PROCEEDINGS OF SCIENCE

# Detector characterization of KAGRA for the fourth observing run

**Hirotaka Yuzurihara**[a,*] **on behalf of KAGRA collaboration**

[a] *Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan Institution*

*E-mail:* yuzu@icrr.u-tokyo.ac.jp

KAGRA is a ground-based gravitational wave detector located in the Kamioka mine, Gifu, Japan. The fourth international joint observing run (Observation-4; O4) by LIGO, Virgo, and KAGRA started from May 2023. The KAGRA detector characterization group aims to enhance the reliability of data analysis and GW detection by supporting detector commissioning and improving our understanding of detector instruments and acquired data. We provide various tools for monitoring, understanding, and mitigating noise sources, which help enhance the performance of the KAGRA detector and data analysis. Here, we report the recent activities and status of the detector characterization of KAGRA for O4.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker



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PoS(ICRC2023)1564

## 1. Introduction

A gravitational wave (GW) is a wave solution obtained when the Einstein equation is solved considering the approximation of a weak gravitational field. It propagates at the speed of light and is predicted based on the general relativity theory, which was established by Einstein in 1915 [1]. While the evidence of the existence of GWs has been inferred indirectly based on the change in the revolution period of the binary pulsar PSR B1913+16 [2], the first direct detection of the GW was finally achieved using enhanced LIGO detectors on September 15, 2015 [3]. To date, three international observation runs (i.e., O1, O2, and O3) were performed, and 90 GW events [4] were detected by LIGO [5] and Virgo [6]. From 25 May 2023, the fourth international observing run (O4) initiated with the International Gravitational-Wave Observatory Network (IGWN) comprising LIGO, Virgo, and KAGRA.

KAGRA is a cryogenic underground GW detector comprising of a laser interferometer with 3-km arms located in Kamioka, Gifu, Japan [7]. It possesses more improved features than other detectors with the arm length of km scale. The first feature is the silent underground environment where the detector operates. By installing the detector underground, the effects of noise, e.g., wind, temperature, and human activities, can be mitigated. The second feature is to cool down mirrors to reduce thermal noise. KAGRA plans to cool down four sapphire mirrors comprising the Fabry–Perot cavity to approximately 20 K.

During the O3 run, KAGRA performed the first international observation run with GEO600 detector starting from April 2020, which is known as O3GK [8]. The joint analysis of the GEO–KAGRA data for transient GW signals was performed [9]. To improve sensitivity toward the O4 run, the contribution of various noise sources to sensitivity (known as a noise budget) was investigated for the detailed understanding of the noise limiting the sensitivity [8]. According to the obtained noise budget, the measured sensitivity could be approximated by adding up noise sources. The sensitivity was dominated by the noise generated by sensors used for locally controlling vibration isolation systems, acoustic noise, shot noise, and laser frequency noise. The task regarding O4 is to mitigate noise and improve sensitivity [10].

Herein, we describe the status of the detector characterization group in KAGRA related to the O4 run. The detector characterization (DetChar) group performs two roles. The first role is to improve the sensitivity and stability of the interferometer controls. We have investigated the noise origin and path contaminating the external noise by analyzing multiple control signals and witness sensors for noise hunting [10]. We propose data-monitoring tools to analyze the long-term stability. Section 2 describes the tools for the commissioning support. The second role is to provide the data quality information to prevent the false detection of GWs in data analysis. Section 3 describes activities related to data quality.

## 2. Noise-hunting tools

### 2.1 Summary page

An interferometer is controlled based on the feedback control of mirror suspensions and laser. Data acquisition and control are performed using a the real-time system. These signals are constantly monitored for maintaining their stability. Currently, there are more than 100,000 channels related to controls, and it is not possible to monitor all of them. The summary page is a tool that continuously monitors sensors and important signals to control the interferometer.

