Perspectives for multi-messenger astronomy with the next generation of gravitational-wave detectors and high-energy satellites

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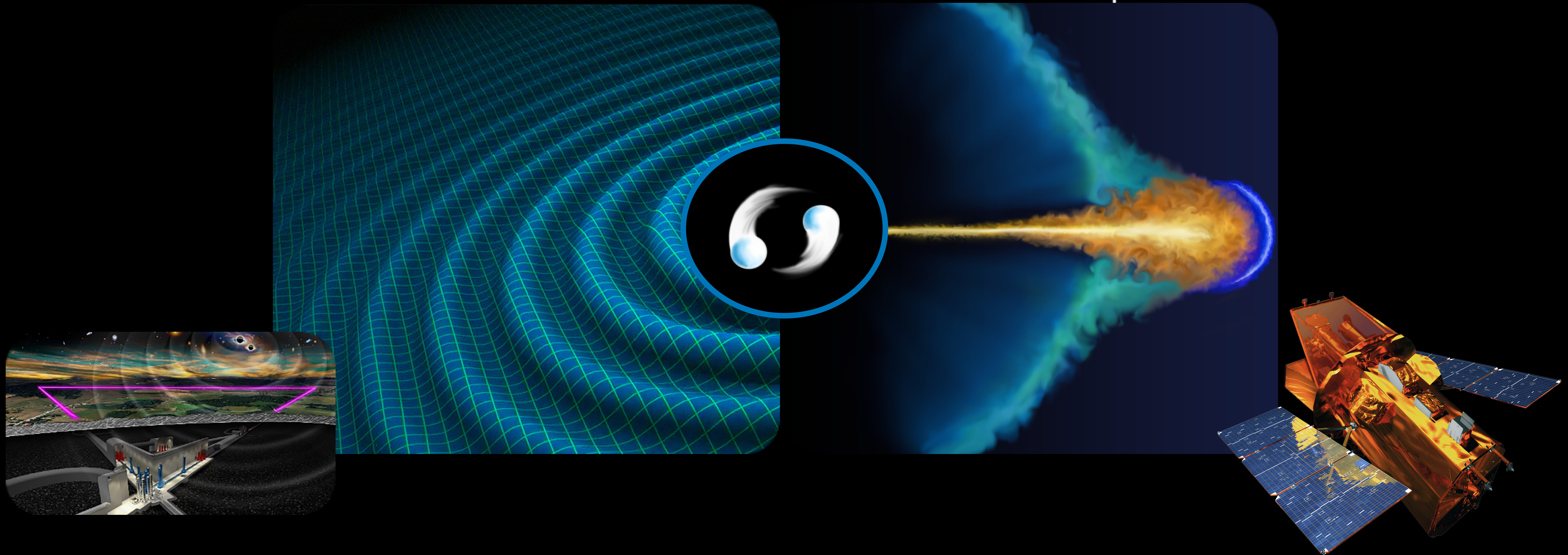
GSSI GRAN SASSO SCIENCE INSTITUTE SCHOOL OF ADVANCED STUDIES Scuola Universitaria Superiore

GSSI GW team

AHEAD 2020 HIGH ENERGY ASTROPHYSICS

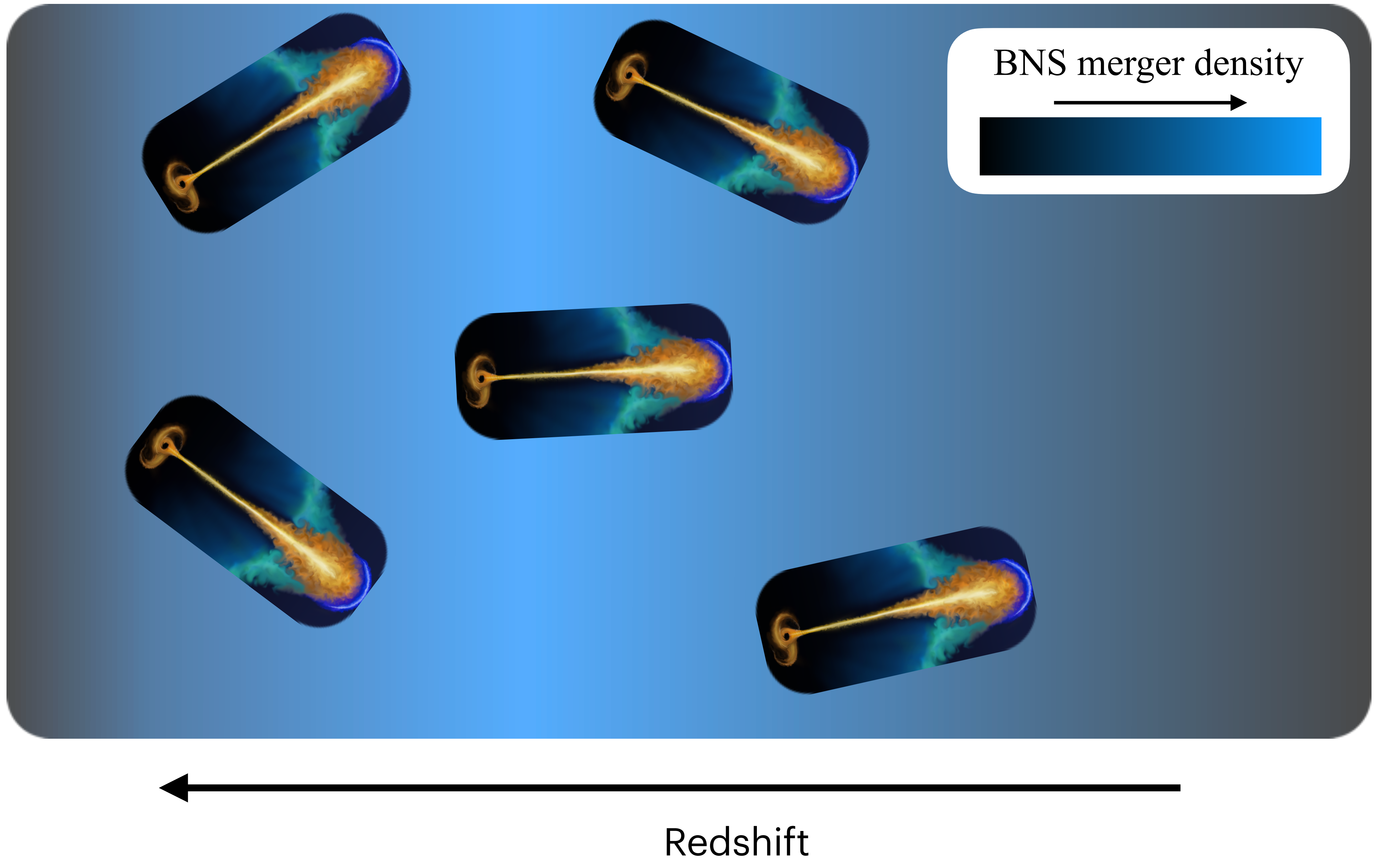


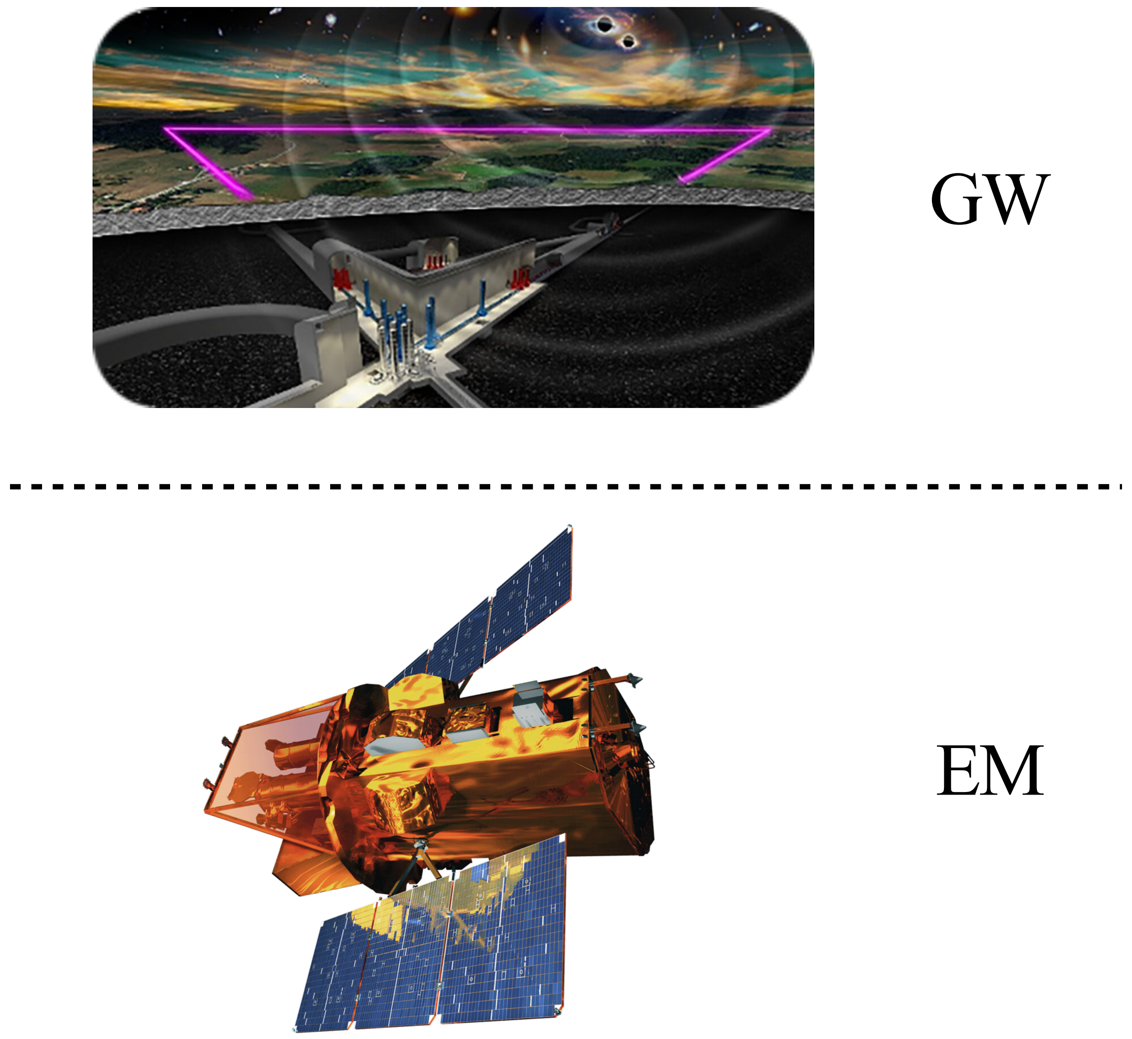
Ronchini et al. 2022, doi.org/10.1051/0004-6361/202243705

