A picture of a dark monster. The image is the first direct visual evidence of a black hole. This particularly massive specimen is at the center of the supergiant galaxy Messier 87 and was acquired by the Event Horizon Telescope (EHT), an array of eight ground-based radio telescopes distributed around the globe.

A portrait of a black hole

Black holes swallow all light, making them invisible. That's what you'd think anyway, but astronomers thankfully know that this isn't quite the case. They are, in fact, surrounded by a glowing disc of gas, which makes them visible against this bright background, like a black cat on a white sofa. And that's how the Event Horizon Telescope has now succeeded in taking the first picture of a black hole. Researchers from the **Max Planck Institute for Radio Astronomy** in Bonn and the **Institute for Radio Astronomy in the Millimeter Range (IRAM)** in Grenoble, France, were among those making the observations.

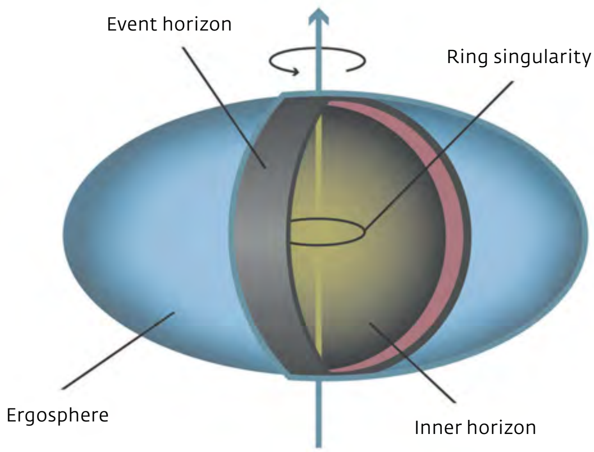
Photo: EHT Collaboration

TEXT **HELMUT HORNUNG**

In spring 2017, scientists linked up eight telescopes spread out over one face of the globe for the first time, forming a virtual telescope with an effective aperture close to the diameter of the entire planet. The technique is called Very Long Baseline Interferometry (VLBI), which combines the signals of the individual antennas into one image. This synchronization requires highly-precise atomic clocks, accurate to a billionth of a second. The technique makes it possible to resolve objects at extremely small angles of less than 20 microarcseconds. With that resolution, our eyes would see individual molecules on our own hands.

THE DATA ARE PROCESSED IN A SUPERCOMPUTER

The Event Horizon Telescope (EHT), as the network of observatories is known, included the 30-meter IRAM dish in Spain and the APEX telescope in Chile, which is operated with the participation of the Max Planck Institute for Radio Astronomy. In the 2017 observing session alone, the telescopes recorded approximately four petabytes of data. This is such a huge volume that it was actually faster and more effective to send the data by post than via the Internet. The data were calibrated and analyzed at the Massachusetts Institute of Technology (MIT) in the U.S. and at the Max Planck Institute for Radio Astronomy using supercomputers known as correlators. >



Left Beyond the horizon. The graphic depicts a rotating black hole. The ergosphere is the area in which no particles can remain at rest. The event horizon can be regarded as the surface of the black hole; anything that moves beyond it, quite literally vanishes from the world.

Right Space antenna. The 30-meter IRAM dish is the most sensitive single telescope in the Event Horizon Telescope's worldwide array.

"The results have given us the first clear glimpse of a supermassive black hole. They mark an important milestone in our understanding of the fundamental processes underlying the formation and evolution of galaxies in the universe," says Anton Zensus, Director at the Max Planck Institute in Bonn and Chairman of the EHT Collaboration Board. Zensus considers it remarkable that the project's astronomical observations and theoretical interpretation were achieved faster than expected.

According to IRAM Director Karl Schuster, the success is based on "decades of European expertise" in millimeter astronomy: "Back in the 1990s, the Max Planck Institute for Radio Astronomy and our Institute with its two observatories was demonstrating technically and scientifically that our high-resolution radio observations represented a unique method for analyzing the immediate vicinity of supermassive black holes."

