西暦　2025 年 12 月 9 日
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Research Summary

Black holes (BHs) are among the most fascinating objects predicted by general relativity. More than a century after their prediction, they remain central topics of debate at the cutting edge of theoretical physics. Recent observations, most notably gravitational-wave detections, have provided increasingly strong support for the actual existence of BHs in our Universe. Despite their theoretical and observational importance, many mysteries remain. On the theoretical side, representative open problems include the presence of curvature singularities and the information paradox associated with BH evaporation, both of which stem from the incompleteness of a quantum theory of gravity. Although we do not yet have a complete quantum theory of gravity, physics in strong gravitational fields can serve as a useful probe of its nature. Motivated by this viewpoint, I have been working mainly on the following four topics: "Thermal radiation in spacetimes without event horizons," "Creation of quantum universes and exact computation of the wave function of the Universe," "Gravitational waves and greybody factors," and "Dynamical black hole shadows."

I. Thermal radiation in spacetimes without event horizons

While a complete quantum theory of gravity remains elusive, BH thermodynamics, arising from quantum effects in strong gravitational fields, is widely regarded as a key feature of its structure. In this context, we have recently shown that quantum thermal radiation can occur even in compact objects without any horizons. This result challenges the conventional paradigm that identifies BHs themselves as the source of such thermal radiation, and instead suggests that we must reconsider where the heat source of quantum thermal radiation in a gravitational field is actually located.

II. Creation of quantum universes and exact computation of the wave function of the Universe

In modern cosmology, it is actively discussed that the early Universe could have been created "from nothing" by quantum effects. Two major proposals for the underlying mechanism are the no-boundary proposal and the tunneling proposal, and there has been a long-standing debate over which of them is correct. Using the framework of resurgence, we have succeeded in computing the wave function of the Universe from first principles, without artificially imposing either proposal by hand. Under certain assumptions, we have rigorously shown that the resulting wave function agrees with that predicted by the tunneling proposal rather than the no-boundary proposal. These results are expected to represent an important step toward resolving the long-standing debate between the two scenarios.

III. Gravitational waves and greybody factors

In current analyses of observed gravitational waves, the mass and angular momentum of a BH are typically inferred from the quasinormal modes. However, this method is prone to overfitting due to the superposition of multiple modes. We have statistically and numerically demonstrated that the gravitational-wave waveform emitted during the merger of BH binaries can be characterized by the greybody factor of the remnant BH, even in systems with comparable mass ratios. This provides an

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alternative way to estimate the mass and spin of a BH that avoids the overfitting problem due to the superposition of multiple modes.

IV. Dynamical black hole shadows

Since the Event Horizon Telescope obtained the first images, theoretical interest in a black hole shadow has increased dramatically. Most existing studies, however, assume static or stationary spacetimes, and the interpretation of images in dynamical situations, such as BH binary mergers, has not been fully clarified. As a result, there has been room for misunderstanding regarding the time evolution and shape changes of shadows in actual observations. We have shown that, even when a BH binary merges and the event horizons themselves coalesce, the corresponding shadows do not, in principle, merge into a single shadow. This result provides a theoretical guideline for correctly interpreting dynamical BH images obtained from future high-resolution observations and numerical-relativity simulations, and helps to avoid confusing shadows with event horizons.