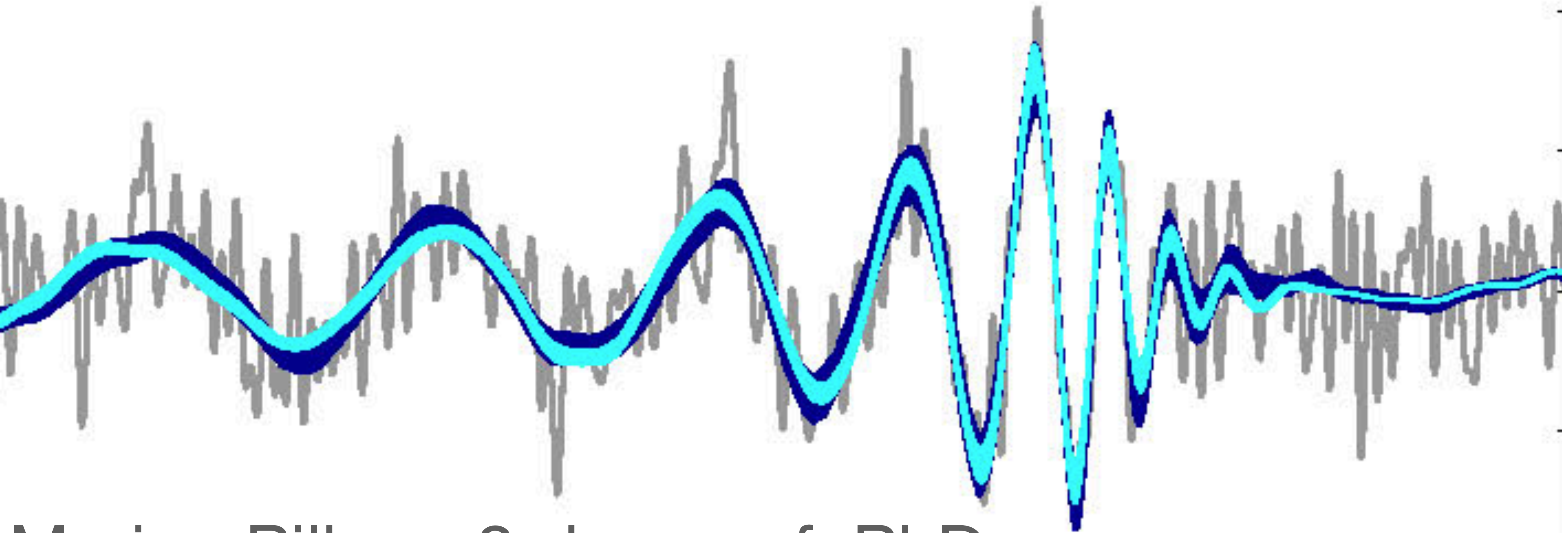
Exploring the physics of neutron star mergers with gravitational waves and gamma ray bursts



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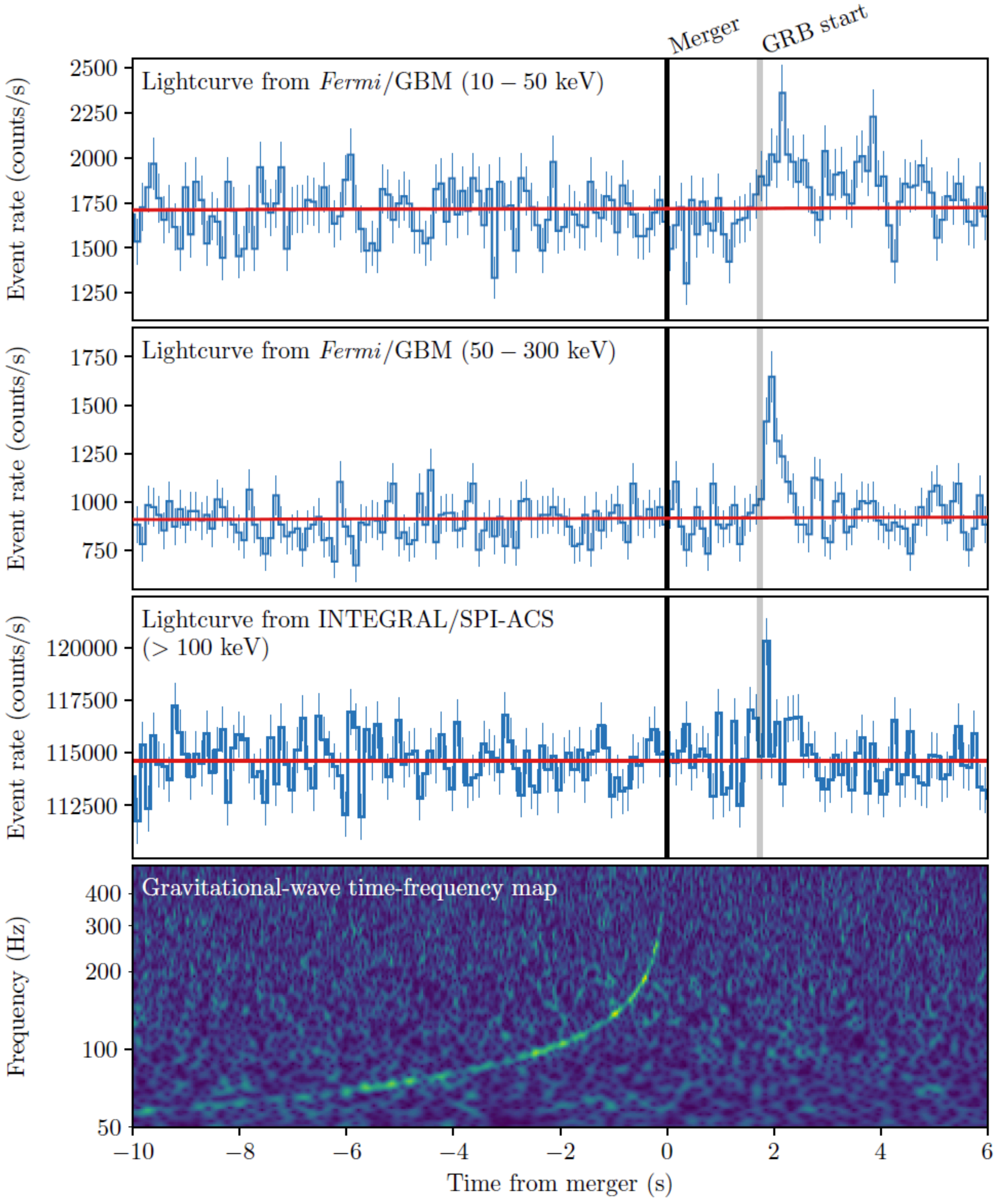
Pheniics Fest 19-20/05/22



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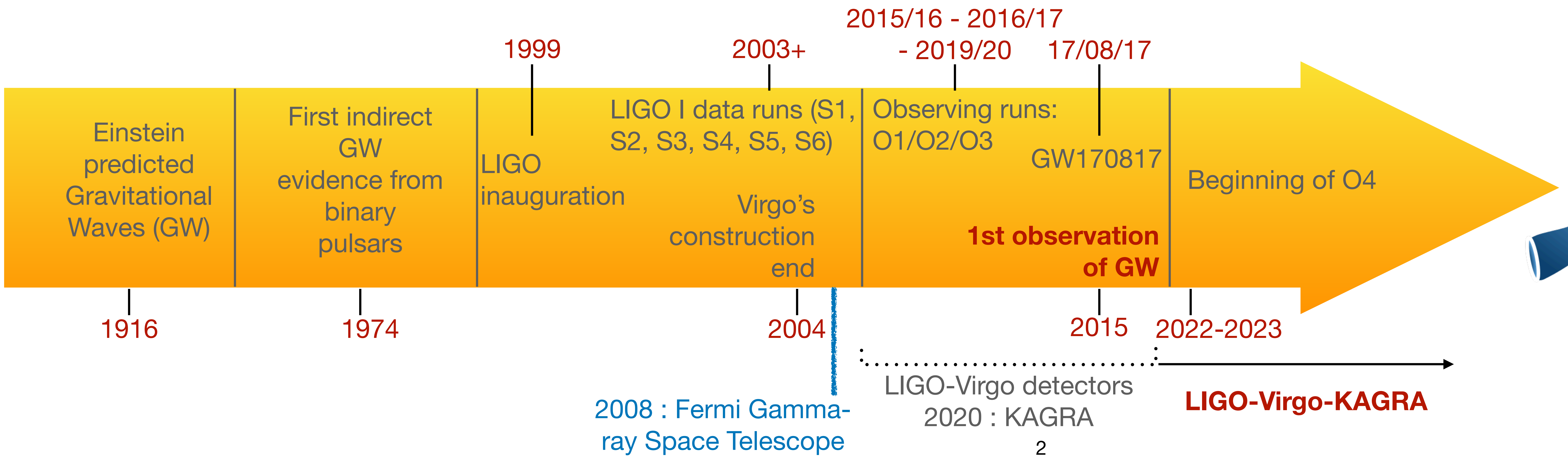


Introduction

Neutron star : NSs are the densest matter in the Universe, with BHs the only known denser object. Canonical multimessenger events. Observed through photons for half a century, gravitational waves since 2017 & likely to be sources of neutrinos and cosmic rays.

Studies of these events enable unique insights into astrophysics, particles in the ultrarelativistic regime, the heavy element enrichment history through cosmic time, cosmology, …

GRBs : most energetic form of light

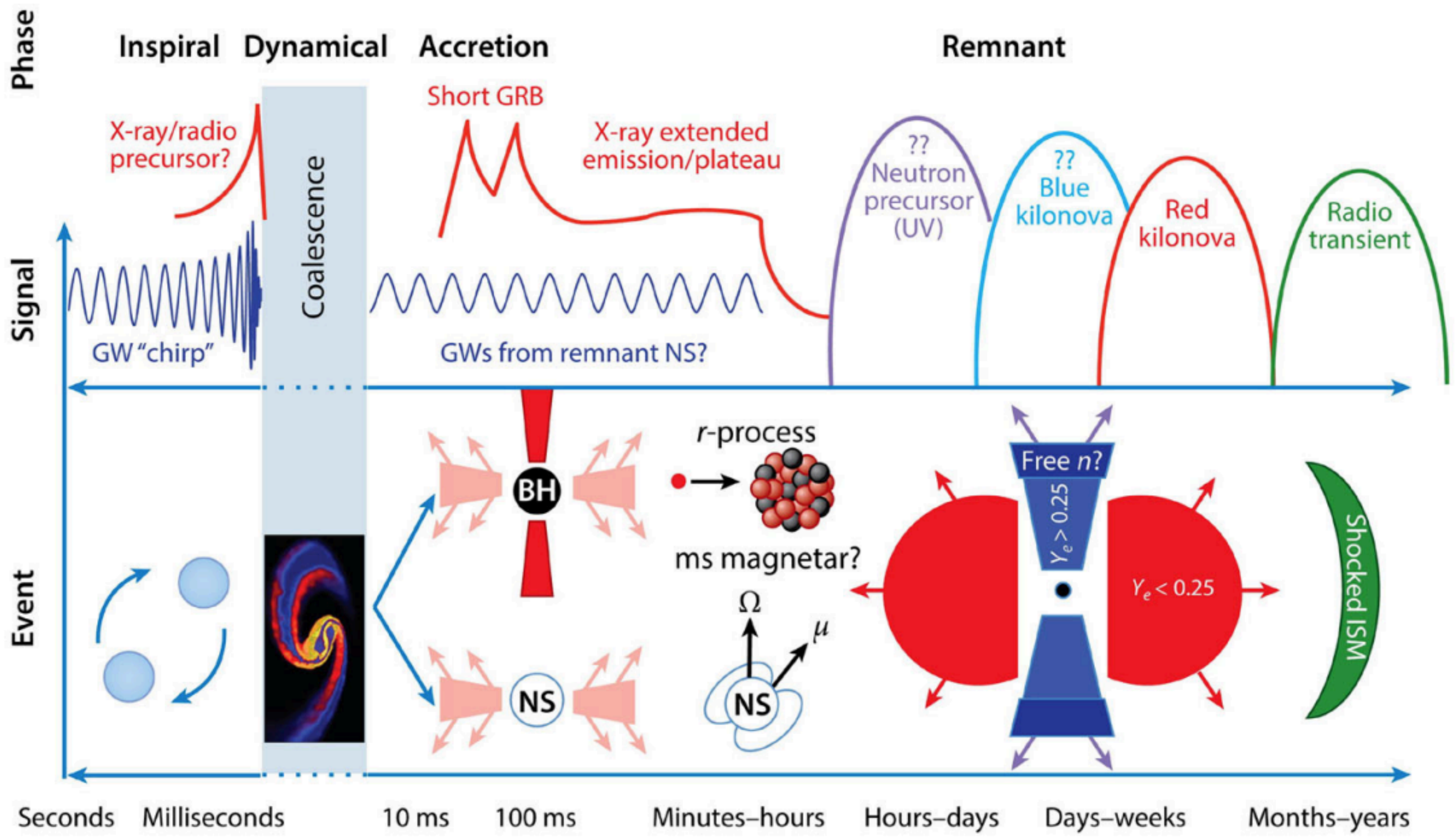
2 categories: **long GRBs** (associated with a sub-class of core-collapse supernovae), and **short GRBs**, < 2s (believed to originate in CBC systems containing at least one neutron star).

Fundamental questions :

- Are the properties of GW170817 common to all neutron star mergers or represented an exceptional case ?

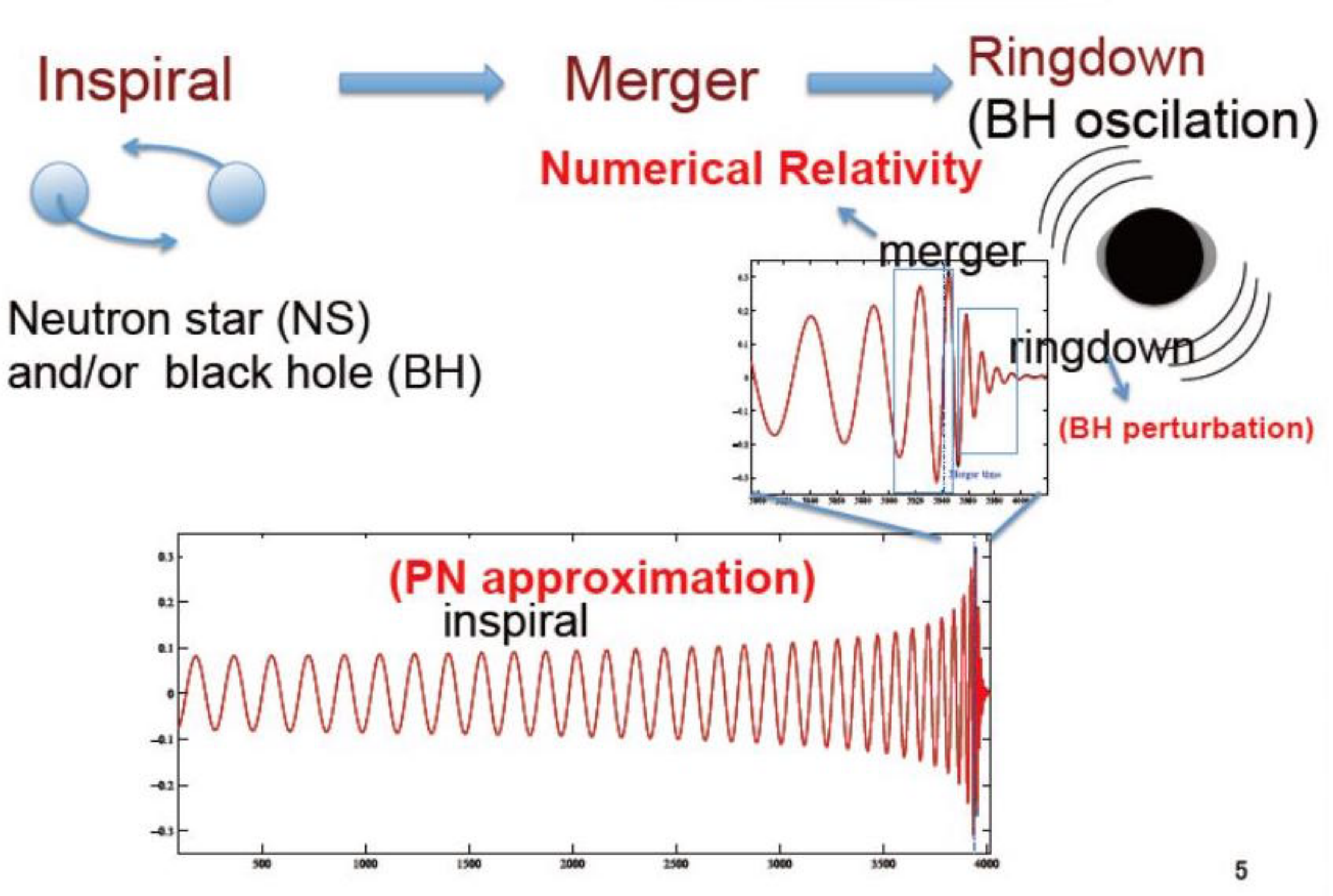
- Are all short GRB associated with BNS ? Or just a fraction of them ?

