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Science Focus
MAGAZINE

INSTANT GENIUS

DOES DARK MATTER REALLY EXIST?

THE HUNT FOR ANTIGRAVITY

WHAT ARE GRAVITATIONAL WAVES?

GRAVITY

THE NATURE OF GRAVITY

BY BRIAN CLEGG

What goes up must come down, as the old saying goes. But why that's the case is a mystery that took some of humanity's greatest minds centuries to figure out – and some aspects of gravity remain a puzzle

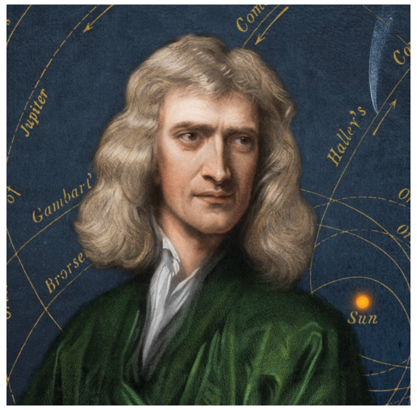
THERE ARE FOUR fundamental forces that operate in the Universe: the strong nuclear force, the weak nuclear force, the electromagnetic force and gravity. Gravity is the most obvious of these – yet it has proved a difficult puzzle to crack.

To the ancient Greeks, gravity reflected the nature of the elements. Aristotle described how earth and water had gravity, and there was a tendency of motion towards the centre of the Universe (the Earth). Air and fire, he said, had levity, which encouraged them to move away from the centre. But these tendencies were only present in the imperfect, sub-lunar realm. In the Greek world view, everything from the Moon upwards depended on the fifth element, quintessence, which allowed the heavenly bodies to rotate undisturbed.

To understand Aristotle's viewpoint, we need to forget all we learned about physics at school. Gravity was not a force – it simply described the nature of earth and water. It was their natural tendency to seek out the centre of the Universe, just as it is a dog's natural tendency to fight cats. Although gravity would be refined over the years, there were few serious challenges to Aristotle's domination of the physical sciences for 2,000 years.

DOWN TO EARTH

The great 7th Century Indian mathematician Brahmagupta briefly flirted with the idea that gravity might work in a similar way to a magnet, as did the Islamic scholar al-Biruni 300 years later, but this wasn't enough to shake Aristotle's dominance. The first cracks appeared with the transformation of the Solar System by Copernicus and Galileo. If they were correct, and the Earth travelled around the Sun – making that the new centre of the Universe – then Aristotle's model of gravity fell apart. Based on reasoning rather than observation and experiment, Aristotle's ideas required the Earth to be the centre of the Universe. If it were the Sun instead, all heavy matter should fly off into space.



Newton was the first to realise that gravity is a force that all objects, however small, exert on each other

What's more, Aristotle's model of gravity made heavy objects fall faster than light ones. With more material in them, the heavy objects should feel a stronger urge and therefore move faster. Aristotle stated this as fact – yet Galileo demolished the idea. He asked what would happen if you tied together two objects of different weight. The heavier weight, according to Aristotle, would want to fall faster and would speed up the lighter one – but the light weight should slow down the heavier one, leaving them falling at an intermediate speed. Yet the combined object was heavier than either, so the whole should fall faster. It didn't make sense.

Although Galileo almost certainly didn't, as legend has it,

> IN A NUTSHELL

The ancient Greeks thought that earth and water were drawn towards the centre of the Universe, then believed to be the Earth. But thanks to Galileo, Newton and Einstein, our knowledge of this fundamental force has come a long way since the 4th Century BC.

drop weights off the Leaning Tower of Pisa to discover that they arrived at the ground at the same time, he did experiment with pendulums that had bobs made of cork and lead, one "more than 100 times heavier" than the other, and showed that they swung (and hence fell under gravity) at the same rate. He also repeatedly rolled balls down sloping channels to measure the effects of gravity. And Galileo explicitly described a 'force of gravitation' that pulled weights towards the Earth.

But it was Isaac Newton who brought gravity fully under the auspices of science and mathematics. It's not clear whether he was truly inspired by seeing an apple fall (it certainly didn't fall on his head), though he did make this claim. In a long chat with the antiquarian William Stukeley in April 1726, the elderly Newton described how the fall of an apple made him think, "Why should the apple always descend perpendicularly to the ground?"

In Stukeley's account, Newton says that the apple is pulled by a 'drawing power' to the Earth, and that this force must be proportional to its quantity. The apple draws the Earth, and the Earth draws the apple. But more than this, Newton made the leap of proposing 'universal gravitation'. He broke Aristotle's lunar barrier and applied the same force throughout the Universe, realising that gravity was responsible for keeping the planets in their orbits, where otherwise they would fly off in a straight line.

All this and more Newton put into his masterpiece, *Philosophiae Naturalis Principia Mathematica*, usually known as the *Principia*. The book itself, originally written in Latin, is not easy to read and relies far more on geometry than we would expect today, but here we get the key understanding that the force of gravity is dependent on the masses of the objects involved divided by the square of the distance between them. This and his laws of motion were enough for Newton to describe the way that planets and moons move and the way that things fall when they drop. It was, without doubt, a triumph.

However, Newton did leave one aspect hanging – which is how this strange force acting at a distance could work. He writes in *Principia* 'hypothesis non fingo', translated as 'I frame no hypothesis'. This was a sly comment: in using the word 'frame', as in framing someone, Newton was suggesting that his competitors were making things up. Still, this gap in explanation left Newton open to attack, particularly for his use of the word 'attraction'. Today we are familiar with 'attraction' being applied to gravity, but at the time it was only used in the romantic sense. He seemed, to 17th Century ears, to be saying that the Earth orbited the Sun due to some kind of planetary crush.

Newton had not worked in isolation. His great rival Robert Hooke, for instance, had suggested that gravity was an 'inverse square law' that reduced with the square of the distance, but Hooke had been unable to manage the maths to support his idea. It took Newton to assemble the magnificent whole.

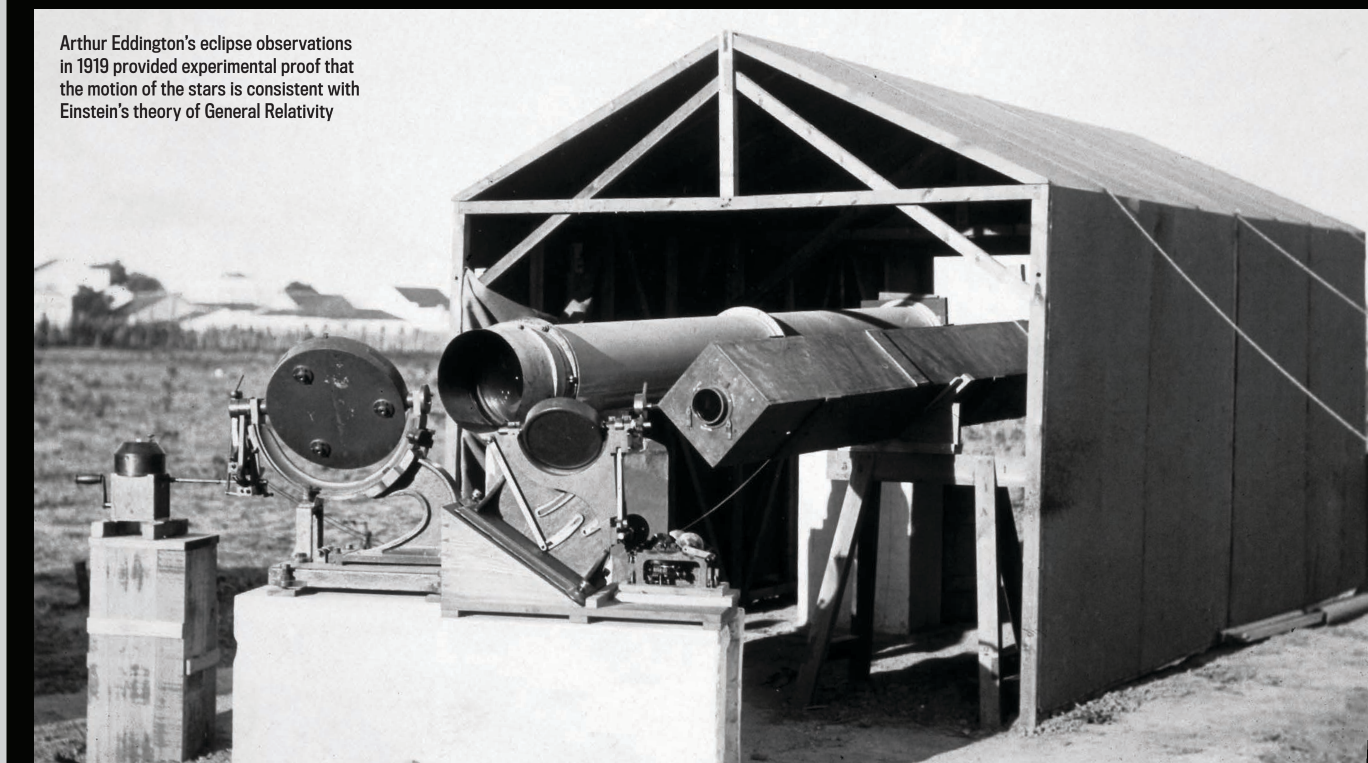
GRAVITY EXPLAINED

Despite his protestations, Newton did have some thoughts on how gravity might work. He suspected, as many did, that there was an invisible material in space that could transmit the force. Such mechanical models for gravity became more sophisticated with time. The most popular was that of Nicolas Fatio de Duillier and George-Louis Le Sage, both Swiss scientists who independently developed the idea that space was full of tiny invisible particles that constantly bombarded bodies from all directions. When something got in the way, like the Earth, it sheltered other objects from particles coming from its direction. This meant that the remaining particles pushed objects towards the Earth.

This sounded very unlikely. But it would take the remarkable mind of Albert Einstein to come up with a better suggestion. His breakthrough thought on gravity came shortly after the remarkable year of 1905,

THE KEY EXPERIMENT

Published in 1915, Einstein's theory of General Relativity caused a stir, but it wasn't until four years later that its practical effects were observed for the first time


Arthur Eddington's eclipse observations in 1919 provided experimental proof that the motion of the stars is consistent with Einstein's theory of General Relativity

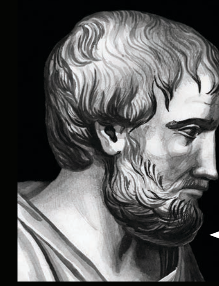
GENERAL RELATIVITY LARGELY agrees with the predictions of Newton's theories, but the most obvious difference is in the way gravity bends the path of light. When light from a star passes close to the Sun, its path should, according to General Relativity, bend inwards, shifting the star's apparent position. This could only be seen when the Sun's light is blotted out.

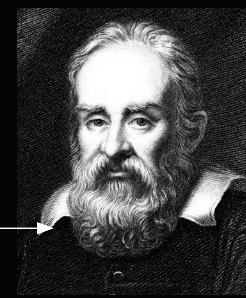
In 1919, Arthur Eddington led an expedition to Principe Island off West Africa to make measurements during the total eclipse on 29 May. That morning brought thick cloud and rain until around noon. With the eclipse due at two, hopes were low. Eddington commented, "We had to carry out our photographs in faith. I did not see the eclipse, being too busy changing plates, except for one glance to make sure that it had begun, and another halfway through to see how much cloud there was. We took 16 photographs." But image after image showed no clear stars; only two plates proved usable. Yet with supporting information from an expedition to Sobral in Brazil, Eddington confirmed General Relativity's predictions and boosted Einstein to celebrity status.

Ironically, later tests suggest Eddington could not have had accurate enough measurements to confirm the theory. But since then, huge amounts of data have proved Einstein's predictions rock solid.

