Omicron-X:
cross-correlating spectrograms to search for core-collapse supernova GWs

Adrien Paquis, PhD in IJCLAB Orsay (Paris)- Warsaw SN2025 LVK SYMPOSIUM 24/07/25
with Florent Robinet

OVERVIEW

1. Omicron-x pipeline: technical overview
2. Background and sensitivity studies
3. Going further: SASI and neutrinos

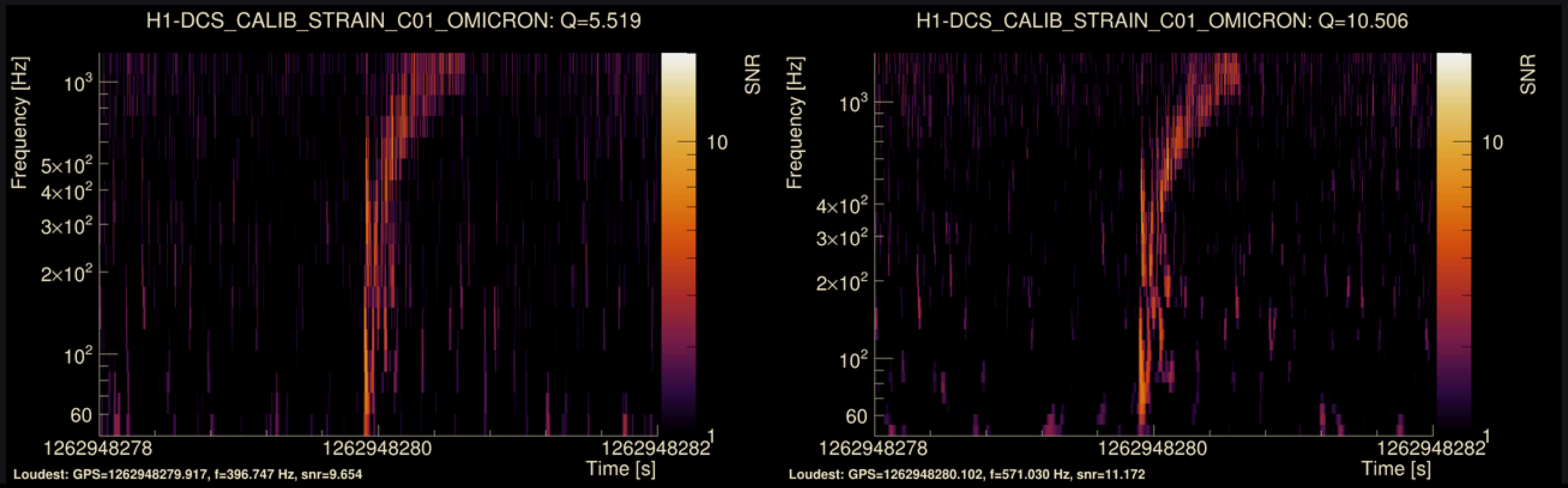
1.OMICRON-X PIPELINE: TECHNICAL OVERVIEW

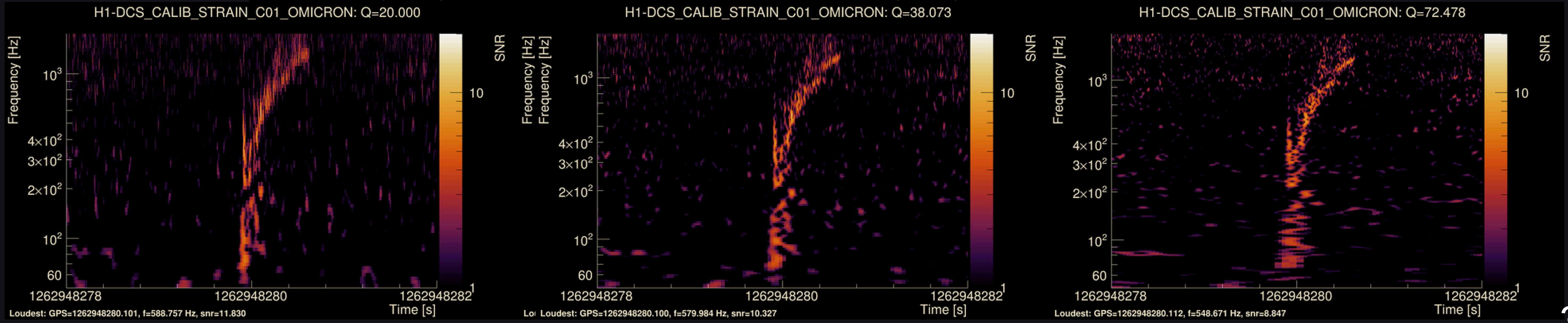
OMICRON

Based on Omicron* software which produces multi-resolution spectrograms by performing Q-transforms of GW timeseries

$$Q = \frac{f_k}{\delta f_k}$$

Radice’s 2019 s10** supernova waveform for different Q values :





All data shown in this presentation are LIGO data from O3:
Jan 5 2020 → Jan 26 2020

*: Omicron: A tool to characterize transient noise in gravitational-wave detectors, Florent Robinet, Nicolas Arnaud, Nicolas Leroy, Andrew Lundgren, Duncan Macleod, and Jessica McIver, July 2020

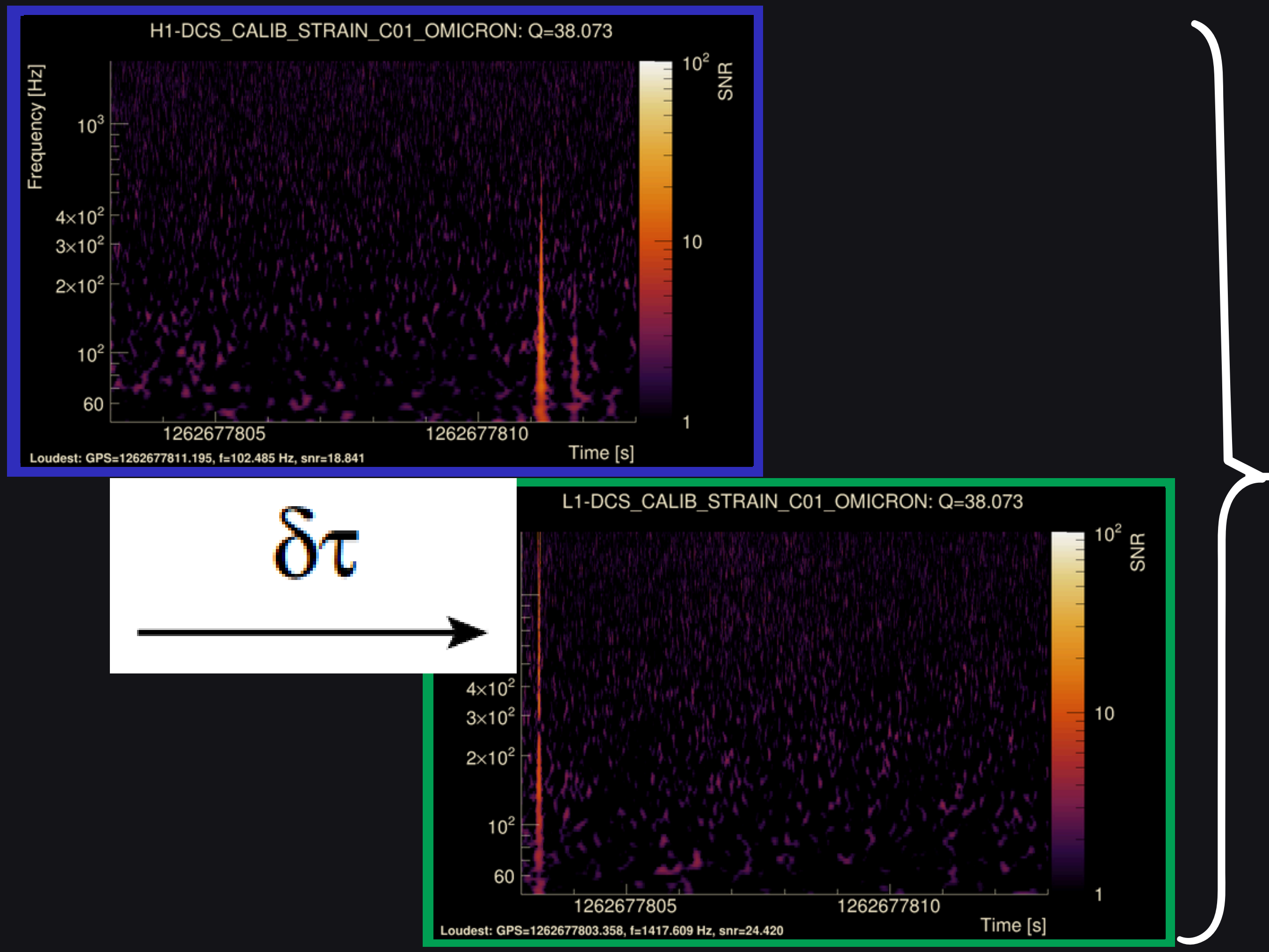
**: Characterizing the gravitational wave signal from core-collapse supernovae, David Radice, Viktoriya Morozova, Adam Burrows, David Vartanyan, and Hiroki Nagakura 2019.

