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

## PUMA2022
## 26th - 30th of September

**Marion Pillas, PhD student IJCLab**
**Université Paris-Saclay** marion.pillas@ijclab.in2p3.fr

**Tito Dal Canton, CNRS Researcher, IJCLab,**
**Université Paris Saclay**

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

*Reminder:*
**GRB:** Gamma-Ray-burst, **BNS:** Binary Neutron Star Mergers, **CBC:** Compact Binary Coalescence, **GWB:** Gravitational Wave Burst, **LLR:** Log-Likehood Ratio, **FAR:** False Alarm Rate

# Introduction

## Overview of joint GW-GRB searches

**RAVEN**

**Rapid VOEvent Coincidence Monitor**

- *Low-latency search (seconds)*
- *Time & Sky proximity between candidates*

**PyGRB**

**Neutron Star Binary Search Method**

- *Offline search (hours to days)*
- *Deep modelled search for a GW signal nearby a GRB*

**X-Pipeline**

**Generic Transient Search Method**

- *Offline search (hours to days)*
- *Unmodelled GWBs associated with GRBs*

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*

# A deeper method to search for joint detections

## Motivations & Method

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

**Why more are needed ?** Answer some fundamental questions e.g 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 ?

**What we want to do :** 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** [s]) to them.

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

**No prior preference assumption**

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

$H_c$ : both GW & GBM data sets contain signal & 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

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

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

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

**References:**

- *Cosmin Stachie et al.: Search for Advanced LIGO Single Interferometer Compact Binary Coalescence Signals in Coincidence with Gamma-Ray Events in Fermi-GBM*
- *Greg Ashton et. Al. : Coincident Detection Significance in Multimessenger Astronomy*

# A deeper method to search for joint detections
## Motivations & Method

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

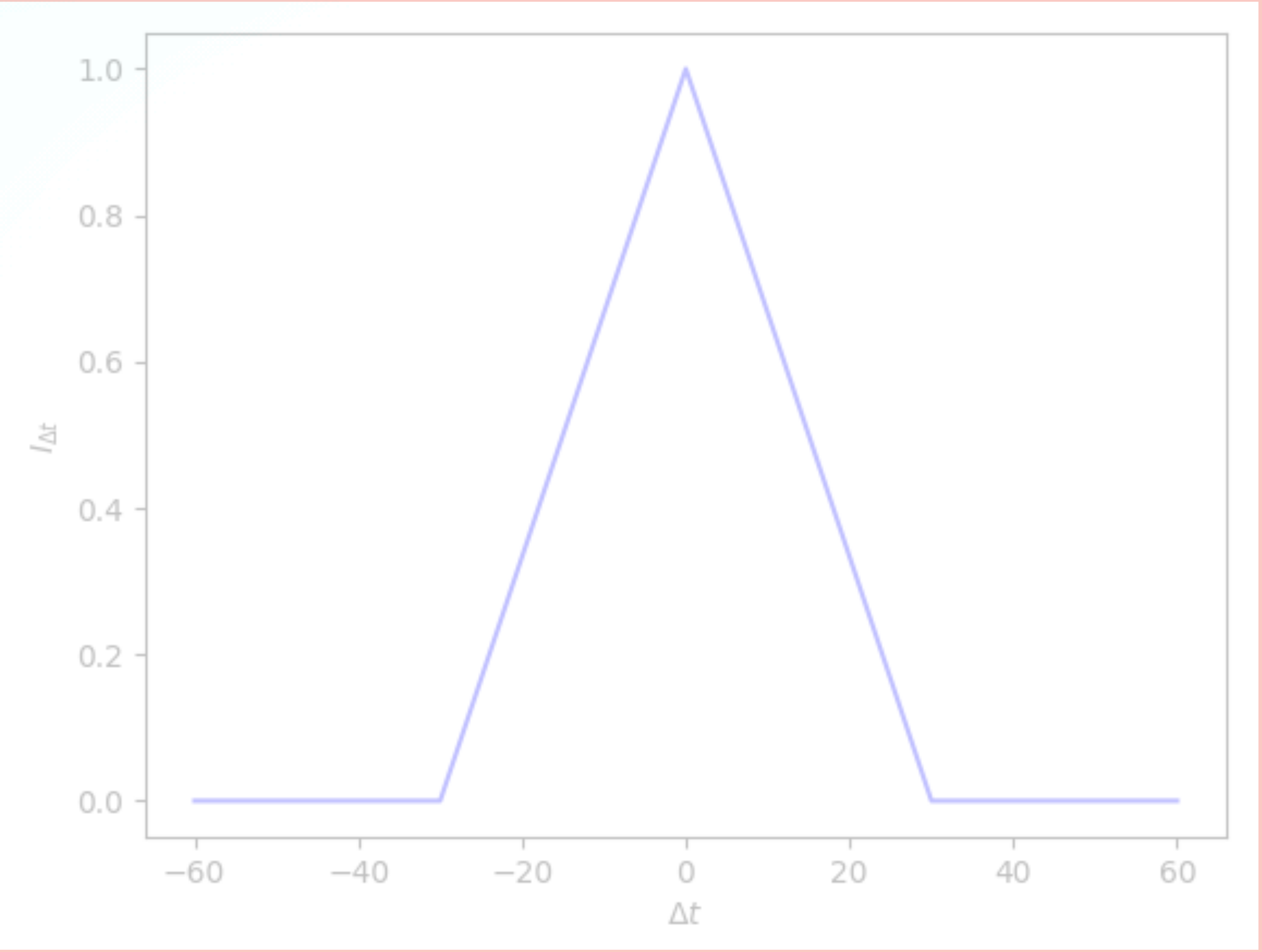
$$I_{\Omega}^{EA} = 4\pi f_{vis} \int_{\bar{\otimes}} P(\Omega \,|\, GW) P(\Omega \,|\, GBM) d\Omega \quad (3)$$

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

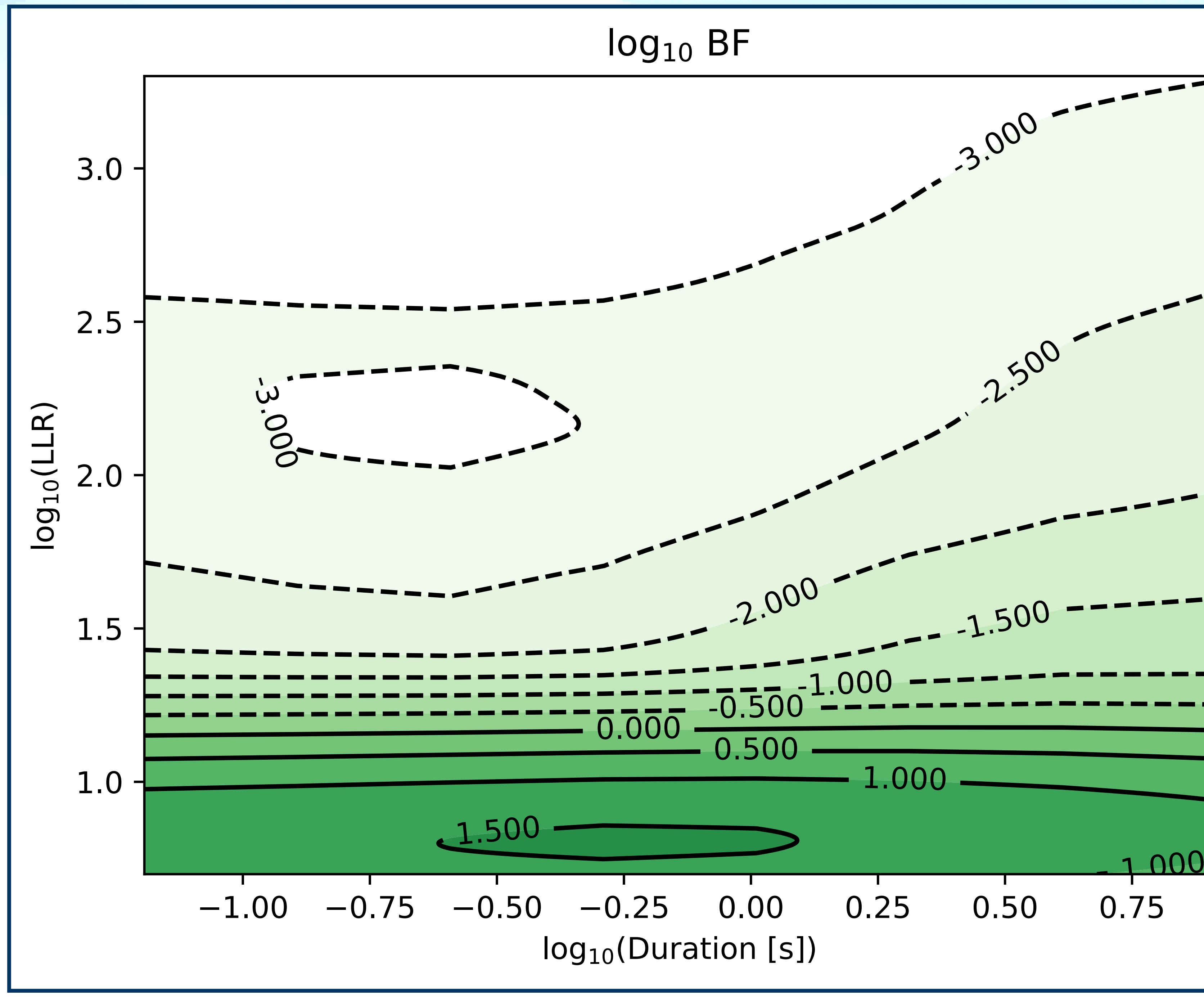
$I_{\Omega}$: Sky overlap

Bayes factor Coherent VS Incoherent signal (from Bayestar)

$Q_L$: GW Bayes Factor:




