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

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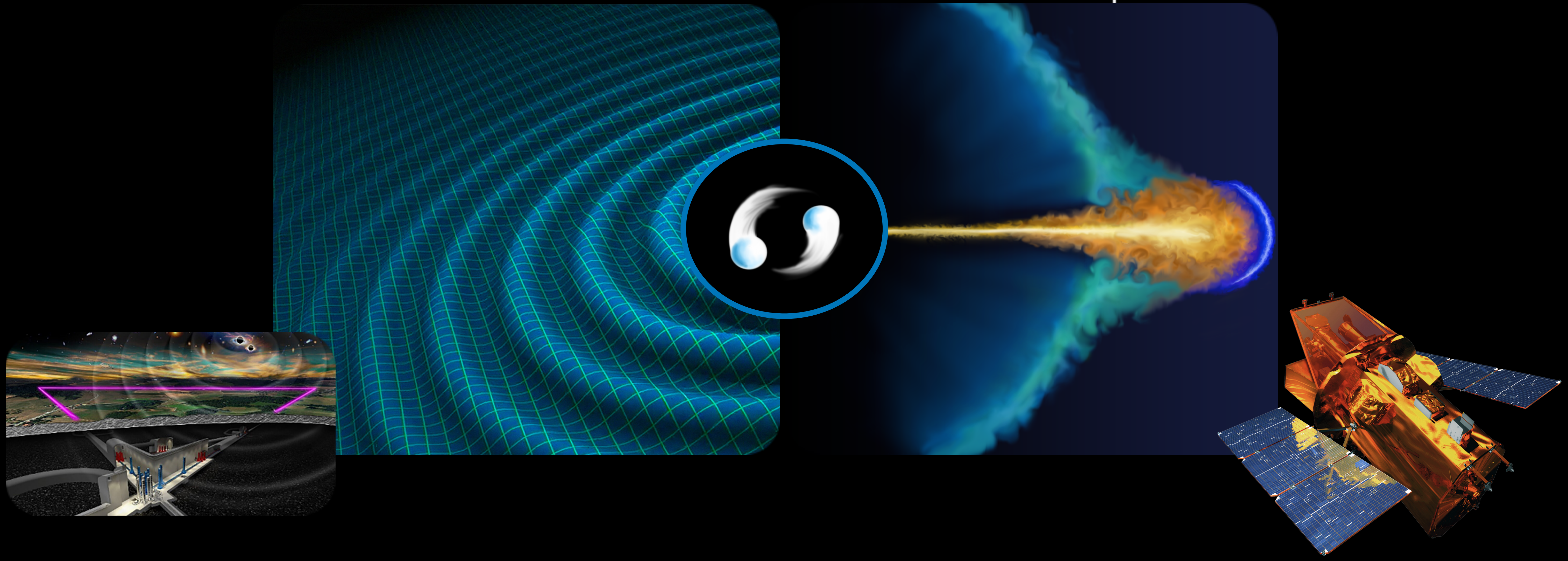
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

GSSI GW team

AHEAD 2020
HIGH ENERGY ASTROPHYSICS

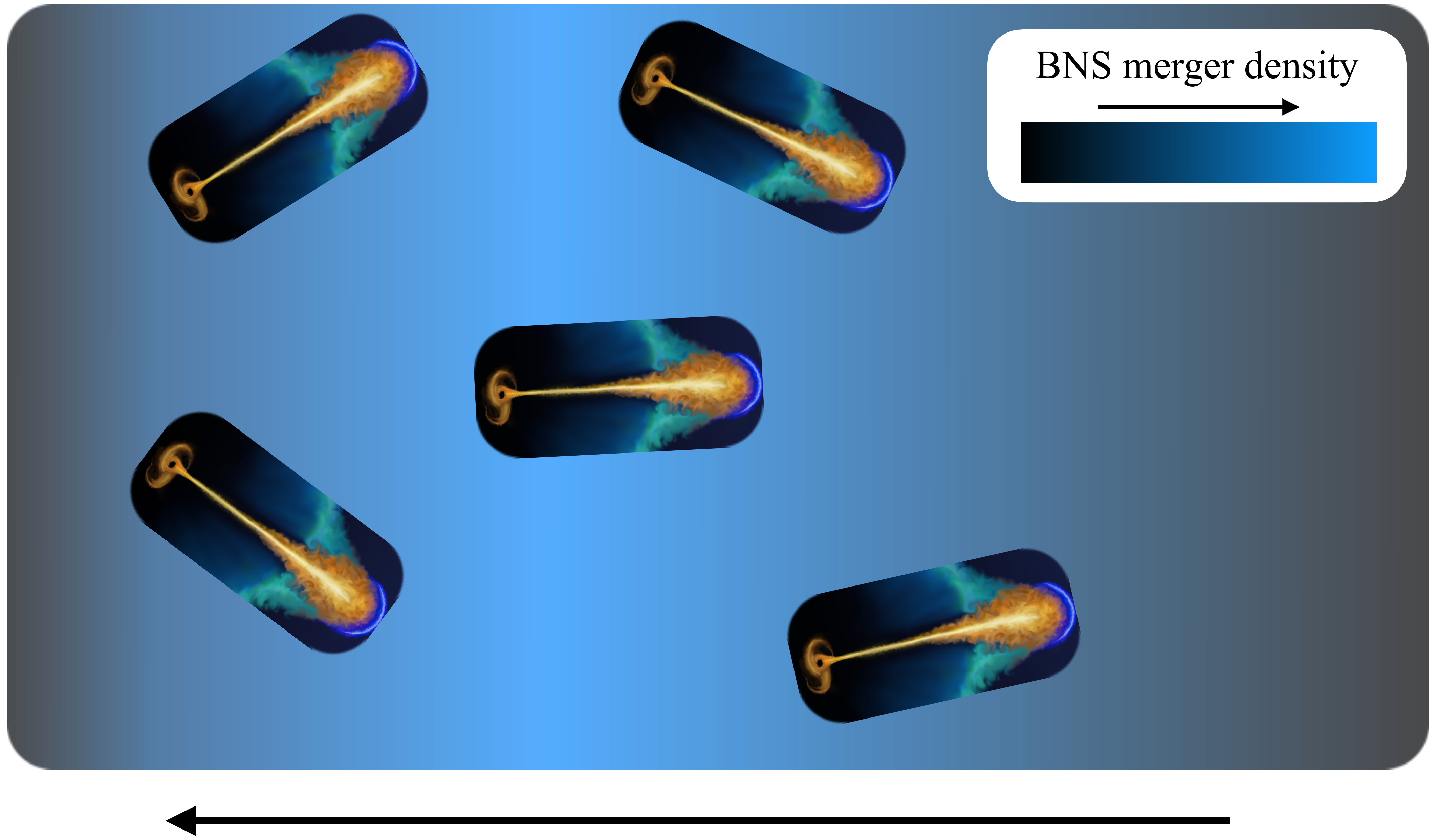


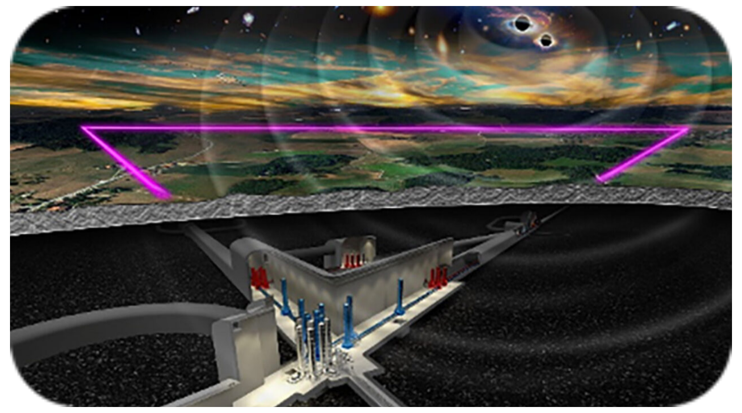
Ronchini et al. 2022, doi.org/10.1051/0004-6361/202243705

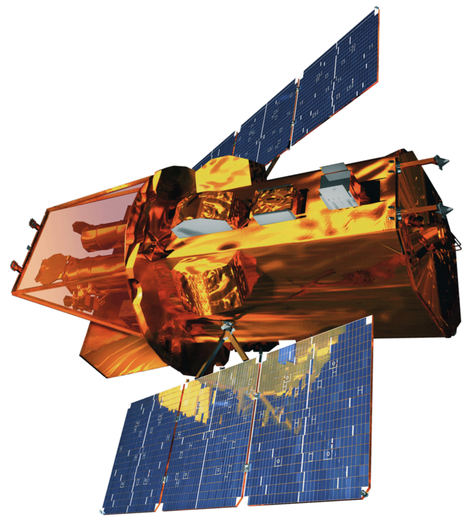
We acknowledge the INFN Computing Center of Turin for computational resources

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 **NS binaries**, 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

Why we need joint detections?

Info from GWs:

- masses of the system
- inclination of the orbital plane
- nature of the remnant

- luminosity distance

Relativistic astrophysics and fundamental physics

- Who are the progenitors of short GRBs
- How the jet properties depend on the central engine (BH vs NS)
- EoS of NS

