Searching for continuous gravitational wave signals from rotating neutron stars

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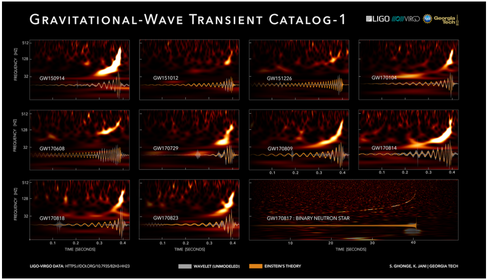
LSC LIGO Scientific Collaboration

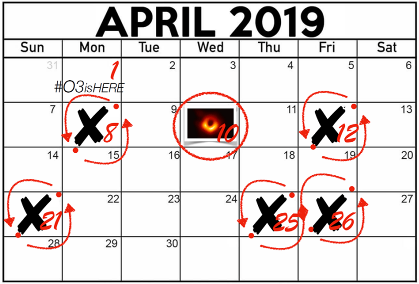
VIRGO

Motivation, Model & Method

O1/O2: 10 BH-BH mergers, 1 NS-NS merger

(catalog: https://www.gw-openscience.org)

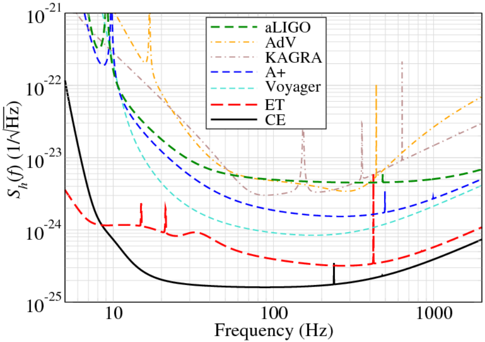




O3: public alerts!

(Gravitational Wave Candidate Event Database: https://gracedb.ligo.org)

Signal-to-noise ratio (SNR)



Regimbau et al. (2017)

Signal-to-noise ratio

$$SNR \propto \frac{h_0}{\sqrt{S_n}}\sqrt{T}$$

S_n - strain noise
(aLIGO: $\sqrt{S_n} \sim 10^{-23}\mathrm{Hz}^{-1/2}$)

T - observational time

Network of the detectors

$$SNR \propto \sqrt{N}$$

N - number of detectors with comparable sensitivity

- GW150914: $h_0 \sim 10^{-21}$, $T \sim 0.2\mathrm{s} \rightarrow SNR \sim 24$
- CGW: $h_0 \lesssim 10^{-25}$, $T \sim$ days, months, years...

Continuous gravitational waves radiation model

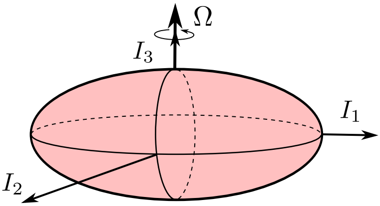
Neutron stars as a sources of CGW radiation

Non-axisymmetric rotating NS (described as a triaxial ellipsoid) radiating purely quadrupolar CGW.

Strain amplitude

$$h_0 = 4 \times 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I_3}{10^{45}\ \mathrm{g\ cm^2}}\right) \left(\frac{f}{100\ \mathrm{Hz}}\right)^2 \left(\frac{100\ \mathrm{pc}}{d}\right)$$

$\epsilon = (I_1 - I_2)/I_3$
$f = \Omega/2\pi$
d - distance



$\mathcal{F}$-statistics and optimal grid

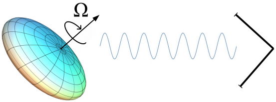
$\mathcal{F}$-statistics (Jaranowski, Królak & Schutz 1998) on the 4-dimensional $(f, \dot{f}, \alpha, \delta)$ optimal grid of parameters (Pisarski & Jaranowski 2015):

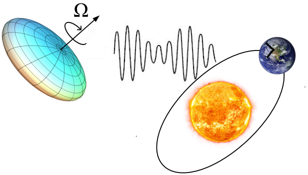
$$\mathcal{F} = \frac{2}{\sigma^2}\left(\frac{|F_a|^2}{\langle a^2\rangle} + \frac{|F_b|^2}{\langle b^2\rangle}\right)$$

$$F_a = \sum_{t=1}^{N} x(t)a(t)exp[-i\phi(t)]$$
$$F_b = \sum_{t=1}^{N} x(t)b(t)exp[-i\phi(t)]$$

