Ultralight vector dark matter search using data from the KAGRA O3GK run

A. G. Abac *et al.*[*]
(LIGO Scientific, Virgo, and KAGRA Collaborations)

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Among the various candidates for dark matter (DM), ultralight vector DM can be probed by laser interferometric gravitational wave detectors through the measurement of oscillating length changes in the arm cavities. In this context, KAGRA has a unique feature due to differing compositions of its mirrors, enhancing the signal of vector DM in the length change in the auxiliary channels. Here we present the result of a search for $U(1)_{B-L}$ gauge boson DM using the KAGRA data from auxiliary length channels during the first joint observation run together with GEO600. By applying our search pipeline, which takes into account the stochastic nature of ultralight DM, upper bounds on the coupling strength between the $U(1)_{B-L}$ gauge boson and ordinary matter are obtained for a range of DM masses. While our constraints are less stringent than those derived from previous experiments, this study demonstrates the applicability of our method to the lower-mass vector DM search, which is made difficult in this measurement by the short observation time compared to the auto-correlation timescale of DM.

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I. INTRODUCTION

Recently, a number of novel dark matter (DM) searches using laser interferometric gravitational wave (GW) detectors have been proposed [1–6] and conducted [7–11]. Because of their extremely high sensitivity to the differential length changes of their arms in the frequency range $\mathcal{O}(10-10^3)$ Hz, they can probe the interaction between the detector and DMs, which have masses of $\mathcal{O}(10^{-14}\text{–}10^{-11})$ eV$/c^2$ and therefore oscillate coherently within this frequency band. Vector DM (or so-called dark photon DM) interacts with test masses of the interferometer, for example, via a coupling to the baryon (B) or baryon minus lepton ($B-L$) number current. Because of the nonrelativistic dispersion (under the standard halo model [12,13]), the vector DM field exerted on the test masses behave as an oscillating dark electric force, inducing a measurable change in the differential length of the arm cavity. Vector DMs of this type, which we refer to as $U(1)_B$ and $U(1)_{B-L}$ gauge boson, were previously searched in Ref. [9] by using the latest observational data from the Advanced LIGO [14–16] and Virgo [17,18] detectors. Remarkably, the constraint on the coupling strength of vector DM to baryons from GW interferometers surpasses those from existing experiments such as the Eöt-Wash torsion balance [19,20] and MICROSCOPE [21–23], by orders of magnitude for certain frequency bands. Similarly, dilatonic DM, whose interaction alters the apparent electron mass or the fine structure constant, was probed with data from the GEO600 interferometer [10,24,25]. These searches highlight the potential of GW detectors as direct probes of ultralight DM.

A Japanese laser interferometric GW detector, KAGRA [26–28], can also probe the vector DM interaction, but in a relatively unique way compared to the previous searches. For the Advanced LIGO and Virgo detectors, all the mirrors (including test masses) are made of the same material (fused silica), in other words, they have a common charge-to-mass ratio with respect to the dark electric field. Because the spatial variation scale (so-called coherence length) of the ultralight DM field is $\mathcal{O}(10^5\text{–}10^8)$ km in our target mass range, all mirrors of each detector, which are separated only a few kilo-meters, respond to the vector field nearly identically. In contrast, KAGRA employs sapphire for cryogenic test masses and fused silica for room temperature auxiliary mirrors. Therefore, owing to the difference in the charge-to-mass ratios, those mirrors respond differently to the vector field, and the vector DM signal in the (differential) length change can be enhanced for auxiliary length monitors [3,29]. Especially in the case of $U(1)_{B-L}$, where the difference in charge-mass ratio is relatively large, these channels are shown to have better sensitivity to vector DM than existing experiments in certain low frequency bands, when KAGRA reaches design sensitivity [3].

In this work, we conduct an ultralight vector DM search with KAGRA using the data of its auxiliary length change monitors during the first joint observation run together with GEO600 (O3GK) [30]. Although the detector was in operation for two weeks during O3GK, the durations of the

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[*] Full author list given at the end of the article.

contiguous data segments were at most about 7 hours [31]. For our target mass range, this duration can be comparable to or smaller than the so-called coherence time, within which the amplitude and the phase of DM can be regarded as a constant. Since each such measurement is one realization of a random field, their stochasticity needs to be taken into account, especially when setting the upper bound on the coupling strength of the ultralight DM. Therefore, our pipeline is constructed based on a recent study [32], which thoroughly investigates the stochastic nature of the ultralight vector DM. Using the detection statistic discussed in Ref. [32], we numerically derive upper limits on the coupling strength incorporating the stochastic nature of the DM. On the other hand, various noise lines [31] result in a false detection as a DM signal. In order to distinguish outliers, we have implemented veto procedures making use of expected features of ultralight DM signals.

The rest of the paper is organized as follows. We first introduce our model of ultralight vector DM and discuss its stochastic nature in Sec. II. After describing our search method in Sec. III, the results of our analysis using O3GK data are presented in Sec. IV. Section V provides a discussion of these results and of the prospects for future searches.

II. DARK MATTER SEARCH WITH KAGRA

A. Vector dark matter model

In this work, we consider a ultralight vector dark matter field $A_\mu(t,x)$, which is regarded as a gauge boson of $U(1)_D$ gauge symmetry with D being a label for a charge, such as B and $B-L$. We assume it interacts with ordinary matter through the coupling to the $U(1)_D$ current J^μ_D. The Lagrangian density $\mathcal{L}$ is then given as

$$\mathcal{L} = -\frac{\varepsilon_0 c^2}{4} F^{\mu\nu}F_{\mu\nu} + \frac{\varepsilon_0}{2}\left(\frac{m_A c^2}{\hbar}\right)^2 A^\mu A_\mu - \epsilon_D e J^\mu_D A_\mu, \quad (1)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the field strength, c is the speed of light, $\hbar$ is the reduced Planck constant, m_A is the mass of the vector field, ε_0 is the permittivity of vacuum and ϵ_D is the gauge coupling constant normalized by the electromagnetic coupling constant. Since the temporal component of the vector field A_0 is negligibly small, we consider only its spatial components $\vec{A} = (A_x, A_y, A_z)$ in the following discussion.

Assuming the standard halo model, the local density of DM is $\rho_{\mathrm{DM}} \sim 0.4\ \mathrm{GeV/cm^3}$, and its virial velocity is $v_{\mathrm{vir}} \simeq 220$ km/sec around the solar system in our Galaxy [12,13]. These profiles imply that DM would have an extremely large number density for the mass range $10^{-22}\ \mathrm{eV}/c^2 \lesssim m \lesssim 1\ \mathrm{eV}/c^2$ and behave as a classical wave oscillating at about the Compton frequency $f_c = m_A c^2/2\pi\hbar$. Then, one can describe it as the superposition of plane waves with different velocities $\vec{v}_{(i,n)}$ and phases $\theta_{(i,n)}$ as

$$A_i(t,\vec{x}) = \frac{A}{\sqrt{N}} \sum_{n=1}^{N} \cos\left(2\pi f_c (1 + v^2_{(i,n)}/2c^2)t - \hbar^{-1} m_A \vec{v}_{(i,n)} \cdot \vec{x} + \theta_{(i,n)}\right), \quad (2)$$

where $\theta_{(i,n)}$ is a random variable following a uniform distribution over $[0, 2\pi]$ and $A \equiv \sqrt{2\rho_{\mathrm{DM}}\hbar^2/\varepsilon_0 3 m_A^2 c^4}$. Note that, for simplicity, the absence of correlation between the direction of $\vec{A}$ and $\vec{v}$ is assumed. Here $\vec{v}_{(i,n)}$ follows the DM velocity distribution of the standard halo model [13]:

$$f_{\mathrm{SHM}}(\vec{v})\mathrm{d}^3\vec{v} = \frac{1}{(\pi v^2_{\mathrm{vir}})^{3/2}} \exp\left[-\frac{(\vec{v}+\vec{v}_\odot)^2}{v^2_{\mathrm{vir}}}\right]\mathrm{d}^3\vec{v}, \quad (3)$$

with the solar velocity $|\vec{v}_\odot| \simeq 232$ km/sec. This distribution results in the velocity dispersion of the DM as $\bar{v}^2 = v_\odot^2 + (3/2)v^2_{\mathrm{vir}} \simeq \mathcal{O}(10^{-6}c^2)$. In such a nonrelativistic regime, the time derivative of the field dominates over the spatial derivative. Hence, it can be regarded as a oscillating dark "electric" field, which induces displacements of the test masses in GW interferometers as $\delta\ddot{x}_i = \epsilon_D e (Q/M)\dot{A}_i$.

