NTU OIA Fellowship Report

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I. Research Topic:
A New Perspective on Particle Creation from Analog Black Holes

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II. Motivation & Goal:

The research I conducted at the University of Chicago focuses on a fundamental question in quantum field theory and gravitation: how quantum particles are created by accelerating flying mirrors. This phenomenon—known as Hawking radiation from analog black holes—connects general relativity, quantum mechanics, and thermodynamics. Since direct observation of Hawking radiation from astrophysical black holes is practically impossible, analog systems such as accelerating mirrors in flat spacetime serve as powerful theoretical models that mimic the essential physics of horizons and allow us to explore the mechanism of particle creation in a controlled setting.

The main goal of my project was to develop a new method to compute particle creation from non-ideal mirror trajectories, where analytic solutions are not available. Traditional approaches face two major challenges: the integral defining the Bogoliubov coefficients—which quantify the amount of particle creation—is highly oscillatory and often divergent at infinity, and the mirror's motion, which determines how spacetime modes mix, can be too complex for exact evaluation. To overcome these challenges, I proposed and tested a new **Inertial Replacement Method (IRM)**, which provides both analytic insight and numerical tractability.

III. Method: Inertial Replacement Method (IRM)

The IRM divides the mirror trajectory into three regions:

1. **Region I & III:** asymptotically inertial segments (the mirror nearly moves at constant velocity).
2. **Region II:** the accelerated segment where most particle creation occurs.

By replacing the asymptotic parts of the trajectory with analytic inertial approximations and numerically integrating only over the central accelerating region, the **Inertial Replacement Method (IRM)** significantly simplifies the computation of Bogoliubov coefficients and extends the applicability of particle-creation calculations to a wider range of mirror trajectories. The method can be further validated perturbatively by expanding the full integral around the inertial limit and confirming that the higher-order corrections remain sufficiently small, ensuring both accuracy and physical consistency.

IV. Results and Validation

To test the IRM, I applied it to the Logex trajectory, a benchmark case with known analytic results, as shown in the Fig. 1.

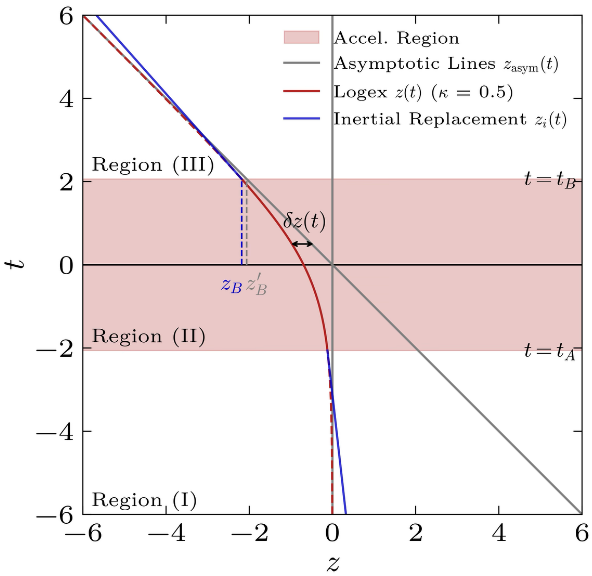

Fig. 1. Schematic diagram of the accelerating mirror trajectory divided into three IRM regions. The original trajectory is shown in the red curve. The inertial replacement and asymptotic lines are shown in the blue and gray curves, respectively. As you can see, three regions are split by the boundaries $t = t_A$ and $t = t_B$, which are implicitly determined by the parameter $a_{thres} \sim t_A, t_B$.

The calculation result of $|\beta_{\omega\omega'}|^2$ for some specific values of frequency parameters ω and ω' is shown in Fig. 2. The results show that as the parameter $1/a_{thres}$ increases, the residual difference between IRM and the exact analytic spectrum decreases rapidly. This confirms that IRM can reproduce the correct particle-creation spectrum with controllable error, and it provides a robust framework to analyze non-ideal or experimentally motivated trajectories that cannot be solved exactly.

