SEARCH FOR GRAVITATIONAL-WAVE BURSTS IN THE LIGO DATA AT THE SCHENBERG ANTENNA SENSITIVITY RANGE

arXiv:2301.06751

Julio César Martins (INPE)

Ik Siong Heng (University of Glasgow)
Iara Tosta e Melo (UniCT - INFN)
Odylio Denys Aguiar (INPE)

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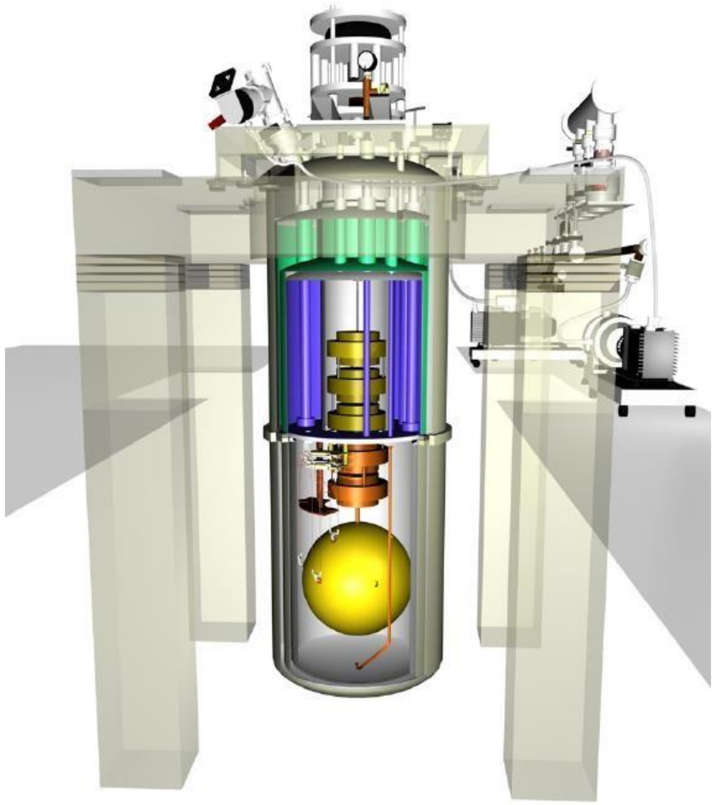
GWINPE

LIGO
VIRGO
KAGRA

Introduction



(C. A. Costa, et al., 2008. Drawn by Xavier Gratens)

In recent years, Brazil has emerged as an active participant in the global landscape of experimental gravitational wave research, spearheaded by the Mario Schenberg antenna. Unlike its predecessors, which employed bar-shaped resonant-mass detectors, the Schenberg antenna features a spherical mass configuration.

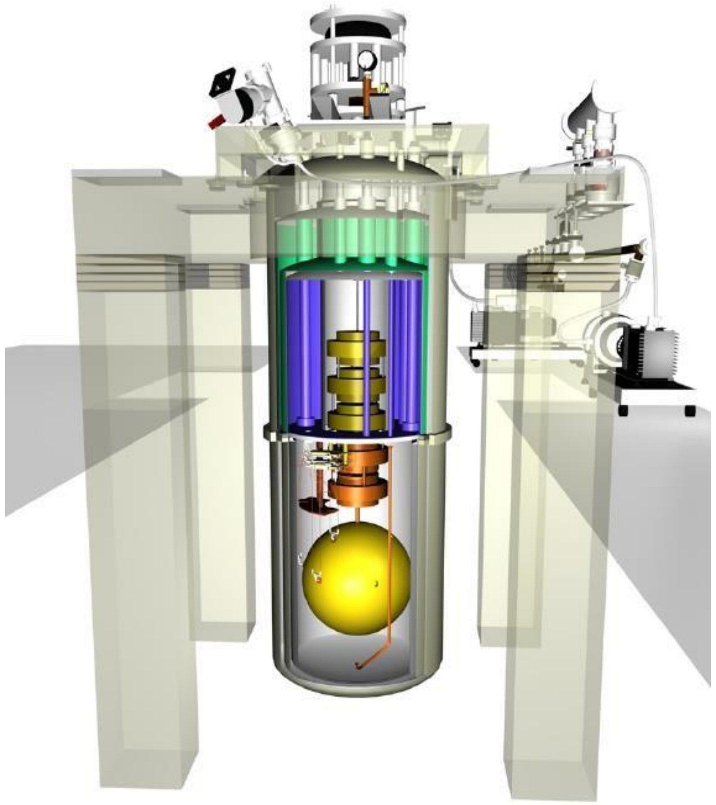
The main component of the detector, weighing approximately 1150 kg and measuring 65 cm in diameter, is composed of a copper-aluminum alloy.

After completing its final observational run in 2015 at a temperature of 5.0 Kelvin, the entire detector was disassembled at the University of São Paulo's Physics Institute in 2016.

Sensitivity in the frequency range [3150 - 3260] Hz (Δf_{Sch} = 110Hz).

Introduction

Purpose: Different analysis techniques on O3 LIGO data to evaluate the reassembly of the Mario chenberg antenna in an advanced configuration (aSchenberg).



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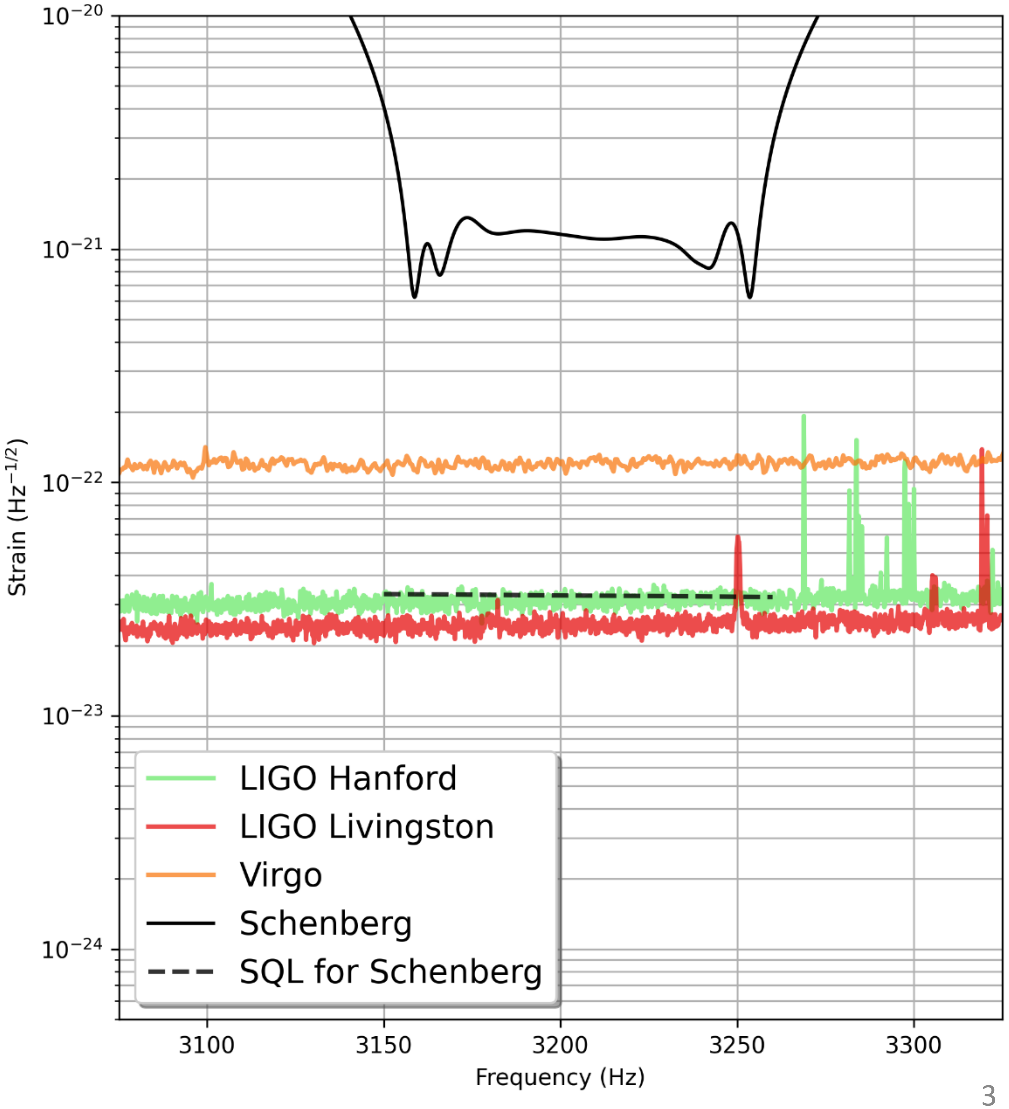

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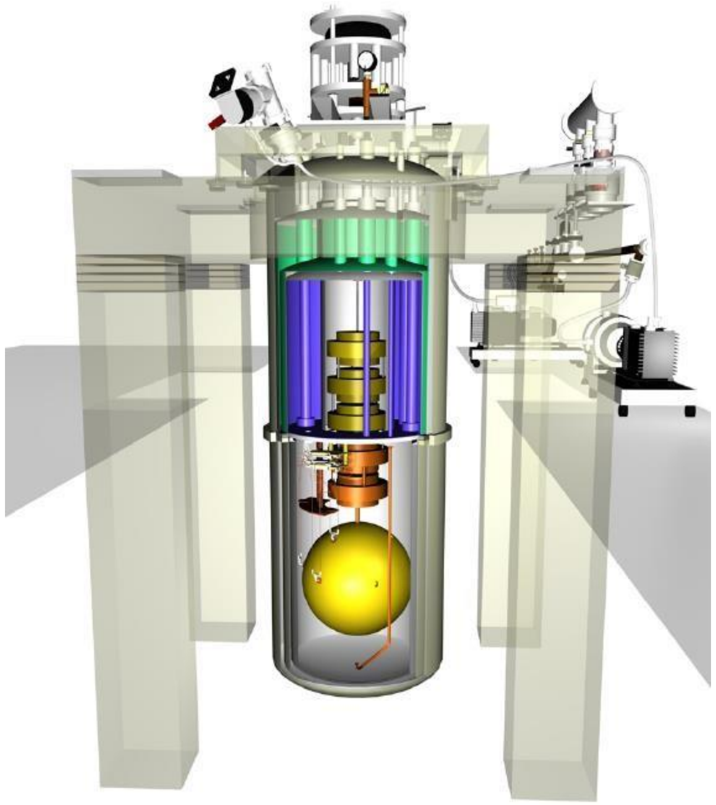

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- Verify the possibility that GW burts can be detected by Schenberg antenna at ultimate sensitivity level;
- Spherical antennas have omnidirectional response, making them sensitive to gravitational waves of all polarizations and directions;
- A single spherical detector can provide source direction estimates with reasonable resolution (better than a 3 interferometer network);
- Antennas can measure all tensorial components of a GW, providing valuable information to test alternative theories of gravitation;
- Combination of ground-based interferometers and spherical antennas could enhance understanding of GW sources and result in a network with interesting features for multi-messenger astrophysics.