Another feature is that there appears a length scale, called "coherence length," which is evaluated as $L = 2\pi\hbar/m_A\sqrt{\bar{v}^2} \sim 10^7\ \mathrm{km}\ (10^{-13}\ \mathrm{eV}\cdot c^{-2}/m_A)$. This scale characterizes the spatial variation of the ultralight DMs. As we will see below, the separation of test masses here is much shorter than L, we can take $\vec{x} = 0$ in Eq. (2) without loss of generality and hereafter neglect the position dependence of the vector field.

B. Auxiliary length channels of KAGRA

From April 7 to April 21, 2020, KAGRA conducted its first joint observation run (O3GK) [30,31], together with GEO600. The configuration of KAGRA interferometer during O3GK is shown in Fig. 1. Similarly to that of LIGO and Virgo, it is based on a Michelson interferometer with a Fabry-Pérot cavity in two perpendicular arms. Each arm cavity is formed by the input test mass (ITM) and the end test mass (ETM). The main channel to monitor the differential changes caused by GWs is called the differential arm length (DARM). The differential length between the beam splitter (BS) and two ITMs are controlled so that the Michelson fringe will be at the dark fringe at the antisymmetric port, and the channel to monitor the differential Michelson interferometer length is called MICH. The power recycling mirror (PRM) and two ITMs form a power recycling cavity to effectively enhance the input power. The channel to monitor the power recycling cavity length is called PRCL.

During O3GK, a signal recycling mirror (SRM) was tilted, and the signal recycling cavity was not formed [33]. Instead, this tilted SRM introduced an optical loss of 70%, which led to degraded shot noise for the DARM readout.

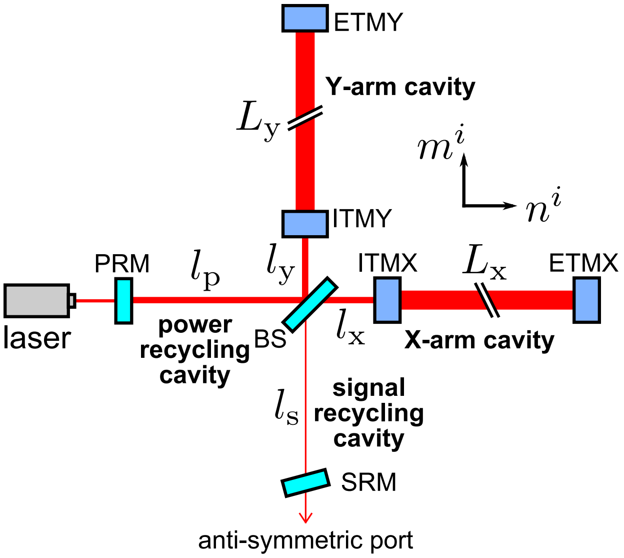

FIG. 1. The schematic of the KAGRA interferometer. ITM (ETM): input (end) test mass, BS: beam splitter, PRM: power recycling mirror, SRM: signal recycling mirror.

Two auxiliary channels, MICH and PRCL were recorded using different interferometer sensing ports, and were not affected by this optical loss. Using the length symbols in Fig. 1, changes in DARM, MICH and PRCL can be written as

$$\delta L_{\mathrm{DARM}} = \delta(L_{\mathrm{x}} - L_{\mathrm{y}}), \tag{4}$$

$$\delta L_{\mathrm{MICH}} = \delta(l_{\mathrm{x}} - l_{\mathrm{y}}), \tag{5}$$

$$\delta L_{\mathrm{PRCL}} = \delta[(l_{\mathrm{x}} + l_{\mathrm{y}})/2 + l_{\mathrm{p}}], \tag{6}$$

respectively. Note that each length parameter is given as $L_x = L_y = 3000$ m, $l_x = 26.7$ m, $l_y = 23.3$ m and $l_p = 41.6$ m, all of which are much shorter than the coherence length of DM.

Previous vector DM searches using LIGO and Virgo focused on DARM channels with the highest displacement sensitivity. This sensitivity is equivalent to the sensitivity to vector DM interactions for both LIGO and Virgo employing room temperature fused silica mirrors for all the mirrors. This situation, however, drastically changes for KAGRA, which employs cryogenic sapphire mirrors for the test masses. As pointed out in Ref. [3], MICH and PRCL contain both the fused silica mirrors such as PRM and BS, and the sapphire test masses that respond differently to the vector DM due to the different charge-to-mass ratio. This results in the enhancement of the (differential) length change caused by vector DM in those channels. Since the difference becomes larger especially for the $U(1)_{B-L}$ gauge boson, hereafter we focus on the $D = B - L$ case.

C. Signal in the KAGRA's auxiliary length channels

Since the frequency of each plane wave is localized near the Compton frequency as $f_i = f_c\sqrt{1 + v_i^2/c^2} \sim f_c(1 + \mathcal{O}(10^{-6}))$, it is convenient to work in the Fourier space. Let us consider the Fourier transform of the signal in X channel with duration T and center time t_0

$$\tilde{h}_X(f; t_0) \equiv \int_{t_0-T/2}^{t_0+T/2} dt h_X(t) \mathrm{e}^{-2\pi \mathrm{i} f(t-t_0+T/2)}. \tag{7}$$

To simplify the discussion, T is taken to be much shorter than the timescale of Earth's rotation. As discussed in [32], the oscillating length changes of an arm cavity can be decomposed into three contributions referred to as charge asymmetry, spatial difference and finite light traveling time [8]. For auxiliary length monitors of interest here, the dominant contribution is the one from charge asymmetry expressed as

$$\tilde{h}_X(f; t_0) = \mathrm{i}\frac{\epsilon_D e}{2\pi f}\Delta\left(\frac{Q_D}{M}\right) l_X^i(t_0)\tilde{A}_i(f; t_0), \tag{8}$$

where $\Delta(Q_D/M)$ is the difference of charge to mass ratio between two mirrors (BS and ITMX/Y) and in our case, it is $\Delta(Q_{B-L}/M) \sim 0.009/m_n$ with m_n being the neutron mass [3]. The vector $l_X^i(t_0)$ is given as

$$l_X^i(t) = \begin{cases} n^i(t) - m^i(t), & (X = \mathrm{MICH}) \\ \frac{1}{2}(n^i(t) + m^i(t)), & (X = \mathrm{PRCL}), \end{cases} \tag{9}$$

where n^i and m^i are unit vectors pointing along the orthogonal arm axes depicted in Fig. 1. Here $\tilde{A}_i(f; t_0)$ is the Fourier transform of the field amplitude. Since it is a superposition of a huge number of partial waves, the central limit theorem assures that $\tilde{A}_i(f; t_0)$ and consequently $\tilde{h}_X(f; t_0)$ follow a Gaussian distribution. Note that, when the DM density and the distance between the test masses are fixed, this type of contribution results in a larger field amplitude and hence in a larger signal for the lower frequencies [3,32]. This is the reason why MICH and SRCL (not available in O3GK) has, under the design sensitivity, the capability of limiting the DM coupling beyond existing limits in the lower frequency band.

At this point, it is convenient to introduce the so-called coherence time

$$\tau \equiv 2\pi/m_A v_{\mathrm{vir}}^2 \sim 0.3\ \mathrm{day}\left(\frac{10^{-13}\ \mathrm{eV}\cdot c^{-2}}{m_A}\right), \tag{10}$$

which quantifies the characteristic correlation lifetime of the DM field at different times $\langle \tilde{h}_X^*(f; t_0)\tilde{h}_X(f; t_1)\rangle$. Let T be the duration of a single chunk of data and N_{ch} be the number of equal-length chunks. For higher mass ranges, in general, the coherence time becomes shorter than the duration of each chunk as $\tau < T$. In this case, the amplitude and phase of the DM randomly evolve within the chunks. While this decoherence reduces the growth of the signal-to-noise (SNR) ratio in amplitude as $\propto (N_{\mathrm{ch}}T)^{1/4}$ [32], each data chunk can be regarded as an independent measurement of DM, and in fact the statistical treatment can be simplified [32]. For a lower mass range ($\tau > T$), however, the correlation of the DM field between different data chunks cannot be neglected. This issue will be addressed in the following section describing the search pipeline.

