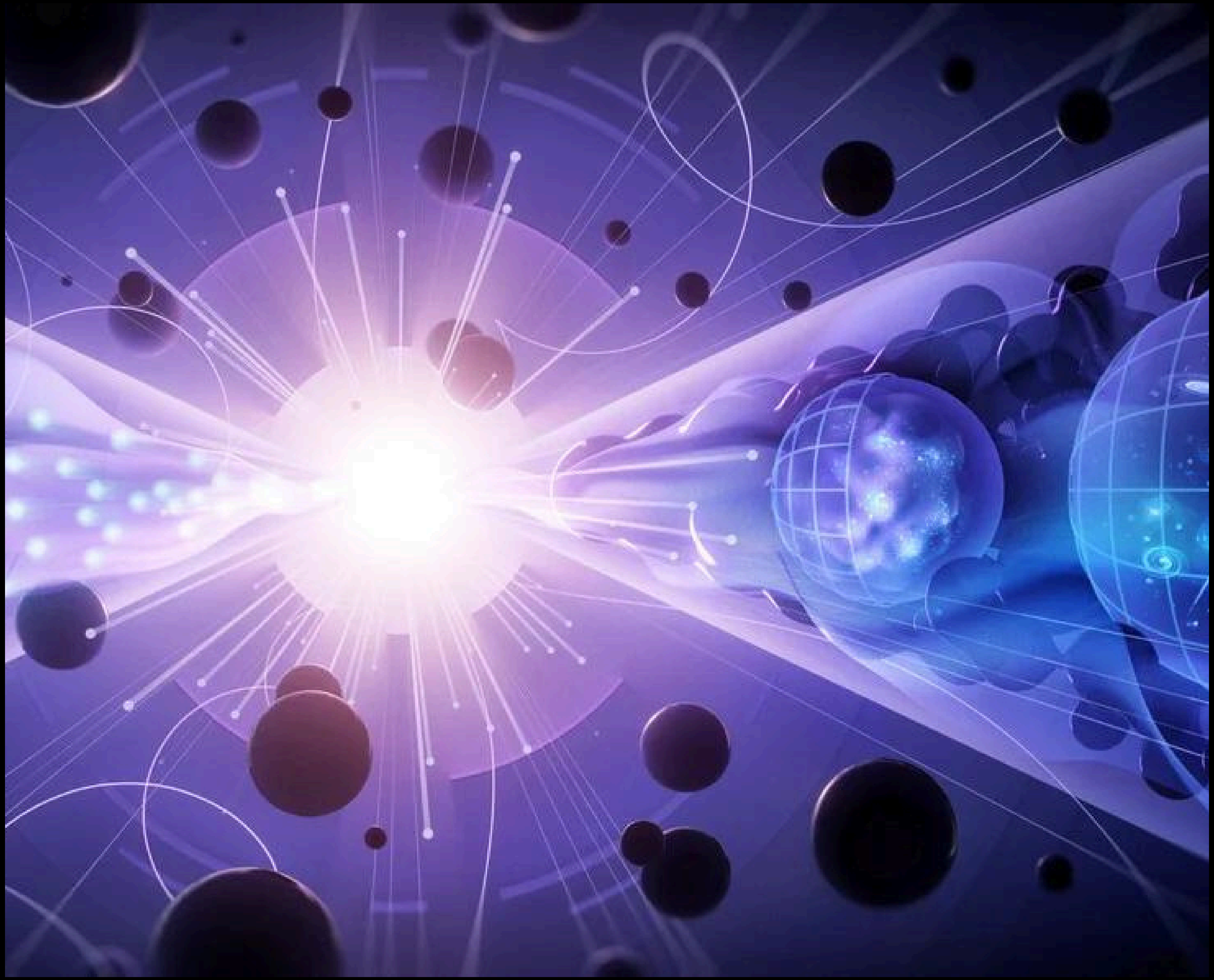
FRONTIER IN PHYSICS

Exploring the mysteries of the universe



cosmology and particle physics

Explore the vast mysteries of the cosmos and the fascinating world of subatomic particles in this presentation on cosmology and particle physics, delving into the fundamental nature of our universe.


COSMOLOGY

Cosmology is the study of the character and evolution of the universe. What are the major characteristics of the universe as we know them today? First, there are approximately 1011 galaxies in the observable part of the universe. An average galaxy contains more than 1011 stars, with our Milky Way galaxy being larger than average, both in its number of stars and its dimensions. Ours is a spiral-shaped galaxy with a diameter of about 100,000 light years and a thickness of about 2000 light years in the arms with a central bulge about 10,000 light years across. The Sun lies about 30,000 light years from the center near the galactic plane. There are significant clouds of gas, and there is a halo of less-dense regions of stars surrounding the main body.


Evidence strongly suggests the existence of a large amount of additional matter in galaxies that does not produce light which we call it dark matter.Light is super fast, and a light year is the distance it travels in one year. Our galaxy, the Milky Way, is so big that light takes 160,000 years to reach nearby small galaxies, like the Magellanic Clouds. Meanwhile, the Andromeda galaxy is a huge spiral galaxy, similar to ours, but it's much farther away, and light takes 2 million years to get from there to Earth. We can barely see Andromeda with our eyes as a dim spot in the sky. And the farthest galaxy we've found is incredibly distant, sitting 14 billion light years from Earth, which is an enormous distance. Light from distant galaxies is like a time machine; it shows us the universe's past. The light from Andromeda took2 million years to reach us, so we're seeing it as it was 2 million years ago. The farthest galaxy's light left 14 billion years ago, giving us a glimpse into the universe's early days. However, studying the universe is tricky because there's a lot we don't know, leading to many theories and discoveries.

In modern cosmology, we understand that the universe is expanding. Galaxies that are relatively close to each other don’t move apart uniformly. But for galaxies more than 50 million light years away, this expansion is consistent. We can calculate how fast a galaxy is moving away from us using the formula v= Hod where v is the galaxy’s recession velocity, d is the distance to the galaxy, and Ho is the Hubble constant. The Hubble constant helps us measure the universe’s expansion rate, which we find by looking at how the speed at which a galaxy moves away from us changes with distance.One of the most intriguing developments recently has been the discovery that the expansion of the universe may be faster now than in the past, rather than slowing due to gravity as expected.

There are many connections of cosmology (physics on the largest scale) with particle physics (physics on the smallest scale). Among these are.

• the dominance of matter over antimatter: In the universe, there's a lot more matter than antimatter. We know this because we don't see big explosions that would happen if there were lots of antimatter around. Even though the laws of physics are almost the same for matter and antimatter, there's a tiny difference. This small difference long ago made a bit more matter than antimatter right after the Big Bang. Because of this, after everything that could cancel out did, we're left with the stars and galaxies made of matter, like the ones we see in the sky.

· the nearly perfect uniformity of the cosmic microwave background: The Cosmic Microwave Background Radiation (CMBR) is very smooth, which puzzled scientists because the early universe needed uneven spots to form galaxies. However, sensitive instruments like COBE and WMAP found tiny fluctuations in the CMBR, proving that the early universe wasn't perfectly smooth after all. These small differences were crucial for the formation of galaxies.

· the mere existence of galaxies: As we look back in time, closer to the Big Bang, the universe was much hotter and denser. At first, it was too hot for galaxies or even atoms to form. Going further back, particles like protons and neutrons couldn't exist due to the extreme conditions.

Even earlier, at about a trillionth of a second after the Big Bang, the universe was so hot that particles associated with the weak force could be created. This period is known as the electroweak epoch. Before that, all forces except gravity were unified, and at an even earlier stage, all forces, including gravity, might have been one, which we call theTheory of Everything. But our understanding of these earliest moments is still incomplete. Since the amount of matter and radiation dominate the universe at early times,

these constituents have the overall cosmological behavior. The present acceleration of the universe can be explained by introducing the cosmological constant or by the existence of quintessence. However, the problem is that the vacuum energy density of quantum particles possesses the same order of magnitudes as the order of the current matter density at ground-based laboratories.

Recently, it has been found a nice coincidence, the so-called late-time cosmic acceleration observation problem between particle physics and cosmology if neutrinos are the source of the former puzzle. The landscape in the present particle theory development is very rich, and various theoretical models are proposed for several couplings and for various energy regions. These can be tested by the experiments at the LHC and from cosmological observations.

General Relativity and Quantum Gravity

- General relativity encompasses special relativity and classical relativity in situations where acceleration is zero and relative velocity is small compared with the speed of light.
- Quantum gravity is the theory that deals with particle exchange of gravitons as the mechanism for the force,

General Relativity

Black Holes

Wormholes and Time Travel

Quantum Gravity

The shortest time

General relativity, also known as the general theory of relativity and Einstein's theory of gravity, is the geometric theory of gravitation published by Albert Einstein in 1915 and is the current description of gravitation in modern physics. General relativity generalizes special relativity and refines Newton's law of universal gravitation, providing a unified description of gravity as a geometric property of space and time or four-dimensional spacetime. In particular, the curvature of spacetime is directly related to the energy and momentum of whatever matter and radiation are present. The relation is specified by the Einstein field equations, a system of second order partial differential equations.

Newton's law of universal gravitation, which describes classical gravity, can be seen as a prediction of general relativity for the almost flat spacetime geometry around stationary mass distributions. Some predictions of general relativity, however, are beyond Newton's law of universal gravitation in classical physics. These predictions concern the passage of time, the geometry of space, the motion of bodies in free fall, and the propagation of light, and include gravitational time dilation, gravitational lensing, the gravitational redshift of light, the Shapiro time delay and singularities/black holes. So far, all tests of general relativity have been shown to be in agreement with the theory. The time-dependent solutions of general relativity enable us to talk about the history of the universe and have provided the modern framework for cosmology, thus leading to the discovery of the Big Bang and cosmic microwave background radiation. Despite the introduction of a number of alternative theories, general relativity continues to be the simplest theory consistent with experimental data.

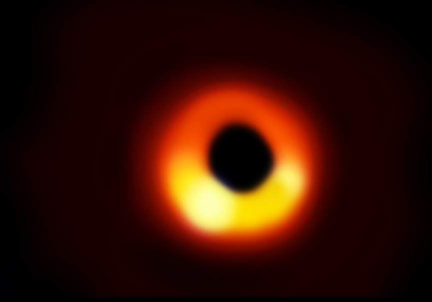
Quantum gravity is the theory that deals with particle exchange of gravitons as the mechanism for the force, and with extreme conditions where quantum mechanics and general relativity must both be used. A good theory of quantum gravity does not yet exist, but one will be needed to understand how all four forces may be unified. If we are successful, the theory of quantum gravity will encompass all others, from classical physics to relativity to quantum mechanics—truly a Theory of Everything (TOE). Quantum gravity is important in those situations where gravity is so extremely strong that it has effects on the quantum scale, where the other forces are ordinarily much stronger.