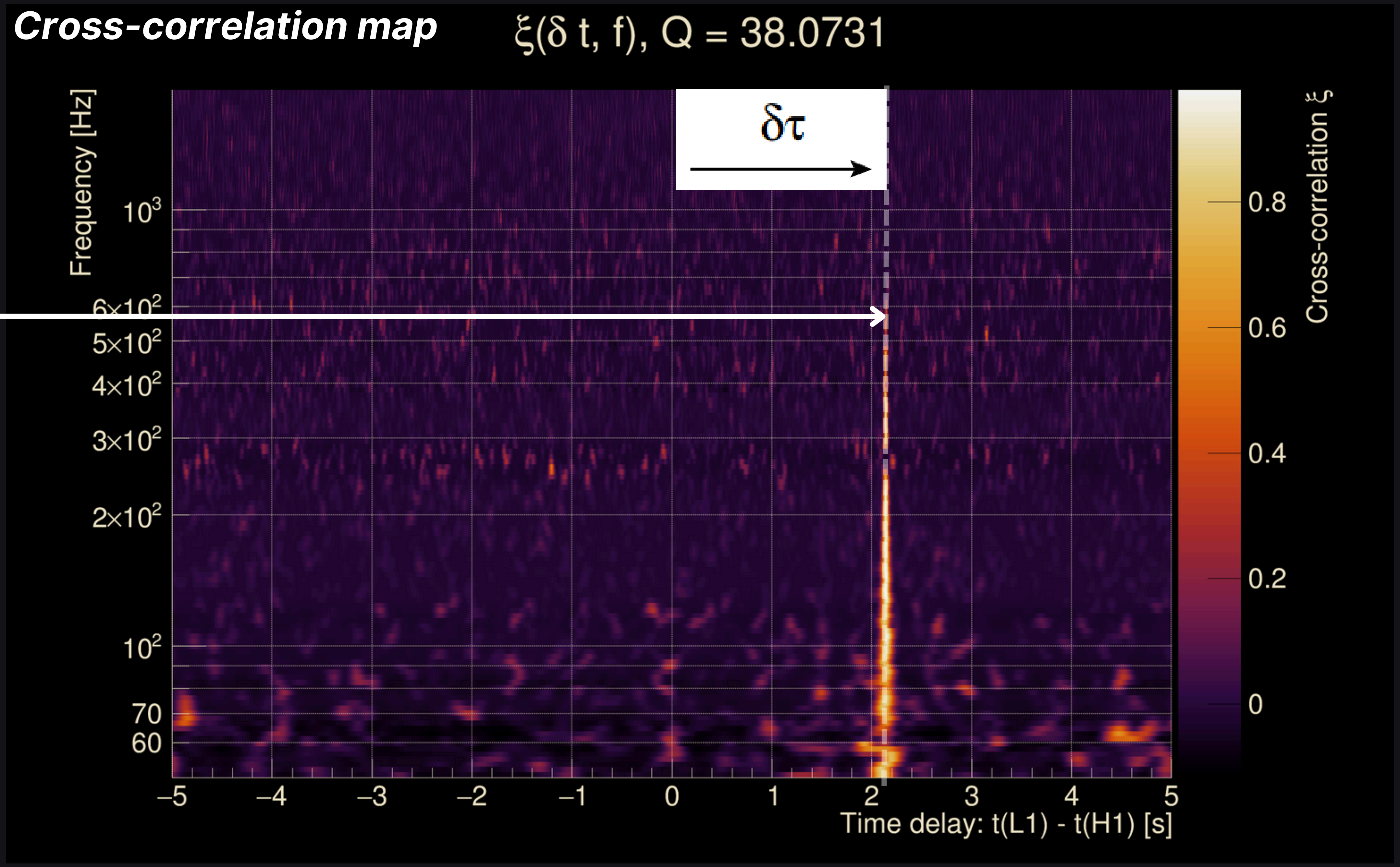
CROSS-CORRELATION MAP

Time-shift 2 spectrograms from different detectors and sum multiplied bins, for each frequency row :

$$\xi[m][l] = \sum_{m'=0}^{N-1} A_H[m'][l] A_L[N/2 + m - m'][l]$$

l = frequency row index, m = time shift index





BACKGROUND: contains glitches and noise only

Unphysical delay of 2s

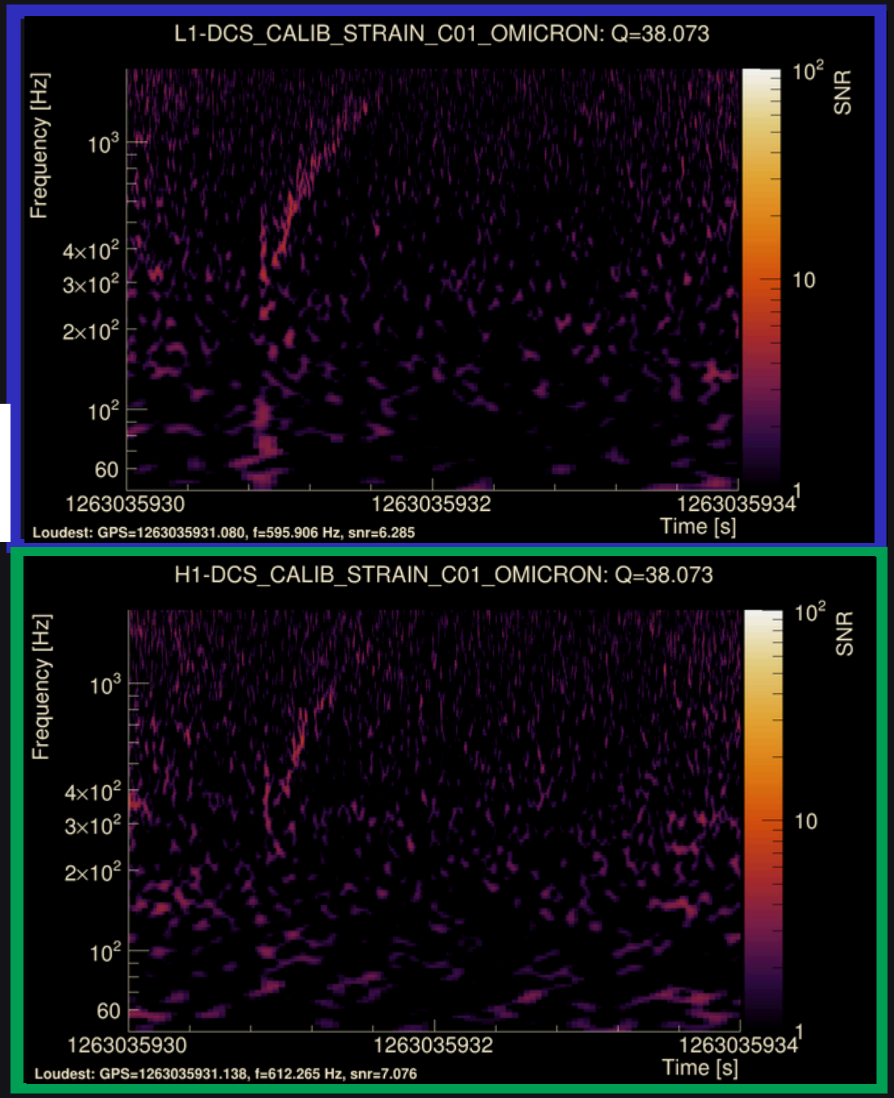
CROSS-CORRELATION MAP

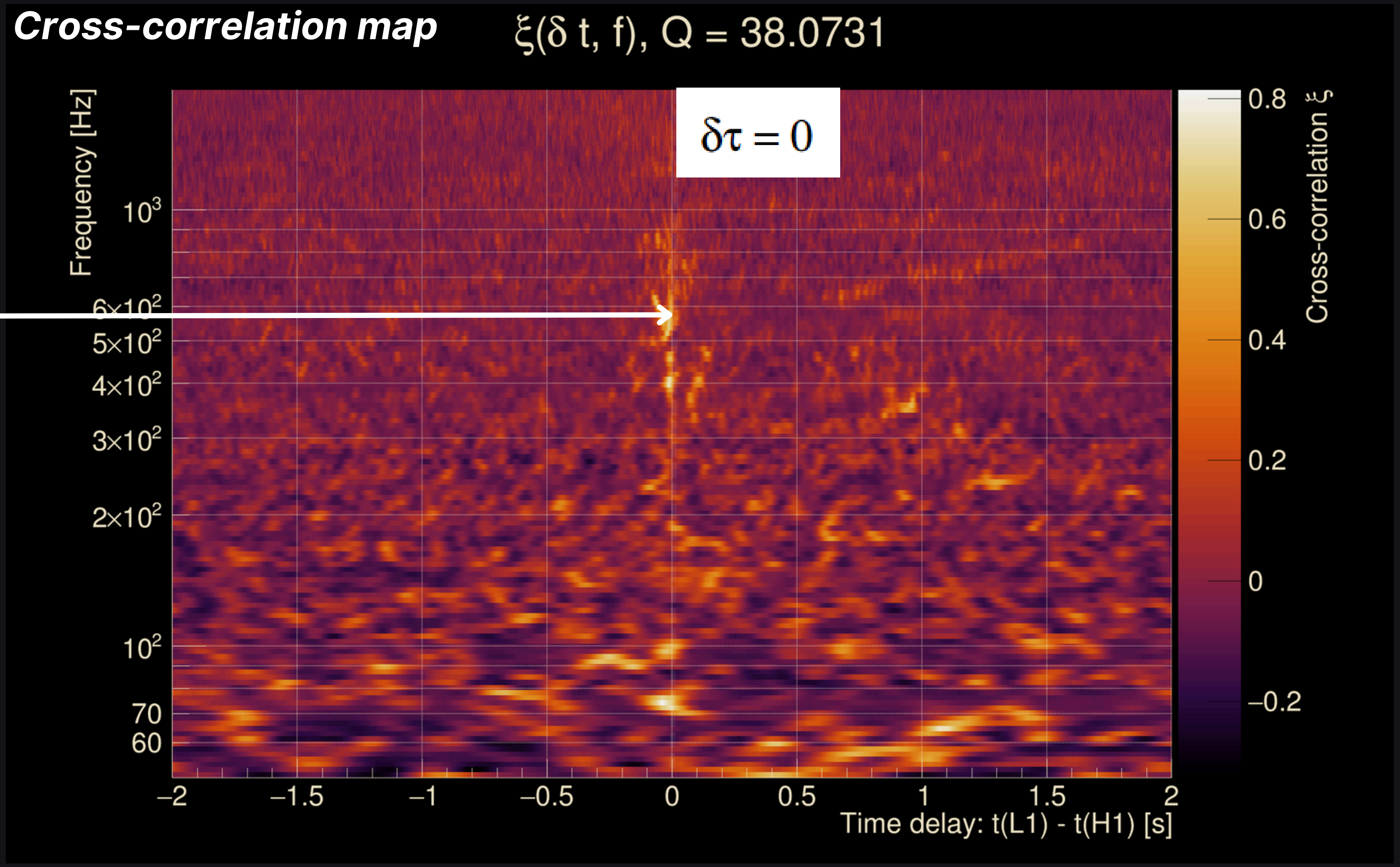
Time-shift 2 spectrograms from different detectors and sum multiplied bins, for each frequency row :

