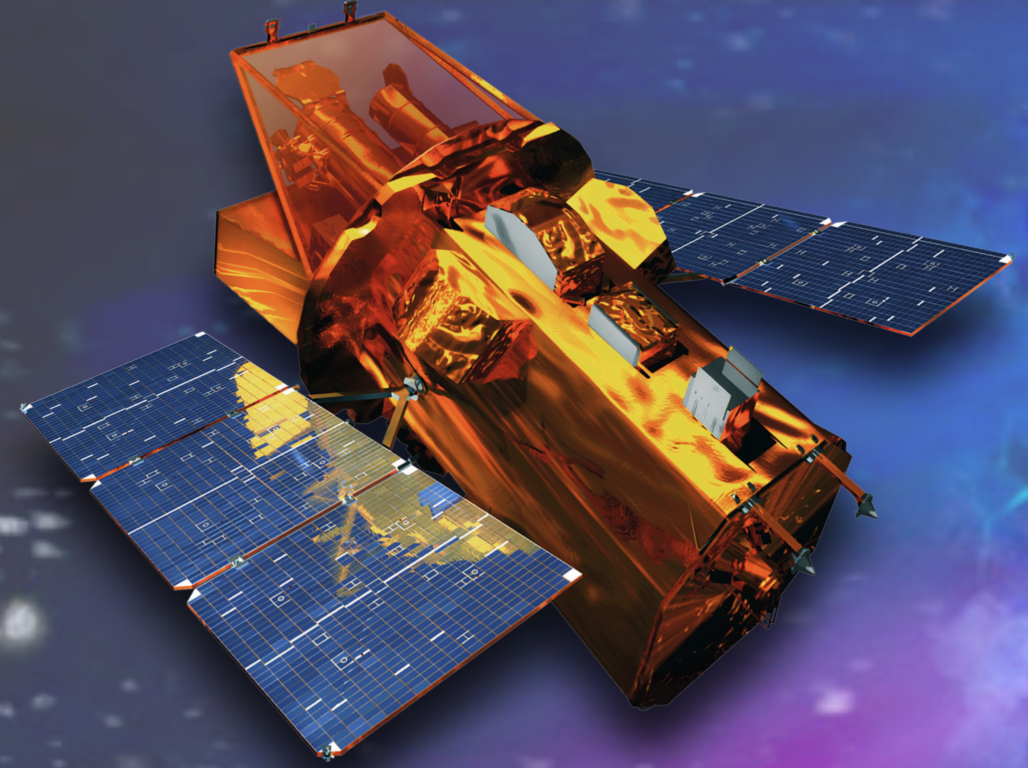
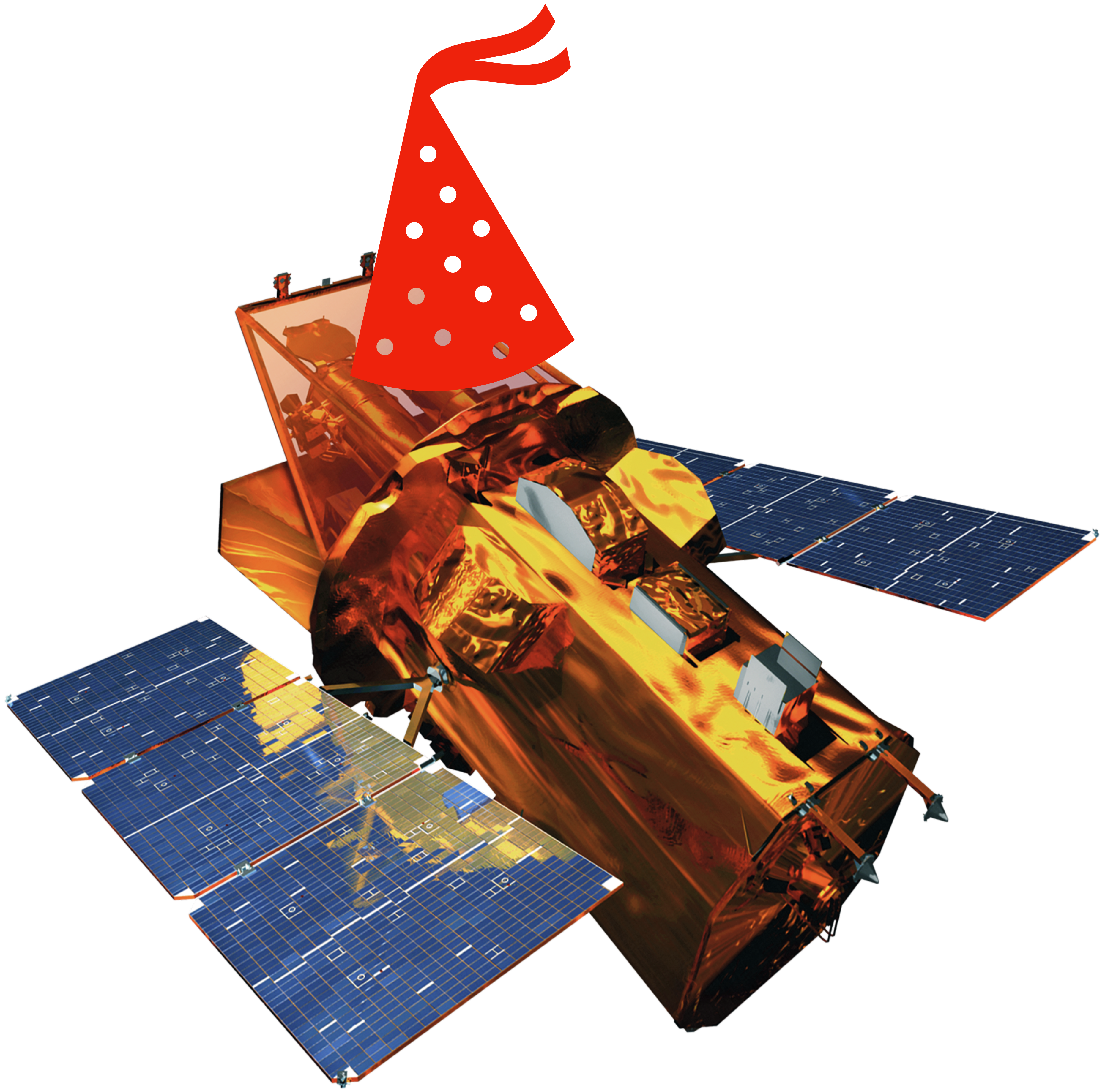
The role of *Swift* in the detection and follow-up of EM counterparts of GWs during O4



Samuele Ronchini

Postdoc @ Swift Mission Operation Center,
PennState University

PennState



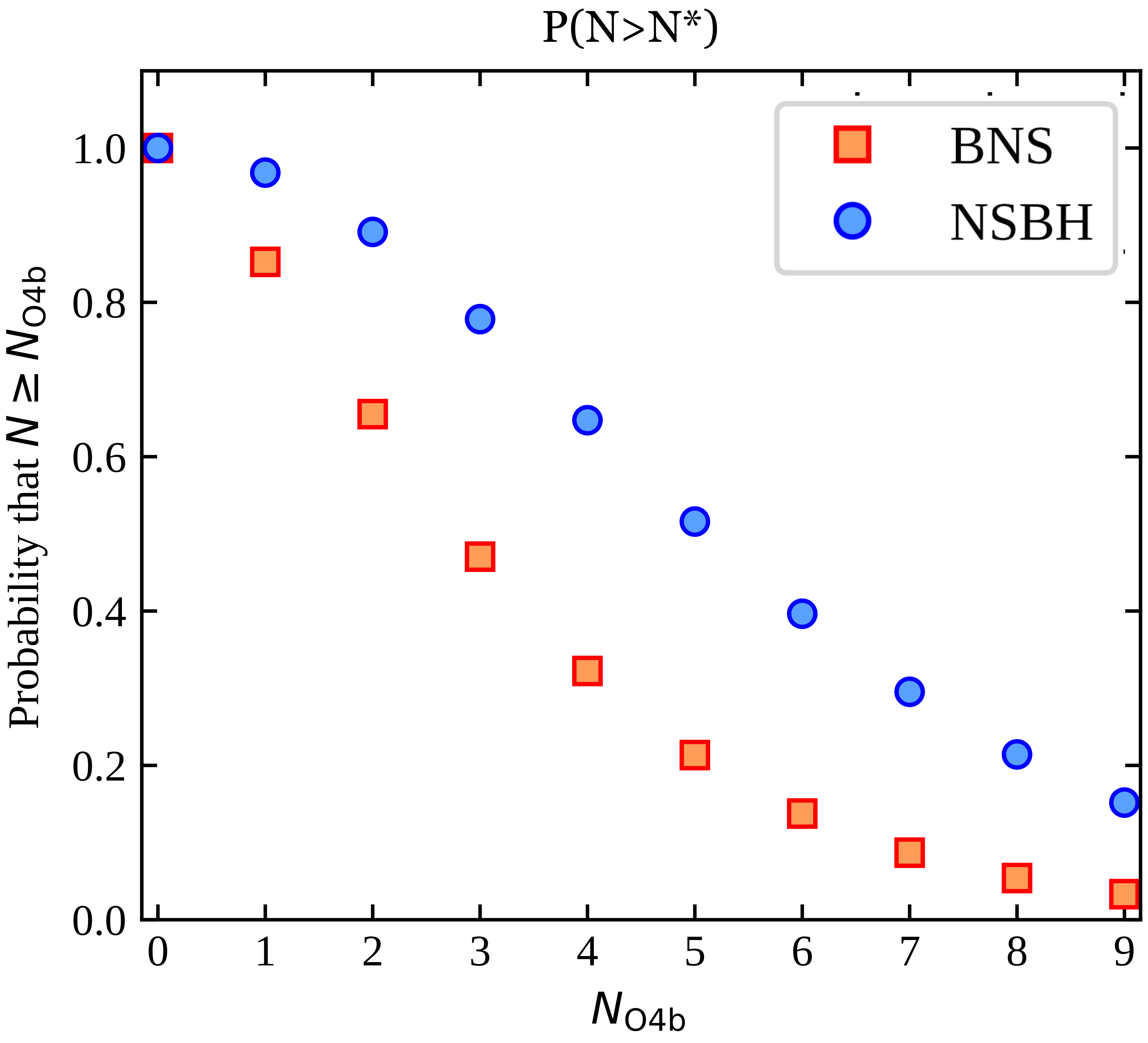
We are close to the celebration of 20 years!!

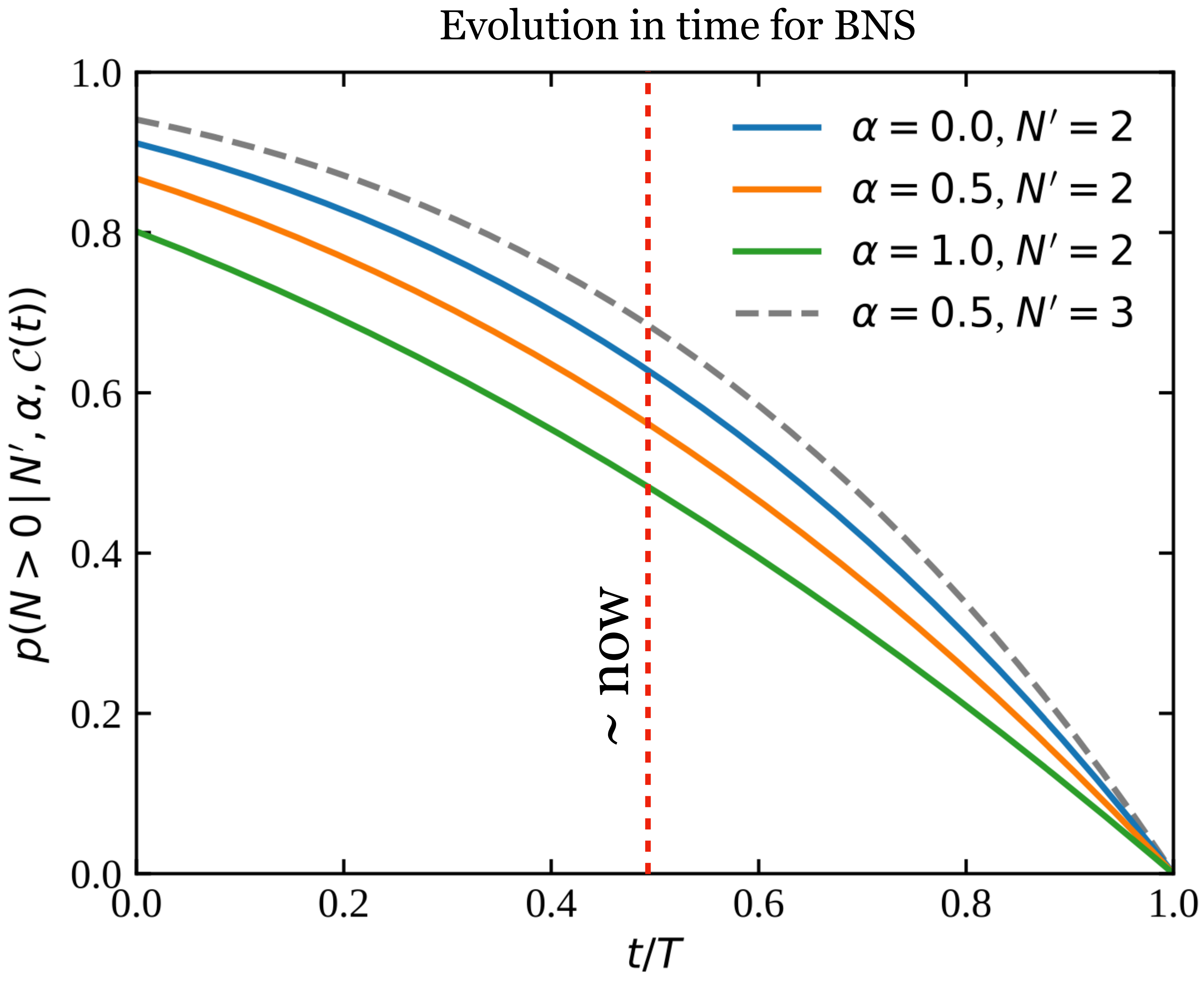
Mar 24–28, 2025, Florence, Italy

https://indico.ict.inaf.it/event/3000/overview

Abstract deadline Dec 31st

What to expect





Credits: Om Sharan Salafia

Swift hunting for GW counterparts: possible scenarios

BAT

1. **Best case scenario**: **BAT triggers onboard** and starts the slew—> arcmin position disseminated to the astro community

2. Performing a subthreshold targeted BAT analysis on a significant/sub-threshold GW, **we find a potential counterpart**:

   - The source is **in FOV**, and an **arcmin position is immediately circulated** (after few hr)
   - The source is in/out FOV and we can produce a **localization skymap**, to be combined with the GW one

3. The external GW trigger is significant, but **no signal in the sub-threshold analysis**

4. The external **GW trigger is low significance**, and **no signal in the sub-threshold BAT analysis —> constraints on population models for the EM counterpart** of a specific CBC class

XRT/UVOT

1. **XRT and UVOT point to the position provided by BAT**
2. **XRT/UVOT start to tile the GW+BAT localization, possibly combined with localizations from other gamma detectors**
3. **XRT/UVOT start to tile the GW area, if some criteria are met (see later)**

Scientific outcome

In case of detection:

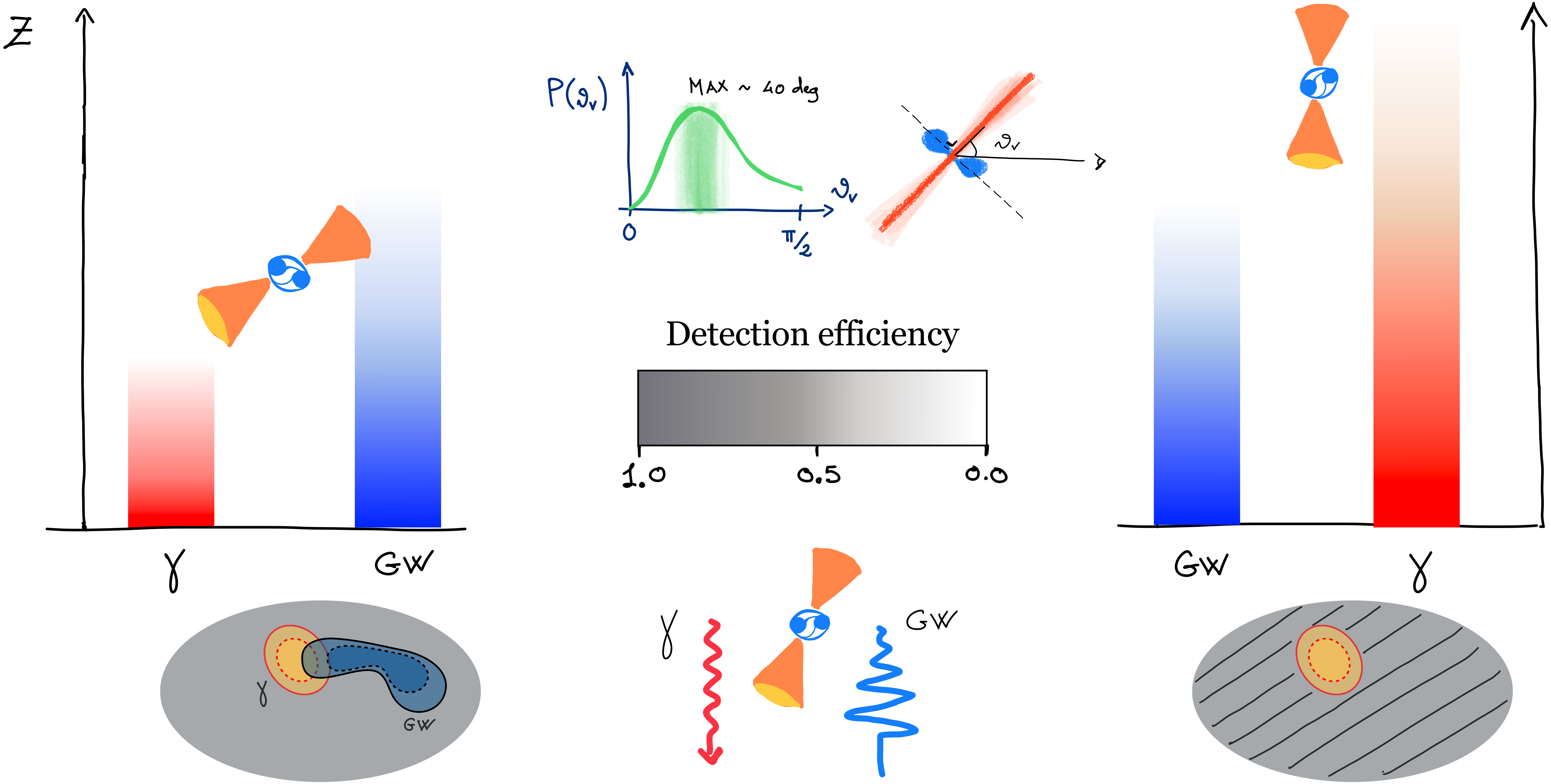
Study the **GW-gamma-ray delay**, **connection** between **GW intrinsic properties** (masses, spins) and the **GRB** prompt and afterglow, jet structure, KN properties, host galaxy, cosmology, tests of general relativity

In case of non-detection:

Constraints on the EM model, performing a joint GW+EM parameter estimation

Sub-threshold searches with *Swift*-BAT

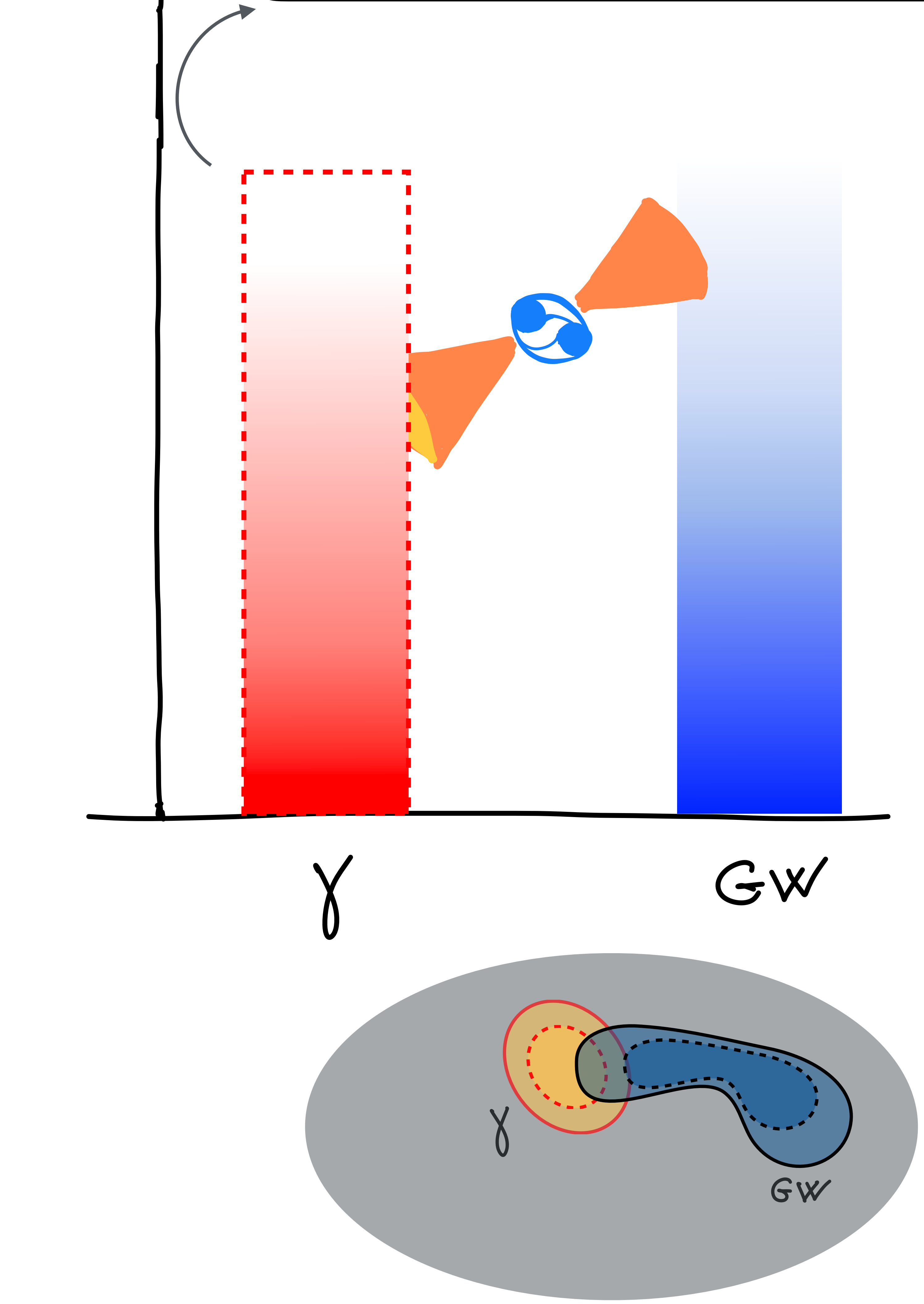
Why to go subthreshold?

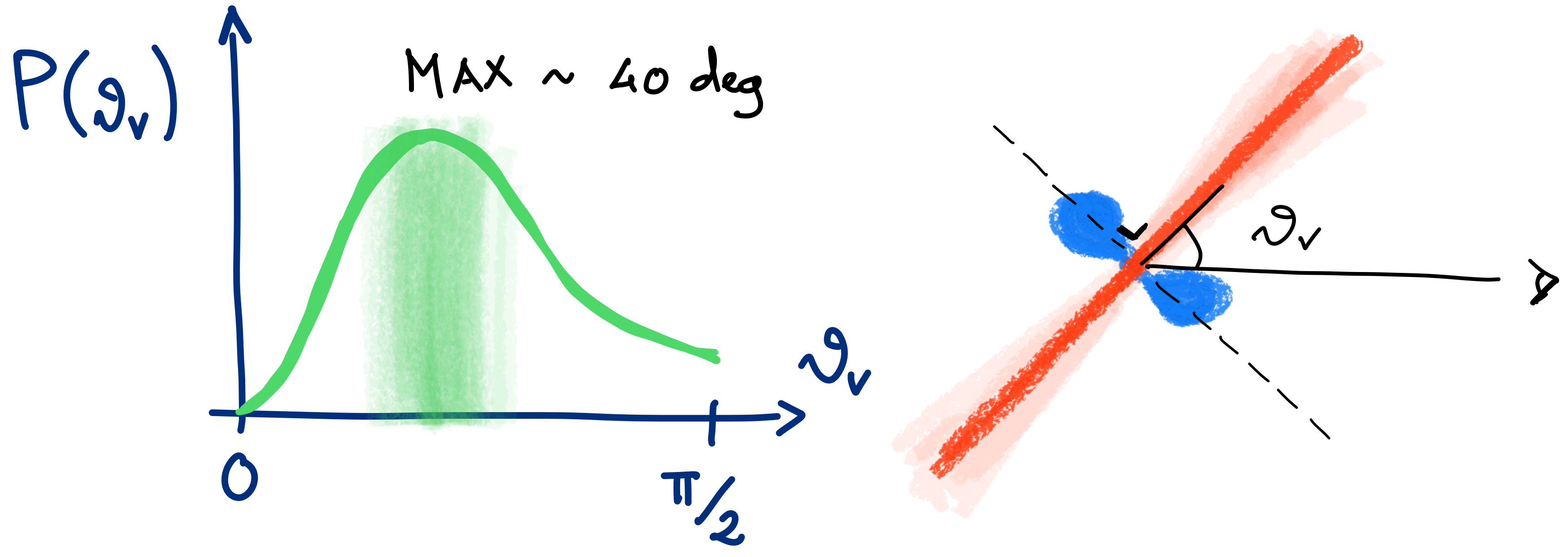


Why to go subthreshold?

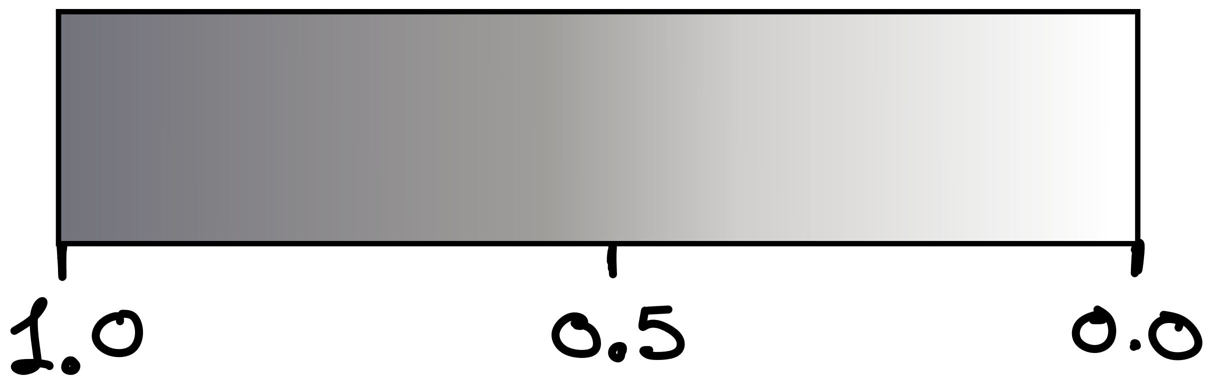
Lowering the S/N threshold, we increase the horizon.

