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KAGRA and Genesis of Gravitational Wave Physics and Astronomy

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The recent detection of gravitational waves, with six events reported by LIGO/Virgo so far, has made significant impact on astronomy and physics. A global network of gravitational-wave observatories is a key to solving the unknown nature of sources. In addition to the existing LIGO-Virgo network, more observatories on Earth will make it possible to locate a gravitational-wave source more accurately and to determine the source parameters with higher precision. Here we introduce KAGRA, a new observatory joining the gravitational-wave search. KAGRA is a *cryogenic* ground-based laser interferometer with 3-km arms located in Kamioka, Japan. The installation and commissioning of KAGRA are on-going and its cryogenic systems have been successfully tested in May, 2018. KAGRA's first observation run is scheduled in late 2019, aiming to join the third observation run (O3) of the LIGO/Virgo network. In addition to KAGRA science, we also describe efforts of gravitational-wave community in Japan: Collaborations for electromagnetic follow-up observations (J-GEM, MAXI, CALET) and the JSPS grant supporting research on the innovative area with the title, "Gravitational wave physics and astronomy: Genesis".

Seeing is believing. We are reminded of this proverb when we received the news of the first direct detection of gravitational waves (GWs), GW150914 [1]. Researchers have believed in the existence of GWs, since Russel Hulse and Joseph Taylor discovered the binary pulsar PSR B1913+16 in 1974 [2], and the long-term observation of this system showed that the observed orbital decay matches the theoretical emission of GWs as predicted by Einstein [3]. However, the direct detection of GW had an extraordinary impact not only to the researchers but also to the general public.

The first five events reported by Advanced LIGO observatories were identified to be binary black holes (BHs). The existence of binary BHs themselves is one of the scientific achievements of the GW detections. The BH masses estimated from GW observations range from $20 \sim 60\ M_\odot$, which is a mass range in which BHs had not been ever observed, and it is possible to constrain a scenario of the evolution of binary BHs by observations. The latest event GW170817 [4], on the other hand, was from the merger of a neutron star (NS) binary, which was one of the prime targets for ground-based detectors and was thought to be a guaranteed source as their existence (in our galaxy) has already been confirmed by radio observations. The location of the source was narrowed down to 30 deg^2 by the LIGO-Virgo network, allowed astronomers to identify an electromagnetic counterpart. NS-NS mergers emit electromagnetic (EM) waves as well as GWs via various nuclear or matter interactions. These EM waves are observable in a broad band from radio to γ-rays by observatories in and around the Earth. The so-called "multi-messenger astronomy" era was suddenly started with this single event.

LIGO consists of two 4-km laser interferometers in Livingston, Louisiana and Hanford, Washington in the USA. Virgo is a 3-km interferometer located in Pisa, Italy. Coincident signal-extraction analyses of these three detectors can eliminate false detections due to noise, and by using triangulation, the source location in the sky can be determined within several tens of square degrees. For a more precise source localization and binary parameter estimation, it is essential to extend the global network of GW observatories, with KAGRA being the next to come online.

KAGRA is a 3-km laser interferometer located in Kamioka, Gifu, Japan, which shares the area with the neutrino detectors, Super-Kamiokande and KamLAND. Kamioka is a small town, with its biggest claim to fame being an old mine located at 1.5 hour driving distance from the city of Toyama.

Comparing to existing laser interferometers, KAGRA is technologically unique in two features. It is located in an *underground* site in order to reduce the seismic noise. In addition, KAGRA's test masses are sapphire mirrors that are designed to be operated at cryogenic temperatures ($\sim$20 K) in order to reduce thermal noise. KAGRA is a resonant sideband extraction (RSE) interferometer, and quantum non-demolition techniques are planned to be applied to beat the standard quantum limit of displacement measurements. As a result, KAGRA is expected to reach an equivalent sensitivity to those of LIGO and Virgo.

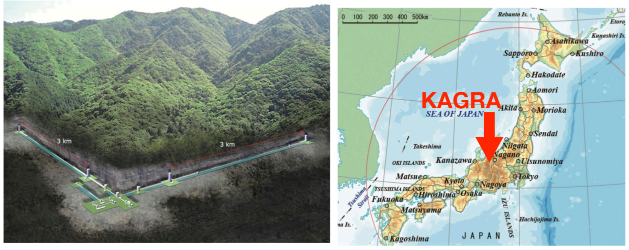

Figure 1: (Left) Concept image of KAGRA: a 3-km cryogenic interferometer inside of the Kamioka mountain. (Right) KAGRA is located in Kamioka, Gifu, Japan.

