Deep multimessenger search for compact binary mergers in LIGO, Virgo and Fermi/GBM data from 2016-2017

GdR Ondes Gravitationnelles
16-17 October 2023

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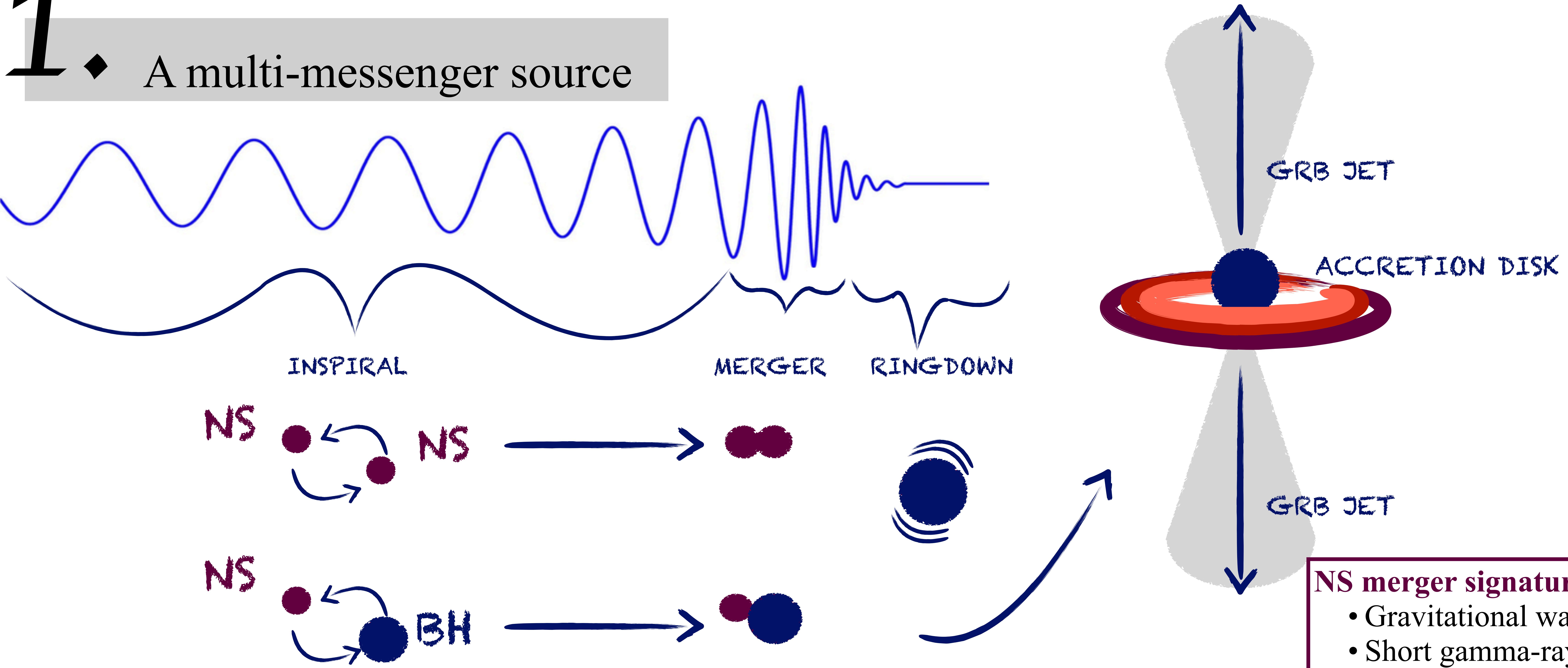
1.1 Introduction: Neutron star mergers

1. ◆ A multi-messenger source

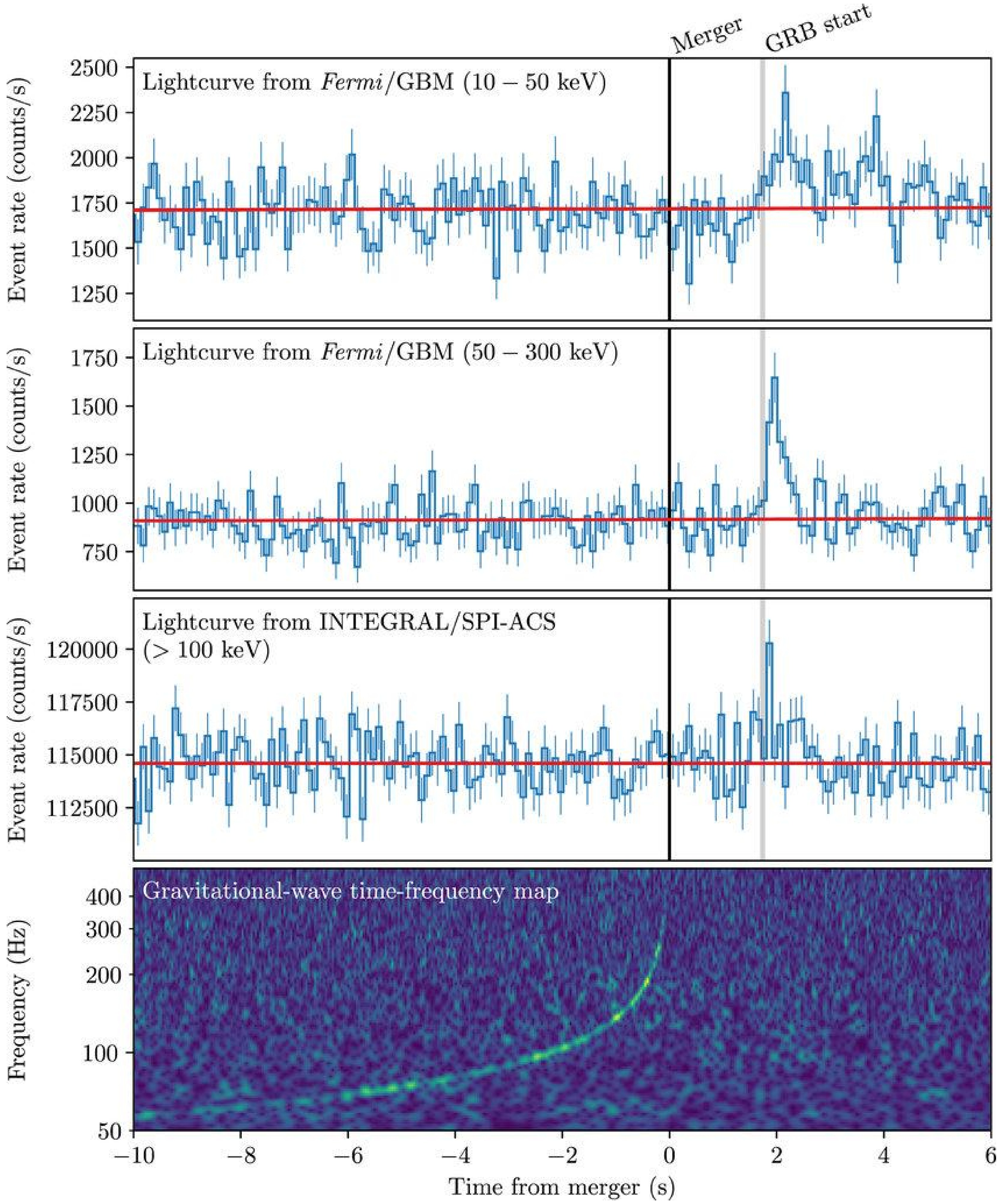


NS merger signatures:

- Gravitational waves (GW)
- Short gamma-ray burst (sGRB)
- Optical signature
- Cosmic rays (?)
- Neutrinos (?)

* CBC: Compact Binary Coalescence

◆ GW170817-GRB 170817A



August 17th, 2017

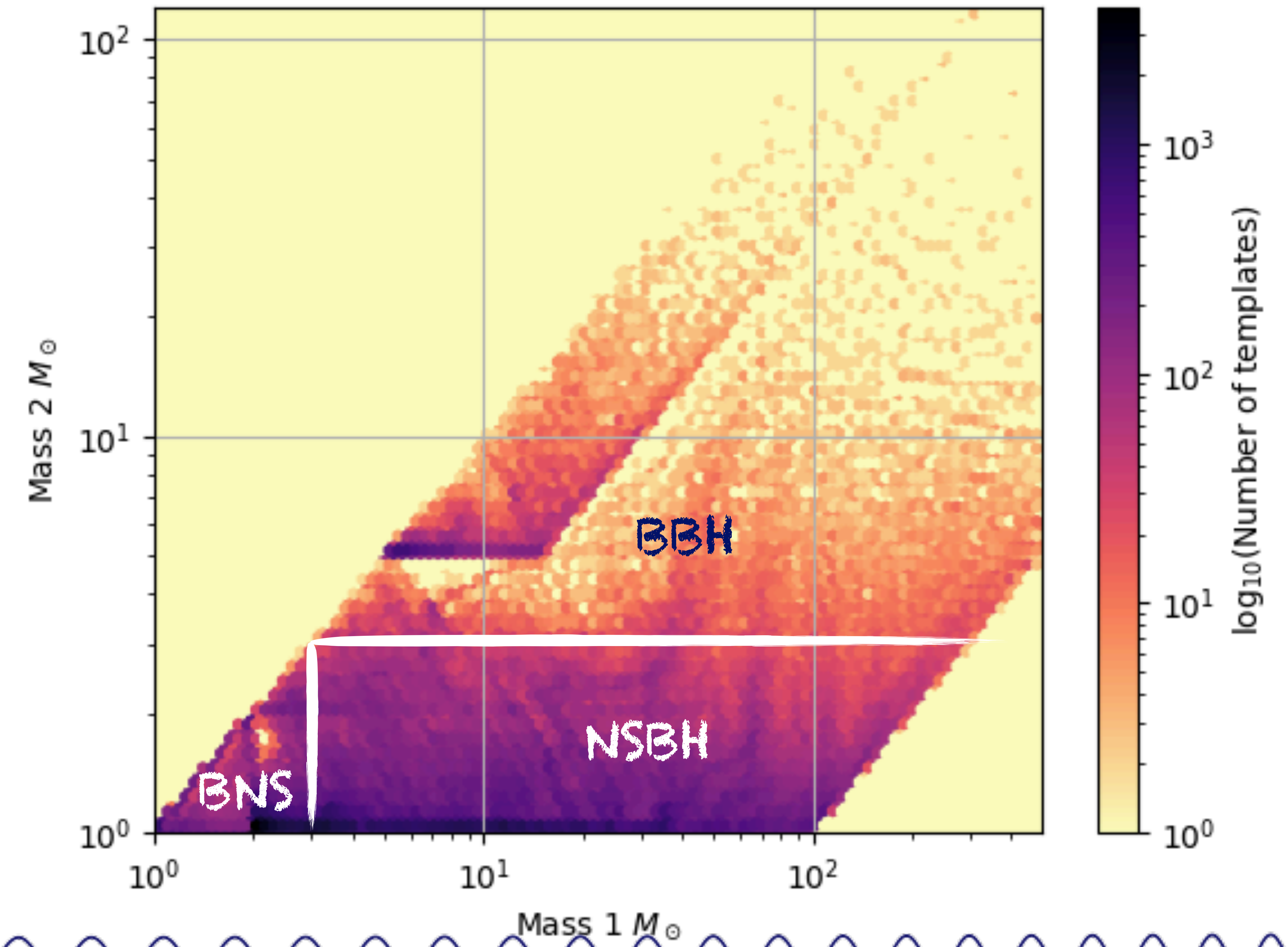
Fundamental questions still remain:

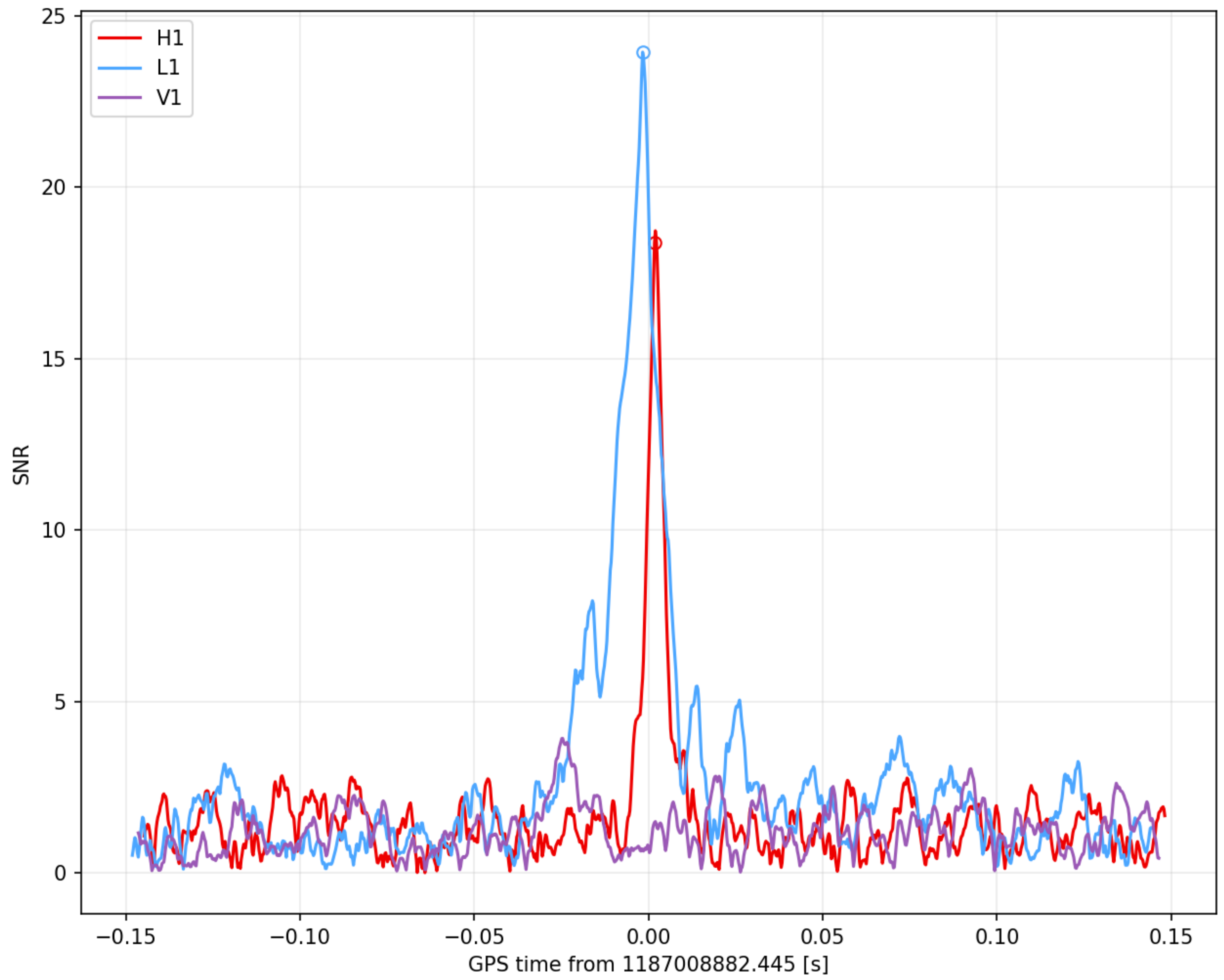
- Are the properties of GW170817 common to all NS mergers or do they represent an exceptional case?
- What is the fraction of short and long GRBs associated with NS mergers?
- Bring information and constraints in fundamental physics (NS EoS, celerity of GWs…), astrophysics (BNS merger rate, …), in cosmology (Hubble constant …), in GRB physics (about the jet formation, the ejecta …)

