VOL FOUR / ISSUE ONE

NewScientist THE COLLECTION

RELATIVITY: EINSTEIN'S MIND-BENDING UNIVERSE

SPACE-TIME... BIG BANG... BLACK HOLES... GRAVITATIONAL WAVES... TIME TRAVEL... AND THE SEARCH FOR A THEORY OF EVERYTHING

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NewScientist
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EINSTEIN'S
UNIVERSE

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Everything's relative

IN A few short years in the early 20th century, an iconoclastic young physicist transformed our understanding of the universe. With his special and general theories of relativity, Albert Einstein overturned the solid certainty that was Newton's clockwork universe and replaced it with a picture that defied common sense. His work brought us the famous equation $E=mc^2$, defined light as the cosmic speed limit, unified space and time, redefined gravity and ushered in the idea that the universe began in a hot, dense fireball we now call the big bang.

These insights later gave rise to some of the most intriguing and mind-boggling ideas in modern physics: black holes, time travel, dark matter and dark energy. Today's physicists are still wrestling with his revelations and their consequences. Only last year was one of Einstein's key predictions – the existence of gravitational waves – finally confirmed.

His early work was all the more remarkable given that he did not hold an academic position and was forming his theories largely alone, in his spare time, while working as an examiner at the patent office in Bern, Switzerland. Despite this estrangement from mainstream academia – or maybe because of it – in 1905 he published four groundbreaking papers including the special theory of relativity. This "wunderjahr" won him scientific fame and, in 1908, he was appointed to a post at the University of Bern.

It is hard to overstate Einstein's influence on modern science, and yet his theories remain arcane and often misunderstood. This issue of *New Scientist: The Collection* introduces his astonishing ideas and explains how they could lead to the next revolution in physics.

Chapter 1 lays the groundwork, introducing the special and general theories of relativity and their counter-intuitive implications. It throws some historical light on the febrile scientific world of the early 20th century. And it explains how relativity went through the doldrums before emerging into a new golden age in the 1950s.

Chapter 2 works through some of the consequences of general relativity for the universe as a whole. These include its beginning as a hot, dense fireball, its ongoing expansion and the maddening presence of "dark" forms of matter and energy, which we know must form the majority of the universe but struggle to understand.

In chapter 3 we meet one of Einstein's most fearsome predictions, the black hole – a region of space-time so dense that even light cannot escape. We consider the conundrum of supermassive black holes and the intriguing possibility of wormholes.

Chapter 4 tells the story of the last piece of the puzzle, gravitational waves, which were predicted by Einstein himself but only confirmed last year. Even so, the search for more exotic waves goes on.

Chapters 5 and 6 look at the problems with relativity and some possible solutions. Despite its astonishing success there are cracks in the theory, not least that it is incompatible with quantum mechanics. Einstein spent the latter part of his career trying to reconcile the two in a theory of everything. Can today's scientists succeed where he failed?

Graham Lawton, Editor-in-chief

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With the exception of "A very special theory", which is new to this collection, the articles here were first published in *New Scientist* between July 2010 and January 2017. They have been updated and revised.

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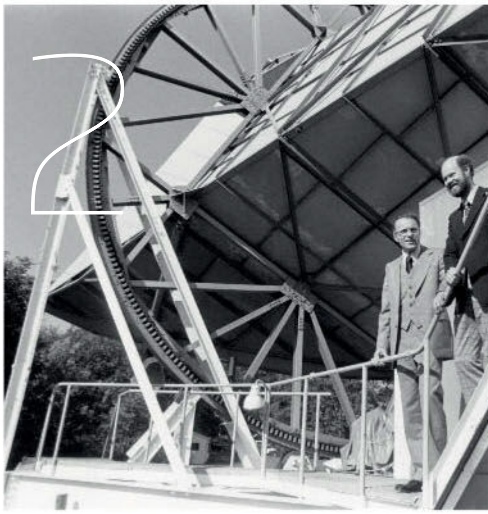

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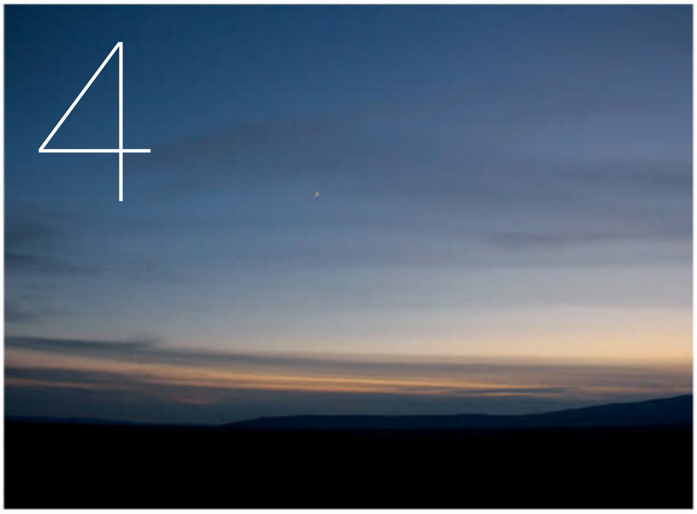

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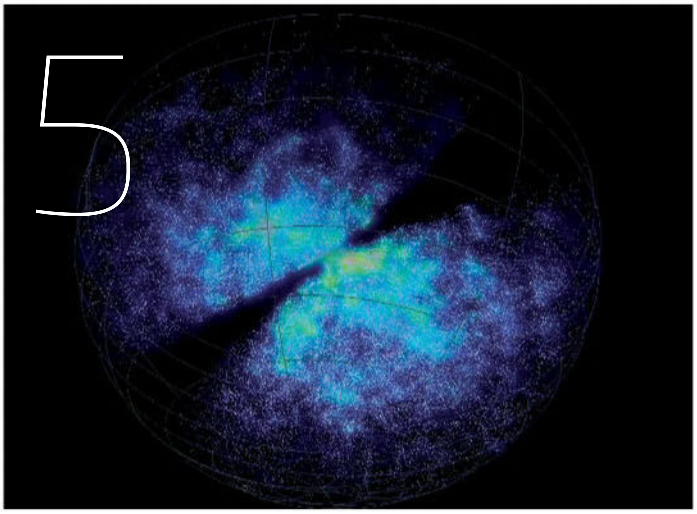

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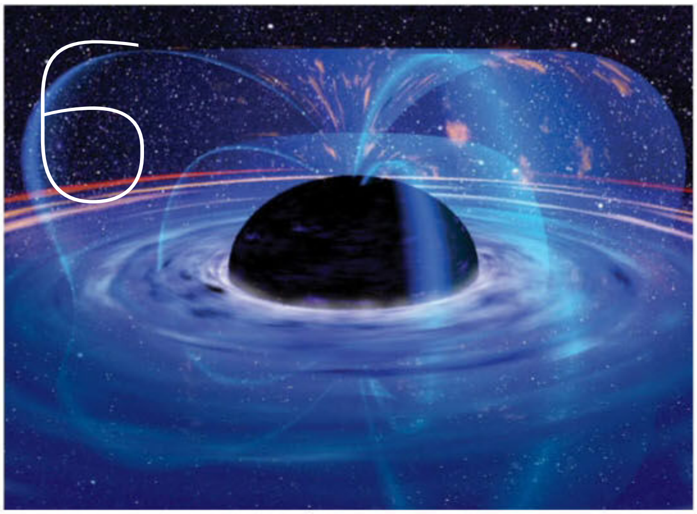

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A very special theory

Einstein's first really big idea introduced the world to some mind-bending concepts. Michael Brooks explains

PAUL FUSCO/MAGNUM PHOTOS

"A STORM broke loose in my mind." This was how Albert Einstein felt when inspiration finally struck about how to solve a problem he had been wrestling with for years. That storm has been provoking thunderous revelations ever since.

It was 1905 and Einstein was working as an examiner in the patent office in Bern, Switzerland. The job did not give him easy access to scientific journals and conferences, but it gave him plenty of time to think. And that was all he needed.

Einstein's problem was this: if two people are moving relative to one another, do the laws of physics seem the same to both?

To 19th-century physicists, the answer was a resounding "yes". Say I am standing motionless on a station platform and you are on a train travelling past at a constant velocity. To you, I am the one who seems to be moving. But as far as the laws of physics are concerned, it doesn't really matter who is moving relative to whom: the rules governing motion stay the same. If we both perform the same simple experiment – say, throwing a ball in the air and catching it – we will get the same result.

But in some respects, relative motion does make a difference. If I roll a ball along the platform parallel to the direction of the train, it will obey the laws of motion but its velocity will seem different from my point of view and yours.

In the late 19th century this distinction became an urgent problem. James Clerk Maxwell's theory of electricity and magnetism made it clear that light was a wave travelling at a constant speed – around 300,000 kilometres per second. But his theory did not specify whether light looked and behaved the same when an observer was travelling relative to the light beam.

Einstein had been puzzling over this for years. As a 16 year old, he daydreamed about running alongside a light beam. Once he reached the speed of light, the beam would appear to stop. Elsewhere, astronomical experiments had suggested that light always travelled at a constant speed, regardless of an observers' motion relative to it.

Something had to give. That something is our notion of space and time. We tend to think of a metre as a fixed length and a second as a well-defined and non-negotiable interval of time. If we talk about a particular moment – a "now" – that, to us, seems universal. Einstein's insight was that none of this needs to be true.

The only way to make the laws of physics identical to all observers, regardless of how they are moving through the universe, is to say that certain phenomena, such as the speed of light in vacuum (known as *c*), are always the same, regardless of motion.

That means that if you were to measure the speed of the light shining from the headlights of a train travelling towards you at 100 kilometres per hour, your reading would be *c*, not *c* plus 100 km/h. Similarly, the light from a train moving away from you wouldn't appear slower. Ditto a spaceship travelling towards or away from you at 90 per cent of the speed of light: its light still travels towards you at speed *c*.

The implications of this are extraordinary and contrary to everyday experience. The only way to keep a constant speed of light for all observers is if distance and time are pliable.

Let's face up to squishy space first. This phenomenon, known as Lorentz contraction, is seen when an object is moving relative to an observer trying to measure its length. Measure the length of a 100-metre long space ship that is flying past you at 99 per cent of the speed of light, and your reading will be just 14 metres. To people inside the ship, it remains 100 metres long.

It's a similar deal with "time dilation", which is even more mind-bending. Anything capable

EINSTEIN'S RIVALS

Special relativity will always belong to Einstein, but things could have been different. Einstein told one biographer that the theory was "ripe for discovery". He knew the Dutch theorist Hendrik Lorentz had derived much of it, for instance. The French mathematician Henri Poincaré was also far along the road. In the end, though, it was Einstein who reached the finish line first.

A young patent examiner ready to change the universe

of marking the passage of time, from the hands of a wristwatch to the oscillations of electrons within an atomic clock or the processes within a biological cell, must run at different rates depending on relative motion through the universe.

It sounds impossible, but it has been proven by flying atomic clocks on airliners travelling in different directions around the world. And in theory, it works the same for human ageing – the famous "twin paradox". If twins are separated, with one remaining on Earth and the other travelling close to the speed of light across a large distance in space, when they are reunited on Earth, the twin that stayed at home will have aged more.

Unless you are travelling at a significant fraction of the speed of light, these effects are negligible. Nonetheless, time dilation has to be taken into account when operating the clocks on GPS satellites whizzing around Earth at 14,000 km/h: because of their relative motion, they lose seven milliseconds a day compared to clocks on Earth's surface.

The passage of time, then, is malleable – you might even say that it is an illusion. That's certainly true of the concept we call "now".

Einstein once joked that the only reason for time's existence is "so that everything doesn't happen at once". The quip wasn't entirely without foundation. The equations he came up with to describe these weird phenomena say that as long as things are taking different paths through the universe, simultaneity is impossible to define. In Einstein's universe, one observer can move through space in a way that means they will see supernova A explode before supernova B, while another person moving in a different way will see B explode before A. In the same way, it is not always possible for two observers to agree that a certain moment is "now".

You might have thought that all of these profound revelations would be enough for Einstein to give his brain a rest. Not a bit of it: he kept drawing more and more implications. Probably the most famous was his observation that energy (E) and mass (m) are interchangeable, linked together by the equation $E=mc^2$.

He also concluded that the inertia – resistance to acceleration, often just labelled mass – of a body increases with its energy. That makes a fast-moving body ever harder to accelerate, which is why nothing with mass can be accelerated right up to the speed of light. It also works with heat energy: a hot saucepan is infinitesimally heavier than a cold one. Einstein called the idea "jolly and beguiling" and suggested it might be tested by examining radium salts. It eventually passed a much more dramatic test: the energy released in atomic explosion obeyed the $E=mc^2$ rule. It was equivalent to the bomb's change in mass multiplied by the square of the speed of light.

This set of mind-bending ideas became known as relativity. Strictly speaking, it only applies under very specific circumstances – to "inertial observers" in "inertial frames of reference", which just means observers moving in straight lines at constant speeds relative to one another. But within a decade, Einstein went one better, producing a more general theory by incorporating acceleration and gravity into the picture (see page 8). In 1915 Einstein himself coined the terms "special" and "general relativity" to distinguish his two theories.

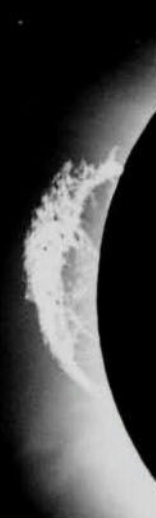
Special relativity remains at the heart of physics. It has to be taken into account in any situation where bodies are moving relative to one another at velocities near the speed of light. From the design of particle accelerators to interpretations of cosmological data, special relativity is an essential part of the modern world. ■

GENERAL RELATIVITY: A PRIMER

Albert Einstein's general theory of relativity is one of the towering achievements of 20th-century physics. Published in 1915, it explains that what we perceive as the force of gravity in fact arises from the curvature of space and time.

Einstein proposed that objects such as the sun and Earth change this geometry. In the presence of matter and energy, space-time can evolve, stretch and warp, forming ridges, mountains and valleys that cause bodies moving through it to zigzag and curve. So although Earth appears to be pulled towards the sun by gravity, there is no such force. It is simply the geometry of space-time around the sun telling Earth how to move.

The general theory of relativity has far-reaching consequences. It not only explains the motion of the planets; it can also describe the history and expansion of the universe, the physics of black holes and the bending of light from distant stars and galaxies. By physicist Pedro Ferreira



GRAVITY BEFORE EINSTEIN

In 1686, Isaac Newton proposed an incredibly powerful theory of motion. At its core was the law of universal gravitation, which states that the force of gravity between two objects is proportional to each of their masses and inversely proportional to the square of their distance apart. Newton's law is universal because it can be applied to any situation where gravity is important: apples falling from trees, planets orbiting the sun, and many, many more.

For more than 200 years, Newton's theory of gravity was successfully used to predict the motions of celestial bodies and accurately describe the orbits of the planets in the solar system. Such was its power that in 1846 the French astronomer Urbain Le Verrier was able to use it to predict the existence of Neptune.

There was, however, one case where Newton's theory didn't seem to give the correct answer. Le Verrier measured Mercury's orbit with exquisite precision and found that it drifted by a tiny amount – less than one-hundredth of a degree over a century – relative to what would be expected from Newton's theory. The discrepancy between Newton's theory and Mercury's orbit was still unresolved at the beginning of the 20th century.

EINSTEIN'S INSIGHT

In 1905, at the age of 26, Albert Einstein proposed his special theory of relativity. The theory reconciled the physics of moving bodies developed by Galileo Galilei and Newton with the laws of electromagnetic radiation. It posits that the speed of light is always the same, irrespective of the motion of the person who measures it. Special relativity implies that space and time are intertwined to a degree never previously imagined.

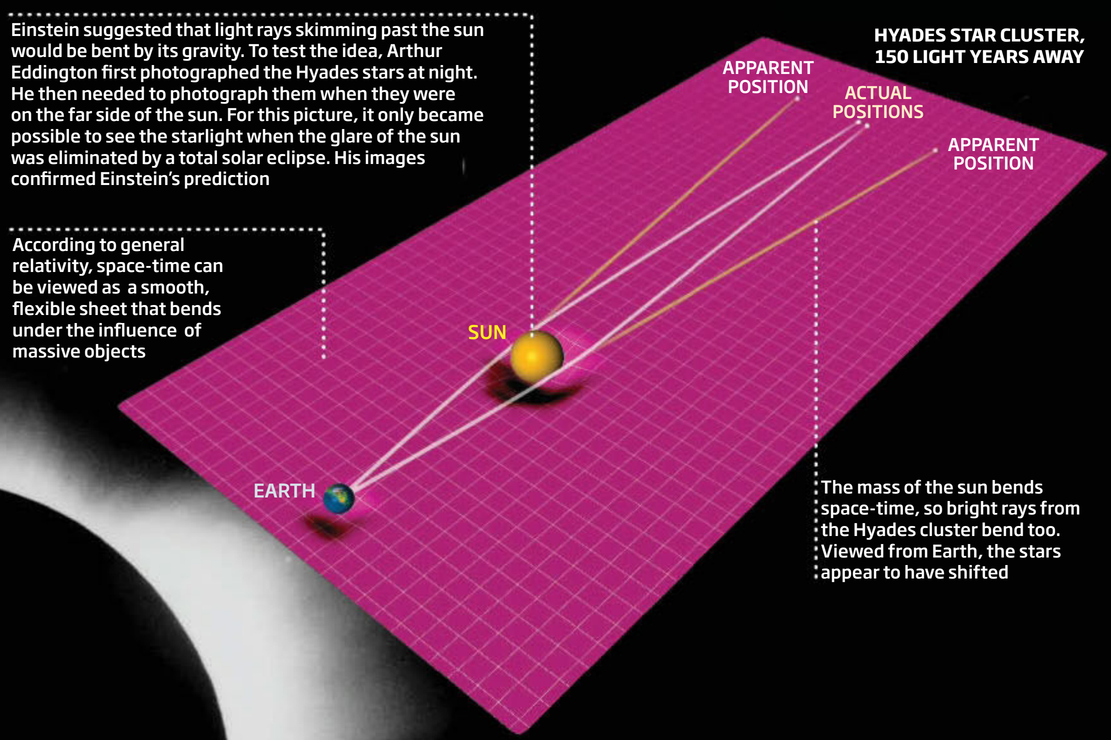
Starting in 1907, Einstein began trying to broaden special relativity to include gravity. His first breakthrough came when he was working in a patent office in Bern, Switzerland. "Suddenly a thought struck me," he recalled. "If a man falls freely, he would not feel his weight… This simple thought experiment… led me to the theory of gravity." He realised that there is a deep relationship between systems affected by gravity and ones that are accelerating.

SCIENCE PHOTO LIBRARY

The next big step forward came when Einstein was introduced to the mathematics of geometry developed by the 19th-century German mathematicians Carl Friedrich Gauss and Bernhard Riemann. Einstein applied their work to write down the equations that relate the geometry of space-time to the amount of energy that it contains. Now known as the Einstein field equations, and published in 1915, they supplanted Newton's law of universal gravitation and are still used today, a century later.

Using general relativity, Einstein made three key predictions. He showed how his theory explained a hitherto mysterious drift in Mercury's orbit. He predicted that a massive object, such as the sun, should distort the path taken by light passing close to it: in effect, the geometry of space should act as a lens (see diagram top right). Finally, he argued that the wavelength of light emitted close to a massive body such as a star should be stretched, or red-shifted, as it climbs out of the warped space-time near the massive object.

These three predictions are now called the three classical tests of general relativity.



"Space tells matter how to move and matter tells space how to curve"
John Archibald Wheeler

PASSING THE TESTS

In 1919, the English astronomer Arthur Eddington travelled to the island of Príncipe off the coast of west Africa to test the second of Einstein's predictions: the gravitational lensing of light. His plan was to observe a bright cluster of stars called the Hyades as the sun passed in front of them. To see the starlight, Eddington needed a total solar eclipse to blot out the glare of the sun.

If Einstein's theory was correct, the positions of the stars in the Hyades would appear to shift by about 1/2000th of a degree.

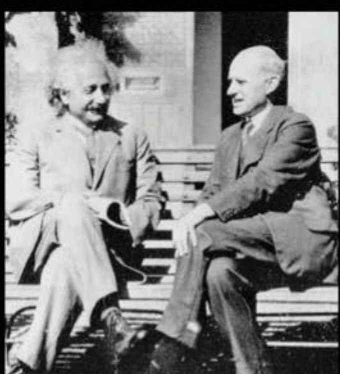
To pinpoint the position of the Hyades in the sky, Eddington first took a picture at night from Oxford. Then, on 29 May 1919, he photographed the Hyades as they lay almost directly behind the sun during the total eclipse that Príncipe experienced that day. Comparing the two measurements, Eddington was able to show that the shift was as Einstein had predicted and too large to be explained by Newton's theory.

Following the eclipse expedition, there was some controversy that Eddington's analysis had been biased towards general relativity. Matters were not laid to rest until the late 1970s, when the photographs were analysed again and Eddington's analysis was shown to be correct.

Eddington's result turned Einstein into an international superstar: "Einstein's theory triumphs" was the headline of *The Times* of London. From then on, as more consequences of his theory were discovered, general relativity became entrenched in the popular imagination, with its descriptions of expanding universes and black holes.

In 1959, the American physicists Robert Pound and Glen Rebka measured the gravitational red-shifting of light in their laboratory at Harvard University, thereby confirming the last of the three classical tests of general relativity.

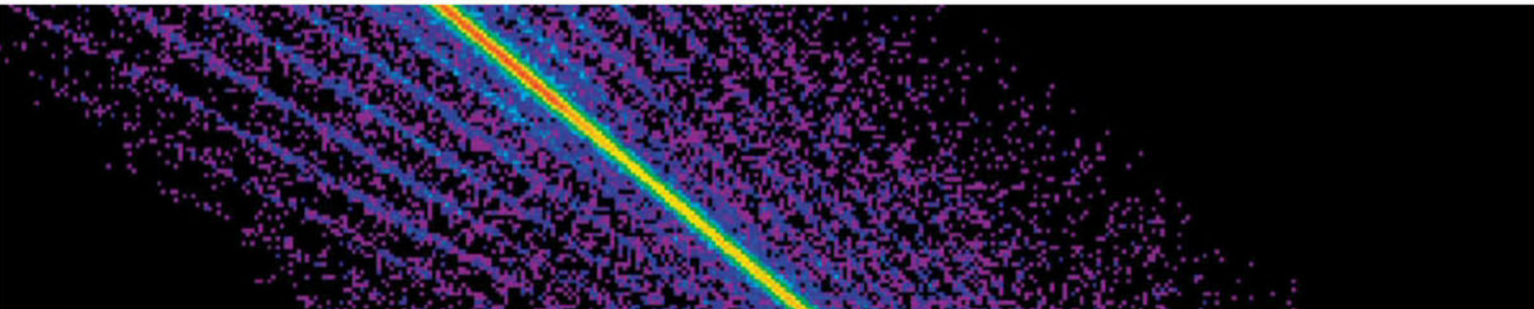
Images of the 1919 solar eclipse like the one above proved that gravity bends starlight


ROYAL ASTRONOMICAL SOCIETY/SPL

By 1930, Albert Einstein and Arthur Eddington were famous for their work on general relativity

HOW GENERAL RELATIVITY SHAPES OUR UNIVERSE

Einstein's general theory of relativity has revealed that the universe is an extreme place. We now know it was hot and dense and has been expanding for the past 13.8 billion years. It is also populated with incredibly warped regions of space-time called black holes that trap anything falling within their clutches.



BLACK HOLES

Shortly after Einstein proposed his general theory of relativity, a German physicist called Karl Schwarzschild found one of the first and most important solutions to Einstein's field equations. Now known as the Schwarzschild solution, it describes the geometry of space-time around extremely dense stars – and it has some very strange features.

For a start, right at the centre of such bodies, the curvature of space-time becomes infinite – forming a feature called a singularity. An even stranger feature is an invisible spherical surface, known as the event horizon, surrounding the singularity. Nothing, not even light, can escape the event horizon. You can almost think of the Schwarzschild singularity as a hole in the fabric of space-time.

In the 1960s, the New Zealand mathematician Roy Kerr discovered a more general class of solutions to Einstein's field equations. These describe dense objects that are spinning, and they are even more bizarre than Schwarzschild's solution.

The objects that Schwarzschild and Kerr's solutions describe are known as black holes. Although no black holes have been seen directly, there is overwhelming evidence that they exist. They are normally detected through the effect they have on nearby astrophysical bodies such as stars or gas.

The smallest black holes can be found paired up with normal stars. As a star orbits the black hole, it slowly sheds some of its material and emits X-rays. The first such black hole to be observed was Cygnus X-1, and there are now a number of well-measured X-ray binaries with black holes of about 10 times the mass of the sun.

Evidence for much larger black holes came in the 1960s when a number of very bright and distant objects were observed in the sky. Known as quasars, they arise from the havoc black holes seem to create at the cores of galaxies. Gas at the centre of a galaxy forms a swirling disc as it is sucked into the black hole. Such is the strength of the black hole's pull that the swirling gas emits copious amounts of energy that can be seen many billions of light years away. Current estimates place these black holes at between a million and a billion times the mass of the sun. As a result, they are called supermassive black holes.

The evidence now points to there being a supermassive black hole at the centre of every galaxy, including our own. Indeed, observations of the orbits of stars near the centre of the Milky Way show that they are moving in very tightly bound orbits. These can be understood if the space-time they live in is deeply distorted by the presence of a supermassive black hole with more than 4 million times the mass of the sun.

Despite their names, British physicist Stephen Hawking has pointed out that black holes may not be completely black. He argues that, near the event horizon, the quantum creation of particles and antiparticles may lead to a very faint glow. This glow, which has become known as Hawking radiation, has not been detected yet because it is so faint. Yet, over time, Hawking radiation would be enough to remove all the energy and mass from a black hole, causing all black holes to eventually evaporate and disappear.

"No black holes have been seen directly yet, though there is overwhelming evidence that they exist"

NASA

THE EXPANDING UNIVERSE

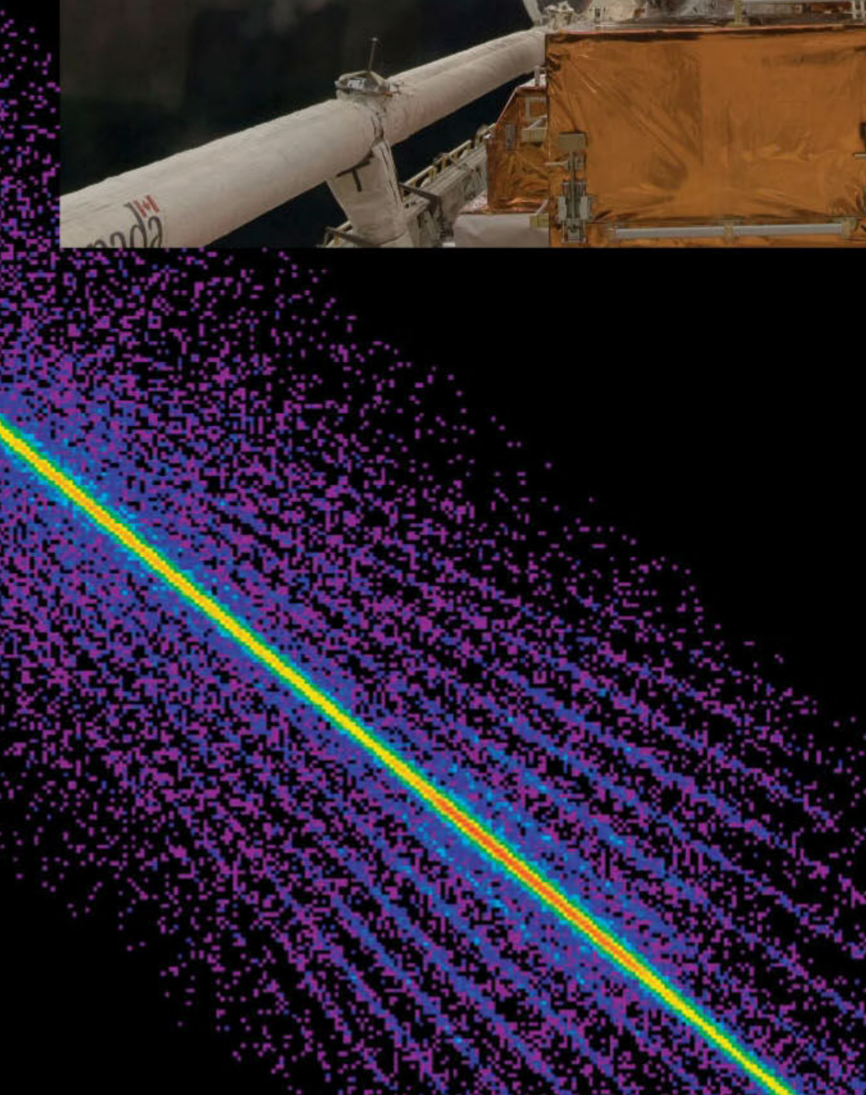
One of general relativity's most striking predictions arises if we consider what happens to the universe as a whole.

Shortly after Einstein published his theory, Russian meteorologist and mathematician Alexander Friedmann and Belgian priest Georges Lemaître showed that it predicted that the universe should evolve in response to all the energy it contains. They argued that the universe should start off small and dense, and expand and dilute with time. As a result, galaxies should drift away from each other.

Einstein was initially sceptical, even introducing a fudge factor called the cosmological constant into his theory to keep the universe static. But a discovery by astronomer Edwin Hubble changed his mind.

Hubble analysed how galaxies recede from the Milky Way. He found that distant galaxies move away faster than those that are relatively nearby – proof that the universe was indeed expanding. This model later became known as the big bang.

Over the past 20 years, a plethora of observations by satellites and large telescopes have further firmed up the evidence for an expanding and evolving universe. We have scrutinised the cosmic microwave background radiation, often called the afterglow of the big bang, obtained an accurate measure of the expansion rate of the universe and observed young galaxies as they were when the universe was in its infancy. It is now accepted that the universe began with a big bang about 13.8 billion years ago.

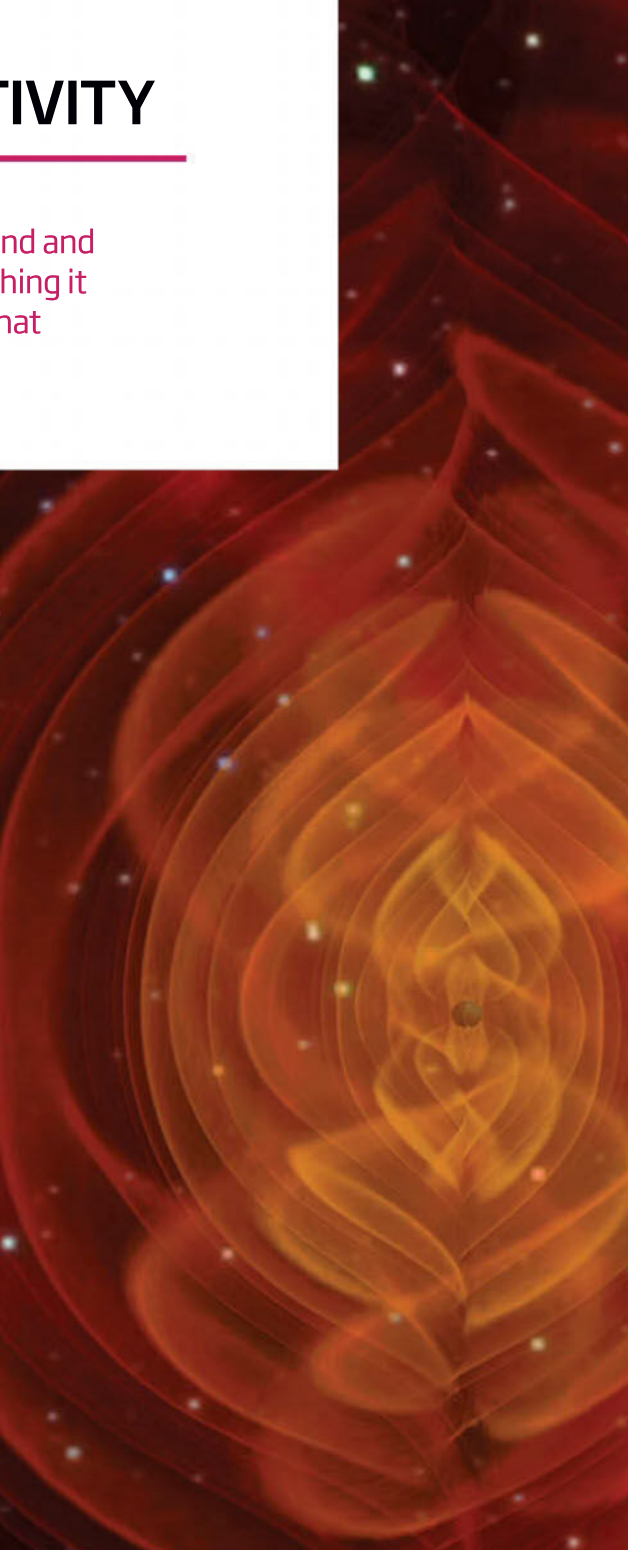


NASA/CXC/SAO

Images from the Hubble Space Telescope (above) and Chandra X-ray Observatory have firmed up our relativity-based ideas about the universe

FRONTIERS OF GENERAL RELATIVITY

General relativity predicts that the universe is full of exotic phenomena. Space-time can tremble like the surface of a pond and it seems to be full of a mysterious form of energy that is pushing it apart. It is also conceivable for space-time to be so warped that travelling backwards in time becomes possible.



GRAVITATIONAL WAVES

According to general relativity, even empty space-time, devoid of stars and galaxies, can have a life of its own. Ripples known as gravitational waves can propagate across space in much the same way that ripples spread across the surface of a pond.

Until very recently, the direct detection of gravitational waves was the biggest remaining test of general relativity. But in 2016, the Laser Interferometer Gravitational-Wave Observatory (LIGO) at Hanford, Washington, and Livingston, Louisiana, finally nailed them (see page 65). LIGO consists of laser beams that are reflected between mirrors 4 kilometres apart. When a gravitational wave passes through, it slightly distorts space-time, leading to a minuscule but detectable shift in the beams.

The signal seen by LIGO was emitted by a violent collision of two black holes. As they spiralled in towards each other, they emitted a burst of gravitational waves with a tell-tale signature.

Gravitational waves should also be emitted by rotating neutron stars called pulsars. When they are in orbit around another very dense star, we expect them to emit a steady stream of gravitational waves, losing energy in the process so that their orbits gradually decay. Measurements of binary pulsars' orbits confirm that they do indeed lose energy and the best explanation is that they are losing it in the form of gravitational waves. Indeed, before the direct detection of of the waves by LIGO, this was the best evidence we had that gravitational waves existed.

Pulsars are not the only expected source. The big bang should have created gravitational waves that still propagate through the cosmos as gentle ripples in space-time. These primordial gravitational waves are too faint to be detectable directly, but it should be possible to see their imprint on the relic radiation from the big bang – the cosmic microwave background. Detecting primordial gravitational waves is now a priority for physicists, and experiments are under way to search for them.

One project that may do so is the Evolved Laser Interferometer Space Antenna (eLISA), made up of a trio of satellites that will follow Earth in its orbit around the sun. They will emit precisely calibrated laser beams towards each other, much like LIGO. Any passing gravitational wave will slightly distort space-time and lead to a detectable shift in the laser beams. NASA and the European Space Agency hope to launch eLISA in the next decade.

The LIGO detectors (left) pick up gravitational waves ringing through space

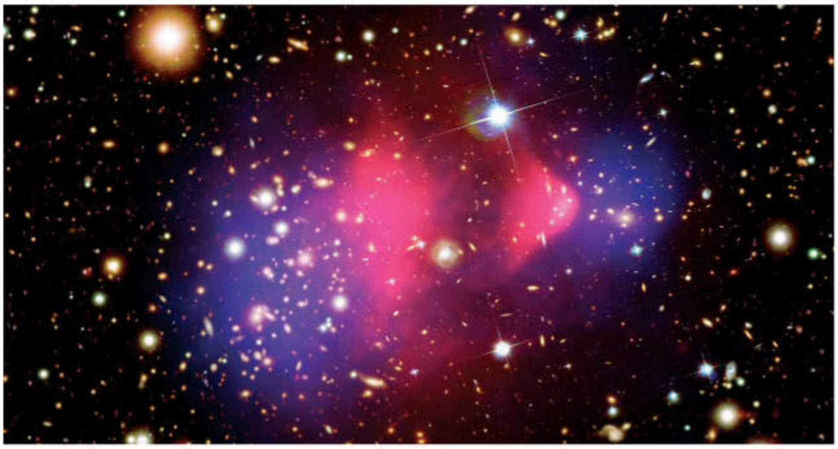
"It is possible to build tunnels linking different parts of space and different parts of time – in theory, at least"

TIME TRAVEL

Einstein's theory allows for the intriguing possibility of time travel. One suggested way of achieving this involves the construction of tunnels called wormholes that link different parts of space at different times. It is possible to build wormholes – in theory. But unfortunately they would require matter with negative energy, and other unnatural physical circumstances, not only to open them up but also to allow them to be traversed. Another possibility is to create a large region of space that rotates, or use hypothetical objects called cosmic strings.

The possibility of time travel can lead to physical paradoxes, such as the grandfather paradox in which the time traveller goes back in time and kills her grandfather before he has met her grandmother. As a result, one of her parents would not have been conceived and the time traveller herself would not exist. It has been argued, however, that physical paradoxes such as these are, in practice, impossible to create.

THE DARK UNIVERSE



The Bullet cluster group of galaxies (right) gives good evidence for dark matter (added in blue)

The expanding universe predicted by general relativity has become firmly entrenched in modern science. As our ability to observe distant galaxies and map out the cosmos has improved, our picture of the universe has revealed some even more exotic features.

For a start, astronomers have been able to measure how fast distant spiral galaxies spin, and this shows that the outskirts of galaxies are rotating far too quickly to be reined in by the mass of the stars and gas at their centres. More matter is needed in galaxies to generate enough gravity to prevent galaxies from flying apart.

The mainstream explanation is that galaxies contain large quantities of other forms of matter – known as dark matter because it does not emit or reflect light. Dark matter is thought to clump around galaxies and clusters of galaxies in gigantic balls known as halos. Dark matter halos can be dense enough to significantly distort space-time and bend the path of any light rays that pass close by. This gravitational lensing has been observed in a number of clusters of galaxies, and is one of the strongest pieces of evidence for the existence of dark matter.

But that's not all. Cosmologists have been able to figure out how fast the universe expanded at different times in its history. This is done by measuring the distance to exploding stars called supernovae, and how quickly they are receding due to the expansion of space-time. The ground-breaking results from these observations, which emerged around two decades ago, is that the expansion of the universe seems to be speeding up.

One explanation for this accelerating expansion is that the universe is permeated by an exotic form of energy known as dark energy. Unlike ordinary matter and dark matter, which bend space-time in a way that draws masses together, dark energy pushes space apart, making it expand ever more quickly over time.

If we add together all the forms of matter and energy in the universe we end up with a striking conclusion: only 4 per cent of the universe is made up of the form of matter we are familiar with. Around 24 per cent is invisible dark matter and 72 per cent is dark energy.

This result emerged from the marriage of the general theory of relativity and modern astronomy and it has become a prime focus of physics. Experimenters and theorists are directing their efforts at trying to answer the burning questions: what exactly are dark matter and dark energy? And why do they have such strange properties?

HENZE/NASA; FAR LEFT: DAVE BULLOCK; RIGHT: CXC/CFA/M.MARKEVITCH ET AL.; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.; ESO WFI; NASA/STSCIW

The four-dimensional entity at the centre of general relativity is a hard concept to grasp. Here's how physicists do it.

How to think about space-time

OFTEN described as the fabric of reality, space-time is a four-dimensional amalgamation of two entities that were once thought of as separate: space and time. It is all around us, but we cannot see it. So what is it?

A popular way of envisaging space-time is as a stretchy rubber sheet that deforms when a mass is placed on it. The resulting curvature is analogous to the warping of space-time by gravity.

It's a picture that might lead us to believe space-time is itself something physical or tangible. For most physicists, though, space-time itself is a lot more abstract – a purely mathematical backdrop for the unfolding drama of the cosmos.

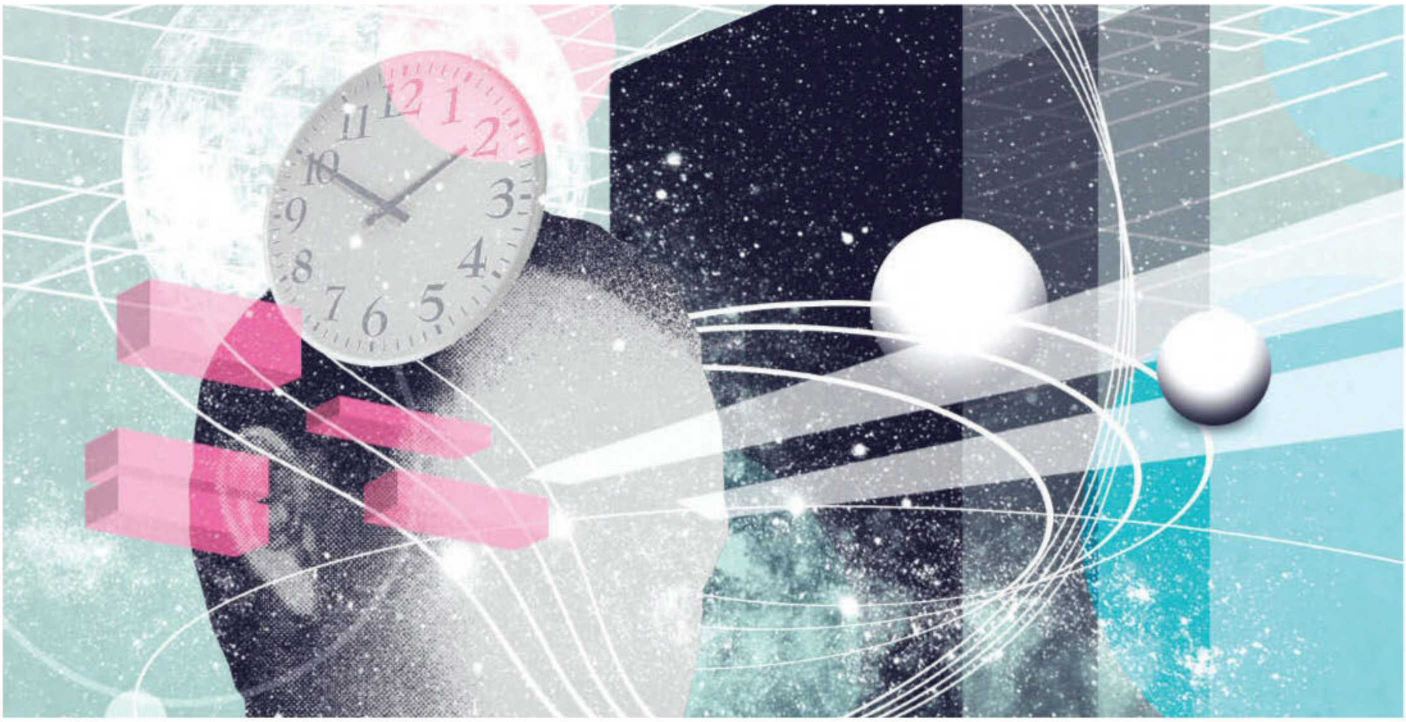
Physicist Martin Bojowald of Penn State University in Philadelphia sees it as a mathematical entity called a manifold. The equations of general relativity allow us to calculate the evolution of this manifold, and so of the universe itself, over time. "The rubber sheet is a picture for such a manifold, so in an abstract way I am indeed using the analogy," he says.

Don Marolf of the University of California, Santa Barbara, goes even further. "Visualising the 'shape' of space-time is very useful," he says. "But most of us don't visualise it as something particularly physical. To the extent that we draw pictures, they are just chalk lines on the blackboard."

One thing that unifies all of these conceptions of space-time is that it is a continuum, something that varies smoothly with no abrupt knobs, bumps or tears. But if we want to combine general relativity with quantum mechanics to create a unified theory of quantum gravity, that notion must change. In quantum gravity, space-time is made up of tiny discrete quanta just like everything else – making it a fabric with a discernible warp and weft.

"Fabric as opposed to a rubber sheet means that we are focusing more on what possible microstructures space-time may have," says Bojowald. Carlo Rovelli of the University of Marseilles, France, visualises this woven microstructure as being made of "tiny fuzzy blobs", the starting point of his theoretical investigations of quantum gravity. It's still just a device, though – something that helps him work with the intangible. "If I do not have an image in my head, I cannot even start thinking," he says.

Anil Ananthaswamy



MARIO WAGNER

RELATIVELY SUCCESSFUL

Einstein's general theory of relativity is an undoubted work of genius. Yet it still raises many questions – and physicists continue to look for something better

ALBERT EINSTEIN'S contributions to modern physics are unmatched, but his stellar reputation rests above all on a theory he presented to the Prussian Academy of Sciences in Berlin in a series of lectures in November 1915. The general theory of relativity is at its heart a theory of gravity. But in explaining how the force that sculpts large-scale reality works, it revolutionised our world view.

Ten years before, in 1905, Einstein had already shown how motion warps space and time. Starting with the assumption baked into James Clerk Maxwell's theory of the electromagnetic force, formulated 40 years earlier, that light always travels at the same speed, the special theory of relativity demonstrated how two observers in motion relative to each other will not perceive ruler lengths and clock ticks the same way.

For the general theory, Einstein combined this with another observation: that gravity's effects on a body with mass cannot be distinguished from the effects of an acceleration. After a decade of calculation, he reached his conclusion: gravity is a product of warped space-time. The sun keeps Earth in orbit not by exerting a physical force on it, but because its mass distorts the surrounding space and forces Earth to move that way. In the words of physicist John Archibald Wheeler, "space tells matter how to move and matter tells space how to curve".

A PERFECT THEORY?

Observations led by the British astronomer Arthur Eddington during a solar eclipse in 1919 showed how the sun's bulk bent the light reaching Earth from distant stars, just as the new theory predicted. In the past century, general relativity has never failed an experimental test, and has become the foundation of a new picture of an expanding universe that began in a big bang 13.8 billion years ago. The detection of gravitational waves in 2016 almost completed the picture (see chapter 4, page 56), now physicists are searching for primordial waves from the big bang itself.

Yet for all its success, general relativity makes many physicists uneasy. Its prediction of black holes, monsters that suck in everything they come into contact with, is a perennial cause of discomfort – even though these bodies do seem to exist. The theory's incompatibility with quantum theory, which explains how all the other forces of nature work, remains a glaring problem. Even so, there is much to celebrate – and also to look forward to.

EINSTEIN'S WITNESS

General relativity's story of the universe is writ large in the sky, says physicist Pedro Ferreira

THE general-relativistic model of the universe based on Einstein's theory has delivered many triumphs. Perhaps the greatest was the discovery of the cosmic microwave background (CMB), often called the afterglow of the big bang. Predicted in the 1940s as a direct consequence of general relativity, it was accidentally detected in 1964 as an unexplained hiss in an antenna built for experiments on microwave communication (see page 32). Since then, studies of the CMB have provided convincing proof that our universe began in a hot, dense pinprick and has been expanding ever since.

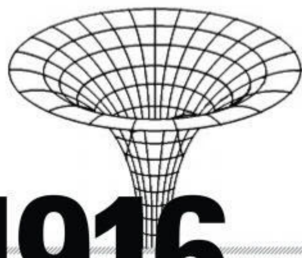
Studying the CMB has allowed us to characterise the universe's beginnings at energy scales unreachable by CERN's Large Hadron Collider particle accelerator, or any conceivable successor. Ground-based experiments, and latterly space ›

100 YEARS OF GENERAL RELATIVITY

In a century, Einstein's theory has revolutionised our picture of the universe

1915

Einstein presents his **field equations of general relativity** to the Prussian Academy of Sciences in Berlin



1916

Einstein uses general relativity to predict the existence of **gravitational waves**, ripples in space-time produced when massive bodies interact

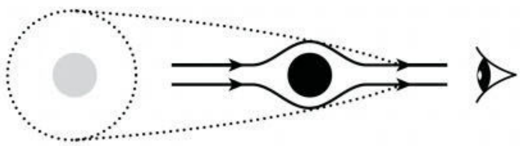
missions such as the WMAP and Planck satellites, have used the radiation to measure the geometry of the universe with incredible precision and provide our best figure yet for its age – 13.8 billion years. They have also elucidated the astounding facts, first flagged in studies of galactic rotation and far-off supernovae, that the vast majority of cosmic stuff comes in forms that we cannot see: dark matter and dark energy (see chapter 2, page 32).

Although we expect to increase the accuracy of the measurements already made, and the mysteries of dark matter and energy remain, the big picture of the general-relativistic universe has been largely fleshed out. Too many observations agree too well for it all to be a house of cards.

Comprehensive surveys of how galaxies are distributed will help fill in the gaps and shed light on how dark matter and energy have influenced the universe's evolution. But there is much detail still to be gleaned from the CMB itself. Our most compelling description of the early universe says it underwent a period of accelerated expansion, known

Lens on the past

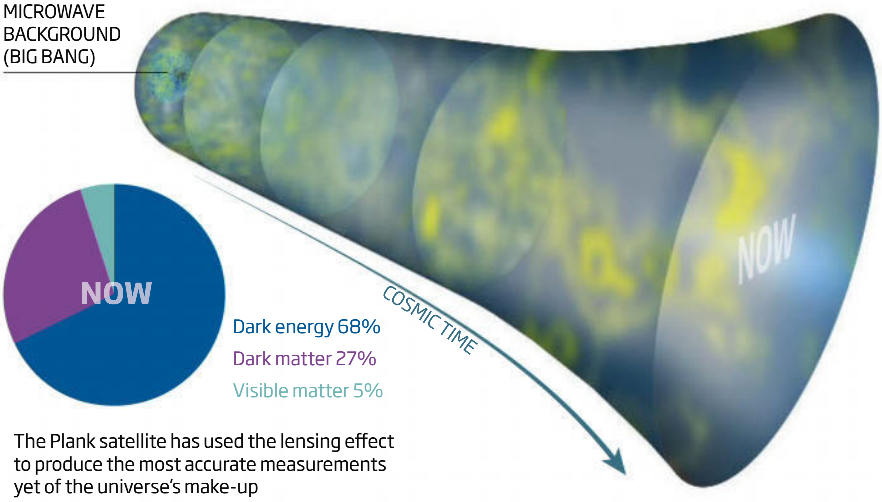
Photons from the cosmic microwave background left over from the big bang get distorted on their way to us. Measuring those distortions tells us how the balance of **dark matter** and **dark energy** has changed all the universe's life



General relativity says massive objects warp light, distorting our view of far off objects – **gravitational lensing**

Dark matter causes galaxies to cluster closer...

...**Dark energy** has acted against gravity in recent times to make galaxies fly apart from each other



The Plank satellite has used the lensing effect to produce the most accurate measurements yet of the universe's make-up

1917

Einstein introduces an extra term into his equations, the cosmological constant, to balance out gravity and produce a static universe that is neither expanding nor contracting

FROM LEFT: AKG, DE AGOSTINI PICTURE LIB. / AKG-IMAGES, ROYAL ASTRONOMICAL SOCIETY/SPL

1919

Arthur Eddington observes the sun's mass bending light during an eclipse over the island of Principe – the gravitational lensing effect predicted by Einstein

as inflation, that stretched microscopic quantum fluctuations of space-time out to astronomical scales. According to the precepts of general relativity, these events should have sent ripples out through space-time. Early in 2014, to great fanfare, measurements of the CMB made by the BICEP2 telescope at the South Pole seemed to have found these primordial gravitational waves – although under closer scrutiny, it turned out that the observed effect was caused by dust within our own galaxy. The discovery of a gravitational wave arising from the collision of two black holes was announced in 2016, but the search for primordial gravitational waves continues (see chapter 4, page 56).

Up to now, we have pored over the CMB rather as we would a picture of a distant ancestor, trying to discern the traits in it that led to what we see today. But it can also be a backlight to illuminate the present or, at least in cosmological terms, the very recent past – and so show up the subtleties of how gravity has shaped our universe.

Take the gravitational lensing of CMB light as it propagates towards us – the effect that Arthur Eddington used to provide the first proof of general relativity in 1919. CMB photons will be deflected by warps and folds in space-time caused by the large-scale distribution of matter in the universe, ever so slightly distorting our view. By tracking this effect over time, lensing measurements from the Planck satellite have confirmed that the universe's expansion is indeed accelerating under the influence of dark energy.

Still more sensitive measurements of the distorted CMB should allow us to work backwards to the distribution of dark matter, which apparently makes up more than 80 per cent of every galaxy. This gives us a new window on how the complex filaments, walls, clusters and voids of the "cosmic web" have formed over time, without having to worry about the messy details of normal matter's interactions (see diagram, left).

Distortions introduced when photons from the CMB scatter off electrons in intervening galaxy clusters will also allow us to measure how fast these clusters are moving around, and how quickly they are collapsing gravitationally, sucked into denser forms through dark matter's influence. That gives us a new way of testing general relativity's predictions. For although the theory has been exquisitely studied on the scale of the solar system and in the orbits of neutron stars, it has yet to be tested on scales spanning billions of light years.

The safe bet is that general relativity correctly describes the universe out to cosmological scales, for all that we are baffled by the dark spectres it calls into life. If general relativity were ever proved wrong that would be a true revolution. It would call into question the existence of dark energy as the driving force behind the universe's expansion in recent eras. But it would also force us to figure out what hallowed principles we need to jettison to obtain a description of gravity on cosmic scales that is different to the one we have been using for the past century. That is a question to which few people as yet have wagered an answer. ■

> "If general relativity were ever proved wrong that would be a true revolution"

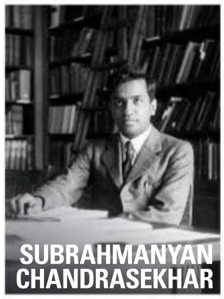
1920s

CORBIS

Alexander Friedmann and Georges Lemaître independently find a solution to Einstein's equations that describes a uniformly expanding universe

1920s

Edwin Hubble and others show far-off galaxies are moving away from us - the first hint of an expanding "big bang" universe. Einstein decries his cosmological constant as his "greatest blunder"



AMERICAN INSTITUTE OF PHYSICS/SPL

1930

Subrahmanyan Chandrasekhar shows that certain massive stars could collapse into bodies so dense that no light could escape from them: what later become known as black holes

DARK DESTROYERS

Black holes are general relativity's most mind-bending prediction – and could yet swallow the theory, finds **Anil Ananthaswamy**

IT WAS while serving in the German army on the Russian front that, in the winter of 1915-1916, that the physicist Karl Schwarzschild sent Albert Einstein some papers. He had solved Einstein's equations of general relativity for the first time, and shown what happens to space-time inside and outside a massive object – in this case, a perfectly spherical, non-spinning star. Einstein was thrilled.

He wouldn't be so thrilled with a prediction that eventually emerged from Schwarzschild's work. Make a star compact enough and it could develop a gravitational pull so great, and warp space-time so much, that even light would not escape.

Just months after his exchange with Einstein, Schwarzschild was dead. It was left to others to work through the details of these curious compact objects, the surfaces of which became known as Schwarzschild singularities.

Chief among them was a young Indian physicist named Subrahmanyan Chandrasekhar. In 1930 he boarded a steamer from India to the UK, where he was to take up a scholarship at the University of Cambridge. Whiling away the 18-day voyage, he worked on the properties of highly compact white-dwarf stars. He found that if they had more than 1.4 times the sun's mass, they would implode under their own gravity, forming a Schwarzschild singularity.

This did not go down well. At a meeting of the Royal Astronomical Society in 1935, the eminent astrophysicist Arthur Eddington declared that "there should be a law of nature to prevent a star from behaving in this absurd way". In 1939, Einstein himself published a paper to explain why Schwarzschild singularities could not exist outside the minds of theorists.

The impasse remained until the 1960s, when physicists such as Roger Penrose proved that black holes – a term coined at about this time, probably by astrophysicist John Archibald Wheeler – were a seemingly inevitable consequence of the collapse of massive stars. At a black hole, physical quantities such as the curvature of space-time would become infinite, and the equations of general relativity would break down.