We acknowledge the INFN Computing Center of Turin for computational resources

Overview

Goal of this presentation:
Provide an exhaustive view about the **joint detection** of:
1. **gravitational waves (GWs)**
2. Electromagnetic counterpart in the **high energy domain**
from the coalescence of **binary NS**, in the era of **3G GW detectors**





Points on which I will focus:

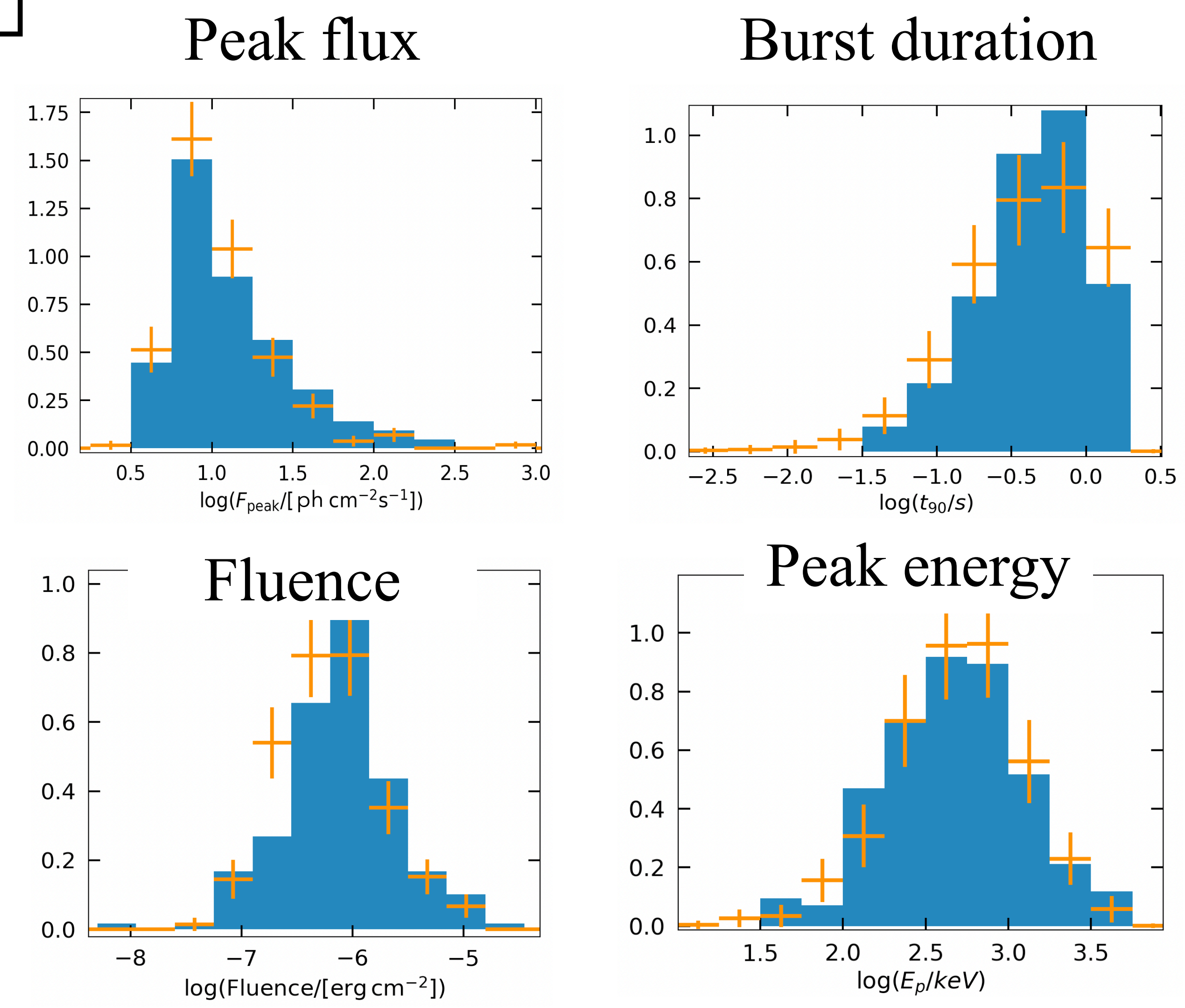
- Role of **wide field instruments** for the identification of the EM counterpart
- GW **sky localisation**
- For the follow-up, define a strategy to **prioritise the GW sources** with highest probability to have detectable EM emission
- Role of **sensitive telescopes** to characterise the multi-wavelength emission

Method: from BNS mergers to short GRBs

Redshift distribution of BNS mergers from population synthesis model

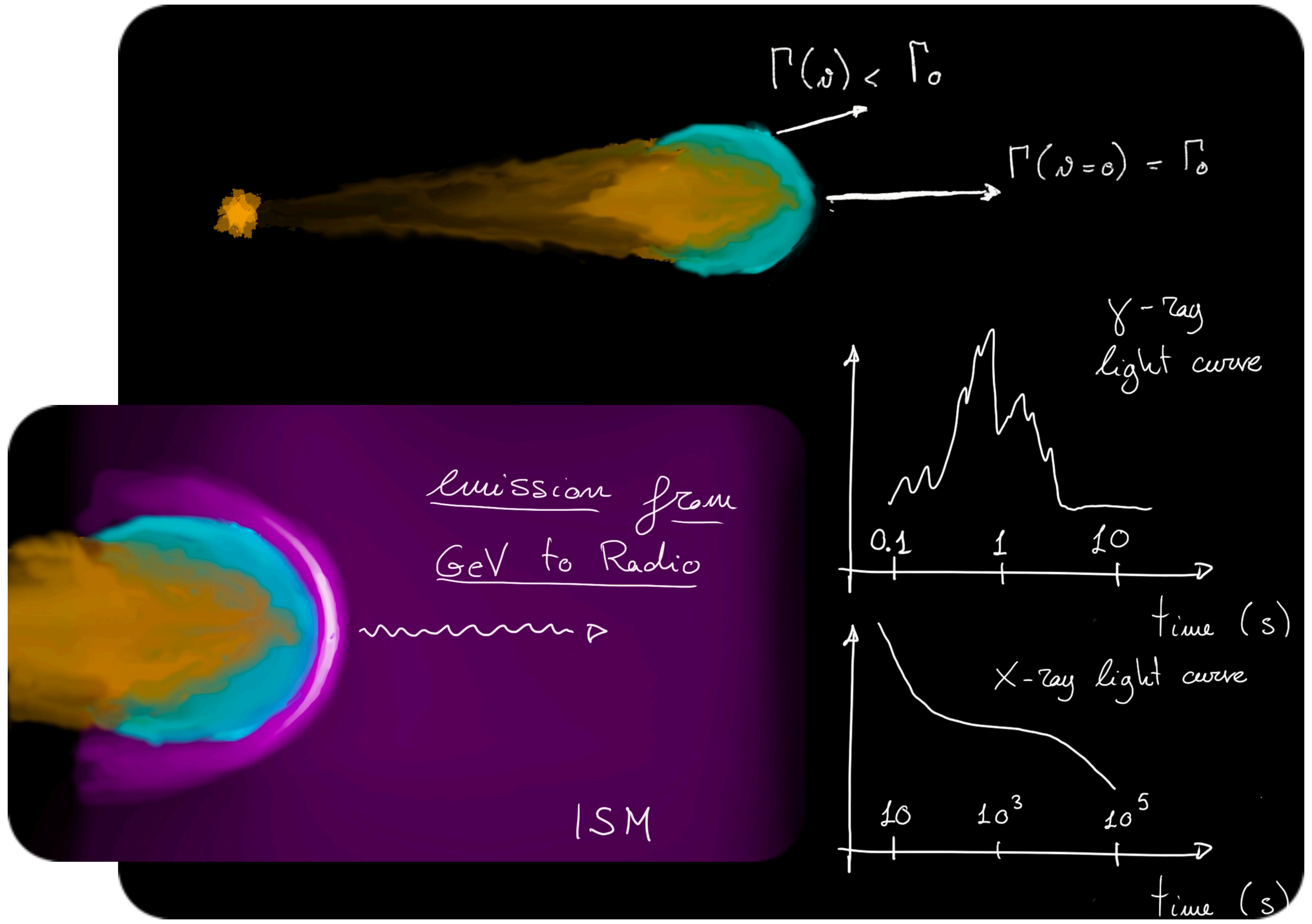
Phenomenological model for prompt emission

