Constraining the dynamics of rotating black holes via the gauge symmetry principle

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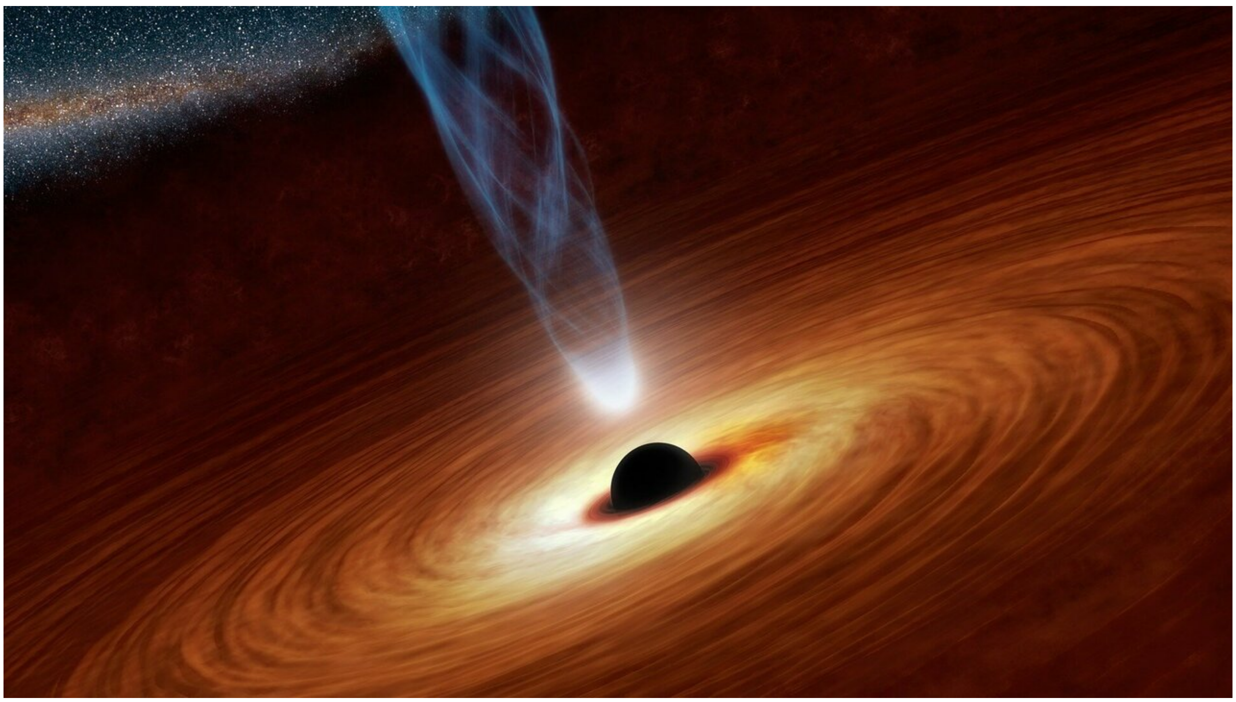

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In 2015, the LIGO/Virgo experiment, a large-scale research effort based at two observatories in the United States, led to the first direct observation of gravitational waves. This important milestone has since prompted physicists worldwide to devise new theoretical descriptions for the dynamics of blackholes, building on the data collected by the LIGO/Virgo collaboration.

Researchers at Uppsala University, University of Oxford, and Université de Mons recently set out to explain the dynamics of Kerr black holes, theoretically predicted black holes that rotate at a constant rate, using theory of massive high-spin particles. Their paper, published in *Physical Review Letters*, specifically proposes that the dynamics of these rotating black holes is constrained by the principle of gauge symmetry, which suggests that some changes of parameters of a physical system would have no measurable effect.

"We pursued a connection between rotating Kerr black holes and massive higher-spin particles," Henrik Johansson, co-author of the paper, told Phys.org. "In other words, we modeled the black hole as a spinning fundamental particle, similar to how the electron is treated in quantum electrodynamics."

The connection between Kerr black holes and higher-spin theory was first explored in two distinct papers published in 2019. The first of these studies was carried out by Alfredo Guevara at the Perimeter Institute for Theoretical Physics and his collaborators in Europe, while the second by Ming-Zhi Chung at National Taiwan University and his colleagues at Seoul National University.