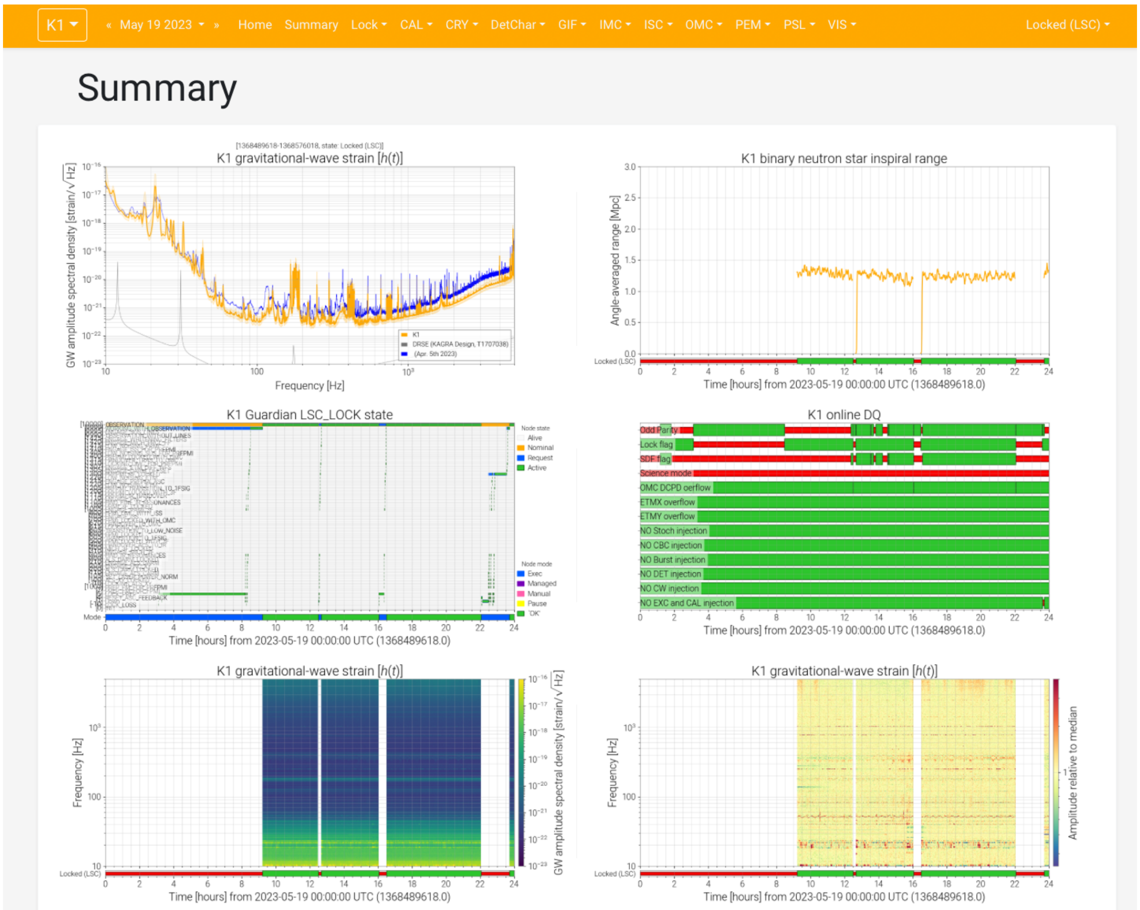


**Figure 1:** Top page of the summary page on May 19, 2023. Left top: The orange curve indicates the sensitivity of KAGRA in the lock state with the deviation of the sensitivity. The blue curve shows the reference sensitivity recorded on April 5, 2023. Right top: The time variation of the inspiral range. The bottom bar shows the status of the interferometer. The green color indicates the locked time, i.e., the interferometer is under control. The red color indicates the unlocked data, i.e., the interferometer is not under control. Left middle : The changes in the state of the guardian, which manages the interferometer state based on the commissioner's request. Right middle : The bit status of the online DQ flag. Green (red) indicates that the bit flag is active (inactive). Left bottom : The time-frequency map (known as spectrogram) of the strain data. The color bar shows the amplitude spectrum density. Right bottom : The whitened time–frequency map of the strain data. The color bar depicts the normalized spectrum divided by the median amplitude spectrum density improving the visibility of the transient signal.