- **Black holes**

Black holes are objects having such large gravitational fields that things can fall in, but nothing, not even light, can escape.

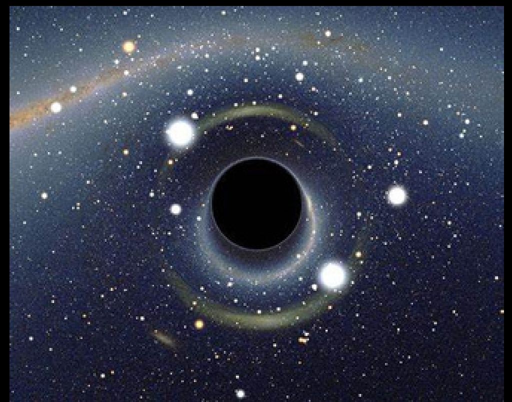
• Black holes

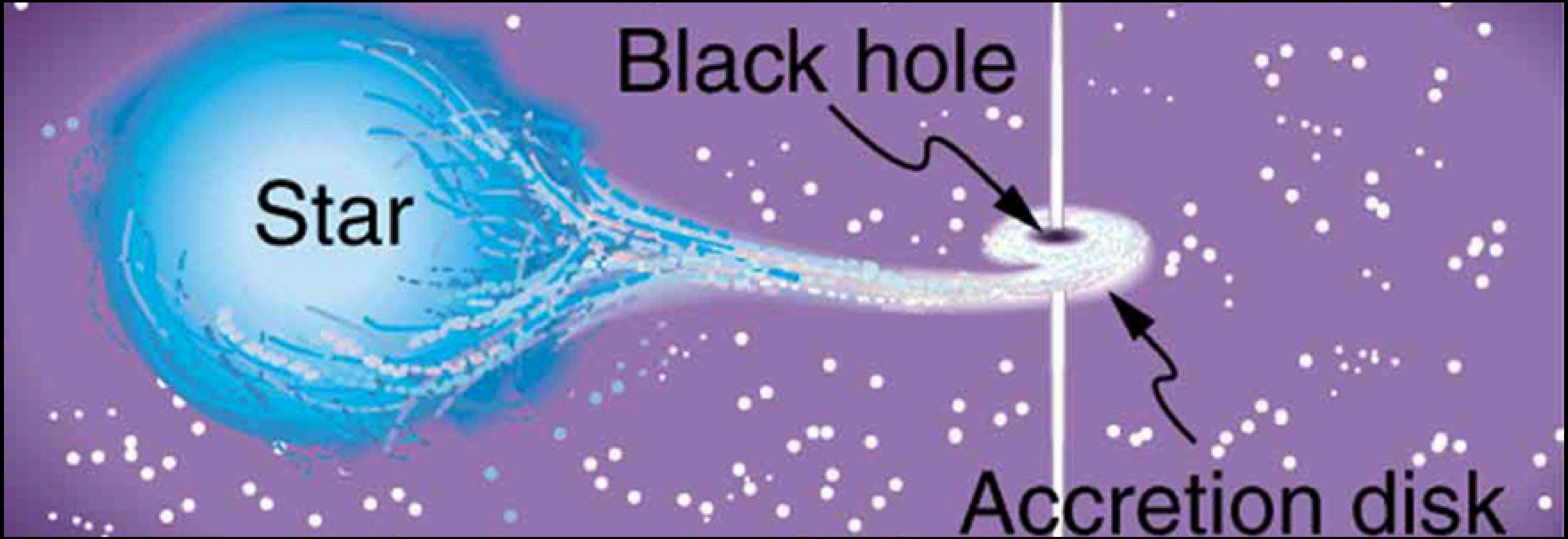
. Bodies, like the Earth or the Sun, have what is called an escape velocity. If an object moves straight up from the body, starting at the escape velocity, it will just be able to escape the gravity of the body. The greater the acceleration of gravity on the body, the greater is the escape velocity. As long ago as the late 1700s, it was proposed that if the escape velocity is greater than the speed of light, then light cannot escape. Simon Laplace (1749–1827), the French astronomer and mathematician, even incorporated this idea of a dark star into his writings. But the idea was dropped after Young's double slit experiment showed light to be a wave. For some time, light was thought not to have particle characteristics and, thus, could not be acted upon by gravity. The idea of a black hole was very quickly reincarnated in 1916 after Einstein's theory of general relativity was published. It is now thought that black holes can form in the supernova collapse of a massive star, forming an object perhaps 10 km across and having a mass greater than that of our Sun.



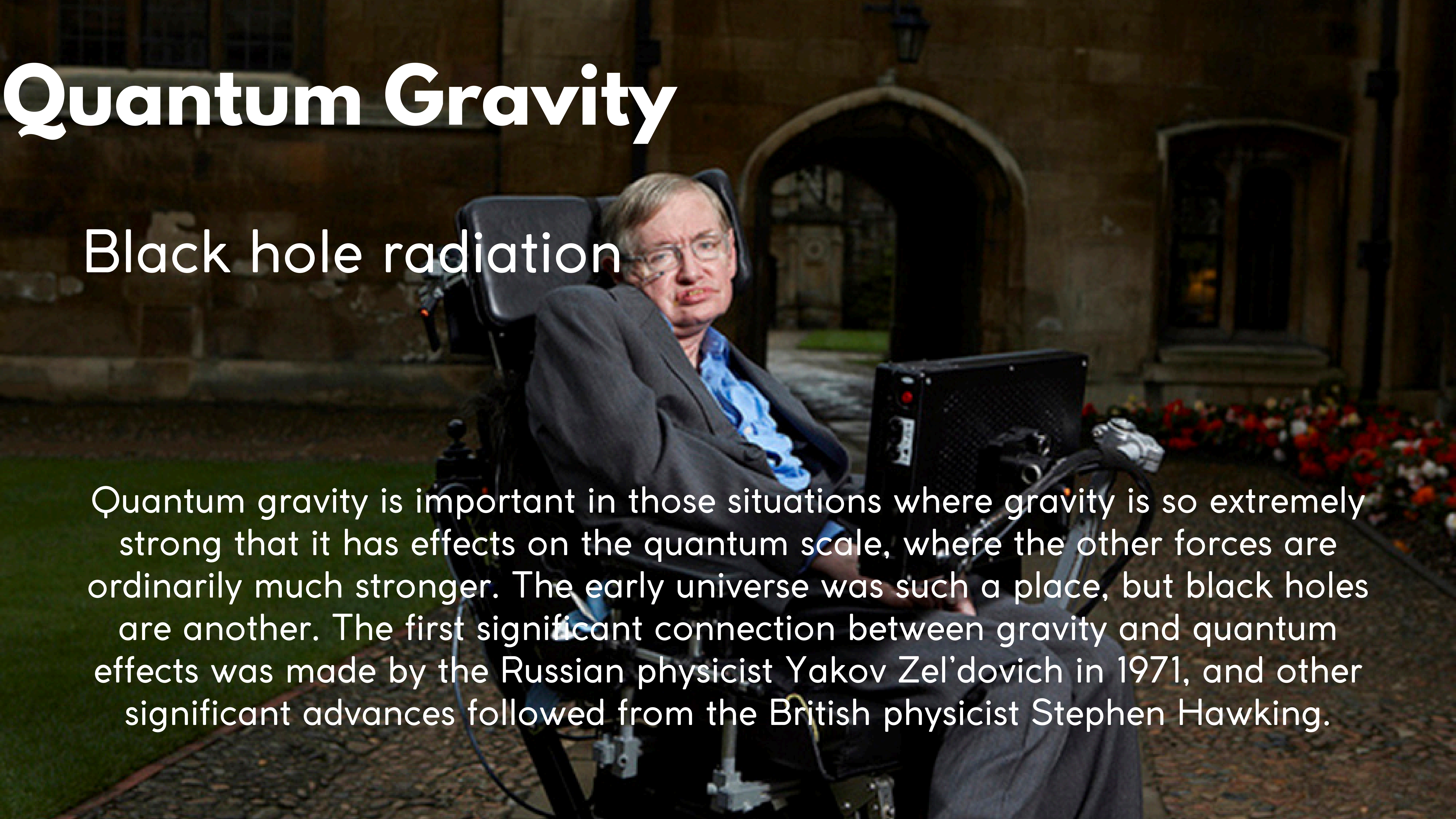
Black holes are difficult to observe directly, because they are small and no light comes directly from them. In fact, no light comes from inside the event horizon, which is defined to be at a distance from the object at which the escape velocity is exactly the speed of light. The radius of the event horizon is known as the Schwarzschild radius RS*R*S and is given by $RS=2GMc^2$

where G is the universal gravitational constant, M is the mass of the body, and c is the speed of light. The event horizon is the edge of the black hole and RS is its radius (that is, the size of a black hole is twice RS). Since G is small and c2 is large, you can see that black holes are extremely small, only a few kilometers for masses a little greater than the Sun's. The object itself is inside the event horizon.





Physics near a black hole is fascinating. Gravity increases so rapidly that, as you approach a black hole, the tidal effects tear matter apart, with matter closer to the hole being pulled in with much more force than that only slightly farther away. This can pull a companion star apart and heat inflowing gases to the point of producing X rays.



Quantum Gravity

Black hole radiation

Quantum gravity is important in those situations where gravity is so extremely strong that it has effects on the quantum scale, where the other forces are ordinarily much stronger. The early universe was such a place, but black holes are another. The first significant connection between gravity and quantum effects was made by the Russian physicist Yakov Zel'dovich in 1971, and other significant advances followed from the British physicist Stephen Hawking.

These two showed that black holes could radiate away energy by quantum effects just outside the event horizon (nothing can escape from inside the event horizon). Black holes are, thus, expected to radiate energy and shrink to nothing, although extremely slowly for most black holes. The mechanism is the creation of a particle-antiparticle pair from energy in the extremely strong gravitational field near the event horizon.One member of the pair falls into the hole and the other escapes, conserving momentum.(see figure 3.24) When a black hole loses energy and, hence, rest mass, its event horizon shrinks, creating an even greater gravitational field. This increases the rate of pair production so that the process grows exponentially until the black hole is nuclear in size. A final burst of particles and γγ rays ensues. This is an extremely slow process for black holes about the mass of the Sun (produced by supernovas) or larger ones (like those thought to be at galactic centers), taking on the order of 10^67 years or longer!