$I_{\Delta t}$: Time overlap




$Q_G$: GBM pseudo Bayes Factor

$Q_G < 0 \rightarrow$ *signal-like*

# A deeper method to search for joint detections

## Motivations & Method

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

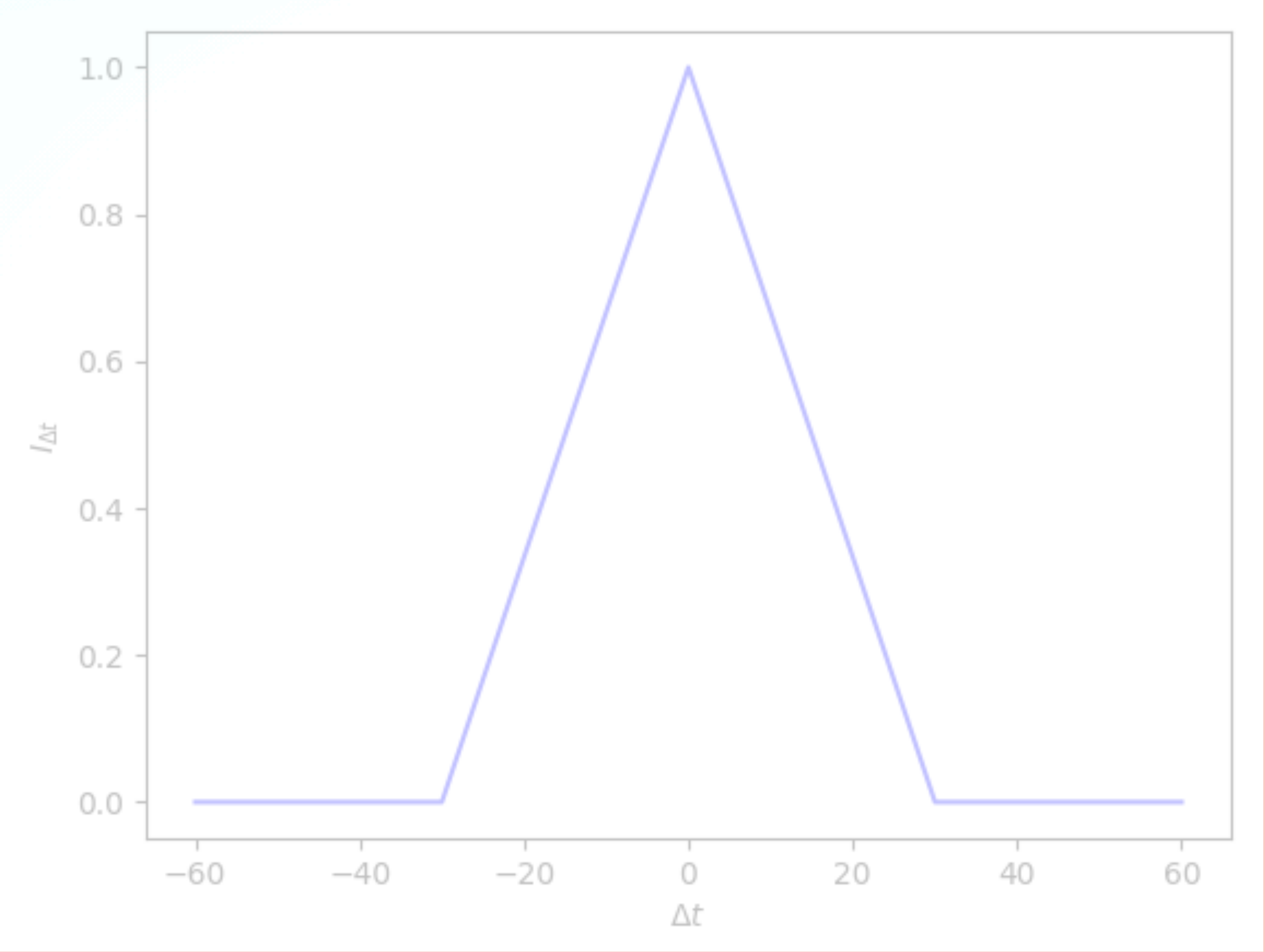
$$I_{\Omega}^{EA} = 4\pi f_{vis} \int_{\bar{\otimes}} P(\Omega|GW) P(\Omega|GBM) d\Omega \quad (3)$$

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

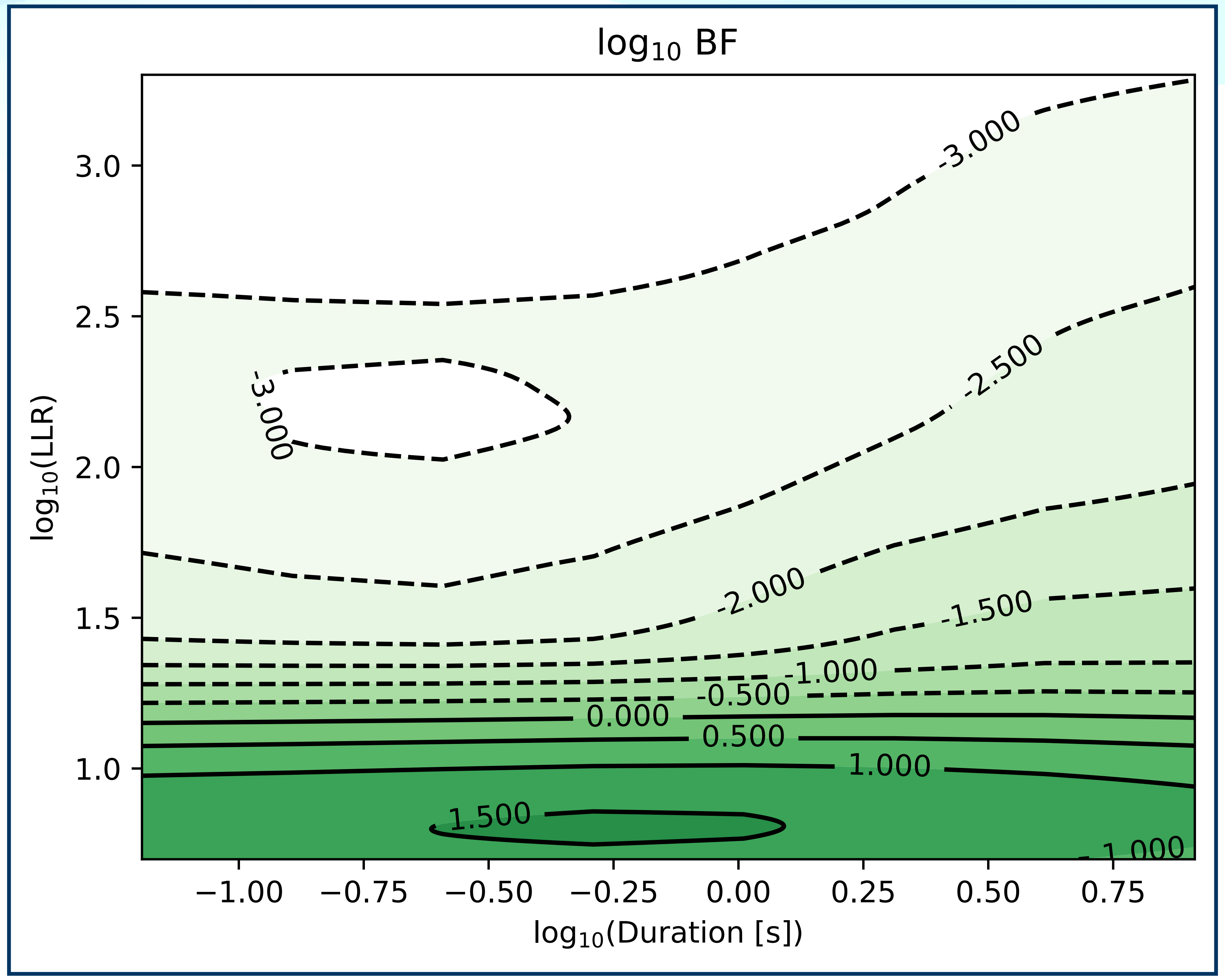
$I_{\Omega}$: Sky overlap

Bayes factor Coherent VS Incoherent signal (from Bayestar)

$Q_L$: GW Bayes Factor:




$I_{\Delta t}$: Time overlap




$Q_G$: GBM pseudo Bayes Factor

!

$Q_G < 0 \rightarrow$ *signal-like*

# A deeper method to search for joint detections
## Motivations & Method

TABLE OF CONTENTS



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

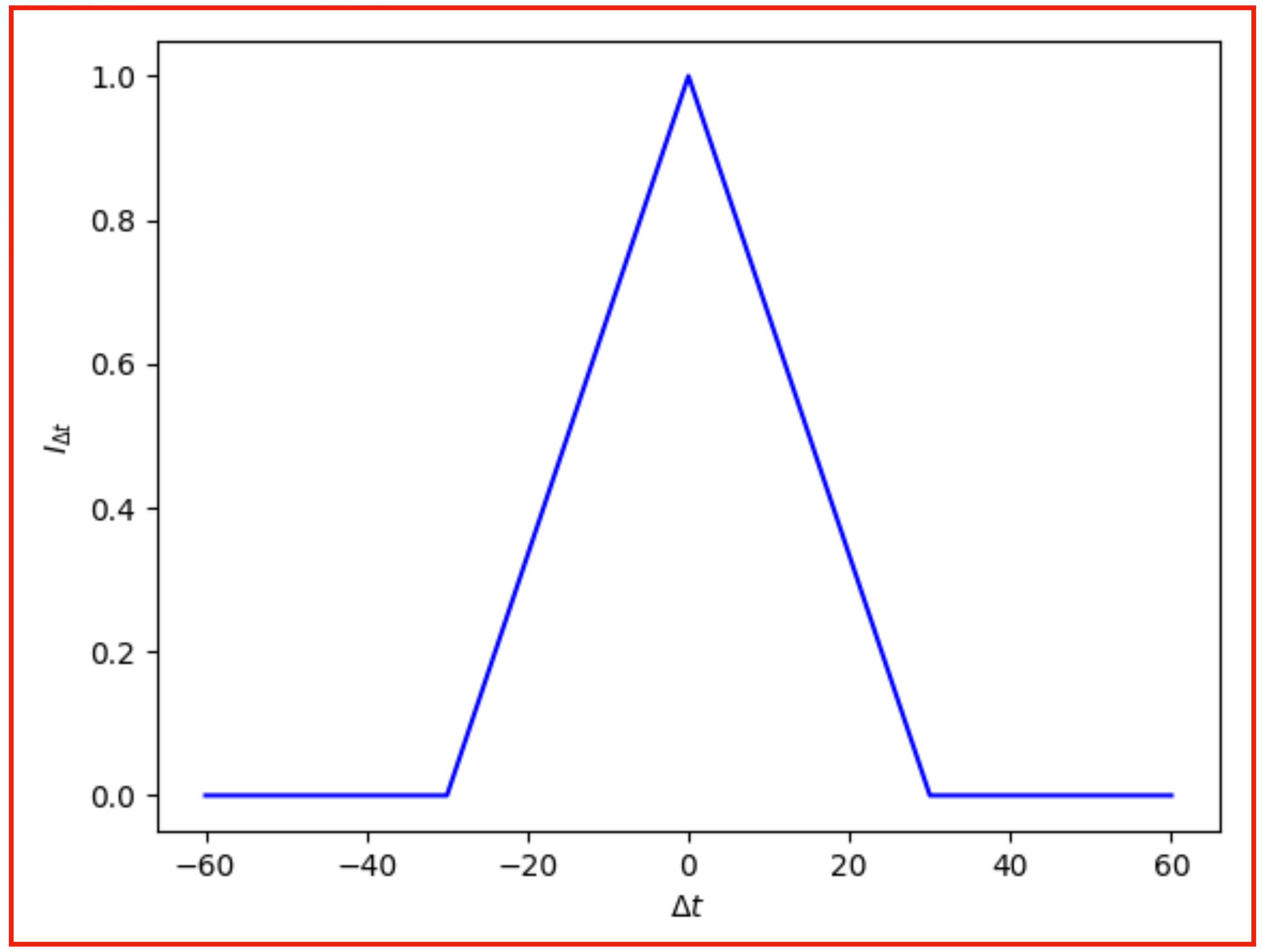
$$I_{\Omega}^{EA} = 4\pi f_{vis} \int_{\bar{\otimes}} P(\Omega | GW) P(\Omega | GBM) d\Omega \qquad (3)$$

