ASPIRE KAGRA-OzGrav Collaboration

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1. Overview of the collaboration

Since the historic first observation by LIGO in 2015, 91 cases of gravitational wave events have been observed. These events capture the motion of binary systems involving black holes or neutron stars, but unknown physics is embedded in the waveform after the merger. In the case of neutron star binaries, the internal structure of neutron stars is not well understood, leading to significant differences in the waveform before and after the merger based on different models. To obtain detailed information, a strain sensitivity of 10^{-24} (1/rtHz) at 3-4 kHz is predicted to be necessary, a sensitivity currently unattainable with existing telescopes.

Considering the above circumstances, a development plan for a new telescope specialized in high frequencies is being considered in Australia. The Neutron star Extreme Matter Observatory (NEMO) is a new telescope with a baseline length of 4 km. It employs a different approach from current telescopes by cooling silicon mirrors to 120K and introducing a so-called long SRC (signal recycling interferometer) technique. In Japan, there is ongoing discussion about the future "KAGRA+" project, with a proposed upgrade using the long SRC technique. KAGRA's sapphire mirrors are cooled to 20K, and the logic of observing high-frequency gravitational waves by cooling the mirrors is similar to NEMO's. Detection itself can be delegated to the broadband detectors, and the role of the high-frequency telescope is to observe the moment of merger seconds after the detection of orbital motion.

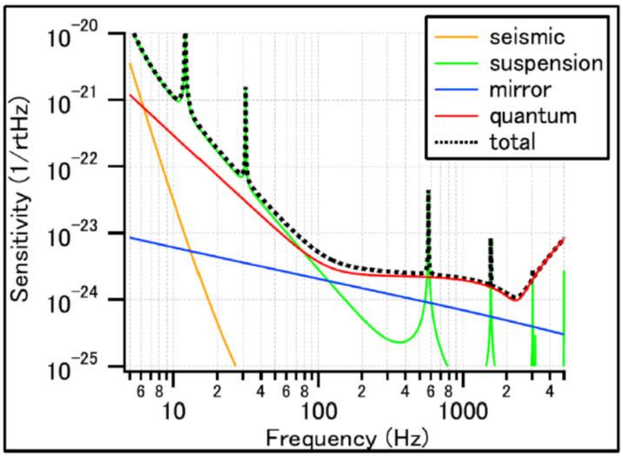


Fig.1: Calculated sensitivity of KAGRA+ (HF) with the long SRC technique.

The limiting factor for sensitivity in the high-frequency band is shot noise. Shot noise is white noise, and since gravitational wave signals decay outside the resonator linewidth, high-frequency sensitivity worsens proportionally to frequency. The linewidth is defined by a compound cavity of the arm and the recycling cavities. With the long signal recycling cavity, the double pole structure improves sensitivity to the 3-4 kHz range relevant to observing neutron star binary mergers (Fig.1). Introducing a squeeze field causes the phase to rotate with the gravitational wave signal, reducing quantum noise over a wide bandwidth. Methods such as stiffening the optical spring with a quantum filter, expanding the linewidth with a quantum filter (white-light cavity), and combining the long SRC with a quantum filter (quantum expander) can further improve sensitivity. Long SRC is under development experimentation by JAXA and ANU, and expansion to a quantum expander is also being considered. The method of stiffening the optical spring is being developed by Tokyo Tech and UWA.

2. Research Contents

<Research Theme 1: Comparative Study of NEMO and KAGRA+>

Research Items:

- Comparison of silicon and sapphire mirrors
- Consideration of crystalline vs. amorphous coatings
- Selection of Laser wavelength
- Selection of quantum technologies to implement
- Improvement of KAGRA's sensitivity
- Development of data analysis techniques using machine learning

Research Overview:

The goal of NEMO project is to construct a new interferometric telescope with a baseline length of 4 km in Australia, achieving a sensitivity of 10^{-24} (1/rtHz) at 3-4 kHz and observing signals after the merger of neutron star binaries. In the current design, silicon crystals are used for the mirror substrate, cooled to 120K through thermal radiation. With the thermal expansion coefficient of silicon becoming zero at 120K, operating under these conditions makes thermoelastic noise negligible. The telescope utilizes a laser with a wavelength of 1.5um or 2um since the 1um wavelength, commonly used in existing telescopes, does not transmit through silicon. While stability with high power has been achieved with the former, the latter requires substantial R&D. Longer wavelengths, however, result in lower scattering losses within the optical resonator, enabling higher intracavity light power for the same incident light power.