Figure 1 shows the top page of the summary page. Each plot summarizes the results of 1 day. Other plots for the past dates are accumulated, and past pages can be easily viewed through the calendar feature. Pages are updated automatically.

The summary page is created using a python package known as *gwsumm*, which is developed by LIGO members based on a python package known as *gwpy* [11]. To create a page, it is necessary to set in advance the channels that will be monitored and determine their monitoring methods, e.g., time series, whitened time series, amplitude spectrum density, spectrogram, and so on. Since O3GK, sensors (such as oplev for length direction and new physical environmental sensors) and new interferometer controls (such as angular sensing and control, fiber noise cancellation, and phase locking loop) have been implemented and added to the summary page.

### 2.2 Pastavi

All data acquired at the KAGRA site is transferred to the main data storage located in Kashiwa, Chiba, Japan. To view past data, derive plots, and perform various analyses, users need to log in to the main data storage and develop codes to read the data. The data are stored in the frame format and is divided into 32-s data. To read the data, it is necessary to realize channel names in advance and correctly handle the divided data. In addition, it requires to use the python package known as *gwpy* [11] to plot the data. Sometimes this will be a barrier for users who are not familiar with code development and data handling. Therefore, we have developed a web-based tool to assist users to easily plot and analyze past data. This tool complements the automatically generated summary page. To ensure computing resources, Pastavi is executed on the dedicated server.

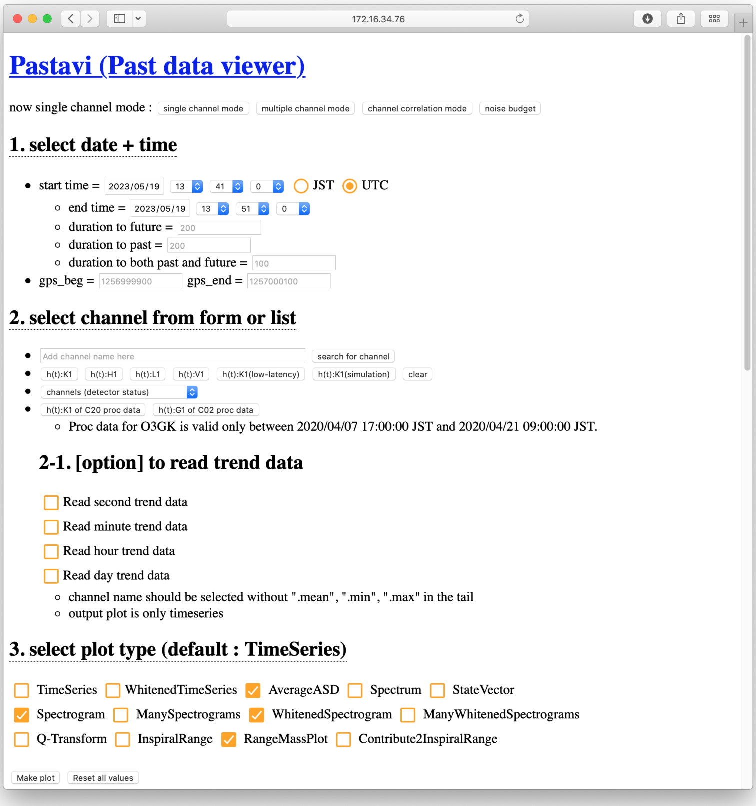


**Figure 2:** Top page of the web-based tool, i.e., Pastavi

Figure 2 shows the web page of Pastavi. The following three steps are considered for plotting:

In step 1 (top of Fig.2), the user selects the time and date for reading data in the JST (Japan Standard Time), UTC (Universal time coordinated) timezone, or GPS (Global Positioning System) time. In step 2 (middle of Fig.2), the user selects the channel name to plot. The user can enter directly or search the full channel name using a partial channel name. In step 3 (bottom of Fig.2), the user selects the types of plots including the time series, whitened time–series, averaged amplitude spectrum density(ASD), time–frequency map (spectrogram), whitened time–frequency map (whitened spectrogram), calculation of detectable distance, and so on. The plotting options required for typical plots, such as the axis scale selection, plotting range selection, and data output in the text format, are available. The web page is designed to be simple, light, and user-friendly.

