ALL-SKY SEARCH FOR LONG-DURATION GRAVITATIONAL-WAVE TRANSIENTS IN THE FIRST EIGHT MONTHS OF THE FOURTH ADVANCED LIGO-VIRGO-KAGRA OBSERVING RUN

All of LIGO–Virgo–KAGRA's detected gravitational wave (GW) signals have thus far come from compact binary coalescences, where pairs of neutron stars or black holes merge after a long cosmic dance. One of the great successes of Einstein's theory of general relativity is in accurately predicting the GW signals that are emitted in these cataclysmic events. But there are almost certainly other sources of GWs out there, not quite as well understood and yet to be detected. Some of the most promising sources emit "bursts": GW transients for which no shape is known ahead of time.

This paper presents a search for these types of signals from the first part of the latest LVK observing run, O4a, which ran from May 2023 to January 2024. Specifically, this is a search for long-lived transients, lasting from approximately 1-1000 seconds. While we don't know exactly where these signals may arise, theories predict that they may be emitted by non-spherical deformations in newly-born neutron stars, wobbly or unstable accretion disks around black holes, or neutron star or black hole binaries in highly eccentric (i.e., non-circular) orbits. In particular, these types of bursts might give us insight into what happens *after a neutron star merger* like the spectacular GW170817: whether the resulting remnant is a very massive neutron star or a black hole.

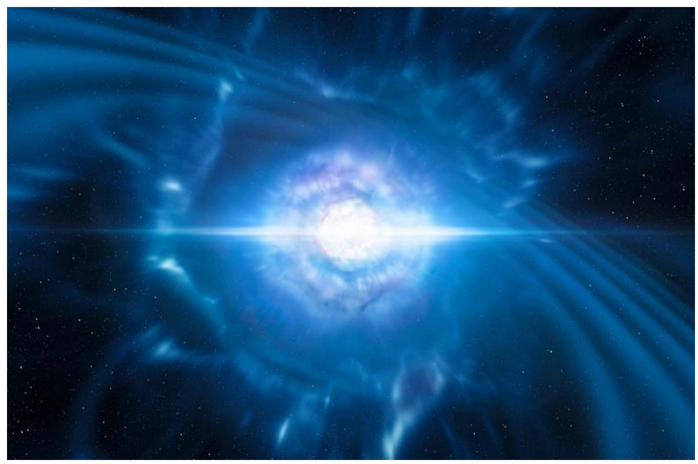

Figure 1: An artist's impression of a hypermassive neutron star formed in the aftermath of a neutron star merger. These exotic objects may create long-duration gravitational-wave bursts. Credit: ESO/L. Calçada/M. Kornmesser

The search was performed using two independent algorithms, looking through about 120 days of data where both the LIGO Livingston and LIGO Hanford detectors were collecting science-quality data—crucial to distinguish astrophysical signals, which should be present in both detectors, from noise that might only show up in one. One of the search algorithms, coherent WaveBurst (cWB), has been upgraded to be more sensitive to these particular types of signals compared to the previous search conducted in the previous observing run (O3). This improvement includes the use of XGBoost, a machine learning-based gradient-boosted decision tree algorithm, which serves as a classifier to distinguish between noise and signal, thereby enhancing the search sensitivity.

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This is the first time machine learning has been used in a LVK search. The other algorithm, PySTAMPAS, is performing a search across the whole sky for the first time.

After removing candidates corresponding to known black hole mergers, no new astrophysical events were found. The most significant cWB and PySTAMPAS triggers had false alarm rates of 1 per 8 months and 1 per 6 months respectively, both consistent with noise.

Despite this lack of detections, we can still make interesting astrophysical statements with this search. Using sample signals that represent particular classes of sources, we can quantify the sensitivity of each search, and learn about how often each class of source might occur in the Universe. Indeed, the fact that we didn't detect anything means that these long-duration bursts might be rarer or weaker than a derived "upper limit". **Figure 2** shows these upper limits on the gravitational-wave amplitude in black compared to the previous best limits from the O3 search in grey. For most signal types, these limits are about 1.2-2x more stringent, owing to improved detector sensitivity and more advanced search algorithms. Future searches in remaining O4 data (slated to run until late 2025) will have even better sensitivity, making the limits tighter and taking a step further in the path toward enabling new groundbreaking discoveries.