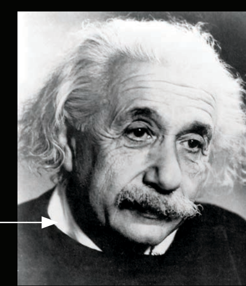
CAST OF CHARACTERS

Five great thinkers whose work was crucial in shaping our understanding of gravity


Aristotle
(384-322 BC)
The definitive ancient Greek philosopher, born in Stagirus, Aristotle set the agenda for science for over 1,800 years. This is a pity, as his theories – based on reasoning rather than observation – were almost universally misleading. Gravity as Aristotle saw it was a tendency for heavy things to prefer the centre of the Universe.


Galileo Galilei
(1564-1642)
This natural philosopher from Pisa believed in the importance of experiment, and as a result dismissed Aristotle's ideas on gravity. Though famous for being tried for promoting the Copernican model of the Solar System, Galileo's greatest contribution was his methodical exploration of mechanics and motion, including the influence of gravity.


Isaac Newton
(1643-1727)
The greatest English physicist. Most of his work on light, motion, gravity and calculus was done in Cambridge, though much was achieved when he was confined to his home in Lincolnshire due to the plague. He was later an MP, Master of the Mint and President of the Royal Society – but physics remains his most significant legacy.


Albert Einstein
(1879-1955)
Einstein was born in Ulm, Germany, though he was a Swiss citizen from his teens. He produced three papers in 1905, while working in the patent office, that would show atoms were real, lay the foundation of quantum theory and establish Special Relativity. His theory of General Relativity from 1915 is still the standard theory of gravitation.


Arthur Eddington
(1882-1944)
Born in Kendal in the Lake District, Eddington worked as an astronomer and astrophysicist in Cambridge. When asked if it were true that only three people in the world understood the theory of General Relativity, Eddington is said to have replied, 'Who is the third?'

TIMELINE

Six important steps on the road to our modern understanding of how gravity works

350 BC

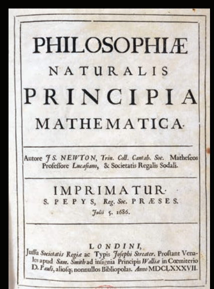
Aristotle adds *The Physics* to his works, a collection of eight books that describe his theories on the behaviour of natural and moving things, including gravity and the opposing concept of 'levity'.

1638

Galileo's last book, *Discorsi E Dimostrazioni Matematiche, Intorno À Due Nuove Scienze* [*Discourses And Mathematical Demonstrations Relating To Two New Sciences*] is published, including his ideas on gravitation.

1687

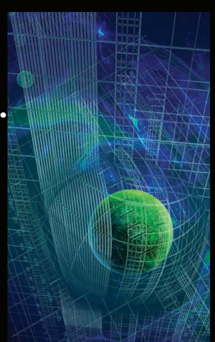
Newton's *Philosophiae Naturalis Principia Mathematica* is published, a three-volume work in which he outlines his theory of gravity as well as his famous laws of motion.


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA
IMPRIMATUR
LONDINI,

1907

Sitting in his office in the Swiss Patent Office in Bern, the amateur scientist Albert Einstein discovers the 'principle of equivalence', which states that gravity and acceleration are indistinguishable.

1915



Albert Einstein publishes a series of papers on his General Theory of Relativity, which describes gravity as a warp in spacetime that is caused by massive objects.

1919

Arthur Eddington observes a solar eclipse on Principe Island, demonstrating the shift of stars appearing near the Sun. He uses this as confirmation of General Relativity.

PHOTO: ALAMY, SCIENCE & SOCIETY, SCIENCE PHOTO LIBRARY

when Einstein wrote three papers that transformed physics. These established the existence of atoms, formed the foundations of quantum theory (for which he won his Nobel Prize) and introduced Special Relativity, which showed how apparently fixed quantities like mass, length and the flow of time varied depending on your viewpoint.

Two years later, Einstein was sitting in the patent office in Bern and had what he described as his happiest thought. Einstein later commented: "All of a sudden a thought occurred to me: if a person falls freely, he will not feel his own weight. I was startled. The simple thought made a deep impression on me. It impelled me towards a theory of gravitation."

GRAVITY AND LIGHT

What Einstein had realised was that gravity and acceleration were equivalent and indistinguishable. If, for instance, you were in a spaceship with no windows and found that you were experiencing a pull of 1g, there are two possible explanations. You could be sitting still on the surface of the Earth, or you could be in space and the craft could be accelerating at 9.81 metres per second per second – the same acceleration as due to Earth's gravity. Your instruments could not detect a difference. But if this is true it tells us something odd about gravity.

If we imagine a beam of light crossing the accelerating spaceship, the beam will appear to bend to someone inside the ship as a result of its motion. But since acceleration and gravity are equivalent, the same light beam should also bend in a gravitational field. Einstein had realised that gravity warps space, twisting it near a massive body so that anything travelling in a straight line curves around it. This is as true of an orbiting planet as it is of a beam of light.

In fact, his discovery proved stranger still. While the warping of space explains the orbits of the planets, it doesn't tell us why the apple falls. There is no reason for something to start moving. But it is space-time – the mash-up of space and time that emerged from Special Relativity – that is warped by massive objects, and it is the warp that initiates motion. The mathematics to support all this is fiendishly complex – even Einstein had to get help to understand it – but the principle is simple enough.

Einstein had given Newton's theory a framework, a reason for working. More than that, General Relativity, as Einstein's theory became known, made some predictions that were different from those Newton would have expected – and experiments have verified that it is General Relativity that matches reality.

It seemed in many ways that the theory of gravitation was complete. Einstein's development would be used to predict everything from the existence of black holes to the way the Universe changes with time. But there is still one big gap in our understanding. All the other forces of nature are quantized. They aren't continuous, but are granular with tiny divisions called quanta. The expectation is that there should also be a quantum theory of gravity, but as yet one has not been established. For a while it seemed as if string theory would provide the answer, but there is increasing concern that this mathematically-driven concept will never make useful predictions, leaving growing interest in alternative theories like loop quantum gravity.

NEED TO KNOW

Key terms used when discussing the nature of gravity

1 FUNDAMENTAL FORCES
The four forces of nature: gravity, electromagnetism and the strong and weak nuclear forces. Between them they're responsible for all interactions between particles (and between matter and light).

2 INVERSE SQUARE LAW
This describes a quantity that gets smaller as the square of a value gets bigger. For instance, if you double the distance between two bodies the gravitational pull is reduced by a factor of four.

3 MASS
A concept introduced by Isaac Newton to describe the amount of matter present. The mass of a body is what causes its gravitational attraction and doesn't vary, whereas its weight is the force of gravity on the mass at a particular location.

4 RELATIVITY
Galileo observed that motion is relative. If we move at the same velocity as something else, it doesn't move with respect to us. Einstein developed this idea in his theories of Special Relativity, reflecting the effect of the fixed speed of light, and General Relativity, which brings in gravity and acceleration.

String theory, also known as M-theory, is an attempt to reconcile gravity and quantum mechanics, but supporters of the theory have so far been unable to demonstrate any of its predictions experimentally

GRAVITY AND US

Our modern understanding of gravity reveals that it's far more important than the ancients thought. Gravity not only keeps things in place on the Earth, it was responsible for the formation of the Solar System as it coalesced out of a spinning cloud of dust and gas. It's gravity that produces the temperature and pressure in the Sun that, along with quantum effects, make it undergo nuclear fusion to generate the heat and light that gives us life.

Experiments in space have even shown that gravity is essential for living things. Plants struggle to grow with no gravity to direct their roots. In an experiment on the International Space Station, it has been shown that birds' eggs need gravity to develop. And human beings deteriorate in low gravity, losing bone density and muscle tone, while lungs suffer compression as organs drift upwards with no gravity to keep them in place.

Gravity maintains some secrets. We don't know, for instance, why it is so much weaker than the other forces. If you doubt this, compare it with electromagnetism: in picking up a paperclip, a small fridge magnet overcomes all the gravity the entire Earth can muster. Nor do we know how to bring gravity into the quantum fold. But thanks to the work of Newton and Einstein, this fundamental force is no longer a total mystery. ■

BRIAN CLEGG is a popular science author with books including *Gravity: Why What Goes Up, Must Come Down*

Find out more

Listen to an episode of BBC Radio 4's *In Our Time* with Melvyn Bragg on the hunt for the graviton: **http://bbc.in/KsKLYr**

SOMETHING'S WRONG WITH GRAVITY

A new theory could rewrite the laws of physics as we know them, and finally explain what dark matter is

WORDS: ***PROF ROBERT MATTHEWS***

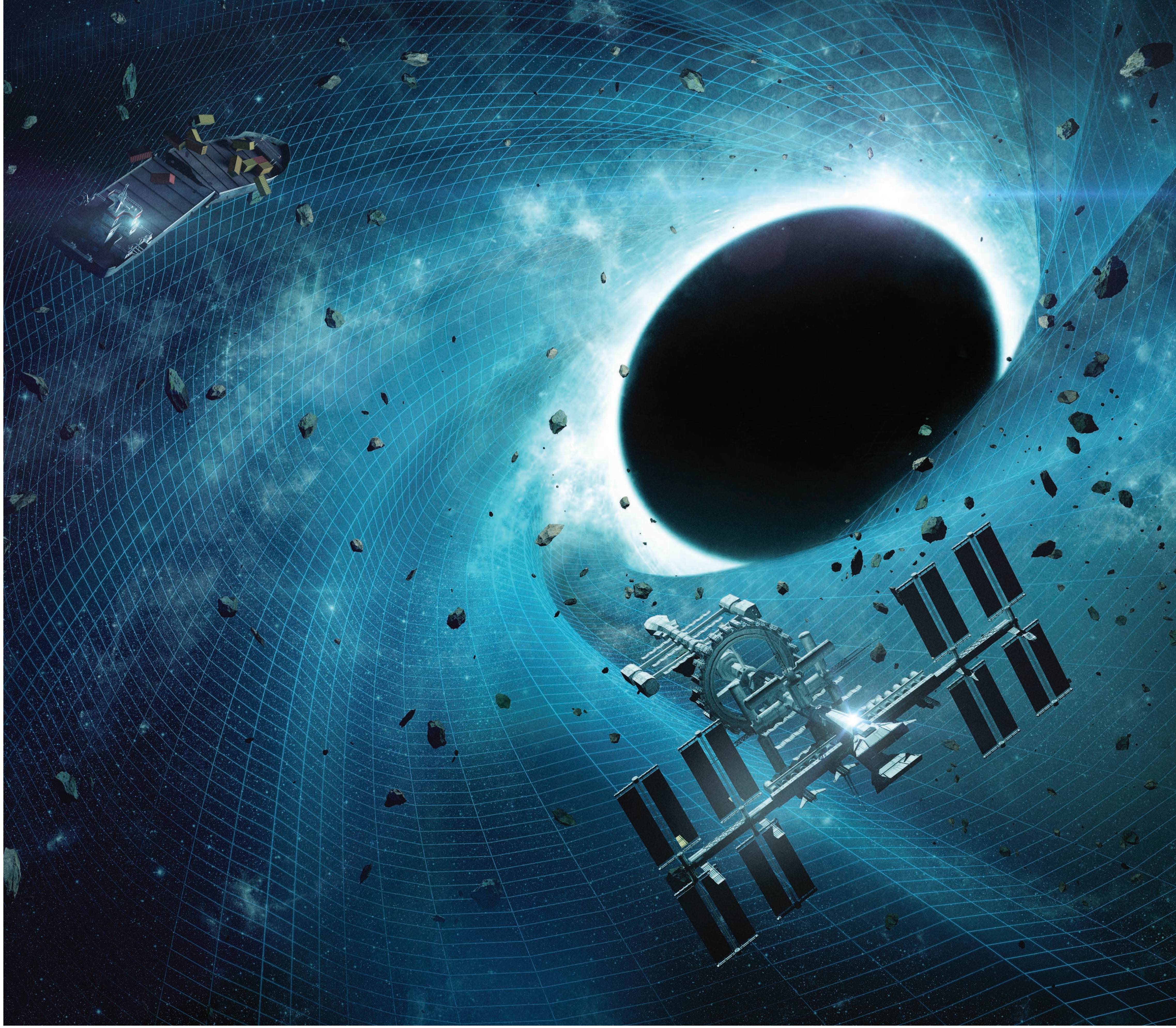


ILLUSTRATION: MAGIC TORCH

SCIENTIFIC RIDDLES DON'T COME MUCH MORE BAFFLING

Scientific riddles don't come much more baffling than this: entire galaxies seem to be in the grip of something that affects their behaviour, but no one knows what this 'something' is. If it's a form of matter, then it must be the most abundant matter in the cosmos, yet all attempts to get a sample of it have failed. Not even the Large Hadron Collider has seen a glimpse of it. It remains as enigmatic as its name: dark matter.

