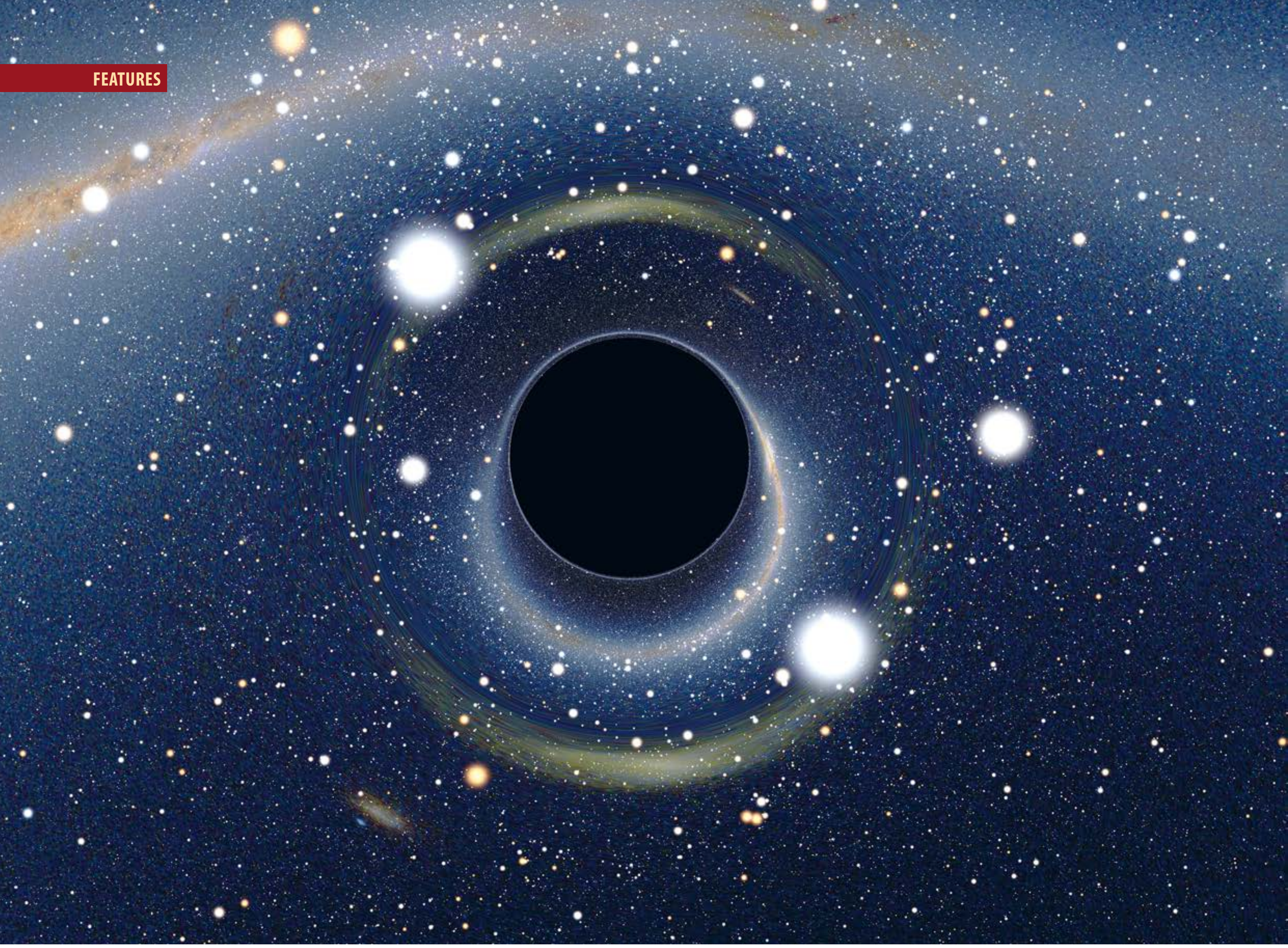

BLACK HOLES

Carlo Rovelli – DOI: https://doi.org/10.1051/epn/2021102

Centre for Theoretical Physics, CNRS, Aix-Marseille Université and Université de Toulon, CNRS, France.
Rotmann Institute, Western Ontario University, Canada. Perimeter Institute, Canada.

They are out there in the sky in huge numbers. They are the most astonishing objects in the universe. Their existence was predicted and understood before we detected them. They behave precisely as the theory predicted. Yet, we do not know what happens at their center, nor in their future. But this confusion is our key towards what we most lack in fundamental physics: understanding quantum gravity.

Albert Einstein was totally wrong about it. It was a mathematical solution of his equations that appeared to describe a funny perfectly round object surrounded by a surface where clocks appeared to slow down to stillness. Einstein thought that space would end at this surface: nothing behind it. The entire physical community was confused about the nature of this solution. Ideas begun to clear in the 1960s. But many viewed this solution just as a peculiar quirk of the equations, perhaps due to its unrealistic perfect symmetry.

It took Roger Penrose, recognised for this by the 2020 Nobel Prize, to develop mathematical tools showing that the strangeness of this solution was not a quirk: quite generically, Einstein theory predicts that if a bunch of matter-energy is sufficiently compressed, it closes itself within a "trapping surface", from which there is no escape: everything will inevitably sink into a locus where energy density becomes infinite and the theory becomes meaningless: a "singularity". Einstein's theory, that is, predicts that sufficiently compressed matter collapses into a black hole.

Still in the 1970s, people doubted all this could have anything to do with the real world. I studied general relativity -Einstein's theory- in that decade, on the textbook by Steven Weinberg, Nobel in particle physics: it still presented black holes as mathematical objects probably irrelevant for reality. After all, to create a trapping surface we'd have to squeeze the entire the mass of the Earth into something like a centimetre cube, not an easy task, it seemed, even for the universe.