KAGRA+, an upgrade plan for KAGRA constructed in Japan, focuses on enhancing sensitivity in the high-frequency range among several proposed plans. As indicated in

Fig.1, achieving a sensitivity of 10^{-24} (1/rtHz) around 3 kHz is possible, albeit with a slightly narrower bandwidth compared to NEMO. In the current plan, sapphire crystals are used as the mirror substrate, and cooling is achieved through thermal conduction via sapphire fibers. While KAGRA's design temperature is around 20-23K, KAGRA+ raises the temperature to about 40K to increase the intracavity light power. The optical source wavelength remains at 1um.

Thus, NEMO and KAGRA+ have different fundamental designs for the interferometer. While NEMO exhibits superior final sensitivity, the need for new construction makes its cost higher. By exchanging knowledge between the two and conducting a more detailed comparative study, along with advancing quantum technology development, the decision of adopting NEMO or KAGRA+ will be considered.

This theme also includes the development of KAGRA's commissioning and data analysis techniques using machine learning. To secure a large budget for KAGRA+, it is essential to first enhance the sensitivity of KAGRA and observe gravitational waves. Young Australian researchers will be invited to participate in the interferometer commissioning in Kamioka. Regarding data analysis techniques, machine learning is considered effective in reconstructing post-merger waveforms from signals observed by NEMO or KAGRA+ and distinguishing burst-like gravitational waves from supernova explosions and interferometer non-stationary noise. The goal is to develop new analytical methods for observing high-frequency gravitational waves.

<Research Theme 2: High-Power Cryogenic Interferometer>

<2-1. 120K Silicon Interferometer>

Research Topics:

- Radiative cooling and temperature control
- Construction of optical systems using 1.5um or 2um lasers
- Reduction of thermoelastic noise

Research Overview:

Prototype experiments for NEMO, incorporating silicon mirrors, have commenced at UWA's 80m interferometer. The interferometer structure consists of a composite resonator with three mirrors. In the first stage, a short resonator uses silica mirrors, followed by a long resonator using silicon low-temperature mirrors in the second stage. The third stage combines both to achieve high output. By controlling silicon to a temperature of 120K through radiative cooling, thermoelastic noise is reduced. The laser wavelength will be 1.5um or 2um. The experience gained from KAGRA for interferometer operation in cryogenic temperature will be useful. With a target temperature of 120K, issues like wire expansion and frost are less likely, but technical contributions, such as vibration isolation for cryocoolers, remain significant.

<2-2. 2um Laser>

Research Topics:

- Development of 2um laser light sources
- Development of 2um laser amplifiers
- Stabilization of 2um lasers

Research Overview:

NEMO plans to use a 2um laser as a light source. While a 1.5um fiber laser source is plausible, 2um is favored for its lower scattering on mirror surfaces, enabling higher accumulated light levels within the arms. Since there is limited experience with 2um laser sources, stability records are scarce, and various optical components such as photodetectors, sensor cards, image devices, isolators, and modulators need development. The University of Adelaide is developing a 2um light source and amplifier.

<2-3. Crystal Mirror Characterization>

Research Topics:

- Measurement of non-uniform birefringence in crystal mirrors and coatings
- Measurement of non-uniform thermal absorption in crystal mirrors and coatings
- Measurement of scattering characteristics in crystal mirrors and coatings
- Development of better crystal mirrors

Research Overview:

To reduce thermal noise by cooling mirrors, high thermal conductivity materials like sapphire or silicon crystals are required. Crystal mirrors pose challenges like non-uniform birefringence, and our research uses devices like the Fizeau interferometer and Photo-thermal Common-path Interferometer for measurements. Understanding the distribution of non-uniform birefringence and thermal absorption aids in investigating their impact on interferometers. Collaborating with national astronomical observatories and ANU, we plan to evaluate various mirrors using developing measurement devices.

<2-4. Development of New Alignment Sensing and Control>

Research Topics:

- Development of phase cameras

- Interferometer control with machine learning
- Demonstration of new control scheme through prototype experiments

Research Overview:

Due to non-uniform birefringence in KAGRA's sapphire mirrors, conventional control signals exhibit offsets dependent on the beam spot position, hindering stable control. A similar phenomenon occurs in LIGO. Promising new technologies involve alignment control using image recognition and machine learning. Our research explores various image recognition methods, including a phase camera utilizing an optical speed beam shutter developed at the University of Adelaide and a method employing a 64 photodetector array developed at Tokyo Tech. Both methods will be compared for their advantages, and alignment control using machine learning and linear control optimized by least squares will be developed. The effectiveness of these methods will be verified through prototype experiments at Tokyo Tech.