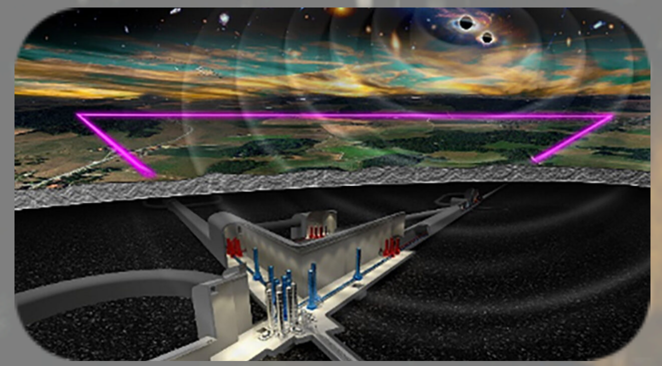
Cosmological studies

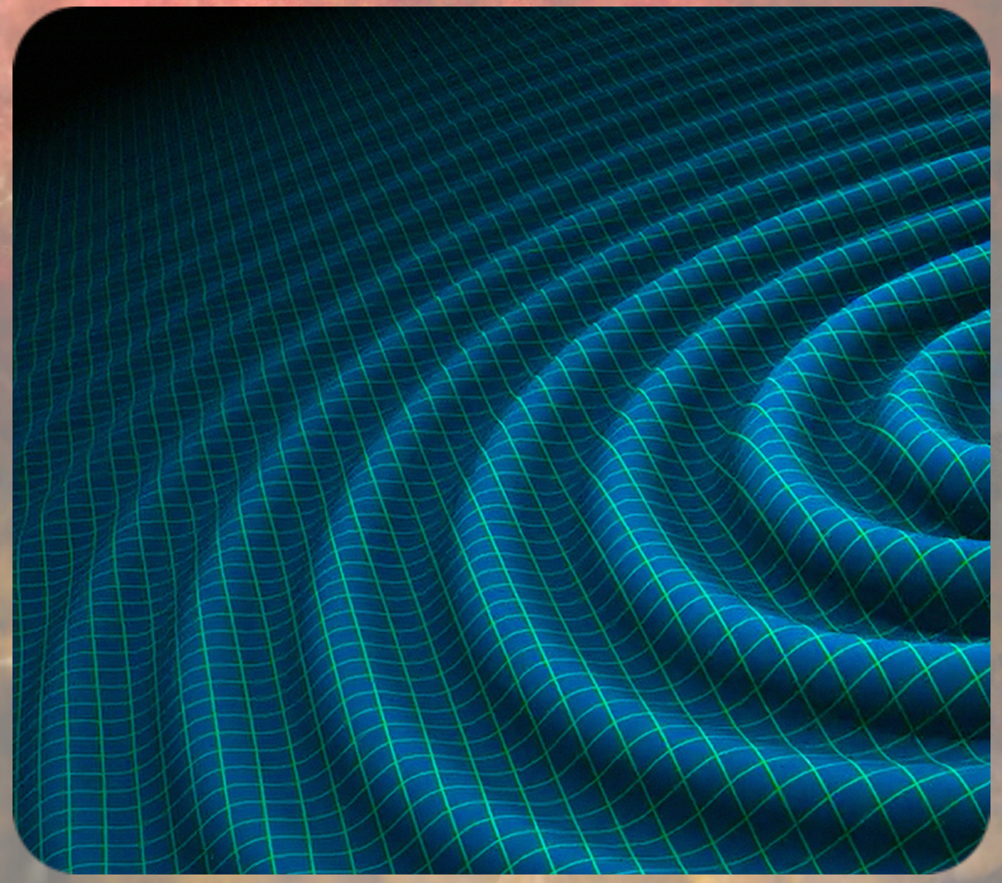
- Hubble diagram
- Tests of GR

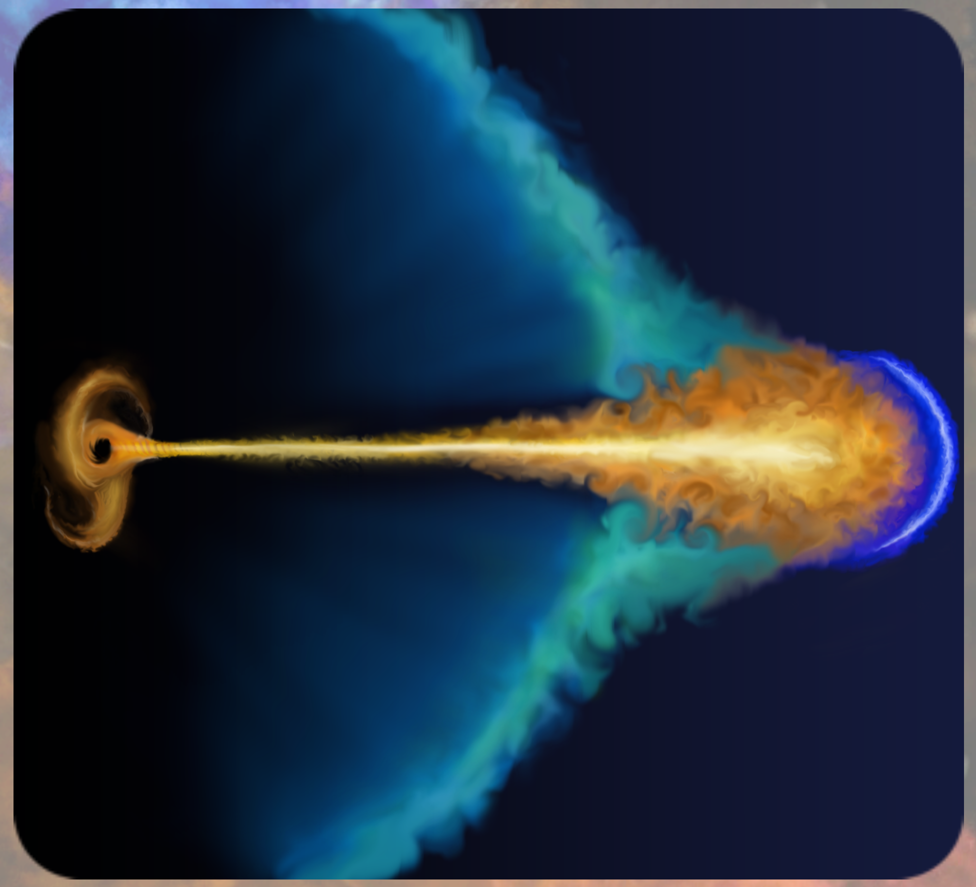
Info from EM signals:

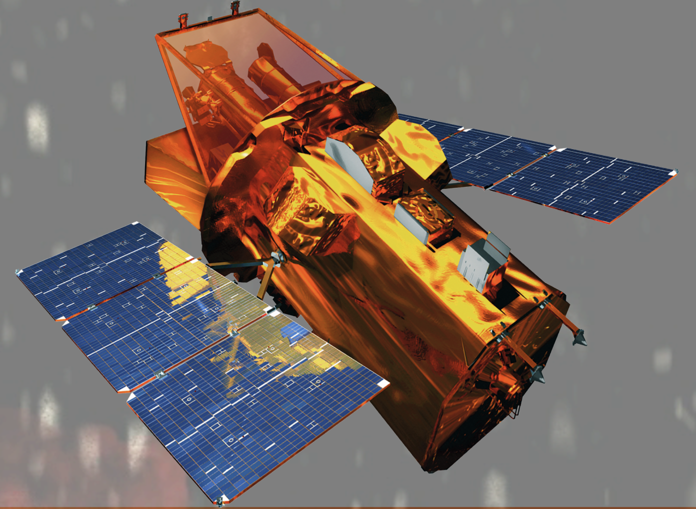
- energetic and dynamical properties of the outflow (jet+kilonova ejecta)

- redshift

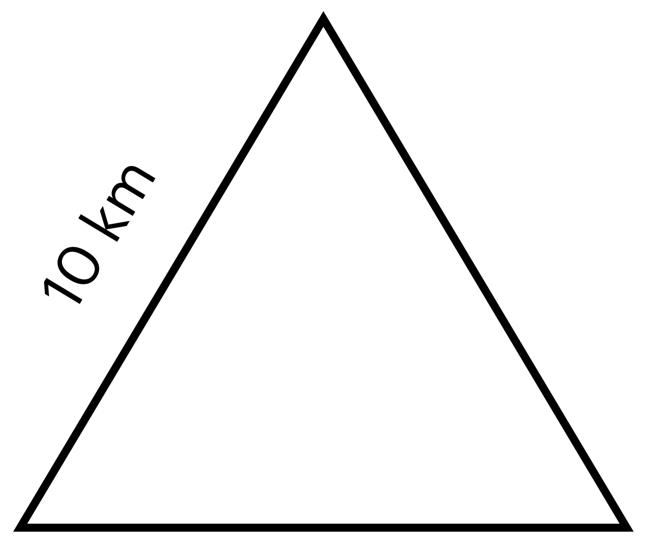






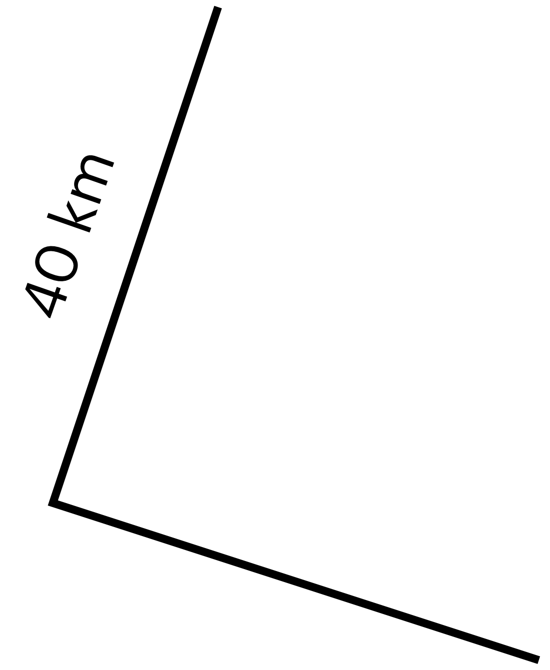


The 3rd generation of GW detectors: steps forwards



Einstein Telescope
(ET)

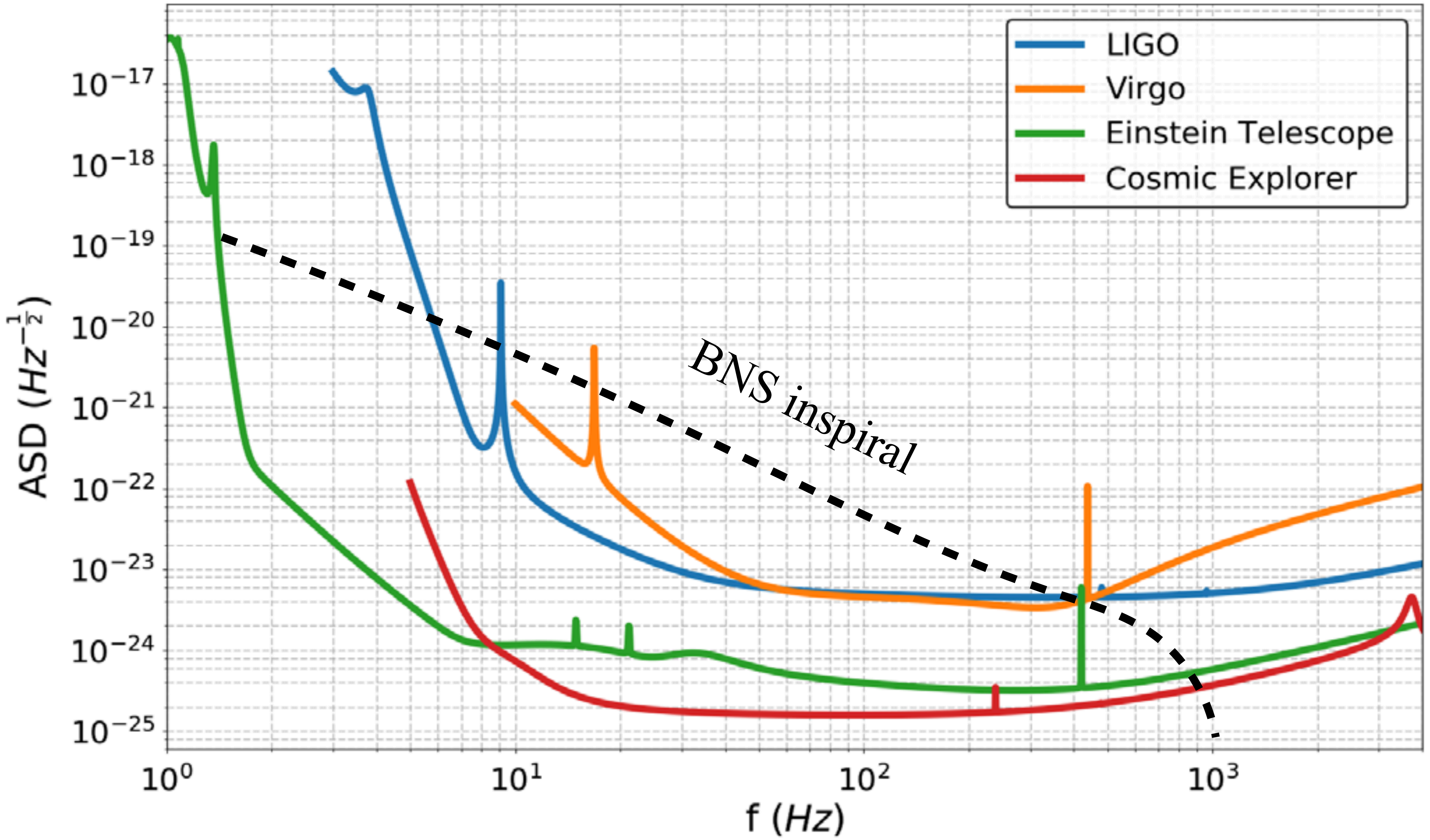
- **Triangle** geometry
- Xilophone concept: **low frequency** at cryogenic temperature + **high frequency** at room temperature
- Underground to **minimise seismic noise**



Cosmic Explorer
(CE)