IRAM, a facility co-financed by the Max Planck Society, actively participated in the campaign with the 30-meter telescope. At 2800 meters above sea level on Mount Pico Veleta in the Spanish Sierra Nevada, it is the most sensitive single telescope in the EHT array. "We can adjust the antenna's surface with a precision on the scale of a human hair," says astronomer Pablo Torne.

IDEAL WEATHER CONDITIONS AND FUNCTIONING TECHNOLOGY

Over four days in April 2017, Torne and his colleagues at IRAM simultaneously aligned their telescopes on the center of the galaxy M87 and its gigantic black hole for the first time, along with the other EHT stations located around the globe. "We couldn't have wished for better weather conditions for the time of year. Most importantly, the observatory's equipment worked perfectly, from its high-precision atomic clock and receiver systems to its data recorders," says Torne. In total, the observations recorded at the 30-meter antenna alone exceeded 500 terabytes of data.

The heart of the supergiant galaxy M87 has two particular characteristics that make it a good candidate for the project. It is both unusually massive and relatively close to Earth, which makes it easier to see. This makes it a perfect target for astronomers who, with the global telescope array, finally have an instrument capable of directly targeting such an exotic object.

The regions around supermassive black holes are subject to the most extreme conditions known in space. Black holes are fascinating cosmic objects that incorporate an incredible total mass within a tiny volume of space. Their mass and thus their gravitational pull are so great that even light can't escape them. That's what makes them black, making it impossible to directly observe them.

The only way to actually observe such cosmic gravity traps is to image their "shadow". This is caused by the extreme bending of light – shortly before it irretrievably vanishes into the black hole. By making extremely pre-

Graphic: designergold based on a draft from the MPI for Gravitational Physics

» The event horizon itself is not visible in the image; it is smaller and lies within the dark area.

cise observations in the millimeter range, astronomers can see through the dense dust and gas clouds right through to the edges of black holes.

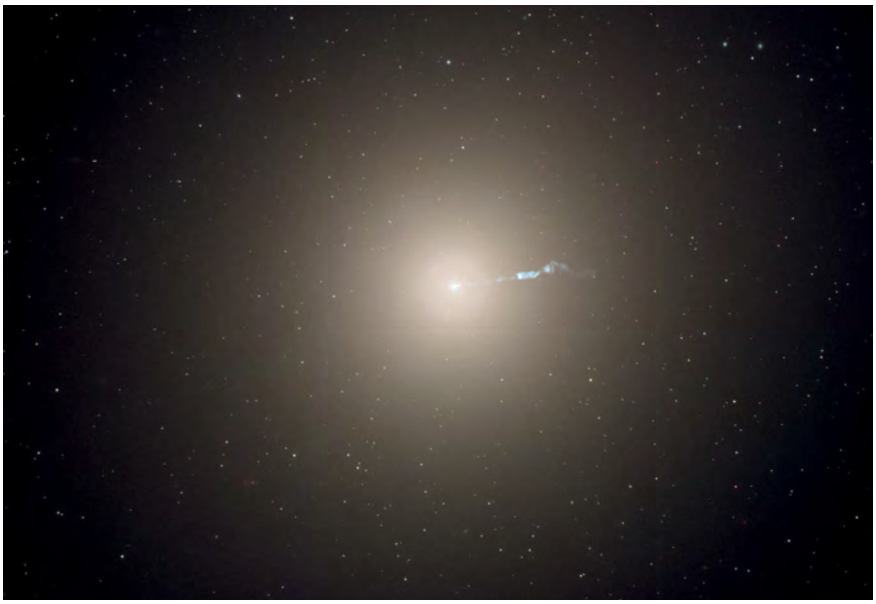
The image, which has now been released, was obtained at a wavelength of 1.3 millimeters (corresponding to a frequency of 230 gigahertz) and clearly shows a ring-shaped structure with a dark central region – the shadow of the black hole. A hot gas plasma is moving at high speeds around this very massive and compact object. This explains the ring-like structure in the image: the light from the strongly heated matter around the massive monster is being bent and amplified like by a lens. After a journey of around 55 million light years, it arrives at the EHT telescope array. The variations in brightness within the ring are due to a relativistic effect. As the black hole is rotating, light coming toward us appears brighter than light that moving away. The event horizon itself is not visible in the image; it is smaller and lies within the dark area.

