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Mad, bad and…

Black holes are perhaps the wildest objects ever to have emerged from the imagination of physicists. In the second ever *New Scientist* live virtual event on 30 April, astronomer **Chris Impey** wowed the audience with what we know – starting, in this edited version of his talk, with why we know they must exist

AN ENGLISH clergyman called John Michell first speculated in the 18th century what would happen if you had a star so massive that its escape velocity exceeded light speed. Back then, however, most people thought of light as waves, and nobody really understood how waves could be trapped by gravity. So the whole idea of dark stars disappeared for about a century – until we entered the world of Albert Einstein.

Einstein was a rock star of physics back in the day. His general theory of relativity is a geometric theory of gravity. It says that mass curves space, or to be more accurate mass-energy (because Einstein had demonstrated these were equivalent with his equation $E = mc^2$), curves a unified space-time, creating what we call gravity.

A black hole is just an object so massive and dense that it curves space-time to the limit. That has truly odd effects. For example, in general relativity, gravity slows time, a fact that's been confirmed in experiments on Earth. At the boundary of a black hole, called the event horizon, gravity is so strong that time stops completely.

Essentially any object sufficiently compressed can be a black hole. Physics allows for black holes the mass of dead stars, which is to say the size of a small town, but also ones that are much larger and smaller. In principle, if an evil alien genius empire decided to squash Earth down, it would form a black hole about the size of a peanut, two centimetres across.

The theory of how to make the first sort of black hole, the dead star, was done in the 1940s by Robert Oppenheimer and Hans Bethe, as a by-product of the Manhattan Project to build a nuclear bomb. They showed that when a massive star ran out of fuel at the end of its life, its core would collapse. Their calculations, performed without computers, with just pure physics and equations, showed that this collapsed core would meet the definition of a black hole. The hunt was on to find examples in nature.

What were we looking for? According to the theory, black holes essentially have only two features. There's the event horizon, which is not a physical surface, but an information membrane, a boundary between the outside universe and the things and information trapped in the black hole. Then there is a point of infinite mass density called the singularity at the object's centre.

Now that's a problem. Stephen Hawking once said black holes contain the seeds of their own demise, because a singularity is a nonsensical thing; you cannot have infinite mass density. That's one of the things we still don't know about black holes: do singularities exist, and what does it mean if they do?

A black hole sitting alone in empty space alone would not emit any radiation, so would be very hard to find. It wasn't until 1969 that we found the first, and we still only have 40 or 50 really good cases. That was when painstaking observations revealed that a dark companion in Cygnus X-1, a binary star system emitting an enormous amount of X rays, was a black hole. This dead star is pulling material from the visible companion onto it, accelerating the surrounding gas and heating it up so it radiates.

It was Hawking, another rock star of science, who showed that even without this

EVENT HORIZON TELESCOPE COLLABORATION

The Event Horizon Telescope team captured the first direct image of a black hole in 2019

light show, black holes are, amazingly, not entirely black. In the vacuum of space, particle-antiparticle pairs appear and disappear all the time. If this pair creation happens near the event horizon, Hawking theorised that one member of the pair could become trapped inside the black hole, while the other escapes. The net effect is that black holes slowly lose mass or, equivalently, energy: they radiate and eventually fizzle away to nothing.

The Hawking radiation from a normal dead-star black hole has a temperature of about a billionth of a degree above absolute zero, which would be impossible to measure even if the black holes we see weren't in messy binary systems. So we still don't know

"Stephen Hawking showed that black holes slowly lose mass: they radiate and eventually fizzle away to nothing"

if Hawking's prediction is correct – but nobody's found any flaws in his arguments.

A similar problem came along when people wondered what happens to information in a black hole. If it simply disappears, that creates a profound paradox in quantum theory, which says that information can't be lost. Getting round it has led to clever, untested ideas such as the holographic principle, which says that as stuff falls towards the event horizon, information becomes encoded on it, as in a hologram. Or there's the firewall idea, which is a way of explaining how information might actually be destroyed at a black hole's edge.

Another speculation is whether tiny black holes, sometimes called primordial black holes, were made early in the big bang. At the moment we've got no evidence to suggest black holes the size of Earth squashed to a peanut – or smaller – do exist. But one of the most exciting discoveries has been black holes vastly larger and more massive than dead-star black holes, up to an incredible 20 billion times the mass of the sun.

We have a ringside seat for an

intermediate-mass black hole 4 million times the sun's mass at the centre of our galaxy. Starting in the 1980s, astronomers proved its existence using clever imaging techniques called adaptive optics to tease out the orbits of individual stars around it. We've even measured how the bending of space-time tweaks the orbit of one close star, an effect called the precession of the perihelion. When Einstein heard that this effect had been detected at a much smaller level with the planet Mercury, he got so excited that he had palpitations, as he knew it verified his theory. The black hole at the centre of our galaxy is a graphic demonstration of how general relativity works.

