Newton

Graphic Science

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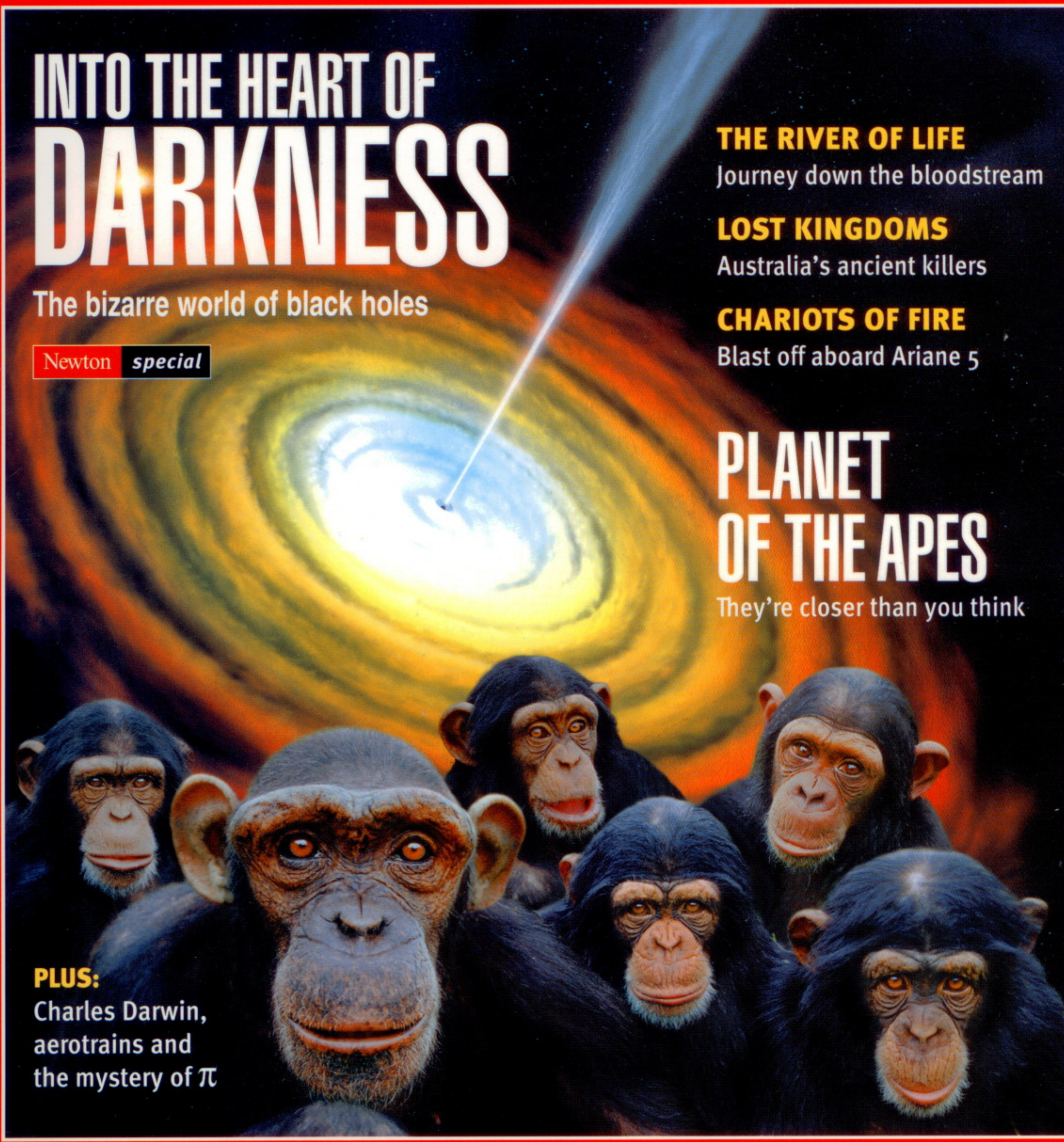

INTO THE HEART OF DARKNESS

The bizarre world of black holes

Newton *special*

THE RIVER OF LIFE
Journey down the bloodstream

LOST KINGDOMS
Australia's ancient killers

CHARIOTS OF FIRE
Blast off aboard Ariane 5

PLANET OF THE APES

They're closer than you think

PLUS:
Charles Darwin, aerotrains and the mystery of π

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AN AUSTRALIAN GEOGRAPHIC PUBLICATION

CYGNUS X-1

Cygnus X-1 was the first black hole to be identified by astronomers. The black hole is the tiny black dot in the centre of the pinwheel of gas. It is seven times more massive than our Sun and lies 8000 light-years away. Like a cannibal swirling in fire, it is ripping off the outer envelope of its companion star, which is 100,000 times larger.

THE HEART OF DARKNESS

THE BIZARRE WORLD OF BLACK HOLES

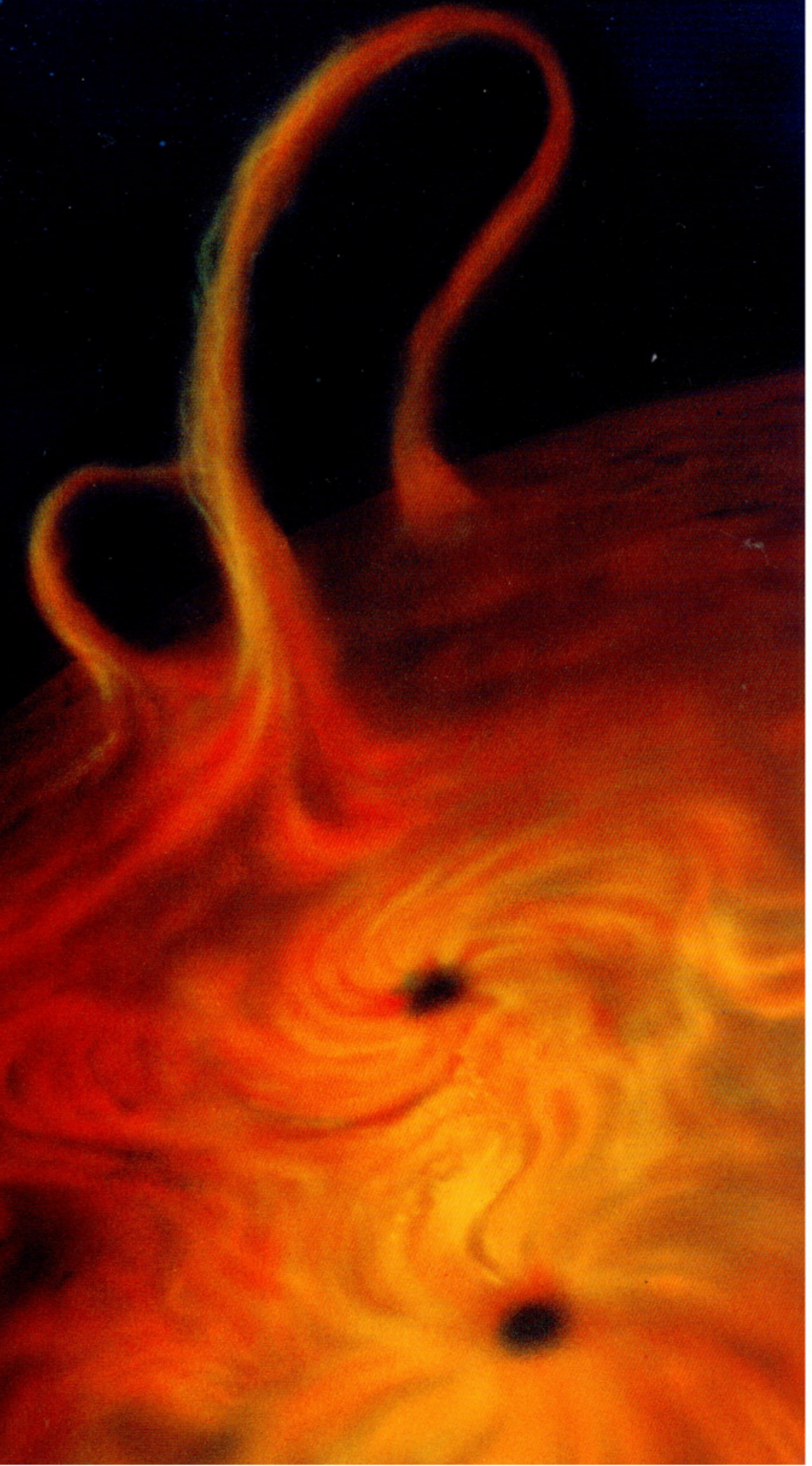
By Charles Lineweaver

Black holes are the craziest damn things science has ever come up with. They're mysterious objects from which even light cannot escape.

We can't *see* black holes directly, but we can see their *effect* on the stars and gas around them. Every year astronomers discover more of them. The harder we look, the more we find.

What role do they play in the Universe? Scientists still aren't sure but they may provide shortcuts through our Universe, or even link us to other universes. Understanding black holes may even unlock the secret of how our Universe was born.

What lies inside these gravity-powered vacuum cleaners?



Where are they?

EVERYWHERE WE LOOK

Our heads are filled with weird fantasies: dragons and Dracula, gargoyles and Godzilla, *Star Trek* and *The Matrix*. Black holes are weirder than almost anything you could imagine – and they're real. They're so weird they're almost not part of our Universe.

Black holes used to be theoretical oddities. We didn't know if they actually existed. But around 30 years ago new astronomical instruments began finding evidence for them. Today, black holes are being discovered everywhere. The list of known black holes keeps getting longer.

Black holes are the corpses of huge stars that were among the brightest lights in the sky. There are a billion of them now drifting inconspicuously through the Galaxy.

Right now, as you read this article, you are orbiting the biggest black hole in our Galaxy. It's about two million times more massive than the Sun and is right in the middle of the Milky Way. The Sun and every other star in the galaxy are in orbit around it.

There are 100 billion other galaxies in the observable Universe. We think most of them have a gigantic black hole in their centre because in every galaxy where our observations have been sensitive enough to detect a black hole, we've found one. For example, our nearest neighbouring galaxy, Andromeda, has a gigantic black hole in its centre.

Not only are we orbiting a black hole, our whole Galaxy is falling towards a black hole a thousand times bigger than the one at its centre. This super-massive black hole lives in the centre of a nearby group of galaxies called the Virgo cluster.

DRIFTING THROUGH THE GALAXY
If we could look at our Galaxy from above, and a black hole lay between us and the Galaxy, this is how it would look. This black hole does not have a swirling disc of hot gas around it like Cygnus X-1. It is isolated in space. Notice the distorted second image of our Galaxy along the lower right edge of the black hole. The massive black hole in the centre of the Galaxy is hidden behind the bright white glare of stars.

A brief history of gravity

GALILEO, NEWTON AND EINSTEIN

Where did the idea for black holes come from? It all started by watching things fall.

Gravity is like air: we're so used to it, it's difficult to think about. Why do things fall? Things fall because that is what they do and that's all there is to it. So people thought until an Italian scientist named Galileo started to measure falling objects.

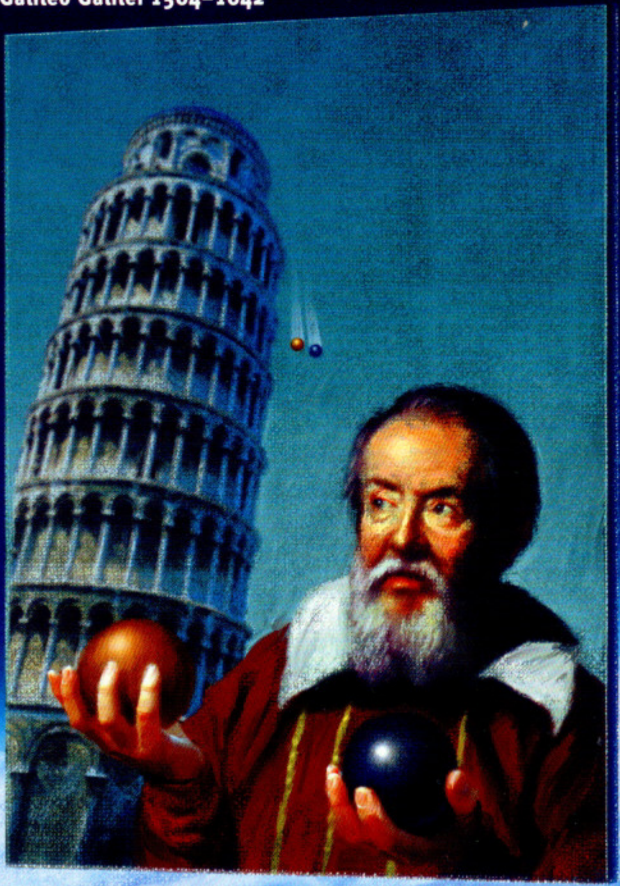
When you hold a golf ball in one hand and a bowling ball in the other, the bowling ball feels heavier. It pulls on your hand and feels as though it would fall faster. Galileo had the brilliant idea of checking this and found that it wasn't true. It is said that in 1638 he dropped an iron ball and a wooden ball of the same size from the Tower of Pisa. They hit the ground at the same time. Light wood fell as fast as heavy iron!

