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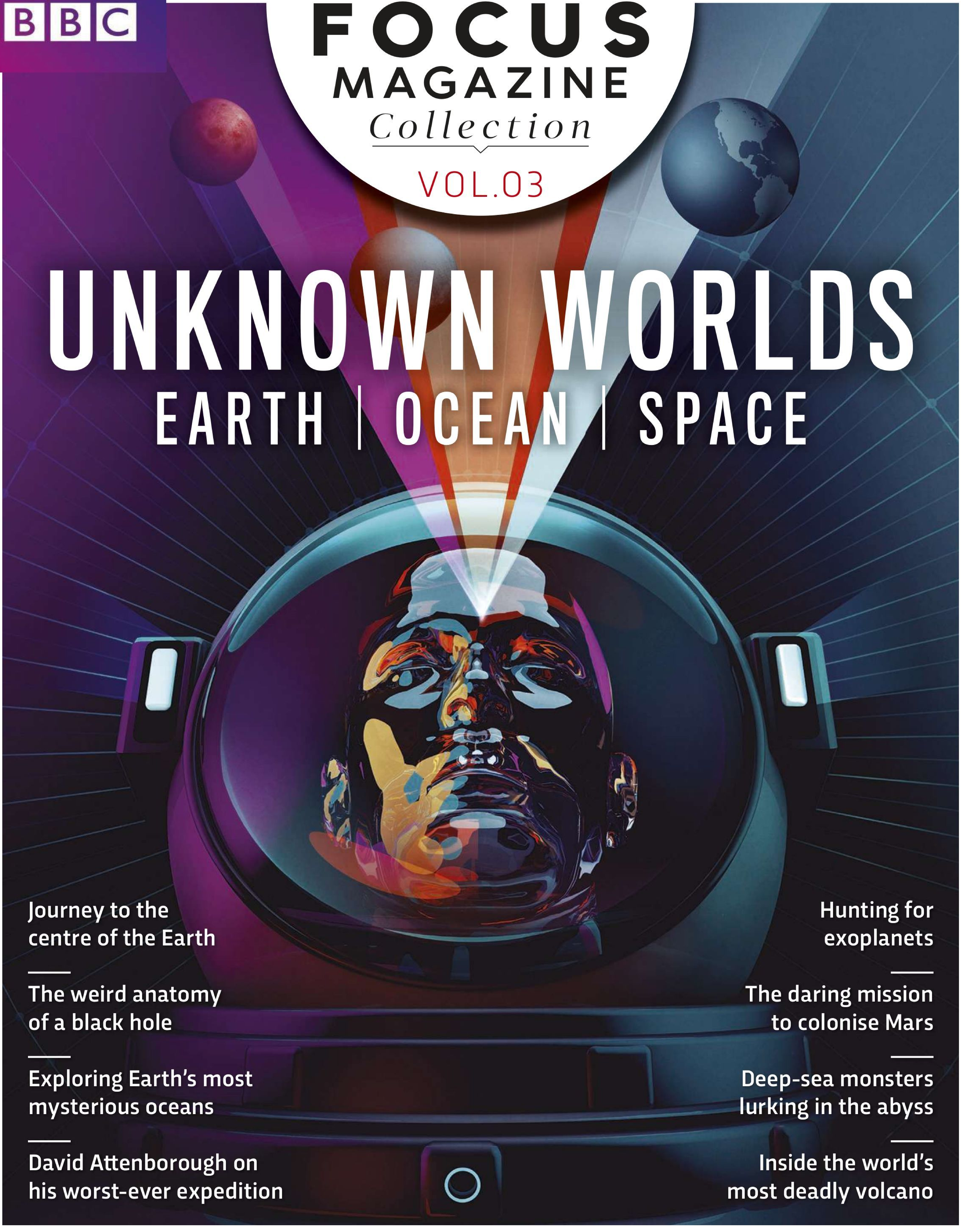

UNKNOWN WORLDS

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Journey to the centre of the Earth

The weird anatomy of a black hole

Exploring Earth's most mysterious oceans

David Attenborough on his worst-ever expedition

Hunting for exoplanets

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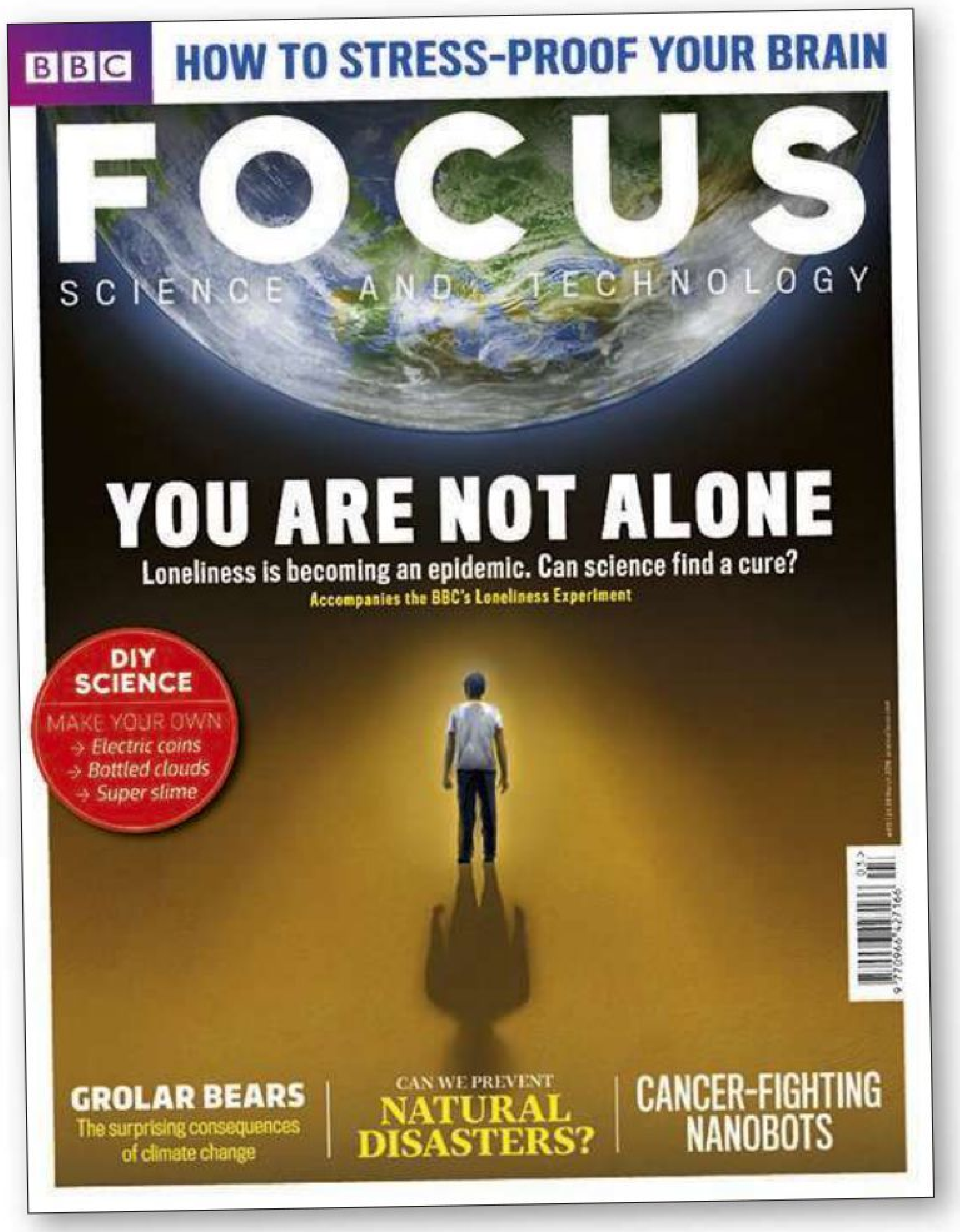

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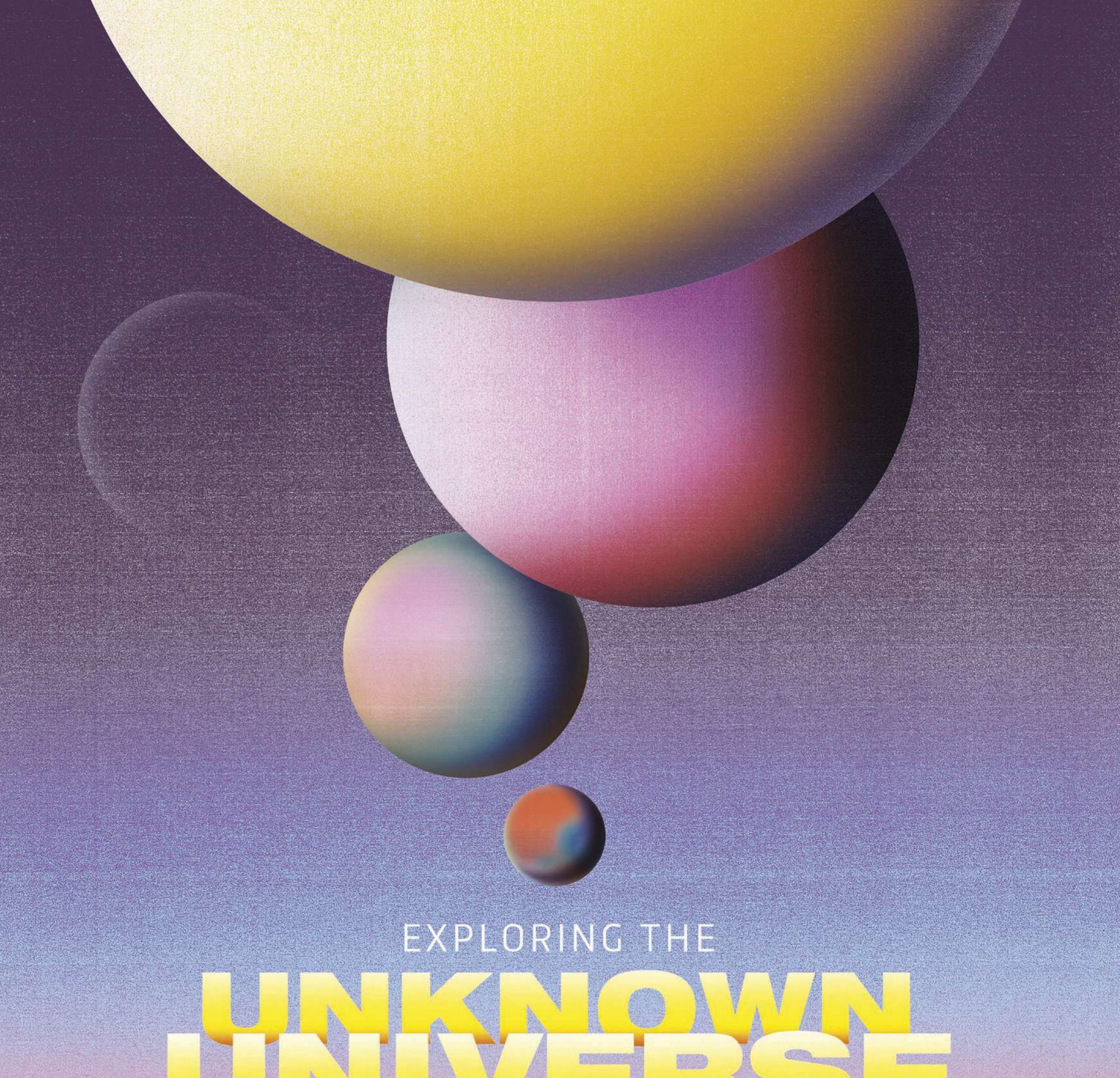