More joint detections are needed! → Smoking gun on BNS progenitor

1. CBC search

- Carried out by several independent pipelines:
  - Modeled searches (PyCBC, GstLal, MBTA)
  - Minimally modeled search (cWB)
- In this analysis : triggers from **PyCBC** (from **O2**) which is a matched-filtering based analysis pipeline.





1.2 Introduction: GW & GRB Searches

2. ◆ GBM Targeted Search

- Look for **excesses of photon counts** — search timescales from **0.064 s to 8.192 s**
- For each time window: **log-likelihood ratio** (LLR) — GBM triggers generated by only keeping the window having the highest LLR if ≥ 5
- Use three template spectra (**soft - normal - hard**)
- **Sky localization** of the GBM triggers

1.3 Introduction: Existing Joint Searches

Joint searches already exist since O1:

<table>
<tr><th>Search</th><th>Inputs</th><th>Description</th><th>Time scale</th></tr>
<tr><td>RAVEN</td><td rowspan="3">GW data
(RAVEN: GW candidate)
(X-pipeline: Unmodeled GWBs triggers)
<u>associated with</u>
External astrophysical trigger
(e.g. a GRB)</td><td>Joint False Alarm Rate: $FAR_c = FAR_{GW} R_{EM} \Delta t / I_{\Omega}$
Result in an alert</td><td>A few seconds</td></tr>
<tr><td>PyGRB</td><td>Deep & coherent search for a nearby GW signal
Compute a p-value or put a lower limits on the luminosity distance to the GRB</td><td rowspan="2">Hours to days for GW data around 1 GRB</td></tr>
<tr><td>X-pipeline</td><td>Deep & coherent search
Use time-frequency maps to generate candidates
Compute a p-value</td></tr>
</table>

However, many of these searches have statistical or computational limitations that prevent their application to a large number of weak candidate events.

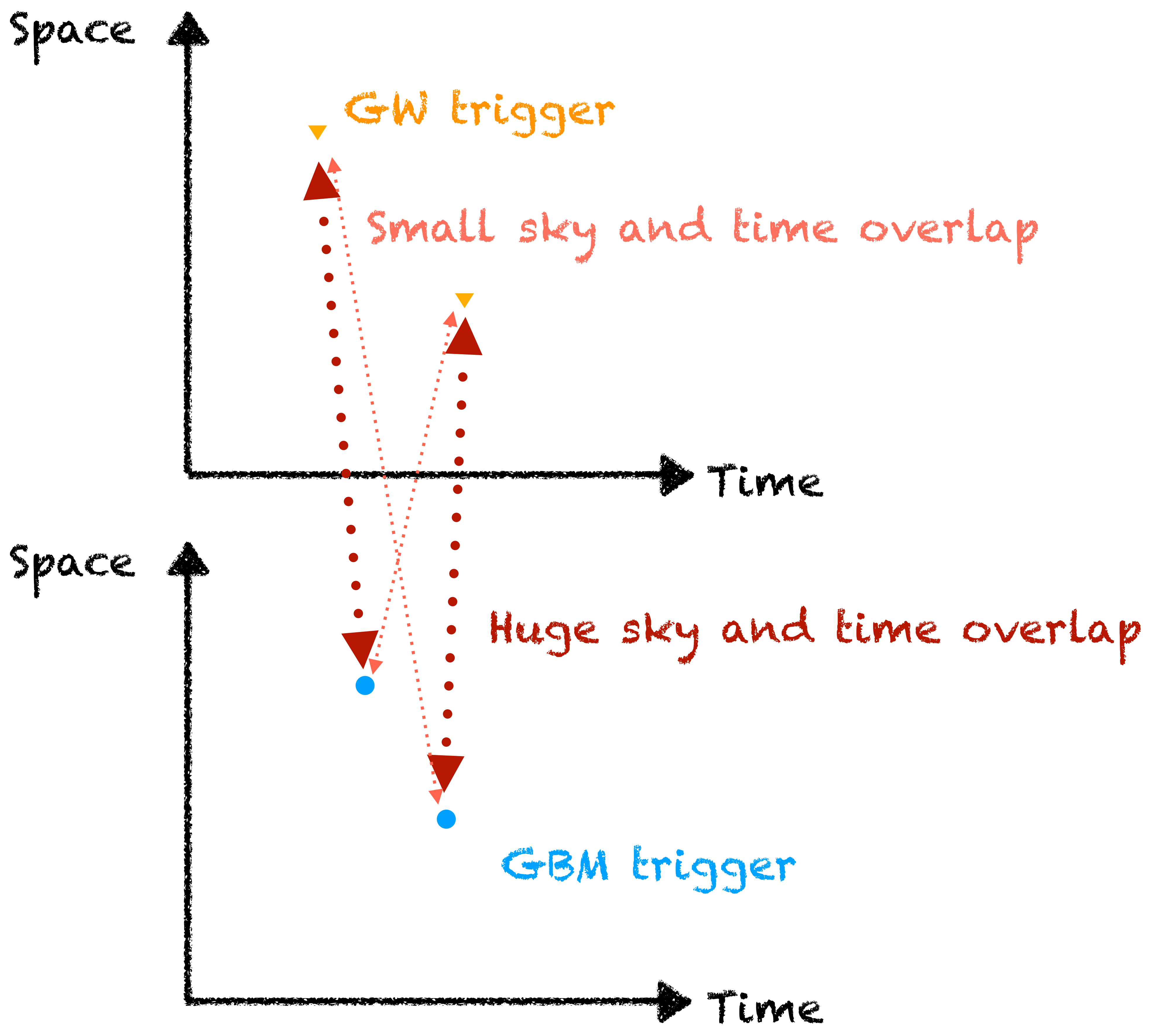
Note: Other searches have been performed for specific events: Blackburn's method to search for a GW150914 counterpart, p-value for the GW170817 and GRB 170817A association …

2.1 A deeper method to search for joint detections: method

1. Procedure

We developed a **deep** search for GW/GRB associations (Pillas et al. 2023, *Deep multimessenger search for compact binary mergers in LIGO, Virgo and Fermi/GBM data from 2016-2017*, published in ApJ):

- Does **not consider confident events only** but instead use the **full list** of GW triggers and Fermi/GBM triggers covering the same run
- Find **pairs** of Fermi/GBM and GW triggers that **could possibly have a common origin**
- Rank the pairs with a **ranking statistic**
- Assign a **FAR** to them *



* *False Alarm Rate (FAR): How likely it is for noise to produce a trigger with the same ranking statistic as the candidate in question?*

2.1 A deeper method to search for joint detections: method

2. ◆ Ranking statistic Λ

[G. Ashton *et al* 2018]

$$\Lambda = \frac{P(D_g, D_\gamma \,|\, \text{signal})}{P(D_g, D_\gamma \,|\, \text{noise})}$$

→ No prior preference assumption

$$\Lambda = \frac{I_{\Delta t} I_{\Omega}}{1 + Q_g + Q_\gamma + Q_g Q_\gamma}$$

signal
- H_c : both D_g & D_γ contain **signals** & **common** source

noise
- H_{NN} : **noise** in both D_g & D_γ
- H_{SN} : **signal** in D_g and **noise** in D_γ
- H_{NS} : the **inverse**
- H_{SS} : **signals** in both D_g & D_γ but **unrelated** sources

$Q_g = \frac{P(D_g \,|\, \text{noise})}{P(D_g \,|\, \text{signal})}$ Bayes factor noise-vs-signal , g : GW data

$Q_\gamma = \frac{P(D_\gamma \,|\, \text{noise})}{P(D_\gamma \,|\, \text{signal})}$ Bayes factor noise-vs-signal , γ : GBM data

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

2. Ranking statistic Λ

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2.1 A deeper method to search for joint detections: method

3. ◆ Bayes Factors

$$\Lambda = \frac{I_{\Delta t} I_{\Omega}}{1 + Q_g + Q_\gamma + Q_g Q_\gamma}$$

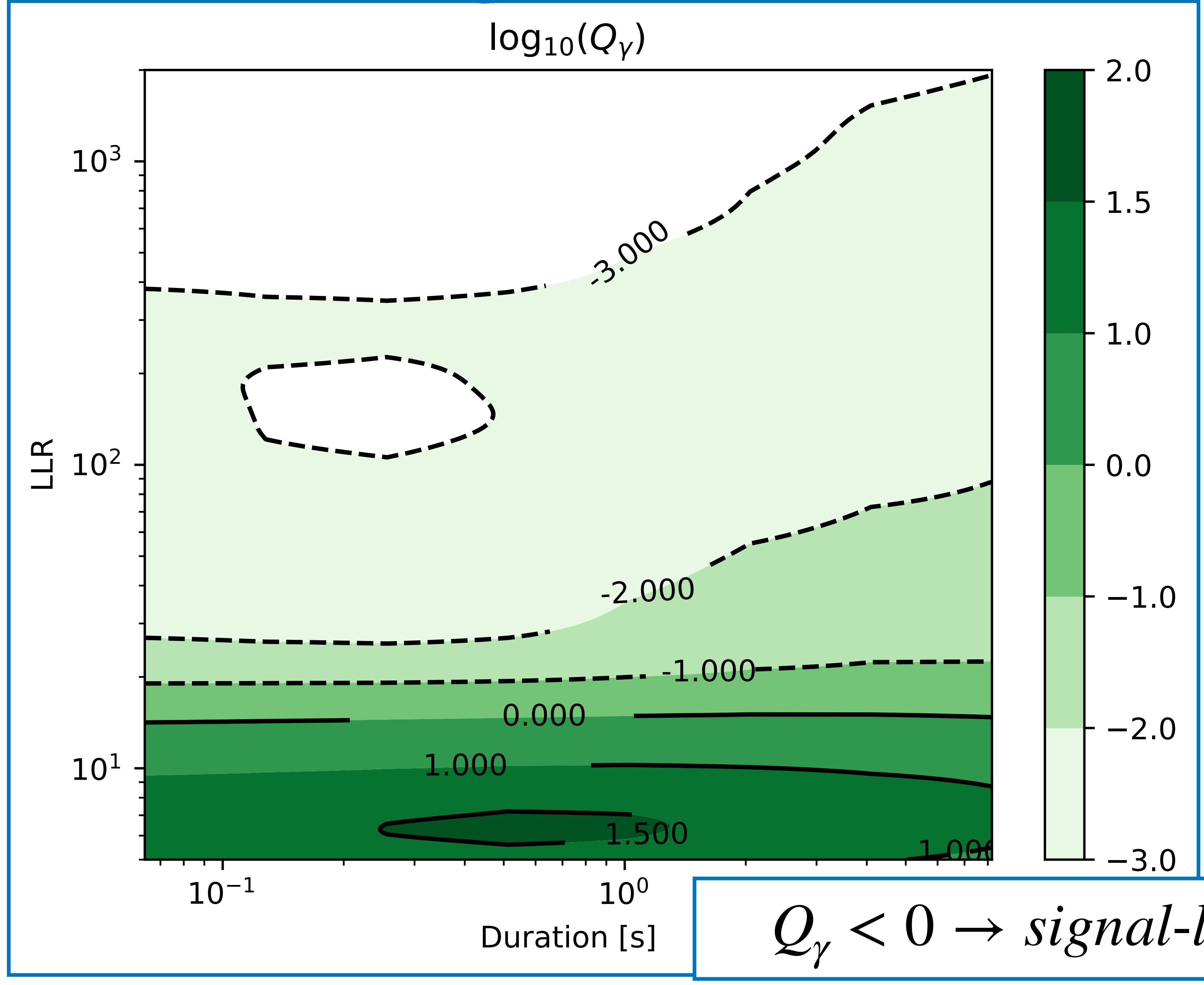
Bayes factor Coherent VS Incoherent signal (from Bayestar)