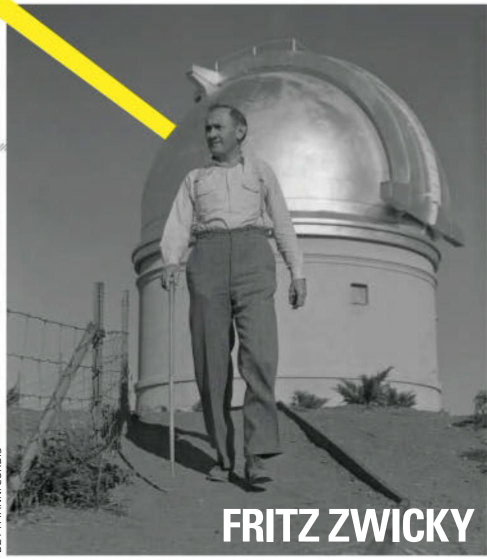
Not only that, but a black hole's interior would be permanently hidden behind its event horizon, the surface of no return for light. That in turn meant that nothing happening in the interior could influence events outside, because no matter or energy could escape. "The first major paradigm shift was the understanding that these solutions [of general relativity] are meaningful, and that there is a notion called a horizon, and that it is a causal barrier separating the inside from the outside," says theorist Don Marolf of the University of California, Santa Barbara.

Although we can't see a black hole directly, in 1970 astronomers observing a compact object in the constellation Cygnus saw jets of X-rays consistent with theoretical predictions of radiation streaming from hot matter spiralling towards an event horizon. Since then, our appreciation of black holes' reality has only grown. It seems most galaxies, including our Milky Way, have a supermassive example lurking at their heart (see "Black hole paparazzo", page 22).

Yet the ins and outs of black holes remain hotly disputed – not least for what they say about general relativity's failure to mesh with quantum theory (see "Unhappy marriage", page 23). "You have to go to pretty extreme environments for both of these theories to be important at the same time, and a black hole turns out to be one of the most ideal," says theorist Joseph Polchinski, also at the University of California, Santa Barbara.

1933

Fritz Zwicky observes that galaxies in clusters are seemingly being whirled around by the gravity of invisible matter – the first hint of the existence of dark matter



BETTMANN/CORBIS

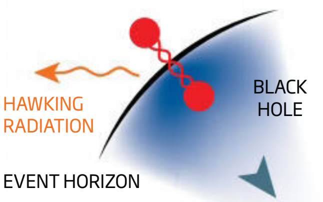
1940s

Theorists predict that if the universe is expanding from a hot and dense beginning in a big bang, it should have left behind an afterglow: the cosmic microwave background

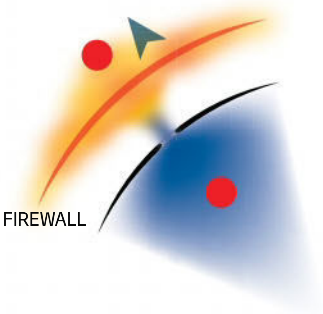
The great firewall paradox

Pairs of quantum-entangled particles constantly pop into existence at a black hole's event horizon. What if one member of a pair falls in?

The entanglement encodes information, and that can't vanish, according to **quantum theory**. It might escape via photons of Hawking radiation, which black holes should emit...



... but that would create a fiery barrier surrounding the entire event horizon, contradicting **general relativity**



Tensions rose in the 1970s, when physicists Jacob Bekenstein and Stephen Hawking showed that black holes must have a temperature. Bodies with a temperature have an associated entropy, and in quantum mechanics, entropy – a measure of a body's disorder – implies the existence of a microstructure. Einstein's equations, meanwhile, describe black holes as smooth, featureless distortions of space-time. Hawking also showed that quantum effects in and around the event horizon imply the black hole should steadily evaporate, emitting a stream of what we now call Hawking radiation.

But if a black hole does eventually dwindle to nothing, what happens to the stuff that falls in? At a fundamental level, matter and energy carry some information, and quantum mechanics says information cannot be destroyed. Perhaps the information encoded slips out with the Hawking radiation, but this idea runs into another problem: it leads to the black hole being surrounded by a "firewall" of blazing, energetic particles, again something general relativity forbids. In 2012, Polchinski, Marolf and their colleagues showed that black holes cannot simultaneously preserve information and possess an uneventful horizon (see diagram, left).

DISAPPEARING ACT

This "firewall paradox" is still a hot topic. One emerging and tantalising suggestion is that the smooth fabric of Einsteinian space-time results from particles inside and outside the event horizon being linked quantum mechanically, via structures known as wormholes.

In August 2015, speaking at a meeting in Stockholm, Sweden, Hawking set out an alternative stall, suggesting that information is never actually swallowed by a black hole. Instead, it persists at its event horizon in a form that is garbled and hard to decode. The very next month, Nobel laureate Gerard 't Hooft of Utrecht University in the Netherlands suggested that when matter and energy fall in, their information just bounces back.

Some sidestep such problems by returning to arguments reminiscent of Eddington's and Einstein's denial of black holes. Laura Mersini-Houghton of the University of North Carolina, Chapel Hill, has argued that massive stars cannot collapse to black holes – the emission of Hawking radiation during the collapse stops the star ever getting that far. So there are no event horizons and no singularities.

Few subscribe to that view, not least because of the considerable indirect observational evidence for black holes. Instead, the firewall paradox has opened up a new front in the struggle to unite general relativity and quantum mechanics. In that tussle, there's a sense that the successful theory will be closer to quantum theory than general relativity, given the overwhelming success of quantum theory in explaining all the forces of nature besides gravity. Marolf, a general relativist, says he feels bad admitting that "general relativity is losing". Einstein, who was troubled both by black holes and what he saw as quantum theory's excesses, may have felt worse. Black holes could end up being the prediction that ate the theory. ■

1964

E. SEGRE VISUAL ARCHIVES/AIP/SPL

The cosmic microwave background is accidentally discovered by Arno Penzias and John Wilson as unexplained noise in a radio antenna, kicking off relativity's "golden age"

1970s

Vera Rubin provides convincing evidence that most galaxies contain dark matter, which is causing them to rotate faster

E. SEGRE VISUAL ARCHIVES/AIP/SPL

1972

X-ray emissions from a body known as X-1 in the constellation Cygnus provide the first evidence for a star's collapse into a stellar-mass black hole

BLACK HOLE PAPARAZZO

Astronomer **Heino Falcke** plans to use a global network of radio telescopes to snap the black hole at the Milky Way's heart

Why do you want to photograph a black hole?
Black holes were predicted a century ago, but I have the feeling that we understand them even less these days. We still don't have conclusive evidence for the presence of an event horizon – their point-of-no-return surface. Also, event horizons and quantum theory just don't go together. Something needs to change, and it's not entirely clear what that is.

How do we even know there's a black hole in the Milky Way's core?
Stars in the galactic centre orbit at some 10,000 kilometres per second, meaning there must be a central mass that is more than 4 million times our sun's mass. The only thing that we "see" in the very centre is a radio source called Sagittarius A*. Its very short, sub-millimetre radio waves probably arise from jets of hot gas emitted by material plunging into a supermassive black hole.

How on Earth do you plan to photograph that?
The black hole's event horizon is probably 25 million kilometres across, but it's 27,000 light-years away. To image it at sub-millimetre wavelengths you need a telescope as big as Earth. A worldwide network of radio telescopes can obtain the same resolution.

Your project, BlackHoleCam, isn't the only one aiming to image a black hole. Who else is in the game?
I first discussed these ideas 10 years ago with Shep Doeleman of the Massachusetts Institute of Technology, who now heads the US-led Event Horizon Telescope project. It makes no sense for us or them to work with a subset of the available telescopes, so we are now trying to set up a global project. We need each other.

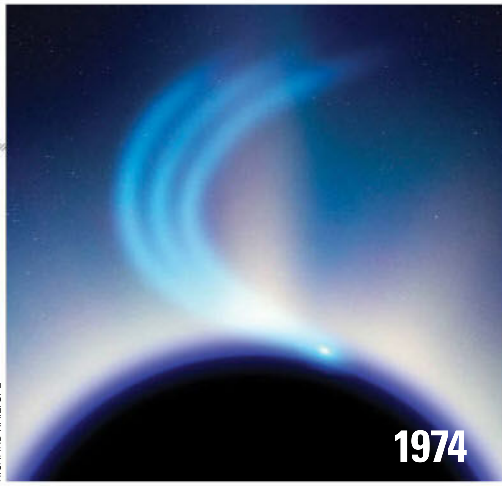
DICK VAN AALST/©2011 RADBOUD UNIVERSITY

Profile
Heino Falcke is a radio astronomer and astroparticle physicist at Radboud University in Nijmegen, the Netherlands. He is co-founder of the BlackHoleCam project

Where are the telescopes you'll use?
The European groups are working with sub-millimetre telescopes in Spain, France and Chile. The US teams use telescopes in Hawaii, Arizona, Mexico and at the South Pole. Ideally, to

1974

Russell Hulse and Joseph Taylor discover a pair of neutron stars whose orbits are slowing exactly as if they were losing energy by emitting gravitational waves



RICHARD KAIL/SPL

1974

Stephen Hawking shows theoretically that quantum effects can cause black holes to evaporate, emitting Hawking radiation - posing the question of what happens to the matter they swallow

increase the efficiency, we need a new instrument in Africa.

What exactly are you looking for?
We hope to see how radio waves from the black hole's surroundings are bent and absorbed, just as in Christopher Nolan's movie *Interstellar*. The result should be a sort of central "shadow". By comparing the size, shape and sharpness of this shadow with theoretical predictions, we can test general relativity. If the shadow is half as big - or twice as large as predicted, say, general relativity can't be correct.

What are the biggest challenges?
The technology is daunting, but now under control. For each telescope you have to record hours of data at a rate of 64 gigabits per second and ship hard discs with petabytes of data between continents. Budget issues have eased a little bit with grants from the European Research Council and the US National Science Foundation.

When will we have our first black hole portrait?
In 2000 I said a result might be in within a decade, so I'd better temper expectations a little bit. Will it be another 10 years? I hope not, but in the end it takes the time it takes. ■

Interview by Govert Schilling

UNHAPPY MARRIAGE

General relativity and quantum theory don't agree. How so, asks physicist **Eugene Lim** – and what can we do about it?

A RATHER glib distinction is often made between the two pillars of modern physics. Quantum mechanics is the physics of the very small, while general relativity is the physics of the very large. That's not quite accurate – for example, quantum-mechanical effects have been observed spanning hundreds of kilometres. And at some scale, surely these two supremely accurate theories must come together.

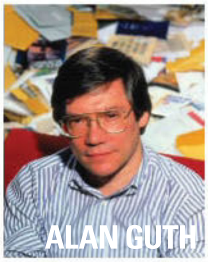
Yet wherever they do cross paths, the two theories fail to play nicely together – such as around black holes (see "Dark destroyers", page 20). Efforts to establish a quantum theory of gravity have stumped many physicists over the past century. Einstein himself became extremely unproductive in his later years as he sought such a "theory of everything".

To understand why, we must start with a fundamental tenet of quantum physics. Heisenberg's uncertainty principle embodies the fuzziness of the quantum world. It allows particles, such as electrons or photons of light, the equivalent of an interest-free loan: they may borrow energy from empty space and use it to make mass, according to Einstein's famous equation $E = mc^2$. This mass takes the form of short-lived "virtual" particles. The only caveat is they must pay this energy back – the particles must disappear once again – before anyone asks any questions. The more energy they borrow, the quicker this must happen.

Given such freedom, one can imagine an electron, photon or any other particle going to town, taking out many zero-interest loans in succession. As a result, calculating even a prosaic quantum process – an electron ›

1980

Alan Guth and others propose the big-bang universe was smoothed out by undergoing a period of breakneck expansion in its first instants – inflation



DAVID PARKER/SPL

COBE SCIENCE TEAM/NASA

1989

NASA launches COBE, a satellite to study the cosmic microwave background. It reveals a largely homogeneous radiation field, supporting the idea of an inflationary big bang

> "Few people want to believe reality has no single consistent underpinning"

travelling from left to right, say – becomes enormously complex. In the words of physicist Richard Feynman, we must "sum over all possible histories", taking into account the infinite variety of ways virtual particles can be produced (see diagram, right).

The history of applying quantum theory to nature's forces is a history of getting to grips with these unruly infinities. One huge success story is electroweak theory, the theory that combines the electromagnetic and weak nuclear forces to explain how electrons and photons work. Its predictions, of everything from particle masses to their decay rates, are accurate up to 10 decimal places.

The winding way to electroweak theory is marked by at least nine Nobel prizes. The eventually successful variant, a bedrock of today's "standard model" of particle physics, tamed the mathematics using a bunch of undiscovered massive particles, the W, Z and Higgs bosons.

Fortune eventually favoured this brave conjecture: the W and Z bosons were discovered at CERN in 1983, with the Higgs following in 2012. The first of those successes, in particular, led many physicists to believe this strategy was something like a general prescription for developing quantum theories: if your model produced infinities, just add in extra particles of large mass to solve the problem.

Suppose, then, gravity is made of quantum particles called gravitons, much as light is made of photons. Following the uncertainty principle, gravitons borrow energy to make other, virtual gravitons. As we sum over all possible histories, the calculations rapidly spiral as expected into a chaos of infinities.

But this time, the fix doesn't work. Eliminating these infinities requires inventing a second particle with a mass 10 billion billion times that of a proton. As ever, the larger the amount of energy borrowed, the more quickly it must be paid back, so these fixer particles are very short-lived. This means they can't get very far, and so occupy only a minute amount of space.

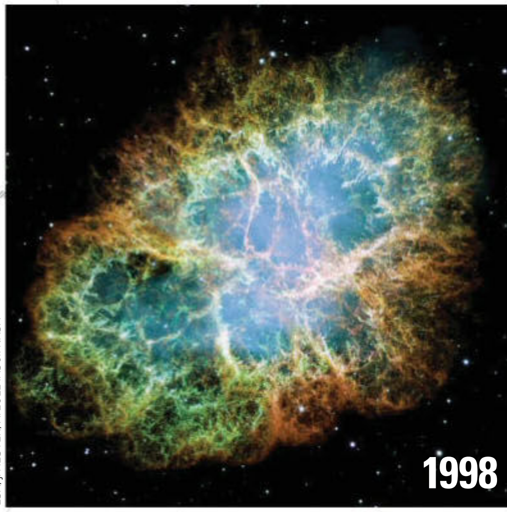
But general relativity says that mass bends space-time. Concentrate enough mass into a small area, and a black hole will form, a point of infinite curvature in space-time. And this is exactly the guise our new particle takes. Nature plays a cruel joke on us: our scheme to eliminate one sort of infinity creates another.

CHANGING THE GAME

Attempts to get round this fundamental roadblock have led us to destinations such as string theory, which assumes all particles are manifestations of more fundamental vibrating strings. When we start summing over all possible histories of

1998

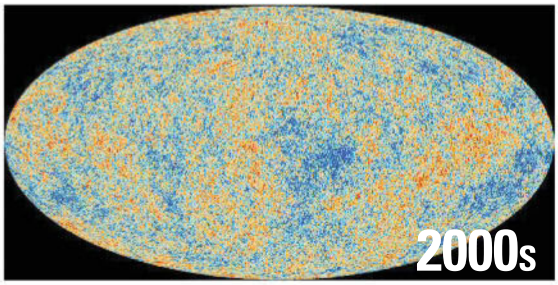
Studies of far-off supernovae surprisingly reveal that the universe's expansion is accelerating. Einstein's cosmological constant is revived as one identity for the dark energy causing this effect



ESA, J. HESTER, A. LOLL (ASU)/NASA

2000s

Ever-more detailed studies of the cosmic microwave background support the picture of a cosmos that began in an inflationary big bang dominated by dark matter and dark energy



CMB: ESA AND THE PLANCK COLLABORATION

these "fluffier" objects, the hard infinities produced by virtual particles drop away almost by magic. Another commonly considered idea is loop quantum gravity, which suggests that space-time itself is chopped up into discrete blocks. This pixelation imposes an upper limit on the amount of energy any particle can borrow, again rendering calculations finite.

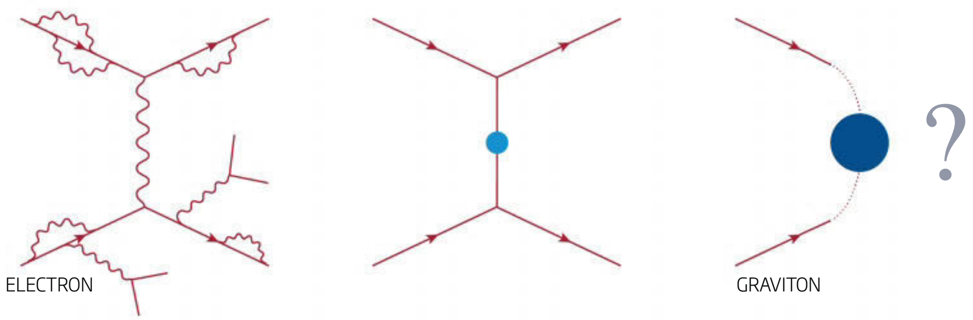
Despite their seemingly radical assumptions, these two candidate unified theories are in many ways the most conservative extensions of current models: both attempt to preserve as much of the theoretical underpinnings of quantum mechanics and general relativity as possible.

What about more esoteric ideas, such as changing the rules of the existing game? For instance, if general relativity were to treat space and time separately again, rather than lumping them into one combined space-time, that might provide some wiggle room. But relativity and quantum mechanics both tally so well with reality in their respective spheres that it is devilishly difficult to formulate such tweaks. Few physicists would care to consider an even more radical possibility: that quantum mechanics and general relativity cannot be unified, and reality has no single, consistent logical underpinning.

In the first century of general relativity, all these considerations have been theoretical. But now technology is finally catching up. Despite liberal use of gravitons for calculations, we have yet to detect their existence directly. Gravitational-wave experiments such as Advanced LIGO in Louisiana and Washington state and the proposed eLISA spacecraft will hopefully close that gap, and perhaps lead us to a deeper understanding of how gravity really works. ■

Infinite problem

Gravitons are conjectured quantum particles of gravity – but theories incorporating them tend to be unruly



Particles such as electrons can interact by producing and exchanging massless photons in countless ways, often resulting in infinities in the calculations

The situation is saved by the existence of heavier particles – the **W, Z and Higgs bosons** that aren't so easily produced, cancelling out the infinities

Performing the same trick with graviton interactions requires a particle so massive it acts like a **black hole** – and all calculations are off again

The relativity deniers

General relativity is considered one of the greatest theories of all time but it was not always seen in such glowing terms, as historian **Milena Wazeck** explains

"THIS world is a strange madhouse," remarked Albert Einstein in 1920 in a letter to his close friend, the mathematician Marcel Grossmann. "Every coachman and every waiter is debating whether relativity theory is correct. Belief in this matter depends on political affiliation."

Einstein's general theory of relativity, published in 1915, received an overwhelming public response – not all of it positive. Numerous accounts which appeared during the 1920s claimed to show relativity was wrong, and Einstein received many letters from laypeople who claimed to have found the ultimate refutation of his theory.

Many of today's physicists and astronomers (not to mention science journalists) continue to receive this kind of mail. On densely written pages – and, increasingly, in rambling emails, blog posts and online comments – self-proclaimed scientists keep trying to foist their astonishingly simple solutions to much-discussed problems upon genuine academics. Yet what flourishes today on the fringes of the internet was much more prominent in the 1920s, in the activities of a movement that included physics professors and even Nobel laureates.

ALEX WILLIAMSON

Who were Einstein's opponents? Why did they oppose one of the most important scientific theories of the 20th century? And was Einstein right in saying "political affiliation" was responsible for the fierce opposition to relativity theory?

A few years ago, I had the opportunity to access papers belonging to the physicist Ernst Gehrcke, one of the most outspoken critics of Einstein in Germany. As I delved into the material he had neatly collected in banana boxes, a whole world of anti-relativity emerged from hundreds of pamphlets, thousands of newspaper clippings, and piles of letters from Einstein's opponents across Europe and the US.

I discovered that the group opposing relativity was much broader than many historians believed till now, and that their tactics had much in common with those used by creationists and climate-change deniers today. Their reasons for countering relativity were also more complex and varied than is usually thought. Even Einstein misjudged the motivations of many of his opponents.

Don't mess with time

Gehrcke was an experimental physicist at the Imperial Technical Institute in Berlin. Like many experimentalists of that era, he felt uncomfortable with the rise of a theory that demanded a reformulation of the fundamental concepts of space and time. Relativity messes with these to the extent that events which one observer deems simultaneous are no longer simultaneous as viewed by observers moving in different frames of reference.

Gehrcke could not imagine such a scenario. In 1921 he argued that giving up the idea of absolute time threatened to confuse the basis of cause and effect in natural phenomena.

What's more, the theory of relativity abandoned one of the most important concepts of 19th-century physics: that light waves and electric and magnetic forces were carried in a medium called the ether. For a classical physicist like Gehrcke, giving up this notion was akin to someone today claiming that sound waves travel in a vacuum.

These objections were first raised in scholarly journals, with discussion restricted to academia. But after a key prediction of general relativity was confirmed during an eclipse in 1919, Einstein was transformed into a media star and the debate acquired a much broader public impact. In 1919, *The New York Times* published an article headlined "Lights all askew in the heavens. Men of science more or less agog over results of eclipse observations", while a German magazine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"Einstein's opponents saw themselves as victims. The mere existence of relativity and non-acceptance of their arguments was an attack on them"

celebrated Einstein as "A new giant of world history". In the years that followed, the newspapers reported on everything from his clothing and Jewish background to his affection for music.

People were also troubled by more fundamental questions. In December 1921, the letters pages of *The Times* of London carried a lively discussion of whether space is actually endowed with physical qualities as general relativity required. Opinion was clearly divided.

The controversy in Germany intensified in August 1920 with the launch of a series of public lectures against Einstein at the Berlin Philharmonic hall. The event included a lecture by Gehrcke, who repeated the arguments he had been raising unsuccessfully for years, as well as an impassioned speech by the anti-Semitic activist Paul Weyland, who had organised the series. The event made a clear impact, prompting Einstein to think seriously about leaving Germany.

Gehrcke's papers show that opposition to Einstein extended well beyond a handful of sidelined physicists and politically motivated troublemakers. Gehrcke was in touch with physics Nobel laureates Johannes Stark and Philipp Lenard, and an international network comprising not just physicists, astronomers and philosophers, but also engineers, physicians and schoolmasters.

One of Gehrcke's boxes contained documents from a mysterious organisation called the Academy of Nations, whose title and letter-headed paper contrived to give it the aura of a scholarly academy. In fact, it served as a home for an international network of Einstein's opponents. Its founder was Arvid Reuterdahl, then dean of the faculty of engineering and architecture at the University of St Thomas in St Paul, Minnesota. He was also a devoted theist who attempted to reconcile religion and science in what he termed "new science".

Concerned that science was becoming ever more specialised, the Academy of Nations aimed to reconnect different branches of knowledge by integrating scientific findings into a unified, religious account of nature. To Reuterdahl, nothing better symbolised the modern specialisation and incomprehensibility of science than relativity. Almost half the Academy of Nations' founding declaration consisted of polemics against Einstein's theory. "We are emerging from a period of material and intellectual chaos. Nations have clashed in war. The intellectual world is still in conflict on the fields of knowledge. Never before has the demarcation between intellectual camps been so clearly defined… Einstein has served as a chemical reagent which has precipitated relativity from the present content of knowledge as a mass insoluble to the average man."

Reuterdahl was eager to establish contact with Einstein's opponents all over the world, and the American section of the academy united some prominent anti-Einstein figures. One of these was the astronomer Thomas J. J. See of the US Naval Observatory at Mare Island, California, who in the early 1920s published several harsh articles in which he accused Einstein of plagiarism and denounced his theory as "a crazy vagary". Though popular with the broader public, See was largely isolated from his colleagues because of the eccentric theories he advanced on the evolution of the solar system and almost every phenomenon in the universe.

Other members included Charles Lane Poor, professor of celestial mechanics at Columbia University, New York, who published several articles discounting the experimental confirmation of general relativity, and the inventor Charles Francis Brush, a pioneer of the commercial development of electricity, who espoused a kinetic theory of gravitation that stood in opposition to general relativity.

When Reuterdahl approached Gehrcke in 1921 with the idea of setting up a German branch of the Academy of Nations, Gehrcke immediately welcomed this new forum for activities against Einstein. His first recruits were German physicists who argued that there was no need for relativity because classical physics could explain all astronomical observations. Philosophers, engineers, physicians and even a retired major general joined too. A partial membership list from 1921 included 30 members from 10 countries.

But why did this ramshackle alliance between laymen and scientists emerge? What did it take to get a conservative physicist like Gehrcke involved with American theists?

The chance to cooperate with allies in the fight against relativity was obviously one reason. Einstein's opponents found themselves in the unenviable position of outsider, their arguments dismissed as "old crop" by most physicists. Scholarly journals and scientific associations closed their doors to them. The establishment of a self-governing academy and journal must have come as a welcome opportunity to break out of this marginalised position.

Another motivation was more noble. Einstein's opponents were seriously concerned about the future of science. They did not simply disagree with the theory of general relativity; they opposed the new foundations of physics altogether. The increasingly mathematical approach of theoretical physics collided with the then widely held view that science is essentially

MAX PLANCK INSTITUTE FOR THE HISTORY OF SCIENCE/ TOPICAL PRESS AGENCY/GETTY

The papers of physicist Ernst Gehrcke (left) reveal what really motivated Einstein's critics simple mechanics, comprehensible to every educated layperson.

This way of thinking can be traced back to the 19th-century heyday of popular science, when many citizens devoted their leisure to the pursuit of scientific understanding, and simple theories of gravity or electricity were widely discussed in scientific magazines. Relativity represented a quite different way of understanding the world. It was a theory that "only 12 wise men" could comprehend, *The New York Times* declared in 1919.

The increasing role played by advanced mathematics seemed to disconnect physics from reality. "Mathematics is the science of the imaginable, but natural science is the science of the real," Gehrcke stated in 1921. Engineer Eyvind Heidenreich, who found relativity incomprehensible, went further: "This is not science. On the contrary, it is a new brand of metaphysics."

The Academy of Nations therefore saw itself as directed not only against the theory of relativity, but also towards the salvation of what it considered to be real science. Gehrcke insisted that the Academy "must become an alliance of truth".

Compounding all this was the fact that the 1920s was an unsettling decade for Germany. The country was experiencing hyperinflation and political upheavals, as well as radical cultural developments such as Dadaism and expressionism. In a world of uncertainties, some felt science at least should be relied upon to provide firm ground. For Einstein's opponents, relativity theory was endangering not only science but also culture and society.

So was Einstein right to blame political affiliation for the opposition to the theory of relativity? The answer is more complex than a simple yes or no.

Conspiracy theories

For a start, someone's views about whether time could be stretched were not defined by ethnicity, nationality, religion or political convictions. Einstein's opponents included people who held progressive views, and some who were of Jewish descent. So it would be simplistic to characterise the fight against relativity theory in the 1920s as a one-sided nationalistic or anti-Semitic campaign.

Nevertheless, those who opposed the theory were not above attacking Einstein the person – the democrat, the pacifist, the Jew. Lenard, for instance, was an early adherent of Nazism and a proponent of the nationalist and anti-Semitic "German physics". By 1922, he was already ranting about the Jewish "alien spirit" that he claimed the theory of relativity incorporated.

Aware of their marginalised position, many of Einstein's opponents turned to anti-Semitic conspiracy theories. "Our trouble in America is that all scientific journals are closed to the anti-relativists through Jewish influence. The daily press is almost entirely under the control of the Jews," Reuterdahl wrote in 1923. From this position, it was easy for Einstein's opponents to see themselves as victims rather than aggressors. In their interpretation of reality, the mere existence of relativity theory and the non-acceptance of arguments against it qualified as an attack on them.

By the mid-1920s Einstein's opponents were facing overwhelming resistance, and most refrained from taking a public stance against the theory of relativity. Many of them simply gave up, and the Academy of Nations ceased to serve as the central organisation campaigning against Einstein, though it lingered on until the early 1930s.

But the anti-relativists did not revise their opinion. In 1951, Gehrcke was still writing letters about the fight against relativity. "The day will come where everything, but everything about this theory will be abandoned by the world at large, but when will this be?" he asked.

Relativity denial lingers on today, largely on fringe conservative websites. The critics continue to perceive relativity as a threat to their world view, and often invoke conspiracy theories to explain their marginalised position.

There is a difference, though. The protest against relativity in the 1920s had closer ties to the academic world. This was not because Einstein's opponents back then offered more convincing arguments, but because the paradigm shift that was moving physics onto new foundations was still under way.

The controversy over relativity represents a scientific dispute that is crucially shaped by the participants' world views and draws heavily on metaphysical conceptions of reality. Like those who oppose Darwin's theory of evolution, Einstein's opponents back in the 1920s were impervious to reasoned criticism Physicists do sometimes try to discuss relativity theory with their opponents and point out their misunderstandings, just as physicists did 90 years ago. But this will not resolve the controversy. The opponents' understanding of the very nature of science differs so fundamentally from the academic consensus that it may be impossible to find common ground. ■

Einstein wins out

1905
Einstein publishes his special theory of relativity

$G_{\mu\nu}$ 1915
General relativity theory completed

1919
Arthur Eddington's eclipse expedition confirms general relativity

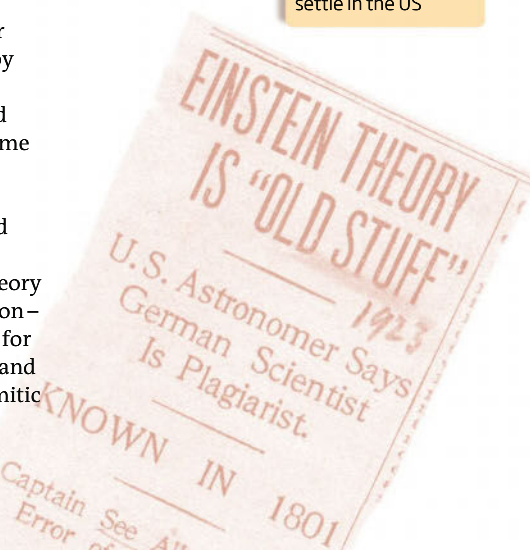
1920
Series of anti-relativity lectures launched in Berlin, where Einstein had lived since 1914

1921
Einstein wins Nobel prize for services to theoretical physics, especially the photoelectric effect

1921
Arvid Reuterdahl co-founds the Academy of Nations, a network of people hostile to Einstein

1933
Focused opposition to Einstein from the Academy of Nations peters out

1933
With the Nazis in power in Germany, Einstein decides to settle in the US



The universe expects

Relativity is the theory that keeps on giving, and cosmologist Pedro Ferreira is ready and waiting

IN FEBRUARY 2016, a team of physicists announced that they had seen ripples in space-time produced by the collision of two black holes (see page 63). The detection of gravitational waves was the biggest discovery in science since the Higgs boson in 2012.

It supplied the final missing piece of the general theory of relativity. But it was not the last word on the subject. I have come to believe that we are in a new golden age of relativity and that there are many great discoveries to look forward to, from the direct imaging of a black hole to untangling the fundamental nature of space and time.

To understand my optimism, we need to look at the biography of Einstein's theory and follow it over a century of discovery and turmoil. When Einstein started thinking about gravity in 1907, he had already figured out his special theory of relativity. Space and time became intertwined and the speed of light became sacrosanct and invariant, a cosmic speed limit on any physical process. It all worked beautifully – except for one thing. Isaac Newton's gravitational force, which explains how the planets move around the sun and why things fall to Earth's surface, didn't fit in. And so Einstein set out to come up with a more general formulation that could include gravity. It took him eight years.

The new general theory of relativity needed a completely different form of mathematics and a fresh way of thinking about physics. When he finally worked it all out, he had the most stunning set of equations that changed our view of the nature of reality.

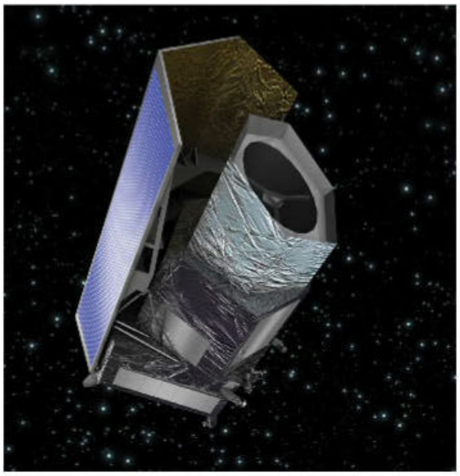
After Einstein revealed his theory to the wider world in a series of lectures at the Prussian Academy of Sciences in Berlin, it took on a life of its own. And in the decade that followed, Einstein himself and other brilliant scientists used it to come up with amazing insights, including black holes, the expanding universe and Einstein's own prediction: gravitational waves.

By the early 1930s, the theory had captivated many of the leading lights of physics. Arthur Eddington, Wolfgang Pauli, Werner Heisenberg and Erwin Schrödinger all wrote textbooks with their own take on how the theory should be understood.

However, once the low-hanging fruit had been picked, general relativity slowly faded as an object of physicists' interest. The discovery of quantum physics punted it into the long grass. Quantum physics was a far more practical theory that explained things that could actually be measured in the laboratory and could be used to build bombs. General relativity became a beautiful yet esoteric theory, with little to say about the real world.

Relativity's revival

And then, after almost a quarter of a century, the green shoots of recovery started to break out. In the 1950s, a new generation of astronomers working at radio frequencies started to map out a universe littered with incredibly energetic objects at staggering distances. These powerful beacons seemed far too heavy to be explained using Newtonian gravity and the general theory of relativity beckoned. A new generation of physicists began turning their attention to the mysteries of Einstein's theory and, slowly but surely, began to unpick many of the intriguing and bizarre results that had been ignored.



ESA

The Euclid space telescope is designed to map the geometry of the dark universe

Mathematics revealed the inner workings of black holes in exquisite detail, while observational evidence for them started to amass. The discovery of a relic bath of light – the cosmic microwave background – showed that the universe was hot and dense early on, adding weight to the idea that an expanding universe was a plausible description of our cosmic history. Things just seemed to fall into place during this "golden age of general relativity", as Kip Thorne of the California Institute of Technology called it.

I began working in science in the early 1990s, mesmerised by this "golden age" and all the wonderful thinkers involved. General relativity still had a bit of an esoteric, almost tainted, aura about it and working on it wasn't particularly recommended. But it was at the heart of what was really interesting in modern physics.

Now things are moving quickly again. For a start, satellites are the latest outposts of science. These sophisticated laboratories float in space at the boundaries of our reach doing once-unimaginable experiments.

One mission, called eLISA, proposes to probe gravitational waves in more detail. Another, called Euclid, will measure how much the universe has expanded since it was half its current age to figure out the effects of the elusive dark matter and dark energy. Yet another mission, called ATHENA, will look at the powerful X-rays given off as matter and light are shredded by the titanic gravitational forces near a black hole's surface. We would, for the first time, be delving into the most extreme conditions of space imaginable.

But we don't need to wait for such giants to be launched into space to explore these extremes. Two very similar projects, BlackHoleCam and The Event Horizon

Relativity's extremes are captured by radio telescopes across the world

HALDEN KROG/THE TIMES/GALLO IMAGES/GETTY IMAGES

Telescope, both networks of telescopes scattered across the globe, may see the black hole at the centre of the Milky Way (see page 22). For the first time we could image the black hole's dark shadow surrounded by the swirling morass of stars, gas and dust being torn apart by its gravitational pull.

And then there is my favourite: a collection of tens of thousands of radio antennas scattered across many thousands of kilometres. Known as the Square Kilometre Array, or SKA, because the collecting area of all the antennas should add up to a square kilometre, it will be based in two continents: Australia and South Africa. In the spirit of Arthur Eddington, who used a small telescope on Príncipe to establish the primacy of general relativity (see page 9), the SKA will be the beast that can test Einstein's theory on galactic and cosmological scales with unprecedented precision. The SKA will also detect if there are any cracks in his grand idea.

While general relativity seems to be driving observations and experiments to new levels of sophistication, the realm of ideas is also undergoing dramatic changes. One notable example is when discussing the beginning of time. Every time I give a public lecture about what I do I am asked the same thing: "What was there before the big bang?" I resort to various explanations. There is the "there was no before, no time, before the big bang" answer. Or there is the more Zen-like answer: "That is like asking what is north of the north pole." But recently, I've found my answers becoming much more diverse and much less definitive.

"We are in a new golden age of relativity. We should expect fantastic things to happen"

Over the past few years, the beginning of time has been thrown wide open by developments in quantum physics and cosmology. When you wind back the clock the universe becomes denser, hotter and messier – the perfect conditions for quantum physics to have more sway. One possibility is that our universe popped into existence out of a vacuum, a bubble of space-time that grew and grew to become what we are today.

A grander possibility is that space-time is much vaster than we had previously envisioned and our universe is just one of countless universes that together make up the "multiverse". Throughout the multiverse, universes are coming into existence and growing to cosmic proportions, each one at its own pace and made in its own particular way. The multiverse is a wild, immense realm of what is ultimately stasis: a steady state of creation and destruction. In this scenario our own universe is like a pustule in a much wider space-time that has existed for all eternity. It is a hugely speculative idea that is pushing the boundaries of what we can reasonably call science, but it is still in the realm of space-time.

There is also a much deeper revolution quietly taking place that is shaking the foundations of Einstein's theory. Attempts to unite general relativity and quantum theory into a theory of everything, and all the issues that these approaches raise, are shattering our hallowed notions of space-time. And they all seem to indicate that, at a fundamental level, we should give up on space-time as smooth and malleable, evolving, twisting and warping according to Einstein's theory. Instead we should think of it as something fragmented and atomised, where notions of locality – the here and now that we are so familiar with – are thrown away.

If we do away with space-time then we need to recast the laws of physics. The new rules may be unfamiliar but, ultimately, they may be much simpler and many of the paradoxes and conundrums should disappear. A simple example is if we wind back the clock in our universe's history towards the moment when the whole of space-time was concentrated at a point and our current laws of physics break down. Given that we can't say much about what happened then, it is fair to speculate that there was an era before the big bang, a time very different from our own.

All the experiments, observations and ideas that are captivating so many of us are part of the vibrant and active life of the general theory of relativity. It has had a long and convoluted history that isn't over yet. While the discovery of gravitational waves is one fantastic example, I expect there will be many more. And so, while the 20th century was dominated by the weird and wonderful discoveries of quantum physics, we should brace ourselves to witness the glorious consequences of Einstein's amazing theory. ■

There at the birth

Few people doubt the big bang now. Not so when the radical idea was accidentally proved a half-century ago, recalls cosmologist **Jim Peebles**

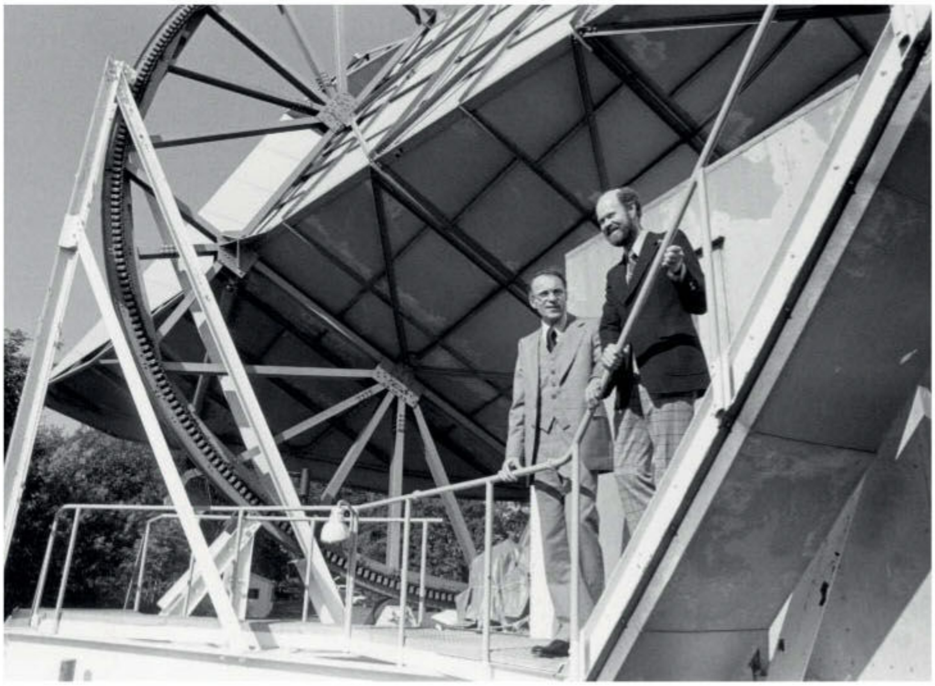
IN 1964 I was a young theorist in the physics department at Princeton University, in the research group of Bob Dicke. Bob was a fan of the then-controversial idea that the universe began in a hot, dense state – a big bang. One idea he was exploring was that a big bang should have left behind a sea of radiation uniformly spread across the sky. Bob had tasked two members of our group, Peter Roll and David Wilkinson, with building a receiver capable of detecting this radiation. I was set the job of looking into the theoretical consequences of detecting (or not detecting) it.

A few weeks later, Bob received a phone call from Arno Penzias of the Bell Telephone Laboratories in Holmdel, New Jersey. On 20 May, he and his colleague Robert Wilson had recorded some astronomical measurements of microwave radiation from the supernova remnant Cassiopeia A. They were using a horn antenna system first assembled in 1959 to study microwave communication – an early step in the development of today's cellphone technology.

The antenna had been carefully engineered to reject radiation from the ground. But once all known sources in the sky had been painstakingly accounted for, Penzias and Wilson were left with a problem. The microwave sky seemed to be about 2 degrees warmer than anyone expected. Bob, Peter and David later visited Bell Labs and concluded that we had been scooped. The radiation we were looking for had been discovered by Penzias and Wilson as an unintended consequence of a communications engineering project.

The sea of noise that was so troubling to Penzias and Wilson is the cosmic microwave background (CMB), which is now known to be clinching evidence for a big bang. But it wasn't immediately seen that way. Looking back, it is easy to forget that, back then, many physicists dismissed any investigations into how the universe began as empty speculation.

At the time, the big bang was competing with steady state theory. Both had their origin in the discovery in the 1920s that distant galaxies are moving away from us, as if the universe were expanding. The big bang theory postulated that everything here now was also there back then, so the universe must be expanding from a denser early state. The steady state theory suggested instead that matter is continually created in the expanding universe, with new galaxies forming to fill the spaces that open up as already existing ones move apart. In this picture, the universe's past was no hotter or denser than its present.



FAR LEFT: ESA/SPL LEFT: PHYSICS TODAY COLLECTION/AIP/SPL

Penzias (left) and Wilson's horn antenna that discovered the cosmic microwave background

This is where we were in 1964. Bob was taken by the idea that an expanding big-bang universe might have bounced back after a previous cycle of expansion had collapsed. During such a collapse, starlight would be compressed along with the matter, reaching temperatures and densities high enough to pull apart the heavy elements produced by stars in the last cycle and so provide new nuclear fuel for our cycle. This process would cause the radiation to reach thermodynamic equilibrium, with the same temperature everywhere, producing a characteristic spectrum of intensities at different wavelengths known as a thermal Planck spectrum – a sure sign of our universe's origin in a hot, dense state.

I don't remember any expression of regret by Bob or any of us at being scooped. Instead, there was excitement that something was there to be measured and analysed. Early on, our focus was on finding out whether the CMB did indeed have that telltale Planck spectrum.

Roll and Wilkinson's experiment soon added another data point, and Wilkinson eventually added many more, culminating in his leading role in the COBE satellite mission that in the early 1990s finally showed the CMB spectrum is close to a Planck form with a temperature of around 2.73 kelvin.

Few doubted the universe's origin in a big bang by then.

Penzias and Wilson received a share of a Nobel prize in 1978, which is fair enough: they tracked down every conceivable terrestrial source of excess microwave radiation, and complained about their inability to account for the anomaly until someone at last paid attention. But Bob ought to have shared it, both for inventing much of the technology used to discover the CMB, and for proposing the search that led the Bell researchers to recognise they had already found it.

Meanwhile, my own theoretical thinking was moving on. The CMB would be disturbed by the gravitational attraction of matter, which in our universe is now quite clumped up, and by interactions with matter in the form of plasma in the hot young universe. More accurate measurements of how much the CMB departs from uniformity drove me to devise the now established cosmological model called ΛCDM.

With ΛCDM, we now have an excellent fit of cosmological theory and measurements, albeit one that requires two hypothetical components: cold dark matter – the CDM – to keep galaxies clumped together, and the cosmological constant, lambda (Λ). This constant is the quantity Einstein introduced into his equations of relativity to create a static universe, and then regretted as an inelegant and unneeded complication. Now it is needed to account for the accelerated expansion of the universe revealed by measurements of far-off supernovae, and also for details of the distribution of the CMB. Its new name, "dark energy", isn't a sign of progress: we still don't understand its nature.

Not least because of these two hypothetical interlopers, caution is in order. The fit of the ΛCDM cosmological model also depends on an optimistic extrapolation of general relativity from the largest tested scale of the solar system to the vastly bigger scale of the observable universe. But tests from the CMB and elsewhere are abundant enough now that I am forced to conclude that we have a convincing approximation to what happened as the universe expanded and cooled.

However the story pans out from here, cosmology has matured beyond all recognition in a century. In 1914, Einstein was putting the finishing touches to general relativity, the theory on which it is all based. Today, ever more detailed explorations of the CMB could be taking us back to a universe even beyond general relativity. But a crucial way station was reached just over 50 years ago: the accidental discovery of an unexpected hiss that tells the story of the universe's origin. ■

KEY FIGURES


EMILIO SEGRE VISUAL ARCHIVES/AIP/SPL

Robert (Bob) Dicke (1916-1997)
A wide-ranging physicist who, besides his contributions to microwave physics, worked in laser and atomic physics, and developed precision tests of Einstein's theory of general relativity.


EMILIO SEGRE VISUAL ARCHIVES/AIP/SPL

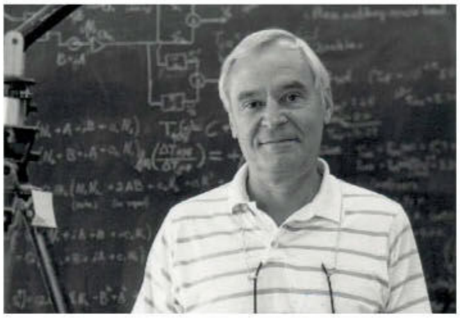
George Gamow (1904-1968)
A Russian-born US cosmologist who was an early champion of the big bang theory, he also made pioneering contributions to the fields of nuclear physics and molecular genetics. Gamow is also remembered for his *Mr Tompkins* series of popular-science books.


EVENING STANDARD/GETTY IMAGES

Fred Hoyle (1915-2001)
A British theoretical astronomer who played an important part in explaining the physics of stars and challenging ideas about an evolving universe. A champion of the steady-state universe theory, he coined the term "big bang" as a disparaging reference to its rival.


TED THAI/TIME LIFE PICTURES/GETTY IMAGES

Robert Wilson (1936-)
and Arno Penzias (1933-)
The Bell labs duo shared the 1978 Nobel prize in physics for their demonstration, published in 1965, that Bell's microwave antenna had detected what proved to be the cosmic microwave background (CMB).


PRINCETON UNIVERSITY, OFFICE OF COMMUNICATIONS

David Wilkinson (1935-2002)
A cosmologist whose seminal contributions to CMB measurements were honoured with the naming of NASA's Wilkinson Microwave Anisotropy Probe, which was launched in 2001.

Cosmic history frozen in time

For 25 years the cosmic microwave background has gradually been giving up its secrets

THE cosmic microwave background (CMB) is often called the "afterglow of the big bang". When the universe was 380,000 years old, the matter that filled space had cooled enough to become transparent and light could travel freely. The faint radiation that still lingers from then comes from all directions and has been cooling ever since it was emitted. Its temperature now averages a chilly 2.735 kelvin.

The first mission to map the CMB was a NASA satellite called the Cosmic Background Explorer (COBE). In 1992 it made headlines worldwide when it detected faint temperature variations in the sea of radiation, evidence that the early universe was not uniform, but riddled with minuscule fluctuations. It was a thrilling glimpse at conditions in the infant universe.

COBE's successor, the Wilkinson Microwave Anisotropy Probe (WMAP), was launched in 2001 to probe the CMB in more detail. From WMAP's measurements, NASA scientists created an even clearer picture of the early cosmos. For the first time, we knew accurately its age, rate of expansion and the proportions of its main ingredients. WMAP also provided strong evidence that the big bang got its kick from a process called inflation.

WMAP concluded that the universe was 13.7 billion years old, which we now think is slightly off (the current figure is 13.8). It also revealed that each megaparsec-long stretch of space is getting longer at 71 kilometres per second (a parsec is 3.26 light years), and that just 4 per cent of the universe is ordinary matter. Of the rest, 23 per cent is dark matter and 73 per cent is dark energy.

In 2013, NASA's groundbreaking map was superseded by an even more detailed one created from data gathered by the European Space Agency's Planck satellite. Here's how we reported it at the time. **By Joshua Sokol, Lisa Grossman and Jacob Aron**

"TOMORROW will be like a birthday for cosmologists, with many gifts arranged on the table and us opening them one by one."

So said Dragan Huterer of the University of Michigan, Ann Arbor, the night before the European Space Agency released the highest-resolution map yet of the entire cosmic microwave background (CMB), relic light from the primordial universe.

And what a birthday it turned out to be. Like real presents, some of the map's insights are expected, others are complete surprises and not all are exactly welcome. Several anomalies, including a so-called Axis of Evil (white line in picture, right), raise more questions than they answer.

The map was drawn from data collected by ESA's Planck satellite, which records temperature variations in the CMB. These arose from quantum fluctuations that were stretched during a brief period of accelerated expansion just after the birth of the universe, known as inflation, and went on to seed the distribution of stars and galaxies we see today.

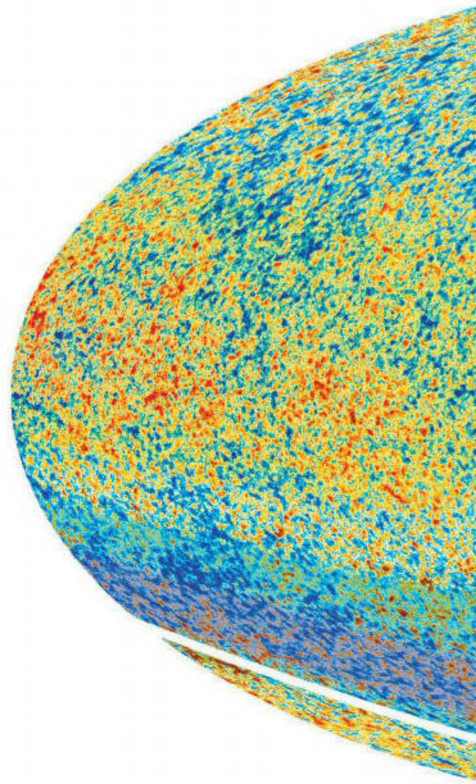
A hotly anticipated insight was new data on whether and how the process of inflation occurred. "Inflation is the initial condition of our universe. It's one of the most fundamental things out there," says Huterer, who is not a member of the Planck team.

"A large cold spot in the map could be a 'bruise' from another universe"

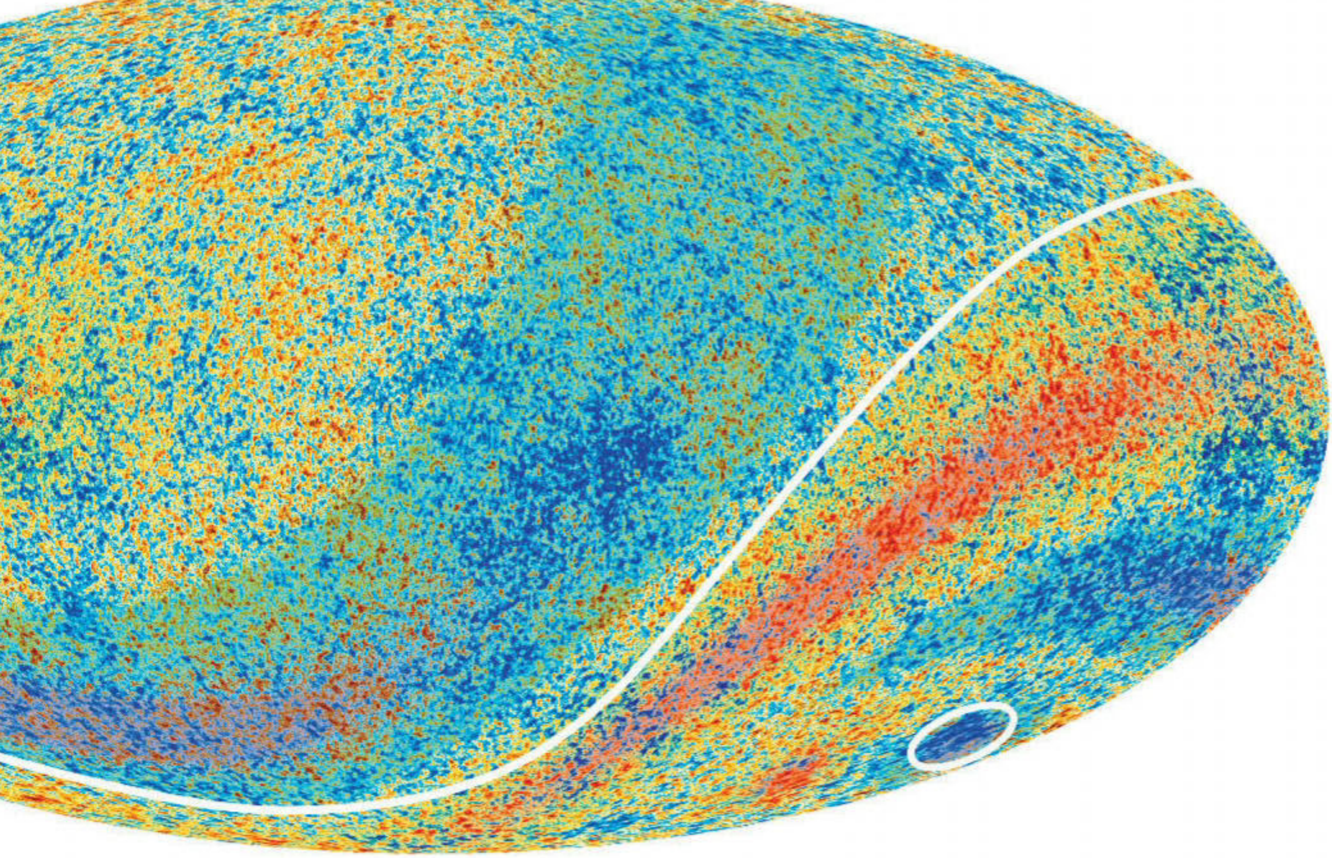
Previous, lower resolution maps couldn't distinguish how the process played out. If inflation picks up speed in the same way as a ball rolling down a hill, it wasn't clear whether the hill was like the inside of a bowl – amounting to inflation that is fast to begin with and slows down at the end – or the outside. Also unclear was whether it was a shallow pasta dish or a steep vase. Planck's improved view of the distribution of CMB hotspots points to a slide down the outside of a shallow bowl; team member Martin White says 70 per cent of the concave models can be ruled out.

Further details still aren't clear though, such as whether the speed-up was a spiral around the bowl or a dash straight down. Nor can we answer the biggest question of all: why inflation happened in the first place. Theories built on the new Planck data will doubtless come up with suggestions. "We absolutely know a crime was committed," says White. "But we're kind of stuck until Sherlock Holmes comes along and tells us what's going on."

Another Planck gift, if you can call it that, is a package of anomalies, including the Axis of Evil. If inflation follows the simplest path, then the universe should look the same in all directions and the pattern of hot and cold spots should be random, but earlier maps



The Axis of Evil and a mystery cold spot stand out in this enhanced version of the Planck map



showed this wasn't the case. The most famous anomaly – a line that seems to separate small temperature differences from large ones – came to be known as the Axis of Evil, because it tracked the plane of the solar system.

As its name suggests, many don't like the Axis, taking its apparent alignment with the solar system as a sign that it is an artefact of the way we are viewing the CMB. They hoped it would disappear with Planck's increased resolution, but the opposite has happened. The Planck data confirms the Axis and other anomalies exist, suggesting they are not just errors from dust in the galaxy or the workings of the telescopes as many were hoping.

