

Traps in Space-Time

Black holes are a permanent fixture in science fiction literature. In reality, there is hardly a more extreme location in the universe. These mass monsters swallow everything that ventures too close to them: light, gas, dust and even entire stars. It sounds quite simple, but the nature of black holes is complex. **Maria Rodriguez**, Minerva Group Leader at the **Max Planck Institute for Gravitational Physics** in Golm, wants to solve some of the puzzles these exotic cosmic bodies present.

TEXT **FELICITAS MOKLER**

For a long time it seemed that they existed only in the minds of theoretical physicists – black holes. But since at least a year ago now, we finally have clarity: they really do exist. On September 14, 2015, gravitational waves caused space-time to oscillate to a measurable extent in the American LIGO detectors for the first time.

The detection of the undulation of space-time predicted 100 years earlier by Albert Einstein (1879 to 1955) is simultaneously deemed to be experimental proof of the physical existence of black holes. The first measured signal GW150914 originated from two black holes with 36 and 29 solar masses, respectively, that used to orbit one another in a kind of binary star system until they finally merged into one object

with 62 solar masses. Only a few months later, the researchers registered gravitational waves of source GW151226 from a similar system. These events gave the space-time structure a violent shake – and provided impressive confirmation of the existence of the mass monsters. (MAXPLANCKRESEARCH 2/2016, page 78 ff.)

EINSTEIN'S THEORY REPLACES THE CLASSICAL CONCEPT

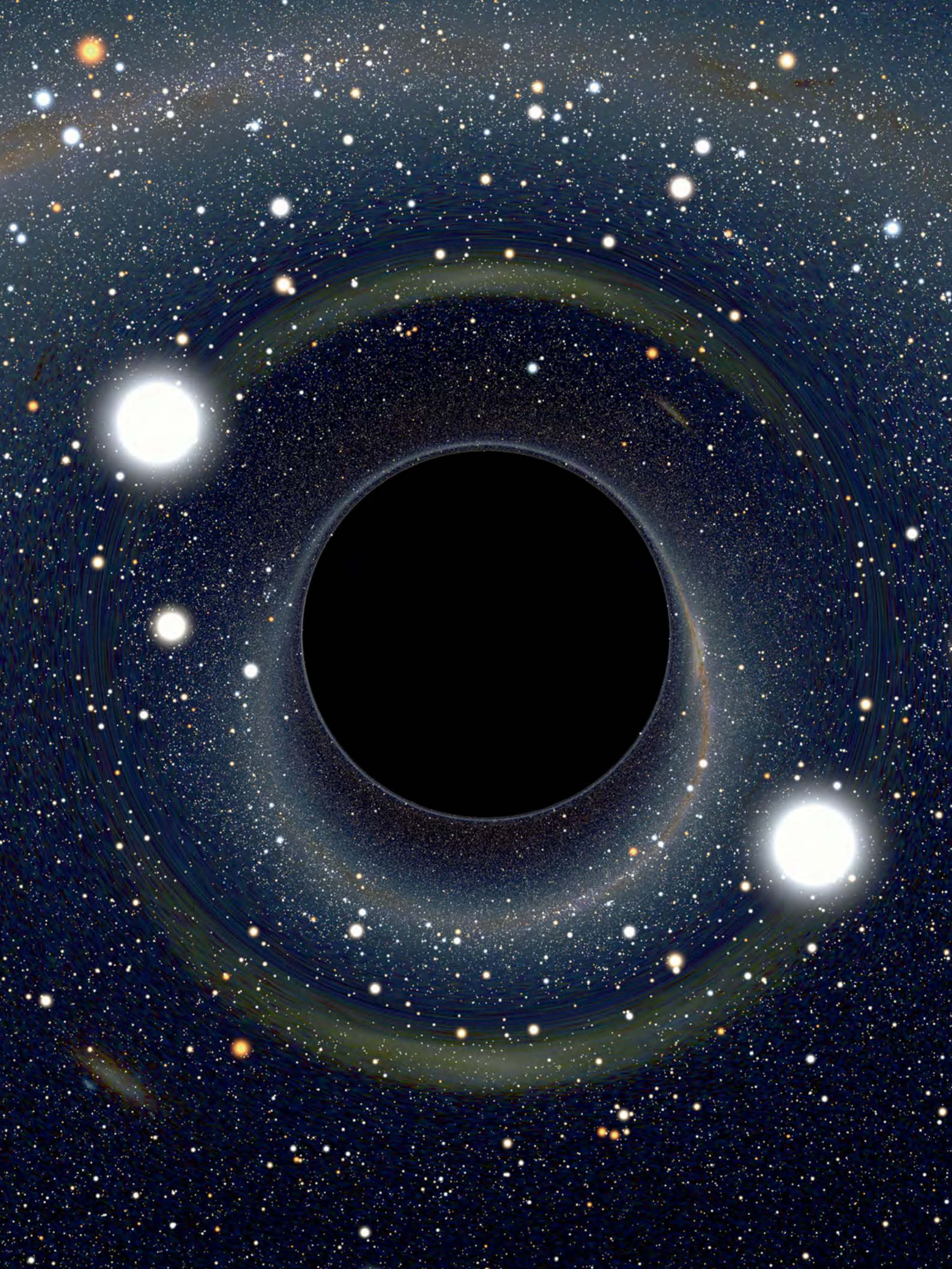
Naturalists John Mitchell (1724 to 1793) and Pierre Simon de Laplace (1749 to 1827) were already speculating in the late 18th century about dark stars or dark astrophysical bodies whose gravity was so strong that light couldn't escape them. The ideas of the two researchers were still within the frame-