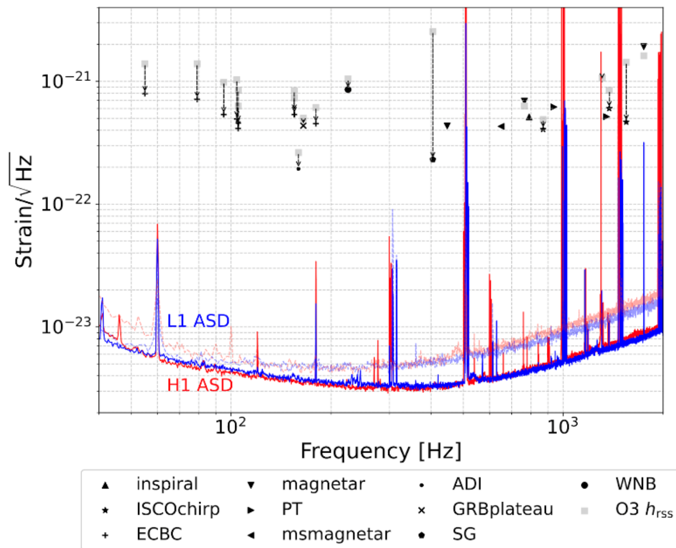

Figure 2: The upper limits on gravitational wave amplitude compared to the LIGO detector sensitivity (blue and red), for various types of long-duration burst signals. The amplitude ("strain") is on the vertical axis, and the gravitational-wave frequency is on the horizontal axis. Each black marker represents the O4a amplitude upper limit for a given type of burst signal, compared to its counterpart from O3 in grey. Most limits are improved by a factor of 1.2 – 2. For example, the "magnetar" (downward arrow) and "msmagnetar" (millisecond magnetar, left arrow) represent signals that arise from two different types of magnetars, while "ECBC" (eccentric compact binary coalescence, + symbol) refers to binaries in eccentric orbits. Other types include "inspiral" (binary NS mergers), "ISCOchirp" (innermost stable circular orbit waves around rotating BHs), "PT" (fallback accretion onto neutron stars), "ADI" (accretion disk instability), "GRBplateau" (newly formed magnetars powering gamma-ray burst plateaus), "SG" (sine-Gaussian waveforms), and "WNB" (white noise bursts).

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GLOSSARY

Compact binary coalescence – commonly abbreviated as CBC, it consists of two black holes, two neutron stars, or one black hole and one neutron star that inspiral and eventually merge. The whole process produces gravitational waves that increase in frequency and amplitude as the two objects get closer to each other and accelerate. The resulting object of the merger can be either a neutron star or a black hole, depending on the initial system. The objects forming the binary are called its components, the primary component being defined as the one having the largest mass.

General relativity – The theory of gravity proposed by Albert Einstein in 1915. In this theory, space and time are like a malleable fabric that warps in the presence of matter and energy, and objects follow trajectories through this curved space.

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

Transient – Astronomical phenomenon of short timescales; in contrast to astrophysical events lasting from thousands to billions of years.

Observing run – A period of observation in which gravitational-wave detectors are taking data.

False alarm rate – The false alarm rate is used to quantify how likely an event is to have been caused by noise. It is computed by simulating events coming from noise and looking at their signal strength, to derive a distribution of the expected rate of such events as a function of the signal strength. In more concrete terms, if an event has a false alarm rate of 1 per day, this means that we expect the noise of our detector to produce such an event about once every day. We would therefore have little confidence in this event.

Upper limit – A statement about the maximum value some quantity can have while still being consistent with the non-detection. We use a 95% degree-of-belief limit, i.e., given the data there is a 95% probability that the quantity is below this limit.