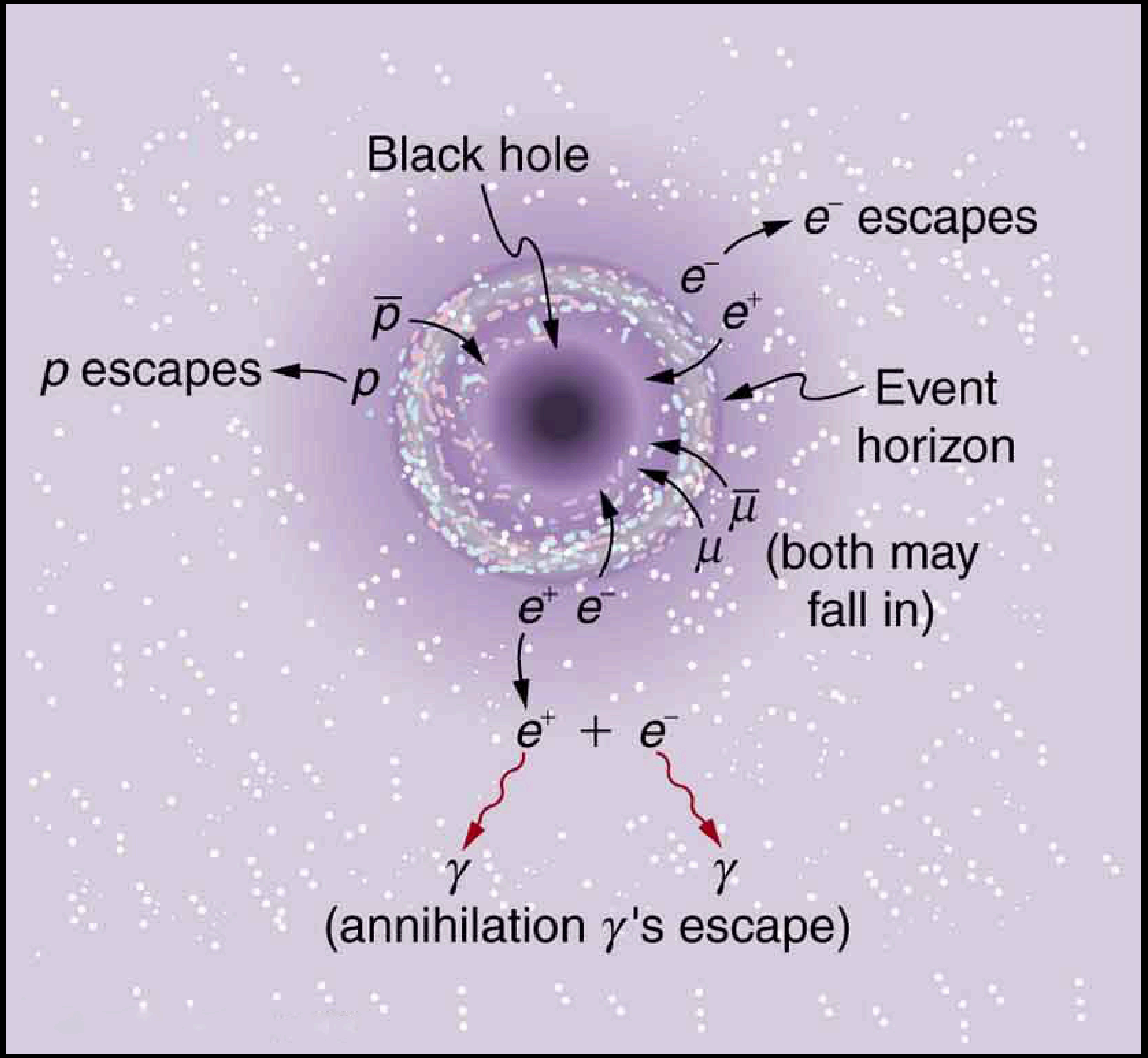
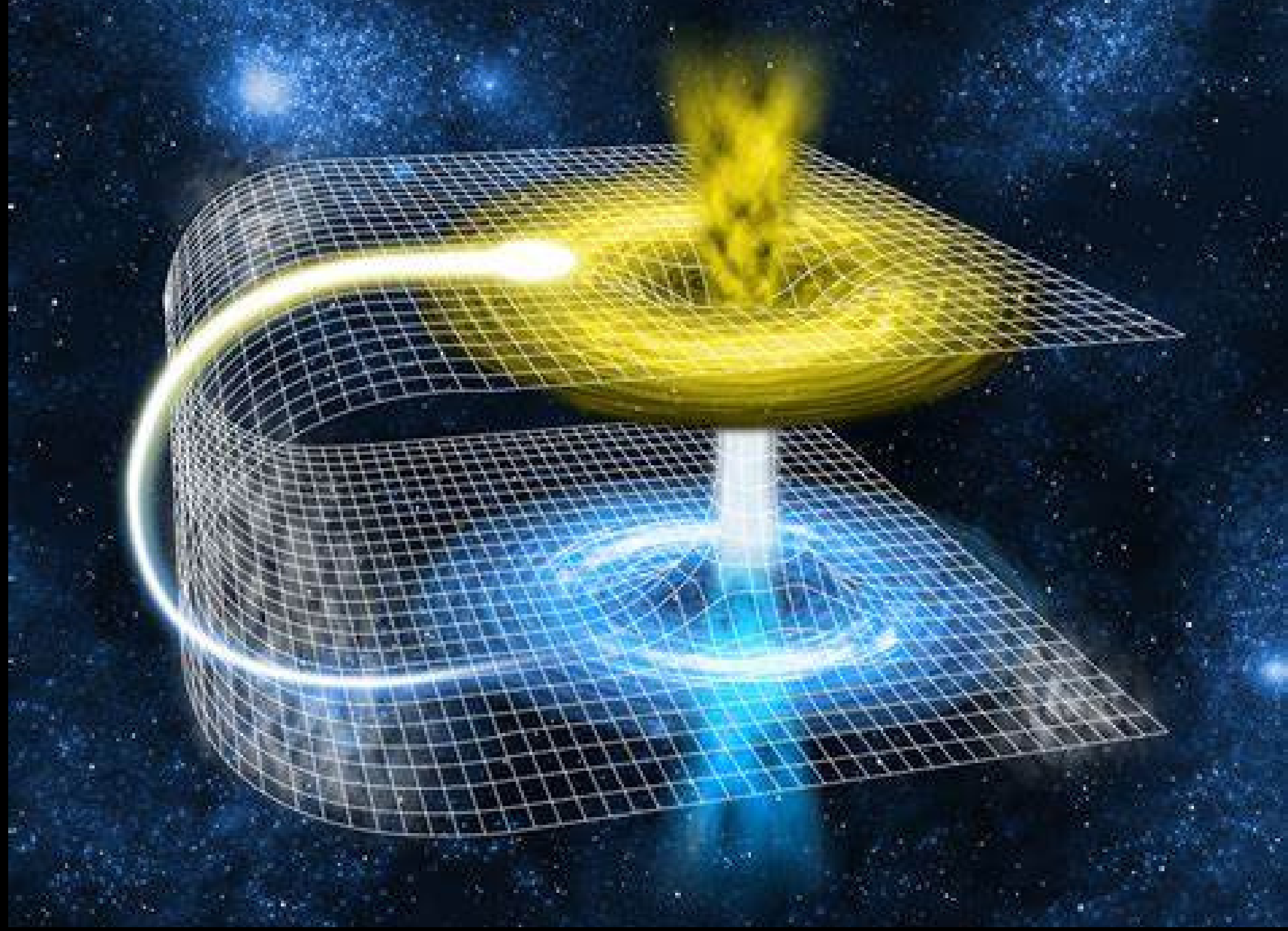


figure 3.24 Gravity and quantum mechanics come into play when a black hole creates a particle-antiparticle pair from the energy in its gravitational field. One member of the pair falls into the hole while the other escapes, removing energy and shrinking the black hole. The search is on for the characteristic energy.

Wormholes and time travel



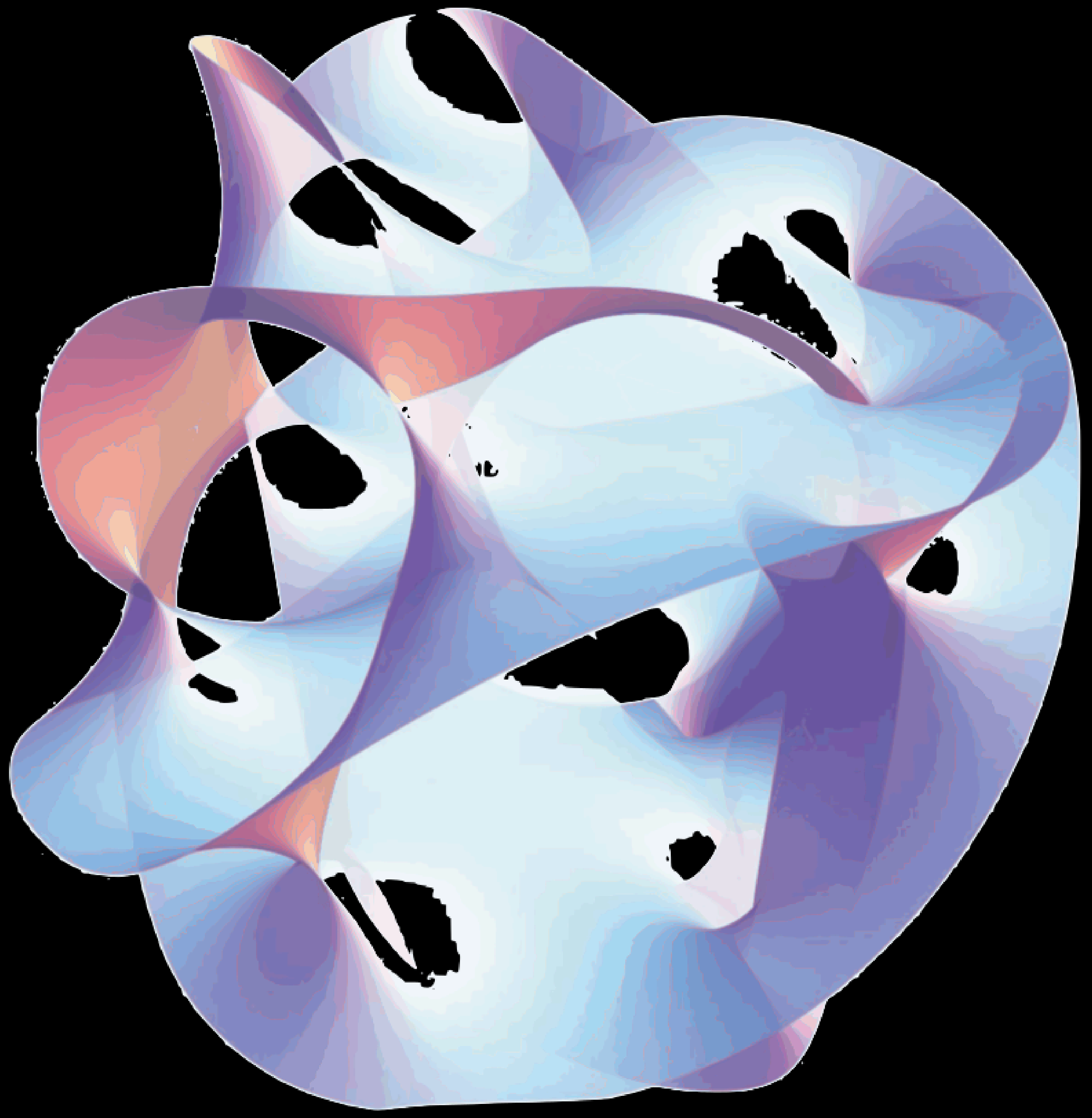
The subject of time travel captures the imagination. Theoretical physicists, such as the American Kip Thorne, have treated the subject seriously, looking into the possibility that falling into a black hole could result in popping up in another time and place—a trip through a so-called wormhole. Time travel and wormholes appear in innumerable science fiction dramatizations, but the consensus is that time travel is not possible in theory. While still debated, it appears that quantum gravity effects inside a black hole prevent time travel due to the creation of particle pairs. Direct evidence is elusive.

