All-sky search for continuous gravitational waves with the Frequency-Hough pipeline

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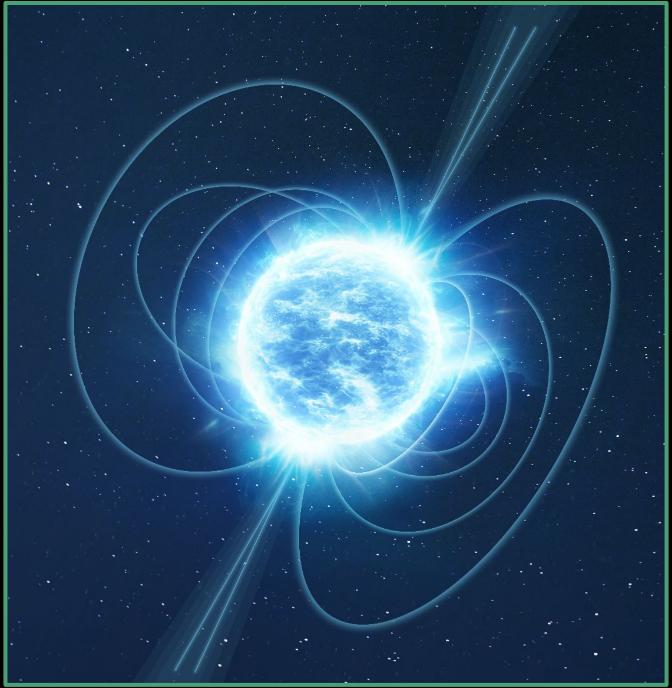
Quick intro on continuous waves (CWs)

Emission mechanism

Fast rotating, non-axisymmetric neutron stars can emit CWs, that are weak and persistent signals (duration >> years)



Signal characteristics

Frequency is nearly constant, while its amplitude is

$$h = \frac{4\pi^2 G}{c^4} \frac{\varepsilon I_{zz}}{r} f_{\mathrm{GW}}^2$$

Frequency-Hough search

All-sky search for CWs emitted by **isolated** sources

Parameter space

Frequency: [10, 2048] Hz
Spin-down: [-10, +2] nHz/s
Latitude: [-90, +90] deg
Longitude: [0, 360) deg

Pros: few physical assumptions

Cons: computationally demanding

P. Astone et al., *Method for all-sky searches of continuous gravitational wave signals using the frequency-Hough transform*, 2014

Frequency-Hough search

Input files: Band-Sampled Data (BSD)

↓

Band extraction, *peakmap* creation

↓

Doppler correction:

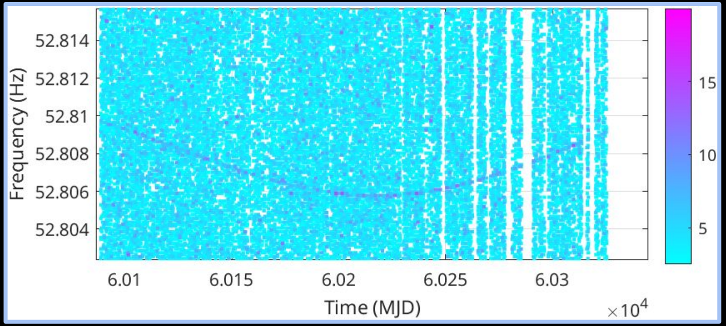
$$f(t) = f_0\left(1 + \frac{\vec{v}\cdot\hat{n}}{c}\right)$$

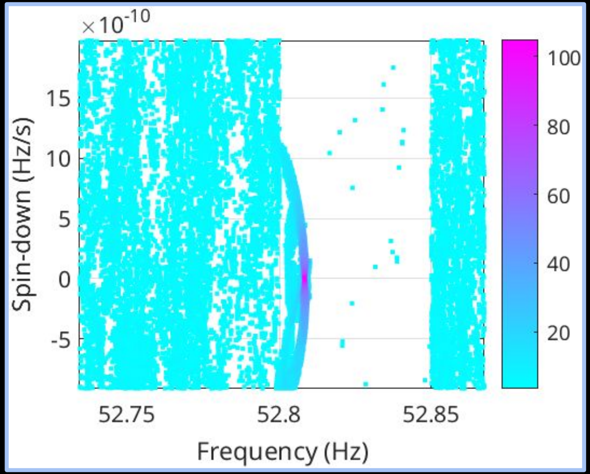
↓

$$f(t) \approx f_0 + \dot{f}_0(t - t_0)$$

Hough transform: map between time/frequency plane and source frequency/spin-down plane