Now, one theorist has provoked controversy with a devastatingly simple explanation for why dark matter still hasn't been found: it doesn't exist.

But that's not the only reason Prof Erik Verlinde of the University of Amsterdam is attracting so much attention. After all, others have previously suggested dark matter may be some kind of illusion.

What sets Verlinde apart is his explanation for the source of the illusion. He believes it's the result of nothing less than a fundamental misconception about the most familiar force in the Universe: gravity.

It's a claim that brings Verlinde up against the work of some of the greatest minds in science – including Albert Einstein, whose celebrated theory of gravity is one of the cornerstones of modern physics. Known as General Relativity, it has led to a host of triumphs, including the detection in 2015 of gravitational waves – ripples in the fabric of space-time caused by the collision of two black holes.

THE TRUTH ABOUT GRAVITY

Verlinde has spent years piecing together clues from theory and observation to create a whole new vision of the force we call gravity. Now his ideas are being put to the test, with intriguing results. And at the centre of them all is the mystery of dark matter.

Verlinde has been hailed as the intellectual successor to Einstein in the media, yet he sees his goal in more down to earth terms. "I'm just trying to explain where gravity comes from," he says.

That might seem a bizarre statement, coming a century after Einstein showed that gravity is the result of matter warping space and time around it. Yet according to Verlinde, this overlooks the fact that General Relativity remains just a description of the force we call gravity. It leaves unanswered the key question of exactly *how* matter affects space and time.

To carry out his research, Verlinde has had to grapple with some of the deepest problems in science, including the quest for the so-called Theory of Everything – a theory that unites gravity with quantum mechanics that has been considered the holy grail of physics for decades.

Theorists have long known that General Relativity cannot be the last word about gravity. That's because it fails to incorporate the other cornerstone of modern physics, quantum theory. As well as describing the subatomic world with astonishing precision, quantum theory has been able to account for all the fundamental forces of nature apart from one: gravity. Since the 1950s, theorists have tried to marry the two views of nature to produce one overarching theory.

The problem, says Verlinde, is that they are based on such radically different views of reality. For example, General Relativity presumes that it's possible to pin down precisely where particles are and how they're moving, while quantum theory shows that's impossible. "So taking gravity into account gives us a bit of a problem", explains Verlinde.

For years, he worked on superstring theory, which many believe to be the most promising way of overcoming these problems. Yet despite decades of effort and a host of mind-boggling ideas, there is still no hard evidence that it works.

This has led Verlinde down a different path in search for the truth about gravity. The origins of this truth lie in a series of surprising connections between gravity and an apparently unrelated part of science: thermodynamics, the physics of heat.

In the early 1970s, theorists studying black holes – notorious for the intensity of their gravity – discovered they must also be packed with something called entropy. Widely used to understand the behaviour of hot objects, entropy reflects the number of ways of rearranging the constituents of objects without changing their appearance. Calculations showed that black holes contain the highest possible entropy that can be crammed into a given volume of space. But they also

PHOTO: ILVY NJIOKIKTJIEN

RIGHT: **Erik Verlinde argues that dark matter doesn't exist**

revealed something else. Common sense suggests that as it depends on the constituents of objects, the entropy of a black hole should depend on its volume. Yet theorists found it depends only on the hole's surface area. Stranger still, the calculations suggest the black hole's surface is made up of a vast patchwork of so-called Planck areas. Named after the eponymous German pioneer of quantum theory, Planck areas are far smaller even than a subatomic particle, and appear to be the building blocks of space-time itself.

Pondering these mind-bending connections between the physics of heat and space-time, Verlinde began to wonder if they were hints of a radical new way of thinking about gravity. Heat was once thought to be a fundamental property of matter that exists in and of itself, like electric charge, for example, but it's now known to ultimately be the result of collisions between the millions of atoms and molecules that make up a gas, liquid or solid. The faster the atoms and molecules that make up a material move, the more energy they have and the hotter the material

BELOW: Visualisation of dust falling into a black hole. The bright flash of light is Hawking radiation – one way in which black holes can lose mass

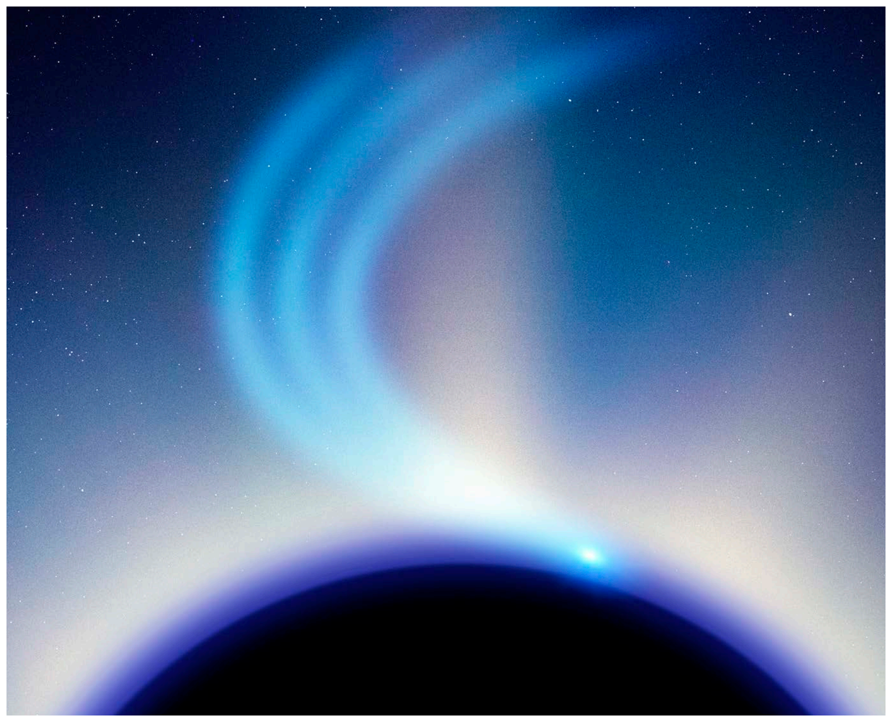


PHOTO: SCIENCE PHOTO LIBRARY

JARGON BUSTER

Swot up on your physics with our handy glossary, by popular science writer **Brian Clegg**

ENTROPY

Central to the second law of thermodynamics, entropy is a measure of the disorder in a system. It reflects the number of different ways the components of a system can be rearranged. The letters making up the words on this page have low entropy – there's only one way to arrange them (assuming each individual a, b, c, etc. is unique) to produce the text you're reading. But if you scramble the letters, it will have higher entropy, as there are lots of ways to arrange them jumbled up. The second law of thermodynamics reflects that it's easier to go from an ordered page to scrambled letters than it is to go from a pile of letters to the contents of this magazine. Similarly, it's easier to break an egg than to unbreak it.

FUNDAMENTAL FORCES OF NATURE

Physics recognises four fundamental forces: electromagnetism, which deals with interactions in matter and light; the strong nuclear force, which holds the particles of atomic nuclei together; the weak nuclear force, which is involved in nuclear decay; and gravity. All except gravity fit with quantum theory.

GENERAL RELATIVITY

The General Theory of Relativity, published by Einstein in 1915, explains how mass warps space and time, and how these warps influence the way that matter moves. It provides equations that give us a precise description of gravity, indirectly predicting phenomena like black holes, gravitational waves and the Big Bang.

GRAVITATIONAL LENSING

Einstein's General Relativity predicts that massive objects warp space enough to make passing light curve around them. This means that large cosmic structures like galaxies can act like lenses. Light coming from behind the galaxy is bent around it towards the viewer, bringing distant bodies into focus.

MOND

This stands for Modified Newtonian Dynamics – a theory that expands on Newton's laws of motion. It offers a potential explanation for the unexpected behaviour of spiral galaxies and galactic clusters usually attributed to dark matter. It is based on the idea that the effect of gravity behaves in a subtly different manner on a vast scale. Even so, it still doesn't explain all the observed oddities – but then neither does dark matter.

PLANCK AREAS

German physicist Max Planck mathematically derived the Planck length, a unit of distance around 100 billion billion times smaller than the nucleus of an atom, using constants of nature such as the speed of light. If space is not continuous but made up of quanta – the minimum amount of a physical property that can be interacted with – it has been suggested that its quanta might be a Planck length across (see below for more on quantum theory). Below this distance, measurement would not be possible. A Planck area is a Planck length squared. In black hole theory, when a black hole absorbs a single bit of information, its event horizon – the boundary around it from which not even light can escape – expands by one Planck area.

QUANTUM THEORY

This theory describes the behaviour of light and matter on a very small scale – that of individual particles such as atoms, electrons and photons. The theory takes its name from its central idea that phenomena are not continuous in nature but are instead broken down into tiny indivisible chunks or packets called quanta. In classical mechanics, objects always exist in a specific place at a specific time. But in quantum theory we can only determine the probability of an object being in a certain place at a certain time. This seems counter-intuitive, but the theory is incredibly successful in explaining the interactions of light and matter.

STRING THEORY

String theory was devised to explain inconsistencies in particle physics. It is a leading approach in the attempt to produce the so-called Theory of Everything. In string theory, particles are replaced with vibrating strings, but for the maths to work there need to be nine spatial dimensions rather than the three we observe.

THERMODYNAMICS

Originally developed to provide a theoretical basis for the design and operation of steam engines, thermodynamics – literally the movement of heat – is now a fundamental area of study in physics. It has four laws, of which the most important are the first 'energy is always conserved', and the second 'heat always moves from a hotter to a colder body'. The second law also shows that, on average, in a system that's isolated from its surroundings, entropy stays the same or increases – to decrease it requires energy.

TULLY-FISHER RELATION

The amount of light energy emitted by a spiral galaxy such as the Milky Way is roughly proportional to its speed of rotation. The faster the galaxies spin, the brighter they are. This is known as the Tully-Fisher relation, named after the astronomers Brent Tully and Richard Fisher who discovered it.

"IT IS TIME WE NOT ONLY NOTICE THE ANALOGY, AND TALK ABOUT THE SIMILARITY, BUT FINALLY DO AWAY WITH GRAVITY AS A FUNDAMENTAL FORCE"

appears. Thus heat is actually an 'emergent' property. So could the supposedly fundamental force of gravity also be emergent, its real origins being linked to entropy and those incredibly tiny Planck areas of space-time?

NEWTON AND EINSTEIN

In 2010, Verlinde created a stir among theorists when he published a paper showing how his theory could be used to accurately derive both Newton's and Einstein's laws of gravitation. "The similarities with other known emergent phenomena such as thermodynamics have been mostly regarded as just suggestive analogies," declared Verlinde. "It is time we not only notice the analogy, and talk about the similarity, but finally do away with gravity as a fundamental force."

While intriguing, many theorists remained unconvinced the finding was anything more than a quirk of physics. Verlinde needed to come up with something that didn't merely reproduce existing theories, but predicted something new – and testable. He now believes he's found it with the enigma of dark matter.

While hints of its existence emerged over 80 years ago in studies of clusters of galaxies, it was a discovery of a curious effect inside galaxies that first convinced astronomers to take dark matter seriously.

