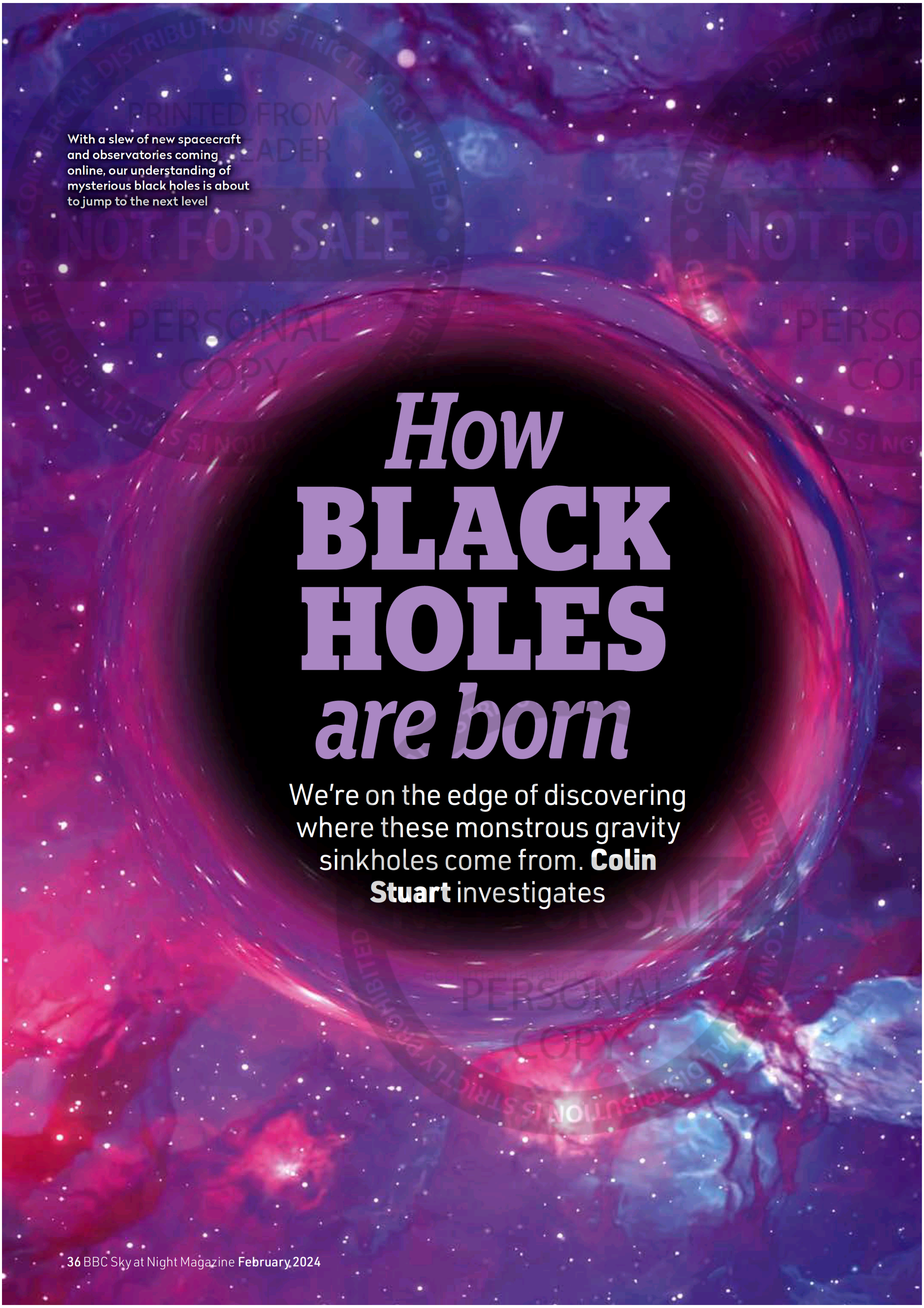
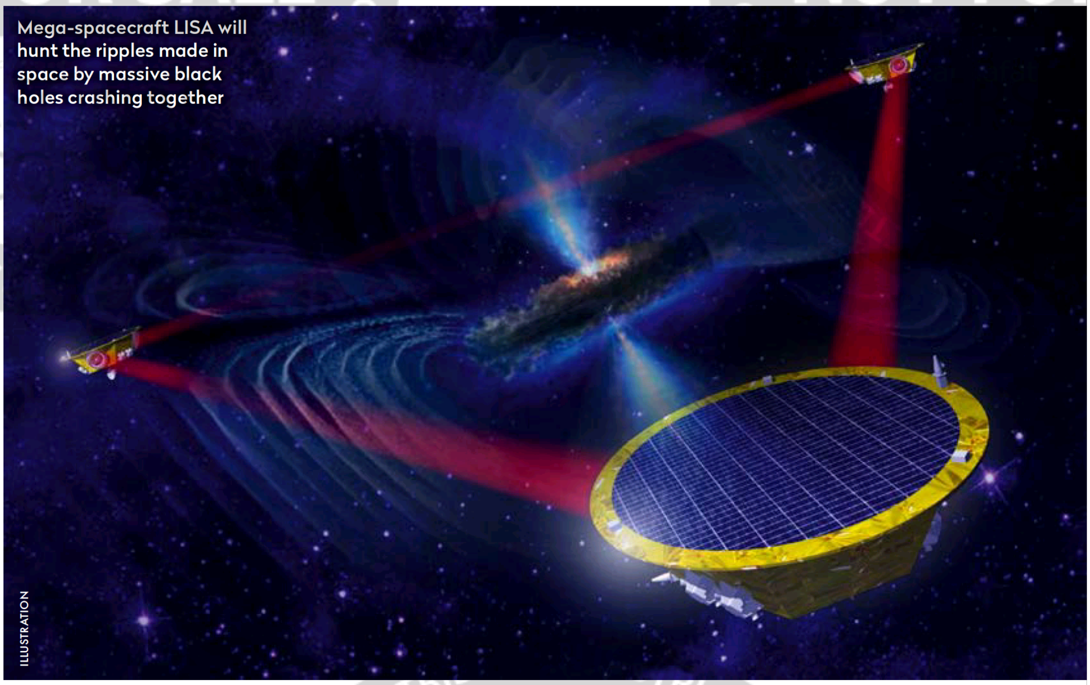
- Black holes (Astronomy)