Finally, let us give a concrete expression of the signal covariance $\langle \tilde{h}_X^*(f;t_0)\tilde{h}_X(f;t_1)\rangle$ used in our analysis. By combining Eqs. (2) and (3), it is derived as

$$\begin{aligned}\langle \tilde{h}_X^*(f;t_0)\tilde{h}_X(f;t_1)\rangle &= \frac{\epsilon_D^2 e^2 A^2 T^2 v_{\mathrm{vir}}^3}{32\pi^{\frac{5}{2}} f^2 v_\odot^3}\left\{\Delta\left(\frac{Q_D}{M}\right)\right\}^2 \\ &\quad\times l_X^i(t_0) l_{X,i}(t_1) \mathrm{e}^{-\frac{v_\odot^2}{v_{\mathrm{vir}}^2}+2\pi \mathrm{i} f_{\mathrm{DM}}(t_1-t_0)} \\ &\quad\times (I(x_+) - I(x_-)). \end{aligned} \tag{11}$$

Here $I(x)$ is a function of the DM frequency and the time

$$\begin{aligned} I(x) = \frac{X^2}{8}\Bigg[\sqrt{\pi}X\mathrm{e}^{X^2/4}\Bigg\{&\mathrm{erf}\left(\frac{x}{X}-\frac{X}{2}\right) \\ &+\mathrm{erf}\left(\frac{x}{X}+\frac{X}{2}\right)\Bigg\} - 4\mathrm{e}^{-x^2/X^2}\sinh(x)\Bigg], \end{aligned} \tag{12}$$

where we use the following parametrization,

$$x = \frac{2v_\odot}{v_{\mathrm{vir}}^2}v, \qquad X = \frac{2v_\odot}{v_{\mathrm{vir}}\sqrt{1-\mathrm{i}\pi v_{\mathrm{vir}}^2 c^{-2} f_c (t_1 - t_0)}}, \tag{13}$$

and

$$\frac{v_\pm}{c} \equiv \sqrt{2\left(\frac{f \pm 1/(2T)}{f_c} - 1\right)}, \qquad x_\pm \equiv \frac{2v_\odot}{v_{\mathrm{vir}}^2} v_\pm. \tag{14}$$

For $t_0 = t_1$, our $I(x)$ coincides with the function $\Delta_s(f_n)$ in Ref. [32], which gives the deterministic part of the spectral shape.

III. SEARCH METHOD

A. Detection statistics

Here we introduce, and slightly extend, the detection statistic discussed in Ref. [32]. It is based on the existing methods of continuous GW searches [34–36] that also look for a narrow band signal similarly to our case. For comprehensive reviews of those method, see e.g. Refs. [37–39] The search method discussed in Ref. [32] is generally applicable to the ultralight DM searches using a single detector and interested readers could refer to Ref. [40] for the application of this detection statistic to the ultralight axion search.

As we discussed in Sec. II, the spectrum of the DM signal is localized within the narrow frequency band. From Eqs. (2) and (3), the frequency $f_c(1+\kappa^2 v_{\mathrm{vir}}^2/c^2)$ above which the fraction of signal power becomes 1% can be derived. Note that the value of κ does not depend on the DM mass due to the dispersion $f_c(1+v_{(i,n)}^2/2c^2)$ in Eq. (2). We numerically find the value $\kappa = 3.17$, which is determined by the observed virial velocity and characteristics of the standard halo model [32].

Following Ref. [32], we sum up the spectra over this frequency range for each single data chunk

$$\rho_i(f_c) \equiv \sum_{f_c \le f_n \le f_c(1+\kappa^2 v_{\mathrm{vir}}^2/c^2)} \frac{4|\tilde{d}(f_n;t_i)|^2}{TS(f_n;t_i)}, \tag{15}$$

which guarantees that the fractional loss of signal power becomes less than 1%. Here T again is the duration of the data chunks, $\tilde{d}(f_n;t_i)$ represents the Fourier transform of the ith data chunk and $S(f_n;t_i)$ is the one-sided noise power spectral density (PSD) around $t = t_i$. The number of bins involved in $\rho_i(f_c)$ is given as

$$N_{\mathrm{bin}} = \left\lceil \frac{\kappa\bar{v}^2 f_c}{\Delta f}\right\rceil = \left\lceil \kappa\frac{T}{\tau}\right\rceil, \tag{16}$$

where $\lceil x \rceil$ represents the minimum integer larger than x. Therefore, when T is fixed, N_{bin} will increase as f_c increases. Note that in order to neglect the effect of Earth's rotation as in Sec. II, T should be small enough and hereafter we take $T = 30$ min. In Fig. 2, we present the normalized spectra of the simulated vector DM signal, which is generated from the covariance (11), for two different signal frequencies $f_c = 20$ Hz and $f_c = 600$ Hz. Here the spectra $|\tilde{h}_X(f;t_i)|^2$ is averaged over 100 chunks and normalized by the total power to show the fractional power at each frequency bin. One can clearly see that most of the power of DM signal is localized in this narrow band consisting of N_{bin} bins (left side of the orange line).

In our pipeline, $S(f_n;t_i)$ is estimated from $\tilde{d}(f_n;t_i)$ by applying the running median and then converting it to the mean value by multiplying a correction factor (see Appendix A of Ref. [41]). In the median estimation, 180 neighboring frequency bins corresponding to 0.1 Hz band width are involved so that the effect of DM signal with narrow bandwidth can be smeared out. By performing the summation over all chunks, we can define the detection statistics ρ as

$$\rho(f_c) \equiv \sum_i^{N_{\mathrm{ch}}} \rho_i(f_c), \tag{17}$$

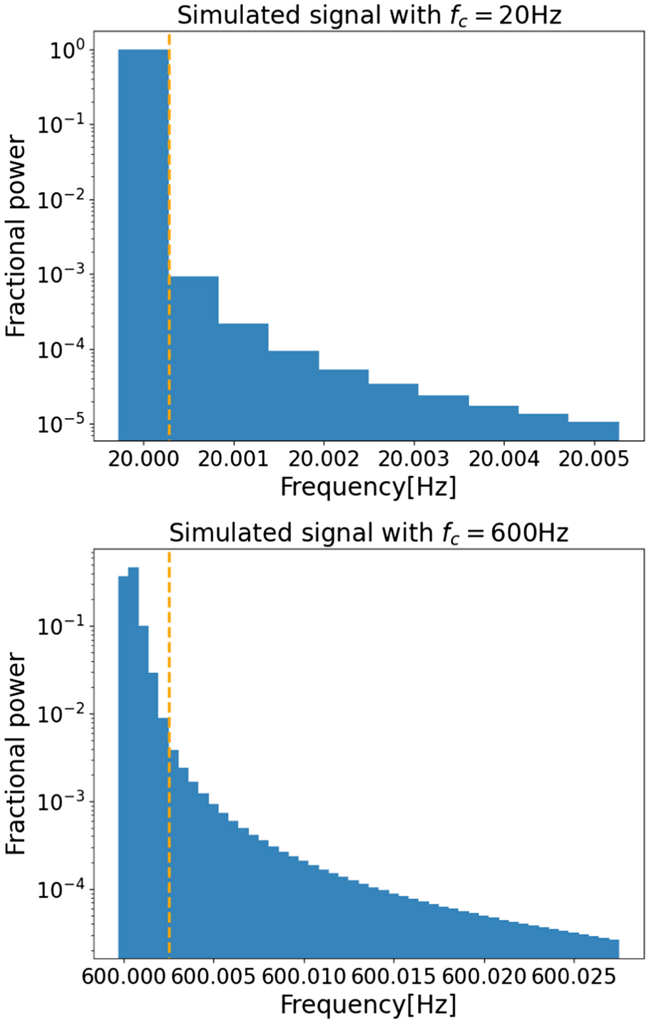

FIG. 2. The spectra of simulated vector DM signal normalized by the total power for nominal signal frequencies of 20 Hz and 600 Hz. Here the spectra is averaged over 100 half-hour chunks of simulated signal data. The orange line indicates N_{bin}-th bin above which the fraction of power is less than 1%.

where N_{ch} represents the number of chunks. Under the assumption of the stationarity and Gaussian distribution of noise, ρ follows a χ^2 distribution with $2N_{\mathrm{bin}}N_{\mathrm{ch}}$ degrees of freedom in the absence of signal. We chose the threshold to be the 95% percentile of this distribution.

B. Upper limit estimation

In this study, we derive upper limits based on the frequentist's method where $\beta\%$ confidence level upper limit is derived through the integration of the likelihood function $\mathcal{L}(\rho(f_c); \epsilon_D^{\beta\%})$ as

$$1 - \frac{\beta}{100} = \int_0^{\rho_{\mathrm{obs}}} d\rho \mathcal{L}(\rho(f_c); \epsilon_D^{\beta\%}). \tag{18}$$

One might expect the central limit theorem to be applicable to $\rho(f_c)$ since the number of chunks is relatively large. There is, however, a nonvanishing cross-correlation between different segments $\langle \rho_i \rho_j \rangle|_{i \neq j} \neq 0$ for $|t_i - t_j| < \tau$. This correlation prevents the convergence to a Gaussian distribution especially for lower-mass DM and makes the analytical expression of $\mathcal{L}(\rho(f_c); \epsilon_D)$ complicated [32]. In fact, this analytical expression suffers from numerical instability for intermediate regimes where the coherence time and the duration of chunks are comparable. In our pipeline, therefore, the 95% upper limit on the coupling constant was numerically derived as follows.