…

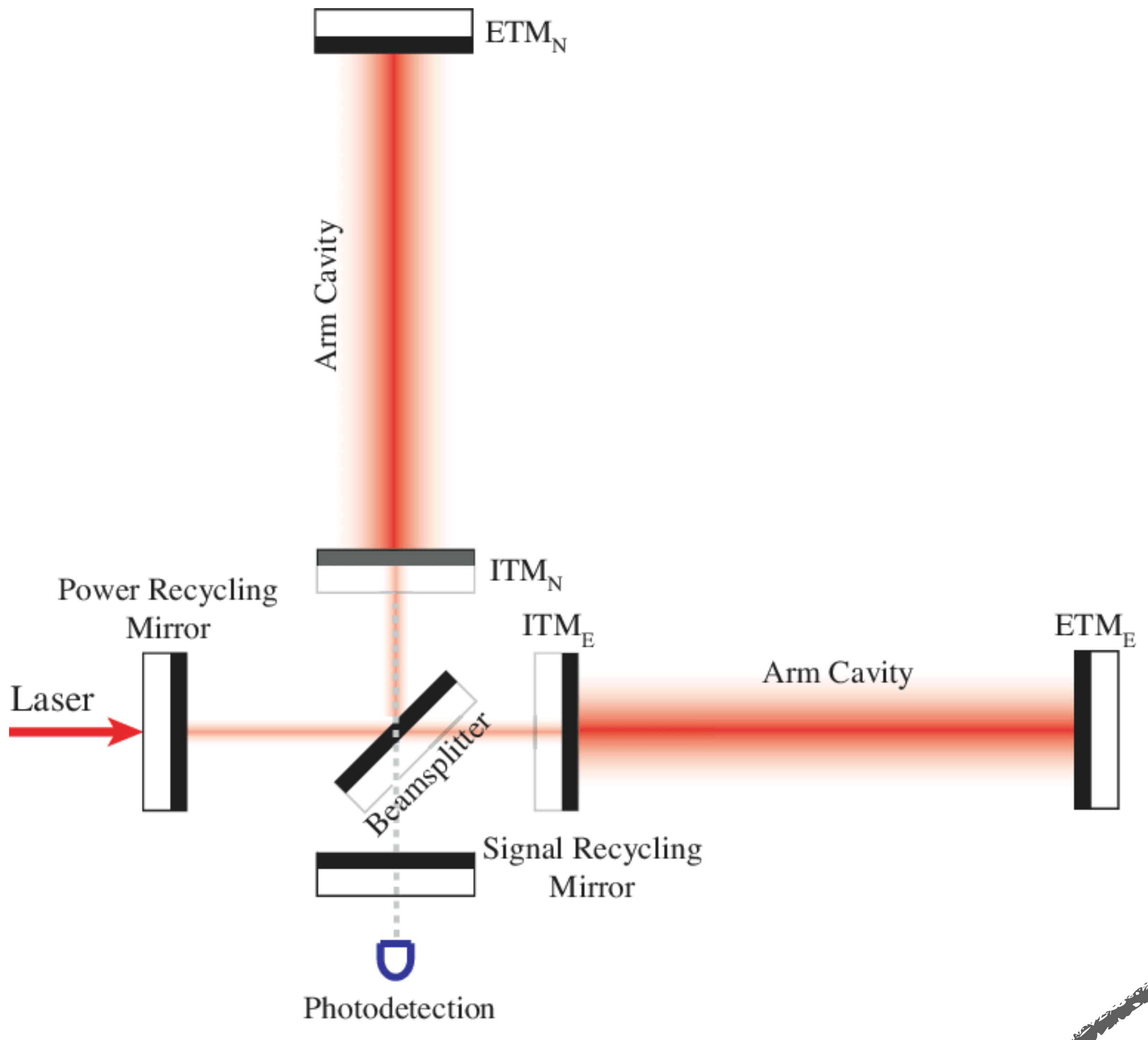


An overview of the expected GW and EM signatures from minutes before until years after merger (picture from Fernandez and Metzger)

Introduction



Three stages of a GW event coming from CBC



GW detector

GW170817 : first observation of gravitational waves from a neutron star merger associated with transient counterparts across the entire electromagnetic spectrum

Goal of the PhD: Develop and perform searches for these neutron star mergers using the data from Advanced LIGO, Advanced Virgo & Fermi satellite .

PhD divided into 2 parts :

GW data analysis part

Improving the sensitivity of the GW search
+
Offline analysis & sub-solar-mass search

GW triggers

GBM data analysis part

GBM triggers

GRB part

GW-GBM joint analysis

Joint GW-GRB subthreshold detection

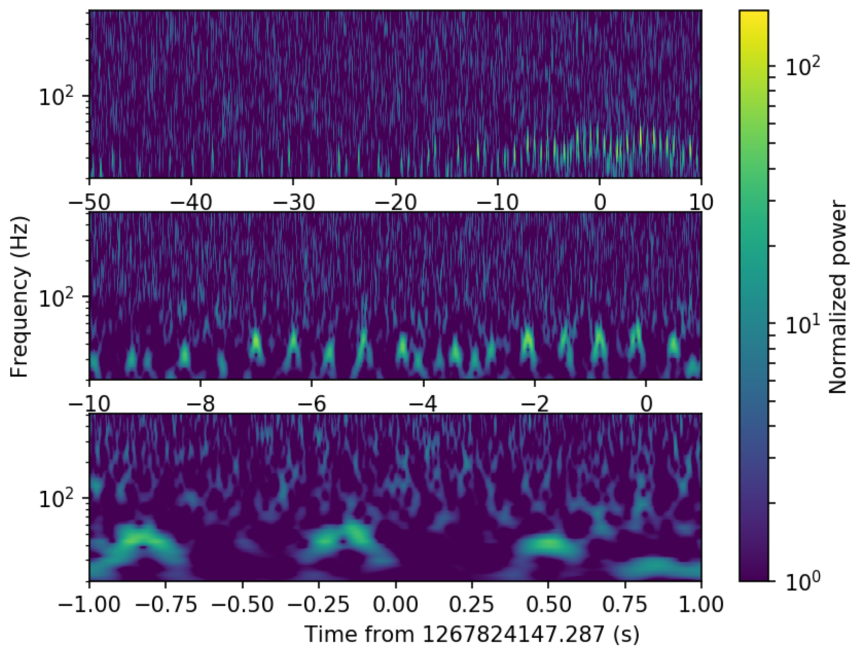
Study BNS mergers

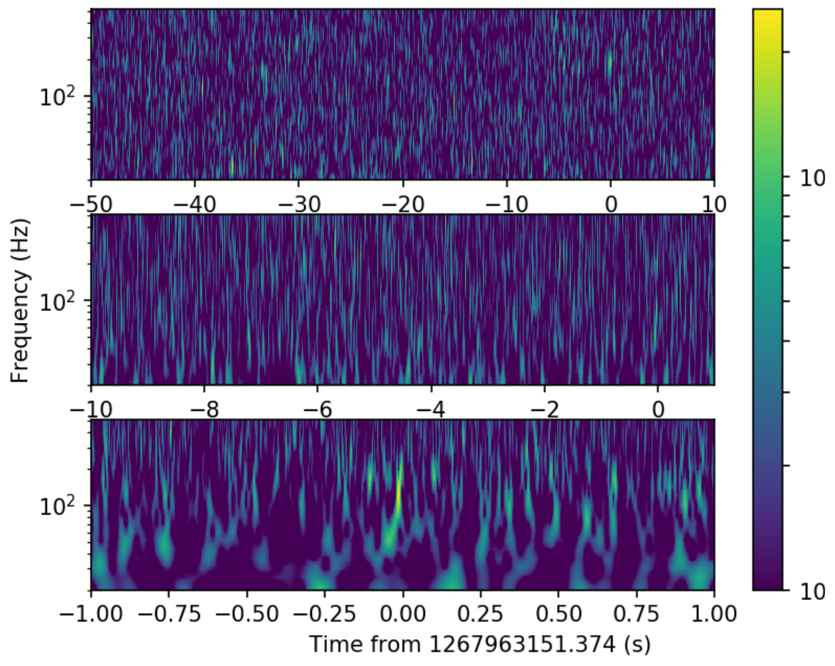
CBC : Compact Binary Coalescence
BNS : Binary Neutron Star
GW : Gravitational Wave
GRB : Gamma-Ray Burst
GBM : Gamma-ray Burst Monitor

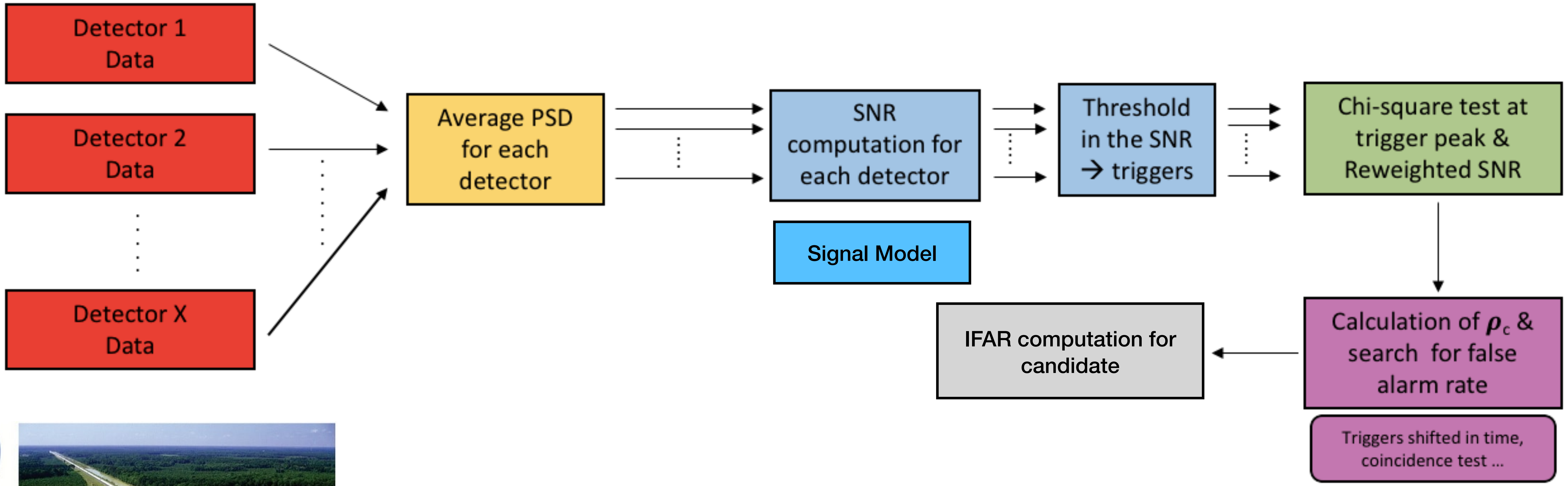
Improving PyCBC search's sensitivity

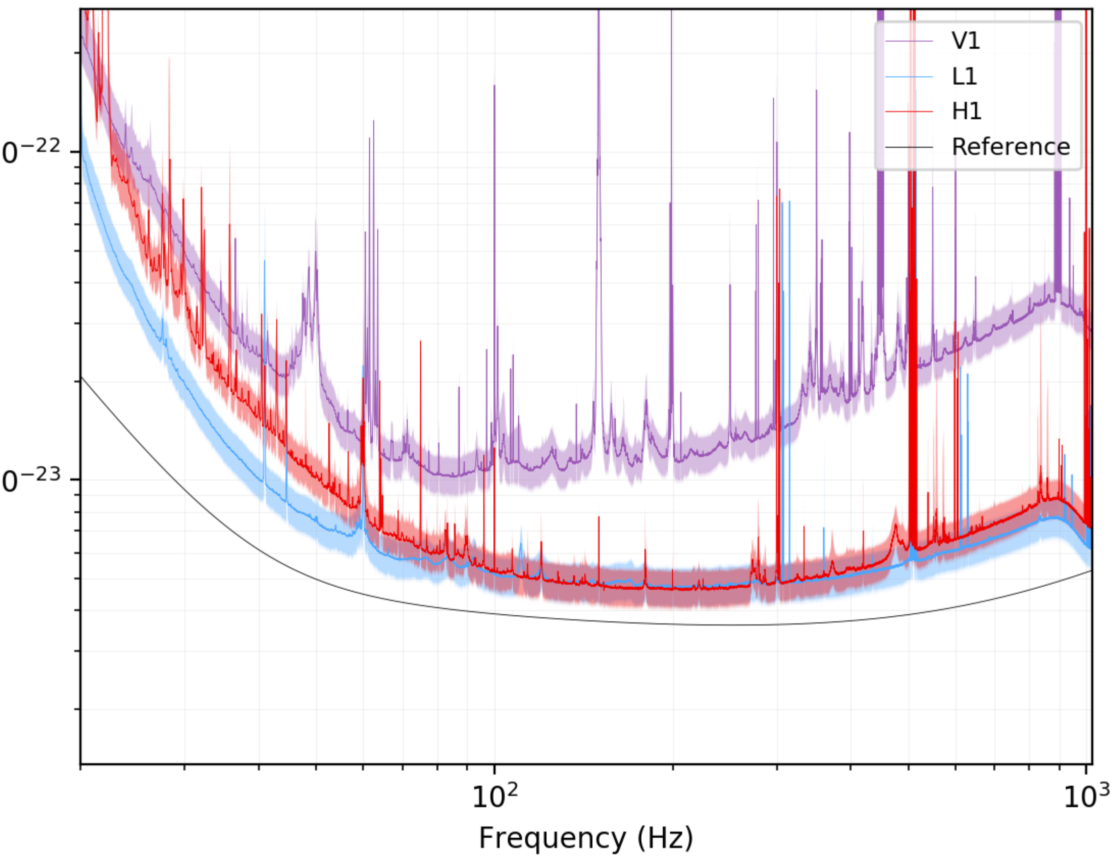
Introduction : GW data analysis

PyCBC is a software package used to explore astrophysical sources of gravitational waves. It contains algorithms that can detect coalescing compact binaries and measure the astrophysical parameters of detected sources. Use of matched-filtering methods (computation of the Signal-to-Noise ratio, the Inverse False Alarm Rate ..)









Improving PyCBC search's sensitivity

Data are contaminated with transient noise events, "glitches".

- These glitches can both produce false triggers in the search (reducing the significance of astrophysical triggers) and contaminate long astrophysical signals
- Understanding glitches is important to claim the astrophysical nature of a gravitational-wave candidate.
- Omicron algorithm (implemented by Florent Robinet) was developed to detect and study transient events in data of gravitational-wave detectors.

The idea of Omicron : Omicron metric to reject CBC glitches

CBC inspiral has a very specific time-frequency curve, which most glitches do not generally respect.
→ Exclude triggers for which the power is not distributed over the expected CBC track in the time-frequency plane

The time-frequency plane is tiled and, for each tile, the SNR is measured.

- Measure the **time distance dt** between the CBC track and the Omicron tiles
- **Use the standard deviation of dt ($\sigma = \sqrt{V}$) to measure how compatible the power distribution is with the CBC track**
- **Reweight** the SNR of the trigger depending on its metric & duration values

$$M = \frac{\sum_{t=0}^{N_t} d_t \times SNR_t^2}{\sum_{t=0}^{N_t} SNR_t^2}$$

$$V = \frac{\sum_{t=0}^{N_t} d_t^2 \times SNR_t^2}{\sum_{t=0}^{N_t} SNR_t^2} - M^2$$