Comparison with properties of Fermi-GBM sample



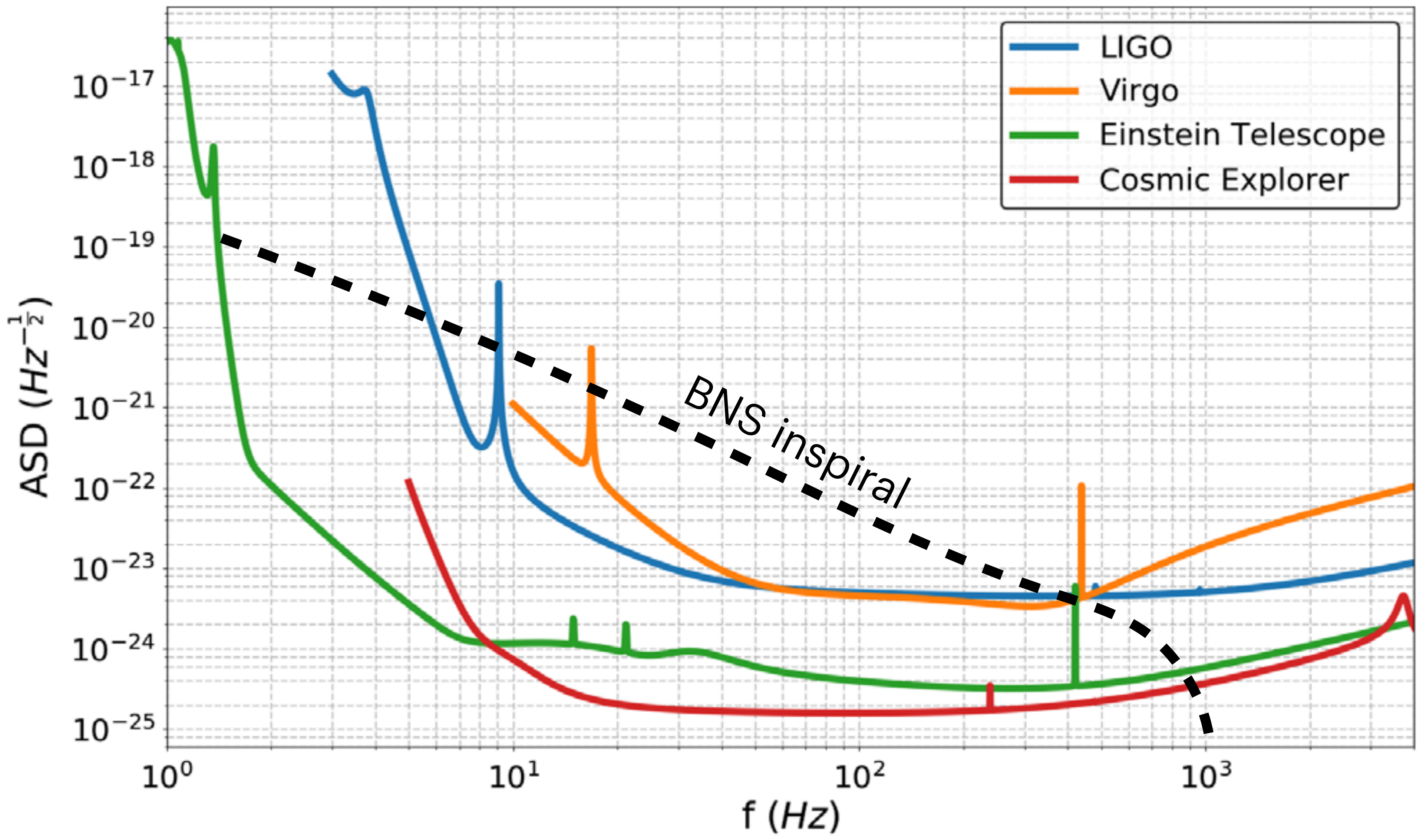
+ Fermi-GBM rate of short GRBs

Estimate of the prompt and afterglow emission, assuming the same jet structure derived for GW 170817

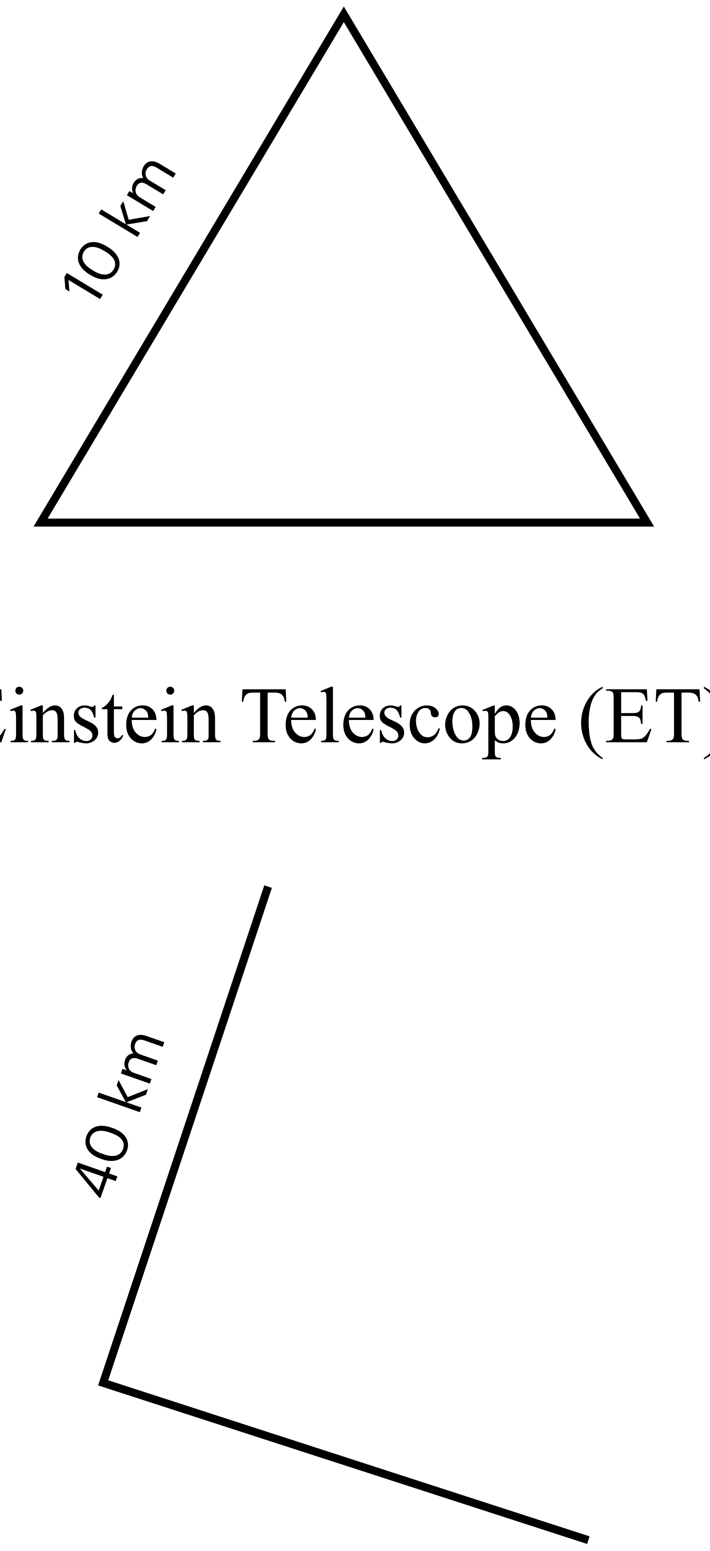


Reliable predictions for future high-energy satellites

The 3rd generation of GW detectors



From Chan et al. 2018



Einstein Telescope (ET)

Cosmic Explorer (CE)

GW Parameter estimation

GWFISH

Harms et al. 2022
arXiv:2205.02499

1. Unprecedented sensitivity which allows to **have access to a yet unexplored region of the Universe**, beyond the star formation peak time

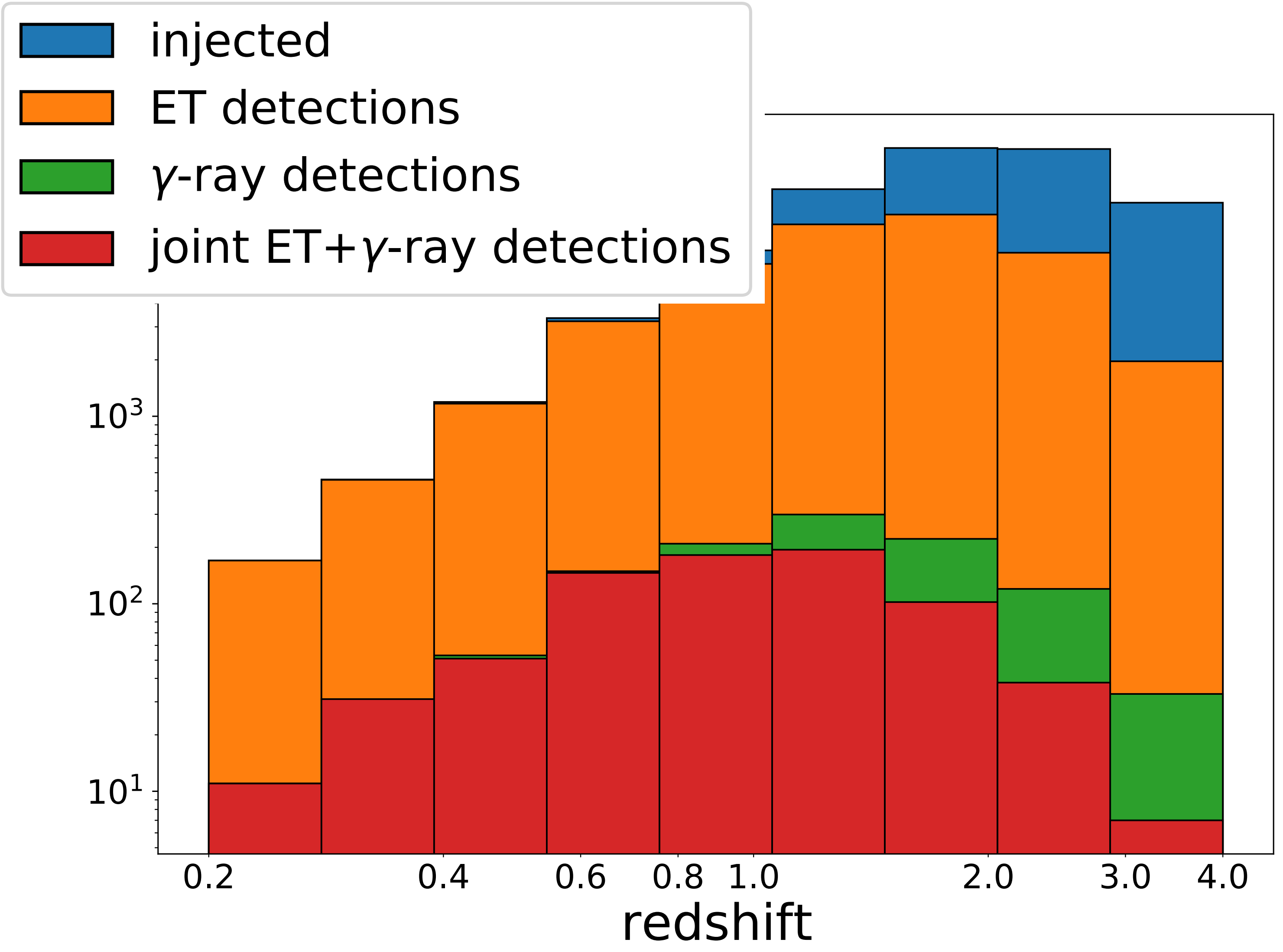
2. Possibility to **probe the early inspiral phase**, relevant for a good estimation of the sky localisation, thanks to the exploitation of Earth rotation

