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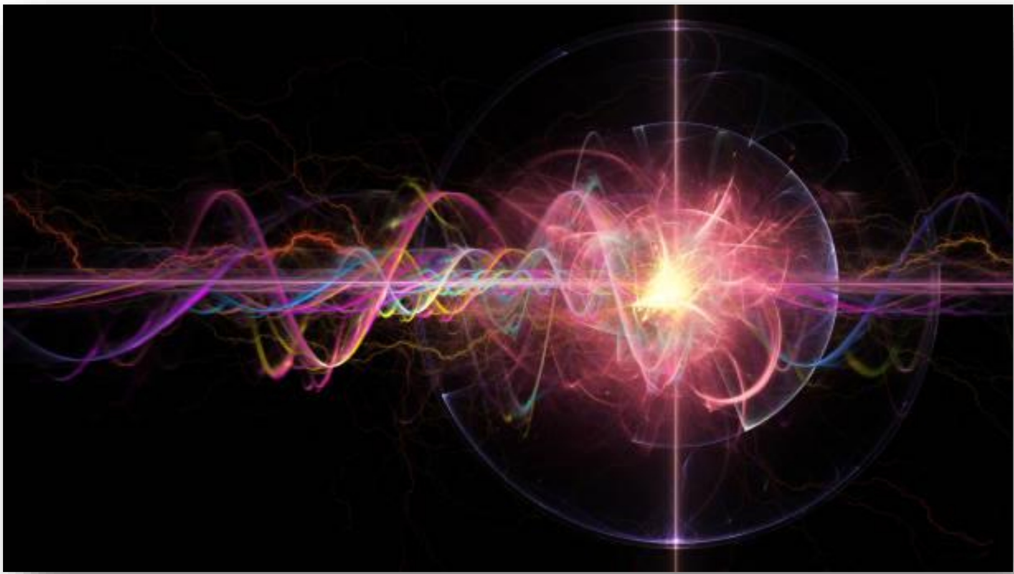
Quantum phenomena



„Not only is the Universe stranger than we think, it is stranger than we can think."

- Werner Heisenberg

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Foreword

Our universe is vast. Achingly beautiful. Remarkably simple in some ways, intricately complex in others. From our universe's smallest distance, where models of physics can make meaningful statements (Plank distance= $1.616255(18)\times10^{-35}$ m) to the observable universe (46.508 billion light years), this vast space has hidden some of the most interesting phenomena, which the human, in his smallness, could not comprehend even a billionth of its spectacularity.

From the seventeenth century onward physicists have struggled to discover the physical laws that shape and control our universe. This has been like European explorers struggling to discover the Earth's geography.

By 1690 the Newtonian laws of physics had come into focus. With concepts such as force, mass, and acceleration and equations that link them, such as $F = ma$, the Newtonian laws accurately describe the motion of the Moon around the Earth and the Earth around the Sun, the flight of an airplane, the construction of a bridge, and collisions of a child's marbles.

By 1915 Einstein and others had found strong evidence that the Newtonian laws fail in the realm of the very fast (objects that move at nearly the speed of light), the realm of the very large (our universe as a whole), and the realm of intense gravity (for example, black holes). To remedy these failures, Einstein gave us his revolutionary relativistic laws of physics. Using the concepts of warped time and warped space, the relativistic laws predicted and explained the expansion of the universe, black holes, neutron stars and wormholes.

By 1924 it was crystal clear that the Newtonian laws also fail in the realm of the very small (molecules, atoms, and fundamental particles). To deal with this Niels Bohr, Werner Heisenberg, Erwin Schrödinger, and others gave us the quantum laws of physics. Using the concepts that everything fluctuates randomly at least a little bit, and that these fluctuations can produce new particles and radiation where before there were none, the quantum laws have brought us lasers, nuclear energy, light-emitting diodes, and a deep understanding of chemistry.

Also, Quantum mechanics seems to contradict some traditionally accepted beliefs on science and scientific thinking. Thus, following its acceptance, should we abandon the traditional principles of physical and scientific thinking, and adopt new ways of thinking in their place? Or rather, we should suppose the whole thing to be a temporary misunderstanding, hoping that with further progress, some way will be found to reconcile quantum mechanics within the traditional principles of science?

With the massive expansion of science in all domains it became clearer to me that the universe is a complexe machine with infinite outcomes and possibilities, thus it is worth to be studied in all its depth to uncover its mysteries, since I was always fascinated by the unknown.