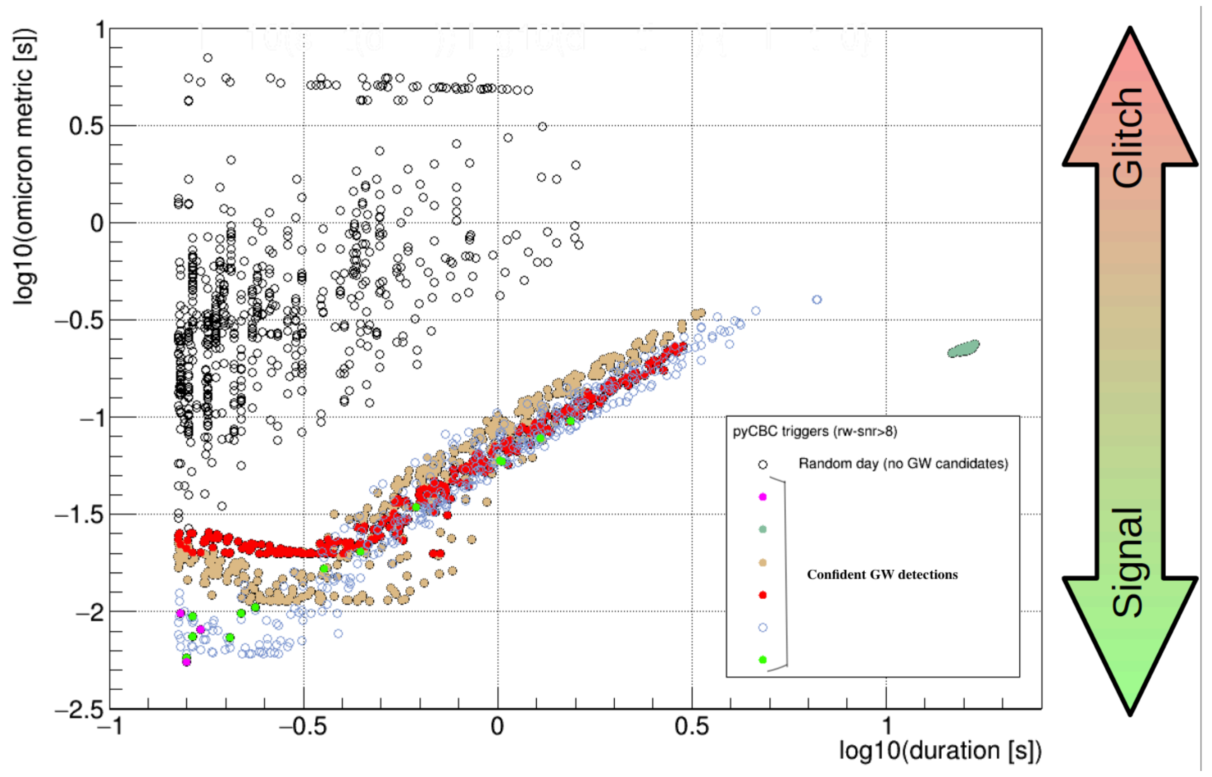
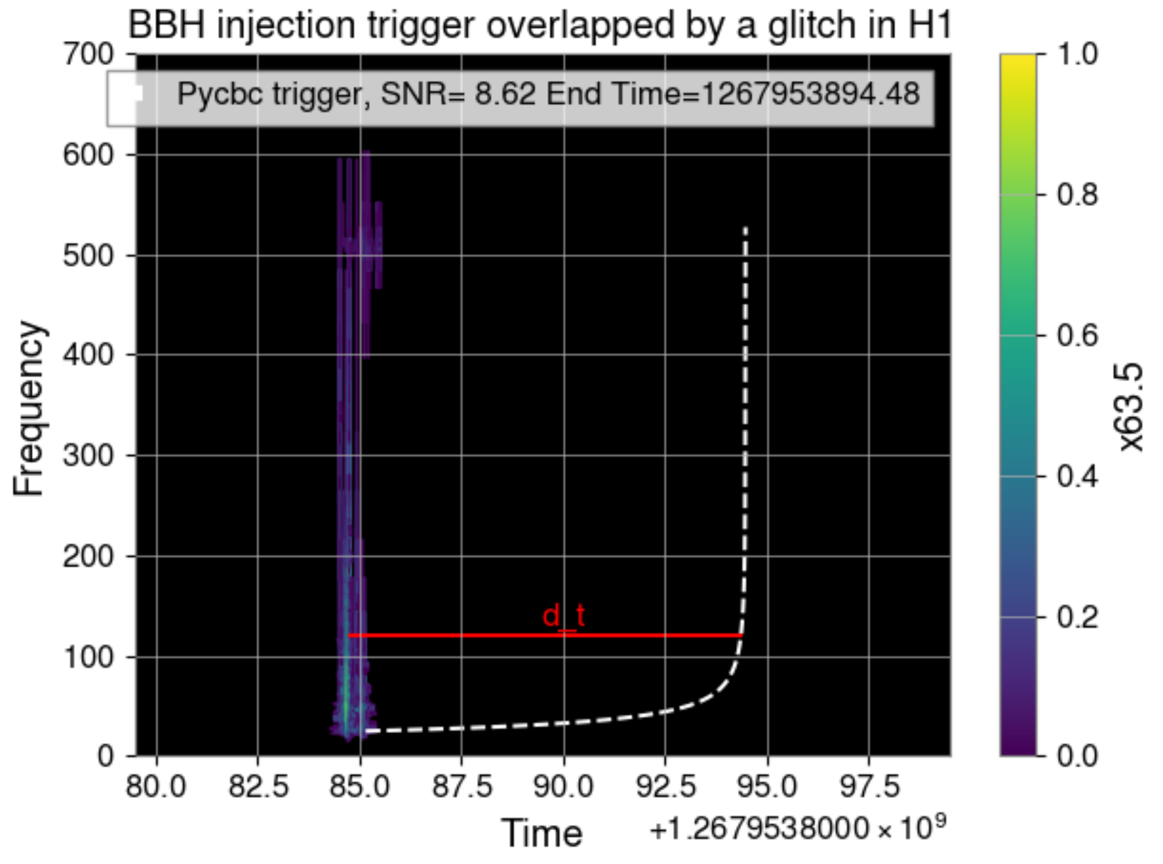
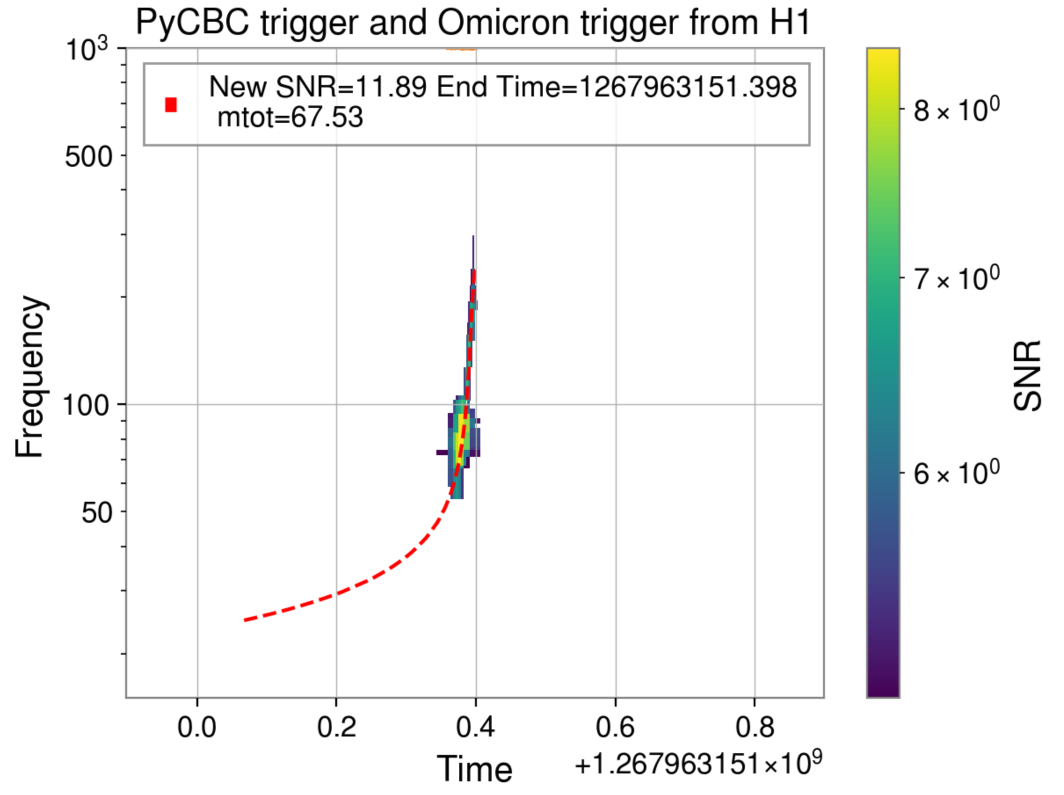


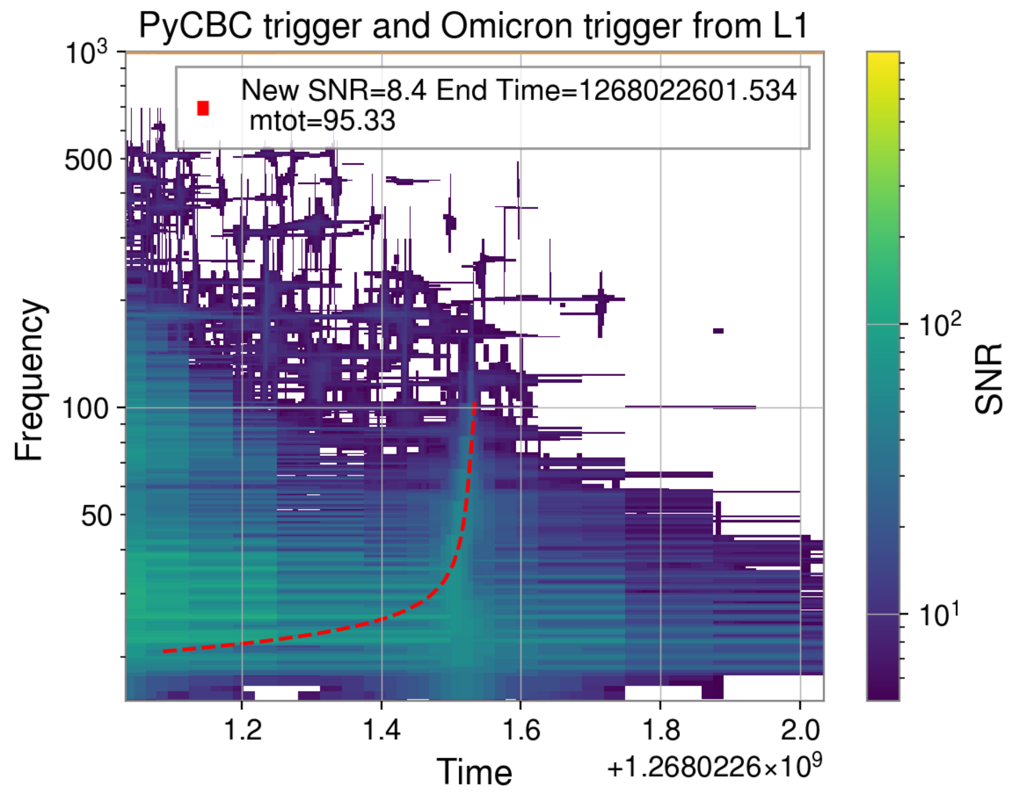
Figure made by Florent Robinet



For GW200311 :
Metric ~ 0.007 s



For a glitch :
Metric ~ 0.15 s

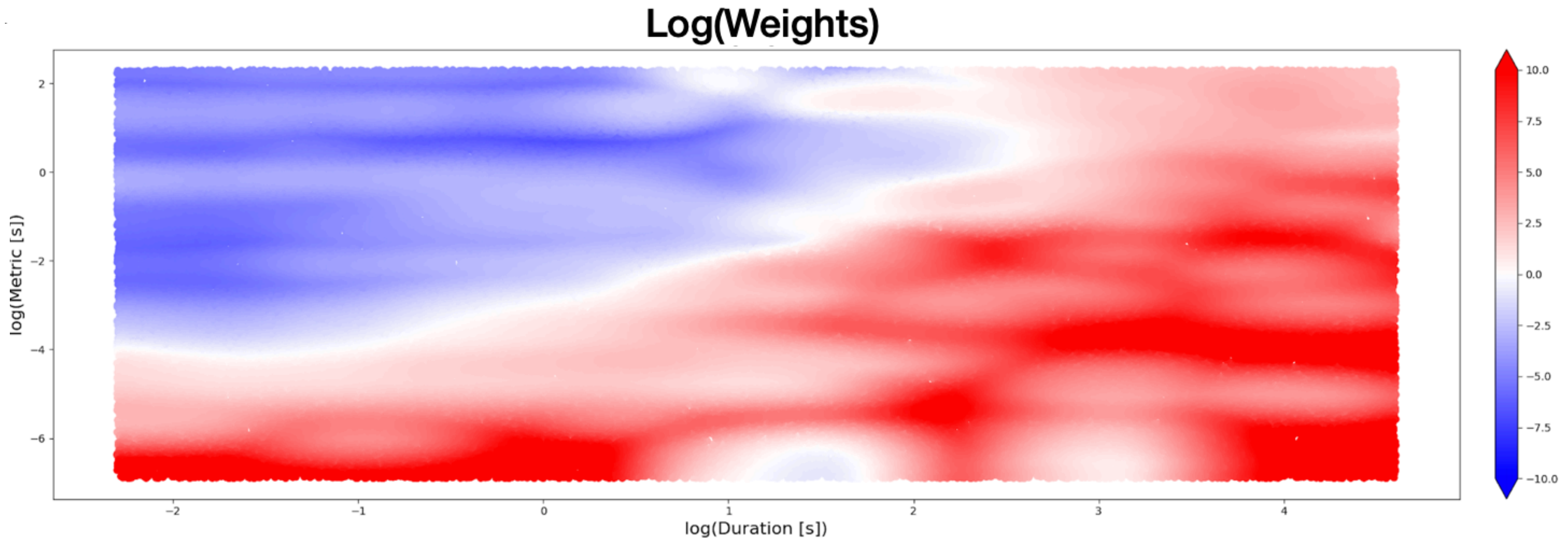


DEFINITIONS

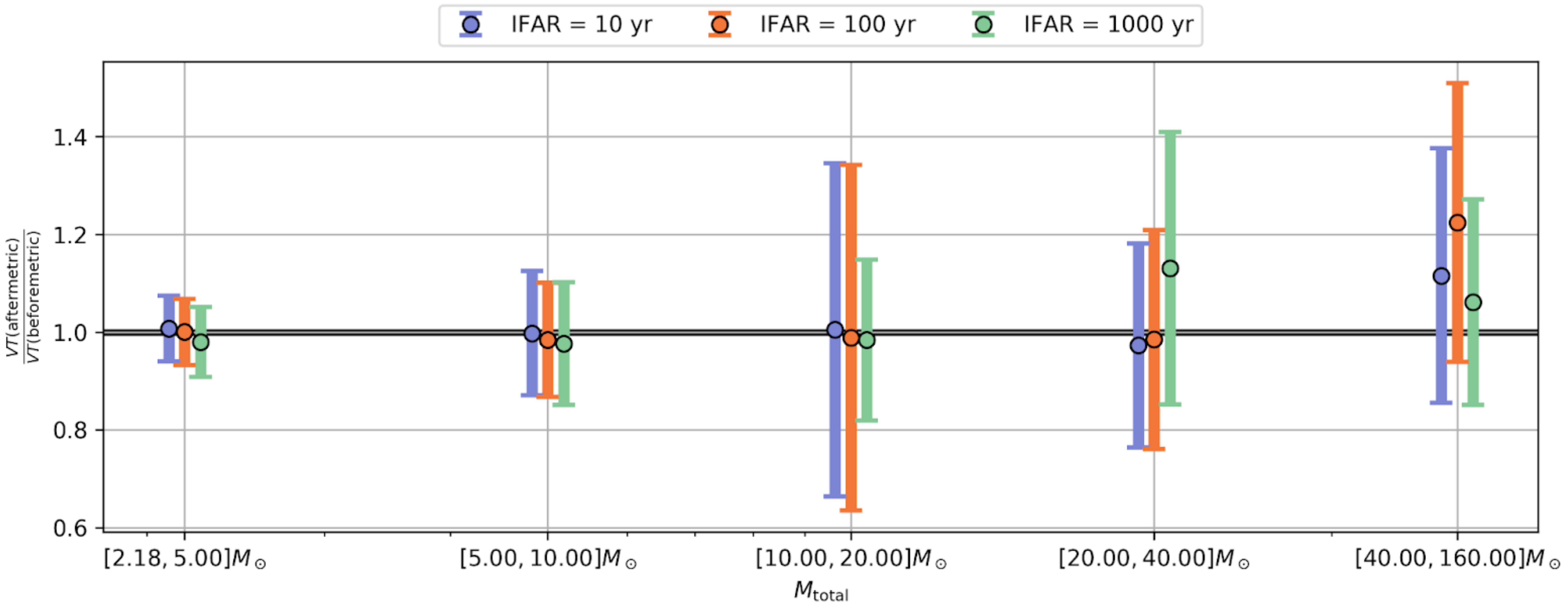
Signal-to-noise ratio (SNR) : Indicator that compares the level of a desired signal to the level of background noise

Triggers : when there is a peak in the SNR above a predetermined threshold, a trigger is stored

Improving PyCBC search's sensitivity



Weights in the log(Metric)-log(Duration) plane: noise-like region (blue) and signal-like region (red)



Sensitivity comparison before/ after the reweighting

Paper ongoing !

