'We're building a telescope bigger than Earth'

Alex Lupsasca is part of an ambitious plan to send a radio dish into space to image a nearby black hole. He tells Thomas Lewton how this could test the limits of relativity

WE ARE living in the era of black hole photography. In 2019, the first picture taken of a black hole was released. Unsurprisingly, it was difficult to get – in fact, it required a telescope essentially the size of Earth. Yet for researchers such as Alex Lupsasca at Vanderbilt University in Tennessee, that wasn't good enough. He and his colleagues have set their sights on a more detailed image, but to get it we will need an even larger telescope.

The groundbreaking 2019 picture was taken by a network of radio observatories dotted around Earth, collectively known as the Event Horizon Telescope (EHT). Working together, eight of them created an image as clear as would a single dish larger than any that could actually be built. Lupsasca is part of a team planning to launch the Black Hole Explorer (BHEX) telescope, which would extend this network into space 20,000 kilometres from Earth – creating a receiver effectively bigger than the planet. Doing so, he says, would give researchers the precision needed to measure a mysterious part of a black hole known as a photon ring, in this case one created by M87*, the supermassive black hole in a nearby galaxy that featured in that first picture.

Lupsasca, the BHEX mission's deputy project scientist, is a theorist who specialises in the physics of extreme environments, like the centres of black holes. He told us about why he thinks this is our best hope yet of breaking Albert Einstein's theory of gravity and why ambitious space missions are the key to finally cracking one of the biggest mysteries in physics: the fundamental structure of reality.

Thomas Lewton: Why do we need such a big telescope?

Alex Lupsasca: To observe a tiny object in the sky, you need to resolve rays that are very close to each other. If you have a bigger telescope dish, then you can bounce them off the dish and focus them more precisely. We want to take a sharp image of M87*, a nearby supermassive black hole, which has roughly the same size in the sky as an orange on the surface of the moon. We want to see what is called the black hole's photon ring by making high-resolution movies of M87*. To do that, we need a dish that is bigger than the size of Earth.

Is the telescope really bigger than Earth?

Imagine you have a big, mirrored dish and you shatter the mirror into shards, and then you carry the shards far apart to opposite sides of Earth and beyond. In each shard, you can only see a sliver of the black hole, but if you record that information very carefully, you can virtually bring the shards back together to reconstruct the full image. Given sufficiently many shards, this image has almost the same precision as a telescope dish that is bigger than Earth.

Has the Black Hole Explorer mission been approved by NASA?

Not yet, but in the past few months, we've made rapid strides towards that goal. We are

PAUL RYDING

> "Space missions like this are the cathedrals of our era"

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The Event Horizon Telescope uses dishes (bottom three images) dotted around the world (top). Black Hole Explorer would extend this ground-based telescope network into space

now working with NASA's Goddard Space Flight Center, and we've brought on engineers to figure out the remaining technical challenges. We've also raised private funding, including seed funding from tech investor Fred Ehrsam. We're running full steam ahead to put together a full proposal for NASA next spring. If that's adopted, then we'll get a satellite to fly in 2031, which feels far away, but in space mission terms that's not long at all. Hopefully before my hair turns grey, we can actually make a movie of a photon ring.

What is a photon ring?

Suppose there's some hot gas giving off photons around a black hole. Most of these swerve a little bit around the black hole's gravity, and these will show you an image of the gas around it – as in the EHT images of black holes. But there are a small fraction of photons that, if aimed just right, orbit exactly around the edge of the black hole, called its event horizon. This is the edge of our visible universe – we really have no idea what happens to particles that pass over its precipice, and perhaps we never will. So the photon ring is light that skirted the edge of our universe and then escaped [the event horizon], carrying information about the space-time geometry there.

Why do you want to measure the photon ring?

We want to explore how gravity works in the most extreme conditions imaginable. Gravity is by far the weakest of the four forces of nature that we're aware of. That makes it the hardest to measure. Its effects are the most subtle, the least well understood.

We have a perfectly good, internally consistent theory – called quantum field theory – for the other forces of nature, which are electromagnetism and the weak and strong nuclear forces. But it isn't fully compatible with Einstein's general theory of relativity, which is our best description of gravity. We want to be able to write down mathematical equations that describe all these forces together. But there is a tension – when we try to combine these two things, we find that they don't play well with each other.

So what can we do? We can look to black holes, which are, by definition, the most extreme gravitational fields that can exist. They are the best place to look to glean clues about the next deeper layer of fundamental theory. These are pre-made experiments with strong gravity that we can study – and photon rings are a stamp placed on an image of a black hole by its strong gravity.

Can you describe the signature that the rings contain in more detail?

This first photon ring that we plan to observe with BHEX is created by light travelling towards the black hole that makes one half turn around the edge and then is sent on towards our telescopes. This is the brightest and outermost ring, but nested within it there are many fainter sub-rings. They are labelled according to the number of times that photons orbit around the black hole.