The origin of the black hole is a supergiant elliptical galaxy known as M87, near the center of the Virgo galaxy cluster. In 1781, the French astronomer Charles Messier cataloged the object under number 87. The galaxy is also known as a strong radio source called Virgo A and is very active. Its nucleus shoots out a "jet" of matter at least 5000 light years long. This has been accelerated in the accretion disk of the black hole at its center and emitted at high velocity as a tightly focused beam perpendicular to the disk.

A GLIMPSE INTO THE CENTRAL MACHINERY OF A GALAXY

The shadow tells the researchers a great deal about the nature of the galaxy's central machinery and allows them to accurately determine the enormous mass of the black hole in M87. This has been calculated as equivalent to 6.5 billion Suns. The figure is highly consistent with that derived from previous observations. >

Photo: IRAM/DiVertiCimes



A giant in the sky. The supergiant galaxy Messier 87 was one of the targets of the Event Horizon Telescope observation campaign. The jet visible in this optical image of the galactic nucleus clearly originates from the supermassive black hole in the center of the elliptical galaxy.

"For many decades, the only way to detect black holes was indirectly," says Michael Kramer, Director at the Max Planck Institute for Radio Astronomy. Then, a few years ago, scientists succeeded in detecting gravitational waves for the first time, allowing us to "hear" the effect of merging black holes on space-time.

"Now we can finally see them as well, giving us the fascinating chance to study in a unique way these exotic objects and the extreme curvature they impose on space-time," says Michael Kramer, a leading scientist in the *BlackHoleCam* project, which is part of the Event Horizon Telescope consortium totaling roughly 200 researchers.

THE OBSERVATION REPRESENTS A WATERSHED MOMENT

The observations are ongoing. At the end of 2018, NOEMA in the French Alps joined the global array. This second IRAM observatory has twelve highly sensitive antennas, making it the most powerful in the EHT in the northern hemisphere. "NOEMA will allow us to venture into a new sensitivity range and gain even more fascinating insights," says IRAM Director Karl Schuster.

Anton Zensus considers the success to be a watershed moment in astronomy. "In the future, researchers both in and well beyond our field will clearly delineate periods before and after this discovery," says the Max Planck researcher. He believes astronomers will learn more about galactic nuclei and obtain a complete picture of how active galaxies are formed and evolve. In addition, he anticipates the discovery will allow us to test Einstein's general theory of relativity ever more rigorously. "Black holes, after all, are an ideal laboratory to test what happens in strong gravity." ◂

SUMMARY

- **Astronomers have taken the first picture of a black hole. It resides at the center of the supergiant elliptical galaxy M87, about 55 million light years away.**
- **The discovery was made by combining observations made in April 2017 from an array of radio antennas distributed around the Earth to form a virtual telescope.**
- **This was done using very-long-baseline interferometry (VLBI), a technique that combines the signals of the individual antennas.**
- **Researchers hope that images of black holes will help them better understand galactic nuclei and provide insights into the formation and evolution of active galaxies.**

GLOSSARY

Accretion disc: A disk of matter rotating and coalescing towards (accreting) a central object, for instance a black hole. It can be composed of atomic gas, plasma (ionized gas) or interstellar dust. Toward the center, the speed of rotation and temperature rise sharply.

Arc second: The term arc second is often employed as an expression of a telescope's resolving power, the smallest angle it can successfully resolve. An arc second corresponds to one 3600th of a degree. A microarcsecond is one millionth of an arcsecond.

Charles Messier: French astronomer (1730–1817) whose career began in the French Navy, before leading him to France's Bureau of Longitude. He discovered 20 comets and created a catalog of 103 diffuse astronomical objects, which have since been discovered to be gas nebulae, star clusters, and galaxies.

