Fast Identification of Continuous Gravitational Wave signals

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The project

Gravitational waves all-sky searches for asymmetrically rotating neutron stars.
Constraining the parameters space with the fast stochastic background (SGWB) search pipeline, giving targets to the continuous waves (CW) directed narrowband search pipeline.

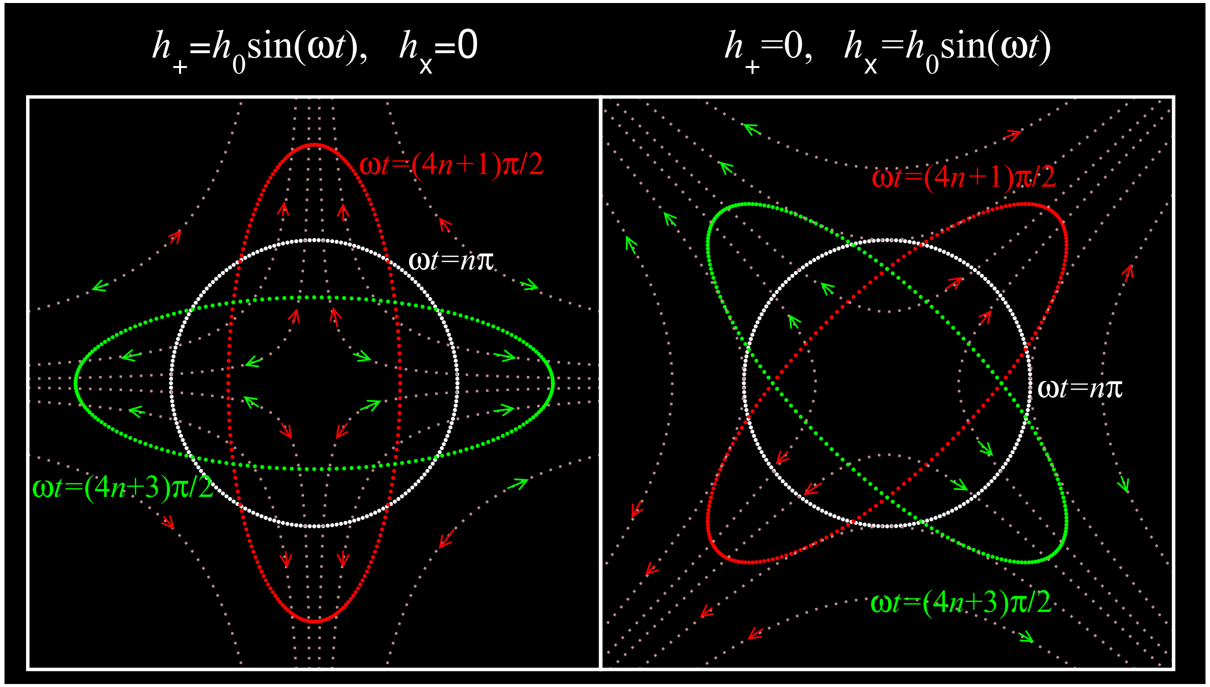
Contents

- Introduction on the gravitational waves
- The troubles of the all sky search
- The radiometer method
- The notable results of my studies

Gravitational waves

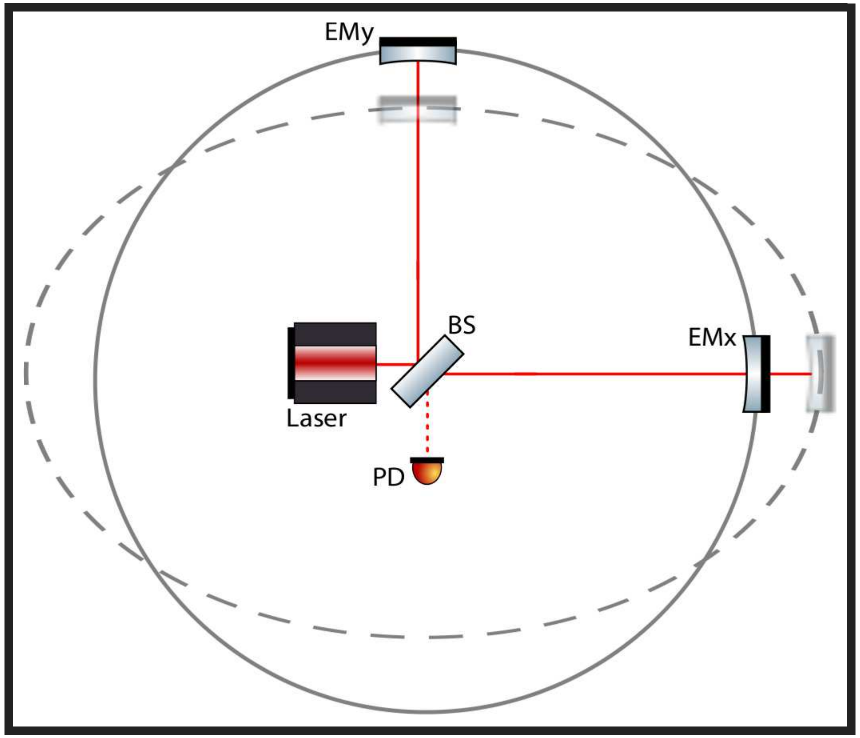
Perturbation $h_{\mu\nu}$ of the metric tensor. In small field and small perturbation approximations, we have in vacuum

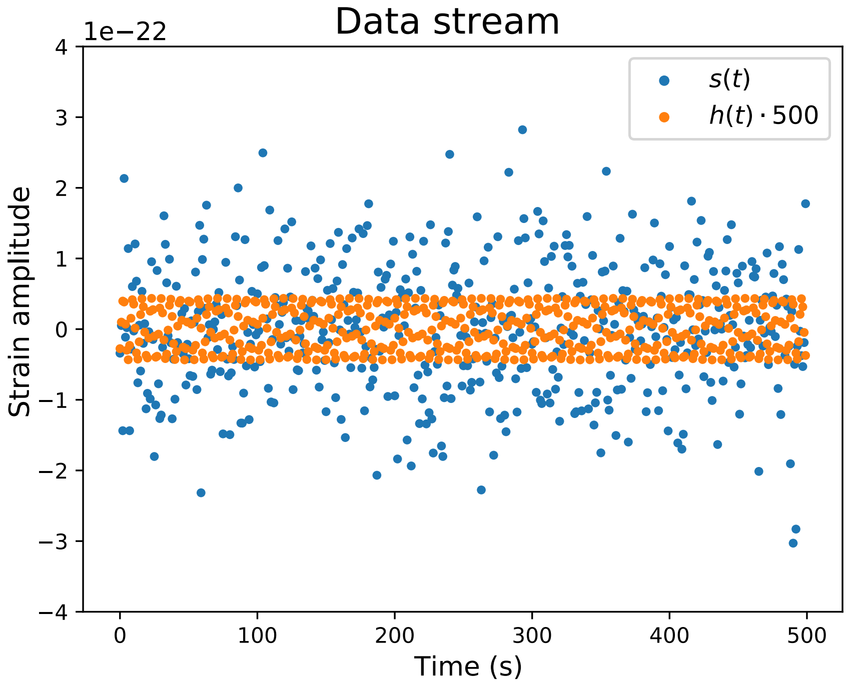
$$\left(\nabla^2 + \frac{\omega^2}{c^2}\right) h_{\mu\nu}(\omega, x^i) = 0$$



The data

Time series $s(t) = n(t) + h(t)$





The analysis

Matched filtering

$$S \propto \Re\left[\int_0^\infty \tilde{s}_1^*(f)\,\frac{\gamma(f)H(f)}{P_1(f)P_2(f)}\,\tilde{s}_2(f)\right]$$

Where the filter is determined by the detectors overlap factor (ORF) γ, their PSDs P_i and by the signal template function H, which depends on the source's parameters.

