Research into black holes awarded the 2020 Nobel Prize in Physics

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The 2020 Nobel Prize in Physics has been awarded to Roger Penrose for his theoretical work showing that the formation of black holes is a direct consequence of Albert Einstein's theory of general relativity, and to Reinhard Genzel and Andrea Ghez for each discovering the supermassive black hole in the center of our own galaxy, the Milky Way.

"The discoveries of this year's Laureates have broken new ground in the study of compact and supermassive objects," said David Haviland, chair of the Nobel Committee for Physics, in the organization's press release. He continued, "But these exotic objects still pose many questions that beg for answers and motivate future research. Not only questions about their inner structure, but also questions about how to test our theory of gravity under the extreme conditions in the immediate vicinity of a black hole."

Roger Penrose began to make inroads into general relativity early on in his career. Penrose, born in Colchester, Essex in 1931, developed new methods of studying the the geometric properties and spatial relations of various shapes and figures, a field known as topology, in his early 20s. Penrose specialized in making objects that folded in on themselves and were cyclical in nature, and was so proficient that he inspired many of the most famous geometrical illusions of Dutch artist M.C. Escher.

During the next decade, Penrose applied these talents to studying the inherently curved nature of spacetime described by general relativity to answer a very basic question: can black holes exist?

The concept of a black hole, an object so dense and with such a large gravitational attraction not even light can escape, is not new to general relativity. The idea was first proposed by English astronomer John Mitchell in 1783, and by French mathematician Pierre-Simon Laplace in 1796–1799. Using the framework provided by Newton during the previous century, they realized, with minimal assumptions, it is in theory possible to make an object so massive that no light can escape its gravitational pull.

This work was expanded upon by Einstein and many others in the months and years after Einstein completed his work on a theory of universal gravitation in November 1915. The very first solution to Einstein's equations, derived by Karl Schwarzschild in January 1916 while deployed in the German army during World War I on the Russian front, suggested an object that has so much gravity that at some point, no matter, not even light, can escape it. Moreover, the result matched the Newtonian value proposed by Mitchell and Laplace. Schwarzschild died while still deployed as an artillery officer four months later and was unable to make further contributions.

While the mathematics was worked out, however, there was disagreement for decades as to whether or not such an object could actually be formed. American physicist Robert Oppenheimer suggested that a massive spherical ball of matter, such as a star, might be able to collapse into such an incredibly dense object, known as a singularity. Einstein himself disagreed, and the debate continued into the 1960s.

Enter Penrose in 1964 and 1965, who applied his understanding of topology to the concept of black holes. He found that he was able to connect the point of no return, the event horizon, to the theoretical singularity hidden within using a concept now known as trapped surfaces. Penrose showed that once beyond the event horizon, it is not that matter can't escape, it's that its motion is always directed toward the singularity.

This has a variety of implications. One of the most counter-intuitive is that trying to escape a black hole only makes the problem worse. To escape Earth's gravity, for example, one can use a rocket to thrust above the planet's escape velocity and visit other parts of the Solar System. In contrast, any such attempts to escape out of an event horizon actually speeds one's descent toward the singularity, a sort of cosmic quicksand.

Such results have been central to our understanding of black holes since and provided a framework for the experimental discoveries that made up the other half of this year's Nobel.

While Penrose and many others were establishing the theoretical underpinnings of black holes, a variety of experiments at the time were strongly suggesting that such supermassive objects exist and that they can be indirectly observed by their gravitational interactions with other pieces of matter. Observations in the 1950s and 1960s discovered astronomical bodies that were roughly the size of our Solar System but with an energy output one thousand times that of our entire galaxy.

As more of these objects—so-called quasars—were discovered, the only plausible explanation was that immense amounts of matter was spiraling into black holes, in turn emitting enough light to shine across hundreds of millions or even billions of light years. It was then postulated that these quasars were actually the initial stages of galactic formation, and that most if not all galaxies have a black hole at their center, forming the core of the most common visible structures in the Universe.

The most immediate difficulty studying black holes arose from the fact that the largest ones, and thus the most extreme, are so far away. The only suspected supermassive black hole near Earth, in cosmic terms, was the object at the center of our own galaxy, known as Sagittarius A*. The other option was that there could be a collection of large stars that are energetic enough to mimic the energy output of a black hole.

This led two observational teams, one led by Genzel at the Max Planck Institute for Extraterrestrial Physics in Germany and the other by Ghez at the University of California, Los Angeles, to attempt to follow the orbits of stars near the galactic center starting in the 1990s. If the motion of the stars is generally random, that is evidence that there is no large central object. If, however, the stars speed up the closer they get to the galactic core, like comets orbiting the Sun, that is evidence of a black hole.

The task was daunting. Genzel and Ghez had to track individual stars in the most crowded region of the galaxy, and one which visible light does not easily pass through. As such, they had to use the latest and most advanced new optical techniques to pierce through the dust and gas clouds of such a dense area. Their efforts were supported and largely made possible by the hundreds of other astronomers, engineers and technicians who helped them make and operate some of the most advanced contemporary ground-based imaging equipment.

The results bore fruit after more than ten years of observations. One star in particular, labeled S2, had an orbit around a small region with high gravity once every 16 years. This immediately pointed to the existence of a supermassive black hole. Other studies published in the late 2000s ruled out other options, while at the same time establishing that Sagittarius A* is an object about 4 million times the mass of the Sun with a density well beyond what is theoretically needed to form a black hole. It is no longer postulated but now accepted that supermassive black holes are at the center of virtually every galaxy.

This experimental breakthrough is one of many probing black holes in recent years. The observations made by LIGO, which won the Nobel Prize in 2017, and the imagery of the accretion disk surrounding the supermassive black hole in galaxy M87 by the Event Horizon Telescope, are further confirmations both of the existence of black holes and the role they play in cosmic evolution. They also continue to confirm Einstein's original theory, while at the same time opening up new avenues to study the cosmos.