PROCEEDINGS OF SCIENCE

The first joint observation by KAGRA with GEO 600

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KAGRA conducted its first joint observation with GEO 600 for two weeks in April, 2020. We performed two types of all-sky searches and two searches dedicated to gravitational wave signals associated with gamma-ray burst events observed during the run. We did not detect any gravitational wave signals, which was expected given the sensitivity of both detectors at that time. However, we did confirm that several search pipelines used in the LIGO-Virgo-KAGRA collaborations worked effectively on the KAGRA data. In this presentation we will report on the data quality of detectors and the search results. The contents and figures are based on [1].

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1. Introduction

Three gravitational wave (GW) observing runs have successfully completed by Advanced LIGO and Advanced Virgo [2]. During these runs, 90 GW events originated from compact binary coalescences were detected. On May 24, 2023, the fourth observing run has started. As of the time of this presentation, about 20 significant detection candidates were reported[1].

KAGRA [3], the fourth detector as the second generation detectors, was also planning to join the third observing run (O3) with LIGO and Virgo detectors. KAGRA achieved the binary neutron stars (BNS) observable range of 1 Mpc in March 2020. This sensitivity was threshold to join the observing run as a member of the GW detector network. However, due to the COVID-19 pandemic, the LIGO and Virgo detectors terminated the operations in March 2020, which was one month earlier than the planned end of the O3 period. Fortunately, the GEO 600 (hereafter GEO)[4–6] detector was still in the operation, therefore, KAGRA started the observation with GEO, which is called O3GK run.

KAGRA took the scientific data from April 7 to 20, 2020 and the data are analyzed to search for GW signals with GEO data. We perform two all sky searches: one is a search for the BNS signals and the other is a search for generic short transient (burst) signals. In addition, we also perform two searches for GW signals associated with gamma-ray bursts (GRB) events observed during the run. In this proceeding, we briefly summarize the search results from KAGRA's first observation.

2. Detector properties

In this section, we show the representative detector sensitivities during the run in Fig. 1. Left panel shows the amplitude spectral density for GEO and KAGRA, and the right panel shows the time evolution of the sensitivity as the observable BNS ranges.

During two weeks of the observation, the duty cycles were 79.8 % for GEO and 53.5 % for KAGRA. The coincident duty cycle was 46.8 %.

In both detectors, there were many transient noise fluctuations. During the run, medians rate of such noise with signal-to-noise ratio (SNR) larger than 6.5 are 10.3 per minute for GEO and 6.8 per minute for KAGRA. More detail properties of the KAGRA detector during the run are summarized in [7].

3. All-sky searches

In this section, we show the results from the all-sky search. All-sky search means that we analyze all of the data assuming that signals are arriving from any direction at any time.

3.1 Search for binary neutron stars

We first show the results of the search for BNS signals using the GstLAL library [8–10]. GstLAL performs a matched filter for various template waveforms with the component masses from 1 $M_\odot$ to 3 $M_\odot$. GstLAL defines triggers when the maximum of SNR in 1 s window is larger than 4.

[1]https://gracedb.ligo.org/superevents/public/O4/

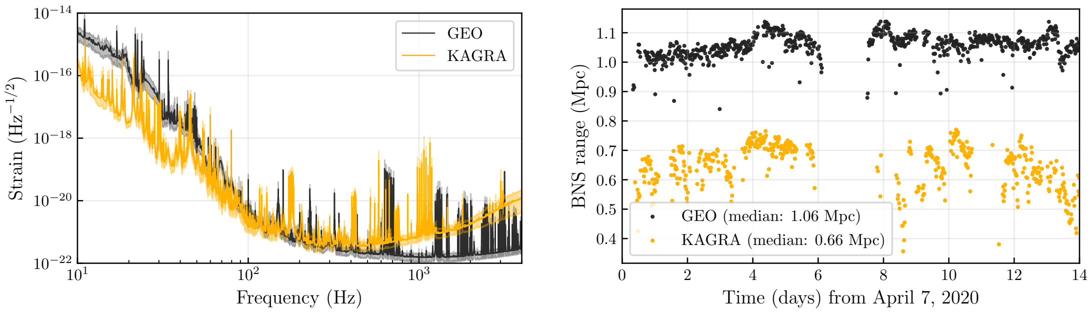

Figure 1: Left panel: The amplitude spectral density for GEO and KAGRA. The solid curves show the mean sensitivity for each frequency bin and the shaded regions show the 5th and 95th percentile over the period. Right panel: The time evolution of the BNS inspiral ranges for GEO and KAGRA. Both figures are from [1].