work of Newtonian gravitational theory and the corpuscular theory of light.

At the beginning of the 20th century, Albert Einstein revolutionized our understanding of gravitation – and thus also of matter, space and time – with his general theory of relativity. His idea replaced the classical concept of gravity as the direct interaction between two masses that move through rigid, Euclidian space. Instead, it held that three-dimensional space and time are united to form a four-dimensional space-time and are themselves now deformable and dynamic. A mass such as the Sun bends space-time in its vicinity – the larger and, in particular, the denser a mass, the stronger the effect.

The motion of a second, smaller mass, such as a planet, then follows this curvature. If the local curvature chang-

Under the spell of gravity: Black holes have been keeping astrophysicists busy for more than a century. None has yet been observed directly, but the discovery of gravitational waves at least shows that these bizarre structures really do exist.



es because a mass accelerates across this space, this change propagates at the speed of light as a gravitational wave in the space-time structure.

Einstein used Riemannian geometry as the mathematical basis for dynamic space-time. Black holes emerge from the field equations, which describe the curvature of space brought about by matter and, conversely, the effect of curvature on matter, as a natural solution for matter concentrated at one point. The gravity there is infinitely large, and space-time has an infinitely large curvature: mathematically, it is a singularity.

“Physically, however, such infinities don’t tell us anything,” says Maria Rodriguez. “What is relevant is the separation from the point mass below which gravity becomes so strong that nothing can escape from it and can only fall into

the black hole,” says the Minerva Group Leader at the Max Planck Institute for Gravitational Physics in Golm.

There is no escape for either matter or light. This is what makes it so difficult for astronomers to observe these objects. The explanation is simple: in order to leave a conventional celestial body such as Earth, objects require a minimum kinetic energy that depends on the body’s mass. The velocity that rockets require, for example, is called the escape velocity. For a black hole, this velocity corresponds to the speed of light.

