Joint detection of BNS mergers in the ET era: the crucial role of Swift-like space missions

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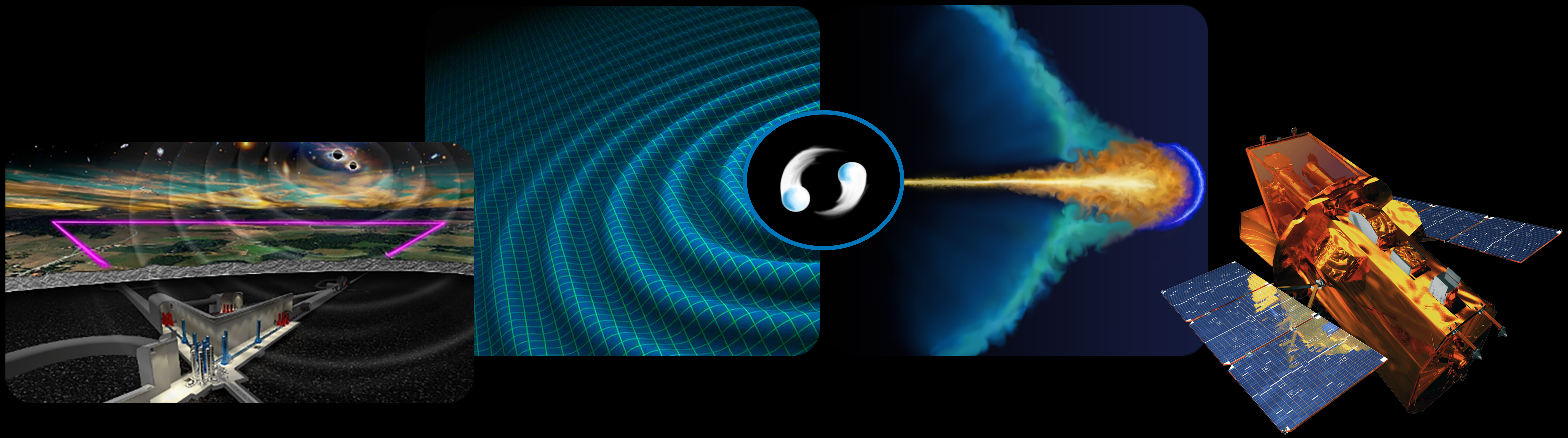
Swift



We acknowledge the INFN Computing Center of Turin for computational resources

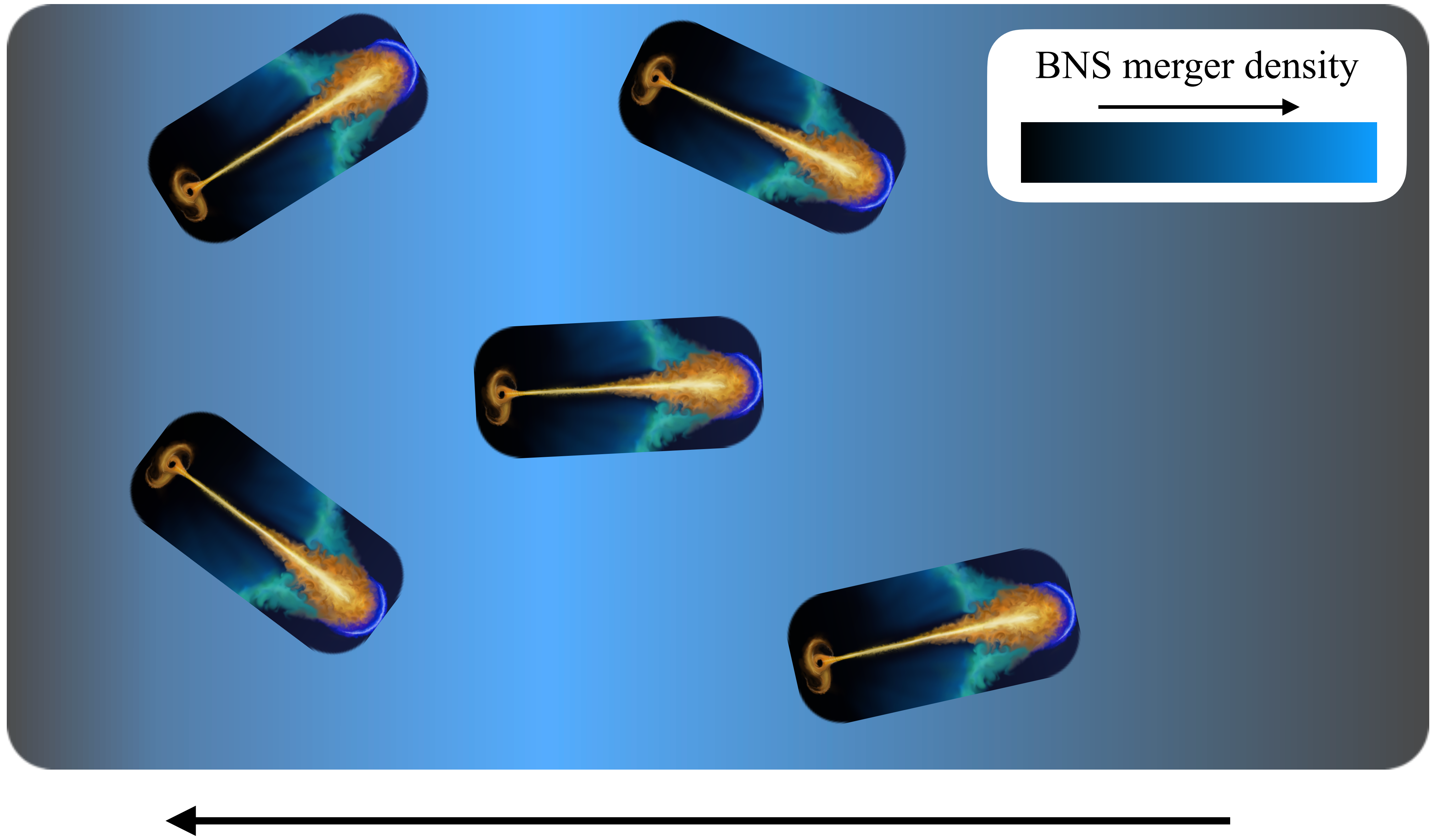
Overview

Goal of this work:

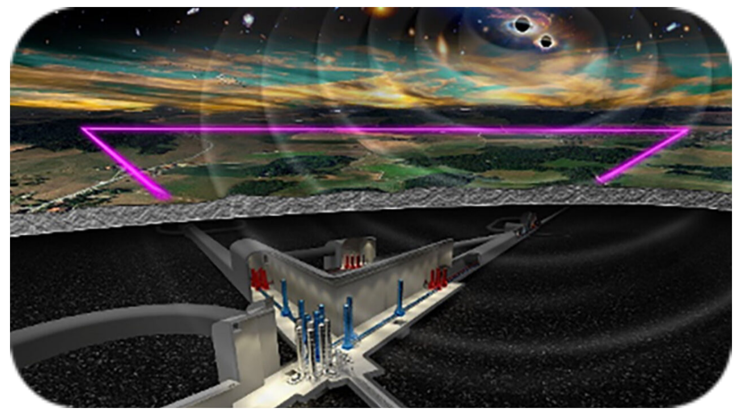
Provide an exhaustive overview about the **joint detection** of:

1. **gravitational waves (GWs)**
2. Electromagnetic (EM) counterpart in the **high energy domain**

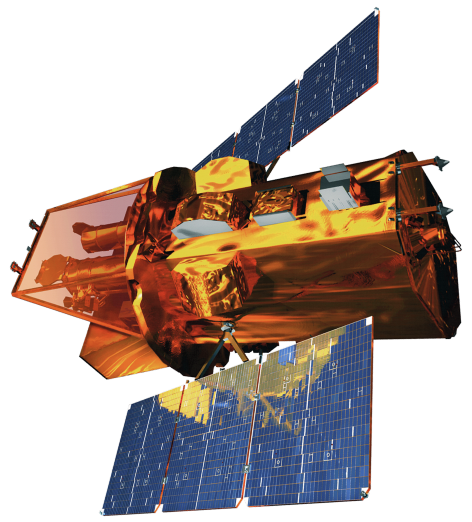
from the coalescence of **NS binaries**, in the era of **3G GW detectors**



Redshift



GW

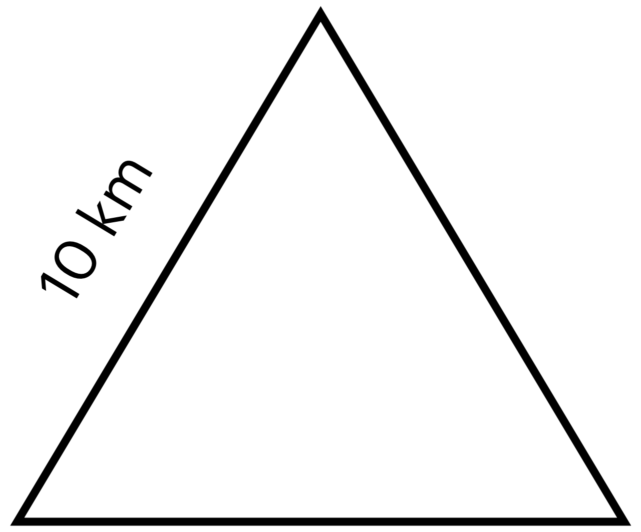


EM

Relevance of this work:

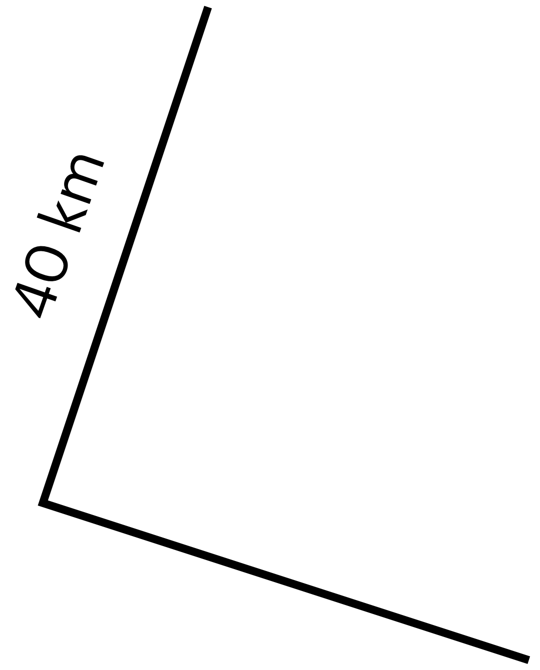
- Highlight the **role of wide field space telescopes** for the identification of the EM counterpart
- Evaluate the **scientific return** of future GW-EM synergies
- **Define the best technical design** of future GW and EM instruments, to optimally achieve the multi-messenger science goals

The 3rd generation of GW detectors: steps forwards



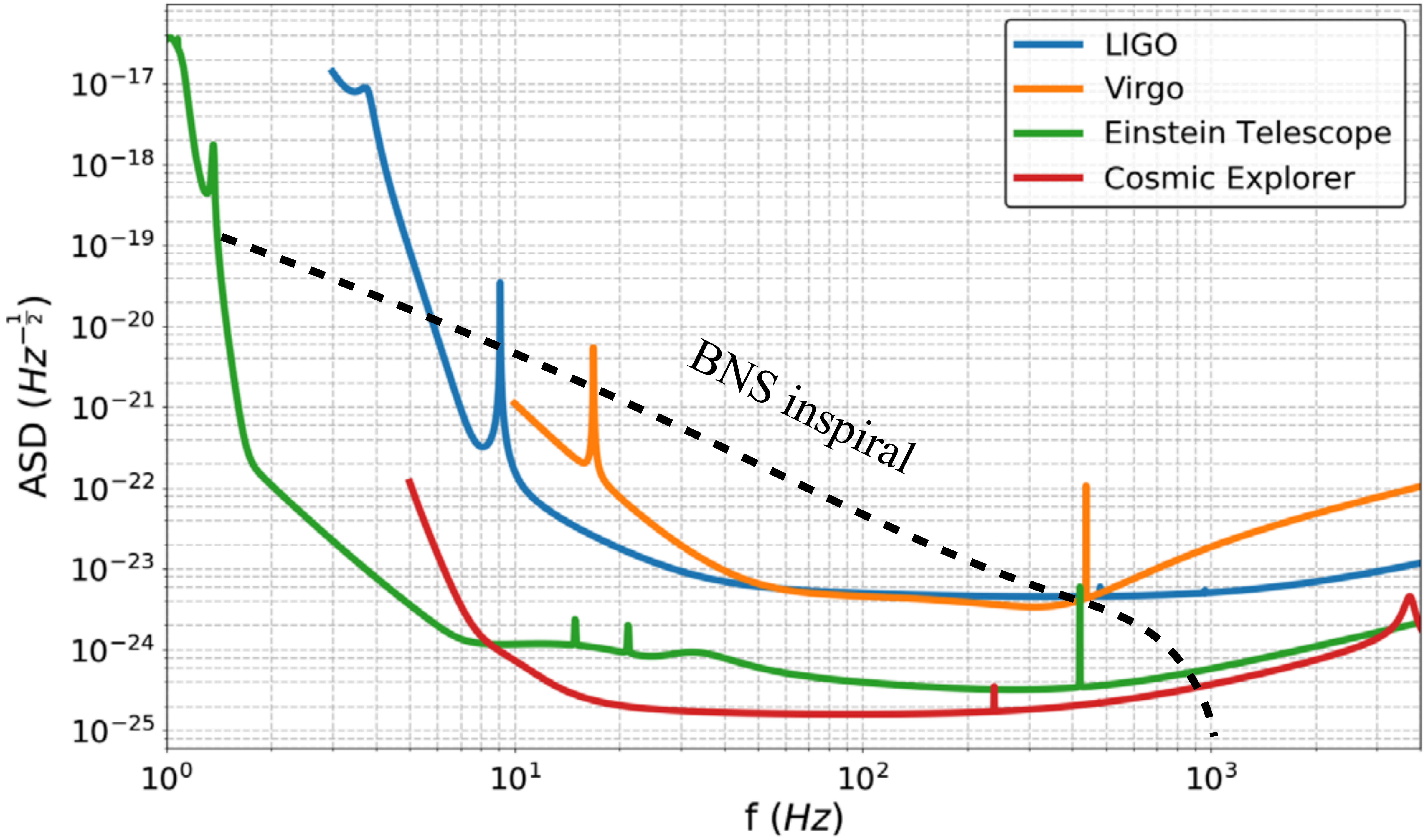
Einstein Telescope
(ET)

- **Triangle** geometry
- Xilophone concept: **low frequency** at cryogenic temperature + **high frequency** at room temperature
- Underground to **minimise seismic noise**



Cosmic Explorer
(CE)

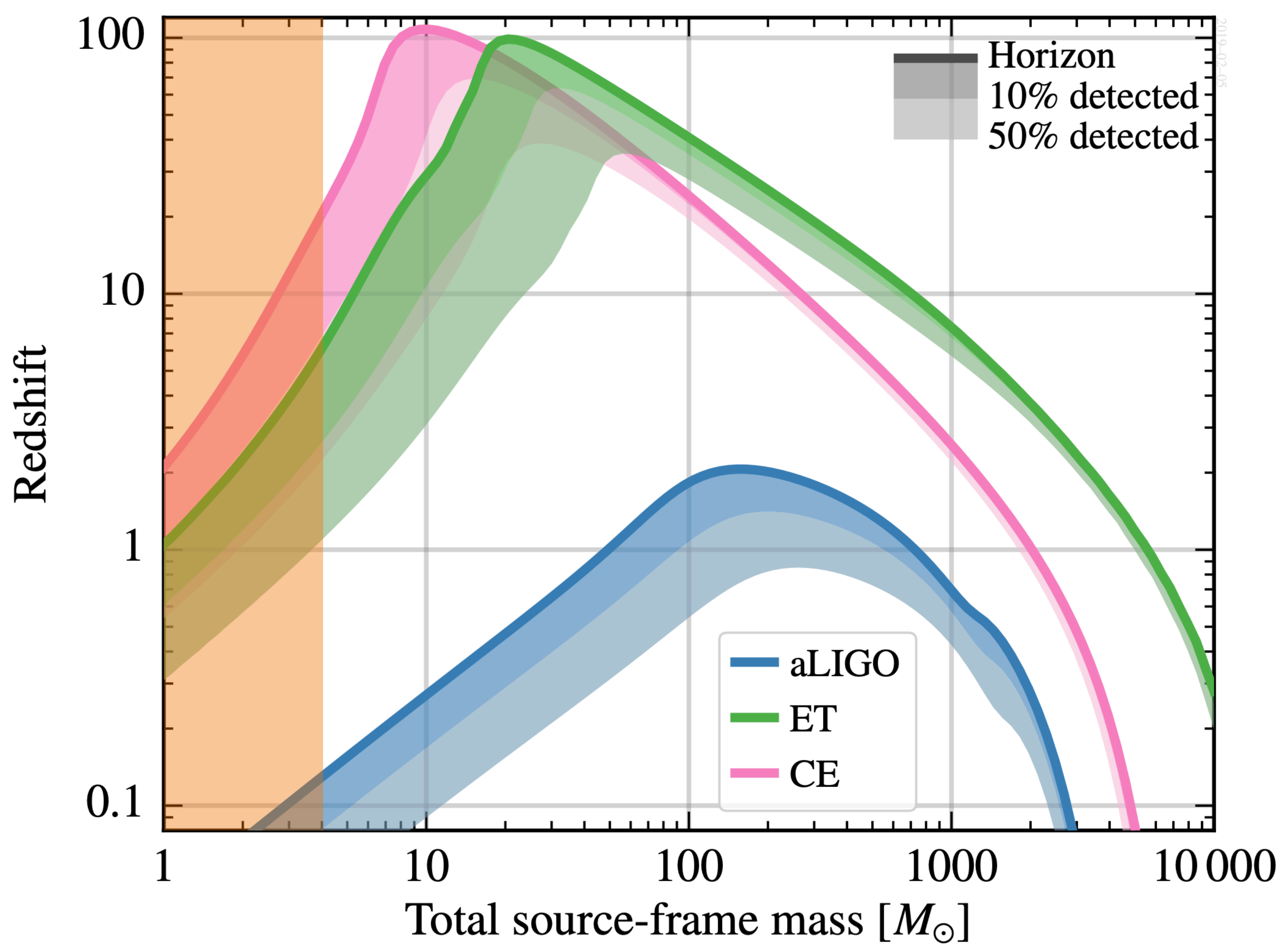
Extension of LIGO concept with **10x longer arms**