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

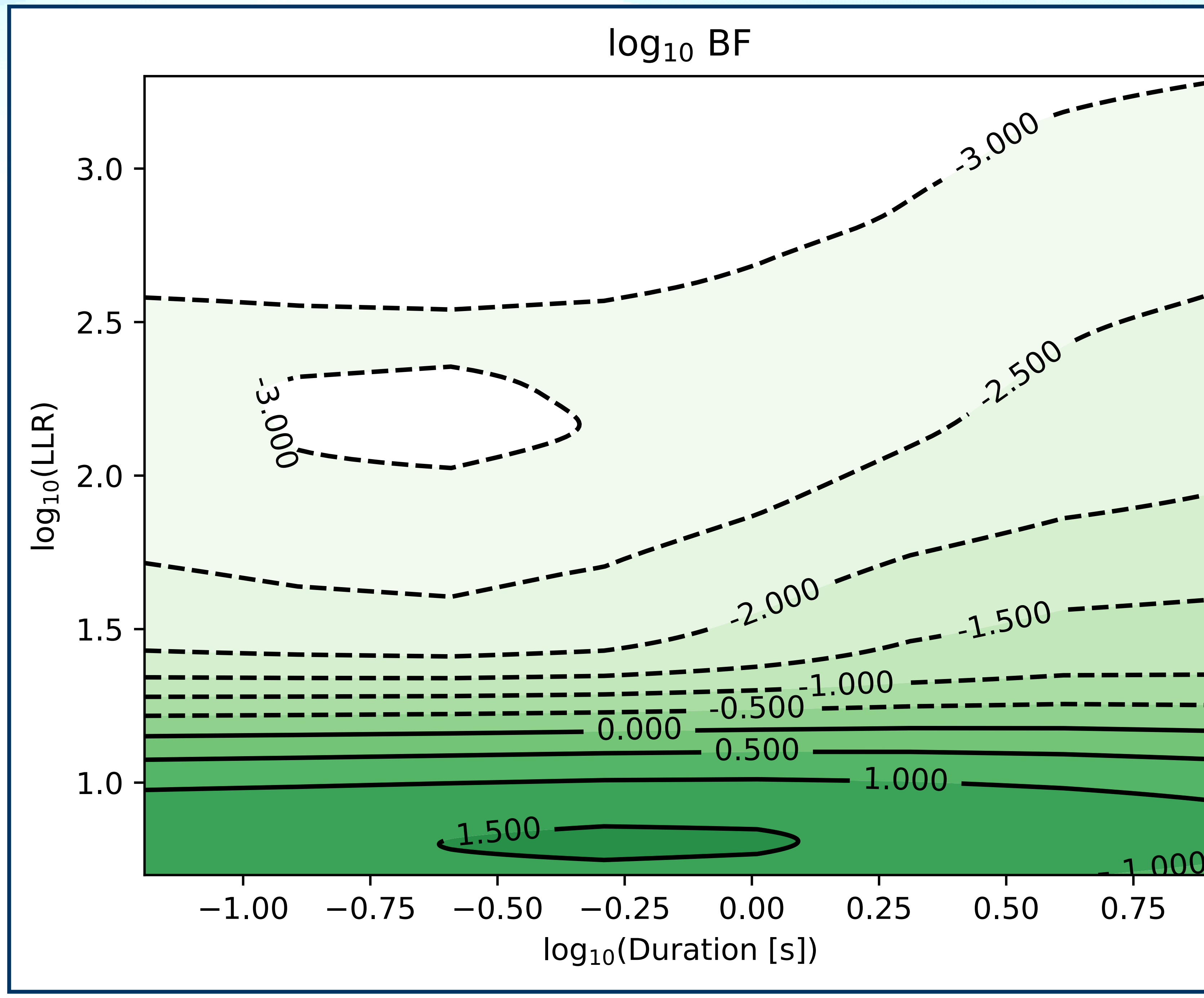
$I_{\Omega}$: Sky overlap

Bayes factor Coherent VS Incoherent signal (from Bayestar)

$Q_L$: GW Bayes Factor:




$I_{\Delta t}$: Time overlap




$Q_G$: GBM pseudo Bayes Factor

$Q_G < 0 \rightarrow \textit{signal-like}$

# A deeper method to search for joint detections

## Motivations & Method



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

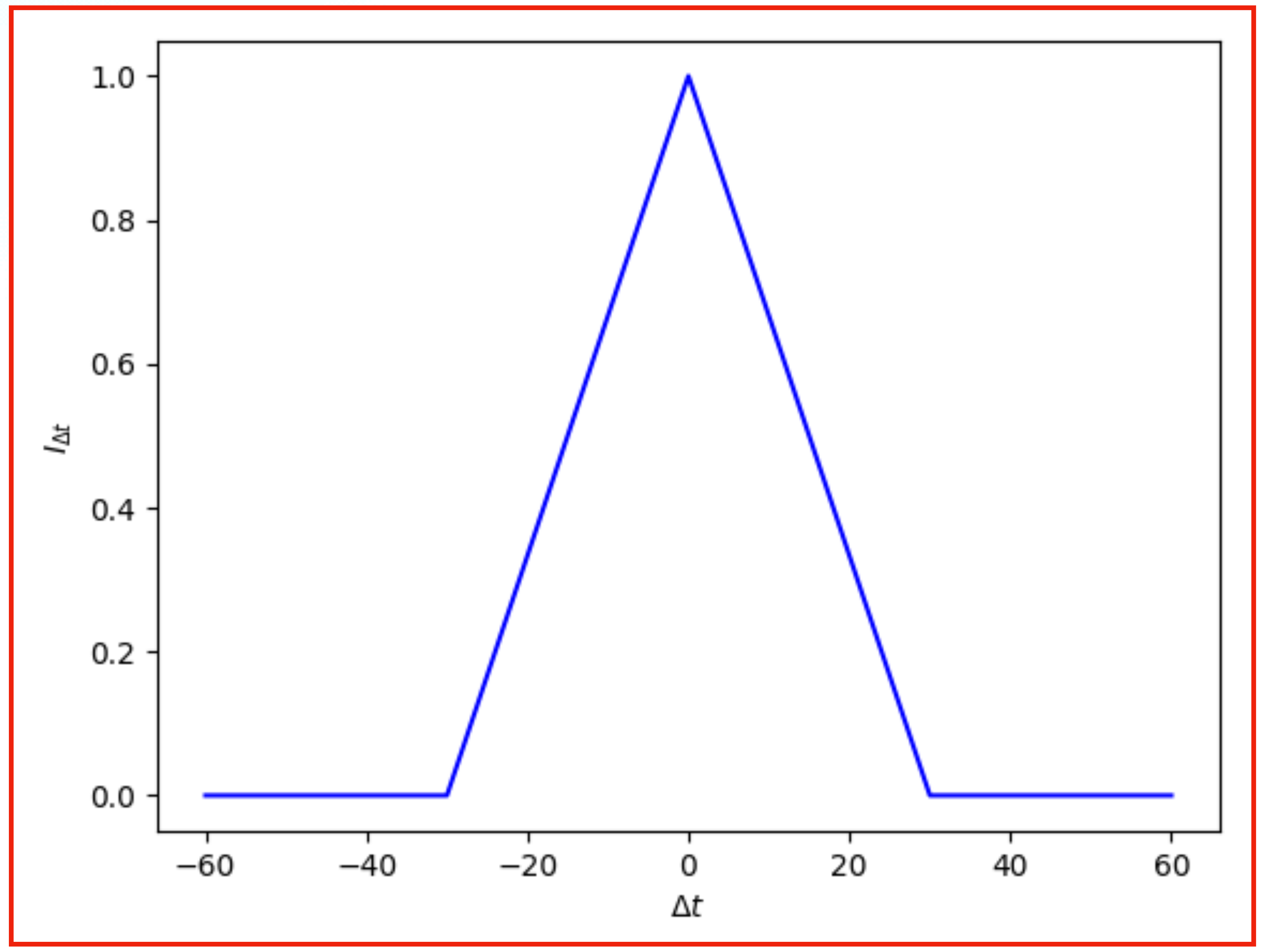
$$I_{\Omega}^{EA} = 4\pi f_{vis} \int_{\bar{\otimes}} P(\Omega | GW) P(\Omega | GBM) d\Omega \quad (3)$$

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

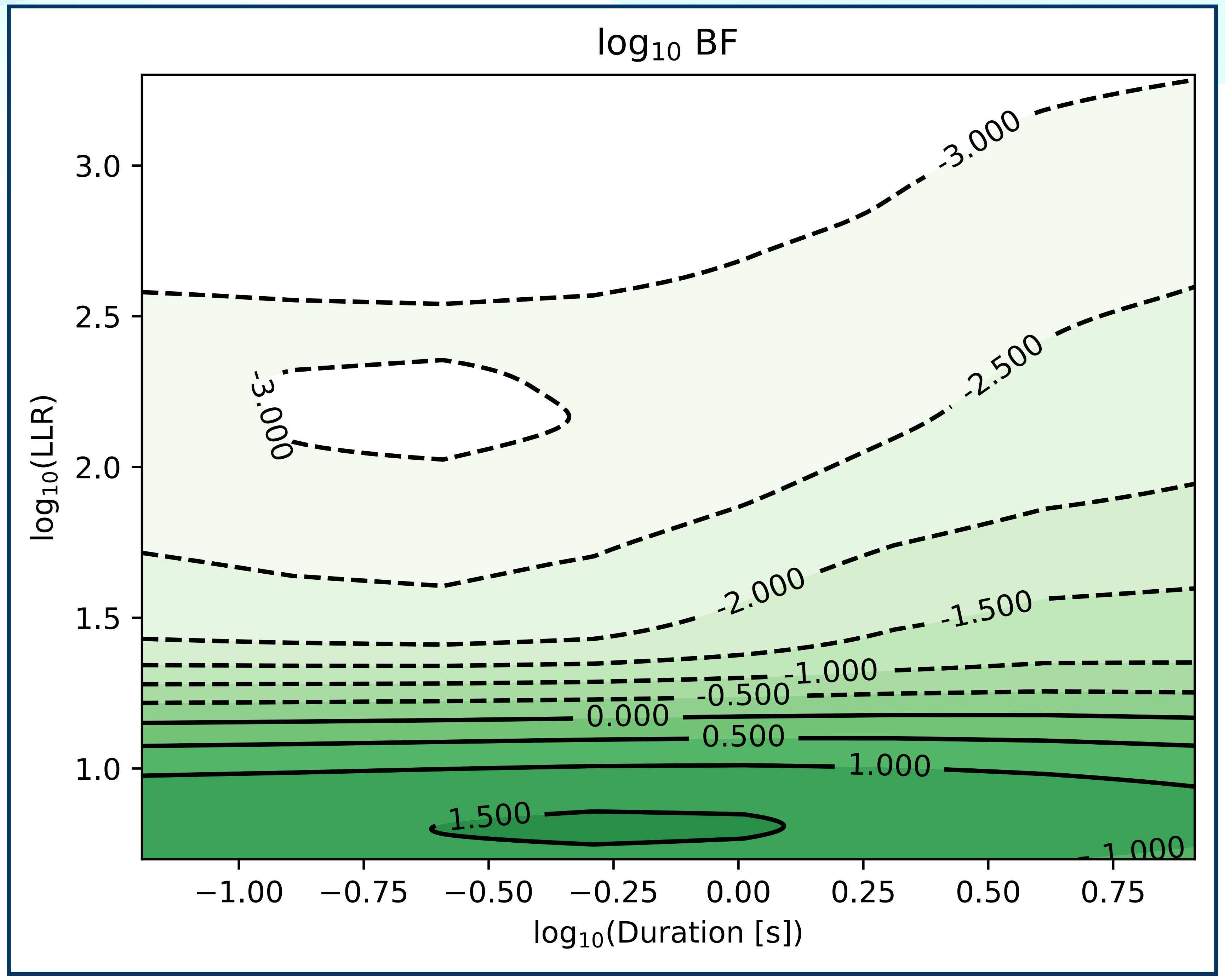
$I_\Omega$: Sky overlap

Bayes factor Coherent VS Incoherent signal (from Bayestar)

$Q_L$: GW Bayes Factor:




$I_{\Delta t}$: Time overlap




$Q_G$: GBM pseudo Bayes Factor

!

