Form 8

Research Result Report
ICRR Inter-University Research Program 2024

Research Subject: Test Run Analysis of KAGRA O4 data for Stochastic Gravitational-Wave Background Search
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Summary of Research Result :

Abstract

This project aims to explore the potential of incorporating KAGRA data into future stochastic gravitational-wave background (SGWB) analyses. Although KAGRA's sensitivity is currently limited compared to other detectors, we carried out a test analysis using data from the O4 observing run to evaluate the stability and quality of the KAGRA data stream. As part of this effort, we also participated in on-site detector characterization work at the KAGRA facility, particularly in understanding and mitigating lock loss events, and contributed to the development of the veto definer file.

To further enhance KAGRA's scientific value in SGWB searches, we proposed a novel 4-point cross-correlation method that can access non-Gaussian

features in the background—such as those arising from binary black hole mergers. This approach enables a unique role for KAGRA, even with lower sensitivity, by leveraging the full four-detector network in a way that cannot be achieved through standard two-detector correlations alone. Our study demonstrates that, with appropriate analysis techniques, KAGRA can meaningfully contribute to future SGWB investigations.

Introduction

Stochastic Gravitational-Wave Background

The stochastic gravitational-wave background is expected to arise from the superposition of a large number of unresolved gravitational-wave sources, such as those originating from the early universe (e.g., phase transitions, cosmic strings) or from numerous astrophysical events (e.g., compact binary mergers). Detecting the SGWB would open a new observational window into previously inaccessible epochs and energy scales of the universe, offering valuable insights into early-universe physics, high-energy models, and the population of distant gravitational-wave sources. As such, searching for the SGWB is one of the central goals of modern gravitational-wave astronomy, linking observational efforts to fundamental cosmology and theoretical physics.

Importance of KAGRA's Participation

KAGRA is the world's first underground, cryogenically-cooled laser interferometer designed for gravitational-wave detection. Its participation in the international LIGO-Virgo-KAGRA (LVK) network provides a geographically and technically complementary baseline that enhances the sensitivity and directional resolution of the global detector array in stochastic background searches. When all four detectors—two LIGO sites, Virgo, and KAGRA—are operating simultaneously, we are presented with a unique opportunity to perform four-detector cross-correlation analyses. Such analyses not only improve the robustness of stochastic background searches but also allow us to probe non-Gaussian features of the background, such as intermittent signals potentially arising from compact binary coalescences like binary black hole mergers. By leveraging this multi-detector configuration, we can go beyond standard Gaussian assumptions and explore richer statistical structures in the gravitational-wave background, offering a deeper understanding of its astrophysical origins. This test analysis project utilizes data from KAGRA and other detectors to validate the analysis pipeline and assess KAGRA's contribution to the scientific capability of the full detector network.

Objectives and Site Activities Involving KAGRA

Although KAGRA data were not included in the LIGO-Virgo stochastic gravitational-wave background (SGWB) analysis during the O4 run due to its limited sensitivity, we aim to explore how KAGRA data can contribute to future joint analyses. Our current study serves two main purposes: first, to assess the quality and characteristics of KAGRA data during O4; second, to identify what additional developments or information are needed for KAGRA to participate effectively in future LIGO-Virgo SGWB searches. By gaining a deeper understanding of KAGRA's data properties and limitations, we hope to pave the way for its inclusion in upcoming observing runs.

Despite the sensitivity limitations, we propose a novel four-point cross-correlation method that can target non-Gaussian features associated with binary black hole (BBH) mergers. This approach leverages the unique configuration of four detectors—LIGO Hanford, LIGO Livingston, Virgo, and KAGRA—and allows us to investigate intermittent signals that are not well captured by standard two-detector correlation analyses. In this framework, KAGRA plays a crucial and irreplaceable role, enabling us to probe aspects of the SGWB that would otherwise be inaccessible. Our analysis not only highlights KAGRA's potential scientific value but also outlines a path toward its future integration into global SGWB efforts.

Methodology

Checking KAGRA Data Qualities with Official Pipeline

Currently, the stochastic gravitational-wave background (SGWB) has not yet been detected by ground-based interferometers. Therefore, the primary goal of such searches is to estimate the energy density of the SGWB and to establish upper limits based on observational data,

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f},$$

where ρ_{GW} is the energy density of gravitational-wave background, ρ_c is the critical density to make the universe.

The official search method employed in the stochastic working group is the cross-correlation of the data in two detectors. Assuming the noise in two detectors are not correlated, it follows that the expected correlation of the data is just the correlation of the gravitational-wave signal in two detectors $\langle d_I d_J \rangle = \langle h_I h_J \rangle$. And the correlation of the signals of two detectors in Fourier domain directly measure the spectral density of the gravitational-wave, ,

$$\left\langle \tilde{h}_I^*(f)\tilde{h}_J(f)\right\rangle = \frac{1}{2}\delta(f-f')\Gamma_{IJ}(f)S_h(f),$$

where $\tilde{h}$ is the strain data in Fourier domain, f is the frequency, $\Gamma_{IJ}(f)$ is the so-called overlap function of the two detectors, which describes the geometry information such as alignments of the arms, relative vertex directions of two interferometers I and J. The spectral density of gravitational-wave, is related to the gravitational-wave energy density by

$$S_h(f) = \frac{3H_0^2}{2\pi^2}\frac{\Omega_{GW}(f)}{f^3},$$

where H_0 is the Hubble constant. This methodology has been used to search for isotropic gravitational-wave background for several observing runs [1, 2]. And we have developed a new pipeline, pygwb, a python-based pipeline, to analyze the data[3].

