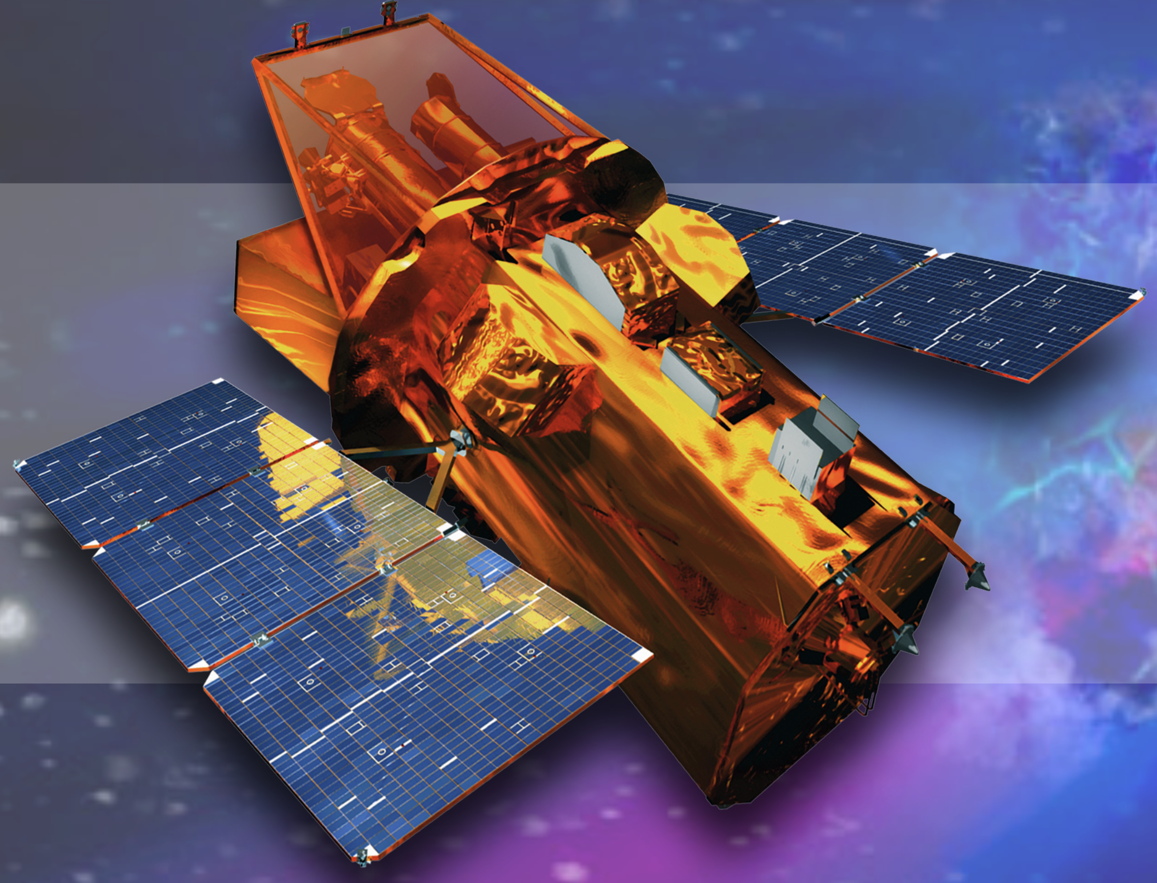
The impact of *Swift* on gravitational wave astronomy



Samuele Ronchini

Postdoc @ Swift Mission Operation Center,
PennState University

Member of the LIGO-Virgo-Kagra collaboration
Member of the Einstein Telescope collaboration
Coordinator of the LVK-Fermi-Swift liaison

PennState

Angular and instrument dependency of detetectability of NS mergers

BAT - XRT - UVOT

BAT - XRT - UVOT

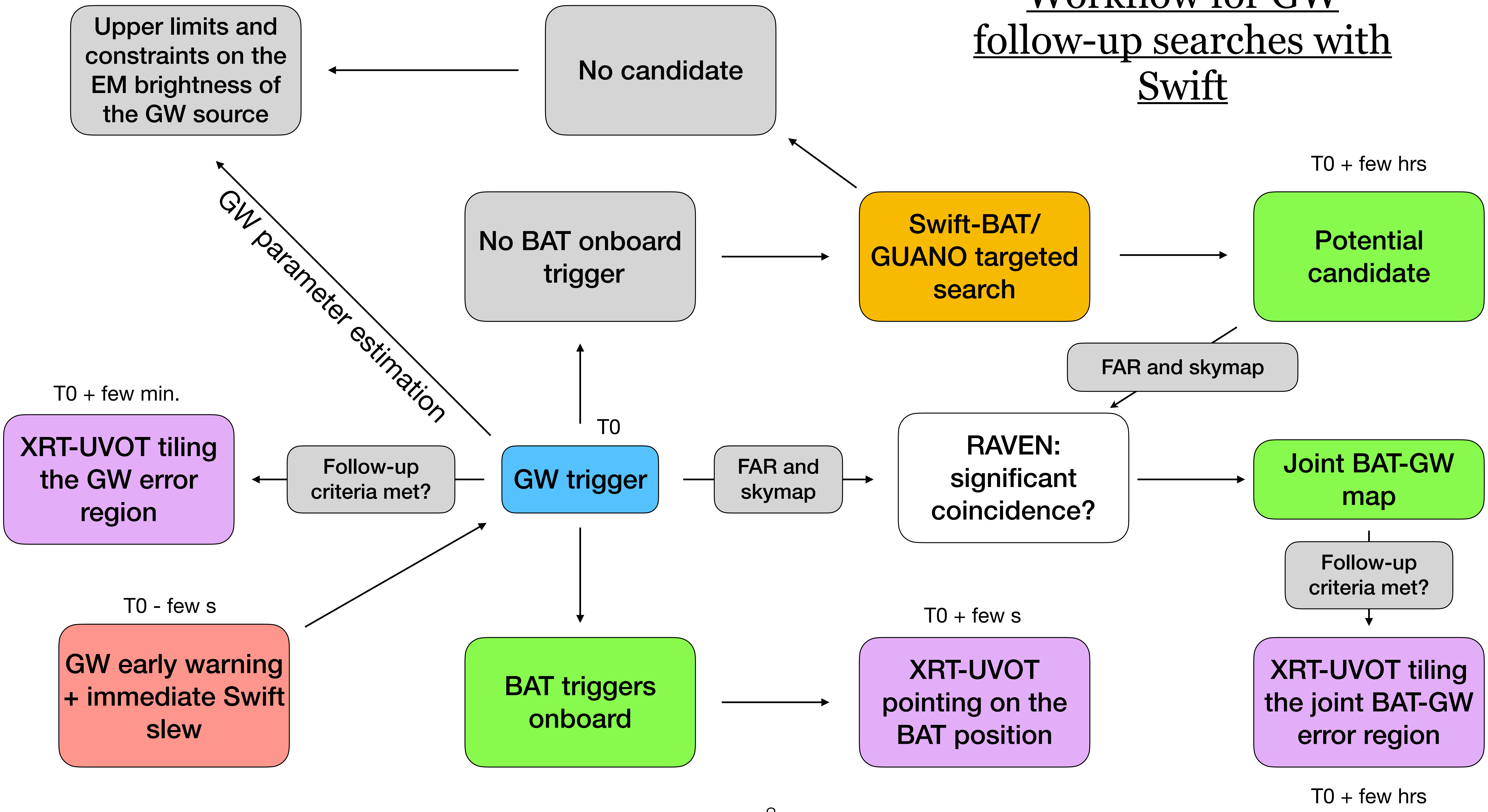
BAT - XRT - UVOT

— detectable

— possibly detectable

— non detectable

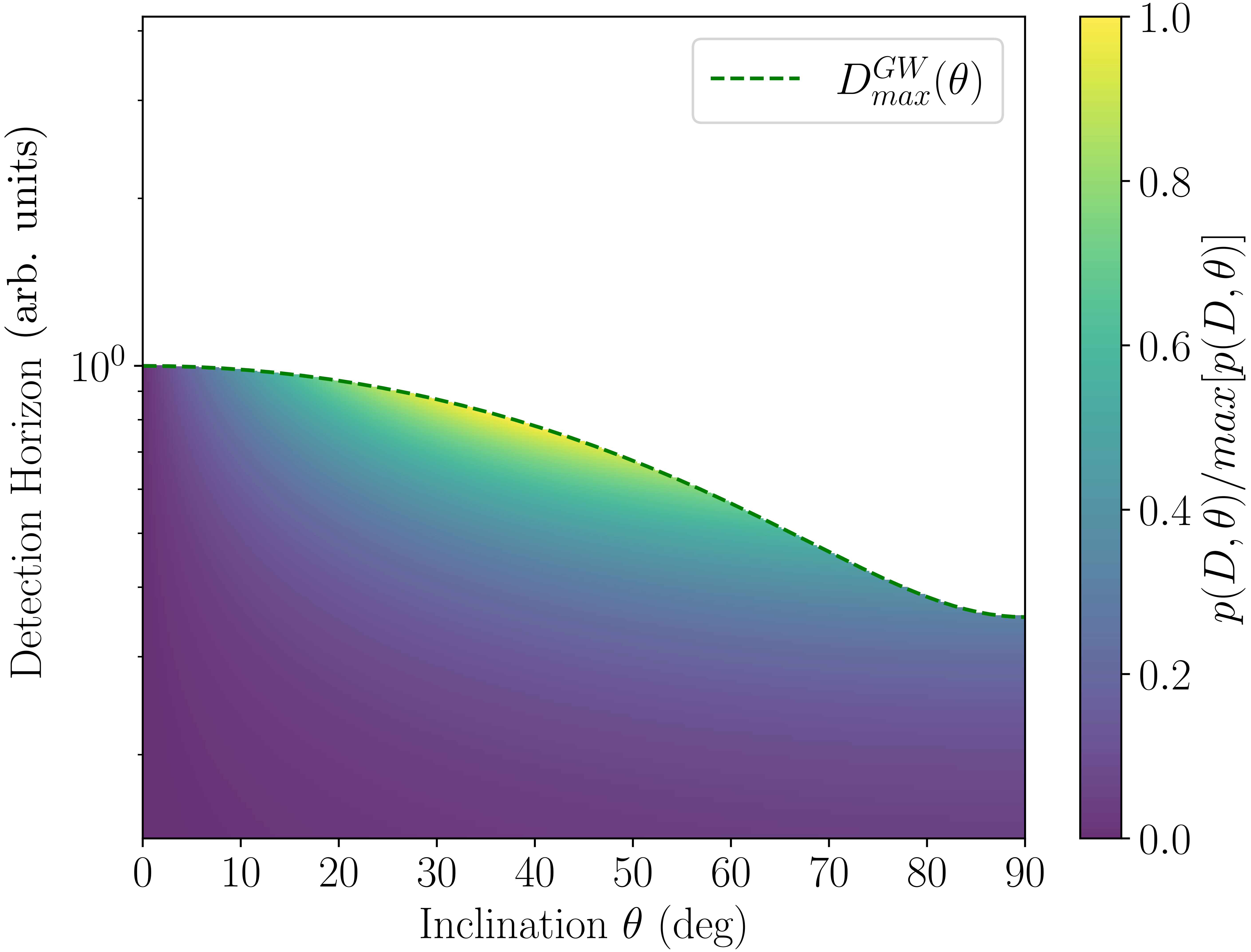
Workflow for GW follow-up searches with Swift