This magazine is named after Isaac Newton, a long-haired, irascible genius. While sitting in an orchard under a tree in 1666, Newton saw an apple fall. The beautiful Moon hanging in the sky caught his eye. He wondered: "Why doesn't it fall like the apple?" After some calculation, Newton discovered that the Moon *is* falling towards the Earth, but the surface of the Earth keeps curving away from it. Such a curved fall is what we now call an orbit. Before Newton, there was no connection between an apple falling and the Moon hanging in the sky. Newton gave us this connection. We call it gravity.

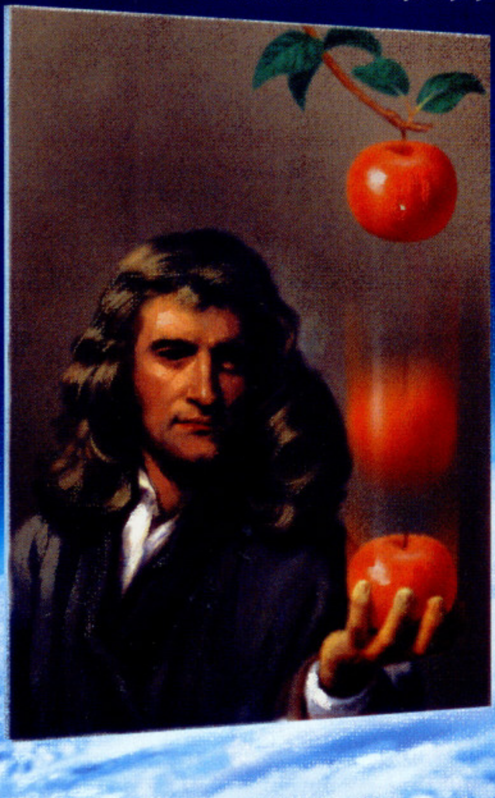
Some 250 years later, Albert Einstein made his own insights into gravity. They were simple and profound. A man enclosed in an elevator with no windows cannot tell if he is standing in a gravitational field or is being accelerated by a rocket. Similarly, a man in a falling elevator cannot tell if he is falling in a gravitational field or is simply floating in outer space.

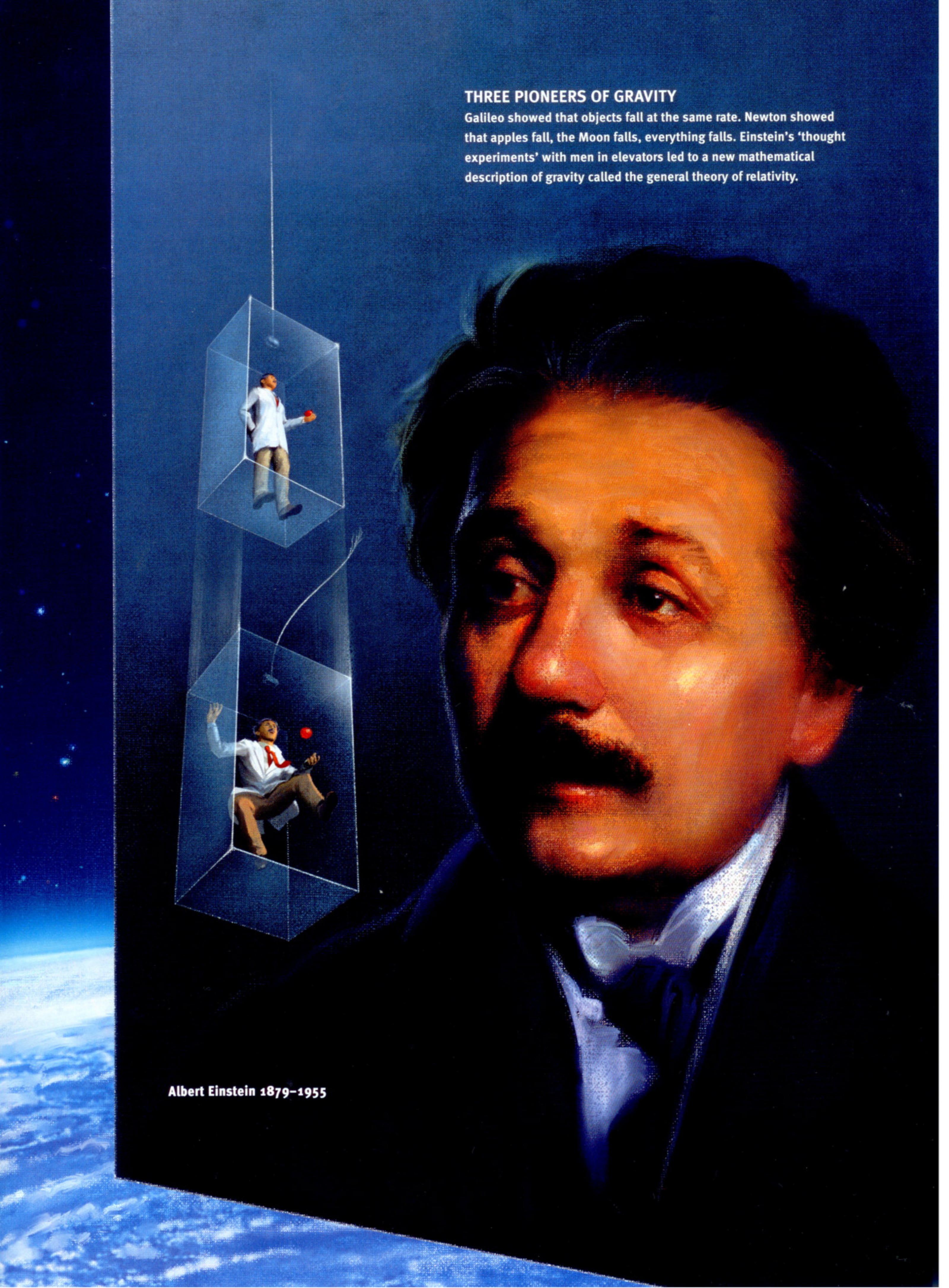
These basic ideas led to new equations describing gravity that suggested the existence of completely gravitationally collapsed objects. At the surface of these objects, light couldn't escape and time appeared to stop. These objects remained theoretical curiosities for another 50 years until evidence for them began to show up. In 1967, John Wheeler gave them a popular name: 'black holes'.

Galileo Galilei 1564–1642



Isaac Newton 1642–1727





THREE PIONEERS OF GRAVITY

Galileo showed that objects fall at the same rate. Newton showed that apples fall, the Moon falls, everything falls. Einstein's 'thought experiments' with men in elevators led to a new mathematical description of gravity called the general theory of relativity.

Albert Einstein 1879–1955

Testing Einstein

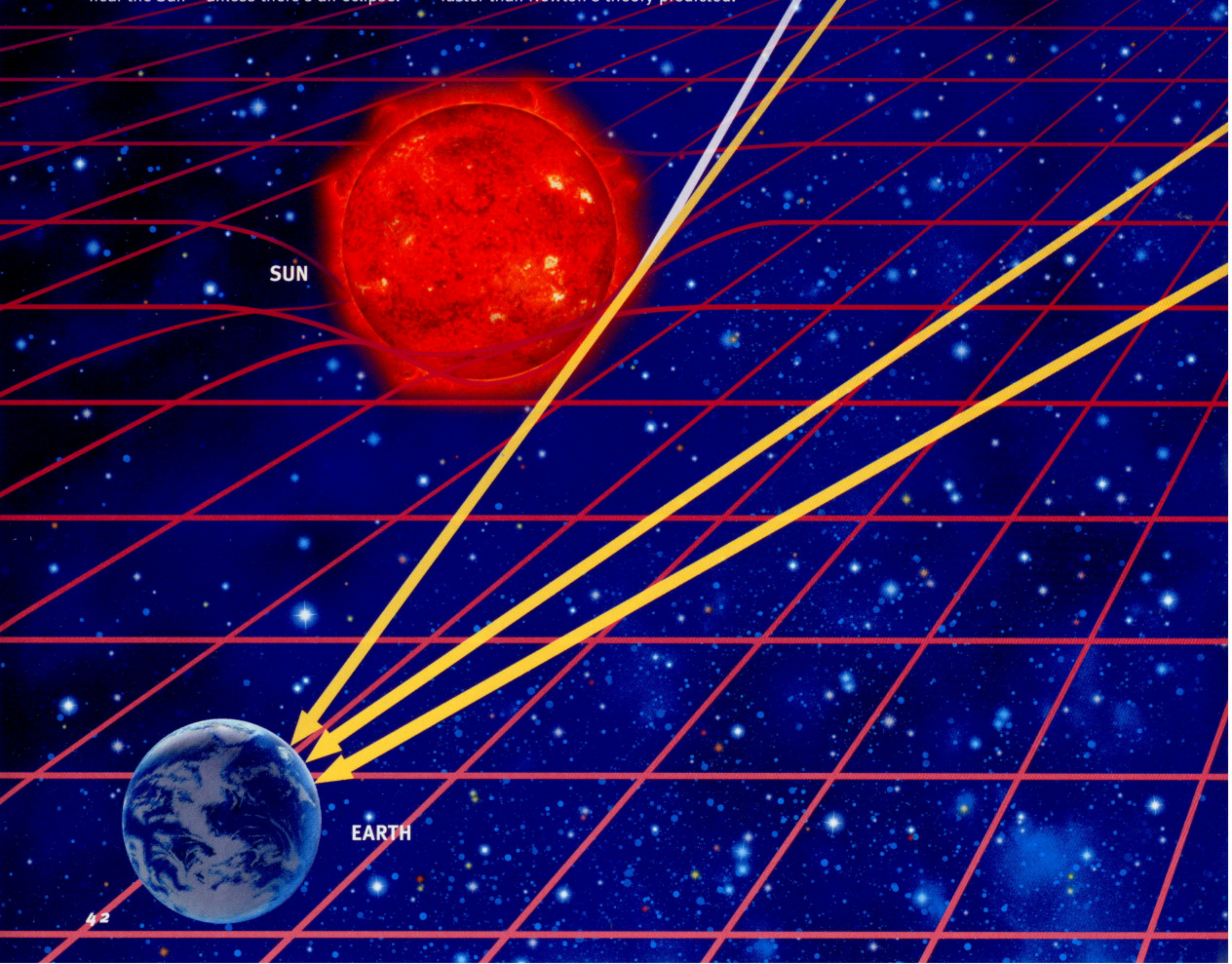
MEASURING DENTS IN THE FABRIC OF SPACE

According to Einstein's theory of general relativity, strong gravitational fields, as produced by massive objects, bend light and slow time. When Einstein first announced his ideas there wasn't much reaction to them. They were so revolutionary that few people understood them. Anyway, how could you test them?

One way of testing them was looking at the effect of nearby massive objects. The Sun is more than 300,000 times the mass of Earth. Did it bend the light of stars? Unfortunately, the Sun is so bright that it's impossible to make accurate measurements of stars when they appear near the Sun – unless there's an eclipse.

In 1919, an English astronomer named Eddington led an expedition to Sobral, Brazil, to observe a total eclipse of the Sun and measure the difference between the normal position of a distant star (shown as the white line in the illustration) and where it appeared when it was close to the Sun. His measurements showed that the Sun did bend light from the star in exactly the way Einstein predicted.

Another important test of general relativity concerned Mercury's orbit. It had been known for more than 100 years that Mercury's orbit was changing slightly faster than Newton's theory predicted.

