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The black hole photographer

Astrophysicist **Feryal Özel** was a pioneer in working out how to capture vivid portraits of distant black holes. Abigail Beall asked her how she did it – and what we can learn from the two photos in the album so far

A FEW weeks ago, we got our first look at a portrait of the mysterious behemoth at the centre of the Milky Way, the supermassive black hole known as Sagittarius A*. The image is an amazing feat of astronomical endeavour, made possible thanks to a planet-sized array of telescopes called the Event Horizon Telescope (EHT). It was even harder to capture than the previous black hole picture taken by the EHT, which was the first ever. But it is also special because this black hole is at the heart of our home galaxy.

Feryal Özel at the University of Arizona was one of the first people to come up with a way of photographing black holes and she is now a key member of the EHT collaboration. *New Scientist* caught up with her to find out what we have learned from the latest image, how it puts our understanding of gravity to the test and what to expect next from the nascent field of black hole photography.

Abigail Beall: What first drew you to black holes?
Feryal Özel: When I started graduate school, astronomy was having a golden age. Part of that was the age of discovery of how black holes and neutron stars behave. Then I realised these are basically extreme laboratories in space. I can combine what I love about theoretical physics with this amazing data and explore things that we can't with a lab on Earth.

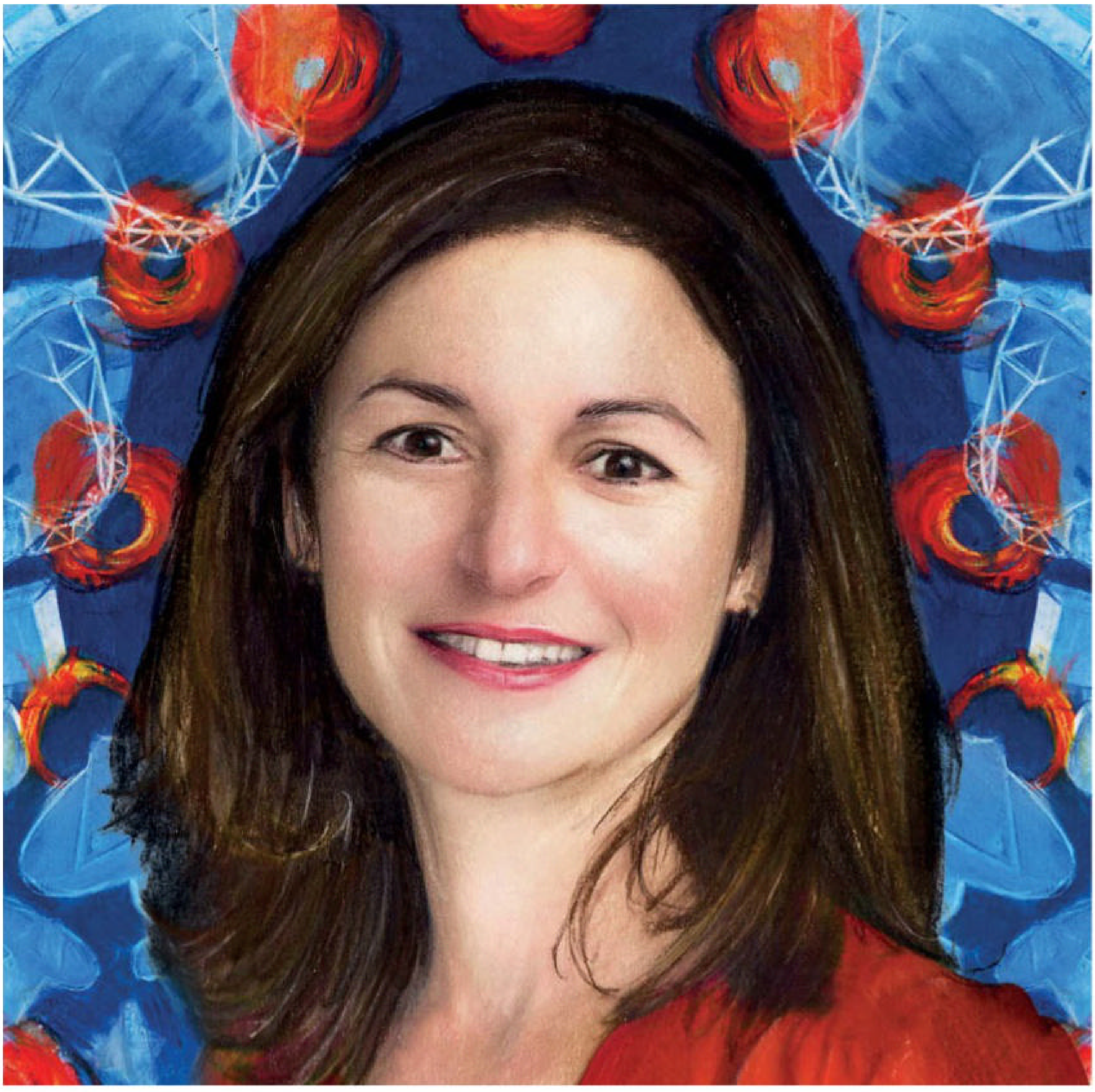
What is so mysterious about black holes?
Black holes were, at first, a mathematical construct from Einstein's theory of gravity, general relativity. When gravity is strong enough, the theory allows for a singularity to form, a region with infinite energy density.

