Research Statement

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1. Research Background and Motivation

Since the groundbreaking discovery of a gravitational wave from a binary black hole in 2015 (GW150914), several hundred gravitational waves have been detected, providing an unprecedented opportunity to explore the nature of black holes. In particular, a gravitational wave signal with an highest signal-to-noise ratio of approximately 80 has recently been detected by LIGO (GW250114). Remarkably, both the fundamental mode and the first overtone have been identified in the post-merger data of this signal (Figure 1), marking the beginning of direct observational tests of black hole properties such as the no-hair theorem and Hawking's area law. These observations highlight an urgent need for theoretically rigorous tools to interpret black hole dynamics in the strong-field regime, especially concerning the universal structures hidden within black hole physics.

The gravitational waveform in the post-merger phase (**ringdown**) is well described by a superposition of **quasinormal modes (QNMs)**, which are complex eigenfrequencies of the perturbed black hole spacetime. Recent work has also highlighted the importance of related quantities such as the **excitation factors**, which determine the relative amplitudes of each mode, and the **greybody factors**, which characterize the transmission of waves through the black hole potential barrier.

Despite their importance, a comprehensive analytical framework for these quantities has been lacking. Conventional methods rely on numerics or approximate expansions, which obscure the underlying mathematical structure and make it difficult to compare different gravitational theories.

2. My Research Contributions

To address this, I have developed an analytical framework based on the **exact WKB analysis**. This method, rooted in resurgent analysis and global analysis of differential equations, allows one to describe the connection formulas between different asymptotic regions without relying on special functions.

My primary achievements include:

- Construction of a complete WKB formalism for black hole perturbation equations.
- Development of a Mathematica package to visualize and analyze the Stokes curves and turning point structure in the complexified radial plane.
- Application of this framework to compute the QNM spectrum of the Schwarzschild black hole, analytically recovering known high-overtone results.
- Identification of logarithmic spiral structures in Stokes geometry, which had not been pointed out in physics literature.

These results are compiled in my first-author paper (List of publications [P2]), which provides a rigorous and reproducible method to compute QNMs using only the differential equation and boundary conditions.