# Searching for Gravitational-Waves/Gamma-Ray-Bursts associations in LIGO/Virgo & Fermi-GBM data

## Gravi-Gamma Workshop
## 5-7th of October, 2022


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**Cosmin Stachie, Brandon Piotrzkowski, Fergus Hayes, Eric Burns, Josh Woods, Nelson Christensen, others …**

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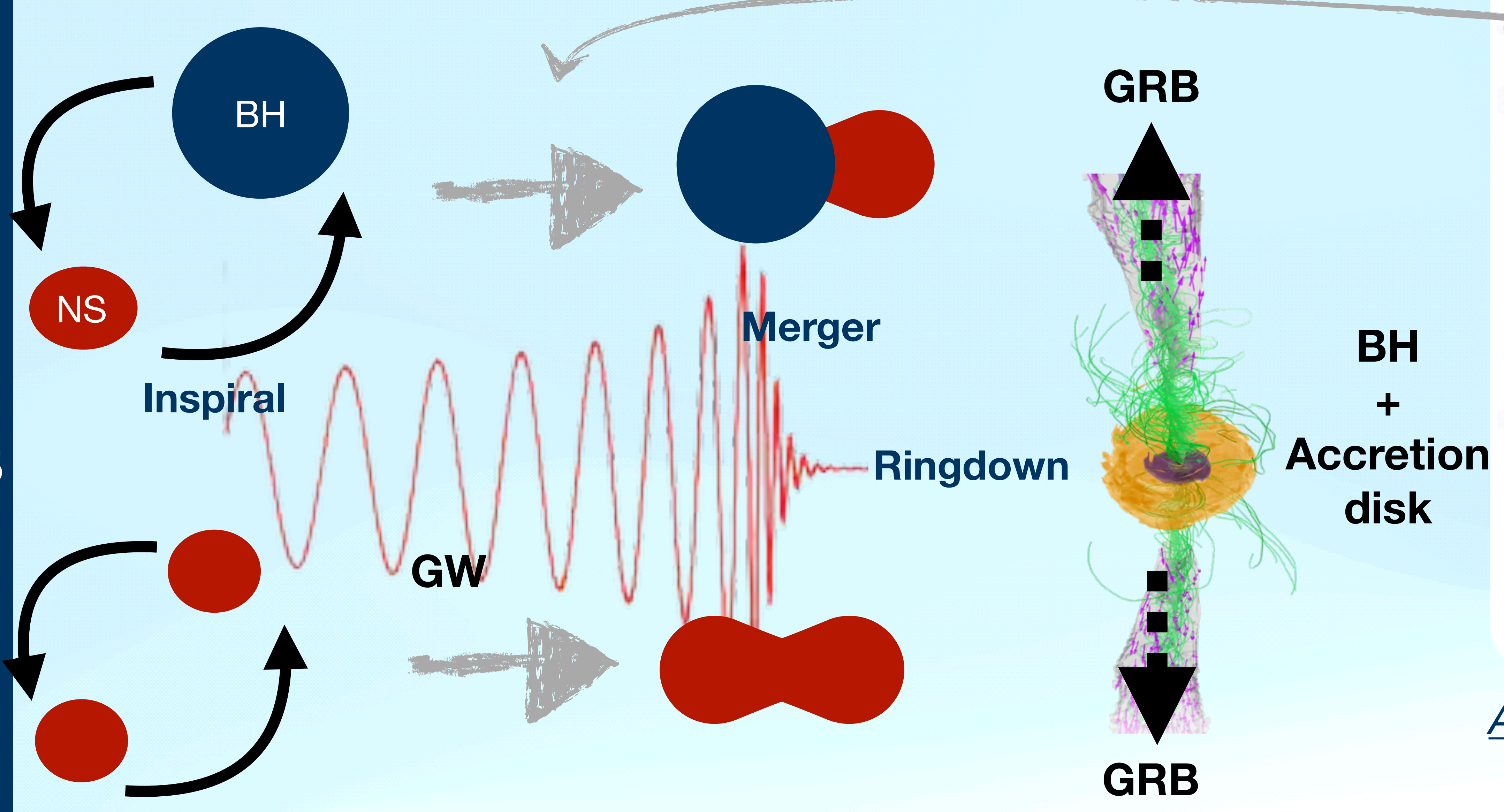
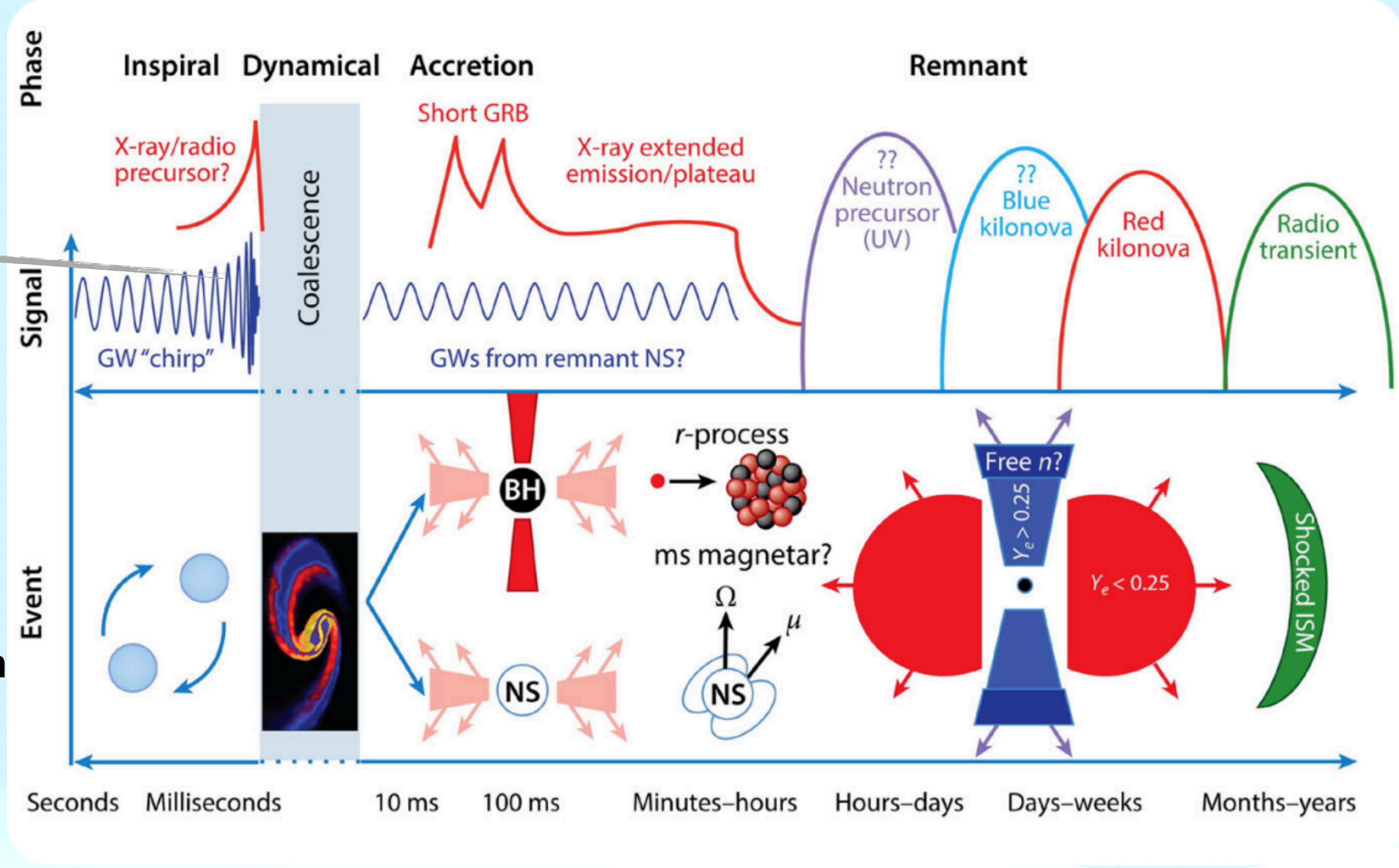
# Introduction

## Binary Neutron Star mergers




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

**Currently:** only one GW-GRB joint detection (GW170817/GRB170817A)

**Fundamental questions:**

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

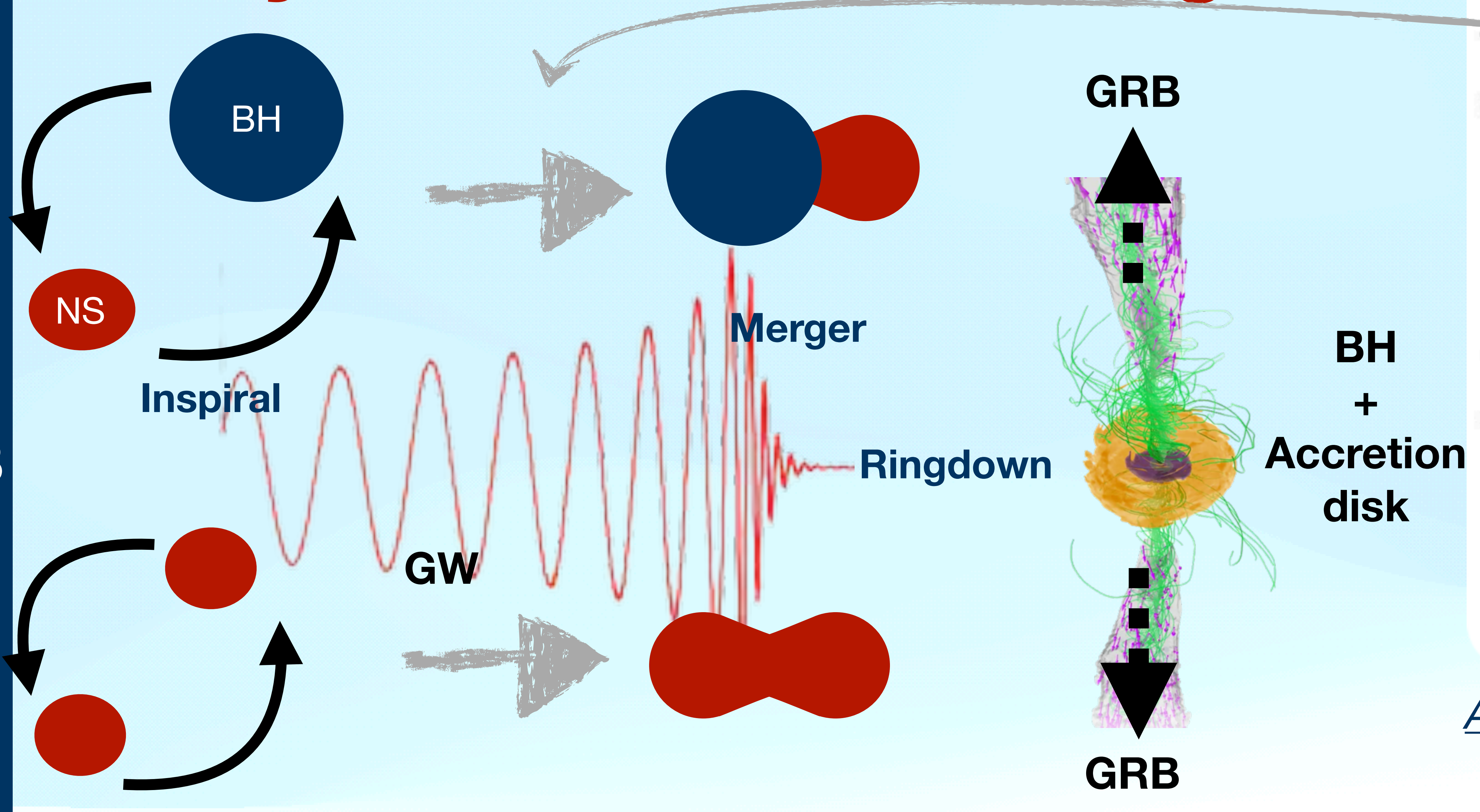
★ What is the fraction of **short** and **long** GRBs associated to BNS mergers ?

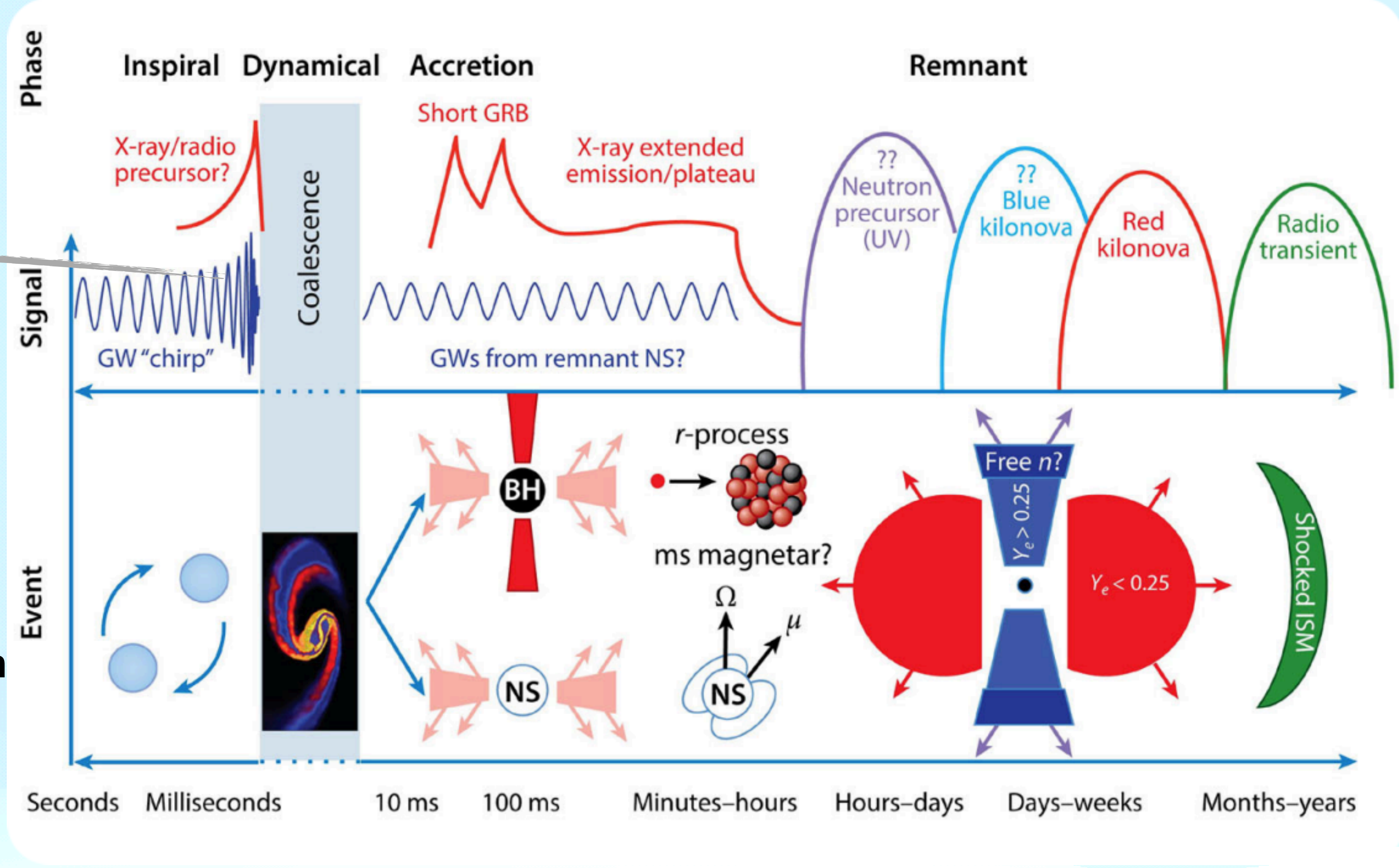
…

**GRB:** Gamma-Ray-Burst
**GBM:** Gamma-Ray-Burst Monitor
**GW:** Gravitational-Wave
**BNS:** Binary Neutron Star Mergers
**BH:** Black Hole
**NS:** Neutron Star
**CBC:** Compact Binary Coalescence
**GWB:** Gravitational Wave Burst
**LLR:** Log-Likehood Ratio
**SNR:** Signal-to-Noise ratio
**FAR:** False Alarm Rate
**IFAR:** Inverse False Alarm Rate