According to Newton's law of gravity, stars further from the centre of a galaxy should orbit more slowly than those closer in. But during the 1970s, studies of stars within spiral galaxies showed that beyond a certain distance from the centre, this effect simply vanished. The most obvious explanation was that the stars were being affected by the gravity of an invisible cloud of matter surrounding the galaxies. It soon became clear that whatever this stuff was, it couldn't be made from the standard building blocks of matter. That sparked a global effort to detect a viable alternative, which continues to this day – with no success.

This has led to growing suspicions that the most obvious explanation is simply wrong. In 1983, physicist Prof Mordehai Milgrom of the Weizmann Institute in Israel, pointed out a curious fact about the galactic evidence for dark matter: it can also be explained if Newton's law fails to accurately explain the motions of stars in the outer reaches of galaxies feeling an acceleration due to gravity at a rate less than a certain critical value: around 100-billionth that generated by the Earth.

TESTING, TESTING

While intriguing, what Milgrom called Modified Newtonian Dynamics (MOND) simply replaced one mystery with another: where did this 'critical acceleration' come from? That's what Verlinde decided to find out using his ideas of emergent gravity. "I quickly found a back-of-the-envelope calculation that might explain it, but I had to work for a number of years to make this more precise," he says. And now believes he has succeeded.

The key lies in the effect of the entire Universe on the vital ingredient needed for the existence of gravity: entropy. According to both Newton and Einstein's theories, the entropy of objects like black holes increases with their area. But Verlinde has shown things change on the scale of the whole Universe, because of dark energy. First identified in the 1990s, dark energy is a kind of anti-gravitational force that is propelling the expansion of the Universe. Its origins remain mysterious, but calculations by Verlinde show that dark energy leads to entropy increasing with volume, not just area. That changes the behaviour of gravity at cosmic scales – and, says Verlinde, the result is an acceleration effect creating the illusion that dark matter exists.

"In an expanding Universe, the gravitational laws have to be adjusted at the acceleration scale indicated by MOND," he says. Unlike MOND, however, he has been able to calculate the effect using basic physics.

Verlinde's theory does more than explain why dark matter has never been found. Astronomers have long been puzzled by a 'law' linking the brightness of spiral galaxies to their spin rate. Known as the Tully-Fisher relation, it makes no sense using conventional theories of gravity, but Verlinde has shown that it's a natural consequence of the link between gravity and entropy.

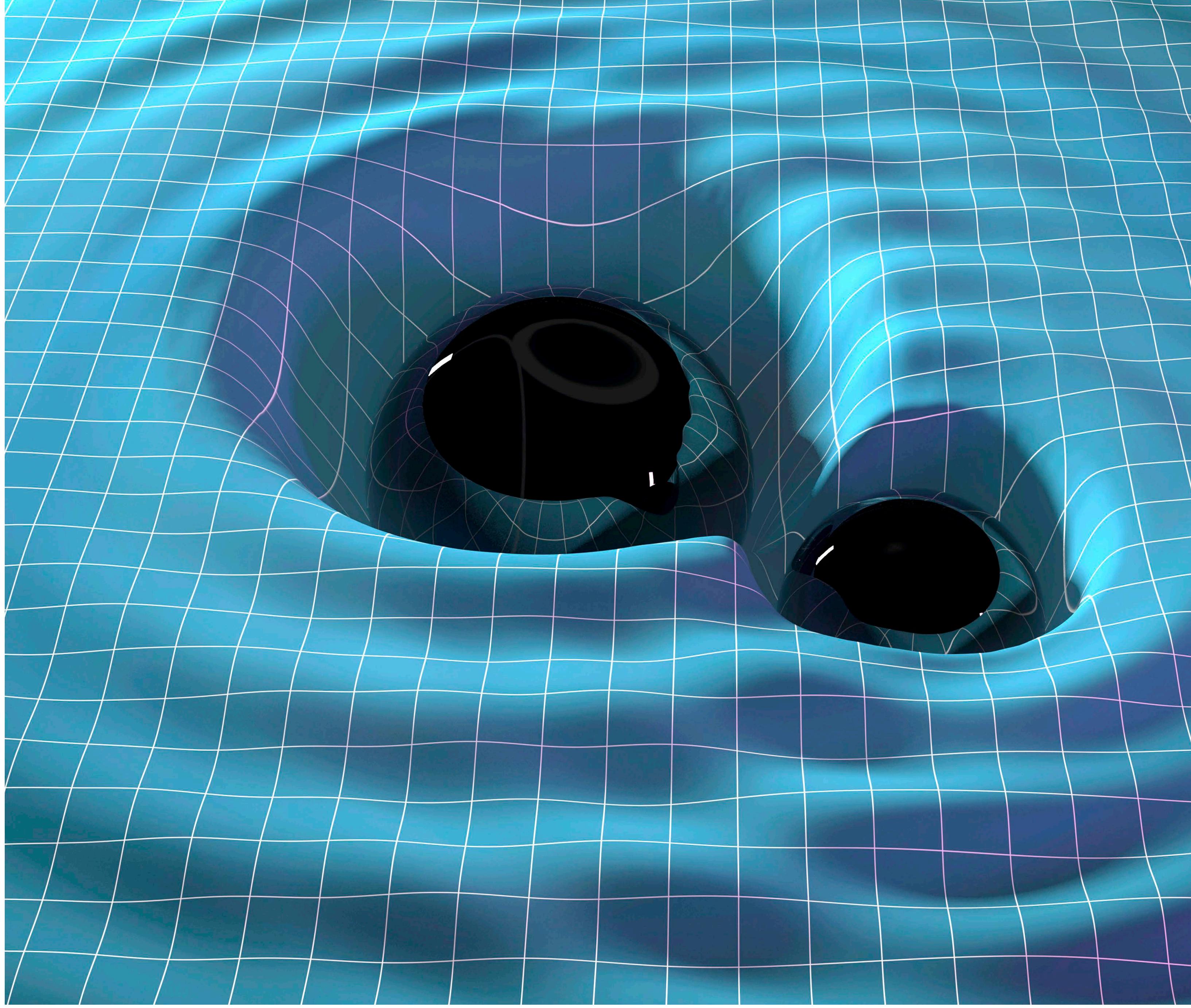
Further evidence backing Verlinde's theory comes from recent studies of the light from distant galaxies. According to Einstein, the gravity field of galaxies can bend the path of light rays. This is known as the 'gravitational lens' effect. An international team of astronomers has found that this effect is consistent with the predictions of Verlinde's theory, without the need for dark matter.

Now the search is on for evidence that Verlinde's theory does not just explain MOND, but outperforms it. And here some problems have emerged. Astronomer Dr Frederico Lelli and his colleagues at the European Southern Observatory have been studying the orbits of stars in galaxies, and they're not behaving as expected. "Verlinde's theory predicts a stronger gravitational pull than MOND in the inner regions," explains Lelli. But this effect doesn't seem to exist: "This seems to be a serious issue," he says.

"WE'RE IN A PERIOD WHEN IT IS NECESSARY TO EXPLORE MANY NEW IDEAS, AND IT TAKES A LONG TIME FOR SUCH THINGS TO SETTLE OUT"

BELOW: **According to the Tully-Fisher relation, the faster a spiral galaxy spins, the brighter it will be**

PHOTOS: GETTY X2



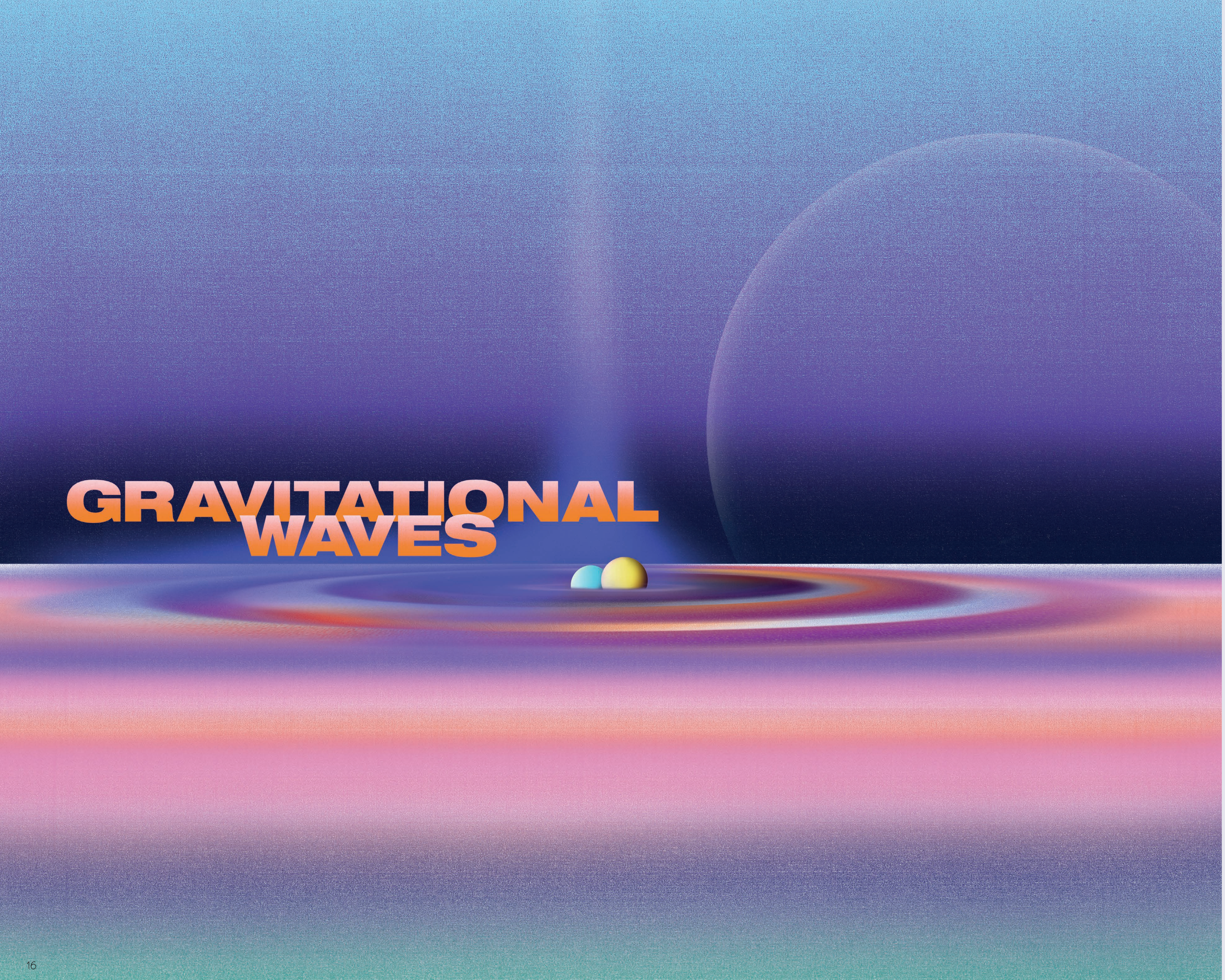
ABOVE: **Visualisation of two black holes orbiting each other, warping space-time and emitting gravitational waves**

The biggest problem facing Verlinde, however, is explaining a cosmic 'coincidence'. Why does the amount of dark matter needed to explain galaxy rotation curves match the amount needed to explain observations of the early Universe? "The observational evidence for dark matter from a variety of methods is all amazingly consistent," says astrophysicist Prof Neta Bahcall of Princeton University.

The simplest explanation is that dark matter really does exist, but just hasn't been found yet. But Verlinde points out that his work on the nature of gravity is far from complete. "To explain these effects one has to develop the theory to the point where one can describe the cosmological evolution of the Universe," he says. "I am currently working on these ideas, but it will take some time."

Given the huge pay-off if he's right, many scientists are willing to cut Verlinde some slack. "We're in a period when it is necessary to explore many new ideas," says astronomer Prof Stacy McGaugh of Case Western Reserve University, Ohio. "And it takes a long time for such things to settle out."

