RESULTS FROM THE O3 GEO-KAGRA OBSERVING RUN

INTRODUCTION

KAGRA is a new gravitational-wave (GW) detector in Japan that has recently joined the international network of detectors, along with Advanced LIGO and Advanced Virgo, as of October 2019. KAGRA planned to start joint observation with Advanced LIGO and Advanced Virgo in the last month (April) of the third Observing Run (O3) in 2020. However, due to the COVID-19 pandemic, Advanced LIGO and Advanced Virgo had to shut down on March 27, 2020. Fortunately, KAGRA found a partner, GEO 600 (abbreviated in this document as GEO) in Germany, which continuously operates under the LIGO collaboration.

In April 2020, GEO and KAGRA made joint observations for two weeks. We call this GEO--KAGRA joint **observing run** O3GK. The results are reported in a scientific paper. Due to the weak **sensitivity** of both detectors, no confident GW detection is reported. However, during the two weeks, several **gamma-ray bursts (GRBs)** were observed by astronomers and the LIGO-Virgo-KAGRA (LVK) collaboration made a series of associated GW searches: **all-sky searches** for **binary neutron star (BNS)** coalescences and generic unmodelled bursts, as well as targeted searches for compact binary coalescences (CBCs) and unmodelled bursts associated with the GRBs reported during the run (**GRB-targeted searches**).

No GW signals were identified from the resulting data, as expected given the sensitivity of the detectors. However, these analyses demonstrate that the analysis efforts are ready to incorporate KAGRA data, which will be increasingly important as KAGRA nears its design sensitivity.

KAGRA AND GEO 600

The O3GK run was KAGRA's first joint observation with another GW detector. KAGRA is a laser interferometric GW detector with 3 kilometer arms, located in Kamioka, Gifu, Japan. KAGRA is built underground in a mine, and uses cryogenic mirrors for four test masses, which reduces seismic and thermal noise. By April 2019, most of the interferometer components had been installed, and the commissioning (tuning the detectors to make them more sensitive) work started. After commissioning, the sensitivity of KAGRA was improved to reach a **BNS observable range** of approximately 1 **megaparsec** (3.26 million light years) by the end of March 2020. Since KAGRA is a new detector that is still undergoing improvements, it is not yet at its design sensitivity.

GEO is one of the oldest GW detectors of interferometric design and, while being a smaller detector with 600 meter arms, plays an important role as a testbed of new detector technologies. The sensitivity of GW detectors is limited by the noise produced by the instruments.

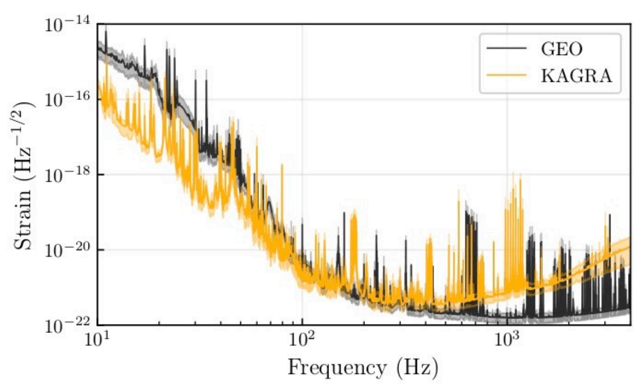

Figure 1: *(The left panel of Fig. 1 from our publication) Plot showing the typical sensitivity of KAGRA (yellow) and GEO (black) during the joint observing period. The vertical axis gives the average* ***strain noise*** *in the detectors, which is a measure of how much the mirrors typically move as a function of frequency (horizontal axis). The solid curves show the mean sensitivity for each frequency bin and the shaded regions show the 5th and 95th percentile over the period.*

On top of a noise floor, which is essentially the same over time, there are short duration instrumental artifacts in the data, which we call glitches. While a lot of effort is put into making the noise as low as possible and as glitch-free as possible, the glitches can mimic short duration GW signals. By running two detectors concurrently, we significantly reduce the number of glitches that can be mistaken for real signals.

