Fast Identification of Continuous Gravitational Wave signals

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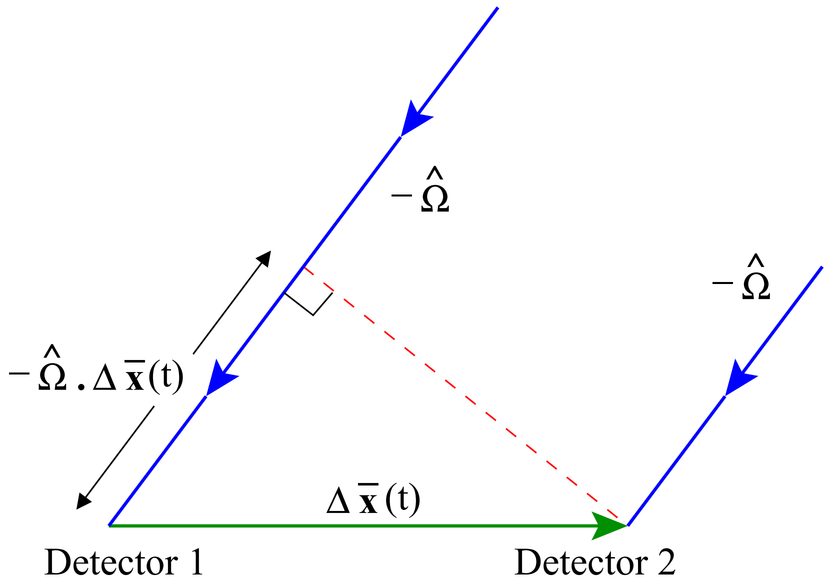
The project

Gravitational waves all-sky searches for asymmetrically rotating neutron stars.

- CW all-sky searches are computationally very demanding: very large parameters space to cover
- SGWB directional searches used the radiometer method for unmodeled directed narrowband analysis
- Characterization for CW signals $\Rightarrow$ we can exploit the speed of the radiometer search for all sky analyses
- Outlier selection and follow-up with a CW pipeline
- Recently the GPU FrequencyHough pipeline has been deployed for the O3 all sky analysis with a significant increase in computing performances
- Adaptability and robustness of the algorithm $\Rightarrow$ still very efficient in a reduced parameters space

The radiometer method

The phase difference between the two detectors in the baseline is used to cross-correlate the data



* Mitra, Sanjit, et al., Physical Review D 77.4 (2008): 042002.
Thrane, Eric, et al., Physical Review D 80.12 (2009): 122002.
Abbott, R., et al., Physical Review D 104.2 (2021): 022005.

The sky map

$$X_{p,f} = \frac{4}{t_s} H_f \sum_t \tilde{\boldsymbol{s}}^*_{1,ft} \frac{\gamma^*_{p,ft}}{P_{1,ft} P_{2,ft}} \tilde{\boldsymbol{s}}_{2,ft}$$

The detection statistics, so called clean map is

$$Y_{p',f} = \Gamma^{-1}_{p'p'',f} X_{p'',f}$$

The Fisher Matrix Γ (~correlation between two sky points) is considered diagonal and it becomes

$$\Gamma_p = \sigma_p^2 \Rightarrow Y_p = X_p / \sigma_p$$

Where:

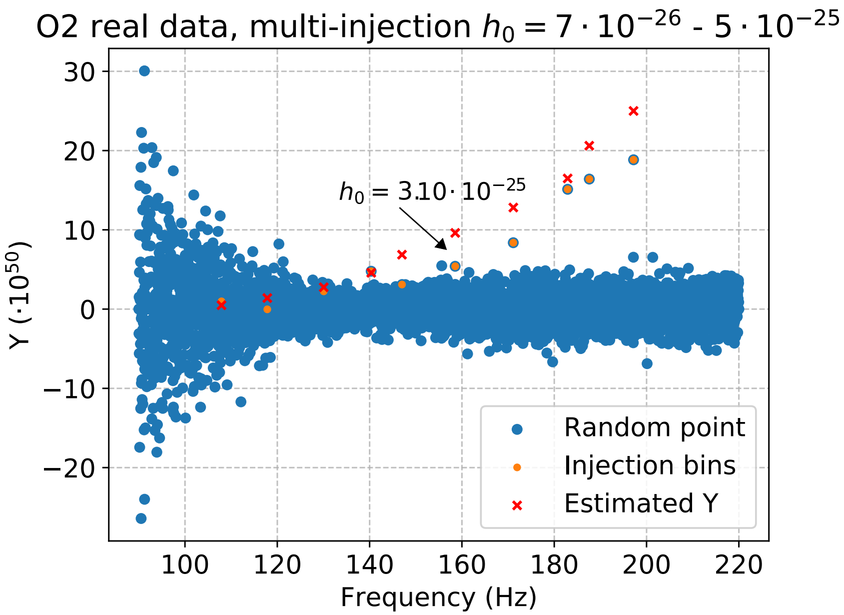
- p a sky point and p', p'' two different positions
- t the time of the i-th segment with length t_s and f the frequency of the j-th bin
- H the filter, γ the ORF, $P_{1,2}$ the PSDs and $\tilde{s}_{1,2}$ the SFT of the i-th segment

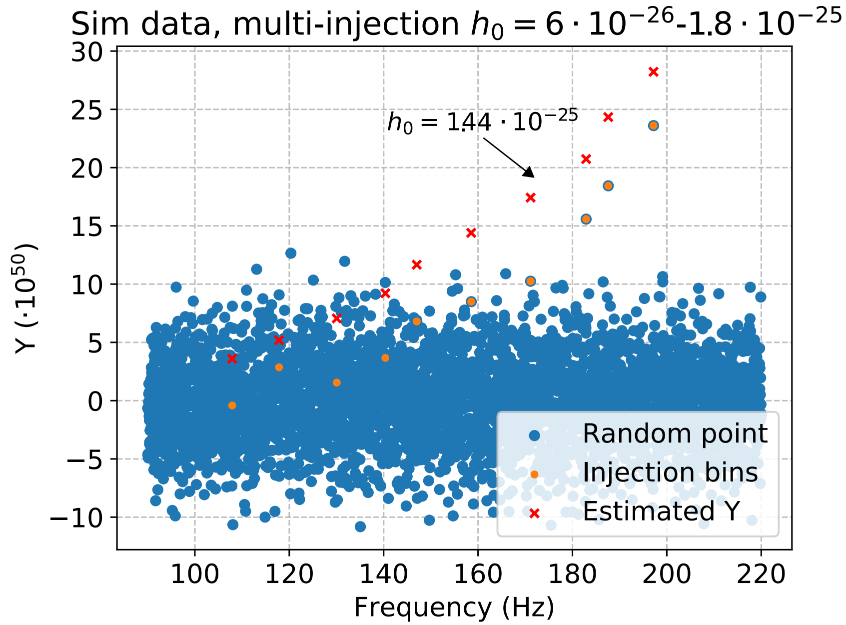
Tests with `stochastic.m`

- Many tests on simulated noise and on real data from the O2 and O3 data with software injections
- Directed narrowband analyses producing SNR ($= Y/\sigma$) vs frequency plots for each sky position fed to the pipeline