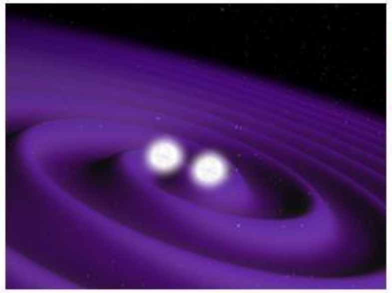
Sources

Know waveforms
(Well modeled)

Unknown waveforms
(Weakly modeled or un-modeled)

Short Duration
(~ 1s)

Long Duration
(∞)

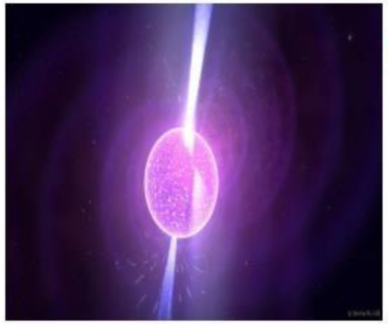


Compact Binary Coalescence

Binaries of Neutron Stars (NS) and/or Black Holes (BH)

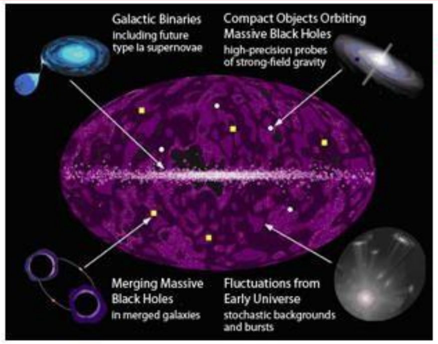
Bursts

Core Collapse Supernovae,
Post-merger of NS,
NS glitches,
???



Continuous Waves

Spinning Neutron Stars,
Crustal deformations,
Accretion…



Stochastic Waves

Astrophysical and cosmic GW background

- Fundamental oscillation modes (f-modes) of neutron stars;
- Core-collapse supernova events (CCSNe);
- Magnetar Flares (may associate with gamma-ray bursts);
- … and the unexpected.

Methods

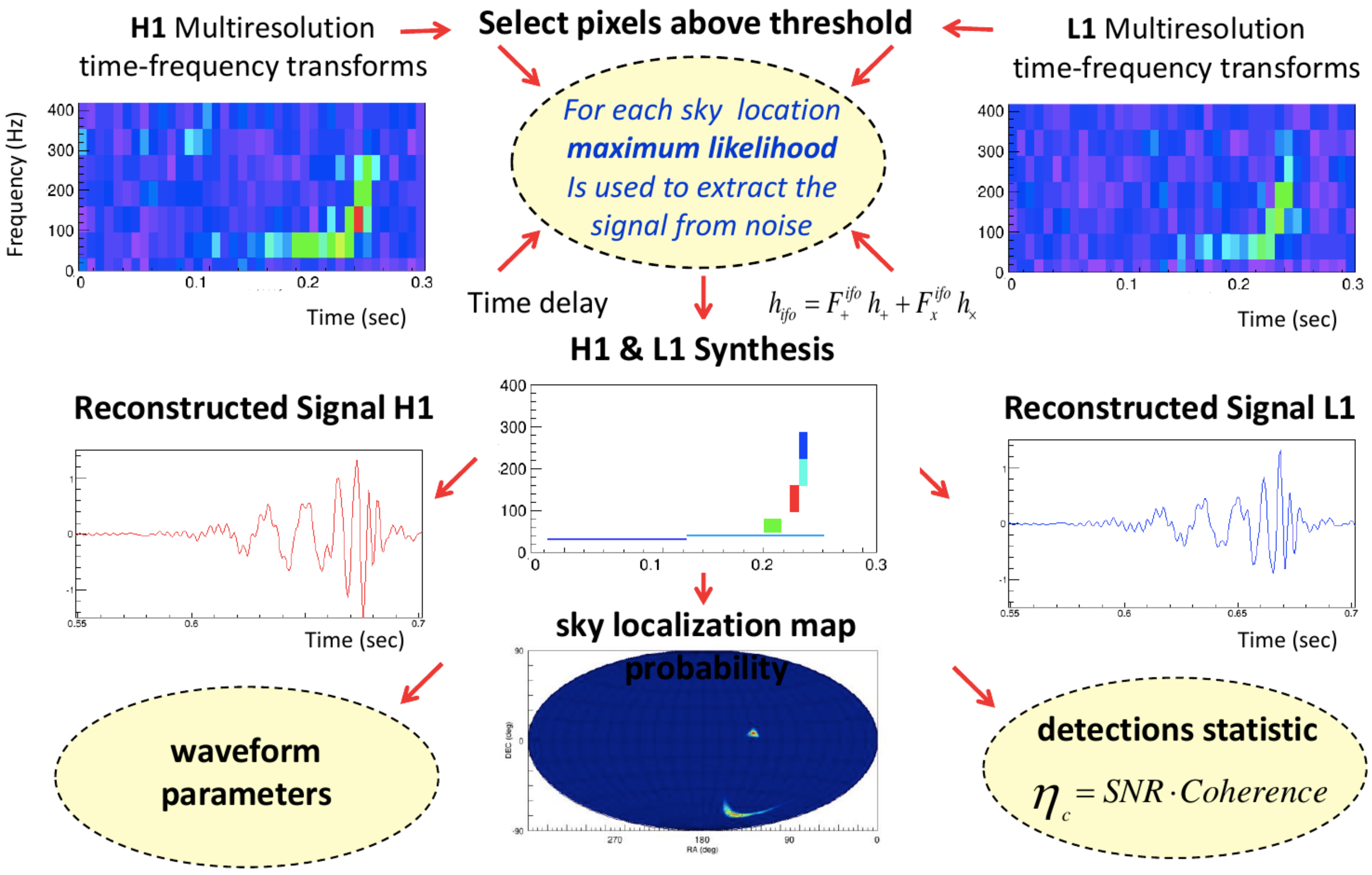
We follow a methodology of searching for bursts signals well established by the LIGO Scientific Collaboration (LSC) with the coherent WaveBurst (cWB) pipeline. There is no other work that looks specifically at this frequency band.

The candidate events are selected in the post-production stage by setting thresholds on trigger parameters.

- Signals with duration of milliseconds to a few seconds;
- From the frequency band of 512-4096 Hz, we select candidates with central frequency f_0 within the Schenberg band ($f_0 \in \Delta f_{Sch}$) or if their bandwidth Δf partially overlaps with the Schenberg band ($\Delta f \cap \Delta f_{Sch} \neq \emptyset$);
- Without any prior assumptions on the signal morphology or the time of arrival during O3.

Methods

Coherent analysis – coherent WaveBurst (cWB) pipeline



The sky location with highest probability is used to reconstruct signal & its detection statistic (M. A. Bizouard, 2018)

For each trigger selected by cWB, we have two main detections parameters:

- The correlation coefficient c_c

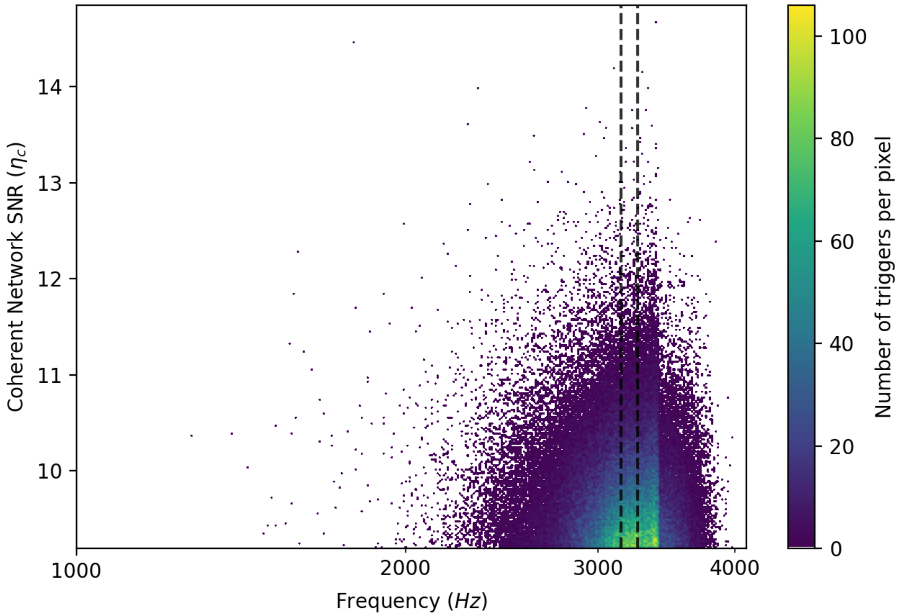
GW signals are expected to have $c_c \approx 1$ and accidental glitches $c_c \ll 1$.