The shortest Time

Theoretical studies indicate that, at extremely high energies and correspondingly early in the universe, quantum fluctuations may make time intervals meaningful only down to some finite time limit. Early work indicated that this might be the case for times as long as 10^-43s
, the time at which all forces were unified. If so, then it would be meaningless to consider the universe at times earlier than this. Subsequent studies indicate that the crucial time may be as short as 10^-95s
. But the point remains—quantum gravity seems to imply that there is no such thing as a vanishingly short time. Time may, in fact, be grainy with no meaning to time intervals shorter than some tiny but finite size.

Superstrings

- Superstring theory holds that fundamental particles are one-dimensional vibrations analogous to those on strings and is an attempt at a theory of quantum gravity.

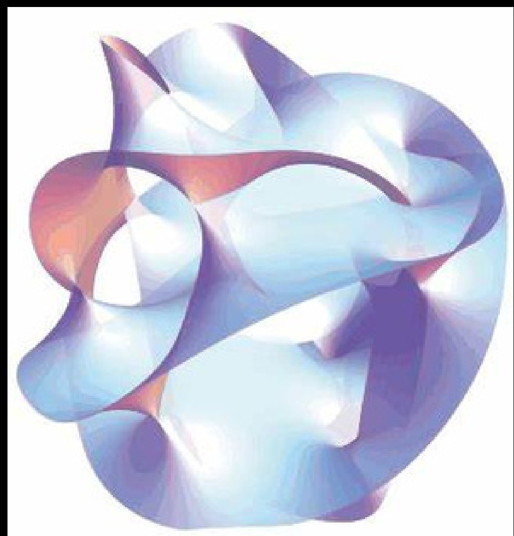


Introduced earlier in GUTS: The Unification of Forces Superstring theory is an attempt to unify gravity with the other three forces and, thus, must contain quantum gravity. The main tenet of Superstring theory is that fundamental particles, including the graviton that carries the gravitational force, act like one-dimensional vibrating strings. Since gravity affects the time and space in which all else exists, Superstring theory is an attempt at a Theory of Everything (TOE). Each independent quantum number is thought of as a separate dimension in some super space (analogous to the fact that the familiar dimensions of space are independent of one another) and is represented by a different type of Superstring. As the universe evolved after the Big Bang and forces became distinct (spontaneous symmetry breaking), some of the dimensions of super space are imagined to have curled up and become unnoticed.

Forces are expected to be unified only at extremely high energies and at particle separations on the order of 10-35m

. This could mean that Superstrings must have dimensions or wavelengths of this size or smaller. Just as quantum gravity may imply that there are no time intervals shorter than some finite value, it also implies that there may be no sizes smaller than some tiny but finite value. That may be about 10-35m

. If so, and if Superstring theory can explain all it strives to, then the structures of Superstrings are at the lower limit of the smallest possible size and can have no further substructure. This would be the ultimate answer to the question the ancient Greeks considered. There is a finite lower limit to space.

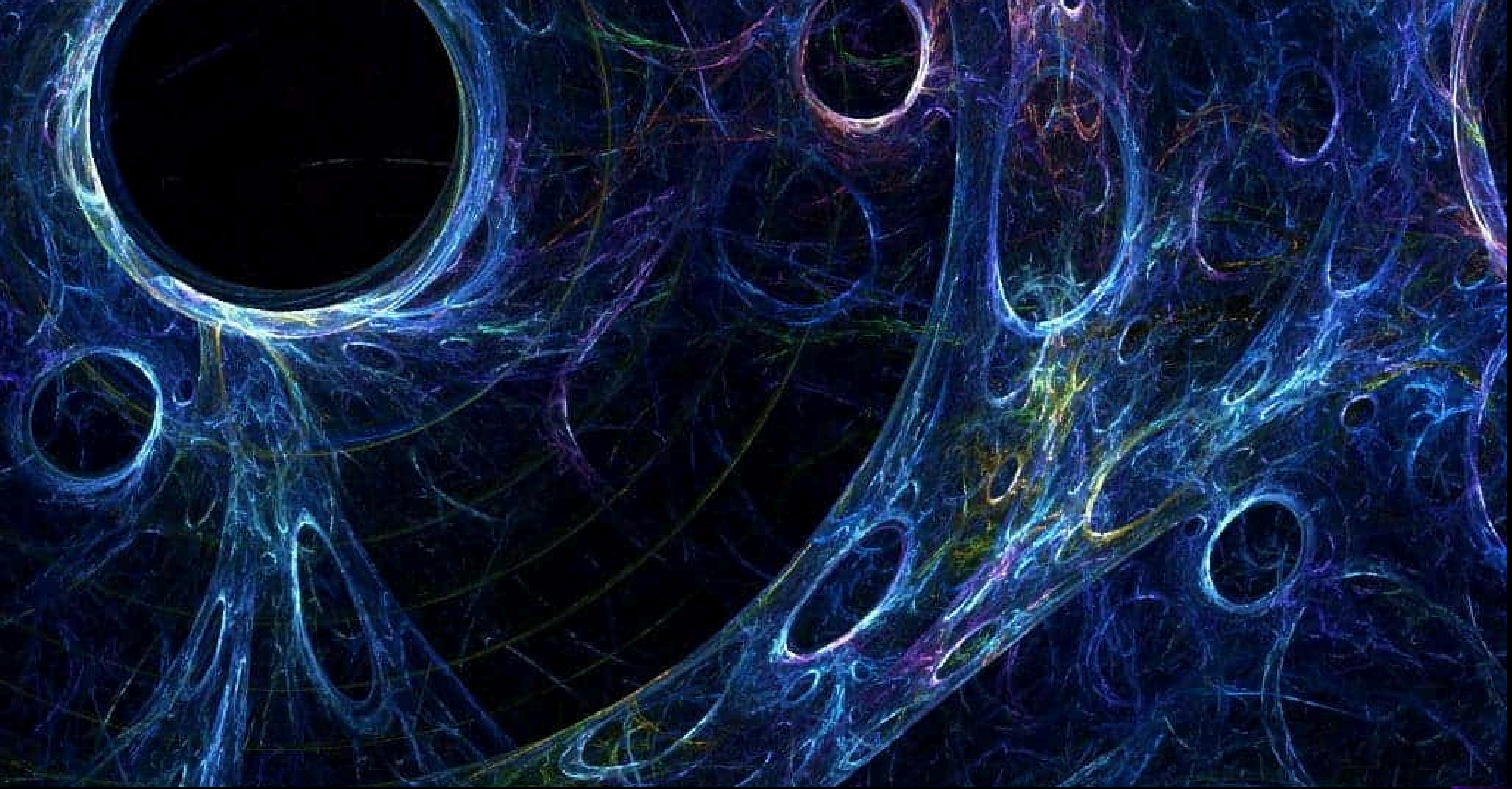
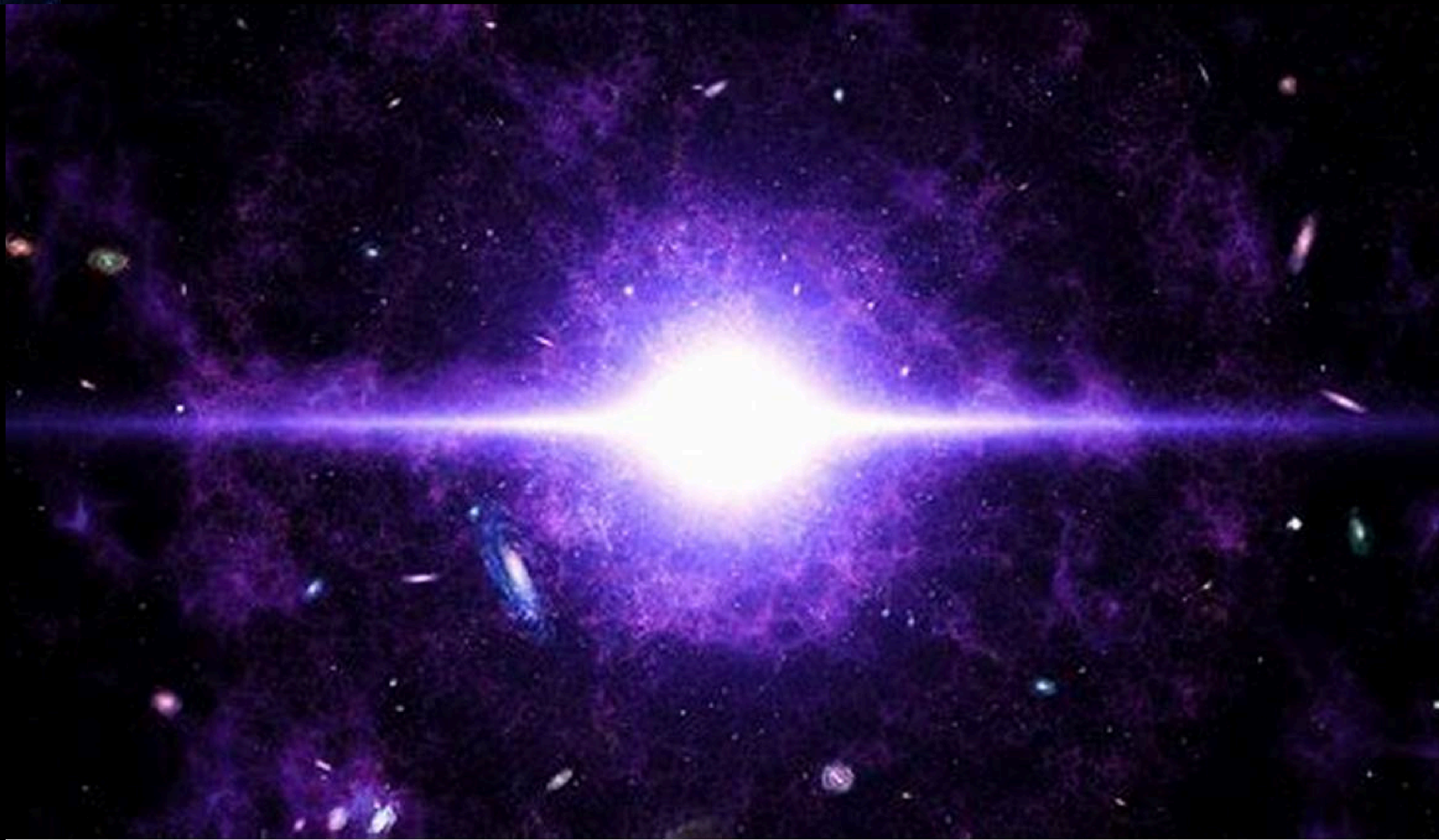


