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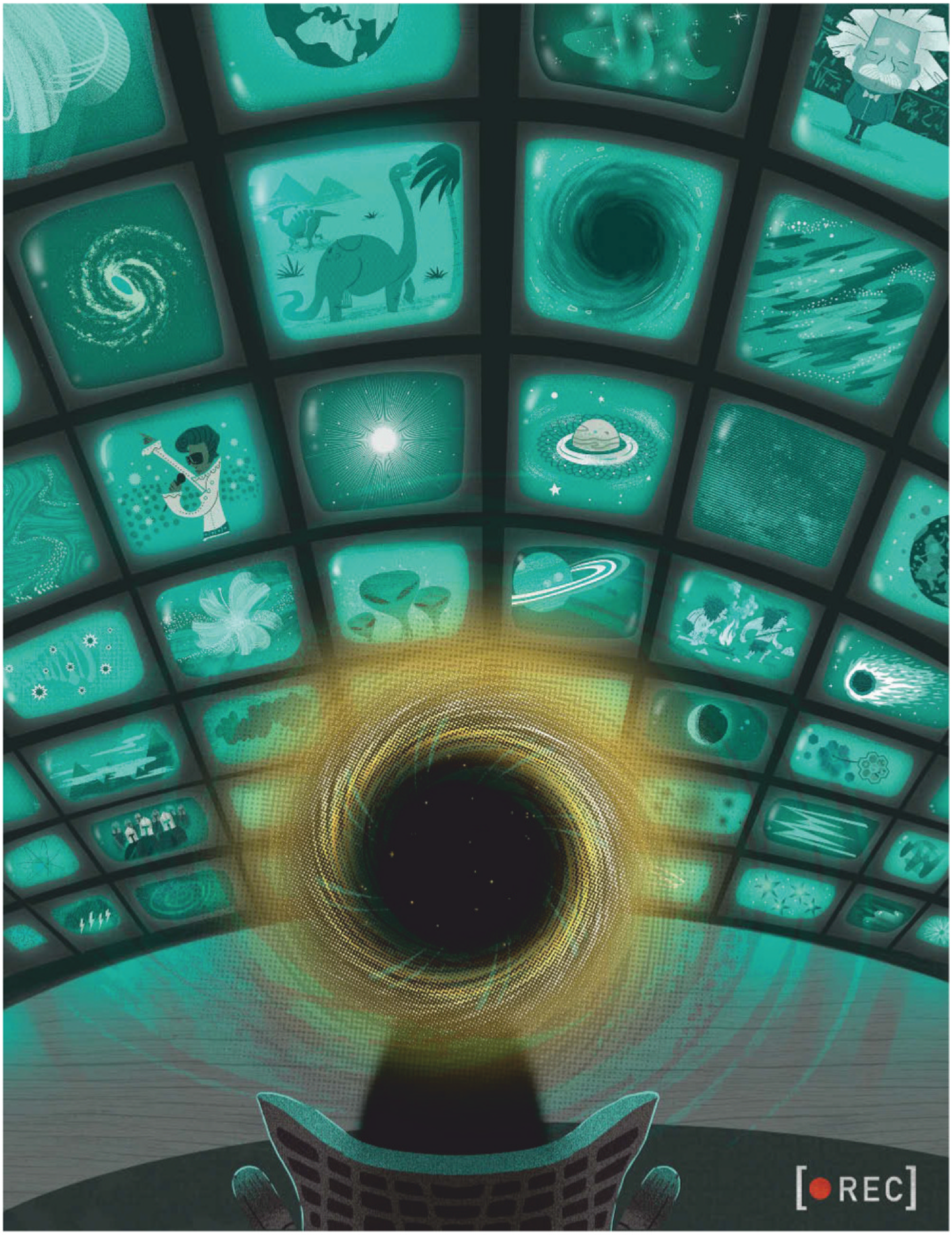


GRAHAM CARTER

Black hole movies

Einstein's monsters are broadcasting footage of the universe's history – and there are ways we could get a clearer view, says **Stephen Battersby**

THE picture was seen by billions: a hazy ring, glowing orange-bright, surrounding a heart of darkness. The work of many minds over decades, it was above all a tribute to the brilliance of one. Yet as the world marvelled at the first ever direct image of a black hole – one of the cosmic monsters predicted by Albert Einstein's theories – the researchers behind it found themselves confronted with a rather basic puzzle.

"After the result was published, we were all getting together and asking: what does this thing mean?" says radio astronomer Michael Johnson at Harvard University. They had been so wrapped up in turning their data into a picture that no one had really stepped back and tried to digest what it was telling them.

Over the past year, their quest to find answers has led them into a cosmic hall of mirrors, where the black hole's gravity takes light from all directions, warps it and beams it to us as an infinitely recast image of the hole's surroundings. The result is an epic movie of the history of the universe, as witnessed by a black hole, playing on a dramatically curved screen tens of billions of kilometres across.

