The Multi-IFO Hough Search using LIGO S4 Data

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Outline

Overview

Rapidly rotating and non-axisymmetric isolated Neutron stars are the most promising sources for long-lived periodic gravitational wave signals. Possible mechanisms for GW emission:

- Deformation of the crust due to elastic stresses or magnetic fields
- Unstable fluid oscillation modes (the r-modes)
- Free precession of the whole star

The Waveform

In the rest frame of the star, the signal is a slowly varying sinusoid with a quadrupole pattern:

$$
\begin{aligned}
h_+(t) &= A_+ \cos\Phi(t) \qquad h_\times(t) = A_\times \sin\Phi(t) \\
A_+ &= h_0 \frac{1+\cos^2\iota}{2} \qquad A_\times = h_0 \cos\iota \\
h_0 &= \frac{16\pi^2 G}{c^4}\frac{I\epsilon f_r^2}{d}
\end{aligned}
$$

- ι: pulsar orientation w.r.t line of sight
- ϵ: equatorial ellipticity
- f_r: rotation frequency
- d: distance to star

The Waveform

The received signal is amplitude modulated due to the detector antenna pattern

$$h(t) = F_{+}(t; \alpha, \delta, \psi) h_{+}(t) + F_{\times}(t; \alpha, \delta, \psi) h_{\times}(t) \quad (1)$$

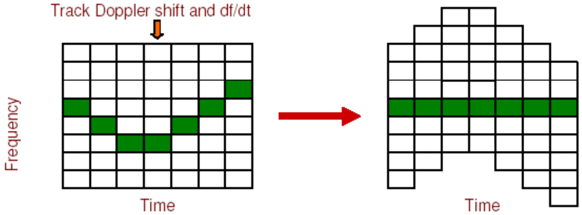
and the frequency is also Doppler modulated

$$f(t) - \hat{f}(t) = \hat{f}(t) \frac{\mathbf{v}(t) \cdot \mathbf{n}}{c} \,. \quad (2)$$

The Doppler modulation allows us to locate the pulsar in the sky but it is also responsible for the computational cost – each sky location has to be demodulated separately.

Semicoherent Searches

- Fully coherent searches are computationally expensive – analysis of, say, 1 year of data is not possible with these methods alone
- Semi-coherent methods are computationally efficient but less sensitive for a given observation time
- These methods combine short segments of Fourier transformed data (SFTs)



Semicoherent Searches

- Three methods are used currently within the LSC
  - Stackslide sums normalized SFT power

$$\rho = \sum_{i=1}^{N} |\tilde{x}_k^{(i)}|^2$$

  - Power-Flux sums weighted SFT power

$$\rho = \sum_{i=1}^{N} w_i |\tilde{x}_k^{(i)}|^2$$

  - Hough sums weighted binary counts

$$n = \sum_{i=1}^{N} w_i n_k^{(i)} \quad \text{where} \quad n_k^{(i)} = \begin{cases} 1 & \text{if} \quad |\tilde{x}_k^{(i)}|^2 \geq \rho_0 \\ 0 & \text{if} \quad |\tilde{x}_k^{(i)}|^2 < \rho_0 \end{cases}$$

Semicoherent Searches

- The three methods have different advantages
  - Powerflux is the most sensitive
  - Hough is more robust and computationally efficient
  - Stackslide is the simplest and also does quite well on sensitivity and cost
- The weights are (optimally) proportional to the SNR of a signal in the different SFTs. For Hough, the weights are:

$$w_i \propto \frac{F_+^2(t_i) + F_\times^2(t_i)}{S_n^{(i)}(f)}$$

- Weights normalized so that $n \in [0, N]$:

$$\sum_{i=1}^{N} w_i = N$$

Sensitivity

- Hough weights suggested by Palomba et al (GWDAW 9)
- Improvement in sensitivity due to weights is important when non-stationarities in SNR are large
- For a given false dismissal rate β, weakest signal that can cross a threshold corresponding to a false alarm rate α is