# Introduction

## Binary Neutron Star mergers

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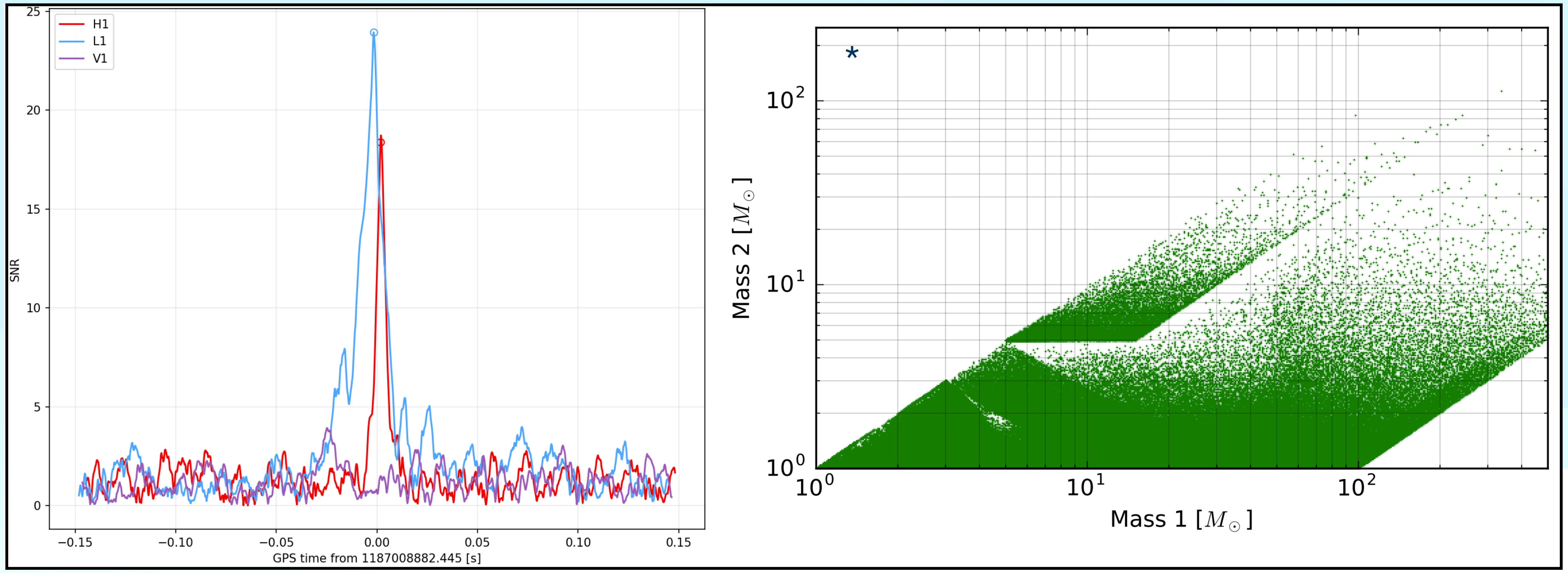
# Introduction
## GW and GRB search

* *Designing a template bank to observe compact binary coalescences in Advanced LIGO's second observing run*, Tito Dal Canton and Ian W.Harry

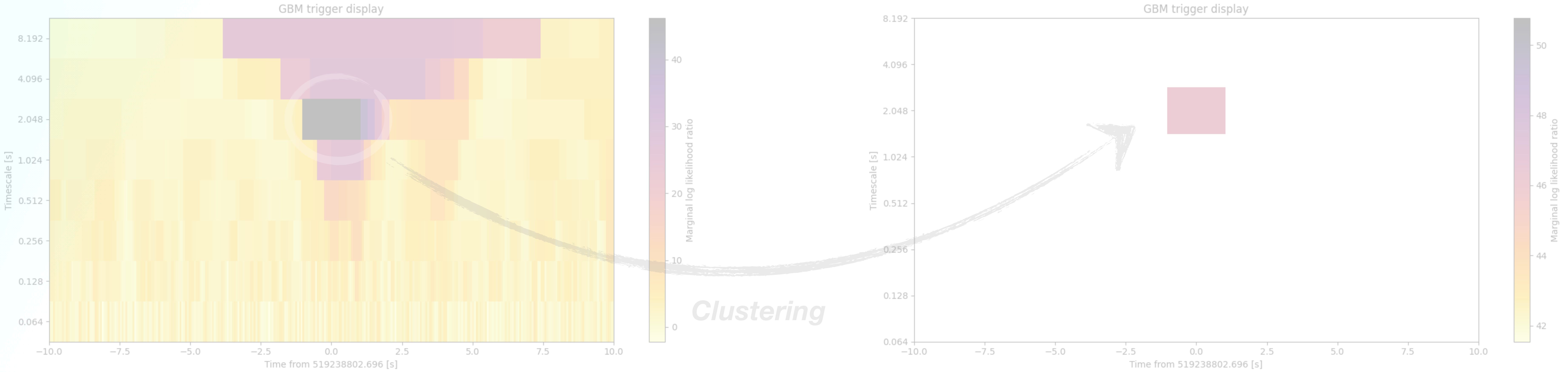
### CBC search

- Carried by several independent pipelines
  - Modeled searches (PyCBC GstLal, MBTA)
  - Minimally modeled search (cWB)
- In the analysis presented in the following slides: triggers from **PyCBC** (from **GWTC-1**) which is a matched-filtering based analysis pipeline that rapidly identify compact binary merger events.




### GBM Targeted search

- The Targeted Search produces GBM triggers by looking for excesses of photon counts compatible with GRBs over a variety of overlapping time windows $\pm 30s$ from the input GW trigger time, using search timescales from 0.064 s to 8.192 s.
- For each time window, a log-likelihood ratio (LLR) is computed. GBM triggers are generated by only keeping the window having the highest LLR if it fulfills the condition LLR $\geq 5$.



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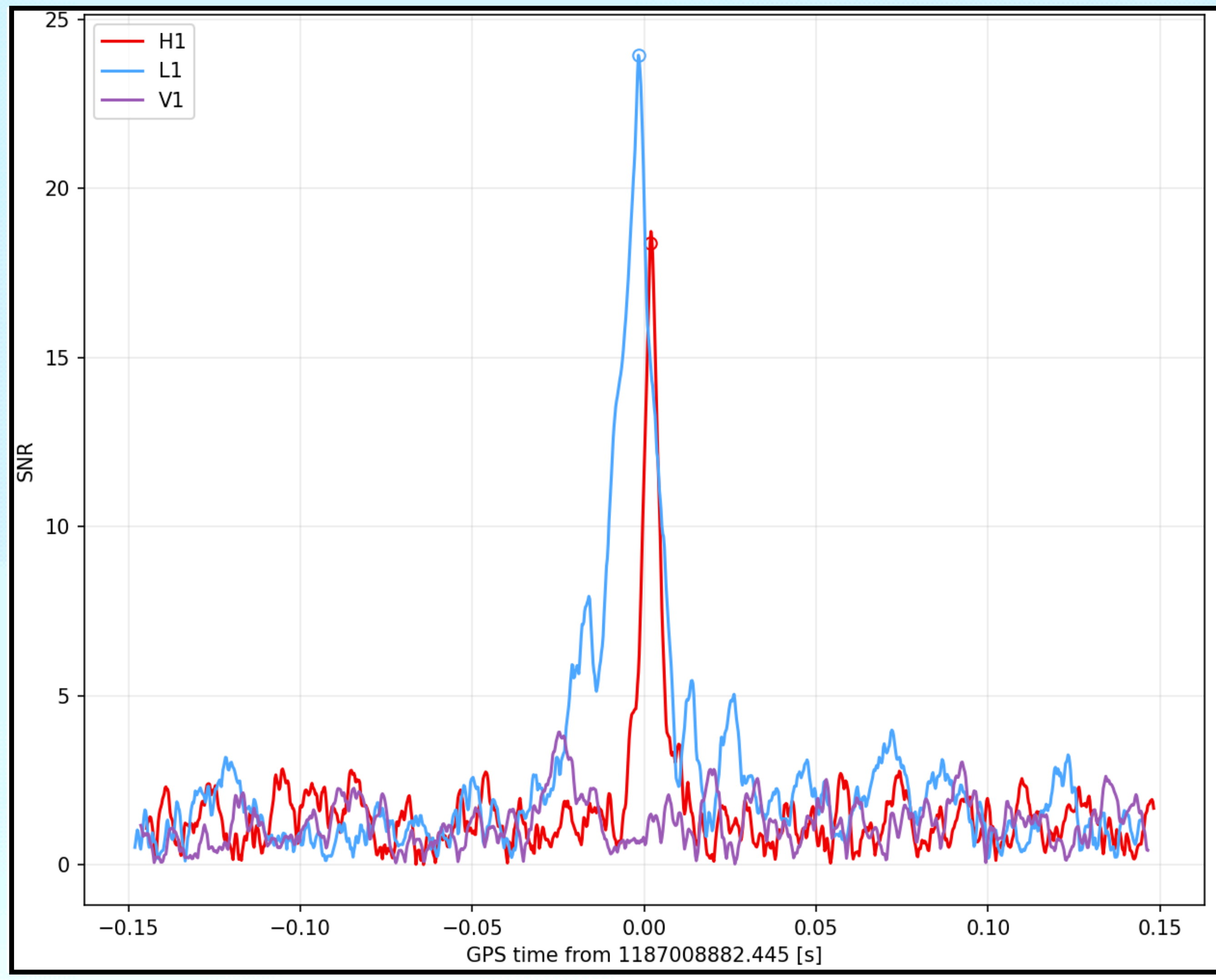


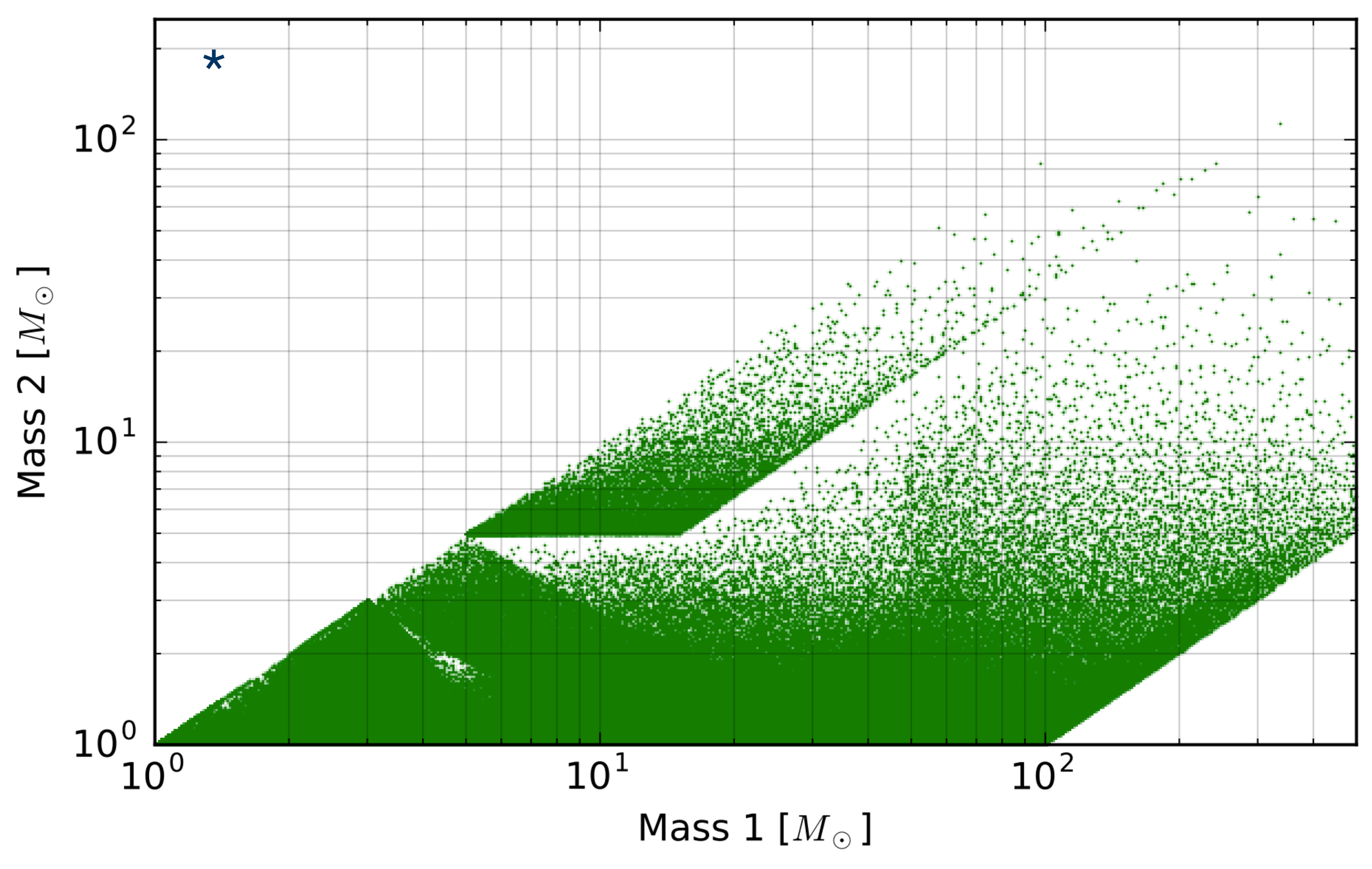


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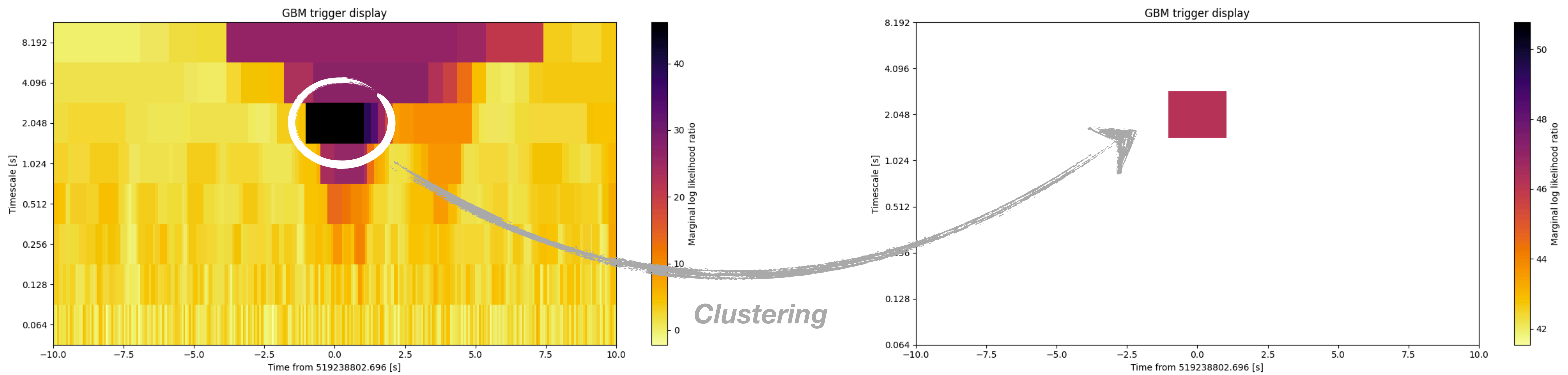


