A method for directed searches of continuous gravitational waves in advanced detector data

Ornella Juliana Piccinni for the Rome CW group

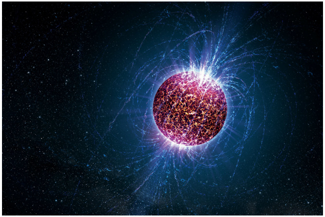
University of Rome "La Sapienza" & INFN Roma1

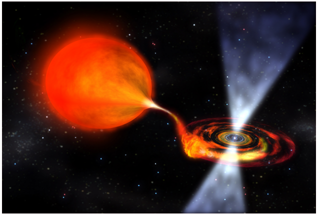
February 20, 2019

Overview

- What is a continuous gravitational wave (CW)?
- CWs searches and the computational problem
- highlights of a directed search pipeline
- Potential sources of CWs signals form Fermi and INTEGRAL
- Can we detect something in O3?

What is a Continuous Wave (CW)?





Credit: C. Reed, Penn State/Mc Gill University

- Long-lived signals emitted by fast spinning (asymmetric) compact objects
- Expected sources in LIGO-Virgo band involve isolated neutron stars (NS) or in a binary system
- Orders of magnitude weaker than transient events from black hole and neutron star mergers

[For a CW review: Lasky 2015]

The signal

In the general case of an isolated spinning NS, non-axisymmetric with respect to the rotational axis. The GW-strain amplitude is given by:

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2}{r} \epsilon, \quad I_{zz} : \text{moment of inertia} \quad \epsilon : \text{ellipticity} \qquad (1)$$

- The emitted frequency is proportional to the star rotational frequency and depends on the emission scenario
- The ellipticity can be due to different mechanisms: elastic stress, strong internal magnetic fields, thermal gradients, etc. (theoretical max: $\epsilon_{max} \sim 10^{-5} - 10^{-3}$), depending on the EOS

[For a CW review: Lasky 2015]

The signal modulations

a CW received at the detector is not exactly monochromatic (there is a frequency and amplitude modulation)

- there is a **spin-down** due to the loss of energy of the star

$$f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \ldots \tag{2}$$

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- due to the orbital and rotational motion of the Earth, there is a detector **Doppler shift**, dependent on the sky direction of the source.

$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v}\cdot\widehat{n}}{c}\right), \quad \vec{v} = \vec{v}_{orb} + \vec{v}_{rot} \qquad (3)$$

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- Furthermore there is a **sidereal day variation** of the phase and amplitude of the detected signal

Correction of the signal

For a source with known rotational parameters $[f_0, \dot{f}_0, \ddot{f}_0, \ldots]$ at a given reference time:

- The **Doppler shift** can be corrected by simply multiplying the data by $\exp(-i\phi_{dc}(t))$ where:

$$\phi_{dc}(t) = 2\pi p_{\hat{n}}(t) f_0(t) \tag{4}$$

  $p_{\hat{n}}(t)$ position of the detector projected along the source sky position $\hat{n}$

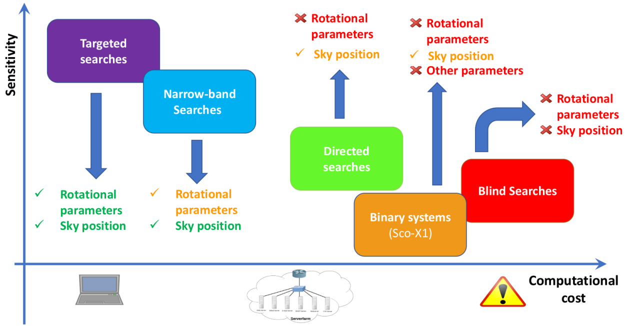
- While the **spin-down** phase correction is :

$$\phi_{sd}(t) = 2\pi \int \dot{f}_0 \cdot (t - t_0) + \ldots dt \tag{5}$$

- other effects like the *Einstein delay* and the *Shapiro delay* should be considered if needed