Looking for GW-GRB joint detections

GW-GBM subthreshold analysis

Gamma-ray Burst Monitor (Fermi/GBM) instrument : used to observe GRBs (the most energetic form of light)
Energy range: [8 keV, 40 MeV],
Field of view : all sky not occulted by the Earth

Currently : only one GW-GRB detection, more detection needed

→ look at many **weak** candidates in the hope of finding more joint detections

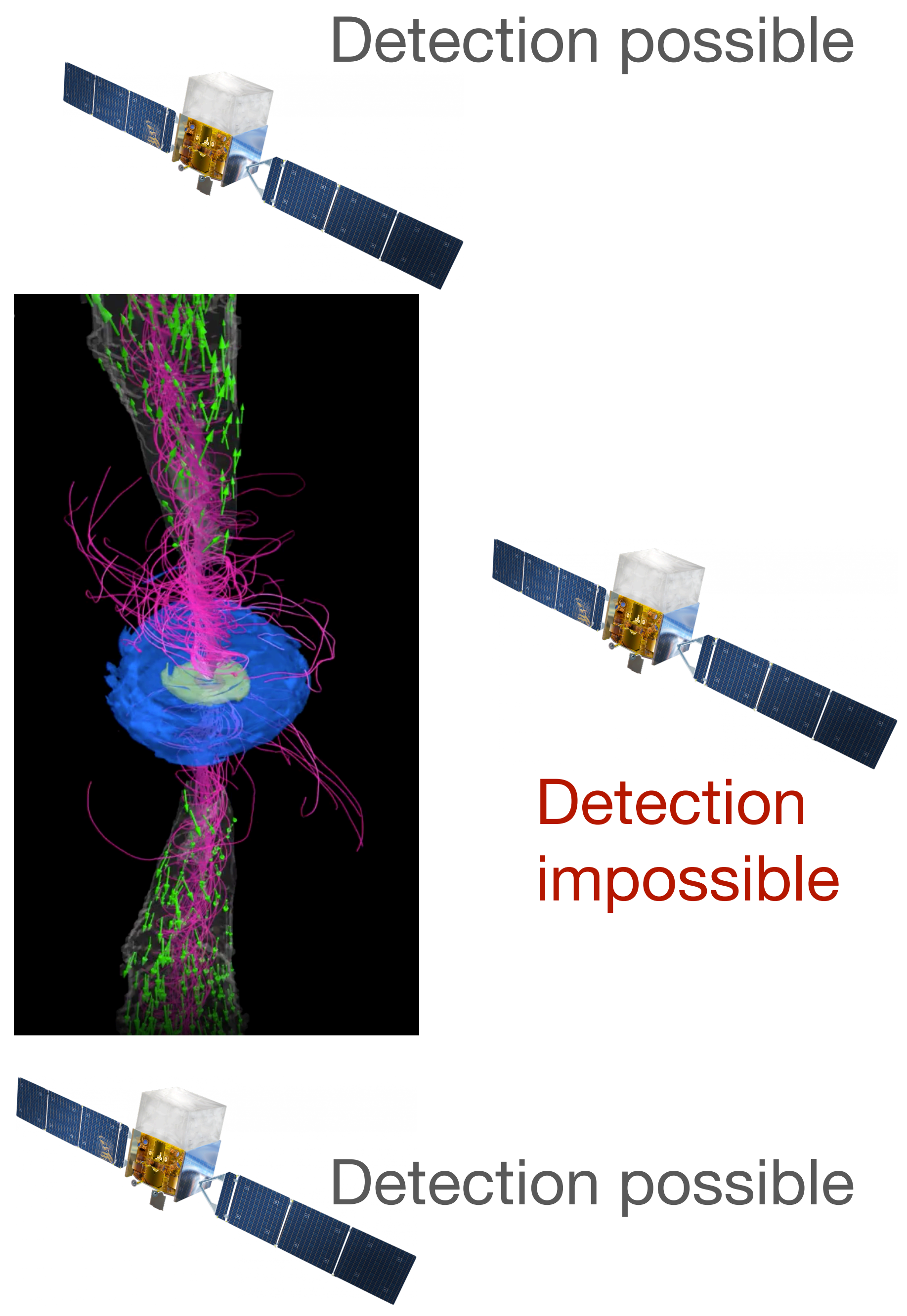
Identify **pairs of GW-GBM triggers** which could plausibly originate from a common astrophysical event, rank the pairs thanks to a **ranking statistics**, and assign a statistical significance (**False Alarm Rate**) to them.

$$\Lambda = \frac{I_{\Delta t} I_{\Omega}}{1 + Q_L + Q_G + Q_L Q_G}.$$

I_Δt and I_Ω quantify the overlap of the posterior distributions for the time offset and sky locations (skymap overlap)
Bayes factor noise-vs-signal: Q_L = P(D_L|noise)/P(D_L|signal) where D_L the data from LIGO (same for G : Fermi GBM)

Cosmin Stachie et al. : https://arxiv.org/pdf/2001.01462.pdf

Numerical Simulation : Accretion disk and GRB jet formed after the merger



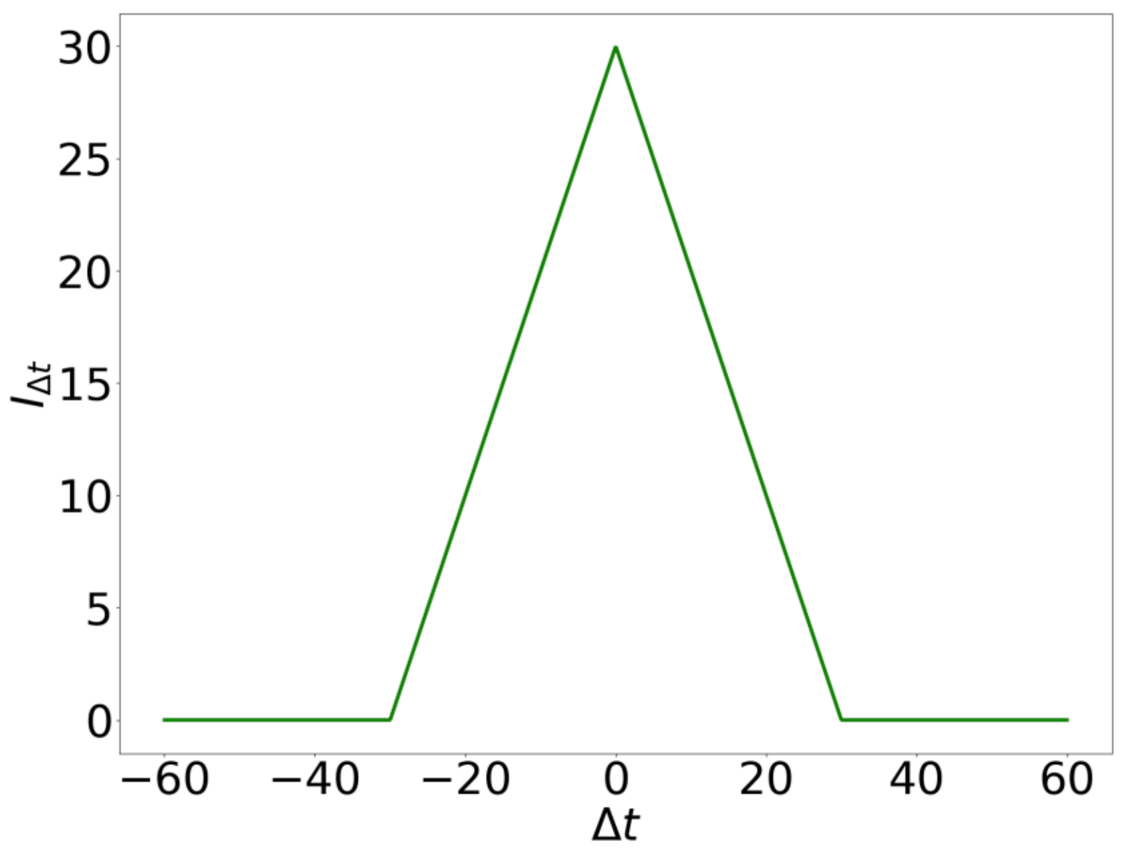
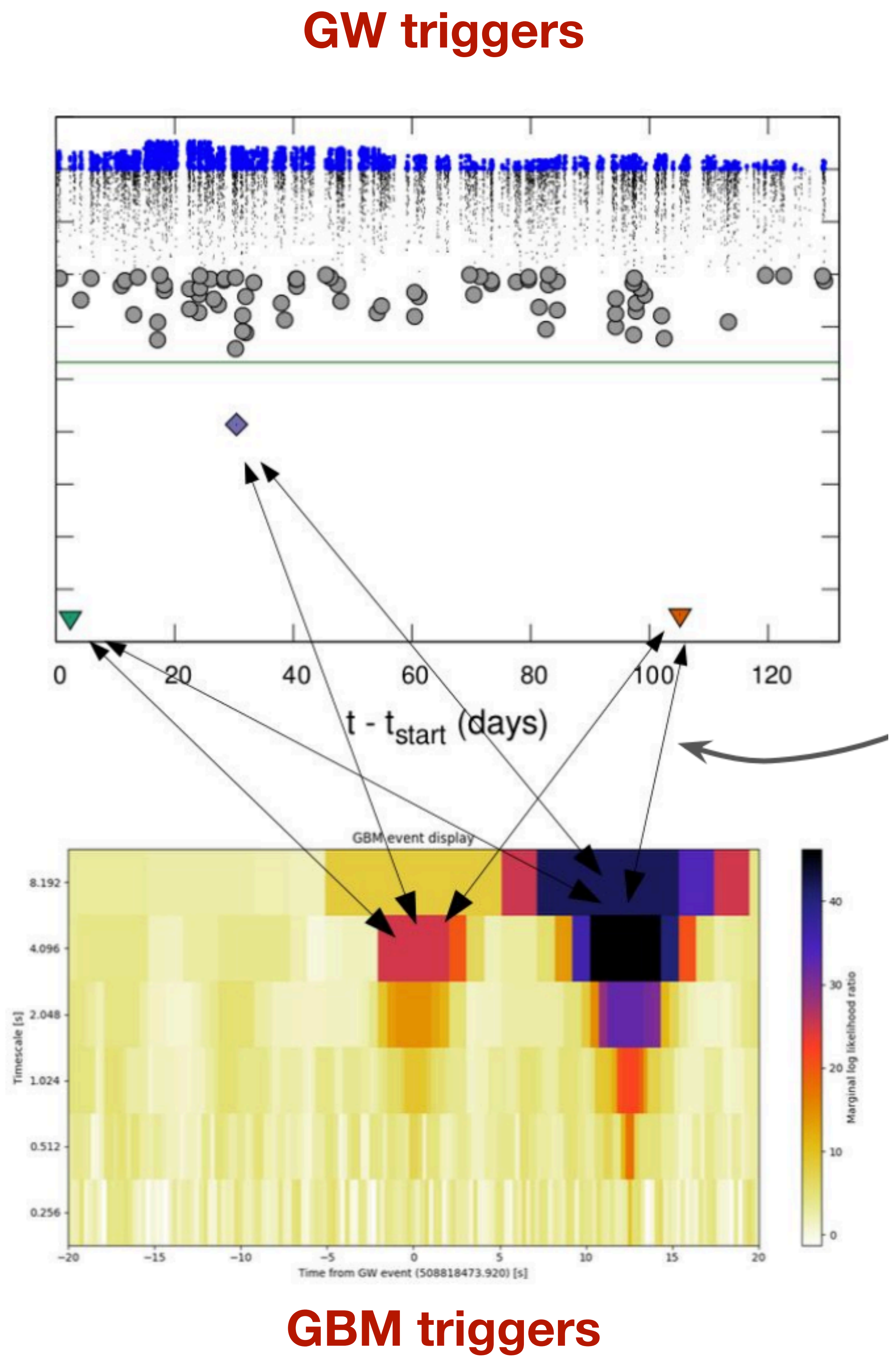


Figure 4. Time overlap term $I_{\Delta t}$ as a function of the time offset Δt.

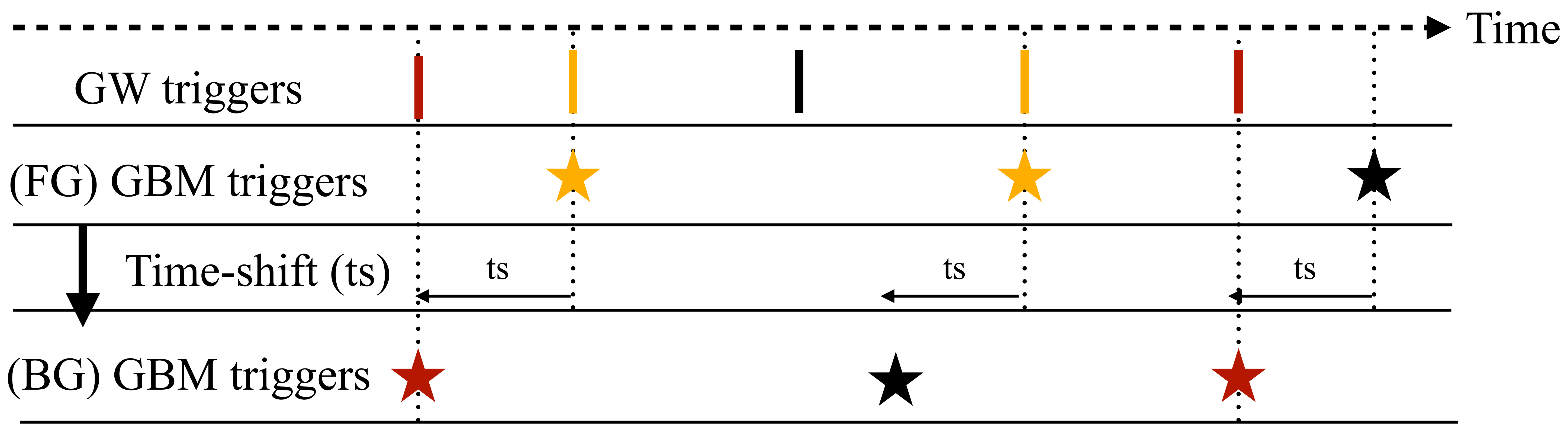
Figure from Cosmin Stachie



Candidate associations

Looking for GW-GRB joint detection

GW-GBM subthreshold analysis: Background computation



Background association computation method. FG: Foreground, BG: Background

To assign a FAR to each foreground pair, a background sample is needed. To generate it, we **time-shift** the GBM triggers by a predetermined offset and we look for coincidences between the GW triggers and the time-shifted GBM triggers

Repeat for several time shifts to accumulate the background

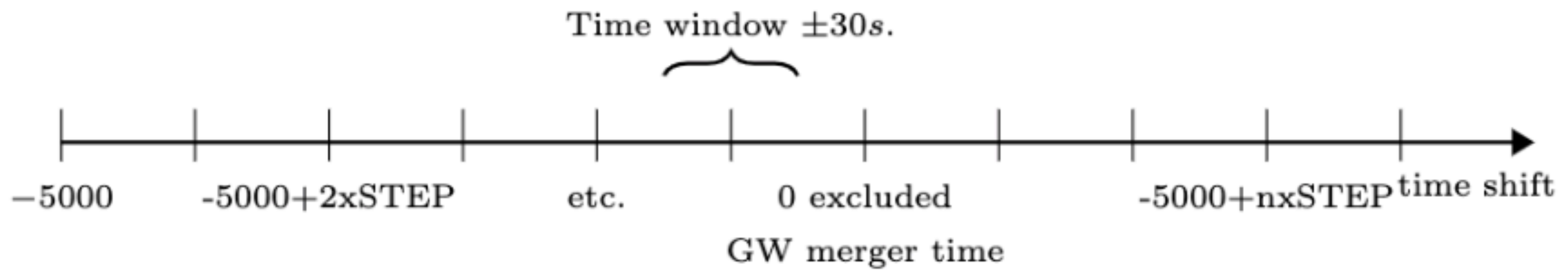


FIG. 1: Background association computation. In the analysis STEP=100 and different time shifts go from -50000 to 50000

O3* results : not public yet (paper ongoing). Here I will present the O2* GW-GBM subthreshold analysis

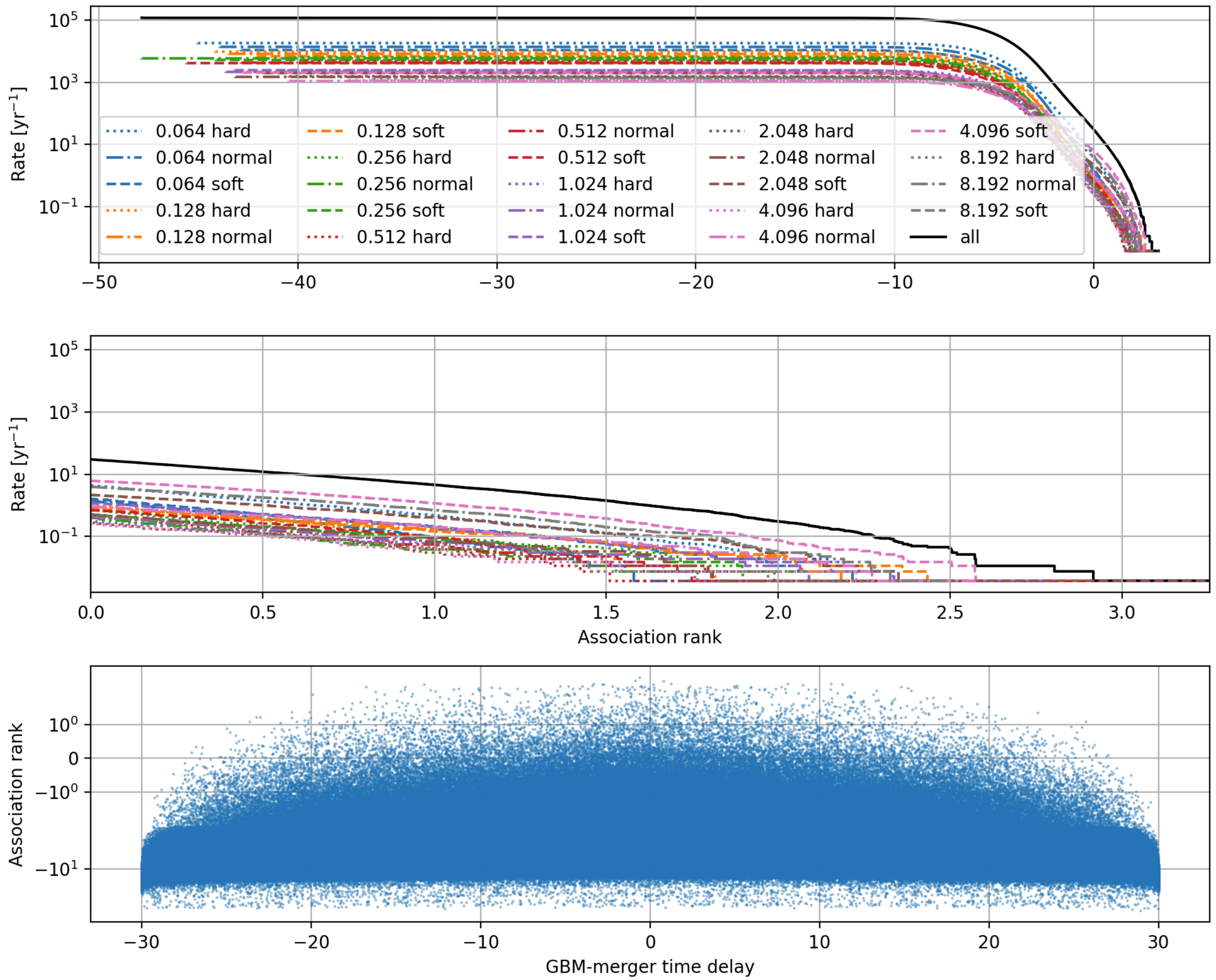
*O2 : 2nd GW observing run
*O3 : 3rd GW observing run

GW-GBM subthreshold analysis

Background association

gw_merger_time	gbm_merger_delay	gbm_duration	gbm_llr	gbm_best_spec	assoc_rank	sky_term	ln(gbm_BF)	-ln(gw_BF)
1181618716.304	-0.608	2.048	46.155	2	3.255	3.573	-4.302	1.111
1169635035.712	-0.888	0.512	21.070	2	2.917	3.448	-3.012	0.556
1171486002.071	0.793	1.024	177.482	1	2.804	2.889	-6.501	2.841
1169901594.667	-3.323	4.096	28.821	2	2.575	2.889	-3.036	1.822
1187222511.096	1.240	4.096	25.741	2	2.575	2.826	-2.778	1.833
1165070949.872	10.680	4.096	27.658	2	2.572	3.300	-2.951	1.320
1181447137.093	8.107	4.096	58.758	1	2.572	3.089	-4.245	1.579
1173860807.818	-13.338	0.064	94.937	0	2.520	3.183	-6.538	2.579

...