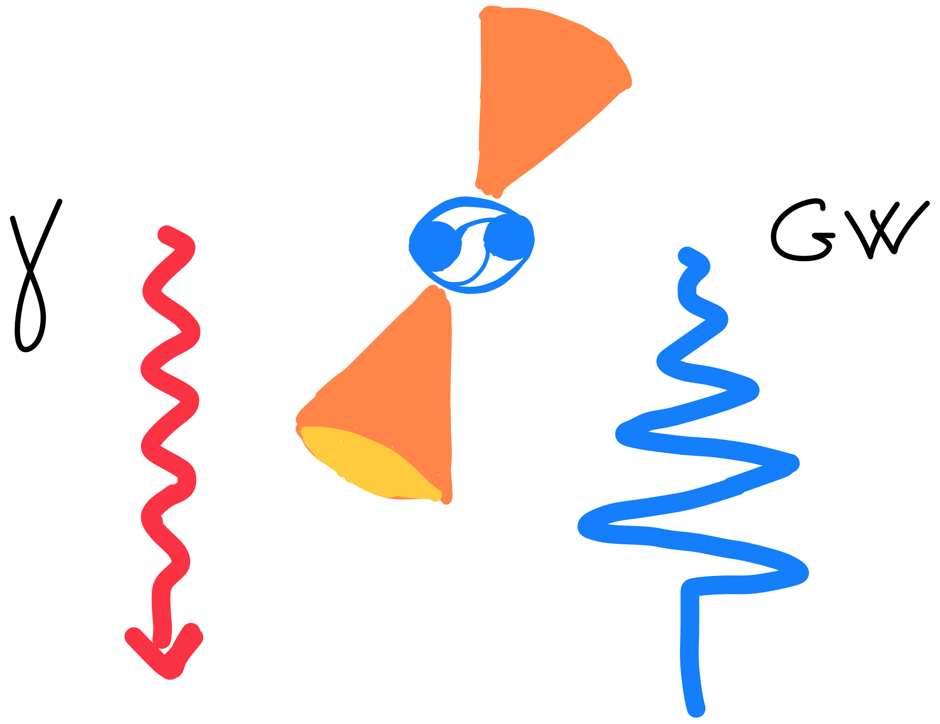
The presence of a second messenger increases the significance

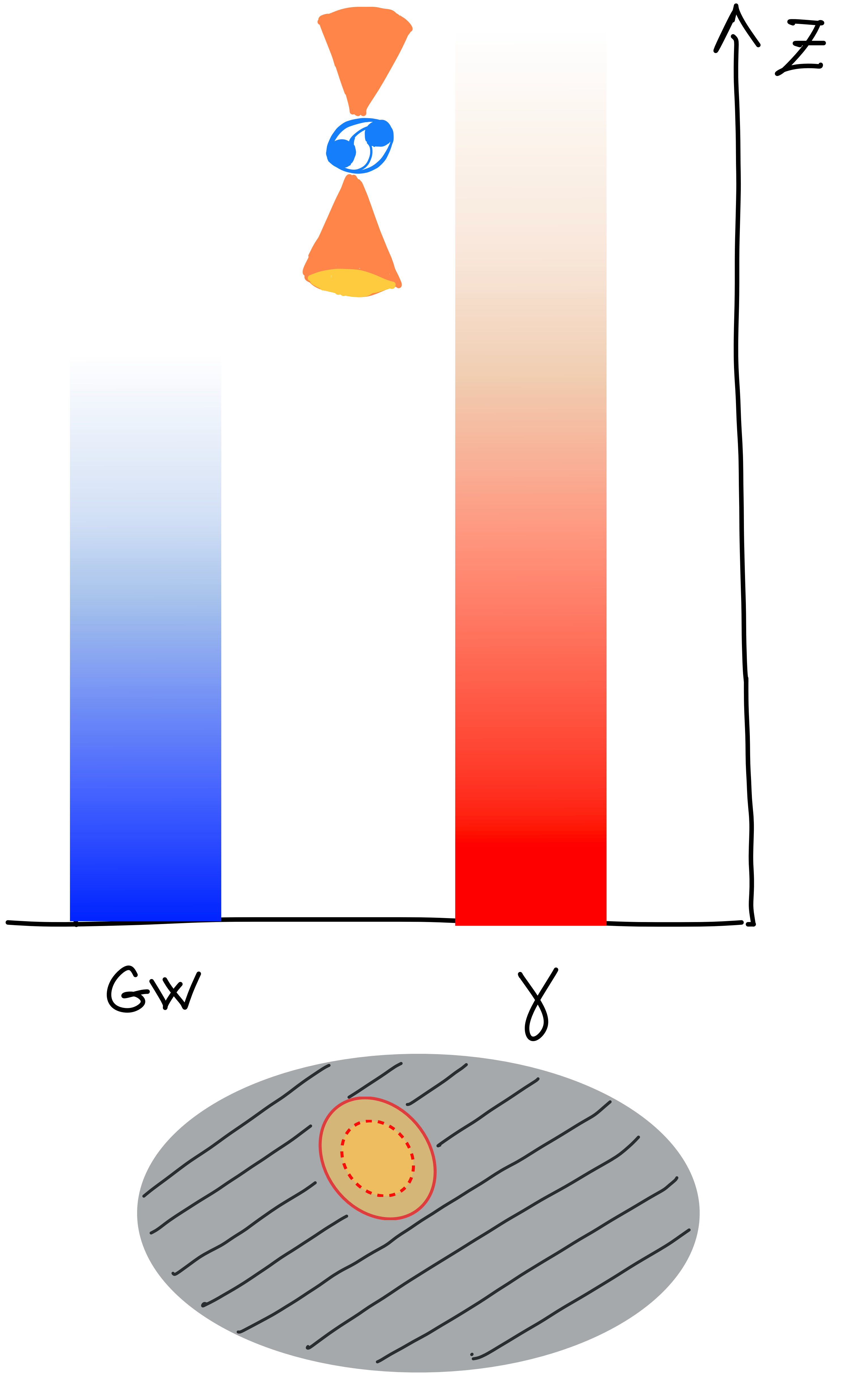




Detection efficiency







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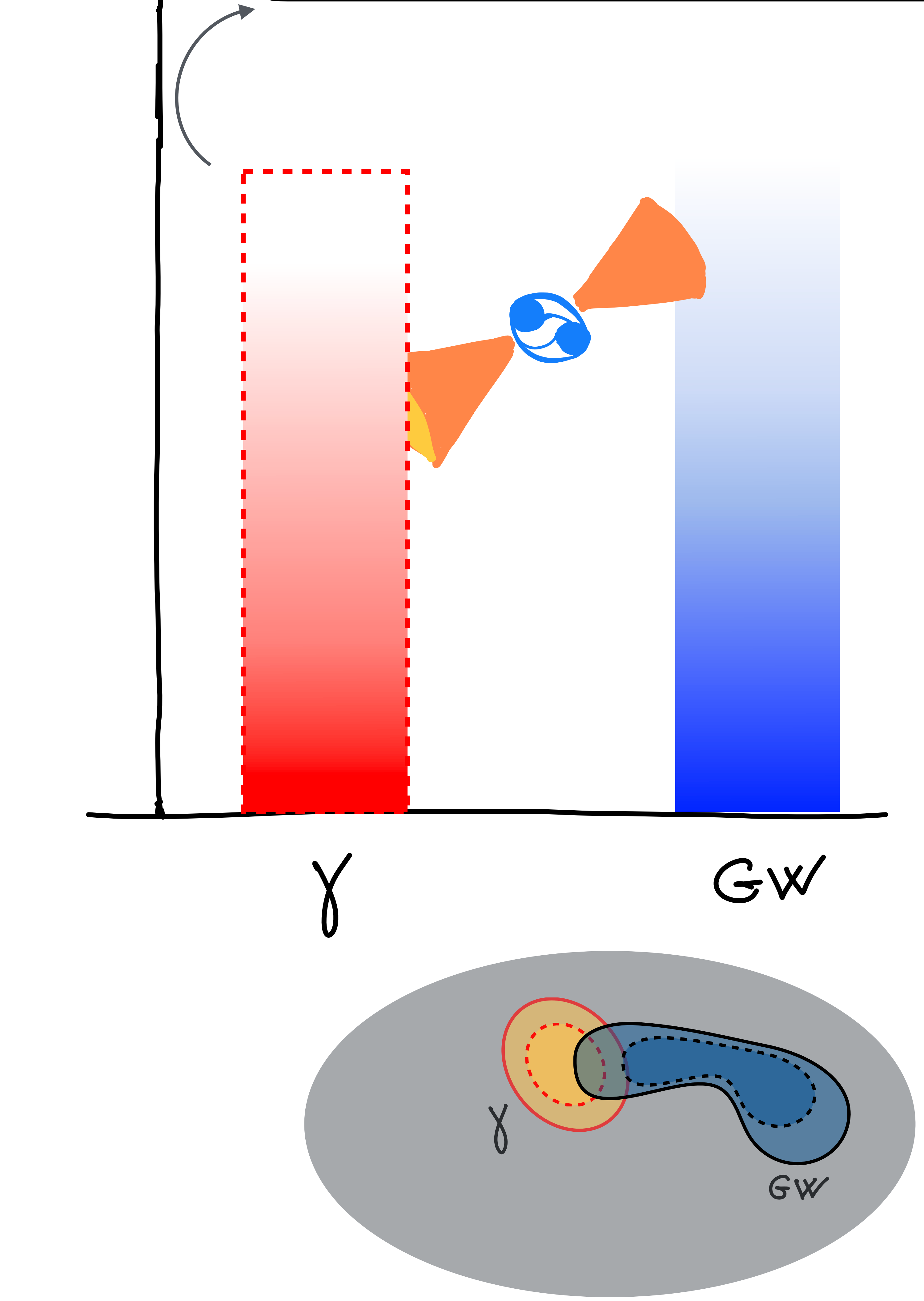
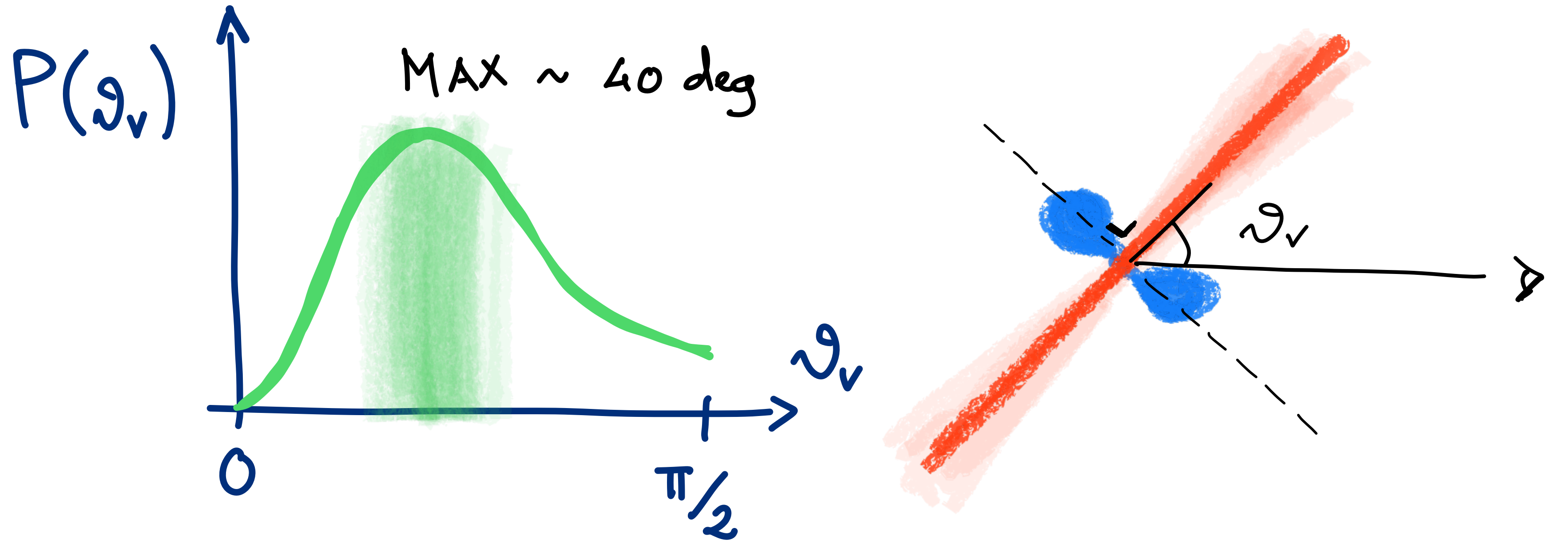
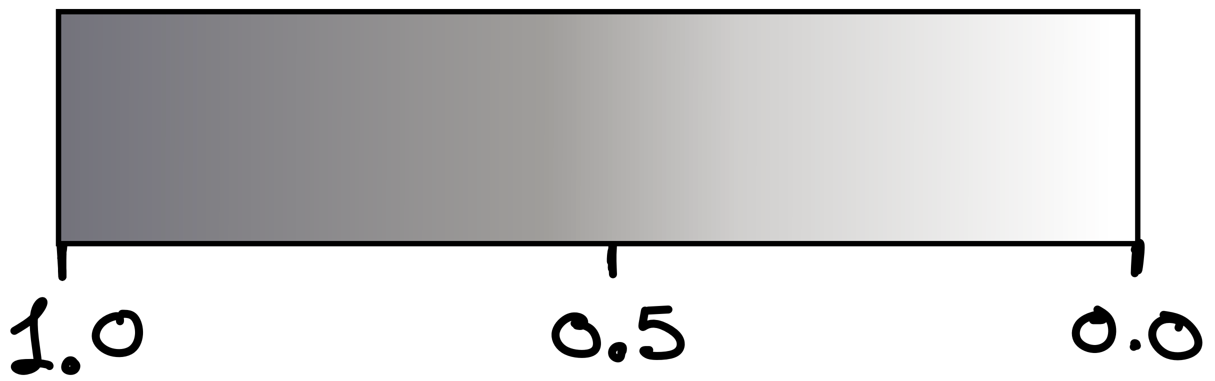
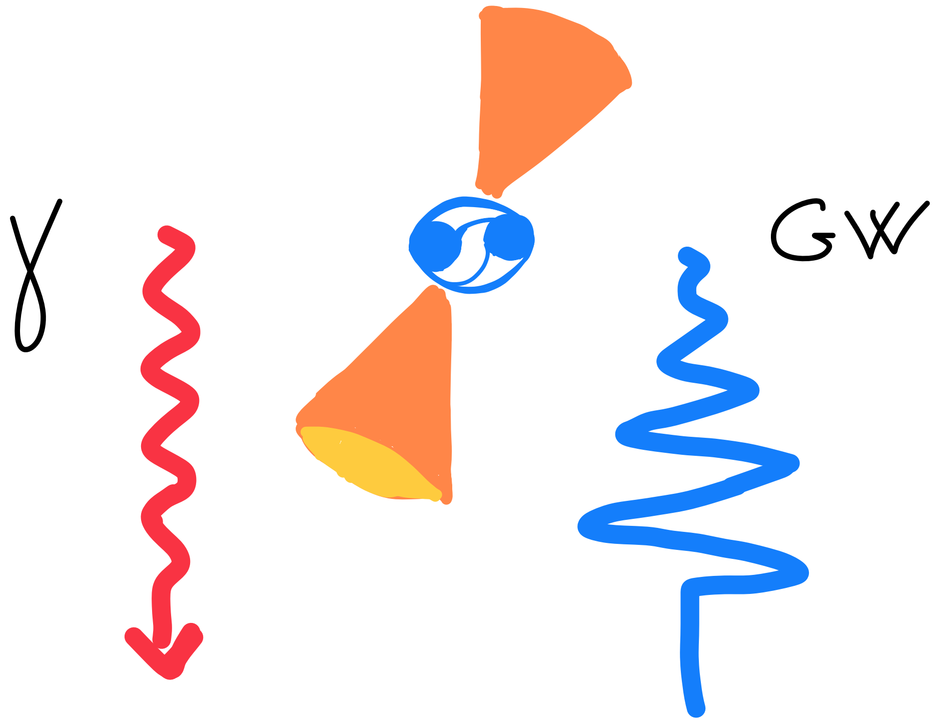
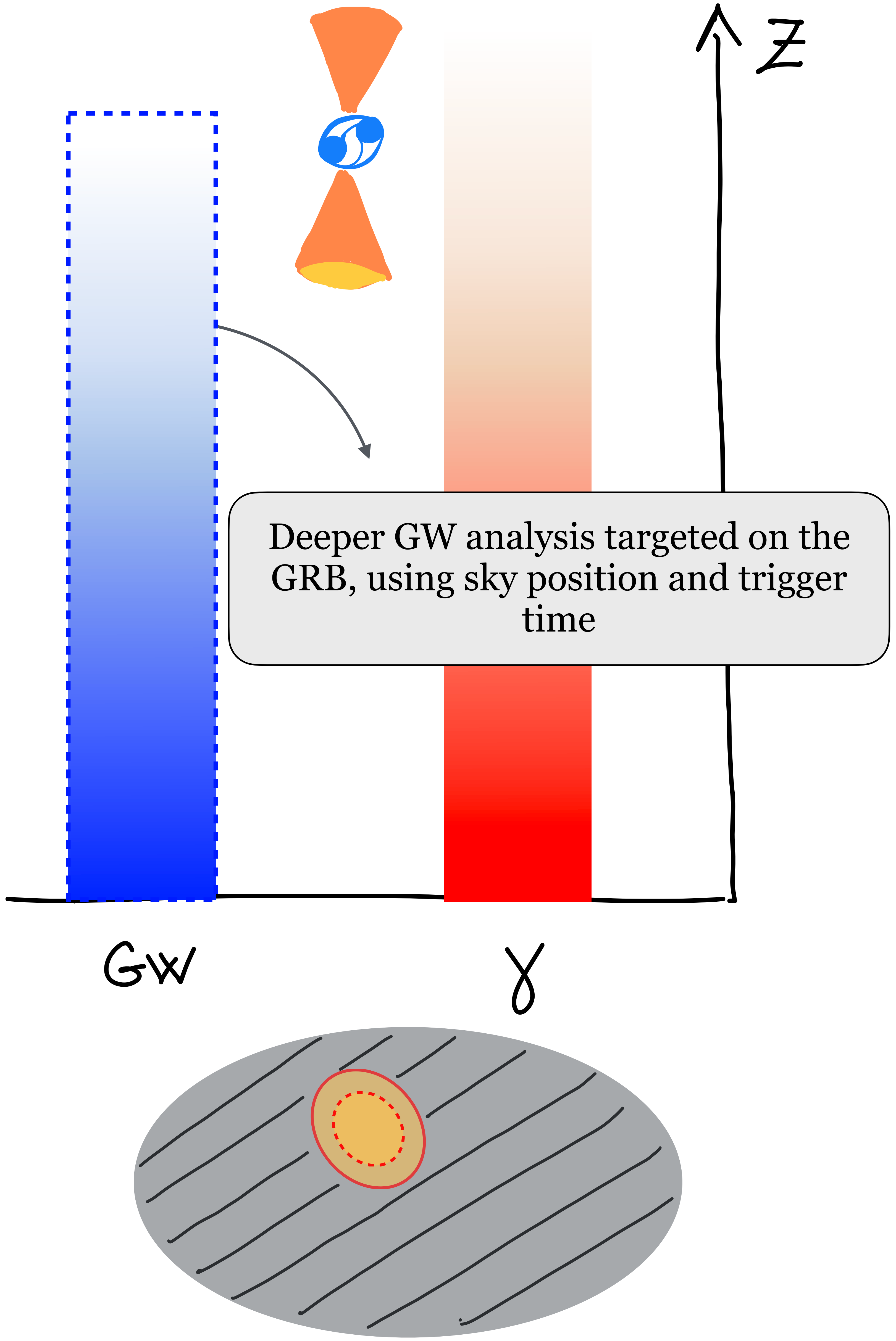




Detection efficiency





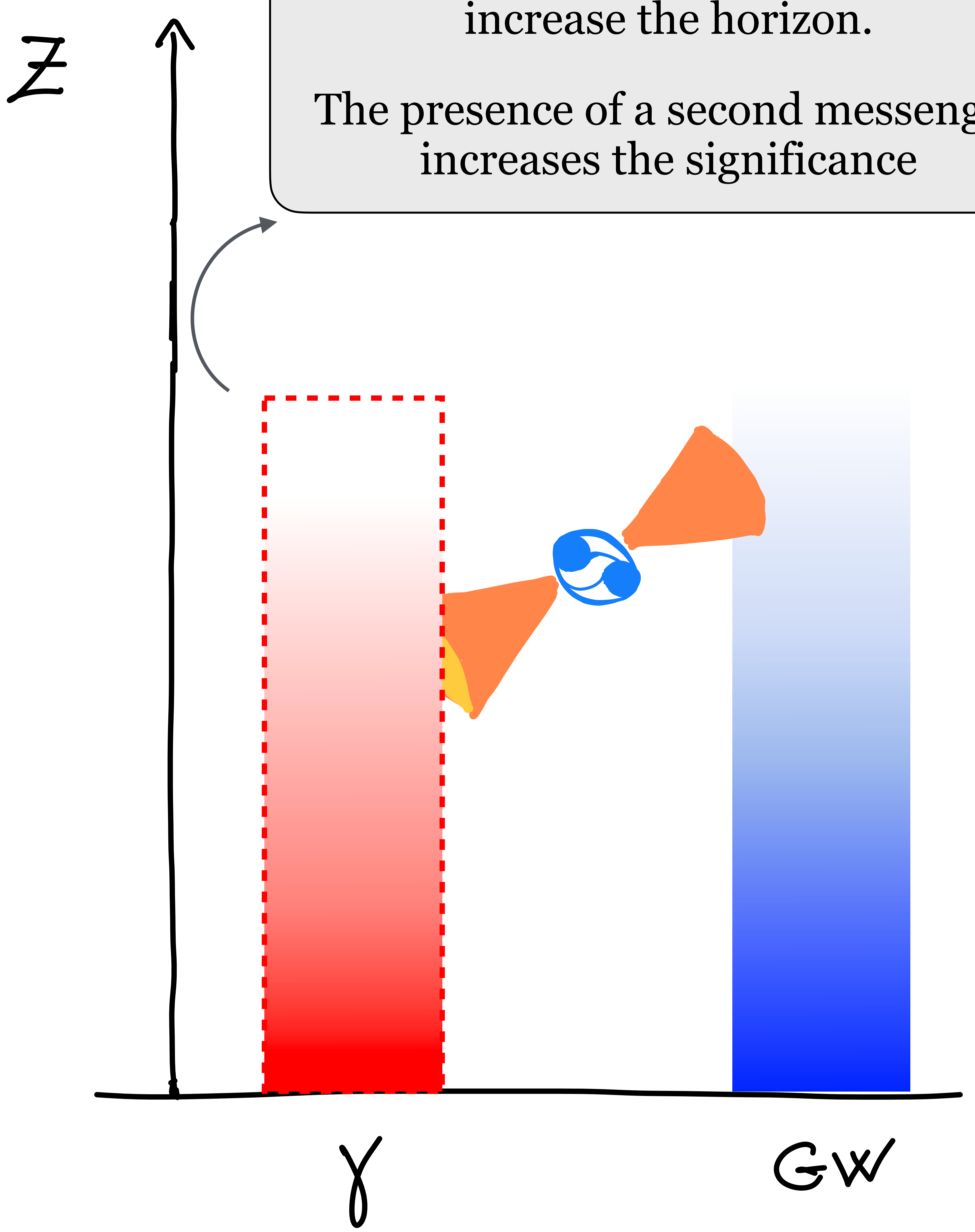


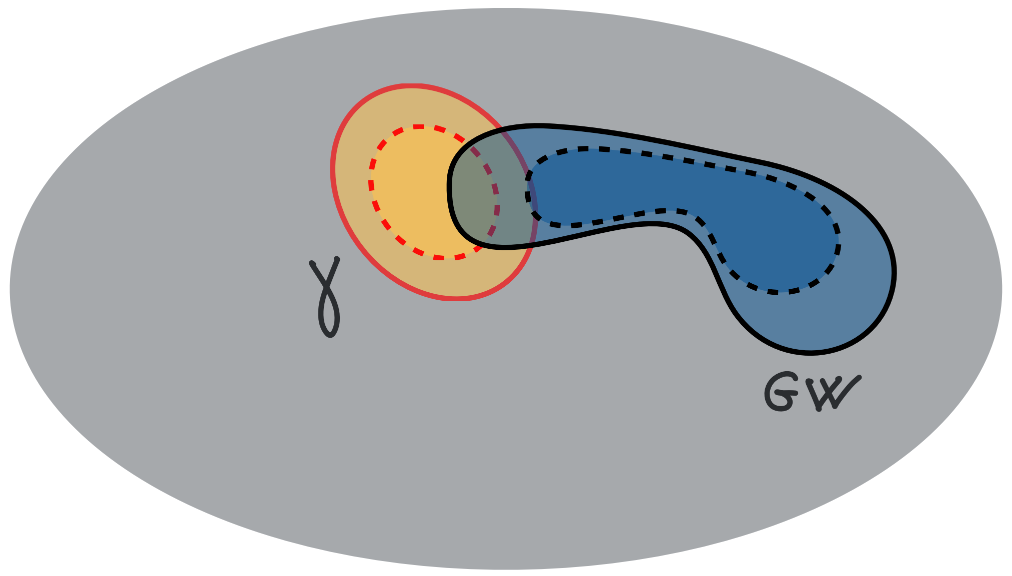
Deeper GW analysis targeted on the GRB, using sky position and trigger time

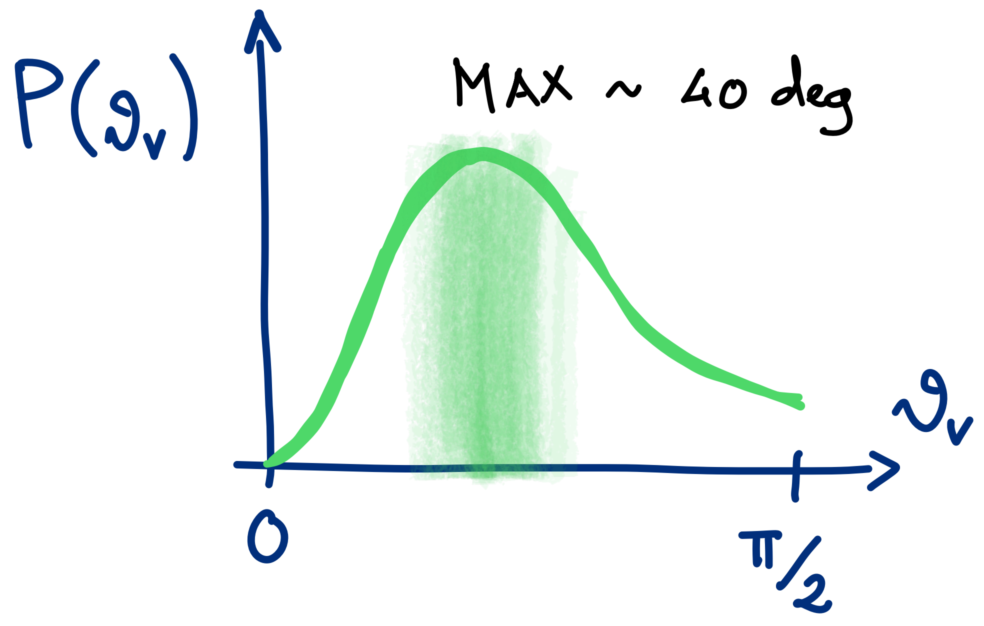
Why to go subthreshold?

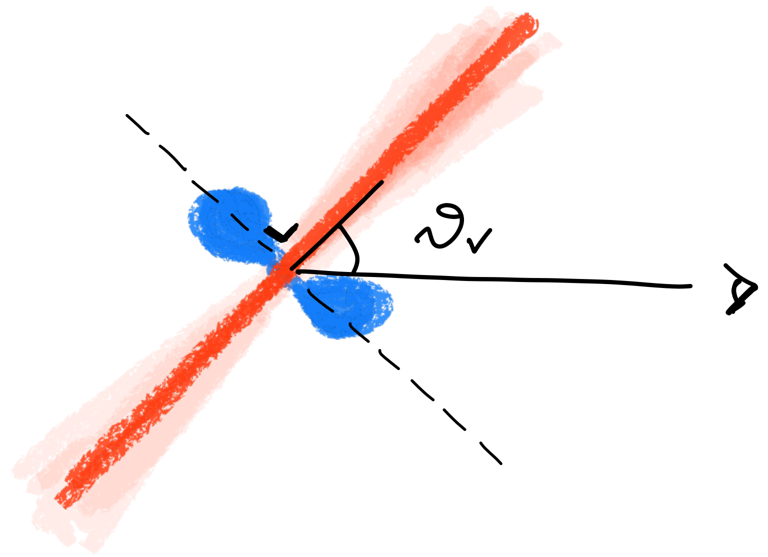
Lowering the S/N threshold, we increase the horizon.