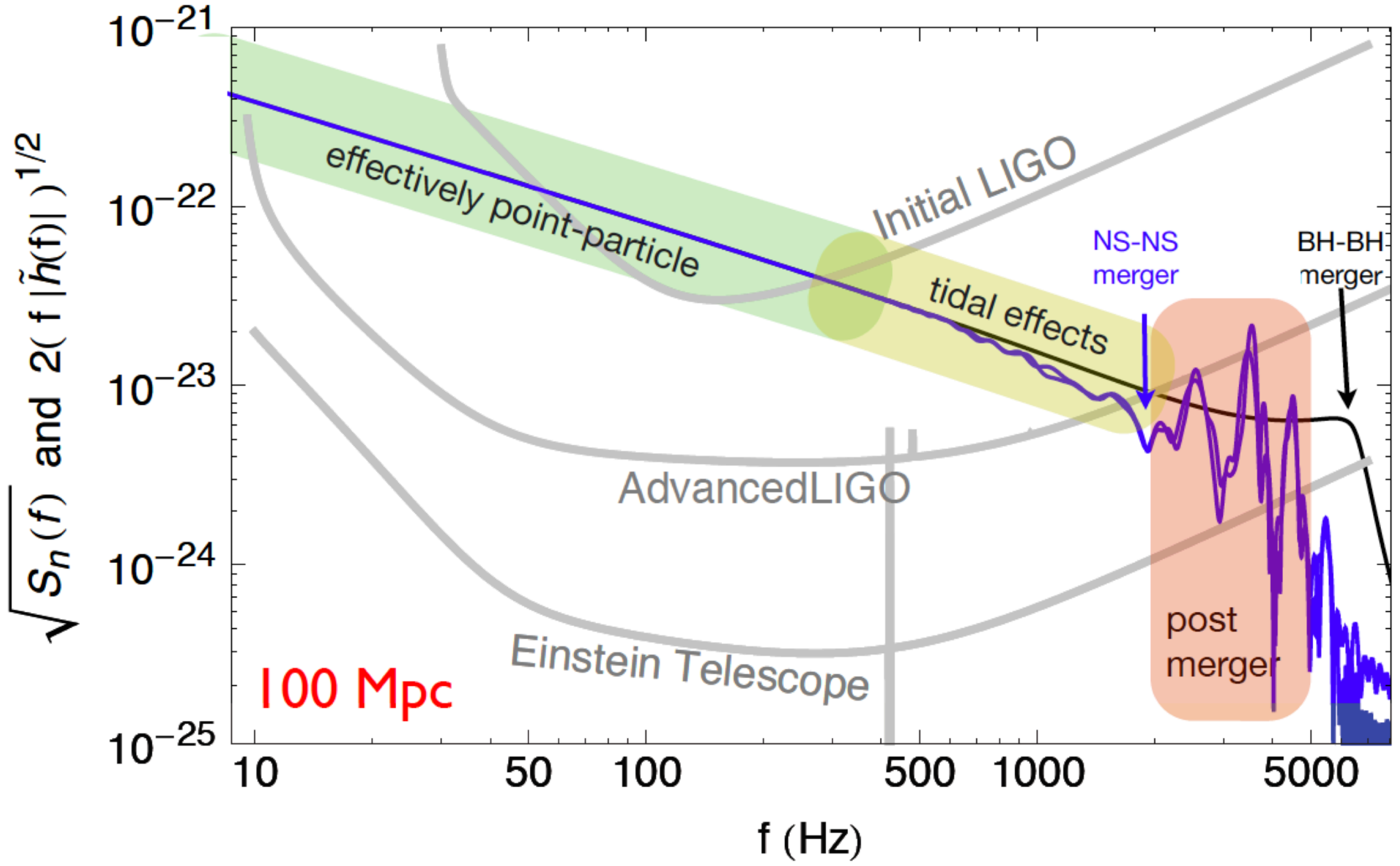


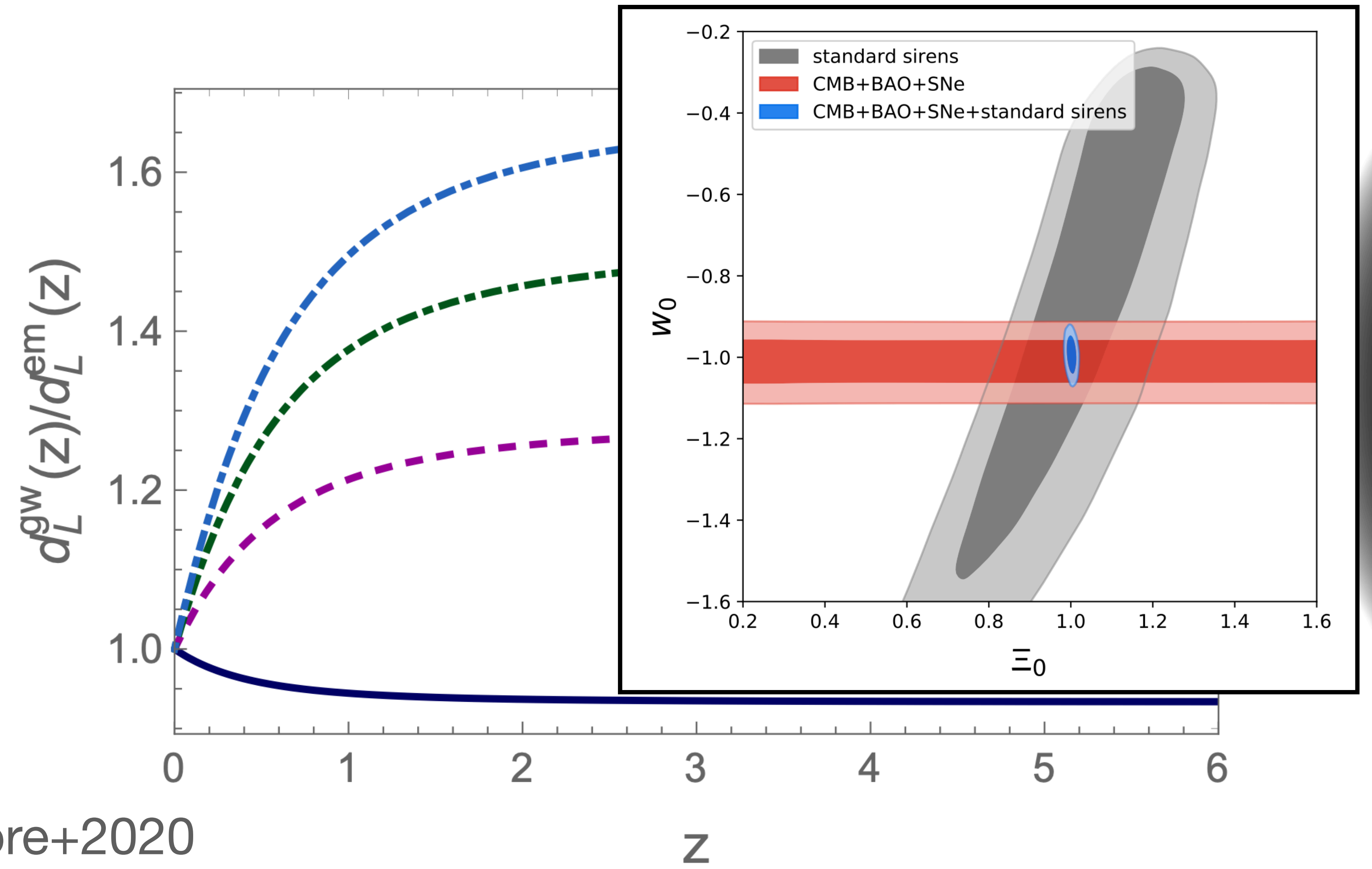
From Chan et al. 2018

The 3rd generation of GW detectors: science case

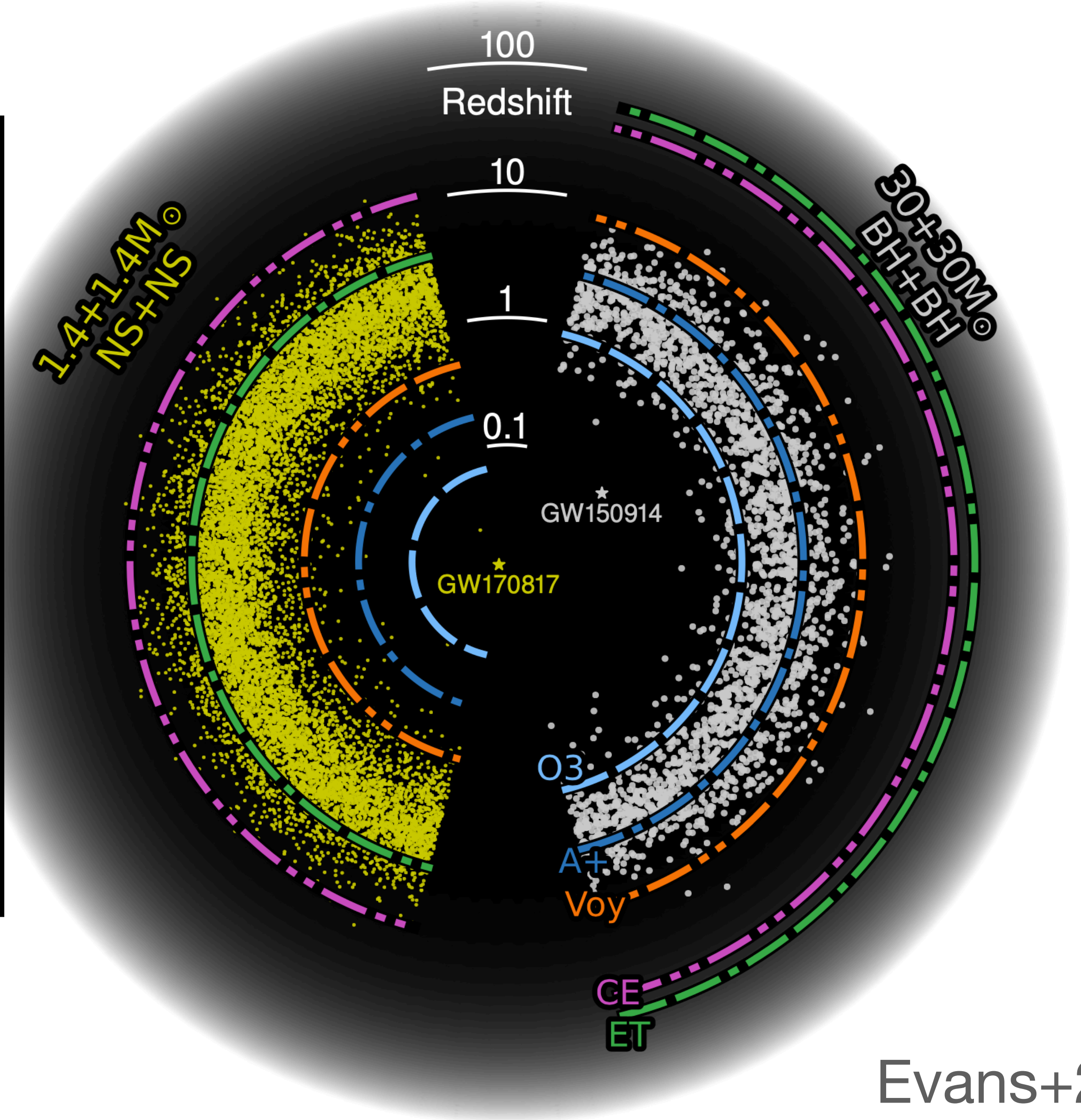
- 10^5-10^6 detections / yr of stellar mass BH mergers up to z~100
- Detection of primordial BH
- Detection of ~10^5 BNS mergers/yr beyond the star formation peak
  - ET more **sensitive at low frequency** → the inspiral is followed for a longer time → **better sky localisation**
  - Access the **effects of tidal deformations** at the moment of the merger → **NS EoS**
- Test of GR during the inspiral and in the post-merger (e.g. BH ringdown)
- Nature of dark energy and modifications of GR at cosmological distances







Maggiore+2020



Evans+2021

The 3rd generation of GW detectors: population studies

Expected number of BNS detections / yr $\sim 10^5$

↓

Bayesian parameter estimation $\rightarrow$ Fisher matrix

In the limit of high SNR: quadratic approximation of the likelihood

→

GWFISH

Dupletsa et al. 2022

- Parameter estimation based on **Fisher-matrix** approximation
- Includes the effect of **Earth rotation** (not negligible for long-lasting signals)
- Computationally **efficient**
- Ideal to process **large amount of injections** and to obtain average population properties
- Gives robust results in the **limit of high SNR**

From BNS mergers to short GRBs

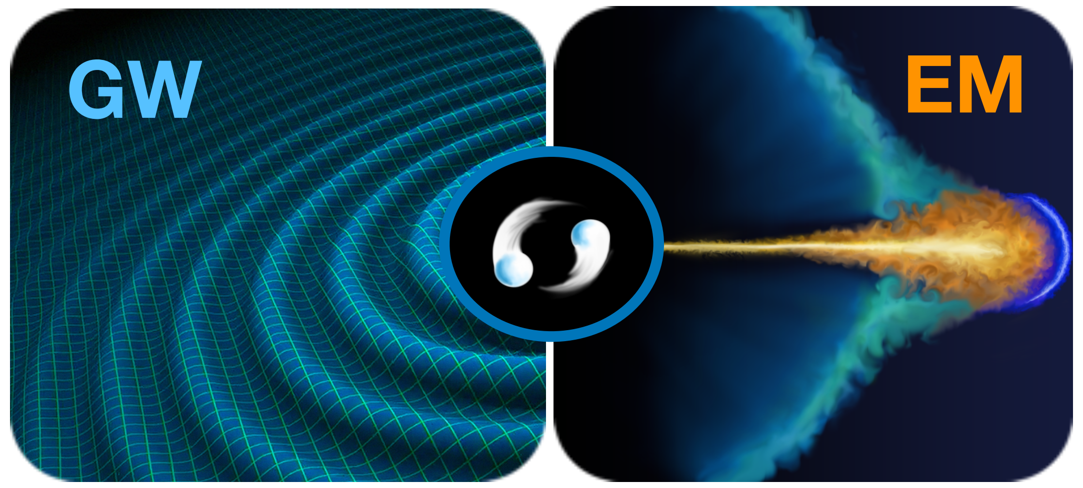
Population of BNS mergers from compact binary population synthesis model

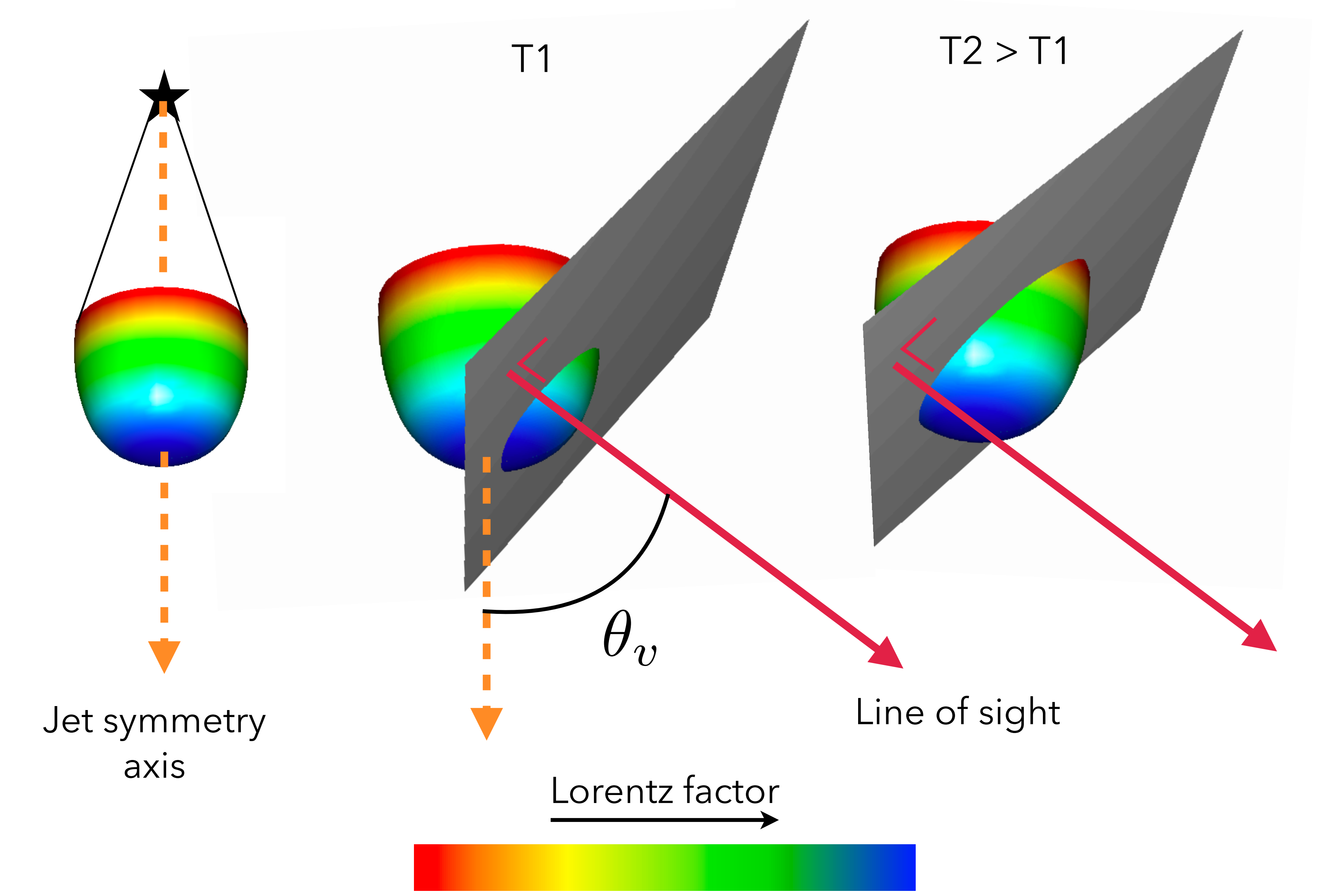
Phenomenological model for prompt emission

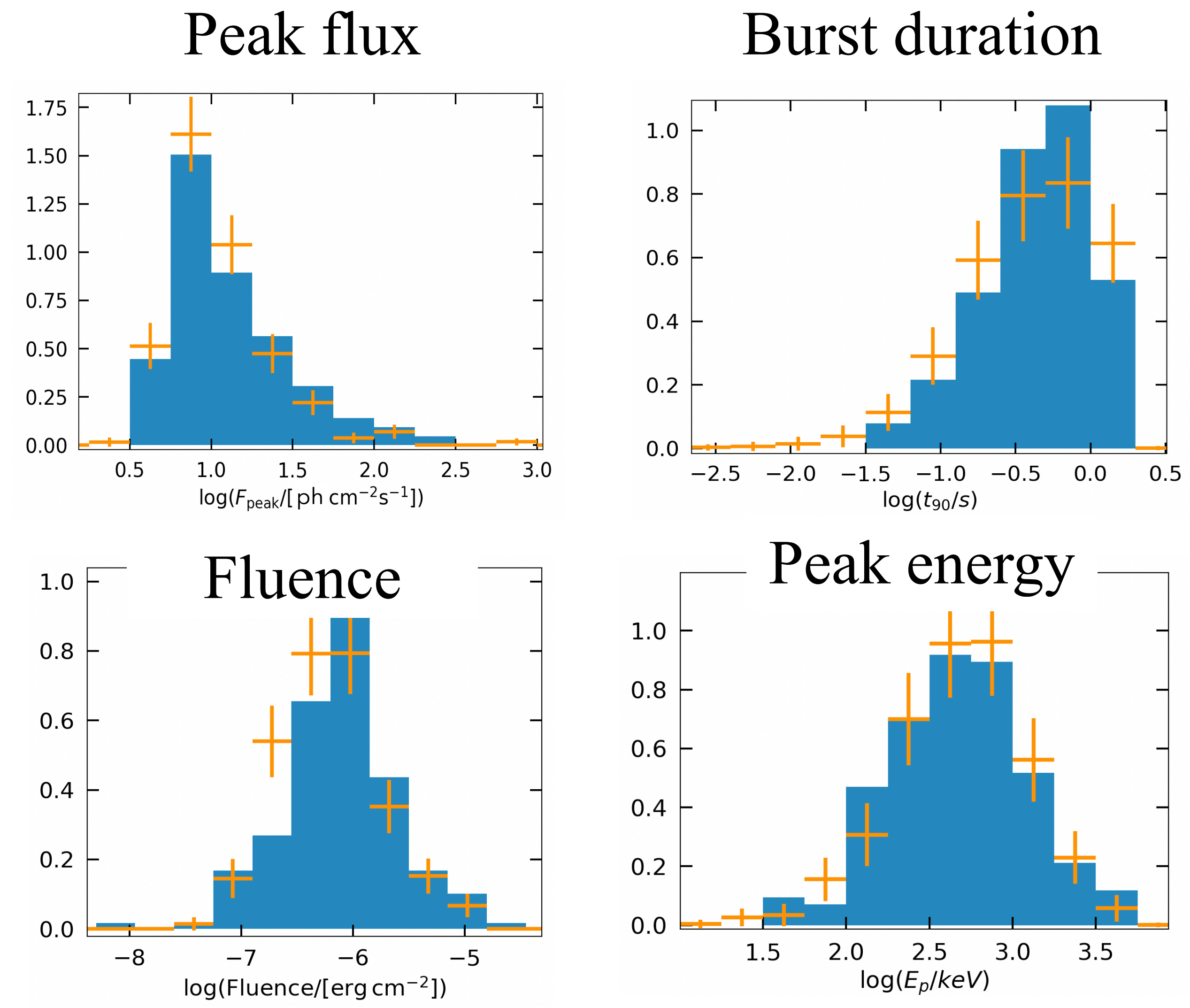
Comparison with properties of Fermi-GBM sample

Estimation of the prompt and afterglow emission

Prediction of the joint detection rate







+ Fermi-GBM rate of short GRBs

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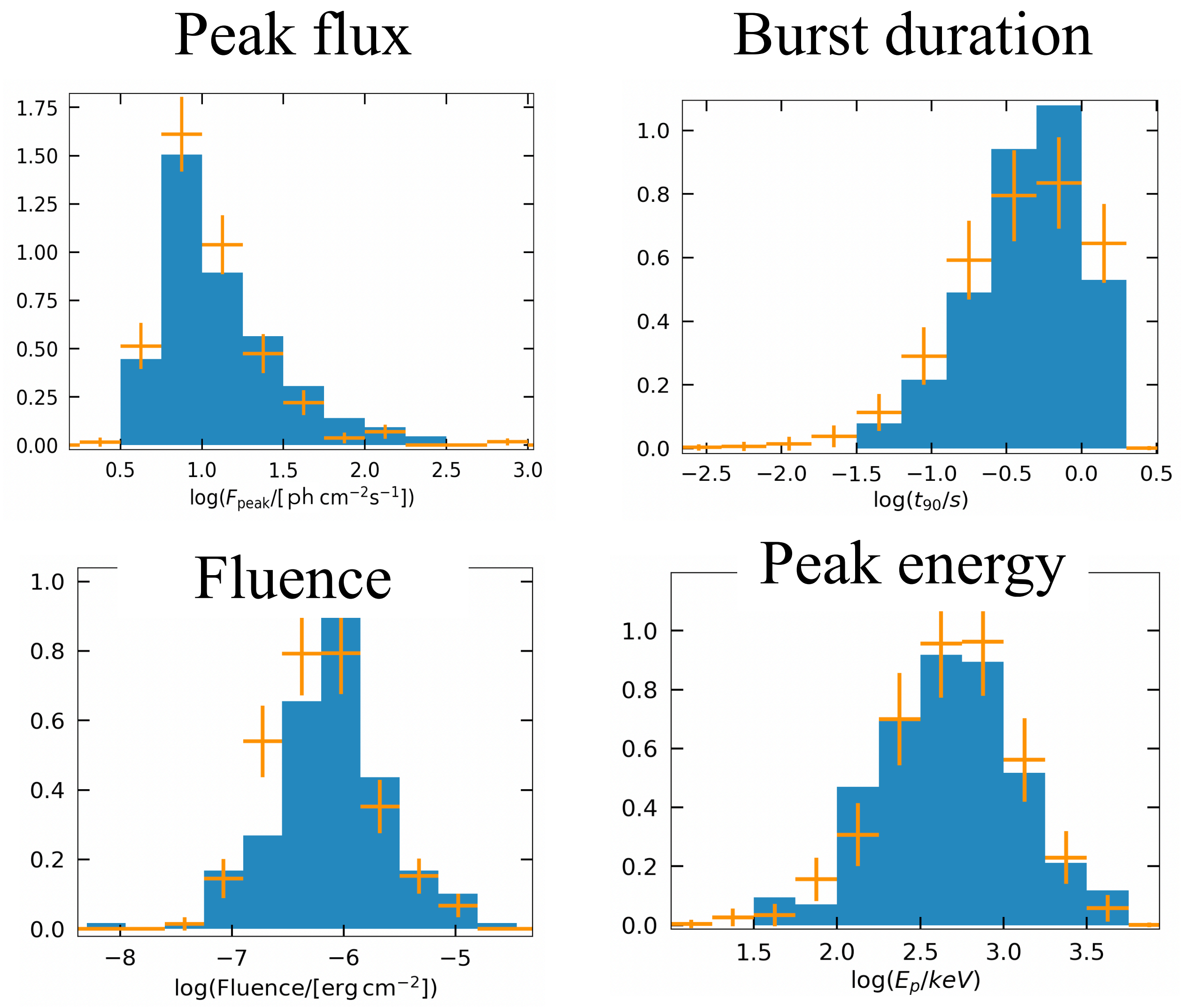
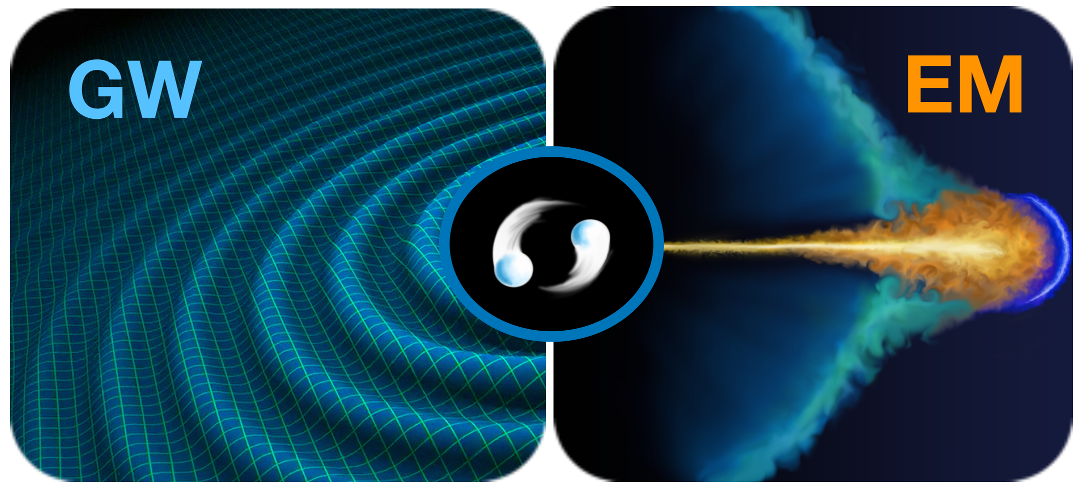