We have modified and developed functions based on user requests and comments. Most recently, we have implemented a function to prepare a noise budget by combining the measured transfer function and the noise curve of the sensor.

### 2.3 DetChar cluster at the KAGRA site

The new cluster computer has been built at the KAGRA site to enhance online analysis resources for DetChar. HTCondor manages compute jobs and has been set up with the cooperation of NAOJ's astronomy data center. In addition to the summary page, various analyses related to detchar are being performed at the KAGRA site, i.e., the analysis to determine transient glitches (known as Omicron [12]), coincidence analysis between triggers (called Hveto [13]), analysis to compute the coherence between multiple channels (known as Bruco), and data quality production (Section 3.1). These analyses are being performed on dedicated computers; however, in the future, they will be integrated, so that they are conducted within the detchar cluster, thereby allowing for easier maintenance and the unification of the computing environments of tools basedon IGWN computing.

## 3. Event validation tools

### 3.1 Data quality information

One of the most important roles of DetChar is to prevent the false detection of GWs [14]. GWs are very weak signals and are hindered by various disturbances, such as the vibration of the mirrors that constitute an interferometer and the instability of the laser power and frequency. Such disturbances can be detected as false GW events as well. To separate GWs from such false events, it is necessary to understand the statistical behavior of the detector noise.

While detecting GWs, the observational data, which include known disturbances, are tagged with data quality (DQ) flags and data category flags. Tagged data are removed from the input data for searching GWs to reduce the false event rate. For O3GK data, the basic operating status of the interferometer was provided as an online process, i.e., $O$(10s), and other information about noise behavior was provided as an offline process with $O$(month) delay. As one of DetChar's activities, we optimized the criteria of DQ flags and updated the software to provide DQ flags with a shorter delay. The optimization was conducted based on the understanding of the hardware problem, which occurred during hardware upgrade and the commissioning of the interferometer. DQ flags contain disturbances due to the environmental noise transients caused by the electrical glitches of instruments and the operational errors of human activities. The generated DQ flags were uploaded to the dedicated server and shared with the data analysis members of the LVK collaboration.



