

4 A glimpse into the machinery of a gravitational monster

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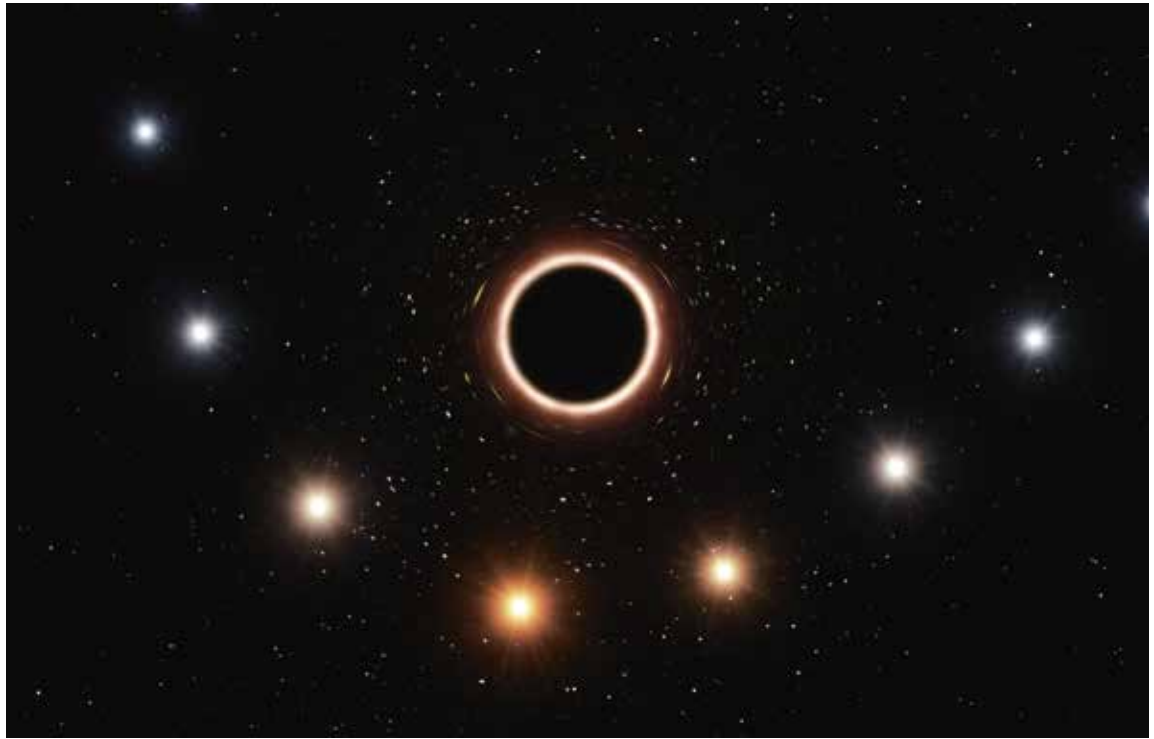
More than a century ago, Albert Einstein completed his general theory of relativity. The predictions of this theory can be tested in the universe – for example in the centre of our Milky Way, where a black hole with enormous gravitational force presents fantastic opportunities for such measurements. In 2018, we succeeded in three ground-breaking experiments with the Gravity instrument that was developed at our Institute. For the first time, we were able to prove the gravitational redshift around a massive black hole, we tracked orbital motions very close to the point of no return, and we determined the mass of cosmic gravitational traps more than a billion light years away. Gravity, with its unique image sharpness and sensitivity, is revolutionizing astronomy.

With the description of gravity in his general theory of relativity, Albert Einstein laid the foundations for our understanding of space and time. Numerous experiments in the weak gravitational fields of our sun and earth have impressively confirmed this theory. We all profit from its practical applications, for example with our worldwide navigation systems. In the extreme environment of a black hole, gravity shows utterly amazing effects: time slows down, space is curved, and entire worlds are irrevocably separated from their surroundings. For those who want to decode the universe, a black hole is like the “Rosetta Stone”.

With the Gravity instrument, developed under the leadership of our Institute, we are now able for the first time to make precise observations of the characteristics of black holes. By combining the four largest telescopes in the European Southern Observatory (ESO), we have created a virtual 130-metre telescope. This

technique, called interferometry, dates back to Albert Michelson (1852-1931), the first person to succeed in measuring the diameter of a star. The light waves received by the individual telescopes are superimposed, resulting in a sharper image of the object. This means that Gravity, in combination with the four 8-metre mirrors of the above-mentioned Very Large Telescope (VLT), can measure the distance between two cars on the moon with an error of only 2 centimetres. After decades of intensive observations of the Galactic Center Black Hole with single telescopes, Gravity represents a technical breakthrough. We are now truly ready to explore the mysteries of black holes.

The black hole in the centre of the Milky Way is an ideal laboratory for our research. After all, there exists no other black hole with a similar mass (about 4 million times the mass of our sun) in closer proximity. Yet even the diameter of this black hole appears no larger than a 1-euro coin on the moon. Using Gravity, we have



Colour change: this illustration shows the star S2 passing the black hole in the galactic centre. The gravitational red shift caused by the extremely strong gravitational field is clearly visible.

been able to track precisely the movements of stars and hot gas orbiting around the black hole. Gravity's accuracy and sensitivity outperforms its predecessors by hundreds to thousands of times, and is unrivalled in the world.