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

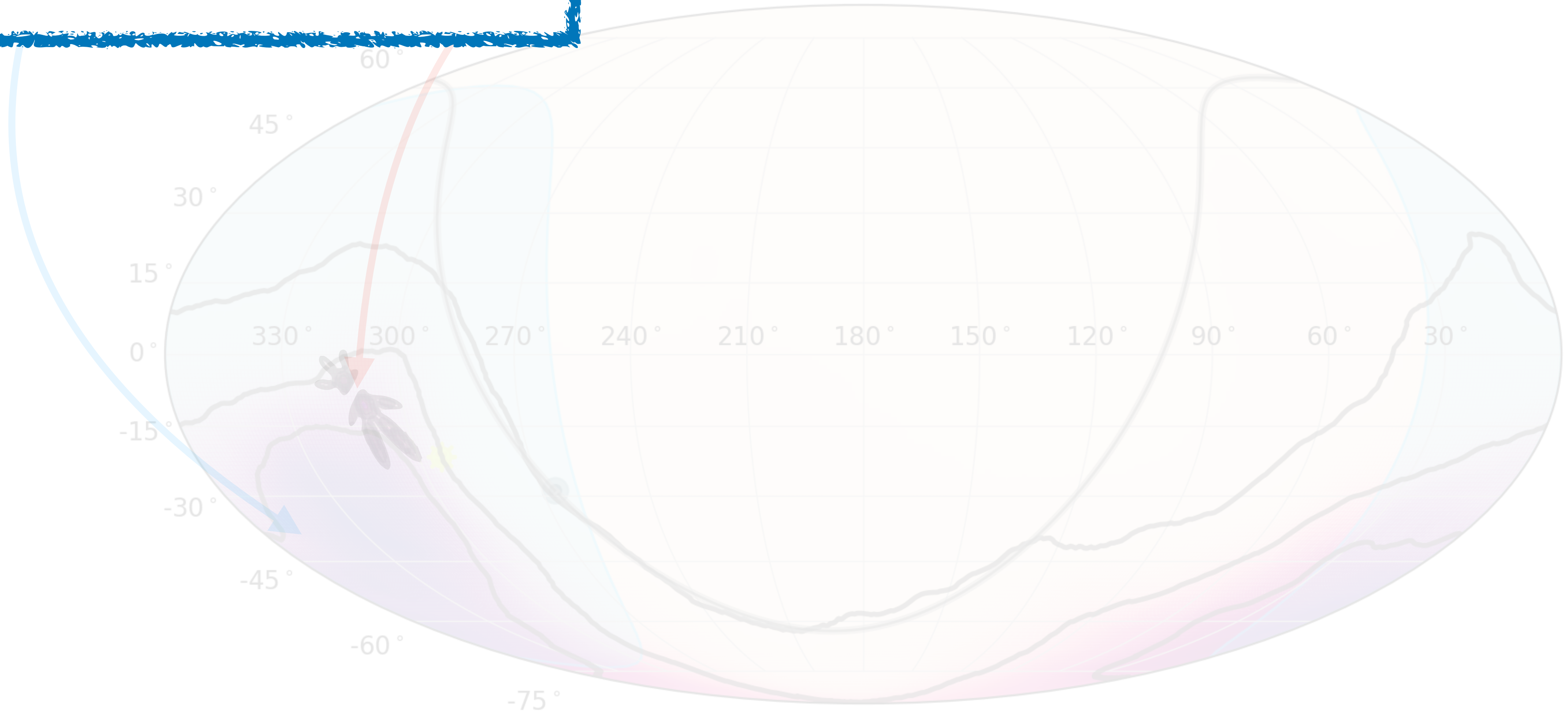
with $f_{vis} = \frac{1}{4\pi}\int_{\bar{\otimes}} d\Omega$

kymap: glitch

GBM Bayes Factor



$Q_\gamma < 0 \rightarrow$ *signal-like*



Low ranked background association in our analysis

Earth occultation

(P_{GBM}(Earth occultation) ~ 83 %)

$I_\Omega^{EA} \approx e^{-21.9}$ & $I_\Omega^{AS} \approx e^{1.4}$ (EA: Earth Avoiding, & AS: All-Sky)

noise-like *signal-like*

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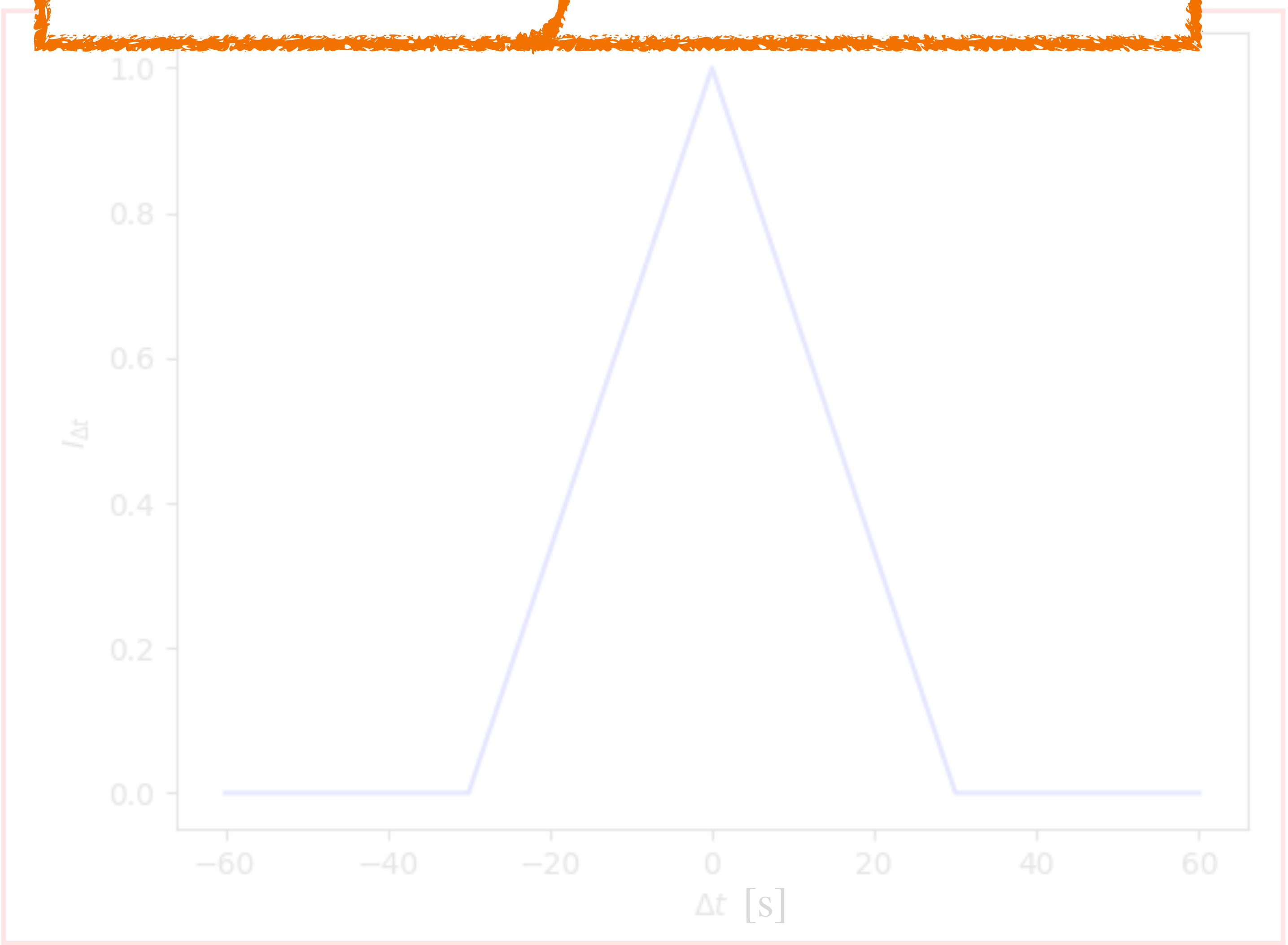
GW Bayes Factor



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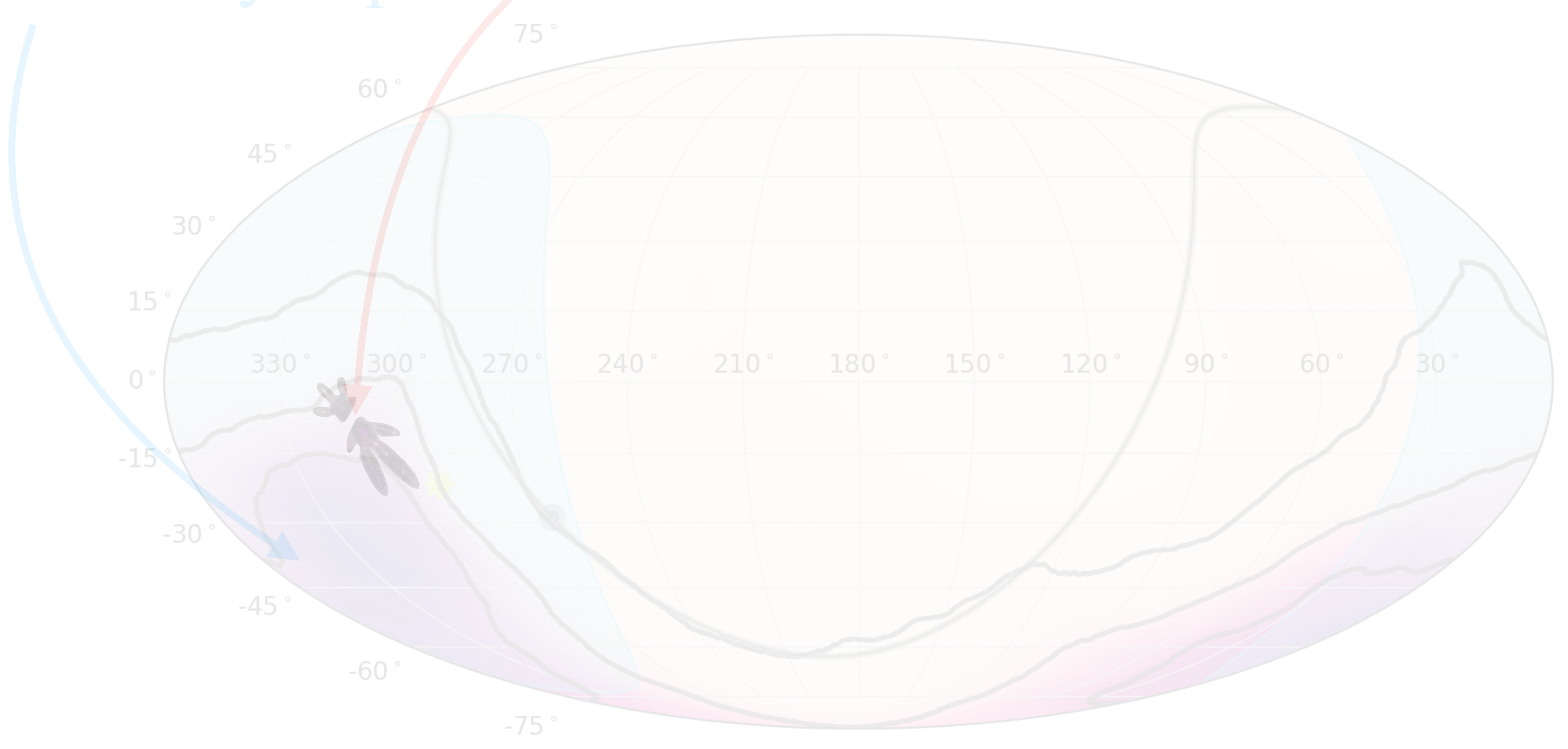
GBM skymap