Not only is Superstring theory in its infancy, it deals with dimensions about 17 orders of magnitude smaller than the 10-18m10-18m details that we have been able to observe directly. It is thus relatively unconstrained by experiment, and there are a host of theoretical possibilities to choose from. This has led theorists to make choices subjectively (as always) on what is the most elegant theory, with less hope than usual that experiment will guide them. It has also led to speculation of alternate universes, with their Big Bangs creating each new universe with a random set of rules. These speculations may not be tested even in principle, since an alternate universe is by definition unattainable. It is something like exploring a self-consistent field of mathematics, with its axioms and rules of logic that are not consistent with nature. Such endeavors have often given insight to mathematicians and scientists alike and occasionally have been directly related to the description of new discoveries.

Dark Matter

What is Dark Matter?

There is as yet no answer to this question, but it is becoming increasingly clear what it is not. Detailed observations of the cosmic microwave background with the WMAP satellite show that the dark matter cannot be in the form of normal, baryonic matter, that is, protons and neutrons that compose stars, planets, and interstellar matter. That rules out hot gas, cold gas, brown dwarfs, red dwarfs, white dwarfs, neutron stars and black holes. Dark matter is hypothetical form of matter that is thought to make up approximately 27% of the universe's mass-energy density. It is called "dark" because it does not emit, absorb, or reflect any electromagnetic radiation, making it invisible to our telescopes. Despite its elusive nature, dark matter's presence can be inferred through its gravitational effects on visible matter and the way galaxies and galaxy clusters move.

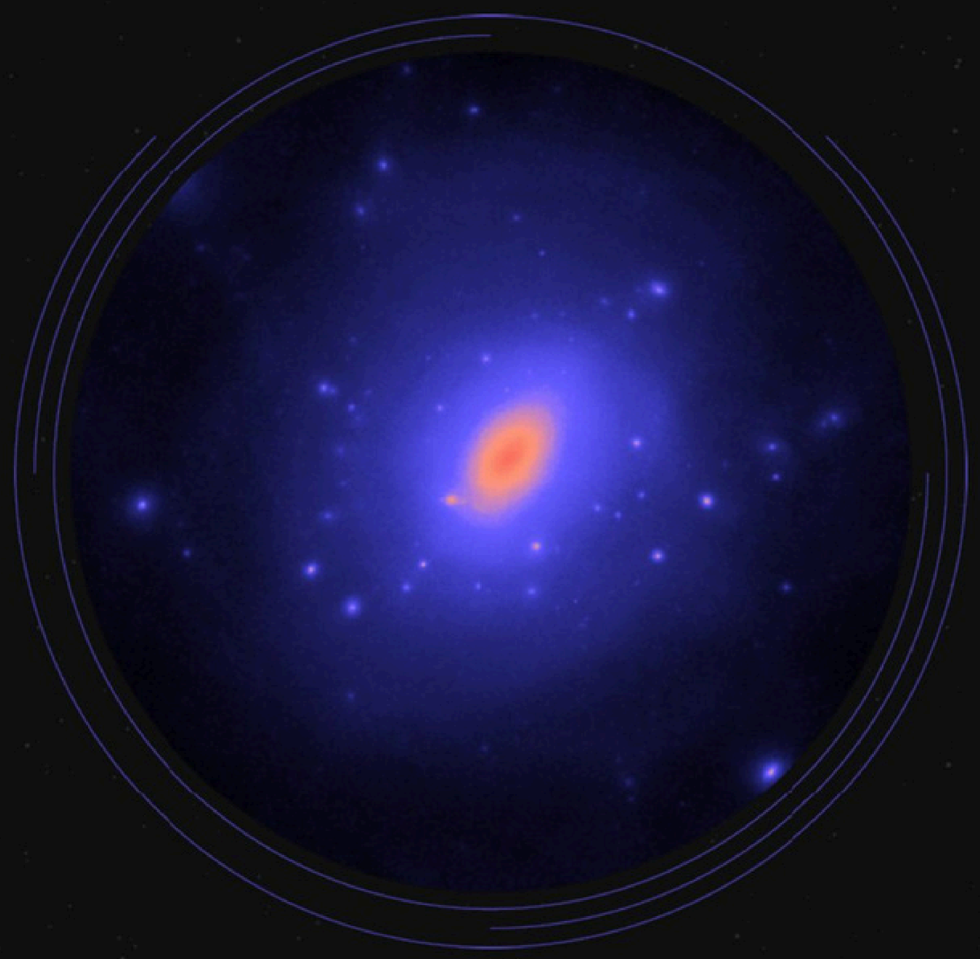



The existence of dark matter was first proposed by Swiss astrophysicist Fritz Zwicky in the 1930's, based on observations of the Coma galaxy cluster. Since then, a wealth of observational evidence has accumulated, including the rotation curves of galaxies, the formation of galaxy clusters, and the large-scale structure of the universe. Black holes would seem to be the ideal dark matter candidate,

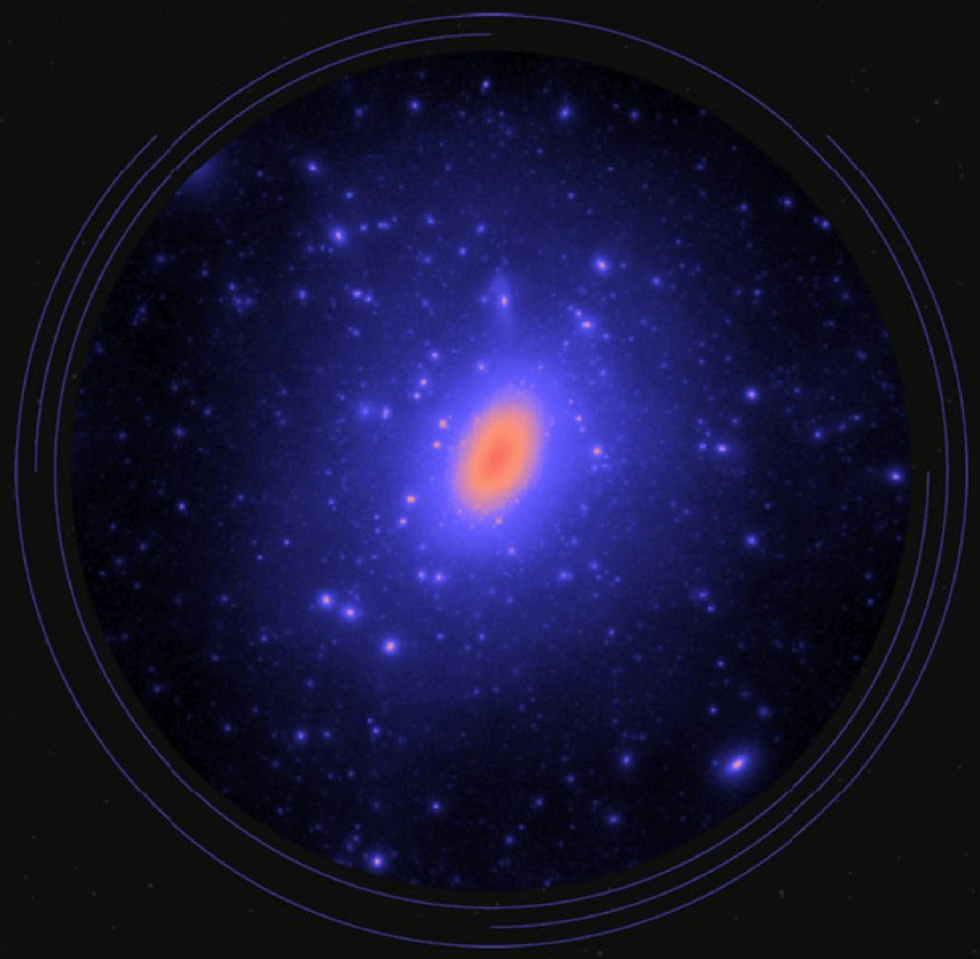
and they are indeed very dark. However stellar mass black holes are produced by the collapse of massive stars which are much scarcer than normal stars, which contain at most one-fifth of the mass of dark matter. Also, the processes that would produce enough black holes to explain the dark matter would release a lot of energy and heavy elements; there is no evidence of such a release. The non-baryonic candidates can be grouped into three broad categories: hot, warm and cold. Hot dark matter refers to particles, such as the known types of neutrinos, which are moving at near the speed of light when the clumps that would form galaxies and clusters of galaxies first began to grow. Cold dark matter refers to particles that were moving slowly when the pre-galactic clumps began to form, and warm dark matter refers to particles with speeds intermediate between hot and cold dark matter.

This classification has observational consequences for the size of clumps that can collapse in the expanding universe. Hot dark matter particles are moving so rapidly that clumps with the mass of a galaxy will quickly disperse. Only clouds with the mass of thousands of galaxies, that is, the size of galaxy clusters, can form. Individual galaxies would form later as the large cluster-sized clouds fragmented, in a top-down process. In contrast, cold dark matter can form into clumps of galaxy-sized mass or less. Galaxies would form first, and clusters would form as galaxies merge into groups,
and groups into clusters in a bottom-up process. The leading candidates for cold dark matter are particles called WIMPs, for Weakly Interacting Massive Particles. WIMPs are not predicted by the so-called Standard Model for elementary particles, but attempts to construct a unified theory of all elementary particles suggest that WIMPs might have been produced in great numbers when the universe was a fraction of a second old. A typical WIMP is predicted to be at least 100 times as massive as a hydrogen atom.