Many people did not believe these would really exist in the physical universe. Then we realised eventually that, yes, when massive stars collapse, they do form something unlike anything else we know of in this universe. There is a region of space that becomes disconnected from our universe called an event horizon. We can no longer receive any information from this region and not even light can escape from it.

One of the things we want to understand is if black holes are exactly what Einstein's theory predicts or if there are some deviations from general relativity that occur when we get close to an event horizon. There is a very basic discrepancy between how general relativity describes the universe and how quantum mechanics, our theory of the subatomic world, describes it. At some point, we would like to reconcile these two theories. And we think that black hole event horizons are places where we could get some clues on how to do this, because you need both theories to work together to describe the extreme physics of black holes.

How did the idea of imaging a black hole first come about?
There were efforts in the 1990s to image black holes. That is when the concept of very-long-baseline interferometry was developed. The idea is to have several telescopes spaced apart from each other and hook them up together to get better resolution (see "How to build an Earth-sized telescope", page 49). Researchers wanted to see how well they could see the black hole at the centre of our galaxy – the trouble was that there is a lot of gas and dust around the black hole that gets in the way.

In the late 1990s and early 2000s, we developed much better models of the environment around black holes. I had the idea of asking: are there any wavelengths of light that we could observe so that we could see the black hole without our view being impeded by the torus of gas and dust surrounding it? What will it take to get down to the event horizon? ›



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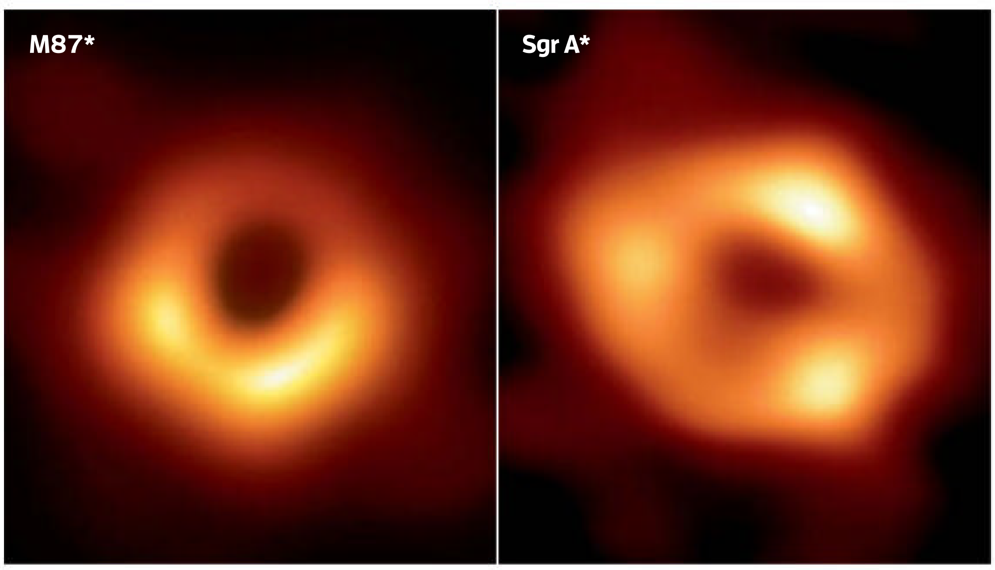
And what does it take?
I realised that the types of black holes we have in our vicinity have a peculiar property: they belong to a class of low-luminosity black holes that make their imaging possible with radio telescopes. I started doing simulations to determine the wavelength at which we would be able to see all the way down to the horizon of these black holes. That helped set the initial observations of black holes at 1.3 millimetres, which is the current observing wavelength of the Event Horizon Telescope. Then it just went from there.