GW skymap: glitch



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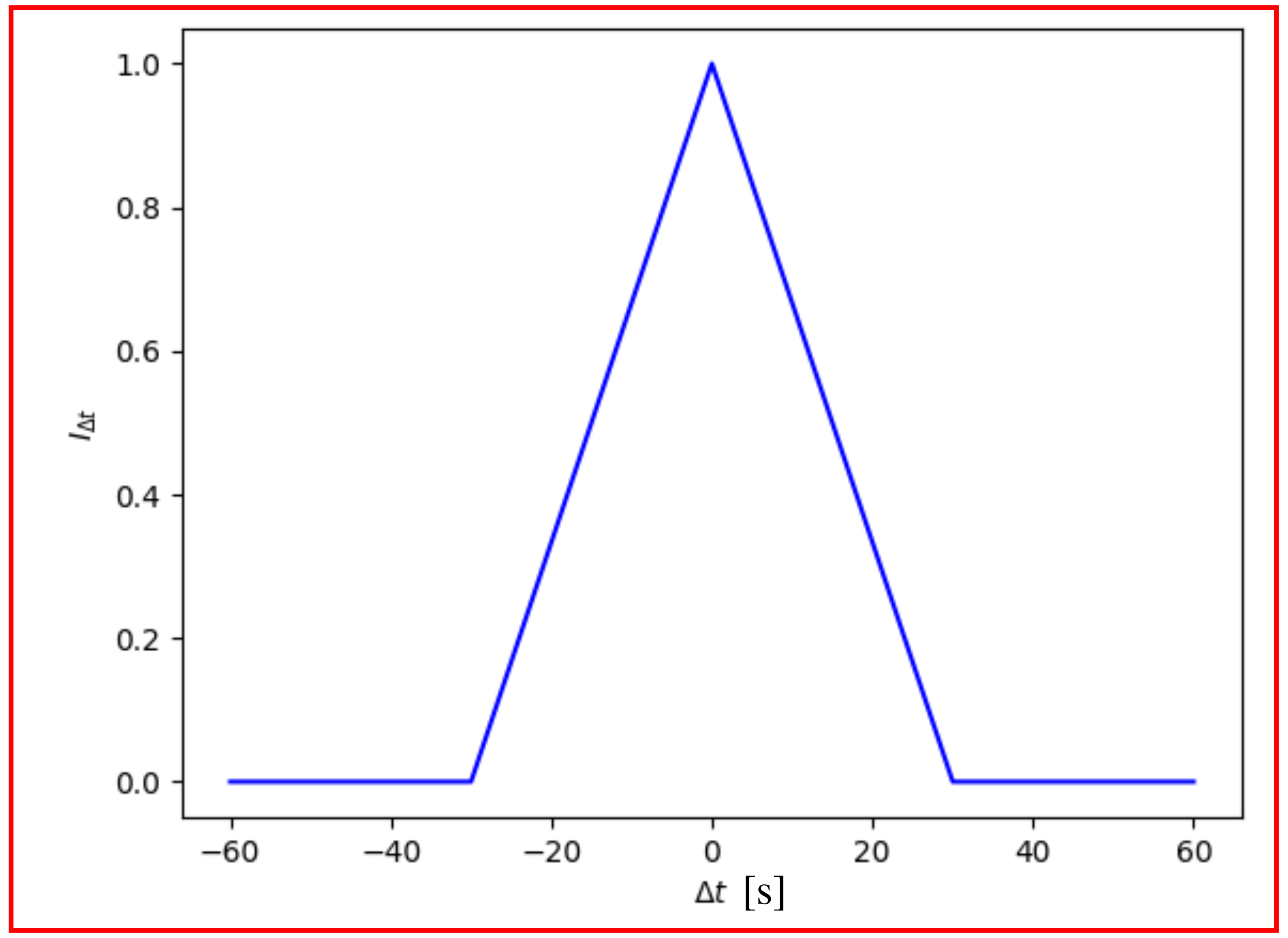
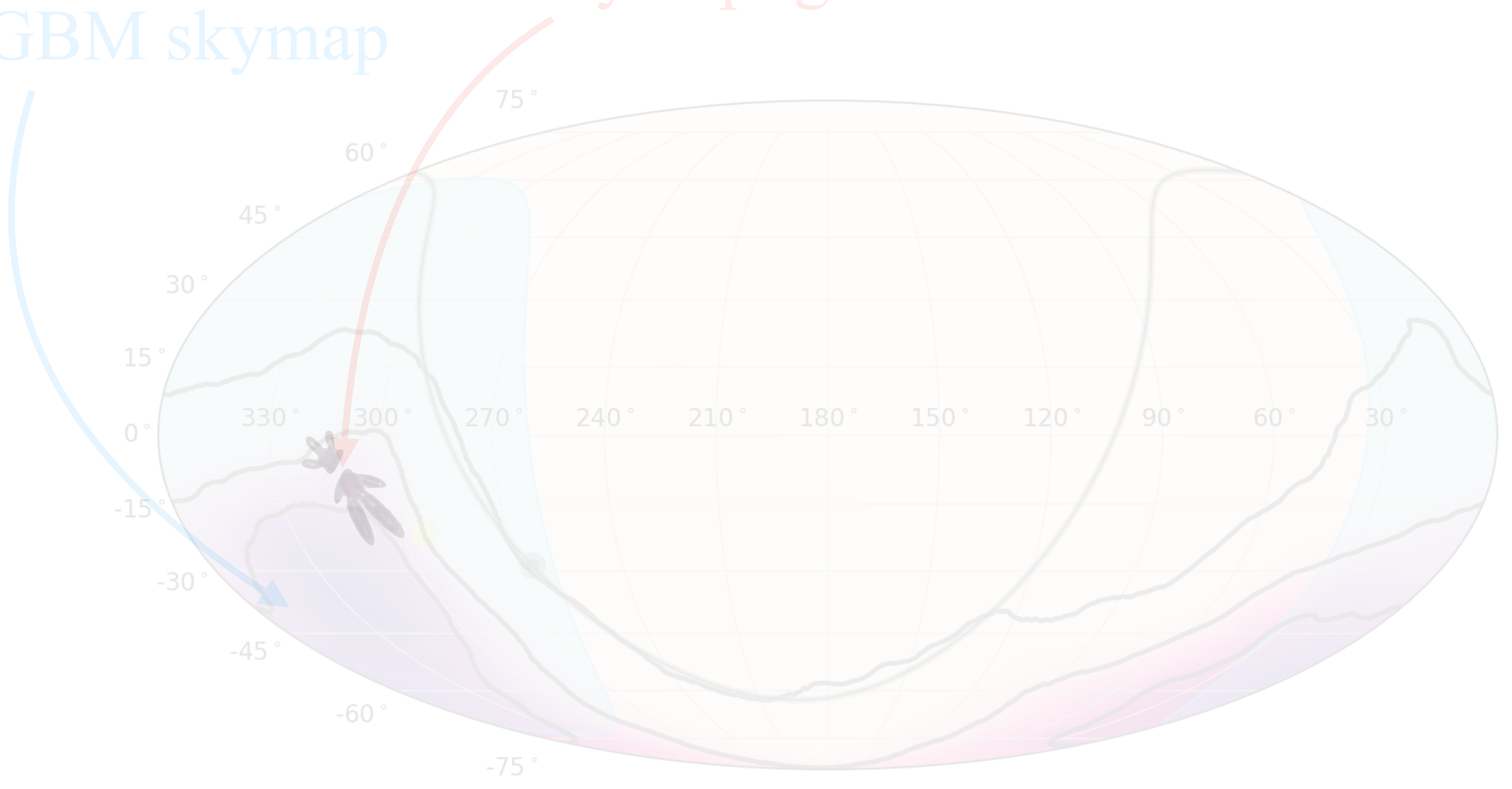


Time offset prior

$Q_\gamma < 0 \rightarrow$ *signal-like*

GW skymap: glitch

GBM skymap



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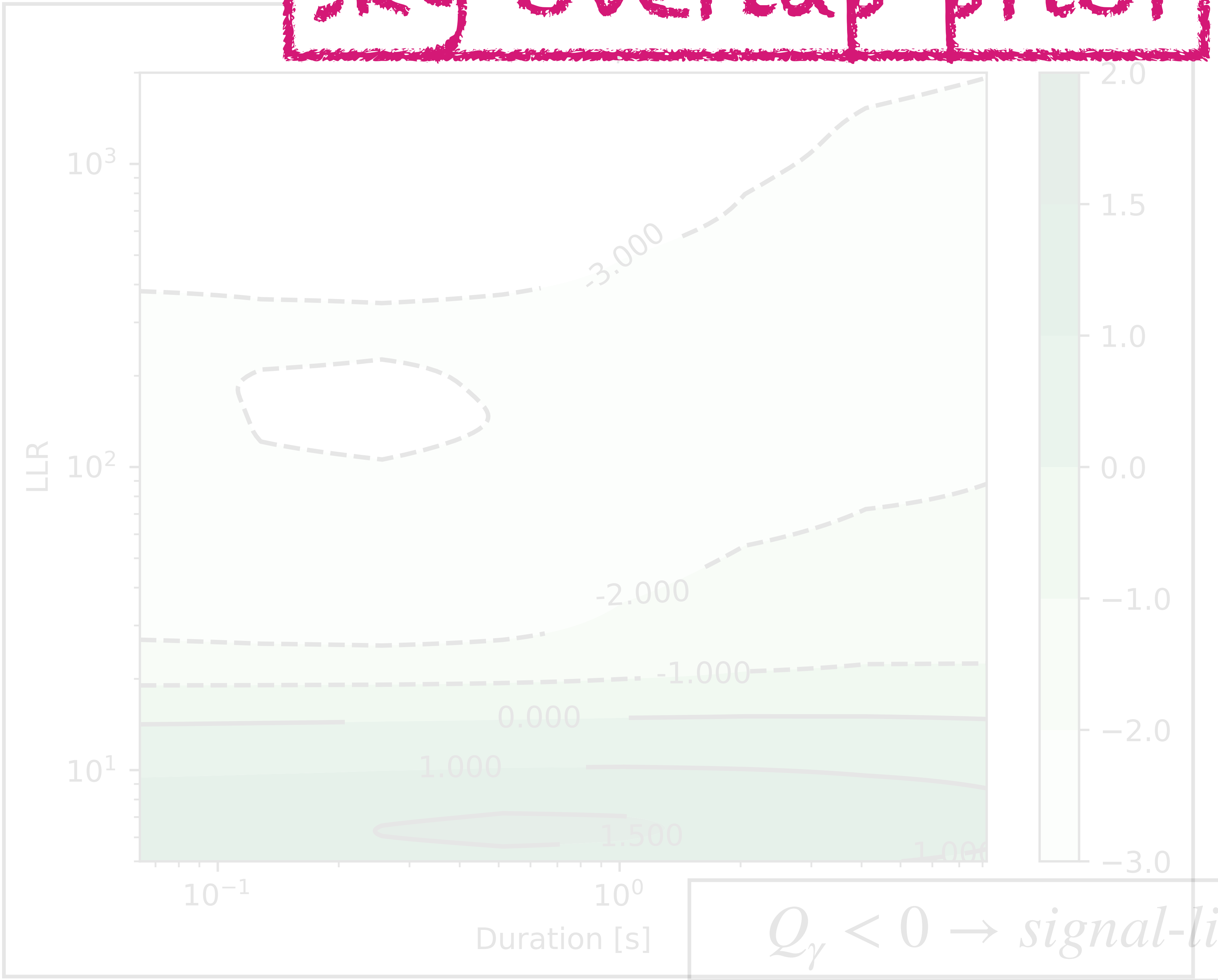
Bayes factor Coherent VS Incoherent signal (from Bayestar)

Sky overlap prior



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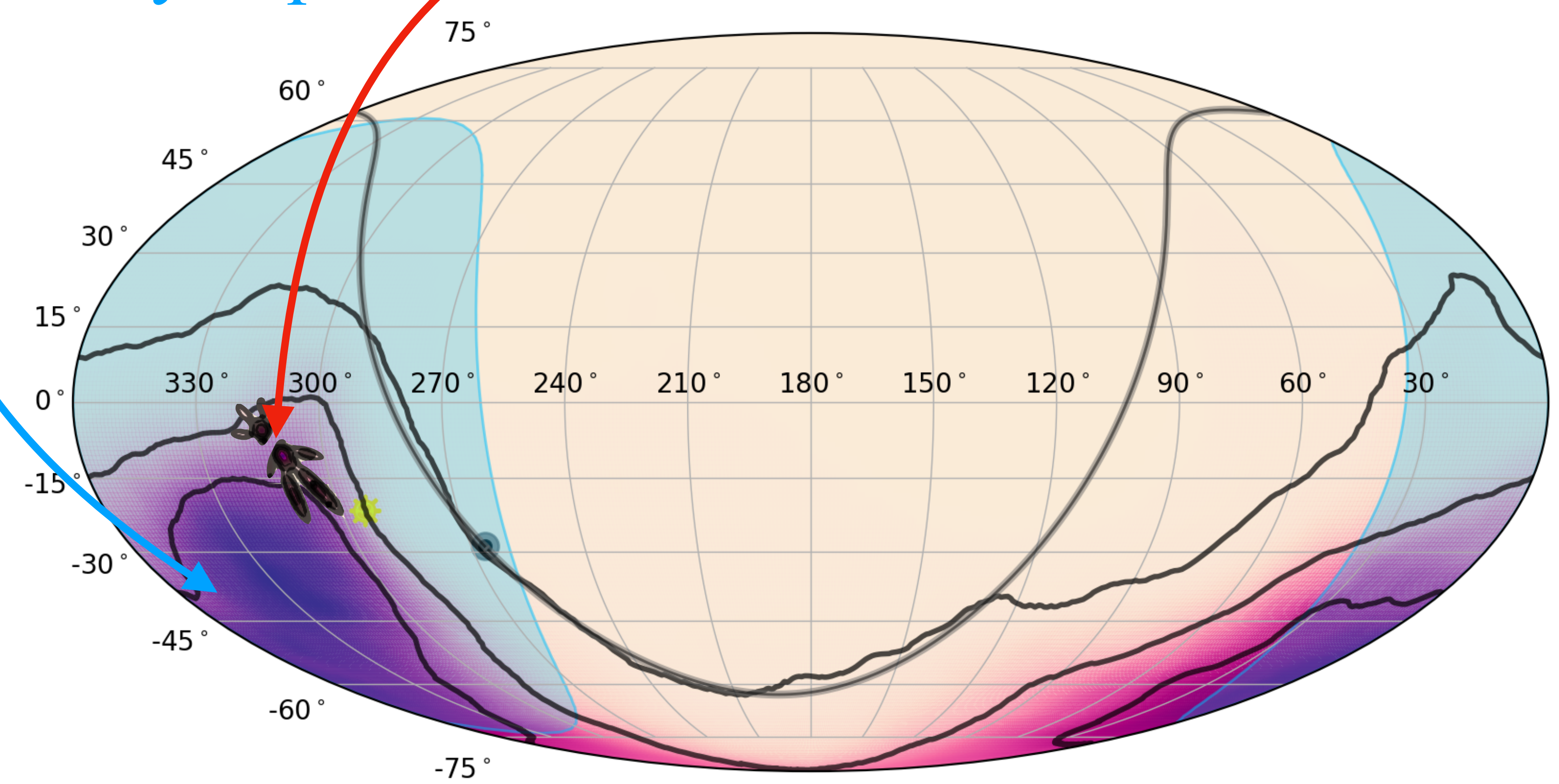