Prof Robert Matthews is a physicist and science writer at Aston University Birmingham.



GRAVITATIONAL WAVES

Over 100 years ago, Albert Einstein predicted that space-time could be warped and stretched. It turns out, he was correct

Gravitational waves are ripples in the fabric of space-time. They were predicted to exist by Albert Einstein in 1916, although he then got cold feet and retracted his prediction the following year, only to re-make it in 1936.

Specifically, gravitational waves are a prediction of Einstein's revolutionary theory of gravity, the 'General Theory of Relativity', which he presented in Berlin in November 1915, at the height of WWI. Whereas Isaac Newton had maintained that there was a 'force' of gravity between the Sun and Earth, like a piece the invisible elastic tethering the Earth to the Sun and keeping it forever in orbit, Einstein showed that this is an illusion. No such force exists. Instead, the Sun creates a 'valley' in the space-time around it, and the Earth travels around the edge of the valley rather like a roulette bowl in a roulette wheel.

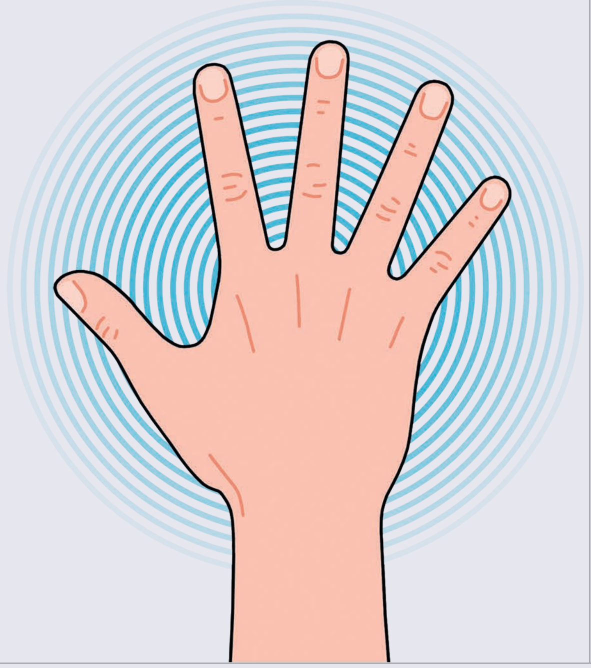
We cannot see the landscape of space-time because space-time – a seamless amalgam of three space dimensions and one of time – is a four-dimensional thing, and we are mere three-dimensional creatures. That is why it took a genius like Einstein to realise that what we think of as matter moving under the influence of the force of gravity is in fact matter moving through warped space-time. As the American physicist John Wheeler said: "Matter tells space-time how to warp and warped space-time tells matter how to move."

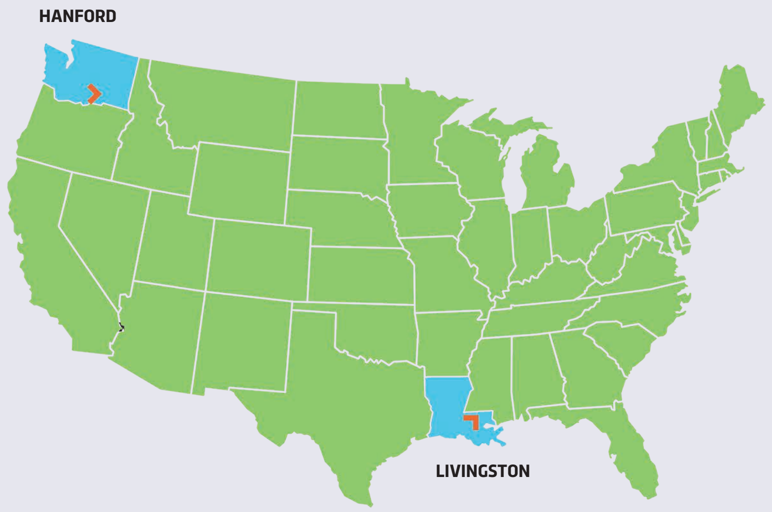
According to General Relativity, space-time is no mere passive backdrop to the events of the Universe. Instead it is 'thing', which can be bent and stretched and warped by the presence of matter. And, if it can be distorted in this way, argued Einstein, it can also be jiggled. When this happens, an undulation of space-time spreads outwards at the speed of light like concentric ripples on a pond: a gravitational wave.

HOW ARE GRAVITATIONAL WAVES MADE?

Wave your hand in the air. You just created gravitational waves. Already, they are rippling outwards through space-time. They have left the Earth. They have passed the Moon. In fact, they are well on their way to Mars. In about four years' time they will reach the nearest star system. We already know that one of the three stars of Alpha Centauri is circled by a planet. If it hosts a technological civilisation that has built a gravitational wave detector, at the beginning of 2022, it will be able to pick up the gravitational waves you created by waving your hand a moment ago!

Mind you, the detector will have to be super-sensitive. This is because gravitational waves, which are produced whenever mass changes its velocity, or 'accelerates', are extremely weak. The reason for this is that gravity itself is extremely weak. An equivalent statement is that space-time is extremely stiff. Imagine banging a drum. Now imagine replacing the drum skin with something a billion billion times stiffer than steel. That's the stiffness of space-time. This extreme stiffness means that only the most violent movements, such as the merging of super-dense bodies like neutron stars and black holes, can create appreciable gravitational waves.





ABOVE: **The two LIGO observatories are located 3,002km apart, in Hanford and Livingston**

10,000 billion billion billion billion
The factor by which the force of gravity is weaker than the electromagnetic force gluing together the atoms of your body.

44
Number of years between the construction of the first LIGO prototype at the California Institute of Technology in Pasadena and LIGO's first detection of gravitational waves.

1.3 billion
The number of years the gravitational waves detected on 14 September 2015 had been travelling across space to Earth.

5
Number of gravitational wave researchers so far awarded Nobel Prizes: Russell Hulse, Joseph Taylor, Rainer Weiss, Kip Thorne and Barry Barish.

99.999
Percentage of incident light reflected by the mirrors at each end of LIGO's four-kilometre 'arms'.

"AS GRAVITATIONAL WAVES PASS, THEY STRETCH SPACE IN ONE DIRECTION AND SQUEEZE IT IN A PERPENDICULAR DIRECTION, THEN ALTERNATE"

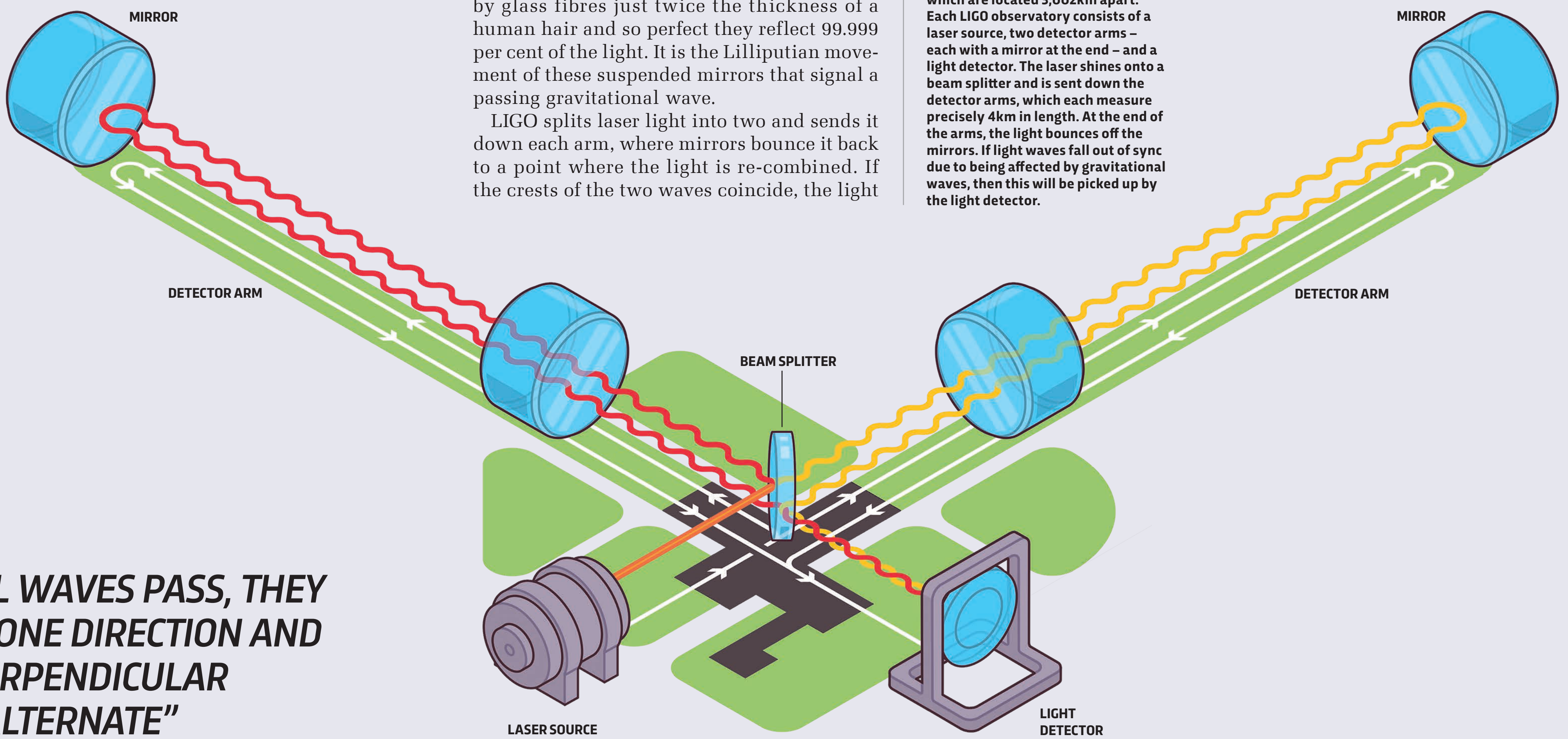
HOW ARE GRAVITATIONAL WAVES DETECTED?

As gravitational waves pass, they stretch space in one direction and squeeze it in a perpendicular direction, then alternate, repeatedly. The effect felt on Earth of the waves from a black hole merger is extremely small, typically a change in the length of a body by a mere billion billionth of its size. Consequently, the only way to detect such a small effect is with a big ruler. Enter the Laser Interferometer Gravitational Wave Observatory (LIGO) – a 20th-Century technological marvel. At Hanford in the state of Washington is a four-kilometre ruler made from laser light. Three thousand kilometres away at Livingston, Louisiana, is an identical ruler. Each site actually consists of two tubes 1.2 metre in diameter, which form an L-shape down which a megawatt of laser light travels in a vacuum more empty than space. At each end the light bounces off 42kg mirrors, suspended by glass fibres just twice the thickness of a human hair and so perfect they reflect 99.999 per cent of the light. It is the Lilliputian movement of these suspended mirrors that signal a passing gravitational wave.

LIGO splits laser light into two and sends it down each arm, where mirrors bounce it back to a point where the light is re-combined. If the crests of the two waves coincide, the light detected is boosted. If the crest of one coincides with the trough of the other, the light is cancelled out. Consequently, LIGO is sensitive to changes in the length of one arm relative to the other of a fraction of the wavelength of light. A lot of ingenuity is expended in getting that measurement down even further to a hundred-thousandth the diameter of an atom.

At 5:51am EDT on 14 September 2015, first in Livingston, then 6.9 milliseconds later in Hanford, the rulers repeatedly expanded and contracted by a hundred-thousandth the diameter of an atom marking the first ever direct detection of gravitational waves.

THE LIGO EXPERIMENT
There are two LIGO observatories, which are located 3,002km apart. Each LIGO observatory consists of a laser source, two detector arms – each with a mirror at the end – and a light detector. The laser shines onto a beam splitter and is sent down the detector arms, which each measure precisely 4km in length. At the end of the arms, the light bounces off the mirrors. If light waves fall out of sync due to being affected by gravitational waves, then this will be picked up by the light detector.