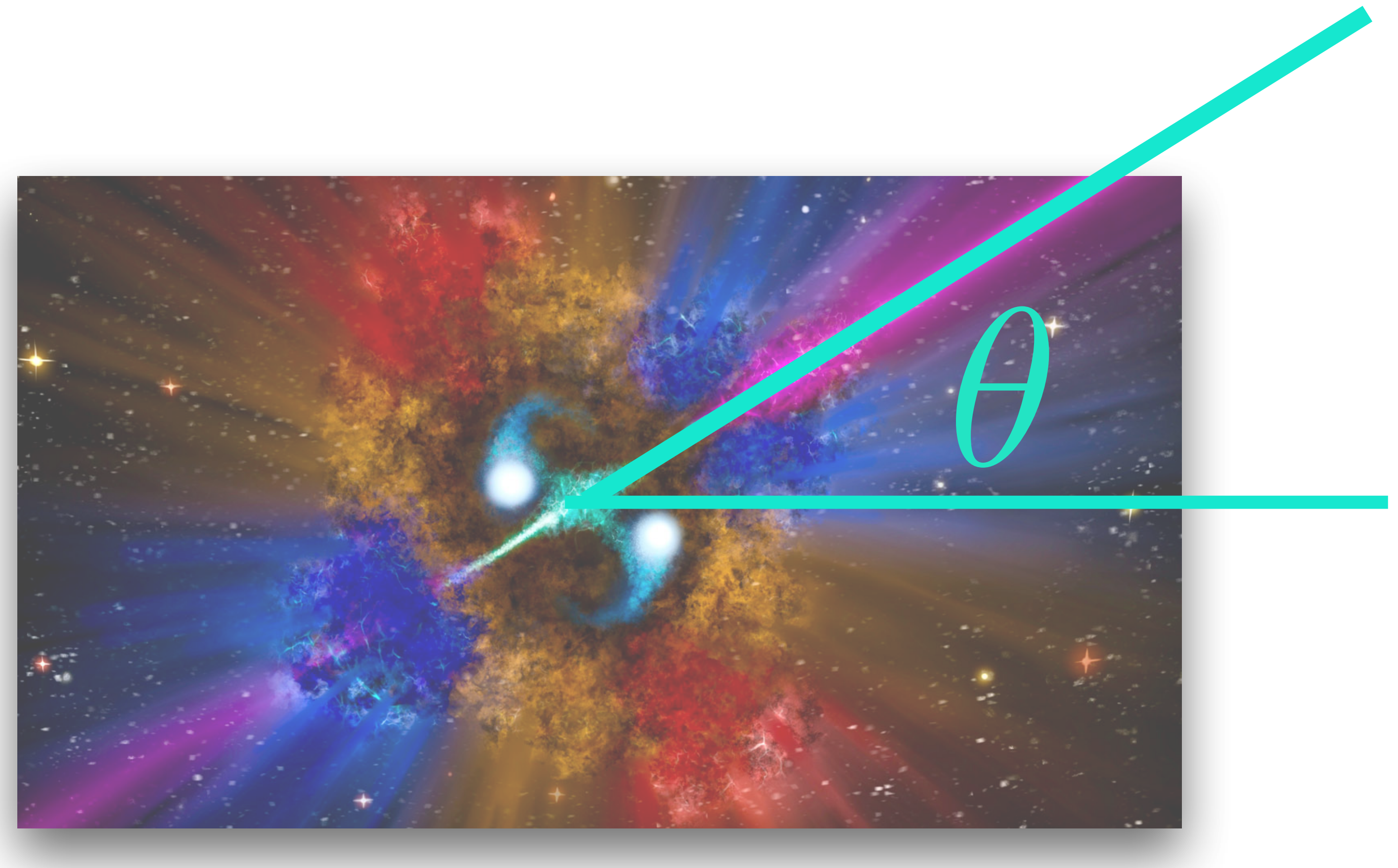
Few ingredients for a joint GW-EM detection

The GW detection space

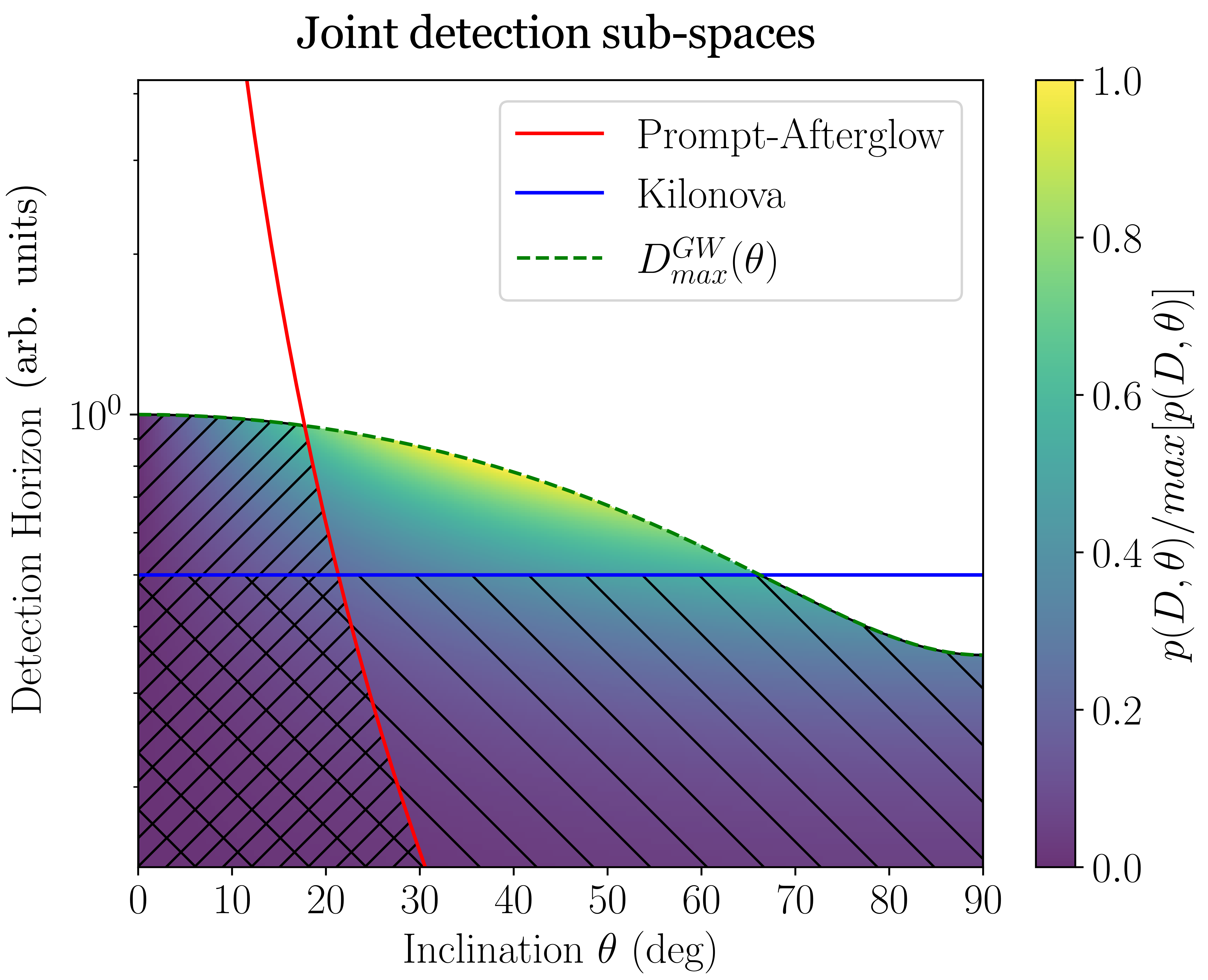
Prior distribution of detectable GW sources



Given a CBC class (i.e., BNS, NSBH…), let us consider the prior distribution of GW parameters, after we impose a detection cut



The EM detection space

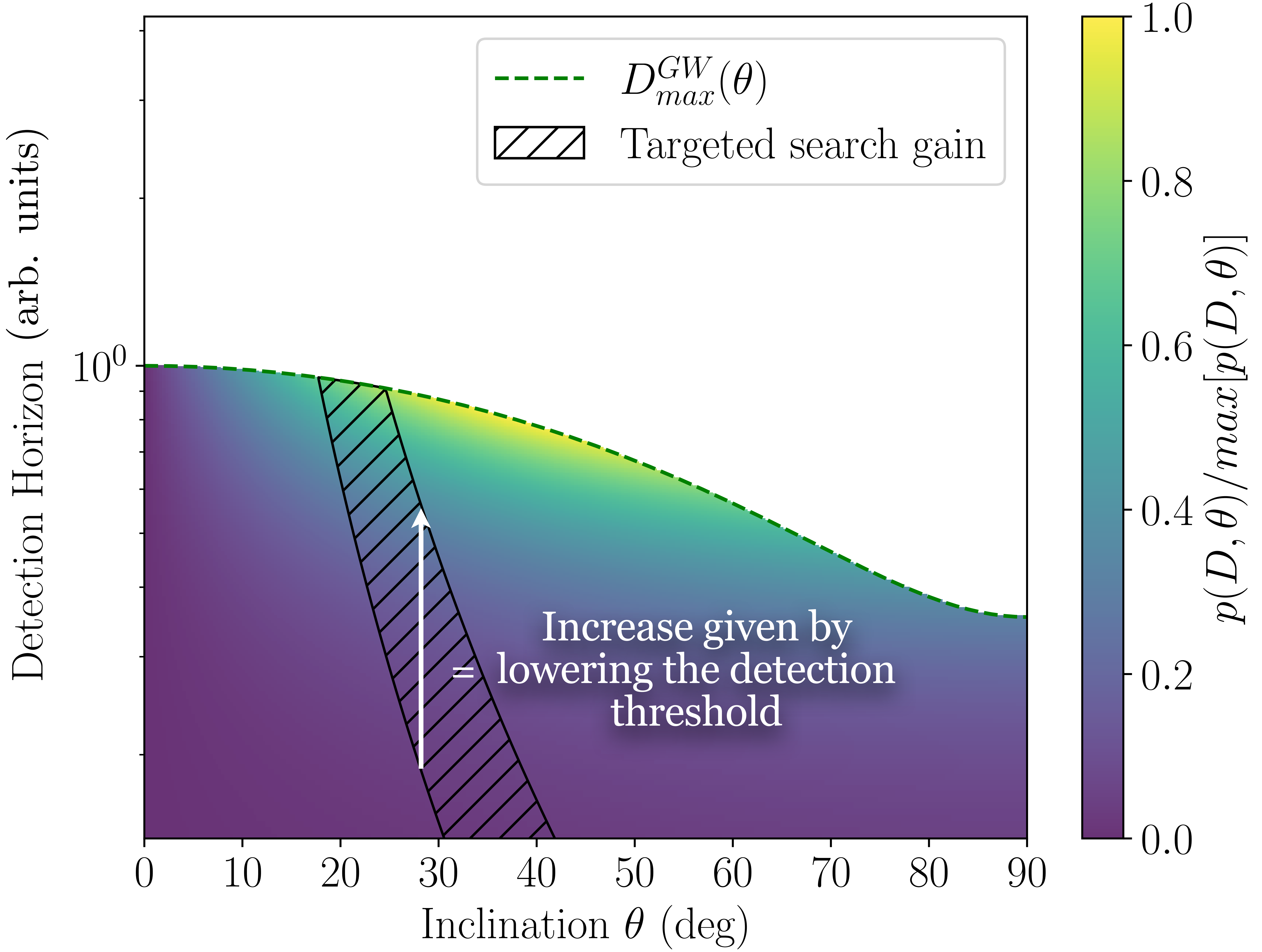


Let's add detection cuts for different EM components

The hatched areas show those sub-regions of the parameter space where a joint GW+EM detection is attainable