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

~ factor 10 improvement in sensitivity

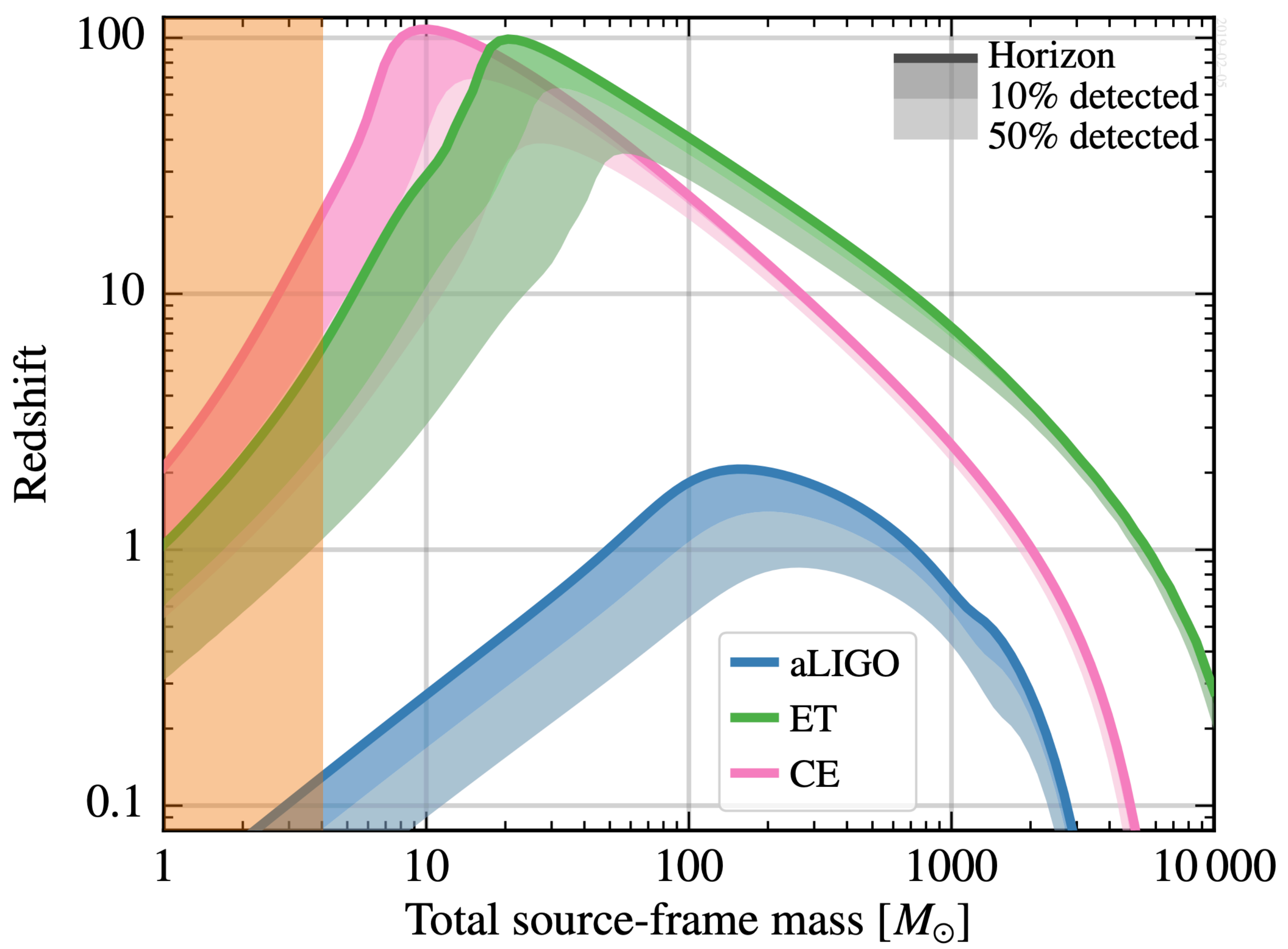


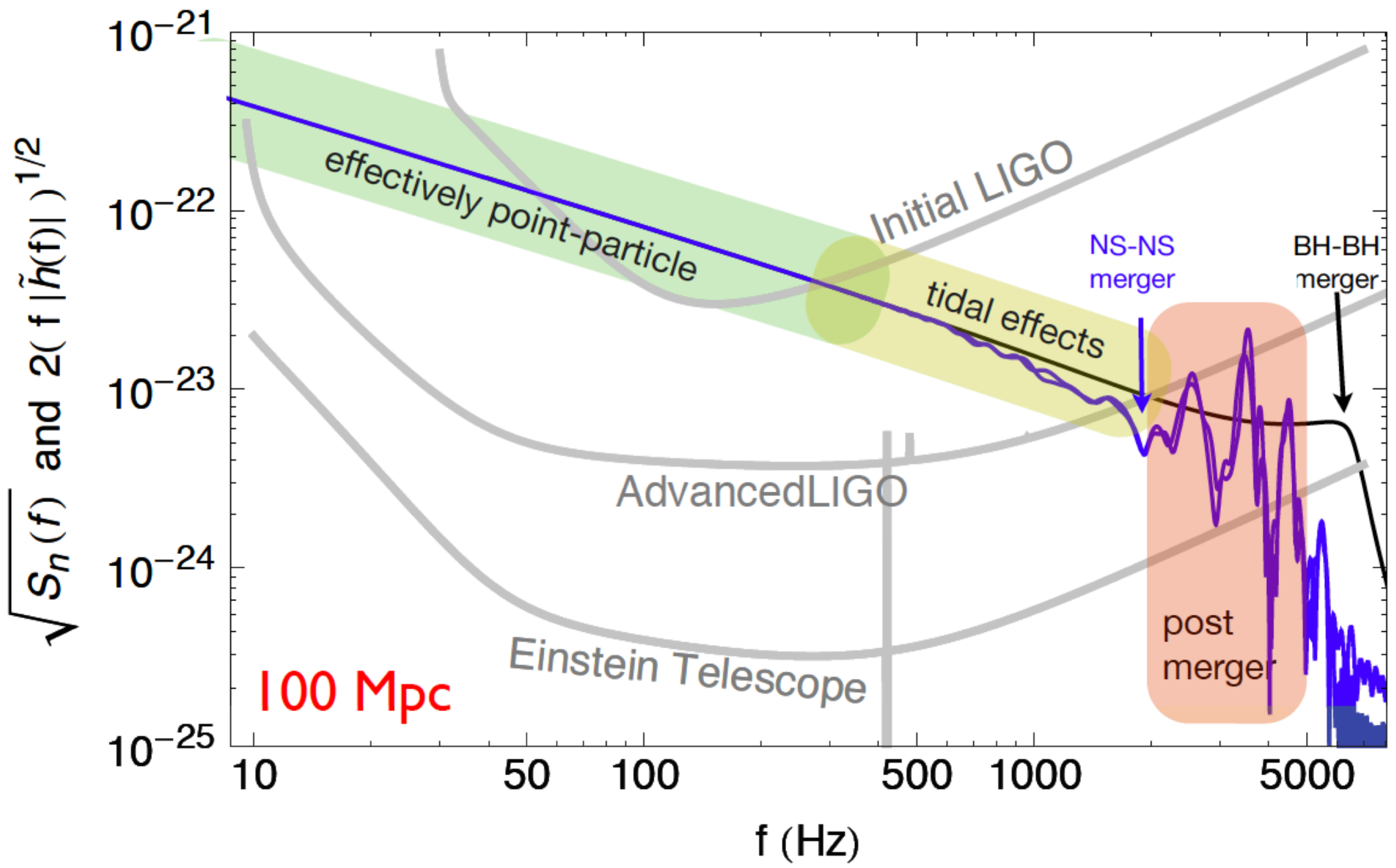
From Chan et al. 2018

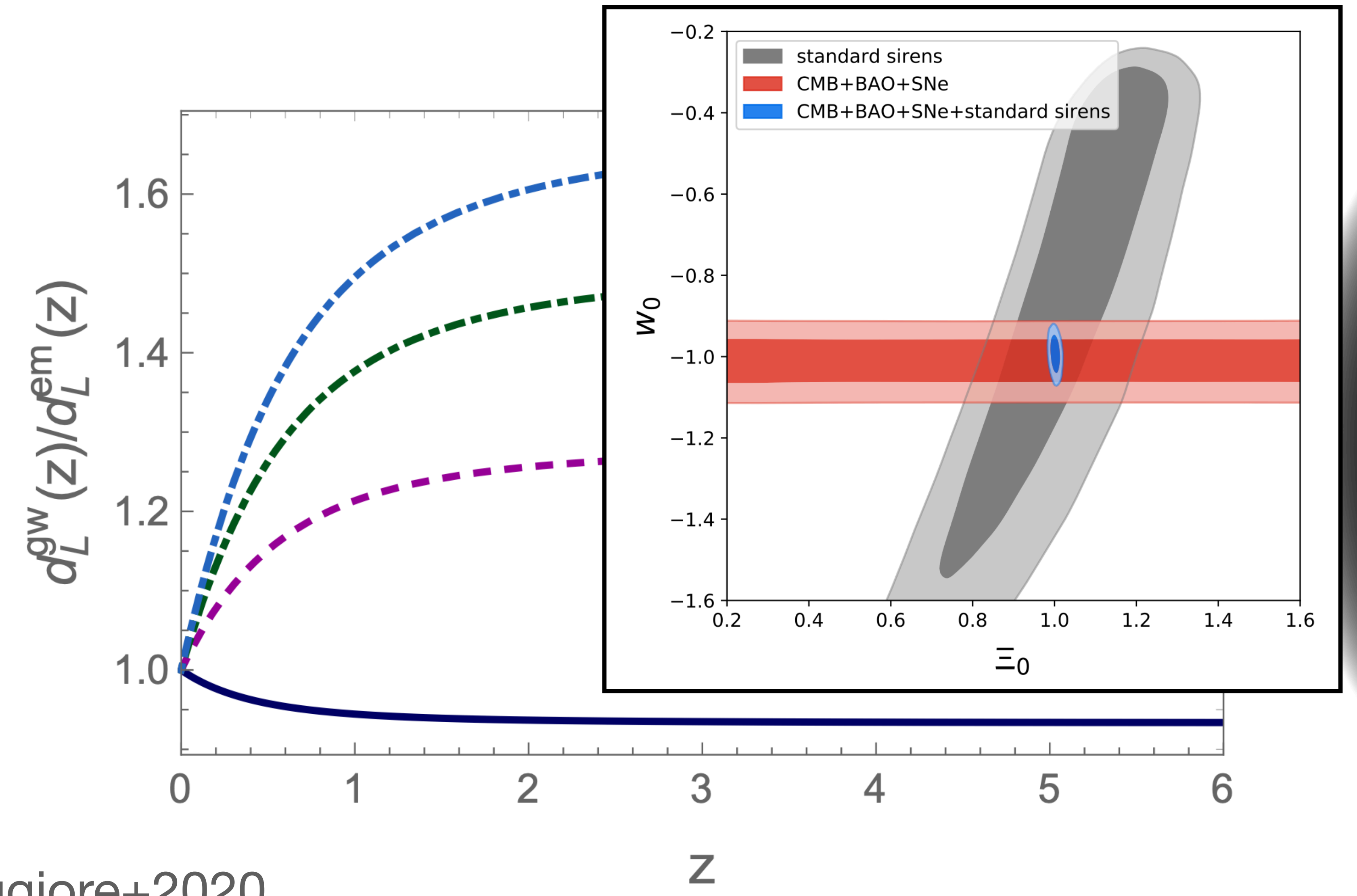
Both should start to be operative around 2035

