The surprising behavior of black holes in an expanding universe

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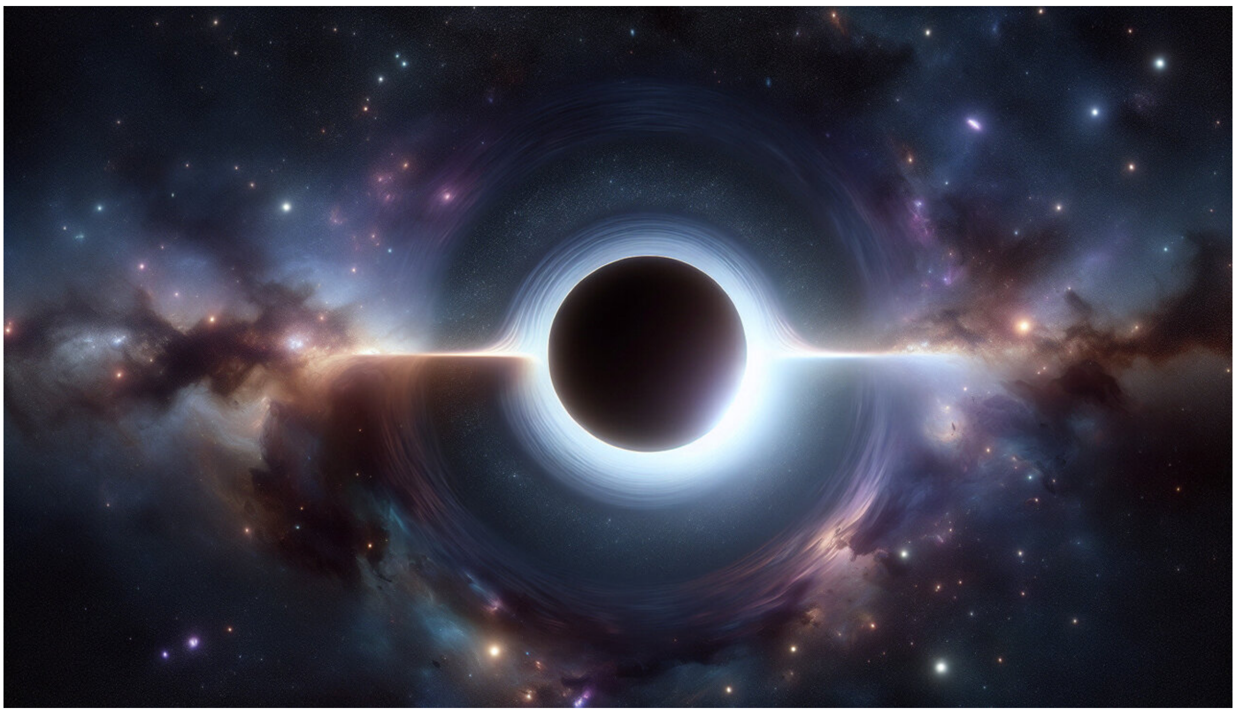

Credit: AI-generated image

A physicist investigating black holes has found that, in an expanding universe, Einstein's equations require that the rate of the universe's expansion at the event horizon of every black hole must be a constant, the same for all black holes. In turn this means that the only energy at the event horizon is dark energy, the so-called cosmological constant. The study is published on the *arXiv* preprint server.

"Otherwise," said Nikodem Popławski, a Distinguished Lecturer at the University of New Haven, "the pressure of matter and curvature of spacetime would have to be infinite at a horizon, but that is unphysical."

Black holes are a fascinating topic because they are about the simplest things in the universe: their only properties are mass, electric charge and angular momentum (spin). Yet their simplicity gives rise to a fantastical property—they have an event horizon at a critical distance from the black hole, a nonphysical surface around it, spherical in the simplest cases. Anything closer to the black hole, that is, inside the event horizon, can never escape the black hole.

Black holes were predicted in 1916 by Karl Schwarzschild while serving as a German soldier at the Russian front, while he was suffering from the painful autoimmune skin disease pemphigus.

Using Einstein's equations of general relativity, he assumed a massive, nonrotating, perfectly round object in an otherwise empty and unchanging universe and discovered the event horizon. The radius of the event horizon is proportional to a black hole's mass. Inside the horizon, not even light, the fastest object in the universe, can escape the hole.

Schwarzschild also found an apparent singularity at the black hole's center, a place of infinite density where Einstein's laws of gravity apparently breakdown.

Astronomers have since found that most galaxies appear to have a supermassive black hole at their center; for the Milky Way it is Sagittarius A*, with a mass over four million times that of the sun. A black hole was directly imaged only in 2019, a black spot with a halo of light around it, located in the center of the galaxy Messier 87, 55 million light-years from Earth.

Going beyond Schwarzschild, Popławski assumed a massive, centrally symmetric object in an expanding universe. In this case, the solution to Einstein's equations for the structure of spacetime around the mass was first obtained in 1933 by the British mathematician and cosmologist George McVittie.

McVittie found that near the mass, spacetime is like that of Schwarzschild's, with an event horizon, but far from the mass the universe is expanding like our universe is today. The Hubble parameter, also called the Hubble constant, specifies the rate of expansion of the universe.

Popławski used McVittie's solution to find that the rate of the expansion of space at the event horizon must be a constant, related only to the cosmological constant (which can be interpreted as the energy density of the vacuum of spacetime). Today we know this as the density of dark energy. That is, the only energy at the horizon is dark energy. The consequence, he said, is that different parts of the universe expand at different rates.

In fact, something similar has been found with the so-called "Hubble tension," a statistically significant discrepancy between two different measured values of the Hubble parameter, depending on whether "late universe" measurements are used or "early universe" techniques based on measurements of the cosmic microwave background. In his work, Popławski said this discrepancy "is a natural consequence of a correct analysis of the spacetime of a black hole in an expanding universe within Einstein's general theory of relativity."

Furthermore, his equations show that a consequence of the universe expanding at different rates is that the cosmological constant—and hence the value of dark energy—must be positive. Otherwise, without that constant, Popławski said, "a closed universe would be oscillatory and could not create cosmic voids."

"It is the simplest explanation of the observed current acceleration of the universe."

For a star, say, the universe is also expanding at its surface boundary, but the body does not expand because it is gravitationally and electromagnetically bound.

An event horizon, though, is a mathematically-abstract thing, not anything made of matter or energy but made simply of points of space, so a constant expansion rate of space there is not surprising. The event horizon itself (and thus a black hole) is not expanding; points of space outside the horizon are moving away from it.

Real black holes rotate, but if the rotation is typically slow, Popławski's conclusions should apply to them as well to a good approximation. But measuring the Hubble parameter at an event horizon is currently impossible, unless new techniques are developed.

An observer at the event horizon could in principle measure the Hubble parameter there but would be forever unable to communicate his value to the rest of the universe as he is falling past the event horizon, and no information can possibly be sent back across it.

This ties in, Popławski said, with a hypothesis he published in 2010: that every black hole is actually a wormhole (an Einstein-Rosen bridge) to a new universe on the other side of its event horizon.

"The event horizon is a doorway from one universe to another," he said. "This doorway does not grow with the expansion of the universe ... If this occurs for the event horizon of the black hole forming a universe, it should also work for the event horizons of other black holes in that universe."

More information: Nikodem Popławski, Black holes in the expanding Universe, *arXiv* (2024). DOI: 10.48550/arxiv.2405.16673