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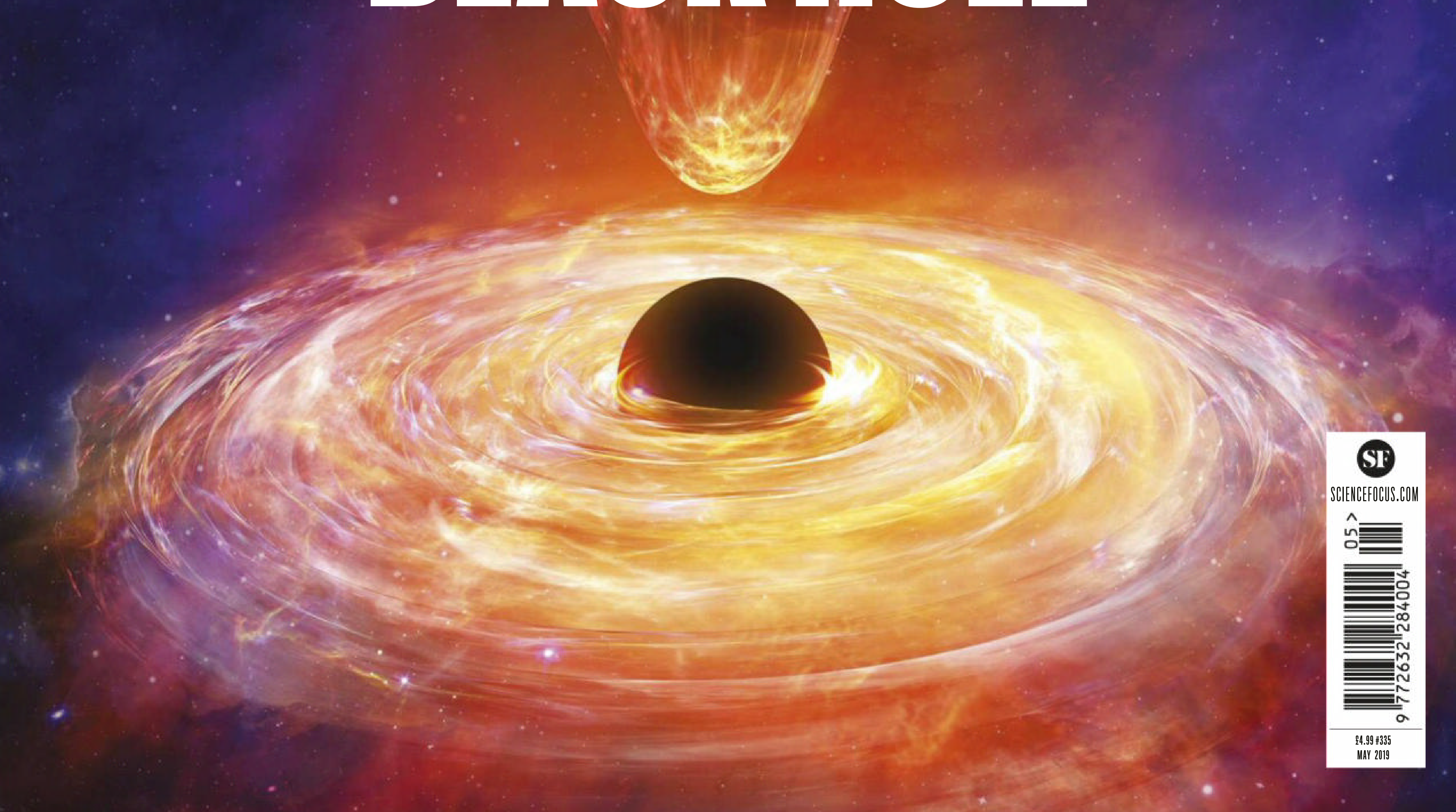

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NEW SECRETS OF THE

SUPERMASSIVE BLACK HOLE

LAST MONTH, SCIENTISTS UNVEILED A PHOTOGRAPH OF A COSMIC PHENOMENON THAT DEFIES THE LAWS OF PHYSICS, MAKING HEADLINES WORLDWIDE. SO HOW DID THEY DO IT, AND WHAT DOES THIS LANDMARK ACHIEVEMENT ACTUALLY TEACH US?

by MARCUS CHOWN
(@marcuschown)

Wednesday 10 April was an epoch-making moment in the history of science. At six simultaneous press conferences worldwide, an international team of astronomers unveiled the first ever image of a black hole. "It was one of the most exciting days of my life," says Feryal Özel of the University of Arizona in Tucson, who heads the modelling team. "For me, it's the culmination of nearly two decades of work."