Both non-coincident triggers and coincident triggers form the event candidates[2], which are ranked by the log-likelihood ratio. TaylorF2 [11] and SEOBNRv4 [12] are used for template waveforms depend on the mass range. The distribution function for the log-likelihood ratios due to the noise process is estimated form the Monte Carlo techniques. The total amount of the data are 11.70 days (0.032 years) including GEO-only, KAGRA-only, and coincident time. The number of candidate events is plotted as a function of inverse false alarm rate (iFAR) in the left panel of Fig. 2. The most significant candidate is found as a coincident trigger at April 20, 2020 14:03:28 UTC with FAR of $\sim$ 30 per year. This is consistent with the predicted noise distribution within the error.

By injection simulated signals into the data, we can measure the search sensitivity as the sensitive spacetime volume. We inject many simulated BNS signals with mean component mass $1.4M_\odot$ and a standard deviation of $0.01M_\odot$. Their sources are uniformly distributed between 0.1 Mpc and 3 Mpc, and isotropically across the sky and in orientation. By converting the sensitivity volume to the equivalent sensitive range, the most significant candidate corresponds to a range of $\sim$ 0.6 Mpc, which agrees with the average detector sensitivity of KAGRA during the run shown in Fig. 1.

3.2 Search for transient signals

Next, we show the results of the search for unmodelled transient signals using the coherent WaveBurst (cWB) pipeline [13, 14]. This pipeline searches for coincident excess signal power in a network of GW detectors for the frequency range of 64–1024 Hz. Candidate events are ranked by their coherent network SNR, where the threshold of 5 is applied. The total coincident time is 4.38 days (0.012 years). The pipeline also estimated the background event distribution by artificially time-shifting the data from one detector with respect to the other. The background distribution and the candidate event are shown in the right panel of Fig. 2. The candidate event is identified at April 12 2020 18:10:15 UTC with an FAR of $\sim$ 10 per year, which is consistent with the noise background within the error.

[2]Candidate events with network SNR below 7 are discarded for this analysis due to many background noise events.

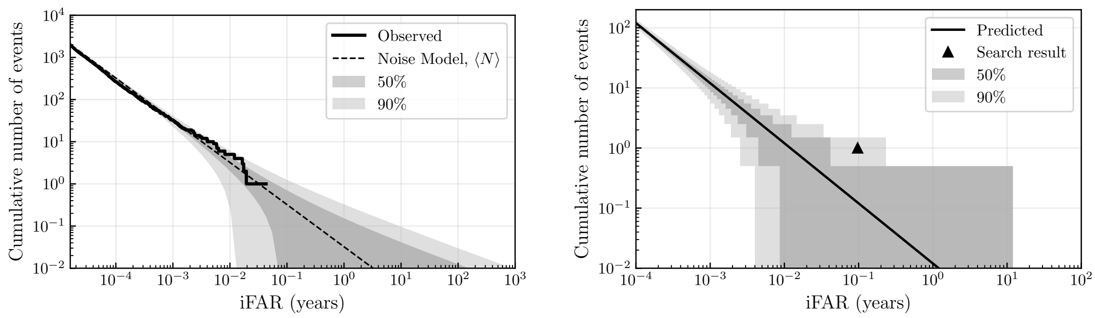

Figure 2: Left panel: The number of events as a function of iFAR for the BNS search by GstLAL. The solid line is obtained from the data and the the dashed line is the predicted distribution due to noise. The shaded region corresponds to the 50% and 90% error regions. Right panel: Background event distribution (solid line) and the candidate event (triangle) as a function of iFAR obtained by the cWB search. The shaded region corresponds to the 50% and 90% error regions. Both figures are from [1]

We also estimate the search sensitivity by injecting various types of burst signals and astrophysical signals. For GW150914-like signals, the distance of 50 % detection efficiency at FAR of one per year is $\sim$ 800 kpc. For a supernova-like signal, it is 80 kpc for 50 % detection efficiency and 10 kpc for 90 % detection efficiency.

4. Gamma-ray bursts targeted search

In this section, we show the results from searches for GW signals associated with GRBs. Four GRBs were observed during the run when both detectors were operating: GRB 200412A, GRB 200415A, GRB 200418A, and GRB 200420A. Among four GRB events, GRB 200415A is thought to be a magnetar giant flare in the nearby galaxy NGC 253 at 3.5 Mpc.