- The coherent network SNR η_c

All-sky Search For GW Bursts

Detection Statistics: Expected and observed results

BACKGROUND



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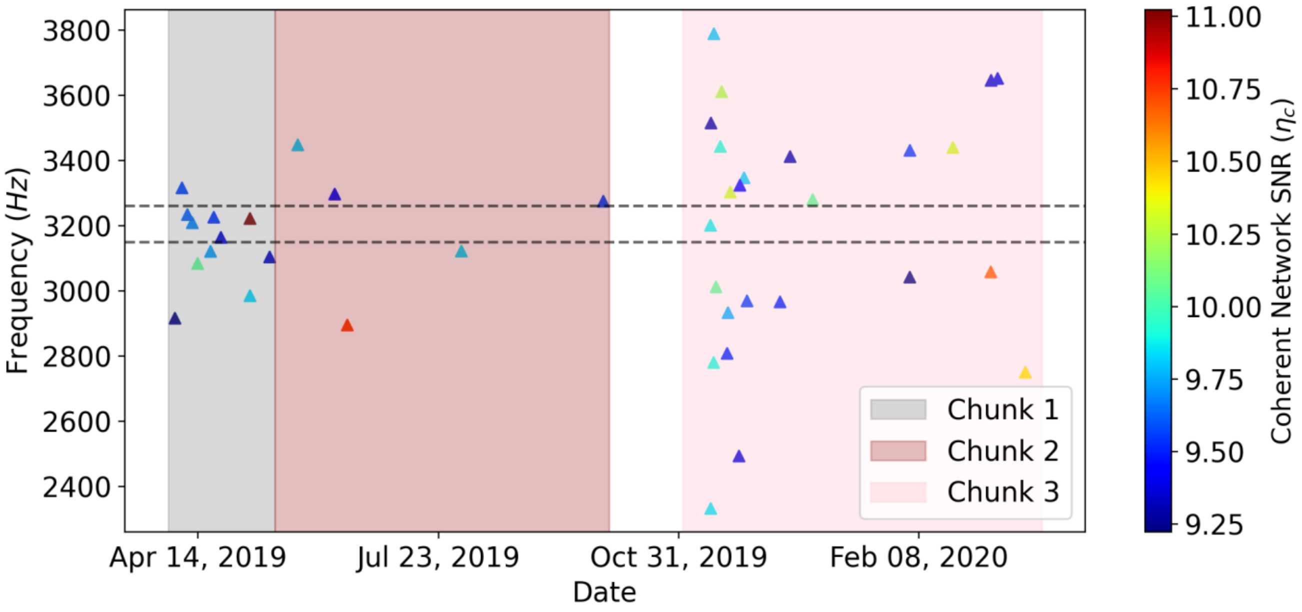
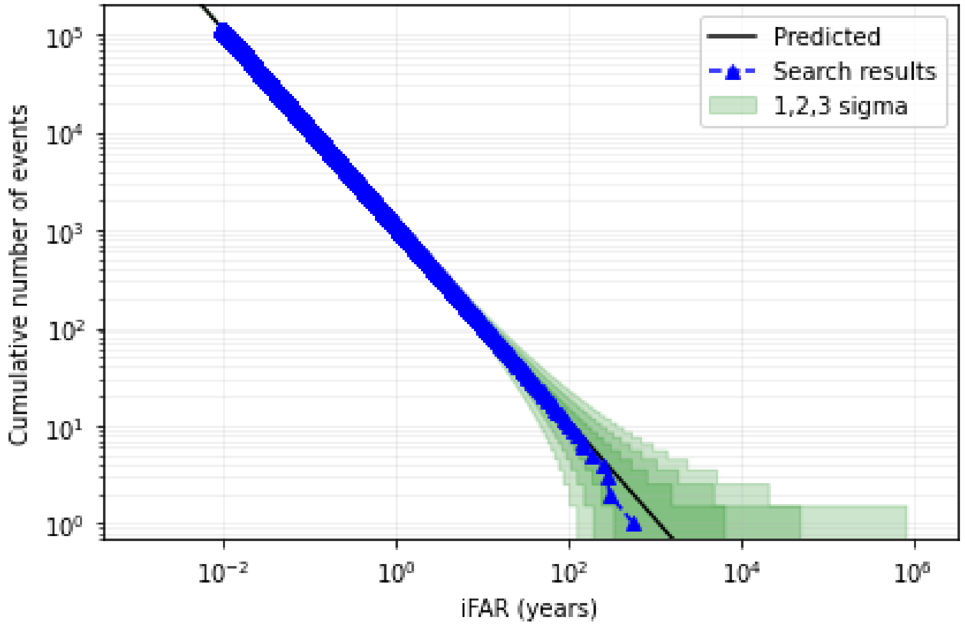


All-sky Search For GW Bursts

Detection Statistics: Expected and observed results

O3 data in the [3150 3260] Hz interval analyzed with the coherent WaveBurst (cWB) pipeline. Using the False Alarm Rate, we asses significance of the candidate events an interval of a Poisson probability distribution of the expected values of the background.

BACKGROUND



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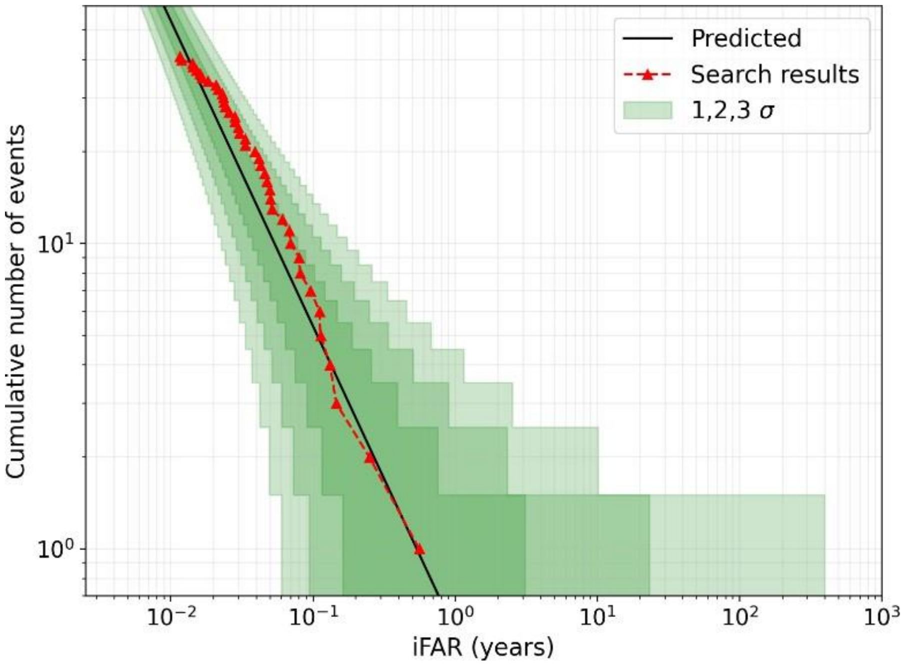


Martins et al. (2023)

No deviations were observed in the significance compared to the background

No GW signal found in the data

Astrophysical Interpretation

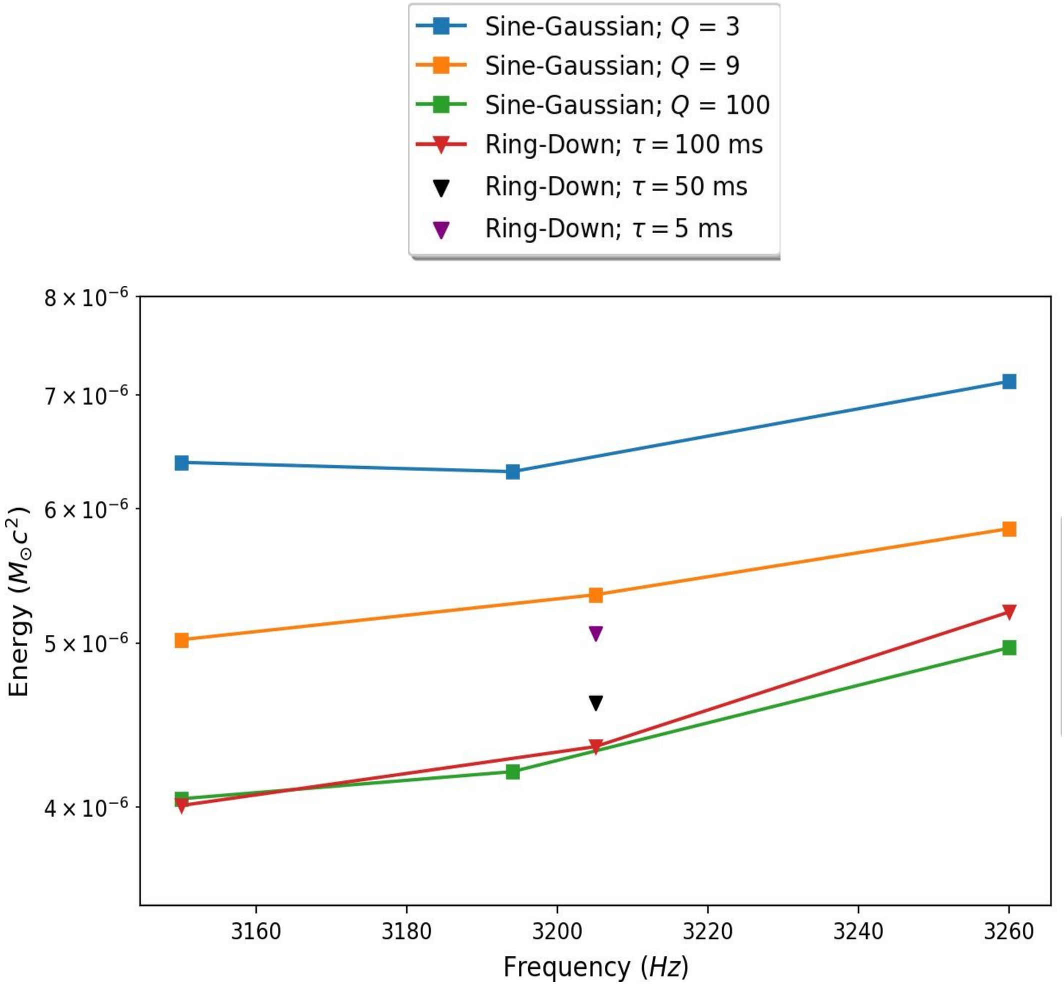
Search efficiency: Values of strain amplitude h_{rss} in units of $10^{-22}\ Hz^{-1/2}$ for 10%, 50% and 90% detection efficiency in O3 at a False Alarm Rate (FAR) threshold of 1 per 100 years.

Morphology
Ring-Down damped oscillation (circular)
$f_0 = 3205$ Hz, $\tau = 5$ ms
$f_0 = 3205$ Hz, $\tau = 50$ ms
$f_0 = 3150$ Hz, $\tau = 100$ ms
$f_0 = 3205$ Hz, $\tau = 100$ ms
$f_0 = 3260$ Hz, $\tau = 100$ ms
Sine-Gaussian wavelets (circular)
$f_0 = 3150$ Hz, $Q = 3$
$f_0 = 3194$ Hz, $Q = 3$
$f_0 = 3260$ Hz, $Q = 3$
$f_0 = 3150$ Hz, $Q = 9$
$f_0 = 3205$ Hz, $Q = 9$
$f_0 = 3260$ Hz, $Q = 9$
$f_0 = 3150$ Hz, $Q = 100$
$f_0 = 3194$ Hz, $Q = 100$
$f_0 = 3260$ Hz, $Q = 100$

Astrophysical Interpretation

Search efficiency: Values of strain amplitude h_{rss} in units of $10^{-22}\ Hz^{-1/2}$ for 10%, 50% and 90% detection efficiency in O3 at a False Alarm Rate (FAR) threshold of 1 per 100 years.

Detection Energy Range: The isotropically emitted energy of a GW burst expressed which correspond to 50% detection efficiency at an iFAR ≥ 100 years, for standard candle sources emitting at 10 kpc.