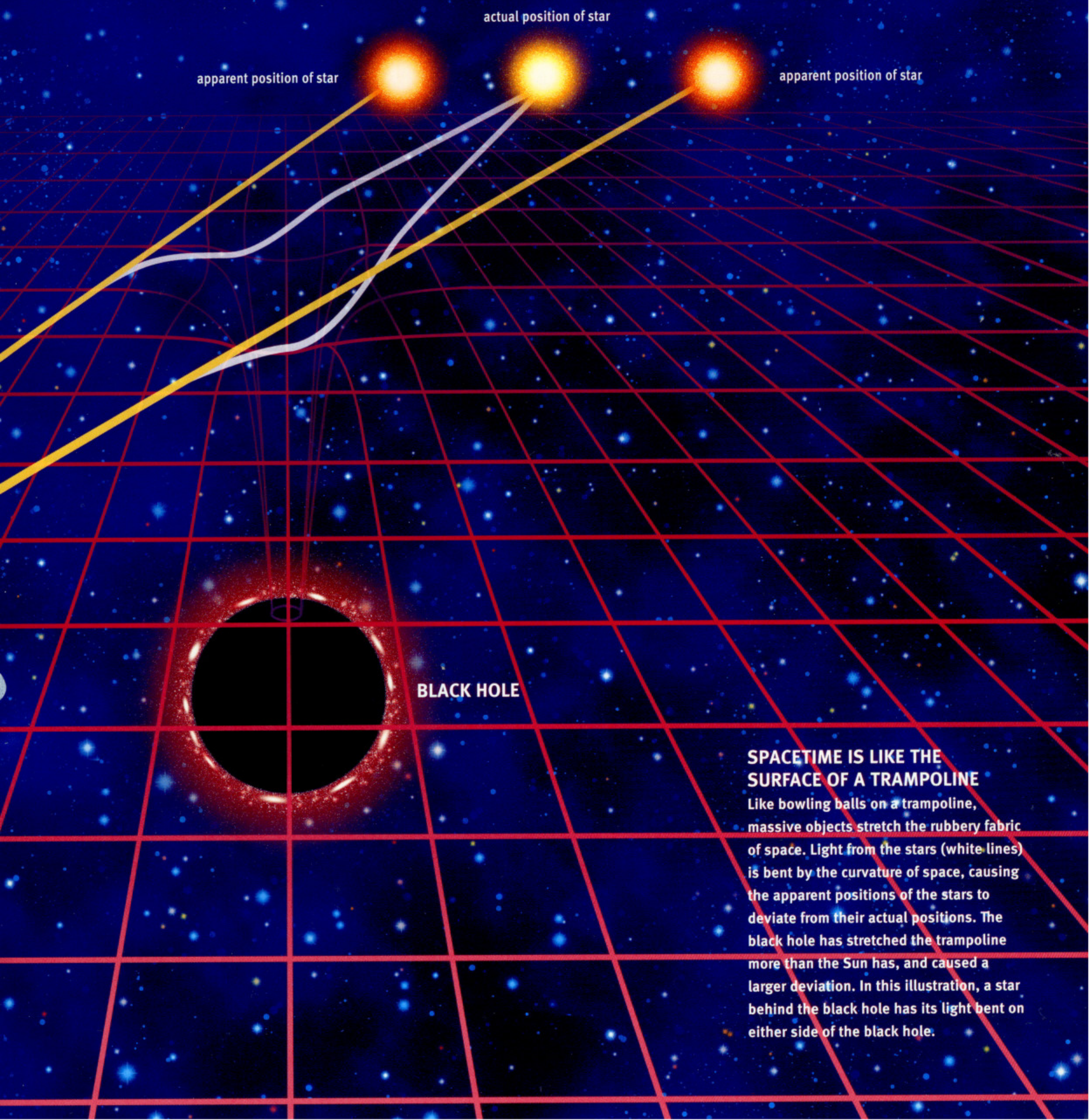


Einstein's new theory correctly predicted the observed amount of change.

Einstein's theory also predicts that a photon (a particle of light) would lose energy as it climbed out of a gravitational field. In 1960, this effect was measured; the result confirmed Einstein's findings.

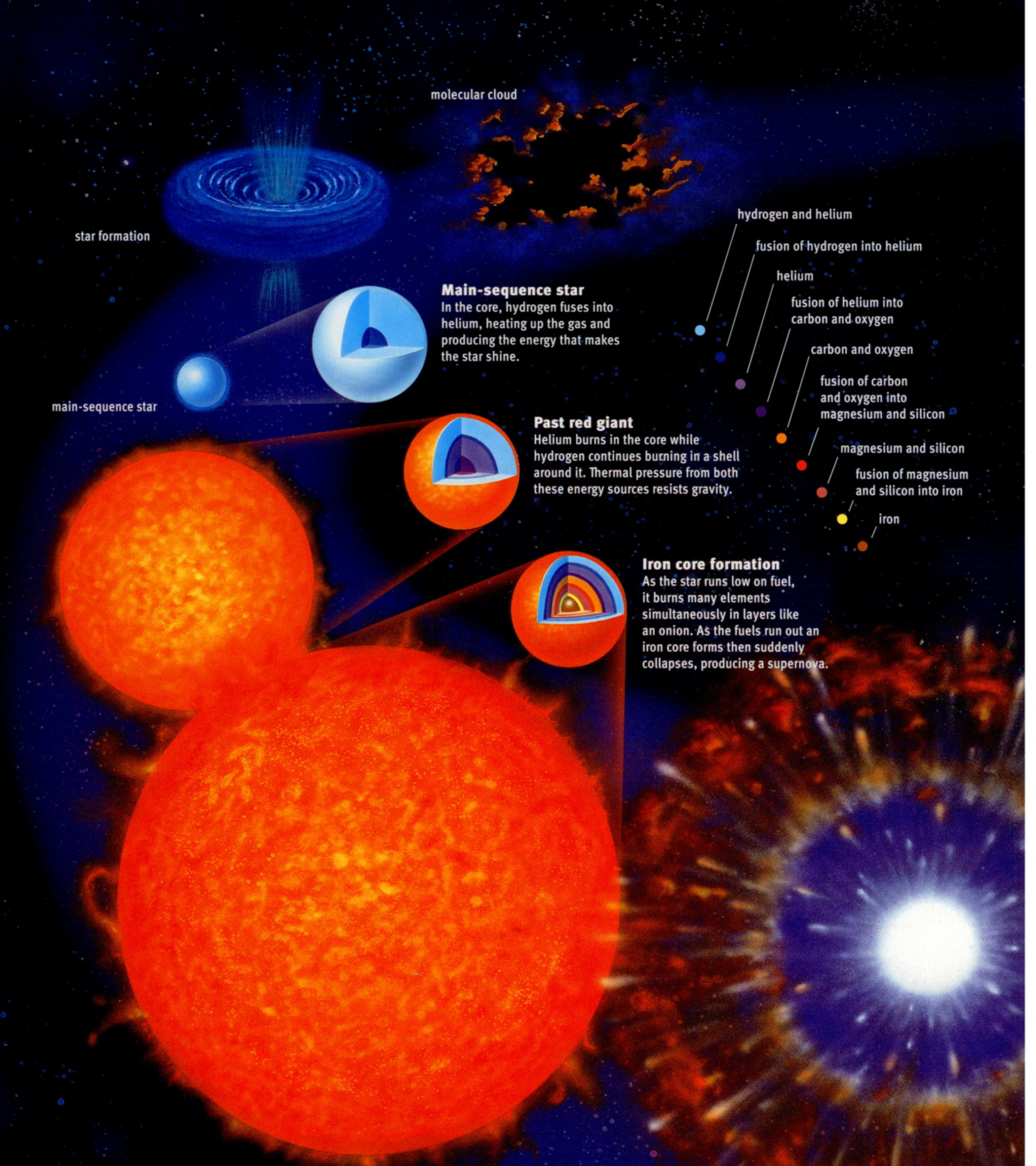
Einstein's prediction that gravity slowed time was further confirmed with the development of ultra-precise atomic clocks. The gravitational field of the Earth is much stronger at the surface of the planet than it is high above it. Atomic clocks orbiting above Earth ticked faster than those on its surface. They were the minutest of differences but consistent, and enough to show again that Einstein was right.

Gravity bends light and slows time. A black hole takes these effects to their ultimate expression.



SPACETIME IS LIKE THE SURFACE OF A TRAMPOLINE

Like bowling balls on a trampoline, massive objects stretch the rubbery fabric of space. Light from the stars (white lines) is bent by the curvature of space, causing the apparent positions of the stars to deviate from their actual positions. The black hole has stretched the trampoline more than the Sun has, and caused a larger deviation. In this illustration, a star behind the black hole has its light bent on either side of the black hole.



A STAR IS BORN

These are the stages in the life of a star massive enough to produce a supernova and form either a neutron star or a black hole. Massive stars are so luminous that they quickly use up their fuel. Unable to hold up their own weight they implode, rebound from the stiff neutron core and explode. The implosion produces in the core either a black hole or a neutron star depending on whether the mass of the core is more or less than 2 solar masses.

How are black holes formed?

BUILDING A GRAVITY VACUUM CLEANER

Mass is destiny. The fate of a star forming in a molecular cloud is determined by how massive it is. In about 5 billion years our Sun will burn itself out, settle down into a white dwarf and slowly fade. More massive stars have more violent deaths. They run out of fuel, explode and collapse into black holes.

A star is a balance between gravity pulling in, and gas, heated by nuclear fusion, pushing out. The main fuel is hydrogen. As it runs low, nuclear fusion shifts to burning heavier elements such as helium, carbon, oxygen, magnesium and silicon. In the process, the star gets bigger and redder.

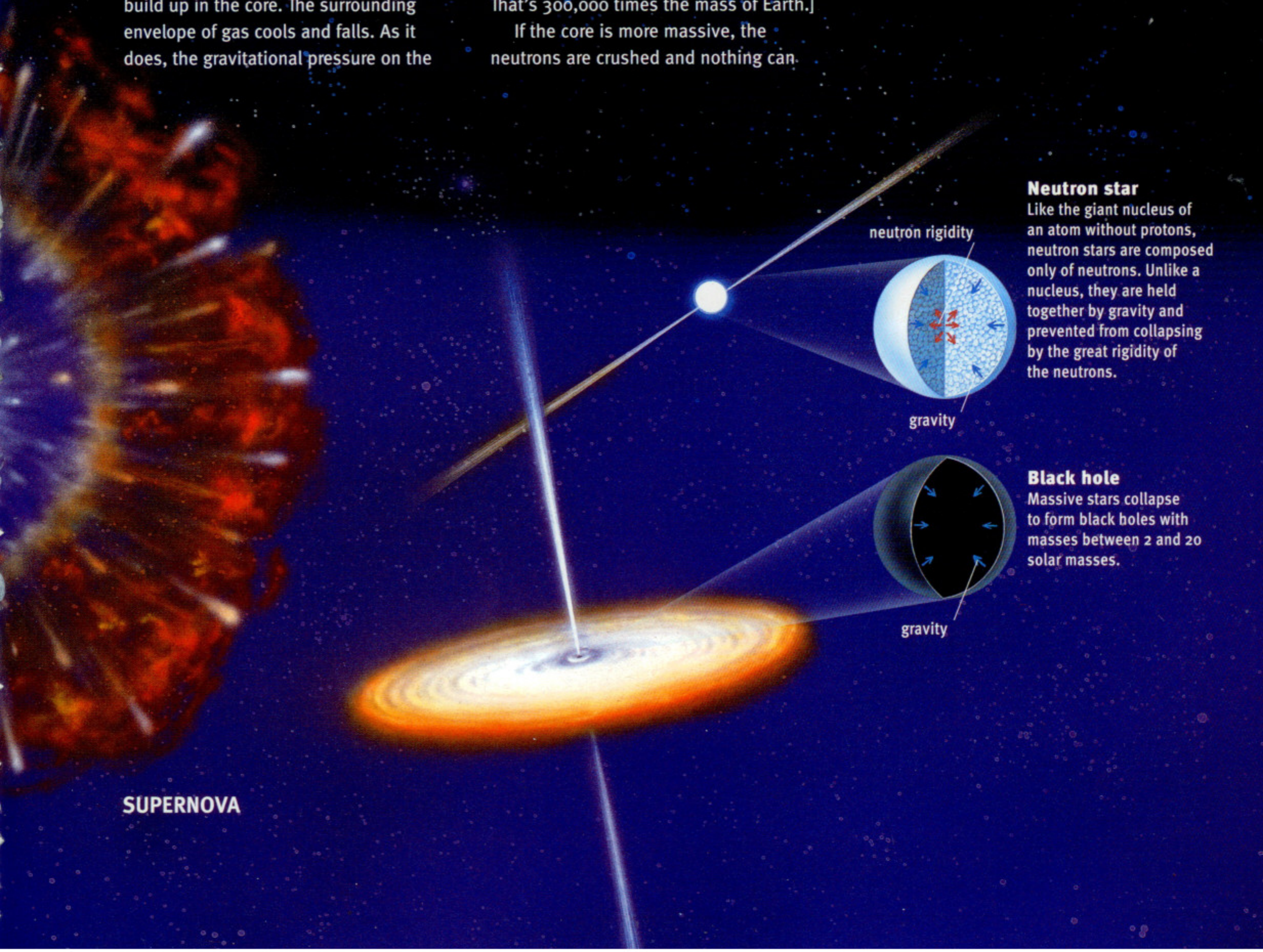
As the last fuels are burnt, iron ashes build up in the core. The surrounding envelope of gas cools and falls. As it does, the gravitational pressure on the iron core becomes so strong that the electrons in the iron atoms get crushed into the nuclei, fuse with the protons and produce neutrons. The iron core collapses into a neutron core with a volume 10,000 times smaller. The rest of the star, with the bottom taken out from under it, comes crashing down on the core. The rigidity of the neutrons sends the imploding envelope rebounding into outer space as a supernova.