Prediction of the joint detection rate

Joint GW + prompt γ-ray emission

Joint GW + X-ray afterglow emission

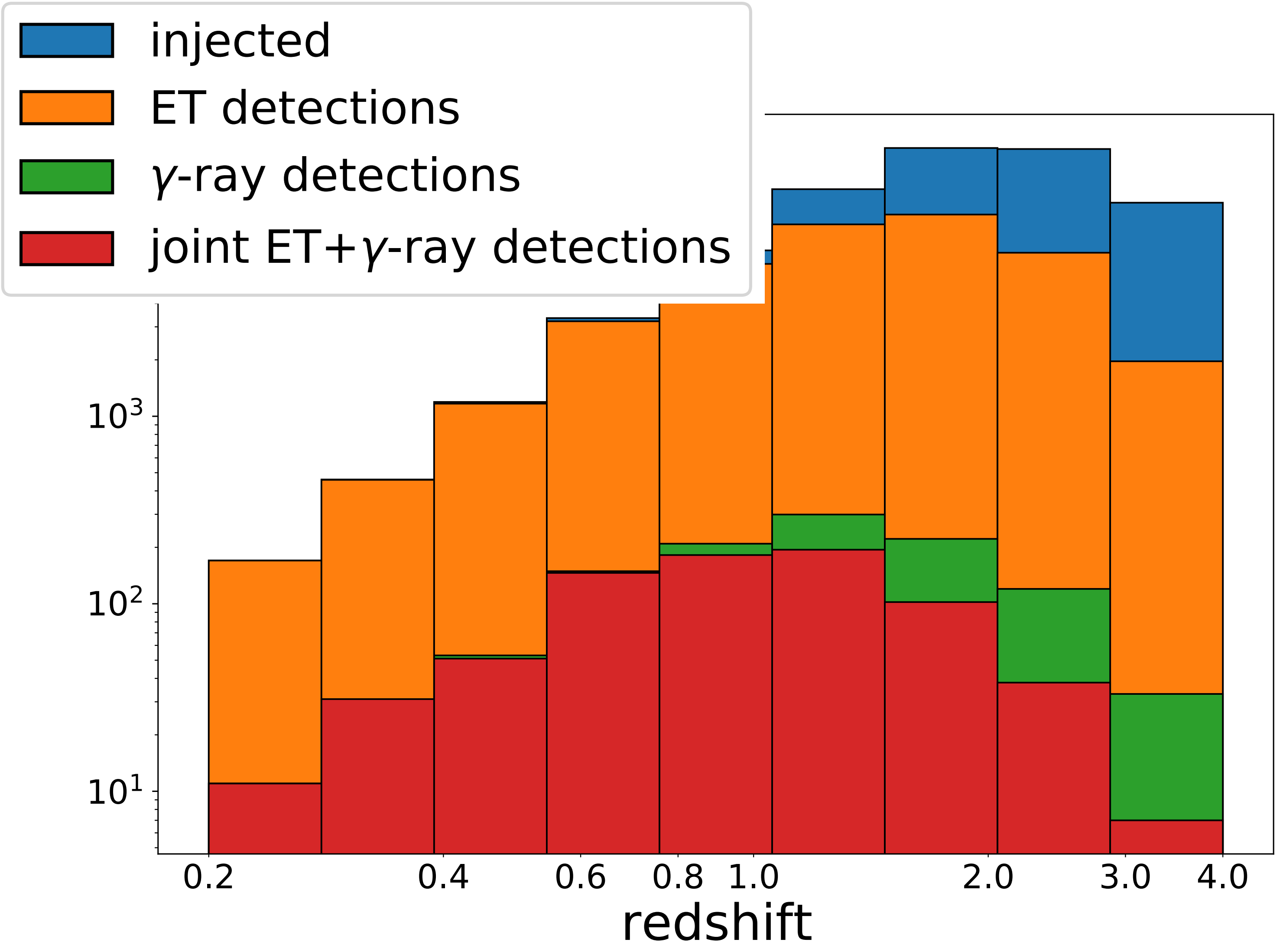
\+ Fermi-GBM rate of short GRBs



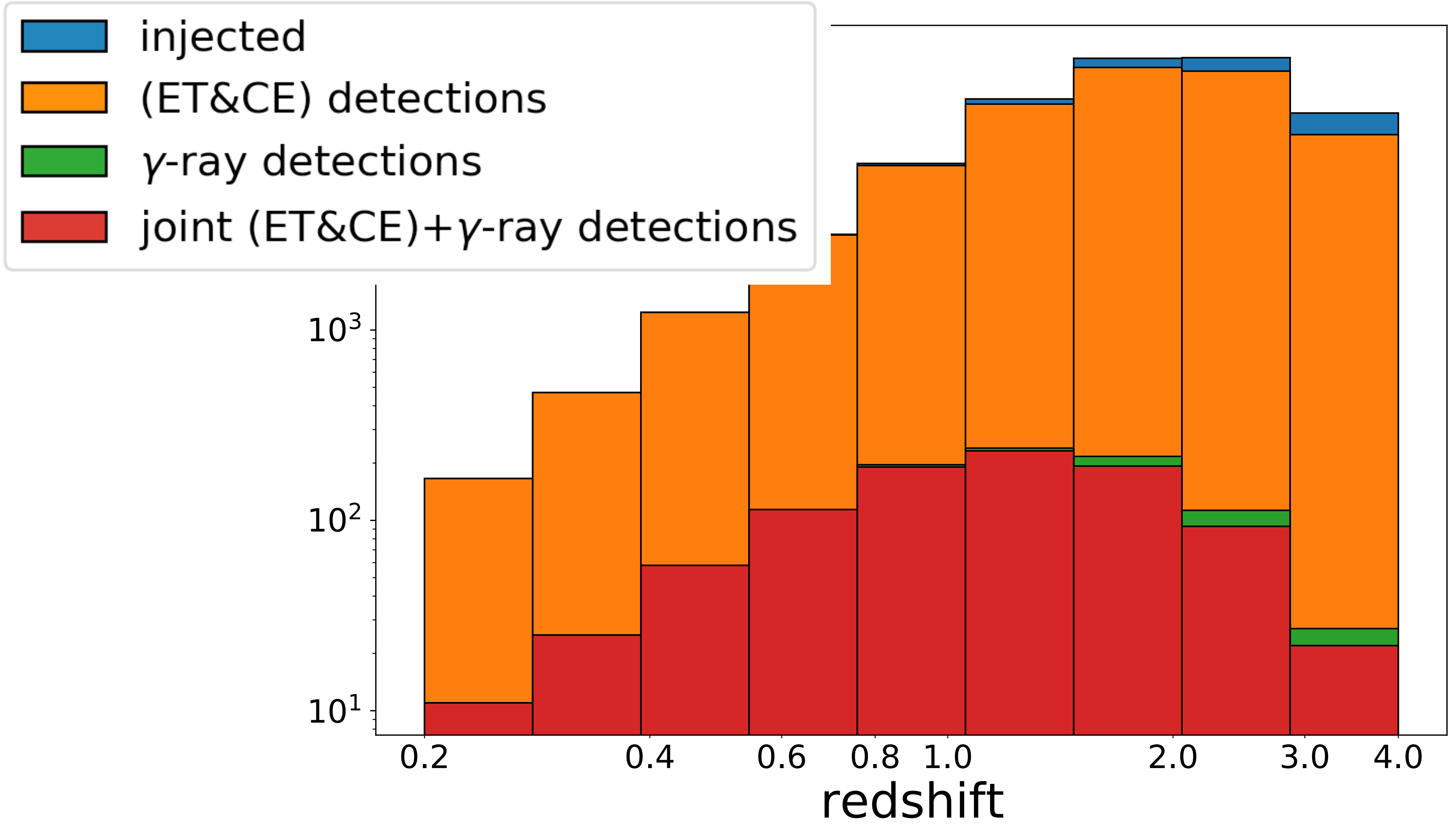
Joint detection of γ-ray emission and GWs

INSTRUMENT	band MeV	$F_{\rm lim}$ erg cm^{-2} s^{-1}	FOV/4π	loc. acc.	Joint ET $+\gamma$-ray	N_{JD}/N_{γ}	Joint (ET+CE) $+\gamma$-ray	N_{JD}/N_{γ}
Fermi-GBM	0.01 - 25	0.5(*)	0.75	5 deg (^{a})	33^{+14}_{-11}	$68^{+13}_{-18}\%$	47^{+14}_{-14}	$95^{+5}_{-7}\%$
Swift-BAT	0.015 - 0.15	2×10^{-8}	0.11	1-3 arcmin	10^{+3}_{-3}	$62^{+11}_{-14}\%$	13^{+5}_{-4}	$94^{+6}_{-7}\%$
SVOM-ECLAIRs	0.004 - 0.250	1.792(*)	0.16	< 10 arcmin	3^{+1}_{-1}	$69^{+10}_{-9}\%$	4^{+1}_{-1}	$95^{+5}_{-4}\%$
SVOM-GRM	0.03 - 5	0.23(*)	0.16	$\sim$ 5 deg	9^{+4}_{-3}	$59^{+6}_{-6}\%$	14^{+6}_{-4}	$92^{+3}_{-3}\%$
THESEUS-XGIS	0.002 - 10	3×10^{-8}	0.16	< 15 arcmin	10^{+5}_{-4}	$63^{+13}_{-13}\%$	15^{+6}_{-4}	$94^{+6}_{-7}\%$
HERMES	0.05 - 0.3	0.2(*)	1.0	1 deg	84^{+42}_{-30}	$61^{+10}_{-11}\%$	139^{+54}_{-36}	$94^{+6}_{-6}\%$
TAP-GTM	0.01 - 1	1(*)	1.0	20 deg	60^{+24}_{-24}	$67^{+13}_{-14}\%$	84^{+30}_{-24}	$95^{+5}_{-6}\%$

Fermi GBM+ET



Fermi GBM+(ET&CE)



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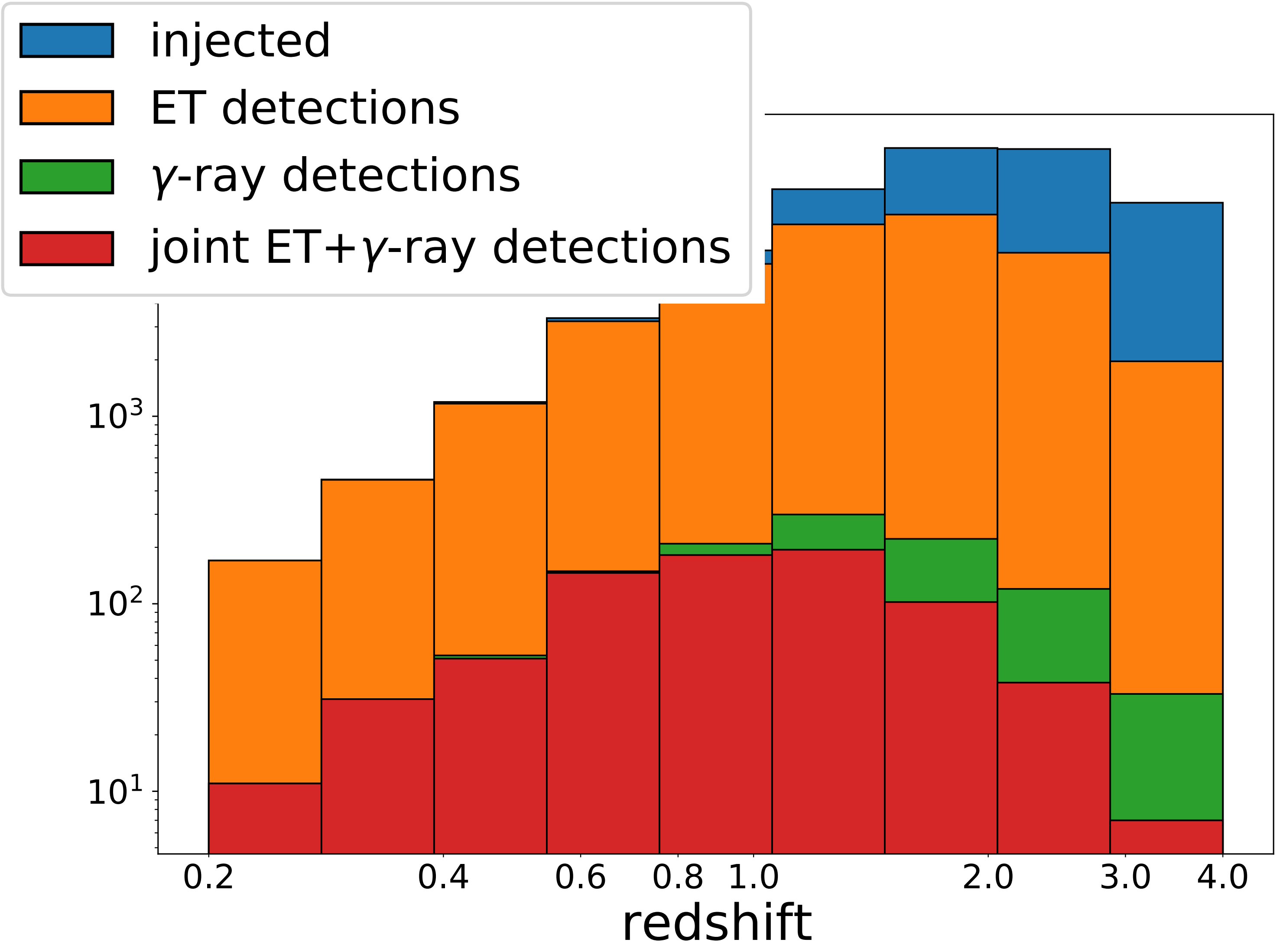
~ 60-70 % of short GRBs will have a GW detectable emission with ET and close to 100% with ET+CE

Fermi GBM+ET



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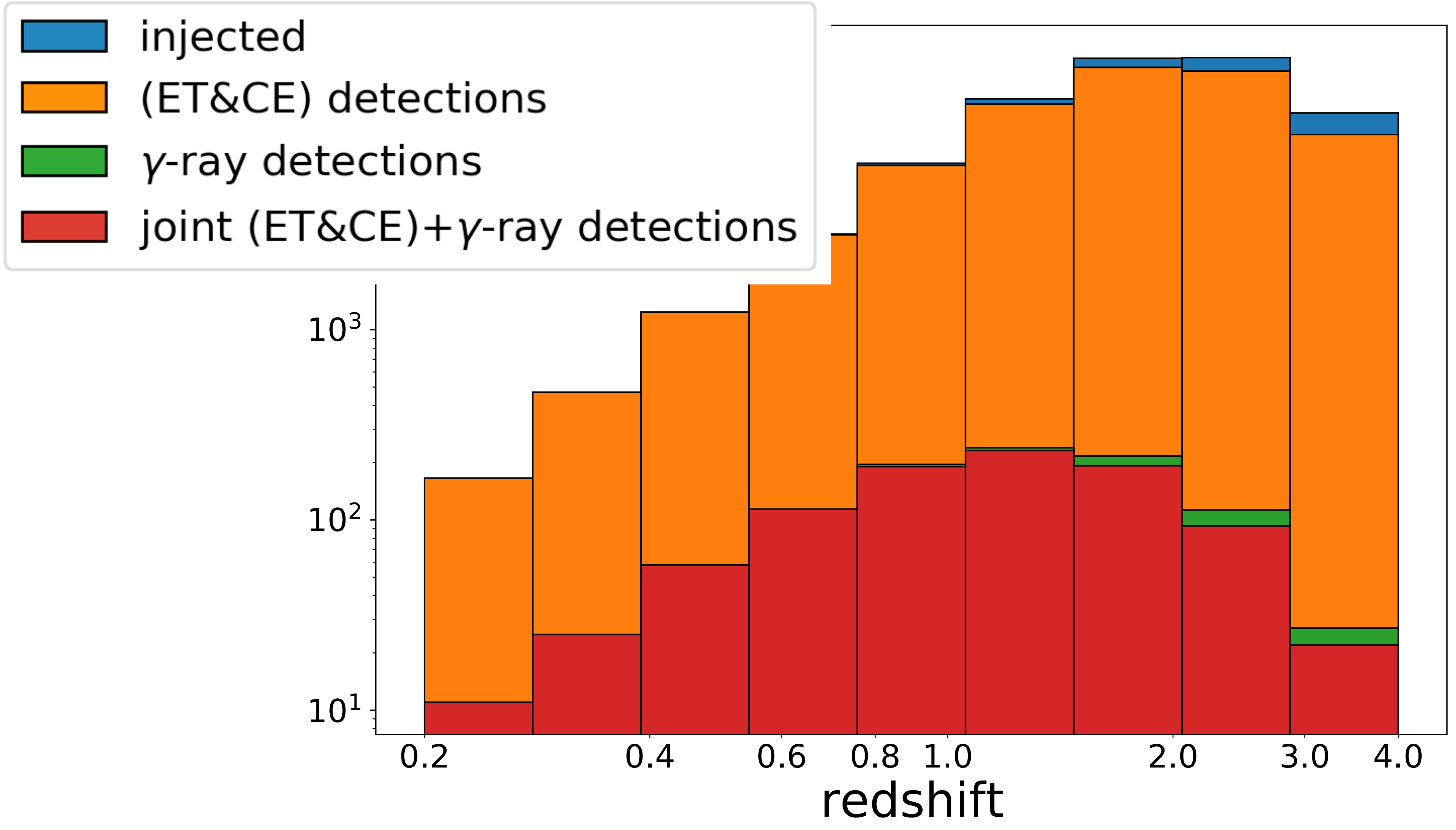

