(1) Summary of my past research

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I have been studying physical phenomena in strong gravitational environment, in particular, black holes. The purpose of my research is to find phenomena with verifiability/falsifiability of the theory of general relativity through black hole physics, and further, to clarify the method for finding evidences of new physics that have not been established so far. Technically, I am very good at performing heavy numerical simulations. At the same time, I also study properties of black holes with purely mathematical approaches. I list up my research topics one by one.

Higher-dimensional black holes (Before 2011)

In this period, I studied gravitational phenomena in higher-dimensional spacetimes. The motivation is that many theories, e.g., string theories, suggest 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 $O(\text{TeV})$ and mini black holes could be produced by particle accelerators. My papers with particular importance are:

- [I-32, I-37]: Calculation of black hole production cross section in high-energy particle collisions;
- [I-17]: Formulation and code development of higher-dimensional numerical relativity.

Using the method developed in [I-17], I and a collaborator have shown that rapidly rotating higher-dimensional black holes are unstable against non-axisymmetric perturbation [I-14].

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 the trial to detect low energy phenomena caused by string theories. There are various modes of changing shape of extra-dimensions, and they behave as fields in the four-dimensional spacetime. Some of them are scalar field (axion-like field) with tiny mass. Such axion-like fields may cause observable phenomena in the context of cosmology and astrophysics. My important results obtained so far are

- [I-7, I-12]: Simulations of axion-like field around a rotating black hole.

Around a rotating black hole, the 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 the axion field, 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-2, I-3, I-4, I-5, I-6]. The recent success in an observation of the black hole neighborhood (the black hole shadow) suggests that it will become possible to access validity of general relativity through more detailed near-future observations. So, it is important to study propagation of light around a black hole in advance. 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 suggested its extended concept that is applicable to dynamically changing spacetimes, and named it "the dynamically transversely trapping surfaces (DTTS)". This concept is defined so that the analogy with an apparent horizon holds, and I have proved that the area of a DTTS on time-symmetric initial data is bounded from above as $A \lesssim 4\pi(3M)^2$ [I-2].

As a topic that is 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-3]. 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 per unit time, while the redshift of arriving photons remains finite.