The presence of a second messenger increases the significance

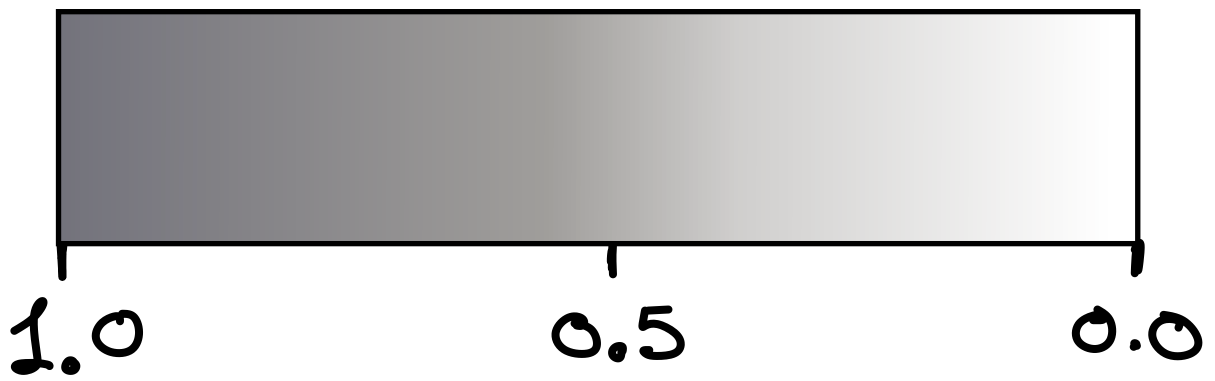






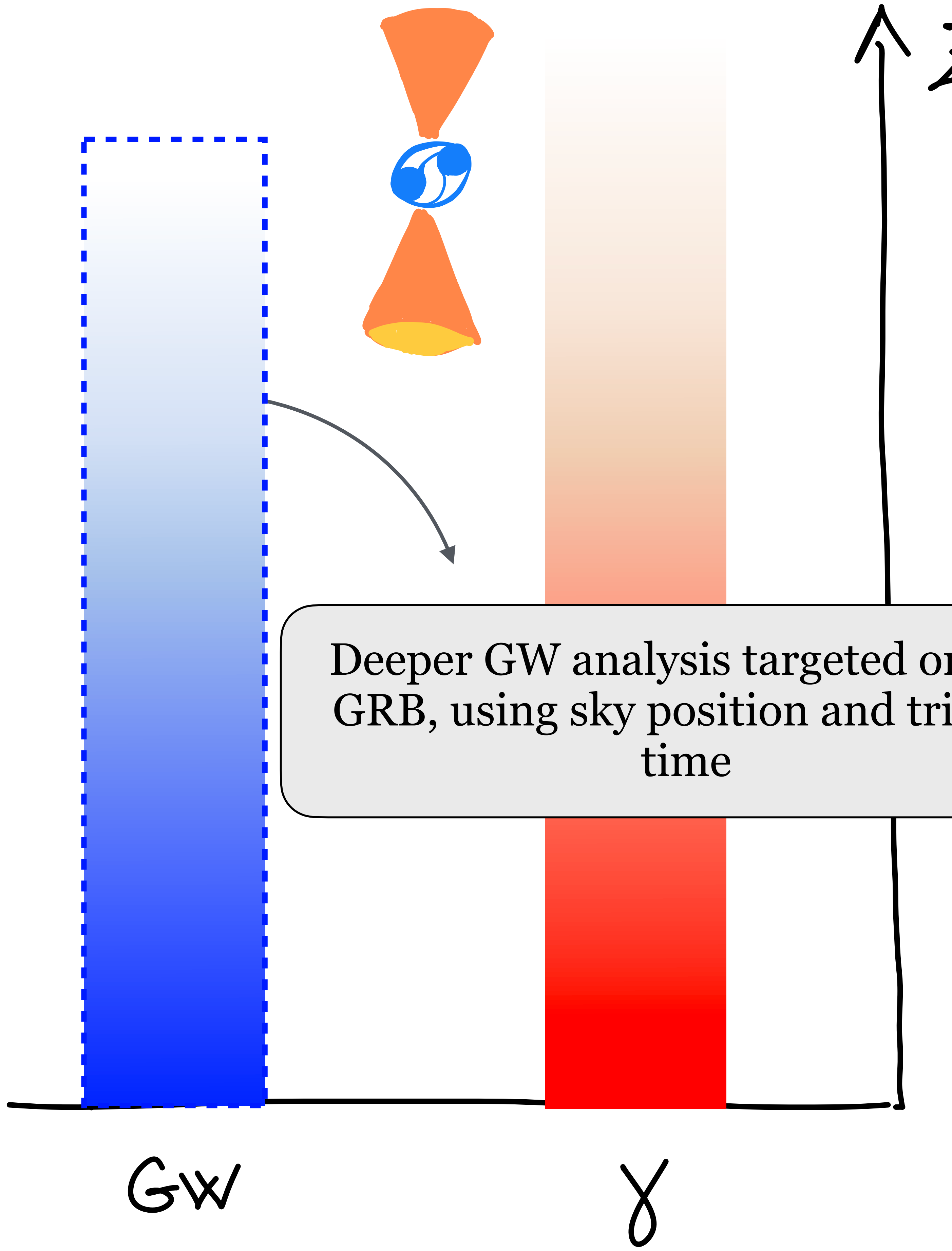


Detection efficiency

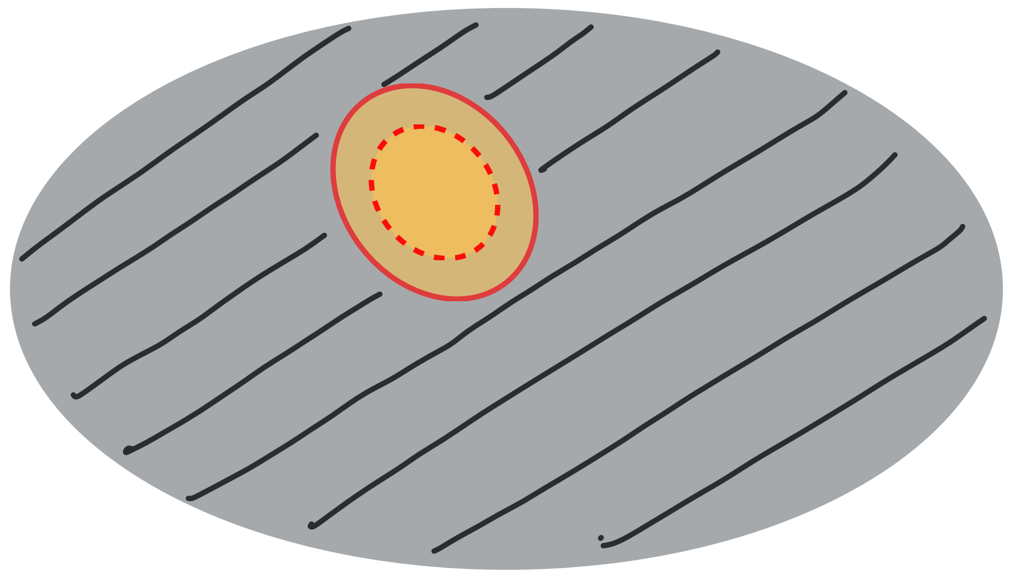


Joint sub-threshold searches essential to:

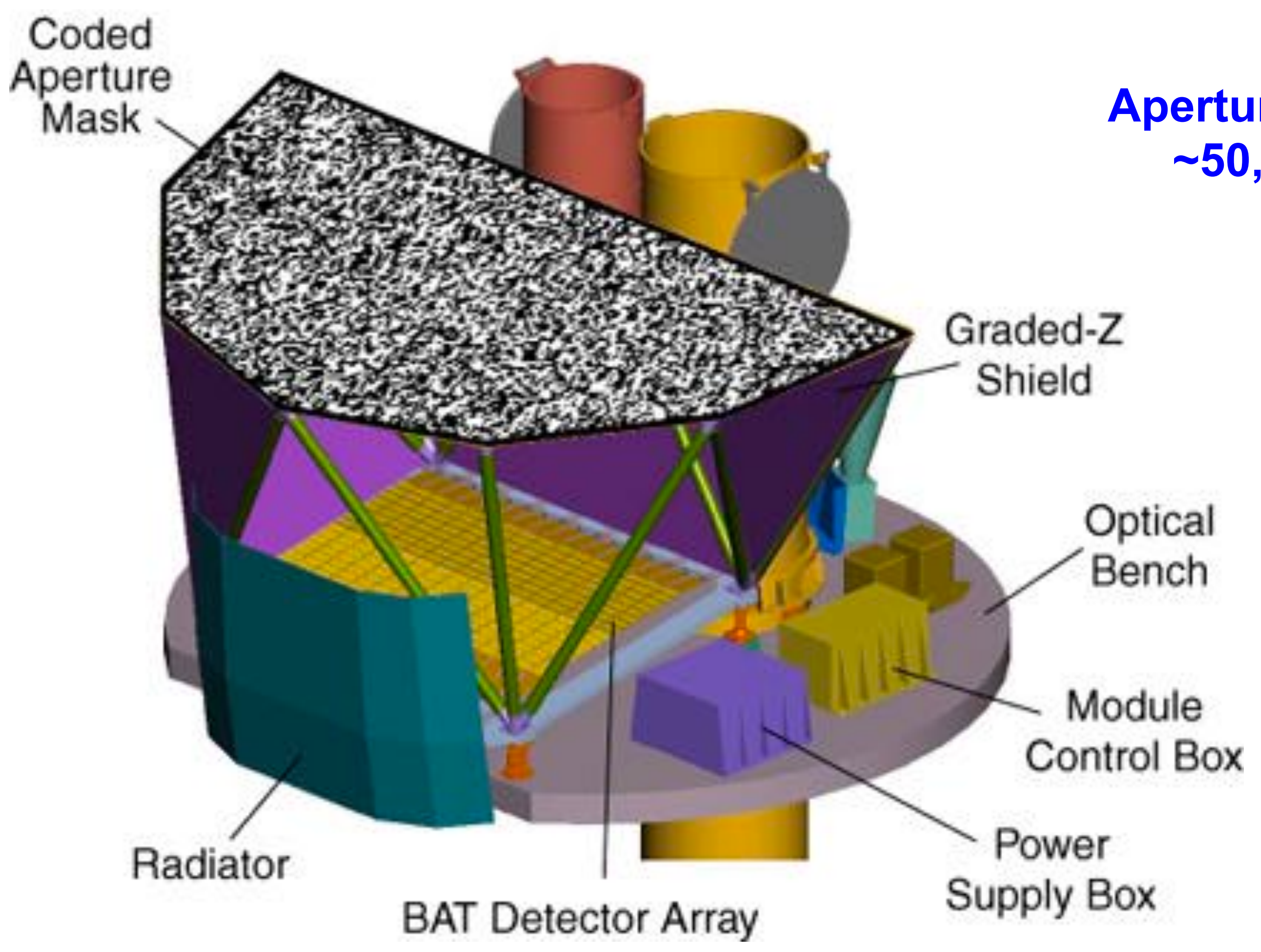
- discover more EM-bright GW mergers
- trigger possible EM follow-up campaigns —> the discovery of other EM candidates could increase even more the joint detection significance.



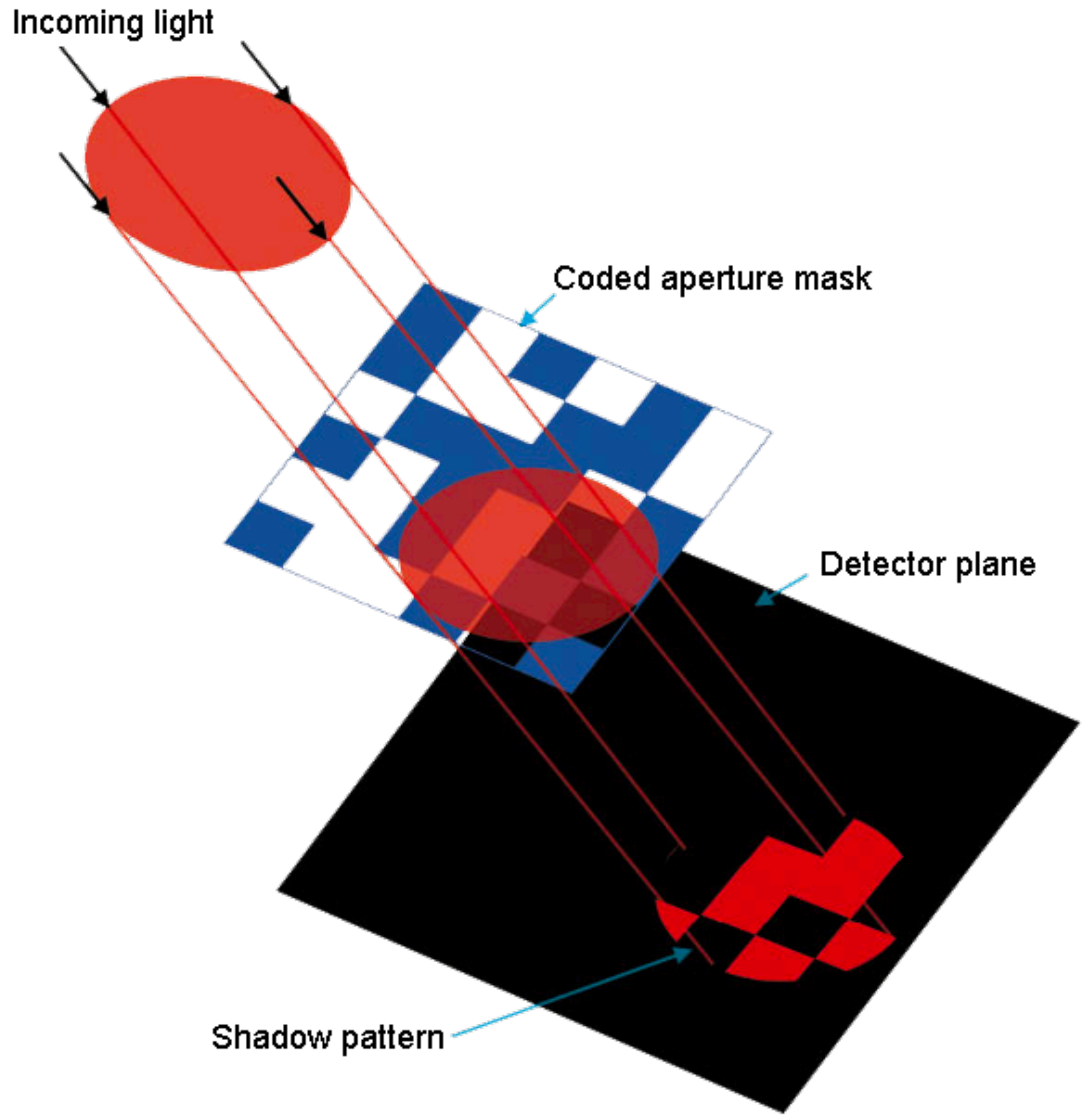
Deeper GW analysis targeted on the GRB, using sky position and trigger time



How BAT Works - A coded mask imager (15 - 350 keV)



Aperture Mask is 50% open and consists of ~50,000 lead tiles in a random pattern



- **BAT - large field of view** (FOV) ~ 2sr —> ~ **1/6 of the sky**
- Creates an image on board whenever there is a rate excess
- Can instruct the satellite to **re-point promptly in ~ 1 min** and **detect afterglow**
- Creates detector plane images that can be used to generate sky images, mask weighted and background subtracted light curves and also spectra
- BAT imaging - **computationally cheap algorithm**
- **Mask weighted** coded aperture imaging (onboard algorithm) → rejects photons that do not pass through the mask

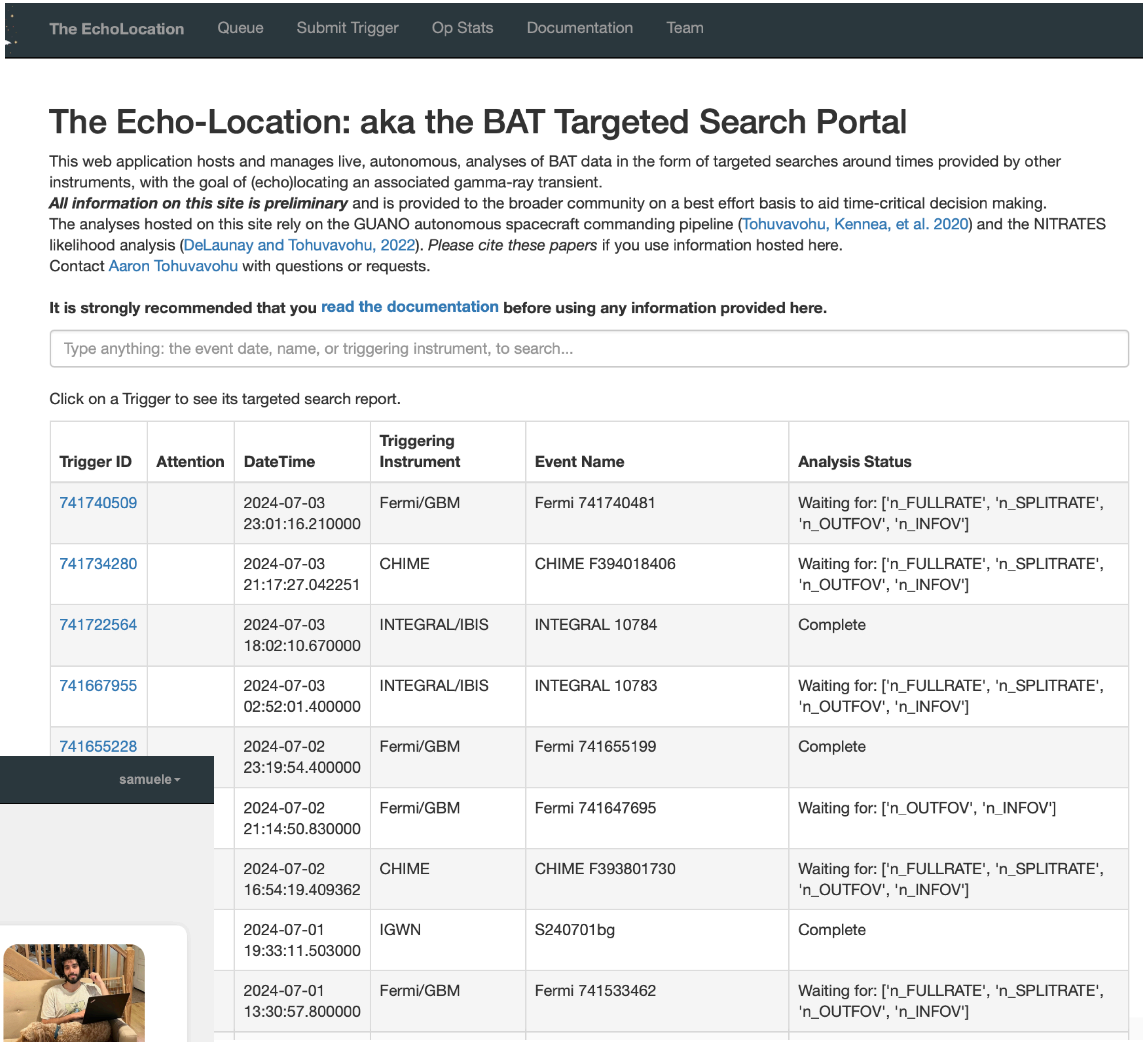
Drawbacks

We are not sensitive to signals outside the FOV	Signals during slew do not produce triggers onboard	Limited downlink bandpass —> possible to perform subthreshold searches only upon request to the spacecraft

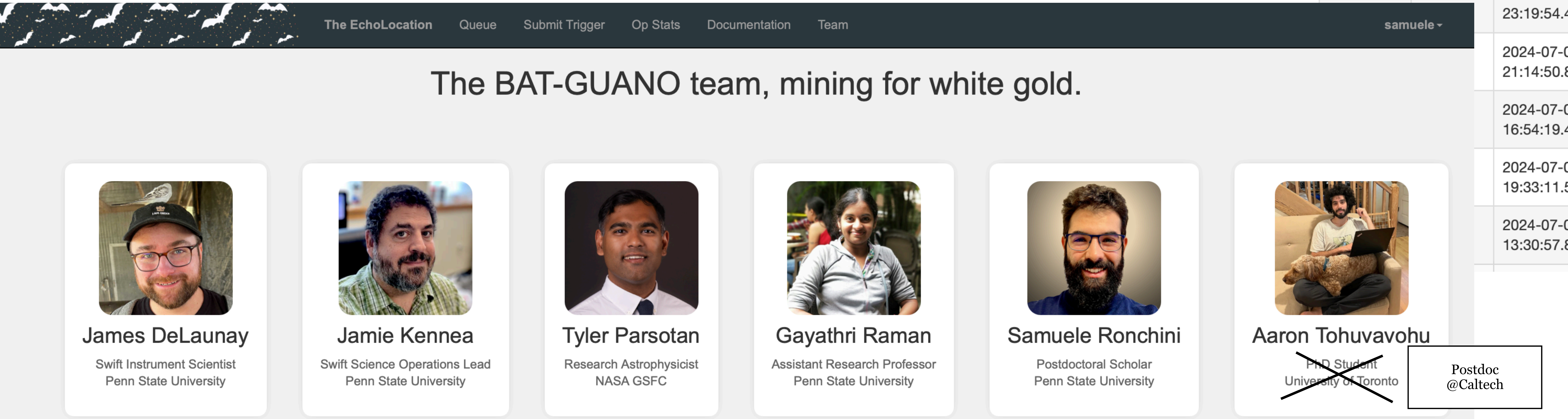
GUANO - Gamma-ray Urgent Archiver for Novel Opportunities

Tohuvavohu+2020

- Time tagged event (TTE) data normally only available around onboard triggered GRBs
- GUANO allows for TTE data to be available on command
  - 90 - 200 s of data around time of interest
- **Command needs to be prompt (<20 minutes)**
  - Event buffer lasts ~30 minutes
- Dumping data for **GRBs, GWs, Neutrinos, FRBs**
- See https://www.swift.psu.edu/guano/ for triggers to GUANO
- See https://guano.swift.psu.edu for real-time results



Trigger ID	Attention	DateTime	Triggering Instrument	Event Name	Analysis Status
741740509		2024-07-03 23:01:16.210000	Fermi/GBM	Fermi 741740481	Waiting for: ['n_FULLRATE', 'n_SPLITRATE', 'n_OUTFOV', 'n_INFOV']
741734280		2024-07-03 21:17:27.042251	CHIME	CHIME F394018406	Waiting for: ['n_FULLRATE', 'n_SPLITRATE', 'n_OUTFOV', 'n_INFOV']
741722564		2024-07-03 18:02:10.670000	INTEGRAL/IBIS	INTEGRAL 10784	Complete
741667955		2024-07-03 02:52:01.400000	INTEGRAL/IBIS	INTEGRAL 10783	Waiting for: ['n_FULLRATE', 'n_SPLITRATE', 'n_OUTFOV', 'n_INFOV']
741655228		2024-07-02 23:19:54.400000	Fermi/GBM	Fermi 741655199	Complete
		2024-07-02 21:14:50.830000	Fermi/GBM	Fermi 741647695	Waiting for: ['n_OUTFOV', 'n_INFOV']
		2024-07-02 16:54:19.409362	CHIME	CHIME F393801730	Waiting for: ['n_FULLRATE', 'n_SPLITRATE', 'n_OUTFOV', 'n_INFOV']
		2024-07-01 19:33:11.503000	IGWN	S240701bg	Complete
		2024-07-01 13:30:57.800000	Fermi/GBM	Fermi 741533462	Waiting for: ['n_FULLRATE', 'n_SPLITRATE', 'n_OUTFOV', 'n_INFOV']



NITRATES: Non Imaging Transient Reconstruction and TEmporal Search

DeLaunay + Tohuvavohu 2022

- **likelihood-based approach to BAT analysis** that forward models different signals through the entire instrument response
- has the advantage of fully exploiting the spectral and timing content of the time-tagged event data
- Uses also photons not coming through the coded mask

Doubling the effective area at the cost of a drastic **increase of computational time** —> ~200 CPU hrs per trigger

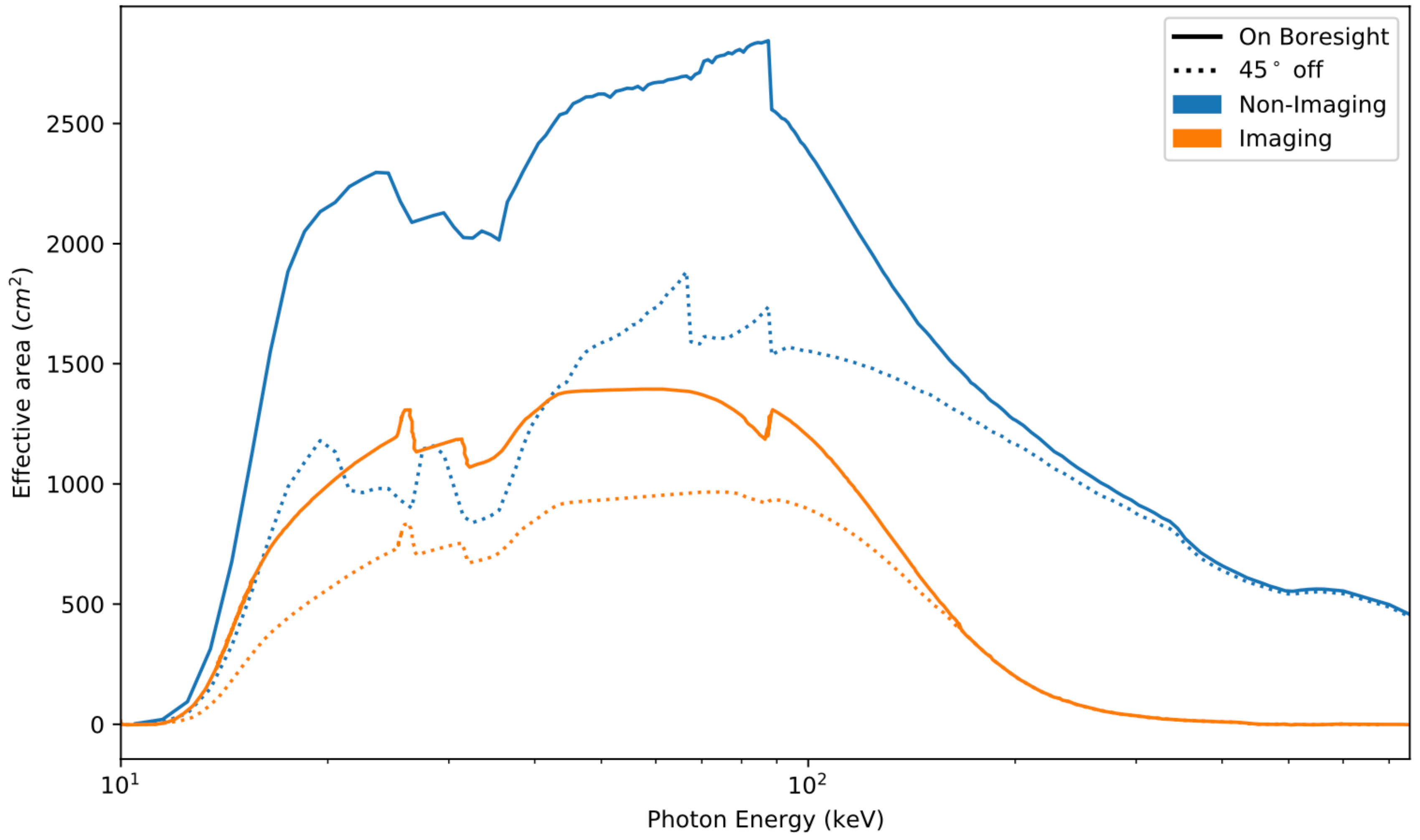
Realtime analysis performed 24/7 on

- PSU ROAR cluster
- NASA NCCS cluster

NITRATES makes BAT a full-sky (minus Earth) gamma-ray monitor

Essential to recover sub-threshold EM signals in Swift-BAT in temporal and spatial **coincidence with GW event**

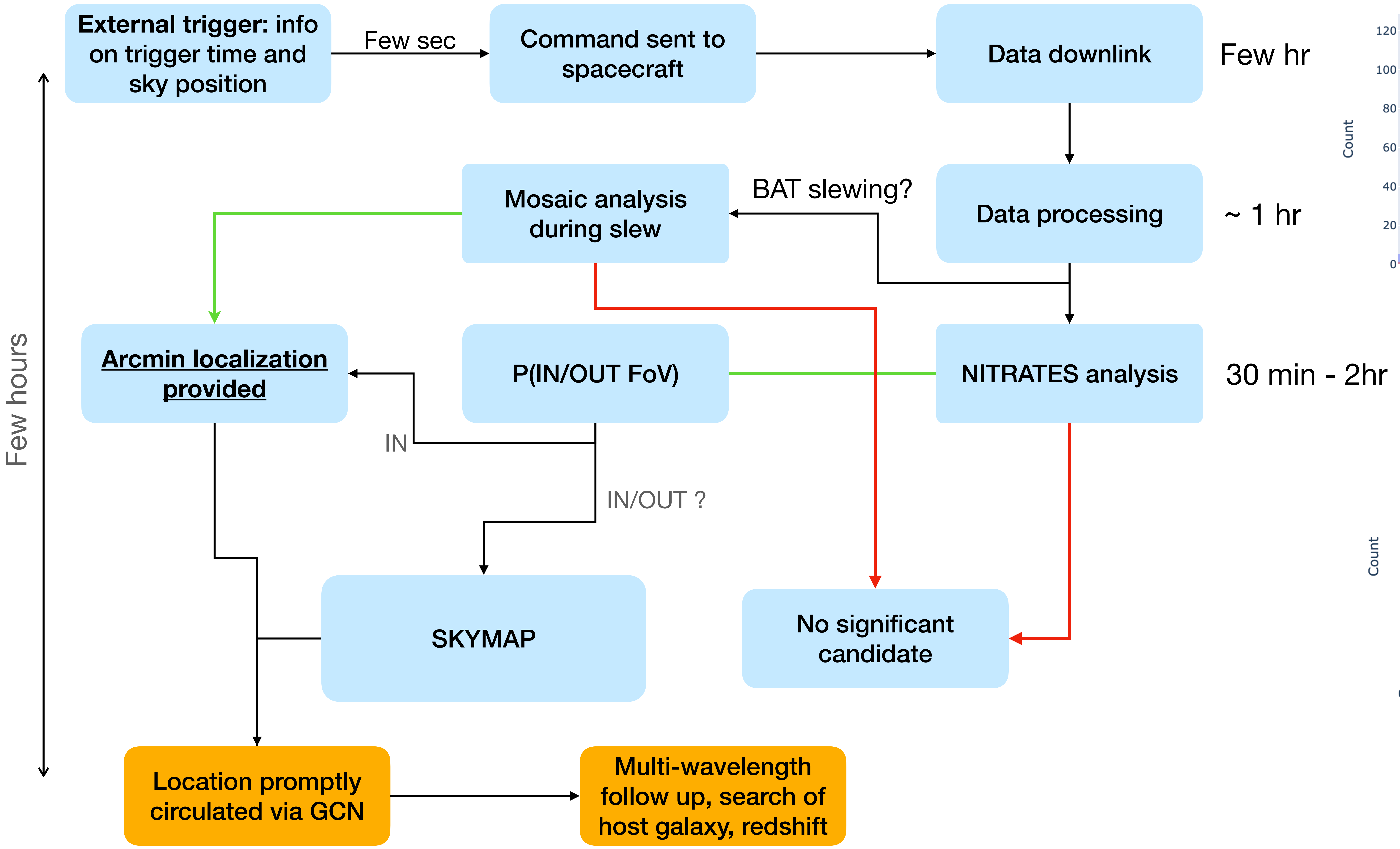
A non-imaging analysis improves significantly the effective area and extends the sensitivity of BAT from 15-150 keV to 15-350 keV



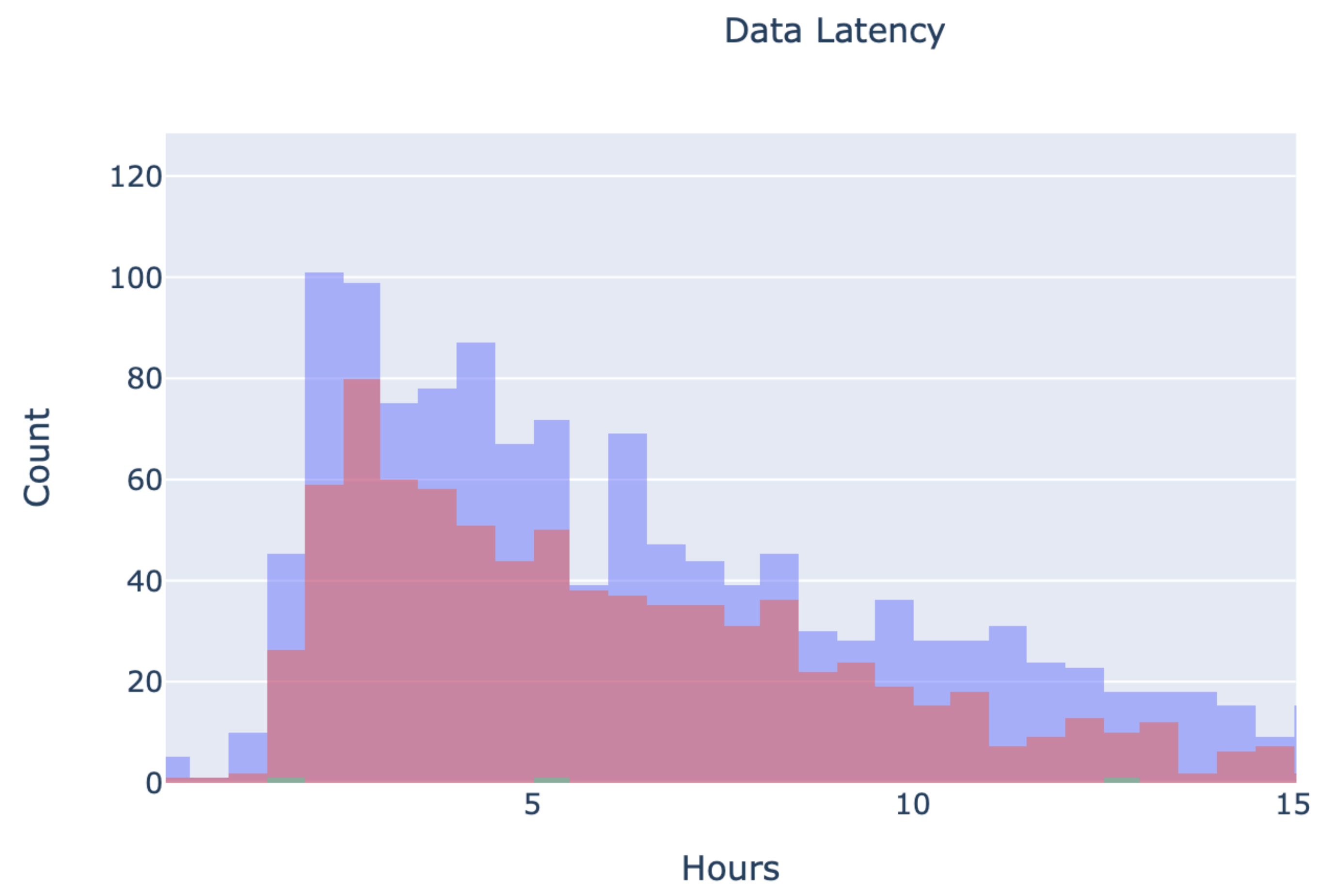
Quick facts:

- **more than 100 GRBs recovered with NITRATES** so far, **40 of which are <u>short GRB</u>**
- **44 with arcmin position**
- **In ~ half** of them **the afterglow emission was detected thanks to GUANO+NITRATES**

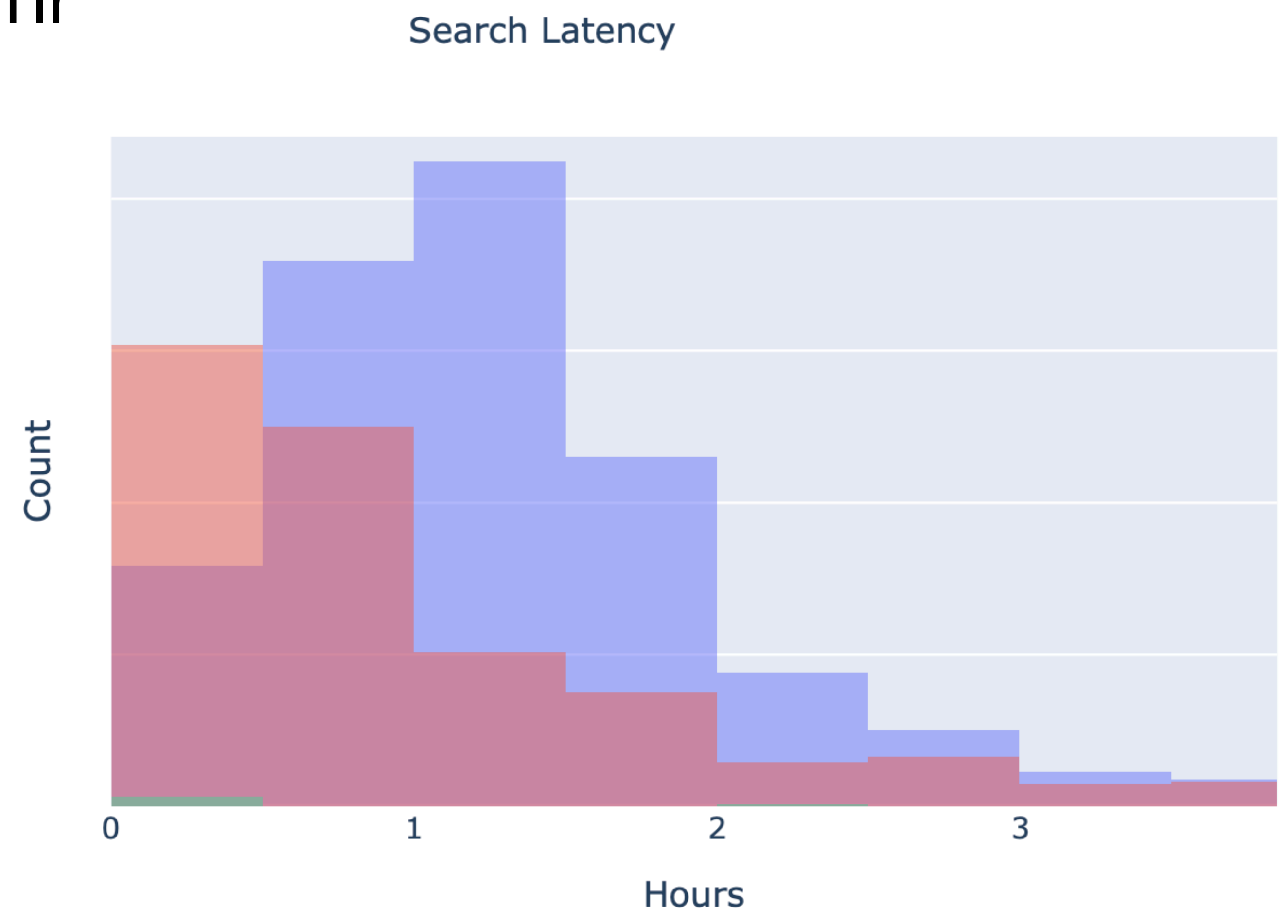
Workflow



External trigger: info on trigger time and sky position
Few sec
Command sent to spacecraft
Data downlink
Few hr
Data processing
~ 1 hr
Mosaic analysis during slew
BAT slewing?
Arcmin localization provided
P(IN/OUT FoV)
NITRATES analysis
30 min - 2hr
IN
IN/OUT ?
SKYMAP
No significant candidate
Location promptly circulated via GCN
Multi-wavelength follow up, search of host galaxy, redshift
Few hours



Data Latency
Count
Hours
0
20
40
60
80
100
120
5
10
15

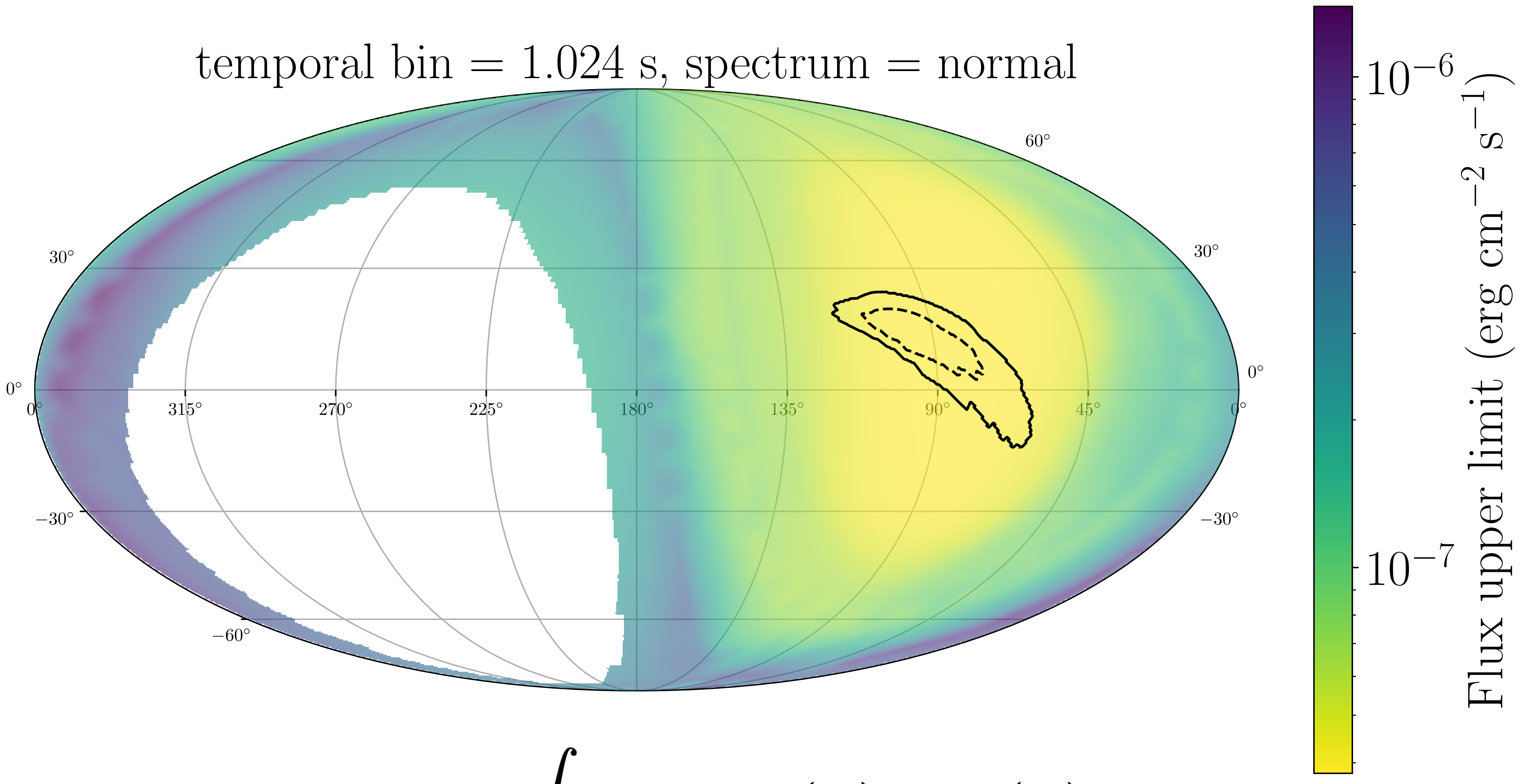


Search Latency
Count
Hours
0
1
2
3

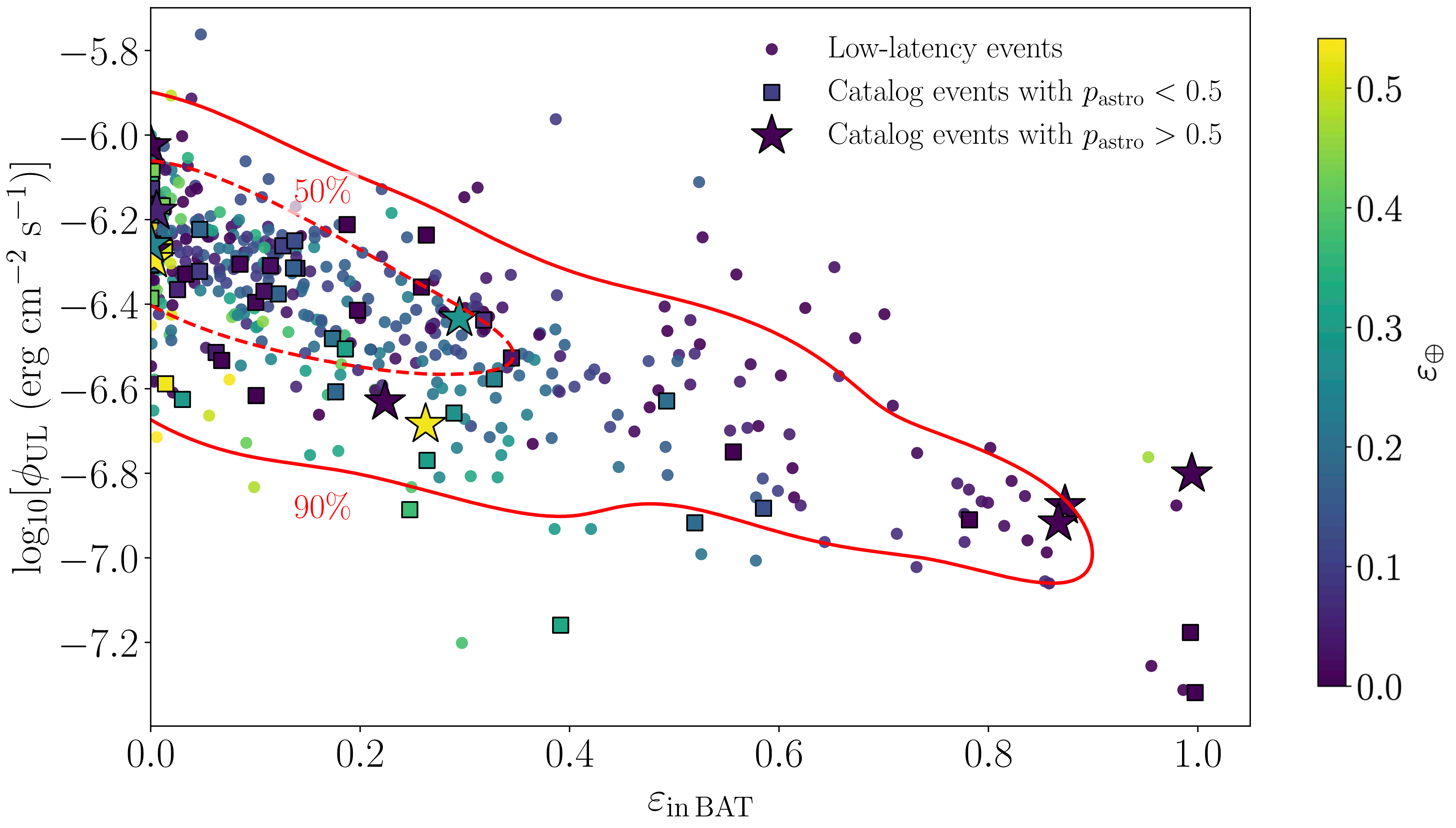
GW targeted analyses with Swift-BAT: O3

Raman+2024

- **636 GW triggers analysed**, selecting all those with FAR< 2/day
- Both CBC + Burst classes
- **12 GW triggers** with p_astro>0.5
- **78 GW triggers confirmed** by offline analysis with p_astro<0.5



$$\phi_{\rm UL} = \int_{\Omega \notin \Omega_\oplus} \phi_{\rm UL}(\Omega) P_{\rm GW}(\Omega) {\rm d}\Omega$$



$$\epsilon_{\rm in\,BAT} = \int_{\Omega \in \Omega_{\rm in}} P_{\rm GW}(\Omega) {\rm d}\Omega \qquad \epsilon_\oplus = \int_{\Omega \in \Omega_\oplus} P_{GW}(\Omega) {\rm d}\Omega$$

During O4 upper limits maps are publicly released via GCN for GW triggers labelled as 'SIGNIFICANT', with eps_earth < 50% and eps_inBAT > 30%

Constraints on the BBH population

Raman+2024

1. We carry out a **population analysis**, considering a single CBC population

$$P(L) = (1-f)\delta(L=0) + f\Pi(L).$$

2. Focus on BBH mergers, assuming

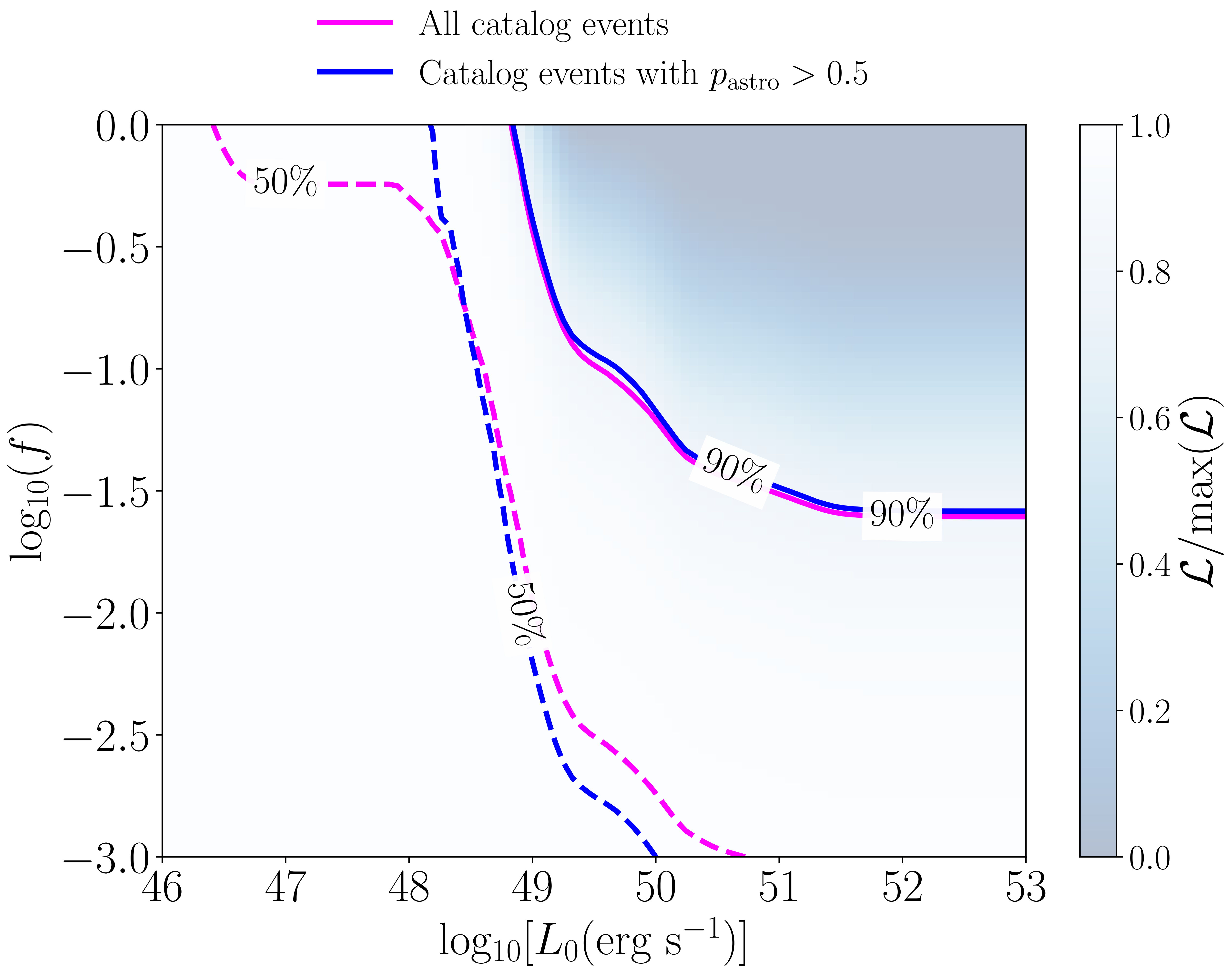
$$\Pi(L) = \delta(L - L_0)$$

Simulation setup:

- We consider all the BBHs with a FAR<2/day
- For each GW candidate, we simulate the observed flux in the BAT energy band, considering the GW posterior distribution of the luminosity distance
- The simulation takes into account the GW p_{astro} and the possibility that the source is behind the Earth wrt Swift

p_{astro} → π_i

$$\mathcal{L}_i = (1-\pi_i) + \pi_i[\epsilon_\oplus + (1-\epsilon_\oplus)P_i(\phi < \phi_{0,i})]$$

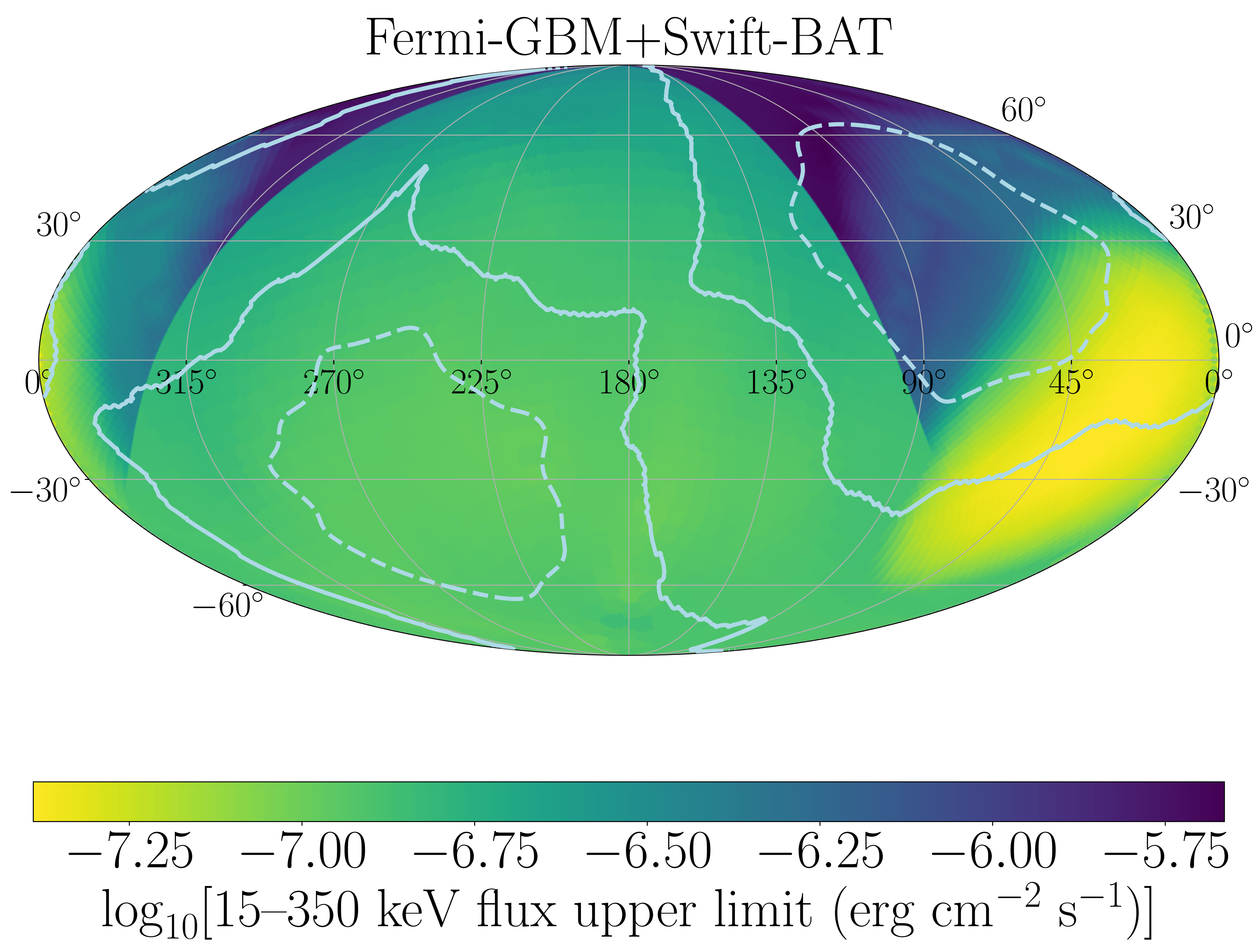


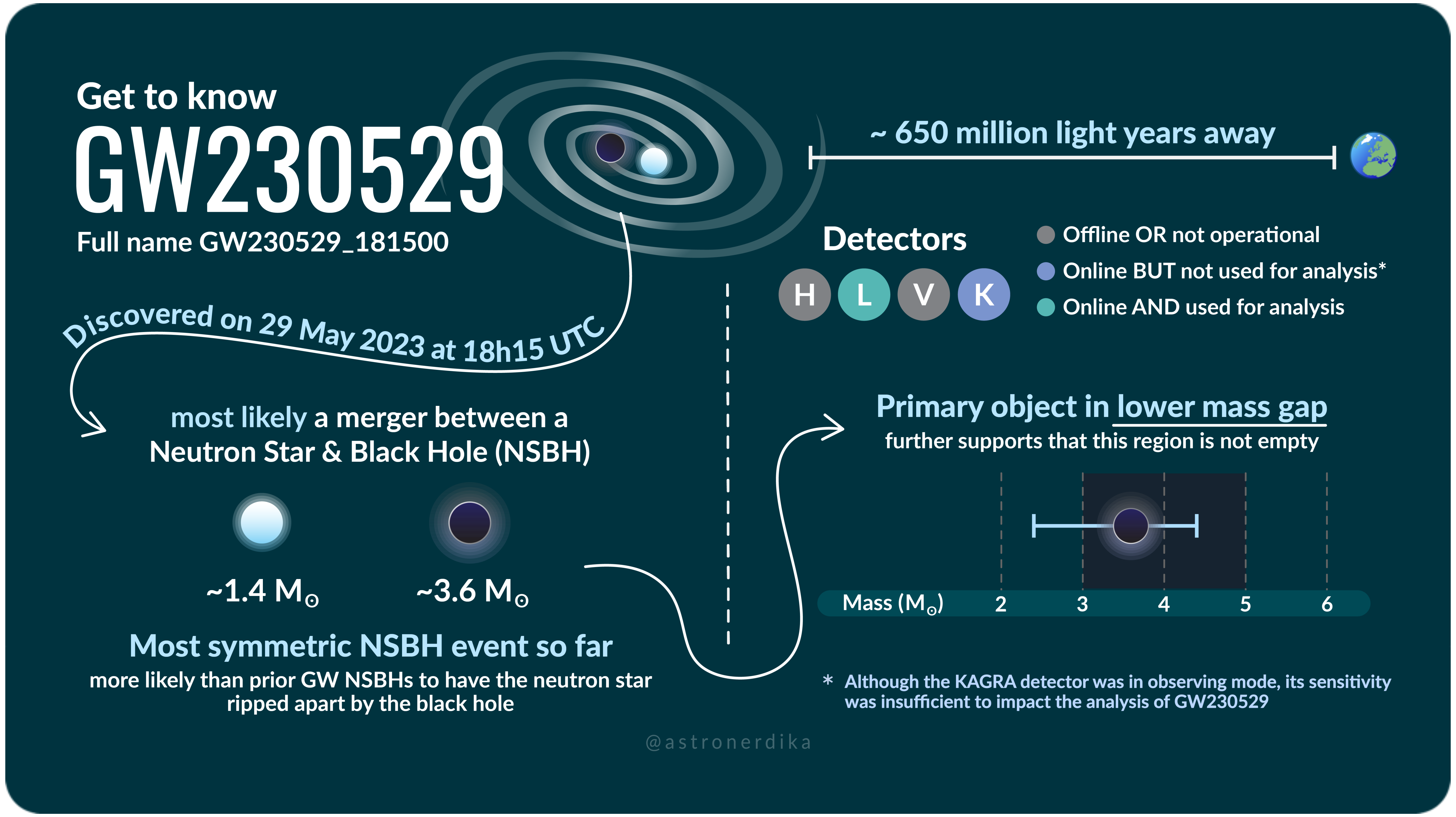
GW 230529: upper limits from Swift and Fermi

Ronchini+2024

1. **First** CBC with a component in the **mass gap 3-5 M☉**
2. **NSBH with lowest mass ratio so far** —> relatively high chance to have a remnant mass>0
3. **Potentially EM-bright**

Even if the uncertainty in sky localization is huge, **100 % of the sky covered by Swift+Fermi at the merger time**





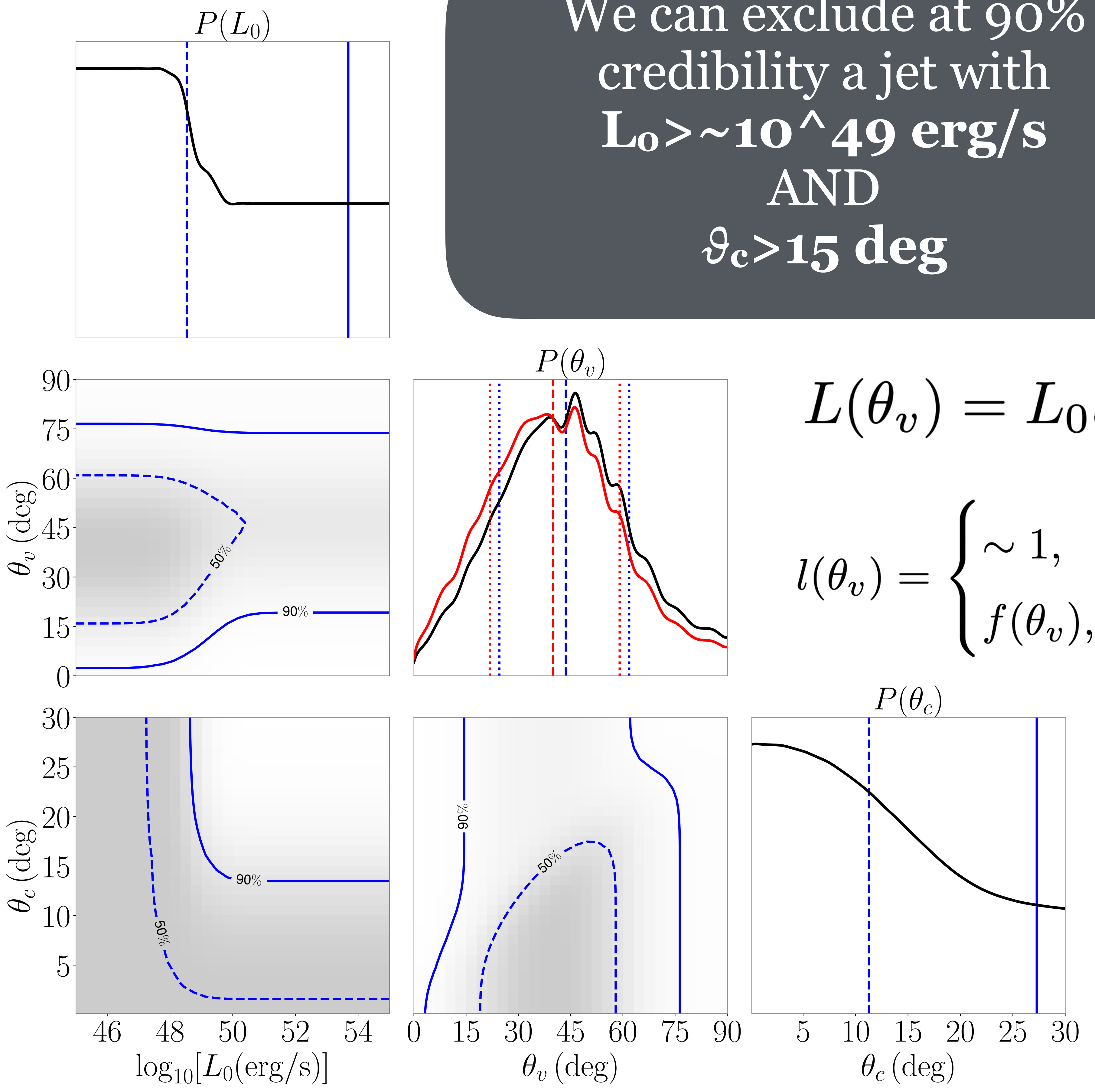
GW 230529: upper limits from Swift and Fermi