<u>Low ranked background association in our analysis</u>

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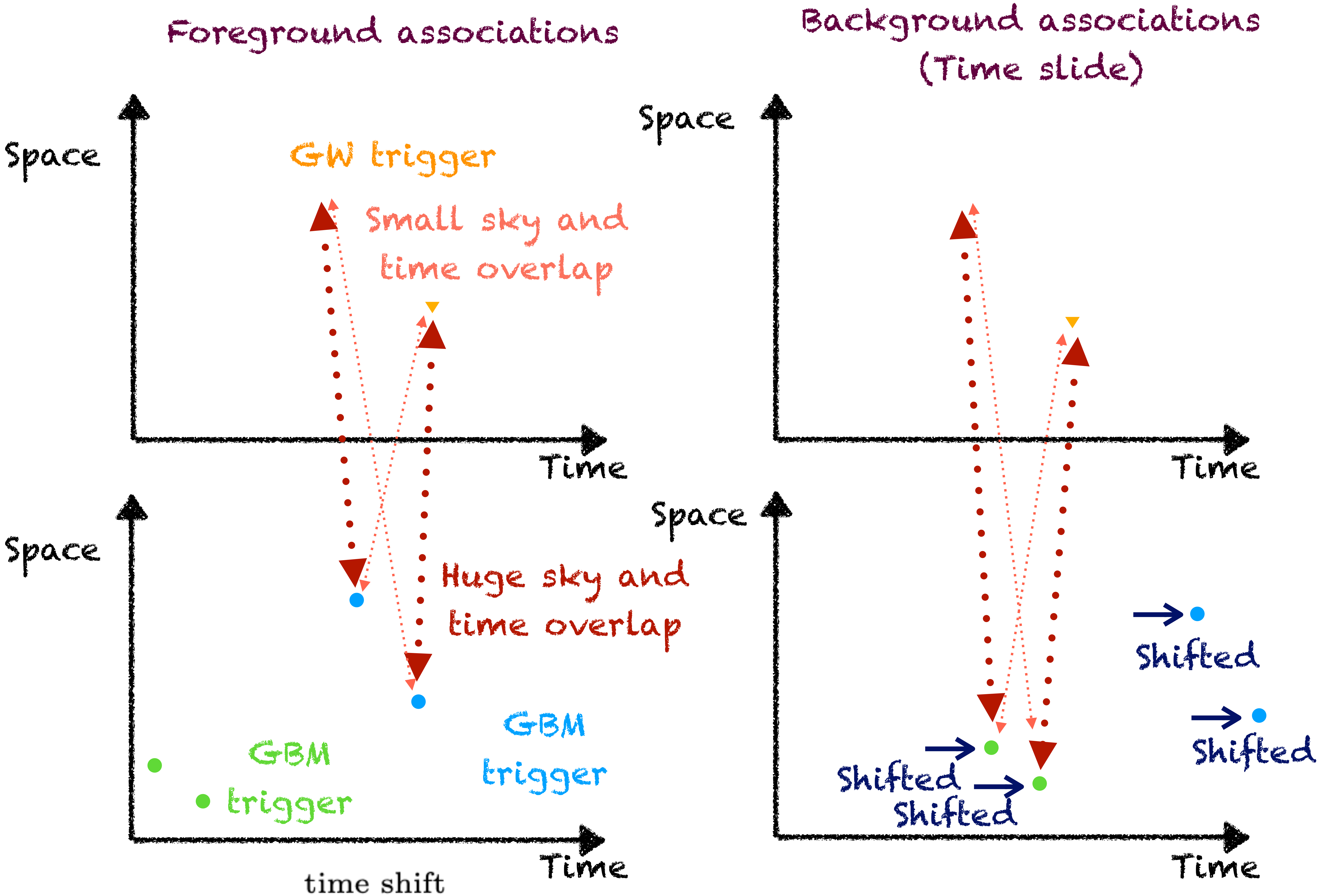
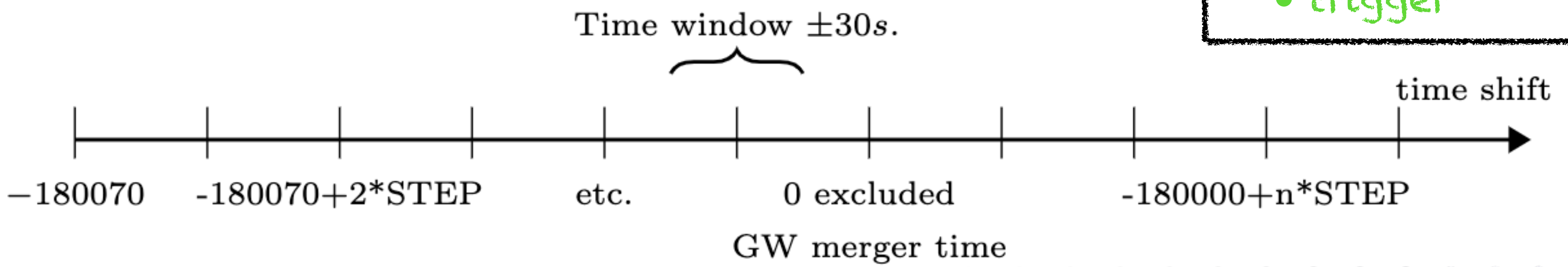
noise-like | *signal-like*

4 ◆ Background computation

Standard method (similar to what PyCBC does):

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





2.2 A deeper method to search for joint detections: results

1. ◆ Configurations

✓ Analysis with PyCBC triggers coming from the 2nd Gravitational-Waves Observing Run: **check the validity of our method against GW170817 — GRB 170817A**

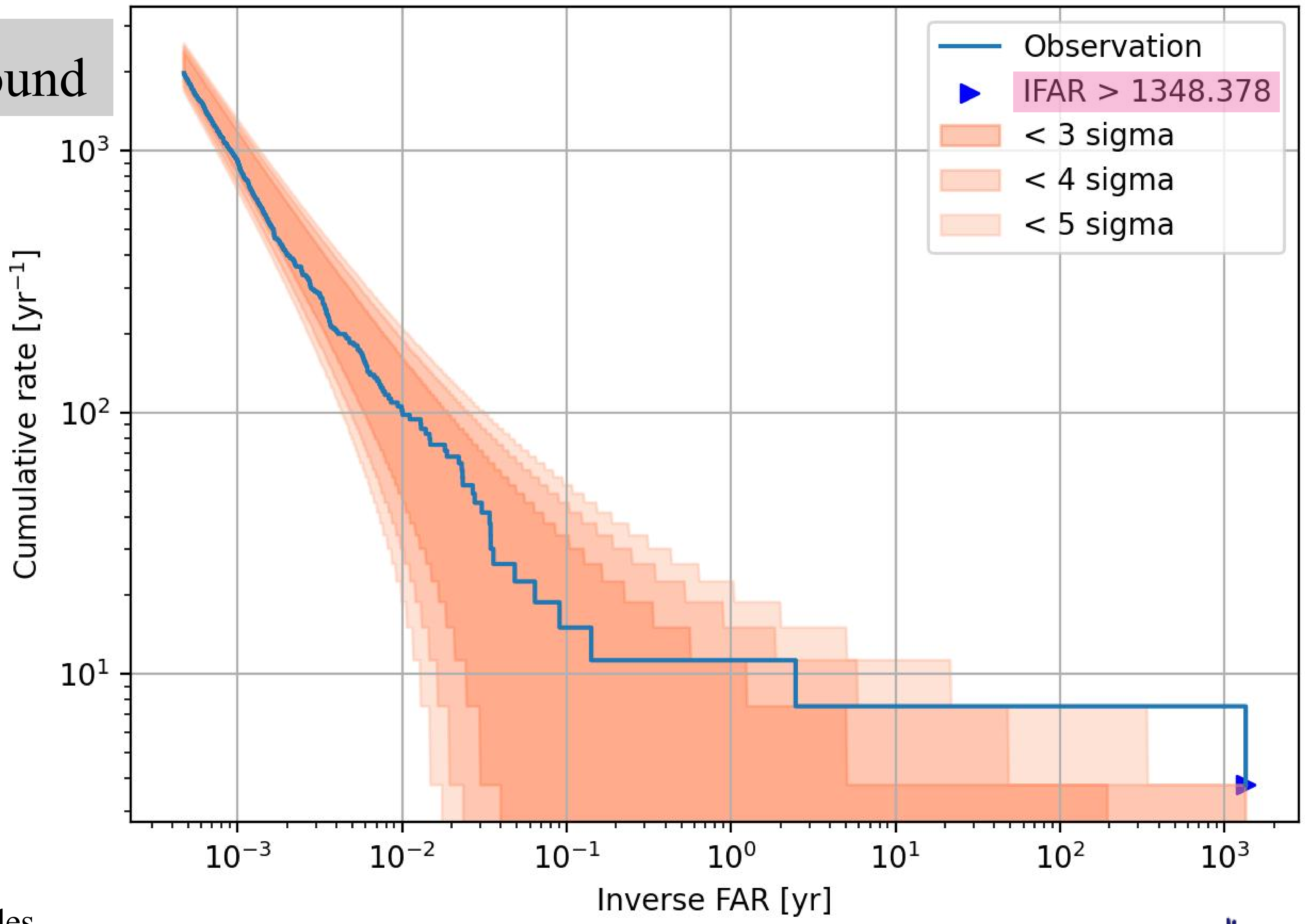
✓ Different configurations have been tested to **maximize the significance** of this joint detection

Only the optimized configuration presented here:

- Background computation with time-slides ± 180000 s with step of 70 s
- Including Virgo contribution in the sky localization
- Applying a preliminary cut of the GW triggers based on their FAR_{GW} Threshold of 2/day (based on GWTC-3)

~800000 GBM triggers & ~500 GW triggers

2. ◆ Significance of the foreground

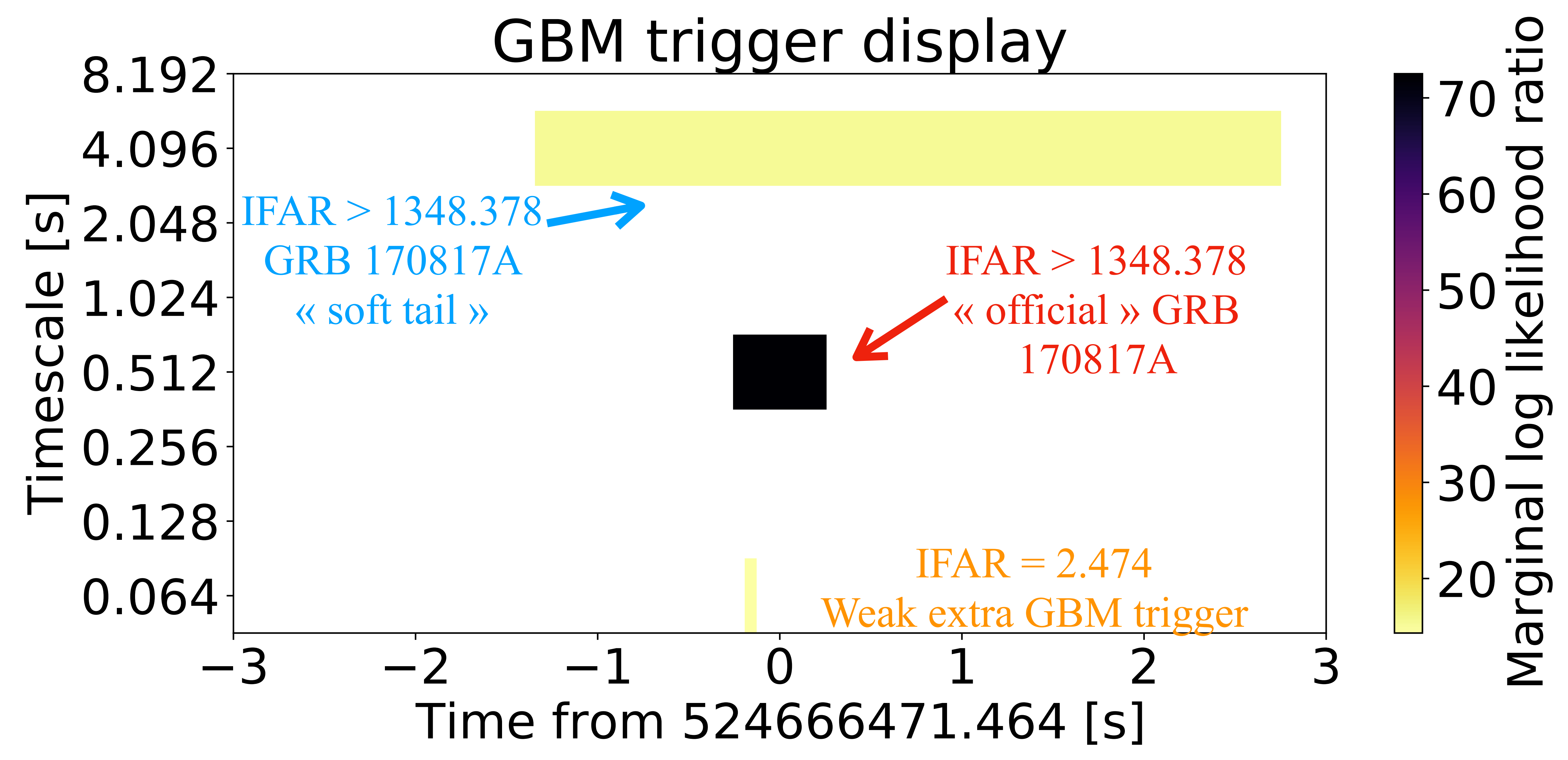


Lower limit on the significance: 4σ

Limited by the amount of accumulated time slides

3. Most significant foreground associations

	GW properties		GBM properties				Joint properties			
Rank	Merger time	Q_g	Duration [s]	Spectrum	LLR	Q_γ	Δt [s]	I_Ω^{EA}	Λ	IFAR [yr]
1	1187008882.445	6.31×10^{-6}	0.512	normal	72.51	1.91×10^{-3}	2.02	17.2	16.0	>1348
2	1187008882.445	6.31×10^{-6}	4.096	soft	15.38	8.67×10^{-1}	2.72	27.9	13.6	>1348
3	1187008882.445	6.31×10^{-6}	0.064	hard	14.32	9.20×10^{-1}	1.86	2.86	1.40	2.474
* 4	1185284217.254	1.18×10^{-2}	0.064	normal	9.457	10.0	12.71	5.05	0.261	0.142



* Next one: not significant

3. Conclusion

1. ◆ Validity of the method

- We were able to analyze a large amount of triggers (~**800000** GBM triggers & ~**500** GW triggers)
- Found GW170817-GRB 1707817A with a high significance!
- Lot of noise on the GW side → GW170817-GRB 170817A is not highly significant (Not presented here).
- We found a configuration that works (presented here): has been used in O3 (paper under review by the LIGO/Virgo collaboration).

