【Grant-in-Aid for Scientific Research (S)】

Pioneering High-Frequency Gravitational Wave Astronomy for Elucidating the Physics of High-Density Extreme Matter



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Project Information	Project Number : 26K21721　Project Period (FY) : 2026-2030 Keywords: gravitational wave astronomy, neutron star merger, high-density matter, KAGRA, QCD equation of state

Purpose and Background of the Research

● Outline of the Research

Matter is ultimately made of quarks. Understanding how quark-based hadronic matter behaves is a major goal of modern physics. However, its behavior at the extreme densities inside neutron stars is still unknown. The only way to probe this regime is to observe the high-frequency gravitational waves emitted when two neutron stars merge. These observations can reveal the equation of state of ultra-dense matter inside neutron stars, describing the relation between pressure, density, and temperature. To enable such measurements, upgrades for high-frequency observations are required for the Japanese gravitational-wave detector KAGRA. This project tackles the problem through an interdisciplinary approach that combines three efforts: developing technologies for upgrading KAGRA, creating numerical simulations and data-analysis methods to interpret the observations, and calculating the hadronic equation of state using quantum computers (Fig.1).

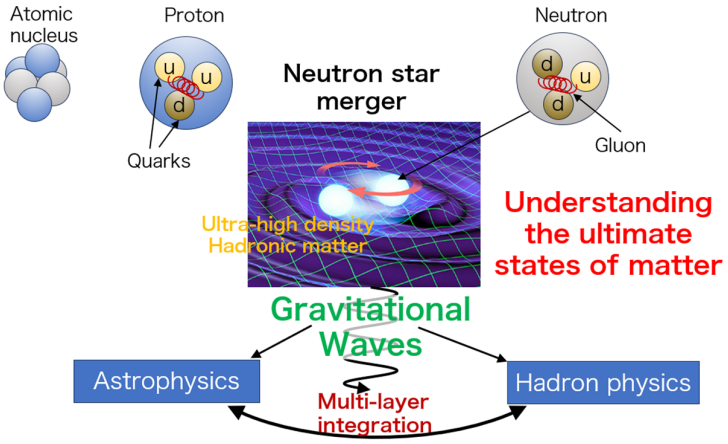


Figure 1. Overview of the research

● Background: Neutron star mergers and high-frequency gravitational waves

A neutron star is an extremely dense object about 10 km in radius, composed almost entirely of neutrons. When two neutron stars form a binary and merge, the dense remnant produced after the merger emits high-frequency gravitational waves in the kHz range, known as post-merger (PM) gravitational waves (Fig.2). The frequency and waveform of these PM gravitational waves reflect the equation of state of matter inside neutron stars. Observing them therefore provides a unique probe of the still-unknown regime of quantum chromodynamics (QCD) that governs the behavior of hadrons. However, current detectors—LIGO, Virgo, and KAGRA—have their sensitivity optimized around 100 Hz, while their sensitivity in the kHz band remains insufficient. As a result, PM gravitational waves have not yet been detected.

● High-frequency upgrade of KAGRA

We will implement three upgrades to KAGRA—increasing the laser power, injecting a squeezed vacuum, and optimizing the signal recycling mirror—to realize a high-frequency–focused configuration called KAGRA-HF. Improving sensitivity at high frequencies requires increasing the laser power by more than a factor of four. In room-temperature interferometers, however, thermal deformation of the mirrors becomes a serious problem, making such power increases difficult. KAGRA, in contrast, uses cryogenic sapphire mirrors with extremely high thermal conductivity, so thermal deformation is negligibly small. For this reason, KAGRA is particularly well suited for high-frequency optimization compared with room-temperature detectors such as LIGO and Virgo (Fig.3). This will allow KAGRA to play a unique role within the global gravitational-wave detector network.

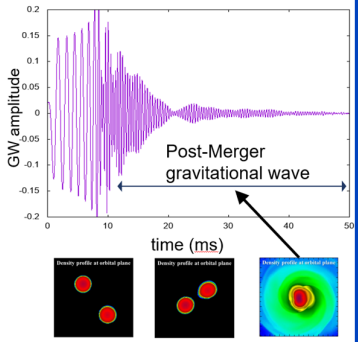


Figure 2. Gravitational wave from the merger of neutron stars

Expected Research Achievements

● Expected Research Achievements

This project aims to achieve the following outcomes over five years (FY2026–2030). (1) Development and demonstration of a 300 W high-power laser, low-absorption sapphire mirrors, and a squeezing system achieving 10 dB at 1 kHz. (2) High-precision calculations of PM gravitational-wave waveforms using numerical models including magnetohydrodynamics and neutrino transport, and development of data-analysis methods to extract these signals from noise. (3) First-principles derivation of the equation of state required for waveform simulations using quantum–classical hybrid QCD calculations that combine the Fugaku supercomputer with quantum computers. Achieving these goals by the end of FY2029 will complete preparations for the KAGRA-HF upgrade of KAGRA. Detecting high-frequency gravitational waves from the post-merger phase of binary neutron star mergers would allow direct tests of the quark–hadron crossover predicted by modern hadron physics and open a path toward resolving the unknown region of the QCD phase diagram (Fig.4).

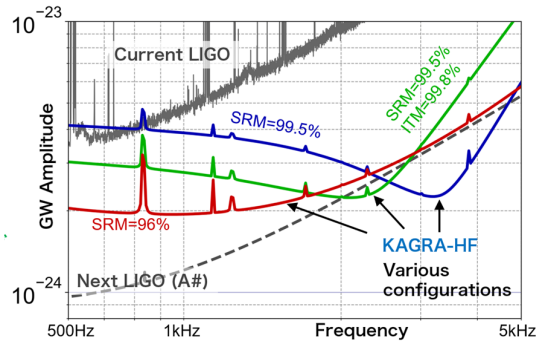


Figure 3. Expected sensitivities of KAGRA-HF
This figure shows the gravitational-wave amplitude detectable at each frequency; lower values indicate higher sensitivity. Above 2 kHz, KAGRA-HF can surpass the sensitivity of LIGO.

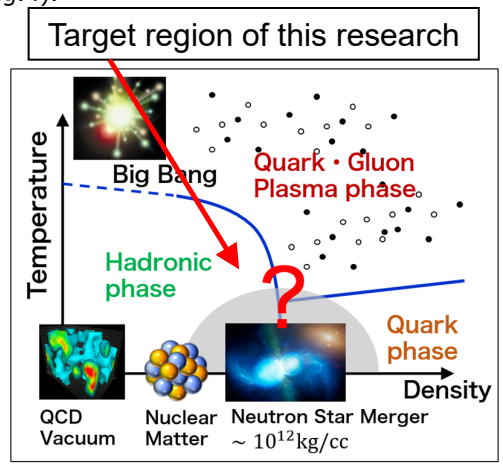


Figure 4. QCD phase-diagram

Website(s)	https://gwcenter.icrr.u-tokyo.ac.jp/