(1) Summary of my past research

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I have been studying physical phenomena in strong gravity, in particular, in black hole spacetimes. The purpose of my research is to find phenomena with verifiability/falsifiability of the theory of general relativity, and further, to clairfy the method for finding evidences of new physics. Technically, I am good at performing heavy numerical simulations. At the same time, I also study strong gravity with purely mathematical approaches. I list up my research topics one by one.

Higher-dimensional black holes (Before 2011)

In this period, I studied higher-dimensional gravity. The motivation is that many theories, e.g. string theories, indicate that our spacetime has invisible extra dimensions. In particular, the "braneworld model" suggests that gauge particles and interactions are confined on a three-dimensional brane, and thus, the extra dimensions can be as large as 1mm. Then, the Planck energy, at which all four interactions are supposed to be unified, becomes as low as $O(\mathrm{TeV})$ and mini black holes could be produced by particle accelerators. My papers with particular importance are:

- [I-34, I-39]: Calculation of black hole production cross section in high-energy particle collisions;
- [I-19]: Formulation and code development of higher-dimensional numerical relativity.

Using the method developed in [I-19], I and a collaborator have shown that rapidly rotating higher-dimensional black holes are unstable against non-axisymmetric perturbation [I-16].

Phenomena caused by axion fields around a black hole (2011–present)

From 2011, I have been studying the behavior of massive scalar fields in four-dimensional black hole spacetime. This study is a trial to detect low energy phenomena caused by string theories. String theories predict the existence of various fields that orginate from the dynamics of extra dimensions, and some of them behave as scalar fields (axion-like fields) with tiny mass. Such fields may cause observable phenomena in cosmology and astrophysics. My important results obtained so far are

- [I-9, I-14]: Simulations of axion-like field around a rotating black hole.

Around a rotating black hole, an axion-like field grows by extracting the rotation energy of the black hole (i.e. superradinat instability) to form an axion cloud. I have developed a highly accurate code to simulate its behavior, and indicated that nonlinear interaction causes violent phenomena. Also, I have developed codes to calculate gravitational waves emitted by scalar fields around a nonrotating black hole. The results indicate that continuous gravitational waves with a large amplitude are emitted when nonlinear effect of the scalar field becomes important.

Behavior of light around black holes (Recent research)

Recently, I am interested in the behavior of photons around black holes [I-1–I-8]. This is because the recent success in observing the black hole neighborhood (i.e., the black hole shadow) suggests that it will become possible to access validity of general relativity by near-future observations. The edge of the black hole shadow is determined by the "photon sphere" on which propagating photons stay eternally. Since the concept of the photon sphere is limited to spherically symmetric static spacetimes, I proposed its extended concept, "the dynamically transversely trapping surfaces (DTTS)". It is applicable to dynamical spacetimes and has analogy with the concept of an apparent horizon. I have proved that the area of a DTTS is bounded from above as $A \lesssim 4\pi(3M)^2$ in certain conditions [I-2, I-3, I-4]. Furthermore, we now develop a concept to characterize strength of gravity from a bit different view point [I-1].

As a topic related to observations more directly, I have been studying optical image of a gravitationally collapsing star with Prof. K.-i. Nakao and Mr. K. Takahashi [I-5]. It was clarified that as the gravitational collapse proceeds, the image is generated primarily by photons that orbit around the photon sphere. The star image becomes darker due to the decrease in the number of arriving photons, while the redshift of arriving photons remains finite.