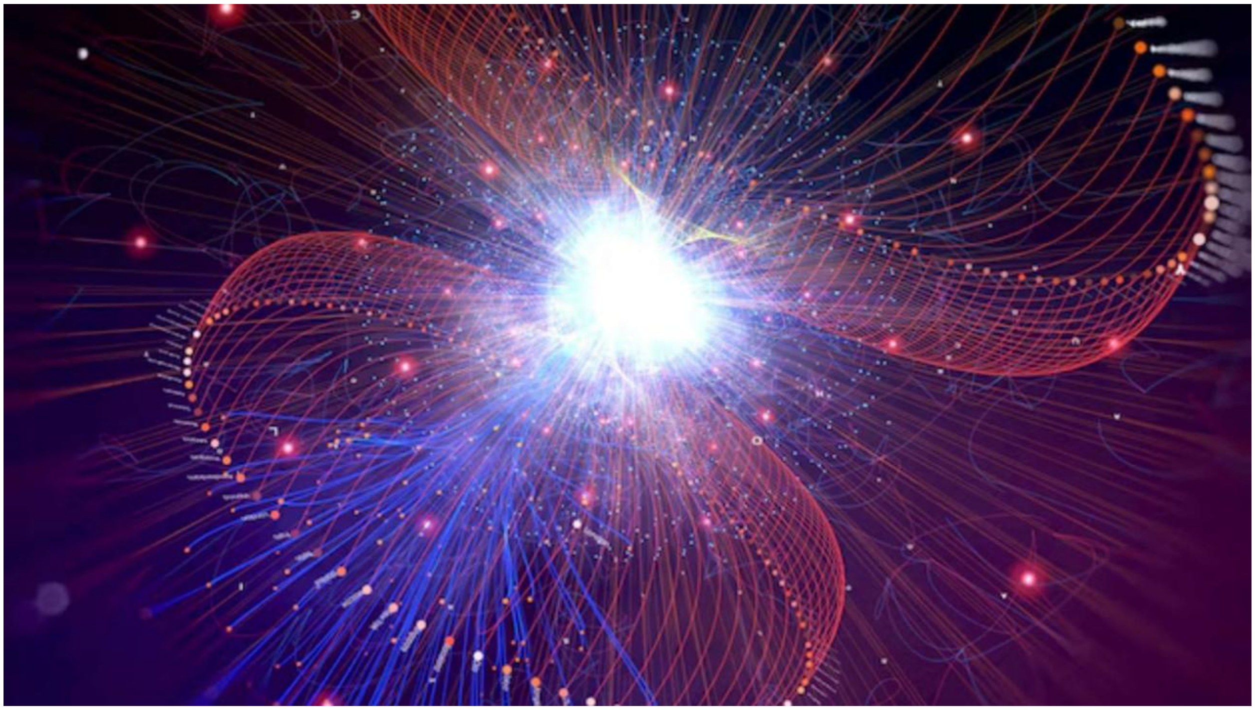
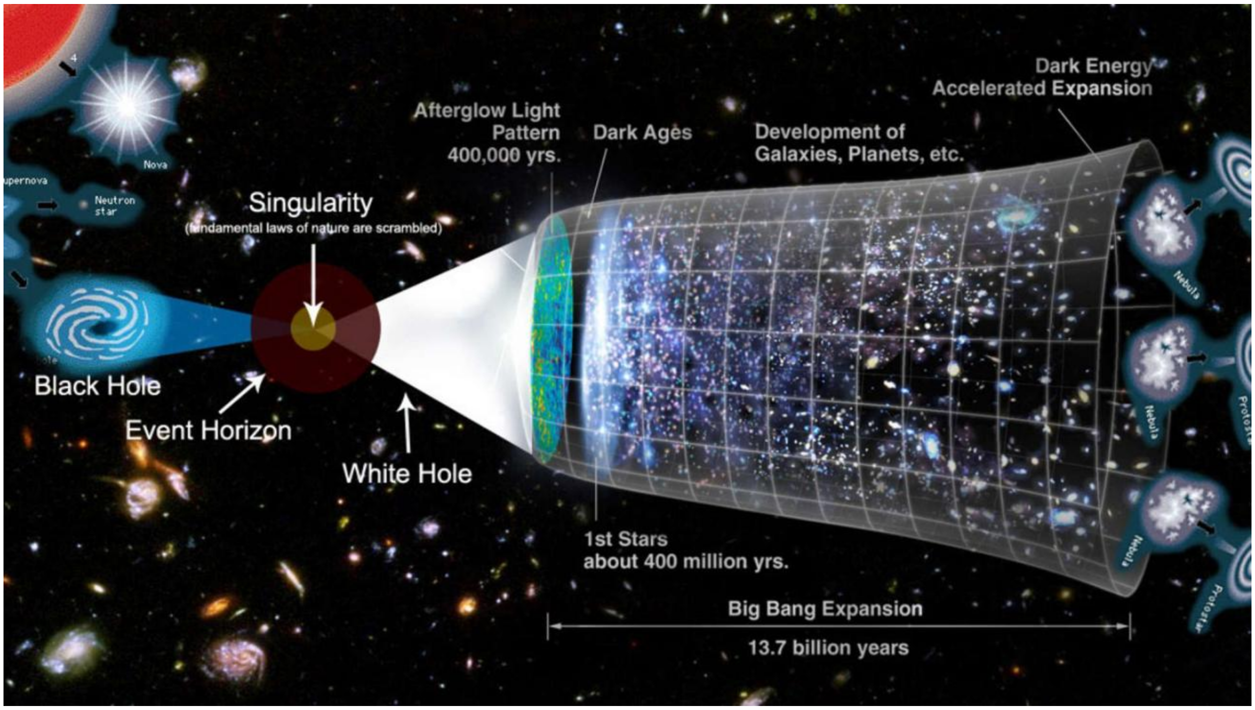
Quantum experiments simulate effects akin to parallel universes



We’re diving headfirst into the captivating realm of quantum physics, focusing on a series of intriguing experiments that seek to replicate phenomena akin to the existence of parallel universes. The journey will navigate through the multiverse concept, the role quantum mechanics play, and the pioneering experiments being carried out in this field.

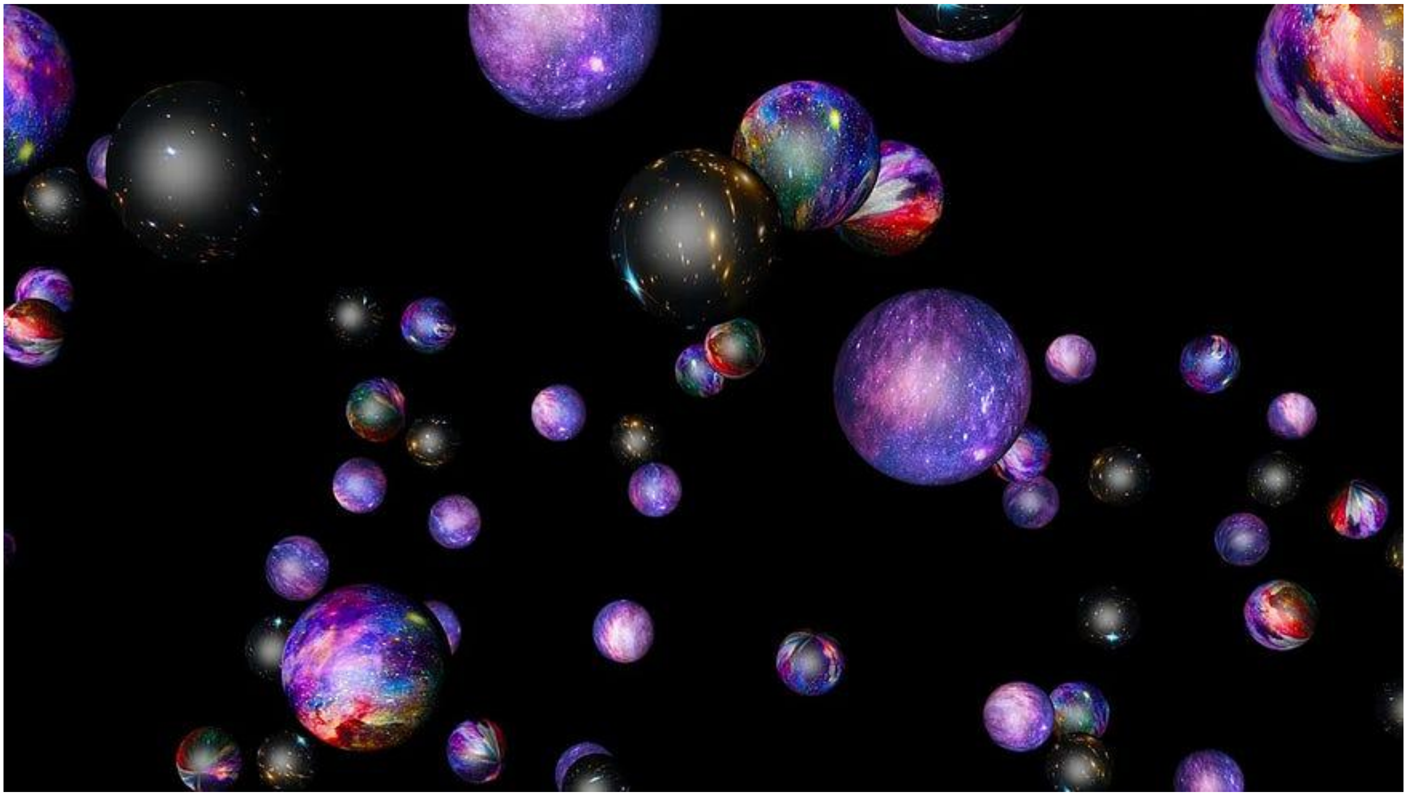
Understanding the Multiverse Theory



The multiverse theory, as its name suggests, proposes the existence of multiple universes, each with its own set of physical laws. This concept is not new. In fact, it has been a topic of discussion among philosophers and scientists for centuries. The theory gained momentum in the 20th century with the advent of quantum mechanics and is now a major talking point in theoretical physics.