$$\xi[m][l] = \sum_{m'=0}^{N-1} A_H[m'][l] A_L[N/2 + m - m'][l]$$

l = frequency row index, m = time shift index

$\delta\tau = 0$





ZERO LAG: contains glitches, noise and GWs

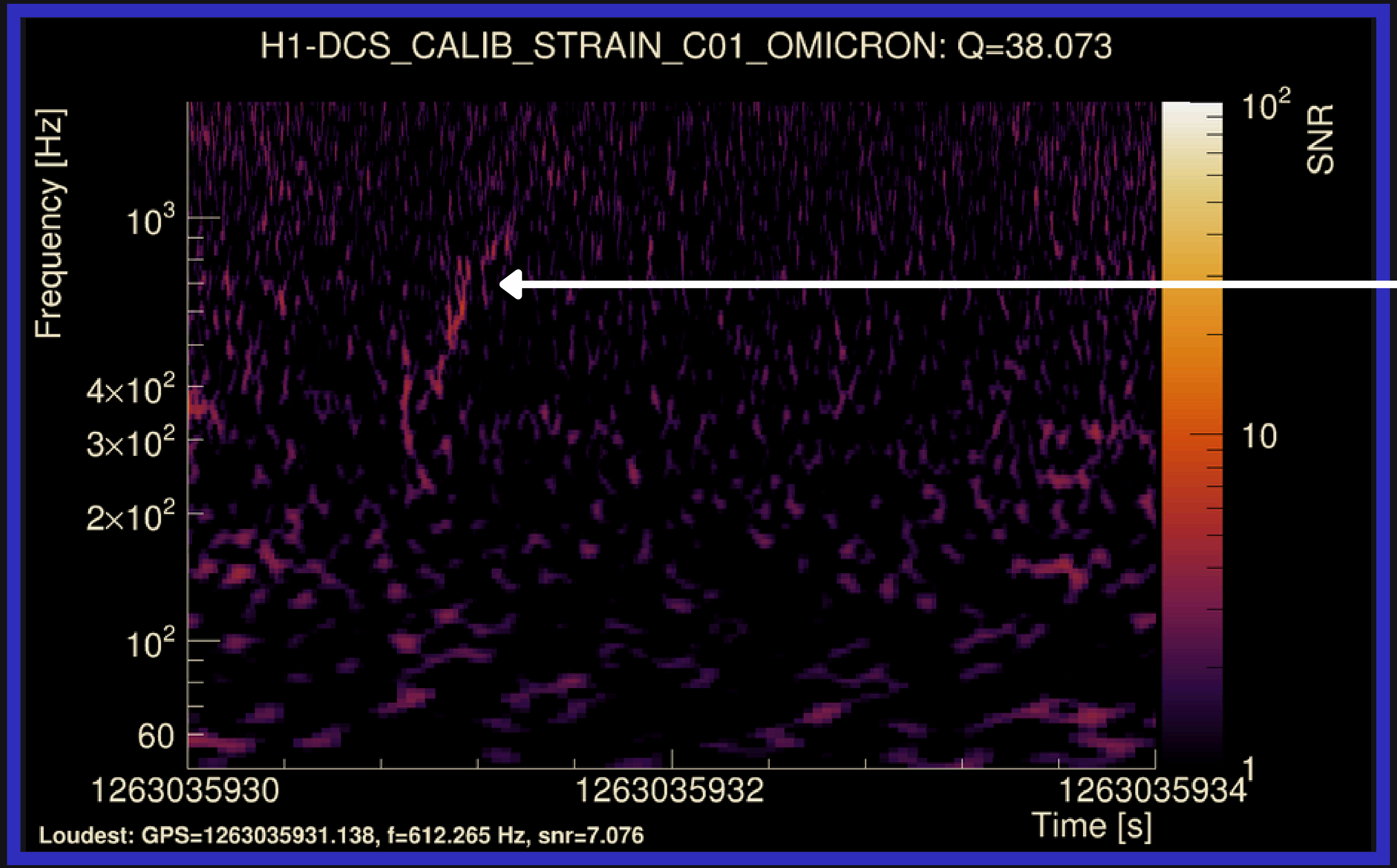
No delay (or < 12ms)

(waveform is Radice19 s10, 3D)

WHY CROSS CORRELATE FOR CCSN?

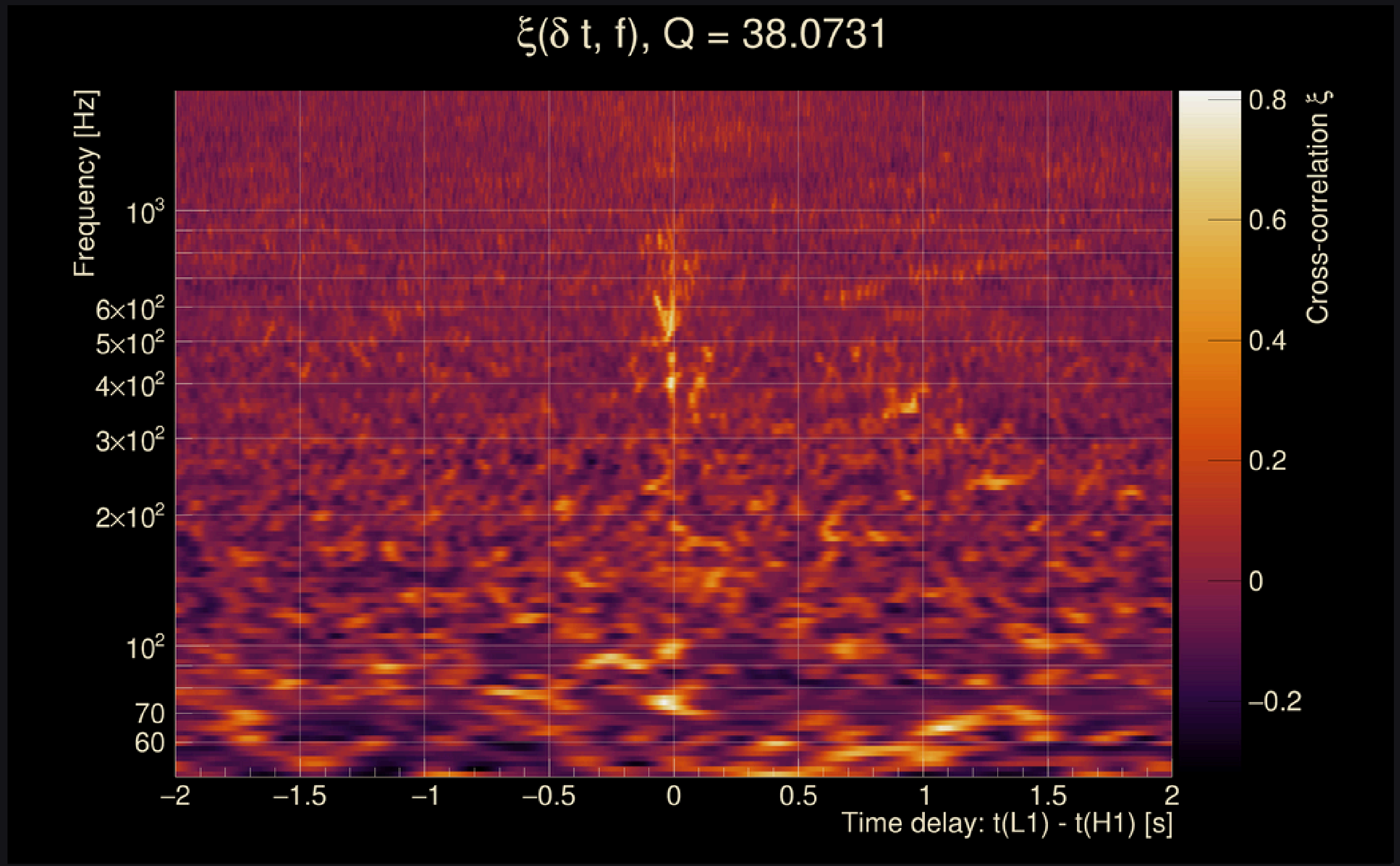
- Cross-correlation is effective at matching unknown patterns
- Events are produced without SNR thresholds, no clustering: the full spectrograms are used

=> **Great for complex and structured waveforms signal morphologies**, like CCSNe's



