Future research plans

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The Kerr black hole spacetime possesses a "hidden symmetry" characterized by the conformal Killing-Yano (CKY) tensor. This symmetry plays an essential role in the separability of perturbation equations and in the analysis of the (in)stability of black hole spacetimes. In four dimensions, this hidden symmetry was discovered by Walker and Penrose (1970), while the notion of CKY tensors traces back to the mathematical work of Kashiwada (1968) and Tachibana (1969). With the development of superstring theory and supergravity theory, higher-dimensional black holes have become increasingly important. Within this context, we have shown that CKY structures can be naturally extended to higher dimensions [45-69]. In particular, we proved that the Kerr-NUT-(A)dS black hole spacetime is the unique spacetime admitting a non-degenerate CKY tensor [51,52]. Building on these results, we are currently investigating the stability and rigidity of spacetimes admitting CKY structures.

Another significant development is that analytic continuation of black hole spacetimes with CKY structures naturally induces Einstein metrics on compact manifolds. The new Einstein metric obtained in joint work with Hashimoto and Sakaguchi [35] also finds a unified explanation in this framework. Moreover, several Einstein metrics, including the Page metric, toric Sasaki-Einstein metrics, and Einstein metrics on sphere bundles with torus actions, can be constructed from higher-dimensional black hole geometries. This indicates a deeper correspondence between Lorentzian and Riemannian geometries. In the future, we aim to pursue a systematic classification of Einstein metrics induced from higher-dimensional black holes and to clarify geometric transitions arising from CKY structures.

Recent breakthroughs in black hole research, including the direct detection of gravitational waves (2015) and the imaging of the black hole at the center of our galaxy (2019), have shifted our understanding of black holes from theoretical exact solutions to observable astrophysical objects. Motivated by X-ray observations of accretion disks and jets, this research project aims to construct black hole spacetimes with a perfect fluid as the background field. Specifically, we will incorporate the degrees of freedom of a perfect fluid into the CKY framework by interpreting them as torsion, and thereby reformulate the Einstein equations as harmonic map equations. This method already reproduces rigidly rotating perfect fluid configurations around black holes (the Wahlquist-type solutions) [62,68], and we will further generalize and systematize this approach.

Furthermore, the project seeks to reconstruct Wald's "fourfold" structure, a set of differential operators introduced by Wald (1978), from the viewpoint of CKY geometry in the Kerr spacetime. The fourfold structure provides a geometric explanation for the separability of the gravitational perturbation equations (Teukolsky equations) and is expected to play a key role in the analysis of gravitational waves. By integrating the CKY framework with Wald's operator formalism, this research aims to clarify the geometric foundation of black hole perturbation theory and ultimately construct unified models of black hole spacetimes that incorporate geometry, fluid dynamics, and gravitational perturbations. This will contribute to the theoretical framework necessary for the precise interpretation of forthcoming observational data.