From way back here in the cheap seats, about 55 million light years away, we will never be able to see the action's full sweep, but we can catch glimpses. They could be enough to unlock the true history of giant black holes, put Einstein to the test like never before and maybe even lead to a deeper understanding of space and time.

Black holes are perhaps the most breathtaking prediction of Einstein's general theory of relativity, the description of gravity he presented in 1915. No cosmological observation has been found to contradict its depiction of massive objects warping space and time around them. A black hole takes that idea to the extreme: it is a concentration of mass so great that space-time is warped to an infinite degree. Anything venturing too close is drawn across its event horizon, beyond which we can never see.

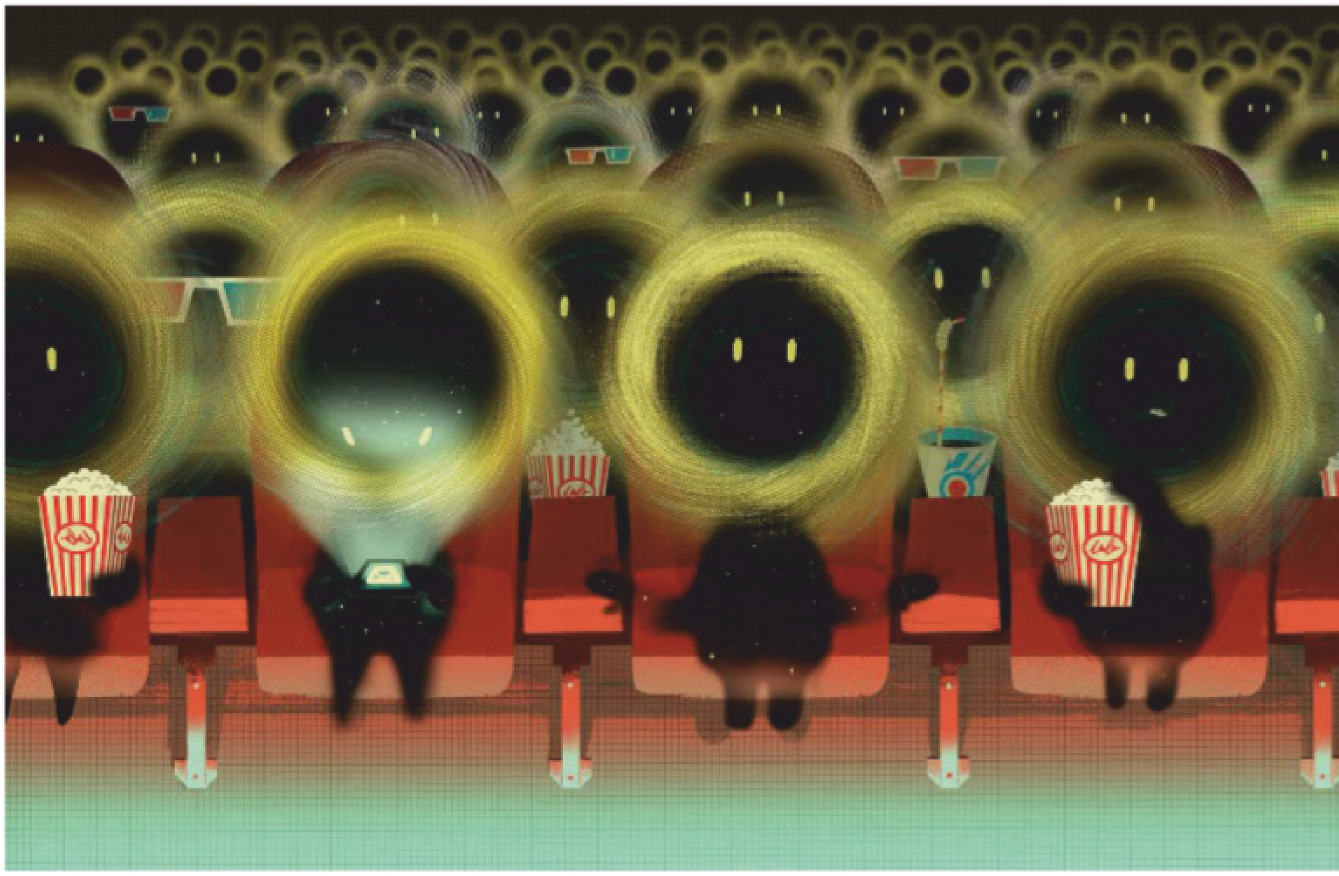
Although Einstein doubted that they actually existed, observations in recent decades have persuaded us that black holes are real. Small ones, just 10 or 20 times the mass of our sun, form when huge stars collapse at the end of their working lives. The gravitational waves detected by the LIGO collaboration in 2015 were ripples in space-time caused by two such objects merging. These are dwarfed by supermassive black holes of millions to billions of solar masses that appear at the heart of almost every galaxy, including our own Milky Way.