With a slew of new spacecraft and observatories coming online, our understanding of mysterious black holes is about to jump to the next level

How BLACK HOLES *are born*

We're on the edge of discovering where these monstrous gravity sinkholes come from. **Colin Stuart** investigates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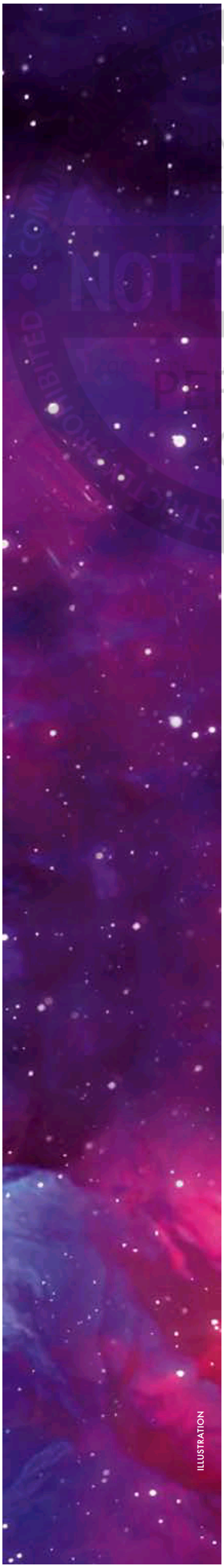
ILLUSTRATION

Mega-spacecraft LISA will hunt the ripples made in space by massive black holes crashing together

In just a few years, a rocket will tear into the night sky, lighting it up in deep shades of crimson. It will carry extremely precious astronomical cargo – the Laser Interferometer Space Antenna (LISA), an audacious feat of engineering that's been decades in the making. Once in space, three identical spacecraft will swarm in triangle formation, each separated by a *million miles*, all in the hunt for answers to one of the deepest mysteries about our Universe: where did black holes come from?