(waveform is Radice19 s10, 3D)

low SNR pixels also contribute to the final cross-correlation

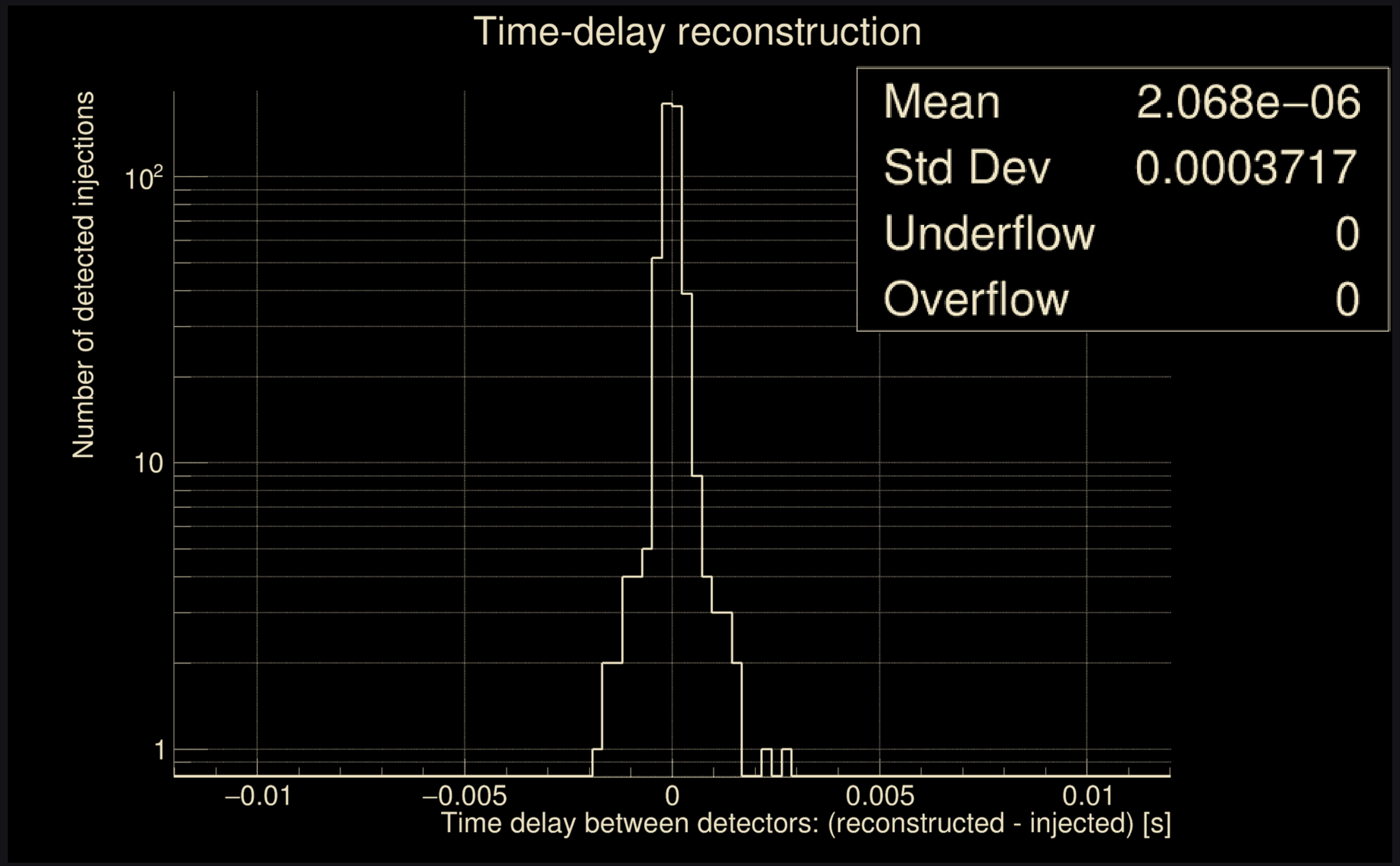


Cross-correlation map

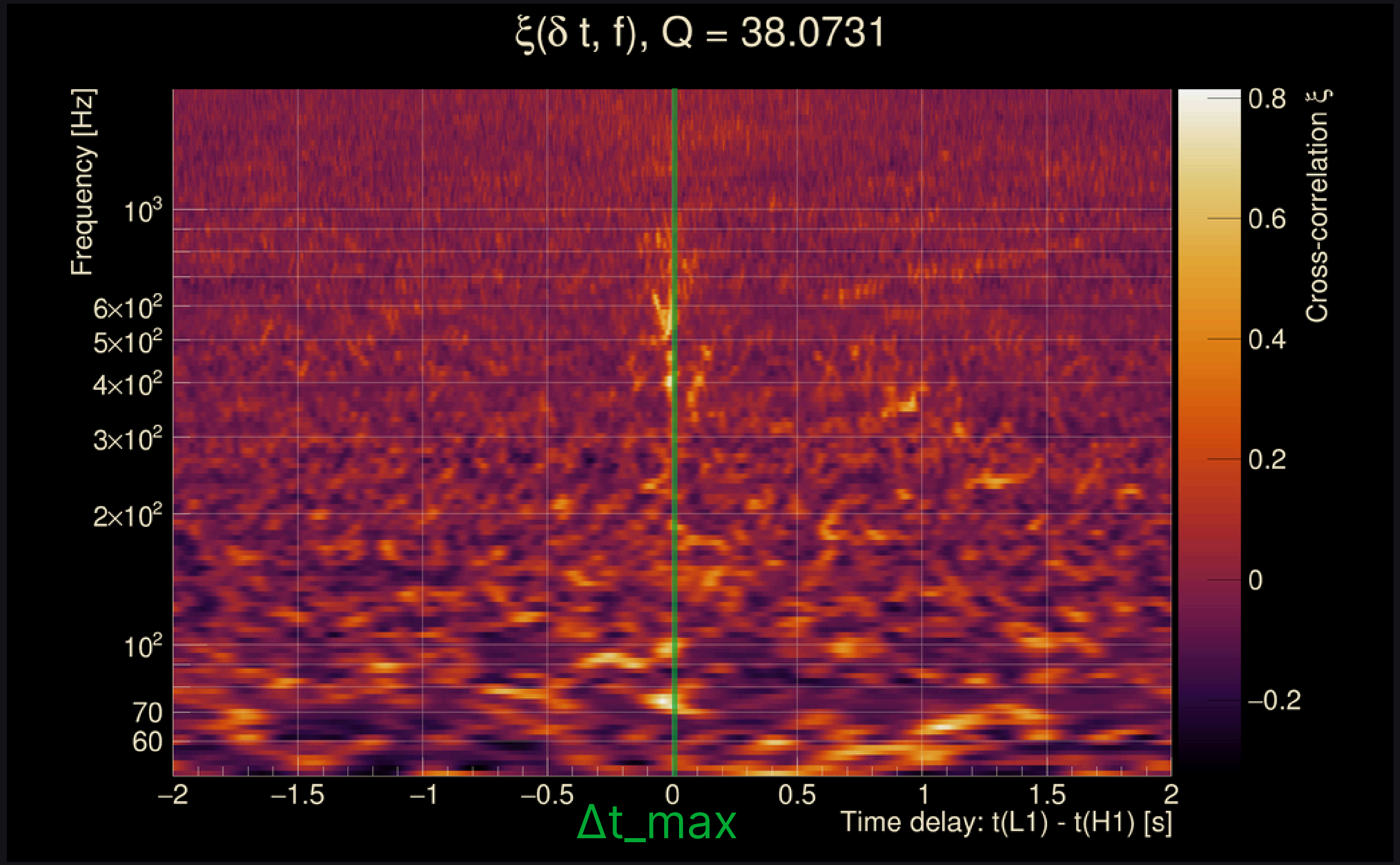
RANKING STATISTIC

We find the time-delay bin Δt_max that maximizes the integrated cross-correlation along frequencies

=> Precise time reconstruction : < 0.4 ms



waveform is Radice19 s10, 3D*



We sum the cross- correlation bins to produce a ranking statistic:

$$R = \frac{1}{N_f} \sum_f \xi[\Delta_{tmax}][f]$$

- R close to 0 => probably noise or a glitch
- R close to 1 => probably signal

*

OTHER TECHNICALITIES…

Other interesting features, weights, vetos, that I do not have time to explain here and now:

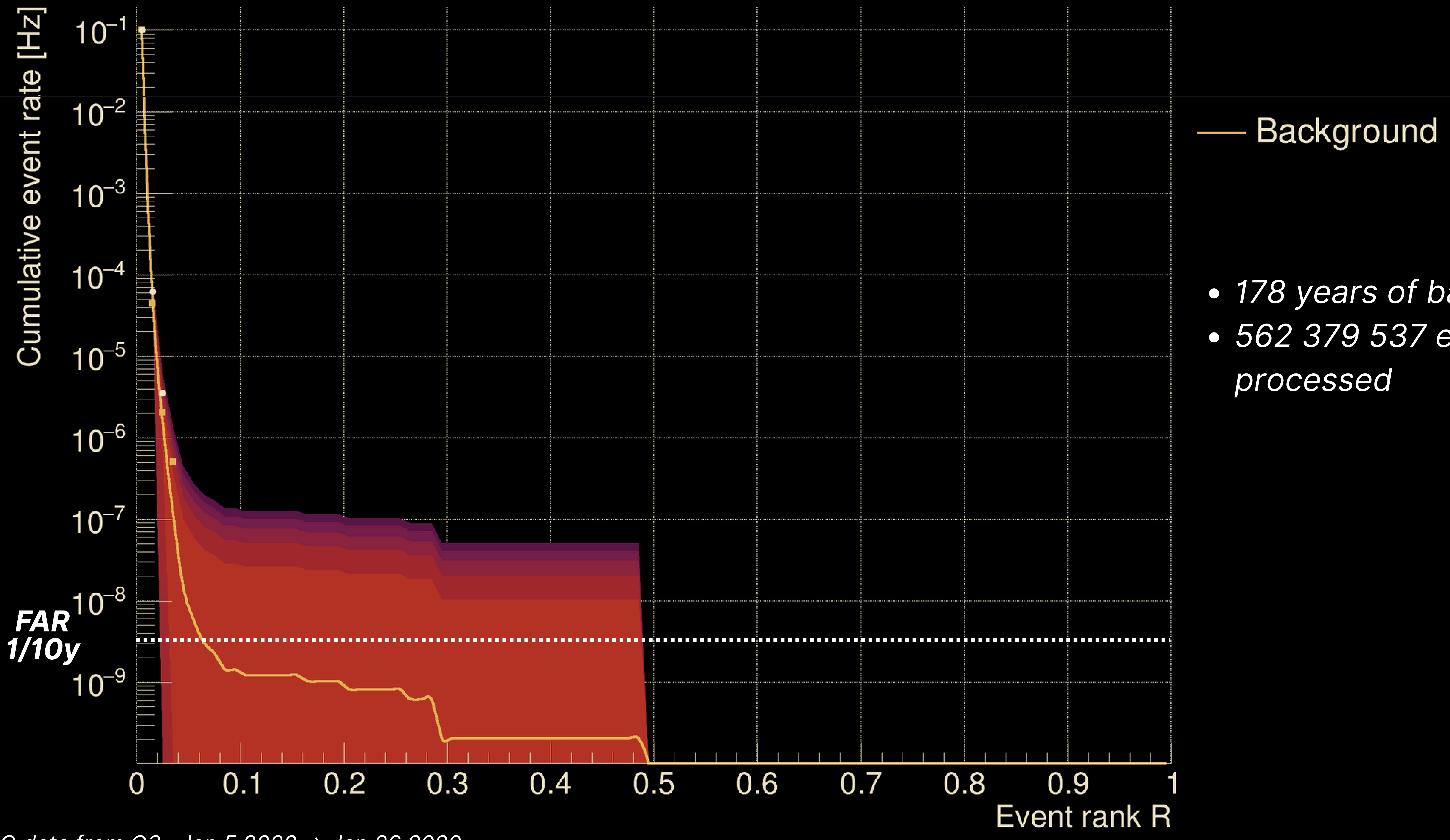
- *One cross-correlation map = one zero lag event + 210 background event*
- *Background comes naturally from the cross-correlation analysis*
- *Cross-correlation must be consistent between the different spectrograms of different q values*
- *Time delay and antenna factor compatibility is tested*

Methods paper currently in draft!