Assuming that only Gaussian noise $\tilde{n}(f_n; t_i)$ and ultralight DM signals are present in the data, it can be expressed as $\tilde{d}(f_n; t_i) = \tilde{n}(f_n; t_i) + \tilde{h}_X(f_n; t_i)$. Therefore, dependence of ρ on the coupling constant can be decomposed as

$$\begin{aligned} \rho(f_c; \epsilon_D) &= \sum_{t_i, f_n} \frac{4}{TS} (|\tilde{n}|^2 + 2\mathrm{Re}[\tilde{n}^* \tilde{h}_X] + |\tilde{h}_X|^2) \\ &= \mathcal{N}^2 + \epsilon_D \mathcal{N} \cdot \mathcal{S} + \epsilon_D^2 \mathcal{S}^2. \end{aligned} \tag{19}$$

Here $\mathcal{N}^2$ represents contributions from $2N_{\mathrm{bin}}N_{\mathrm{ch}}$ unit Gaussian variables since the noise component in ρ is normalized by the PSD. On the other hand, $\mathcal{S}^2$ represents contributions solely from the Gaussian signal $\tilde{h}_X(f_n; t_i)$ (also normalized by noise PSD) whose correlation function is given as Eq. (11) under the standard halo model assumption. $\mathcal{N} \cdot \mathcal{S}$ is the contribution from the cross term of the unit Gaussian and the normalized signal. For a fixed DM mass (or f_c), we simulated 10^5 realizations of $\mathcal{N}^2, \mathcal{S}^2, \mathcal{N} \cdot \mathcal{S}$ from the covariance of the DM signal (11) and the estimated noise PSD $S_n(f_n; t_i)$. Then we can obtain a histogram of ρ that approximates the likelihood $\mathcal{L}(\rho(f_c); \epsilon_D)$ and depends on the value of ϵ_D. Then the value of ϵ_D, for which the observed value of the detection statistics $\rho_{\mathrm{obs}}(f_c)$ coincides with the 5% percentile of this realization, is identified as the 95% upper limit. We would like to emphasize that our method does not suffer from the numerical instability mentioned above and that it is applicable to arbitrary masses of DM.

IV. ANALYSIS

A. Data

We analyzed the O3GK data collected from the KAGRA detector in the observation mode, and the data from GEO600 is not used. During the O3GK run, the KAGRA detector had duty factors, the fraction of time the detector is in the observing mode to the total time, of ~53%. The length channels considered in this study are the differential Michelson interferometer length (MICH) and the power recycling cavity length (PRCL). For both the MICH and PRCL channels, calibrations of data were performed offline for this study, whose parameters and information are summarized in Ref. [42]. For the frequency

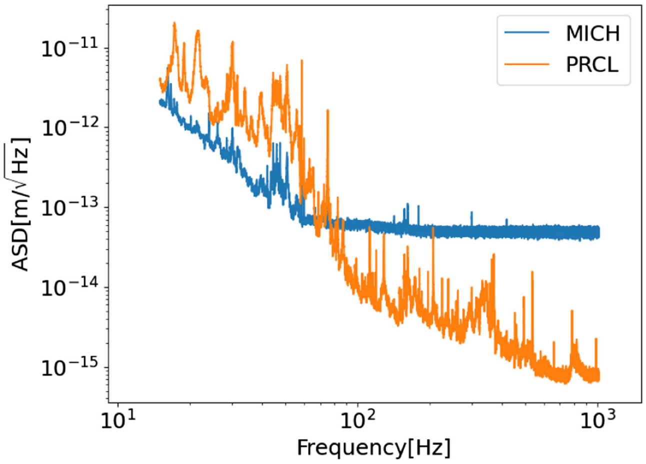

FIG. 3. ASDs of the MICH and PRCL estimated from the first 30 min chunk during O3GK.

band we used for the analysis, calibration uncertainty in MICH and PRCL channels are 20–30% in amplitude.

The amplitude spectral densities (ASDs), derived from $S(f_n; t_i)$, of these channels during O3GK are plotted in Fig. 3. We should note that, for the last few days of O3GK, alignments of mirrors were dithered at significantly large amplitude for the beam position control [31]. These injected lines were accompanied by a large number of sidebands. Since our pipeline simply searches power excesses within narrow bandwidth, it is not straightforward to distinguish those noise lines from the DM signals. Hence the segments from the last three days of the O3GK, where the efficiency of the DM search was spoiled, were not included in our analysis. Consequently, the number of 30 minute chunks subject to our pipeline was 217.

Another limitation is that the vibration isolation systems for mirrors in MICH and PRCL were simplified compared to those in the full-design [31]. Consequently, there are many noise peaks in the lower frequency range, where the KAGRA's auxiliary degrees of freedom become more and more sensitive. Although our pipeline can be used in the lower frequency range $\lesssim 10$ Hz, the analysis was performed over the frequency range from 15 Hz to 1015 Hz for this demonstration analysis.

B. Candidates and veto procedure

In Fig. 4, the detection statistics $\rho(f_c)$ computed in our pipeline are shown respectively for MICH and PRCL. As expected from the many lines in ASDs shown in Fig. 3, more non-Gaussian power excess within an expected signal bandwidth is observed in the PRCL data. Under the 5% false-alarm-probability derived from χ^2 distribution for Gaussian noise, 1944 and 4133 lines are identified as candidates for MICH and PRCL, respectively. These candidates are then subject to the veto analysis as follows. First, according to the expected narrow band feature of DM signal, the peak of $\rho(f_c)$ should also have a comparable width if it has DM origin. As illustrated in the top panel of Fig. 5, we vetoed candidates if the peak width of $\rho(f_c)$ is more than two times broader than the expected DM signal width $\Delta f = f_c \kappa^2 v_{\rm vir}^2/c^2 \simeq 10^{-6} f_c$. One may wonder whether we could reduce this broadening factor of 2 in our width criterion. Indeed, the power of the DM signal rapidly falls for higher frequencies as shown in Fig. 2. However, if the SNR is sufficiently large, a part of the high frequency tail can also be detected in our pipeline. While such a high SNR is not plausible for current detector sensitivity, we conservatively set the broadening factor to be 2. We also vetoed lines that were less than the peak width away from the vetoed peaks of ρ, as there is a possibility that they originated from the same source as those broad peaks. Note that to automate the analysis as much as possible, this veto is solely based on $\rho(f)$, not on the spectrum of the data. While we believe that this is sufficient for our present demonstrative study, we plan to check the consistency of the spectral shape of candidates that could not be vetoed in future analysis.

Second, in contrast to transient noise, expected to produce outliers in the O3GK data, DM signals should

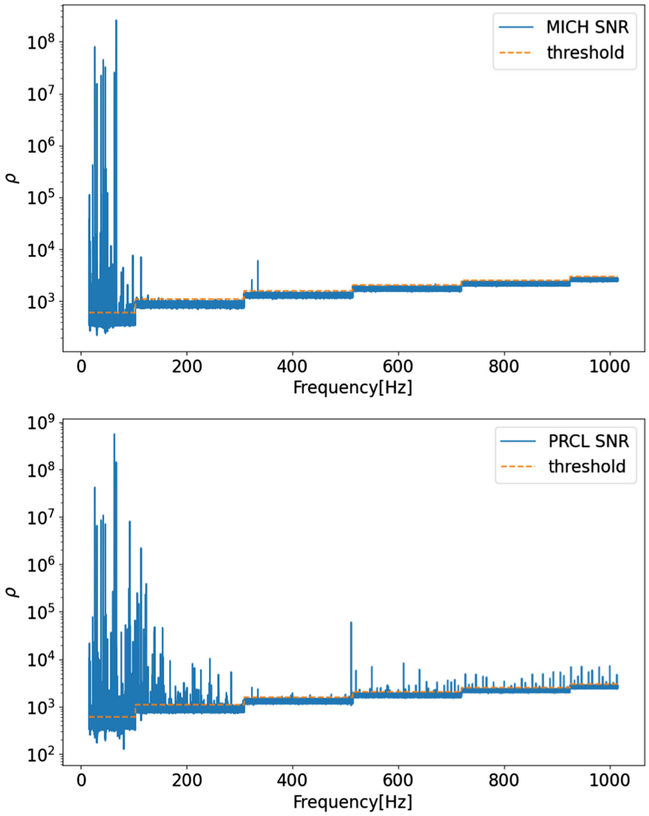

FIG. 4. The detection statistics ρ computed from 217 half-hour chunks during O3GK with MICH (top panel) and PRCL (bottom panel) channel. A step appears about every 200 Hz because of the increase in $N_{\rm bin}$, which varies from 1 to 6. The step height depends on the number of chunks.