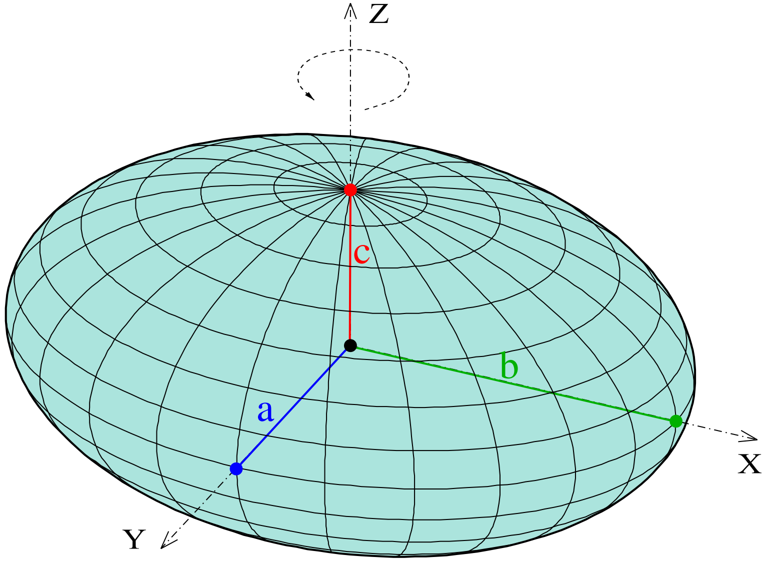
Continuous Waves

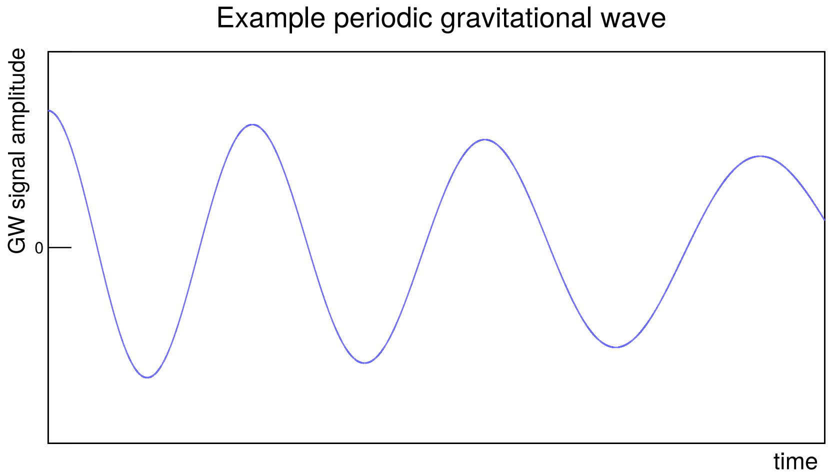
Generated by asymmetrically rotating neutron stars.

For isolated objects: signal amplitude $h_0 = \frac{4GI\epsilon}{c^4 r}\omega^2(t)$.

Tipically $\omega(t) = \omega_0 + k\dot{\omega}$.

(parameters space dimensions count: 2 $(\omega_0, \dot{\omega})$)





A general case

We have to take into account:

- Binary systems: signal's shape is doppler shifted by the orbital motion of the object

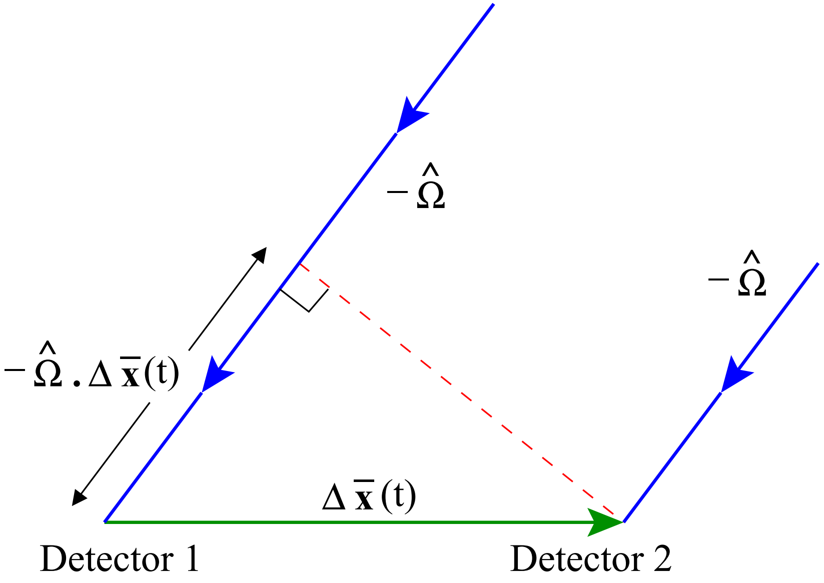
  (parameters space dimensions count: 5 ($\omega_0, \dot{\omega}, i, r_o, T_o$)

- Earth motion: doppler effect which depends on the source coordinates

  (parameters space dimensions count: +2 (α, δ))

A more general search: SGWB 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.

The sky map

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

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

For any point p a semi-coherent search that cross-correlates segments of length t_s, and then integrates over them along the whole run

Tests

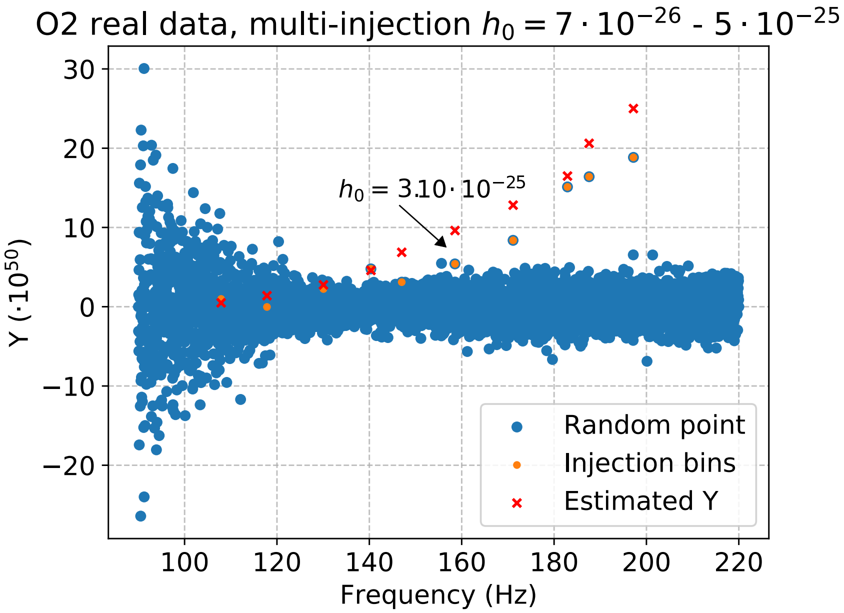
- Software injections on real data from the LIGO Hanford and Livingston detectors (11/30/2016 - 08/25/2017 O2 run)
- Tests on simulated noise with flat design noise levels ($\sqrt{S_h} = 4 \times 10^{-24} Hz^{-1/2}$)