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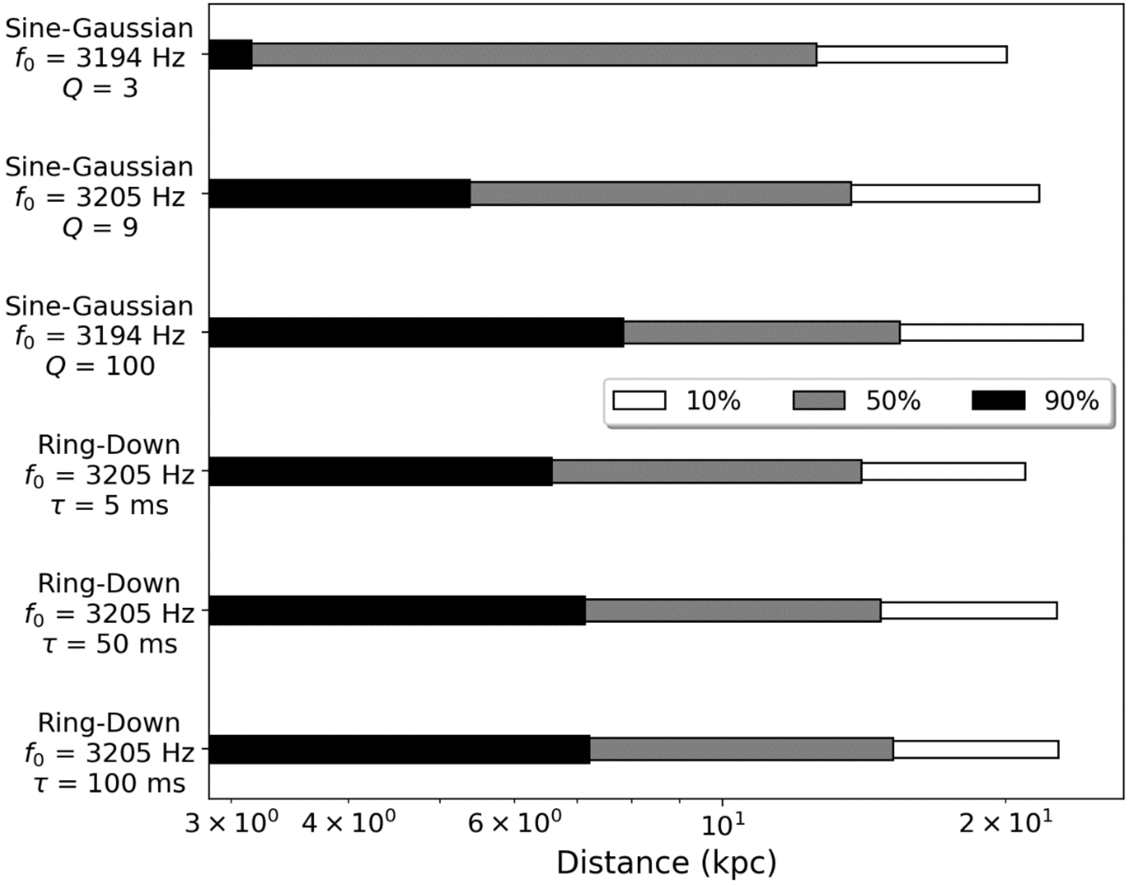
Detection Distance Range: The minimum distance to achieve detection efficiencies of 10%, 50%, and 90% at iFAR ≥ 100 years for the waveforms centered on the Schenberg band.

$$E_{GW}^{iso} = 1 \times 10^{-5} M_{\odot} c^2$$



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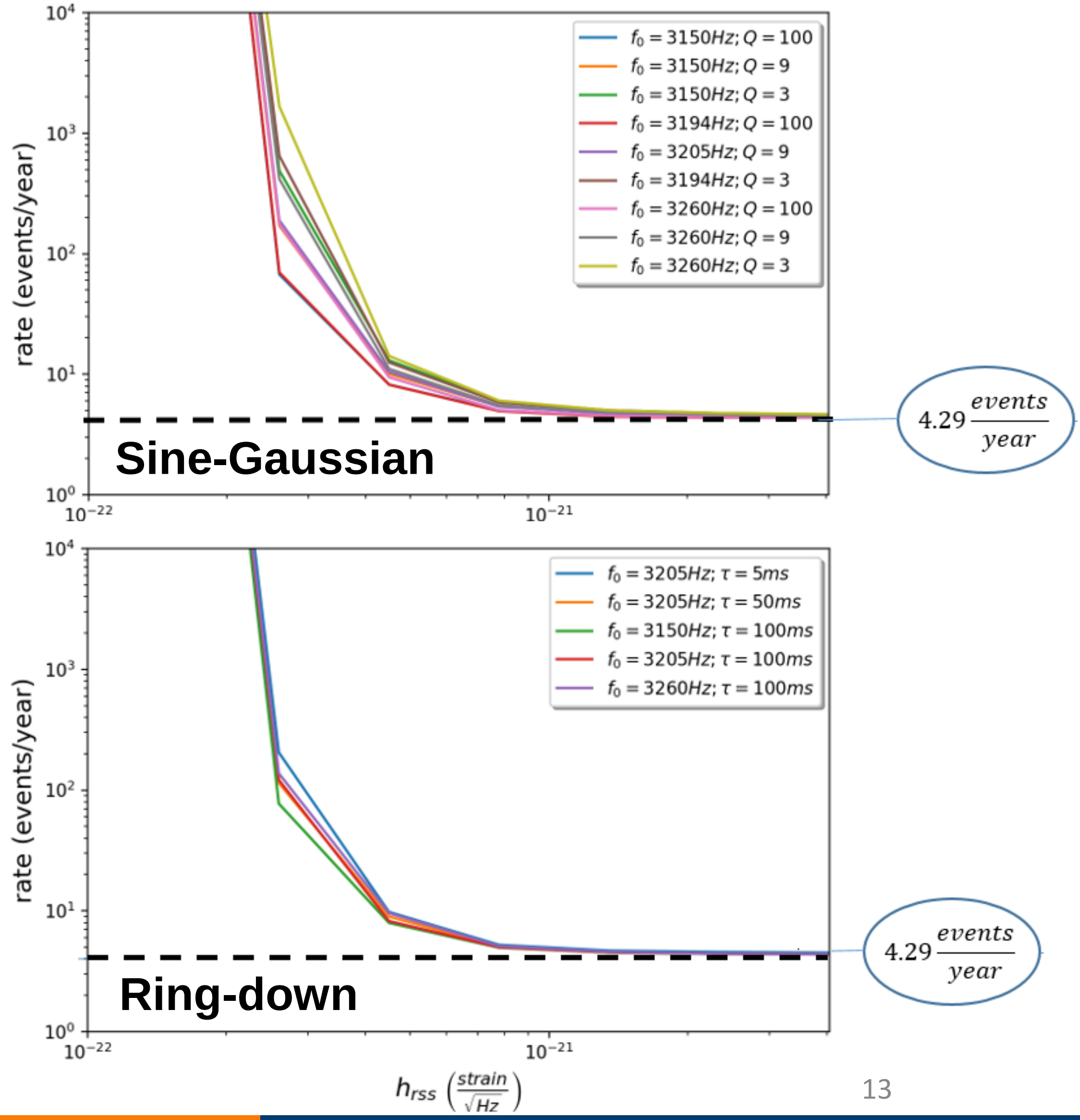
Detection Distance Range: The minimum distance to achieve detection efficiencies of 10%, 50%, and 90% at iFAR ≥ 100 years for the waveforms centered on the Schenberg band.

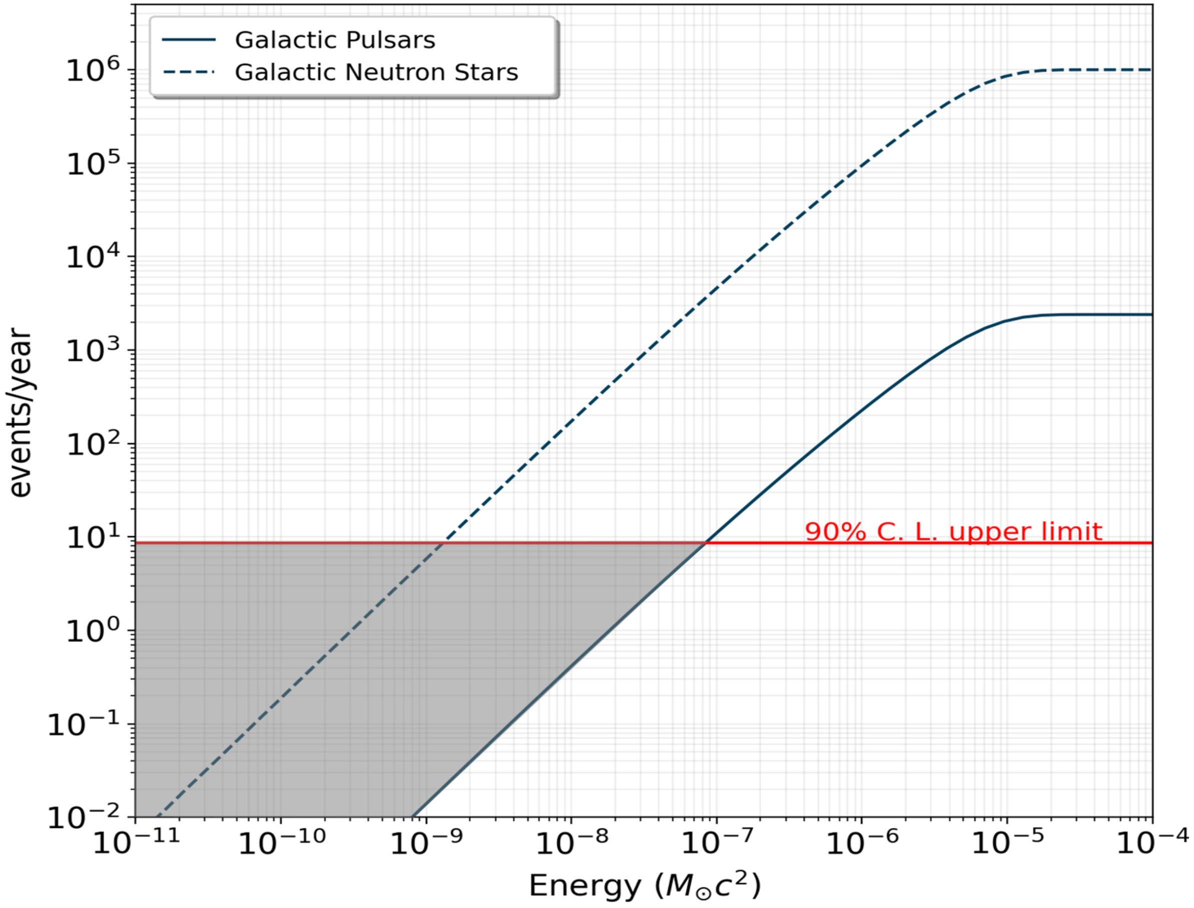
Upper limits: For the special case of no surviving events on the main search, the 90% confidence upper limit on the burst event rate with two families of simulated signals (injections).