Figure 1 shows the typical sensitivity of the two detectors during the joint observing period. Lower strain means more sensitivity. At lower frequencies KAGRA is more sensitive while at higher frequencies GEO is more sensitive. During the observing run, KAGRA could detect BNS inspirals up to a distance of approximately 0.8 megaparsecs (2.6 million light years) and GEO could do so up to a distance of about 1.1 megaparsecs (3.6 million light years).

Figure 2 shows the BNS observable ranges for the two detectors over the joint run.

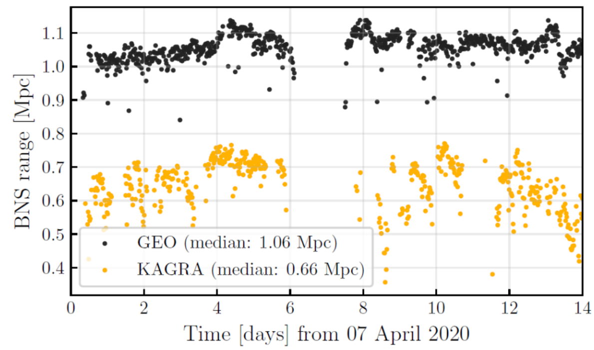

***Figure 2**: (The right panel of Fig. 1 from our publication) The BNS observable ranges for KAGRA (yellow) and GEO (black) during the joint observing run. The evolution of the ranges during the observing run is shown. The gap around day 6 and 7 was caused when both detectors were affected by bad weather and were unable to lock. The median range values are 0.66 megaparsecs for KAGRA and 1.06 megaparsecs for GEO.*

ALL-SKY SEARCHES

The LVK collaboration performed **all-sky binary and burst searches**. The all-sky binary search is a **matched-filter** search which compares the data with a set of template **waveforms** based on theoretical models of the GWs emitted from CBCs. The all-sky burst search is a search for unmodeled GW transient signals. The results of the two all-sky searches conclude that no GW signals have been detected. A plot of the result is shown in **figure 3**.

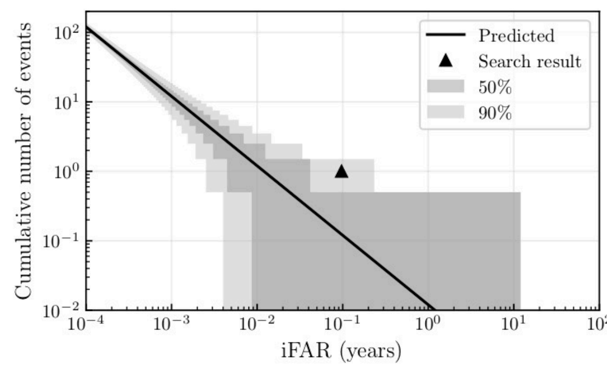

***Figure 3**: (Fig. 5 from our publication) Cumulative number of events as a function of the inverse of **false-alarm-rate** (iFAR) found by the all-sky generic burst search. Only a single event is identified (triangle), which is the loudest event. It is within the 90% interval meaning that it is considered to be due to noise. The shaded regions show the 50% and 90% Poisson uncertainties.*

GRB-TARGETED SEARCHES

During the observing run, there were a few interesting astronomical events, GRBs, which could potentially have accompanied GWs. Data was searched more carefully around these events. Four GRBs, consisting of two **long GRBs** (of duration greater than two seconds) and two **short GRBs** (of duration less than two seconds), were detected coinciding with science data taking in both KAGRA and GEO. The LVK collaboration performed **GRB-targeted binary and burst searches**, which search the time-band and sky-location limited by electro-magnetic observations of the GRBs. The LVK collaboration concludes that there is no evidence for GW emission associated with any of four GRBs analyzed by both GRB-targeted binary and burst searches.

One of the analyzed GRBs, GRB 200415A, has been associated with **a giant flare of a magnetar** in the Sculptor galaxy (NGC 253) at a distance of 3.5 megaparsecs.

The result for the GRB-targeted binary search for GRB 200415A is shown in **figure 4**. The **exclusion distance** based on our analysis is only a few **kiloparsecs** and this is not enough to exclude a CBC progenitor and test the magnetar giant flare hypothesis. The result for the GRB-targeted generic burst search is shown in **figure 5**. For each GRB, an exclusion distance is calculated.