O.J. Piccinni et al., *A new data analysis framework for the search of continuous gravitational wave signals*, 2018





Hardware injection
$$\begin{cases} f_0 = 52.8083\mathrm{Hz} \\ \dot{f}_0 = -4.03\times 10^{-18}\mathrm{Hz/s} \\ h_0 = 3.985\times 10^{-25} \end{cases}$$

Selection of candidates

For each sky direction, the most significant candidates in each 0.05 Hz sub-band are selected, basing on Critical Ratio (CR)

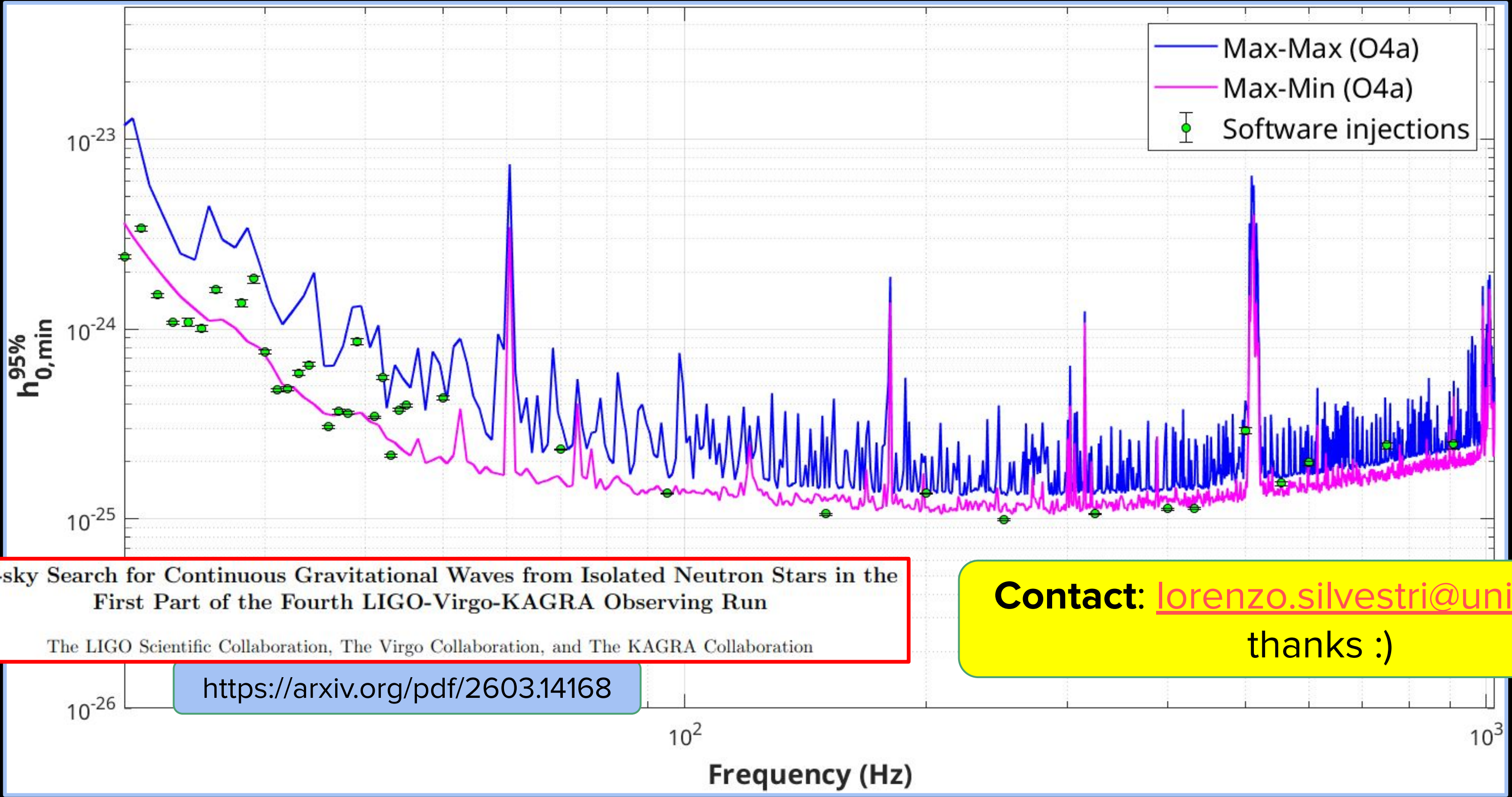
Coincidences between detectors based on a dimensionless distance $d_{FH} < 3$