During the O4a period, KAGRA had approximately one month of observation time, starting from May 24, 2024. Coincidentally, both LIGO detectors, H1 and L1, were also operating during this period. This overlap provided a valuable opportunity to compute the cross-correlation for the H1—K1 and L1—K1 baselines. At that time, however, Virgo was not in operation, so cross-correlation analysis involving Virgo could not be performed.

To assess the quality of KAGRA's data, we employed a standard 1-second time-shift technique on one of the detector's data streams. This method enables statistical consistency checks by removing genuine gravitational-wave correlations. Notably, we found that both H1—K1 and L1—K1 baselines passed the Kolmogorov—Smirnov (KS) test, indicating that the noise in KAGRA and LIGO data is consistent with Gaussian statistics. Figure 1 presents the KS test result for the H1—K1 baseline, and we observed similar results for the L1—K1 pair.

The delta sigma cut was also applied in our analysis. If the uncertainty of a point estimate deviated beyond a specified threshold between neighboring segments, the affected segment was removed to suppress the influence of non-Gaussian noise. Over the one-month observation period, only a few percentage of the data was excluded by this cut—comparable to the rate observed in the two LIGO detectors—indicating that the KAGRA data was highly stable during the observing run.

Some glitches were identified in KAGRA's data and were automatically gated by the pipeline. In the O4a analysis of the H1—L1 baseline, we observed several long-duration gates (on the order of tens of seconds), which were associated with interferometer-related issues. To improve analysis efficiency, such long gates are required to be documented in the veto definer file. Similar long gates were also found in the H1—K1 and L1—K1 baselines; however, we determined that these were caused by glitches in the LIGO interferometers. In contrast, most of the gates in KAGRA data were short-duration IPC glitches. The overall gating fraction in KAGRA was less than 0.05%, indicating a high level of data stability.

We also found that there is currently no veto definer file available, which records the timing of long glitches in the science-mode data. After discussions with members of the detector characterization (DetChar) group, we confirmed that the KAGRA team can generate such a file. Creating this veto definer file is one of the important preparatory steps for KAGRA's participation in the SGWB analysis during the O5 run.

On site Lock Loss Studies

To maximize the amount of data available for scientific analysis within a fixed observation period, it is essential to improve the duty cycle of science-mode data. Therefore, understanding and mitigating lock loss events is critical for enhancing both the duty cycle and data quality of KAGRA. Lock loss occurs when the interferometer loses resonance in one or more of its optical cavities, often due to environmental disturbances, control system instabilities, or transient glitches. Frequent lock losses not only reduce the usable observation time but can also introduce artifacts near segment boundaries, thereby degrading the sensitivity of gravitational-wave searches—particularly in stochastic background analyses.

To contribute to resolving this issue, two students from my lab and I visited the KAGRA site from January 20 to January 24, 2025, supported by the ICRR Inter-University Program and additional funding from Taiwan. By systematically investigating the causes and characteristics of lock loss at KAGRA, we aim to identify the dominant sources and develop mitigation strategies to ensure more stable and continuous operation in future observation runs.

During our one-week stay in Kamioka, we focused on two main investigations. The first involved examining the Beam Position Control (BPC) signals. Prior to our visit, transient behavior and feedback signals in the BPC system were observed to coincide, raising the possibility that additional noise in the LSC-DARM channel might mimic beam spot shifts, inadvertently causing feedback signals to drift the suspension. To explore this further, we analyzed the behavior of the POP channel preceding lock loss events. We categorized BPC-related anomalies into two types: (a) burst-like signals occurring less than two seconds before lock loss, and (b) multiple signals appearing within one minute prior to lock loss. However, we found no clear coincidence between these BPC signals and POP channel behavior. We also reported instances of BPC drift prior to lock loss, but further investigation is needed to draw definitive conclusions.

The second investigation focused on excess low-frequency power in the PRCL and MICH channels preceding lock loss. We examined amplitude increases in other channels associated with these excess-power events. After reviewing all lock loss events related to PRCL and MICH low-frequency excursions from December 2024 to January 2025, we found that amplitude increases in other channels were not consistently coincident. We therefore conclude that these issues are not strongly correlated. This work is closely connected to the ongoing commissioning efforts at KAGRA.

