LOOKING FOR NEUTRON STARS AS CW-EMITTERS IN THE GALACTIC CENTER USING LIGO/VIRGO O3 DATA

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OVERVIEW

- Continuous gravitational waves (CW) signals and sources
  - standard isolated neutron star (NS)
- The Galactic Center (GC) search
- Pipeline technicalities: the Band-Sampled-Data (BSD)
- Candidates and followup
- Final remarks and perspectives
WHAT IS A CONTINUOUS WAVE (CW)?

Persistent signal (long-lived)
Produced by a periodic mass quadrupole moment variation

Expected sources
Non-axisymmetric isolated neutron stars (NS)
NSs in binary systems (e.g. in accreting systems)
More objects: bosons clouds around spinning BH, newborn NSs

Expected strain
\[ h_0 \approx 10^{-27} \left( \frac{I_{zz}}{10^{38} \text{ kg m}^2} \right) \left( \frac{10 \text{ kpc}}{d} \right) \left( \frac{f}{100 \text{ Hz}} \right)^2 \left( \frac{e}{10^{-6}} \right) \ll h_{0\text{CBC}} \]

EASY CASE: ISOLATED NEUTRON STAR

Expected strain

\[ h_0 \cong 10^{-27} \left( \frac{I_{zz}}{10^{38} \text{ kg m}^2} \right) \left( \frac{10 \text{ kpc}}{d} \right) \left( \frac{f}{100 \text{ Hz}} \right)^2 \left( \frac{\epsilon}{10^{-6}} \right) \ll h_{0CBC} \]

non-precessing, rotating around z

here \( f = 2f_{\text{spin}} \)

\[ h_0 = \frac{4\pi^2 G I_{zz} f^2}{\epsilon^4 \frac{d}{e}} \]

\( I_{zz} \): moment of inertia

\( \epsilon \): ellipticity

\[ \epsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}} \]

What is the actual value of \( \epsilon \)?

\( 10^{-9} \leq \epsilon \leq 10^{-4} \)

from previous estimates
A CW received at the detector is NOT exactly monochromatic

- **SPIN-DOWN** due to the loss of energy of the star
  \[ f_0(t) = f_0 + \dot{f}_0 (t - t_0) + \frac{\ddot{f}_0}{2} (t - t_0)^2 + \ldots \]
- **DOPPLER** shift due to the motion of the Earth
  \[ f(t) = \frac{1}{2\pi} \frac{d\Phi(t)}{dt} = f_0(t) \left( 1 + \frac{\mathbf{v} \cdot \mathbf{n}}{c} \right) \]
- **SIDEREAL VARIATION** of the amplitude
TYPE OF CW SEARCHES

Targeted searches

Narrow-band searches

Directed searches

Directed for binary (Sco-X1)

Blind all-sky searches

Sensitivity

Computational cost
WHY THE GC

- Several independent lines of evidence predict a sizable population of NSs in the region (\(O(10^8 - 10^9)\) expected in the full Galaxy, only a fraction observed \(~3000\))
- Given the large number of massive stars, the central parsec likely hosts a large NS population (mostly millisecond pulsars (MSP) [Macquart, J.P. et al. 2015])
- The size of the potentially EM observable population (i.e. those beaming towards us) could include up to 50 canonical pulsars and 10000 millisecond pulsars [Rajwade et al. 2016]
- A GC pulsar population could explain the GC GeV excess measured by Fermi and H.E.S.S. [Bartels et al. 2016, Lee et al. 2016, Fermi-LAT coll. 2017]
- Potentially solve the debate about the presence (or not) of dark matter (DM) in the GC

The Galactic center is a good place to look for CWs since it is likely to host several candidates
We use data in the BSD format

Piccinni et al., CQG 36, 1 (2018)
Given a sky position: apply barycentric correction
Selection of time frequency peaks using a $T_{coh}$

Peaks CR after correction (H1)

BSD time series

Partial Doppler correction

Peakmap Creation

Frequency Hough map creation

(Astone+ CQG 22, S1197, 2005)
The BSD pipeline - A directed search

- The peakmap will be the input for the FrequencyHough map.
- A peak becomes a line in the $(f_0, \dot{f}_0)$ plane

(Astone+ PRD 90, 042002, 2014)
The BSD Pipeline – A Directed Search

- Candidates selected on a final FH map, sum of the monthly-based FH maps

![Diagram](image)

Candidates are selected with a ranking procedure over the Critical Ratio computed from the FH number counts.

Using the BSD-directed search pipeline on O3 data from LIGO and Virgo interferometers we can search for CWs in the direction of Sgr A*

**Frequency range:** $[10 - 2000] \text{ Hz}$

**min spin-down range:** $-1.8 \times 10^{-8} \text{ Hz/s}$

**Data:** full O3 clean data (April 2019 - March 2020)

**Sky position (Sgr A*):**

$\alpha = 4.650 \text{ rad \hspace{1cm} } \delta = -0.506 \text{ rad}$

Assuming that $f_{\text{start}} \gg f_{\text{today}}$, the decay time gives an estimate of the age as $\tau \sim -f/f_{\text{today}}$

Parameter space:

Candidates selected per detector.
First level of vetoes are applied (e.g. removal of candidates near known lines).
Coincidences between the datasets.
Selection based on the significance (Critical Ratio).
Remaining candidates need to be investigated.

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<tr>
<td>starting (per det)</td>
<td>~ 3 × 10^6</td>
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<td>excluded by known lines veto (per det)</td>
<td>~10k</td>
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<td>&lt;10</td>
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FOLLOWUP OF SURVIVING CANDIDATES – ONGOING

Assuming a phase evolution of the signal, \( \phi(f_0, \dot{f}_0) \), as fully described by the frequency and spin-down parameters of the candidate, given by \( f_0 \) and \( \dot{f}_0 \), respectively.

Assuming a phase evolution of the signal, $\phi(f_0, f_0')$, as fully described by the frequency and spin-down parameters of the candidate, given by $f_0$ and $f_0'$, respectively.

Assuming a phase evolution of the signal, $\phi(f_0, \dot{f}_0)$, as fully described by the frequency and spin-down parameters of the candidate, given by $f_0$ and $\dot{f}_0$, respectively.
O2: 9 months, O3: 10 months, O4, O5, ET: 1 year
FUTURE PROSPECTS: GC SEARCH ELLIPTICITY

\[ h_0 \propto \frac{I_{zz}}{d} \epsilon f^2 \rightarrow \epsilon = \frac{c^4}{4\pi^2G} \left( \frac{d}{I_{zz}} \right) \frac{h_0}{f^2} \]

 Galactic center distance \( d = 8 \text{ kpc} \)

\[ I_{zz} = I_{\text{fid}} = 10^{38} \text{ kg m}^2 \]

\( 10^{-9} \leq \epsilon \leq 10^{-4} \) from previous estimates
CONCLUSION

➤ CW could be the next surprise in GW astronomy given the enhanced sensitivity of the detectors

➤ Noise characterization is fundamental for the removal of potential outliers

➤ The GC search could shed light on the actual main components of the neighboring region of Sgr A* (debated to be DM)

➤ For the standard NS case scenario we are probing ellipticities very close to the lowest estimates

➤ Exciting times especially if a joint CW and EM observation occurs (constraints on NS interior), remarking the importance of multi-messenger astronomy

➤ We expect (and hope) to find several surprises in O3/O4