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

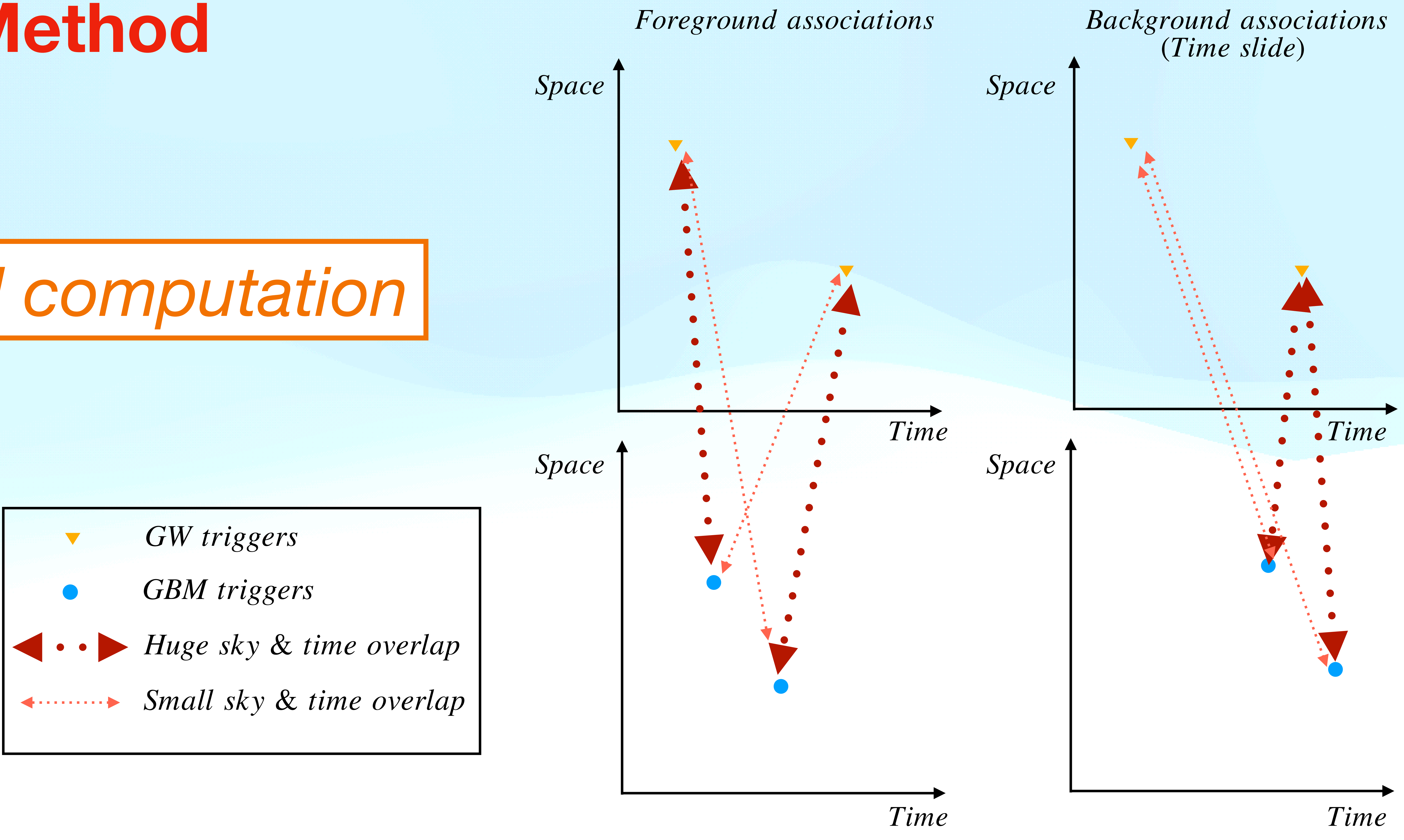
# A deeper method to search for joint detections

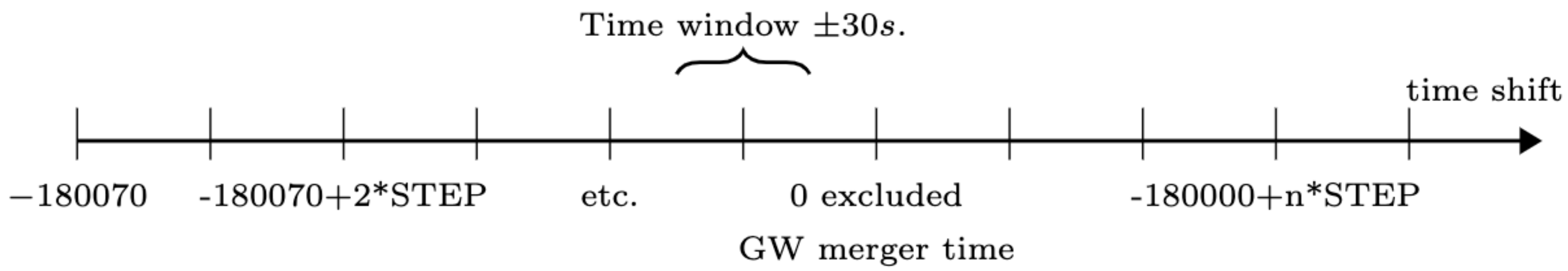
TABLE OF CONTENTS



## Motivations & Method

*Background computation*




*Background computation needed to assign a FAR to each foreground pair. In this analysis STEP = 70s*

TABLE OF CONTENTS



# 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.
- Test of different configurations 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 the false alarm rate (FAR > 2 /day inspired from GWTC-3) | No | No | Yes |