# Introduction

## Overview of joint GW-GRB searches

**RAVEN** — Rapid VOEvent Coincidence Monitor
Low-latency search (seconds)

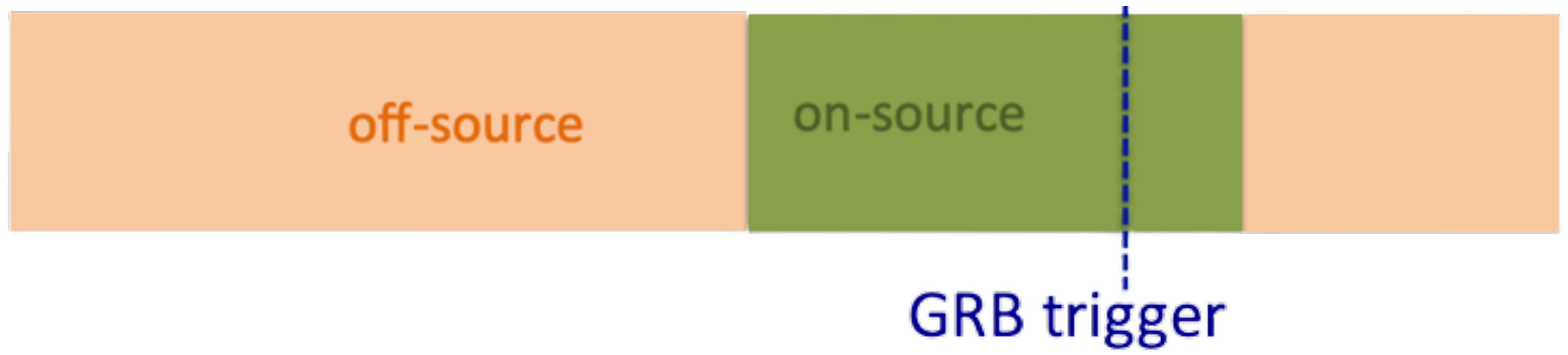
GRB detection + GW candidate → Compatibility in time and sky → Joint FAR threshold → Alert

**PyGRB** — Neutron Star Binary Search Method
Offline search (hours to days)

Non GW detection (e.g. GRB detection) + GW data → Deep search for a nearby GW signal → P-value or Lower limits on the luminosity distance to the GRB

**X-Pipeline** — Generic Transient Search Method
Offline search (hours to days)

GRB detection
Unmodelled GWBs




All these searches have computational or statistical limitations that prevent us from looking at a large number of weak candidates.

**References :**

- *Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift During the LIGO-Virgo Run O3b*: https://arxiv.org/pdf/2111.03608.pdf
- *Searching for Sub-threshold Gravitational Wave Candidates with RAVEN*: Piotrzkowski, Brandon ; LIGO Team
- *X-Pipeline: An analysis package for autonomous gravitational-wave burst searches*: https://arxiv.org/abs/0908.3665

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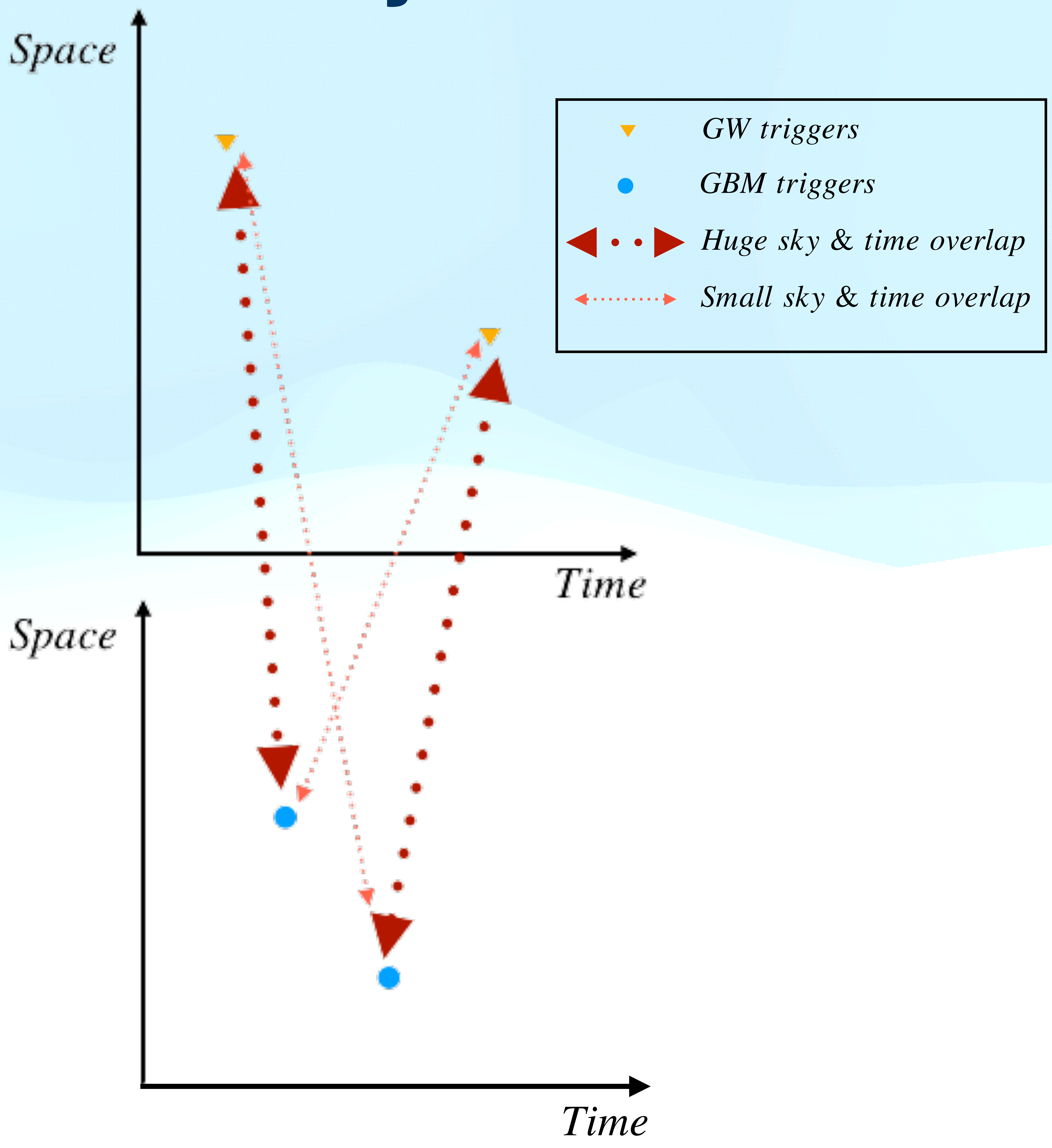
# A deeper method to search for joint detections

## Motivations/Goal

**What we want to do:** look at many weak candidates in the hope of finding more joint detections.

1. Identify **pairs of GW-GBM triggers** which could plausibly originate from a common astrophysical event,
2. Rank the pairs thanks to a **ranking statistics**,
3. And assign a statistical significance (**False Alarm Rate** [s]) to them.




***DEFINITION:***
False Alarm Rate: How often do we expect noise to produce a trigger with the same ranking statistic as the candidate in question?

# A deeper method to search for joint detections

## Method: Ranking statistic

$$\Lambda = \frac{P(D_L, D_G \,|\, H_C)}{P(D_L, D_G \,|\, H_{NN} \bigvee H_{SN} \bigvee H_{NS} \bigvee H_{SS})} \quad (1)$$

**No prior preference assumption** →

$$\Lambda = \frac{I_{\Delta t} I_{\Omega}}{1 + Q_L + Q_G + Q_L Q_G} \quad (2)$$

$H_c$ : both GW & GBM data sets contain **signals** & **common** source

$H_{NN}$ : **noise** in both channels

$H_{SN}$ : **signal** in GW channel and **noise** in GBM data

$H_{NS}$ : the **inverse**

$H_{SS}$ : **signals** in both channels but **unrelated** sources

$Q_L = \frac{P(D_L \,|\, noise)}{P(D_L \,|\, signal)}$ Bayes factor noise-vs-signal , L : GW data

$Q_G = \frac{P(D_G \,|\, noise)}{P(D_G \,|\, signal)}$ Bayes factor noise-vs-signal , G : GBM data

$I_{\Delta t}$ , $I_{\Omega}$ quantify the overlap of the posterior distributions for the time offset and sky locations

Cosmin Stachie et al.: *Search for Advanced LIGO Single Interferometer Compact Binary Coalescence Signals in Coincidence with Gamma-Ray Events in Fermi-GBM* (https://arxiv.org/pdf/2001.01462.pdf)

Greg Ashton et al. : *Coincident Detection Significance in Multimessenger Astronomy* (*https://researchmgt.monash.edu/ws/portalfiles/portal/246473250/246472169_oa.pdf*)

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# A deeper method to search for joint detections

## Method: Ranking statistic

**Association ranking statistic :** $\Lambda = \dfrac{I_{\Delta t} I_{\Omega}}{1 + Q_L + Q_G + Q_L Q_G}$

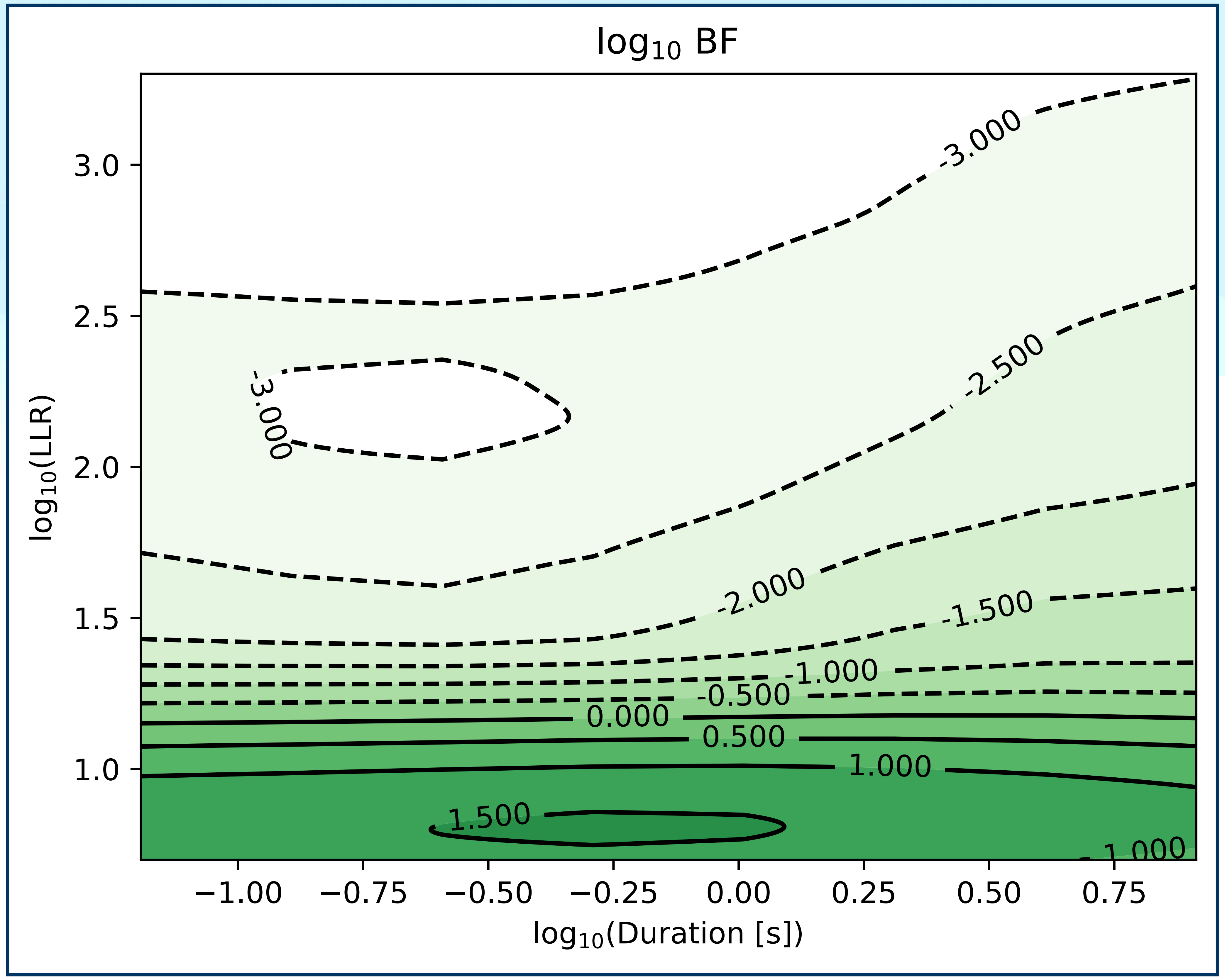
☑ ***GBM Bayes Factor $Q_G$:***

**Method :**

Kernel Density Estimation Method (**KDE**) to compute the probability density function (**PDF**) :

- **Train** a KDE on a training sample in the $log_{10}(duration) - log_{10}(LLR)$ plane:
  - 1 sample of background (**negative** triggers) : **detector noise instances or known non-sGRB source.**
  - 1 of **real* sGRB events** (**positive** triggers) :
- **Evaluate** the KDE on the **data** and get the PDF
- Compute the **ratio of the PDF = Bayes Factor**

$log(Q_G) < 0 \rightarrow signal\text{-}like$




GBM Bayes factor

☐ ***GW Bayes Factor $Q_L$:***

- All GW triggers : skymaps produced with Bayestar give us the BCI : Bayes Factor incoherent signal VS Coherent signal



* GBM triggered targeted search events with T90<2s and >90% probability of being a sGRB

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# A deeper method to search for joint detections

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### GBM Bayes Factor $Q_G$:

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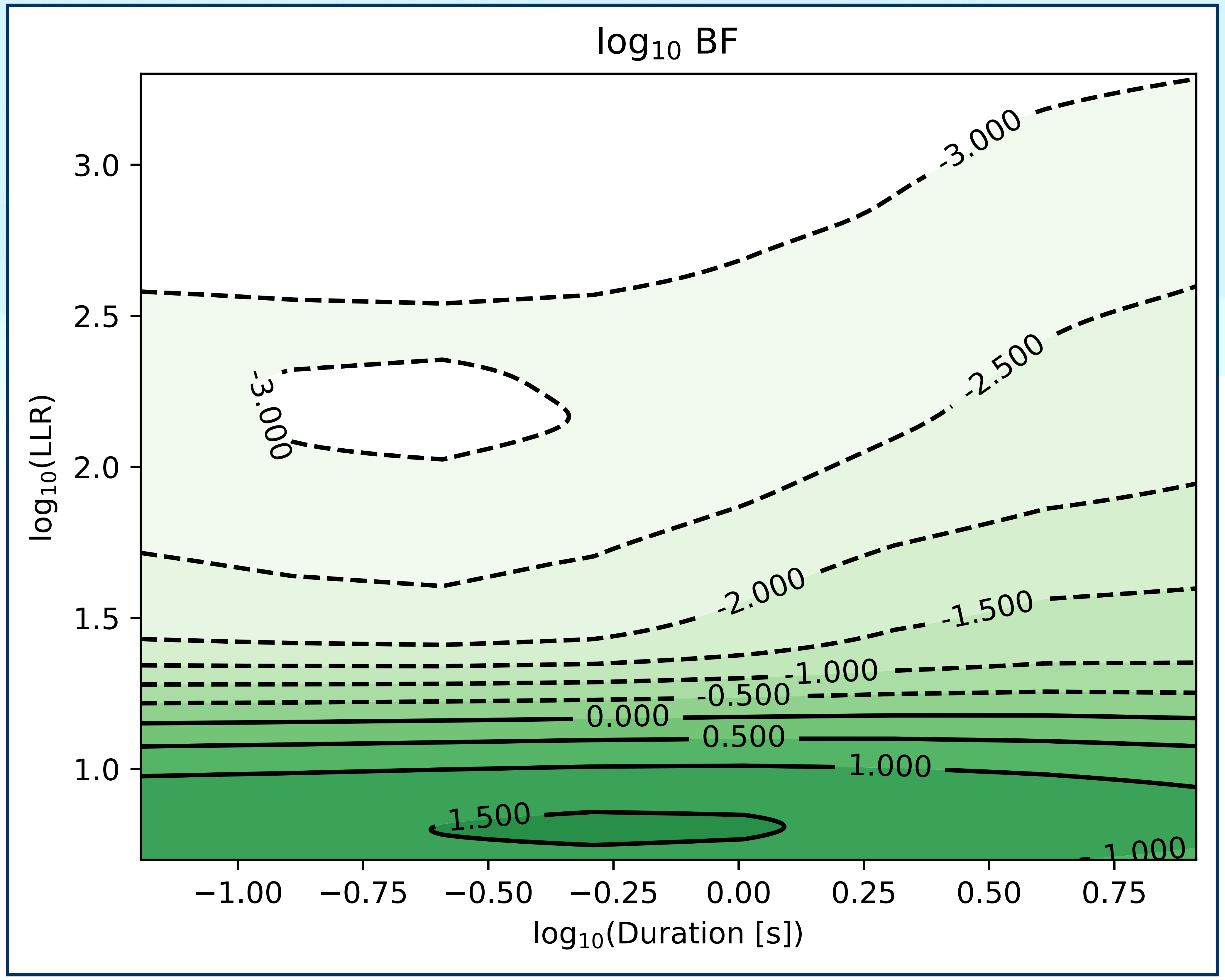


GBM Bayes factor

### GW Bayes Factor $Q_L$:

- All GW triggers : skymaps produced with Bayestar give us the BCI : Bayes Factor Coherent signal VS Incoherent signal

* GBM triggered targeted search events with T90<2s and >90% probability of being a sGRB

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# A deeper method to search for joint detections

## Method: Ranking statistic

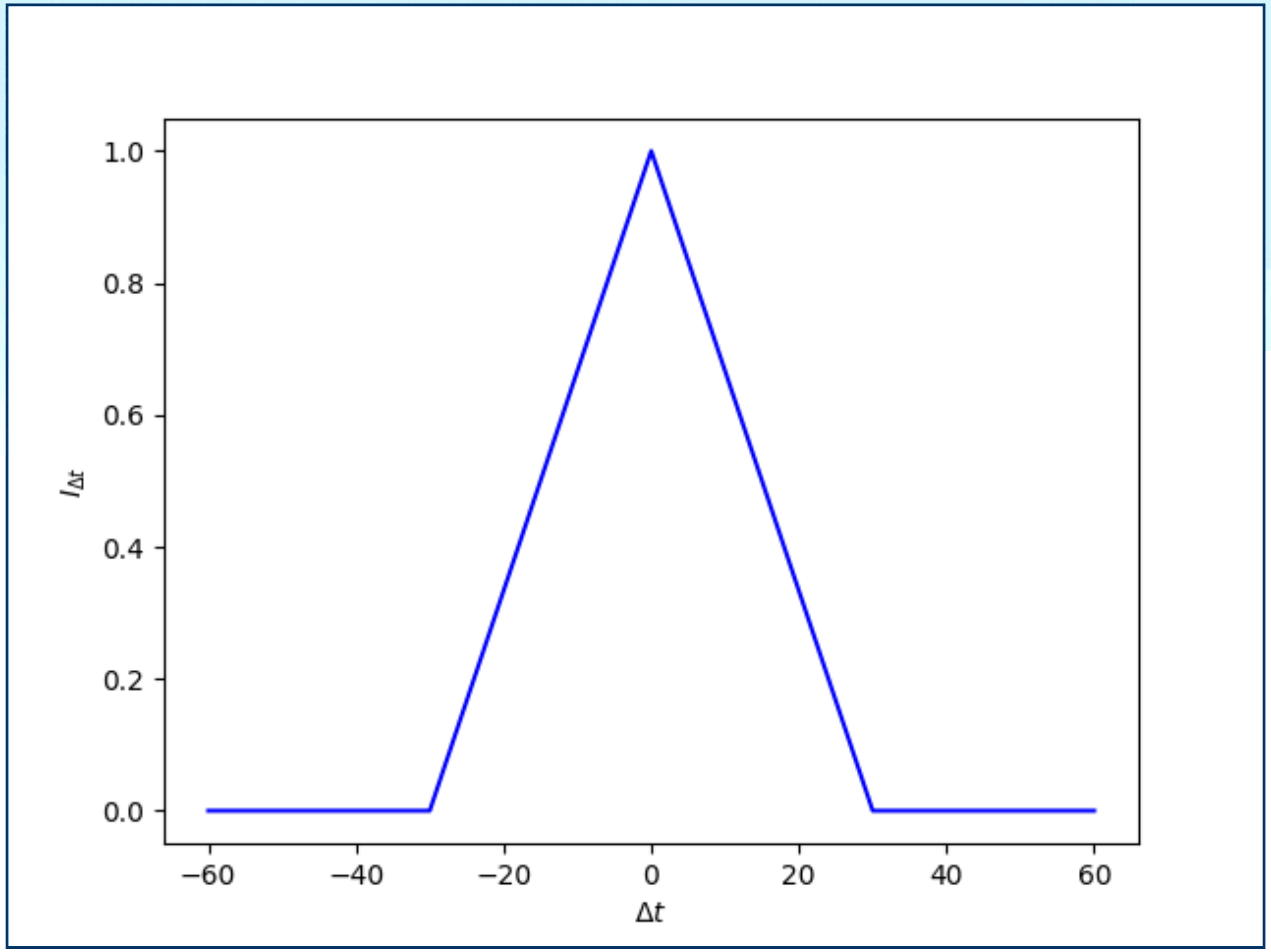
**Association ranking statistic :** $\Lambda = \dfrac{I_{\Delta t} I_{\Omega}}{1 + Q_L + Q_G + Q_L Q_G}$

☑ *Time overlap $I_{\Delta t}$:*

*We introduce:*

$$\Delta t = t_{EM} - t_{GW}$$

$$I_{\Delta t} = \begin{cases} 1 - \dfrac{|\Delta t|}{30} & if\,|\Delta t| < 30s, \\ 0 & otherwise\,. \end{cases} \quad (3)$$




*Time overlap term $I_{\Delta t}$ as a function of the time offset $\Delta t$*

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# A deeper method to search for joint detections

## Method: Ranking statistic

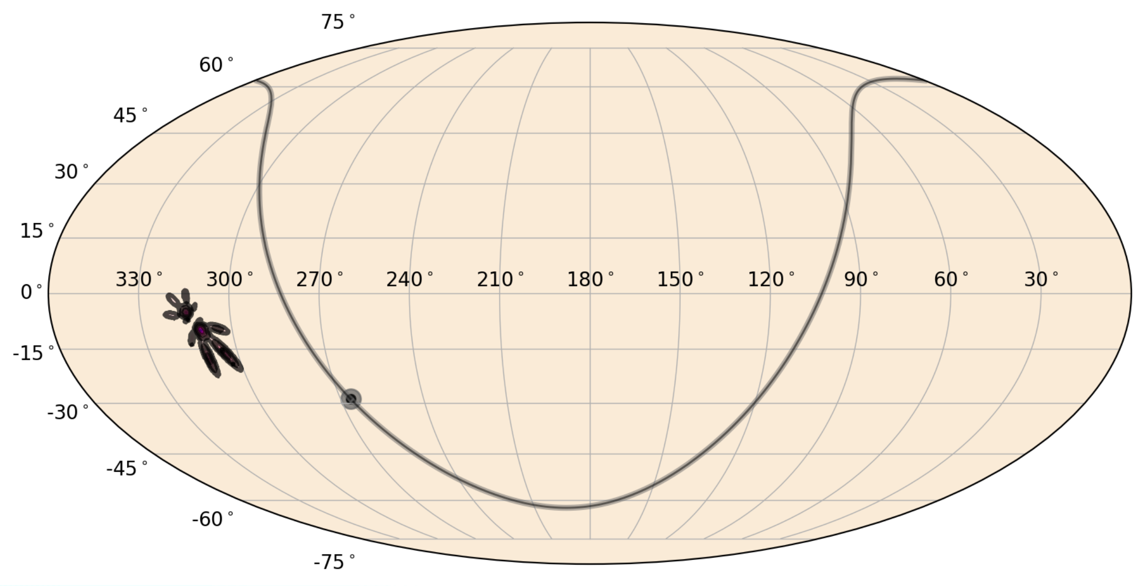
☑ *Sky overlap $I_\Omega$:*

**Ranking statistic :** $\Lambda = \frac{I_{\Delta t} I_\Omega}{1 + Q_L + Q_G + Q_L Q_G}$

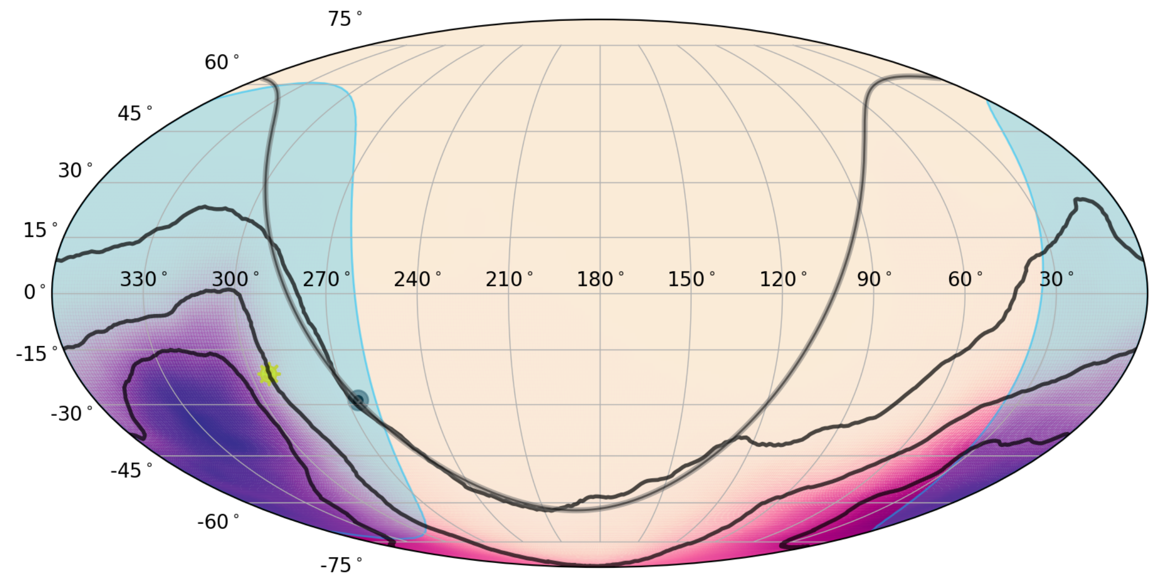
$$I_\Omega^{EA} = 4\pi f_{vis} \int_{\bar{\otimes}} P(\Omega \,|\, GW) P(\Omega \,|\, GBM) d\Omega \quad (4)$$

with $$f_{vis} = \frac{1}{4\pi} \int_{\bar{\otimes}} d\Omega$$

GW skymap



GBM skymap



*When we set to zero the probability behind the Earth the sky term is $I_\Omega^{EA} \approx e^{-21.9}$ and otherwise it is $I_\Omega \approx e^{1.4}$ for a probability for the GBM trigger to be behind the Earth of $83\,\%$. Here the GW trigger is a glitch.*