OBSERVATIONS :

- Background dominated by : 2.048 s - soft GBM triggers
- Background very diverse (different LLR, duration, spectral value …)
- Signal-like GBM & GW Bayes Factor
- High sky term
- Background rate going to ~1 / century

Here I computed the Bayes Factor as :

NB

$$Q_L \approx \frac{P(observing\ GW\ data\,|\,signal)}{P(observing\ GW\ data\,|\,noise)} \qquad Q_G = \frac{P(observing\ GBM\ data\,|\,noise)}{P(observing\ GBM\ data\,|\,signal)}$$

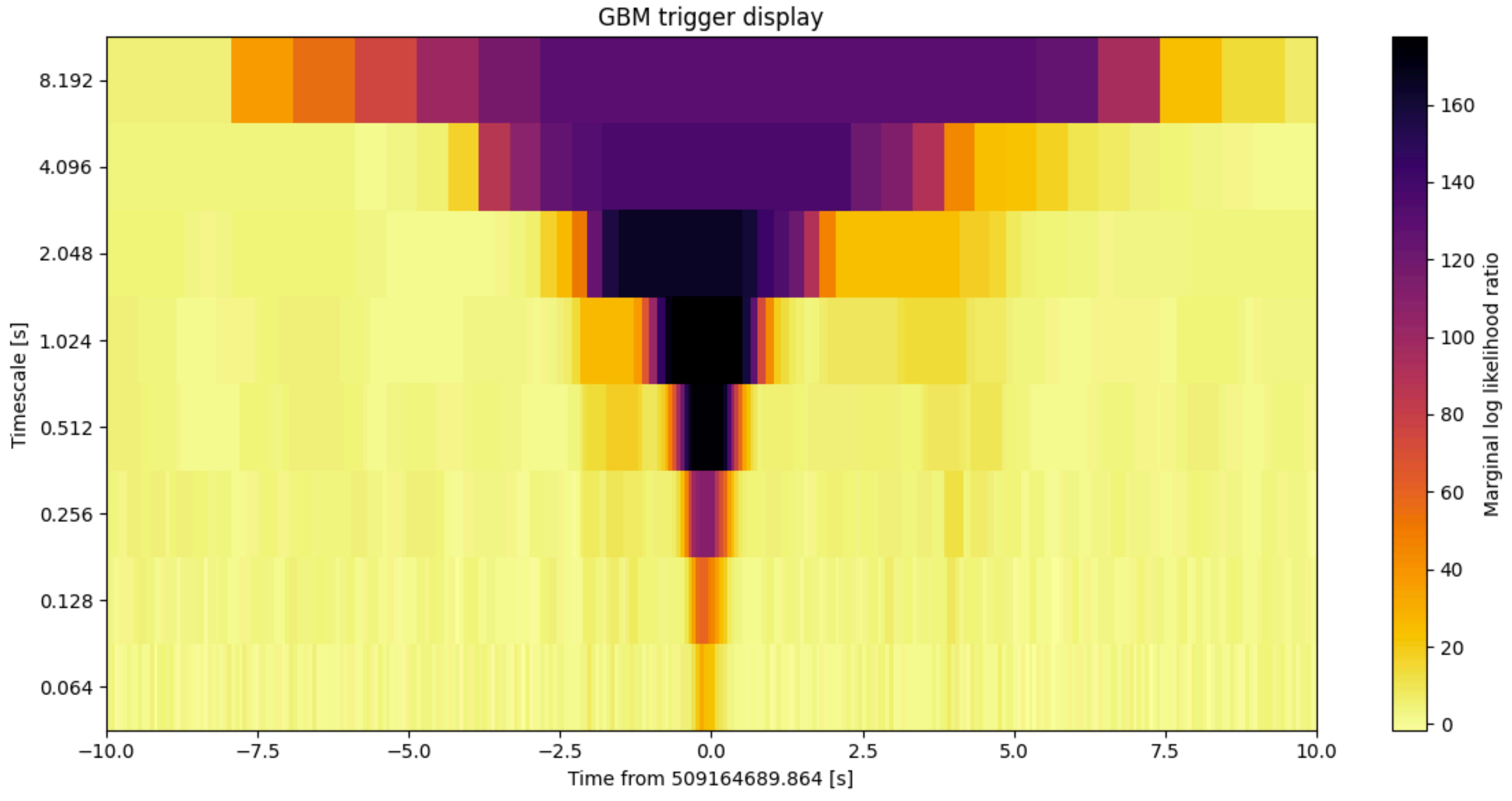
GW-GBM subthreshold analysis

Background association

1st background association of the table (cf. previous slide) :

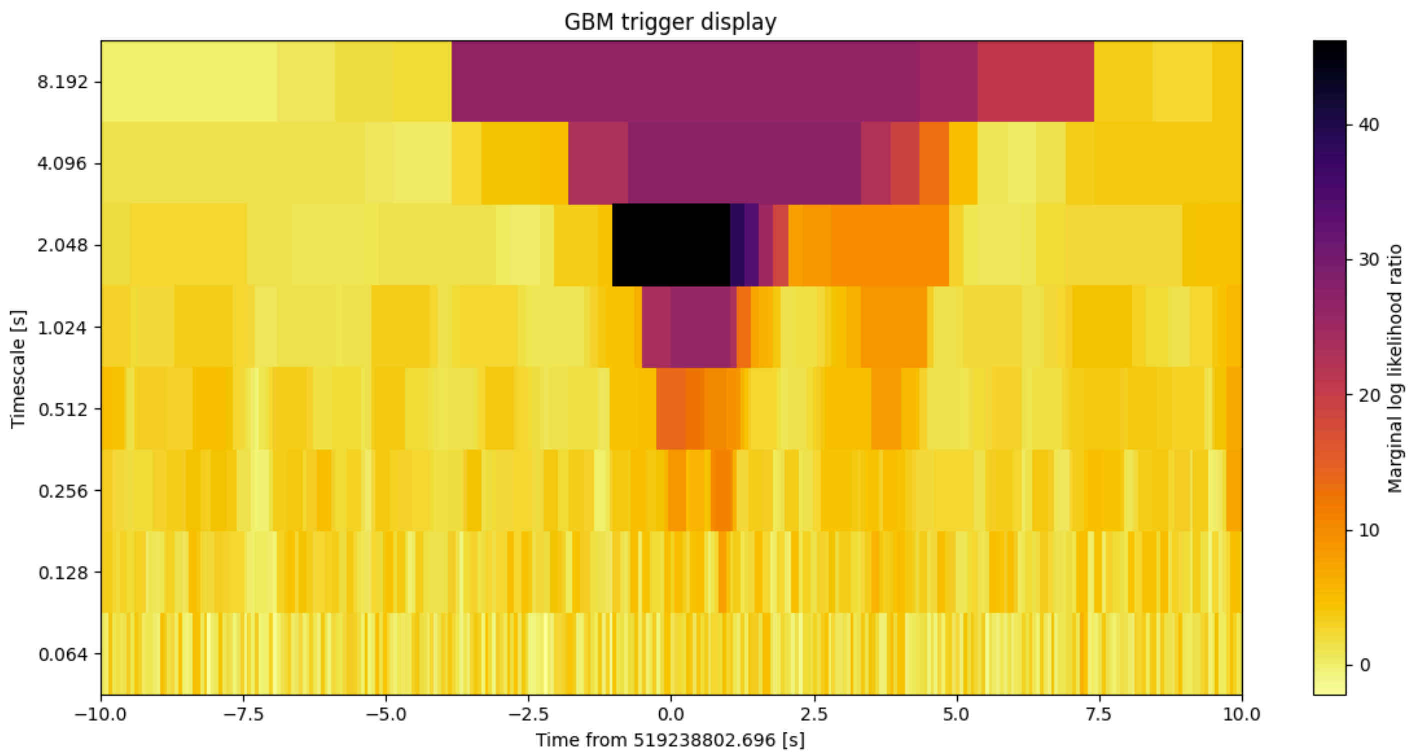
- 1st association : no real GRB and GW event have been found at the time of both triggers

- Other associations : some real GRBs

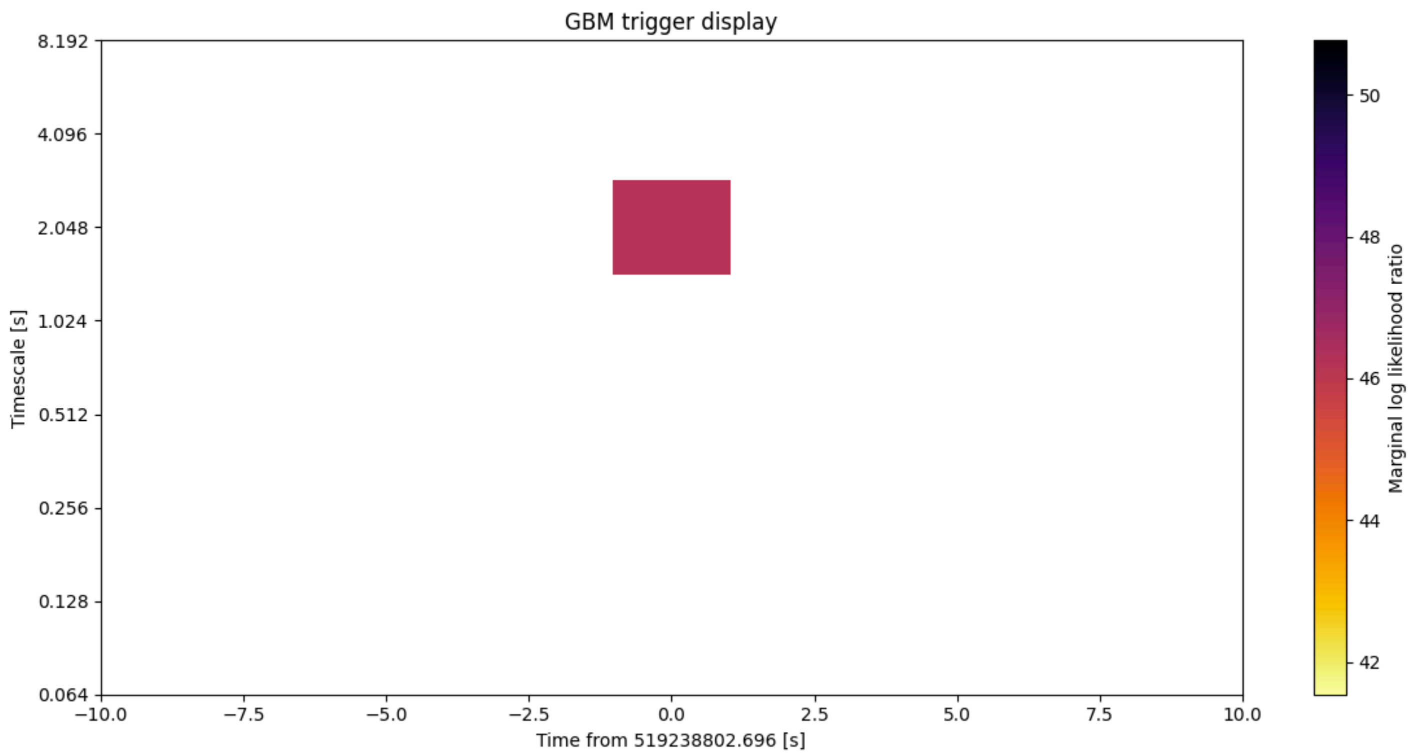


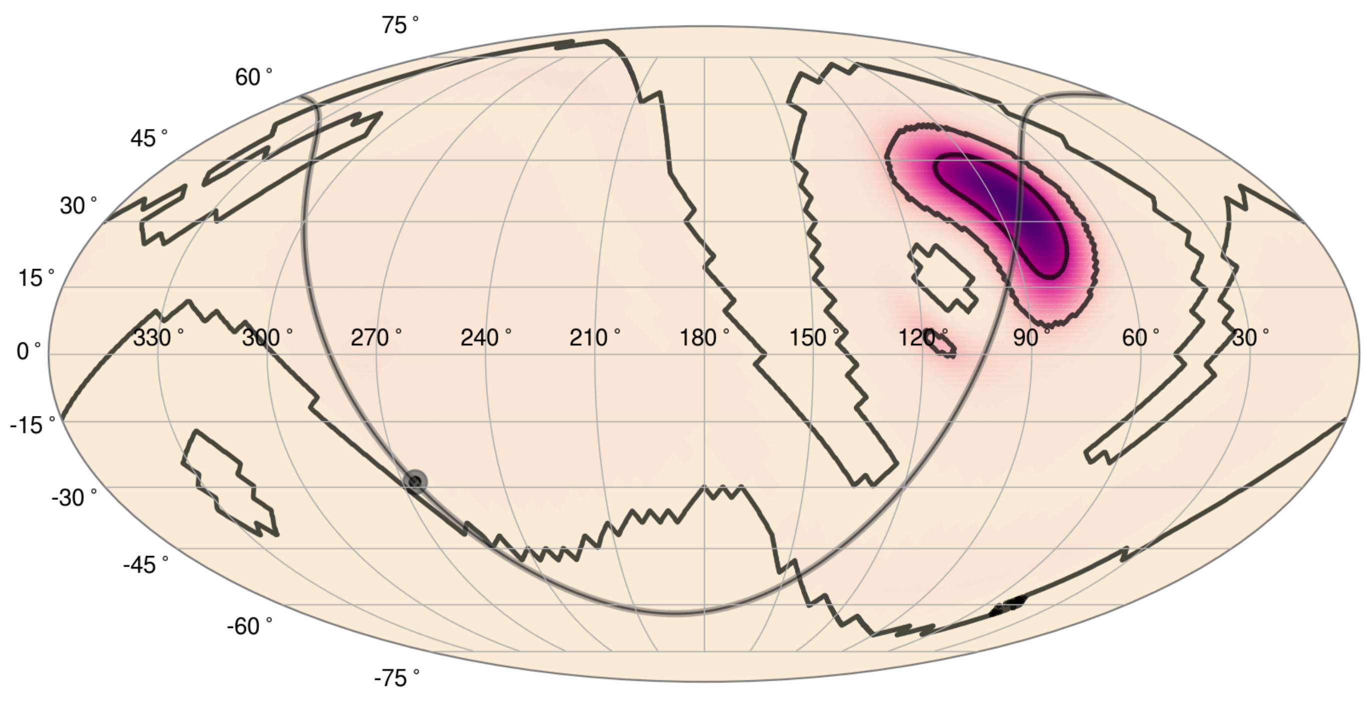
- Noise on GW side
- Skymaps : very well localized