In fact, the team observed two black holes: Sagittarius A*, a supermassive black hole in our own Milky Way weighing 4.3 million times the mass of the Sun, and a cousin in the galaxy M87, which is about 1,000 times bigger. The first image revealed is of the supermassive black hole at the heart of M87. Sagittarius A*, because it's smaller, was circled by matter many times while being observed, yielding a blurrier picture.

The image of the black hole in M87, since named Powehi, shows detail smaller than the extent of its event horizon, the point of no return for in-falling light and matter. It is only possible to see such exquisite detail because the intense gravity of each black hole acts like a lens, which makes the image appear five times larger than its horizon.

The horizon in M87 shows up as a dark shadow backlit by intense radio waves, emitted by matter heated to incandescence as it swirls down through an accretion disk (gas and dust that is orbiting the object) onto the black hole. The halo around it is brighter on one side than on the other. "This is because the accretion disk is spinning, causing the light from the part coming towards us to be boosted relative to that from the part that's receding," says Özel.

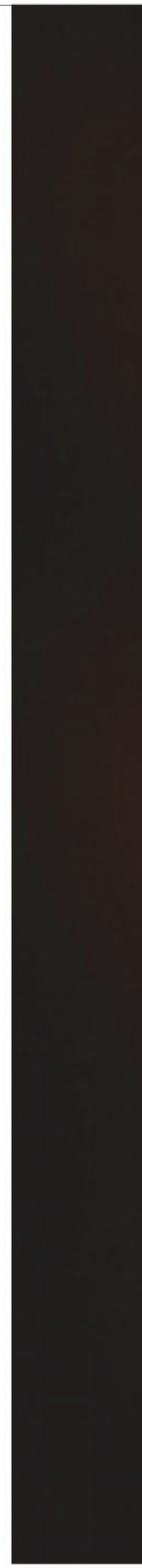
The remarkable M87 image was obtained by the Event Horizon Telescope (EHT), an array of radio dishes scattered around the globe which have been harnessed together to simulate a giant telescope the size of the Earth. Having an Earth-sized telescope is the key to imaging a target as tiny as a black hole, because the resolution of such a telescope – the fineness of the detail it can discern – depends on the maximum separation of its component parts.

STELLAR OR SUPERMASSIVE?

A black hole forms when matter is compressed into a volume so small that its gravity becomes too intense for anything, even light, to escape. This makes a stellar-mass black hole anywhere in our Galaxy too small for us to see with any Earthbound telescope. But nature has seen fit to create a second population of black holes. These are 'supermassive' ones with masses of up to 50 billion times the mass of the Sun, one of which lurks in the heart of almost every galaxy. However, on account of being very far away, these behemoths are as difficult to image as stellar-mass black holes in our own neighbourhood. Except in two cases: Sagittarius A*, which is just 27,000 light-years away, and its more massive seven billion solar-mass cousin in M87, at a distance of 56 million light years. "This is why they were chosen as targets for the EHT," says Özel.

There is also the matter of where to look in the light spectrum. High-energy electrons spiralling in the intense magnetic fields extending from a black hole's accretion disk generate radio waves, which have the advantage that they can easily penetrate the dust shrouding the centres of galaxies and so reach the Earth. Özel is an ►

"THE EVENT HORIZON TELESCOPE (EHT) IS AN ARRAY OF RADIO DISHES HARNESSED TOGETHER TO SIMULATE A GIANT TELESCOPE THE SIZE OF THE EARTH"



ESO/EHT COLLABORATION

↖ The black hole picture made headlines worldwide. Astronomers and physicists were very excited, although the general public were, in many cases, somewhat underwhelmed...

HOW DO BLACK HOLES FORM?

We're still unsure how the supermassive black holes that lurk in the centre of galaxies, such as Powehi in M87, took seed. Some theories attribute their origin to some of the earliest stars formed in our Universe, while others posit their formation by 'dark matter halos'.

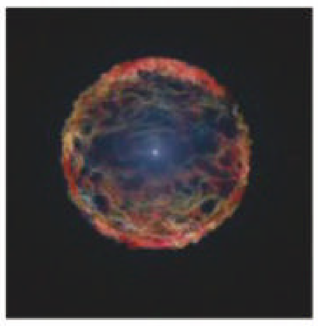
We do, however, have a reasonable understanding of how stellar black holes form...

DYING STAR

Once stars run out of fuel, they die in one of two ways. Smaller, Sun-like stars splutter out of existence and form red giants and white dwarfs, while stars 10 or more times larger go supernova before becoming a black hole.

SUPERNOVA

With the fuel spent, the outward pressure of the nuclear reaction can no longer resist the star's own gravity. The remaining material collapses in on itself and implodes in a supernova, spitting material into space.



COLLAPSE

After this violent explosion, gravity pulls the remaining material together. These gravitational forces crush what's left into a singularity: a single point of almost zero volume but infinite mass, and hence infinite density.