$$d_{\mathrm{FH}} = \sqrt{\left(\frac{\Delta f}{\delta f}\right)^2 + \left(\frac{\Delta \dot{f}}{\delta \dot{f}}\right)^2 + \left(\frac{\Delta \lambda}{\delta \lambda}\right)^2 + \left(\frac{\Delta \beta}{\delta \beta}\right)^2}$$

Ranking procedure on coincident candidates, where we select the 8 most significant candidates per 0.01 Hz

Follow-up on remaining candidates to validate or reject them

O4a results - Search sensitivity



All-sky Search for Continuous Gravitational Waves from Isolated Neutron Stars in the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run

The LIGO Scientific Collaboration, The Virgo Collaboration, and The KAGRA Collaboration

https://arxiv.org/pdf/2603.14168

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thanks :)

Backup

Gravitational Waves (GWs)

Perturbative solutions of Einstein equations,

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Continuous GWs (CWs):

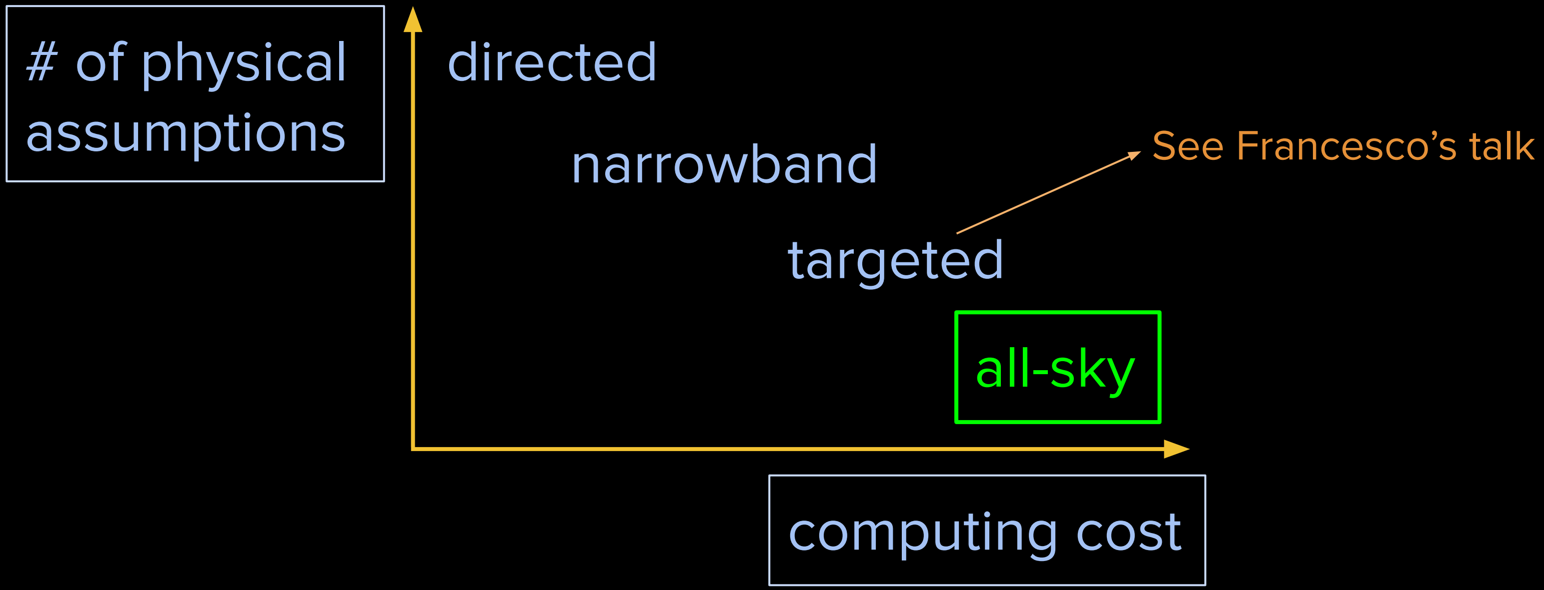
Persistent and quasi-monochromatic signals emitted by fast-rotating and non-axisymmetric neutron stars