Seeing is believing – and the first image of a black hole, produced in 2019 by a vast network of radio telescopes effectively the size of Earth, truly showed us they are real. This is a phenomenally sized black hole, 6 or 7 billion times the mass of the sun, at the centre of one of the most massive elliptical galaxies that we've found, M87. The picture (see the previous page) shows the accretion disk of material around the black hole, and a central black blob that's not quite circular because of distortions due to general relativity. This is the event horizon itself – which is larger than our solar system.

Gravitational engines

In principle, the region near a black hole acts as an incredible magnifying glass for light. If we could get better resolution with our radio telescopes, we would see a series of narrow rings around the event horizon, each capturing light that arrives from different directions in the universe – each one essentially, like frames of a movie, an image of the entire universe at an earlier time. It's a truly extraordinary idea. We don't have these observations yet, but we're hoping for them in the next five or six years.

Meanwhile, measurements from the Hubble Space Telescope and elsewhere have showed us that essentially every galaxy has dark masses or massive central black holes. When they are active, these are spectacular "gravitational engines", emitting enormous amounts of radiation as they consume surrounding matter, converting it into energy far more efficiently than any star. But most are quiet, like the one in our galaxy. And while black holes are very interesting, exciting and fun, they do not dominate the

Your black hole questions answered

Chris Impey also took questions from audience members after his talk. Here's a selection of the best

How do supermassive black holes form?

We don't completely know. In the present-day universe, every galaxy has a black hole that scales in size and mass with the galaxy. So which came first? Was there a tiny galaxy that formed a little black hole within it, and they both grew together? Or did the black holes form first, and become the seeds for galaxies?

All this happened probably a few hundred million years after the big bang, a time we can't probe with telescopes. But the betting is actually that the black holes formed first from a massive generation of stars very early in the universe. They would have been pretty beefy, 50 to 100 times the mass of the sun, and formed the nuclei for the first small galaxies where they grew in tandem.

How long do the black hole mergers that produce gravitational waves take?

The black holes are doing a stately dance through the universe, circuiting each other and gradually falling in. They are emitting low-level gravitational waves probably for several years before they get close enough to do their final death spiral. LIGO only detects the crescendo, the last falling-in that takes minutes – with a peak pulse that lasts literally just seconds.

If black holes compress everything, how come they're so big themselves?

The truth is, we don't know the internal structure of a black hole within the event horizon. All we can say is that within this radius there's a certain amount of mass. The theory says that the density goes up and up and becomes infinite at the centre, but we don't know – the event horizon is a veil on our knowledge.

Could black holes be dark matter?

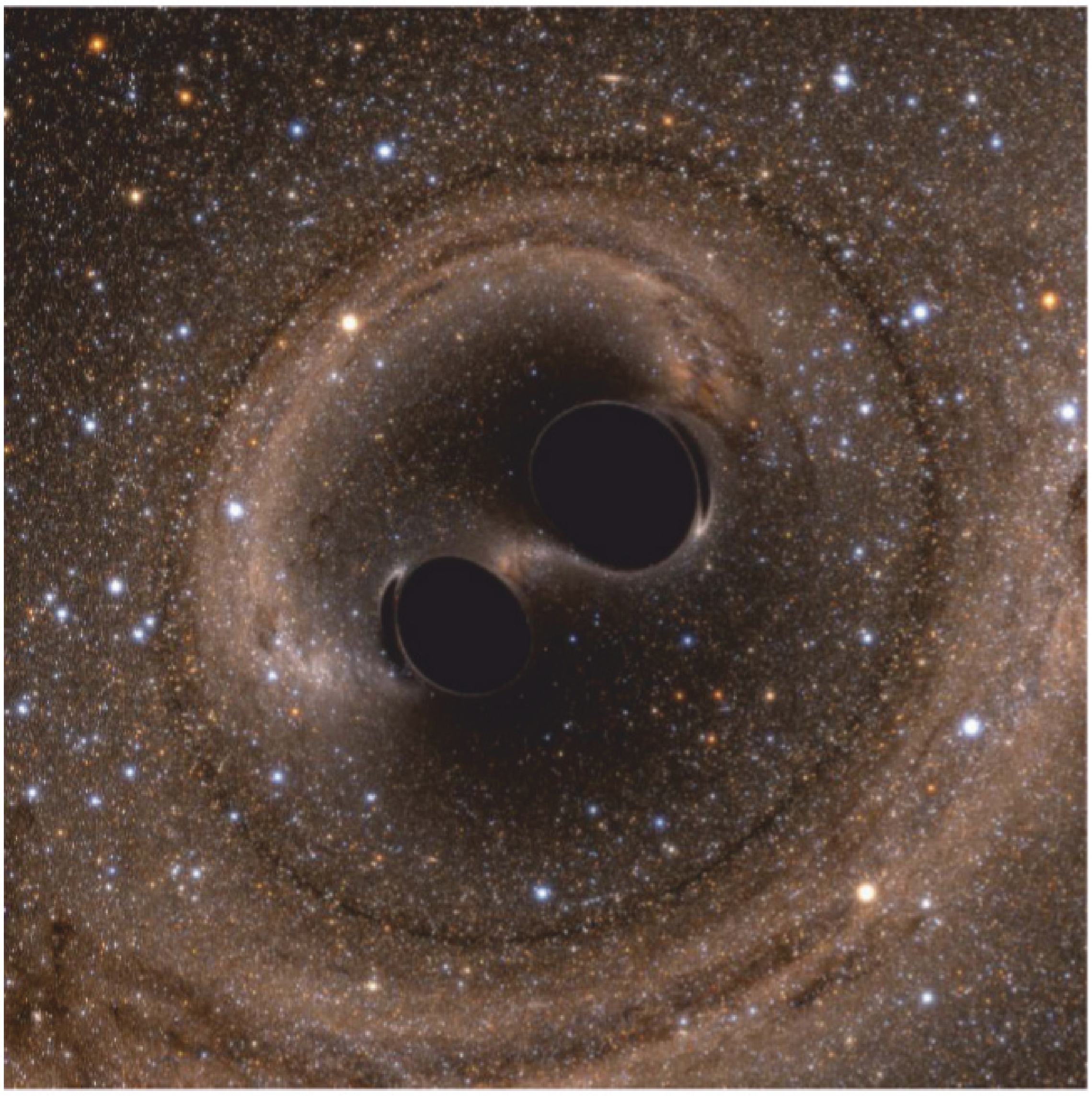
The idea of normal dead-star black holes being dark matter was ruled out pretty easily a long time ago. Every black hole is preceded by a supernova, and we'd see plenty of evidence for the supernovae, even if we couldn't see the black holes. Equally, we can probably rule out dark matter being made of very small black holes. If black holes evaporate by Hawking radiation, small black holes evaporate quicker, and would have been gone long before the present time.