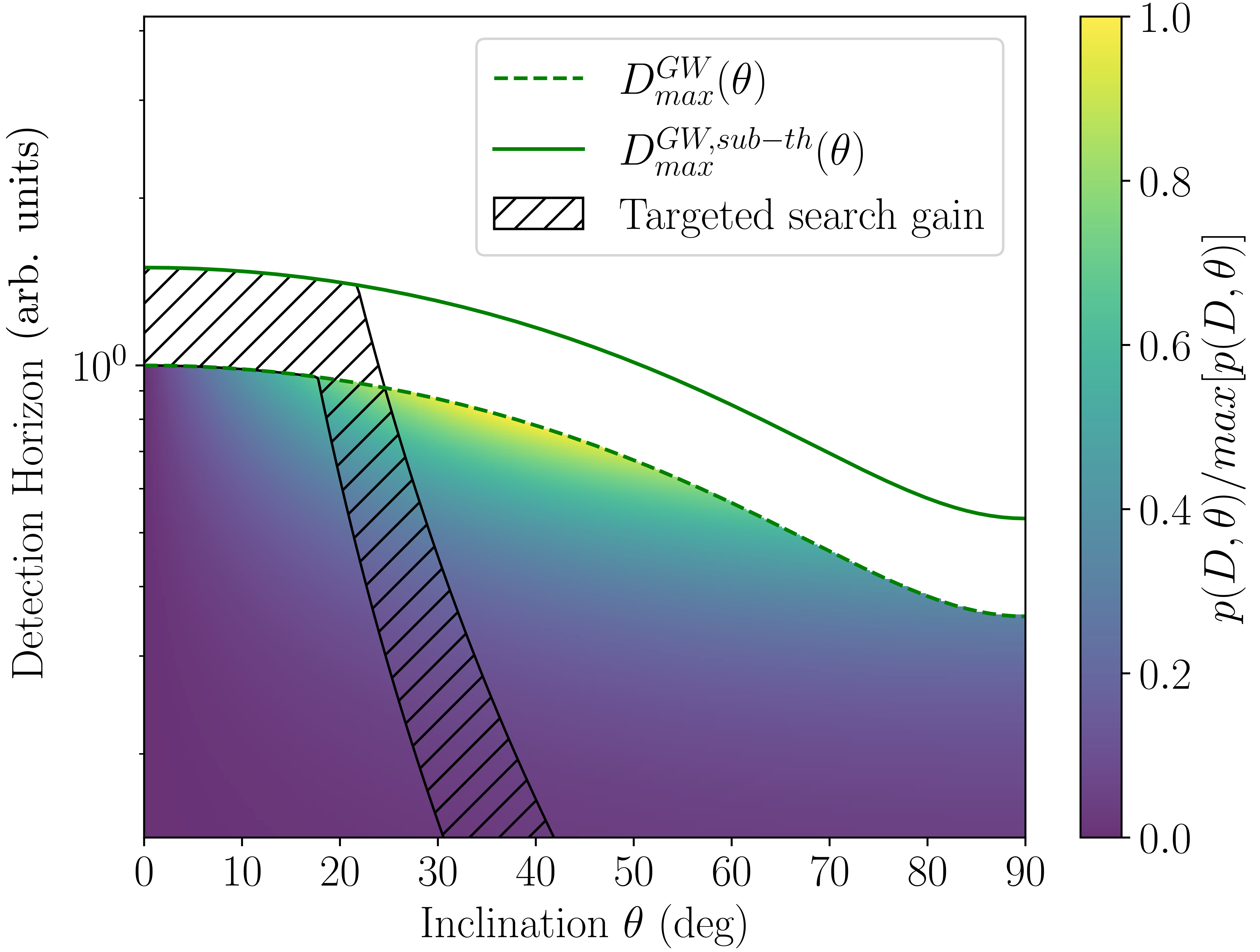
The probability peak is outside the joint detection space!!

Let's focus on the γ-ray emission



Going deeper brings an overall increase in the detection horizon

Let's focus on the γ-ray emission



Going deeper brings an overall increase in the detection horizon

The increase is even larger if the γ-ray search is targeted both on above- and sub-threshold GWs

Sub-threshold γ-GW searches

Enabled by the Swift-BAT/ GUANO infrastructure

Tohuvavohu+20

Performed 24/7 by the NITRATES pipeline

DeLaunay+22

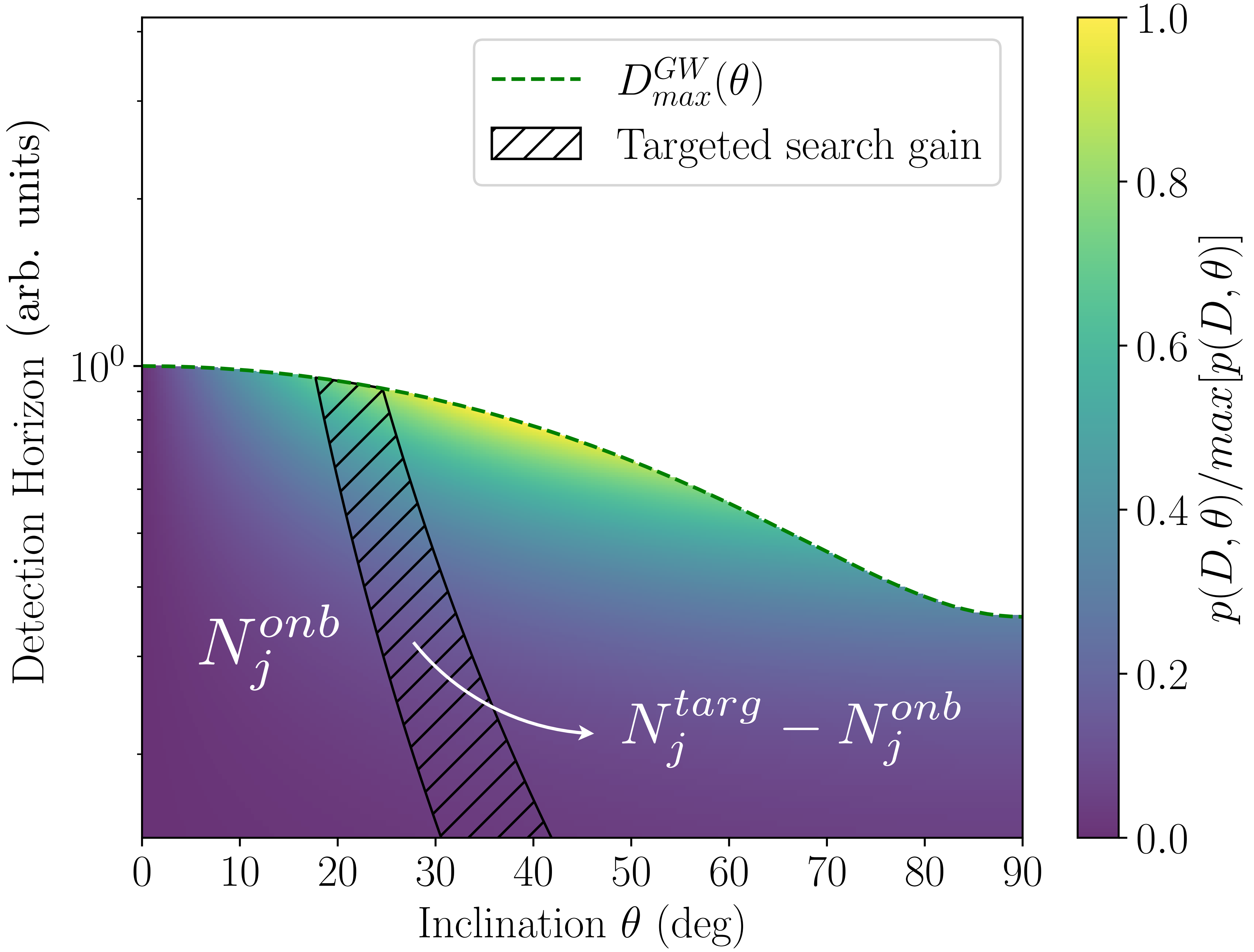
Details presented in Jimmy DeLaunay's talk

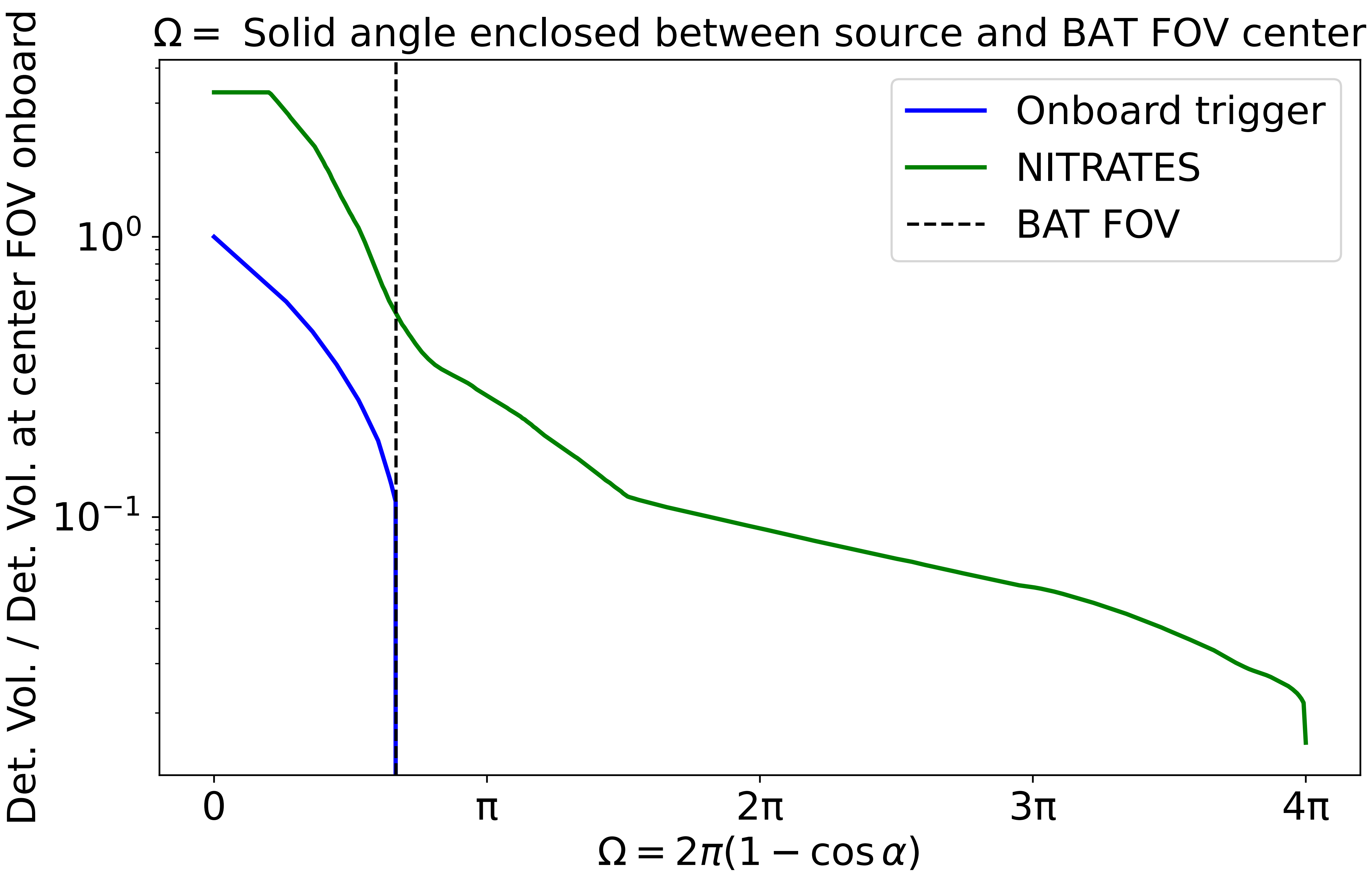
Some numbers

During O3 and O4 NITRATES analyzed an amount of GW triggers that would have required…

… ~ **220 yr on a single CPU**

What we gain going sub-threshold in γ?