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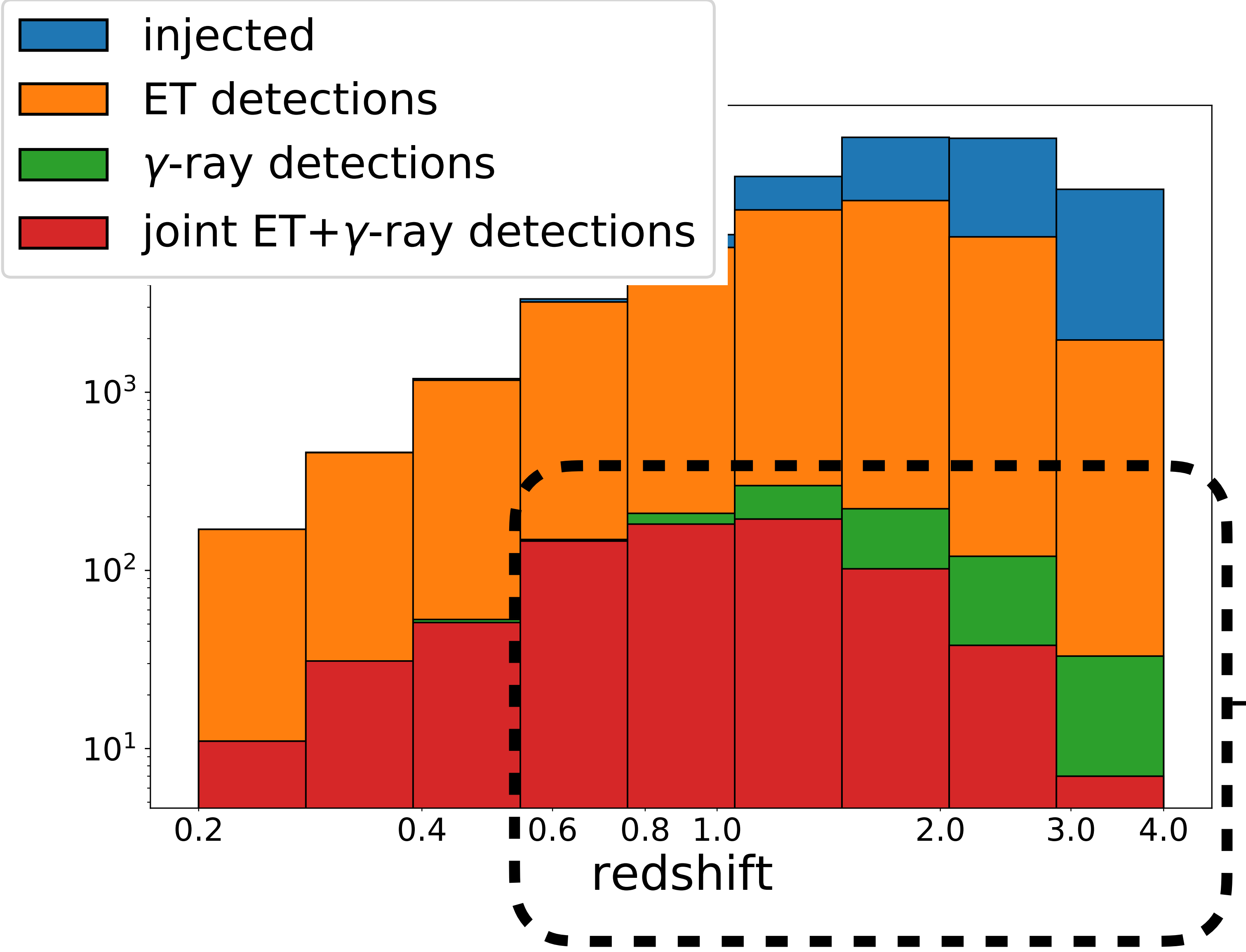
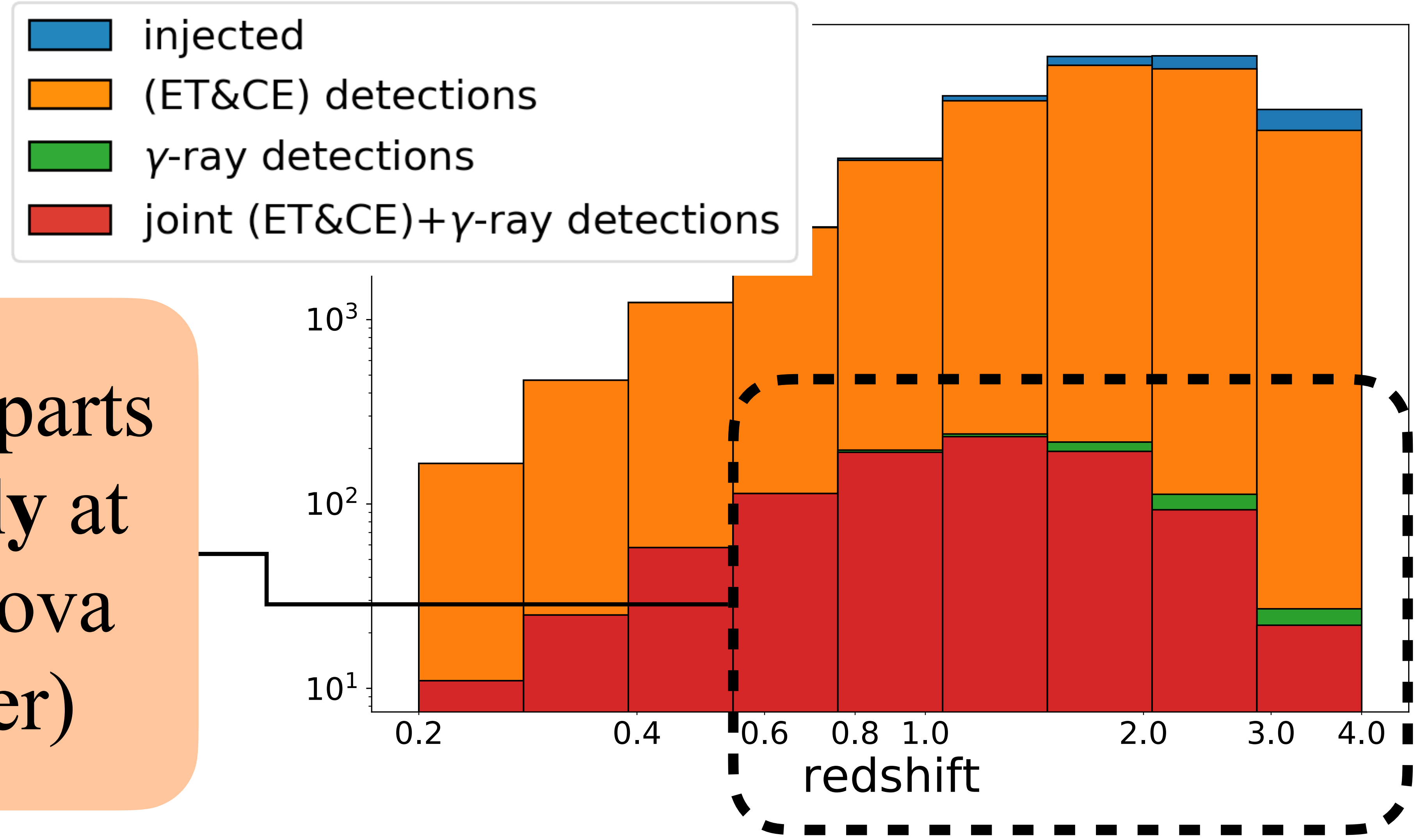


High-z GW counterparts can be detected **only** at high-energy (kilonova intrinsically fainter)

Fermi GBM+(ET&CE)



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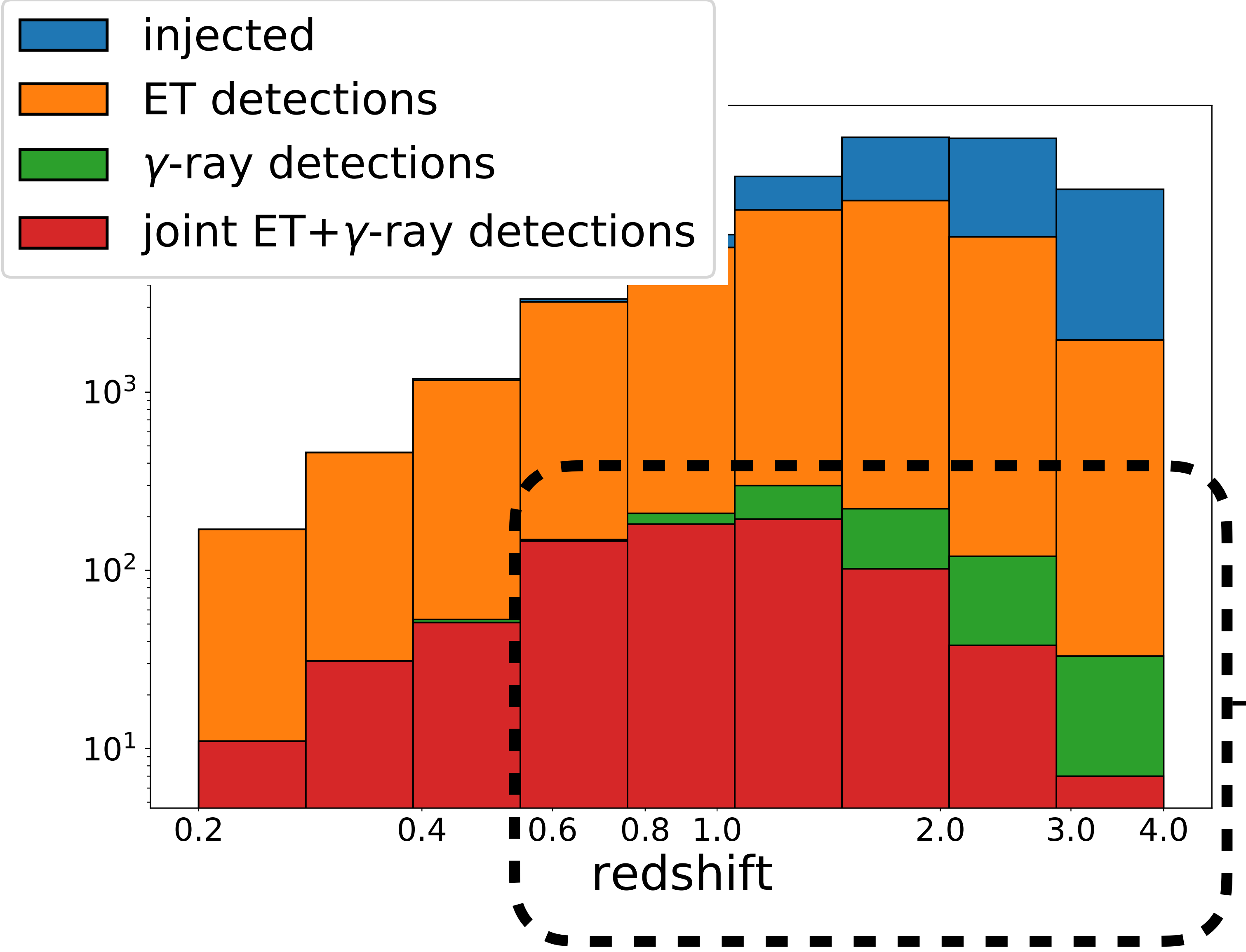
Few but **well localised** events

Fermi GBM+ET



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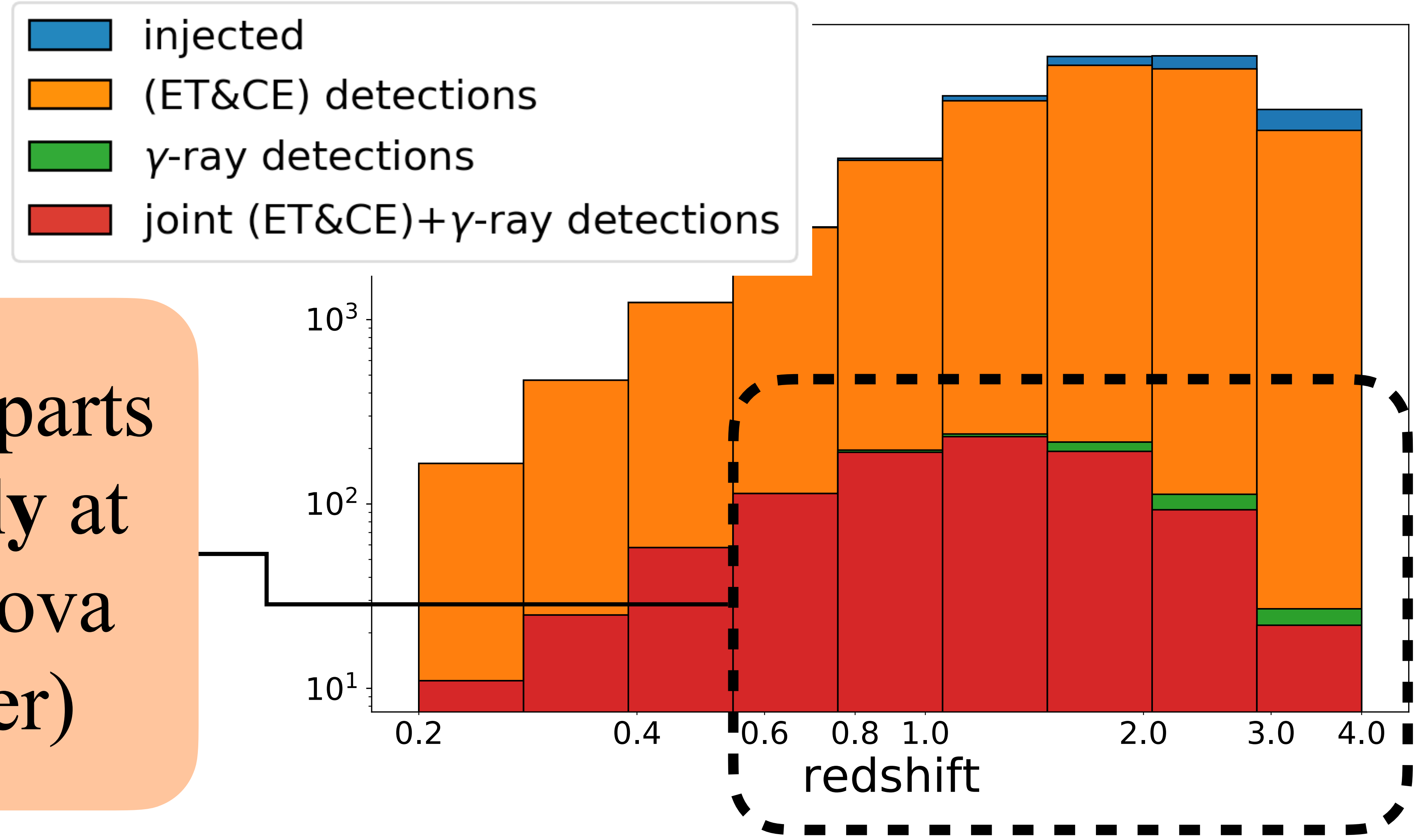


Two kinds of joint detections

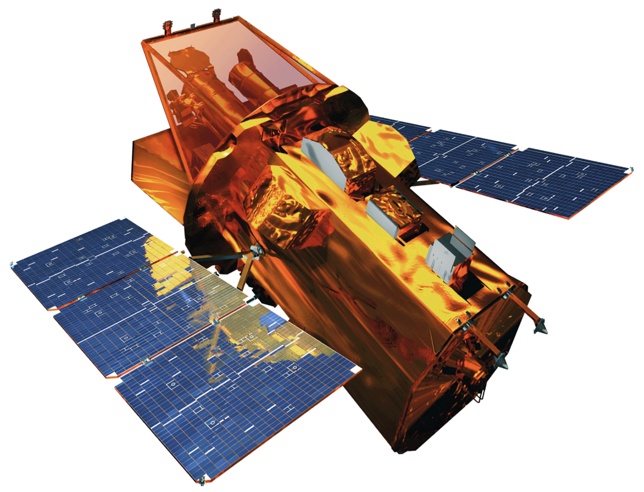
Fermi-like telescopes

- ~ **all sky** monitors
- Possibility to build constellations at fairly low cost
- **Best sensitivity** around the sGRB **peak energy**
- ~ deg location accuracy

PROS

- Confirm the spatial and temporal coincidence with the GW
- Characterise the spectral shape up to high energies
- High number of joint detections ⇒ **statistical studies**

Swift-like telescopes

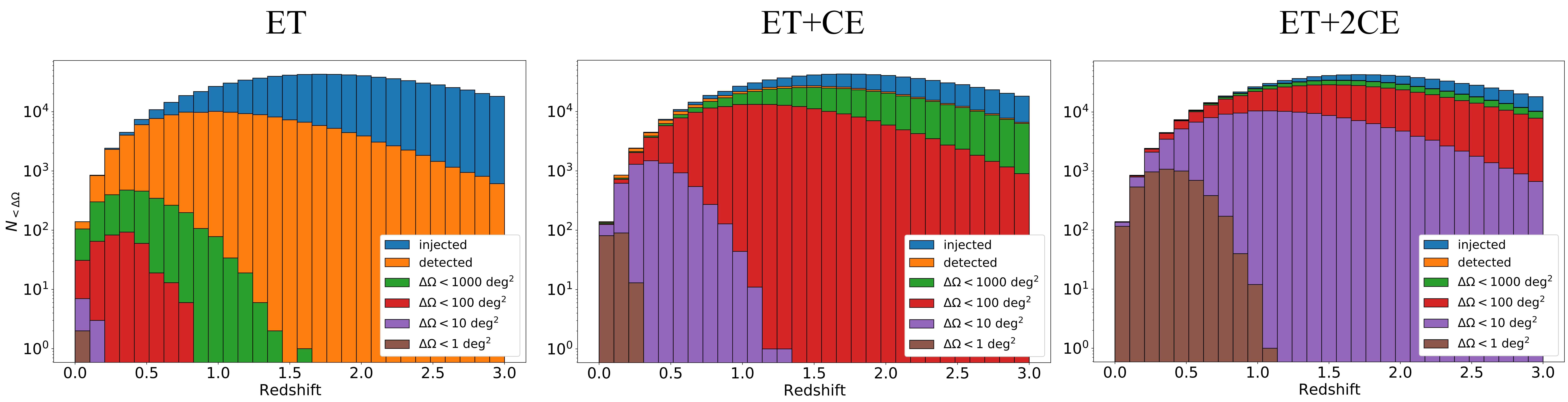


- Good sky coverage
- **Arcmin location accuracy**
- Possibility to promptly follow up with ground-based telescopes

PROS

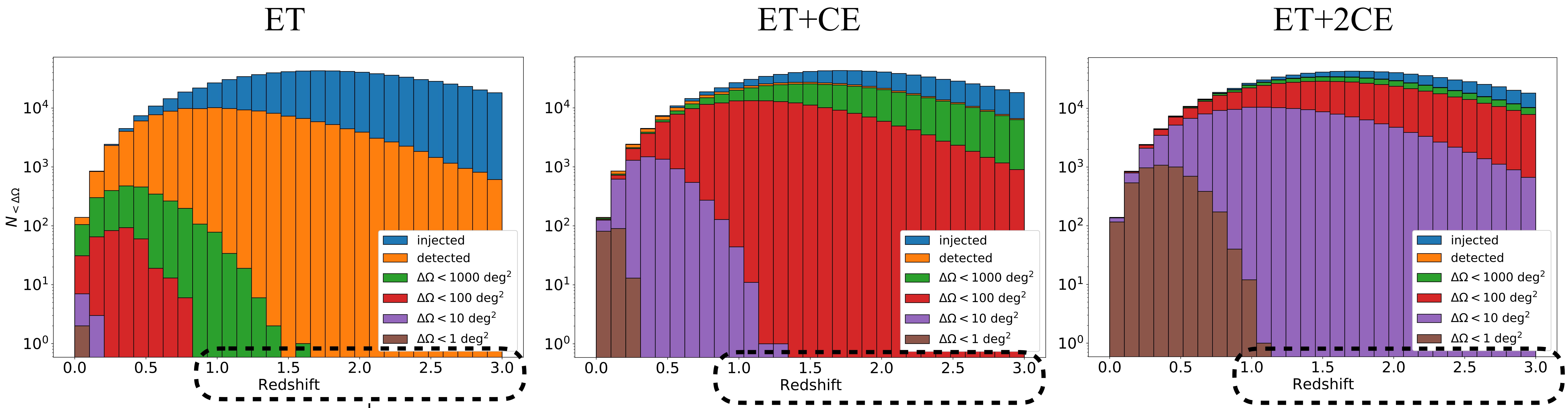
- Identification of the host galaxy
- Determination of the redshift
- Detection of X-ray counterparts (standard GRB afterglow, jet-KN ejecta interaction, SBO, wind from magnetar…)
- Less number of events but with **deeper understanding of the GRB physics**

GW sky localisation



	ET	ET+CE	ET+2CE
N_{det}	143970	458801	592565
$N_{\text{det}}(\Delta\Omega < 1\ \text{deg}^2)$	2	184	5009
$N_{\text{det}}(\Delta\Omega < 10\ \text{deg}^2)$	10	6797	154167
$N_{\text{det}}(\Delta\Omega < 100\ \text{deg}^2)$	370	192468	493819
$N_{\text{det}}(\Delta\Omega < 1000\ \text{deg}^2)$	2791	428484	585317

GW sky localisation



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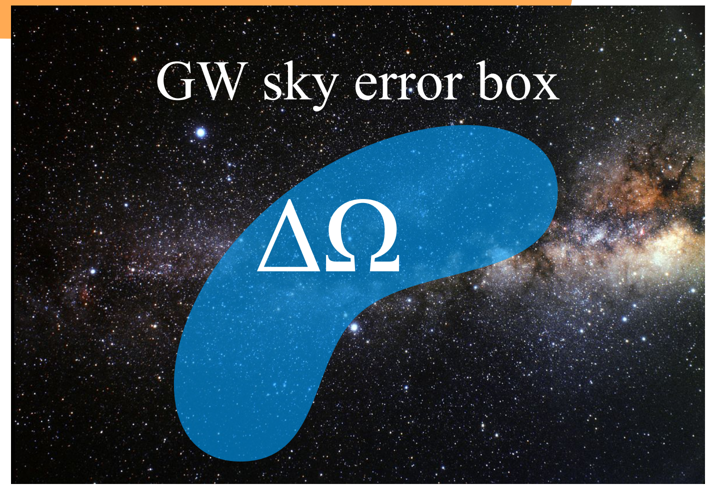
High-z GW source localisation is given by counterparts detected by **wide field X-ray and γ-ray telescopes** with arcmin localisation capabilities

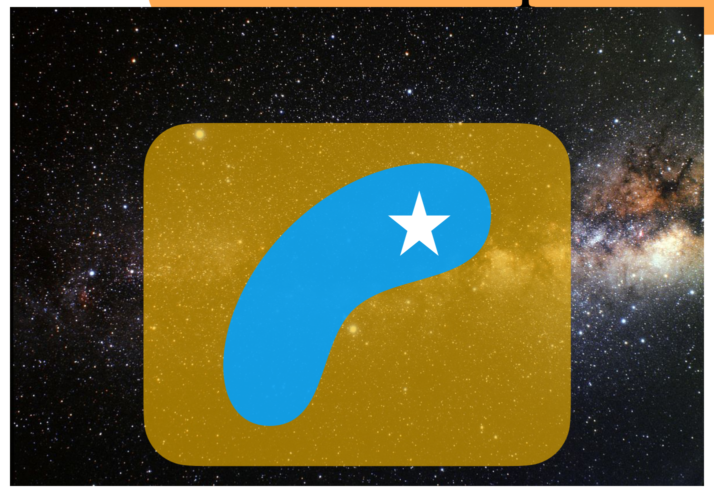
Detectability of the afterglow emission: survey vs pointing