That does leave a little window open for in-between-sized primordial black holes that came from the big bang. They're awfully difficult to detect or design an experiment for. So while the answer is probably that dark matter is not made of black holes, we don't know absolutely for sure yet.

universe in any way. If you make a pie chart of the universe, most of it is stuff we don't understand: dark energy and dark matter. Normal atomic matter, the stuff we're made of, makes up about 5 per cent, and black holes are 1000 times less abundant than that. The nearest black hole to the sun is several hundred light years away – which is probably a good thing.

Another big innovation in our understanding of black holes came in 2015, when the Laser Interferometer Gravitational-Wave Observatory, or LIGO, detected two black holes merging at a distance of a billion light years. Einstein's theory predicts that any time masses change configuration, ripples in space-time radiate out at the speed of light. Detecting them took an incredible physics experiment capable of measuring disturbances in distance accurate to one part in 10^{21} – a one with 21 zeros after it. LIGO has now made about a dozen detections of merging black holes. When it comes back with increased sensitivity next year, it should be detecting black-hole mergers about once every week, turning this into routine, industrial science.

"Falling into a black hole left over when a star dies would be a very unpleasant fate"



SXS, THE SIMULATING EXTREME SPACETIMES (SXS) PROJECT

The gravitational waves now routinely detected by LIGO are ripples in space-time sent out by merging black holes or other massive objects

Let's deal now with an issue that sometimes comes up: death by black hole. Falling into a black hole that's left over when a star dies would be a very unpleasant fate, with extreme tidal forces between your head and your feet or either side of your body. Spaghettification is the technical word, as you are stretched out at the level of muscles, bone fibres, and individual molecules. It's not a pretty sight.

But if you do the math, big black holes are not quite as dangerous. Their gravity is bigger, but it turns out the stretching tidal force is less. In principle, you could fall into a black hole above 1000 times the mass of the sun and survive. Seen from afar, your time would slow down, so that as you reach the event horizon, people would see you frozen for eternity at the point of falling in. Of course, even if you could survive falling into a black hole, you couldn't get out or transmit the information out to tell anyone what you'd seen – what a shame.

Let me close with how black holes play into the far future of the universe. As much as we like stars and galaxies, the sun and all stars will eventually die. The lowest mass stars, red dwarfs, live for hundreds of billions of years, but after a trillion years, all will be gone. What does a dead universe with no starlight, no fusion and no energy from stars hold for life? Could a civilisation like ours survive?

And the answer is, absolutely. The best place to get energy is a strong gravity source, and black holes are the best gravity source of all. Just send probes in close to a black hole, but not too close, and extract a little bit of their rotational energy. Even after all the black holes have been spun down, a civilisation could live off their feeble Hawking radiation. That way we could use black holes to power life long after the stars are gone.

Chris Impey is an astronomer at the University of Arizona in Tucson, where he studies the large-scale structure and evolution of the universe. His latest book *Einstein's Monsters: The Life and Times of Black Holes* tells you even more of what you need to know about black holes