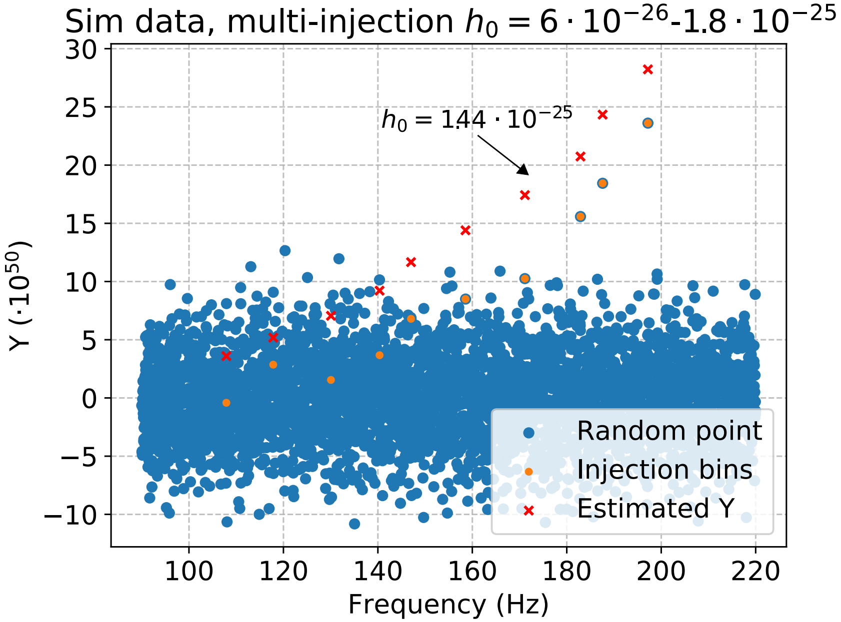
In both cases ~3 months of contiguous data,
data sampled at 256 Hz,
analyzed between 100 and 200 Hz,

$$\delta f = 1/32 \; Hz, t_s = 192 \; s$$

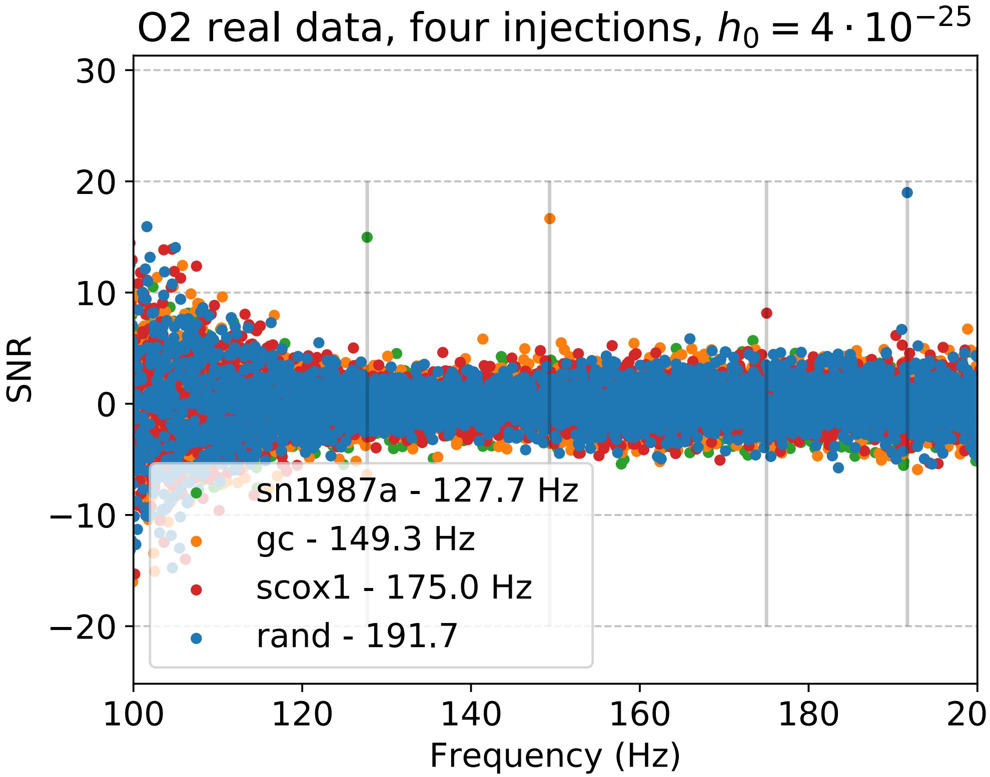
Detection statistics

$$Y_p = \sum_t \tilde{s}^*_{1,ft} \frac{\gamma^*_{p,ft}}{P_{1,ft} P_{2,ft}} \tilde{s}_{2,ft}$$





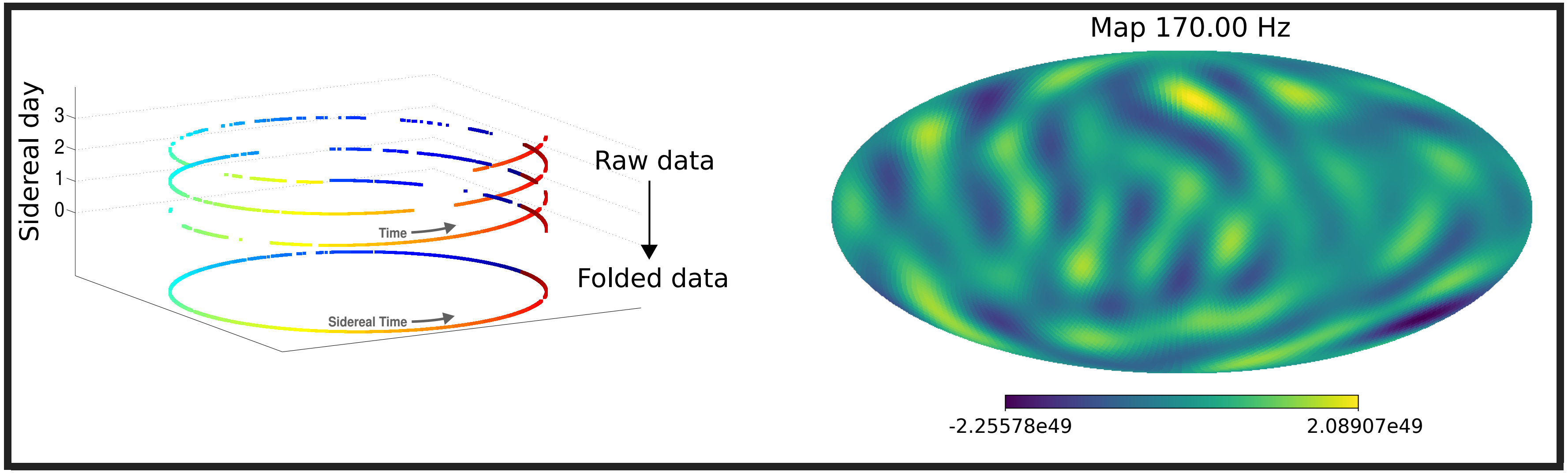
The stochastic narrowband search case



The signal are loud and they are retrieved correctly, probably `scox1` is lower because the overlap reduction function