Detection statistics

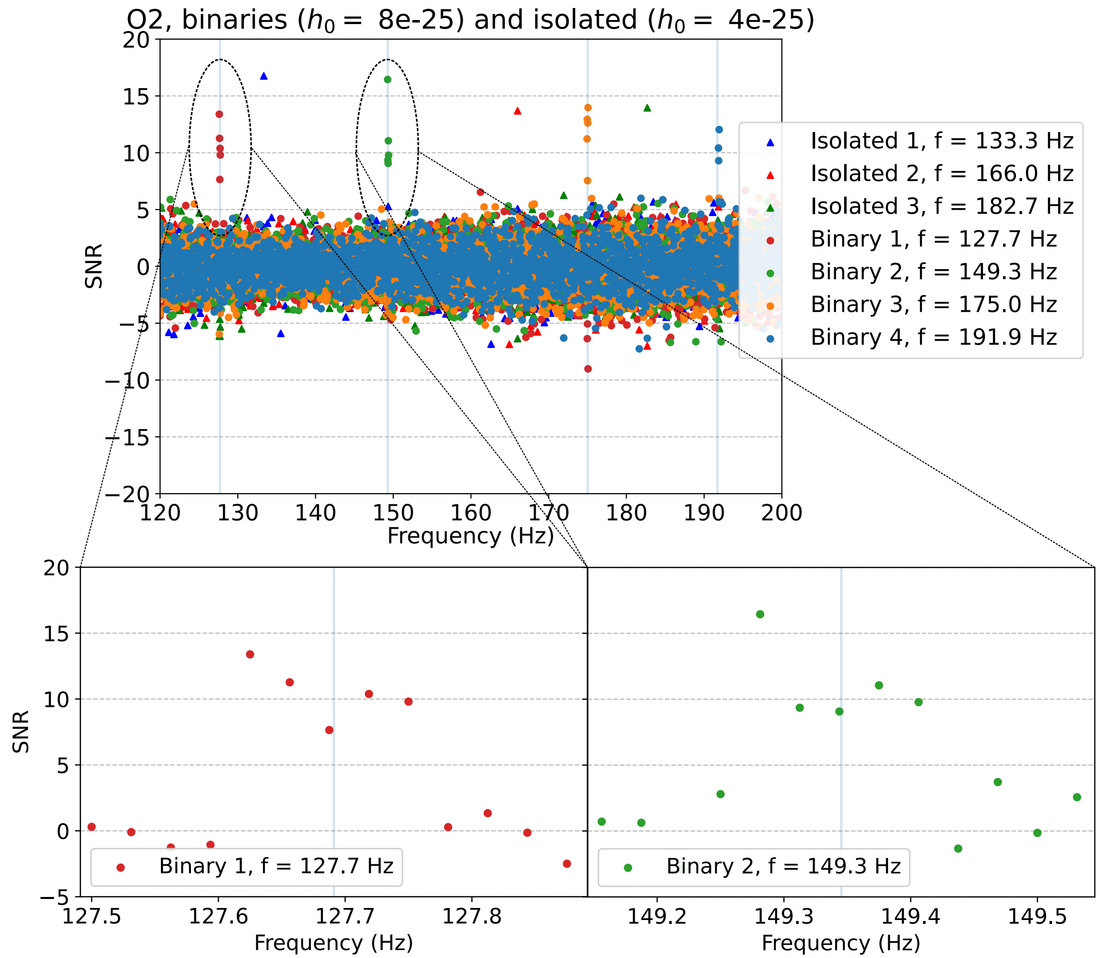
Several pulsars injected with same coordinates and with increasing amplitude h_0





O2 data and simulated noise with design noise levels ($\sqrt{S_h} = 4 \times 10^{-24} Hz^{-1/2}$),
in both cases ~3 months of contiguous data,
data sampled at 256 Hz,
analyzed between 100 and 200 Hz,
$\delta f = 1/32\ Hz, t_s = 192\ s$