BLACK HOLE

All that mass squeezed into an infinitely small point means that the singularity's gravity becomes so strong that nothing, not even light, can escape its pull, giving rise to what we know as a black hole.

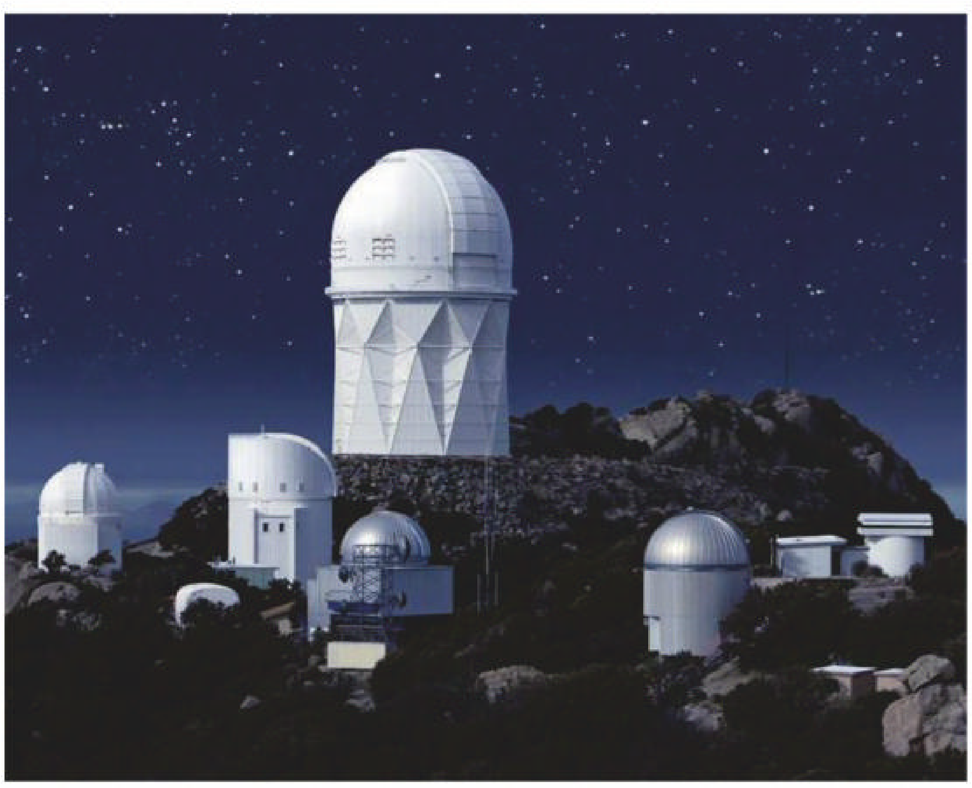
expert in simulating what the turbulent environment of a black hole surrounded by a super-heated accretion disk should look like at different wavelengths. "It turns out that the optimum wavelength is 1.3mm," says Özel. "Not only is it possible to see through the accretion disk to the hole, but our Galaxy and the Earth's atmosphere are transparent to radio waves at this wavelength." Despite this wavelength being used, though, water vapour in the atmosphere can still absorb some of the precious radio waves. For this reason, the EHT's astronomers have chosen a time of the year to make observations that maximises the dryness at all telescopes, which are located in places as far-flung as Chile, Hawaii and Greenland. "The optimum time is from the end of March till the end of April," says Özel.

In April 2017, the EHT observed with telescopes at eight sites; in 2018, a dish in Greenland was added, upping the total to nine. Now, with the addition of a radio dish at Kitt Peak National Observatory in Arizona, there are 10, but it's the observations made in 2017 that have yielded the images of Sagittarius A* and M87.