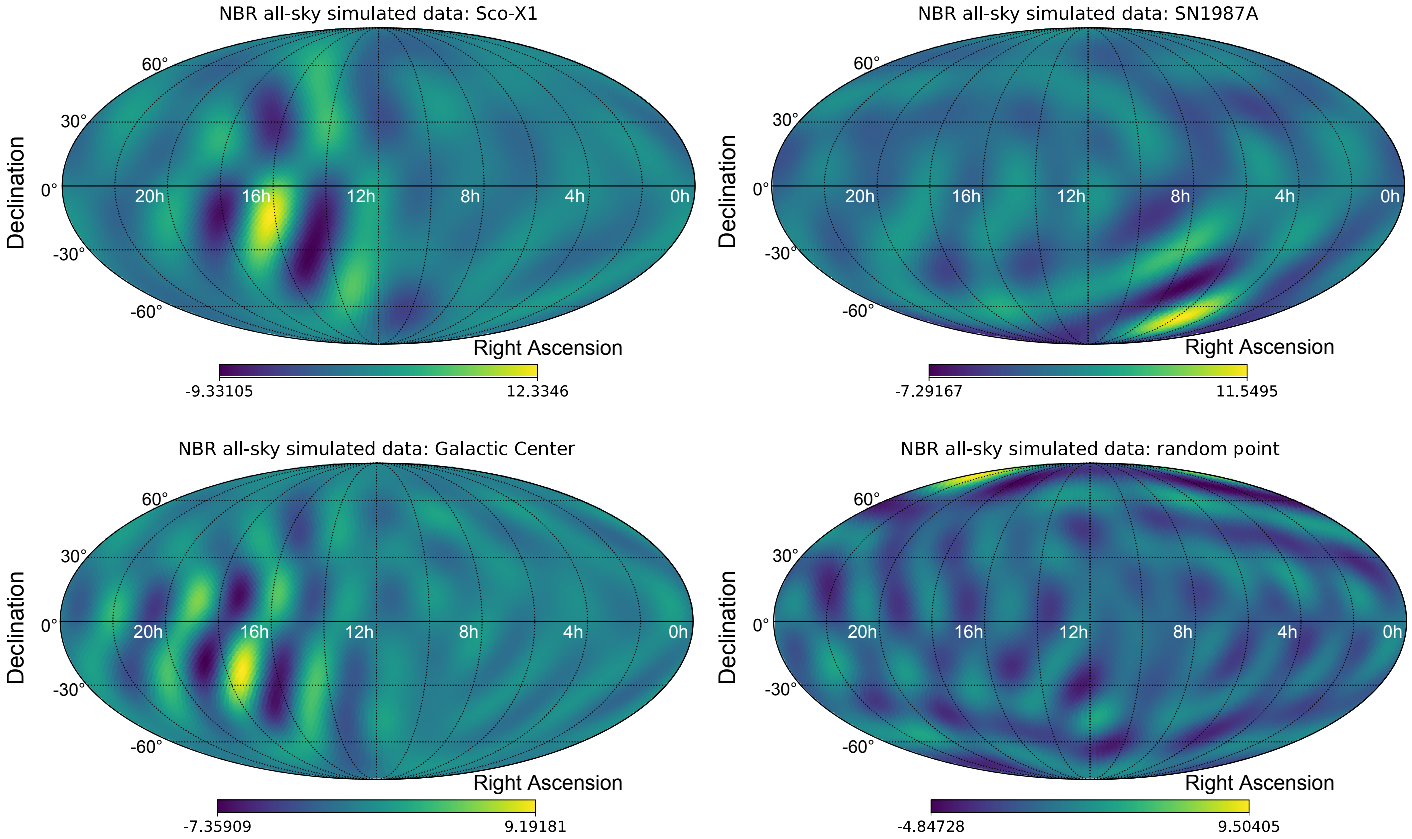
New tools

- Use of the folded data
- A new version of the pipeline that builds the full narrowband map at once for each frequency bin



Parameters space selection

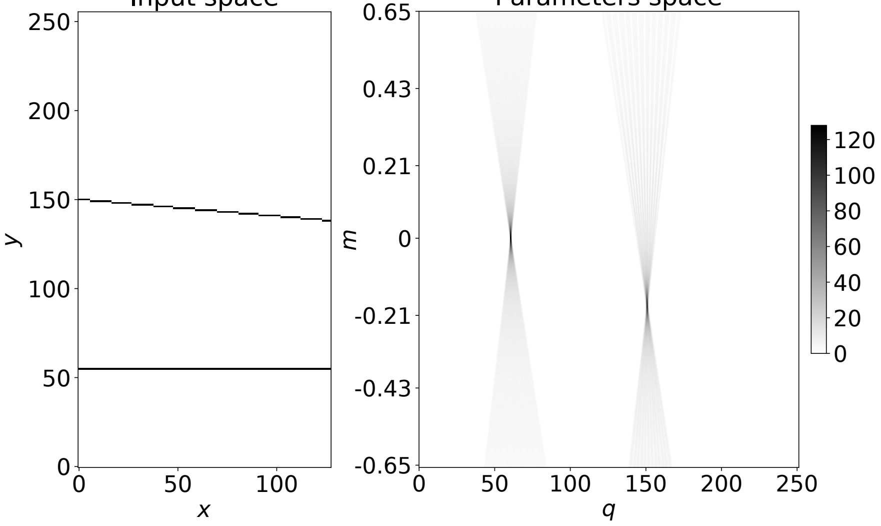
A "tomography" of the sky through f, using Pystoch

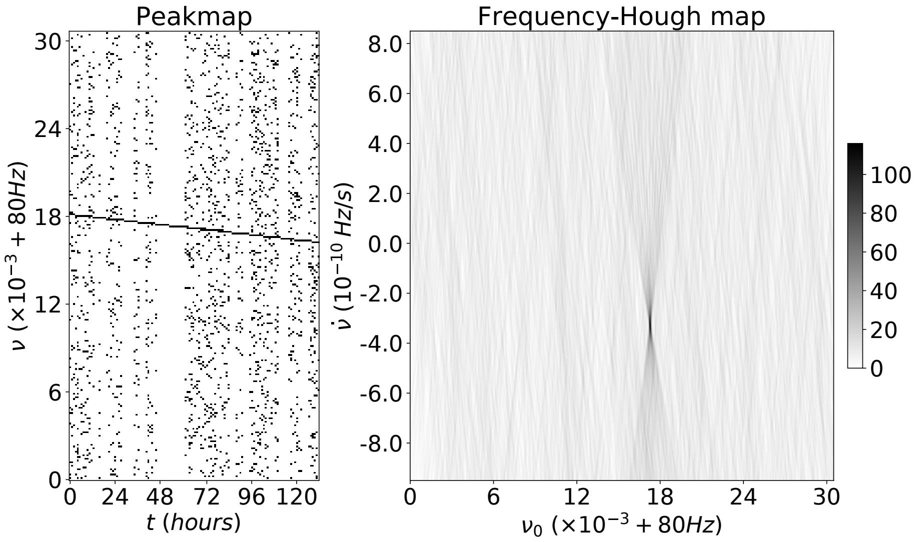


* Ain, Anirban, et al., Physical Review D 98.2 (2018): 024001.

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


The Hough transform


The Frequency-Hough

[1] Abbott, B. P., et al., Physical Review D 100.6 (2019): 062001.

[2] Astone, Pia, et al., Physical Review D 90.4 (2014): 042002.