- Based on **Fisher matrix** approximation
- **Fast** and computationally efficient

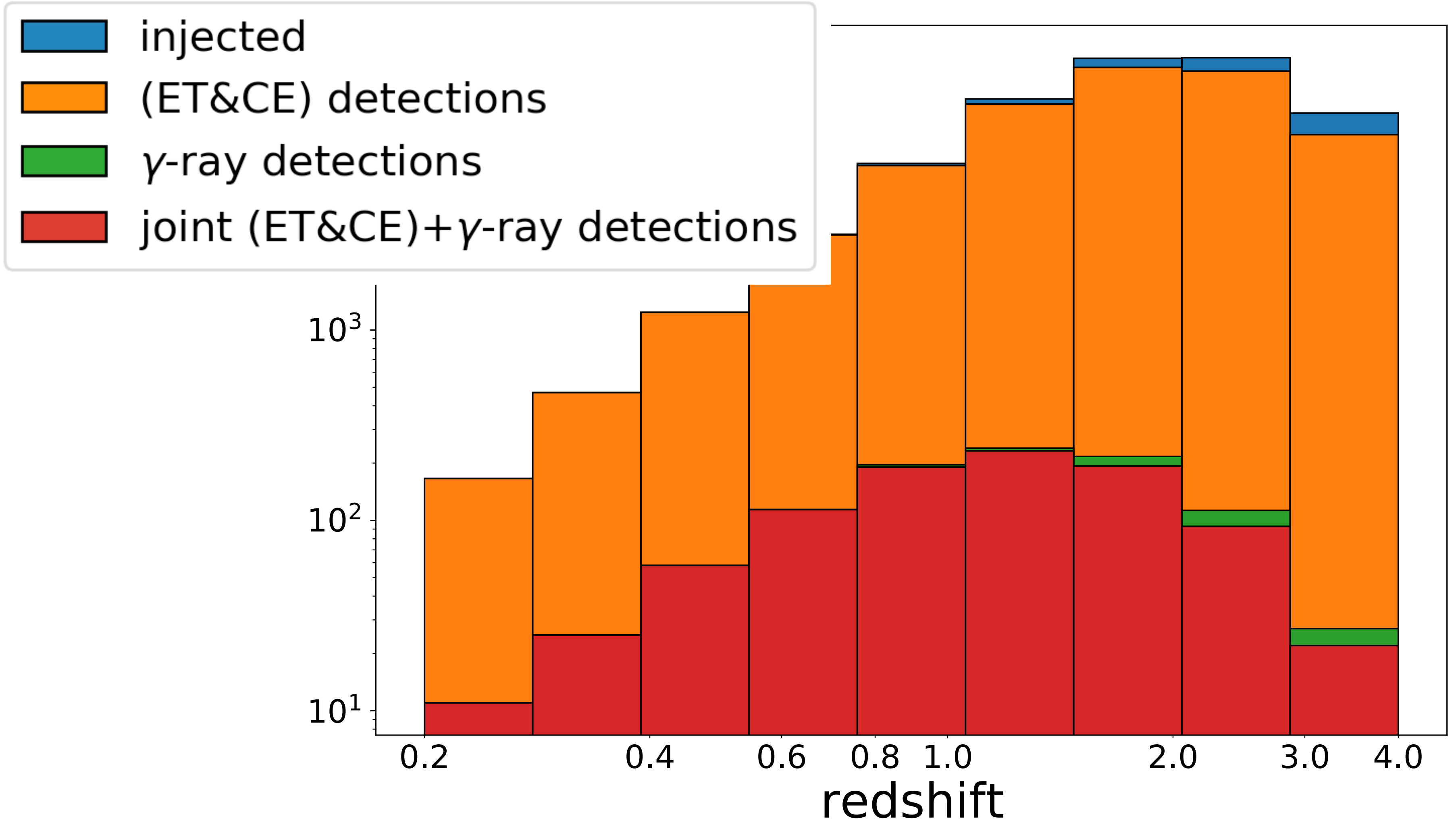
Joint detection of γ-ray emission and GWs

INSTRUMENT	band MeV	$F_{\rm lim}$ erg cm^{-2} s^{-1}	FOV/4π	loc. acc.	Joint ET +γ-ray	N_{JD}/N_γ	Joint (ET+CE) +γ-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	~ 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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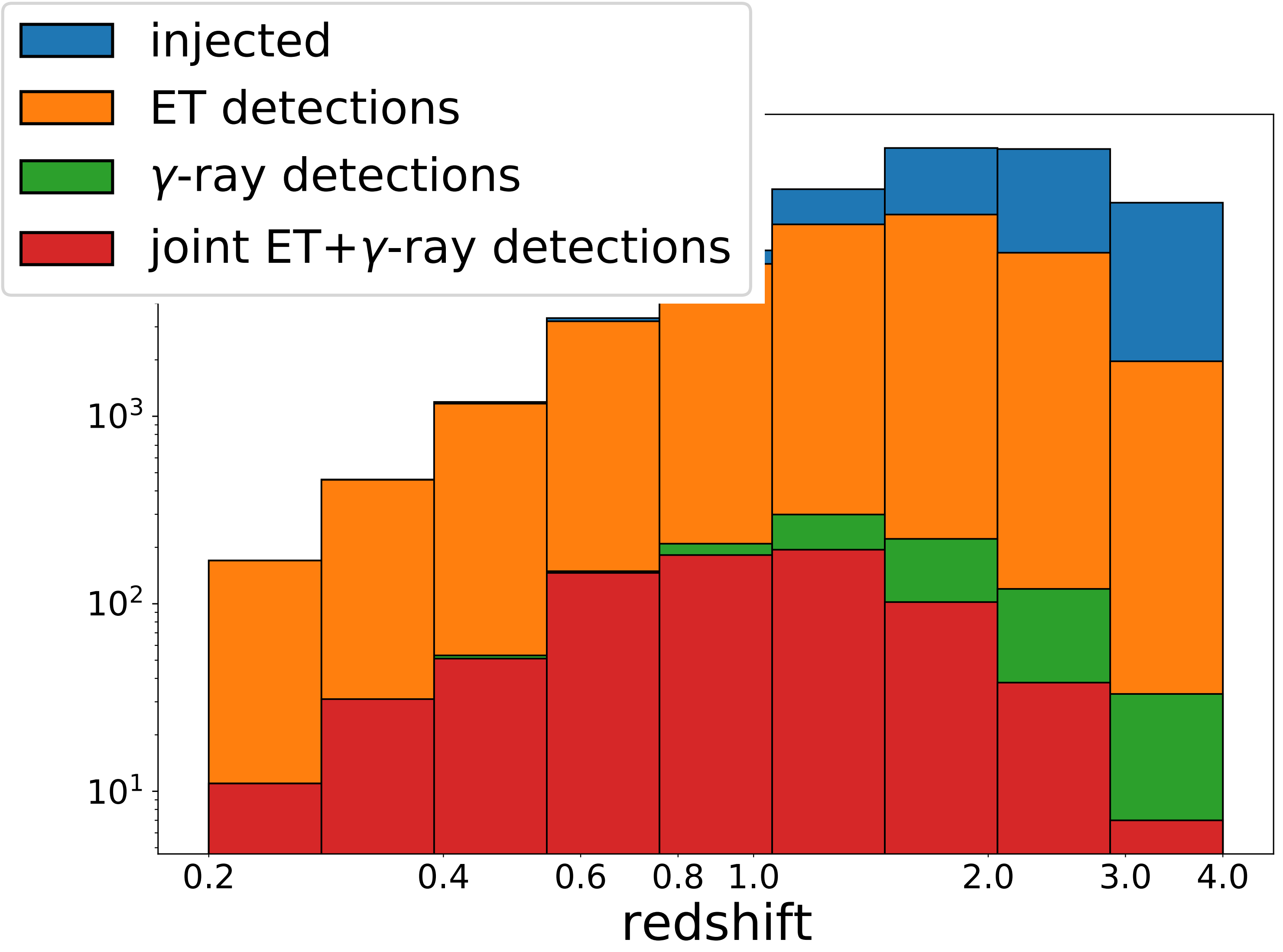
Few but **well localised** events