$$h_0 = 3.38\mathcal{S}^{1/2}\left(\frac{||\vec{w}||}{\vec{w}\cdot\vec{X}}\right)^{1/2}\sqrt{\frac{S_n^{(eff)}}{T_{sft}}}$$

where

$$X_i = S_n^{(eff)}\frac{F_+^2(t_i)+F_\times^2(t_i)}{S_n^{(i)}(f)}$$

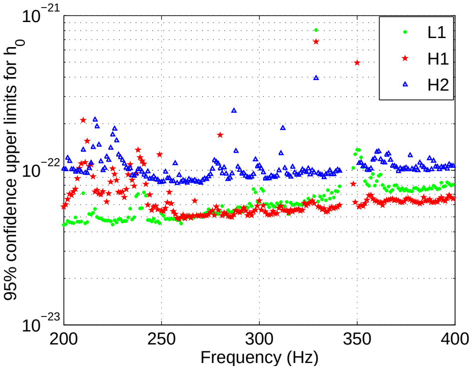
and

$$\mathcal{S} = \mathrm{erfc}^{-1}(2\alpha)+\mathrm{erfc}^{-1}(2\beta)$$

The S2 Search

- All sky search, 200-400 Hz, 11 spindowns including 0 with $\delta\dot{f} = 1.1 \times 10^{-10}$Hz/s.
- No weights used: $n = \sum n_i$.
- L1, H1 and H2 analyzed separately using 1800s SFTs
- No signal detected
- Population based frequentist upper limit set by Monte-Carlo signal injections using loudest event in 1Hz bands
- Known spectral lines consistently avoided while finding loudest events and also during signal injections
- Phys. Rev. D **72**, 102004 (2005)

The S2 Hough Upper-Limits



- Best UL: 4.43×10^{-23} (L1 at 200Hz)

Parameter Space for the S4 Search

- Weights allow us to use SFTs from all three IFOs together
- Sensitivity increases by $\sim$ 10% due to weights
- 899 SFTs from L1, 1004 from H1, and 1063 from H2
- Frequency band is 50-1000 Hz
- All sky search
- Sky is broken up into 92 patches each $\sim$ 0.4 rad wide
- 10 spindown parameters analysed with resolution $\delta\dot{f} = (T_{obs} T_{sft})^{-1} \approx 2.2 \times 10^{-10}$ Hz
- All-sky upper limits set in 0.25 Hz bands based on loudest event

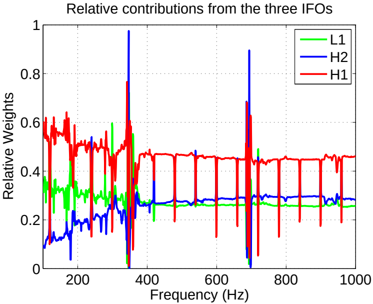
Skypatch size

- Size of skypatch is limited because weights are not valid for entire sky
- Size of each skypatch depends on angular variation of $F_{+,\times}$
- Sky broken up into 92 patches, each $\sim 0.4\mathrm{rad} \times 0.4\mathrm{rad}$.
- For this choise of skypatch size, mismatch between sky-position where weights are calculated and where signal is injected can lead to loss of $\sim$ 5% in SNR

Contribution of the Different IFOs

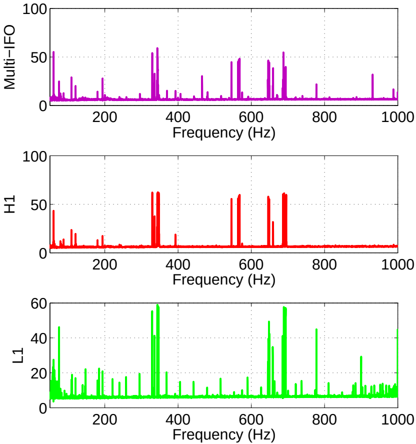
- Look at the quantity fractional noise weight contribution of each IFO, for example

$$\frac{\sum_{H1} w_i}{\sum_{H1} w_i + \sum_{L1} w_i + \sum_{H2} w_i}$$



It is worthwhile to include H2 in multi-IFO search, especially at high frequencies. H1 always contributes most.

