is quite tricky and hard to swallow (though hopefully my wardrobe analogy has made it a little bit easier). The theory does not say what these extra dimensions are: they are not something as concrete as space or time that we can add on. However, they do behave a bit like our usual spatial dimensions, and they are curved too in a special way, inspired by relativity.

So how many extra dimensions do we need to describe the geometry of our world? Well, it varies, but most string theories use 10 dimensions, so six more than the usual four. This seems like a lot, but in the past string theorists have considered using as many as 26, and for mathematicians the number six is still pretty small.

M-theory happens in 11 dimensions, so seven more than our usual space and time

Actually, when I said there is a theory called string theory in 10 dimensions, this is not quite true. There are actually several different string theories in 10 dimensions. This is quite embarrassing, because if we are looking for a unified theory then there should be just one. This problem caused consternation in the field until theoretical physicist and Fields Medal winner Edward Witten proposed a new theory of physics called M-theory.

M-theory happens in 11 dimensions, so seven more than our usual space and time. It has the great property that it shows that all of the string theories in 10 dimensions, which as I said all look different, are actually all special cases of this single 11D theory. So M-theory seems to be the unification of the string theories that the community was looking for. This means adding another dimension, but since we were already at 10, going to 11 does not seem like much of a stretch.

There is some debate as to what the M actually stands for. Some say it is for master theory or mother-of-all theory (since there is also an F-theory that

might be father-of-all), or perhaps membrane theory. The last one makes sense because M-theory is not a string theory, as the fundamental objects are no longer 1D, but are instead higher-dimensional surfaces or membranes.

Inspired by bubbles

We can write down equations for the seven-dimensional objects we are interested in, but it is hard to solve them. This should come as no surprise, as Albert Einstein's equations describing only four dimensions gave rise to the same problem. Solving such equations is the key reason why studying gravity, and the analogous geometric problems that arise, is particularly challenging. However, I have been looking into a new approach to solving these equations that takes inspiration from a much more mundane topic in physics: bubbles.

When you blow a soap bubble, it starts off as some weird blob, but gradually becomes a sphere, as long as it does not pop. The reason is simple physics: the bubble will reach equilibrium when the pressure on the inside and outside match, which means the bubble will become a sphere. The bubble's route to equilibrium can also be phrased in terms of its surface tension, which mathematically can be expressed as the fact that the bubble wants to minimize its surface area, given the volume of air it contains. The bubble does this automatically, and since we can model its evolution using an equation similar to one of the simplest evolution equations in physics, which describes how heat dissipates, we can solve it, or at least analyse it quite effectively.

Now, it turns out that the 7D objects we are looking for minimize a kind of area or energy like a bubble. This is not so surprising since these objects are supposed to come from physics, and we know that physical objects try to reach the state of least energy if they can. So, when starting from some (not quite random) 7D blob, we can write down a kind of heat equation, as devised by mathematician Robert Bryant of Duke University, North Carolina, US. When we solve this, it should hopefully lead us to the G_2 geometry we are looking for (see main article), just like a soap bubble blob eventually becomes a sphere.

As I warned you before, the soap bubble can pop, and this is a real problem for our 7D equation, where the blob may well burst before we can reach the answer we want.

However, I have been able to show that sometimes it does work and finds the 7D spaces we want.

The seven extra dimensions can be studied completely separately from the four dimensions we are familiar with from space–time, before being later combined in the full 11D M-theory. Although we cannot say what the seven extra dimensions are, they are not completely arbitrary. In fact, they are very special, satisfying equations similar to those appearing in general relativity, which makes sense because they are supposed to help us describe gravity.

The key to why 7D geometry is interesting in mathematics and physics is symmetry

What is really fascinating is that the simplest case of these equations also appears in geometry and is a key equation that mathematicians have long been studying and continue to explore. Some of the best mathematicians study this geometry, including three Fields Medallists: Michael Atiyah, as well as Simon Donaldson and Witten. This is something I have also been working on, taking inspiration from physics (see “Inspired by bubbles” box above).

The key to why 7D geometry is interesting in mathematics and physics is symmetry. We know that objects like cubes and spheres have lots of symmetry, in that they look the same from many (and sometimes all) angles, whereas other shapes such as oblongs and rugby balls have less symmetry. A crucial mathematical fact is that the types of symmetries that can occur for various geometric objects depends very much on how many dimensions we are working in. Even more important is that there is a special type of symmetry that can occur only in seven dimensions. This symmetry leads to so-called G_2 geometry in seven dimensions, and it is this geometry that plays a major role both in modern mathematics and in M-theory.

Progress through collaboration

Theory is all well and good, but can we link any of this M-theory stuff to experiments? Well, yes we can. I have been discussing research with King’s College London physicist Bobby Acharya, who has worked with Witten on

studying fermions in M-theory and is currently focused on trying to link the theory to observations in cosmology as well as experiments at CERN's Large Hadron Collider.

One of the most exciting recent discoveries in particle physics has been the Higgs boson, but why does it have the mass we observed? This is a question that M-theorists hope to answer. As we get more information from space telescopes, and powerful ground-based telescopes too, we learn more about black holes, the acceleration of the universe and the rotation of galaxies. As a consequence, we get more observations that help us to understand dark matter and dark energy, and their effects. With these insights, it is hoped that one can use M-theory to give a satisfying explanation of these phenomena, which currently cannot be explained well by general relativity.

Again, in order to achieve this, we need to know a lot about the possible 7D geometries that can occur, and so I (and other mathematicians) have been talking with Acharya and other physicists such as Sergei Gukov at the California Institute of Technology, US, and James Sparks at the University of Oxford, UK, to see if we can make progress in both maths and physics through collaboration.

Although G_2 geometry plays a key role in M-theory, there is still much that we do not understand. On the mathematical side, we have a limited understanding of 7D geometry and so we need to work hard to find and analyse the kinds of objects that are needed to make M-theory work. On the physics side, we need to continue to strive to connect M-theory to concrete observations so it can be tested, and we need to pin down precisely the 7D geometry that forms the extra dimensions in M-theory. These are certainly difficult problems, but there has been a recent upsurge in activity in this area so it is an exciting time in the field, on both the maths and the physics side. I am hopeful that soon, by having mathematicians and physicists working together, we will have major breakthroughs that will shed light on 7D geometry and bring us a step closer to that elusive unified theory of physics.

Cosmological Evidence Emerges That Dark Energy Is An Illusion

Back in 1998, astronomers made a curious discovery. By studying the behavior of distant supernovas, they concluded that the universe is not just expanding, but that this expansion is accelerating. The cosmos, they concluded, is exploding.

The discovery rocked cosmology. It implied that the universe would probably experience a long cold death as its components raced inexorably away from each other. It also raised the question of what was causing this acceleration. Cosmologists eventually decided that the expansion was being driven by a force they called dark energy and began to develop a cosmological model that could account for it, called the Lambda-Cold Dark Matter (ΛCDM) model.

The story reached a climax in 2011 when the astronomers behind the discovery were awarded the Nobel Prize for physics. But important questions remain and understanding this enigmatic phenomenon has since been a central challenge for modern cosmology.

Dark Illusion

Now the puzzle may finally be drawing to a close thanks to the work of Antonia Seifert and colleagues at the University of Canterbury in New Zealand. This group has analyzed the most recent and most comprehensive observations of type-Ia supernovas and say the evidence is consistent with a model of the universe that isn't exploding after all. In other words, dark energy is merely an illusion.

"These results provide evidence for a need to revisit the foundations of theoretical and observational cosmology," say the team.

At the heart of this debate is the distinction between the Friedmann-Lemaître-Robertson-Walker model and a different model called "timescape" cosmology put forward by David Wiltshire and others in 2007 (Wiltshire is one of the authors of the new paper).

The Friedmann et al model assumes the universe is homogeneous on the largest scales so that light propagates evenly in all directions. But various theorists have

pointed out that the universe is far from homogeneous and instead peppered with high density galaxies and giant voids that form into giant filamentary-type structures on an even larger scale.

Galaxies are well known to bend and distort light waves, and some cosmologists say the voids must do as well and have developed the mathematical tools to study how this might make the universe look to observers on Earth.

Wiltshire's contribution is a model based on this thinking called timescape cosmology that explores how the variations in gravitational forces across the universe can make time slow down for light waves. The effect is to make type-Ia supernovas look further away than expected and so appear to be moving faster. All this, he said, would create the illusion that the universe was exploding when, in actuality, the expansion of the universe might be slowing. Crucially, this perspective eliminates the need for dark energy.

Of course, the ultimate test for cosmological theories is whether they are backed by observational evidence. So to test the timescape hypothesis, Seifert, Wiltshire, and co-conducted a model-independent analysis of the most extensive compilation of type-Ia supernovae observations to date, called the Pantheon+ dataset.

Type-Ia supernovae are crucial here because they have a consistent intrinsic brightness that allows astronomers to determine their distance accurately.

Seifert and co compared the predictions of the ΛCDM model and the timescape model. The analysis revealed strong evidence favoring the timescape model. Notably, the Bayes factor - a statistical metric used to compare models - indicated a decisive preference for the timescape cosmology over ΛCDM. "When considering the entire Pantheon+ sample, we find very strong evidence in favor of timescape over ΛCDM," say Seifert and co.

Nuanced Theory

Of course, other groups will need to validate and repeat these findings. But if validated, the implications are profound. Dark energy, the distinct force driving the universe's acceleration, would be rendered unnecessary. Instead, the

observed effects would stem from a nuanced understanding of general relativity applied to a clumpy, inhomogeneous universe.

That means cosmologists will need to revise the ΛCDM model, which has been the cornerstone of modern cosmology for decades. The ΛCDM model incorporates dark energy using the cosmological constant, Λ, but it also attempts to account for the powerful gravitational effects thought to be generated by cold dark matter, even though they have yet to observe dark matter directly. If dark energy is indeed an illusion, cosmologists will have to revisit this paradigm.

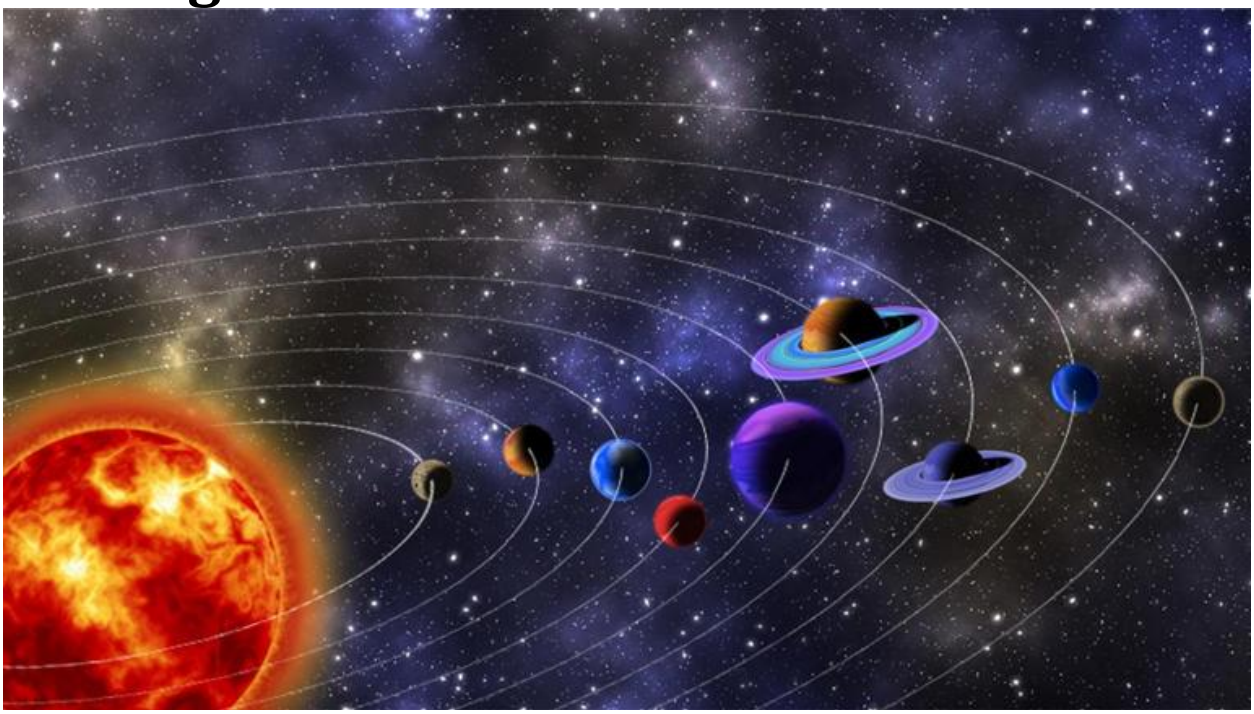
That will be a relief for physicists who have long pondered how the universe can create so much energy - dark or otherwise- seemingly from nowhere.

The paper by Seifert and co is by no means the last word. But they emphasize that their results are a compelling case for reevaluating the foundations of theoretical and observational cosmology. "Our results imply profound consequences for cosmology and astrophysics," say Seifert and co. Whether dark energy will ultimately remain a cornerstone of cosmology or fade into history as an illusion of perception remains to be seen, but either way, the journey ahead looks exciting.

Ref: Supernovae evidence for foundational change to cosmological models: arxiv.org/abs/2412.15143

THIS TOPIC NEEDS MUCH MORE EMPIRICAL DATA TO BE CONFIRMED AS TRUE. THE DEBATE GOES ON.

Why is everything in space always moving?



Nothing in our universe stands still: Earth orbits the sun, the sun circles the galaxy, and even galaxies are constantly on the move. So why is everything in space in motion?

It all comes down to how the universe and the objects within it were made, Edward Gomez, an astrophysicist and the education director at Las Cumbres Observatory, told Live Science. Scientists think the universe began with the Big Bang, a superfast expansion from an infinitely dense single point that eventually led to the formation of everything we see today.

"From the very beginning of the universe, it started expanding outwards because the force of the Big Bang caused everything to move apart," Gomez said.

"It's sort of the imprint of the beginning," said Carol Christian, an astrophysicist and outreach project scientist for the Hubble Space Telescope at the Space Telescope Science Institute in Baltimore. "The beginning was movement, and so movement has been built into the universe from the very beginning."

Related: Does the universe rotate?

So one reason everything in space is in motion is because the universe is expanding. But that expansion has effects only on very large scales. "We only see it really happening on things that are very far apart or far away, because it's not necessarily that these objects are moving through space," Gomez said. "It's that the space in between objects is getting bigger."

On smaller scales, though, rotation is the movement that rules objects in space. "This spinning thing is kind of endemic in the universe, too," Christian told Live Science. "There isn't anything that doesn't rotate."

That's due to angular momentum: When two objects in space move close together, their mutual gravity pulls them toward each other, and if they don't collide or fly in different directions, they tend to orbit each other. This phenomenon affects everything, from the smallest mineral grains to the largest galaxies.

"The solar system was made like a pizza is made … If you're making an Italian pizza, you throw the pizza dough up, and as you spin it, it flattens out into a disc," Gomez said. "And that's fundamentally how our solar system is made: This thing called angular momentum, that spinning effect stretches things out into a disc."

That's why the planets in the solar system orbit the sun: The solar system began as a spinning mass of gas and dust that eventually coalesced into a star and planets. Along the way, angular momentum ensured it never stopped spinning.

But a galaxy's spinning effect happens differently than you'd expect from just the stuff we can see.

"It spins as if it were like a pizza base, as if it was solid instead of being made up of individual components, stars," Gomez said. "It should be that the [stars] further out should be going slower than the ones in the center. But actually, you don't see that … and that's one of the first indicators that the universe had something crazy that you can't see that we now call dark matter."

Dark matter doesn't interact with light, so we can't see it with telescopes. However, it does have mass and interacts with other objects that have mass through gravitational effects. Dark matter also experiences angular momentum. It's another reason everything in space is moving.

In the end, motion is a fundamental ingredient in the universe. It "shows that the universe is alive — not in a sense of being conscious, but you know, things are happening — chemical reactions, physical reactions are happening, and that requires energy," Gomez said. "And the most basic form of energy is motion."

The **observable universe** is estimated to be around **93 billion light-years in diameter**[1]. Compared to this vastness, **human beings are incredibly small**, less than 1/5,000,000 of the scale of Earth, which itself is just a tiny speck in the cosmic ocean[2]. An interactive map reveals the true size of the cosmos[3]. An image of over 1,500 galaxies shows a tiny sliver of the universe[45].

Wednesday, Jan 1st 2025

How big is the universe? Mind-boggling interactive map reveals the sheer scale of objects across the cosmos - with more Suns than grains of sand on Earth

- **This interactive map lets you explore the true scale of the observable universe**
- **Our Sun is only one of 70 septillions stars spread out through the cosmos**

Sometimes even being in a big city can be enough to make you feel small.

But looking up into the empty vastness of space, the sheer size of the universe is almost impossible to comprehend.

This incredible interactive graphic lets you explore the sheer scale of our universe, and get some appreciation for our small place within it.

The video player is currently playing an ad.

As we zoom out from our human perspective we see that the city that once seemed so overwhelming is only a tiny smudge on an insignificant rock amidst billions of others like it.

And, at the scale of the Universe, we can see that the number of stars like our own is greater than all the grains of sand on Earth.

Our Universe in numbers

10 million superclusters

- There are more superclusters in the universe than there are people living in London and Birmingham combined

2 trillion galaxies

- At its maximum flow 100,000 cubic feet of water flows over Niagra Falls every second. If every galaxy were shrunk down to one foot they would take 115 days to all flow over the falls.

40 quintillion black holes

- If every black hole in the Universe were shrunk down to the size of a single human hair and stacked up, the resulting would still be 0.25 light-years long.

70 septillion stars

- There are more stars than there are grains of sand on all the beaches of the world.

10 to the 25th power planets orbiting stars

- This number is so absurdly big that if every planet in the Universe were a carbon atom, stretched out in a single line this would stretch from the Sun to Neptune and back more than 50 times.

The interactive map is titled 'Scale of the Universe' and was created by computer scientist Cary Huang.
To see just how small we are compared to the world around us, simply scroll out and watch as familiar landmarks vanish into insignificance.

Or, to explore the world at the microscopic scale, zoom in to see everything from bacteria right down to the fundamental particles that make up the universe.

To move faster, use the slider at the bottom (or side on mobile) to zoom in and out to smaller or larger objects.

To learn more about any object you see, tap or click on any of the images which will bring up a fact box with extra information.

You can also keep selecting smaller or larger objects to zoom in and out.

As we move outwards from the size of a human, it is surprising just how fast we appear to be vanishingly small.

Even compared to objects on Earth like the Great Pyramid of Giza, humans start to appear tiny.

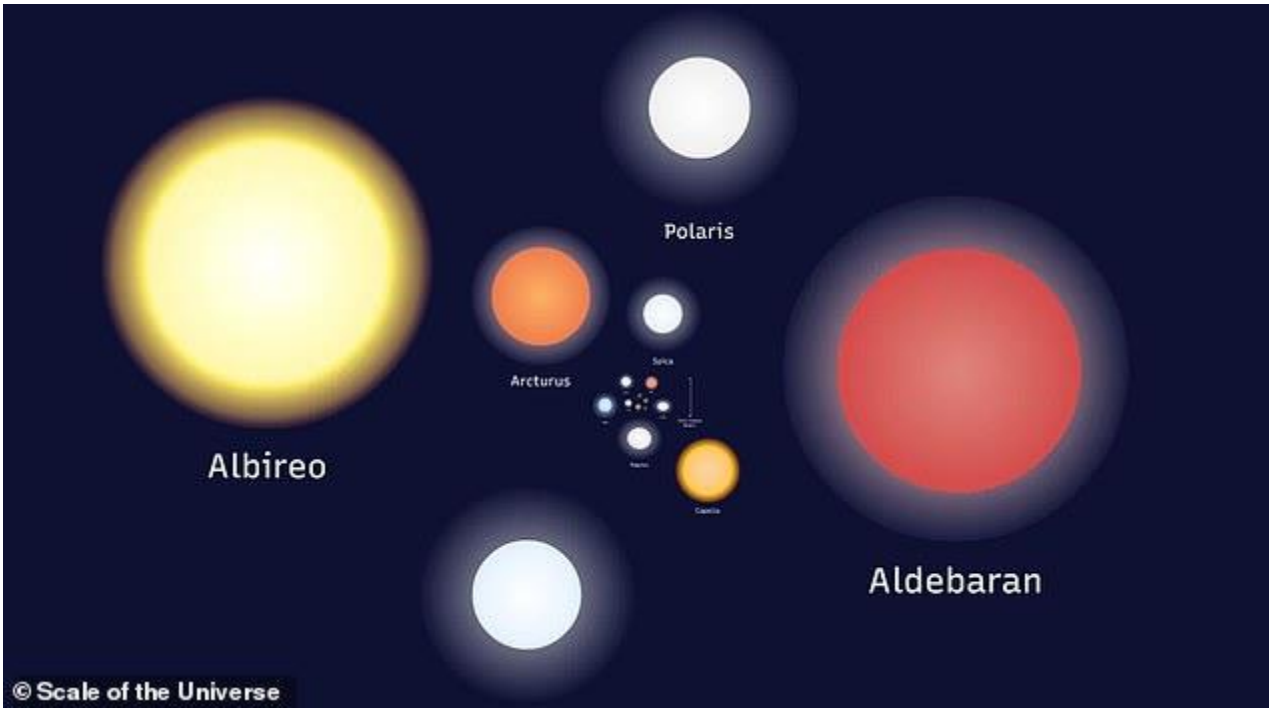
But as we reach the scale of planets and moons, thinking in terms of human sizes starts to become tricky.

Professor Rob Crittenden, a cosmologist from the University of Plymouth, is an expert in the formation of the Universe and studies some of the biggest structures possible.

He told MailOnline that even he struggles to wrap his head around the vastness of the Universe.

He said: 'Comprehending such massive scales is difficult, and probably depends on the individual.

'I can work out from a human scale and try to picture larger and larger things; that provides some intuition, but my understanding in the end is mostly mathematical.'



Our Sun might seem vast, but it is not even one of the largest stars. Aldebaran, for example, is 44 times larger than our star

How many stars are out there?

Our Solar System revolves around one star, the Sun.

But, the Sun is only one of between 100 and 400 billion stars in the Milky Way.

This is only one of more than 100 galaxies in the Virgo Supercluster which, itself only one part of even larger structures.

It is estimated that there could be between 100-200 billion and two trillion galaxies in the Universe.

Overall, scientists estimate that there could be around 70 septilion stars in the Universe.

That's 70 followed by 23 zeros.

But even turning to numbers starts to become baffling quickly, and to see why we only need to think about our solar system.

The Earth is a ball of rock and water 7,917 miles (2,742 km) in diameter.

While that might sound pretty big, as we zoom out into the solar system it is quickly clear just how small that really is.

Diagrams of the solar system generally show the planets neatly aligned and fairly close to one another.

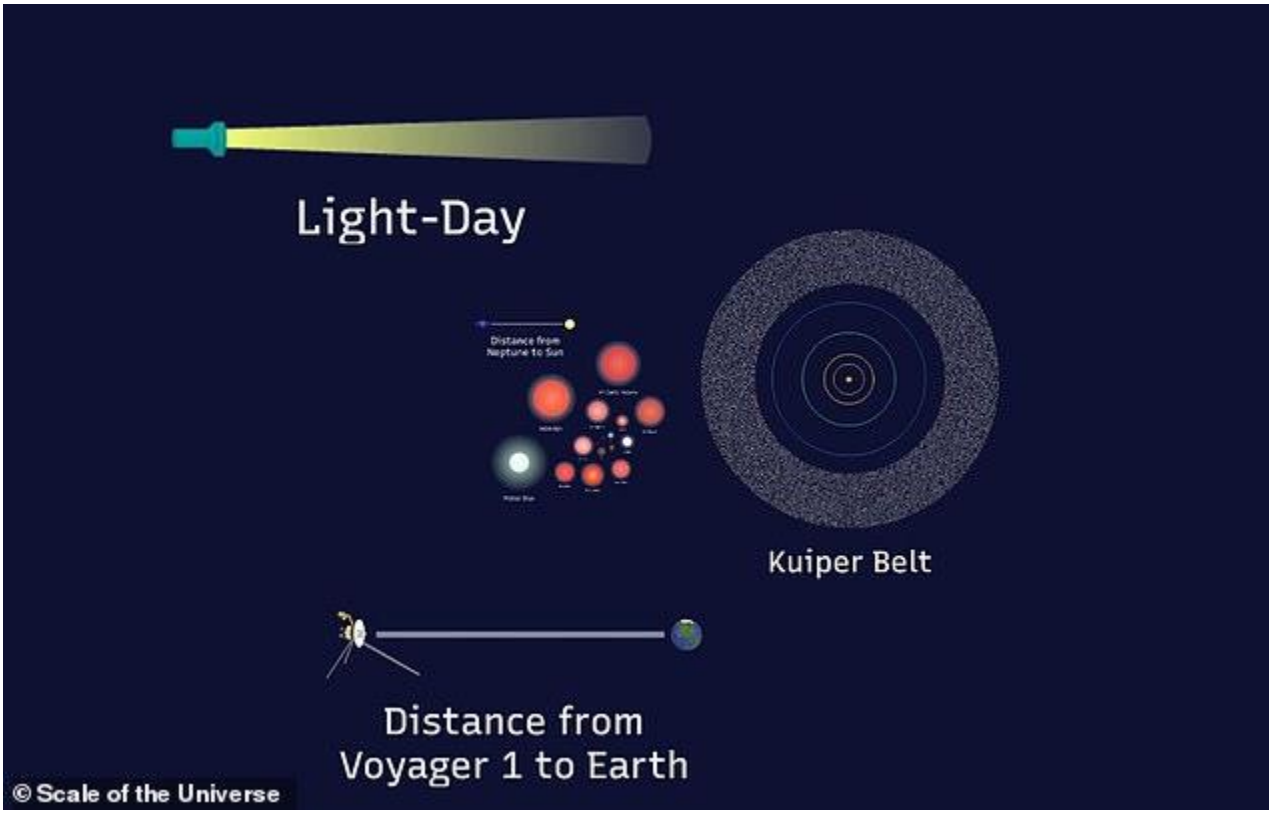
But the planets are only shown this way because showing their true distances is impossible in most formats.

Even the moon, which seems so close, is actually 238,855 miles (384,400 km) from Earth - more than 140 times further than the Earth's diameter.

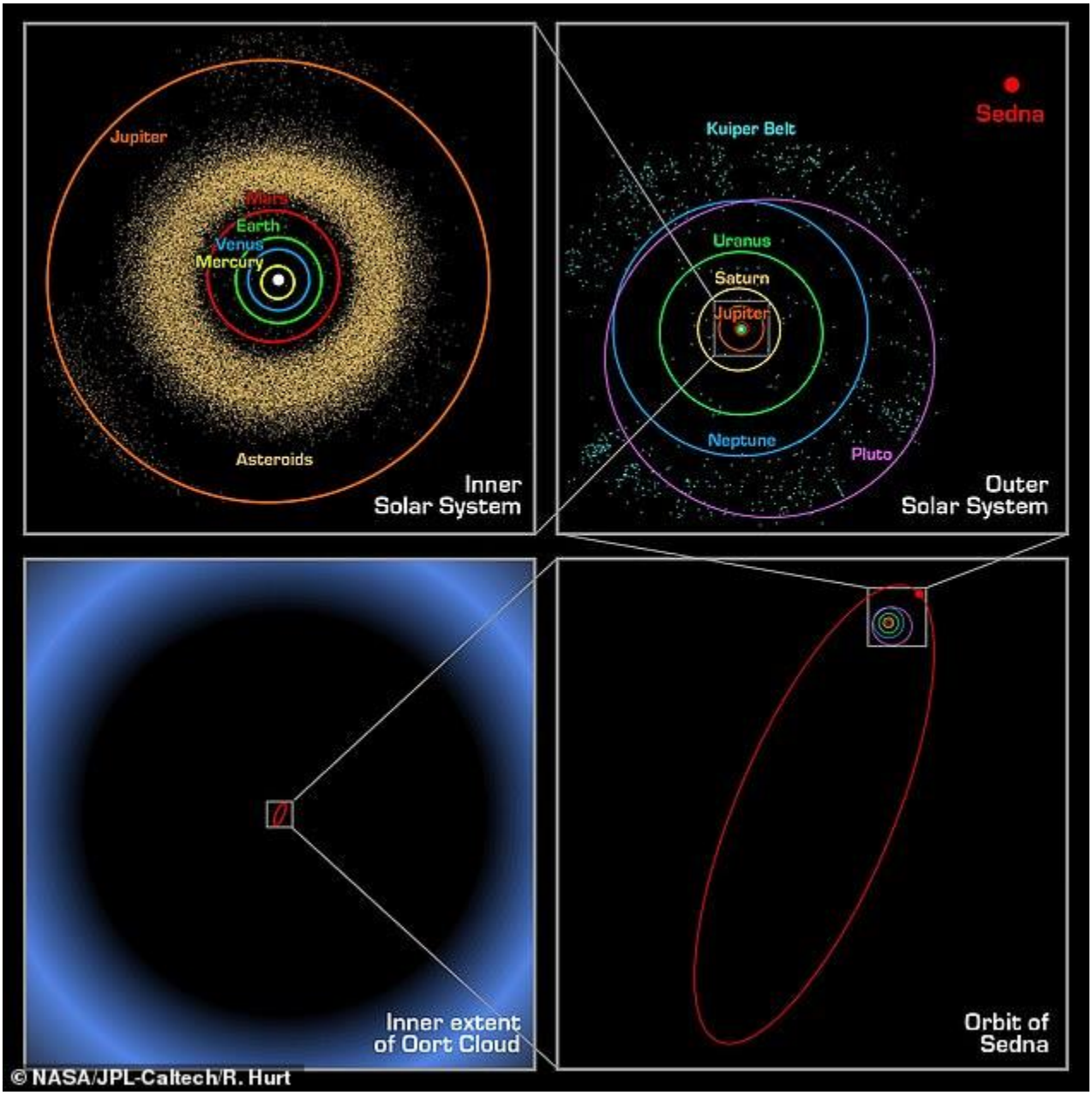
The distance of the Earth from the Sun meanwhile is a massive 93 million miles (150 million km).

Neptune, the last planet in the solar system, is an average of 2.8 billion miles (4.5 billion km) from the Sun, a distance so vast that light takes four hours to travel it.

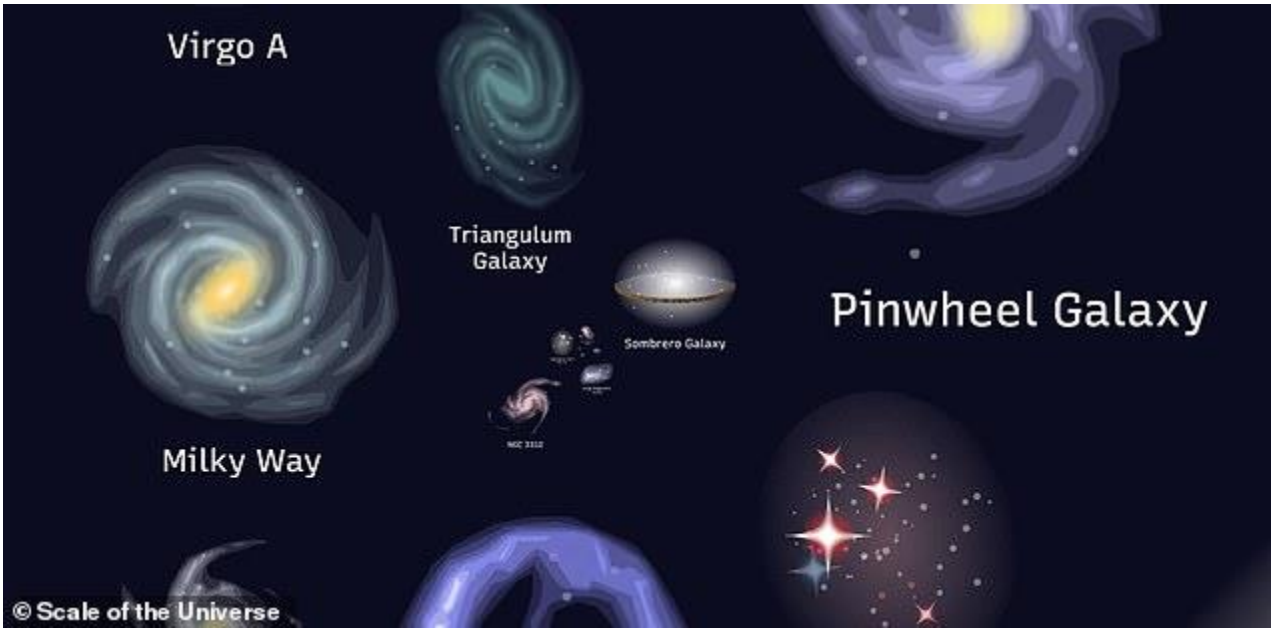
But, keep zooming out and even our solar system starts to feel quite small as we see that our sun is just a tiny part of the Milky Way Galaxy.



Zooming out further we need to start looking at things in terms of distance travelled by light. For example, Voyager has travelled a little less than one light day from Earth



This diagram attempts to show the true distance between the objects in our solar system. When we zoom out to the Oort Cloud at the edge of the Solar System the inner planets almost vanish



If our sun were the size of a penny the the Milky Way would be 7.5 million miles across, more than 30 times the distance from Earth to the Moon

Where could aliens be hiding?

Based on what we know from Earth, for a planet to support life it needs to be the right distance from its star to keep some water liquid.

In the Milky Way, NASA estimates that there are 300 million potentially habitable planets by the most conservative estimate.

In the universe at large, it is estimated that there could be as many as ten thousand billion billion.

Even if there is a very low chance of intelligent life emerging on any of these planets, the staggeringly high numbers make it very likely that at least some intelligent life is out there.

However, the odds of any life emerging at the same time as our civilisation and being close enough to reach us is extremely low.

This difference is often called the Fermi Paradox.

Professor Crittenden said: 'Within the Milky Way galaxy, our solar system is some distance from the centre, in an outer arm.'

To measure the Milky Way itself we can no longer use miles and kilometres but must start thinking in terms of light-years.

This is the distance light travels in one Earth year, which is 5.88 trillion miles (9.46 trillion kilometers).

The Milky Way itself is 100,000 light-years across, while the Sun is about 25,000 light-years from its centre.

If it helps your imagination, look at a penny and pretend that our sun is the size of that little coin.

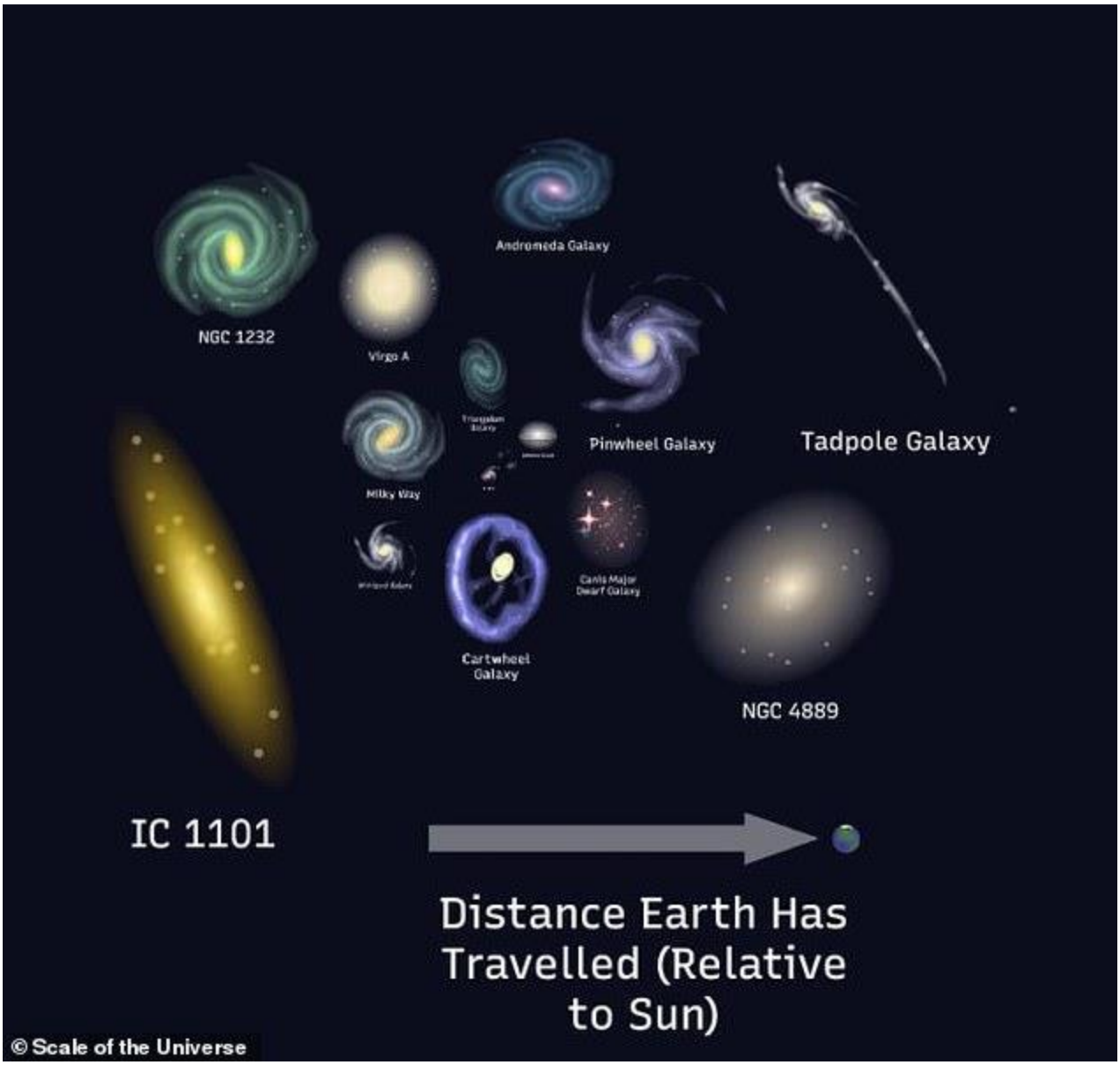
On this scale, the nearest star to the Sun, Alpha Centauri, would be 350 miles away.

The Milky Way, meanwhile, would be more than 7.5 million miles across; that's more than 30 times the distance from the Earth to the moon.

But the Sun is only one between 100 and 400 billion stars within the Milky Way.

To try and get a handle on that number, if you stacked up 100 billion dollar bills on Earth the resulting tower would stretch into space 28 times higher than the orbit of the International Space Station.

Zoom out even further still and you will soon find that even our Galaxy starts to look pretty small at the cosmic scale.



Our solar system is only of between 100 and 400 billion in the Milky Way galaxy (middle left). The Milky Way itself is 100,000 light-years in diameter

Professor Crittenden said: 'Galaxies either live on their own, in smaller structures known as groups, or in larger associations called galaxy clusters.'

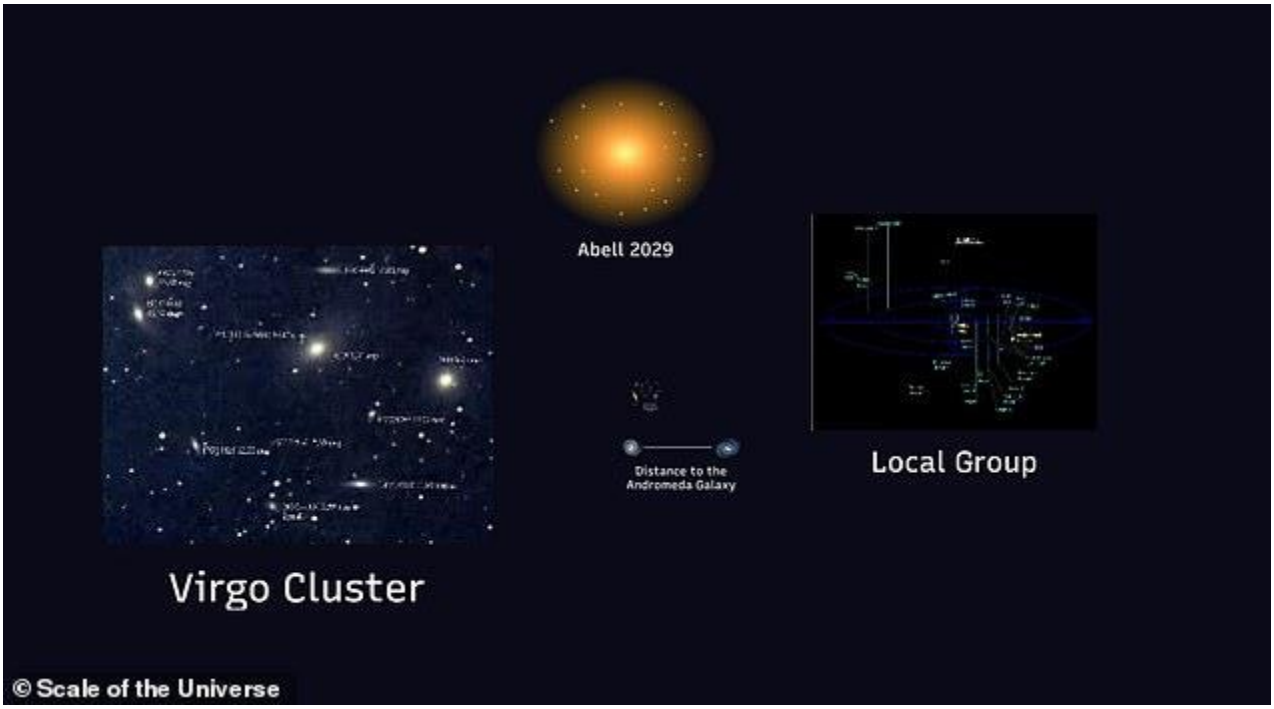
Due to the pull of gravity, structures like galaxies tend to be drawn together into tighter blobs of matter.

The Milky Way is one of about 30 galaxies in the Local Group, a cluster of galaxies spread over about 10 million light-years.

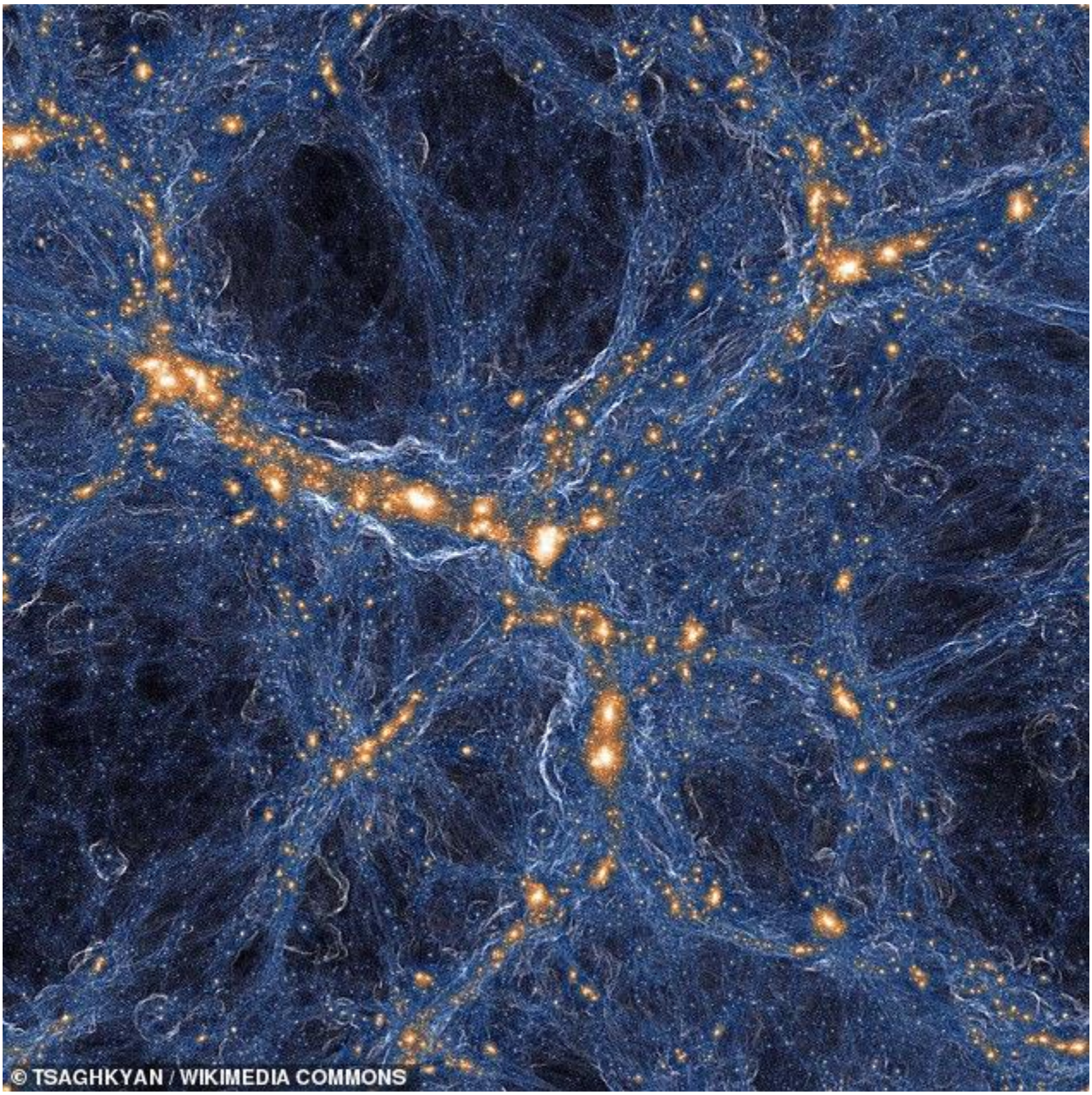
The Local Group includes our largest galactic neighbour, the Andromeda Galaxy which is 2.537 million light-years away.

That is so far that the light that is now reaching us from Andromeda started its journey to our eyes more than two million years ago.

This means when we look at Andromeda, we are actually looking back into the distant past.



The Milky Way is one part of the Local Group (right), a cluster of galaxies spread over 10 million light-years. But this is only one part of the Virgo Supercluster which is more than 110 million light-years across



This visualisation of the Laniakea filament or supercluster shows the arrangement of more than 100,000 galaxies over hundreds of thousands of light-years. Our own Galaxy is within this superstructure

What galaxies are in our Local Group?

Our local group is a cluster of about 30 galaxies.The four largest are:

- The Milky Way
- The Andromeda Galaxy
- The Triangulum Galaxy
- The Large Magellanic Cloud

The group also contains a number of other dwarf galaxies and star clusters but these are mainly satellites of the main galaxies.

Finally, as we pull out even further, we begin to see the largest structures in the universe revealing themselves.

At this scale, we can see that our local group is just a small neighbourhood on the outskirts of a massive structure called the Virgo Supercluster which is more than 110 million light-years across.

However, Virgo is just one of about 10 million superclusters in the universe.

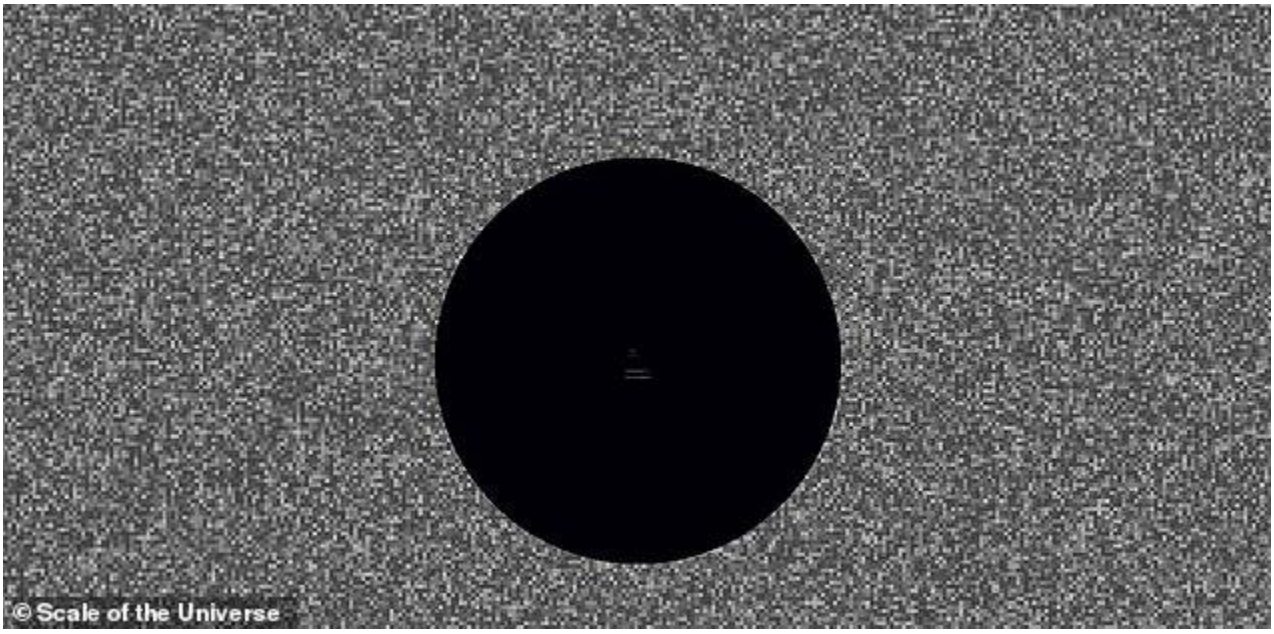
At the cosmic scale, these superclusters clump together alongside individual galaxies to form sheets and walls of matter called filaments.

These are impossibly vast structures, each of which contains hundreds of thousands of galaxies, themselves made up of hundreds of billions of stars; around one of which is orbiting the small rock upon which you are living.

Our own filament, named Laniakea, is more than 500 million light-years across.

But the Universe is even vaster still.

Professor Crittenden explains that while the Universe is infinitely large there is a finite limit to what we can observe or what astronomers call a 'horizon'.



Zooming out all the way on the interactive map brings you to the edge of the observable universe. We can only see as far as light has had time to travel, making the limits of the known universe 46.508 billion light-years across

How big is the Universe?

We don't actually know how big the Universe is or could be.

Because the speed of light is limited we can only see as far as light has had time to travel.

This means that the observable Universe has a Horizon.

This Horizon is 46.508 billion light-years across.

All we know is that the Universe is bigger than this, but there are no signs that it is even finite.

He said: 'The region of the Universe that we can observe is limited to our neighbourhood where light signals could have reached us in the finite age of the Universe.

'The full Universe must be larger than this horizon, and we haven't seen any indications that the Universe is finite; all we really know is that it is bigger than the part of it that we can see.'

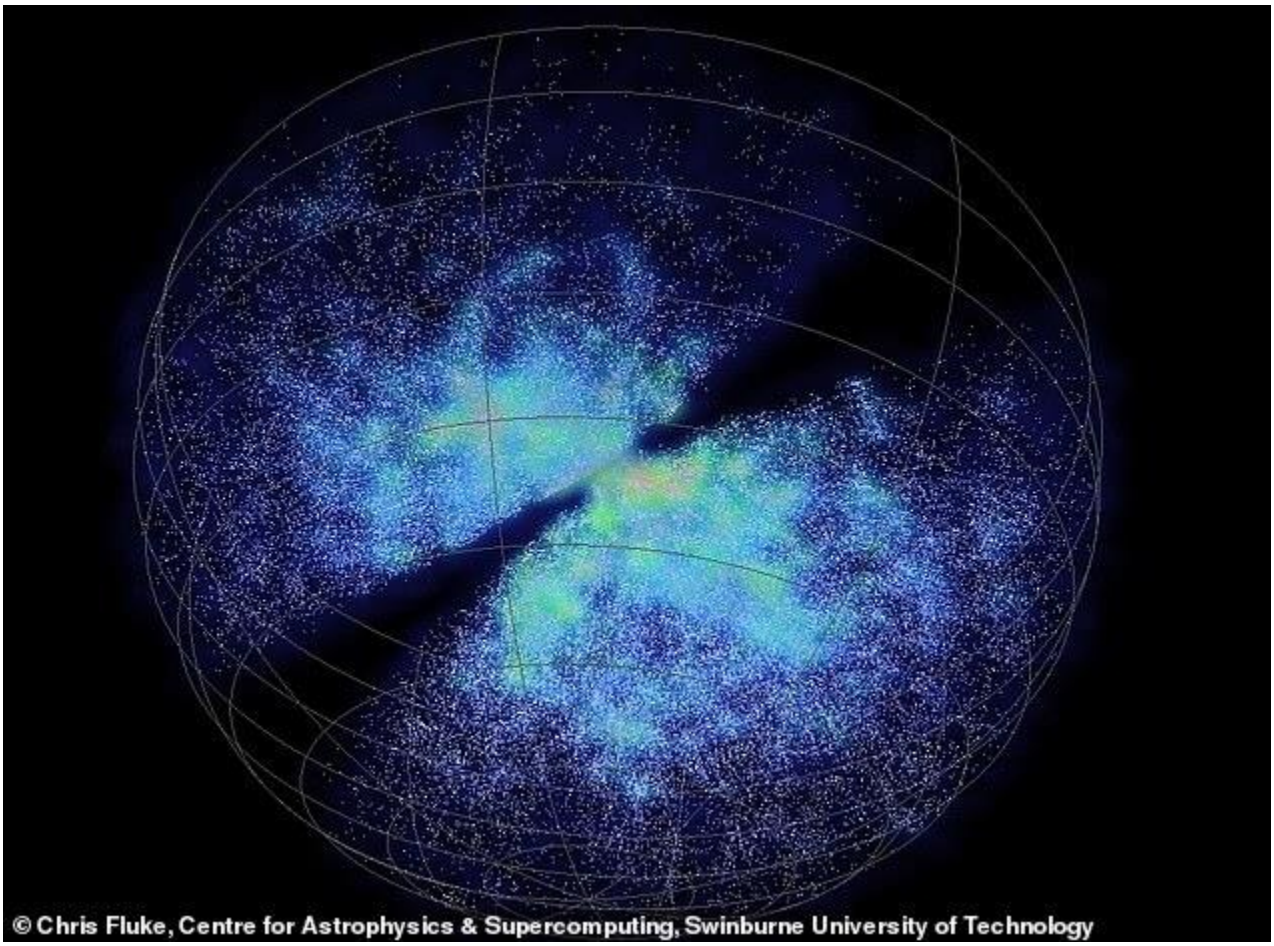
The most distant thing that we can see is something called the Cosmic Microwave Background Radiation (CMBR).

'When the Universe was young, it was incredibly hot, and there were all kinds of particles bouncing off each other, moving very quickly,' Professor Crittenden explains.

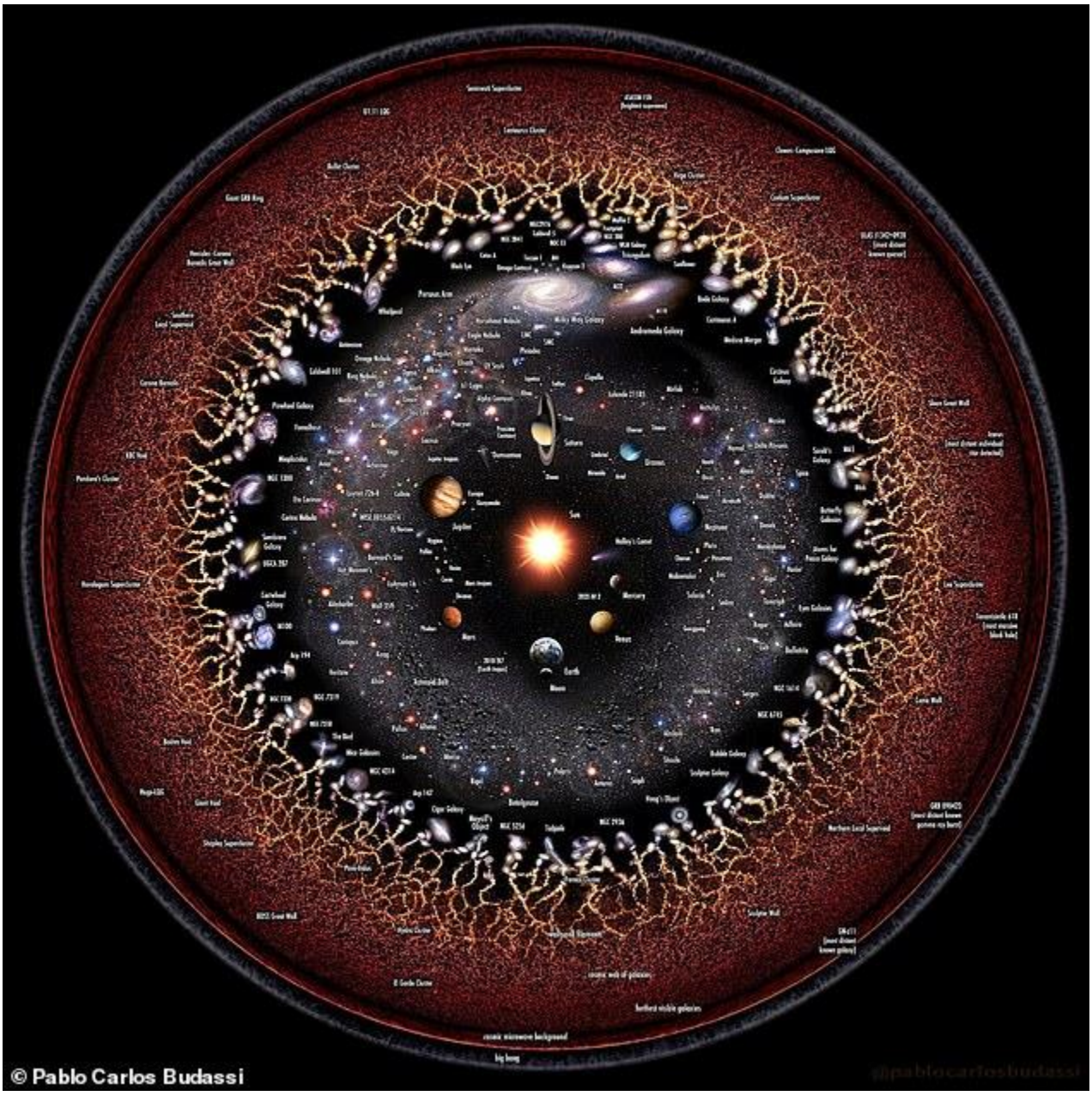
As these particles cooled they eventually settled to 2.7 degrees Kelvin and the tiny amounts of radiation it produces gives us the final limit to what we can see.

This means that the observable universe is estimated to be 46.508 billion light-years across.

At this point, we are now dealing with numbers that are so absurdly large that they cease to lose any real meaning.



This diagram is the biggest map we have showing the distribution of galaxies within the Universe. It gets its unusual shape because the centre of the Milky Way blocks a section of the Universe from Earth



This artist's impression shows the universe on a logarithmic scale, which means that distances are shown on an exponentially smaller scale as it moves outwards. With this representation, you are able to see the whole universe from our Sun right out to the honeycomb structure of superclusters

The size of the Universe in numbers

Diameter of Earth - 7,917 miles (2,742 km)

Distance from Earth to the Sun - 93 million miles (150 million km)

Diameter of the Solar System (to the Oort Cloud) - 18.6 trillion miles (30 trillion km)

Diameter of the Milky Way - 100,000 light-years

Size of the Local Group of Galaxies - 10 million light-years

Size of the Virgo Supercluster - 110 million light-years

Size of the Observable Universe - 46.508 billion light-years

Having started with the size of a single human being, the universe is on a scale that makes even our own Galaxy fade into nothingness.

But, it is also important to remember that by looking down rather than up, our own planet can seem impossibly vast as well.

Imagine you are sitting on a beach at night; if you look up into the sky, even on a clear night you may only a few thousand stars; that's about as many as there are grains of sand in a handful taken from the beach.

In fact, each cubic meter of sand contains 9 billion grains of sand meaning that there are, very roughly, 7.5 quintillion grains of sand on all the beaches of the world; that's 75 followed by 17 zeros.

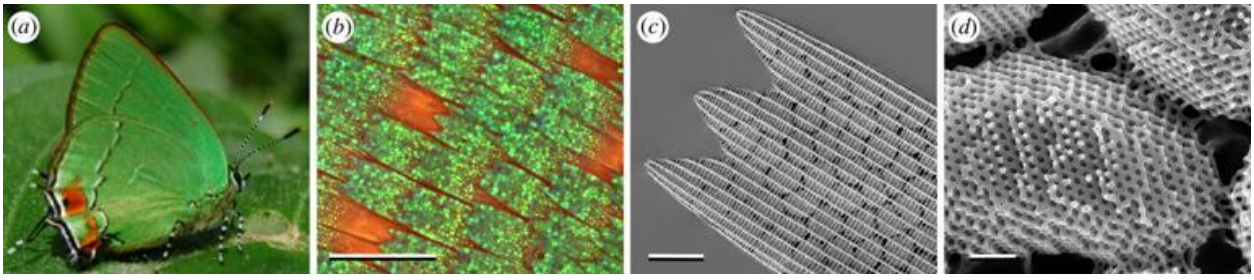
If you remember, there were only between 100 and 400 billion stars in the Milky Way.

However, the Universe itself is believed to contain an estimated 70 septillion stars, that's 7 followed by 23 zeros - or 70 thousand million, million, million stars in the observable universe.

But before you start to get lost in the vastness of space, imagine dipping your hand in the sea and letting ten drops fall.

In those ten drops of water alone there were more molecules of water than there are stars in the observable universe.

Hyperspectral microscopy reveals the nanostructures that give butterflies their colors



The green wings of Erora opisena originate from wing scales containing photonic gyroid nanostructures. Credit: Journal of The Royal Society Interface (2024). DOI: 10.1098/rsif.2024.0185

Scientists have found a new way to see how butterflies develop their colors.

Butterflies use color for a number of important functions, including as signals for mate-choice or to ward off predators.

Dr. Annie Jessop, a post-doctoral fellow from Murdoch University's School of Mathematics, Statistics, Chemistry and Physics led the revealing new research.

She said that butterflies and many other insects use tiny structures to create colors rather than pigments, but there were mysteries surrounding them.

The article "Elucidating nanostructural organisation and photonic properties of butterfly wing scales using hyperspectral microscopy" is published in the *Journal of the Royal Society Interface*.

"Butterflies, and many other insects use nanostructures to generate color, a phenomenon known as structural color," Dr. Jessop said.

"While we have lots of knowledge about how color is produced from these structures, we have much less knowledge about how these structures develop in biological systems.

"Our study set out to develop a method that would allow scientists to measure the color that these structures produce throughout development.

"This would then allow us to infer certain structural details at different time points, like the size of the structures.

"Our research successfully demonstrated that the method proposed, hyperspectral microscopy, has the appropriate spatial, temporal, and spectral resolution to do this and could reveal the development of optical nanostructures in living biological systems."