Fermi GBM+ET



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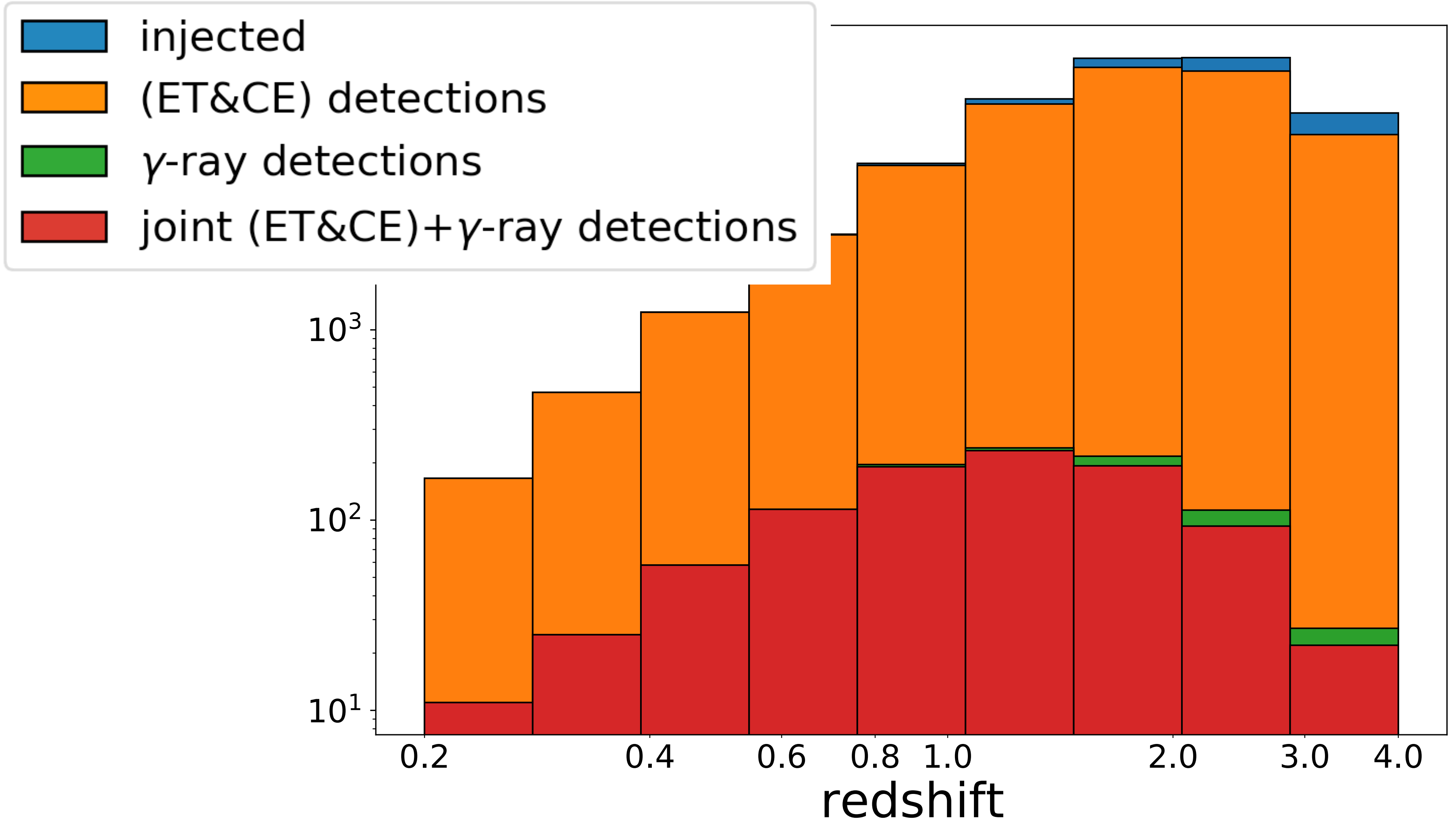

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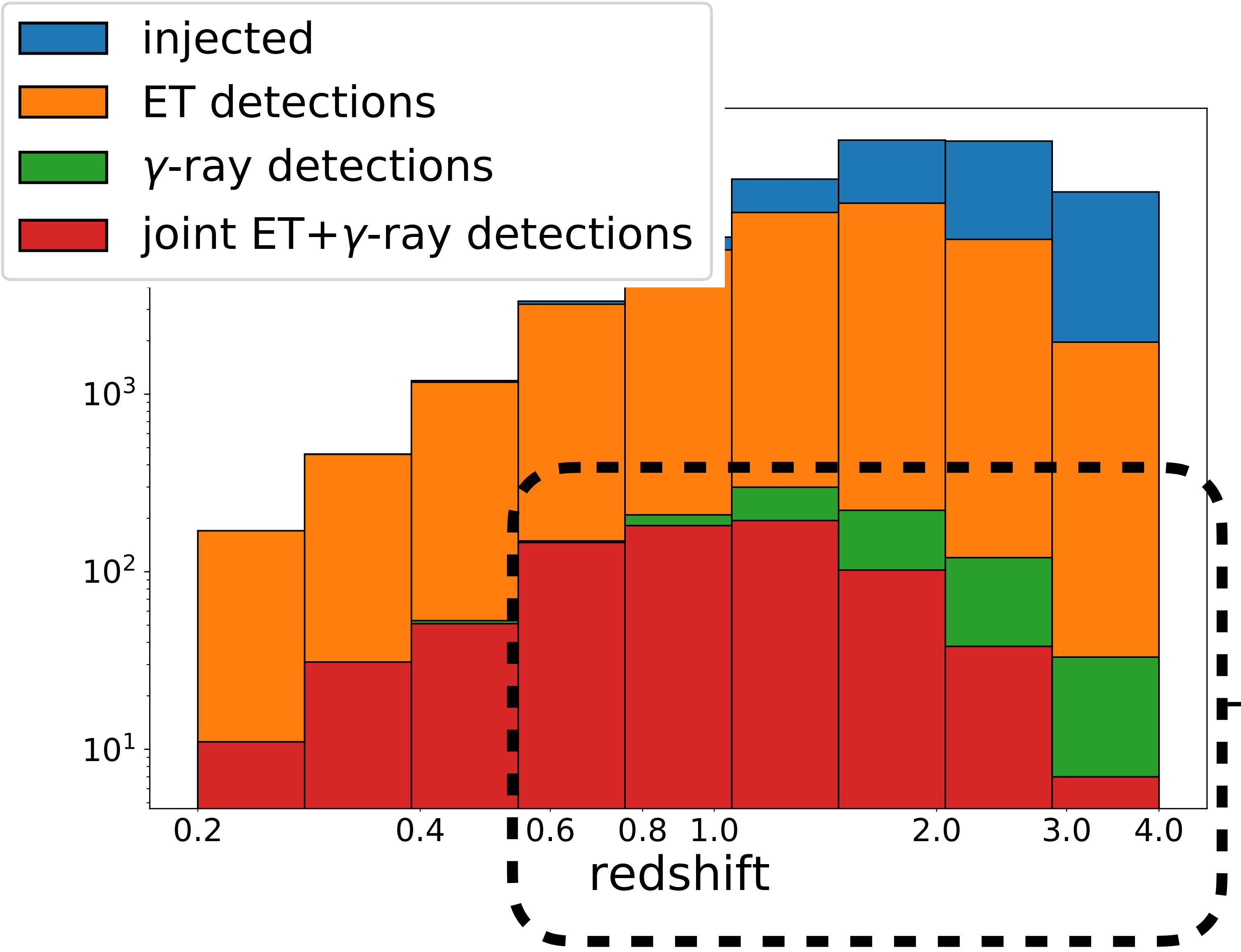
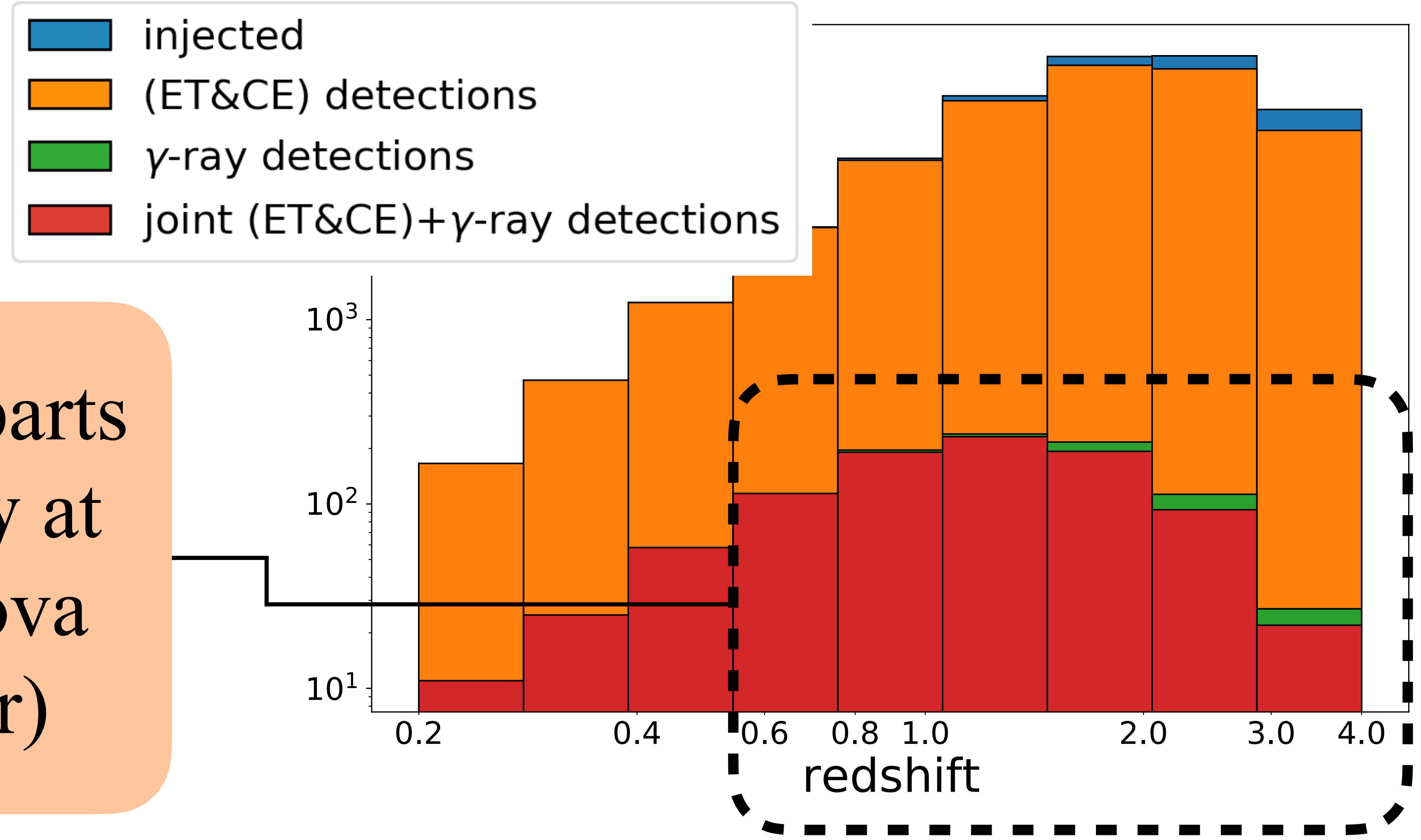
Fermi GBM+ET