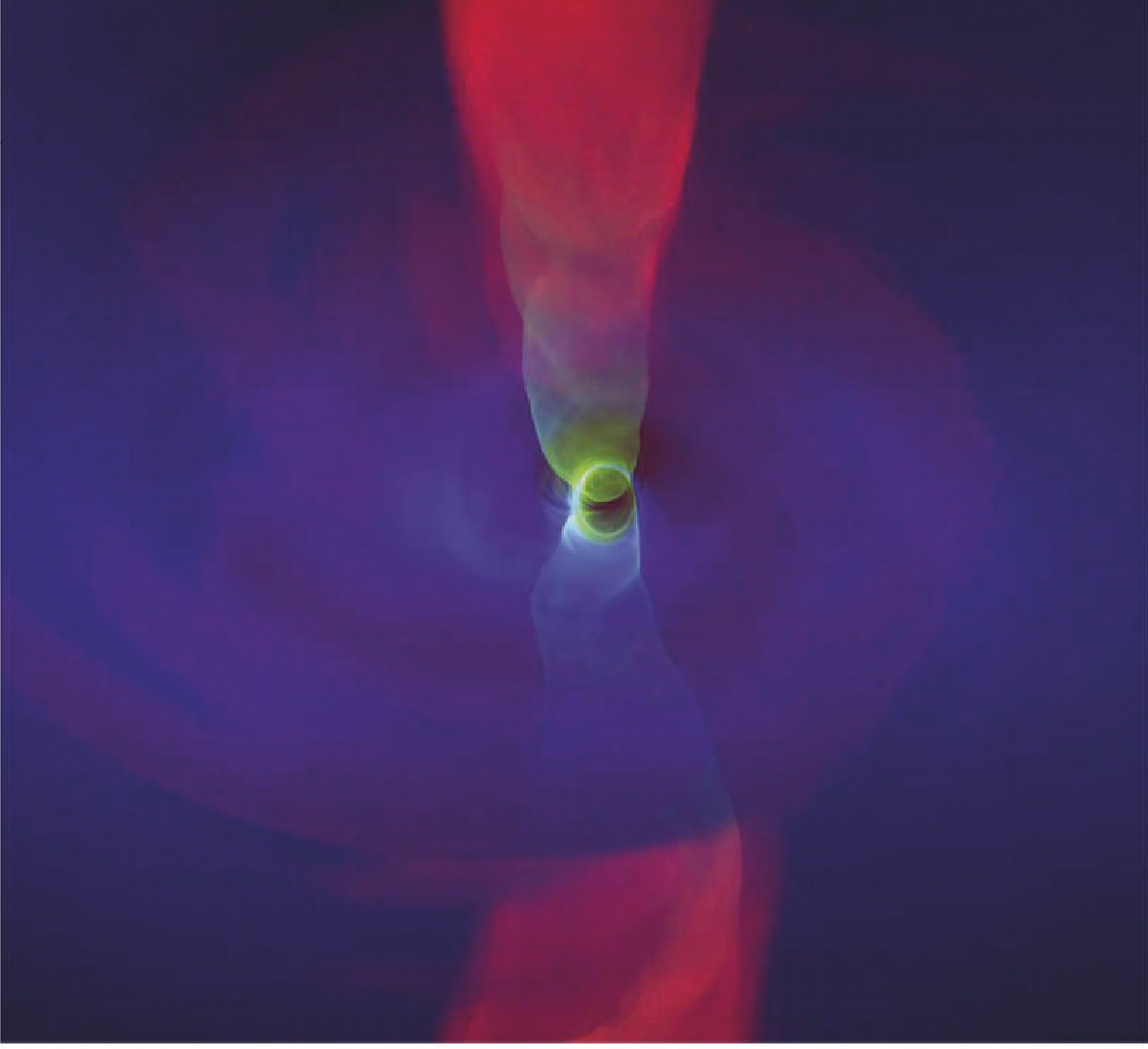
In each observing run, data from each site is recorded on hard drives. Ordinary drives malfunctioned in the low pressure at the high-altitude telescope sites, and had to be replaced by special ones developed for the space programme. In 2017, a total of 960 drives, each with a capacity of six or seven terabytes – capable of storing 1-2 billion photos – recorded a whopping five petabytes of data. The disks, which together weighed more than half a tonne, were flown to Massachusetts and Bonn in Germany, where the signals from each site were combined on purpose-built supercomputers known as 'correlators'.

The individual dishes of the EHT can be considered as tiny elements of a filled-in dish the size of the Earth. But whereas the radio waves impinging on each element of a filled-in dish

BELOW Kitt Peak National Observatory is the latest telescope to be added to the network of 10 that together constitute the Event Horizon Telescope



SCIENCE PHOTO LIBRARY, NASA/HUBBLE SPACE TELESCOPE, GETTY IMAGES X2, CHI-KWAN CHAN



ABOVE
Until now, computer generated images like this offered the best picture we had of what black holes look like

are reflected to a focus where they are naturally combined, this does not happen for the 'elements' of the EHT. The process must be mimicked by playing back the signals on a computer and exactly reproducing the time delays there would naturally have been between them at the focal point.

Getting the signals perfectly synchronised is only possible because at each dish they are recorded alongside clock signals from a super-stable atomic clock. But combining the signals is still hugely time-consuming, because you need to compensate for delays caused by things such as different atmospheric conditions. This is why it has taken so long to analyse the data.

Even this tremendous feat of computing is still only half the job, though. Once that's been done, it's still necessary to determine what distribution of matter actually caused the pattern of radio waves observed. "Understanding what's going on requires figuring out what's happening over a huge range of scales," says Özel.