The 3rd generation of GW detectors: science case

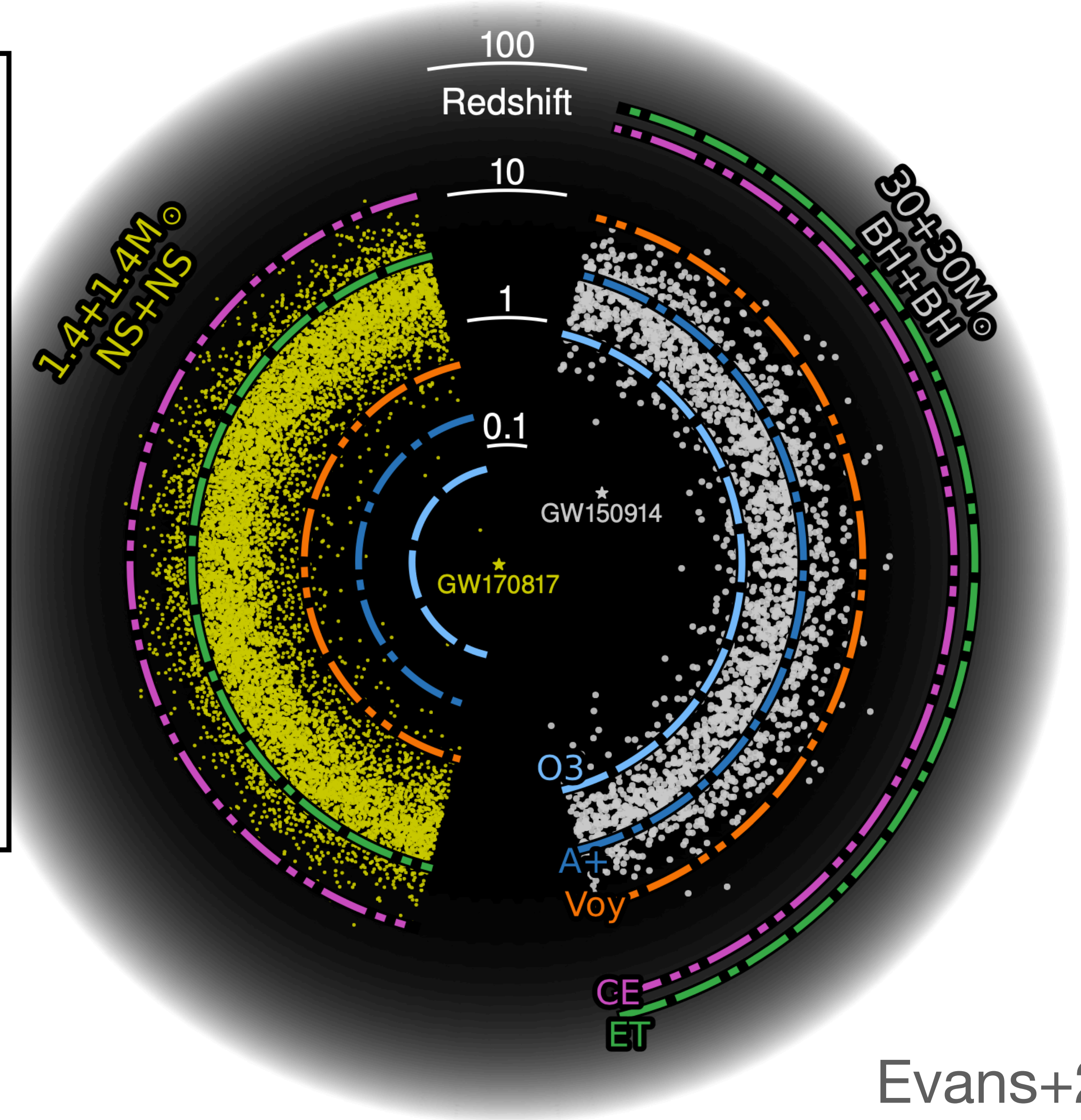
1. Detection of 10^5-10^6 stellar mass BH mergers/yr up to z~20
2. Detection of primordial BH
3. Detection of ~10^5 BNS mergers/yr beyond the star formation peak
   - ET more **sensitive at low frequency** → the inspiral is followed for a longer time → **better sky localisation**
   - Access the **effects of tidal deformations** at the moment of the merger → **NS EoS**
4. Test of GR during the inspiral and in the post-merger (e.g. BH ringdown)
5. Nature of dark energy and modifications of GR at cosmological distances







Maggiore+2020



Evans+2021

The 3rd generation of GW detectors: population studies

	ET	ET+CE	ET+2CE
$N_{\rm det}$ (NS)	143970	458801	592565

Advantages:

- **systematic census** of the NS population across the cosmic history

Related issues:

- **Overlapping** signals
- **Selection** of the best candidates: which one should be followed up?
- Need for **fast parameter estimation** in case of population studies

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↓

MCMC → Fisher matrix

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

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GWFISH

Harms et al. 2022 arXiv:2205.02499

- 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**

Advantages:

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Related issues:

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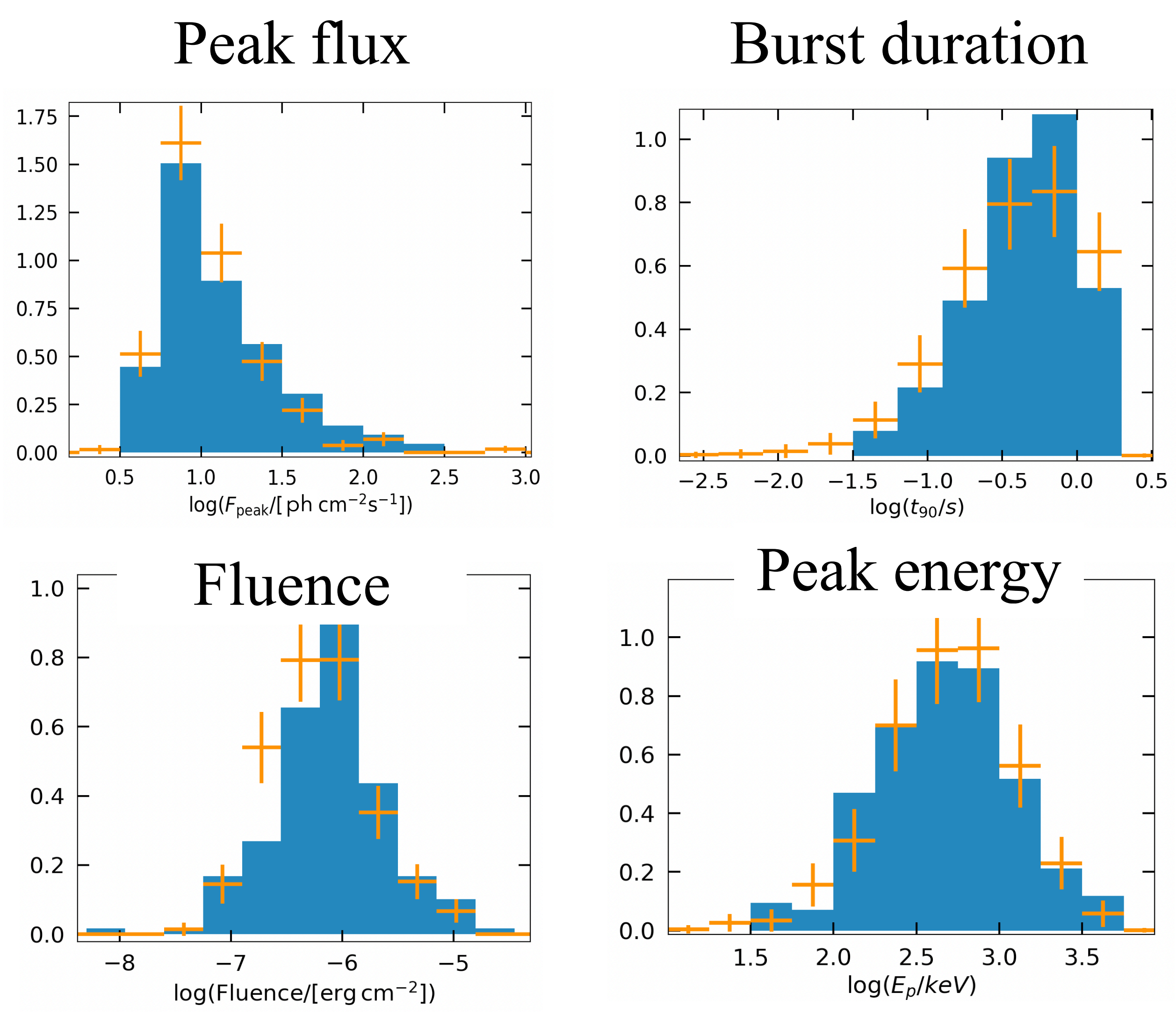
From BNS mergers to short GRBs

Redshift distribution of BNS mergers from population synthesis model

From Santoliquido et al. 2021

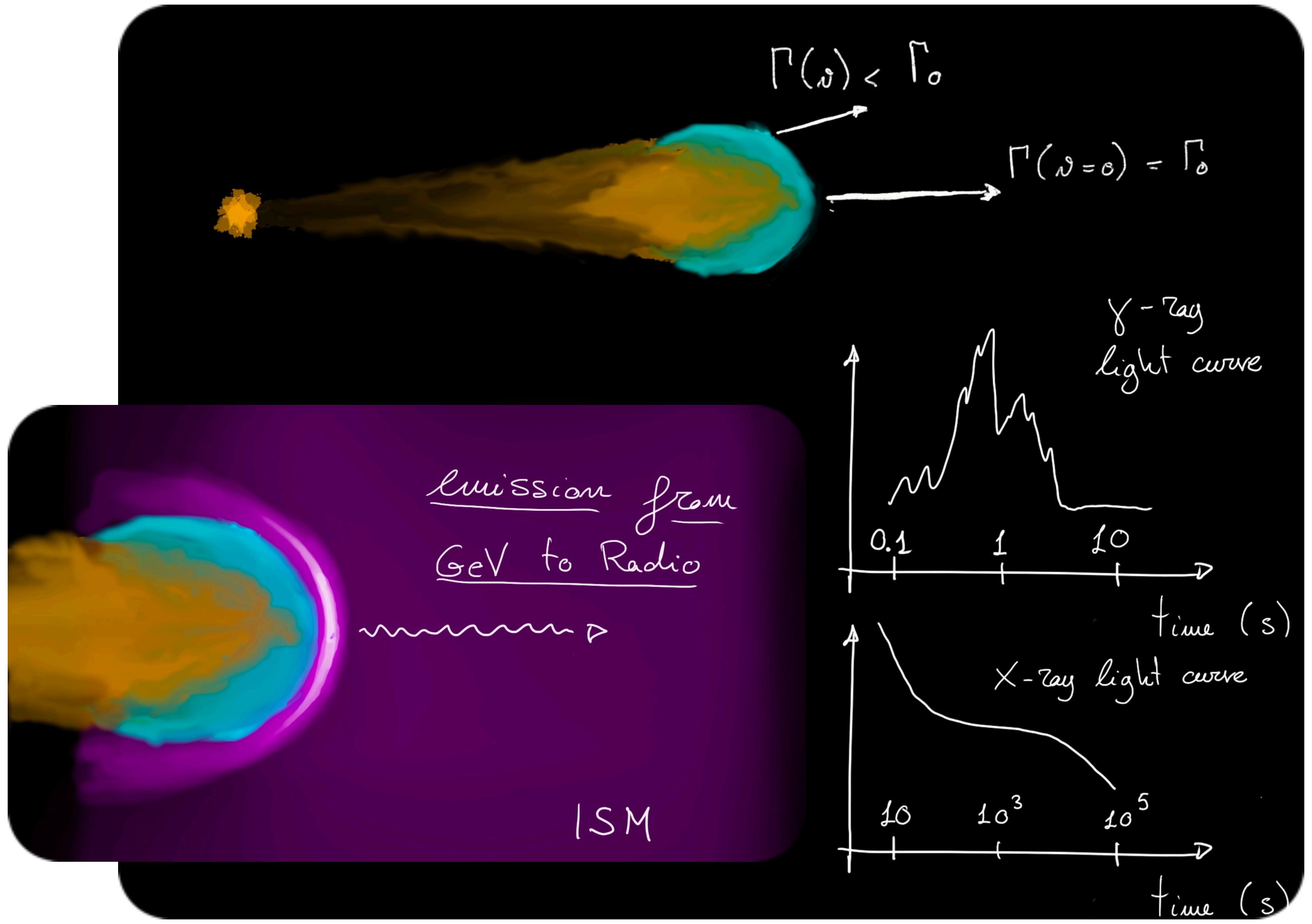
Phenomenological model for prompt emission