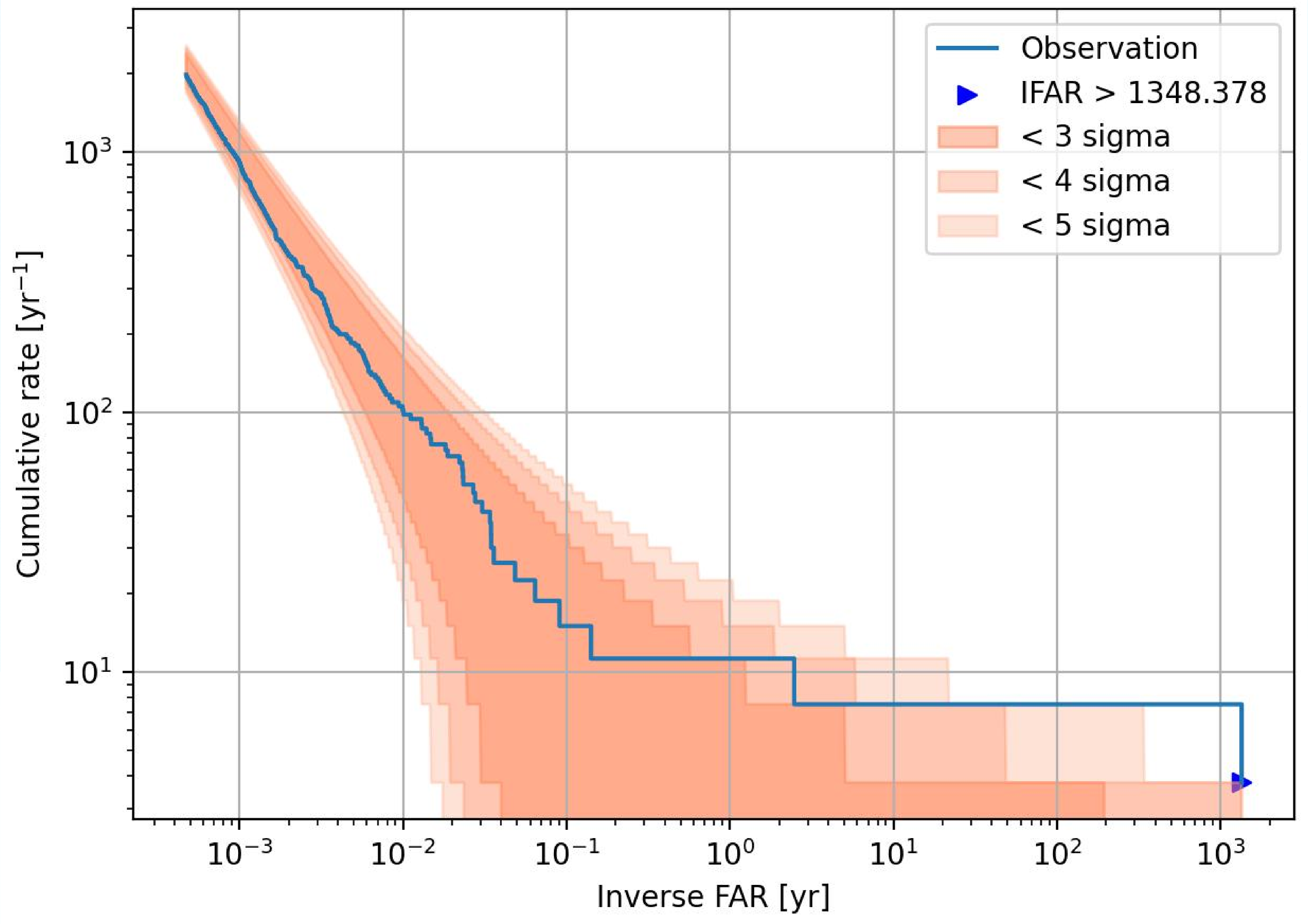
Results presented here

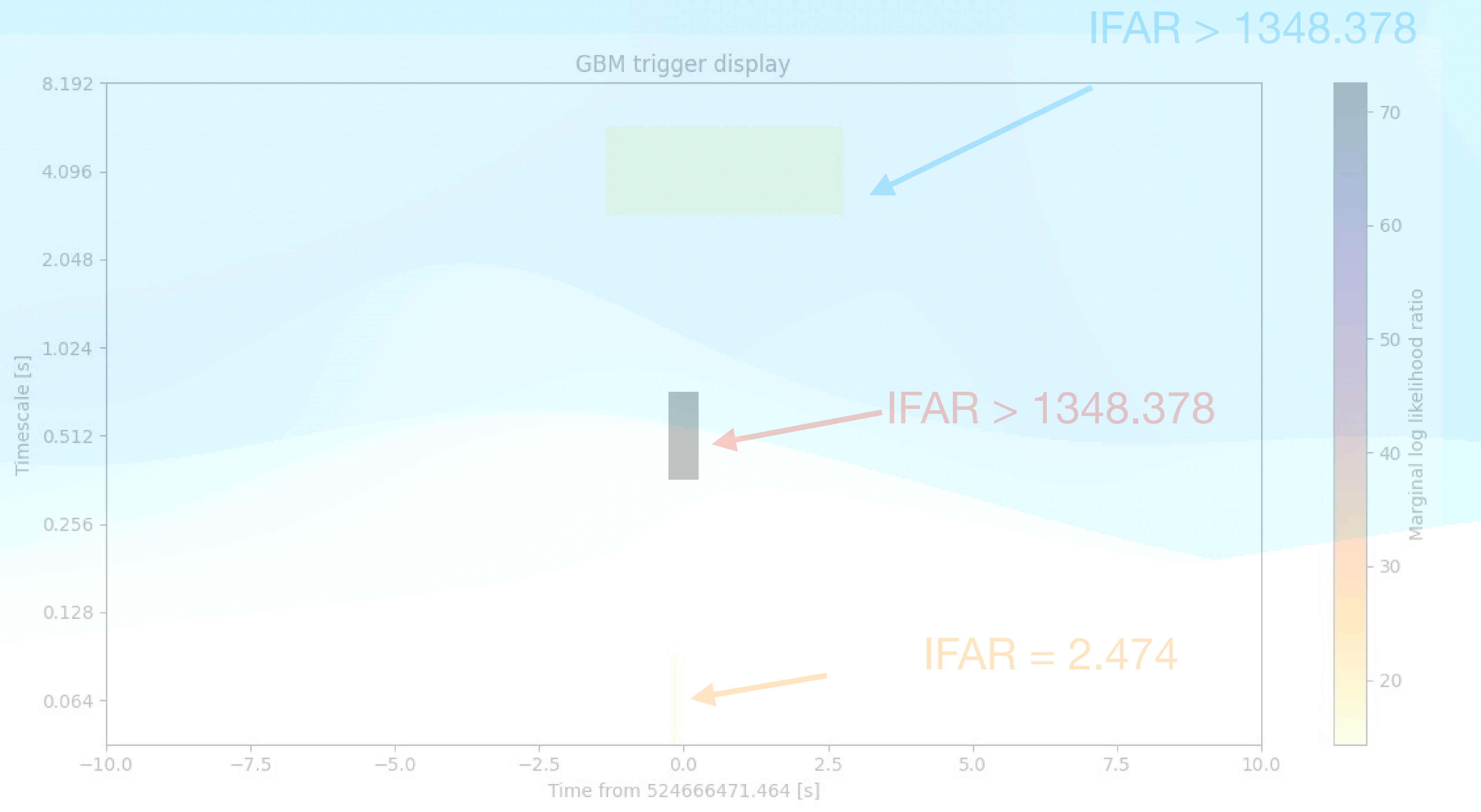
***DEFINITION:***
False Alarm Rate: How often do we expect noise to produce a trigger with the same ranking statistic as the candidate in question?

# A deeper method to search for joint detections

## Results : Foreground most significant associations





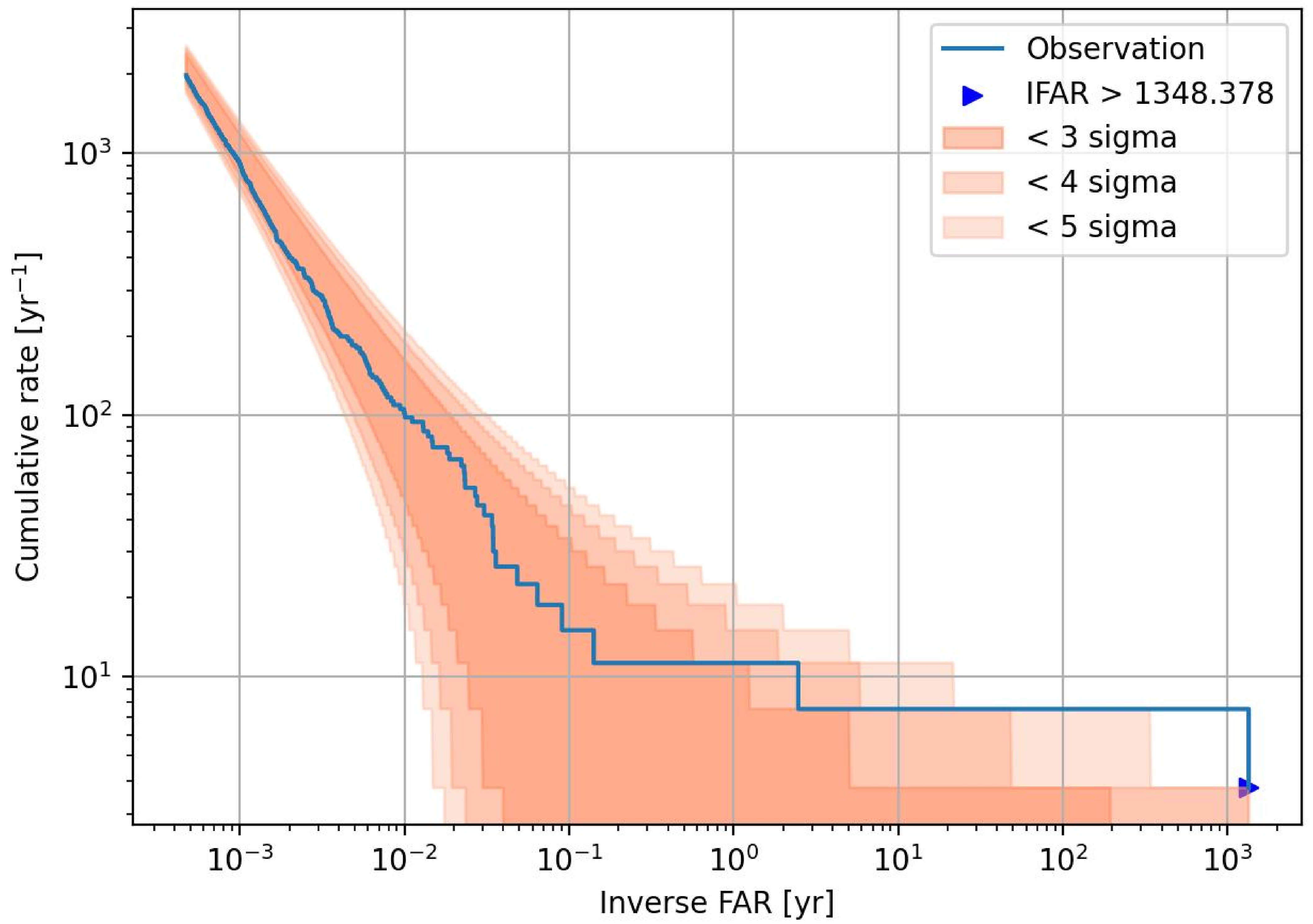



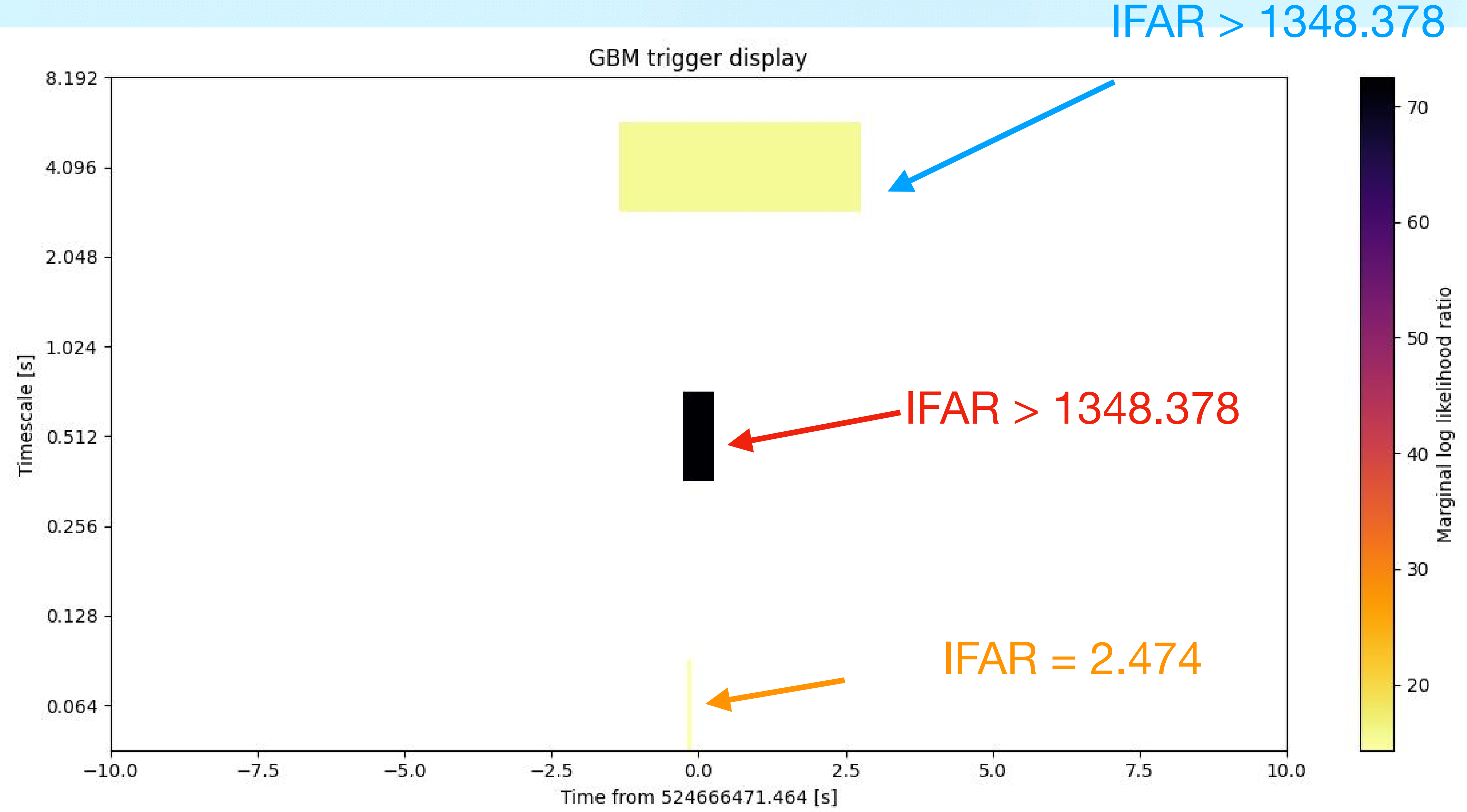

| Rank | GW merger time | GBM delay | GBM duration | GBM Spectrum | GBM LLR | GBM BF | GW BF | Sky term | Assoc rank | IFAR [yr] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1187008882.44 | 2.02 s. | 0.512 s. | 1 | 72.514 | -6.263 | -11.974 | 2.846 | 2.774 | >1348.378 |
| 2 | 1187008882.44 |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

* Duration, delay & time shift : in seconds

# A deeper method to search for joint detections

## Results : Foreground most significant associations




| 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 s. | 0.512 s. | 1 | 72.514 | -6.263 | -11.974 | 2.846 | 2.774 | >1348.378 |
| 2 | 1187008882.44 | 2.72 s. | 4.096 s. | 2 | 15.381 | -0.143 | -11.974 | 3.330 | 2.611 | >1348.378 |
| 3 | 1187008882.44 | 1.859 s. | 0.064 s. | 0 | 14.328 | -0.084 | -11.974 | 1.052 | 0.336 | 2.474 |