CW searches

- explore a $4 + N$ dimensional space $(\alpha, \delta, f, \dot{f} + \text{derivatives})$
- Long integration time is needed in order to increase the Signal-to-Noise Ratio



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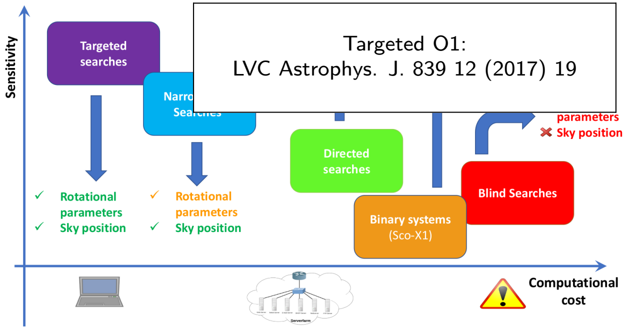

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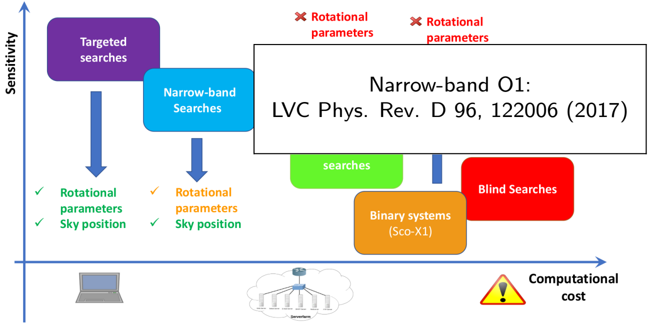

Narrow-band O1:
LVC Phys. Rev. D 96, 122006 (2017)

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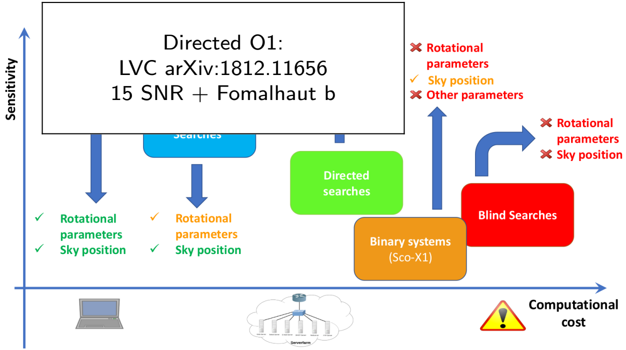

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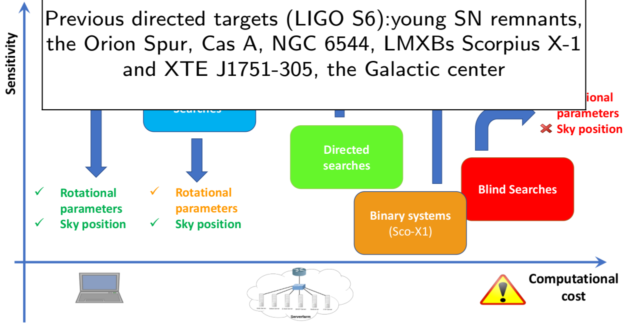
Previous directed targets (LIGO S6):young SN remnants, the Orion Spur, Cas A, NGC 6544, LMXBs Scorpius X-1 and XTE J1751-305, the Galactic center