PoS(ICRC2023)1564

### 3.2 Data quality report

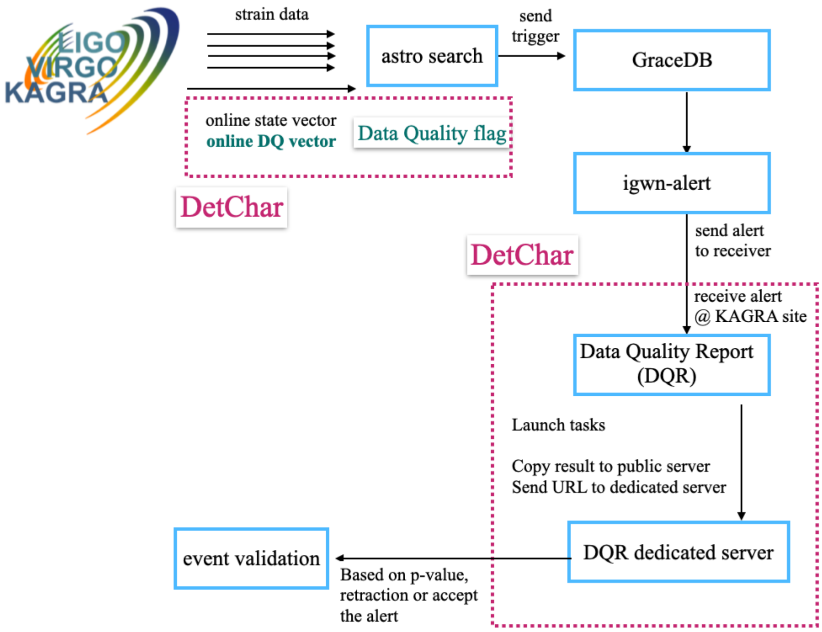


**Figure 3:** DQR process. The data are collected at the CIT and analyzed using low-latency pipelines. The detected GW candidate (trigger) is send to a server known as GraceDB, and receivers are alerted via *igwn-alert*. We receive the alert at the KAGRA site and launch the tasks to provide the data quality information based on the trigger. The results are transferred to the DQR–dedicated server. Event validation is performed.

To access the physics related to the neutron star merger or supernovae, it is important to perform follow-up observations using electromagnetic telescopes immediately after locating the GW candidate, e.g., GW170817 [15]. The data from GW observatories (LIGO, Virgo, and KAGRA) are collected and clustered at the California Institute of Technology (CIT). The low-latency search pipelines analyze the data set and provide a GW alert with a latency of a few seconds. Details, such as the mass of the binary star, merger time, estimated sky map, and signal-to-noise ratio, are registered in the database (known as GraceDB) to share with the collaborators.

The task of DetChar is to provide the data quality report (DQR) based on the time of the GW candidate. In the past observation run (O3), the DQR was organized by LIGO and Virgo. The DQR played an important role in the number of retracted candidates and increased the confidence of candidates for the astronomers of electromagnetic telescopes.

With regard to the next observation run, LVK DetChar plans to introduce tools standardized across collaborations and launch the DQR process automatically triggered by the GW alert at each observatory site. Figure 3 shows DQR process. We have participated in the development of DQR tools and have contributed to the operational test with LIGO and Virgo DetChar members.

## 4. Summary

KAGRA is a cryogenic underground GW detector comprising a laser interferometer; it is located in Kamioka, Gifu, Japan. The O4 run has started from 25, May 2023. KAGRA has been in a stable observation mode since 24 May. KAGRA resumed commissioning from June 21, 4 weeks after the start of the first half of O4 (called O4a) and will restart observation (O4b) in spring 2024. For the first detection of GW by KAGRA, the DetChar group for KAGRA performed two tasks.

First, we contributed the improvement of sensitivity and the stability of the interferometer controls. We investigated the noise origin and path contaminated by the external noise by analyzing multiple control signals and witness sensors for noise hunting. To monitor multiple sensors and control signals, we have provided the data–monitoring tools, such as the summary page to analyze the long-term stability and the web-based tool for simple data analysis.

Second, we provide the data quality information to prevent the false detection of GW in analyzing the data. In GW searches, the strain data containing known disturbances are tagged by DQ flags. The tagged data were removed from the input data for searching GWs to reduce the false event rate. For O3GK data, the basic operating status of the interferometer and other known noise issue information were provided. Toward the O4 run, we developed a software tool to rapidly generate DQ flags. Moreover, we started the project to provide the DQR of the GW candidate triggered by low-latency search. The infra tools for the DQR was standardized over the LVK collaboration.

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## Full Authors List: Collaboration