How to detect X-ray emission:

1. In **survey mode**: probability ~FOV/4π of detecting by chance the source
2. In **pointing mode**: selection of the sources with $\Delta\Omega$ < 100 deg^2

Sky localisation from GW → Response time → Detection with wide field X-ray telescopes





	THESEUS-SXI	TAP	Einstein Probe	Gamow
Energy band	0.3-5 keV	0.3-5 keV	0.5-4 keV	0.3-5 keV
Field of view	0.5 sr	0.4 sr	1.1 sr	0.4 sr

Number of BNS mergers / yr detected in GWs and X-rays

Survey mode

	ET	ET+2CE
EP	50^{+15}_{-16}	64^{+12}_{-20}
Gamow	9^{+2}_{-2}	10^{+3}_{-3}
THESEUS-SXI	11^{+3}_{-3}	13^{+4}_{-3}
THESEUS-(SXI+XGIS)	23^{+6}_{-5}	27^{+7}_{-5}
TAP-WFI	16^{+3}_{-4}	17^{+6}_{-3}

Pointing mode

	ET	ET+CE	ET+2CE
EP	9^{+5}_{-3}	294^{+80}_{-59}	359^{+168}_{-110}
THESEUS-SXI/ *Gamow*	7^{+5}_{-3}	95^{+43}_{-14}	122^{+41}_{-23}
TAP-WFI	8^{+5}_{-3}	182^{+43}_{-31}	225^{+76}_{-72}

For 2-3 GW detectors active, pointing better than survey, but…

Caveats about the pointing strategy

	ET	ET+CE	ET+2CE
EP	9^{+5}_{-3}	294^{+80}_{-59}	359^{+168}_{-110}
THESEUS-SXI/ *Gamow*	7^{+5}_{-3}	95^{+43}_{-14}	122^{+41}_{-23}
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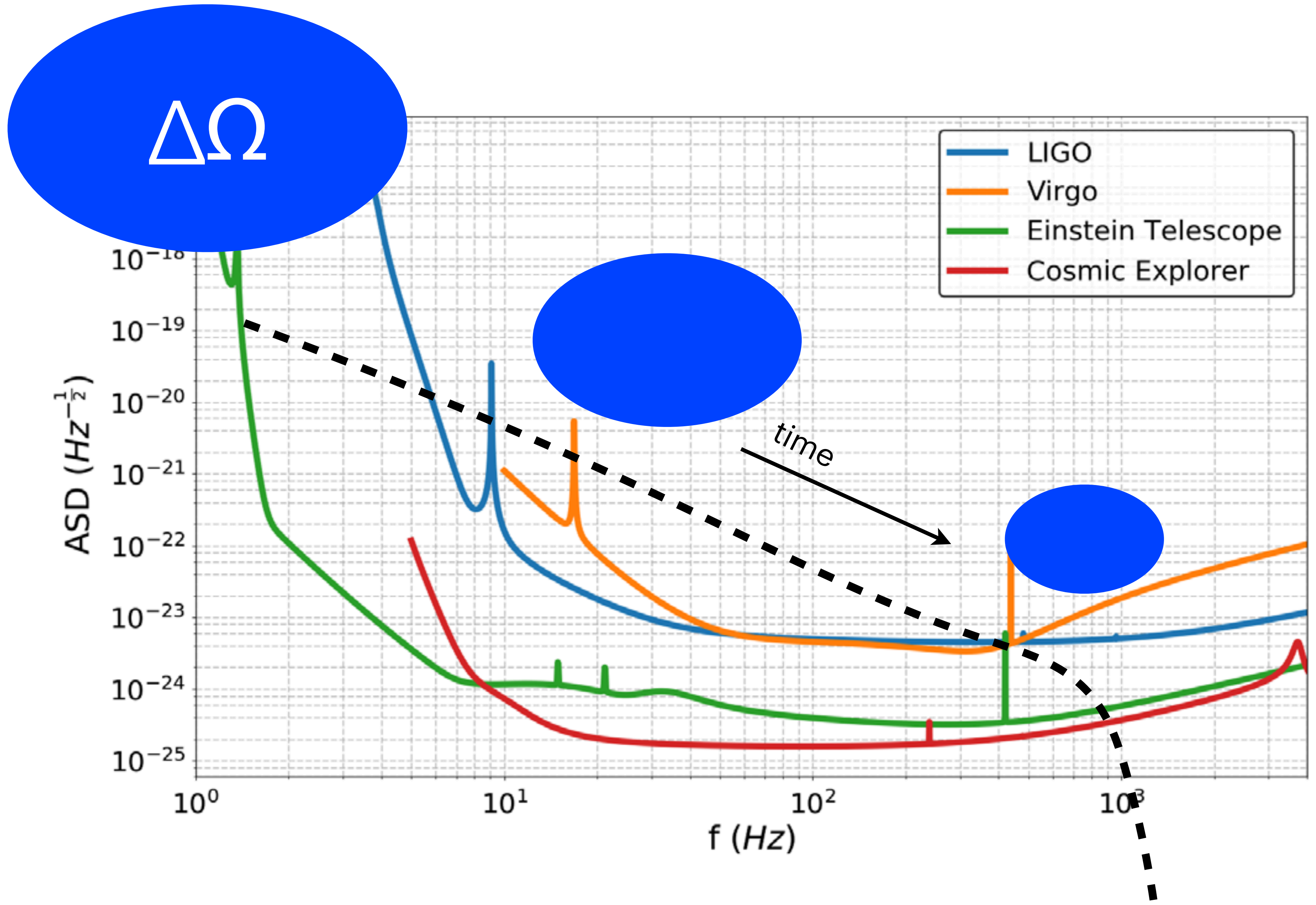
Following-up all the sources with $\Delta\Omega <$ 100 deg^2 is **unfeasible**

	100 s	1 hr	4 hr
Einstein Probe	359^{+168}_{-110}	48^{+24}_{-15}	17^{+15}_{-10}
THESEUS-SXI/ *Gamow*	122^{+41}_{-23}	12 ± 7	< 9
TAP-WFI	225^{+76}_{-72}	50^{+20}_{-10}	17^{+10}_{-5}

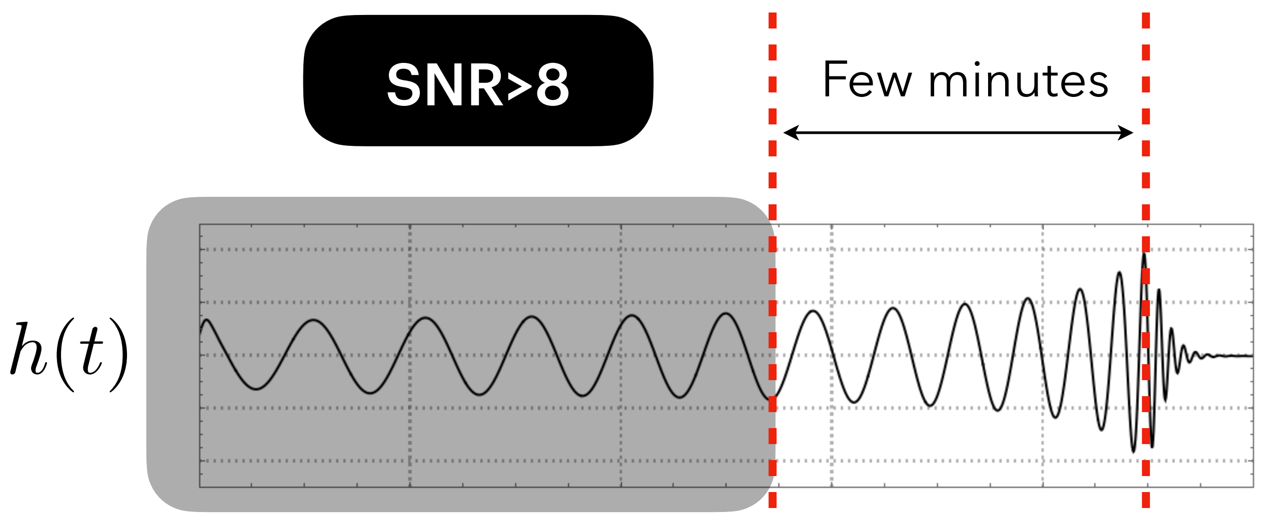
A **rapid response** is necessary to catch the brighter phase of the afterglow

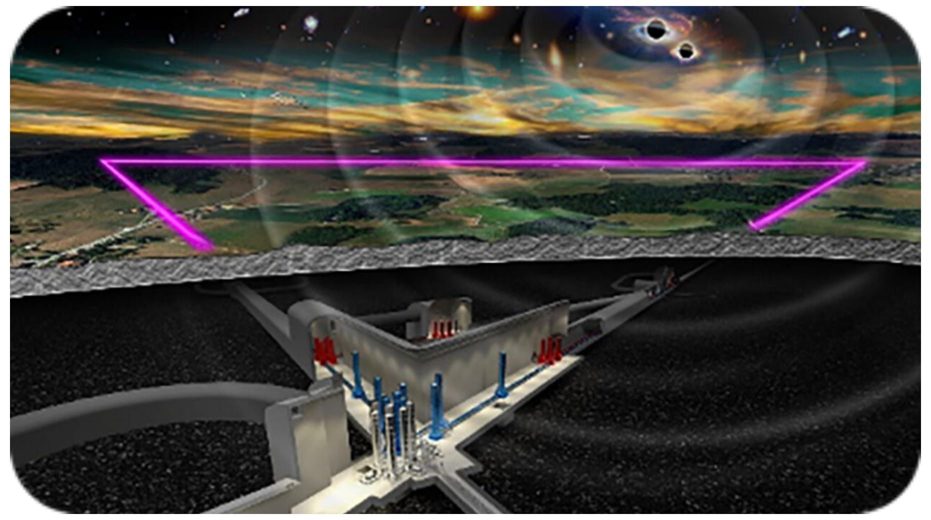
Other GW parameters should be exploited to restrict the selection:

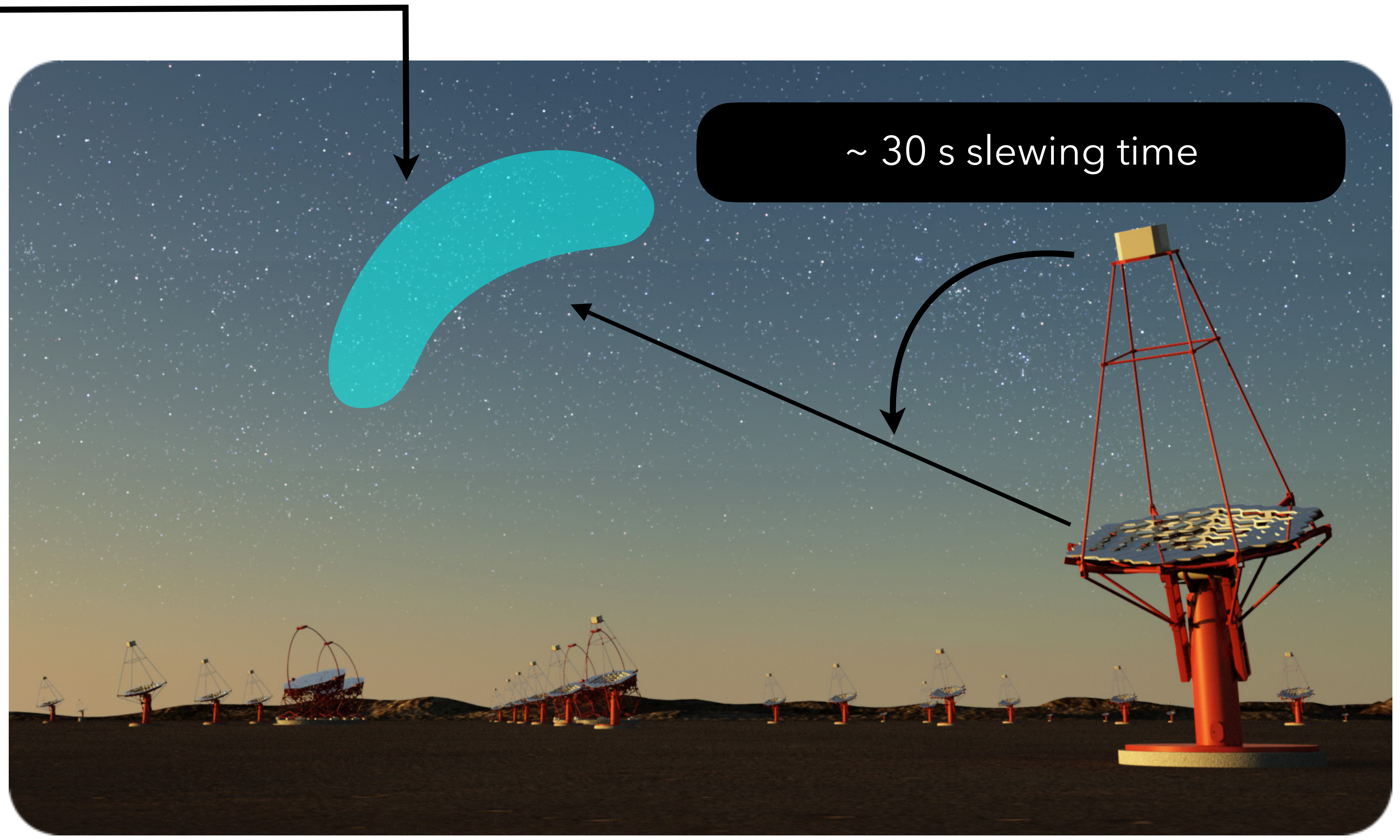
- **SNR**
- **Viewing angle** and relative error
- **Luminosity distance** and relative error



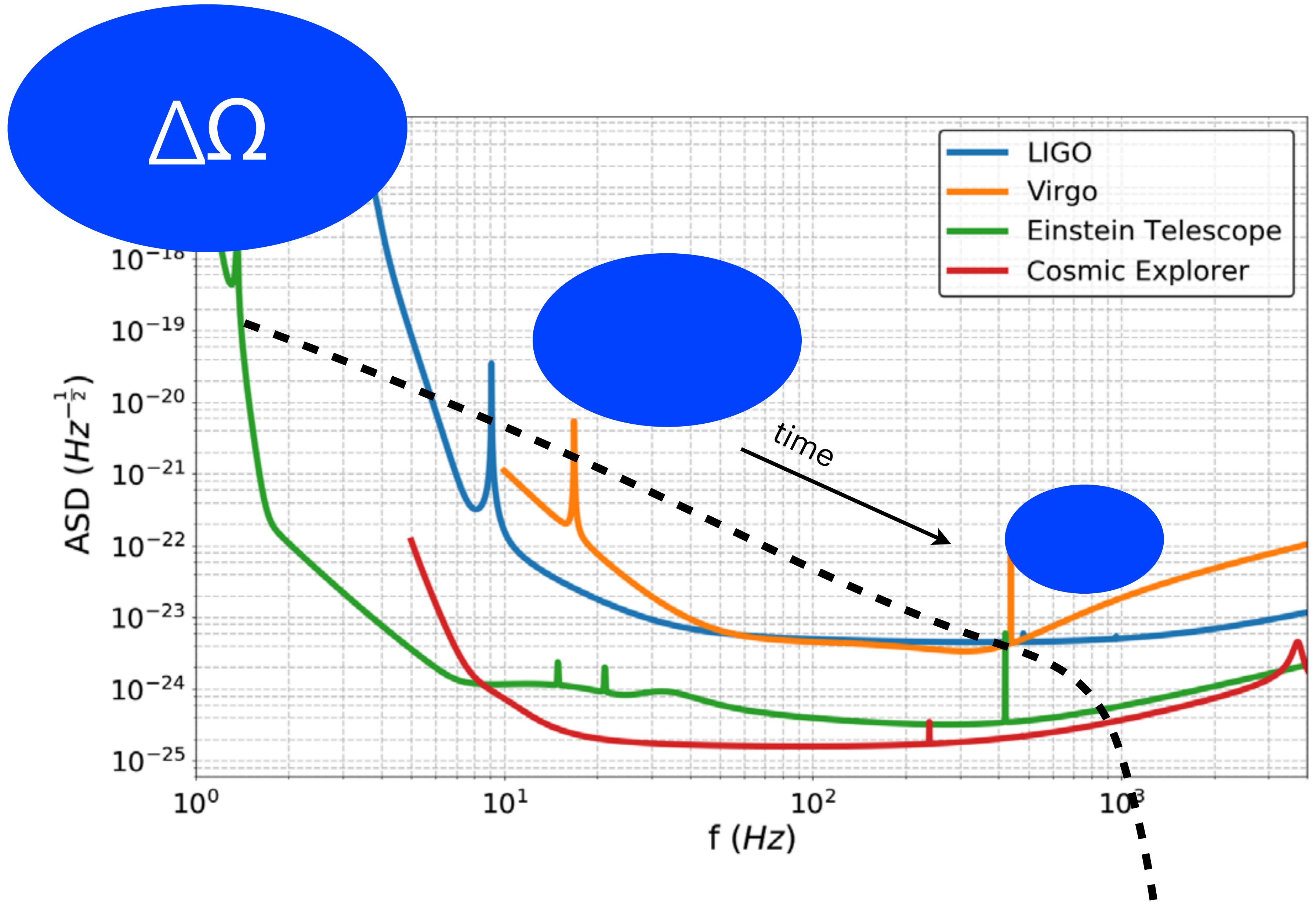
For some golden cases, enough SNR can be accumulated already **before the merger**







Future Cherenkov telescopes, like CTA, will be able to point in the direction of the GRB at the moment of the merger, allowing to **detect possible very-high energy emission during the prompt phase**



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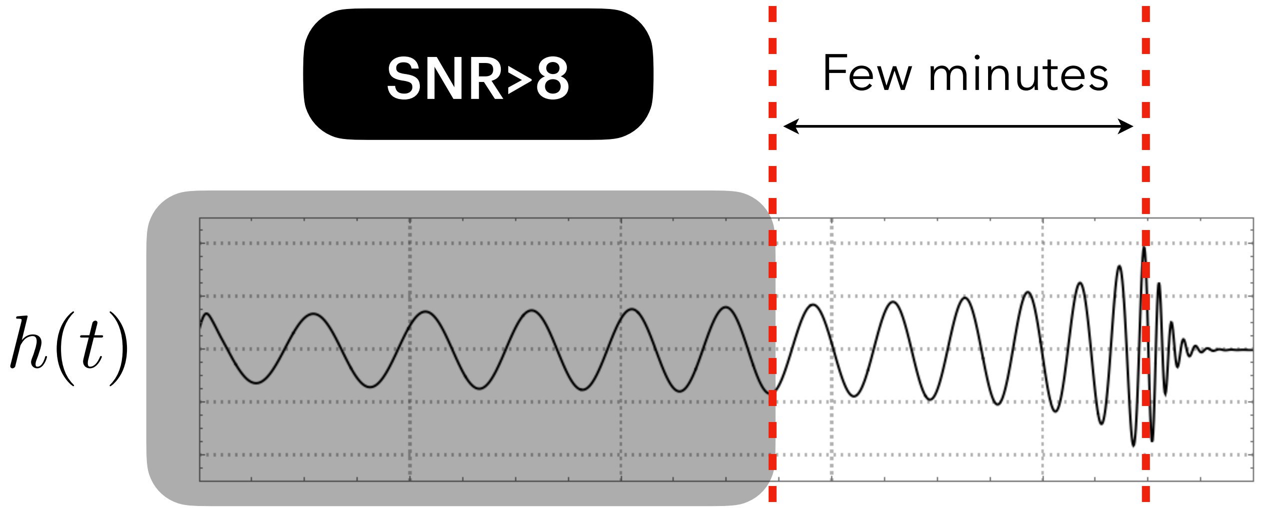
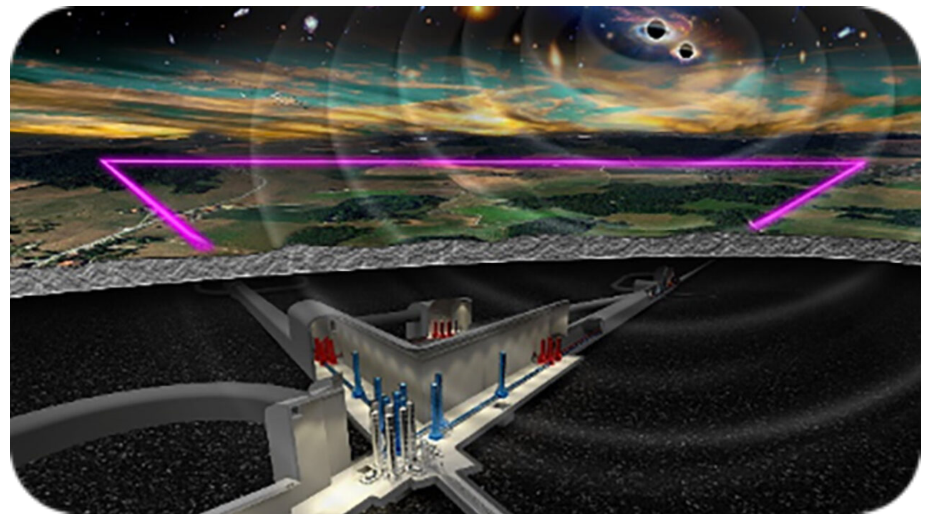
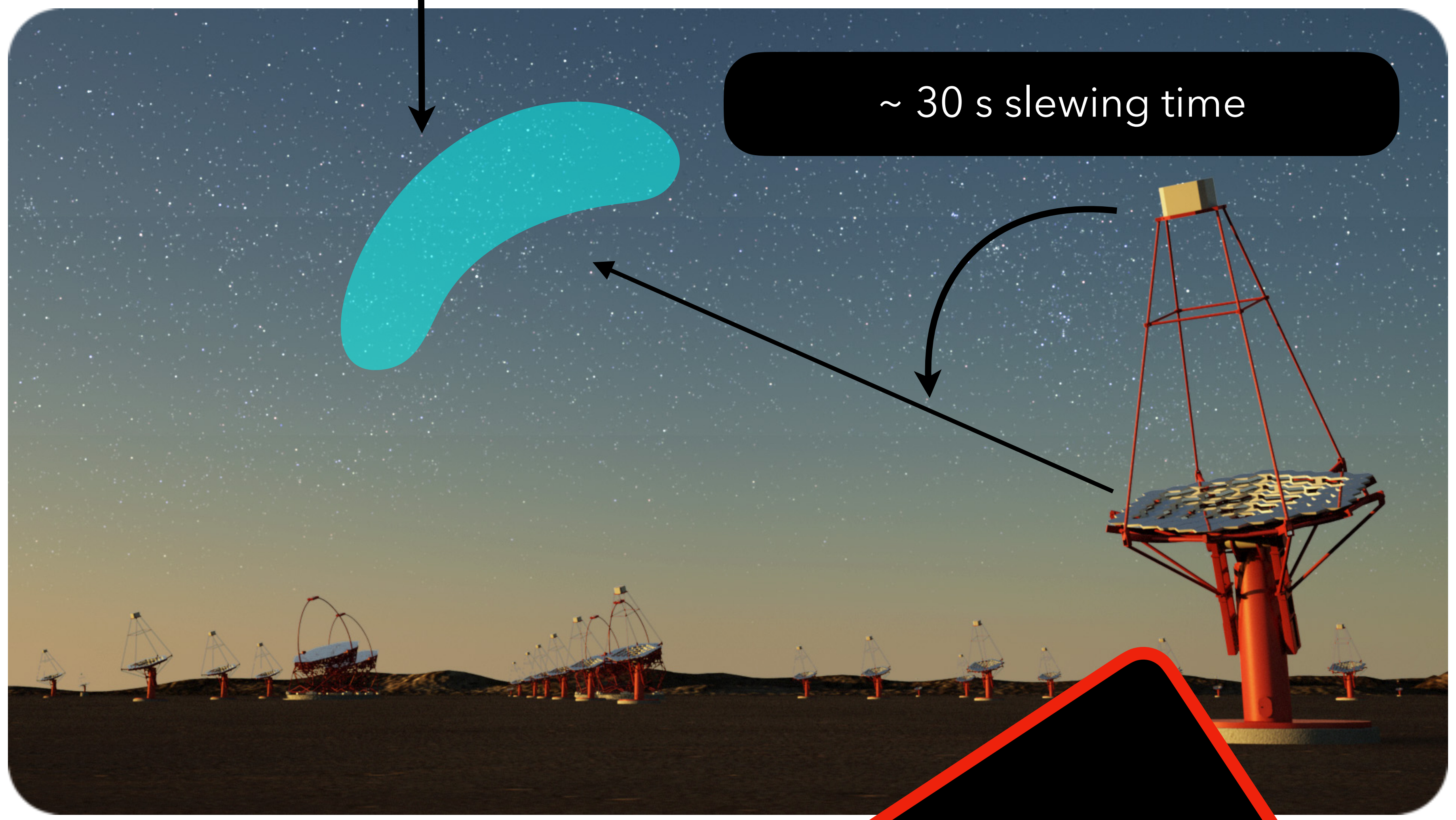