Hyperspectral microscopy is a microscopy technique that provides spectral data for each image pixel and that can record in many hundreds of color channels, depending on setup.

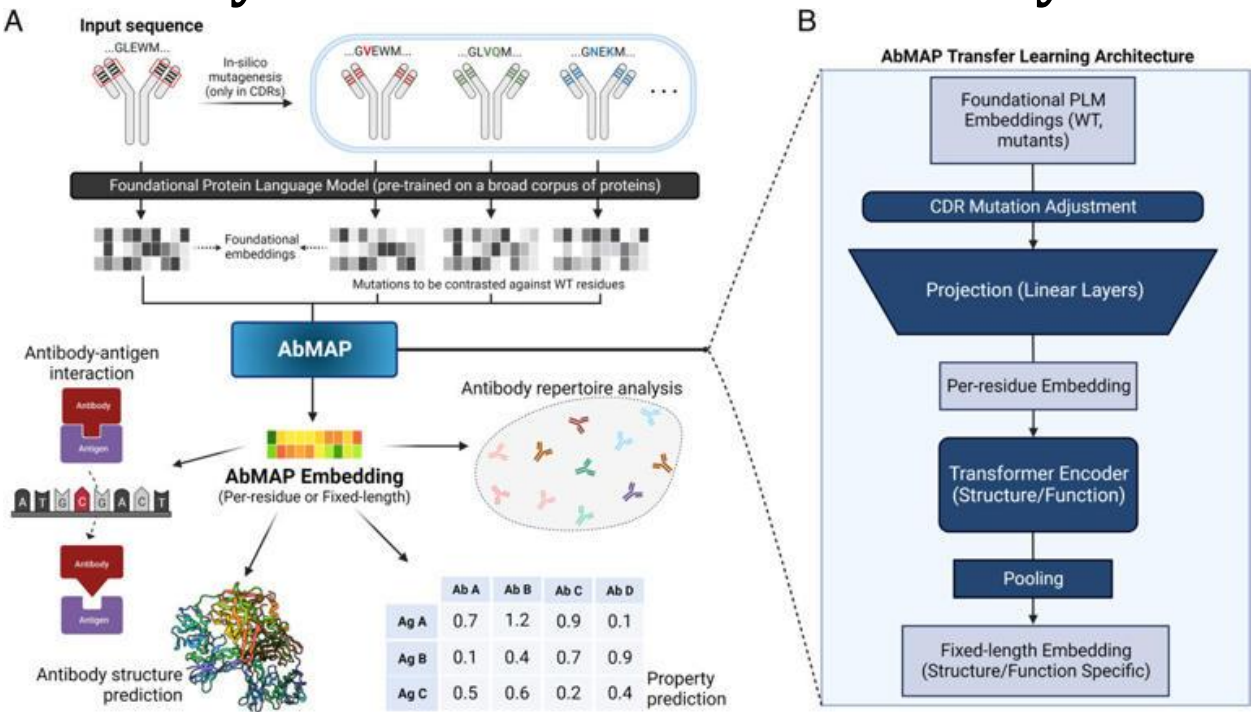
This differs from conventional light microscopy that only records in three color channels (red, blue, and green) and from multispectral imaging that records in three to fifteen color channels.

"The microscope can measure the colors the structures produce over time, helping us to understand for the first time, how these tiny structures develop in living butterflies," Dr. Jessop said.

More information: Anna-Lee Jessop et al, Elucidating nanostructural organization and photonic properties of butterfly wing scales using hyperspectral microscopy, *Journal of The Royal Society Interface* (2024). DOI: 10.1098/rsif.2024.0185

Provided by Murdoch University

New computational model can predict antibody structures more accurately



Overview of AbMAP embedding generation and its architecture. (A) Given an input antibody sequence, our pipeline generates an embedding that can be applied to various downstream tasks including structure/property prediction as well as antibody repertoire analysis. (B) The AbMAP pipeline starts with in silico mutagenesis focused on the CDRs of the input antibody sequence. These are fed into the AbMAP transformer architecture that comprises a projection module which applies contrastive augmentation, reduces the dimensionality of the input foundational PLM embedding to generate a variable length embedding, and invokes a Transformer Encoder module that creates a {structure/function}-specific fixed-length embedding. Credit: Proceedings of the National Academy of Sciences (2024). DOI: 10.1073/pnas.2418918121

By adapting artificial intelligence models known as large language models, researchers have made great progress in their ability to predict a protein's structure from its sequence. However, this approach hasn't been as successful for antibodies, in part because of the hypervariability seen in this type of protein.

To overcome that limitation, MIT researchers have developed a computational technique that allows large language models to predict antibody structures more accurately. Their work could enable researchers to sift through millions of possible antibodies to identify those that could be used to treat SARS-CoV-2 and other infectious diseases.

The findings are published in the journal *Proceedings of the National Academy of Sciences*.

"Our method allows us to scale, whereas others do not, to the point where we can actually find a few needles in the haystack," says Bonnie Berger, the Simons Professor of Mathematics, the head of the Computation and Biology group in MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL), and one of the senior authors of the new study. "If we could help to stop drug companies from going into clinical trials with the wrong thing, it would really save a lot of money."

The technique, which focuses on modeling the hypervariable regions of antibodies, also holds potential for analyzing entire antibody repertoires from individual people. This could be useful for studying the immune response of people who are super-responders to diseases such as HIV, to help figure out why their antibodies fend off the virus so effectively.

Bryan Bryson, an associate professor of biological engineering at MIT and a member of the Ragon Institute of MGH, MIT, and Harvard, is also a senior author of the paper. Rohit Singh, a former CSAIL research scientist who is now an assistant professor of biostatistics and bioinformatics and cell biology at Duke University, and recent graduate Chiho Im are the lead authors of the paper. Researchers from Sanofi and ETH Zurich also contributed to the research.

Modeling hypervariability

Proteins consist of long chains of amino acids, which can fold into an enormous number of possible structures. In recent years, predicting these structures has become much easier to do, using artificial intelligence programs such as AlphaFold.

Many of these programs, such as ESMFold and OmegaFold, are based on large language models, which were originally developed to analyze vast amounts of text, allowing them to learn to predict the next word in a sequence. This same approach can work for protein sequences—by learning which protein structures are most likely to be formed from different patterns of amino acids.

However, this technique doesn't always work on antibodies, especially on a segment of the antibody known as the hypervariable region. Antibodies usually have a Y-shaped structure, and these hypervariable regions are located in the tips of the Y, where they detect and bind to foreign proteins, also known as antigens. The bottom part of the Y provides structural support and helps antibodies to interact with immune cells.

Hypervariable regions vary in length but usually contain fewer than 40 amino acids. It has been estimated that the human immune system can produce up to 1 quintillion different antibodies by changing the sequence of these amino acids, helping to ensure that the body can respond to a huge variety of potential antigens. Those sequences aren't evolutionarily constrained the same way that other protein sequences are, so it's difficult for large language models to learn to predict their structures accurately.

"Part of the reason why language models can predict protein structure well is that evolution constrains these sequences in ways in which the model can decipher what those constraints would have meant," Singh says. "It's similar to learning the rules of grammar by looking at the context of words in a sentence, allowing you to figure out what it means."

To model those hypervariable regions, the researchers created two modules that build on existing protein language models. One of these modules was trained on hypervariable sequences from about 3,000 antibody structures found in the Protein Data Bank (PDB), allowing it to learn which sequences tend to generate similar structures. The other module was trained on data that correlates about 3,700 antibody sequences to how strongly they bind three different antigens.

The resulting computational model, known as AbMap, can predict antibody structures and binding strength based on their amino acid sequences. To demonstrate the usefulness of this model, the researchers used it to predict antibody structures that would strongly neutralize the spike protein of the SARS-CoV-2 virus.

The researchers started with a set of antibodies that had been predicted to bind to this target, then generated millions of variants by changing the hypervariable regions. Their model was able to identify antibody structures that would be the most successful, much more accurately than traditional protein-structure models based on large language models.

Then, the researchers took the additional step of clustering the antibodies into groups that had similar structures. They chose antibodies from each of these clusters to test experimentally, working with researchers at Sanofi. Those experiments found that 82% of these antibodies had better binding strength than the original antibodies that went into the model.

Identifying a variety of good candidates early in the development process could help drug companies avoid spending a lot of money on testing candidates that end up failing later on, the researchers say.

"They don't want to put all their eggs in one basket," Singh says. "They don't want to say, I'm going to take this one antibody and take it through preclinical trials, and then it turns out to be toxic. They would rather have a set of good possibilities and move all of them through, so that they have some choices if one goes wrong."

Comparing antibodies

Using this technique, researchers could also try to answer some longstanding questions about why different people respond to infection differently. For example, why do some people develop much more severe forms of COVID, and why do some people who are exposed to HIV never become infected?

Scientists have been trying to answer those questions by performing single-cell RNA sequencing of immune cells from individuals and comparing them—a process known as antibody repertoire analysis. Previous work has shown that antibody repertoires from two different people may overlap as little as 10%. However, sequencing doesn't offer as comprehensive a picture of antibody performance as structural information, because two antibodies that have different sequences may have similar structures and functions.

The new model can help to solve that problem by quickly generating structures for all of the antibodies found in an individual. In this study, the researchers showed that when structure is taken into account, there is much more overlap between individuals than the 10% seen in sequence comparisons. They now plan to further investigate how these structures may contribute to the body's overall immune response against a particular pathogen.

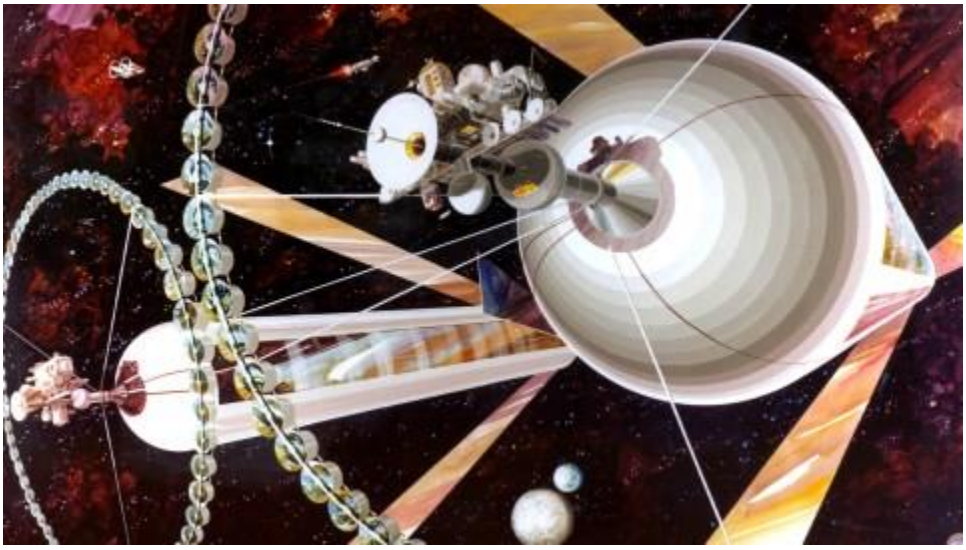
"This is where a language model fits in very beautifully because it has the scalability of sequence-based analysis, but it approaches the accuracy of structure-based analysis," Singh says.

More information: Rohit Singh et al, Learning the language of antibody hypervariability, *Proceedings of the National Academy of Sciences* (2024). DOI: 10.1073/pnas.2418918121

HARD SCIENCE —

7 Types of Advanced Cosmic Civilizations

The Kardashev Scale measures the advancement of cosmic societies.



As we go about our daily lives, it helps to step back and take a look at the bigger picture. We are living in what seems like an advanced civilization, but let's not kid ourselves – we are still technological infants.

In 1963, the Russian astrophysicist **Nikolai S. Kardashev** came up with a hypothetical way to understand just where exactly we fit in. He created what's come to be known as the **Kardashev Scale,** a method of measuring how advanced a civilization's technological achievements are based on the amount of **energy** it can harness.

As he outlined it in his influential paper "Transmission of Information by Extraterrestrial Civilizations", an advanced (probably alien) civilization would have the capacity to transmit radio signals far into the cosmos. Kardashev initially came up with 3 types of civilizations, a scale that has since been expanded in a variety of ways by others, focusing not only on communication technology but additional factors.

A **Type 1 civilization** (also known as the **planetary civilization**) has the capacity to harness all the energy of its **home planet**, utilizing all the energy that reaches the planet (like solar) and all the energy it can produce (thermal, hydro, wind, etc). Kardashev described it as having "technological level close to the level presently attained on the Earth".

Physicist Michio Kaku thinks a planetary civilization should be able to control such things as **earthquakes**, the **weather** and **volcanoes** and would be building ocean cities. If that's the case, we are not quite there yet. Kaku thinks it'll take another **100-200 or so years** for us to get to Type 1 status. Carl Sagan thought we are currently at about **0.7** of the way to type 1.

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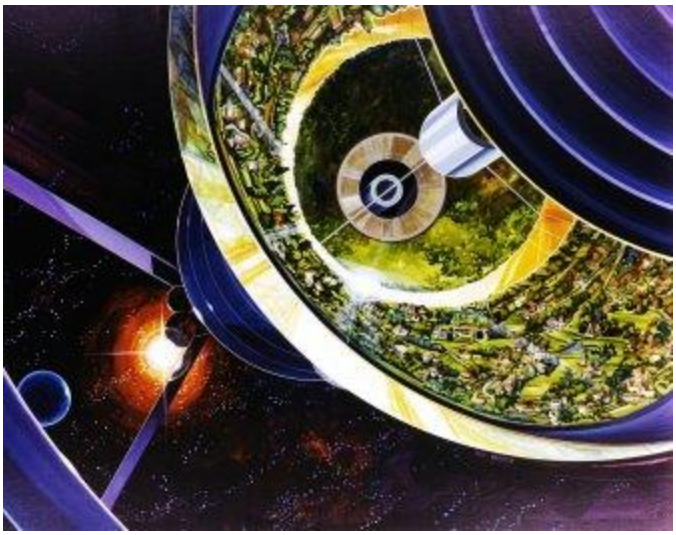
Once we get to Type 1, what's next? We are likely to leave Earth, looking to draw energy from other planets. If we can become an interplanetary civilization that can make use of the **total energy potential of a star**, we'd become a **type 2 civilization**.

One way to harness the energy of a star is to build a megastructure around called the **Dyson Sphere**. It would completely enclose a star and capture all of its energy, then be able to transfer the energy for use by the home planet. Of course, this kind of contraption would dwarf the Death Star of the Star Wars universe, requiring amazing technology to build, and could take different forms. The initial idea by the physicist and mathematician **Freeman Dyson** in 1960 was that such a structure would cover an area 600 million times greater than the surface area of the Earth.

Understandably, the Dyson Sphere has become a staple in the search for extraterrestrial life. If you can spot a Dyson Sphere out in space, aliens should be not far behind.

How close are we to becoming the **type 2** megastructure builders? It's a big jump in capabilities and would probably take **1000-2000 years** to reach.



Source – NASA

A **type 3** civilization is of another order of evolution altogether, probably taking **100,000 years** or longer to get there. Kardashev saw it as "a civilization in possession of energy on the scale of its own **galaxy**". Yep, you have to get a whole galaxy's worth of energy to get this advanced. Humans would probably be long since gone by that point, becoming some kind of post-biological cybernetic beings.

We are talking about a world where robots build Dyson Spheres at will all over the galaxy, utilizing some yet-inconceivable space propulsion technology to move around. Perhaps, such a civilization would also be able to get **energy from black holes** or create energy-producing stars at will.

Source – NASA

What's next after such an advancement? Kardashev didn't see a need to hypothesize any further civilizations, but prognosticators since then have proposed that a **type 4** world would be able to harness the energy of an **entire universe**, while a **type 5** can do the same in a multiverse, drawing power from **multiple universes**.

What about **type 6**? We are talking god stuff here, controlling time and space, creating universes at will. **Type 7**? We can't even imagine and understand what that could be like.

Since a century ago, new physics theories and ideas have led to many revolutionary results.

Quantum mechanics and relativity theory and their profound concepts have not only changed our basic understanding of physics from the domain of elementary particles to that of the whole universe.

Their weird interpretation of space, time, the structure of matter, the universe, elementary particles, etc. has led to predictions that were unthinkable even a decade ago.

The introduction of such concepts as strings, branes, multiverses, parallel worlds, multi-dimensional space, etc. is a consequence of these two physics theories that with many other predictions that are yet to be verified in the future.

The fact is that some of these ideas and theories are so ahead of our time that, according to estimates, their verification needs centuries of technological advancement. **In this article, some of these weird physics theories are discussed**.

1. Quantum consciousness

This theory was developed to resolve the issue of measurement in quantum physics and the fact that results of physical measurements may be closely dependent on what we think about their outcome.

In an attempt to solve the measurement problem in quantum physics, physicists are frequently faced with the unresolved dilemma of consciousness.

Although most physicists try to by-pass the issue, it seems that there is a link between the conscious choice of experiments at the quantum level and the result of the experiment. Although not quite confirmed, recent empirical results at the elementary particle level suggest a close connection.

Some physicists, most notably **Roger Penrose**, believe that current physics is not capable of explaining consciousness and that consciousness itself has a link to the strange quantum realm.

2. The Many World theory

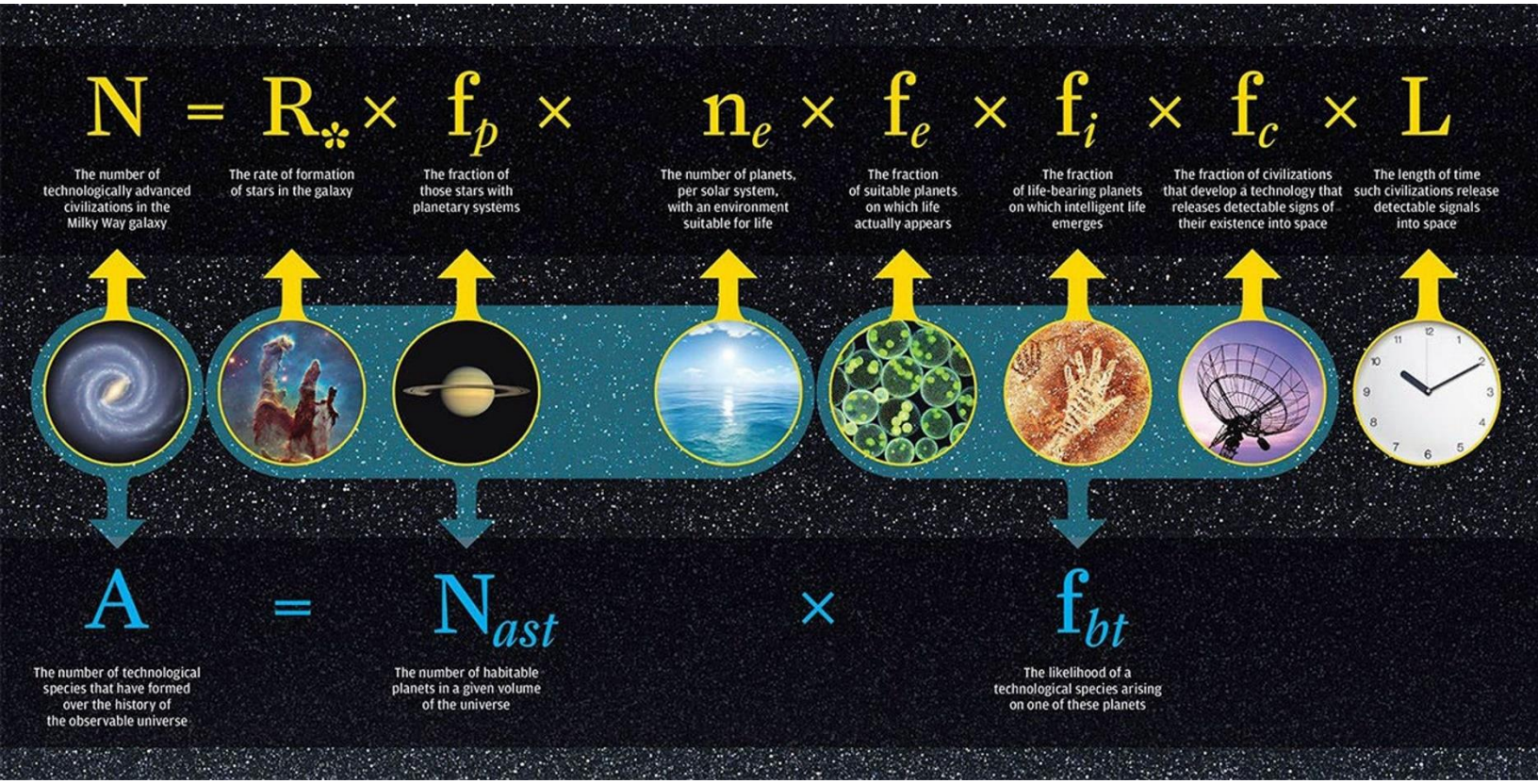
According to this theory, in addition to our universe, there is an **infinite number of other universes.** The theory was originally offered to resolve strange quantum interpretation of particles and their wave-particle dual nature and causality principle.
In many world theory, you are not living in just one space; rather, there are infinite transcripts of you in other worlds that may happen to have completely different behavior. In multiple universe theory, each of your versions can have a completely different fate.

The theory has many varieties, like the one that describes **the whole universe as countless bubble universes constantly appearing and disappearing.** This notion of the universe is rather opposed to the Big Bang theory that suggests the creation of the universe at 13.7 billion light-years ago.

Scientists have gone even further to suggest that equivalently for every there are many brains that act independently, and what we observe is the reflection of one of our many brains while others may observe something totally different.

Are We Alone in the Universe? Revisiting the Drake Equation

NASA Science Editorial Team



Two researchers have revised the Drake equation, a mathematical formula for the probability of finding life or advanced civilizations in the universe.
University of Rochester.

Are humans unique and alone in the vast universe? This question--summed up in the famous Drake equation--has for a half-century been one of the most intractable and uncertain in science.

But a new paper shows that the recent discoveries of exoplanets combined with a broader approach to the question makes it possible to assign a new empirically valid probability to whether any other advanced technological civilizations have ever existed.

And it shows that unless the odds of advanced life evolving on a habitable planet are astonishingly low, then human kind is not the universe's first technological, or advanced, civilization.

The paper, published in *Astrobiology*, also shows for the first time just what "pessimism" or "optimism" mean when it comes to estimating the likelihood of advanced extraterrestrial life.

"The question of whether advanced civilizations exist elsewhere in the universe has always been vexed with three large uncertainties in the Drake equation," said Adam Frank, professor of physics and astronomy at the University of Rochester and co-author of the paper. "We've known for a long time approximately how many stars exist. We didn't know how many of those stars had planets that could potentially harbor life, how often life might evolve and lead to intelligent beings, and how long any civilizations might last before becoming extinct."

"Of course, we have no idea how likely it is that an intelligent technological species will evolve on a given habitable planet," says Frank. But using our method we can tell exactly how low that probability would have to be for us to be the ONLY civilization the Universe has produced. We call that the pessimism line. If the actual probability is greater than the pessimism line, then a technological species and civilization has likely happened before."

Using this approach, Frank and Sullivan calculate how unlikely advanced life must be if there has never been another example among the universe's ten billion trillion stars, or even among our own Milky Way galaxy's hundred billion.

Rather than asking how many civilizations may exist now, we ask ‘Are we the only technological species that has ever arisen?'- Woodruff Sullivan, University of Washington

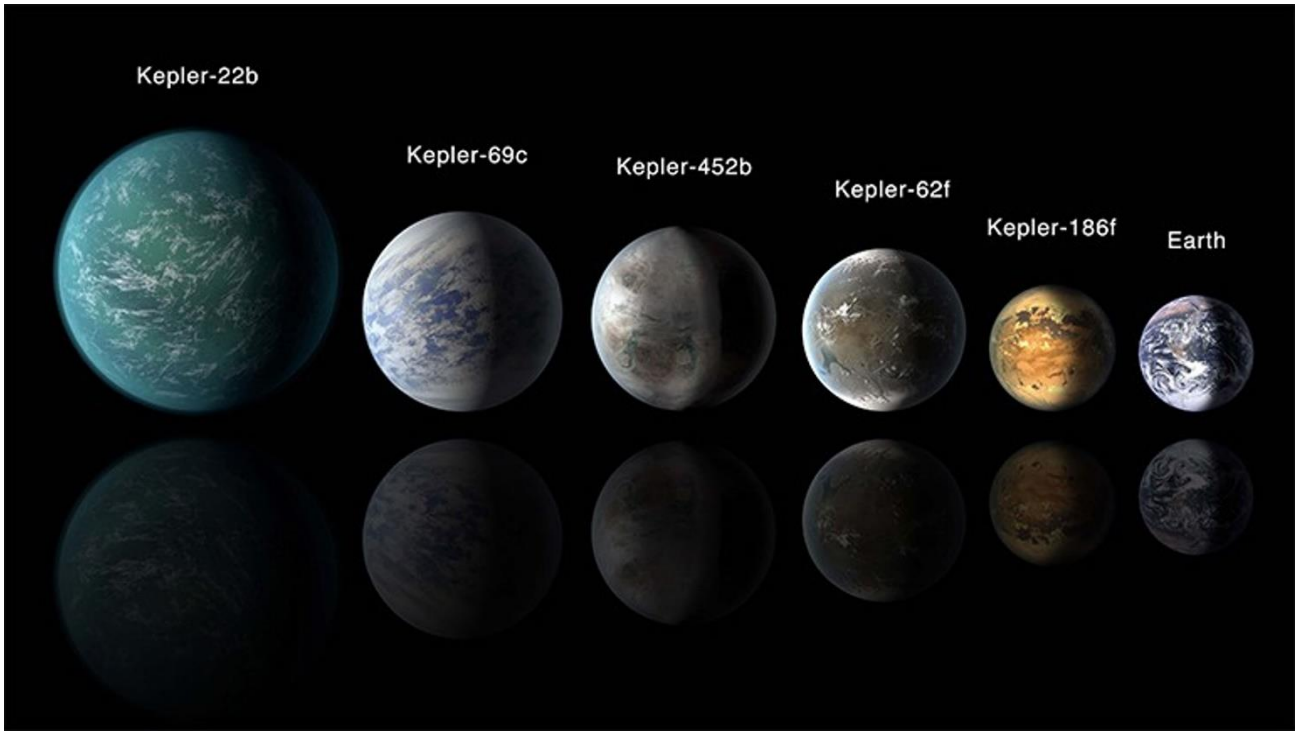
The result? By applying the new exoplanet data to the universe’s 2 x 10 to the 22nd power stars, Frank and Sullivan find that human civilization is likely to be unique in the cosmos only if the odds of a civilization developing on a habitable planet are less than about one in 10 billion trillion, or one part in 10 to the 22nd power.

“One in 10 billion trillion is incredibly small,” says Frank. “To me, this implies that other intelligent, technology producing species very likely have evolved before us. Think of it this way. Before our result you’d be considered a pessimist if you imagined the probability of evolving a civilization on a habitable planet were, say, one in a trillion. But even that guess, one chance in a trillion, implies that what has happened here on Earth with humanity has in fact happened about a 10 billion other times over cosmic history!”

For smaller volumes the numbers are less extreme. For example, another technological species likely has evolved on a habitable planet in our own Milky Way galaxy if the odds against it evolving on any one habitable planet are better than one chance in 60 billion.

But if those numbers seem to give ammunition to the “optimists” about the existence of alien civilizations, Sullivan points out that the full Drake equation—which calculates the odds that other civilizations are around today—may give solace to the pessimists.

“Thanks to NASA's Kepler satellite and other searches, we now know that roughly one-fifth of stars have planets in “habitable zones,” where temperatures could support life as we know it. So one of the three big uncertainties has now been constrained.”



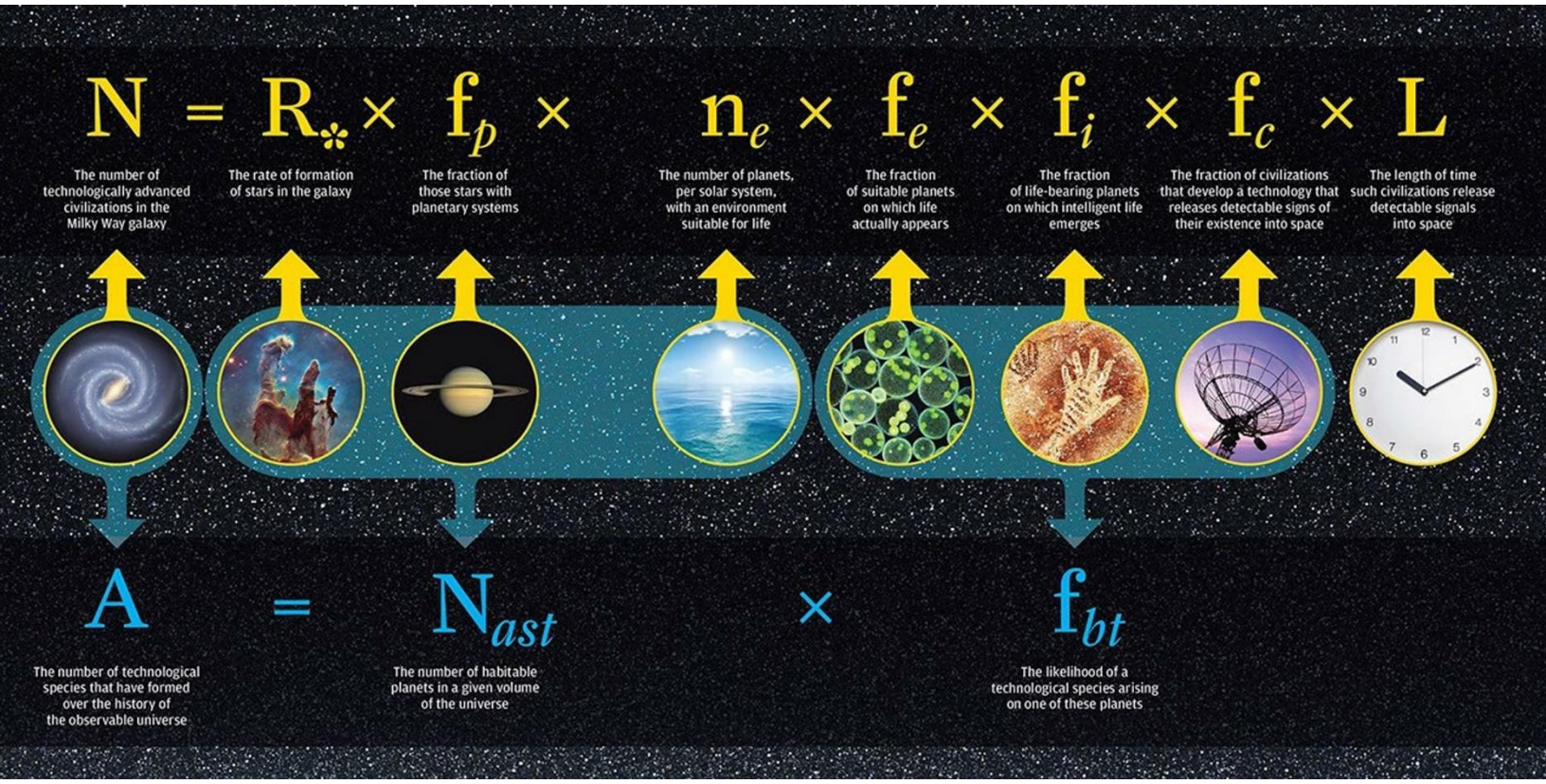
This artist's conception of a planetary lineup shows habitable zone planets with similarities to Earth: from left, Kepler-22b, Kepler-69c, Kepler-452b, Kepler-62f and Kepler-186f. Last in line is Earth itself.
NASA/JPL-Caltech

Frank said that the third big question--how long civilizations might survive--is still completely unknown. "The fact that humans have had rudimentary technology for roughly ten thousand years doesn't really tell us if other societies would last that long or perhaps much longer," he explained.

But Frank and his coauthor, Woodruff Sullivan of the astronomy department and astrobiology program at the University of Washington, found they could eliminate that term altogether by simply expanding the question.

"Rather than asking how many civilizations may exist now, we ask 'Are we the only technological species that has ever arisen?" said Sullivan. "This shifted focus eliminates the uncertainty of the civilization lifetime question and allows us to address what we call the 'cosmic archaeological question'—how often in the history of the universe has life evolved to an advanced state?"

That still leaves huge uncertainties in calculating the probability for advanced life to evolve on habitable planets. It's here that Frank and Sullivan flip the question around. Rather than guessing at the odds of advanced life developing, they calculate the odds against it occurring in order for humanity to be the only advanced civilization in the entire history of the observable universe. With that, Frank and Sullivan then calculated the line between a Universe where humanity has been the sole experiment in civilization and one where others have come before us.



The Drake equation, a mathematical formula for the probability of finding life or advanced civilizations in the universe.
University of Rochester.

In 1961, astrophysicist Frank Drake developed an equation to estimate the number of advanced civilizations likely to exist in the Milky Way galaxy. The Drake equation (top row) has proven to be a durable framework for research, and space technology has advanced scientists' knowledge of several variables. But it is impossible to do anything more than guess at variables such as *L*, the probably longevity of other advanced civilizations.

In new research, Adam Frank and Woodruff Sullivan offer a new equation (bottom row) to address a slightly different question: What is the number of advanced civilizations likely to have developed over the history of the observable universe? Frank and Sullivan's equation draws on Drake's, but eliminates the need for *L.*

Their argument hinges upon the recent discovery of how many planets exist and how many of those lie in what scientists call the “habitable zone” – planets in which liquid water, and therefore life, could exist. This allows Frank and Sullivan to define a number they call N_{ast}. N_{ast} is the product of N*, the total number of stars; f_p, the fraction of those stars that form planets; and n_p, the average number of those planets in the habitable zones of their stars.

They then set out what they call the “Archaelogical-form” of the Drake equation, which defines A as the “number of technological species that have ever formed over the history of the observable Universe.”

Their equation, $A=N_{ast}*f_{bt}$, describes A as the product of Nast – the number of habitable planets in a given volume of the Universe – multiplied by f_{bt} – the likelihood of a technological species arising on one of these planets. The volume considered could be, for example, the entire Universe, or just our Galaxy.

“The universe is more than 13 billion years old,” said Sullivan. “That means that even if there have been a thousand civilizations in our own galaxy, if they live only as long as we have been around—roughly ten thousand years—then all of them are likely already extinct. And others won’t evolve until we are long gone. For us to have much chance of success in finding another "contemporary" active technological civilization, on average they must last much longer than our present lifetime.”

“Given the vast distances between stars and the fixed speed of light we might never really be able to have a conversation with another civilization anyway,” said Frank. “If they were 20,000 light years away then every exchange would take 40,000 years to go back and forth.”

But, as Frank and Sullivan point out, even if there aren’t other civilizations in our galaxy to communicate with now, the new result still has a profound scientific and philosophical

importance. “From a fundamental perspective the question is ‘has it ever happened anywhere before?’” said Frank. Our result is the first time anyone has been able to set any empirical answer for that question and it is astonishingly likely that we are not the only time and place that an advance civilization has evolved.”

According to Frank and Sullivan their result has a practical application as well. As humanity faces its crisis in sustainability and climate change we can wonder if other civilization-building species on other planets have gone through a similar bottleneck and made it to the other side. As Frank puts it “We don’t even know if it’s possible to have a high-tech civilization that lasts more than a few centuries.” With Frank and Sullivan’s new result, scientists can begin using everything they know about planets and climate to begin modeling the interactions of an energy-intensive species with their home world knowing that a large sample of such cases has already existed in the cosmos. “Our results imply that our evolution has not been unique and has probably happened many times before. The other cases are likely to include many energy intensive civilizations dealing with their feedbacks onto their planets as their civilizations grow. That means we can begin exploring the problem using simulations to get a sense of what leads to long lived civilizations and what doesn’t.”

5 Mind-Blowing Theories That Could Change Our Understanding of the Universe: Unraveling Cosmic Mysteries

The article explores if our basic assumptions about the universe are wrong, discussing theories like the simulation hypothesis and quantum immortality.

Our universe is vast and filled with mysteries that challenge our understanding.
Scientists and thinkers have proposed many theories that push the boundaries of what we know.

These ideas spark curiosity and bring new perspectives to light.

What if our basic assumptions about the universe are wrong? Some theories offer surprising answers that could reshape how we view everything from time and space to the nature of reality itself.
The following exploration delves into some of the most intriguing theories, offering fresh insights into our universe.

What This Article Will Teach You

1) Simulation Hypothesis

The Simulation Hypothesis suggests that our universe might be a computer simulation.
This idea is supported by some scientists and philosophers who argue that technological advancements could make creating such simulations possible.

An MIT computer scientist explores how advancements in AI and quantum computing make this theory more plausible.
He argues that if humans could simulate a reality, they might already be living in one.
Some believe that strange phenomena, like the Mandela Effect, where many people remember events differently, support this theory.
This idea links to the thought that any glitches in the simulation could cause these discrepancies in collective memory.
Eastern mystics and philosophers have also pondered the nature of reality.
They often conclude that what we see and experience might not be the true essence of the universe, aligning with the core of the Simulation Hypothesis.

Though it sounds like science fiction, the theory raises questions about the nature of existence.
It encourages people to think about the possibilities of advanced civilizations and their ability to create highly detailed simulations.

This theory might change the way individuals perceive their everyday lives and the world around them.

2) Quantum Immortality

Quantum immortality is an idea from quantum mechanics that suggests there might be a way to outlive death.
It comes from the many-worlds interpretation, which says every possible outcome of a decision actually happens in some universe.
In quantum immortality, if someone were to face a life-threatening event, their consciousness would continue in a universe where they survive.
This means that from their perspective, they would never truly die.
The theory plays with the idea of Schrödinger's cat, where a cat in a box is both alive and dead until observed.
Similarly, a person would experience being alive in another universe even if they are dead in this one.
Some scientists and philosophers believe this theory could explain why individuals escape seemingly fatal situations.
Though it's a fascinating concept, it remains purely theoretical, and many physicists debate its validity.

Despite the controversies, quantum immortality sparks interesting discussions about life, death, and the nature of the universe.
It challenges what people think about their own existence and what might happen after death, adding a new layer to the mystery of the cosmos.
To read more about this theory, you can explore these ideas in A New Model Regarding the Survival of Consciousness After Death.

3) Multiverse Theory

Multiverse Theory suggests that our universe is just one of many.
This idea opens up the possibility of parallel universes existing alongside our own.
Each universe might have different physical laws, particles, and even different versions of ourselves.
One approach to the Multiverse Theory comes from cosmology.
The idea is that the Big Bang created multiple, separate universes.
These universes could be infinitely expanding and never intersect with ours.
Quantum mechanics also offers an angle on Multiverse Theory.
It proposes that every possible outcome of a quantum event actually occurs in a different universe.
This is often referred to as the "Many-Worlds Interpretation."

String theory adds another layer.
It posits that there could be multiple dimensions beyond the three we experience.
These dimensions could contain parallel universes.
Some theories even suggest there are universes just a “fifth dimension” away (The Allure of the Multiverse).
The Multiverse Theory is still just a theory but it fascinates scientists and the public alike.
It challenges how we think about space, time, and our place in the grand scheme of things (In search of the multiverse).

4) Holographic Universe

The Holographic Universe theory suggests that our entire universe can be described as a two-dimensional information structure “painted” on the cosmological horizon.
This means that everything we experience in our 3D world might be a projection from this 2D surface.
This idea comes from principles in quantum physics and general relativity.
It states that the volume of space can be viewed as encoded on a boundary to the region, like an observer on a distant surface.
In simple terms, just like a hologram, which is a three-dimensional image formed from a two-dimensional one, our entire universe might be like this.

This theory helps explain how two particles can remain connected over vast distances, a phenomenon known as quantum entanglement.
Supporters of the Holographic Universe theory believe it can solve some puzzles about black holes.
Black holes have a surface area that can encode information.
This fits well with the idea that the universe is a hologram, storing information on its outer boundary.
For more information on how this theory impacts our view of quantum physics and the cosmos, take a closer look at scientific discussions surrounding it.
The concept might seem strange, but it opens up new ways of thinking about the nature of reality.

5) Cosmic Consciousness

Cosmic Consciousness is the idea that the universe itself may possess a type of consciousness.
This theory suggests that consciousness is not just a product of the human brain but is a fundamental feature of the universe.
Some thinkers propose that the universe is an evolving entity, realizing its own “higher self” as it grows.
This may imply that all things in the universe are interconnected, sharing a collective consciousness.

Certain scientists and philosophers explore the concept of an Akashic field.
This is a cosmic intelligence and memory bank that contains all the information of the universe.
Such a field could underlie and shape physical reality.
In quantum theory, consciousness may play a role in the behavior of particles.
Observing a particle seems to influence its state, hinting at a possible link between mind and matter.
This mind-blowing idea could change how we view both science and spirituality.
Some theories, such as string theory, attempt to explain the universe's fundamental nature.
In this context, consciousness might be a part of the entire framework that makes up reality.

This idea opens up many new avenues for understanding our place in the cosmos.
For more insights, check out this discussion on the consciousness revolution.
Such ideas invite us to ponder not only our minds but the mind of the universe itself.

The Multiverse Theory

The Multiverse Theory suggests that our universe is just one of many, existing alongside countless others.
This idea could fundamentally change our perspective on reality and our place in the cosmos.

Parallel Universes Explained

The concept of parallel universes comes from the idea that there could be an infinite number of universes existing simultaneously.
Each universe might have different laws of physics or varied historical events.
For example, in one universe, you might decide to pursue a different career or live in another city.
This means every possible outcome of every decision ever made could exist somewhere in the multiverse.
Scientists have different hypotheses about how these universes might be structured.

One possibility is that they are stacked like layers of a cake, each layer representing a different universe.
Another idea is that they could be branching out like the leaves of a tree, where each leaf is a separate universe with different outcomes.
The mathematical backing for these ideas comes from quantum mechanics, where particles can exist in multiple states at once.
This principle, applied on a larger scale, implies the existence of multiple, parallel realities.

Implications for Our Reality

If the multiverse exists, it could drastically affect how we see our place in the universe.
For instance, it might explain why our universe seems so perfectly tuned for life.
If there are countless universes, some would naturally have conditions just right for life by chance.

It also raises questions about the nature of existence and reality.
Are we living in the only universe, or is our reality just one of many possible ones? This could also change our approach to scientific research, pushing scientists to consider broader possibilities beyond our observable universe.
Moreover, this theory has philosophical implications.
It challenges the idea of a singular reality and opens up discussions about fate, free will, and the uniqueness of individual experiences.
In a multiverse, every possible reality could be playing out somewhere, suggesting that our reality is just one of many threads in the vast tapestry of existence.

String Theory

String theory suggests that the fundamental particles we know, like electrons and quarks, are not point particles but rather tiny strings.
These strings vibrate at different frequencies, which determine the particles' unique properties.
Understanding this helps us grasp the basics of the universe on an even smaller scale.

Basic Principles of String Theory

String theory posits that the smallest building blocks of matter are not tiny dots, but minuscule strings.

These strings can vibrate in multiple ways.
Each vibration pattern corresponds to a different particle.
This concept provides a way to unify all the forces of nature, including gravity, into a single theoretical framework.
There are different types of string theory, but the most known include Type I, Type IIA, Type IIB, and heterotic string theories.
Each type suggests different properties and dimensions for these strings.
Additionally, string theory solves many inconsistencies found in traditional physics models by theorizing that particles are one-dimensional "strings" rather than zero-dimensional points.

The Role of Dimensions in String Theory

Dimensions play a crucial role in string theory.
Unlike our familiar three-dimensional world, string theory requires additional dimensions to function correctly.

Most string theories suggest that there are ten dimensions: the three we know, plus six more that are compactified or hidden from us.
These additional dimensions allow strings to vibrate in ways that create the various forces and particles we observe.
This extra space is theorized to be compactified into tiny, complex shapes known as Calabi-Yau manifolds.
While we cannot see these extra dimensions, their existence helps provide a comprehensive explanation for how forces like gravity and electromagnetism fit into a unified physical model.

To learn more about how dimensions affect string theory, you can read about the concept of string theory and dimensions.

Dark Matter and Dark Energy

Dark matter and dark energy are crucial to understanding the universe's structure and expansion. They make up most of the universe's mass and energy.

What Is Dark Matter?

Dark matter is an invisible substance that doesn't emit or absorb light.
Scientists know it exists because of its gravitational effects on visible matter.
For instance, galaxies spin faster than they should if only visible matter were present and need dark matter to explain this.

Another important fact about dark matter is that it helps in the formation of galaxies.
Without it, galaxies might not hold together.
It also plays a role in cosmic web structures, where clusters of galaxies are connected by dark matter.
Scientists are still trying to detect dark matter particles directly.
Experiments are set up deep underground to avoid interference from cosmic rays.

Dark Energy's Impact on the Universe

Dark energy makes up about 68% of the universe.
It is responsible for the universe's accelerating expansion.
Edwin Hubble first discovered that galaxies are moving away from each other, and later, scientists realized this movement was speeding up.

This expansion affects the fate of the universe.
One possibility is that it could lead to the "Big Freeze," where galaxies move so far apart that star formation stops.
To study dark energy, scientists use telescopes to observe distant supernovae.
These observations help measure the rate of expansion.
Dark energy theories are still developing, and understanding it is one of the biggest challenges in cosmology.
Learn more about the theories of dark energy from The dark-energy deniers.
For a deeper exploration of the universe's secrets with dark matter, check out Einstein's telescope.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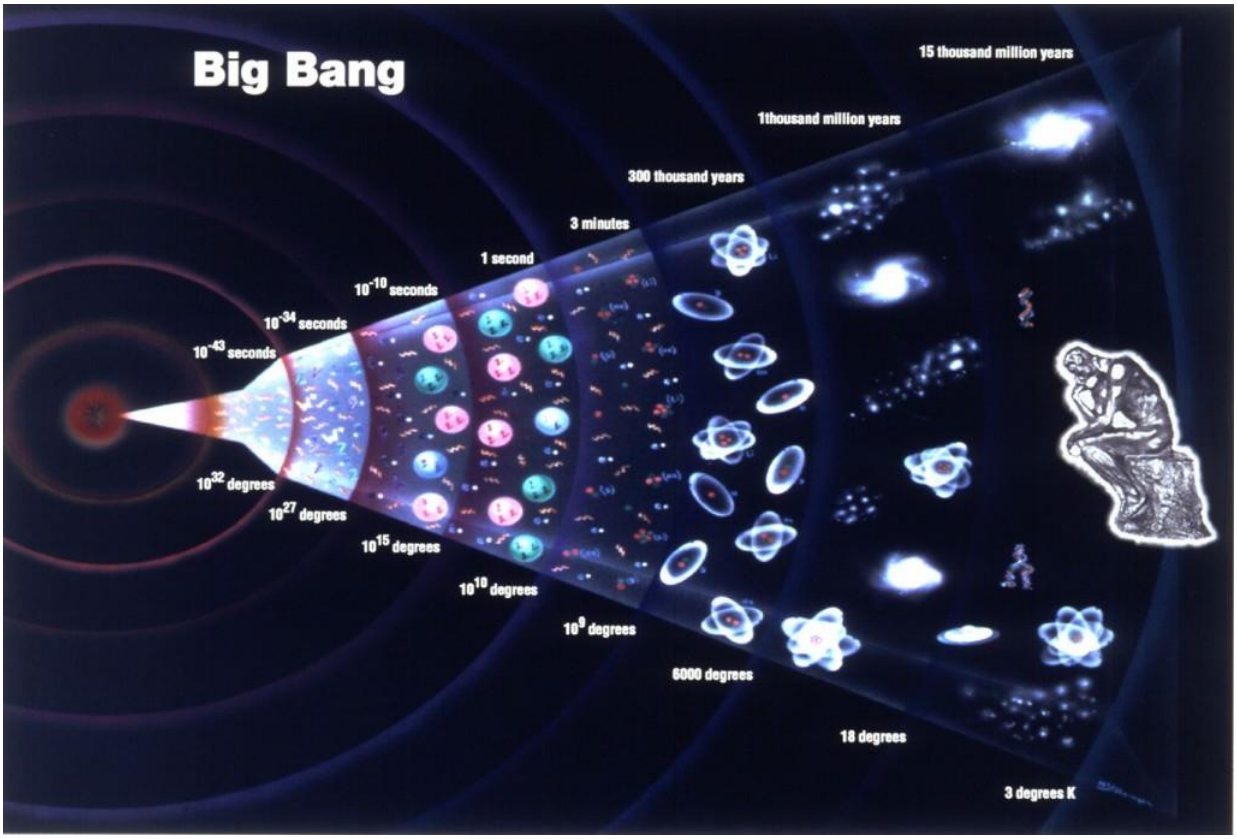
An illustration of cosmic expansion. Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

Civilizations are Probably Spreading Quickly Through the Universe

The Search for Extraterrestrial Intelligence (SETI) has always been plagued by uncertainty. With only one habitable planet (Earth) and one technologically advanced civilization (humanity) as examples, scientists are still confined to theorizing where other intelligent life forms could be (and what they might be up to). Sixty years later, the answer to Fermi's famous question ("Where is Everybody?") remains unanswered. On the plus side, this presents us with many opportunities to hypothesize possible locations, activities, and technosignatures that future observations can test.

One possibility is that the growth of civilizations is limited by the laws of physics and the carrying capacity of the planetary environments – aka. The Percolation Theory Hypothesis. In a recent study, a team from the University of the Philippines Los Banos looked beyond traditional Percolation Theory to consider how civilizations might grow in three different types of Universes (static, dark energy-dominated, and matter-dominated). Their results indicate that, depending on the framework, intelligent life has a finite amount of time to populate the Universe and is likely to do so exponentially.

The study was conducted by Allan L. Alinea and Cedrix Jake C. Jadrin, an Assistant Professor of Physics and a Teaching Associate with the Institute of Mathematical Sciences and Physics at the University of the Philippines Los Banos. The preprint of their paper, "Percolation of 'Civilization' in a Homogeneous Isotropic Universe," recently appeared online. For their study, the team considered how traditional Percolation Theory could be interpreted in terms of a Logistic Growth Function (LGF), where a population's per capita growth rate gets smaller as population size approaches a maximum imposed by the limits of local resources (aka. carrying capacity).



The Big Bang Theory: A history of the Universe starting from a singularity and expanding ever since. Credit: grandunificationtheory.com

Percolation Theory

In brief, Percolation Theory describes how networks behave when nodes or links are removed, wherein they will break down into smaller connected clusters. The first known instance of this theory being applied to the Fermi Paradox was perhaps made by Carl Sagan and William I. Newman in 1981. In a paper titled "Galactic Civilizations: Population Dynamics and Interstellar Diffusion," they argued that the reason humanity has not encountered extraterrestrial civilizations (ETCs) is because interstellar exploration and settlement are not linear phenomena.

In contrast to the Hart-Tipler Conjecture, which argues that advanced ETCs would have colonized our galaxy long ago (hence, they do not exist), Sagan and Newman postulated that interstellar exploration is a matter of diffusion. Geoffrey A. Landis argued these same sentiments in his 1993 paper, "The Fermi Paradox: An Approach Based on Percolation Theory," where he argued that the laws of physics impose limits on interstellar growth. According to Landis, there is no "uniformity of motive" to be expected from extraterrestrial civilizations:

"Since it is possible, given a large enough number of extraterrestrial civilizations, one or more would have certainly undertaken to do so, possibly for motives

unknowable to us. Colonization will take an extremely longtime, and will be very expensive. It is quite reasonable to suppose that not all civilizations will be interested in making such a large expenditure for a pay off far in the future. Human society consists of a mixture of cultures which explore and colonize, some times over extremely large distances, and cultures which have no interest in doing so."

Similarly, Prof. Adam Frank and colleagues from NASA's Nexus for Exoplanetary Systems Science (NExSS) wrote a paper in 2019 titled "The Fermi Paradox and the Aurora Effect: Exo-civilization Settlement, Expansion, and Steady States." Inspired by the 2015 novel *Aurora* by Kim Stanley Robinson, they argued that the interstellar settlement would occur in clusters since not all potentially habitable planets would be hospitable to an alien species. In short, the laws of physics, biology, and evolution impose limits on how far and fast a species can settle our galaxy.

Solve for T & H

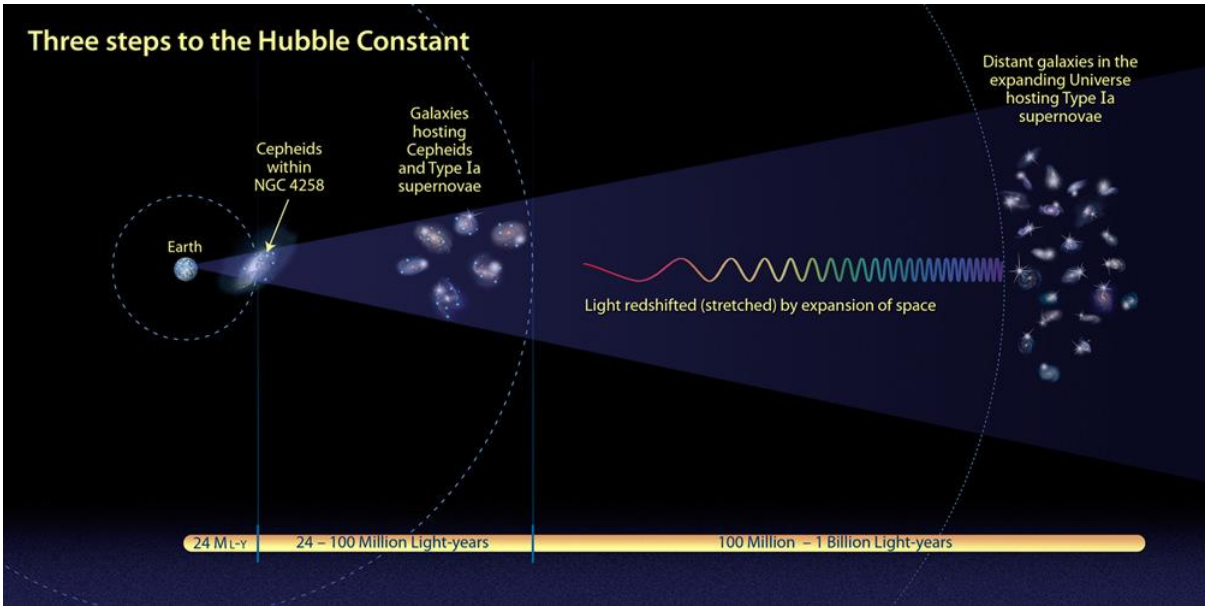
To constrain those limits, the team considered the three main cosmological models of the Universe, including static, matter-dominated, and dark energy-dominated. A static Universe, as originally described by Einstein and his Cosmological Constant, is infinite in terms of space and time and is neither expanding nor contracting. A matter-dominated Universe describes the state of the Universe prior to 9.8 billion years after the Big Bang, a time when the energy density of matter exceeded both the energy density of radiation and the vacuum energy density.

A dark energy-dominated Universe describes the latest phase of cosmic evolution, which began roughly 9.8 billion years ago and is characterized by an accelerated rate of expansion. The team also considered all three scenarios in terms of a Logistic Growth Function to determine the number of planets settled with time. From this, the team obtained the two parameters of their study: ***T***, the time needed to settle a spherical section of an ideal Universe that is both homogeneous and isotropic, and H, the Hubble parameter that describes the rate of cosmic expansion – a.k.a. the Hubble Law or Hubble-Lemaitre Law.

For a static Universe, they found that settlement follows the LGF, similar to how population growth, the spread of infectious diseases, and chemical reactions do. As they noted in their study, these dynamical systems follow a general pattern beginning with a relatively slow start due to limited sources (in this case, habitable planets). But, as they continue to expand and acquire new sources, this multiplies the number available, and the propagation speeds up. This continues until the number of sources begins to dwindle and/or the elements of the system are exhausted.

To their surprise, the team noted similar behaviors when looking at a matter-dominated and dark-energy Universe. As Dr. Alinea told Universe Today via email.

"Remarkably, when the space itself is expanding as in the dark-energy and matter-dominated Universes, the process of settlement, for the most part, still follows the Logistic Growth Function. We did not expect this result because a system with expanding space appeared to us as vastly different from a static system. Most of the studies we know on percolation are based on a static lattice (e.g., spread of forest fire, propagation of disease, information diffusion) where the logistic growth behavior is usually observed. Our study 'extends' this behavior to cases where the lattice is expanding like our very own Universe."



Steps to the Hubble Constant. Credit: NASA, ESA, and A. Feild (STScI)

Nevertheless, they did find there was a delay in an expanding Universe in terms of the rate of settlement compared to a static one. For a dark energy-dominated universe, they found that the total settlement time (T) was marked with divergence for a large enough expansion rate (H). In accordance with Hubble's Law, when H is large enough, some planets would expand beyond the horizon and become "unreachable." In essence, distant planets can be receding faster than the speed of light, making it improbable that an expanding civilization would ever reach them.

They also found that in cases where the Hubble Sphere (H) was smaller, the relation between T and H was linear – in other words, T was roughly equal to H (T ~ H). For a matter-dominated Universe, their findings indicated that where H was similarly small, the same relation applied, but where H became larger, the relation changed significantly to $T \sim H^2$. In comparison to that of a dark energy-dominated Universe, T did not increase exponentially or reach infinity unless H was infinite. Said Alinea:

“This is interesting because a matter-dominated Universe is also characterized by a horizon. It means that for planets far enough from a reference planet in this Universe, they are receding at a velocity faster than light, making it appear that they are unreachable. However, for a matter-dominated universe, in accordance with Friedmann Equation, the comoving Hubble Sphere is shrinking instead of expanding. Put simply and informally, those planets far away from a reference planet in this Universe (that are initially ‘moving’ faster than the speed of light) are ‘slowing down,’ making them reachable, at least in principle.”

So… Where Are They?

From their results, the team determined that advanced civilizations will generally follow a growth trend that is slow to start but will take off over time, eventually slowing and stopping as the number of “reachable” planets is exhausted. As Dr. Alinea described, “This model is marked by a three-phase pattern: slow settlement rate –> fast settlement rate –> slow settlement rate.” The question remains: what does this mean for Fermi’s time-honored question? How does this three-phase pattern help us refine the search for advanced civilizations expanding across the galaxy?

To that, the team concludes that our galaxy may currently be in Phase I, characterized by a slow settlement rate. This could be because only a few intelligent, advanced civilizations are engaged in interstellar settlement right now. “This slow phase can be exacerbated by large distances between”living” planets. But once some number of traveling civilizations is reached, we may enter Phase II, characterized by a fast settlement rate. Given enough time upon entering this phase, we may finally say hello to aliens out there.”

 *The center of the Milky Way as seen from Chile. The core contains very old stars that date back to early in cosmic history. Credit: ESO/P.Horalek CC by 4.0.*

Moreover, their results address the possibility of humanity becoming an interstellar species someday, perhaps as a means of ensuring the continued survival and development of our species. This represents a challenge in an ever-expanding, ever-accelerating Universe dominated by Dark Energy. But as Dr. Alinea summarized, there are options:

"Given enough technology to travel near the speed of light, it is still challenging to reach any planet in the Universe, particularly the far away planets. Having said this, there is a spherical section of this Universe, centered in our location, whose planets are reachable, at least in principle, for possible settlement. Beyond this

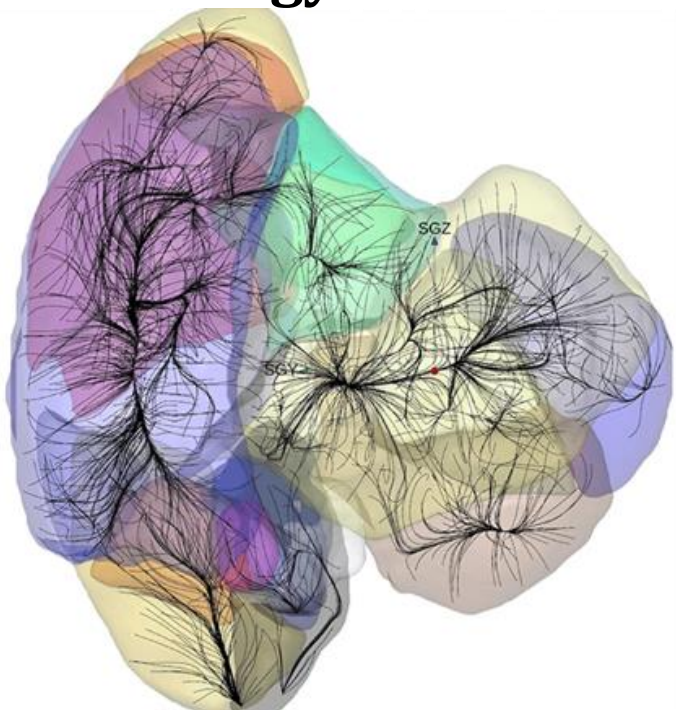
are planets that "move" away from us at a speed higher than that of light and may not be reachable. Unfortunately, this sphere is shrinking, so a section of the universe that we can inhabit, although large on the human scale, becomes smaller and smaller with time."

"If there is a mechanism to drive the universe to a state such that its expansion rate is the same or similar to that of a matter-dominated universe, then we would be lucky enough to have a Universe that can, in principle, be colonized up to any distance from us; that is, the colonization and human influence in the Universe is not bounded by any sphere unlike that of the dark-energy dominated Universe."

In summary, the answer to Fermi's question may be that advanced civilizations are in an early, slow phase of expansion that has (so far) prevented us from making contact. But as there spherical volume of Hubble Space (H) that we could occupy expands, we are more likely to get close enough to someone else's that we will finally know that we're not alone in the Universe. Similarly, while Dark Energy may limit how far we can reach (within our galaxy, not much farther), a sufficient volume of space would enable our continued development and could prevent a single cataclysmic fate from claiming all of our species.

And who knows? Perhaps cosmic expansion will not carry on as it has for the past 4 billion years, and the Universe will slow down and achieve a sort of homeostasis – the kind Einstein preferred to believe in. In that case, our Hubble Spheres may continue to expand indefinitely, and there will be no shortage of intermingling between cosmic civilizations. It does make for some exciting prospects, doesn't it?

Our Galaxy Appears To Be Part Of Structure So Large It Challenges Our Models Of Cosmology



The map of the basin of attraction. - Image credit: University of Hawai'i at Mānoa© IFL Science

Astronomers have found that our galaxy, the Milky Way, may be a tiny part of an even larger local structure than we thought. The research, if confirmed by further observations and studies, may be evidence that we haven't quite nailed down our model of the evolution of the universe.

As we study the universe more, we have found ourselves to be part of much larger structures, formed by gravitational interactions. We orbit the Sun, the Sun is part of the Milky Way, and the Milky Way is part of the Local Group, which includes several small galaxies as well as Andromeda, of "it may collide with us" fame.