GRAVITY EVENTUALLY GAINS THE UPPER HAND

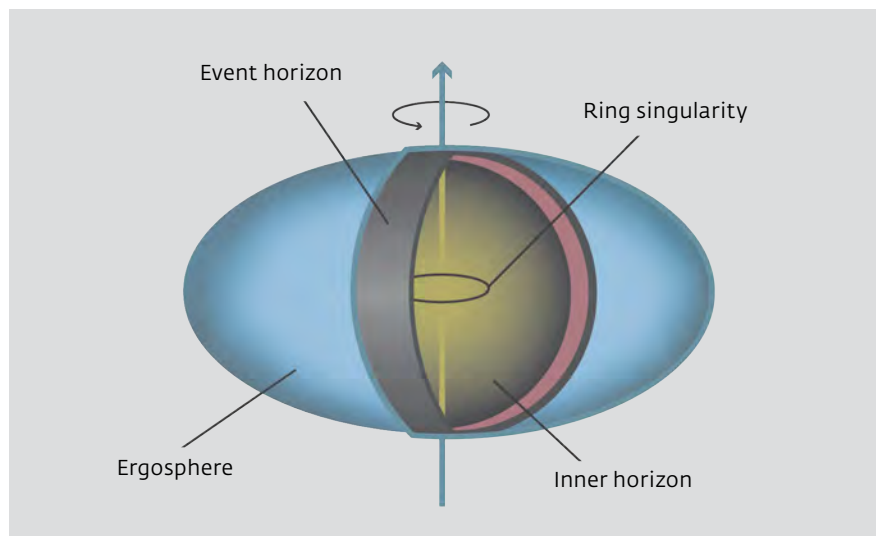
How space-time behaves under these conditions was first described in 1916 by astrophysicist Karl Schwarzschild

(1873 to 1916) in the metric that bears his name. The so-called event horizon that shields the interior of the black hole from the outside world is defined by the Schwarzschild radius, which depends on the mass. “Its shape is a perfect sphere for conventional black holes, which don’t rotate and have no electric charge,” says Rodriguez. The researcher investigates the boundary surfaces of black holes with different properties.

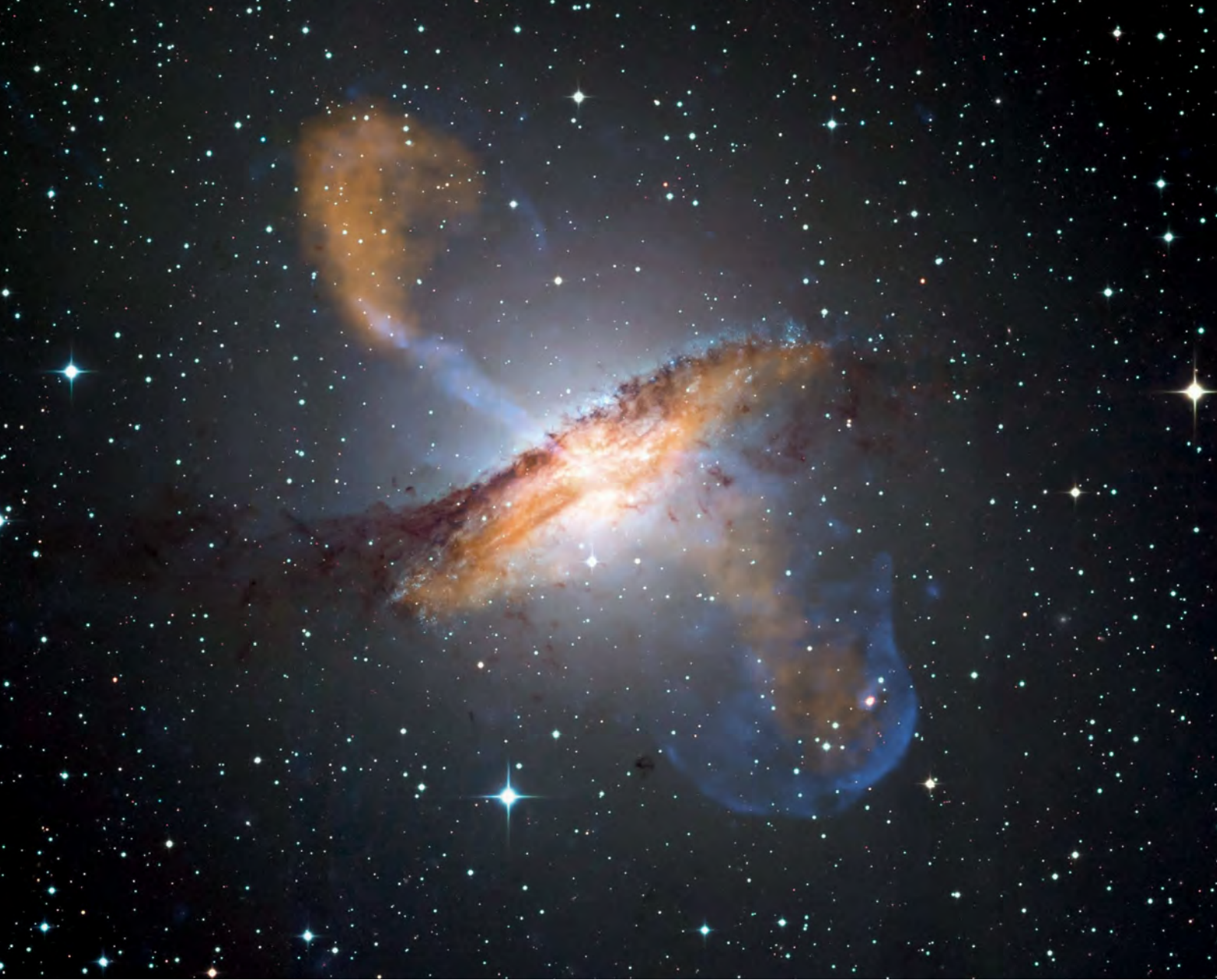
But black holes with no angular momentum are probably very rare in nature. This is because these objects are formed, for instance, when particularly massive stars have exhausted the supply of fusionable material in their interior toward the end of their life. The temperature there then drops and thermal and radiation pressure are no longer sufficient to counteract the star’s gravitation.