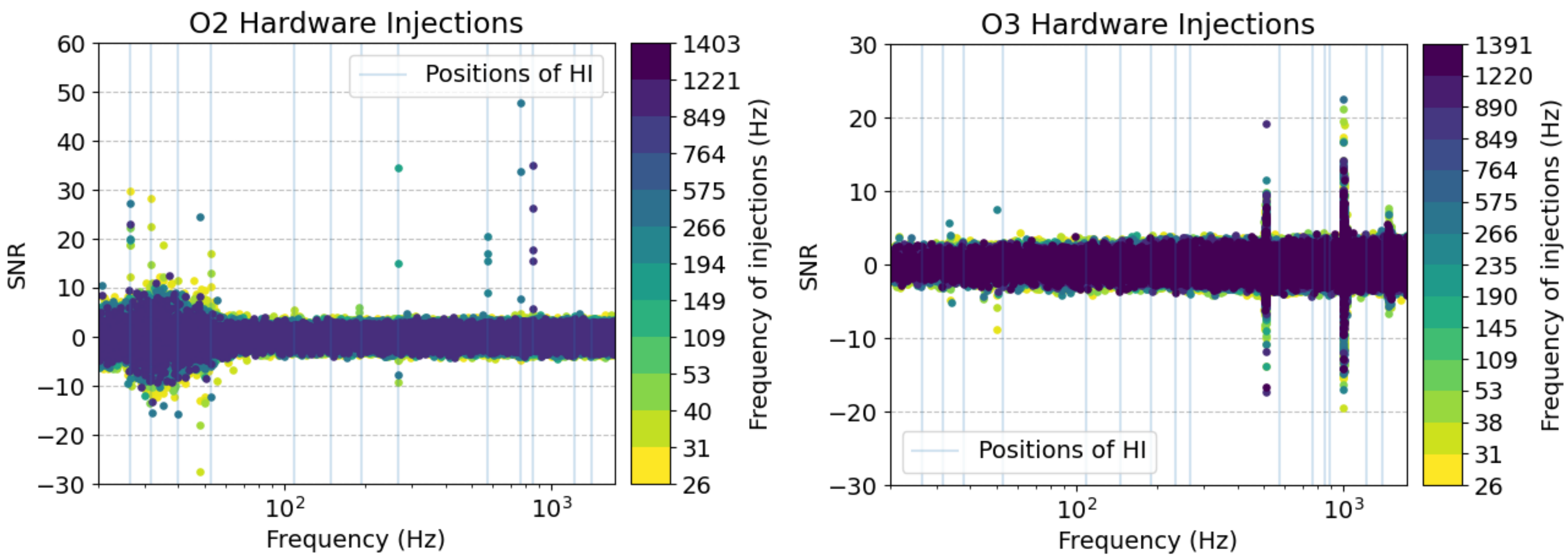
Isolated and binary pulsars



Injections of pulsars both isolated and in binary systems retrieved correctly

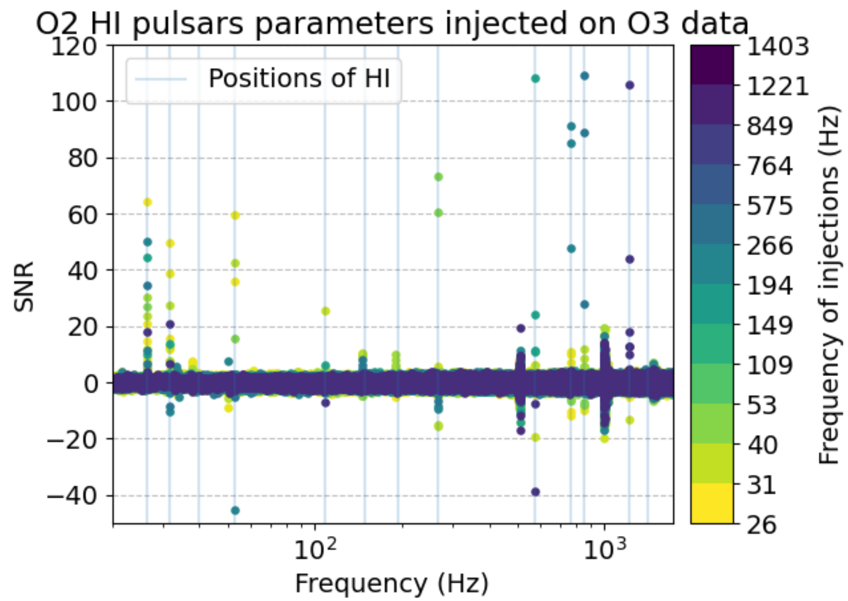
The parameters of the binaries have been chosen to have 5 bins of Doppler spread