* Duration, delay & time shift : in seconds

# Conclusion

## Conclusion

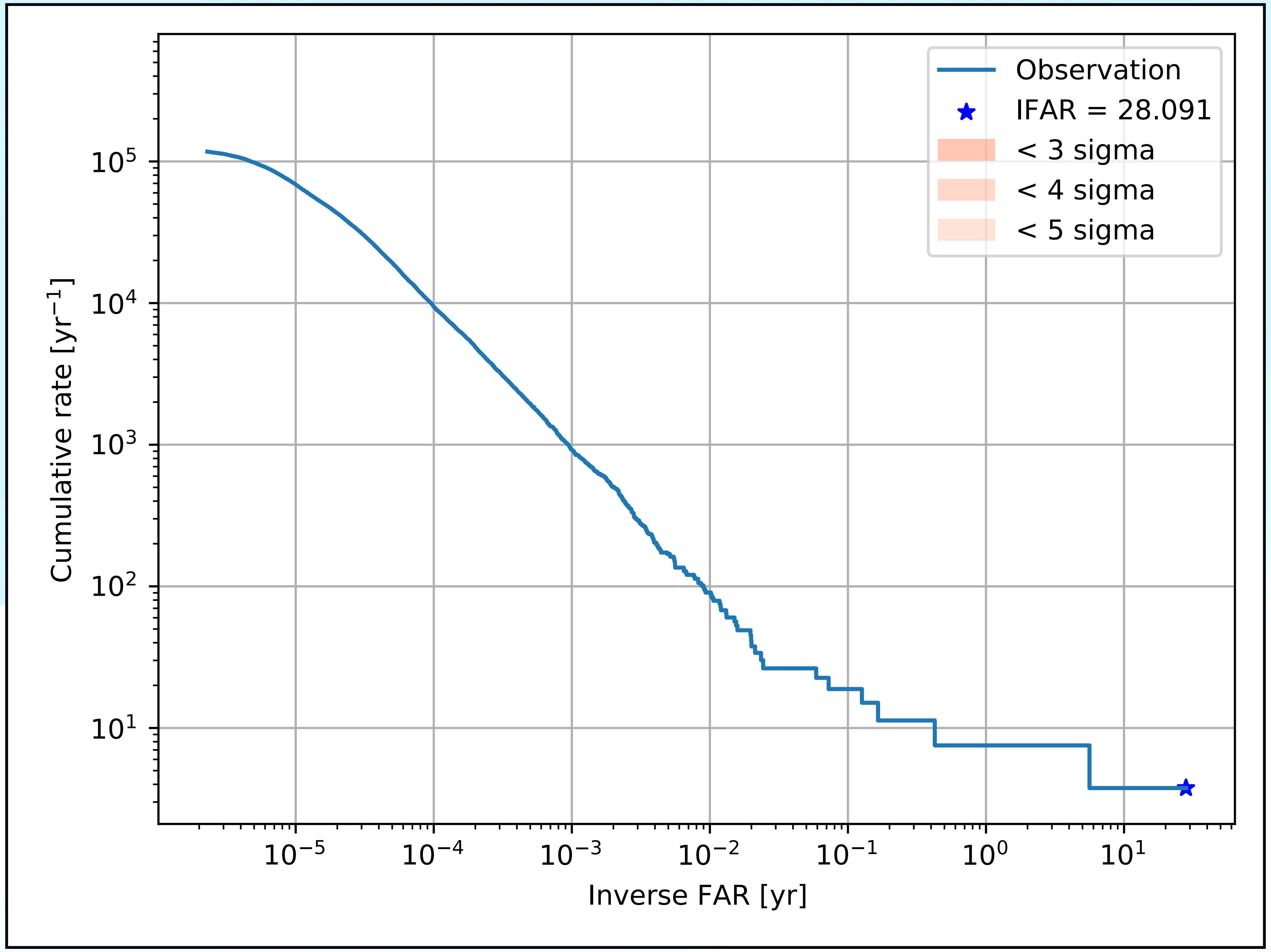
- We were able to analyze a large amount of triggers (~800000 GBM triggers & ~500 GW triggers) and find GW170817 with a high significance!
- When we have to deal with a lot of noise on the GW side, GW170817/GRB170817A is not highly significant (not presented here).
- We found a configuration that works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

## Next Steps

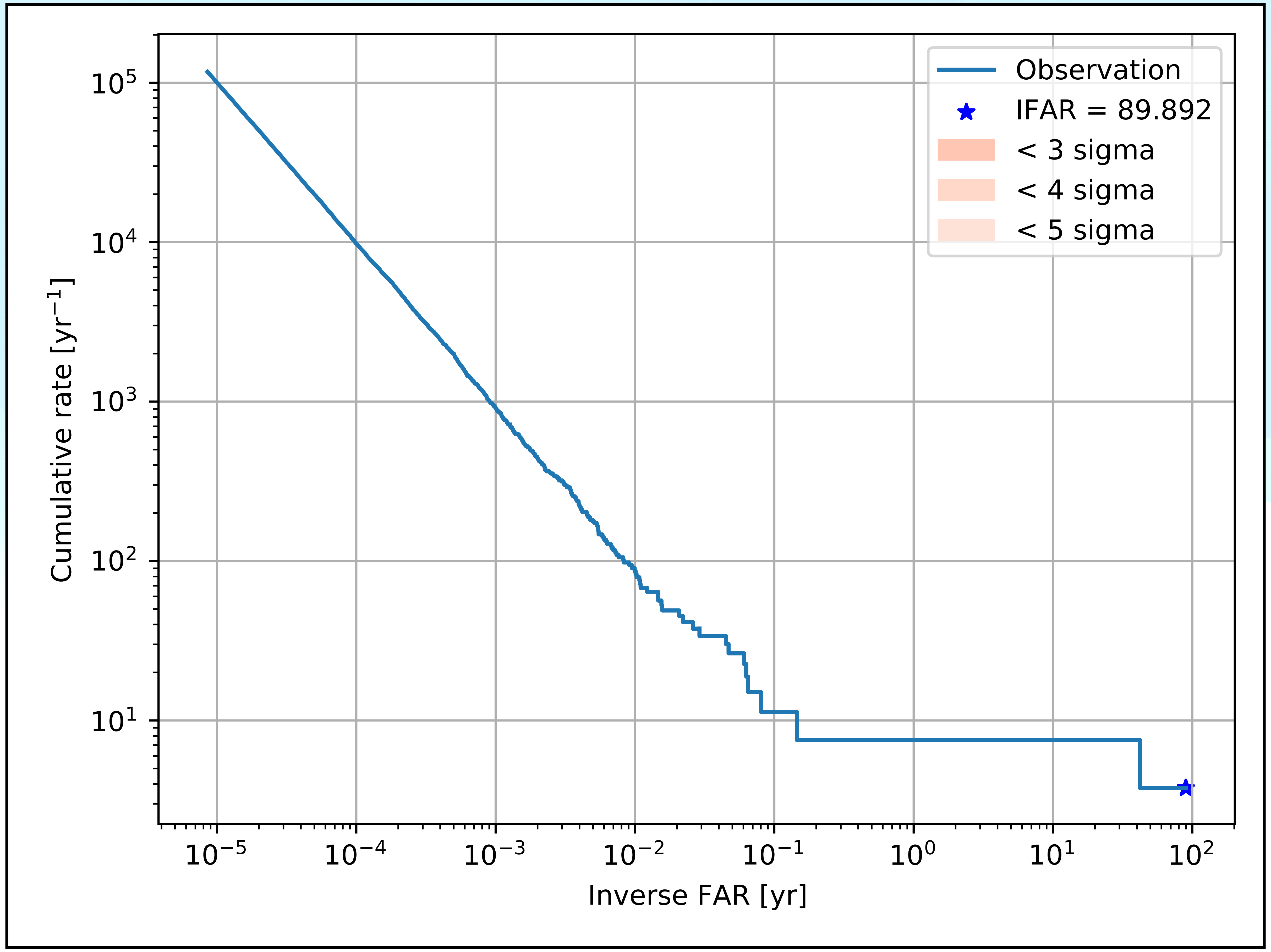
- The GW Bayes Factor should be improved : it doesn't discriminate properly between noise and signal.
- Apply this method applied on the 3rd Gravitational-Waves Observing Run (O3) data.
- Same for future observing runs.

# Thank you for your attention !

# Backup



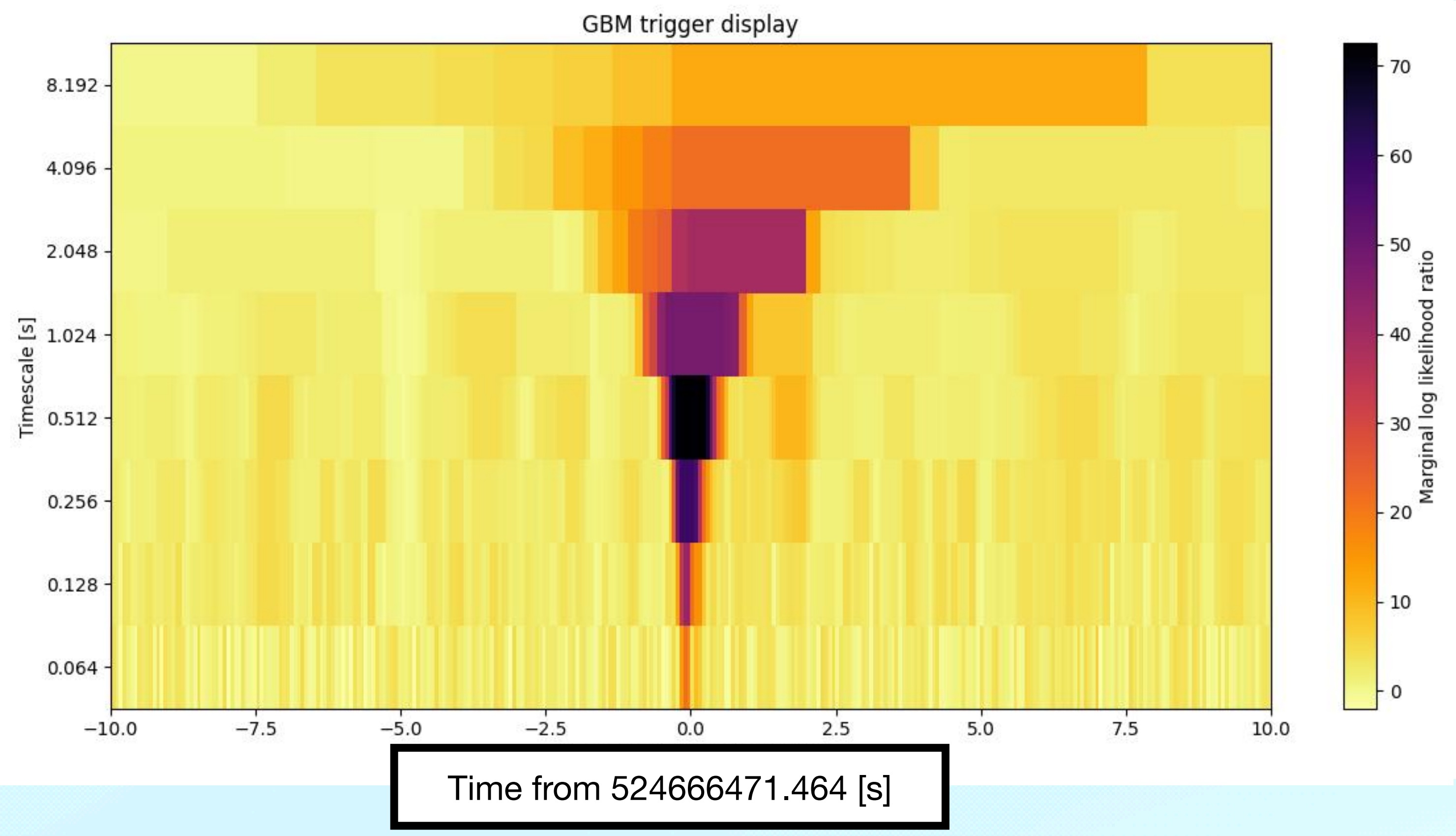

*Cumulative rate as a function of the inverse false alarm rate (IFAR [yr]) for foreground (in solid line) with configuration 1. The foregrounds represent associations between Fermi-GBM candidates and LIGO triggers with no time shift.*