GWs detectors

Earth-based interferometers (LIGO, Virgo, KAGRA)

https://gwosc.org/

Several types of CWs searches



K. Wette, *Searches for continuous gravitational waves from neutron stars: A twenty-year retrospective*, 2023

O4a results

Search completed in the [10-1024] Hz band with data from LIGO detectors Hanford and Livingston

Coincident candidates after the ranking procedure: **3 x 10^6**
Followed-up the **6 x 10^5** candidates crossing a fixed CR threshold

Sensitivity estimation

Theoretical relation between $h_{0,\mathrm{MIN}}$ and CR threshold:

$$h_{0,\mathrm{MIN}} \propto \frac{S_n^{1/2}}{N^{1/4}\sqrt{T_{\mathrm{FFT}}}} \times \left(\frac{p_0(1-p_0)}{p_1^2}\right)^{1/4} \sqrt{\mathrm{CR}_{\mathrm{max}} - \sqrt{2}\,\mathrm{erfc}^{-1}(2\Gamma)}$$

Leads to conservative upper limits estimation, validated through a large set of software injections in 40 1-Hz frequency bands

Parameter space split for job submissions

The parameter space is properly split to have jobs with the same expected runtime of 1 day, resulting to a total of $O(10^6)$ jobs.
Submissions are managed through a PostgreSQL to keep track of the status of the search:

```
jobman=# select * from o4bjobs_fh where split_part(args,' ',1)::int=850 limit 10;
   id    |                  args                    | status | numtry |         lastupdate         | summaryfile | skypoints
---------+------------------------------------------+--------+--------+----------------------------+-------------+-----------
 240481 | 850 1 -1e-08 2e-09 -25 25 0 3 LL          |    100 |      1 | 2025-09-08 06:44:38.378294 |             |       970
 240124 | 850 1 -1e-08 2e-09 -90 -50 183 186 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1067
 240096 | 850 1 -1e-08 2e-09 -90 -50 141 144 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1070
 240158 | 850 1 -1e-08 2e-09 -90 -50 234 237 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1071
 240118 | 850 1 -1e-08 2e-09 -90 -50 174 177 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1068
 240108 | 850 1 -1e-08 2e-09 -90 -50 159 162 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1065
 240152 | 850 1 -1e-08 2e-09 -90 -50 225 228 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1078
 240110 | 850 1 -1e-08 2e-09 -90 -50 162 165 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1070
 240102 | 850 1 -1e-08 2e-09 -90 -50 150 153 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1074
 240088 | 850 1 -1e-08 2e-09 -90 -50 129 132 LH    |    100 |      1 | 2025-09-08 06:45:36.381149 |             |      1065
(10 rows)
```

Peaks selection

Peakmap: Select a coherence time (T_{FFT}) and perform interlaced-by-half FFTs, total of $N = 2 \times T_{obs}/T_{FFT}$.
From this collection of peaks select only those above a threshold θ.