PREDICTIONS PROVED ACCURATE

What's remarkable is that physicists like Özel have been so successful, and that the image of the black hole in M87 is so close to what they expected to see. But, although this is cause for celebration among physicists, it's likely to leave laypeople underwhelmed, thinking that they have seen a black hole before. "We are victims of our own success!" admits Özel. "Artist's impressions and movie simulations of black holes, based on physicists' predictions, have turned out to be correct. But those holes were pretend ones. The difference now is that we are seeing the real thing."

Özel says she's "ecstatic" at being part of the team that obtained the first image of a black hole, but that it's also a huge relief. "Our predictions could have been completely off," she says. "Thankfully, we got the physics right!"

Among other things, the image of the nucleus of M87 has yielded the mass of its black hole. The diameter of a hole's event horizon goes up by 6km for each solar mass. Consequently, by measuring the width of the hole in the image and knowing the distance to M87, it has been possible to determine that it weighs in at 6.5 billion times the mass of the Sun. "This chimes perfectly with the mass deduced from how fast the hole's gravity is whirling round nearby stars," says Özel. "That puts it in the top 10 per cent of black holes by mass."

Perhaps the most remarkable thing about the image, however, is the sharp 'photon ring' that marks the inner edge of the doughnut of light around the hole. This is the point at which light plunges across the event horizon, never to be seen in our Universe again. EHT team member Heino Falcke of Radboud University in Nijmegen, the Netherlands, puts it in perspective: "We have seen the gates of Hell at the end of space and time."

"The hole is a part of our Universe permanently screened from view," explains Özel. "A place where our current physics cannot reach."

Our best current description of black holes is Einstein's theory of gravity. ➲

"WE HAVE SEEN THE GATES OF HELL AT THE END OF SPACE AND TIME"

LEFT For Feryal Özel, the image unveiled by NASA on 10 April was the culmination of 20 years' work

"STEPHEN HAWKING SUGGESTED THAT GENERAL RELATIVITY MAY BREAK DOWN AT THE HORIZON OF A BLACK HOLE"

However, the General Theory of Relativity is likely to be an approximation of a deeper theory, since it breaks down at the centre of a black hole, where it predicts the existence of a nonsensical point of infinite density. Such a 'singularity' is screened from view by the horizon. The late Stephen Hawking suggested that General Relativity may also break down at the horizon of a black hole, and that the horizon might not actually be the surface of no return everyone believes it to be.

"We have not seen a departure from Einstein's theory yet," says Özel, "but finding such a discrepancy would be hugely important."

Einstein, who never actually believed that black holes could exist in reality, would have both been pleased that his theory has survived, and astonished that such a nightmarish prediction of this theory turns out to be real.

"The fact that Einstein's theory, formulated in 1915, so accurately predicts what we have seen in such an extreme environment, is a triumph for science," says Özel. "Until now, the horizon of a black hole was no more than a mathematical formula on piece of paper," she says. "Now it is a real thing in the real Universe."

LOOKING TO THE FUTURE

The long-term plan with the EHT is to observe Sagittarius A* and Powehi over many years, to see how they evolve as they swallow gas and rip apart stars. The hope is that we will get to understand things such as how they launch their jets. It is via these channels of super-fast matter – often accelerated to close to the speed of light – that supermassive black holes, despite their relatively tiny size, control the stellar content of their parent galaxies.

"We want to know whether the jets are launched at the horizon and how they are focused and collimated," says Özel.

In the 1990s, astronomers using NASA's Hubble Space Telescope in Earth orbit discovered that there is a supermassive black hole lurking in the heart of pretty much every galaxy. Why this is the case remains one of the great unsolved mysteries of cosmology, and it's one that's unlikely to be solved by the EHT. Other mysteries also persist. How quickly after the Big Bang were supermassive black holes born? Did they form in the hearts of newborn galaxies, or were they actually the seeds around which galaxies formed? Watch this space!

In the meantime, the first ever image of a black hole may look fuzzy, but sharper images will be obtained in the years to come. Very probably, it will go on to become one of the most iconic images in the history of science, alongside other famous pictures such as the Apollo 8 image of Earth rising above the Moon, or our first glimpse of the double spiral staircase of DNA.

"We humans should be proud of ourselves," says Özel. "It's easy to be overwhelmed by everyday events on Earth, but we should take some time to think, 'We have done this amazing thing. We have seen to the edge of space and time'."

ESO

ANATOMY OF A BLACK HOLE

1. ACCRETION DISK

The part of the black hole that gives away its location. Here, stars, gas and any other material nearby spiral towards the hole at blistering speeds, producing enormous amounts of electromagnetic radiation that we can detect here on Earth. The objects sucked into the black hole become more frantic and crowded as they near the event horizon. Some are dragged beyond this point into the hole itself, while others are blasted outwards to create a jet.