EXPLORING THE UNKNOWN UNIVERSE

Breakthroughs in 2017 have opened up new frontiers in cosmology. Find out about the latest research into some of the most mysterious phenomena in the cosmos

WORDS: **MARCUS CHOWN**

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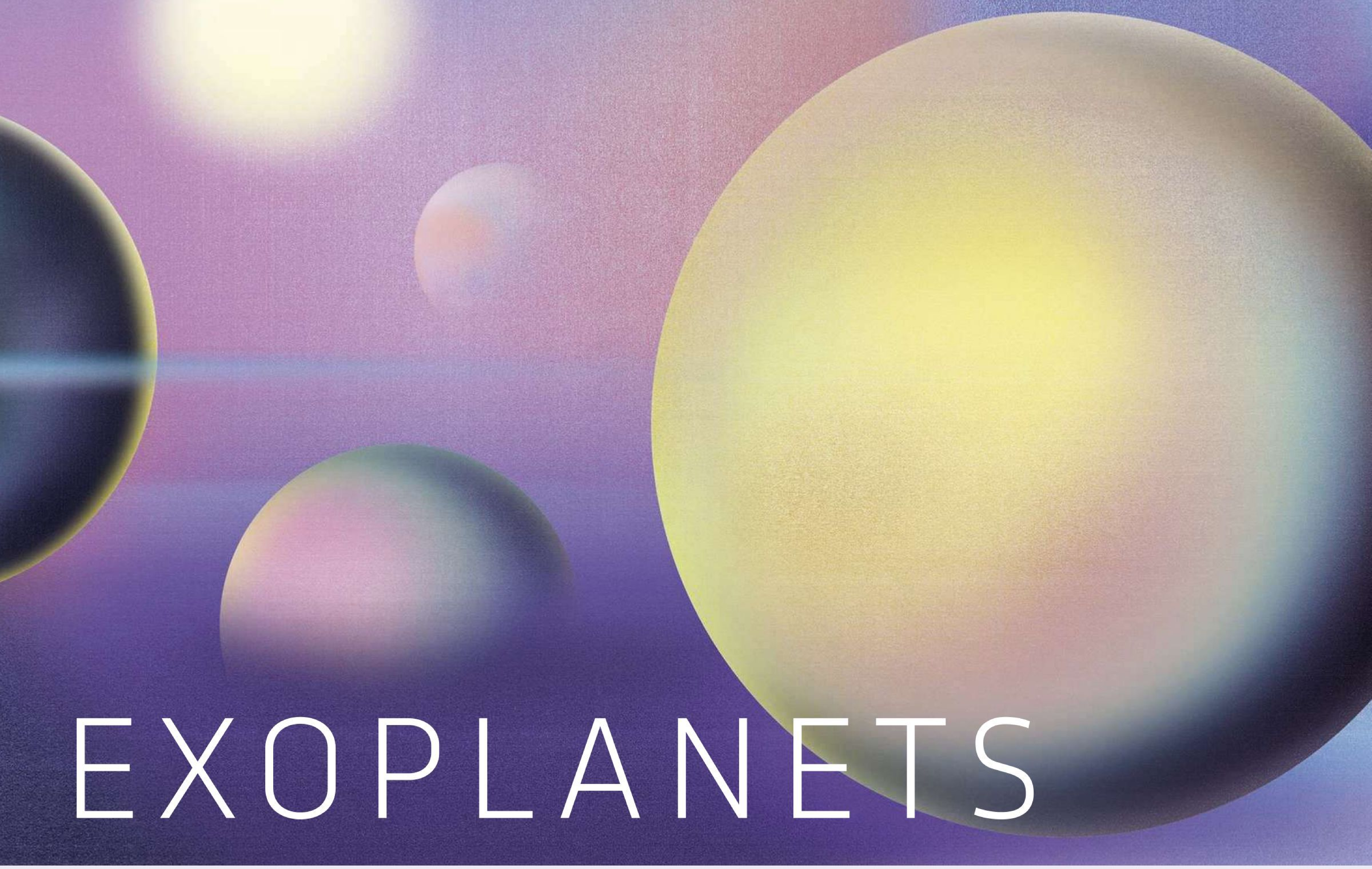


EXOPLANETS

Planets lurking in solar systems many light-years away could help us learn more about the Universe and life itself

Exoplanets are planets that orbit stars other than our Sun. We currently know of 3,584, and the number rises every week.

About one-third of nearby stars have planets, and a further third have dust disks from which planets congeal. Consequently, in our Milky Way, there are almost certainly more planets than stars – and there are several hundred billion of those.

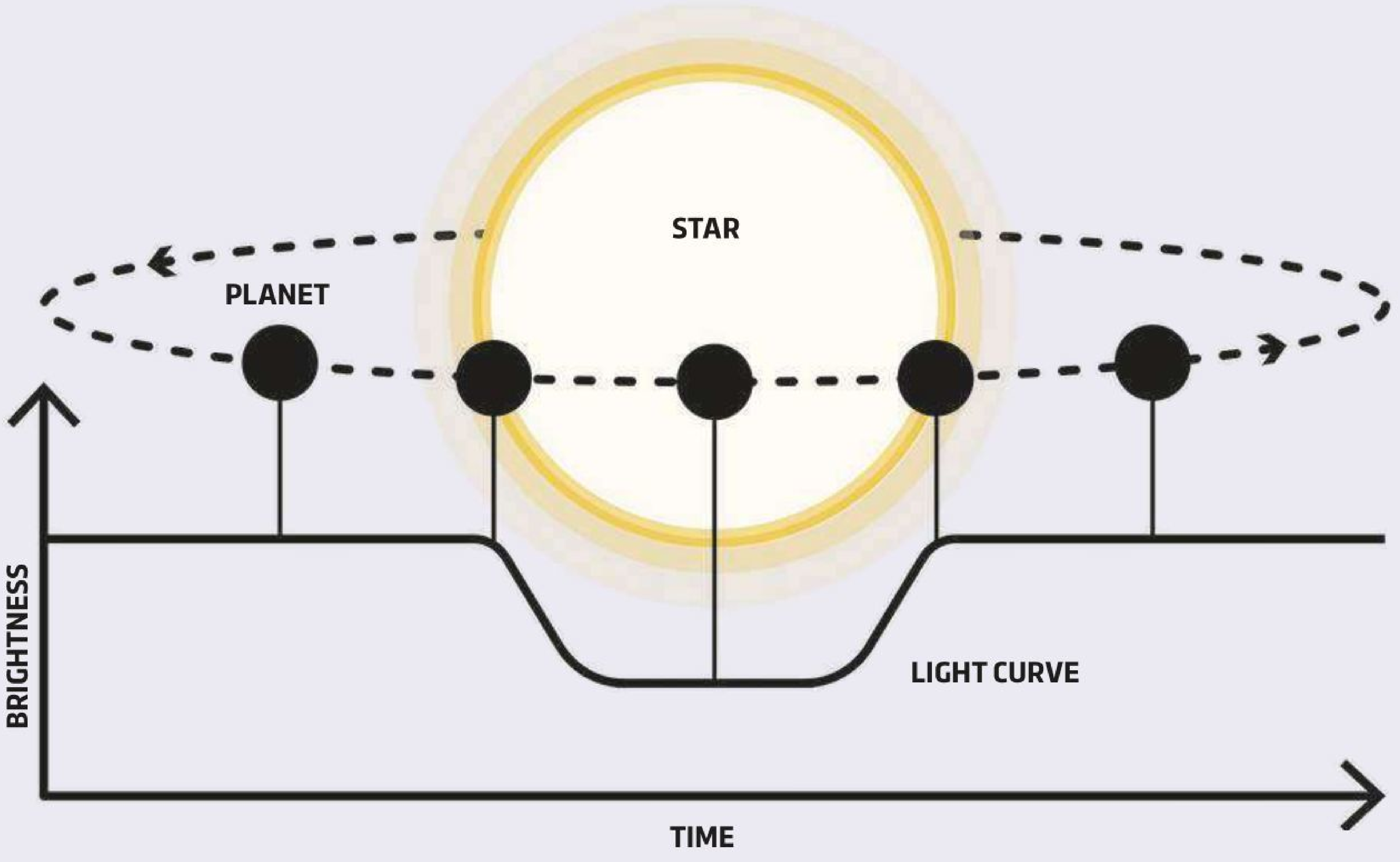
Before the discovery of the first extrasolar planetary system, the expectation was they would be like the Solar System, with rocky inner planets like Earth and Mars, and gas giant worlds like Jupiter and Saturn orbiting farther out. The shock has been that most extrasolar systems are utterly unlike ours.

Many extrasolar systems have giant planets, known as 'hot Jupiters', orbiting closer to their stars than the orbit of the Sun's innermost planet, Mercury. If they had been born there, their gas would have been blown away, so they must have formed farther out and 'migrated' inward. Many alien planetary systems have planets many times the mass of our Earth. Such 'super-Earths' are conspicuous by their absence in our Solar System, although there is a claim that such a planet, dubbed Planet Nine, orbits way beyond the outermost planet, Neptune.