Hardware injections



The analysis of the hardware injections of O2 was successful for most of them, althought the O3 ones couldn't be seen

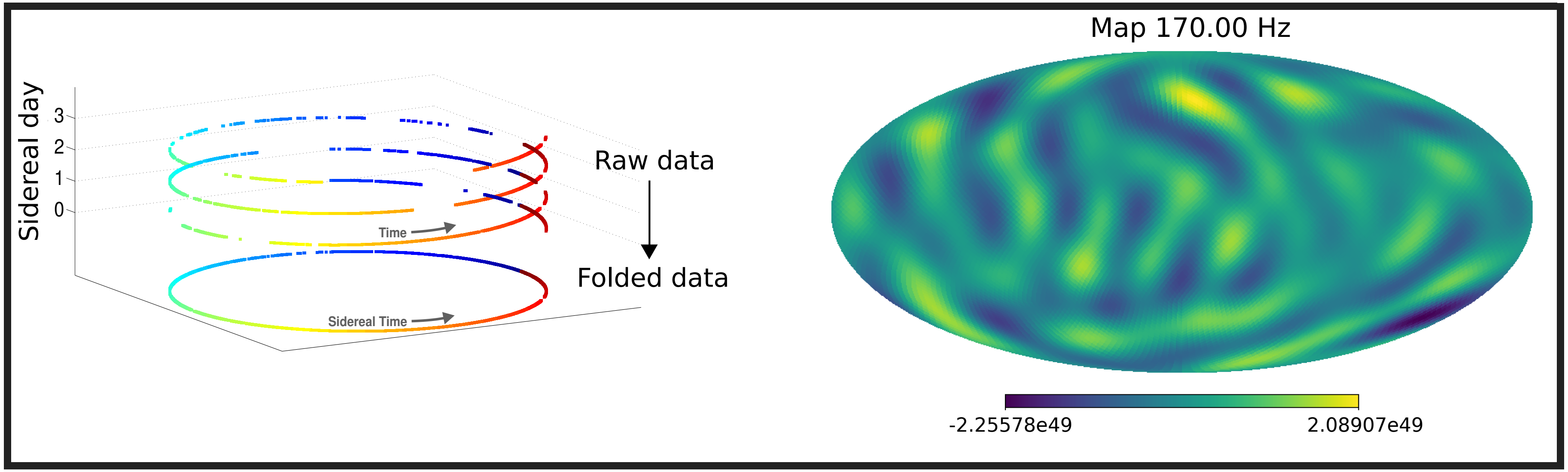
Hardware injections



The most likely explanation is because they are too faint for the radiometer search: injecting via software the O2 HI parameters on O3 data de signals appear very loud.