General relativity tells you that each ring is almost a perfect circle, but there is a slight deviation that follows a periodic pattern – the periodicity tells you about the diameter of the ring at that angle. It also tells you the precise relationship between these rings. Recently, Michael Johnson at Harvard University – who is part of the BHEX team – and I found that a single telescope orbiting Earth, looking at the photon ring from different angles, is all you need to measure this complex form. That isn't obvious; there's some mathematical magic at play here. Together, Johnson and I won the New Horizons in Physics prize for that result. Several of our colleagues, including Sam Gralla and Dan Marrone from the University of Arizona, have also done important theoretical work in this area.

Is the hope that the photon ring will deviate from general relativity?

BHEX's observations would be qualitatively different from all tests of general relativity that have been done on Earth or in the solar system so far, because they will really probe this strong gravity regime. So they give us a shot at seeing something totally radical and surprising. That's the aspirational goal of BHEX. If we're lucky, maybe some signature of something different from general relativity will appear, but I'm not holding my breath for it. However, we are guaranteed to learn a whole lot of exciting new astrophysical results about magnetic fields and matter falling into a supermassive black hole.

How hard is it to link up telescopes dotted across Earth to one in space?

The main issue is we need to record a lot of data. The EHT, which took the first black hole pictures, is an Earth-sized array of telescopes. Each one recorded petabytes [10^{15} bytes] of data. That was the most data-intensive experiment in history.

Imagine a big room filled with racks of hard drives that all get filled. Then, to isolate a tiny source in the sky, like a black hole, they had to correlate the data from each telescope using a supercomputer at the Massachusetts Institute of Technology. But there's not enough capacity on the internet to do that – the cables just aren't big enough – so they literally put the hard drives on airplanes and flew them there.

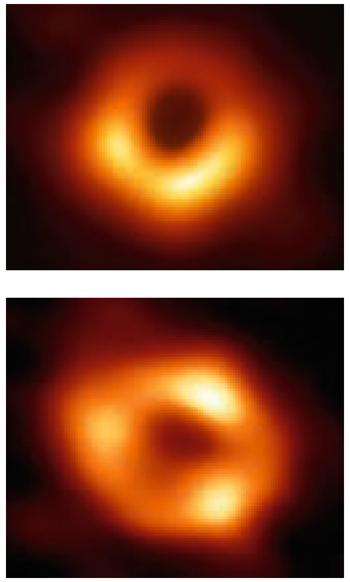
But now we're going to have a telescope in space. You can't have a room full of hard drives on your satellite, as it would be too heavy. So we will have to record data live, dumping it down to Earth almost immediately. The hardest part of this mission technologically is that downlink. Encouragingly, MIT's Lincoln Laboratory has just flown a cubesat called TBIRD that demonstrated a 200-gigabits-per-second laser downlink, more than we need, from Earth orbit.

What else can you do with BHEX?

We don't really have a good way of measuring spin for black holes, or even the black hole mass for that matter. It's really tricky. We know the mass of the black hole at the centre of our galaxy, Sagittarius A*, very well. That's thanks to Reinhard Genzel at the Max Planck Institute for Extraterrestrial Physics in Germany and Andrea Ghez at the University of California, Los Angeles, who measured the orbital motion of stars around the black hole over two decades. But for us, measuring the black hole will be as simple as putting a ruler across the photon ring.

Black holes are thought to be described only by their mass and spin. This is called the no-hair theorem in general relativity [the idea that "hairy" black holes with more observable features, or "hair", are impossible]. So testing this by measuring the mass and spin of a black hole for the first time is a huge deal. The assumption that black holes really are described by general relativity underlies all of our models in astrophysics. It's a workhorse of astronomy, but it's something that we haven't really tested with great precision yet, at least for supermassive black holes.

The first images of the supermassive black holes M87* (top) and Sagittarius A* (bottom)



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What is the next step, after the first photon ring movie?

After seeing the first photon ring, the next thing will be to set a satellite even farther out, at a lunar distance. That will let us see the second photon ring, which you can now compare with the first one. Once you can see multiple rings, you have a super-sharp probe of general relativity. Each ring gives you an exponential bump in the precision of your test.

The 20th century was the century of the particle collider. Smashing particles together at high energies helped us figure out how three of the forces of nature work. But you're never going to smash particles hard enough to see how these quantum forces can be united with gravity. Recently, it has become much cheaper to launch sensitive instruments that can do this into space because of private space companies. I think 21st-century physics is going to be defined by the study of extreme phenomena in space.

The technology involved is just mind-boggling. I went to Paris recently and saw the Sacré Coeur, this ginormous cathedral. You go in and you see how the stones were erected, the ceiling is so tall, and you think, "wow, our ancestors built this, but what are we doing that's like this in our time?" Space missions like the James Webb Space Telescope and BHEX are pushing the envelope theoretically, experimentally, technologically. They are the cathedrals of our era. ∎

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