The stellar interior implodes and the once free electrons are pushed into the positively charged atomic nuclei. In such a supernova, the neutrinos released in this process transport a large portion of the energy away and hurl the outer stellar shell into space. The matter in the core, in contrast, contracts more and more under its own gravity. If the original mass of the star was more than eight solar masses, the ultimate result is a black hole. Since stars usually rotate about their own axis and the angular momentum is conserved, they pass it on to the black hole.

Astronomers are still puzzled by the birth of the particularly massive black holes – with a few million to a billion solar masses – that are presumed to lie at the centers of galaxies. They may possibly have formed from the first generation of extremely heavy stars that, having become a black hole, rapidly accreted more and more mass and thus more and more angular momentum.



Clear structures: The physics might be complex, but the explanation of the structure is simple. The graphic shows a rotating black hole with a ring singularity in the center and the inner horizon. The event horizon is something like the surface of the black hole; when something disappears behind it, it is truly out of this world. The ergosphere marks the region in which every object is forced to co-rotate.



Engine at the center: Centaurus A is around 15 million light-years away, making it the nearest radio galaxy, but it also emits intense X-ray and gamma radiation. The jet structure visible in this image is apparently caused by the activity of the central black hole with around 55 million solar masses.

The hypothesis of so-called primordial black holes, according to which these cosmic heavyweights formed shortly after the Big Bang together with the first galaxies, is also being discussed. Astronomers also speculate about the existence of medium-weight black holes, with 100 to one million solar masses, that could be present at the centers of large globular clusters.

PARTICLES ARE EJECTED

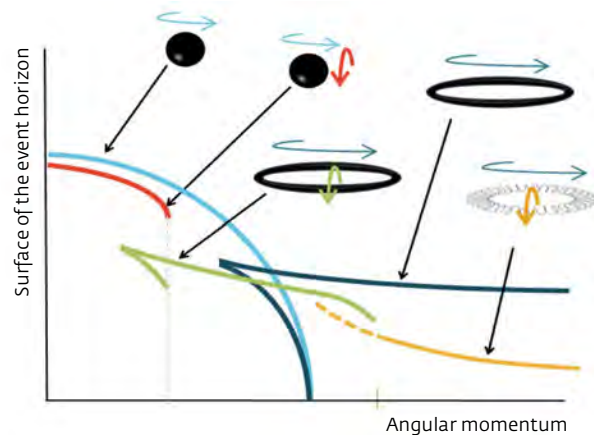
When a black hole rotates, its event horizon deforms slightly. Furthermore, the space-time of its immediate vicinity and the matter located there rotate with it. This sphere of influence of the

black hole is called its ergosphere and is ellipsoid in shape. Matter from outside that gets caught up in it doesn't necessarily plunge directly into the space-time trap, but rather initially co-rotates with it. Nevertheless, it is unable to escape from it.