"A black hole is a dense part of space that nothing can escape from," says Dr Sean McGee, from the University of Birmingham. A black hole is the Universe's wild-child, the ultimate extreme. "They are a rare part of physics," McGee says, "our understanding of the Universe might break down in their extreme environments."

Perhaps even more importantly, black holes shape a lot of what it takes for galaxies to form and for them to start forming stars. We wouldn't be here without them. Understanding the history of black holes is understanding the history of *us*.

Every galaxy is thought to have a supermassive black hole (SMBH) at its centre. These behemoths tip the scales at millions and even billions of times the mass of the Sun. What's more, the giants seem to have appeared just 300,000 years after the Big Bang.

Such an early debut means that black holes and stars have astronomers in the cosmic equivalent of the chicken and egg debate. Which came first? "We don't have a definitive answer," says Dr Sandra De Jesus Raimundo, from the University of Southampton. "Black holes seem to start from some kind of seed."

Small seedlings theory

The first contender are so-called 'light' seeds. In the modern Universe, black holes form through the deaths of massive stars. The stars detonate as supernovae at the ends of their lives and then their cores collapse into the gravitational trapdoors we call black holes. The supernovae rocket material away at 10 per cent of the speed of light before the black hole fully forms, which is why that material can outrun the black hole's gravitational embrace.

Yet to square away the giant size of the black holes that astronomers have seen in the early Universe, Raimundo says that the culprit stars would have needed to weigh between 1,000 and 10,000 times the mass of the Sun. "That's bigger than the stars we see today," she says. The current record-holder has a mass no more than 300 times that of the Sun. It's a big difference.

An alternative is that the first generations of stars went supernova incredibly quickly and lots of small ▶

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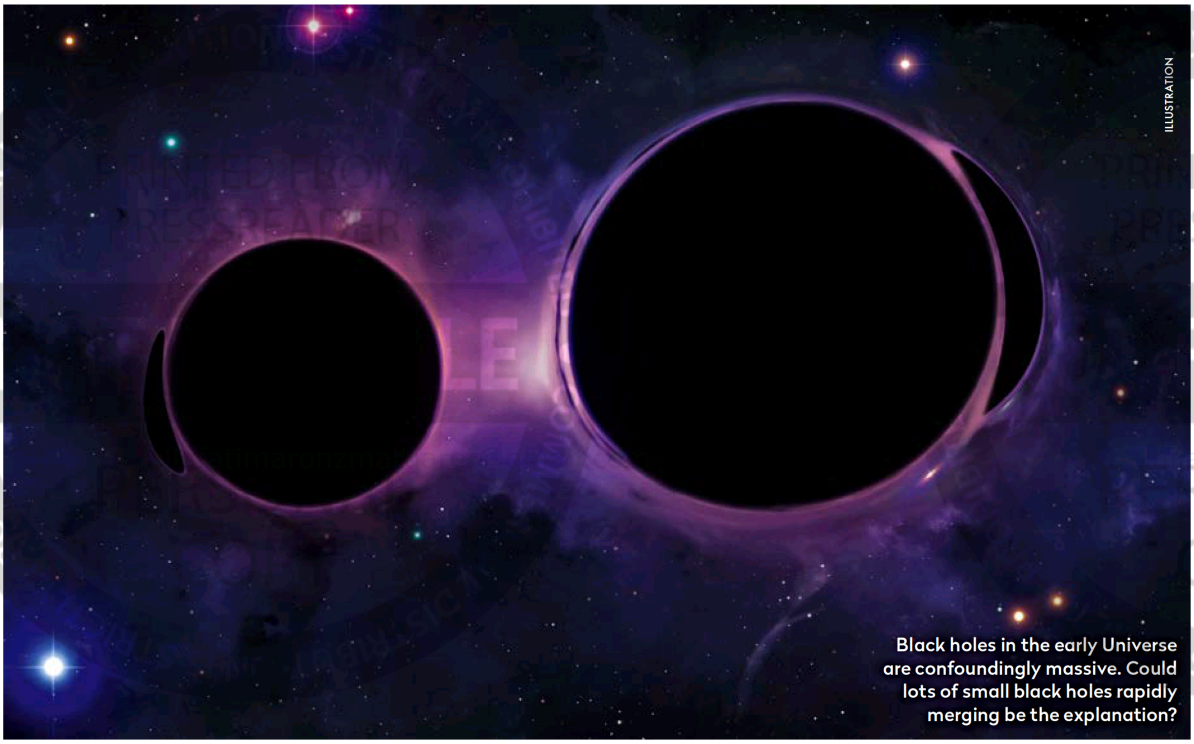