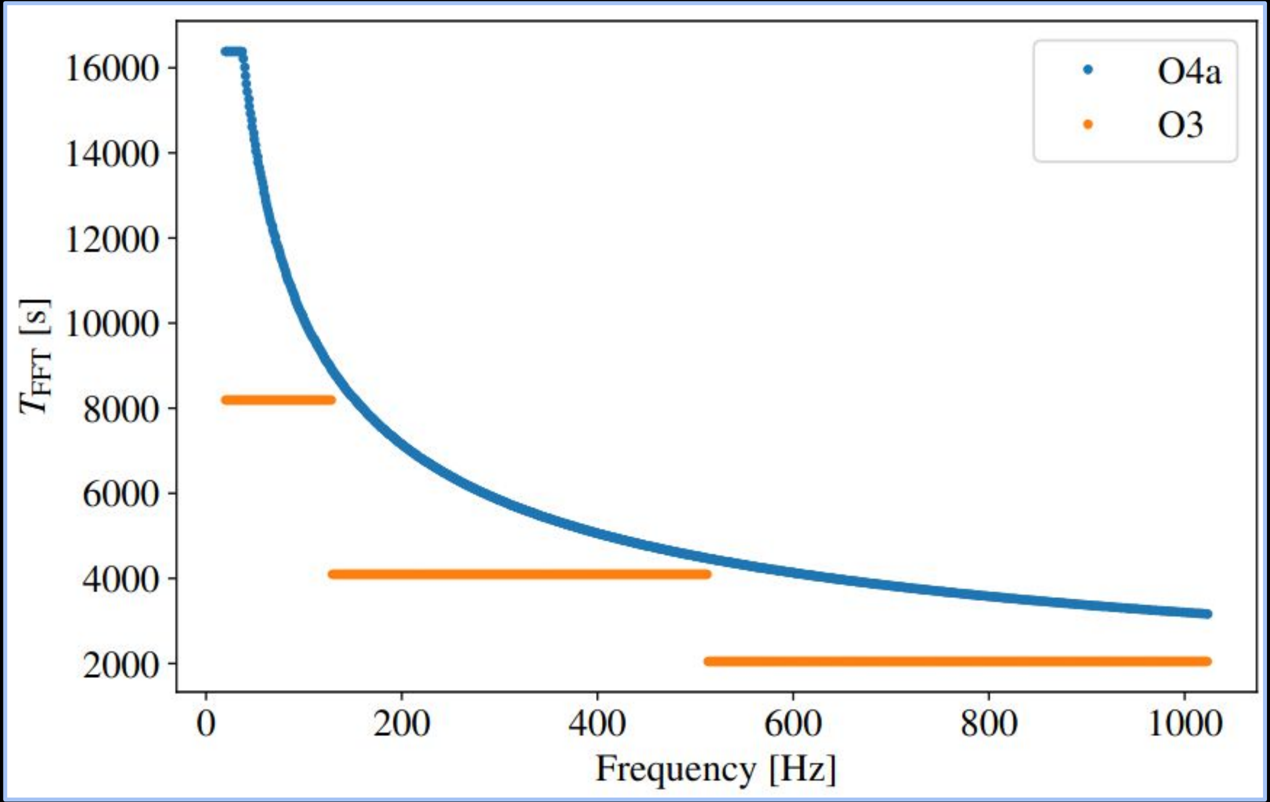
Hough map: after the Hough transform, select peaks above a Critical Ratio (CR) threshold,