"Unless the matter is electrically charged," says Rodriguez, because the co-rotating charged matter causes a magnetosphere to form. Some of the charged particles are deflected along the magnetic field lines. Depending on the sign of the charge and the orientation of the field lines, the particles then fall more rapidly into the black hole – or are ejected along the rotational axis. "Astronomers have since observed very

high-energy jets in around 20 active galaxies or quasars. These objects probably have an extremely massive, rapidly rotating black hole at their center," says the Max Planck researcher.

To be able to correctly interpret these phenomena, the researchers are attempting to compute the behavior of rotating black holes and the physical processes in their immediate vicinity according to the laws of the general theory of relativity. Analytically, they have initially succeeded in doing this only for very slowly rotating black holes, but Maria Rodriguez is interested in the very opposite: objects that rotate about their own axis at almost the speed of light. >



Advanced mathematics: During her time as a postdoc at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI), Maria Rodriguez computed possible surface configurations of event horizons of black holes in more than three spatial dimensions. The diagram depicts analytical solutions for five dimensions. Their shapes depend on mass and rotation (angular momentum). Depicted are the projections of the configurations from five to two and three dimensions.

To this end, she solves the equations of electrodynamics and, simultaneously, the field equations of the general theory of relativity on the basis of one and the same formalism. “The solution can be found either by trial and error or by adopting a systematic approach,” says Rodriguez. “We used a method from string theory.”

This theory originated in the 1960s. At that time, particle physicists discovered that the building blocks (nucleons) of an atomic nucleus are themselves composed of quarks. The scientists attempted to use string theory to unify the strong force, which keeps the quarks together to form protons and neutrons, with the weak force and the electromagnetic force. Quantum chromodynamics ultimately turned out to be more suitable for describing the strong force.

However, scientists later returned to string theory in order to unify gravitation with the other three fundamen-

tal forces. In addition to the four dimensions of space-time, it introduces six further spatial dimensions. “This is quite compatible with the concept of the general theory of relativity, since it doesn’t specify the number of spatial dimensions at all. The four dimensions of space-time form a purely heuristic basis,” says Maria Rodriguez.

AN ANT IN A CABLE KNOWS ONLY ONE DIMENSION

The reason we can’t perceive these additional dimensions – if indeed they really do exist – could be that they are either particularly tiny or particularly large. “An ant, for example, that crawls through a cable will register only the direction straight ahead and experience its world as one-dimensional,” says Rodriguez. Two additional dimensions are required in order to describe the cable as a long, thin (flexible) tube.

With this extension, the different energy regimes in which the four fundamental forces act, as well as their different dependencies on distance, can be unified in one theory. Rodriguez’ model to generate jets for rotating black holes is independent of mass and angular momentum; it can be applied both to such extremely massive cosmic heavyweights as presumably exist in all spiral galaxies and to their less massive counterparts that were generated by a stellar explosion.

The researcher’s computations indicate that the jets can differ significantly from each other in terms of form and energy involved: they can be extremely focused or broadly fanned out. “We still have to find out which of the solutions nature favors under which conditions,” says Maria Rodriguez. There are also some cases in which no jets at all are generated.

One example here is the object at the center of our Milky Way. Its vicini-

ty emits radio emissions, but there are no high-energy jets. In years of hard work, Reinhard Genzel and his colleagues from the Max Planck Institute for Extraterrestrial Physics observed the orbits of individual stars around the Sagittarius A* radio source at the center of the galaxy.

The breakthrough came in 2002, when the astronomers used the interferometers of the Very Large Telescope at the European Southern Observatory (ESO) in Chile to observe how the star S2 came to within a distance of 12 milli-arcseconds from the source of Sagittarius A*. This corresponds to a distance of just 17 light-hours. By comparison, light takes around five hours to travel from the Sun to Pluto. With the aid of earlier images, Genzel and his colleagues, among others, completely reconstructed the extremely elliptical orbit of the star S2 about the compact radio source, which has a period of 15.2 years.

Using Kepler's third law, the researchers estimated the mass of the central object to be around 3.7 million solar masses. Limited to such a narrow spatial area, it could only be a black hole. Thanks to more accurate measurements on other stellar orbits, astronomers today assume it has around 4.5 million solar masses.

