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Results from high-frequency all-sky search for continuous gravitational waves from small-ellipticity sources

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We present the results of an all-sky search for continuous gravitational wave signals with frequencies in the 1700-2000 Hz range from neutron stars with ellipticity of $\approx 10^{-8}$. The search employs the Falcon analysis pipeline on LIGO O2 public data. Our results improve by a factor greater than 5 over [5]. Within the probed frequency range and aside from the detected outliers, we can exclude neutron stars with ellipticity of 10^{-8} within 65 pc of Earth. We set upper limits on the gravitational wave amplitude that hold even for worst-case signal parameters. New outliers are found, some of which we are unable to associate with any instrumental cause. If any were associated with a rotating neutron star, this would likely be the fastest neutron star today.

Detectable continuous gravitational waves are expected from fast rotating neutron stars if they present some sort of non-axially symmetric deformation. The deformation in this context is usefully described by the *ellipticity* of the object, defined as $I_{zz}/(I_{xx} - I_{yy})$, where I is the moment of inertia tensor of the star and $\hat{z}$ is along the star's rotation axis [1].

In our previous paper [2] we searched for gravitational wave emission in the 500-1700 Hz range, targeting objects with ellipticity of 10^{-8}. Such ellipticities are thought to be in range of typical values for observed pulsars [3]. We found a number of outliers, some corresponding to known instrumental artifacts, some in data with pristine frequency spectrum.

The search [2] was performed on public LIGO data from the O2 science run. No more data has been released since, so we could not investigate the consistency of our candidate waveforms with new data. The first six months of O3 will in fact be made public only in spring 2021 [4], two full years after the beginning of the O3 run.

The LIGO data releases do not include any auxiliary-channel data, thus we are limited to analysis of the gravitational wave channel to identify detector artifacts. Given the amount of contamination found in the O1 data set, we would not be surprised if some of the outliers from [2] could be easily attributed to detector disturbances.

However, in the several months since the release of our paper [2] none of our outliers have been linked to any instrumental cause, which makes us wonder if in fact no instrumental cause could be identified.

With this prospect in mind we further expand the search range reaching the 2000 Hz mark on the O2 data, that we have access to. In the new $1700 - 2000$ Hz band we expand the first-order frequency derivative search range to $-7.5 \times 10^{-12} \leq f_1 \leq 2.5 \times 10^{-12}$ Hz/s, consistent with our ellipticity target at a level $\lesssim 10^{-8}$. We leave unchanged the rest of the search parameters. This search is considerably more computationally intensive per unit frequency interval compared to [2], and in fact it took approximately the same amount of compute cycles to cover 300 Hz in this frequency range than it did to cover 1200 Hz at the lower frequencies investigated in [2].

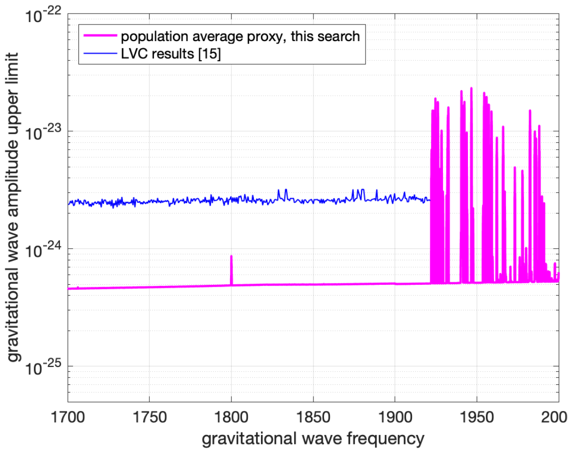

FIG. 1. Gravitational wave intrinsic amplitude h_0 upper limits at 95% confidence as a function of signal frequency. The upper limits are a measure of the sensitivity of the search. We compare with the latest LIGO/Virgo all-sky results in this frequency range [5], which are a factor $\gtrsim 5$ less constraining than ours. The results in [6] are a factor of 2 less constraining.

High-frequency searches are not only interesting because they can probe lower neutron star deformations. Detecting continuous gravitational waves between 1700 and 2000 Hz would also unveil the fastest rotating neutron star.