Photo: NASA, ESA and the Hubble Heritage Team (STScI/AURA)

"An astounding coincidence with theory"

Max Planck Director Anton Zensus on the first observation of the shadow of a black hole

What sounds paradoxical is reality: Black holes have a shadow! In the Messier 87 galaxy, astronomers were able to observe such a phenomenon for the first time with the Event Horizon Telescope (EHT). The Max Planck Institute for Radio Astronomy in Bonn had a first row seat. Anton Zensus heads the "Very-Long-Baseline Interferometry" Department. The Department deals with a technique that enabled discovery in the first place. We talked to Anton Zensus, Chairman of the EHT Collaboration Board, about how the successful observation came about and what the results mean.

Mr Zensus, how long has the Event Horizon Telescope project been running?

Anton Zensus: Officially, it started two years ago. But the preparations have been going on for a decade. And if you factor in the preparatory and pioneering work, it's actually 20 years. During this time, we have fundamentally improved the quality of our measurements and have already investigated important questions about active galaxies like M87 – such as the nature of the gigantic matter jets from their central regions. In this sense, we have now reached the peak of a long development.

You say that EHT had only been conducting observations for two years. Were you surprised by your success after this relatively short time?

Yes indeed! It was also astonishing that so many things worked right away. After all, the Event Horizon Telescope consists of a combination of eight different telescopes. One of these telescopes – which is called ALMA – is located at an altitude of 5000 m in the Chilean Atacama Desert and comprises 66 individual antennas. In order to be able to integrate this system into the EHT, we had to interconnect all individual antennas via software. This "phasing" was an enormous technical challenge for us and was essential for the EHT. The weather conditions also played into our hands – they were really good right from the start.

What does an observation with eight telescopes look like?

The key word is very long baseline interferometry (VLBI). We aim several radio telescopes, which are far away from each other, at the same celestial object at the same time. The signals collected are combined in a special computer – the correlator. In this way, a virtual telescope is created. This provides an image sharpness corresponding to

» This marks the culmination of a long period of development.

Anton Zensus, Director at the Max Planck Institute for Radio Astronomy and Chairman of the EHT Collaboration Council.

Photo: Helge Horn Photography

that of a single antenna with the diameter of the distance between the most distant antennas – in the case of the Event Horizon Telescope, this is about 8000 km. Just imagine: if your eyes were as sharp as the EHT, you could theoretically read a newspaper in New York from Bonn. However, the EHT does not see any optical light but rather radio radiation with wavelengths of just over one millimeter.

How is your Institute involved in the Event Horizon Telescope?
The EHT includes the 12-meter APEX telescope, which is operated by our Max Planck Institute for Radio Astronomy together with the European Southern Observatory and the Swedish Onsala Space Observatory. It is located close to the ALMA site. The Max Planck Society is also involved with the IRAM 30-meter antenna on the Pico Veleta in the Spanish Sierra Nevada and will be involved with the NOEMA telescope near Grenoble in the future. A total of thirteen partner organizations from all over the world work for EHT. Our Institute operates a supercomputer that calibrates and evaluates the data. In fact, enormous amounts of data are generated. Each of the EHT's individual telescopes deliver around 350 terabytes per day.

You knew what you were looking for: the shadow of a black hole. I suppose theoretical considerations played an important role?
Yes, Einstein's general theory of relativity of 1915 provides the theoretical background. Also about a hundred years ago, astronomers observed jets for the first time. These are gas flows that shoot out of the center of active galaxies and must be generated at enormously high energies. Since the 1970s, we have suspected that there are super-massive black holes behind it. The theory of relativity predicts that a massive object can deflect light. The English astronomer Arthur Eddington measured this phenomenon during a total solar eclipse when he observed a small shift of the star positions near the solar disk. By the way, that was on 29th of May 1919 – exactly one hundred years ago. This completes the circle.