Planck team member Krzysztof Gorski points out that the Axis is not as aligned with the solar system as previously thought, though it still needs an explanation, such as a bulge in the early fabric of the universe that made inflation asymmetric. "It would be absolutely amazing if there was a fundamental, early-universe reason," says Huterer.

Another anomaly from earlier maps that has survived is a large cold spot (circled above) that could be a sign of another universe. The suggestion that there are multiple universes pops up in cosmology but remains unproven. When the cold spot showed up in earlier CMB maps, some cosmologists suggested it was a "bruise" caused by a collision with another universe.

Planck may also hold clues to the future. One surprise gift is a new figure for the speed of the universe's expansion. The rate is described by a parameter called the Hubble constant. Pre-Planck, this was obtained from stars called cepheids, which can be used to compare expansion rates in the recent past to now. The CMB solves the problem from the other end, allowing us to deduce the rate at the beginning of the universe.

"The data could mean the universe will end in a Big Rip, not gradual heat death"

If the acceleration is constant – and leading theories say it is – the two figures should agree. But they don't. One possible explanation is that dark energy's density is increasing with time, which would pave the way for a universe that ends in a dramatic "Big Rip" rather than the gradual heat death currently expected. "That's fairly radical," says White, but he admits it is the "kind of thing that people will have to start exploring to figure out what's going on".

It's a positively welcome development compared with one of the revelations: the Planck data has killed the sterile neutrino. This hypothetical particle promised to explain the identity of dark matter.

Earlier CMB maps showed a universe that was smoother than expected. That left room for the sterile neutrino, which would be even ghostlier than the existing muon, tau and electron neutrinos, allowing it to carry energy from one part of the universe to another without getting stuck like ordinary matter does. But Planck showed a universe clumpy enough to be explained by just the three existing neutrinos, removing the need for the sterile neutrino. ■

Dark matter

Einstein's theory of gravity led to some unexpected predictions. One was the existence of black holes, which Einstein knew about. But there was another, no less peculiar, that he probably didn't. By measuring the movement of galaxies under the influence of gravity, it became clear that something was missing. We now know that everything visible in the cosmos – from galaxies to interstellar dust – represents less than 20 per cent of the total matter out there. The remaining 80 per cent is a mysterious substance called dark matter. Astrophysicist **Dan Hooper** explains

THE EVIDENCE

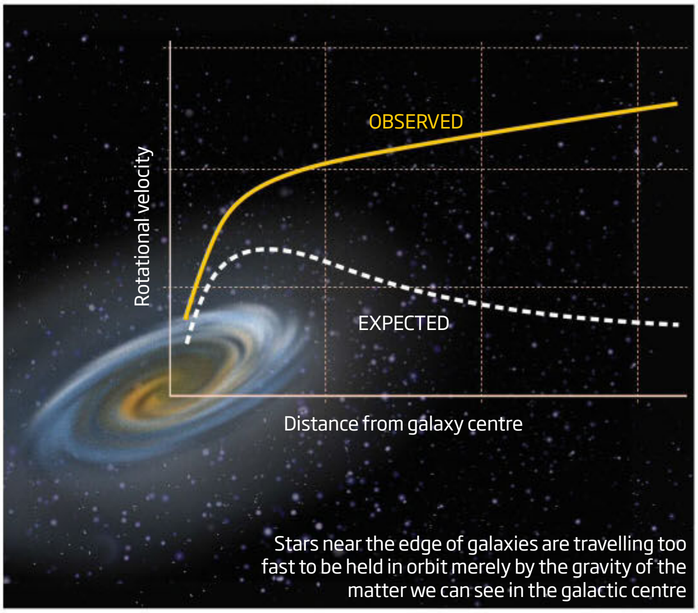
We can't weigh the sun or a planet directly. Instead, we determine its mass by measuring how its gravitational pull influences the motion of objects around it.

In the same way, it should be possible to measure the mass of a galaxy, or even a cluster of galaxies, by observing how fast stars or other objects move around it. In 1933, the Swiss astronomer Fritz Zwicky (pictured, right), working at the California Institute of Technology in Pasadena, applied this principle to the motion of galaxies that make up the Coma cluster, a group of over 1000 galaxies some 300 million light years from us. He found that the individual galaxies were zipping round far too rapidly for their gravity to keep them bound together in a cluster. By rights they should have been flying off in different directions.

Zwicky's puzzling results didn't get much attention until the late 1960s, when the astronomer Vera Rubin at the Carnegie Institution in Washington DC measured the Doppler shift of clouds of hydrogen gas in several distant galaxies. This showed that the speeds at which the clouds were orbiting the centre of their galaxies seemed to require far more mass than could be accounted for by visible material (see diagram, left).

The discrepancy between the amount of visible matter and the strength of gravity is most pronounced in some of the very smallest galaxies, known as dwarf spheroidals. These objects contain as few as tens or hundreds of thousands of stars, but produce a gravitational attraction equivalent to tens of millions times the mass of our sun. Even our own Milky Way galaxy generates a gravitational pull of an object of roughly 800 billion solar masses, despite containing a total visible mass of only a couple of hundred million suns.

Without dark matter, the very existence of many apparently stable galaxies would defy the laws of physics. The fact that they do exist remains among the most compelling reasons to think that there must be more to the cosmos than meets the eye.



Stars near the edge of galaxies are travelling too fast to be held in orbit merely by the gravity of the matter we can see in the galactic centre

Fritz Zwicky and Vera Rubin showed that visible matter alone cannot account for galactic properties

PHYSICS TODAY COLLECTION/AIP EMILIO SEGRE VISUAL ARCHIVES


RUBIN COLLECTION/AIP EMILIO SEGRE VISUAL ARCHIVES

UNEVEN BACKGROUND

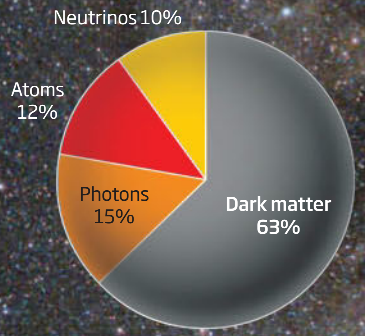
Although we still can't see the stuff itself, we see evidence for dark matter everywhere we look, for example in the radiation known as the cosmic microwave background (CMB), which was created in the infancy of the universe.

About 380,000 years after the big bang, the temperature of the universe dropped below about 3000 degrees kelvin, making it possible for the first time for atoms to form (see diagram, right). The transition from disconnected nuclei and electrons to electrically neutral atoms released a huge amount of energy in the form of light, and the expansion of the universe has since stretched this light to microwave wavelengths. This radiation today fills all of space, a relic of our universe's hot youth.

By studying the patterns of slightly hotter and colder patches in the CMB, we have been able to learn a great deal about our universe's history and composition. Among other things, these variations in the CMB tell us how matter was distributed throughout space in the early universe. Because dark matter began clumping under the influence of gravity earlier than normal matter did (see "The invisible hand", below right), its influence can be seen in numerous small hot and cold patches, each covering an angle in the sky of 0.25 degrees or so.

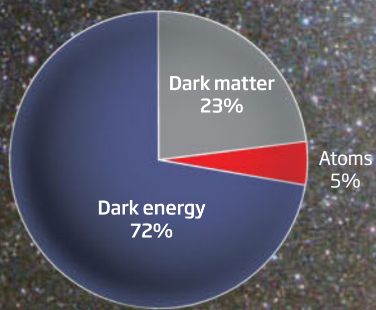
The pattern of these spots even allows us to determine how much dark matter must be present. It turns out that for every gram of stuff that we can see in the cosmos there must be 4 or 5 grams that we can't. That doesn't even include another, perhaps even more mysterious, substance whose existence can be inferred from the CMB: dark energy, a force that seems to be causing our universe to expand ever faster. Totting up all the mass and energy in the universe, dark energy trumps normal matter and dark matter combined by a factor of almost 3 to 1.

UNIVERSE 380,000 YEARS OLD



The imprint left on the cosmic microwave background shows that dark matter accounted for most of the mass and energy of the early universe

MODERN UNIVERSE



Today, both dark matter and visible matter seem to be dwarfed by dark energy, an even more mysterious substance accelerating the expansion of the universe

SOURCE: NASA

THE INVISIBLE HAND

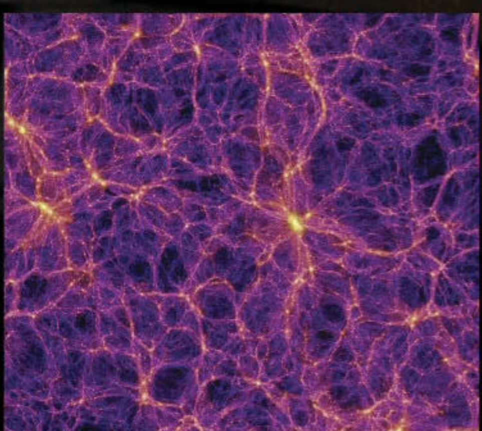
Even if dark matter weren't needed to prevent galaxies flying apart, supercomputer simulations suggest that the cosmos would look very different if it didn't exist. These simulations track the movement of billions of particles through cosmic time, with the aim of better understanding why the universe has ended up the way it has.

When atoms in a gas of ordinary matter are compressed, they collide more frequently. This interaction tends to push the atoms apart and so hinders gravity from compressing the gas any more. Dark matter particles, on the other hand, interact with each other only feebly and so clump much more readily. Simulations that embody these properties show that as the universe expanded and evolved, the first structures to form would have been clumps, or "halos", of dark matter.

The first dark matter halos to form were probably about as massive as Earth, but far more diffuse. Over time, they began to merge and became steadily larger. Eventually, some became massive enough to attract large quantities of hydrogen, helium and other conventional matter – the seeds of the first stars and galaxies.

The agreement between the shapes and sizes of the structures derived in dark-matter simulations and those observed in our universe is striking (see picture, left). That leaves little doubt that dark matter is not only real, but also that it formed the nurseries in which galaxies such as our own Milky Way formed.

Dark matter simulations accurately reproduce the large-scale cosmos



COURTESY OF V. SPRINGEL/MAX-PLANCK INSTITUTE FOR ASTROPHYSICS

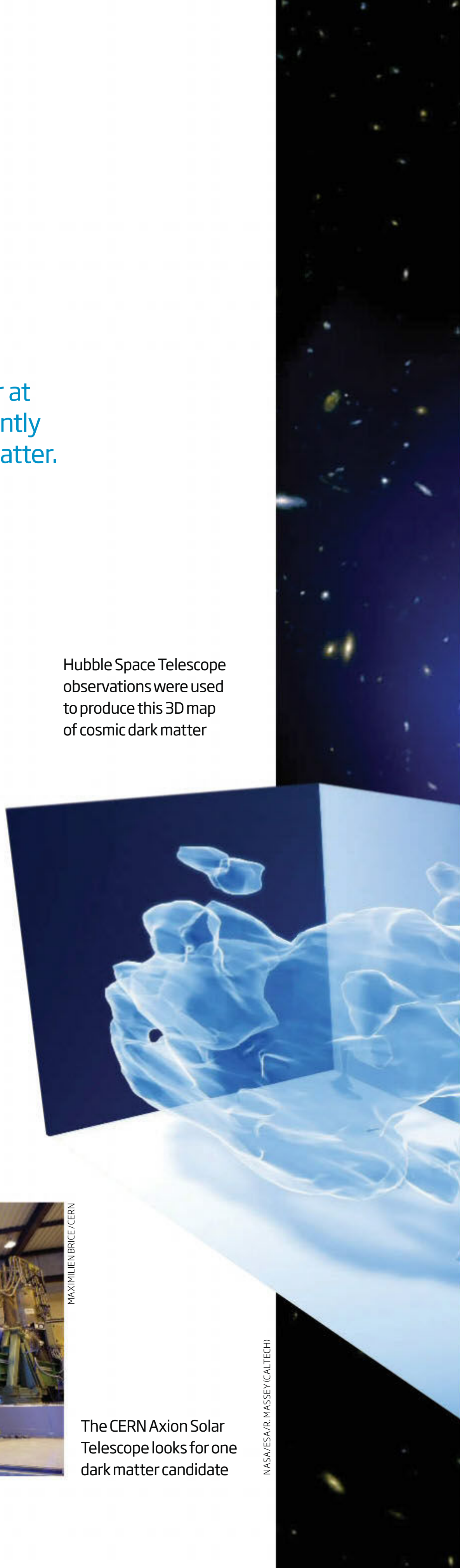
What is dark matter?

The short answer is that we don't know. It must be invisible, or at least very faint, so it cannot be made of anything that significantly radiates, reflects or absorbs light. That rules out atom-based matter. Other observations provide further clues to its identity.

MACHO OR WIMP?

We once thought that dark matter might be made up of large objects such as black holes or exotic types of faint stars – neutron stars or white dwarfs – that are nearly invisible to our telescopes. But observations seem to have ruled out these "massive astrophysical compact halo objects", or MACHOs.

The concentrated gravity of a MACHO would deflect passing light on its way to us from distant stars. We do observe such "gravitational lensing" effects, but only often enough for MACHOs to account for at most a few per cent of the mass we do not see. So most cosmologists now think instead that we are submerged in a sea of dark matter – a gas of "weakly interacting massive particles", or WIMPs – that pervades the entire volume of our galaxy, including our solar system.



Hubble Space Telescope observations were used to produce this 3D map of cosmic dark matter

NASA/ESA/R. MASSEY (CALTECH)

HOT OR COLD?

The only particles we know about that are both stable and do not carry electric charge – and so do not interact with light – are the elusive entities known as neutrinos. Might they be dark matter?

Unfortunately not. Neutrinos are very light and fast-moving, or "hot", and so resist gravity's efforts to clump them together. For galaxies and even larger structures to have formed with their observed shapes and sizes, dark matter particles must have been moving slowly, far below the speed of light, over much of the universe's history. Dark matter must be "cold".

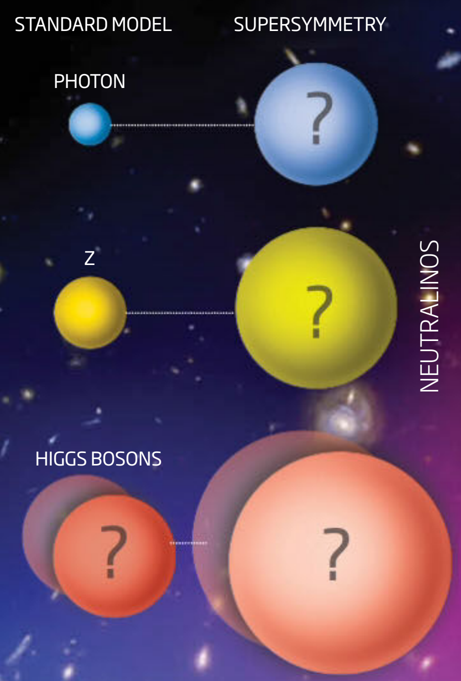
What might this lethargic gas of invisible matter be made of? None of the many types of particles discovered over the past century fits the bill: not electrons, quarks, muons, Z bosons or any other known form of matter. Dark matter must be something completely new. Proposals for dark matter's identity range from heavy, neutrino-like particles, to ultra-light and cold species of matter known as axions, to truly bizarre possibilities such as particles that are moving through extra dimensions of space.

Dozens of different possibilities have been suggested over the years, and scientists are even searching for dark matter in the lab. To many physicists there is a clear favourite: particles predicted by a class of theories that goes by the name of supersymmetry (see "An elegant symmetry", above right).

MAXIMILIEN BRICE/CERN

The CERN Axion Solar Telescope looks for one dark matter candidate

In supersymmetry theories, neutralinos pop up as heavier partners of the photon, the Z boson that mediates the strong nuclear force and the as-yet undiscovered Higgs bosons



AN ELEGANT SYMMETRY

Few ideas currently enthral particle physicists more than supersymmetry. The theory is mathematically elegant and could solve some persistent problems - including, perhaps, the nature of dark matter.

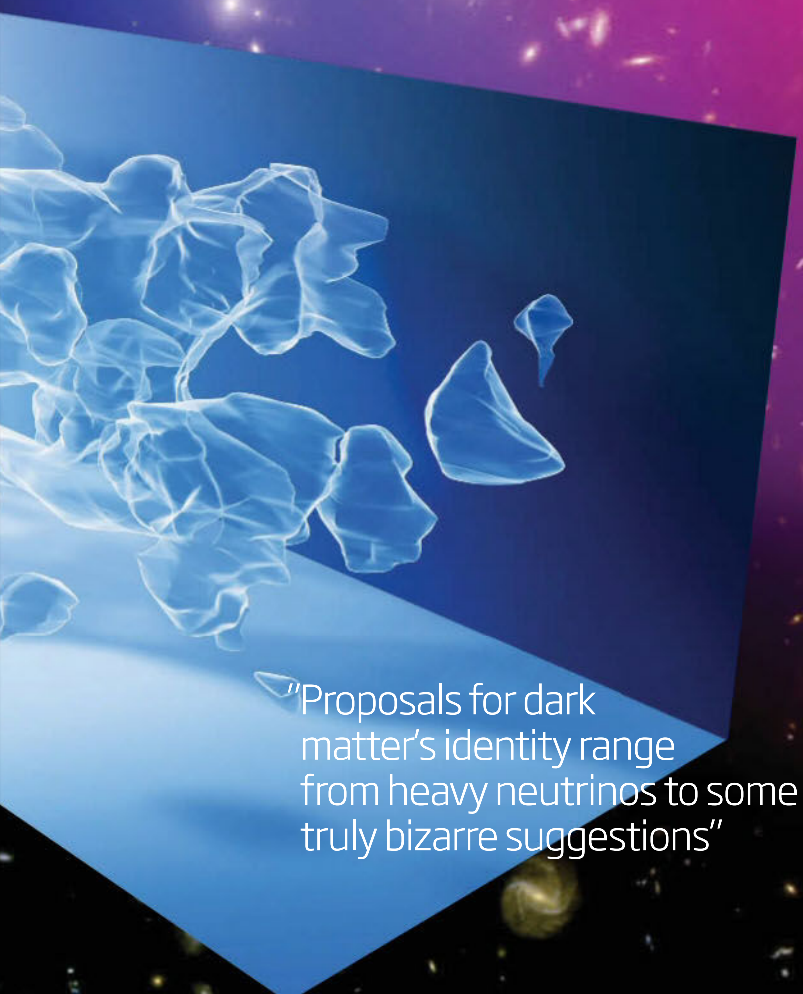
In our world, there are two classes of particles: fermions and bosons. Fermions are particles such as electrons, neutrinos and quarks that make up what we normally think of as matter. Bosons are the particles responsible for transmitting the forces of nature. The electromagnetic force, for example, is nothing more than bosons - photons, in this case - shuttling back and forth between electrically charged particles.

Supersymmetry postulates that fermions and bosons cannot exist independently of each other: for each type of fermion, a type of boson with many of the same properties must also exist. The electron, for example, has an as-yet undiscovered bosonic partner called a selectron. Similarly, the photon should have a fermionic analogue known as a photino.

Among the many new particles predicted by supersymmetry is one that is likely to be stable and have all the characteristics required of a viable dark matter candidate. It is the lightest version of a class of particle known as a neutralino. Supersymmetric theories contain at least four neutralinos, which are quantum-mechanical mixtures of the superpartners of the photon, the Z boson that transmits the weak nuclear force and the Higgs boson. Tantalisingly, if neutralinos do exist, the lightest version would probably have been produced in the first seconds after the big bang in quantities similar to what is needed to account for the dark matter in our universe today.

There is, of course, a catch: to date, no one has seen a supersymmetric particle. Physicists generally suspect that the superpartner particles - if they exist - are considerably heavier than their ordinary counterparts, making them very difficult to create or discover in experiments. Huge particle accelerators such as the Large Hadron Collider at CERN are on the case, but until we have hard evidence, the supersymmetry hypothesis will continue to be just that - a hypothesis.

X-RAY: CXC/STANFORD/S. ALLEN; OPTICAL: STSCI/UCSANTABARBARA/M. BRADAC/NASA



"Proposals for dark matter's identity range from heavy neutrinos to some truly bizarre suggestions"

DID WE GET GRAVITY WRONG?

Is dark matter strictly necessary? In 1983, the Israeli physicist Mordehai Milgrom suggested that the higher-than-expected speeds of stars moving around galaxies might be explained another way - if gravity worked differently than predicted by the theories of Newton or Einstein. In particular, he pointed out that the observed galactic rotations could be explained if Newton's second law of motion - force equals mass times acceleration, or *F = ma* - were modified to make the force of gravity proportional to the square of the acceleration at very low accelerations.

In recent years, however, Milgrom's proposal - called MOND, for "modified Newtonian dynamics" - has suffered some serious setbacks. In particular, it has not managed to explain convincingly the dynamics of galaxies within clusters. Observations in 2006 revealed a pair of merging galaxy clusters, known collectively as the Bullet cluster, whose motion indicated that their gravity was not centred on the gas and stars, as would be expected according to MOND. That suggests dark matter has shifted the centre of gravity elsewhere.

While some cosmologists don't yet accept that the evidence against MOND is conclusive, most no longer consider it to be a viable alternative to dark matter.

Ghosts among us

We might already have seen hints of a shadow world of matter we just can't touch, says **Stuart Clark**

SPARE a thought for the dark-matter hunters. Every time they're on the verge of trapping the elusive stuff thought to make up the bulk of the universe's matter, it slips away. They don't see the expected signals, or they spot something exciting only to watch it fade into background noise. Each time it's the same: put on a brave face, go back to the drawing board and begin the hunt again.

Perhaps it's time for a change of tack. Instead of going after a single species of dark matter particle, maybe we should be looking for a menagerie of dark particles and forces – a whole new "dark sector". After all, there is no reason to think dark matter will be any less intricate than the visible stuff we consider ordinary, with its panoply of particles from electrons to quarks.

LEVENTE SZABO

"If you look at normal matter, our universe is enormously complicated," says Alex Drlica-Wagner, a dark matter hunter at Fermilab near Chicago, Illinois. "So it may be naive to think that the dark sector is exceptionally simple."

The talk is of an entire shadow world in which invisible particles influence one another through forces unfelt by the familiar stuff of stars and planets and us. A quixotic idea? Perhaps not. If the faint hints of a dark force emerging from one lab stand up to scrutiny, this shadow realm may already have revealed itself.

From as early as the 1930s, astronomers could see that galaxies orbit each other much faster than expected given the gravitational tug produced by their visible stars. Forty years on, we spotted that stars within galaxies also seemed to rotate too fast. Either the laws of gravity drawn up by Newton and Einstein required a substantial rewrite, or some invisible form of matter was producing more gravitational heft. Most astronomers favoured the second option – dark matter.

Whatever this stuff is made of, it must have mass so that it feels and generates gravity, but no electric charge, so it does not interact with light. Gravity's effects are so weak that physicists have to hope that dark matter does interact with some component of ordinary matter in some other way, just barely, or else we may never identify it.

For decades, the leading candidate has been the weakly interacting massive particle, or WIMP. The trouble is, a long line of exceedingly sensitive detectors has failed to record a single

sign of them. Last year, the LUX experiment in South Dakota came to the end of a two-year search without a sniff.

WIMPs aren't quite dead yet. Some astronomers think we have seen their signature in ultra-faint dwarf galaxies surrounding the Milky Way (see "Dwarfs to the rescue?", page 43). But for others it's time to move on. "We've been looking for these for decades and we haven't found anything," says Jonathan Feng at the University of California, Irvine. "This naturally leads people to consider other, more baroque ideas."

Dark matter has taken various guises besides WIMPs over the years (see "Seven ways to make dark matter", page 42). But now there are compelling reasons to consider more extravagant alternatives. For a start, we can measure the rotation of galaxies in such detail that we can figure out how dark matter is distributed within them. Simple models suggest it should be very dense in the middle of galaxies. The latest observations, however, show that it is spread more evenly. One way to explain that is by appealing to a force that acts only between dark matter particles, pushing them apart.

That could be a game changer. "Once you start thinking about forces acting just between dark matter particles, then you are led into a whole new arena," says Feng. "You can think about a zoo of dark particles and forces all of its own. It's a brand new world."

"With the dark matter search failure, we must consider other, more baroque ideas"

The idea of a dark sector is not entirely novel. Back in 2006, astronomers studying the Bullet Cluster, an ongoing smash-up between two groups of galaxies, proposed that the collision speed was too high for the gravity of the matter involved – dark and ordinary – to be solely responsible. They figured that the additional pull must be coming from a force of attraction between dark matter particles.

More detailed simulations proved that the speed of the Bullet Cluster collision was not beyond what we might expect. But the suspicion of dark forces never went away, with researchers suggesting that anomalies thrown up by particle experiments on Earth might ›

SEVEN WAYS TO MAKE DARK MATTER

WIMPS The textbook solution to dark matter is that it is a thick, slow-moving soup of weakly interacting massive particles (WIMPs). That could explain the odd way galaxies rotate – yet no detector has yet found a WIMP. If they do exist, it seems they must be lighter than we thought.

MACHOS This is the idea that dark matter is just normal stuff hiding at the edges of galaxies – "massive astrophysical compact halo objects" that are so dim as to be invisible. Candidates include black holes or failed stars. Alas, MACHOs could only account for a tiny fraction of the universe's missing mass.

MACROS It could be that the dark stuff is made of dense clumps of quarks, the particles that, in pairs or triplets, form ordinary matter. These "macros" could be as dense as neutron stars and extremely heavy. Unfortunately, the experiments needed to spot them, such as deploying seismometers on the moon, are too outlandish to carry out.

AXIONS A punier version of the WIMP, axions would interact even less with ordinary matter. That suggests WIMP detectors might have spotted them – but they haven't. The jury is still out, at least until dedicated experiments such as the Axion Dark Matter Experiment return a verdict.

GRAVITINOS The graviton is a particle proposed by the theory of supersymmetry (see page 39) to mediate the force of gravity, and the gravitino is its hypothetical "superpartner". It nicely fits the bill for a dark matter particle. The trouble is there is still no sign of the many heavy partner particles predicted by supersymmetry.

MOND Modified Newtonian dynamics (MOND) doesn't make dark matter so much as remove the need for it, by tweaking the laws of gravity. That makes many physicists uncomfortable. Now a hybrid model exists in which a phase-changing form of dark matter acts like WIMPs inside galaxies but modifies gravity on larger cosmological scales.

STERILE NEUTRINOS Neutrinos pass through other matter almost as if it doesn't exist, but they are too light and zippy to be dark matter. Sterile neutrinos are a heavier, more aloof version. But despite strenuous efforts to detect them, they have never been spotted and the consensus now is that they almost certainly do not exist.

also hint at their existence. For example, a long-standing discrepancy between theory and experiment over the magnetic properties of ordinary matter particles called muons, a heavier version of the electron, might be explained by invoking a dark-force carrying particle. Now Feng thinks we might have found the most compelling evidence for such a particle so far – in a nuclear physics lab in Hungary.

Attila Krasznahorkay of the Institute for Nuclear Research at the Hungarian Academy of Science in Debrecen leads a team looking at the radioactive decay of beryllium-8 nuclei. Beryllium is a naturally occurring light element that is stable when its nucleus contains four protons and five neutrons. But with just four of each, the isotope Be-8 splits into two helium nuclei in the blink of an eye. Previous experiments had hinted at something odd about this particular decay, and Krasznahorkay and his colleagues wanted to pin it down.

To make Be-8, they fired protons at a wafer-thin sheet of lithium-7. The beryllium decayed, releasing pairs of electrons and their antimatter counterparts, positrons. In standard particle theory, most of those pairs should be emitted in roughly the same direction as the incoming proton beam. But the Hungarians found that there were two unexpectedly prominent side streams, coming out almost at right angles to their expected direction. This was the sort of behaviour you would expect if the decay created a slow-moving particle that lived for short time before itself decaying into an electron and positron, which it would spit out in almost opposite directions.

When the team calculated the mass of this hypothetical particle, they found that it fitted nothing in the standard model of particle physics. Instead, their numbers suggest it has a mass of around 17 megaelectronvolts – just 33 times that of an electron and far lighter than any WIMP. No known force of nature could create such a particle.

Having investigated the anomaly for three years, the team published their results in 2015. They refer to their particle as a "dark photon". By analogy with the way the photon carries electromagnetism, this particle would carry an unknown force between dark matter particles.

The paper passed pretty much unnoticed – until Feng came across it. From the description, he could see nothing wrong with the experimental set-up. "They did a lot of cross-checks and they could not make the effect go away," says Feng. "They have seen hundreds of events now. The likelihood of this result happening by chance is one in 200 billion."

Taking the results at face value, Feng and his colleagues sought their own explanation. They also wanted to address a nagging doubt: given that the Hungarian team spotted this putative new particle with an experiment well within the capabilities of most physics labs

X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.; OPTICAL: NASA/STSCI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.; LENSING MAP: NASA/STSCI; ESO WFI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.

XENON

Even the cleanest, most sensitive detectors have failed to lay a glove on dark matter particles

Galactic smash-ups hint that dark matter is more complex than we thought

around the world, why had no one else noticed anything before?

The hypothetical dark photon, as well as carrying the dark force between dark matter particles, should also carry a little bit of ordinary electromagnetism. So it should occasionally interact with the protons and electrons in normal matter. But when Feng and his colleagues calculated the strength of this interaction, the plot thickened. "There was no way this could be a dark photon," says Feng. "If it were, we should have seen hundreds and thousands of other effects in other experiments and particle accelerators."

If not a dark photon, then what? Feng's team searched for other ways a dark particle could be interacting, albeit slightly, with familiar matter to cause the anomalous beryllium decay. They found that, to be consistent with everything we have seen in experiments designed to characterise the known forces of nature, it must interact not with protons and electrons, as a conventional photon does, but with the neutrons inside the beryllium nuclei. This is a property beyond the scope of physics as we know it, which might explain how the particle slipped by unseen in previous dark matter searches. Feng's team call the interloper a "protophobic X boson".

Not everyone is convinced of claims of a whole shadow world beyond the visible material universe. Rouven Essig at Stony Brook University, New York, is sceptical of both the experimental result and the attempts to deduce a particle that might explain it. "I don't think anyone has written down a compelling or natural candidate yet," he says.

At least the theory can be tested. Feng's X boson is of a size that should allow several current experiments to show definitively whether it exists or not. "The nice thing is that we have a concrete target now and these experiments can actually check this," says Essig. "I don't think this anomaly is going to stick around forever."

Indeed, the race is on to confirm or refute the Hungarian group's original findings and look for more examples of the X boson at work. The DarkLight experiment at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, is already

"Sooner or later the standard model must break, so every anomaly must be looked at"

searching for particles in the mass regions where Feng's team calculated it should be. The LHCb experiment at CERN's Large Hadron Collider near Geneva, Switzerland, will also look for it in the decays of quarks and their antimatter counterparts.

Some researchers have expressed reservations because the Hungarian team has reported anomalies before, only for them to disappear on further investigation. Feng is undeterred. "No one has identified a weakness of this experiment," he says. "Do they have a specific problem with the experimental results, or is it just general scepticism?"

To his mind, the current situation of general cluelessness surrounding dark matter means the X boson is well worth pursuing, regardless of any qualms. "We know there is dark matter and it is not explained in the standard model," he says. "There must be an explanation, so sooner or later the standard model will have to break. Every anomaly must be looked at."

Others are yet to be persuaded. "All of these ideas are very interesting, but I wouldn't say that we have a compelling reason to abandon the simpler dark matter picture yet," says Josh Simon, an astrophysicist at the Carnegie Observatories in Pasadena, California. The problem with a complex dark sector, he says, is that it is going to be even harder to put to the test than the elusive WIMPs and their ilk. "It becomes very difficult to make any predictions about what we should observe."

But then again, Simon goes on to say, just because a theory is complicated doesn't make it wrong. "Nature doesn't have to give us something that is easy to test." ■

DWARFS TO THE RESCUE?

Dark matter might not be as gloomy as its name suggests. If this mysterious substance is made of weakly interacting massive particles (WIMPs), as most physicists believe, then they would come in matter and antimatter versions. When the two come into contact, they would produce a shower of high-energy photons known as gamma rays.

In 2009, researchers at Fermilab in Batavia, Illinois, thought they had caught a glimpse of such a signal coming from the centre of the Milky Way. Most astronomers now think that was a false alarm. Galaxies tend to be crowded with billions of stars, making it almost impossible to rule out other sources for the gamma rays.

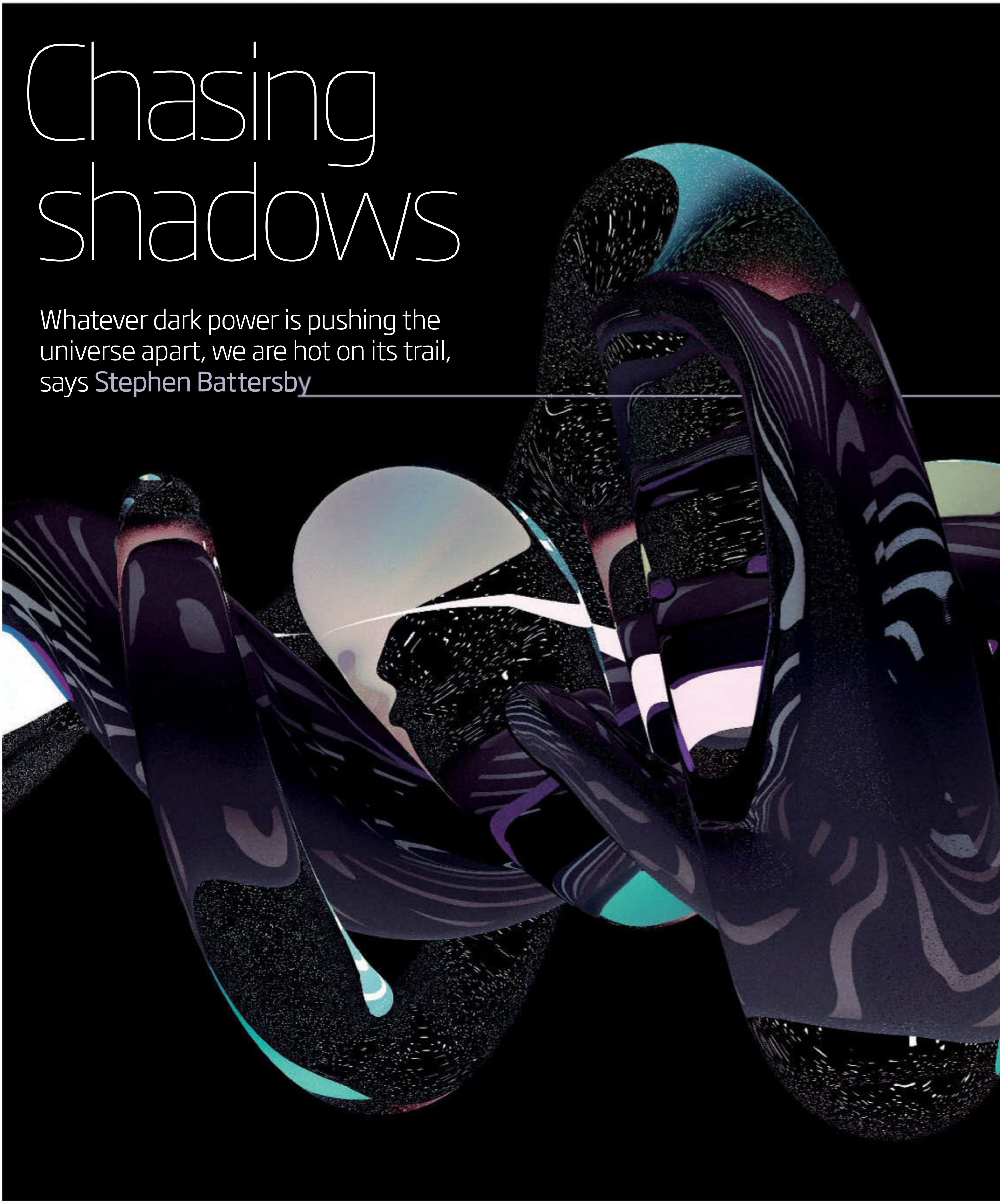
It's not quite game over, however. In the past few years, astronomers have discovered a nearby population of ultra-faint dwarf galaxies, so named because each contains no more than a few hundred million stars. These mini-galaxies are also thought to hold unusually high concentrations of dark matter, making them the ideal place to look for its gamma-ray glow. "If we don't see it here, we never will," says Josh Simon at the Carnegie Observatories in Pasadena, California.

Maybe we already have. In 2015, we found a new dwarf galaxy called Reticulum II just 100,000 light years away, prompting Alex Geringer-Sameth at Carnegie Mellon University in Pittsburgh, Pennsylvania, and his colleagues to take a closer look. They downloaded observations from the archive of NASA's Fermi gamma-ray space telescope and, sure enough, they found what appeared to be an excess of gamma rays.

Critics say there could be hidden gamma-ray sources beyond Reticulum II. The possibility is hard to rule out and there are no plans for new instruments to provide more accurate observations. Unless we discover more nearby dwarf galaxies to test, a certain identification of WIMPs remains a long shot (see main story).

Chasing shadows

Whatever dark power is pushing the universe apart, we are hot on its trail, says Stephen Battersby



DOUGLAS BOWDEN

SOMETHING mysterious is pushing the universe apart. It isn't obvious, which is why it took physicists until 1998 to discover it. It is everywhere but we can't see it, and we don't know what it is. It makes up more than two-thirds of the universe, but we have no idea where it comes from or what it is made of. "Nature has not been ready to give us any clues yet," says Sean Carroll, a theoretical physicist at the California Institute of Technology in Pasadena.

We do at least have a name for this enigmatic beast: dark energy. Now the hunt for it is on. Astronomers are searching for it among exploding stars and ancient galaxy clusters. Meanwhile, some physicists are pursuing an unorthodox idea: that we might snare dark energy in the lab.

As yet, our knowledge of the quarry is desperately scarce. It is limited to perhaps three things. First, dark energy pushes. We first noted that in 1998, in the unexpected dimness of certain supernova explosions which told us they were further away than we expected. Space seems at some point to have begun expanding faster, as if driven outwards by a repulsive force acting against the attractive gravity of matter.

Second, there is a lot of the stuff. The motion and clustering of galaxies tells us how much matter is abroad in the universe, while the cosmic microwave background radiation emitted 380,000 years after the big bang allows us to work out the total density of matter plus energy. This second number is much bigger. According to the latest data, about 68 per cent of the universe is in some non-material, pushy energy That works out at about 1 joule per cubic kilometre of space.

Third, dark energy makes excellent fuel for the creative minds of physicists. They see it in hundreds of different and fantastical forms.

The tamest of these is the cosmological constant, and even that is a wild thing. It is an energy density inherent to space that creates a repulsive gravity.

Einstein himself introduced the cosmological constant as a fudge factor in general relativity to achieve a universe that was neither expanding nor contracting. He dropped it almost immediately when observations proved that the universe was expanding, calling it his "greatest blunder".

The 1998 discovery revived the need for a cosmological constant to provide the impetus for the accelerating expansion. As space expands there is more and more of the inherent energy, making its repulsion stronger relative to the fading gravity of the universe's increasingly scattered matter. Particle physics even seems to provide an origin for it, in virtual particles that appear and disappear in the bubbling, uncertain quantum vacuum. The trouble is that these particles have far, far too much energy, by a factor of about 10^{120}.

This catastrophic discrepancy leaves room for a menagerie of alternative theories. Dark energy could be quintessence, a hypothetical energy field that permeates space, changing over time and perhaps even clumping in different places. Or it might be a modified form of gravity that repels at long range, or even an illusion born of Earth's position in the cosmos. Dark energy could take the form of radio waves trillions of times larger than the observable universe – or something even more exotic (see "Arcane energies", page 46).

"Many clever people have tried to devise something better than the cosmological constant, or understand why the cosmological constant has the value it does," says Carroll. "Roughly speaking, they have failed."

The dark is rising

One way to cut to the chase might be to find out whether dark energy is changing over time. If it is, that would exclude the cosmological constant: as an inherent property of space, its density should remain unchanged. In most models of quintessence, by contrast, the energy becomes slowly diluted as space stretches – although in some it actually intensifies, pumped up by the universe's expansion. In most modified theories of gravity, dark energy's density is also variable. It can even go up for a while and then down, or vice versa.

The fate of the universe hangs in this balance. If dark energy remains steady, most of the cosmos will accelerate off into the

ARCANE ENERGIES

Energy is ignorance, says Salvatore Capozziello of the University of Naples, Italy – and that could explain where dark energy comes from (see main story). If different eras of the universe are in entangled quantum states, when we try to measure some property of the early universe such as its expansion speed, quantum theory puts a limit on the information we can extract. Information loss is intimately linked to a rise in entropy, which implies energy sloshing around the cosmos. "It is possible to interpret this as dark energy," says Capozziello. By his calculations, our cosmic energy of ignorance would have the right properties to cause the real acceleration of the universe.

Or perhaps dark energy is a hologram. The holographic principle, devised to help link gravity with quantum mechanics, says that nothing can contain more energy or information than a black hole. A black hole's total energy increases with its circumference, not its volume, so perhaps the universe's energy is related to the length of some boundary akin to a black hole's event horizon. "It is an appealing idea because you get the right energy scale," says one of the idea's originators, Stephen Hsu at Michigan State University. This could reduce the excessive energy of quantum particles popping out of the vacuum to the level of dark energy. Even so, there are all sorts of technical issues, he says – not least that it is difficult to define such a boundary of the universe.

Meanwhile, Edmund Copeland and colleagues at the University of Nottingham, UK, think an unimaginable tumult of dark energy could sit beneath our serene existence. In an obscure paper published in 1974, they found the most general mathematical form of scalar-tensor theories, in which an added energy field allows the strength of gravity to vary from place to place. When they adapted these equations to produce an accelerating universe like ours, they found it includes a huge amount of vacuum energy – perhaps more than 10^{60} joules of energy per cubic metre of space. We don't feel the powerful anti-gravity effect of this dark energy because it is almost entirely blocked by the added field. If that is right, you can hold enough dark energy between your hands to disintegrate a million galaxies.

distance, leaving us in a small island universe forever cut off from the rest of the cosmos. If it intensifies, it might eventually shred all matter in a "big rip", or even make the fabric of space unstable here and now. Our best estimate today, based mainly on supernova observations, is that dark energy's density is fairly stable. There is a suggestion that it is increasing slightly, but the uncertainties are too large for us to worry about this just yet.

The Dark Energy Survey aims to tighten things up. It uses the 4-metre-wide Víctor M. Blanco telescope at the Cerro Tololo Inter-American Observatory in Chile, attached to a specially designed infrared-sensitive camera, to look for several telltale signs of dark energy over a wide swathe of the sky. "This is not the world's biggest telescope, but it has a very large field of view," says Joshua Frieman of the University of Chicago, who is director of the project.

For a start, the telescope will catch many more supernovae. The apparent brightness of each stellar explosion tells us how long ago it happened. During the time the light has taken to reach us, its wavelength has been stretched, or redshifted, by the expansion of space. Put these two things together and we can plot expansion over time.

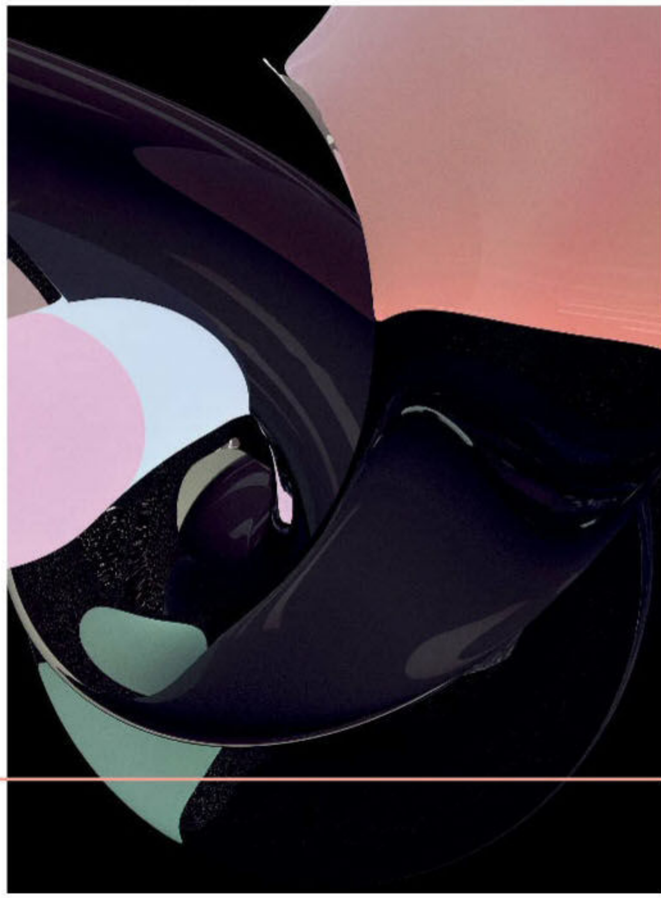
The survey is also drawing an intricate sky map that marks the positions of a few hundred million galaxies and their distances from us. Sound waves reverberating around the infant cosmos gave vast superclusters of galaxies a characteristic scale. By measuring the apparent size of superclusters, we can get a new perspective on the expansion history of the universe (see diagram, right).

Eyes on the sky

The map will also reveal dark influences on smaller scales. Dark energy hinders galaxies from coming together to form clusters. The survey team will count clusters directly, and also follow their growth using an effect known as gravitational lensing, which happens when clusters bend light passing through them from even more distant cosmic objects.

These various measurements should give us a handle on how dark energy has changed over time – if at all. The survey

"If dark energy is a new field or particle, it will create a fifth force we don't feel in the solar system"



DOUGLAS BOWDEN

should reduce the uncertainty on existing results by a factor of four, says Frieman.

A full posse of dark energy hunters will set out over the next few years. The Large Synoptic Survey Telescope, a US-led project, is due to open its great eye in 2021. Other mega-scopes such as the Thirty Meter Telescope in Hawaii and the European Extremely Large Telescope and the Giant Magellan Telescope, both in Chile, should also swing into action around the same time. So should a huge cosmic radio receiver based in Australia and South Africa, the Square Kilometre Array, which will trace cosmic structure through the radio glow of hydrogen clouds. In 2020, the European Space Agency and NASA plan to launch a dark-energy-hunting space mission called Euclid that will trace gravitational lensing and galaxy clumping to even earlier cosmic times. The US Wide-Field Infrared Survey Telescope will follow soon after.

This chase through space will be thrilling, but the quarry may still elude us. Say we find that dark energy maintains a near constant density over time. That would seem to support the cosmological constant, but it would not rule out some quintessence fields that just happen to have a nearly constant density. Even if we find the dark energy density to be increasing or decreasing, we might not be able to tell whether that is due to quintessence, or to some kind of varying gravity.

That leads some physicists to suggest laying traps for the beast here on Earth. "If you introduce a new field or particle to be your dark energy, then it will also act as the carrier of a new force," says Clare Burrage at the University of Nottingham, UK. Something like quintessence would produce a fifth fundamental force, separate from gravity, electromagnetism and the nuclear forces. The same holds for most forms of modified gravity. "But we don't see a fifth force within the solar system," says Burrage.

Theorists generally extricate themselves from this sticking point by adding a screening mechanism that weakens the fifth force in comparatively dense environments such as the solar neighbourhood. A project called the GammeV experiment, at Fermilab in Illinois, is already looking for one particular screened dark energy field called the chameleon.

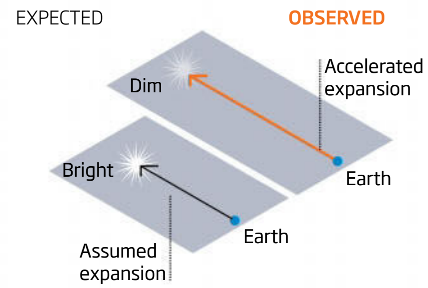
So far GammeV has seen nothing, but now Burrage aims to search for a much wider range of dark energies, and with higher sensitivity. Along with Nottingham colleague Edmund Copeland and Ed Hinds of Imperial College London, she wants to expose it using a

Stretch the rules

Many lines of evidence indicate that a mysterious **dark energy** is countering gravity's pull and accelerating the universe's expansion

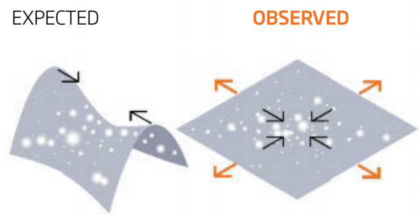
SUPERNOVAE

Distant type Ia supernovae are dimmer than expected, suggesting they are further away



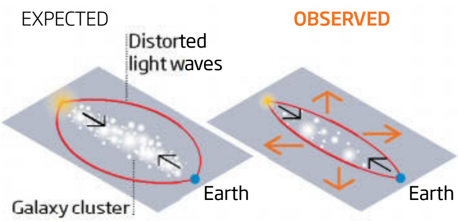
COSMIC MICROWAVE BACKGROUND

With only matter's gravity at work, the universe should be curved. Patterns in the big bang's afterglow suggest it is nearly flat



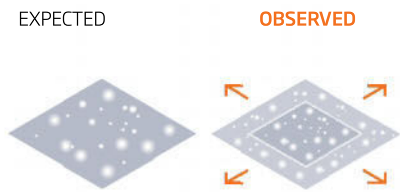
GRAVITATIONAL LENSING

Images of distant galaxies are less distorted by intervening matter than we expected. A repulsive force seems to be stopping matter clumping



ACOUSTIC IMPRINTS

Sound waves rippling through the early universe gave galaxy superclusters a typical scale. Far-off superclusters appear smaller than expected – and so are farther away



cloud of cold atoms called a Bose-Einstein condensate, which oscillate together in a collective quantum wave. Dark energy should just slightly slow down the frequency of this oscillation. The team plans to split a condensate in two and place a dense object near one of the halves. If the object screens out dark energy, waves in the two halves will get out of sync, and when brought back together the two condensates will interfere.

Electric effects

At the University of Washington in Seattle, the Eöt-Wash torsion pendulum experiment is probing other forms of cosmic repulsion. In one theory, extra dimensions of space less than a millimetre across can play host to dark energy. That would also increase the strength of gravity on these scales. A type of screened quintessence called the symmetron would generate a similarly small-scale extra force – a tiny effect that the subtle twistings of the Eöt-Wash pendulums should expose.

Meanwhile, Michael Romalis at Princeton University and Robert Caldwell at Dartmouth College in Hanover, New Hampshire, proposed in 2013 that if ordinary photons or electrons can feel quintessence even very faintly, then a magnetic field on Earth should generate a tiny electrostatic charge. This effect is potentially simple to detect, although any apparatus designed to do it would need to be extremely precise.

Carroll points out that we might see another electromagnetic effect in space. If photons interact with dark energy, it could rotate their polarisation as they travel across the universe. This may be visible in the cosmic microwave background.

Few imagine that the hunt will be over soon. "Dark energy is one of the greatest mysteries, and I don't expect to still be around when we solve it," says Stephen Hsu of Michigan State University. After nearly 20 years of puzzlement we have no clue as to dark energy's identity. But on the bright side, we do have some clues to where the clues may lie. ■

Black holes are one of the most mysterious entities to drop out of Einstein's theory, and could even point the way to the next physics revolution

The hole story

RELATIVITY has plenty of mind-bending consequences, but one is especially warped. Concentrate enough mass in a small enough space and you form something called a "singularity". The mass bends space-time so much that its curvature becomes infinite and nothing, not even light, can escape. This is what is known as a black hole.

The idea was formulated in 1916 by astronomer Karl Schwarzschild. Einstein was impressed with the mathematics, but did not believe such an entity could actually exist. In 1938 he published a paper apparently proving that black holes were a purely theoretical entity.

That changed in the 1950s when physicists revived their interest in general relativity as a tool to probe massive and distant celestial objects. By the end of the 1960s, most accepted that black holes were an inevitable consequence of Einstein's equations.

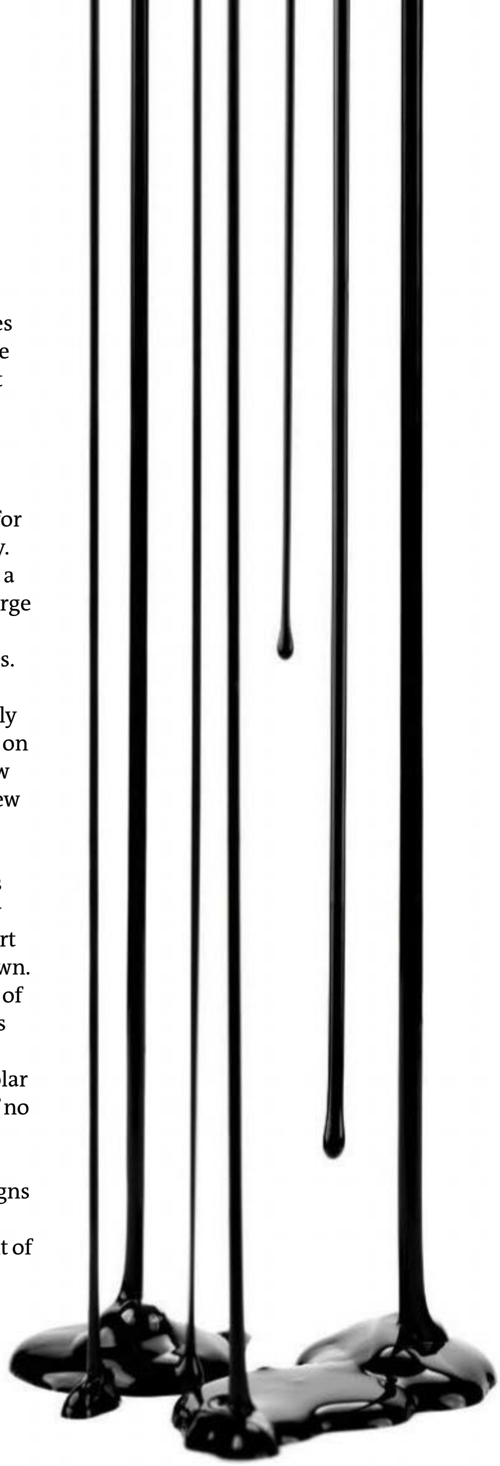
One way these beasts can form is when massive stars run out of fuel and collapse in on themselves. As the collapsing material gets denser and denser, its gravitational field forms an event horizon – a point of no return. This boundary in space-time is where gravity is so strong that nothing can escape.

That's the theory, anyway. Nobody has ever seen a black hole. However, we're pretty sure that there is one at the heart of the Milky Way because of the way nearby stars whirl around, as if orbiting an object 4 million times the mass of our sun. "We have a spectacularly good case for this, considering that we can't see it directly," says Daniel Marrone of the University of Arizona.

Last year's detection of a gravitational wave apparently rippling out from the merger of two small black holes is the latest circumstantial evidence. Plans to image a black hole directly may finally confirm their existence (see page 22).

Problems will remain, however. Collapsing stars can't explain supermassive black holes (see page 49). These cosmic heavyweights also throw up paradoxes between relativity and quantum theory. Solving them may lead us to a theory of everything, which would be quite something for an entity Einstein didn't think even existed. ■

MARIO WANGER



Monster mix

Giant black holes pop up even in the deep recesses of time. How did they get so vast so fast, asks Stephen Battersby

THEY are the great dark spots of the universe. Not merely black holes, but enormous black holes, billions of times the mass of our sun. They are everywhere we look, even looming distantly out of the light of the cosmic dawn.

Supermassive black holes have all the space-warping strangeness of their smaller kin, which we see dotted about our galaxy; they too swallow all matter, light and cries for help. But they hold another level of mystery. We know that small black holes with a mass a few times that of the sun are born when a large star's heart collapses in a supernova, but nobody can explain the genesis of the giants.

We thought we could. We thought supermassive black holes simply grew slowly from very small seeds, bloating themselves on surrounding gas. But our observations show this cannot be the whole story. We need a new explanation for these ancient monsters.

Whatever did make supermassive black holes, it had to make an army. Observations of stars whirled around by powerful gravity suggest there is a huge black hole at the heart of almost all large galaxies, including our own. The Milky Way's is 5 million times the mass of the sun. Wander some 50 million light years away to the giant elliptical galaxy M87, and you will find a black hole of over 6 billion solar masses. Its event horizon – the boundary of no return for any passing object – is nearly five times as wide as the orbit of Neptune.