The image presented in 2019 was of M87, a giant elliptical galaxy in the Virgo cluster. It houses a beast of a supermassive black hole, with a mass probably 6.5 billion times that of the sun. The international Event Horizon Telescope team, which includes Johnson, used sophisticated signal processing to combine data from radio › telescopes from around the world into one image of M87's core. The resulting resolution matched that from a single radio dish the size of our planet.

The darkness at the image's centre is a shadow of the black hole; an image of the event horizon, magnified and distorted by the hole's gravity. But what exactly is that surrounding glow? That was the question that initially no one could really answer.

To help decode the image, Johnson reached out to some more theory-minded researchers, including Alex Lupsasca, also at Harvard. "We had been colleagues side by side for many years," says Lupsasca. "They were listening to us, but only with half an ear because they were busy doing their experiment."

"My role was finding the common language," says Johnson. "We have black hole observers, black hole simulators, black hole theorists… It sounds so silly. But actually it is extremely difficult to communicate between these subfields; they are all very technical."



Space opera

Since the image came out, physicists have run many models of the maelstrom around M87's black hole. Called GRMHD simulations, these combine general relativity with magnetohydrodynamics, which describes the behaviour of the hot, ionised gases that surround the hole. Each simulation starts with some assumptions about what might be producing the radio waves – for example, matter spiralling inwards – and follows the waves that would be produced by such a source as the hole's gravity bends their path, to predict what we would see on Earth.

It turns out that a wide range of possible sources lead to a fuzzy glow like the one seen by the Event Horizon Telescope: the black hole stamps its form with such force that the emission's true origin is hidden. But although the models weren't useful in distinguishing between the sources, they revealed something unexpected and intriguing. They all predicted that there should be a very bright, thin ring embedded in the broad fuzzy orange one. "To start with, there was a lot of confusion about what this meant," says Lupsasca.

It turned out that we had been here before, some time ago. Back in 1959, Charles Darwin had predicted something very similar – not that Charles Darwin, but his grandson, physicist Charles Galton Darwin. He showed how light from the surrounding universe passing very close to the black hole might take a swing around it before heading our way. Photons passing even closer would be caught for more orbits. Later work suggested that light taking a given number of orbits would be squeezed down into a thin ring.

That all assumed a black hole that isn't rotating, whereas real ones are expected to spin to some degree, preserving the angular momentum of material they have sucked in. "When a black hole spins, it literally drags space-time into a kind of whirlpool around it," says astrophysicist Janna Levin at Barnard College in New York. Anything nearby is dragged around with it, including light. "Nobody had studied this case," says Lupsasca. "It is way more complicated."

But the basic picture was confirmed by finer-grained GRMHD simulations. They show that, if you look closely, the thin bright photon ring should be made up of infinite, nested subrings, each corresponding to photons taking a certain number of turns

"When a black hole spins, it drags space-time into a kind of whirlpool around it"

around the black hole, getting exponentially fainter and thinner as they get closer to the edge of the black hole's shadow. Because the inner subrings are made of light that has made more orbits, this light was captured earlier on. As the team write in their paper, published in March this year: "Together, the set of subrings are akin to the frames of a movie, capturing the history of the visible universe as seen from the black hole."

Admittedly, this movie is highly biased to stuff near the black hole. Each subring is also only around six days older than the last, so there is a limit to how much of the reflected universe just a few frames show us. "We're not going to see dinosaurs," says Johnson.

But there is treasure in these golden rings, nonetheless. For a start, their size and shape don't depend on where the photons came from, but on the properties of the black hole alone. That could allow us to pin down these properties like never before. Our current best figure for the M87 black hole's mass, 6.5 billion solar masses, is only accurate to within 15 per cent or so. But the thickness of its rings is highly dependent on its mass. "If you can resolve the super thin photon ring and put a ruler across it, now you are talking precision measurement," says Lupsasca – perhaps to better than 1 per cent.

The spinning space-time around the hole should also squash the rings a little, so they aren't perfect circles. By tracing their shapes, we could get an accurate figure for the black hole's spin. That could tell us about the history of M87's monster. Did the black hole form in a series of random collisions between smaller ones, probably giving it a low overall spin? Or did it grow by hoovering up gas spiralling in from its host galaxy, consistently cranking up its rotation?

Elusive theory

Measuring black hole spin could also hold the answer to how black holes send out powerful jets of material, travelling at close to the speed of light. These jets can travel for hundreds of thousands of light years, blasting out of a host galaxy and ending in enormous plasma plumes that shine across the cosmos. One leading theory is that a black hole's spin combines with surrounding magnetic fields to act as a dynamo. This generates an electric field so intense that it wrenches electrons and positrons out of the vacuum, accelerating them into two jets, each speeding away from a pole of the black hole.