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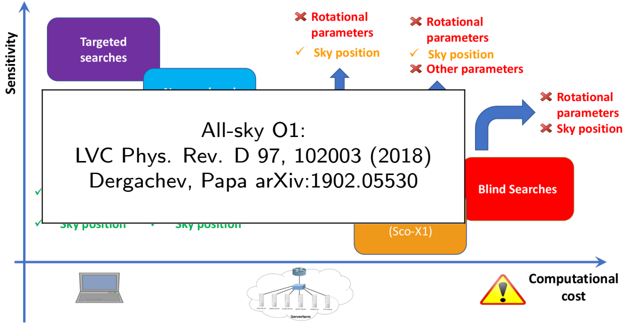
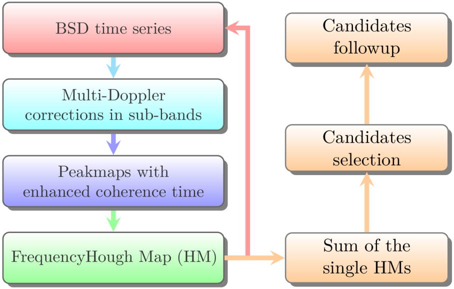
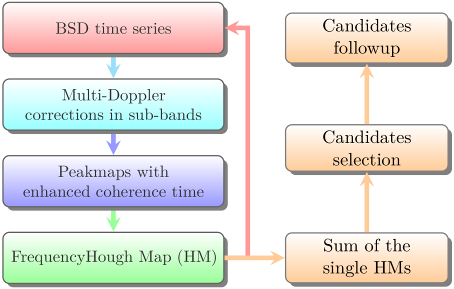


The BSD-directed pipeline



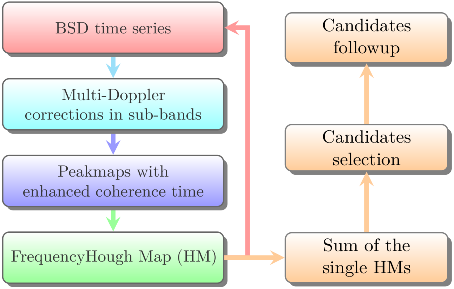
1. The starting point is the Band-Sampled-Data (BSD) framework (Piccinni+ 2019)

The BSD-directed pipeline



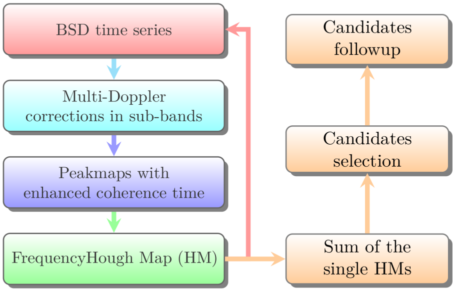
2. Since $(f_0, \dot{f}_0)$ are unknown we partially correct the data for the Doppler in each 1 Hz band

The BSD-directed pipeline



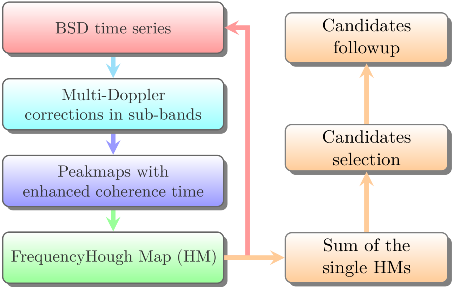
3. **Peakmap:** The most significant time-frequency peaks selected in the equalized spectrum (Astone+ 2005)

The BSD-directed pipeline



4. **FrequencyHough** transform maps the time frequency peaks to the source intrinsic frequency and spin-down (Astone+ 2014)

The BSD-directed pipeline



The most significant candidates are selected on the final HM. The total computational power needed for this search is ~ 100 CPU hours per target for a "wide" frequency/spin-down range

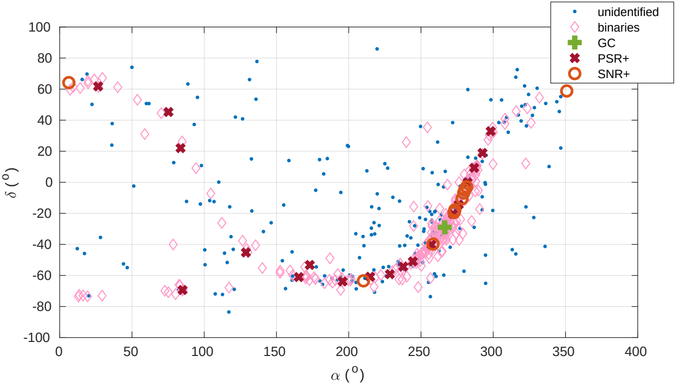
Potential sources

- Sources which are likely hosting a NS are interesting candidates for our searches.
- Several potential sources are present in the astronomical catalogs like:
  - the pre-release of the 8-years Fermi-LAT point sources catalog[1]
  - the IBIS-INTEGRAL soft gamma-ray source catalog (Bird+ 2016).
- most of the sources lie on the Galactic plane
- in addition to these targets the Galactic center itself is a good place to look for CW since it is likely to host several candidates (Bartels+ 2016, Lee+ 2016, Fermi-LAT coll. 2017)