But it doesn't stop there. The Local Group is on the outer edge of the Virgo Supercluster, which is itself part of a giant basin known as Laniakea. According to the new study, Laniakea too resides within a larger "basin of attraction" (BoA) potentially 10 times its volume.

"The entire Universe can be considered a patchwork of abutting BoA, just as the terrestrial landscape is separated into watersheds," the team explains in their paper. "A BoA is generally not gravitationally bound because the relative motion of distant points within it is usually dominated by cosmic expansion."

The basins of attraction are enormous structures, so much so that gravity is not the dominant force, but there is nevertheless evidence of common flow. The team looked at the motions of 56,000 galaxies, and attempted to make a "probabilistic map" of the local universe, given errors that occur when attempting to measure the velocity and motion of galaxies. In doing so, they hoped to narrow down the possibility of the existence of these basins of attraction.

“Our universe is like a giant web, with galaxies lying along filaments and clustering at nodes where gravitational forces pull them together,” University of Hawai'i at Manoa astronomer R. Brent Tully explained in a statement. “Just as water flows within watersheds, galaxies flow within cosmic basins of attraction. The discovery of these larger basins could fundamentally change our understanding of cosmic structure.”

Running simulations on the data, they found that the BoA encompassed many gigantic structures, including the mysterious Great Attractor.

"Nearby, evidence emerges for a BoA centred in proximity to the highly obscured Ophiuchus cluster that lies behind the centre of the Milky Way Galaxy," the team explained. "This BoA may include the so-called Great Attractor region and the entity Laniakea, including ourselves. In the extension [...] the Sloan Great Wall and the associated structure are overwhelmingly dominant."

Creating such maps of the universe is a messy business, tracking the movement of galaxies and their effect on each other in order to model these cosmic "currents" and flows. As such, there is a lot of uncertainty. According to the team's simulations, there is a 60 percent chance that our own Milky Way is in fact not in Laniakea, but in the Shapley concentration.

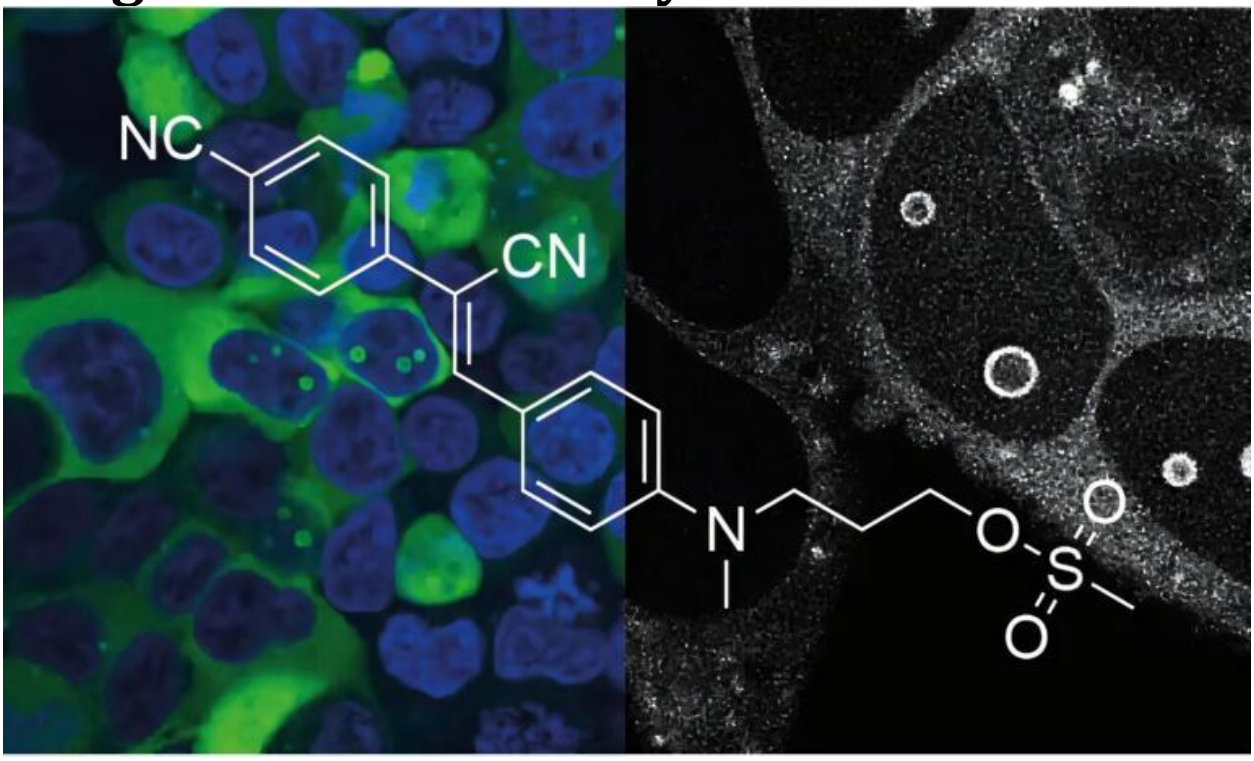
As well as being nice to really nail down our home address, the study could have much larger implications for our models of the universe, if the same structure continues to be found with further observation and analysis. Simply put, structures of gargantuan size challenge our understanding of the cosmos.

Given what we see in the cosmic microwave background, the first light we can detect after the inflation of the universe, structures can only grow so large within our current models. Yet this, and other similar discoveries, appear to be larger than our current models predict. For now, the team plans to continue mapping the largest structures in the cosmos.

"It is perhaps unsurprising that the further into the cosmos we look, we find that our home supercluster is more connected and more extensive than we thought," Noam Libeskind, astronomer at the Leibniz Institute for Astrophysics Potsdam, said in a separate statement. "Discovering that there is a good chance that we are part of a much larger structure is exciting. At the moment it's just a hint: more observations will have to be made to confirm the size of our home supercluster."

The study is published in Nature Astronomy.

Fluorescent RNA complexes offer new insights into cellular dynamics



Chemically modified RNA can be made to fluoresce and is also suitable for the search for new active substances. Credit: University of Innsbruck

The specific labeling of RNA in living cells poses many challenges. In a new article published in the journal *Nature Chemical Biology*, researchers from the University of Innsbruck describe a structure-guided approach to the formation of covalent (i.e., irreversibly tethered) RNA-ligand complexes.

The key to this is the modification of the original ligand with a reactive "handle" that allows it to react with a nucleobase at the RNA binding site. This was first demonstrated in vitro and in vivo using the example of an RNA riboswitch.

The versatility of the approach is highlighted by the first covalent "fluorescent light-up RNA aptamer" (coFLAP). This system retains its strong fluorescence during imaging in living cells even after washing, can be used for high-resolution microscopy and is particularly suitable for FRAP (fluorescence recovery after photobleaching) for monitoring intracellular RNA dynamics.

"In addition, we were able to develop a fluorophore with a second handle for bioorthogonal chemistry, which enables a simple pull-down of the covalently bound target RNA (traceable by fluorescence spectroscopy)," explains chemist Ronald Micura from the Department of Organic Chemistry and the Center for Molecular Biosciences Innsbruck (CMBI) at the University of Innsbruck. "Finally, we have shown the suitability of this strategy for the development of potential drug lead structures that bind covalently to an RNA target."

Joint success

One key to the success of the study lies in the willingness to overcome seemingly insurmountable experimental hurdles with complementary methods. A total of four working groups from the Innsbruck universities, which are jointly based at the Center for Chemistry and Biomedicine, have brought together the chemical synthesis of the fluorophores and the RNA (team led by Ronald Micura), their mass spectrometric sequencing (team led by Kathrin Breuker), the crucial in vivo applications (team led by Alexandra Lusser) and finally the necessary high-resolution microscopy.

"We benefit greatly from working together in a joint research center, where we can exchange ideas between the working groups regardless of institutional

affiliation and quickly try out new approaches," says Lusser from the Institute of Molecular Biology and Biocenter at the Medical University Innsbruck.

More information: Raphael Bereiter et al, Engineering covalent small molecule–RNA complexes in living cells, *Nature Chemical Biology* (2025). DOI: 10.1038/s41589-024-01801-3

Provided by University of Innsbruck

Supramolecular scaffolds support growth of human and plant cells

Your body is one of the most complex natural structures ever. Billions of cells are put together in a specific way with the result being you. If you look closely between the cells you'll find the extracellular matrix, a gel-like environment where cells reside and which helps them to talk to each other. However, when disease strikes, cells and the matrix alike can be irreparably damaged, which could lead to the loss of cell function.

In her Ph.D. research, Maritza Rovers looked at ways to make microgel-based scaffolds for cells, which could be used to support eye cells or even promote nerve growth in spinal cord injuries.

Every person on the planet is made up of billions of cells, which are the building blocks of our bodies. Between these cells lies the so-called extracellular matrix (ECM), a gel-like environment in which cells live out their lives.

"The matrix provides stability and facilitates communication between the cells and the matrix itself," says Rovers, who defended her Ph.D. thesis at the Department of Biomedical Engineering on December 17. "When disease occurs though, the ECM can be damaged and the cells too. However, sometimes the body cannot repair the damage, which leads to loss of function for the cells and the organ where the cells are located."

Becoming a scaffold builder

Motivated to help cells heal better when disease strikes, Rovers decided to become a scaffold builder for her Ph.D. researcher, creating structures that mimic this complex ECM.

"I didn't decide to build the metal ones that you see around houses under construction," says Rovers. "Instead, my aim was to build scaffolds from molecular building blocks that support human and plant cells, as well as help them to grow."

To realize such scaffolds, Rovers turned to the world of supramolecular chemistry, which uses synthetic building blocks (known as monomers) that self-assemble into networks. "The networks or scaffolds formed lead to hydrogels with properties that mimic the ECM."

However, such hydrogels are often quite dense or bulky with limited spatial control. "The natural ECM is finely regulated by processes at various length scales and bulk hydrogels can't always capture this. Microgels, as small building blocks for larger scaffolds, offer a solution to mimic the ECM," says Rovers.

Microfluidic origins

Creating these supramolecular microgels involved the use of droplet-based microfluidics, which is a technique where tiny droplets of water are formed inside an oil phase. Eventually, this gelates into a microgel.

"Taking this approach allowed for the careful modulation of the microgel properties by varying the concentration of building blocks, crosslinkers, and bioactive peptides," points out Rovers.

"These tiny supramolecular building blocks are like different types of K'NEX toy building blocks. With the same K'NEX blocks, you can create a whole range of different designs. It's the same for the supramolecular building blocks—we can create a range of structures, each with completely different purposes. I worked on creating small micro-building blocks (microgels) from these molecules that could be used for different types of cells."

Applications aplenty

Which cell types did the young researcher want to help with her new scaffolds? Well, with plenty of expertise on supramolecular chemistry and applications to be found in the lab of Patricia Dankers, Rovers' supervisor, she had plenty of colleagues to work with on various applications.

"Together with my colleague Annika Vrehen, we combined our research efforts. Annika worked on a replacing synthetic matrix to design a microenvironment in which cells from the stroma—the thickest layer of the cornea—could live and survive. We encapsulated the cells she used in my tiny microgels. We observed that the cells were able to escape from their microgel and interact with other neighboring microgels and cells."

"The cells started to use the microgels as building blocks to build their own tissue structure. This was completely autonomous, and cells were able to organize this themselves."

In addition, Rovers used the same building blocks to create microgel scaffolds to help grow nerve cells after a spinal cord injury and to even cultivate plant cells.

Challenging plant cells

For Rovers, the biggest challenge was growing plant cells. "When we started, we thought it would be easy. Unlike humans, plants grow everywhere, and if you prune them, they grow back. That's obviously not the case for the human body. However, it turned out to be more difficult than expected—plant cells were much harder to grow in the lab because they are so fragile."

Eventually, Rovers and her colleagues did manage to get the plant cells to grow in combination with their supramolecular-based materials.

"We tried to show that while it's still far from ideal, the field of plant cultivation can learn a lot from biomedical tissue engineering and regenerative medicine. And vice versa, of course."

Learning how to act

During her Ph.D. journey, Rovers gained many new lab skills and learned how to work independently, but she highlights something else as being more significant.

"The biggest change that I saw in myself was learning to act and just start, instead of overthinking everything before doing anything in the lab. In the first year of my Ph.D., I would try to plan out every step in the lab. But this doesn't work as things don't always go as planned in the lab. Experiments go wrong, and it's in those moments that you learn to adapt and arrive at creative solutions. These aren't skills that you can learn by sitting at the desk and overplanning."

In addition, the researcher notes the importance of finding balance and letting go of things that are outside one's control. "Perfectionism is a good thing to have in research, but it shouldn't dominate. I'll keep reminding myself that for the rest of my scientific career."

After spending four years working with cells, Rovers is planning to continue making advancements in the world of the small. "I'll stay with my current research group after my defense for a short period. After that I want to go abroad for a postdoctoral position. But there are factors that aren't entirely within my control, like securing grants. Nonetheless, I'll put in my best effort and look to the future with optimism."

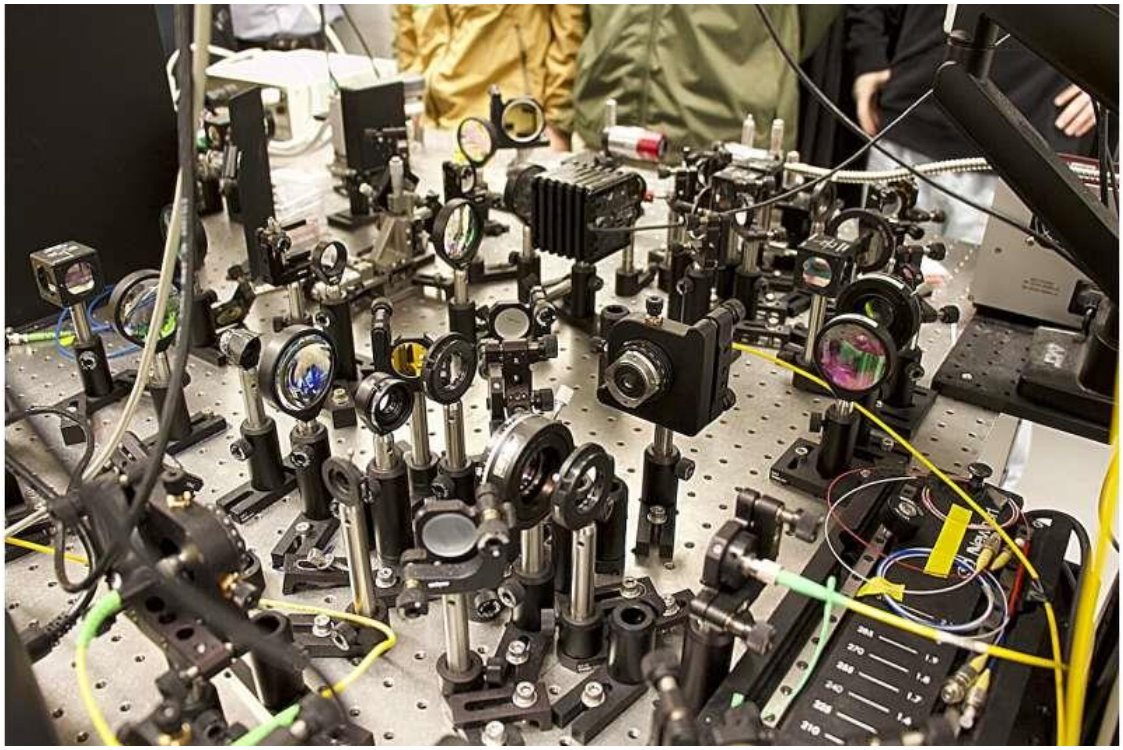
More information: Engineering supramolecular microgels into artificial matrices. For applications in human tissue engineering and cellular agriculture. research.tue.nl/nl/publication ... ificial-matrices-for

Provided by Eindhoven University of Technology

JANUARY 7, 2025

Engineers create photonic switch that overcomes routing size–speed tradeoffs

by University of Pennsylvania


Some of the equipment used by the Feng Group for transmitting light. Credit: Bella Ciervo

Every second, terabytes of data—the equivalent of downloading thousands upon thousands of movies at once—travel around the world as light in fiber-optic cables, like so many cars packed onto a super-fast highway. When that information reaches data centers, it needs a switching system, just as cars need traffic lights, to exit the highway in an orderly fashion.

Until now, the photonic switches used for routing optical signals have been hindered by a fundamental tradeoff between size and speed: Larger switches can handle higher speeds and more data but also consume more energy, occupy more physical space and drive up costs.

In a new paper in *Nature Photonics*, researchers at the University of Pennsylvania School of Engineering and Applied Science (Penn Engineering) describe the creation of a novel photonic switch that overcomes this size–speed tradeoff. And at just 85 by 85 micrometers, the new switch's units are smaller than a grain of salt.

By manipulating light at the nanoscale with unprecedented efficiency, the new switch speeds up the process of getting data on and off the literal information superhighway of fiber-optic cables that encircles the globe.

"This has the potential to accelerate everything from streaming movies to training AI," says Liang Feng, Professor in Materials Science and Engineering (MSE) and in Electrical and Systems Engineering (ESE) and the paper's senior author.

Quantum mechanics meets optics

The new switch relies on non-Hermitian physics, a branch of quantum mechanics that explores how certain systems behave in unusual ways, giving researchers more control over light's behavior.

"We can tune the gain and loss of the material to guide the optical signal towards the right information highway exit," says Xilin Feng, a doctoral student in ESE and the paper's first author. In other words, the unique physics at play allows the researchers to tame the flow of light on the tiny chip, enabling precise control over any light-based network's connectivity.

The upshot is that the new switch can redirect signals in trillionths of a second with minimal power consumption. "This is about a billion times faster than the blink of an eye," says Shuang Wu, a doctoral student in MSE and co-author of the paper. "Previous switches were either small or fast, but it's very, very difficult to achieve these two properties simultaneously."

Using silicon for scalability

The new switch is also notable for being made partly of silicon, the inexpensive and widely available industry-standard material. "Non-Hermitian switching has never been demonstrated in a silicon photonics platform before," says Wu.

In theory, the incorporation of silicon into the switch will facilitate scaling the device for mass production and wide adoption in industry. Silicon is a key component in most technologies, from computers to smartphones; building the device using silicon makes it fully compatible with existing silicon photonic foundries, which make advanced chips for devices like graphics processing units (GPUs).

From concept to prototype

On top of the silicon layer, the switch consists of a particular type of semiconductor, made of Indium Gallium Arsenide Phosphide (InGaAsP), a material that is particularly effective at manipulating infrared wavelengths of light, such as those typically transmitted in undersea optical cables.

Joining the two layers proved challenging, and required numerous attempts to build a working prototype. "It's similar to making a sandwich," says Xilin Feng, referring to adding the layers to one another.

Only, in this case, if any of those layers were misaligned by even a tiny degree, the sandwich would be entirely inedible. "The alignment requires nanometer accuracy," Wu notes.

Transforming data centers

Ultimately, the researchers say, the new switch will benefit not just academic physicists, who can now further explore the non-Hermitian physics upon which the switch depends, but companies that maintain and build data centers, and the billions of users who rely on them.

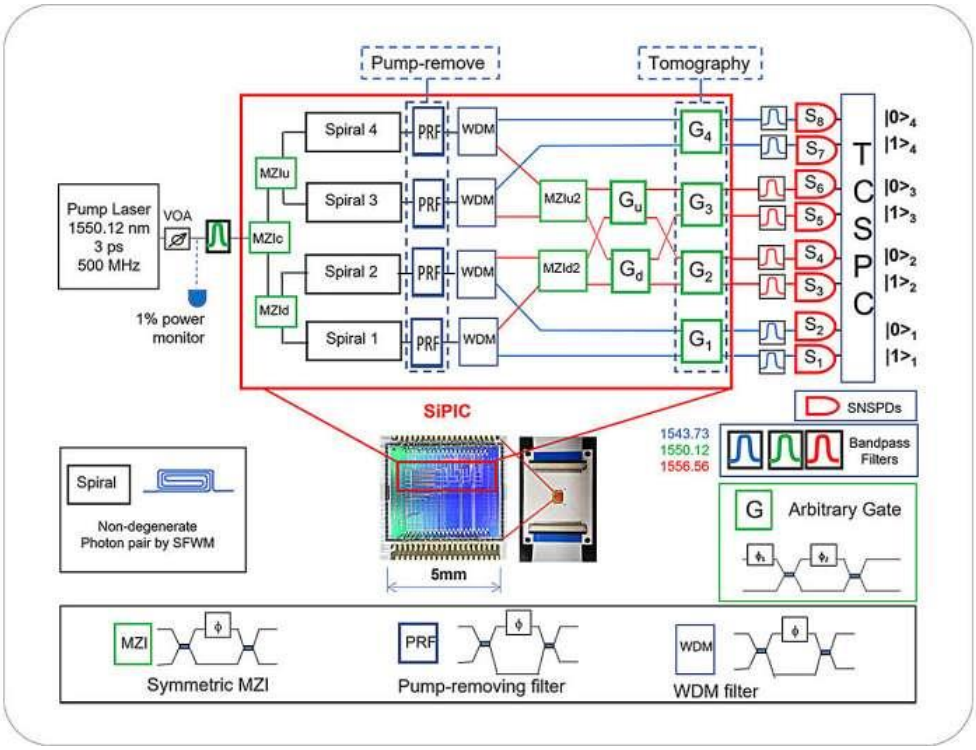
"Data can only go as fast as we can control it," says Liang Feng. "And in our experiments we showed that the speed limit of our system is just 100 picoseconds."

More information: Xilin Feng et al, Non-Hermitian hybrid silicon photonic switching, *Nature Photonics* (2025). DOI: 10.1038/s41566-024-01579-9
Journal information: Nature Photonics
Provided by University of Pennsylvania

NOVEMBER 14, 2024

Quantum computing researchers develop an 8-photon qubit chip

by National Research Council of Science and Technology



Package Image & Conceptual Chart of a Recon Photonics 4-Qubit Chip. Credit: Electronics and Telecommunications Research Institute(ETRI)

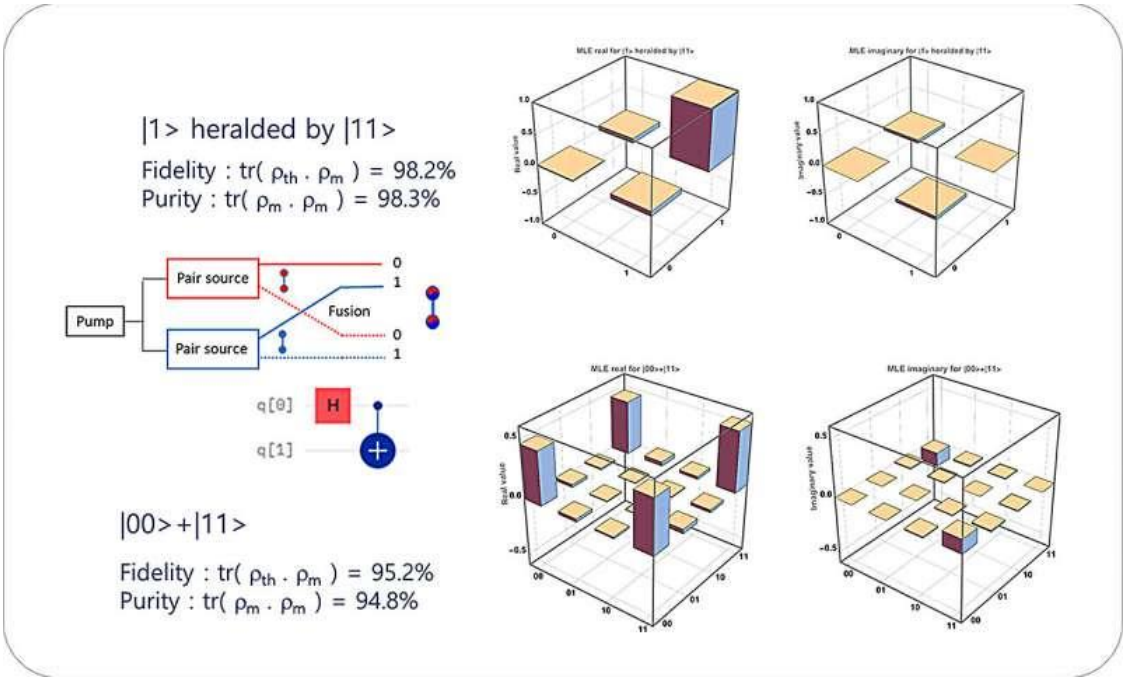
A group of South Korean researchers has successfully developed an integrated quantum circuit chip using photons (light particles). It is a system capable of controlling eight photons using a photonic integrated-circuit chip. With this system, they can explore various quantum phenomena, such as multipartite entanglement resulting from the interaction of the photons.

ETRI's extensive research on silicon-photonic quantum circuits has led to the demonstration of 2-qubit and 4-qubit quantum entanglement, achieving the best performance from a 4-qubit silicon photonics chip. These achievements resulted from their collaborative effort with KAIST and the University of Trento in Italy and were published in the prestigious scientific journals, Photonics Research and APL Photonics.

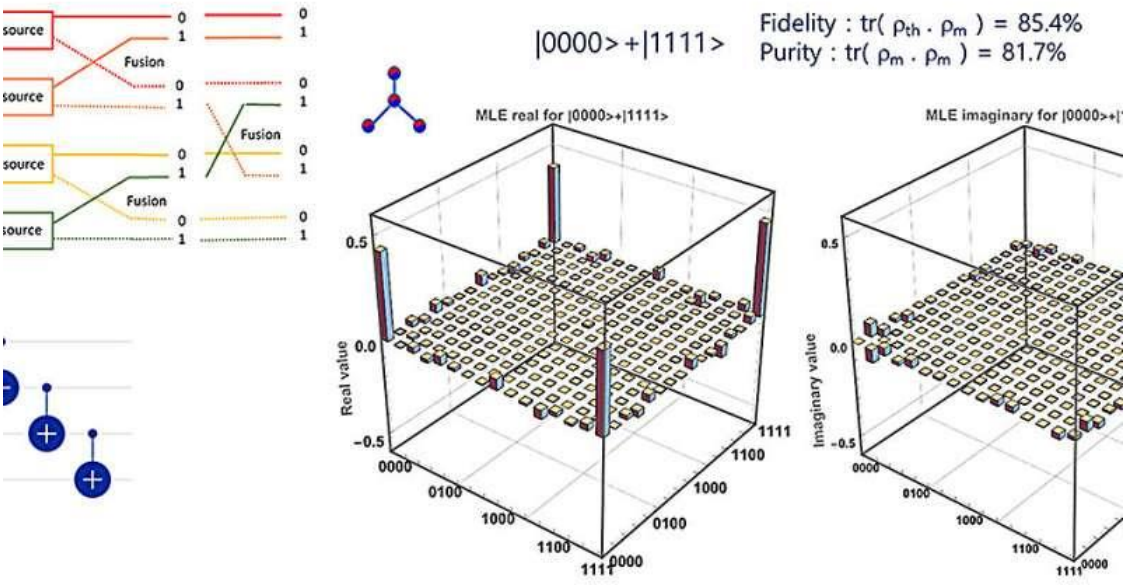
As a further advancement, ETRI recently demonstrated 6-qubit entanglement using a chip designed to control 8-photonic qubits. The 6-qubit entanglement represents a record-breaking achievement in quantum states based on a silicon-photonic chip.

Quantum circuits based on photonic qubits are among the most promising technologies currently under active research for building a universal quantum computer. Several photonic qubits can be integrated into a tiny silicon chip as small as a fingernail, and a large number of these tiny chips can be connected via optical fibers to form a vast network of qubits, enabling the realization of a universal quantum computer. Photonic quantum computers offer advantages in terms of scalability through optical networking, room-temperature operation, and the low energy consumption.

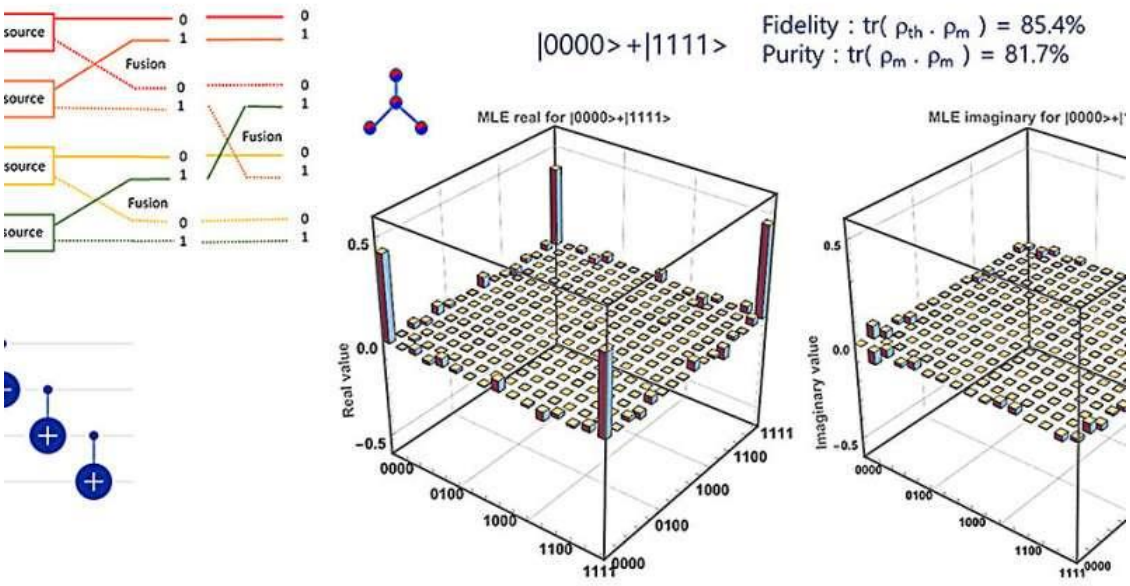
A photonic qubit can be encoded using a pair of propagation paths of a photon, with one path assigned as 0 and the other as 1. For a 4-qubit circuit, 8 propagation paths are required, and for 8 qubits, 16 paths are needed. Quantum states can be manipulated on a photonic chip, which includes photon sources, optical filters and linear-optic switches, and are finally measured using highly sensitive single-photon detectors.

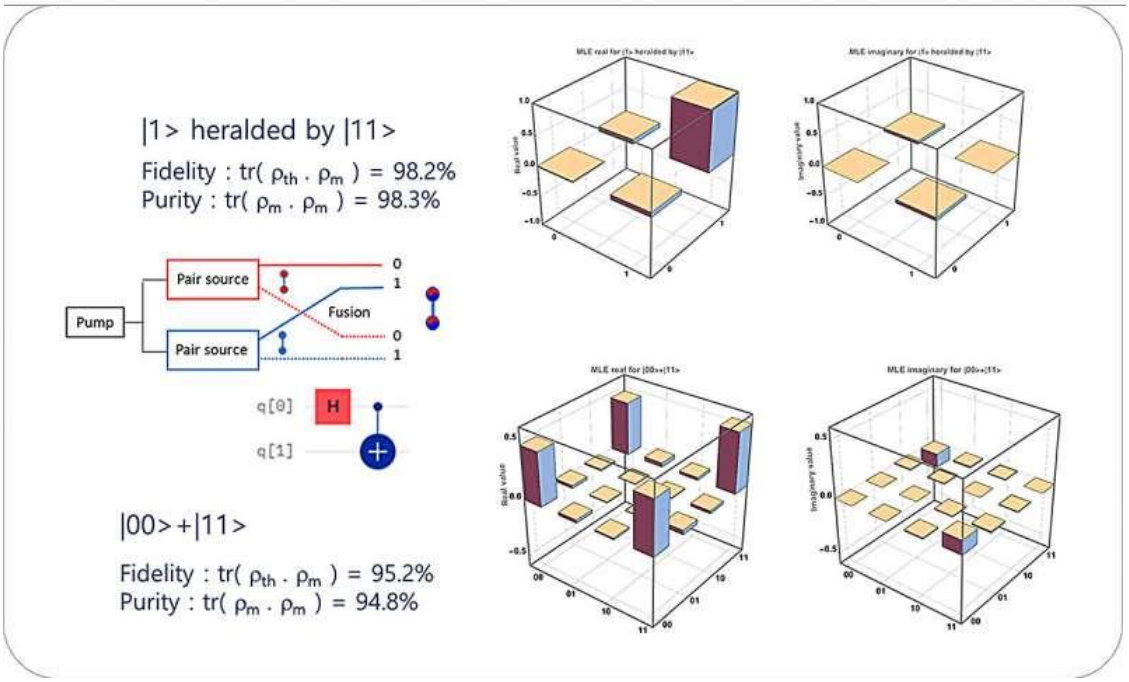


- Tomography Measurements of a Quantum Circuit (1-Qubit & 2-Qubit State). Credit: Electronics and Telecommunications Research Institute(ETRI)



- Tomography Measurements of a Quantum Circuit (4-Qubit GHZ State). Credit: Electronics and Telecommunications Research Institute(ETRI)





- Tomography Measurements of a Quantum Circuit (1-Qubit & 2-Qubit State). Credit: Electronics and Telecommunications Research Institute(ETRI)
- Tomography Measurements of a Quantum Circuit (4-Qubit GHZ State). Credit: Electronics and Telecommunications Research Institute(ETRI)

The 8-qubit chip includes 8 photonic sources and approximately 40 optical switches that control the propagation paths of the photons. About half of these 40 switches are specifically used as linear-optic quantum gates. The setup provides the fundamental framework for a quantum computer by measuring the final quantum states using single-photon detectors.

The research team measured the Hong-Ou-Mandel effect, a fascinating quantum phenomenon in which two different photons entering from different directions can interfere and travel together along the same path. In another notable quantum experiment, they demonstrated a 4-qubit entangled state on a 4-qubit integrated circuit (5mm x 5mm).

Recently, they have expanded their research to 8 photon experiments using an 8-qubit integrated circuit (10mm x 5mm). The researchers plan to fabricate 16-qubit chips within this year, followed by scaling up to 32-qubits as part of their ongoing research toward quantum computation.

Yoon Chun-Ju, Assistant Vice President of the Quantum Research Division of ETRI, said, "We plan to advance our quantum hardware technology for a cloud-based quantum computing service. Our main goal is to develop a lab-scale system to strengthen our research capabilities in quantum computation."

Lee Jong-Moo with ETRI's Quantum Computing Research Section, who led this achievement, stated, "Research for the practical implementation of quantum computers is highly active worldwide. However, extensive long-term research is still needed to realize practical quantum computation, especially to overcome computational errors caused by noise in the quantum processes."

More information: Jong-Moo Lee et al, Quantum states generation and manipulation in a programmable silicon-photonic four-qubit system with high-fidelity and purity, *APL Photonics* (2024). DOI: 10.1063/5.0207714
Provided by National Research Council of Science and Technology

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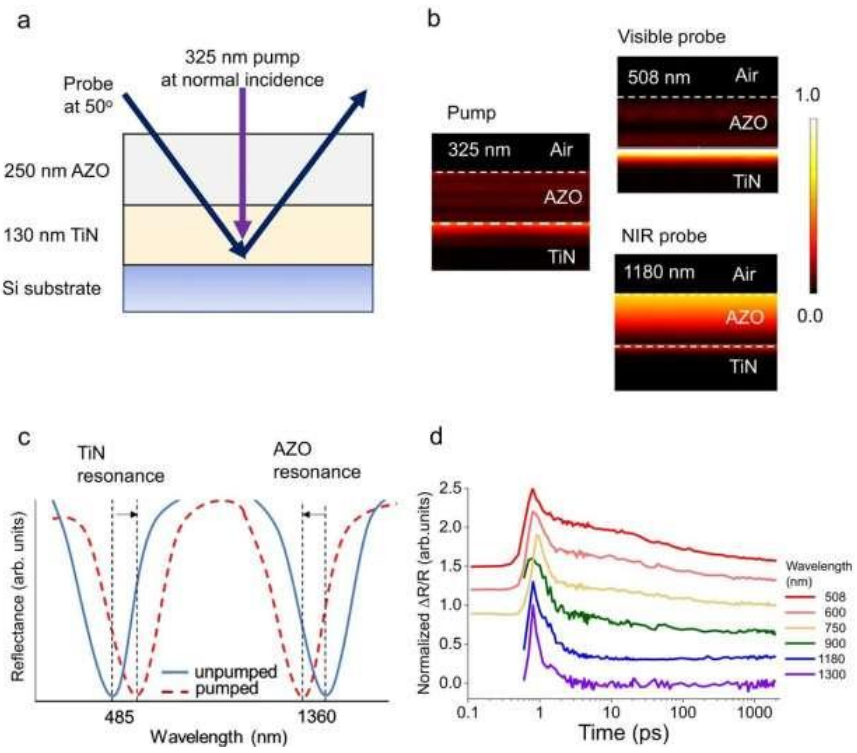
DECEMBER 21, 2023

Editors' notes

Researchers develop all-optical switches that could lead to faster computer processors

by Jared Sagoff, Argonne National Laboratory



Basic principle for adjustable switching dynamics. **a** The double-resonant two-layer device comprises a 130-nm-thick TiN layer grown on silicon, with a 250-nm-thick AZO layer deposited on top. **b** Normalized power dissipation density of probe in the different layers simulated by COMSOL Multiphysics. At normal incidence, the 325-nm wavelength pump is strongly absorbed in the AZO and TiN by exciting electrons in both materials. The materials interact most strongly with light near their respective ENZ wavelengths. Thus, at visible wavelengths, most of the probe interacts with the TiN, whereas the NIR probes interact more with the AZO layer. **c** The pump causes the reflectance spectrum to redshift at visible wavelengths, whereas, at near-infrared wavelengths, the pump blueshifts the reflectance spectrum. **d** The mechanism of fast and slow switching: TiN has a nanosecond response time, and AZO a picosecond response time. When excited by the same pump, the device has a slower observed response time in the visible probe wavelengths, where its behavior is dominated by the TiN response. At increasing wavelengths, its response speeds up as the relative light-matter interaction of the probe with the AZO increases. Credit: *Nature Communications* (2023). DOI: 10.1038/s41467-023-41377-5

Conventional computer processors have pretty much maxed out their "clock speeds"—a measurement of how fast they can toggle on and off—due to the limitations of electronic switching. Scientists looking to improve computer processors have become intrigued by the potential of all-optical switching, which uses light instead of electricity to control how data is processed and stored on a chip.

Researchers at the U.S. Department of Energy's (DOE) Argonne National Laboratory and Purdue University have recently created a new kind of all-optical switch that could realize this potential.

"Previous iterations of optical switches had fixed switching times that were 'baked in' to the device upon its fabrication," said Argonne's Soham Saha, one of the laboratory's Maria

Goeppert Mayer postdoctoral fellows who is working in the Argonne Center for Nanoscale Materials, a DOE Office of Science user facility.

Saha and his colleagues have made an optical switch out of two different materials, each with a different switching time. One material, aluminum-doped zinc oxide, has a switching time in the picosecond range, while the other material, plasmonic titanium nitride, has a switching time more than a hundred times slower in the nanosecond range.

"When you use optical components instead of electronic circuits, there are no resistive-capacitive delays, which means that, in theory, you could operate these chips a thousand times faster than conventional computer chips," Saha said.

The difference in switching times between the two metal components means that the switch can be more flexible and transmit data quickly while storing it effectively, according to Saha. "The bimetallic nature of the switch means that it can be used for multiple purposes depending on the wavelength of the light that you use," he said. "When you want slower applications, like memory storage, you switch with one material; for faster applications, you switch with the other one. This capability is new."

In the experimental configuration, the materials of the switch function as light absorbers or reflectors, depending on the wavelength of operation. When they are switched on by a light beam, they switch state.

Controlling the speed of all-optical switches is crucial for optimizing their performance in various applications. These findings offer promise for the development of highly adaptable and efficient switches in fields like enhanced fiber optic communication, optical computing, and ultrafast science.

The ability to adjust switch speeds also brings us closer to bridging the gap between optical and electronic communications, enabling faster and more efficient data transmission.

This research provides valuable insights into the fundamental understanding of all-optical switches and paves the way for the design of advanced devices for computing and telecommunications.

A paper based on the research, "Engineering the temporal dynamics of all-optical switching with fast and slow materials," is published in *Nature Communications*.

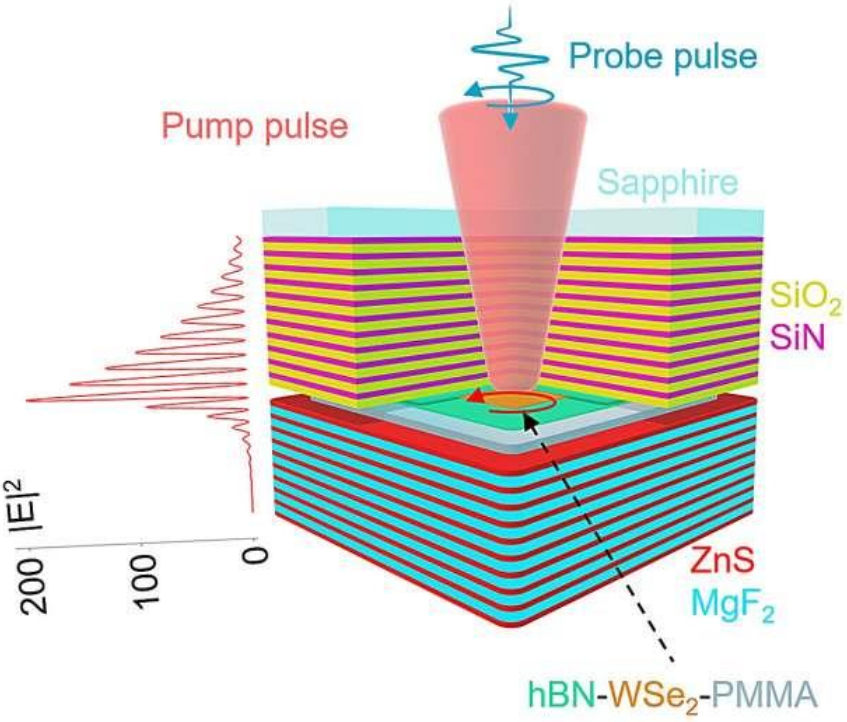
More information: Soham Saha et al, Engineering the temporal dynamics of all-optical switching with fast and slow materials, *Nature Communications* (2023). DOI: 10.1038/s41467-023-41377-5
Journal information: Nature Communications
Provided by Argonne National Laboratory

OCTOBER 19, 2024

Editors' notes

All-optical switch device paves way for faster fiber-optic communication

by Patricia DeLacey, University of Michigan College of Engineering



Schematic of the optical cavity with a one molecule thick layer of tungsten diselenide (WSe2) at the antinode, the point where the light field intensity is at its maximum. Credit: Deng Laboratory, University of Michigan

Modern high-speed internet uses light to quickly and reliably transmit large amounts of data through fiber-optic cables, but currently, light signals hit a bottleneck when data processing is necessary. For that, they must convert into electrical signals for processing before further transmission.

A device called an all-optical switch could instead use light to control other light signals without the need for electrical conversion, saving both time and energy in fiber-optic communication.

A University of Michigan-led research team demonstrated an ultrafast all-optical switch by pulsing circularly polarized light, which twists like a helix, through an optical cavity lined with an ultrathin semiconductor. The study was recently published in *Nature Communications*.

The device could function as a standard optical switch, where turning a control laser on or off switches the signal beam of the same polarization, or as a type of logic gate called Exclusive OR (XOR) switch, which would produce an output signal when one light input twists clockwise and the other is counterclockwise but not when both inputs are the same.

"Because a switch is the most elementary building block of any information processing unit, an all-optical switch is the first step towards all optical computing or building optical neural networks," said Lingxiao Zhou, a physics doctoral student at U-M and lead author of the study.

Optical computing's low loss makes it more desirable than electronic computing.

"Extremely low power consumption is a key to optical computing's success. The work done by our team addresses just this problem, using unusual two dimensional materials to switch data at very low energies per bit," said Stephen Forrest, the Peter A. Franken Distinguished University Professor of Electrical Engineering at U-M and contributing author of the study.

To achieve this, the researchers pulsed a helical laser at regular intervals through an optical cavity—a set of mirrors that trap and bounce light back and forth multiple times—boosting the strength of the laser by two orders of magnitude.

When a one-molecule-thick layer of the semiconductor tungsten diselenide (WSe_2) is embedded within the optical cavity, the strong, oscillating light enlarges the electronic bands of the available electrons in the semiconductor—a nonlinear optical effect known as the optical Stark effect. This means that when an electron jumps to a higher orbital, it absorbs more energy, and it emits more energy when it jumps down, known as blue shifting. This in turn modifies the signal light's fluence, the amount of energy delivered or reflected per unit area.

In addition to modulating the signal light, the optical Stark effect produced a pseudo-magnetic field, which influences electronic bands similarly to those of a magnetic field. Its effective strength was 210 Tesla, far stronger than Earth's strongest magnet with a strength of 100 Tesla. The enormously strong force is felt only by electrons whose spins are aligned with the helicity of the light, temporarily splitting the electronic bands of different spin orientations, directing the electrons in the aligned bands all in the same orientation.

The team could change the ordering of the electronic bands of different spins by changing the direction the light twists.

The brief uniform spin directionality of the electrons in different bands also breaks something called time reversal symmetry. Essentially, time reversal symmetry means that the physics underlying a process is the same forwards and backwards, implying conservation of energy.

While we typically can't observe this in the macroscopic world due to the way energy dissipates through forces like friction, if you could take a video of electrons spinning, it would obey the laws of physics whether you played it forward or backward—the electron spinning one way would turn into an electron spinning the opposite way with the same energy. But in the pseudo-magnetic field, time reversal symmetry is broken because if rewound, the electron spinning in the opposite direction has a different energy—and the energy of different spins can be controlled through the laser.

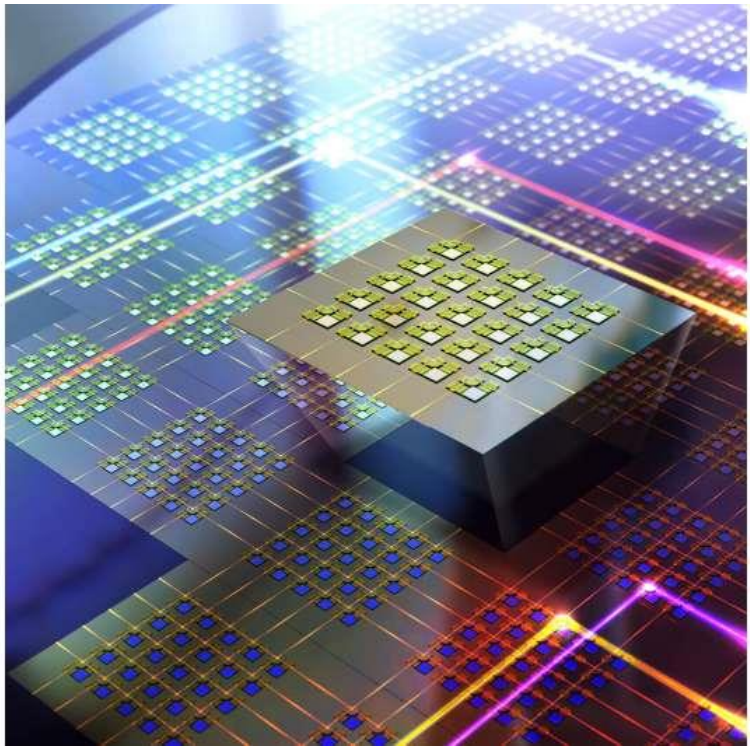
"Our results open doors to a lot of new possibilities, both in fundamental science where controlling time reversal symmetry is a requirement for creating exotic states of matter and for technology, where leveraging such a huge magnetic field becomes possible," said Hui Deng, a professor of physics and electrical and computer engineering at U-M and corresponding author of the study.

More information: Lingxiao Zhou et al, Cavity Floquet engineering, *Nature Communications* (2024). DOI: 10.1038/s41467-024-52014-0
Journal information: Nature Communications
Provided by University of Michigan College of Engineering

APRIL 12, 2019

Largest, fastest array of microscopic 'traffic cops' for optical communications

by Kara Manke, University of California - Berkeley



The photonic switch is built with more than 50,000 microscopic "light switches" etched into a silicon wafer. Each light switch (small raised squares) directs one of 240 tiny beams of light to either make a right turn when the switch is on, or to pass straight through when the switch is off. Credit: Younghee Lee graphic

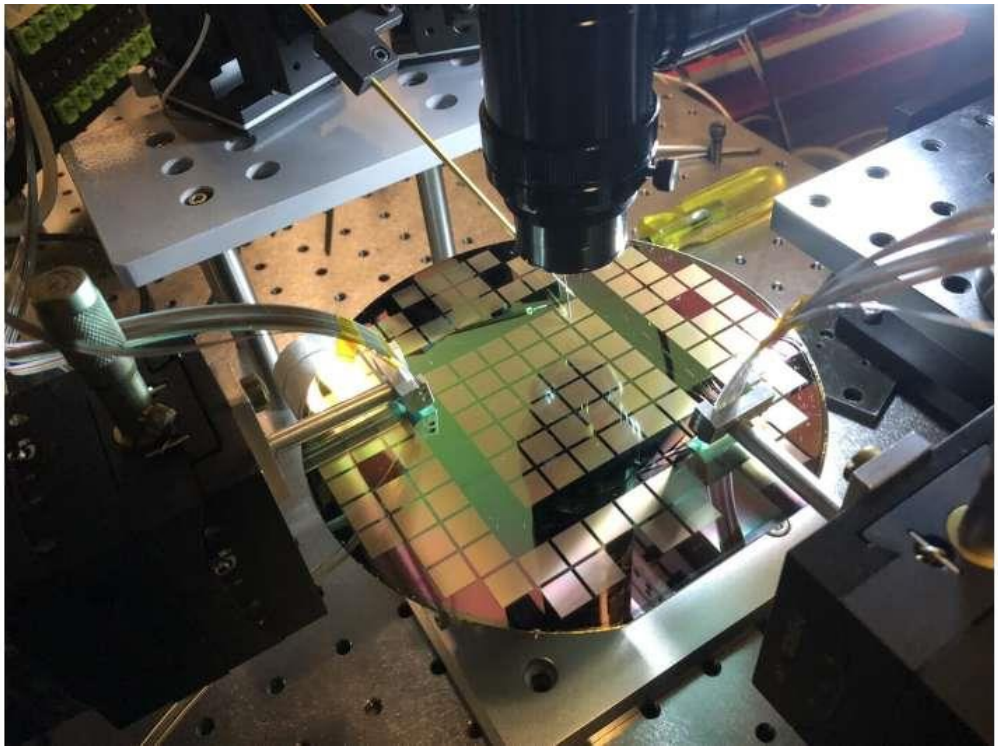
Engineers at the University of California, Berkeley have built a new photonic switch that can control the direction of light passing through optical fibers faster and more efficiently than ever. This optical "traffic cop" could one day revolutionize how information travels through data centers and high-performance supercomputers that are used for artificial intelligence and other data-intensive applications.

The photonic switch is built with more than 50,000 microscopic "light switches," each of which directs one of 240 tiny beams of light to either make a right turn when the switch is on, or to pass straight through when the switch is off. The 240-by-240 array of switches is etched into a silicon wafer and covers an area only slightly larger than a postage stamp.

"For the first time in a silicon switch, we are approaching the large switches that people can only build using bulk optics," said Ming Wu, professor of electrical engineering and computer sciences at UC Berkeley and senior author of the paper, which appears WHEN in

the journal *Optica*. "Our switches are not only large, but they are 10,000 times faster, so we can switch data networks in interesting ways that not many people have thought about."

Currently, the only photonic switches that can control hundreds of light beams at once are built with mirrors or lenses that must be physically turned to switch the direction of light. Each turn takes about one-tenth of a second to complete, which is eons compared to electronic data transfer rates. The new photonic switch is built using tiny integrated silicon structures that can switch on and off in a fraction of a microsecond, approaching the speed necessary for use in high-speed data networks.



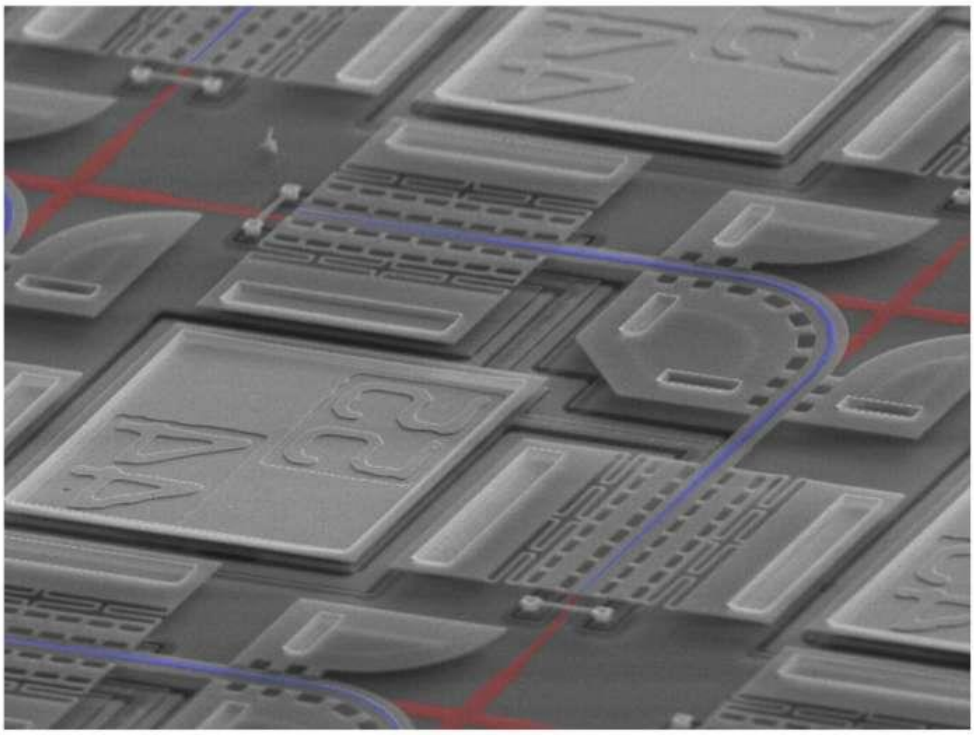
The photonic switch is manufactured using a technique called photolithography, in which each "light switch" structure is etched into a silicon wafer. Each light gray square on the wafer contains 6,400 of these switches. Credit: Kyungmok Kwon

Traffic cops on the information highway

Data centers—where our photos, videos and documents saved in the cloud are stored—are composed of hundreds of thousands of servers that are constantly sending information back and forth. Electrical switches act as traffic cops, making sure that information sent from one server reaches the target server and doesn't get lost along the way.

But as data transfer rates continue to grow, we are reaching the limits of what electrical switches can handle, Wu said.

"Electrical switches generate so much heat, so even though we could cram more transistors onto a switch, the heat they generate is starting to pose certain limits," he said. "Industry expects to continue the trend for maybe two more generations and, after that, something more fundamental has to change. Some people are thinking optics can help."



Each individual "light switch" is constructed like a microscopic highway overpass. When the switch is off, the light passes straight through a lower channel (red lines). Turning the switch on lowers a tiny ramp, directing the light to an upper channel to make a right turn (blue lines). A second ramp lowers the light back down. Credit: Tae Joon Seok image

Server networks could instead be connected by optical fibers, with photonic switches acting as the traffic cops, Wu said. Photonic switches require very little power and don't generate any heat, so they don't face the same limitations as electrical switches. However, current photonic switches cannot accommodate as many connections and also are plagued by signal loss—essentially "dimming" the light as it passes through the switch—which makes it hard to read the encoded data once it reaches its destination.

In the new photonic switch, beams of light travel through a crisscrossing array of nanometer-thin channels until they reach these individual light switches, each of which is built like a microscopic freeway overpass. When the switch is off, the light travels straight through the channel. Applying a voltage turns the switch on, lowering a ramp that directs the light into a higher channel, which turns it 90 degrees. Another ramp lowers the light back into a perpendicular channel.

"It's literally like a freeway ramp," Wu said. "All of the light goes up, makes a 90-degree turn and then goes back down. And this is a very efficient process, more efficient than what everybody else is doing on silicon photonics. It is this mechanism that allows us to make lower-loss switches."

The team uses a technique called photolithography to etch the switching structures into silicon wafers. The researchers can currently make structures in a 240-by-240 array—240 light inputs and 240 light outputs—with limited light loss, making it the largest silicon-based switch ever reported. They are working on perfecting their manufacturing technique to create even bigger switches.

"Larger switches that use bulk optics are commercially available, but they are very slow, so they are usable in a network that you don't change too frequently," Wu said. "Now, computers work very fast, so if you want to keep up with the computer speed, you need much faster switch response. Our switch is the same size, but much faster, so it will enable new functions in data center networks."

More information: Tae Joon Seok et al, Wafer-scale silicon photonic switches beyond die size limit, *Optica* (2019). DOI: 10.1364/OPTICA.6.000490
Journal information: Optica
Provided by University of California - Berkeley

FEBRUARY 28, 2019

Integrated silicon photonic switch has lowest signal loss in high-speed data transmission

by Optical Society of America

Experimental photonic switches tested by researchers at the University of California, Berkeley, U.S.A., show promise toward the goal of fully optical, high-capacity switching for future high-speed data transmission networks. The switch developed and tested for this research demonstrated capabilities not seen before in photonic switches.

In a paper to be presented at OFC: The Optical Fiber Communications Conference and Exhibition, to be held 3-7 March in San Diego, Calif., U.S.A., researchers Tae Joon Seok and colleagues will report successful scale up of a 240x240 integrated silicon photonic switch. The device is so-named because it accepts 240 optical communication input channels and sends them into 240 output channels.

Using experimental photonic switches manufactured at the Marvell Nanofabrication Laboratory at UC Berkeley, the research team demonstrated signal loss lower than any previously reported, said Seok, who is assistant professor at the Gwangju Institute of Science and Technology in South Korea and a visiting scholar at UC Berkeley.

Addressing industry needs with advanced optical switching

The telecommunications industry long ago embraced fiber-optic technology as a better solution to meet exploding demand for higher speeds and greater capacity data transmission over the electrical copper wires of old. Now a similar revolution is occurring at the points where the messages transmitted over long-haul fibers are sent and received. Instead of power-hungry electrical switches that require optical-electrical-optical conversions and cause signal loss, researchers are developing and deploying photonic switches to improve transmission quality and link a single transmission to tens and sometimes thousands of servers.

In particular, silicon-based photonic switches using advanced complementary metal-oxide semi-conductor (CMOS) technology are drawing a lot of attention from researchers as a powerful platform due to their low cost and high capacity. They have the potential to replace electrical switches, which will soon face scalability limits in performance and energy efficiency. In order to realize this potential, researchers are now working to overcome limitations related to the size of today's silicon photonic chips and improve their performance.

"Recently, many research groups competitively reported silicon photonic switches with large input/ouput port counts," said Seok. However, the physical size of a silicon photonic chip has been limited to 2 to 3 cm because of the limitations of the lithography tools necessary to etch the required geometric patterns on the silicon wafers used as a base for the integrated chips.

Seok and his colleagues overcame this limitation by using a process known as lithography stitching, creating a wafer-scale 240x240 silicon photonic switch by stitching together nine 80x80 switch blocks in a 3x3 array, with three input and three output coupler blocks. The switches developed as part of the experiment coupled light coming in and out of the chip through grating couplers. The switch cells were actuated by electrical probes.

The resulting switch area was 4 cm x 4 cm—nearly doubling the size of existing silicon photonic switches. "To the best of our knowledge, this is the largest integrated photonic switch ever reported on any platform," Seok said.

Measured results from the experimental switch also broke records. "The on-chip loss to port-count ratio (0.04 dB/port) is the lowest demonstrated," Seok added.

"This technology can be applied not only to silicon photonic switches but also to any silicon photonics applications that require ultra-large-scale devices such as programmable photonic processors, and so on," Seok said.

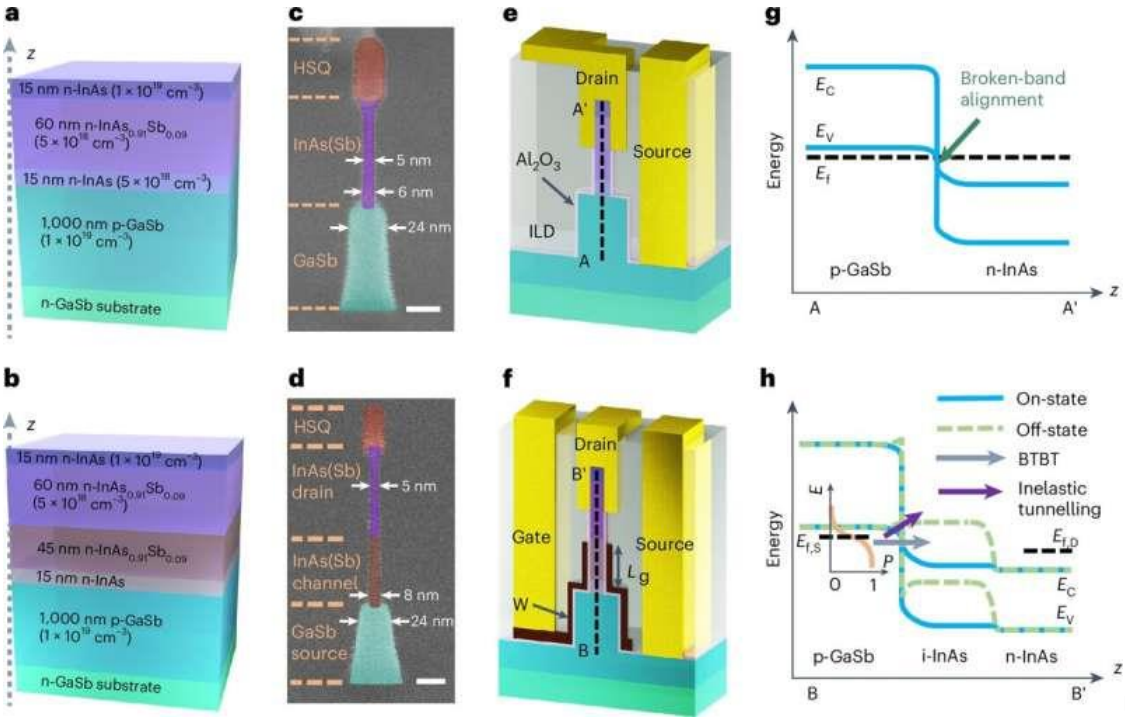
Provided by Optical Society of America

NOVEMBER 4, 2024

Editors' notes

Nanoscale transistors could enable more efficient electronics

by Adam Zewe, Massachusetts Institute of Technology



Ultra-scaled vertical-nanowire device design. Credit: *Nature Electronics* (2024). DOI: 10.1038/s41928-024-01279-w

Silicon transistors, which are used to amplify and switch signals, are a critical component in most electronic devices, from smartphones to automobiles. But silicon semiconductor technology is held back by a fundamental physical limit that prevents transistors from operating below a certain voltage.