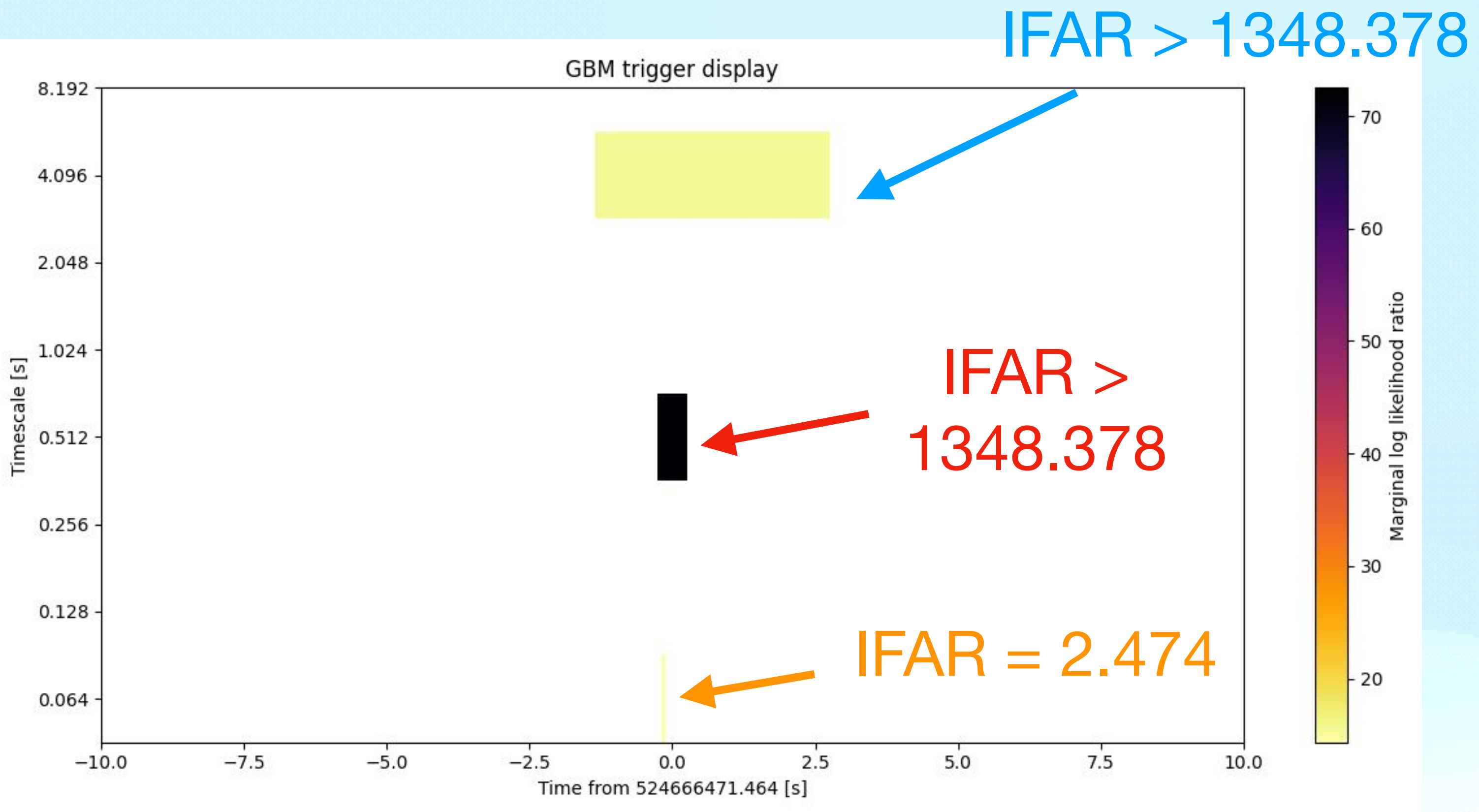


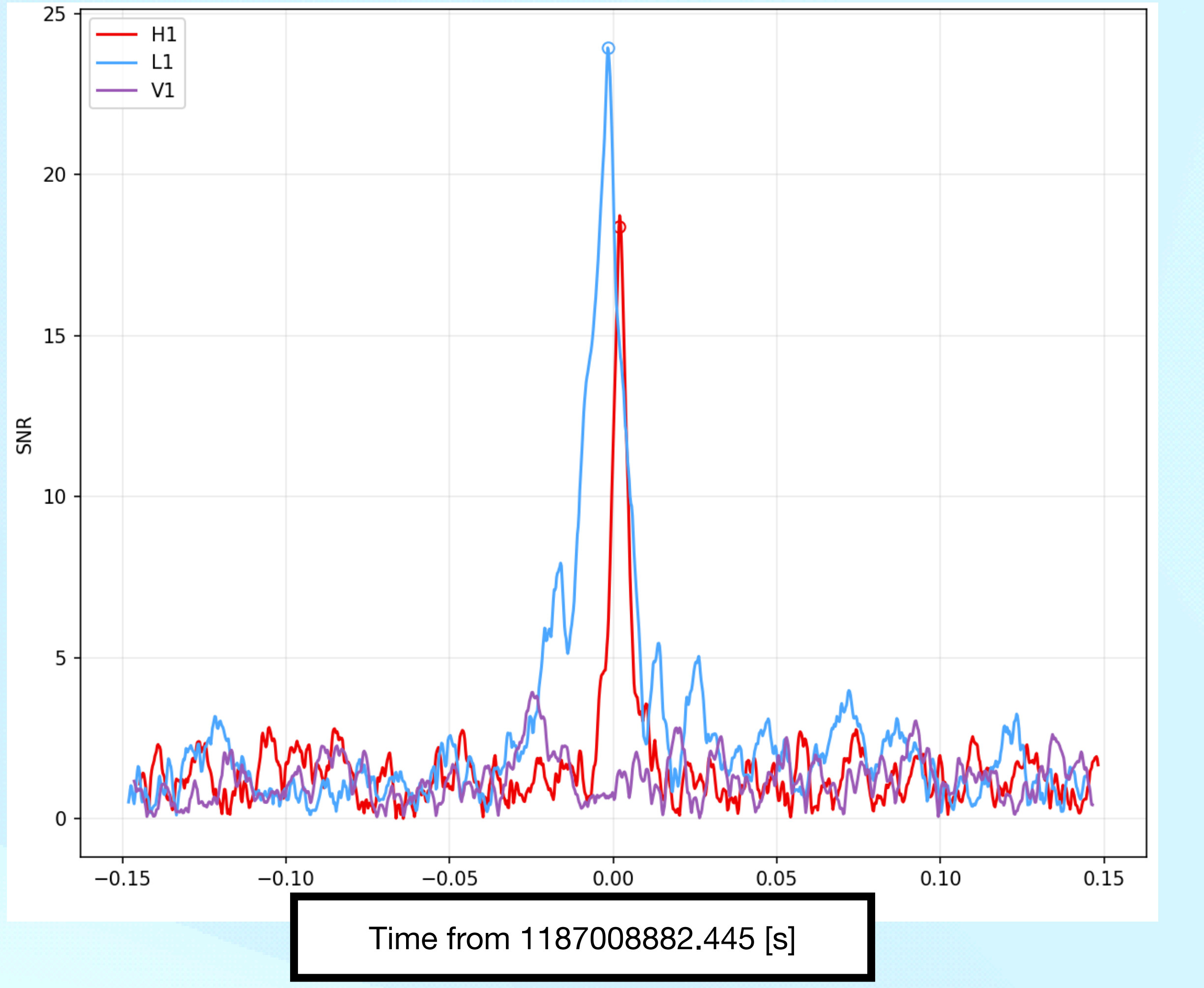

*Cumulative rate as a function of the inverse false alarm rate (IFAR [yr]) for foreground (in solid line) with configuration 2: no separation in spectral value and duration. The foregrounds represent associations between Fermi-GBM candidates and LIGO triggers with no time shift.*

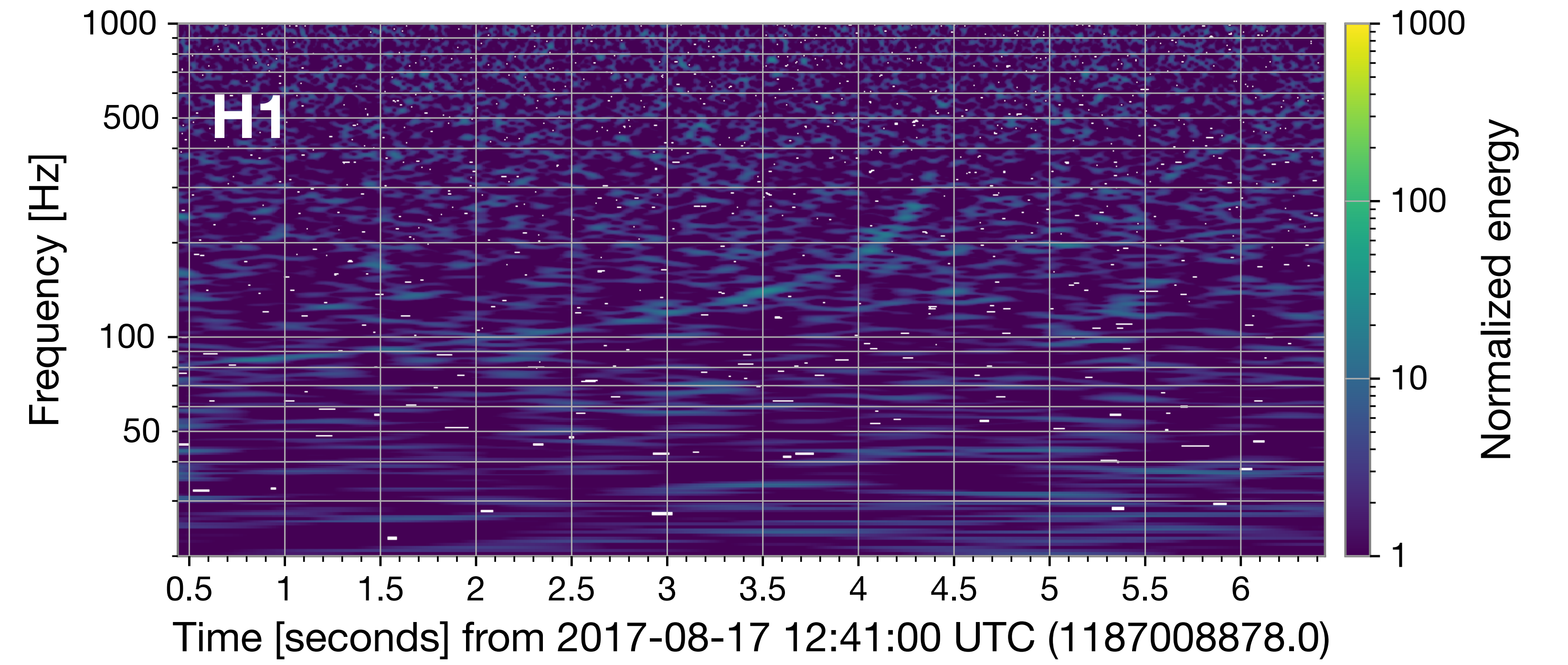
# Results : Foreground most significant associations

