（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）

国外連携機関長期研修　報告書

氏　　名	Hyun Jeong (鄭　玄)
所属部局	理学系　　研究科　　物理学　　専攻
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Overview

From February to March 2026, I visited the Department of Physics, National Taiwan University (NTU) in Taipei, and worked under the supervision of Prof. Yu-tin Huang. Prof. Huang is one of the leading figures in the field of scattering amplitudes, known for uncovering hidden structures in the S-matrix of gauge and gravity theories and for pioneering applications of on-shell methods to black-hole physics. His textbook "Scattering Amplitudes in Gauge Theory and Gravity" (coauthored with H. Elvang) is the standard reference in the field. The purpose of my visit was to carry out, in close collaboration with him and his group, the second stage of an ongoing project on an on-shell (S-matrix) description of black-hole mergers: the computation of the higher-order correction to the gravitational waveform emitted during a merger process.

Let me briefly explain the scientific context. An analytical understanding of the merger and scattering of compact binaries is a central problem of modern gravitational physics, since it directly feeds into the interpretation of gravitational-wave observations. Working directly with the field degrees of freedom of general relativity, however, is notoriously difficult because of non-linearity and gauge redundancy. A powerful alternative is to describe the compact objects as point particles in an effective theory and to build the relevant quantities from gauge-invariant on-shell data — scattering amplitudes constrained by Poincaré symmetry, locality and unitarity — and then to extract classical observables through the Kosower–Maybee–O'Connell (KMOC) formalism. This "on-shell program" has been highly successful for two-body scattering, but it had not been extended to the merger phase until the work of Prof. Huang and his collaborators. My stay was devoted precisely to extending their leading-order analysis to higher orders in the Newtonian constant of gravitation G.

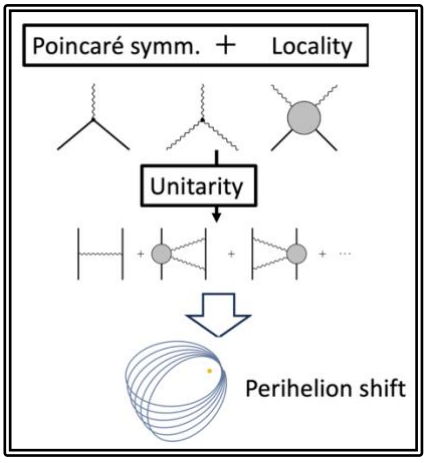


Figure 1 An example of the on-shell program. The amplitude is constructed from Poincaré symmetry, locality, and unitarity, and reproduces the perihelion precession. Solid lines represent massive scalar fields (celestial bodies), and wavy lines represent gravitons.

Research at NTU

The central task during my stay was the computation of the one-loop radiative amplitude relevant to the $O(G^2)$ correction to the low-frequency merger waveform. At first, we chose to use *FeynGrav*, a relatively new Mathematica package for perturbative quantum gravity. Applying it to our setup revealed several issues, so I devoted much of my first week to diagnosing and debugging them.

The one-loop amplitude was subsequently computed in two completely independent ways. The first is the

brute-force Feynman-diagram calculation. This is far beyond what can be done by hand, so the computation was implemented in Mathematica. The second is the on-shell approach, in which the amplitude is reconstructed from lower-point on-shell data using symmetry and unitarity, without ever referring to off-shell Feynman rules. Bringing the two methods into agreement took about one month. Every mismatch forced us to reexamine conventions, symmetry factors, contact terms, topology by topology. In the end, the two computations agreed for all topologies, which gave us a fully verified result for the one-loop amplitude. Prof. Huang's guidance here was invaluable: he gave well-targeted suggestions about which intermediate quantities to check and how to isolate the problem, and with these hints I was able to locate and fix the errors in the package.

Working with Prof. Huang and the NTU group

Beyond the main project, I had the opportunity to discuss a wide range of topics with Prof. Huang. He was at the university essentially all the time — including weekends and even during the Lunar New Year holiday — so there was never a shortage of opportunities for discussion. His comments were always fast, sharp and full of physical insight, and following his line of thought in real time was a genuinely thrilling and stimulating experience. These interactions taught me a great deal about how a leading researcher in the field actually thinks and works, something that is impossible to learn from papers alone.



Figure 2 The desk I used for two months. It is full of great memories of discussions. I was sad when I had to leave on the last day.

I was also invited to speak twice at the NTU Strings Seminar on my previous work, "Quantum Effects for Black Holes with On-Shell Amplitudes" (arXiv:2509.12111, JHEP 12 (2025) 163): a slide presentation on February 6 and a blackboard talk on March 18, 2026. In this work we describe absorption and emission by a Schwarzschild black hole, including Hawking radiation, in terms of on-shell absorptive amplitudes, and compute their effects on the observables in the scattering process. In both seminars the audience asked many sharp questions, and the discussion was lively.

The NTU theory group was also home to Prof. Hikaru Kawai, a renowned Japanese string theorist, Prof. Pei-Ming Ho, and Prof. Chia-Hsien Shen, as well as several postdocs. They gave me valuable feedback, not only on physics but also on broader questions about research and careers, and they regularly invited me to lunch and dinner. Through these conversations I was exposed to perspectives from string (field) theory and conformal field theory that go well beyond amplitudes, and by the end of the stay these interactions had led us to initiate three new research projects in addition to the main project. The group as a whole was remarkably warm and welcoming, and I felt part of it from the first week.

Daily Life

Life in Taipei was very comfortable. Although Taiwan is subtropical, February and March are mild, and the weather was pleasant for the whole stay. In front of the physics building at NTU there is the Drunken Moon Lake (醉月湖), a beautiful pond on campus. Whenever a calculation got stuck, a walk around the lake was the best way to refresh, and walking around it with Prof. Huang while discussing physics is one of the memories of the stay I treasure most.



Figure 3 Drunken Moon Lake. It is full of turtles and lovely ducks.

Outcome and Acknowledgement

After returning to Japan, we continued to meet regularly on Zoom with Prof. Huang and the other collaborators,

and the project was recently completed and posted as a paper: *"An Effective S-Matrix Approach to Low-Frequency Waveforms from Black Hole Mergers"* (arXiv:2609.10329). In this work we treat the strongly coupled merger as effective hard S-matrix data and organize its long-wavelength response using soft theorems and the KMOC formalism, obtaining the logarithmic tails, the recoil correction and the (Christodoulou) non-linear memory in the low-frequency waveform. Part of these results was also presented at the workshop "Theoretical Developments in Gravitational Wave Physics" at Kyoto University in June 2026.

I am convinced that this paper would not have taken shape without the FoPM long-term overseas training program. The stay turned a loose online collaboration into a real, daily working relationship with one of the leaders of the field, and it allowed me to acquire, within a few weeks, skills and intuition that I could not have developed on my own in Japan. More than anything, it was without doubt one of the best experiences of my life. I am deeply grateful to Prof. Yu-tin Huang, Dr. Katsuki Aoki, Profs. Hikaru Kawai, Pei-Ming Ho and Chia-Hsien Shen, the members of the NTU theory group, and the FoPM program for making this possible.