Most Significant Events in 0.25 Hz bands – Preliminary



Following up the outliers

- Set a significance threshold of 7 in multi-IFO results
- For every candidate, look for coincident events in L1 and H1 with threshold 6.6
- Exclude 60Hz harmonics and violin modes
- 7 events survive these criteria
- Further follow-ups of these 7 candidates shows them not to be of astrophysical origin
- Aim to perform a coherent $\mathcal{F}$-statistic follow-up in future searches

Following up the outliers

	Band (Hz)	Hough significance Multi-IFO	H1	L1	Comment
1	78.602-78.631	12.466	12.023	10.953	Inst. Lines
2	108.850-108.875	29.006	23.528	16.090	Inj. Pulsar3
3	130.402-130.407	7.146	6.637	6.989	?
4	193.92-193.96	27.911	17.327	20.890	Inj. Pulsar8
5	575.15-575.23	13.584	9.620	10.097	Inj. Pulsar2
6	721.45-721.50	8.560	6.821	13.647	L1 Inst. Lines
7	988.80-988.95	7.873	8.322	7.475	Inst. Lines

Following up the outliers

- Parameters of the outlier at 130.4 Hz

Detector	s	f_0 (Hz)	df/dt (Hz/s)	α (rad)	δ (rad)
Multi-IFO	7.146	130.4028	-1.745×10^{-9}	0.8798	-1.2385
H1	6.622	130.4039	-1.334×10^{-9}	2.1889	0.7797
H1	6.637	130.4050	-1.334×10^{-9}	2.0556	0.6115
L1	6.989	130.4067	-1.963×10^{-9}	1.1690	-1.0104

- Candidate does not pass coincidence test in sky-location

Preliminary Upper Limits

- Hough ULs are predicted by

$$h_0^{95\%} = 11.0\mathcal{S}^{1/2}\sqrt{\frac{S_n^{(eff)}}{T_{sft}}}$$

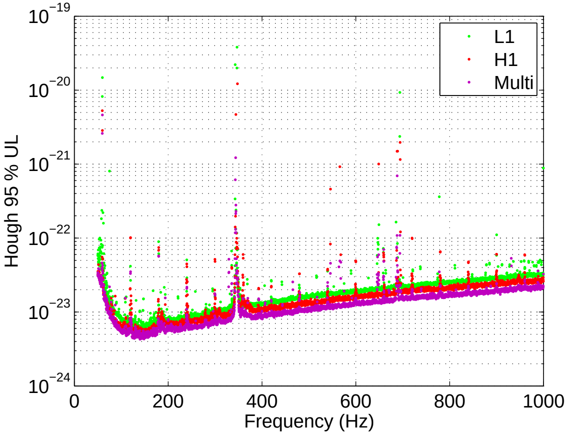
where

$$S_n^{(eff)} = \left(\sum_{i=0}^{N} \frac{1}{\left(S_n^{(i)}\right)^2}\right)^{-1/2}$$

and

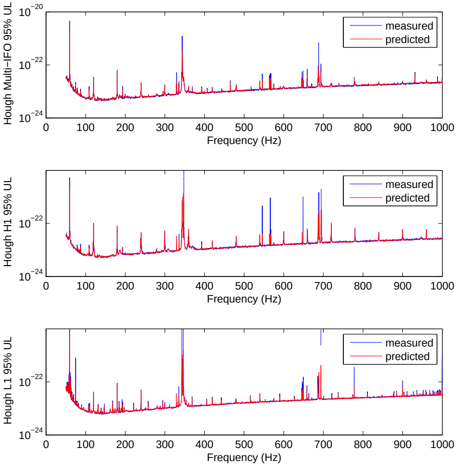
$$\mathcal{S} = \mathrm{erfc}^{-1}(2\alpha) + \mathrm{erfc}^{-1}(2\beta)$$