Some of the key proponents of the multiverse concept include Hugh Everett III, who proposed the Many-Worlds Interpretation, and Max Tegmark, who classified these universes into four levels. Various interpretations of the multiverse theory exist, ranging from the notion of infinite space-time domains to the existence of universes with different physical laws. You can delve deeper into these interpretations in this comprehensive guide.

It Starts With A Bang!



We can imagine a very large number of possible outcomes that could have resulted from the conditions our Universe was born with. The fact that all 10^{90} *particles contained within our Universe unfolded with the interactions they experienced and the outcomes that they arrived at over the past 13.8 billion years led to all the intricacies of our experiences, including our very existence. It is possible, if there were enough chances, that this could occur many times, leading to a scenario that we think of as "infinite parallel Universes" that contain all possible outcomes, including the roads our Universe didn't travel.*

Parallel universes are among the most profound notions in all of quantum physics. It's a compelling and fascinating idea, but is it true?

The ultimate goal of science, if we were to boil it down to the essentials, is to accurately describe and model reality in the most predictively powerful way possible. When we talk about the question of "what is real," however, we're not simply looking at the question of, "can my model make predictions about reality that agree with measurement, observation and experiment?" Instead, we're asking a more profound series of questions, looking at aspects like:

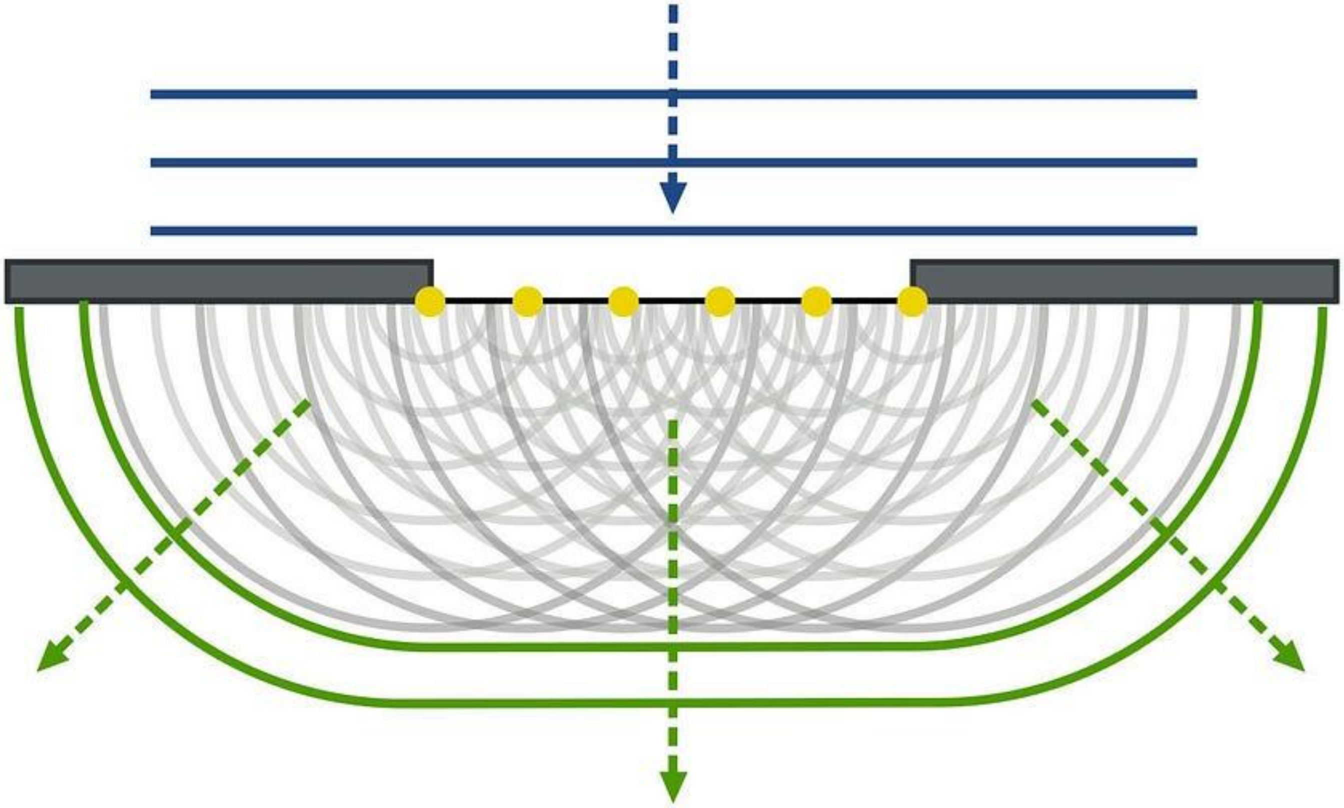
- Is my model of reality self-consistent, or does it have logical flaws?
- Does my model of reality maximize our predictive power about what we're going to measure, or are there limitations to it that are surpassed by alternative models?
- Is my model of reality unique as far as its scope and explanatory power goes, or are there other models just as good?
- And are all of the predictions of my model able to be tested and validated experimentally or observationally, or are some of them hidden from our view in some fashion?

Predictive power is an important aspect when it comes to understanding our reality, but many of our best current ideas started out as theories that were very disconnected from experiments and observations, but were later tested (and sometimes validated) directly. So where do we stand, today, on the big ideas of parallel universes and the multiverse? That's the question of Amirali M., who writes in to ask:

"I'm really interested in big theories like parallel universes and I've literally been doing so much research on it but I just cannot seem to

reach a conclusion on whether or not it's true. [What about] the multiverse? Could you please help me on this and tell me… whether or not if parallel universes are real?"

This is a big question that isn't unique to you, Amirali, but rather is a question that pretty much every physicist working on the foundations of physics would like to know the answer to. Here's where we are today.



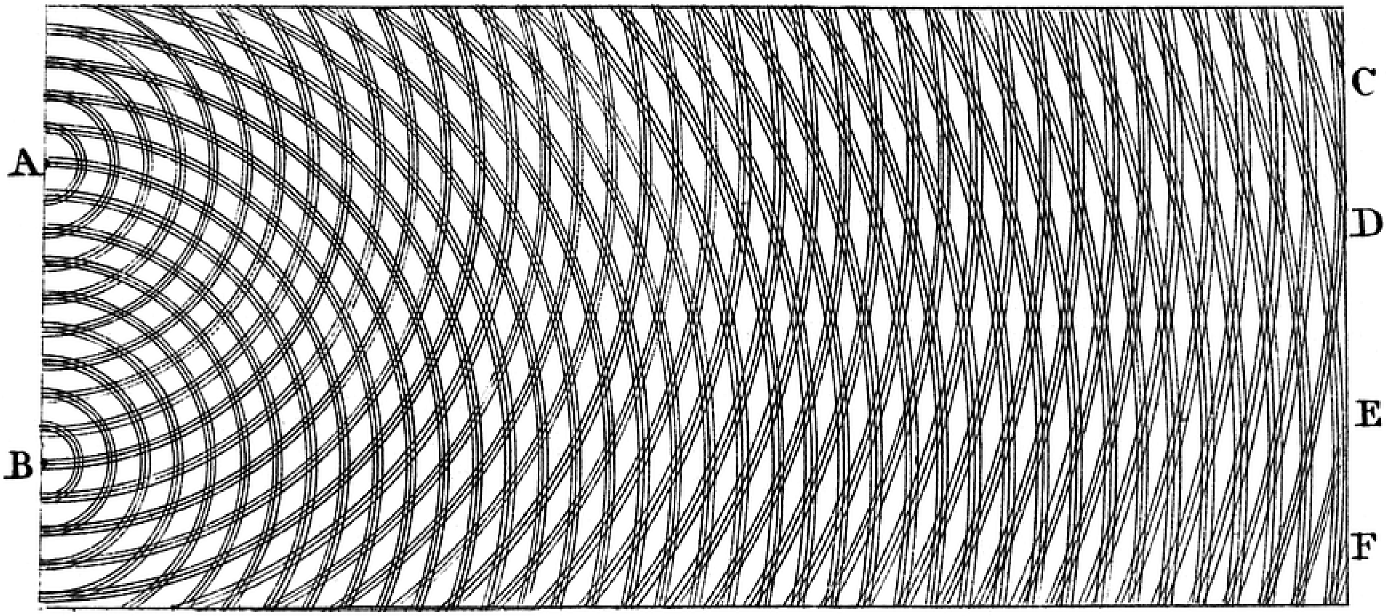
What appears to be a simple plane wave, such as light or water passing through a partly obscured barrier, was conceived of (brilliantly) by Christiaan Huygens as a series of waves that propagate spherically outward, all superimposed atop one another. This idea of wave mechanics would apply not only to scalar waves such as water waves, bu.t to light and particles as well.

The notion of parallel universes goes all the way back to how we think about reality at a fundamental level in the first place, with a specific view towards the results of quantum physics experiments. Attempting to make “sense” of our counterintuitive quantum reality — including concepts like uncertainty, indeterminism, wave/particle duality and predicting probabilistic (rather than certain) outcomes — is something that we’ve been struggling to do ever since we first began uncovering the bizarre, inherently quantum nature of our Universe. And make no mistake about it: the rules that quantum mechanics plays by are not at all similar to the rules we’re used to here in our everyday, macroscopic experience.

Perhaps the most famous experiment in all of quantum physics, and the one that best showcases the bizarre properties of our quantum reality, is the double slit experiment. Very simply, what you need is:

- some sort of physical entity, like a wave or a particle, to propagate forward, in one direction, through space,
- a barrier in that space that prevents the forward propagation of that entity,
- with two narrow, closely spaced slits in that barrier, enabling the entity to pass through the barrier in those two locations only,
- and then a screen on the opposite side of the barrier, displaying the pattern of whatever portion of that (wave-like or particle-like) entity arrived on that screen.

That’s the setup of the double slit experiment. Although it was initially performed by Christiaan Huygens back in the 1600s with water waves, it came to prominence around the turn of the 19th century when it was performed with light by Thomas Young.