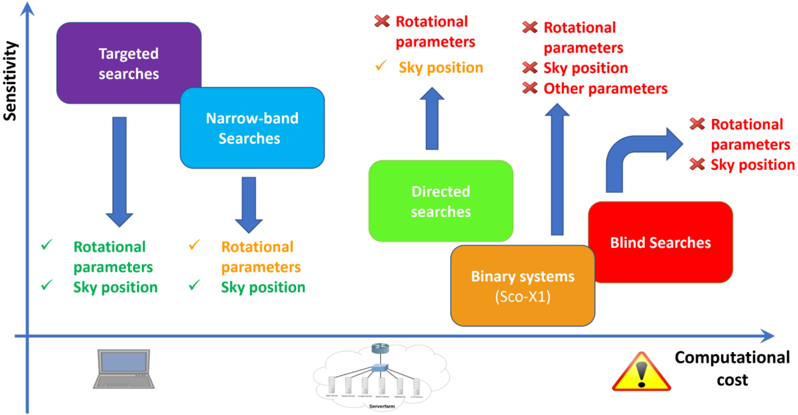
$a(t)$, $b(t)$ - amplitude modulation
$\phi(t)$ - phase modulation

Model of the rotating, triaxial ellipsoid.

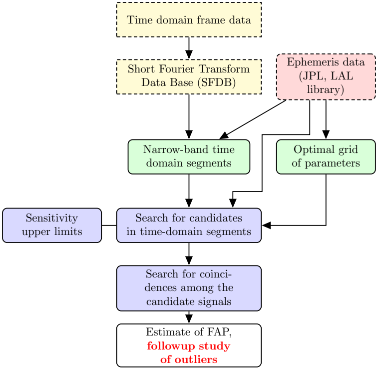




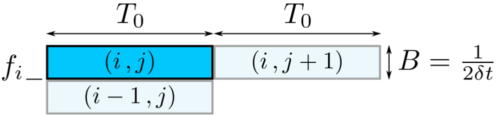
Computational cost



Blind searches computational cost



For `Search` code computing power scales as $\sim T^5 log(T)$
$\rightarrow$ one needs to divide data into shorter chunks (e.g. 6 days)



In `Follow-up` code one can go back to the longer time series.

Main goal

To find $\mathcal{F}$-statistic maximum and $f, \dot{f}, \alpha, \delta$ associated with it.

$$SNR = \sqrt{2(\mathcal{F} - 2)}$$

Code:
https://github.com/mbejger/polgraw-allsky

Documentation page:
http://mbejger.github.io/polgraw-allsky/

Results

O1→O2 data improvement

Abbott et al., 2019, arxiv:1903.01901

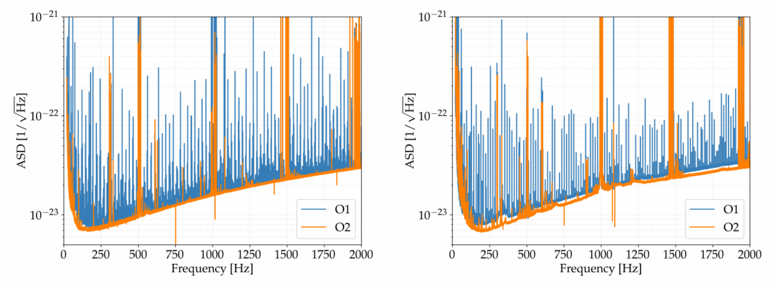


FIG. 1. Amplitude spectral density (ASD) $\sqrt{S_n}$ plots for the L1 (left panel) and H1 (right panel) detectors during O1 (blue trace) and O2 (orange trace). The ASD is obtained by averaging over FFTs of 1800 s obtained for the entire run.