Further off we see even more dramatic signs of the supermassive. Extraordinarily active galaxies called quasars have a brilliant point of light at their heart that often outshines all the billions of surrounding stars together. Many spit out searing flares of X-rays and gamma rays and colossal jets of material at 99 per cent of the speed of light. These are the signs of a giant black hole's voracious appetite. Gas spiralling inwards heats through friction and glows white-hot, generating magnetic fields that send the jets of matter hurtling outwards.

The conventional tale of supermassive black holes begins a few tens of millions of years after

"There is a limit to how fast a black hole can grow: eventually it is starved by its own brilliant belching"

the big bang, as the very first stars formed from the densest clouds of primordial hydrogen and helium gas. These pioneers, the story goes, were several hundred times the mass of our sun. The core of such a star soon collapses to form a black hole of around 100 solar masses. As this seed gorges on gas it sinks towards the centre of its galaxy, eventually becoming the powerful heart of a quasar.

In 2000, however, NASA's Chandra X-ray telescope spied a very distant and powerful quasar. We see SDSS J1030+0524 as it was just 900 million years after the big bang, and its power output must come from a hole of more than a billion solar masses.

How did this monster get so vast so fast? The more gas a black hole gulps, the more light and other radiation shines out. Eventually, the hole is starved by its own brilliant belching: the flood of light grows so fierce that it sweeps away any incoming gas, cutting off the food supply. Theory, backed by the behaviour of black holes nearby, says that a hole can double in size at most once every 30 million years.

To make the leap from 100 to a billion solar masses means doubling in mass 23 times, so in theory the black hole in SDSS J1030+0524 could have developed in around 700 million years. But that would require a gas supply perfectly tuned to the hole's needs. A black hole's surroundings are likely to be messy and changeable, so gorging so fast for so long is not so easy. "It is a problem to imagine they can accrete gas at all times," says theorist Zoltan Haiman of Columbia University in New York.

Still, SDSS J1030+0524 might be a freakish example of a black hole managing to live the high life for the best part of a billion years. "One peculiar object you can always explain," says astrophysicist Priya Natarajan of Yale University. But we have discovered scores more. "When there's a population of these things, there has to be a natural way to make them," says Natarajan.

Each discovery piles on the pressure. In 2012, a team using the UK Infrared Telescope in Hawaii observed a quasar, ULAS J1120+0641, with a mass about 2 billion times that of the sun just 770 million years after the big bang. Theory dictates a minimum of about 750 million years to grow that large from a 100-solar-mass start.

The story of supersized holes growing from small seeds looks even less plausible after recent work on how the first stars formed.

> **"Perhaps the most radical suggestion is that giant black holes were forged directly in the big bang"**

New simulations have followed the shrinking gas clouds that gave birth to them for a longer spell, and found that they tend to split up into smaller fragments than we thought, making stars no larger than about 50 solar masses. After exploding, these would make black holes of only about 10 solar masses – a disappointing size for would-be quasar seeds. "They are just not oomphy enough," says Natarajan.

What's more, common-or-garden stellar-mass black holes should pop up all over every young galaxy. Some of these holes would sink to the centre of their galaxy and seed more massive ones, so even fairly small galaxies should sport a fairly impressive central black hole by now. But that is not what we see. Jenny Greene of Princeton University has found that among smallish galaxies with a total mass of about a billion suns, only about half have a central hole.

There seems to be only one conclusion. We're going to need a bigger seed.

One possibility is that supermassive black holes began not with single stars, but many. "We know that early in the history of the universe, stars tended to form in bursts – regions that were spectacularly active," says Fred Rasio of Northwestern University in Evanston, Illinois. In 2003, he ran simulations of ancient clusters where hundreds of bright young things were forming. The most massive tended to pile up near the centre, where they almost inevitably run into one another. "You form a thing – I don't want to call it a star – with many thousands of solar masses," he says. What happens next is very difficult to model. Rasio's educated guess is that this object might well collapse to form a black hole of perhaps a few thousand solar masses.

It's a nice idea. It would be nicer still if we could find similar middleweight black holes in star clusters today. A few promising objects called ultraluminous X-ray sources (ULXs) have been found in nearby galaxies. They are seemingly bright enough to be based around biggish holes. But in 2011, observations of one ULX in our neighbouring galaxy Andromeda showed that it has the same characteristic spectrum and behaviour as small black holes in our galaxy, with around 10 solar masses. The other ULXs may be this small too.

In any case, even a seed hole of a 1000 solar masses would have to double its mass 20 times over to become a gigasun giant. Almost constant gorging would still be needed to explain an object like ULAS J1120+0641.

Perhaps, then, we need to think a little bigger still. If a small black hole springs from the collapsing heart of a star, might a big one come from the collapsing heart of a galaxy?

This was originally suggested as an outside possibility in 1978 by Martin Rees at the University of Cambridge. It sounds seductively simple, but it is not easy to cram so much matter into a galaxy's heart.

The first hurdle is spin. Even the earliest protogalaxies rotated a little, tweaked by their neighbours' gravity. As they contracted, their gas whirled faster, like air drawn into a tornado. Eventually, the rotation balanced gravity, producing a spinning disc of gas with little material within the innermost few hundred light years.

Slow and dense

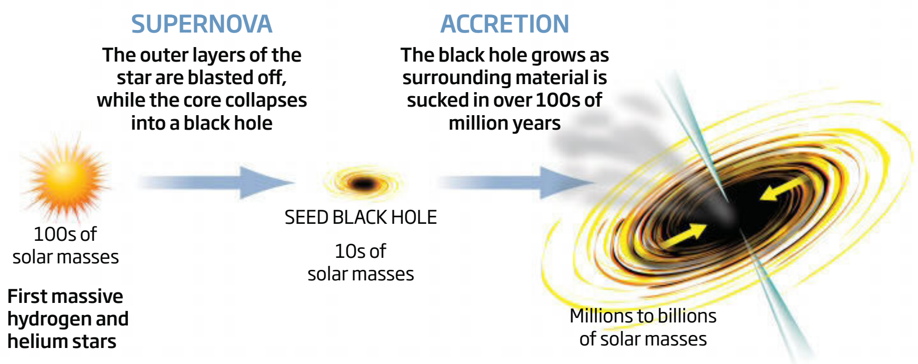
Rasio and Abraham Loeb of Harvard University showed in the 1990s how this barrier might be overcome. If a protogalaxy is slow-spinning and dense, its core can become unstable. Excess gas collects into rotating, elongated bars, which act like gravitational gear-wheels transferring the rotation outwards. The heart of the protogalaxy can then collapse into a much denser knot.

The next stage is uncertain, but according to calculations performed in 2006 by Rees, his then colleague Marta Volonteri and Mitchell Begelman of the University of Colorado at Boulder, one possibility is a monstrous "quasistar": a dense cocoon of gas a few hundred million kilometres across surrounding a small central black hole. The cocoon's great weight would force matter into the hole, incubating it to a million solar masses in just a few tens of millions of years. Such a heavy seed could square the theory with observations: it would need to double in size just 10 times to make a billion-sun black hole. Even without a carefully balanced gas supply, that could happen within the allotted time frame of about 700 million years.

Problems remain. During its initial collapse, the gas is liable to split up into little blobs that will coalesce and ignite into stars, denying material to the quasistar. Some of these stars will go supernova, blasting away fresh gas supplies and halting the black hole's growth. There are ways around this: ultraviolet radiation from nearby starbursts could heat the blobs and stop them coalescing, or turbulence might prevent fragmentation.

Making a big one

The old picture of supermassive black hole formation has the cosmic giants feeding constantly on surrounding gas over hundreds of millions of years



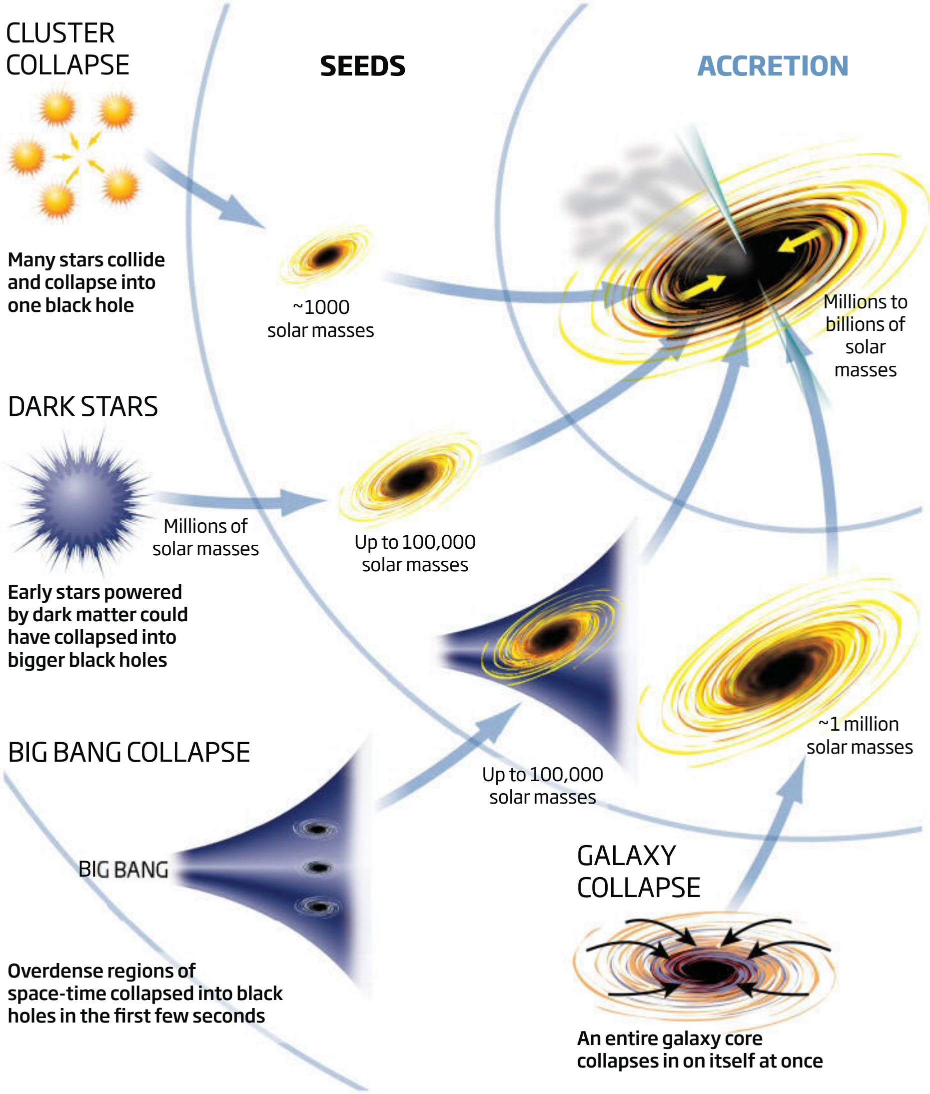
To many astronomers, however, these remedies seem too contrived. "Direct collapse needs a lot of fine-tuning," says Rasio.

Do these failures mean something altogether stranger is going on? Perhaps the most radical suggestion is that giant black holes were forged directly in the fires of the big bang, during tumultuous moments known as phase transitions when matter and radiation suddenly rearranged themselves. About one microsecond after the beginning of time, for example, quarks were coming together to form protons and neutrons. This process could have been uneven, producing sharp spikes in density that turned into black holes of around one solar mass.

That is too small to make our seeds, but Sergey Rubin at the National Research Nuclear University in Moscow, Russia, has suggested that these holes might cluster together and swiftly merge into one giant. Another promising phase transition happens when the universe is about 10 seconds old, when a haze of electrons and positrons destroy one another to leave space filled instead with gamma ray photons. At this point, holes of up to 100,000 solar masses might form spontaneously.

Growth spurt

Quasar observations suggest supermassive black holes already existed in the early universe – meaning we need to explain how their seeds got big so quick



These mammoths of the universal dawn would suck in hot gas around them and shine brightly in X-rays, leaving marks on the cosmic microwave background radiation. Searches have so far found nothing, but do not rule out a few rare giant primordial holes, enough to form the seeds of early quasars.

Even so, most astronomers trying to fathom the origin of supermassive holes think that primordial seeds are an unnecessarily exotic option. "There is no compelling argument for why they should have formed," says Begelman. "You need some weird cosmology."

Perhaps more palatable is the notion of dark stars. In 2007, Douglas Spolyar, then at the University of California, Santa Cruz, and colleagues suggested that some of the very first stars might have been powered by dark matter. Dark matter particles would settle into the stellar core, where they could collide with and annihilate one another, providing a gentler heat than the nuclear furnaces of hydrogen and helium-powered giants. With no harsh radiation to blow away incoming gas, dark stars could keep growing almost indefinitely, finally collapsing to form a seed black hole of up to 100,000 solar masses.

Point of no return

This idea is very testable. Dark stars would emit enough infrared radiation to be seen by the successor of Hubble, the James Webb Space Telescope, which is scheduled for launch in 2018. It might also be able to detect quasistars.

If it sees nothing, we will need an even more sophisticated piece of kit to spy on the origin of supermassive black holes. The Laser Interferometer Space Antenna (eLISA), a spacecraft designed to detect gravitational waves, could do the job. The mission has spent a long time trying to get off the drawing board, but if it finally blasts into space it could detect the gravitational waves from merging holes across the universe. "Then it should be easy to tell whether the seeds are small or massive," says Volonteri, who is now at the Institut d'Astrophysique de Paris in France.

Meanwhile, astronomers will be searching for quasars yet deeper in space and time. What happens if they keep finding them ever earlier in the history of the universe? Eventually, they will reach a point a couple of hundred million years after the big bang when their black centres would not have had time to grow even from a million-sun seed. Then none of these stories would work. We would truly be in the dark about why the universe is full of holes. ■

If intergalactic travel is on your wish list we have plenty of wormholes to choose from, says Marcus Chown

Return ticket to Andromeda, please

IT IS not every day that a piece of science fiction takes a step closer to nuts-and-bolts reality. But that is what seems to be happening to wormholes. Enter one of these tunnels through space-time, and a few short steps later you may emerge near Pluto or even in the Andromeda galaxy millions of light years away.

You probably won't be surprised to learn that no one has yet come close to constructing such a wormhole. One reason is that they are notoriously unstable. Even on paper, they have a tendency to snap shut in the blink of an eye unless they are propped open by an exotic form of matter with negative energy, whose existence is itself in doubt.

Now, all that has changed. A team of physicists from Germany and Greece has shown that building wormholes may be possible without any input from negative energy at all. "You don't even need normal matter with positive energy," says Burkhard Kleihaus of the University of Oldenburg in Germany. "Wormholes can be propped open with nothing."

The findings raise the tantalising possibility that we might finally be able to detect a wormhole in space. Civilisations far more advanced than ours may already be shuttling back and forth through a galactic-wide subway system constructed from wormholes. And eventually we might even be able to use them ourselves as portals to other universes.

Wormholes first emerged in Einstein's general theory of relativity, which famously shows that gravity is nothing more than the hidden warping of space-time by energy, usually the mass-energy of stars and galaxies. Soon after Einstein published his equations in 1916, Austrian physicist Ludwig Flamm discovered that they also predicted conduits through space and time.

But it was Einstein himself who made detailed investigations of wormholes. In 1935 he and Nathan Rosen, his assistant at the Institute for Advanced Study in Princeton, concocted one consisting of two black holes connected by a tunnel through space-time. Travelling through their wormhole was only possible if the black holes at either end were of a special kind. A conventional black hole has such a powerful gravitational field that material sucked in can never escape once it has crossed what is called the event horizon. The black holes at the end of an Einstein-Rosen wormhole would be unencumbered by such points of no return.

"Wormholes are well and truly on the menu of astrophysical possibilities in any post-Einstein world"

Einstein and Rosen's wormholes seemed a mere curiosity for another reason: their destination was inconceivable. The only connection the wormholes offered from our universe was to a region of space in a parallel universe, perhaps with its own stars, galaxies and planets. While today's theorists are comfortable with the idea of our universe being just one of many, in Einstein and Rosen's day such a multiverse was unthinkable.

Fortunately, it turned out that general relativity permitted the existence of another type of wormhole. In 1955, American physicist John Wheeler showed that it was possible to connect two regions of space in our universe, which would be far more useful for fast intergalactic travel. He coined the catchy name wormhole to add to black holes, which he can also take credit for.

The trouble is, the wormholes concocted by Wheeler, Einstein and Rosen all have the same flaw. They are unstable. Send even a single photon of light zooming through and it instantly triggers the formation of an event horizon, which effectively snaps shut the wormhole.

Somewhat bizarrely, it is the American science populariser (and also planetary astronomer) Carl Sagan who is credited with moving the field on. In his 1985 science fiction novel *Contact* he needed a quick and scientifically sound method of galactic transport for his heroine Ellie Arroway – played by Jodie Foster in the movie. Sagan asked theorist Kip Thorne at the California Institute of Technology in Pasadena for help, and Thorne realised a wormhole would do the trick. In 1987, he and his graduate students Michael Morris and Uri Yertsever worked out the recipe to create a traversable wormhole. It turned out that the mouths could be kept open by hypothetical material possessing a negative energy. Given enough negative energy, such a material has a repulsive form of gravity, which physically pushes open the wormhole mouth.

Negative energy is not such a ridiculous idea. Imagine two parallel metal plates sitting in a vacuum. If you place them close together the vacuum between them has negative energy – that is, less energy than the vacuum outside. This is because a normal vacuum is like a roiling sea of waves, and the waves that are too big to fit between the plates are

PHOTO: LIGHT PAINTING BY PATRICK ROCHON

naturally excluded. This leaves less energy inside the plates than outside.

Unfortunately, this kind of negative energy exists in quantities far too feeble to prop open a wormhole mouth. Not only that but a Thorne-Morris-Yertsever wormhole that is big enough for someone to crawl through requires a tremendous amount of energy – equivalent to the energy pumped out in a year by an appreciable fraction of the stars in the galaxy.

Back to the drawing board then? Not quite. There may be a way to bypass those difficulties. All the wormholes envisioned until recently assume that Einstein's theory of gravity is correct. In fact, this is unlikely to be the case. For a start, the theory breaks down at the heart of a black hole, as well as at the beginning of time in the big bang. Also, quantum theory, which describes the microscopic world of atoms, is incompatible with general relativity. Since quantum theory is supremely successful – explaining everything from why the ground is solid to how the sun shines – many researchers believe that Einstein's theory of gravity must be an approximation of a deeper theory.

A world beyond Einstein

A hint of what a deeper theory would look like came in 1921. Theodor Kaluza and Oskar Klein were inspired by Einstein's success in showing that gravity is the curvature of a four-dimensional sheet made by melding together the three dimensions of space with time. They went on to show that both gravity and the electromagnetic force could be explained by the curvature of a five-dimensional space-time. More recently, string theorists claim that all four fundamental forces might be explained by warping 10-dimensional space-time.

Crucially, when space-time has more than four dimensions, the powerful theorems that forbid a wormhole unless it is propped open by negative energy may not apply.

In 2002, Kirill Bronnikov at the Centre of Gravitation and Fundamental Metrology in Moscow, Russia, and Sung-Won Kim at Ewha Womans University in Seoul, South Korea, raised the possibility of a wormhole existing without exotic matter. They uncovered a wealth of wormhole solutions in one of the popular versions of brane-world gravity, which describes our world as a 4D island or "brane" floating in higher dimensions. "No phantom matter is required, and the wormholes can have an arbitrary size," says Bronnikov.

Such higher-dimensional theories of gravity such as string theory are notoriously difficult to work with, however. Enter Kleihaus and his colleagues Jutta Kunz, also at the University of Oldenburg, and Panagiota Kanti of the University of Ioannina in Greece. They were exploring hypothetical but plausible extensions of Einstein's theory of gravity that are easier to handle. The simplest of these theoretical frameworks goes by the unwieldy name of dilatonic Einstein-Gauss-Bonnet theory, or the much snappier DEGB theory.

If the extra dimensions of higher dimensional theories are rolled up very small, or "compactified", that would explain why we do not experience them directly. The process of compactifying the extra six dimensions ›

"Even the supermassive black hole at the centre of our Milky Way might be a wormhole"

of string theory creates several new force fields, such as the so-called dilaton field. In the same way that general relativity describes gravity as the curvature of space, gravity in DEGB theory depends on the curvature plus the curvature raised to a higher power.

Using this extra term in the gravitational equations, Kleihaus and his colleagues discovered a solution for a wormhole. It needs no stuff made of negative energy to prop it open, or, indeed, any matter at all.

Taken together with Bronnikov and Kim's work, it seems that wormholes are well and truly on the menu of astrophysical possibilities in any post-Einstein world. Excitingly, the wormholes Kleihaus's team envisage are of the type that connects two regions in separate universes. What seemed a mere exotic curiosity in Einstein's day is not the case now. The advent of string theory has led some theorists to speculate that our universe with its three dimensions of space is a 3-brane floating in a higher-dimensional space. But out there, there could be other universes that are 4-branes, 5-branes and so on. Suddenly a wormhole that connects different universes is an exciting prospect.

Could such wormholes exist out there in space? Quite possibly. Wheeler suggested that quantum fluctuations would transform the gently undulating fabric of space-time at close range into a seething mass of complex shapes, known as quantum foam. According to this picture, exceedingly small wormholes with different topologies would appear and disappear in a flash.

Yet there is a natural process that could already have magnified these wormholes, making them large enough to travel through today. Inflation, as we call it, is widely thought to have operated in the first split-second of the universe's existence, prompting it to balloon enormously and at breathtaking speed. "At the same time, it could have ballooned the tiny wormholes that make up the sub-microscopic fabric of space," says Kleihaus.

He and his colleagues have thoroughly investigated the properties of their wormhole inflated this way. For it to be traversable, the differences in gravity across a body travelling through the wormhole must be small enough to keep the body intact. The good news, says Kleihaus, is that the photons and subatomic particles can easily travel through. The bad news is that for a massive human being to travel through unscathed by gravity, the wormhole mouth needs to curve very gently and this means it must be tens to hundreds of light years across.

If this seems a bit excessive, consider the upside. According to Kleihaus, the scale of such wormholes presents us with a golden opportunity to spot them out in space. As a telescope scans across the star field and hits a wormhole it would see an abrupt change in the view. "The wormhole mouth, after all, is a window on another universe," says Kleihaus.

In general, though, even enormous wormholes will be difficult to spot. When hidden by dust and gas and stars, they look very similar to black holes. It is even possible that Sagittarius A*, the supermassive black hole at the centre of our Milky Way, could be a wormhole. One way to be sure, says Kleihaus, would be to study matter falling in.

Observations show that gas swirling around a black hole forms a disc of matter so hot it emits X-rays, and we expect the same at the mouths of wormholes. No one has yet built a telescope of sufficiently high resolution to image the very core of a black hole, though astronomers are constructing one capable of snapping Sagittarius A* . If Sagittarius A* is indeed a black hole, then we would expect the X-rays to cut off suddenly as the gas crosses the event horizon never to be seen again. On the other hand, if it is the entrance to a wormhole, then we would still see the X-rays because wormholes do not have event horizons.

Kleihaus and his colleagues are also hoping astronomers will help them to deduce what other signatures of wormholes might look like. One possibility is that, if a wormhole passes between a distant star and Earth, its gravity will distort, or gravitationally lens, the light of the distant star in a distinctive way.

While the wormhole solution found so far in DEGB theory connects our universe to another, it is still possible that other solutions exist that connect different parts of our universe. Such a wormhole would open up the prospect of an extraterrestrial subway system.

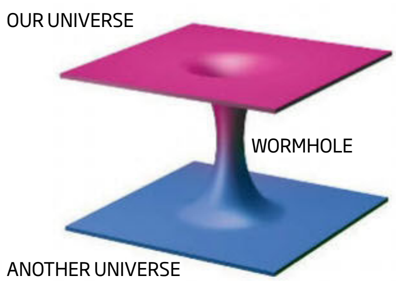
Before you start saving for a season ticket, though, be warned that the Milky Way may not be a destination on the subway map. That's because our galaxy's stars are crowded together within a few light years of each other. While this doesn't prevent the existence of a wormhole with a mouth tens of light years across, it makes it hard to position it so that star systems don't accidentally fall in. Fallen stars would surely disrupt the timetable and so users might avoid our galaxy altogether.

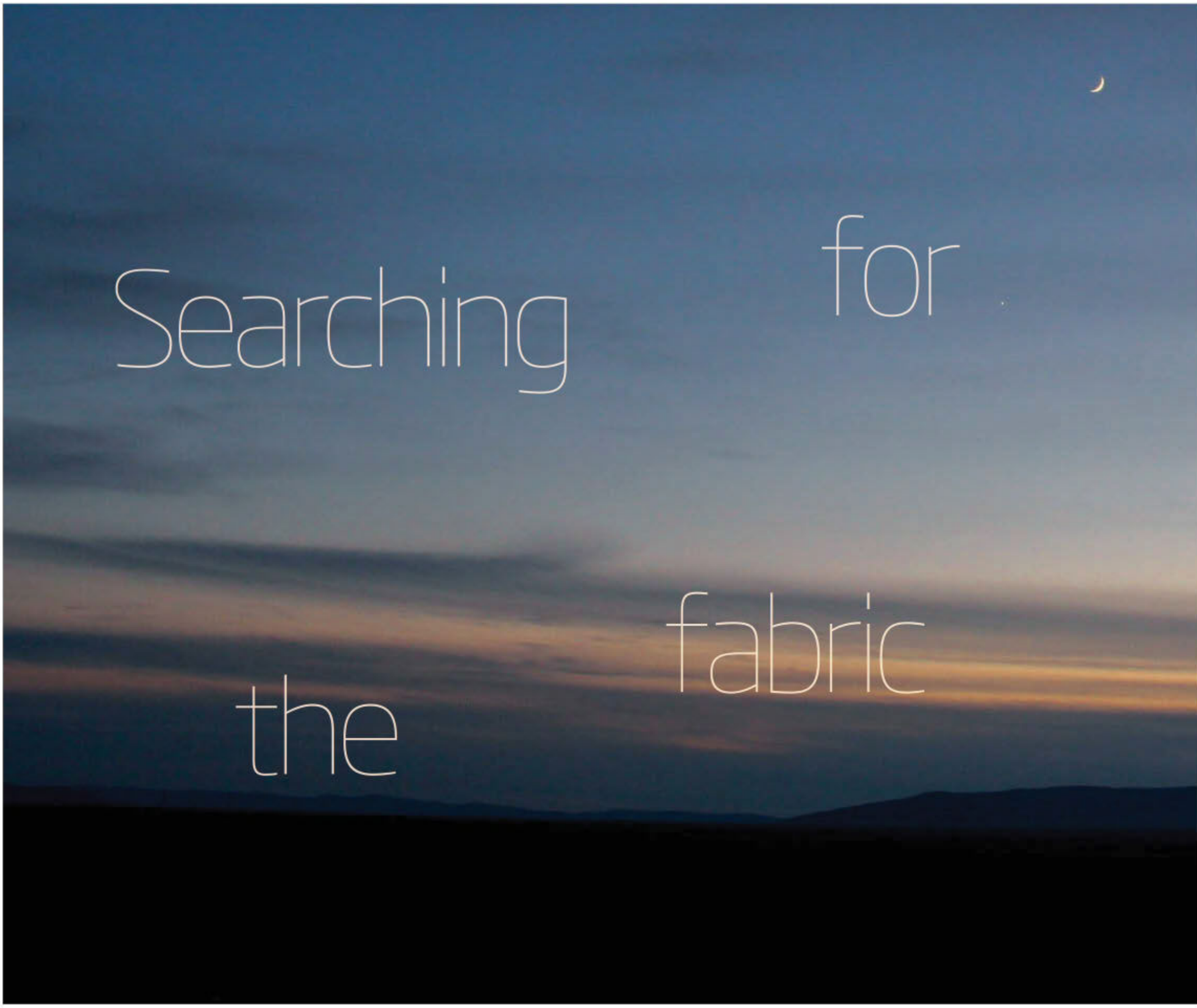
There is no such problem, of course, in the emptiness between galaxies. Perhaps, at this very moment, there is an intergalactic subway system connecting the region just beyond the Milky Way to Andromeda, the Large Magellanic Cloud or the Whirlpool galaxy. What Einstein – who didn't even like black holes – would have made of such a bizarre spin-off of his ideas we can only speculate. ■

A tale of two wormholes

In general relativity, wormholes permit travel between different places in our universe, but they require matter with negative energy

A minor modification to general relativity allows wormholes between our universe and another to exist without the need for exotic matter





Searching for the fabric

The discovery of gravitational waves required a place quieter than quietness itself. **Anil Ananthaswamy** paid a visit to the facility while it was gearing up for the search and wrote this piece anticipating its eventual triumph. Originally published on 12 April 2014.

PHOTOS BY ANIL ANANTHASWAMY

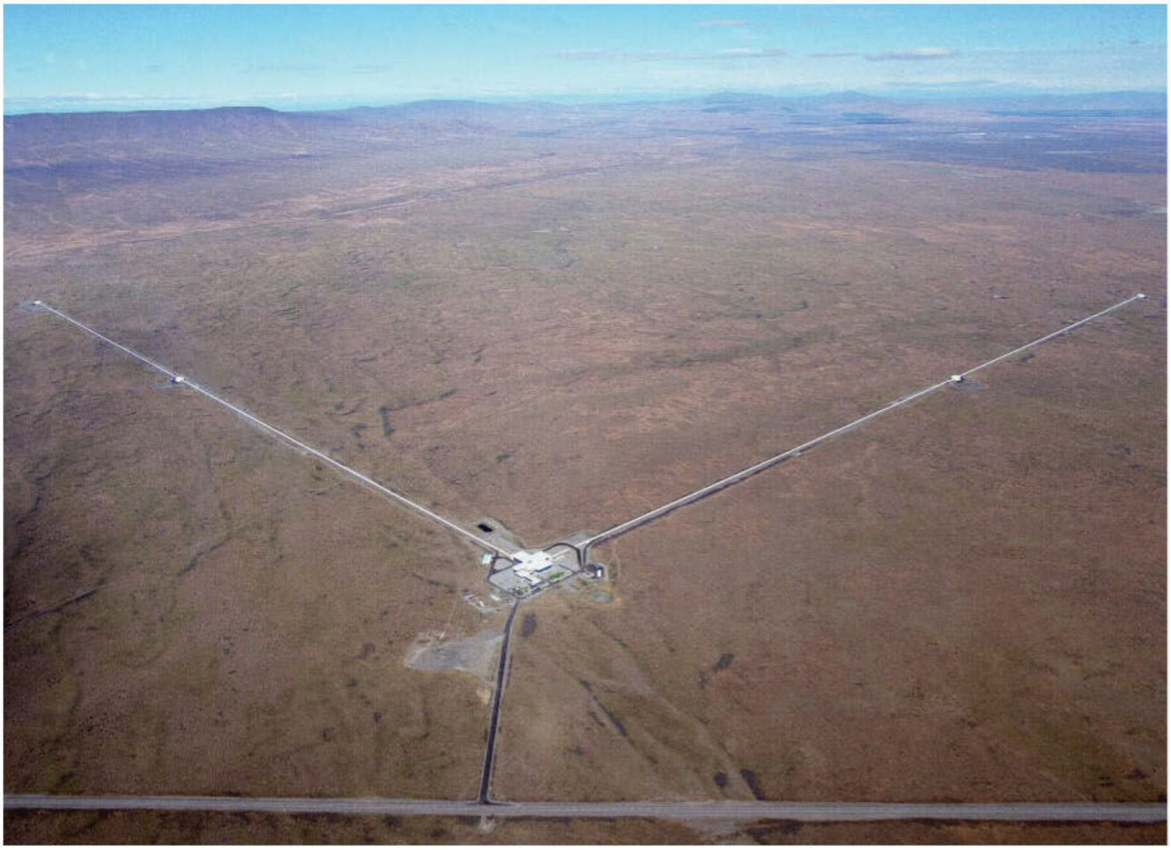
DUSK has descended on Rattlesnake Mountain. A thin crescent moon hangs over the ridge, while Venus shines through thin wisps of cirrus clouds. The Yakima people call Rattlesnake "the land above the water", apparently because it once stood untouched while floods ravaged the plains below.

Today the treeless ridge stands 1000 metres high overlooking a silent sagebrush-covered steppe in the east of Washington state. Its silence holds secrets. "...The mountain's folds and shadows / roll with stars, soft April greens, and lupine / belying missile silos hidden in catacombs / and the waste of 50 years of atomic bombs," wrote Washington's poet laureate, Kathleen Flenniken, who grew up nearby.

In December 1942, US military personnel flying over Rattlesnake saw what they described as the perfect "isolated wasteland" in which to produce plutonium for the wartime push to build an atomic bomb. The fissile core of Fat Man, which laid waste to Nagasaki, was made here at the Hanford nuclear site. At the height of the cold war, it was home to nine nuclear reactors and five fuel-processing factories.

Fly over Rattlesnake today and two rather different, enigmatic features stand out: a pair of concrete pipes, kilometres long and metres in diameter, shooting off arrow-straight at right angles to one another on the stark plain below.

The ghosts of Hanford's nuclear past are gathered in by the night, and the silence seems to intensify. But for what is going on inside those concrete tubes, no ordinary silence will be enough. ›



LIGO HANFORD OBSERVATORY

LIGO's tumbleweed-strewn detector arms (left and below) were designed to provide the final test for relativity

Albert Einstein's shadow looms large over the past century of physics. Though he would have baulked at the association, the Hanford nuclear site owes its existence to $E=mc^2$, his equation that describes how mass is just a concentrated form of energy waiting to be released.

Mass-energy equivalence was born of Einstein's special theory of relativity of 1905. This was the theory that fixed the speed of light, c, as an ultimate cosmic speed limit, and began to distort long-held notions of an absolute, unchanging, separate space and time.

But special relativity was merely an hors d'oeuvre to general relativity. Laid out in 1915, Einstein's masterwork fleshes out the full connections between mass, the force we call gravity, and a pliable fabric on which the universe's events play out: space-time.

In Einstein's universe, gravity is not a magical force that two objects instantaneously exert on one another, as Isaac Newton envisaged in his universal law of gravitation more than two centuries earlier. Instead, a massive object warps space-time around it, much as an iron ball would dent a stretched sheet of rubber. The distortions the sun introduces into the surrounding space-time forces Earth and our companion planets to run rings round it; Earth's warping of its environment keeps our feet pinned to the ground. Gravity just follows the curvature of space-time.

In the past century, general relativity's predictions have been tested over and over again, from the British astronomer Arthur Eddington's efforts in 1919 to show how the sun bent passing starlight during a solar eclipse, to modern measurements of galaxy clusters warping light from even-more-distant quasars. The theory has never been found wanting. But oddly, one of its central predictions has yet to be directly verified, even after all these years.

LIGO HANFORD, CALTECH

It was Einstein himself who first ventured it. In a paper called simply "*Über Gravitationswellen*" – "On Gravitational Waves" – he suggested that if matter warps space-time, perhaps moving matter shakes it so as to create waves. The equations of general relativity at least seemed to indicate it was possible: Einstein showed how a rotating oblong object – something like a very large American football – might generate ripples in the universe's fabric.

But he wasn't quite convinced. Almost two decades later, together with a young colleague, Nathan Rosen, he titled another paper sent to the *Physical Review* "Do gravitational waves exist?", only now to answer the question with a cautious "no". The paper never appeared: the journal's editor, John Tate, sent it on to an anonymous referee. Offended, Einstein withdrew it. He did not take kindly to being peer-reviewed.

But that gave him time to realise the mistake in his calculations and reverse his prediction before the paper was eventually published in 1937 in the *Journal of the Franklin Institute*. The existence of ripples in the fabric of reality, extending every which way throughout the cosmos, finally had Einstein's personal seal of approval.

"In 1969, aluminium cylinders 1000 kilometres apart in Illinois and Maryland vibrated in tandem. A seismic, acoustic or electromagnetic trigger was not apparent"

"The master," says Vernon Sandberg, proudly pointing to Einstein in a photograph taped to the corner of his whiteboard. It is the famous photograph of Einstein at the Solvay Conference in Brussels, Belgium, in 1927. He sits at the centre of the front row, to present-day eyes an iconic figure outshining the anonymous-looking luminaries of the young science of quantum mechanics who surround him: Niels Bohr, Werner Heisenberg, Max Planck, Erwin Schrödinger.

Trained as a theorist, Sandberg now swims in a sea of experimentalists at the Hanford Laser Interferometer Gravitational-Wave Observatory (LIGO), which stands beside the old nuclear site. Sandberg first fell in love with Einstein's ideas about space and time in the early 1970s. It was around this time that Joseph Weber, a physicist at the University of Maryland, claimed the first detection of gravitational waves.

Weber's detectors are now museum pieces: one literally, at the Smithsonian Institution in Washington DC. Another stands in the entrance lobby of the main LIGO building at Hanford. Beautifully machined, giantly proportioned cylinders of aluminium, they were once suspended from steel wires some 1000 kilometres apart on the Maryland campus and the Argonne National Laboratory near Chicago, Illinois. In 1969, Weber reported that the cylinders had vibrated in tandem 17 times over an 81-day period. A seismic, acoustic or electromagnetic trigger for this sudden resonance was not apparent. "This is good evidence that gravitational radiation has been discovered," he wrote in *Physical Review Letters*.

He had enough reason to be optimistic. Follow the lessons of general relativity, and gravitational waves should be everywhere. The many violent events that define the cosmos should all generate ripples that spread through space-time at the speed of light, from the collapse of massive stars as they go supernova, to the spiralling-in and merging of dense objects such as neutron stars and black holes, to the violent convulsions of space-time soon after the big bang.

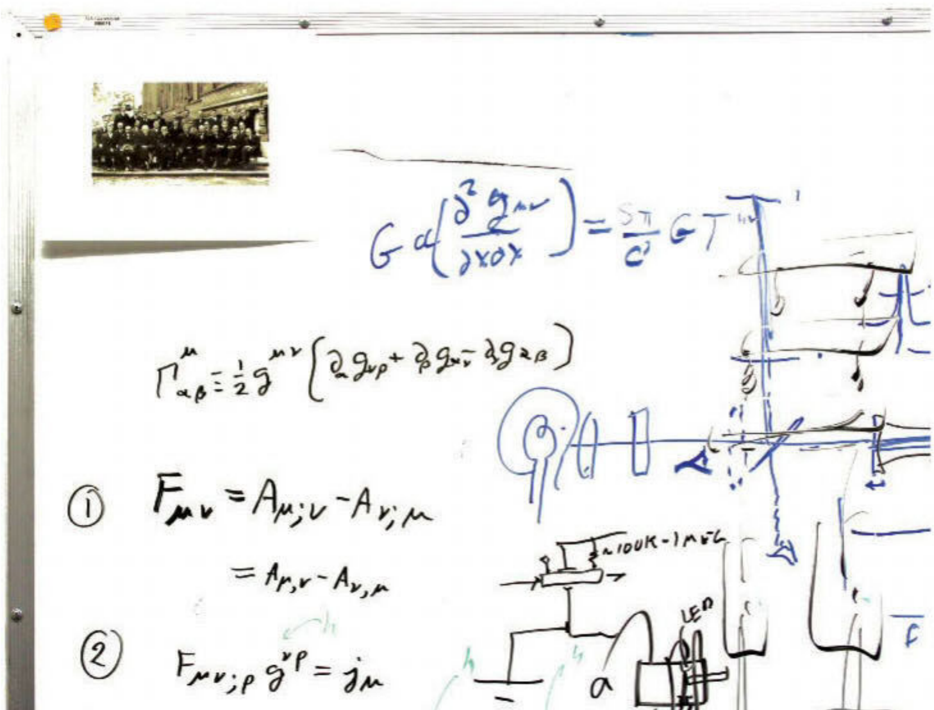
And yet the consensus today is that Weber was mistaken. To set the cylinders vibrating as he claimed, the nearby universe would have to be filled with extremely strong sources of gravitational waves, but that doesn't seem to be the case.

The only widely accepted evidence that gravitational waves exist is indirect. In 1974 the astrophysicists Joseph Taylor and Russell Hulse discovered a double-star system 21,000 light years away. At least one of them is a fast-rotating neutron star – a pulsar. Observations of the two bodies show that they are spiralling inwards towards mutual obliteration exactly as they should if they are losing energy by radiating gravitational waves.

There's a reason why gravitational waves are hard to find. "Space-time is really, really stiff," says Sandberg. Something like a thousand billion billion times stiffer than diamond, so even mighty cosmic events generate pitifully weak, murmuring waves in it. A gravitational wave from the death tango of two neutron stars each with a mass of 1.4 suns – the benchmark used by gravitational-wave astronomers – would squeeze or stretch the 4.3 light years between us and Alpha Centauri by less than half the width of a human hair.

That distortion would be eminently measurable, if we could build an instrument that stretched from here to Alpha Centauri. As things stand, LIGO's rather more modest arms are probably our best chance.

Similar laser interferometers have been built in a handful of locations across the globe – in Germany, Italy and Japan – expressly to catch gravitational waves, but LIGO is the biggest. Its two arms, each 4 kilometres long, are identical in almost every respect. One extends out from the experiment's main building towards Rattlesnake Mountain and the other lies at a right angle, pointing towards the ›



"A gravitational wave will expand and contract LIGO's arms by just one ten-thousandth of the width of a proton"

decommissioned reactors of the Hanford nuclear site.

Each contains a steel pipe housing a vacuum through which one half of a split laser beam pings back and forth, bouncing off a mirror at the far end. Back at the main building, this reflected laser beam is reunited with its twin that has zipped up and down the other arm.

Any change in the length of either arm caused by a passing gravitational wave distorting space-time would alter the patterns of constructive and destructive interference that form when the two light waves recombine. Gravitational waves squeeze space in one direction while stretching it in the other, making the LIGO detector with its arms splayed at right angles doubly sensitive: one arm of the interferometer should lengthen and then shorten as a gravitational wave passes, while the other shortens and lengthens.

But forget a hair's breadth. A standard-issue gravitational wave will expand and contract LIGO's arms by just 10^{-19} metres, a distance one ten-thousandth the width of a proton.

If you ever saw a movement that small in just one place, you could never be sure that it wasn't just an innocuous blip, so just as with Weber's bars, LIGO-Hanford is one of a pair. Its twin is 3000 kilometres away down by the bayou in Livingston, Louisiana. See the same signature in one and 10 milliseconds later in the other (the time it would take a wave to travel between the two) and then you would be talking.

Or perhaps not: to make that delicate a measurement, every possible disturbance, every tiniest reverberation that might put things out of kilter must be suppressed. Only absolute silence will do.

Winter's first cold snap has hit as I arrive at Hanford, Rattlesnake looming to my left as I drive along Highway 240. The still-warm surface water of the Yakima river flowing alongside is evaporating and condensing, making the river look like a steaming hot spring. Every shrub and tree lining the river is covered in fine frost, a picture-postcard of winter stillness.

Parts of the Hanford nuclear site count as some of the most contaminated spots on Earth, dotted with underground tanks containing leftover plutonium, uranium, caustics and acids. Jokes abound of radioactive rabbits roaming the site. For LIGO, though, the problem is the 18-wheeler clean-up trucks that bump along the gentle undulations of Highway 240. "That's a big low-frequency whomp into the Earth," says Mike Landry.

Vibrations of air or earth is noise that might throw the LIGO instrument "out of lock". It is a phrase I hear often from Landry, a rugged but soft-spoken Canadian physicist who came to Hanford in 2000 and never left. After a decade working on the basic instrument, he is overseeing an upgrade due to be ready at the end of the year. Like almost everyone else at LIGO, he spends his days preoccupied by noise.

To increase the detector's sensitivity, light is made to bounce back and forth

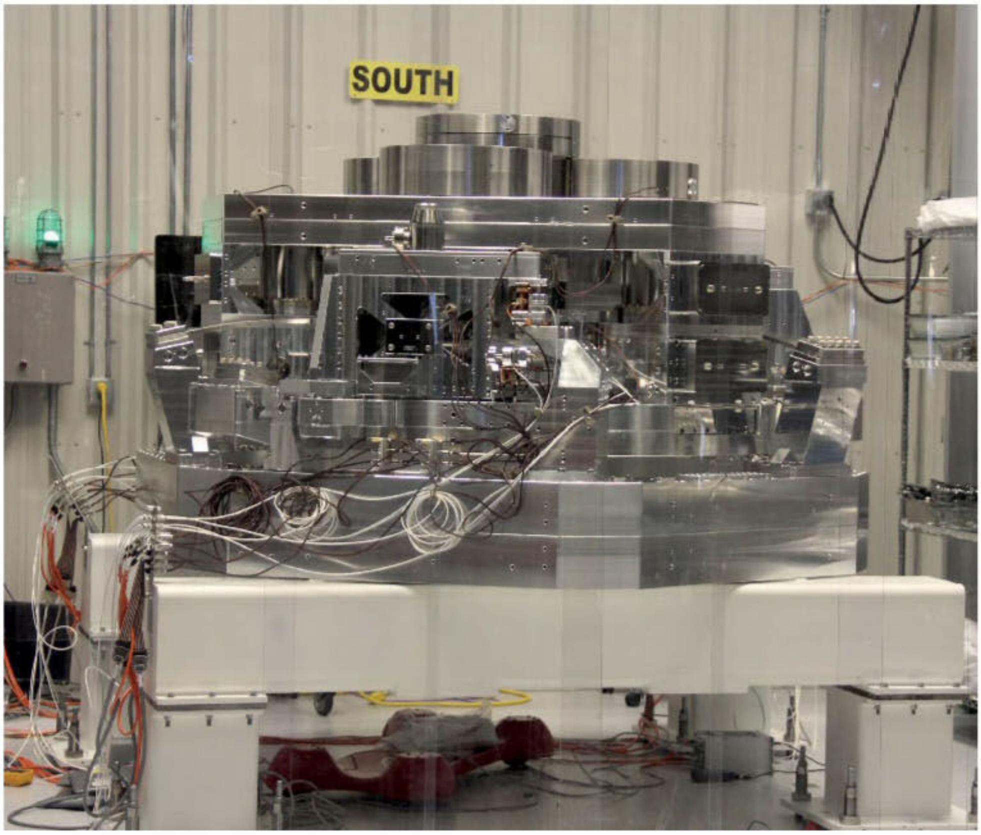
many times along the interferometer arms. In the upgraded "Advanced LIGO", the aim is for 100 reflections, making each 4-kilometre arm effectively 400 kilometres long. For that to work, the reflecting mirrors must be held unerringly still.

The world conspires against that in an almost literal sense. The problems start with Earth's ceaseless seismic groans. Then there are the distortions of its surface caused by the moon's changing gravitational pull as it orbits. That alters the length of LIGO's arms by about a tenth of a millimetre every 12 hours – a tiny amount, perhaps, but huge compared with what a passing gravitational wave is expected to be capable of. But this source of noise is, at least, predictable, and the frequency of the laser entering the interferometer, and the distance between its mirrors, is continuously adjusted to compensate for the passage of the tides.

The mirrors themselves hang free on wires of fused silica barely a millimetre thick, isolating them from motions of the ground as far as possible. A befuddling stack of blade springs and pendulums helps to filter out high-frequency noise. Servo motors pitch, roll and yaw the entire 5-tonne stack to counter lower-frequency ground motions. They are a product of harsh lessons learned in the early days of LIGO-Livingston, where the low-frequency din of heavy machinery working at logging sites in the surrounding forests was a constant and unpredictable bugbear. "It was like a continuous cacophony of noise punctuated by some falling trees," says Landry.

His catalogue of unexpected and irritating noises is long. Mysterious, irregular, Doppler-shifted acoustic noise at LIGO-Hanford coincided with arrival and departure times at Richland airport some 20 kilometres away. Then there were the times every few nights in spring when a mysterious noise would roll to a sudden crescendo and ebb away slowly – the rumble of rushing meltwater released from nearby dams. Sometimes, the sources of noise were neither local, nor obvious. "When we were running, we saw storms in the North Sea," says Sandberg. "We certainly see storms when they hit the coast at Seattle."

For LIGO, Hanford's winter stillness is only skin-deep.



A bulky outfit is needed to protect LIGO's mirrors from the noisy world outside

I never saw LIGO's mirrors, each one a refulgent 40-kilogram disc of highly polished fused silica. "If you move around them, you see this beautiful florid display of colours," says Sandberg. "They are gorgeous."

It is no mean feat to get the mirrors to that state. A company in Los Angeles first gives their surfaces a super-polish to make them glassy. Near San Francisco, material is etched away molecule by molecule so they assume the required curvature to within the width of an atom of silicon. From there, they are flown to France, where the surfaces are given a final coating to constrain the thermal jiggling of the mirror's molecules to known frequencies. They vibrate together rather like the ringing of a crystal wine glass – just another source of noise to take into account.

"And what do we do with them?" says Sandberg. "We put them in a vacuum tank where no one will ever see them again." LIGO's mirrors and laser beams are protected within the largest volume of ultra-high vacuum anywhere below near-Earth orbit. About 10,000 cubic metres of it ensure that no stray molecules deflect the laser beams as they dart back and forth. The price of my entering even the vicinity of this vacuum is to stick my shoes in a rotating scrubber to rid them of dirt, slip on overshoe covers and cover my head in a bouffant-style cap, the better to contain my own unruly molecules.

"Our asset," says Sandberg, "is a whole lot of nothing."

In the cliché of the Wild West, tumbleweed blows where a whole lot of nothing is going on. At Hanford, it skitters frequently across the steppe and piles up against LIGO's concrete arms, creating a fire hazard. Besides noise, catching tumbleweed and baling it like hay is a constant preoccupation.

In theory, the basic LIGO detector was sensitive to waves from standard sources up to 65 million light years away. After a decade of operations in which no hint of a gravitational wave was seen, we now at least have an upper limit on how large such waves can be. (The presumed double-star system source spotted by Taylor and Hulse back in 1974, though in cosmic terms nearby, is rotating so slowly that its signal frequency is well below the threshold of LIGO's hearing. Just before its two stars finally coalesce its chirping should become audible to gravitational wave detectors on Earth, but that is not expected to happen for another 300 million years or so.)

The Advanced LIGO detector will extend its cosmic reach tenfold, and the volume of space it can search a thousand-fold – a huge leap in this game of statistics. The past decade has also served to tame or characterise all known sources of conventional, or classical, noise that might move its mirrors and mimic or hide a gravitational-wave signal, from seismic disturbances to the thermal jostling of molecules. If a gravitational wave passes it will be seen, says Landry with quiet confidence. "We are not looking to push down upper limits any longer. The goal now is detection."

Not so fast, says the quantum world. ›

"The mirrors and laser beams are protected by the largest volume of ultra-high vacuum anywhere below near-Earth orbit"

Laser light will ping back and forth 100 times down LIGO's arms for each measurement

Einstein never liked quantum theory. Even as he as posed for his picture with the stalwarts of quantum mechanics at the Solvay conference, he was arguing against their favoured depictions of reality as an arena governed by rules of chance. Over the years, that sentiment only grew. "God does not play dice with the world," he took to saying.

In this Einstein seems to have been wrong. The quantum world is rife with dice-throwing deities. At the heart of our relationship with it lies a principle whose validity Einstein debated over decades with Bohr: quantum uncertainty.

According to the uncertainty principle, there are pairs of properties in the quantum world that we can never know simultaneously with complete accuracy. Position and momentum form one such pair: the better we know where a quantum particle is, the less we know where it is going. Energy and time are another. This sounds ominous for LIGO, since knowing the precise timing and energies of photons pinging on mirrors is the key to catching a gravitational wave.

Odder still, the noise of uncertainty smears not just light, but also its absence. A gravitational wave's passage will ultimately be traced in the patterns of light and dark fringes where LIGO's two laser beams recombine and interfere constructively and destructively. When there is no wave, the darkness should be complete. But quantum uncertainty says that even in darkness there will be light. The quantum fluctuations of the vacuum of space-time will generate photons where there should be none, and obscure the subtle shifts of light and shade that signal a passing wave.

So even when every source of noise in the classical world has been identified and accounted for, the effort to find the missing piece of Einstein's relativity might ultimately be limited by the theory he struggled to accept. "I find it somehow a very beautiful twist of fate," says physicist Nergis Mavalvala of the Massachusetts Institute of Technology. "It's kind of a poetic injustice, if you will."

The physicist Carlton Caves first understood this bizarre quantum noise in the early 1980s, and showed how you might eliminate some of it. Uncertainty does not limit how much we can know about single quantities, but pairs of them in tandem, so it implies a certain elasticity. If you need to measure a photon's time of arrival, for example, you might constrain its uncertainty by agreeing to know less about its energy.

That is perfectly doable: starting with one photon you can squeeze it to make two whose uncertainty is concentrated in one of a pair of properties, allowing the other to be measured almost noise-free. Even odder, in theory at least you can do the same thing not to a photon of light, but to an absence of one. Gradually reduce the stream of light entering a squeezer to nothing, and a squeezed field of nothing will emerge from the other end, a vacuum whose nothingness has been manipulated in just the way you wanted. "It's a pretty remarkable thing," says David McClelland of the Australian National University in Canberra. "It's almost like magic; it's vacuum but it's not." A few years back, his team actually built a nothing squeezer. By shining squeezed vacuum onto a photodetector, they reduced the detector's intrinsic noise to below its natural floor.

"The effort to find the missing piece of Einstein's relativity may ultimately be limited by the theory he struggled to accept"

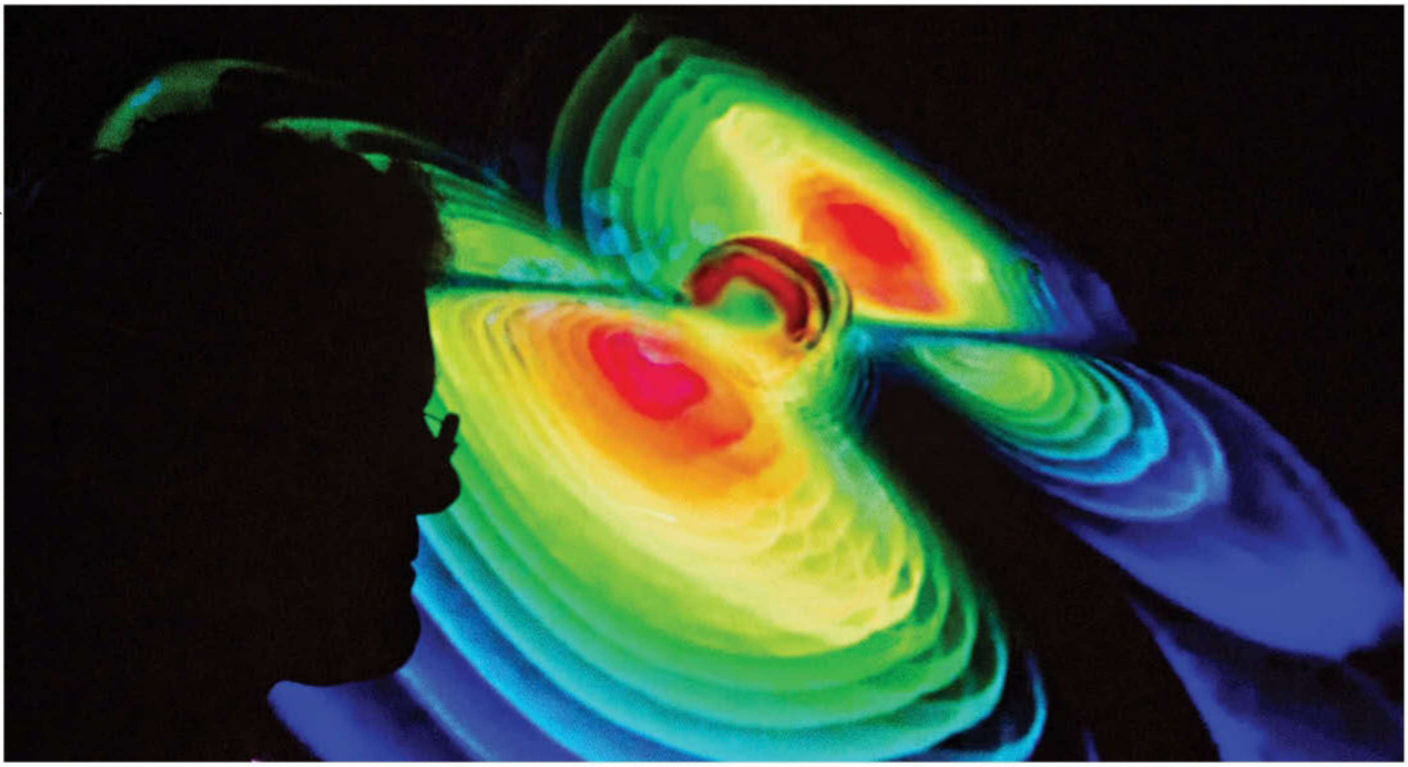
"This is beyond spooky, right?" says Mavalvala. Together with her MIT colleague Sheila Dwyer, she has since sent squeezed vacuum into the LIGO interferometer, and seen its quantum noise drop, too. The detector becomes quieter than nothing.