This diagram, dating back to Thomas Young’s work in the early 1800s, is one of the oldest pictures that demonstrate both constructive and destructive interference as arising from wave sources originating at two points: A and B. This is a physically identical setup to a double slit experiment, even though it applies just as well to water waves propagated through a tank. The locations marked C, D, E, and F correspond to 100% destructive interference.

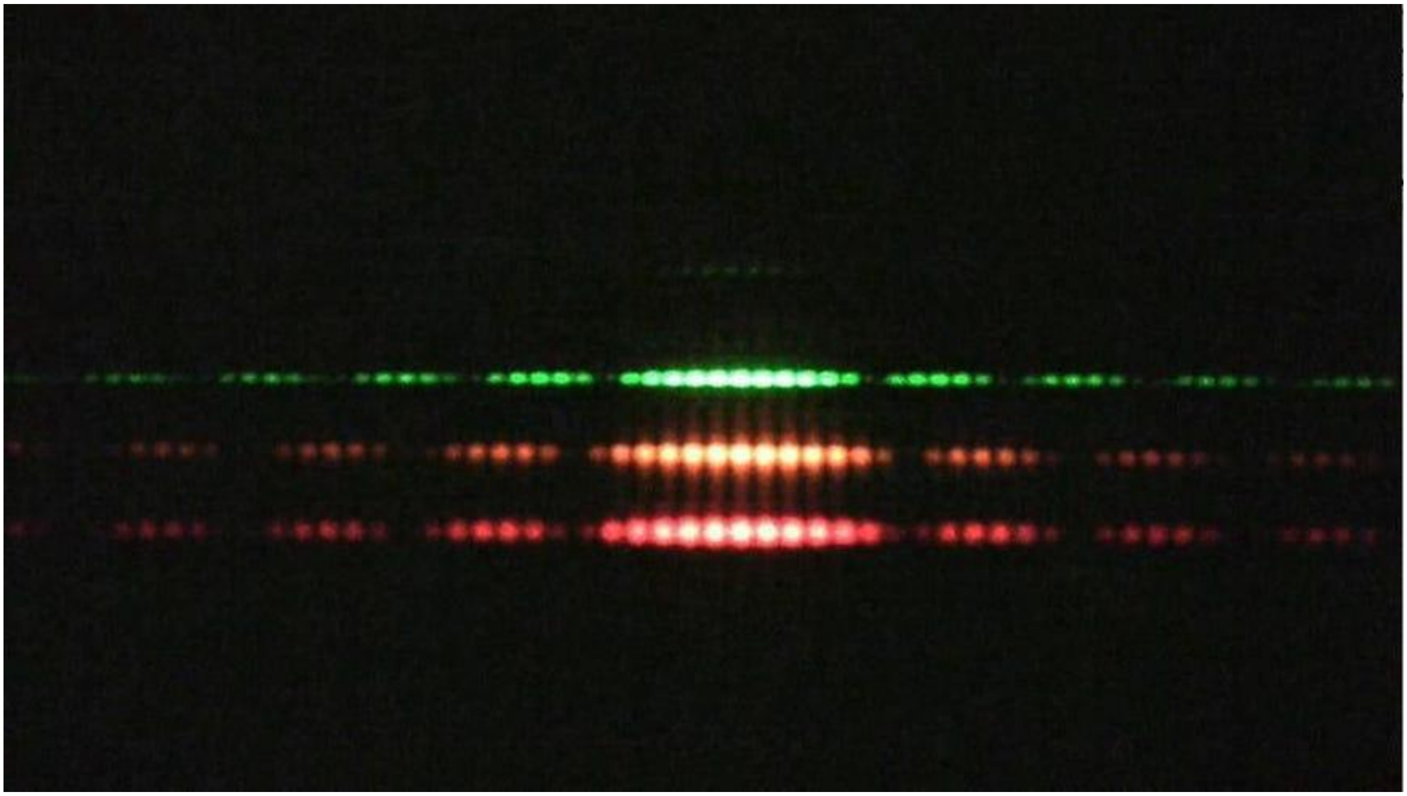
If light had behaved like particles — or corpuscles, as Newton had theorized — then the screen would have been completely dark everywhere, with the exception of two bright “bands” that would appear: corresponding to each of the two slits through which light could have passed. That’s what you’d expect if light behaved in a particle-like fashion: dark area wherever the barrier blocks the light from shining, and illuminated area corresponding to where the light passed through the slits in the barrier.

On the other hand, if the light exhibited wave-like behavior, then what you’d expect would instead display alternating bands of light-and-dark, corresponding to regions where the light interfered constructively (additively) between the two slits, leading to bright bands, and regions where the light interfered destructively (subtractively, or cancelling out) between the two slits, leading to dark bands.

Young’s experiments, conducted in the late 1790s and early 1800s, decisively demonstrated the wave-like behavior of light under these conditions. Just as water waves propagating through two slits in a barrier would:

- create two sources of circularly-outward propagating waves,
- that would interfere both constructively and destructively when they met,
- leading to a pattern of peaks-and-valleys in the water,

light’s wave-like nature ensured that it did the same.



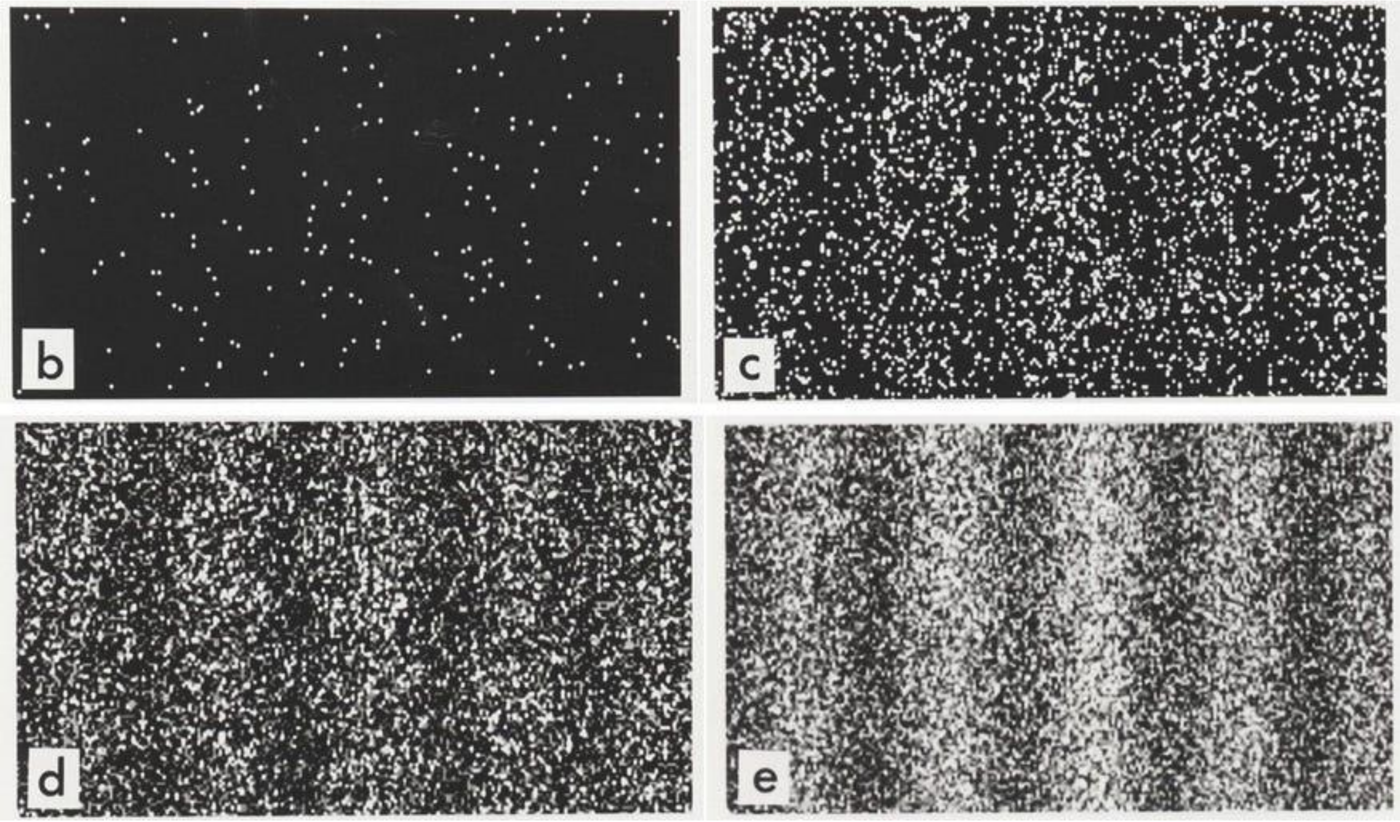
Light of different wavelengths, when passed through a double slit, exhibit the same wave-like properties that other waves do. Changing the wavelength of light, as well as changing the spacing between the slits, will change the specifics of the pattern that emerges.

Further experiments conducted in the 1800s confirmed light's wave-like nature, and Maxwell's electromagnetism brought forth an understanding of light as the propagation of a sourceless (uncharged) electromagnetic wave at the speed of light.

But then things got weird. As in, *really*, eerily weird.

