All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems

Based on R. Abbot et al. (LIGO Scientific Collaboration, Virgo Collaboration)

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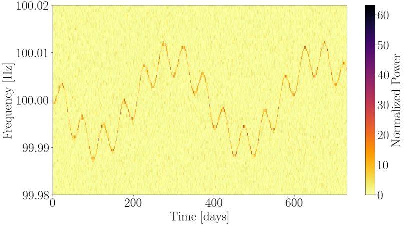
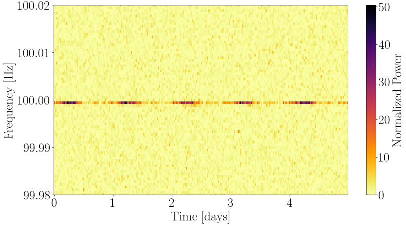
Introduction

- Continuous waves (CWs) are long-duration quasi-monochromatic gravitational waves (GWs). No direct detection up to date.
- Expected sources are Neutron Stars (NS) presenting a non-axisymmetry (crust deformations, r-modes, free precession).
- CWs are described by amplitude $\mathcal{A}$ and phase-evolution λ parameters:
  - $\mathcal{A} \rightarrow$ source orientation $(\cos\iota, \psi, \phi_0)$, nominal GW amplitude h_0.
  - $\lambda \rightarrow$ source spinup/spindown $(f_0, f_1, \dots)$, Doppler modulation due to the Earth's motion (α, δ), Doppler modulation due to a binary companion $(a_{\mathrm{p}}, P, t_{\mathrm{asc}})$





Introduction [Sieniawska & Bejger Universe 2019, 5(11), 217]

Amplitude of CWs

- Basic model: quadrupolar deformation / triaxial ellipsoid

$$h_0 = \frac{4\pi^2 G}{c} \frac{I_z \epsilon}{d} [2 f_{\text{rot}}]^2 \simeq 4.2 \cdot 10^{-26} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{f_{\text{rot}}}{100 \text{ Hz}}\right)^2 \left(\frac{d}{1 \text{ kpc}}\right)^{-1}$$

- Amplitude is orders of magnitude lower than that of CBC signals.
- Realistic searches focus on the galactic NS population.
- EOS dependency mainly enters through the ellipticity ϵ.

CW searches place constraints on the galactic NS population:

$$\text{Upper limits on } h_0(f_{\text{rot}}) \rightarrow \text{ Constraints on } \epsilon(f_{\text{rot}}, d)$$

Blind searches (such as this one!) probe the EM-quiet NS population.

The early O3 BinarySkyHough search

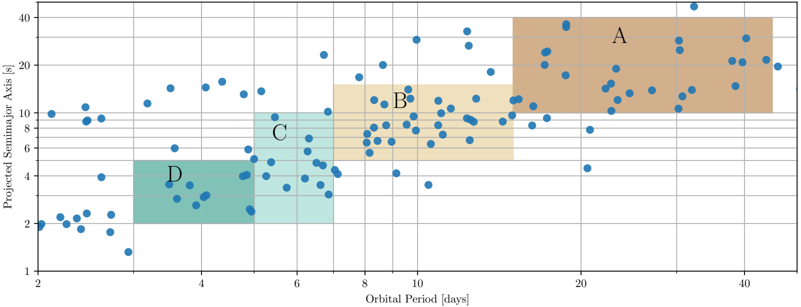
Searching for CW from NS in binary systems

- Look for CW emission from unknown NSs in circular binary systems.
- BinarySkyHough = SkyHough (Isolated CW) + GPU parallelization.
- Previously used on O2 open data [P. B. Covas & A. M. Sintes PRL 124, 191102 (2020)].
- Main search stage ran at the Barcelona Supercomputing Center (CTE-Power) under the Spanish Supercomputing Network (RES) grant AECT-2019-3-0011.