Black holes in the early Universe are confoundingly massive. Could lots of small black holes rapidly merging be the explanation?

MARK GARLICK/SCIENCE PHOTO LIBRARY/ISTOCK/GETTY IMAGES, ESA/HUBBLE/ESO/M. KORNMESSER, OPTICAL: DSS/ILLUSTRATION: NASA/CXC/M.WEISS, CHRISTIAN OFFENBERG/ALAMY STOCK PHOTO

▶ black holes subsequently merged. "You'd need a lot of mergers," McGee says. It would only be possible in extremely dense regions of the infant Universe, where stars were packed so closely together that mergers triggered yet more mergers in a runaway process. Possible, but not necessarily commonplace.

There's also the possibility that the earliest black holes formed far earlier, in the very first seconds of the Universe. These so called primordial black holes (PBHs) would be tiny in size but big in stature. A PBH the size of an atom would still weigh as much as Mount Everest. They are one of the options being considered for the true nature of dark matter, the mysterious gravitational glue that seems to bind

Anatomy of a black hole

There's more to a black hole than a giant ball of matter in space

Event horizon

The radius around the singularity that forms the point of no return. Anything, even light, that falls within the event horizon will be trapped inside, hence the 'black' part of its moniker.

Photon sphere

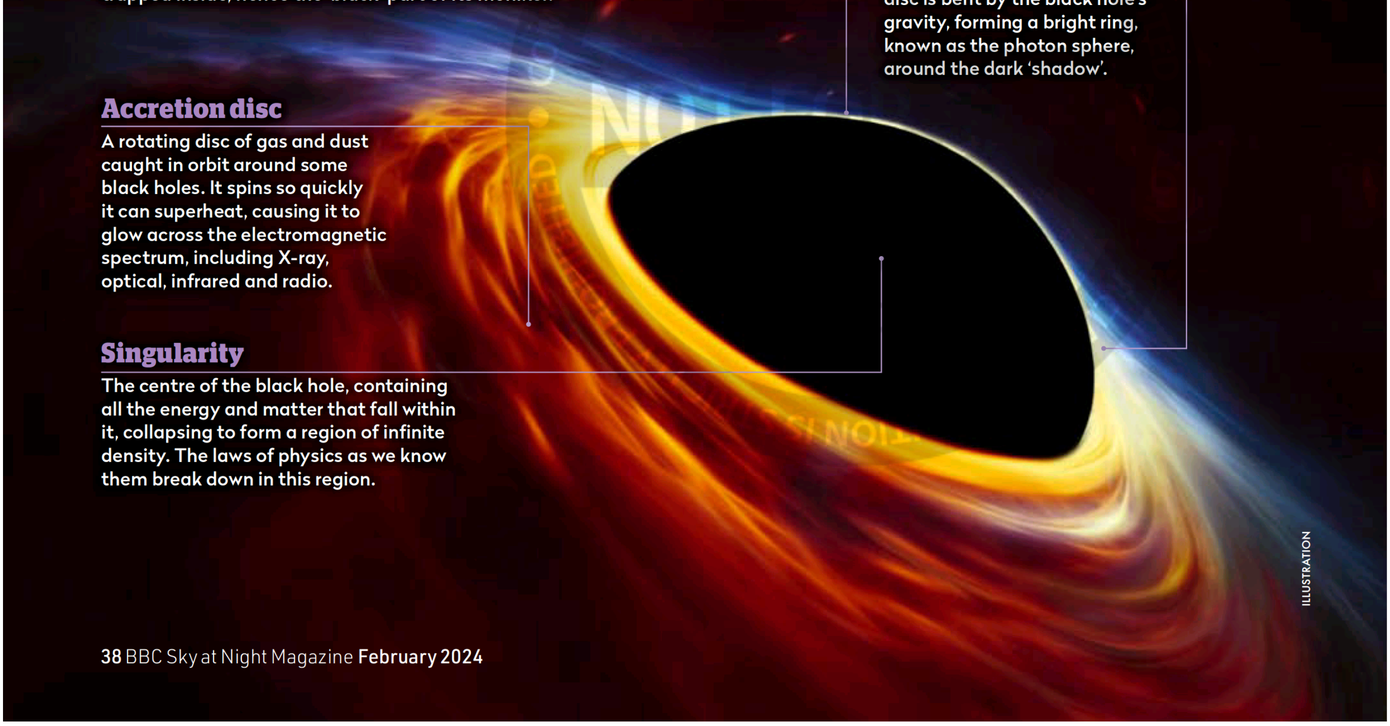
Light emitted from the accretion disc is bent by the black hole's gravity, forming a bright ring, known as the photon sphere, around the dark 'shadow'.