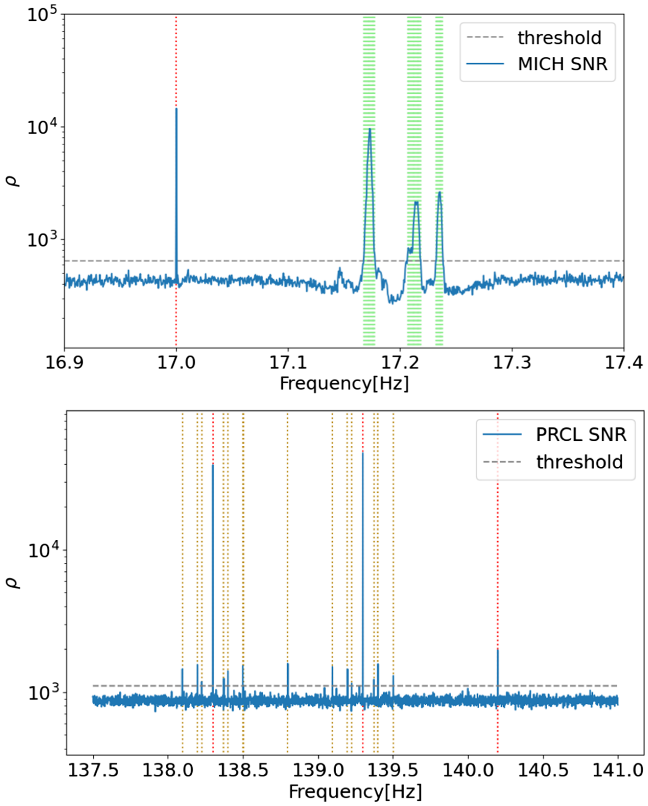

FIG. 5. A schematic picture of the veto procedure. For both cases, the vertical red lines denote surviving candidates after two veto procedure. Top panel: green vertical bands indicate the broad peak structures vetoed by the bandwidth criterion. Bottom panel: the yellow vertical lines represent candidates with power excess that fails coincidence requirements.

be more persistent on average, albeit with random statistical fluctuations. In the analysis, we chronologically divide the whole data chunks into two subsets and perform the same analyses within the first half 108 chunks and the second half 108 chunks. Then we take a coincidence between the candidates found in those two subsets to exclude transients that only appear during a limited duration. However, it must be noted that this procedure inevitably vetoes weaker DM signals with which $\rho(f_c)$ exceeds the detection threshold only after summing over all the chunks. Furthermore, unless the signal coherence time is sufficiently shorter than the data length of the subset, the field amplitude [and therefore the value of $\rho(f_c)$] can be significantly different for each subset. By examining the spectrum, we found that in the case of present data, such lines with the values of ρ close to the threshold are mostly sidebands of more intense lines, but this issue must be considered in future studies. For possible improvements to our veto procedure, see the discussion below.

After applying these two veto procedures, 77 lines remain as candidates in the MICH data while 202 lines remain in the PRCL data. Many of them are in the low frequency range below 100 Hz, where there are many lines due to injected signals and the suspension noise. By referring to, for example, the Appendix A. of Ref. [31] discussing the noise lines of DARM during O3GK, we found that 57 out of 77 lines in the MICH data and 54 out of 202 lines in the PRCL data come from known lines. Note that there were few dedicated studies of the line identification for MICH and PRCL channels during O3GK, and lines of unknown origin still remain. Therefore, for our future reference, the candidate lines identified in this study are listed in Ref. [43].

C. Upper limit

There are several lines that have passed our pipeline detection criteria, but they cannot be claimed as DM signals given the current level of displacement sensitivity shown in Fig. 3 and the much shorter total observation time, compared to those assumed in Ref. [3]. With the scaling of $\mathrm{SNR} \propto (N_{\mathrm{ch}}T)^{1/4}$, their prediction on upper limits derived by setting $\mathrm{SNR} = 1$ can be scaled to give an order of magnitude estimate of the upper limits we can derive from ρ. By comparing the design sensitivity (Fig. 2 in Ref. [3]) with our Fig. 3 and considering another suppression factor of $(N_{\mathrm{ch}} \cdot 30\ \mathrm{min}/1\ \mathrm{yr})^{1/4} \sim 0.01^{1/4}$ that comes from the difference between the real and assumed observation time, we expect that the upper limit on ϵ_{B-L} from O3GK data will be at best $\mathcal{O}(10^{-20})$. This is much weaker than those derived from the Eöt-Wash torsion balance [19,20] and MICROSCOPE [21–23], predicting 10^{-24} to 10^{-23} in the frequency band of our interest.

Therefore, the upper limit estimation here should be considered as a demonstration of our pipeline, which can accurately analyze low-frequency regions and high-frequency regions as well. As such a demonstration, upper limits on the coupling constant are derived over the whole frequency range analyzed in this study. Note that in principle, upper limits can be derived even for $\rho(f_c)$ that exceed the detection threshold.

In Fig. 6, 95% upper limits on the coupling constant ϵ_{B-L} are shown. Here the constraint is smoothed by collecting the maximum value of $\rho(f_c)$ within a 0.1 Hz bandwidth. For clarity, uncertainty of the calibration is not displayed. Let us stress that the stochastic nature of DM is properly taken into account in deriving this bound, by using the covariance of DM signal (11) for simulating the realization of $\rho(f_c)$. As demonstrated in Ref. [32], for example, incorrect deterministic treatment predicts a noncentral χ^2 distribution of $\rho(f_c)$ and overestimates the upper bound by up to a factor of 3 in low mass (or long coherence time) regions. We also found that our result is consistent with the above rough estimate on the upper limit based on the SNR scaling, which is also a consequence of the stochastic nature of ultralight DMs [3,32].

As expected, these upper limits derived from the KAGRA O3GK data are weaker than previous published

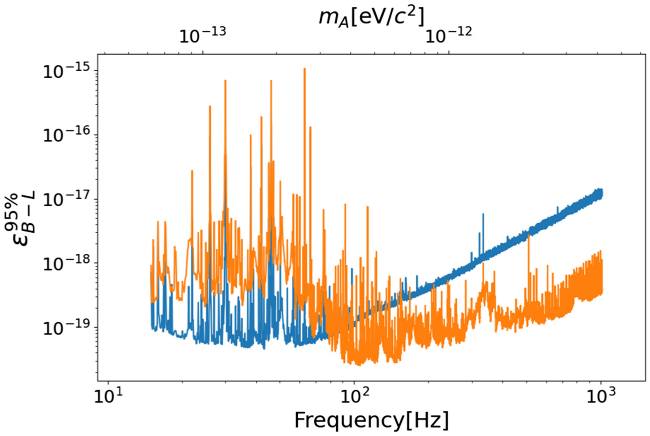

FIG. 6. 95% upper limit on the $B-L$ gauge coupling constant derived from MICH data (blue line) and PRCL data (orange line). Many narrow peaks observed in lower mass range are due to unknown line artifacts in the lower frequency range.

limits by several orders of magnitude. Again, this is owing to both the current noise level of the KAGRA detector and the limited duration of the measurement time. In order to reach the unexplored parameter space, reduction of the dominant low-frequency noise and longer stable detector operation are indispensable.

V. DISCUSSION

In this work, an ultralight vector DM search with KAGRA was conducted for the first time by using the KAGRA data from the O3GK run. Our pipeline design is guided by a recent study on the stochastic nature of the ultralight vector DM [32]. Consequently, the KAGRA O3GK data, which has a relatively short measurement time compared to the DM coherence time for low DM masses, can be analyzed.

We found that our pipeline can discriminate candidates for vector DM signal from the broad peaks and transient lines, which are expected to have an instrumental origin. Nonetheless, there are several lines with unspecified origin meeting our criteria, especially for the lower frequency range. We expect that the number of such lines will decrease in upcoming observations because of, for example, an updated system for the suspension control and an improved understanding of the noise. Although the upper limits derived in this analysis are weaker than previous ones, they are found to be consistent with the prediction given in prior studies [3,32]. Achieving the designed sensitivity and future upgrades of the KAGRA detector [44] will allow us to fully appreciate its unique feature as a vector DM detector exploiting the mirrors made of different materials to yield new constraints.

There are several directions for improving our DM search pipeline. First, as outlined in Sec. II, our analysis is performed assuming the equilibration of vector polarization. Depending on the production mechanism, however, only a specific polarization mode might be produced. Therefore, the formalism beyond this assumption may allow us to probe the cosmological origin of vector DM. Second, while the bandwidth criterion for the veto analysis is relatively robust, the appropriateness of taking coincidence between subsets of whole data should depend on the strength and coherence time of the signal being searched for. Since the covariance of the vector DM signal is known, it is possible to implement a test to check whether the candidates follow a distribution consistent with the given covariance. In addition to the use of spectral information mentioned in Sec. III B, this could provide a more robust way to distinguish a DM signal from the noise lines. Finally, our pipeline can be extended to include the analysis of the DARM channel data, which has been used in DM searches in other GW detectors.