SOURCES OF GRAVITATIONAL WAVES

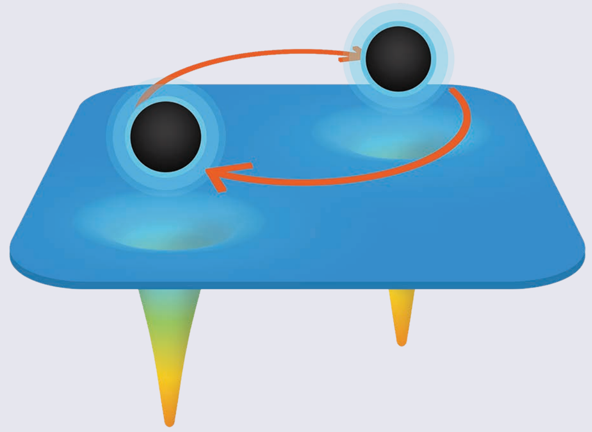
Neutron stars and black holes are the endpoints of the evolution of massive stars. When they explode as supernovas, paradoxically their cores implode. If the core is below a threshold mass, the stiffness of 'neutrons' – a so-called quantum property – can stop the shrinkage, leaving a star about the size of Mount Everest, but so dense that if you took a lump of its material measuring the same size as a sugar cube, it would weigh as much as the entire human race. If the core is above the threshold mass, no known force can stop the shrinkage and the star collapses to become a black hole.

Since most stars are born in pairs – our Sun being a rare exception – the expectation is that the most massive binaries end their lives as a pair of black holes, a pair of neutron stars, or a black hole orbiting a neutron star. The mere fact that the stars are orbiting each other – and changing their velocity, or accelerating – means that they radiate gravitational waves. This saps the stars of orbital energy, causing them to spiral in towards each other, at first very slowly, but, as time goes by, faster and faster.

Such an event, known as the 'binary pulsar', was observed for the first time in 1974, netting Russell Hulse and Joseph Taylor a Nobel Prize for the first indirect detection of gravitational waves. The first direct detection of gravitational waves, however, was on 14 September 2015. The source was two black holes of 29 and 36 solar masses in a galaxy located 1.3 billion light-years away. It is plausible that they had been spiralling together for most of the age of the Universe. However, only as they swung around each other for their last dozen or so orbits, at half the speed of light, were their gravitational waves strong enough for us to detect on Earth. First, there was a 'chirp', repeated roughly every 15 milliseconds. Then there was a final powerful burst of gravitational waves as space-time buckled and contorted and the two holes kissed and coalesced into a single giant black hole.

Six bursts of gravitational waves have now been detected, five of which were from merging black holes. But, on 17 August 2017, for the first time, a signal was picked up from merging neutron stars.

BEFORE MERGER

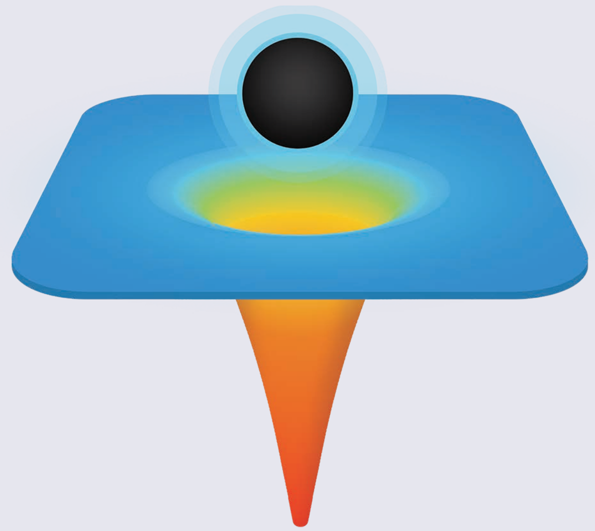


The two black holes were held in orbit around each other by their mutual gravitational pull. Their huge mass caused space-time to warp around them. Energy radiated away from them in the form of gravitational waves, leading to their orbits drawing closer.

DURING MERGER

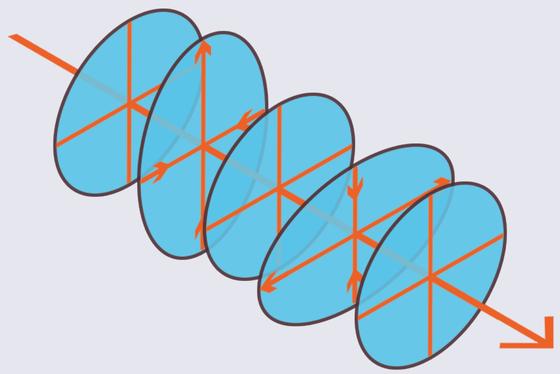
The black holes accelerated as they grew closer, reaching speeds close to the speed of light. Eventually, they merged into a single deformed black hole that radiated enormous amounts of energy as gravitational waves.

AFTER MERGER

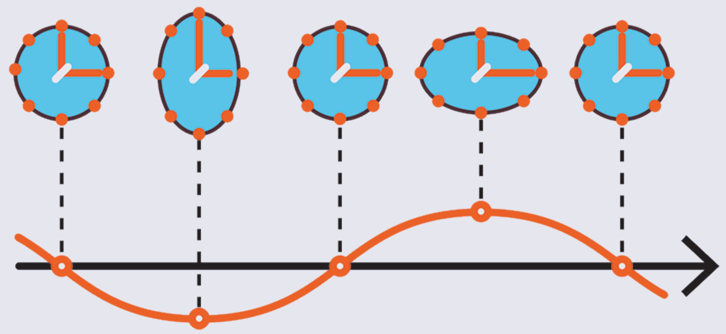


Once the black holes had merged into a single entity, the system settled into equilibrium with a regular spherical shape, and the emission of gravitational waves dropped rapidly. This is known as the 'ringdown'.

1. CATCH A WAVE
Einstein's General Theory of Relativity tells us that if two massive objects, such as two black holes, are bound together by gravity, they should create ripples in the fabric of space-time. These ripples are called gravitational waves.



2. SPACE GYMNASTICS
As a wave travelling at the speed of light passes through space-time, it first stretches space in one direction and squeezes it in the perpendicular plane, then reverses the process.



3. DETECT IT
On 14 September 2015, first in Livingston, then in Hanford, LIGO's arms repeatedly expanded and contracted by a hundred-thousandth the diameter of an atom, marking the first ever direct detection of gravitational waves.

WHAT CAN GRAVITATIONAL WAVES TELL US?

Gravitational waves have the potential to point towards a better, deeper theory of gravity. We know that Einstein's theory breaks down in the infinitely dense 'singularity' found at the heart of a black hole and at the beginning of time in the Big Bang. The hope is that gravitational waves will lead us to a long-sought quantum theory of gravity.

They also have the potential to reveal the behaviour of super-dense matter inside neutron stars. Perhaps, even more excitingly, they could tell us about the birth of the Universe. In the standard picture, the Universe in its first split-second of existence went through an incredibly violent expansion known as inflation. This should have left a relic background of gravitational waves in today's Universe, which we may be able to detect and decode.

Gravitational waves truly provide us with a new 'sense'. We have always been able to see the Universe, with our eyes and telescopes. Now, for the first time, we can hear the Universe too. Gravitational waves are the 'voice of space'. So far, we have heard some sounds at the edge of audibility. Nobody knows what the cosmic symphony will sound like, but as we improve the sensitivity of gravitational wave detectors, we hope that we will discover things of which nobody has ever dreamed.

> ***"THE HOPE IS THAT GRAVITATIONAL WAVES WILL LEAD US TO A LONG-SOUGHT QUANTUM THEORY OF GRAVITY"***

THE HUNT FOR ANTIGRAVITY

A material that defies gravity would transform transport, energy and even the weather. Paul Parsons examines the latest progress in the experiment that could find it

THE HG WELLS novel *The First Men In The Moon*, published in 1901, saw human beings travel from Earth to our planet's natural satellite in a spacecraft powered by 'cavorite'. This was a fictional antigravity material, capable of blocking the Earth's gravitational pull. For centuries, scientists and philosophers have pondered this problem – how might we counteract gravity, that most fundamental of the forces, which keeps us all stuck firmly to the Earth's surface?

Of course, aircraft and space rockets manage to overcome gravitational pull, but only at considerable cost and effort. True antigravity would allow a vehicle to rise gracefully upwards at the flick of a switch – not just overcoming gravity, but altering its very essence. Now, antigravity may be about to make the leap from science fiction to science fact. Earlier this year, a team at CERN – the European centre for particle physics, on the border between France and Switzerland – announced plans to look for signs of antigravity in particles of antimatter.

FALLING UPWARDS

Antimatter can be thought of as the opposite of ordinary matter – with all its key properties, like electric charge, reversed. All properties except one, that is. Matter and antimatter both have positive mass, so most physicists had expected them both to behave in the same way when placed in a gravitational field. But now scientists at CERN say this might not be the case after all. They think antimatter might fall at a different rate to ordinary matter – and could even 'fall upwards'.

"Is there such a thing as antigravity? Based on free-fall tests so far, we can't say yes or no," says team member Prof Joel Fajans, of Lawrence Berkeley National Laboratory (LBNL), California. "We certainly expect antimatter to fall down, but just maybe we will be surprised."

Their tests involve an experiment at CERN called ALPHA (short for Antihydrogen Laser Physics Apparatus). The experiment combines antiprotons with antielectrons to make antihydrogen atoms, which are stored briefly in a magnetic field. When the field is switched off, the atoms fall out and move under the action of gravity until they collide with the walls of the apparatus.

When this happens, a flash of light is given off. By looking at when and where these flashes occur in the ALPHA experiment, the scientists are able to get a handle on how the

ILLUSTRATOR: MAGICTORCH

ANTIGRAVITY

antihydrogen atoms are falling in the Earth's gravitational field. Making these measurements, however, is not straightforward. There's much uncertainty owing to the unknown starting positions and speeds of each antihydrogen atom when the magnetic field is switched off. At present, this statistical error is 100 times the size of the expected measurements. "We need to do better," says Prof Jonathan Wurtele, also of LBNL. "We hope to do so in the next few years."

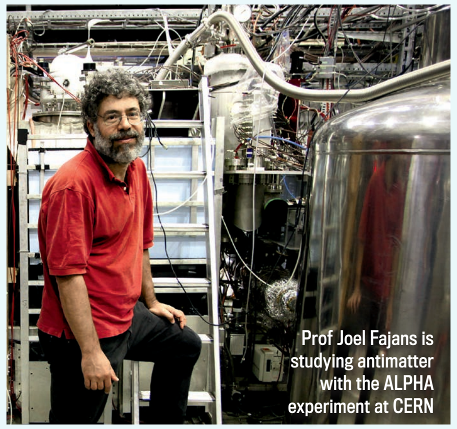
To that end, the equipment at CERN is now being upgraded. When complete in 2014, ALPHA-2 will incorporate a laser cooling system to reduce the energy of antiatoms – so that their speed and position can be more precisely determined. If ALPHA-2 does show matter and antimatter to be falling at different rates, it could be time to rewrite the textbooks on gravity. "That would be new physics," says Dr Michael Doser, of CERN. "While there are not many viable models, a number have been developed which would allow additional gravity-like forces, or modified forms of gravity between matter and antimatter."

WHAT IS ANTIMATTER?

The Universe's yin-yang nature

Matter is made of particles such as electrons and protons. But each type of particle has a counterpart with opposite electric charge: antimatter. Antimatter was postulated in 1928 by British physicist Paul Dirac, who had deduced a new theory of the electron. It predicted the existence of positively charged antimatter electrons, now known as positrons. Antimatter was first observed in 1932 and is now regularly made in particle accelerators. When matter meets antimatter the two annihilate, turning their mass into energy. In 1996 scientists put an antiproton and a positron together to make antihydrogen – the world's first antiatom.