H. Abe[1], T. Akutsu[2,3], M. Ando[4,5], M. Aoumi[6], A. Araya[7], N. Aritomi[8], Y. Aso[2,9], S. Bae[10], R. Bajpai[2], K. Cannon[5], Z. Cao[11], R.-J. Chang[12], A. H.-Y. Chen[13], D. Chen[14], H. Chen[15], Y. Chen[15], A. Chiba[16], R. Chiba[17], C. Chou[18], M. Eisenmann[2], S. Fujii[17], I. Fukunaga[19], D. Haba[1], S. Haino[20], W.-B. Han[21], H. Hayakawa[6], K. Hayama[22], Y. Himemoto[23], N. Hirata[2], C. Hirose[24], S. Hoshino[24], H.-F. Hsieh[25], C. Hsiung[26], S.-C. Hsu[27,25], D. C. Y. Hui[28], K. Inayoshi[29], Y. Itoh[19,30], M. Iwaya[17], H.-B. Jin[31,32], K. Jung[33], T. Kajita[34], M. Kamiizumi[6], N. Kanda[30,19], J. Kato[16], T. Kato[17], S. Kim[28], N. Kimura[6], T. Kiyota[19], K. Kohri[35], K. Kokeyama[36], K. Komori[5,4], A. K. H. Kong[25], N. Koyama[24], J. Kume[5], S. Kuroyanagi[38,37], S. Kuwahara[5], K. Kwak[33], S. Lai[18], H. W. Lee[39], R. Lee[15], S. Lee[40], M. Leonardi[41,2], K. L. Li[12], L. C.-C. Lin[12], C-Y. Lin[42], E. T. Lin[25], G. C. Liu[26], L.-T. Ma[25], K. Maeda[16], M. Matsuyama[19], M. Meyer-Conde[19], Y. Michimura[43,5], N. Mio[44], O. Miyakawa[6], S. Miyamoto[17], S. Miyoki[6], S. Morisaki[17], Y. Moriwaki[16], M. Murakoshi[45], K. Nakamura[2], H. Nakano[46], T. Narikawa[17], L. Nguyen Quynh[47], Y. Nishino[2,48], A. Nishizawa[5], K. Obayashi[45], J. J. Oh[49], K. Oh[28], M. Ohashi[6], M. Ohkawa[24], K. Oohara[50,51], Y. Oshima[4], S. Oshino[6], M. A. Page[2], K.-C. Pan[15,25], J. Park[40], F. E. Peña Arellano[6], S. Saha[25], K. Sakai[52], T. Sako[16], R. Sato[24], S. Sato[16], Y. Sato[16], T. Sawada[6], Y. Sekiguchi[53], L. Shao[29], Y. Shikano[54,55], K. Shimode[6], H. Shinkai[56], J. Shiota[45], K. Somiya[1], T. Suzuki[24], T. Suzuki[1], H. Tagoshi[17], H. Takahashi[57], R. Takahashi[2], A. Takamori[7], K. Takatani[19], H. Takeda[58], M. Takeda[19], M. Tamaki[17], K. Tanaka[59], S. J. Tanaka[45], T. Tanaka[58], A. Taruya[60], T. Tomaru[2], K. Tomita[19], T. Tomura[6], A. Toriyama[45], A. A. Trani[5], S. Tsuchida[61], N. Uchikata[17], T. Uchiyama[6], T. Uehara[62], K. Ueno[5], T. Ushiba[6], M. H. P. M. van Putten[63], H. Wang[4], T. Washimi[2], C. Wu[15], H. Wu[15], K. Yamamoto[16], M. Yamamoto[16], T. Yamamoto[6], T. S. Yamamoto[37], S. Yamamura[17], R. Yamazaki[45], L.-C. Yang[18], Y. Yang[18], S.-W. Yeh[15], J. Yokoyama[5,4], T. Yokozawa[6], H. Yuzurihara[6], Y. Zhao[17,2], Z.-H. Zhu[11,64]