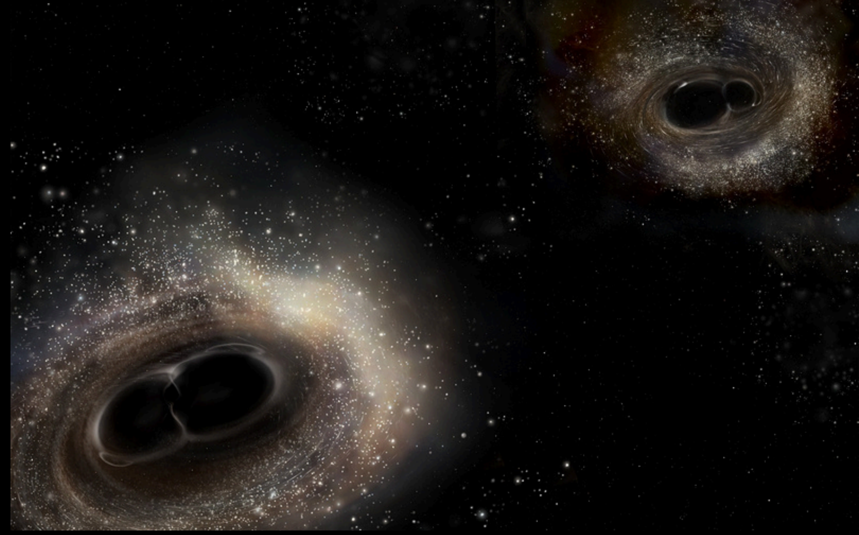
WDM



CDM



Source: Bullock & Boylan-Kolchin 2017 / Simulations by V. Robles, T. Kelley, and B. Bozek+



The search for dark matter is an active area of research, with scientists employing a variety of methods to detect and study it. These include gravitational lensing, which involves measuring the bending of light around massive objects, and the observation of the cosmic microwave background radiation. Several theories havebeen proposed to explain the nature of dark matter, including the possibility that it is composed of weakly interacting massive particles (WIMPs). However, none of these theories have been proven conclusively, and the search for dark matter remains an open problem in physics. In popular culture, dark matter has been featured in various works of science fiction, often with extraordinary physical or magical properties. However, in the scientific community, dark matter remains a fascinating and mysterious component of the universe, with much still to be learned about its properties and behavior.

What is the evidence for the existence of dark matter?

The evidence for the existence of dark matter includes:

· Galactic Rotation Curves: Observations of the rotation curves of galaxies show that stars at the outskirts move faster than expected based on visible matter alone, indicating the presence of unseen matter that increases the gravity experienced by these stars.

· Gravitational Lensing: Studies of the Bullet Cluster, where two galaxies collided, revealed the mass of celestial objects using gravitational lensing. This technique relies on the fact that mass influences the density of space, causing light to bend. The observed bending of light supports the presence of unseen mass.

· Galactic Dynamics: Vera Rubin's observations of spiral galaxies showed that stars at the edges moved as fast as those closer to the center, suggesting a significant amount of invisible matter in the outer regions. This discrepancy between visible and inferred mass supports the existence of dark matter.

· Cosmic Microwave Background: The large-scale wave patterns of mass density in the universe provide indirect evidence for dark matter, as they suggest the presence of additional energy that is not ordinary matter or dark matter, contributing to the universe's flatness.

Theoretical Yearnings for Closure

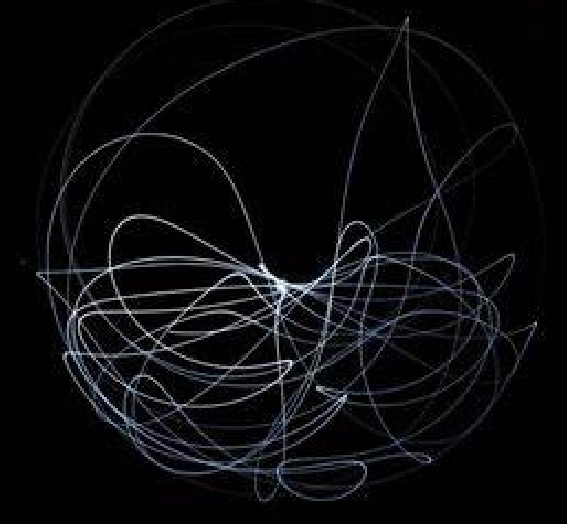
Is the universe open or closed? That is, will the universe expand forever or will it stop, perhaps to contract? This, until recently, was a question of whether there is enough gravitation to stop the expansion of the universe. In the past few years, it has become a question of the combination of gravitation and what is called the cosmological constant. The cosmological constant was invented by Einstein to prohibit the expansion or contraction of the universe. At the time he developed general relativity, Einstein considered that an illogical possibility. The cosmological constant was discarded after Hubble discovered the expansion, but has been re-invoked in recent years.

Gravitational attraction between galaxies is slowing the expansion of the universe, but the amount of slowing down is not known directly. In fact, the cosmological constant can counteract gravity's effect. As recent measurements indicate, the universe is expanding faster now than in the past—perhaps a "modern inflationary era" in which the dark energy is thought to be causing the expansion of the present-day universe to accelerate. If the expansion rate were affected by gravity alone, we should be able to see that the expansion rate between distant galaxies was once greater than it is now. However, measurements show it was less than now. We can, however, calculate the amount of slowing based on the average density of matter we observe directly. Here we have a definite answer—there is far less visible matter than needed to stop expansion. The critical density ρc is defined to be the density needed to just halt universal expansion in a universe with no cosmological constant. It is estimated to be about ρc ≈ 10^-26 kg/m3.

However, this estimate of ρc is only good to about a factor of two, due to uncertainties in the expansion rate of the universe. The critical density is equivalent to an average of only a few nucleons per cubic meter, remarkably small and indicative of how truly empty intergalactic space is. Luminous matter seems to account for roughly 0.5% to 2% of the critical density, far less than that needed for closure. Taking into account the amount of dark matter we detect indirectly and all other types of indirectly observed normal matter, there is only 10% to 40% of what is needed for closure. If we are able to refine the measurements of expansion rates now and in the past, we will have our answer regarding the curvature of space and we will determine a value for the cosmological constant to justify this observation. Finally, the most recent measurements of the CMBR have implications for the cosmological constant, so it is not simply a device concocted for a single purpose.

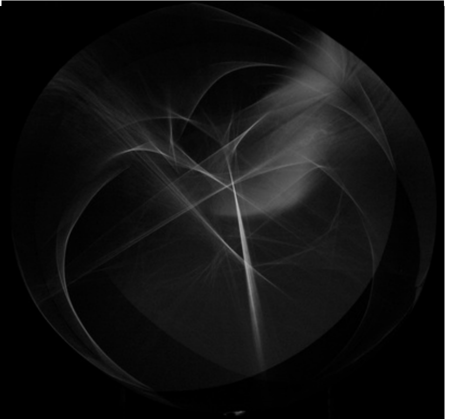
After the recent experimental discovery of the cosmological constant, most researchers feel that the universe should be just barely open. Since matter can be thought to curve the space around it, we call an open universe negatively curved. This means that you can in principle travel an unlimited distance in any direction. A universe that is closed is called positively curved. This means that if you travel far enough in any direction, you will return to your starting point, analogous to circumnavigating the Earth. In between these two is a flat (zero curvature) universe. The recent discovery of the cosmological constant has shown the universe is very close to flat, and will expand forever. Why do theorists feel the universe is flat? Flatness is a part of the inflationary scenario that helps explain the flatness of the microwave background. In fact, since general relativity implies that matter creates the space in which it exists, there is a special symmetry to a flat universe.

Complexity and Chaos



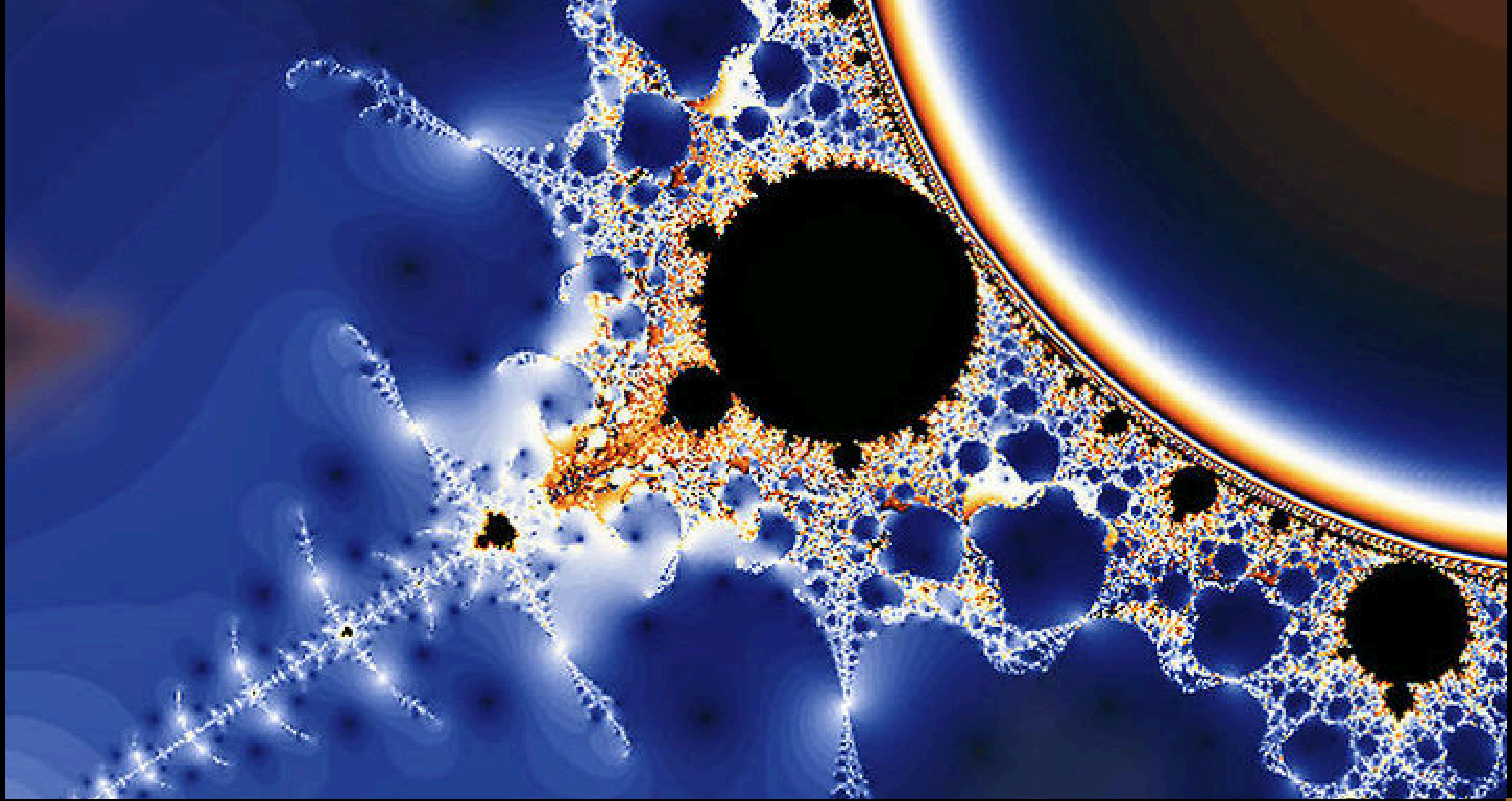
The simple laws of physics apply, of course, but complex systems may reveal patterns that simple systems do not. The emerging field of complexity is devoted to the study of complex systems, including those outside the traditional bounds of physics. Of particula interest is the ability of complex systems to adapt and evolve.Complexity as a discipline examines complex systems, how they adapt and evolve, looking for similarities with other complex adaptive systems.What are some examples of complex adaptive systems' One is the primordial ocean. When the oceans first formed, they were a random mix o elements and compounds that obeyed the laws of physics and chemistry. In a relatively short geological time (about 500 million years), life had emerged. Laboratory simulations indicate that the emergence of life was far too fast to have come from random combinations of compounds, even if driven by lightning and heat. There must be an underlying ability of the complex system to organize itself, resulting in the self-replication we recognize as life.