Gain given by Swift-BAT/GUANO with respect to onboard joint detections

$L \ll 4\pi (D_{max}^{GW})^2 min(F_{lim}(\Omega))$

$$\frac{N_j^{targ} - N_j^{onb}}{N_j^{onb}} = 414\%$$

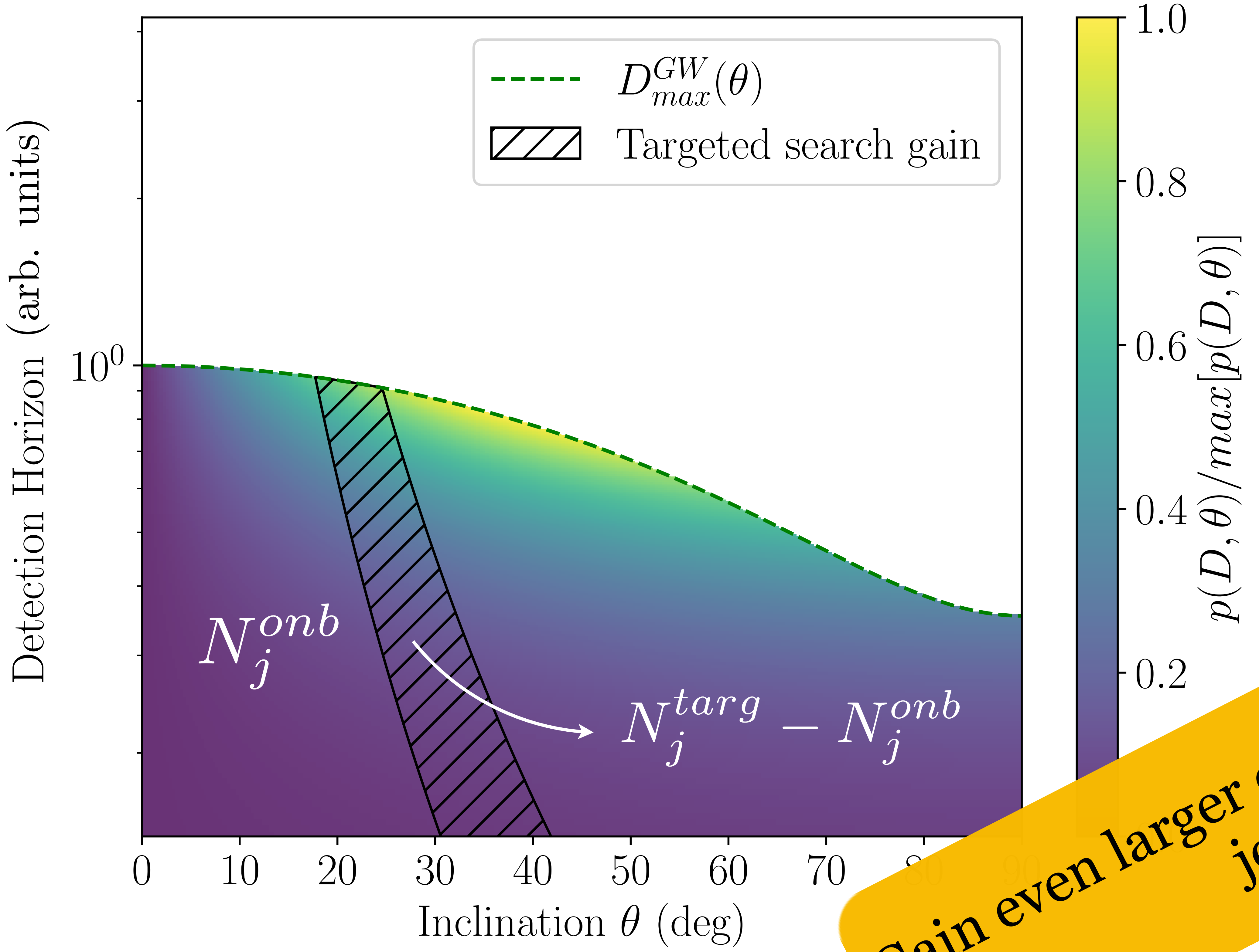
Structured jet $L(\theta) \sim \theta^{-k}, \theta > \theta_c$

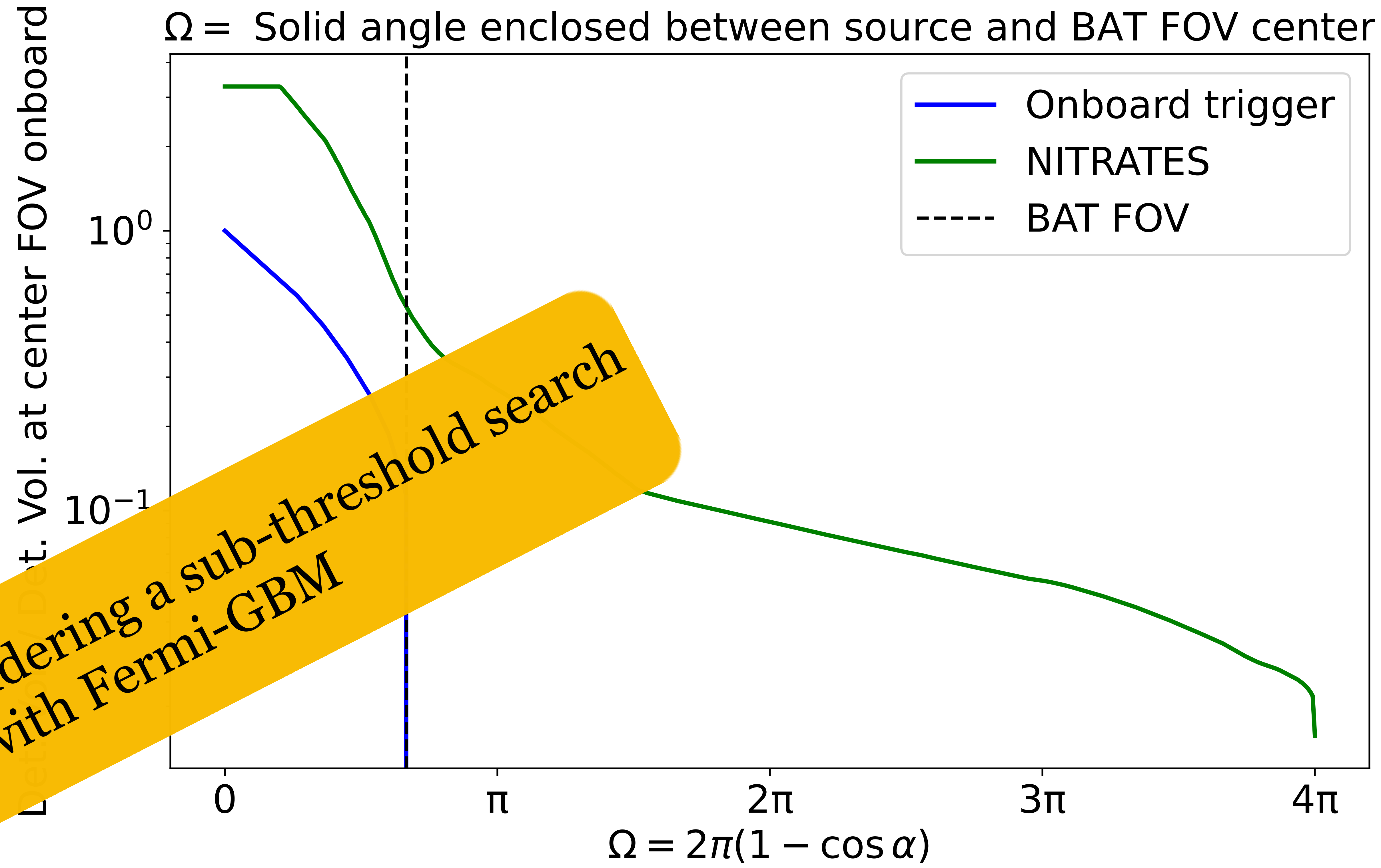
$$\frac{N_j^{targ} - N_j^{onb}}{N_j^{onb}} = 380\%$$

$L \gg 4\pi (D_{max}^{GW})^2 max(F_{lim}(\Omega))$

$$\frac{N_j^{targ} - N_j^{onb}}{N_j^{onb}} \rightarrow \frac{4\pi}{FOV} - 1$$

What we gain going sub-threshold in γ?





Gain even larger considering a sub-threshold search joint with Fermi-GBM

Gain given by Swift-BAT/GUANO with respect to onboard joint detections

$L \ll 4\pi (D^{GW}_{max})^2 min(F_{lim}(\Omega))$

$$\frac{N^{targ}_j - N^{onb}_j}{N^{onb}_j} = 414\%$$

Structured jet $L(\theta) \sim \theta^{-k}, \theta > \theta_c$

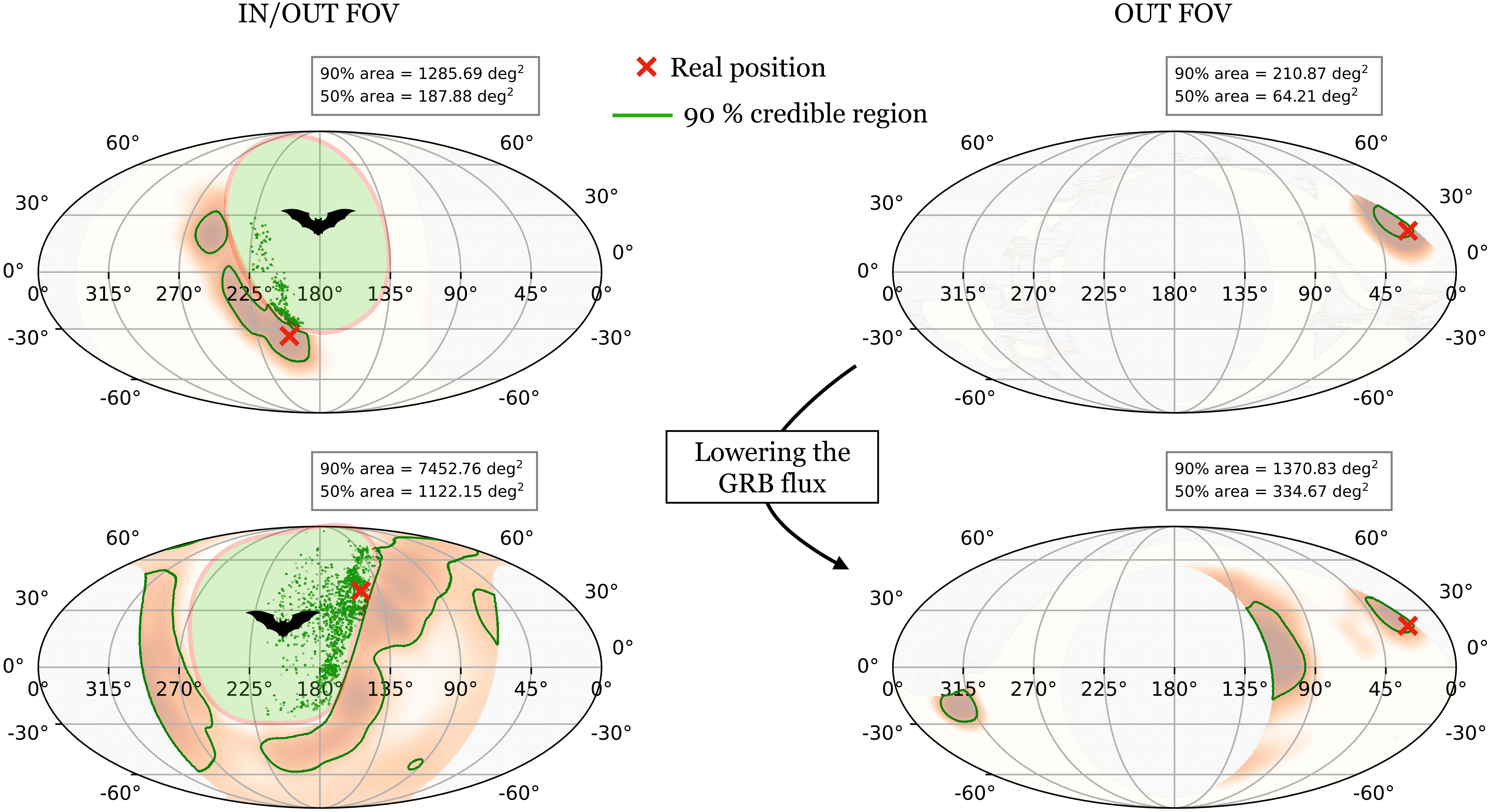
$$\frac{N^{targ}_j - N^{onb}_j}{N^{onb}_j} = 380\%$$