It will be a while before squeezed light regularly enters the LIGO vacuum. Then, when the surrounds are quieter than quiet, our ear may finally be attuned to the gravitational whispers of space-time. Sandberg hesitates before letting his mind savour the implications. "We'll be able see what goes on right up to the event horizon of a black hole, we'll be able to see details inside of a neutron star exploding," he says.

He pauses, unable to think up things more fantastic. "I am too impoverished in my imagination, and so is everybody else at this point, to figure what we are really going to see with this stuff, and what we are going to use it for," he says. "It really will be exciting. It'll represent over a 100 years' worth of damn hard intellectual effort to try to figure out what the hell is going on with the most fundamental aspect of the relationship between matter, energy and fundamental concepts of distance and space. I can't think of anything deeper and more profound."

The floods of Native-American lore may never return to Hanford's plains. But perhaps soon, we will become aware of a different sort of wave crossing them. That first detection will be an epochal event, says McClelland. "It will be like being able to hear for the first time." ■

JULIAN STRATENSCHULTE/DPA/CORBIS



Catching a wave

Two black holes became one

The detection of gravitational waves has opened a new window on the universe, say Joshua Sokol, Lisa Grossman and Jacob Aron

ON 11 February 2016, the Laser Interferometer Gravitational-Wave observatory, or LIGO, announced it had spotted gravitational waves, the stretching and squeezing of space-time caused by the movement of massive objects.

The announcement caused a sensation among physicists and astronomers across the world, and they quickly geared up to exploit this new window on the universe. "There's going to be a revolution," said Erik Katsavounidis of the Massachusetts Institute of Technology, one of the team behind the long-awaited discovery.

Gravitational waves will allow us to explore fundamental physics, examine the weirdest objects in the universe and possibly even peer back to the universe's earliest moments. "We can potentially see almost all the way to the big bang," says Dejan Stojkovic of the State University of New York in Buffalo.

The signal was picked up by LIGO's two observatories in Hanford, Washington, and Livingston, Louisiana, on 14 September 2015. It was created by two black holes colliding, each about 30 times the mass of the sun. The details of the signal suggest they circled each other closer and closer until they finally merged.

This immediately resolved one open question for astronomers. Before the signal came in, the very existence of such black hole binaries was contested. Because they are dark, black holes of these masses are almost impossible to spot unless something bright – like a star – orbits them.

The next target is to observe gravitational waves from the death spiral of two neutron stars. Unlike black holes, which hide their mass behind an event horizon even as they crash, colliding neutron stars spew hot, bright matter across space, which could help us explore other mysteries. For example, studying these explosions may explain short gamma-ray bursts – mysterious and incredibly bright electromagnetic phenomena. They might also help explain where much of the universe's heavy elements, like uranium, thorium and gold, are forged.

LIGO should soon be sensitive enough to detect gravitational waves from any neutron star mergers that happen within the nearest 300,000 galaxies. That means we should see about one signal per month.

These single event detections are just the start, however. Put several together and we should be able to get new insights into the history and composition of the universe as a whole, says Avi Loeb of Harvard University. The signals from a number of black hole mergers, for example, can be combined to help understand the nature of dark energy, which is causing the universe's expansion to accelerate. ›

From the "shape" of the signal – how the waves' frequency and volume rise and fall – we can discern the sizes of the black holes involved, and determine how loud the event was at its source. Comparing how powerful it really was to the faint vibrations LIGO detected tells us how far away it occurred. Combined with observations from standard telescopes, this can tell us how space has expanded during the time the waves took to reach us, providing a measure of dark energy's influence.

This measure should be stronger and more reliable than anything we have used so far. Spotting just a few black hole mergers would change everything, Loeb says. "If you have tens of them, it will be a new branch in cosmology."

Other researchers are hoping to use gravitational wave signals to put Einstein's general theory of relativity to even more stringent tests. One way is through the equivalence principle, an assumption that gravity affects all masses in the same way (see page 86). "In the age of GPS and space travel, where even minute deviations from the assumed theory of gravity would have major consequences, it is of enormous importance," says Xue-Feng Wu of Purple Mountain Observatory in Nanjing, China.

Erminia Calabrese, an astronomer at the University of Oxford, sees gravitational waves as a way to check whether gravity behaves as relativity predicts it should over large distances. "If their strength fell off with distance in a surprising way we could detect this with the upcoming LIGO data," she says.

More detectors

LIGO's success could see an explosion in gravitational wave detection. India, for example, has long been slated to host a third LIGO detector. Funding has yet to materialise, but after the discovery, Indian prime minister Narendra Modi tweeted that he hopes "to move forward to make even bigger contribution with an advanced gravitational wave detector in the country".

Other types of detectors could come on the scene, too. "Now that we know gravitational waves exist, it will be much easier to convince people to invest money and make all kinds of gravitational wave detectors," Stojkovic says.

New designs are already in the pipeline. The European Space Agency has been testing equipment for the Evolved Laser Interferometer Antenna (eLISA), a huge, space-based detector. A preparatory experiment, LISA Pathfinder, is already in orbit.

CALTECH/LIGO

LIGO has a big reach

Further ahead, we might see more sensitive gravitational wave detectors, working at shorter wavelengths than LIGO. These may allow us to sense primordial gravitational waves from the very young universe. These waves should have been produced in the period of inflation – the tremendous growth spurt in the first instants after the big bang. Unlike photons and other electromagnetic radiation, they would have travelled freely through the newborn universe. At the moment we can only see as far back as 380,000 years after the big bang, when the universe became transparent to light.

Gravitational waves may even point the way toward a grand unified theory of the universe. Theory suggests that at some point in the universe's history, all four fundamental forces were united into a single force. As the universe expanded and cooled, the forces split off from one another in a series of as-yet poorly understood events. "Gravitational wave observatories that can detect much shorter wavelengths could probe those," Stojkovic says.

For now, physicists already have a mystery to solve: a faint gamma-ray burst that seems to be related to LIGO's signal. No one expected merging black holes to give off gamma rays. "Everything lines up except the physics," says Valerie Connaughton of NASA's Marshall Spaceflight Center.

LIGO team member Daniel Holz at the University of Chicago reckons this surprise is just the beginning. "Every time we've opened a window to the universe, we've found all sorts of unexpected things," Holz says. "I'd be surprised if I wasn't surprised." ■

HOW THEY SAW IT

"It's hard to describe; after years of dreaming about this, writing all these papers saying, 'Maybe we could even see two big black holes collide, it would be phenomenal!' And here it is."

Daniel Holz, LIGO team member

"It's been a very long road, but this is just the beginning. Now that we have detectors able to detect these systems, now that we know that binary black holes are out there, we can begin listening to the universe."

Gabriela Gonzalez, LIGO spokesperson

"What we've learned: LIGO works, black holes exist, black holes collide, new black holes are born, general relativity works. Need I keep going?"

Nergis Mavalvala, LIGO team member

"The era of gravitational wave astronomy is under way."

Avi Loeb of Harvard University

"This is truly marvellous! It opens a whole new window onto observing the universe, as well as further confirming Einstein's general theory of relativity."

Russell Hulse, co-recipient of the 1993 Nobel prize in physics for his discovery of indirect evidence of gravitational waves

"It's a fabulous discovery. It will be a rich source of information."

Alan Guth of MIT, one of the authors of the theory of inflation

EVERYTHING YOU WANTED TO KNOW ABOUT THE DISCOVERY OF THE DECADE

The historic detection of gravitational waves, announced in February 2016, left *New Scientist* with an unprecedented postbag of questions from readers.

We put a selection of them to gravitational wave expert Martin Hendry of the University of Glasgow, UK, who is a member of the LIGO collaboration that made the discovery

I feel slightly let down by the tiny "chirp" that signalled the gravitational wave – it seemed rather insignificant for an event as momentous as the merger of two black holes. Why was it so brief?

Over the past decade or so, our theoretical understanding of general relativity has improved a great deal, allowing us to calculate the precise pattern of gravitational waves the theory predicts such a merger would create.

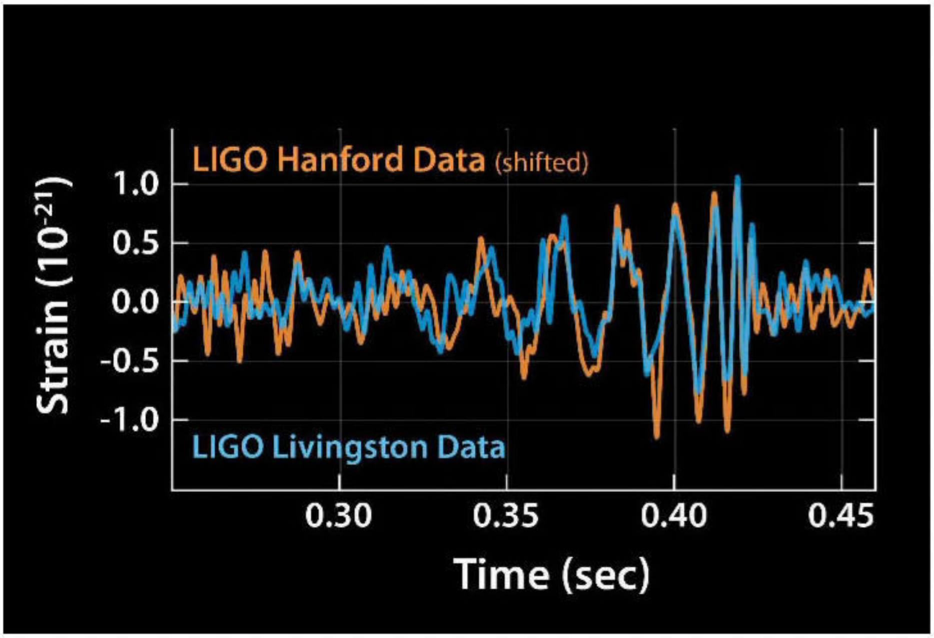
The gravitational waveform produced by the black holes as they spiralled towards each other and finally merged would have lasted for many millions, perhaps even billions of years. This waveform is very distinctive, and features a pattern in which both frequency and amplitude increase as the black holes approach each other, orbiting ever faster. Remarkably, however, it was only within the final second that the signal reached high enough frequencies and high enough amplitudes for LIGO to detect it, above the general background noise from other non-cosmic sources.

I mean noise in a quite literal sense: the gravitational wave frequencies to which LIGO is sensitive are frequencies that our ears can hear. So we can take the signal and turn it into sound waves – as indeed our collaboration spokesperson Gaby Gonzalez showed when she broke the news of the discovery. This sound file first translates the frequencies of the gravitational wave signal to the identical audio frequency, and then shifts the audio frequencies upwards by a few hundred hertz. The second representation is analogous to how, for example, astronomers working with the Hubble Space Telescope might use false colour on their images to better bring out contrast. It is somewhat easier to hear the chirp in the shifted representation, but with good quality speakers or headphones it should be audible in the first, un-shifted representation too.

Surely the universe must contain many other sources of gravitational waves. If so, then how much information can actually be gathered from the chirp? Could the signal just be the end result of interference from multiple other as-yet-unknown sources?

We believe that the universe does indeed contain very many sources of gravitational waves. In fact, we estimate that an event like the one we detected occurs somewhere in the universe every 15 minutes. But most of these sources are very far away and the waves from them spread out in all directions, meaning they are far too weak to be detected by the time they reach Earth. That is why it took 100 years from Einstein's predictions of gravitational waves for us to have instruments with the sensitivity necessary to make the first detections.

The other aspect is that space-time is ›



CALTECH/MIT/LIGO LAB

This is what a ripple in space-time looks like

A very big instrument to detect minuscule fluctuations

incredibly stiff: that's why you need a cataclysmic event like the merger of two black holes to produce a distortion that we can measure. In turn it means that gravitational waves interact only very, very weakly with matter. That is another factor that makes them difficult to detect, but it also means that they will pass virtually unimpeded through everything they encounter. This includes our LIGO interferometers: we were able to detect the presence of GW150914, as we called the signal, but we extracted virtually none of its energy, and it just carried on its merry way almost completely unaffected.

The upshot is that we do not generally expect gravitational waves to be attenuated or absorbed by intervening matter, or to exhibit interference effects, or to be otherwise affected in ways that would render them difficult to interpret. Although the signal we detected was incredibly weak, it was a pristine representation of the waves emitted by the source, unaffected by its 1.3 billion year journey to us. This is one of the main reasons why gravitational wave astronomy offers such exciting prospects: we will be able to use gravitational waves to probe regions of the universe that would be completely inaccessible using light signals alone.

How does the gravity of large bodies like the sun, Earth or black holes warp space? If space is a vacuum, what is there for gravity get hold of?
This is a very interesting question. There is a phrase, originally attributed to the physicist John Wheeler, that is often used when describing general relativity: "space-time tells matter how to move and matter tells space-time how to curve". This phrase captures the essence of Einstein's big idea:

"The signal tells us about the graviton – the quantum particle of gravity"

that we should not think of gravity as a force between massive bodies, but as a curving or bending of space-time itself.

However, Wheeler's phrase does rather side-step an even deeper question: how is it that matter "tells" space-time how to curve? To fully answer this we need to understand something about the fundamental nature of space-time. We expect that this will require linking general relativity and the weird rules of quantum physics as they apply to the vacuum of empty space.

We don't yet have such a description, but we do know that the quantum notion of "empty" space involves a bubbling mass of virtual particles that pop in and out of existence.

Future observations of gravitational waves may lead to further insights about how a quantum gravity theory would work. In truth, though, for most of the sources that LIGO will see, our measurements should be perfectly consistent with the general relativity description. Our data won't have the detail or resolution necessary to allow us to investigate many aspects of quantum gravity.

That said, our results can already be used to constrain aspects of those quantum gravity theories by putting limits on the mass of the graviton, the hypothetical quantum particle of gravity.

When people talk about distorting space-time, what does it distort into? If I distort a (more or less) 2D piece of paper, it moves into a third dimension. So do gravitational waves require more than three dimensions of space and one of time? Is this a dumb question?
This isn't a dumb question at all. It relates closely to a broader question that cosmologists have wrestled with over the past century, often phrased as "if space is

ENRICO SACCHETTI

expanding, what's it expanding into?" The short answer is that it doesn't have to be expanding into anything!

We often use a 2D metaphor for the expansion of space, thinking about how, for example, dots on the surface of a balloon appear to move apart as the balloon inflates. Here, the 2D surface of the balloon is the counterpart of our three dimensions of space. Of course, from the three dimensions that we inhabit, we can see the balloon is expanding into that third dimension. But the crucial point is that we can still tell something about the 2D surface while being completely embedded within it.

To elaborate, by looking at the properties of those dots on the surface and how curved lines and angles behave as the balloon expands, we can distinguish its surface from that of a flat piece of paper, without needing to think about any higher dimensions.

This is what we call the intrinsic curvature of the balloon's surface. In a similar way, the changes in the curvature of space-time that produce gravitational waves can be characterised in terms of the intrinsic curvature of space-time – without requiring us to think about a higher dimensional "surface".

What's in these waves that are coming across 1.3 billion light years of space at the speed of light? Is it like electromagnetism – where we talk about waves, but really it's particles called photons? Does the discovery tell us that particles of gravity must exist – and that they must be massless like photons?

The analogy with light and electromagnetism is very interesting. About 150 years ago, James Clerk Maxwell devised a set of equations that predicted the existence of electromagnetic waves propagating at the speed of light. That was what physicists today call a classical field theory, and it works very well for longer-wavelength electromagnetic waves such as radio waves. It was only through considering shorter wavelength, higher frequency light – such as visible light, ultraviolet and X-rays – that a quantum description emerged in the early 20th century, leading to the notion of photons.

> "Space-time is very stiff: you need a cataclysmic event to produce a distortion"

General relativity, Einstein's theory that predicts gravitational waves, is a classical field theory like Maxwell's. And just as we can regard radio emissions as waves and not as photons because of their long wavelength, the gravitational waves that we detected were of sufficiently long wavelength that we could regard them as waves. In the future, we hope to be able to detect gravitational radiation with shorter wavelengths – where the wave-like description starts to break down and we would need to consider it in terms of particles of gravity: gravitons.

The idea that gravitational waves travel at the speed of light is hard-wired into general relativity. Our observations of GW150914 did not allow us to put tight constraints on the speed of the gravitational waves, but the time delay between the arrival of the signal at the two LIGO detectors is consistent with them travelling at the speed of light.

If so, and if the waves are at some level made of particles, then those particles would have to be massless. That's all speculation with the data we have for the moment, but our results can already be used to put an upper limit on the graviton's mass, because a very massive graviton would affect the shape of the waves predicted by general relativity for the merger of two black holes. ■

LIGO strikes again

The age of gravitational wave astronomy is truly here, says **Lisa Grossman**

Another one in the bag

ON 15 June 2016, the team at the Laser Interferometer Gravitational Wave Observatory (LIGO) announced that they had caught another set of ripples in space-time produced by the death spiral of a pair of black holes. This second detection confirmed that we are officially in the era of gravitational wave astronomy.

"This gives us confidence," said Salvatore Vitale at the Massachusetts Institute of Technology, one of the LIGO team. "It was not just a lucky accident. Seeing a second one tells us clearly that there is a population of black holes there, and we will see a lot of them."

The LIGO team had already made history in February 2016 when they announced the first detection. Einstein predicted that gravitational waves would be produced when massive objects like black holes move around. Dubbed GW150914, the signal arrived at twin detectors in Hanford, Washington, and Livingston, Louisiana, on 14 September 2015.

The detectors picked up the minuscule stretching of space-time spurred by the collision of a pair of black holes about 30 and 35 times the mass of the sun, 1.3 billion light years away.

The second signal, called GW151226, was detected on 26 December 2015. It also came from a pair of black holes merging. But these were much lighter – about 14.2 and 7.5 times the mass of the sun. They merged to form a black hole of 20.8 solar masses, meaning about 1 solar mass of energy radiated away in gravitational waves during the collision.

"This event radiated the equivalent of the mass of our sun in a couple of seconds," Vitale says. "Our own sun radiated about a millionth of its mass in 5 billion years. This really gives you the scale of how violent and sudden this release of energy is, as compared to our everyday experience."

If you could see it, the collision would be 10,000 times brighter than a gamma-ray burst, the brightest explosions we know of in the universe, says Avi Loeb at Harvard University.

Those smaller masses are reassuring, because they fit squarely in the 5 to 20 solar mass range of black holes, the kind already observed with X-ray telescopes. Those black holes usually pair up with ordinary stars, and we can see the disc of hot gas that accumulates around the black hole as it steals material from its companion.

"The fact that they detected lower mass black holes brings it closer to mainstream astronomy, where such black holes are often seen," Loeb says. "It establishes gravitational wave astronomy as a field."

"When we made the first discovery, it was kind of surprising because they have zero overlap with the known distribution of black holes," Vitale says. "Now we are back on two black holes with masses that are totally compatible with what we expect. It's nice to see that we can target a similar population."

It also meant that LIGO watched more of their deadly waltz. The black holes in the first event were so massive that they swung around each other less than 10 times before merging. In the second collision, the team watched 55 full orbits before the end.

But the signal from the smaller black holes was also more difficult to detect. The first one was so powerful that you could see it in the data with the naked eye. You could even hear it: translating the signal into sound waves gave a "chirp", a rise in pitch and volume as the black holes circle each other faster and faster.

This new one required more targeted algorithms and sophisticated processing, to tease the signal out of the noise.

"The first event was so loud and so screaming in the data, it was found by algorithms that just looked for anything really, not particularly binary black holes," Vitale says. "For this one it was important to know we were looking for compact binaries."

"If you tried to make a chirp out of the data

THE G-WAVE THAT STOLE CHRISTMAS

LIGO saw its second signal at 03:38:53 UTC on Boxing Day 2015, which was still 25 December in the US. "It was a Christmas gift," says team member Salvatore Vitale.

That means its discovery was a bit of a lucky break, as there had been some debate among the team whether to keep the detector running over the holidays.

It was especially awkward timing for Vitale. When the first signal arrived in September, he was visiting family in Italy. As part of the front-line team studying the signal , his holiday was abruptly cut short by frantic data analysis.

"Obviously my time there was totally destroyed by the first event," he says. The team was sworn to secrecy, so he couldn't even tell his parents what had happened.

"I had to just say, it's important, but don't worry, I will make it up to you at Christmas," he says. "The morning of the 26th, I woke up, and this is what happens. This teaches you a lesson: never check your email the morning of the 26th."

WILLIAM WIDMER/REDUX/EYEVINE

all you would hear is 'ksshhhhhhh'," says LIGO team member Nergis Mavalvala, also at MIT.

Regardless, seeing more cycles makes this system a better laboratory to test Einstein's theory of general relativity.

"If there is any small deviation from general relativity, it will accumulate," Vitale says. "If you have more cycles you have a better hope to see if there is something wrong." So far, the event matches general relativity perfectly.

The team also measured a new attribute of the black holes: one of the behemoths was spinning slowly.

Measuring spin is a way to probe how the black holes formed. If they came from a pair of stars that both exploded and became black holes together, they ought to spin in the same direction. If they were already black holes when they found each other in a dense environment like a globular cluster, they should not.

More detections will help gauge the size of the universe, probe the nature of matter and test general relativity to ever higher precision.

"These are the kinds of things we want to do, and we can hardly do them in any other way," Vitale says.

But we will need a lot more signals to answer such questions.

"The significance of this paper is it establishes a population, rather than a single example," says Loeb. "There is a big qualitative difference between having one data point and having two. I look forward to improving the statistics." ■

The ultimate target:

Primordial gravitational waves

WHEN the champagne has been on ice for nigh on a century, the corks pop all the louder. So it was when physicists at the Advanced LIGO experiment announced the detection of a gravitational wave passing through Earth (see page 63). That was indeed a triumph – but what about the ones that got away?

LIGO's first catch emanated from two black holes falling into each other's arms. LIGO is being upgraded to make it even more sensitive (see page 70) but that still won't open its eyes to everything astronomers want to see.

For starters, mergers of bigger black holes, such as the supermassive ones thought to sit at the centres of mature galaxies (see page 49), will emit gravitational waves with much longer wavelengths than the ones LIGO has already detected. "LIGO will not be sensitive to them," says astronomer Avi Loeb of Harvard University. "We need different observatories."

A planned space-based detector known as eLISA should be sensitive to these waves, and a test probe for this project, LISA Pathfinder, blasted off in December 2015.

But even eLISA won't detect the most eagerly sought-after gravitational waves of all. Our most cogent, but untested, model of the universe's birth in the big bang suggests space-time underwent a period of breakneck expansion known as inflation, sending out extremely low frequency gravitational waves with wavelengths perhaps as big as the visible universe.

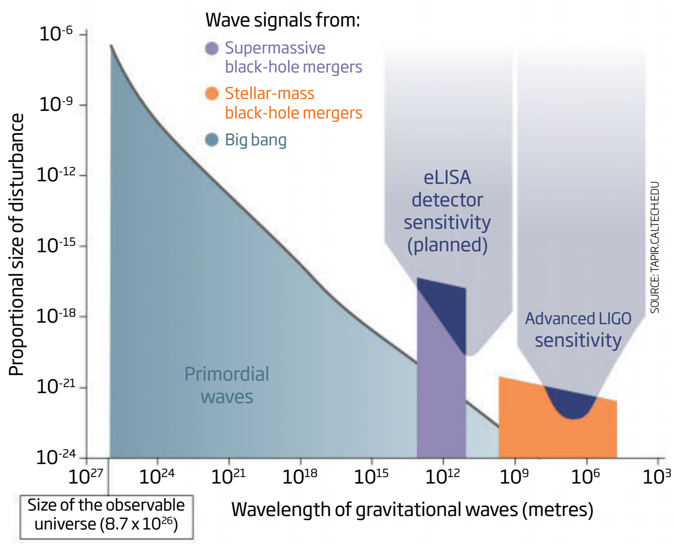
No detector yet conceived is large enough to sense these "primordial" gravitational waves (see diagram, below), so evidence is likely to be indirect.

Back in March 2014, researchers at the BICEP2 experiment at the South Pole thought they had found that indirect evidence in patterns of light polarisation in the cosmic microwave background. That proved to be a false alarm – but last year's detection of gravitational waves from a black hole collision provides a fresh spur to think how we might detect these echoes of creation, says Loeb.

Richard Webb

Signals from the big bang

The Advanced LIGO and eLISA detectors have the sensitivity to spot gravitational wave signals from black holes combining – but "primordial" waves created in the big bang have far bigger wavelengths



Next move for cosmic wave-hunter

Having sighted gravitational waves, LIGO has much more up its sleeve, says **Lisa Grossman**

GET ready for gravitational waves: the sequel. In 2016, the LIGO collaboration announced its groundbreaking detection of two sets of gravitational waves produced by colliding black holes. Now the team is preparing for their next feat: spotting ever fainter cosmic sources of these waves.

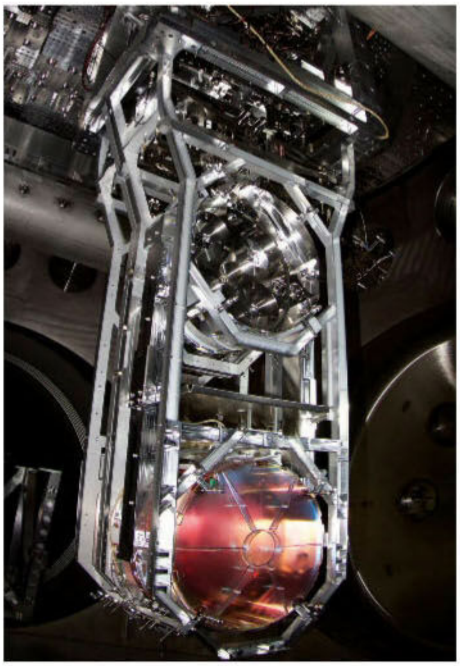
Although recently upgraded to become Advanced LIGO, the Laser Interferometer Gravitational-Wave Observatory isn't at full strength yet. When it is, it will be able to measure changes in distance as small as one-ten-thousandth the width of a proton. But there are several hurdles to overcome first, not least the laws of physics.

LIGO's twin detectors, one in Washington state and one in Louisiana, are L-shaped tunnels 4 kilometres long. To pick up the stretching and squeezing of space-time, physicists shine a laser down each arm to reflect off a mirror at the end. When the beam returns to the detector's elbow, they recombine it with the light from the other arm to see if the beams are still in phase, meaning they went the same distance. If not, they have caught a gravitational wave.

But to be sure of this, every wobble of the tunnels must be accounted for. That includes tiny movements caused by the ocean, the rumble of passing cars, even the laser itself.

One strategy is to keep the mirrors away from the ground. "The noisy ground is producing a very steep limit to our sensitivity," says Katherine Dooley of the University of Mississippi in Lewis. "You get to a point where you can tell from the shape of the signal, oh, that's a train coming."

To counter this noise, the team suspend the mirrors from an isolated scaffold. They also measure the ground's motion with seismometers and nudge the mirrors in real time to cancel it out. But this can't distinguish


CALTECH/MIT/LIGO LAB

LIGO's mirrors are a suspended from an isolated scaffold that cuts out noise

between a quake shaking the mirrors and local effects that affect only the seismometers. A strong wind can tilt the building housing the seismometers, for example, leading to mirrors being nudged when they shouldn't be. So Dooley and her colleagues are working on suspending the seismometers from a scaffold as well. .

There's a more fundamental limit to LIGO's sensitivity: quantum mechanics. At higher gravitational wave frequencies, the Heisenberg uncertainty principle becomes a factor. It says that for certain pairs of properties, the more accurately you can measure one, the less accurately you can measure the other. For LIGO, the limiting properties are the brightness of the light that returns to the detector, and the phase of the light waves, which is what the team measure.

Surprisingly, there is a loophole. "We can never get around Heisenberg, but we can trick him," says team member Nergis Mavalvala at the Massachusetts Institute of Technology.

It turns out you can send the light through

"An instrument 10 times the size of LIGO could pick up gravitational waves from the first collapsed stars"

a special kind of crystal to "squeeze" it into favouring one property. In this case, they can reduce brightness to boost phase detection.

"It's a little bit magical," says Jonathan Cripe of Louisiana State University in Baton Rouge, who wants to use specialised micro-mirrors instead of crystals to do the squeezing. The team plans to include this and all the other possible fixes in an upgrade called A+, to happen in a few years' time.

Only a bigger detector can outdo A+. Physicists are already dreaming of one with arms 10 times as long as LIGO's. Tentatively called the Cosmic Explorer, it would pick up gravitational waves of much lower frequency arriving from much greater distances – potentially glimpsing the collapsed remnants of the very first stars.

In some ways, this is actually a modest undertaking, says Sheila Dwyer of the California Institute of Technology in Pasadena. With funding and a suitable site, we could build it today. "There's no assumption that technology would need to advance to make this happen," she says. ■

WAVE HELLO

The discovery of gravitational waves fulfilled a prediction made a century ago by Albert Einstein and was the culmination of decades of experimental work. We spoke to the researchers involved, and also got an insider's view of the detector that finally made the breakthrough.

*Interviews by **Daniel Cossins**. Photos of the LIGO experimental site at Livingston, Louisiana, by **Enrico Sacchetti***

In 1969, ***Rainer Weiss*** *was a young MIT professor. At the time, gravitational waves were a theoretical curiosity: Einstein himself took years to be convinced by his own prediction that moving cosmic bodies would send out ripples through space-time. Then physicist Joseph Weber claimed to have recorded one on a xylophone-like instrument he called a resonant bar detector. Weiss takes up the story.*

The students on my course were fascinated by the idea that gravitational waves might exist. I didn't know much about them at all, and for the life of me I could not understand how a bar interacts with a gravitational wave.

I kept thinking, well, there's one way I can explain how gravitational waves interact with matter. I said, suppose you take a light – I was thinking of just light bulbs because, in those days, lasers were not yet really there – and sent a light pulse between two masses. Then you do the same when there's a gravitational wave.

Lo and behold, you see that the time it takes light to go from one mass to the other changes because of the wave. If the wave is getting bigger, it causes the time to grow a little bit. If the wave is trying to contract, it reduces it a little bit. So, you can see this oscillation in time on the clock.

I was hiding in this little office in Building 20 at MIT and for about three months I thought about how you might do this. First I thought you couldn't get clocks good enough. But we did some experiments and I learned you could do unbelievably exquisite measurements with lasers.

I wrote this up but I didn't publish it. The people at MIT wanted to know where the hell I'd been spending my time, so I put it into the quarterly progress report for my lab. I came to the conclusion that, if you built this thing big enough, you could probably detect gravitational waves.

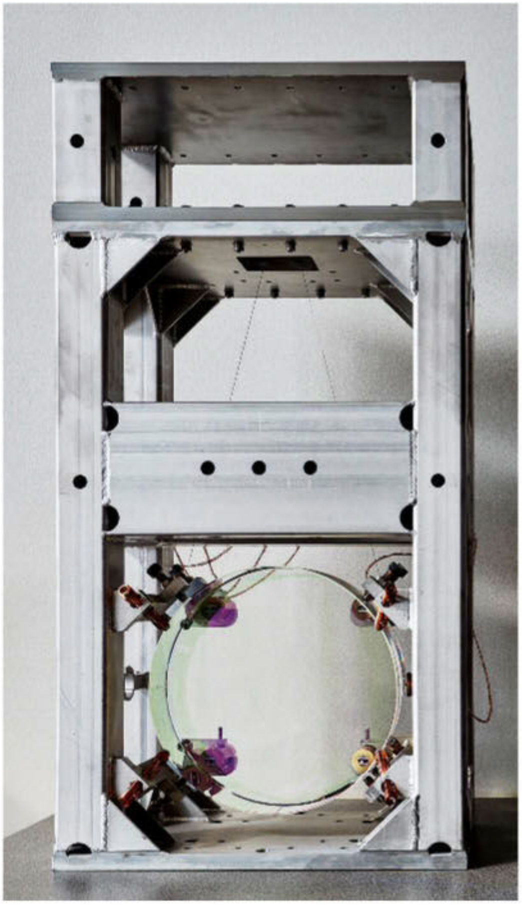
Above, left: The LIGO detector consists of two beam tubes at right angles to one another, each die-straight and 4 kilometres long. Within each tube, lasers ping back and forth many hundreds of times, reflected by mirrors at both ends

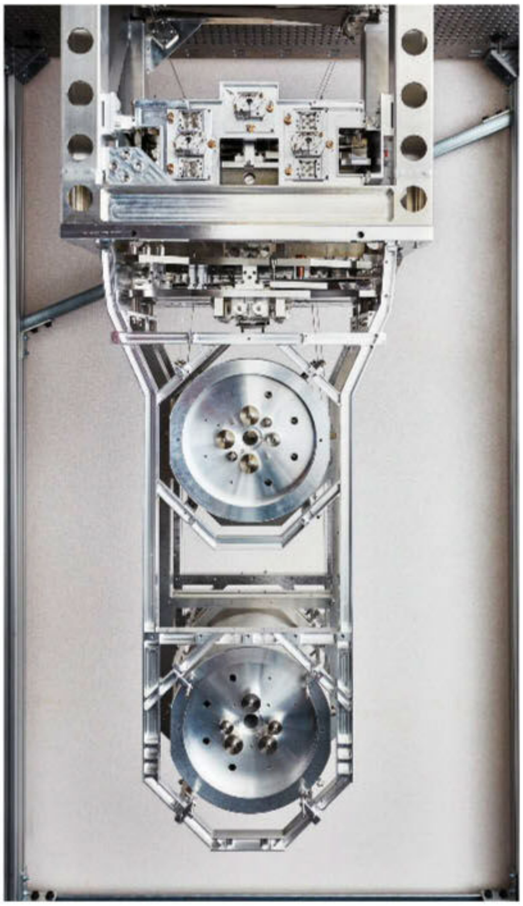
Above: The "vertex" where the two tubes meet. The laser beams are recombined here, and the interference pattern they create will change when a gravitational wave disturbs either beam

*Based on Weiss's idea, the US National Science Foundation (NSF) eventually began funding the development of what became the Laser Interferometer Gravitational Wave Observatory (LIGO) in 1979. But progress was slow, and when Caltech physicist **Barry Barish** took the lead on the project in 1994, questions were being asked*

The NSF had lost confidence and were basically giving up on it. There was a lot of resistance. It represented the extreme of what you might call a high-risk, high-pay-off project. So we revamped it entirely. Over a period of six months we made it look like a new project. And it was hard because if you had asked me then, could we build what we now know we need to detect gravitational waves, the answer would have been no.

So the idea, and the words that I used, was that with the initial version of LIGO it would be *possible* to detect gravitational waves. And then we would evolve into a detector, which we called Advanced LIGO, where it would be *probable*. But in all honesty, we had nothing more than ideas on how to do the Advanced LIGO part. To me, the miracle in this whole thing is that we somehow got financial support for 22 years until we succeeded.





LIGO's detectors occupy two sites in Livingston, Louisiana, and Hanford, Washington. Since joining the project in 2000, Hanford's lead detection scientist ***Michael Landry*** *has been ensuring the instrument is as sensitive as possible to the minuscule signals it was built to detect*

Space is a stiff medium, so it doesn't want to vibrate. The detector has to register changes that are about a thousandth the size of a proton. If you were trying to measure the distance between here and our nearest star, Proxima Centauri, it would be like watching that distance change by the width of a human hair.

It's an ongoing battle to suppress noise in the instrument. There are ground noises like earthquakes, but a less obvious example is Earth's ringing – at low frequencies, it rings like a bell because of ocean waves hitting against the continental shelf.

If you get storms off the coast of Alaska or the Gulf of Mexico, ground motions increase. We have to suppress that motion by registering it with seismometers and feeding it into seismic suppression systems – kind of the way noise-cancelling headphones work by sampling the ambient noise and then playing it with the right phase to cancel it out at your ear.

There are also a lot of internal noises that we have to suppress. Things like electronic noise, or quantum noise in the laser. All of that means the LIGO detectors are absolutely the most quiet and the most sensitive detectors ever built.

Above, left: LIGO's cylindrical mirrors are polished to nanometre precision to reflect the laser beams without absorption and ensure no surface roughness affects the detector's timing

Above: The ultrapure silica mirrors are suspended on glass fibres. Their suspension cage adjusts for the changing motions of the ground that might otherwise disturb the measurement

Above: The LIGO Livingston control room, where a distinctive "chirp" was recorded at 09:51 UTC on 14 September 2015. It lasted just a fraction of a second, but was registered almost simultaneously 3000 km away in Hanford – the expected signal of a gravitational wave travelling at light speed

In September 2015, just a few days after Advanced LIGO finally came on stream, ***Michael Landry*** *received notice of an unexplained signal. At first he was convinced it was an "injection" – an artificial pulse used occasionally to test the instrument*

On the morning of 14 September, I opened my computer and saw an email indicating this event seen in the data literally tens of minutes earlier. I thought, it's probably an injection. It was so early in the observation phase. It wasn't until later, in the lab, that we determined there was no such injection. We did a whole lot more investigation and it took months to validate it. But it was immediately obvious that if this thing wasn't an injection, it was the best damn thing we had ever seen.

The gravitational wave apparently came from the collision of two black holes, formed from collapsed stars, 1.3 billion light years away. For ***Rainer Weiss****, now 83 years old and a professor emeritus at MIT, it was a long-sought vindication*

The discovery itself was spectacular. To me, it was the thing that I would have wanted most, to see the collision of two black holes. If you want to ask, what was the reason for building this thing in the first place, it's to check up on whether Einstein's theory works in strong gravitational fields. That was the one place where general relativity had not been tested. And here, suddenly, we have in our hands a thing that says Einstein's field equations, the whole thing, is absolutely right.

For ***Nergis Mavalvala****, an MIT physicist who has worked on LIGO for 25 years, this detection is just the beginning*

I don't think this was some master plan from nature, as in "let's be nice to these people here on this little Earth place". Black holes collide all the time. What was lucky was that we happened to have a detector with sufficient sensitivity to see this one at the moment it went up. If we continue, we will see more.

One of the amazing things about general relativity is you solve the equations – although that's taken decades – and create templates for how signals should look. Nature was kind in that the very first signal we saw was so clear. Many people expected we would see really weak signals, barely poking above the noise, and that there would be a lot of discussion about whether it was a detection or not. None of that happened. That's where we lucked out.

The discovery drives us harder because we know there is stuff out there waiting to be observed. You might imagine we would think, "OK, now we've seen it we can pack up and go home". But in fact it's just the opposite. We've seen the very first gravitational wave, but we have so much more to discover.

We have a lot to learn about black holes, and then there are neutron stars. Personally, my hope is that we will see something that really has us scratching our heads. Maybe we will have discovered some new object that I can't begin to describe or name. ■

Relativity's next tests

Einstein's theory has stood up well for more than 100 years but still has some explaining to do, says Pedro Ferreira

GENERAL relativity has served us well. Yet what if Einstein was off the mark? Sure, the theory is remarkably successful at explaining many different phenomena: it allows us to calculate the orbits of all the planets of the solar system with extraordinary accuracy. It also enables us to work out how light is deflected by the deformed space-time around stars and planets. But could we have taken general relativity too far in attempting to predict the evolution of the universe?

It is a striking fact that general relativity has remained unchanged since Einstein first proposed it in 1915. At its heart is our understanding of the force of gravity. Einstein put forward the idea that there is no force of gravity per se. Instead, what we perceive as gravity results from the bending of the fabric of space-time.

That basic rule is with us today, and we have long been mining it, extracting predictions that range from black holes to the big bang.

One of the first predictions to emerge was the notion that the universe is expanding. This was spectacularly confirmed by Edwin Hubble in 1929 and, since then, ever improving observations have enabled us to unravel the history of the expanding universe with increasing precision.

Dark clouds

But there's the rub. If general relativity is correct, it has some explaining to do. That's because observations seem to indicate that the universe is not just expanding, its expansion is actually accelerating. This is not at odds with relativity: Einstein's theory suggests that there is something else out there, a form of energy that is pushing space apart. Two-thirds of the total energy budget of the universe must be made up of this elusive dark energy.

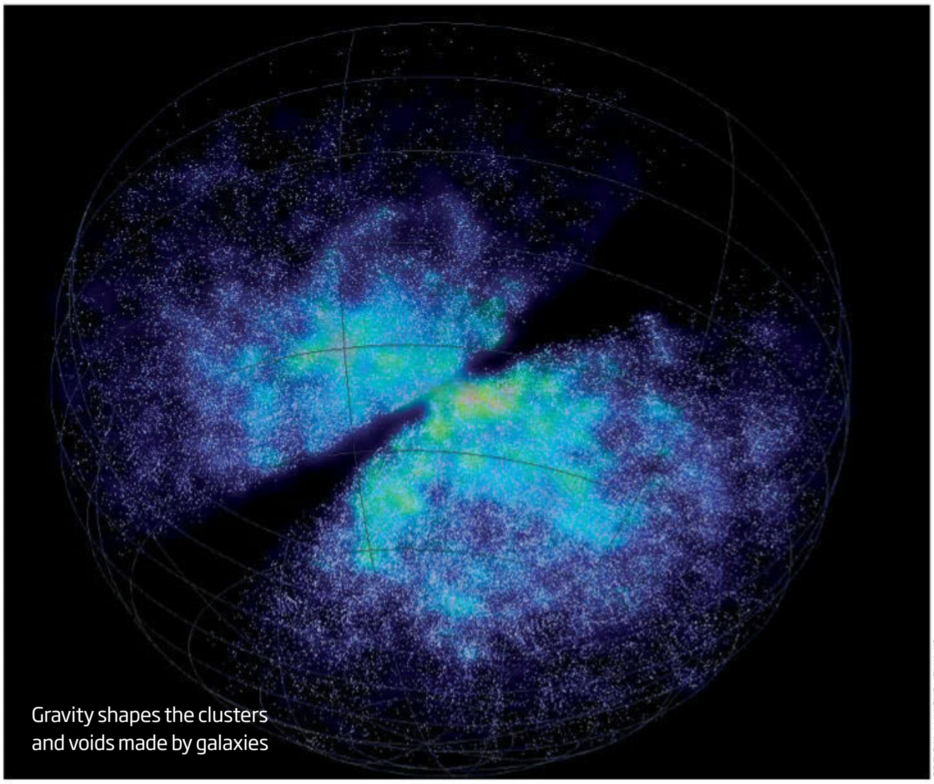
The problem is, our observations so far have found no indication of what dark energy is and what it was doing at different times in the history of the universe. It is possible that the concept of dark energy is concealing something fundamentally wrong with our notions of gravity.

So could we have reached the limits of Einstein's tremendous insight and be in need of some new theory? It would not be the first time that suspicions have been raised about general relativity's accuracy and completeness; luminaries such as Paul Dirac and Andrei Sakharov have questioned it (see "Replacements for relativity", right).

Despite the plethora of alternatives, Einstein's theory has remained the favourite. It is still by far the simplest and most elegant proposal for how space-time behaves. Furthermore, dark energy does seem to fit the wealth of cosmological data that we have accumulated over the past few decades.

The thing is, there is now a real possibility that we may actually be able to test Einstein's theory on the scale of the universe. In doing so, we might have to find a more powerful theory that subsumes general relativity or take one of the alternatives more seriously.

One possible way forward is to study in detail how large and complex structures grow in the universe. The current paradigm is that they are driven primarily by gravitational collapse, which is itself explained by general relativity: in areas where there are more galaxies, space will warp in such a way as to pull even more galaxies towards it, leading to massive concentrations of light and energy, in the form of clusters and superclusters. Conversely, empty regions of space will tend to become even emptier, resulting in cosmic



Gravity shapes the clusters and voids made by galaxies

6DF GALAXY SURVEY/AAO

voids of gigantic proportions. The tapestry of full and empty regions form what has become known as the cosmic web.

The last few decades have seen an explosion in our understanding of the cosmic web. Huge surveys of galaxies, such as the 2-degree-Field Survey and the Sloan Digital Sky Survey, have constructed detailed maps of the structure of the universe, identifying how the clusters, walls, filaments and voids are distributed around us. What's more, maps of the universe made at different wavelengths, including those supplied by the WMAP satellite and the Herschel space telescope, show how the cosmos looked at different times. So these should allow us to see how gravitational collapse has played a role at different epochs in the universe's history.

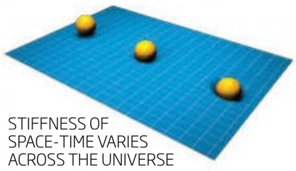
Given that the primary driver behind the cosmic web is gravity, it isn't surprising that the fine details of the web's structure and history may be used to search for deviations from general relativity. By studying how quickly it is evolving and by mapping out how the space-time around it distorts light rays, it should be possible to tease out even small discrepancies in how gravity behaves.

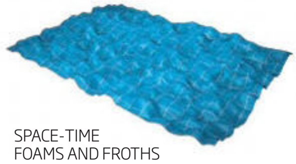
For now, general relativity is still the front runner as a theory of gravity. However, we can't yet rule out all of the alternatives.

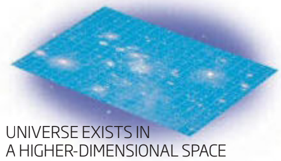
We have entered a truly exciting era as we start to look critically at one of the pillars of modern physics. Einstein's general theory of relativity underlies almost all modern discoveries in cosmology. But we now need to take a step back and check if we have been right all along, or if some different ideas are needed to truly understand how the universe is put together. ■

COMING UP NEXT:
Challenges to space-time pages 78 and 82;
The elephant in relativity's room page 86;
Where Einstein's gravity falls down pages 90 and 94;
How to banish dark energy page 98;
Intruders from another dimension page 101;
The quest for antigravity page 104

REPLACEMENTS FOR RELATIVITY


STIFFNESS OF SPACE-TIME VARIES ACROSS THE UNIVERSE


SPACE-TIME FOAMS AND FROTHS


UNIVERSE EXISTS IN A HIGHER-DIMENSIONAL SPACE

British theoretician Paul Dirac devoted a large part of his later life to cracking the complex structure of general relativity. He was puzzled by the extraordinary similarity between certain large numbers in the universe, such as why the size and total energy of the visible universe seemed to be related to the strength of gravity on Earth's surface. To Dirac, Einstein's theory was incomplete because it was unable to explain these coincidences; he felt there might be something more to gravity.

So in 1938, he proposed a change to general relativity. Although it would still be a theory of space and time, its strength could vary from place to place – as if the actual fabric of space-time had a different stiffness depending on where you were sitting. So a star in one place would bend space around it by a certain amount, while an identical star in a different area might warp space much more or less.

Dirac was able to do what very few have managed since – to sow the seeds for an alternative theory. It was later taken up by some researchers in the 1960s as a counterfoil to general relativity. Known as the scalar-tensor theory of gravity, it is actively studied to this day.

An altogether different idea was brewing in the Soviet Union in the 1960s. Physicist Andrei Sakharov conjectured that space and time would be much more warped and deformed on microscopic scales than predicted. His idea was simple: when we look at atomic and subatomic scales, quantum physics comes into play and this means that, much like children on a long car journey, nothing can keep still. Sakharov reasoned that we can apply the same principle to space-time itself and that if we were able to look at it on subatomic scales, it wouldn't look smooth but more like a froth, or a quantum foam.

Sakharov suggested that Einstein's theory would have to be changed if one took into account the frothy nature of space-time. While he was motivated by what happens on small scales, the past few years has seen a resurgence of the idea applied to all scales, even the very largest.

Another recent major development has been the idea that the universe may have more than three spatial dimensions. Although this was first suggested by Theodor Kaluza and Oskar Klein in the 1920s, it has been given a new lease of life thanks to developments in the field of string theory.

In 2001, New York University physicists Gia Dvali, Gregory Gabadadze and Massimo Porrati proposed that we live on a three-dimensional surface, known as a brane, within a higher-dimensional world called the bulk. All the fundamental forces we experience would be confined to the brane except gravity, which can leak out. Dvali and colleagues reasoned that gravity would be affected by what happens on the brane and in the bulk.

According to this picture, general relativity is still an accurate description of the gravitational force on the scale of the solar system, galaxies and even clusters of galaxies. But the intricate interplay between the bulk and the brane comes into effect when we look at the whole visible universe, and this can severely affect gravity. As a result, Einstein's theory is modified on very large scales.

Does some deeper level of reality lurk beneath Einstein's universe? Amanda Gefter investigates

Beyond space-time

IT WASN'T so long ago we thought space and time were the absolute and unchanging scaffolding of the universe. Then along came Albert Einstein, who showed that different observers can disagree about the length of objects and the timing of events. His theory of relativity unified space and time into a single entity – space-time. It meant the way we thought about the fabric of reality would never be the same again. "Henceforth space by itself, and time by itself, are doomed to fade into mere shadows," declared mathematician Hermann Minkowski. "Only a kind of union of the two will preserve an independent reality."

But did Einstein's revolution go far enough? Physicist Lee Smolin at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario,

LUKE BROOKES

Canada, doesn't think so. He and a trio of colleagues are aiming to take relativity to a whole new level, and they have space-time in their sights. They say we need to forget about the home Einstein invented for us: we live instead in a place called phase space.

If this radical claim is true, it could solve a troubling paradox about black holes that has stumped physicists for decades. What's more, it could set them on the path towards their heart's desire: a "theory of everything" that will finally unite general relativity and quantum mechanics.

So what is phase space? It is a curious eight-dimensional world that merges our familiar four dimensions of space and time and a four-dimensional world called momentum space.

"If Einstein's space-time is no longer something all observers can agree on, is it the true fabric of reality?"

Momentum space isn't as alien as it first sounds. When you look at the world around you, says Smolin, you don't ever observe space or time – instead you see energy and momentum. When you look at your watch, for example, photons bounce off a surface and land on your retina. By detecting the energy and momentum of the photons, your brain reconstructs events in space and time.

The same is true of physics experiments. Inside particle smashers, physicists measure the energy and momentum of particles as they speed toward one another and collide, and the energy and momentum of the debris that comes flying out. Likewise, telescopes measure the energy and momentum of photons streaming in from the far reaches of the universe. "If you go by what we observe, we don't live in space-time," Smolin says. "We live in momentum space."

And just as space-time can be pictured as a coordinate system with time on one axis and space – its three dimensions condensed to one – on the other axis, the same is true of momentum space. In this case energy is on one axis and momentum – which, like space, has three components – is on the other (see diagram, page 80).

Simple mathematical transformations exist to translate measurements in this momentum space into measurements in space-time, and the common wisdom is that momentum space is a mere mathematical tool. After all, Einstein showed that space-time is reality's true arena, in which the dramas of the cosmos are played out.

Smolin and his colleagues aren't the first to wonder whether that is the full story. As far back as 1938, the German physicist Max Born noticed that several pivotal equations in quantum mechanics remain the same whether expressed in space-time coordinates or in momentum-space coordinates. He wondered whether it might be possible to use this connection to unite the seemingly incompatible theories of general relativity, which deals with space-time, and quantum mechanics, whose particles have momentum and energy. Maybe it could provide the key to the long-sought theory of quantum gravity.

Born's idea that space-time and momentum space should be interchangeable – a theory now known as "Born reciprocity" – had a remarkable consequence: if space-time can be curved by the masses of stars and galaxies, as Einstein's theory showed, then it should be possible to curve momentum space too.

At the time it was not clear what kind of physical entity might curve momentum › space, and the mathematics necessary to make such an idea work hadn't even been invented. So Born never fulfilled his dream of putting space-time and momentum space on an equal footing.

That is where Smolin and his colleagues enter the story. Together with Laurent Freidel, also at the Perimeter Institute, Jerzy Kowalski-Glikman at the University of Wroclaw, Poland, and Giovanni Amelino-Camelia at Sapienza University of Rome in Italy, Smolin has been investigating the effects of a curvature of momentum space.

"Relative locality deals a huge blow to our understanding of the nature of reality"

The quartet took the standard mathematical rules for translating between momentum space and space-time and applied them to a curved momentum space. What they discovered is shocking: observers living in a curved momentum space will no longer agree on measurements made in a unified space-time. That goes entirely against the grain of Einstein's relativity. He had shown that while space and time were relative, space-time was the same for everyone. For observers in a curved momentum space, however, even space-time is relative (see diagram, below right).

This mismatch between one observer's space-time measurements and another's grows with distance or over time, which means that although space-time in your immediate vicinity will always be sharply defined, objects and events in the far distance become fuzzier. "The further away you are and the more energy is involved, the larger the event seems to spread out in space-time," says Smolin.

For instance, if you are 10 billion light years from a supernova and the energy of its light is about 10 gigaelectronvolts, then your measurement of its location in space-time would differ from a local observer's by a light second. That may not sound like much, but it amounts to 300,000 kilometres. Neither of you would be wrong – it's just that locations in space-time are relative, a phenomenon the researchers have dubbed "relative locality".

Relative locality would deal a huge blow to our picture of reality. If space-time is no longer an invariant backdrop of the universe on which all observers can agree, in what sense can it be considered the true fabric of reality?

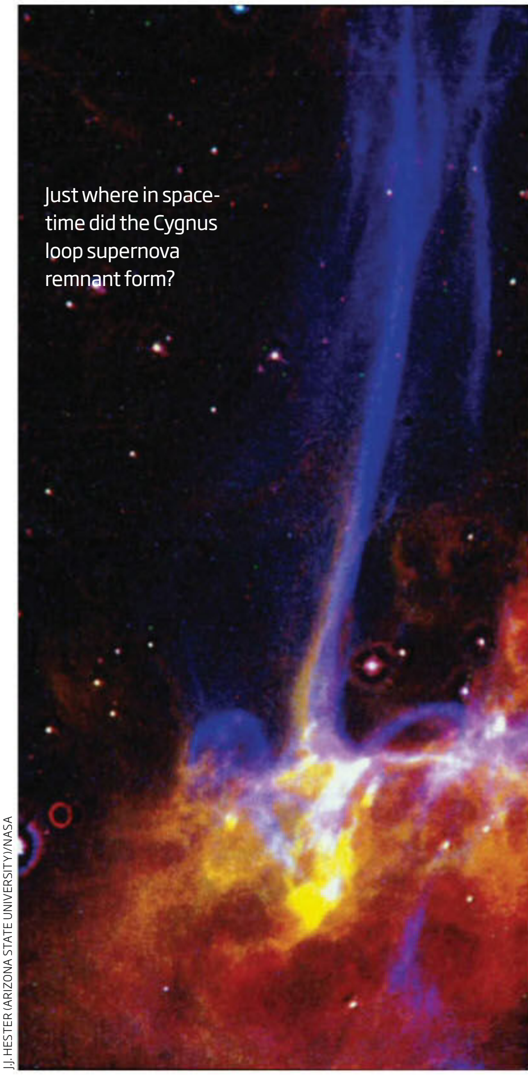
That is a question still to be wrestled with, but relative locality has its benefits, too. For one thing, it could shed light on a stubborn puzzle known as the black hole information-loss paradox. In the 1970s, Stephen Hawking discovered that black holes radiate away their mass, eventually evaporating and disappearing altogether. That posed an intriguing question: what happens to all the stuff that fell into the black hole in the first place?

Relativity prevents anything that falls into a black hole from escaping, because it would have to travel faster than light to do so – a cosmic speed limit that is strictly enforced. But quantum mechanics enforces its own strict law: things, or more precisely the information that they contain, cannot simply vanish from reality. Black hole evaporation put physicists between a rock and a hard place.

According to Smolin, relative locality saves the day. Let's say you were patient enough to wait around while a black hole evaporated, a process that could take billions of years. Once it had vanished, you could ask what happened to, say, an elephant that had once succumbed to its gravitational grip. But as you look back to the time at which you thought the elephant had fallen in, you would find that locations in space-time had grown so fuzzy and uncertain that there would be no way to tell whether the elephant actually fell into the black hole or narrowly missed it. The information-loss paradox dissolves.

Big questions still remain. For instance, how can we know if momentum space is really curved? To find the answer, the team has proposed several experiments.