Ronchini+2024

$$P_{ND}(\vec{\theta}, \theta_v) =$$

$$\int P(F < \mathrm{UL}(\Omega)) P_{GW}(\Omega, D_L|\theta_v) d\Omega dD_L$$

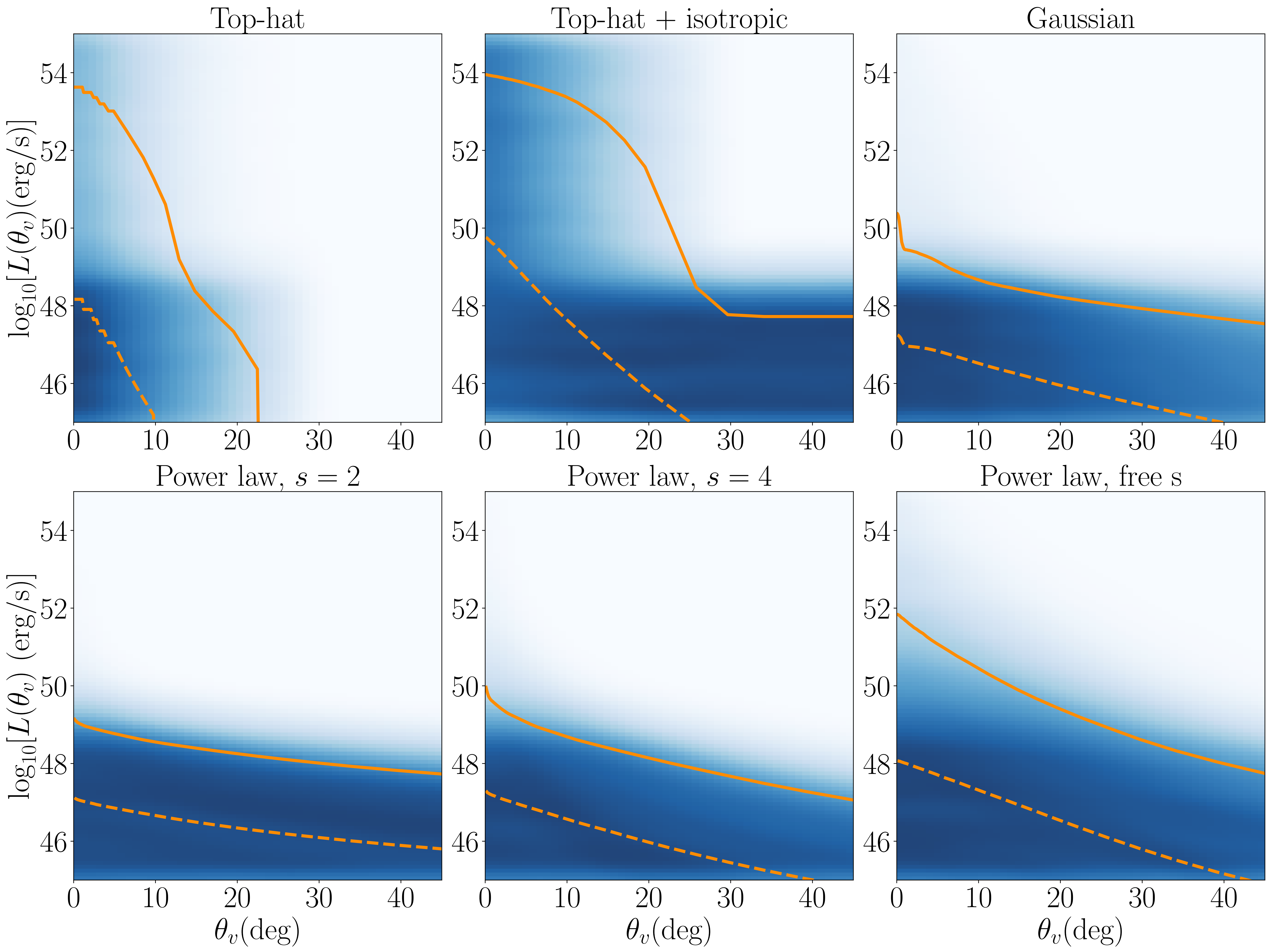
We can exclude at 90% credibility a jet with
L_0>~10^49 erg/s
AND
ϑ_c>15 deg



$$L(\theta_v) = L_0 l(\theta_v)$$

$$l(\theta_v) = \begin{cases} \sim 1, & \theta < \theta_c \\ f(\theta_v), & \theta > \theta_c \end{cases}$$

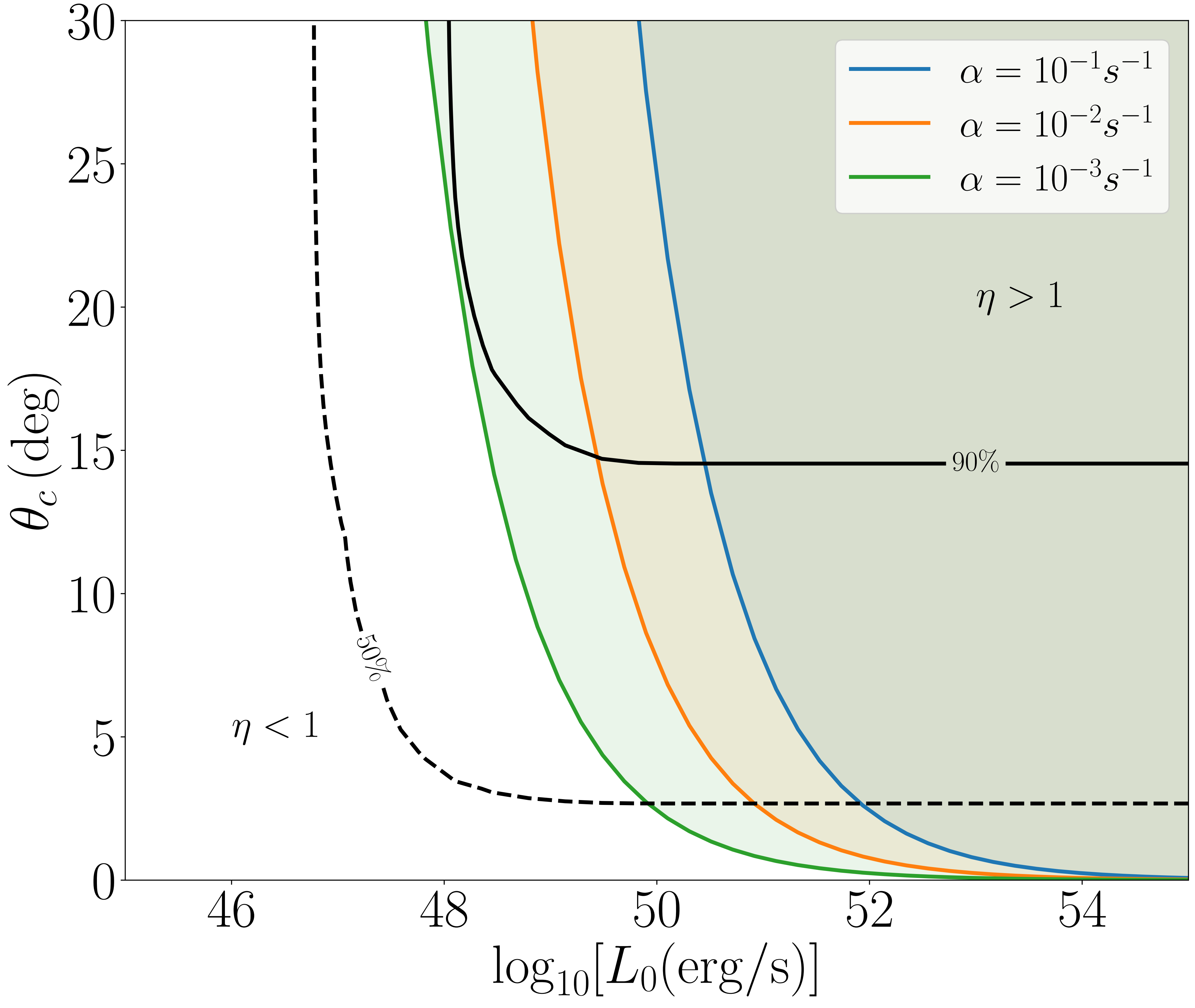
Constraints with different assumptions on the jet structure



Connection between accreted mass and luminosity

$$L_b = \eta \frac{M_{acc} c^2}{t_{acc}}$$

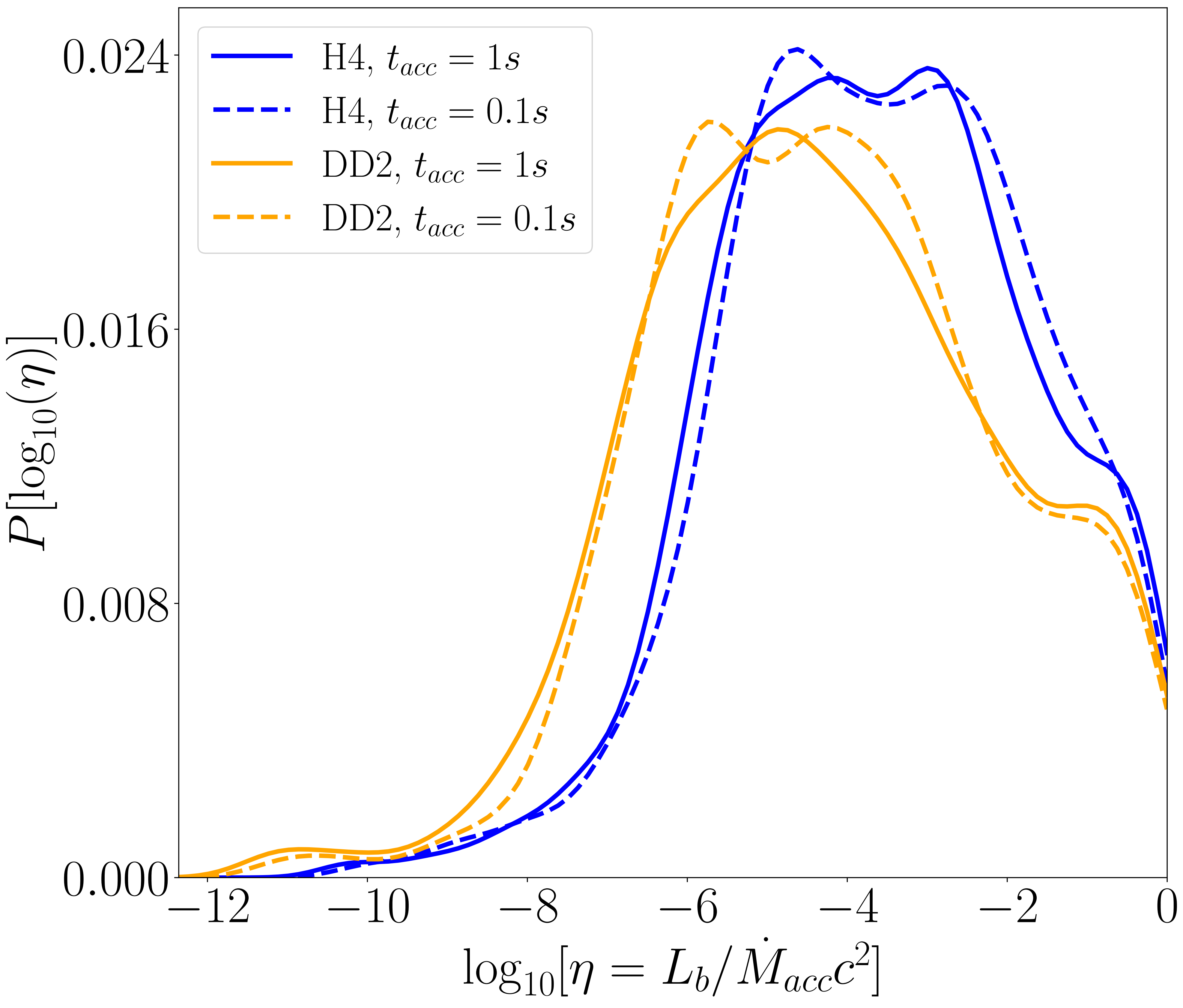
$\eta < 1, M_{acc} < 0.052 M_\odot$



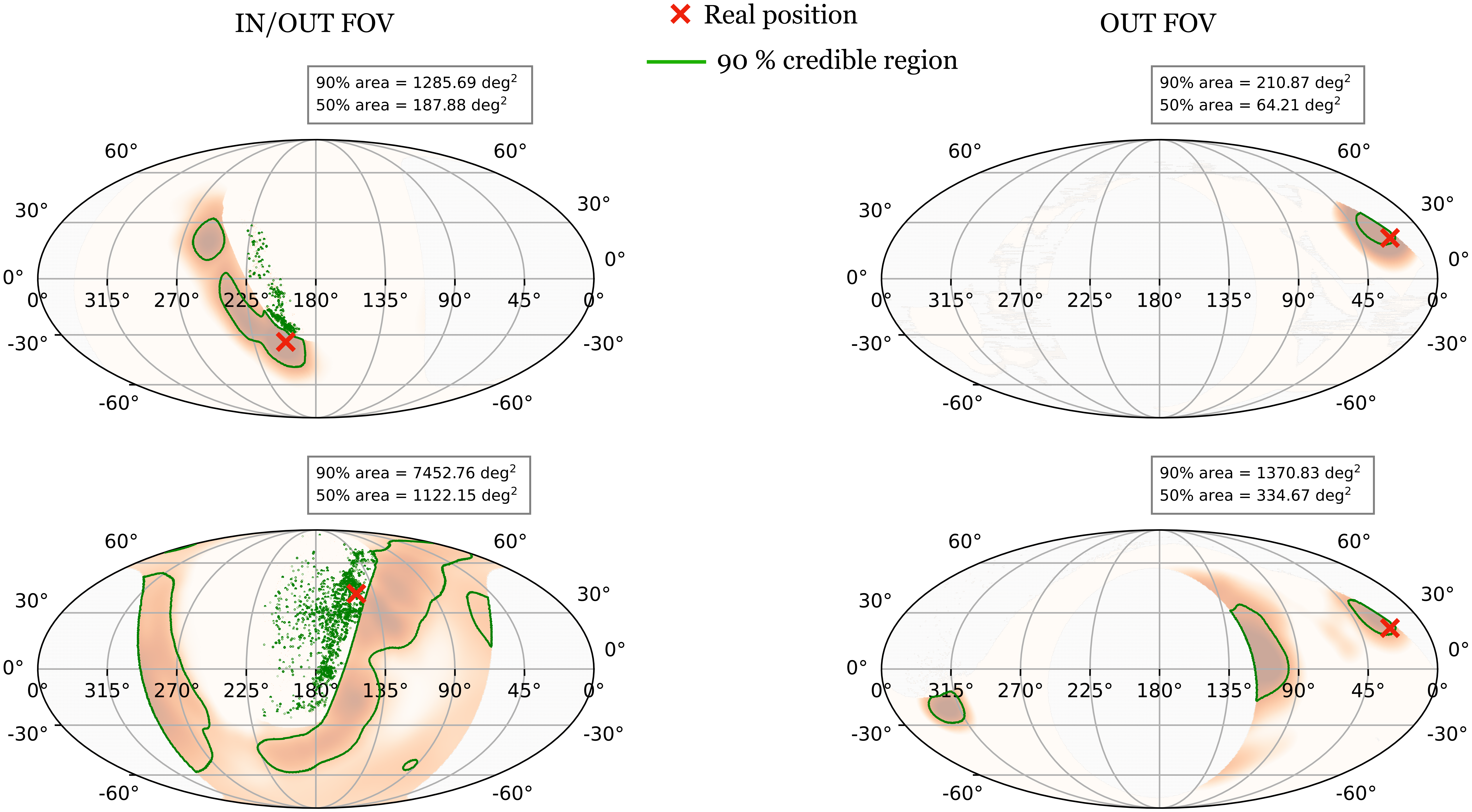
Mass priors

EoS

$P(M_1, M_2) \rightarrow P(M_{acc})$



Yes, we finally have NITRATES sky localization maps!



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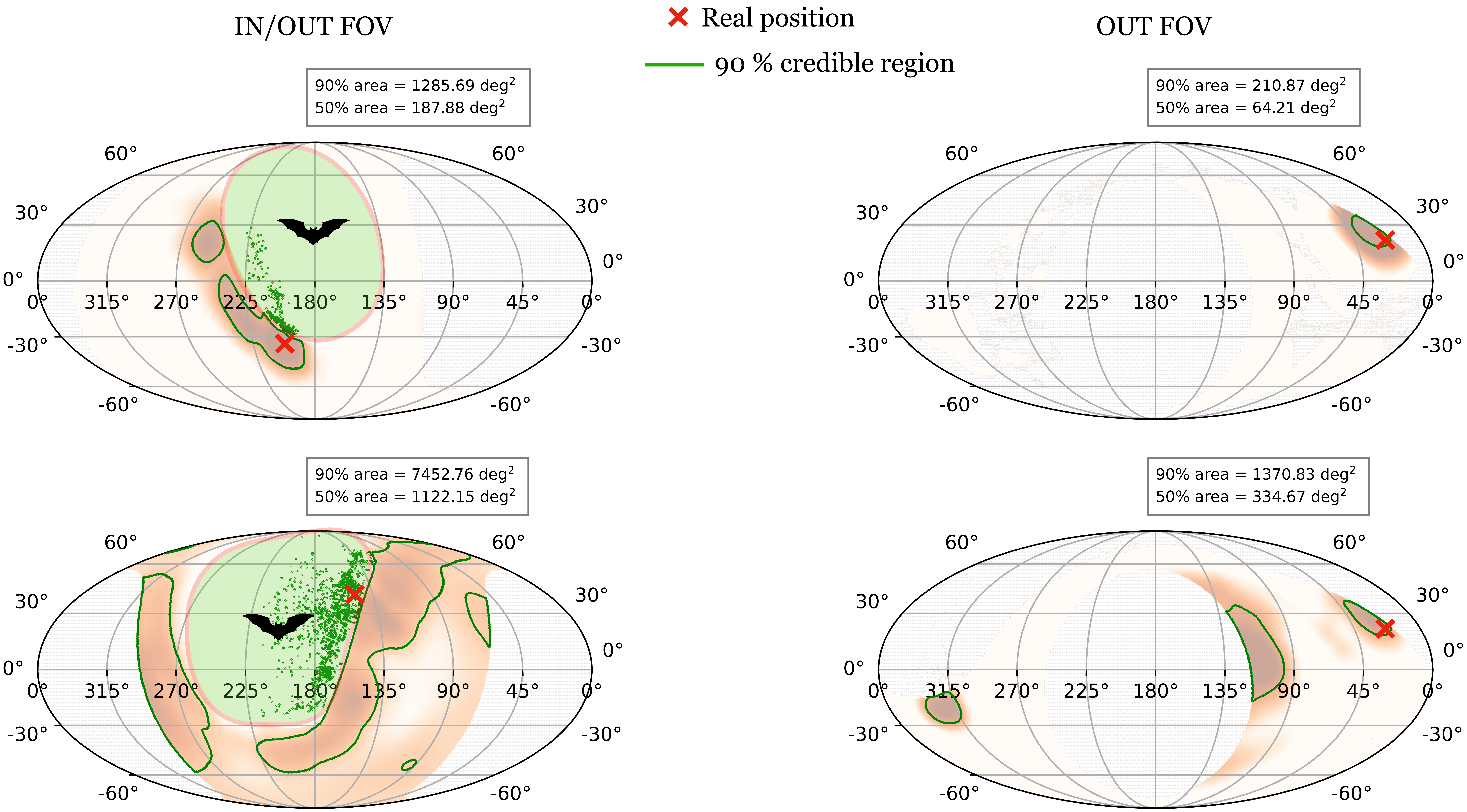

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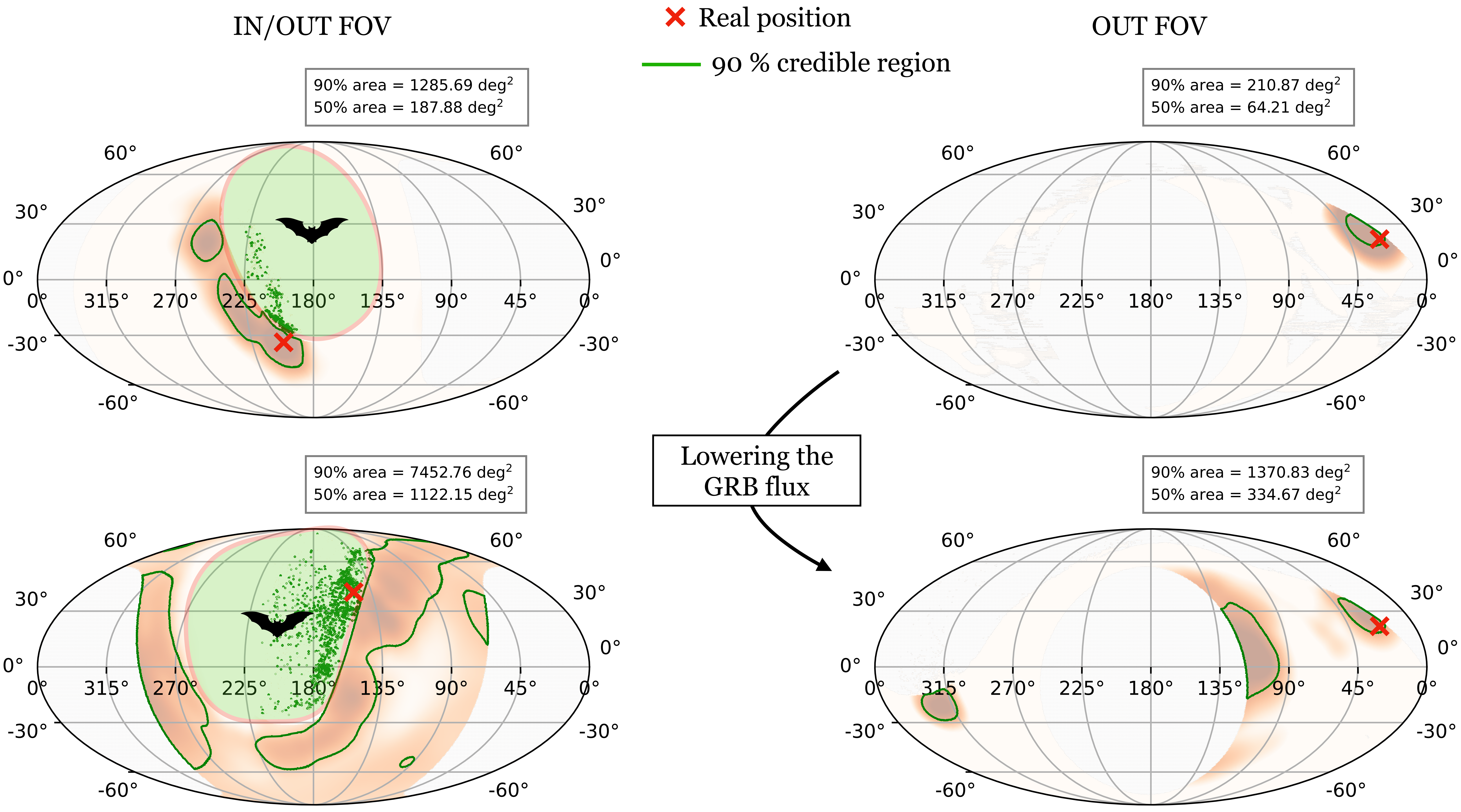
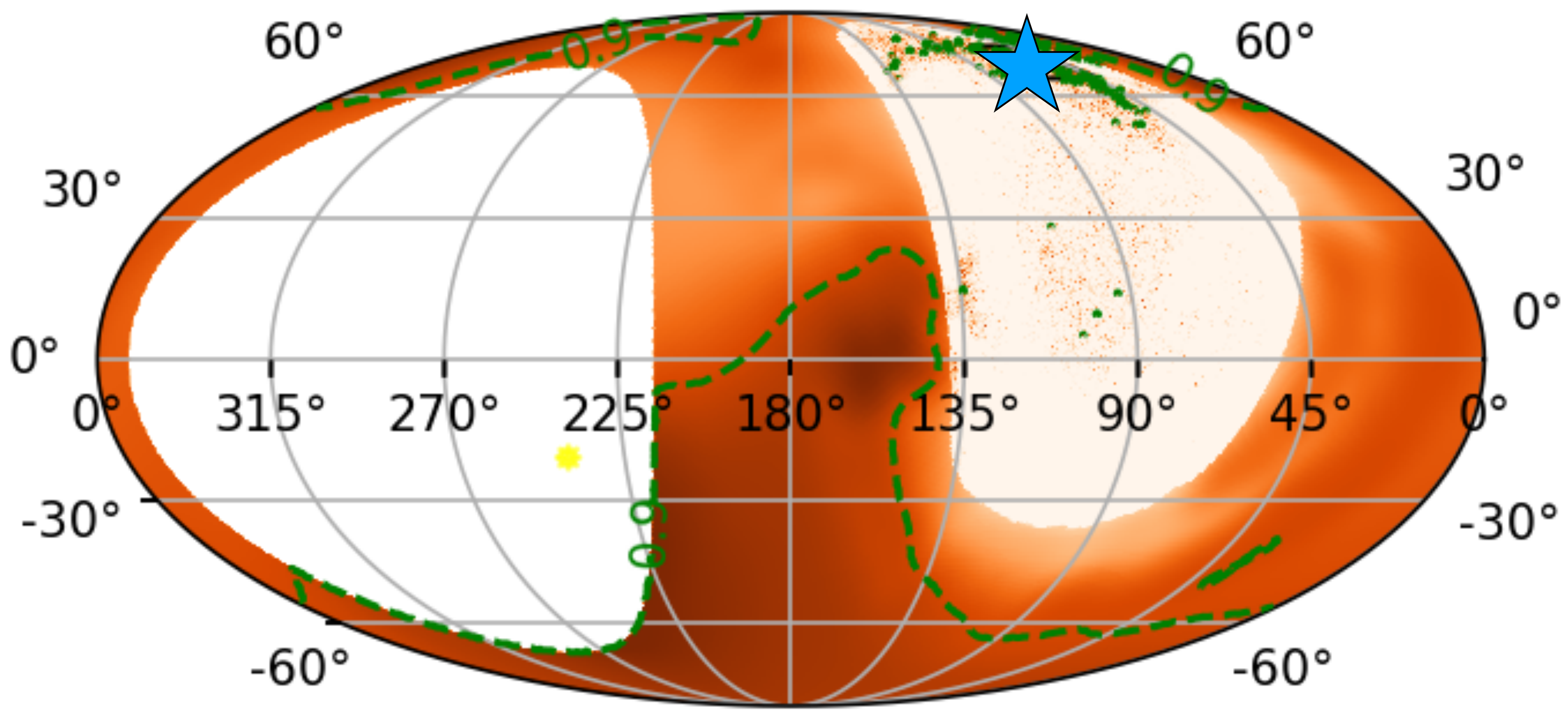
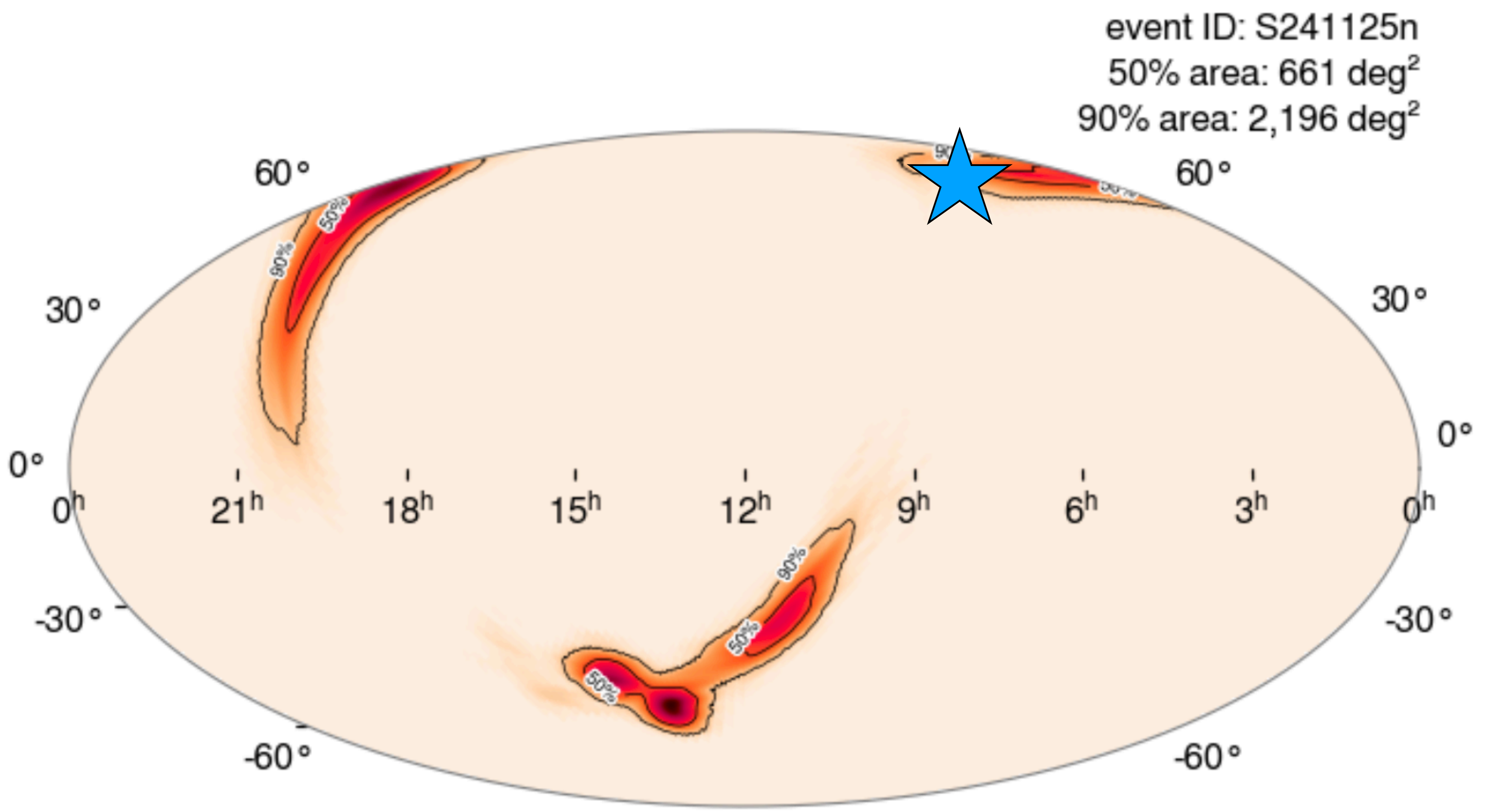
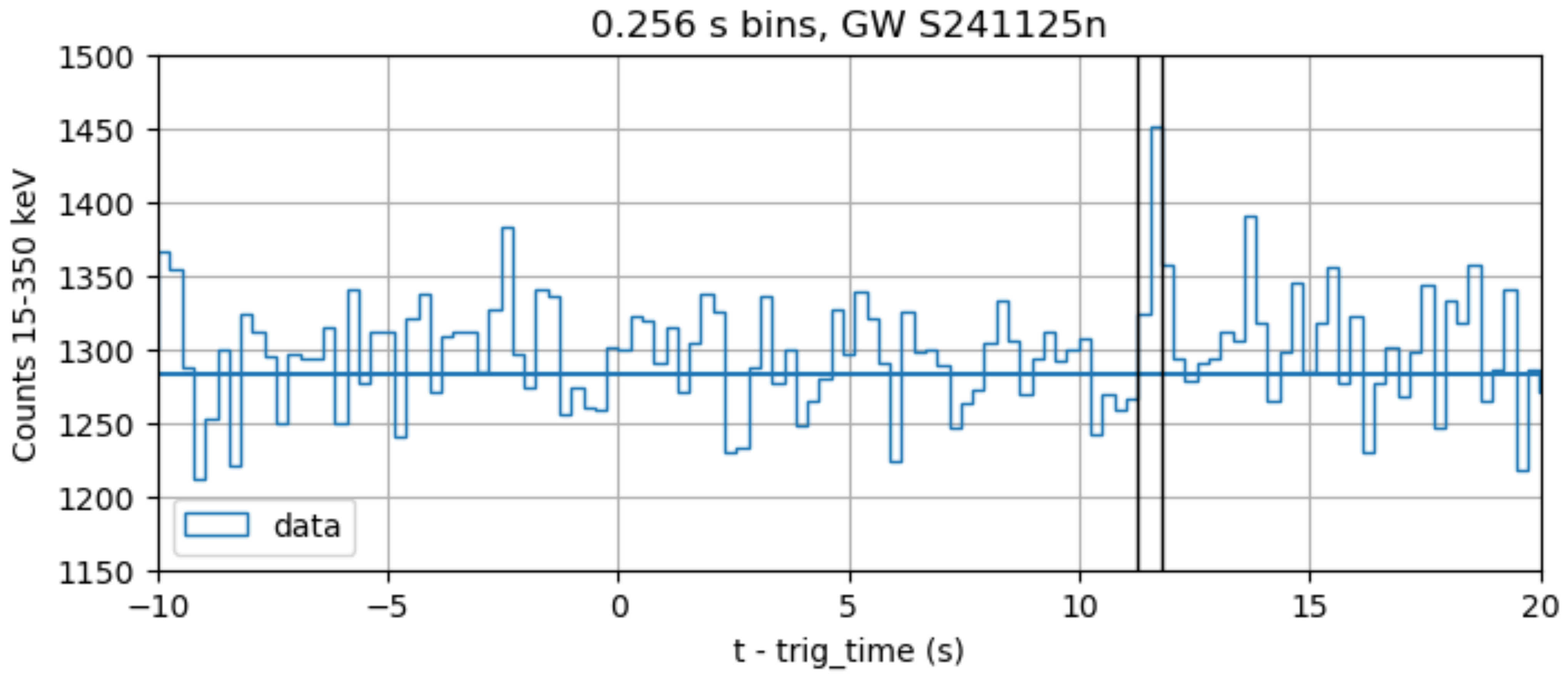