[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/

IBIS-INTEGRAL

INTEGRAL catalog presents the following interesting sources: 10 **SNR**, 19 *pulsar-like* sources and 216 *unidentified* ones (23%) which sky distribution is shown below:



Fermi-LAT (1)

The Fermi catalog potential CW sources are:

Identified:

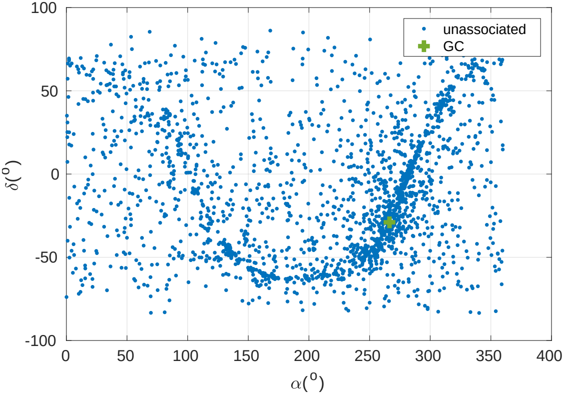
Source	#	Frequency	position	CW search
Pulsar (PSR)	184	well known	well known	targeted
Pulsar Wind Nebula (PWN)	8	not known	known	directed
Supernova remnant (SNR)	22	not known	known	directed

Associated: no pulsations seen yet

Source	#	Frequency	position	CW search
Pulsar (psr)	34	not well known	known	Narrow-band
Pulsar Wind Nebula (pwn)	11	not known	not well known	semi-directed
Supernova remnant (snr)	17	not known	not well known	semi-directed
Potential pwn or snr (spp)	96	not known	not well known	semi-directed

Fermi-LAT (2)

Unassociated: 2132 in Fermi-LAT ($\sim 39\%$) we have only gamma-rays observation, no counterparts at other wavelengths

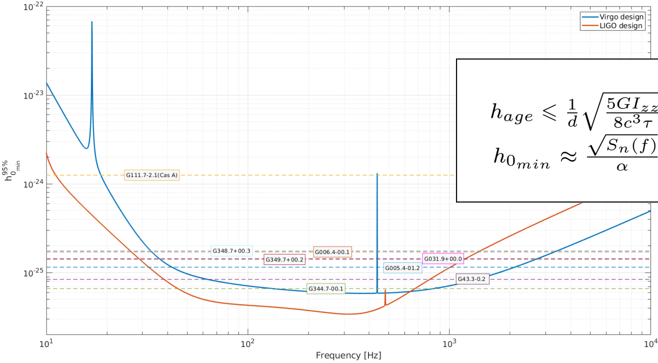


How "good" is a target

- for a given pipeline we can have an estimate of the search sensitivity (Astone+ 2014) which is given by $h_{0_{min}} \approx \frac{\sqrt{S_n(f)}}{\alpha}$ (minimum detectable GW strain amplitude, α depends on the coherence time and peaks/candidates thresholds used)
- typically for targeted searches we can compute the indirect spin-down limit using the frequency and the spin-down parameters of a source
- for directed searches we use the *age based upper limit* h_{age} for those sources whose *age* and *distance* is known (Wette 2008)
- a good target will have $h_{age} \geqslant h_{0_{min}}$
- all these quantities can be translated in terms of the star ellipticity ϵ_{age} and ϵ_{min} (see Eq. (1))

Theoretical indirect upper limits

The sources shown in the plot are potentially detectable by our directed search pipeline since they have a theoretical indirect age based limit (among them Cas A) bigger than our search sensitivity. Other sources from the catalog were discarded because the age or the distance was unknown.