2. RELATIVISTIC JETS

Pop culture suggests that nothing escapes a black hole, but that's not quite true. Astronomers have observed jets of particles streaming out of black holes so long and fierce that they break out from their galaxy. To borrow an analogy from Konstantinos Gourgaouliatos, a theoretical physicist at the University of Durham, this is like water coming out of a 1cm-wide hose pipe and travelling 80 per cent of the way around the Earth (that's 10,000km).

Our best models suggest that black holes twist the fabric of space-time at their poles. This effect coils magnetic fields, creating a cosmic corkscrew that accelerates particles close to the speed of light before firing them out into the void. At the same time, a magnetic dual-carriageway forms at the black hole's equator – this causes the magnetic field lines to twist and tangle, producing another particle accelerator effect.

These two effects create the fastest particles in the Universe, knocking at the door of the cosmic speed limit: the speed of light. In the long term, data from the EHT should help us understand this comic marvel in better detail.

3. PHOTON SPHERE

As material nears the event horizon, it emits photons (light particles). Normally these would travel outwards in straight lines, but at the cusp of the black hole its gravity bends the photon's path so that we observe a bright ring surrounding a spherical 'shadow'. The EHT will hopefully, in time, reveal more about both.

4. INNERMOST STABLE ORBIT

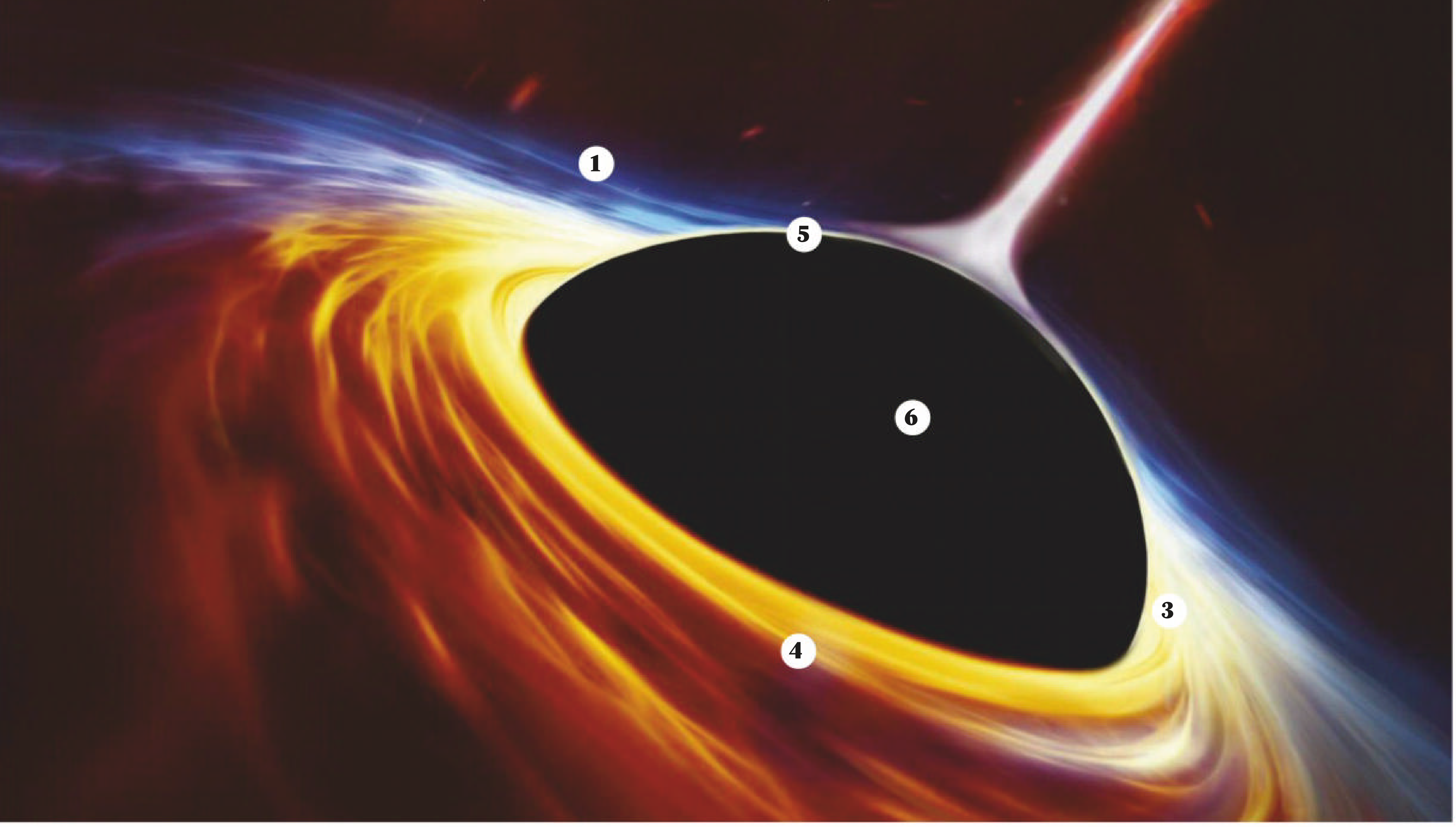
The inner edge of the accretion disk. This is the final region that material orbits before tumbling past the point of no return.