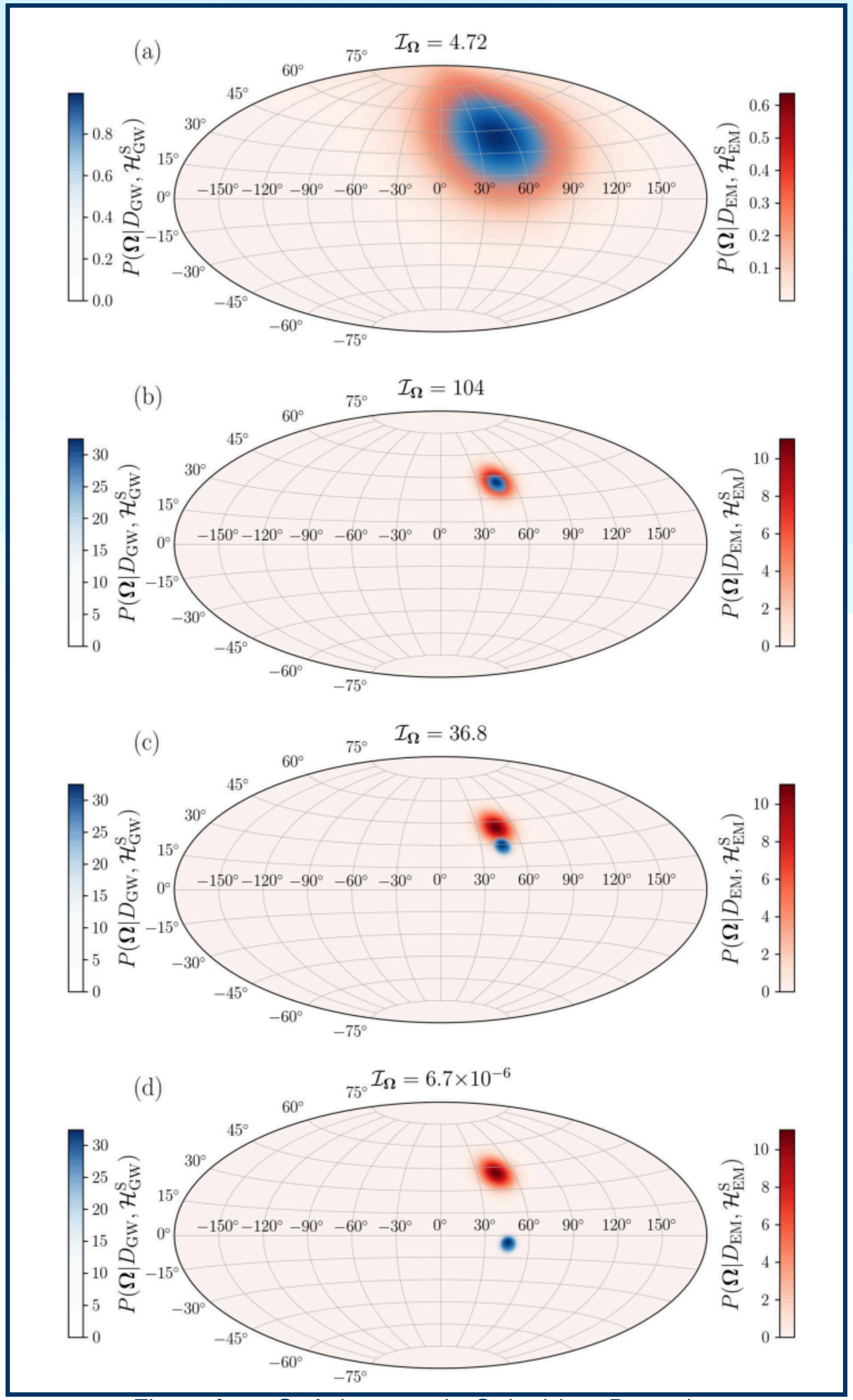


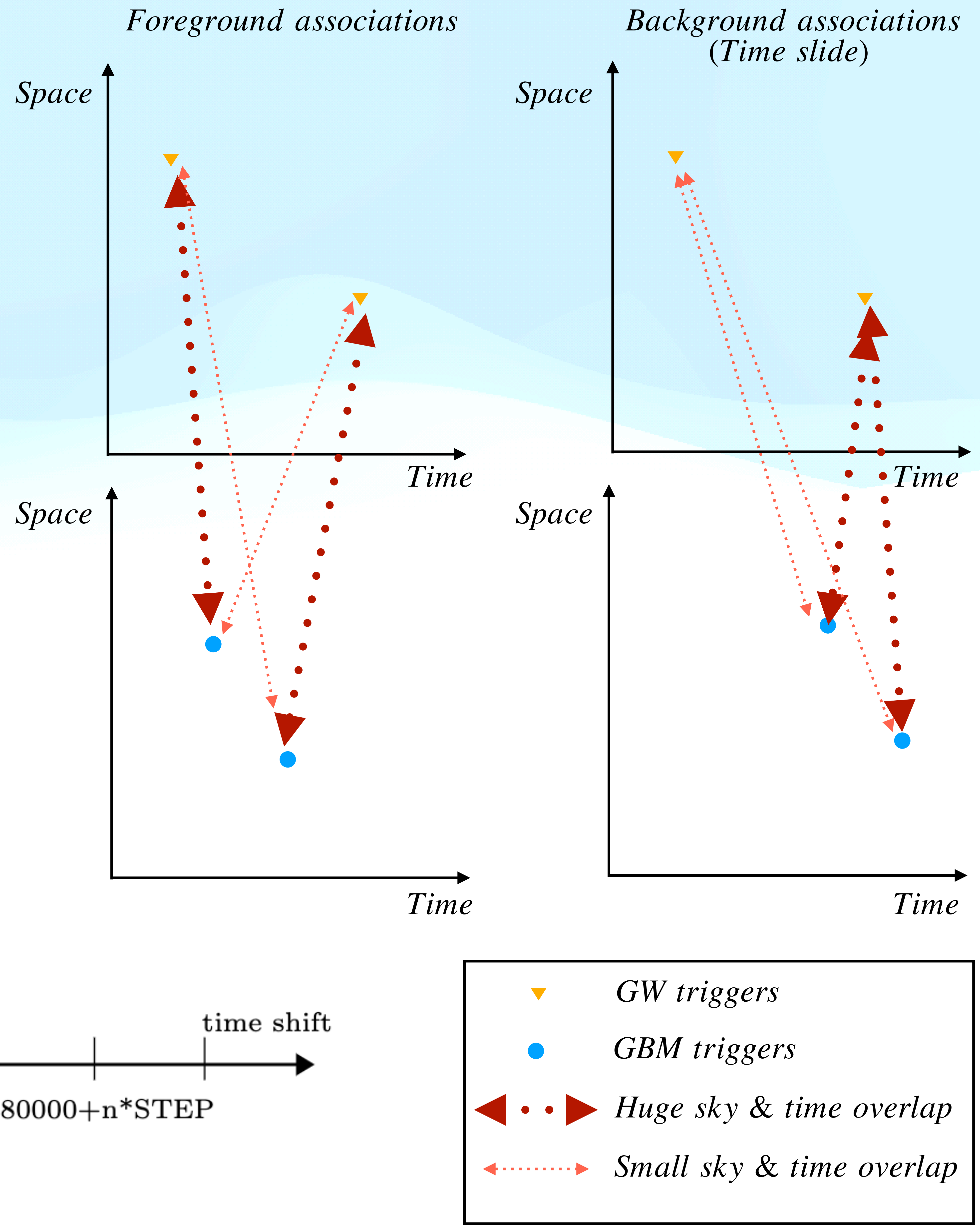

Figure from G. Ashton et al.: *Coincident Detection Significance in Multimessenger Astronomy*

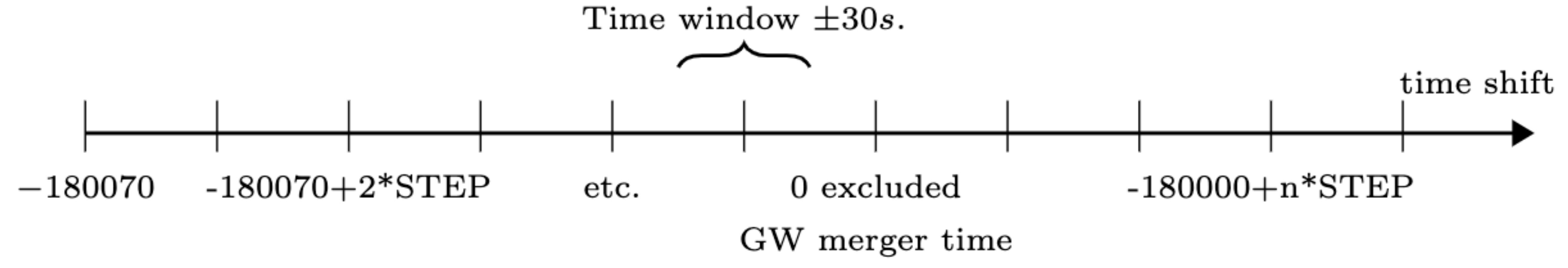
# A deeper method to search for joint detections

## Method: Background computation

***Standard method:***

- Time shift the GBM triggers
- Look for coincidences between GW triggers & time shifted GBM triggers
- Repeat the process for several time shifts




*In this analysis : STEP = 70s*

# A deeper method to search for joint detections

## Results:

- Presentation the results using the PyCBC triggers coming from **the $2^{nd}$ Gravitational-Waves Observing Run** which allowed us to check the validity of our method against **GW170817+GRB170817A**.
- Presentation of the different **configurations** we tested to increase the significance of this joint detection.

| **Configurations:** | **Config 1.** | **Config 2.** | **Config 3.** |
|---|---|---|---|
| • Separating the associations by GBM spectral values and GBM duration. | Yes | No | No |
| • Applying a preliminary cut of the GW triggers based on their false alarm rate. | No | No | Yes |

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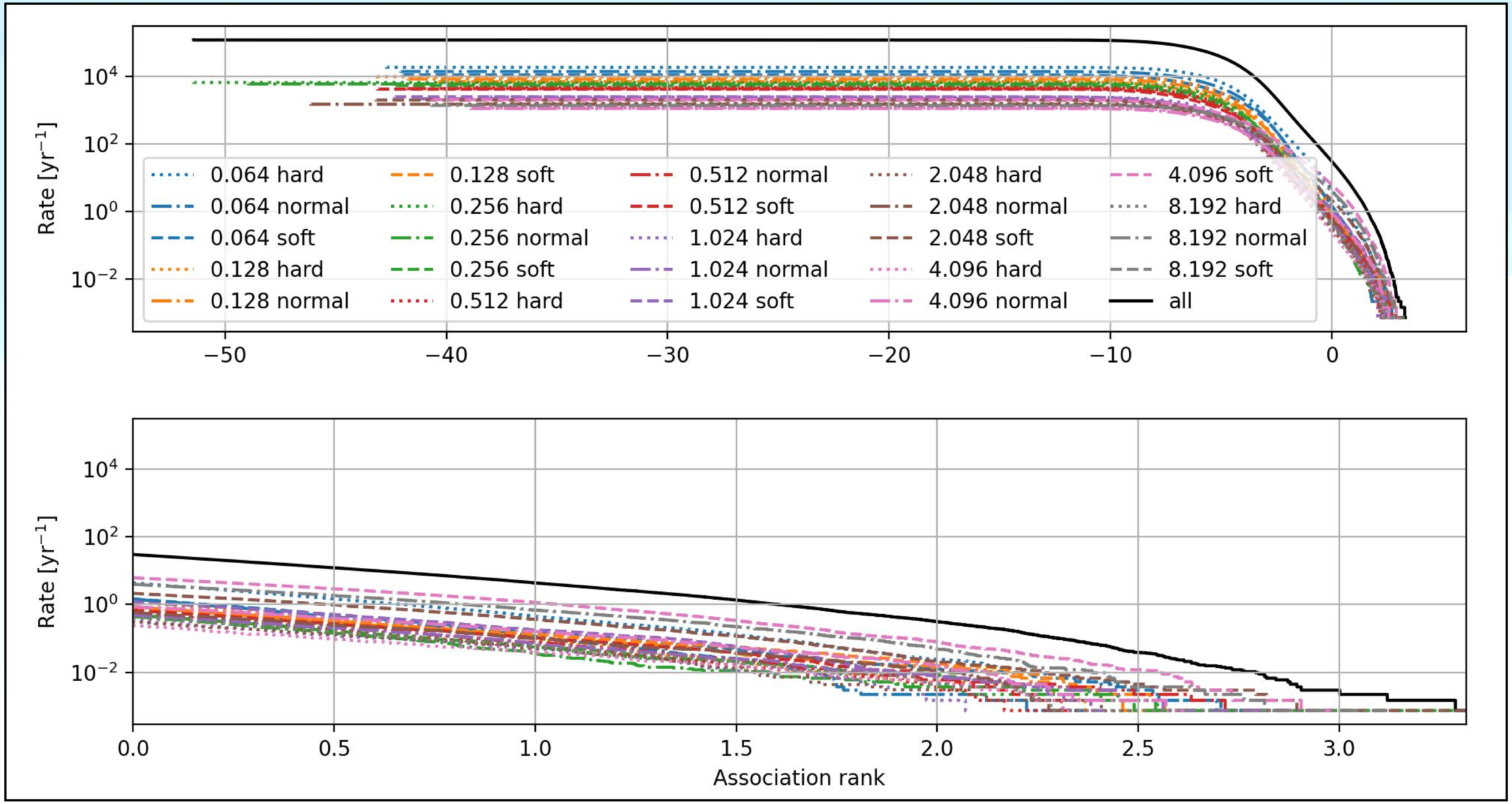
# A deeper method to search for joint detections

## Results: Configuration 1 - Background



# A deeper method to search for joint detections

## Results: Configuration 1 - Most significant background association

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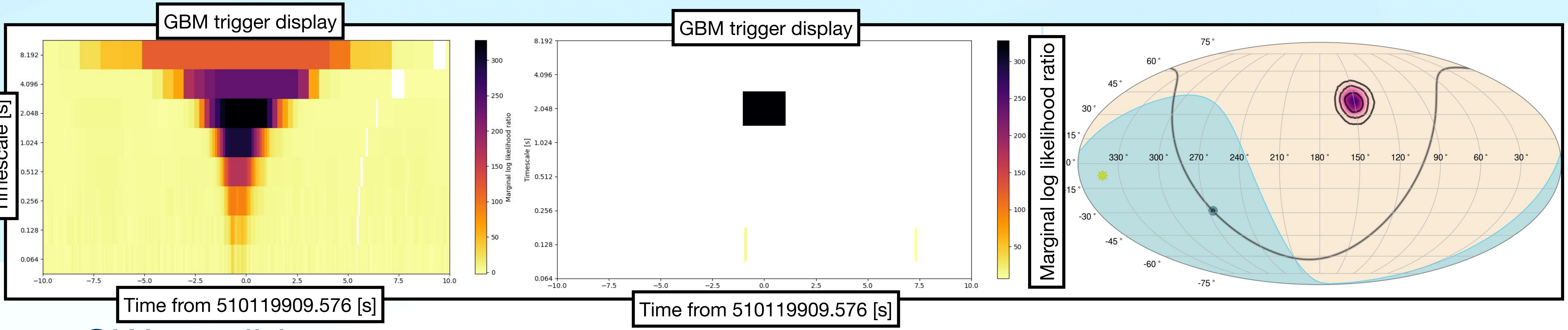
| GW merger time | GBM delay | GBM duration | GBM Spectrum | GBM LLR | GBM BF | GW BF | Sky term | Time shift | Assoc rank |
|---|---|---|---|---|---|---|---|---|---|
| 1172327682.42 | 0.158 | 2.048 | 2 | 328.093 | -6.300 | -0.292 | 3.879 | -134640 | 3.314 |

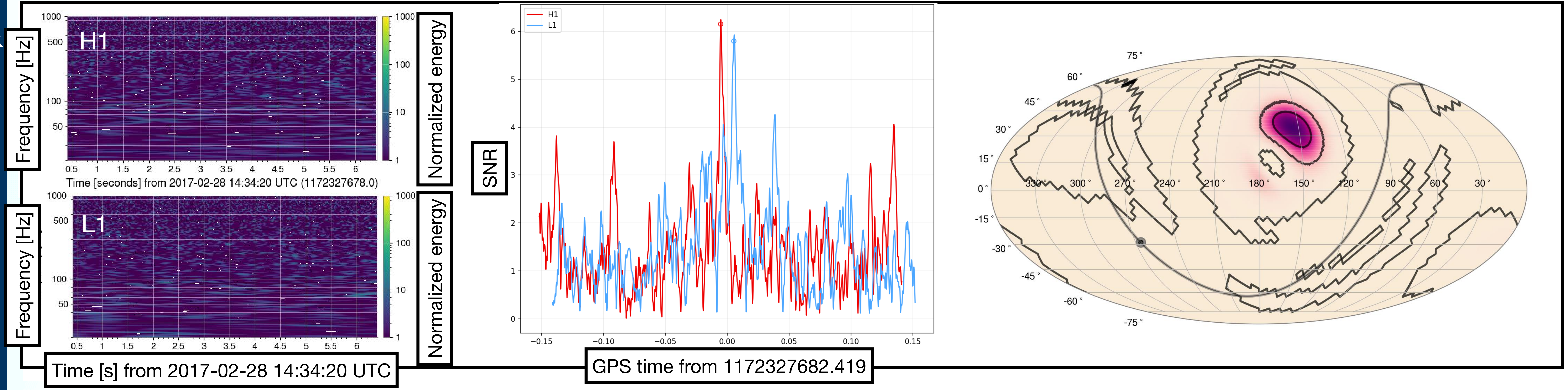
* Duration, delay & time shift : in seconds