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Milestones of KAGRA construction and operations

In Japan, plans to construct interferometric GW detectors started in the 1980s. In the early 90s, Institute of Space and Astronautical Science (ISAS) and National Astronomical Observatory of Japan (NAOJ) constructed a 100-m delay-line Michelson interferometer (TENKO-100) and a 20-m Fabry-Perot Michelson interferometer, respectively. The former realized 102-times-long light paths of the arm length (the equivalent of a 10.2-km arm length) and reached a sensitivity of $1.1 \times 10^{-19}/\sqrt{\mathrm{Hz}}$ in the frequency range of 800 Hz – 2.5 kHz.

In 1995, the construction of a 300-m Fabry-Perot Michelson interferometer (TAMA) at NAOJ, Tokyo was started in Japan. (TAMA is the name of the area where NAOJ is located in.) TAMA was first locked in 1998 and its sensitivity ($5 \times 10^{-21}/\sqrt{\mathrm{Hz}}$) went beyond that of LIGO 40-m prototype in 2000. In 2001, TAMA was successfully operated for more than 1000 hours and in 2002, it also took part in a joint operation with the initial LIGO's 2nd science run (S2) for two months. TAMA was planned as a prototype in order to develop future technologies for a km-scale interferometer such as a power-recycling system, seismic attenuation system (SAS), etc. TAMA's final (and best) sensitivity of $1.3 \times 10^{-21}/\sqrt{\mathrm{Hz}}$ was obtained at around 1 kHz.

Since TAMA was located in Mitaka, which is a suburban area of Tokyo, seismic noise in the frequency band below 100 Hz were inevitable due to human activities in this mega city. In order to overcome the large seismic noise, it was decided to put an interferometer underground, and began experiments in an old mine in a mountain in Kamioka. The LISM (Laser Interferometer Small Observatory in a Mine) project (2000–2002) brought a 20-m Fabry-Perot interferometer in NAOJ to Kamioka and confirmed that the Kamioka site is quieter than the Tokyo/Mitaka area. LISM and TAMA groups performed a simultaneous observation and the first veto analysis.

The Cryogenic Laser Interferometer Observatory (CLIO) [8] was constructed next in Kamioka. CLIO was an interferometer with two perpendicular 100-m arms, and sapphire mirrors were installed and cooled down to 20 K. This system reduced various thermal noises and the seismic noise was two orders of magnitude lower than that of the Tokyo area.

Although various experiments showcased the advantages of the project and the plausibility of fundamental technologies, the proposal for developing a km-scale cryogenic GW detector, LCGT (Large Scale Cryogenic Gravitational Wave Telescope) was in limbo for many years until it was finally awarded a budget by the government. That was because there was no GW detection reported in 2000s. Without a detection, LCGT was considered to be too expensive and too risky. After Takaaki Kajita, who later received a Novel prize in physics (2015) for his contributions in discovering neutrino oscillations, became the director of the institute for cosmic ray research (ICRR, Univ. of Tokyo) in 2008, he decided to lead the GW project himself. The LCGT project was finally approved in 2010, and the excavation of the tunnels in Kamioka was started in 2012, after an one-year delay due to the 2011 Tohoku Earthquake.

During the construction, LCGT was given its nickname, KAGRA, chosen from a public naming contest. The name KAGRA is taken from KAmioka (the location) plus GRAvity; *kagra* is also the Japanese word for a type of traditional sacred dance accompanied by music in front of gods.

After a two-year excavation and another two-year facility installation period, KAGRA performed a test operation in March and April 2016 with a simple 3-km Michelson interferometer configuration, called *iKAGRA* (initial KAGRA) [9]. The strain sensitivity of iKAGRA was limited by seismic noise below 3 Hz, by acoustic noise over 100 Hz to 3 kHz, and by sensor noise at 3–5 kHz. Unfortunately, a series of large earthquakes hit the Kumamoto area in the period of iKAGRA operations. Such noise sources were not avoidable with the iKAGRA configuration, but iKAGRA still provided the collaboration with invaluable experiences in controlling the km-scale laser interferometer with unprecedented sensitivity.

Current status of KAGRA

Right after the iKAGRA operation, the KAGRA collaboration worked hard for two more years to upgrade the whole system: installing cryogenic facilities, upgrading vibration-isolation systems, high vacuum systems (the world's third largest vacuum system), and adopting better whitening filters. This period is called the *phase-1* of *bKAGRA* (baseline KAGRA). After the major upgrades, KAGRA now has the world's tallest vibration isolation systems (13.5 m) which help to reduce seismic noise at low frequencies. Two 23-kg sapphire mirrors have been installed at both ends, and one of them was kept at 18 K for 30 days continuously. Due to a leakage of the vacuum that was found in April 2018, the experimental operation was delayed for 5 days, but the phase-1 operation was successfully undertaken for 9 days from April 28 to May 6, 2018.