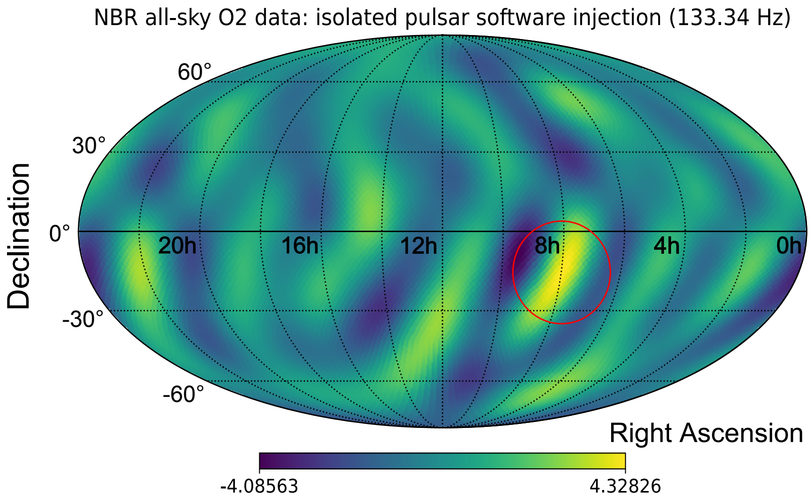
Tests with FrequencyHough

- Same injections on real data used for the directed NBR tests
- An integrated time of ~3 months
- Sampling at 256 Hz analyzed between 100 and 200 Hz
- Used all-sky NBR and then FrequencyHough on selected parameters space
- In this test: injected positions, ~1Hz interval around the signal frequency, spindown range [-1e-08,+1e-09])

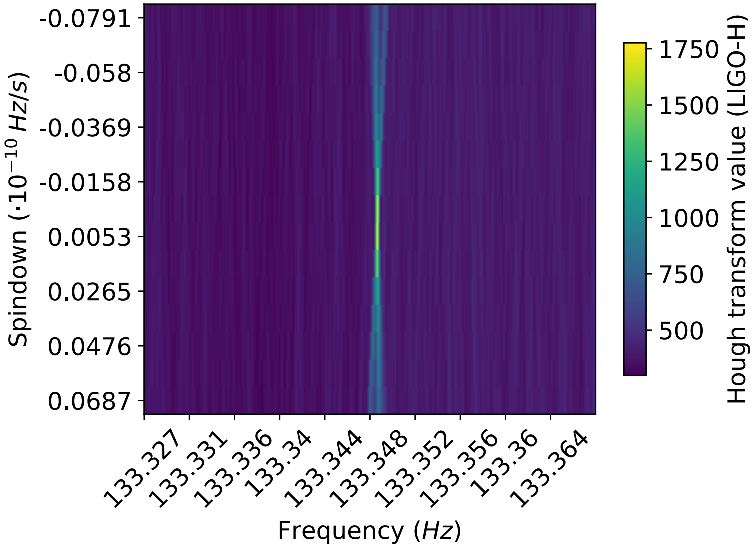
Using the GPU implementation* of the FH on many sky positions the analysis can take just few minutes with a proper choice of the candidate parameters space

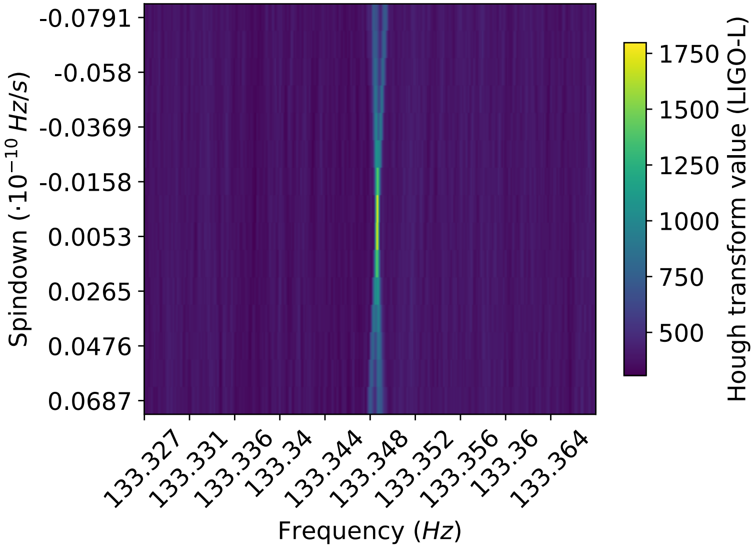
* La Rosa et al., `wiki.ligo.org/CW/FrequencyHoughTensorFlow`

Results example



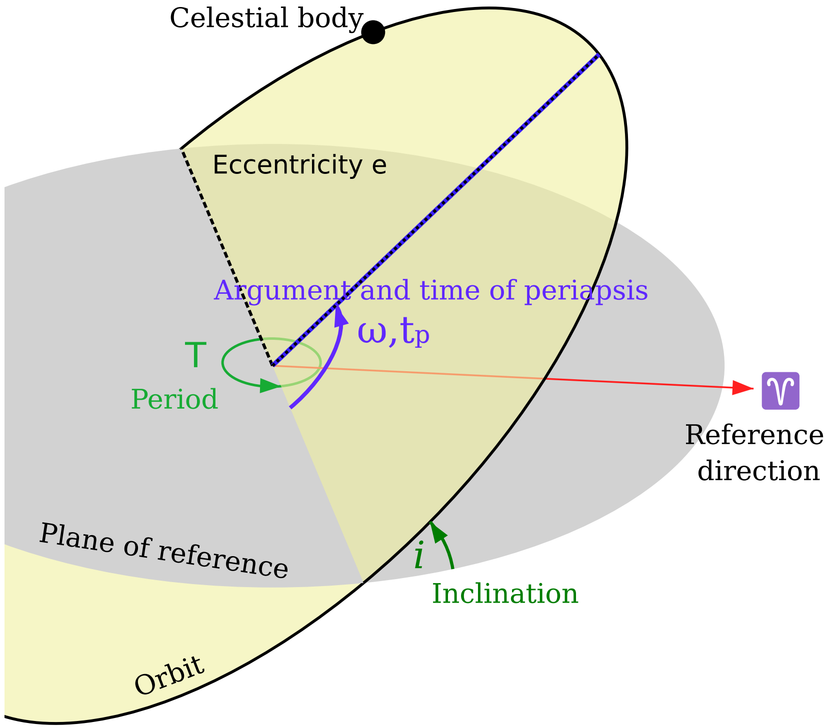
NBR all-sky O2 data: isolated pulsar software injection (133.34 Hz)