Preliminary Hough S4 Upper Limits

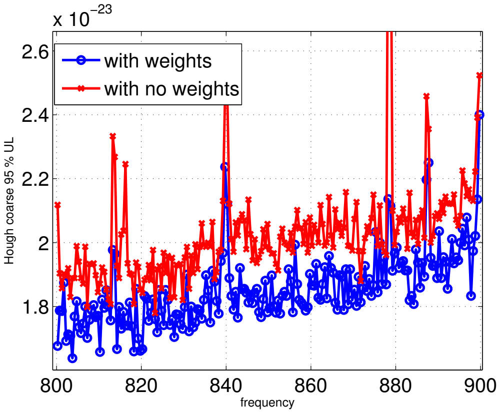


Best upper-limit on h_0: 4.3×10^{-24} (140.25 Hz-140.50 Hz)

Preliminary Hough S4 Upper Limits

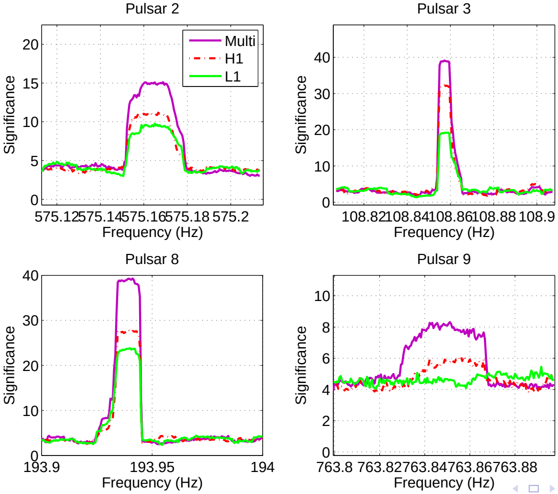


Improvements Due to the Weights – Preliminary

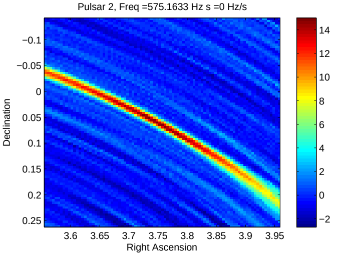


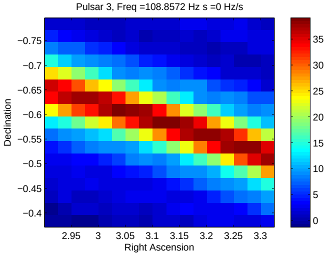
Average improvement by using weights in this band is 9.25% for multi-IFO case (but only $\sim$ 6% for single IFO)

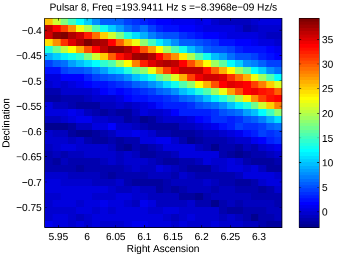
Hardware Injections – Preliminary

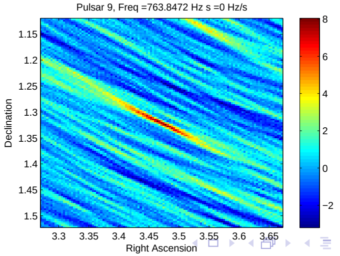


Hardware Injections – Preliminary









Where we are going

Wide parameter space searches:

- We aim to carry out a multi-IFO Hierarchical search consisting of Hough on $\mathcal{F}$-statistic segments to optimize sensitivity
- We aim to implement this for the S5 search

The "Big Picture"