

HUNTING LOW-FREQUENCY CONTINUOUS GRAVITATIONAL WAVES WITH THE EINSTEIN@HOME DISTRIBUTED COMPUTING SYSTEM

[Gravitational waves](#) (GWs) are ripples in the gravitational field, predicted to exist by Einstein's [General Theory of Relativity](#). A **neutron star** is the extremely dense remnant of the core of a massive star. Born in a supernova explosion, neutron stars are some of the most interesting objects in the universe. They have the mass of about the sun but the size of a small city. All the forces of nature — gravity, the strong and weak nuclear interactions, and electromagnetism — play huge roles in their properties and behavior.

Rapidly rotating neutron stars are expected to **emit GWs continuously** as they spin, if they are not perfectly spherical. The amount by which a neutron star deviates from being perfectly spherical can be described by a parameter called the **ellipticity**. The larger the ellipticity, the stronger the GWs emitted by the neutron star. Neutron stars are expected to have very small ellipticities: the astrophysics of their structure predicts that they are among the most spherical objects in the universe, with ellipticities of 10^{-5} or lower. The best human technology produces spheres that are close to perfect at that level (for example, the quartz sphere gyroscopes that flew on [Gravity Probe B](#)). For normal neutron star material, the maximum deformation that the neutron star crust could sustain before collapsing is about 10 cm. Nevertheless, by analyzing a long stretch of data from the LIGO detectors with carefully prepared software, we could pick even such a very weak signal out of the detector noise. At present, a few thousand neutron stars in our Galaxy have been identified as **pulsars** by their radio, X-ray or gamma-ray emissions, but our Galaxy is estimated to contain roughly 100 million neutron stars that are not observed through their electromagnetic emissions. With a search for continuous GWs that scans the entire sky, we have the potential to make new detections of neutron stars and learn about their structure.

GWs from rapidly spinning neutron stars will be detected at some specific (but unknown) signal frequency, close to a perfect [sine wave](#). We nominally expect the GW signal frequency to be twice the neutron star spin frequency, but it could also be at any multiple of the spin frequency. The spin frequency is the number of revolutions of the neutron star per second, measured in Hertz (Hz). These all-sky searches need to look for unknown sources located everywhere in the sky, for a wide range of possible signal frequencies and **frequency derivatives**, where the frequency derivative is the rate of change of the frequency. The ideal data analysis strategy used to extract the faint continuous wave signals from the detector noise is given by the **matched filtering** method, applied to many months of data. Matched filtering is a data analysis method in which the data are correlated against a simulated waveform in order to try to identify that signal buried in the detector noise. However, this data analysis technique requires a huge amount of computing power, more than is available to the LIGO Collaboration, when data stretches of the order of months or years are used and a wide fraction of the parameter space is searched over. Hence, to search for these signals using a realistic amount of computing power, we use a "hierarchical" approach in which the entire data set is broken into shorter segments and afterwards the information from the different segments is combined. The huge computational effort is distributed through the volunteer computing project [Einstein@Home](#), which relies on members of the public to donate their idle computing power to GW searches. Hundreds of thousands of host machines, that contributed a total of approximately 25000 [CPU](#) (Central Processing Unit) years, were needed to carry out the computations. We can use segments of a few days, allowing for very **sensitive** searches. As a bonus, it provides an opportunity to involve the public in the search for GWs!

This all-sky search for GWs from isolated neutron stars uses data from the LIGO detectors (LIGO Hanford in Washington and LIGO Livingston in Louisiana) collected in 2015 – 2016 during the first Advanced LIGO **run** (O1). The Advanced LIGO detectors have undergone many upgrades to make them more sensitive than the Initial LIGO detectors. The sensitivity improvement is especially significant at low frequencies.

FIGURES FROM THE PUBLICATION

For more information on how these figures were generated and their meaning see [the preprint at arXiv.org](#).

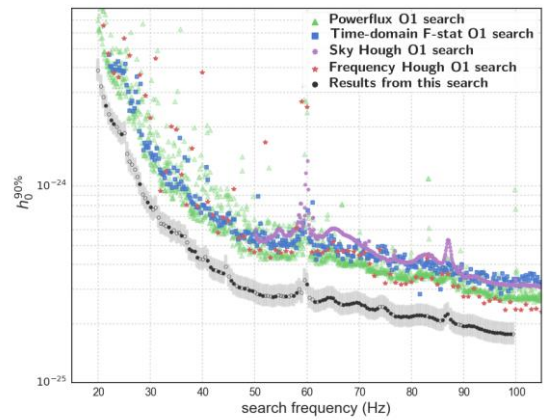


Figure 1: This plot shows the upper limits on the GW strain amplitude for this search (black curve) and for [four other all-sky searches](#) (red, blue, purple and green). The curves represent the source strain amplitude at which 90% of simulated signals could be confidently detected.



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In fact, [the previous Einstein@Home all-sky search](#), using Initial LIGO data, did not look at frequencies below 50 Hz due to lack of detector sensitivity in that range. In this search, we focused the immense computing resources of the Einstein@Home computing project on an all-sky search for GWs from spinning neutron stars in the low frequency range of Advanced LIGO data, from 20 Hz to 100 Hz. Under the assumption that the GW frequency is twice the neutron star frequency, this means we are looking for neutron stars spinning between 10 and 50 revolutions per second. Our goal is to perform a deep all-sky search in a region much of which had not previously been explored with LIGO.

The search considers neutron stars with frequency derivative ranging from about -26×10^{-10} Hz/s to 3×10^{-10} Hz/s. We mainly consider negative frequency derivatives, as we would expect the spin frequency of the neutron star to decrease over time as it loses energy. For example, if a neutron star is spinning at 50 Hz and emitting GWs at 100 Hz, after 12 years the signal frequency will fall to as low as 99 Hz. The observed frequency derivative can differ from the actual frequency derivative due to radial acceleration of the neutron star, which is why we consider a small range of positive frequency derivatives.