From Planck to….

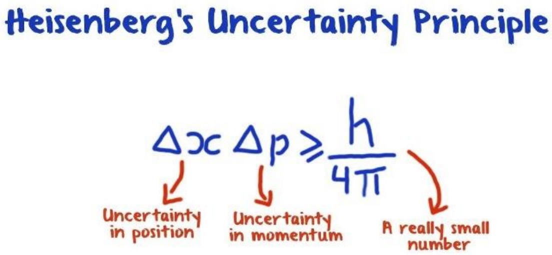
I. Certain, probable or both?

The “uncertainty principle” was discovered by the German physicist Werner Heisenberg in 1927 and has a precise technical meaning that is typically relevant only to microscopic particles. But it does have implications for how we understand the universe and our relation to it, and also to new technologies of the 21st century.

While the Heisenberg Uncertainty Principle (HUP) does not mean “there are some things you can never be sure of”, it does imply “you can never be sure of everything.” How can this be? If you can never be sure of everything, does not that mean there are some things you can never be sure of? Surprisingly, no.

The simplest example of the HUP is the following: You can never be certain of both the position and the speed of a microscopic particle. It is possible to arrange an experiment so you can predict the position of a particle. A different experiment would let you predict its speed. But you will never be able to arrange things so that you can be certain of both its position and its speed.

An application of the HUP would be quantum communication, which allows the sending of encoded messages that are un-hackable by any computer. This is possible because the messages are carried by tiny particles of light called photons. If an eavesdropper attempts to read out the message in transit, they will be discovered by the disturbance their measurement causes to the particles as an inevitable consequence of the HUP.



A. Erwin Rudolf Josef Alexander Schrödinger

Another great physicist was Erwin Rudolf Josef Alexander Schrödinger who was born in Austria’s capital city, Vienna, on August 12, 1887. His father was Rudolf Schrödinger, a botanist. His mother was Georgine Bauer, the daughter of a chemistry professor.

Erwin was their only child. He was a gifted student in the local Gymnasium. His strengths and interests lay not only in the physics and maths courses that he mastered with effortless enjoyment, but in languages, both ancient and modern, as well as poetry.

Schrödinger's book “What is life?” contains something far more important than his attempt to fuse physics and biology. In that lecture 70 years ago, he introduced some of the most important concepts in the history of biology, which continue to frame how we see life.

At a time when it was thought that proteins, not DNA, were the hereditary material, Schrödinger argued the genetic material had to have a non-repetitive molecular structure. He claimed that this structure flowed from the fact that the hereditary molecule must contain a "code-script" that determined "the entire pattern of the individual's future development and of its functioning in the mature state".

This was the first clear suggestion that genes contained some kind of "code", although Schrödinger's meaning was apparently not exactly the same as ours – he did not suggest there was a correspondence between each part of the "code-script" and precise biochemical reactions.

In 1935 Schrödinger published a three-part essay on “The present situation in quantum mechanics”. As an illustration, it contained a thought experiment (hypothetical only) as follows: A cat is in a box with a source of poison gas that would be triggered (or not) by the decay of one electron in one direction or another. Because of the uncertainty of the electron’s behavior, there exists a moment in time when the observer is unsure whether the cat is alive or dead, and in some sense, it is both! However, the modern laws of physics have already been submitted to this ancient goddess.

B. Discrete amounts of physics

It is right there in the name -- the word "quantum" comes from the Latin for "how much" and reflects the fact that quantum models always involve something coming in discrete amounts. The energy contained in a quantum field comes in integer multiples of some fundamental energy. For light, this is associated with the frequency and wavelength of the light -- high-frequency, short-wavelength light has a large characteristic energy, while low-frequency, long-wavelength light has a small characteristic energy.

In both cases, though, the total energy contained in a particular light field is an integer multiple of that energy-- 1, 2, 14, 137 times -- never a weird fraction like one-and-a-half, π, or the square root of two. This property is also seen in the discrete energy levels of atoms, and the energy bands of solids -- certain values of energy are allowed, others are not. Atomic clocks work because of the discreteness of quantum physics, using the frequency of light associated with a transition between two allowed states in cesium to keep time unmodified.

II. Quantum entanglement

=„Spooky action at a distance"

Quantum computers, quantum cryptography and quantum (insert anything here) are often in the news these days. Articles about them inevitably refer to entanglement, a property of quantum physics that makes all these magical devices possible.