If the mass of the core is less than 2 solar masses* the neutrons can withstand the force of gravity and a new equilibrium is reached called a neutron star. [*A 'solar mass' is the mass of the Sun and equals 2 x 10^{30} kilograms. That's 300,000 times the mass of Earth.]

If the core is more massive, the neutrons are crushed and nothing can stop the gravitational collapse of the star into a black hole.

After the dust clears – but that dust is important because all life in the Universe is made of it – all that's left is the gravitational field of a black hole. Like the Cheshire cat, the star has disappeared, leaving only its grin.

Massive stars shed lots of material during the various stages of their evolution. But if a star starts out with more than 40 solar masses, it will probably end up as a black hole of more than 2 solar masses. The estimated masses of known stellar black holes are between 2 and 20 solar masses.



Neutron star
Like the giant nucleus of an atom without protons, neutron stars are composed only of neutrons. Unlike a nucleus, they are held together by gravity and prevented from collapsing by the great rigidity of the neutrons.

Black hole
Massive stars collapse to form black holes with masses between 2 and 20 solar masses.

Spotting a black hole

WHAT DO YOU LOOK FOR?

If you were travelling along in a spaceship, would you be able to see a black hole coming? Yes, if there are other stars nearby; no, if there aren't.

If there are stars near a black hole, we can detect its presence by its effect on them: ripping the stars apart or causing them to move at high velocities. Isolated black holes with no stars around them are nearly impossible to detect.

Black holes in our galaxy are most easily found as X-ray sources in which a bright star is rapidly orbiting something we can't see. If the mass of the invisible companion (determined by the velocity and mass of the visible star) is greater than 2 solar masses, it must be a black hole. There are a dozen or so such candidates in our galaxy.

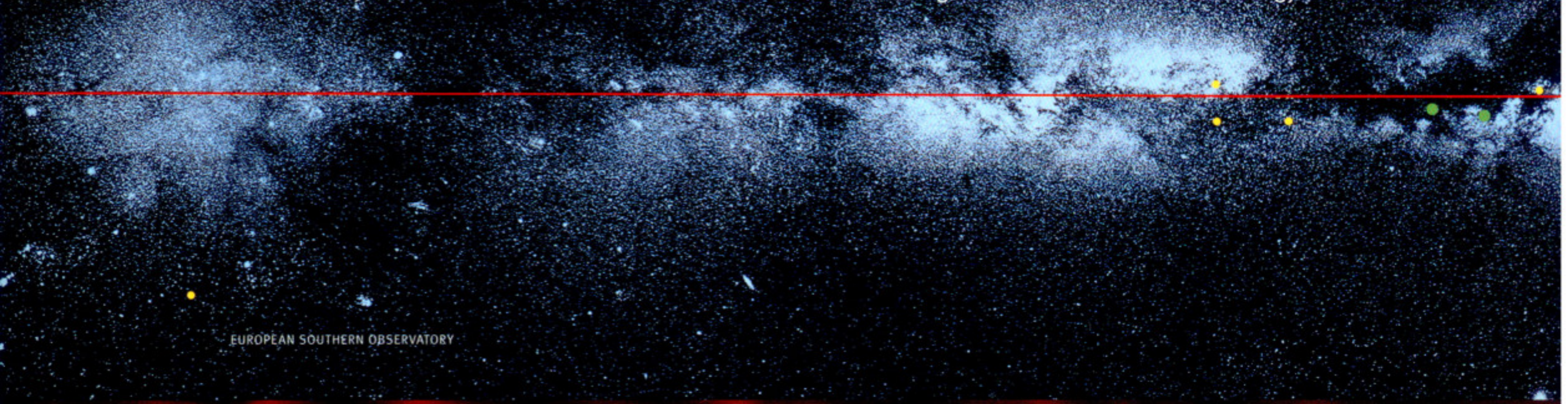
Matter emits X-rays as it falls towards a black hole, forming a hot 'accretion disc' that's gathered around the black hole. When driving down long hills, the energy of your moving car (resulting from gravity pulling you down the hill) is converted to heat in the disc brakes (as you slow down). Around a black hole, the gravitational energy of the in-falling gas is converted to heat in the accretion disc of a black hole.

The hot blue jet being shot out along the spin axis of the black hole is caused by hot ionised gas being pinched and focused by a twisted spindle of magnetic field lines.

At the very centre of our Milky Way Galaxy, stars are rotating so fast that there must be 2.5 million solar masses of material in a very small volume. The only object we know of that is so small and yet so massive is a black hole. The Sun, the Earth, this magazine, and every other star in the galaxy, are in orbit around this hole. It takes us 200 million years to go around once.

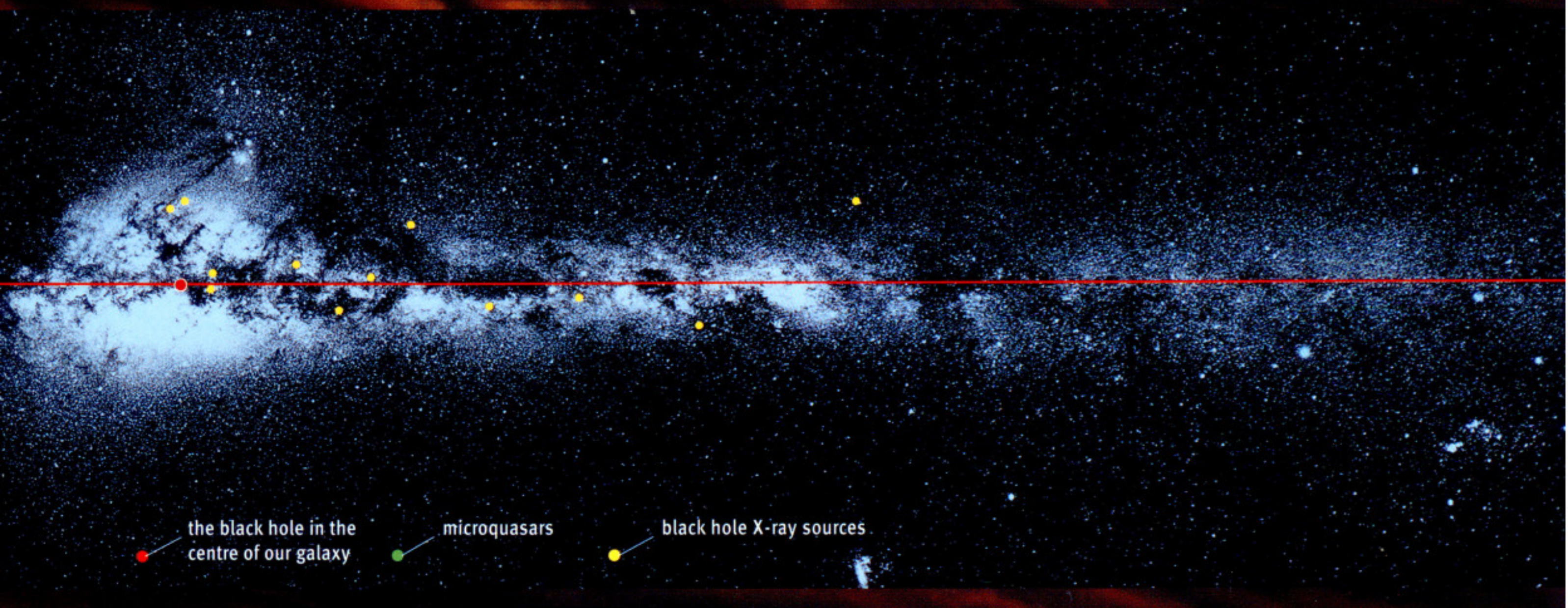
Why aren't we getting sucked into it? For the same reason we don't get sucked into our own Sun: we are in orbit around it. At a distance, there is nothing abnormal about the gravitational field of a black hole. Black holes don't 'suck' more than any other object of the same mass. Black holes are like porcupines – there is no danger until you get close.

Black holes of the Milky Way Galaxy
The black hole in the centre of our galaxy is marked with a red dot (for a close-up, see the illustration above). It is in the constellation Sagittarius, near the tail of the Scorpion. About a dozen X-ray sources similar to Cygnus X-1 are marked in yellow. These are objects in which a visible star is in orbit around something invisible with more than twice the mass of the Sun. Microquasars are stellar-mass black holes in our galaxy that look like tiny quasars. They emit more than a million times as much energy as our Sun.


EUROPEAN SOUTHERN OBSERVATORY

THE BLACK HOLE AT THE CENTRE

In the centre of the Milky Way, near the tail of the Scorpion, behind the dust and bright stars, is a black hole. This is what it looks like up close: a pinwheel of in-spiralling gas that gets hotter towards the centre. The thin blue jet is caused by hot ionised gas being pinched and focused by a twisted spindle of magnetic field lines.



Know your black holes

THERE ARE THREE KINDS

Black holes come in many sizes but there are only three properties a black hole can have: mass, spin and charge. Consequently, there are three different kinds of black hole.

We've talked about the 'size' of a black hole but a black hole has no solid surface. It has an abstract surface called the event horizon, but there is nothing at this surface – no solid ground, no sign saying: "All hope abandon, ye who enter here" – just empty space.

If you shine a light from inside this surface, the light will not escape. Since nothing can travel faster than the speed of light, nothing else can escape either. The gravitational field at the event horizon is so strong that clocks there – when viewed from outside the black hole – don't tick any more. Time has stopped.

The event horizon really is a horizon. You can't see beyond it into the black hole. It is a boundary in space where our Universe comes to an end. But it is a boundary with a one-way door: you can go in but you can't come out. Once inside the black hole, the event horizon is like a secret mirror. From the inside you can see out, but from the outside you can't see in.

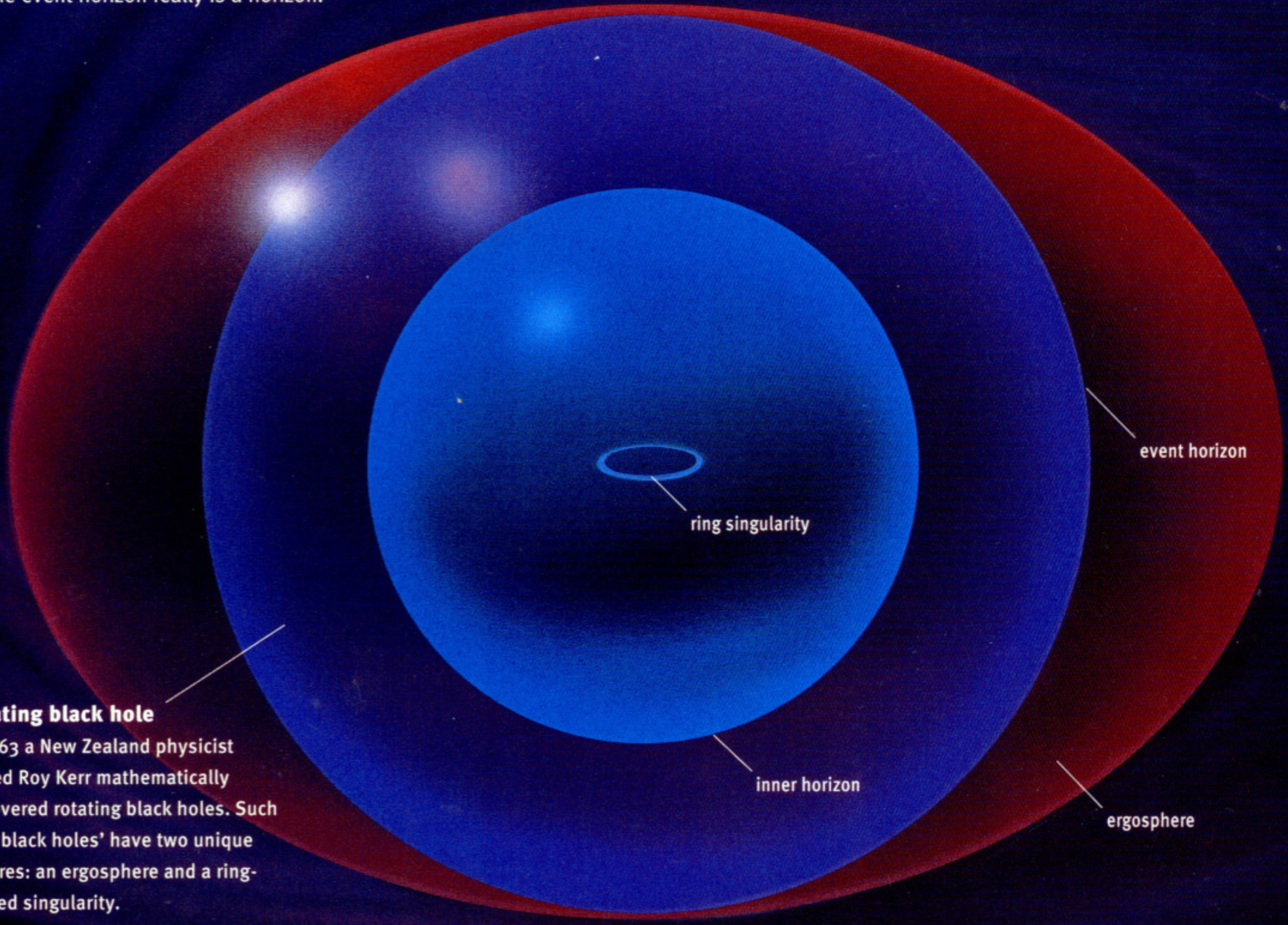
Because of these features the event horizon is sometimes described as a place where time stops and space comes to an end. If the Universe ends at the event horizon, the inside of a black hole is not really part of the Universe.