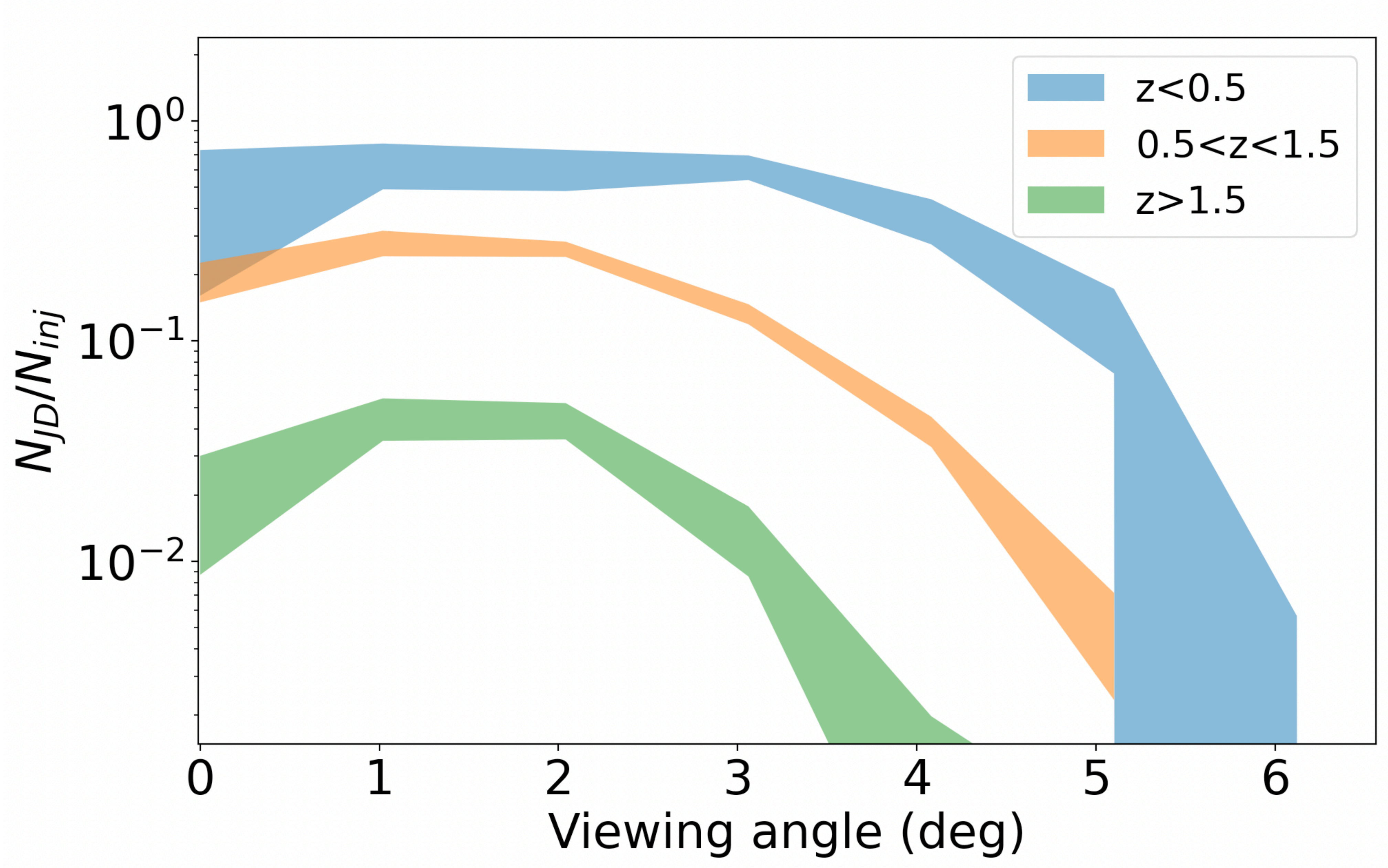


Future Cherenko… …A, will be able t… …n of the GRB… …merger, allow… **…sible very-high energy… …during the prompt phase**

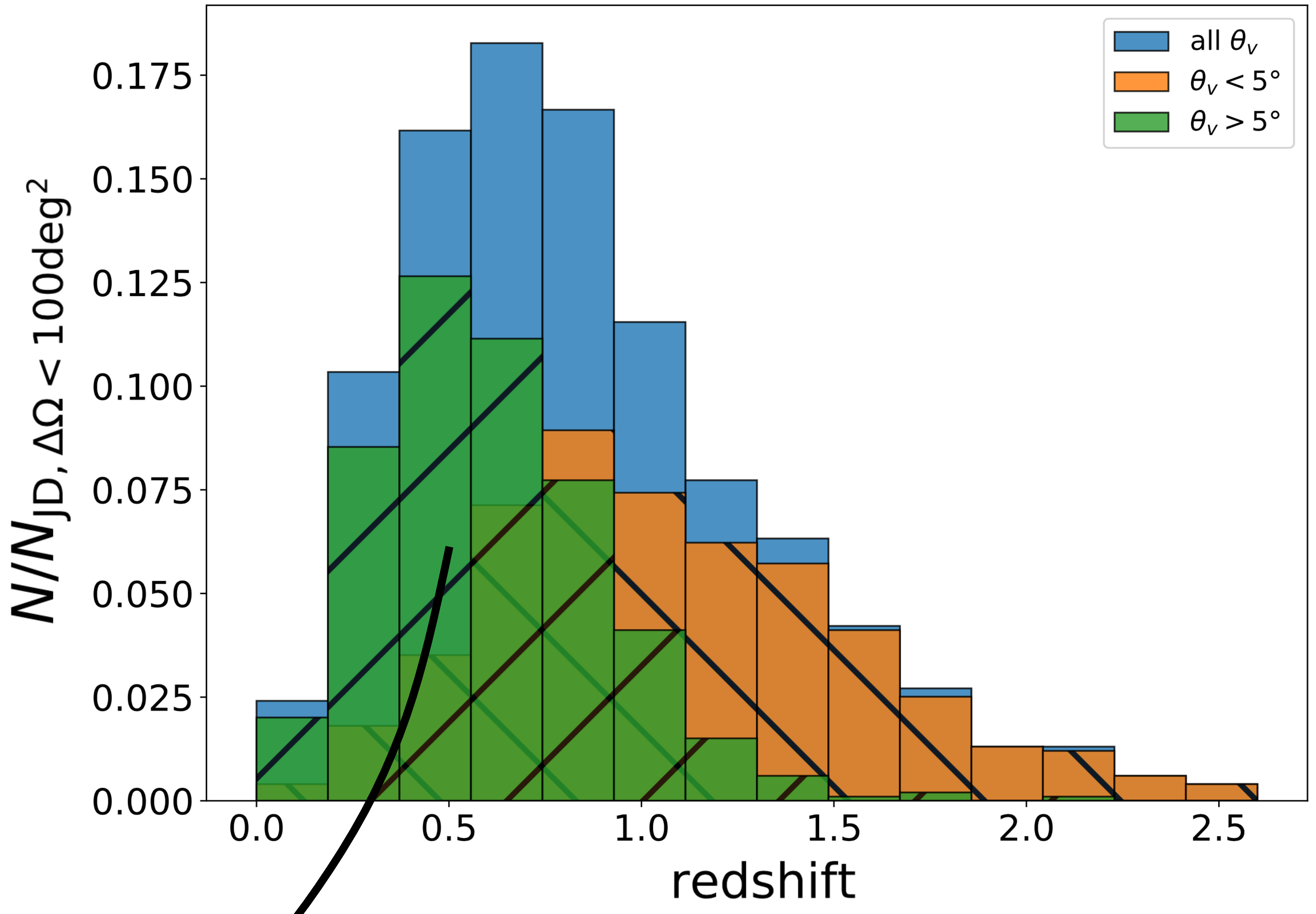
Look at the B. Banerjee's talk!

The importance of WFX-ray telescopes

Joint γ-ray+GW detection efficiency (ET+Fermi-GBM)



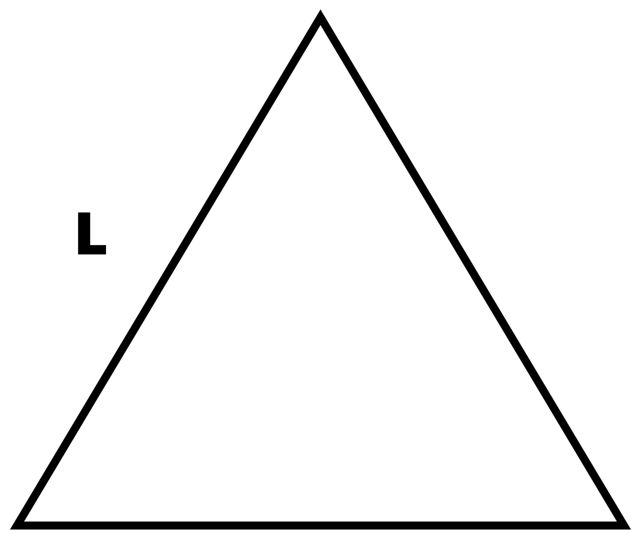
Redshift distribution of joint X-ray+GW detections, in pointing mode



Too off-axis to have a detectable γ-ray emission

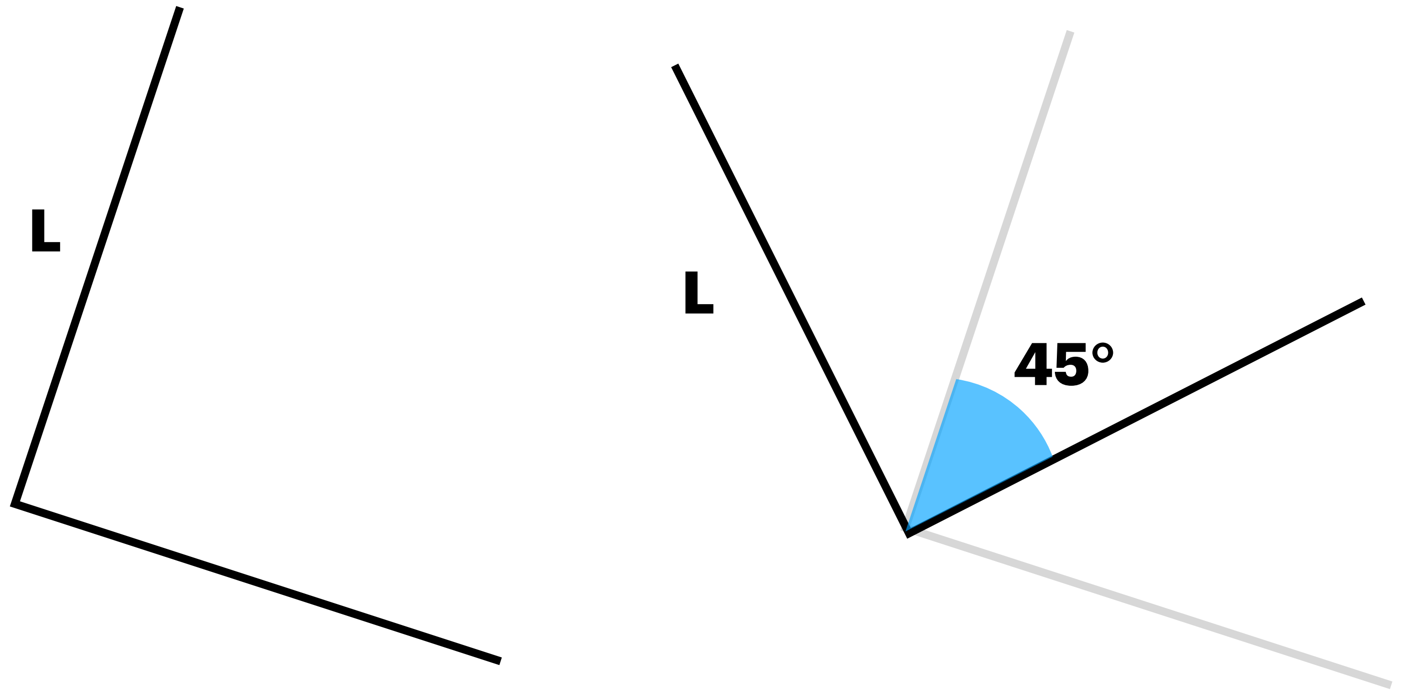
WFX-ray telescopes can significantly **enhance the probability of a joint detection**

Delta: 10 km or 15 km



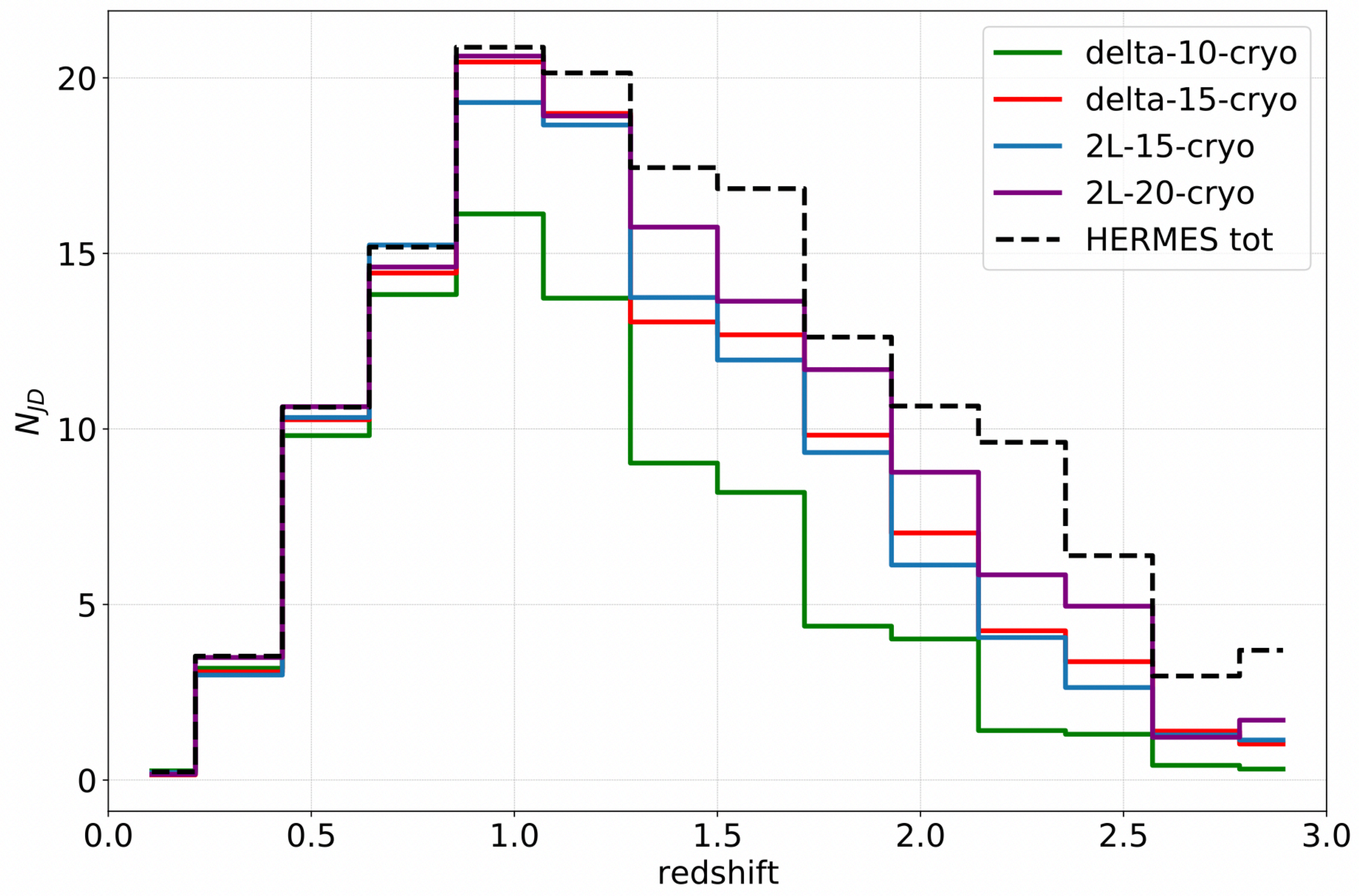
Sardinia

2L misaligned: 15 km or 20 km



Sardinia Meuse-Rhine

Joint GW + prompt emission



$$\Delta\, 10\, km < \Delta\, 15\, km \sim 2L\, 15\, km < 2L\, 20\, km$$

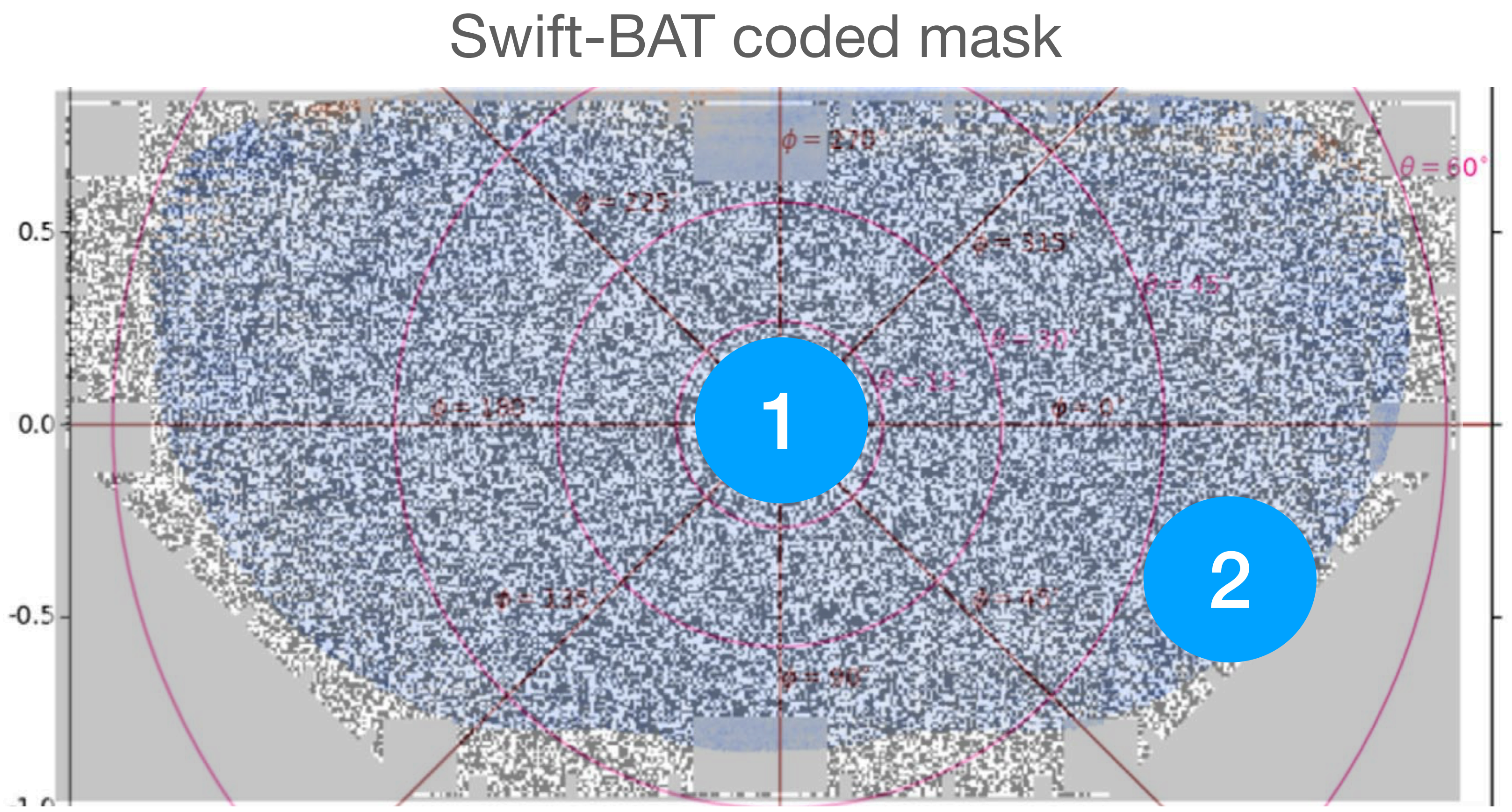
Joint GW + afterglow emission

Full (HFLF cryo) sensitivity detectors

Instrument	$\Delta 10$	$\Delta 15$	2L 15	2L 20
THESEUS-SXI survey	10^{+3}_{-2}	13^{+3}_{-4}	12^{+3}_{-3}	12^{+3}_{-3}
THESEUS-(SXI+XGIS) survey	21^{+6}_{-7}	21^{+8}_{-6}	20^{+7}_{-5}	21^{+7}_{-7}