$L \gg 4\pi (D^{GW}_{max})^2 max(F_{lim}(\Omega))$

$$\frac{N^{targ}_j - N^{onb}_j}{N^{onb}_j} \rightarrow \frac{4\pi}{FOV} - 1$$

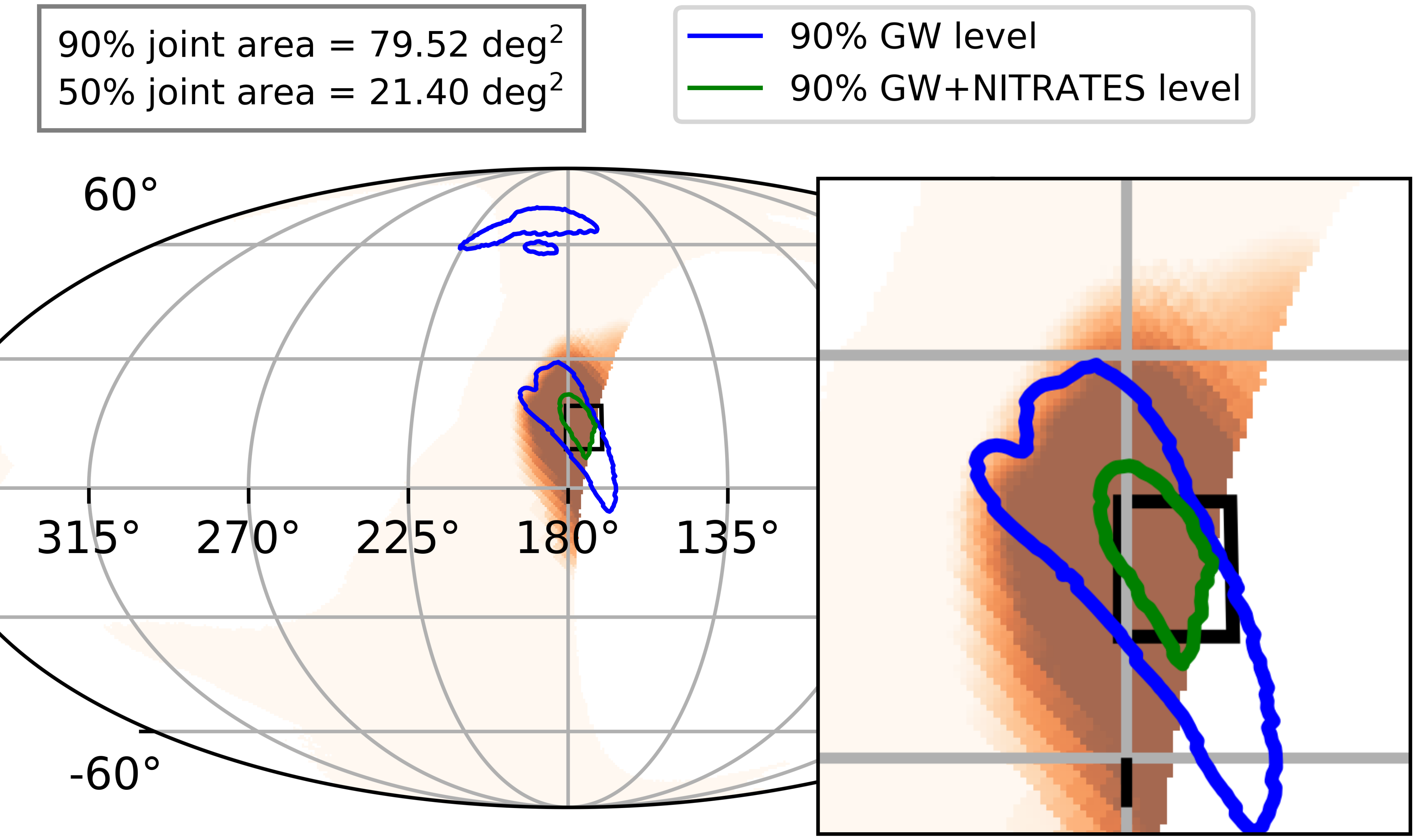
NITRATES sky localization maps

DeLaunay, S.R. + (in prep.)

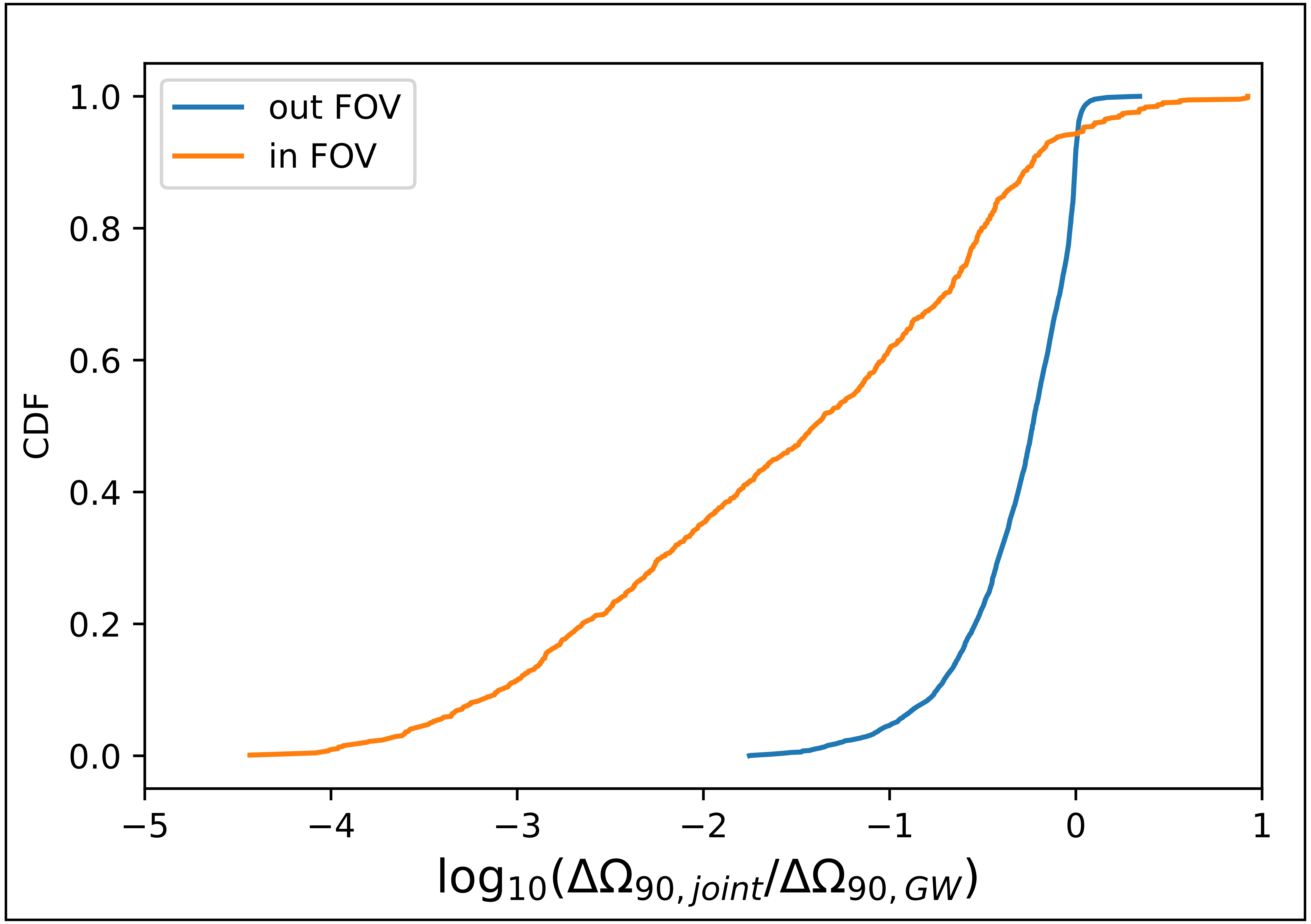


NITRATES sky localization maps combined with GW ones

Example of joint GW+NITRATES map



Shrinking of the GW 90% area, including NITRATES localization



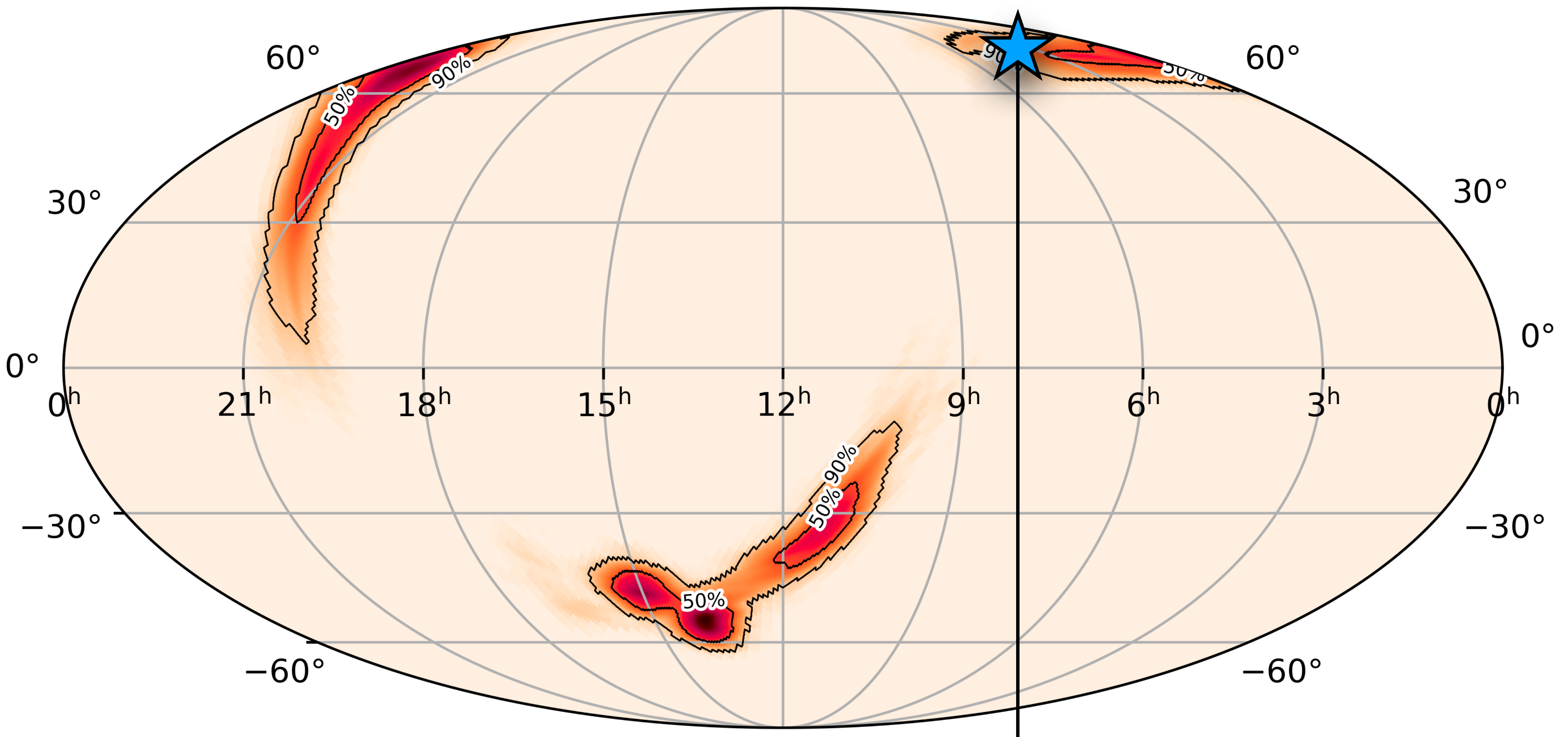
The estimate is conservative, since it assumes 2 LIGO + Virgo online, and @ design sensitivity

Plausibly, real GW 90% areas are larger than the simulated ones, so the <u>improvement given by NITRATES map could be even better</u>

NITRATES sky localization maps combined with GW ones

GW-γ sky overlap essential to assess the significance of possible joint coincidences

Example: S241125n (high-significance BBH)



- Sub-threshold NITRATES candidate 11 s after the merger
- 84% of the NITRATES sky localization probability is inside 5 arcmin around the peak position (blue star). The remaining 16% is spread around the sky

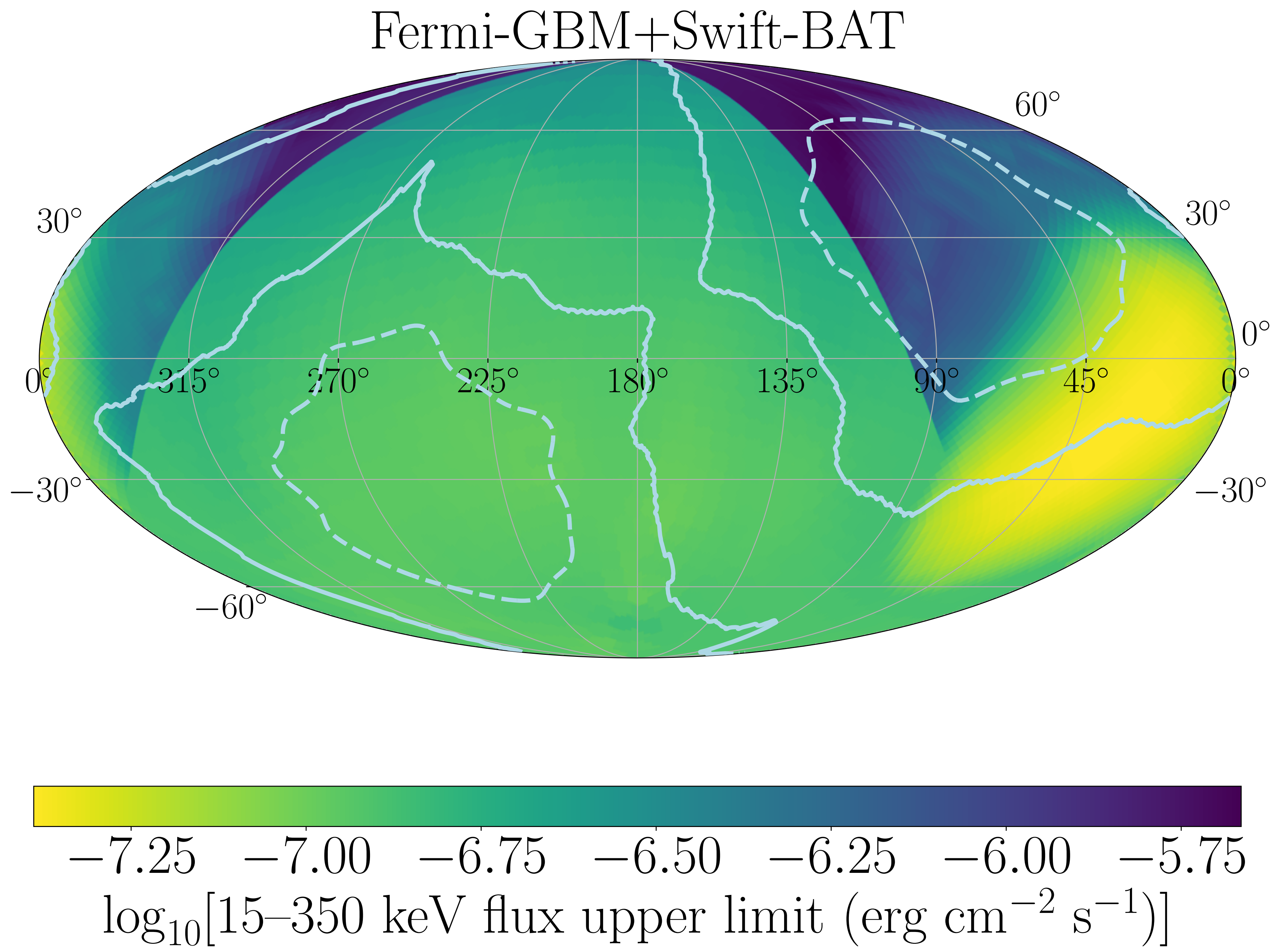
Joint FAR ~ $R_{GW} \times FAR_{\gamma} \times \frac{\Delta t}{I_{\Omega}}$ ~ 1 / 6 yr