- improvement of the amplitude spectral density
- number of narrow lines and combs greatly reduced

$\mathcal{F}$-statistic pipeline in O2 all-sky search

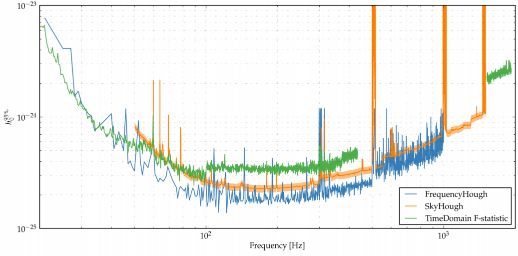


FIG. 3. Upper limits on the strain amplitude $h_0^{95\%}$ for the three pipelines.

Hardware injections recovery:

Label	FA	Frequency [Hz]	Spin-down [nHz/s]	α [deg]	δ [deg]
ip0	$< 10^{-8}$	265.5746 (0.0007)	−0.0466 (−0.0425)	69.42 (2.12)	−57.21 (0.99)
ip3	$< 10^{-8}$	108.8573 (−0.0001)	−0.1386 (0.1386)	174.96 (3.42)	−34.81 (−1.37)
ip5	2.9×10^{-4}	52.8085 (0.0002)	−0.1865 (0.1865)	236.90 (65.72)	−74.18 (9.66)
ip6	$< 10^{-8}$	145.8721 (0.0048)	−6.0512 (0.6788)	358.75 (58.00)	−68.01 (2.58)
ip8	$< 10^{-8}$	190.6428 (0.0002)	−8.5306 (0.1193)	331.41 (19.98)	−35.87 (2.45)
ip10	2.2×10^{-4}	26.3380 (0.0001)	−0.0683 (0.0167)	223.10 (1.54)	37.23 (5.64)
ip11	4.0×10^{-4}	31.42475 (0.00001)	−0.0056 (0.0051)	286.25 (1.10)	−58.39 (0.11)
ip12	5.7×10^{-2}	38.2005 (0.0001)	−6.1165 (0.1335)	326.26 (5.60)	−33.71 (16.73)

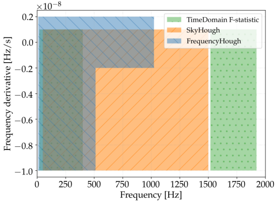
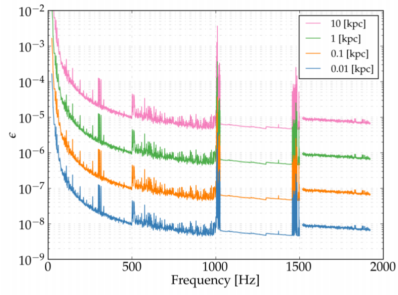
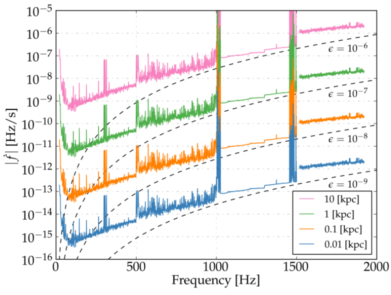


FIG. 2. Regions in frequency and first frequency derivative covered by each pipeline.

O2 all-sky search upper limits





Spin-down limit (assumption: NS looses energy only due to the CGW)

$$h_{sd} = 2.5 \times 10^{-25} \left(\frac{1\text{kpc}}{d}\right) \sqrt{\left(\frac{1\text{kHz}}{f_{GW}}\right) \left(\frac{-\dot{f}_{GW}}{10^{-10}\text{Hz/s}}\right) \left(\frac{I_3}{10^{38}\text{kg}\cdot\text{m}^2}\right)}$$

Corresponding spin-down limit on the equatorial fiducial ellipticity

$$\epsilon_{sd} = 0.237 \times \left(\frac{I_3}{10^{38}\text{kg}\cdot\text{m}^2}\right)^{-1} \left(\frac{\text{Hz}}{\nu}\right)^2 \left(\frac{h_{sd}}{10^{-24}}\right) \left(\frac{d}{1\text{kpc}}\right)$$

Targeted searches in 2015-2017 LIGO Data

- 222 pulsars with rotation frequencies $\gtrsim$ 10 Hz
- young pulsars, Crab & Vela, recycled millisecond pulsar
- O1+O2 data
- two harmonics: $1f$ and $2f$

