

SEARCHING FOR DANCING PULSARS AMIDST THE UNIVERSE'S GRAVITATIONAL SYMPHONY

Not all [gravitational waves](#) are the same. Some are born in [cosmic collisions](#), when [black holes](#) or [neutron stars](#) (NSs) smash together, sending ripples through space-time. Others, like the ones in this study, are far weaker, but last much longer. These are [continuous gravitational waves](#) (CWs): the steady, cosmic “heartbeat” of a spinning, imperfect neutron star.

Neutron stars are the dense, compact cores left behind after [massive stars](#), roughly 10 to 25 times the [mass of our Sun](#), end their lives in [supernova explosions](#). Despite being only about 20 kilometers across, they can pack in more mass than the Sun itself. Some spin hundreds of times per second, and if their matter content is not perfectly symmetric, this slight imperfection can make them emit CWs. When a neutron star is part of a [binary system](#) (see [Figure 1](#)), its signal becomes more complex, but it may also be stronger. This is because mass transferred from a companion star through [accretion](#) can speed up its rotation, boosting the likelihood of detectable gravitational waves.

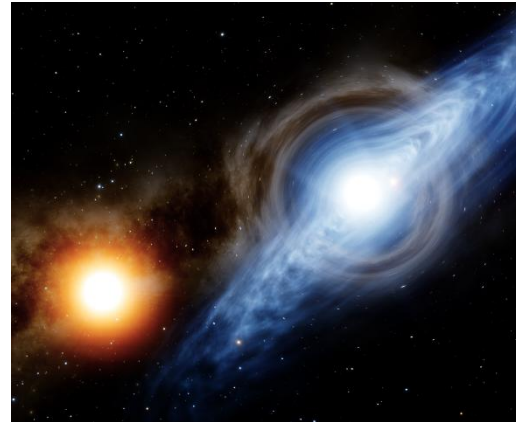


Figure 1. A neutron star (right) in a binary system with a companion star (left). Source: [SpaceEngine](#) simulator.

Neutron stars are among the most compact objects in the universe, and detecting CWs from them would give us valuable insight into the physics of matter under extreme conditions. Astronomers estimate there may be around one hundred million neutron stars in our galaxy, yet only a few thousand have been identified. Resolving this discrepancy is one of the main motivations for searches like the one described in this study.

HOW DO WE SEARCH FOR THESE SIGNALS?

The more a neutron star deviates from a perfectly spherical shape, the stronger the continuous gravitational waves (CWs) it can produce. To find these faint signals, scientists search through data from the [LIGO-Virgo-KAGRA](#) (LVK) gravitational-wave detectors, looking for evidence of CWs from the Milky Way’s neutron star population.

This study focused on unknown neutron stars in binary systems, using data from the first part of the LVK’s fourth [observing run](#), O4a (May 2023 to January 2024). We searched the entire sky, considering all possible source locations, for signals in the frequency range from 100 to 350 Hz. This range corresponds to the most sensitive bands in the O4a run.

The CW signal from the source NS appears as a single, steady frequency in the source’s frame of reference. But our detectors are moving, rotating with the Earth and orbiting the Sun, which causes a [Doppler modulation](#) of the signal. For a neutron star in a binary system, its own orbit adds a second layer of Doppler modulation. This “double Doppler” effect means that the signal’s frequency is modulated in a distinctive pattern.

To describe a neutron star’s motion in its orbit, we use three parameters: projected semi-major axis (the size of its orbit as seen from Earth), orbital period (how long it takes to complete one orbit), and orbital phase (its position in the orbit at a given time). In this search, we considered projected semi-major axes between 5 and 15 **light-seconds** and orbital periods between 7 and 15 days; ranges where many known neutron stars are found.

We used a new analysis tool called **FastTracks**, a GPU-accelerated pipeline designed to speed up CW searches. FastTracks checks whether tracks in the time–frequency data (see [Figure 2](#)) are consistent with what a CW signal should look like.

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Our search was performed in the time–frequency domain, using **short Fourier transforms (SFTs)** of 1024 seconds each. The search consisted of two steps, first, we applied the **Hough transform** to the data and searched for persistent signals in the **spectrogram**. In the second step, for the tracks that were most promising, we recomputed them again using the power tracks from the SFTs.

SEARCH SENSITIVITY AND ASTROPHYSICAL IMPLICATIONS

We did not find any evidence of continuous gravitational wave signals in this search. However, this null result still allows us to determine how sensitive our search was, that is, how far away we could have detected such signals if they had been present. To do this, we injected thousands of simulated CW signals into the data and measured how often our analysis recovered them. From these tests, we determined the smallest signal amplitude our search could detect, achieving the best sensitivities to date for this region of parameter space.

We show the sensitivity of our search in two ways: **Figure 3** shows the maximum distance at which our search could detect a neutron star, for different possible values of its **ellipticity** (a measure of how much the star’s shape deviates from perfect axial symmetry). More deformed stars can produce stronger CW signals, making them detectable from greater distances. **Figure 4** presents the same results from a different perspective: the maximum allowed deformation of a neutron star without being detected by our search, as a function of frequency. Our search considered sources with negligible source emission frequency **spindown** rates (double the spindown rate of the emitting neutron star). In both figures, the shaded regions mark cases with required spindown rates that were beyond the range we explored.