In their centres, all black holes have a 'singularity'. This is just a fancy word that means 'a place where Einstein's theory stops working'. Only our tentative notions of quantum gravity can guide us here.

Rotating black holes have some interesting properties. Like dough being spun in the air by a pizza maker, the singularity has been flattened into a disc with a hole in the middle.

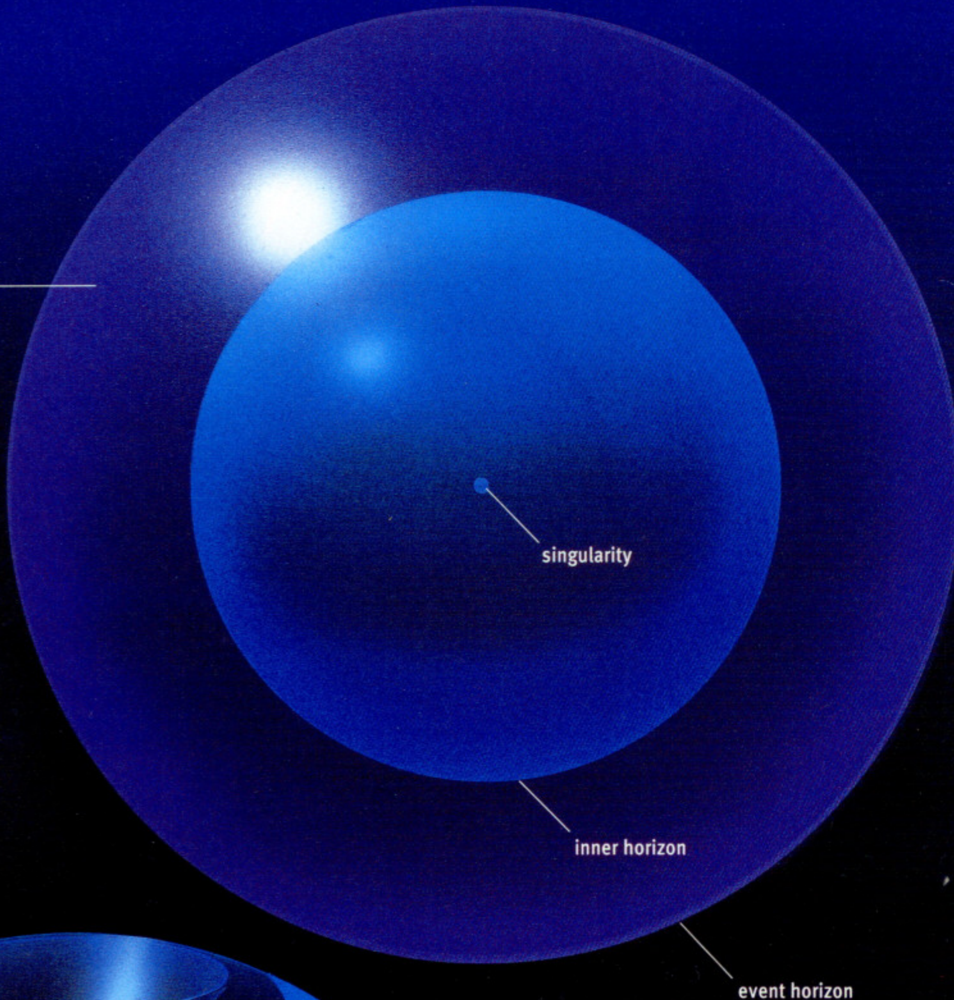
Outside the event horizon, a rotating black hole has a region shaped like a discus called the ergosphere. Inside this ergosphere, space swirls around like a tornado at the speed of light and you cannot keep yourself from rotating around the hole no matter what you do.

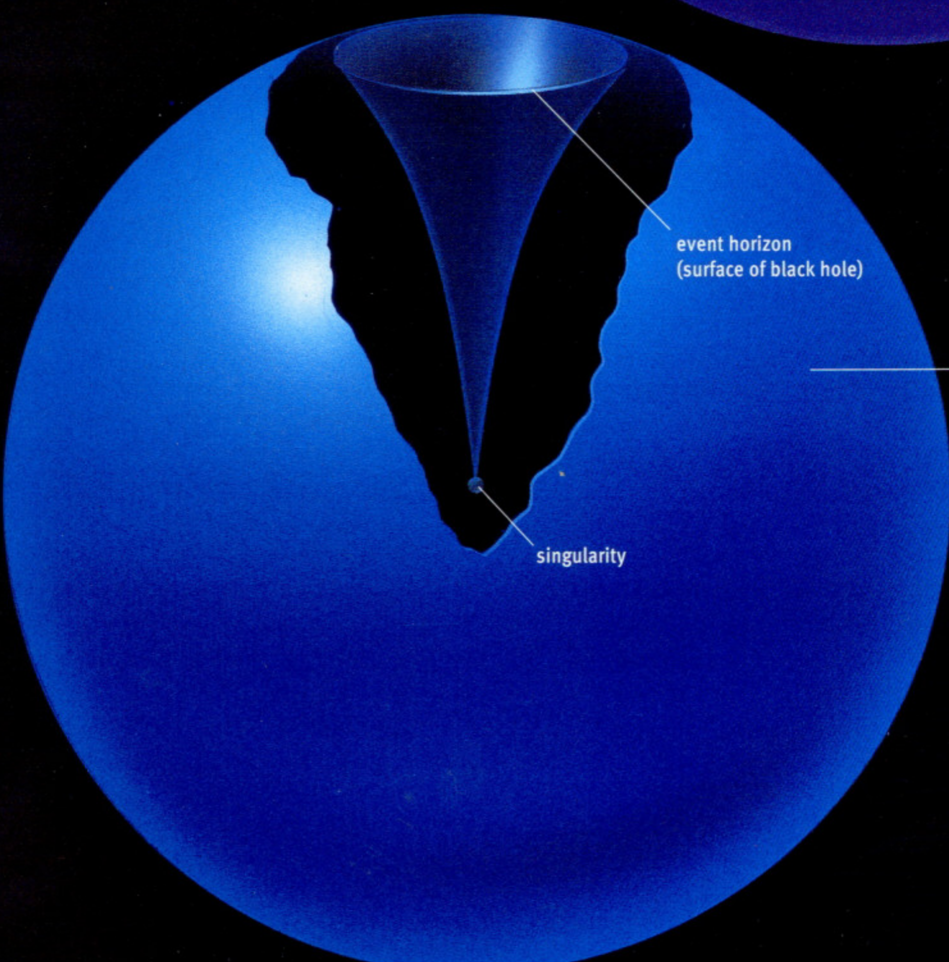
The inner horizons of rotating and charged black holes are also bizarre. Like veils, they protect the naked singularities from being seen. If we can pass through the inner horizon without being ripped apart, it is here that we may catch a glimpse of the naked singularity.



Rotating black hole
In 1963 a New Zealand physicist named Roy Kerr mathematically discovered rotating black holes. Such 'Kerr black holes' have two unique features: an ergosphere and a ring-shaped singularity.

Charged black hole
Like rotating black holes, charged black holes have an inner horizon and an event horizon. A real black hole cannot have much charge; otherwise it would quickly attract electrons or ions and neutralise itself.





Schwarzschild black hole
In 1916, Karl Schwarzschild found the first solution to Einstein's equations. The black hole described by his solution was simple. It had no rotation and no charge.

BLACK HOLES COME IN THREE VARIETIES
Black holes can have spin, charge or just mass. These are the only three properties a black hole can have. Since these are also the properties that distinguish elementary particles from each other, black holes are, in some sense, gigantic elementary particles.

Into the heart of darkness

DESCENT INTO A BLACK HOLE

What would it be like to fall into a black hole? Let's consider what would happen if we flew into the simplest type of black hole, a small (3-solar-mass) Schwarzschild black hole (above left). As we fall in we begin to feel sick. Gravitational tides are stretching our bodies and our spaceship.

If the Moon were twice as massive, the tides on Earth would be twice as high. As we increase the mass of the Moon the tides get higher, which means that the tidal bulges on either side of the Earth get more pronounced. Not just the water, the Earth is also getting tidally stretched. If you continue to increase the mass of the Moon, the Earth would stretch like rubber.

Extreme tidal stretching where gravitational forces stretch all matter into long spaghetti-like strands is called 'spaghettification'. As we approach the small 3-solar-mass black hole, the tidal stretching is enormous. At the event horizon, it's like hanging from the Sydney Harbour Bridge with the entire population of Sydney dangling from your ankles. Spaghettification is ugly. It doesn't just stretch you like a gravitational torture rack, it also squeezes you and keeps tightening like a boa constrictor. Before we even reach the event horizon, we are completely spaghettified.

Let's try the massive black hole on the right. We approach without discomfort and even fall through the event horizon without feeling a thing. We believe descents into black holes are like going down a slide. Small black holes are steep slides and the fall is very short and uncomfortable. Massive black holes are slides with a very shallow incline. The fall is slow and comfortable ... until we get to the end, when we get ripped apart before meeting the singularity. From now on, to avoid premature spaghettification, we will only explore massive black holes.

As we fall into a massive black hole, we see the clocks in the outside Universe ticking like crazy. The people are ageing enormously quickly, like the evil archaeologist in *Indiana Jones and the Last Crusade* who drank from the wrong cup. The Earth is orbiting the Sun once a second and the stars are evolving before our eyes. From our in-falling perspective, the clocks outside the black hole have sped up. From their perspective, our clocks have slowed down. Such is the paradoxical and reciprocal nature of gravitational time dilation.

BLACK HOLE DIVING

Our precipitous descent into the small black hole (left) was exhilarating but lasted only 50 microseconds. We were tidally stretched and spaghettified before we even entered the hole. After our atoms were crushed out of existence in the singularity we decided to try out a bigger black hole (right). There we enjoyed a leisurely glide into the darkness that lasted 20 hours before we were spaghettified and died near the singularity.

These trips seemed short, but viewed from the outside both took forever. As the spaceships approached the surface of the black holes, they slowly turned yellow, then red, then hung in space and just faded like a cooling ember. Signals from the ship's clocks sent out every second would be received by the home station once a minute, then once an hour, then once a day; they are still waiting for the next signal.

Black holes evaporate

HAWKING'S QUANTUM INSIGHTS

Until 1974, everyone thought that once a black hole forms, it lives forever. But then Stephen Hawking discovered black hole evaporation. This is a quantum effect that cannot be explained using Einstein's gravity. It depends on the quantum idea that the vacuum is full of ephemeral fluctuations: virtual particle pairs of all kinds that come into and go out of existence before ever becoming real. Sounds crazy, but these zero-point fluctuations are not some wild theory. Their effects have been measured and confirmed many times.

If you increase the electric field in a vacuum (for example between two metal plates with opposite charges) the virtual particle pairs in the vacuum become real particle pairs. The energy required to create these real particles comes from the energy of the electric field. Similarly, the strong gravitational field just outside the event horizon of a black hole supplies the energy to create real particle pairs.

Virtual particles become real in very strong electric or gravitational fields when the energy expended by the field to accelerate them during their brief existence is equal to the mass of the particles. When one of these real particles escapes from the black hole, the gravitational field of the black hole, and thus the black hole itself, has lost energy. With large numbers of particles escaping, the black hole evaporates.