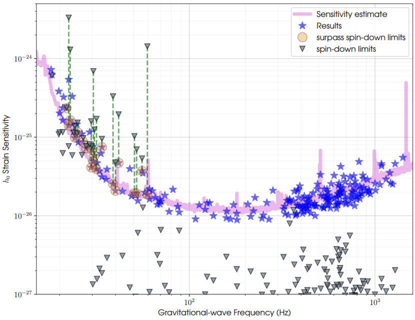


Figure 2. Upper limits on h_0 for 222 pulsars. The stars show the observed 95% credible upper limits on observed amplitude for each pulsar. The solid line shows an estimate of the expected sensitivity of the search. Triangles show the limits on gravitational-wave amplitude derived from each pulsar's observed spin-down.

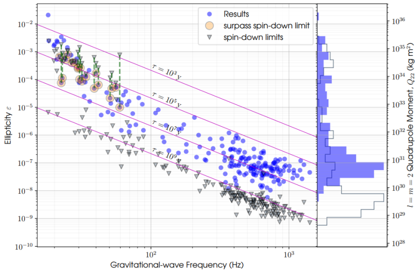


Figure 4. Upper limits on mass quadrupole Q_{22} and fiducial ellipticity ε for 222 pulsars. The filled circles show the limits as derived from the observed upper limits on the gravitational-wave amplitude h_0 assuming the canonical moment of inertia and distances given in Tables 1 and 2. Triangles show the limits based derived from each pulsar's observed spin-down. The diagonal lines show contours of equal characteristic age τ assuming braking is entirely through gravitational-wave emission. The distributions of these limits are also show in histogram form to the right of the figure, with the filled and unfilled histograms showing our observed limits and the spin-down limits, respectively.

Targeted search - summary

So far, no CGW signal was found, but interesting upper limits were set

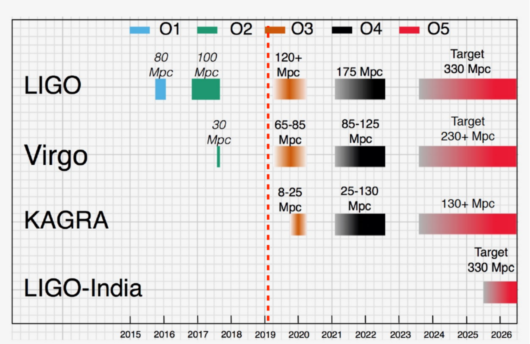
e.g. the newest limits for Crab pulsar (J0534+2200) are:

$$h_{sd} = (1.4 \pm 0.4) \cdot 10^{-24}$$
$$\epsilon_{sd} = 7.56 \cdot 10^{-4}$$

Abbott et al., 2017, Phys. Rev. D 96, 122006
Abbott et al., 2019, arXiv:1902.08442

O3 Plans

- Targeted searches - searches for around 30 high value pulsars at $1f$ and $2f$ frequencies. Search for dipole radiation predicted by Brans-Dicke theory.
- Directed searches - search for r-mode driven GW signal from pulsar J0537-6910.
- All sky searches - search of the band [20 – 750] Hz with 6-24 day coherence time. Implementation of the coherent follow-up procedure.

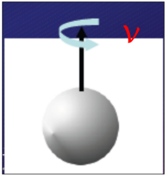


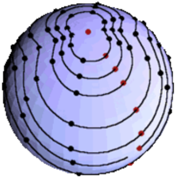
Backup slides

There is more to detect!