<2-5. Thermal Compensation>

Research Topics:

- Thermal lens measurement system
- Thermal compensation demonstration experiments

Research Overview:

As of 2023, LIGO's intracavity light power exceeds 300kW, and the thermal lens effect becomes significant. When mechanical resonant modes of mirrors overlap with spatial modes of the optical resonator, the fundamental mode light inside the arms scatters into higher-order modes, amplifying and destabilizing the system. This parametric instability, associated with the thermal lens effect, causes problems on a long timescale, a few minutes after the start of operation. While LIGO has control systems like thermal compensation, the testing process for stabilization takes a long time, depriving interferometer commissioning time. Therefore, the University of Adelaide has constructed a large prototype experimental apparatus equipped with the thermal lens and thermal compensation systems. Although NEMO and KAGRA+ use high thermal conductivity crystal mirrors, making the thermal lens effect low, as they strive for higher output, the thermal lens effect may become significant. This experiment is crucial for the development of high-frequency telescopes.

<2-6. Single photon detection>

Research Topics:

- Single-photon detector

- Multiple OMCs
- Demonstration of shot-noise reduction

Research Overview:

Conventional detection scheme is based on linear amplification of electric field and the sensitivity is limited by the vacuum fluctuation of the electric field. In contrast, single-photon detection, proposed for the dark matter search, directly measures the number of signal photons and the sensitivity is not limited by the vacuum fluctuation. The signal-to-noise ratio with the single-photon detector exceeds the linear amplifier if the number of photon per unit time is less than unity. Thus the new method is useful for a gravitational-wave detection at high frequencies. A question is if we can reduce the number of light at the detector. A series of narrow bandwidth output mode-cleaner would be necessary.

<Research Theme 3: Quantum Control for Quantum Noise Reduction>

<3-1. Intracavity Quantum Filters>

Research Topics:

- Long SRC technique
- Parametric signal amplification technology
- Signal amplification by optical Kerr effect
- Quantum expander
- White light cavity (PT symmetry)

Research Overview:

Gravitational wave telescopes compose Michelson interferometers operated at the dark fringe. Gravitational waves cause differential optical path length changes in both arms of the interferometer, leading to a leakage of signal light at the dark port. Each arm has an optical resonator, and a signal-recycling cavity is composed at the dark port. By introducing a quantum filter into the signal-recycling cavity, active signal amplification is possible, raising the optical spring frequency. Simply increasing the optical path length of the signal-recycling cavity can rotate the phase of the signal light, improving the shot noise level in a narrow band. Similar technologies, such as quantum expander and white resonator technologies, are proposed. This study aims to demonstrate these technologies in prototype experiments and discuss their effectiveness for high-frequency telescopes. Techniques utilizing optical parametric amplification have been developed by Tokyo Institute of Technology and the University of Western Australia (UWA), and knowledge sharing will occur. Considering the nonlinear optical effects like the optical Kerr effect and photothermal effect is essential due to concerns about their impact on arm cavities and the main interferometer beam splitter with increased power.

<3-2. Quantum Teleportation>

Research Topics:

- EPR entanglement-type frequency-dependent squeezing
- Frequency-dependent squeezing using quantum teleportation

Research Overview:

Quantum noise in gravitational wave telescopes consists of two types: shot noise caused by fluctuations in the arrangement of photons and radiation pressure noise caused by fluctuations in the number of photons. Introducing optical squeezing technology can reduce one type of noise while increasing the other. By introducing frequency-dependent squeezing using quantum teleportation, it is possible to perform squeezing in the phase direction for dominating scattering noise at high frequencies and squeezing in the amplitude direction for dominating radiation pressure noise at low frequencies. This requires long-filter resonators. While LIGO and Virgo use 300m filter resonators, third-generation telescopes require longer resonators, posing a cost challenge. Moreover, in interferometers using optical springs, squeezing rotates around the optical spring frequency, requiring two filter cavities, presenting a more serious challenge. A proposed method called EPR entanglement is introduced to achieve frequency-dependent squeezing without filter cavities. This method involves preparing entangled Alice and Bob with a multi-mode OPA. Bob, like regular vacuum fields, is incident on the gravitational wave telescope and detected together with the gravitational wave signal. Alice has a different frequency field than Bob, and for Alice, the telescope's optical cavity is detuned. The incident light is filtered and emitted. Further, a third field, the squeeze field for Victor, is prepared. Victor, with a different frequency than Alice and Bob, has the telescope's optical cavity detuned at a different angle than Alice. The frequency-filtered Alice and Victor undergo a Bell measurement, and the frequency difference is decoded to obtain I-phase and Q-phase signals. Bob becomes the gravitational wave signal and the frequency-filtered squeeze field by adding and subtracting each signal accordingly.