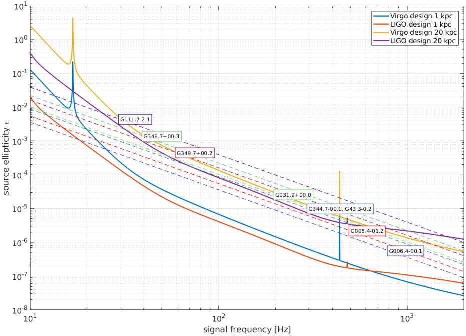


$$h_{age} \leqslant \frac{1}{d}\sqrt{\frac{5GI_{zz}}{8c^3\tau}}$$

$$h_{0_{min}} \approx \frac{\sqrt{S_n(f)}}{\alpha}$$

Theoretical indirect upper limits on the ellipticity

Since $h_0 \propto \frac{I_{zz}}{d} \epsilon f^2 \rightarrow \epsilon_{min} = \frac{c^4}{4\pi^2 G} \left(\frac{d}{I_{zz}} \right) \frac{h_{0_{min}}}{f^2}$



Curve of ϵ_{min} at 95 % C.L. for the case of LIGO and Virgo detectors with $d = 1$ kpc and 20 kpc and the 8 SNR ellipticity indirect upper limits ϵ_{age}. The theoretical indirect upper limit for the star ellipticity is

$$\epsilon_{age} \leq \sqrt{\frac{5c^5}{128\pi^4 G I_{zz} \tau f^4}}$$

Conclusion

- CW could be the next surprise for GW astronomy given the enhanced sensitivity of the detectors
- In parallel, new fast and computationally robust pipelines are needed to increase the chance of detection
- Astronomical catalogs (Fermi, INTEGRAL,...) provide good targets for our directed pipelines if they beat the indirect limit
- It's a good practice to keep track also of those sources which couldn't beat the limit and include them as target in future searches

References

[1] *P. Lasky* Pubs. Astron. Soc. Australia 32 34 (2015)

[2] *Piccinni O. J. et al.* CQG 36 015008 (2019)

[3] `https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/`

[4] *A. J. Bird et al.* Astro. J. Supp. S., 223 1 (2016)

[5] *Astone P. et al.* PRD 90, 042002 (2014)

[6] *Wette, K.* CQG, 25, 235011 (2008)

[7] *Abbott P.B. et al.* Liv. Rev. in Rel., 21 3 (2018)

[8] *Bartels, R. et al.* C. Phys. Rev. Lett. 116, 051102 (2016)

References

[9] *Lee, S. K. et al.* Phys. Rev. Lett. 116, 051103 (2016)

[10] Fermi-LAT collaboration 2017 arXiv:1705.00009

[11] *P. Astone et al.* Class. Quant. Grav. 22,S1197 (2005)

The sensitivity of the search

$$h_{0,min} \propto \frac{\Lambda_1}{N(f)^{1/4}} \sqrt{\frac{S_n(f)}{T_{coh}(f)}}$$

$$h_{0,min} \approx \frac{4.02}{N(f)^{1/4}\theta_{thr}^{1/2}}\sqrt{\frac{S_n(f)}{T_{coh}(f)}}\left(\frac{p_0(1-p_0)}{p_1^2}\right)^{1/4}\sqrt{CR_{thr}(f)-\sqrt{2}\mathrm{erfc}^{-1}(2\Gamma$$

$\Gamma = 95\% C.L.$, $\theta_{thr} = 2.5$, $p_0 = 0.0755$, $p1 = 0.0692$, p0 prob of selecting a noise peak
$CR_{thr} = \sqrt{2}\mathrm{erfc}^{-1}(2 * N_{cand}/N_{tot}) = 6.50$
$P_{fa} = \frac{1}{N_{tot}} = \frac{1}{\sum n_{if} n_{isd}} = 3.98e - 11$ if $N_{cand} = 1$

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz} f^2}{r}\epsilon \qquad (6)$$