Astrophysical Interpretation

Detectability of f-modes

Considering the available information of monitored pulsars that exhibits glitch, the lower limit on the glitch rate, the spatial distribution of Galactic NS, and the approximated number of Galactic NS and pulsars we get the region values of f-mode events per year as a function of glitch energy.



We assume the bulk of the energy in GW goes into the f-mode emission modelled by damped sinusoids.

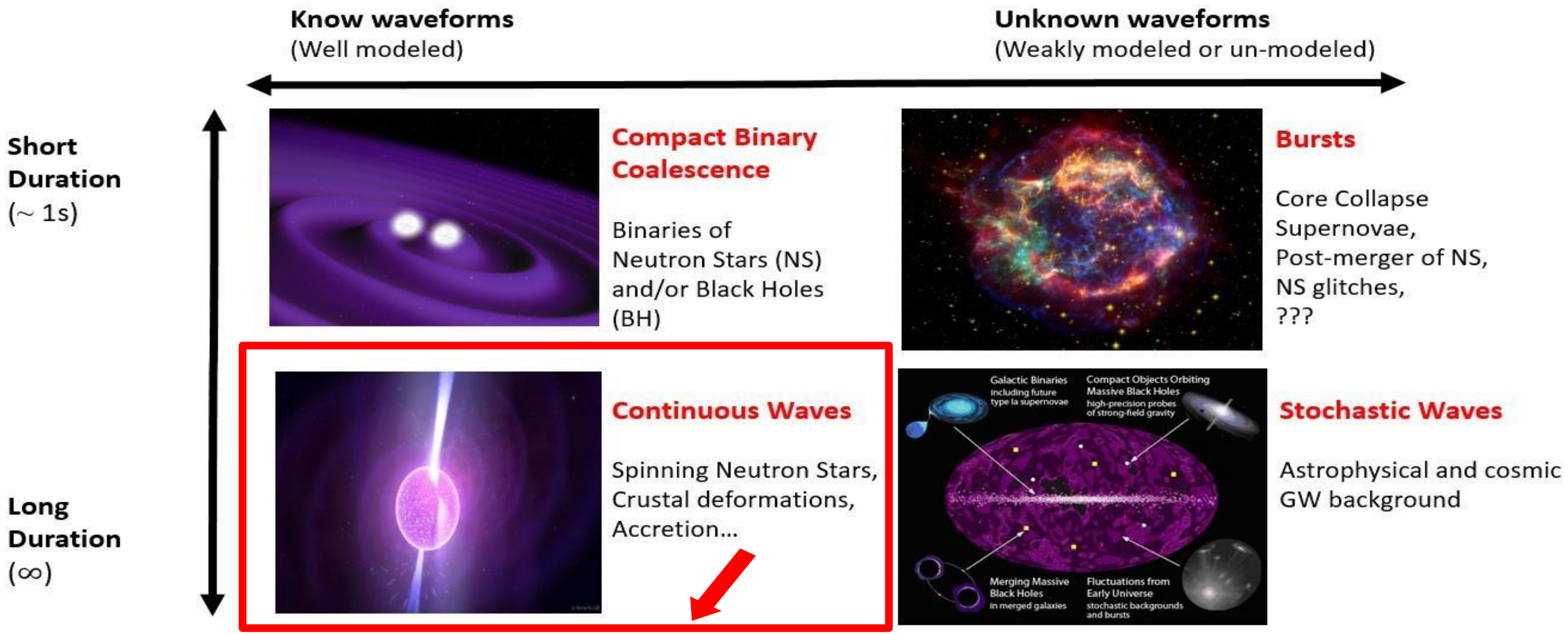
The sources are assumed to be uniformly distributed over the sky and optimally oriented to the line of sight.

$$\rho(d) = \frac{N_0 d^2}{\sigma_r^2 z_0} \int_0^1 \exp\left[-\frac{xd}{z_0}\right] I_0\left[\frac{R_e d\sqrt{1-x^2}}{\sigma_r^2}\right] \exp\left[-\frac{R_e^2 + d^2(1-x^2)}{2\sigma_r^2}\right] dx$$

Next Steps

Past → Analysis for **burst** sources

Present → Analysis for continuous waves (**CW**)



Unexplored range in the data:

- Spinning strange stars;
- Binary system of primordial black holes (PBH).

Thank you!

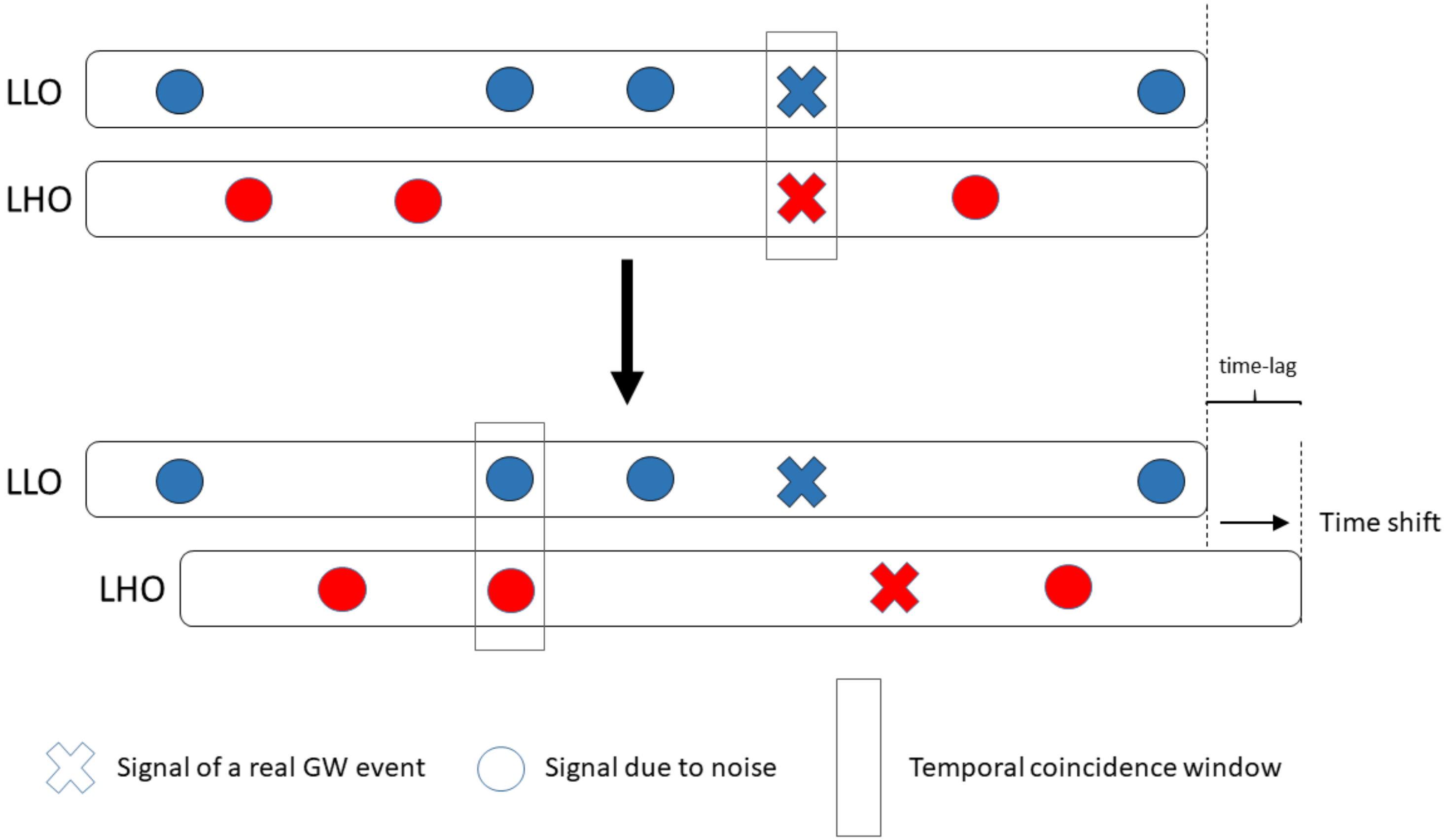
Contact: julio.martins@inpe.br

All-sky Search For GW Burts

Background analysis

- It is necessary to know the statistical properties of transient accidentals due to noise (background triggers) to evaluate the significance of a burst candidate event.