New tools: from narrowband directed to all-sky, all-frequencies with Pystoch

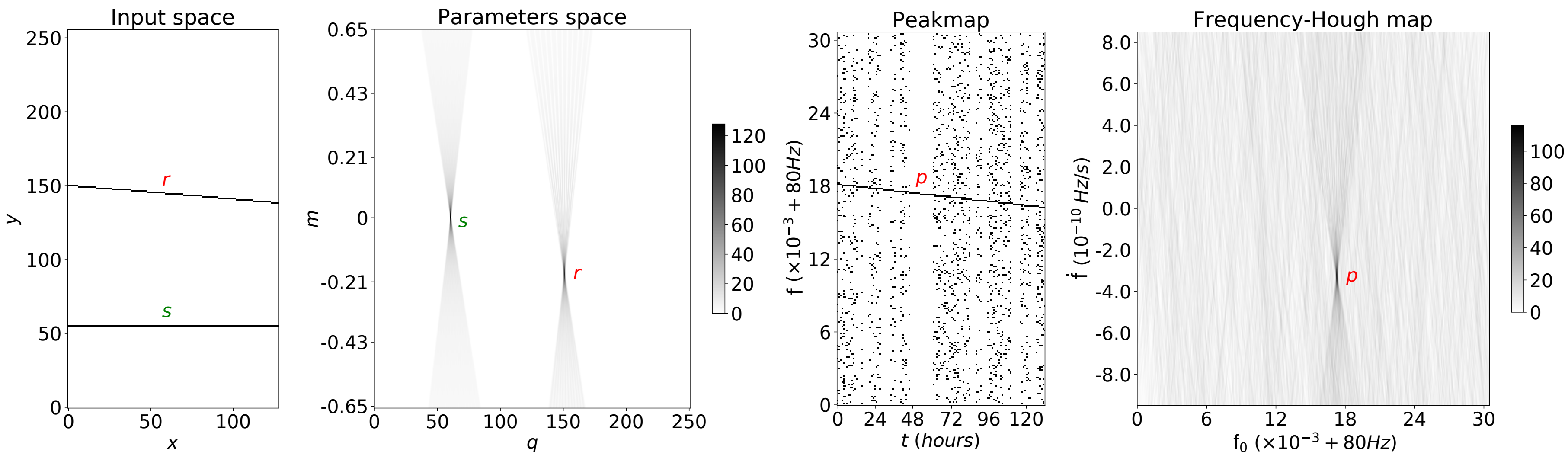
- Use of the folded data
- A tomography of the full sky through the frequency range



* Ain, Anirban, et al., Physical Review D 98.2 (2018): 024001.

The follow-up: FrequencyHough

Instead of the standard follow up used for directional narrowband searches in the SGWB group[1], we use the FrequencyHough[2] (FH) pipeline on the candidate parameters space regions



[1] Abbott, R., et al., Physical Review D 104.2 (2021): 022005.
[2] Astone, Pia, et al., Physical Review D 90.4 (2014): 042002.