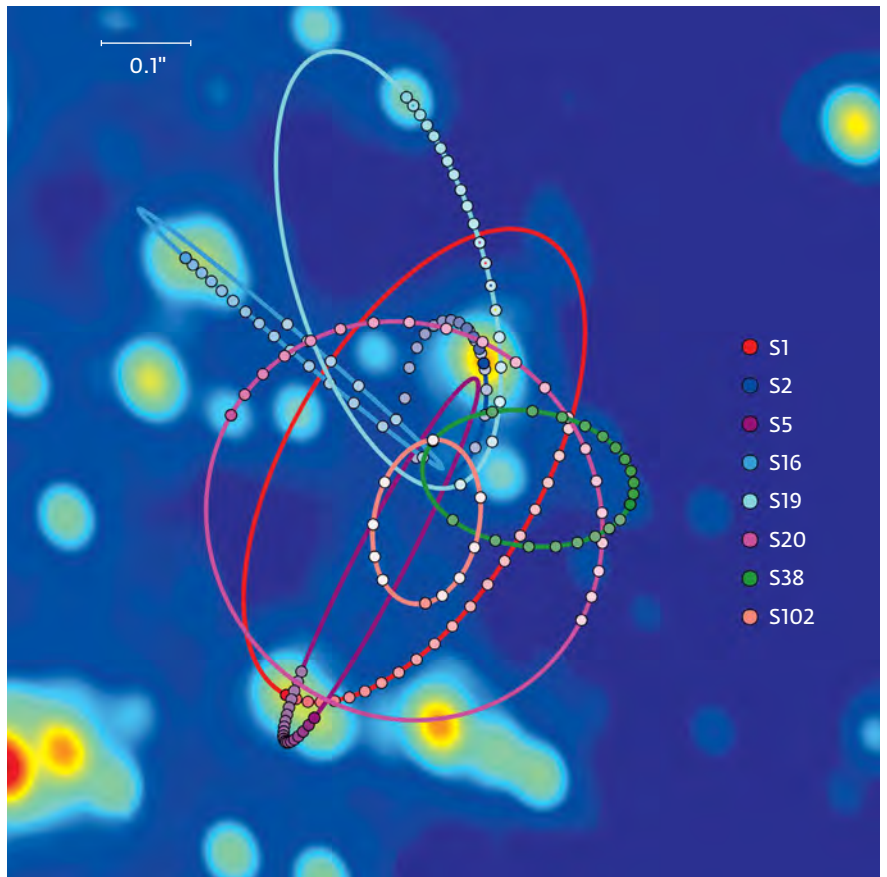
But maybe black holes could make their presence felt in a completely different way. Perhaps the conventional view that says that these compact objects can be persuaded to reveal information about only very few properties, such as mass and – possibly – angular momentum and charge, is incomplete. Stephen Hawking already proposed in the mid-1970s that black holes really could emit a specific form of radiation – the Hawking radiation named after him. Theoretician Jacob Bekenstein had speculated shortly before this that

the surface of the event horizon could represent a measure for the thermodynamic entropy.

INFORMATION MAY POTENTIALLY BE PRESERVED

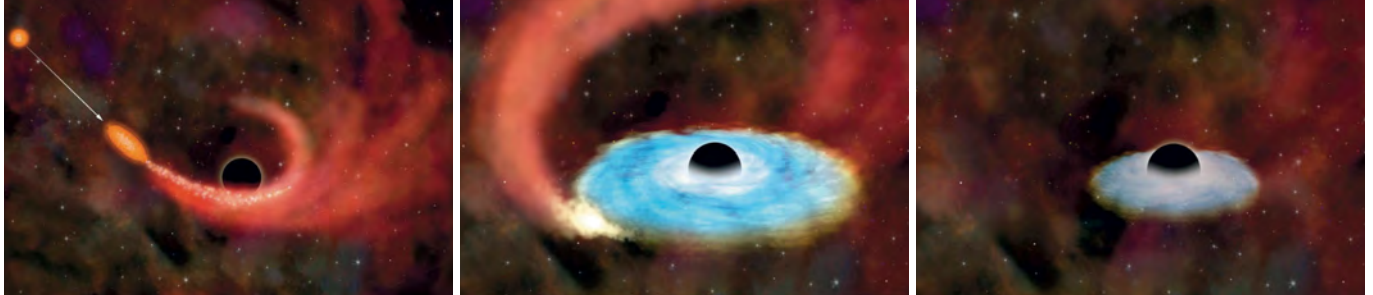
Entropy can be considered to be a measure of the information content of a system: the higher the entropy, the more information is contained in the system. Bekenstein and Hawking were the first

to compute the entropy of a black hole, but it didn't match at all with that of the precursor star from which the hole was formed. Scientists have still not been able to fully clarify what happens with entropy and information in a black hole. Within the scope of the theory of relativity, information could be destroyed in the hole; this, however, is contradicted by the concepts of quantum physics. String theory also tackles the problem of entropy and provides