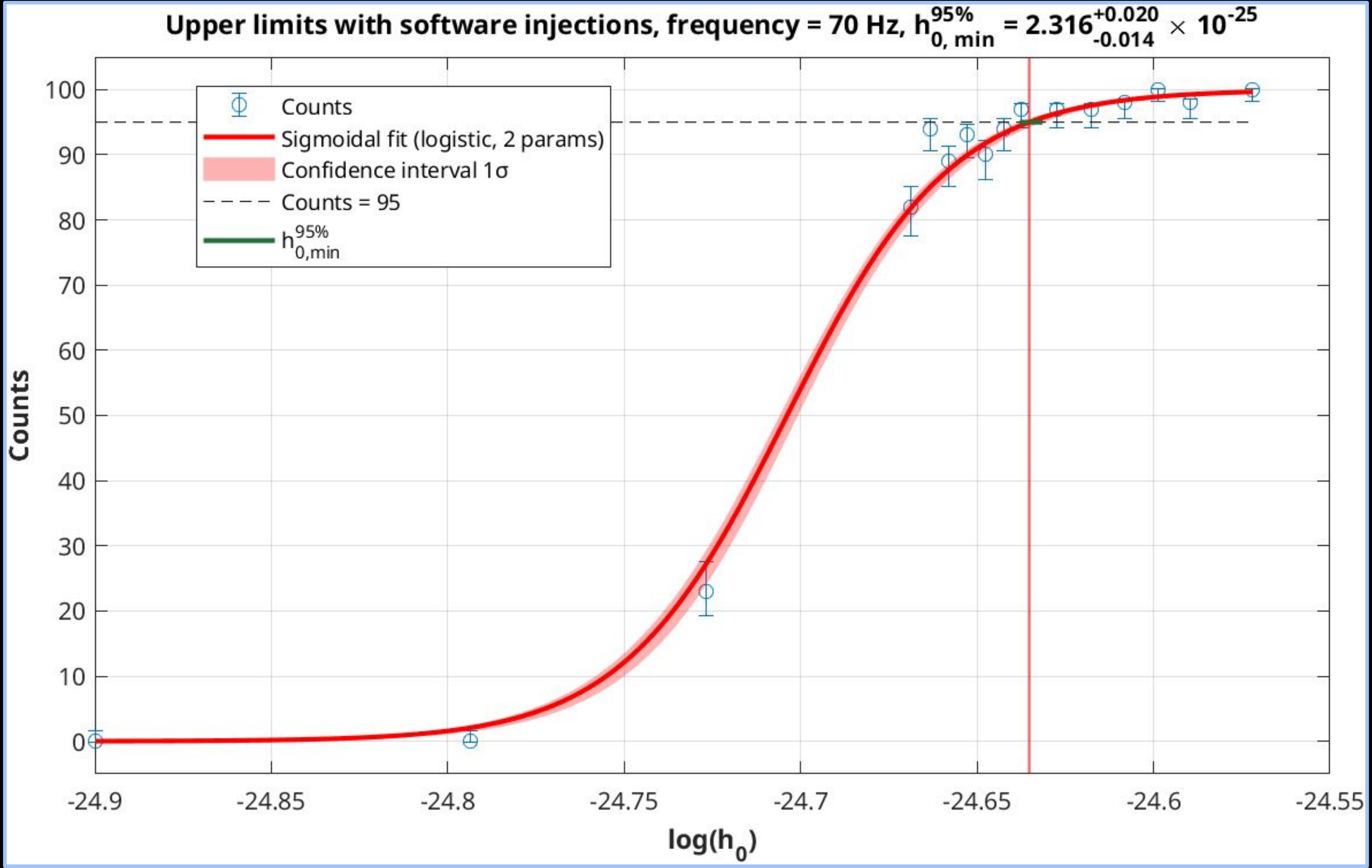
$$\mathrm{CR} = \frac{n - Np_0}{\sqrt{Np_0(1-p_0)}}$$

n: number count for each pixel in the Hough map
N: number of FFTs
p0: probability of having a local maxima above a threshold θ