The black hole in the center of the Milky Way is much closer than that in Messier 87. Why was the EHT still successful with M87?
Our Milky Way is a bit hesitant to disclose its deepest secrets (laughs). But joking aside, there are, of course, sound reasons. On one hand, the heart of our Milky Way is hidden in a dense fog of charged particles. This leads to a flickering of the radio radiation and thus to blurred images of the center of the Milky Way. But I am confident that we can still solve this problem. On the other hand, galaxy M87 is about 2000 times further away. However, the black hole in its center is also 1000 times more massive than the one in our Milky Way. The greater mass makes up for the greater distance. The shadow of the black hole in M87 therefore appears to us to be about half the size of the one from the gravity trap in our Milky Way.

Just what is the shadow of a black hole?
A black hole deflects the light even more than our sun. The theory of relativity predicts that a radiation ring should be observed around a dark spot where the black hole is located. Right where the black hole is. Some casually refer to this dark spot as the shadow of the black hole.

But where does the light come from? Black holes are black, aren't they?
According to the general theory of relativity, black holes have an "event horizon". It describes the region within which nothing can escape from the black hole. The event horizon – but also the area within – should therefore appear black to us. According to theory, outside the event horizon, attracted by the enormous mass, there is a huge amount of gas swirling around in a vortex-like disk structure at tremendous speeds. The gas heats up and begins to glow. Relativistic particles – those that move at almost the speed of light in a magnetic field – also release synchrotron radiation. So around a black hole, it "shines", while the hole itself, as the name suggests, appears black. It is this blackness that we've been observing.

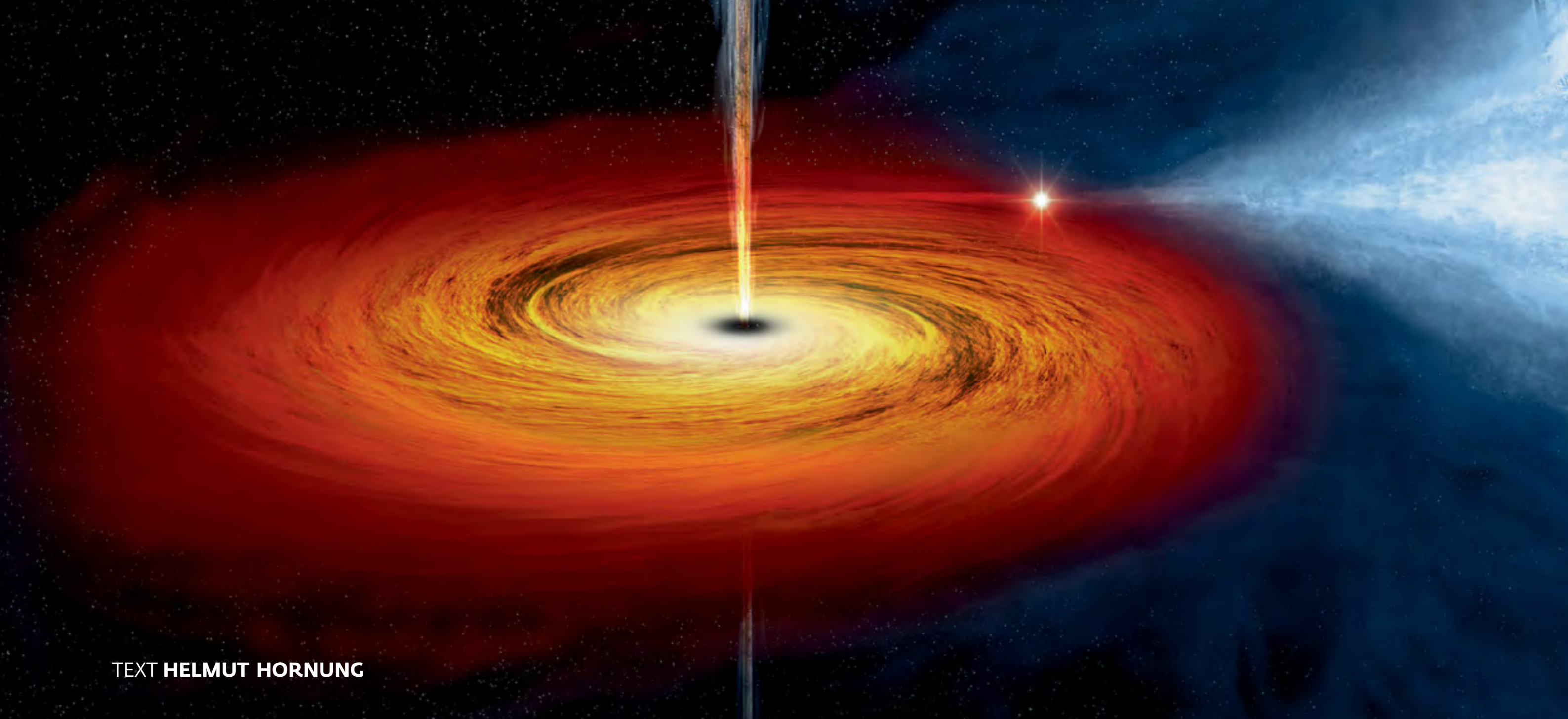
What did you discern from the shadow?
To be honest, we were amazed at how well the dark spot we observed matches the structure predicted by our computer simulations. From the shadow itself, the mass, the rotation, and the magnetic field of the black hole can be derived. For this purpose, 60,000 different simulations of black holes were carried out on the computer and compared with the EHT results.