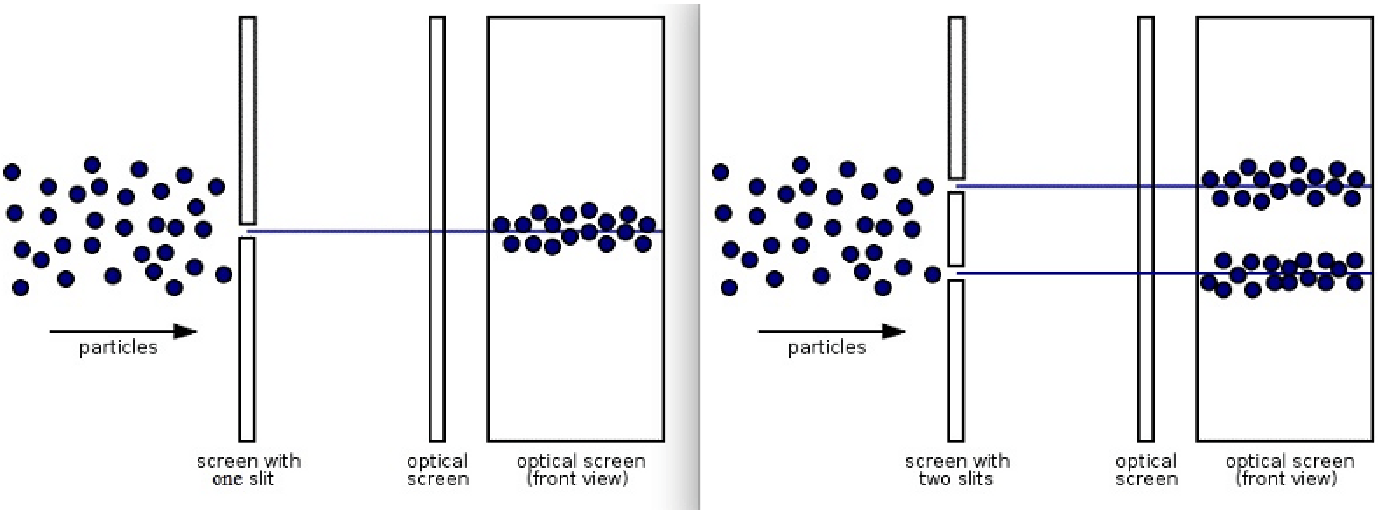
Max Planck demonstrated that the energy emitted in the form of light must be quantized, and therefore couldn't be made exclusively of continuous waves, but rather must be in the form of "energy packets" where each packet possessed a specific, finite energy. Albert Einstein demonstrated, through the photoelectric effect, that light could only ionize electrons if it had sufficiently short wavelength, irrespective of the light's intensity. In other words, it wasn't the total energy of a beam of light, but rather the energy of each individual "packet" in which light was quantized — packets that are today known as photons — that determined the properties and capabilities of that light.

And then, in 1924, Louis de Broglie came along and recognized that things were even weirder than we had previously realized. It wasn't just light that exhibited this strange property of having particle-like behaviors under certain circumstances while exhibiting wave-like behaviors under others, but that everything, including electrons, protons, atomic nuclei, and even whole atoms that exhibited this wave/particle duality.



We performed those experiments, and found that, perhaps shockingly, the interference pattern still remains. By measuring particle-after-particle, a pattern begins to emerge, and it's the interference pattern, not the classical "two piles" that you might have expected. It's as though each individual quantum, like a photon or an electron, is somehow going through both slits at once, and interfering with itself.

Perhaps you'll think, "I know, we'll catch each particle in the act, and measure which slit it goes through as it's passing through it!" And you can do that, setting up a detector (like a gate for a photon or an induction loop for a charged particle like an electron) to measure which slit the quantum you're using is passing through. It works! The first particle passes through slit #1, and shows up on the screen. The second passes through slit #2, the third through slit #2, the fourth and fifth through slit #1, etc. But this time, there is no interference pattern on the screen. Instead, there are just two piles. It's as though the various quanta can tell whether they're being measured or not, and alter their behavior in response.



including the experimental setup, and the positions and motions of every particle in it, then what will the result be?"

The rules of quantum physics, to the best of our understanding, don't give you absolute, 100% certain answers. Instead, they only allow you to predict the probability of obtaining each and every one of the various outcomes. For a question like, "where will this electron that I'm passing through a double slit land," we know how to calculate the spectrum of probabilities, but the only way to determine where the electron actually lands is to perform the experiment and make the key measurement for ourselves.

All physicists agree on this much; this is simply how nature behaves. It may not be intuitive — and many of us may not find it satisfying — but that's the nature of our quantum reality. But then we do something that's only human, and ask, "okay, but what's *really* happening with reality, and how does our notion that an objective, observer-independent reality exists square with these types of observations?" And, as you might expect, it turns out there are a number of equivalent ways to interpret quantum physics. They include:

- the Copenhagen interpretation, which posits that everything propagates like waves but interacts like particles, and that an interaction "collapses" the wavefunction,
- hidden variable theories, like the de Broglie-Bohm interpretation, which posits that there are deterministic

“hidden variables” that we cannot see, access, or measure, but that if we could, we could make 100% accurate predictions about the outcome of any experiment,

- the ensemble interpretation, which states that the quantum state doesn’t represent one individual system, but only an infinite number of identically prepared systems,
- and the many-worlds interpretation, which asserts that the wavefunction is real, there is no wavefunction collapse, and that all outcomes really do happen, but that we only live in one “world” and so only measure one particular outcome with each experiment that we perform.

Much attention has been given to these various interpretations (as well as others), and trying to perform experiments that test their predictions against one another is an active area of research. In fact, quantum entanglement was the subject of 2022’s recent Nobel Prize in Physics, which helped make quantum information systems the modern robust scientific field it is today. But the question that most people — physicists, philosophers, physics students, and laypersons alike — want the answer to is simply, “okay, but which interpretation of quantum mechanics is correct? Which one is right, and how do we know that the others are wrong?”

A variety of quantum interpretations and their differing assignments of a variety of properties. Despite their differences, there are no experiments known that can tell these various interpretations apart from one another, although certain interpretations, like those with local, real, deterministic hidden variables, can be ruled out.

Interpretation	Year published	Author(s)	Deterministic?	Ontic wavefunction?	Unique history?	Hidden variables?	Collapsing wavefunctions?	Observer role?	Local dynamics?	Counterfactually definite?	Extant universal wavefunction?
Ensemble interpretation	1926	Max Born	Agnostic	No	Yes	Agnostic	No	No	No	No	No
Copenhagen interpretation	1927–	Niels Bohr, Werner Heisenberg	No	Some[59]	Yes	No	Some[60]	No[61][62]	Yes[citation needed]	No	No
de Broglie–Bohm theory	1927–1952	Louis de Broglie, David Bohm	Yes	Yes[a]	Yes[b]	Yes	Phenomenological	No	No	Yes	Yes
Quantum logic	1936	Garrett Birkhoff	Agnostic	Agnostic	Yes[c]	No	No	Interpretational[d]	Agnostic	No	No
Time-symmetric theories	1955	Satosi Watanabe	Yes	No	Yes	Yes	No	No	No[63]	No	Yes
Many-worlds interpretation	1957	Hugh Everett	Yes	Yes	No	No	No	No	Yes	Ill-posed	Yes
Consciousness causes collapse	1961–1993	John von Neumann, Eugene Wigner, Henry Stapp	No	Yes	Yes	No	Yes	Causal	No	No	Yes
Many-minds interpretation	1970	H. Dieter Zeh	Yes	Yes	No	No	No	Interpretational[e]	Yes	Ill-posed	Yes
Consistent histories	1984	Robert B. Griffiths	No	No	No	No	No[f]	No	Yes	No	Yes
Transactional interpretation	1986	John G. Cramer	No	Yes	Yes	No	Yes[g]	No	No[h]	Yes	No
Objective-collapse theories	1986–1989	Ghirardi–Rimini–Weber, Penrose interpretation	No	Yes	Yes	No	Yes	No	No	No	No
Relational interpretation	1994	Carlo Rovelli	No[64]	No	Agnostic[i]	No	Yes[j]	Intrinsic[k]	Possibly[l]	No	No
QBism	2010	Christopher Fuchs, Rüdiger Schack	No	No[m]	Agnostic[n]	No	Yes[o]	Intrinsic[p]	Yes	No	No

And to this question, for better or for worse, we have no answer, no consensus, and really no further clues than what I've presented here. Until, and unless, you can concoct an experimental test that can distinguish between these various interpretations, and can measure reality to either be one way or another, all these interpretations remain equally valid. We have just the one "world" that we can perform observations, measurements, and experiments in, and each time we only see one outcome. Meanwhile, when we calculate our predictions for what should happen, we can only arrive at a weighted probability distribution, not determining what the actual answer is going to be.