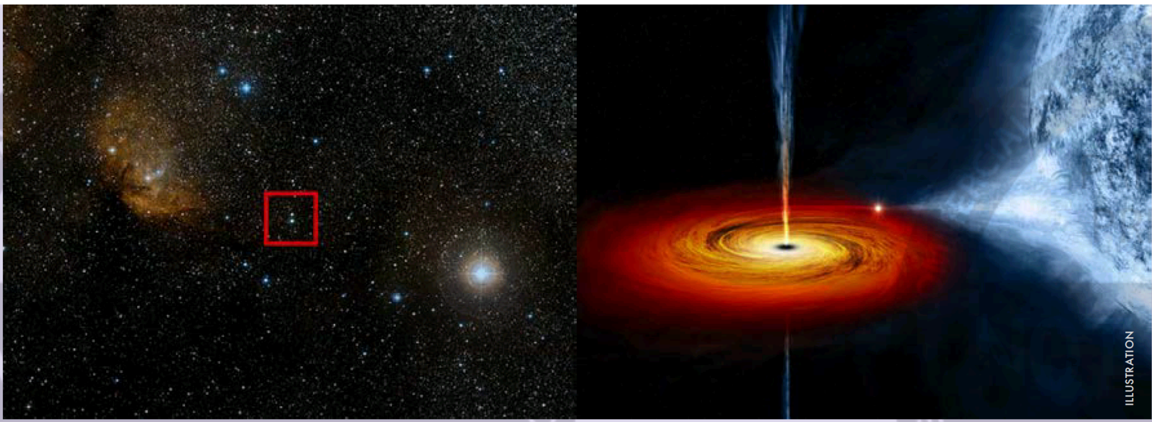
Accretion disc

A rotating disc of gas and dust caught in orbit around some black holes. It spins so quickly it can superheat, causing it to glow across the electromagnetic spectrum, including X-ray, optical, infrared and radio.

Singularity

The centre of the black hole, containing all the energy and matter that fall within it, collapsing to form a region of infinite density. The laws of physics as we know them break down in this region.