4.1 Search for compact binary coalescences

We search for BNS or neutron star-black hole binary (NSBH) signals by targeting the times and sky positions of two short GRBs (GRB 200415A and GRB 200420A) by using the PyGRB library [15]. The search performs a matched filter coherently across the operational detector network from -5 seconds to $+1$ second around the time of each GRB (on-source). To estimate the background distribution, $\sim$ 90 min of data surrounding the on-source time are used (off-source). Similar to the cWB search, the time shifting is applied to the off-source data to enhance the effective observing time. Then, the same analysis is done to the off-source data. IMRPhenomD [16, 17] is used as a template for this analysis. The p-values for the loudest candidates are 0.43 and 0.45 for GRB 200415A and GRB 200420A, respectively. They are consistent with the background noise.

By injecting simulated signals to the off-source data, we estimate the exclusion distances. A 90% exclusion distance means that we can recover 90% of a population of simulated signals as large as the loudest on-source candidate at the distance. The exclusion distances for GRB 200415A is shown in the left panel of Fig. 3 for three compact binary models. The largest 90% exclusion distance is 1.45 Mpc given by aligned spin NSBH model, which is less than the distance of NGC 253. Therefore, we cannot confidently exclude any binary merger as the progenitor of GRB 200415A.

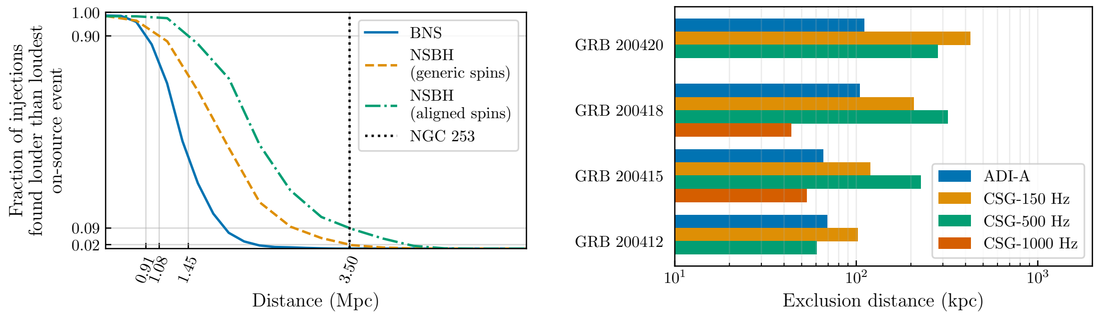

Figure 3: Left panel: Exclusion distance for GRB 200415A obtained by PyGRB for three different compact binary models. Right panel: Exclusion distances for four GRBs obtained by X-pipeline assuming different transient signals. Both figures are from [1]

For GRB 200420A, the largest 90% exclusion distance is 0.21 Mpc given by isotropically spinning NSBH model.

4.2 Search for transient signals

We also search for transient signals around the time for four GRBs by using X-pipeline [18]. X-pipeline searches excess signal power coherently across the detector network with specific sky location (with errors) and the time window identified by the GRB detections for each GRB . The search is done for the frequency range of 30–1100 Hz. For the on-source data, the period from −600 seconds to +60 second around the time of each GRB is used[3]. For the off-source data, the period of ±90 min around the GRB event is used and time shifting is also applied for the background estimation to achieve p-values of order of 10^{-4}. The lowest p-value was 0.132 for GRB 200420A, which is consistent with the null hypothesis.

Exclusion distances are estimated by injecting burst signals with several central frequencies and the accretion disk instability (ADI) model for four GRBs as shown in the right panel of Fig. 3. The 90% exclusion distances are from O(10 kpc) to O(100 kpc) for all GRB events.

5. Summary

KAGRA conducted its first joint observation with GEO 600 for two weeks from April 7 to 20 2020. We perform two all sky searches and two searches dedicated to gravitational wave signals associated with gamma-ray burst events observed during the run. All of four pipelines are standard ones already used in the analysis of the LIGO and Virgo data. We have not found any significant GW signals from four searches, which was expected from the sensitivity of KAGRA and GEO at that time. However, we have shown that these pipelines work well for the KAGRA data, which was an important milestone for KAGRA to become a member of the GW detector network. KAGRA has joined O4a for one month and shown better duty cycle and detector sensitivity than those in the O3GK run.

[3]For GRB 200415A, the data from −519 seconds to +60 seconds are used.

All data used in the analyses are available though the Gravitational Wave Open Science Center [19].

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