New Proposal: Four-Point Cross-Correlation

Cross-correlating data from two detectors is an optimal method for studying the stochastic gravitational-wave background (SGWB), assuming the background signals are Gaussian. This assumption is generally valid, as the SGWB arises from the superposition of many faint, unresolved gravitational-wave signals. According to the central limit theorem, such a superposition results in a Gaussian distribution. However, based on current estimates of the duty cycle of binary black hole (BBH) mergers, these signals are expected to be intermittent, producing a non-Gaussian background. Higher-order statistics, such as fourth-order correlations, can help disentangle the non-Gaussian contribution from the dominant Gaussian components.

Following the proposal in Seto 2009[4], we define a Kurtosis parameter,

$$K = \left\langle s_H^* s_L^* s_V s_K \right\rangle - \left\langle s_H^* s_L^* \right\rangle \left\langle s_V s_K \right\rangle - \left\langle s_H^* s_V \right\rangle \left\langle s_H^* s_K \right\rangle - \left\langle s_H^* s_K \right\rangle \left\langle s_L^* s_V \right\rangle,$$

where s_X is the data in Fourier domain with $X = \{H, L, V, K\}$ four ground-based detectors. The signals in each detectors can be classified into the Gaussian and non-Gaussian background produced by intermittent signals. For Gaussian signals in four detectors, we have,

$$\left\langle X_1 X_2 X_3 X_4 \right\rangle = \left\langle X_1 X_2 \right\rangle \left\langle X_3 X_4 \right\rangle + \left\langle X_1 X_3 \right\rangle \left\langle X_2 X_4 \right\rangle + \left\langle X_1 X_4 \right\rangle \left\langle X_2 X_3 \right\rangle,$$

so the last three terms in the Kurtosis parameter can be used to remove the Gaussian background. With some details derivation, the Kurtosis parameter becomes,

$$K = q\gamma_4 \left\langle (v\,v*)^2 \right\rangle_P - q^2 \gamma^{I*}_{HL}\gamma^{I}_{VK} \left\langle v^{*2} \right\rangle_P \left\langle v^2 \right\rangle_P - q^2 \gamma^{II}_{HV}\gamma^{II}_{LK} \left(\langle v\,v* \rangle_P \right)^2 - q^2 \gamma^{II}_{HK}\gamma^{II}_{LV} \left(\langle v\,v* \rangle_P \right)^2$$

, where v is the intermittent signals, $\langle\rangle_P$ is the population average, q is the average event number in one segment, γ_4 is the overlap reduction function of four detectors and γ_{XY} are overlap reduction function of any pair of detectors. According to the current event rate of binary black holes, if we take 4 seconds as the segment duration, the $q \sim 10^{-3}$. We can further omit the high order terms with q^2. The final result is

$$K = q\gamma_4 \left\langle (v\,v*)^2 \right\rangle_P.$$

Because the waveform of BBH is well known, we can compute the population average spectrum $\left\langle (v\,v*)^2 \right\rangle_P$ if we have the information of population for BBH. We forecast the detectability of the signal using one year of data from the O5 detectors. For LIGO, we adopt the A+ design sensitivity curve, and for Virgo, the advanced design sensitivity. For KAGRA, we use the sensitivity curve corresponding to a binary neutron star (BNS) range of 80 Mpc. This choice is slightly optimistic. The ordering of the four detectors in the kurtosis parameter can affect detectability due to differences in their responses governed by the overlap reduction functions. We pick up the most sensitive case, in which the order is $\{H, L, V, K\}$.

The population information can be obtained from the LIGO-Virgo-KAGRA released BBH catalog. We adopt a power law model for the primary mass distribution, i.e., $p(M_1) \propto M_1^{-2.5}$ for m_1 ranges $5 - 80\ M_\odot$. And mass ratio distribution $p(q_m) \propto q_m^{1.3}$. The luminosity distance of the sources distributes uniformly in comoving volume from 400-15800 Mpc (z~2). In the case, the energy density of gravitational-wave $\Omega_{GW}(f_{ref}) = 1.33 \times 10^{-10}$, is still below the observation limit we have so far. With the current event rate, we conclude the Kurtosis parameter have one-sigma detection within one year observation.

Conclusion

Although KAGRA's sensitivity remains lower than that of LIGO and Virgo, our analysis shows that the data quality is remarkably stable, with noise exhibiting Gaussian behavior. Through a systematic investigation of lock loss events, we have successfully contributed to increasing the interferometer's duty cycle. In addition, we have completed the construction of the veto definer file, which marks an important milestone toward making KAGRA data suitable for stochastic background analysis.

With most of the groundwork complete, improving sensitivity remains the primary challenge. It is expected that KAGRA will begin O5 operations with a binary neutron star (BNS) range of around 25 Mpc, which may still fall short of the inclusion threshold for standard LIGO-Virgo SGWB analyses. However, we advocate for the use of a novel four-point cross-correlation method, which has the potential to leverage KAGRA data despite its lower sensitivity. We are currently implementing this method within the data analysis pipeline and working to revise KAGRA's existing analysis threads accordingly. This effort may open a viable path for KAGRA to contribute meaningfully to SGWB searches in O5 and beyond.

References:

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