** We show the natural log of the Bayes Factor here

*GBM candidate*




*GW candidate*

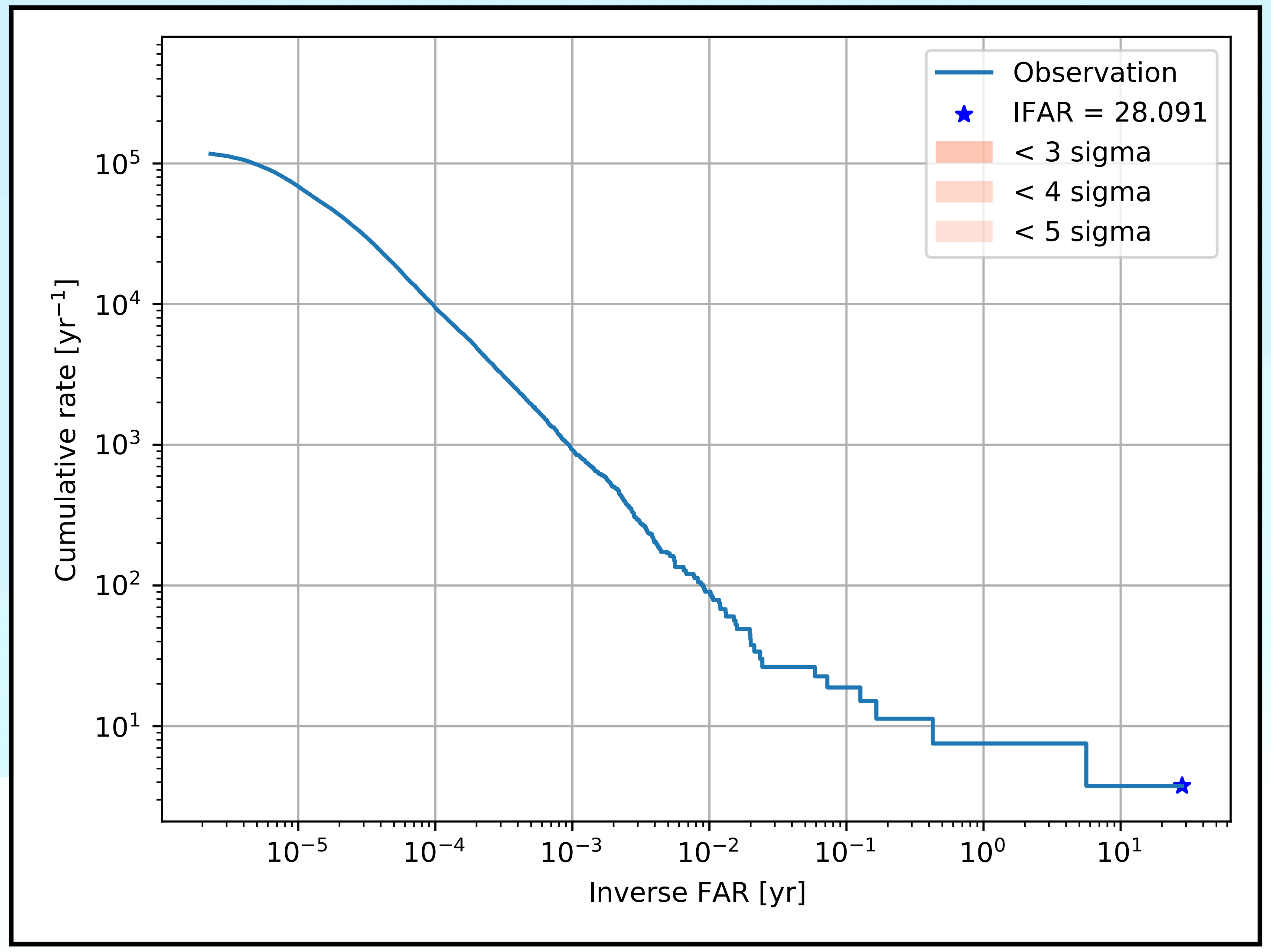


# A deeper method to search for joint detections

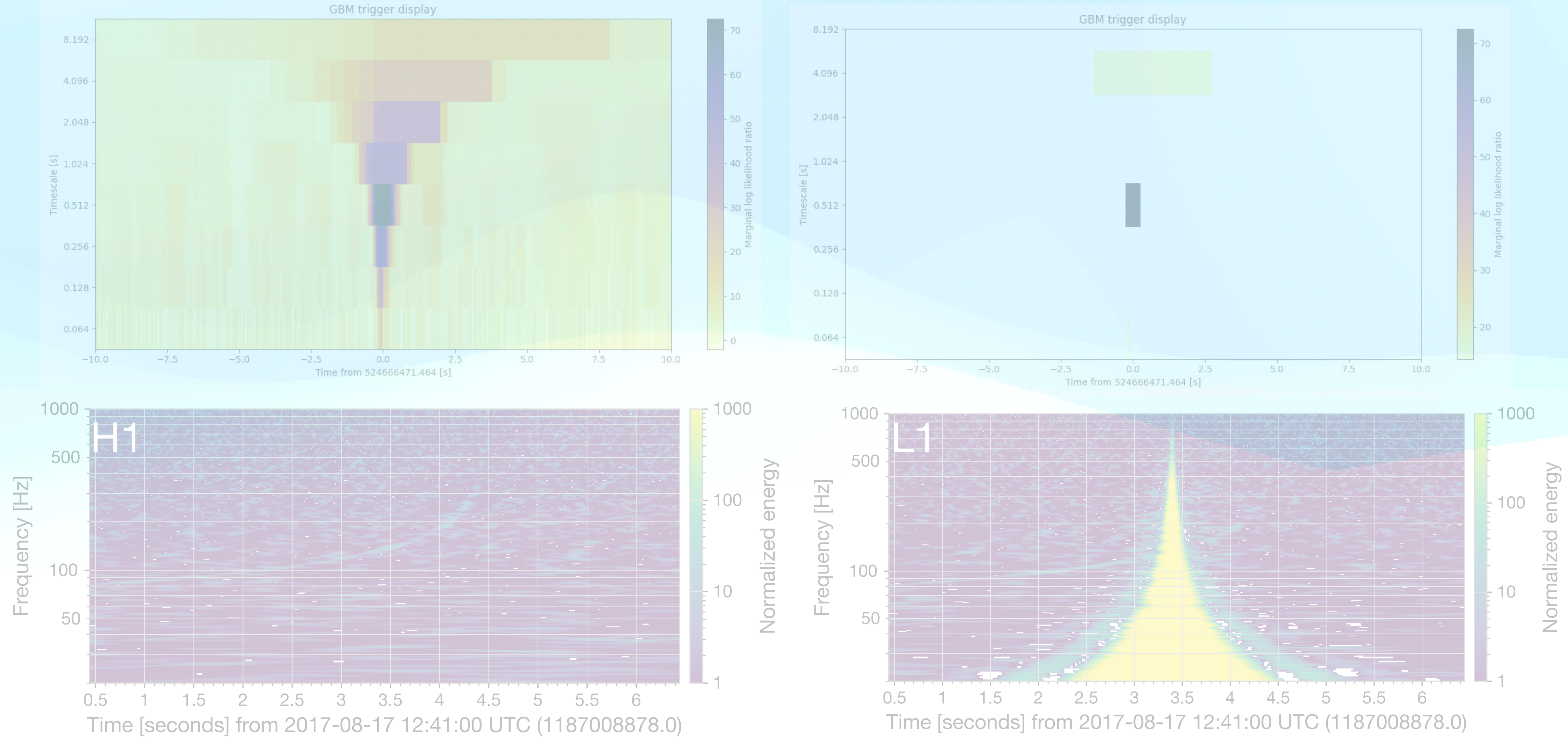
## Results: Configuration 1 - Foreground

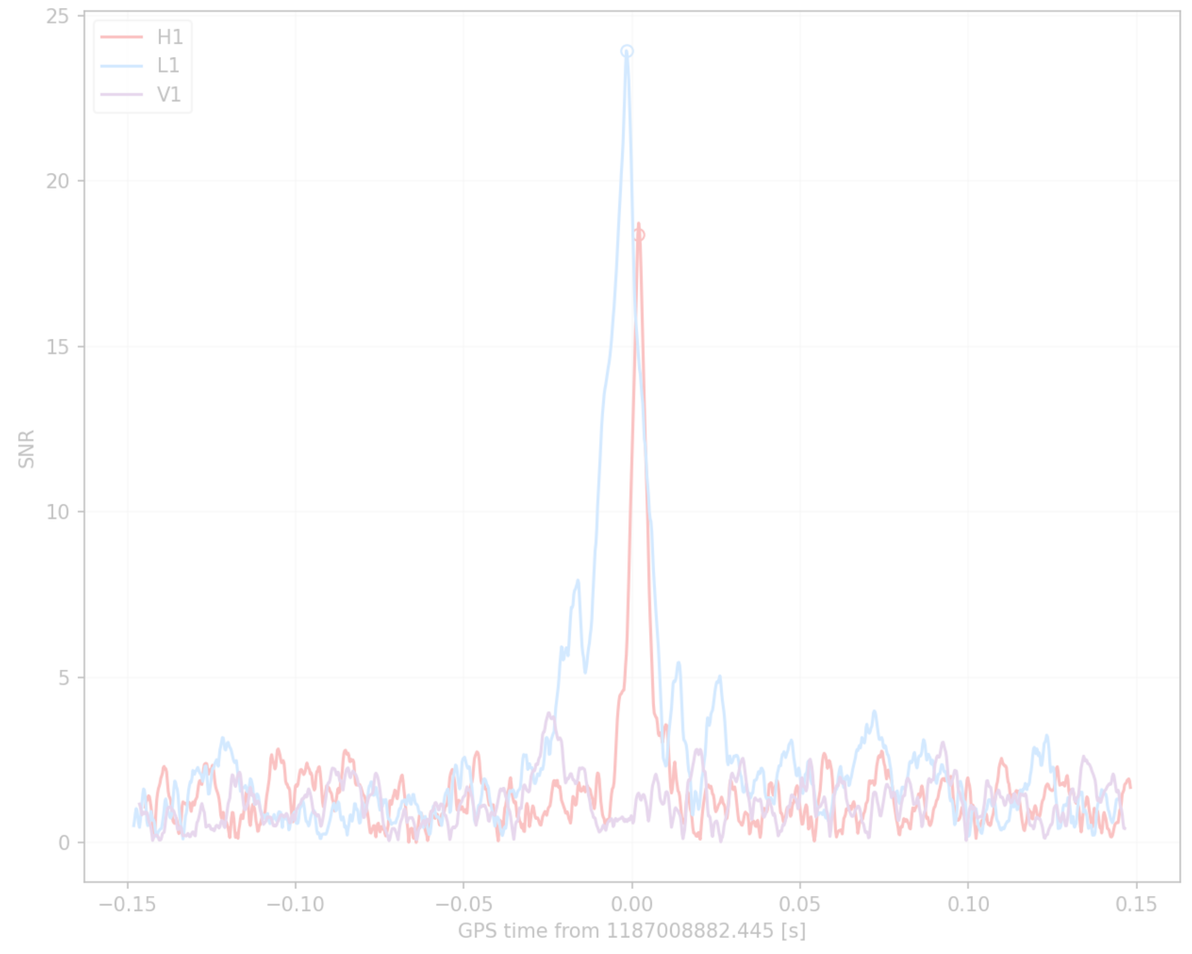
| Rank | GW merger time | GBM delay | GBM duration | GBM Spectrum | GBM LLR | GBM BF | GW BF | Sky term | Assoc rank | IFAR [yr] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1187008882.44 | 2.02 | 0.512 | 1 | 72.514 | -6.263 | -11.974 | 2.846 | 2.774 | 28.091 |
| 2 | 1187008882.44 | 2.72 | 4.096 | 2 | 15.381 | -0.143 | -11.974 | 3.330 | 2.611 | 5.618 |

* Duration, delay & time shift : in seconds
** We show the natural log of the Bayes Factor here

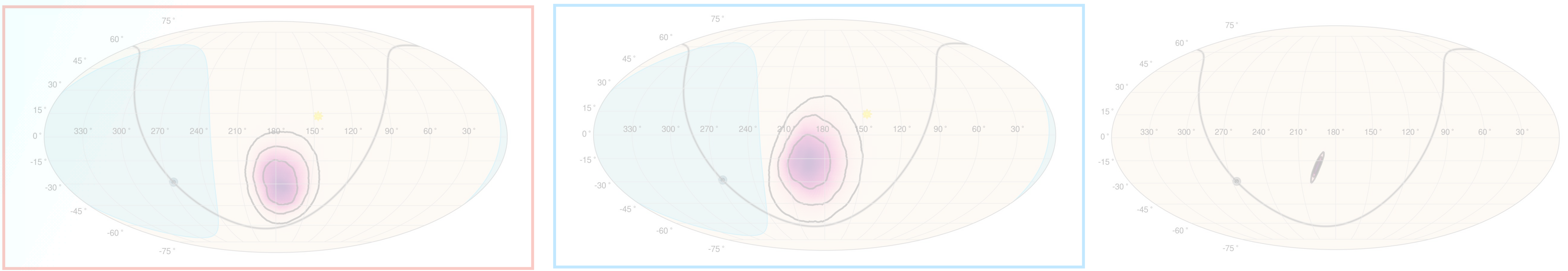



*Cumulative rate as a function of the inverse false alarm rate (IFAR [yr]) for foreground (in solid line) with configuration 1. The foregrounds represent associations between Fermi-GBM candidates and LIGO triggers with no time shift.*




GW skymap



GBM skymap

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# A deeper method to search for joint detections

## Results: Configuration 1 - Foreground

| Rank | GW merger time | GBM delay | GBM duration | GBM Spectrum | GBM LLR | GBM BF | GW BF | Sky term | Assoc rank | IFAR [yr] |
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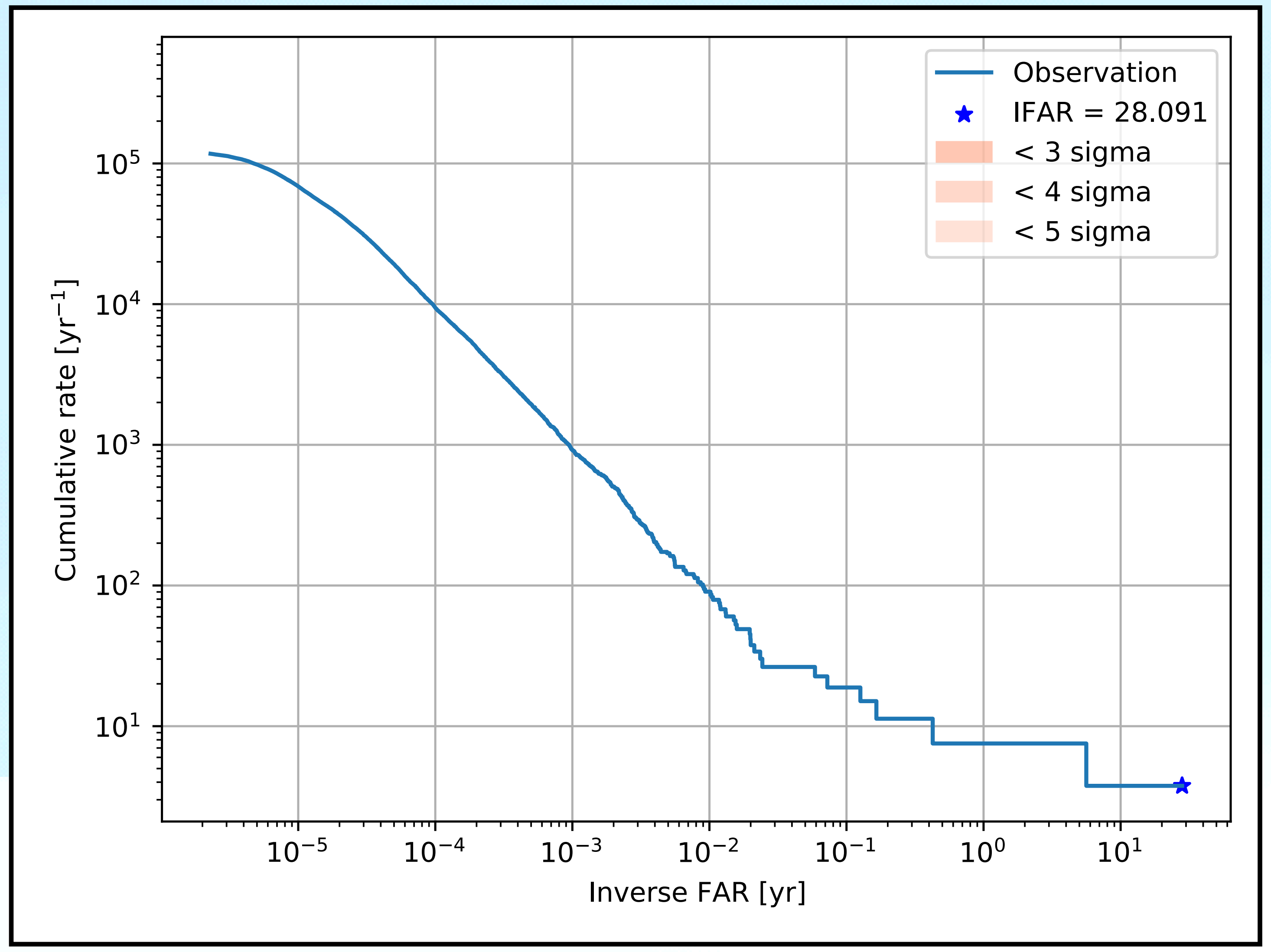