The ET design does not impact sensibly the joint detection efficiency with WFX-ray telescopes

Optimize the synergy with Swift-like telescopes



Some GRBs potentially detectable by Swift-BAT are missed because, e.g.:

- occurring close to the edge of the coded mask
- Occurring during slew
- Located out of the FOV

We can recover them, with a deeper low-latency analysis

↓

GUANO

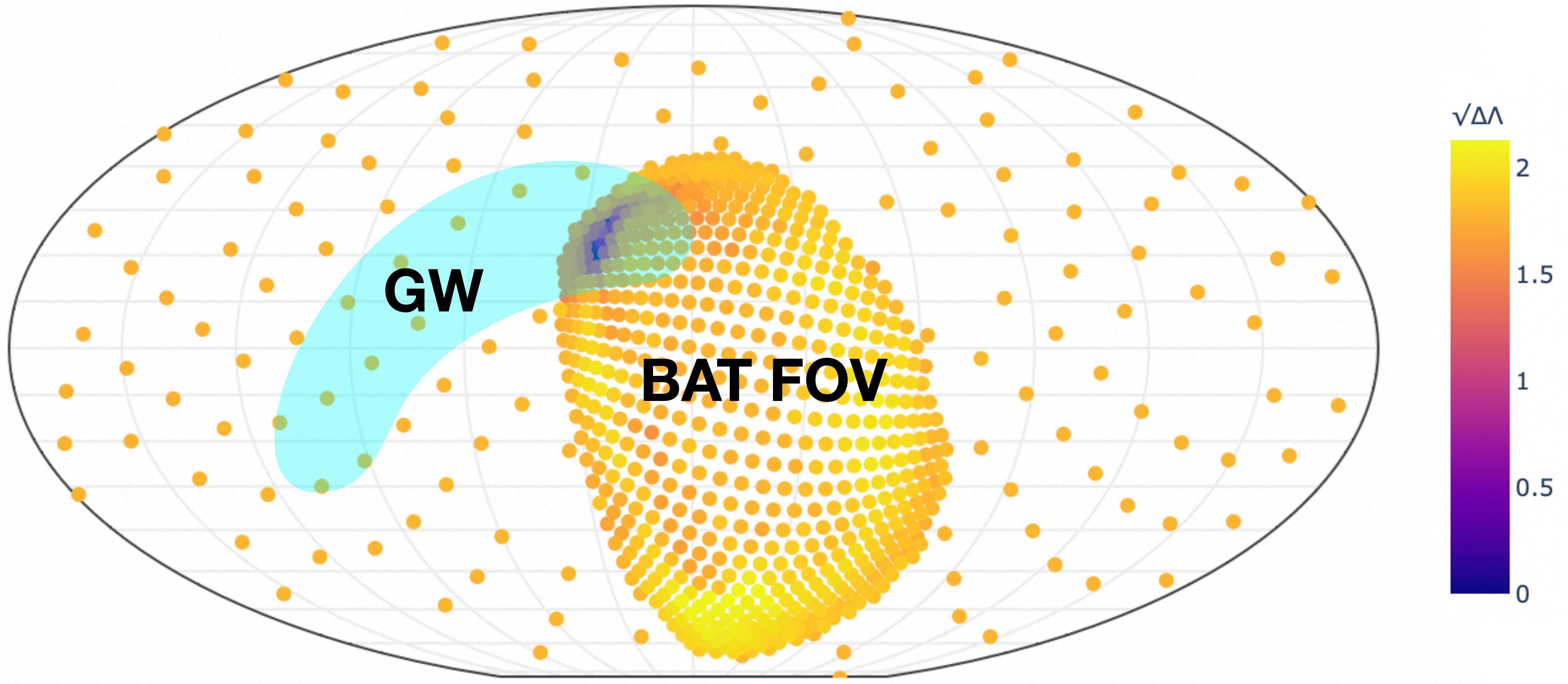
Tohuvavohu et al. 2020

The efficiency of the trigger algorithm degrades as we move from the center of the FoV

1 $P(det|F > F_{th}) = 100\%$

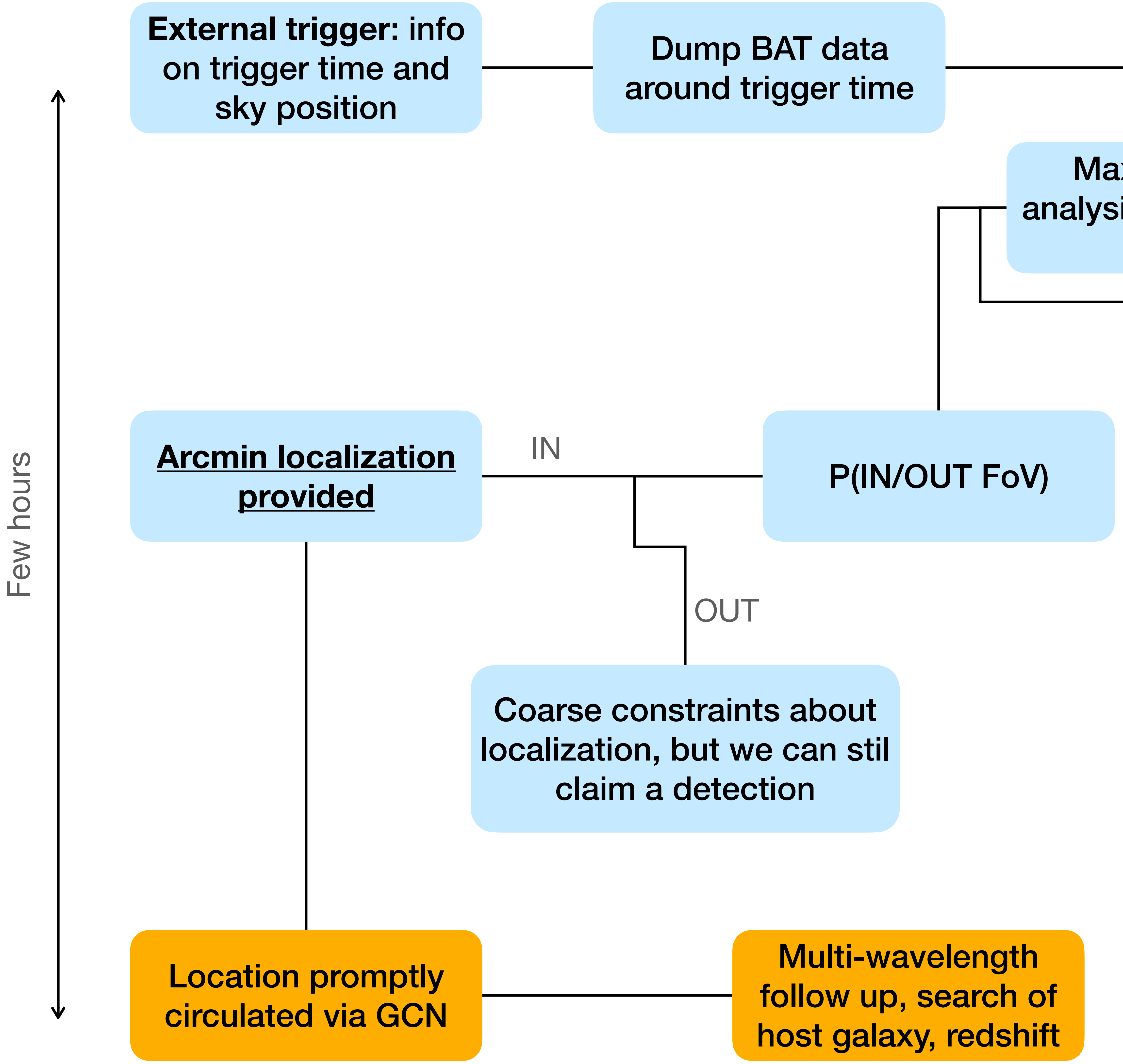
2 $P(det|F > F_{th}) < 100\%$

Application to the multi-messenger science case:



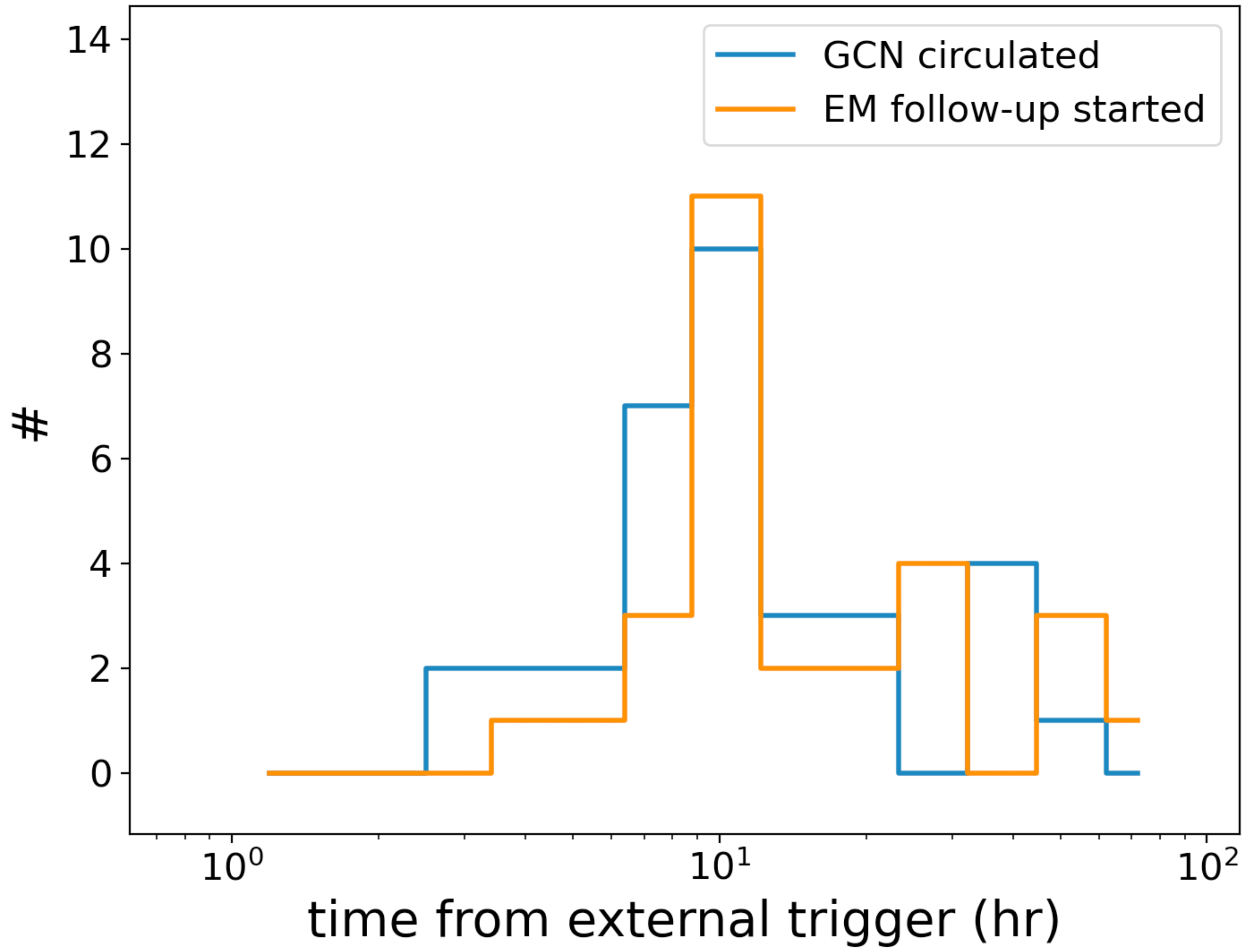
1. GW trigger
2. Swift-BAT does not trigger
3. The GUANO analysis reveals a significant event, **providing arcmin localization**
4. EM follow up

GUANO workflow and results



Successfully operative in O3, both for above- and sub-threshold events

Ready to run in low-latency also **during O4**



Ingested external triggers:

- Fermi/GBM, Integral, Calet, GECAM
- **GWs**
- IceCube
- HAWC
- FRBs

Success rate:

- **more than 100 GRBs recovered with GUANO** so far
- **32 with arcmin position** (24 long + 8 short)
- **In 14** of them **the afterglow emission was detected** (1/2 of which are short)

Summary

- The remarkable capabilities of next generation GW detectors will allow us to **probe compact binary mergers at cosmological distances**

- The existence of **wide field** X-ray and γ-ray monitors in the next decades will be **crucial,** in order to localize the EM counterpart and possibly identify the host galaxy with ground-based telescopes

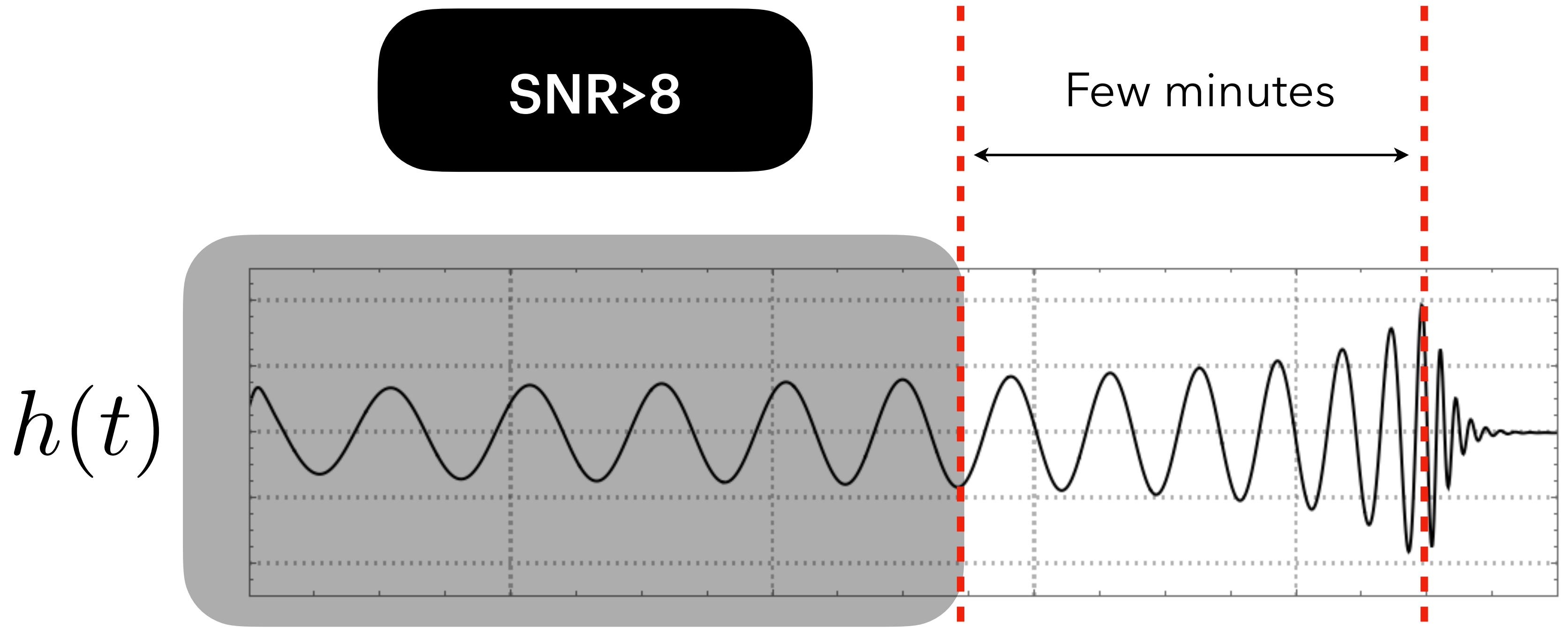
- It is necessary to define an **optimal strategy to select GW events, based on the estimation of the GW parameters,** for which the detection probability of the EM signal is higher

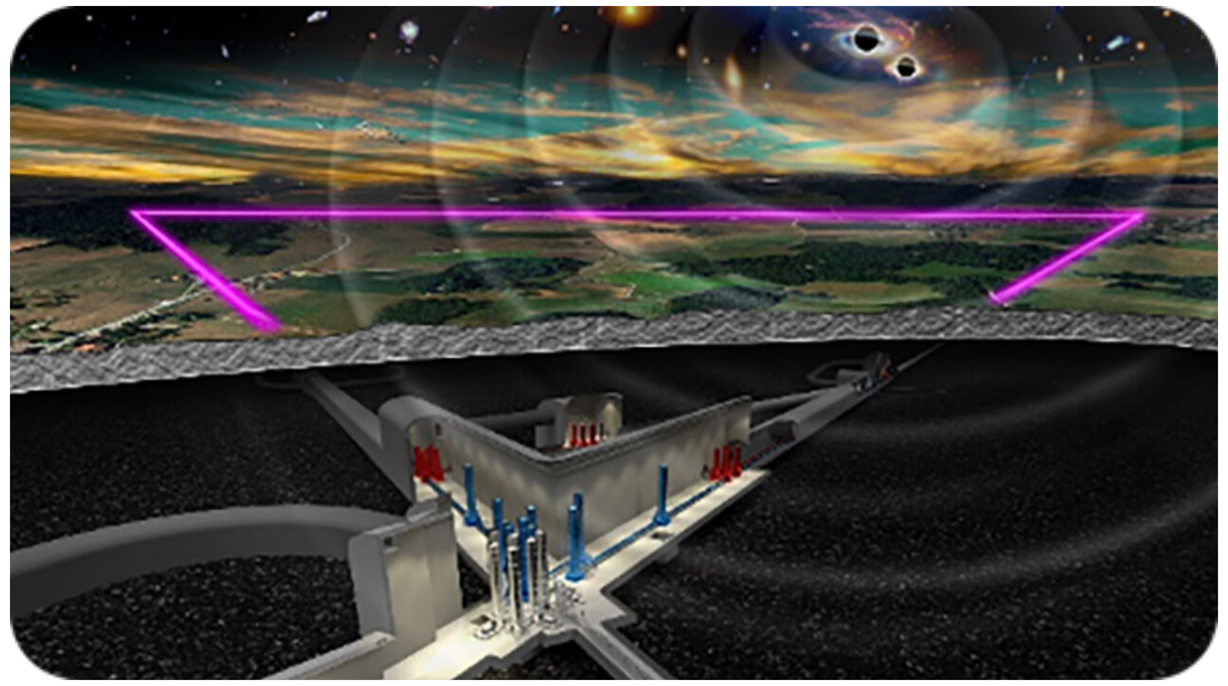
- The developed methodology for the estimation of GW+EM detection is **highly versatile** $\Rightarrow$ applicable to different combinations of instruments and for different models of emission

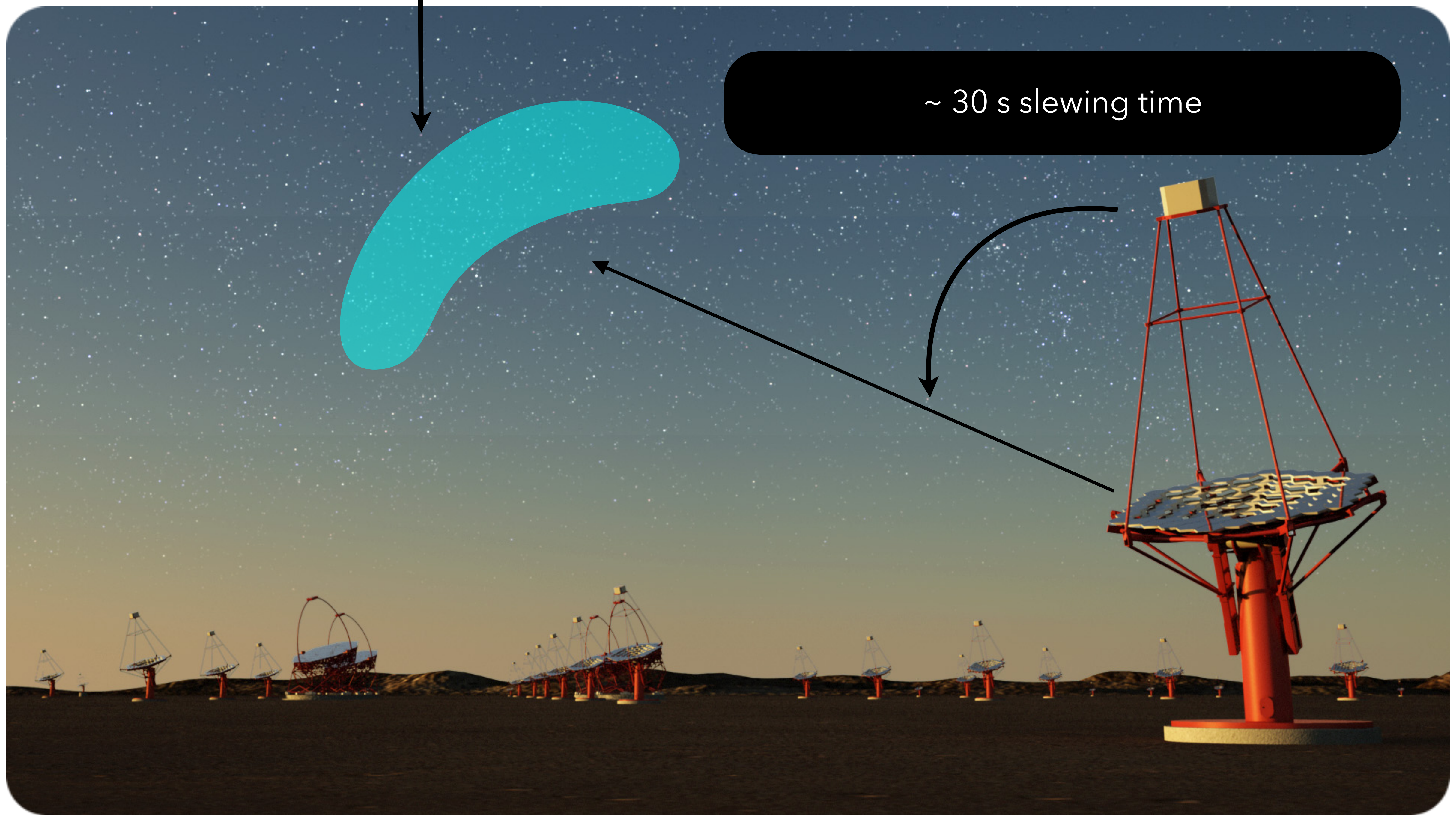
- **Low-latency analysis** with pipelines like GUANO can **further enhance the detection potential of Swift-like instruments**, maximizing the probability of detecting and localizing the EM counterpart

Thank you!