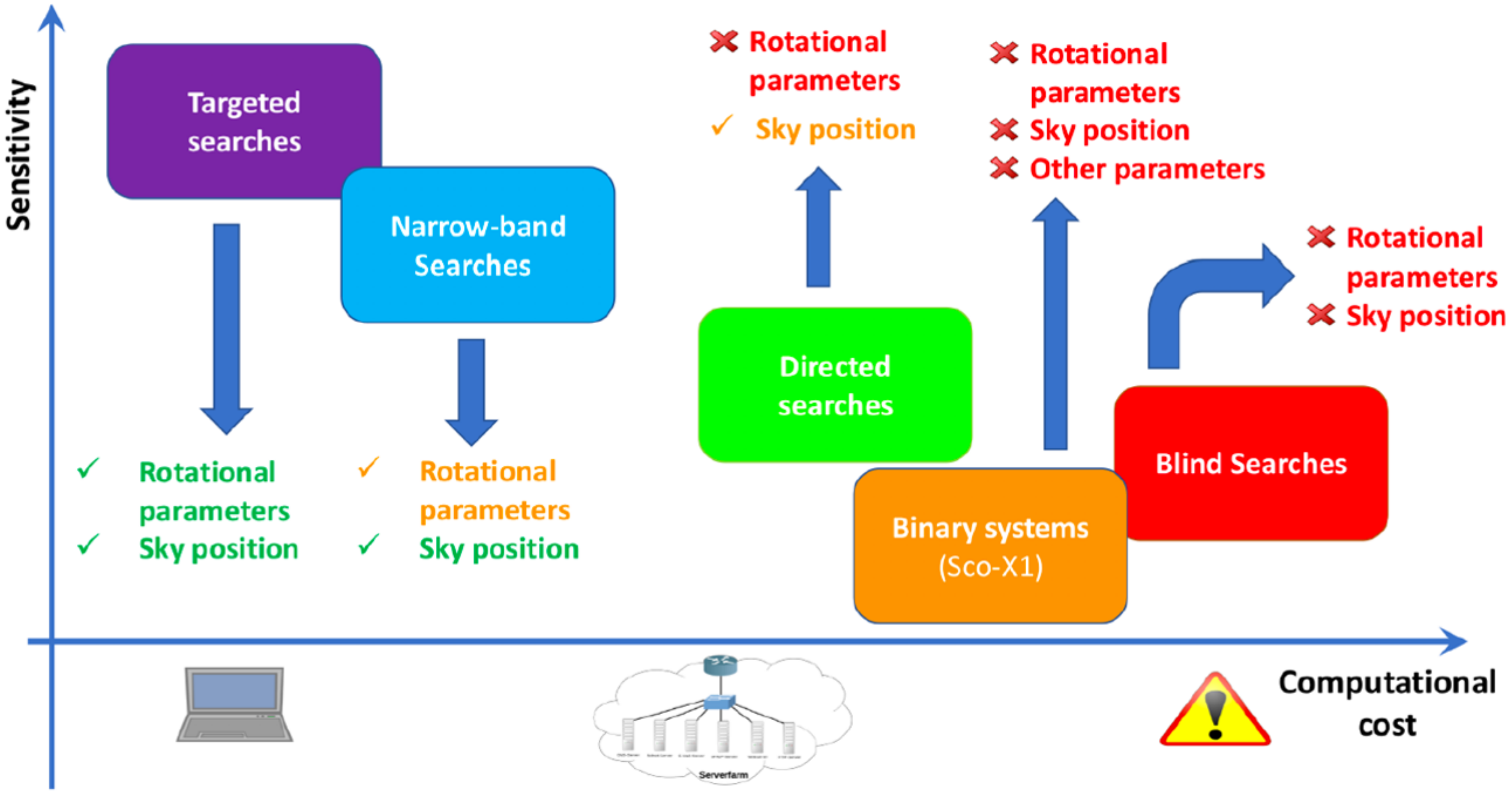
Time Shift Procedure



$$T_{bkg} = \sum_i T_i$$

Search for Continuous Waves

The computational problem

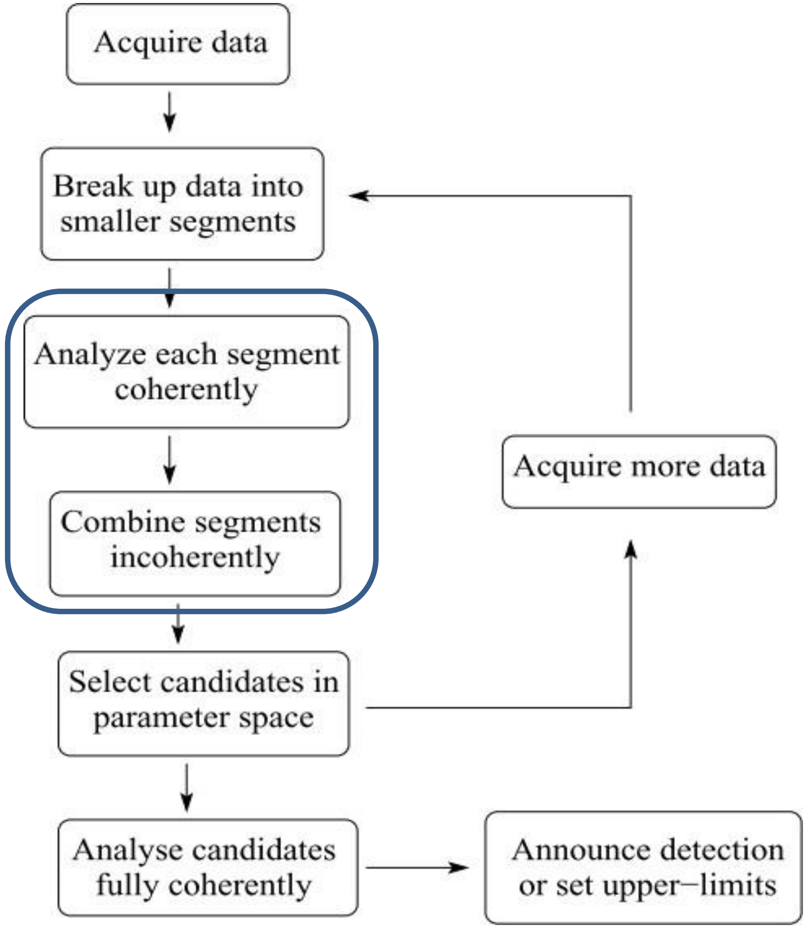


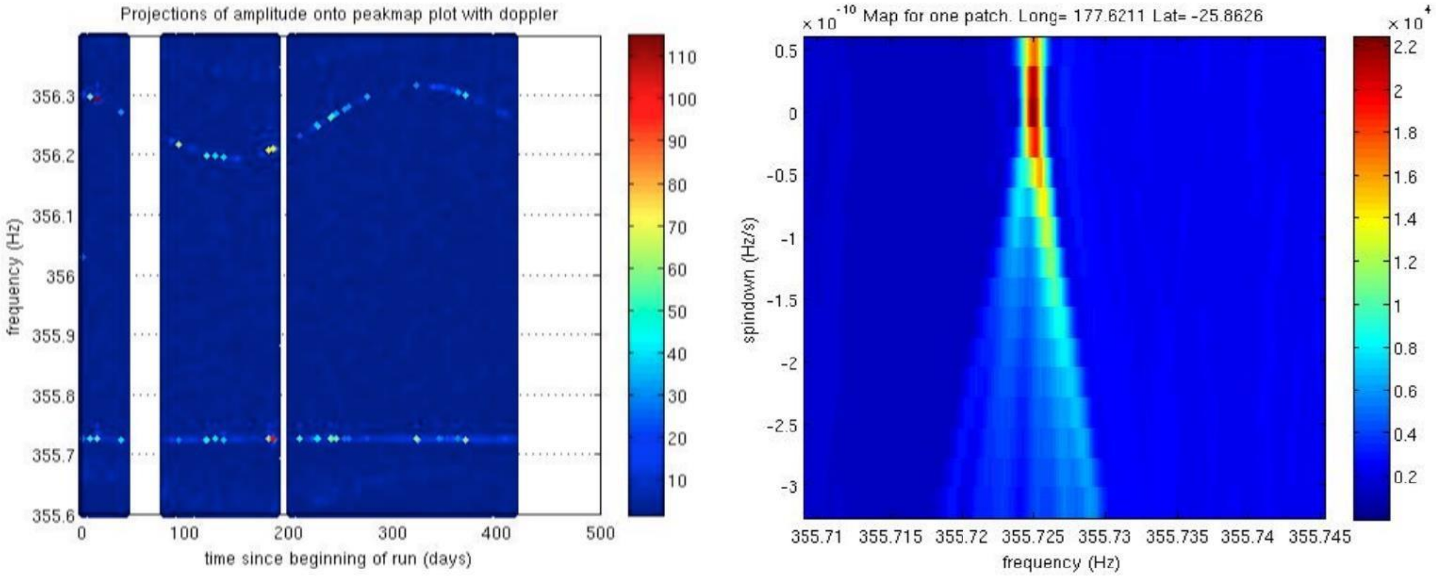
It is necessary demodulate the signal. With a full coherent procedure the computational cost is prohibitive, hence the best strategy is a hierarchical approach.

In collaboration with Pia Astone (INFN), Ornella Piccinni (IFAE) and Martina Di Cesare (INFN).

Search for Continuous Waves

FrequencyHough pipeline





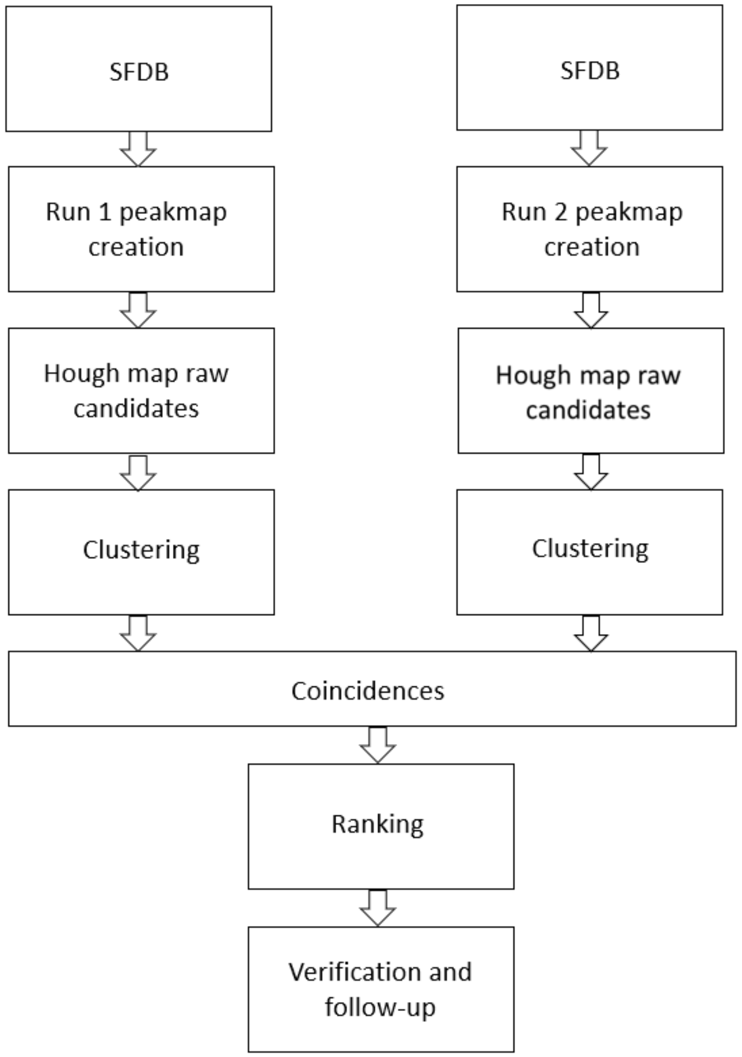
(A. Miller, 2014)

Search for Continuous Waves

FrequencyHough pipeline

Analysis of O3 LIGO data in **[3150 –3260] Hz** with the **FrequencyHough**(FH) pipeline.