Comparison with properties of Fermi-GBM sample



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

Reliable predictions for future high-energy satellites



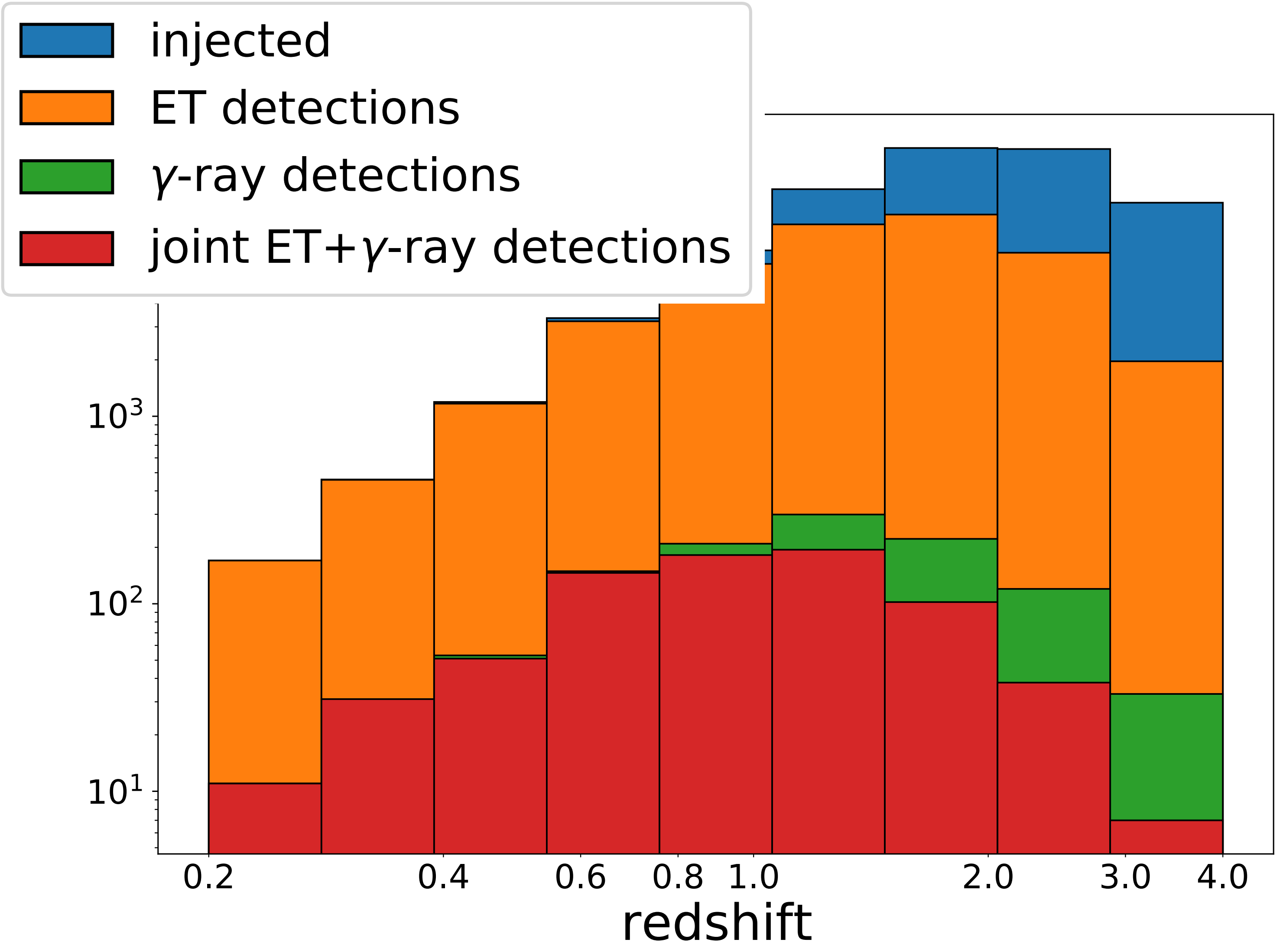
+

Fermi-GBM rate of short GRBs

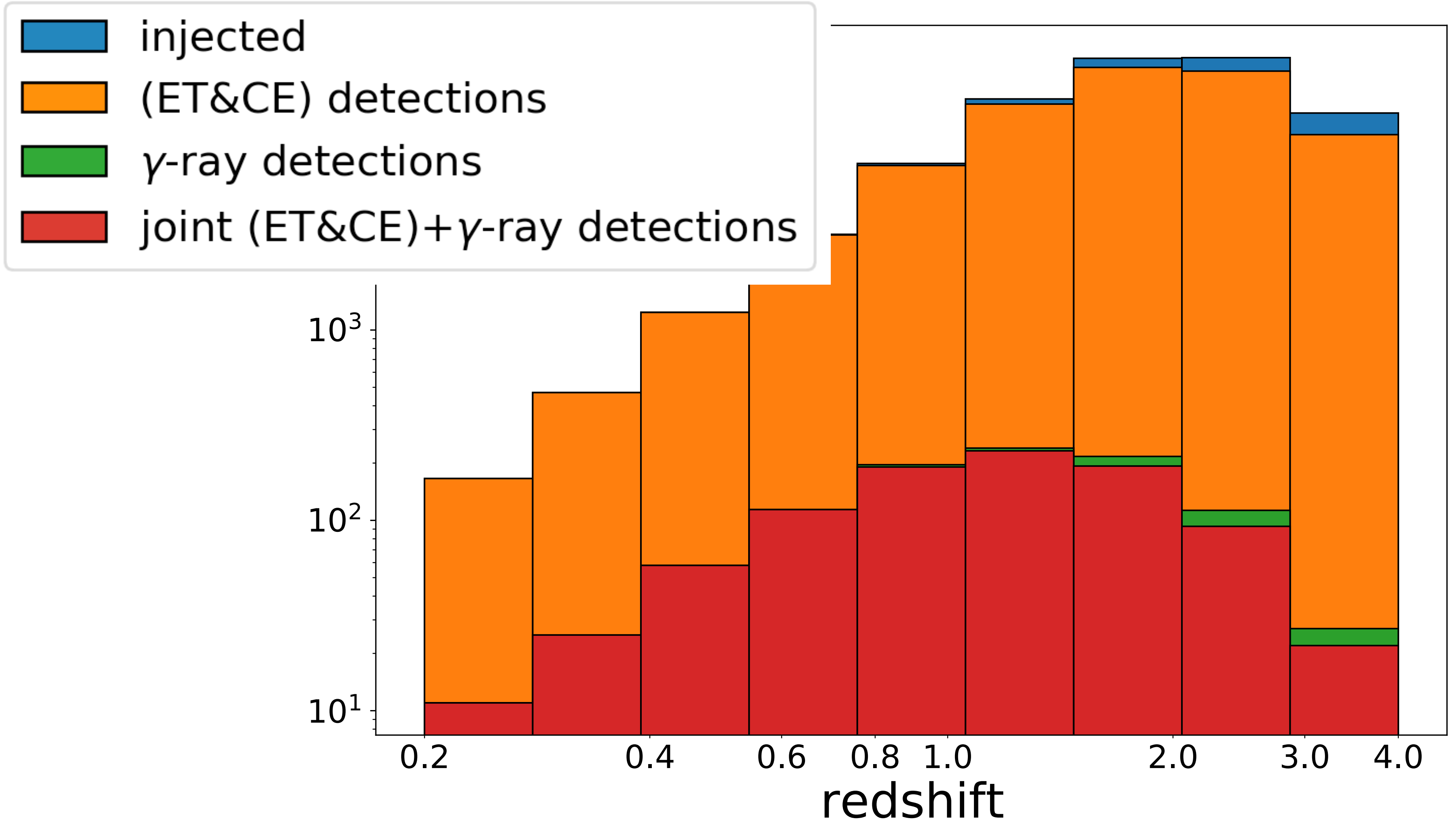
Joint detection of γ-ray emission and GWs

INSTRUMENT	band MeV	$F_{\rm lim}$ erg cm^{-2} s^{-1}	FOV/4π	loc. acc.	Joint ET +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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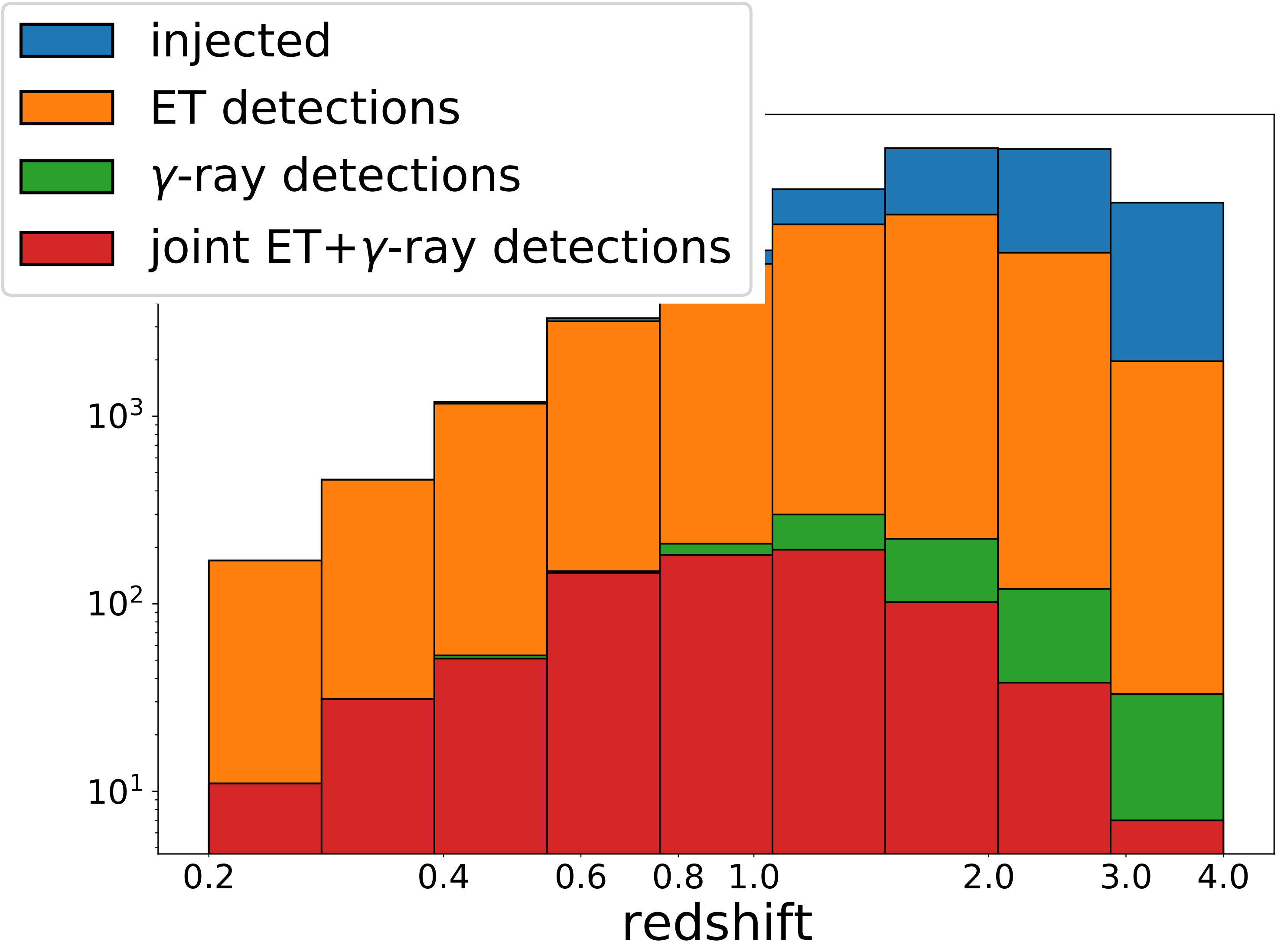
Few but **well localised** events