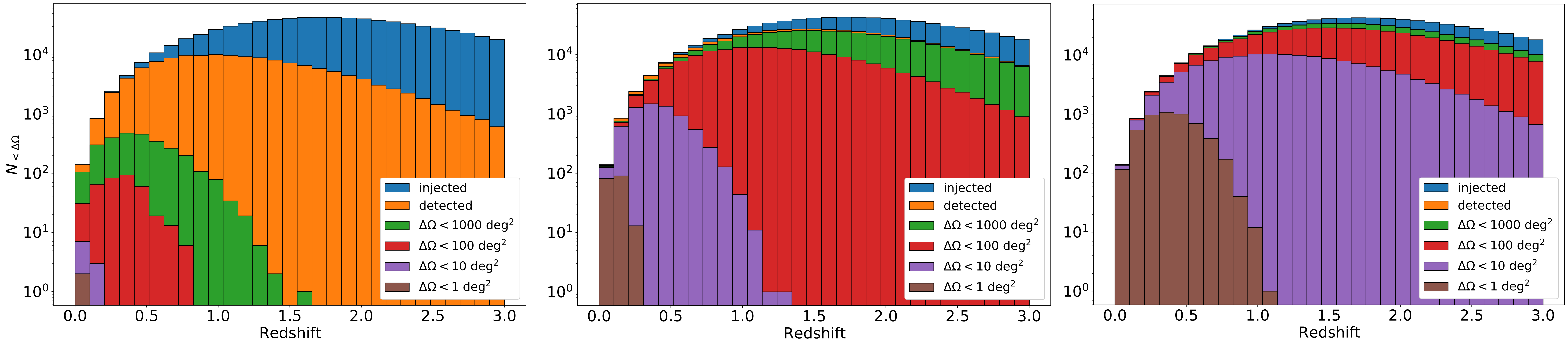
High-z GW counterparts can be detected **only** at high-energy (kilonova intrinsically fainter)

Fermi GBM+(ET&CE)



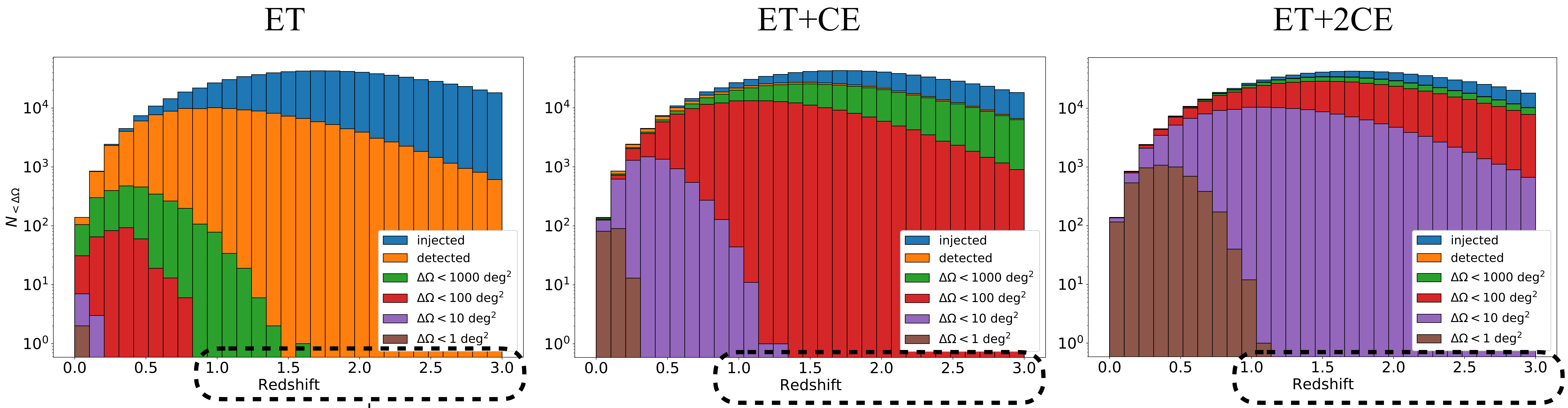
GW sky localisation

ET ET+CE ET+2CE



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

GW sky localisation



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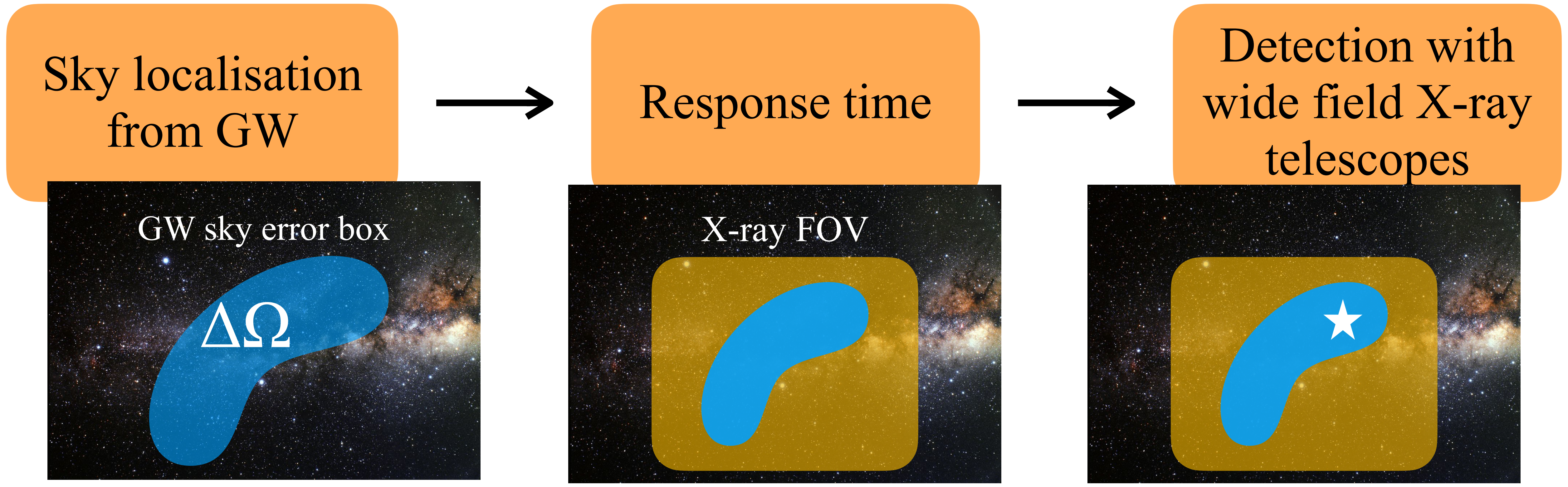
High-z GW source localisation is given by counterparts detected by **wide field X-ray and γ-ray telescopes** with arcmin localisation capabilities

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



	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 pointing

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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}

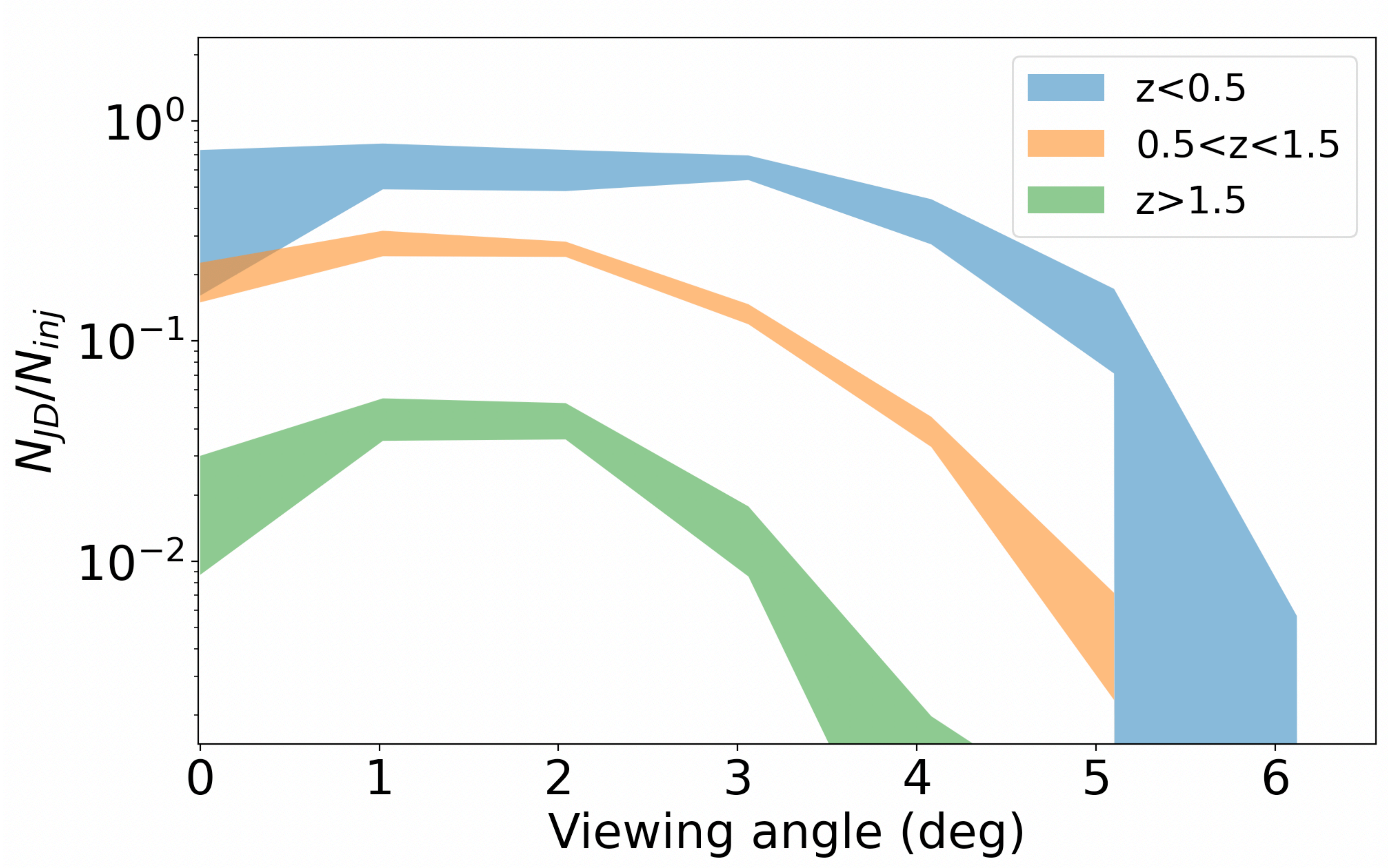
Other GW parameters should be exploited to restrict the selection:

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

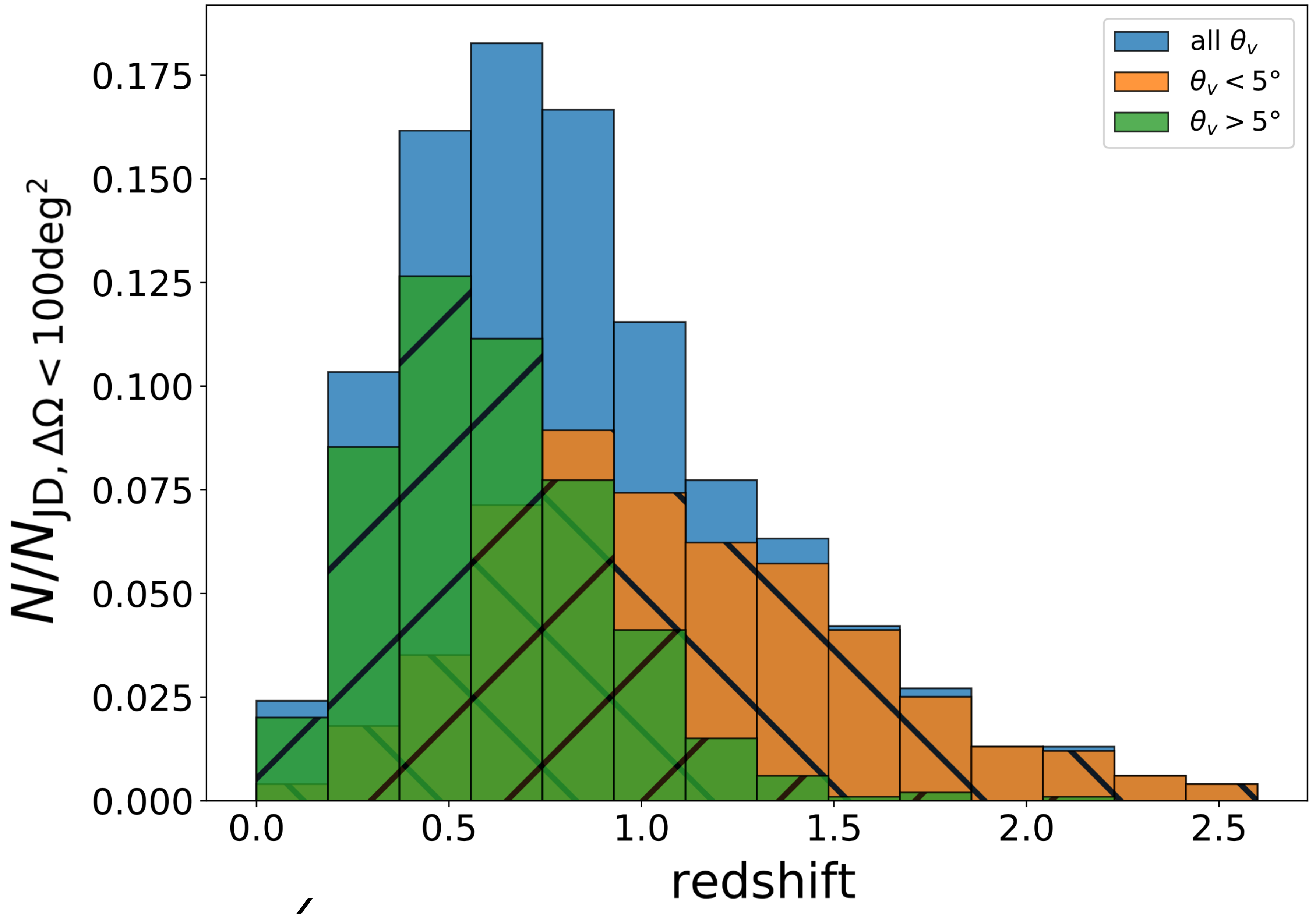
A **rapid response** is necessary to catch the brighter phase of the afterglow

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

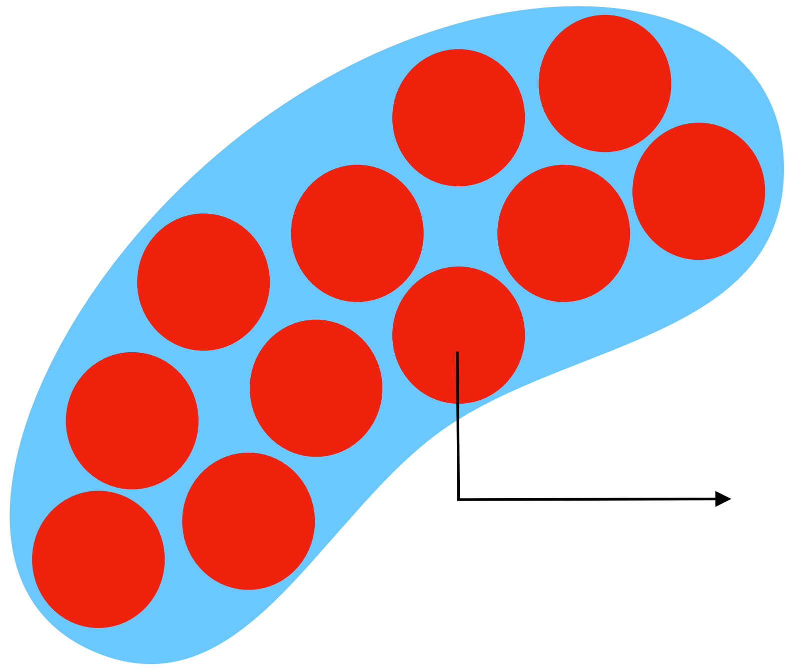
WFX-ray telescopes can significantly **enhance the probability of a joint detection**

The role of sensitive X-ray instruments

1. **X-IFU**: needs arcmin localisation, provided by WFX-ray telescopes

The **totality** of sources identified with WFX-ray monitors can be detected by X-IFU

2. **WFI:** can carry out a **mosaic of a sky region of ~10 deg²** localisation provided by GW detectors



For ET+2CE

~5 joint detections per year, excluding cases with ϑ_v**>50°**

~15 joint detections per year, excluding cases with ϑ_v**>30°**

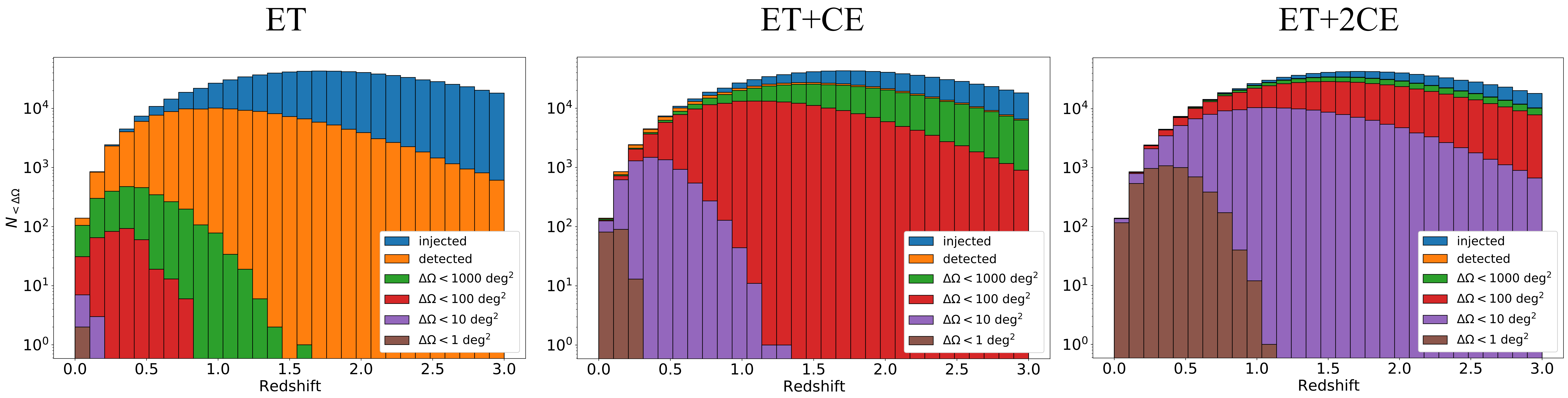
Summary

- 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 localise the EM counterpart and possibly the host galaxy with ground-based telescopes
- **γ-ray telescopes** are ideal to detect sources up to cosmological distances, while **WFX-ray instruments** are optimal for off-axis and sub-luminous events in the local Universe
- Exploiting the **localisation of GW sources** (only with ET or also in synergy with other GW observatories, e.g. Cosmic Explorer) **enhances the probability of having a joint GW+EM detection**
- It is necessary to define an **optimal strategy to select GW events** for which the detection of EM signal is higher

Thank you!