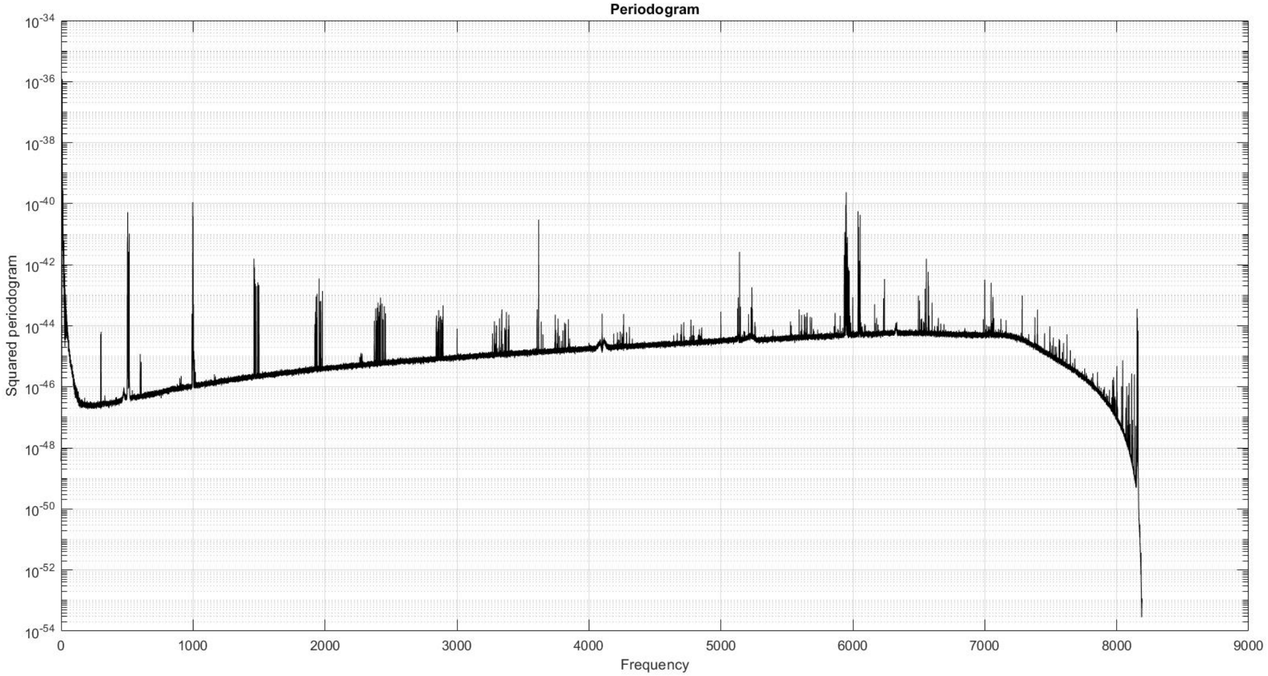
Current stage:
Preparing the Short Fast-Fourier Database (SFDB) and A (t, f) map called Peakmap

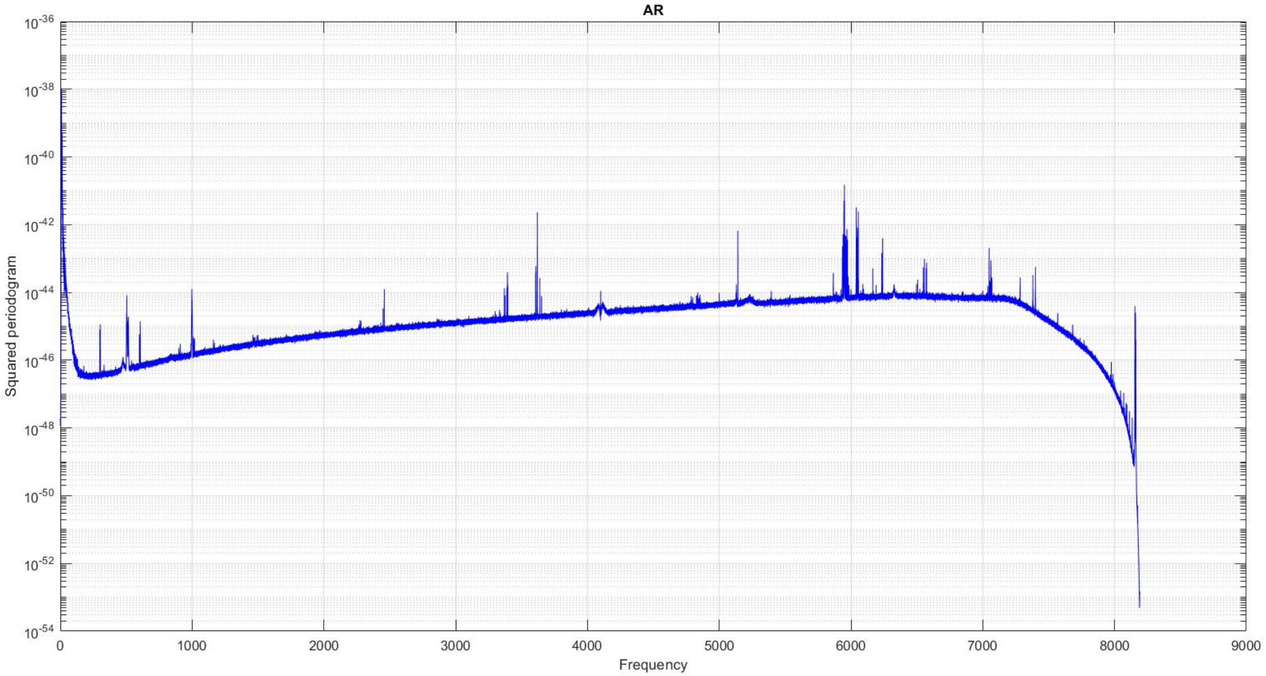


(P. Astone, et al., 2014)

Search for Continuous Waves

FrequencyHough pipeline





Periodogram

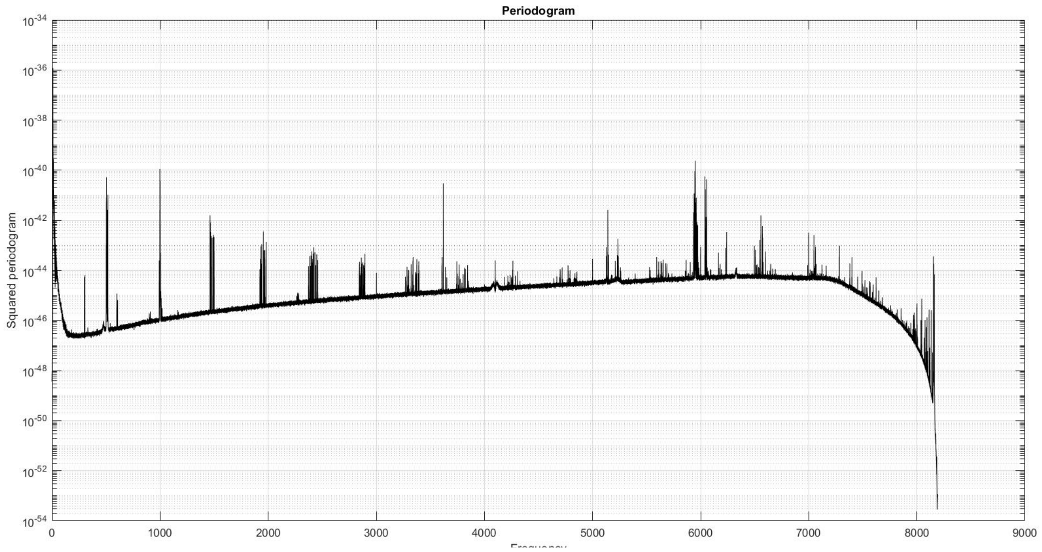
Auto-regressive spectrum

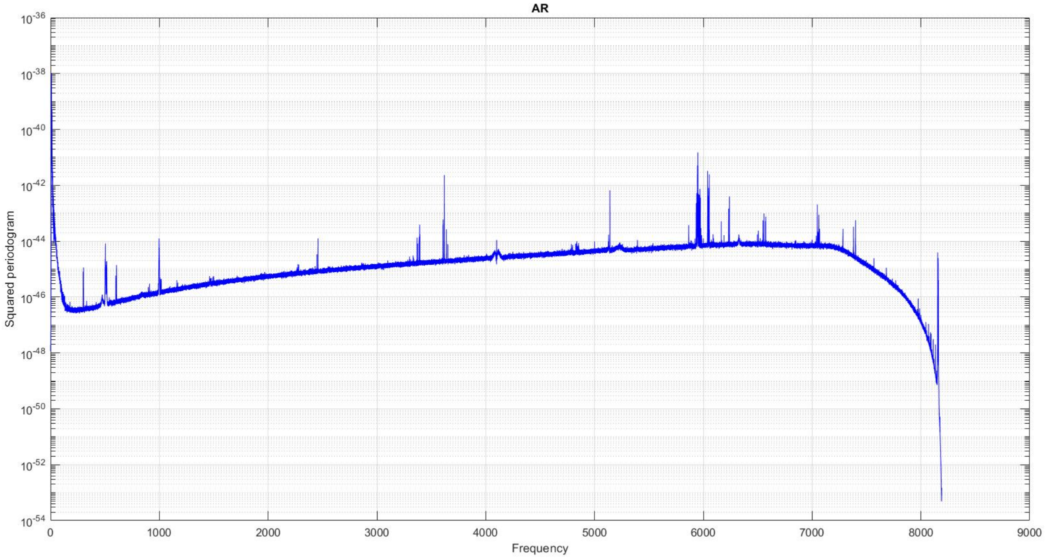
The length of FFT is optimized for the max frequency of the analysis [$fmin$, $fmax$].

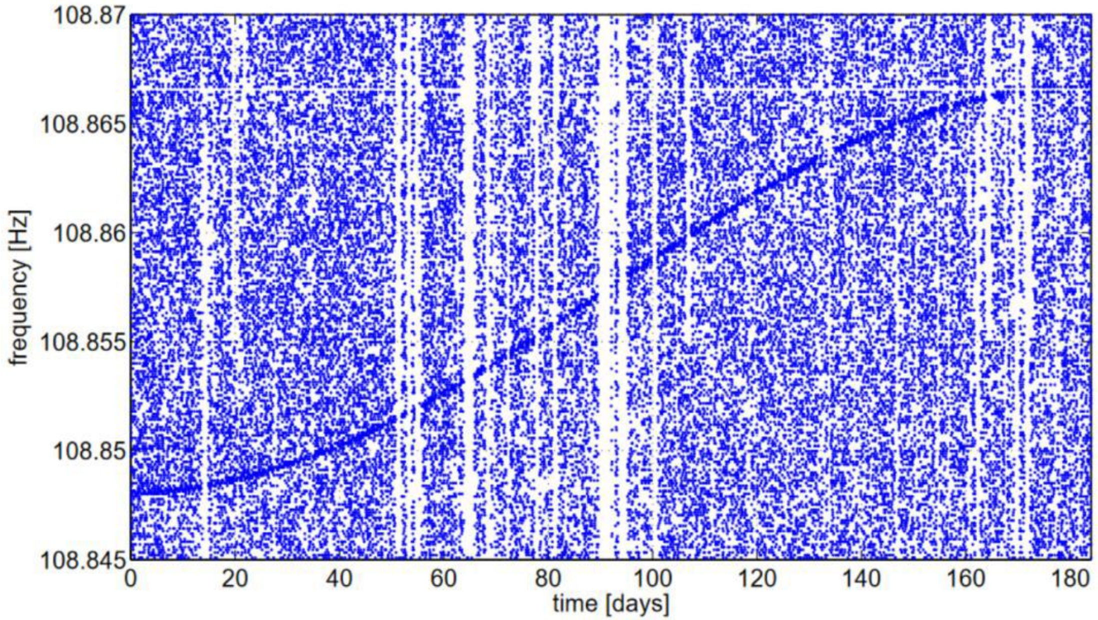
For Schenberg in band [0,4096] Hz, the length of FFT is 1024 s.