Fermi GBM+ET



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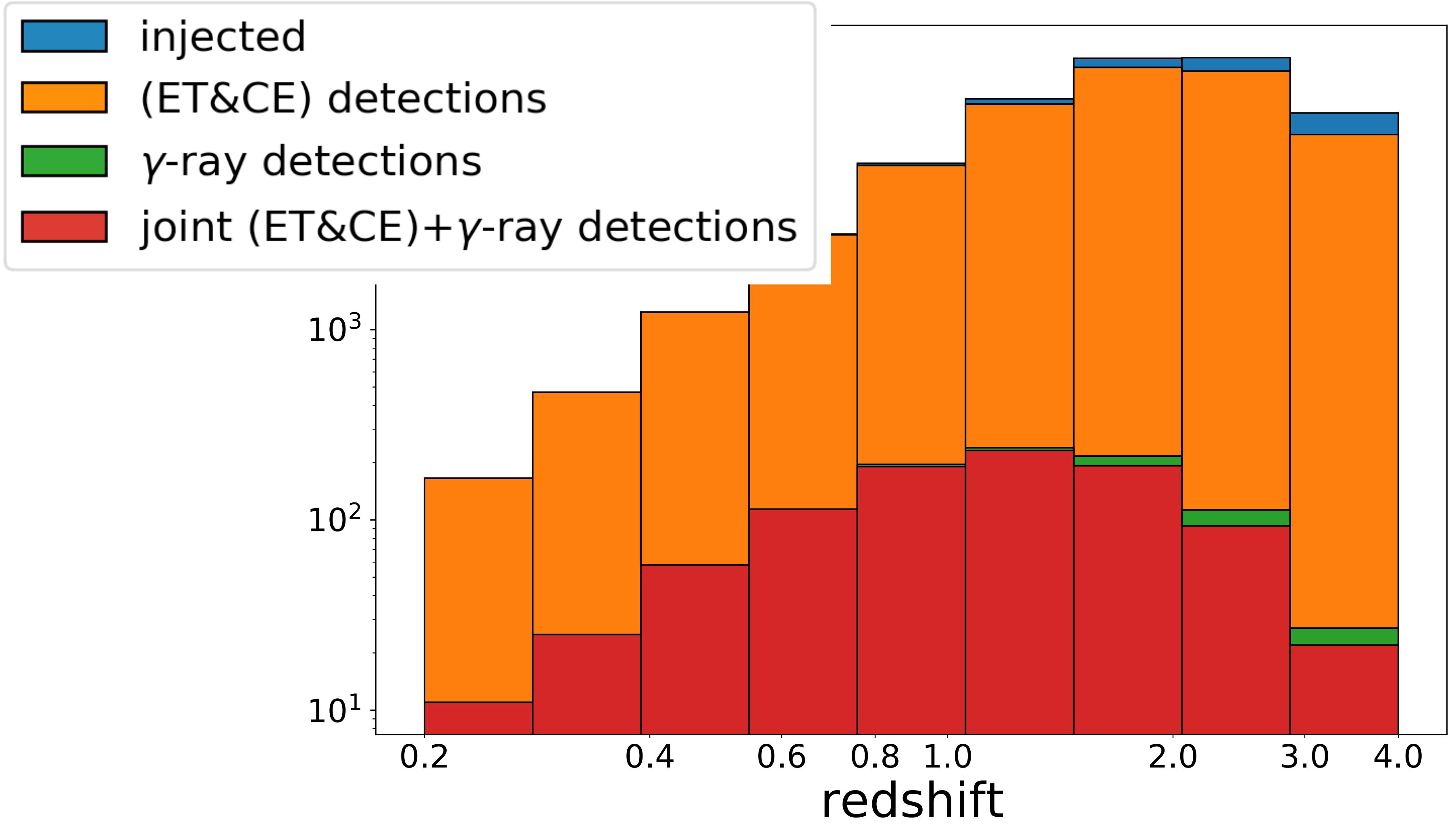

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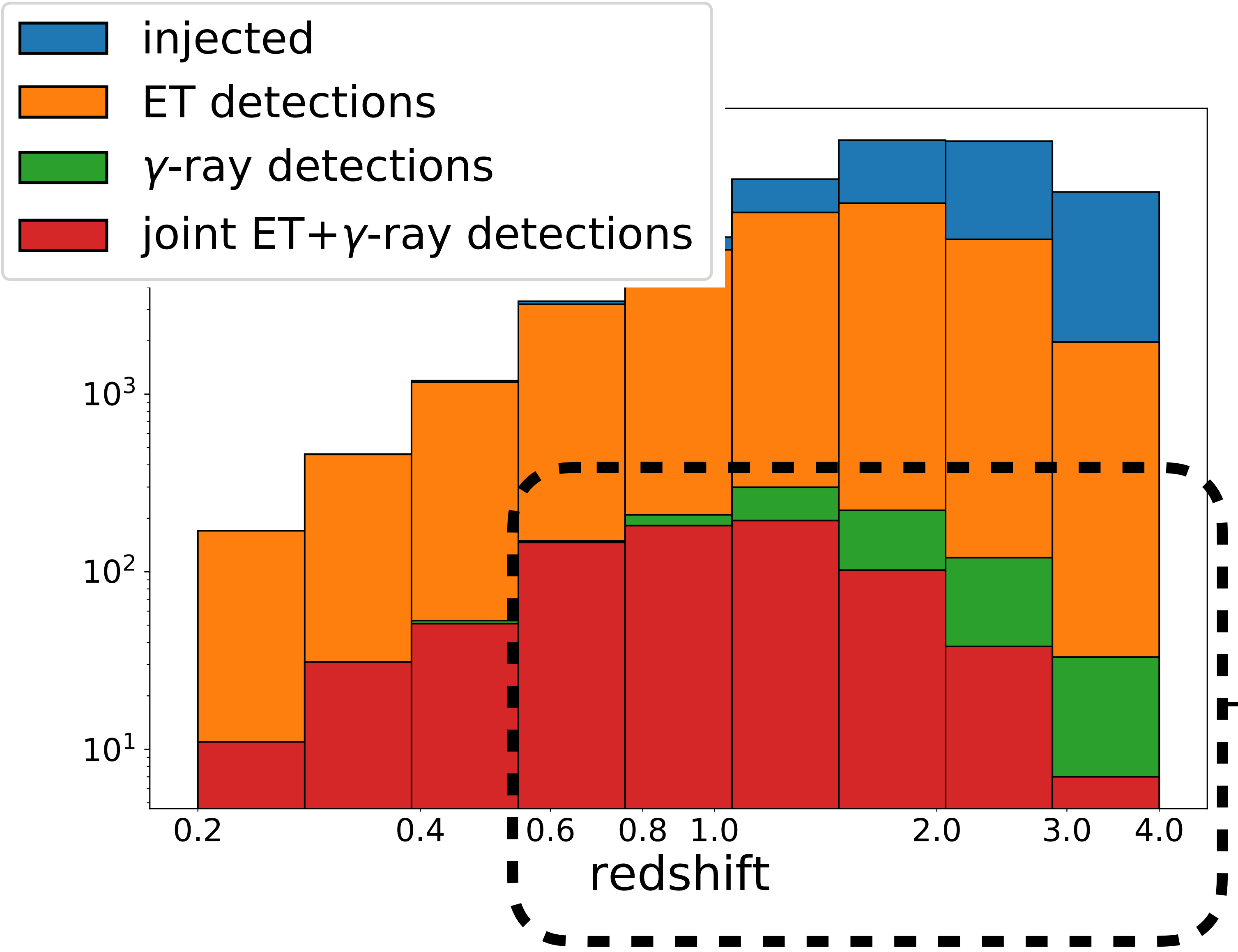
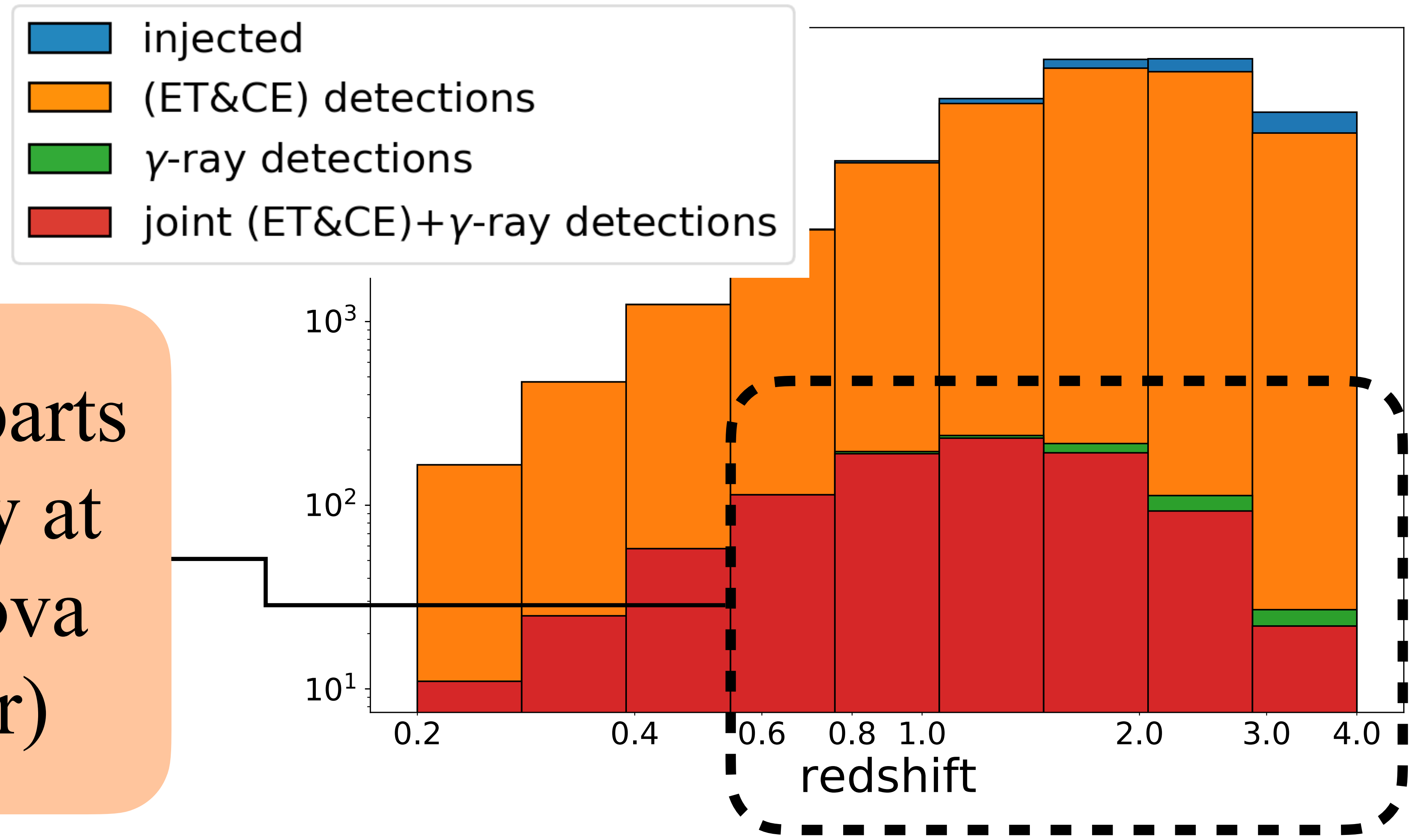


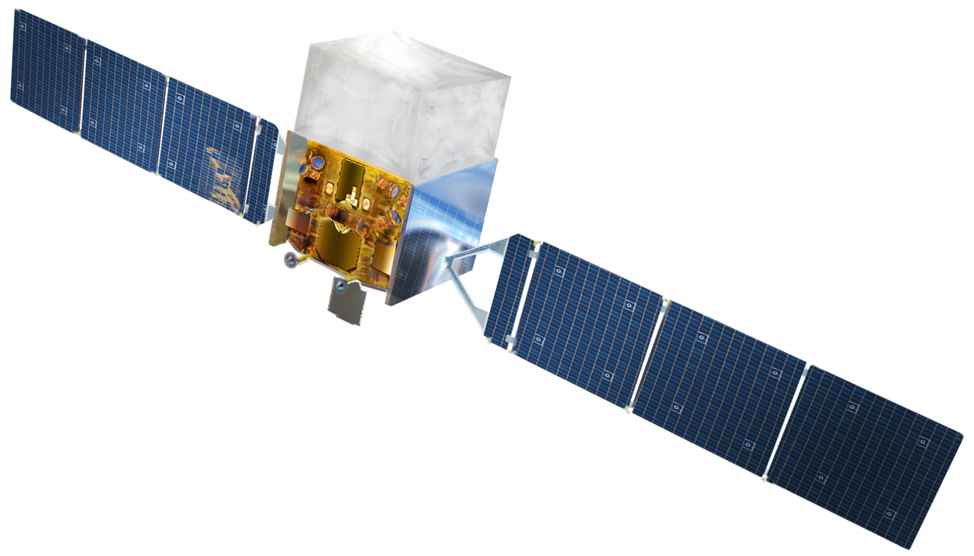
Fermi GBM+(ET&CE)