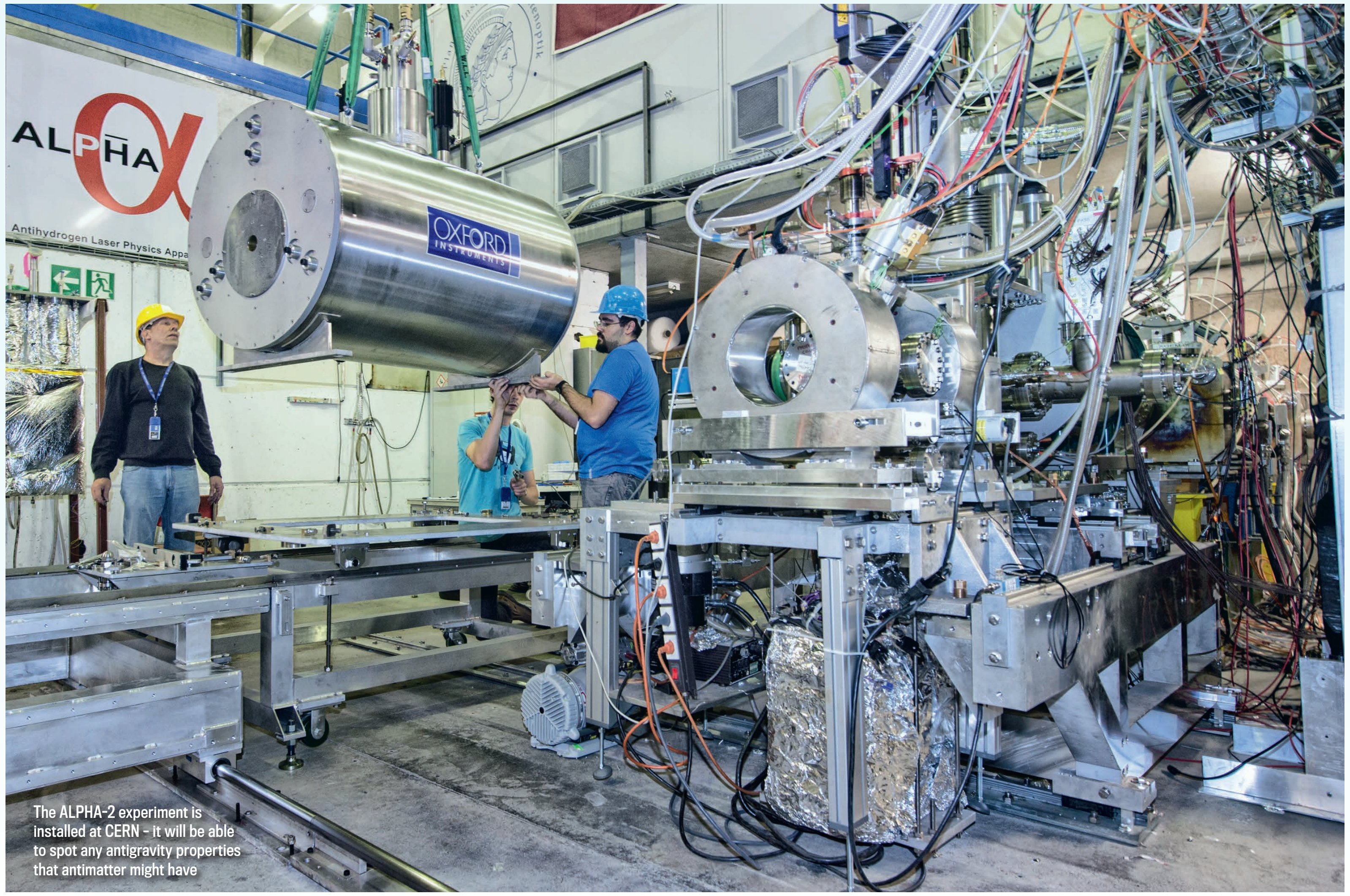
While Earth-bound experiments are ongoing, so are searches further from home. Astronomers have found something that most definitely is falling up – galaxies lurking at the edge of our observable Universe. The ordinary matter filling our expanding Universe creates attractive gravity. It was thought this gravity would slow down the cosmic expansion. But when, in the late 1990s, astronomers studied galaxies at different distances from Earth – seen as they were at different cosmic epochs (because of the finite speed of light) – they were in for a surprise. The expansion wasn't slowing down at all, but



Prof Joel Fajans is studying antimatter with the ALPHA experiment at CERN

"We certainly expect antimatter to fall down, but just maybe we will be surprised"

Professor Joel Fajans, of Lawrence Berkeley National Laboratory



The ALPHA-2 experiment is installed at CERN – it will be able to spot any antigravity properties that antimatter might have

was actually getting faster. Distant galaxies were accelerating away from us, and the astronomers concluded that some kind of antigravitating material must be responsible.

They called this material 'dark energy'. It's actually an old idea. In 1917, shortly after Einstein had formulated his General Theory of Relativity, he used it to build a model of the Universe at large. But his calculations quickly revealed the model to be unstable, recollapsing under its own gravity. To solve the problem, Einstein added dark energy (although it wasn't called that at the time) to his model – essentially an antigravity-like term in the equations governing his theory. In 1929, when American astronomer Edwin Hubble found that space was expanding, Einstein removed the dark energy term from General Relativity. But by the end of the century, astronomers had found that Einstein's 'biggest blunder' (as he called it) is in fact a real feature of our Universe.

IN THE DARK

In September, UK astronomers announced a new project, called the Dark Energy Survey (DES), to map the distribution of dark energy throughout space – and to chart how this distribution has changed as the Universe evolved. Although dark energy is invisible, astronomers can infer its presence through its anti-gravitational influence on distant galaxies and the light that they emit. Over a period of five years, DES will survey 300 million galaxies in an area covering one-eighth of the night sky.

The study will help scientists better understand the nature and ultimate origin of this curious substance. "We know dark energy exists, but that's about it. How this substance changes with time and location remains unclear, but we'll have a better view after DES," says team member Dr David Bacon, of the University of Portsmouth.

An extreme form of this antigravitating dark energy is believed to have existed shortly after the Big Bang. Called 'inflation', it prevented the embryonic Universe from recollapsing back on itself – instead blasting it up from

WHAT WILL WE DO WITH ANTIGRAVITY?

A technological revolution awaits when we finally master this bizarre phenomenon

TRANSPORT

With no need to fight the downward pull of gravity, aircraft will be able to skirt around the Earth at high speed and at a fraction of the cost.

CHEAP ENERGY

Water flowing downhill can generate energy. If you could get the water back to the top of the hill with minimal effort you could generate the same energy all over again.

SPACE FLIGHT

Cosmologist Hermann Bondi showed that if you placed antigravitating matter next to normal matter then the two will 'self accelerate'. Robert Forward suggested this could be used to build a space drive.

WEAPONS

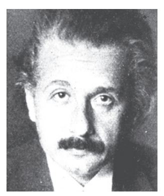
Antigravity will make it easy to reach orbit. Throw a big rock down from space and it will strike the ground with the force of a nuclear bomb.

WEATHER CONTROL

Altering gravity would have an effect on atmospheric pressure. This in turn could enable us to control the weather, for example to prevent hurricanes.

A short history of defying gravity

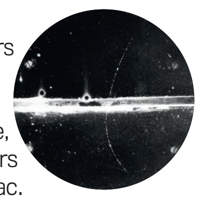
1915 Albert Einstein publishes the General Theory of Relativity (GR), which remains our best description of gravity.



1917 Using GR to build a model of the Universe, Einstein proposes the 'cosmological constant', later known as 'dark energy'.

1921 American physicist Thomas Townsend Brown discovers the 'ionic wind' effect that causes 'lifters' to levitate.

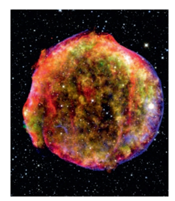
1932 Carl David Anderson discovers the positron, the first known antimatter particle, predicted four years earlier by Paul Dirac.



1933 Walther Meissner and Robert Ochsenfeld find that superconductors can levitate magnets.

1996 Russian Eugene Podkletnov claims to have found evidence for gravity shielding in spinning superconductors.

1999 Supernova explosions provide the first evidence for the existence of dark energy.



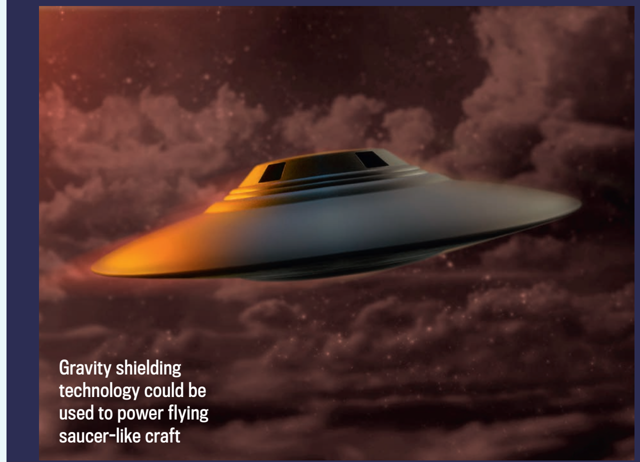
2000 The first superconducting maglev train (using the Meissner effect) is successfully tested by scientists in China.

2002 Stories emerge of NASA attempting to reproduce Podkletnov's work to build antigravity craft.

2013 Physicists at CERN announce details of experiments to discover whether antimatter possesses antigravitating properties.

UP IN THE AIR

The world of antigravity is filled with lofty concepts. Here are some key terms to help you get off the ground

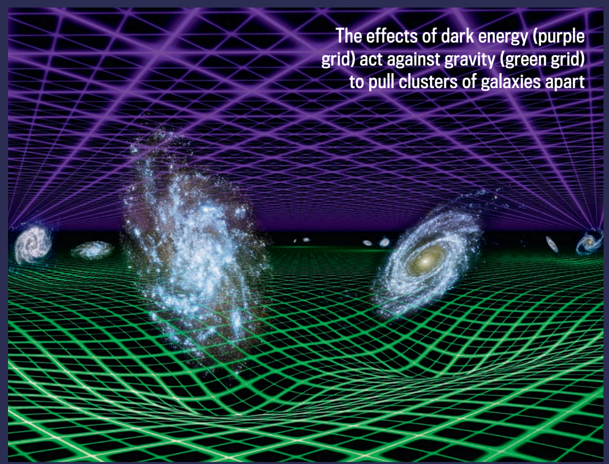

Gravity shielding technology could be used to power flying saucer-like craft

GRAVITY SHIELDING

Russian physicist Eugene Podkletnov claims to have created a device that can partially block the force of gravity. If correct, this would be an example of 'gravity shielding', with the device able to screen out the particles carrying the gravitational force, much like a screen of lead can block particles of radiation like X-rays.

REPULSIVE GRAVITY

The gravitational force between lumps of ordinary matter is always attractive, pulling the objects together. But some forms of matter generate repulsive gravity, whereby the gravitational force pushes objects apart. An example is 'dark energy', which cosmologists believe is causing the expansion of the Universe to accelerate.


The effects of dark energy (purple grid) act against gravity (green grid) to pull clusters of galaxies apart


An artist's impression of a string, which forms the basis of string theory

ALTERNATIVE GRAVITY THEORIES

It may be that Einstein's General Theory of Relativity is not the last word on gravity. Another, deeper physical law may lie beneath, such as string theory. If we find in experiments that antimatter demonstrates antigravitating behaviour then an alternative gravity theory could be the best explanation.