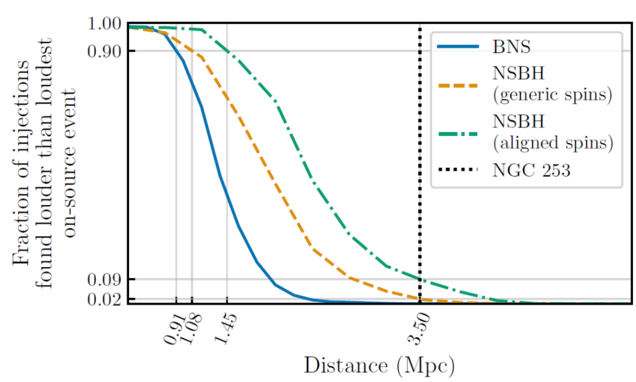

***Figure 4**: (Fig. 7 from our publication) Exclusion distances for GRB 200415A analyzed by the GRB-targeted binary search for a BNS and neutron star and black hole (NSBH) signals. The curves correspond to the three simulated populations: BNSs (blue solid), NSBHs with generically oriented spins (orange dashed), and NSBHs whose spins are aligned with the orbital angular momentum (green dot-dashed). The 90% exclusion distances of 0.91 megaparsecs, 1.08 megaparsecs, and 1.45 megaparsecs are marked by the vertical lines, and the distance to NGC 253 (3.5 megaparsecs) is also shown. The confidence levels corresponding to the distance to NGC 253 for BNS, NSBH (generic spins), and NSBH (aligned spins) are marked by the horizontal lines: 0%, 2%, and 9%, respectively. Thus the search sensitivity is not sufficient to exclude CBCs.*

FUTURE PROSPECTS

Through the analyses presented here, the LVK collaboration has demonstrated the promise of KAGRA becoming a part of the GW detector network. The LVK detectors are now offline for improvements before the upcoming fourth observing run (O4), currently planned to start in mid-December 2022 (https://www.ligo.org/scientists/GWEMalerts.php).

Once KAGRA is operational at its design configuration, it will achieve a sensitivity that is comparable with the Advanced LIGO and Advanced Virgo detectors; KAGRA will then play an essential role in detecting GW signals. It is vital to have more detectors become part of the network in terms of recovering more information and improving our ability to pinpoint source locations. The fact that KAGRA's arms are oriented very differently from the other detectors makes its contribution even more important.

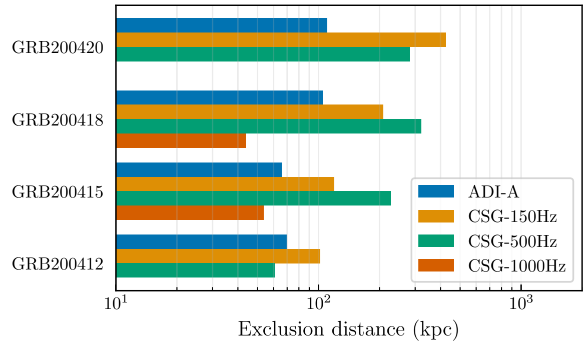

***Figure 5:** (Fig. 8 from our publication) Exclusion distance for each of the four GRBs analyzed by the GRB-targeted generic burst search. Here, each color corresponds to a different assumed GW signal model; the four models considered are known as the accretion disk instability (ADI) signal model A and circular sine-Gaussian (CSG) signals with the central frequencies of 150 Hz, 500 Hz, and 1000 Hz.*

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Glossary

All-sky searches: These are the standard searches. For the O3GK data, LVK collaboration has performed a matched-filter search for the BNS coalescences and generic unmodelled bursts.

Binary Neutron Star: A system consisting of two neutron stars in close orbit around each other. (See here)

Binary neutron star observable range: A standard measure of interferometer sensitivity, which is the average distance at which the inspiral of a binary system consisting of double neutron stars can be detected with a matched-filter signal-to-noise ratio of 8.