In some extrasolar systems there are planets in highly elliptical orbits reminiscent of comets, and in others there are planets that share a single orbit. There are even planets that orbit the wrong way around their stars. Such 'retrograde' planets are hard to explain since planets are believed to congeal out of the leftover debris of star formation. Since the debris swirls around a star in a single direction, any planets should do too, as in our Solar System.

We thought we knew a lot about planet formation from studying our Solar System. But it turns out we have much to learn. The hope is that NASA's new exoplanet hunting telescope TESS and ESA's CHEOPS spacecraft will improve our current understanding.

HOW DO WE DETECT EXOPLANETS?



ABOVE: If a planet's orbit regularly takes it across the face of its star, then the star's light will dip slightly, which means that the planet's size can be calculated

Planets shine by reflecting the light of their parent stars. But since they are small compared with their stars, they are faint. And, since they orbit close to their stars, it is virtually impossible to detect them directly. Think of a firefly flying in the beam of a search light. So most exoplanets are instead found indirectly, through their influence on their parent stars.

One method exploits the fact that gravity is a mutual force – a star tugs on a planet but a planet also tugs on the star, causing the star to wobble slightly. The effect is hard to see but quite easy to measure in the light of the star. As the star moves towards and away from us, it creates a periodic shift in frequency of its light. This 'Doppler effect' is the light equivalent of a police siren becoming shriller (higher frequency) as it approaches and deeper (lower frequency) as it recedes.

Another method for finding planets is possible if the orbit of a planet regularly takes it across the face of its star as seen from Earth. Such 'transits' dim the light of the star slightly. If the size of the star is known, the dip reveals the size of planet. If its mass is known from the Doppler method, then its density can be deduced. Very few planetary systems are edge-on from our point of view, so observing transits requires monitoring huge numbers of stars.

Yet another method of finding planets relies on the focusing, or 'gravitational lensing' of the light of a more distant star, by a star and its planet. As the planet orbits its star, the brightness of the background star varies, revealing the presence of the planet.

Though these indirect methods have proven successful, astronomers would like to be able to dispense with indirect methods and photograph extrasolar planets directly. In 2004, a group of astronomers reported the first detection of a giant planet candidate by direct imaging.

THE FIVE MOST INTERESTING EXOPLANETS IN THE SEARCH FOR LIFE

PROXIMA CENTAURI B

This is an Earth-mass planet orbiting the cool red dwarf star, Proxima Centauri, once every 11.2 days. Being the closest exoplanet to Earth, it has the most exciting potential.

TRAPPIST-1 E

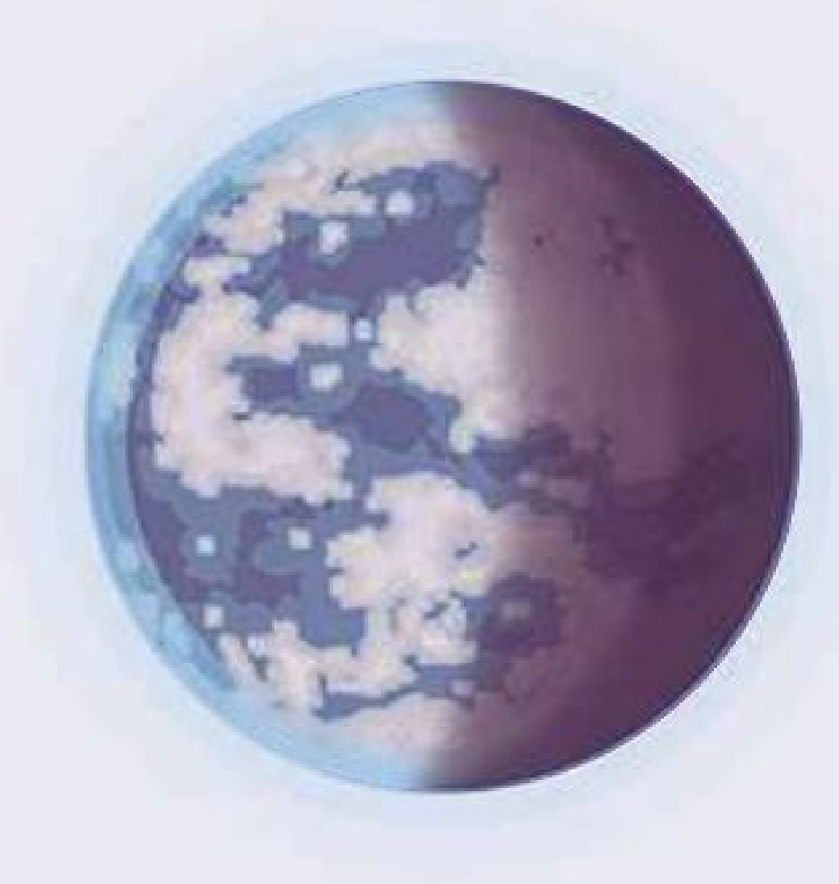
This is just over half the mass of Earth and orbits its red dwarf parent every 6.1 days. It is one of seven known planets in the Trappist-1 system, three of which are in the 'habitable zone' (see p92).

KEPLER-62F

This has a mass about three times bigger than Earth's. It orbits a dwarf star once every 267 days. The star is cooler than the Sun, so for it to be warm enough for oceans, it needs a thick atmosphere.

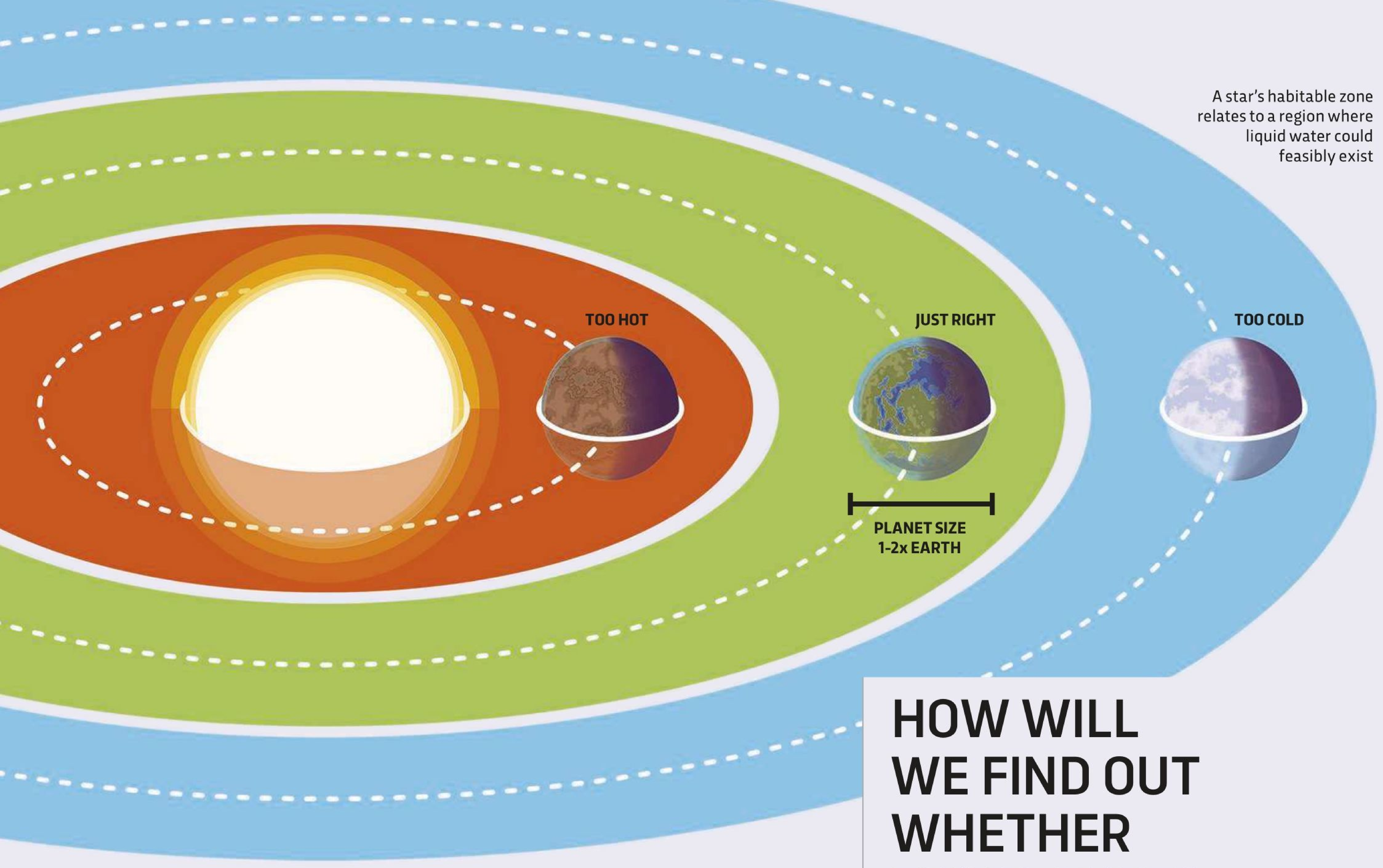
KEPLER-186F

This is about 1.5 times more massive than the Earth. It orbits once every 130 days in the habitable zone of its parent star. It is colder than Earth, but a thick atmosphere might make it cosy for life.



KEPLER-452B

This planet is about five times as massive as Earth and 60 per cent bigger. Crucially, it orbits a star that is like the Sun, and is 1,400 light-years from Earth. The orbit takes just over one Earth-year.



A star's habitable zone relates to a region where liquid water could feasibly exist

HOW DO WE KNOW WHAT EXOPLANETS ARE MADE OF?

"Never, by any means shall we be able to study the chemical composition of the stars," said French philosopher Auguste Comte in 1835. He was wrong. When heated, atoms and molecules shine with light at characteristic wavelengths (energies). If they are in the cool atmosphere of a star, then they absorb light at those same wavelengths. This creates a series of black lines like a supermarket barcode in the stellar 'spectrum'. In the same way, when an exoplanet moves in front of its star, so that the starlight passes through the planet's atmosphere on its way to Earth, there is the potential to see the barcode of substances in the planet's atmosphere.

