

Quantum mechanical wormholes fill gaps in black hole entropy

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Behind the veil: A black hole's event horizon contains an infinite number of microstates, but expressing these microstates in terms of a finite set of representative quantum superpositions makes it possible to quantify the entropy within. (Courtesy: Shutterstock/oorka)

A new theoretical model could solve a 50-year-old puzzle on the entropy of black holes. Developed by physicists in the US, Belgium and Argentina, the model uses the concept of quantum-mechanical wormholes to count the number of quantum microstates within a black hole. The resulting counts agree with predictions made by the so-called Bekenstein-Hawking entropy formula and may lead to a deeper understanding of these extreme astrophysical objects.

Black hole thermodynamics

Black holes get their name because their intense gravity warps space-time so much that not even light can escape after entering them. This makes it impossible to observe what goes on inside them directly. However, thanks to theoretical work done by Jacob Bekenstein and Stephen Hawking in the 1970s, we know that black holes have entropy, and the amount of entropy is given by a formula that bears their names.

In classical thermodynamics, entropy arises from microscopic chaos and disorder, and the amount of entropy in a system is related to the number of microstates consistent with a macroscopic description of that system. For quantum objects, a quantum superposition of microstates also counts as a microstate, and entropy is related to the number of ways in which all quantum microstates can be built out of such superpositions.

The causes of black hole entropy are an open question, and a purely quantum mechanical description has so far eluded scientists. In the mid-1990s, string theorists derived a way of counting a black hole's quantum microstates that agrees with the Bekenstein-Hawking formula for certain black holes. However, their methods only apply to a special class of supersymmetric black holes with finely tuned charges and masses. Most black holes, including those produced when stars collapse, are not covered.

Beyond the horizon

In the new work, researchers from the University of Pennsylvania, Brandeis University and the Santa Fe Institute, all in the US, together with colleagues at Belgium's Vrije Universiteit Brussel and Argentina's Instituto Balseiro, developed an approach that allows us to peek inside a black hole's interior. Writing in [Physical Review Letters](#), they note that an infinite number of possible microstates exists behind a black hole's event horizon – the boundary surface from which no light can escape. Due to quantum effects, these microstates can slightly overlap via tunnels in space-time known as wormholes. These overlaps make it possible to describe the infinite microstates in terms of a finite set of representative quantum superpositions. These representative quantum superpositions can, in turn, be counted and related to the Bekenstein-Hawking entropy.

According to [Vijay Balasubramanian](#), a physicist at the University of Pennsylvania who led the research, the team's approach applies to black holes of any mass, electric charge and rotational speed. It could therefore offer a complete explanation of the microscopic origin of black hole thermodynamics. In his view, black hole microstates are "paradigmatic examples of complex quantum states with chaotic dynamics", and the team's results may even hold lessons for how we think about such systems in general. One possible extension would be to search for a way to use subtle quantum effects to detect black hole microstates from outside the horizon.

[Juan Maldacena](#), a theorist at the Institute for Advanced Study in Princeton, US, who was not involved in this study, calls the research an interesting perspective on black hole microstates. He notes that it is based on computing statistical properties of the overlap of black hole pure states that are prepared via different processes; while one cannot compute the inner product between these different states, gravity theory, through wormhole contributions, makes it possible to compute statistical properties of their overlap. The answer, he says, is statistical in nature and in the same spirit as another computation of black hole entropy performed by Hawking and Gary Gibbons in 1977, but it provides a more vivid picture of the possible microstates.

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