The weird case of Dr. S241125n (BBH) and Mr. 754189311 (γ-ray candidate)

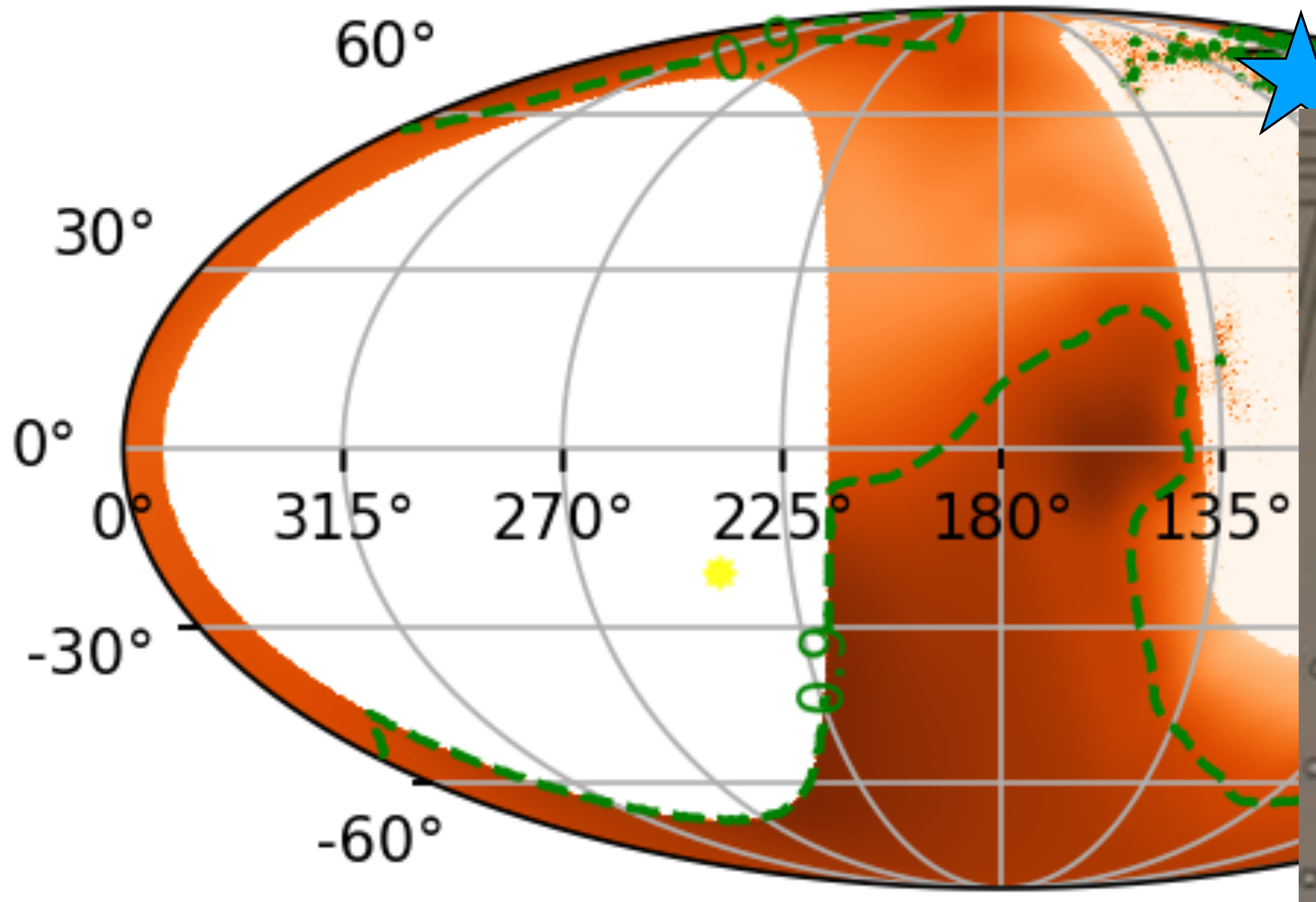


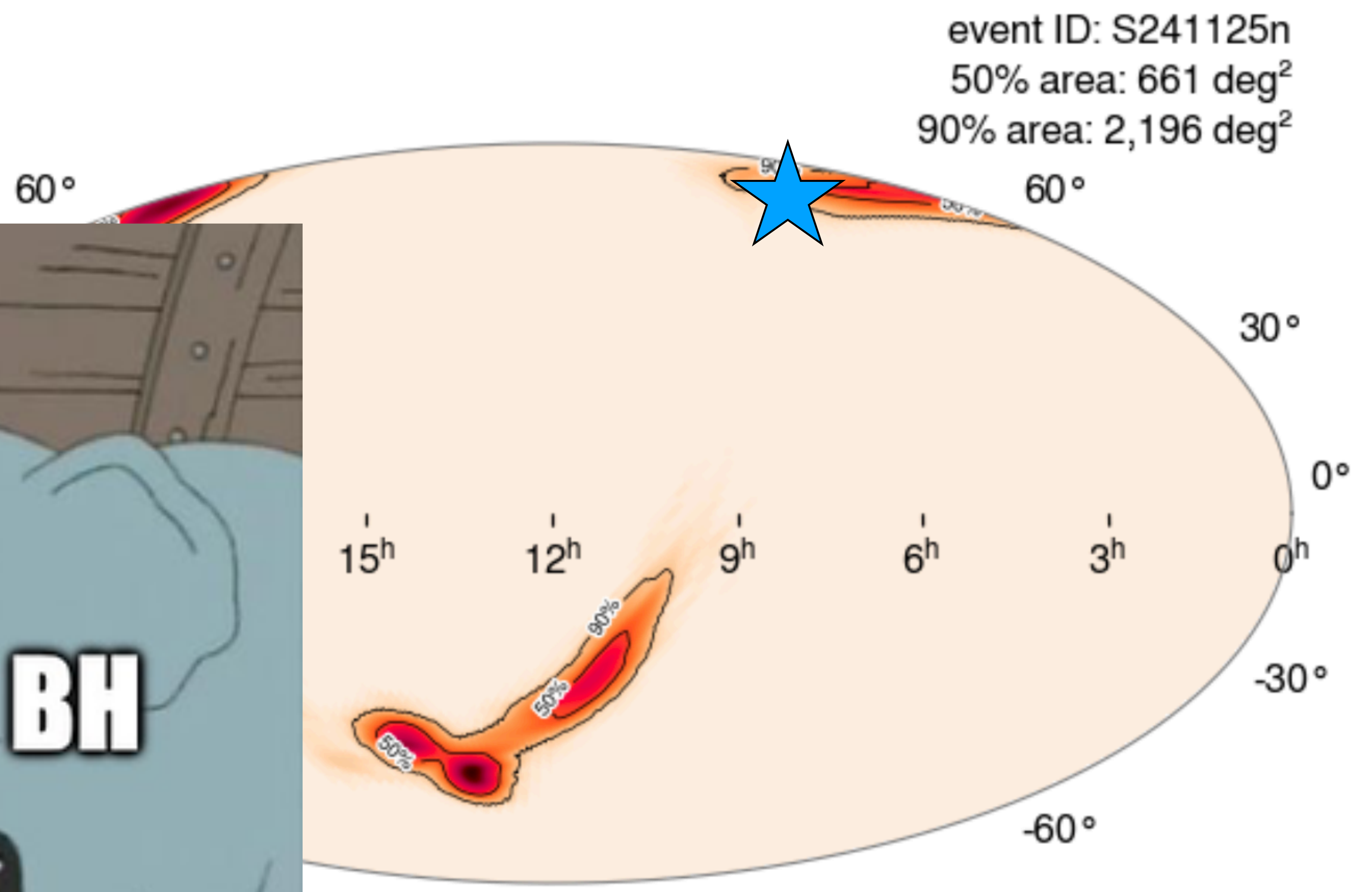


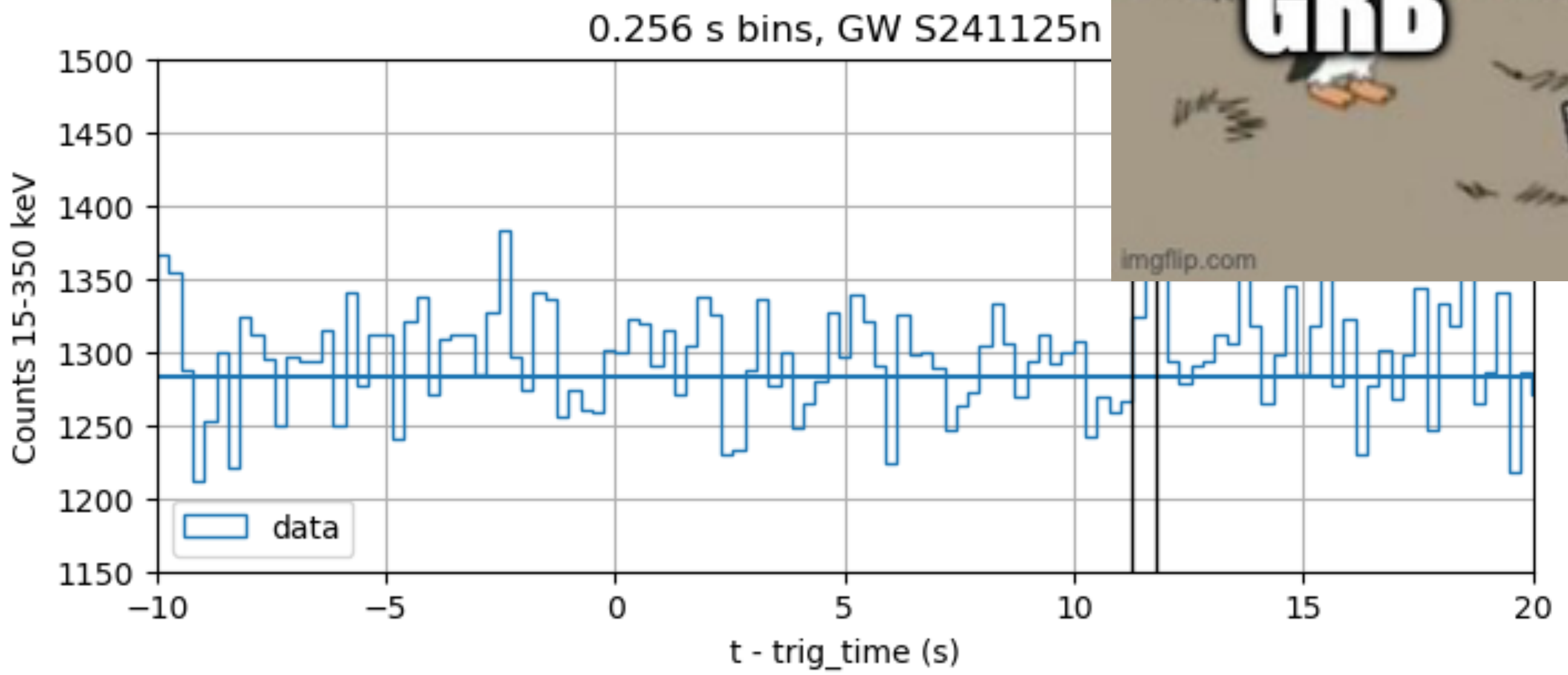


- 84% of the sky localization probability is inside 5 arcmin around the BAT best position (blue star). The remaining 16% is spread around the sky
- 11 secs between the GW and the γ-ray candidate
- The BAT position is at the 74% credible level of the GW skymap
- The BAT candidate has a FAR = 1/44 min
- The GW candidate has a FAR = 1/33 yr

The weird case of Dr. S241125n (BBH) and Mr. 754189311 (γ-ray candidate)







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lue star). The remaining 16% is spread

- 11 secs between the GW and the γ-ray candidate
- The BAT position is at the 74% credible level of the GW skymap
- The BAT candidate has a FAR = 1/44 min
- The GW candidate has a FAR = 1/33 yr

The weird case of Dr. S241125n (BBH) and Mr. 754189311 (γ-ray candidate)

How likely is to obtain such an association by chance?

1 / 6 yr		1 / 50 yr		1 / 200 yr		Negligible
True GW - False γ	>	False GW - False γ	>	True GW - True γ, but not from the same source	>	False GW - True γ
$R_{GW} \times FAR_\gamma \times \frac{\Delta t}{I_\Omega}$		$Z\left(1+\ln\left(Z_{\max}/Z\right)\right)/I_\Omega$		$R_{GW} \times R_\gamma \times \frac{\Delta t}{I_\Omega}$		$FAR_{GW} \times R_\gamma \times \frac{\Delta t}{I_\Omega}$

$I_\Omega = \int p_{GW}(\Omega) p_\gamma(\Omega) d\Omega$ $\quad Z = FAR_{GW} FAR_\gamma \Delta t$ $\quad R_\gamma \sim 1/\text{day}$ $\quad R_{GW} \sim 2/\text{week}$

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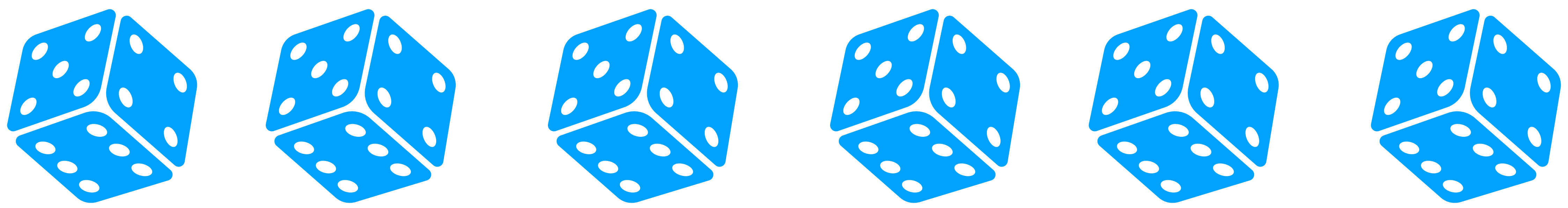
1st yr 2nd yr …



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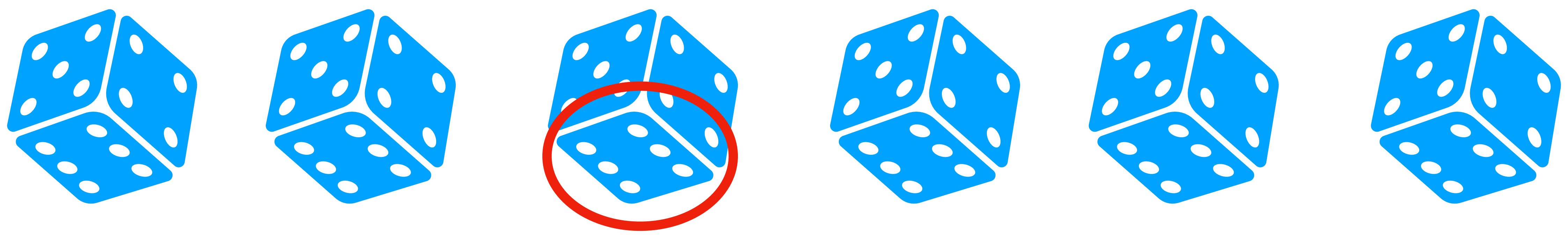
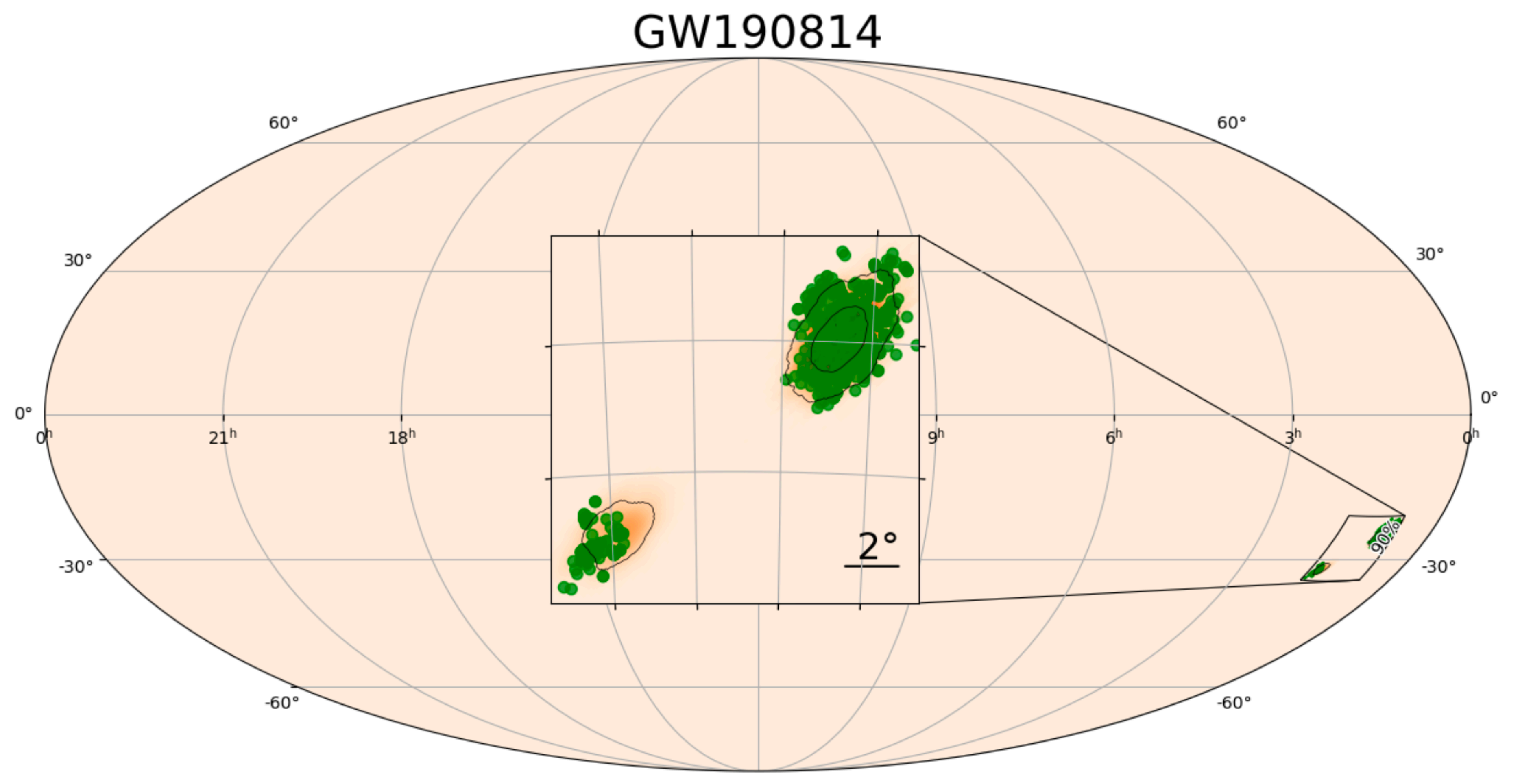


Follow up with *Swift* XRT/UVOT

XRT/UVOT follow-up



	MAX FAR	MAX DISTANCE	MAX 90% AREA
P_disrupt =0	1/10 yr	/	30 deg^2
P_disrupt <0.5	1/90 days	150 Mpc	300 deg^2
P_disrupt >0.5	1/90 days	400 Mpc	300 deg^2
Bursts	1/yr	/	/

To decide when to follow-up we consider:

- GW significance in terms of FAR
- Probability of being EM bright

$$P_{disrupt} = P(HasRemnant) * (1 - P(Terr))$$

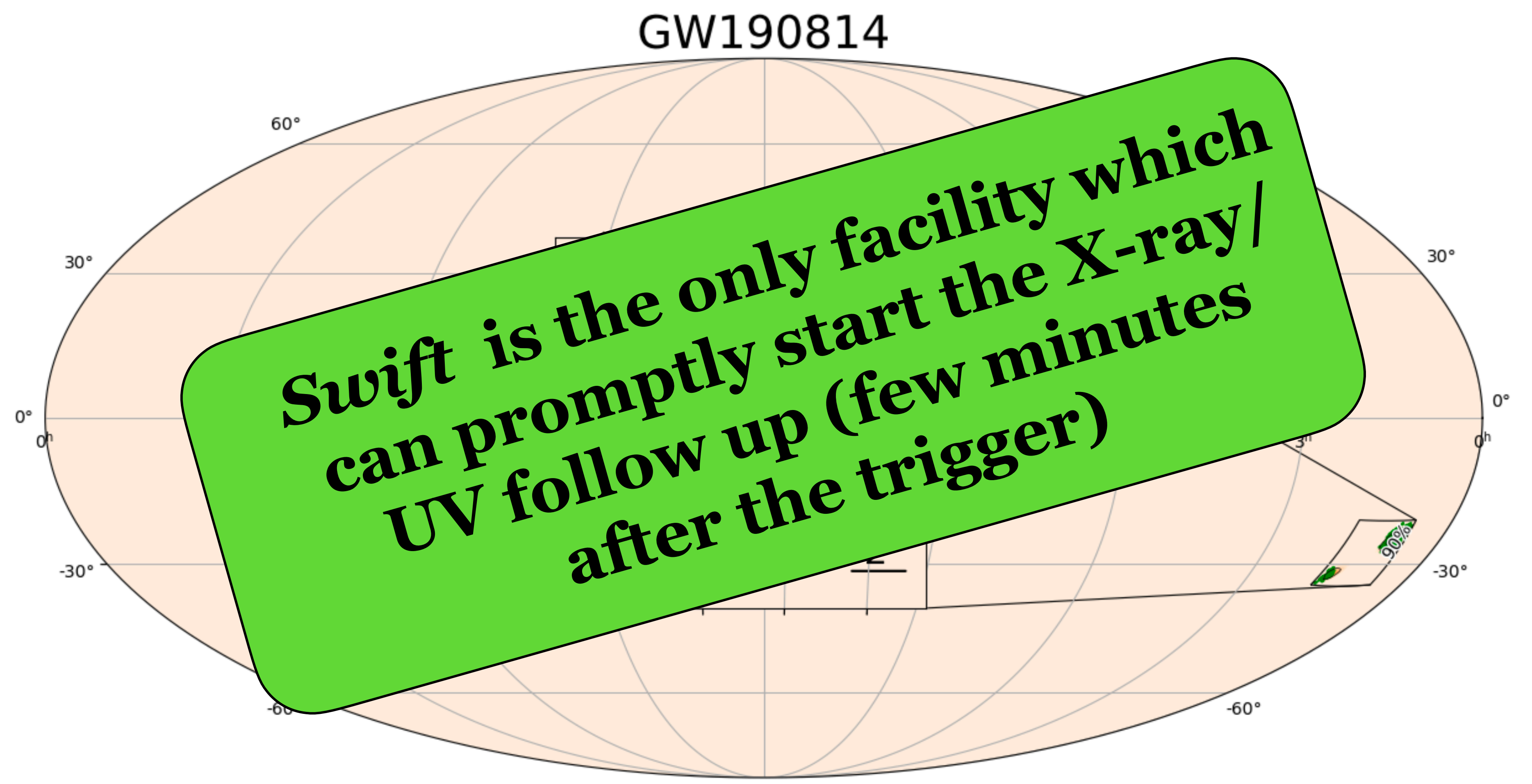
- Sky localization
- Distance

The ordering and selection of fields to observe is done performing a convolution of the GW sky map with galaxy catalogs

$$\mathcal{P}_{\mathrm{gal},p} = \mathcal{P}_{\mathrm{GW},p} C_p N \sum_g \left(\mathcal{P}(g|P_p(D)) \frac{L_g}{L_{\mathrm{tot}}} \right)$$

Preference given to the fields with more luminous galaxies

XRT/UVOT follow-up



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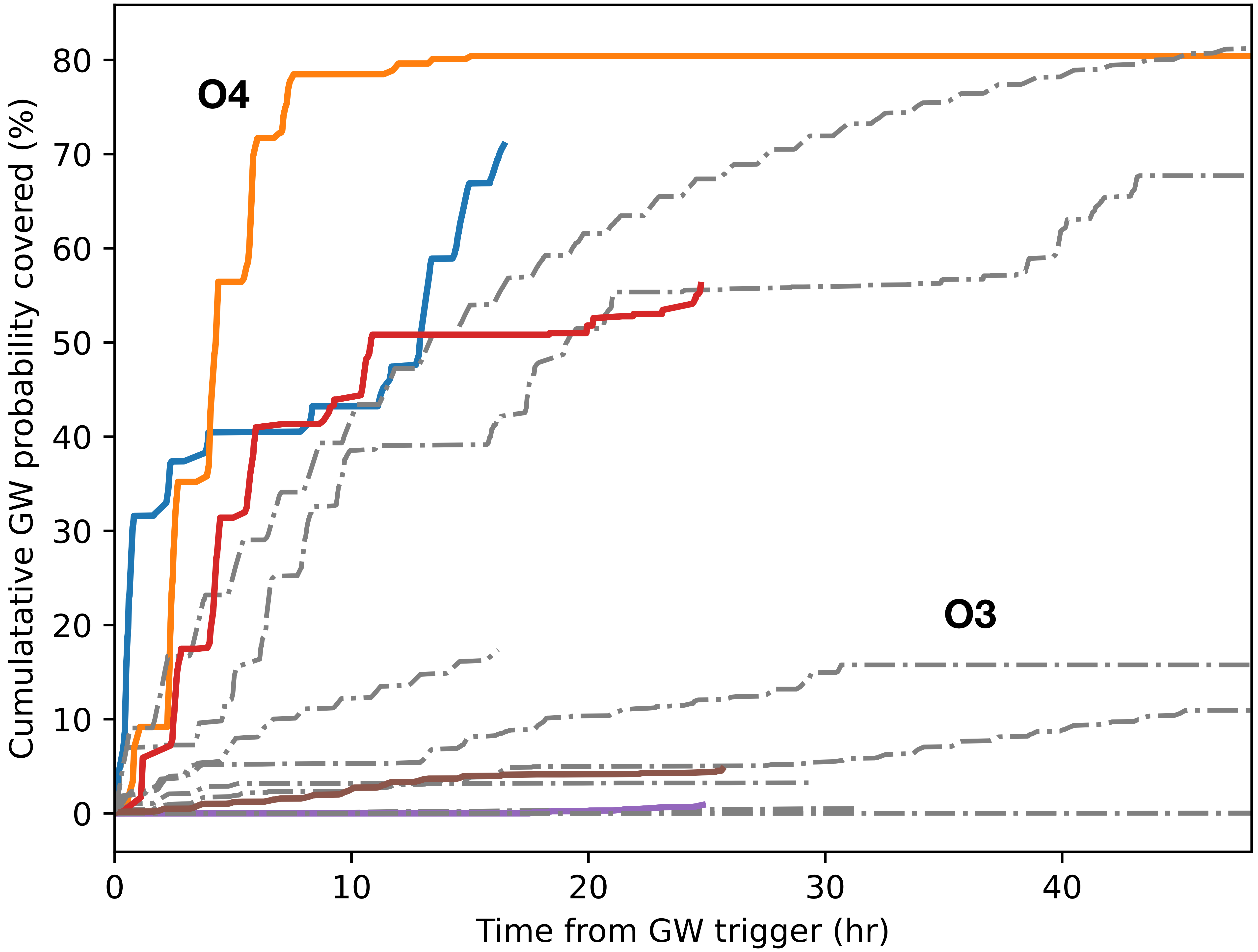
XRT/UVOT follow-up: performances during O3-O4