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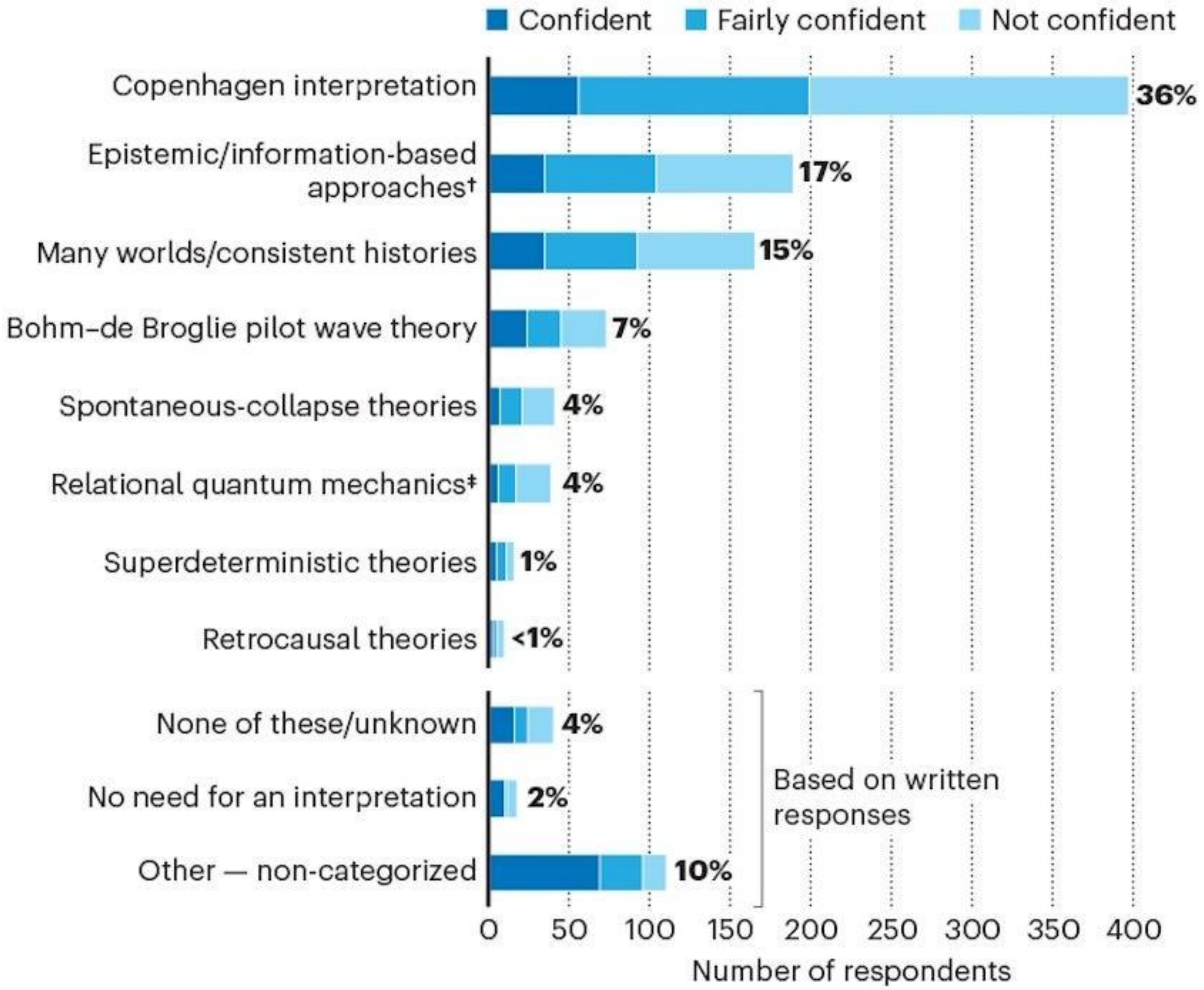
FAVOURED EXPLANATIONS OF QUANTUM THEORY

The Copenhagen interpretation of quantum mechanics was chosen by more than one-third of the 1,101 respondents to *Nature*'s survey*. But many respondents were not confident in their chosen answer.



*Questions: 'Which of the following, in your opinion, provides the best interpretation of quantum phenomena and interactions?', followed by:

How confident are you in your answer above about the best interpretation?, with these options:

Confident: I think this is the correct interpretation.

Fairly confident: I think this is an adequate interpretation.

Not confident: I think this is just the best interpretation I am aware of or one that is useful as a tool in certain situations.

†Includes six respondents (<1%) who selected 'Other' and wrote in 'QBism', which is an epistemic theory.

‡Also an epistemic approach.

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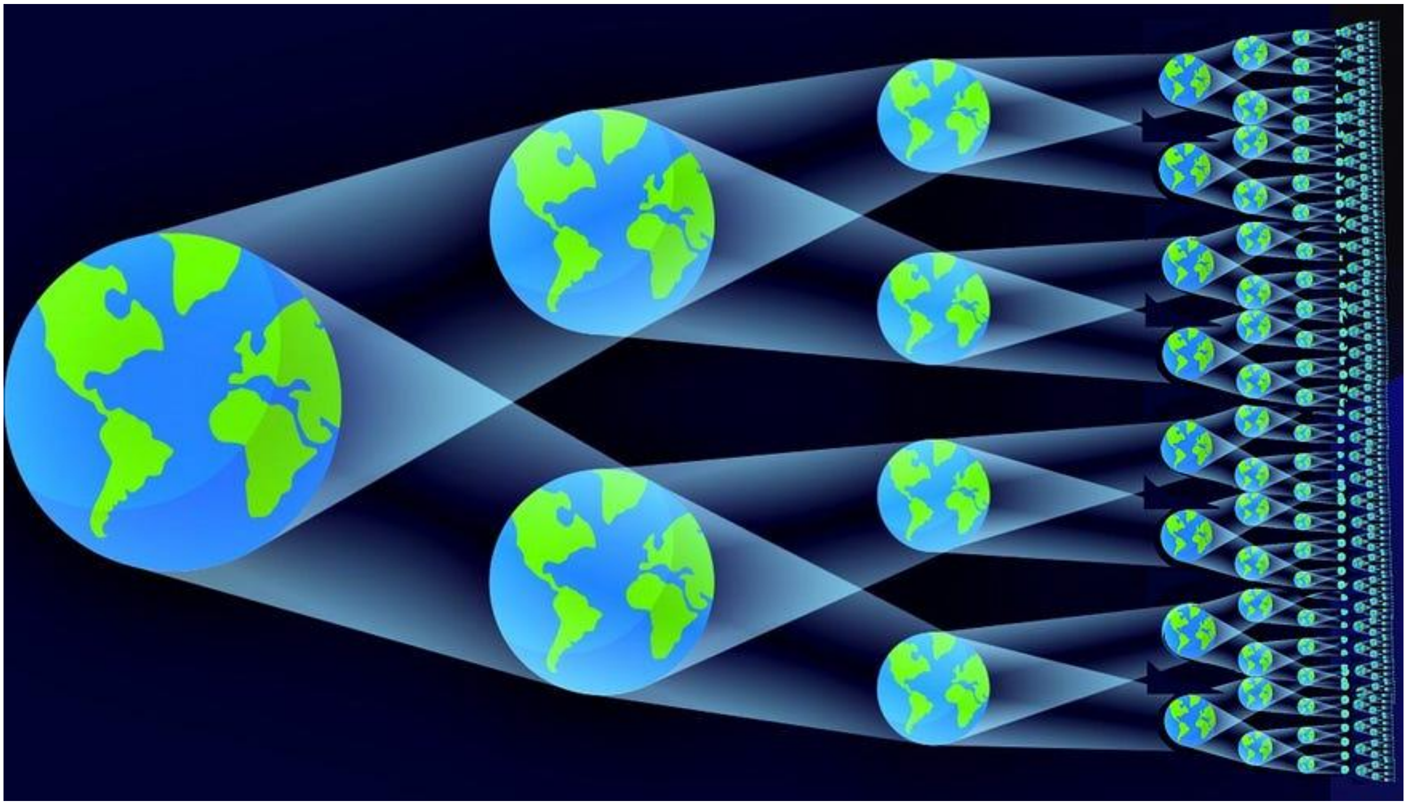
In 2025, Nature conducted a survey of more than 1000 physicists, asking them "which of the following, in your opinion, provides the best interpretation of quantum phenomena and interactions?" The results are shown above, not only revealing no consensus, but revealing a strong lack-of-confidence in whatever answer was provided.

So, are parallel universes real? Based on what we can say for certain about quantum physics, possibly, but there's no conclusive evidence supporting the notion. One big follow-up question we can ask is, "okay, if parallel universes were real, where would they all live?"

The answer, according to standard quantum mechanics, is that they live in the same mathematical structure where the wavefunction lives: in a physical Hilbert space. That's all well and good, but our Universe isn't well-described as a physical Hilbert space, so that isn't a compelling argument.

You could argue that if our Universe is infinite, then because there are a finite number of possible configurations for the (also finite number of) particles that exist within our observable Universe, then every configuration which arises in our Universe must also exist elsewhere. In fact, if the Universe is truly infinite, then that configuration must exist an infinite number of times elsewhere, and that would give these "parallel universes" somewhere physically real to live. Of course, we have no upper limit on how big the unobservable Universe is; it could well be infinite. But "finite" is also an option, and if the Universe is finite in extent, then it would stand to reason that parallel universes wouldn't be physically real.

After all, if we're splitting off more parallel universes every time we have an interaction, make a measurement, or otherwise uniquely "determine" our quantum state, the number of parallel universes required to hold all of these outcomes swiftly approaches infinity.



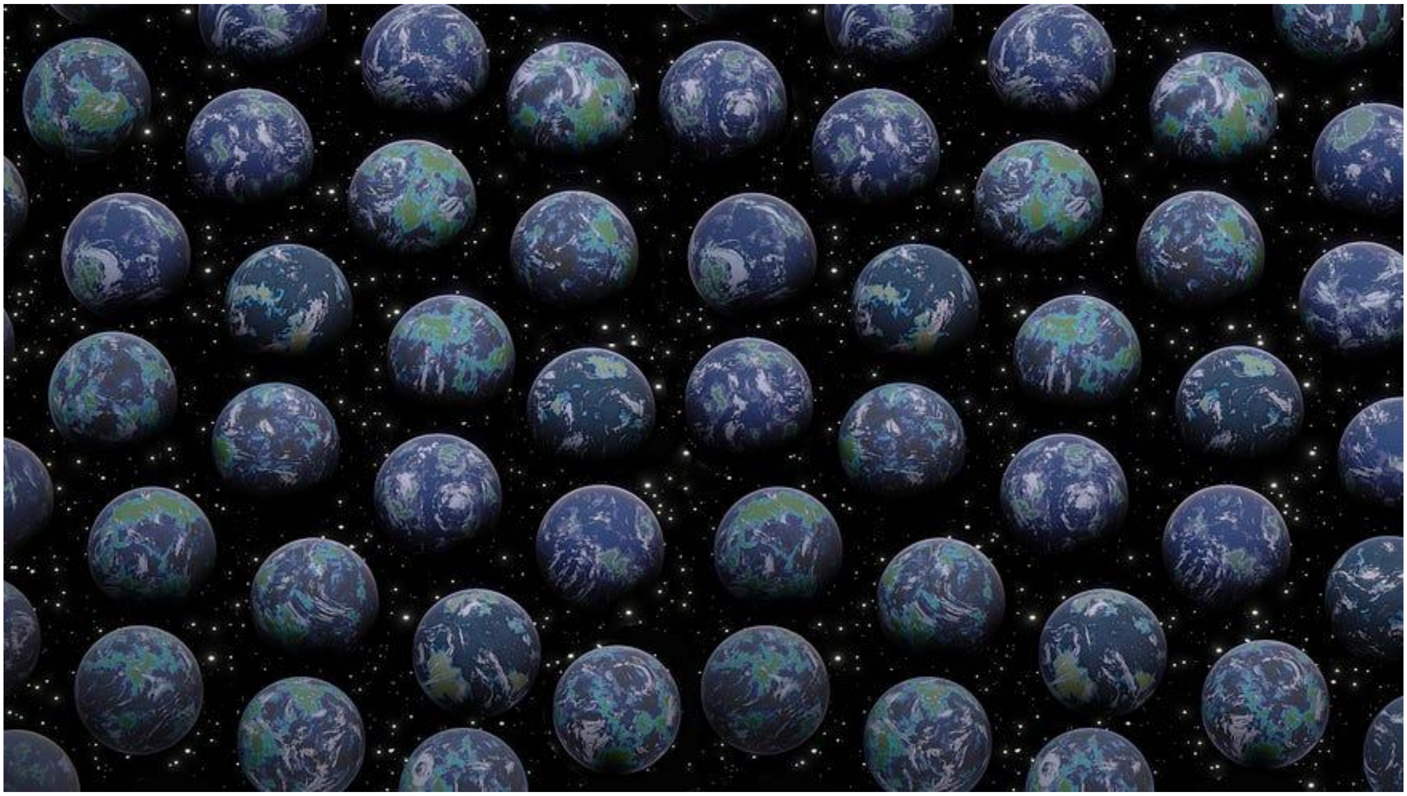
If each time a quantum decision were made, our timeline split to allow for two (and only two) possible outcomes, then the number of overall possibilities would increase incredibly rapidly, depending on which combinations of outcomes and what order-of-interactions are allowed. These possibilities cannot all fit within our physical, observable Universe, but the mathematical structure known as a Hilbert space can contain them all.