No GW signals have been detected in this search, presumably because there are no neutron stars emitting strongly enough in our frequency band to be detected at our sensitivity level. We quantify that conclusion by calculating **upper limits** on the GW **strain** amplitude. The upper limit is the smallest GW signal amplitude that we would have been able to detect with a confidence of 90%. Since we have not detected any signal, we can exclude the existence of signals of this type that we have searched for with amplitudes greater than our upper limit value. For example, at the highest frequency of this search near 100 Hz, where the detector is most sensitive, we can exclude the presence of signals with a GW strain amplitude of 1.8×10^{-25} or higher with a 90% confidence level. We can only compute upper limits with a finite statistical confidence level because detector noise is random and thus has to be described using probability and statistics. As shown in Figure 1, the upper limits set by this analysis (black curve) are ~ 1.5 to 2 times more constraining than those set by [other all-sky searches](#) at the same frequency. This improvement is primarily thanks to the significant computing resources of the Einstein@Home project, but also partly due to the methods and post-processing techniques used in the Einstein@Home search. One should also keep in mind that the other all-sky searches cover a broader range of frequency and frequency derivatives. The upper limits set by this analysis show a factor of 5 to 10 improvement with respect to the [best results from the initial LIGO detectors](#).

If you have been running Einstein@Home on your computer, we thank you very much for your donated computations! If you haven't been participating, but want to, you can get started by going to <https://einsteinathome.org/>.

GLOSSARY

Neutron star: The extremely dense remnant of the core of a massive star, born in a supernova explosion.

Continuous gravitational waves: Nearly single-frequency sine waves of GW strain. The strength (i.e., strain) of GW emission from rotating neutron stars depends primarily on their spin frequency, ellipticity (strain is proportional to ellipticity), and distance from the earth (strain is proportional to $1/\text{distance}$)

Ellipticity: A measure of the asymmetry of the neutron star around the axis of rotation. Roughly, it can be thought of the amount by which the neutron star deviates from being perfectly spherical, measured as a fraction of the star's radius. Because neutron stars are such extremely dense objects, we expect them to have very small deformation from spherical. For normal neutron star material, the maximum deformation that the neutron star crust could contain before collapsing is about 10 cm.

Pulsars: Neutron stars that have been observed through the pulses of electromagnetic radiation (usually in the radio band) that they emit. A large fraction of the neutron stars we expect to exist can not be observed as pulsars, either because they do not emit electromagnetic radiation, or because their electromagnetic radiation is not emitted in the direction of Earth.

Frequency derivative: The rate of change of the frequency.

Matched filtering: Data-analysis method consisting of correlating the data against a simulated waveform in order to try to identify that signal buried in the detector noise.

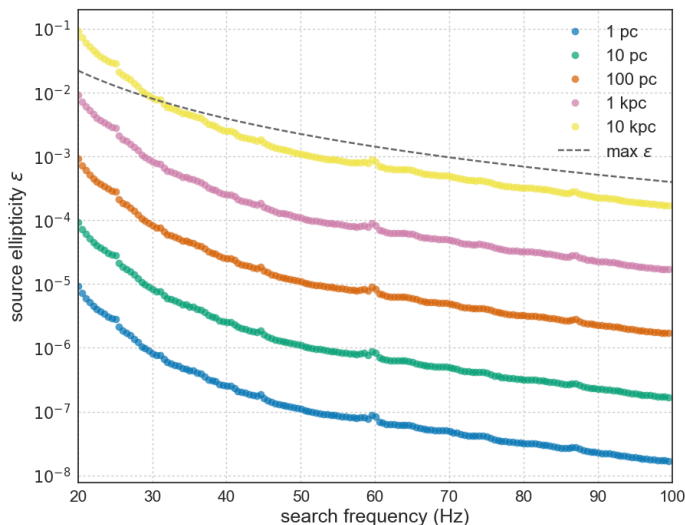


Figure 2: This plot shows the ellipticity of a source at different distances (indicated by the colors) that would have been detected by this search, with 90% confidence, if it was emitting continuous gravitational waves.

Einstein@Home: A system that uses the idle time on volunteer computers to solve scientific problems that require large amounts of computer power, such as processing data from GW detectors and performing all-sky searches for continuous wave signals. The reader interested to become one of these volunteers, and help us to find GWs, can join the Einstein@Home project following instructions at [this link](#).

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.

Observational run: A period of observation in which data is taken. Advanced LIGO conducted the O1 observational run from September 2015 to January 2016, and conducted O2 from November 2016 until August 2017. Initial LIGO had 6 periods of data taking between 2000 and 2010, which were referred to as "science runs."

Upper limit: A statement on the maximum value some quantity can have while still being consistent with the data. Here, the quantity of interest is the maximum intrinsic GW strain amplitude of a given continuous wave signal arriving at Earth. By 90% confidence level we mean that, when repeating the same experiment, the corresponding upper limits would be greater than the true GW strain amplitude at least 9 times out of 10.

Strain: Fractional change in the distance between two measurement points due to the deformation of spacetime by a passing GW. The typical strain from GWs reaching Earth is very small. The LIGO detectors are currently capable of detecting strains as small as 2×10^{-23} in the frequency band between 30 and 1200 Hz.

READ MORE: Freely readable preprint of the paper describing the details of the full analysis and results: [First low-frequency Einstein@Home all-sky search for continuous gravitational waves in Advanced LIGO data](#), by B. P. Abbott, et al. (LIGO and Virgo collaborations).