Einstein called entanglement "spooky action at a distance," a name that has stuck and become increasingly popular. Beyond just building better quantum computers, understanding and harnessing entanglement is also useful in other ways.

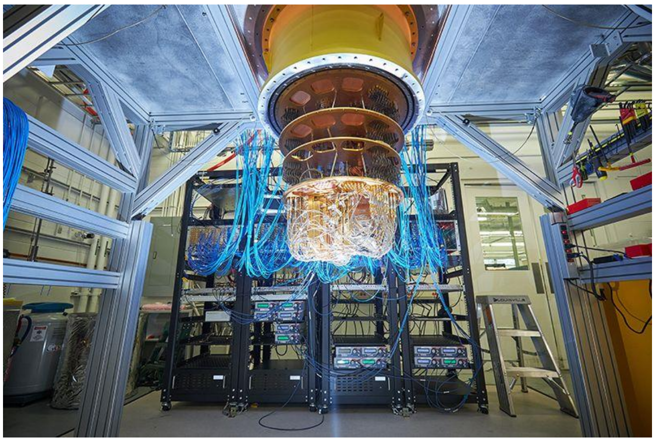
For example, it can be used to make more accurate measurements of gravitational waves, and to better understand the properties of exotic materials. It also subtly shows up in other places: how atoms bumping into each other become entangled, resulting in the accuracy of atomic clocks.

Imagine a pair of quantum particles (say atoms) that start off with a total of 100 units of energy. You and your friend separate the pair, taking one each. You find that yours has 40 units of energy. Using the law of conservation of energy, you deduce that the one your friend has must have 60 units of energy. As soon as you know the energy of your atom, you immediately also know the energy of your friend's atom. You would know this even if your friend never revealed any information to you. And you would know this even if your friend was off on the other side of the galaxy at the time you measured the energy of your atom. Nothing spooky about it (once you realize this is just correlation, not causation).

But the quantum states of a pair of atoms can be more interesting. The energy of the pair can be partitioned in many possible ways (consistent with energy conservation). The combined state of the pair of atoms can be in a superposition, for example:

[YOUR ATOM: 60 UNITS; FRIEND'S ATOM: 40 UNITS] + [YOUR ATOM: 70 UNITS; FRIEND'S ATOM: 30 UNITS].

This is an entangled state of the two atoms. Neither your atom, nor your friend's, has a definite energy in this superposition. Nevertheless, the properties of the two atoms are correlated because of conservation of energy: their energies always add up to 100 units.



A. "Sycamore"

Between the mountainous and coastal vistas of Goleta, California, sits an unassuming office on the side of a building next to the freeway. It could belong to any Southern California company; workers sit in gray cubicles beneath fluorescent lights, and there is a rack to hold employees' bikes and surfboards. But at those desks are physicists and computer scientists developing a computer like none you have ever seen before. Behind a set of double doors, cylindrical machines hold computer chips at temperatures colder than the vacuum of space.

Here, Google's scientists have been toiling to create a computer processor that can solve a problem that is too hard for the world's best supercomputers. They finally announced they had succeeded: Their Sycamore quantum computer was able to complete a problem in 200 seconds that a supercomputer would need 10,000- years to solve, according to their estimates.

It is a single, contrived problem, and the chip would fail in a race with a supercomputer to add two and two together. But Google's scientists think they have achieved a historical computing milestone. That is why we should compare it to a Sputnik moment. Sputnik did not do much either. All it did was circle Earth. Yet it was the start of the Space Age.

While classical computers use transistors to represent data in zeroes and ones, quantum computers represent data using artificial atoms, called qubits. Rather than simply using the rules of logic, these qubits interact via the weird mathematics of quantum mechanics. They take on zero or one and produce long strings of binary code just like classical computers do, but during the calculation, they can take on states between zero and one, which determine how likely you are to get zero or one on the final measurement. Despite the technological accomplishment, the computer is prone to errors. Any interaction with the outside world can cause the qubit to spit out the wrong values. But the experiment demonstrated that as they add more qubits, the number of errors will increase in a predictable way.

"We've shown that we have an understanding of these errors," said Google scientist Marissa Giustina. "That's a key engineering and physics piece of the breakthrough."