So far, this technique has revealed a number of substances such as sodium, carbon monoxide, carbon dioxide and water in the atmospheres of extrasolar planets. The detection of molecular oxygen, an unstable gas, would indicate its continuous creation by living things.

27,710

Distance in light-years of farthest confirmed exoplanets, SWEEPS-04 and SWEEPS-11.

3,584

Number of known exoplanets.

165,000

The number of years it would take a modern spacecraft to reach Alpha Centauri, the closest star system to the Solar System.

41.32 trillion

Distance in km to nearest exoplanet, Proxima Centauri b.

4,300

Temperature in °C of the hottest exoplanet, KELT-9b.

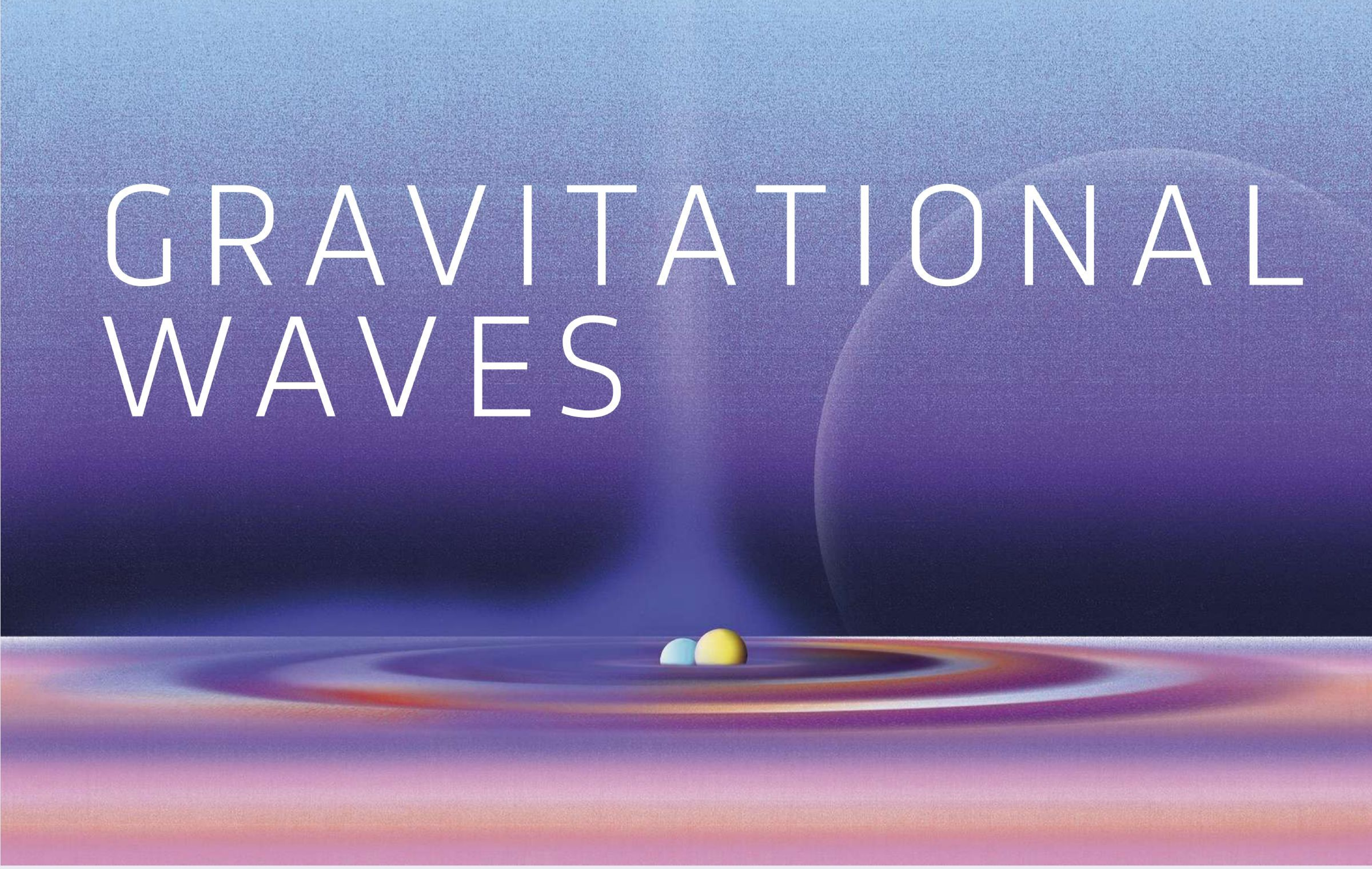
HOW WILL WE FIND OUT WHETHER EXOPLANETS ARE INHABITED?

Since we have only one example of life – what's found here on Earth – we have no choice but to look for 'life as we know it'. And all life on Earth requires water. This has given rise to the idea of a star's 'habitable zone'. A planet orbiting within this region is close enough to its star that water does not freeze and far enough away that it does not boil. This not-too-cold, not-too-hot 'Goldilocks zone' is quite narrow around the huge majority of stars, which are red dwarfs, but wider around Sun-like stars.

Recently, the concept of the habitable zone has been considerably widened. This is because of the discovery of ice-covered oceans located on Jupiter's moon Europa and Saturn's moon Enceladus. Although they intercept so little light that they should be frozen solid, they are heated by tidal stretching and squeezing from their parent planets. There is also the possibility that a planet orbiting far from its star might be kept warm by radioactive heat from its own rocks if it is swaddled in a blanket of greenhouse gases.

Life, it seems, might survive in environments far removed from those on Earth.

GRAVITATIONAL WAVES



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

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 World War I.

Whereas Isaac Newton had maintained that there was a 'force' of gravity between the Sun and Earth, like a piece of 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 ball 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 a '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 (like 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.

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.

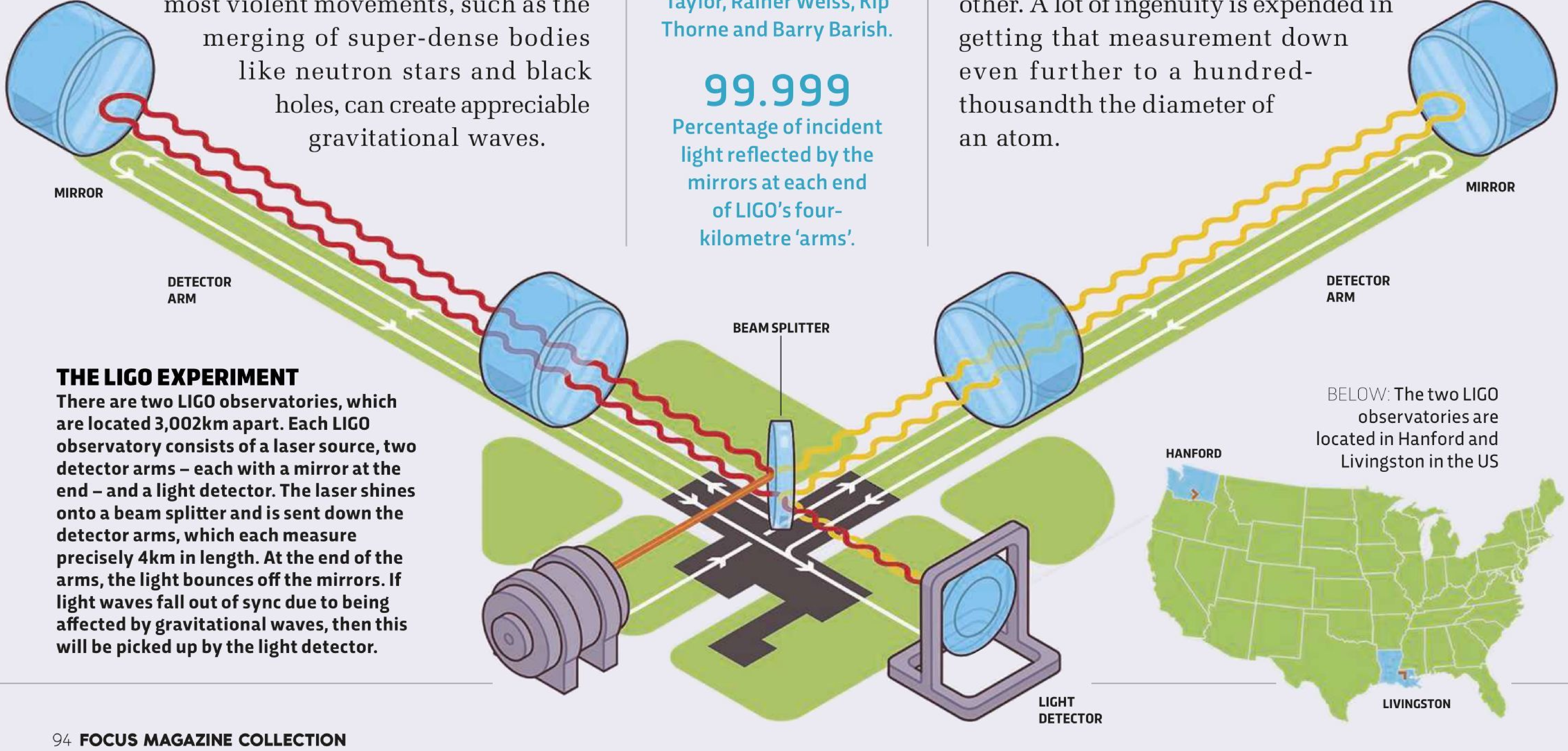
5
Number of gravitational wave researchers so far awarded Nobel Prizes: Russell Hulse, Joseph Taylor, Rainer Weiss, Kip Thorne and Barry Barish.

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

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. So the only way to detect such a small effect is with a big ruler. Enter the Laser Interferometer Gravitational Wave Observatory (LIGO). 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 has two tubes, which form an L-shape down which a megawatt of laser light travels in a vacuum more empty than space.

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. So LIGO is sensitive to changes in the length of one arm relative to the other. A lot of ingenuity is expended in getting that measurement down even further to a hundred-thousandth the diameter of an atom.



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.

BELOW: The two LIGO observatories are located in Hanford and Livingston in the US

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.