But all these doubts were misplaced. The evidence for the real existence of black holes in the Sky continued to pile up during the following decades. Examples are the radio observations of the accretion disks formed by matter that spirals around black holes before plunging in, the observations of gigantic jets emitted in the polar directions by these accretion disks, the detection of gravitational waves formed by two black holes merging that led to the 2017 Nobel Prize to Rainer Weiss, Barry C. Barish and Kip S. Thorne, and others. Perhaps the most spectacular is the direct observations of the Keplerian orbits of the stars orbiting the great black hole at the center of our galaxy: they show that a mass 4 million times our Sun is concentrated in a small region, which coincides with a strong radio source located within one Astronomical Unit (the distance between the Sun and the Earth). Nothing else that we can imagine could concentrate a similar immense mas in such a small space. These observations were awarded with the other half of the 2020 Nobel prize, given to Andrea Ghez and Reinhard Genzel. Today nobody doubts anymore that there are objects in the sky for which the best understanding we have is in terms of Einstein theory's black holes.

We see in the sky black holes with stellar-size masses, clearly formed by star that have ended up their fuel and sank under their own weight, when the burning became insufficient to provide the pressure to keep them open. We see other black holes, much larger, at the centres of most galaxies. They can be millions or even billions times bigger than starts. They feed on matter and even stars falling in. Their origin, and the full relation between them and the galaxy that host them is under intense investigation and perhaps not completely clear yet. We also see other kinds of black holes, such as those whose merging has generated the gravitational waves we have detected, which are a few dozen of times larger than the stellar ones, and whose origin is not fully clear either. I would not be surprised if black holes of other sizes would soon add to this list. One likely possibility for instance is that smaller black holes formed in the very hot and dense environment of the early universe, and hang around in great numbers. A small black hole is not easily detectable: it interacts only gravitationally, while to see things we need them to interact with light, namely electromagnetically. As for myself, I have long suspected that the mysterious dark matter that we know fills the universe, and about which we have very little clue, could well be related to small black holes.

"Our knowledge of black holes is a combination of understanding and ignorance. We understand well their observed behaviour; we are in the dark about what happens at their center and in their distant future."

What is remarkable about our current knowledge about black holes is that it is a combination of nearly perfect understanding and total ignorance. On the one hand, general relativity appears capable to perfectly account for all the features of the black hole that we observe. For instance it shows that the reason a clock approaching the surface of a black hole slows down to zero is purely perspectival. That is, there is nothing particularly strange that happens on the black hole surface itself, if we look at a small enough portion of it. What is strange is the way all small regions of space and time are patched together: a short time for somebody staying put near the surface is viewed as a long time from somebody watching from outside. Beyond the horizon, contrary to what Einstein thought, space and time continue normally, except that everything irresistibly sinks towards the center. All this is clear.

On the other hand, however, we are totally in the dark about two aspects of the black hole. The first is what happens then at the center. At a moment of reflection, this is shocking: we literally see huge amount of matter sinking into the holes. Where does it go? We do not know. The second thing we do not know is what is going to happen to a black holes in the distant future. Steven Hawking as convincingly argued that because of a quantum mechanical effect energy can slowly leak out of a black hole and, as we say, the black hole slowly "evaporate". Because of this a black hole, if left alone, will slowly loose mass until becoming very small. What happens next? Again, we do not know.

The reason we are in the dark about the center and the future of black holes is that their center and their life's end belong to a physical regime that escapes our established fundamental physical theories. This is the regime where quantum effects on the dynamics of space and time cannot be neglected. We need a quantum theory of gravity to figure out what goes on there.

There are are few tentative theories of quantum gravity, but they are difficult to work with and we do not know if they are right. But this means that black holes are the perfect object to study if we hope to get some clarity about quantum gravity. Black holes are the perfect testing ground for quantum gravity.

Among the best developed tentative theories of quantum gravity are loop quantum gravity and string theory. The first appears to predict that spacetime continues beyond the center of the hole: matter falling-in can cross a central quantum region and find itself in a novel spacetime region which, using Penrose's terminology, is not "trapped" but "anti-trapped". There is a solution of Einstein theory describing such region, which is called "white hole". The white hole solution to Einstein's equations was long considered an unphysical mathematical quirk. But so were black holes, for that matter. At the end of the black hole's life, the white hole would be found in its place, possibly emitting out some of what sank in the black hole.

Many scientists trained in string theory, on the other hand, consider models where the black hole just disappears into nothing at the end of its evaporation, and try to find ways in which any information about matter sank in could be emitted mixed up with outgoing Hawking's radiation. Who is right? One of the two? Both (this is possible)? Neither? We do not know. But given the huge amount of previous confusion that I have seen been clarified in the course of my life as a scientists, I trust that clarity will come also about this.

Contrary to some complains that we have heard, fundamental physics is not stagnant. To the opposite: it is a moment of vibrant development, especially in its gravitational sector, as testified by the string or recent Nobels in the field, and by the rapidity at which our understanding of these fantastic objects that fill the sky has evolved. ■

About the Author

Carlo Rovelli is theoretical physics known for his work in quantum gravity. He was born in Italy in 1956 and has worked in Italy, the Unites States and France. He directs the quantum gravity group of the Center for the Theoretical Physics of Luminy in France, holds a Distinguished Visiting Chair at the Perimeter Institute, and is affiliated with the Rotman Institute of Philosophy at the University of Western Ontario. He was awarded the Xanthopoulos Prize for his work on spacetime physics. He has written popularisation best sellers, translated in more than 40 languages and has been included in the 2019 list of the 100 most influential global thinkers by Foreign Policy magazine.