2. ◆ Improvement & Perspectives

- Change the time offset prior into a more realistic one.
  - Can we try: $\Delta t_{\mathrm{GW-GRB}} = (\Delta t_{\mathrm{jet}} + \Delta t_{\mathrm{bo}} + \Delta t_{\mathrm{GRB}})(1+z)$ [B. Zhang, 2019]
- Not shown here: The GW Bayes Factor should be improved: it doesn't discriminate properly between noise and signal.
  - We tried another method: use both the BSN and BCI.
  - Use the p_{astro}?

- To be used in O4.

Thank you!

BACKUP

1. Configurations

✓ Analysis with PyCBC triggers coming from the 2nd Gravitational-Waves Observing Run: **check the validity of our method against GW170817 — GRB 170817A**

✓ Different configurations have been tested to **maximize the significance** of this joint detection

~800000 GBM triggers & ~15000 GW triggers (Config 1.–4.)

~800000 GBM triggers & ~500 GW triggers (Config 5.)

Configurations:	**Config 1.**	**Config 2.**	**Config 3.**	**Config 4.**	**Config 5.**
• Separating the associations by GBM spectral values and GBM durations	Yes	Yes	Yes	No	No
• Background computation with time-slides ± 50000 s with step of 100 s	Yes	Yes	No	No	No
• Background computation with time-slides ± 180000 s with step of 70 s	No	No	Yes	Yes	Yes
• Including Virgo contribution in the sky localization	No	Yes	Yes	Yes	Yes
• Applying a preliminary cut of the GW triggers based on their FAR_{GW}	No	No	No	No	Yes

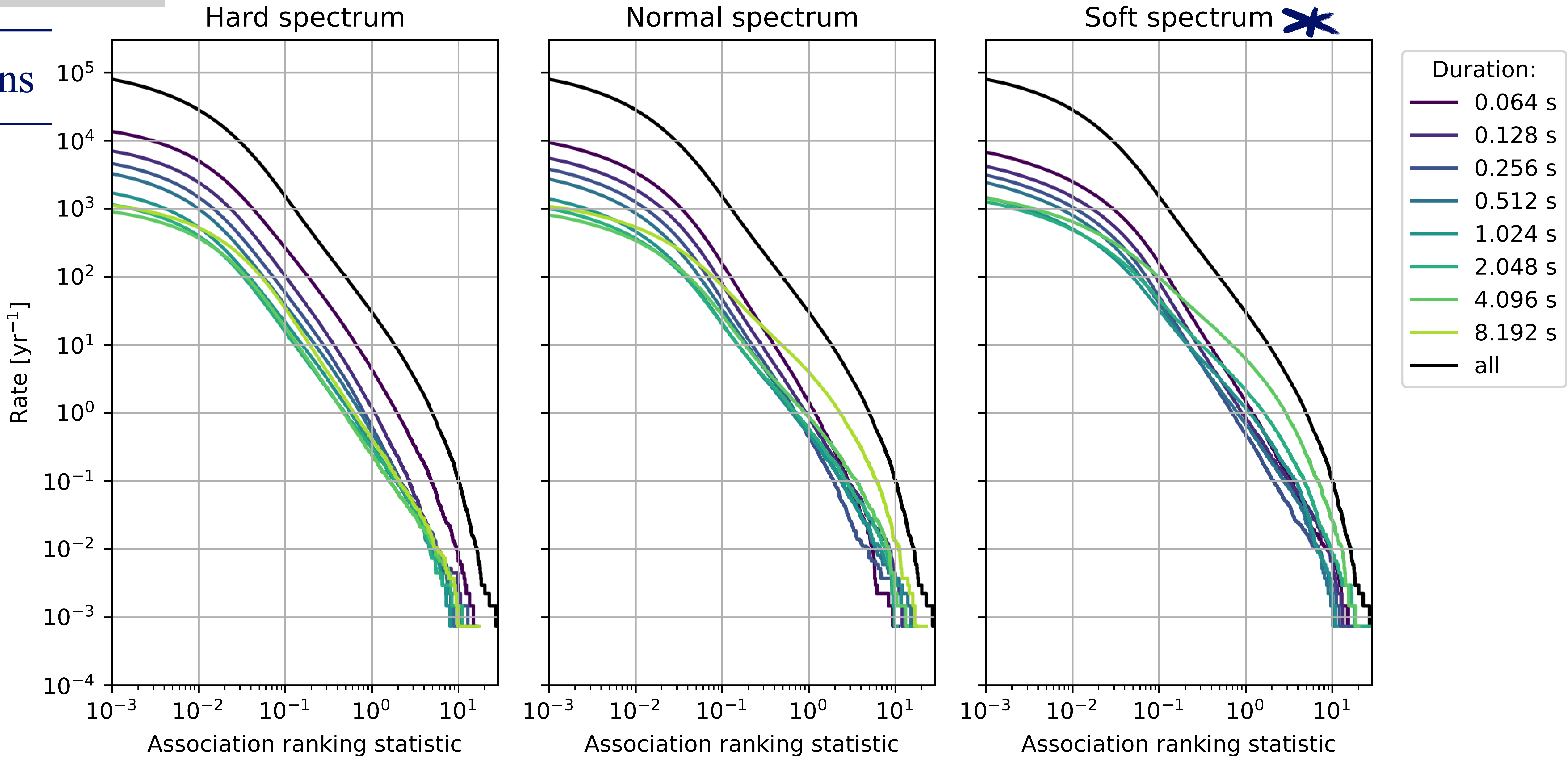
Only config 5. presented here

BACKUP

2 ◆ Configuration n°3

Background associations

No 8.192 s - soft (—) GBM triggers: intentionally removed by the GBM Targeted Search (because they contaminate the background above all)

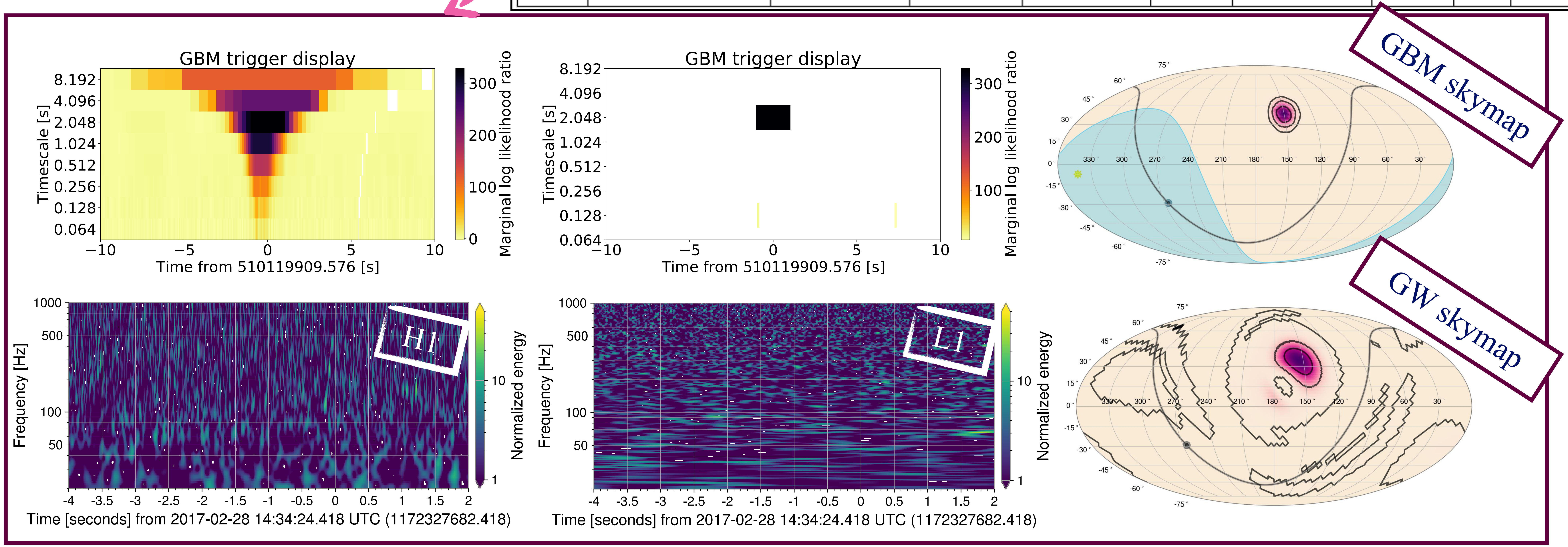


BACKUP

2. ◆ Configuration n°3

Highest ranked background associations

	GW properties		GBM properties				Joint properties			
Rank	Merger time	Q_g	Duration [s]	Spectrum	LLR	Q_γ	Δt [s]	I_Ω^{EA}	Time shift [s]	Λ
1	1172327682.418	7.47×10^{-1}	2.048	soft	328.1	1.84×10^{-3}	0.158	48.4	-134640	27.5
2	1177306450.914	1.13×10^{-1}	0.256	soft	1595.4	2.15×10^{-4}	13.854	55.4	22650	26.8
3	1165069774.280	2.05×10^{-1}	8.192	normal	64.28	1.53×10^{-2}	1.216	28.8	-104540	22.6
4	1165070949.873	1.63×10^{-1}	4.096	soft	27.66	5.23×10^{-2}	0.679	25.2	-16410	20.1



2. ◆ Configuration n°3

Significance of the foreground

Rank	GW properties		GBM properties				Joint properties			
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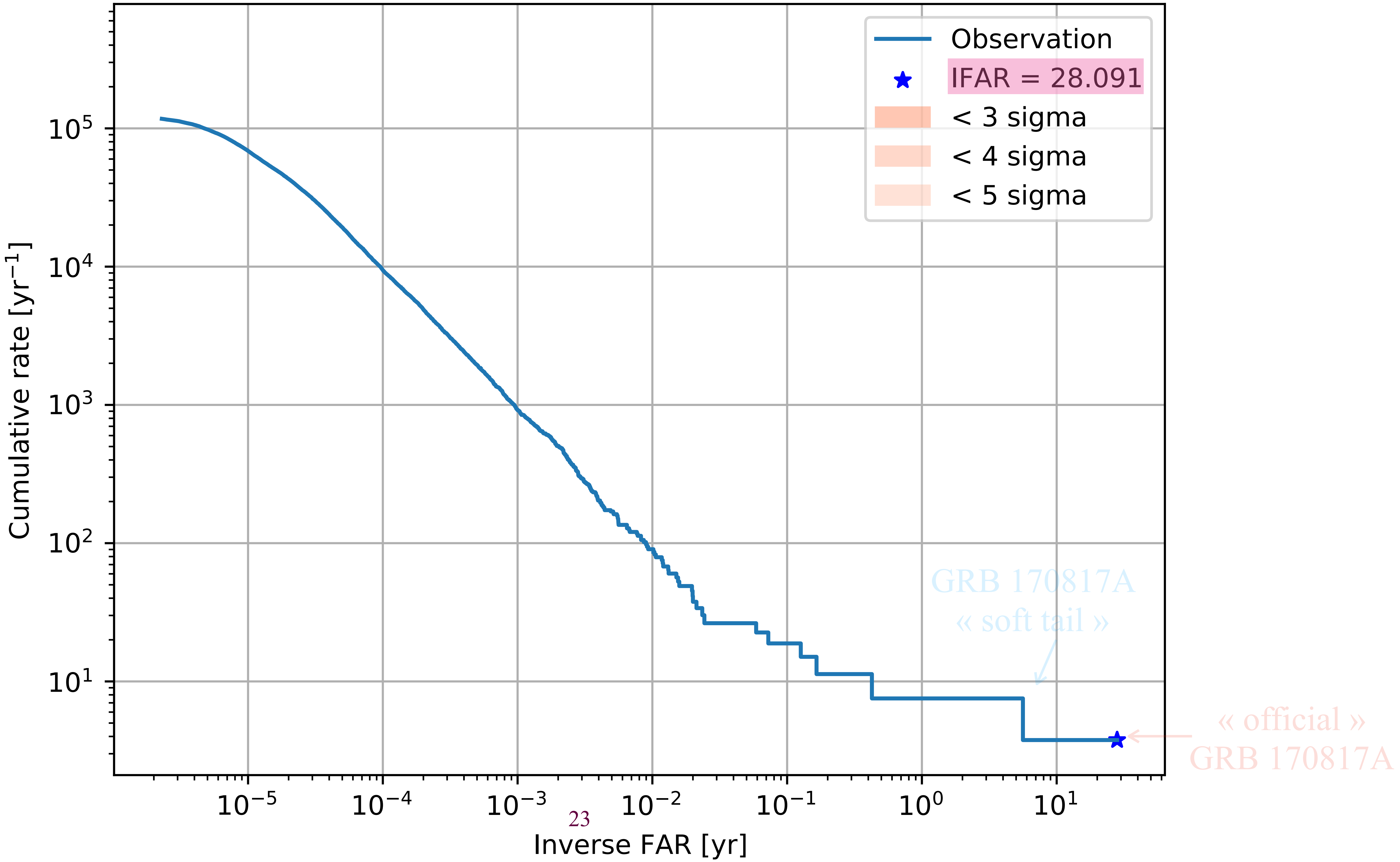
3	1168226845.160	3.76×10^{-2}	4.096	hard	16.61	5.31×10^{-1}	-6.62	3.31	1.63	0.426
4	1185721264.338	7.29×10^{-3}	0.064	soft	13.05	1.75	0.638	6.22	2.20	0.165

Significance: ~3σ detection



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Significance of the foreground