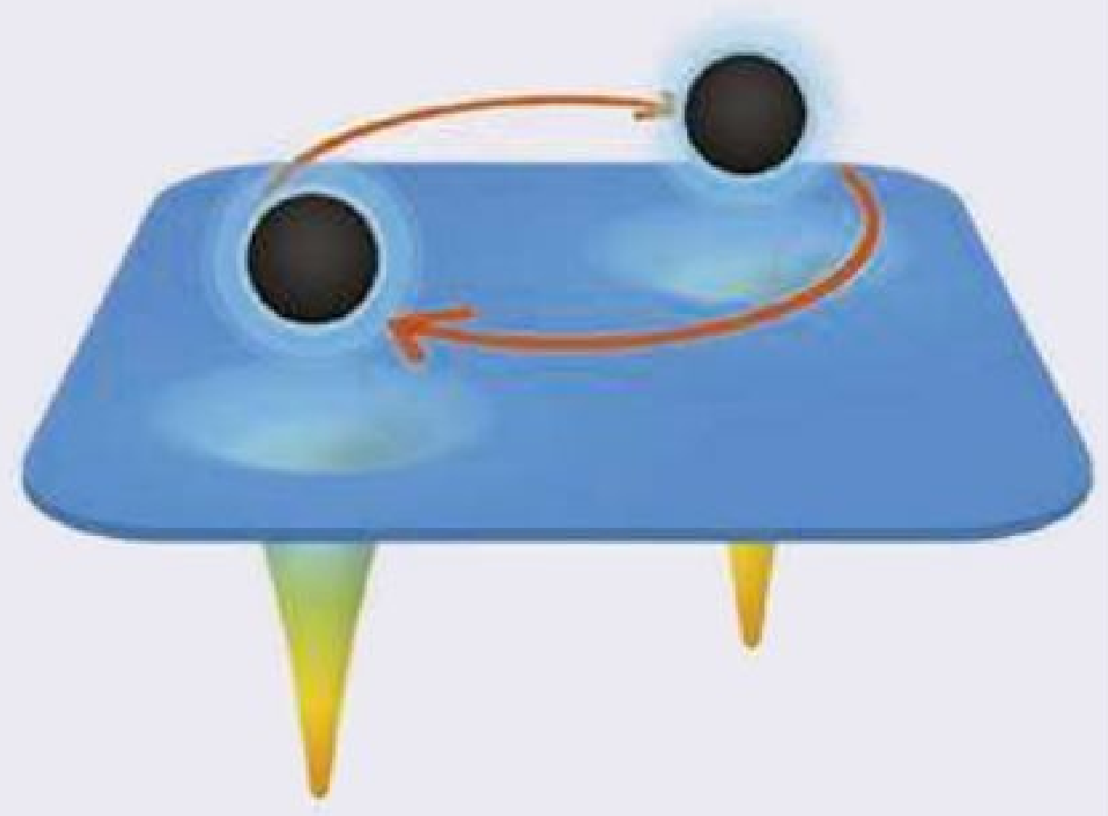
Since most stars are born in pairs – our Sun being a rare exception – the expectation is that the most massive binaries end their lives as a pair of black holes, a pair of neutron stars, or a black hole orbiting a neutron star. The mere fact that the stars are orbiting each other – and changing their 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. The source was two black holes that smashed together, coalescing into a single giant black hole and releasing a powerful burst of gravitational waves as space-time buckled and contorted.

Six bursts of gravitational waves have now been detected.

> The hope is that gravitational waves will lead us to a long sought-after quantum theory of gravity

BEFORE MERGER

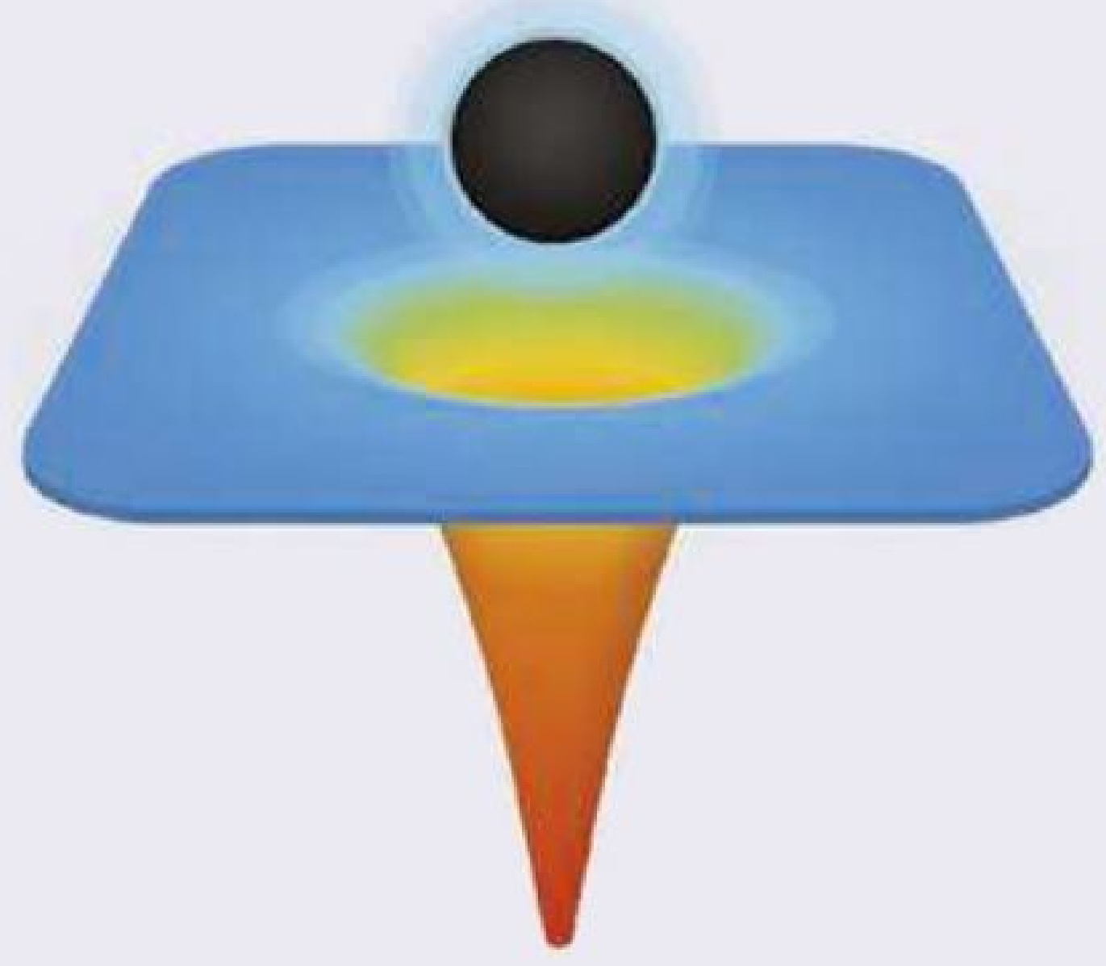


The two black holes were held in orbit around each other by their mutual gravitational pull. Their huge mass caused space-time to warp around them. Energy radiated away in the form of gravitational waves, leading to their orbits drawing closer.

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



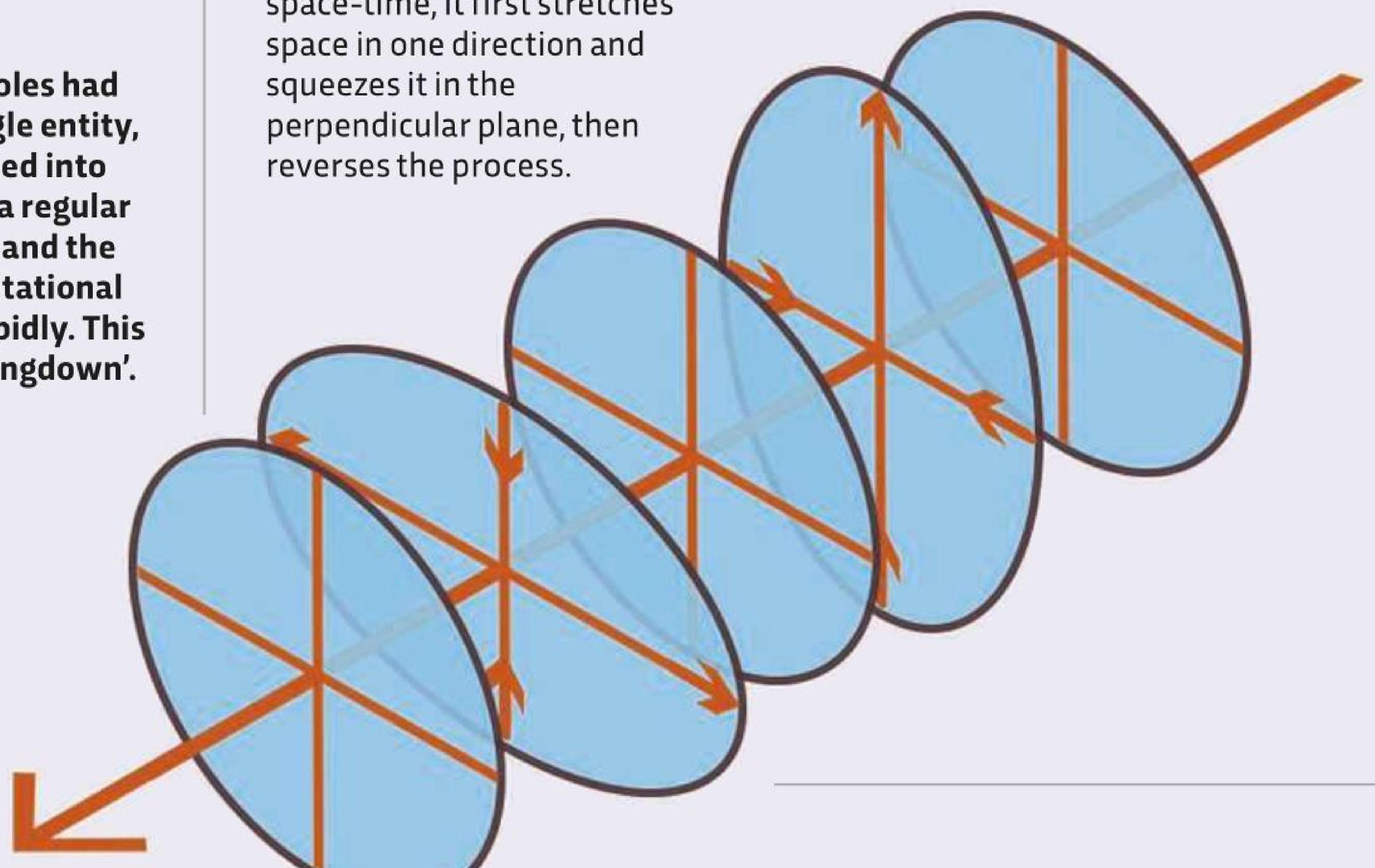
Once the black holes had merged into a single entity, the system settled into equilibrium with a regular spherical shape, and the emission of gravitational waves dropped rapidly. This is known as the 'ringdown'.