B. String theory

As a so-called "Theory of Everything" candidate, string theory aims to address various theoretical conundrums; the most fundamental of which is how gravity works for tiny objects like electrons and photons. General relativity describes gravity as a reaction of large objects, like planets, to curved regions of space, but theoretical physicists think gravity should ultimately behave more like magnetism — fridge magnets stick because their particles are swapping photons with fridge particles. Of the four forces in nature, only gravity lacks this description from the perspective of small particles. Theorists can predict what a gravity particle should look like, but when they try to calculate what happens when two "gravitons" smash together, they get an infinite amount of energy packed into a small space — a sure sign that the math is missing something.

One possible solution, which theorists borrowed from nuclear physicists in the 1970s, is to get rid of the problematic, point-like graviton particles. Strings, and only strings, can collide and rebound cleanly without implying physically impossible infinities. "A one-dimensional object - that's the thing that really tames the infinities that come up in the calculations" said Marika Taylor, a theoretical physicist at the University of Southampton in England.

String theory turns the page on the standard description of the universe by replacing all matter and force particles with just one element: tiny vibrating strings that twist and turn in complicated ways that, from our perspective, look like particles. A string of a particular length striking a particular note gains the properties of a photon, and another string folded and vibrating with a different frequency plays the role of a quark, and so on. In addition to taming gravity, the framework proved attractive for its potential to explain so-called fundamental constants like the electron's mass. The next step is to find the right way to describe the folding and movement of strings, theorists hope, and everything else will follow.

But that initial simplicity turned out to come at the cost of unexpected complexity - string math didn't work in the familiar four dimensions (three of space and one of time). It needed six additional dimensions (for a total of 10) visible only to the little strings, much as a powerline looks like a 1D line to birds flying far overhead but a 3D cylinder to an ant crawling on the wire. Adding to the conundrum, physicists had come up with five conflicting string theories by the mid-1980s. The theory of everything was fractured.

Over the next decade, scientists exploring the relationships between the five theories began to find unexpected connections, which Edward Witten, a theorist at the Institute for Advanced Study in Princeton, New Jersey, gathered up and presented at a 1995 string theory conference at the University of Southern California. Witten argued that the five string theories each represented an approximation of a more fundamental, 11-dimensional theory in a particular situation, much as how Einstein's space- and time-bending theories of relativity match Newton's description of objects moving at normal speeds.

The novel theory is called M-theory, although to this day no one knows what mathematical form it might take. The "M" is likely inspired by higher-dimensional objects called membranes, Taylor said, but since the theory has no concrete mathematical equations, the "M" remains a placeholder with no official meaning. "It was really a parametrization of our ignorance," Taylor said. "This parent theory that would describe absolutely everything."

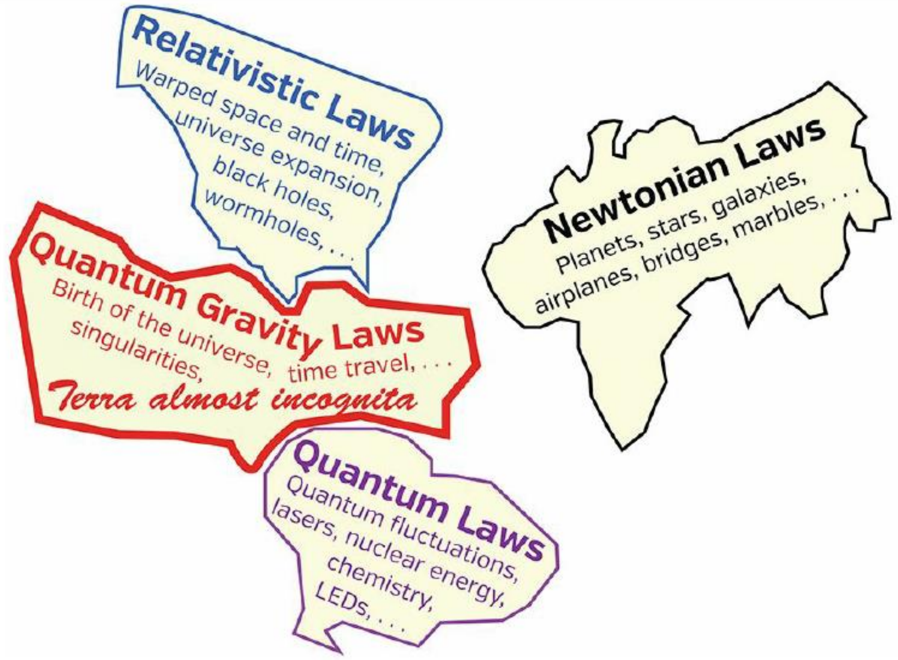
Attempts to find those general equations that would work in every possible situation made little progress, but the alleged existence of the fundamental theory gave theorists the understanding and confidence needed to develop mathematical techniques for the five versions of string theory and apply them in the right context. Strings are far too small to detect with any conceivable technology, but one early theoretical success was their ability to describe black hole entropy in 1996. Entropy refers to the number of ways that you can arrange the parts of a system, but without being able to see into the impenetrable depths of a black hole, no one knows what type of particles might lie inside, or what arrangements they can take. And yet, in the early 1970s Stephen Hawking and others showed how to calculate the entropy, suggesting that black holes have some sort of internal structure. Most attempts to describe the black hole's makeup fall short, but tallying the configurations of hypothetical strings does the trick. "String theory has been able to give a spot-on counting," Taylor says, "not just roughly getting it right."