<Research Theme 4: Quantum Sensor>

<4-1. Low-Frequency Sensors and Control>

Research Topics:

- Development of a torsion pendulum-type gravity gradient detection device
- Development of adaptive control using machine learning

Research Overview:

Ground vibrations and particle vibrations in the atmosphere change the gravity gradient, and this effect becomes significant in the low-frequency range. Not only steady-state noise but also non-steady-state gravity gradient noise could hinder gravitational wave observations. Therefore, developing low-frequency sensors with quantum-level sensitivity and conducting observations and analysis of non-steady-state gravity gradient noise are crucial. Although related to Research Theme 2-4, the development of low-frequency sensors is also effective for verifying macroscopic quantum mechanics. Since effects such as gravity decoherence are expected to be observed at low frequencies, this research is also related to the development of high-frequency gravitational wave telescopes using optical springs. In this theme, not only sensor development but also the development of adaptive control using machine learning is conducted. By combining information from auxiliary detection systems such as the torsion pendulum sensor and implementing feedforward control to the seismic isolation system using a Wiener filter, vibrations of the test mass can be reduced.

<4-2. Levitation System for Macroscopic Quantum Mechanics>

Research Topics

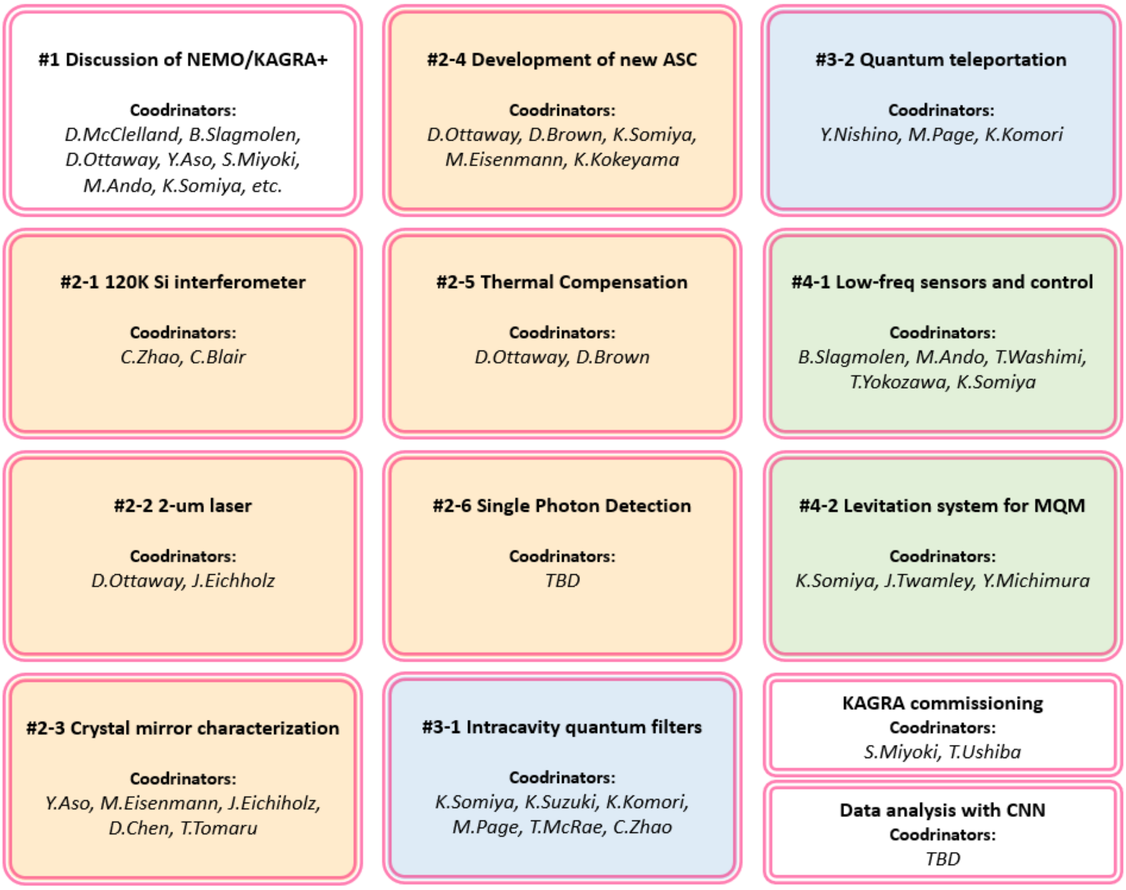
- Diamagnetic levitation system using graphite
- Diamagnetic levitation system using fused silica
- Development of optical levitation system