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A. Ramos-Buades,[1] D. Rana,[15] E. Randel,[98] S. Ranjan,[53] P. Rapagnani,[107,60] B. Ratto,[43] S. Rawat,[89] A. Ray,[10]
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E. J. Sanchez,[2] J. H. Sanchez,[71] L. E. Sanchez,[2] N. Sanchis-Gual,[282,135] J. R. Sanders,[283] E. M. Sänger,[1]
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M. G. Schiworski,[88] P. Schmidt,[110] S. Schmidt,[68] R. Schnabel,[76] M. Schneewind,[13,14] R. M. S. Schofield,[69]
K. Schouteden,[101] H. Schuler,[9] B. W. Schulte,[13,14] B. F. Schutz,[19,13,14] E. Schwartz,[19] J. Scott,[26] S. M. Scott,[12]
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J. W. Seo,[101] V. Sequino,[29,6] A. Sergeev,[215] M. Serra,[60] G. Servignat,[264] Y. Setyawati,[68] T. Shaffer,[4] U. S. Shah,[53]
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H. Siegel,[159,178,179] M. Sieniawska,[115] D. Sigg,[4] L. Silenzi,[46,47] M. Simmonds,[88] L. P. Singer,[75] A. Singh,[201]
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A. Taruya,[299] J. D. Tasson,[172] M. Teloi,[33] R. Tenorio,[91] H. Themann,[194] A. Theodoropoulos,[135]
M. P. Thirugnanasambandam,[15] L. M. Thomas,[110] M. Thomas,[59] P. Thomas,[4] J. E. Thompson,[148] S. R. Thondapu,[95]
K. A. Thorne,[59] E. Thrane,[8] J. Tissino,[39] A. Tiwari,[15] Shubhanshu Tiwari,[176] Srishti Tiwari,[15] V. Tiwari,[110] M. R. Todd,[70]
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R. Tso,[148,‡] S. Tsuchida,[302] L. Tsukada,[9] T. Tsutsui,[36] K. Turbang,[175,106] M. Turconi,[44] C. Turski,[84] H. Ubach,[37,72]
A. S. Ubhi,[110] T. Uchiyama,[45] R. P. Udall,[2] T. Uehara,[303] K. Ueno,[36] C. S. Unnikrishnan,[255] T. Ushiba,[45]
A. Utina,[31,32] M. Vacatello,[20,77] H. Vahlbruch,[13,14] N. Vaidya,[2] G. Vajente,[2] A. Vajpeyi,[8] G. Valdes,[128]
J. Valencia,[91] M. Valentini,[99,32] S. A. Vallejo-Peña,[279] S. Vallero,[25] V. Valsan,[10] N. van Bakel,[32] M. van Beuzekom,[32]
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A. Van de Walle,[35] J. van Dongen,[32,99] K. Vandra,[94] H. van Haevermaet,[106] J. V. van Heijningen,[115] J. Vanosky,[2] M. H. P. M. van Putten,[305] Z. van Ranst,[31,32] N. van Remortel,[106] M. Vardaro,[31,32] A. F. Vargas,[129] V. Varma,[1] M. Vasúth,[74] A. Vecchio,[110] G. Vedovato,[81] J. Veitch,[26] P. J. Veitch,[88] S. Venikoudis,[115] J. Venneberg,[13,14] P. Verdier,[153] D. Verkindt,[28] B. Verma,[134] P. Verma,[173] Y. Verma,[95] S. M. Vermeulen,[2] D. Veske,[159] F. Vetrano,[57] A. Veutro,[60] A. M. Vibhute,[4] A. Viceré,[57,58] S. Vidyant,[70] A. D. Viets,[306] A. Vijaykumar,[21] A. Vilkha,[206] V. Villa-Ortega,[124] E. T. Vincent,[53] J.-Y. Vinet,[44] S. Viret,[153] A. Virtuoso,[252,42] S. Vitale,[30] H. Vocca,[78,46] D. Voigt,[76] E. R. G. von Reis,[4] J. S. A. von Wrangel,[13,14] S. P. Vyatchanin,[100] L. E. Wade,[67] M. Wade,[67] K. J. Wagner,[206] R. C. Walet,[32] M. Walker,[116] G. S. Wallace,[90] L. Wallace,[2] H. Wang,[190] J. Z. Wang,[79] W. H. Wang,[161] Z. Wang,[142] G. Waratkar,[139] R. L. Ward,[12] J. Warner,[4] M. Was,[28] T. Washimi,[22] N. Y. Washington,[2] D. Watarai,[36] K. E. Wayt,[67] B. Weaver,[4] C. R. Weaving,[122] S. A. Webster,[26] M. Weinert,[13,14] A. J. Weinstein,[2] R. Weiss,[30] C. M. Weller,[48] R. A. Weller,[192] F. Wellmann,[13,14] L. Wen,[27] P. Weßels,[13,14] K. Wette,[12] J. T. Whelan,[206] D. D. White,[50] B. F. Whiting,[40] C. Whittle,[30] J. B. Wildberger,[1] O. S. Wilk,[67] D. Wilken,[13,14,14] K. Willetts,[19] D. Williams,[26] M. J. Williams,[26] N. S. Williams,[110] J. L. Willis,[2] B. Willke,[14,13,14] M. Wils,[101] C. C. Wipf,[2] G. Woan,[26] J. Woehler,[31,32] J. K. Wofford,[206] N. E. Wolfe,[30] D. Wong,[138] H. T. Wong,[142] H. W. Y. Wong,[137] I. C. F. Wong,[137] J. L. Wright,[12] M. Wright,[26] C. Wu,[141] D. S. Wu,[13,14] H. Wu,[141] D. M. Wysocki,[10] L. Xiao,[2] V. A. Xu,[30] Y. Xu,[176] N. Yadav,[85] H. Yamamoto,[2] K. Yamamoto,[151] M. Yamamoto,[151] T. S. Yamamoto,[238] T. Yamamoto,[45] S. Yamamura,[152] R. Yamazaki,[257] S. Yan,[18] T. Yan,[110] F. W. Yang,[186] F. Yang,[159] K. Z. Yang,[89] L.-C. Yang,[145] Y. Yang,[145] Z. Yarbrough,[11] S.-W. Yeh,[141] A. B. Yelikar,[206] S. M. C. Yeung,[10] X. Yin,[30] J. Yokoyama,[36] T. Yokozawa,[45] J. Yoo,[149] H. Yu,[148] H. Yuzurihara,[45] A. Zadrożny,[173] A. J. Zannelli,[116] M. Zanolin,[43] M. Zeeshan,[206] T. Zelenova,[52] J.-P. Zendri,[81] M. Zeoli,[111,115] M. Zerrad,[34,228] M. Zevin,[71] A. C. Zhang,[159] J. Zhang,[12] L. Zhang,[2] R. Zhang,[40] T. Zhang,[110] Y. Zhang,[12] C. Zhao,[27] Yue Zhao,[186] Yuhang Zhao,[152,22,63] Y. Zheng,[97] H. Zhong,[89] S. Zhong,[27] R. Zhou,[208] Z.-H. Zhu,[127,307] A. B. Zimmerman,[147] M. E. Zucker,[30,2] and J. Zweizig[2]

(LIGO Scientific, Virgo, and KAGRA Collaborations)

[1]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany*
[2]*LIGO Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[3]*Graduate School of Science, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan*
[4]*LIGO Hanford Observatory, Richland, Washington 99352, USA*
[5]*Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[6]*INFN, Sezione di Napoli, I-80126 Napoli, Italy*
[7]*University of Warwick, Coventry CV4 7AL, United Kingdom*
[8]*OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
[9]*The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
[10]*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*
[11]*Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[12]*OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia*
[13]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany*
[14]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[15]*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[16]*University of Cambridge, Cambridge CB2 1TN, United Kingdom*
[17]*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*
[18]*Stanford University, Stanford, California 94305, USA*
[19]*Cardiff University, Cardiff CF24 3AA, United Kingdom*
[20]*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[21]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
[22]*Gravitational Wave Science Project, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
[23]*Advanced Technology Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
[24]*Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy*
[25]*INFN Sezione di Torino, I-10125 Torino, Italy*
[26]*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