WHAT CAN GRAVITATIONAL WAVES TELL US?

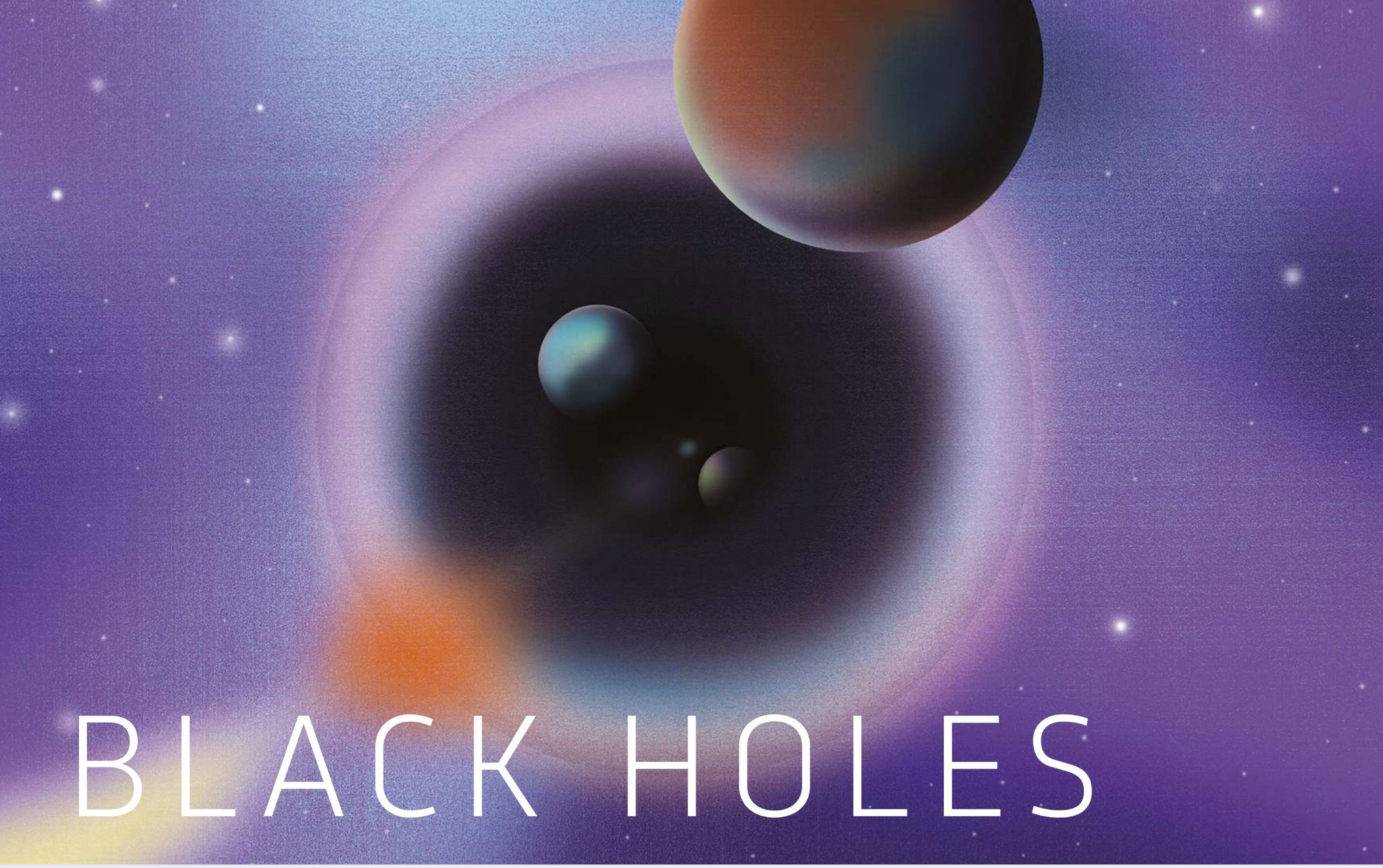
Gravitational waves have the potential to point towards a better, deeper theory of gravity. We know that Einstein's theory breaks down in the infinitely dense 'singularity' found at the heart of a black hole and at the beginning of time in the Big Bang. The hope is that gravitational waves will lead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



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.



BLACK HOLES

These weird, yet fascinating bodies are characterised by gravity so immense that not even light can escape

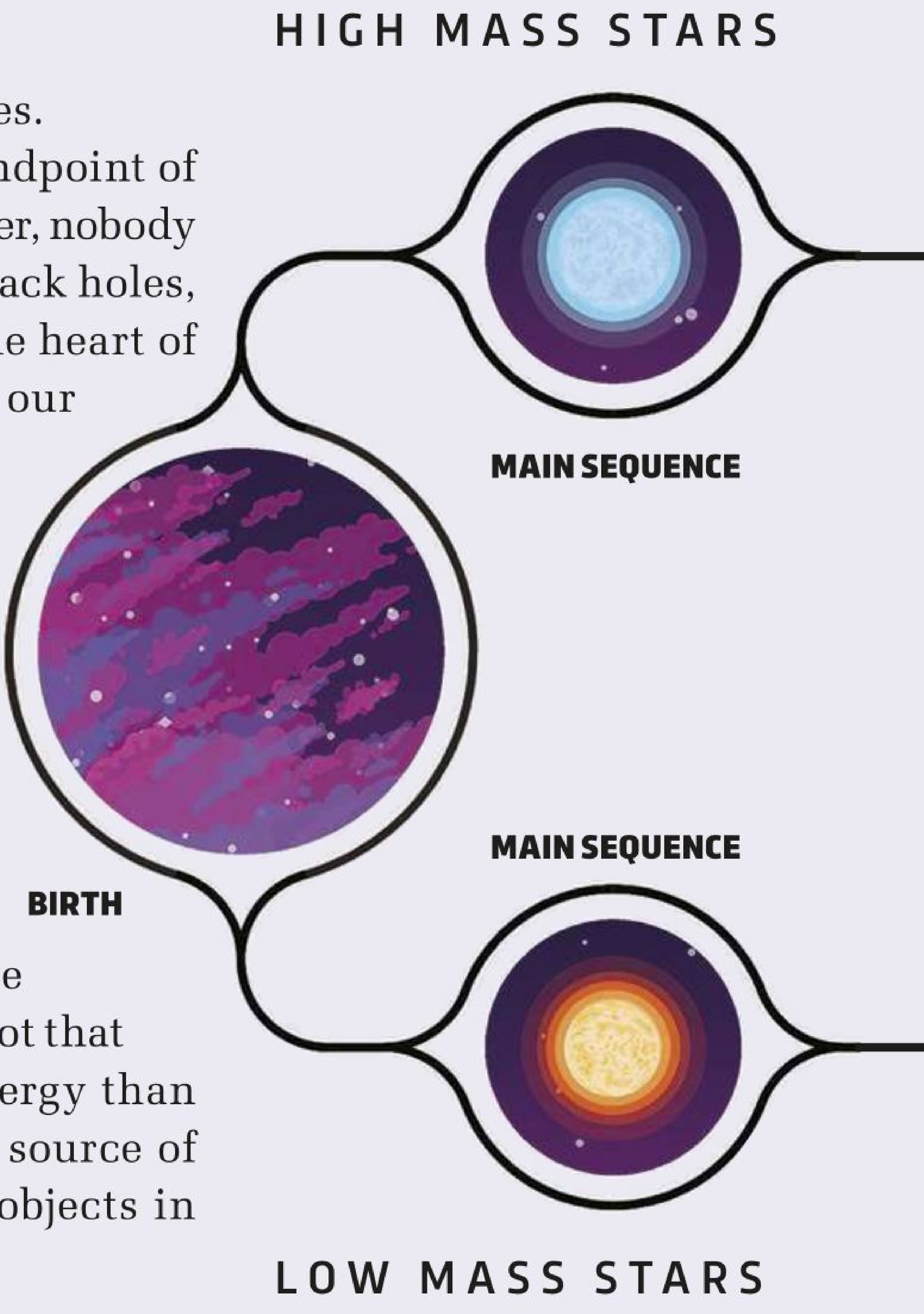
Black holes are regions of space where gravity is so strong that nothing, including light, can escape. Hence the blackness of a black hole.

The modern picture of black holes is provided by Einstein's General Theory of Relativity. The theory tells us that a mass like the Sun creates a valley in the space-time around it, into which other bodies fall. In this picture, a black hole is a bottomless well from which light cannot escape without being sapped of every last shred of its energy.

For reasons we do not fully understand, nature appears to have created two main classes of black holes: 'stellar-mass' black holes and 'supermassive' black holes, ranging in mass from millions of times the mass of the Sun to almost 50 billion times its mass. There is some evidence of the existence of a class of black holes between stellar-mass and supermassive, but so far astronomers have found very few of these 'intermediate mass' black holes.

Stellar-mass black holes are the endpoint of the evolution of massive stars. However, nobody knows the origin of supermassive black holes, or why there appears to be one in the heart of pretty much every galaxy, including our very own Milky Way. It is a chicken-and-egg puzzle. Does a galaxy of stars form first, and then later a supermassive black hole in its heart? Or does a supermassive black hole pre-date a galaxy and form the seed about which a galaxy of stars congeals?

The heating of matter as it swirls down onto a supermassive black hole creates an 'accretion disk' so super-hot that it can pump out 100 times more energy than a galaxy of stars. This is the power source of active galaxies, the most energetic objects in the Universe.