▲ Left: where the first black hole Cygnus X-1 – or rather its giant X-ray footprint – was spotted in 1964. Right: an artist's impression

The discovery of black holes

With no way to directly observe one, confirming black holes even exist has taken decades

The first object widely accepted as a black hole is known as Cygnus X-1. As its name suggests, it's an X-ray source in the constellation of Cygnus. X-rays don't penetrate Earth's atmosphere, so astronomers discovered it using a rocket launched to the edge of space in 1964.

The system in question is home to a supergiant star known as HDE 226868. However, a star alone could not be producing the huge quantities of X-rays observed. More careful observations at the start of the 1970s revealed the influence of a hidden companion pulling the invisible puppet strings: a black hole.

Not that the situation was immediately obvious. Cygnus X-1 was the subject of a bet between Kip Thorne, who argued for a black hole, and Stephen Hawking, who argued against it. The bet wasn't settled in Thorne's favour until 1990, but to this day there is still only circumstantial evidence for a black hole in the Cygnus X-1 system.

The first direct evidence of black holes came when the LIGO team found the first gravitational waves from colliding black holes in 2015. That was followed in 2019 by the first photograph of a black hole, or rather its shadow. A network of radio telescopes across the world were able to capture the light being bent around the supermassive black hole in the heart of M87. Now no one can doubt the existence of these (mostly) invisible giants.

"We're at the dawn of a new era, much like the flood of discoveries that followed the invention of the telescope"

▲ **The LIGO gravitational detector picks up small black hole mergers, but lets the largest holes through the net**

galaxies and clusters of galaxies together. If PBHs did indeed form soon after the Big Bang, then they could have bulked up significantly through mergers in the Universe's first few hundred millennia.

Heavy collapsing clouds

These are all 'bottom-up' scenarios – small black holes gradually growing into bigger ones. The other family of theories rely on a 'heavy' seed, or a so-called direct collapse scenario or 'top-down'. That would see a vast cloud of primordial hydrogen buckle under its own weight, condense and bolster its gravitational might until nothing could escape from its clutches. Yet we have no evidence that this process really happened, because we're talking about events a very long time ago and extremely far away. "We'd need incredibly powerful instruments," Raimundo says.

Enter LISA. Although not due for launch until the 2030s, it will represent a step-change in our ability to tackle these questions. LISA is a gravitational wave observatory, meaning it looks for ripples in the very fabric of the Universe set in motion by catastrophic events such as black-hole mergers. Gravitational wave astronomy is still very much in its infancy, with the first detection only coming in 2015. We're at the dawn of a new era, much like the flood of discoveries that followed the invention of the telescope 400 years ago.

Given the number of quick-fire mergers required to build the SMBHs we see, the Universe should be playing us a silent symphony of vibrating gravitational waves – a gravitational wave background to rival the more famous cosmic microwave background that's the echo of the Big Bang. Yet right now we don't have the tools to listen to every member of the orchestra.

The ground-based gravitational wave observatories that we do have – such as LIGO and VIRGO – are sensitive to the smallest black hole mergers; and in 2023, an international collaboration of astronomers, using 15 years of data precisely timing the 'heartbeats' of dozens of pulsars, listened in to the waves from colliding supermassive black holes. But that leaves a huge gap between these ▶

Can black holes die?