Pre-merger sky localisation and VHE from sGRBs

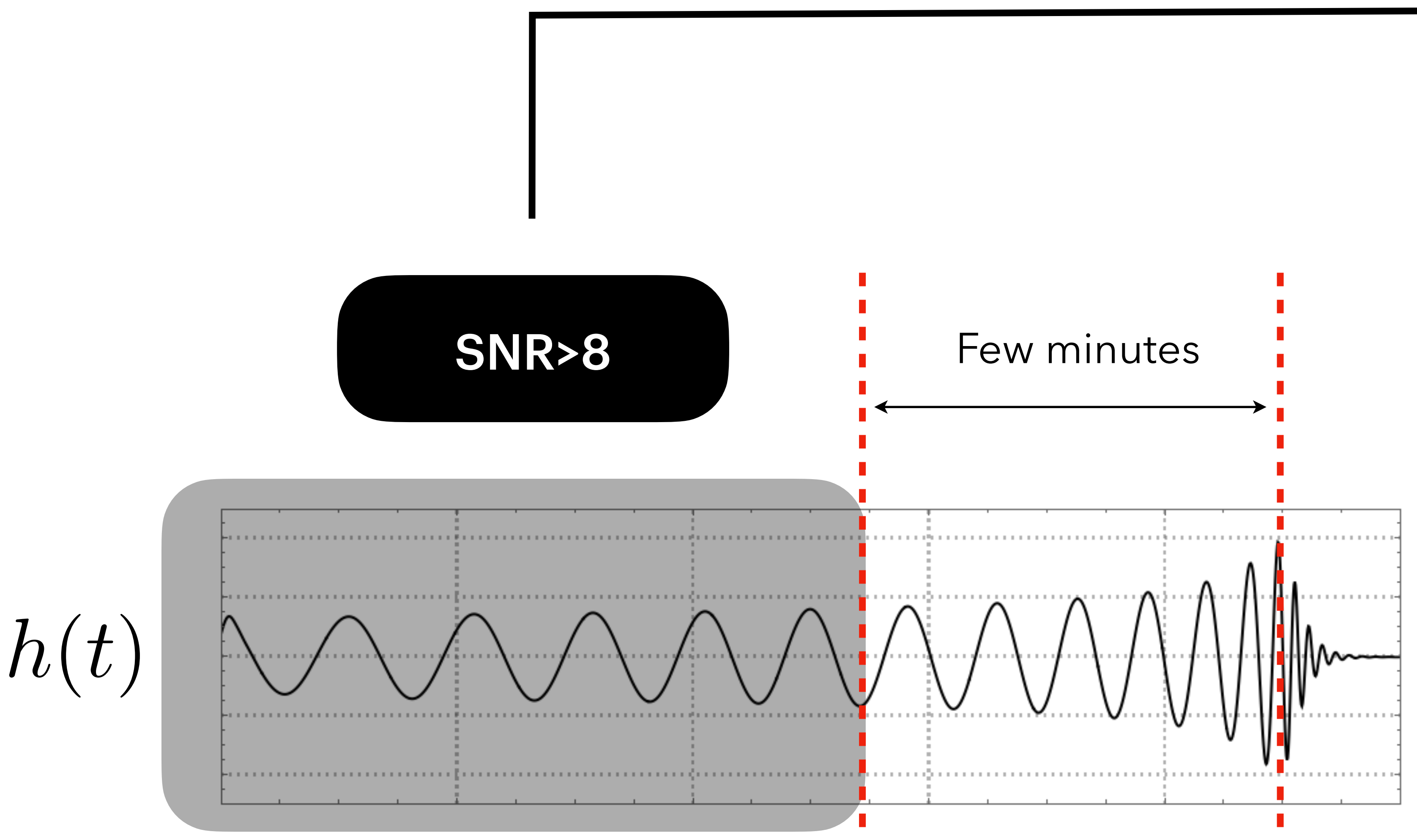


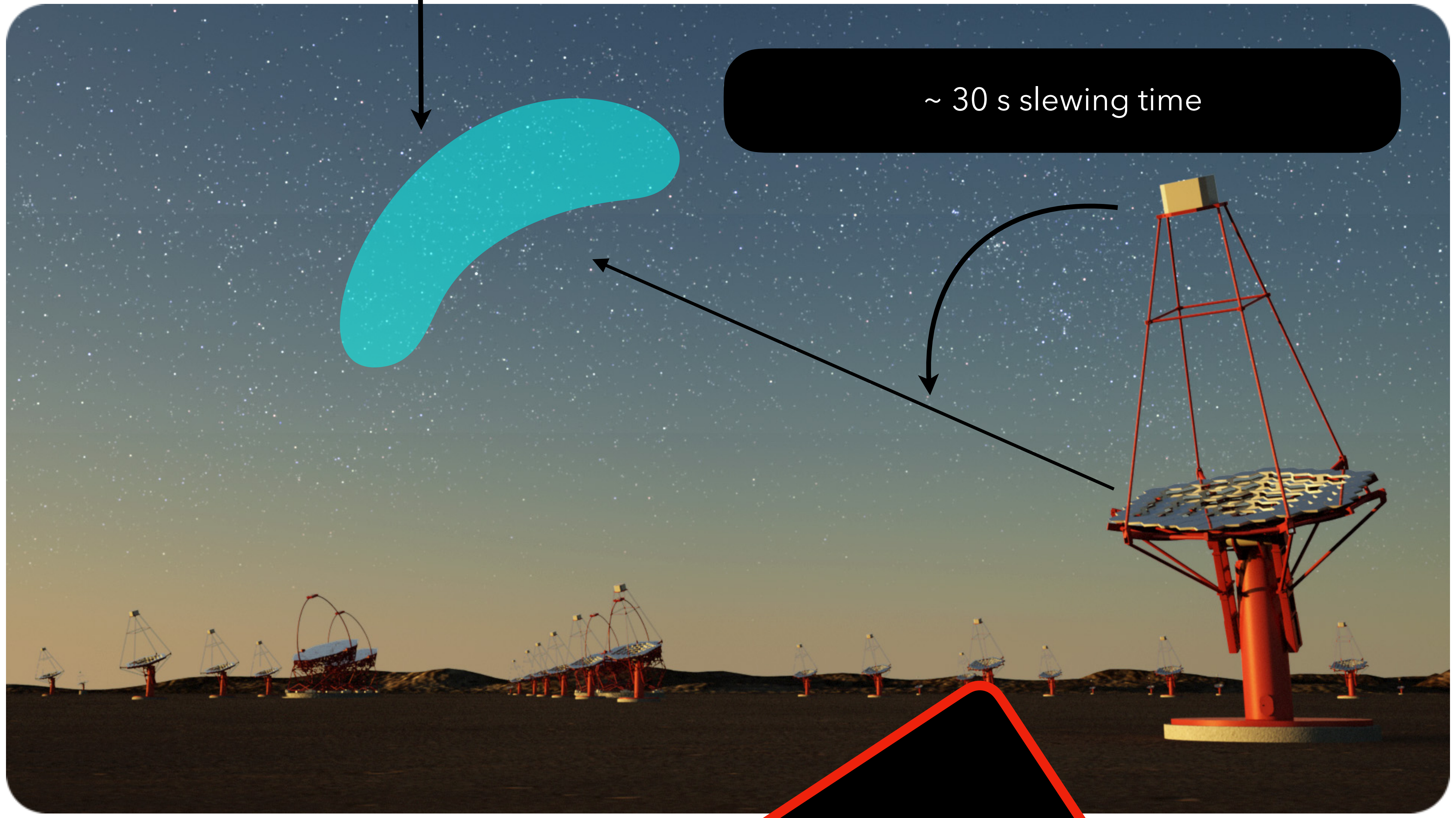


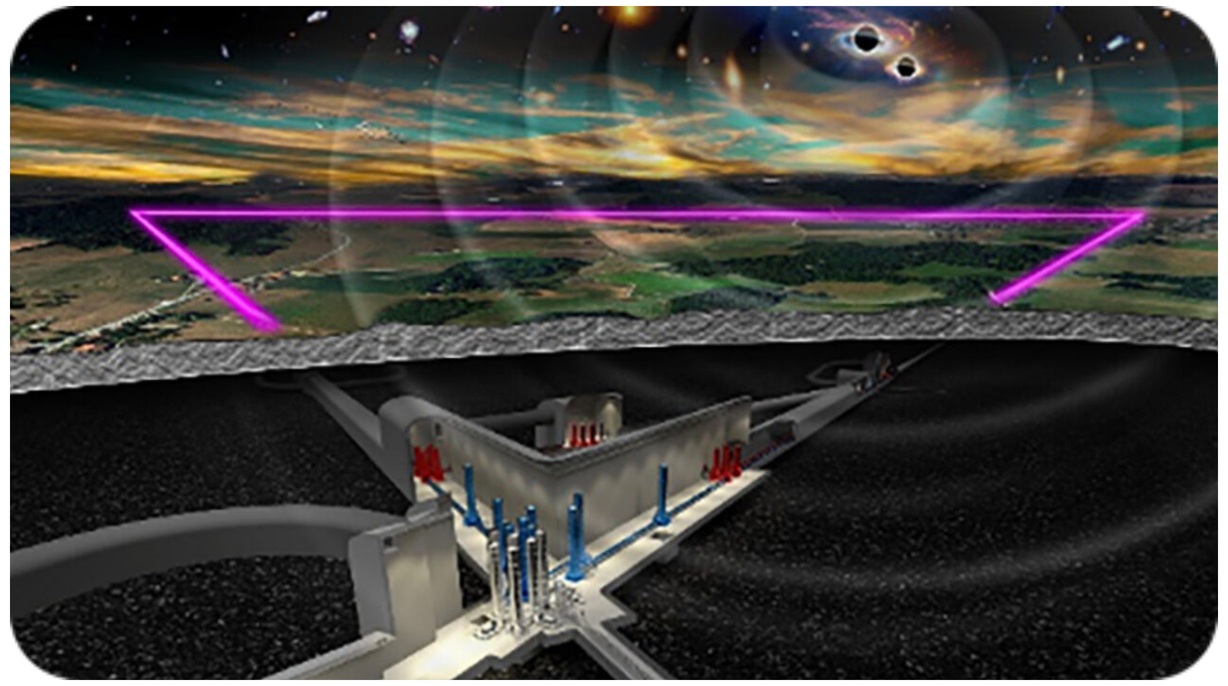


Future Cherenkov telescopes, like CTA, will be able to point in the direction of the GRB at the moment of the merger, allowing to **detect possible very-high energy emission during the prompt phase**

Pre-merger sky localisation and VHE from sGRBs





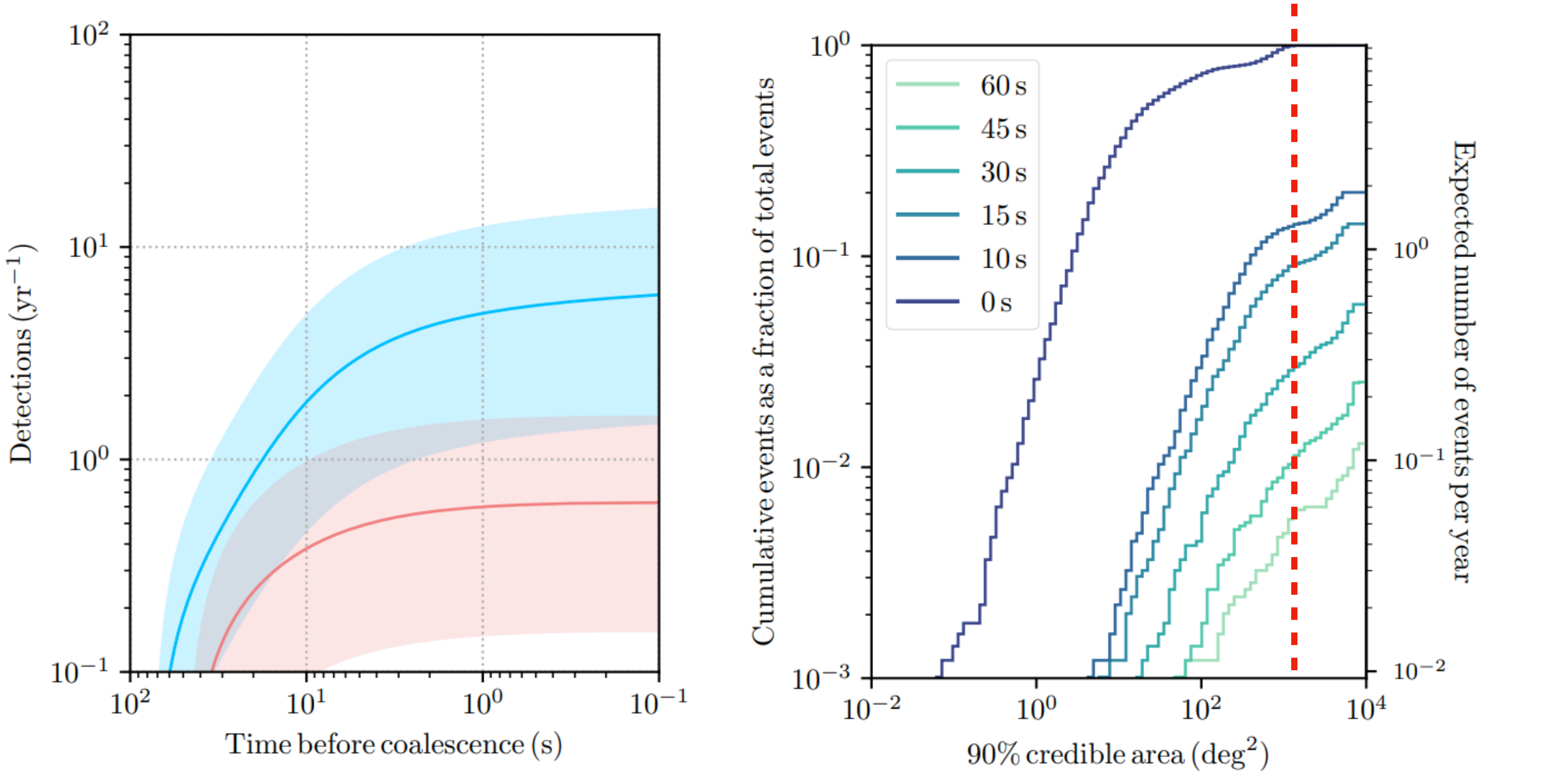


Future Cherenk… CTA,
will be able t… ion of the
GR… he merger,
al… **ssible very-high**
e… during the prompt
phase

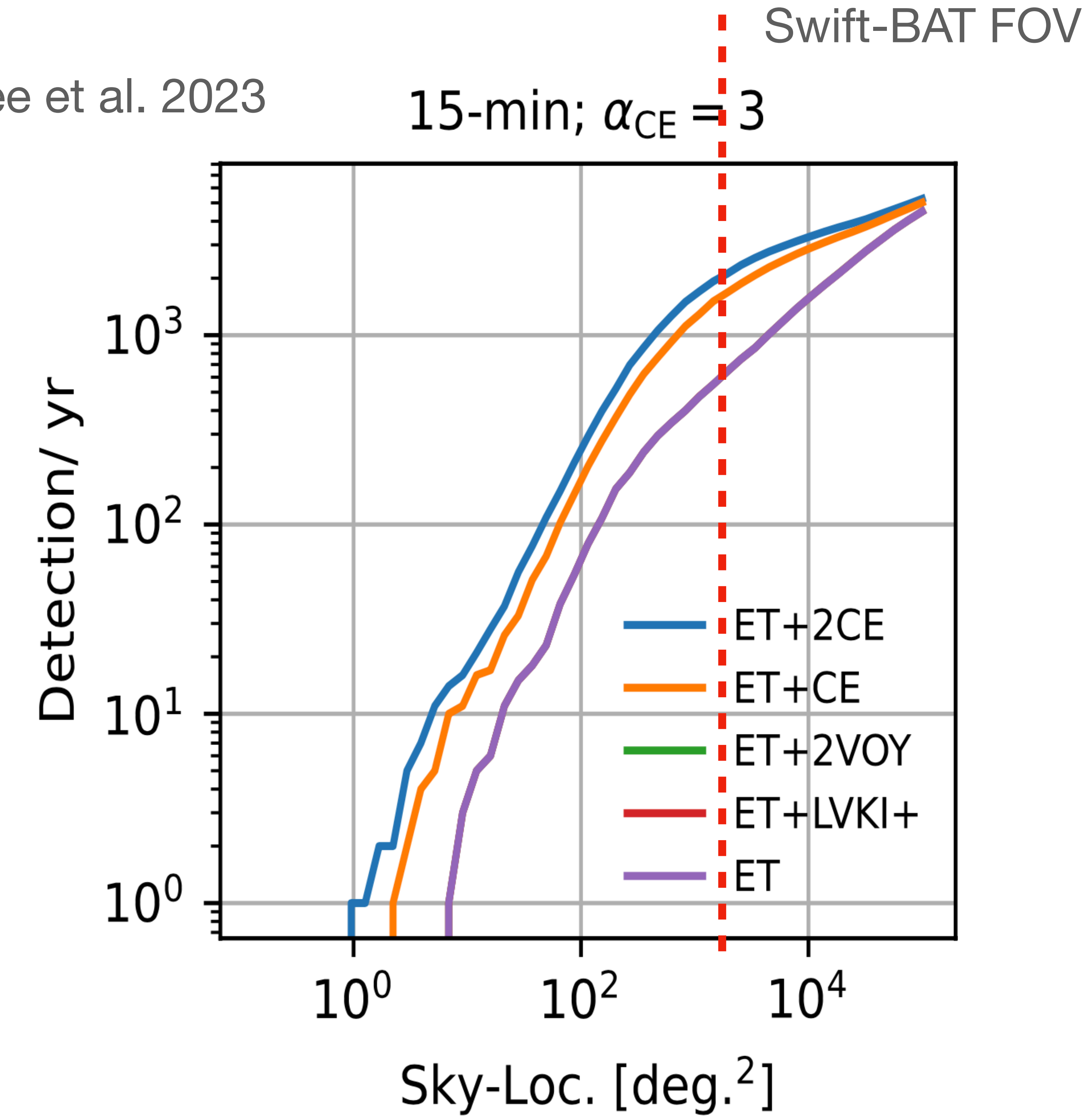
Look at the B. Banerjee's talk!

Pre-merger localization with Swift-like telescopes in the ET era

From Magee et al. 2021



Banerjee et al. 2023



In O4: < ~ 1 BNS pre-merger detections

In the ET era: ~ **100 BNS pre-merger detections** with $\Delta\Omega$ < Swift/BAT field of view

Continuous commanding already tested: few seconds between command sent from ground and start of spacecraft slew → Further feasibility tests will be performed in O4 → To be ready to routinely ingest pre-merger alerts in the ET era