Come ask me if you're interested

2.BACKGROUND AND SENSITIVITY STUDIES

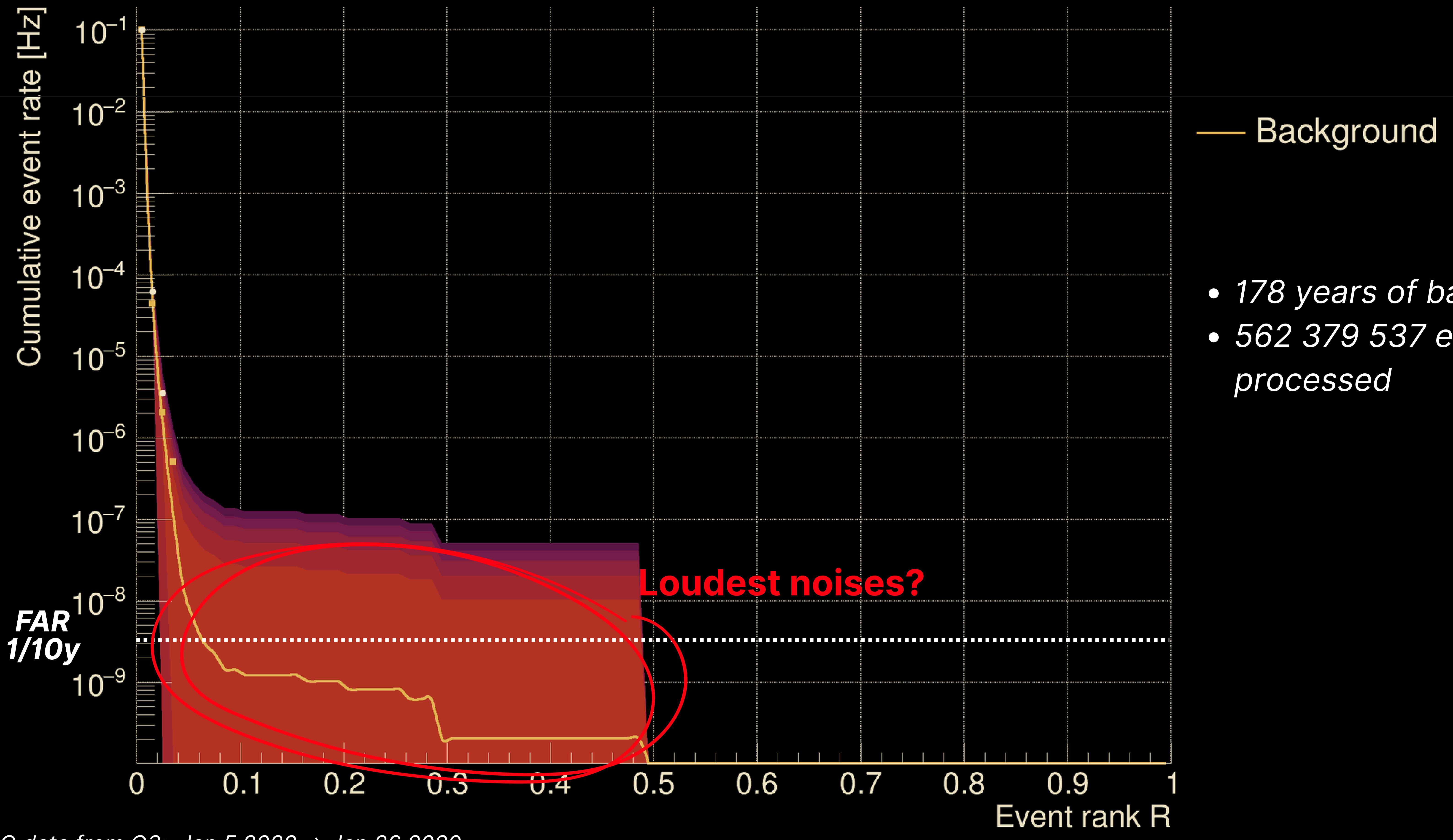
BACKGROUND DISTRIBUTION



- *178 years of background*
- *562 379 537 events processed*

LIGO data from O3: Jan 5 2020 → Jan 26 2020

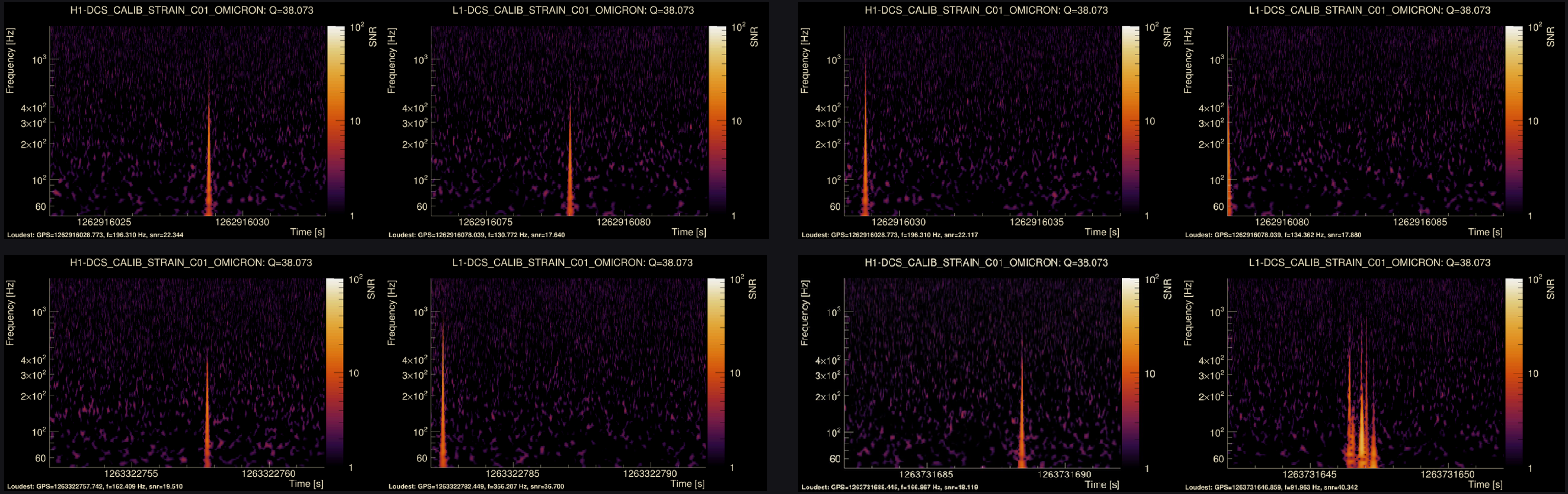
BACKGROUND DISTRIBUTION



- *178 years of background*
- *562 379 537 events processed*

LIGO data from O3: Jan 5 2020 → Jan 26 2020

Top #1, #2, #3, #13 ranked noises in 22 days



LOUDEST NOISE: “Blip”* glitches:

- Loud and broadband
- Simple pattern matching well on frequency summation

How to discriminate them?

=> Use ML software trained to recognize blips (wip)