Black hole: A region of extremely warped space-time caused by an extremely compact mass where the gravity is so intense it prevents anything, including light, from leaving.

Burst search: A search for coincident excess energy in a network of GW detectors that operates without assuming a specific waveform model.

Compact object: An extremely dense astrophysical object such as a black hole, neutron star, or white dwarf.

Exclusion distance: The exclusion distance is the distance within which 90% of a population of simulated signals would be recovered at least as confidently as the loudest candidate event caused by detector noise near the time of the GRB.

False Alarm Rate: This rate measures how often a detector noise fluctuation could produce a signal similar to the candidate event being considered. The smaller this false-alarm rate is, the more likely the candidate event is to be astrophysical.

Gamma Rays: Extremely high energy photons, even higher in energy than X-rays.

Gamma-ray burst (GRB): A flash of gamma rays coming from a distant astrophysical source and lasting for up to hundreds of seconds, in many cases even less than a few seconds.

GEO 600: The GEO detector is a ground-based interferometer located in Hannover, Germany.

Gravitational waveform: A representation of a gravitational-wave signal's evolution with time.

GRB-targeted searches: Those are targeted searches for GW signals associated with GRBs reported during the run. By targeting the times and sky positions of GRBs we can potentially detect weaker associated GW signals than would be identified with all-sky searches. For the O3GK data, LVK collaboration has performed a matched-filter search for the BNS and NSBH coalescences and generic unmodelled bursts.

KAGRA: The KAGRA detector is an underground interferometer located in Kamioka mine, Gifu, Japan. It is also a laser interferometer, but with 3-km long arms, and cryogenically cooled mirrors.

Kiloparsec (kpc): A thousand times the distance of a parsec, equal to about 3.26 kilo light years.

Light-year: A unit of distance equivalent to the distance that light travels in one year. A light year is approximately equal to 9.46 trillion kilometers (or roughly 5.88 trillion miles).

LIGO: The Laser Interferometer Gravitational-wave Observatory consists of two 4-km long interferometric gravitational wave detectors separated by around 3000 km (1900 mi) located in Livingston, LA and Hanford, WA in the United States.

Long GRB: The duration is longer than 2 seconds. This is thought to occur when the core of massive stars collapse.

Magnetar: A neutron star whose strong magnetic field powers unusual behaviors, like short bursts.

Magnetar Giant Flare: A much larger version of the short burst, emitting the amount of energy the Sun would in 100,000 years in less than a second.

Matched filter: A technique to detect signals buried within noisy data. Templates of gravitational waveforms calculated from general relativity are scanned across the data, and ring off when matching patterns are found in the data.

Megaparsec (Mpc): A unit of distance. A million times the distance of a parsec, equal to about 3.26 million light-years.

Neutron star: Extremely dense object which remains after the collapse of a massive star. A star so dense that atoms cannot stay separate and the whole star is analogous to a giant nucleus. They weigh about 1 to 2 times the mass of the Sun, but are only about 10 kilometers in radius.

Neutron Star-Black Hole binary: A system consisting of one black hole and one neutron star in close orbit around each other. (See here.)

Noise: Fluctuations in the gravitational-wave measurement signal due to various instrumental and environmental effects. The sensitivity of a gravitational-wave detector is limited by noise.

Observing run: A period of time in which gravitational wave detectors are taking observational data.

Parsec (pc): A unit of distance largely used in astronomy, equal to about 3.26 light years. It corresponds approximately to 31 trillion kilometers.

Sensitivity: A description of a detector's ability to detect a signal. Detectors with lower noise are able to detect weaker signals and therefore are said to have higher (or greater) sensitivity.

Short GRB: The duration is less than 2 seconds. This is thought to come from the coalescence of compact objects (BNS or NSBH).

Signal-to-noise ratio: The ratio of the signal power to the noise power, used to compare the level of signal to the level of the noise. It measures the strength of the signal compared with the sources of noise that could potentially contaminate it.

Strain: The change in the detector arm length, due to the deformation of space time by gravitational waves passing through each detector, divided by the total arm length.

Virgo: The Virgo detector is a ground-based interferometer located in Cascina, Italy, near Pisa.