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

Two kinds of joint detections

Fermi-like telescopes

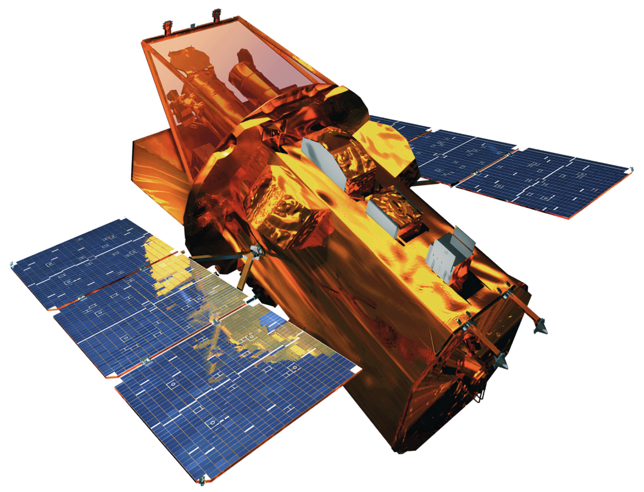


- ~ **all sky** monitors
- Possibility to build constellations at fairly low cost
- **Best sensitivity** around the sGRB **peak energy**
- ~ deg location accuracy

PROS

- Confirm the spatial and temporal coincidence with the GW
- Characterise the spectral shape up to high energies

Swift-like telescopes

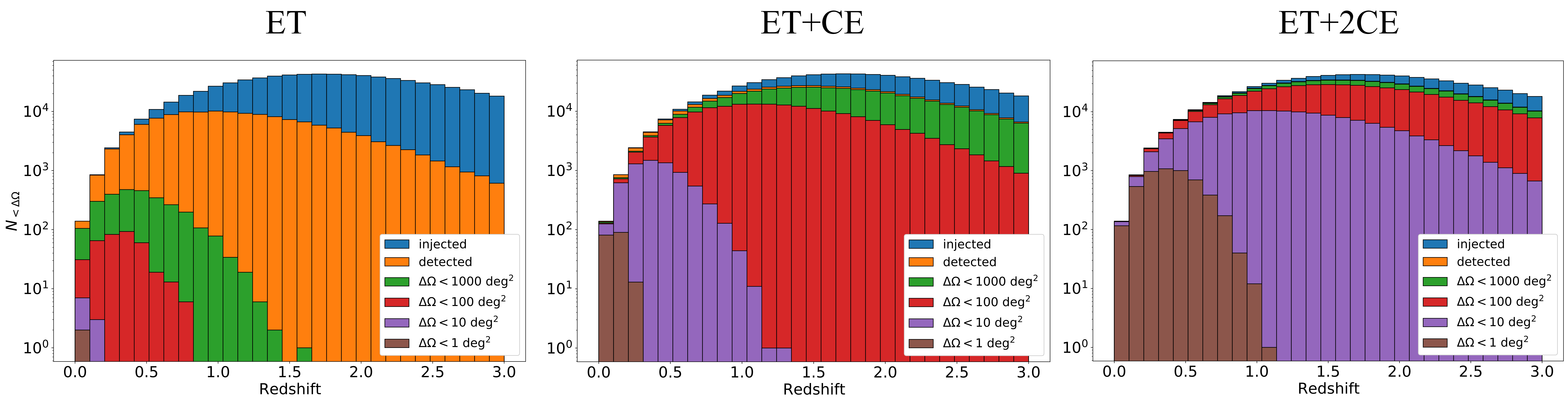


- Good sky coverage
- **Arcmin location accuracy**
- Possibility to promptly follow up with ground-based telescopes

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…)

GW sky localisation



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$N_{\rm det}(\Delta\Omega < 1\ \mathrm{deg}^2)$	2	184	5009
$N_{\rm det}(\Delta\Omega < 10\ \mathrm{deg}^2)$	10	6797	154167
$N_{\rm det}(\Delta\Omega < 100\ \mathrm{deg}^2)$	370	192468	493819
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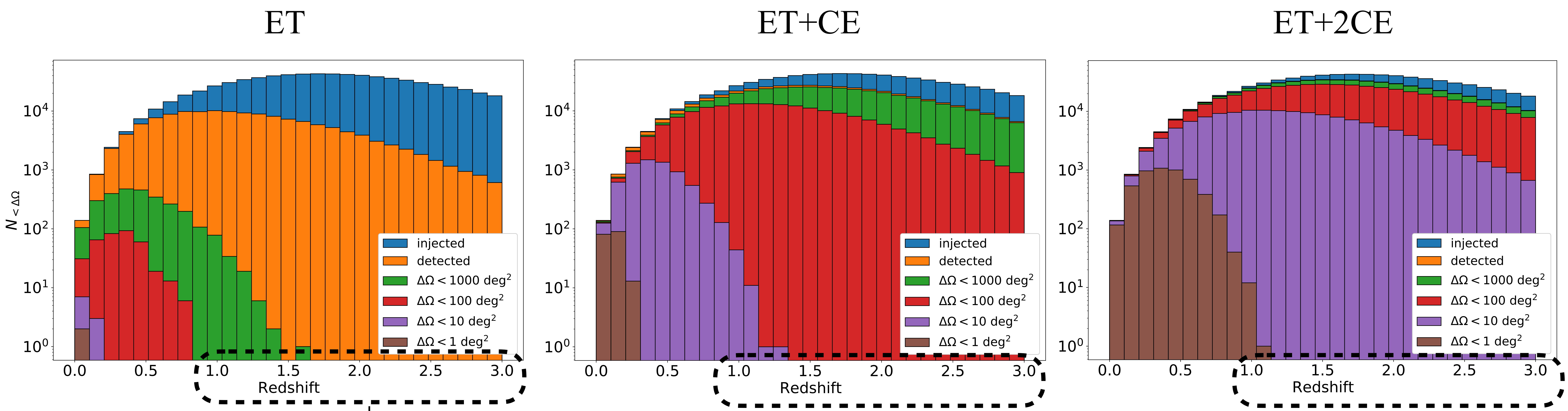
GW sky localisation



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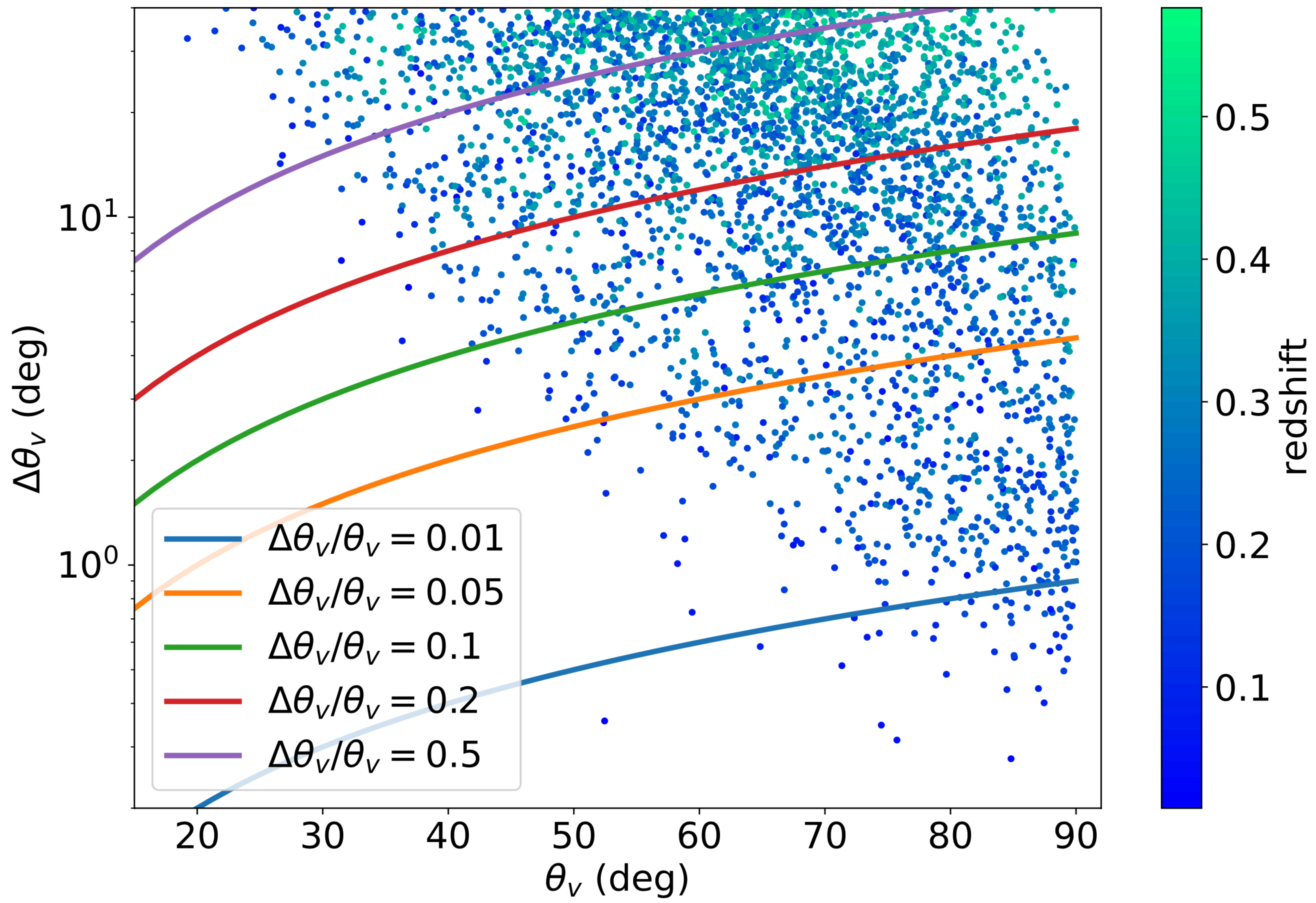
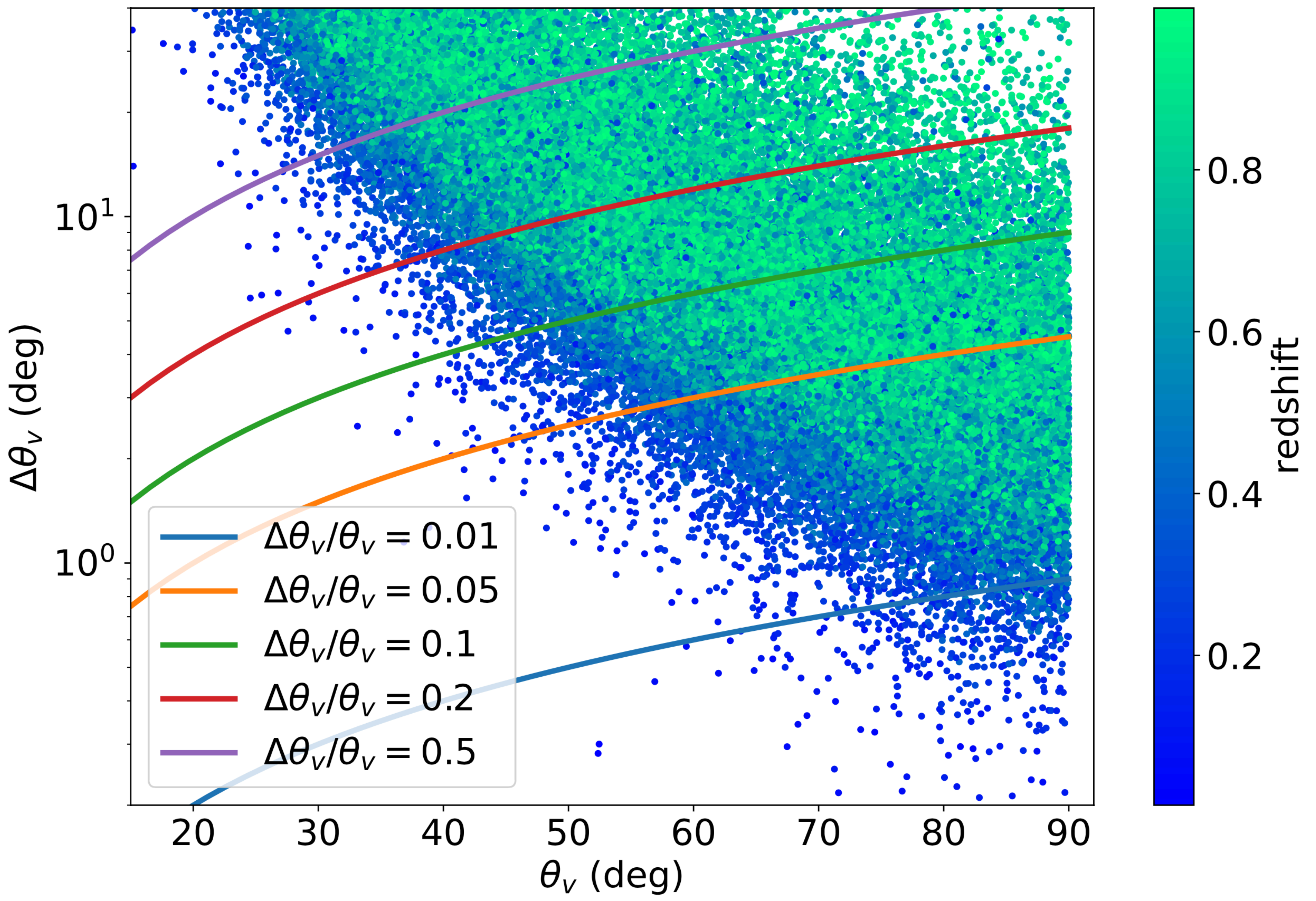
High-z GW source localisation is given by counterparts detected by **wide field X-ray and γ-ray telescopes** with arcmin localisation capabilities