The new search could see such objects up to 200 pc away (Figure 2) for circularly polarized signals, and we would expect to detect an arbitrary oriented source within 65 pc. The upper limits from this search are available in numerical form in [7].

Our upper limits can be translated into limits on gravitational waves from boson condensates around black holes [8, 9], which are expected to emit monochromatic

SNR	Frequency Hz	Spindown pHz/s	$\mathrm{RA}_{\mathrm{J2000}}$ degrees	$\mathrm{DEC}_{\mathrm{J2000}}$ degrees	Comment
1025.8	1991.09236	-1.08	300.802	-14.320	ip14
19.6	1991.12667	-1.42	300.898	11.804	ip14 echo
17.7	1998.75364	-7.86	238.873	84.926	H1 line
17.4	1891.75674	-8.22	171.140	57.628	
16.1	1892.99106	-1.08	216.530	-46.769	
16.1	1985.75899	3.22	198.326	-73.539	L1 line

TABLE I. Outliers produced by the detection pipeline. Only the highest-SNR outlier is shown for each 0.1 Hz frequency region. Outliers marked "ip14" are due to a simulated signal "hardware-injected" during the science run for validation purposes. Its parameters are listed in Table II. Outliers marked with "line" have strong narrowband disturbances near the outlier frequency. Signal frequencies refer to GPS epoch 1183375935.

Label	Frequency Hz	Spindown pHz/s	$\mathrm{RA}_{\mathrm{J2000}}$ degrees	$\mathrm{DEC}_{\mathrm{J2000}}$ degrees
p14	1991.092400	-1	300.80284	-14.32394

TABLE II. Parameters of the hardware-injected simulated continuous wave signals during the O2 data run (GPS epoch 1130529362).

continuous wave signals [10]. We leave it to the interested reader to constrain from our upper limits physical quantities of interest, based on the specific model they wish to consider. Assuming the ensemble signal of [11] from a galactic population of $O(10^8)$ isolated stellar mass black holes with maximum mass 30 $M_\odot$ and maximum initial spin uniformly distributed in [0,1], our results extend the boson mass exclusion region to 4.0×10^{-12} eV.

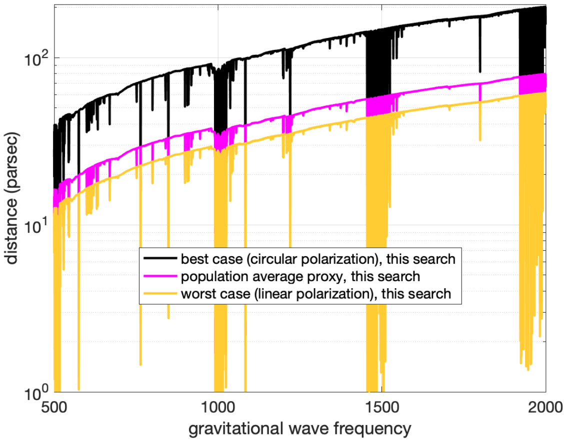

FIG. 2. Reach of the search for stars with ellipticity of 10^{-8}, including the results from previous paper [2] below 1700 Hz. The X axis is the gravitational wave frequency, which is twice the pulsar rotation frequency for emission due to an equatorial ellipticity. R-modes and other emission mechanisms give rise to emission at different frequencies.

A key result of our search are several outliers (Table I), two of which are located in bands with clean frequency spectrum. If any of them comes from an astrophysical source it would likely be the fastest spinning neutron star known to date.