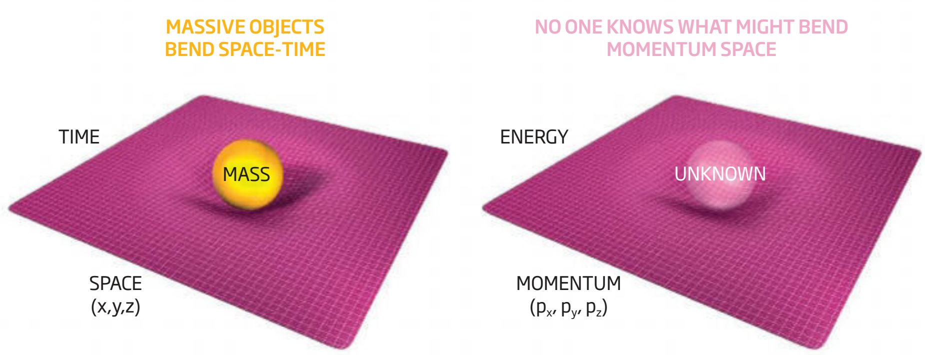
One idea is to look at light arriving at Earth from distant gamma-ray bursts. If momentum space is curved in a particular way that mathematicians refer to as "non-metric", then a high-energy photon in the gamma-ray burst should arrive at our telescope a little later than a lower-energy photon from the same burst, despite the

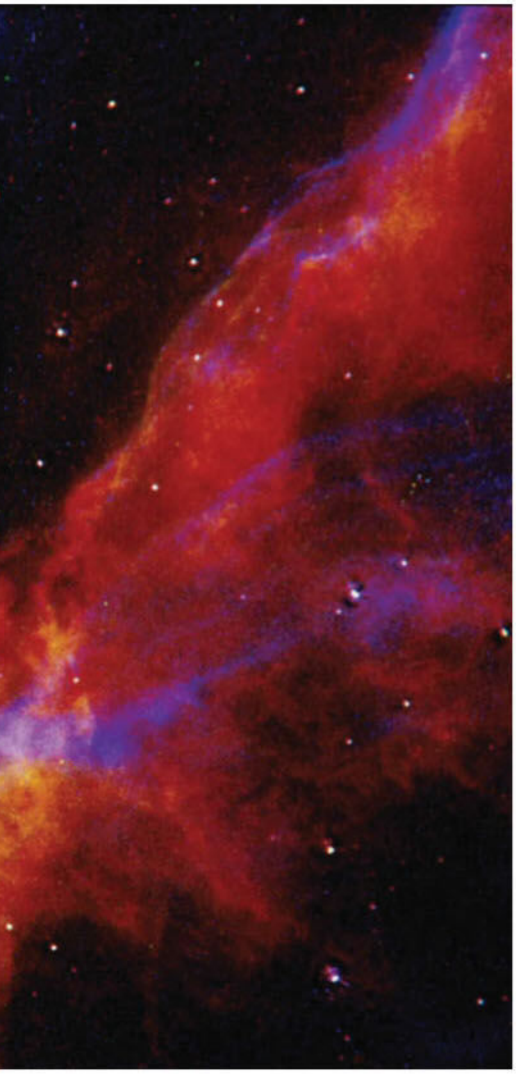

Just where in space-time did the Cygnus loop supernova remnant form?

J.J. HESTER (ARIZONA STATE UNIVERSITY)/NASA

Fabrics of reality

Space-time is like a malleable sheet with the three spatial coordinates on one side and time on the other. Momentum space is similar, with three coordinates of momentum and energy





two being emitted at the same time.

Just that phenomenon has already been seen, starting with some unusual observations made by the MAGIC telescope in the Canary Islands in 2005 (see page 82). The effect has since been confirmed by NASA's Fermi gamma-ray space telescope, which has been collecting light from cosmic explosions since it launched in 2008. "The Fermi data show that it is an undeniable experimental fact that there is a correlation between arrival time and energy – high-energy photons arrive later than low-energy photons," says Amelino-Camelia.

Still, he is not popping the champagne just yet. It is not clear whether the observed delays are true signatures of curved momentum space, or whether they are down to "unknown properties of the explosions themselves", as Amelino-Camelia puts it. Calculations of gamma-ray bursts idealise the explosions as instantaneous, but in reality they last for several seconds. Although there is no obvious reason to think so, it is possible that the bursts occur in such a way that they emit lower-energy photons a second or two before higher-energy photons, which would account for the observed delays.

In order to disentangle the properties of the explosions from properties of relative locality, we need a large sample of gamma-ray bursts taking place at various known distances. If the delay is a property of the explosion, its length will not depend on how far away the burst is from our telescope; if it is a sign of relative locality, it will. Amelino-Camelia and the rest of Smolin's team are watching carefully as more data come in.

The questions don't end there, however. Even if Fermi's observations confirm that momentum space is curved, they still won't tell us what is doing the curving. In general relativity, it is momentum and energy in the form of mass that warp space-time. In a world in which momentum space is fundamental, could space and time somehow be responsible for curving momentum space?

Work by Shahn Majid, a mathematical physicist at Queen Mary University of London, might hold some clues. In the 1990s, he showed that curved momentum space is equivalent to what's known as a noncommutative space-time. In familiar space-time, coordinates commute – that is, if we want to reach the point with coordinates (x,y), it doesn't matter whether we take x steps to the right and then y steps forward, or if we travel y steps forward followed by x steps to the right. But mathematicians can construct space-times in which this order no longer holds, leaving space-time with an inherent fuzziness.

In a sense, such fuzziness is exactly what you might expect once quantum effects take hold. What makes quantum mechanics different from ordinary mechanics is Heisenberg's uncertainty principle: when you fix a particle's momentum – by measuring it, for example – then its position becomes completely uncertain, and vice versa. The order in which you measure position and momentum determines their values; in other words, these properties do not commute. This, Majid says, implies that curved momentum space is just quantum space-time in another guise.

What's more, Majid suspects that this relationship between curvature and quantum uncertainty works two ways: the curvature of space-time – a manifestation of gravity in Einstein's relativity – implies that momentum space is also quantum. Smolin and colleagues' model does not yet include gravity, but once it does, Majid says, observers will not agree on measurements in momentum space either. So if both space-time and momentum space are relative, where does objective reality lie? What is the true fabric of reality?

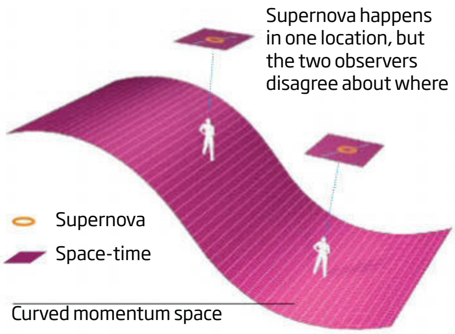
> "There would be no way to tell whether an elephant actually fell into the black hole or narrowly missed it"

Smolin's hunch is that we will find ourselves in a place where space-time and momentum space meet: an eight-dimensional phase space that represents all possible values of position, time, energy and momentum. In relativity, what one observer views as space, another views as time and vice versa, because ultimately they are two sides of a single coin – a unified space-time. Likewise, in Smolin's picture of quantum gravity, what one observer sees as space-time another sees as momentum space, and the two are unified in a higher-dimensional phase space that is absolute and invariant to all observers. With relativity bumped up another level, it will be goodbye to both space-time and momentum space, and hello phase space.

"It has been obvious for a long time that the separation between space-time and energy-momentum is misleading when dealing with quantum gravity," says physicist João Magueijo of Imperial College London. In ordinary physics, it is easy enough to treat space-time and momentum space as separate things, he explains, "but quantum gravity may require their complete entanglement". Once we figure out how the puzzle pieces of space-time and momentum space fit together, Born's dream will finally be realised and the true scaffolding of reality will be revealed. ■

Where's the supernova?

Observers in curved momentum space disagree about where in space-time an event such as a supernova takes place



SAM CHIVERS

Strange signals travelling from distant galaxies hint at turbulence for Einstein's theory of space-time, says **Stuart Clark**

Warning light

WE LIVE in an invisible landscape: a landscape that, although we cannot perceive it directly, determines everything that we see and do. Every object there is, from a planet orbiting the sun to a rocket coasting to the moon or a pencil dropped carelessly on the floor, follows its imperceptible contours. We battle against them each time we labour up a hill or staircase.

This is the landscape of space-time: the underlying fabric of the physical universe, perhaps of reality itself. Although we don't see its ups and downs, we feel them as the force we call gravity. Developed by the physicist Hermann Minkowski in the 20th century, and used by Albert Einstein in his general theory of relativity, space-time has become one of the most powerful concepts in all of physics.

> **"Space-time is the fabric of the universe, perhaps of reality itself. But no one knows what it is"**

There is just one nagging problem: no one knows what it is. Einstein envisaged space-time as a perfectly smooth surface warped by the mass of stars, planets and galaxies to produce gravity. But signals from a variety of celestial objects are hinting at something different. If the observations are confirmed – and they are controversial – they suggest that the landscape of reality is altogether more rugged than Einstein thought. That would mean his isn't the last word on space-time or gravity, and would change our perception of the universe fundamentally.

Before Einstein, space and time were thought to be separate properties of the universe. For Isaac Newton, they were a rigid framework of creation, and perhaps even some sort of embodiment of God – a "sensorium" through which He viewed the world – with gravity and movement the Almighty's will made manifest. For many, this strayed too far into the realms of maverick theology, and Newton's religious interpretations were soon sidelined. But few questioned the underlying science.

Only in the mid-19th century did it become clear that Newton's dynamics couldn't explain the subtleties of Mercury's orbital motion around the sun. Einstein's relativity could, but only by melding space and time into one mathematically indistinguishable whole, in which what happened to one also affected the other: the space-time continuum.

But although the mathematics of relativity describes space-time's properties very well, it is silent on its underlying nature. We are left to scratch around for observational clues. Everything in the universe, from the largest galaxy to the smallest particle, the dullest radio wave to the brightest ray of light, is immersed in space-time and so presumably must interact with it in some way. The question becomes whether those interactions imprint any signature that we might measure and interpret, and so see the true physical guise of space-time.

"This is a beautiful question, and we are at the beginning of answering it," says Giovanni Amelino-Camelia of the La Sapienza University of Rome in Italy.

In 2005, we seemed to have glimpsed an answer. MAGIC – the Major Atmospheric Gamma-ray Imaging Cherenkov telescope – is a series of giant receivers on La Palma in ›

Spain's Canary Islands tuned to detect cosmic light of the highest energy: gamma rays. On the night of 30 June, the array detected a burst of gamma radiation from a giant black hole at the heart of Markarian 501, a galaxy some 500 million light years away. This wasn't so unexpected. Our theories predict that every time something falls into such a black hole, a flare of radiation will be given off. But those large enough to be caught by an earthbound telescope, even a mighty receiver like MAGIC, are few and far between, and the Markarian flare was pretty much the first of its type to be seen.

Quantum foam

And detailed analysis revealed something decidedly unusual about the burst: the lower-energy radiation seemed to have arrived up to 4 minutes before the higher-energy radiation. This is a big no-no if space-time behaves according to Einstein's relativity. In relativity's smooth space-time, all light travels at the same speed regardless of its energy. But the effect was entirely compatible with other, rival theories that attempt to characterise space-time in terms of quantum mechanics – the theory entirely separate to, and incompatible with, general relativity that explains how everything besides gravity works.

In quantum theory, nothing is static or certain. Particles and energy can fluctuate and pop in and out of existence on the briefest of timescales. Many theories of quantum gravity – candidates for the "theory of everything" that will unify our descriptions of space-time and gravity with quantum mechanics – suggest something similar is true of space-time: instead of a smooth continuum, it is a turbulent quantum foam with no clearly defined surface. Einstein's undulating landscape becomes more like a choppy seascape through which particles and radiation must fight their way. Lower-energy light with its longer wavelengths would be akin to an ocean liner, gliding through the foamy quantum sea largely undisturbed. Light of higher energy and shorter wavelengths, on the other hand, would be more like a small dinghy battling through the waves.

In 1998, Amelino-Camelia and John Ellis, then at CERN near Geneva, Switzerland, had proposed that high-energy light from distant, active galaxies could be used to check for this effect. The huge distance would allow for even subtle effects to build into a detectable time lag. On the face of it, this was exactly what MAGIC had seen.

Things are seldom that simple in physics, and the MAGIC observations generated lively discussion. "Quite a musical," is how Robert Wagner of the Max Planck Institute for Physics in Munich, part of the team that made the initial observation, described it. When a similar gamma-ray telescope, HESS – the High Energy Stereoscopic System in the Namibian outback – caught sight of another giant galactic flare in July 2006, it was the perfect opportunity to test the theory. The galaxy in question, PKS 2155-304, is four times as far away from Earth as Markarian 501, so the time delay should have been even bigger.

But… nothing. "We saw no hint of a time delay," says Agnieszka Jacholkowska, one of the team analysing the signals who was then at Pierre and Marie Curie University in Paris, France. If we assume that space-time, whatever it may be, is probably the same everywhere, this suggests that the original time delay was something intrinsic to the source of the gamma rays in Markarian 501. It is conceivable, for example, that particles were accelerated along magnetic fields near the centre of the galaxy, which would naturally result in the emission of lower-energy gamma rays first. But since no one quite knows what processes take place in these dark galactic hearts, there was still plenty of room for debate.

And so things remained until 2013, when the most energetic gamma rays ever seen in our short history of observations hit Earth.

It was a gamma-ray burst (GRB): a short, intense flash of radiation not from the heart of an active galaxy but from the explosive death of a hypergiant star. GRBs are so bright that modern telescopes can see them across the entire universe, meaning that their light has travelled through space-time for several billions of years.

> **"Nothing is static or certain. Particles and energy can pop in and out of existence on the briefest timescales"**

Even so, the one observed by NASA's Fermi telescope on 27 April 2013 – known prosaically as GRB130427A – was eye-popping. It showered Earth with 10 times as many high-energy gamma rays as a run-of-the-mill burst, and included one gamma-ray photon that carried 35 billion times more energy than a visible photon. Automatic alerts were sent out to observatories across the world and within hours a battery of telescopes was scrutinising the burst's aftermath. One of the scientists alerted was Amelino-Camelia.

ALEX CHERNEY, TERRASTRO.COM/SPL

The following month, he and his colleagues circulated a paper claiming to see a time lag of hundreds of seconds between the burst's lower- and higher-energy gamma rays. "The numbers work out remarkably well. This is the first time there is robust evidence of this feature," says Amelino-Camelia.

Robust, because unlike the Markarian 501 observations, it was possible to match the arrival times of photons of various energies with those predicted by a simple equation. This relationship is pleasing to the mathematical eye and might also help us to see what lies beyond relativity if it is indeed broken: different variants of quantum gravity sketch different pictures of space-time and might have different effects on light.

In string theory, for instance, quantum space-time is a tangle of six extra dimensions of space, in addition to the usual three of space and one of time. Photons of different energies will propagate through this arrangement in quite a different way than is predicted in loop quantum gravity, another popular theory that

Has MAGIC seen signs of quantum space-time?

imagines space-time as a form of chain mail composed of interwoven loops.

The next stage is to see what predictions the time-delay equation makes about time lags in bursts of radiation from other sources. In their paper, Amelino-Camelia and his team report four other GRBs whose behaviour was consistent with the equation, although not conclusively. Others find no such evidence. Just days after Amelino-Camelia's paper came out, Jacholkowska and her colleagues published their analysis of four other, less energetic GRBs observed by the Fermi telescope. They found no hint of time lags.

In Jacholkowska's view we cannot draw any firm conclusions, because Amelino-Camelia's interpretation assumes, like the Markarian 501 analysis before it, that the gamma rays were emitted simultaneously regardless of their energy. This is always going to be a problem as long as interpretations are based on single observations of one type of source, Ellis says. "If you found an effect that was similar in two, you'd really begin to think you had found something," he says.

One test that might clear things up involves neutrinos. These ghostly particles travel at virtually the speed of light, interacting with hardly anything. Because they carry energy, however, they should interact with space-time, and, if Amelino-Camelia is correct, suffer an energy-dependent time lag – although one that is only measurable if we can find neutrinos that have travelled far enough.

"In string theory, quantum space-time is a tangle of six extra dimensions of space on top of the usual three"

That was always a problem. Nuclear fusion reactions make the sun such a prodigious neutrino factory that it washes out almost all signals from further away. Besides solar neutrinos, the only cosmic neutrinos ever seen have been from the supernova SN1987A, a star that just happened to explode in our cosmic backyard, in the Large Magellanic Cloud some 170,000 light years away. This is still too close for its neutrinos to manifest any measurable time lag.

Decisive help could now be at hand. IceCube is a neutrino detector buried in a cubic kilometre of Antarctic ice that came fully on stream in 2011. In April 2012, it found two neutrinos that set tongues wagging. Called, in a fit of whimsy, Bert and Ernie, after two characters from the TV show *Sesame Street*, they were far more energetic than those generated by the sun. For that reason alone, Dan Hooper of Fermilab in Batavia, Illinois, thinks it's likely that they come from a gamma-ray burst. "There aren't that many things that can make that amount of energy in a single particle. GRBs top the list," he says. In May 2013, IceCube announced the discovery of a further 26 neutrinos whose energies possibly betrayed an extragalactic source.

Amelino-Camelia thinks he has found three more in earlier IceCube data – ones that perfectly fit the idea of quantum space-time effects taking place. They all arrived from the general direction of three independently verified GRBs – but, if they are indeed associated with the bursts, got to Earth thousands of seconds earlier than the gamma rays.

Neutrinos are expected to escape from a collapsing star sooner than the light of a GRB because they don't interact, whereas the visible blast has to fight its way through the collapsing gas before speeding through space. But even taking this into account, Amelino-Camelia maintains that the huge size of the gap between the neutrinos and gamma-ray light is consistent with the different effects of a space-time interaction on them.

Ellis remains sceptical. "Every once in a while, somebody gets a little bit excited but I don't think there's any statistically solid evidence yet," he says. "One of the problems is that extraordinary claims require extraordinary proof, so you have to do something that is really convincing."

That will inevitably require larger telescopes capable of spotting more gamma rays and neutrinos more quickly. Wagner is involved in an international collaboration working on a giant successor to MAGIC and HESS. The Cherenkov Telescope Array will be 10 times as sensitive, and capable of seeing between 10 and 20 active galaxy flare-ups every year.

Will it finally open our eyes to the landscape around us? Those involved hope so. "There is no reason to be pessimistic," says Wagner. To find any kind of structure in space-time would be a revolution to rival Einstein's, and could show the way forward when physics is struggling to see its next step. "It would be hard to overstate how important that would be," says Hooper. ■

Our hopes of finding an ultimate theory depend on upsetting a balance that Einstein cherished, says Stuart Clark

Differently equal

COINCIDENCE is not generally something scientists have much truck with. If two things are genuinely unrelated, there is little further of interest to be said. If the coincidence keeps turning up, however, there must be some deeper underlying link. Then it is the job of science to tease out what it is and so explain why there was no coincidence in the first place.

That makes it rather odd that a large chunk of modern physics is precariously balanced on a whopping coincidence.

This coincidence is essential to the way we view and define mass. It is so fundamental to the world's workings that most of us encounter its consequences every day without giving them another thought. Yet it has vexed some of the best minds in physics for centuries. Galileo and Newton grappled with it and ended up just accepting it, rather than understanding it. Einstein went one better: he declared it a principle of nature. He went on to use this "equivalence principle" as the fundament of his general theory of relativity, still our best stab at explaining the mysterious force of gravity.

But there is a problem. If we want to find some bigger, better theory that can unify gravity with the other forces that dictate the world's workings, the equivalence principle cannot stay. We must either unmask this coincidence – or radically rethink how physics can progress from here.

There are many versions of the equivalence principle, but all boil down to one idea: that the effects of gravitational fields are indistinguishable from the effects of accelerated motion. A thought experiment of Einstein's expresses it best. Imagine a person standing inside an elevator on Earth. What keeps their feet firmly planted on the floor? The inexorable downward pull of gravity, of course. Now imagine the same person standing in the same elevator, but in empty space far from any gravitating object. In this case a rocket just so happens to be pushing the lift up in empty space with the same acceleration that Earth's gravity produces. The passenger will remain squarely on the lift floor in exactly the same way (see diagram, right).

How so, when there is no gravity involved? In this case, it is the person's inertia that is preventing them floating upwards. Inertia is the natural resistance of any body to acceleration – the same effect that pushes you back into your car seat when the driver puts their foot down.

The two elevator situations have a common property, mass. But the two masses come from very different places. One, gravitational mass, is something that responds to the pull of gravity, tending to accelerate a body in a gravitational field. The other, inertial mass, is the property of a body that opposes any acceleration.

"Gravity looks like a duck and swims like a duck – but it can't quite be made to quack like a duck"

Another way of stating the equivalence principle is to say that these two masses are always numerically exactly the same. The consequences of this coincidence are profound. If the two masses weren't the same, objects of different masses could fall to Earth at different rates, rather than all accelerating in the same way in a gravitational field. This "universality of freefall" was apocryphally first tested by Galileo dropping a bag of feathers and a bag of lead shot from the Leaning Tower of Pisa. In fact, the equality of gravitational and inertial mass dictates all gravitational motion throughout the universe. If gravitational mass responded just a little bit more to gravity than inertial mass does to acceleration, for example, then planets would orbit their stars and stars orbit their galaxies just a little bit faster than they do.

Yet there is no obvious reason why this correspondence should be so. It was only by assuming it was that Einstein fully developed the strange contortions and contractions of time and space he had introduced in his special theory of relativity in 1905. What if a massive object such as a planet, Einstein wondered, squeezes the surrounding space into successively more compact volumes the closer you get to it? As something moved towards the planet's surface, it would then take less and less time to cross these compacted spaces: it would appear to accelerate.

The odd force

By 1916, this thought had guided Einstein to his general theory of relativity. What looks like gravity is just uniform motion through a progressively compacted space. And if there is no gravity, gravitational mass is fictitious too. The only mass at work in the universe is the one that gives a body its inertia. The coincidence behind equivalence disappears.

General relativity is, as far as we have tested it, peerlessly accurate, predicting the positions of celestial bodies and guiding our satellites with minute precision. Yet there is something odd about it that physicists don't like. All the other forces of nature are transmitted between bodies by physical, if ethereal, quantum particles. The electromagnetic force, for example, is transmitted between bodies with electrical charge by the exchange of the massless particles called photons. Outwardly, gravity works in exactly the same way. It looks like a duck, swims like a duck – but it can't quite be made to quack like a duck.

Attempts to make gravity quack with a quantum voice are the guiding thought behind string theory and other projects to construct an all-embracing "theory of everything". But if gravity is to be reborn as a real force, it needs something to latch on to, just as electromagnetism latches on to electric charge. It needs a gravitational mass that is separate and distinct from inertial mass.

That means progress towards a theory of everything has an essential first step: slaying Einstein's holy cow. "Any theory of quantum gravity must violate the equivalence principle at some level," says Ben Gripaios, a theoretical physicist at the University of Cambridge.

How? One tried-and-tested method is to attempt to prove that the two masses aren't actually equivalent at all – just very, very close. Even the slightest sliver of a difference would mean that general relativity is built on an approximation and that a deeper, more precise theory must exist. "If someone finds a difference then we have made a major breakthrough," says Claus Lämmerzahl of the University of Bremen in Germany.

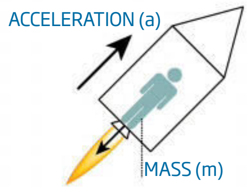
A way to do this is to continue on in the spirit of Galileo's Leaning Tower experiments, testing the universality of free fall and other consequences of the equivalence principle in the hope of teasing out some tiny anomaly – so far with little success.

Meanwhile, theorists are picking at a different thread. They point out that whether or not Einstein was right about there being no gravity, just inertia, no one has yet come up with a convincing explanation of inertia. "We do not yet know how to define it," says Gripaios. "We know it must be related closely to mass, but until we can define it precisely and know how to measure it, there can be no theory for it."

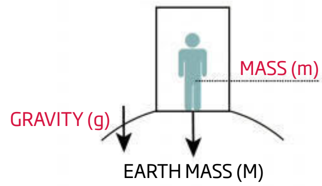
An enigmatic equivalence

Einstein's equivalence principle states that the physics of acceleration and gravity work in exactly the same way. But there's no reason why that should be the case

Accelerate a rocket in gravity-free space and a body's inertial mass will resist the motion



The mutual attraction between gravitational masses is what keeps our feet on the ground



In all situations

inertial mass ≡ gravitational mass

acceleration ≡ gravity

It's only by assuming the equivalence principle is true that we can explain that bodies at the same distance from Earth fall to the ground at the same rate

Newton's 2nd law of motion — Newton's gravitational law

(mass, acceleration; mass, Gravitational constant, Mass of Earth, Distance between body and centre of the Earth)

$$\textbf{force} = m \times a = m \times \frac{G\,M}{r^2}$$

If $m = m$

then $a = \dfrac{G\,M}{r^2} = g$

At a distance (r) from Earth's centre, the acceleration due to gravity (g) is ALWAYS THE SAME

One thing's for sure: it doesn't all come from the Higgs field, feted as the giver of mass. Evidence for the existence of this field and its associated particle was presented by physicists sifting through the debris of particle collisions at the Large Hadron Collider at CERN near Geneva, Switzerland, in 2012. But while the Higgs field is thought to give fundamental particles such as electrons and quarks their mass, when quarks combine into the heavier particles, protons and neutrons that make up the bulk of normal matter, the resulting mass is roughly a thousand times the summed mass of the constituent quarks. This extra mass comes not from the Higgs mechanism, but from the energy needed to keep the quarks together. Somehow, these two effects must combine and latch on to something else to create the property of a body's resistance to acceleration. "There is no way the Higgs alone can be some sort of mysterious ingredient that gives inertia," says Gripaios.

What then? One suggestion has its origins in work by Stephen Hawking in the 1970s. Ironically, it was motivated back then by a strict application of the equivalence principle. Hawking was investigating the properties of black holes, the unimaginably dense gravitating bodies whose existence is a central prediction of general relativity. He suggested that a black hole should be an apparent source of radiation, because pairs of quantum particles that constantly pop up in space would become separated close to a black hole, with one being sucked in and the other spat out. That led the Canadian physicist William Unruh and others to suggest that, if gravitation and acceleration really are one and the same thing, similar emissions should be a feature of any body accelerating in a vacuum.

If objects fall at different rates under gravity, the equivalence principle is broken

Nothing doing

Like Hawking's radiation, Unruh's has never been unambiguously detected. The accelerations necessary to achieve a measurable effect in a lab are generally too high, although some argue the effect has been seen with electrons accelerated in the high magnetic fields of particle accelerators.

A decade or so on from Unruh's original work, astrophysicist Bernard Haisch, then at the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, and electrical engineer Alfonso Rueda of California State University in Long Beach were playing with a similar idea when they realised the vacuum's interaction with an accelerating body would not just occur on its surface, but permeate its entire volume. That could produce a force that acts in the opposite direction to the body's movement. They originally likened it to the way in which charged particles moving through a magnetic field experience a force – the Lorentz force – that affects their motion. In this case there were electromagnetic interactions with the quantum vacuum. "It appears to be exactly what you need for inertia," says Haisch.

"By looking at the anomalous motions of most spiral galaxies, this mechanism could also explain dark matter"

Anomalous accelerations

Mike McCulloch of the University of Plymouth, UK, thinks such interactions are also just what you need to break the equivalence principle. One prediction made of Unruh radiation is that, like the rays emitted from a hot body, it comes in a spectrum of many different wavelengths. For very small accelerations, the temperature of the radiation that a body "sees" from the vacuum is low, and dominated by very long wavelengths. Make the acceleration very small indeed, and some of these wavelengths become longer than the size of the observable universe, effectively cutting them off.

In this case, according to calculations McCulloch did in 2007, originally to explain the seemingly anomalous accelerations of the Pioneer spacecraft as they crossed the solar system, the total amount of Unruh radiation experienced by a body would drop, and it would feel less of an opposing force. Its inertia would thus fall, making it easier to move than Newton's standard laws of motion dictate – and cutting the connection with gravitational mass.

The problem with this idea is testing it. In the high-gravity environment of Earth, accelerations small enough for the effect to be observed would not be easy to manufacture. But its effects might well be seen in a low-gravity environment such as that found at the edge of a galaxy. Indeed, looking at the anomalous motions of most spiral galaxies, McCulloch suggests this mechanism could also explain another enduring cosmic mystery – that of dark matter.

It's fair to say such ideas have not set the world alight. When Haisch and Rueda came up with their mechanism, NASA was sufficiently impressed to fund further study and the duo also attracted some $2 million in private investment. But the lack of testable predictions of how the effect might manifest itself led the money and interest to dry up.

Nevertheless, a traditionalist such as Lämmerzahl thinks we should not dismiss the idea out of hand. "Even though I follow more the ideas of string theory, these ideas of vacuum interactions are not nonsense," he says. "We need to look at them seriously and decide whether they give us new ways to test the equivalence principle."

One proposal to do that was made in 2010 by a trio of Brazilian astronomers led by Vitorio De Lorenci of the Federal University of Itajubá. They suggested using a spinning disc to cancel out the accelerations produced by Earth's rotation and its movement through space. At minuscule accelerations, the disc's inertia would drop, meaning it would spin faster than expected from Newton's laws. Despite a relatively modest cost, however, no money was forthcoming.

And so the deadlock remains until someone delivers either an experiment that exposes the equivalence principle as a sham, or a theoretical idea that shows why it must be just so.

But if in the end gravitational mass is indeed just inertial mass in another guise – whatever inertial mass is – then it will be the quantum theories of gravity, including string theories, that will find themselves laid upon the sacrificial altar. Paths to a theory of everything will become even more winding. If gravity is not a force, but truly an illusion that springs from the warping of space, we will have to look more closely to understand at a basic level what makes that warping come about.

Just a coincidence? This is one that science is not finding so easy to dismiss. ■

SMASH AND GRAB

The Milky Way's dwarf satellites were violently acquired – and that spells trouble for established ideas of gravity, says **Stuart Clark**

THE end of the Milky Way is already scheduled, and will be marked with fireworks. Some 4 billion years from now, the night skies will be lit by the glow of hundreds of billions of stars as the nearby Andromeda galaxy bears down on us. The two celestial giants will become one and stars, planets and gas clouds will be hurled into intergalactic space by titanic gravitational forces. Surviving stars and planets will be pitched into a jumbled cloud flaring up with new stars – floating into a long future not in the Milky Way, nor Andromeda, but a monstrous "Milkomeda" galaxy.

It's a well-established picture of our galaxy's cataclysmic future. More controversially, it might also be a vision of its past.

Observations indicate that the eviscerated remains of a past encounter between two celestial giants encircle our galaxy's neighbourhood. Forbidden alignments of satellite galaxies, globular clusters and streams of stars trailing in our galactic wake all hint that our local cosmic history needs a rewrite. And not only that: to explain what our telescopes are telling us, we may need to rethink that most mysterious of substances, dark matter – and perhaps our entire conception of how gravity works, too.

Like many big problems, this one started out small: in a strange configuration of tiny dwarf galaxies surrounding the Milky Way. In 2012, astronomer Marcel Pawlowski, then of the University of Bonn in Germany, dubbed it the "vast polar structure". This was for the way the dwarfs line up in a ring that circles the galaxy at right angles to the main disc of stars, which contains our sun and everything else.

But he was by no means the first to see it. That was Donald Lyndon-Bell of the University of Cambridge, who in 1976 pointed out that the satellite galaxies surrounding the Milky Way are not scattered randomly, but look as if something has corralled them into a distinct alignment. "They thought it could be the break-up of a larger galaxy, making it some form of debris stream," says Pawlowski. "There was an open discussion at the time, but then the topic became unpopular."

The thing that made it unpopular was the rise of dark matter. Dark matter became

TATIANA PLAKHOVA

"THE ALIGNMENT IS EXACTLY WHAT YOU WOULD EXPECT IF THE TWO GALAXIES HAD INTERACTED IN THE PAST"

a fixture in the 1970s to explain a glaring discrepancy between our standard cosmological models, rooted in the picture of gravity teased out by Newton and Einstein, and observations of reality. When astronomers measured the speed at which distant galaxies were rotating, they found these celestial bodies to be whirling round so fast they would fly apart if they relied only on visible matter's gravity to hold them together. This frenzied rotation could be explained if there were more to the galaxies than met the eye – if most of their matter were not made of conventional atoms, but of particles that did not interact with light and so were invisible.

Dark matter fitted ideas being floated by physicists studying the universe's rambunctious early years, before stars and galaxies formed. In this searing environment, a panoply of new particles would have popped up to carry forces and energy. As the universe expanded and its temperature dropped, these particles would have lost their potency and become an inert, invisible soup.

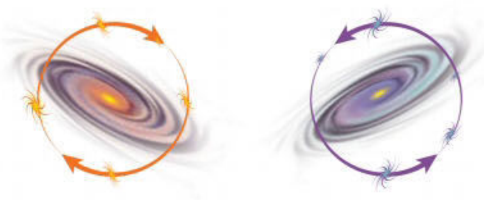
No one has ever detected or fabricated so much as a single particle of dark matter, yet its popularity has grown and grown. Our current standard model of cosmology has it outweighing normal matter by five to one. Existing in such quantities, dark matter not only explains galactic rotation, but also seems to be just the thing to allow galaxies such as the Milky Way to form. Tiny irregularities in the initial density of dark

When galaxies collide

An earlier encounter between two galaxies could be responsible for the strange ring of dwarf galaxies around the Milky Way

The close encounter of two galaxies rips off huge tails of gas

These tails coalesce to form dwarf galaxies in a ring at right angles to the main disc



matter caused pockets of the stuff, unimpeded by interactions with anything else, to begin to collapse under their own weight. This pulled in normal matter, which collapsed down into flat, spinning discs of matter – galaxies.

Simulations of this reproduce the observed form of galaxies like the Milky Way perfectly. Hot and cold spots we see in the cosmic microwave background, light sent pinging around the cosmos when it was just 380,000 years old, are interpreted as indicating the seeds of this process. And so we believe that galaxies today are surrounded by a cosseting "halo" of dark matter that generates gravity and keeps everything together.

Those same simulations show how, as dark matter collapses to form a galaxy halo, parts of it fragment, trapping in-falling normal matter and giving rise to a population of dwarf galaxies randomly scattered around the larger parent galaxy. So it is a bit of a problem that the Milky Way's dwarf satellites are by no means randomly scattered.

The huge success of the dark matter model meant most astronomers were content to turn a blind eye to this small embarrassment: the thought was we had simply not yet seen all the Milky Way's accompanying dwarfs. But in 2005, Pavel Kroupa, also at the University of Bonn, reanalysed the satellite galaxy data and confirmed the striking mismatch with dark matter theory.

Pawlowski, Kroupa's doctoral student, then went further. He studied the alignment of other objects in the halo of the Milky Way – spherical collections of stars much smaller than dwarf galaxies known as globular clusters, and long wispy trails of stars thought to form when dwarf galaxies break up. He found them marshalled just like the dwarf galaxies.

To explain it all, Pawlowski channelled Lyndon-Bell's original suggestion that it could be the debris of an intergalactic collision and looked to see what the fallout of such a collision might be. He investigated whether dwarf galaxies could indeed form from the stuff left behind when two galaxies interacted. Astronomers see quite a few such galactic dances throughout the universe throwing out huge tails of stars and gas into space. Pawlowski's simulations confirmed that the Milky Way's dwarf galaxies could indeed form in their observed positions following such an encounter (see "When galaxies collide", above right).

But what was it that danced with us?

There was no obvious candidate until 2013, when Rodrigo Ibata of the Observatory of Strasbourg in France and his colleagues published observations that showed a similar polar structure of dwarf galaxies exists around Andromeda, our nearest galactic neighbour some 2.5 million light years away. The dwarfs above the plane of Andromeda are moving away from us, while those at the bottom are heading towards us – convincing evidence that the disc is not a chance alignment, but a coherent, rotating structure. Andromeda's satellite disc is also rotating in the same sense as ours, and pointing at the Milky Way, albeit with a slight misalignment of about 35 degrees from our galaxy's polar structure. It is all exactly what you would expect if the two galaxies had interacted in the past.

Except they couldn't have done. Even counting their presumed dark matter haloes, Andromeda and the Milky Way simply don't have enough mass, and thus mutual gravity, to have pulled them into a collision in the time available since the big bang.

So it's a stalemate. Unless, that is, something is up with gravity. Newton's and Einstein's theories assume that gravity is a force whose strength declines with the square of the distance between two massive objects. That indeed seems to be the case on scales up to that of our solar system – the orbit of a body as far out as Pluto conforms to expectations. But it is an assumption we've never been able to test on larger scales.

The heretical idea that gravity's strength is not the same everywhere was proposed back in the 1980s as an alternative to dark matter. Known as MOND for "modified Newtonian dynamics", the idea was floated by Mordechai Milgrom, then at Princeton University in New Jersey. He found that the rotation of galaxies could be almost perfectly described if, in situations where the gravitational field is comparatively weak, its strength did not continue to decline with the square of distance, but flattens out. In such environments, for example in the outer reaches of galaxies, gravity will be stronger than expected (see diagram, below right).

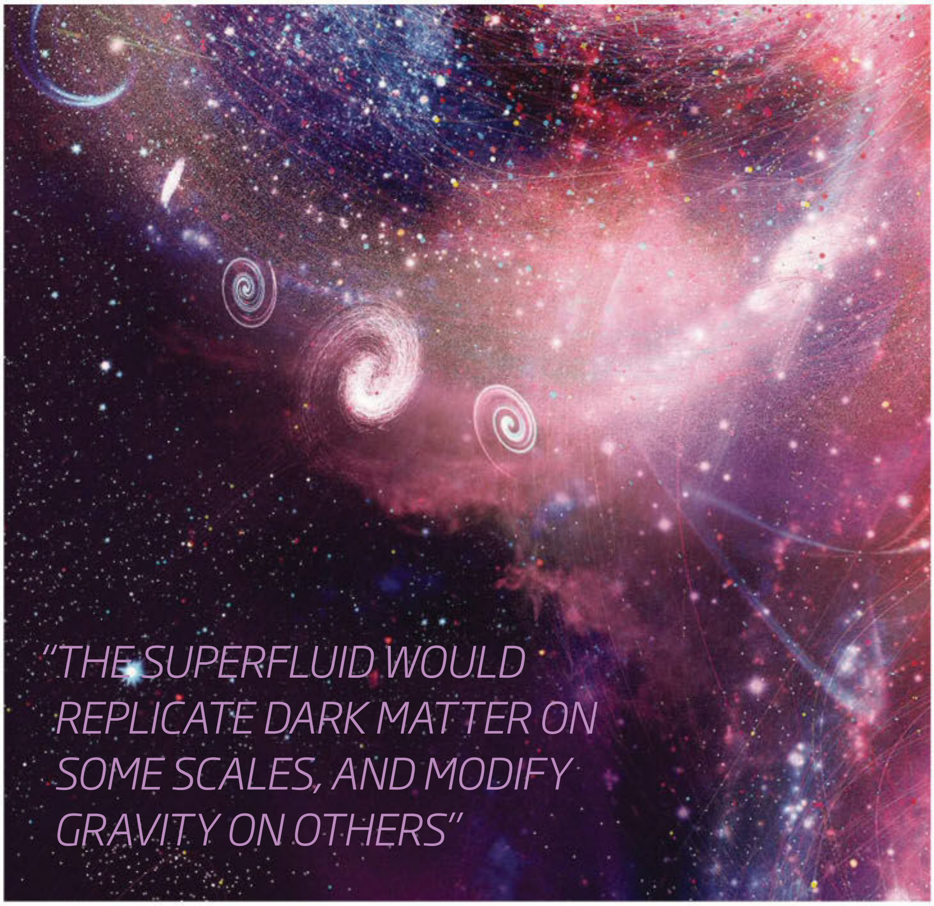
In 2014, Hongsheng Zhao of the University of St Andrews, UK, working with Kroupa and others, showed that such a subtle change allowed for an interaction between the Milky Way and Andromeda between 7 and 11 billion years ago. "Simply speaking, MONDian dynamics demands that there was a past interaction between the two," says Pawlowski.

Superfluid epiphany

But MOND is not exactly flavour of the month among physicists. Even though the strength of gravity has never been tested in very weak fields, the idea that a force of nature should change its strength so readily is unpalatable to most. And MOND runs into problems when the scales get extremely large. In clusters of many galaxies, dark matter is still needed to hold everything together. And those hot and cold spots in the cosmic microwave background are very hard to explain without some form of dark matter assisting the collapse of normal matter into galaxies.

All of this gave Pawlowski pause for thought, wondering whether the MOND idea might itself be modified not just to explain a past collision between the Milky Way and Andromeda, but also to fit all other observations. "Maybe MOND is telling us something about gravity," he says. "Or maybe it is telling us something about dark matter."

Enter Justin Khoury with the self-same question – and perhaps an answer. A theoretical physicist at the University of Pennsylvania in Philadelphia, Khoury has long



"THE SUPERFLUID WOULD REPLICATE DARK MATTER ON SOME SCALES, AND MODIFY GRAVITY ON OTHERS"

TATIANA PLAKHOVA

been fascinated by the success of MOND in describing cosmic dynamics up to the scale of galaxies – and its failure with anything bigger. "You need the component that modifies gravity on galaxy scales to go quiet on cosmological scales," he says. "How do you accommodate that?" His answer: with superfluids.

Khoury's epiphany involves a superfluid state known as a Bose-Einstein condensate, which kicks in among some types of normal matter atoms once they drop below a certain temperature. In this state, the constituent particles begin to behave as one single, coherent mass that has no viscosity and flows without impediment. When the temperature rises again, they snap back out into a normal, viscous fluid state.

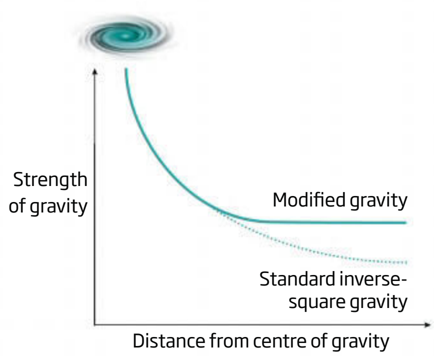
If dark matter particles could enter a Bose-Einstein state, Khoury reasoned, that would be just the thing to replicate MOND on certain scales, and ordinary dark matter on others. In the relatively weak gravitational fields of galaxies, dark matter would be slow-moving and have a low effective temperature. It would slip into a Bose-Einstein state whose energy would be spread uniformly across its extent, curving space and creating a MOND-like additional gravitational force. But in stronger gravitational fields, as found in galaxy clusters, the coherence would break and the matter would behave just like ordinary dark matter, contributing its own minuscule force of gravity particle by particle.

This would also explain why we see no MONDian behaviour on the scale of our solar system. With our sun, we have a very strong local source of gravity, so the condensate would break down on this local level. The same would be true of each of the Milky Way's stars, which would behave like impurities in the condensate. But because our galaxy, like all galaxies, is mainly empty space, the overall galactic condensate would still dominate.

Khoury is not the first to suggest dark matter dynamics would naturally mimic those of a Bose-Einstein condensate, but he is the first to suggest it would lead to MOND-like variations in gravity, thus unifying bits of two models previously regarded as implacably opposed. For this hybrid model to work, his calculations suggest that the dark matter itself is a billion times lighter than current models indicate.

Gravity assist

Modified Newtonian dynamics provides a boost to gravity's strength at large distances



Stark mismatch

Khoury is currently developing computer models to see how superfluid dark-matter haloes would affect how galaxies merge, and so see if there are any observations he could make to test the idea. He is also collaborating with a condensed-matter physicist colleague at the University of Pennsylvania, Tom Lubensky, to see if there is any supercooled atomic fluid known to create exactly the predicted effect. "If so, then perhaps we can use cold atom gases to simulate galaxies and mergers in the laboratory," he says.

Some regard talk of superfluid dark matter modifying gravity as an unnecessary and unwelcome complication – a big disruption to explain the relatively small problem of strangely aligned dwarf galaxies. Ed Shaya of the University of Maryland in College Park, for instance, thinks that the mismatch between simulations and the reality of the dwarf galaxies is simply down to a lack of computing power, which limits the resolution of simulations. He believes that there are still solutions invoking ordinary physics and ordinary dark matter. "It is not yet time to give up on the standard model," he says.

The distance between simulation and reality is stark for now. The vast polar structure's ring shape is about 500,000 light years in diameter, yet no more than 50,000 light years wide. Although some standard galaxy formation simulations can be rigged to produce similar alignments, they never produce rings less than a million light years in width.

For Pawlowski, this mismatch is a big deal. "There are a number of problems that the standard model has on the scale of galaxies, but this is the biggest."

None of this will affect our ultimate fate, as we serenely spiral towards the giant firework show at the end of our galaxy. But will that shock and awe display be a repeat performance? Who knows – and if we have to modify our ideas of gravity and dark matter, we can't pencil the next date into our diaries with much certainty, either. The fireworks could be going off a fair bit earlier than expected. ■

DARREN HOPES

Pulling power

Dark energy may not be such a mysterious force after all, says Stephen Battersby

WE WILL be lonely in the late days of the cosmos. Its glittering vastness will slowly fade as countless galaxies retreat beyond the horizon of our vision. Tens of billions of years from now, only a dense huddle of nearby galaxies will be left, gazing out into otherwise blank space.

That gloomy future comes about because space is expanding ever faster, allowing far-off regions to slip across the boundary from which light has time to reach us. We call the author of these woes dark energy, but we are no nearer to discovering its identity. Might the culprit be a repulsive force that emerges from the energy of empty space, or perhaps a modification of gravity at the largest scales? Each option has its charms, but also profound problems.

But what if that mysterious force making off with the light of the cosmos is an alien echo of light itself? Light is just an expression of the force of electromagnetism, and vast electromagnetic waves of a kind forbidden by conventional physics, with wavelengths trillions of times larger than the observable universe, might explain dark energy's baleful presence. That is the bold notion of two cosmologists who think that such waves could also account for the mysterious magnetic fields that we see threading through even the emptiest parts of our universe. Smaller versions could be emanating from black holes within our galaxy.

It is two decades since we realised that the universe is running away with itself. The discovery came from observations of supernovae that were dimmer, and so further away, than was expected, and earned its discoverers the Nobel prize in physics in 2011.

Prime suspect in the dark-energy mystery is the cosmological constant, an unchanging energy which might emerge from the froth of short-lived, virtual particles that according to quantum theory are fizzing about constantly in otherwise empty space.

Mutant gravity

To cause the cosmic acceleration we see, dark energy would need to have an energy density of about one joule per cubic kilometre of space. When physicists try to tot up the energy of all those virtual particles, however, the answer comes to either exactly zero (which is bad), or something so enormous that empty space would rip all matter to shreds (which is very bad). In this latter case the answer is a staggering 120 orders of magnitude out, making it a shoo-in for the least accurate prediction in all of physics.

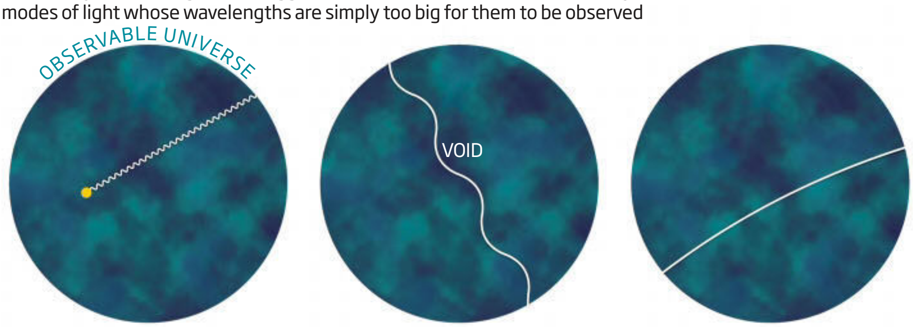
This stumbling block has sent some researchers down another path. They argue that in dark energy we are seeing an entirely new side to gravity. At distances of many billions of light years, it might turn from an attractive to a repulsive force.

But it is dangerous to be so cavalier with gravity. Einstein's general theory of relativity describes gravity as the bending of space and time, and predicts the motions of planets and spacecraft in our own solar system with cast-iron accuracy. Try bending the theory to make it fit acceleration on a cosmic scale, and it usually comes unstuck closer to home.

That hasn't stopped many physicists persevering along this route. Until relatively recently, Jose Beltrán and Antonio Maroto were among them. In 2008 at the Complutense University of Madrid, Spain, they were playing with a particular version of a mutant gravity model called a vector-tensor theory, which they had found could mimic dark energy. Then came a sudden realisation. The new theory was supposed to be describing a strange version of gravity, but its equations bore an uncanny resemblance to some of the mathematics underlying another force.

Elongated light

The theory of dark magnetism suggests that a period of inflation in the early universe could have unleashed modes of light whose wavelengths are simply too big for them to be observed



NORMAL PHOTON
Observable wavelengths from trillionths of a metre to billions of metres

LONGITUDINAL MODE
Longer wavelengths, but still less than observable universe. Their presence could explain magnetic fields in voids

TEMPORAL MODE
Wavelengths larger than observable universe. Their energy could account for dark energy and the accelerating expansion of the universe

"They looked like electromagnetism," says Beltrán. "We started to think there could be a connection."

So they decided to see what would happen if their mathematics described not masses and space-time, but magnets and voltages. That meant taking a fresh look at electromagnetism. Like most of nature's fundamental forces, electromagnetism is best understood as a phenomenon in which things come chopped into little pieces, or quanta. In this case the quanta are photons: massless, chargeless particles carrying fluctuating electric and magnetic fields that point at right angles to their direction of motion.

Alien photons

This description, known as quantum electrodynamics or QED, can explain a vast range of phenomena, from the behaviour of light to the forces that bind molecules together. QED has arguably been tested more precisely than any other physical theory, but it has a dark secret. It wants to spit out not only photons, but also two other, alien entities.

The first kind is a wave in which the electric field points along the direction of motion, rather than at right angles as it does with ordinary photons. This longitudinal mode moves rather like a sound wave in air. The second kind, called a temporal mode, has no magnetic field. Instead, it is a wave of pure electric potential, or voltage. Like all quantum entities, these waves come in particle packets, forming two new kinds of photon.

As we have never actually seen either of these alien photons in reality, physicists found a way to hide them. They are spirited away using a mathematical fix called the Lorenz condition, which means that all their attributes are always equal and opposite, cancelling each other out exactly. "They are there, but you cannot see them," says Beltrán.

Beltrán and Maroto's theory looked like electromagnetism, but without the Lorenz condition. So they worked through their equations to see what cosmological implications that might have.

The strange waves normally banished by the Lorenz condition may come into being as brief quantum fluctuations – virtual waves in the vacuum – and then disappear again. In the early moments of the universe, however, there is thought to have been an episode of violent expansion called inflation, which was driven by very powerful repulsive gravity. The force of this expansion grabbed all kinds of quantum fluctuations and amplified them hugely. It created ripples in the density of matter, for example, which eventually seeded galaxies and other structures in the universe.

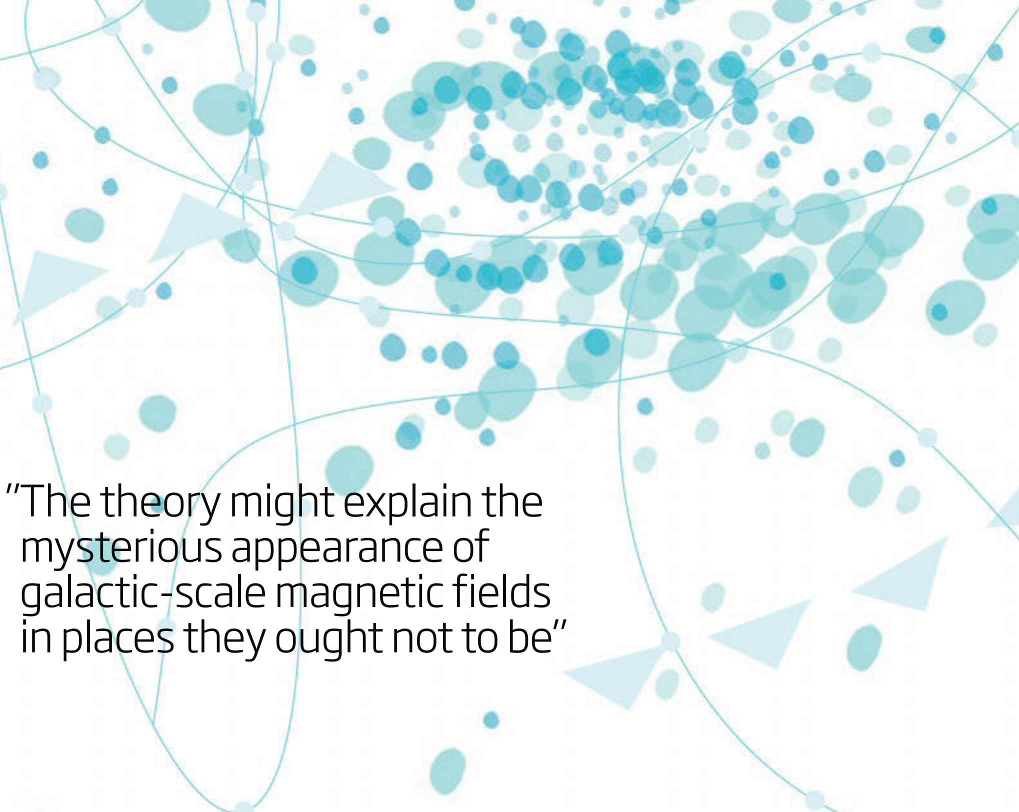
Crucially, inflation could also have boosted the new electromagnetic waves. Beltrán and Maroto found that this process would leave behind vast temporal modes: waves of electric potential with wavelengths many orders of magnitude larger than the observable universe. These waves contain some energy but because they are so vast we do not perceive them as waves at all. So their energy would be invisible, dark… perhaps, dark energy?

Beltrán and Maroto called their idea dark magnetism. Unlike the cosmological constant, it may be able to explain the actual quantity of dark energy in the universe. The energy in those temporal modes depends on the exact time inflation started. One plausible moment is about 10 trillionths of a second after the big bang, when the universe cooled below a critical temperature and electromagnetism split from the weak nuclear force to become a force in its own right. Physics would have suffered a sudden wrench, enough perhaps to provide the impetus for inflation.

If inflation did happen at this "electroweak transition", Beltrán and Maroto calculate that it would have produced temporal modes with an energy density close to that of dark energy. The correspondence is only within an order of magnitude, which may not seem all that precise. In comparison with the cosmological constant, however, it is mildly miraculous.

The theory might also explain the mysterious existence of large-scale cosmic magnetic fields. Within galaxies we see the unmistakable mark of magnetic fields as they twist the polarisation of light. Although the

> "The equations for this strange gravity bear an uncanny resemblance to those of another force: electromagnetism"



"The theory might explain the mysterious appearance of galactic-scale magnetic fields in places they ought not to be"

turbulent formation and growth of galaxies could boost a pre-existing field, is it not clear where that seed field would have come from.

Even more strangely, magnetic fields seem to have infiltrated the emptiest deserts of the cosmos. Their influence was noticed in 2010 by Andrii Neronov and Ievgen Vovk at the Geneva Observatory, Switzerland. Some distant galaxies emit blistering gamma rays with energies in the teraelectronvolt range. These hugely energetic photons should smack into background starlight on their way to us, creating electrons and positrons that in turn will boost other photons up to gamma energies of around 100 gigaelectronvolts. The trouble is that astronomers see relatively little of this secondary radiation. Neronov and Vovk suggest that is because a diffuse magnetic field is randomly bending the path of electrons and positrons, making their emission more diffuse.

"It is difficult to explain cosmic magnetic fields on the largest scales by conventional mechanisms," says astrophysicist Larry Widrow of Queen's University in Kingston, Ontario, Canada. "Their existence in the voids might signal an exotic mechanism." One suggestion is that giant flaws in space-time called cosmic strings are whipping them up.

With dark magnetism, such a stringy solution would be superfluous. As well as the gigantic temporal modes, dark magnetism should also lead to smaller longitudinal waves bouncing around the cosmos. These waves could generate magnetism on the largest scales and in the emptiest voids.

To begin with, Beltrán and Maroto had some qualms. "It is always dangerous to modify a well-established theory," says Beltrán. Cosmologist Sean Carroll at the California Institute of Technology in Pasadena, echoes this concern. "They are doing extreme violence to electromagnetism. There are all sorts of dangers that things might go wrong," he says. Such meddling could easily throw up absurdities, predicting that electromagnetic forces are different from what we actually see.

The duo soon reassured themselves, however. Although the theory means that temporal and longitudinal modes can make themselves felt, the only thing that can generate them is an ultra-strong gravitational field such as the repulsive field that sprang up in the era of inflation. So within the atom, in all our lab experiments, and out there among the planets, electromagnetism carries on in just the same way as QED predicts.