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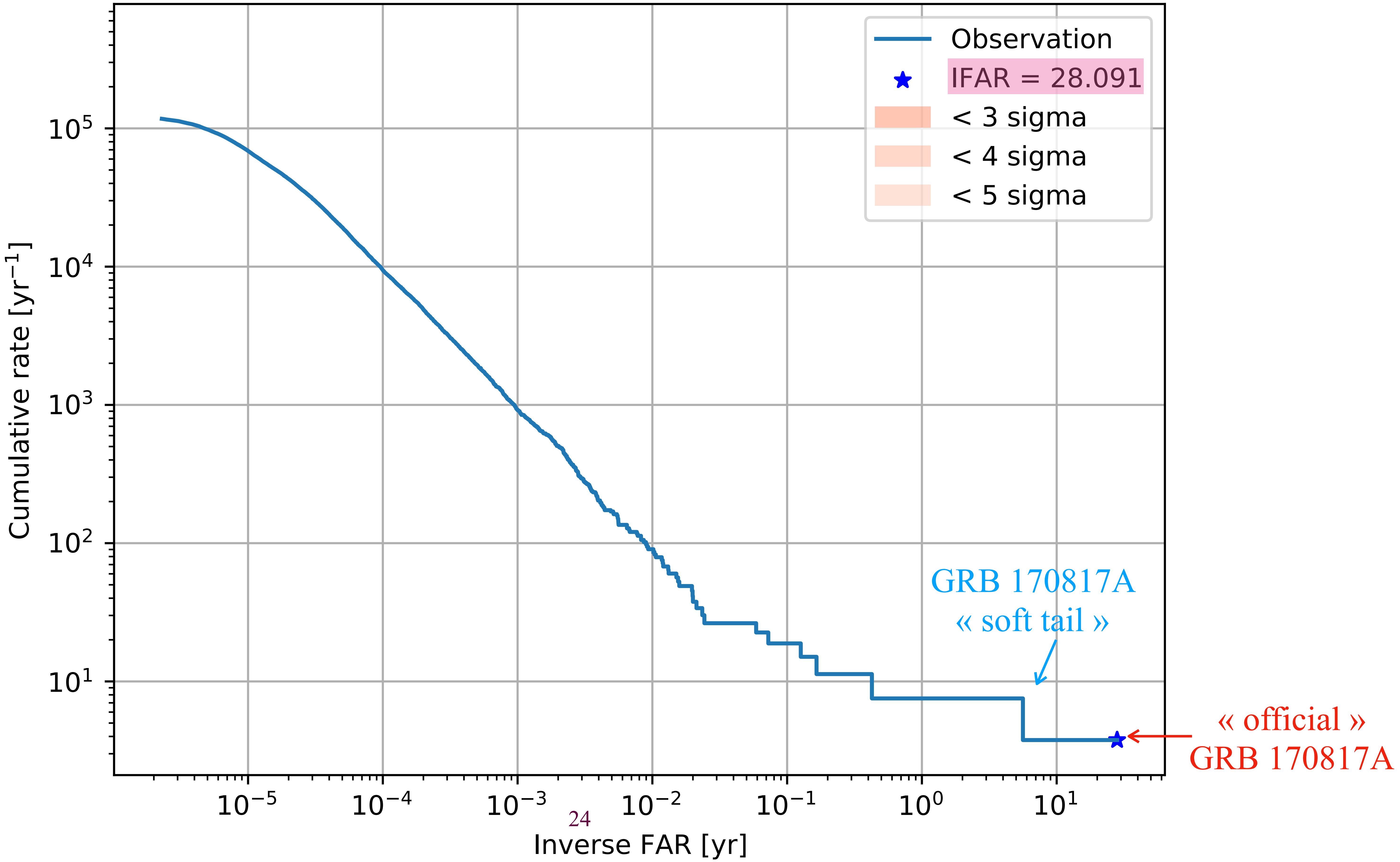

BACKUP

2. ◆ Configuration n°3

Most significant foreground associations

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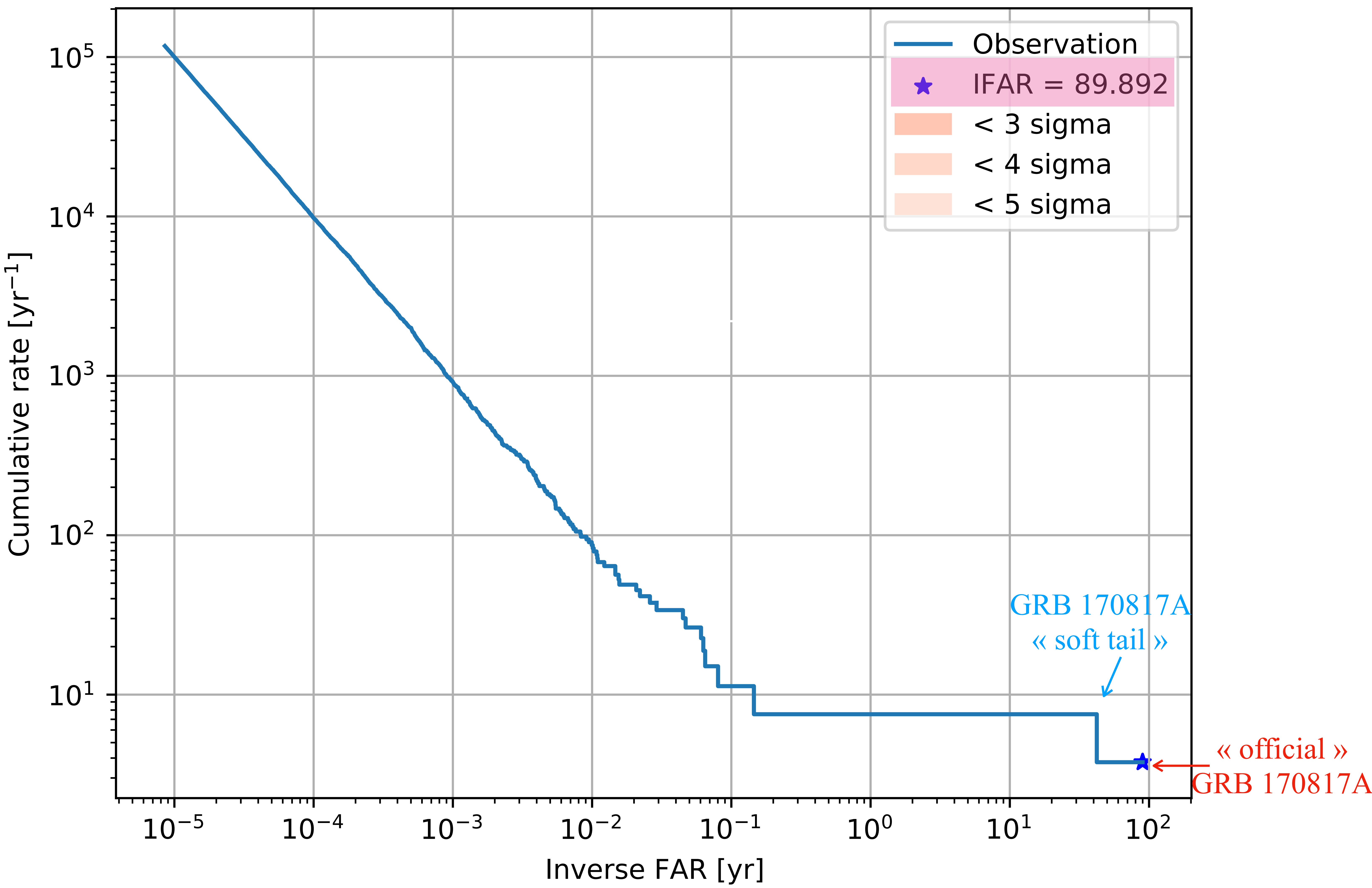
BACKUP

3 ◆ Configuration n°4

Significance of the foreground

Significance: ~3σ detection



4 ◆ Configurations n°3 & n°4

What limits GW170817 — GRB 170817A significance?

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

	GW properties		GBM properties				Joint properties		
Rank	Merger time	Q_g	Duration [s]	Spectrum	LLR	Q_γ	Δt [s]	I_Ω^{EA}	Λ
1	1176213122.254	2.98×10^{-1}	0.512	normal	176.6	1.05×10^{-3}	-6.78	17.2	17.8

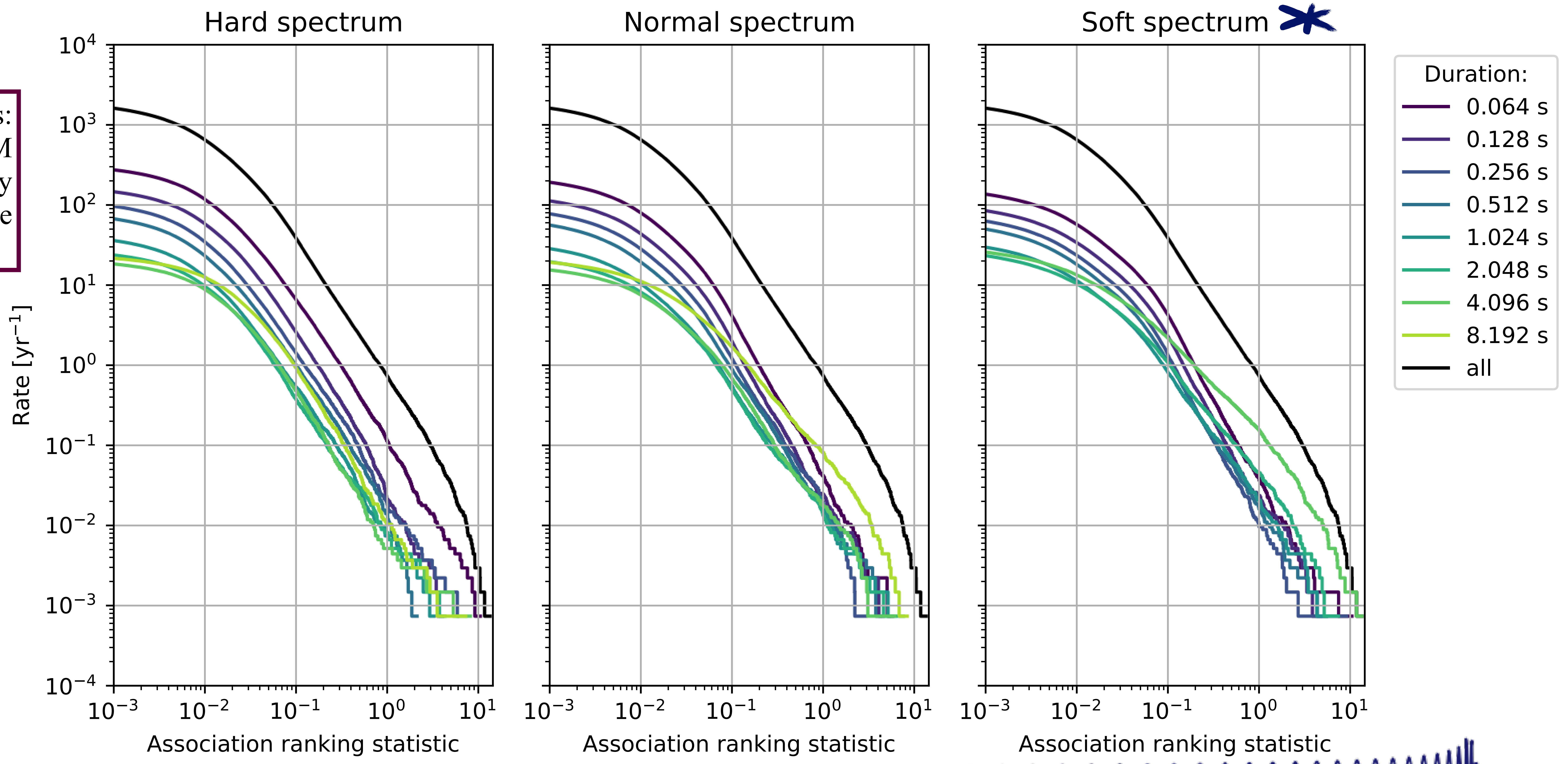
This association contains a real GRB and noise in the GW channel (with an **IFAR** = $4.265 \times 10^{-5} yr$)

To maximize the significance we decide to apply a cut on the GW triggers based on their false alarm rate value. We choose a threshold of 2 per day, inspired from GWTC-3 (configuration 5).