The theoretical spin-down limit

- A spinning star loses energy (spin-down)
  - Rotational energy loss: $\dot{E}_{rot} \propto I_{zz} f_{rot} \dot{f}_{rot}$
  - Gravitational energy loss: $\dot{E}_{GW} \propto I_{zz}^2 f_{rot}^6 \epsilon^2$
- We can assume that all the loss of energy of a rotating NS is caused by GW emission. In other words we assume that the observed star spin-down (the decrease of the rotation period) is due to GWs:

$$\dot{E}_{rot} = \dot{E}_{GW} \implies \epsilon_{sd} \propto \sqrt{\frac{1}{I_{zz}} \frac{|\dot{f}_{rot}|}{f_{rot}^5}} \tag{7}$$

From h_0 we can express a theoretical upper limit for the GW amplitude:

$$h_{sd} \propto \frac{1}{r} \sqrt{I_{zz} \frac{|\dot{f}_{rot}|}{f_{rot}}} \tag{8}$$

The age based limit

If we assume that the star is spinning down with $\dot{f} \propto f^n$ and it is spinning significantly more slowly than it was at birth, we can relate the frequency evolution to the characteristic age τ and braking index n:

$$\tau = \frac{1}{n-1}\left(\frac{f}{-\dot{f}}\right)$$

$$n = \frac{f\ddot{f}}{\dot{f}^2}$$

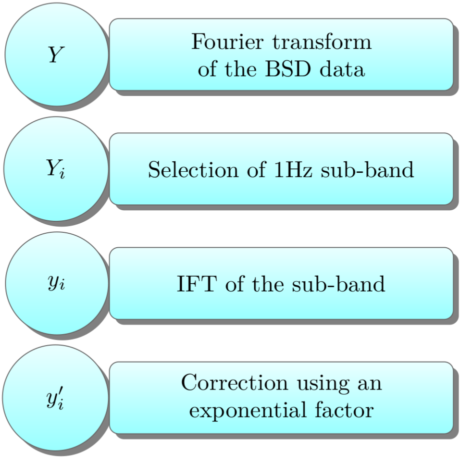
If the spin-down is dominated by GW from a constant mass quadrupole, then $n = 5$ and τ is the true age of the star and the spindown limit becomes:

$$h_{age} \leqslant \frac{1}{d}\sqrt{\frac{5GI_{zz}}{8c^3\tau}}$$

The *Band-Sampled-Data* framework

- **What has been done:** development of routines to create and manage band-limited time series (BSD), down-sampled and partially cleaned from disturbances
- **Which data**: time series is under the form of *reduced*-analytic signal
- **A DB of DBs:** each BSD file covers 1 month of data and 10 Hz frequency band + routines to switch to a different configuration
- **Flexibility:** optimized FFT length for a given search or step of the analysis (e.g. targeted, follow-up)

The Multi-Doppler correction



- classical heterodyne

$$\phi_d(t) = \frac{2\pi}{c} \cdot p_{\hat{n}}(t) \cdot f_0(t)$$

- *divide et impera:* the 10 Hz BSD band is divided in sub-bands
- modified heterodyne ($f_0(t)$ unknown)

$$\phi_i(t) = \frac{2\pi}{c} \cdot p_{\hat{n}}(t) \cdot f_i$$

- corrected time series

$$y_{MD} = \sum_{i=1}^{10} y'_i(t) = \sum_{i=1}^{10} y_i(t) \cdot \mathrm{e}^{-i\phi_i}$$

The peak selection

a peak is selected when the following relation holds:

$$\mathcal{R}(i,j) = \frac{S_{P;i}(f_j)}{S_{AR;i}(f_j)} > \theta_{thr} = 2.5 \qquad (9)$$

where $S_{P;i}(f_j)$ is the square modulus of the $i-$th FFT, also known as periodogram, and $S_{AR;i}(f_j)$ an auto-regressive average spectrum estimation. The ratio is computed for each $j-$th frequency bin of a given FFT. Each pair (i,j) made by the i-th initial time of a selected FFT and the corresponding $j-$th frequency bin is a peak.