GBM display with full results

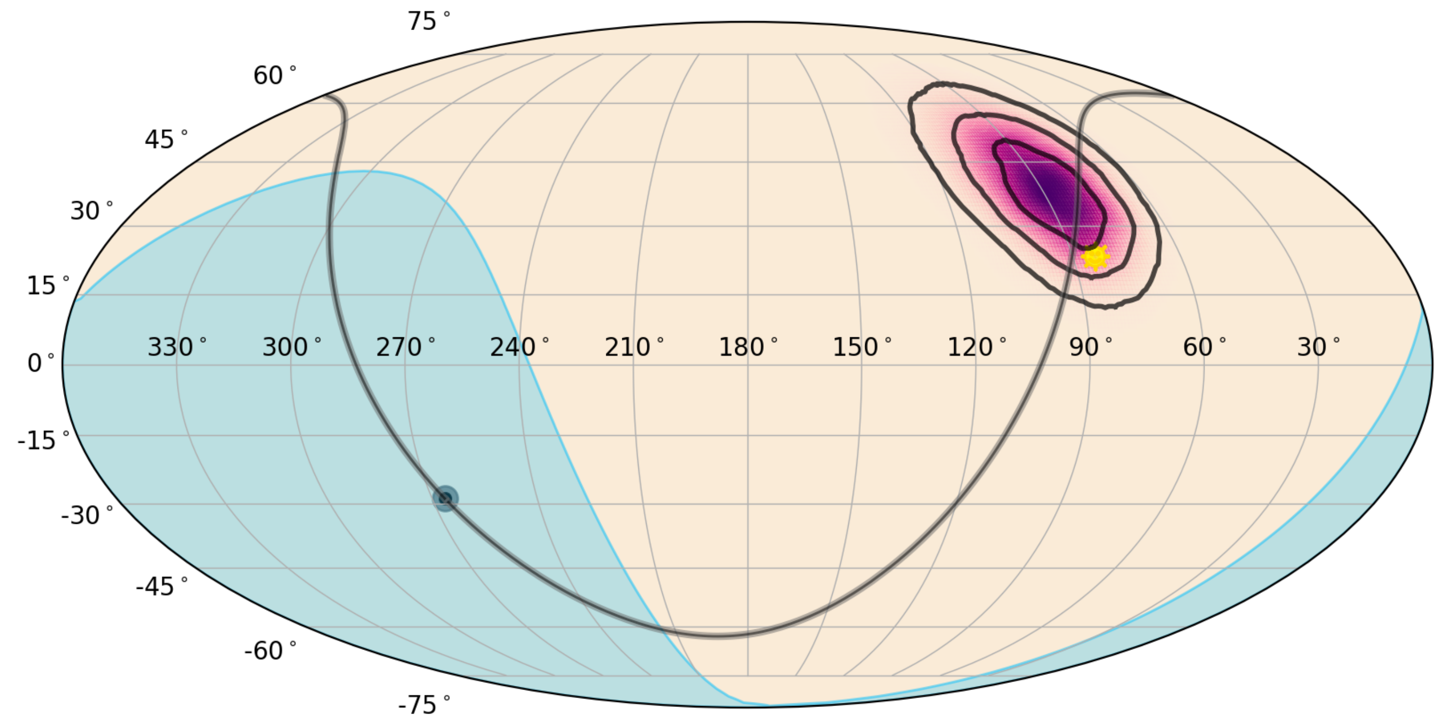


GBM display with filtered results





GW skymap



GBM skymap

GW-GBM subthreshold analysis

Foreground association

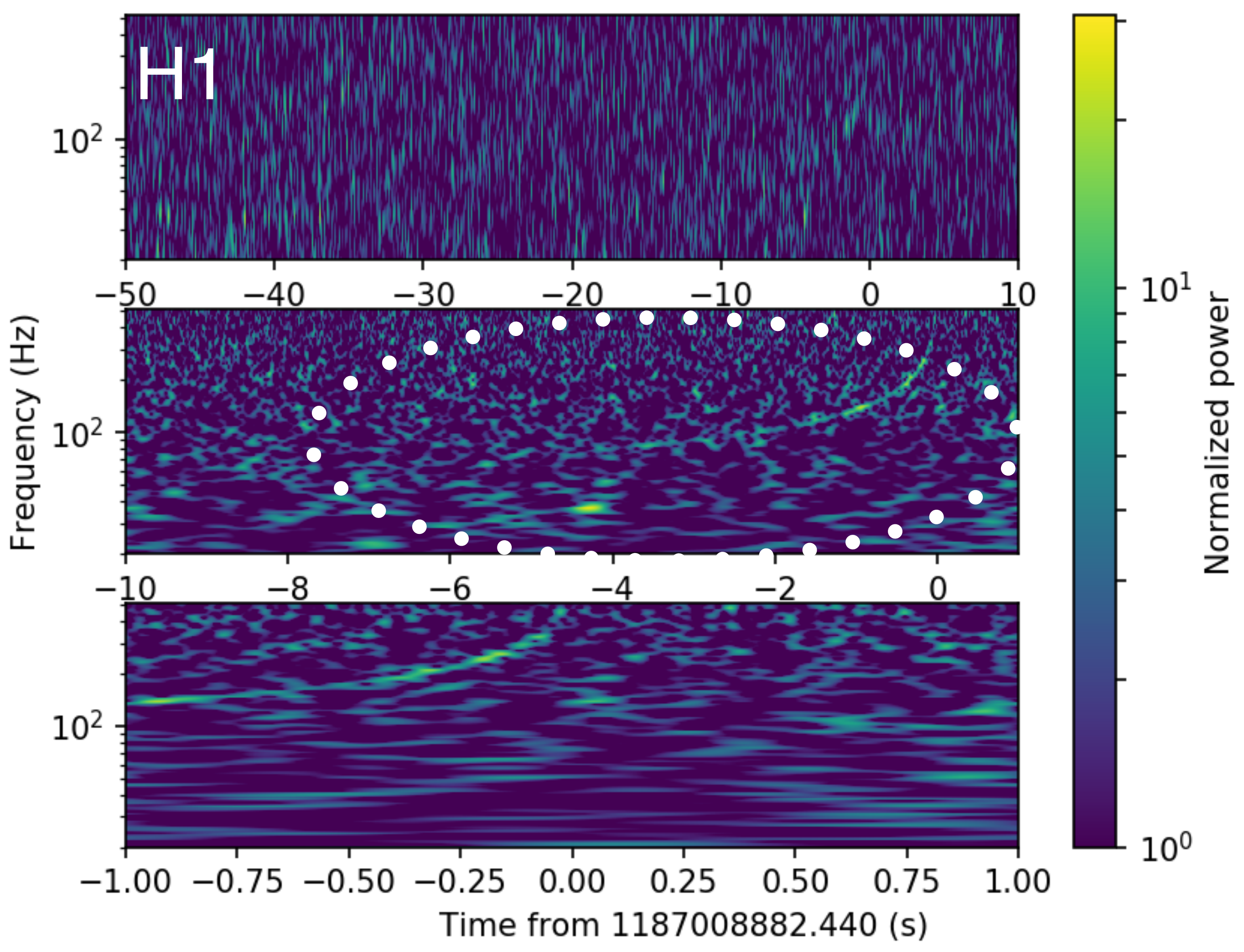
gw_merger_time	gbm_merger_delay	gbm_duration	gbm_llr	gbm_best_spec	assoc_rank	sky_term	ln_BF	-ln_BF
1187008882.445	2.723	4.096	15.381	2	1.435	2.154	-0.143	9.733
1187008882.445	2.019	0.512	72.514	1	1.158	1.230	-6.263	9.733
1185721264.338	0.638	0.064	13.052	2	0.788	1.914	0.557	2.311
1168226845.160	-6.624	4.096	16.606	0	0.485	1.196	-0.633	3.326
1164821117.249	-3.737	0.064	14.452	0	0.378	1.152	-0.146	4.008
1176884101.581	-15.677	2.048	245.324	1	0.202	0.971	-6.157	3.580
1164684086.868	-11.404	4.096	17.599	2	0.185	1.214	-1.001	1.313
1187008882.445	1.859	0.064	14.328	0	-0.016	0.700	-0.084	9.733

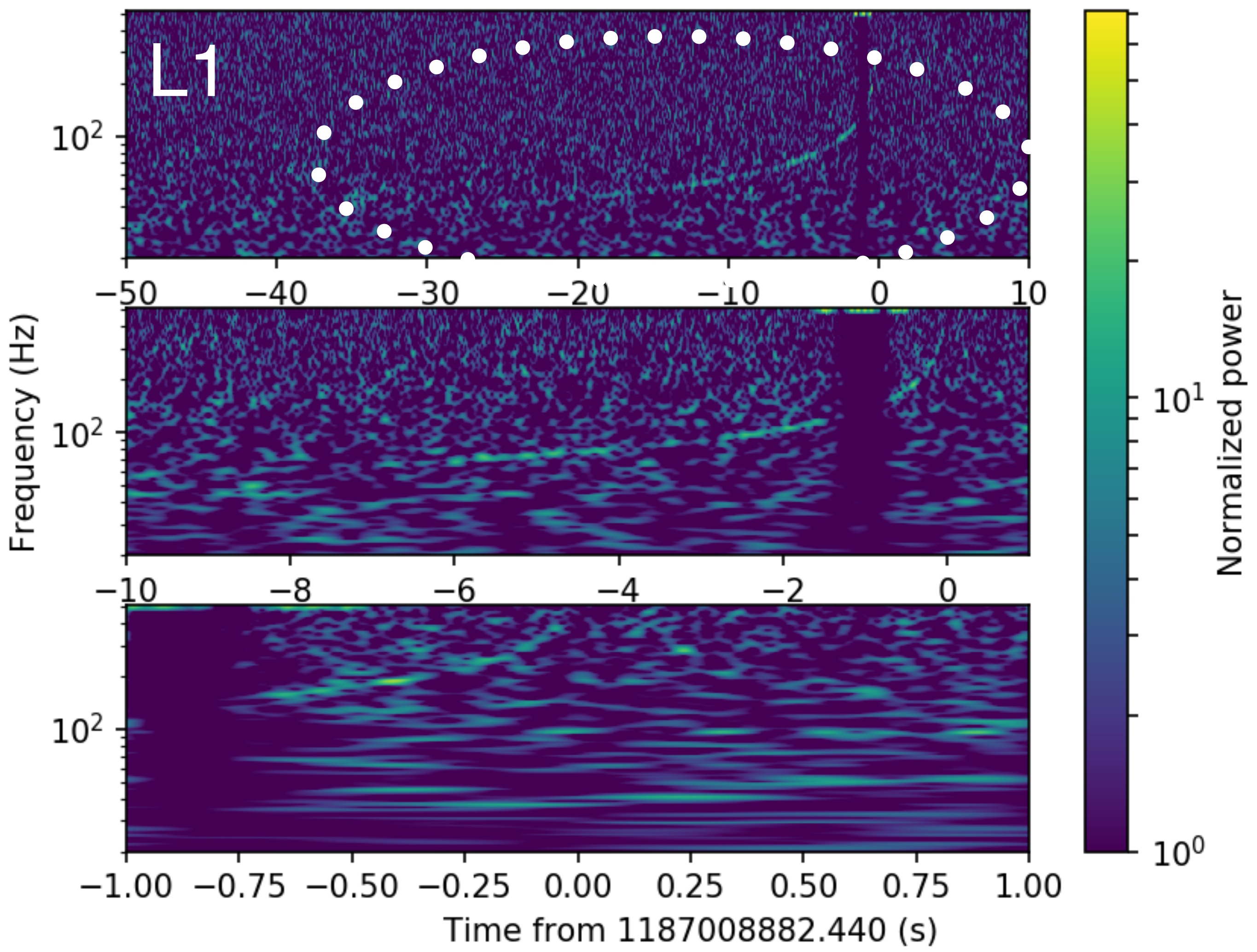
...

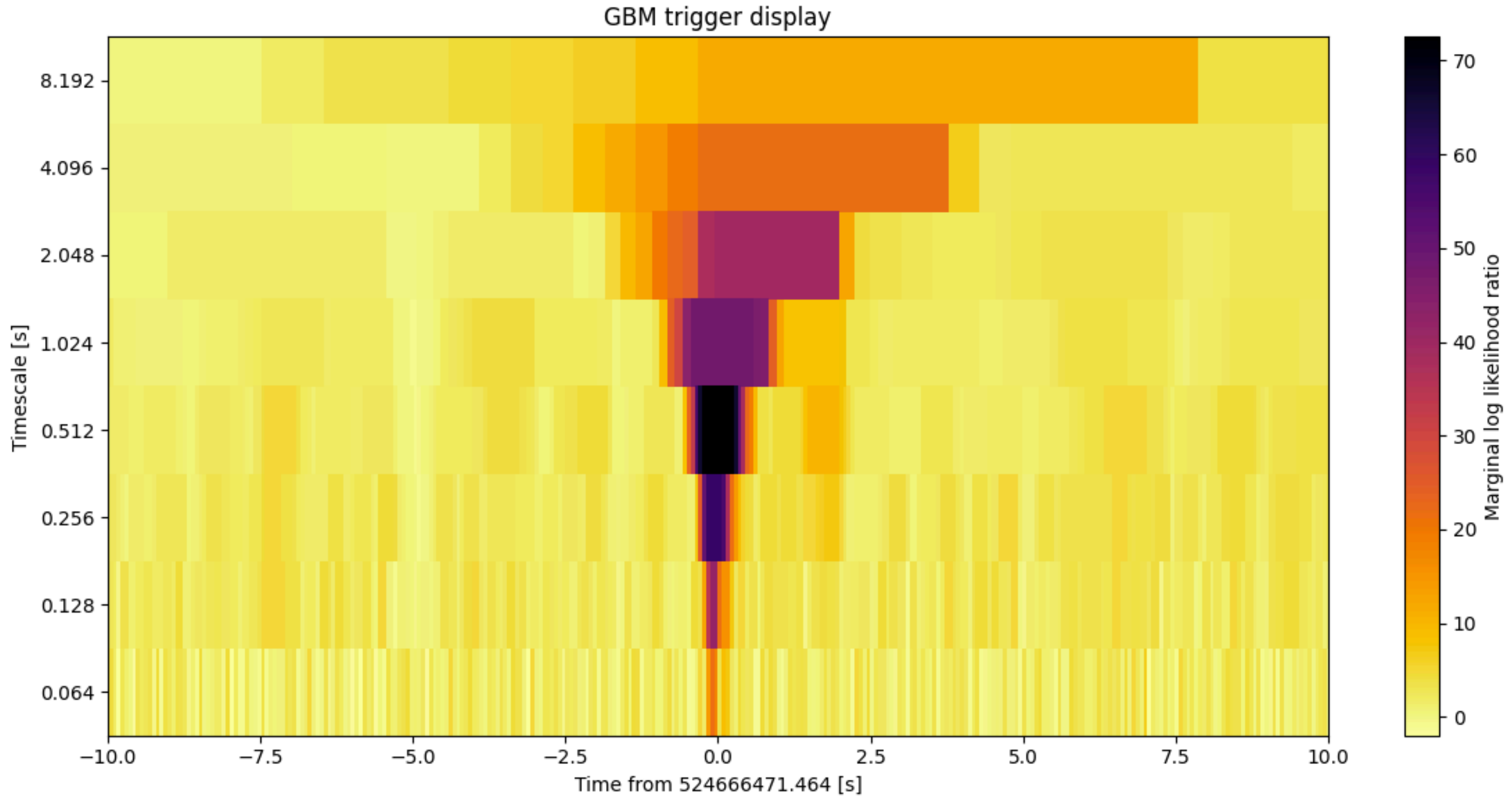
We see GW170817+GRB170817A on the top !

GW-GBM subthreshold analysis

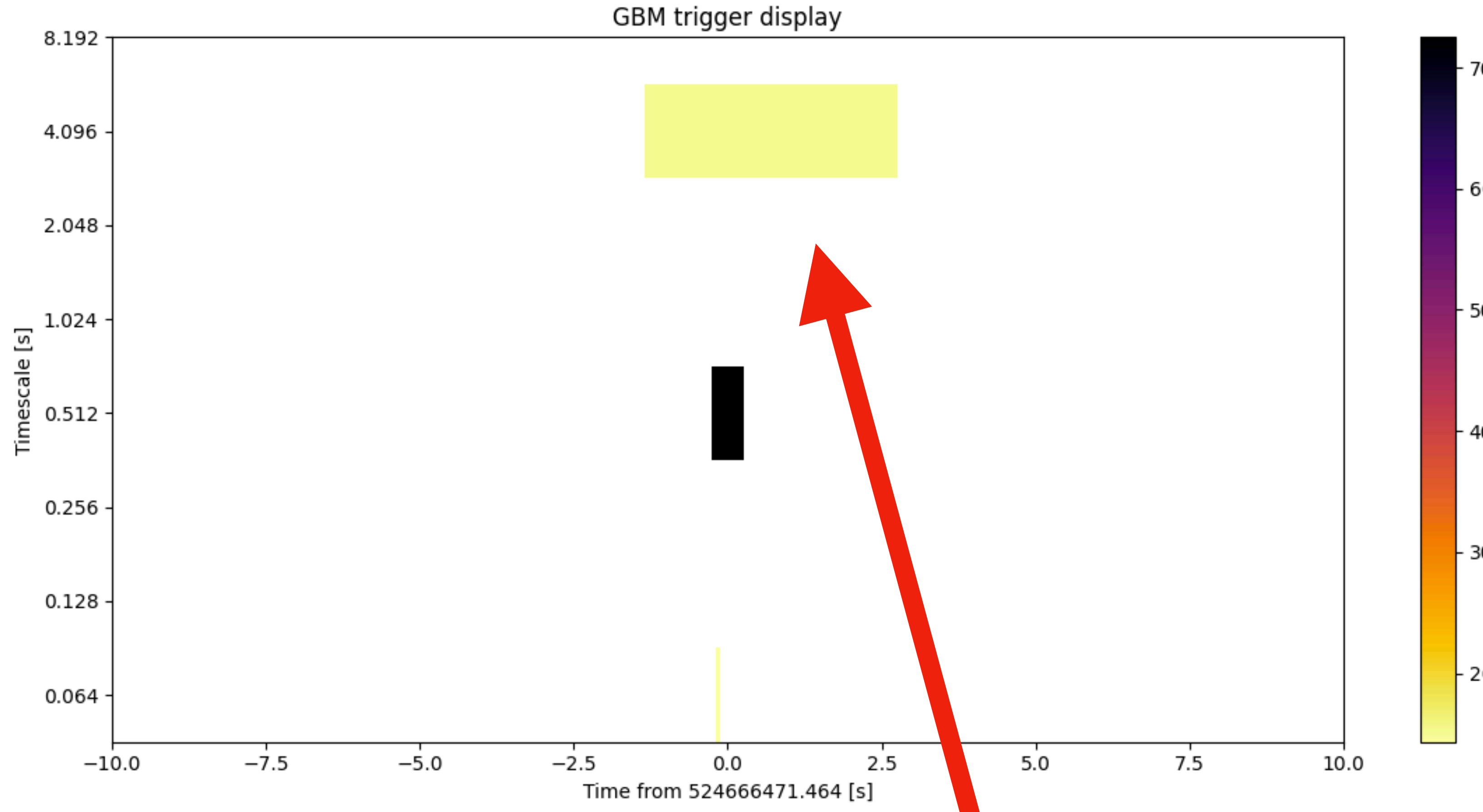
Foreground association







[GBM display with full results]