The string framework still faces many challenges, however: It produces an impossible number of ways to fold up the extra dimensions that all seem to fit the broad features of the Standard Model of particle physics, with little hope of distinguishing which is the right one. Moreover, all of those models rely on an equivalence between force particles and matter particles called supersymmetry that, like the extra dimensions, we don't observe in our world. The models also don't seem to describe an expanding universe.

A number of physicists, such as Peter Woit of Columbia University, view these divergences from reality as fatal flaws. "The basic problem with string theory unification research is not that progress has been slow over the past 30 years," he wrote on his blog, "but that it has been negative, with everything learned showing more clearly why the idea doesn't work."

Taylor, however, maintains that today's models are overly simplistic, and that features like cosmological expansion and a lack of supersymmetry may someday be built into future versions. Taylor expects that, while the new era of gravitational wave astronomy may bring new tidbits of information about quantum gravity, more progress will be made by continuing to follow the math deeper into string theory. "I have a theoretical bias," she said, "but I think the kind of breakthrough I'm describing would come from a chalkboard; from thought."

….the observable universe…



⇨ The physical laws that govern the universe.

III. Space-time bulk

Einstein struggled to understand gravity on and off from 1907 onward. Finally in 1912 he had a brilliant inspiration. Time, he realized, must be warped by the masses of heavy bodies such as the Earth or a black hole, and that warping is responsible for gravity. He embodied this insight in what is called "Einstein's law of time warps", a precise mathematical formula that it is described qualitatively this way: Everything likes to live where it will age the most slowly, and gravity pulls it there.

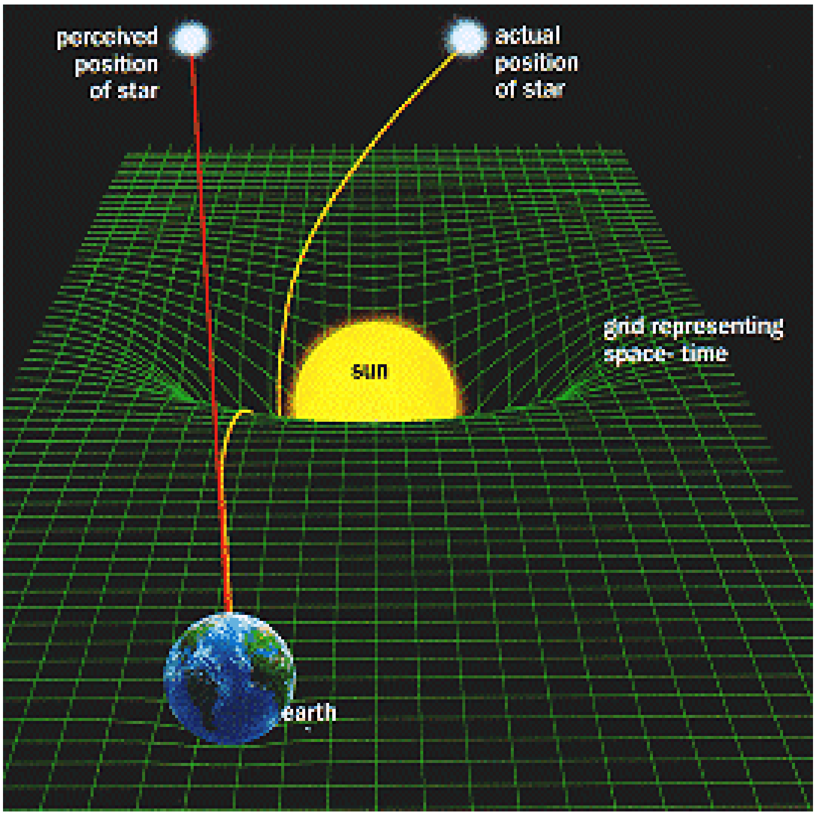
The greater the slowing of time, the stronger gravity's pull. On Earth, where time is slowed by only a few microseconds per day, gravity's pull is modest. On the surface of a neutron star, where time is slowed by a few hours per day, gravity's pull is enormous. At the surface of a black hole, time is slowed to a halt, whence gravity's pull is so humungous that nothing can escape, not even light.