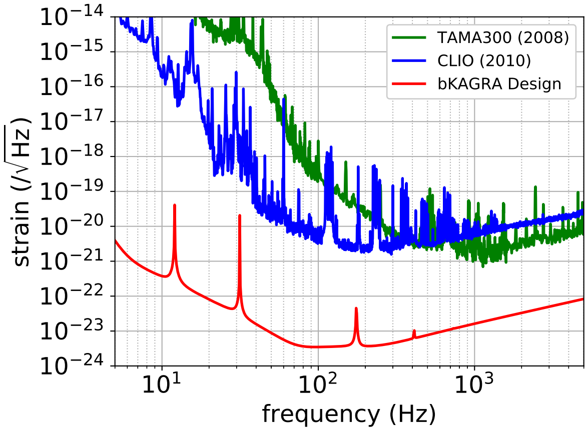

Figure 2: Comparison of sensitivity curves obtained from TAMA300, CLIO, and the bKAGRA design sensitivity.

The duty cycle of the first 5 days of the phase-1 operation reached 88.6% between April 28 and May 2, while the duty cycle on May 3 & 4 dropped to 26.8%, and slightly improved to 59.8% on the final days (May 5 & 6). The low duty cycle on May 3 and afterwards were mainly attributed to the micro-seismic noise caused by a heavy storm, local earthquakes, and volcano eruptions on Hawaii. The obtained sensitivity during phase-1 was worse than the final sensitivities of TAMA and CLIO, but KAGRA's sensitivity was better than TAMA in lower frequencies. (We show the designed sensitivity of bKAGRA in Fig.2. The results of the phase-1 operation will be reported elsewhere [10]). From May 7 2018, KAGRA collaboration announced the beginning of *phase-2* and has been working on the installations/upgrades of more instruments, such as additional optics and a new laser source.

Since the beginning of the iKAGRA commissioning, one of the important goals of KAGRA is to contribute to the international efforts in GW detection. As shown by the LIGO-Virgo joint observation of GW170814 and GW170817, the multiple coincident detections are important. With this fact in mind, there have been calls from both in and out of the collaboration to take part in the joint observations. In order to take the advantage of a quadrupole detector network around the Earth for GW search, KAGRA collaboration has been putting in great efforts to accelerate its schedule. If all goes well, KAGRA will join the LIGO/Virgo's 3rd observation run (O3), which is planned to start from February 2019 and lasts for a year.

The latest road map is shown in Fig.3. By March 2019, almost all the optics for the final interferometer configuration are to be installed. After some tuning of the interferometer, KAGRA plans to begin its observation phase no later than October 2019.

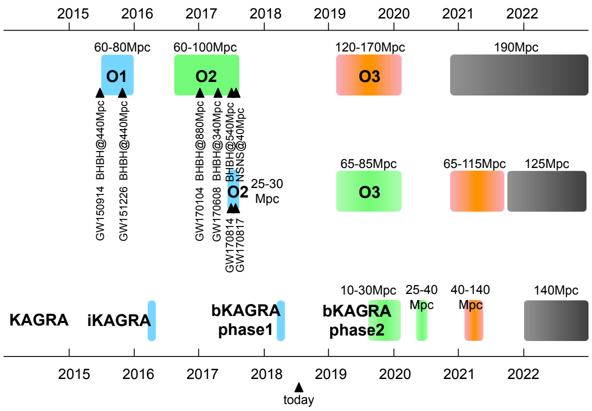

Figure 3: Observation plans of LIGO, Virgo, and KAGRA. An update of Fig.2 in [5].

KAGRA's future

The LIGO and Virgo collaboration has plans to upgrade their detectors to A+ and AdV+ to improve the sensitivity by a factor of roughly 2 compared with original Advanced LIGO and Advanced Virgo design. Both A+ and AdV+ detectors incorporate frequency dependent squeezing to reduce quantum noise, and lower loss coating to reduce coating thermal noise.

Similarly, we have recently started the planning for an upgrade of KAGRA. KAGRA has an unique potential to improve the sensitivity because of its cryogenic operation and lower seismic noise compared with LIGO and Virgo. The completion of A+ and AdV+ upgrades is expected in $\sim$ 2023, and we are considering a similar timeline for KAGRA.

Cryogenic operation and underground construction are expected to be key technologies of next generation detectors, such as Einstein Telescope [11] and Cosmic Explorer [12]. There are fully collaborative R&D activities between KAGRA and the next generation projects, as represented by the ELiTES (ET-LCGT Telescopes: Exchange of Scientists) project in 2012-2017.