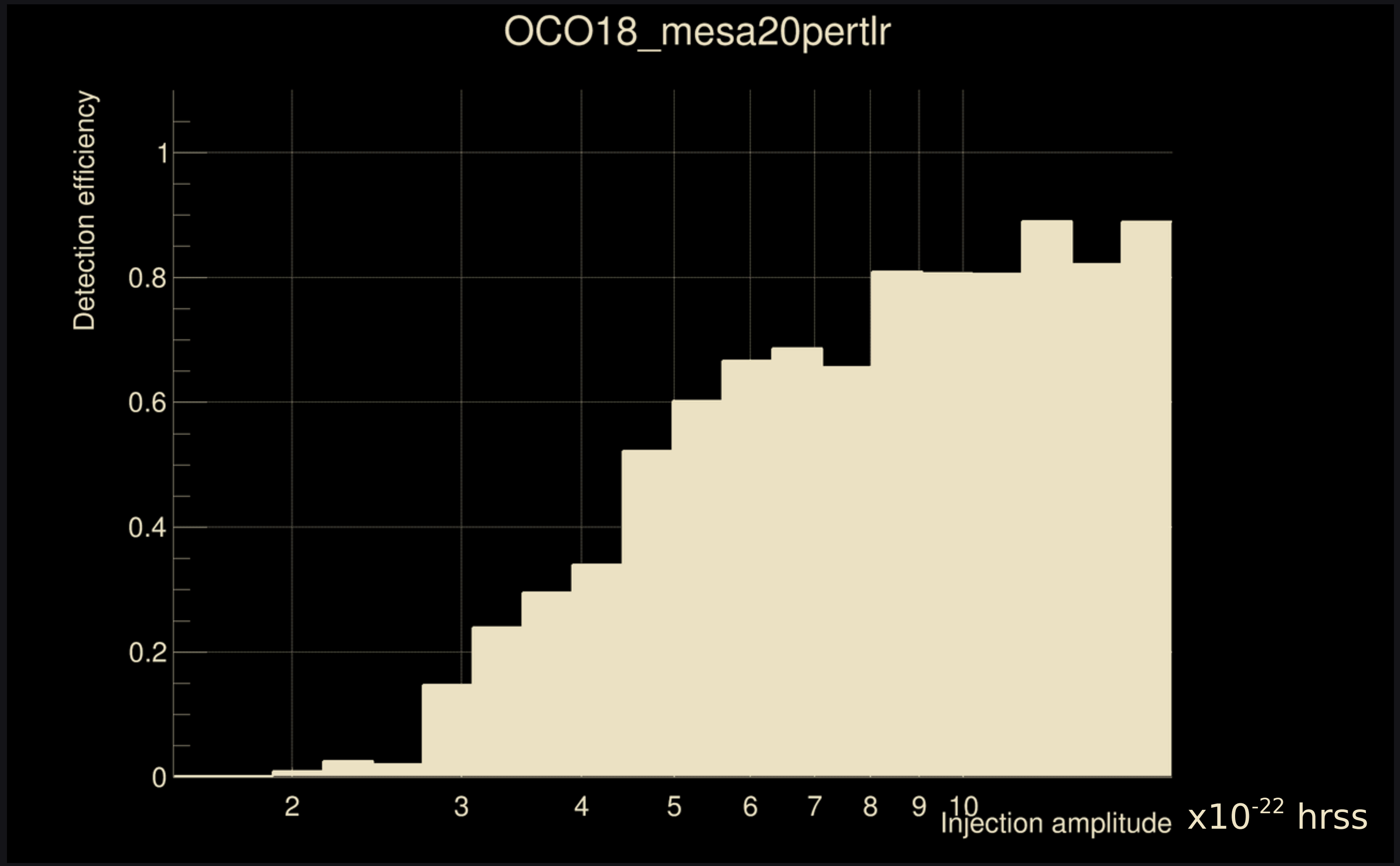
→ Improving the background of gravitational-wave searches for core collapse supernovae: a machine learning approach., M Cavaglia, S Gaudio, T Hansen, K Staats, M Szczepanczyk, and M Zanolin, 2020.

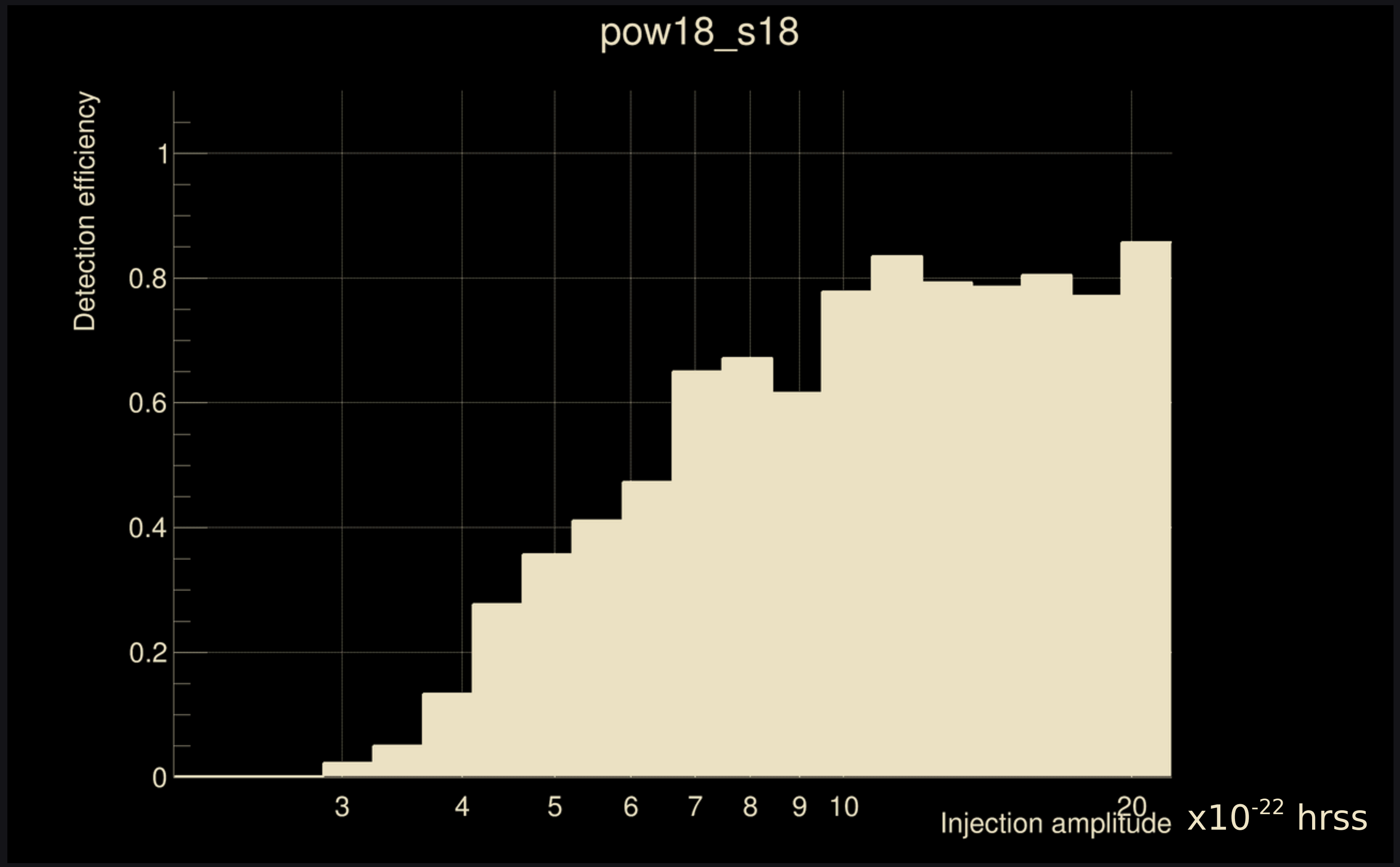
*: Gravity spy: integrating advanced ligo detector characterization, machine learning, and citizen science, M Zevin, S Coughlin, S Bahaadini, E Besler, N Rohani, S Allen, M Cabero, K Crowston, A K Katsaggelos, S L Larson, T K Lee, C Lintott, T B Littenberg, A Lundgren, C Østerlund, J R Smith, L Trouille, and V Kalogera, February 2017

SENSITIVITY ESTIMATION

13 CCSNe simulations* injected in O3 data *(+ 1 BBH + 1 sine-Gaussian)*

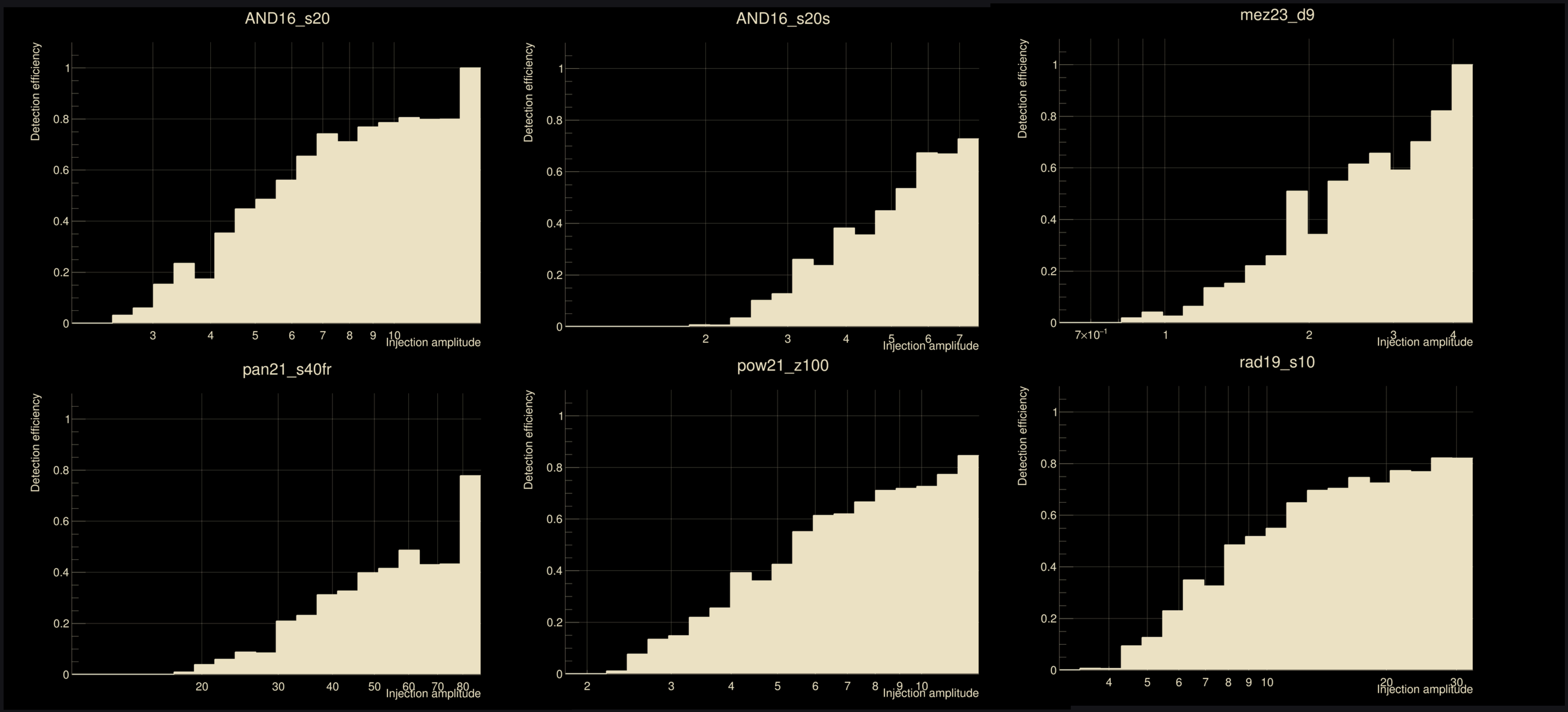
Sensitivities for OConnor's 2018 mesa20pertlr *(m20)* and Powell's 2018 *s18* waveforms, present in the O3 Burst Benchmark:





Our current sensitivity in O3 is ~2.2 and ~4.5 times lower than state-of-the-art Burst pipeline
(CWB-XP O3 50% detection efficiency taken for reference)

*: Andersen2016_s20, Andersen2016_s20s, Mezzacappa2023_d15, Mezzacappa2023_d9, Morozova2018_m13, OConnor2018_mesa20pertlr, Pan2018_s402d_dd2, Pan2021_s40fr, Powell2018_s18, Powell2020_y20, Powell2021_z100, Powell2023_m39_1e12, Radice2019_s10



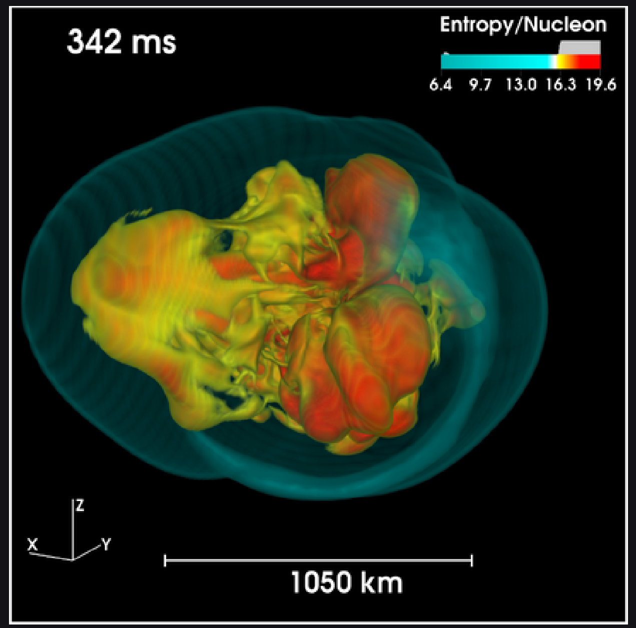
6 other sensitivites: *: Andersen2016_s20, Andersen2016_s20s, Mezzacappa2023_d9, Pan2021_s40fr, Powell2021_z100, Radice2019_s10

Promising starting sensitivity to start looking at science

3. GOING FURTHER:

SASI AND NEUTRINOS

SASI



H Andresen, E M¨uller, H-Th Janka, A Summa, K Gill, and M Zanolin, 2019

Asymetry due to standing accretion shock instability (SASI)...

→ Neutrino signature

→ GWs signature
low freq ~50-500Hz

Exploit it for signal reconstruction or detection!

->Multimessenger observations of core-collapse supernovae: Exploiting the standing accretion shock instability, Marco Drago, Haakon Andresen, Irene Di Palma, Irene Tamborra, and Alejandro Torres-Forn´e., 2023.

Omicron-X: cross correlation, multi-resolution, optimised for faint complex patterns => suitable tool to analyze SASI signals!

List of CCSN simulations* with ν + GW data, and SASI

*simulations and papers about simulations

Built from LVK Burst waveform repositories, publicly available data and direct contact.

LEGEND: ν + GW available, GW only, ν only, underlined contains some SASI

Most probably incomplete and lacking, please get in touch if you see an error or to add data ! → adrien.paquis@ijclab.in2p3.fr

Abdikamalov_2014: Phys.Rev.D 90 (2014) 4, 044001
Andresen_2019: Astrophys.J. 876 (2019) 2, 105,
Andresen2021: Phys. Rev. D 103 (2021) 043009
Bugli 2020: Mon.Not.Roy.Astron.Soc. 492 (2020) 1, 58-71
Burrows 2023: Phys.Rev.D 107 (2023) 10, 103015
Cerda-Duran 2013: Phys. Rev. D 88 (2013) 044045
Couch-Ott 2013: Astrophys. J. 778 (2013) L7
Eggenberger 2021: Mon. Not. Roy. Astron. Soc. 504 (2021) 4, 5126-5141
Kuroda 2015: Astrophys.J. 793 (2014) 45
Kuroda 2016: *Astrophys.J.Lett* . 829 (2016) 1, L14
Kuroda 2017: Phys. Rev. D 95 (2017) 6, 064041
Kuroda 2020: Phys. Rev. D 102 (2020) 123025
Kuroda 2022: *Astrophys.J* . 924 (2022) 1, 38
Kuroda 2023: Mon.Not.Roy.Astron.Soc. 531 (2024) 3, 3732-3743
Melson 2015 (1504.07631): Astrophys. J. 801 (2015) L24
Mezzacappa 2020: *Phys.Rev.D* 102 (2020) 2, 023027
Mezzacappa 2023: Phys. Rev. D 107, 043008
Morozova 2018: Astrophys. J. 861 (2018) 10
Mueller 2012: Astron.Astrophys. 537 (2012) A63
O'Connor-Couch 2015: Astrophys. J. 808 (2015) 70
O'Connor-Couch 2018: Astrophys. J. 865 (2018) 2, 81
Pan 2018: Astrophys.J. 857 (2018) 1, 13
Pan 2021: Astrophys.J. 914 (2021) 2, 140
Powell-Muller 2018: Mon.Not.Roy.Astron.Soc. 487 (2019) 1, 1178-1190
Powell-Muller 2020: Mon. Not. R. Astron. Soc. 500 (2020) 1, 1-15
Powell 2023 Mon.Not.Roy.Astron.Soc. 522 (2023) 4, 6070-6086
Radice 2019: Astrophys. J. Lett. 876 (2019) L9
Richers 2017: Astrophys. J. 836 (2017) 2, 198
Tamborra 2014: Astrophys. J. 792 (2014) 96
Andresen 2016: Mon.Not.Roy.Astron.Soc. 468 (2017) 2, 2032 - 2051
Walk 2020: Phys. Rev. D 101 (2020) 123013
Warren 2020: Astrophys. J. 906 (2021) 93
Yakunin 2015: Astrophys. J. Lett. 807 (2015) L31
Yakunin 2017: Astrophys. J. 851 (2017) L35
Zha 2021: Phys. Rev. Lett. 127 (2021) 051102

GWs+ν simulations are precious, especially if they contain SASI!

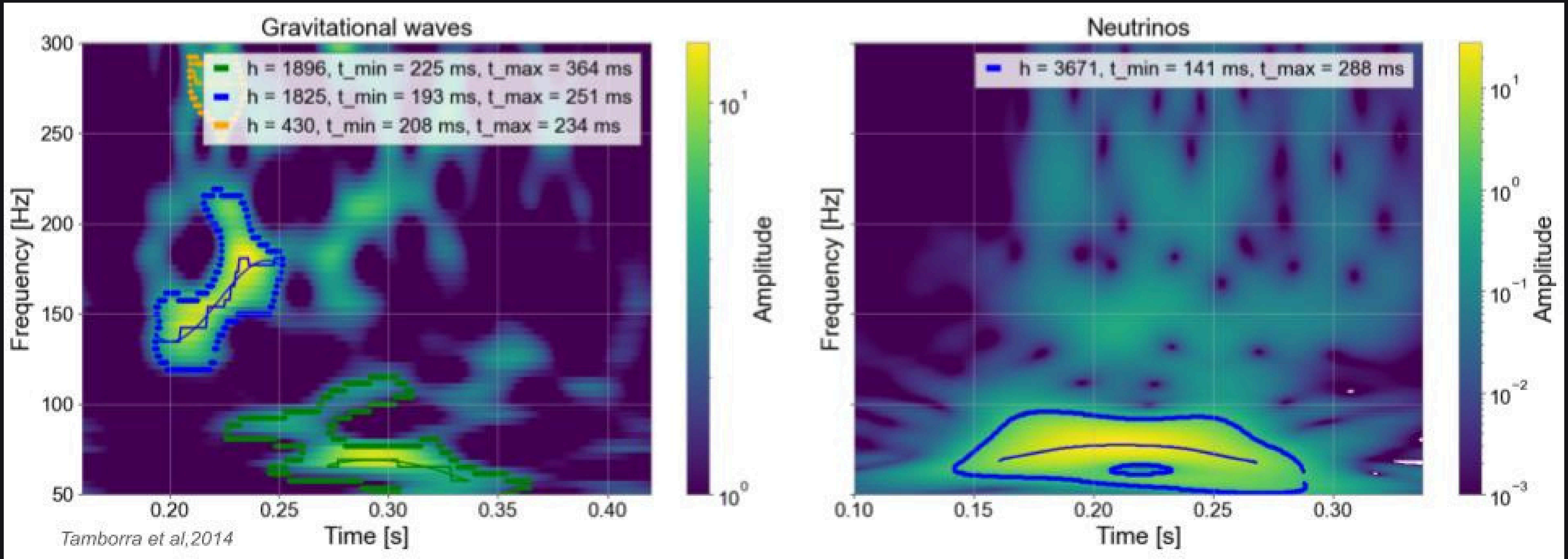
To explore SASI detection, we need more available waveforms

SASI CARACTERISATION IN Q-TRANSFORMS

Exploratory work with Emile Weissman (intern) and Sonia El Hedri (APC, Paris):

- visualise both ν+GWs signals with q-transform
- identify SASI as time-frequency paths
- matching SASI candidates between messengers

=> towards a p_SASI?