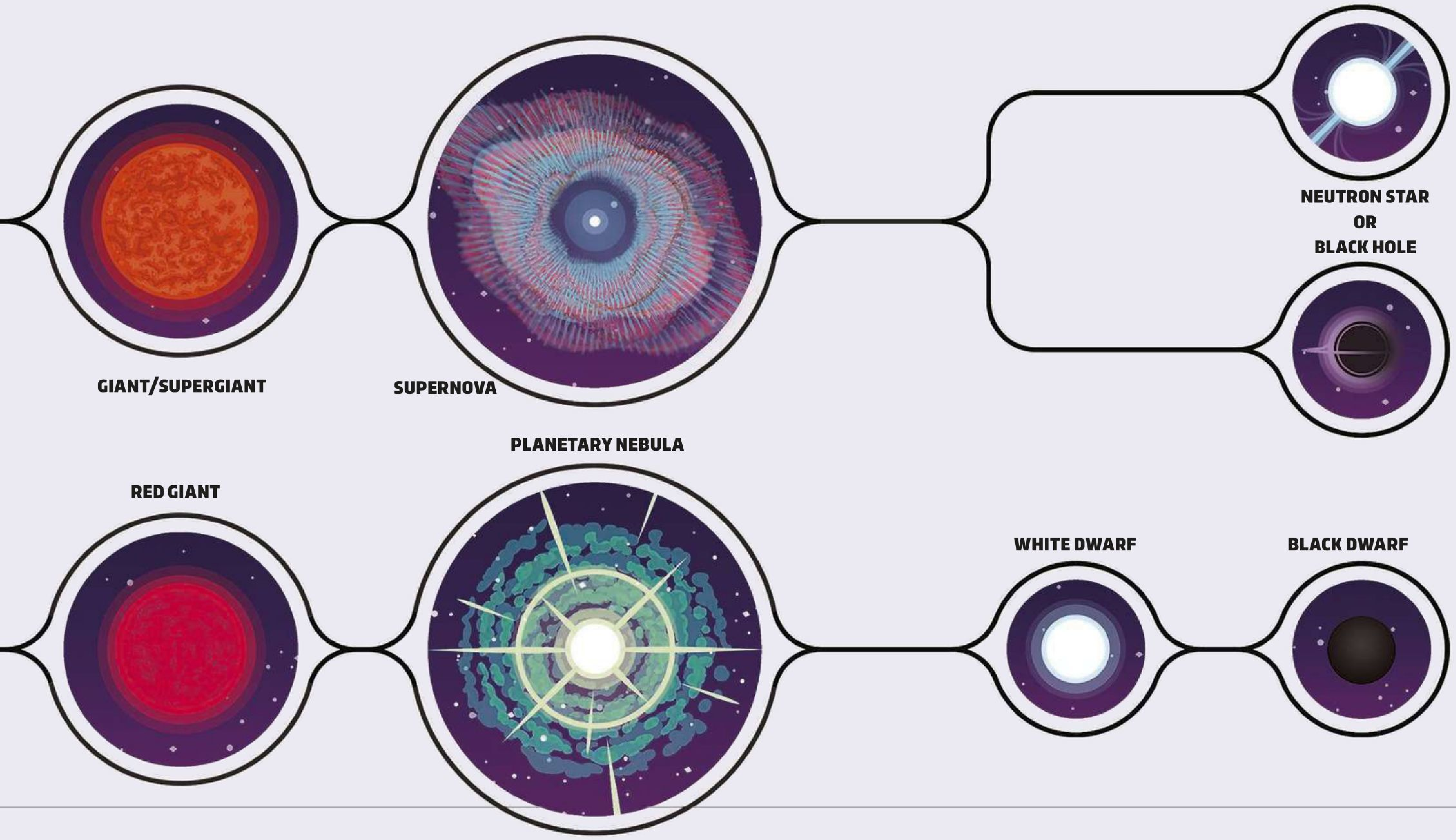
THE LIFE CYCLE OF A STAR

When a cold, dark cloud of interstellar gas and dust shrinks under its own gravity, a star is born. As the gas is squeezed, it gets hotter. When the core temperature exceeds 10,000,000°C, nuclear reactions ignite, and the ball of gas lights up as a star.

A star represents a temporary balance between the forces of gravity trying to shrink a ball of gas and its internal heat pushing outwards. The star fuses the cores, or 'nuclei', of hydrogen, the lightest atom, into the second lightest, helium. The mass difference between the initial and final product appears as the energy of sunlight, according to Einstein's famous formula $E=mc^2$. This conversion has an important effect on a star like the Sun. As helium is heavier than hydrogen, it falls to the centre. The nuclei of atoms repel each other, and the bigger the nucleus, the stronger the repulsion. For two new nuclei to stick together and make a heavier nucleus, they must slam into each other at high speed, which in practice means at high temperature. The core of the Sun will only ever be dense and hot enough to fuse together hydrogen into helium. But this is not the case with more massive stars. Their cores eventually become dense and hot enough to fuse helium into carbon, carbon into oxygen, oxygen into neon, and so on. Such stars end up with an internal structure reminiscent of an onion, with the heaviest elements in the centre surrounded by concentric shells of less and less heavy elements.

The end point of this build-up process is iron. Its creation sucks nuclear energy from the core of the star, shrinking it into a tiny, ultra-dense ball of neutrons – a neutron star. In-falling material converts implosion into explosion – a supernova. But, if the core is massive enough, no known force can stop gravity crushing the core out of existence – in fact, crushing it all the way down to a point of infinite density known as a 'singularity'. Cloaked in the impenetrable wall of an 'event horizon', this is a black hole.

BELOW: Stars are born when a gas cloud collapses and matter accumulates on a protostar. A high-mass star is 10-150 solar masses (one solar mass = the mass of our Sun), a low-mass star is 0.08-10 solar masses. The main sequence takes up 90 per cent of a star's life – the Sun is currently at this stage. High-mass stars have shorter lives, and will become giants or supergiants before exploding into a supernova, where all but 10 per cent of the original mass is ejected. The star's core will then collapse. Depending on the size of the core's mass, it will either become a neutron star or a black hole. Low-mass stars have longer lives. After the main sequence, they will become red giants. Eventually, the outer layers of gas will be ejected and the star's core will contract to form a white dwarf. Theoretically, the star could then cool to form a black dwarf, but the Universe is still too young for this to be proved.



THE ANATOMY OF A BLACK HOLE

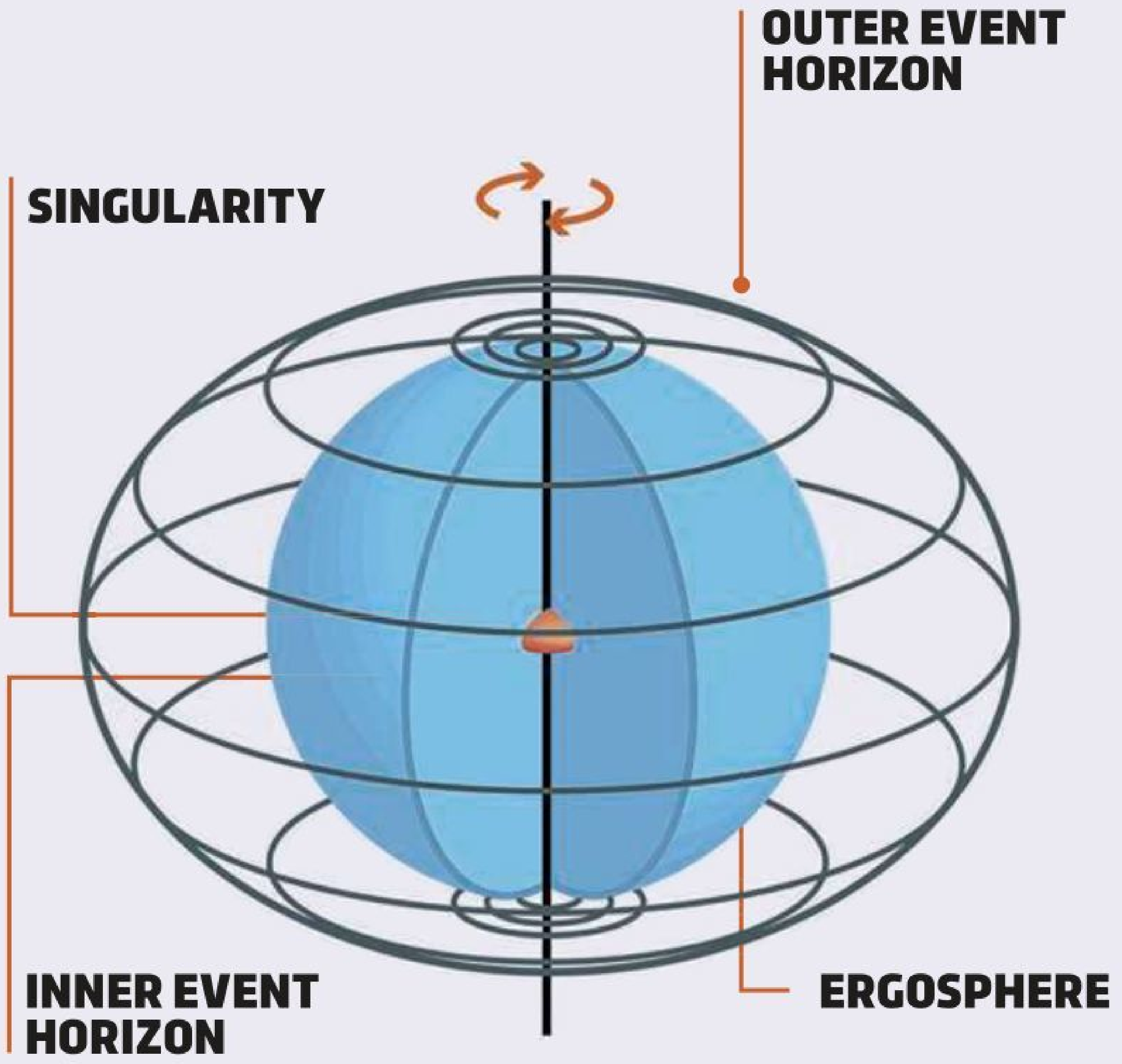
Once a massive star has shrunk to form a black hole, nothing is left (as far as we know) but a bottomless pit of space-time. A black hole is surrounded by an event horizon, an imaginary membrane that marks the point of no return for in-falling matter and light. Inside the event horizon, and at the heart of the black hole, Einstein's General Relativity predicts the existence of a point of infinite density called a 'singularity'. Yet once you reach this, Einstein's theory – and all of physics as we know it – breaks down.

