NO CONTINUOUS GRAVITATIONAL WAVES IN O4A DATA FROM 45 KNOWN PULSARS

The LIGO-Virgo-KAGRA (LVK) collaboration recently conducted a new search for extremely faint continuous gravitational waves (CWs) from neutron stars. This search on data from the first part of the fourth observing run (O4a) marks another step forward in the quest to capture gravitational waves emitted by stable, isolated objects rather than from dramatic events like black hole mergers. CWs are faint, steady, almost periodic signals that might tell us about the insides of neutron stars, the densest objects in the universe apart from black holes.

WHAT ARE CWs, AND WHY ARE THEY IMPORTANT?

Gravitational waves are ripples in spacetime caused by massive objects in motion. So far, the LVK collaboration has published the detection of almost 100 gravitational wave signals, mostly from black hole mergers. However, unlike these explosive events, CWs are thought to come from individual neutron stars with tiny "imperfections". Neutron stars are the remnants of massive stars that exploded as supernovae, leaving behind an incredibly dense core that can weigh more than our Sun packed into a ball just 20 kilometers wide. If one of these neutron stars has even a tiny bump or deformation, it could release faint, periodic gravitational waves as it spins. Detecting these waves would be a breakthrough, as it would allow scientists to study the "stiffness" and structure of neutron stars revealing new information about matter under extreme conditions.

Figure 1: The Crab Nebula as seen in the X-ray and optical band. The Crab pulsar is in the center of the image. Image credit: X-ray – NASA/CXC/ASU/ J. Hester et al.; optical – NASA/HST/ASU/J. Hester et al.

WHY PULSARS?

Pulsars are especially interesting targets for CW searches. They are neutron stars with powerful magnetic fields that cause the emission of beams of electromagnetic waves across different frequency bands (radio, X-rays, gamma-rays). As they rotate, these beams sweep across space like a cosmic lighthouse, creating pulses every time they reach us on Earth. Electromagnetic observations of pulsars with different observatories provide accurate information about their sky position, spin rate and its time evolution. This information makes pulsars prime candidates for CW searches because we can focus precisely on the frequency range where CWs might appear. In this search, LVK scientists focused on 45 known pulsars (see **Figure 2**) to listen for their faint, continuous emission. The team considered two different theoretical emission models that predict CW emission at twice the spin frequency (*single harmonic model*) or at both once and twice the spin frequency (*dual harmonic emission model*).

HOW THE SEARCH WORKS

The LVK collaboration uses some of the most sensitive instruments in the world to search for gravitational waves. These detectors, which are sophisticated interferometers, can pick up incredibly small distortions in spacetime, but even with their sensitivity, detecting CWs is extremely challenging. CWs are so faint that they are expected to be buried under background noise, so scientists have to rely on sophisticated algorithms and data analysis techniques to dig deep into the noise.

The team used detailed information from different electromagnetic observatories about each pulsar’s position and rotation. This is called *multi-messenger astronomy*: electromagnetic waves inform CW searches to improve the chance of detection by tuning the search specifically to each pulsar’s unique characteristics.

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These *targeted searches* are different from "all-sky" searches, where scientists look for any signal across the entire sky, not knowing where it might come from. Here, by using known pulsars as guides, the researchers are able to focus on the frequency ranges where a CW might be expected. Targeted searches are the most sensitive analyses but strongly depend on the emission model considered, i.e. on the physical mechanism that generates the CW emission that fixes the characteristics of the expected signals.

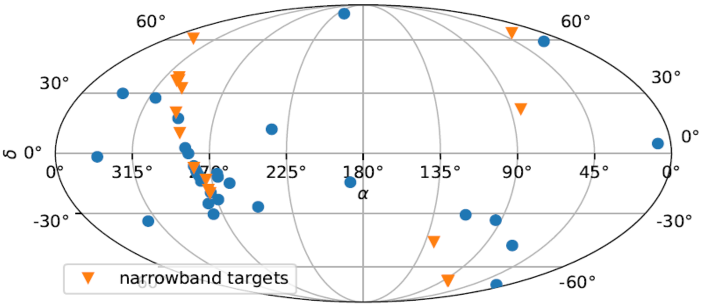

Figure 2: Sky location in equatorial coordinates of the analyzed targets.