KAGRA international collaboration

KAGRA group is by all means international. As of May, 2018, KAGRA collaboration consists of 370 researchers from 90 institutions in 15 countries. KAGRA collaboration has a decision making body in science, named KAGRA Scientific Congress (KSC). KSC organizes the KAGRA international workshops outside of Japan three times every year and interact with a broader scientific community. KSC is also setting the organization for future joint observations. Including the ELiTES project in 2012-2017, KAGRA collaboration has been trying to expand international collaboration. For example, the "core-to-core (C2C)" program funded by JSPS is dedicated to human resource exchanges and organizing academic meetings relevant to KAGRA and GW science. In addition to local computing centers in Kamioka observatory, ICRR, and Osaka City Univ., etc., KAGRA collaboration runs two mirror sites for data storage in Korea (KISTI) and in Taiwan (Academia Sinica). KISTI and Academia Sinica also provide computing resources for data analysis.

Supporting theorists and astronomers

Most of the competitive research funding in Japan are provided by JSPS (Japan Society for the Promotion of Science, or Gakushin for short in Japanese), which is an independent administrative institution of the Japanese government. Among the JSPS Grants-in-Aid programs for scientific research (Kakenhi for short), one of the biggest programs is the "Scientific Research on Innovative Areas" (Shin-Gakujutsu for short), which is aimed at pioneering new scientific frontiers by combining groups of researchers. This funding program started in 2008, and every year up to 10 new proposals are selected in science and technology. The GW-research community in Japan has been supported by this grant since 2011.

In the period of FY2012–2016 (2012 Apr – 2017 Mar), the program "New development in astrophysics through multi-messenger observations of gravitational wave sources" (PI: Takashi Nakamura, Kyoto University) was selected[13], with a total budget 798.5 M JPY (7.25M US$). The grant helped to create a GW follow-up observation network, called J-GEM (Japanese Collaboration for Gravitational-Wave Electro-Magnetic Follow-up Observation). J-GEM consists of more than 10 telescopes, not only in Japan but also in Chile, South Africa, and New Zealand. J-GEM and Japanese X-ray and γ-ray telescopes, MAXI (Monitor of All-sky X-ray Image) and CALET (CALorimetric Electron Telescope), both of which are in the International Space Station, established a Memorandum of Understanding (MOU) with LIGO in order to provide data analysis and results mutually. These collaboration worked effectively in responding to detection alerts from LIGO/Virgo.

Successively, from FY2017 (2017 Apr – 2022 Mar), the next program, "Gravitational wave physics and astronomy: Genesis" (PI: Takahiro Tanaka, Kyoto University, total 1,079M JPY (9.8M US$) [14]), has been selected and is currently on-going. The targets of this program is to promote comprehensive analysis of GWs and to expand the frontiers of GW physics/astronomy. To accomplish these targets, eight subgroups are organized with 41 core researchers (Table. 1). Each group consists of theory, data-analysis, and astronomy based researchers, and group numbers (A01, B01, $\cdots$) are named to facilitate discussion within and between A-, B-, or C-groups, or between 01 groups. It will be interesting to report how such "synergy" helps for future research.

Japanese researchers have contributed a lot on theoretical and numerical works of waveform predictions. On the other hand, in Japan, only few are known to be "general relativity researchers"; which means that many researchers conduct research not only in GR but also in cosmology, astrophysics, and/or astronomy. One reason for this is the small number of academic positions in a small country, and thus researchers are expected to have activities in multiple fields. The situation around getting academic positions in Japan has been getting worse in the last decades, since Japan is an aging society with a low birth rate, so the government tries to reduce the total number of students for each universities by reducing the budget of the public university 1% every year which has been continued for more than a decade.

All the big scientific projects in Japan will receive severe achievement-reviews in 2022. GW research is not an exception. KAGRA is rushing to have a detection as soon as possible, and if not, the project will most likely be forced to terminate. As collaborators of KAGRA, we do not have the right to say that this style of research is good or not for science. But this is actually an aspect of big science.

Table 1: Research groups of the Innovative Area Research, "Gravitational wave physics and astronomy: Genesis" (PI: Takahiro Tanaka)

A01	Testing gravity theories using GW data
A02	New developments of gravity theory research in GW physics / astronomy
A03	Theoretical study on binary BH formation
B01	Physics and Astrophysics with GWs from Binary NS Coalescences, BH-NS Coalescences, Pulsars and Magnetars
B02	GW Sources Probed with High Energy Observations
B03	Study of nucleosynthesis in NS merger with optical-infrared follow-up observations of GW sources
C01	Deciphering Physics of Core-Collapse Supernovae via GW Astronomy
C02	Studying supernova explosions via their neutrino emissions

Thanks to enormous support from the scientific community as well as a great effort by researchers around the world, KAGRA is about to see the "first light" in a few years. Nobody doubts the importance of GW research in astronomy, physics, and also in engineering. We believe KAGRA will definitely contribute to these fields, especially to GW science.

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