Backup slides

GW sky localisation



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$N_{\rm det}(\Delta\Omega < 1\,{\rm deg}^2)/{\rm N_{det}}$	$< 0.1\%$	$< 0.1\%$	0.8 %
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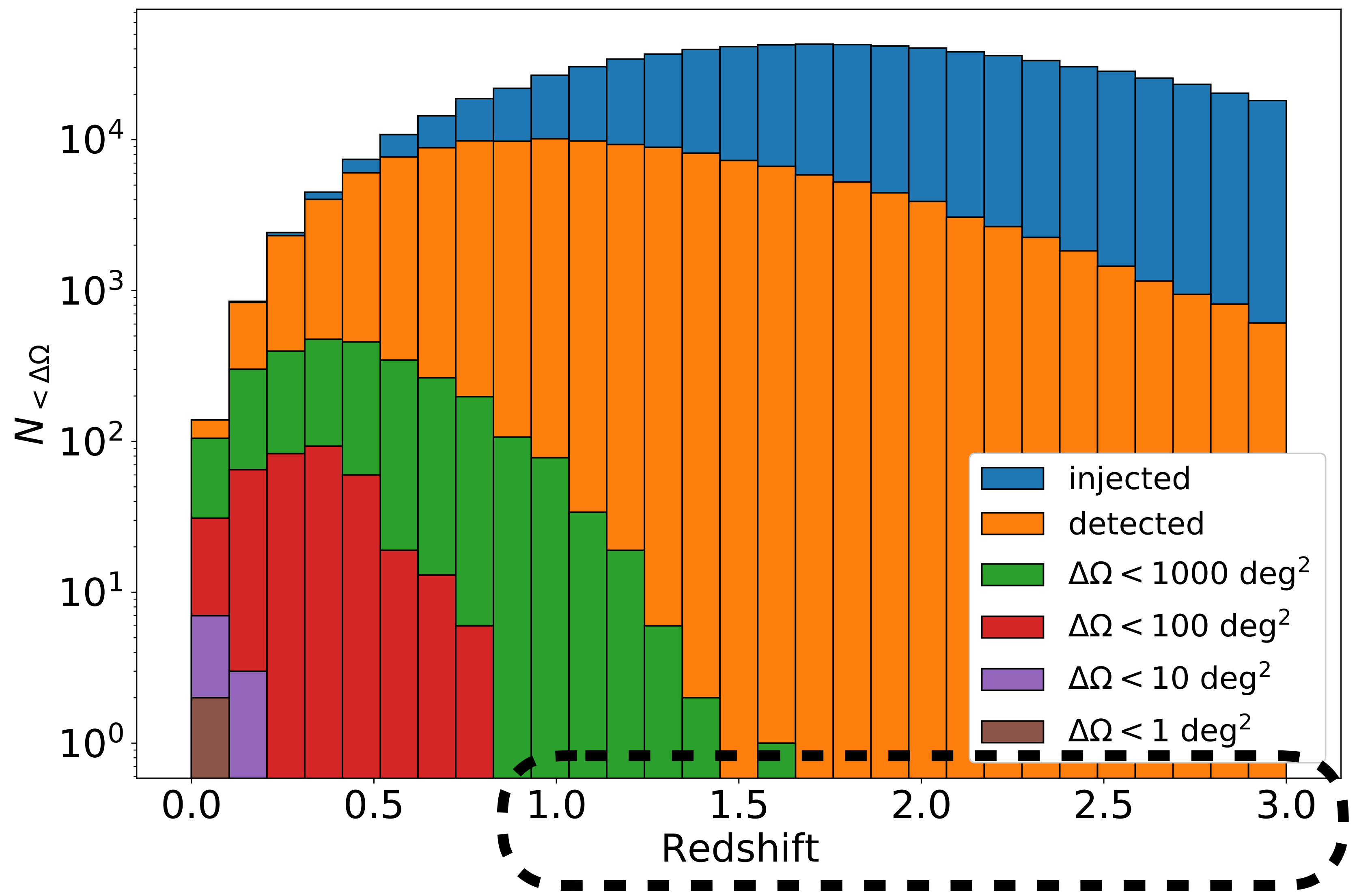
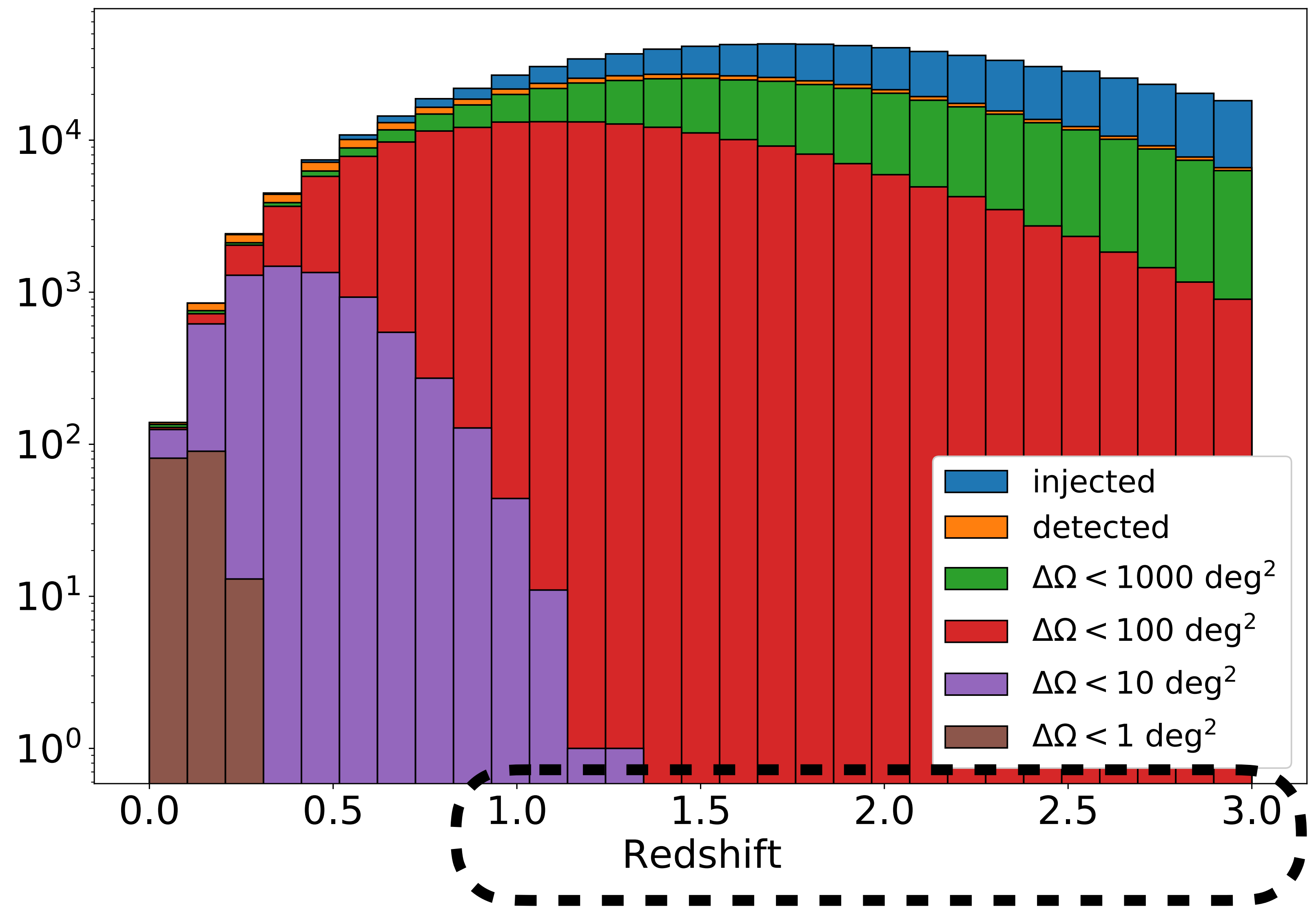
GW sky localisation

ET



ET+CE



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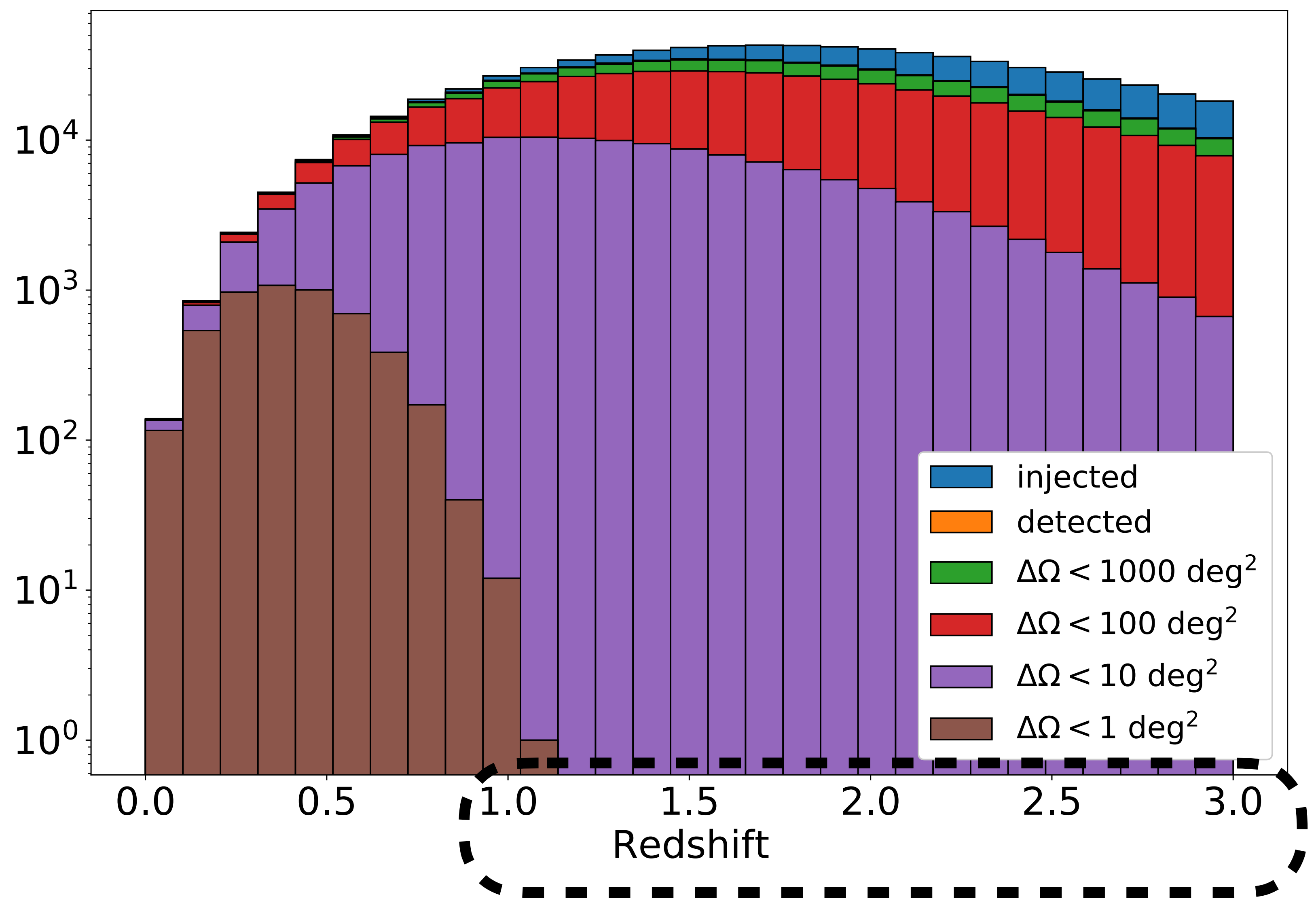

High-z sources can be **well localised only with wide field** X-ray and γ-ray telescopes

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