Virgo offline for most of the time —> **only 6 GW followed up so far** due to large sky areas

During O4, **only S240422ed possibly EM bright**, but then down-ranked by LVK

More than 50% of the area of the well localized events (~ 10 deg^2) **can be covered within 24 hr from the GW trigger**

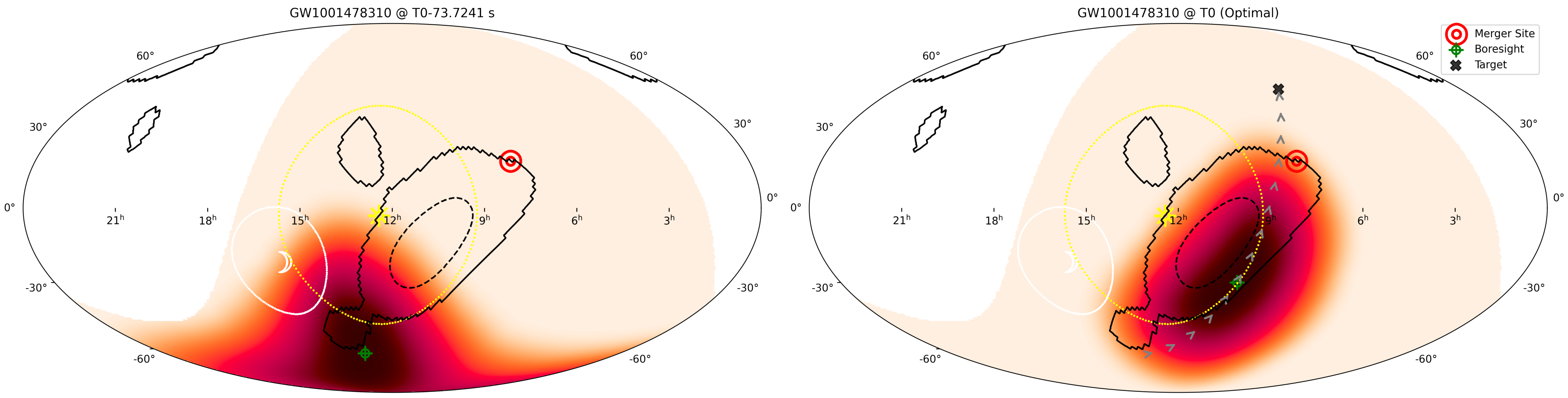
Swift responding to pre-merger GW alerts

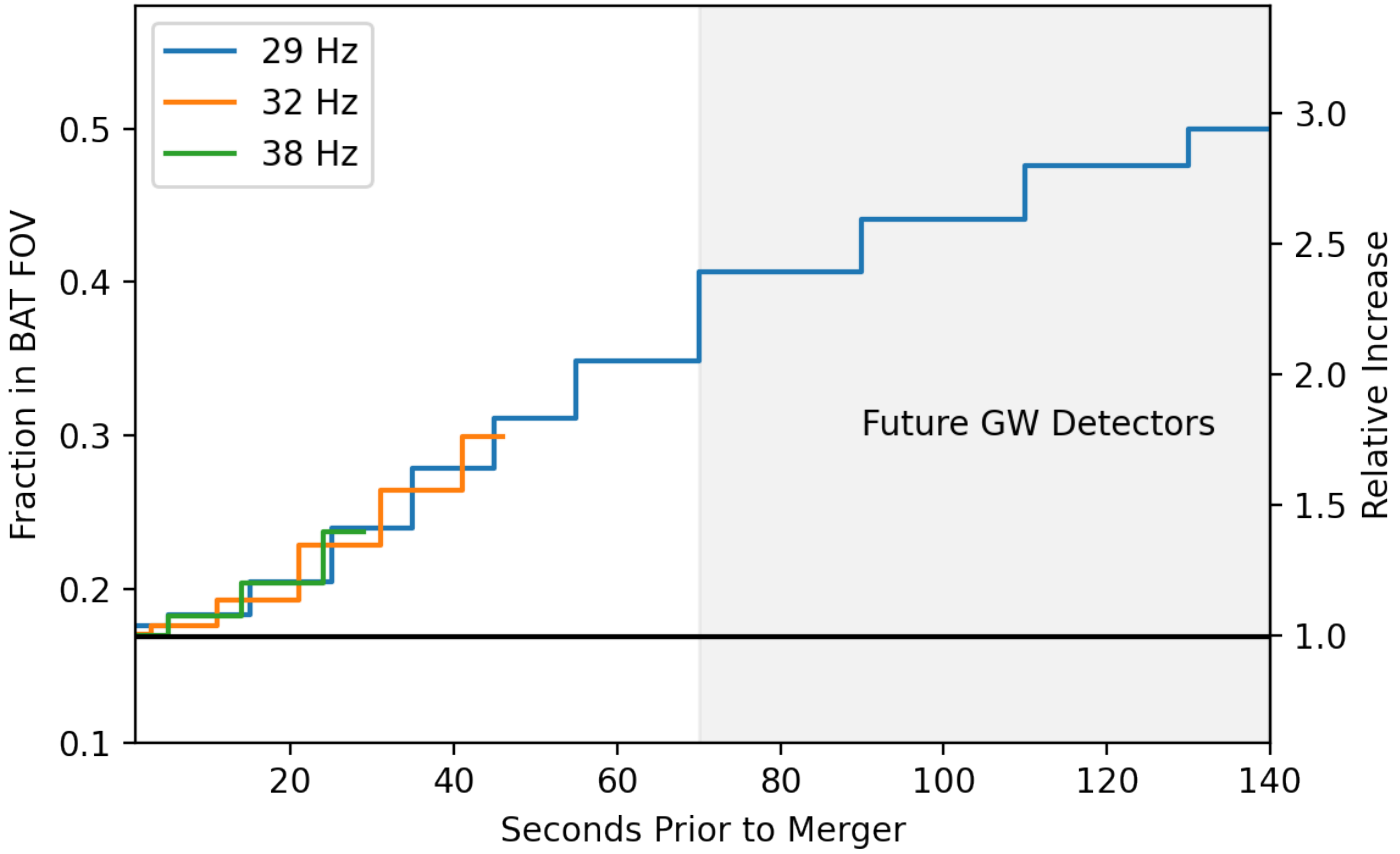
Concept: GW skymaps can be available up to 30-60 s pre-merger (very loud nearby NS merger) —> **quickly re-orient Swift to have the GW in FOV**

Now feasible thanks to the extremely low-latency response given by the *continuous commanding*

Around 3 sec of latency between the notice reaching MOC and Swift starting slew

Tohuvavohu+24





- On average, **slewing asap is always the best strategy** (even if sometimes BAT can point in the wrong direction)
- **Up to a factor 2 increase in the chance to have the GW in BAT FOV**
- **Dominant source of latency from the LVK side** (can be improved!)
- Everything ready to be tested in realtime (using GBM GRBs as triggers) and to be implemented for O4 and O5
- **Pioneering concept for the 3G GW detectors** (ET and CE) where early warning alerts will happen routinely

Summary

- **Swift-BAT/GUANO** essential to perform **subthreshold searches targeted on GWs**

- **NITRATES** pipeline running 24/7 **increases the joint detection horizon**

- Now NITRATES **sky localization maps are available and calibrated** —> crucial to assess the significance of joint GW-gamma associations

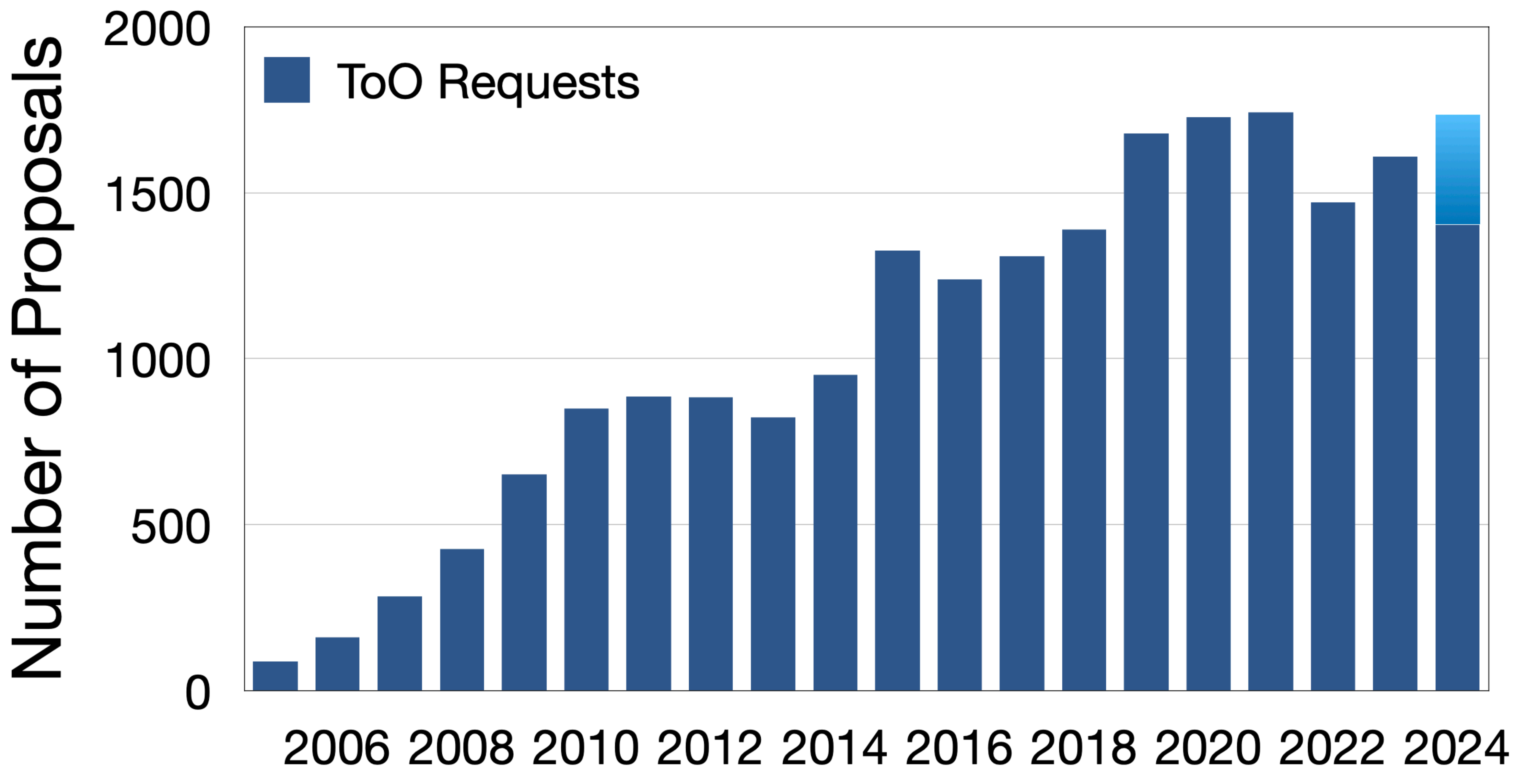
- Even in the case of **non-detection**, e.g. GW230529, we are able to **infer strong constraints** on the jet luminosity and opening angle, once the flux-upper limits are combined with the GW parameter estimation

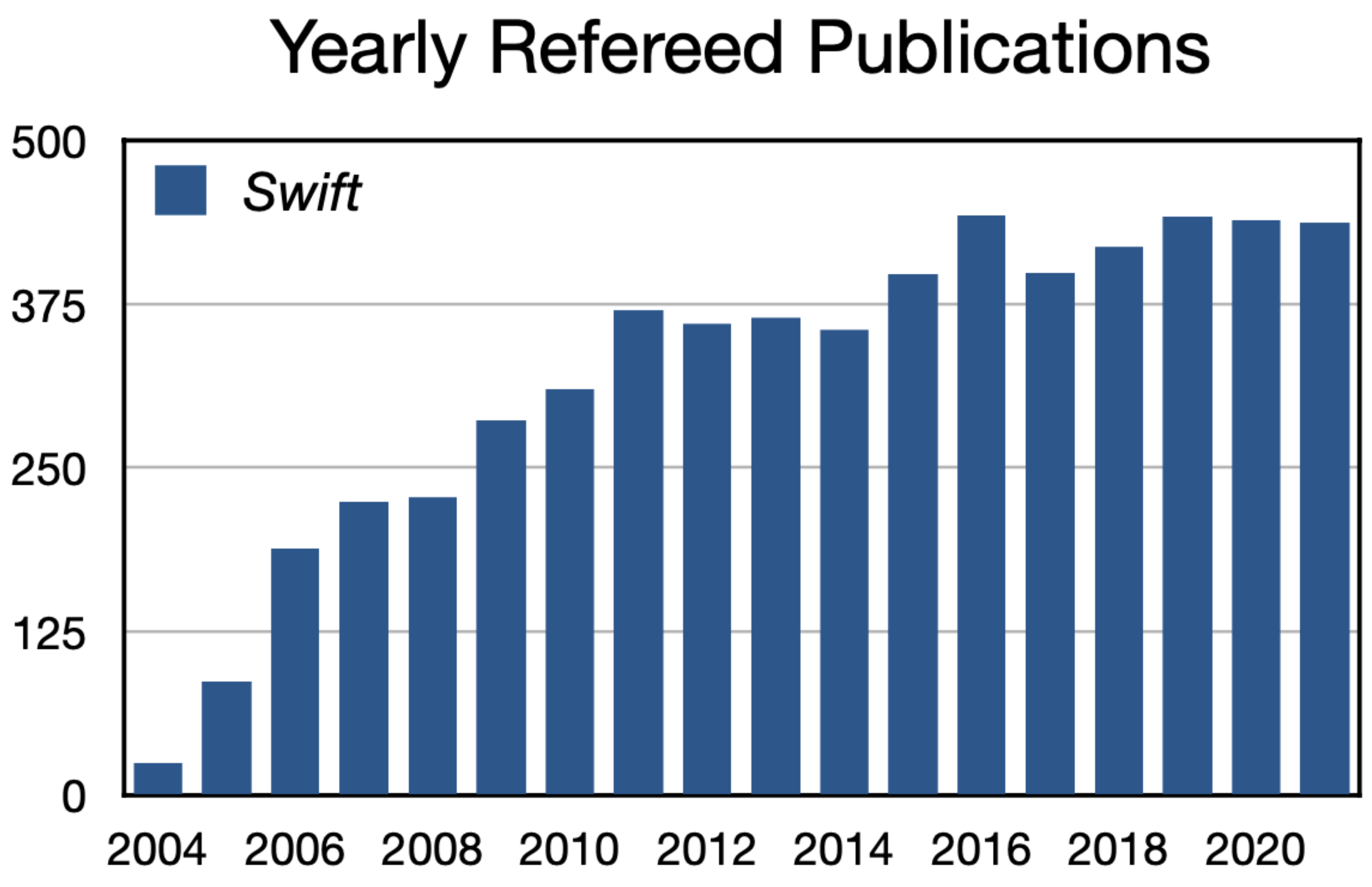
- **Swift XRT/UVOT** tiling follow-up **now optimized for the search of KN**

- Ready to **re-point *Swift*** in extremely low-latency in response to Early Warning **pre-merger alerts**

BACKUP

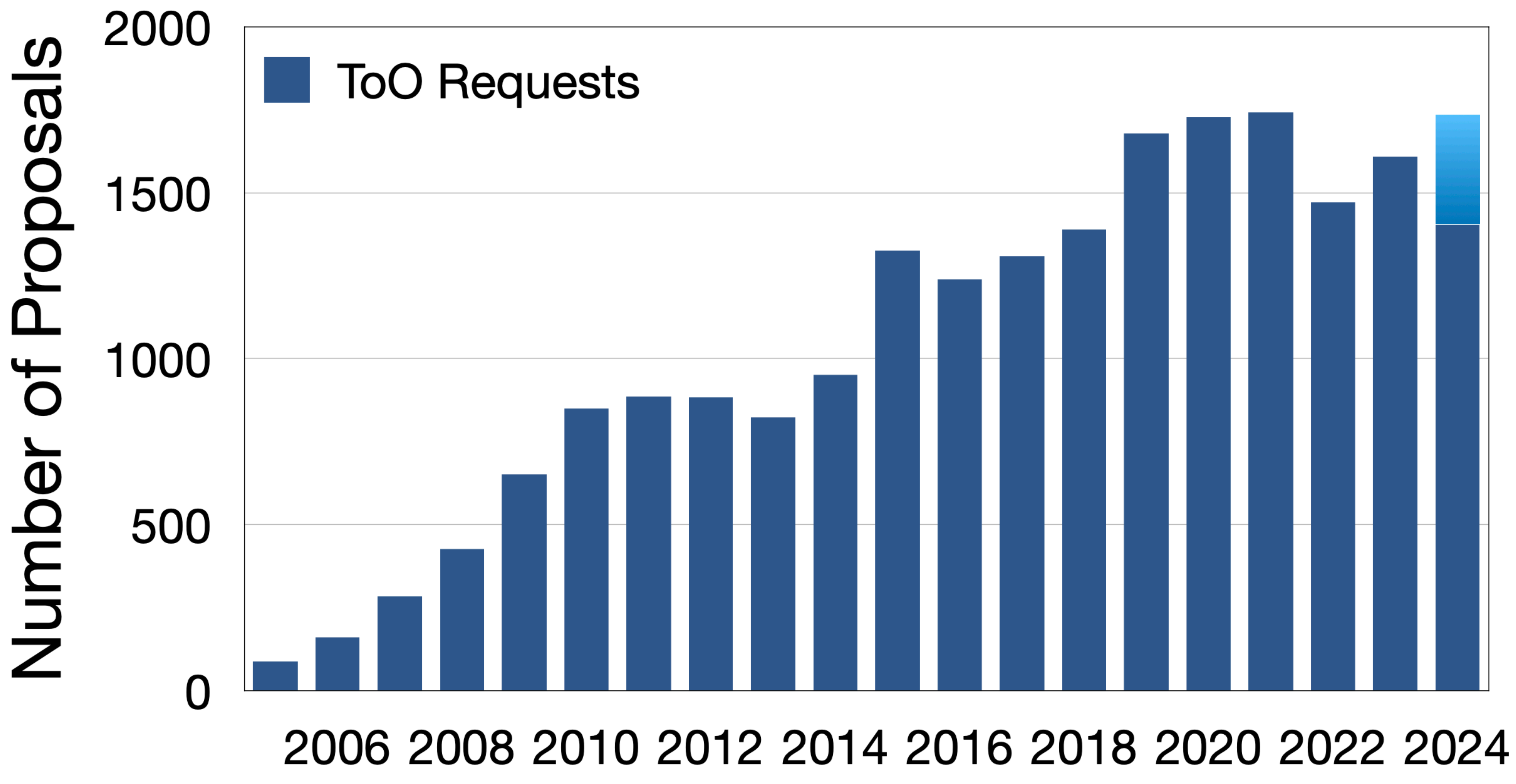
Swift is still successful …

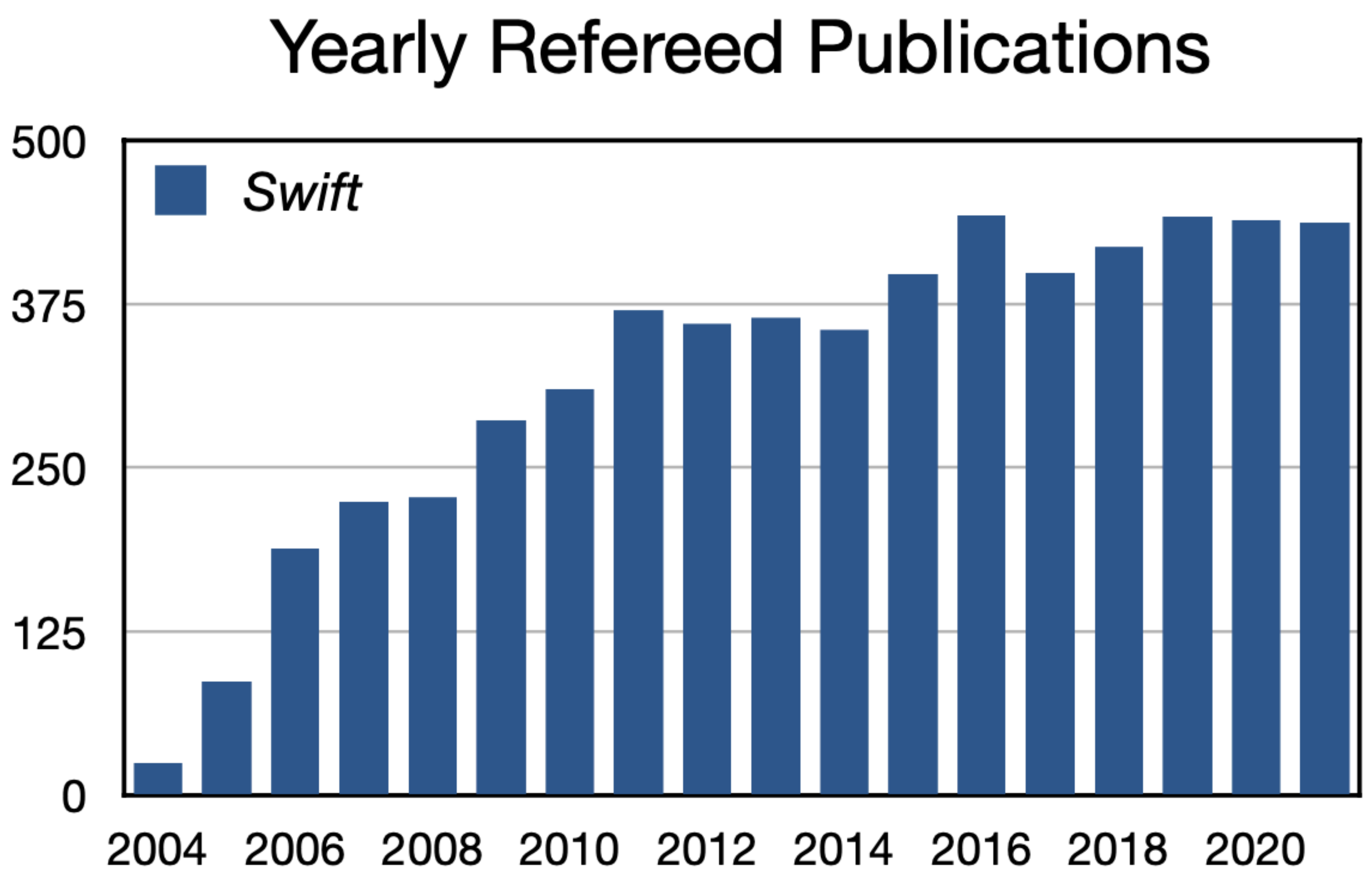




…but

Swift is still successful …

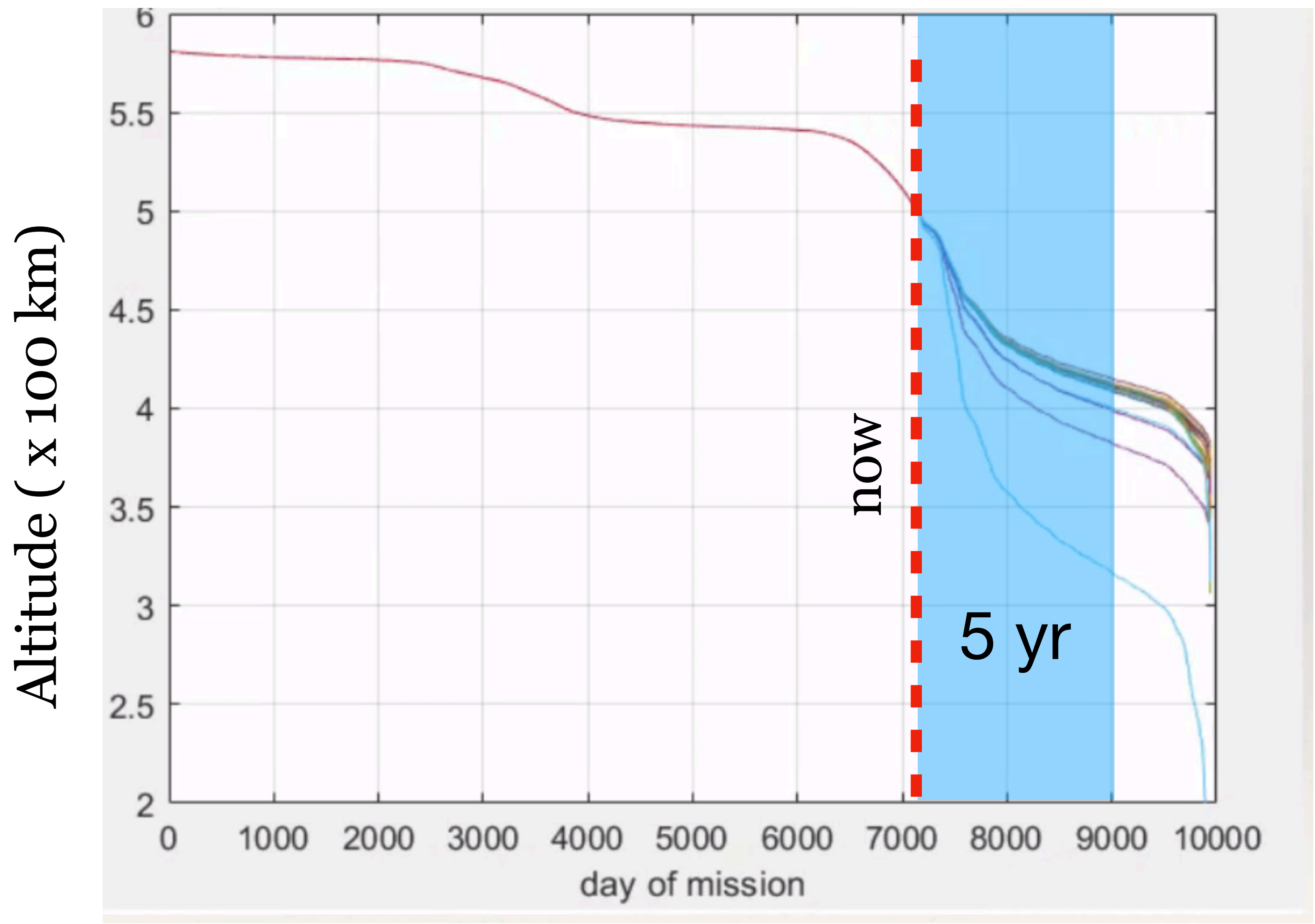




…but

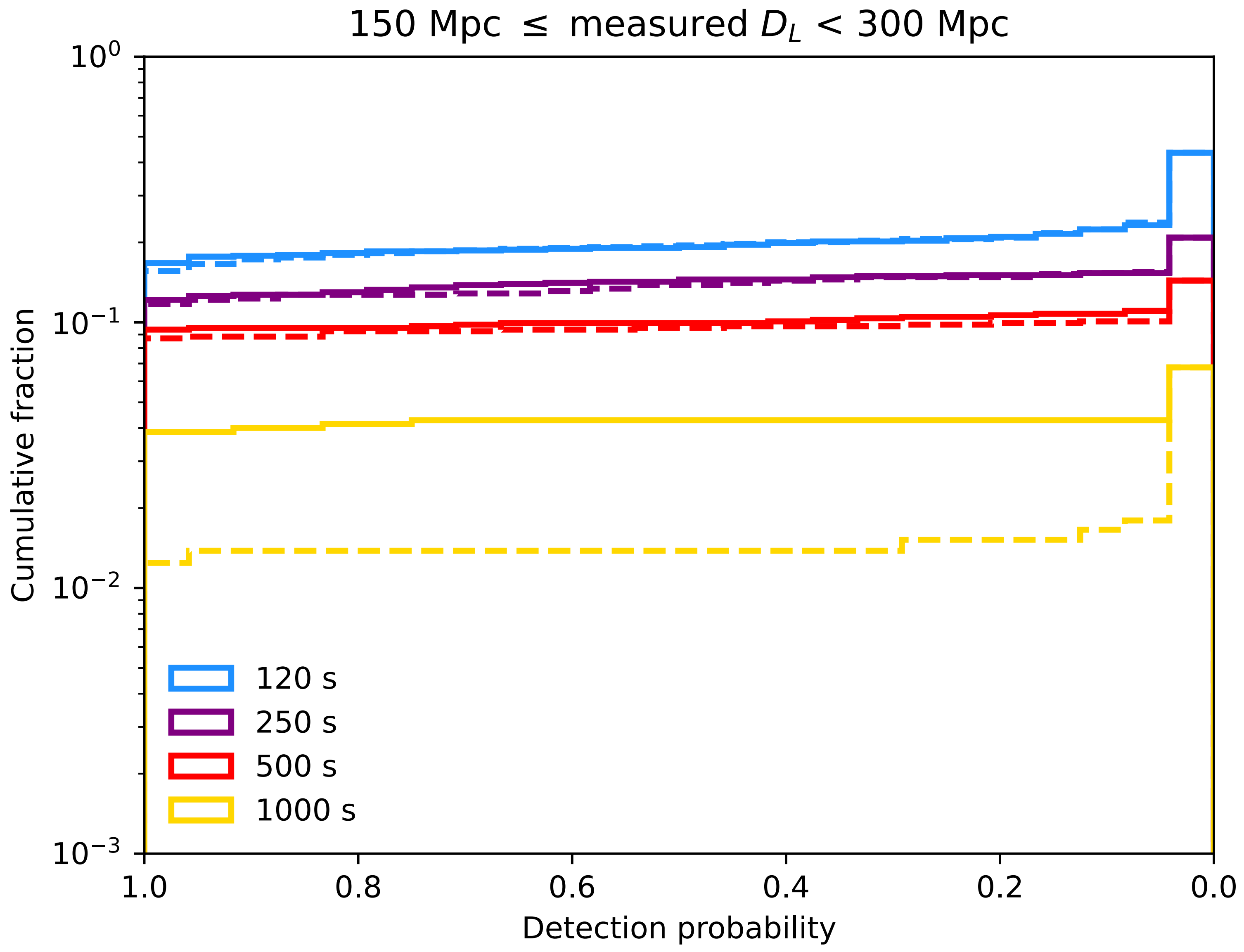
Bald Eagle Lake, PA

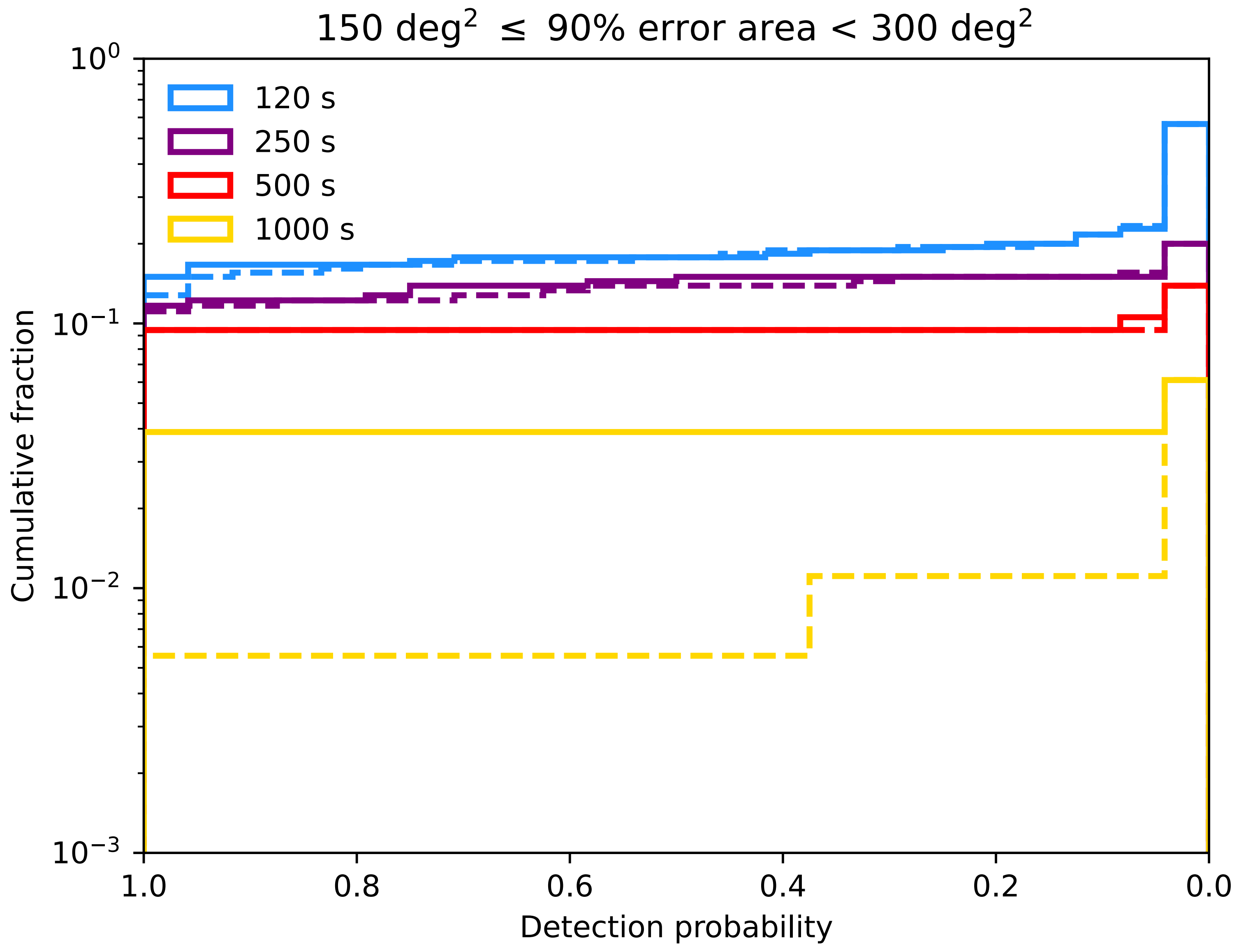
→



XRT/UVOT follow-up: future improvements

Eyles-Ferris+2024





Swift follow-up strategy currently optimized to maximize the chance to detect the KN component with UVOT