Search for Continuous Waves

The Peakmap







$$R(i,j) = \frac{S_{p;i}(f)}{S_{AR;i}(f)} \qquad i = 1, 2, \ldots N$$

All-sky Search For GW Bursts

Detection Statistics: Expected and observed results

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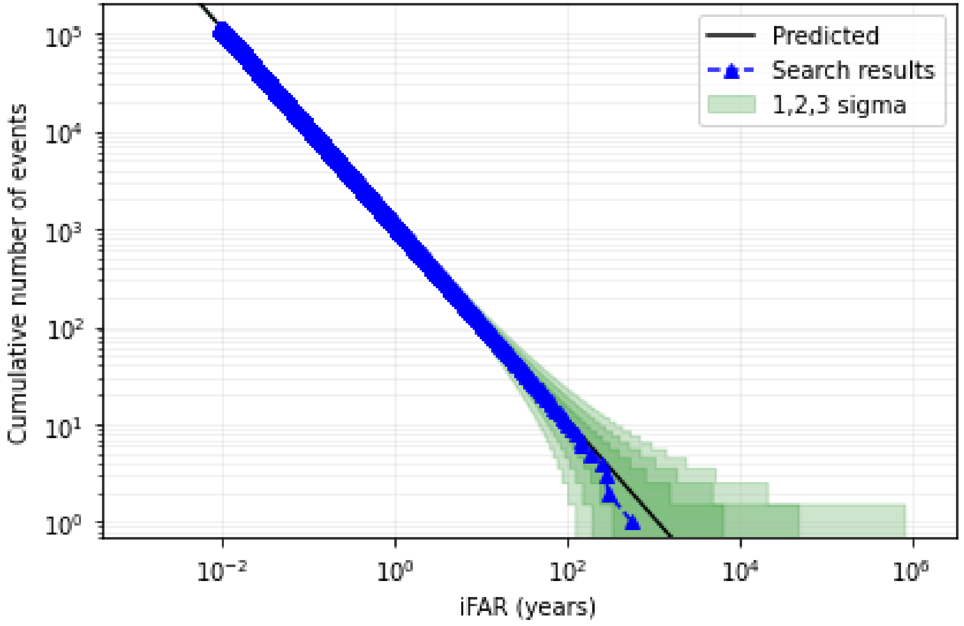

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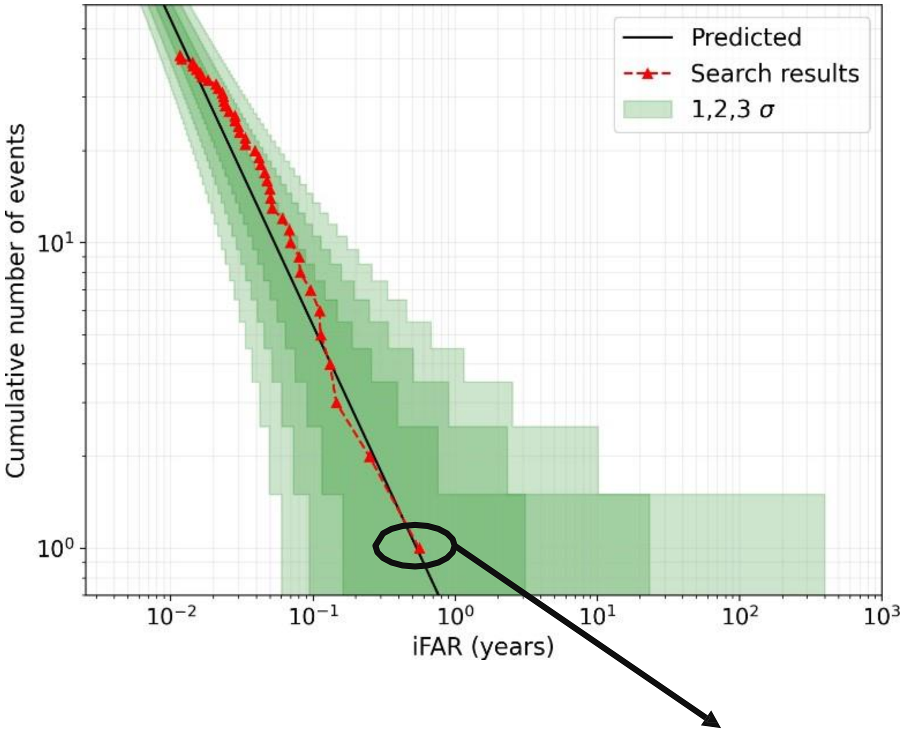


The criteria for a significant detection of an event is set at: iFAR ≥ 100 year or FAP $\leq 0.5\%$

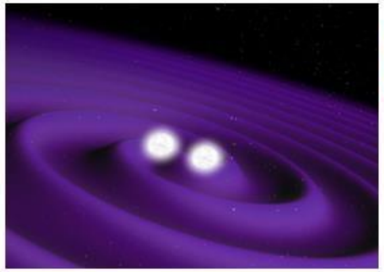
Most significant event has **iFAR = 0.6 years** and **False Alarm Probability = 32.8%**

New Searches

Know waveforms
(Well modeled)

Unknown waveforms
(Weakly modeled or un-modeled)

Short Duration
(~ 1s)



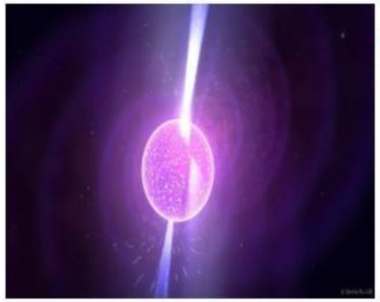
Compact Binary Coalescence

Binaries of Neutron Stars (NS) and/or Black Holes (BH)

Bursts

Core Collapse Supernovae,
Post-merger of NS,
NS glitches,
???

Long Duration
(∞)



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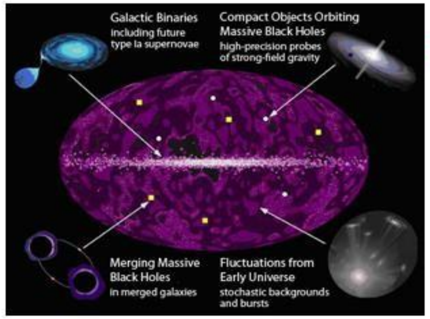
Spinning Neutron Stars,
Crustal deformations,
Accretion...



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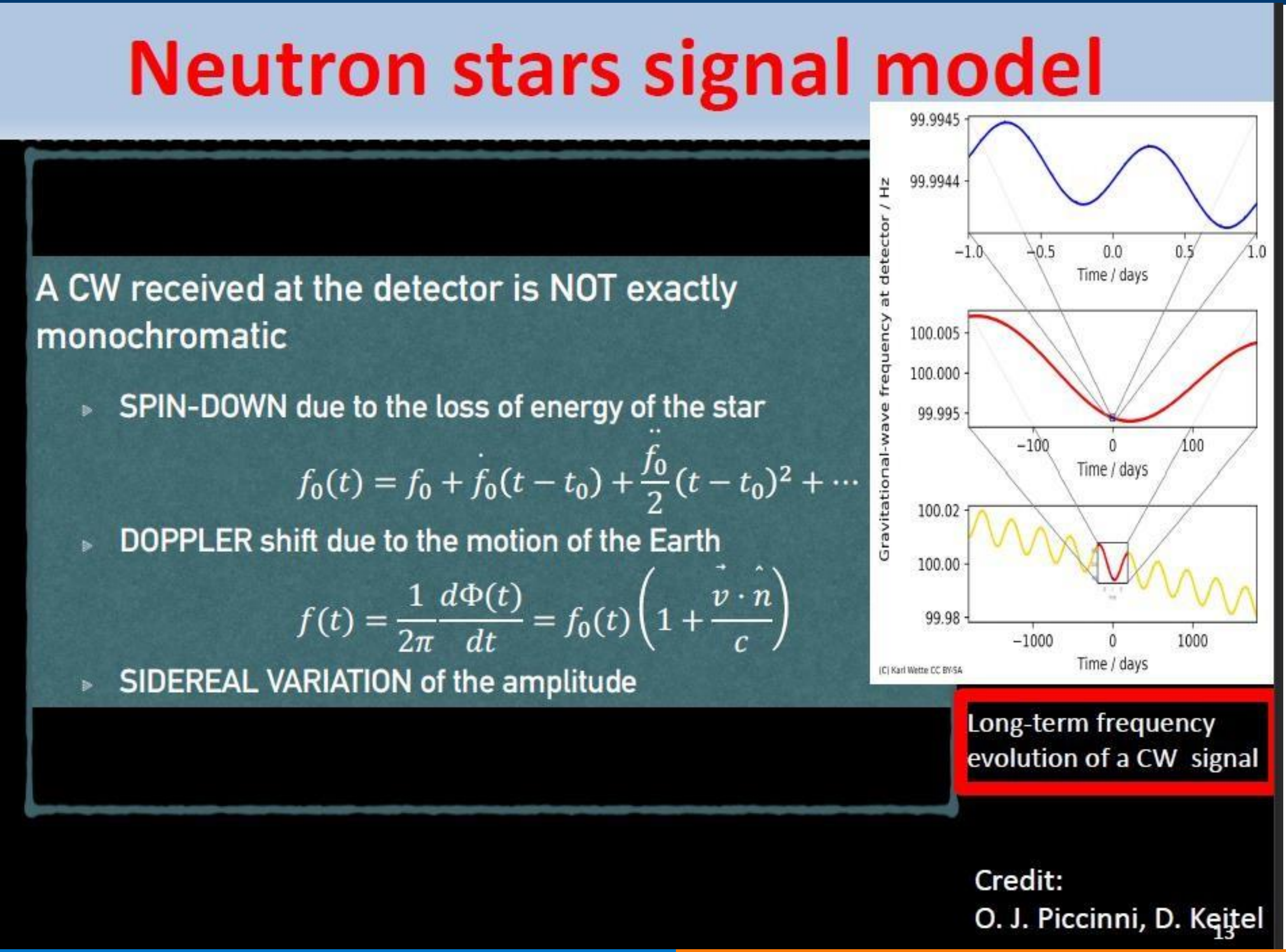
Search for Continuous Waves



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