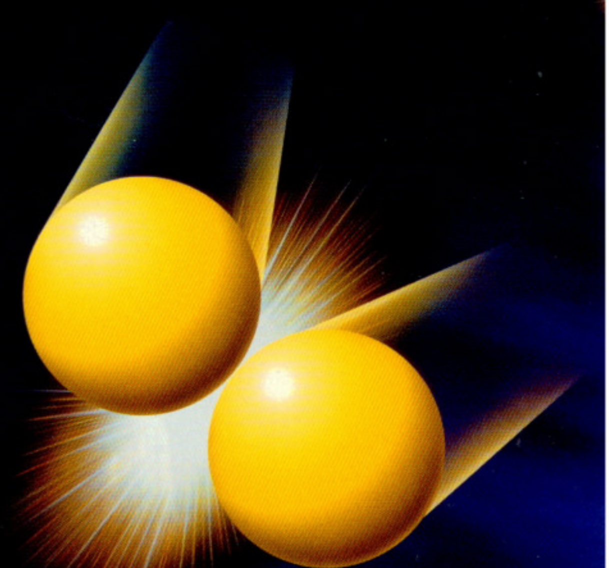
The evaporation of a black hole can also be thought of as the spaghettification of the vacuum. It's not just unsuspecting tourists who get spaghettified, the vacuum is getting ripped apart too.

Large black holes have weaker tidal fields at the event horizon. That is why they are so comfortable to fall into and that is why they spaghettify the vacuum less vigorously. Thus, they give off fewer particles, take much longer to evaporate and are cooler.

Smaller black holes are hotter and give off more particles. As a black hole evaporates, its mass diminishes and its surface gets hotter. As the rate of evaporation increases the surface begins to glow, then shines brightly and finally explodes in a burst of gamma rays. The black hole is gone.

Hawking calculated the time it would take for a black hole to evaporate. A stellar-mass black hole will completely evaporate in 10^{67} years. That's 10^{57} times longer than the current age of the Universe. It is not coincidental that this time interval is also how long it takes for someone to fall into a black hole as seen by a distant observer.

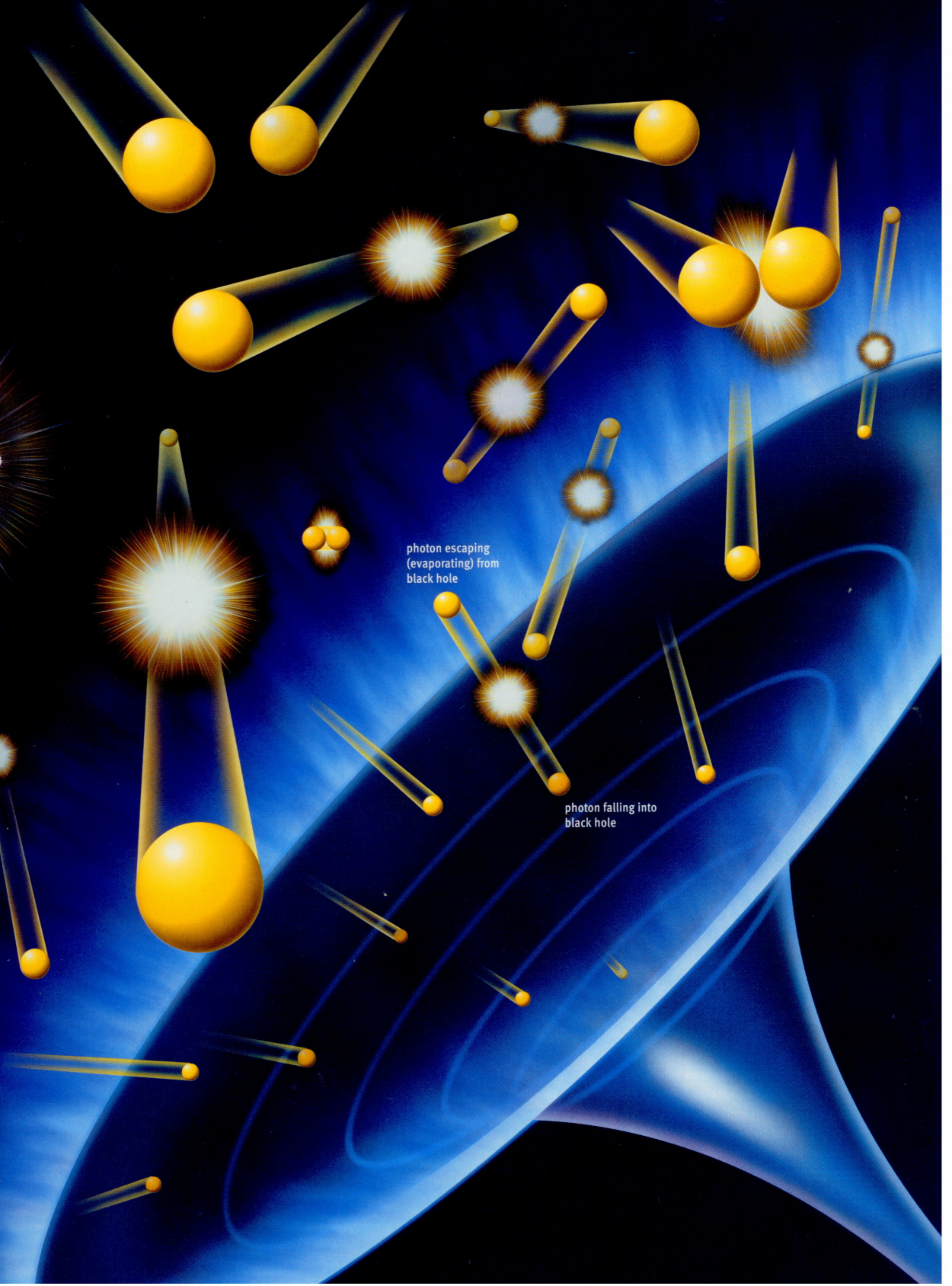
virtual photon pair creation



virtual photon pair annihilation

GLOWING BLACK HOLE

In this view of the glowing surface of a black hole, virtual photons are being created and annihilated continuously everywhere. They borrow and then pay back energy to the vacuum. These are vacuum fluctuations. Near the surface of a black hole, the gravitational field provides the energy to make them real. They don't have to pay back their energy debt to the vacuum because the gravitational field pays it for them. Having become real, the particles are free to separate. Occasionally one will escape from the black hole while the other falls in. This is how black holes evaporate.


photon escaping (evaporating) from black hole
photon falling into black hole

What's at the centre?

RIPPING MATTER TO SHREDS

On our way down into the black hole, our bodies were spaghettified and our atoms torn apart into elementary particles. What happens to our remains as we continue our imaginary journey into the singularity? Do our electrons and quarks, photons and even gravitons get spaghettified? Are they too ripped apart into something more fundamental as they approach the singularity?

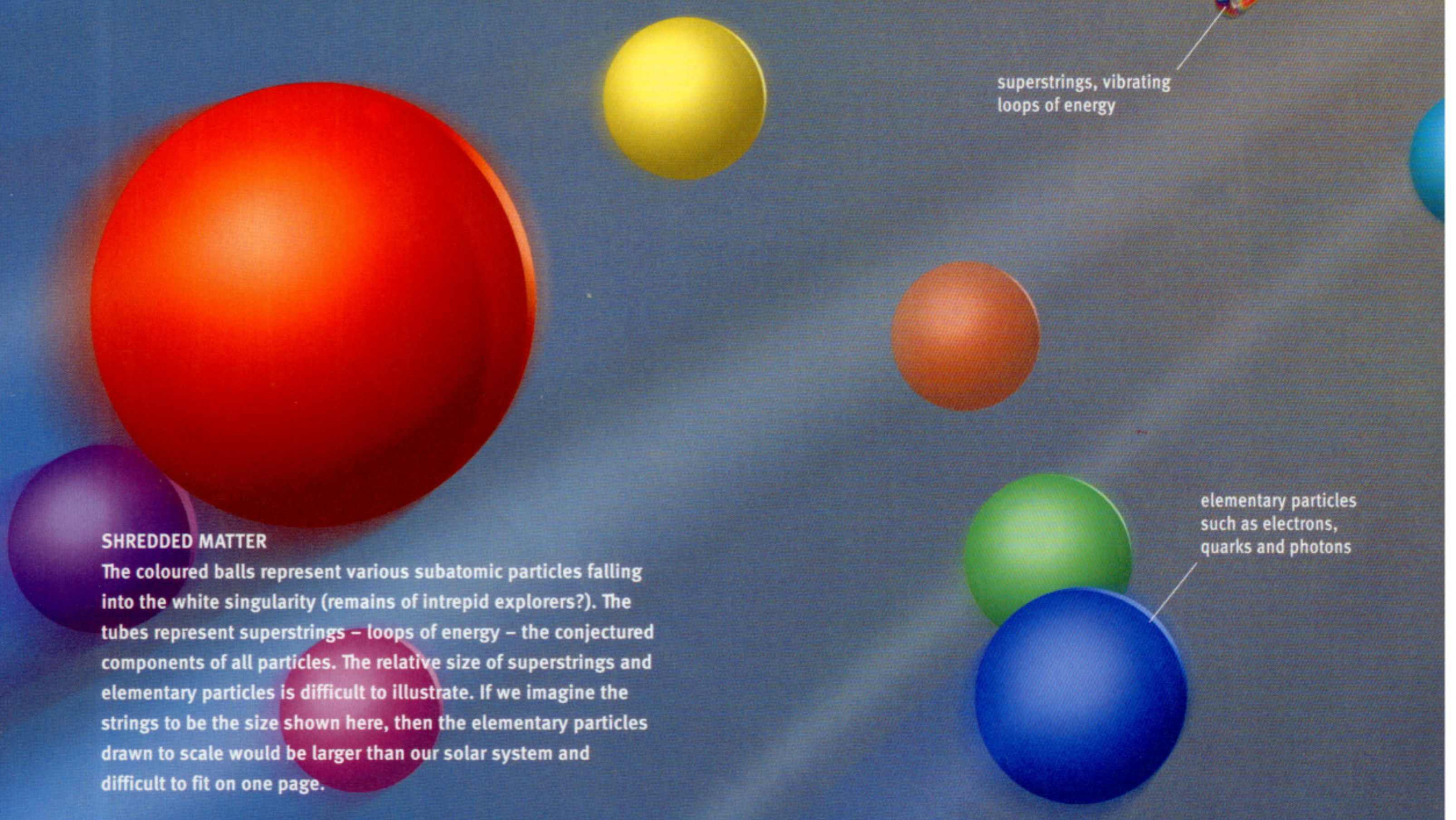
The extreme physical conditions at the moment of the Big Bang and at the central singularity of a black hole are similar. We understand very little about them because they are outside the domain of general relativity.

The exact nature of the singularity is a topic of intense current research. In a singularity, our familiar three dimensions of space are not crushed out of existence as general relativity predicts. Rather, our tentative versions of quantum gravity suggest that the dimensions of space depend on the scale we are dealing with. On the smallest scale of 10^{-32} mm, there may be nine dimensions.

In the centre of a black hole, perhaps our three normal spatial dimensions curl up to resemble the six other dimensions that we are so unfamiliar with. This nine-dimensional place is full of strange vibes – music that we will not be able to hear until we are able to combine general relativity and quantum theory. Different vibrations of minuscule energy loops may correspond to different elementary particles: middle C is an electron, G sharp is a quark, F is a photon and so on.

In the centre of a black hole, the curvature of space fluctuates wildly. Imagine a world where the strength of gravity changed. One morning you'd wake up, jump out of bed and go into orbit. Other mornings you'd wake up, fall out of bed and crush your ribs as you hit the floor. Now imagine that happening billions of times each second. This is what fluctuations in the curvature of space means.

Time is also weird. Any orderly sequence of events has vanished. Space and time are so curved and bent, fluctuating and overlapping, so inextricably scrambled together that the where and when of any event have no meaning. Perhaps this quantum spacetime froth is made out of vibrating nine-dimensional rubber-band-like loops of energy called superstrings. Perhaps not.



SHREDDED MATTER
The coloured balls represent various subatomic particles falling into the white singularity (remains of intrepid explorers?). The tubes represent superstrings – loops of energy – the conjectured components of all particles. The relative size of superstrings and elementary particles is difficult to illustrate. If we imagine the strings to be the size shown here, then the elementary particles drawn to scale would be larger than our solar system and difficult to fit on one page.


star
ring singularity
trajectory of star
as it is swallowed

Swallowed by a giant whirlpool

CAUGHT IN AN IRRESISTIBLE FLOW

When we descended into a Schwarzschild black hole we were inevitably spaghettified. But we may be able to survive a plunge into a super-massive rotating black hole.