WHAT DID WE FIND?

From the analysis of the O4a data, the LVK did not find any definitive CW signals coming from the analyzed 45 pulsars. However, our findings were still valuable. By analyzing the data, we were able to set new limits on how large the deformations, or “ellipticity,” of these neutron stars could be without emitting detectable CWs (the so-called *upper limits*, see **Figure 3**). This means that scientists now have more precise estimates on the maximum amount of deformation these pulsars might have, even if the deformations weren’t large enough to produce a detectable signal. For the bright, nearby millisecond pulsar J0437-4715, the strongest constraint on ellipticity is approximately 9 parts per billion, corresponding to a deformation of less than 100 microns assuming a neutron star radius of 10km!

WHAT’S NEXT?

Although CW signals remain elusive, every search pushes the field closer to a future detection. Each improvement in sensitivity increases the chance that we will someday catch a CW signal, and with it, a new way of studying the universe. The LVK will continue refining their techniques and enhancing detector sensitivity in future observing runs, bringing us closer to the day when we might find a CW signal. Along the way, even non-detections can be very interesting as they keep improving our knowledge of the maximum amount that neutron stars can be deformed.

The search for CWs is a long game and each round of research brings us closer to tuning into that faint, steady emission from neutron stars. When detected, these waves could offer a steady stream of information about some of the most mysterious objects in the universe, helping us answer big questions about what happens to matter at extreme densities.

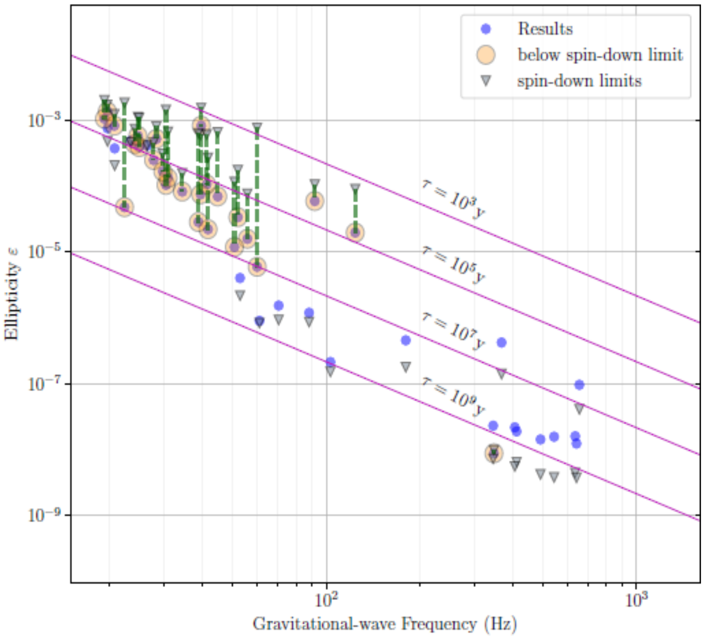

Figure 3: *Blue circles*: experimental upper limit on the ellipticity for each pulsar as a function of the expected CW frequency. *Grey triangles*: theoretical upper limit on the ellipticity assuming that the spin down of the pulsars is completely due to the CW emission.

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GLOSSARY

Continuous gravitational waves (CWs): Steady gravitational waves, usually expected to come from rotating neutron stars with minor deformations.

Neutron stars: Incredibly dense remnants of massive stars that exploded as supernovae.

Pulsars: A type of neutron star with strong magnetic fields that emits regular beams of electromagnetic radiation as it spins, creating a pulsing effect when observed from Earth.

Ellipticity: A measure of how much a neutron star’s shape deviates from a perfect sphere, which might cause it to emit CWs.