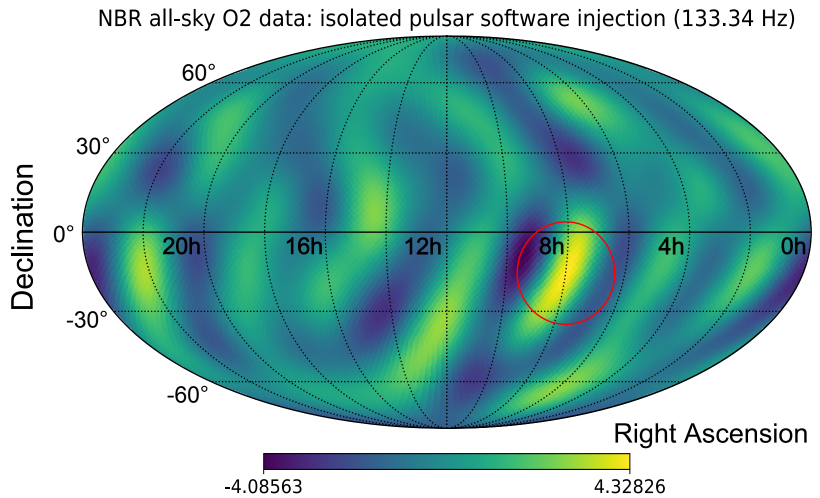
Tests with FrequencyHough

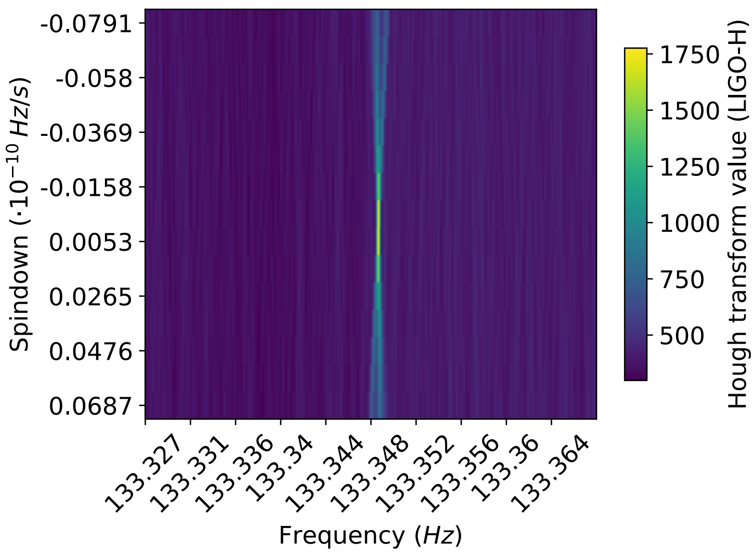
- Again software injections on resampled O2 data
- Integrated time of ~3 months, sampling at 256 Hz
- Analyzed with all-sky PyStoch between 100 and 200 Hz
- Used the FrequencyHough on the spotted outliers at retrieved position, $\pm$0.5 Hz around the signal frequency, spindown range [-1e-08,+1e-09]

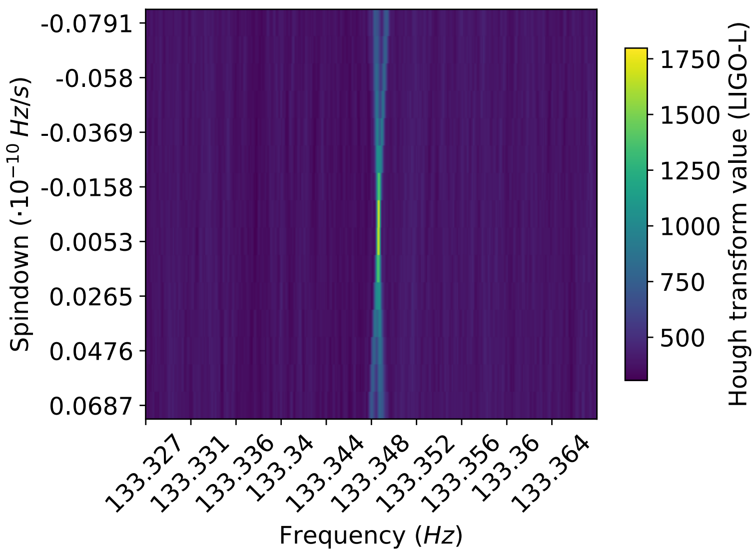
Using the GPU implementation[1] of the FH on many sky positions the analysis can take just few minutes with a proper choice of the candidate parameters space

[1] La Rosa, Iuri, et al., Universe 7.7 (2021): 218.

Results example







Conclusion

The project is now almost at the end but some thing needs still to be done:

- The follow-up for isolated needs to be refined with the standard procedure of the FrequencyHough analysis
- The follow-up for binaries is still yet to be defined
- To have a better knowledge on the expectations from the radiometer analysis, the role of the ORF in the obtained SNR should be studied further

The plan is to publish a method paper within the next months and use the chained pipelines for O4

Thank you!

Backup slides

The overlap reduction function

$$\gamma_{ft,p} = \sum_A \int_{S^2} d\hat{\mathbf{\Omega}} F^A_{1,ft}(\hat{\mathbf{\Omega}}) F^A_{2,ft}(\hat{\mathbf{\Omega}}) e^{2\pi i f \hat{\mathbf{\Omega}} \cdot \frac{\mathbf{d}_t}{c}} e_p(\hat{\mathbf{\Omega}})$$

With:

- $A = \{+, \times\}$ the polarization
- F_i the antenna patterns
- $\mathbf{d}$ the baseline vector
- e_p the basis chosen

Detection statistics

$$\langle Y \rangle = \frac{\sum_j ({A^{+}}^2 F^{+}_{1j} F^{+}_{2j} + {A^{\times}}^2 F^{\times}_{1j} F^{\times}_{2j})(F^{+}_{1j} F^{+}_{2j} + F^{\times}_{1j} F^{\times}_{2j})}{\sum_j (F^{+}_{1j} F^{+}_{2j} + F^{\times}_{1j} F^{\times}_{2j})^2}$$