[1]Graduate School of Science, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
[2]Gravitational Wave Science Project, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
[3]Advanced Technology Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
[4]Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[5]Research Center for the Early Universe (RESCEU), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[6]Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan
[7]Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[8]LIGO Hanford Observatory, Richland, WA 99352, USA
[9]The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
[10]Korea Institute of Science and Technology Information (KISTI), 245 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[11]Department of Astronomy, Beijing Normal University, Xinjiekouwai Street 19, Haidian District, Beijing 100875, China
[12]Department of Physics, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan
[13]Institute of Physics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan
[14]Kamioka Branch, National Astronomical Observatory of Japan, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan
[15]Department of Physics, National Tsing Hua University, No. 101 Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan
[16]Faculty of Science, University of Toyama, 3190 Gofuku, Toyama City, Toyama 930-8555, Japan
[17]Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan
[18]Department of Electrophysics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan
[19]Department of Physics, Graduate School of Science, Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
[20]Institute of Physics, Academia Sinica, 128 Sec. 2, Academia Rd., Nankang, Taipei 11529, Taiwan
[21]Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
[22]Department of Applied Physics, Fukuoka University, 8-19-1 Nanakuma, Jonan, Fukuoka City, Fukuoka 814-0180, Japan
[23]College of Industrial Technology, Nihon University, 1-2-1 Izumi, Narashino City, Chiba 275-8575, Japan
[24]Faculty of Engineering, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan
[25]Institute of Astronomy, National Tsing Hua University, No. 101 Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan
[26]Department of Physics, Tamkang University, No. 151, Yingzhuan Rd., Danshui Dist., New Taipei City 25137, Taiwan
[27]Department of Physics, University of Washington, 3910 15th Ave NE, Seattle, WA 98195, USA
[28]Department of Astronomy and Space Science, Chungnam National University, 9 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea
[29]Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Road 5, Haidian District, Beijing 100871, China
[30]Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
[31]National Astronomical Observatories, Chinese Academic of Sciences, 20A Datun Road, Chaoyang District, Beijing, China
[32]School of Astronomy and Space Science, University of Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, China
[33]Department of Physics, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea

[34]Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan
[35]Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki 305-0801, Japan
[36]School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, UK
[37]Department of Physics, Nagoya University, ES building, Furocho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
[38]Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain
[39]Department of Computer Simulation, Inje University, 197 Inje-ro, Gimhae, Gyeongsangnam-do 50834, Republic of Korea
[40]Technology Center for Astronomy and Space Science, Korea Astronomy and Space Science Institute (KASI), 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea
[41]Department of Physics, University of Trento, via Sommarive 14, Povo, 38123 TN, Italy
[42]National Center for High-performance computing, National Applied Research Laboratories, No. 7, R&D 6th Rd., Hsinchu Science Park, Hsinchu City 30076, Taiwan
[43]LIGO Laboratory , California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA
[44]Institute for Photon Science and Technology, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan
[45]Department of Physical Sciences, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara City, Kanagawa 252-5258, Japan
[46]Faculty of Law, Ryukoku University, 67 Fukakusa Tsukamoto-cho, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan
[47]Department of Physics and Astronomy, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556, USA
[48]Department of Astronomy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[49]National Institute for Mathematical Sciences, 70 Yuseong-daero, 1689 Beon-gil, Yuseong-gu, Daejeon 34047, Republic of Korea
[50]Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan
[51]Niigata Study Center, The Open University of Japan, 754 Ichibancho, Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8122, Japan
[52]Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, 888 Nishikatakai, Nagaoka City, Niigata 940-8532, Japan
[53]Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi City, Chiba 274-8510, Japan
[54]Graduate School of Science and Technology, Gunma University, 4-2 Aramaki, Maebashi, Gunma 371-8510, Japan
[55]Institute for Quantum Studies, Chapman University, 1 University Dr., Orange, CA 92866, USA
[56]Faculty of Information Science and Technology, Osaka Institute of Technology, 1-79-1 Kitayama, Hirakata City, Osaka 573-0196, Japan
[57]Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, 8-15-1 Todoroki, Setagaya, Tokyo 158-0082, Japan
[58]Department of Physics, Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
[59]Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan
[60]Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
[61]National Institute of Technology, Fukui College, Geshi-cho, Sabae-shi, Fukui 916-8507, Japan
[62]Department of Communications Engineering, National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka City, Kanagawa 239-8686, Japan
[63]Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea
[64]School of Physics and Technology, Wuhan University, Bayi Road 299, Wuchang District, Wuhan, Hubei, 430072, China