Human technology was too puny to test Einstein's law until nearly half a century after he formulated it. The first good test came in 1959 when Bob Pound and Glen Rebca used a new technique called the Mössbauer effect to compare the rate of flow of time in the basement of a 73- foot tower at Harvard University with time in the tower's penthouse. Their experiment was exquisitely accurate: good enough to detect differences of 0.0000000000016 seconds (1.6 trillionths of a second) in one day. Remarkably, they found a difference 130 times larger than this accuracy and in excellent agreement with Einstein's law: Time flows more slowly in the basement than in the penthouse by 210-trillionths of a second each day.

The accuracy improved in 1976, when Robert Vessot of Harvard flew an atomic clock on a NASA rocket to a 10,000-kilometer height, and used radio signals to compare its ticking rate with clocks on the ground. Vessot found that time on the ground flows more slowly than at a height of 10,000 kilometers by about 30 microseconds (0.00003 seconds) in one day, and his measurement agreed with Einstein's law of time warps to within his experimental accuracy. That accuracy (the uncertainty in Vessot's measurement) was seven parts in a hundred thousand: 0.00007 of 30 microseconds in a day.

The global positioning system (GPS), by which our smartphones can tell us where we are to 10 meters accuracy, relies on radio signals from a set of 27 satellites at a height of 20,000 kilometers. Typically only four to twelve satellites can be seen at once from any location on Earth. Each radio signal from a viewable satellite tells the smart phone where the satellite is located and the time the signal was transmitted. The smart phone measures the signal's arrival time and compares it with its transmission time to learn how far the signal traveled–the distance between satellite and phone. Knowing the locations and distances to several satellites, the smart phone can triangulate to learn its own location.

This scheme would fail if the signal transmission times were the true times measured on the satellite. Time at a 20,000-kilometer height flows more rapidly than on Earth by forty microseconds each day, and the satellites must correct for this. They measure time with their own clocks, then slow that time down to the rate of time flow on Earth before transmitting it to our phones.

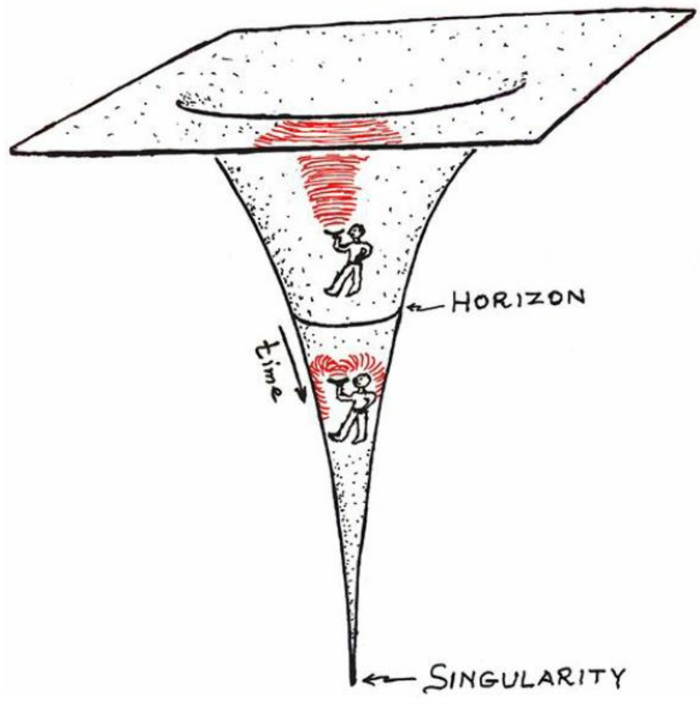


⇨ Space-time dilation

IV.Black Holes

When you first hear mention of a black hole, you probably think of its trapping power, not its warped space. If I fall into a black hole carrying a microwave transmitter, then once I pass through the hole's event horizon, I'm pulled inexorably on downward, into the hole's singularity. And any signals I try to transmit in any manner whatsoever get pulled down with me. Nobody above the horizon can ever see the signals I send after I cross the horizon. My signals and I are trapped inside the black hole. This trapping is actually caused by the hole's time warp.