Carroll is not convinced. "It seems like a long shot," he says. So how might we tell whether the idea is correct? Dark magnetism is not that easy to test. It is almost unchanging, and would stretch space in almost exactly the same way as a cosmological constant, so we can't tell the two ideas apart simply by watching how cosmic acceleration has changed over time.

Ancient mark

Instead, the theory might be challenged by peering deep into the cosmic microwave background, a sea of radiation emitted when the universe was 380,000 years old. Imprinted on this radiation are the original ripples of matter density caused by inflation, and it may bear another ancient mark. The turmoil of inflation should have energised gravitational waves, travelling warps in space-time that stretch and squeeze everything they pass through. These waves should affect the polarisation of cosmic microwaves in a distinctive way, which could tell us about the timing and the violence of inflation. The European Space Agency's Planck spacecraft is looking for this signature. If astrononomers find that inflation happened before the electroweak transition, at a higher energy scale, then that would rule out dark magnetism in its current form.

The model might anyhow need some numerical tweaking, so that might not be fatal, although it would be a blow to lose the link between the electroweak transition and the correct amount of dark energy.

One day, we might even be able to see the twisted light of dark magnetism. In its present incarnation with inflation at the electroweak scale, the longitudinal waves would all have wavelengths greater than a few hundred million kilometres, longer than the distance from Earth to the sun. Detecting a light wave efficiently requires an instrument not much smaller than the wavelength, but in the distant future it might just be possible to pick up such waves using space-based radio telescopes linked up across the solar system. If inflation kicked in earlier at an even higher energy, some of the longitudinal waves could be much shorter. That would bring them within reach of Earth-based technology. Beltrán suggests that they might be detected with the Square Kilometre Array – a massive radio instrument due to come on stream within the next few years.

If these dark electromagnetic waves can be created by strong gravitational fields, then they could also be produced by the strongest fields in the cosmos today, those generated around black holes. Beltrán suggests that waves may be emitted by the black hole at the centre of the Milky Way. They might be short enough for us to see – but they could easily be invisibly faint.

One thing Beltrán and Maroto have calculated is the voltage of the universe. The voltage of the vast temporal waves of electric potential started at zero when they were first created at the time of inflation, and ramped up steadily. Today, it has reached a pretty lively 10^{27} volts, or a billion billion gigavolts.

Just as well for us that it has nowhere to discharge. Unless, that is, some other strange quirk of cosmology brings a parallel universe nearby. The encounter would probably destroy the universe as we know it, but at least then our otherwise dark and lonely future would end with the mother of all lightning bolts. ■

Out of the shadows

We could banish the universe's dark spectres by accepting we live in a curvy cosmos, says **Anil Ananthaswamy**

NOT so long ago, in a galaxy really rather close by, a small band of rebels has taken up arms to overthrow a dark empire…

No, this isn't bad *Star Wars* fan fiction. It's a pretty good description of a battle for cosmology going on right now. On one side is the mighty firepower of cosmology's standard model. It brings order to everything from the patterns in the big bang's afterglow to the evolution of galaxies. But it can only do so using dark powers. There's dark matter, an additional unseen stuff amounting to a quarter of everything in the universe, which keeps galaxies and clusters of galaxies in line and stops them from flying apart. Far outgunning even this, however, is dark energy. Representing more than two-thirds of the universe, dark energy is a mysterious, expansionist force whose very identity is unknown – but which has dominated the cosmos for the past 5 billion years.

Not for much longer, if the rebels lining up on the other side against the universe's established order have anything to do with it. "In 10 years' time, dark energy is gone," says Thomas Buchert of the École Normale Supérieure in Lyon, France. Dark energy's power, the insurgents claim, is a mere illusion created by the machinery of the standard model itself. They now aim to bring it down.

At the heart of this unbalanced conflict lies a founding principle of the universe – or at least, of cosmology since the days of Copernicus. He argued in the 16th century that Earth didn't occupy any special place in the universe. This assertion has since morphed into the "cosmological principle", which states that the universe is more or less the same no matter where you are or whichever direction you look. These twin assumptions of homogeneity and isotropy amount to saying the universe has no special places whatsoever.

They proved a boon when trying to extract workable models of the universe from the equations of general relativity. General relativity is Einstein's theory of how matter, space and time interact to produce the force we know as gravity. Its guiding principle was once succinctly summed up by physicist John Wheeler as "Matter tells space how to curve; space tells matter how to move".

The devil is in the detail. General relativity's equations are notoriously intractable. On one side of them are mathematical terms for things that warp space and time – matter and energy. On the other side are descriptions of their effects: how fast space-time is expanding and its curvature.

With curvature, there are three main options. Space-time can be folded in on itself as if it were on the surface of a four-dimensional sphere, producing a "closed" universe with positive curvature. Or it can be folded outwards to produce an "open" geometry said to have negative curvature.

> "Dark energy is an illusion created by the machinery of our cosmological model"

Lastly, it can be broadly "flat" with zero curvature, like the surface of a sheet of paper, only in four dimensions.

Building a cosmological model means balancing all these terms for the entire universe: the right amount of stuff to produce the right expansion and curvature. Assuming a uniform universe where matter and energy are evenly spread and an overall average curvature that doesn't change in time or space makes that job more manageable. "It's an assumption that is made for reasons of mathematical simplicity," says David Wiltshire of the University of Canterbury in Christchurch, New Zealand.

It's still a hard task. When Einstein first attempted it, the universe was thought to be static, neither expanding nor contracting, but the solutions he came up with predicted a dynamic universe that was either expanding or contracting, and definitely not static. His sticking-plaster fix was to introduce a new term, a "cosmological constant", to provide some extra energy that stabilised the universe.

Soon after, Edwin Hubble and others showed that the universe was indeed expanding. Einstein graciously took out the cosmological constant, calling it his greatest blunder. Others then found the solutions to his equations that corresponded to just the sort of expanding cosmos that the universe seemed to be. This "Friedmann–Lemaître–Robertson–Walker" (FLRW) solution, which assumes the universe to be flat, homogeneous and isotropic, became the bedrock of the standard model of the big bang universe.

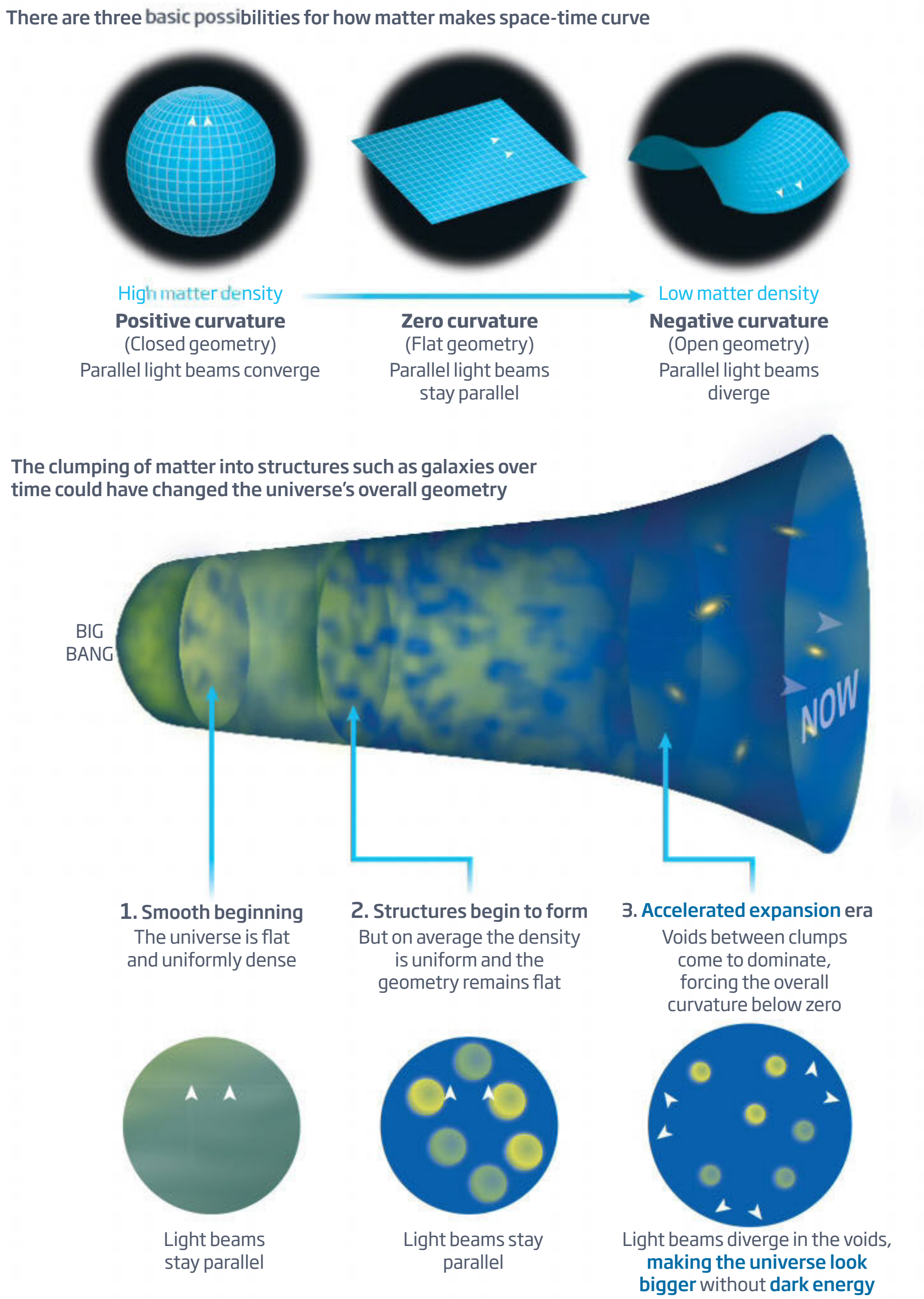
Over the years, this model has been refined with observational evidence. Studies of the cosmic microwave background – light emitted when the cosmos was about 380,000 years old – confirm the idea of a smooth, largely homogeneous universe, and also indicate that the universe back then was almost completely flat, with zero curvature.

The standard model has also proved itself adept at adapting to changing realities. The discovery that galaxies and clusters of galaxies were rotating too fast for the amount of visible matter they contained was solved by adding dark matter to the mix – more matter for the matter side of the equations.

The shock discovery by two teams independently in 1998 that distant supernovae were fainter than expected was more problematic. These supernovae seemed to be farther away than they would have been if the universe had been expanding at the same rate since the big bang. Sometime around 5 billion years ago, the universe's expansion had begun to accelerate – an odd development, given that the gravitational pull of all the matter in the universe should, if

Bending space

A change in the universe's geometry could create the illusion that its **expansion is accelerating**, an effect usually ascribed to **dark energy**



anything, have put a brake on the expansion.

This is where dark energy entered the picture. It was effectively a new lease of life for Einstein's cosmological constant. Add this extra term back into the FLRW model on the matter and energy side and you can make the equations balance out, while reproducing an accelerating expansion of a flat universe.

The vast majority of cosmologists are perfectly happy with this solution: it works, sort of. But while recent measurements suggest the amount of extra expansion is bigger than even dark energy can explain on its own, there is a bigger problem. The latest calculations suggest dark energy makes up 68.3 per cent of all the stuff there is – yet no one has the slightest clue what it is.

This wobbly orthodoxy is what the rebels are seeking to undermine. Abandon the assumption that the universe is uniform and unchangingly flat, they say, and you can eliminate dark energy, too.

As heretical as Copernicus back in the day? Perhaps, but perhaps not. The universe might once have looked broadly homogeneous, but it is hard to claim that today. Already in the cosmic microwave background you see the seeds of the galaxies and clusters of galaxies that gravity's pull has constructed over time. As the universe has evolved, a web of over-dense regions has gradually formed, with huge under-dense voids opening up between them. The question is, what effect has this changing distribution of matter had on the space-time around it? "Are the effects of structures really negligible?" says Syksy Räsänen of the University of Helsinki, Finland. "That has not been satisfactorily answered."

The simple answer is there must be some sort of effect. Matter tells space how to curve, so the extra mass of galaxies and galaxy clusters will increase the curvature of nearby space-time, making it more positive. Meanwhile voids will cause their local space-time to warp the other way, giving it a negative curvature. That much is bog-standard general relativity.

The controversial question is whether these "backreaction" effects between matter and space-time add up to enough to change the geometry of the universe as a whole. For matter and energy, a strict law of conservation means their total amount cannot change over time. But no such restriction exists for curvature.

In the alternative backreaction picture, as matter clumps into ever denser, more compact structures, the proportion of the universe that is void increases, pushing its overall average curvature into negative territory. In a model with backreaction and a ›

MATTER OF FICTION

If dark energy is a full-on mystery (see main story), dark matter is only marginally less confounding. Entirely invisible, it makes up about a quarter of the universe, and is thought to provide the gravity needed to hold together galaxies and clusters of galaxies.

But like dark energy, dark matter might be an illusion born of false assumptions about the universe, says Thomas Buchert of the École Normale Supérieure in Lyon, France. The standard model of cosmology assumes that the geometry of the universe doesn't change as large-scale structures such as galaxies and galaxy clusters form. But according to Einstein's general relativity, the mass of these structures will start to bend space-time around them – and the resulting curvature might make it look as if there is additional stuff there. "You get positive curvatures in over-dense regions," says Buchert. "And they act as dark matter."

It's a speculative idea, he emphasises. Syksy Räsänen of the University of Helsinki in Finland points out that many lines of evidence lead to the conclusion that dark matter must exist and some of them – for example, patterns of sound waves imprinted on the cosmic microwave background in the early years of the universe – can't be explained away in this way. Also, unlike for dark energy, we do have a simple, if unverified, explanation for dark matter: it's a stable, heavy, electrically neutral particle. "There are many, many candidates for that which are quite reasonable," says Räsänen. This dark spectre may not be so easily banished.

universe whose curvature goes negative over time, light's path will become distorted that things look more distant than in a flat space-time (see diagram, page 99). Thus you can build models in which there is no accelerated expansion, and hence no dark energy.

This does away with another problem, too. In the standard model, it's difficult to explain why dark energy's effects kick in only about 5 billion years ago, some 9 billion years into the universe's history. That's a crucial point: had dark energy dominated earlier, the universe would have blown apart so quickly we would have had no galaxies, no life and no physicists wondering about appropriate models of the universe. With backreaction, there's nothing to explain: 5 billion years ago is the point in the progressive evolution of structures when voids begin to dominate and the overall curvature goes negative.

So there's a case to answer, says Räsänen.

> "It's as if someone claimed rounding errors explained the entire national debt"

"It's not been established beyond reasonable doubt that dark energy exists," he says. "But I'd never say that it has been established that dark energy does not exist," he adds. Wiltshire, like Buchert, is more forthright, styling himself an out-and-out "backreactionista". "There is no dark energy, as far as I'm concerned," he says. Buchert even thinks that backreaction might get rid of that other dark spectre, dark matter (see "Matter of fiction", left).

Bold statements – but where's the proof? The backreactionistas say they can fit existing observations to models that don't include dark energy. The key is to figure out how the changes in the local curvature of space-time alter the overall, average curvature. But that's easier said than done. The mathematics is as intractable as ever, and there is no single accepted way of calculating the average curvature of space-time in a lumpy universe.

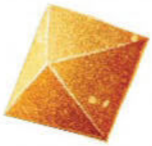
All this leaves some unimpressed. Adam Riess of Johns Hopkins University in Baltimore, Maryland, was a leader of one of the teams that made the 1998 supernova measurements, and won a share of the 2011 Nobel prize in physics for his efforts. "In the mainstream cosmology community this is not even discussed," he says. Local changes in curvature are unlikely to change the overall average curvature of the universe, he says. "It is as if someone wondered what the impact of many rounding errors was on the national debt and then claimed it was enough to cover the whole debt."

Stephen Green of the Perimeter Institute in Waterloo, Canada, and Robert Wald of the University of Chicago have put the mathematical boot in. In 2014, they claimed proof that backreaction would not have any significant effect. Last year Buchert, Räsänen, Wiltshire and others hit back, arguing that Green and Wald's assumptions fail to include the essential physics of backreaction. In a paper titled "Is there proof that backreaction of inhomogeneities is irrelevant in cosmology?" they open with the blunt statement "No."

The best way to mediate the conflict would be to build general relativistic models that simulate the evolution of a realistic universe containing the sort of structures that our cosmos does. Until recently, the huge computational demands of such an endeavour made it impossible. But now Glenn Starkman of Case Western Reserve University in Cleveland, Ohio, and his colleagues have been having a go, as has another team. The results suggest that backreaction effects do exist – but they aren't enough to provide the sort of effects needed to square with observations.

Buchert and Wiltshire point out that these models don't yet allow the average curvature of space-time to evolve over time. And Starkman himself cautions that the models are still crude: the distribution of matter is still not fine-grained enough to be entirely realistic, and matter is modelled as a fluid, not particles. Still, he thinks that the backreaction is unlikely to have the large effect that the renegades expect. "It's not how I'd bet, from my understanding of our preliminary results," he says. "It's not how I'd have bet before, but I respect the people in the backreaction group far too much to be willing to say that they are wrong without checking."

So could this revolution be a damp squib – leaving the dark shadows to continue to haunt the cosmos? The backreactionistas aren't giving up the fight in a hurry. They are working on models that can be tested against more observations, while Wiltshire and Buchert are also studying backreaction in the primordial universe. For Wiltshire, in the end it's not about necessarily being correct, but about asking the right questions – and as long as dark energy can't be explained, those questions are there to be asked. "As far as I'm concerned, whether I'm right or wrong, I'm doing the right thing," he says. ■



The universe's largest objects could conceal intruders from dimensions beyond our own. **Colin Stuart** tracks them down

WHEN WORLDS COLLIDE

A GIANT hole in the web of galaxies that fills the cosmos. A colossal string of quasars billions of light years across. A ring made out of hugely energetic bursts of radiation that spans 6 per cent of the visible universe. As our observations of the cosmos come into ever sharper focus, astronomers are beginning to identify structures bigger than any seen before. There's only one problem: none of them should be there.

Ever since Copernicus proposed his revolutionary idea that Earth's place among the stars is nothing special, astronomers have regarded it as fundamental. The cosmological principle it has evolved into goes a step further, stating that nowhere in the universe is special. You're allowed to have patches of individuality on the level of solar systems, galaxies and galaxy clusters, of course, but zoom out far enough and the universe should exhibit a drab homogeneity. No vast galactic walls or bald spots, and no huge structures.

Small wonder that the spate of recent findings has got cosmologists hot under the collar. But the solution could prove equally controversial. One researcher claims these massive structures are illusions projected from another dimension, the first tantalising evidence of realities beyond our own. If he is right, and these behemoths don't exist as physical objects within our universe, then the cosmological principle might still be safe.

The concept of favoured regions in the universe is anathema to modern cosmology. "All our thinking since the Renaissance has been working against that idea," says Seshadri Nadathur, a cosmologist at the University of Portsmouth in the UK. It also makes using Einstein's general theory of relativity to understand gravity's role in the evolution of our universe an even more fiendish task than it already is. "Einstein's equations are much easier to solve if you assume a universe that's almost homogeneous," says Nadathur. But, at the moment, the cosmological principle is just that – an assumption. There is no concrete evidence that it is true, and the evidence we do have seems increasingly against it.

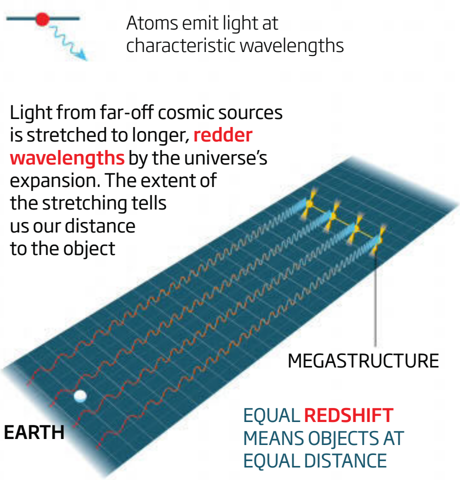
Take that giant hole in the universe – a void almost 2 billion light years wide, according to its co-discoverer, András Kovács of the Institute for High Energy Physics in Barcelona, Spain. "There are 10,000 fewer galaxies in that part of the sky compared with the universal average," says Kovács. Based on the latest data, astronomers believe that the cosmological principle must apply on scales of roughly a billion light years, with the average amount of material in any given volume more or less the same. A big empty patch almost double the size of the cut-off stands out like a sore thumb. Kovács and his team call this vast expanse a supervoid, and believe it might explain away the giant cold spot in the cosmic microwave background, an observation that has been puzzling astronomers for over a decade (see "CMB cold spot", page 34).

And the supervoid isn't the half of it. As far back as 2012, a team led by Roger Clowes at the University of Central Lancashire, UK, claimed to have found an enormous structure strung out over 4 billion light years – more than twice the size of the supervoid. "We thought 'what is that!?' It was obviously something very unusual," says Clowes. Yet this time it wasn't an empty patch of space, but a particularly ›

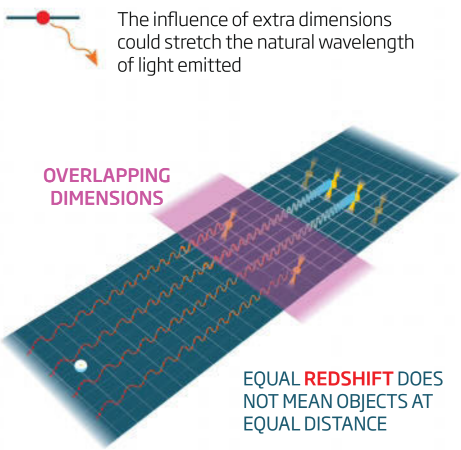
Trick of the light

Vast cosmic megastructures exist – or do they?

TRADITIONAL EXPLANATION



ALTERNATIVE EXPLANATION



crowded one. Known as the Huge Large Quasar Group, it contains 73 quasars – the bright, active central regions of very distant galaxies. Astronomers have known since the early 1980s that quasars tend to huddle together, but never before had a grouping been found on such a large scale.

Then in 2015 a team of Hungarian astronomers uncovered a colossal group of gamma-ray bursts (GRBs) – highly energetic, short-lived flashes of energy erupting from distant galaxies. The galaxies emitting these GRBs appear to form a ring a whopping 5.6 billion light years across – 6 per cent of the size of the entire visible universe. "We really didn't expect to find something this big," says Lajos Balázs from the Konkoly Observatory in Budapest, Hungary, who led the study. Its size makes it five times larger than the typical scale at which the cosmological principle tells us that homogeneity should kick in.

So fundamental is the cosmological principle to our understanding of the universe that such apparent violations make astronomers and cosmologists deeply uncomfortable, even those who discovered them in the first place. When it comes to the intense flashes of light that make up the GRB ring, for instance, there's a possibility they might be surrounded by other galaxies, currently shining less brightly because of an absence of GRBs. It's like being in a darkened room in which light bulbs are evenly distributed: if only a few are illuminated when you look into the room, you're likely to draw the wrong conclusions about how they are arranged. "It doesn't necessarily contradict the cosmological principle," says Balázs.


ESO/M. KORNMESSER

Rise of the giant-killers

The huge large quasar group is also the subject of intense debate. "I don't think it's really a structure at all," says Nadathur. In 2013, he published a paper studying the algorithm Clowes and his team used to analyse their data, calculating the probability that a random distribution of quasars would also yield an apparent structure. "The chances of seeing a pattern like the one they see, even if there is nothing there, is quite high," he says. But the giant might not be dead just yet. Clowes's PhD student, Gabriel Marinello, is working on a paper countering Nadathur's claims, which he describes as "conservative and unrealistic". He argues that instead of modelling a random distribution, Nadathur should have included the fact that quasars – just like other galaxies – are known to huddle together on scales of around 300 million light years.

As well as the quasar group, Nadathur thinks the supervoid could also be reconciled with the cosmological principle. "The principle is not saying that any one place cannot fluctuate from the norm, just that on average the large-scale universe must be homogeneous," says Nadathur. In short, the probability of finding objects like the supervoid is not zero. There just can't be too many of them.

But Rainer Dick, a theoretical physicist at the University of Saskatchewan, Canada, believes such attempts to brush these cosmic megastructures aside are misguided. In fact, he says they should be embraced as our best bet of keeping the cosmological principle alive. All we have to do is accept that they don't actually exist. Instead, they represent the first evidence of other dimensions intruding into our own, leaving dirty footprints behind on our otherwise smooth and homogeneous cosmic background.

It seems a breathtakingly audacious proposal – but it builds on a solid foundation of theoretical work. For one thing, conjuring up other dimensions beyond our own is nothing new. For decades, many theorists have regarded the existence of extra dimensions as our best hope of reconciling Einstein's general relativity with that other bastion of 20th century physics: quantum theory. A marriage between these two seemingly disparate concepts, one dealing with the very large and the other with the very small, would yield what is often called a theory of everything, a one-size-fits-all framework capable of describing the universe in its entirety.

One popular candidate is M-theory, an extension of string theory that famously suggests we live in an 11 dimensional universe, with the other seven dimensions curled up so tightly as to drop out of sight. It's an elegant and mathematically appealing framework with a number of influential supporters. But it has one major failing: the lack of solid predictions offering opportunities to verify it. Dick's work on a generalisation of string theory known as brane theory might provide just such a prediction, and resolve the cosmological principle dilemma to boot.

At the heart of brane theory is the idea

Quasars emit jets of radiation that make them among the brightest objects in the universe

that what we perceive as our universe is a single four dimensional membrane floating in a sea of similar branes spanning multiple extra dimensions. Such an idea is not inconsistent with our established theory of gravity, says Dick, as "you can add infinitely large extra dimensions and still get back general relativity".

Although the other branes occupy extra dimensions, and so would be impossible to observe directly, the theory suggests we might be able to spot the effects of a neighbouring brane overlapping with ours.

So how does this help with the problem of the cosmological principle? Well, in order to measure our distance to far-off objects, astronomers exploit an effect known as redshift. They break down the light from the object using a spectrometer – a fancy version of a prism – to reveal bands known as spectral lines. Any object moving away from us because of the universe's ongoing expansion will have its light stretched out to longer, redder wavelengths and the lines will appear shifted towards the red end of the spectrum. The further away the object, the faster it will appear to recede and the more the lines will shift. If astronomers see many objects all exhibiting the same redshift, they will interpret that as some form of structure, just like the GRB ring or the huge quasar group.

Except, looking into a region where another brane is overlapping with our own might skew our redshift measurements. Under these conditions, photons in one brane would exert a force on charged particles in another – a phenomenon Dick calls brane crosstalk. "This would change the distance between the energy levels within hydrogen atoms in the overlap region," he says. Electrons moving between these energy levels either emit or absorb photons, producing the spectral lines we rely on for working out their distance from Earth.

But if brane crosstalk were to narrow the energy-level gap, this would produce photons of a slightly longer wavelength – a redshift that has nothing to do with the expansion of the universe. If you fail to take this into account, and assume the overall redshift you measure is solely the result of distance, then you will systematically overestimate how far away an object in the overlap region actually is, with large swathes of empty space visible in its true location (see diagram, far left).

> "That really would be compelling evidence that our universe is not alone"

If such a model held true, areas of brane overlap would produce an apparent pile-up of objects at one redshift and a distinct lack of objects at another – an optical illusion that would make a homogeneous universe appear to contain massive structures and enormous voids. In a stroke, this would explain the origins of the quasar group and the GRB ring as well as the supervoid, says Dick. "These structures match the potential signal of brane crosstalk."

Of course, it's hardly an open-and-shut case. "There are many assumptions that one must accept in order for this to happen, and some of them may just be taking things a bit too far," says Moataz Emam from the State University of New York College at Cortland. Emam also warns that some of the assumptions about gravity that Dick's theory relies on have been severely criticised in the past, not least by string theorists who have had difficulty reconciling them with their calculations. "But his model is certainly testable," he says.

Emam suggests that the necessary evidence could be found by observing parts of the sky where high density regions coexist next to apparent barren patches. Provided the discrepancy in redshift measurements is identical in all cases, it might well suggest that our brane is overlapping with another.

With the help of the Sloan Digital Sky Survey (SDSS) – the most detailed three-dimensional map of the universe ever made – Dick is now planning to scour the databases for redshift data that could support his theory. "That really would be compelling evidence that our universe is not alone," he says. Such a discovery would not only explain away some of the most perplexing observations in astronomy, but give the abstract field of string theory a tantalising experimental foundation.

But his quest to cut the universe's largest objects down to size might lead to new monsters arising in their place. The discovery of branes beyond our own, for instance, would pose a serious challenge to humanity's fragile sense of its place in the cosmos, and make a nonsense of our concept of cosmic homogeneity. In a vast multiverse of interacting membranes, the cosmological principle might not be worth saving after all. ■

CMB COLD SPOT

The cosmic microwave background (CMB), radiation left over after the big bang, bears an impression from when the universe was only around 380,000 years old. Its distinctive maps are littered with red and blue speckles representing the slightly hotter and cooler regions of the infant universe. Our understanding of the physics governing this period predicts that these variations should be small, and for the most part they are. However, in 2004, scientists using the WMAP satellite claimed to have found a cold spot significantly larger than the others. They thought it might be an error in their measurements. Then the European Space Agency's Planck satellite observed it too. An alternative model was badly needed.

Among the most promising remains the supervoid theory, a thorn in the side of those who defend the idea of a uniform universe (see main story). This proposes that a large patch of empty space sits slap bang in the direction of the cold spot. In order to reach us, CMB photons originating from beyond the supervoid would have had to pass right through it. Thanks to the accelerating expansion of the universe, the photons emerging from this barren area would find that matter was less densely packed than when they went in, leading to a drop in the gravitational potential they experienced, and consequently their energy. As photon energies are used to calculate a source's temperature, this would in turn lead us to incorrectly interpret their home region as colder than any other point on the sky.

Upwardly mobile

If anything ever fell up, it would rewrite the textbooks. Antimatter might be that thing, says Joshua Howgego

ON 11 November last year, a small birthday party was held in an apparently unremarkable hangar on the outskirts of Geneva, Switzerland. Nothing too fancy, just a few people gathered around a cake. The honourees were there. Well, sort of – they were still locked in the cage where they had spent their first year. But then again, there is no other way to treat a brood of antimatter particles.

The antimatter realm is so bizarre as to be almost unbelievable: a mirror world of particles that destroy themselves and normal matter whenever the two come into contact. But it's real enough. Cosmic rays containing antiparticles constantly bombard Earth. A banana blurts out an anti-electron every hour or so. Thunderstorms produce beams of the stuff above the planet.

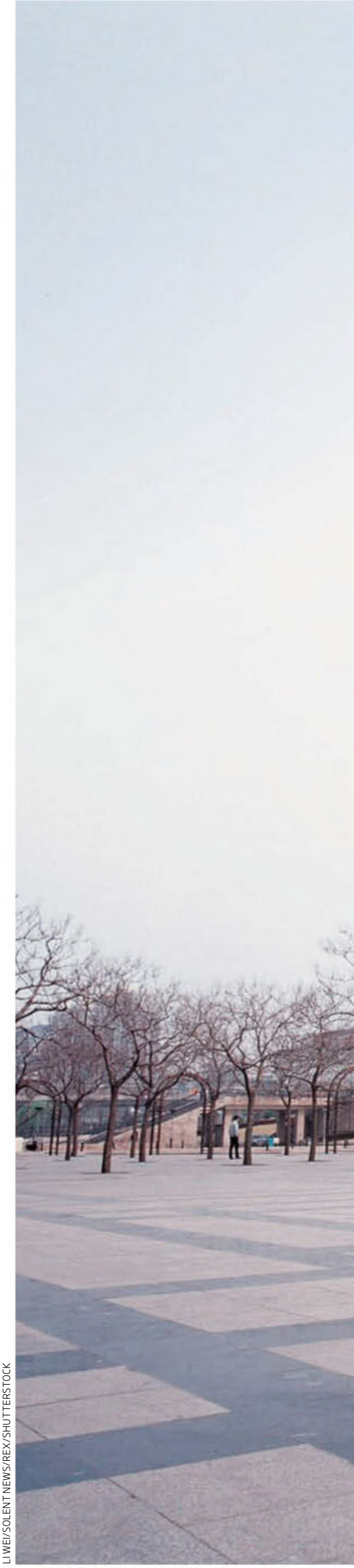
Making and manipulating antimatter ourselves is a different kettle of fish. Hence that birthday party held at the particle physics centre CERN, celebrating on behalf of a quadruplet of antiprotons. There's a lot we would like to learn from these caged beasts and their ilk, not least this: do they fall up?

Cards on the table, few physicists believe that such "antigravity" effects exist – that if you released one of those antiprotons and somehow ensured it free passage through the hostile world of matter, it would magically float up. But the recalcitrant nature of antimatter means we've never done the experiments, and until we do, we simply don't know. "Progress is often made by asking the questions we think we already know the answer to," says Daniel Kaplan of the Illinois Institute of Technology in Chicago.

The scepticism about all forms of antigravity dates back to the 1950s, when the physicist Hermann Bondi was pondering the implications of general relativity, Einstein's theory of how gravity arises from warping the fabric of the universe. Gravity is an odd sort of force, not least because it only ever works one way. With electromagnetism, say, there are positive and negative charges that attract and repel. With gravity, however, there are only positive masses that always attract.

Bondi showed what a bizarre world it would be if this were not the case, demonstrating how negative mass would end up pursuing positive mass across the universe (see diagram, page 106). This sort of "runaway motion" does not appear to exist – but we should be careful about what we draw from that, says Sabine Hossenfelder of the Frankfurt Institute for Advanced Studies in Germany. "People who speak of the runaway problem often jump to conclusions from Bondi's argument and conclude that anti-gravitation itself is inconsistent," she says. "But it merely requires a modification of general relativity."

And here's the thing: general relativity is probably due a modification. The theory is incompatible with quantum mechanics,



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the other great pillar of modern physics, and if we are to find a way to make a unified description of the universe, that must change. Then everything is up for grabs.

So in a few labs around the world, the search for negative mass and its associated effects goes on (see "Losing weight", page 107). Antimatter is a particularly promising place to look. It is just like normal matter but with the opposite electric charge and a few other mirrored quantum properties. There's no reason to think it has the opposite mass and anti-gravitates, and some good reasons to think it can't have.

But if antimatter did anti-gravitate, that might help with another of its central mysteries: where most of it is. Our theories say matter and antimatter should have been created in equal proportions in the big bang, and yet we live in a matter-dominated world.

The emptiest box

Explaining this glaring inconsistency has largely been a case of trying to find asymmetries in the processes of particle physics that favour normal matter. Such asymmetries do exist – but they are about a trillionth of the size needed to explain matter's supremacy. "People have been trying to make it work – and it doesn't work," says Kaplan.

Antigravity could provide a better explanation. A repulsive gravitational interaction could have driven matter and antimatter away from each other so they never had the chance to annihilate in the early universe. Since then, the ongoing expansion of the universe would have driven the twain ever farther apart – and the antimatter might eventually have created its own galaxies in other corners of the universe. "Then the missing antimatter would be hiding in plain sight," says Kaplan's colleague Thomas Phillips.

Add to that the technological possibilities that levitating matter away from Earth's surface might bring, and even the US air force wants in – it has given millions of dollars to antimatter researchers over the years. Unfortunately, doing the experiments turns out to be quite an ask.

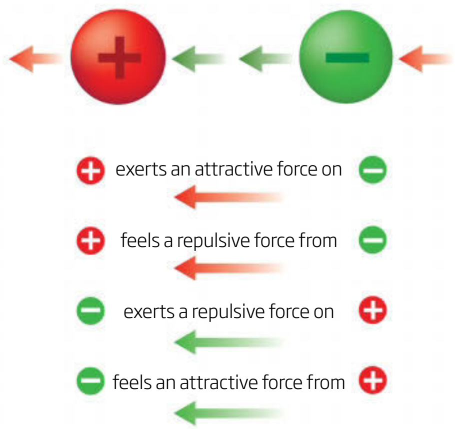
The problems start with needing a home for antimatter that is almost entirely free of normal matter. That requires some of the emptiest boxes on Earth, containing just hundreds of gas molecules per litre (there are about 10^{22} in a typical litre of air). But even these boxes have sides. To stop › the antimatter banging into them and instantly annihilating, you must slow it down by cooling it to within a few degrees of absolute zero and then catch it in a vortex of electromagnetic fields. Little by little, we've been perfecting these arts, holding antimatter particles for seconds, minutes, days – and for a year, as celebrated at November's party.

That milestone was reached by CERN's Baryon Antibaryon Asymmetry Experiment (BASE), one of six experiments competing to measure antimatter's fundamental properties that are all housed in CERN's vast Antimatter Deceleration Hall. Inside, past a sign marked "Antimatter factory", the most noticeable things are the bright yellow cranes, swinging around the vats of liquid nitrogen required for cooling. Somewhere below, a beam of particles from CERN's Proton Synchrotron accelerator smashes into a block of metal, creating a plethora of particles. A system of magnets selects the antiprotons and funnels them into a ring of more magnets that keep them on course as they are decelerated for trapping.

Experiments have been running here since the 1990s, studying whether antimatter and matter particles truly are as close to identical as we think. In 2015, by measuring how antiprotons danced around in a magnetic enclosure known as a Penning trap, BASE produced the most precise measurement yet of their mass-to-charge ratio. They showed it was the same as a proton's, to about 69 parts per trillion, four times more precise than the previous best value. Last November, the neighbouring ASACUSA

Runaway problem

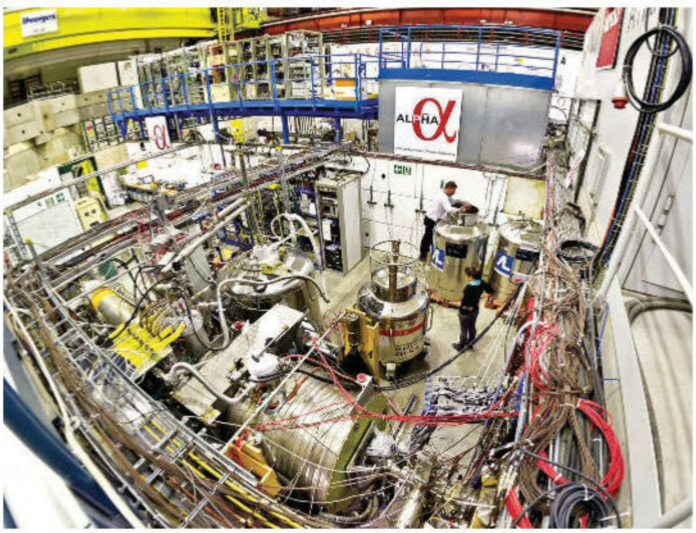
Standard positive masses attract each other, giving rise to gravity. But if negative mass exists, the combination of attractive and repulsive forces would cause negative masses to chase after positive ones



experiment produced the most accurate measurement yet of the antiproton's mass, finding no evidence of a different value from the proton's.

The same value – but is the mass positive or negative? That is the multimillion dollar question, and it takes the experiments to a new level of fiddliness. Gravity is weak and easily overwhelmed by the electromagnetic force, so using charged particles such as antiprotons and controlling them with magnetic fields won't do. You could try getting an antiproton in position and shutting off the magnets to see which way it falls, but the antimatter's electrostatic interactions with its surroundings would overwhelm any gravitational push or pull it might feel.

A better bet is neutral atoms of antimatter, such as antihydrogen. Making these is no cakewalk, but they have a tiny electric polarity that makes it worth going the distance – their electrostatic interaction isn't strong enough to swamp gravity, but very strong magnetic fields will still hold them in place. CERN's Antihydrogen Laser Physics Apparatus (ALPHA) experiment has been doing this since 2005, and now routinely traps and holds bunches of antihydrogen atoms for about 15 minutes. "Just the other day we trapped 350," says Jeff Hangst, head of ALPHA.


CERN

The ALPHA experiment is one of six at CERN studying antimatter's properties

Not up, just less down

In 2013, ALPHA published a proof of principle measurement, briefly collecting a cloud of 434 antiatoms, turning off the magnets and tracking their subsequent motion by where they annihilated. It was a crude test, and inconclusive – the final answer was compatible with the antiparticles having either negative or positive gravitational mass.

Work on a souped-up version that gives the particles more space to fall should start this year. "We're going to knock out a wall and build a vertical version of the experiment next door," says Hangst. Getting the necessary accuracy won't be easy, because the antiatoms ALPHA uses are relatively hot and so jiggle around, which clouds the issue. But large enough numbers of antiatoms should help us answer the central question. "Up or down – that should be possible," says Hangst.

A further CERN experiment, AEGIS, also aims to perform tests within a few years. Kaplan is planning experiments with muons, heavier cousins of the electron, and a team led by David Cassidy of University College London is planning to use positronium, an "atom" consisting of an electron and its antimatter partner, a positron, orbiting one another.

Back at CERN, the Gravitational Behaviour of Antimatter at Rest, or GBAR, experiment intends to tackle the question using a single antihydrogen ion, a combination of one antiproton and two positrons. In theory, it should be easy to hold this charged speck in place with magnetic fields and cool it with lasers. The idea is then to knock off a positron using another laser, making the antiatom neutral. At this point it would cease to feel the effect of the trapping field and fall – up or down. GBAR's head, Patrice Perez, says they expect to make measurements sensitive to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detect even a 1 per cent deviation from the gravity felt by normal matter.

Construction of the experiment won't start until later this year, and requires new lasers and an extra antiproton decelerator called ELENA. Hangst is confident of beating the upstart to the punch. "I view GBAR as a case of five miracles happen and then it works," he says. One telling fact is that GBAR plans on using only one detector, below the trap. "We really do not expect antimatter to fall up," says Perez.

Even if it falls at all differently, however, that would still be hugely interesting. "In all the descriptions I know, antimatter cannot antigravitate," says Sergey Sibiryakov of CERN. What's more plausible, he thinks, is that there might be other forces that modify gravity whose effects cancel out on normal matter, but not on antimatter. In that case, antimatter might not fall up – just less down. "Now, that's not natural, but it is logically possible," he says. Similar gravity-modifying effects might be produced if the graviton, a quantum particle proposed to carry the force of gravity, has a small mass, rather than being massless as is usually assumed.

Even so, we probably shouldn't be holding our breath for amazing self-levitating machines any time soon. A more immediately practicable way of using antimatter to beat gravity might be to harness the energy released when it annihilates. One firm, Positron Dynamics in Livermore, California, has been developing the idea with financial support from PayPal co-founder Peter Thiel, among others.

Positron-fuelled rockets could power spacecraft much further and faster than is currently possible, according to Positron Dynamics co-founder Ryan Weed. "Our vision is to create technology that allows humanity to venture outside of our solar system," he says. The company's patented system involves harvesting positrons from radioactive sodium-22 and using these to start off a nuclear fusion reaction that generates thrust. Weed says the team is set to test the device in a lab and wants to test it in orbit in the next few years.

But experience makes Stefan Ulmer, the head of the BASE experiment, cheerfully sceptical of immediate progress. Antimatter won't be easily tamed. "In the whole history of the CERN Antimatter Deceleration Hall, we've produced about enough to heat up a cup of water by about 5 °," he says. Not even enough, in other words, to make a pot of tea to wash down that birthday cake. ■

LOSING WEIGHT

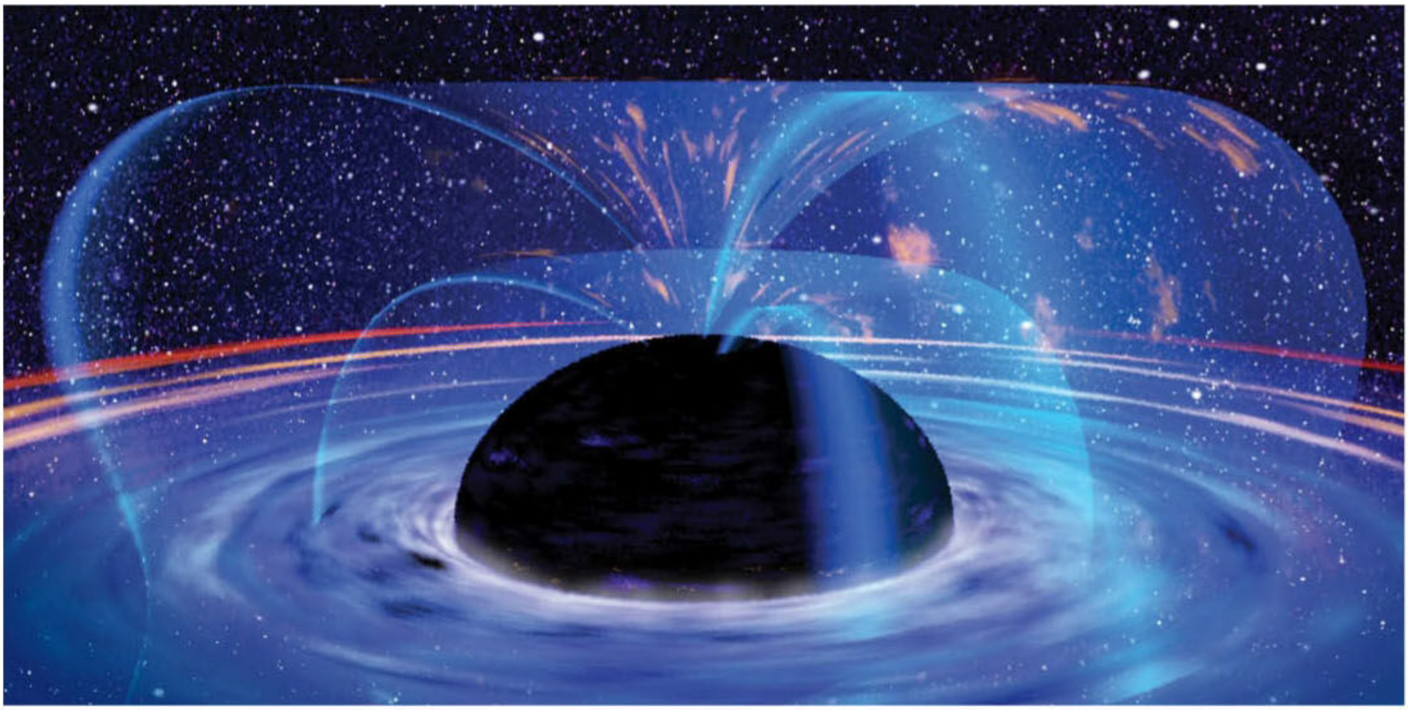
Is it crazy to think something might have less than zero mass? It seems like it, but Martin Tajmar, a physicist at the Dresden Institute of Technology in Germany, is not so sure. "It's a bit like walking on top of a mountain and seeing the ground beneath you," he says. "You think, 'hey I'm on the ground'. But there are lower bits of ground that are not up a mountain."

The question isn't necessarily the same as whether anything can anti-gravitate (see main story). There are two types of mass: gravitational mass quantifies how strongly an object feels the force of gravity, whereas inertial mass quantifies an object's resistance to acceleration. Experiment after experiment has shown that these two quantities always have the same value – a mysterious equivalence that lies at the heart of Einstein's description of gravity (see page 86).

Break the equivalence principle and you could have an object with normal gravitational mass, but a negative inertial mass. Such a body would fall normally in a gravitational field, but give it a push and it would accelerate towards whatever is pushing it, not away from it. Pair that with normal mass and you could create a system that self-accelerates. "My motivation is to build something like a warp drive," says Tajmar.

There are a few theoretical avenues for creating negative mass, says Tajmar. One comes from the US historian and physicist James Woodward, who proposes that by cobbling together bits of general relativity you can make particle masses fluctuate, even into negative territory. Woodward has been trying to experimentally verify this effect since the early 2000s.

Tajmar is working to test this too, as well as investigating another proposal. This hinges on a theory called Weber electrodynamics that is viewed with narrowed eyes by most theorists – a position Tajmar's latest unpublished results seem to support. "What I can say, is that if it is there, the effect is very small," he says. Plus, he thinks it could only be turned into a propulsion system inside a charged cage. "So that's not very useful."



XMM-NEWTON/ESA/NASA

The search for QUANTUM GRAVITY

GENERAL relativity is only one of the pillars of modern physics. The other is quantum mechanics, which describes what happens at the atomic and subatomic scale. Its modern incarnation, quantum field theory, has been spectacularly successful at describing and predicting the behaviour of fundamental particles and forces.

The main challenge now is to combine the two ideas into one overarching theory, to be known as quantum gravity. Such a theory would be crucial for explaining the first moments of the big bang, when the universe was dense, hot and small, or what happens near the singularity at the cores of black holes, where the effects of quantum physics may compete with those of general relativity.

Although there is as yet no final theory of quantum gravity, there are several candidate theories being actively explored. One is string theory, which describes the fundamental constituents of matter not as point-like particles but as microscopic vibrating strings. Depending on how they vibrate, the strings will be perceived as different particles – including the graviton, the particle thought to carry the gravitational force.

Another possibility is that space-time is not smooth but built up of discrete building blocks that interact with each other. As a result, if we were able to peer at its fine structure, it might look like a frothy space-time foam. In such theories, what we perceive as the space-time that bends and warps smoothly in the presence of matter is merely an emergent phenomenon masking more radical behaviour on small scales.

The quest for the theory of quantum gravity is arguably the biggest challenge facing modern physics. One of the difficulties is that it only really manifests itself at extremely high energies, well beyond our experimental reach. Physicists now face the task of devising experiments and astronomical observations that can test candidate theories of quantum gravity in the real world. **Pedro Ferreira**

RECOMMENDED READING

The State of the Universe by Pedro G. Ferreira (Phoenix)

The Perfect Theory: A Century of Geniuses and the Battle over General Relativity by Pedro G. Ferreira (Abacus)

Black Holes and Time Warps: Einstein's Outrageous Legacy by Kip Thorne (Papermac)

Gravity: An Introduction to Einstein's General Theory of Relativity by James B. Hartle (Addison-Wesley)

Time Travel in Einstein's Universe by Richard Gott (Phoenix)

Was Einstein Right? Putting General Relativity to the Test by Clifford Will (Basic Books)

SPACE *against* TIME

Is space the warp and weft of reality, or time – or both, or neither? **Anil Ananthaswamy** picks up the threads

TO ISAAC NEWTON, space was the "sensorium of God", the organ through which the deity surveyed His creation. It was absolute, unchanging, infinite. Flowing through it "equably without regard to anything external", as Newton wrote in his great physical treatise *Principia*, was another similarly absolute heavenly creation: time.

Not everyone bought that idea. Newton's perennial antagonist Gottfried Leibniz was notably sniffy of a God who needed an organ to perceive things, and asked pointedly whether a clockmaker deity would need to "wind up his watch from time to time".

A few centuries on, God features less prominently in the debate, but arguments about the nature of space and time swirl on. Are both basic constituents of reality, or neither – or does one perhaps emerge from the other in some way? We are yet to reach a conclusive answer, but it is becoming clear that if we wish to make further progress in physics, we must. The route to a truly powerful theory of reality passes through an intimate understanding of space and time.

The search for reality's building blocks goes to the heart of what physics is about. "When we find the simplest equations for everything in the universe, the fundamental quantities would be what appear in those equations," says theorist Joe Polchinski of the University of California, Santa Barbara.

That makes it all the more embarrassing that the two sets of equations we use to describe the physical world differ so radically in form and content. Einstein's relativity, which covers gravity, does a stellar job in describing the universe at large. The theory of quantum mechanics, meanwhile, describes all the other forces and paints a peerless picture of the world at the smallest scales.

Problems emerge when the large meets the small: in the first instants after the big bang, for example, when the entire universe was a mere pinprick; or at the immense maw of a black hole, whose gravitational pull is so great that not even photons of light can escape. The contradictions that rear up have, at least in part, a very basic origin. "One of the tensions comes from the fact that the relation between space and time is very, very different in general relativity than it is in quantum mechanics," says theorist Sean Carroll of the California Institute of Technology in Pasadena.

When Einstein developed the theory of special relativity in 1905, it undid Newton's notions of a clockwork universe, in which objects in an absolute space followed the beat of a heavenly timepiece. Space and time are intertwined into one four-dimensional fabric called space-time. People moving at different speeds measure space-time differently. Just as "here" does not mean the same thing to people in different places, so it is with "now" in Einstein's relativistic space-time. "What we call now doesn't have any unique translation to what a person on Alpha Centauri calls now," says Carroll.

General relativity, which came along in 1916, muddied the waters still further: massive objects curve space-time, and measurements of ruler lengths and clock ticks depend on the strength of the prevailing gravitational field.

In quantum mechanics, things are even more abstruse. A quantum object's state is described by a wave function, a mathematical object living in an abstract space, known as Hilbert space, that encompasses all the possible states of the object. We can tell how the wave function evolves in time, moving from one state in its Hilbert space to another, using the Schrödinger equation.

In this picture, time is itself not part of the Hilbert space where everything else physical sits, but somehow lives outside it. When we measure the evolution of a quantum state, it is to the beat of an external timepiece of unknown provenance. "Somebody gave us a clock, a grandfather clock, and we just use this clock," says Nathan Seiberg of Institute for Advanced Study in Princeton, New Jersey.

As for space, its status depends on what you are measuring. The wave function of an electron orbiting the atomic nucleus will include properties of physical space such as the electron's distance from the nucleus. But the wave function describing the quantum spin of an isolated electron has no mention of space: according to the mathematics, the picture we often paint of an electron physically rotating is meaningless.

"This is one sense in which there are attributes of physical systems which don't refer to space, but which change in time," says Abhay Ashtekar of Pennsylvania State University. "One could say that for those attributes, time is more fundamental than space." ›

That is how things stand if you consider general relativity and quantum mechanics in isolation. Relativity says space and time are on the same footing – together they are the fabric of reality. Quantum mechanics, on the other hand, treats time and space differently, with time occasionally seeming more fundamental.

All this starts unravelling, however, whenever we attempt to combine the two theories to find a greater theory capable of describing reality on all scales, large and small.

One of the most ambitious such attempts is string theory. It has an odd relationship with space. One of the theory's key characteristics is the existence of extra dimensions of space so tightly curled up as to be almost undetectable. It needs at least 10 space-time dimensions to be mathematically consistent. But a celebrated result derived in 1997 by theorist Juan Maldacena suggests mathematical trapdoors exist between these different dimensions. According to his "anti-de Sitter/conformal field theory correspondence" – AdS/CFT for short – under certain circumstances, you can swap the fiendishly complex 10D representations of string theory that include gravity for a more tractable 4D representation that dispenses with gravity.

As you do this, one-dimensional time remains seemingly unchanged, but space is transformed: a point in the 4D world translates to multiple points within the 10D world. "In this example it seems perfectly clear that space is not fundamental. It is very, very different depending on what description of the world you are using," says Carroll.

"Relativity says space and time are on the same footing. Quantum mechanics treats them differently, with time more fundamental"

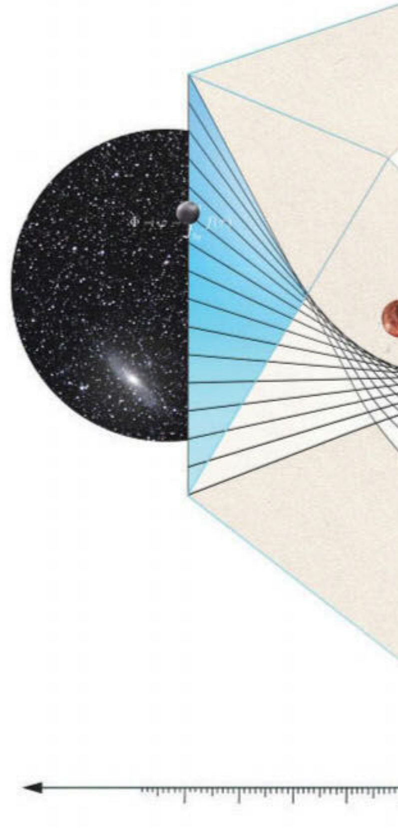
Black hole drama

But things may not be so clear-cut. Polchinski, for one, has started to wonder if such insights from Maldacena's conjecture are entirely justified. We already know that the AdS/CFT correspondence is only valid for a specific sort of space-time that is not quite the space-time of our universe. The fabric of our universe is geometrically almost flat: two light rays that start out parallel stay so. But the space-time for which the AdS/CFT correspondence is valid is negatively curved, such that two initially parallel light rays slowly start to diverge. The intractable mathematics of string theory means that no one has yet worked out an AdS/CFT-like correspondence for our space-time.