These results set the most stringent limits yet on CW signals from unknown neutron stars in binary systems for the explored orbital parameters. They were made possible by two key factors: the improved sensitivity of the detectors during the O4a observing run, and the optimized performance of our new FastTracks pipeline. Even without a detection, such constraints are valuable since they narrow the range of possible properties for the unseen neutron star population in our galaxy.

GLOSSARY

Accretion: Transfer of matter between two orbiting bodies due to the action of gravity. The infalling matter usually forms an **accretion disk** due to conservation of angular momentum. In this disk, gas spirals towards the centre, becoming hotter as gravitational potential is converted into thermal energy.

Binary system: A pair of astronomical objects bound together by their gravitational attraction. ([Wikipedia](#))

Continuous gravitational waves: Gravitational waves that last for long times at an approximately constant frequency. Such waves are created by sources like rapidly rotating neutron stars with, for example, a small deviation from perfect axial symmetry: the waves are extremely weak, but they last over time scales much longer than the observation time. This allows us to analyze long data stretches to dig out the weak signal from the noise. This is unlike other gravitational wave phenomena, like e.g. compact binary coalescences, where strong but short-lived signals are emitted. ([LIGO](#), [AET](#))

Ellipticity: Measure of how far from spherical a body is, defined as the relative deformation across the equatorial plane with respect to the deformation along the perpendicular direction.

FastTracks: A massive-parallel engine designed to evaluate detection statistics for continuous gravitational wave signals using GPU computing on Short Fourier Transform-like data.

Graphics Processing Unit (GPU): Specialized hardware suited for the processing of data using massive parallelization.

Hough Transform : Algorithm to identify well-described shapes in images, such as the ones described by a spectrogram. ([Wikipedia](#))

Kiloparsec (kpc): A thousand parsecs. A **parsec** is an astronomical unit of length, corresponding to roughly 3.26 light-years or 30 trillion kilometers.

Light-second: The distance light travels in one second. ([Wikipedia](#))

Massive star: Massive stars have masses more than about 8 times the **mass of the Sun**. Only such massive stars can form a neutron star after they explode as a supernova. If they have lower masses, the remnant becomes a white dwarf star.

Neutron star: Remnant of the supernova process undergone by a star with a mass between 8 and 25 times the mass of our Sun. Typical neutron stars have a mass of around 1-2 Solar masses and a radius of 10-15 kilometers, being some of the most compact objects ever discovered.

Observing run: Period during which our interferometers are, taking data for astrophysical analysis.

Spectrogram: Visual representation of the frequency composition of a time series. ([Wikipedia](#))

Spindown rate: Rate at which a spinning neutron star slows down due to the emission of energy via electromagnetic or gravitational waves.

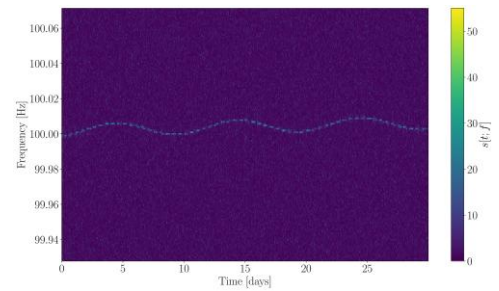


Figure 2: A simulated CW signal in a *spectrogram* (plot showing signal frequency vs. time). This example shows a neutron star spinning 50 times per second, orbiting a companion every 10 days. Amplitude modulations are due to the detectors’ daily change in sensitivity for that part of the sky.

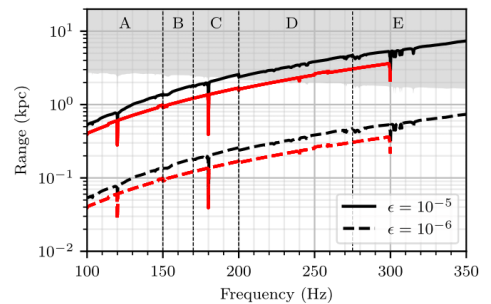


Figure 3: Maximum astrophysical reach in **kiloparsecs (kpc)** covered by the search as a function of frequency. The two black curves represent different values of neutron star **ellipticity**. The higher the ellipticity, the stronger CWs would be generated. The gray shaded region indicates distances excluded by the limit imposed by the maximum spindown used in the analysis. The figure shows a comparison between the previous search results (O3a BinarySkyHough, in red), and the results of this present search (in black).

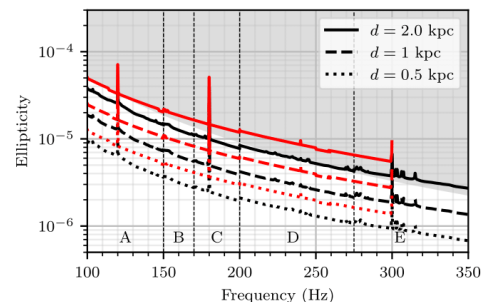


Figure 4: Maximum deformation (ellipticity) allowed for a NS without our search’s reach as a function of frequency. The curves represent, at different frequencies, how deformed a NS should be to produce a CW detectable with our search. The gray shaded region indicates values excluded by being larger than the maximum spindown used in our search. The figure shows a comparison between the previous search results (O3a BinarySkyHough, in red), and the results of this present search (in black).

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