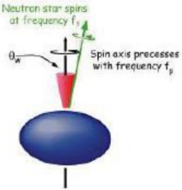
	Known Waveform	Unknown Waveform
Long-lived (continuous)	Rotating neutron stars $h_0 \sim 10^{-25}$	Stochastic background $h_0 \sim 10^{-28}$
Short-lived (transients, bursts, T~0.1s)	Compact binaries coalescences $h_0 \sim 10^{-21}$	Supernovae $h_0 \sim 10^{-21}$

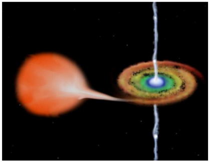
- Mountains (elastic, magnetic, viscosity stresses)
  $f_{GW} = 2f_{rot}$
- Oscillations (r-modes)
  $f_{GW} = 4/3f_{rot}$
- Free precession
  $f_{GW} \propto f_{rot} + f_{prec}$
- Accretion (thermal gradients)
  $f_{GW} \approx f_{rot}$





Courtesy: B. J.Owen



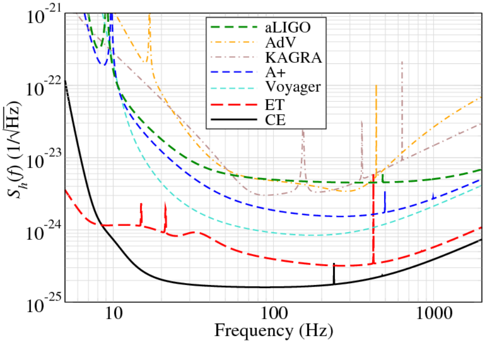


Courtesy: McGill U.

Reviews

Bejger (2018)
Lasky (2015)
Andersson et al. (2011)

Signal-to-noise ratio (SNR)



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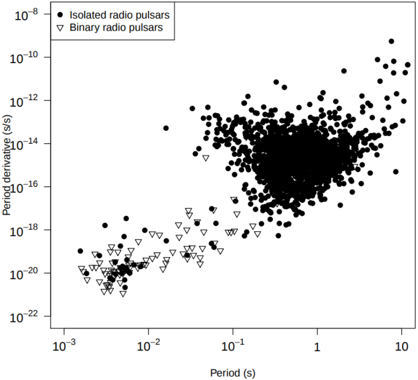
Spin-down

NS is loosing energy and spinning-down, due to the CGW emission, magnetic braking, neutrino emission, accretion (e.g. Greenstein & Cameron 1969, Illarionov & Kompaneets 1990, Dvornikov & Dib 2009, Staff et al. 2012).

We can measure it e.g. from radio-observations.



Spin-down limit (assumption: NS looses energy only due to the CGW)

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Targeted searches in 2015-2017 LIGO Data

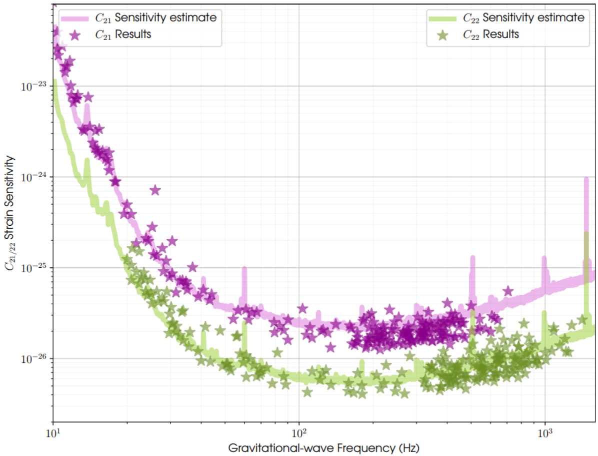
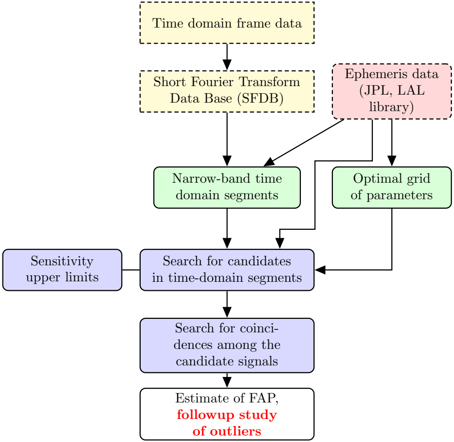


Figure 1. Upper limits on C_{21} and C_{22} for 222 pulsars. The stars show the observed 95% credible upper limits on observed amplitudes for each pulsar. The solid lines show an estimate of the expected sensitivity of the searches.