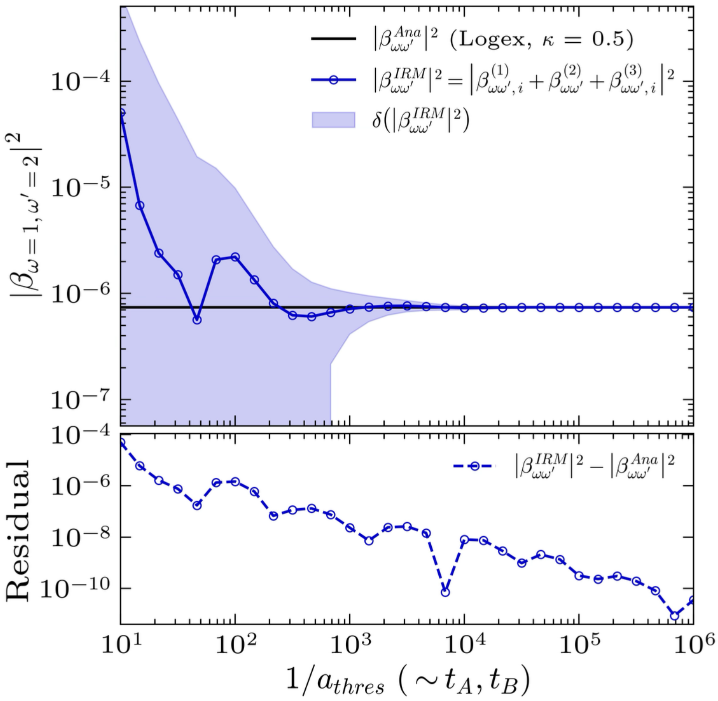

Fig. 2. Plot of IRM results and residuals vs. acceleration threshold. The IRM result shows convergence toward the analytic result, which is as expected.

V. Research Experience

Working with **Prof. Robert Wald**, one of the pioneers of the field gravity and quantum field theory in curved spacetime, I learned how to rigorously treat quantum fields from the perspective of general covariance and the algebraic formalism. Weekly discussions with Prof. Wald and Dr. Daine Danielson helped me refine both the mathematical structure and physical interpretation of my work.

The University of Chicago provided an inspiring research environment where open discussions between theorists and experimentalists are highly encouraged. I also had opportunities to attend group meetings and seminars at the **Enrico Fermi Institute and Kavli Institute for Cosmological Physics**, where I interacted with graduate students and researchers working on quantum gravity and cosmology.

Beyond research, this program allowed me to experience the collaborative spirit of an international research community and develop stronger confidence in presenting and discussing scientific ideas in English.

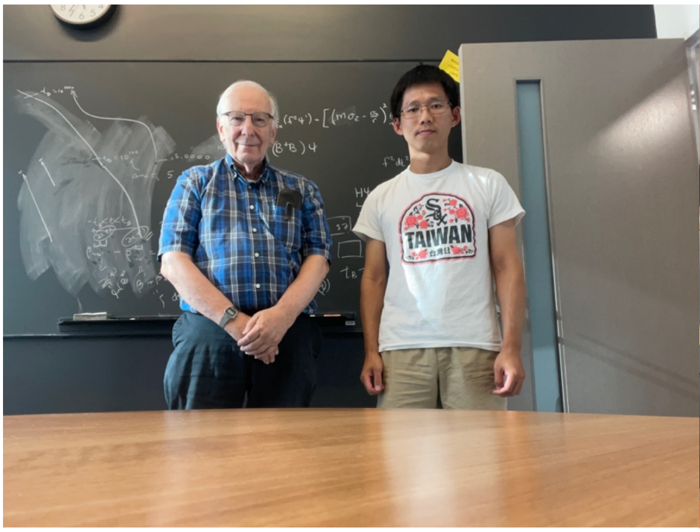

Photo 1: The photo taken after the discussion with Prof. Robert Wald.
Photo 2: The photo taken after the discussion with Dr. Daine Danielson.

Vi. Reflections

Through this exchange program, I deepened my understanding of the connection between black hole physics and quantum field theory, and I developed an independent approach to handle difficult integrals encountered in theoretical physics. More importantly, this experience strengthened my passion for pursuing a Ph.D. in theoretical physics and contributing to the ongoing effort to understand quantum aspects of gravity.