This limit, known as "Boltzmann tyranny," hinders the energy efficiency of computers and other electronics, especially with the rapid development of artificial intelligence technologies that demand faster computation.

In an effort to overcome this fundamental limit of silicon, MIT researchers fabricated a different type of three-dimensional transistor using a unique set of ultrathin semiconductor materials. The research appears in *Nature Electronics.*

Their devices, featuring vertical nanowires only a few nanometers wide, can deliver performance comparable to state-of-the-art silicon transistors while operating efficiently at much lower voltages than conventional devices.

"This is a technology with the potential to replace silicon, so you could use it with all the functions that silicon currently has, but with much better energy efficiency," says Yanjie Shao, an MIT postdoc and lead author of a paper on the new transistors.

The transistors leverage quantum mechanical properties to simultaneously achieve low-voltage operation and high performance within an area of just a few square nanometers. Their extremely small size would enable more of these 3D transistors to be packed onto a computer chip, resulting in fast, powerful electronics that are also more energy-efficient.

"With conventional physics, there is only so far you can go. The work of Yanjie shows that we can do better than that, but we have to use different physics. There are many challenges yet to be overcome for this approach to be commercial in the future, but conceptually, it really is a breakthrough," says senior author Jesús del Alamo, the Donner Professor of Engineering in the MIT Department of Electrical Engineering and Computer Science (EECS).

They are joined on the paper by Ju Li, the Tokyo Electric Power Company Professor in Nuclear Engineering and professor of materials science and engineering at MIT; EECS graduate student Hao Tang; MIT postdoc Baoming Wang; and professors Marco Pala and David Esseni of the University of Udine in Italy.

Surpassing silicon

In electronic devices, silicon transistors often operate as switches. Applying a voltage to the transistor causes electrons to move over an energy barrier from one side to the other, switching the transistor from "off" to "on." By switching, transistors represent binary digits to perform computation.

A transistor's switching slope reflects the sharpness of the "off" to "on" transition. The steeper the slope, the less voltage is needed to turn on the transistor and the greater its energy efficiency.

But because of how electrons move across an energy barrier, Boltzmann tyranny requires a certain minimum voltage to switch the transistor at room temperature.

To overcome the physical limit of silicon, the MIT researchers used a different set of semiconductor materials—gallium antimonide and indium arsenide—and designed their devices to leverage a unique phenomenon in quantum mechanics called quantum tunneling.

Quantum tunneling is the ability of electrons to penetrate barriers. The researchers fabricated tunneling transistors, which leverage this property to encourage electrons to push through the energy barrier rather than going over it.

"Now, you can turn the device on and off very easily," Shao says.

But while tunneling transistors can enable sharp switching slopes, they typically operate with low current, which hampers the performance of an electronic device. Higher current is necessary to create powerful transistor switches for demanding applications.

Fine-grained fabrication

Using tools at MIT.nano, MIT's state-of-the-art facility for nanoscale research, the engineers were able to carefully control the 3D geometry of their transistors, creating vertical nanowire heterostructures with a diameter of only 6 nanometers. They believe these are the smallest 3D transistors reported to date.

Such precise engineering enabled them to achieve a sharp switching slope and high current simultaneously. This is possible because of a phenomenon called quantum confinement.

Quantum confinement occurs when an electron is confined to a space that is so small that it can't move around. When this happens, the effective mass of the electron and the properties of the material change, enabling stronger tunneling of the electron through a barrier.

Because the transistors are so small, the researchers can engineer a very strong quantum confinement effect while also fabricating an extremely thin barrier.

"We have a lot of flexibility to design these material heterostructures so we can achieve a very thin tunneling barrier, which enables us to get very high current," Shao says.

Precisely fabricating devices that were small enough to accomplish this was a major challenge.

"We are really into single-nanometer dimensions with this work. Very few groups in the world can make good transistors in that range. Yanjie is extraordinarily capable to craft such well-functioning transistors that are so extremely small," says del Alamo.

When the researchers tested their devices, the sharpness of the switching slope was below the fundamental limit that can be achieved with conventional silicon transistors. Their devices also performed about 20 times better than similar tunneling transistors.

"This is the first time we have been able to achieve such sharp switching steepness with this design," Shao adds.

The researchers are now striving to enhance their fabrication methods to make transistors more uniform across an entire chip. With such small devices, even a 1-nanometer variance can change the behavior of the electrons and affect device operation.

They are also exploring vertical fin-shaped structures, in addition to vertical nanowire transistors, which could potentially improve the uniformity of devices on a chip.

More information: Yanjie Shao et al, Scaled vertical-nanowire heterojunction tunnelling transistors with extreme quantum confinement, *Nature Electronics* (2024). DOI: 10.1038/s41928-024-01279-w
Journal information: Nature Electronics
Provided by Massachusetts Institute of Technology

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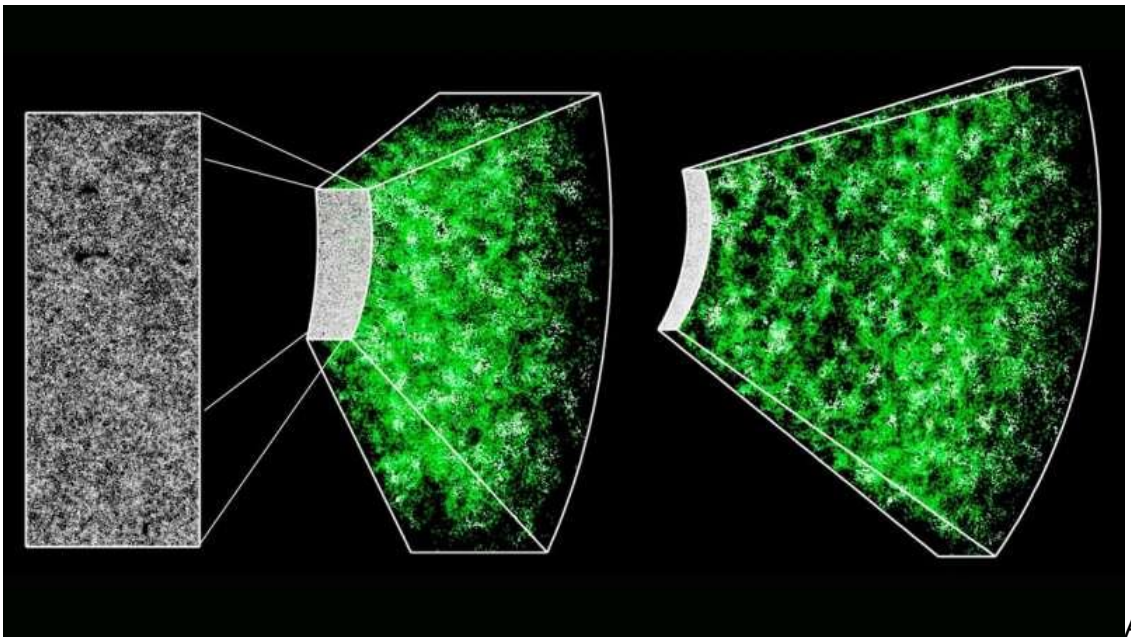
JANUARY 3, 2025 FEATURE

Scientists detect mysterious suppression in cosmic structure growth

by Tejasri Gururaj , Phys.org



A section of the three-dimensional map constructed by BOSS. Image credit: Jeremy Tinker and the SDSS-III collaboration. Credit: Jeremy Tinker and the SDSS-III collaboration

A new study in published in *Physical Review Letters* analyzes the most complete set of galaxy clustering data to test the ΛCDM model, revealing discrepancies in the formation of cosmic structures in the universe, hinting at a new physics.

The ΛCDM model is the standard model of cosmology describing the universe's evolution, expansion, and structure. It encompasses cold dark matter (CDM), normal matter and radiation, and the cosmological constant (Λ), which accounts for dark energy.

The model has been successful in explaining several cosmological observations, including the large-scale structure of the universe, the accelerating expansion of the universe, and the cosmic microwave background (CMB) radiation, which is the afterglow of the Big Bang.

Despite this, ΛCDM fails to account for phenomena like cosmic inflation, dark energy, and dark matter. Recent observations, like data from DESI (Dark Energy Survey Instrument), have suggested potential anomalies in ΛCDM.

The research team aimed to analyze whether these anomalies might be connected and could point to a specific new physical model.

The team consisted of Dr. Shi-Fan Chen, from the Institute for Advanced Study, New Jersey; Prof. Mikhail Ivanov, from the Massachusetts Institute of Technology; Dr. Oliver Philcox, from Columbia University; and Lukas Wenzl, a graduate student at Cornell.

Speaking of the motivation behind their work, Dr. Chen said, "Being able to predict anything about the universe is cool, but what's especially neat is that we have many different observables from many surveys whose measurements we can model using one consistent effective theory."

Connecting the cosmic dots

As mentioned, the ΛCDM model fails to account for certain phenomena based on recent observations.

These include the disagreement between direct and indirect measurements of the expansion rate of the universe (the Hubble tension), the disagreement between the direct and indirect measurements of matter clustering, i.e., structure growth (The σ_8 tension), and recent DESI data suggesting possible evidence for dynamical dark energy.

The research team's approach is new because they want to see if the same underlying physics could explain these anomalies. To test the hypothesis, the researchers combined measurements from multiple sources to create a comprehensive data set.

This included the BOSS (Baryon Oscillation Spectroscopic Survey) DR12 dataset with northern and southern galactic caps, LOWZ (low-redshift galaxies) and CMASS (high-mass galaxies) samples covering different redshift ranges, and cross-correlation with Planck CMB gravitational lensing maps.

This data was analyzed in two settings, within the standard ΛCDM model and within a dynamical dark energy model to test DESI's findings.

Dr. Philcox explained how they maintained high accuracy of the chosen data. "We really tried to pick consistent definitions for galaxy samples, throwing out parts of the available data with accidental mistakes in the selection criteria, at the expense of our statistical constraints even when past analyses have used these data."

"In addition, we performed many tests on the cross-correlations with CMB lensing as part of previous papers to make sure that no obvious systematics were there."

A universe growing too slowly?

The ΛCDM analysis revealed a slightly lower growth rate of cosmic structures than predicted, showing a significant disagreement (4.5σ tension) with Planck's results.

Additionally, it confirmed existing values for matter density, the Hubble constant, and structure growth.

In the dynamical dark energy analysis, the team found no strong evidence for dynamical dark energy, suggesting that dark energy behaves like a cosmological constant. The suppression of structure growth observed is similar to those predicted by the ΛCDM analysis.

Finally, the value of the Hubble constant aligns with Planck data but disagrees with direct, local measurements.

Prof. Ivanov explained, "We found that the structure formation in the late universe where the effects of dark energy are most pronounced, at least as measured by galaxies in the BOSS survey, seems substantially suppressed compared to expectations from the early universe and the CMB."

"This is true even when we allow the expansion history to deviate from the standard cosmological constant form of dark energy."

New physics or errors in data

According to the team, the odds of suppressed structure growth being a random chance is 1 in 300,000, which strongly suggests that something unexplained is happening in the form of unknown systematics in the data or new physics.

The findings also provide the strongest evidence to date for the σ_8 tension and show that dynamical dark energy cannot resolve it.

Wenzl explained, "In addition to new observational techniques and systematics tests mentioned, if this signal survives, it will be interesting to see what kinds of new physics can help resolve the tension with the CMB."

"For example, it would be very cool if non-standard dark matter candidates like axionic dark matter or dark matter that interacts with itself or baryons in some way, which would alter the formation of structure, can explain the signal."

The study's findings challenge our understanding of cosmic structure formation and, more importantly, one of the most fundamental models in cosmology.

Data from upcoming galaxy surveys will provide clarity on these discrepancies, and if we need a fundamental change in our understanding of large-scale structures in the universe.

More information: Shi-Fan Chen et al, Suppression without Thawing: Constraining Structure Formation and Dark Energy with Galaxy Clustering, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.133.231001. On *arXiv*: DOI: 10.48550/arxiv.2406.13388
Journal information: Physical Review Letters , arXiv

NOVEMBER 25, 2024

Editors' notes

Einstein predicted how gravity should work at the largest scales. And he was right, suggests new research

by Brian Koberlein, Universe Today


The sparkling band of the Milky Way Galaxy backdrops the Nicholas U. Mayall 4-meter Telescope, located at Kitt Peak National Observatory. Credit: KPNO/NOIRLab/NSF/AURA/R.T. Sparks

When Albert Einstein introduced his theory of general relativity in 1915, it changed the way we viewed the universe. His gravitational model showed how Newtonian gravity, which had dominated astronomy and physics for more than three centuries, was merely an approximation of a more subtle and elegant model.

Einstein showed us that gravity is not a mere force but is rather the foundation of cosmic structure. Gravity, Einstein said, defined the structure of space and time itself.

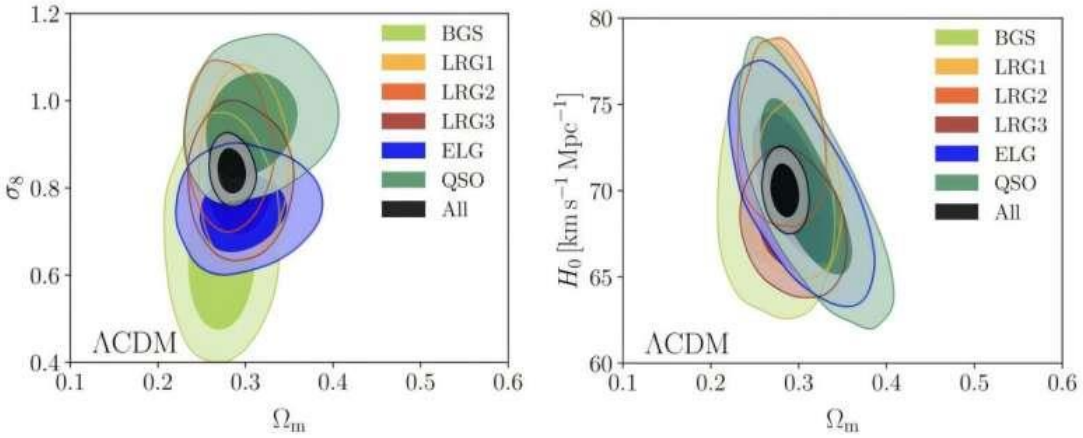
But in the past century, we have learned far more about the cosmos than even Einstein could have imagined. Some of our observations, such as gravitational lensing clearly confirm general relativity, but others seem to poke holes in the model. The rotational motion

of galaxies doesn't match the predictions of gravity alone, leading astronomers to introduce dark matter.

The expansion of the universe is not steady but is accelerating, pointing to the presence of dark energy. For some astronomers, this points to the need for a new model. Something that can account for the motions of stars and galaxies without the need for those dark materials that remain undetected in the lab. The most popular alternatives focus on theories of modified gravity.

The standard model of cosmology is known as the LCDM model. The L, for lambda, is the symbol used in general relativity to represent the rate of cosmic expansion and represents dark energy, while CDM stands for cold dark matter. This model describes an expanding universe that began as a hot, dense state about 13.78 billion years ago.

It is a universe made up of about 5% regular matter, 25% dark matter, and 70% dark energy. It is currently the model best supported by observational evidence. Modified gravity models have a big hill to climb. To topple LCDM they have to account for everything it predicts as well as eliminate the need for dark matter and energy.



Observations confirm the validity of general relativity and the standard model of cosmology. Credit: The DESI Collaboration.

This year, that hill has become much steeper. In a series of publications released by the Dark Energy Spectroscopic Instrument (DESI) collaboration and posted to the *arXiv* preprint server, the standard cosmological model has been confirmed to be in complete agreement with Einstein's model. The DESI survey mapped nearly 6 million galaxies across 11 billion years of cosmic time, allowing astronomers to see not just how galaxies cluster but how that clustering changes over time. It is the largest 3D map of the universe made thus far.

The LCDM model makes very stringent predictions of cosmic structure. If dark energy were a kind of repulsive force rather than an inherent property of spacetime, clustering would evolve differently than observed. If dark matter was an illusion of modified gravitational forces, the scale of galactic clustering would be different.

This latest survey shows in explicit detail that modified gravity models don't hold up. The results strongly constrain which modified gravity models are possible and rule out many of

the models currently proposed. Based on these new results, the standard cosmological model of Einsteinian gravity, dark matter, and dark energy is the one that best fits the observed universe.

There are still mysteries that still need to be solved, most significantly the issue of the Hubble tension problem. Perhaps a novel modified gravity model will solve this mystery and finally topple Einstein, but for now, the wild-haired genius remains king of the hill.

More information: DESI Collaboration et al, DESI 2024 II: Sample Definitions, Characteristics, and Two-point Clustering Statistics, *arXiv* (2024). DOI: 10.48550/arxiv.2411.12020

DESI Collaboration et al, DESI 2024 V: Full-Shape Galaxy Clustering from Galaxies and Quasars, *arXiv* (2024). DOI: 10.48550/arxiv.2411.12021

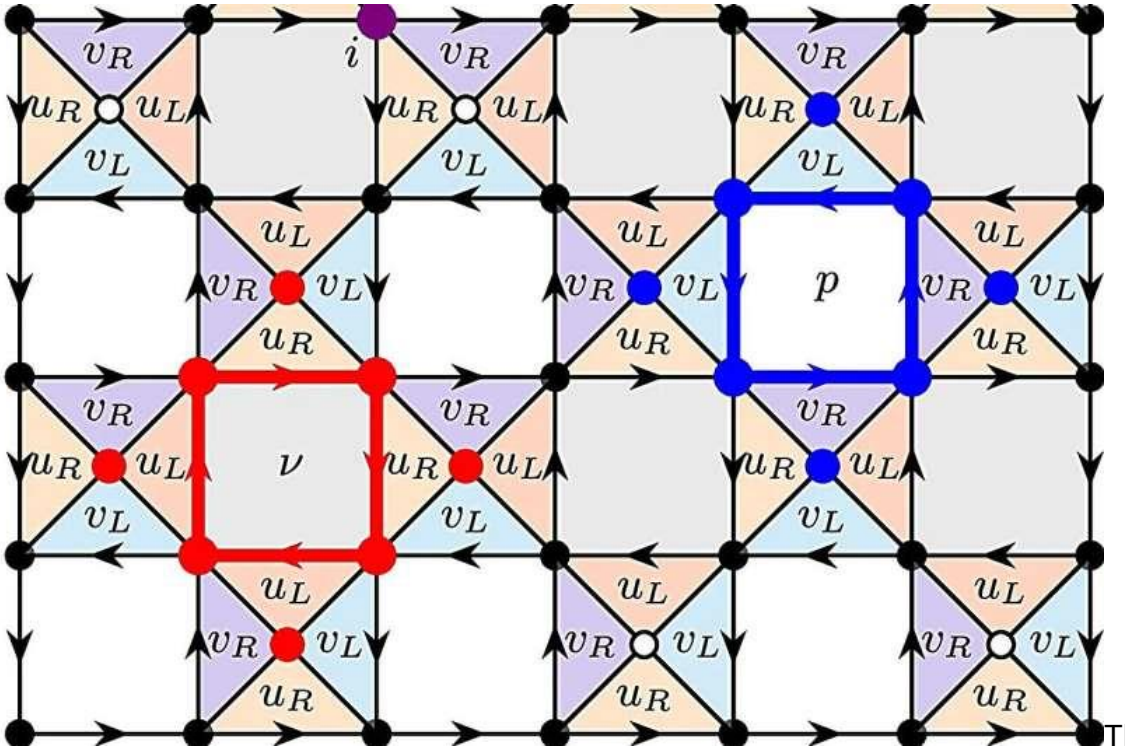
DESI Collaboration et al, DESI 2024 VII: Cosmological Constraints from the Full-Shape Modeling of Clustering Measurements, *arXiv* (2024). DOI: 10.48550/arxiv.2411.12022
Journal information: arXiv
Provided by Universe Today

JANUARY 8, 2025

Editors' notes

Mathematical methods point to possibility of particles long thought impossible

by George Hale, Rice University



The 2D exactly solvable spin model on a 7 × 7 lattice with open boundary conditions.
Credit: *Nature* (2025). DOI: 10.1038/s41586-024-08262-7

From the early days of quantum mechanics, scientists have thought that all particles can be categorized into one of two groups—bosons or fermions—based on their behavior.

However, new research by Rice University physicist Kaden Hazzard and former Rice graduate student Zhiyuan Wang shows the possibility of particles that are neither bosons nor fermions. Their study, published in *Nature*, mathematically demonstrates the potential existence of paraparticles that have long been thought impossible.

"We determined that new types of particles we never knew of before are possible," said Hazzard, associate professor of physics and astronomy.

Quantum mechanics has long held that all observable particles are either fermions or bosons. These two types of particles are distinguished by how they behave when near other

particles in a given quantum state. Bosons are able to congregate in unlimited numbers, whereas only one fermion can exist in a given state. This behavior of fermions is referred to as the Pauli exclusion principle, which states that no more than two electrons, each with opposite spins, can occupy the same orbital in an atom.

"This behavior is responsible for the whole structure of the periodic table," said Hazzard. "It's also why you don't just go through your chair when you sit down."

In the 1930s and 1940s, researchers began trying to understand whether other types of particles could exist. A concrete quantum theory of such particles, known as paraparticles, was formulated in 1953 and extensively studied by the high energy physics community. However, by the 1970s, mathematical studies seemed to show that so-called paraparticles were actually just bosons or fermions in disguise. The one exception was the existence of anyons, an exotic type of particle that exists only in two dimensions.

However, the mathematical theories of the 1970s and beyond were based on assumptions that are not always true in physical systems. Using a solution to the Yang-Baxter equation, an equation useful for describing the interchange of particles, along with group theory and other mathematical tools, Hazzard and Wang set to work to show that paraparticles could theoretically exist and be fully compatible with the known constraints of physics.

The researchers focused on excitations—which can be thought of as particles—in condensed matter systems such as magnets to provide a concrete example of how paraparticles can emerge in nature.

"Particles aren't just these fundamental things," said Hazzard. "They're also important in describing materials."

"This is cross-disciplinary research that involves several areas of theoretical physics and mathematics," said Wang, now a postdoctoral researcher at the Max Planck Institute of Quantum Optics in Germany.

Using advanced mathematics, such as Lie algebra, Hopf algebra and representation theory, as well as a pictorial method based on something known as tensor network diagrams to better handle equations, Hazzard and Wang were able to perform abstract algebraic calculations to develop models of condensed matter systems where paraparticles emerge.

They showed that, unlike fermions or bosons, paraparticles behave in strange ways when they exchange their positions with the internal states of the particles transmuting during the process.

While they are groundbreaking on their own, these models are the first step toward a better understanding of many new physical phenomena that could occur in paraparticle systems.

Further development of this theory could guide experiments that could detect paraparticles in the excitations of condensed matter systems.

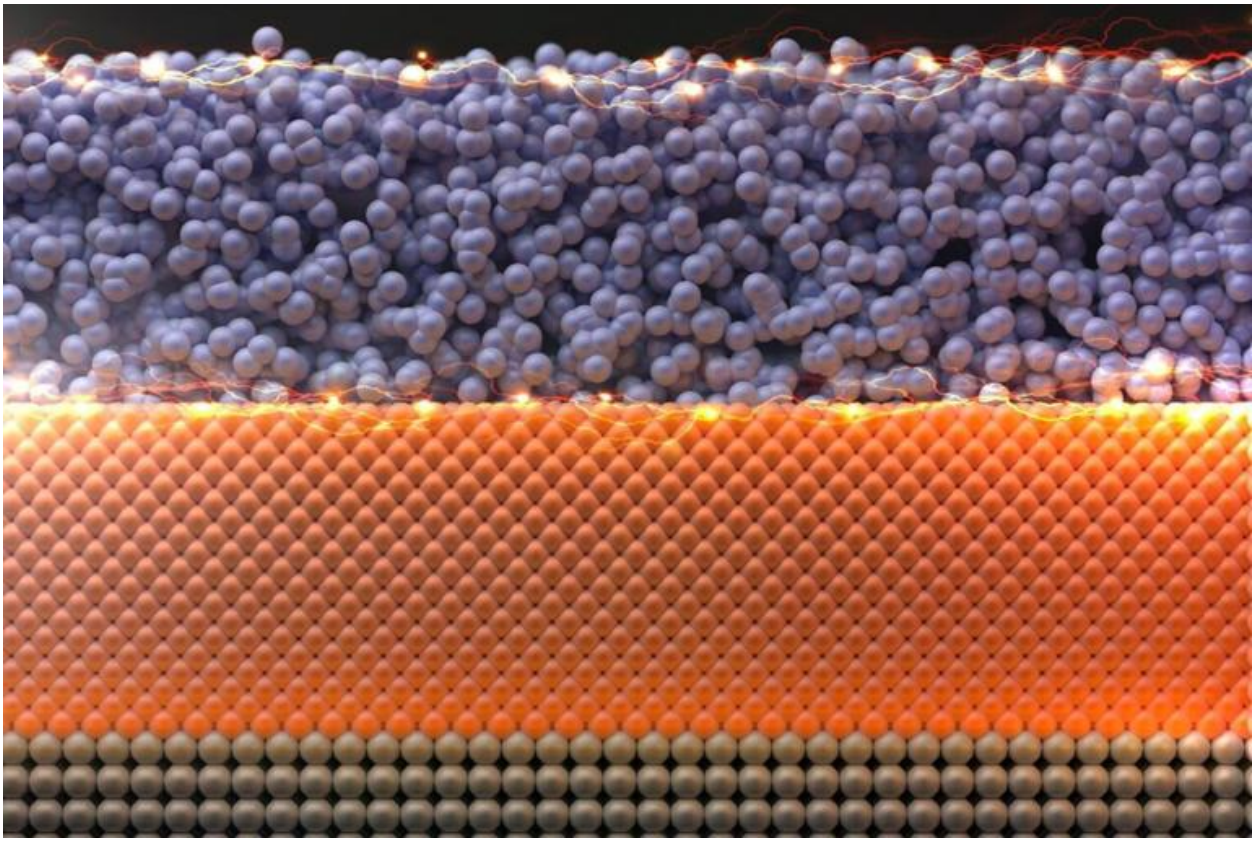
"To realize paraparticles in experiments, we need more realistic theoretical proposals," said Wang.

The discovery of new elementary particles and properties in materials could be used in quantum information and computation such as secretly communicating information by manipulating the internal states of particles.

Contemplating possible applications is in its infancy and still mostly speculation. This study is an early step in the study of parastatistics in condensed matter systems, but where these findings could lead is uncertain. Further exploration of the new types of theories discovered and observation of paraparticles in condensed matter systems and other materials will be subjects for research in the future.

"I don't know where it will go, but I know it will be exciting to find out," said Hazzard.

More information: Zhiyuan Wang et al, Particle exchange statistics beyond fermions and bosons, *Nature* (2025). DOI: 10.1038/s41586-024-08262-7
Journal information: Nature
Provided by Rice University



Ultrathin conductor surpasses copper for more energy-efficient nanoelectronics

A film a few atoms thick of non-crystalline niobium phosphide conducts better through the surface to make the material, as a whole, a better conductor. Credit: Il-Kwon Oh / Asir Khan

As computer chips continue to get smaller and more complex, the ultrathin metallic wires that carry electrical signals within these chips have become a weak link. Standard metal wires get worse at conducting electricity as they get thinner, ultimately limiting the size, efficiency, and performance of nanoscale electronics.

In a paper published in *Science*, Stanford researchers show that niobium phosphide can conduct electricity better than copper in films that are only a few atoms thick. Moreover, these films can be created and deposited at sufficiently low temperatures to be compatible with modern computer chip fabrication. Their work could help make future electronics more powerful and more energy efficient.

"We are breaking a fundamental bottleneck of traditional materials like copper," said Asir Intisar Khan, who received his doctorate from Stanford and is now a visiting postdoctoral scholar and first author on the paper.

"Our niobium phosphide conductors show that it's possible to send faster, more efficient signals through ultrathin wires. This could improve the energy efficiency of future chips, and even small gains add up when many chips are used, such as in the massive data centers that store and process information today."

A new class of conductors

Niobium phosphide is what researchers call a topological semimetal, which means that the whole material can conduct electricity, but its outer surfaces are more conductive than the middle. As a film of niobium phosphide gets thinner, the middle region shrinks but its surfaces stay the same, allowing the surfaces to contribute a greater share to the flow of electricity and the material as a whole to become a better conductor. Traditional metals like copper, on the other hand, become worse at conducting electricity once they are thinner than about 50 nanometers.

The researchers found that niobium phosphide became a better conductor than copper at film thicknesses below 5 nanometers, even when operating at room temperature. At this size, copper wires struggle to keep up with rapid-fire electrical signals and lose a lot more energy to heat.

"Really high-density electronics need very thin metal connections, and if those metals are not conducting well, they are losing a lot of power and energy," said Eric Pop, the Pease-Ye Professor in the School of Engineering, a professor of electrical engineering, and senior author on the paper. "Better materials could help us spend less energy in small wires and more energy actually doing computation."

Many researchers have been working to find better conductors for nanoscale electronics, but so far the best candidates have had extremely precise crystalline structures, which need to be formed at very high temperatures. The niobium phosphide films made by Khan and his colleagues are the first examples of non-crystalline materials that become better conductors as they get thinner.

"It has been thought that if we want to leverage these topological surfaces, we need nice single-crystalline films that are really hard to deposit," said Akash Ramdas, a doctoral student at Stanford and co-author on the paper. "Now we have another class of materials—these topological semimetals—that could potentially act as a way to reduce energy usage in electronics."

Because the niobium phosphide films don't need to be single crystals, they can be created at lower temperatures. The researchers deposited the films at 400°C, a temperature that is low enough to avoid damaging or destroying existing silicon computer chips.

"If you have to make perfect crystalline wires, that's not going to work for nanoelectronics," said Yuri Suzuki, the Stanley G. Wojcicki Professor in the School of Humanities and Sciences, a professor of applied physics and co-author on the paper. "But if you can make them amorphous or slightly disordered and they still give you the properties you need, that opens the door to potential real-world applications."

Enabling future nanoelectronics

Although niobium phosphide films are a promising start, Pop and his colleagues don't expect them to suddenly replace copper in all computer chips—copper is still a better conductor in thicker films and wires. But niobium phosphide could be used for the very thinnest connections, and it paves the way for research into conductors made of other topological semimetals. The researchers are already looking into similar materials to see if they can improve niobium phosphide's performance.

"For this class of materials to be adopted in future electronics, we need them to be even better conductors," said Xiangjin Wu, a doctoral student at Stanford and co-author on the paper. "To that end, we are exploring alternative topological semimetals."

Pop and his team are also working on turning their niobium phosphide films into narrow wires for additional testing. They want to determine how reliable and effective the material could be in real-world applications.

"We've taken some really cool physics and ported it into the applied electronics world," Pop said. "This kind of breakthrough in non-crystalline materials could help address power and energy challenges in both current and future electronics."

More information: Asir Intisar Khan et al, Surface conduction and reduced electrical resistivity in ultrathin noncrystalline NbP semimetal, *Science* (2025). DOI: 10.1126/science.adq7096

Provided by Stanford University

This 200-Year-Old Law Of Heat Has A Blind Spot. It Could Change Engineering.

The rules of thermal engagement are being rewritten by an unexpected scientific anomaly.© Tawanna08 - Getty Images

- For 200 years, Fourier's law has been the go-to explanation for how heat diffuses through solid materials (at least on macro scales).
- However, a new study by scientists at the University of Massachusetts Amherst has detected heat behavior in translucent polymers and inorganic glass that this time-tested law can't explain.
- Fleshing out a deeper understanding of how heat works could help engineers craft electronic components that are even more heat-resistant.

In 1822, French mathematician and physicist Jean-Baptise Joseph Fourier published the treatise *Théorie analytique de la chaleur*, or The Analytical Theory of Heat. In this treatise, Fourier describes a law of physics that would eventually become his namesake. This law of heat conduction, known today as Fourier's Law, mathematically described the rate at which heat transfers through a solid material. That hot cup of coffee slowly warming your hand? That's Fourier's law in action.

In the 200 years since, Fourier's law has held up pretty well. But things changed during the dawn of nanotechnology, because the law breaks down when predicting thermal performance across nanodevices. And a new study, published in the *Proceedings of the National Academy of Sciences*, argues that these exceptions aren't limited to the world of the miniscule. By analyzing the heat performance of translucent polymers and inorganic glasses, scientists from the University of Massachusetts Amherst were able to detect anomalies that could not be explained with Fourier's Law.

"This research began with a simple question," UMass Amherst's Steve Granick, the senior author on the paper, said in a press statement. "What if heat could be transmitted by another pathway, not just the one that people had assumed?"

Although textbooks have, for 200 years, explained heat transfer through a process known as diffusion, Granick explains that his team needed to get creative and "put the textbook aside for a moment." The researchers' idea was that

translucent polymers and inorganic glasses would diffuse heat as normal, but their translucence would *also* allow electromagnetic thermal energy to radiate through the material.

With samples situated in a vacuum chamber, the scientists eliminated the air necessary for the convective distribution of heat. Then, as the best experiments always do, the research team turned on some lasers. In one sample, they pulsed heat in a small area while another sample was warmed on one side and kept cold on the other. To track heat spread across the samples, the team relied on incredibly precise infrared cameras. Once the data was collected, they confirmed their suspicions—Fourier's law had failed on a macro scale.

Granick and his team came to the conclusion that these translucent materials radiate energy internally. But crucially, this heat interacts with structure imperfections, which the researchers say creates "secondary heat sources."

"It's not that Fourier's Law is wrong," Granick said in a press statement. "Just that it doesn't explain everything we see when it comes to heat transmission."

Understanding the behavior of heat is vitally important for creating computing devices, where heat is the ultimate enemy. By poking holes in this 200-year-old law, these scientists hope to gain a deeper understanding of heat behavior—something you *won't* find in your usual scientific textbook.

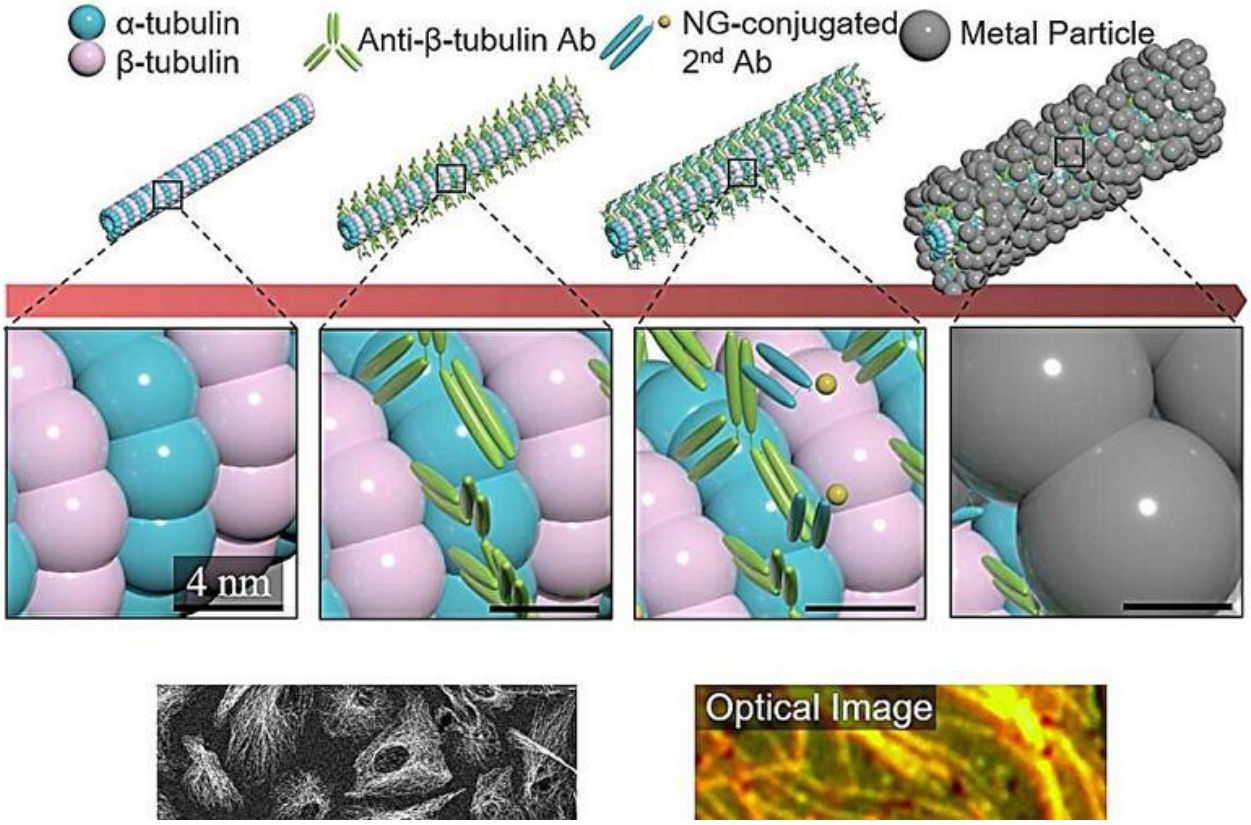
Scientists develop high-impact materials for optoelectronic technologies

Every day, people are reaping the benefits of work by scientists and engineers to make more effective X-ray machines, computers, cell phones and televisions. Florida State University researchers are pushing the boundaries of those technologies and developing new more cost-effective and environmentally friendly materials for these devices.

FSU Professor of Chemistry and Biochemistry Biwu Ma and his lab have spent years pioneering the use of hybrid materials known as organic metal halide hybrids, or OMHHs. These materials combine organic molecules with metal halide units, resulting in structures with easily manipulated properties that are used in solar cells, light-emitting diodes (LEDs) and more. This fall, their work related to various aspects of these materials was published in three different scientific journals.

"Our group is widely recognized as a pioneer in the development of this new class of hybrid materials known as organic metal halide hybrids, or OMHHs," Ma said. "What's fascinating about these materials is their exceptional structure and property tunability—much like assembling Lego pieces, we can combine organic and metal halide building blocks in countless ways to produce materials with all kinds of functionalities for use in various industries."

Highly tunable biotemplating method expands nanostructure synthesis options



CamBio utilizing microtubules, an intracellular protein structure. The silver nanoparticle chains synthesized along the microtubules that span the entire cell interior can be observed through an electron microscope, and it is shown that this can be used as a successful SERS substrate. Credit: Advanced Science (2024). DOI: 10.1002/advs.202406492

A joint research team has developed a biotemplating method that utilizes specific internal proteins in biological samples and has high tunability. The study is published in *Advanced Science*.

Existing biotemplate methods mainly utilize only the external surface of biological samples or have limitations in utilizing the structure-function correlation of various biological structures due to limited dimensions and sample sizes, making it difficult to create functional nanostructures.

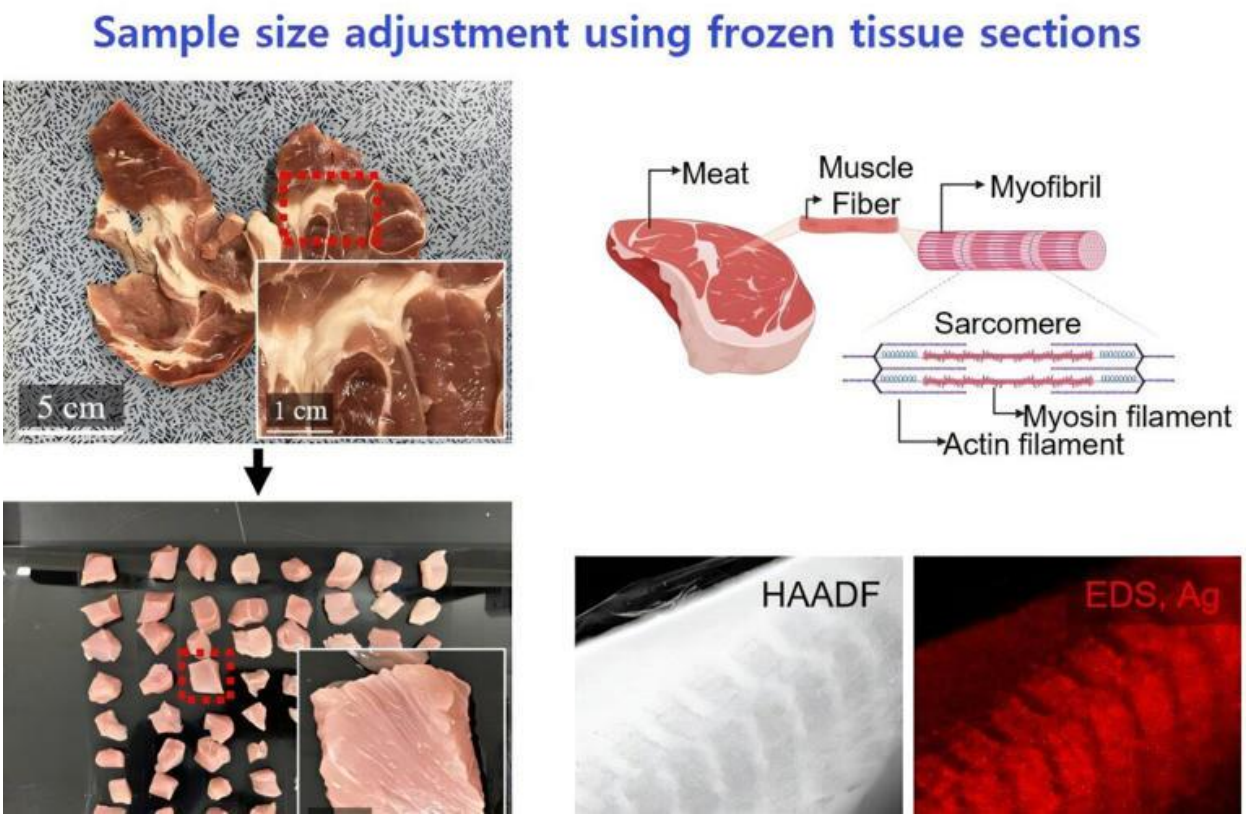
Amazing Process

Seamless Process Of Tissue Production In Factories

The research team found that the nanoparticle chains made using the intracellular protein structures through the process of repeated labeling with antibodies allowed easier control, and improved SERS performance by up to 230%.

The research team included Professors Jae-Byum Chang and Professor Yeon Sik Jung, and first authors Ph.D. candidate Dae-Hyeon Song, along with Dr. Chang Woo Song, and Dr. Seunghee Cho of KAIST.

In addition, the research team expanded from utilizing the structures inside cells to obtaining samples of muscle tissues inside meat using a cryosectioner and successfully producing a substrate with periodic bands made of metal particles by performing the CamBio process. This method of producing a substrate not only allows large-scale production using biological samples, but also shows that it is a cost-effective method.



A method for securing tunability using CamBio at the tissue level. In order to utilize proteins inside muscle tissue, the frozen tissue sectioning technology is combined, and through this, a substrate with a periodic nanoparticle band pattern is successfully produced, and it is shown that large-area acquisition of samples and price competitiveness can be achieved. Credit: Advanced Science (2024). DOI: 10.1002/advs.202406492

The CamBio developed by the research team is expected to be used as a way to solve problems faced by various research fields as it is to expand the range of bio-samples that can be produced for various usage.

The first author, Dae-Hyeon Song, "Through CamBio, we have comprehensively accumulated bioprototyping methods that can utilize more diverse protein structures.

Scientists explore photosynthesis for better plant growth under artificial light

Photosynthesis, the process by which plants, algae and certain kinds of bacteria convert solar radiation into chemical energy, must adjust itself to changes in the intensity of sunlight, so as to ensure its efficient use.

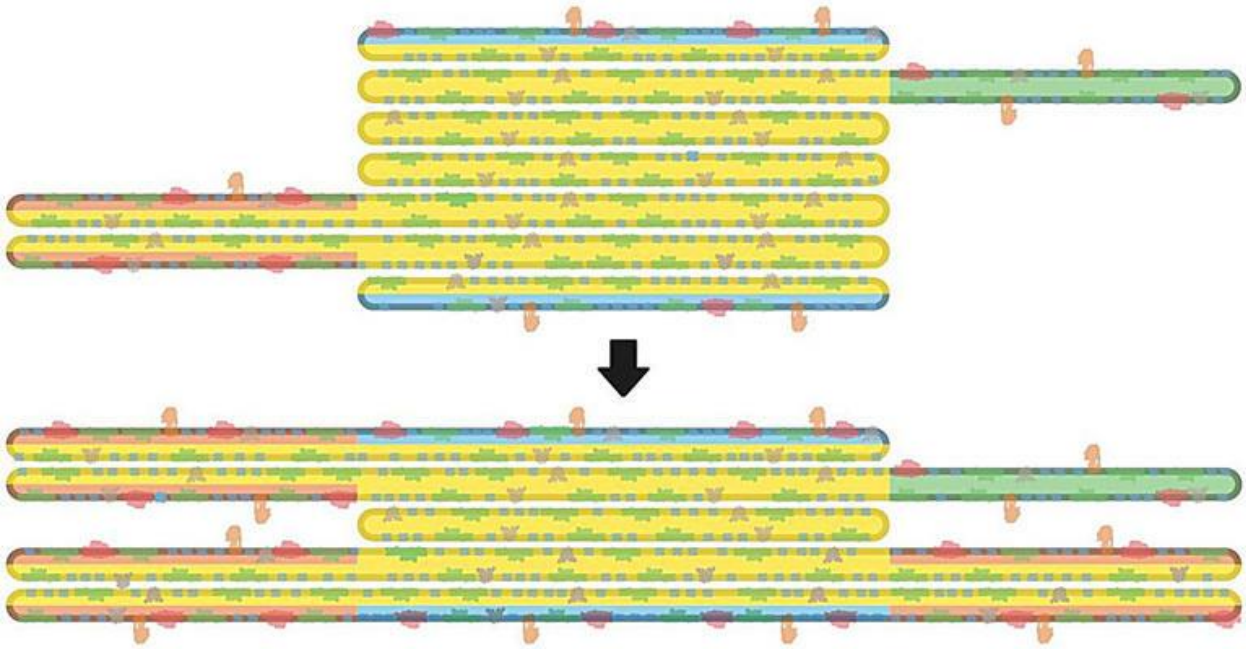
Just like our pupils, which react to varying degrees of light exposure with dilation or constriction, organelles in plant cells undergo changes in response to sunlight. But unlike ourselves, plants cannot avert their eyes or rest in the shade to avoid excessively intense sunlight; they must be able to cope with different levels of solar radiation, as well as with its absence at night.

Without photosynthesis, life as we know it on Earth would be impossible. Not only is this process responsible for generating most of the oxygen in Earth's atmosphere, but it also secures food availability, sequesters carbon from the atmosphere and mitigates the effects of climate change. Understanding photosynthesis in all its intricacies is therefore crucial for dealing with the impending challenges facing our planet.

Research conducted in Prof. Ziv Reich's lab in the Weizmann Institute of Science's Biomolecular Sciences Department aims to uncover the mysteries of photosynthesis so it can be used more efficiently to meet humanity's needs or imitated by artificial methods that would mimic natural photosynthetic processes.

In photosynthesis, harnessing the power of the sun is made possible by the flow of electrons from one protein to another inside an organelle called the chloroplast. This organelle contains a complex system of membranes, some of which are densely stacked, and others that are organized into more expansive assemblies.

Until now, the scientific consensus was that this spatial structure forces the electrons to cover large distances between proteins, slowing down the process of photosynthesis. But in a paper recently published in *Nature Plants*, a research team led by staff scientist Dr. Reinat Nevo from Reich's lab revealed that the membranes change their organization in space during the transition from darkness to light, enabling the proteins to come closer to one another and thus shortening the distance the electrons must cross.



A diagram showing changes in the spatial structure of chloroplast membranes during the transition from darkness (top) to light (bottom). Credit: Nature Plants (2024). DOI: 10.1038/s41477-024-01628-9

These revelations were made when the researchers examined the chloroplast membranes under a cryo-scanning electron microscope and compared the alignment of proteins in the membranes under both light and darkness conditions.

"When we looked into the protein density, we realized that the proteins themselves were not changing their positions, as previously thought—rather, the change occurred in the way the membranes were organized in space," explains Nevo.

Further tests, this time using a transmission electron microscope, confirmed the researchers' hypothesis and showed that membranes indeed rearrange

themselves in space, bringing the proteins closer to one another. Apparently, one of the reasons that the proteins aren't permanently in close proximity to one another—and that the membranes distance themselves from each other under darkness—is that the distancing protects the proteins by isolating them when the light is weak and little photosynthetic activity is taking place.

After discovering how membranes realign themselves according to light conditions, the research team conducted an experiment with two groups of genetically modified plants: one in which the spatial structure of the chloroplast membranes is "locked" in an active light and photosynthesis mode and another in which the membranes are organized in a perpetual darkness mode, preventing them from getting closer to one other. The plants in the first group grew larger and performed more photosynthesis compared to their dark-mode counterparts.

In the future, Nevo and her colleagues plan to investigate whether genetically engineered plants, in which the spatial structure of membranes is regulated, can be grown in relatively weak light. This could help conserve energy when cultivating plants under artificial light—a need that might be imposed by climate change.

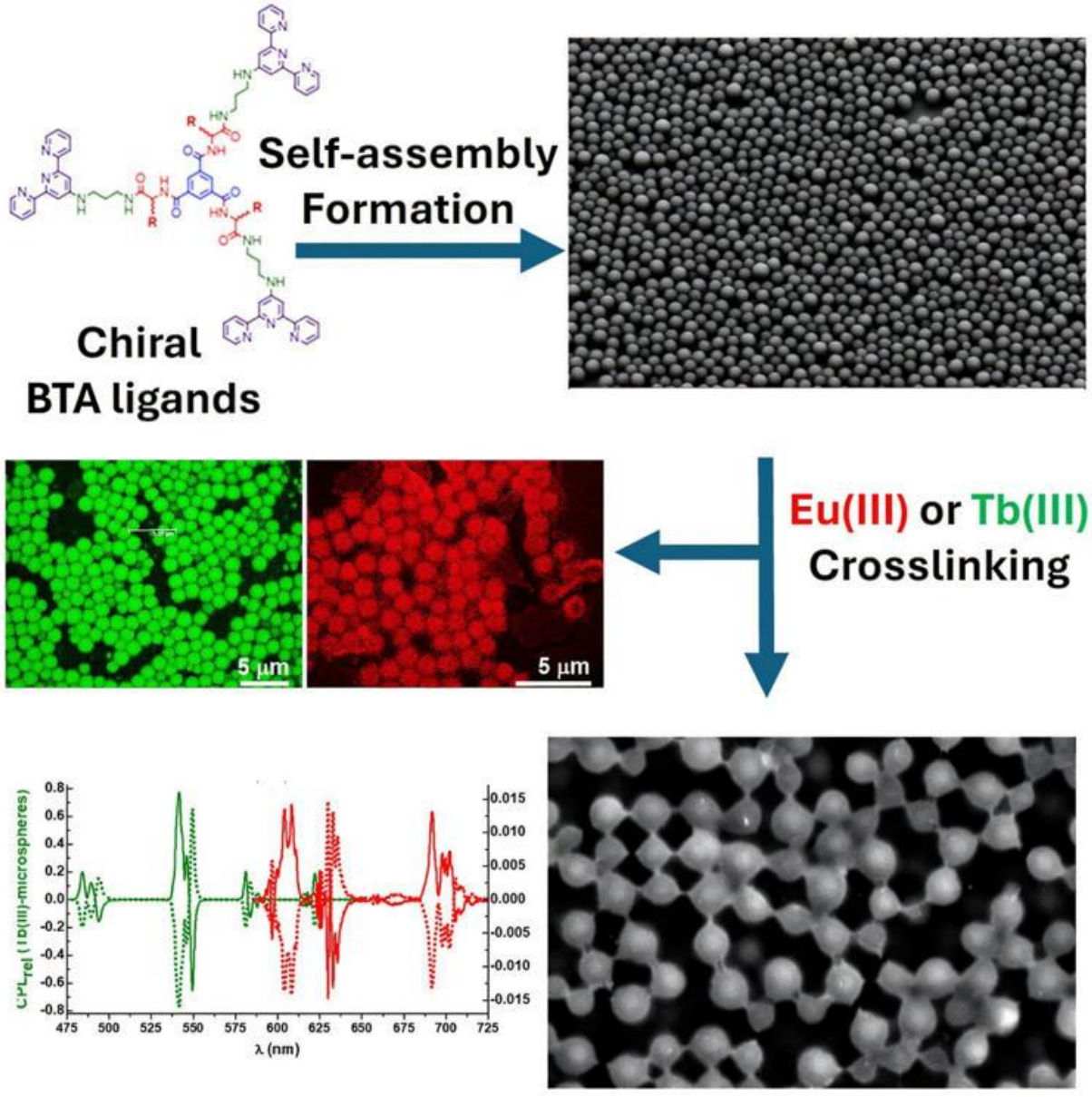
This study is dedicated to the memory of Dr. Eyal Shimoni, a staff scientist in Weizmann's Chemical Research Support Department, who contributed essential expertise in microscopy to this research before he prematurely passed away in 2023.

Other participants included Dr. Yuval Garty and Yuval Bussi of Reich's group; Dr. Smadar Levin-Zaidman of the Chemical Research Support Department; Prof. Helmut Kirchhoff of Washington State University; and Dr. Dana Charuvi of the Volcani Institute, Rishon LeZion, Israel.

More information: Yuval Garty et al, Thylakoid membrane stacking controls electron transport mode during the dark-to-light transition by adjusting the distances between PSI and PSII, *Nature Plants* (2024). DOI: 10.1038/s41477-024-01628-9

Provided by Weizmann Institute of Science

Scientists develop self-assembling molecules with potential applications in targeted drug delivery



Credit: Chem (2024). DOI: 10.1016/j.chempr.2024.09.020

Scientists have taken a major step forward in tackling one of the greatest abiding challenges in chemistry, by learning how to program the self-assembly of molecules in such a way that the end result is predictable and desirable.

Their "Malteser-like" molecules could one day have a suite of applications—from highly sensitive and specific sensors, to next-gen, targeted drug delivery agents. (Editor's note: For our non-UK readers, Maltesers are a British candy with a spheroid malted milk center—covered in chocolate, of course, and similar to Whoppers in the US.)

Virtually all the components of biological systems show an extraordinary and precise ability to self-assemble in the exact way they need to in order to produce the molecules that do the billions of vital things that allow organisms to not only survive, but to thrive, in ever-changing environments.

But despite tremendous scientific advances, researchers are still largely in the dark as to precisely how these processes are governed. The challenge—and tremendous opportunity—for chemists is to decode these processes and then exert control over them to reproducibly program molecules to do certain things.

We are now closer to that realization thanks to a new study published in *Chem*.

The work was performed by a team of scientists led by Prof. Thorfinnur Gunnlaugsson, based in the Trinity Biomedical Sciences Institute (TBSI), in collaboration with Prof. John Boland, based in CRANN. Both groups are part of Trinity College Dublin's School of Chemistry and the AMBER Research Ireland Centre; while Prof. Robert Pal, Department of Chemistry, Durham University, was also a key collaborator.

First author, Aramballi Savyasachi, a former Ph.D. student in Trinity's School of Chemistry, who is based in TBSI, said, "We have been able to make amino-acid-based ligands whose self-assembly structures vary—predictably and reproducibly—depending on which amino acid we use. Amino acids are known as the building blocks of life, as they combine to make proteins. Different sequences of amino acids build a huge diversity of different proteins, which have billions of different functions.

"With that in mind, it is perhaps unsurprising that different amino acids produce different self-assembly results—sometimes giving a soft, gel-like material, and other times giving much harder, 'Malteser molecules.' What did surprise—and delight—us was the discovery that we can largely govern the process and the outcome by selecting specific amino acids. And when we added other molecules, like lanthanide ions, we can tap into luminescence applications."

Prof. Gunnlaugsson, from the TBSI team, said, "There are so many potential applications of this work and, as always, a lot more to learn. But the molecules we have developed already could one day be useful in photonics and optical systems, where highly specific sensors are prized, or in highly targeted drug delivery applications.

"For example, key enzymes appear in greater numbers when the body is fighting an infection and start to break molecules down. The products of this molecular breakdown could stimulate activity in such a way that a drug is released where and when it is needed, which would minimize some of the side effects that come with many, less targeted therapeutics."

An additional benefit is that you could potentially monitor activity in the body, in real time, based on luminescence.

Dr. Oxana Kotova, Trinity, from the TBSI team, added, "Luminescence is a very useful product of some molecular interactions from a biomedical perspective. In collaboration with Professor Robert Pal at the University of Durham we found that our 'Malteser-like' assemblies functionalized with lanthanide ions emit circularly polarized light. This property can allow for visualization of site-specific interactions within biological media or find an application in optoelectronic devices.

"I would like to say that this work was only possible thanks to the multidisciplinary collaboration between chemists, biochemists, materials scientists, and physicists lead by Profs. Thorfinnur Gunnlaugsson, John J. Boland, Robert Pal, Matthias E. Möbius and D. Clive Williams."

Commenting on the significance of the work, Professor Ronan Daly, from the Department of Engineering, University of Cambridge, who was not involved in this study but who is an expert in the field, said, "Engineers and scientists have been pushing the boundaries of manufacturing for a long time, taking materials around us and machining or shaping them into ever smaller and more precise structures.

"We can do this 'top-down' approach so well that it is used in pretty much every manufactured component you see, all the way down to the micro and nanoscale structures in computer chips.

"Nature, however, never ceases to inspire scientists and engineers, with the incredible ability to create complex molecular structures that somehow click together perfectly at the molecular scale, then those click together at a nano scale and can build up entirely on their own to form things we see and take for granted every day.

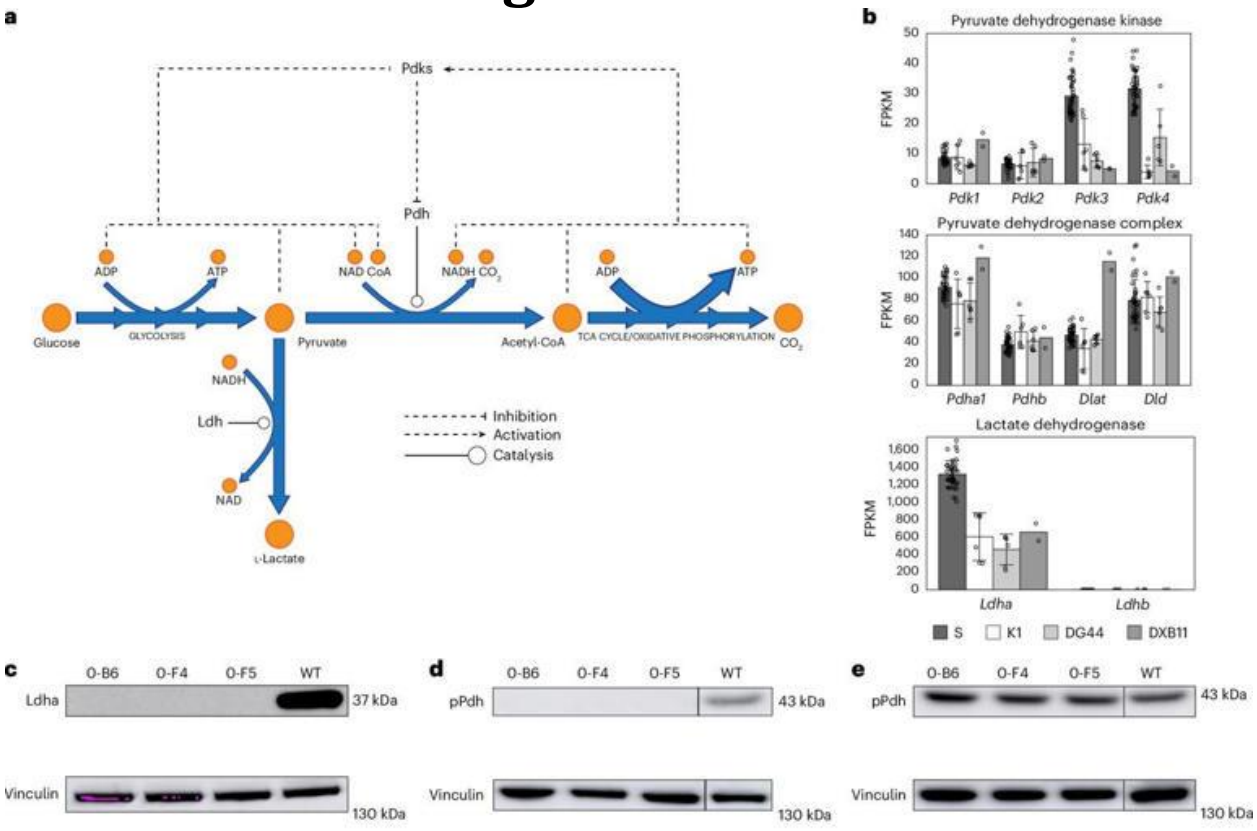
"This self-assembly is an incredibly exciting topic of research where we design materials 'bottom-up' with molecules naturally coming together to form what we need. It is, of course, really complicated and very difficult to design and control—we are just not as good as nature yet!

"This is a very exciting, highly rigorous piece of work that gives new insights into this molecular-scale control of self-assembly. This helps the whole field move forward by building our understanding and provides a very repeatable and robust way of making these new nanoscale spheres that may one day be used, for example, in the future of drug delivery, flowing around the body and releasing a target drug or gene therapy to the right location."

More information: Aramballi J. Savyasachi et al, Exerting control of self-assembly pathways via morphological switching and patterning in amino-acid-based benzene-1,3,5-tricarboxamide conjugates, *Chem* (2024). DOI: 10.1016/j.chempr.2024.09.020

Provided by Trinity College Dublin

Genetic tweak to drug-making cells resolves a decades-old challenge in biomanufacturing



The Warburg effect is influenced by a regulatory circuit involving multiple metabolites and proteins and can be eliminated by multiplex knockout. Credit: Nature Metabolism (2025). DOI: 10.1038/s42255-024-01193-7

An international team of researchers led by the University of California San Diego has developed a new strategy to enhance pharmaceutical production in Chinese hamster ovary (CHO) cells, which are commonly used to manufacture protein-based drugs for treating cancer, autoimmune diseases and much more.

By knocking out a gene circuit responsible for producing lactic acid—a metabolite that makes the cells' environment toxic—researchers eliminate a primary hurdle in developing cells that can produce higher amounts of pharmaceuticals like Herceptin and Rituximab, without compromising their growth or energy production.

The research, "Multiplex genome editing eliminates the Warburg Effect without impacting growth rate in mammalian cells" published on Jan. 14 in *Nature Metabolism*, also challenges long-held assumptions about the necessity of lactic acid metabolism in cell survival.