The early O3 LIGO-Virgo observing run

- 6 months of data (April 2019 - October 2019)
- 1024s-long Short Fourier Transforms of Advance LIGO data.
- Cleaning procedure was applied due to loud, frequent transient noise artifacts [P. Astone et. al CQG 22 S1197 (2005)].

Parameter space



- All-sky search, L (50-100 Hz) and H (100-300 Hz) frequency bands.
- Binary parameter-space partitioned into four regions:
  A, B, C, D covered along L; B covered along H.
- The entire range of t_{asc} (initial binary phase) is covered by the search.
- EM binary NSs have low spindown values: Neglected in this search.

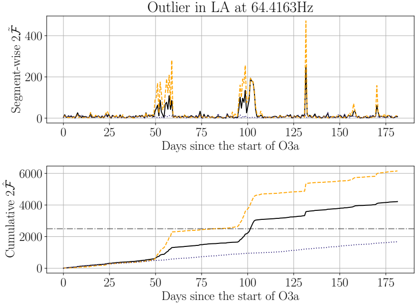
Search results

Regions	LA	LB	LC	LD	H1B	H2B	H3B	H4B	H5B
Initial Clusters	2000	2000	2000	2000	1000	1000	2000	2000	2000
Vetoed by Identified Line	366	359	359	373	44	0	32	30	30
Surviving Clusters	1634	1641	1641	1627	956	1000	1968	1970	1970
Fraction (%)	81.7	82.05	82.05	81.35	95.6	100	98.4	98.5	98.5
Surviving Outliers after $2\hat{\mathcal{F}}_{\mathrm{th}}$ veto	73	72	71	71	7	6	8	3	0

1. Retrieve the best 80.000 outliers in each 0.125 Hz band.
2. Cluster outliers [R. Tenorio et. al PRD 103, 064053 (2021)].
3. Select best 5 clusters per 0.125 Hz band.
4. Apply line veto.
5. Follow-up surviving outliers with `PyFstat` [D. Keitel et. al JOSS 6(60), 3000 (2021)].

Outlier follow-up

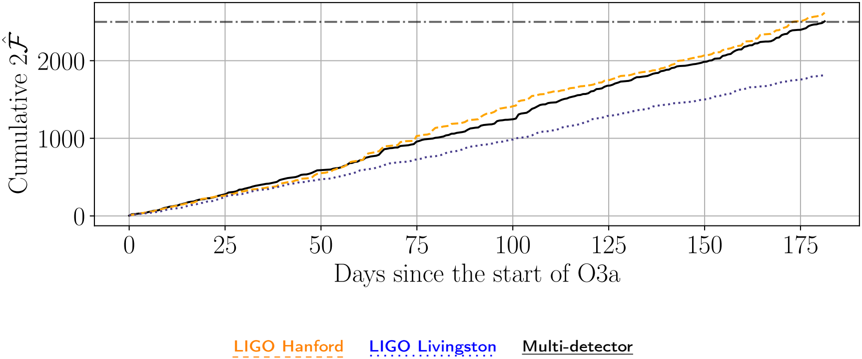
- Compute semicoherent matched-filter $2\mathcal{F}$ [P. Jaranowski et. al PRD 58 063001 (1998)] and calibrate a threshold.
- $\mathcal{O}(300)$ outliers survive the first stage of the follow-up.
- Most of them are related to instrumental lines of unknown origin.



- $\mathcal{O}(250)$ outliers accumulate $2\mathcal{F}$ in short time periods.
- Calibrate a threshold on segment-wise $2\mathcal{F}$ using software injections.
- No outlier is consistent with a CW signal.