5. EVENT HORIZON

This is where the black part of the black hole begins. Beyond this point material cannot escape the black hole's grip. More accurately, the escape velocity needed to free itself from the hole's gravitational pull is greater than the speed of light.

6. SINGULARITY

All the matter and energy sucked into the black hole ends up here, at its centre: huge amounts of matter and energy are crushed into in an infinitely small space, giving rise to the black hole's gravitational pull. World-renowned theoretical physicist (and science consultant on the film *Interstellar*) Kip Thorne has described a singularity as "a location where the laws of physics break down."



HOW WE KNOW BLACK HOLES EXIST...

WHY HAVE PHYSICISTS BELIEVED FOR SO LONG IN OBJECTS THAT UNTIL NOW HAD NEVER BEEN SEEN?

Karl Schwarzschild was a professor of astronomy at Berlin Observatory who, on the outbreak of WWI, volunteered for the German army. He did not have to: he had a good job and was 40 years old. But he was Jewish, anti-Semitism was on the rise in Germany, and he wanted to prove that he was just as German as everyone else.

Schwarzschild ran a weather station in Belgium, calculated shell trajectories with an artillery battery in France and, at the end of 1915, found himself on the Eastern Front. There, he developed blisters in his mouth. They spread over the whole of his body and he was sent to a field hospital, where he was diagnosed with *Pemphigas vulgaris*, a rare autoimmune disease in which the immune system attacks the skin.

Schwarzschild knew it was serious because the skin is the largest organ. It is through the skin that heat is lost and so, when it is compromised, it is not possible to control body temperature. Also, the skin is a barrier against microorganisms and so, when that barrier is breached, a person is prone to life-threatening infection. The condition remains incurable today, although it can be treated with steroids. But in 1915 there was nothing.

To distract himself, Schwarzschild turned to physics. Back in Berlin, he had been aware that Albert Einstein was working on a revolutionary new theory of gravity. And when he learned that Einstein had presented it in four lectures in November 1915, he obtained and devoured a written summary.

> "EINSTEIN WAS AMAZED TO RECEIVE A LETTER FROM THE EASTERN FRONT, AND EVEN MORE AMAZED TO FIND A SOLUTION TO HIS EQUATIONS"

FROM NEWTON TO EINSTEIN

Isaac Newton imagined that there was a force of gravity between the Sun and Earth, like an invisible tether that kept Earth trapped in orbit. Einstein realised this was incorrect. In fact, a massive body like the Sun creates a valley in the space-time around it, and Earth travels around the upper slopes of the valley like a roulette ball in a roulette wheel.

Einstein had replaced Newton's one equation describing gravity by 10. So working out how space-time is warped by a given mass was very difficult. But, incredibly, Schwarzschild found a formula for the valley-like space-time curvature caused by a spherical mass like a star. He sent it to Berlin. Einstein was amazed to receive a letter from the Eastern Front, and even more amazed to find a solution to his equations,

which he had considered impossible. The following week he presented the results at the Prussian Academy.

But Schwarzschild had not finished.