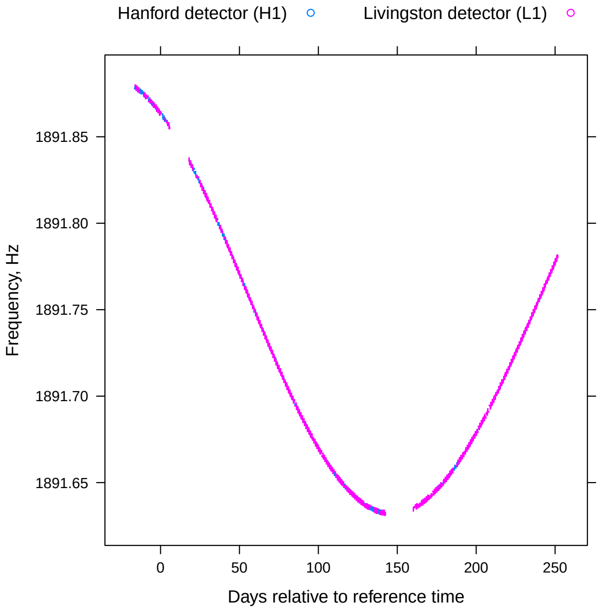

FIG. 3. Apparent frequency of a signal with parameters equal to those of the outlier at 1891.76 Hz, at the detectors. The difference in Doppler shifts between interferometers is small compared to the Doppler shifts from the Earth's orbital motion. We recall that the reference time is at GPS epoch 1183375935.

The outlier with the highest signal-to-noise ratio (SNR) is at 1891.76 Hz and it is not associated with any reported detector artifact [12]. At such high frequency the Doppler shift changes the frequency of the received signal by 0.25 Hz during O2 (Figure 3). The spectrum in this frequency band is clean (Figure 4) with no evidence of any contamination in either detector.

We examine the SNR build-up in the results of a semi-coherent matched-filter search of the type used in [13], for the two highest-SNR unmarked outliers. A "vanilla-flavour" continuous wave signal would be expected to have ≈ constant rate of accumulation of SNR, whereas our two outliers deviate from this behaviour, showing SNR accumulation peaks in subsets of the data. Signals can be imagined that would produce the observed results, but these are a-posteriori exercises that do not add to the significance of the present outliers.

The number of known spectral instrumental artifacts typically decreases with frequency, many of them being harmonics of low-frequency noise sources and the higher frequency "violin" modes being carefully segregated in specific frequency bands to avoid contamination of the

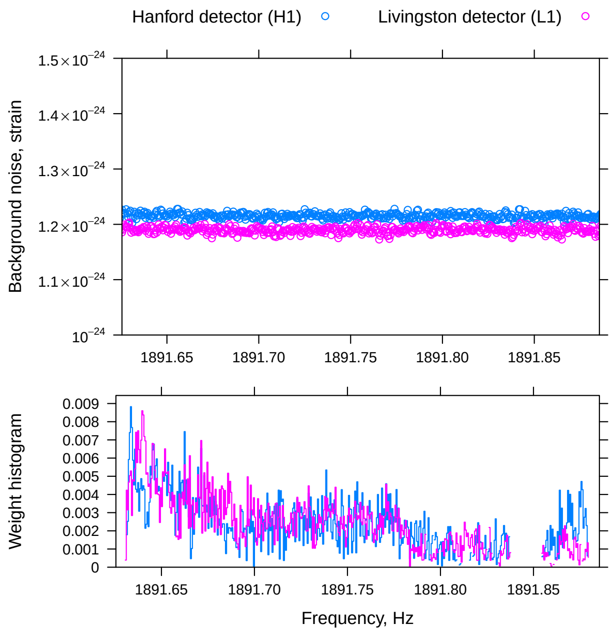

FIG. 4. The top plot shows the average amplitude spectral density around the frequency of the outlier at 1891.76 Hz. The bottom plot shows how much the power in each frequency bin would contribute, over the course of the O2 run, to the total power estimated by the Falcon pipeline for a signal with the parameters of the outlier at ≈ 1891.8 Hz. High-weight values correspond to bins with greater contribution and the sum of all the weights is 1 for each curve. The gap corresponds to a break in the O2 run and matches the gap in the frequency evolution plot 3.

rest of the spectrum. Thus the fact that we see two outliers in a 300 Hz band makes them especially interesting. If they are due to a noise source this provides a unique opportunity to identify it and remove it, perhaps unveiling a new class of "weak" contaminants. If no instrumental noise source is found, these signals should be a focus of thorough future investigations.

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