In traditional physics, the discipline of complexity may yield insights in certain areas. Thermodynamics treats systems on the average, while statistical mechanics deals in some detail with complex systems of atoms and molecules in random thermal motion. Yet there is organization, adaptation, and evolution in those complex systems. Non-equilibrium phenomena, such as heat transfer and phase changes, are characteristically complex in detail, and new approaches to them may evolve from complexity as a discipline. Crystal growth is another example of self-organization spontaneously emerging in a complex system. Alloys are also inherently complex mixtures that show certain simple characteristics implying some self-organization. The organization of iron atoms into magnetic domains as they cool is another. Perhaps insights into these difficult areas will emerge from complexity. But at the minimum, the discipline of complexity is another example of human effort to understand and organize the universe around us, partly rooted in the discipline of physics.

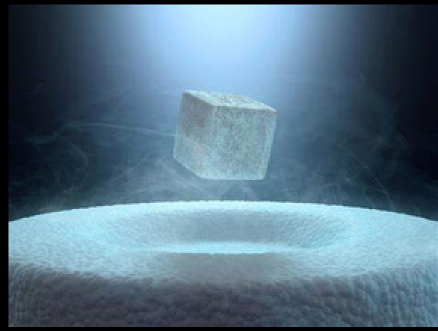


A predecessor to complexity is the topic of chaos, which has been widely publicized and has become a discipline of its own. It is also based partly in physics and treats broad classes of phenomena from many disciplines. Chaos is a word used to describe systems whose outcomes are extremely sensitive to initial conditions. The orbit of the planet Pluto, for example, may be chaotic in that it can change tremendously due to small interactions with other planets. This makes its long-term behavior impossible to predict with precision, just as we cannot tell precisely where a decaying Earth satellite will land or how many pieces it will break into. But the discipline of chaos has found ways to deal with such systems and has been applied to apparently unrelated systems. For example, the heartbeat of people with certain types of potentially lethal arrhythmias seems to be chaotic, and this knowledge may allow more sophisticated monitoring and recognition of the need for intervention. Chaos is related to complexity. Some chaotic systems are also inherently complex;

Examples of chaotic systems are beautiful fractal patterns such as in Figure below. Some chaotic systems exhibit self-organization, a type of stable chaos. The orbits of the planets in our solar system, for example, may be chaotic (we are not certain yet). But they are definitely organized and systematic, with a simple formula describing the orbital radii of the first eight planets and the asteroid belt. Large-scale vortices in Jupiter's atmosphere are chaotic, but the Great Red Spot is a stable self-organization of rotational energy.The Great Red Spot has been in existence for at least 400 years and is a complex self-adaptive system.




High-temperature Superconductors



Superconductors are materials with a resistivity of zero. They are familiar to the general public because of their practical applications and have been mentioned at a number of points in the text. Because the resistance of a piece of superconductor is zero, there are no heat losses for currents through them; they are used in magnets needing high currents, such as in MRI machines, and could cut energy losses in power transmission. But most superconductors must be cooled to temperatures only a few kelvin above absolute zero, a costly procedure limiting their practical applications.

Superconductivity was discovered accidentally in 1911 by the Dutch physicist H. Kamerlingh Onnes (1853–1926) when he used liquid helium to cool mercury. Onnes had been the first person to liquefy helium a few years earlier and was surprised to observe the resistivity of a mediocre conductor like mercury drop to zero at a temperature of 4.2 K. We define the temperature at which and below which a material becomes a superconductor to be its critical temperature, denoted by Tc. Progress in understanding how and why a material became a superconductor was relatively slow, with the first workable theory coming in 1957. Certain other elements were also found to become superconductors, but all had Tc s less than 10 K, which are expensive to maintain. Although Onnes received a Nobel prize in 1913, it was primarily for his work with liquid helium.

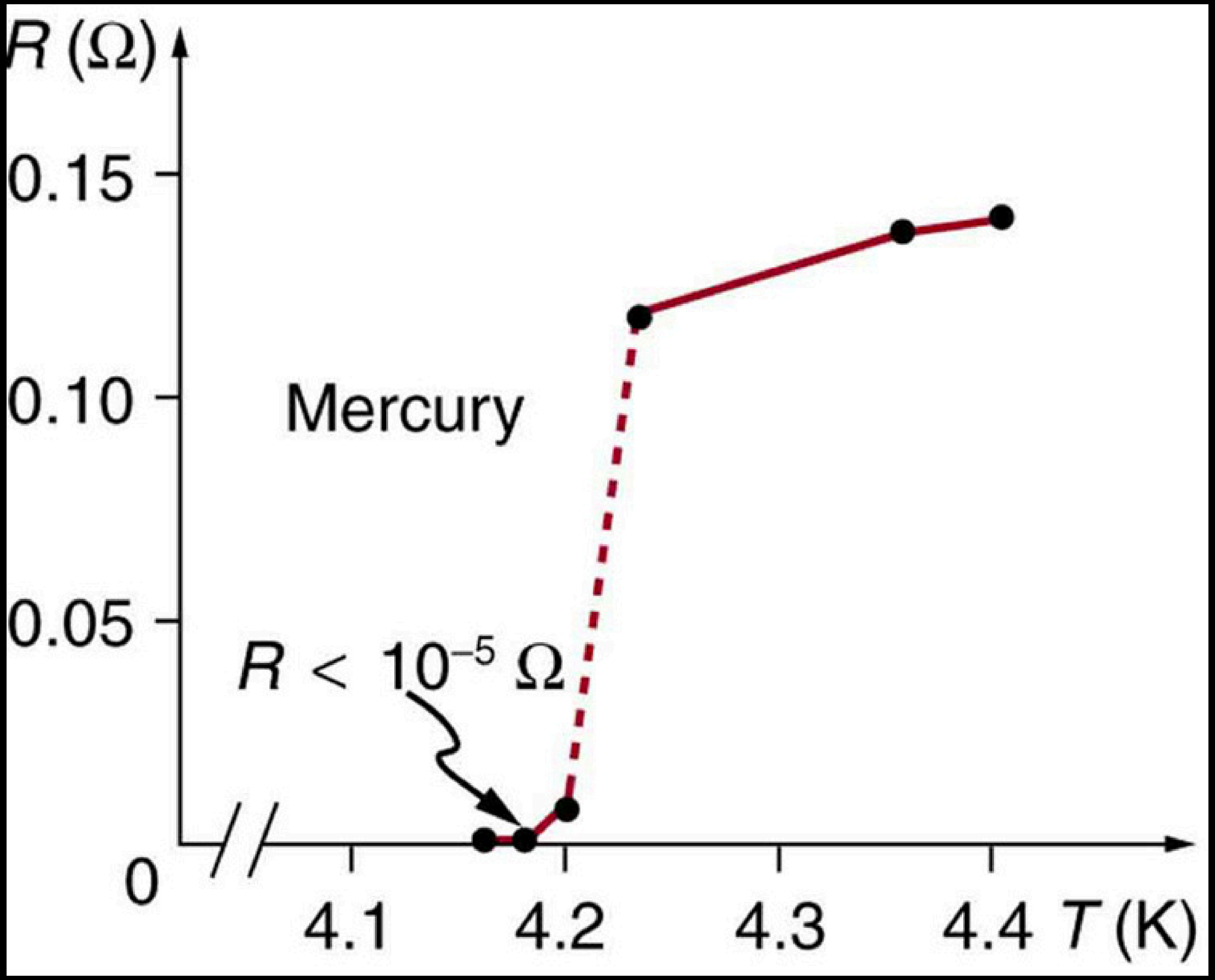


Figure 1. A graph of resistivity versus temperature for a superconductor shows a sharp transition to zero at the critical temperature Tc. High temperature superconductors have verifiable Tcs greater than 125 K, well above the easily achieved 77-K temperature of liquid nitrogen.

In 1986, a breakthrough was announced—a ceramic compound was found to have an unprecedented Tc of 35 K. It looked as if much higher critical temperatures could be possible, and by early 1988 another ceramic (this of thallium, calcium, barium, copper, and oxygen) had been found to have Tc = 125 K (see Figure 2.) The economic potential of perfect conductors saving electric energy is immense for Tc s above 77 K, since that is the temperature of liquid nitrogen. Although liquid helium has a boiling point of 4 K and can be used to make materials superconducting, it costs about $5 per liter. Liquid nitrogen boils at 77 K, but only costs about $0.30 per liter. There was general euphoria at the discovery of these complex ceramic superconductors, but this soon subsided with the sobering difficulty of forming them into usable wires. The first commercial use of a high temperature superconductor is in an electronic filter for cellular phones. High-temperature superconductors are used in experimental apparatus, and they are actively being researched, particularly in thin film applications.