Around the center: A black hole with around 4.5 million solar masses lurks at the heart of the Milky Way. The gravity of the object forces nearby stars onto more or less elliptical orbits. Between 1995 and 2014, astronomers measured these motions very accurately using the Keck telescope in Hawaii.

Graphic: UCLA Galactic Center Group – W.M. Keck Observatory Laser Team



Drama in three acts: A star is torn apart by the tidal effect of a black hole (left). It then devours a portion of the stellar debris, heating up strongly in the process (center). This, in turn, leads to a gigantic outburst of radiation, which subsides again in time (right).

solutions for a finite entropy content. The information from the event horizon would then possibly become available to an external observer.

In this context, earlier work that Maria Rodriguez produced during her postdoc phase at the Max Planck Institute in Golm, in the research group of Director Hermann Nicolai, could also become interesting again. At that time, she developed a whole catalog of solutions for black holes in higher dimensions based on string theory. In the three-dimensional representation we are familiar with, they look like a sphere, a donut-like ring, either on its own or orbiting a sphere, similar to the ringed planet Saturn; or like two entwined rings. In the higher dimensions, all these surfaces are interconnected to give a solution.

If black holes really do emit a specific type of radiation, it will probably be extremely difficult to measure it even at some time in the future. But maybe it will soon be possible to check specific effects from Rodriguez' models for conventional black holes with the aid of observations.

A network of radio telescopes spread all over the world is currently being set up, the so-called Event Horizon Telescope. The astronomers want to use this and the Very Long Baseline Array to image the galactic center with much better resolution. In addition, they want to look more closely at the heart of the active galaxy known as M 87, which has a high-energy jet. This is

thought to be the site of an extremely massive black hole with 6.6 billion solar masses. In this way, the researchers hope to find out whether jets really are formed in the ergosphere of a black hole, or in a disk of matter further out after all.

Certain effects of quantum gravitation, in contrast, should affect the grav-

itational wave signals from black holes. Most recent estimates have shown that the sensitivity of the LIGO detectors during the recently launched measurement campaign should be high enough to either confirm or exclude them. Gravitational wave astronomy will thus one day shed some further light on the nature of black holes. ◀

TO THE POINT

- **The gravity inside a black hole is infinitely large, and space-time has an infinitely large curvature. However, this mathematical singularity has no meaning from a physical point of view.**
- **What is crucial is the separation from the point mass below which gravity becomes so strong that nothing more can escape from it. This boundary is identified by the event horizon. This is a perfect sphere for black holes that aren't rotating and have no electric charge.**
- **But static black holes are very rare in nature. The researchers are therefore attempting to compute the behavior of rotating black holes and the physical processes in their immediate vicinity according to the laws of the general theory of relativity.**
- **Analytically, such computations have been successful only for very slowly rotating black holes. Maria Rodriguez, on the other hand, investigates objects that rotate about their own axis at almost the speed of light. She uses string theory methods for this purpose.**

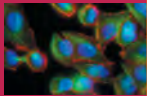
GLOSSARY

LIGO: The Laser Interferometer Gravitation Wave Observatory consists of two detectors sited in the US states of Louisiana and Washington. This is where gravitational waves were first discovered on September 14, 2015. Although the installation, which is called Advanced LIGO in its present upgrade stage, is located in the US, Max Planck researchers made a significant contribution to the discovery through hardware, computer programs and models.

Riemannian space: An object from the branch of mathematics known as Riemannian geometry with special properties. For instance, the shortest connections between different points aren't necessarily straight lines, but can be curved lines. And the angular sum of triangles can be greater or less than 180 degrees.



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