CHO cells have become essential tools in modern medicine, serving as the "living factories" that produce more than half of today's top-selling protein-based drugs, including therapies for cancer, autoimmune diseases and more. But despite their success, they have one main flaw: low protein yield. CHO cells don't always produce enough of the desired drugs to meet demand, which makes these pharmaceuticals more costly.

Now, researchers have developed an approach that promises to improve the yields of CHO cells in drug production. The approach targets a key metabolic process: the secretion of lactic acid.

During protein production, CHO cells release lactic acid as a byproduct of their metabolism. The more active they are, the more lactic acid they produce.

"As we grow cells to produce more drugs, lactic acid builds up and kills the cells, thus reducing the yields of life-saving drugs while driving up manufacturing costs," said study senior author Nathan Lewis, who led the study while serving as a professor in the Shu Chien-Gene Lay Department of Bioengineering and Department of Pediatrics at UC San Diego (now at the University of Georgia).

Efforts to stop lactic acid production have so far focused on inhibiting the enzyme responsible for this process, lactate dehydrogenase. But these efforts have been unsuccessful, as lactate dehydrogenase is essential for cell survival.

"If you try to remove it or block it, the cells die," said Lewis. "This has been demonstrated in multiple studies."

In the new study, Lewis and colleagues, co-led by UC San Diego bioengineering Ph.D. alumnus Hooman Hefzi (now a professor at Technical University of Denmark), took a different approach.

Instead of focusing on lactate dehydrogenase itself, they mapped out a network of genes—five in CHO cells and six in human cells—that work together to control

lactic acid production. The researchers hypothesized that this gene circuit was responsible for the cells' overproduction of lactate.

When the researchers knocked out this gene circuit, the CHO cells stopped producing lactic acid. Moreover, the cells demonstrated improved growth and, compared to similarly treated controls, produced significantly higher yields of protein-based drugs such as Herceptin and Rituximab, which are used to treat breast cancer and lymphoma, respectively.

The modified CHO cells also successfully produced a variety of other therapeutic proteins, including Enbrel, a treatment for rheumatoid arthritis and psoriasis, and erythropoietin, which stimulates red blood cell production.

Challenging the Warburg effect

This work also sheds light on a key biological process known as the Warburg effect. First observed in cancer cells by German scientist Otto Warburg 100 years ago, the Warburg effect refers to a metabolic shift that causes cells to overproduce lactic acid. This process has long been thought to be critical for cell proliferation and energy production.

Yet, the new research challenges that notion. By eliminating the Warburg effect in CHO cells, researchers found that the cells maintained normal growth rates and energy output. This suggests that the Warburg effect may not be as essential as previously hypothesized.

The researchers note that these newly engineered "Warburg-null" CHO cells are also compatible with industrial cell line development processes. That means these cells could easily be integrated into real-world drug production, which could be a game-changer for biomanufacturing.

The team has discovered additional tweaks that further boost the CHO cells' productivity, and are continuing to study their implications on the entire drug manufacturing process.

"Our work has the potential to make drug production far more efficient, which could significantly lower manufacturing costs," said Lewis. "By improving the productivity of these cells, we're taking an important step toward making life-

saving therapies, like cancer treatments and gene therapies, more affordable and accessible to patients worldwide."

More information: Hooman Hefzi et al, Multiplex genome editing eliminates lactate production without impacting growth rate in mammalian cells, *Nature Metabolism* (2025). DOI: 10.1038/s42255-024-01193-7. www.nature.com/articles/s42255-024-01193-7

Provided by University of California - San Diego

JANUARY 13, 2025
4 MIN READ

Exotic 'Paraparticles' That Defy Categorization May Exist in Many Dimensions

Theoretical physicists predict the existence of exotic "paraparticles" that defy classification and could have quantum computing applications

BY DAVIDE CASTELVECCHI & NATURE MAGAZINE

Particles known as fermions (*shown in this illustration*) can't share the same state.

Quantum Physics

Theoretical physicists have proposed the existence of a new type of particle that doesn't fit into the conventional classifications of fermions and bosons. Their 'paraparticle', described in *Nature* on January 8, is not the first to be suggested, but the detailed mathematical model characterizing it could lead to experiments in which it is created using a quantum computer. The research also suggests that undiscovered elementary paraparticles might exist in nature.

In a separate development published late last year in *Science*, physicists experimentally demonstrated another kind of particle that is neither a boson nor a fermion — an 'anyon' — in a virtual one-dimensional universe for the first time. Anyons had previously been created only in 2D systems.

Because of their unusual behaviour, both paraparticles and anyons could one day play a part in making quantum computers less error-prone.

PARTICLE PROPERTIES

Around the time when physicists began to understand the structure of atoms, a century ago, Austrian-born theorist Wolfgang Pauli suggested that no two electrons can occupy the

same state — and that if two electrons are pushed close to being in the same state, a repulsive force arises between them. This 'Pauli exclusion principle' is crucial to the way electrons orbiting an atomic nucleus arrange themselves in shells, instead of all falling to the lowest possible energy state.

Pauli and others soon realized that this empirical rule of exclusion applied not only to electrons but to a broader class of particles, including protons and neutrons, which they called fermions. Conversely, particles that do like to share the same state — which include the photons in a laser beam, for example — became known as bosons. (Pauli and his collaborators also worked out why being a fermion or a boson appeared to relate to a particle's intrinsic angular momentum, or 'spin'.)

Mathematically, the fundamental property of fermions is that when two of them switch positions, the 'wavefunction' that represents their collective quantum state changes sign, meaning that it gets multiplied by –1. For bosons, the wavefunction remains unaltered. Early quantum theorists knew that, in principle, there could be other kinds of particle whose wavefunctions changed in more complicated ways when they swapped positions. In the 1970s, researchers discovered anyons, which can exist only in universes of one or two dimensions.

NOVEMBER 13, 2024
6 MIN READ

Alternate Timelines Can't Help You, Quantum Physicists Say

The multiverse offers no escape from our reality—which might be a very good thing

Quantum Physics

As memes go, it wasn't particularly viral. But for a couple of hours on the morning of November 6, the term "darkest timeline" trended in Google searches, and several physicists posted musings on social media about whether we were actually in it. All the probabilities expressed in opinion polls and prediction markets had collapsed into a single definite outcome, and history went from "what might be" to "that just happened." The two sides in this hyperpolarized U.S. presidential election had agreed on practically nothing—save for their shared belief that its outcome would be a fateful choice between two diverging trajectories for our world.

That raises rather obvious (but perhaps pointless) questions: Could a "darkest timeline" (or any other "timeline," for that matter) be real? Somewhere out there in the great beyond, might there be a parallel world in which Kamala Harris electorally triumphed instead?

It turns out that, outside of fostering escapist sociopolitical fantasies and putting a scientific gloss on the genre of counterfactual history, the notion of alternate timelines is in fact something physicists take very seriously. The concept most famously appears in quantum mechanics, which predicts a multiplicity of outcomes—cats that are both alive and dead and all that. If a particle of light—a photon—strikes a mirror that is only partially silvered, the particle can, in a sense, both pass through and reflect off that surface—two mutually exclusive outcomes, known in physics parlance as a superposition. Only one of those possibilities will manifest itself when an observation is made, but until then, the particle juggles both possibilities simultaneously. That's what the mathematics says—and what experiments confirm. For instance, you can create a superposition and then uncreate it by directing the light onto a second partially silvered mirror. That wouldn't be possible unless both possibilities remained in play. Although this feature is usually framed in terms of subatomic particles, it is thought to be ubiquitous across all scales in the universe.

What supports the idea that these timelines are real, and not just imaginative fictions, is that they can *"interfere" with one another,* either enhancing or diminishing the probability of their occurrence. That is, something that might have happened but *doesn't* has a measurable effect on what *does,* as if the former reaches from the shadowy realm of the possible into the world of the actual.

Consider the bomb detector that physicists Avshalom Elitzur and Lev Vaidman proposed in 1993 and that has since been demonstrated (fortunately not with real bombs): Perform the experiment with the partially silvered mirror but place a light-sensitive bomb along one of the two paths the photon can take. This blockage prevents you from uncreating the superposition to restore the traveling photon to its original state. It does so even if the bomb never goes off, indicating that the photon never touched it. The mere *possibility* that the photon could strike the bomb affects what happens. In theory, you could use this principle—known as counterfactual definiteness—to take x-ray images of cells without subjecting them to damaging radiation. In an emerging subject known as counterfactual quantum computing, a computer outputs a value even if you never press the "run" button.

SEPTEMBER 30, 2024

Evidence of 'Negative Time' Found in Quantum Physics Experiment

Physicists showed that photons can seem to exit a material before entering it, revealing observational evidence of negative time

Time can take on negative values in the quantum realm.

Quantum Physics

Quantum physicists are familiar with wonky, seemingly nonsensical phenomena: atoms and molecules sometimes act as particles, sometimes as waves; particles can be connected to one another by a "spooky action at a distance," even over great distances; and quantum objects can detach themselves from their properties like the Cheshire Cat from *Alice's Adventures in Wonderland* detaches itself from its grin. Now researchers led by Daniela Angulo of the University of Toronto have revealed another oddball quantum outcome: photons, wave-particles of light, can spend a negative amount of time zipping through a cloud of chilled atoms. In other words, photons can seem to exit a material before entering it.

"It took a positive amount of time, but our experiment observing that photons can make atoms seem to spend a *negative* amount of time in the excited state is up!" wrote Aephraim Steinberg, a physicist at the University of Toronto, in a post on X (formerly Twitter) about the new study, which was uploaded to the preprint server arXiv.org on September 5 and has not yet been peer-reviewed.

The idea for this work emerged in 2017. At the time, Steinberg and a lab colleague, then doctoral student Josiah Sinclair, were interested in the interaction of light and matter, specifically a phenomenon called atomic excitation: when photons pass through a medium and get absorbed, electrons swirling around atoms in that medium jump to higher energy levels. When these excited electrons lapse to their original state, they release that absorbed energy as reemitted photons, introducing a time delay in the light's observed transit time through the medium.

Sinclair's team wanted to measure that time delay (which is sometimes technically called a "group delay") and learn whether it depends on the fate of that photon: Was it scattered and absorbed inside the atomic cloud, or was it transmitted with no interaction whatsoever? "At the time, we weren't sure what the answer was, and we felt like such a basic question about something so fundamental should be easy to answer," Sinclair says. "But the more people we talked to, the more we realized that while everyone had their own intuition or guess, there was no expert consensus on what the right answer would be."

Because the nature of these delays can be so strange and counterintuitive, some researchers had written the phenomenon off as effectively meaningless for describing any physical property associated with light.

After three years of planning, his team developed an apparatus to test this question in the lab. Their experiments involved shooting photons through a cloud of ultracold rubidium atoms and measuring the resulting degree of atomic excitation. Two surprises emerged from the experiment: Sometimes photons would pass through unscathed, yet the rubidium atoms would still become excited—and for just as long as if they had absorbed those photons. Stranger still, when photons were absorbed, they would seem to be reemitted almost instantly, well before the rubidium atoms returned to their ground state—as if the photons, on average, were leaving the atoms quicker than expected.

A Scientist Claims He's Solved a Major Time-Travel Paradox

- One of the most famous paradoxes ever, the grandfather paradox, cautions against making changes that could break the timeline if you were to ever travel back in time.
- But, according to one scientist, the paradox may not even be possible in the first place.
- Using a combination of theoretical physics and established quantum mechanics, physicist Lorenzo Gavassino argues that any paradox that were to occur on a time loop would simply undo itself, or be impossible to kickstart at all.

If I go back in time and kill my own grandfather, will I have ever existed at all? And if I suddenly never existed, who killed my grandfather? That's what's known as the "grandfather paradox," and it's one of the most well-known potential paradoxes that could theoretically be caused by human time travel.

Except… maybe it couldn't happen at all. According to a new study—written by, a physicist from Vanderbilt University, and published in the journal *Classical and Quantum Gravity*—even if we *could* figure out how to go back in time, any changes we make might not actually stick, thanks to the laws of physics.

At the center of this idea lie three concepts, the first of which is entropy, which can functionally be thought of as the level of disorder of things. As we move

forward through time, entropy increases as things break down. And it *only* increases. For example, if you have a vase, and you break it, it's now in all sorts of little pieces. Its entropy has increased. Even if you glue all the little pieces back together, they didn't *actually* re-become one single object. You can't undo an increase in disorder, no matter how hard you try

Because of the immutability of that fact, many physicists actually argue that increasing entropy dictates the 'arrow of time,' or the direction in which time moves, rather than time dictating an increase in entropy. In fact, Gavassino states in his paper that "entropy increase is the only physical law that enables us to draw a fundamental distinction between past and future."

The second central concept to Gavassino's attempt at paradox nullification is that of the closed timelike curve. First conceived as a result of Einstein's general theory of relativity, closed timelike curves are the hypothetical results of rotating gravity wells being able to basically drag spacetime (which is both space and time in one) along with their motion. We see weird effects of gravity on spacetime around things like black holes all the time, but if you take the idea that gravity could drag spacetime around to its conclusion, a spinning gravity well could eventually get the time flowing in a circle. That circle is a closed timelike curve, or CTC, which could theoretically be traveled along to go back in time. After all, if time is a circle, you can head into the future for a long while and end up in the past, behind where you started.

But, hold on. If you start off traveling forward in time, you're traveling in the direction of increasing entropy. And if you end up *back* in time, somehow, you would have had to undo entropy. Which is impossible… right?

Maybe not. The overall conclusion of Gavassino's work is that CTCs function not like continuous loops, but like two half-circles, each beginning and ending at the points on the CTC with the least and most entropy, respectively. Which might seem like it flies in the face of a lot of the assertions we've made so far, until we bring to the stage the third and final concept needed to bring this whole argument together—quantum physics.

We might experience the effects of classical physics most prominently in our day-to-day lives, but we live in a quantum universe, and quantum rules all (even in ways we don't understand just yet). And the quantum realm follows what is called a "self-consistency principle" which, according to the paper, means "the only

histories of the Universe that actually happen are those where everything works out consistently." Gavassino argues that this principle would basically make it so that any changes made to the past on a time-traveling adventure wouldn't 'stick,' thus allowing the two-half-circle CTC to function without breaking entropy rules and negate pretty much any time-travel paradoxes that might arise. Basically, you couldn't kill your grandfather *because* you exist. And if you did, it wouldn't hold.

Gavassino claims that this could have a huge number of ramifications, including de-aging, "spontaneous memory erasure," and a complete inability to ever meet your younger self by going back in time. But, to be clear, all of this hinges on the existence of the highly hypothetical CTCs in the first place, which Gavassino does not attempt to assert or prove in his study.

So, interesting? Very much so. But we still have a long way to go—and will need to get very lucky with the realities of a few not-yet-understood laws of physics—before it's even really worth worrying about the ramifications of, say, stepping on a butterfly and winking out of existence.

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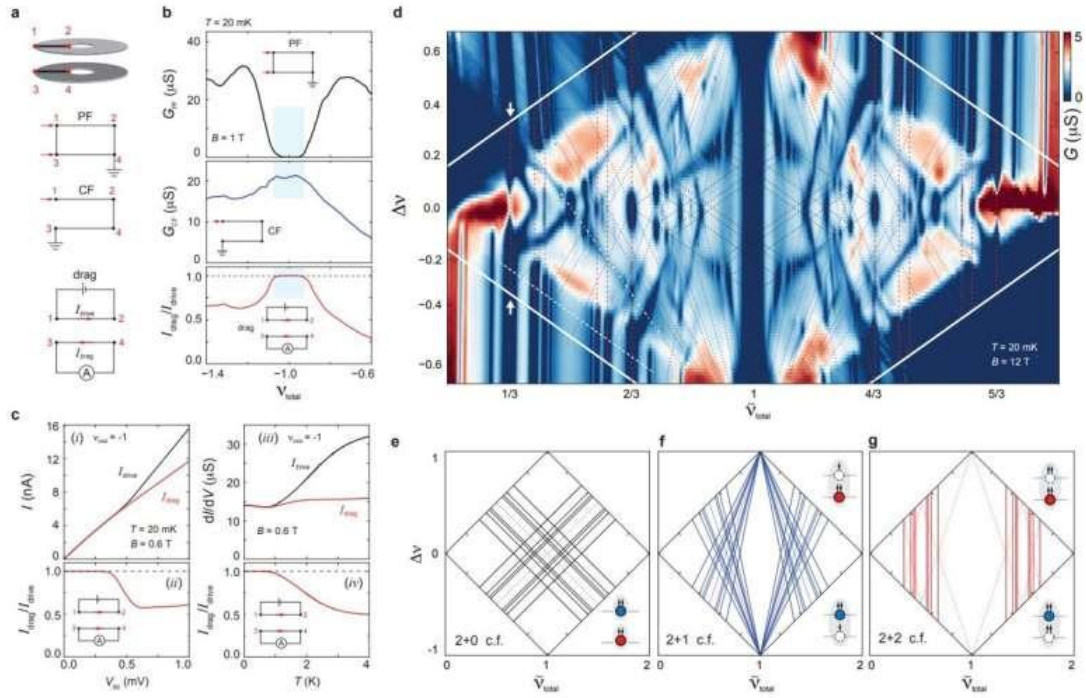
JANUARY 8, 2025

Discovery of new class of particles could take quantum mechanics one step further

by Brown University



Excitonic pairing and fractional quantum Hall effect in quantum Hall bilayer. Credit: Naiyuan J. Zhang et al,

Amid the many mysteries of quantum physics, subatomic particles don't always follow the rules of the physical world. They can exist in two places at once, pass through solid barriers and even communicate across vast distances instantaneously. These behaviors may seem impossible, but in the quantum realm, scientists are exploring an array of properties once thought impossible.

In a new study, physicists at Brown University have now observed a novel class of quantum particles called fractional excitons, which behave in unexpected ways and could significantly expand scientists' understanding of the quantum realm.

"Our findings point toward an entirely new class of quantum particles that carry no overall charge but follow unique quantum statistics," said Jia Li, an associate professor of physics at Brown.

"The most exciting part is that this discovery unlocks a range of novel quantum phases of matter, presenting a new frontier for future research, deepening our understanding of fundamental physics, and even opening up new possibilities in quantum computation."

Along with Li, the research was carried out by three graduate students—Naiyuan Zhang, Ron Nguyen and Navketan Batra—and Dima Feldman, a professor of physics at Brown. Zhang, Nguyen and Batra are co-first authors of the paper, which was published in *Nature* on Wednesday, Jan. 8.

The team's discovery centers around a phenomenon known as the fractional quantum Hall effect, which builds on the classical Hall effect, where a magnetic field is applied to a material with an electric current to create a sideways voltage.

The quantum Hall effect, occurring at extremely low temperatures and high magnetic fields, shows that this sideways voltage increases in clear, separate jumps. In the fractional quantum Hall effect, these steps become even more peculiar, increasing by only fractional amounts—carrying a fraction of an electron's charge.

In their experiments, the researchers built a structure with two thin layers of graphene, a two-dimensional nanomaterial, separated by an insulating crystal of hexagonal boron nitride. This setup allowed them to carefully control the movement of electrical charges. It also allowed them to generate particles known as excitons, which are formed by combining an electron and the absence of an electron known as a hole.

They then exposed the system to incredibly strong magnetic fields that are millions of times stronger than Earth's. This helped the team observe the novel fractional excitons, which showed an unusual set of behaviors.

Fundamental particles typically fall into two categories. Bosons are particles that can share the same quantum state, meaning many of them can exist together without restrictions. Fermions, on the other hand, follow what's known as the Pauli exclusion principle, which says no two fermions can occupy the same quantum state.

The fractional excitons observed in the experiment, however, didn't fit cleanly into either category. While they had the fractional charges expected in the experiment, their behavior showed tendencies of both bosons and fermions, acting almost like a hybrid of the two. That made them more like anyons, a particle type that sits between fermions and bosons—yet the fractional excitons had unique properties that set them apart from anyons, as well.

"This unexpected behavior suggests fractional excitons could represent an entirely new class of particles with unique quantum properties," Zhang said. "We show that excitons can exist in the fractional quantum Hall regime and that some of these excitons arise from the pairing of fractionally charged particles, creating fractional excitons that don't behave like bosons."

The existence of a new class of particles could one day help improve the way information is stored and manipulated at the quantum level, leading to faster and more reliable quantum computers, the team noted.

"We've essentially unlocked a new dimension for exploring and manipulating this phenomenon, and we're only beginning to scratch the surface," Li said. "This is the first time we've shown that these types of particles exist experimentally, and now we are delving deeper into what might come from them."

The team's next steps will involve studying how these fractional excitons interact and whether their behavior can be controlled.

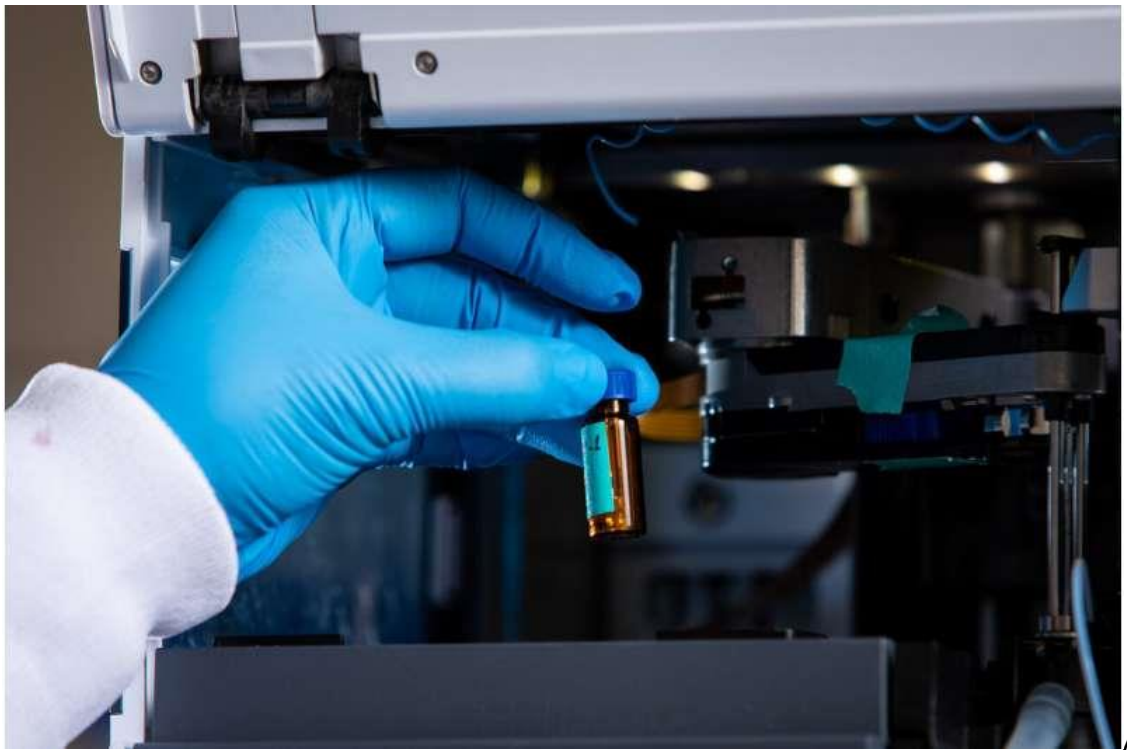
"This feels like we have our finger right on the knob of quantum mechanics," Feldman said. "It's an aspect of quantum mechanics that we didn't know about or, at least, we didn't appreciate before now."

More information: Naiyuan J. Zhang et al, Excitons in the fractional quantum Hall effect, *Nature* (2025). DOI: 10.1038/s41586-024-08274-3. www.nature.com/articles/s41586-024-08274-3
Journal information: Nature
Provided by Brown University

JANUARY 6, 2025

Scientists identify 11 genes affected by PFAS, shedding light on neurotoxicity

by University at Buffalo


A study led by the labs of University at Buffalo chemistry professors G. Ekin Atilla-Gokcumen and Diana Aga has uncovered some molecular clues about the neurotoxic effects of per- and polyfluorinated alkyl substances, better known as forever chemicals. Credit: Meredith Forrest Kulwicki / University at Buffalo

Per- and polyfluorinated alkyl substances (PFAS) earn their "forever chemical" moniker by persisting in water, soil and even the human brain. This unique ability to cross the blood-brain barrier and accumulate in brain tissue makes PFAS particularly concerning, but the underlying mechanism of their neurotoxicity must be studied further.

To that end, a new study by University at Buffalo researchers has identified 11 genes that may hold the key to understanding the brain's response to these pervasive chemicals commonly found in everyday items. The paper is published in the journal *ACS Chemical Neuroscience*.

These genes, some involved in processes vital for neuronal health, were found to be consistently affected by PFAS exposure, either expressing more or less, regardless of the type of PFAS compounds tested. For example, all compounds caused a gene key for

neuronal cell survival to express less, and another gene linked to neuronal cell death to express more.

"Our findings indicate these genes may be markers to detect and monitor PFAS-induced neurotoxicity in the future," says lead co-corresponding author G. Ekin Atilla-Gokcumen, Ph.D., Dr. Marjorie E. Winkler Distinguished Professor in the Department of Chemistry, within the UB College of Arts and Sciences.

Still, the study found that hundreds more genes whose expression changed in different directions based on the compound tested. Plus, there was no correlation between the level at which PFAS accumulates in a cell and the extent to which it causes differential gene expression.

Taken together, this suggests that distinct molecular structures within each type of PFAS drive changes in gene expression.

"PFAS, despite sharing certain chemical characteristics, come in different shapes and sizes, leading to variability in their biological effects. Thus, knowledge on how our own biology reacts to the different types of PFAS is of major biomedical relevance," says the study's other co-corresponding author, Diana Aga, Ph.D., SUNY Distinguished Professor and Henry M. Woodburn Chair in the Department of Chemistry, and director of the UB RENEW Institute.

"Depending on their chain length or headgroup, PFAS can have very different effects on cells," Atilla-Gokcumen adds. "We should not be viewing them as one large class of compounds, but really as compounds that we need to investigate individually."

Other authors include Omer Gokcumen, Ph.D., professor in the Department of Biological Sciences.

Ups and downs of gene expression

PFAS aren't immediately toxic. We're exposed to them practically every day, including through drinking water and food packaging, and don't notice.

"Therefore, researchers need to find points of assessment further upstream in the cellular process than just whether a cell lives or dies," Atilla-Gokcumen says.

The team decided to focus on how PFAS affects the gene expression of neuronal-like cells, as well as how PFAS affects lipids, which are molecules that help make up the cell membrane, among other important functions. Exposure to different PFAS for 24 hours resulted in modest but distinct changes in lipids, and over 700 genes expressing differently.

Of the six types of PFAS tested, perfluorooctanoic acid (PFOA)—once commonly used in nonstick pans and recently deemed hazardous by the EPA—was by far the most impactful. Despite its small uptake, PFOA altered the expression of almost 600 genes—no other

compound altered more than 147. Specifically, PFOA decreased the expression of genes involved in synaptic growth and neural function.

Altogether, the six compounds caused changes in biological pathways involved in hypoxia signaling, oxidative stress, protein synthesis and amino acid metabolism, all of which are crucial for neuronal function and development.

Eleven of the genes were found to express the same way, either more or less, to all six compounds. One of the genes that was consistently downregulated was mesencephalic astrocyte-derived neurotrophic factor, which is important for the survival of neuronal cells and has been shown to reverse symptoms of neurodegenerative diseases in rats. One of the genes consistently upregulated was thioredoxin-interacting protein, which has been linked to neuronal cell death.

"Each of these 11 genes exhibited consistent regulation across all PFAS that we tested. This uniform response suggests that they may serve as promising markers for assessing PFAS exposure, but further research is needed to know how these genes respond to other types of PFAS," Atilla-Gokcumen says.

Identifying the least-worst options

As harmful as PFAS can be, the reality is that good substitutes have yet to be found.

The compounds can perhaps be replaced in applications like food packaging, but their effectiveness in firefighting and semiconductor manufacturing, for example, may need to continue in the long term.

That's why studies like this are crucial, Atilla-Gokcumen says. The varied reactions most genes have to different compounds, as well as the lack of correlation between PFAS uptake into cells and the extent of gene change expression they cause, underscores just how unique each of these compounds is.

"If we understand why some PFAS are more harmful than others, we can prioritize phasing out the worst offenders while seeking safer substitutes. For example, alternatives like short-chain PFAS are being explored, as they tend to persist less in the environment and accumulate less in biological systems," Atilla-Gokcumen explains.

"However, their reduced persistence may come at the cost of effectiveness in certain applications, and there are concerns about potential unknown health effects that require further investigation. Further research is needed to ensure these substitutes are genuinely safer and effective for specific applications. This research is a major step towards achieving this goal."

More information: Logan Running et al, Investigating the Mechanism of Neurotoxic Effects of PFAS in Differentiated Neuronal Cells through Transcriptomics and Lipidomics Analysis, *ACS Chemical Neuroscience* (2024). DOI: 10.1021/acschemneuro.4c00652
Journal information: ACS Chemical Neuroscience
Provided by University at Buffalo

NOVEMBER 14, 2024

Scientists compile library for evaluating exoplanet water

by Cornell University

Credit: Pixabay/CC0 Public Domain

By probing chemical processes observed in the Earth's hot mantle, Cornell scientists have started developing a library of basalt-based spectral signatures that not only will help reveal the composition of planets outside of our solar system but could demonstrate evidence of water on those exoplanets.

"When the Earth's mantle melts, it produces basalts," said Esteban Gazel, professor of engineering. Basalt, a gray-black volcanic rock found throughout the solar system, is a key recorder of geologic history, he said.

"When the Martian mantle melted, it also produced basalts. The moon is mostly basaltic," he said. "We're testing basaltic materials here on Earth to eventually elucidate the composition of exoplanets through the James Webb Space Telescope data."

Gazel and Emily First, a former Cornell postdoctoral researcher and now an assistant professor at Macalester College in Minnesota, are authors of "Potential for observing geological diversity from mid-infrared spectra of rocky exoplanets," which is published November 14 in *Nature Astronomy*.

Understanding how minerals record the processes that created these rocks, and their spectroscopic signatures is the first step in developing their library, Gazel said.

"We know that the majority of exoplanets will produce basalts, given that their host star metallicity will result in mantle minerals (iron-magnesium silicates) so that when they melt, phase equilibria (equilibrium between two states of matter) predicts that the resulting lavas will be basaltic," Gazel said. "It will be prevalent not only in our solar system, but throughout the galaxy, too."

First measured the emissivity—the extent to which a surface radiates the energy it encounters—of 15 basaltic samples for spectral signatures of what the space telescope's mid-infrared spectrometer may detect.

Once basaltic melts erupt on an exoplanet and cool down, the basalts harden into solid rock, known on Earth as lava. This rock can interact with water, if present, which forms new hydrated minerals easy to spot in the infrared spectra. These altered minerals could become amphibole (a hydrous silicate) or serpentine (another hydrous silicate, which looks like a snake's skin).

By examining small spectral differences between the basalt samples, scientists can in theory determine whether an exoplanet once had running surface water or water in its interior, said Gazel.

Proof of water does not emerge instantly, and further work is needed before this type of detection can be employed. It would take the James Webb Space Telescope (JWST)—about 1 million miles from Earth—dozens to hundreds of hours to focus on one system light-years away, then more time to analyze the data.

The research group—in looking for a rocky exoplanet to simulate its hypotheses and consider the 15 different signatures—used data from the super Earth exoplanet LHS 3844b, which orbits a red dwarf a little more than 48 light-years away.

Ishan Mishra, working in the laboratory of Nikole Lewis, associate professor of astronomy, wrote computer code modeling First's spectral data to simulate how differing exoplanet surfaces might appear to the JWST.

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Lewis said that modeling tools were first used for other applications. "Ishan's coding tools were used originally for studying icy moons in the solar system," she said. "We are now finally trying to translate what we've learned of the solar system into exoplanets."

"The goal was not to assess planet LHS 3844b specifically," First said, "but rather to consider a plausible range of basaltic rocky exoplanets that could be observed by JWST and other observatories in the coming years."

In terms of exoplanets, the researchers said exploration of rocky surfaces has been mostly limited to single data points—finding evidence of only one type of chemical—in the scientific literature, but that is changing to multiple components as observers make use of the JWST.

By trying to tease out signatures related to mineralogy and bulk chemical composition—for example, how much silicon, aluminum and magnesium are in a rock—the geologists can tell a little more about the conditions under which the rock formed, the geologists said.

"On Earth, if you have basaltic rocks erupting from mid-ocean ridges deep on the ocean floor, versus those erupting on ocean islands like Hawaii," First said, "you will notice some differences in the bulk chemistry. But even rocks of similar bulk chemistry can contain different minerals, so these are both important characteristics to examine."

More information: Potential for observing geological diversity from mid-infrared spectra of rocky exoplanets, *Nature Astronomy* (2024). DOI: 10.1038/s41550-024-02412-7
Journal information: Nature Astronomy
Provided by Cornell University

DECEMBER 24, 2024

Is the universe a fractal?

by Paul M. Sutter, Universe Today

Formation of complex symmetrical and fractal patterns in snowflakes exemplifies emergence in a physical system. Credit: Unsplash/CC0 Public Domain

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

AUGUST 26, 2024

Editors' notes

What makes a supercluster?

by Paul M. Sutter, Universe Today

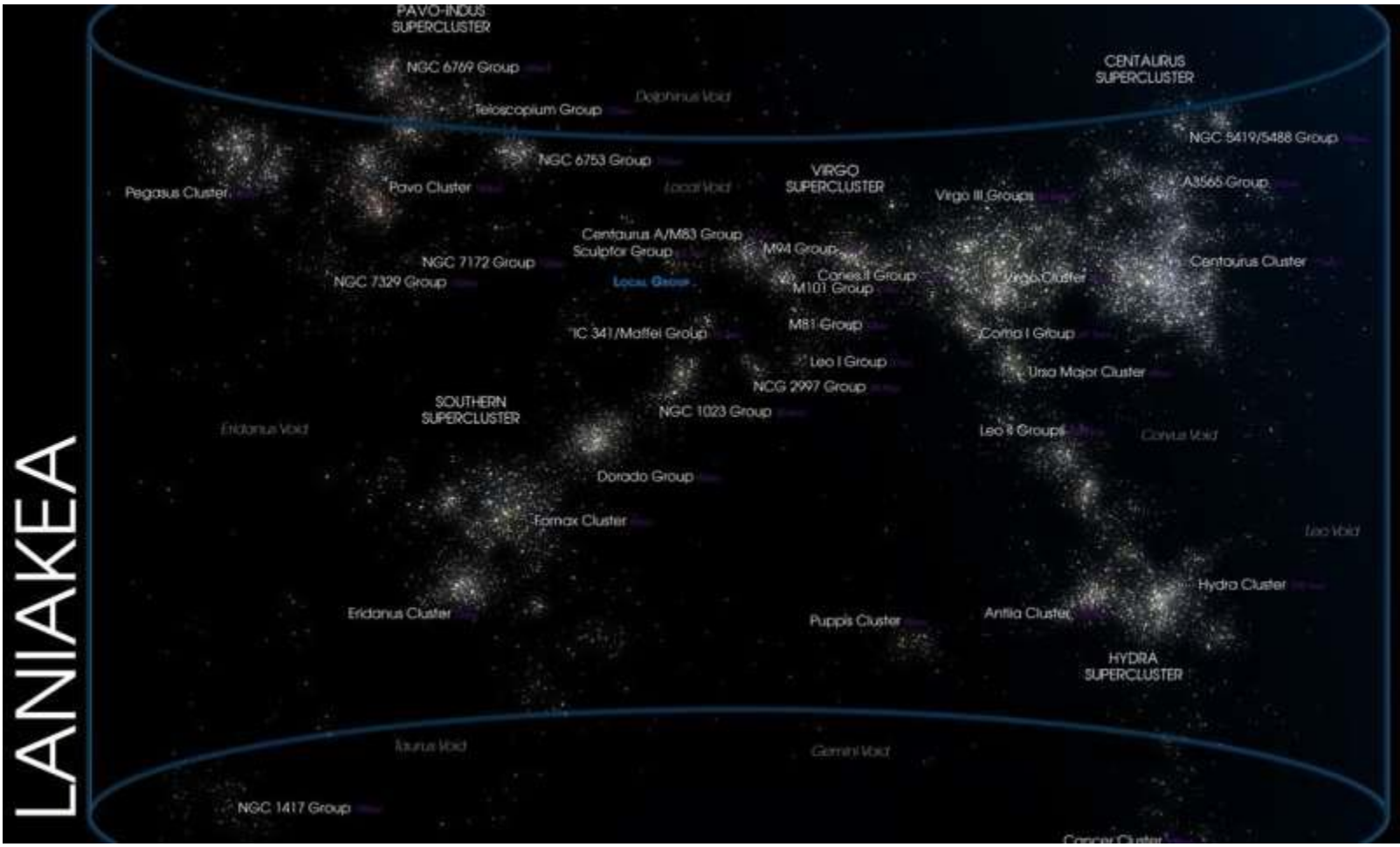


Illustration of the Laniakea Supercluster. Credit: Andrew Z. Colvin

By eye, it's impossible to pick out the exact boundaries of the superclusters, which are among the largest structures in the universe. But that's because they are not defined by their edges, but by the common motion of their components.

The Milky Way galaxy was long thought to be a member of the Virgo supercluster, a complex, twisting branch containing more than 100 individual galaxy groups and clusters stretching for more than a hundred million light-years. Astronomers arrived at that definition through some of the earliest galaxy surveys that attempted to map the nearby portions of the universe.

Those early surveys were not entirely sophisticated. Astronomers could spot the galaxies scattered around, and also dense clumps of galaxies known as clusters. Ever

since the 1950s, astronomers have debated if there were higher-order structures in the pattern of galaxies, wondering if "super-galaxies" (or superclusters) existed.

Once astronomers began to map deep into the universe, however, the cosmic web could not be ignored. While some galaxies found their homes in the clusters, most inhabited long, thin filaments and broad walls. This cosmic web was defined by the voids, the vast regions of almost-nothing that dominate the volume of the universe.

The largest portions of the cosmic web are the superclusters. But unlike the clusters, they are not gravitationally bound. That means that the member galaxies in a supercluster have not yet finished their building project. The superclusters are still in the process of forming. This fact makes it difficult to pick out exactly what a supercluster is.

Recently astronomers have turned to dynamical definitions of a supercluster. This means that they don't just consider the position in space of a particular galaxy, but also its movement. Since superclusters are in the process of continual construction, this method looks at what galaxies are trying to build.

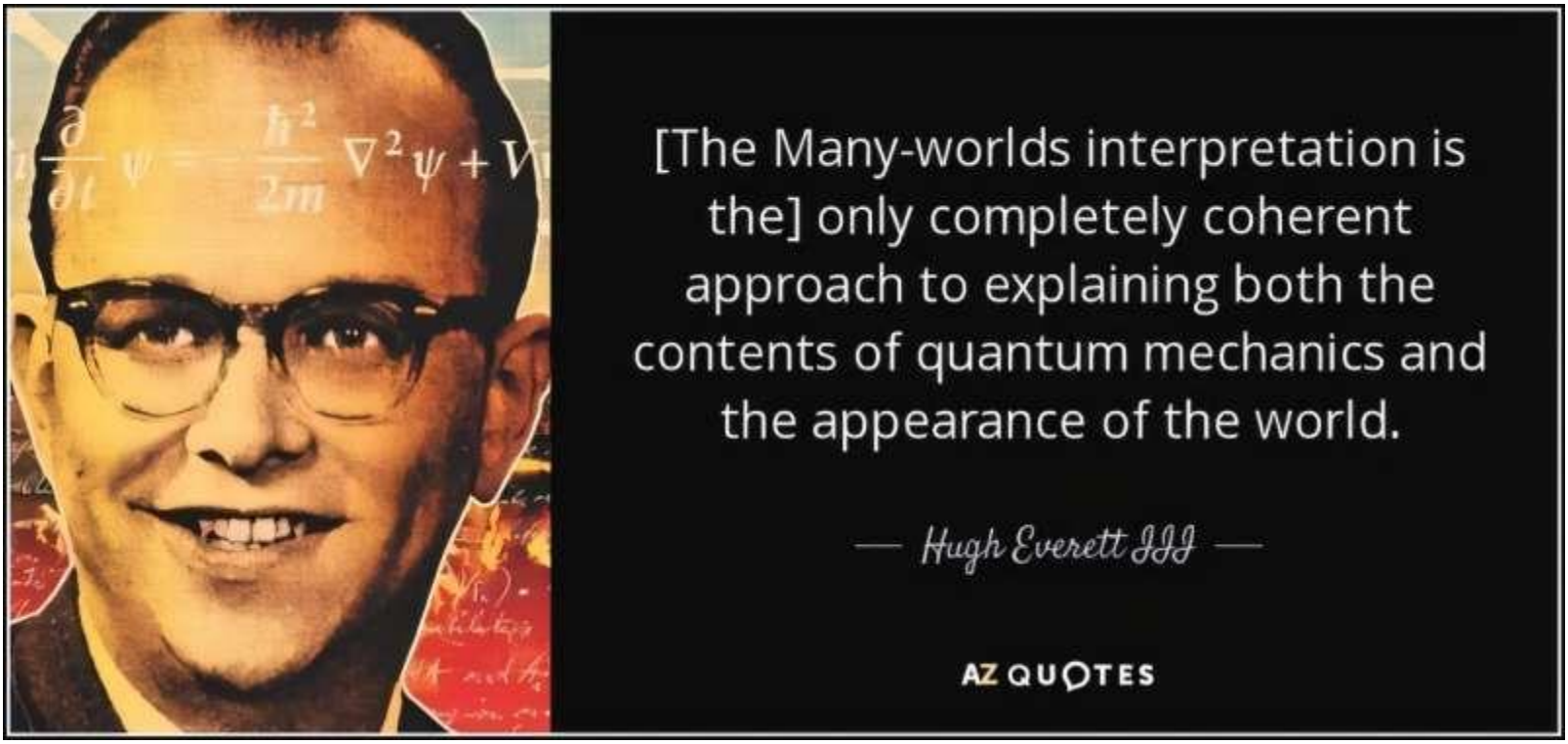
This method allows astronomers to distinguish one supercluster from another, and that's how we've recognized that the Virgo supercluster is just one individual branch of a much larger structure known as Laniakea, which contains an astounding 100,000 galaxies. And that is our home in the universe.

Provided by Universe Today

DECEMBER 27, 2024 FEATURE

Editors' notes

Numerical simulations show how the classical world might emerge from the many-worlds universes of quantum mechanics



by David Appell , Phys.org

Hugh Everett III developed the many-worlds interpretation of quantum mechanics in his 1957 PhD thesis at Princeton. He left physics after graduate school to work for the US military. Credit: AZQuotes.com (with link to https://alchetron.com/Hugh-Everett-III). For copyright policy, see section 3 on https://www.azquotes.com/terms_of_use.html
Students learning quantum mechanics are taught the Schrodinger equation and how to solve it to obtain a wave function. But a crucial step is skipped because it has puzzled scientists since the earliest days—how does the real, classical world emerge from, often, a large number of solutions for the wave functions?

Each of these wave functions has its individual shape and associated energy level, but how does the wave function "collapse" into what we see as the classical world—atoms, cats and

the pool noodles floating in the tepid swimming pool of a seedy hotel in Las Vegas hosting a convention of hungover businessmen trying to sell the world a better mousetrap?

At a high level, this is handled by the "Born rule"—the postulate that the probability density for finding an object at a particular location is proportional to the square of the wave function at that position.

Erwin Schrödinger invented his famous feline as a way to amplify the consequences of the collapsing wave function—a simple event, such as a quantum event of the radioactive decay of an atomic nucleus, somehow translates into the macroscopic cat in the box being, either alive or dead. (This mysterious transition, perhaps theoretical only, is called the Heisenberg Cut.)

Traditional quantum mechanics says that at any time the cat becomes either alive or dead when the box is opened and the cat state is "measured." Before that, the cat is, in a sense, both alive and dead—it exists in a quantum superposition of each state. It is only when the box is opened and its inside is viewed does the wave function of the cat collapse into a definite state of being either alive or dead.

In recent years, physicists have been looking at this process more deeply to understand what's happening. Modifying the Schrödinger equation has had only limited success.

Other ideas than the Copenhagen interpretation described above, such as De Broglie-Bohm pilot wave theory and the many-worlds interpretation of quantum mechanics, are receiving more attention.

Now a team of quantum theorists from Spain have used numerical simulations to show that, on large scales, features of the classical world can emerge from a wide class of quantum systems. Their work is published in the journal *Physical Review X*.

"Quantum physics is at odds with our classical experience as far as the behavior of single electrons, atoms or photons is concerned," lead author Philipp Strasberg of the Autonomous University of Barcelona told Phys.org.

"However, if one zooms out, and considers coarse quantities that we humans can perceive (for example, the temperature of our morning coffee or the position of a stone), our results indicate that quantum interference effects, which are responsible for weird quantum behavior, vanish."

Their finding suggests that the classical world we see can emerge from the many-worlds picture of quantum mechanics, where many universes exist at the same point in spacetime and where almost a potentially huge number of worlds branch off from ours every time a measurement is made.

As a rough analogy, imagine a shower bag filled with water. Poke holes in the bag and water—which inside the bag is a large collection of frequently colliding molecules moving in random directions—will stream out in mostly smooth flows. This is akin to how the complicated jumble of a quantum system nonetheless appears in the classical world as something we recognize and feel familiar with.

But a technical problem remained with the many-worlds portrait: how do we reconcile the many-universes with the classical experience we have within our one universe? After all, we never see cats in a superposition of alive and dead. A priori, how can we speak of other universes or worlds or branches in any meaningful sense?

In their paper, Strasberg and co-authors write "Speaking of different worlds or histories becomes meaningful if we can reason about their past, present, and future in classical terms."

The co-authors attempted to solve this problem in a new way. While previous work has brought in the idea of quantum decoherence—where the objects we see arise out of the many superpositions of a quantum system when it interacts with their environment. But this approach has a fine-tuning problem—it only works for specific types of interactions and types of initial wave functions.

By contrast, the group showed that a stable, self-consistent set of features emerges from the range of many possible evolutions of a wave function (with many energy levels) at observable, non-microscopic scales. This solution does not have a fine-tuning problem, works for a wide choice of initial conditions and the details of the interactions between energy levels.

"In particular," Strasberg told Phys.org, "we provide clear evidence that this vanishing [of quantum interference effects] happens extremely fast—to be precise: exponentially fast—with growing system size. That is, even a few atoms or photons can behave classically. Furthermore, it is a ubiquitous and generic phenomenon that does not require any fine tuning: the emergence of a classical world is inevitable."

The group numerically simulated quantum evolution for up to five time-steps and up to 50,000 energy levels for nontrivial quantum systems. Though that evolution is still small compared to what will be needed to simulate everyday classical phenomena, it's much larger than any previous work.

They considered a broad range of choices of the initial wave function and of coupling strengths and found approximately the same large-scale structure of stable branches exist—the emergence of a stable and slowly evolving macroscopic structure.

"Remarkably, we also explicitly demonstrate that interesting classical worlds can emerge from a quantum system that is overall in thermodynamic equilibrium. Even though it is very unlikely that this is the case in our universe, it nevertheless demonstrates that order, structure and an arrow of time can emerge on single branches of a quantum Multiverse, which overall looks chaotic, unstructured and time-symmetric."

Relating their work to statistical mechanics, where macroscopic features like temperature and pressure emerge from a melange of randomly moving particles, the group found that some branches lead to worlds where entropy increases and others to worlds where entropy decreases. Such worlds would have opposite entropic arrows of time.

More information: Philipp Strasberg et al, First Principles Numerical Demonstration of Emergent Decoherent Histories, *Physical Review X* (2024). DOI: 10.1103/PhysRevX.14.041027
Journal information: Physical Review X

DECEMBER 23, 2024

Can entangled particles communicate faster than light?

by Paul M. Sutter, Universe Today

Illustration depicting quantum entanglement between particles. Credit: ATLAS Experiment
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

OCTOBER 7, 2022

What is quantum entanglement? A physicist explains the science of Einstein's 'spooky action at a distance'

by Andreas Muller, The Conversation

According to quantum mechanics, particles are simultaneously in two or more states until observed – an effect vividly captured by Schrödinger's famous thought experiment of a cat that is both dead and alive simultaneously. Credit: Michael Holloway/Wikimedia Commons, CC BY-SA

The 2022 Nobel Prize in physics recognized three scientists who made groundbreaking contributions in understanding one of the most mysterious of all natural phenomena: quantum entanglement.

In the simplest terms, quantum entanglement means that aspects of one particle of an entangled pair depend on aspects of the other particle, no matter how far apart they are or what lies between them. These particles could be, for example, electrons or photons, and an aspect could be the state it is in, such as whether it is "spinning" in one direction or another.

The strange part of quantum entanglement is that when you measure something about one particle in an entangled pair, you immediately know something about the other particle, even if they are millions of light years apart. This odd connection between the two particles is instantaneous, seemingly breaking a fundamental law of the universe. Albert Einstein famously called the phenomenon "spooky action at a distance."

Having spent the better part of two decades conducting experiments rooted in quantum mechanics, I have come to accept its strangeness. Thanks to ever more precise and reliable instruments and the work of this year's Nobel winners, Alain Aspect, John Clauser and Anton Zeilinger, physicists now integrate quantum phenomena into their knowledge of the world with an exceptional degree of certainty.

However, even until the 1970s, researchers were still divided over whether quantum entanglement was a real phenomenon. And for good reasons—who would dare contradict the great Einstein, who himself doubted it? It took the development of new experimental technology and bold researchers to finally put this mystery to rest.

Existing in multiple states at once

To truly understand the spookiness of quantum entanglement, it is important to first understand quantum superposition. Quantum superposition is the idea that particles exist in

multiple states at once. When a measurement is performed, it is as if the particle selects one of the states in the superposition.

For example, many particles have an attribute called spin that is measured either as "up" or "down" for a given orientation of the analyzer. But until you measure the spin of a particle, it simultaneously exists in a superposition of spin up and spin down.

There is a probability attached to each state, and it is possible to predict the average outcome from many measurements. The likelihood of a single measurement being up or down depends on these probabilities, but is itself unpredictable.

Though very weird, the mathematics and a vast number of experiments have shown that quantum mechanics correctly describes physical reality.

Two entangled particles

The spookiness of quantum entanglement emerges from the reality of quantum superposition, and was clear to the founding fathers of quantum mechanics who developed the theory in the 1920s and 1930s.

To create entangled particles you essentially break a system into two, where the sum of the parts is known. For example, you can split a particle with spin of zero into two particles that necessarily will have opposite spins so that their sum is zero.

In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen published a paper that describes a thought experiment designed to illustrate a seeming absurdity of quantum entanglement that challenged a foundational law of the universe.

A simplified version of this thought experiment, attributed to David Bohm, considers the decay of a particle called the pi meson. When this particle decays, it produces an electron and a positron that have opposite spin and are moving away from each other. Therefore, if the electron spin is measured to be up, then the measured spin of the positron could only be down, and vice versa. This is true even if the particles are billions of miles apart.

This would be fine if the measurement of the electron spin were always up and the measured spin of the positron were always down. But because of quantum mechanics, the spin of each particle is both part up and part down until it is measured. Only when the measurement occurs does the quantum state of the spin "collapse" into either up or down—instantaneously collapsing the other particle into the opposite spin. This seems to suggest that the particles communicate with each other through some means that moves faster than the speed of light. But according to the laws of physics, nothing can travel faster than the speed of light. Surely the measured state of one particle cannot instantaneously determine the state of another particle at the far end of the universe?

Physicists, including Einstein, proposed a number of alternative interpretations of quantum entanglement in the 1930s. They theorized there was some unknown property—dubbed hidden variables—that determined the state of a particle before measurement. But at the time, physicists did not have the technology nor a definition of a clear measurement that could test whether quantum theory needed to be modified to include hidden variables.

Disproving a theory

It took until the 1960s before there were any clues to an answer. John Bell, a brilliant Irish physicist who did not live to receive the Nobel Prize, devised a scheme to test whether the notion of hidden variables made sense.

Bell produced an equation now known as Bell's inequality that is always correct—and only correct—for hidden variable theories, and not always for quantum mechanics. Thus, if Bell's equation was found not to be satisfied in a real-world experiment, local hidden variable theories can be ruled out as an explanation for quantum entanglement.

The experiments of the 2022 Nobel laureates, particularly those of Alain Aspect, were the first tests of the Bell inequality. The experiments used entangled photons, rather than pairs of an electron and a positron, as in many thought experiments. The results conclusively ruled out the existence of hidden variables, a mysterious attribute that would predetermine the states of entangled particles. Collectively, these and many follow-up experiments have vindicated quantum mechanics. Objects can be correlated over large distances in ways that physics before quantum mechanics can not explain.

Importantly, there is also no conflict with special relativity, which forbids faster-than-light communication. The fact that measurements over vast distances are correlated does not imply that information is transmitted between the particles. Two parties far apart performing measurements on entangled particles cannot use the phenomenon to pass along information faster than the speed of light.

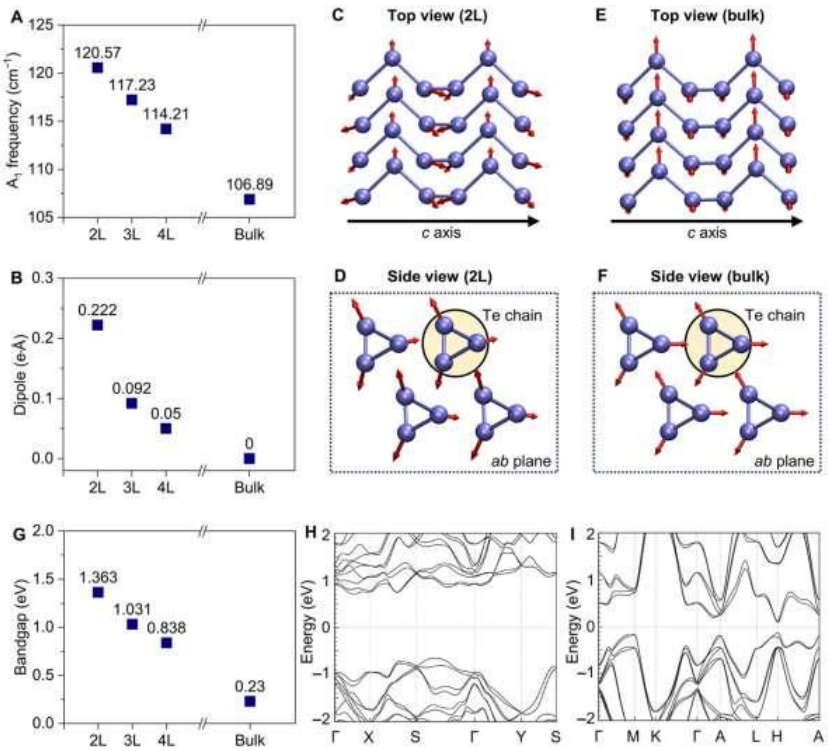
Today, physicists continue to research quantum entanglement and investigate potential practical applications. Although quantum mechanics can predict the probability of a measurement with incredible accuracy, many researchers remain skeptical that it provides a complete description of reality. One thing is certain, though. Much remains to be said about the mysterious world of quantum mechanics.

Provided by The Conversation

JANUARY 14, 2025

Quasiparticle research unlocks new insights into tellurene, paving the way for next-gen electronics

by Rice University



Calculated phonon polarity and band structure for few-layer tellurene and bulk tellurium.(**A**) The calculated A_1 phonon frequency. (**B**) The calculated change of the dipole moment by the A_1 mode as a function of thickness. (**C** to **F**) Top view and side view with respect to the experiment geometry showing the calculated lattice vibrations of the A_1 mode in 2L tellurene and bulk tellurium. The red arrows represent the atomic vibrations. (**G**) The calculated bandgap of tellurene as a function of thickness. Calculated band structure of (**H**) 2L tellurene and (**I**) bulk tellurium. Credit: *Science Advances* (2025). DOI: 10.1126/sciadv.ads4763

To describe how matter works at infinitesimal scales, researchers designate collective behaviors with single concepts, like calling a group of birds flying in sync a "flock" or "murmuration." Known as quasiparticles, the phenomena these concepts refer to could be the key to next-generation technologies.

In a recent study published in *Science Advances*, a team of researchers led by Shengxi Huang, associate professor of electrical and computer engineering and materials science and nanoengineering at Rice, describe how one such type of quasiparticle—polarons—behaves in tellurene, a nanomaterial first synthesized in 2017 that is made up of tiny chains of tellurium atoms and has properties useful in sensing, electronic, optical and energy devices.

"Tellurene exhibits dramatic changes in its electronic and optical properties when its thickness is reduced to a few nanometers compared to its bulk form," said Kunyan Zhang, a Rice doctoral alumna who is a first author on the study. "Specifically, these changes alter how electricity flows and how the material vibrates, which we traced back to the transformation of polarons as tellurene becomes thinner."

A polaron forms when charge-carrying particles such as electrons interact with vibrations in the atomic or molecular lattice of a material. Imagine a phone ringing in a packed auditorium during a lecture: Just as the audience shifts their gaze collectively to the source of the interruption, so do the lattice vibrations adjust their orientation in response to charge carriers, organizing themselves around an aura of polarization—hence the name of the quasiparticle.

Depending on the thinness of the layer of tellurene, the magnitude of this response—i.e., the span of the aura—can vary significantly. Understanding this polaron transition is important because it reveals how fundamental interactions between electrons and vibrations can influence the behavior of materials, particularly in low dimensions.

"This knowledge could inform the design of advanced technologies like more efficient electronic devices or novel sensors and help us understand the physics of materials at the smallest scales," said Huang, who is a corresponding author of the paper.

The researchers hypothesized that as tellurene transitions from bulk to nanometer thickness, polarons change from large, spread-out electron-vibration interactions to smaller, localized interactions. Computations and experimental measurements backed up this scenario.

"We analyzed how the vibration frequencies and linewidths varied with thickness and correlated these with changes in electrical transport properties, complemented by the structural distortions observed in X-ray absorption spectroscopy," Zhang said. "Furthermore, we developed a field theory to explain the effects of enhanced electron-vibration coupling in thinner layers."

The team's comprehensive approach yielded deeper insight into thickness-dependent polaron dynamics in tellurene than previously available. This was possible due to both improvements in the advanced research techniques deployed and the recent development of high-quality tellurene samples.

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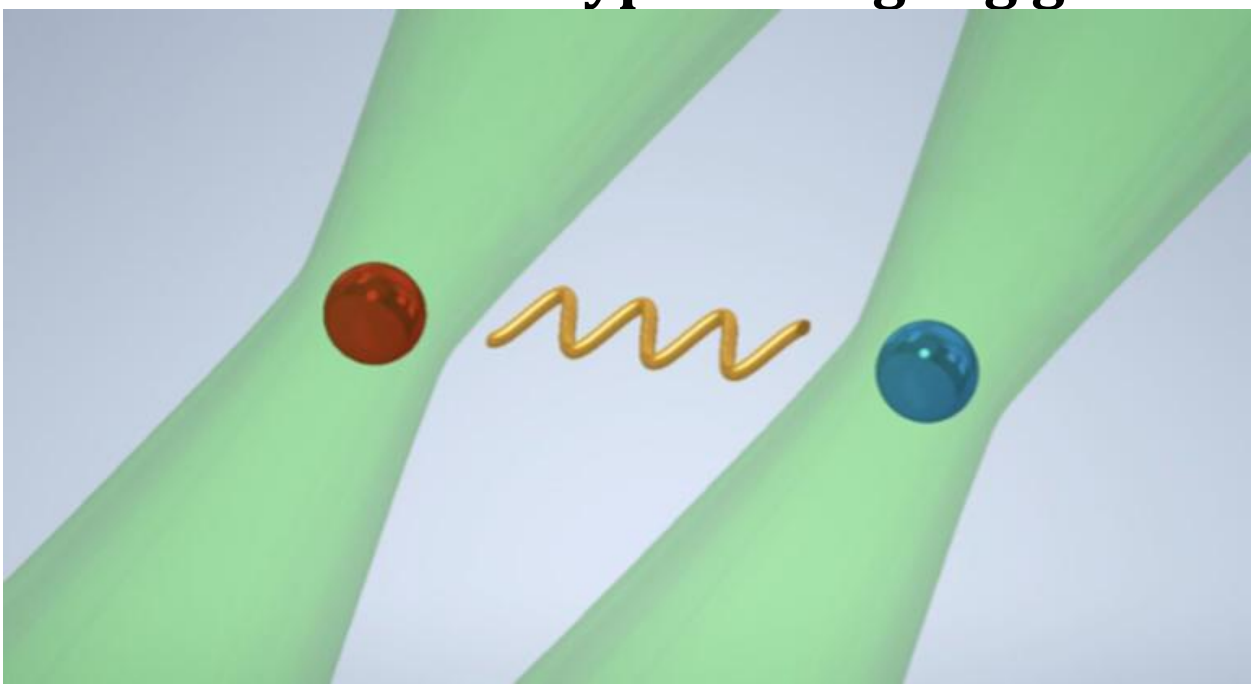
"Our findings highlight how polarons impact electrical transport and optical properties in tellurene as it becomes thinner," Zhang said. "In thinner layers, polarons localize charge carriers, leading to reduced charge carrier mobility. This phenomenon is crucial for designing modern devices, which are continually becoming smaller and rely on thinner materials for functionality."

On the one hand, reduced charge mobility can limit the efficiency of electronic components, especially for applications that require high conductivity such as power transmission lines or high-performance computing hardware. On the other hand, this localization effect could guide the design and development of high-sensitivity sensors and phase-change, ferroelectric, thermoelectric and certain quantum devices.

"Our study provides a foundation for engineering materials like tellurene to balance these trade-offs," Huang said. "It offers valuable insights into designing thinner, more efficient devices while addressing the challenges that arise from the unique behaviors of low-dimensional materials, which is vital for the development of next-generation electronics and sensors."

More information: Kunyan Zhang et al, Thickness-dependent polaron crossover in tellurene, *Science Advances* (2025). DOI: 10.1126/sciadv.ads4763
Journal information: Science Advances
Provided by Rice University

Scientists achieve direct experimental realization of dual-type entangling gates



Using the same laser setup to entangle dual-type qubits. Credit: Chenxi Wang and Chuanxin Huang.

To develop scalable and reliable quantum computers, engineers and physicists will need to devise effective strategies to mitigate errors in their quantum systems without adding complex additional components. A promising strategy to reduce errors entails the use of so-called dual-type qubits.

These are qubits that can encode quantum information in a system across two different types of quantum states. These qubits could increase the flexibility of quantum computing architectures, while also reducing undesirable crosstalk between qubits and enhancing a system's operational fidelity.

Researchers at Tsinghua University and other research institutes in China recently realized an entangling gate between dual-type qubits in an experimental setting.

Their paper, published in *Physical Review Letters*, introduces a promising approach for realizing these gates, which could help to boost the performance of quantum computing systems without the need for additional hardware components.