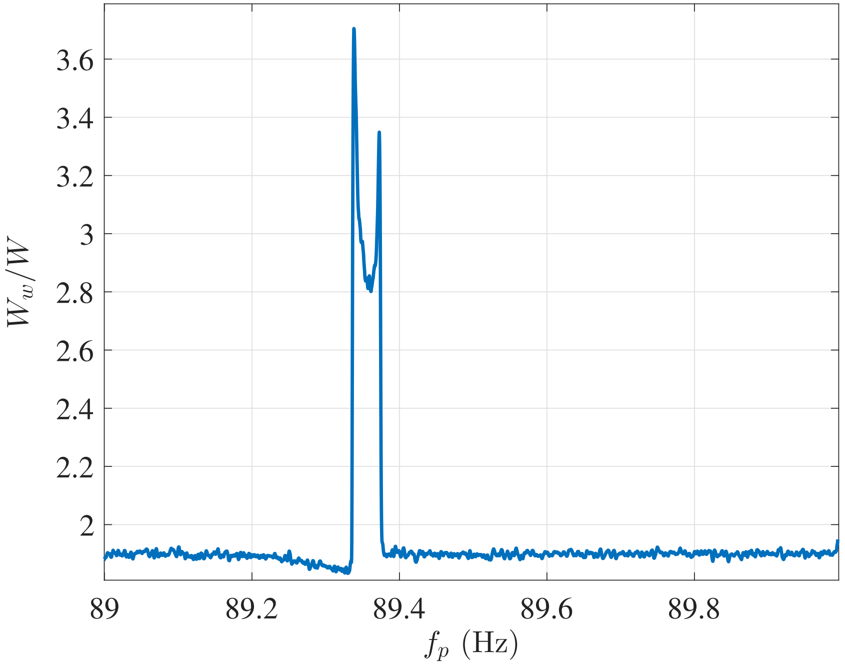




Binary systems

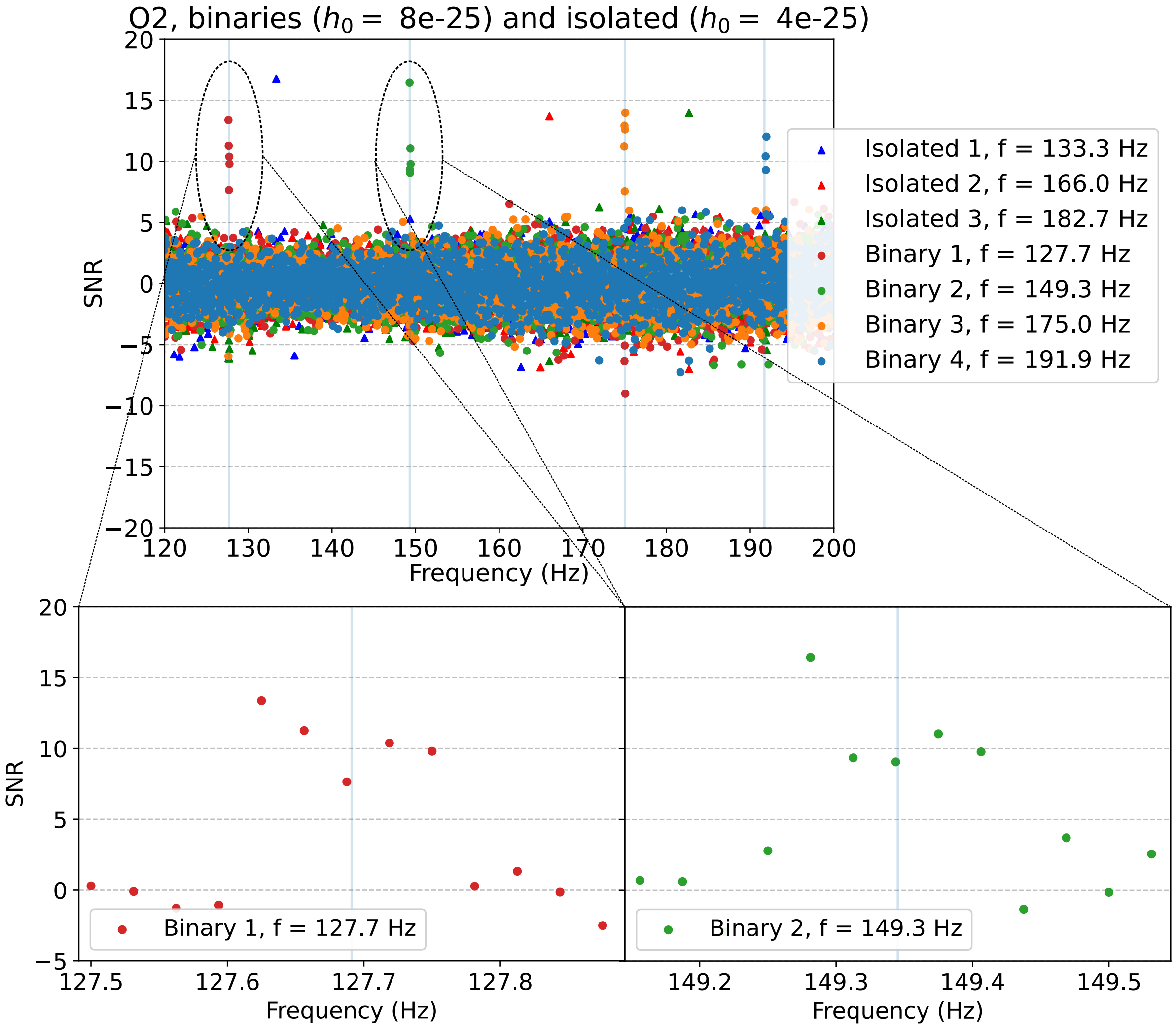
The characteristic double-horn feature of the orbital Doppler effect.





[1] Leaci, P., et al., Physical Review D 95.12 (2017): 122001.

Binary systems: radiometer analysis



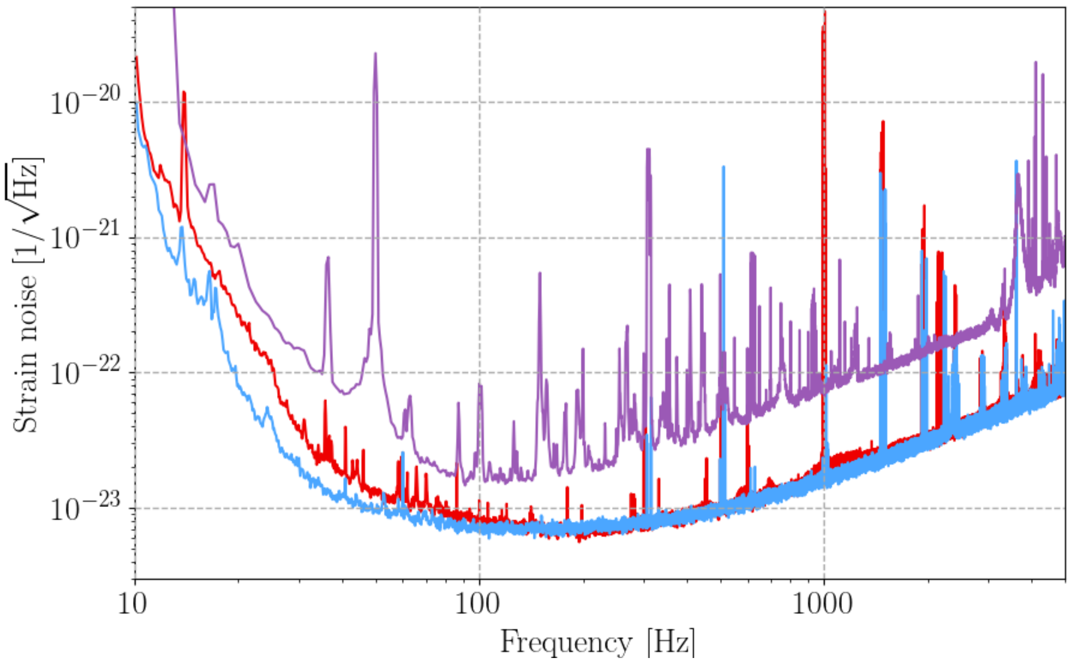
Conclusions

- Signals with spindown and in binary systems need more investigation
- The role of the ORF needs to be understood better
- Properly set up the PyStoch and FrequencyHough chain