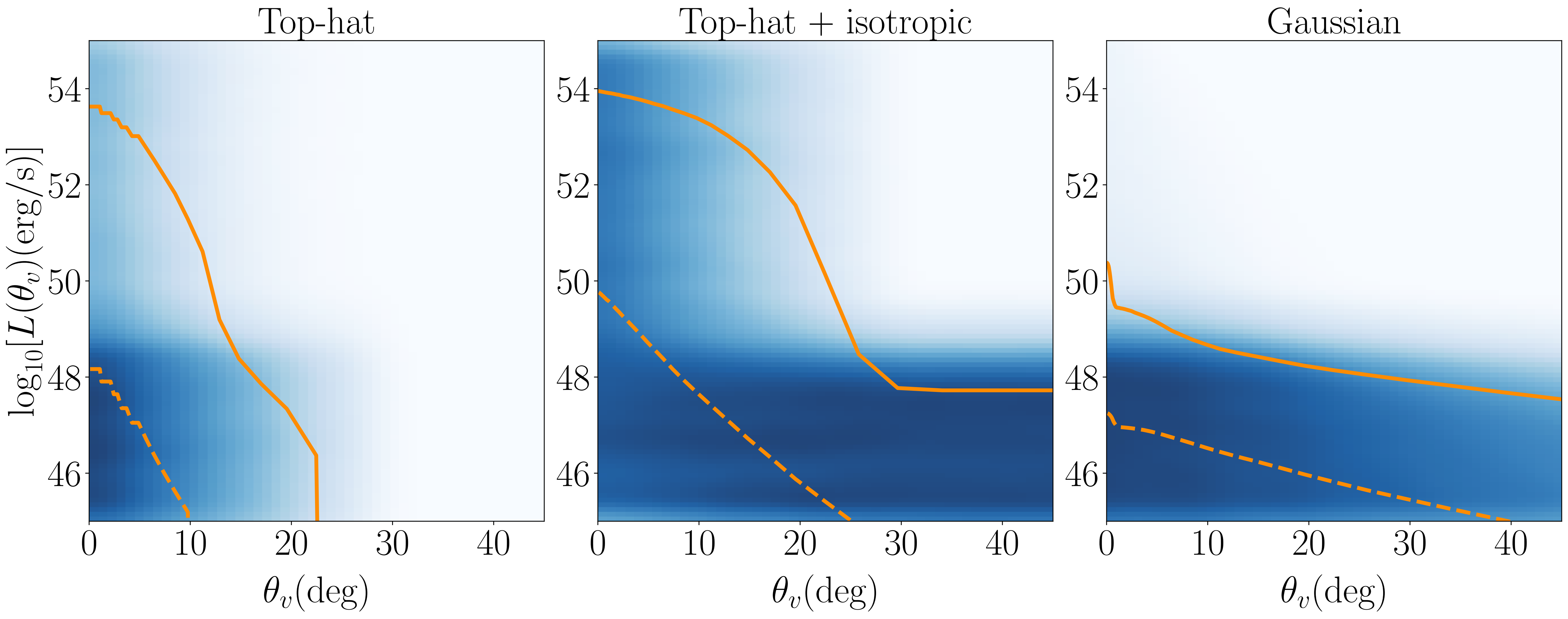
Overlap between GW and γ skymaps

Exploit the non-detection: GW230529

Ronchini+2024

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





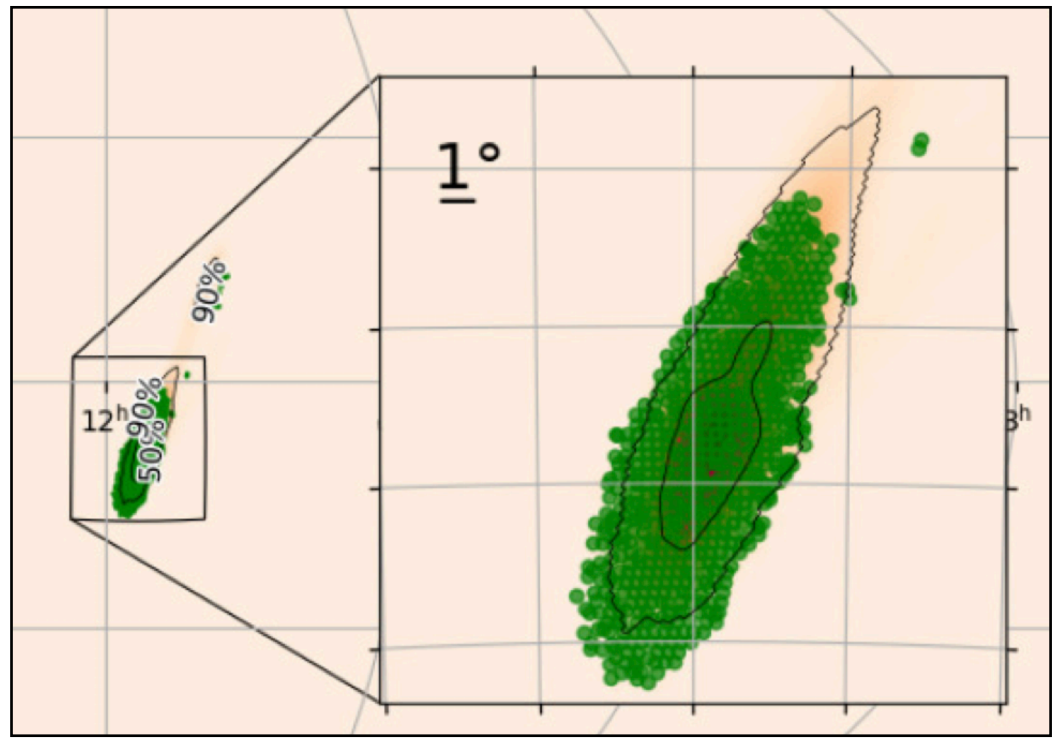
Angle dependent constraints on the apparent luminosity structure of the merger

Combined with GW posteriors

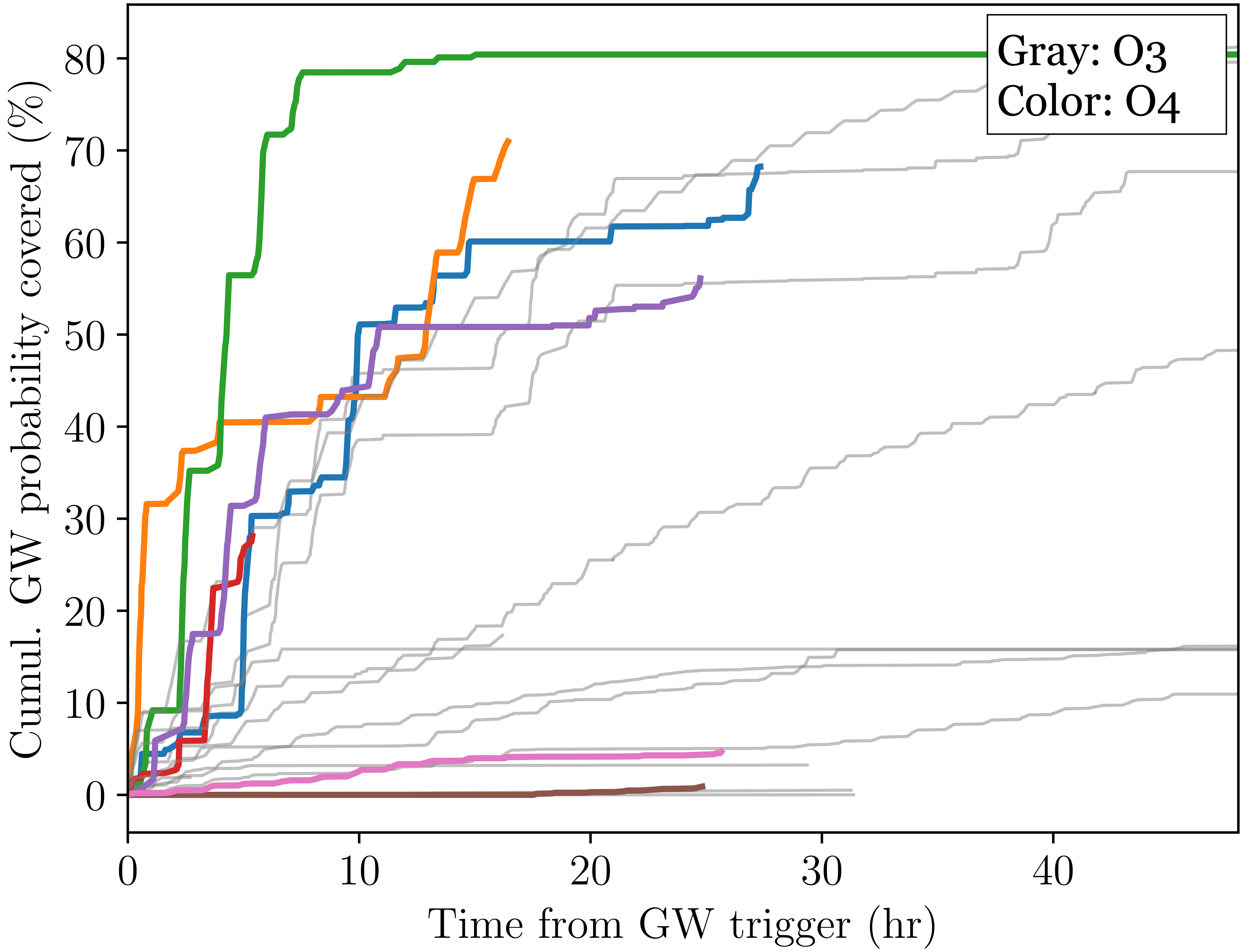
$$P_{GW}(\theta_v, D_L)$$

Follow up with *Swift* XRT/UVOT

XRT/UVOT follow-up



Page+20
Klingler+19



	MAX FAR	MAX DISTANCE	MAX 90% AREA
P_disrupt =0	1/10 yr	/	30 deg²
P_disrupt <0.5	1/90 days	150 Mpc	300 deg²
P_disrupt >0.5	1/90 days	400 Mpc	300 deg²
Bursts	1/yr	/	/
Sub-Solar Mass	1/2yr	400 Mpc	300 deg²

Evans+16

- The ordering and selection of fields 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
- For potentially bright GW sources, exposure optimized to maximize detection chance for Kilonova