How will this successful observation advance astronomy?
Black holes are an ideal laboratory for measurements under strong gravity. We are at the beginning of a phase in which many new insights await us. We will soon be able to confidently exclude alternative explanations for black holes – such as boson stars or gravastars. We will better understand the galactic centers and obtain a complete picture of the formation and evolution of active galaxies. We will also be able to observe pulsars in the vicinity of the black hole in our Milky Way and thus thoroughly check the general theory of relativity.

The interview was conducted by Helmut Hornung

The mystery of the dark bodies

Even though they have a large mass, black holes are not made of matter. Until recently, that meant that they couldn't be directly observed, only indirectly due to the gravitational effect they have on space around them. They bend space and time and exert an irresistible attraction. The Event Horizon Telescope has now allowed us to see the shadow of a black hole for the first time. It is startling that such exotic objects were first predicted more than 230 years ago.



Cosmic swirl: the Cynus X-1 black hole swallows up material from a neighboring blue massive star and emits X-rays in the process.

Optical: DSS; illustration: NASA/CXC/M. Weiss

TEXT **HELMUT HORNUNG**

The story of black holes begins in the quiet little town of Thornhill in the English county of Yorkshire. For 26 years during the 18th century near the town's medieval church lived its priest, John Michell, who, as is clear from his tablet memorial in the church, was also a highly regarded scholar. Indeed, Michell had not only studied theology, Hebrew and Greek at Cambridge University; he was also a dedicated natural philosopher.

His was chiefly interested in geology. In an essay published after the Lisbon earthquake in 1755, he suggested that earthquakes were propagated by waves of different types below the ground. This theory caused quite a stir in the scientific community, and it resulted in John Michell being elected a member of the Royal Society in London.

It was before the members of this august institution that he gave a lecture on the gravity of stars in 1783. In it, he reasoned in a thought experiment that a very massive star's gravity might be so strong that no light would be able to leave its surface. "If there should really exist in nature any [such] bodies ... their light could not arrive at us," he concluded.

More than a decade after John Michell, another natural philosopher took up the subject. The French mathematician, physicist, and astronomer Pierre-Simon de Laplace suggested in his 1796

Left Advanced mathematics. In 1916 the astronomer Karl Schwarzschild calculated the size and behavior of a non-rotating, electrically-charged, static black hole on the basis of general relativity.