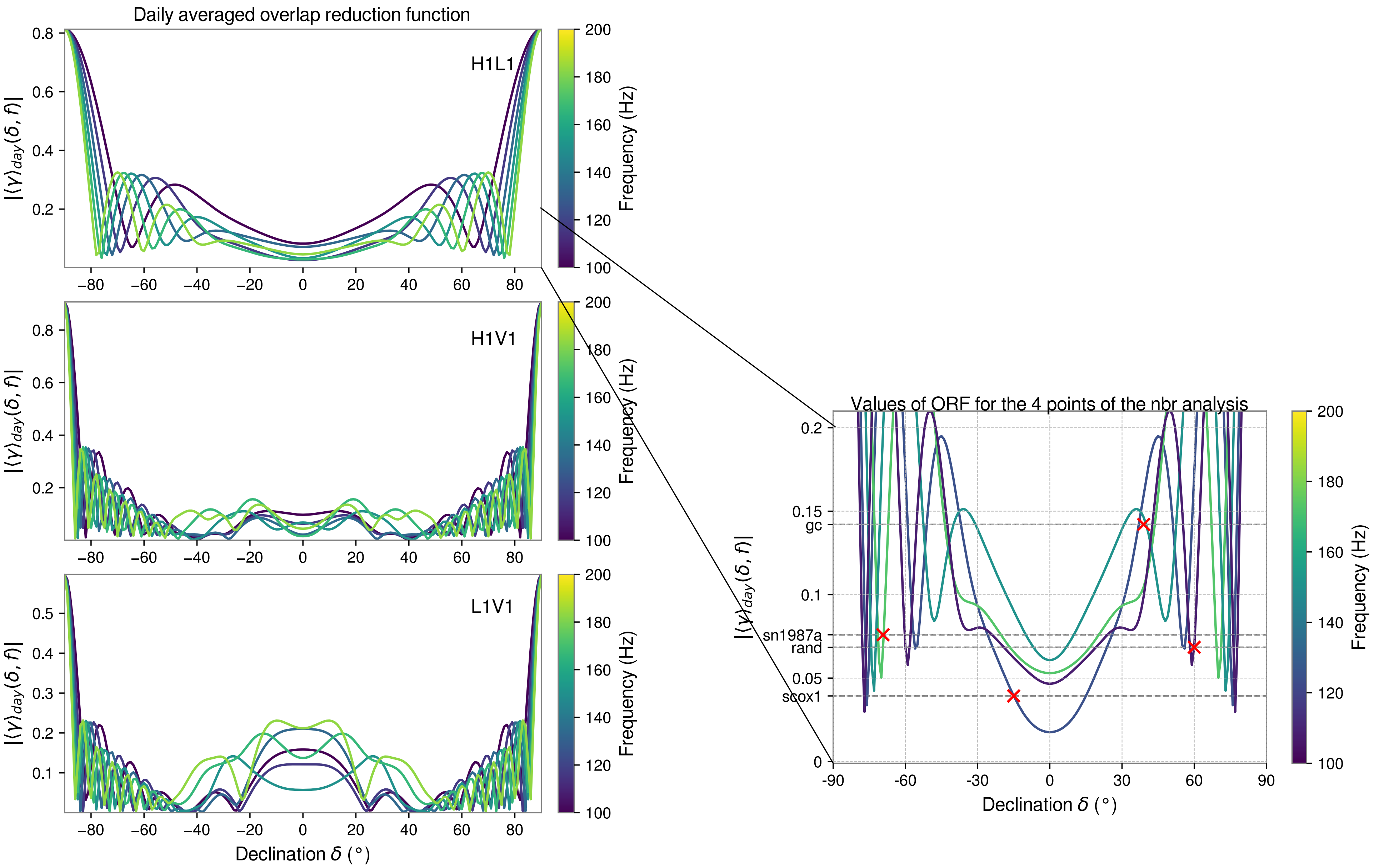
The next step is to study how to apply the chain made by the two pipelines to a real case search: a full set of tests on more recent data, in order to use the combined stochastic-CW method for the upcoming scientific runs of the LIGO and Virgo detectors

Thank you!

- Sensitivity curves

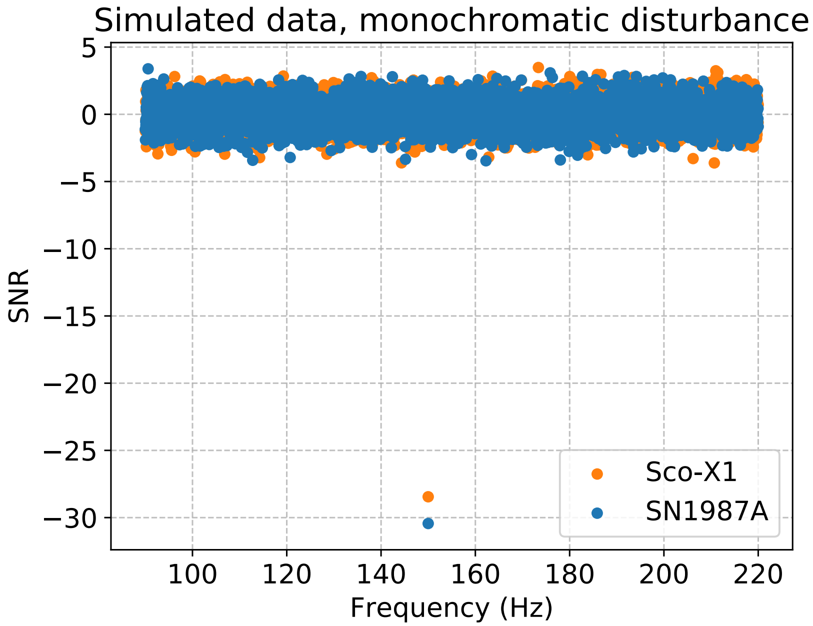


Non trivial behavior of overlapping detectors



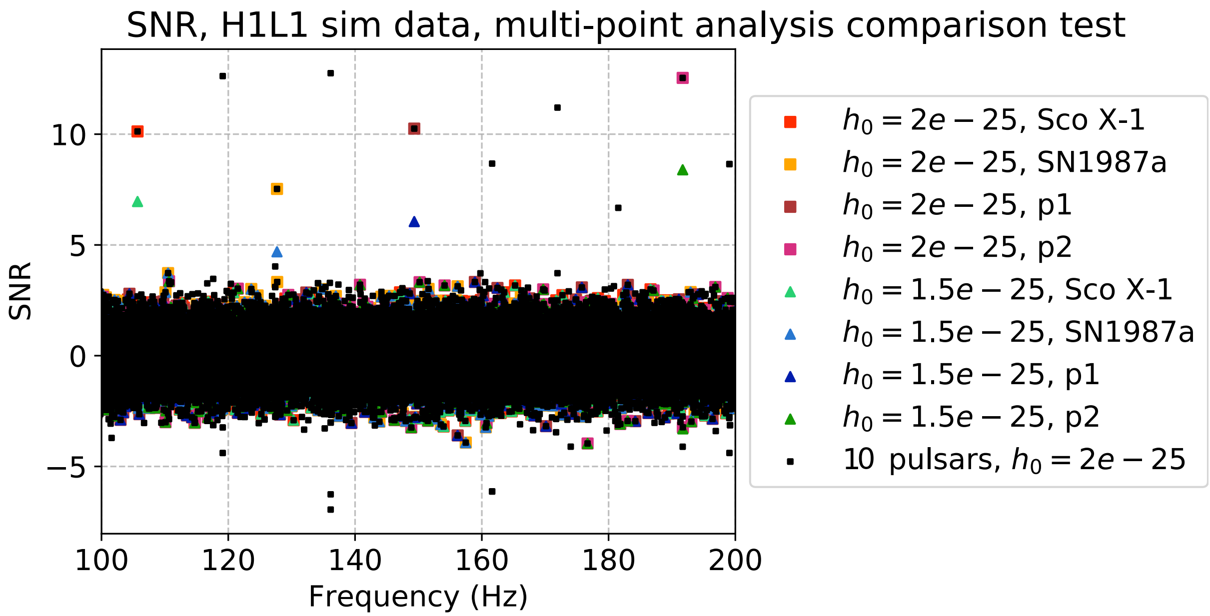
Thanks to the higher control with simulated noise data, several other tests have been done, for example:

- Monochromatic disturbance



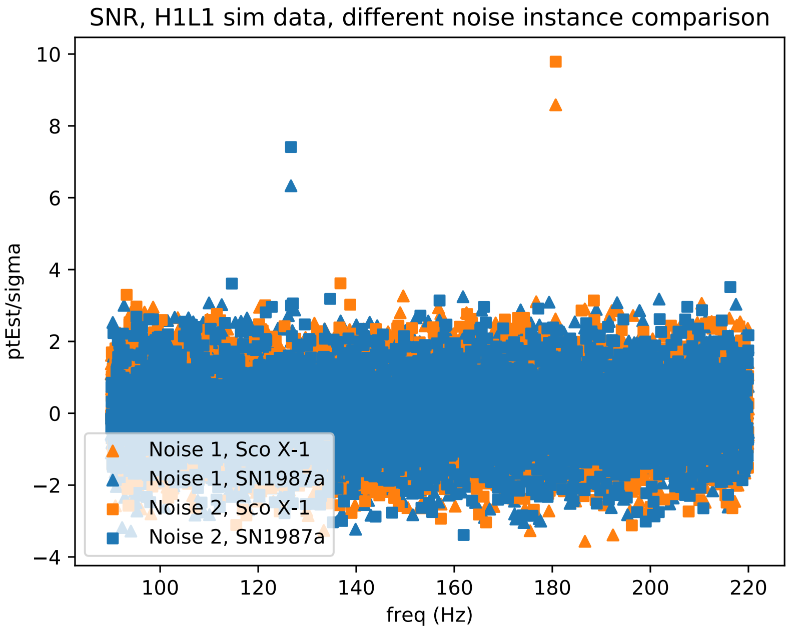
A correlated disturbance is shown as "negative SNR"

- Reproducibility with different number of signals

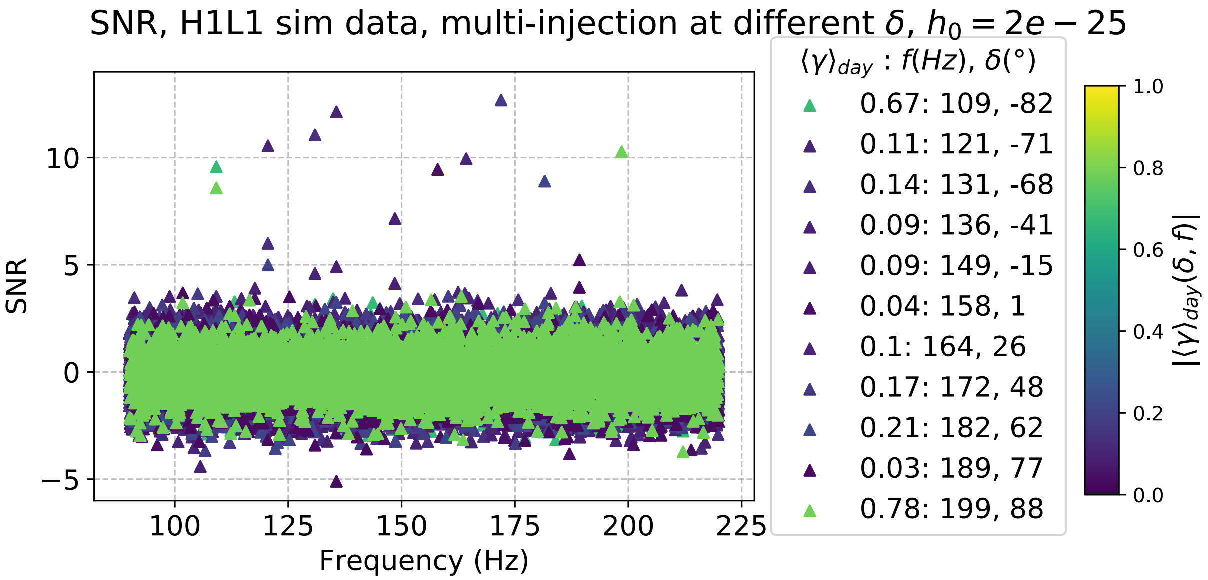


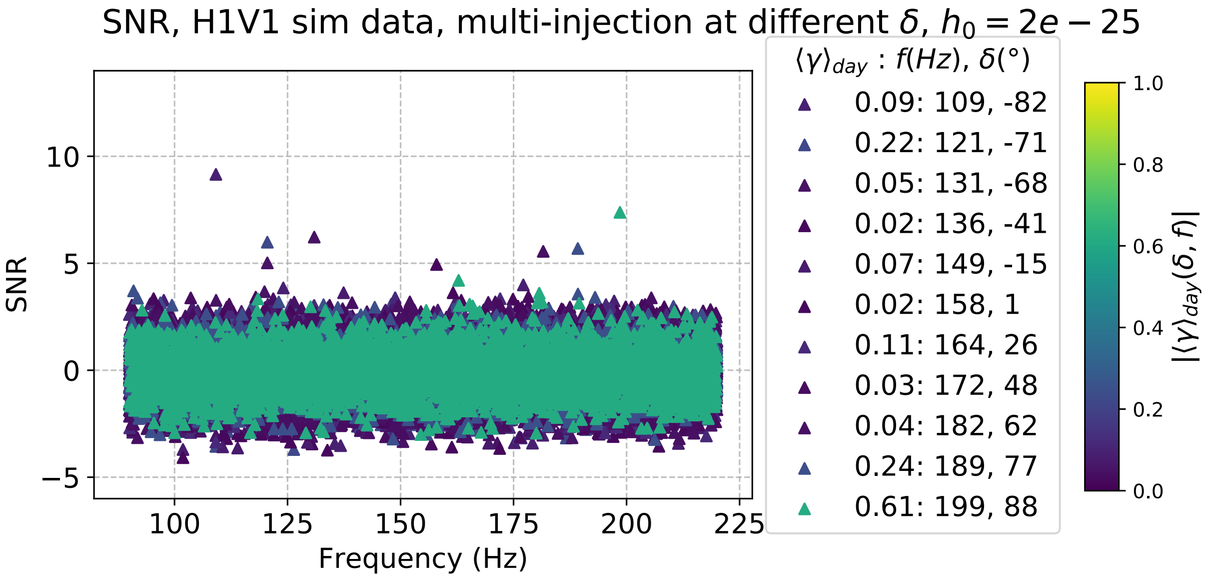
- Colored: 4 pulsars tests at $h_0 = 1.5\text{-}2 \times 10^{-25}$
- Black: 10 pulsars test at $h_0 = 2 \times 10^{-25}$
- SNR doesn't depend on the number of signals

- Different noise instances



- Different baselines


SNR, H1L1 sim data, multi-injection at different δ, $h_0 = 2e-25$


SNR, H1V1 sim data, multi-injection at different δ, $h_0 = 2e-25$