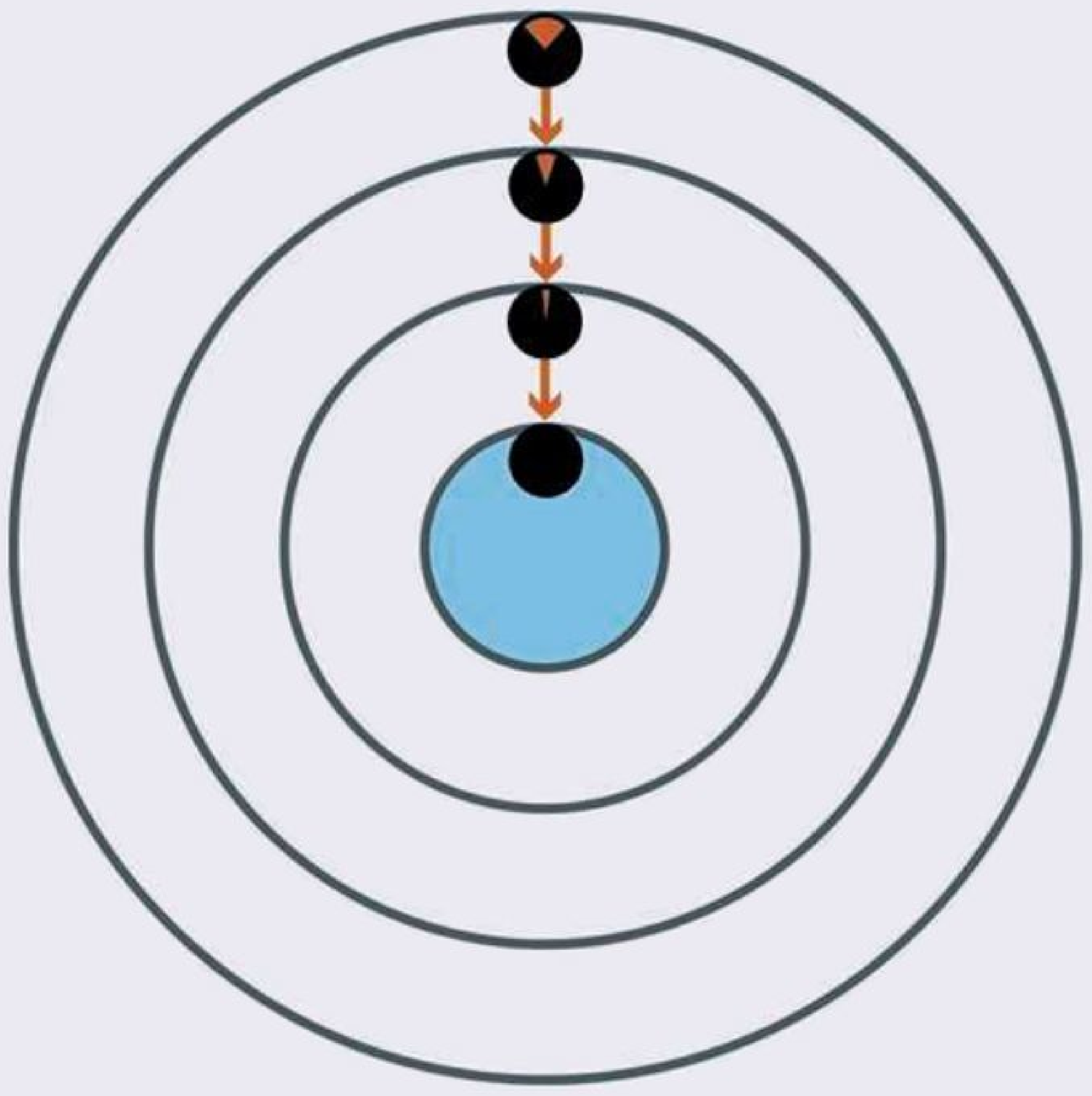
Imagine an astronaut falling feet first into a black hole. When they are at a circumference corresponding to 1.5 times the circumference of the black hole, gravity is so strong it bends light into a circle around the hole, so they can see the back of their head! Near a stellar-mass black hole, the huge difference in gravity between the astronaut's head and feet will tear them apart before they reach the event horizon. However, this tidal effect is negligible near a supermassive black hole, and the astronaut can cross the event horizon with no ill-effect.

Einstein's theory predicts that time flows more slowly in strong gravity. So, if you were to observe the astronaut falling down to the black hole from a safe distance, they would appear to move in ever slower motion, and stop altogether on reaching the event horizon. Although they would fall through into the hole, never to appear again, their image would be frozen on the event horizon, gradually fading as light from the image struggled to climb out.

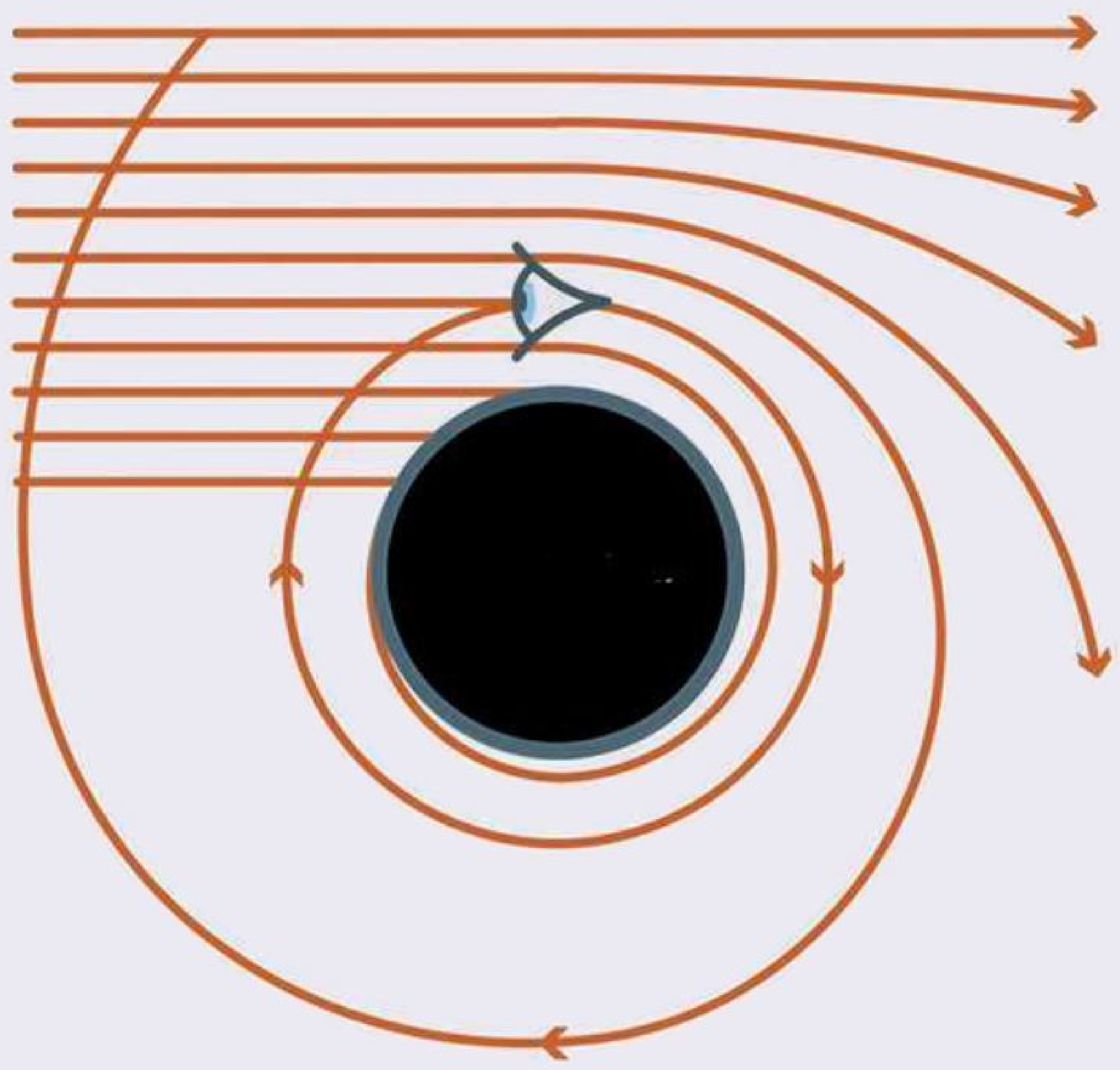
In the case of a rotating, or 'Kerr', black hole, there is a twist. In effect, these have two horizons. When the astronaut crosses the outer one, and enters the 'ergosphere', they are dragged around by a tornado of space-time. They can still gain energy from the hole's rotation and be ejected from the black hole. But once they cross the inner event horizon, there is no going back.

Nobody knows what the inside of a black hole looks like. But the unfortunate astronaut can no more avoid being crushed to death than you can avoid tomorrow.





ABOVE: As a light source nears the event horizon, fewer and fewer photons are able to escape (shown in orange) from the black hole's gravitational clutches. Once the event horizon is reached no photons are able to escape



ABOVE: The gravity of a black hole is so immense that it bends light into a circle round the hole. This means that someone falling in would be able to see the back of their own head

6

Diameter in kilometres of the black hole that would form if the matter of the Sun could be squeezed hard enough.

4.3 million

Mass in multiples of the Sun's mass of Sagittarius A*, the giant black hole at the heart of our Milky Way.

1.8

Diameter in centimetres of the black hole that would form if the matter of the Earth could be squeezed hard enough.

40 billion

Mass in Suns of the biggest known black hole in the Universe: S5 0014+81.

1

Diameter in metres of the Jupiter-mass black holes left over from the Big Bang which some have suggested could make up the Universe's invisible dark matter.

Marcus Chown is an award-winning cosmology writer and broadcaster. His next book *The Ascent Of Gravity* is out in April

Watch episodes of *The Sky at Night* bbc.in/1udo2Je