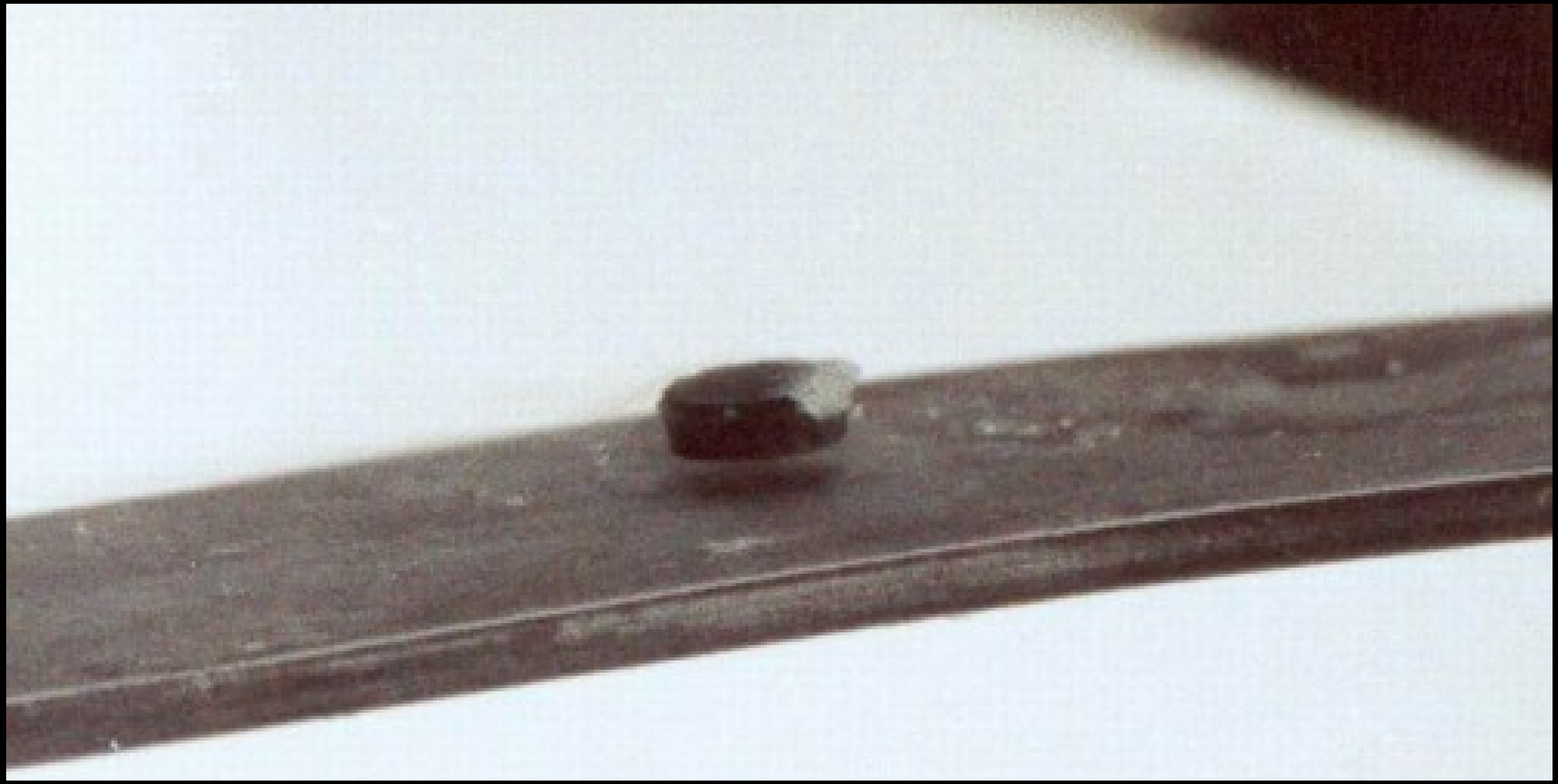


Figure 2. One characteristic of a superconductor is that it excludes magnetic flux and, thus, repels other magnets. The small magnet levitated above a high-temperature superconductor, which is cooled by liquid nitrogen, gives evidence that the material is superconducting. When the material warms and becomes conducting, magnetic flux can penetrate it, and the magnet will rest upon it. (credit: Saperaud)

The search is on for even higher Tc superconductors, many of complex and exotic copper oxide ceramics, sometimes including strontium, mercury, or yttrium as well as barium, calcium, and other elements. Room temperature (about 293 K) would be ideal, but any temperature close to room temperature is relatively cheap to produce and maintain. There are persistent reports of Tc s over 200 K and some in the vicinity of 270 K. Unfortunately, these observations are not routinely reproducible, with samples losing their superconducting nature once heated and recooled (cycled) a few times (see Figure 3.) They are now called USOs or unidentified superconducting objects, out of frustration and the refusal of some samples to show high Tc even though produced in the same manner as others. Reproducibility is crucial to discovery, and researchers are justifiably reluctant to claim the breakthrough they all seek. Time will tell whether USOs are real or an experimental quirk.

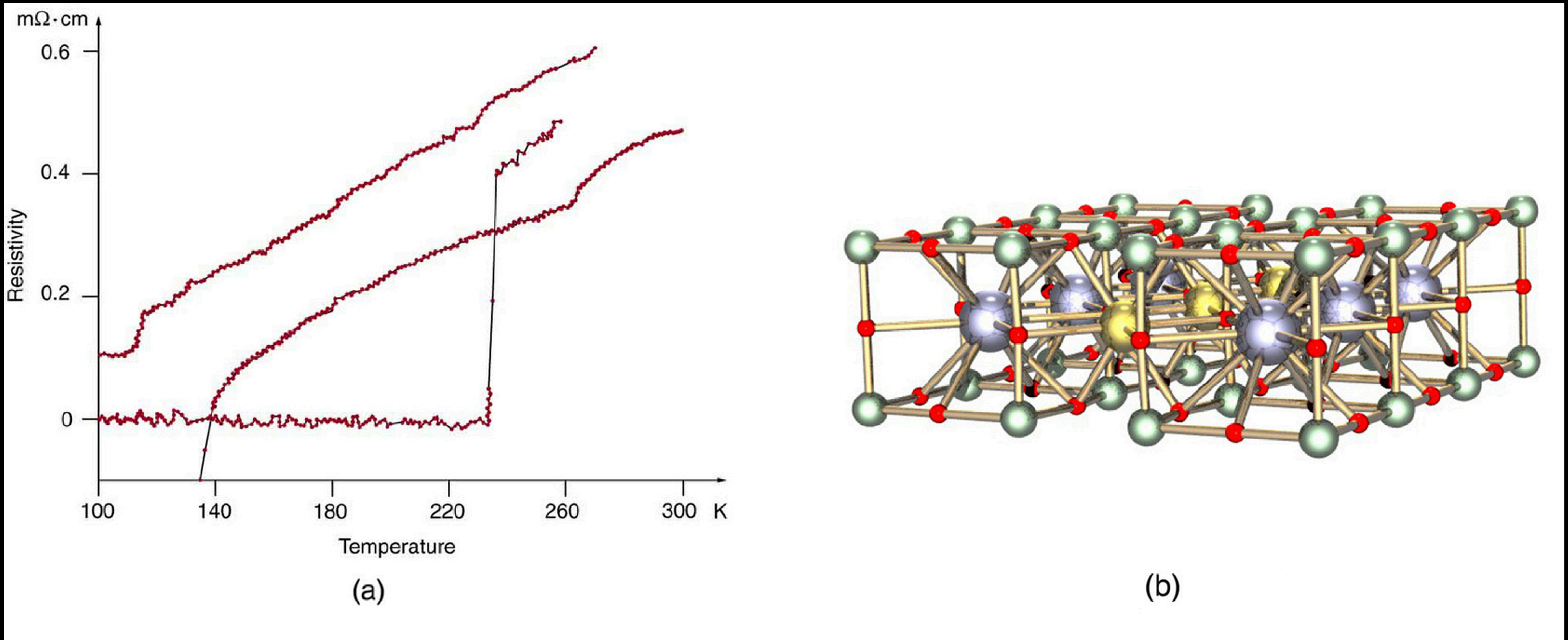


Figure 3. (a) This graph, adapted from an article in Physics Today, shows the behavior of a single sample of a high-temperature superconductor in three different trials. In one case the sample exhibited a Tc of about 230 K, whereas in the others it did not become superconducting at all. The lack of reproducibility is typical of forefront experiments and prohibits definitive conclusions. (b) This colorful diagram shows the complex but systematic nature of the lattice structure of a high-temperature superconducting ceramic. (credit: en:Cadmium, Wikimedia Commons)

On the Largest Scale

1) Is the universe open or closed? Theorists would like it to be just barely closed and evidence is building toward that conclusion. Recent measurements in the expansion rate of the universe and in CMBR support a flat universe. There is a connection to small-scale physics in the type and number of particles that may contribute to closing the universe.

2)What is dark matter? It is definitely there, but we really do not know what it is. Conventional possibilities are being ruled out, but one of them still may explain it. The answer could reveal whole new realms of physics and the disturbing possibility that most of what is out there is unknown to us, a completely different form of matter.

3) How do galaxies form? They exist since very early in the evolution of the universe and it remains difficult to understand how they evolved so quickly. The recent finer measurements of fluctuations in the CMBR may yet allow us to explain galaxy formation

4) What is the nature of various-mass black holes? Only recently have we become confident that many black hole candidates cannot be explained by other, less exotic possibilities. But we still do not know much about how they form, what their role in the history of galactic evolution has been, and the nature of space in their vicinity. However, so many black holes are now known that correlations between black hole mass and galactic nuclei characteristics are being studied.

On the Intermediate Scale

1) How do phase transitions take place on the microscopic scale? We know a lot about phase transitions, such as water freezing, but the details of how they occur molecule by molecule are not well understood. Similar questions about specific heat a century ago led to early quantum mechanics. It is also an example of a complex adaptive system that may yield insights into other self-organizing systems.

2)Is there a way to deal with nonlinear phenomena that reveals underlying connections? Nonlinear phenomena lack a direct or linear proportionality that makes analysis and understanding a little easier. There are implications for nonlinear optics and broader topics such as chaos.

3) How do high- Tc superconductors become resistanceless at such high temperatures? Understanding how they work may help make them more practical or may result in surprises as unexpected as the discovery of superconductivity itself.

4) There are magnetic effects in materials we do not understand—how do they work? Although beyond the scope of this text, there is a great deal to learn in condensed matter physics (the physics of solids and liquids). We may find surprises analogous to lasing, the quantum Hall effect, and the quantization of magnetic flux. Complexity may play a role here, too.

On the Smallest Scale

1) Are quarks and leptons fundamental, or do they have a substructure? The higher energy accelerators that are just completed or being constructed may supply some answers, but there will also be input from cosmology and other systematics.

2)Why do leptons have integral charge while quarks have fractional charge? If both are fundamental and analogous as thought, this question deserves an answer. It is obviously related to the previous question.

3)Why are there three families of quarks and leptons? First, does this imply some relationship? Second, why three and only three families?

4) Is the proton stable? We have discussed this in some detail, but the question is related to fundamental aspects of the unification of forces. We may never know from experiment that the proton is stable, only that it is very long lived.