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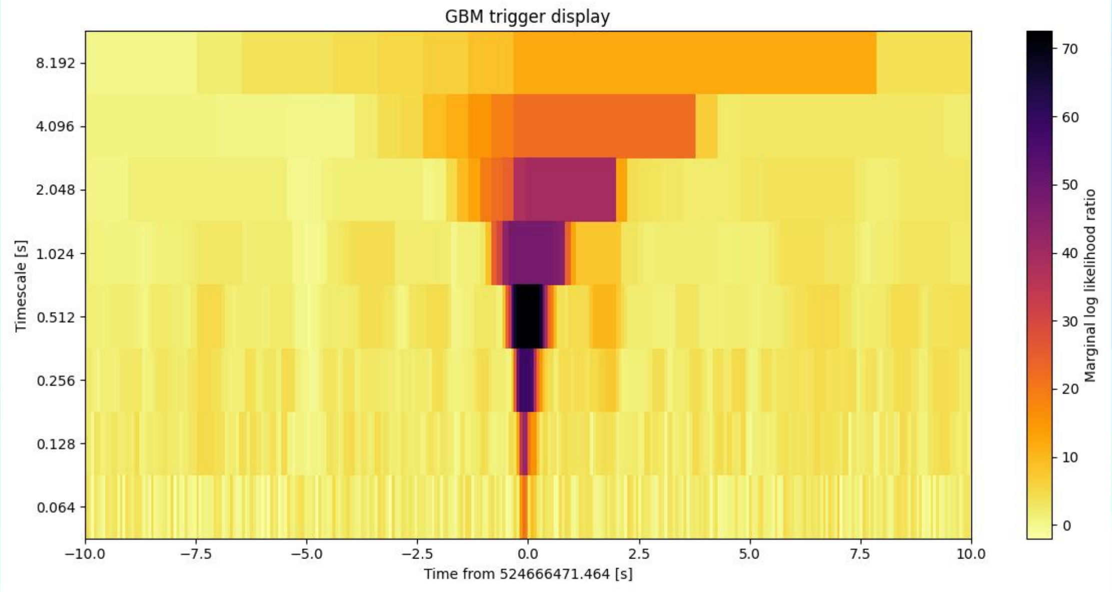
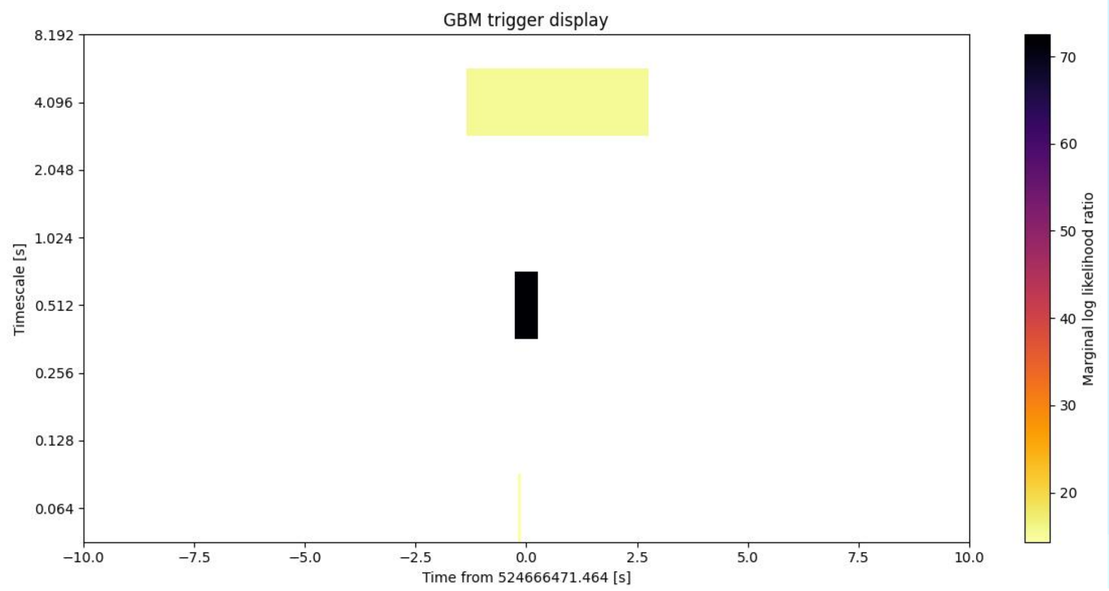
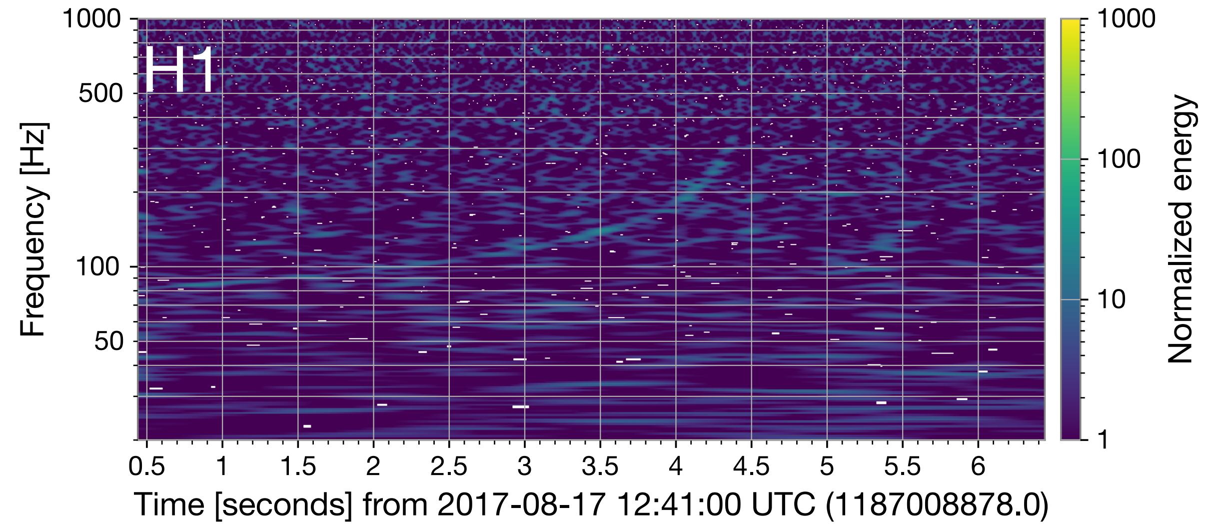
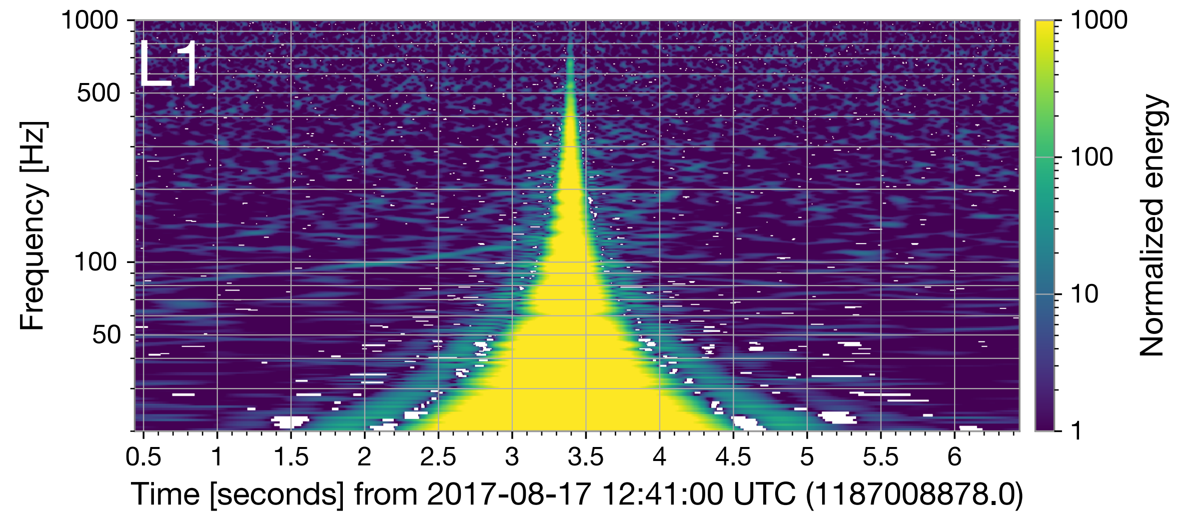
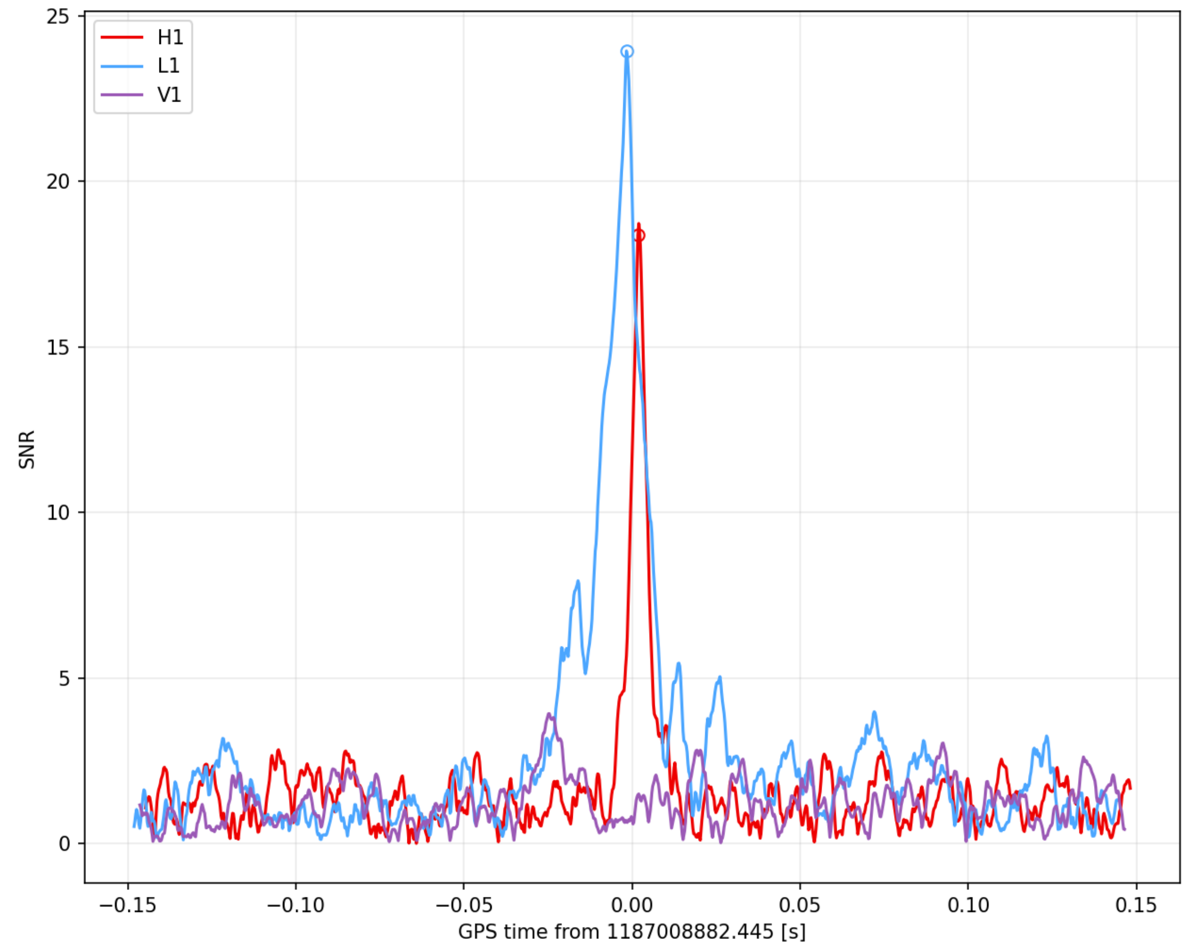