[27]*OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia*
[28]*Université Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules—IN2P3, F-74000 Annecy, France*
[29]*Università di Napoli "Federico II," I-80126 Napoli, Italy*
[30]*LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[31]*Maastricht University, 6200 MD Maastricht, Netherlands*
[32]*Nikhef, 1098 XG Amsterdam, Netherlands*
[33]*Université Libre de Bruxelles, Brussels 1050, Belgium*
[34]*Institut Fresnel, Aix Marseille Université, CNRS, Centrale Marseille, F-13013 Marseille, France*
[35]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[36]*University of Tokyo, Tokyo, 113-0033, Japan*
[37]*Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain*
[38]*Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, E-08193 Bellaterra (Barcelona), Spain*
[39]*Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*
[40]*University of Florida, Gainesville, Florida 32611, USA*
[41]*Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy*
[42]*INFN, Sezione di Trieste, I-34127 Trieste, Italy*
[43]*Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA*
[44]*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Artemis, F-06304 Nice, France*
[45]*Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan*
[46]*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
[47]*Università di Camerino, I-62032 Camerino, Italy*
[48]*University of Washington, Seattle, Washington 98195, USA*
[49]*Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan*
[50]*California State University Fullerton, Fullerton, California 92831, USA*
[51]*INFN, Sezione di Genova, I-16146 Genova, Italy*
[52]*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[53]*Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
[54]*Chennai Mathematical Institute, Chennai 603103, India*
[55]*Royal Holloway, University of London, London TW20 0EX, United Kingdom*
[56]*The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
[57]*Università degli Studi di Urbino "Carlo Bo," I-61029 Urbino, Italy*
[58]*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
[59]*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*
[60]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[61]*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
[62]*Dipartimento di Fisica "E.R. Caianiello," Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[63]*Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France*
[64]*King's College London, University of London, London WC2R 2LS, United Kingdom*
[65]*Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea*
[66]*Université libre de Bruxelles, 1050 Bruxelles, Belgium*
[67]*Kenyon College, Gambier, Ohio 43022, USA*
[68]*Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, 3584 CC Utrecht, Netherlands*
[69]*University of Oregon, Eugene, Oregon 97403, USA*
[70]*Syracuse University, Syracuse, New York 13244, USA*
[71]*Northwestern University, Evanston, Illinois 60208, USA*
[72]*Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franqués, 1, 08028 Barcelona, Spain*
[73]*Dipartimento di Medicina, Chirurgia e Odontoiatria "Scuola Medica Salernitana," Università di Salerno, I-84081 Baronissi, Salerno, Italy*
[74]*Wigner RCP, RMKI, H-1121 Budapest, Hungary*
[75]*NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
[76]*Universität Hamburg, D-22761 Hamburg, Germany*
[77]*Università di Pisa, I-56127 Pisa, Italy*
[78]*Università di Perugia, I-06123 Perugia, Italy*

[79]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[80]*Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
[81]*INFN, Sezione di Padova, I-35131 Padova, Italy*
[82]*Montana State University, Bozeman, Montana 59717, USA*
[83]*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
[84]*Universiteit Gent, B-9000 Gent, Belgium*
[85]*Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland*
[86]*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
[87]*Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy*
[88]*OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia*
[89]*University of Minnesota, Minneapolis, Minnesota 55455, USA*
[90]*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
[91]*IAC3–IEEC, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain*
[92]*Departamento de Matemáticas, Universitat Autònoma de Barcelona,*
08193 Bellaterra (Barcelona), Spain
[93]*Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany*
[94]*Villanova University, Villanova, Pennsylvania 19085, USA*
[95]*RRCAT, Indore, Madhya Pradesh 452013, India*
[96]*GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics,*
University of Amsterdam, 1098 XH Amsterdam, Netherlands
[97]*Missouri University of Science and Technology, Rolla, Missouri 65409, USA*
[98]*Colorado State University, Fort Collins, Colorado 80523, USA*
[99]*Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands*
[100]*Lomonosov Moscow State University, Moscow 119991, Russia*
[101]*Katholieke Universiteit Leuven, Oude Markt 13, 3000 Leuven, Belgium*
[102]*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
[103]*INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
[104]*Bar-Ilan University, Ramat Gan, 5290002, Israel*
[105]*INFN, Sezione di Napoli, Gruppo Collegato di Salerno, I-80126 Napoli, Italy*
[106]*Universiteit Antwerpen, 2000 Antwerpen, Belgium*
[107]*Università di Roma “La Sapienza,” I-00185 Roma, Italy*
[108]*Centre national de la recherche scientifique, 75016 Paris, France*
[109]*Univ Rennes, CNRS, Institut FOTON—UMR 6082, F-35000 Rennes, France*
[110]*University of Birmingham, Birmingham B15 2TT, United Kingdom*
[111]*Université de Liège, B-4000 Liège, Belgium*
[112]*Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain*
[113]*INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
[114]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France,*
F-75005 Paris, France
[115]*Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[116]*Christopher Newport University, Newport News, Virginia 23606, USA*
[117]*Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland*
[118]*University of Maryland, College Park, Maryland 20742, USA*
[119]*Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy*
[120]*INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy*
[121]*L2IT, Laboratoire des 2 Infinis—Toulouse, Université de Toulouse,*
CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France
[122]*University of Portsmouth, Portsmouth, PO1 3FX, United Kingdom*
[123]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière,*
F-69622 Villeurbanne, France
[124]*IGFAE, Universidade de Santiago de Compostela, 15782 Spain*
[125]*University of Chicago, Chicago, Illinois 60637, USA*
[126]*University of California, Riverside, Riverside, California 92521, USA*
[127]*Department of Astronomy, Beijing Normal University, Xinjiekouwai Street 19, Haidian District,*
Beijing 100875, China
[128]*Texas A&M University, College Station, Texas 77843, USA*
[129]*OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia*
[130]*INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy*
[131]*Niels Bohr Institute, Copenhagen University, 2100 København, Denmark*
[132]*Università di Roma Tor Vergata, I-00133 Roma, Italy*

[133]*University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
[134]*University of Massachusetts Dartmouth, North Dartmouth, Massachusetts 02747, USA*
[135]*Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
[136]*Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain*
[137]*The Chinese University of Hong Kong, Shatin, NT, Hong Kong*
[138]*University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada*
[139]*Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India*
[140]*Department of Physics, National Cheng Kung University, No. 1, University Road, Tainan City 701, Taiwan*
[141]*National Tsing Hua University, Hsinchu City 30013, Taiwan*
[142]*National Central University, Taoyuan City 320317, Taiwan*
[143]*OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
[144]*Queen Mary University of London, London E1 4NS, United Kingdom*
[145]*Department of Electrophysics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan*
[146]*Kamioka Branch, National Astronomical Observatory of Japan, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan*
[147]*University of Texas, Austin, Texas 78712, USA*
[148]*CaRT, California Institute of Technology, Pasadena, California 91125, USA*
[149]*Cornell University, Ithaca, New York 14850, USA*
[150]*Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[151]*Faculty of Science, University of Toyama, 3190 Gofuku, Toyama City, Toyama 930-8555, Japan*
[152]*Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan*
[153]*Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
[154]*INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy*
[155]*OzGrav, Swinburne University of Technology, Hawthorn Victoria 3122, Australia*
[156]*INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy*
[157]*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
[158]*Texas Tech University, Lubbock, Texas 79409, USA*
[159]*Columbia University, New York, New York 10027, USA*
[160]*University of Rhode Island, Kingston, Rhode Island 02881, USA*
[161]*The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA*
[162]*Bellevue College, Bellevue, Washington 98007, USA*
[163]*Scuola Normale Superiore, I-56126 Pisa, Italy*
[164]*Università degli Studi di Sassari, I-07100 Sassari, Italy*
[165]*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
[166]*Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
[167]*Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy*
[168]*INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy*
[169]*Perimeter Institute, Waterloo, Ontario N2L 2Y5, Canada*
[170]*Corps des Mines, Mines Paris, Université PSL, 60 Bd Saint-Michel, 75272 Paris, France*
[171]*Indian Institute of Technology Madras, Chennai 600036, India*
[172]*Carleton College, Northfield, Minnesota 55057, USA*
[173]*National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland*
[174]*Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 75014 Paris, France*
[175]*Vrije Universiteit Brussel, 1050 Brussel, Belgium*
[176]*University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[177]*Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada*
[178]*Stony Brook University, Stony Brook, New York 11794, USA*
[179]*Center for Computational Astrophysics, Flatiron Institute, New York, New York 10010, USA*
[180]*Montclair State University, Montclair, New Jersey 07043, USA*
[181]*Institute for Nuclear Research, H-4026 Debrecen, Hungary*
[182]*CNR-SPIN, I-84084 Fisciano, Salerno, Italy*