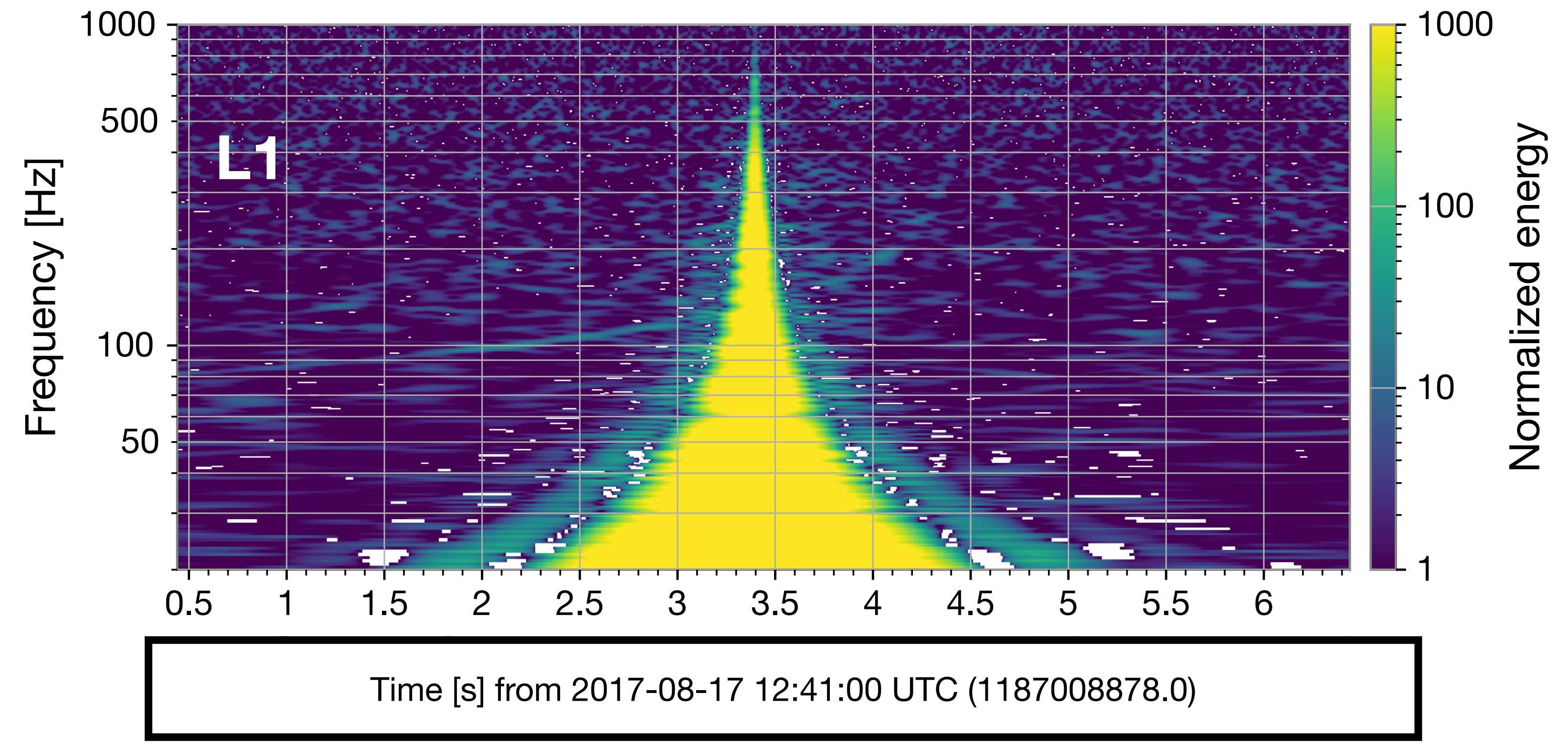
| Rank | GW merger time | GBM delay | GBM duration | GBM Spectrum | GBM LLR | GBM BF | GW BF | Sky term | Assoc rank | IFAR [yr] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1187008882.44 | 2.02 s. | 0.512 s. | 1 | 72.514 | -6.263 | -11.974 | 2.846 | 2.774 | >1348.378 |
| 2 | 1187008882.44 |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



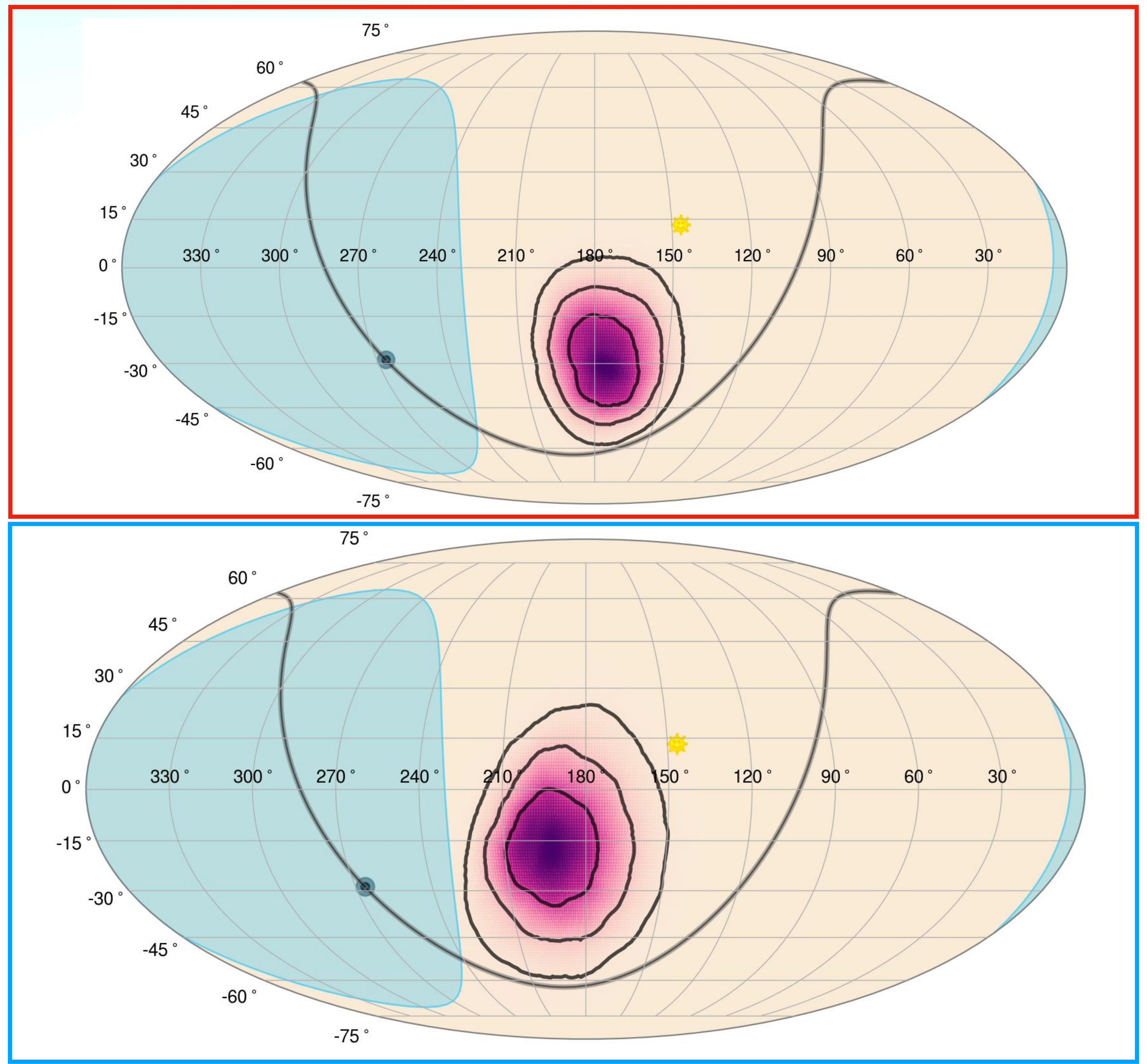



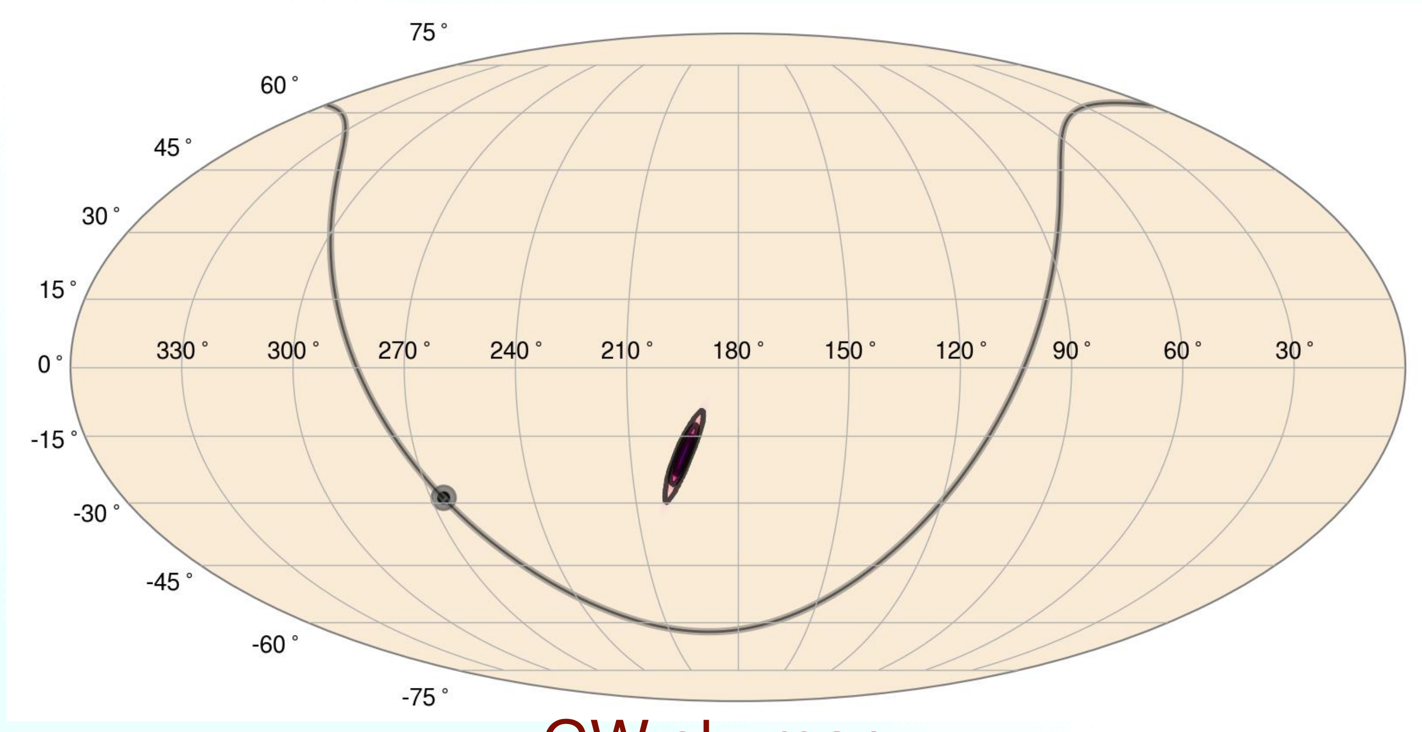




GBM skymap





GW skymap