Research Overview:

Microscopic objects maintain quantum properties, while macroscopic objects behave classically. To answer questions about where the boundary between them lies and how quantum mechanics is described in macroscopic systems, observations of quantum behavior at various mass scales are necessary. One potential criterion for the boundary between micro and macro is the Planck mass (=22 μg). Vibrators with masses on the order of sub-milligrams have large thermal fluctuations, and measuring with sensitivity below the quantum limit is challenging. Below a mass of ~1g, it is difficult to fabricate a pendulum with high dilution effects. Therefore, we aim to perform quantum measurements in the mesoscopic region by levitating the test mass using diamagnetic or radiation pressure to achieve zero thermal vibration from the support system, leading to reduced thermal noise. The first approach to diamagnetic levitation uses graphite with a high magnetic susceptibility. Graphite has a low electrical resistivity, leading to heat dissipation through eddy currents caused by magnetic field inhomogeneity. To reduce this effect, it is necessary to reduce the inhomogeneity of the magnet or finely divide the graphite to decrease the size of the eddy currents. Tokyo Tech is conducting experiments to reduce the impact of magnet inhomogeneity by making the magnet and graphite ring-shaped. OIST is conducting experiments to reduce eddy currents by coating graphite particles with silica. The second approach to diamagnetic levitation is to levitate silica that has high electric resistivity. Since silica has a low magnetic susceptibility, efforts such as increasing the magnetic field gradient are needed. Tokyo Tech has succeeded in diamagnetic levitation of a 2 mg silica mirror.

Another method is to levitate a mirror using the radiation pressure of a laser. With certain radii of curvature of the mirrors located at the top and bottom of the vertical cavity, stability in the vertical and horizontal directions is ensured. Although it is technically challenging to curve a tiny mirror for levitation, the University of Tokyo has succeeded in curving it using the pressure during coating deposition.

3. Research Team



#1 Discussion of NEMO/KAGRA+
Coodrinators:
D.McClelland, B.Slagmolen, D.Ottaway, Y.Aso, S.Miyoki, M.Ando, K.Somiya, etc.

#2-4 Development of new ASC
Coodrinators:
D.Ottaway, D.Brown, K.Somiya, M.Eisenmann, K.Kokeyama

#3-2 Quantum teleportation
Coodrinators:
Y.Nishino, M.Page, K.Komori

#2-1 120K Si interferometer
Coodrinators:
C.Zhao, C.Blair

#2-5 Thermal Compensation
Coodrinators:
D.Ottaway, D.Brown

#4-1 Low-freq sensors and control
Coodrinators:
B.Slagmolen, M.Ando, T.Washimi, T.Yokozawa, K.Somiya

#2-2 2-um laser
Coodrinators:
D.Ottaway, J.Eichholz

#2-6 Single Photon Detection
Coodrinators:
TBD

#4-2 Levitation system for MQM
Coodrinators:
K.Somiya, J.Twamley, Y.Michimura

#2-3 Crystal mirror characterization
Coodrinators:
Y.Aso, M.Eisenmann, J.Eichiholz, D.Chen, T.Tomaru

#3-1 Intracavity quantum filters
Coodrinators:
K.Somiya, K.Suzuki, K.Komori, M.Page, T.McRae, C.Zhao

KAGRA commissioning
Coodrinators:
S.Miyoki, T.Ushiba

Data analysis with CNN
Coodrinators:
TBD

Fig.2: Research themes and coordinators.

Figure 2 shows the 13 research subjects and their coordinators. Coordinators will set up the collaborative research upon a request from a collaboration team member.

**This is English translation of (a part of) the application form performed by ChatGPT.*