Now, it may be fun to speculate about parallel universes, but we have some information about where our own Universe came from that seems to be especially relevant. We didn't just emerge from the hot Big Bang, but rather from a period known as cosmic inflation that preceded and set up the Big Bang. In inflation, the Universe expands rapidly and relentlessly, doubling in size in all three dimensions with each tiny fraction-of-a-second that elapses, and then doubling and doubling again each time that same tiny fraction-of-a-second goes by. This relentless doubling creates a veritable multiverse of independent hot Big Bangs and baby universes that emerge from it, including our own observable Universe. The total number of universes spawned by inflation, just like the number of parallel universes required to hold all possible outcomes, also tends towards infinity as time marches onwards.

But not all infinities are the same size; some are bigger than others. For example, consider the following set of sequences:

- 1, 2, 3, 4, 5, …
- 1, 4, 9, 16, 25, …
- 1, 10, 100, 1000, 10000, …
- 1, 2, 6, 24, 120, ….

and so on. Each sequence goes to infinity, but they do so in different ways. The first sequence goes to infinity linearly (as n), the second as a power law (as n^2), the third as an exponential (as 10n), and the fourth as combinatoric (as $n!$, or n-factorial). Inflation creates more baby universes exponentially (like the third series), but quantum mechanics requires more parallel universes combinatorically (like the fourth series), teaching us that as time goes on, the real, physical multiverse that we inhabit shouldn’t be able to give a real, physical home to all of the parallel universes required by quantum mechanics.



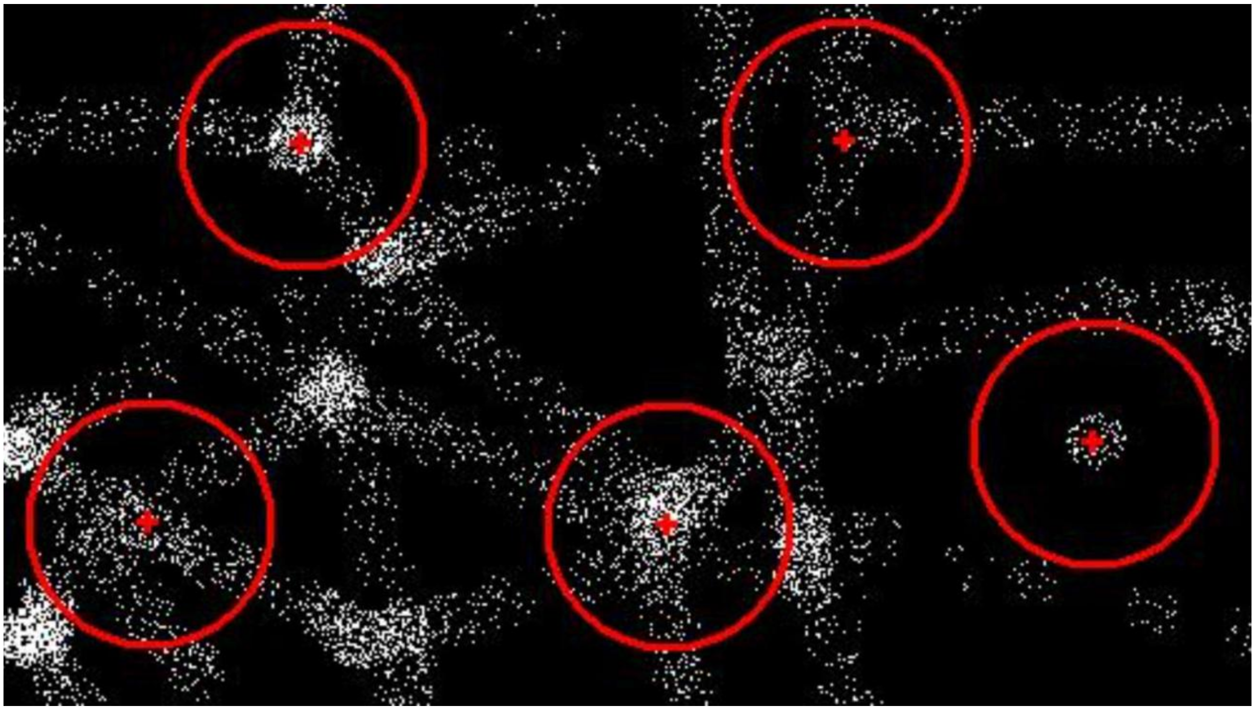
The Many Worlds Interpretation of quantum mechanics holds that there are an infinite number of parallel universes that exist, holding all possible outcomes of a quantum mechanical system, and that making an observation simply chooses one path. This interpretation is philosophically interesting, but has no physical meaning if there isn’t enough “universe” out there to physically hold all of these possibilities within it

Some infinities are bigger than others, and the “infinity” required for parallel universes to be physically real is a larger one than the infinity of universes created by cosmic inflation. That doesn’t necessarily mean that parallel universes aren’t physically real, but it tells us that, based on all that we know, there’s no reason to assume that they are. They would be, if:

- the universe itself were truly infinite in its physical extent,
- the inflationary period was past-eternal, meaning that inflation lasted for an infinite duration before giving rise to our own observable Universe,
- or if we redefine “physically real” to include “within the mathematical structure that we know of as a physical Hilbert space.”

Unfortunately for those of you who were hoping that I’d reach the conclusion that they were physically real, none of these count as the evidence we’d need to draw such a conclusion. In physics, there are different levels of what’s speculative, where the least speculative extensions to what we know (like the existence of the inflationary multiverse) solely involve extending known, established physics into a realm that goes beyond what we know how to observe or measure, and the more speculative extensions involve untested assumptions that compel us to add new layers of complexity atop our already established reality. At this point in time, parallel universes are a fascinating idea and concept worth considering, but there’s no evidence we can point to that suggest they’re likely to be physically real in any way that impacts our observed reality in any way.

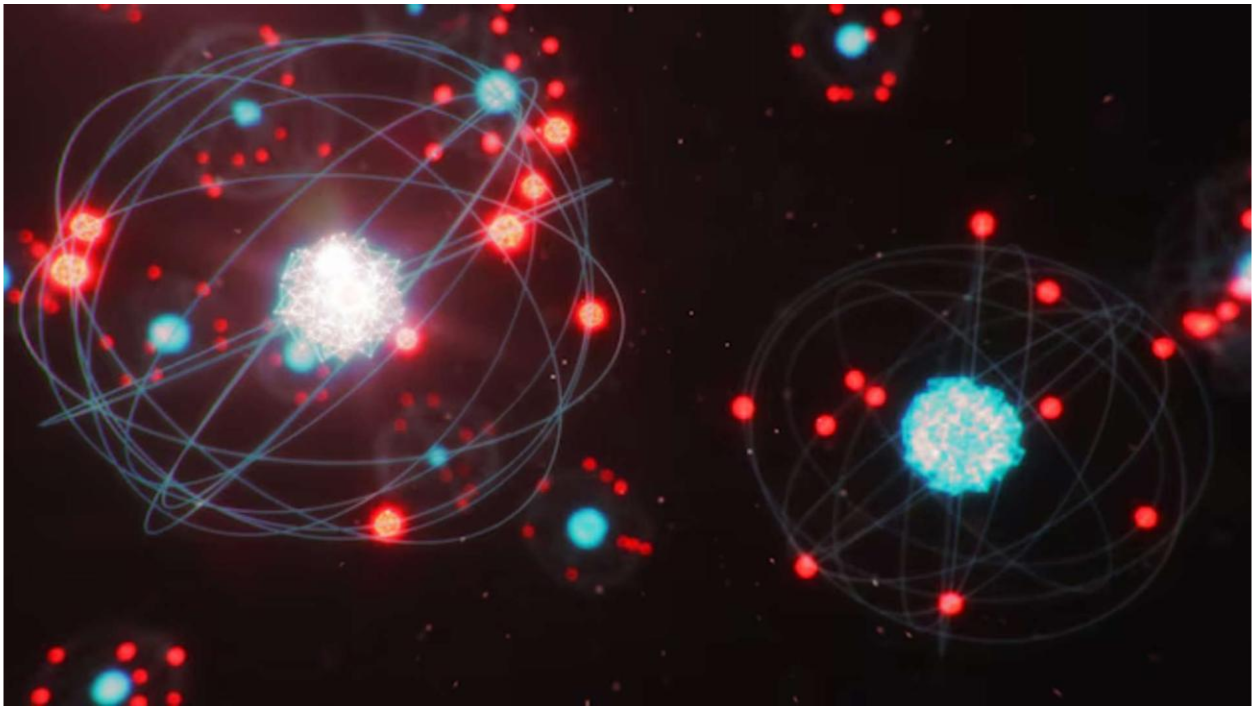
The Role of Quantum Mechanics in Multiverse Theory



Quantum mechanics, with its fundamental principles like superposition and entanglement, forms the backbone of the multiverse theory. This branch of physics, which explains the behavior of particles at the subatomic level, introduces concepts that have profound implications for the idea of parallel universes.