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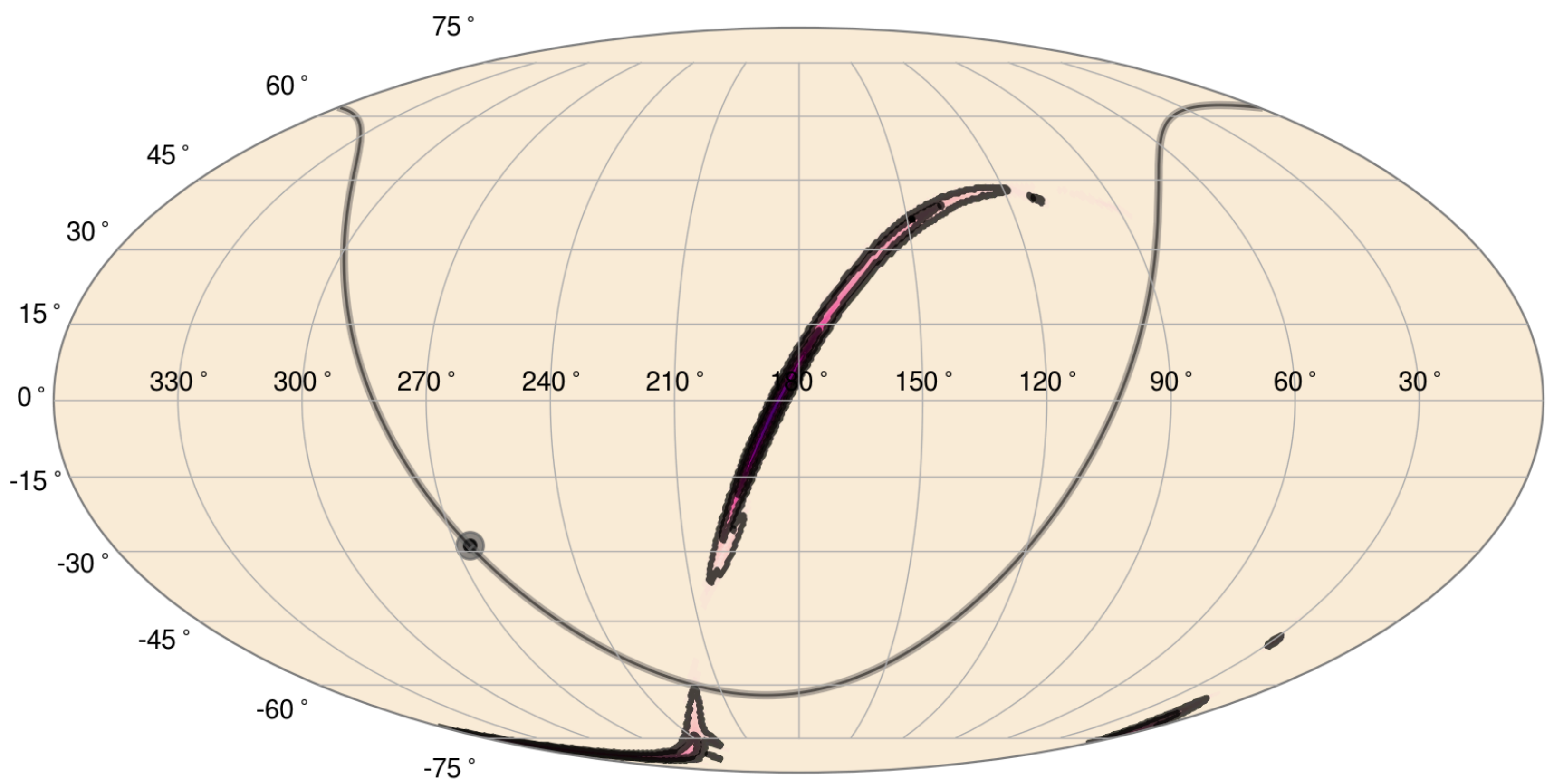
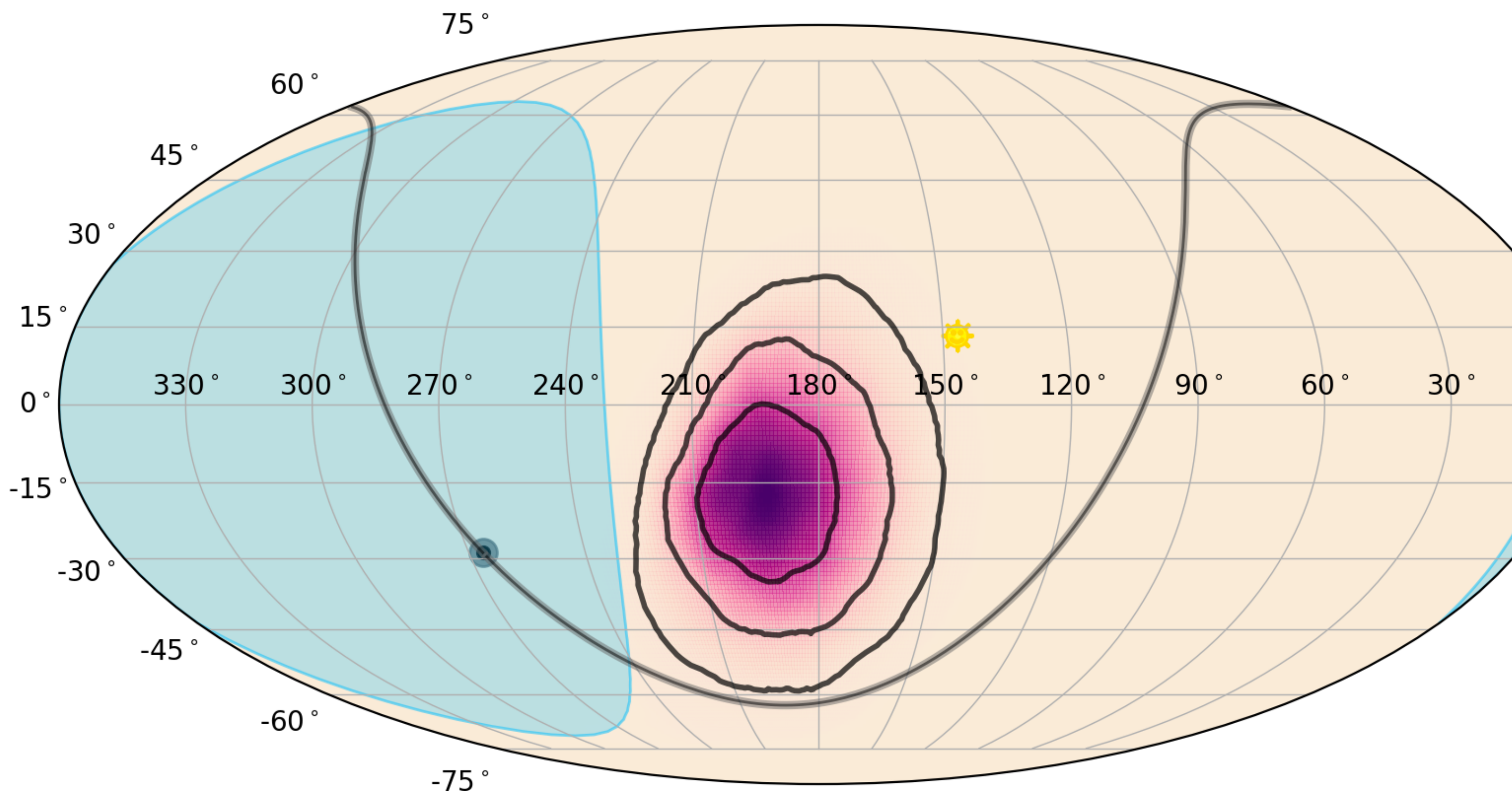


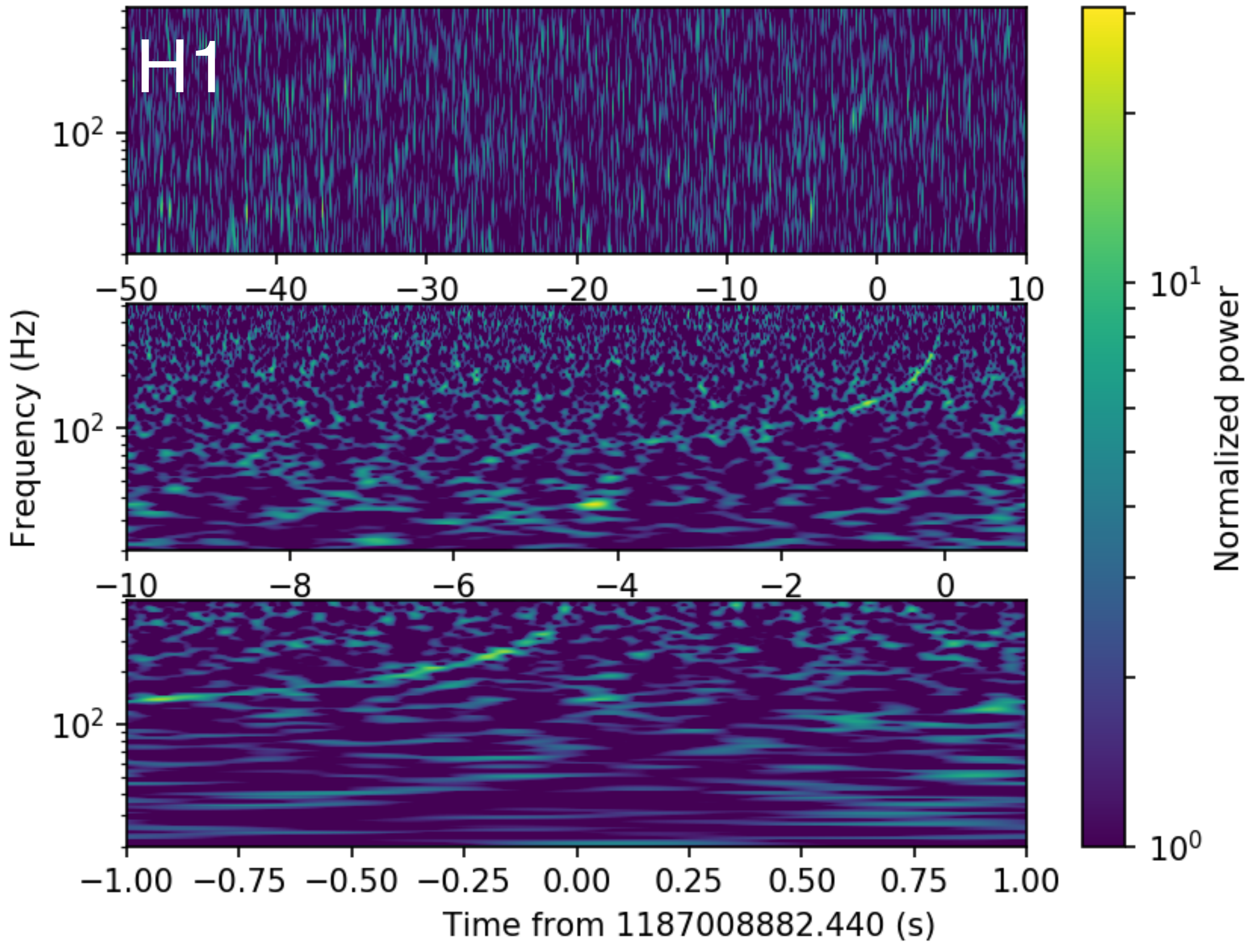
[GW skymap]

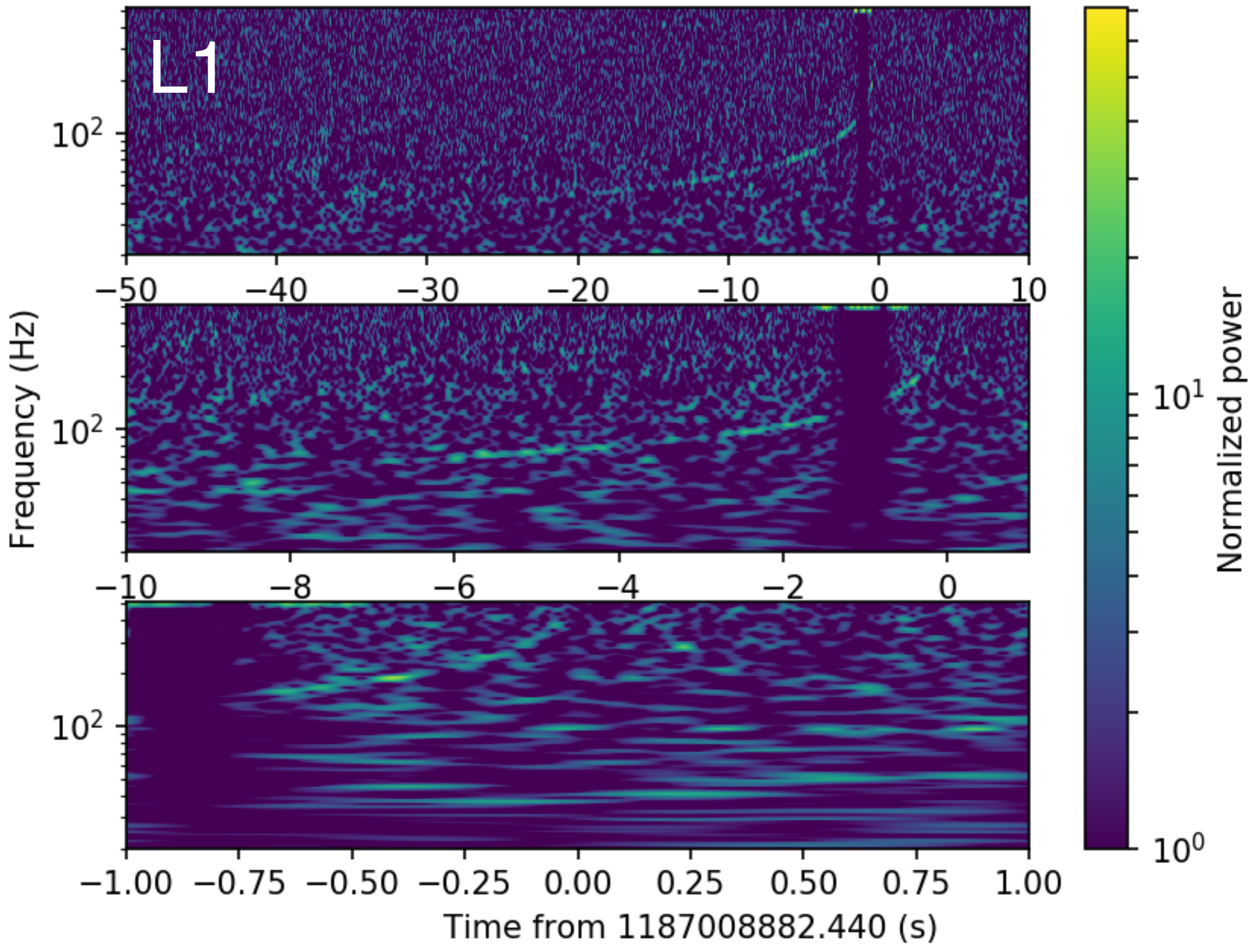


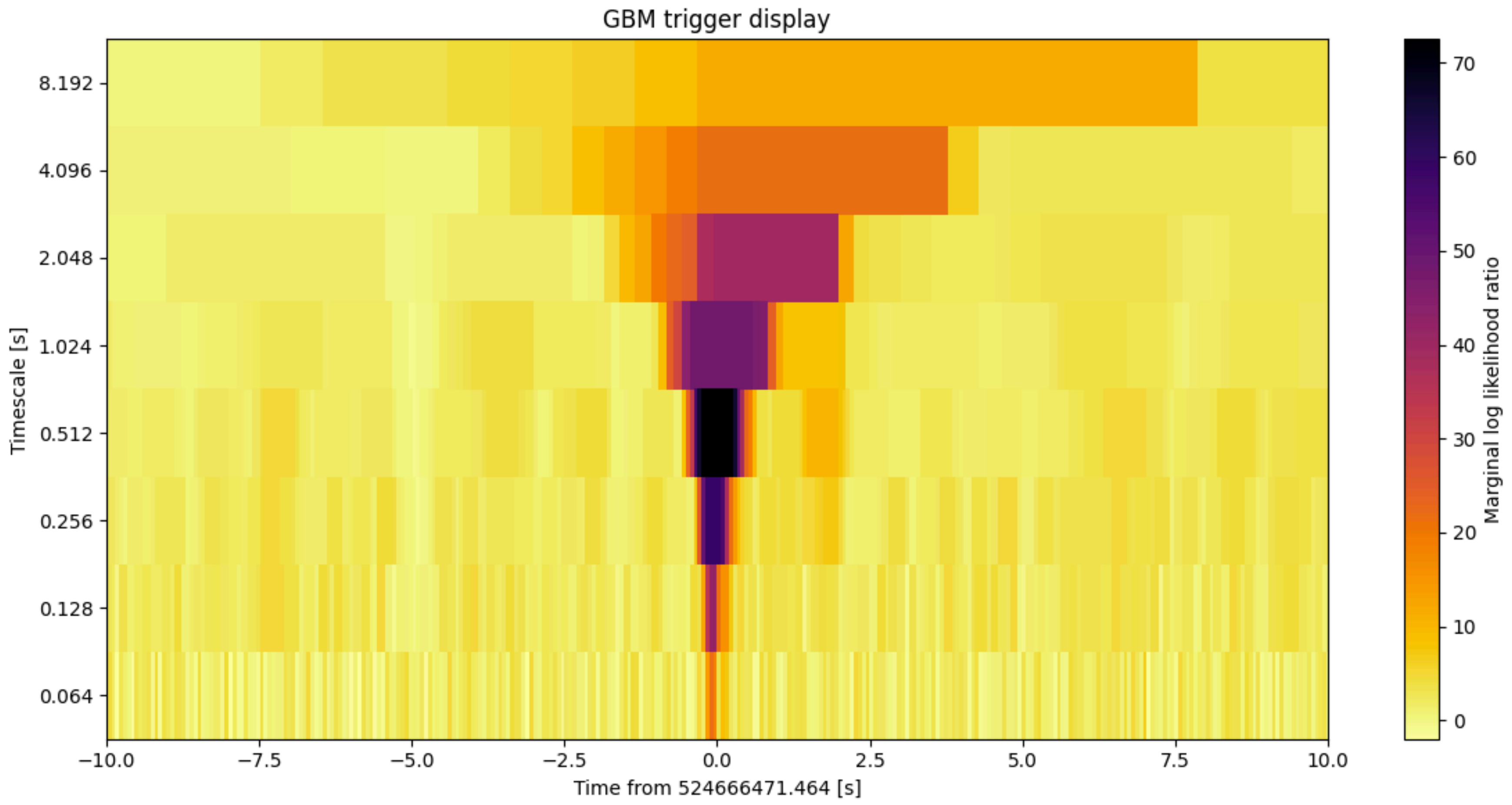
[GBM skymap]