Polchinski's team has raised a more fundamental objection, however – by peering into the dark heart of a black hole. Black holes have a history of testing theories to the limit. Predicted by general relativity and thought to exist where massive stars once lived, as well as at the heart of every galaxy, they have insatiable appetites that appear to gobble up even information, something forbidden by quantum theory. If you try to sidestep the issue by allowing information to escape from a black hole, quantum theory says that a blazing "firewall" of high-energy radiation appears just inside the event horizon, the black hole's point of no return.

That in turn goes against the predictions of general relativity, which says that anything going past a black hole's event horizon should encounter nothing but gently curved space-time – no theatrics, no drama. If you want to keep quantum mechanics intact and avoid a firewall too, something else about space-time needs to give, such as the dictum that nothing can travel faster than the speed of light. "This does point to the fact that we may be missing something in our conceptual description," says Steve Giddings, also at the University of California, Santa Barbara.

It was to crack this conundrum that Polchinski's team turned to Maldacena's conjecture. They started by making a mathematical model of a black hole in a volume of negatively curved space-time. If the conjecture were to hold, then the 4D physics of an observer on the surface of the volume



should be able to account for the physics of an observer deep inside the 10D bulk of a black hole within – only with easier mathematics. Instead, what the two observers see is described by two different quantum theories.

The AdS/CFT correspondence is beloved among string theorists, and Polchinski knows he is going against the grain. "I want to shake people's faith in AdS/CFT," he says. If he succeeds, any conclusions drawn from it and string theory about the status of space and time may not be the last word.

But string theory is just one as-yet-unproven approach to unifying relativity and quantum theory. Another, known as loop quantum gravity, has its origins in the mid-1980s when Ashtekar rewrote Einstein's equations of general relativity using a quantum mechanical framework. Working with physicists Lee Smolin and Carlo Rovelli, he used these equations to arrive at a picture in which space-time is a smooth fabric – until, as with any fabric, you look at it very closely. In the case of the space-time of loop quantum gravity, if you zoom in to tiny scales of about 10^{-35} metres, a distance known as the Planck length, you see a warp and weft of loops of gravitational field lines.

"A light ray always moves at one unit of space per unit of time – in a sense, it is on the edge between space and time"

As with string theory, the equations of loop quantum gravity have proved difficult to work with, and have produced little in terms of verifiable experimental predictions. Still, they provide a different perspective on the primacy of space and time. Chunks of space, one Planck length to a side, appear first in the theory, while time pops up only later as an expression of the relationships between other observable physical properties. For instance, you can define the tick of a clock in terms of changes in the gravitational field and then observe how another field, say the electromagnetic field, changes with respect to the "ticking" of the gravitational field. Here, both space and time seem to emerge from something deeper, says Ashtekar. "But somehow space might emerge first, and time is born by observing relations between various physical subsystems."

In a sense, that's coming full circle to how Newton viewed some aspects of time. Although seeing absolute time as something God-given, he recognised that we measure a "common" time relationally – that is, by keeping track of other properties. Earth's motion around the sun in space represents a unit of time, for example – the year – which we subdivide or multiply to calculate the duration of anything else, like the length of a season.

We do not know as yet what the deeper thing might be from which space and time emerge, but Ashtekar is not the only one thinking along these lines. Seiberg has a similar intuition based on findings in string theory, which suggest space is emergent, and general relativity, which says that space and time are interwoven. "We have many examples where we have emergent space and, given that space and time mix, there's no doubt that time will also be emergent," he says.

Relaxing restrictions

Giddings is also exploring the idea that neither space nor time is fundamental, using that most uncomfortable of theoretical test beds. He has been trying to describe a black hole, from its interior to way outside its event horizon, using a network of interconnected quantum-mechanical Hilbert spaces that do not presuppose the existence of space or time. This allowed him, for example, to relax the restriction that nothing can travel through space-time faster than light – imposed by Einstein's relativity – and see what would happen as a result.

By observing how one attribute of a quantum system changes with respect to another in this set-up, Giddings showed how time can emerge relationally, in another nod to Newton's "common" time. A concept of space also emerges from his calculations by loosely specifying different Hilbert spaces to correspond to different physical locations, such as the interior of a black hole.

Ultimately, Giddings thinks that even this notion of space can be linked to the dynamics of the system, just like time. In this case, neither would be primary.

It is still early days for the idea. To be taken seriously, Giddings must show that general relativity and the normal picture of space-time can be derived from his network of Hilbert spaces for situations that are not as extreme as black holes.

Polchinski is also tugging at that constant speed of light in relativity. In a sense, this provides a reference of both space and time. A light ray always moves at one unit of space per unit of time – a constant diagonal on any graph of space against time.

"The direction that light rays travel in is neither space nor time; we call it 'null'. It's on the edge between space and time," says Polchinski. "A lot of people have this intuition that in some sense the existence of these null directions might be more fundamental than space or time."

Will that or any other intuition lead us anywhere in our quest towards a greater theory? The current impasse in physics is not unlike the situation in the early 20th century, before Einstein's master stroke replaced space and time with one space-time. Today we appear to be facing a similar obstruction to progress. Many potential ways around lead to different worlds of space and time – and we have as yet little clue which route to follow. Space, time, both or neither? It's a cliché, but an appropriate one, to say that perhaps only time will tell. ■

SKIZZOMAT

The end of **space-time**

Unbinding space from time could solve the biggest conundrums in the cosmos. **Anil Ananthaswamy** reports

IT WAS a speech that changed the way we think of space and time. The year was 1908, and the German mathematician Hermann Minowski had been trying to make sense of Albert Einstein's hot new idea – what we now know as special relativity – describing how things shrink as they move faster and time becomes distorted. "Henceforth space by itself and time by itself are doomed to fade into the mere shadows," Minowski proclaimed, "and only a union of the two will preserve an independent reality."

And so space-time – the malleable fabric whose geometry can be changed by the gravity of stars, planets and matter – was born. It is a concept that has served us well, but if physicist Petr Horava is right, it may be no more than a mirage. Horava, who is at the University of California, Berkeley, wants to rip this fabric apart and set time and space free from one another in order to come up with a unified theory that reconciles the disparate worlds of quantum mechanics and gravity – one the most pressing challenges to modern physics.

"If Petr Horava's idea is right, it could change our conception of space and time forever"

When Horava published his work in January 2009, it received an astonishing amount of attention. Over the next 18 months more than 250 papers were written about it. Some researchers started using it to explain away the cosmological mysteries of dark matter and dark energy. Others found that it implied black holes might not behave as we thought. If Horava's idea is right, it could forever change our conception of space and time and lead us to a "theory of everything", applicable to all matter and the forces that act on it.

For decades now, physicists have been stymied in their efforts to reconcile Einstein's general theory of relativity, which describes gravity, and quantum mechanics, which describes particles and forces (except gravity) on the smallest scales. The stumbling block lies with their conflicting views of space and time. As seen by quantum theory, space and time are a static backdrop against which particles move. In Einstein's theories, by contrast, not only are space and time inextricably linked, but the resulting space-time is moulded by the bodies within it.

Part of the motivation behind the quest to marry relativity and quantum theory – to produce a theory of quantum gravity – is an aesthetic desire to unite all the forces ›

CHRISTOS MAGGANAS

"Other theories of quantum gravity, like string theory, are far more difficult for newcomers to embrace"

CHRISTOSMAGGANAS

of nature. But there is much more to it than that. We also need such a theory to understand what happened immediately after the big bang or what's going on near black holes, where the gravitational fields are immense.

One area where the conflict between quantum theory and relativity comes to the fore is in the gravitational constant, G, the quantity that describes the strength of gravity. On large scales – at the scale of the solar system or of the universe itself – the equations of general relativity yield a value of G that tallies with observed behaviour. But when you zoom in to very small distances, general relativity cannot ignore quantum fluctuations of space-time. Take them into account and any calculation of G gives ridiculous answers, making predictions impossible.

Emergent symmetry

Something has to give in this tussle between general relativity and quantum mechanics, and the smart money says that it's relativity that will be the loser. So Horava began looking for ways to tweak Einstein's equations. He found inspiration in an unlikely place: the physics of condensed matter, including a much-hyped wonder material.

Pull apart the soft, grey graphite and you have a flimsy sheet of carbon atoms just one atom thick, called graphene, whose electrons ping around the surface like balls in a pinball machine. Because they are very small particles, their motion can be described using quantum mechanics; and because they are moving at only a small fraction of the speed of light there is no need to take relativistic effects into account.

But cool this graphene down to near absolute zero and something extraordinary happens: the electrons speed up dramatically. Now relativistic theories are needed to describe them correctly. It was this change that sparked Horava's imagination. One of the central ideas of relativity is that space-time must have a property called Lorentz symmetry: to keep the speed of light constant for all observers, no matter how fast they move, time slows and distances contract to exactly the same degree.

What struck Horava about graphene is that Lorentz symmetry isn't always apparent in it. Could the same thing be true of our universe, he wondered. What we see around us today is a cool cosmos, where space and time appear linked by Lorentz symmetry – a fact that experiments have established to astounding precision. But things were very different in the earliest moments. What if the symmetry that is apparent today is not fundamental to nature, but something that emerged as the universe cooled from the big bang fireball, just as it emerges in graphene when it is cooled?

So Horava did the unthinkable and amended Einstein's equations in a way that removed Lorentz symmetry. To his delight, this led to a set of equations that describe gravity in the same quantum framework as the other fundamental forces of nature: gravity emerges as the attractive force due to quantum particles called gravitons, in much the same way that the electromagnetic force is carried by photons. He also made another serious change to general relativity. Einstein's theory does not have a preferred direction for time, from the past to the future. But the universe as we observe it seems to evolve that way. So Horava gave time a preferred direction.

With these modifications in place, he found that quantum field theories could now describe gravity at microscopic scales without producing the nonsensical results that plagued earlier attempts. "All of a sudden, you have new ingredients for modifying the behaviour of gravity at very short distances," Horava says.

"Horava gravity" is, of course, not the first attempt to devise a theory of quantum gravity. Of its many predecessors, the most popular is string theory. But Horava gravity has one particularly appealing feature: unlike string theory, which requires mastery of daunting mathematics, it can be studied using the same mathematical tools that have been developed for the three other forces of nature.

User-friendly mathematics is all very well; the true test is how the theory works out when it is applied to the real world. So how does it fare? Some clues that Horava might be on the right track come from another approach to quantum gravity called causal dynamical triangulation, which stitches space-time together from smaller pieces. Jan Ambjørn of the Niels Bohr Institute in Copenhagen, Denmark, and his colleagues, pioneered the idea. They used computer simulations to

"By breaking apart space-time, Horava's theory alters the physics of black holes"

analyse the behaviour of space-time and were puzzled by what they found in some of their models: as they zoomed in and out, they found that the contributions from the three dimensions of space and one of time varied in a way they did not fully understand. Zoom out and space and time play equal parts, in line with Lorentz symmetry. But zoom in and time plays a far greater role than space.

Beyond Einstein

Ambjørn thinks this means space and time are contracting differently – as you would expect if Lorentz symmetry is broken as it is in Horava's theory of quantum gravity. "So, if you call these computer simulations experiments," says Ambjørn, "then Horava's theory and experiment have met – in a way."

But it's not all been plain sailing for Horava's work. The near-unprecedented spotlight that has been focused on it has, not surprisingly, illuminated some cracks. The first appeared in June 2009 – just five months after Horava published his paper. If his theory works, then at low energies it should look like general relativity. However, Pujolas, along with Diego Blas and Sergey Sibiryakov of the Swiss Federal Institute of Technology in Lausanne, showed that wasn't the case in the system they analysed, meaning that Horava's theory would always be at odds with experimental observations. At first, the theory seemed doomed. Then within months of their initial paper, Pujolas and his colleagues realised that this disparity only appears in special circumstances and that the theory could after all lead to general relativity at low energies.

That was welcome news to those who were using Horava gravity to study astrophysical and cosmological mysteries such as black holes, dark matter and dark energy. Take black holes. In general relativity, black holes are a consequence of space and time being part of the same fabric. Black holes warp space-time so much that they suck in everything around them. Nothing can escape a black hole's gravity because nothing can travel faster than the speed of light.

By breaking the symmetry between space and time, Horava's theory alters the physics of black holes – especially microscopic black holes, which may form at the very highest energies. What this means for the formation of these black holes, and whether they are what they seem to be in general relativity "is a very big question", says Pujolas, and one that researchers are now addressing.

Horava gravity might also help with the long-standing puzzle of dark matter. The motions of stars and galaxies that astronomers have observed seem to require there to be much more matter in the universe than meets the eye; without it, galaxies and clusters of galaxies should fly apart. But this conclusion arises from equations of motion derived from general relativity. What if these equations are slightly off? Could this explain the observed speeds of the stars and galaxies without dark matter playing a role?

Shinji Mukohyama at the University of Tokyo in Japan decided to find out. When he extracted the equations of motion from Horava's theory, he found that they came with an extra term that is not present in equations derived from general relativity – and that this extra term mimics dark matter. Depending on its value, you can do away with some dark matter, or most of it. "It is possible that some fraction of the dark matter picture of the universe could be coming from corrections to Einstein's equations," Horava says.

Dark energy is a more daunting problem still. It appears that the expansion of the universe has started to speed up in the past few billion years, and to explain it physicists have invoked the inherent energy of the vacuum of space-time. This is dark energy. But there is a big problem. The theories of particle physics predict the strength of dark energy to be about 120 orders of magnitude larger than what is observed, and general relativity cannot explain this enormous discrepancy. Here, too, Horava's theory may come to the rescue. It contains a parameter that can be fine-tuned so that the vacuum energy predicted by particle physics is reduced to the small positive value that is in line with the observed motions of stars and galaxies.

It will, however, be hard to show whether or not this picture it correct – as Roberto Casadio of the University of Bologna in Italy and colleagues, who did these calculations, admit. That's because, with the parameter in Horava's equations set to the necessary value, their predictions will deviate from those of Einstein's relativity only at energies far, far higher than can be probed in labs today.

The universe, of course, will have the final say. Improved observations of supermassive black holes, which contain regions of intense gravity, could reveal the necessary corrections to general relativity. This could pave the way for a theory of quantum gravity, such as Horava's, in much the same way that unexplained measurements of Mercury's orbit showed that Newton's laws were incomplete, opening the door for Einstein.

Hanging in Horava's office in Berkeley is a 17th-century map on which California appears as an island off the west coast of America. He takes its lesson to heart. "We have found some new land and it's very exciting. But we are very far from getting all the details right." ■

TELEGRAMME

Silence is olden

Forget the big bang, the birth of the universe was a very quiet affair, whispers Michael Brooks

EVERYONE knows that, in space, no one can hear you scream. Very few people, however, realise just how deep the cosmic quiet can be. The moment our universe came into existence, the silence was truly extraordinary. It was a split second of utter isolation when nothing and nowhere was connected. If you did let out a scream, it wouldn't even make it past your lips. "Each point of space lived its own life," says Aurélien Barrau, a cosmologist at the Joseph Fourier University in Grenoble, France.

This is a radical departure from our usual picture of space-time as a smooth, continuous fabric. And it comes courtesy of researchers trying to work quantum theory into our current understanding of the universe, which is based on Einstein's general theory of relativity. This does a fine job of describing gravity on the scale of stars and galaxies, but when it comes to the entire history of the universe, the theory is left wanting.

In a sense, general relativity predicts its own demise. As we wind back the clock on the cosmos, things get closer together and gravity becomes ever stronger. According to general relativity, the cosmos arose out of a point of infinite density called the singularity, where space and time curved so radically that the physics breaks down. So this theory alone can't tell the full story of the universe's birth.

Once things get very small, quantum theory is king. To describe the start of everything, then, we need the two theories to combine into a single theory of quantum gravity.

Contrary to what you might have heard, we have ways of doing this. String theory is the most widely known example. It describes how the messy array of particles that make up matter and forces, including gravity, can be pared down to vibrations of one-dimensional strings. But it doesn't tell us much about the fundamental nature of space and time, so several alternatives have emerged in recent years.

Although it is early days and we don't know whether any of these theories will work in every detail, we are already seeing some fascinating results. Most tantalising of all is that at least three entirely independent quantum gravity theories have the cosmos kicking off with something we could call a moment of silence.

Winding back the clock, we seem to reach an instant when every point in space becomes disconnected from every other point. This means that nothing – no sound, no information, no light – can travel between them. Perhaps this moment of silence will give us a new telling of the oldest story?

Steven Carlip of the University of California, Davis, was one of the first to spot that the various paths to quantum gravity were converging. In 2012, he gathered up all the theories and found that many of them shed a spatial dimension or two as the universe winds back to its hot, dense start. In other words, geometry appears to have been radically different in the beginning.

The moment of silence goes further and ›

Tabletop cosmology

Did the universe begin not with a bang, but a silence? It's no easy thing to check. But there is one tantalising possibility, and it comes from a surprising source: artificial materials that are being developed as invisibility cloaks.

So-called metamaterials do strange things with radiation. Whereas most materials steer microwaves or visible light in one direction, metamaterials can bend it in the opposite. But they also slow it down or speed it up in the same way that changes in energy densities did in the early universe.

That means metamaterials could be used to create a tabletop simulation of the evolving conditions during the first moments of creation. Igor Smolyaninov is already working on such tabletop universes in his laboratory at the University of Maryland. He has made metamaterials from columns of magnetic particles suspended in a fluid, and shown that changing their temperature can simulate universes appearing and disappearing in the multiverse.

Jakub Mielczarek of the Jagiellonian University in Krakow, Poland, points to a parallel between Smolyaninov's experiment and quantum gravity (see main story). The equivalence, he says, relates to the fact that the atoms in these kinds of magnetic materials have a property called spin that can be oriented randomly or aligned. When the spins are random, which happens above a certain temperature, there is no net magnetic field. Drop the temperature, though, and the spins align to create one.

Similarly, it is possible that chunks of the hot, early universe were randomly aligned, giving a cosmos with four dimensions of space, but no time. As the universe cooled, perhaps a directionality emerged that we refer to as time. Exploring this transition in the lab, Mielczarek says, might give clues that the universe underwent such phase changes.

sees space and time break up completely. Exactly how and when this happened is hard to work out, but it seems to arise from primordial quantum fluctuations. Carlip and his colleagues have done calculations in an offshoot of string theory called dilaton gravity. They showed that space is split into discrete chunks in the first 10^{-43} seconds of the universe. Each chunk experiences nothing from outside its own existence (see diagram right).

The same thing happens in a theory known as causal dynamical triangulation (CDT), in which the universe is composed of units of space-time shaped like triangular-based pyramids. The ways the pyramids fit together give space and time the curvature that general relativity says is caused by the presence of mass and energy.

A quiet birth

In CDT, the chunks of space-time can all be different, and computer simulations combine them in billions of different ways. The idea is that comparing the different outputs lets us identify the scenarios that appear most often. These are the most likely histories of the universe. "We hope that our simulations will give us an indication of how the universe wants to behave near the initial singularity without arranging things by hand," says Renate Loll of Radboud University Nijmegen in the Netherlands, one of the creators of the theory. Interestingly, though, certain combinations of choices result in starkly different universes – as different as ice is from steam.

The CDT universe can exist in one of three distinct "phases". One is familiar to us, where different regions are connected and act on each other through the transmission of signals or forces. Another is a universe that is just one homogeneous lump, with everything effectively part of everything else. The third option has the space-time units completely disconnected – each chunk is alone. A moment of silence, in other words.

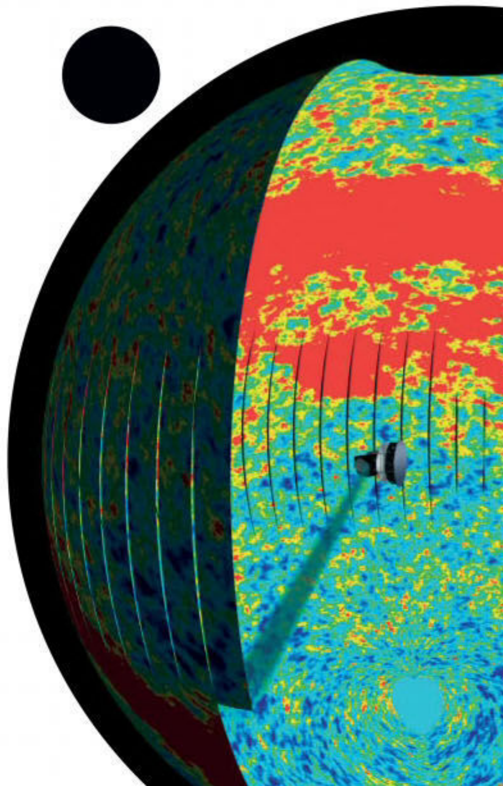
Although it is too soon to say for sure, the idea that the universe could have moved between these phases may herald a fresh understanding of quantum gravity. "The early universe is our most reliable entry door to quantum gravity," says Sabine Hossenfelder of the Nordic Institute for Theoretical Physics in Stockholm, Sweden. "Investigation of such a phase transition in the early universe will allow us to increase our understanding about what space and time fundamentally are."

The most recent manifestation of the moment of silence has come via a theory known as loop quantum gravity. In this theory, space-time is made up of a woven fabric of braids and knots. The way the strands intertwine creates a zoo of particles and forces.

One way researchers can try to validate the theory is through loop quantum cosmology (LQC), which looks for ways that loop quantum gravity could have uniquely shaped cosmic history. It attempts to see how the braids and knots would have fared under the high-energy, high-density conditions at the beginning of the universe.

When Barrau and his colleagues wound back the LQC universe's expansion, they saw conditions that slow the passage of light. When they kept squeezing everything into ever hotter, denser states, the LQC cosmos eventually reached a point where light couldn't travel at all. If light can't travel, communication can't happen, no forces can be transmitted and every region of space-time is disconnected from every other one. It's another moment of silence.

The researchers aren't taking their model too seriously. "We have to make tons of assumptions," Barrau concedes. But they are excited that LQC has now joined the group of theories that point to a quiet cosmic birth. "The silence might help us to understand relations between these formulations," says



Probing the silence might be possible in cosmic microwave maps

Barrau's colleague Jakub Mielczarek of the Jagiellonian University in Krakow, Poland.

One attribute of LQC gives particular cause for optimism: inflation appears in an intriguingly natural way. Inflation is a period of ultra-rapid growth that cosmologists have long believed must have happened in the moments following the creation of the universe. Their faith was bolstered by the recent discovery of a signature in the cosmic microwave background radiation that formed 380,000 years after the big bang.

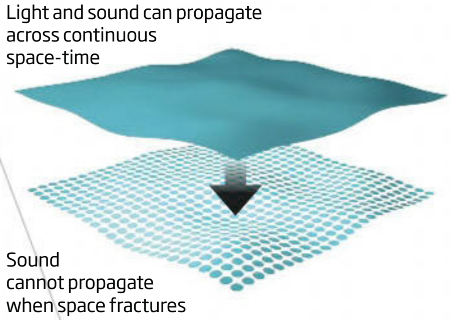
The standard big bang story has a period of inflation put in by hand. In the LQC model, it happens as a natural consequence of what is termed "the bounce". This is the moment before our universe came into being; LQC doesn't see the birth of our universe as the beginning of everything. In 2006, Parampreet Singh, who is based at Louisiana State University, and his colleagues showed that if you wind back the clock on a loop quantum universe, you eventually hit a moment where the braids and knots are overloaded with energy and create a repulsive force that causes space to turn inside out and begin expanding again.

If that universe contains any form of "scalar field", a mist-like quality that exerts a certain kind of force at every point in space, the result is a natural period of inflation. This isn't as artificial as it might sound – all cosmology theories put a scalar field into their universe as the seed for the various forces. In a bouncing universe with a scalar field, inflation is nearly unavoidable. "You have to fine-tune the conditions if you want to prevent inflation," Barrau says.

"Squeeze the universe beyond the moment of silence and time disappears"

A big silence

Several approaches to quantum gravity predict that space-time breaks up into disconnected chunks as you rewind to the birth of the cosmos



The model can even tell us how long that inflation lasts. LQC predicts a period of inflation twice as long as cosmological observations tell us it really lasted. That's not bad, Mielczarek thinks – it could have been 10, 10 thousand or 10 trillion times too big. And at least there is a value. "I don't know any other model where the duration of inflation is computable," he says.

The LQC model does have a peculiarity – one that has caused celebration and consternation in equal measure. If you squeeze the universe a little harder, so that it goes beyond the moment of silence, light begins to move again, albeit in a pretty weird way. On this side of the silence, its speed turns out to be an imaginary number, the square root of a negative number. In the equations, that means time has actually turned into space. We get four dimensions of space and absolutely no time.

All roads converge

Although that is a conceptual problem for most of us, for Barrau and his colleagues it provided a eureka moment. It chimes, they say, with the way Stephen Hawking and James Hartle envisaged bypassing the singularity. They managed to do this using a universe with four space dimensions and no time.

Others, like Martin Bojowald at the Pennsylvania State University, see this transition to 4D space as a problem. Bojowald finds the consequences of this model fascinating, but thinks the way Barrau and his colleagues have modelled quantum fluctuations is misguided and is likely to have pushed them away from reality.

Not that he knows how to do it better, he admits. "The result shows us a lot of new issues that people hadn't expected," he says. "This might actually be very stimulating." Singh is not quite so benevolent. He sees the moment of silence as a consequence of assumptions that are "very preliminary and speculative", as he puts it. "The conclusions are quite premature and unlikely to be true."

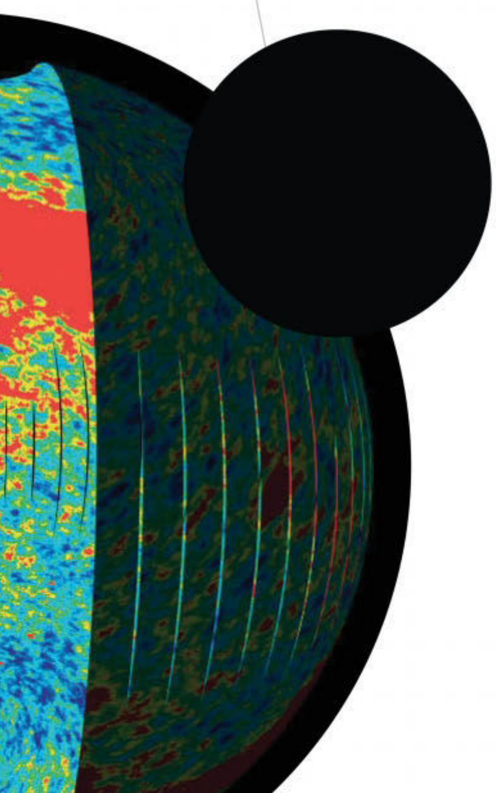
It will be a long time before we can properly test any of these models against the real universe. The best chance lies in subtle features of the cosmic microwave background radiation. Data from the European Space Agency's Planck satellite, for instance, has created our most detailed map of this radiation across the entire sky. Even so, the craft didn't have the sensitivity to check the LQC model of creation. "We'll have to wait for post-Planck measurements," Barrau says.

If Carlip is arm-twisted into speculation, he thinks there is a chance that maps of the cosmic microwave background made by the BICEP2 telescope could be probing regions relevant to the big silence or disappearing dimensions. "It's conceivable that some observational signature exists," he says. He has no clue what it might look like, though.

The LQC researchers agree that nothing is visible yet, but other clues could come from experiments firmly rooted in the laboratory (see "Tabletop cosmology", left).

It is highly speculative stuff, of course – too speculative for some. But the synergy between various quantum gravity models provides good reason to keep exploring this territory. Singh points to the resonance between LQC and CDT when looking at the moment space-time turned from quantum to classical. Even though they arise from very different starting points, both approaches give a fully classical space-time before the universe has had a chance to expand significantly. "This probably tells us that the results are a reflection of a deeper truth about the quantum nature of space-time," Singh says.

Hossenfelder is also excited about the commonalities. "Each approach has its pros and cons," she says. But if different paths lead us to similar conclusions, Hossenfelder thinks we should certainly pay attention. "It looks like this convergence is trying to tell us something." Shhh... ■



ESA/C. CARREAU/SPL

QUANTUM BOUNCE

CAN EXPLODING BLACK HOLES REVEAL THE TRUE FABRIC OF SPACE-TIME? STUART CLARK PICKS AT THE SEAMS

ON 2 NOVEMBER 2012, an intense burst of radio waves flashed across the skies above the Caribbean island of Puerto Rico. There was no spectacular fireworks display visible to human eyes, but the signal was captured by the 305-metre-wide radio dish of the Arecibo Observatory, nestled among the island's forest-covered peaks.

Radio astronomers had been waiting for one of these for a while: a fast radio burst. Lasting only a few thousandths of a second, these super-bright pulses are thought to come from deep space, and are extremely rare. The Arecibo burst was only the eleventh ever detected. There was a suspicion that all previous readings, from a single radio telescope in Australia, were down to a technical glitch.

They weren't. But what these strange pulses are remains a mystery. Some think they come from super-dense stars or black holes dancing with those stars. Some have even floated the idea – one few people are willing to buy – that they could be "hailing signals" from aliens.

The latest idea is that they could encode something equally astonishing: a signal from black holes behaving in an entirely new way. If so, it would transform our understanding of these most enigmatic cosmic objects, and mark the beginning of the end of a quest to reconcile two fundamentally irreconcilable descriptions of the physical universe. It might even explain the beginning of it all.

"That's our big excitement for all this," says theorist Hal Haggard of Bard College in Red Hook, New York, who has worked on the theory. "But I'm being a little cautious."

The idea grows out of the rift between general relativity, which explains how space and time curve to create gravity, and quantum theory. Quantum theory describes the behaviour of natural force fields, such as those associated with electricity and magnetism, and the subatomic particles, or quanta, that make up those fields. To do this, it assumes that space and time are a fixed and rigid framework through which these fields pass – while general relativity, formulated by Einstein just over 100 years ago, insists that space and time are malleable fields in their own right. But if space-time is a field, presumably quantum theory must apply, meaning it can be subdivided into little bits.

It's a fundamentally confusing picture, and nowhere does that become more dramatically apparent than in our attempts to understand black holes. These regions of space-time in which matter is so dense and gravity so overwhelming that nothing can escape are, in essence, the ultimate cosmic trash compactors. Once something falls in, whether it's a photon or an idealistic NASA pilot thrown off course by a Hollywood scriptwriter, it never comes out.

At least this is what general relativity tells us. According to Einstein's theory, all matter

ends up at the centre of the black hole where it forms a singularity: a pinprick of infinite density at which the laws of physics break down. This is where today's cosmologists disagree with Einstein. "No physicist really believes that is what happens," says Haggard.

Hence the search for a successful theory of quantum gravity, which would explain how gravity behaves over extremely small distances, such as those in the centre of a black hole. The problem is, we have little clue what such a theory would look like. General relativity has never flunked a test; no one has ever measured a signal that it can't neatly explain. Until we do, theorists are working in the dark.

"We are in dire need of a guiding light to show us the correct path to quantum gravity," says theorist Thomas Sotiriou at the University of Nottingham, UK. "It would be one of the most important discoveries you could make." Hence the interest in the fast radio bursts. "If you could observe a black hole doing something that does not come from general relativity, that would be a revolution," says Sotiriou.

LOOPY BITS

The new idea comes from work Haggard did with Carlo Rovelli, a theoretical physicist at the University of Aix-Marseille, France. Rovelli is one of the founders of a model for a unified theory known as loop quantum gravity. It proposes that space-time is made of interlocking loops that form a fabric akin to chain mail. When seen from afar, this fabric looks smooth and continuous, but viewed close up it is woven from tiny, indivisible pieces. These loops would be the fundamental quanta of space-time; nothing could be smaller.

When Rovelli and Haggard considered what loop quantum gravity would mean for black holes, they came up with a startling conclusion: a black hole would eventually reach a density at which loopy bits of space-time could shrink no more. According to their calculations, there would be no singularity. Instead the loops would generate an outward pressure, resulting in a "quantum bounce" – an explosion that would destroy the hole. ›

BOSE COLLINS

This is not the first time physicists have toyed with black holes doing unexpected disappearing tricks. Stephen Hawking suggested a mechanism based on the laws of thermodynamics, which govern heat and energy, that would make a black hole evaporate, albeit over a stupendous length of time. More recently, Abraham Loeb of Harvard University suggested that black holes could appear to explode if they were surrounded by a veil of matter that suddenly dissipated.

Rovelli and Haggard's bouncing black holes are different. Most importantly, their quantum bounce would create a white hole, a massive object that spews out particles and radiation. "It's like running a movie of a black hole in reverse," he says. "The white hole emits particles but never absorbs them."

Haggard has calculated that white holes are possible under the mathematical rules laid out by the equations of general relativity for the behaviour of space-time. But that does not mean a black hole actually does turn into its belching alter ego. "Stitching together different space-time solutions does not prove it is possible for a black hole to evolve into a white hole," says Sotiriou.

Haggard and Rovelli think the transition could be the result of a quantum phenomenon called tunnelling, which allows subatomic particles to spontaneously change from one state to another. Quantum tunnelling underlies nuclear fusion, among other things. In our sun, it allows protons to overcome an otherwise insurmountable energy barrier in order to fuse and release energy.

It is not so crazy to think that quantum gravity could be subject to the same peculiar ways. Haggard and Rovelli's idea is that all the matter collapsing to form a black hole singularity can never actually reach that point.

"AT STAKE ARE NOT ONLY BLACK HOLES AND SPACE-TIME, BUT THE START OF EVERYTHING"

As it approaches the size of an individual space-time loop, the probability that the entire black hole undergoes a quantum tunnelling event becomes greater and greater, until boing! It suddenly becomes a white hole (see diagram, below).

Not everyone is convinced: Sotiriou for one thinks the process is too much of a conceptual leap. "That definitely goes against conventional wisdom," he says. "I think that needs clarification before this idea can be taken seriously."

The best way to persuade the doubters would be to spot a black hole in the throes of such an explosive reversal. In 2014, Rovelli and two colleagues – Aurélian Barrau at the University of Grenoble in France and Francesca Vidotto of Radboud University in Nijmegen, the Netherlands – set out to determine how such an event would make itself known.

They got together at a conference in Trieste, Italy, and calculated that an exploding black hole would generate signals at a wavelength equal to its diameter. In that sense, black holes are rather like loudspeakers: larger ones transmit longer wavelengths, or lower pitches, than smaller versions. Assuming that the exploding specimens were primordial black holes – a class of small black hole thought to have formed in the gravitationally violent aftermath of the big bang – they came up with a wavelength of a few millimetres. In other words, the expected signal was on the boundary between infrared and radio waves.

This rang a bell for Vidotto. She thought back to the mysterious ping from the Arecibo Observatory, and realised that its wavelength was in the same ballpark as their prediction for a signal from bouncing black holes.

That was especially exciting given how rare these events seem to be. Fast radio bursts were discovered in 2006, when radio astronomer Duncan Lorimer, then newly arrived at the University of West Virginia in Morgantown, was sifting through an old set of data from the Parkes Observatory in New South Wales, Australia. One signal stood out. "We just didn't know what to make of it, it was so bright," says Lorimer. After a further hard look, he concluded that the signal was not a technical snafu and almost certainly came from the far reaches of the universe – although he could not figure out what had produced it.

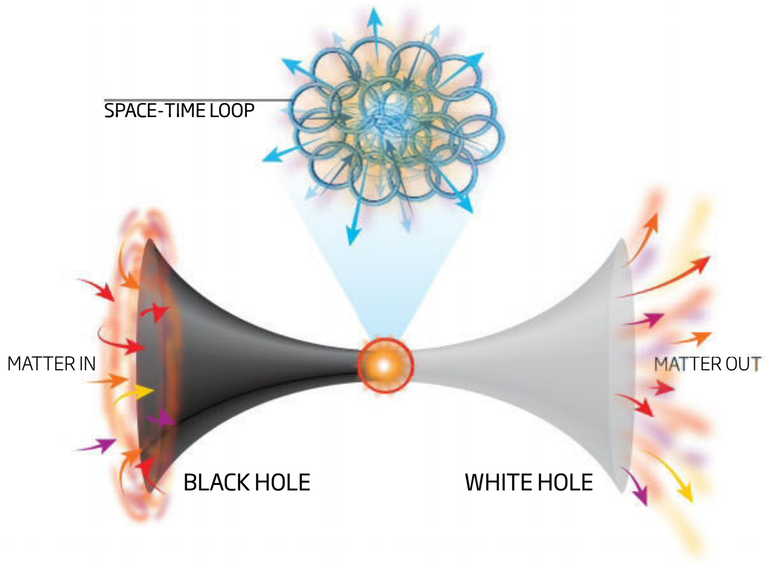
Only nine more of these fast radio bursts have been detected since, all from Parkes data, leading to questions about whether it was a quirk of the telescope – that is, until 2012 and the Arecibo signal.

It is easy to see why Rovelli and his colleagues are energised by that burst, which was announced to the world in 2014. But though their predictions for an exploding black hole signal and the fast radio bursts so far are a close match, they are not a perfect one. Then again, the calculations are based on an estimate for the mass of a black hole, which is in turn based on an estimate of how long a bounce would take.

Narrowing things down means tweaking the theory to take into account effects such

Ultimate rebound

According to the theory of loop quantum gravity, space-time is made of tiny, indivisible loops. As a black hole collapses, the pressure of these loops could cause it to rebound explosively, forming a "white hole" that spews out matter



YURY PROKOPENKO/GETTY

Australia's Parkes Observatory saw most of the mysterious radio bursts

as time dilation. Under the laws of relativity, time slows down in a gravitational field. The stronger the force field produced by a massive object, the slower time will run. A clock on a spacecraft orbiting 10,000 kilometres above Earth runs faster than a clock on the surface because the planet's gravitational field weakens with distance. So in a black hole, where the field is about as strong as it can be, time pretty much comes to a standstill – for an outside observer at least.

The twist is that we experience time passing at the same rate wherever we are. So let's imagine you could witness a quantum bounce from inside a black hole. For you the explosion would take milliseconds, but for anyone outside it would appear to take billions of years because the black hole generates such a strong gravitational field.

Now consider that the more massive the black hole, the stronger its gravity and so the greater the extent of the time dilation, meaning bigger black holes would appear to take longer to bounce. This gives Rovelli and his colleagues a potential way to test their hypothesis. Primordial black holes are generally tiny, isolated objects, their size fixed at their birth shortly after the big bang. If the theory is right, they are like ticking time bombs whose clock is set by their mass. The smaller ones will experience less time dilation, and so from our perspective will explode earlier in cosmic history. These explosions should also generate fast radio bursts at shorter wavelengths.

In other words, distant fast radio bursts should have shorter wavelengths than nearby ones – a pattern we would not expect to observe if the bursts had any other origin. "If we saw this, it would be extremely strong confirmation for our idea," says Rovelli.

At the moment, all known fast radio bursts have been relatively close, so the change of wavelength with distance cannot yet be tested. Also, too few have been observed for serious statistical analysis. So it is a waiting game. Over time, researchers hope to detect more fast radio bursts and build up a proper data set. No one knows how long that might take.

Another type of signal thought to be produced by exploding black holes might offer an alternative route to validation: blasts of super-high-energy photons known as gamma rays. Much like radio bursts, the precise gamma ray signal emitted by an exploding black hole is determined by the total amount of matter and energy contained within. The signals would be distinct from the gamma ray bursts that astronomers regularly see, and right now we wouldn't be able to detect them.

There is, however, an observatory currently under construction: the Cherenkov Telescope Array, which will boast more than a hundred telescopes spread over two sites in Spain and Chile. It should be capable of spotting these signature bursts, but will not be finished until 2024.

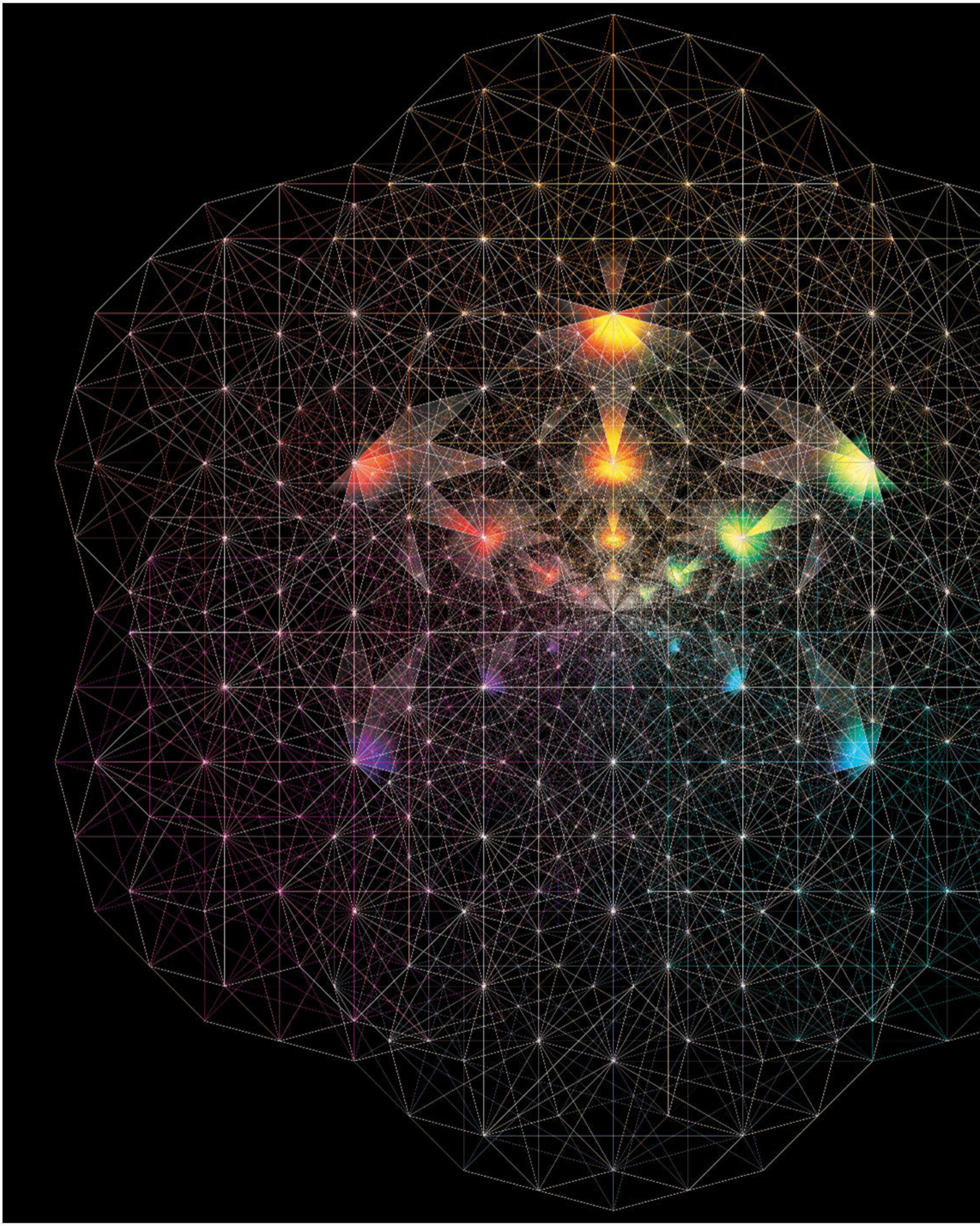
BIG BOING?

There is a lot at stake here – our understanding of not just black holes and space-time, but also the origin of the universe. There is only one other place where general relativity predicts a singularity arising: at the very moment of the big bang. But if the granularity of space-time prevents singularities happening in the first place, how did our cosmos come about? Perhaps not with a big bang, but with a big boing.

The big bounce hypothesis has been around for a while, and says that our universe was not born of an explosion that came out of nothing, but from a previous universe that collapsed. The new idea fits with that picture: as all the matter in that doomed cosmos came together in a catastrophic crunch, an enormous quantum bounce would have taken place once it reached the scale of the individual loops of space-time. This would have set our big bang in motion.

Lest anyone gets too carried away, however, there are more prosaic ideas to consider. Lorimer thinks fast radio bursts are most probably produced by young versions of rapidly-spinning neutron stars known as pulsars. This idea is "perfectly consistent with what we see", he says, and is "grounded in things that we really understand".

If so, it's a little disappointing. After all, it would resign us to yet another false start for quantum gravity. But then perhaps the mysterious signals really are the call sign of a distant alien civilisation. Maybe, if we ask them very nicely indeed, they can tell us where we are going wrong. ■



ENTANGLED UNIVERSE

Weird connections through space-time might be telling us something profound about reality. **Anil Ananthaswamy** pulls at the threads

ANDY GILMORE

IT WAS a cryptic email that Juan Maldacena pinged across the US to fellow physicist Leonard Susskind back in 2013. At its heart lay a single equation: "ER = EPR". The message clicked with its recipient. "I instantly knew what he was getting at," says Susskind. "We both got quite excited."

Excited, because that one equation promises to forge a connection between two very different bits of physics first investigated by Albert Einstein almost 80 years ago. Excited, because it could help resolve paradoxes swirling around those most befuddling of cosmic objects, black holes, and perhaps provide a route to a unified theory of physics. Excited, because it might even answer one of the most fundamental questions of all: what is reality made of?

The origins of the story lie over a century ago. In November 1915, Einstein presented the final form of his revolutionary theory of gravity to the Prussian Academy of Sciences in Berlin. The general theory of relativity overturned notions of gravity that stretched back as far as Isaac Newton's day. It said that everything that happens in the cosmos at large – be it an apple falling from a tree on Earth or the distant whirling of a cluster of galaxies – happens because stuff follows invisible contortions in space and time that are caused by the presence of other stuff. Gravity follows from the geometry of a warped space-time.

In the past century, general relativity has never failed an experimental test. Yet the suspicion has grown that it is missing something. The theory describes space-time as a malleable yet smooth and featureless backdrop to reality. Problems start when a great agglomeration of matter folds this cosmic fabric so tightly that a black hole singularity arises – an object with a gravitational pull so great that nothing can escape, not even light.

Black holes are a prediction from the earliest days of general relativity. But in the 1970s, physicists Jacob Bekenstein and Stephen Hawking derived a strange result about them: black holes have a temperature, and hence a property called entropy. This takes us into the realms of quantum theory where everything, be it forces or matter, comes in discrete chunks. Entropy measures how many ways you can organise a system's various constituents – the arrangement of atoms in a gas, for example. The greater the number of possible configurations, the higher the entropy.

Hole in the theory

But if a black hole is just an extreme scrunching of smooth space-time, it should have no substructure, and thus no entropy. For Susskind, of Stanford University in California, this contradiction points to a hole in Einstein's theory. "We know that general relativity is incomplete," he says. "Its inability to account for the entropy of black holes is probably the most obvious incompleteness of the theory."

That's a turn up for the books. In his lifetime, Einstein levelled a similar charge at quantum theory. In May 1935, the *New York Times* ran a story with the headline "Einstein Attacks Quantum Theory", reporting on a paper Einstein had written with Boris Podolsky and Nathan Rosen. It brought to light a weird property of the quantum world in

PARADOX REGAINED: THE BLACK HOLE PROBLEM

In the 1970s, Stephen Hawking showed that black holes emit radiation. The mechanism has to do with quantum mechanics, which allows pairs of quantum-entangled particles to spontaneously pop into existence. When this happens near a black hole's event horizon, one particle may travel outwards, while the other goes towards the black hole. The result is a steady stream of outgoing particles, called Hawking radiation.

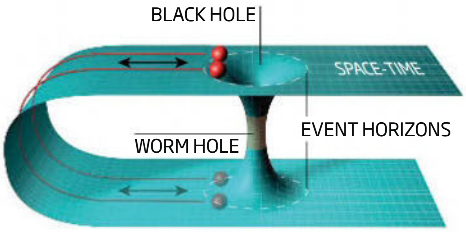
If no new matter falls into the black hole, this emission means the black hole will eventually evaporate. But matter is information, and in quantum theory information is sacrosanct: it can never be destroyed. So if a black hole evaporates, what happens to the matter, and therefore information, that fell into it?

One possible solution to this "black hole information loss paradox" is the idea that information escapes with the Hawking radiation. But in 2012, Joseph Polchinski and Don Marolf of the University of California, Santa Barbara, and colleagues showed this option creates other problems. General relativity demands that the space-time around a black hole's horizon should be smooth and featureless. It turns out that for this to be the case and for information not to be lost, a Hawking particle on its way in would have to be entangled with all other Hawking particles that left the black hole at all earlier times, rather than just its partner outside the horizon.

This offends a fundamental quantum rule known as "monogamy of entanglement" - that a quantum particle can only ever be fully entangled with one particle at a time. But if you break the polyamorous entanglement of Hawking particles, an energetic "firewall" of radiation forms at the event horizon. That, unfortunately, goes against the tenets of general relativity. Paradox preserved.

Quantum web

The fabric of reality might be woven from quantum entanglement



"Wormholes" connecting two black holes in different parts of space-time can exist - but only if particles on the black holes' surfaces are quantum entangled

which two particles could instantly influence each other, even if they were at opposite ends of the universe. In Einstein's view, this "spooky action at a distance" – quantum entanglement, as it became known – was preposterous. It was a clear sign there was something missing from the quantum description of reality.

But quantum theory has breezed through even more precise experimental tests than those devised for general relativity. And it is the very property that Einstein discovered – entanglement – that continues to expose the contradictions between the two theories. Allowing quantum entanglement and general relativity to cohabit in the contorted space-time around black holes yields unpleasant and unsustainable consequences. For example, information seems to be destroyed – an impossibility according to quantum physics – or the black hole becomes surrounded by a blazing "firewall" of energetic particles (see "Paradox regained", left).

So we need some way to square the two schools of thought – to quantise space-time and form a quantum theory of gravity. Susskind and Maldacena, who works at the Institute of Advanced Studies in Princeton, have long been leading lights in perhaps the most promising field with this aim: string theory. It replaces the point-like particles of current quantum theories with wiggling strings of infinitesimal size, and suggests space-time has a grainy substructure – you can't keep chopping it indefinitely into smaller and smaller pieces.

But if string theory does hold the answer, it's well hidden. The theory has more than 10^{500} solutions, each describing a different sort of universe – making it nigh-on impossible to find the one solution that corresponds to the geometrically flat, expanding space-time filled with the exact complement of fundamental particles we observe around us.

A startling insight from Maldacena in 1997 gave new hope. He conjectured that string theory equations describing gravity in some volume of space-time were just the same as a set of quantum equations describing the surface of that volume. If you could solve the surface equations, you could get a viable theory describing gravity inside.

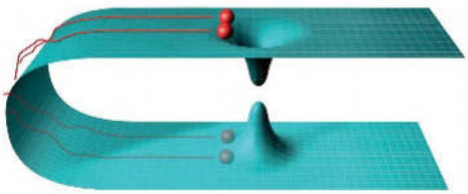
This "Maldacena duality" was a bold leap – but physicists found that it held. "The funny thing was that it was not proven, and it was difficult to even understand why this was happening," says theorist Mark Van Raamsdonk of the University of British Columbia in Vancouver, Canada. "It was very mysterious."

In 2001, Maldacena himself provided an intriguing example, going back to a paper written by – you guessed it – Einstein, again with Rosen, and again in 1935. This one exposed another peculiarity of black holes. It showed how something that looked like two separate black holes from the outside might be connected on the inside. This interior connection formed a shortcut through space-time, and came to be known as an Einstein-Rosen bridge – or in common parlance, a wormhole.

Chewing gum wormhole

The really odd thing, though, was that Maldacena's duality showed that such a wormhole would only form if the outsides of the black holes were quantum-entangled.

By 2009, the underlying mathematics was sufficiently well developed for Van Raamsdonk to explore further. Entanglement is not an on/off thing – it can exist in varying degrees. So what would happen if you were to slowly reduce the amount of entanglement between the black holes' surfaces to nothing? The answer was rather like pulling at two ends of a piece of chewing gum. "The two sides get further apart, and what's connecting them is this really thin piece of gum, and eventually it snaps," he says. The wormhole becomes



Break the entanglement, and the wormhole snaps too, suggesting entanglement is the thread that binds space-time together

thinner until it breaks, and you have two unconnected bits of space-time (see diagram, above). Reverse the process – increase the entanglement – and the wormhole starts to form again.

It took a few more years for the penny to finally drop in Maldacena's mind, and for him to make the suggestion laid out in that excited email. ER = EPR. ER – the paper Einstein wrote with Rosen in 1935 introducing the concept of wormholes. EPR – the paper he wrote with Podolsky and Rosen the same year introducing the concept of entanglement. What if, asked Maldacena, wormholes and entanglement are in fact two sides of the same coin: the same physics in two different guises?

The immediate attraction was that the principle seemed to get rid of those pesky paradoxes involving firewalls around black holes (see "Paradox lost", right). But it also provided some form of explanation for the phenomenon Van Raamsdonk's work had exposed, in which space-time in the form of wormholes could be created and destroyed simply by tweaking the amount of entanglement.

"It's pointing to a statement that is really quite dramatic," says Van Raamsdonk. "Space-time is really just some geometrical manifestation of entanglement." Maldacena comes to the same conclusion. "There is a very close connection between quantum mechanics and space-time," he says. "The continuity of space-time, which seems to be something very solid, could come from the ghostly properties of entanglement."

Susskind speculates further. Quantum entanglement is a form of information, and so "space-time is a manifestation of quantum information", he says.

Heady stuff. But does that really mean that when quantum entanglement exists between two particles – as can easily be made to happen, say between photons in a lab experiment – they are connected by a microscopic wormhole? Or that we live on a backdrop that is nothing more than the 1s and 0s of entangled information?

The short answer is we don't know. One very big caveat is that all of the work linking entanglement with space-time so far has been done with a space-time that isn't expanding. Van Raamsdonk and others are working to extend the results to the sort of expanding, accelerating space-time that makes our cosmos.

But for those involved, this is the most positive lead yet towards a theory of quantum gravity that can unify the forces of nature. The ER = EPR principle is something "that a theory of quantum gravity should obey", says Maldacena. Susskind thinks so too. "We are sure that these things are going to be part of the final story," he says. "But I don't think we have a clear picture of what that final story is yet."

Others are less convinced. Joe Polchinski and Don Marolf are physicists at the University of California, Santa Barbara, and part of the team that exposed the black hole firewall paradox. Polchinski is concerned that the ER = EPR idea will end up modifying a central principle of quantum theory, known as superposition. Exemplified by Schrödinger's cat, this principle explains that a quantum system can exist in two different states at the same time. When quantum objects become entangled, they also enter a superposition.

At first glance, the ER = EPR hypothesis would mean quantum systems that become entangled, and therefore enter a superposition, suddenly gain a wormhole – a conjuring trick the superposition principle doesn't obviously allow. That's problematic, says Polchinski. "Quantum mechanics is weird, but it works," he says. "When you give up superposition, it's just weird."

Still, he remains open to the eventuality. "In the history of science, things that seemed absolute in many important cases have turned out to be not absolute," he says – Newton's law of gravitation, for example. "Maybe superposition is one of them." Maldacena says that it's too early to say if their work is threatening the superposition principle, because the mathematics hasn't been worked out in detail.

Marolf for his part isn't convinced the ER = EPR equality works in all circumstances: Susskind and Maldacena have shown how to avoid the firewall only for a particular entangled state of black holes. "You might think that it shows how to get out of the [firewall] paradox for any highly entangled state, but that's not true," says Marolf.

Given that Einstein developed the ideas of both wormholes and entanglement, one can only wonder what he would have made of it all. "My guess is that the old Einstein would have said poppycock," says Susskind – after all, Einstein spent much of his later years arguing for a hidden reality that wasn't subject to the vagaries of quantum mechanics. "But the young Einstein apparently had a much more flexible mind. My guess [is] that the young Einstein would have embraced these ideas, loved them." ■

PARADOX LOST: THE BLACK HOLE SOLUTION

The main problem with the black hole paradox is the idea of quantum monogamy - a particle can only be entangled with one other particle at a time (see "Paradox regained", left). This means that three quantum systems - say a particle inside a black hole's event horizon, a particle outside it, and a third far, far away – can't all be entangled at the same time.

But physicists Juan Maldacena and Leonard Susskind argue that this can be resolved if the particles just inside the horizon and the particles far away are connected via a wormhole. When a wormhole connects two objects, one must lie to the future of the other.

So, although these two particles might be entangled, their entanglement doesn't necessarily conflict with the entanglement of the particle inside the horizon and its immediate partner outside the horizon - because they aren't all happening at the same time. Uncomfortable apparitions such as blazing firewalls at the event horizon disappear. Paradox removed.