The notion of superposition, for instance, where a quantum system can exist in multiple states simultaneously, lends credence to the multiverse concept. Under this principle, each state of a quantum system could correspond to a different universe in the multiverse.

Quantum Experiments Simulating Parallel Universes



Scientists have been conducting experiments to simulate effects akin to parallel universes. These experiments typically involve manipulating quantum systems and observing the resulting interference patterns. The findings from these experiments have provided fascinating insights into the nature of our universe and its possible counterparts.

For example, a recent experiment involved manipulating photons in a lab setting to simulate the effects of a quantum system interacting with a parallel universe. The results of this experiment provided some of the first experimental evidence in support of the multiverse theory. For more details on this and other similar experiments, you can refer to this article.

The quantum experiment that could help find evidence of the multiverse

Scars of collisions with other universes could show up in radiation from the big bang. A new experiment aims to mimic these collisions and help us look for them

FOR an experiment designed to help us find evidence of other universes, it looks surprisingly modest. As Zoran Hadzibabic walks me into the lab, it feels more like a classroom, complete with linoleum floors, fluorescent lighting and a whiteboard with scribbled equations. And yet it is here, in amongst the tangle of stainless-steel chambers and brightly coloured wires set on a raised platform, that researchers are trying to replicate the primordial quantum bubbling that may have created our universe in a vast multiverse.

The idea that our universe is just one of many is among the most captivating in physics, and the logic seems sound enough, in the sense that the idea is itself an outgrowth of widely accepted theories about how the cosmos came to be what we see today. But there also happens to be zero empirical evidence for its existence – which is where Hadzibabic's experiment at the University of Cambridge comes in.

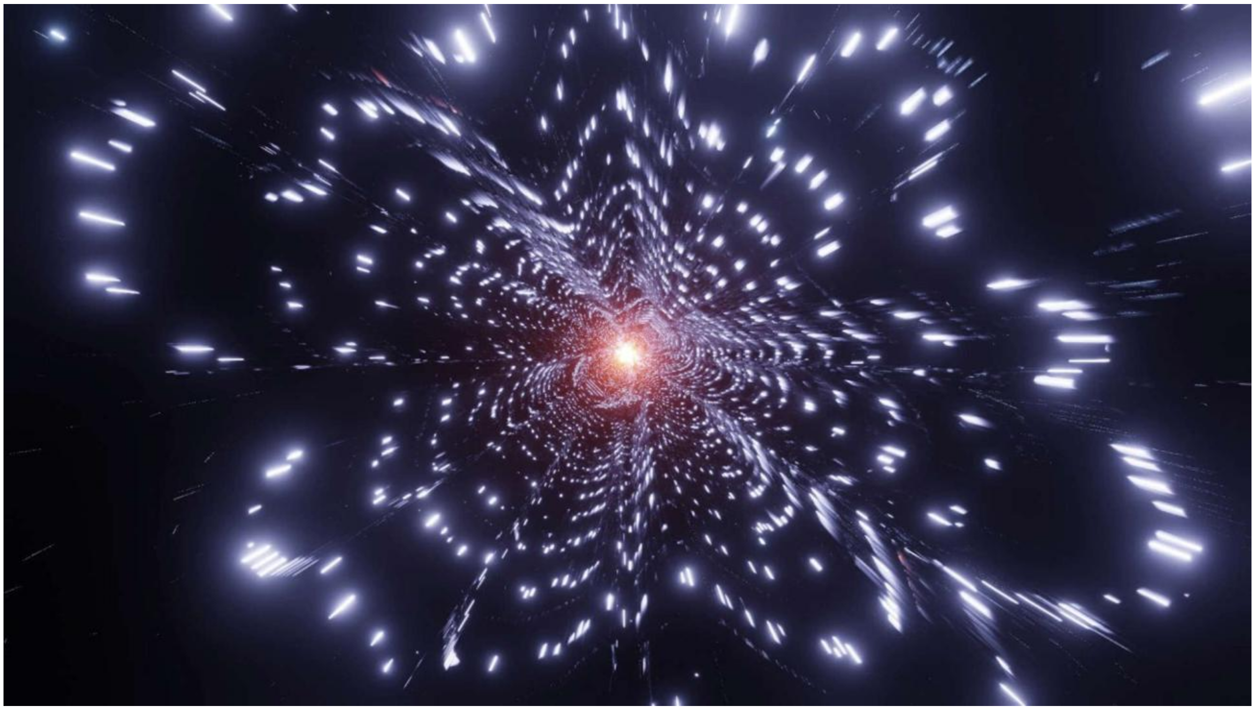
The researchers are betting that if we can cool and manipulate potassium atoms to extremely low temperatures, when tiny bubbles should form spontaneously, we will have a proxy for the otherwise unobservable processes thought to have sired new universes. By studying those bubbles, we could glean fresh clues as to how any past collisions between our universe and others would leave a mark that we might plausibly hunt down in astronomical data.

"The absolute dream would be that there's something in the sky that we observed which confirms what we predicted in this experiment," says Matt Johnson, a theoretical physicist at the Perimeter Institute in Canada.

What is the multiverse?

To be clear, what we are talking about here is the inflationary multiverse. This is not to be confused with the quantum multiverse, predicted by the "many worlds" interpretation of quantum theory, which says that every time we observe a quantum object, and so collapse a cloud of probabilities regarding its properties into something definite, all the possible outcomes persist in parallel universes.

Light Interaction with Empty Space: A Quantum Phenomenon

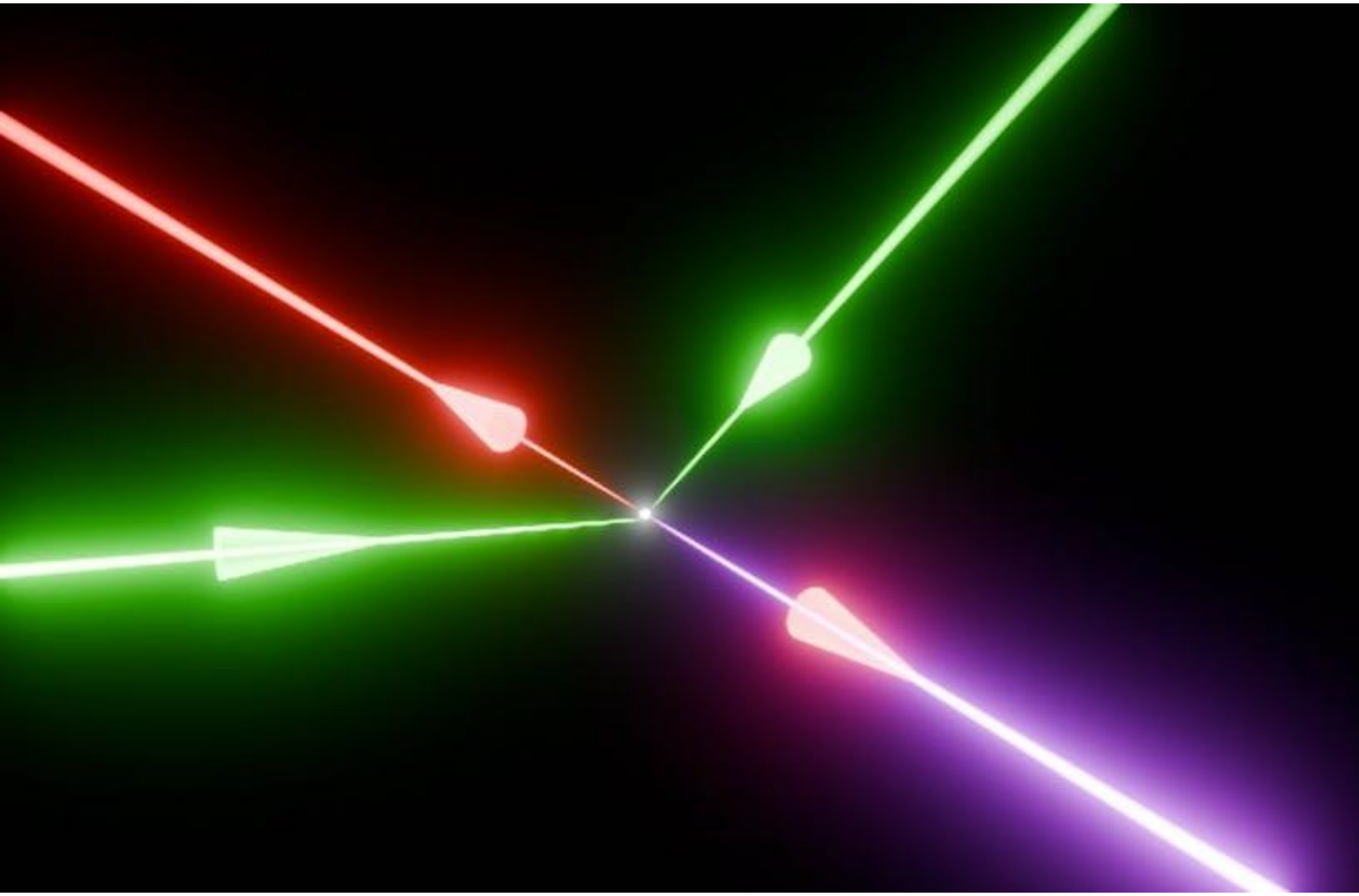


Light plays a crucial role in quantum experiments, including those simulating parallel universes. In the quantum realm, light interacts with what is perceived as ’empty’ space in intriguing ways. This interaction is due to the quantum nature of empty space, which is far from being truly empty.