Eyles-Ferris, ..., S.R.+24

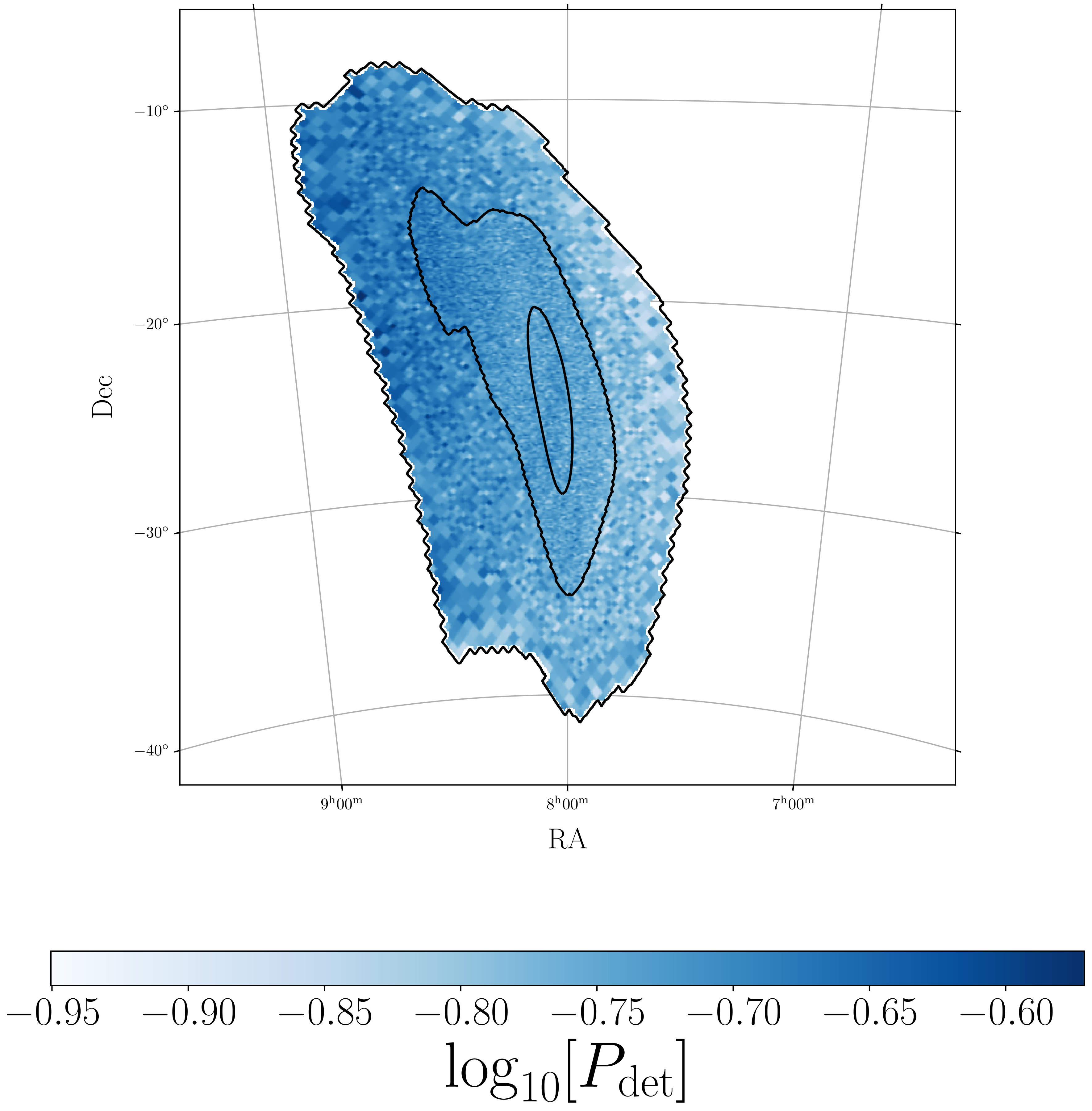
Can we optimize even more?

Possibly YES!! Using posterior distributions from GW parameter estimation

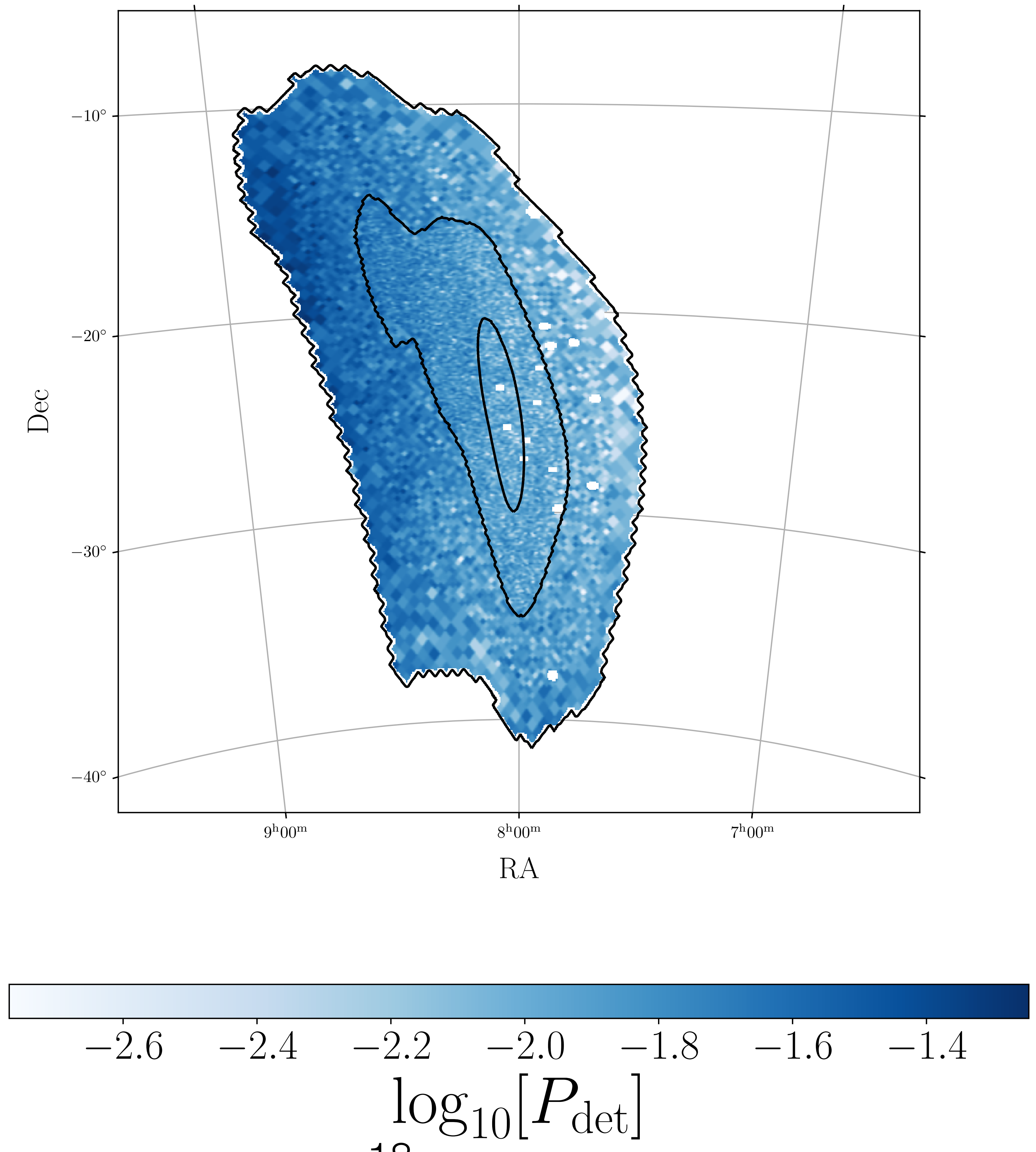
Re-weight

$$\vec{\theta}_{GW} \to P(Flux|t, D_L, RA, Dec) \quad P_{det}(t, D_L, RA, Dec) = \int_{F_{lim}}^{\infty} P(Flux) \qquad \mathcal{P}\left(g \mid P_p(D)\right) \to \mathcal{P}\left(g \mid P_p(D)\right) \times P_{det}(g, t)$$

1 day



3 days



Example done for an NSBH candidate where the chirp mass is known at 10% precision.

Info on chirp mass used to estimate brightness and peak time of the transient

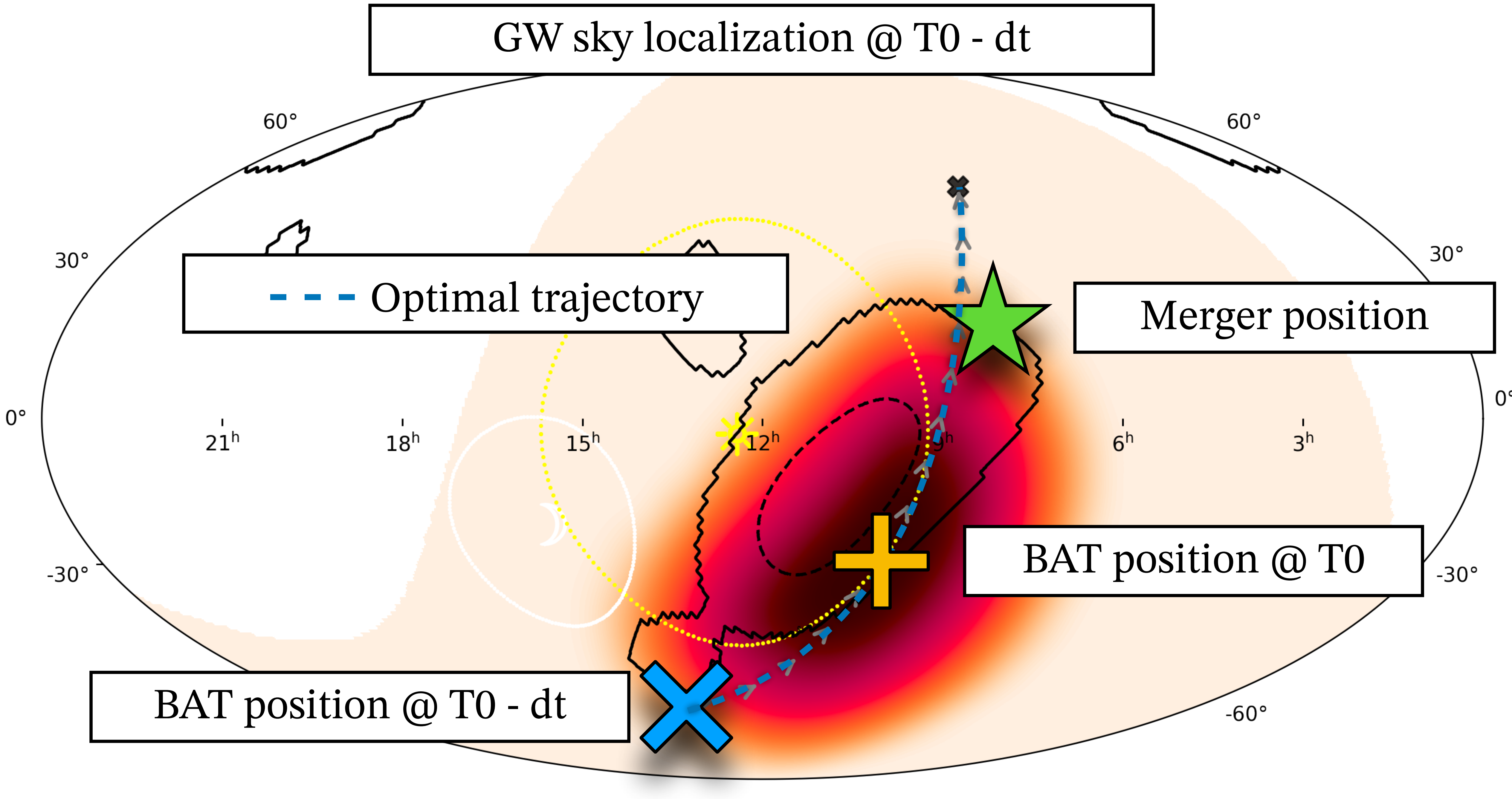
For a given time, the darker regions are the ones with higher chance to have a detectable source

S.R. + (in prep.)