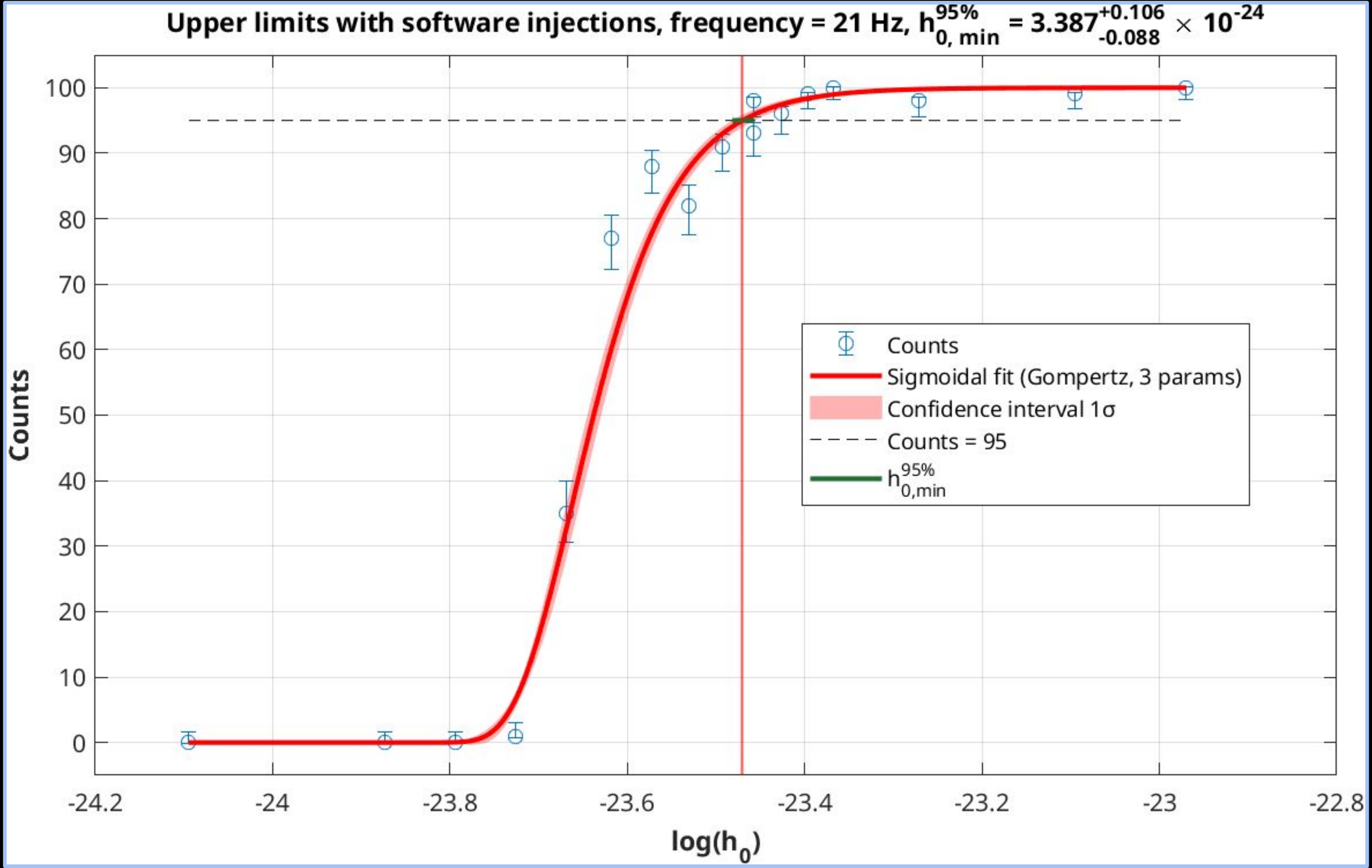
$$p_0 = \int_{\theta}^{+\infty} e^{-x}(1-e^{-x})^2 dx = e^{-\theta} - e^{-2\theta} + \frac{1}{3}e^{-3\theta}$$

T_{FFT} Choice


O4a
O3
16000
14000
12000
10000
8000
6000
4000
2000
T_{FFT} [s]
0
200
400
600
800
1000
Frequency [Hz]



Upper limits with software injections, frequency = 70 Hz, $h_{0,\,min}^{95\%} = 2.316^{+0.020}_{-0.014} \times 10^{-25}$
Counts
Sigmoidal fit (logistic, 2 params)
Confidence interval 1σ
Counts = 95
$h_{0,min}^{95\%}$
Counts
$\log(h_0)$
100
90
80
70
60
50
40
30
20
10
0
-24.9
-24.85
-24.8
-24.75
-24.7
-24.65
-24.6
-24.55



Upper limits with software injections, frequency = 21 Hz, $h_{0,\,min}^{95\%} = 3.387^{+0.106}_{-0.088} \times 10^{-24}$
Counts
log(h_0)
100
90
80
70
60
50
40
30
20
10
0
-24.2
-24
-23.8
-23.6
-23.4
-23.2
-23
-22.8
Counts
Sigmoidal fit (Gompertz, 3 params)
Confidence interval 1σ
Counts = 95
$h_{0,min}^{95\%}$