"In ion trap quantum computation, recently it has been realized that encoding two types of qubits in the same ion species is a promising scheme, one type for

carrying quantum information and the other type for auxiliary operations," Luming Duan, senior author of the paper, told Phys.org.

"A crucial gadget in this scheme is to entangle the qubits encoded in these two types. Although in principle one can first convert the qubits into the same type and then perform the same-type entangling gate, in practice it would lead to considerable overhead."

The main objective of this recent study by Duan and his colleagues was to directly and experimentally realize a dual-type entangling gate. The team achieved this using a single 532 nm laser system to drive Raman transitions, entangling dual-type qubits without employing any additional hardware.

"We carefully design multiple frequency components in the driving laser, such that they couple the two qubit types, one encoded in the hyperfine levels of one ion and the other encoded in the hyperfine levels of another ion, simultaneous to the collective spatial oscillation of the two ions," explained Duan.

"Using these collective oscillation modes as a quantum bus, we generate entanglement between the dual-type qubits."

The researchers evaluated their proposed approach's potential in a series of tests and found that it achieved entanglement between dual-type qubits encoded in the S and D manifolds of ions, respectively, with a remarkable Bell state fidelity of 96.3%. This performance is comparable to that achieved by same-type entangling gates (i.e., S-S or D-D gates).

"Using a single setup, we achieve dual-type and same-type entangling gates with similar gate performance," said Duan. "This suggests that there is no additional fundamental limitation in realizing a dual-type entangling gate, such that it can be applied in practical quantum circuits to help reduce the overhead of back-and-forth qubit type conversions."

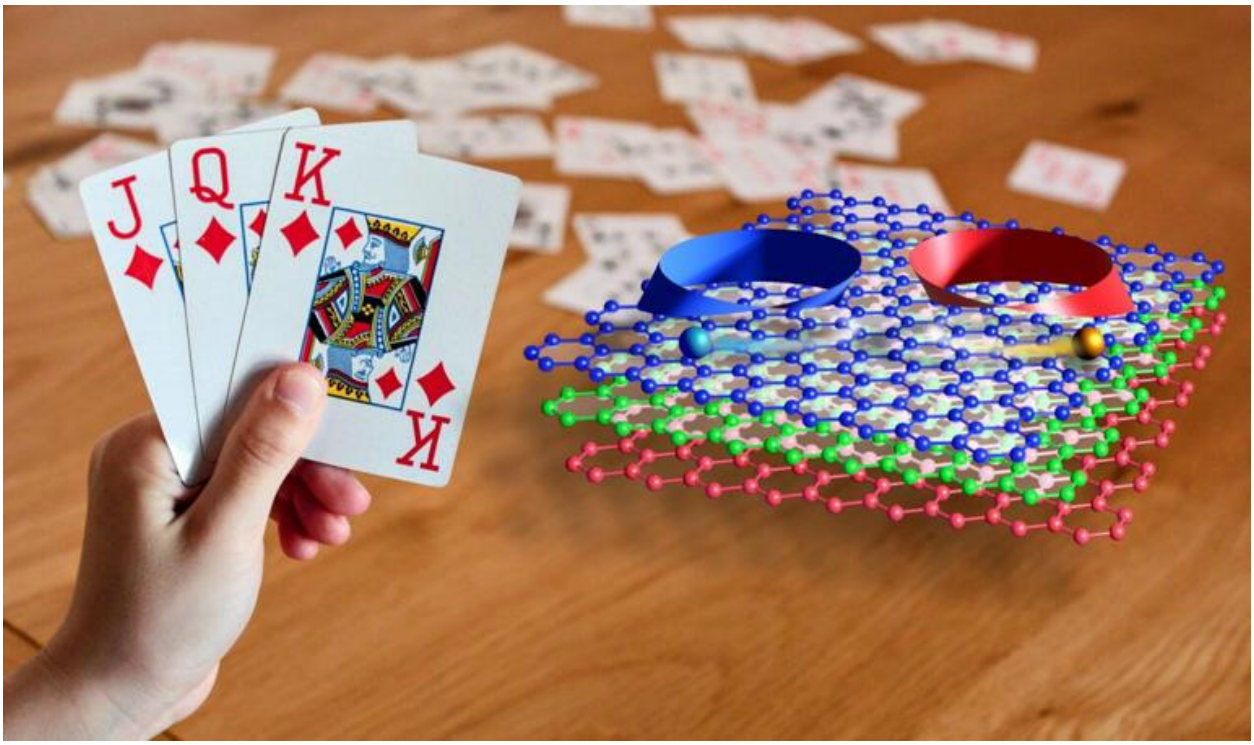
The findings of this study could soon inspire other research groups to experiment with dual-type qubits to reduce errors in quantum systems without increasing their complexity. Meanwhile, Duan and his colleagues will continue building on their methods, to further boost the performance of the dual-type entangling gate they realized.

"We plan to upgrade the system for better stabilization of the optical paths and better locking of the trap frequency," added Duan.

"These will help improve the gate performance. We also plan to apply this dual-type entangling gate to demonstrate mid-circuit quantum state detection for quantum error correction, and to demonstrate the functioning of a trapped-ion-based quantum network node."

More information: Chenxi Wang et al, Experimental Realization of Direct Entangling Gates between Dual-Type Qubits, *Physical Review Letters* (2025). DOI: 10.1103/PhysRevLett.134.010601. On *arXiv*: DOI: 10.48550/arxiv.2410.05659

Physicists discover and explain unexpected magnetism in atomically thin material



MIT physicists have created an ultrathin, two-dimensional material with unusual magnetic properties. They did so by working with three layers of graphene. Each layer is composed of only a single layer of atoms. These were arranged in a helical structure akin to the DNA helix or a hand of three cards that are fanned apart. The image at right represents the resulting material and its unexpected physics. Oppositely twisted Möbius strips represent the quantum mechanical wavefunctions' local topology that alternates on large length scales. The electrons' circular motion gives the observed magnetism. Credit: Jarillo-Herrero lab, MIT

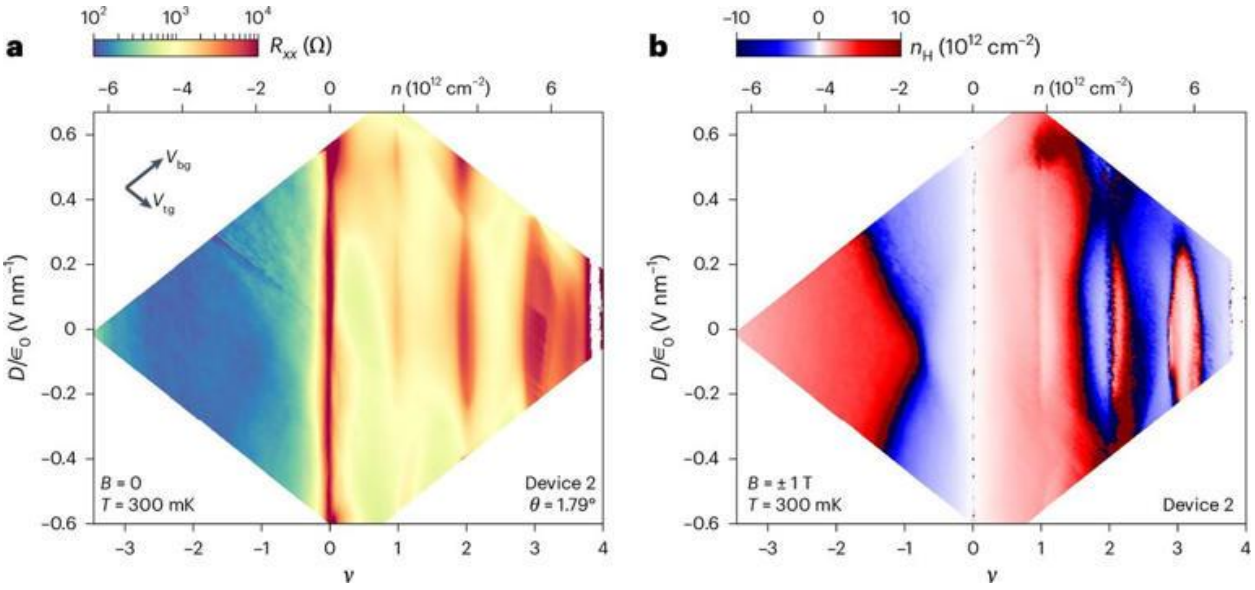
MIT physicists have created a new ultrathin, two-dimensional material with unusual magnetic properties that initially surprised them before they went on to solve the complicated puzzle behind those properties' emergence. As a result, the work introduces a new platform for studying how materials behave at the most fundamental level, the world of quantum physics.

Ultrathin materials made of a single layer of atoms have riveted scientists' attention since the discovery of the first such material—graphene, composed of carbon—about 20 years ago. Among other advances since then, researchers have found that stacking individual sheets of the 2D materials, and sometimes twisting them at a slight angle to each other, can give them new properties, from superconductivity to magnetism. Enter the field of twistronics, which was pioneered at MIT by Pablo Jarillo-Herrero, the Cecil and Ida Green Professor of Physics at MIT.

MIT physicists have created an ultrathin, two-dimensional material with unusual magnetic properties. The three co-first authors of a Nature Physics paper on the work are, L-R, Sergio C. de la Barrera (now at the University of Toronto), Li-Qiao Xia, and Aviram Uri. Credit: Clement Collignon

In the current research, reported in the January 7 issue of *Nature Physics*, the scientists, led by Jarillo-Herrero, worked with three layers of graphene. Each layer was twisted on top of the next at the same angle, creating a helical structure akin to the DNA helix or a hand of three cards that are fanned apart.

"Helicity is a fundamental concept in science, from basic physics to chemistry and molecular biology. With 2D materials, one can create special helical structures, with novel properties which we are just beginning to understand. This work represents a new twist in the field of twistronics and the community is very excited to see what else we can discover using this helical materials platform," says Jarillo-Herrero, who is also affiliated with MIT's Materials Research Laboratory.



Strong electronic interactions. Credit: Nature Physics (2025). DOI: 10.1038/s41567-024-02731-6

Do the twist

Twistronics can lead to new properties in ultrathin materials because arranging sheets of 2D materials in this way results in a unique pattern called a moiré lattice. And a moiré pattern, in turn, has an impact on the behavior of electrons.

"It changes the spectrum of energy levels available to the electrons and can provide the conditions for interesting phenomena to arise," says Sergio C. de la Barrera, one of three co-first authors of the recent paper. De la Barrera, who conducted the work while a postdoctoral associate at MIT, is now an assistant professor at the University of Toronto.

In the current work, the helical structure created by the three graphene layers forms two moiré lattices. One is created by the first two overlapping sheets; the other is formed between the second and third sheets.

The two moiré patterns together form a third moiré, a supermoiré, or "moiré of a moiré," says Li-Qiao Xia, a graduate student in MIT physics and another of the three co-first authors of the paper. "It's like a moiré hierarchy."

While the first two moiré patterns are only nanometers, or billionths of a meter, in scale, the supermoiré appears at a scale of hundreds of nanometers

superimposed over the other two. You can only see it if you zoom out to get a much wider view of the system.

A major surprise

The physicists expected to observe signatures of this moiré hierarchy. They got a huge surprise, however, when they applied and varied a magnetic field. The system responded with an experimental signature for magnetism, one that arises from the motion of electrons. In fact, this orbital magnetism persisted to -263 °C—the highest temperature reported in carbon-based materials to date.

But that magnetism can only occur in a system that lacks a specific symmetry—one that the team's new material should have had. "So the fact that we saw this was very puzzling. We didn't really understand what was going on," says Aviram Uri an MIT Pappalardo postdoctoral fellow in physics and the third co-first author of the new paper.

Other authors of the paper include MIT Professor of Physics Liang Fu; Aaron Sharpe of Sandia National Laboratories; Yves H. Kwan of Princeton University; Ziyan Zhu, David Goldhaber-Gordon, and Trithep Devakul of Stanford; and Kenji Watanabe and Takashi Taniguchi of the National Institute for Materials Science in Japan.

What was happening?

It turns out that the new system did indeed break the symmetry which prohibits the orbital magnetism the team observed, but in a very unusual way. "What happens is that the atoms in this system aren't very comfortable, so they move in a subtle orchestrated way that we call lattice relaxation," says Xia. And the new structure formed by that relaxation does indeed break the symmetry locally, on the moiré length scale.

This opens the possibility for the orbital magnetism the team observed. However, if you zoom out to view the system on the supermoiré scale, the symmetry is restored.

"The moiré hierarchy turns out to support interesting phenomena at different length scales," says de la Barrera.

Uri concludes, "It's a lot of fun when you solve a riddle and it's such an elegant solution. We've gained new insights into how electrons behave in these complex systems, insights that we couldn't have had unless our experimental observations forced to think about these things."

More information: Li-Qiao Xia et al, Topological bands and correlated states in helical trilayer graphene, *Nature Physics* (2025). DOI: 10.1038/s41567-024-02731-6

Provided by Materials Research Laboratory, Massachusetts Institute of Technology

World-first quantum entanglement of molecules at 92% fidelity, UK achieves ‘magic’

In a major accomplishment for quantum mechanics research, scientists at Durham University in the UK have achieved the first-ever quantum entanglement of molecules. The team used precisely controlled optical traps or ‘magic-wavelength optical tweezers’ to create environments that support long-lasting entanglement, a press release said.

Quantum entanglement is an important phenomenon where two particles are linked irrespective of distance. In such a condition, the state of one particle influences the other and is being explored to develop futuristic computational approaches. The phenomenon has various applications ranging from quantum sensing to computing.

Interesting Engineering has previously reported how quantum entanglement can transmit information between two or multiple nodes and achieve lightning-fast communication.

Additionally, the entanglement can be achieved over existing fiber optic cable networks, enabling real-world deployment of quantum networks without building extensive infrastructure.

First-ever entanglement of molecules

Although quantum entanglement between atoms has been demonstrated multiple times before, a research team led by Simon Cornish at Durham University achieved a major milestone by demonstrating it with molecules for the first time.

Since molecules have additional structures and properties, such as vibration and rotation, scientists believe they can leverage them in quantum applications.

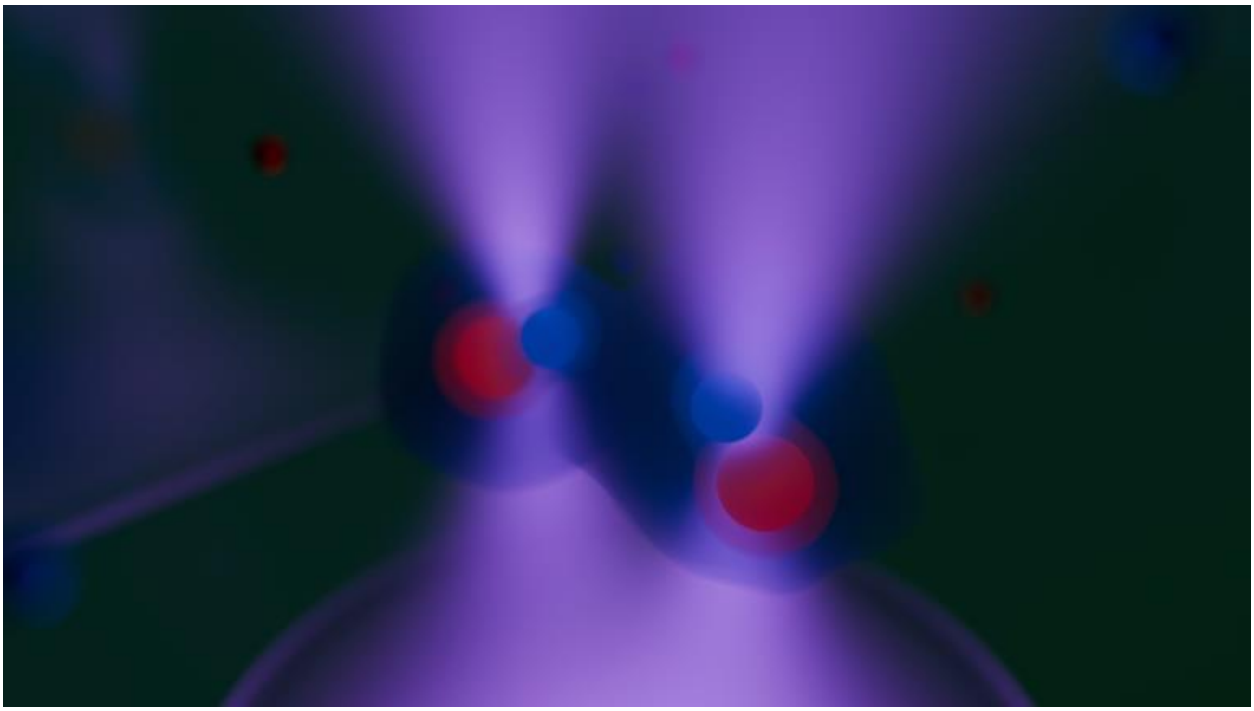
“Quantum entanglement is very fragile, yet we can entangle two molecules using incredibly weak interactions and then prevent loss of the entanglement for a time approaching one second,” explained Cornish in the press release.

However, to achieve this, the research team needed to create a stable environment that supports the coherence of molecules over extended periods.

The Tweezer Team at Durham University and their experimental apparatus. From left: Dr Daniel Ruttley, Prof. Simon Cornish, Dr Alexander Guttridge and Mr Tom Hepworth. Image credit: Durham University .

Optical Tweezers

The team deployed specially tuned laser light to control the molecules with high precision. This resulted in extremely high entanglement fidelity of over 92 percent, even when errors were accounted for.



Two Molecules Render: An illustration of two entangled molecules which are individually trapped in magic-wavelength optical tweezers. Image credit: Durham Universit y .

“The results highlight the remarkable control we have over individual molecules,” added Cornish in the press release. Stability is important for applications that involve long measurement periods and storage of quantum information.

“Our work demonstrates the incredible potential of molecules as building blocks for next-generation quantum technologies,” said Daniel Ruttley, a post-doctoral research associate at the university, who was also involved in the work.

“Long-lived molecular entanglement could be exploited to construct quantum computers or precise quantum sensors and to understand the quantum nature of complex materials.”

Long-lived entanglement could also help achieve precision measurements in quantum sensing, simulate complex quantum materials, and further newer forms of quantum computation.

The research could also help in the development of quantum memories. Much like binary data storage devices, these systems could help store quantum information for longer durations and advance quantum networks.

The research is an important step in the advancement of quantum computing systems. While much of the work in this domain has been focused on attaining computations with a higher number of quantum bits or qubits and error correction, we also need to delve deeper into quantum phenomena such as quantum entanglement to make major advancements in technology.

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

US creates strongest-ever armor material with 100 trillion bonds per cm^2

A research team led by scientists at Northwestern University has developed the first-ever two-dimensional mechanically interlocked material with high flexibility and strength. In the future, this could be used to develop lightweight yet high-performance body armor and other such tough materials, a press release said.

It was in the 1980s that Fraser Stoddart, then a chemist at Northwestern University, first introduced the concept of mechanical bonds. Stoddart then expanded the role of these bonds into molecular machines by enabling functions like switching, rotating, contracting, and expanding in multiple ways and using them to develop interlocked structures, which also won him the Nobel Prize in 2016.

Researchers have been working on developing mechanically interlocked molecules with polymers for decades but have failed. “In organic chemistry, it is pretty straightforward to form so-called “medium-sized rings” that are 5-8 atoms around. But such rings are too small to thread another molecule through them,” explained William Dichtel, a professor of chemistry at Northwestern University in an email to *Interesting Engineering*.

“In our paper, there are new rings formed at each repeat unit of the 2D structure, which are 40 atoms around,” added Dichtel. This was achieved using an innovative and novel approach that even questioned assumptions about how molecules react.

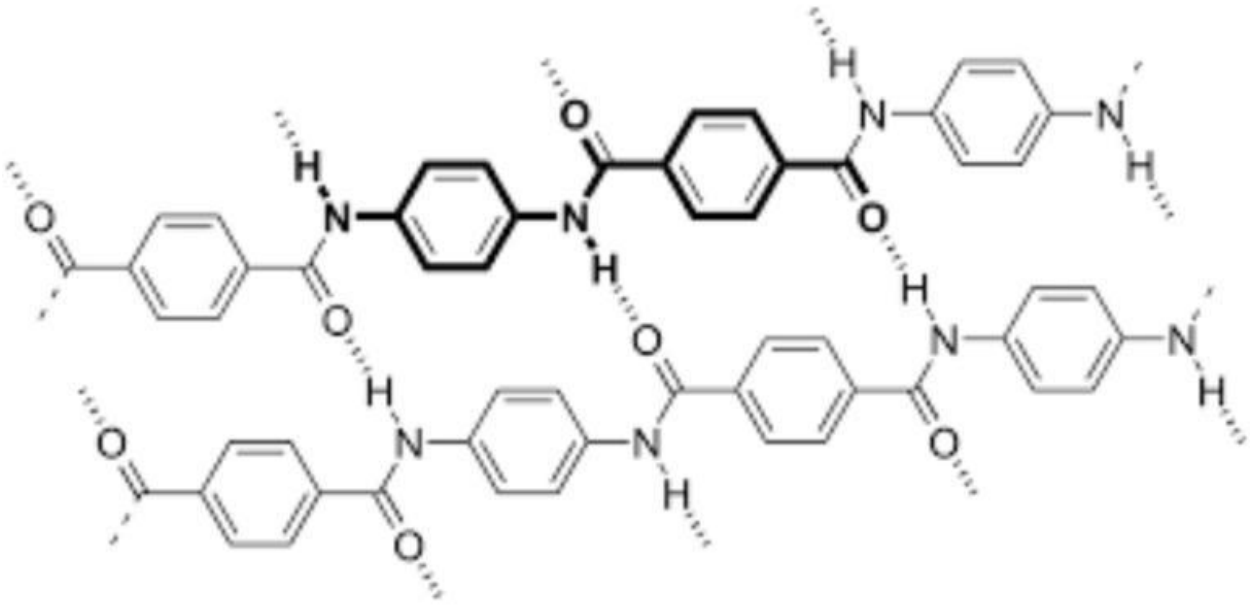
A novel process

Madison Bardot, a Ph.D candidate in Dichtel's lab, developed a novel process using X-shaped monomers as building blocks and arranging them into highly ordered crystalline structures. They then used another molecule to create bonds between molecules of the crystal.

The resulting material consists of layers of two-dimensional (2D) polymer sheets where ends of X-shaped monomers are interlocked with ends of other X-shaped monomers, and more monomers are threaded through the gaps in between. Together, the material consists of 100 trillion mechanical bonds per square centimeter, the highest density ever achieved.

Interestingly, the team also found that dissolving the polymer in the solution allowed the interlocked monomers to peel off each other, enabling the manipulation of individual sheets.

"Many highly crystalline substances are brittle, but our polymer has a regular, ordered structure yet is highly flexible because each mechanical bond has a little bit of space to move around," explained Dichtel in the email to *IE*.



Chemical structure of Kevlar. Image credit: Wikimedia Commons

“When one applies a light force to the polymer, it is extremely flexible, but if more force is applied the material becomes more rigid as the mechanical bonds are stretched locally to their limits. This property is called “strain hardening” and is of great interest for ductile and mechanically tough materials.”

Beyond mechanical properties, the polymer architecture has interesting properties that can be explored for new applications.

Strength to strength

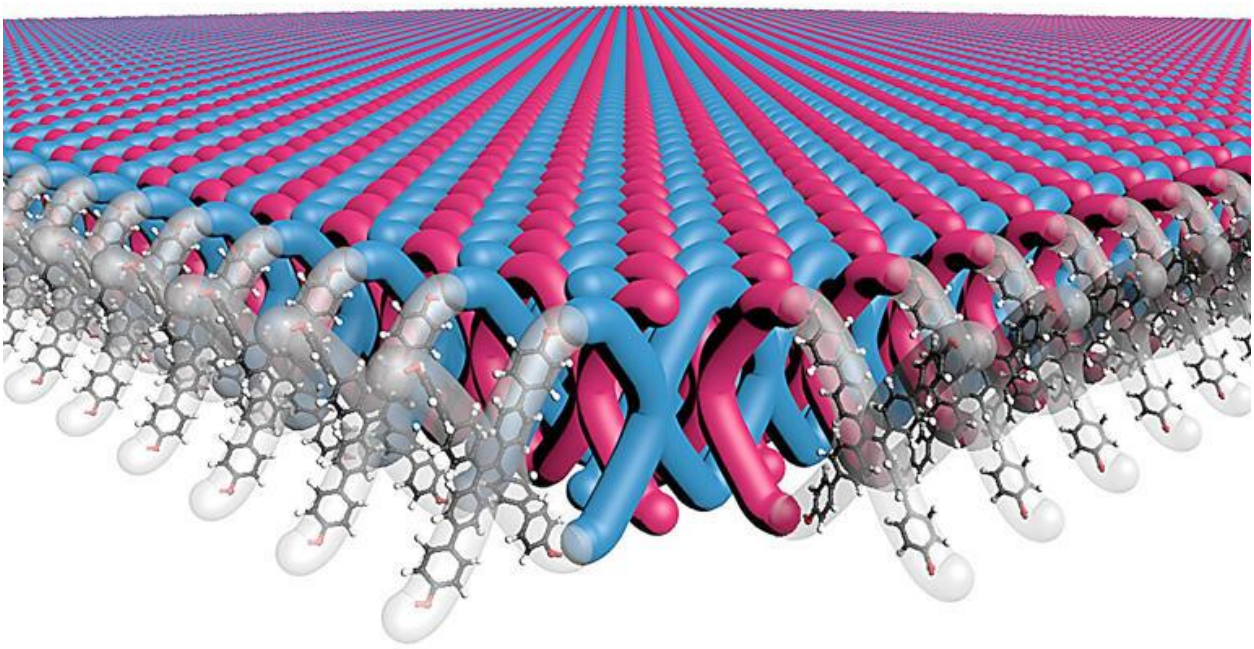
Dichtel’s collaborators at Duke University added this newly developed polymer to Ultem, a fiber in the same family as Kevlar but which can withstand extreme temperatures and chemical exposure. Using just 2.5 percent of the polymer dramatically increased its strength and toughness. This could be used for making armor or ballistics protection.

While polymers containing mechanical bonds have previously been synthesized at a small scale, this approach helped Dichtel’s team easily make almost a pound (half a kilogram) of the material. This also shows that the approach is highly scalable as well.

“Perhaps the most challenging aspect was proving to ourselves that we indeed had the proposed mechanically interlocked structure – it took a team of diverse expertise – synthetic chemists, electron microscopists, polymer engineers – to figure out how to make the materials and then how to actually study them,” added Dichtel in the email.

The research findings were published in the journal *Science*.

New chainmail-like material could be the future of armor



This illustration shows how X-shaped monomers are interlinked to create the first 2D mechanically interlocked polymer. Similar to chainmail, the material exhibits exceptional strength. Credit: Mark Seniw, Center for Regenerative Nanomedicine, Northwestern University

In a remarkable feat of chemistry, a Northwestern University-led research team has developed the first two-dimensional (2D) mechanically interlocked material.

Resembling the interlocking links in chainmail, the nanoscale material exhibits exceptional flexibility and strength. With further work, it holds promise for use in high-performance, light-weight body armor and other uses that demand lightweight, flexible and tough materials.

Publishing on Jan. 17 in the journal *Science*, the study marks several firsts for the field. Not only is it the first 2D mechanically interlocked polymer, but the novel material also contains 100 trillion mechanical bonds per 1 square centimeter—the highest density of mechanical bonds ever achieved.

The researchers produced this material using a new, highly efficient and scalable polymerization process.

"We made a completely new polymer structure," said Northwestern's William Dichtel, the study's corresponding author.

"It's similar to chainmail in that it cannot easily rip because each of the mechanical bonds has a bit of freedom to slide around. If you pull it, it can dissipate the applied force in multiple directions. And if you want to rip it apart, you would have to break it in many, many different places. We are continuing to explore its properties and will probably be studying it for years."

Dichtel is the Robert L. Letsinger Professor of Chemistry at the Weinberg College of Arts and Sciences and a member of the International Institute of Nanotechnology (IIN) and the Paula M. Trienens Institute for Sustainability and Energy. Madison Bardot, a Ph.D. candidate in Dichtel's laboratory and IIN Ryan Fellow, is the study's first author.

Inventing a new process

For years, researchers have attempted to develop mechanically interlocked molecules with polymers but found it near impossible to coax polymers to form mechanical bonds.

To overcome this challenge, Dichtel's team took a whole new approach. They started with X-shaped monomers—which are the building blocks of polymers—and arranged them into a specific, highly ordered crystalline structure. Then, they reacted these crystals with another molecule to create bonds between the molecules within the crystal.

"I give a lot of credit to Madison because she came up with this concept for forming the mechanically interlocked polymer," Dichtel said. "It was a high-risk, high-reward idea where we had to question our assumptions about what types of reactions are possible in molecular crystals."

The resulting crystals comprise layers and layers of 2D interlocked polymer sheets. Within the polymer sheets, the ends of the X-shaped monomers are bonded to the ends of other X-shaped monomers. Then, more monomers are

threaded through the gaps in between. Despite its rigid structure, the polymer is surprisingly flexible.

Dichtel's team also found that dissolving the polymer in solution caused the layers of interlocked monomers to peel off each other.

"After the polymer is formed, there's not a whole lot holding the structure together," Dichtel said. "So, when we put it in solvent, the crystal dissolves, but each 2D layer holds together. We can manipulate those individual sheets."

To examine the structure at the nanoscale, collaborators at Cornell University, led by Professor David Muller, used cutting-edge electron microscopy techniques. The images revealed the polymer's high degree of crystallinity, confirmed its interlocked structure and indicated its high flexibility.

Dichtel's team also found the new material can be produced in large quantities. Previous polymers containing mechanical bonds typically have been prepared in very small quantities using methods that are unlikely to be scalable. Dichtel's team, on the other hand, made half a kilogram of their new material and assume even larger amounts are possible as their most promising applications emerge.

Adding strength to tough polymers

Inspired by the material's inherent strength, Dichtel's collaborators at Duke University, led by Professor Matthew Becker, added it to Ultem. In the same family as Kevlar, Ultem is an incredibly strong material that can withstand extreme temperatures as well as acidic and caustic chemicals.

The researchers developed a composite material of 97.5% Ultem fiber and just 2.5% of the 2D polymer. That small percentage dramatically increased Ultem's overall strength and toughness.

Dichtel envisions his group's new polymer might have a future as a specialty material for light-weight body armor and ballistic fabrics.

"We have a lot more analysis to do, but we can tell that it improves the strength of these composite materials," Dichtel said. "Almost every property we have measured has been exceptional in some way."

Steeped in history

The authors dedicated the paper to the memory of former Northwestern chemist Sir Fraser Stoddart, who introduced the concept of mechanical bonds in the 1980s. Ultimately, he elaborated these bonds into molecular machines that switch, rotate, contract and expand in controllable ways.

Stoddart, who passed away last month, received the 2016 Nobel Prize in Chemistry for this work.

"Molecules don't just thread themselves through each other on their own, so Fraser developed ingenious ways to template interlocked structures," said Dichtel, who was a postdoctoral researcher in Stoddart's lab at UCLA.

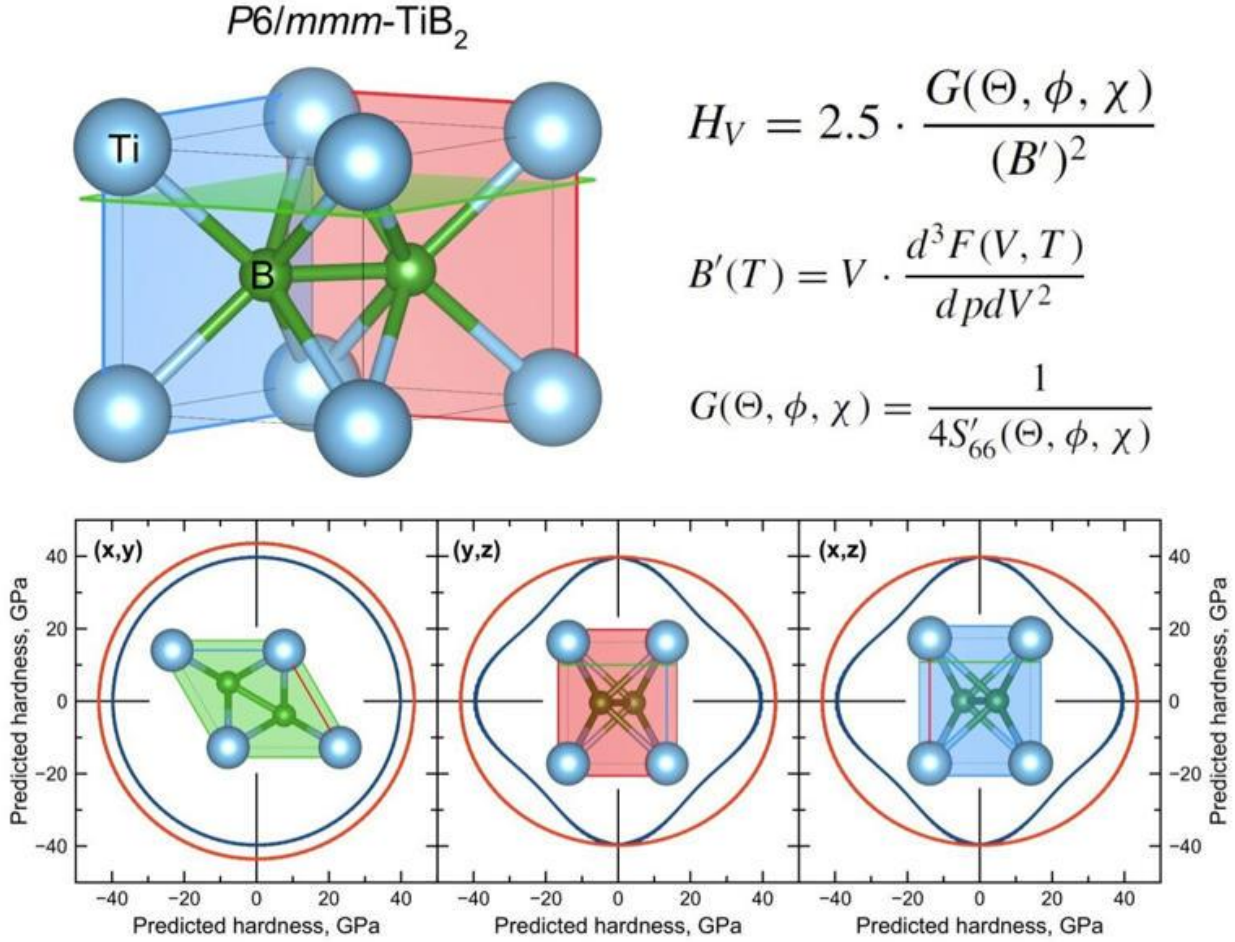
"But even these methods have stopped short of being practical enough to use in big molecules like polymers. In our present work, the molecules are held firmly in place in a crystal, which templates the formation of a mechanical bond around each one.

"So, these mechanical bonds have deep tradition at Northwestern, and we are excited to explore their possibilities in ways that have not yet been possible."

More information: Madison I. Bardot et al, Mechanically interlocked two-dimensional polymers, *Science* (2025). DOI: 10.1126/science.ads4968. www.science.org/doi/10.1126/science.ads4968

Provided by Northwestern University

Researchers propose new physical model for predicting hardness of materials



The structure of titanium diboride and the formula for calculating hardness proposed in the work. The bottom panel shows the dependence of hardness on the direction in the crystal. Credit: Physical Review Materials (2024). DOI: 10.1103/PhysRevMaterials.8.123601

Skoltech researchers have presented a new simple physical model for predicting the hardness of materials based on information about the shear modulus and equations of the state of crystal structures. The model is useful for a wide range of practical applications—all parameters in it can be determined through basic calculations or measured experimentally.

The results of the study are presented in the *Physical Review Materials* journal.

Hardness is an important property of materials that determines their ability to resist deformations and other damage (dents, scratches) due to external forces. It

is typically determined by pressing the indenter into the test sample, and the indenter must be made of a harder material, usually diamond.

In this case, the hardness is determined based on the ratio between the maximum indentation force and the imprint that remains on the sample.

Modern industry needs new hard and superhard materials with improved mechanical properties compared to traditional materials. One of the solutions to this problem is the use of modern computational methods for high-throughput search (screening) of materials with improved properties.

"Today, computational methods are sufficiently advanced to accurately predict the structure and properties of various compounds and materials. However, it is important not only to predict the structure of a material, but also to accurately calculate its mechanical properties, such as hardness, which are necessary for the experimental synthesis of a material with predefined properties," said the lead author of the work, Faridun Jalolov, a Ph.D. student in the Materials Science and Engineering program at Skoltech.

"The existing empirical models for predicting hardness are based on the strength of chemical bonds, the degree of ionization, the electronegativity of crystals, and the elastic moduli of materials.

"We proposed a simple and accurate model based on material properties such as the shear modulus and pressure derivative of bulk modulus. Both properties can be obtained through experiments or atomistic simulations."

The shear modulus is important in the hardness model because it depends on the direction of deformation of the crystal structure, which enabled the authors to calculate the spatial dependence of hardness for a number of materials with the anisotropy of the crystal structure in mind.

By obtaining the pressure derivative of bulk modulus from the equation of state, the team took into account the impact of temperature on hardness.

"We used the examples of rhenium diboride (ReB_2) and boron carbide (B_4C) to demonstrate that the hardness model works for hard and superhard materials. The hardness obtained is consistent with the experimental measurements and predictions made by machine learning models. All values in our model can be

obtained directly from calculations or experiments, so the model is suitable for practical use," added Professor Alexander Kvashnin from the Skoltech Energy Transition Center, a co-author and the scientific supervisor of the study.

More information: Faridun N. Jalolov et al, Physically intuitive anisotropic model of hardness, *Physical Review Materials* (2024). DOI: 10.1103/PhysRevMaterials.8.123601. On *arXiv*: DOI: 10.48550/arxiv.2412.17745

Provided by Skolkovo Institute of Science and Technology

What would happen to the human body moving at near lightspeed?

In science fiction, spaceships moving at or beyond lightspeed enable all manner of universal exploration. But in Earth-bound reality, traveling at the speed of light (299,792,458 meters per second, or 670,616,629 miles per hour, in a vacuum) in a clunky rocket is a physical impossibility. "It's the speed at which massless things travel," says Gerd [...]

In science fiction, spaceships moving at or beyond lightspeed enable all manner of universal exploration. But in Earth-bound reality, traveling at the speed of light (299,792,458 meters per second, or 670,616,629 miles per hour, in a vacuum) in a clunky rocket is a physical impossibility. "It's the speed at which massless things travel," says Gerd Kortemeyer, an associate professor emeritus of physics at Michigan State University. So, anything with mass cannot reach that speed. And even massless particles are limited by lightspeed. "It's often called the cosmic speed limit because nothing will go faster than that," Kortemeyer says.

Doubly unfortunate for those among us eager to visit galaxies far, far away–even moving at *near* lightspeed isn't in the cards. "It's neither possible nor survivable to travel near the speed of light relative to our good old Earth," the physicist says.

Wonky theoretical explanations aside, it would simply take far too much fuel and energy to propel any human-bearing spacecraft up to that speed. By Kortemeyer's calculations, reaching 99% of lightspeed in a vessel weighing 10 metric tons (significantly lighter and smaller than most spacecraft), while

accelerating at a tolerable g-force would use more than 200 times the amount of energy consumed on Earth in a year. And that's assuming a perfectly efficient fuel, where mass converts to propulsive energy without any heat loss–another physical impossibility according to the second law of thermodynamics.

The closest we've come to lightspeed is accelerating teeny tiny individual atomic particles to 99.99999896% the speed of light in the Large Hadron Collider.

But let's ignore all of that and imagine, for a moment, that we could get close to lightspeed. If we had the perfect, efficient fuel source, a ton of it, a vessel crafted to withstand it, and the gumption–what would near-lightspeed travel be like?

Well, perhaps unsurprisingly, things would get weird.

What's so special about lightspeed?

First, it's important to understand a few of the quirks of lightspeed. It isn't *just* a speed, it's also "one of the fundamental constants of nature," explains Kortemeyer. Since the 1600s, celestial observations of planetary movements have hinted at the speed of light. And in 1865, James Clerk Maxwell deduced that light was an electromagnetic wave and calculated its speed, with close agreement to the present-day, known value in his landmark physics paper, "*A dynamical theory of the electromagnetic field*."

Then, Einstein turned our understanding of physics inside out. His theory of special relativity, presented in 1905, conceives of space-time as a unified universal fabric, connected via the constant, "c", which defines the relationship between energy and matter. This value, when he calculated it, just so happened to be equal to the speed of light. This is the famous E=mc^2 equation.

In the most basic terms, special relativity states that lightspeed doesn't change, but rather time– the fourth dimension–bends relative to objects' movements. Therefore, objects in motion experience time differently from objects at rest. At most conceivable speeds on Earth, this isn't noticeable. But at near light speeds, it would be, in a phenomenon known as time dilation (we'll come back to this in the next section).

Plus, because of lightspeed's unique relationship to time-space, it remains the same no matter the speed of an observer. Imagine, for a moment, that you're in a car on the highway. If you're traveling at a constant 30 miles per hour and a car in front of you passes you at 60 miles per hour, then that faster car is moving away from you at 30mph, relative to your speed. However, if you were racing to catch up with a photon, even if you reached 50% the speed of light, that same photon would still be moving away from you at the speed of light. "It's always the speed of light, independent of how you are moving, which is very different from anything else," Kortemeyer says.

Together, these concepts combine to make approaching lightspeed a wild ride.

What would near lightspeed travel be like?

Colors and brightness would distort and look very different, as illustrated in this 2012 simulation developed by Kortemeyer and collaborators at MIT. The simple game is meant to illustrate the relativistic effects of moving near light speed and is premised around a universe where light moves much more slowly, and constantly slows as you navigate the world. In that universe, though one still wouldn't be able to reach or exceed lightspeed, you would be able to approach it at a brisk walking pace.

As you did, you'd experience a visual doppler effect–similar to how an ambulance speeding by with its siren blazing seems to change its tune as it moves. Moving towards an object would make it appear bluer, as its wavelength visually shortens. Moving away from an object would do the opposite, shifting its appearance redder.

Speeding towards something would amplify your perception of its brightness, in a spotlight effect. Kortemeyer compares this phenomenon to running through the rain. Moving fast through a downpour ensures that more drops hit your front, and thus that your shirt is soaked through more quickly. In the simulation game, the proverbial water droplets are photons. Running in a beam of light at near lightspeed means that more light particles would hit your eyes at once.

If that's not strange enough, consider what would happen to time. Remember the concept of time dilation? Because space-time warps to accommodate the constant speed of light, a person traveling through space at near lightspeed

would age more slowly than all the other humans waiting back on Earth. This idea is exemplified in the twin paradox thought experiment. Time dilation, and a change in time at rest relative to a change in time while in motion at a certain velocity, can be precisely calculated.

If you managed to reach 299,792,450 meters per second (i.e. just under lightspeed), two minutes of travel at that speed through space would be equivalent to about six days of time passing on our planet.

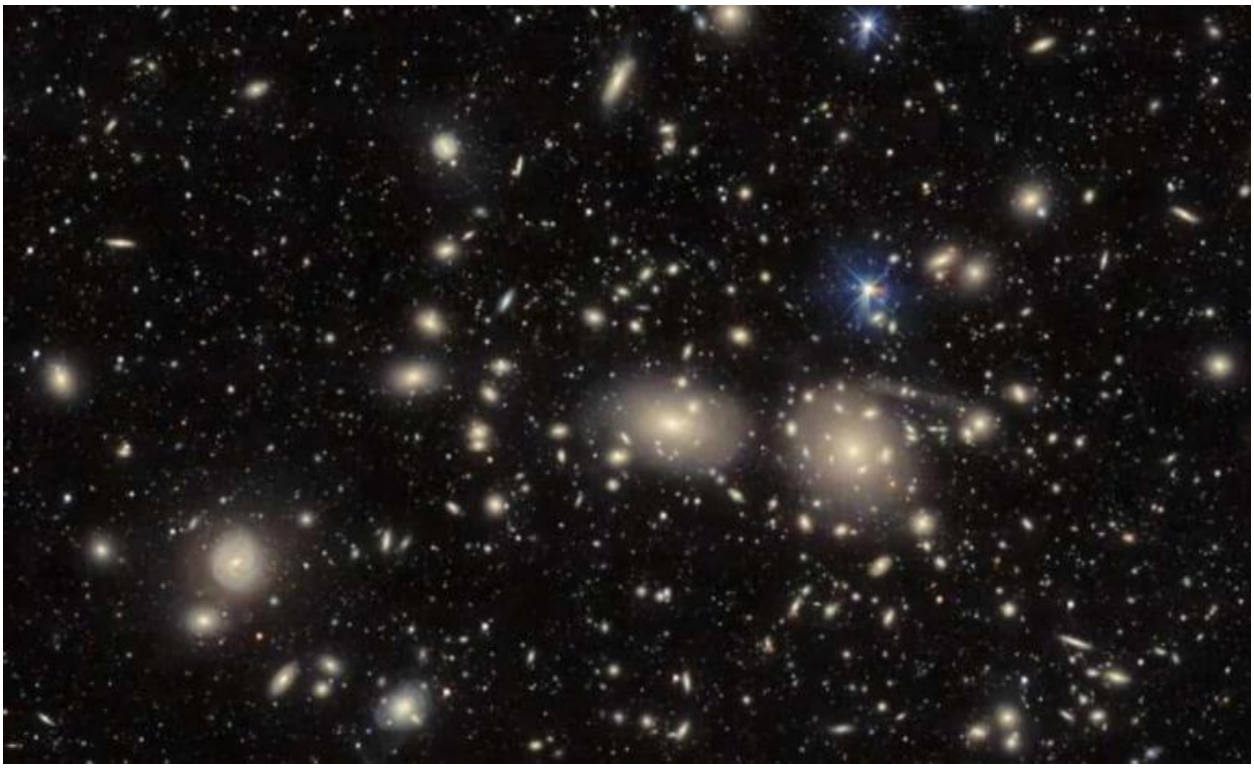
Often, this concept of warped time is used to explain how hyper-lightspeed travel might work. "I'm a very big fan of *Star Trek*, so I don't want to trash talk," says Kortemeyer. However, the show's sci-fi idea of "warp speed" to outrun the speed of light is all fiction and no science, he says. "Warping space is a physical reality," but there's no way to force or control the warping of space to manipulate speed. "There is no such thing as a warp drive in physics. I wouldn't know what physics principle would make that possible," he says.

And to take things back down to Earth even more, *reaching* 299,782,450 meters per second would be a trial all on its own. When it comes to high speeds, the biggest barrier to contend with isn't cruising at a constant velocity, but rather the acceleration. Already, we're moving far faster than you might expect. All of us on Earth are hurtling around the sun at about 67,000 miles per hour. But, because that speed doesn't change, we don't feel it. Yet reaching lightspeed relative to Earth would be a different story. "You can't just take off and reach the speed of light. You would be flattened," says Kortemeyer.

The g-force of getting to near-lightspeed would be monumental, unless you sped up very carefully. Humans are adapted to survive at 1 g, the gravitational force on Earth. Most people can withstand 4-6 g in short bursts of a few seconds to minutes. But for longer periods of time or at higher intensity, g-force becomes fatal as our body's internal fluid dynamics get gunked up.

It would take a person about one year to accelerate to lightspeed, if you wanted to keep the acceleration force under 3 g, per Kortemeyer's calculations. But we don't know how long-term exposure to even that level of acceleration force would impact the body, he notes. It's possible that 12-straight months of acceleration force beyond what we're built for would test, not just the limits of physics, but our own physical limitations.

The Universe Is Expanding Faster Than Physics Can Explain—What's Driving This Cosmic Phenomenon?



Recent research has unveiled a troubling and persistent mystery at the heart of modern cosmology: the universe is expanding at a faster rate than expected, a finding that challenges our fundamental understanding of its mechanics and origins. This puzzling phenomenon, referred to as the **Hubble tension**, describes a significant discrepancy between the observed rates of cosmic expansion in the local universe and the rates predicted using data from the early universe. The tension has sparked intense debate among scientists, with some questioning whether the standard model of cosmology—a framework that has guided our understanding of the universe for decades—is still adequate.

As new measurements continue to refine the precision of these observations, the gap between predictions and reality becomes harder to dismiss. Researchers are now faced with the possibility that key aspects of the universe's behavior, such as the influence of **dark energy**, **dark matter**, or other unknown forces, may not yet be fully understood. This growing challenge to established theories marks a

pivotal moment in cosmology, one that could reshape our grasp of the cosmos and its evolution.

The Roots of the Hubble Tension

The concept of an expanding universe dates back to **Edwin Hubble's groundbreaking discovery in 1929**, which revealed that galaxies are moving away from one another. Since then, scientists have sought to quantify this expansion through a parameter called the **Hubble constant**. Over the years, two primary methods have emerged: measuring cosmic distances in the nearby universe and observing the conditions of the early universe.

However, these methods have consistently produced conflicting results. Measurements of the nearby universe suggest a faster expansion rate than what's predicted by observations of the cosmic microwave background (CMB)—the "baby picture" of the universe just after the Big Bang. "This is saying, to some respect, that our model of cosmology might be broken," said **Dan Scolnic**, associate professor of physics at Duke University and lead author of a recent study on the topic.

Building a Better Cosmic Ladder

To tackle the Hubble tension, researchers have relied on a method called the **cosmic ladder**, which uses a series of calibrated steps to measure distances to celestial objects. Each "rung" on the ladder depends on precise observations, starting with nearby stars and extending to distant galaxies. Scolnic's team, in collaboration with the **Dark Energy Spectroscopic Instrument (DESI)**, sought to refine this ladder by addressing one of its most challenging aspects: the first rung.

"The DESI collaboration did the really hard part, their ladder was missing the first rung," said Scolnic. "I knew how to get it, and I knew that that would give us one of the most precise measurements of the Hubble constant we could get, so when their paper came out, I dropped absolutely everything and worked on this non-stop."

The team's efforts focused on the **Coma Cluster**, a massive collection of galaxies approximately 320 million light-years away. Using **Type Ia supernovae**, which act as reliable cosmic yardsticks due to their consistent brightness, Scolnic's team was able to calculate a precise distance to the cluster. "This measurement isn't influenced by our theories about how the Hubble tension will be resolved," Scolnic explained. "This cluster is pretty close to us, and we've been measuring it long before we knew how important it would become."

Confirming the Hubble Constant

Armed with their refined cosmic ladder, the team calculated a Hubble constant of **76.5 kilometers per second per megaparsec**, meaning that galaxies recede from each other at this rate for every 3.26 million light-years of separation. This value aligns closely with other local measurements but remains at odds with predictions from early-universe data.

"Over the last decade or so, there's been a lot of re-analysis from the community to see if my team's original results were correct," Scolnic noted. "Ultimately, even though we're swapping out so many of the pieces, we all still get a very similar number. So, for me, this is as good of a confirmation as it's ever gotten."

The consistency of these findings underscores the robustness of the local measurements, suggesting that the discrepancy lies not in the data but in the theoretical framework used to interpret it.

The Implications of a Faster Universe

The Hubble tension raises profound questions about the universe's composition and the forces driving its expansion. One possibility is that unknown phenomena, such as **dark energy** or **new physics**, are influencing the rate of expansion. Alternatively, the models used to interpret early-universe observations may require significant adjustments.

"We're at a point where we're pressing really hard against the models we've been using for two and a half decades, and we're seeing that things aren't matching up," Scolnic remarked. "This may be reshaping how we think about the Universe,

and it's exciting! There are still surprises left in cosmology, and who knows what discoveries will come next?"

The challenge now lies in reconciling these discrepancies. Future observations from next-generation instruments like the **James Webb Space Telescope (JWST)** and the **Nancy Grace Roman Space Telescope** will provide more precise data, potentially revealing whether the issue lies in measurement techniques or the underlying physics of the cosmos.

A New Era for Cosmology

The debate over the Hubble tension highlights the dynamic nature of scientific inquiry, where every answer raises new questions. As researchers refine their methods and explore the limits of current theories, the mystery of the universe's expansion serves as a reminder that our understanding of the cosmos is still evolving.

Whether the solution lies in tweaking existing models or embracing entirely new paradigms, one thing is clear: the universe continues to defy expectations, inviting us to push the boundaries of human knowledge. "There are still surprises left in cosmology," Scolnic said, "and who knows what discoveries will come next?"

This era of exploration promises groundbreaking insights that could reshape our understanding of the universe, its origins, and its ultimate fate. For now, the Hubble tension remains a cosmic enigma, challenging scientists to unravel the mysteries of a universe expanding faster than we ever imagined.

Universe expanding faster than physics can explain — New evidence deepens cosmic ‘crisis’

In a nutshell

- Astronomers studying the nearby Coma galaxy cluster have found new evidence that the universe is expanding about 9% faster than predicted by our current physics models – a discrepancy known as the Hubble tension. This finding strengthens concerns that our fundamental understanding of cosmic evolution may need revision.
- The research team measured precise distances to 13 supernovae within the Coma cluster, determining it lies about 98.5 million light-years from Earth – significantly closer than the 111.8 million light-years predicted by models based on observations of the early universe. This difference is too large to be explained by measurement errors.
- Multiple independent measurement techniques all point to the same conclusion, suggesting the problem lies not in our observations but in our theoretical models. This indicates that resolving the Hubble tension may require new physics beyond our current understanding of how the universe works.

DURHAM, N.C. — Our cosmic neighborhood is revealing an uncomfortable and unexplainable truth: the universe seems to be breaking the speed limit set by our best physics models. By precisely measuring the distance to a massive cluster of galaxies relatively close to Earth, scientists have uncovered new evidence that space itself is expanding more rapidly than theoretical predictions allow, a finding that could force a radical revision of our understanding of cosmic evolution.

When scientists measure this expansion rate (known as the Hubble constant) using nearby objects, they consistently get a higher value than when they measure it using light from the early universe. This discrepancy has persisted for years, leading astronomers to wonder if our understanding of cosmic evolution needs a major overhaul.

Dan Scolnic, an associate professor of physics at Duke University who led the research, frames the puzzle in relatable terms: imagine trying to create the universe's growth chart. We have its "baby picture" — the earliest observable state just after the Big Bang — and its current "headshot" showing the local universe containing our Milky Way and neighboring galaxies. The challenge lies in connecting these two points through a coherent growth curve, but the measurements aren't adding up as expected, deeping one of modern cosmology's most perplexing puzzles known as the "Hubble tension."

"The tension now turns into a crisis," says Scolnic, highlighting the significance of his team's findings published in *The Astrophysical Journal Letters*.

Milky Way Panorama at Aoraki Mackenzie International Dark Sky Reserve (Photo by eroxust on Shutterstock)

So what exactly is the Hubble tension? Imagine having two reliable methods for measuring the same thing, like a bathroom scale and a doctor's scale, but getting consistently different results from each. That's what astronomers face when measuring the Hubble constant. When they use nearby objects like supernovae and galaxies to measure this expansion, they find the universe is stretching at about 73-76 kilometers per second for every megaparsec (roughly 3.26 million light-years) of distance. However, when they calculate the expansion rate using observations of the cosmic microwave background — the afterglow of the Big Bang — along with our standard model of physics, they get a significantly slower rate of about 67 kilometers per second per megaparsec.

This discrepancy, about 9% difference between the two methods, is far too large to be explained by measurement errors. Even more troubling, as measurement techniques have improved over the years, the disagreement has only become more pronounced rather than resolving itself.

The new study focuses on the Coma Cluster, one of our nearest massive galaxy clusters, serving as a crucial calibration point for measuring cosmic distances. When the Dark Energy Spectroscopic Instrument (DESI) team published their extensive galaxy observations, Scolnic recognized an opportunity to refine their measurements using the Coma Cluster as an anchor point.

Hubble's Advanced Camera for Surveys has viewed a large portion of the Coma Cluster, stretching across several million light-years across. The entire spherical cluster is more than 20 million light-years in diameter and contains thousands of galaxies. Most of the galaxies that inhabit the central portion of the Coma Cluster are elliptical galaxies. These featureless "fuzz-balls" are a pale golden brown in colour and contain populations of old stars. Both dwarf and giant ellipticals are found in abundance in the Coma Cluster. (Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA).)

"The DESI collaboration did the really hard part, their ladder was missing the first rung," Scolnic explains. "I knew how to get it, and I knew that that would give us one of the most precise measurements of the Hubble constant we could get, so when their paper came out, I dropped absolutely everything and worked on this non-stop."

His team analyzed 12 special stellar explosions called Type Ia supernovae within the Coma Cluster. These cosmic phenomena serve as reliable “standard candles” because they consistently reach the same peak brightness, making them excellent tools for measuring astronomical distances. Much like knowing the wattage of a light bulb allows you to estimate its distance based on how bright it appears, these supernovae enable precise distance calculations.

The results placed the Coma Cluster at approximately 320 million light-years from Earth, aligning well with decades of previous measurements. This consistency provides strong validation for the study’s methodology. “This measurement isn’t biased by how we think the Hubble tension story will end,” notes Scolnic. “This cluster is in our backyard, it has been measured long before anyone knew how important it was going to be.”

The Dark Energy Spectroscopic Instrument (DESI) (Credit: U.S. Department of Energy Office of Science)

Using this precise measurement as a starting point, the team calculated a Hubble constant of 76.5 kilometers per second per megaparsec. This result aligns with other recent measurements of the local universe but conflicts significantly with predictions based on observations of the early universe.

“We’re at a point where we’re pressing really hard against the models we’ve been using for two and a half decades, and we’re seeing that things aren’t matching up,” says Scolnic. “This may be reshaping how we think about the Universe, and it’s exciting! There are still surprises left in cosmology, and who knows what discoveries will come next?”

Moving forward, astronomers will continue refining these measurements using new telescopes and improved techniques. However, the consistency of results across different methods suggests that resolving this cosmic expansion crisis may require more than just better observations – it may demand a complete overhaul of our current physics models.

Paper Summary

Methodology

The researchers identified supernovae within the Coma cluster using publicly available catalogs and light curves. They focused on Type Ia supernovae, which serve as reliable cosmic distance markers due to their consistent peak brightness. The team applied strict quality control measures, analyzing only supernovae with good light curve coverage and spectroscopic confirmation. They used sophisticated modeling techniques to account for various factors that could affect brightness measurements, including dust extinction and observational biases.

Results

The study found that the Coma cluster is approximately 98.5 million light-years away, with a margin of error of about 2.2 million light-years. This measurement conflicts significantly with predictions based on cosmic microwave background observations, which suggest the cluster should be about 111.8 million light-years away. The difference is too large to be explained by random chance or measurement errors.

Limitations

The research team acknowledges several potential limitations, including the relatively small sample size of 13 supernovae and the challenge of precisely determining cluster membership for some objects. They also note that the radial size of the Coma cluster itself (about 2.86 million light-years) could introduce some uncertainty into the measurements.

Discussion and Takeaways

This study provides strong evidence that the Hubble tension extends beyond just measurement techniques and into fundamental aspects of our local cosmic environment. The findings suggest that our understanding of cosmic expansion may need revision, as multiple independent measurement methods consistently show discrepancies with predictions from early-universe observations.

Funding and Disclosures

The research was supported by several organizations, including the Templeton Foundation, the Department of Energy, the David and Lucile Packard Foundation, and the Sloan Foundation. The study also utilized data from the Dark Energy Spectroscopic Instrument (DESI), which is managed by Lawrence Berkeley National Laboratory.

Publication Information

This study, titled "The Hubble Tension in Our Own Backyard: DESI and the Nearness of the Coma Cluster," was published in *The Astrophysical Journal* Letters on January 20, 2025. The research was led by Daniel Scolnic from Duke University, along with colleagues from various institutions including the Space Telescope Science Institute and Johns Hopkins University.

Space itself may have created galaxies

According to new research, the earliest seeds of structures may have been laid down by gravitational waves sloshing around in the infant universe.

Cosmologists strongly suspect that the extremely early universe underwent a period of exceptionally rapid expansion. Known as inflation, this event expanded the universe by a factor of at least 10^{60} in less than a second. Powering this event was a new ingredient in the cosmos known as the inflaton, a strange quantum field that ramped up, drove inflation, and then faded away.

Inflation didn't just make the universe big. It also laid down the seeds of the first structures. It did so by taking the quantum foam, the subatomic fluctuations in spacetime itself, and expanding that along with everything else. Slowly, over time, those fluctuations grew, and hundreds of millions of years later they became the first stars and galaxies, ultimately leading to the largest structure in the universe, the cosmic web.

But mysteries remain. We do not know the identity of the inflaton, or what powered it, or why it turned off when it did. And we have no conclusive evidence that inflation actually happened.

So researchers are always looking for alternatives, especially ones that don't invoke some new and mysterious ingredient. In a recent paper posted to the *arXiv* preprint server, a team of astrophysicists describe a model where inflation happens, leading to the large-scale structure of the universe, all without an inflaton. If you got into a spaceship and traveled long enough.

What If the Universe Isn't Flat But a Giant Loop?

The model described by the researchers is set in the backdrop of an expanding universe that is accelerating in its expansion, just like the modern-day universe is. In that expanding universe, the quantum foam releases gravitational waves. Those ripples in space spread outwards, colliding with each other and amplifying themselves.

Gravitational waves usually can't create structures on their own, but the researchers found that in certain special cases the gravitational waves can amplify each other in just the right way. When that happens, the imprints they make in space are nearly the same at a wide variety of length scales.