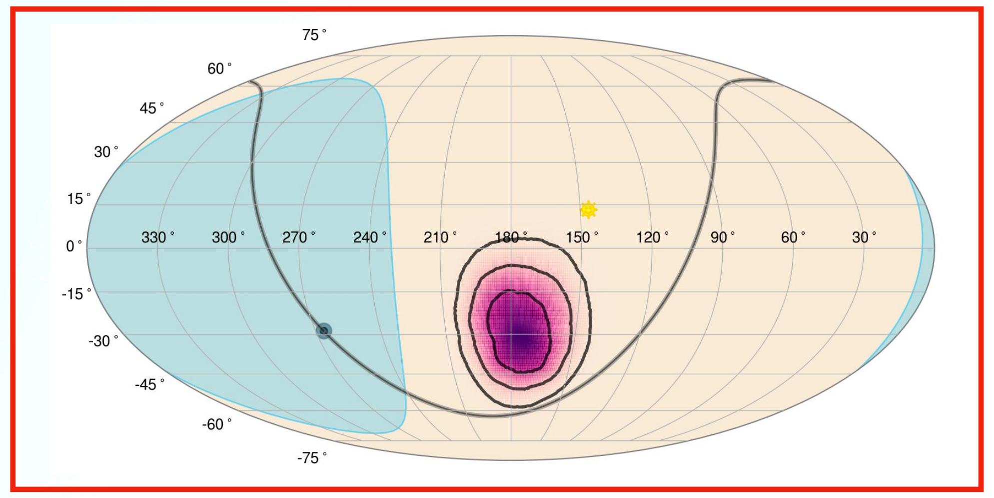



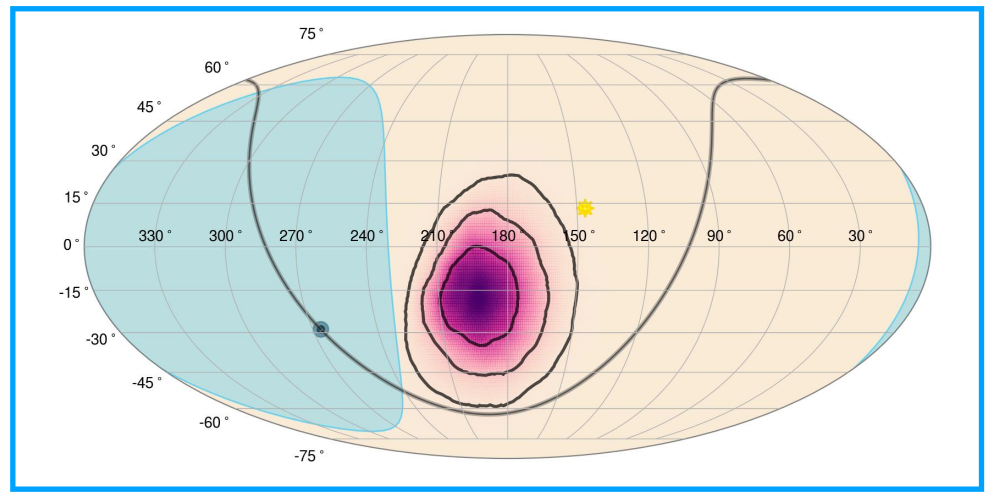



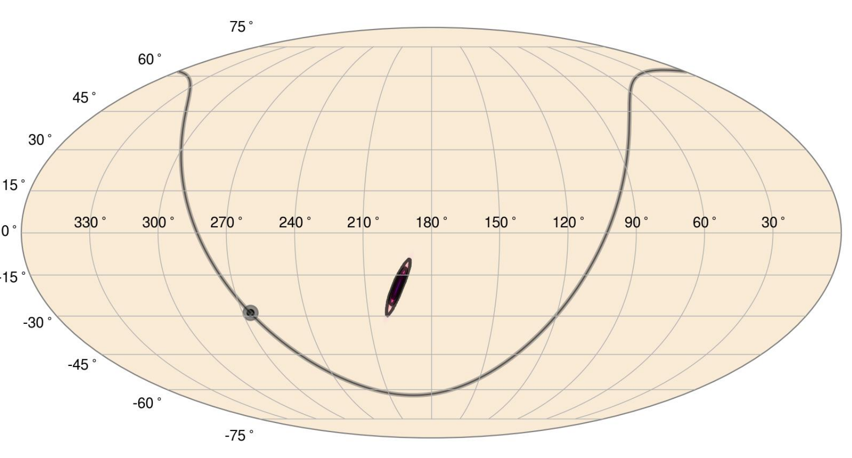




GW skymap



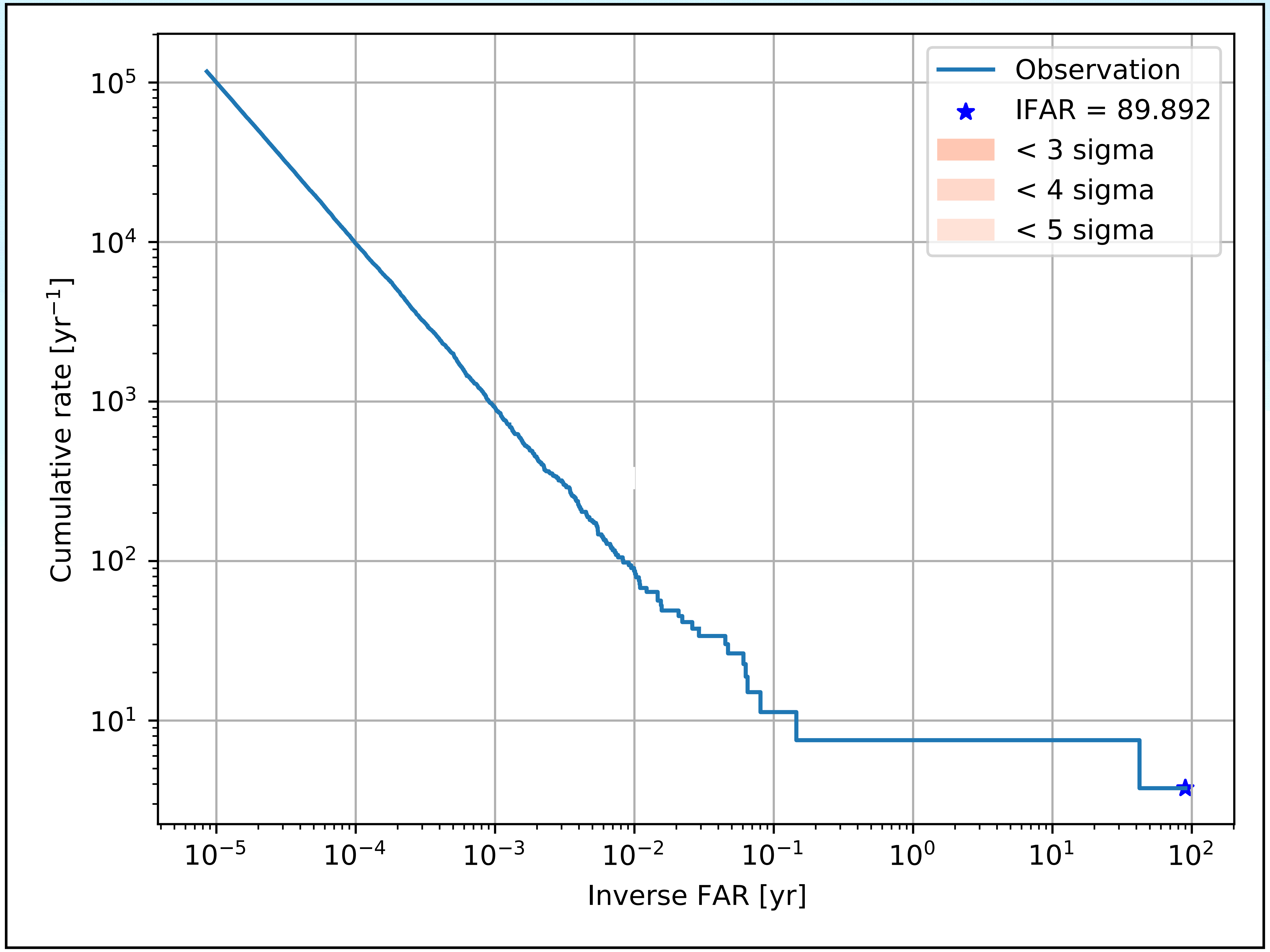




GBM skymap

# A deeper method to search for joint detections

## Results: Configuration 2 - Foreground




*Cumulative rate as a function of the inverse false alarm rate (IFAR [yr]) for foreground (in solid line) with configuration 2: no separation in spectral value and duration. The foregrounds represent associations between Fermi-GBM candidates and LIGO triggers with no time shift.*

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# A deeper method to search for joint detections

## Results: Configuration 1 & 2 - What limits GW170817/GRB170817A significance ?

Some background (time-shifted) associations have a higher association rank.
For example :

| Rank | GW merger time | GBM delay | GBM duration | GBM Spectrum | GBM LLR | GBM BF | GW BF | Sky term | Assoc rank |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1176213122.25 | -6.78 | 0.512 | 1 | 176.576 | -6.857 | -1.209 | 2.846 | 2.878 |

This background association has the same GBM duration and spectral value as GRB170817A so when we separate by spectral value and duration, this association limits the significance of the joint detection.

This association contains a real GRB and noise in the GW channel (with an Inverse **False Alarm Rate =** $4.265 \times 10^{-5} yr$)

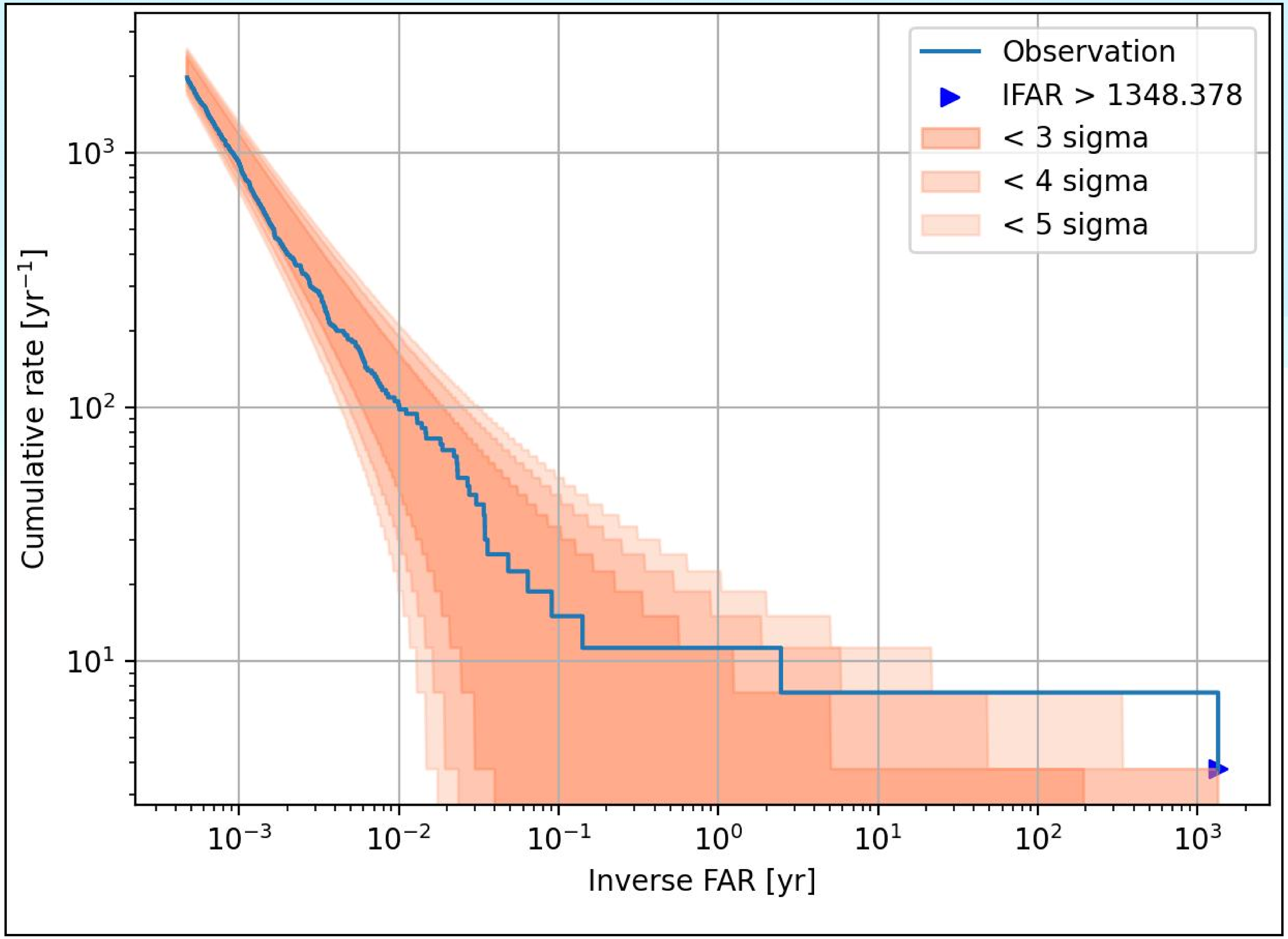
The poor significance of GW170817/GRB170817A is mainly due to the extremely large amount of GW triggers we have to deal with (mainly composed of noise).

**To increase the significance we decide to apply a cut on the GW triggers based on their false alarm rate (FAR) value. We choose a threshold of 2 per day, inspired from GWTC-3 (configuration 3).**

* Duration, delay & time shift : in seconds

# A deeper method to search for joint detections

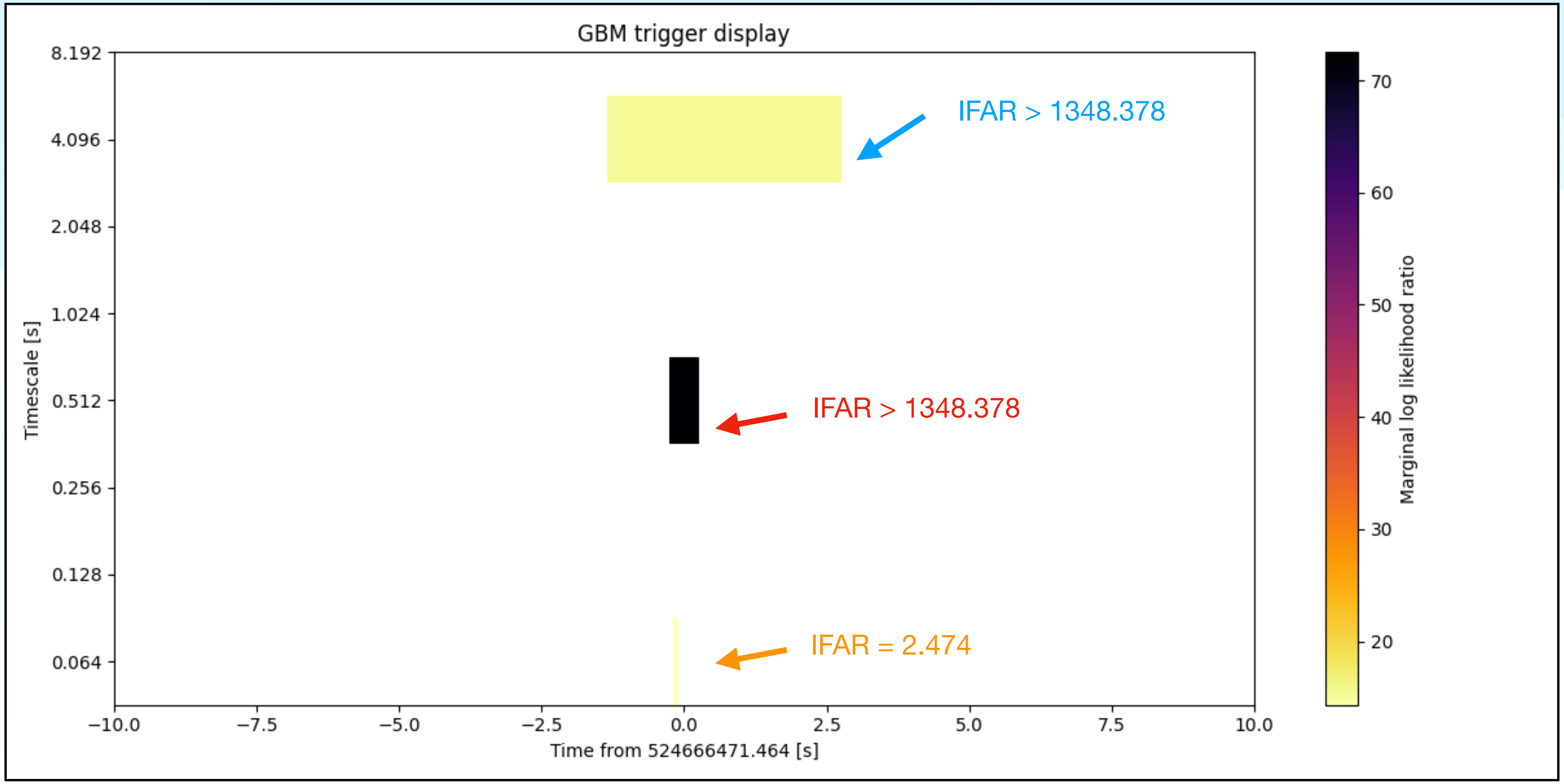
## Results: Configuration 3 - Foreground



# A deeper method to search for joint detections

## Results: Configuration 3 - Foreground

| Rank | GW merger time | GBM delay | GBM duration | GBM Spectrum | GBM LLR | GBM BF | GW BF | Sky term | Assoc rank | IFAR [yr] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1187008882.44 | 2.02 | 0.512 | 1 | 72.514 | -6.263 | -11.974 | 2.846 | 2.774 | >1348.378 |
| 2 | 1187008882.44 | 2.72 | 4.096 | 2 | 15.381 | -0.143 | -11.974 | 3.330 | 2.611 | >1348.378 |
| 3 | 1187008882.44 | 1.859 | 0.064 | 0 | 14.328 | -0.084 | -11.974 | 1.052 | 0.336 | 2.474 |



# Conclusion

## Conclusion

- We were able to analyze a large amount of triggers (~800000 GBM triggers & ~500 GW triggers) and find GW170817 with a high significance!
- When we have to deal with a lot of noise on the GW side, GW170817/GRB170817A is not highly significant.
- We found a configuration that works (number 3).

## Next Steps

- The GW Bayes Factor should be improved: it doesn't discriminate properly between noise and signal.
- Use a stricter time offset prior.
- Apply this method applied on the 3rd Gravitational-Waves Observing Run (O3) data.
- Same for future observing runs.

# Thank you for your attention !