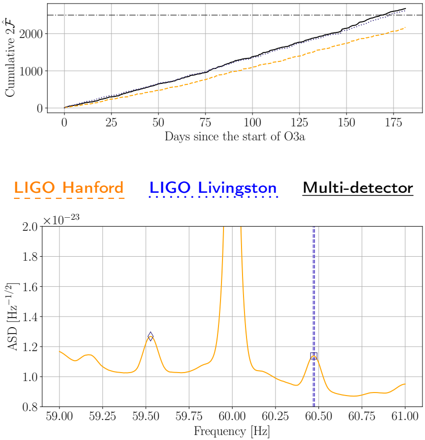
Outlier follow-up

- $\mathcal{O}(25)$ outliers are more present in H1 than L1 ($2\mathcal{F}_{\text{H1}} > 2\mathcal{F}_{\text{L1}}$), as opposed to the displayed sensitivity of the detectors during O3a.
- Calibrate a threshold on relative detector-wise $2\mathcal{F}$.
- No outlier is consistent with a CW signal.

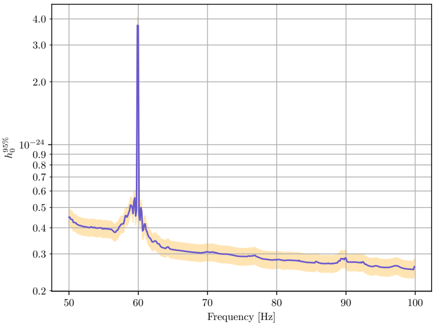


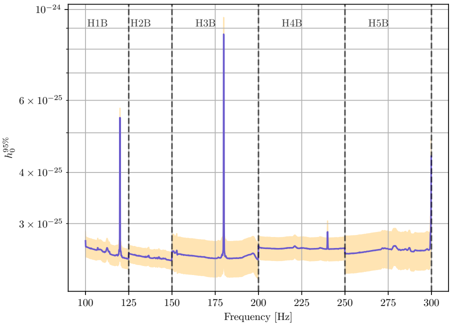
Outlier follow-up

- Final $\mathcal{O}(20)$ outliers are clustered around 60.5 Hz in all binary parameter-space regions A, B, C, D.
- These outliers survived all previous veto stages.
- Close inspection of the ASD reveals a side band of the 60 Hz power-line at the frequency of interest.
- Final set of outliers is deemed as non-astrophysical.



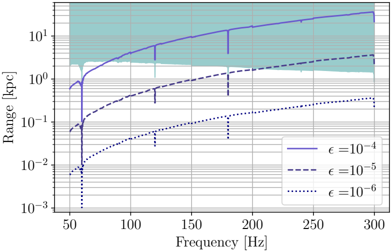
Sensitivity estimation

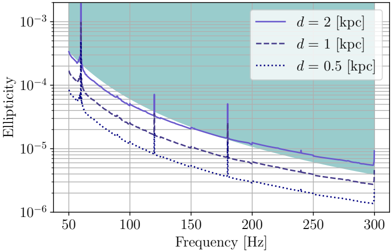




- Estimate the search sensitivity as the 95% detection efficiency h_0.
- Minimum amplitude sensitivity
  $h_0^{95\%} = (2.4 \pm 0.1) \times 10^{-25}$ @ 149.5 Hz.
- Most sensitive result up to that for this kind of searches!

Astrophysical implications





- $h_0^{95\%}$ places constrains on the nearby population of binary NSs.
- Max. astrophysical reach / ellipticity is limited by neglected spindown.
- Ellipticity constrained to $\epsilon \lesssim (10^{-4} - 10^{-5})$ at $d \simeq (1-2)$ kpc depending on the frequency band.
- Results start to probe the regime of exotic equations of state ($\epsilon \simeq 10^{-5}$), but still a while until realistic ones ($\epsilon \simeq 10^{-7} - 10^{-6}$)

Summary

- Continuous waves are yet-to-be detected forms of gravitational radiation potentially able to probe the EM-quiet NS population.
- Different types of NS (isolated, in binary systems, . . .) require different dedicated pipelines to search for CW emission.
- We search for CW from unknown binary NSs in early O3 LIGO data using the GPU-accelerated BinarySkyHough pipeline.
- No detections are reported.
- Search sensitivity is estimated using a simulated set of CW signals, achieving the most sensitive results to date across the analyzed parameter space.