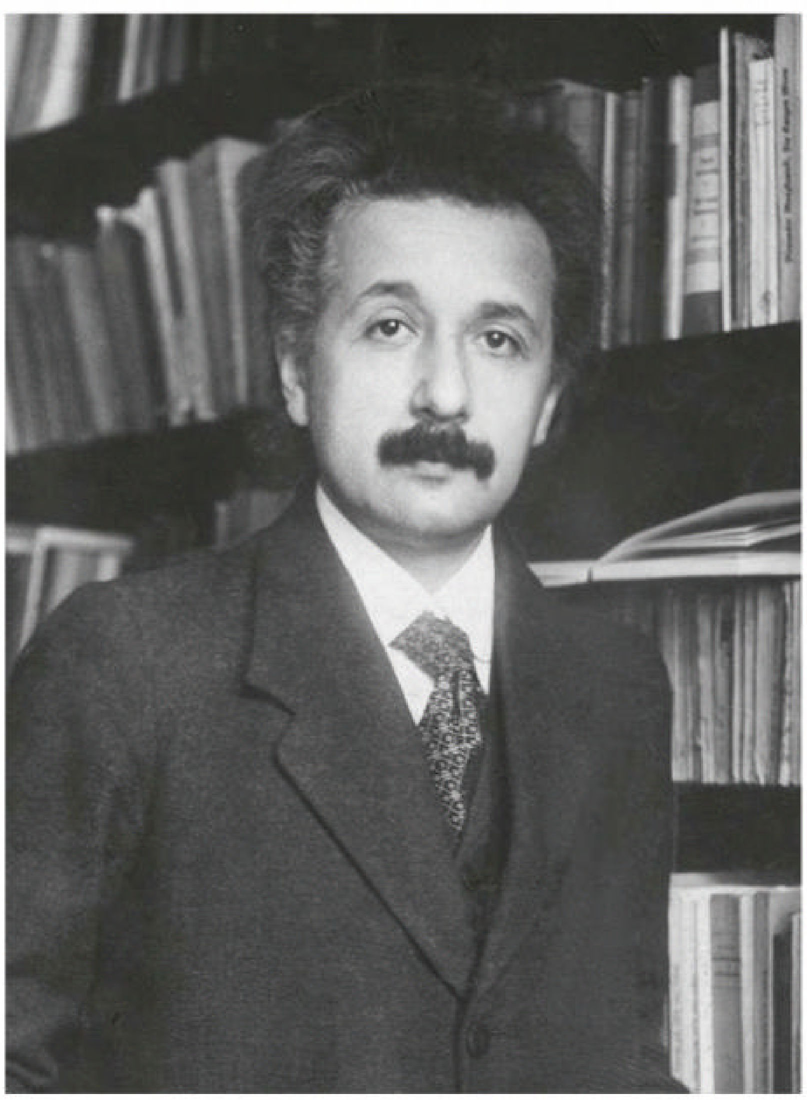
EINSTEIN UNCONVINCED

Lying in his hospital bed, Schwarzschild further realised that, if the mass of a star was squeezed into a smaller and smaller volume, the valley of space-time around it would become steeper and steeper until eventually it would become a bottomless pit out of which nothing, not even light, could escape. Today, everyone in the world knows the name of what Schwarzschild had discovered but the term 'black hole' would not be coined for another half century. He again sent his solution to Einstein, who presented it in Berlin, although he did not believe nature would ever implement such a monstrous entity.

In the spring of 1916, Schwarzschild was moved to a hospital in Berlin, where he died. He was just 42.

ABOVE German astronomer and physicist Karl Schwarzschild

BELOW Physicist Albert Einstein



SCIENCE PHOTO LIBRARY, GETTY IMAGES

Fast forward to 1971 and Herstmonceux Castle, the Sussex home of the Royal Greenwich Observatory. Paul Murdin was a young astronomer with a young family to support in need of a permanent job. He needed to make his name – and he had an inkling how to do it.

HELP FROM UHURU

The main problem in astronomy is that the Universe is big. There are two trillion galaxies, each with about 100 billion stars. Finding an interesting one is harder than finding an interesting sand grain among all the sand grains on Earth's beaches. What sign might reveal that a star was unusual?

Murdin hit on X-rays. Such high-energy light would be emitted by matter heated to millions of degrees. The previous year, NASA had launched Uhuru, the first X-ray satellite, and Murdin obtained the catalogue.

He noticed there was a bright X-ray source, christened Cygnus X-1, In the constellation of Cygnus. The only unusual star in the field was a blue supergiant called HDE 226868, many times the mass of the Sun and pumping out hundreds of thousands of times more light. The star could not be the source of the X-rays – but maybe it was orbiting something that was.

Murdin's colleague Louise Webster was measuring the speeds of stars, so he asked her to measure the speed of the blue supergiant. And, sure enough, she found it was orbiting an invisible companion, once every 5.6 days. From the speed that the supergiant was being whirled around, this companion had to have a mass of at least four, and probably six times the mass of the Sun. The only compact stars that were known – white dwarfs and neutron stars, the latter discovered by Jocelyn Bell only four years earlier – were not massive enough. Only one candidate remained: a black hole.

THEORY BECOMES REALITY

Incredibly, the monstrous, nightmare entity predicted by a man dying in a bed in a field hospital on the Eastern Front half a century earlier, actually existed in the real world! It was matter ripped from the blue supergiant and heated to incandescence as it was sucked down onto the black hole that was generating the X-rays. Murdin and Webster wrote a joint paper in the journal *Nature*. Murdin got his full-time job and a new house, and became the first person in history ever to have his mortgage paid by a black hole. SF

by MARCUS CHOWN
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Marcus Chown is the author of Infinity In The Palm of Your Hand: Fifty Wonders That Reveal An Extraordinary Universe *(Michael O'Mara Books, 2018).*