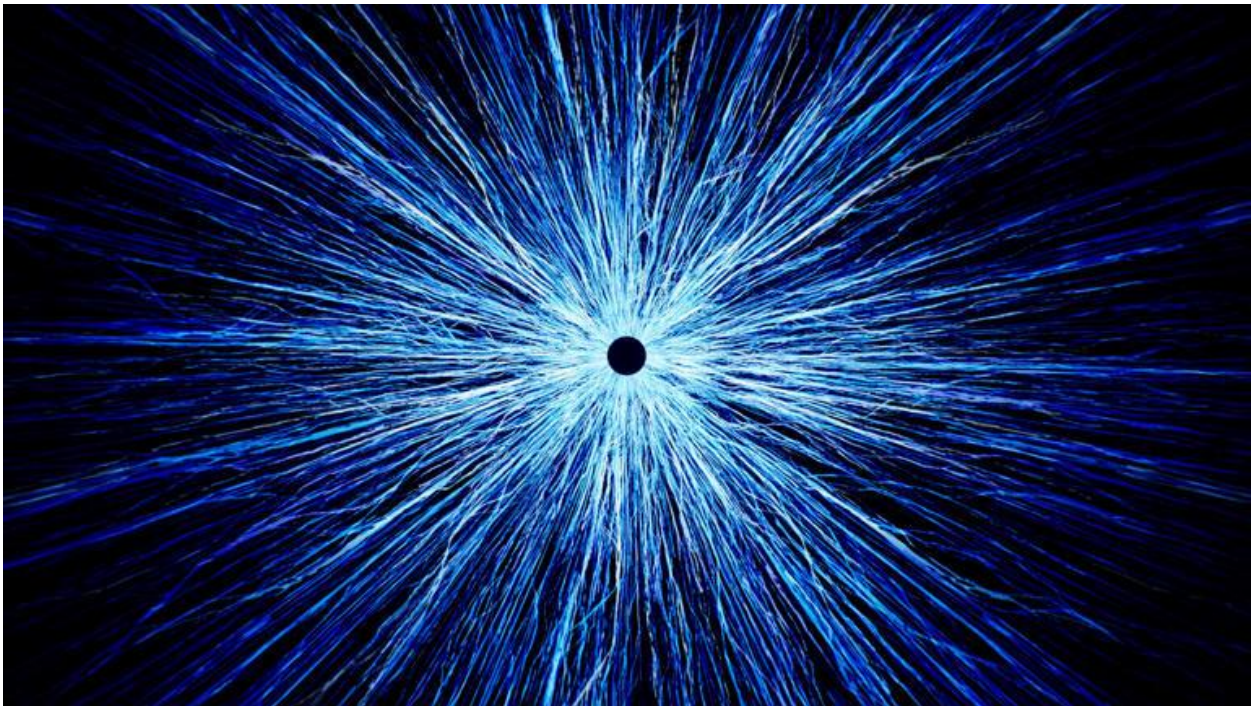
This is precisely what cosmologists observe in the cosmic microwave background, the leftover light from the early universe. This radiation contains a faint impression of the echoes of inflation, and it shows that whatever set the seeds of structure, it had to have that kind of pattern.

There are slight differences between the kinds of structures generated in this inflation-without-inflaton scenario and traditional inflation. In this first paper, the researchers did not yet calculate how strong those differences are, but an important next step is to explore the observational consequences of this model and see if it's worth investigating further.

More information: Daniele Bertacca et al, Inflation without an Inflaton, *arXiv* (2024). DOI: 10.48550/arxiv.2412.14265

Provided by Universe Today

String theory could be real? A bootstrap model reveals solid hint



String theory could be real? A bootstrap model reveals solid hint

String theory suggests that the most fundamental building blocks of the universe are not particles like electrons or quarks, but tiny, vibrating strings of energy.

It is the vibration and arrangement of these strings that then gives rise to particles, matter, energy, and other natural forces. The theory suggests that everything in this universe is interconnected and particles are not point-like objects but, in fact, strings.

However, string theory remains unproven to this date, but a new study reveals a bootstrap approach that strengthens its case.

Using scattering amplitudes to detect strings

Some previous studies estimate that a string is about 10^{-35} m in size. The reason why scientists haven't been able to detect strings is that even the world's most powerful accelerator, the Large Hadron Collider can detect objects up to a size of 10^{-20} m.

So confirming the presence of strings in an experimental setup is impossible for now. This is why the study authors adopted a theoretical bootstrap approach.

"A bootstrap is a mathematical construction in which insight into the physical properties of a system can be obtained without having to know its underlying fundamental dynamics," said Remmen, one of the study authors and a postdoctoral fellow at New York University.

Instead of building everything from scratch, the approach calls for starting with basic rules that a system must follow. These rules are usually related to symmetry, cause-and-effect (causality), and mathematical consistency.

For instance, to describe the interaction of strings, the study authors employed scattering amplitudes, mathematical expressions that describe the likelihood of particles interacting and scattering off each other in a collision.

They used amplitudes called locality, and unitarity. The former means that nothing can affect something far away instantly—forces take time to travel, so causality stays consistent.

The latter, on the other hand, describes that in quantum mechanics, the chances of 'all possible outcomes must always add up to 100%', and those chances can't be negative. This rule also limits how particles can interact with each other.

Surprisingly, when locality and unitarity were applied, the result of the bootstrap equation came out to be Veneziano amplitude, the same formula that describes string scattering.

Compelling evidence but not proof

The study reveals another interesting framework that hints towards the presence of strings and favors the string theory. It suggests that the big idea of string theory can be reduced to a smaller, simpler starting point that still leads to the same conclusions.

However, "this work can't verify the validity of string theory, which like all questions about nature is a question for experiment to resolve," stated Clifford Cheung, first author and a professor of theoretical physics at Caltech.

While scientists develop a particle accelerator powerful enough to detect strings, there is still a lot that theoretical models can reveal. For instance, the researchers plan to test a bootstrap approach involving multiple particles (the current study focuses on only two particles). Hopefully, these efforts will soon bring scientists closer to finding the strings they have been searching for decades.

The study has been published in the journal *Physical Review Letters*.

The universe looks very different at light speed

A new perspective on the universe could emerge if superluminal observers, those who theoretically move faster than light, were to exist. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

A new perspective on the universe could emerge if superluminal observers, those who theoretically move faster than light, were to exist.

Recent research demonstrates that integrating these observers into our understanding of physics does not lead to causal paradoxes as once feared. Instead, this integration reshapes fundamental concepts of causality and space-time, much like quantum mechanics does.

Physicists Andrzej Dragan and Artur Ekert have made strides in this area, proposing that extending Einstein's special relativity to include superluminal frames of reference introduces a new dynamical framework. This approach replaces the deterministic paths of classical mechanics with quantum-like superpositions, where particles travel simultaneously along multiple trajectories.

Superluminal observers would perceive the universe differently from subluminal observers like us. For these observers, traditional spatial dimensions would behave like time dimensions, fundamentally altering their view of the universe.

Andrzej Dragan explains, "From the point of view of the superluminal observer, only one dimension retains a spatial character, the one along which particles can move. The other three dimensions are time dimensions."

This radical reinterpretation demands a shift in physics from point-particle dynamics to field theory. Classical Newtonian mechanics no longer applies; instead, fields govern the behavior of particles.

This shift aligns with principles found in quantum mechanics, such as the quantum superposition of states, suggesting that particles do not follow singular trajectories but move along all possible paths simultaneously.

Reconciling Superluminal Observers with Relativity

Albert Einstein's special theory of relativity transformed our understanding of space-time by introducing a four-dimensional continuum. While it's based on the principles of Galileo's relativity and the constancy of the speed of light, the theory traditionally applies only to subluminal observers.

However, Dragan argues that there is no fundamental reason why superluminal observers should be excluded from these principles.

In their publication, "Relativity of superluminal observers in 1 + 3 spacetime," Dragan, Ekert, and their colleagues outline a framework for including superluminal observers in a four-dimensional space-time model. They show that extending relativity to accommodate superluminal frames does not violate

Einstein's postulates. On the contrary, this extension retains the constancy of the speed of light for all observers, regardless of their velocity relative to light.

Dragan points out that superluminal phenomena might play a crucial role in these processes, particularly in the early universe. Tachyonic fields, often associated with spontaneous symmetry breaking, could offer insights into the mass generation mechanisms for fundamental particles. This line of inquiry may eventually illuminate the underlying principles of the Standard Model and beyond.

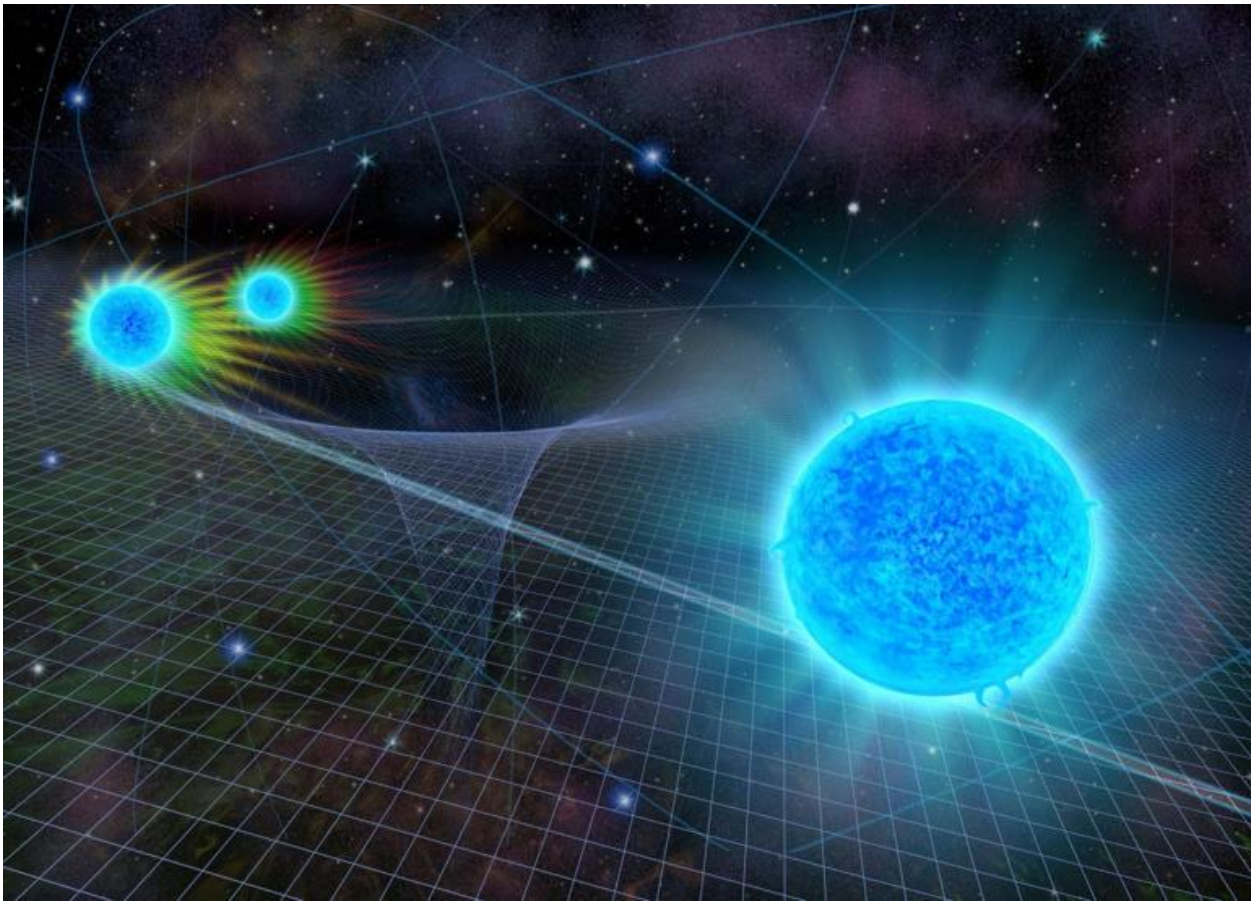
Superluminal observers challenge the classical definitions of velocity and kinematics, requiring new formulations that remain consistent with Einstein's relativity. For instance, the concept of velocity must accommodate the fact that particles exhibit quantum superpositions, appearing to move along multiple trajectories simultaneously.

Dragan and his team's work suggests that quantum theory's foundational postulates, previously considered fundamental, might derive naturally from an extended version of special relativity. This hypothesis could reshape our understanding of quantum mechanics, unifying it with relativity in a single theoretical framework.

While experimental verification of superluminal observers remains elusive, the theoretical groundwork laid by researchers from Warsaw and Oxford provides a robust foundation for future exploration. The potential discovery of superluminal particles or phenomena would revolutionize physics, shedding light on the universe's most profound mysteries.

The University of Warsaw's Contribution

The University of Warsaw's Faculty of Physics plays a pivotal role in advancing this frontier of knowledge. With over 200 academic staff and a history dating back to 1816, the faculty has been at the forefront of modern physics research, from quantum scales to cosmological phenomena.



Superluminal observers challenge the classical definitions of velocity and kinematics, requiring new formulations that remain consistent with Einstein's relativity. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

This vibrant academic community fosters groundbreaking research in areas like quantum field theory and cosmology. Its contributions to the study of superluminal observers and extended relativity highlight its commitment to pushing the boundaries of scientific understanding.

As researchers continue to explore the implications of superluminal observers, the boundaries between classical, quantum, and relativistic physics blur. The integration of these disciplines could lead to a unified theory, addressing long-standing questions about the nature of space, time, and matter.

Dragan's team's findings underscore the importance of reexamining established theories in light of new possibilities. By extending Einstein's relativity to include superluminal frames, they have opened a window into a realm of physics where time and space behave in ways previously unimaginable.

The journey to understanding this realm has only just begun, but its potential to transform our view of the universe is immense.

Major discovery could fundamentally redefine our understanding of time

Standard wave mechanics, the bedrock of our understanding of waves, effectively describes the interactions when light encounters matter.

Published Nov 16, 2024

At the cutting edge of theoretical physics, scientists have discovered new insights that could redefine our understanding of time.

Light and matter's mysterious connection is at the heart of scientific exploration potentially holding the key to unlocking the universe's deepest secrets. For centuries, scientists have been entranced by light's story – its curious detours, its measured pace, and its profound exchange with the fabric of reality itself.
Now, at the cutting edge of theoretical physics, researchers have unearthed revelations that could redefine our grasp of time's arrow and the conservation of momentum, stirring the pot of a longstanding controversy and, in the process, ruling out the fantastical allure of time travel.

The Subtleties of Light's Interaction with Matter

As any high school student might tell you, when light encounters matter, it appears to slow down. This observation is not a groundbreaking one. Standard wave mechanics, the bedrock of our understanding of waves, effectively describes these everyday interactions.

Consider light approaching a boundary between two different media—a classic physics problem. To understand what happens, scientists use the standard wave equation, looking closely at the characteristics of the light wave on either side of this interface.
They then deploy electromagnetic boundary conditions, essentially mathematical tools, to bridge these two scenarios, creating what is known as a piecewise continuous solution.
Yet, this solution omits a crucial detail. At the boundary, the incoming light undergoes acceleration—a fact historically overlooked.

A New Dimension of Wave Dynamics

Assistant Professor Matias Koivurova of the University of Eastern Finland, animated by a spark of curiosity, has pushed the boundaries of this classic problem. "Basically, I found a very neat way to derive the standard wave equation in 1+1 dimensions.

The only assumption I needed was that the speed of the wave is constant. Then I thought to myself: what if it's not always constant? This turned out to be a really good question," he recounts.

This line of inquiry led to the conception of an accelerating wave equation, acknowledging that the speed of a wave could, in theory, fluctuate over time. Writing down the equation was straightforward, but solving it proved to be a more daunting task.

Koivurova faced an intellectual paradox. The solutions to this new equation were enigmatic, failing to correspond with known behaviors of waves—until, he says, "it dawned on me that it behaves in ways that are reminiscent of relativistic effects."

This moment of clarity came in collaboration with the Theoretical Optics and Photonics group at Tampere University, under the guidance of Associate Professor Marco Ornigotti. This partnership bore fruit, revealing an unexpected facet of the accelerating wave equation: it firmly establishes the direction of time. Unlike other systems where the second law of thermodynamics, with its emphasis on ever-increasing entropy, delineates the flow of time, the accelerating wave suggests that time has an immutable forward trajectory.

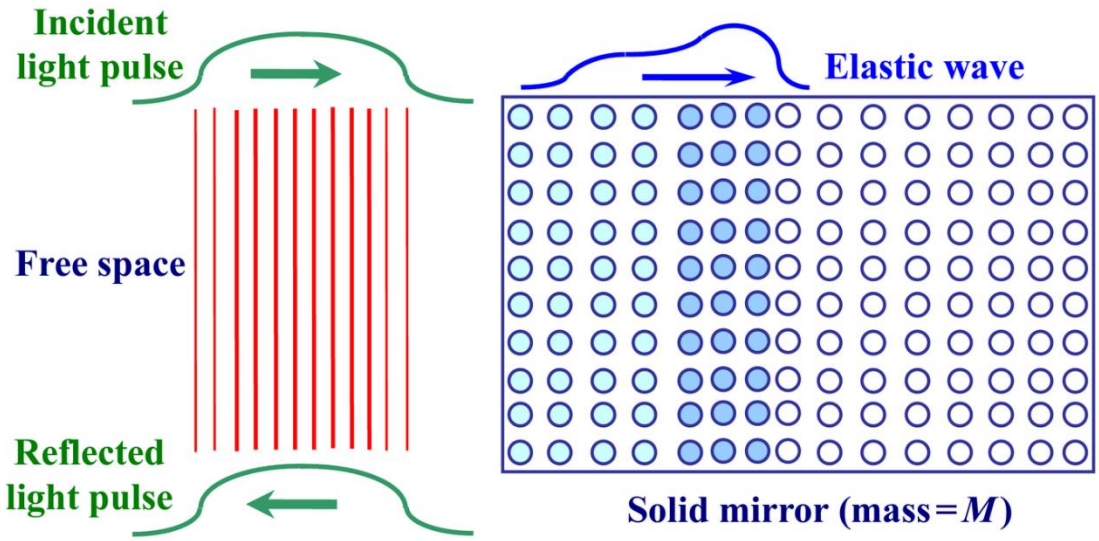
"Usually, the direction of time comes from thermodynamics," Koivurova explains. In systems with reversed temporal flow, entropy would diminish until reaching a state of minimal entropy before increasing once more.

This dichotomy between macroscopic and microscopic time arrows has long puzzled scientists, with larger systems showing clear temporal directionality while the behavior of single particles remains unbound by such constraints.

Despite this, Koivurova asserts, "We expect single particles to behave as if they have a fixed direction of time!" The general applicability of the accelerating wave equation means that this fixed direction of time extends throughout nature.

Settling a Centuries-Old Debate

The implications extend into a domain of physics rife with debate: the conservation of energy and momentum when light transitions into a medium. The Abraham-Minkowski controversy has divided physicists, with experimental evidence ambiguously supporting both the claim that momentum increases (Minkowski) and the counter-claim that it decreases (Abraham) when light enters a medium.



The Abraham-Minkowski controversy dates back to the early years of the 20th Century, when Hermann Minkowski's electromagnetic theory indicated that a light pulse of energy Epulse within a dielectric medium of refractive index n would have a momentum of nEpulse/c (c being the speed of light in vacuum) whereas Max Abraham's theory gave a value of Epulse/(nc) for the same momentum. (CREDIT: arXiv)

"What we have shown is that from the point of view of the wave, nothing happens to its momentum," Koivurova states, suggesting momentum conservation across the boundary. Relativistic effects, akin to those in the general theory of relativity, underpin this conservation. "We found that we can ascribe a 'proper time' to the wave," Ornigotti adds, inferring that waves experience a different kind of time dilation and length contraction, phenomena typically reserved for high-speed travel in the cosmos.

Exotic Phenomena and Time Travel

This novel framework doesn't just replicate standard solutions; it goes further, particularly in the context of time-varying materials. In these media, light undergoes abrupt changes in properties, leading to behaviors not predicted by the standard wave equation. Here, the accelerating wave equation can analytically model situations that previously required numerical simulation.

One such theoretical construct is the disordered photonic time crystal, within which a light wave's energy could, hypothetically, increase exponentially as its speed drops in a similar fashion.

"Our formalism shows that the observed change in the energy of the pulse is due to a curved space-time the pulse experiences," notes Ornigotti, alluding to scenarios where energy conservation appears locally violated.

The reach of this research is vast, with potential applications spanning from everyday optics to experimental tests of general relativity, all while shedding light on the enigma of time's preferred direction.

The findings, detailed in the study "Time-varying media, relativity, and the arrow of time," were published in the journal Optica, marking a significant milestone in the annals of theoretical physics.

Breakthrough Tachyon discovery is a major leap towards time travel reality

The concept of the tachyon, a particle that travels faster than light, has fascinated physicists and sparked decades of exploration

Published Oct 31, 2024

An international research team has reignited interest by proposing that tachyons are indeed possible within the framework of Einstein's special theory of relativity.

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The concept of the tachyon, a theoretical particle that travels faster than light, has fascinated physicists and sparked decades of theoretical exploration. Originally conceived as a solution to certain quantum and relativity puzzles, tachyons remain hypothetical.

Yet, a new study by an international research team has reignited interest by proposing that tachyons are indeed possible within the framework of Einstein's special theory of relativity—a finding that could significantly reshape our understanding of causality, time, and even the structure of reality.

The Origins of the Tachyon

Physicist Gerald Feinberg introduced the idea of tachyons in 1962 as particles that could potentially travel faster than light, always maintaining speeds beyond that limit. This groundbreaking suggestion was rooted in his study of imaginary mass, a concept involving the square root of a negative number.

The blue glow of Cherenkov radiation in a nuclear reactor, one of the ways hypothetical tachyons can be detected. (CREDIT: Argonne National Laboratory)

Imaginary mass, he proposed, could permit particles to exceed the speed of light without conflicting with Einstein's theory of relativity, which prohibits massive particles from accelerating to that speed. Feinberg's tachyon hypothesis ignited curiosity about faster-than-light communication, time travel, and other extreme physical phenomena.

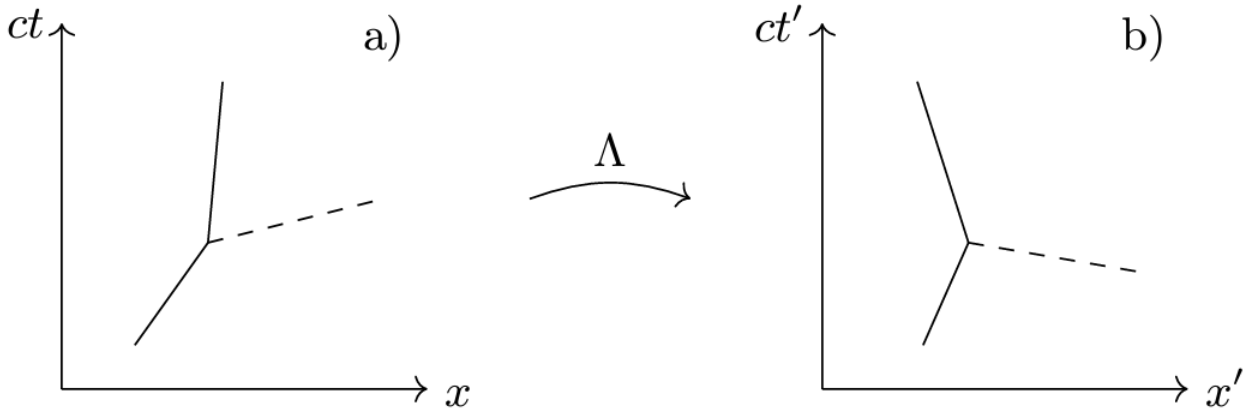
However, integrating tachyons into existing theories posed challenges. For one, their faster-than-light nature seemed to violate causality, a core principle in physics requiring causes to precede effects. Moreover, calculations around tachyons frequently produced "infinite energy," a mathematical impossibility that cast doubt on their physical relevance.

Additionally, theoretical models indicated that the number of observed tachyons would vary depending on the observer's frame of reference, a contradiction to established physical laws. Despite these hurdles, tachyons continued to be studied within quantum field theory and theoretical frameworks like string theory.

A New Study: Tachyons Within Relativity

Recent research led by physicists from the University of Warsaw and the University of Oxford, including Andrzej Dragan and Artur Ekert, has introduced a framework that reconciles tachyons with Einstein's special relativity.

Published in Physical Review D, the study challenges past assumptions and proposes a new approach where tachyons not only exist within relativity but could theoretically travel through time. According to Dragan, this framework allows superluminal particles to carry information backward in time, thereby opening new possibilities in how we understand causality.



An emission of a positive-energy tachyon (a) in one reference frame is Lorentz-transformed by a boost Λ into an emission of a negative-energy tachyon (b) backward in time, which can be reinterpreted as a regular absorption of a positive-energy antitachyon forward in time, in the boosted reference frame. The worldlines of tachyons are shown as dashed lines. (CREDIT: Physical Review D)

Dragan explains, "The idea that the future can influence the present rather than the present determining the future is not new in physics. However, until now, this kind of view has been at best an unorthodox interpretation of certain quantum phenomena, and this time we were forced to this conclusion by the theory itself."

Dragan's explanation illustrates this with a "movie" analogy, where knowing both the beginning and the end simultaneously allows one to understand the entire plot in full—suggesting a model where future events influence current behaviors.

Resolving Tachyon Paradoxes: A New Mathematical Framework

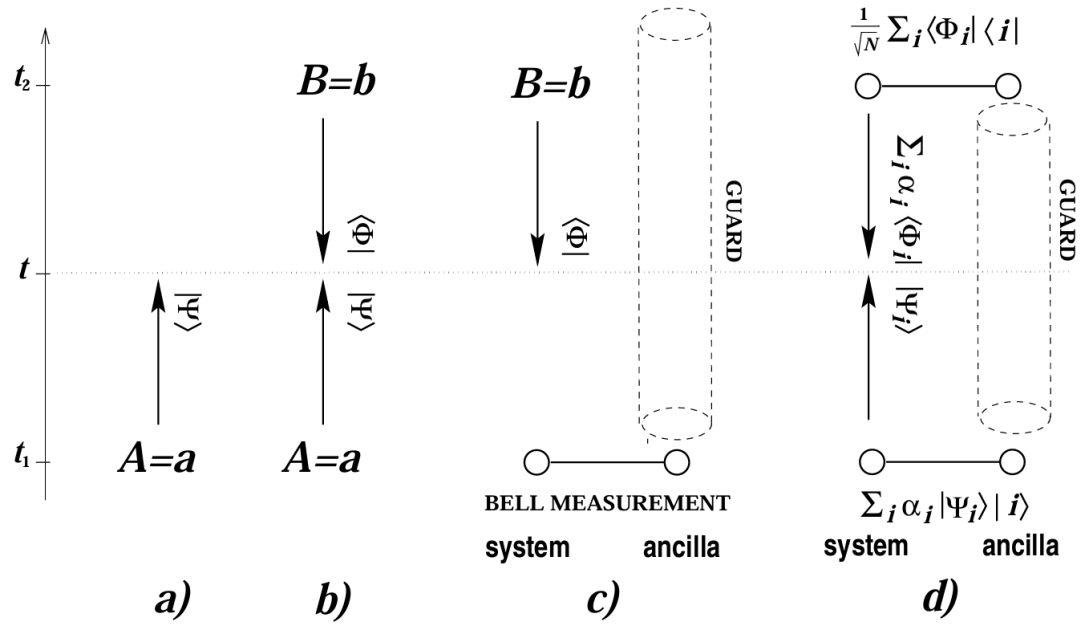
The study by Dragan and his colleagues, including researchers Jerzy Paczos, Kacper Dębski, Szymon Cedrowski, Szymon Charzyński, and Krzysztof Turzyński, addresses some of the primary issues that made tachyons mathematically implausible.

Traditional calculations involving tachyons have resulted in unlimited energy and unstable vacuum states, and models have varied based on the observer's perspective, challenging physical principles. To overcome these problems, the team used an extended mathematical approach, incorporating both initial and final states of the system in a way that allows tachyons to exist stably within the relativity framework.

This new framework has significant implications. By resolving issues such as infinite energy and observer dependency, the researchers created a consistent model for tachyons within special relativity. The study suggests that tachyons, long thought impossible due to mathematical paradoxes, might indeed fit into our current understanding of physics.

The Influence of Quantum Mechanics: Two-State Formalism

One of the study's breakthroughs is in its use of two-state formalism, a concept in quantum mechanics that supports time-reversible processes. This formalism, originally proposed by physicists Aharonov, Bergmann, and Lebowitz, has typically been seen as an exotic interpretation within quantum mechanics.



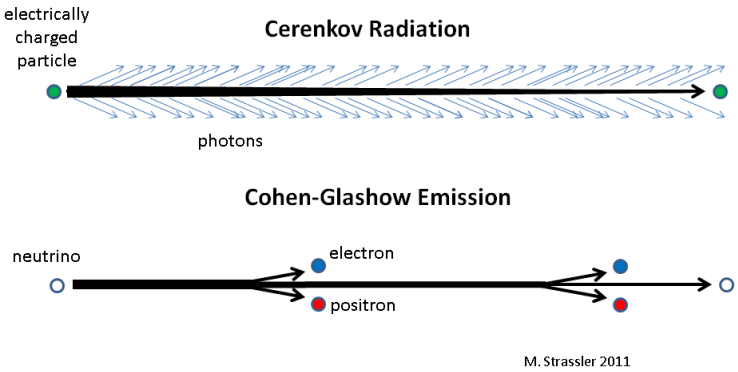
Single forward-evolving quantum state. Description of quantum systems: (a) pre-selected, (b) pre- and post-selected, (c) post-selected, and (d) generalized pre- and post-selected. (CREDIT: arxiv Quantum Physics)

However, the team applied it to their tachyon model to guarantee time-reversibility, suggesting that the processes involving tachyons could operate backward in time without violating causality. Dragan and Ekert further argue that superluminal particles, contrary to prior assumptions, do not create paradoxes but only introduce causal “disturbances” akin to those observed in quantum mechanics.

This two-state formalism provides a stable, relativistic framework that may redefine the tachyon’s place in physics. If validated, this approach could transform theories of time and quantum processes, possibly offering new explanations for complex phenomena such as how particles gain mass or how matter itself forms within the universe.

Previous Research and Experimental Constraints

Over the years, physicists have explored various theories and conducted experiments, albeit inconclusively, in search of tachyons. Notably, Sheldon Glashow and Andrew Cohen from Harvard University published a study on potential faster-than-light neutrinos, a phenomenon resembling tachyons, but later findings disproved this hypothesis. CERN's OPERA experiment also examined superluminal neutrinos, sparking brief excitement, though subsequent tests revealed measurement errors rather than new physics.



Cerenkov radiation involves the nearly continuous emission of photons by a charged particle moving faster than the speed of light in its vicinity. The charged particle gradually radiates away its energy. Cohen-Glashow emission involves the occasional creation, near a speeding neutrino, of an electron-positron pair, in which the neutrino loses a large fraction of its energy in one step. (CREDIT: Matt Strassler)

Beyond particle experiments, tachyonic fields have been studied in other theoretical contexts, including cosmology and the Casimir effect. In cosmology, tachyonic fields are theorized as potential drivers for dark energy and cosmic expansion.

Researchers like Dr. Shinji Tsujikawa from Waseda University have examined tachyonic fields to explore the accelerating universe's mysteries. Although still speculative, this research could eventually link tachyonic fields with observable cosmological phenomena, helping scientists explain why the universe's expansion rate appears to be increasing.

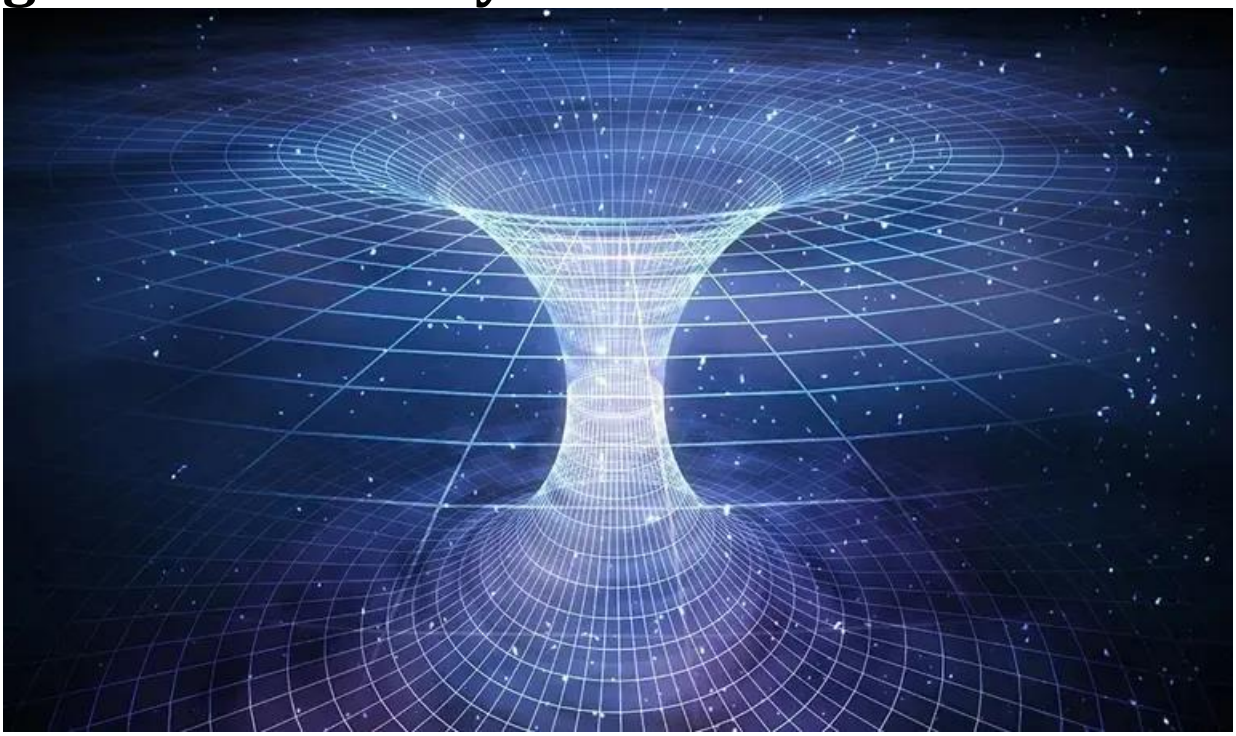
Broader Implications: Changing Our Understanding of Time and Reality

The Dragan team's study may have far-reaching consequences. With a mathematically sound framework for tachyons, physicists now have the opportunity to explore questions around time's nature and quantum reality more deeply. The tachyon framework could reveal hidden aspects of time symmetry and causality, possibly linking it to symmetry-breaking events, such as those theorized to explain mass in the Higgs field.

While tachyons remain hypothetical, the Dragan and Ekert study demonstrates that such particles may indeed have a place in physics, free of past contradictions. This advancement reminds us of science's role in challenging assumptions and stretching the boundaries of what we know.

The new framework could redefine quantum theory and time's nature, reshaping how we understand the universe at its most fundamental level.

Quantum gravity discovery could reconcile quantum mechanics with general relativity



Dive into discoveries transforming science: dynamic molecular interactions in MOFs for chemical separation and visible singularities revealing cosmic mysteries. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

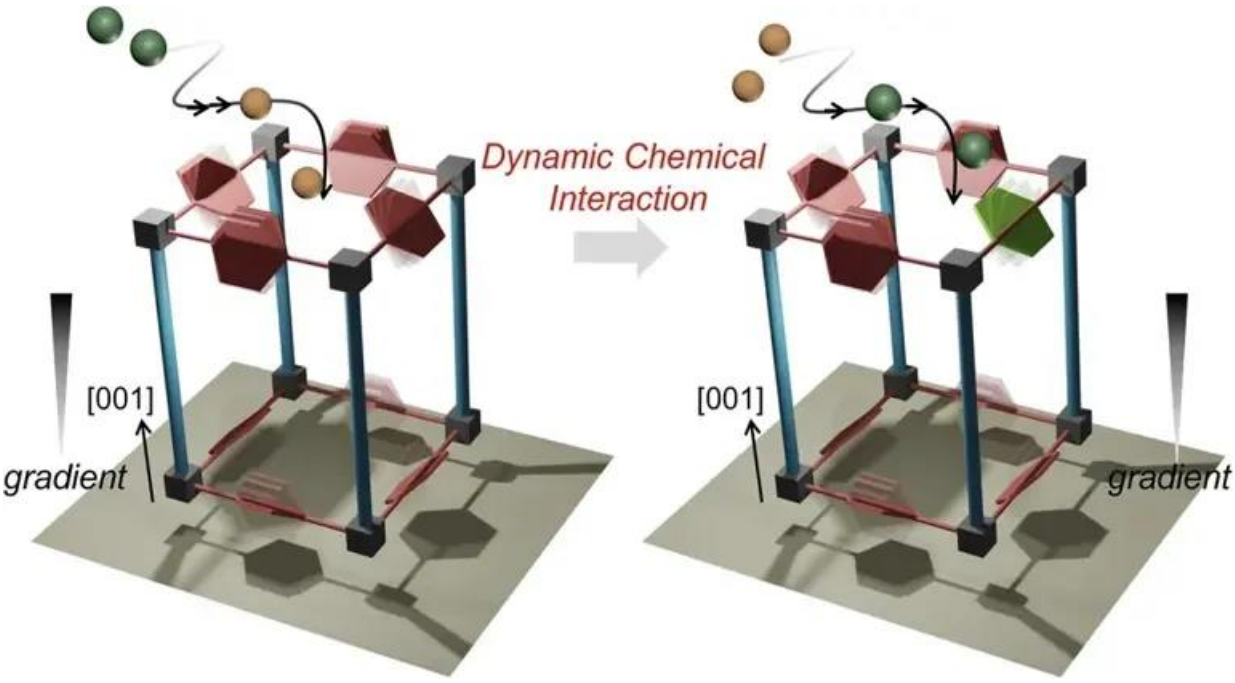
Scientific breakthroughs often stem from the persistent pursuit of understanding complex phenomena. From the nanoscale intricacies of molecular diffusion in advanced materials to the vast cosmic enigma of singularities, these discoveries illuminate new paths for innovation and understanding.

Recent advancements in these fields—dynamic molecular interactions in nanoporous materials and the discovery of visible cosmic singularities—promise transformative applications across science and technology.

Molecular diffusion, the movement of molecules through confined spaces, underpins many technologies, from chemical separation to catalysis and storage. Nanoporous materials like metal-organic frameworks (MOFs) are celebrated for their high porosity, chemical tunability, and structural versatility. Yet, fine-tuning molecular diffusion within these materials remains a daunting challenge, primarily due to the interplay of several factors.

Diffusion is influenced by pore size, channel orientation, chemical functionality, adsorption enthalpy, and framework flexibility. While these elements have been studied individually, understanding their combined effects is a more complex endeavor. This complexity makes designing MOFs for applications like membrane-based separations or catalytic reactions especially challenging.

Researchers recently explored this issue by investigating brominated alkane isomers—commercially important feedstocks used in producing lubricants, pesticides, and PVC. Using a specially designed MOF thin film, they studied the diffusion selectivity of 1-bromopropane (1BP) and 2-bromopropane (2BP).



Dynamic chemical interaction. (CREDIT: Nature Communications)© The Brighter Side of News

The study, published in the journal, Nature Communications, sought to manipulate dynamic chemical interactions to reverse the natural diffusion selectivity of these isomers.

The MOF employed was a pillared-layer structure featuring Cu2+ paddle-wheel nodes linked by benzenedicarboxylic acid (bdc) and azobipyridyl (azbpy) molecules. This design created two distinct pore windows—7.3 × 4.3 Å and 9.7 × 6.9 Å—optimized for separating the isomers.

The film was fabricated using a layer-by-layer epitaxial growth technique, ensuring precise nanochannel alignment. Advanced imaging techniques like X-

ray diffraction and electron microscopy confirmed the structural integrity of the MOF and its pore alignment.

Combining molecular simulations with kinetic experiments revealed that chemical interactions between the adsorbate (the isomers) and the MOF framework could modulate diffusion rates.

Researchers found that the orientation of nanochannels and the chemical functionality on pore surfaces worked synergistically to control molecular movement. Dynamic interactions allowed the team to reverse the diffusion selectivity of 1BP and 2BP, demonstrating how molecular pathways could be manipulated at an atomic scale.

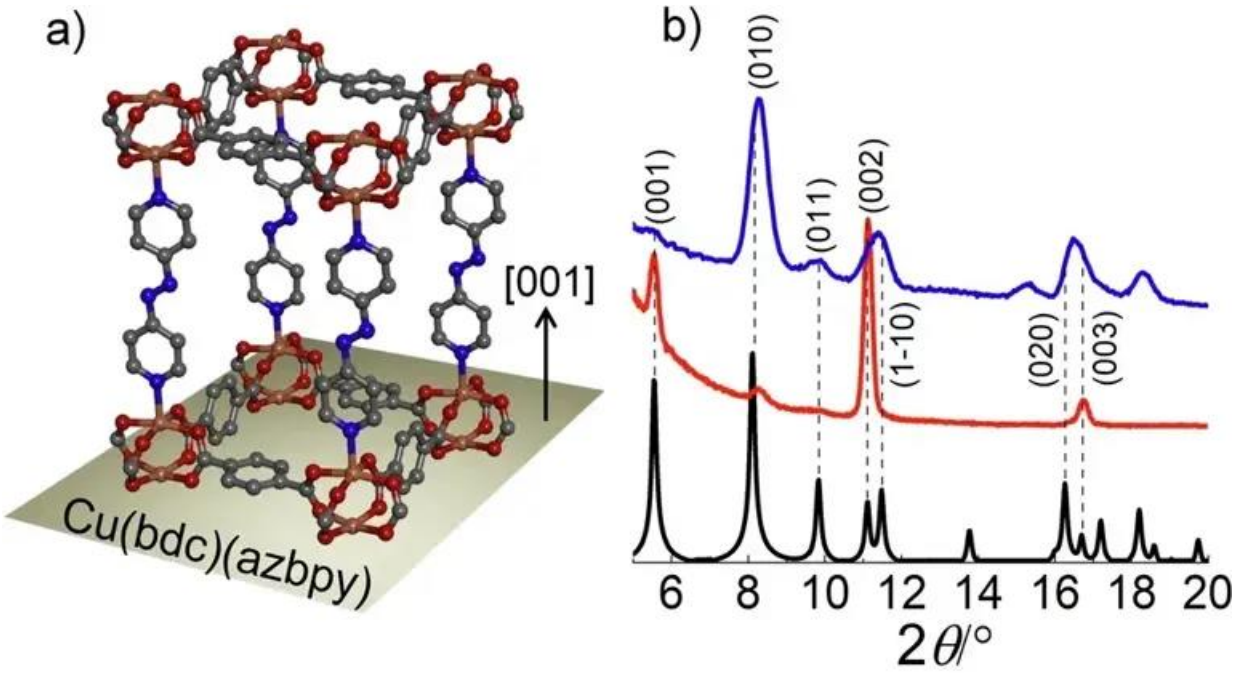
These findings hold significant implications for industrial processes requiring precise chemical separations. "Dynamic chemical interactions within MOFs not only regulate molecular diffusion but also offer a pathway to fine-tune material properties for specific applications," the researchers noted. By leveraging these interactions, MOFs could make separation technologies more energy-efficient and environmentally sustainable.

On a vastly different scale, astrophysicists are challenging conventional understandings of the universe by investigating singularities—points of infinite density resulting from gravitational collapse.

Traditionally, singularities are thought to exist only within black holes, concealed behind event horizons that prevent observation. However, recent research suggests the existence of naked or visible singularities, which could offer unprecedented insights into the universe's fundamental structure.

Professors Pankaj Joshi and Sudip Bhattacharyya proposed that gravitational collapse in the early universe could have produced primordial naked singularities (PNaSs). Unlike black holes, PNaSs are not shrouded by event horizons, making them observable. These singularities could represent a significant fraction of dark matter, which constitutes about 25% of the universe’s total mass-energy content.

Their research builds on earlier hypotheses by Stephen Hawking and others, who suggested that quantum fluctuations in the early universe could lead to the formation of primordial black holes. Joshi and Bhattacharyya extended this idea, showing that sufficiently dense regions of matter could form PNaSs instead.



Diffusion selectivity in oriented nanochannel. (CREDIT: Nature Communications)© The Brighter Side of News

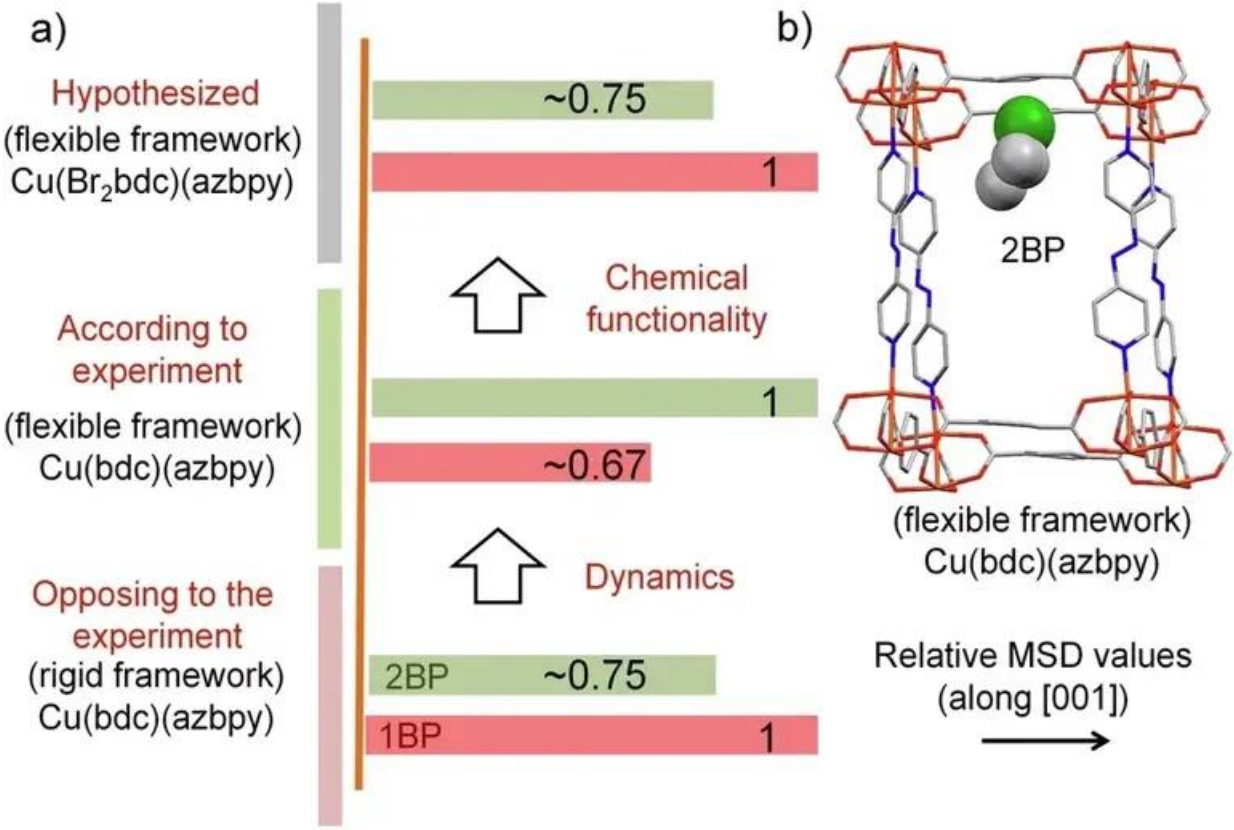
These naked singularities may provide a rare opportunity to study quantum gravity—a theoretical framework that seeks to reconcile quantum mechanics with general relativity. "Understanding quantum gravity is one of the last major frontiers of physics," the researchers stated. "PNaSs offer a unique opportunity to observe phenomena that are otherwise inaccessible in black holes."

If PNaSs form a substantial portion of dark matter, they could fundamentally change how we perceive the universe. Unlike traditional dark matter, which interacts only through gravity, PNaSs could be directly observed and studied. This accessibility opens new avenues for investigating the quantum effects of gravity, which could help physicists develop a unified theory of the universe.

Despite their differences in scale and subject matter, the studies of molecular diffusion in MOFs and cosmic singularities share a common pursuit: understanding complex systems to uncover their underlying principles. Advances in computational modeling and experimental techniques have been critical to both endeavors.

In the realm of MOFs, molecular dynamics simulations provide valuable insights into diffusion pathways and chemical interactions. These tools allow researchers to predict how structural changes in the MOF framework affect molecular movement.

Similarly, in astrophysics, theoretical models and simulations help visualize phenomena like gravitational collapse and quantum fluctuations, guiding researchers in exploring the extreme conditions of the universe.



Framework dynamics and diffusion control. (CREDIT: Nature Communications)© The Brighter Side of News

Both fields also highlight the importance of interdisciplinary collaboration. Chemists, physicists, and computational scientists work together to enhance the functionality of MOFs, while astrophysicists draw on quantum theory and general relativity to develop models of singularities. Such collaborations accelerate progress and open new possibilities for scientific discovery.

The potential applications of these findings are vast. MOFs with tunable diffusion properties could revolutionize industries reliant on chemical separations, such as petrochemicals, pharmaceuticals, and environmental remediation. Their energy efficiency and adaptability make them ideal for developing sustainable technologies, such as carbon capture and hydrogen storage.

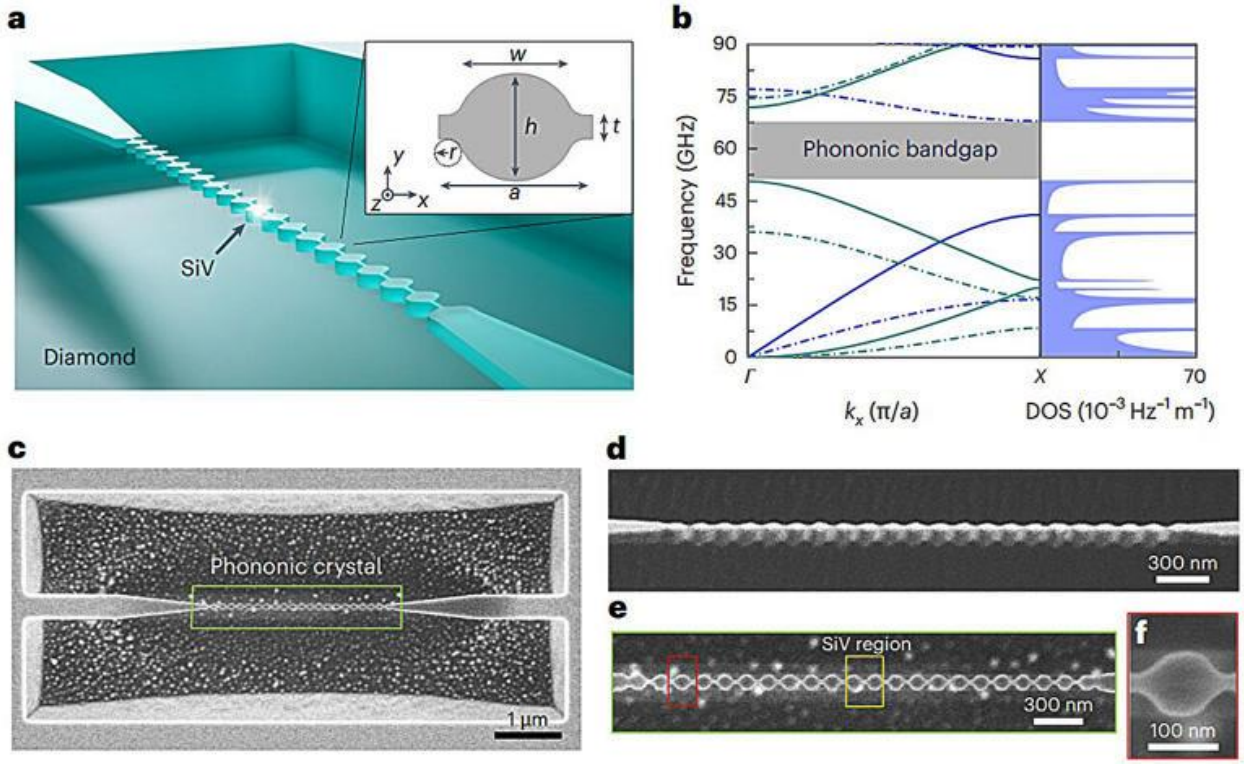
In astrophysics, PNaSs could hold the key to understanding dark matter and quantum gravity, two of the most profound mysteries in modern science. These singularities may reveal quantum effects in gravitational systems, offering insights

that were previously considered unattainable. They could also serve as natural laboratories for testing proposed theories of quantum gravity, bridging the gap between quantum mechanics and general relativity.

Both studies underscore the value of pushing scientific boundaries. By delving into the nanoscale world of MOFs and the cosmic realm of singularities, researchers are unlocking the secrets of the universe at both ends of the scale. These discoveries not only advance scientific knowledge but also lay the groundwork for transformative technologies and theoretical breakthroughs.

As science continues to explore the unknown, the lines between disciplines blur, and the potential for discovery grows. Whether in the confined pores of a MOF or the infinite density of a singularity, the quest for understanding unites us in our search for meaning in the natural world.

Newly fabricated crystals control interactions between high-frequency phonons and single quantum systems



Diamond phononic crystals for suppressing high-frequency phonons that induce decoherence in single silicon-vacancy (SiV) centers. Credit: Kuruma et al. (Nature Physics, 2024. DOI: 10.1038/s41567-024-02697-5)

Phonons, the quantum mechanical vibrations of atoms in solids, are often sources of noise in solid-state quantum systems, including quantum technologies, which can lead to decoherence and thus adversely impact their performance.

Strategies to reliably control phonons and their interactions with quantum systems could help to mitigate the adverse effects of these vibrations on the systems.

Researchers at Harvard University and other institutes have introduced a new approach to control the interactions between high-frequency phonons and single solid-state quantum systems. Their proposed method, outlined in a paper published in *Nature Physics*, relies on new diamond phononic crystals that they designed and fabricated, which can be used to engineer the local density of states in a host material.

"The ability to control phonons in solids is key since they often act as a source of noise and decoherence for solid-state quantum systems," Kazuhiro Kuruma, first author of the paper, told Phys.org.

"The primary objective of our study was to demonstrate the control of the phononic local density of states of the host matrix using phononic crystals to suppress spontaneous single-phonon processes that induce the decoherence in individual quantum systems."

Kuruma and his colleagues were able to design and fabricate diamond-based phononic crystals with nanoscale precision, embedding silicon-vacancy color centers within them. Using their newly fabricated crystals, the team observed an 18-fold reduction in the phonon-induced orbital relaxation rate, suggesting that these crystals suppress single-photon processes in the color centers.

"One of the most difficult parts of this study was the fabrication of phononic crystals in diamond," explained Kuruma. "We carefully optimized a diamond etching process to fabricate these crystals with very small features down to 20 nm into single crystal diamond."

The new diamond phononic crystals designed by the researchers were successfully used to control the interactions between the high-frequency phonons and color centers. Specifically, Kuruma and his colleagues found that these crystals could suppress interactions between single phonons and a quantum emitter at temperatures up to 20K.

"We demonstrated phononic crystals that can suppress high-frequency phonons from 50 to 70 GHz," said Kuruma. "In addition, we demonstrated that spontaneous single-phonon processes in single quantum systems are suppressed by the phononic crystals even when increasing temperatures up to 20 K."

In the future, the approach employed by this team of researchers and the phononic crystals they fabricated could contribute to the development of advanced quantum technologies that can benefit from the reliable control of phonon interactions, such as quantum phononic networks and quantum acoustic systems.

In addition, this recent study could inform future research rooted in acoustodynamics, an emerging field that focuses on quantum phenomena involving acoustic waves.

"Our results not only open the possibility of efficiently controlling specific high-frequency phonons for applications in radio-frequency signal processing, optomechanics, nonlinear phononics and thermoelectrics, but also could improve the properties of solid-state quantum systems at higher temperatures."

More information: Kazuhiro Kuruma et al, Controlling interactions between high-frequency phonons and single quantum systems using phononic crystals, *Nature Physics* (2024). DOI: 10.1038/s41567-024-02697-5.

Scientists discover new, 3rd form of magnetism that may be the 'missing link' in the quest for superconductivity

Researchers have obtained the first conclusive evidence of an elusive third class of magnetism, called altermagnetism. Their findings, published Dec. 11 in the journal Nature, could revolutionize the design of new high-speed magnetic memory devices and provide the missing puzzle piece in the development of better superconducting materials.

"We have previously had two well-established types of magnetism," study author Oliver Amin, a postdoctoral researcher at the University of Nottingham in the U.K., told Live Science. "Ferromagnetism, where the magnetic moments, which you can picture like small compass arrows on the atomic scale, all point in the same direction. And antiferromagnetism, where the neighboring magnetic moments point in opposite directions — you can picture that more like a chessboard of alternating white and black tiles."

Electron spins within an electrical current must point in one of two directions and can align with or against these magnetic moments to store or carry information, forming the basis of magnetic memory devices.

A new form of magnetism

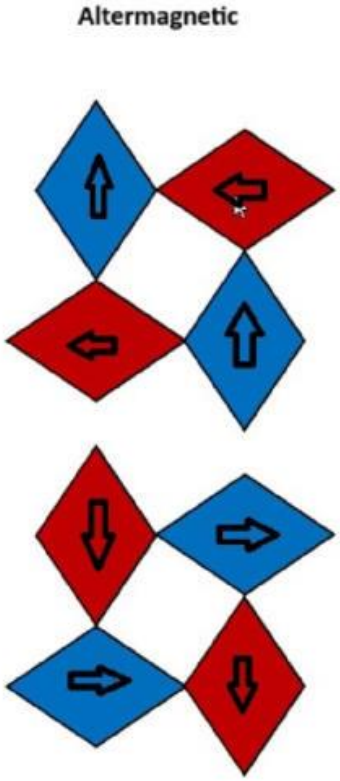
Altermagnetic materials, first theorized in 2022, have a structure that sits somewhere in between. Each individual magnetic moment points in the opposite direction as its neighbor, as in an antiferromagnetic material. But each unit is slightly twisted relative to this adjacent magnetic atom, resulting in some ferromagnetic-like properties.

Altermagnets, therefore, combine the best properties of both ferromagnetic and antiferromagnetic materials. "The benefit of ferromagnets is that we have an easy way of reading and writing memory using these up or down domains," study co-author Alfred Dal Din, a doctoral student also at the University of Nottingham, told Live Science. "But because these materials have a net magnetism, that information is also easy to lose by wiping a magnet over it."

Conversely, antiferromagnetic materials are much more challenging to manipulate for information storage. Because they have a net zero magnetism, however, information in these materials is much more secure and faster to carry. "Altermagnets have the speed and resilience of an antiferromagnet, but they also have this important property of ferromagnets called time reversal symmetry breaking," Dal Din said.

This mind-bending property looks at the symmetry of objects moving forward and backward in time. "For example, gas particles fly around, randomly colliding and filling up the space," Amin said. "If you rewind time, that behavior looks no different.""

This means the symmetry is conserved. However, because electrons possess both a quantum spin and a magnetic moment, reversing time — and, therefore, the direction of travel — flips the spin, meaning the symmetry is broken. "If you look at those two electron systems — one where time is progressing normally and one where you're in rewind — they look different, so the symmetry is broken," Amin explained. "This allows certain electrical phenomena to exist."



A diagram showing how magnetic moments are oriented in altermagnetic materials. (Image credit: Oliver Amin)

Finding ‘the missing link’ of superconductivity

The team — led by Peter Wadley, a professor of physics at the University of Nottingham — used a technique called photoemission electron microscopy to image the structure and magnetic properties of manganese telluride, a material formerly believed to be antiferromagnetic.

"Different aspects of the magnetism become illuminated depending on the polarization of the X-rays we choose," Amin said. Circularly polarized light revealed the different magnetic domains created by the time reversal symmetry breaking, while horizontally or vertically polarized X-rays allowed the team to measure the direction of the magnetic moments throughout the material. By combining the results of both experiments, the researchers created the first-ever map of the different magnetic domains and structures within an altermagnetic material.

With this proof of concept in place, the team fabricated a series of altermagnetic devices by manipulating the internal magnetic structures through a controlled thermal cycling technique.

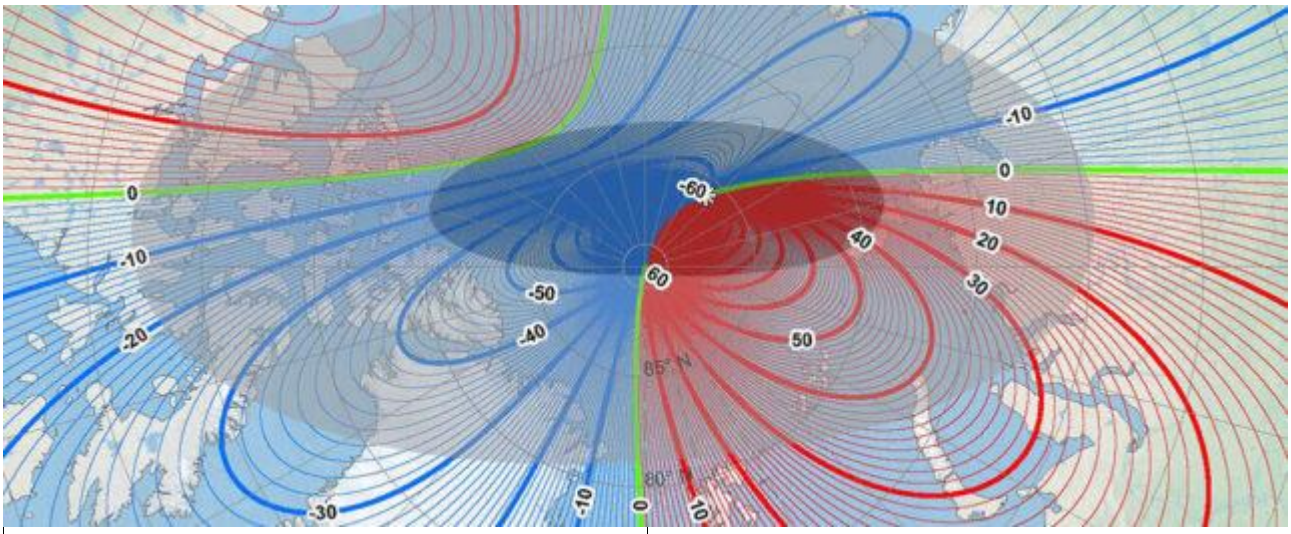
"We were able to form these exotic vortex textures in both hexagonal and triangular devices," Amin said. "These vortices are gaining more and more attention within spintronics as potential carriers of information, so this was a nice first example of how to create a practical device."

The study authors said the power to both image and control this new form of magnetism could revolutionize the design of next-generation memory devices, with increased operational speeds and enhanced resilience and ease of use.

"Altermagnetism will also help with the development of superconductivity," Dal Din said. "For a long time, there's been a hole in the symmetries between these two areas, and this class of magnetic material that has remained elusive up until now turns out to be this missing link in the puzzle."