A rotating black hole is a whirlpool in space – a drain into which space swirls and disappears. Before we dive down that drain, prudence dictates that we measure it carefully. Our goal is to follow the green path around the black hole, loop up and then dive through the ring singularity and enter another universe. If we touch the ring singularity we die of spaghettification.

To obtain a precise orbital entry, we have to measure how fast the hole is rotating. From high above the spin axis of the hole we lower a bucket of water. The water begins to swirl. We measure how fast it swirls and this tells us how fast the hole is rotating.

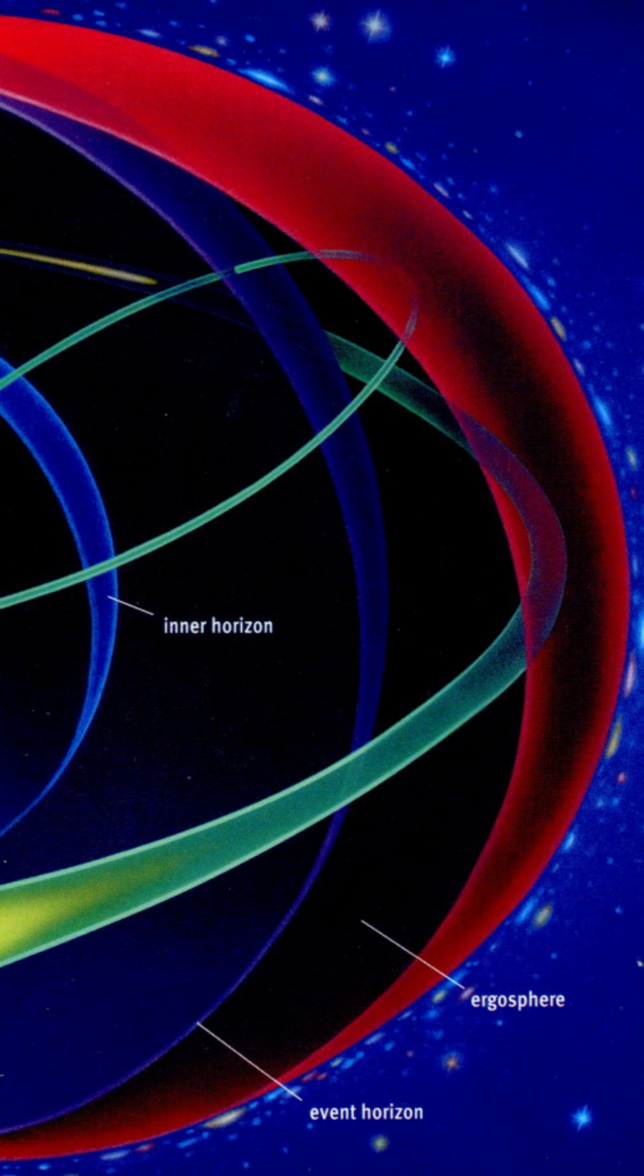
We were able to fall straight into the non-rotating black holes, but here, if we fall straight in, the swirling space will drag us around several times before it swallows us. There is no current of water, or wind of particles. Empty space is rotating and dragging us around.

If we try not to swirl, even if we have the most powerful rocket in the Universe, the surface of the ergosphere is where we have to give up. No non-orbiting observers can exist inside the ergosphere.

The idea that empty space can rotate is a prediction of Einstein's that has never been tested. NASA has been building a satellite called Gravity Probe B, to test it. However, many physicists are so convinced that Einstein is right that the mission may not get funded.

When we pass inside the ergosphere, outside observers no longer see us.

There is no tidal discomfort at all since this is a black hole of 3 billion solar masses.



SWALLOWING A STAR

We have travelled 50 million light-years to explore the most massive black hole known. This rotating black hole is three billion times more massive than the Sun and a thousand times more massive than the black hole in the centre of our galaxy. Here we see it swallowing a star. It doesn't rip off the outer envelope like smaller black holes do. It just neatly swallows the whole star.

WHAT HAPPENS IN THE END?

We would like to find out if the Universe will expand forever or recollapse. Falling through the inner horizon of a black hole is a quick way to find out. If the Universe recollapses we will know about it because as we pass the inner horizon, all the people in the entire Universe will join us inside the black hole for the final moments (or, the equivalent, our black hole gets embedded in the big crunch). If they don't join us, we will know that the Universe has continued to expand forever. As we cross the inner horizon we will see everything that will ever happen in the outside universe. But what will we see outside *after* we pass through the inner horizon. Will we see beyond the infinite future?

Passage to another universe?

THE ULTIMATE TRIP

Where will we go when we dive through the ring singularity? We don't know for sure but the maths point to various weird possibilities.

Stephen Hawking suggests that we will go off into a little self-contained baby universe that has branched off from our Universe. In these bizarre universes, distances are negative and time runs backwards.

The maths also suggest that when a black hole forms, a white hole forms with it, very similar to the way particles are created in pairs. And just as the Universe ends at the surface of a black hole, the Universe would begin at the surface of a white hole. The Big Bang at the origin of our Universe looks like a white hole, acts like a white hole, and so probably is a white hole.

But what kind of black hole is linked to our Big Bang/white hole? One suggestion (see inset) is that our Big Bang is linked to a black hole in another universe. Another suggestion is that every black hole in our own Universe is linked to the Big Bang. This could be called the recycling Universe. It may explain where all the matter goes when it falls into a black hole and where the matter in the Big Bang comes from.

In a recycling Universe, our voyage into a black hole is a return trip complete with a time machine that rejuvenates us by 13 billion years as it turns us back into the vibrating superstrings we came from.

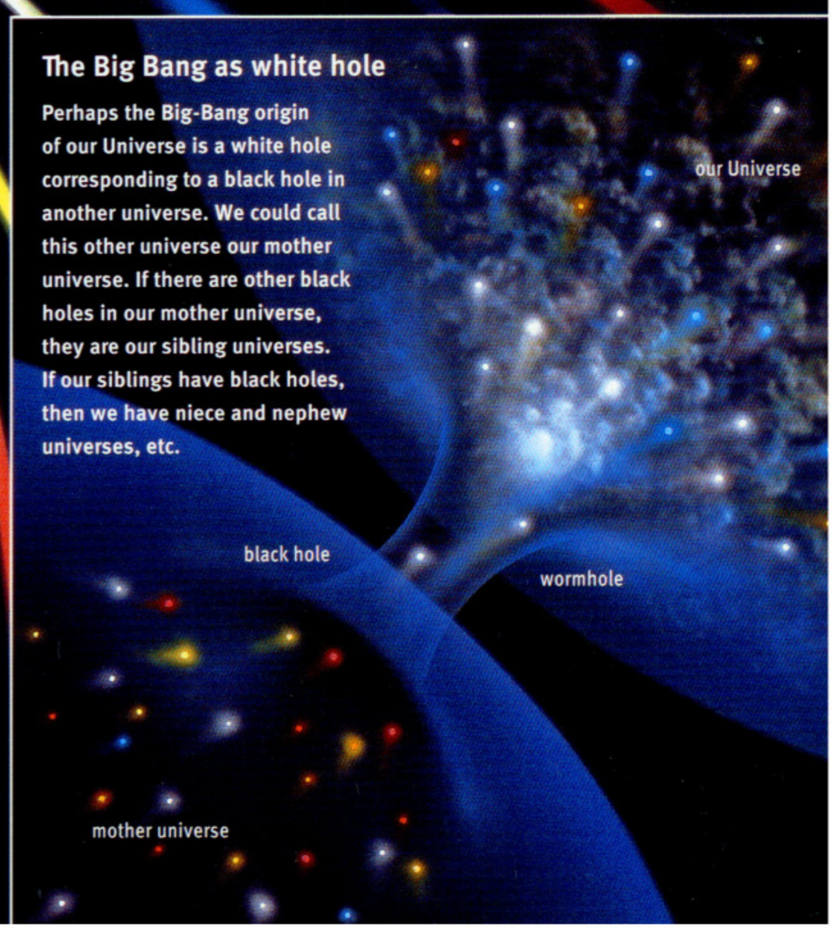
We know our Universe has black holes in it, but it is also possible our Universe is a black hole. We may be living inside a black hole. As a black hole gets more massive, its density decreases. A black hole the size of the visible Universe would also have about the same density as the Universe.

If these visions are true, then we have black holes within black holes, which are universes within universes. Black holes can either be embedded in each other (like Russian dolls) or linked to independent universes (see inset), or even both. This infinite network of interlinked universes has been dubbed the Multiverse.

To be science, ideas have to be testable. What observations can one possibly make to test these ideas? Some day we may be able to visit another universe through a black hole and come back. But for now our best bet is to observe black holes as carefully as we can, find new ones and keep looking for white holes. On the theoretical front we must squeeze our new theories to make them produce specific verifiable predictions about black holes and the Big Bang.

The Big Bang as white hole

Perhaps the Big-Bang origin of our Universe is a white hole corresponding to a black hole in another universe. We could call this other universe our mother universe. If there are other black holes in our mother universe, they are our sibling universes. If our siblings have black holes, then we have niece and nephew universes, etc.



Wormholes

TUNNELS THROUGH SPACE

If we had a super-powerful microscope able to show us spacetime at a scale of 10^{-32} mm and a strobe light powerful enough to illuminate and freeze the scenery every 10^{-43} seconds, we would see miniature black holes and wormholes popping into and out of existence. They occur naturally all the time.

These quantum wormholes in the spacetime foam might look something like the illustration below left. To make a big wormhole from this miniature one, all we need is to reach down into this spacetime foam and enlarge this structure. After all, strong electric and gravitational fields can reach into the vacuum and pull out real particles, so why can't we reach in and pull out wormholes?

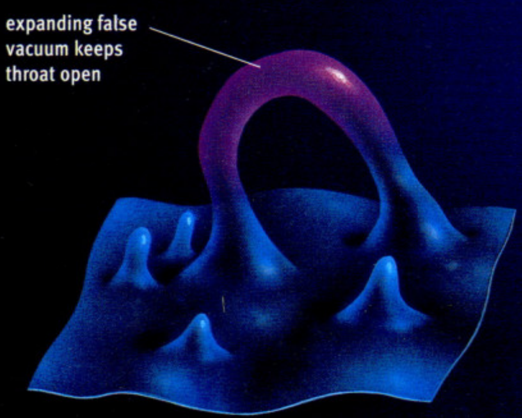
The most famous fictional wormhole you may have heard of is the Bajoran wormhole featured in the *Star Trek* spin-off *Deep Space Nine*. But just because it's on *Star Trek* doesn't mean wormholes really exist. Wormholes have a serious problem. They are unstable. Their throats keep pinching off and collapsing, leaving a pair of disconnected mini black holes.

An advanced civilisation that knows how to manipulate the energy of the vacuum may be able to solve this problem. A vacuum with a very high energy density is known as false vacuum. Like compressed springs or antigravity, it makes things expand. It is the stuff allegedly responsible for the period in the early Universe known as inflation when the Universe expanded very quickly.

If some false vacuum were inserted into the throat of a wormhole, it would expand the throat and might keep it open. If the Big Bang really is a white hole, maybe the false vacuum of inflation is what kept the throat open long enough to make our whole Universe possible.