More complete work by Alessandro Veutro

CONCLUSION

Omicron-X is a complete, simple and efficient pipeline, fully dedicated to CCSNe:

- cross-correlation as an effective tool for CCSN search
- sensitivity at 1/10 years is getting closer to state of the art cWB's
- meant to evolve: add new features, test new techniques
- easy/light to run...

Estimating sensitivity to SASI needs more waveforms, and better sharing methods

NEXT STEPS

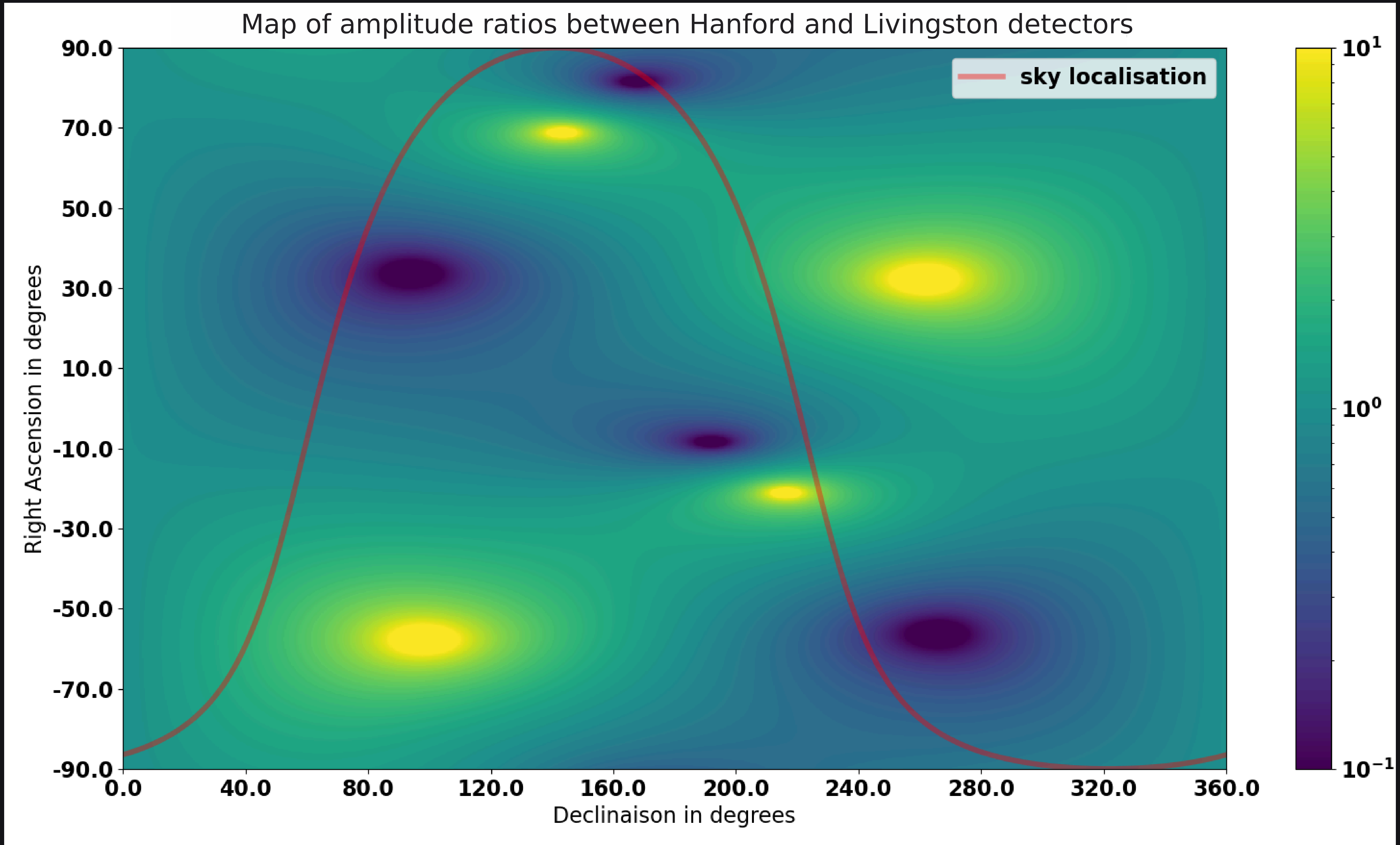
- Add ML glitch detection
- Test SASI's detectability in Omicron-X's triggers
- Joint analysis with neutrino triggers
- All sky → targeted → test on 2023 ixf
- Lightly model with constraints on morphologies: g modes

THANK YOU FOR YOUR ATTENTION

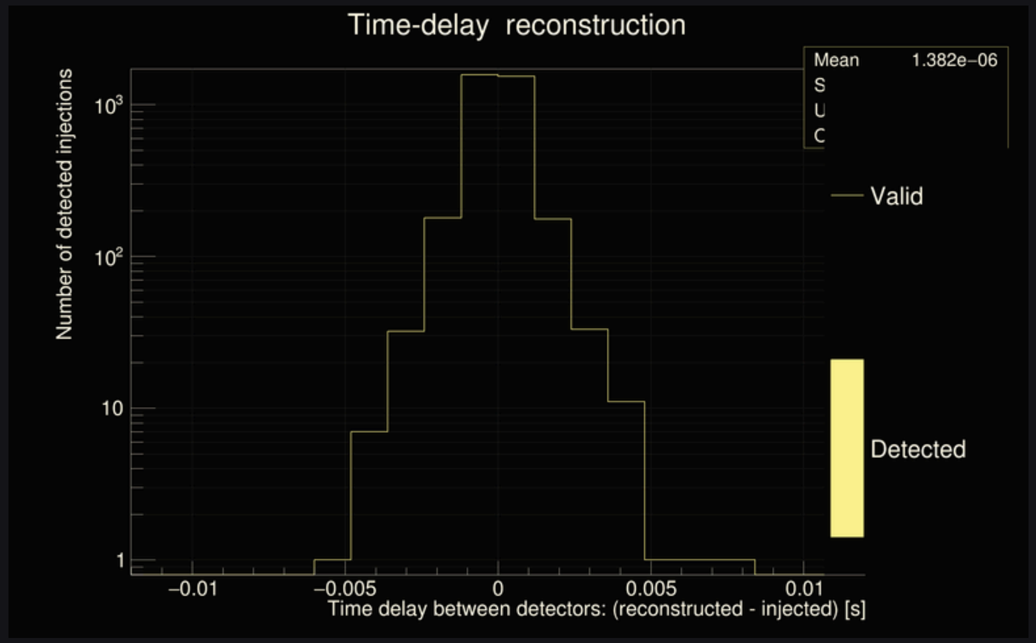
BACK UPS

ANTENNA FACTORS

$$Ratio = \frac{\sqrt{F_{\times\,detector1}^{2} + F_{+\,detector1}^{2}}}{\sqrt{F_{\times\,detector2}^{2} + F_{+\,detector2}^{2}}}$$

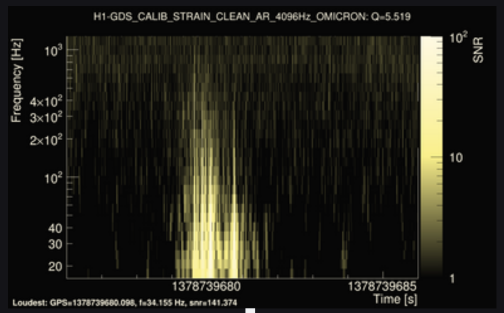
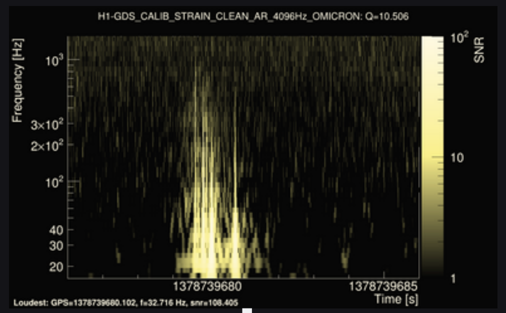
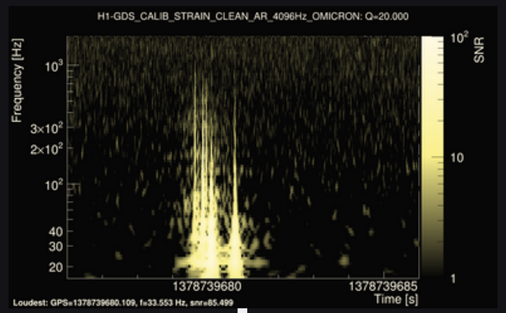
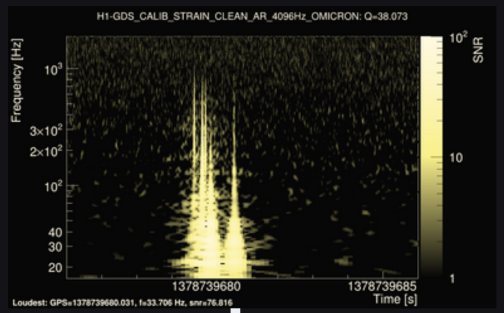
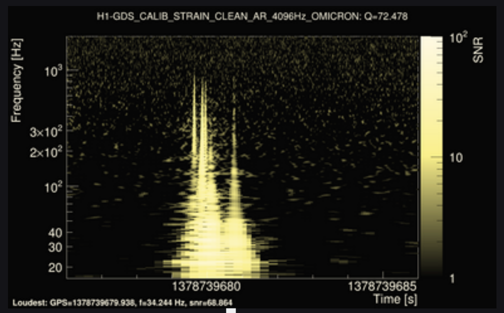


1. Analysis calculates delay Δt between detectors
2. Localise sky positions of possible source
3. Get limits on amplitude ratios
4. Cut out events with amplitude ratios out of this range



XIVAR GATE

For each Q-plane, a factor is Ξ computed with Omicron-x’s cross-correlation based method. Combined, they produce the Ranking Statistic R

Ξ : 0.45 0.21 0.05 0.62 0.39

R

The distribution between different planes is diferent for GW signal (injections) and “bleep” glitches noise