A star accelerates up to 27 million kilometres per hour

The galactic black hole reveals itself primarily by its enormous gravitational force. Just like planets in the sun's gravitational field, stars in the centre of the Milky Way orbit around this gravitational monster. Our group has been tracking the movements of these stars for over 25 years. One star in particular, known as S2, approaches the black hole like a comet every 16 years, down to a distance of no more than 17 light hours or 120 times the distance between sun and earth. The black hole's gravitational pull accelerates the star to a speed of ca. 27 million km/h, or 2.5 % of the speed of light.

Due to this close distance between star and black hole, we are supposed to see a gravitational redshift in the light of the star, according to the general theory of relativity. It is important to note here that this redshift is not caused solely by the Doppler Effect. We are familiar with the Doppler Effect in our daily lives: for example, the pitch of an ambulance siren appears to change as the vehicle rushes past us, because the frequency of the soundwaves reaching us changes as the sound source approaches and recedes. The same effect occurs with

light waves, but here we talk about blueshift or redshift. However, redshift also occurs when light is moving within and, to some extent, fighting against a gravitational field. Thanks to Gravity's spectacular precision and sensitivity and in combination with the Sinfoni spectrometer (also developed at our Institute), we have been able to measure this effect for the first time in the gravity field of a supermassive black hole: an impressive confirmation of Einstein's prediction.

Although the black hole itself is invisible, the effects of gravity renders it visible – specifically, when infalling gas is heated up to temperatures of billions of degrees, causing it to glow. Strong magnetic fields form in this orbiting gas, which then erupt into bursts of radiation similar to solar flares. In summer 2018, we were able to observe three flares from the Galactic Center Black Hole with Gravity.

Flares near the event horizon

The results are spectacular: the radiation bursts appear to come from the so-called "accretion disc" – a gas ring with a diameter of no more than about 10 light minutes, which rotates at extremely high speed around the galactic centre. Matter can orbit safely, as long as it does not get too close to the black hole. However, once matter crosses the event horizon (the point of no return), it is no longer able to escape the tremendous gravitational pull. The flares therefore occur in an orbit close to this event horizon.

In all three cases, we observed the hot gas swirling around the black hole at 30 percent speed of light, orbiting just above the event horizon. A single orbit takes only 45 minutes. This observation allows us to conclude that an enormous mass – more than four million solar masses – must be concentrated in a tiny space. This is exactly what the theory of black holes has predicted, and this result is an overwhelming confirmation of the paradigm of the supermassive black hole at the centre of our Milky Way.

In addition, we were able to use the Very Large Telescope and Gravity to look deep into the universe, far beyond the centre of the galaxy 26,000 light years away. After all, supermassive black holes do not only exist in our own local galaxy: they are at the heart of every large galactic system, and can contain several billion solar

Turbulent gravity trap: this visualization is based on simulations of the motion of gas swirling at about 30 percent of the speed of light in a circular orbit around the black hole in the galactic center.



masses. When matter falls into these black holes, the heated gas glows so brightly that it outshines the whole galaxy and is visible even billions of light years away. However, this very effect also makes it more difficult to measure the mass of such active black holes, as it is no longer possible to see the orbits of the stars.

Up to now, it was only possible to calculate the mass of those objects from the light echo from gas clouds surrounding the black hole, but this means one has to make assumptions about the unknown distribution and movement of these clouds. With Gravity, we have been able to prove that these gas clouds also move in ordered orbits around the cosmic gravitational trap. For this purpose we focused our observations on a quasar named 3C 273 – the first “quasi-stellar

object” identified by astronomer Maarten Schmidt, over 50 years ago. This quasar appears as an extremely bright but distant star. It emits much more energy than a normal galaxy such as our Milky Way, and cannot be explained by fusion processes inside stars. Instead, astronomers believe that gravitational energy is converted into heat when matter swirls into an extremely massive black hole.

Spacetime in rotation

Our team looked deep into the heart of quasar 3C 273 and closely observed the structure of the gases moving rapidly around the central black hole. Until now, such a detailed observation was impossible, because the quasar’s inner region is tiny when observed from earth – the quasar’s size is similar to that of our own solar system, but it is 2.5 billion light years away. With a measured distance of 150 light days between clouds and centre, and the orbital velocity of the clouds, we were able for the first time to determine the mass of an active black hole: 300 million solar masses.

In the future, we plan to measure yet another effect of Einstein’s theory, which is linked to an unusual characteristic of black holes: when they rotate, they are supposed to drag space and time with them, like a spoon, which is dipped in honey and then starts rotating. One highly astounding prediction of the general theory of relativity states that, independent of its complex formation history and internal structure, all observable characteristics of a black hole depend only on two properties: mass and rotation.

Within the next few years, by using Gravity and other instruments being currently developed at the Max Planck Institute for Extraterrestrial Physics, we are going to measure this rotation of space-time from the motion of stars and infalling matter. This will represent another large step towards understanding the general theory of relativity. ◦