2.2 A deeper method to search for joint detections: results

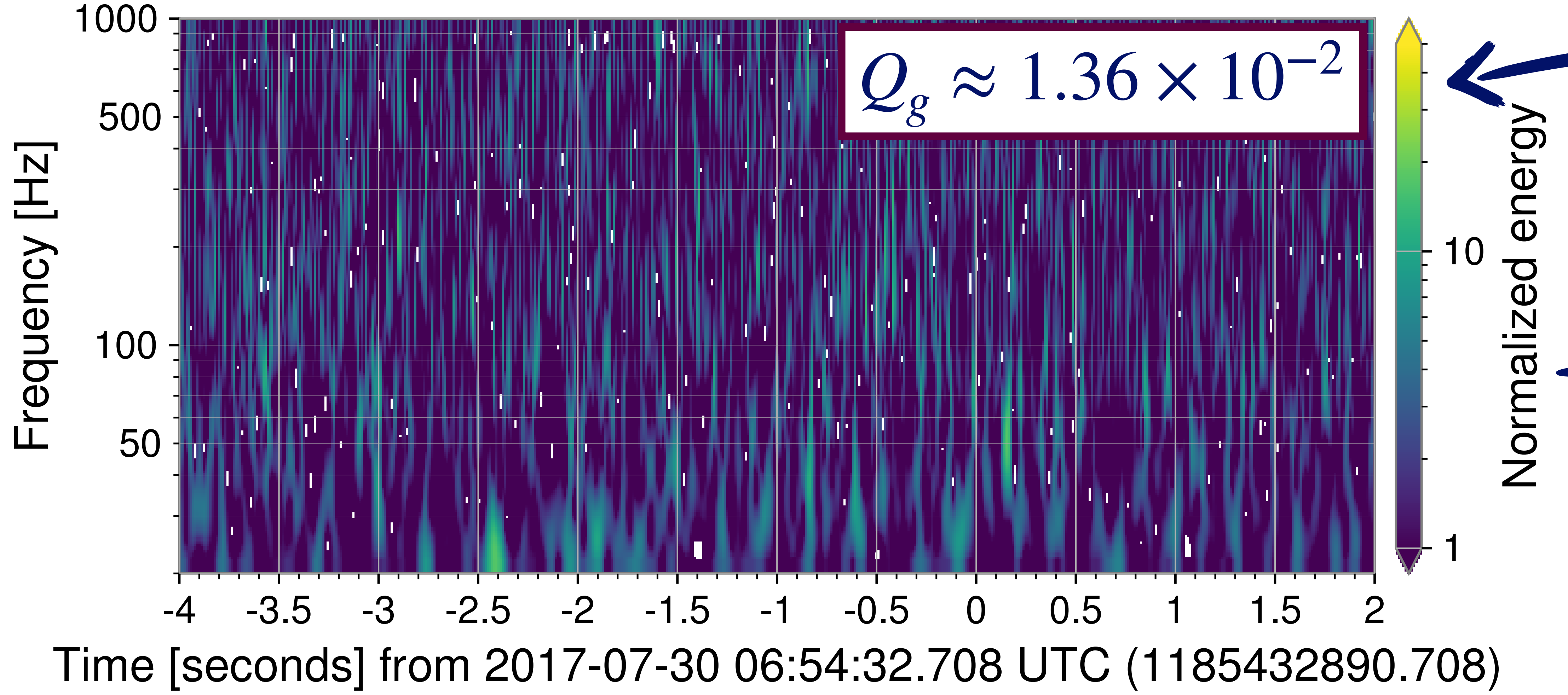
2. Background associations

* No 8.192 s - soft (—) GBM triggers: intentionally removed by the GBM Targeted Search (because they contaminate the background above all)



2.2 A deeper method to search for joint detections: results

3. ◆ Highest ranked background associations

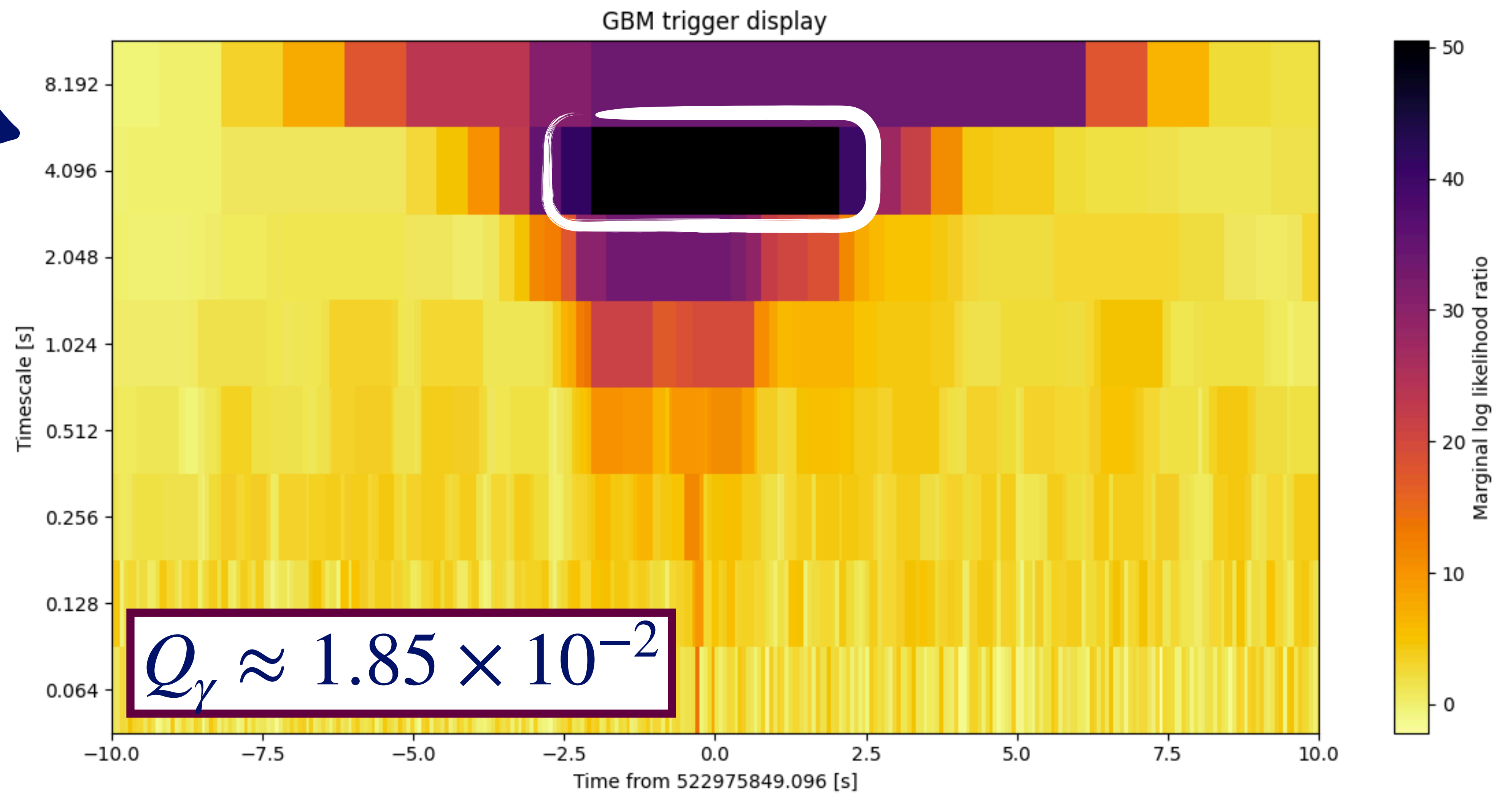


$Q_g \approx 1.36 \times 10^{-2}$

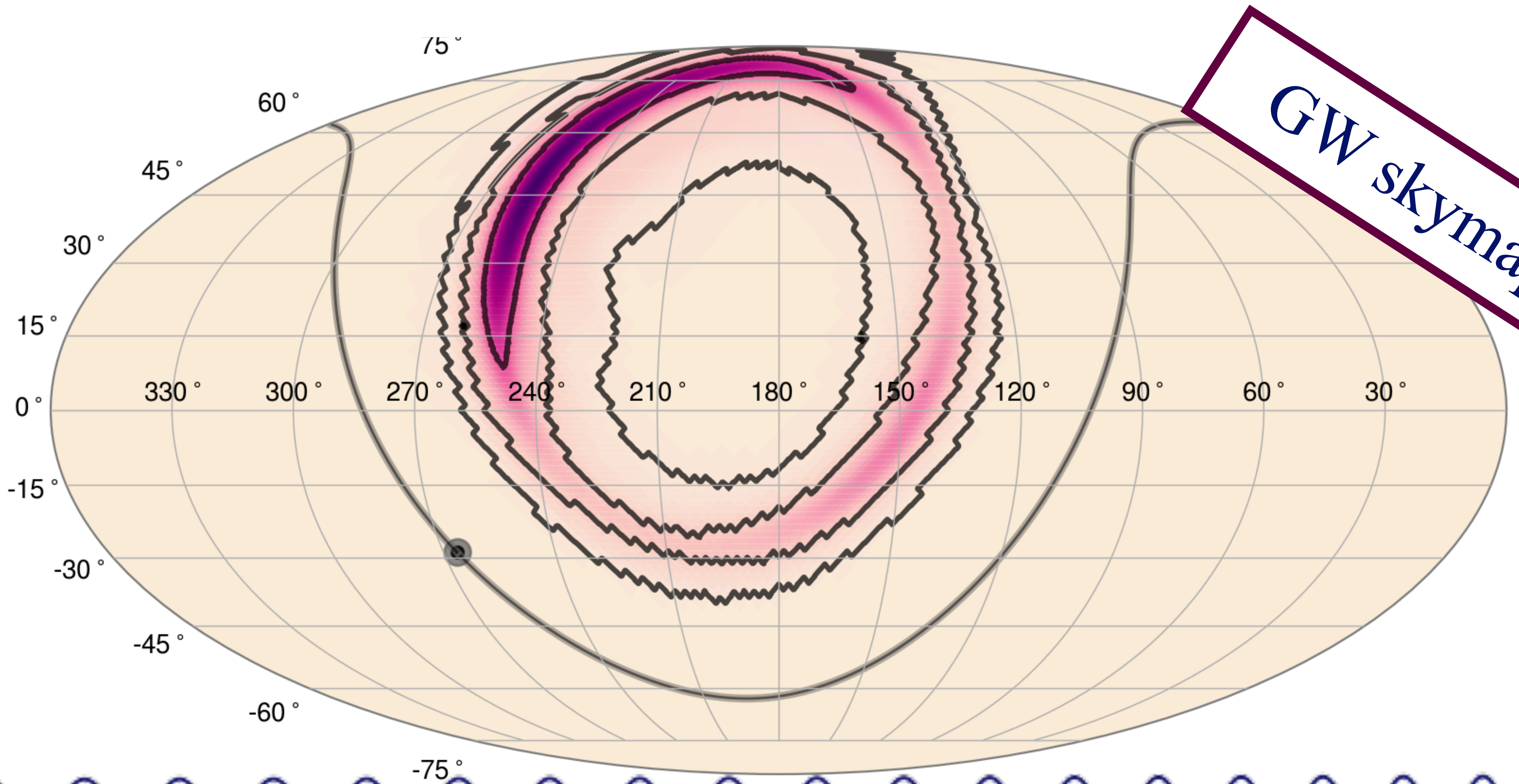
$\Lambda = 13.5$

$I_{\Delta t} \approx -1.39$ s

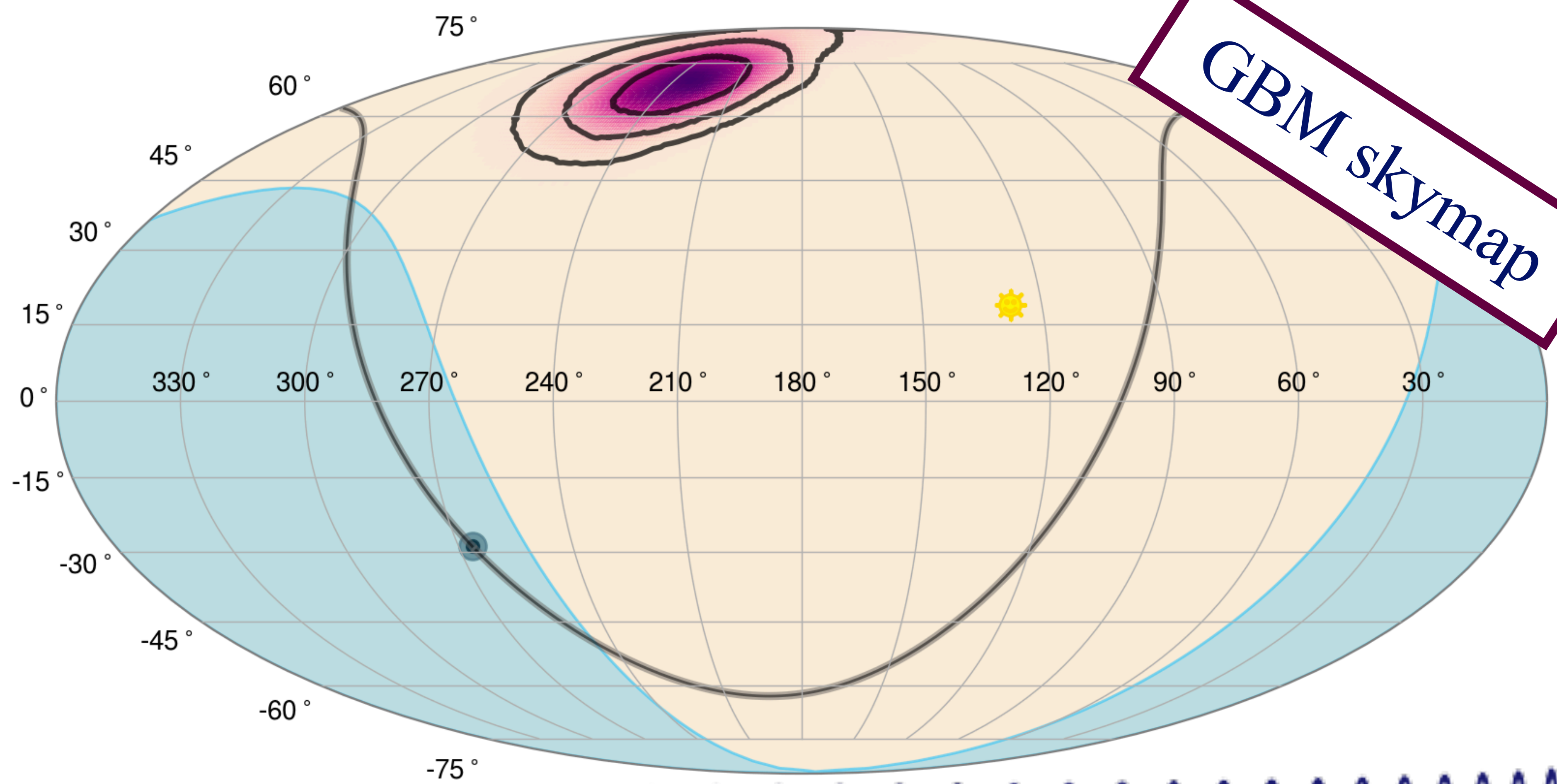
(With a time-shift of 114630 s)



$Q_\gamma \approx 1.85 \times 10^{-2}$



GW skymap



GBM skymap