

# Searches for continuous gravitational waves with the LIGO and Virgo detector

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**Abstract.** The LIGO Scientific Collaboration and Virgo Collaboration have carried out joint searches in LIGO and Virgo data for periodic continuous gravitational waves. These analyses range from targeted searches for gravitational-wave signals from known pulsars, for which precise ephemerides from radio or X-ray observations are used in matched filters, to all-sky searches for unknown neutron stars, including stars in binary systems. Between these extremes lie directed searches for known stars of unknown spin frequency or for new unknown sources at specific locations, such as near the galactic center or in globular clusters. Recent and ongoing searches of each type will be summarized, along with prospects for future searches using data from the Advanced LIGO and Virgo detectors.

**Keywords.** Gravitational waves, Relativity, Instrumentation: interferometers, Stars: neutron, Pulsars

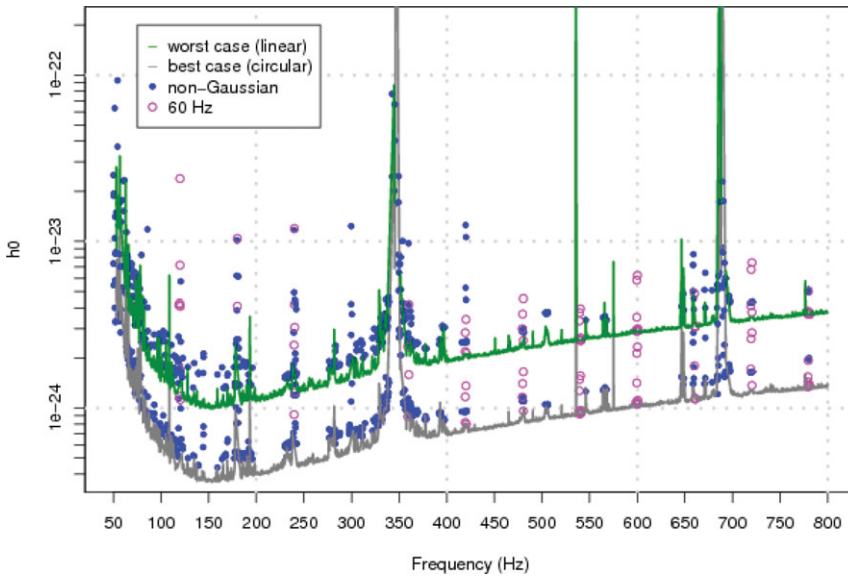
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The hunt for gravitational waves has been a long one, carried out over decades, using instruments ranging from the Earth itself (normal mode excitation), to 1-ton metal bars to multi-km interferometers, to radio telescopes monitoring the precise timing of arrays of millisecond pulsars scattered across the sky. From the timing variations observed in the famous Hulse-Taylor binary pulsar system (Hulse & Taylor 1975), one can be confident that gravitational waves *are* emitted with appreciable magnitude by astrophysical systems, but direct detection of those waves has proven to be an experimental challenge (see Riles 2012).

The focus of this article is the search in data from the LIGO (see Abbott *et al.* 2009) and Virgo (see Acernese *et al.* 2005) laser interferometers for evidence of continuous gravitational waves in the audio band, as might be radiated by nearby, rapidly spinning neutron stars. To emit gravitational waves, a spinning star must be characterized by some non-axisymmetry, e.g. , due to a “mountain” ( $\sim$ mm high) at the star’s equator or due to stellar precession. Because resulting strain amplitudes reaching the Earth are expected to be quite small ( $\sim 10^{-24}$  or much smaller), detection requires integration of data streams over long observation spans (the longest to date being  $\sim 23$  months).

Because of computational cost considerations, it is natural to classify searches for continuous gravitational waves into three broad categories: 1) targeted – in which precise pulsar ephemerides from radio, X-ray or  $\gamma$ -ray observations can be used in a coherent integration over the full observation span; 2) directed – in which the direction of the source is known precisely, but for which little or no frequency information is known; and 3) all-sky – in which there is no information about location or frequency.

Targeted searches for known pulsars have been published based on data from the first five LIGO data runs (S1–S5) and on the second Virgo data run (VSR2), with continuing searches in the sixth LIGO run (S6) and the most recent Virgo run (VSR4). The S5 search determined upper limits (Abadie *et al.* 2010; based on 23 months of observation span) for



**Figure 1.** All-sky upper limits on the GW amplitude of unknown sources. The upper (green) curve shows worst-case upper limits (most unfavorable orientation of a linearly polarized source) in analyzed 0.25 Hz bands. The lower (gray) curve shows upper limits assuming a circularly polarized source. Solid points and circles denote bands with severe instrumental contaminations and hence unreliable limits.

116 known pulsars in the LIGO band. Highlights from the search included a lowest-strain upper limit of  $2.3 \times 10^{-26}$  (J1603-7202) and a lowest stellar ellipticity limit of  $7 \times 10^{-8}$  (J2124-3358). In addition, a limit of 2% was placed on the fraction of rotational energy loss of the Crab pulsar that can be attributed to gravitational radiation. A more recent search (see Abadie *et al.* 2011) in Virgo VSR2 data for the Vela pulsar at an expected gravitational wave frequency of about 22 Hz (for which Virgo sensitivity is substantially better than LIGO's) yielded an upper limit of about 35% on Vela's fractional energy loss due to gravitational waves.

Because of computational costs of searching long observations times without *a priori* knowledge of gravitational wave frequency evolution, one must make tradeoffs in directed searches for particular objects or points in the sky. A published broadband search (see Abbott *et al.* 2010) for the X-ray-emitting compact central object in the Cassiopeia supernova remnant provides one example, based on analysis of a subset of LIGO S5 data (time span of  $\sim 12$  days), for which the lowest strain upper limit was  $7 \times 10^{-25}$  at  $\sim 150$  Hz. Because Cas A is only about 300 years old, this search incorporated a search over spin frequency and over its 1st and 2nd time derivatives. The resulting large parameter space volume for even a single point on the sky led to degraded strain sensitivity, compared to that achieved in the targeted searches described above.

All-sky searches for unknown neutron stars must cope with a still larger parameter space volume (as quantified by number of distinct templates searched for a fixed maximum SNR mismatch). Figure 1 shows all-sky strain upper limits (Abadie *et al.* 2012) on spinning isolated neutron stars, based on analysis of the full S5 data set, using semicoherent sums of Doppler-demodulated Fourier transform powers from tens of thousands of half-hour intervals (“PowerFlux” algorithm). A complementary and wider-band search of S5 data, based on Fourier transforms of longer coherence time (up to 25 hours per

interferometer) and using the Einstein@Home distributed-computing project, led to comparable sensitivity in a search recently submitted for publication (see Aasi *et al.* 2012).

Comparison of the targeted and all-sky strain upper limits shown in figure 1 confirms the expected (substantial) degradation of sensitivity for searches that must search large parameter space volumes and hence must set high SNR thresholds, to cope with otherwise increased statistical outlier counts. For this reason, the “photon astronomer” community is encouraged not only to search for new and exotic objects that could serve as potential gravitational wave candidates, e.g. , nearby pulsars with high rotational energy losses, but also to determine spin rotations for known objects, such as Cas A and Scorpius X-1.

Installation of Advanced LIGO and Advanced Virgo has begun, with early operation expected circa 2015. When these detectors reach design sensitivity near the end of the decade, strain amplitude sensitivities and hence ranges within the galaxy will improve by an order of magnitude. Electromagnetic measurements could well make the difference between discovering and missing a star with a detectable gravitational wave signal.

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