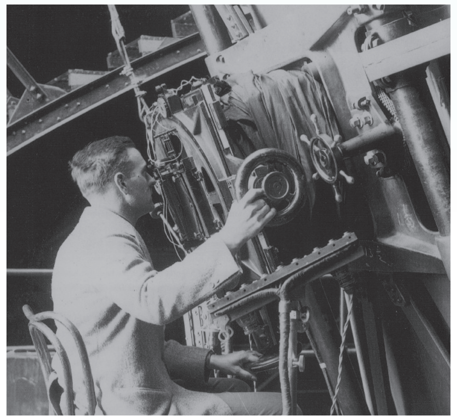
"We know dark energy exists, but how this substance changes with time and location remains unclear"

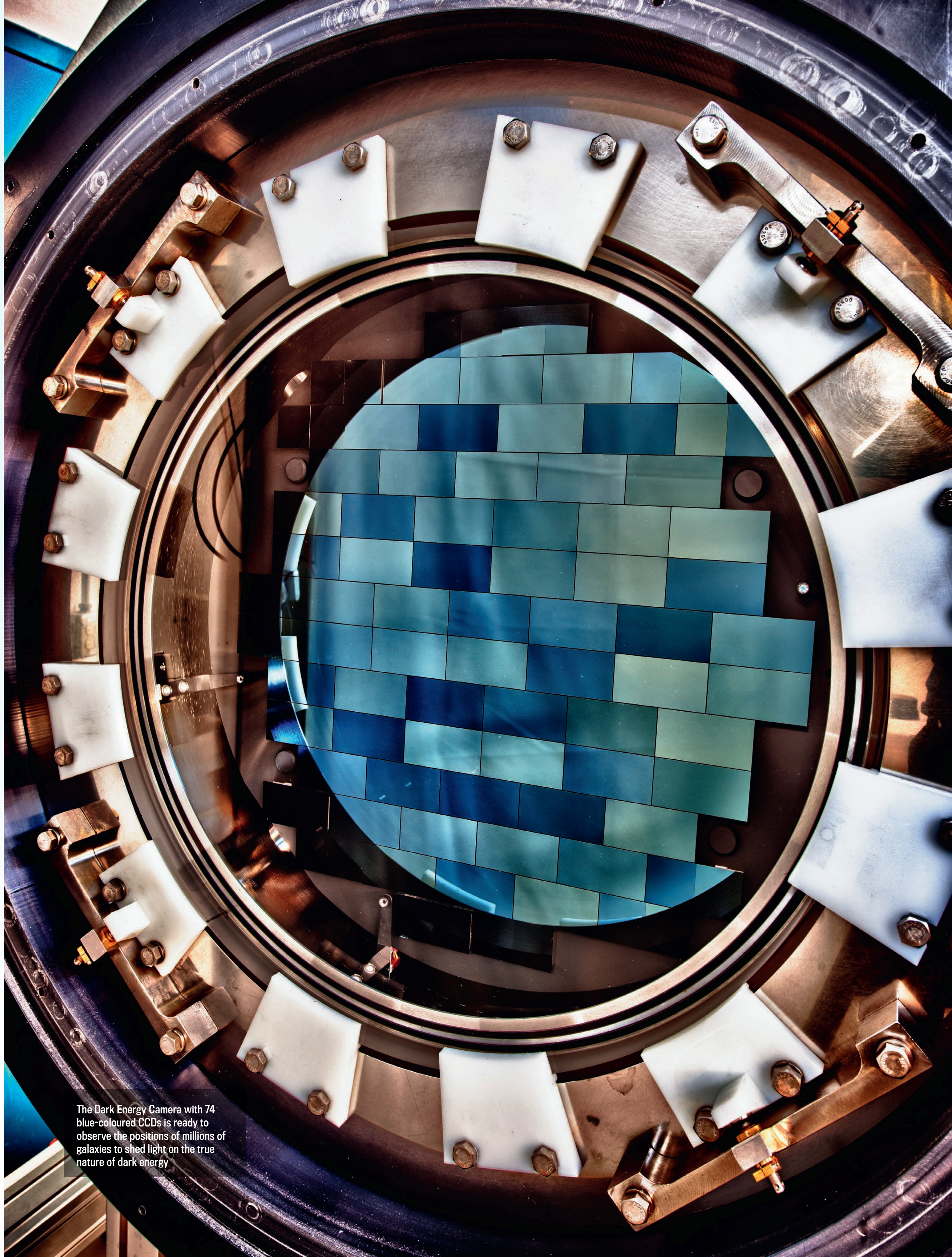
Dr David Bacon of the University of Portsmouth

microcosm to macrocosm in the tiniest fraction of a second.

Indeed, that we are here at all is at least partially thanks to inflation and dark energy. If the precise amount of dark energy was different, the Universe wouldn't evolve in the same way. "In [models of] universes that have much more dark energy than ours, whenever matter tries to clump into galaxies, the repulsive push of the dark energy is so strong that it blows the clump apart and galaxies don't form. Universes with much less dark energy collapse back on themselves so quickly that, again, galaxies don't form," explains physicist Prof Brian Greene, of Columbia University. "Without galaxies there are no stars, no planets, and no chance for our form of life to exist."

We don't need to look into space to see antigravity in action, however. Experimental physicists have already created small amounts of antigravitating material in the lab, and it has nothing to do with antimatter. In the so-called Casimir effect, named after Dutch physicist Hendrik Casimir who discovered it in 1948, negative energy is created between two metal plates positioned just a few billionths of a metre apart in a vacuum – causing the plates to move together. This happens because empty space


Edwin Hubble discovered that the Universe was expanding


The Dark Energy Camera with 74 blue-coloured CCDs is ready to observe the positions of millions of galaxies to shed light on the true nature of dark energy

ANTIGRAVITY

isn't really empty at all. It's actually a bubbling mass of virtual particles popping in and out of existence over very short timescales. According to quantum theory – the physics of the subatomic world – particles can equally be thought of as waves. Outside the plates, waves of all possible wavelengths can exist. But between them the waves are rather like vibrating strings – the only vibrations allowed are those for which the length of the string is a whole number of half wavelengths. Converting back to particles, this means that there is less energy between the plates than there is outside. If the outside is a zero-energy vacuum then the inside must have negative energy. And this creates antigravity.

The Casimir effect was verified experimentally in 1997 by Steve Lamoreaux, at Los Alamos National Laboratory. However, the amount of negative mass created was tiny – around -10^{-27} grammes. That's just one ten-millionth (0.0000001) of the force needed to lift a car. In 2009, experimental physicists at Harvard University measured a repulsive analogue of the Casimir effect – which pushes the two plates apart rather than pulling them together. This is possible by varying the materials that the two plates are made from and adding a fluid between them. The 'anti-Casimir effect' can levitate objects, and will be a significant breakthrough in nanoscale engineering (where attractive Casimir forces can create unwanted friction between moving parts). However, the anti-Casimir effect has nothing to do with modifying gravity itself and so isn't antigravity in the strictest sense.

"There is important, potentially revolutionary research into the phenomenon of antigravity"

Antigravity is one of those fields where amateur scientists frequently feel the urge to contribute. The post bags at *BBC Focus Magazine* regularly bring designs for antigravity machines from inventors, many of whom haven't subjected their creations to adequate testing themselves, let alone the independent scrutiny required to convince a professional scientist.

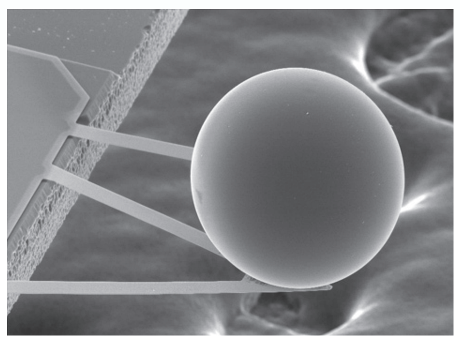
The place to send an idea for defying the force of gravity isn't a popular science magazine like ours but a scientific journal, whose editors will subject it to rigorous peer review before deciding whether or not it merits publication. One researcher who did just that was Russian physicist Eugene Podkletnov. In a paper accepted for publication in 1996 by the *Journal Of Physics D* (though subsequently withdrawn by its author), Podkletnov reported that objects he placed above a spinning superconducting disc lost 2 per cent of their weight. He was careful to stress that he had accounted for other effects such as air currents and magnetic phenomena.

Scientists put together a prototype of the Dark Energy Camera, which will record the positions of 300,000,000 galaxies

Nevertheless, many regard Podkletnov as either deluded or dishonest. That's because in the 17 years since his paper, no one has been able to replicate his claimed results and not for lack of effort. Teams from international universities and organisations like Boeing, BAE Systems, and even NASA have tried but failed.

"I undertook the first serious attempted replication of Podkletnov's work while I was on the academic staff at Sheffield University," says Clive Woods, now a professor of engineering at Louisiana State University. "We saw no effects ascribable to gravity modification by the spinning superconductor." Prof Woods explains that he was simply unable to recreate the extreme experimental conditions that Podkletnov claims to achieve in his paper. "No one, as far as I know, has managed to reproduce all the required and published conditions and measure a result," he says. "The general conclusion seems to be that it is a wild goose chase." *BBC Focus* emailed Podkletnov for comment. He replied, sending a lengthy and technical electronic book on his work, but declined to tell us whether his research had been independently verified.

In an experiment at the University of California, this microscopic ball demonstrates the Casimir effect; the reverse effect can levitate objects



ANTIGRAVITY FAQ

Prof Clive Woods of Louisiana State University and Dr Michael Doser of CERN clear up some tricky questions

Would antigravity vehicles need a counterbalancing force to stop them flying off?
"I think it depends on what the hypothetical antigravity system does," say Prof Clive Woods. "If it is antimatter of some sort, then to keep the vehicle on the ground you'd need an opposing force downwards – but then out in space you would need a rocket to give propulsion."

Would antigravitating matter fall up?
Not necessarily. This all comes down to an idea in physics called the 'weak equivalence principle', which says that all objects fall at the same rate in a gravitational field – and which our current understanding of gravity is built on. "This is precisely what our experiment will test," says Dr Michael Doser. "If antimatter were to fall differently from ordinary matter in the Earth's gravitational field, that would be new physics."

Could you use antigravity to propel spacecraft?
Some pretty outlandish-sounding ideas for antigravity spacecraft propulsion have been suggested. "These spacecraft drives alter the space-time fabric in peculiar ways so that the vehicle is constantly 'falling into' a hole, giving propulsion, and if this could be produced and controlled then presumably you wouldn't need a rocket," says Prof Woods.

Yet there is important, potentially revolutionary research into the phenomenon of antigravity. If science can crack and harness the secrets of this perplexing field, they could lead to breakthroughs in transport, energy generation, spaceflight and even weather modification. Ever since the time of Sir Isaac Newton, the laws of physics have insisted that apples fall downwards and not up. Now, that might just be about to change. ■

DR PAUL PARSONS is a former editor of *BBC Science Focus* and the author of *How To Destroy The Universe* (Quercus, £8.99)

DEFYING GRAVITY

In the absence of a bona fide antigravity effect, here are three other ways to make things float

Catch a floating train from Pudong airport to Shanghai, China

Lifters use a downward wind of charged particles to take off

By nose-diving at a certain speed passengers on the vomit comet become 'weightless'

MAGLEV
Some high-speed trains forsake wheels in favour of magnets, using the magnetic force to make the train hover above the track, massively reducing friction. As with lifters, this so-called maglev technology isn't true antigravity. The most modern maglev trains use powerful superconducting magnets.

LIFTERS
Technically these aren't antigravity; they just look like it. A lifter is a triangle of balsa wood covered in tin foil, with a length of thin wire stretched round posts at each vertex. Apply a high voltage (typically 30,000V+) across the foil and the wire creates a downward wind of charged particles, causing the lifter to hover. Don't try this at home!

VOMIT COMET
Aircraft such as the NASA 'vomit comet' can reduce the gravity experienced by occupants by nose-diving at a rate equal to the acceleration caused by Earth's gravitational pull. A similar technique is used in 'drop-towers' to create a simulated zero-gravity environment for science experiments.

PHOTO: FERMILAB, U MOHIDEEN/UC RIVERSIDE, NASA, PETER TERREN/TESLADOWNUNDER.COM, ALEX NEEDHAM/WIKI