GW-GBM subthreshold analysis

Foreground association







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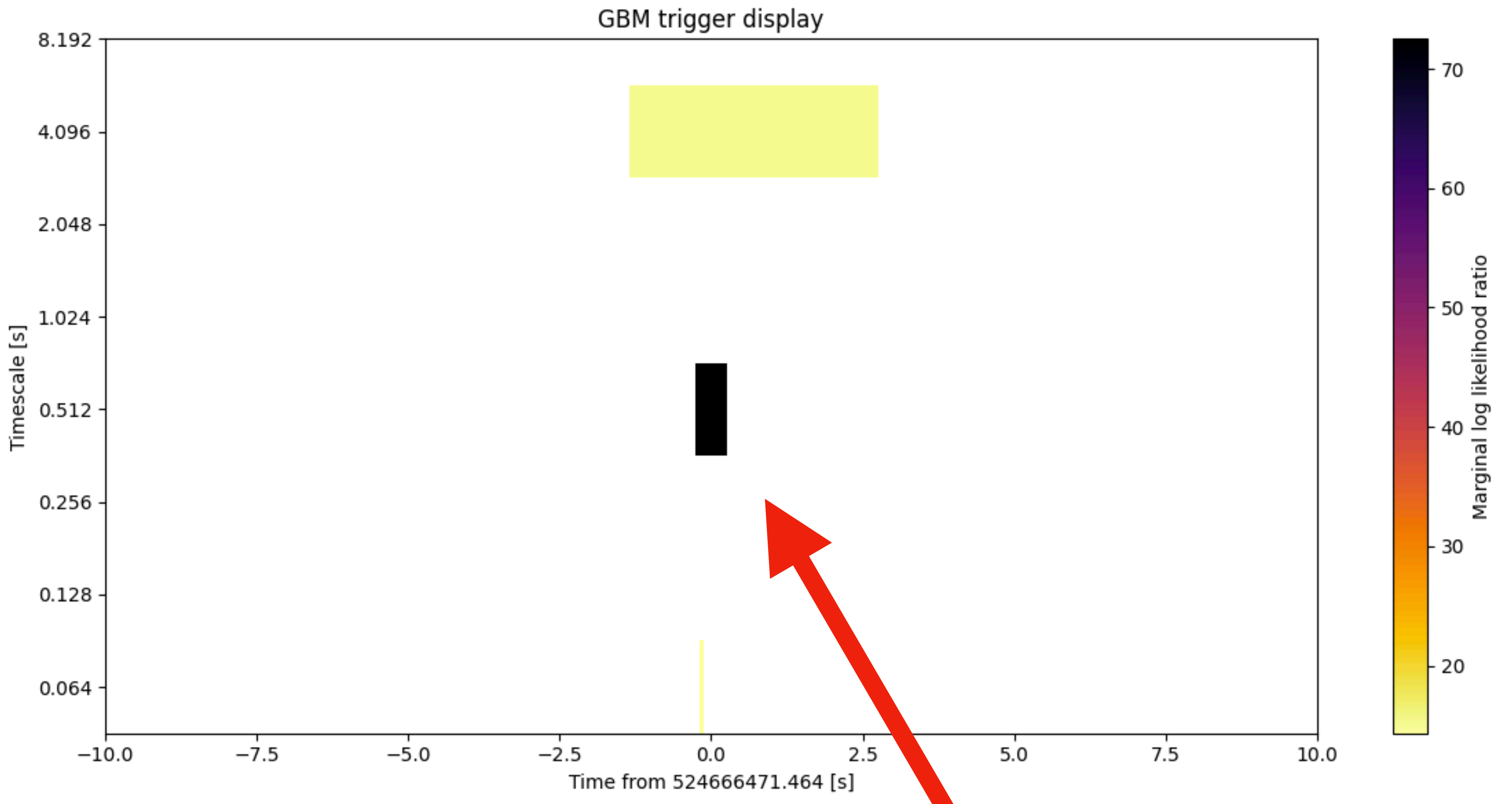

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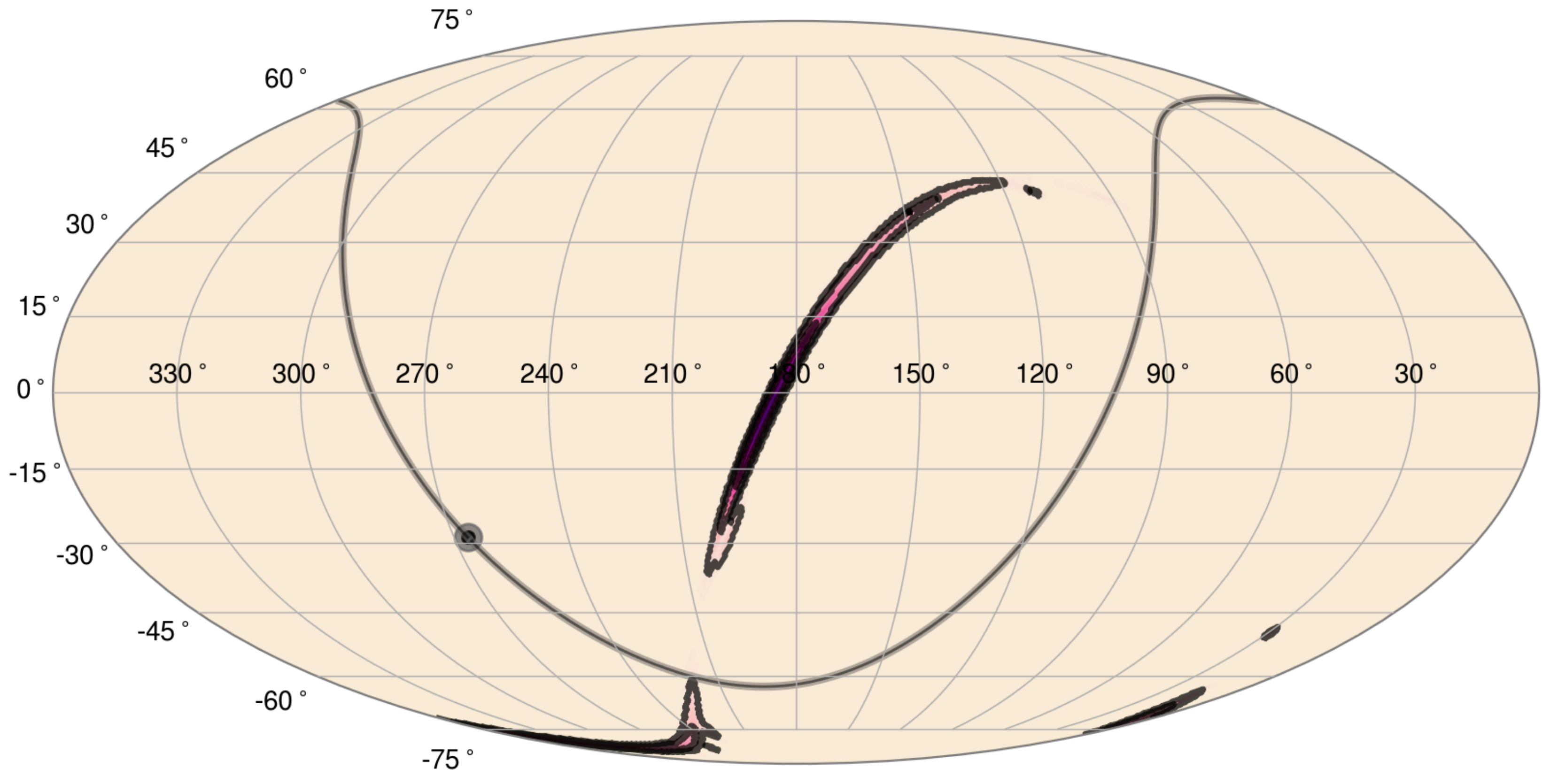
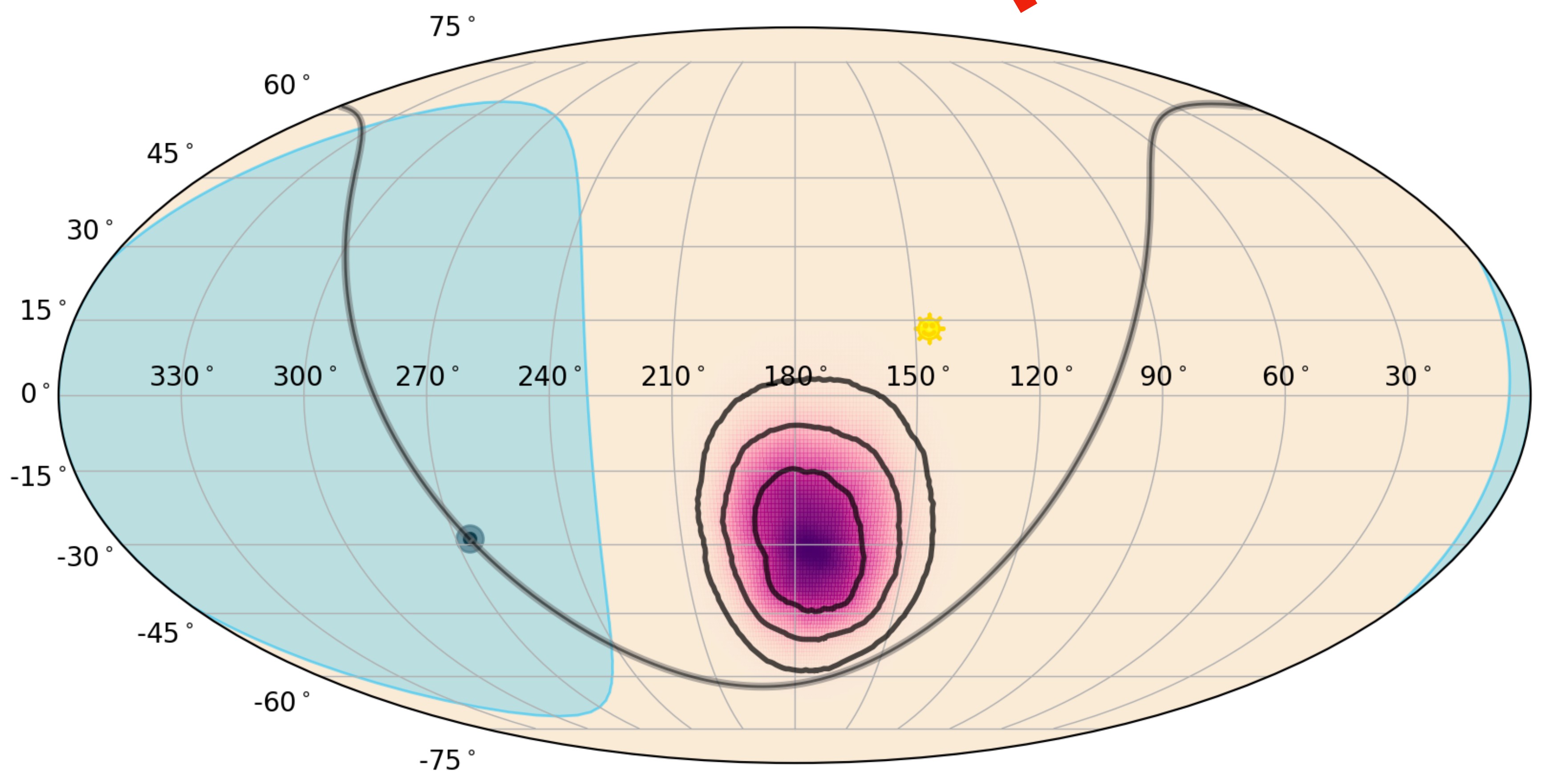


[GW skymap]



[GBM skymap]

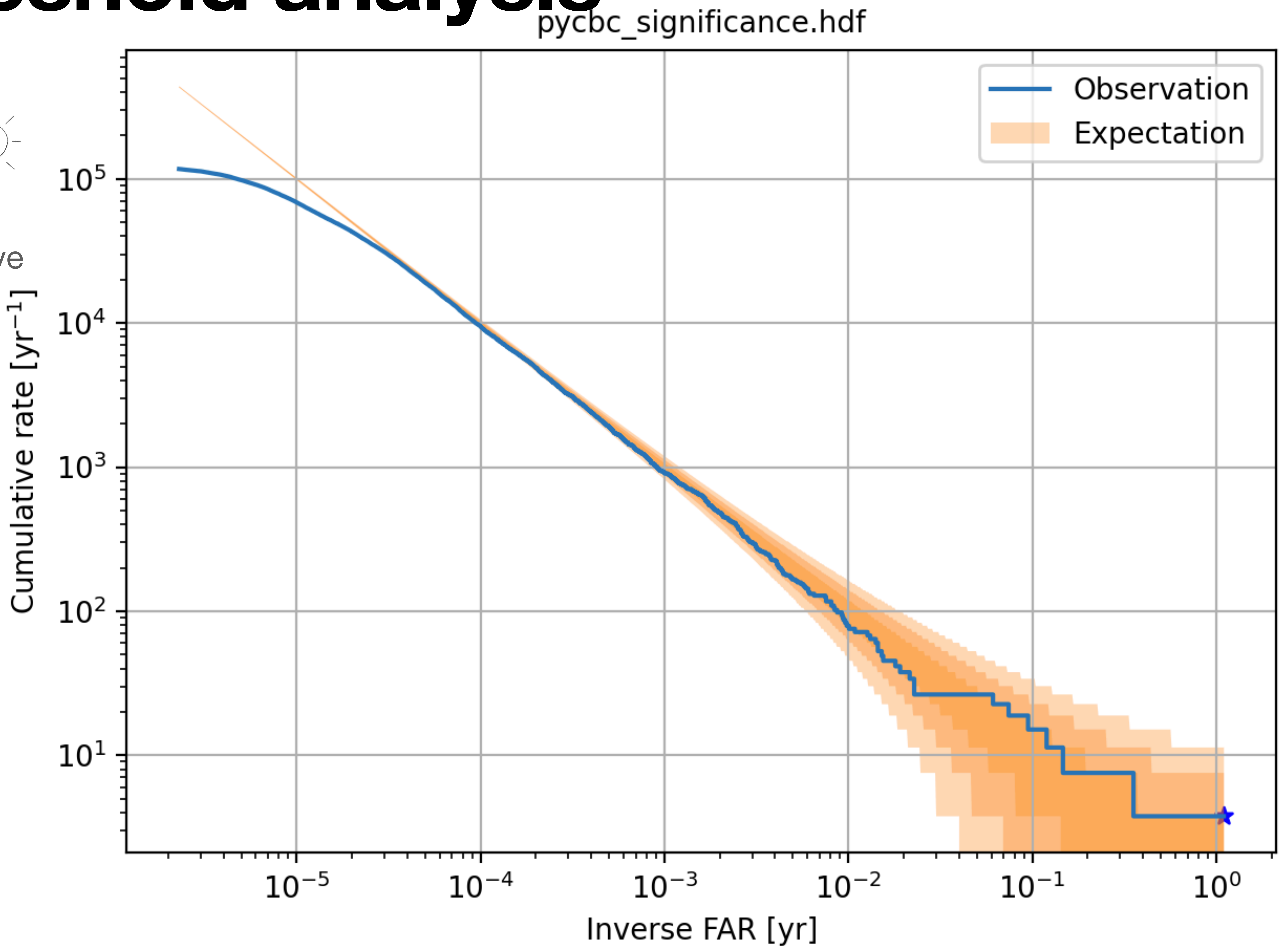
GW-GBM subthreshold analysis

Foreground association

Why aren't we seeing the joint association

A (joint) detection ⇨ The blue curve would have continued in higher IFAR than the orange region

- Even if GW/GRB170817 is the most significant foreground association it's not significant enough !
- The skyterm of the association is quite low : why ? We didn't take into account Virgo in the skymap production (conservative analysis)
- We have a high GBM trigger rate : it increases the background rate
- Agnostic analysis : we look for all type of CBC, not only BNS which reduces the sensitivity
- Even if we don't see the detection of the high hand plot we would have discovered it since it's the most significant association



Conclusion, next step & Paper plan

CONCLUSION & NEXT STEPS OF THIS ANALYSIS :

- Investigations about what we can change (For instance reproduce the skymaps with **Virgo** contribution —> manual test : the IFAR of GW170817+GRB170817 will increase from **1.1 to 2.8** ; or select (**cut**) a bit more carefully the GW triggers before the joint analysis)

OTHER CONTRIBUTIONS :

- Contribution to the **offline** analysis and **Sub-Solar-Mass** analysis in the framework of LIGO/Virgo collaboration
- Contribution to the LVK **GWTC-3 catalog**

PAPER PLAN :

- Analysis of the Fermi subthreshold project still ongoing and one of the main writer of the article
  - 2 paper plans for GW-GBM Subthreshold analysis : 1 on **O3** analysis & 1 **method** paper containing the O2 results
- One other paper going on improving **PyCBC search's sensitivity with Omicron**

THANK YOU !