Instead, it is a seething soup of virtual particles that constantly pop in and out of existence. These particles can interact with photons, resulting in phenomena that could potentially serve as indicators of the existence of parallel universes. You can learn more about this fascinating topic in this article.

Physicists simulate way light interacts with empty space

Simulations via advanced computational modeling recreate vacuum four-wave mixing—a quirky quantum phenomenon—and now this “solver” is poised to unleash new physics at extremely high intensities.



Photon-photon scattering effects within the lab: When two green petawatt lasers’ beams collide at the focus of a third red beam to polarize the quantum vacuum, it enables a fourth blue laser beam to be generated—with a unique direction and color. Credit: Zixin “Lily” Zhang

A group of physicists from the University of Oxford in the U.K. and Instituto Superior Técnico at the University of Lisbon in Portugal recently created real-time three-dimensional (3D) simulations of the way intense laser beams alter the quantum vacuum—a state quantum physics predicts is full of virtual electron-positron pairs—and recreated vacuum four-wave mixing (see video).

What is vacuum four-wave mixing? A theoretical quantum effect in which the combined electromagnetic field of three focused laser pulses can polarize the virtual electron-positron pairs of a vacuum and make photons bounce off each other like balls on a pool table to generate a fourth laser beam during a "light from darkness" process.

This work is a step closer to "experimental confirmation of quantum effects that until now were mostly theoretical," says Peter Norreys, a physics professor at the University of Oxford.

"The quantum vacuum is one of the most fascinating predictions of quantum electrodynamics (QED)," says Zixin "Lily" Zhang, a Ph.D. student working with Norreys, who is a Clarendon scholar and whom Norreys notes has an extraordinary talent for physics. "It challenges the classical perspective of a vacuum as an empty space, and instead pictures it as a sea of virtual particles—like electrons and positrons—that pop in and out of existence. Despite QED being one of the most well-tested physics theories, there have been no successful direct tests on the nature of the quantum vacuum. But the global emergence of multi-petawatt lasers sparked our interest in testing the vacuum using just light."

Simulations/solver

To run their simulations, the group used an advanced version of OSIRIS, which is a simulation software package that models interactions between laser beams and matter of plasma. It essentially provides a time-resolved 3D look into quantum vacuum interactions not previously possible.

The group's solver is based on the Heisenberg-Euler Lagrangian effective theory, which describes how the vacuum responds to the electromagnetic fields when they're strong but still below the Schwinger limit (above it, an electromagnetic field is expected to become nonlinear).

"This approach allows us to shift from a fully quantum picture, where light is treated as photons, to a semiclassical one that treats light as electromagnetic waves," explains Zhang. "Within this framework, the vacuum behaves like a nonlinear optical medium and manifests effects like birefringence similar to those seen within nonlinear crystals."

It's based on nonlinear Maxwell's equations and implemented via a numerical technique—a.k.a. the "Yee method"—widely used for plasma simulations.

"The key challenge is the nonlinear terms, which depend on the electromagnetic fields," says Zhang. "To address it, we combined the Yee method with an iterative loop to update the nonlinear response at each time step until the solution converges. And we integrated our solver into OSIRIS, a state-of-the-art massively parallel particle-in-cell code, which allows us to take advantage of built-in tools like laser pulse initialization and even particle generation."

When the physicists put their method to the test with a three-beam scattering experiment and captured the full range of quantum signatures, they came away with detailed insights into the interaction region and its key time scales. After benchmarking it, they now hope to focus on more complex scenarios like exotic laser beam structures and flying focus pulses.

"We've validated the solver in two dimensions (2D) and 3D against analytical predictions for vacuum birefringence, and extended it to simulate more complex effects like four-wave mixing—with results that match the literature well," says Zhang.

What does this mean for the quantum realm? "Previous numerical tools were limited in scope and often constrained to simplify laser setups or 2D models," says Zhang. "Our solver can simulate realistic real-time and full-scale 3D laser interactions with the quantum vacuum, which provides researchers with a much richer dataset and more accurate estimates for near-future experiments."

Most thrilling aspects of this work? "It was to see the solver running and deliver the expected results," Zhang says. "There certainly was a lot of debugging throughout the process, but watching the simulations behave exactly as predicted was truly satisfying and validating."

High-energy laser experiments to probe quantum phenomena on horizon

As the world's newest generation of ultrapowerful lasers start to come online, such as the U.K.'s Vulcan 20-20, the European Extreme Light Infrastructure (ELI) project, and China's Station for Extreme Light (SEL) and SHINE facilities, they're poised to deliver high enough power levels to potentially confirm photon-photon scattering within the lab—which would be a first. The U.S. National Science Foundation's OPAL dual-beam 25-petawatt laser facility at the University of Rochester, for example, is pursuing photon-photon scattering as one of its flagship experiments.

This is where the group's tool comes in: Its models provide details that experimentalists require to design precise real-world tests such as realistic laser shapes and pulse timings. The simulations also reveal how these types of interactions evolve in real time and how subtle asymmetries in beam geometry can shift outcomes.

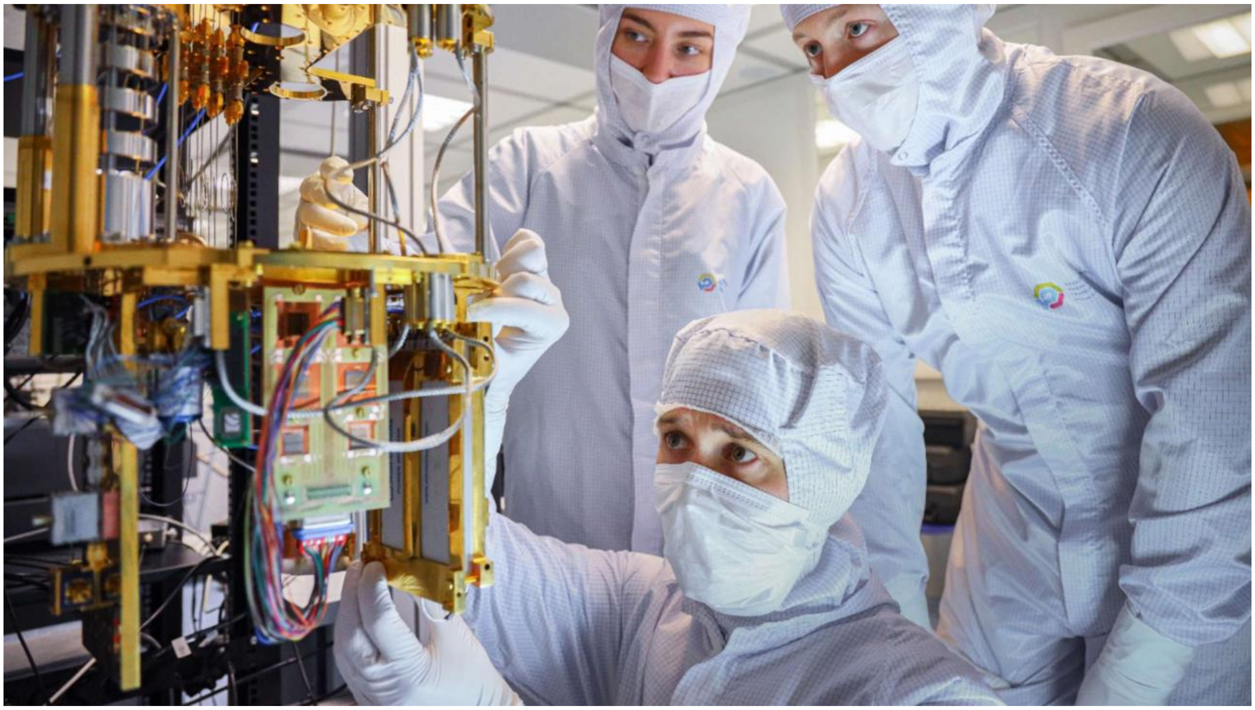
Experiments planned at these advanced laser facilities will be able to take advantage of the group's solver. "The combination of ultra-intense lasers, state-of-the-art detection, and cutting-edge analytical and numerical modeling are the foundations for a new era in laser-matter interactions, which will open up new horizons for fundamental physics," says Luis Silva, a physics professor at the Instituto Superior Técnico, University of Lisbon and visiting professor in physics at the University of Oxford.

3D real-time simulations "have always been computationally costly," points out Zhang. "Our solver uses a matrix-free numerical method that makes the computation process more efficient and allows us to run fully 3D simulations for a three-beam setup, which to our knowledge hasn't previously been achieved. There's still work to be done to improve the speed and scalability to make these simulations more accessible to running on just a few central processing units (CPUs)."

The group's solver is ready to use now and available upon request. It can model a range of quantum vacuum effects in arbitrary laser configurations, such as birefringence and four-wave mixing. And the physicists are looking forward to other researchers applying it to their own experimental designs or theoretical studies.

"We're currently exploring new physics using the simulation results from the solver—including novel beam profiles," says Zhang. "The algorithm of the solver also makes it straightforward to implement other nonlinear theories beyond QED, such as Born-Infeld electrodynamics and Axion fields. Our goal is to build toward a comprehensive simulation toolkit for the quantum vacuum."

Implications and Future Directions



The findings from these quantum experiments have far-reaching implications. They not only challenge our understanding of the universe but could also open up new avenues in technology, such as quantum computing and teleportation. The experiments have opened up a whole new realm of possibilities and questions, making the field of quantum physics and multiverse theory more exciting than ever before.

As we move forward, research in this field is likely to focus on refining our understanding of the multiverse and its implications for physics. This includes improving experimental techniques, developing more accurate quantum models, and exploring ways to harness the power of quantum mechanics for practical applications. To get a glimpse of what the future might hold, check out this book.

The Simulated Multiverse: An MIT Computer Scientist Explores Parallel Universes, The Simulation Hypothesis, Quantum Computing and the Mandela Effect

By Rizwan Virk