If I hover above the black hole, supporting myself by the blast of a rocket engine, then the closer I am to the horizon, the more slowly my time flows. At the horizon itself, time slows to a halt and, therefore, according to Einstein's law of time warps, I must experience an infinitely strong gravitational pull. What happens inside the event horizon? Time is so extremely warped there that it flows in a direction you would have thought was spatial: it flows downward toward the singularity. That downward flow, in fact, is why nothing can escape from a black hole. Everything is drawn inexorably toward the future, and since the future inside the hole is downward, away from the horizon, nothing can escape back upward, through the horizon.



A.Gravitational lensing

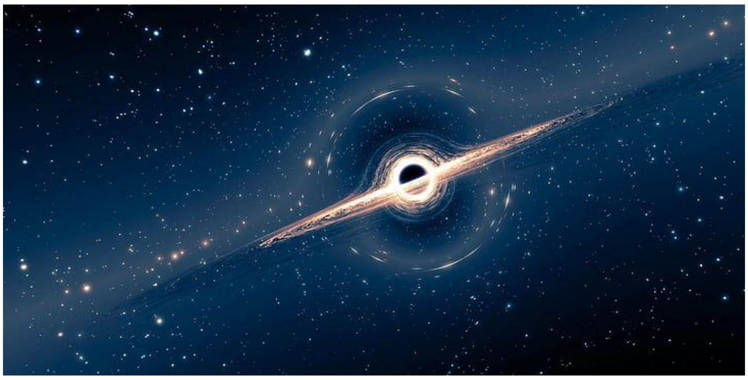
The black hole casts a black shadow on the field of stars behind it. Light rays from the stars are bent by the hole's warped space; they are gravitationally lensed, producing a concentric pattern of distortion. Light rays coming to us from the shadow's left edge move in the same direction as the hole's whirling space. The space whirl gives them a boost, letting them escape from closer to the horizon than light rays on the shadow's right edge, which struggle against the whirl of space. That's why the shadow is flattened on the left and bulges out on the right.

How Do We Know This Is True?

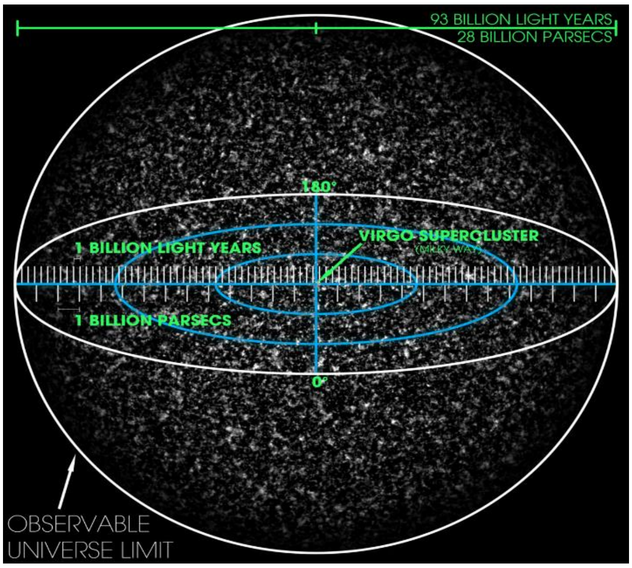
Einstein’s relativistic laws have been tested to high precision, they must right, except when they confront quantum physics. If black holes exist at all in our universe, they must have the properties that Einstein’s relativistic laws dictate, the properties described above.

If we know the mass of a black hole and how fast it spins, then from Einstein’s relativistic laws we can deduce all the hole’s other properties: its size, the strength of its gravitational pull, how much its event horizon is stretched outward near the equator by centrifugal forces, the details of the gravitational lensing of objects behind it. Everything. This is amazing. So different from everyday experience. It is as though knowing my weight and how fast I can run, you could deduce everything about me: the color of my eyes, the length of my nose, my IQ… John Wheeler has described this by the phrase “A black hole has no hair”–no extra, independent properties beyond its mass and its spin.