Right Thought experiments. In 1796, the French mathematician, physicist, and astronomer Pierre-Simon de Laplace suggested that their could be massive stars whose light would not be able to escape them.

work *Exposition du Système du Monde* that their could be massive stars whose light would not be able to escape them; this light, according to the generally accepted theory of Isaac Newton, consisted of corpuscles, its smallest particles. Laplace termed such an object a *corps obscur*, a "dark body."

However, the thought experiments on the physical world of John Michell and Pierre-Simon de Laplace were largely overlooked and quickly fell into obscurity. In the end, it was Albert Einstein, with his general theory of relativity, who paved the way for the entry of these "dark bodies" into science – albeit not intentionally. Based on his equations published in 1915, he did, indeed, predict the existence of point singularities in which matter and radiation would simply disappear from our world.

But in 1939 Einstein published an article in the journal Annals of Mathematics attempting to disprove the possibility of such black holes. Previously in 1916, however, the astronomer Karl Schwarzschild had calculated the size and behavior of a non-rotating, electrically-charged, static black hole on the basis of general relativity. The Schwarzschild radius of such an object, named after the astronomer, is dependent on its mass and is the boundary beyond which nothing can return. For the Earth, this radius would be approximately one centimeter, or the size of a cherry.

EXACT SOLUTIONS OF EINSTEIN'S FIELD EQUATIONS

In his short life, Schwarzschild enjoyed rapid scientific success. Born in 1873 in Frankfurt as the oldest of six children of a German-Jewish family, Schwarzschild's talent was evident at an early age. At the age of 16 he published two papers in a renowned journal calculating the orbits of planets and binary stars. His astronomical career went on to take him via Munich, Vienna, and Goettingen to Potsdam, where he became Director of the Astrophysical Observatory in 1909. A few years later, in the middle of World War I – Schwarzschild was an artillery lieutenant on the Eastern Front in Russia – he formulated the exact solutions of Einstein's field equations. He died on 11 May 1916 of an autoimmune skin disease.

But the subject of black holes was initially disregarded by science. Indeed, after the initial hype, interest in Einstein's system of thought waned steadily. This was in the period between the mid-1920s and mid-1950s. After this, in the words of the physicist Clifford Will, "the renaissance of general relativity" occurred.

General relativity became an important means of describing objects that, initially, were the sole preserve of theoreticians, for example, white dwarfs or neutron stars in which matter is present in extreme states. Their unexpected properties could be described using new concepts derived from theory. And this led to black holes also taking center stage. Scientists who studied them became stars – like the English physicist Stephen Hawking, who died in 2018.

In the early 1970s, the satellite *Uhuru* ushered in a new era of observational astronomy. It was launched specifically to survey the sky in the extremely short wavelength X-ray spectrum. *Uhuru* discovered hundreds of sources, mostly neutron stars. Among these, one particular object in the constellation of Cygnus stood out. It was named Cygnus X-1. Astronomers discovered that the X-ray source was associated with a blue supergiant star approximately 30 times the mass of the Sun. It

Photos: akg-images (2)

» Astronomers concluded that approximately 4.5 million solar masses must be concentrated in a region the size of our planetary system.

has an orbital companion of approximately 15 solar masses, and this must be a black hole.