Simulating BNS mergers and relative KN emission, we can determine the **optimal follow-up strategy as a function of the GW distance and sky localization**

Fraction of sources with detection probability > 50 %, for different time exposures

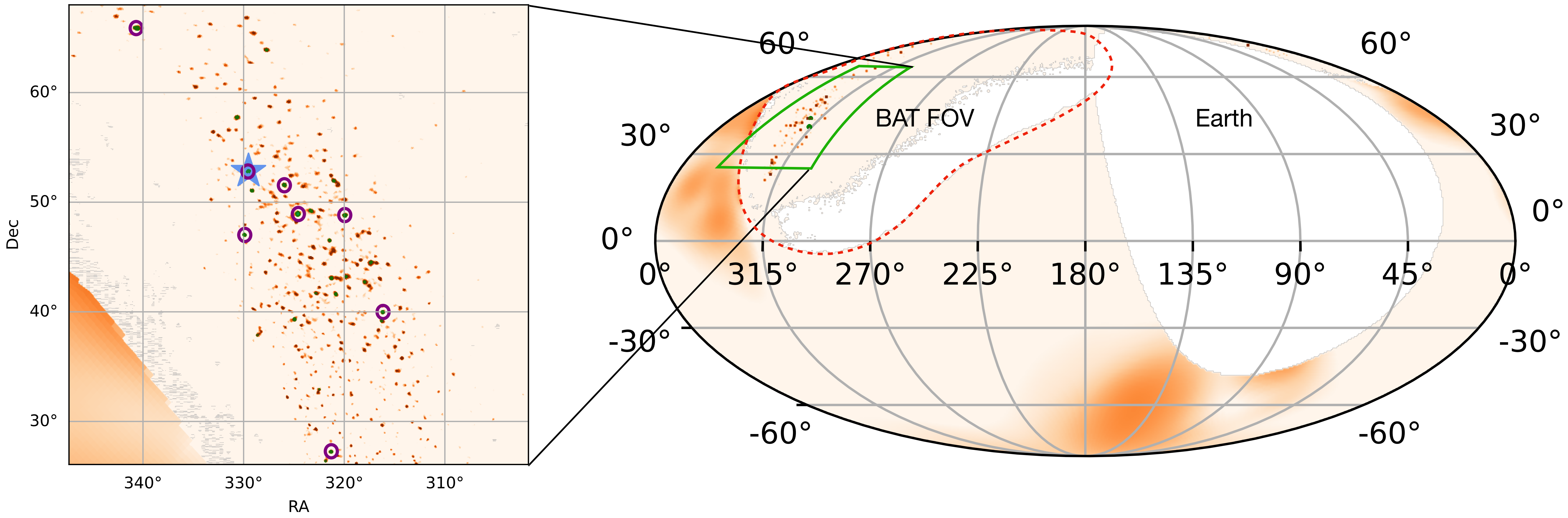
90% error area \ Measured D_L	0 - 150 Mpc	150 - 300 Mpc	300 - 500 Mpc
0 - 150 deg^2	0.43 / 0.42 / 0.39	0.31 / 0.23 / 0.18	0.09 / 0.11 / 0.07
150 - 300 deg^2	0.17 / 0.50 / 0.25	0.26 / 0.14 / 0.11	0.07 / 0.07 / 0.06
300 - 500 deg^2	0.50 / 0.38 / 0.25	0.08 / 0.03 / 0.01	0.02 / 0.09 / 0.09
500 - 1000 deg^2	0.25 / 0.25 / 0.25	0.11 / 0.14 / 0.07	0.02 / 0.02 / 0.02

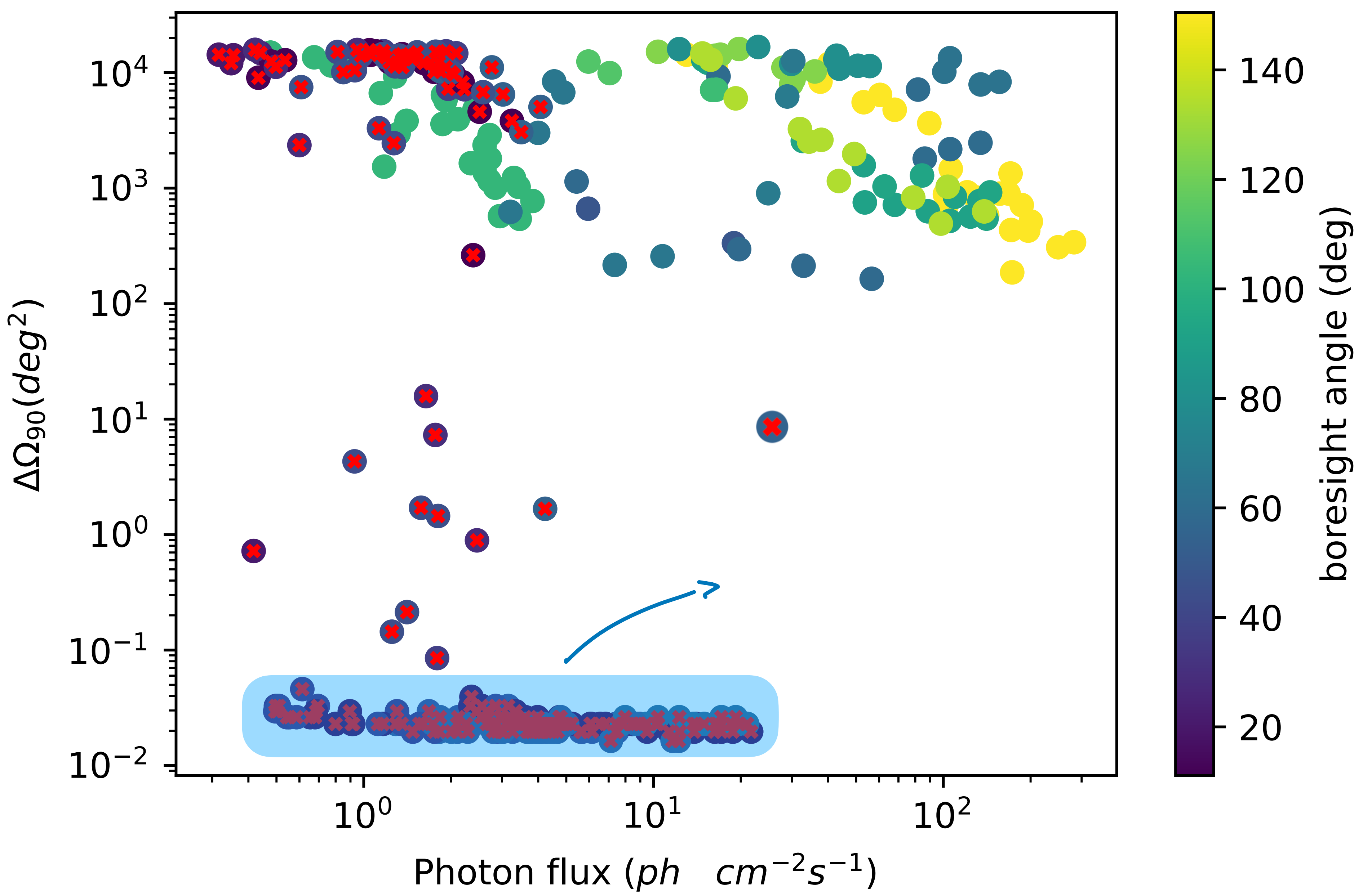
120 s / 250 s / 500 s

Localizing the next GW counterpart with NITRATES

DeLaunay+, in prep.

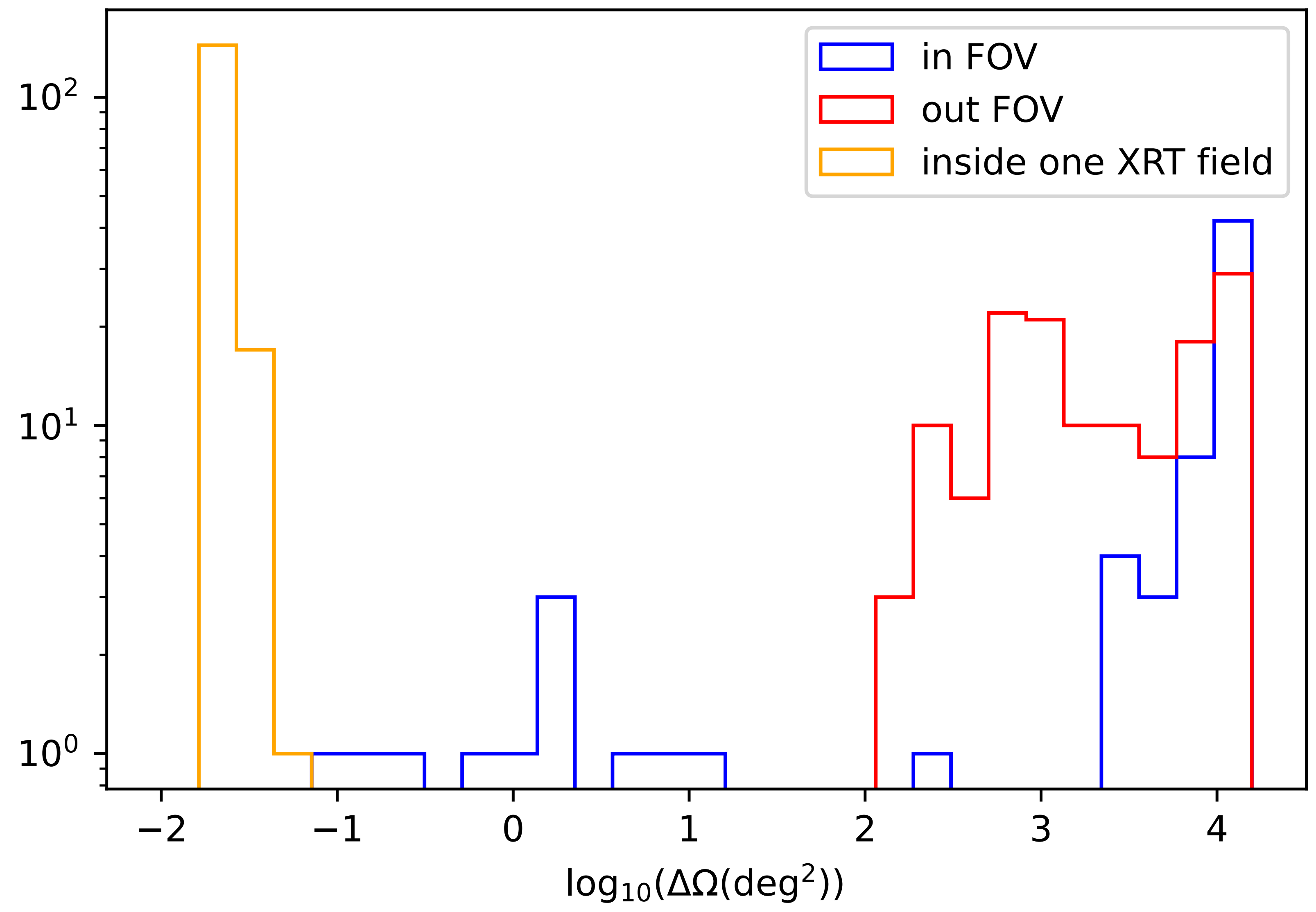
Example of a sub-threshold short GRB analyzed by NITRATES —> the high probability peaks (cumulative 90% localization) can be covered with 8 XRT fields



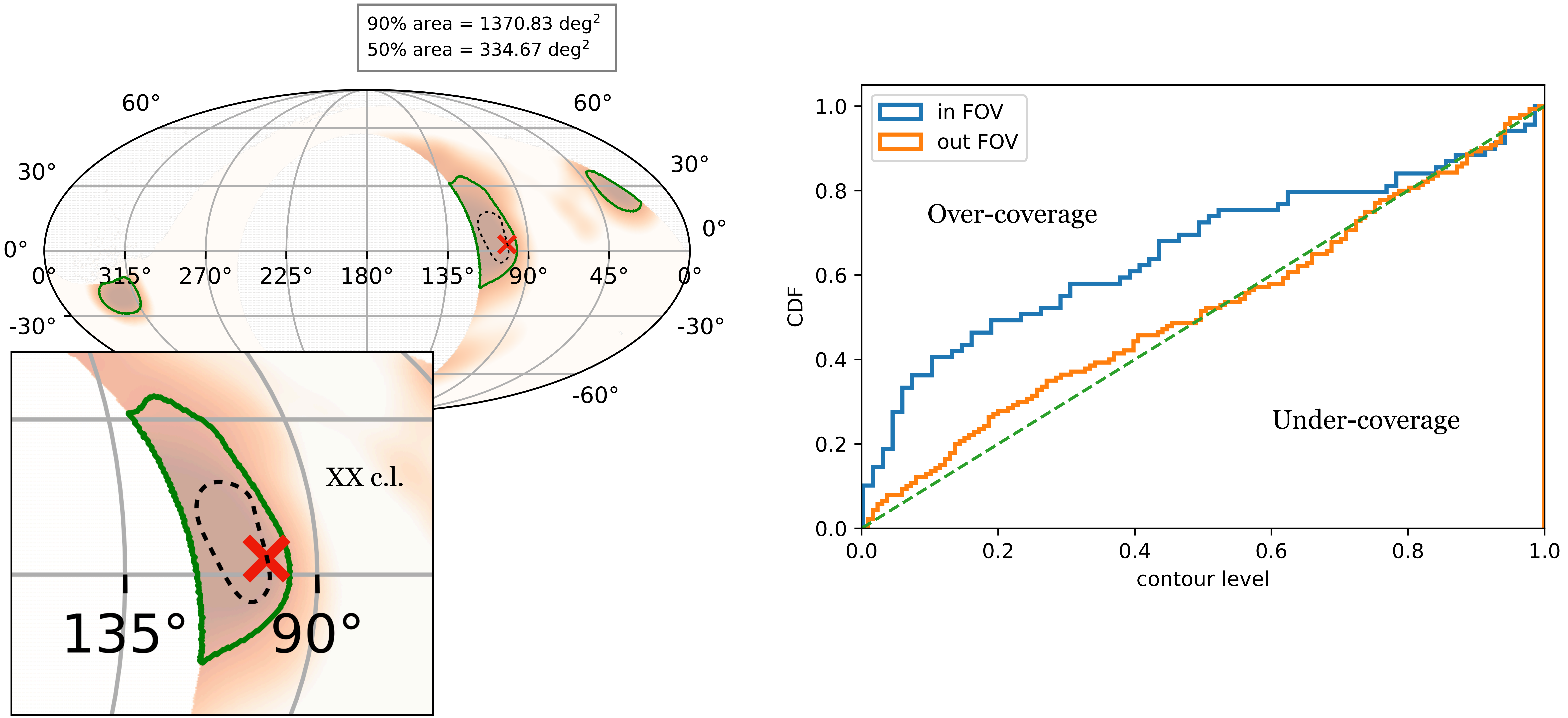


Quick facts:

1. Multi-modal pattern of the localization map, scattered in FOV, smoother outside
2. Calibrated on externally detected GRBs with well known position (e.g., IPN)



Probability-probability plot

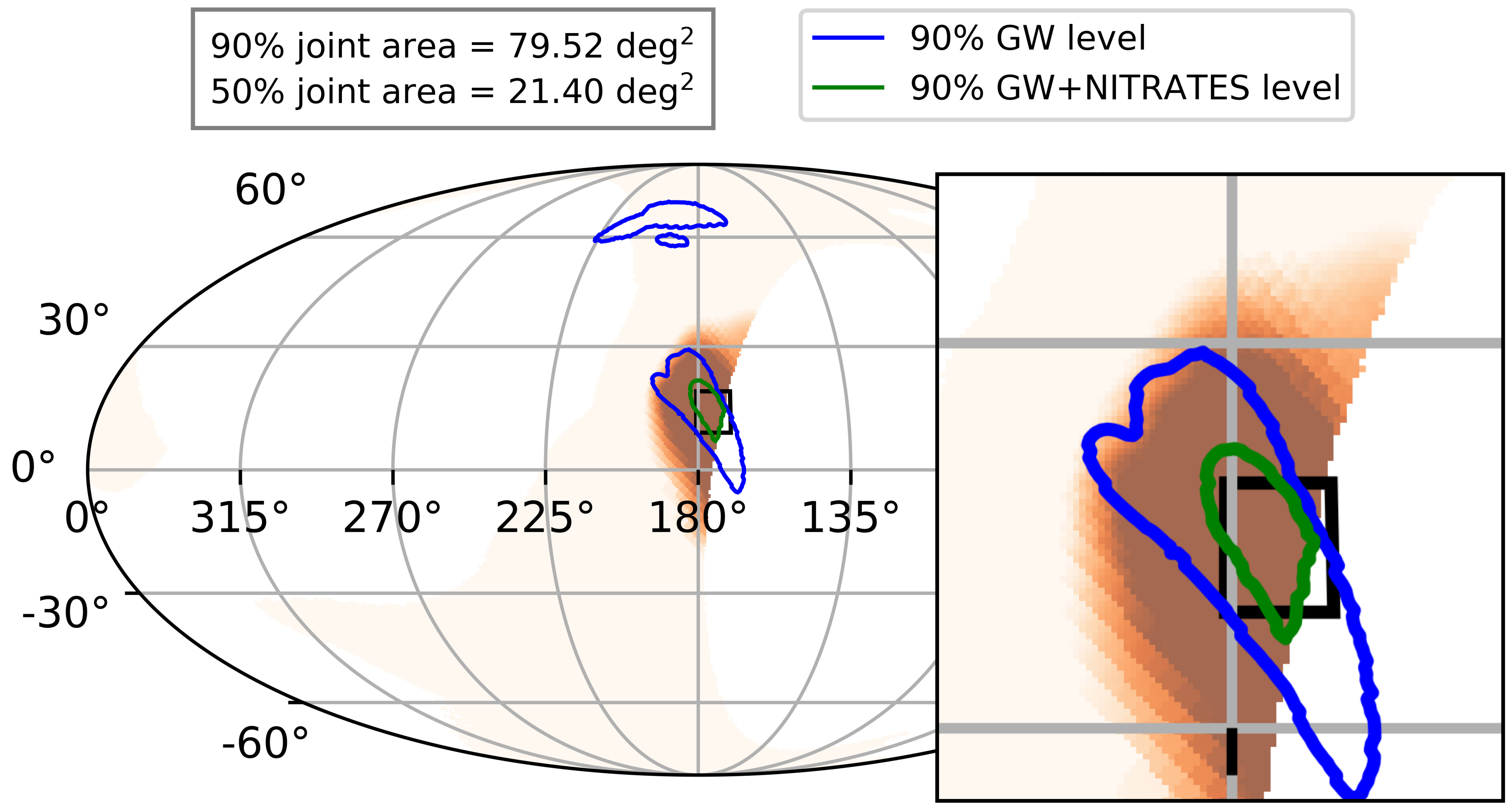


What if we combine with the GW map?

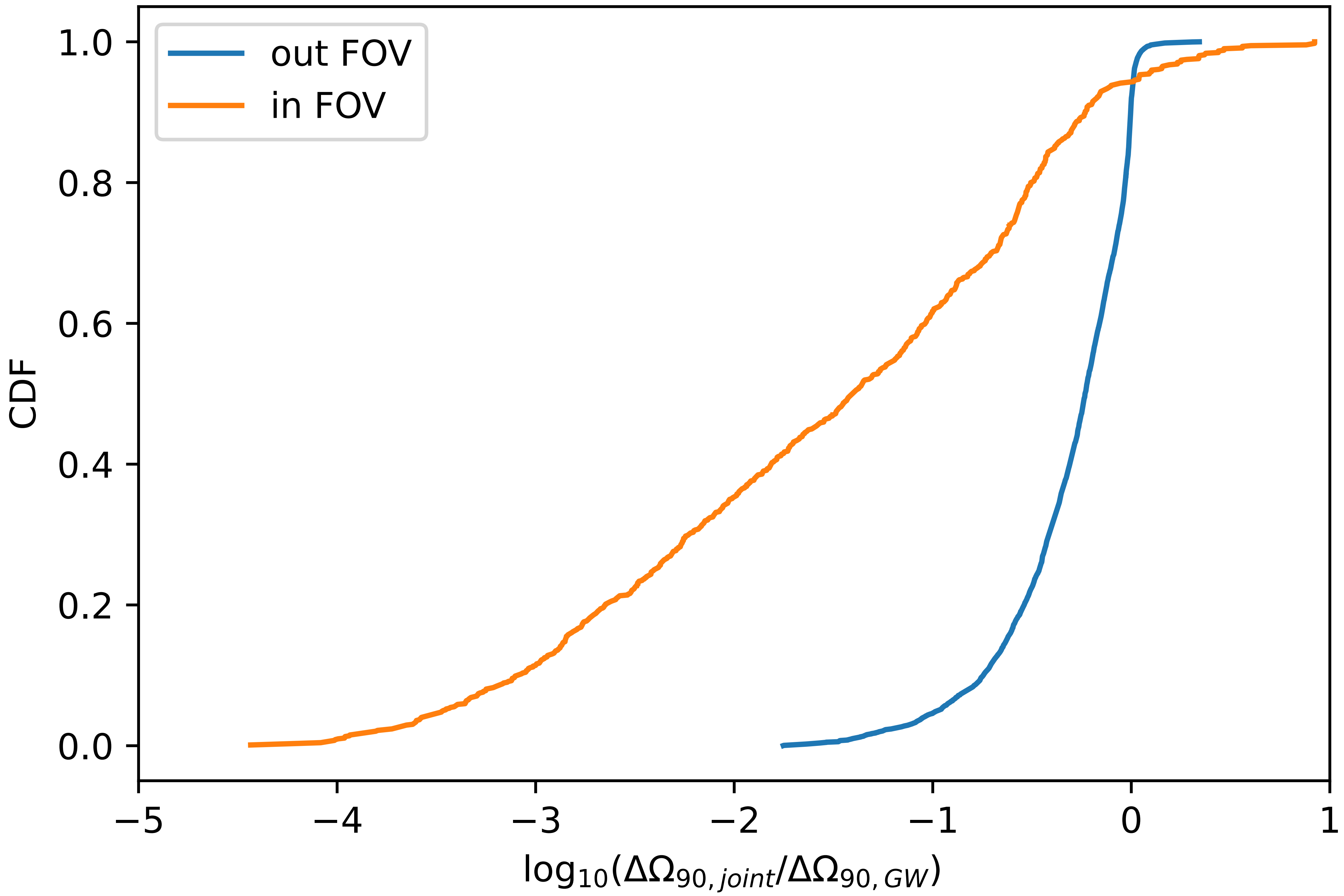
Simulation performed **injecting BNS mergers in the same sky location of GRBs** already analyzed by NITRATES:

- Assuming **O4 sensitivity** for H1-L1-V1
- Considering **3 GW detectors online** —> improvement even better if less detectors are online
- The plot on the right excludes all the cases where the burst is localized by NITRATES to a single position

Example of joint GW+NITRATES map



Average improvement obtained combining GW+NITRATES skymaps



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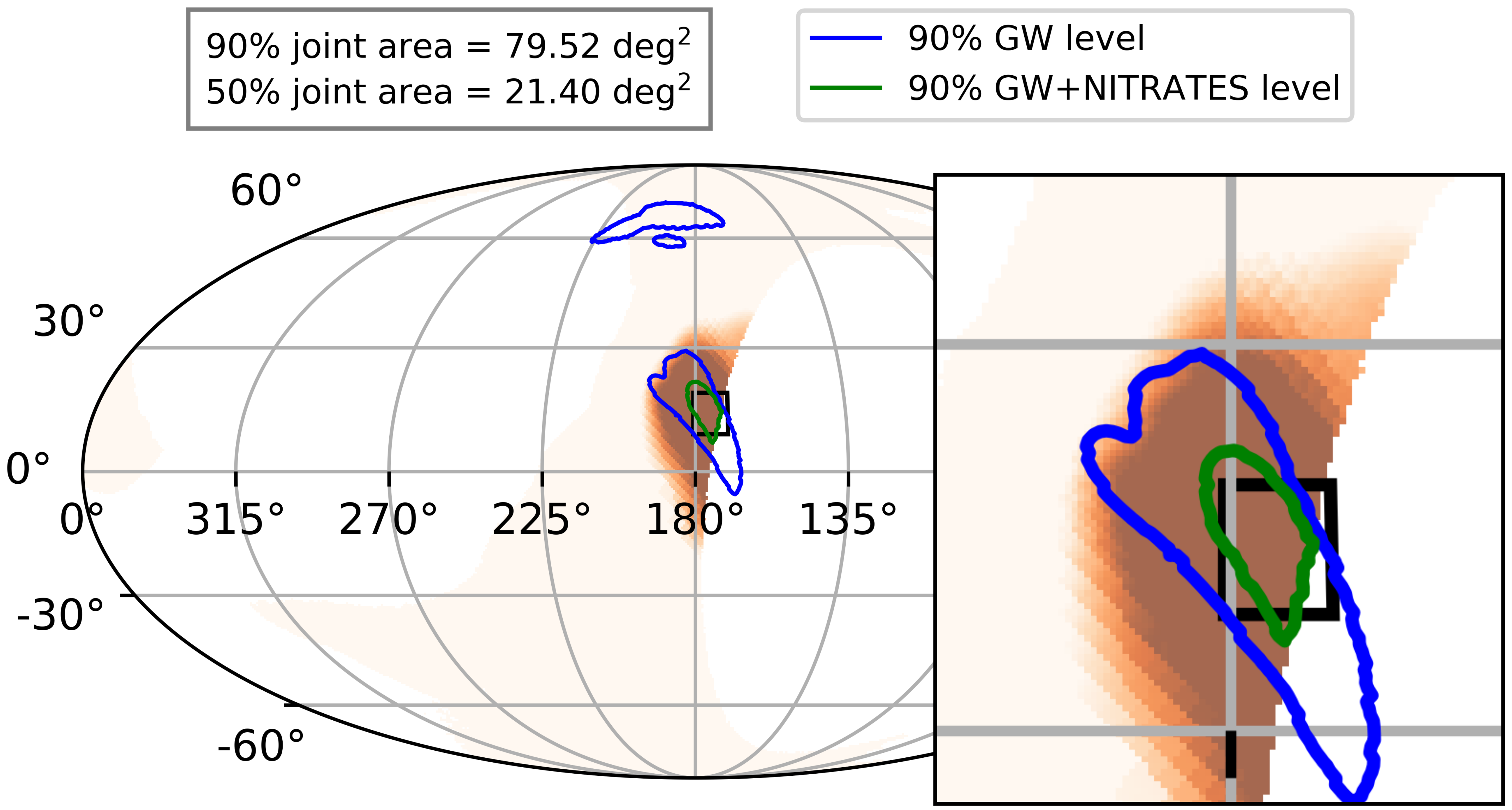

Joint PP plot