The photon rings could also provide our most stringent test of general relativity yet. We know the theory works very well in Earth's gentle gravitational field; it is verified billions of times a day, because satnav can only work by precisely allowing for relativity's time warps. Thanks to Gravity Probe B, a NASA satellite launched in 2004, we have even seen the frame-dragging caused by Earth's spin, our planet's feeble version of the space-time whirlpool around a rotating black hole.

As for the extreme gravitational fields where relativity really gets to work, the echoes of colliding black holes now routinely picked up by gravitational wave detectors square with the predictions of Einstein's theory. But the spacing between black hole photon rings would be a far more precise test.

"I think it's a great way to test relativity because it is very difficult to see those kinds of inner orbits in any other way," says Levin. Any deviation from general relativity's predictions could help physicists to finally devise a long-elusive quantum theory of gravity, which promises to tell us what space and time are made of, what really happened in the first moment of the big bang – and indeed what lies in the heart of a black hole.

With such promise, the prospect of actually seeing these photon rings is exciting. But it won't be easy. Discerning such fine features will require a radio eye even better than the existing Event Horizon Telescope, which is already opened as wide as Earth will allow.

One option would be to use shorter wavelengths, which potentially provide sharper vision. The original image of M87's black hole was based on radio signals at a wavelength of 1.3 millimetres, and Johnson suggests that moving to a quarter of this wavelength might be enough to see the first, most distinct photon subring. Earth's atmosphere blocks this short-wave radio signal, except in very high, dry locations, such as the South Pole and Chile's Atacama desert. These two sites are already home to facilities that are part of the Event Horizon Telescope, but it isn't clear if they can produce the necessary resolution on their own.

Instead, we probably need to add a radio telescope in space. "The further away it can go, the more precisely we could image the subrings," says Lupsasca. A good location would be the second Lagrange point, or L2. Here, the gravity of Earth and sun combine in such a way that a spacecraft can maintain its position relative to Earth with minimal effort. L2 is a handy 1.5 million kilometres away in the opposite direction to the sun. A telescope there, coupled with others on Earth, should provide sufficient resolution to image the first three photon subrings around M87's black hole, as well as those around Sagittarius A*, the smaller supermassive black hole at the centre of the Milky Way.

This isn't as far-fetched as it might sound. Russia has already launched a space-based radio telescope, the now-defunct Spektr-R, that looped out to a distance of 300,000 kilometres from Earth. An improved version, Spektr-M, also known as the Millimetron Space Observatory, is due to launch out to L2 around 2029. And a proposed US mission, the Origins Space Telescope, is also intended for L2. If approved, it could launch around 2035.

Origins would need a few upgrades from its original specifications to perform the measurements required to see the photon rings, including an accurate onboard clock to synchronise observations with those on Earth. "The main difficulty I foresee is the sheer amount of data," says co-leader of the Origins project Asantha Cooray at the University of California, Irvine. Raw data would have to be beamed back for processing with data from the telescopes on Earth, and it would stack up to 230 terabytes for 6 hours of observations. That is far too much to send by radio networks, the usual means of transferring data from a spacecraft, so an optical downlink will be required instead. That has been achieved from low Earth orbit, but not from the great distance of L2.

EVENT HORIZON TELESCOPE COLLABORATION ET AL.

The fuzzy glow of M87's black hole is masking infinite sharp rings of light

Local screenings

The rewards could be huge. The higher resolution of the space set-up could see the shadows of many more supermassive black holes – perhaps a million of them, stretching across the observable universe. This could finally resolve many of the mysteries that swirl around Einstein's monsters, including how they managed to grow so quickly in the early days of the cosmos.

As for that black-hole's-eye movie of the universe, even the million-mile-wide radio array made possible by a dish at L2 would only be enough to show us a trailer, just three frames long. For a feature-length version, it is hard to imagine what kind of distant-future technology would be good enough. "Since the subrings get exponentially thinner, you need to increase your telescope size by roughly a factor of 10 for each additional subring that you want to see," says Lupsasca. A radio array spanning from here to our next nearest star Alpha Centauri, over 4 light years away, would get us up to about 10 subrings.

So perhaps we will have to get closer to the action, and visit a screen showing a good picture nearer by. Our nearest supermassive black hole, at the centre of our galaxy, is still rather inaccessible; but the nearest known black hole, discovered this year, is only around 1000 light years away. Being only about 4 solar masses, its screen size spans only tens of kilometres. Just a little fleapit of a cinema, compared with the movie-palace grandeur of M87's black hole – but at least the programme will have a lot more local interest. ■

"To see the black hole rings, we probably need to put a radio telescope in space"

Stephen Battersby is a consultant for *New Scientist* based in London