> "Black holes are unlike anything else we know of in this universe"

The first image of a black hole was of M87*, the one at the centre of galaxy M87, in 2019. What was it like seeing that for the first time?
It was really amazing. EHT collects data through interferometry: it is pairs of telescopes getting little bits of information, and then we synthesise it into a single image. But even the interferometric data had a telltale shape that was like: "Oh my God, this looks like a ring!" That was the moment we realised it had worked.

And we have just had the second image of a black hole, this time Sagittarius A*, the one at the centre of our own galaxy. It was a little different than the image of the black hole in M87. We collected the observations for this work in 2017 and we knew early on that there was again a ring-like structure, we could tell its size pretty much from the get-go. But we were worried because the gases move much more quickly around this black hole than they do around M87*, largely because it is smaller, and that could blur or produce misleading artefacts in the image. We also had to deal with the blurring that comes from the light travelling through the disc of our own galaxy, which we call interstellar scattering. It took at least a couple of extra years before we could say, "OK, we are sure that we are not baking any artefacts into the results that we will share with the scientific community and the public".

How is M87* different to Sagittarius A*?
They're both what we call "radiatively inefficient" black holes, meaning that, as matter falls into them, we don't get a tonne of light out, because matter can't radiate very efficiently when its density is low. But beyond that, they're very different. The M87 black hole is more massive by a factor of about 1500. Sagittarius A* is in the millions of solar masses, M87* is in the billions of solar masses. They're very different in their environment and what we know about them through our other observations. M87* launches a jet of high-speed particles that is almost the size of the parent galaxy, which is how we suspected there was something at the centre in the first place. We have not been able to see a jet feature in Sagittarius A*, even a small, weak one, in any wavelength that we have studied.