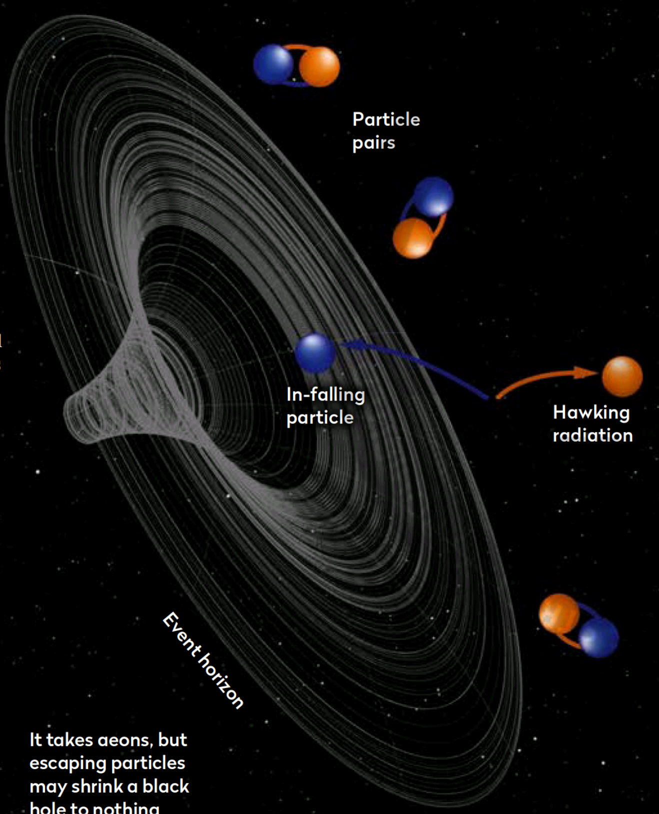
The tiniest particles could slowly chip away at and destroy even the biggest black holes

According to Stephen Hawking's theories, black holes won't be around forever. Instead they will slowly evaporate as they give out what is known as Hawking radiation.

Here's what astronomers think might happen around the event horizon, the boundary between where you can outrun the black hole's gravity and where you can't.

Quantum physics says that pairs of particles are constantly popping into and out of existence. Hawking's genius was to imagine this process unfolding at the event horizon, so that the pair appear on opposite sides of it. One would be free to escape, but the other would be trapped forever. The escaping particles could combine into particles of light that stream out from the region just outside the event horizon. Over time, the black hole would slowly lose this energy and disappear.

Slowly is somewhat of an understatement, though. A black hole with a mass equal to the Sun's would take 10^{67} years to evaporate completely. That's 1 followed by 67 zeroes. For SMBHs, it could be as long as 10^{100} years. However, Hawking radiation is yet to be conclusively discovered and so black hole evaporation remains a theoretical process for now.