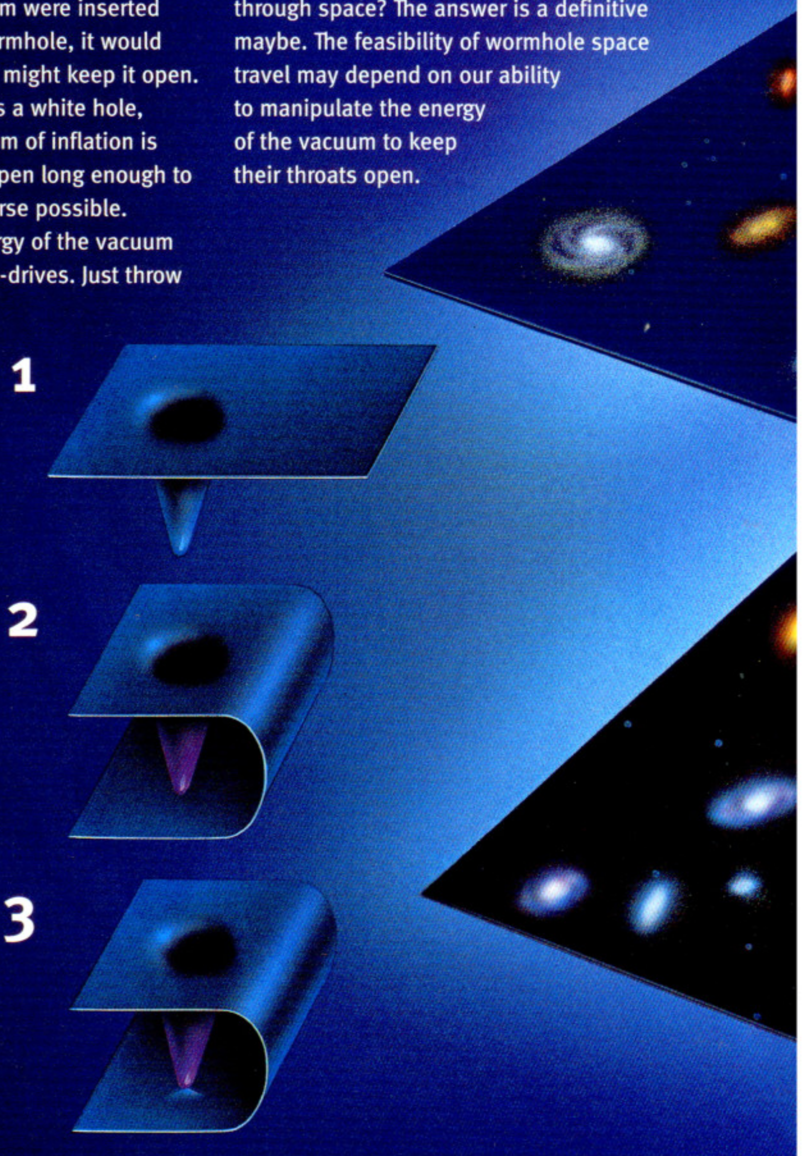
Controlling the energy of the vacuum would also allow warp-drives. Just throw some high-energy vacuum out behind you and some low-energy vacuum in front. That makes the space behind you expand and the space in front of you contract and that enables you to surf through space at warp speed.

How seriously should we take wormholes? Can they be used to travel through space? The answer is a definitive maybe. The feasibility of wormhole space travel may depend on our ability to manipulate the energy of the vacuum to keep their throats open.



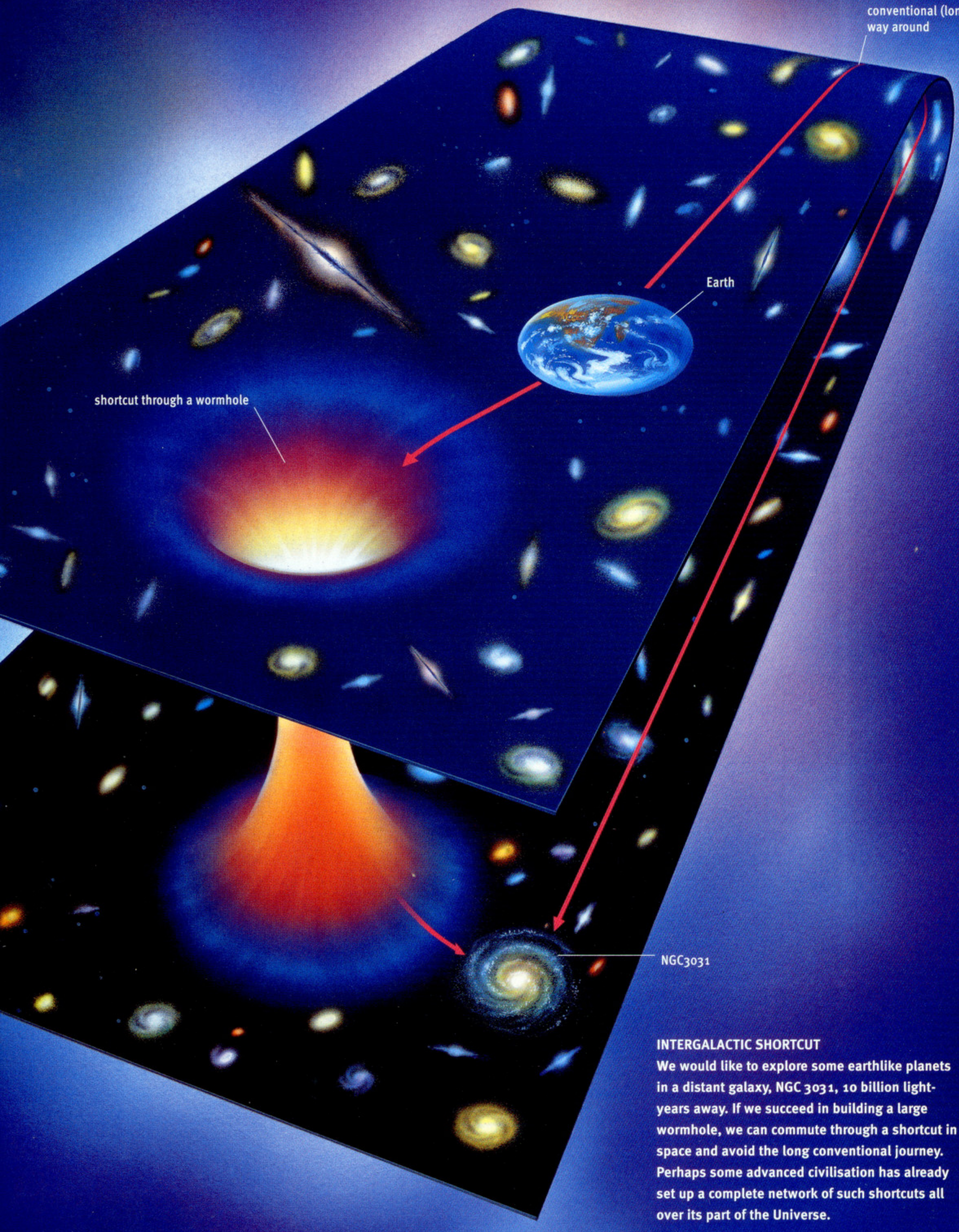
Making wormholes from quantum wormholes

An advanced civilisation may be able to pull quantum wormholes out of spacetime foam. They would have to insert false vacuum into the throats of the wormholes to keep them open for traffic.



Making wormholes from black holes

1. Get a neutron star that is just about to turn into a black hole.
2. Curve space around so that the neutron star's gravitational dent almost touches a distant region of space in the lower surface.
3. Put another neutron star into this region to dent the space. Add matter to each star. They will form black holes and the dents will meet. False vacuum may have to be inserted to stop the throat pinching off.



INTERGALACTIC SHORTCUT
We would like to explore some earthlike planets in a distant galaxy, NGC 3031, 10 billion light-years away. If we succeed in building a large wormhole, we can commute through a shortcut in space and avoid the long conventional journey. Perhaps some advanced civilisation has already set up a complete network of such shortcuts all over its part of the Universe.

Eternity

CHILDREN OF THE STARS

Today stars light up the Universe and the light from one star (the Sun) has given us life. But stars do not last forever. The Sun will last another 5 billion years and then become a dim white dwarf. Smaller stars will last longer but in 100 billion years they too will have used up all their fuel and leave only fading remnants.

The Universe will go dark.

In the life of the Universe, the first 100 billion years is a comparatively minor energetic episode. This short stellar period could be called the birth throes of the black-hole Universe. From this deep-time perspective, the epoch of stars was a fleeting moment, an explosion of fireworks that lasted for a second and faded away. After the last star runs out of fuel and goes dark, the children of the stars, black holes, will inherit the Universe.

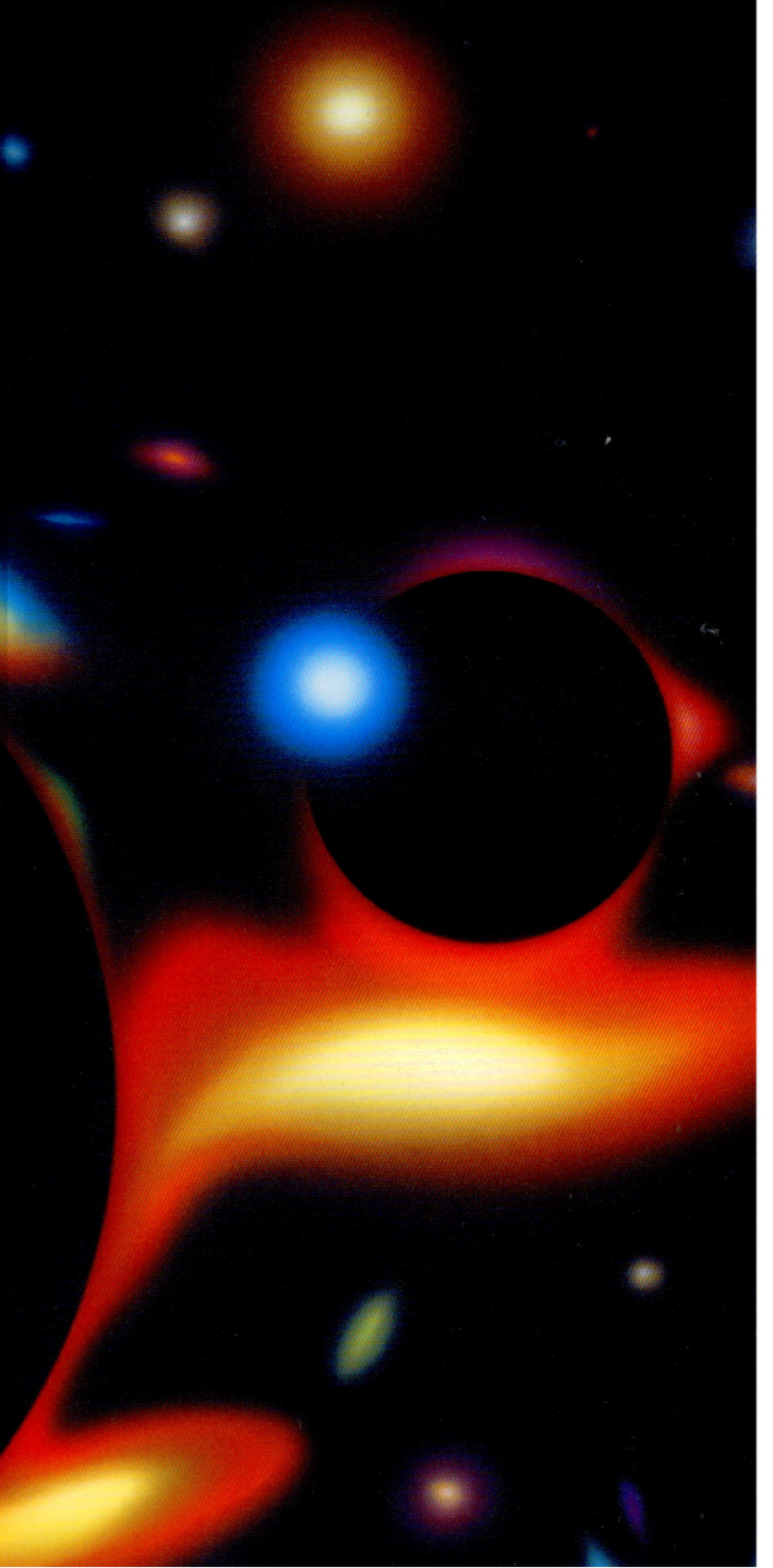
Once a black hole has formed, it sticks around for a very long time. But not forever: black holes evaporate. The shortest-lived stellar mass black hole will evaporate in 10^{67} years. That's 10^{57} times the age of the Universe. For lovers of light there will be some solace. Black holes glow as they evaporate and this will be our eternal night light.

On the largest scales, the evolution of the Universe can be understood as a war going on between the expansion of the Universe on the one side (matter spreading out, the Universe cooling, entropy increasing) and gravitational attraction on the other (galaxy clusters getting larger, black holes sucking up more and more of the Universe).

Each time a black hole forms, gravity has won a little battle. But the Universe will continue to expand and current observations suggest that expansion will win this war. However, if black holes create new universes or create white holes in other universes, this largest-scale description of our Universe becomes a trivial detail, like a storm in a puddle.

Much as Isaac Newton discovered the connection between the apple and the Moon, we are discovering the deep connection between black holes and other universes.

When I'm tired and troubled, I often look up at the benign stars. Like us, they won't be here forever. I find the tail of the Scorpion high in the sky and wonder about the black hole we know is hidden there – so powerful that we and every other star in the Milky Way is orbiting around it. Black holes remain at the edge of the Universe, the end of time and at the limit of our understanding. ●



IN A TRILLION YEARS
After all the stars have burned up all the fuel, the Universe will be a much darker place. The only illumination will come from black hole evaporation. All the sources of light you see here are evaporating black holes of different masses and therefore of different temperatures. The biggest ones are still effectively black. Their gravitational fields distort the glowing black holes in the background. The reddish ones are small. Occasionally, a tiny black hole will explode and disappear (lower right).