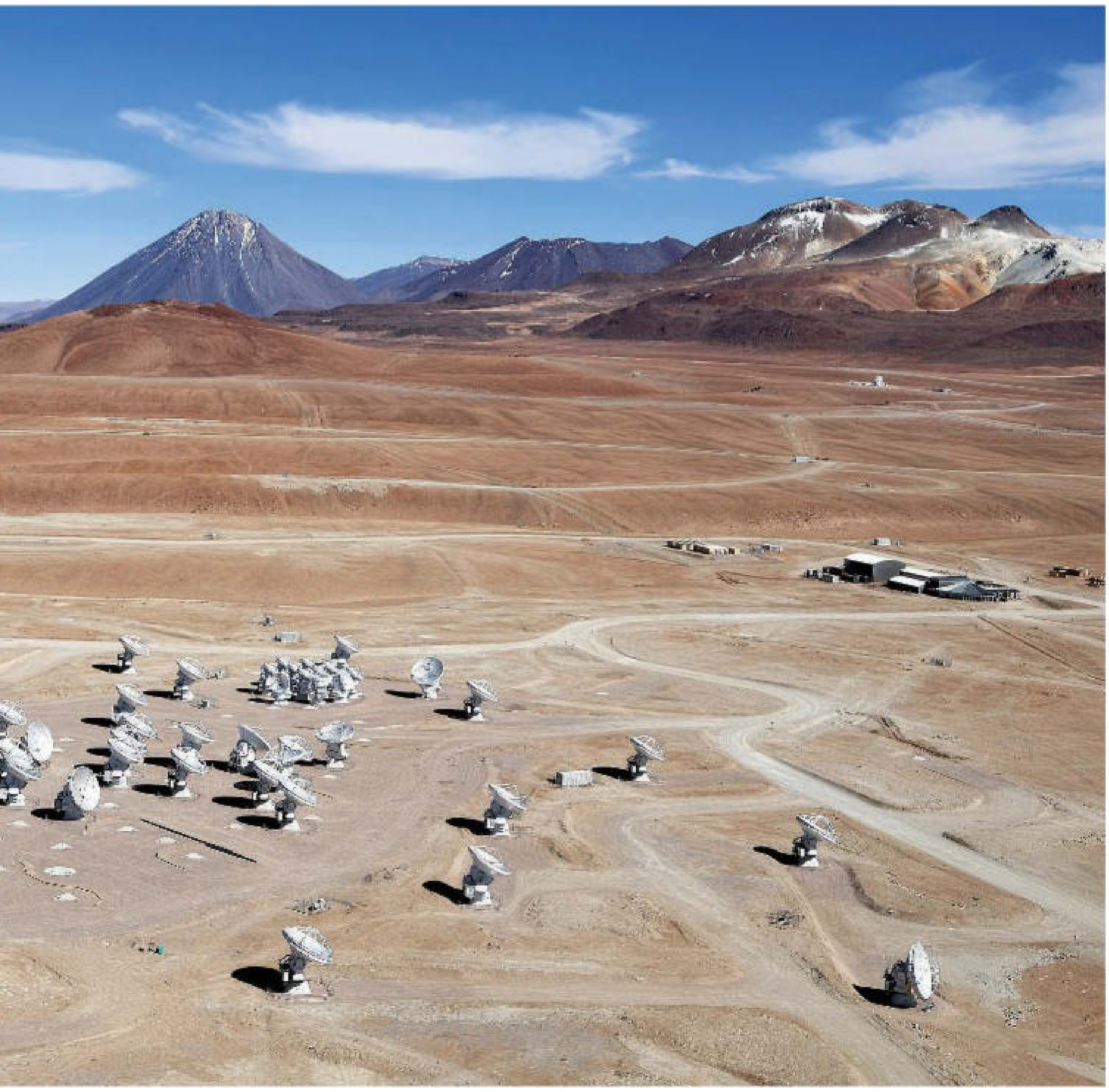


EHT COLLABORATION

Left: The first two black hole photos

Above: The ALMA observatory in Chile, part of a global network of telescopes that captured the images

Although the black holes are quite different, the two portraits of them look very similar. Is this what you expected?
People might assume that it was disappointing to see another doughnut, but it was actually a very joyful and reaffirming feeling. With Sagittarius A*, I was simultaneously delighted to have a picture of our own black hole and to confirm that the features we saw were a result of the universal laws of gravity rather than some



How to build an Earth-sized telescope

To snap a picture of a black hole, you need a telescope with an incredibly high resolution. The way you normally get higher resolution is by building larger telescopes – but there is a physical limit to the size one telescope can be. The Event Horizon Telescope collaboration got around this by using a technique called very-long-baseline interferometry. It uses radio telescopes thousands of kilometres apart, which each observe the same part of the sky at the same time, and then they combine that data into one image. This creates an Earth-sized interferometer, which gives the same kind of resolution as one telescope with a dish thousands of kilometres wide.

consequence of the particular environment of one black hole.

It could be that if you put two similar black holes in different environments, they end up looking very different. There are all sorts of ways these things could look: they could be brighter or dimmer, or look like a quasar, with two jets coming from their middles. If this were the case, it would tell us that the environment mattered more than just the extreme gravity. But what we are seeing is that, in both M87* and Sagittarius A*, the innate properties of the black hole dominate and control what the object looks like.

How can these images help us test general relativity?

We can look for tests of relativity in the black holes' immediate vicinity. Can we see any hint that something is different from what is predicted? Maybe the shape or size is different than what we expected. There are also theories that say the event horizon might change as a function of time. By looking at images of the black holes at different points in time, we want to understand if we can get hints of deviations from relativity that way.

With the Sagittarius A* image, did you expect there to be something that deviates from general relativity?

Secretly, we were hoping. But right now, it is matching up. Especially in the case of Sagittarius A*, where we knew the mass of that compact object extremely well, by looking at the motions of stars around the centre of the galaxy. We have a very definitive prediction for the size of the shadow – the dark, central part of the black hole – and the ring of bright matter around it. It was a no-wiggle-room test, and it matched up extremely well.

Can we expect pictures of other black holes?

In terms of targets where the EHT could get down to the event horizon scale, Sagittarius A* and M87* are the two main ones. We can study numerous other supermassive black holes in our vicinity, but we can't get down to their horizon. If we wanted to get this type of image for other black holes, it would require an even higher resolution. We've exhausted the diameter of Earth, so we would have to go to a longer baseline, which would be space. If we put radio dishes in space, that would open up numerous other black holes for this type of study.

If we did have that technology, which black hole would you pick to look at?

In a paper in 2012, my colleagues and I identified a bunch of black holes that would all of a sudden become picturable if we could do this from space. I don't have a favourite. What is exciting is there are more than 10 that become suddenly doable. If we could make the technology work and invest in a programme to build it, we could image a whole bunch of other black holes in our vicinity, which would be super fun. ∎

Abigail Beall is a features editor at *New Scientist*