Time-domain F-statistic pipeline



Code:
https://github.com/mbejger/polgraw-allsky

Documentation page:
http://mbejger.github.io/polgraw-allsky/

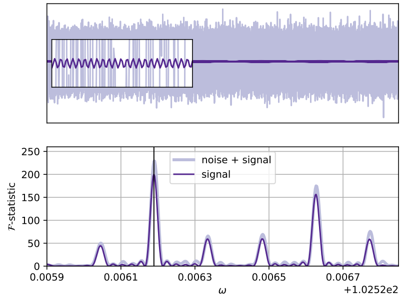
Hierarchical pipeline:

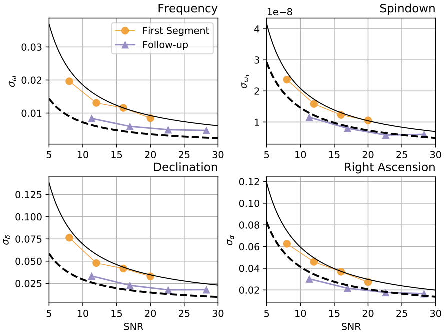
- All-sky search for every time-domain data segment, using relatively loose optimal grid.
- Coincidences between candidates to confirm the existence of signals with the same parameters along the whole observing period.
- New: Follow-up of promising candidates to estimate signal parameters precisely.

Sieniawska, Bejger, Królak (2019) - submitted to CQG

Sieniawska, Bejger, Królak (2019) - submitted to CQG

- Construct precise, optimal grid around the candidate from coincidences
- Find point with the highest $\mathcal{F}$-statistic value (invMADS)
- Repeat for the next data segment
- Find means of the extremum parameters from both segments
- Concatenate 2 (or more) data segments and search for $\mathcal{F}$-statistic maximum





Blind (all-sky) searches

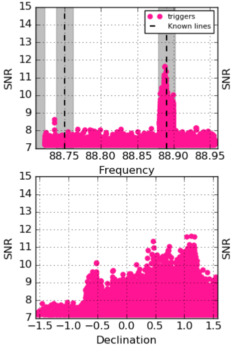
Lines and signals in $\mathcal{F}$-statistics method

Main goal: find $\mathcal{F}$-statistic maximum and $f, \dot{f}, \alpha, \delta$ associated with it.

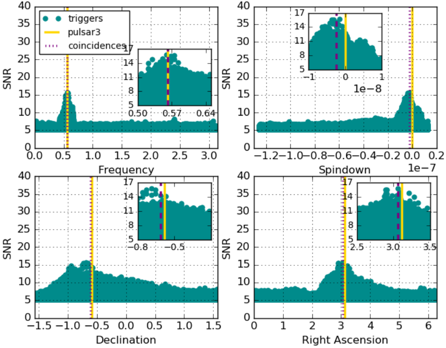
$$SNR = \sqrt{2(\mathcal{F} - 2)}$$

Some lines might mimic signals

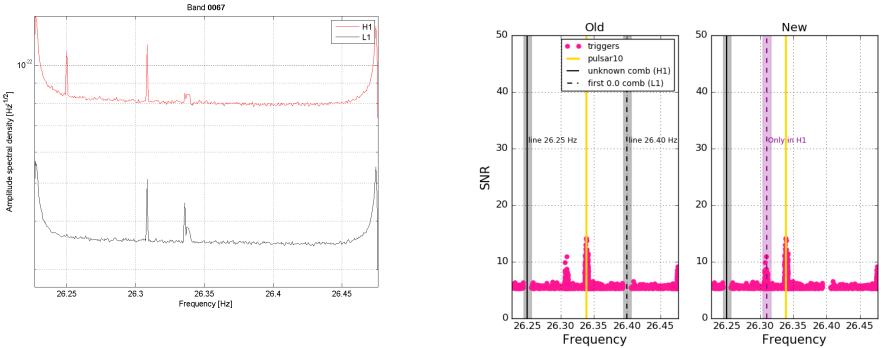
Line:



Signal:



Detector characterisation (DetChar) team provides list of known, stationary lines → vetoing.



Plot courtesy of A. Królak

CW team during data analysis finds new lines, distinguishes lines and astrophysical signals and gives feedback to DetChar.