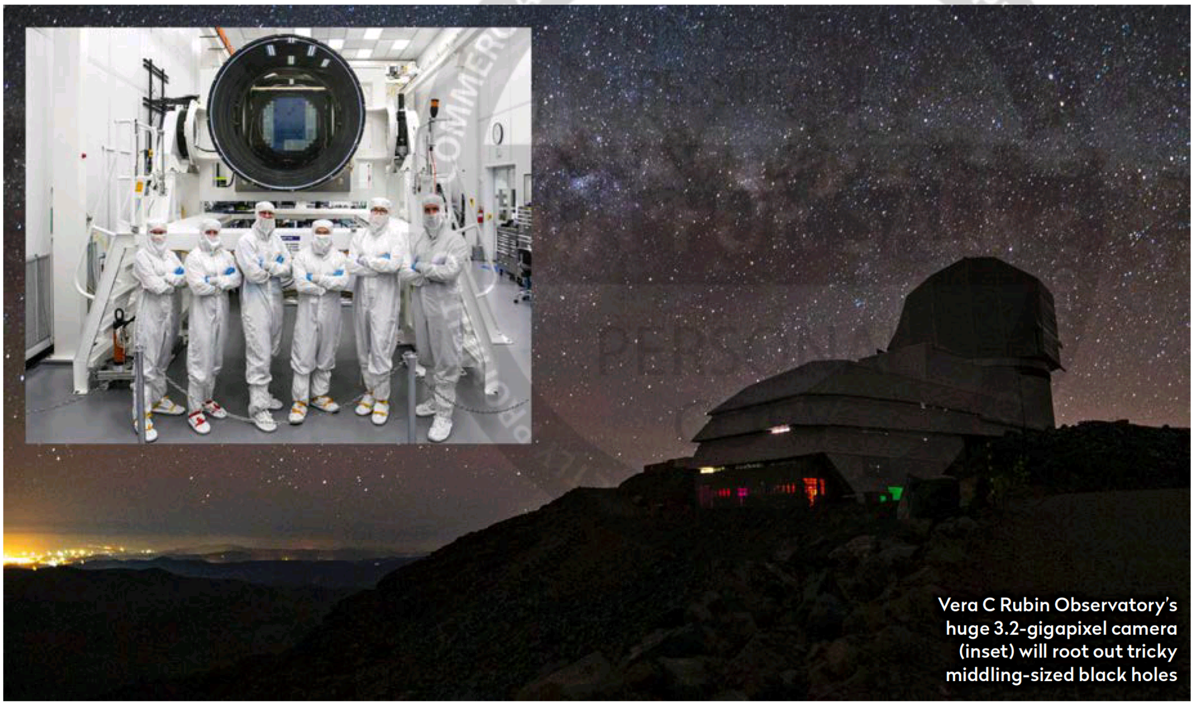


It takes aeons, but escaping particles may shrink a black hole to nothing

▶ two size extremes. If we want to appreciate the complete 'concerto', we need LISA.

If the Universe's SMBHs were indeed built in stages from the ground up, then there should be some middling black holes left over that didn't end up merging into SMBHs. Astronomers call them intermediate-mass black holes, with masses between 100 and 10,000 times the mass of the Sun. However, astronomers have found surprisingly few of them so far. Do they even exist at all?

We might be about to find out. "Rubin will find a lot of them," McGee says. With full survey operations due to start in the summer of 2025, the Vera C Rubin Observatory is home to the largest digital camera ever constructed. Located in Chile's Atacama Desert, it will scan the entire Southern Hemisphere sky every


Vera C Rubin Observatory's huge 3.2-gigapixel camera (inset) will root out tricky middling-sized black holes

GETTY, BRUNO C. QUINT, JACQUELINE RAMSEYER ORRELL/SLAC NATIONAL ACCELERATOR LABORATORY, NRAO/AUI/NSF/NASA, ESA

High-speed jets seen after an unlucky passing star gets shredded to bits are one way intermediate black holes reveal themselves

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three nights. One of the things Rubin will look out for is evidence of tidal disruption events (TDEs).

TDEs involve the immense gravity of a black hole tearing a star apart. "It creates a flare that we can see and from which we can measure the black hole's mass," McGee says. It would be a way to potentially spot intermediate-mass black holes that are otherwise too quiet to see. It could help us find more of the estimated 40 *quintillion* (40 billion billion) black holes that otherwise skulk in the celestial shadows.

Feeding frenzy

The interaction between a black hole and the stars and gas that surround it is an important part of the story of how they continue to grow. Some SMBHs are so busy that astronomers label them 'active'. They are gorging on stellar material, swirling debris into discs around them that then get super-heated and become the source of intense radiation across the electromagnetic spectrum. This process is known as accretion.

Raimundo has been working on what makes some SMBHs active, while others – like the one in our own Milky Way – are quiet. "We looked at galaxies with misaligned gas," she says.

In a typical galaxy, the stars rotate around the SMBH like the planets orbit around the Sun. Misaligned gas is material within the galaxy that rotates in the opposite direction to the stars. "It's created when there is some kind of interaction between the galaxy and its external environment," explains Raimundo. The galaxy could be ripping gas from a neighbouring galaxy or pulling it in from intergalactic space.

The mismatch between the rotation of the gas and the rotation of the stars causes the gas to lose energy, spiral in towards the centre of the galaxy and feed the black hole. "The next stage is to find out how much of a black hole's growth is due to this misaligned gas," Raimundo says.

There is another way to find out. The Advanced Telescope for High-Energy Astrophysics observatory, called NewAthena, is a European Space Agency mission that should launch in 2035 and will look for the X-rays produced by black hole accretion.

We will then have the tools to see whether supermassive black holes grow predominantly through mergers or through accretion.

"Having those two great facilities will help put the whole thing together," says McGee. "I'm actually quite optimistic that we can figure this out and it won't just be this long-standing mystery," he says. Perhaps then we'll finally understand where we came from a little better.

ESA's NewAthena X-ray observatory will pinpoint black holes that are actively gobbling up stellar material