[183]Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
[184]Western Washington University, Bellingham, Washington 98225, USA
[185]SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom
[186]The University of Utah, Salt Lake City, Utah 84112, USA
[187]Eötvös University, Budapest 1117, Hungary
[188]Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, PT-4710-057 Braga, Portugal
[189]Department of Physics, Graduate School of Science, Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
[190]Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[191]Waseda Institute for Advanced Study, Waseda University, 1-6-1 Nishi-Waseda, Shinjuku, Tokyo 169-8050, Japan
[192]Vanderbilt University, Nashville, Tennessee 37235, USA
[193]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, F-06304 Nice, France
[194]California State University, Los Angeles, Los Angeles, California 90032, USA
[195]Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
[196]University of Szeged, Dóm tér 9, Szeged 6720, Hungary
[197]INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
[198]Ariel University, Ramat HaGolan St 65, Ari'el, Israel
[199]Université de Normandie, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France
[200]Laboratoire de Physique Corpusculaire Caen, 6 boulevard du maréchal Juin, F-14050 Caen, France
[201]The University of Mississippi, University, Mississippi 38677, USA
[202]Institute of Physics, Academia Sinica, 128 Sec. II, Academia Road, Nankang, Taipei 11529, Taiwan
[203]Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
[204]American University, Washington, DC 20016, USA
[205]University of Nevada, Las Vegas, Las Vegas, Nevada 89154, USA
[206]Rochester Institute of Technology, Rochester, New York 14623, USA
[207]Department of Applied Physics, Fukuoka University, 8-19-1 Nanakuma, Jonan, Fukuoka City, Fukuoka 814-0180, Japan
[208]University of California, Berkeley, California 94720, USA
[209]University of Lancaster, Lancaster LA1 4YW, United Kingdom
[210]College of Industrial Technology, Nihon University, 1-2-1 Izumi, Narashino City, Chiba 275-8575, Japan
[211]Faculty of Engineering, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan
[212]Department of Physics, Tamkang University, No. 151, Yingzhuan Road, Danshui District, New Taipei City 25137, Taiwan
[213]Rutherford Appleton Laboratory, Didcot OX11 0DE, United Kingdom
[214]Department of Astronomy and Space Science, Chungnam National University, 9 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea
[215]Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
[216]Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Road 5, Haidian District, Beijing 100871, China
[217]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
[218]Directorate of Construction, Services & Estate Management, Mumbai 400094, India
[219]University of Białystok, 15-424 Białystok, Poland
[220]National Astronomical Observatories, Chinese Academic of Sciences, 20A Datun Road, Chaoyang District, Beijing, China
[221]School of Astronomy and Space Science, University of Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, China
[222]University of Southampton, Southampton SO17 1BJ, United Kingdom
[223]Department of Physics, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea
[224]Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan
[225]Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands
[226]Chung-Ang University, Seoul 06974, Republic of Korea

[227]*University of Washington Bothell, Bothell, Washington 98011, USA*
[228]*Aix Marseille Université, Jardin du Pharo, 58 Boulevard Charles Livon, 13007 Marseille, France*
[229]*Laboratoire de Physique et de Chimie de l'Environnement, Université Joseph KI-ZERBO, 9GH2+3V5, Ouagadougou, Burkina Faso*
[230]*Ewha Womans University, Seoul 03760, Republic of Korea*
[231]*Seoul National University, Seoul 08826, Republic of Korea*
[232]*Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea*
[233]*Sungkyunkwan University, Seoul 03063, Republic of Korea*
[234]*National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea*
[235]*Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki 305-0801, Japan*
[236]*Bard College, Annandale-On-Hudson, New York 12504, USA*
[237]*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
[238]*Department of Physics, Nagoya University, ES building, Furocho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan*
[239]*Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
[240]*Inje University Gimhae, South Gyeongsang 50834, Republic of Korea*
[241]*NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France*
[242]*Università di Firenze, Sesto Fiorentino I-50019, Italy*
[243]*Department of Physics, University of Trento, via Sommarive 14, Povo, 38123 Tennessee, Italy*
[244]*National Center for High-performance computing, National Applied Research Laboratories, No. 7, R&D 6th Road, Hsinchu Science Park, Hsinchu City 30076, Taiwan*
[245]*NASA Marshall Space Flight Center, Huntsville, Alabama 35811, USA*
[246]*West Virginia University, Morgantown, West Virginia 26506, USA*
[247]*Department of Physics, Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
[248]*School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*
[249]*Institut d'Estudis Espacials de Catalunya, c. Gran Capità, 2-4, 08034 Barcelona, Spain*
[250]*Institucio Catalana de Recerca i Estudis Avançats (ICREA), Passeig de Lluís Companys, 23, 08010 Barcelona, Spain*
[251]*Tsinghua University, Beijing 100084, China*
[252]*Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
[253]*Institute for Photon Science and Technology, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan*
[254]*INFN Cagliari, Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy*
[255]*Tata Institute of Fundamental Research, Mumbai 400005, India*
[256]*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
[257]*Department of Physical Sciences, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara City, Kanagawa 252-5258, Japan*
[258]*Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
[259]*Faculty of Law, Ryukoku University, 67 Fukakusa Tsukamoto-cho, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan*
[260]*Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India*
[261]*Department of Physics and Astronomy, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, Indiana 46556, USA*
[262]*University of Stavanger, 4021 Stavanger, Norway*
[263]*Department of Astronomy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[264]*Laboratoire Univers et Théories, Observatoire de Paris, 92190 Meudon, France*
[265]*Observatoire de Paris, 75014 Paris, France*
[266]*Université PSL, 75006 Paris, France*
[267]*Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8583, Japan*
[268]*Université de Paris Cité, 75006 Paris, France*
[269]*Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
[270]*Niigata Study Center, The Open University of Japan, 754 Ichibancho, Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8122, Japan*
[271]*CSIR-Central Glass and Ceramic Research Institute, Kolkata, West Bengal 700032, India*
[272]*Consiglio Nazionale delle Ricerche—Istituto dei Sistemi Complessi, I-00185 Roma, Italy*
[273]*Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece*

[274]*Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi," I-00184 Roma, Italy*
[275]*Dipartimento di Ingegneria Industriale, Elettronica e Meccanica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
[276]*INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
[277]*Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy*
[278]*Subatech, CNRS/IN2P3—IMT Atlantique—Nantes Université, 4 rue Alfred Kastler BP 20722 44307 Nantes CÉDEX 03, France*
[279]*Universidad de Antioquia, Medellín, Colombia*
[280]*Departamento de Física—ETSIDI, Universidad Politécnica de Madrid, 28012 Madrid, Spain*
[281]*Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, 888 Nishikatakai, Nagaoka City, Niigata 940-8532, Japan*
[282]*Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications, 3810-183 Aveiro, Portugal*
[283]*Marquette University, Milwaukee, Wisconsin 53233, USA*
[284]*Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi City, Chiba 274-8510, Japan*
[285]*Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India*
[286]*Laboratoire MississippiME, Cité Descartes, 5 Boulevard Descartes, Champs-sur-Marne, 77454 Marne-la-Vallée Cedex 2, France*
[287]*Graduate School of Science and Technology, Gunma University, 4-2 Aramaki, Maebashi, Gunma 371-8510, Japan*
[288]*Institute for Quantum Studies, Chapman University, 1 University Dr., Orange, California 92866, USA*
[289]*Faculty of Information Science and Technology, Osaka Institute of Technology, 1-79-1 Kitayama, Hirakata City, Osaka 573-0196, Japan*
[290]*INAF, Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy*
[291]*Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India*
[292]*Indian Institute of Science Education and Research, Pune, Maharashtra 411008, India*
[293]*Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Max-von-Laue-Straße 1, 60438 Frankfurt am Main, Germany*
[294]*Istituto di Astrofisica e Planetologia Spaziali di Roma, 00133 Roma, Italy*
[295]*INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy*
[296]*Universidade Estadual Paulista, 01140-070 Campinas, São Paulo, Brazil*
[297]*Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, 8-15-1 Todoroki, Setagaya, Tokyo 158-0082, Japan*
[298]*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*
[299]*Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
[300]*University of Catania, Department of Physics and Astronomy, Via S. Sofia, 64, 95123 Catania CT, Italy*
[301]*Dipartimento di Scienze Aziendali—Management and Innovation Systems (DISA-MiguelanS), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[302]*National Institute of Technology, Fukui College, Geshi-cho, Sabae-shi, Fukui 916-8507, Japan*
[303]*Department of Communications Engineering, National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka City, Kanagawa 239-8686, Japan*
[304]*Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands*
[305]*Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea*
[306]*Concordia University Wisconsin, Mequon, Wisconsin 53097, USA*
[307]*School of Physics and Technology, Wuhan University, Bayi Road 299, Wuchang District, Wuhan, Hubei, 430072, China*

[†]Deceased, November 2022.
[‡]Deceased, July 2023.