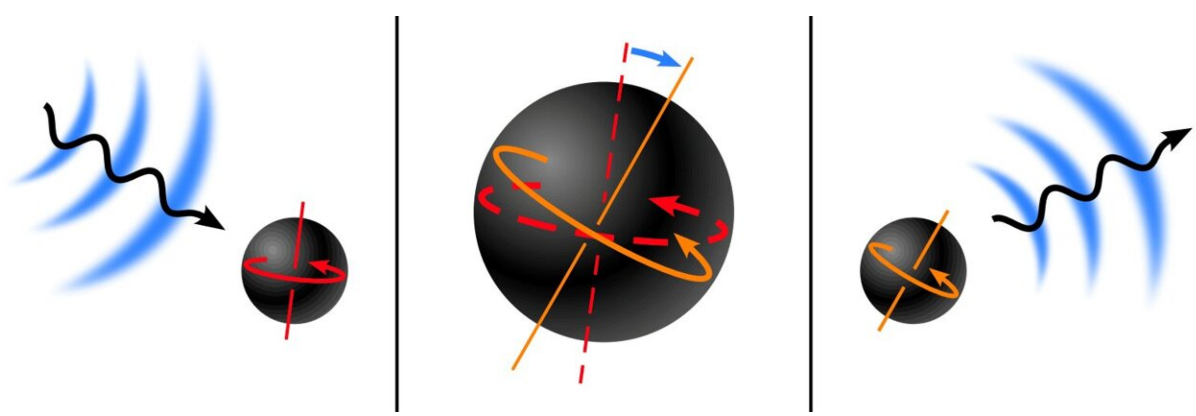

Image illustrating Compton Scattering, the main process discussed in the paper. Credit: Cangemi et al.

Both of these previous works showed that the well-known Kerr metric can be matched to an infinite family of higher-spin scattering amplitudes. These amplitudes were first obtained by physicists Nima Arkani-Hamed, Tzu-Chen Huang and Yu-tin Huang, as part of a previous study.

"While these previous results are remarkable, they are not yet sufficient to accurately describe Kerr black-hole dynamics in view of upcoming experiments, such as the Einstein telescope, LISA and the Cosmic Explorer," Johansson said. "Some important missing information is contained within the black-hole Compton scattering amplitude, which is currently unknown for general spin."

In their paper, Johansson and his colleagues suggest that the principle of gauge symmetry could be used to successfully constrain the dynamics of rotating black holes. The researchers showed that massive higher-spin gauge symmetry, informed by a mechanism first outlined by Ernst Stueckelberg and later formalized by Yurii Zinoviev, can be used to reproduce the Kerr scattering amplitudes reported in previous papers.

"We also showed that the unknown Compton scattering amplitudes are severely constrained, even if achieving uniqueness requires further input," Johansson said.

"Higher-spin quantum field theories (QFTs) are notorious for their complexity. Even low-spin QFTs, such as the spin-1 case of the Standard Model, and the spin-2 case of General Relativity, are of course complicated, and their formulations fundamentally rely on gauge symmetry and diffeomorphism symmetry (general covariance). These two symmetries may be regarded as the lowest two rungs on an infinite ladder that is called higher-spin gauge symmetry."

While gauge symmetry is not necessary for describing the dynamics of massive particles, it has proved to be a valuable tool for outlining consistent interactions. One realization of this massive gauge symmetry is the so-called Higgs mechanism.

"Using massive higher-spin gauge symmetry for black holes, we could ensure that the spin degrees of freedom are treated consistently and write down an effective Lagrangian," Johansson explained, "The Lagrangian both gives the correct higher-spin description of a Kerr black hole and has a reasonably good high-energy behavior. The good high-energy behavior is not important for classical black holes, but it gives some confidence that the effective theory might also describe certain quantum processes."

Johansson and his colleagues were the first to apply higher-spin gauge symmetry to black holes. The outcome of their initial calculations is promising and could soon pave the way for further studies exploring this link.

"While we expect that it will take some time before the full effective theory for rotating black holes is understood, we think that higher-spin gauge symmetry will be a critical component in its formulation, similar to how gauge symmetry and diffeomorphism symmetry guided the theoretical framework of 20th-century physics," Johansson said. "The complete Compton scattering amplitude for a Kerr black hole remains enigmatic, but we have high hopes of being able to fully constrain it in the future. This involves both understanding it for arbitrary spin orders, and to higher orders in Newton's constant."

Fully constraining the scattering amplitude of Kerr black holes will ultimately require close collaboration between theoretical physicists studying massive higher-spin particles and those trying to solve the so-called Teukolsky equation rooted in general relativity theory. Recent collaborations between these distinct research communities suggest that progress could soon be made in this direction.

"In our next works, we would also like to further pursue the connection between black holes and their quantum properties, which are reminiscent of elementary particles," Johansson added.

More information: Lucile Cangemi et al, Kerr Black Holes from Massive Higher-Spin Gauge Symmetry, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.131.221401

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