- ⇨ Gravitational lensing:



…and the end of space time…



Conclusions

We live in a universe governed by physical laws. By laws that we humans are capable of discovering, deciphering, mastering, and using to control our own fate. Even without superior ‘bulk’ beings to help us, we humans are capable of dealing with most any catastrophe the universe may throw at us, and even those catastrophes we throw at ourselves – from climate change to biological and nuclear catastrophes.

But doing so, controlling our own fate, requires that a large fraction of us understand and appreciate science: how it operates. What it can achieve. What its limitations are, due to inadequate knowledge or technology. How those limitations may be overcome. How extremely rare are revolutions in which our perceived truth changes, yet how very important.

“Everything has its wonders, even darkness and silence…” - Hellen Keller

“Deep down, nature is inherently peaceful, calm and beautiful. The universe as a whole is perfect. The chaos is on the surface.” — Amit Ray

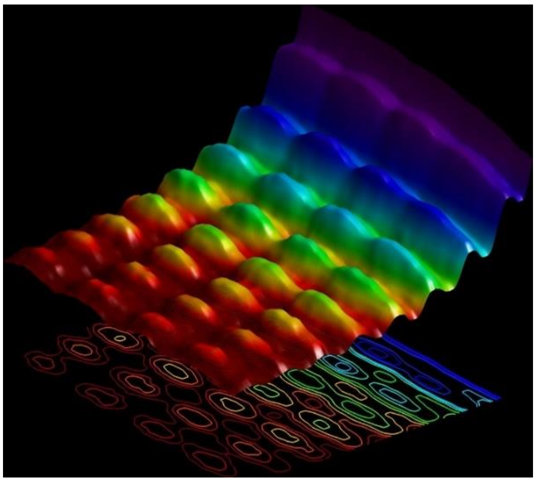
“In the beginning the Universe was created. This has made a lot of people very angry and been widely regarded as a bad move.” – Douglas Adams

“It's not that the universe is confusing; it's that your brain and your lifespan are both too small to understand what's out there.” – Ian Dallas

“God does not play dice with the universe.” — Albert Einstein

“As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality.” — Albert Einstein

Photo Gallery

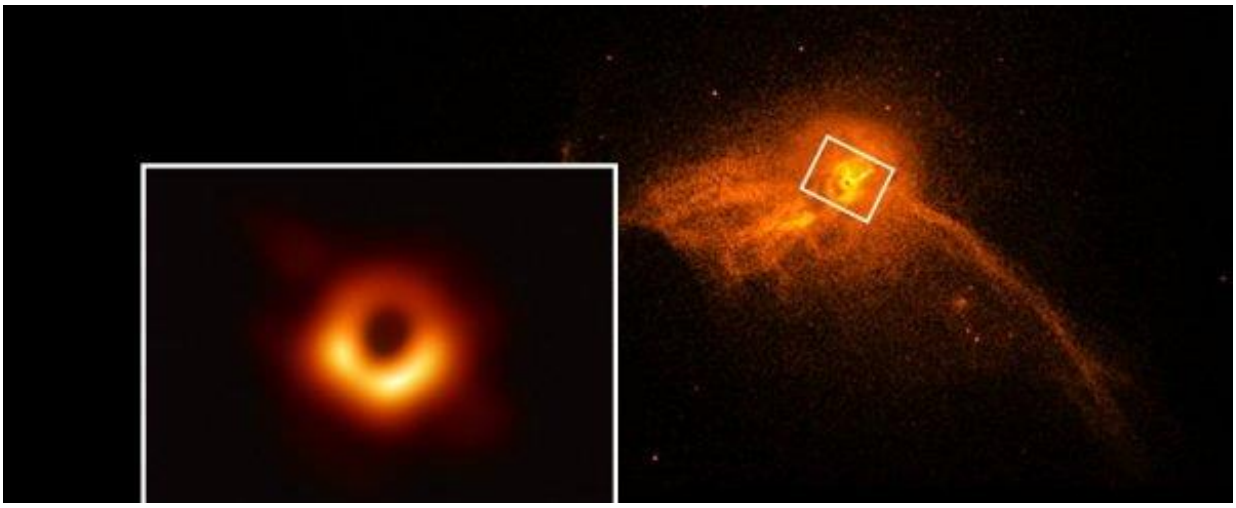


-dual nature of light (particle and wave);

-Albert Einstein;

-the flow of space-time;

-three-dimensional brane;



-first-ever picture of a black hole (2019);

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