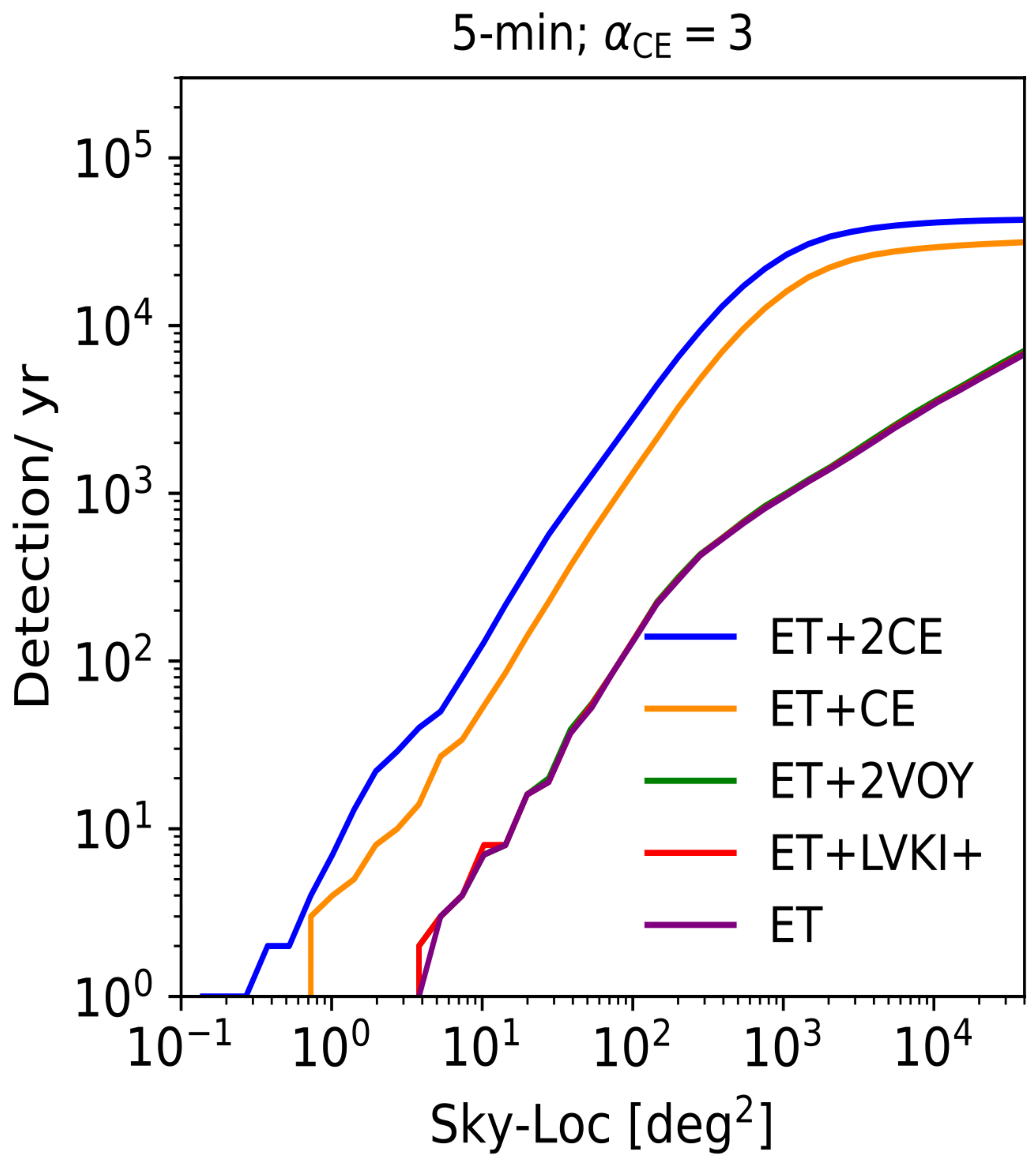
Swift legacy for 3G GW era: pre-merger slew

Concept: in O4-O5 runs, 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**

- 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**
- **Pioneering concept for the 3G GW detectors** (ET and CE) where early warning alerts will happen routinely



Tohuvavohu, …, S.R. +24



~ 10-100 BNS detected / yr with a sky localization better than 10 deg^2 **5 min pre-merger**

Banerjee, …, S.R. +23

Summary

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

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

- NITRATES **sky localization maps crucial** to assess the significance of joint GW-gamma associations

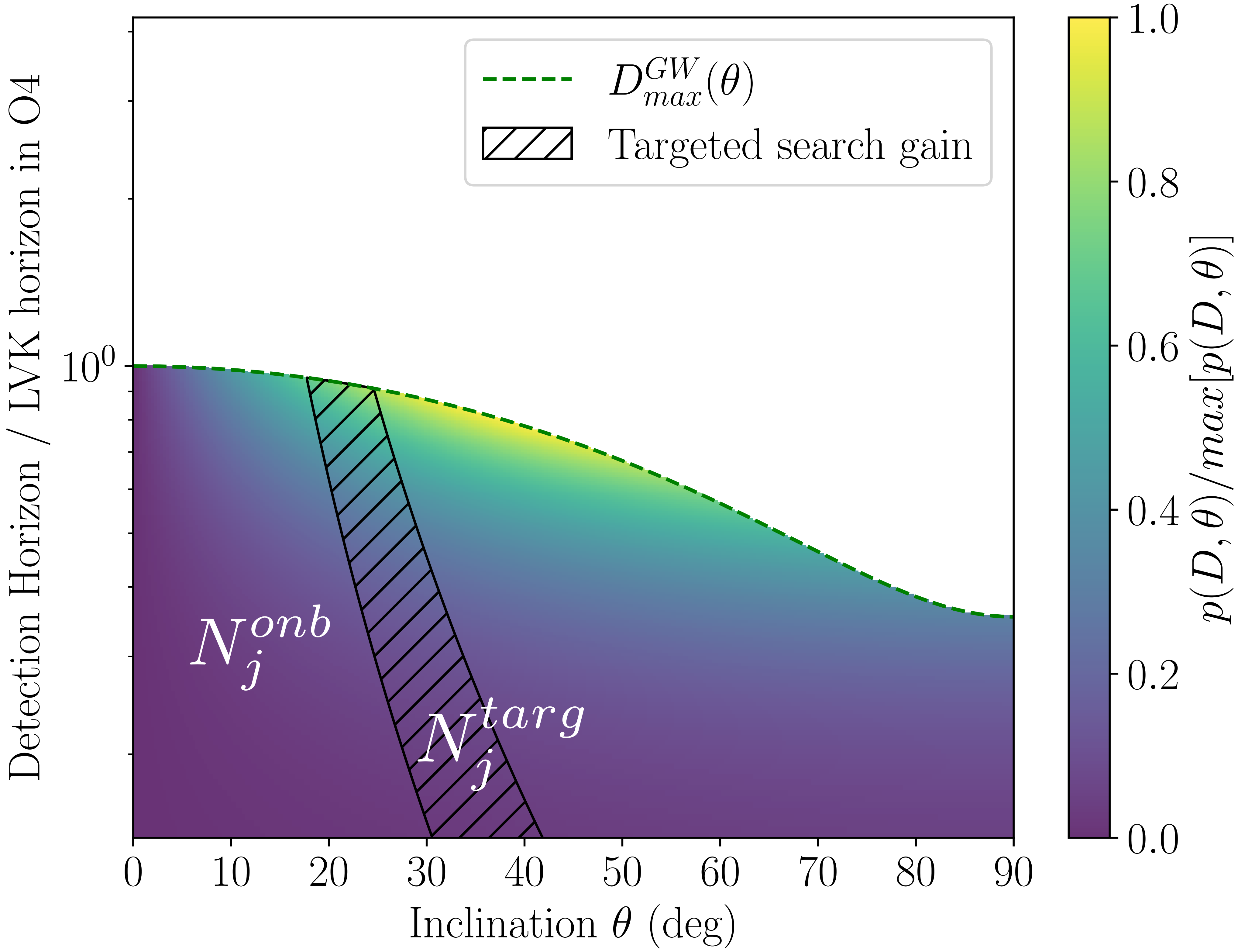
- Even in the case of **non-detection**, e.g. GW230529, we are able to **infer constraints** on the jet luminosity and opening angle, once the flux-upper limits are combined with the GW parameter estimation

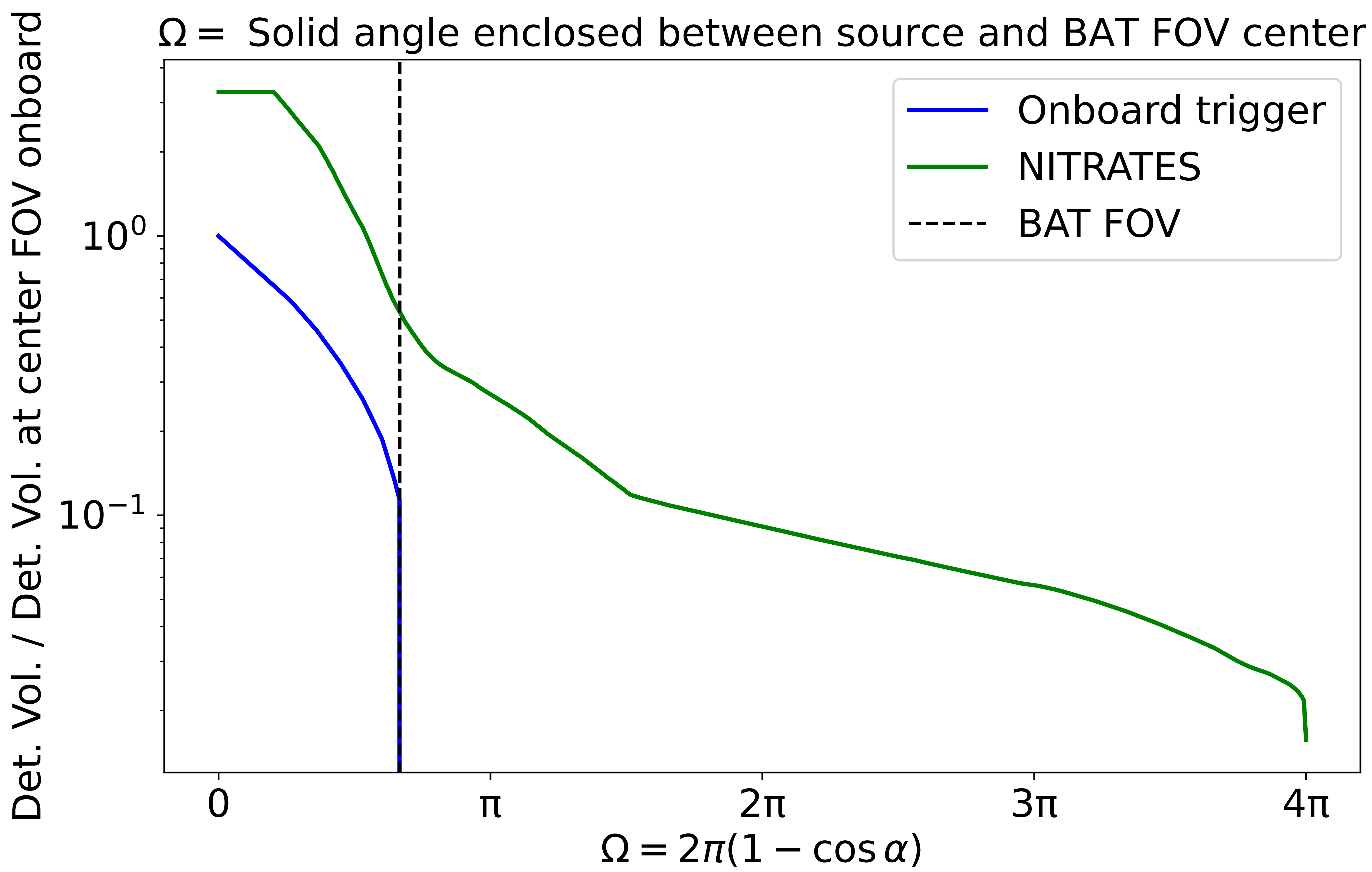
- **Swift XRT/UVOT** tiling follow-up optimized for KN detection, and it **can be even more optimized, if more GW parameters are released publicly in low-latency**

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

BACKUP SLIDES

What we gain going sub-threshold?





Gain given by Swift-BAT/GUANO with respect to onboard joint detections

$L \ll 4\pi(D^{GW}_{max})^2 min(F_{lim}(\Omega))$

$$\frac{N_j^{\rm targ} - N_j^{onb}}{N_j^{\rm onb}} = 400\%$$

Structured jet $L(\theta) \sim \theta^{-k}, \theta > \theta_c$

$$\frac{N_j^{\rm targ} - N_j^{\rm onb}}{N_j^{\rm onb}} = 260\%$$

$L \gg 4\pi(D^{GW}_{max})^2 max(F_{lim}(\Omega))$

$$\frac{N_j^{\rm targ} - N_j^{\rm onb}}{N_j^{\rm onb}} \rightarrow \frac{13}{18}\frac{4\pi}{FOV} - 1 = 333\%$$