The Magnetic North Pole Has Officially Changed Position

PHYSICS20 December 2024

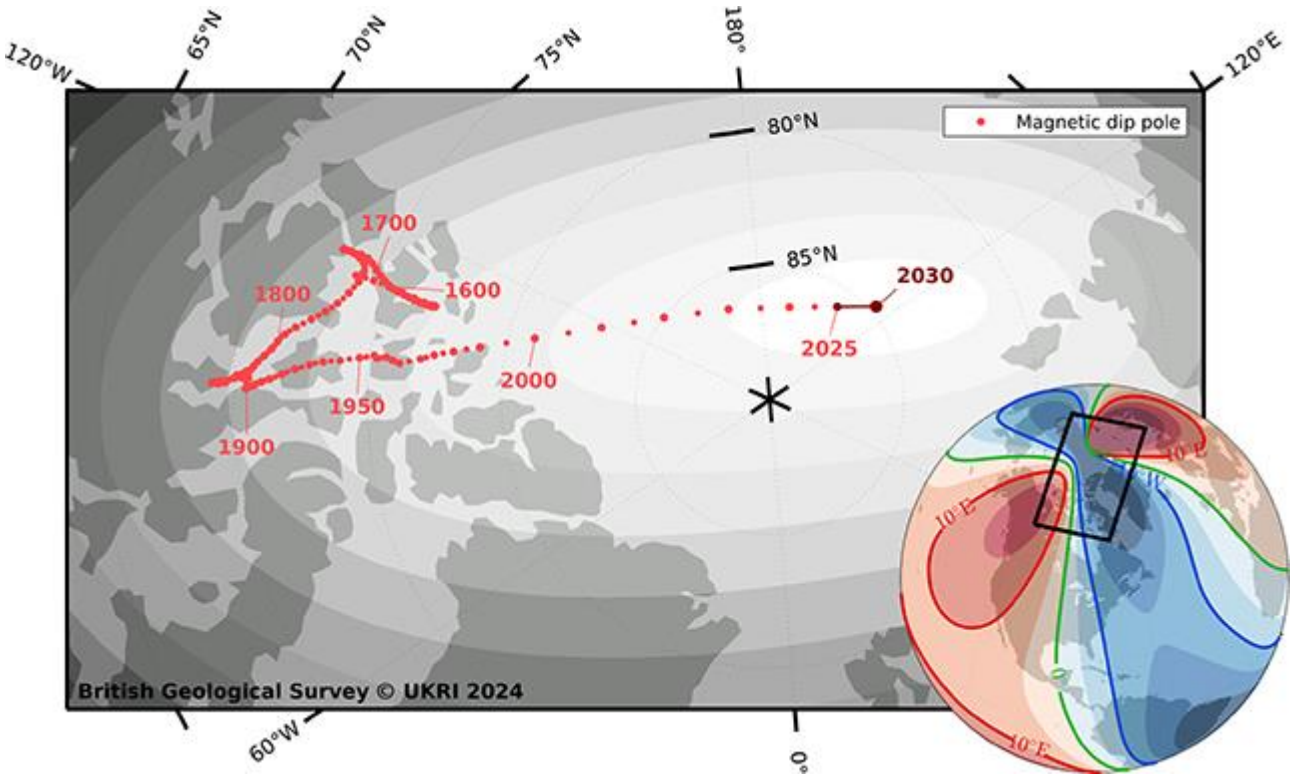


There's a new World Magnetic Model. (NOAA/NCEI/BGS)

It's time to recalibrate the navigation systems on ships, airplanes, and (given the time of year) Santa's sleigh: the position of the magnetic North Pole is officially being changed, continuing its shift away from Canada and towards Siberia.

Experts from the US National Oceanic and Atmospheric Administration (NOAA) and the British Geological Survey (BGS) have joined forces – as they do every five years – to produce a new, more accurate World Magnetic Model (WMM).

While the geographical North Pole stays fixed in place (at the very summit of the Earth's rotational axis), the WMM pinpoints the magnetic North Pole – where Earth's magnetic field points straight down, a perfectly vertical magnetic field.



Magnetic north has shifted a lot over the centuries. (BGS)

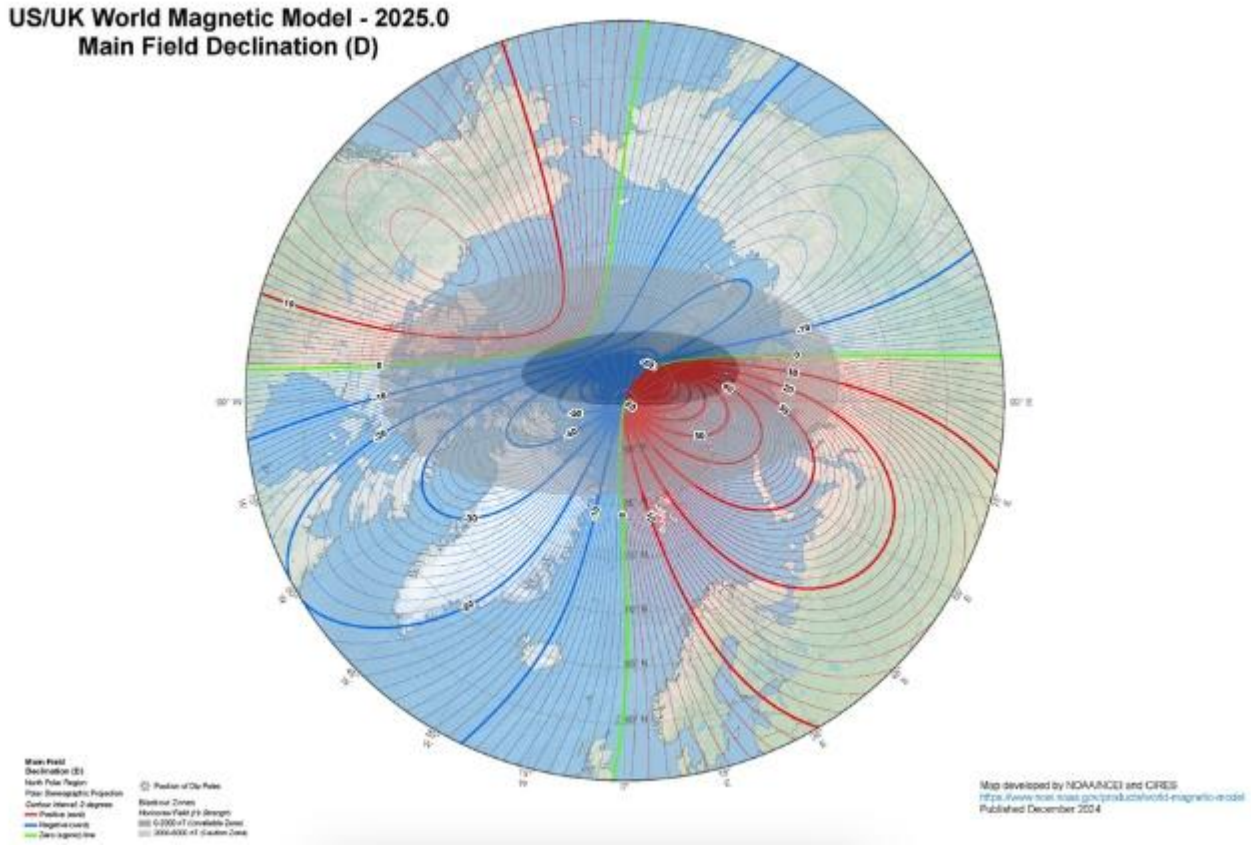
And as the iron and nickel inside our planet shift, so does Earth's magnetic field, meaning the North (and South) Poles are also constantly on the move. If you're using a compass or a GPS system, knowing exactly where these points are is crucial.

"The current behaviour of magnetic north is something that we have never observed before," says global geomagnetic field modeller William Brown, from BGS.

"Magnetic north has been moving slowly around Canada since the 1500s but, in the past 20 years, it accelerated towards Siberia, increasing in speed every year until about five years ago, when it suddenly decelerated from 50 to 35 kilometers [31 to 22 miles] per year, which is the biggest deceleration in speed we've ever seen."

Research suggests that two giant magnetic lobes – one under Canada and one under Siberia – are what's driving the shifting of magnetic north. Sometimes the shifts are dramatic enough that an emergency update is required, outside of the usual 5-year cycle.

Now we have a more accurate map of magnetic north, one that should be good for another half a decade. For the first time, a higher resolution map is also available, which offers more than 10 times more detail: it has a spatial resolution of about 300 km at the equator compared to the standard 3,300 km.



The 2025 World Magnetic Model. (NOAA/NCEI)

According to the BGS team, traveling 8,500 km (5,282 miles) from South Africa to the UK in a straight line would leave you 150 km (93 miles) off course by the end, if you used the old WMM compared to the new WMM for your navigation.

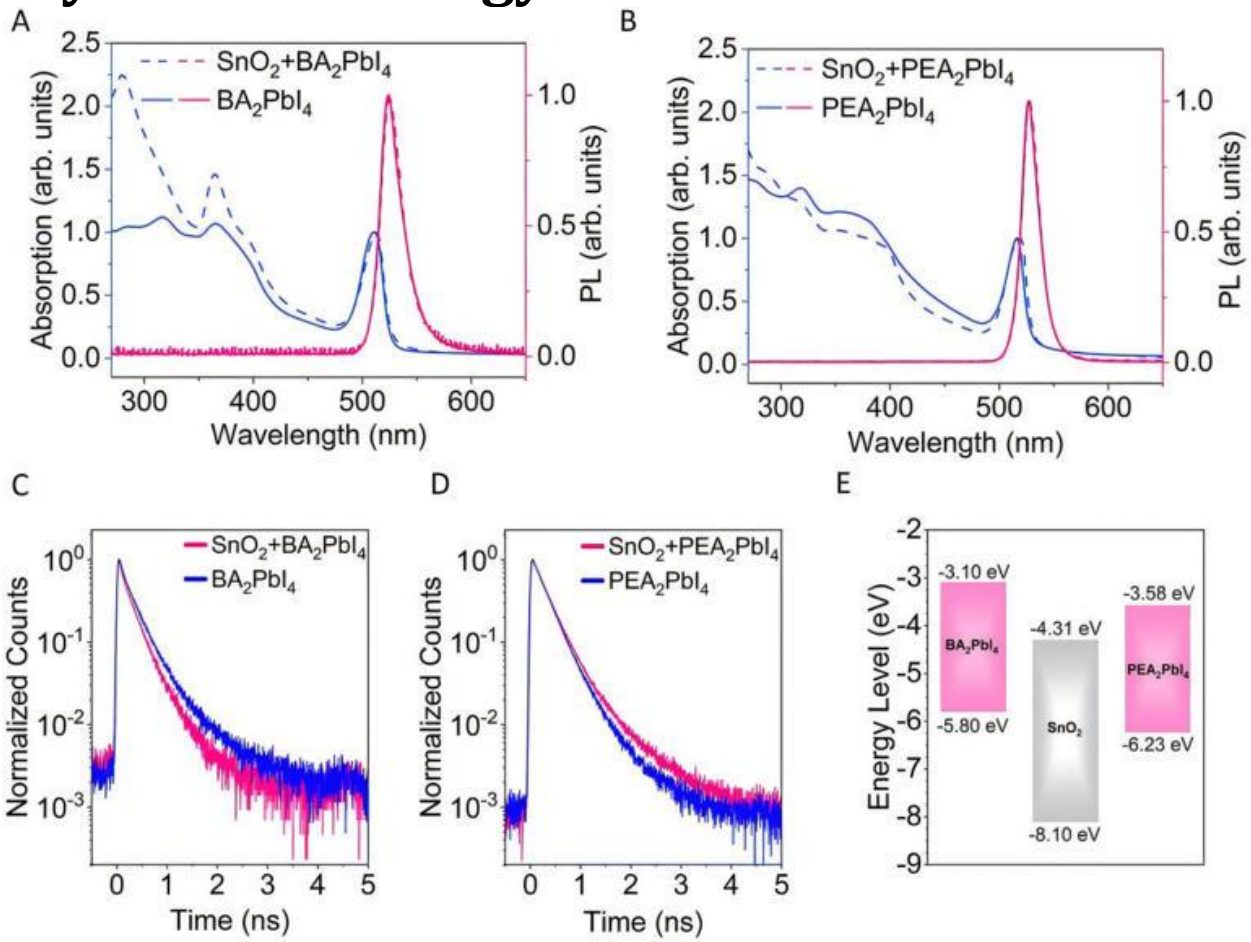
That's how much difference it can make, and mapping and logistics companies, together with governments and official agencies, will now be making updates.

However, we won't have to apply any updates to our own phones or sat navs – it'll all happen automatically.

The magnetic North Pole was first discovered by Sir James Clark Ross in northern Canada back in 1831.

Since then, researchers have gradually been able to track it with more precision, using ground measurements taken all across the globe as well as readings from satellites in space.

Scientists harness the power of 'layered' crystals for energy innovation



Steady-state optical properties and time-resolved PL. Credit: Journal of Materials Chemistry C (2024). DOI: 10.1039/D4TC03014A

University of Missouri scientists are unlocking the secrets of halide perovskites—a material that's poised to reshape our future by bringing us closer to a new age of energy-efficient optoelectronics.

Suchi Guha and Gavin King, two physics professors in Mizzou's College of Arts and Science, are studying the material at the nanoscale: a place where objects are invisible to the naked eye. At this level, the extraordinary properties of halide perovskites come to life, thanks to the material's unique structure of ultra-thin crystals—making it astonishingly efficient at converting sunlight into energy.

Think solar panels that are not only more affordable but also far more effective at powering homes. Or LED lights that burn brighter and last longer while consuming less energy.

"Halide perovskites are being hailed as the semiconductors of the 21st century," said Guha, who specializes in solid-state physics. "Over the past six years, my lab has concentrated on optimizing these materials as a sustainable source for the next generation of optoelectronic devices."

To create the material, the scientists used a method called chemical vapor deposition. It was developed and optimized by Randy Burns, one of Guha's former graduate students, in collaboration with Chris Arendse from the University of the Western Cape in South Africa. And because it's scalable, it can easily be used to mass produce solar cells.

Guha's team explored the fundamental optical properties of halide perovskites using ultrafast laser spectroscopy. To optimize the material for various electronic applications, the team turned to King.

King, who primarily works with organic materials, used a method called ice lithography, known for its ability to fabricate materials at the nanometer scale. Ice lithography requires cooling the material to cryogenic temperatures—typically below -150°C (-238°F). This ultra-cool method allowed the team to create distinct properties for the material using an electron beam.

He equates the method to using a "nanometer-scale chisel."

"By creating intricate patterns on these thin films, we can produce devices with distinct properties and functionalities," King, who specializes in biological physics, said. "These patterns are the equivalent to developing the base or foundational layer in optical electronics."

Finding success through collaboration

While Guha and King work in different areas of physics, they said this collaboration has benefited both them and their students.

"I find it exciting because, on my own, there are only so many things I can do, both experimentally and theoretically," Guha said. "But when you collaborate, you get the full picture and the chance to learn new things. For example, Gavin's lab works with biological materials, and by combining that with our work in solid-state physics, we're discovering new applications that we hadn't considered before."

King agrees.

"Everyone brings a unique perspective, which is what makes it work," King said. "If we were all trained the same way, we'd all think the same, and that wouldn't allow us to accomplish as much as we can here together."

Their work is an example of the innovative energy research at Mizzou that's powering the new Center for Energy Innovation.

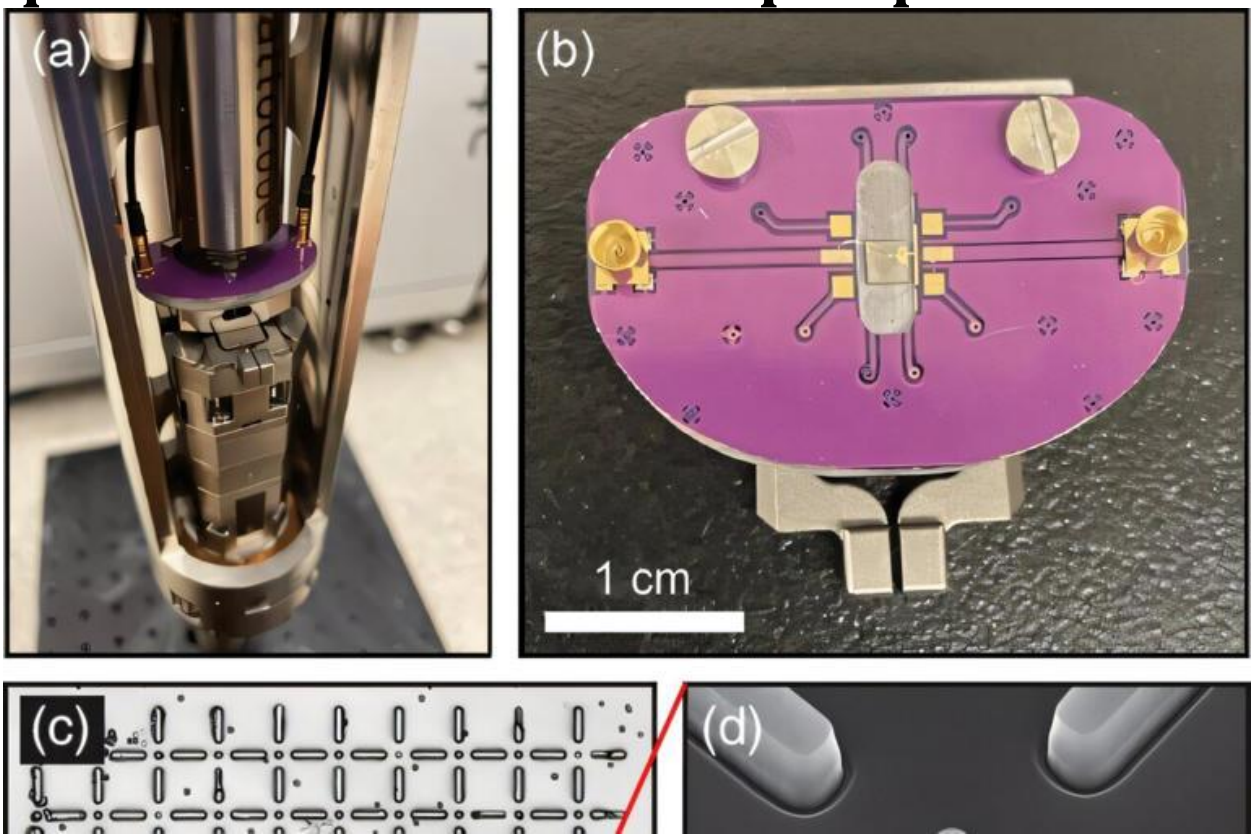
The research is published in the *Journal of Materials Chemistry C* and *Small*.

More information: Dallar Babaian et al, Carrier relaxation and exciton dynamics in chemical-vapor-deposited two-dimensional hybrid halide perovskites, *Journal of Materials Chemistry C* (2024). DOI: 10.1039/D4TC03014A

Randy Burns et al, Stabilizing Metal Halide Perovskite Films via Chemical Vapor Deposition and Cryogenic Electron Beam Patterning, *Small* (2024). DOI: 10.1002/smll.202406815

Provided by University of Missouri

Boosted tin-based qubit signals enhance quantum communication prospects



(a) Photograph of the sample space. Microwaves are routed through cables (thin black lines) that connect to additional microwave cables higher up in the cryostat. (b) Printed circuit board. Coplanar waveguides on the circuit board connect to surface mount soldered connectors on the left and right of the board, and to bonding pads closer to the center. The diamond chip is placed at the center of the circuit board, in a groove milled to be of similar depth as the chip height. (c) Optical image of an array of nanopillars. An example nanopillar is circled in red. (d) Scanning electron microscope image of a single nanopillar. Credit: Physical Review X (2023). DOI: 10.1103/PhysRevX.13.031022

The future of tin-based qubits is brighter thanks to breakthrough work by Stanford University researchers. Qubits are the fundamental carriers of quantum information, and scientists worldwide are engineering atoms to create reliable, long-lived qubits for processing quantum data. Quantum engineering is expected to accelerate advances in areas as diverse as medicine and finance.

The Stanford team achieved their milestone on a type of qubit known as a tin vacancy center in diamond: replace two of diamond's carbon atoms with one atom of tin and voila! A tin vacancy qubit is born.

But of course, it isn't so simple.

A tin vacancy qubit can be in one of two states, called spin-up and spin-down. That spin signal tends to be fuzzy and hard to read, making tin vacancies less useful than other qubit types for transmitting information.

"Before working on this project, measuring this qubit's spin was like trying to pick up a very, very weak light signal, like trying to squint at some dim light to determine whether the qubit was spin-up or spin-down," said Eric Rosenthal, a Stanford University postdoctoral appointee.

But the Stanford team has now turned things around.

As detailed in *Physical Review X*, the group successfully boosted the tin vacancy qubit's signal, reading its spin state with an impressive 87% accuracy.

Typical tin vacancy measurements require averaging hundreds of readings. But the Stanford group was able to read the qubit's spin state in a single shot. The high-accuracy, single-shot readout of the signal with reliable spin control is a first for tin-vacancy qubits.

The research was led by Jelena Vuckovic, the Jensen Huang professor of global leadership, professor of electrical engineering and by courtesy of applied physics at Stanford. Q-NEXT, a DOE National Quantum Information Science Research Center led by Argonne, collaborated on the effort.

The group's advances will enable scientists to take full advantage of the tin vacancy qubit, which boasts long lifetimes and can operate at higher temperatures, helping cut down on cooling costs.

It's also a promising qubit for a future quantum internet—a potential communication network, similar to the internet we're familiar with, that transmits information through quantum principles. A quantum internet will require tight control of a qubit's spin, high confidence in the spin state and compatibility with current communication infrastructure.

"In all of these aspects, the tin vacancy looks very promising as an emerging system for the quantum internet," said Stanford postdoctoral scholar Souvik Biswas. "It checks most of the boxes."

The team's success followed in-depth studies of the way tin vacancies play with their electromagnetic surroundings. By tuning the relevant physics knobs, they

solved tin vacancy's metaphorical dim-light problem, cranking up the brightness of the qubit signal.

The most important knob was the tuner for the magnetic field around the qubit. The Vuckovic group showed that, by orienting the field in the right way, one can amp the tin-vacancy center's quantum signal, like tilting a mirror at just the right angle to maximally reflect the light from a nearby bulb.

"You can have a magnetic field that is not oriented the right way, and then the qubit will not appear bright," Biswas said. "We modified the physical environment using some knobs that people didn't appreciate too much before this."

The group also made major improvements to their experimental setup, especially to the arrangement of the optical instruments that help excite and read out the qubit's spin states.

"It was like making a camera that can see really, really faint images," Biswas said.

In making their measurements, the researchers overcame several engineering hurdles, including the difficulty of flipping a tin vacancy's spin and the trickiness of working with diamond.

"This is generally a bit harder to do because you're limited by the natural qubit itself," Biswas said.

The Stanford researchers note that, by optimizing the diamond device further for light collection, the scientific community could improve on their qubit's already impressive performance.

"The fact that it works that well with this unoptimized structure really speaks well of tin as a qubit," Rosenthal said. "It means it's an easy qubit to work with."

In the same streamlined setup, researchers also carried out so-called weak measurements of the tin vacancy's quantum states, laying out the ways that the very act of measuring spin can affect the system's behavior.

Unlike a strong spin measurement, which forces the spin to fully "collapse" into an up or down state, a weak measurement doesn't always collapse the spin. The extent to which this collapse happens—or doesn't happen—ends up being a precise method to study how strongly the qubit interacts with light.

The technique is an example of how quantum mechanics can be useful for sensing. And the method can be applied to other types of qubits.

The Stanford team worked with scientists at DOE's Sandia National Laboratories to implant the tin atoms in diamond. The multiorganizational effort speaks to the goals of the broader quantum information science community to collaborate across institutions to create new materials for quantum devices.

"Not only can we measure if the tin vacancy qubit is up or down, but we can also control whether it's up or down or somewhere in between very well," Rosenthal said. "I hope our techniques will be helpful for the community at large."

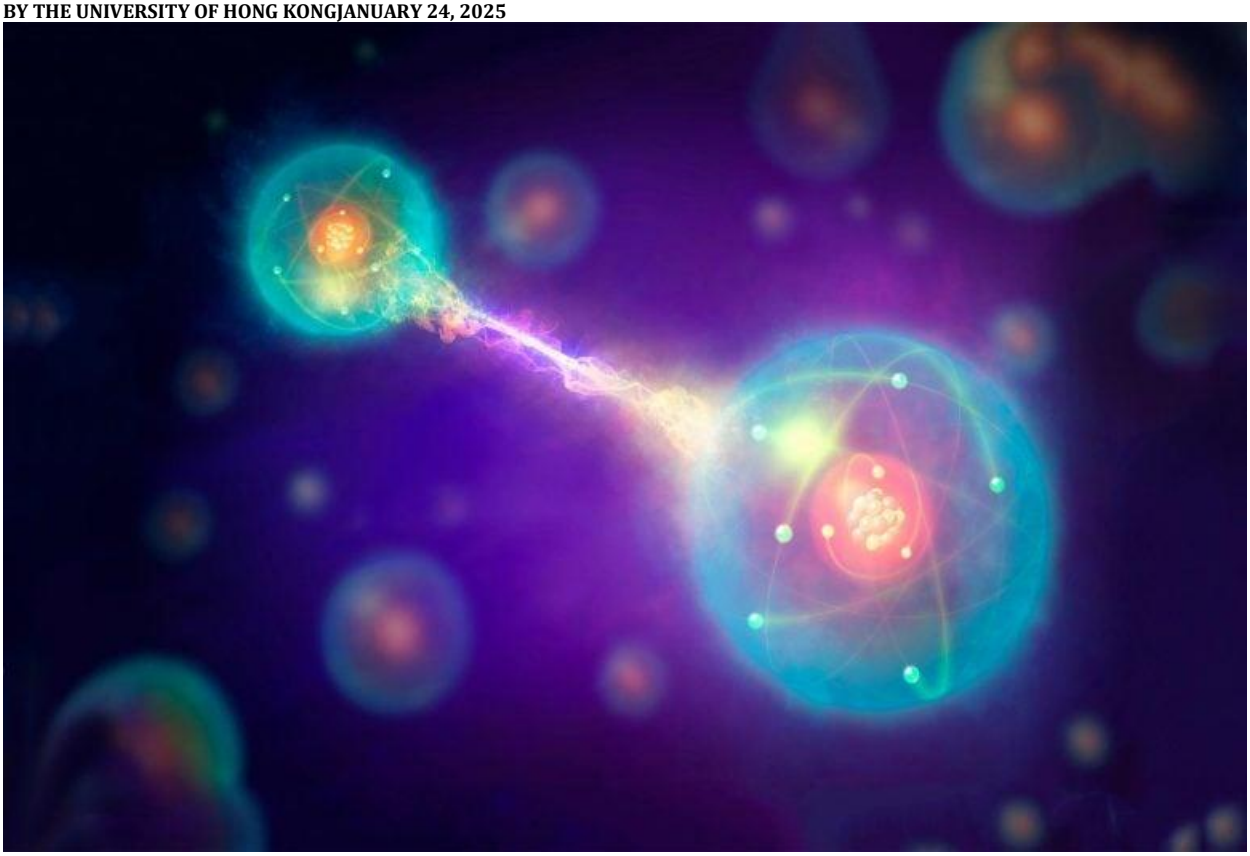
Biswas added, "With the technical advancements made towards tin vacancy centers, the future for diamond-based quantum technology is exciting."

More information: Eric I. Rosenthal et al, Microwave Spin Control of a Tin-Vacancy Qubit in Diamond, *Physical Review X* (2023). DOI: 10.1103/PhysRevX.13.031022

Provided by Argonne National Laboratory

Revolutionary Microscopy Unlocks the Secrets of Quantum Entanglement

BY THE UNIVERSITY OF HONG KONGJANUARY 24, 2025



Researchers have unlocked a way to visualize quantum entanglement through 'entanglement microscopy.'

Scientists have developed 'entanglement microscopy,' a technique that maps quantum entanglement at a microscopic level.

By studying the deep connections between particles, researchers can now visualize the hidden structures of quantum matter, offering new perspectives on particle interaction that could revolutionize technology and our understanding of the universe.

Quantum entanglement is a fascinating phenomenon where particles remain mysteriously linked, even when separated by vast distances. Understanding how this connection works, especially in complex quantum systems, has been a long-standing challenge in physics.

Researchers from the Department of Physics at The University of Hong Kong (HKU), along with their collaborators, have recently developed an innovative algorithm called *entanglement microscopy.* This breakthrough technique allows scientists to visualize

and map entanglement at a microscopic level. By closely examining the intricate interactions between entangled particles, this method reveals hidden structures within quantum matter — offering new insights that could revolutionize technology and expand our understanding of the universe.

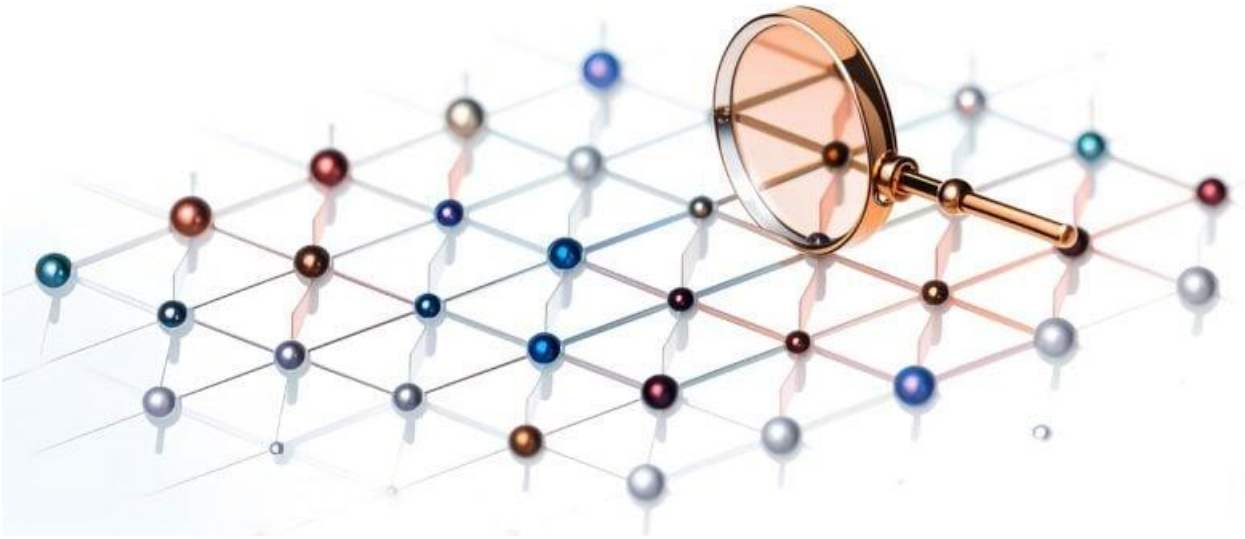


Figure 1. Conceptual picture of 'entanglement microscopy'. Credit: HKU

This study, led by Professor Zi Yang Meng and co-authored by his PhD students Ting-Tung Wang and Menghan Song of HKU Department of Physics, in collaboration with Professor William Witczak-Krempa and PhD student Liuke Lyu from the University of Montreal, unveils the hidden structures of quantum entanglement in many-body systems, offering a fresh perspective on the behavior of quantum matter. Their findings were recently published in the prestigious journal *Nature Communications.*

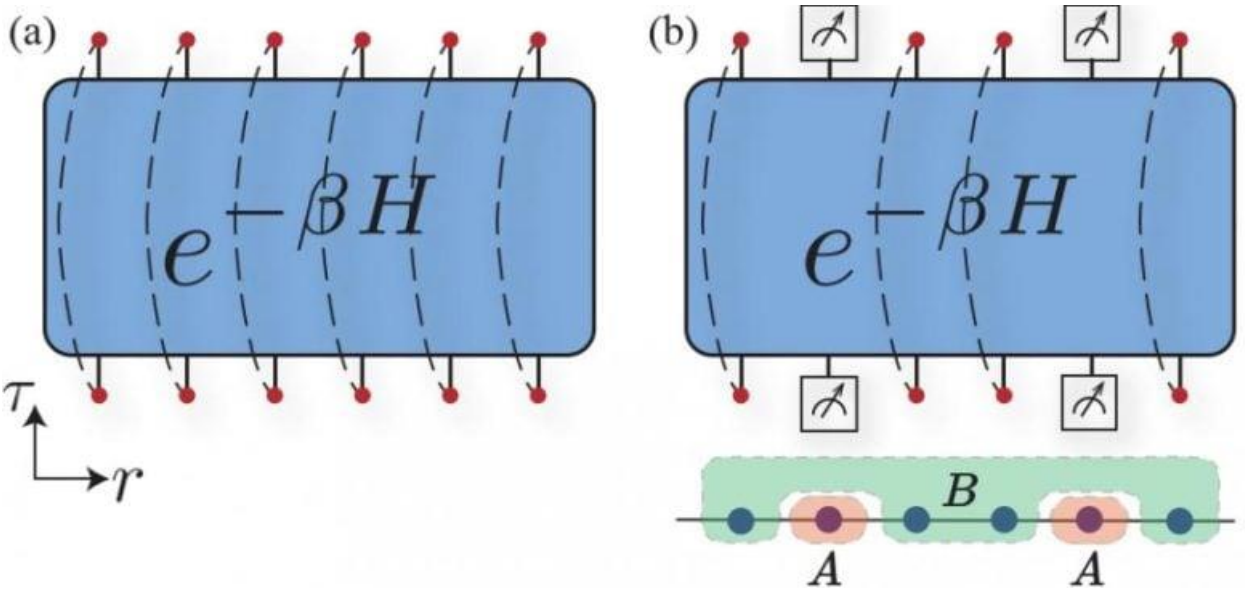


Figure 2. Sampling the reduced density matrix (RDM) in path-integral quantum Monte

Carlo (QMC). Panel (a) shows the partition function in the space time manifold appearing in usual QMC simulations. Panel (b) shows how the RDM is sampled in such QMC simulations, where one imposes open boundary conditions in time for the skeletal sites in subregion A. The lower panel in (b) demonstrates the spatial partition of A and B in such a setting. Credit: HKU

A Breakthrough in Mapping Quantum Entanglement

Quantum entanglement describes a deep connection between particles, where the state of one particle is instantly linked to another, even across vast distances. Imagine rolling two dice in different locations—quantum entanglement is like finding that the outcome of one die always determines the outcome of the other, no matter how far apart they are. This phenomenon, famously called 'spooky action at a distance' by Albert Einstein, is not just a theoretical curiosity but underpins technologies like quantum computing, cryptography, and the study of exotic materials and black holes. However, it is intrinsically difficult to obtain the entanglement information in quantum many-body systems both analytically and numerically due to the exponentially large degree of freedoms.

Researchers have addressed this challenge by developing 'entanglement microscopy', an innovative protocol based on large-scale quantum Monte Carlo simulation that can successfully extract the quantum entanglement information in small regions of quantum systems. By focusing on these microscopic areas, this method reveals how particles interact and organize themselves in intricate ways, especially near critical points in quantum phase transitions—special states where quantum systems undergo profound changes in behavior.

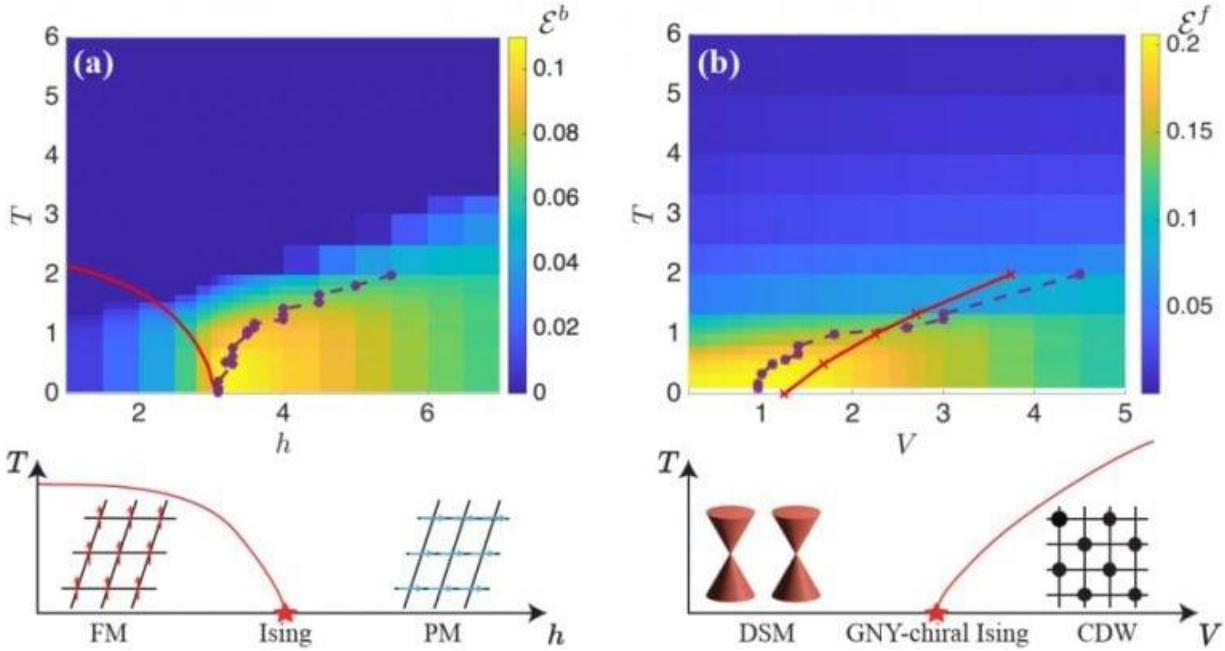


Figure 3. Logarithmic negativity as a measurement of quantum entanglement for adjacent

sites in (a) 2d transverse-field Ising model and (b) 2d fermion t-V model. The bottom panel illustrates the schematic phase diagrams. Credit: HKU
Their exploration focused on two prominent models at two-dimension: the transverse field Ising model and fermionic t-V model that realizes the Gross-Neveu-Yukawa transition of Dirac fermions, each revealing fascinating insights into the nature of quantum entanglement. They discovered that at the Ising quantum critical point, entanglement is short-range, meaning particles are connected only over small distances. This connection can abruptly vanish due to changes in distance or temperature—a phenomenon known as 'sudden death'. In contrast, their investigation of the fermionic transition revealed a more gradual decline in entanglement even at larger separations, indicating that particles can maintain connections despite being far apart.

Intriguingly, the team discovered that in two-dimensional Ising transitions, three-party entanglement was absent, yet present in one-dimensional systems. This implies that system dimensionality significantly affects entanglement behavior. To simplify, low-dimensional systems are akin to a small group of friends where deep connections (complex multi-particle entanglement) are more probable. Conversely, high-dimensional systems, comparable to larger, more complex social networks, often suppress such connections. These findings provide important understanding of how entanglement structure alters with increasing system complexity.

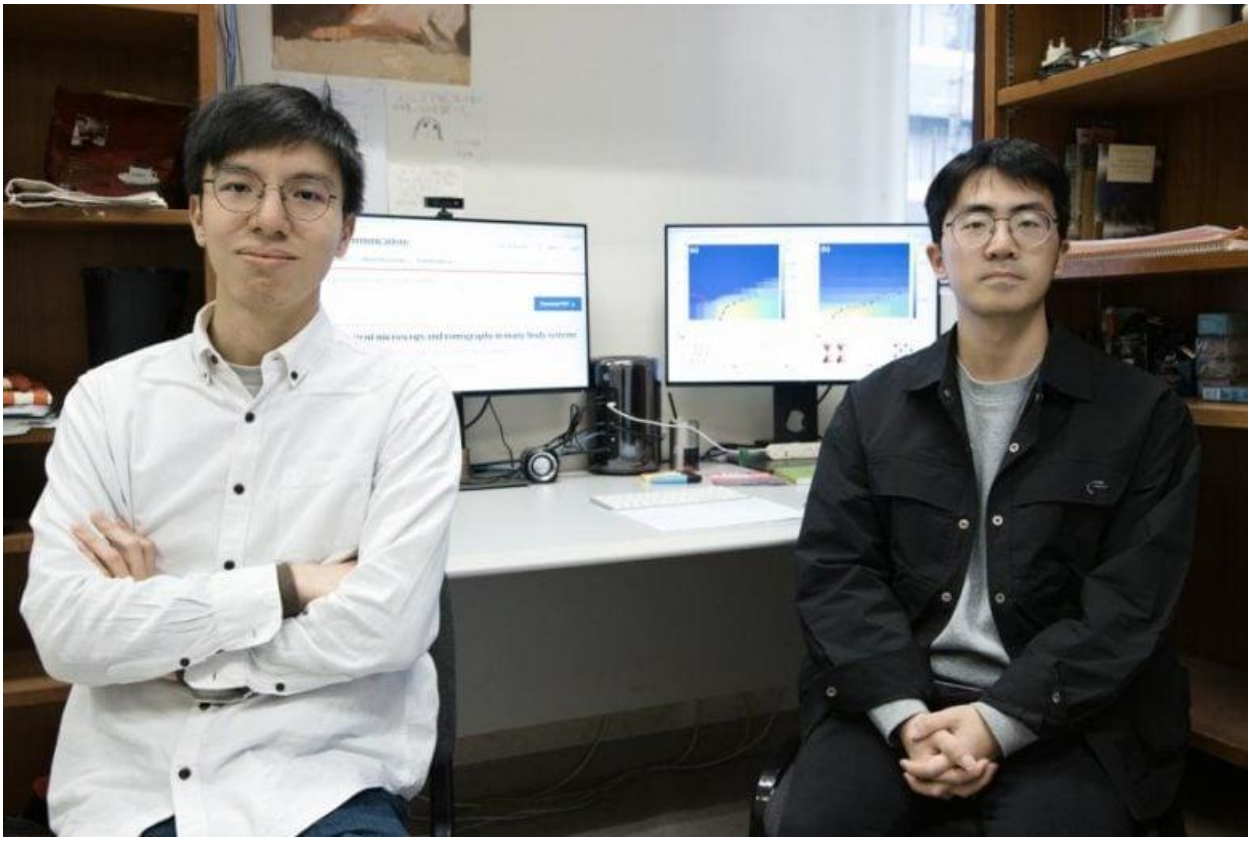


Figure 4. Ting-Tung Wang (left) and Menghan Song, PhD students from the HKU Department of Physics, are co-authors of the journal paper. Credit: HKU

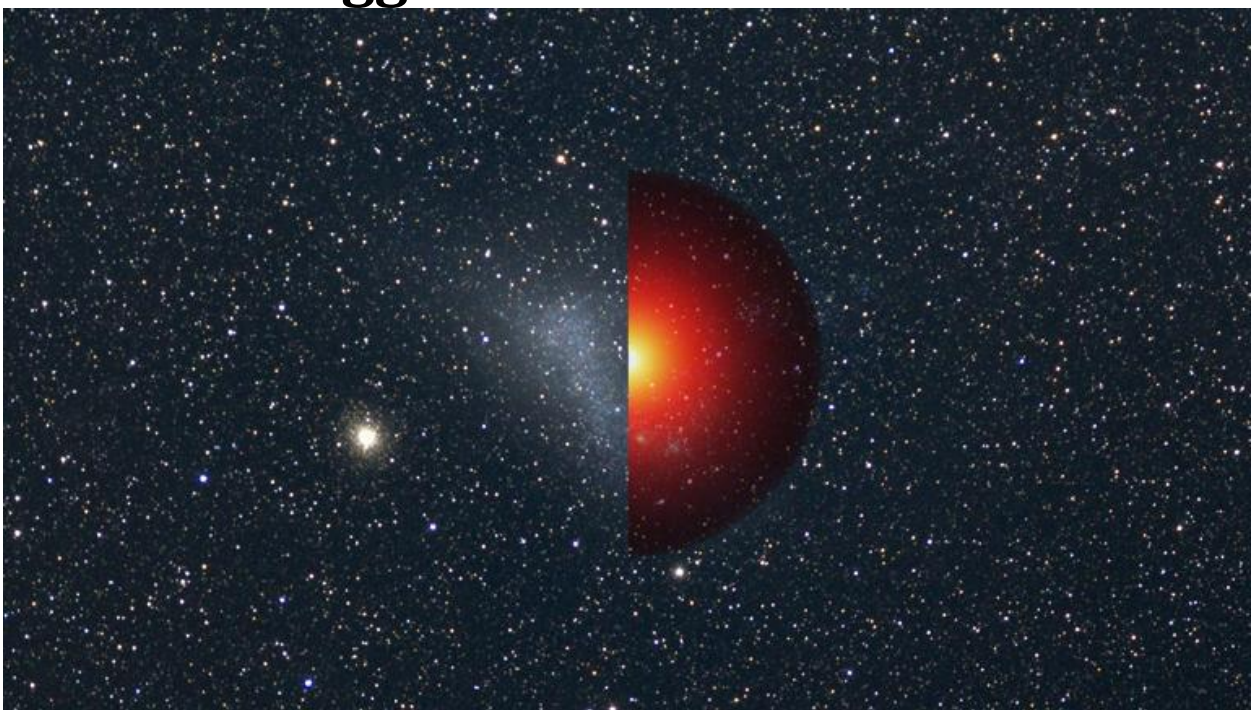
Applications and Impact

This breakthrough has significant implications for advancing quantum technologies. By providing a clearer understanding of entanglement, it could help optimize quantum computing hardware and algorithms, enabling faster problem-solving in fields like cryptography and artificial intelligence. It also opens the door to designing next-generation quantum materials with applications in energy, electronics, and superconductivity. Furthermore, this tool could deepen our understanding of fundamental physics and improve quantum simulations in chemistry and biology.

The findings are detailed in the paper *'Entanglement microscopy and tomography in many-body systems'*, published in the journal *Nature Communications*.

Reference: "Entanglement microscopy and tomography in many-body systems" by Ting-Tung Wang, Menghan Song, Liuke Lyu, William Witczak-Krempa and Zi Yang Meng, 2 January 2025, *Nature Communications*.
DOI: 10.1038/s41467-024-55354-z

'Heavy' dark matter would rip our understanding of the universe apart, new research suggests



Invisible dark matter makes up most of the mass in the universe, far outweighing the amount of matter we can see.© Dark matter, R. Caputo et al. 2016; background, Axel Mellinger, Central Michigan University

Dark matter can't be too heavy or it might break our best model of the universe, new research suggests.

We have an abundance of evidence that something fishy is happening in the universe. Stars orbit within galaxies far too quickly. Galaxies move around inside clusters much too fast. Structures grow and evolve too rapidly. If we count only the matter we can see, there simply isn't enough gravity to explain all of these behaviors.

The vast majority of cosmologists believe all of these phenomena can be explained through the presence of dark matter, a hypothetical form of matter that is massive, electrically neutral and hardly, if ever, interacts with normal matter. This dark matter makes up most of the mass in the universe, far outweighing the amount of luminous matter.

The identity of dark matter remains a mystery, as experiments designed to detect a stray, rare collision have failed to turn up anything. But these experiments have focused on targeting a specific mass range: roughly 10 to 1,000 giga-electron volts (GeV). (A GeV is equivalent to 1 billion electron volts.) That's in the range of the heaviest known particles, like the W boson and the top quark. For decades, theorists favored this mass range because several simple extensions of the Standard Model of particle physics predicted the existence of such particles.

Because we haven't found anything yet, though, we've started to wonder if dark matter might be lighter or heavier than we thought. But heavier dark matter runs into some serious issues, according to a new paper published to the preprint database arXiv.

The problem is that dark matter does sometimes interact with normal matter, if only rarely. But in the early universe, when the cosmos was much hotter and denser, these interactions were much more frequent. Eventually, as the universe expanded and cooled, these interactions slowed and then stopped, leading the dark matter to "freeze out" and remain silent in the background.

While there are many, many models of potential dark matter candidates, many interact with regular particles through exchanges involving the Higgs boson — a fundamental particle that interacts with almost all other particles and, through those interactions, imbues those particles with mass.

We know the mass of the Higgs boson: around 125 GeV. The researchers found that this mass puts a fundamental upper limit on the possible mass of most dark matter candidates.

The problem is that all interactions in physics are two-way streets. The Higgs talks to both dark matter and regular matter and, in many models, mediates interactions between them. But both kinds of matter also talk back to the Higgs. These interactions appear as slight modifications to the Higgs boson's mass.

For Standard Model particles, we can calculate these corrections and feedback interactions, which is how theorists predicted the mass of the Higgs boson well before it was detected.

The researchers found that if the dark matter particle had a mass greater than a few thousand GeV, its contribution to the Higgs mass would be incredibly

important, driving it away from its observed value. And because the Higgs is so central to determining many other fundamental physics, it would essentially shut down particle interactions altogether.

There are possibilities to get around this restriction, however. Dark matter might not interact with regular particles at all, or the interaction might happen through some exotic mechanism that doesn't involve the Higgs. But those models are few and far between and require a lot of fine-tuning and extra steps.

Or it could be that dark matter is lighter than we thought. If we don't think heavy dark matter is a viable candidate, then as we continue to learn about this mysterious component of the universe, we can instead focus our efforts in the other direction. There has already been a surge of interest in axions, ultralight particles that are predicted in some particle physics models and might be a viable dark matter candidate.

On the experimental side, if this result is confirmed and holds to be a widespread restriction on dark matter particle mass, we can refine and redesign our experiments to search for low-mass, instead of high-mass, particles.

Cosmic voids may explain the universe's acceleration without dark energy

Research suggests dark energy may make up a vast amount of the universe, yet know one has determined what it is. Now, research suggests dark energy may be an illusion that arises from cosmic voids.© Iffany via Pixabay

Dark energy, the mysterious force that's driving the accelerating expansion of the universe, may not actually exist, scientists say. Their research has brought into question one of the cornerstones of modern cosmology.

In a new study, published Dec. 19, 2024 in the journal Monthly Notices of the Royal Astronomical Society, the researchers analyzed data from the Pantheon+ survey — the most comprehensive dataset of type Ia supernovae, whose consistent brightness allows astronomers to measure distances across the universe with incredible precision. Their analysis suggests that what we perceive as acceleration might be an illusion caused by the large-scale structure of the cosmos.

Studying the universe with type Ia supernovae

Type Ia supernovae, the explosive deaths of white dwarf stars, have long served as one of cosmology's most powerful tools. These stellar events occur when a white dwarf accretes enough material from a companion star to trigger a thermonuclear explosion. Because type 1a supernovae produce consistent peak

brightness, measuring their brightness when observed from Earth can reveal how far away they are.

"Type Ia supernovae are extremely valuable in astronomy since they act as standardizable candles with which we can measure vast distances in the Universe," study co-author Zachary Lane, a researcher at the University of Canterbury in New Zealand, told Live Science in an email.

By combining this distance information with the redshift of the supernovae — the stretching of light to redder wavelengths due to the universe's expansion — scientists have mapped the universe's growth over time. Decades ago, researchers used this method to show that the universe's expansion was accelerating, a discovery that led to the hypothesis of dark energy — a mysterious, unseen force thought to permeate space and drive this acceleration.

Pantheon+ dataset

The Pantheon+ dataset is the most extensive and precise collection of type Ia supernovae ever assembled. Spanning decades of observations from both ground-based and space telescopes, it contains data on 1,500 supernovae across space-time.

"At the time of this study, the Pantheon+ Type Ia Supernovae spectroscopic dataset was the largest and most pristine collection of purely Type Ia supernovae," Lane said.

The dataset's precision and size make it a goldmine for testing cosmological models. Its detailed records of brightness and redshift offer unparalleled insights into how the universe has evolved, providing a critical testing ground for alternative theories to the standard cosmological model.

Challenging dark energy

While the idea of dark energy explains much of the observed acceleration in the universe, it has always carried an air of mystery. Dark energy has never been directly detected, nor has its origin been explained theoretically, prompting some scientists to explore other explanations.

The new study takes aim at a key assumption of the standard model: that the universe is homogeneous and isotropic on large scales, meaning it looks the same in every direction and from every vantage point.

This assumption underpins the need for dark energy to explain the universe's expansion. However, Lane and his colleagues tested an alternative idea called the timescape model, which suggests that the apparent acceleration could be a byproduct of cosmic structures like voids — vast, near-empty regions of space between galaxy clusters.

"The standard model of cosmology is built on the assumption that the Universe is uniform and featureless on large scales and that cosmic structures do not significantly impact the evolution of the Universe," Lane said. "Timescape abandons these assumptions and finds that the apparent acceleration of the Universe is the result of feedback between cosmic structures."

Because of their sparse matter and gravity, voids expand faster than denser parts of the universe, such as galaxy clusters. According to the timescape model, the dominance of these voids in the cosmic landscape could explain the observed acceleration without the need for dark energy.

Evidence in favor of timescape

The team analyzed the Pantheon+ dataset and found that their results align remarkably well with the timescape model — and in some cases even outperformed the standard cosmological model.

"When considering every supernova, including those very close to us in the Milky Way, which could be influenced by local structures, we find very strong preference in favor of the Timescape model," Lane said. When supernovae in the nearby universe were excluded to account for local differences, the evidence remained supportive, echoing findings from the Dark Energy Survey (DES).

These results pose a direct challenge to the necessity of dark energy. "Consistently finding moderate or stronger evidence for a cosmological model without dark energy using one of the most historically significant observational methods is an exciting prospect to be explored for the future of cosmology," Lane said.

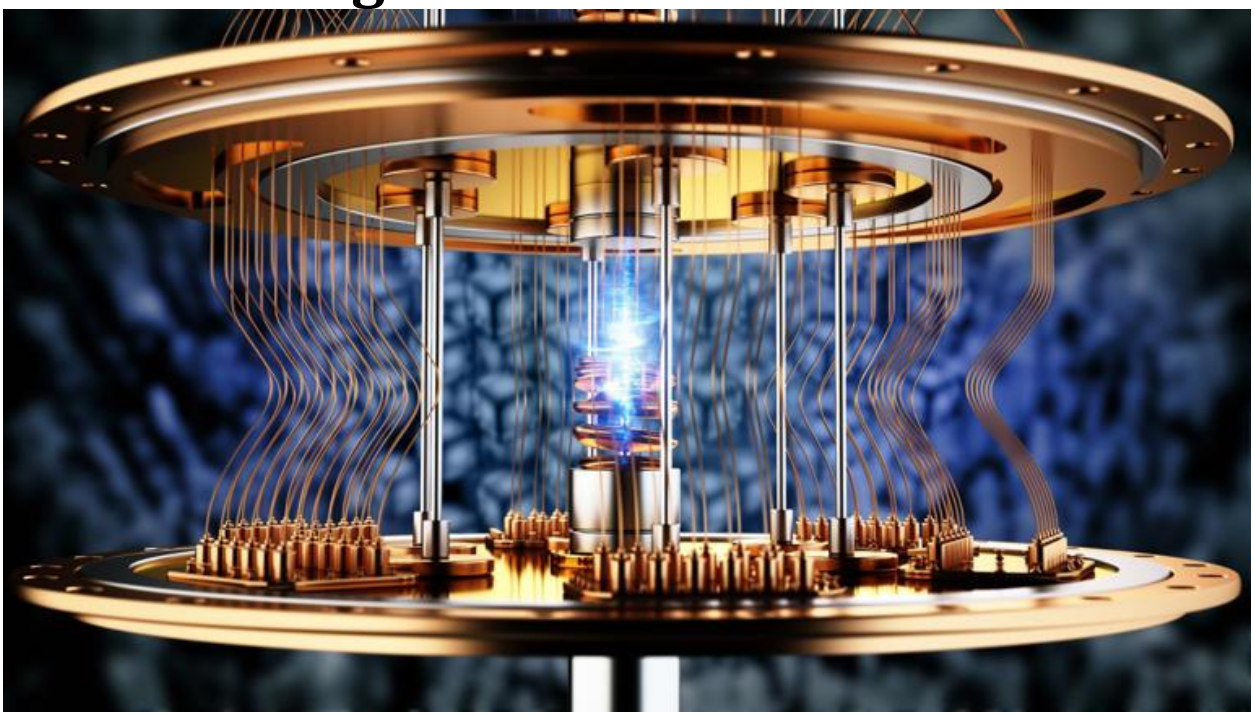
The road ahead

While the findings are compelling, Lane stressed that further research is needed to solidify the case for timescape. "While other factors need to be considered for this to be more established within the cosmology community, it proves a promising initial test," he said.

In the future, the team plans to combine the Pantheon+ dataset with data from the Dark Energy Survey and baryon acoustic oscillations — patterns in the distribution of galaxies that can be used as another cosmic ruler. The astronomers are also conducting simulations of how voids expand under the framework of general relativity and exploring how these effects apply to galaxy formation and evolution.

"Our research group is exploring several extensions to our current work, aiming to challenge foundational aspects of cosmology," Lane said. "A strong competing framework will still enhance the future of cosmology and our current understanding of the challenges facing the field."

Scientists demonstrate first-ever quantum error solving with dual codes



Just like any machine, quantum computers are prone to make errors. These errors can cause the qubits to lose their quantum states, leading to inaccurate computations. To address this problem, quantum computers rely on special protocols called correction codes.

However, there is one big problem with this approach. No single correction code can ensure protection against all errors. This is why when more than one error pops up in a quantum system, the chances of its failure increase dramatically.

A team of European researchers has come up with an interesting solution to this problem.

In their latest study, they reveal a method that allows a quantum computer to switch between two different correction codes. This method will ensure the system performs all computing tasks in an error-free manner.

“No single error-correcting code intrinsically supports a fault-tolerant implementation of all the gates needed for universal quantum computing. One approach for addressing this problem is to switch between two suitable error-correcting codes that in combination provide a fault-tolerant universal gate set,” the study authors note.

Solving errors in the quantum world is tricky

When it comes to classical computers, errors are often fixed using methods like redundancy (storing multiple copies of data) or error-detection techniques, which com However, quantum computers face a unique challenge. You cannot copy an unknown quantum state due to a fundamental rule of quantum mechanics called the no-cloning theorem. This means quantum states cannot be saved or duplicated during calculations, making it impossible to detect errors by comparing copies of the same state.

To overcome this limitation, scientists developed a different approach. Instead of copying quantum states directly, they spread the quantum information across multiple entangled qubits. This allows errors to be detected and corrected without violating quantum rules.

The specific methods for distributing and protecting quantum information are described in protocols known as quantum error correction codes. These codes enable quantum computers to operate reliably by ensuring that even if some qubits are affected by errors, the overall quantum information remains intact.

pare copies of data to identify and correct mistakes.

However, different quantum error correction codes also come with different difficulties. For instance, each code has a limit on how much noise or error it can handle. If the errors in the system exceed this threshold, the correction code won't work.

Nevertheless, a quantum system can encounter different types of errors, such as bit-flips, phase-flips, or some combinations of these. This is why no single correction code can implement all the gate operations and protect against all the errors.

A dual-code approach

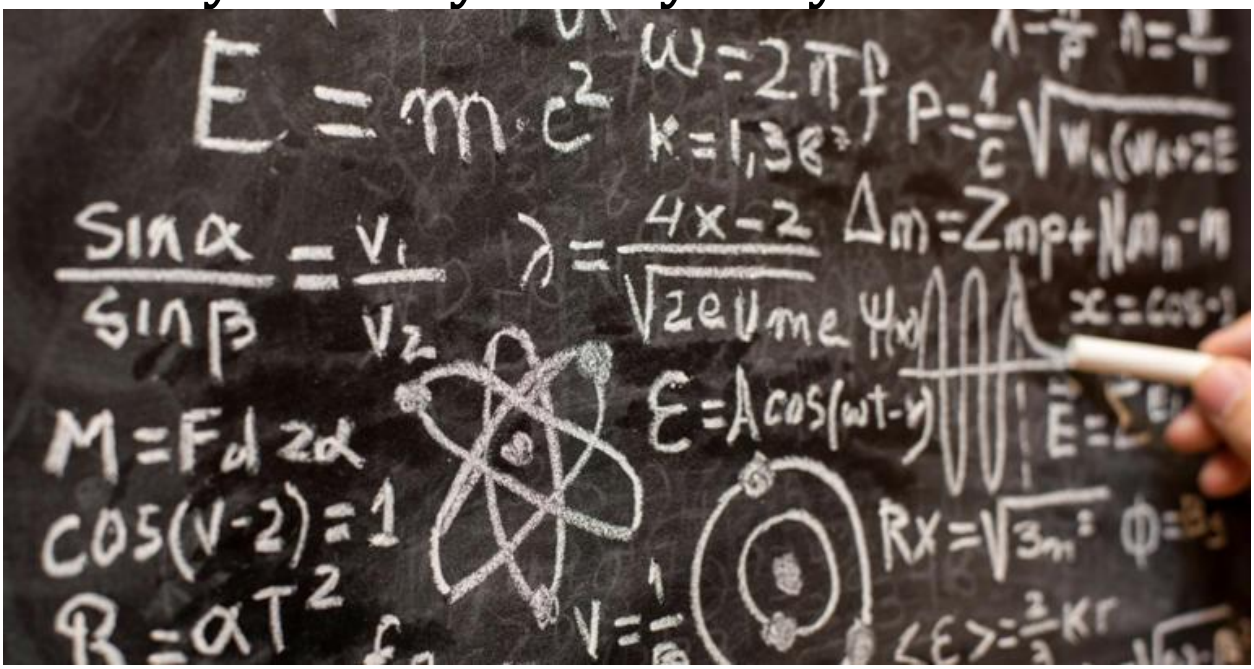
The study authors constructed a unique quantum circuit using a full universal gate set on an ion-trap quantum computer. In this setup, they introduced fault-tolerant code-switching between two different codes and prepared 12 distinct logical states that cannot be supported by a single correction code.

"We switch between the 7-qubit color code, which features fault-tolerant CNOT and H quantum gates, and the 10-qubit code, which allows for a fault-tolerant T gate implementation. Together, these codes form a complementary universal gate set," the study authors said.

This is the first time scientists successfully demonstrated error solving in a quantum system using a combination of two correction codes. This breakthrough could contribute to the development of error-free quantum computing applications.

The study is published in the journal *Nature Physics*.

Century-Old Physics Mystery Solved



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For a hundred years, physicists have grappled with a seemingly simple question: How can the transition of substances into different states be easily predicted?

Understanding the three states of matter—solid, liquid, and gas—has long been guided by diagrams mapping temperature and pressure to show where substances change form. However, the process of transitioning from solid to liquid has remained somewhat elusive.

Now, a breakthrough has been made by Professor Kostya Trachenko of the School of Physical and Chemical Sciences at Queen Mary University of London. Trachenko has developed a simpler method to calculate and predict the melting points of substances, a discovery hailed by several media outlets as both a breakthrough and revolutionary.

The findings have been published in the scientific journal Physical Review E.

Filling in the Blanks

Scientists have relied on phase diagrams for years to determine the states of various substances under specific conditions. These diagrams, while effective in distinguishing between a substance's three forms, have always lacked detailed

descriptions at the transition point between solid and liquid states, according to the media outlet Phys.org.

Trachenko's work may have finally addressed this issue.

By incorporating the latest advances in the theory of liquid matter, Trachenko has shown that a simple equation based on a parabola can accurately describe melting points. This not only provides a practical tool for predicting melting points but also applies to a wide range of substances.

A Universal Equation

The study suggests that this approach can be universally applied across different systems. Phys.org notes its universality stems from its foundation on fundamental physical constants.

Trachenko expressed his excitement about the simplicity and universality of the equation, saying, "It is exciting because it suggests that the melting point, despite the complexity of it, exhibits a fundamental unity across different systems from noble gases to metals."

Understanding Melting Points

A substance's melting point is the temperature at which it transitions from solid to liquid. This transition requires temperatures high enough to break the intermolecular bonds holding the substance together.

Consequently, a substance's melting point depends on the molecular structure of the material—for example, water melts at 0 degrees Celsius, while gold melts at just over 1000 degrees Celsius.