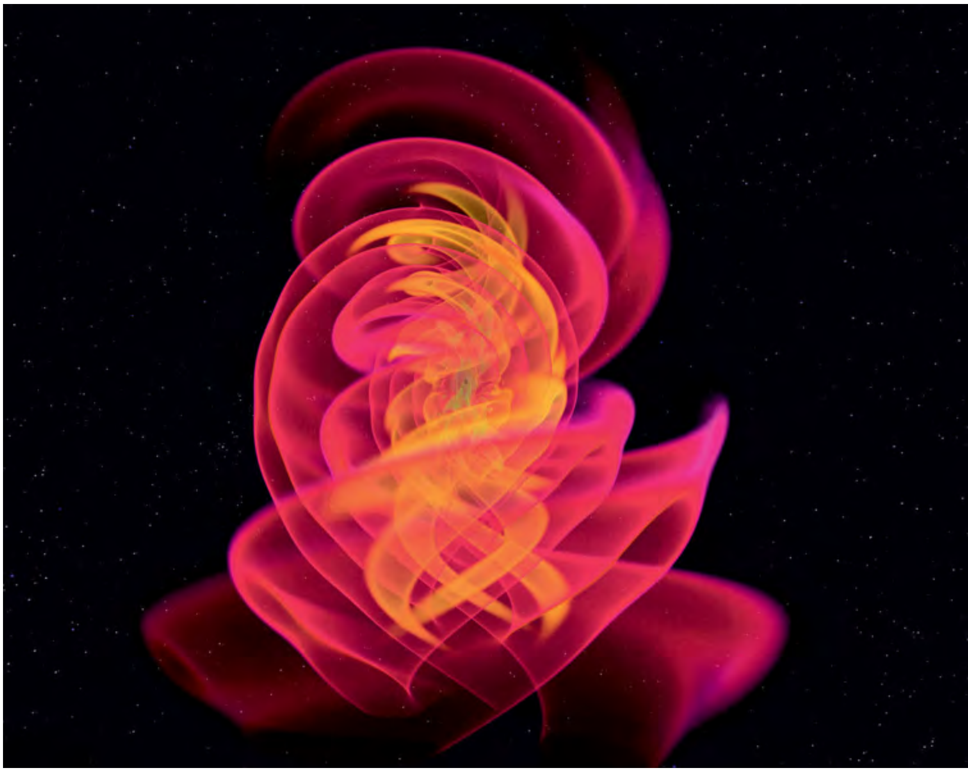
The X-ray emission can be explained by matter falling in toward the black hole due to its gravity. This forms an accretion disk around the companion due to its extreme gravity, swirling around it at unimaginably high speed and heating up to several million degrees due to friction.

Cygnus X-1 is by no means the only black hole that astronomers have indirectly detected. They now know of many, with a mass ranging from four to sixteen solar masses. One, however, is a great deal more massive. It was discovered at the end of the 1990s and resides at the heart of the Milky Way, some 26,000 light years away. In 2002, a group led by Reinhard Genzel from the Max Planck Institute for Extraterrestrial Physics made another sensational discovery. At the Very Large Telescope of the European Southern Observatory (ESO), the scientists made observations of a star that was approaching the center of our galaxy to a distance of only 17 light hours (around 18 billion kilometers).

In the following months and years, they kept track of the orbital motion of this S2 star, as it was termed. It orbits the galaxy's central region, Sagittarius A*, at an average speed of 5,000 kilometers per second and with a period of 15.2 years. The motion of S2 and other stars led astronomers to conclude that some 4.5 million solar masses must be concentrated in a region of space the size of our planetary system. A massively compact mass of that kind can only mean one thing: a gigantic black hole.

Our Milky Way is also not an exception. Scientists believe that such massive monsters lurk in the centers of most galaxies – some even more powerful than Sagittarius A*. The supergiant galaxy Messier 87 has a black hole of about 6.5 billion solar masses! Like Sagittarius A*, this star system, at a distance of approximately 55 million light years, was one of the targets of the Event Horizon Telescope. The team, indeed, have succeeded in their goal. It was announced on 10 April 2019 that they were able to take a picture of its "shadow," an observation which is considered the first direct evidence of a gravity well on a galactic scale.

But black holes had already been making headlines just a few years earlier. In September 2015, scientists confirmed Einstein's prediction of gravitational waves, with the source calculated as the merging of two black holes of 36 and 29 solar masses. The 230-year-old history of black holes is far from over. Instead, these observations mark the beginning of a new era in astronomy, which will shed light on the dark universe – and on the dark monsters that lurk in it. ◂



Ripples in space-time. In 2015, astronomers detected gravitational waves for the first time – the image is based on a "numerical relativity simulation." It depicts two black holes merging deep in space.

Photo: S. Ossokine, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes project, W. Benger (Airborne Hydro Mapping GmbH)