Viewing angle

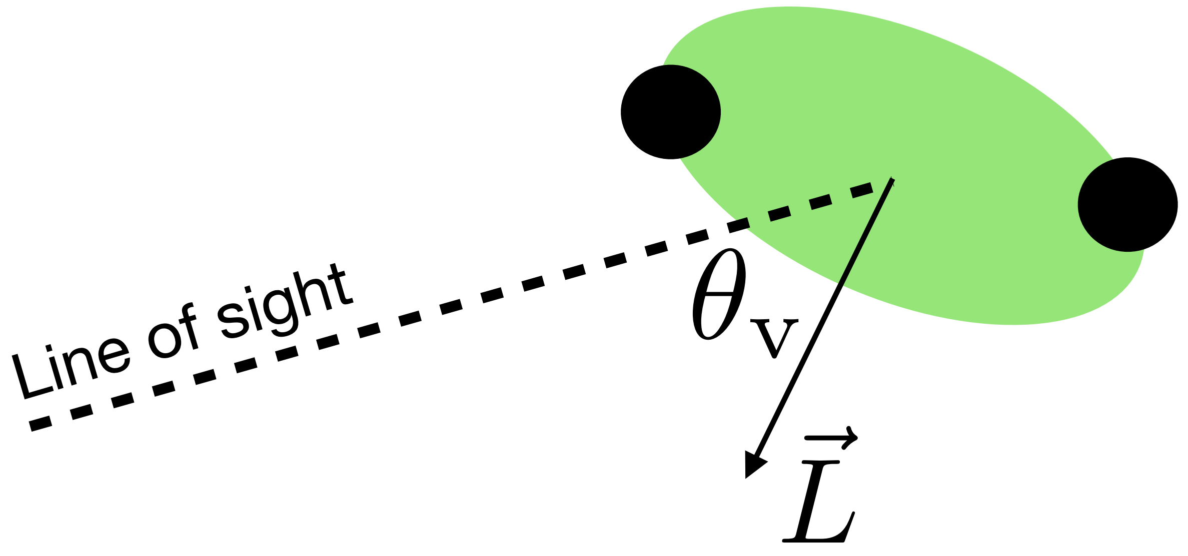
ET



ET+2CE

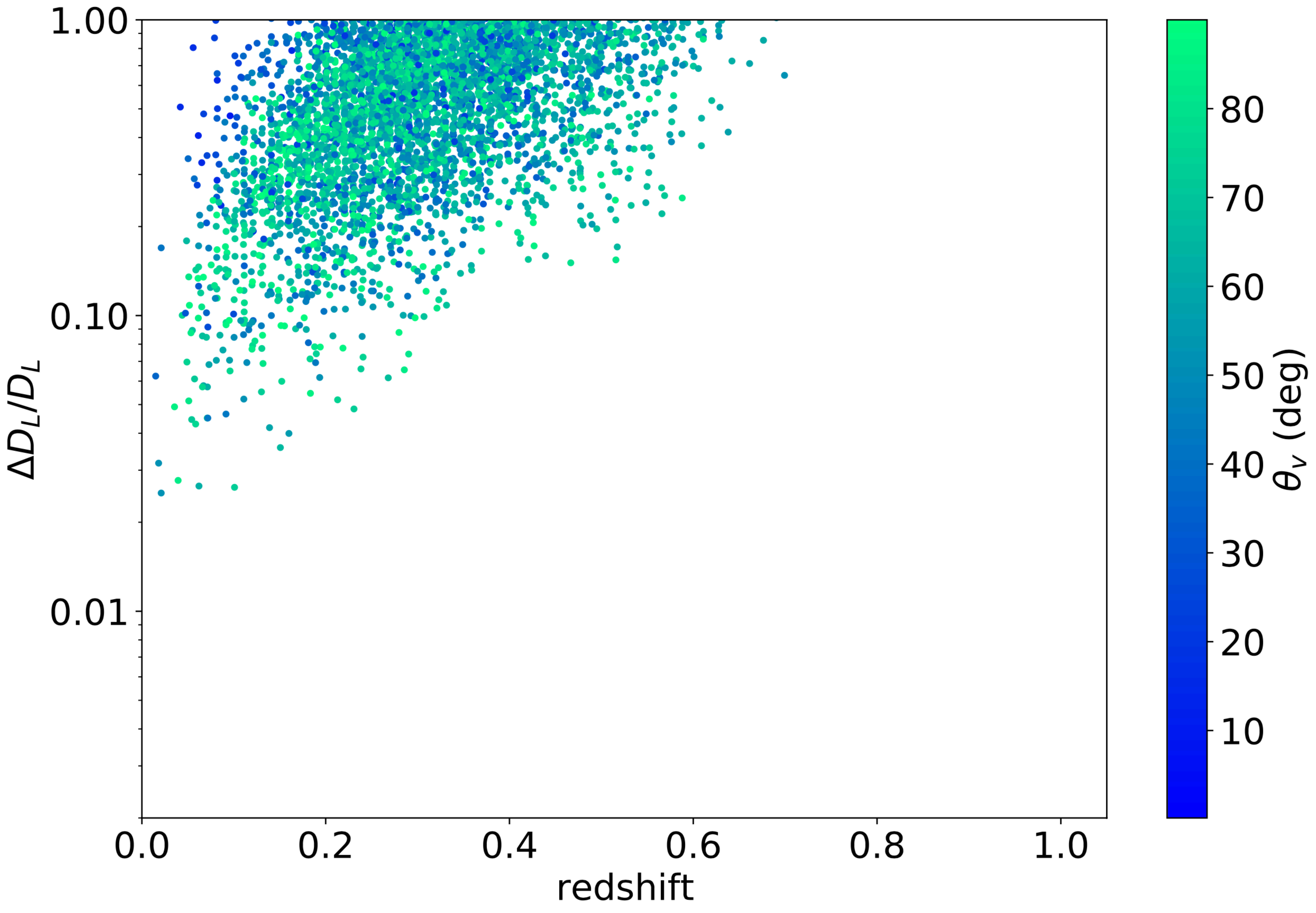


$$h_+ \propto 1 + \cos^2(\theta_v)$$
$$h_\times \propto \cos(\theta_v)$$
$$\longrightarrow \sim \text{const} \quad \text{for} \quad \theta_\text{v} \sim 0$$

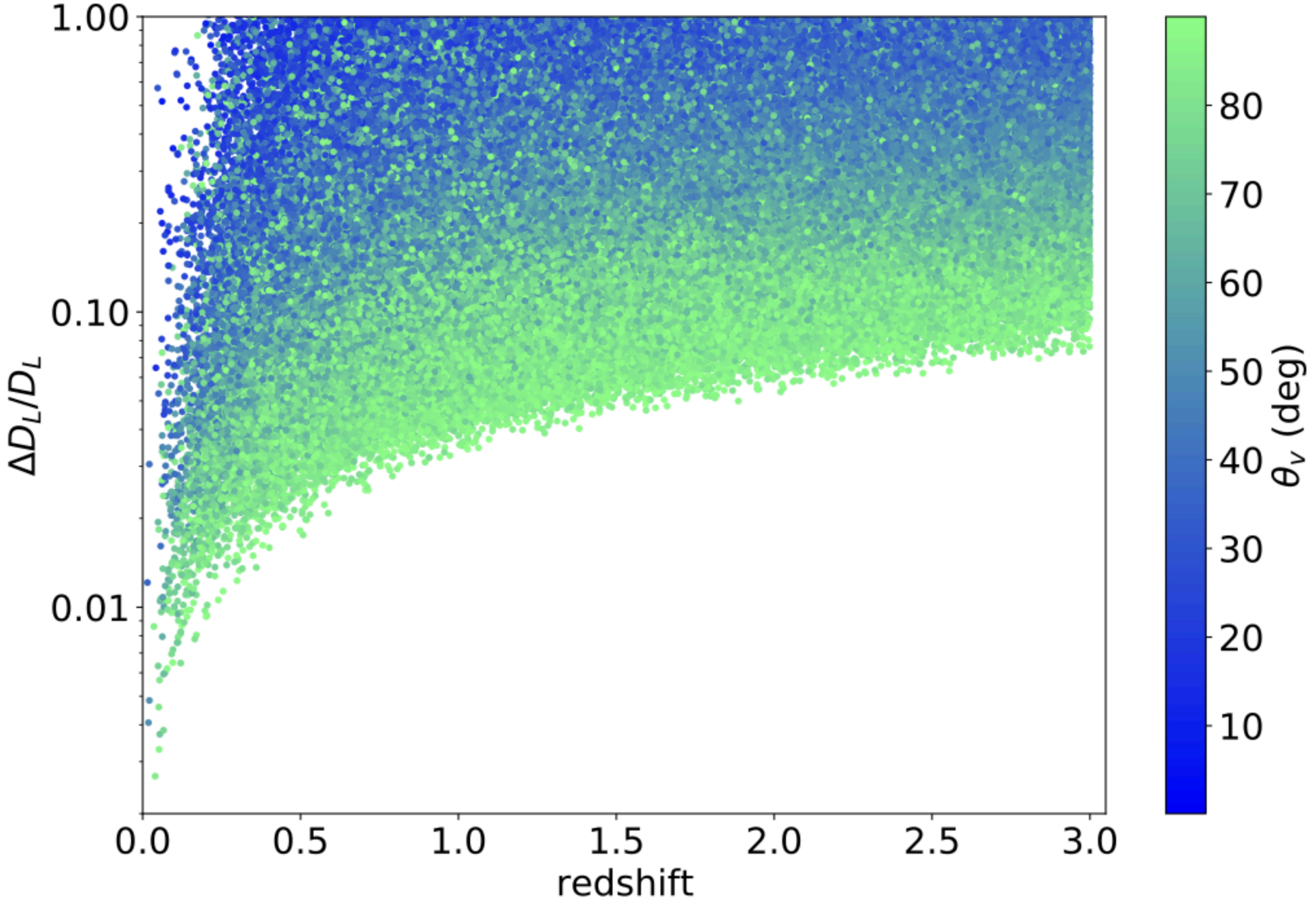


Luminosity distance

ET



ET+2CE



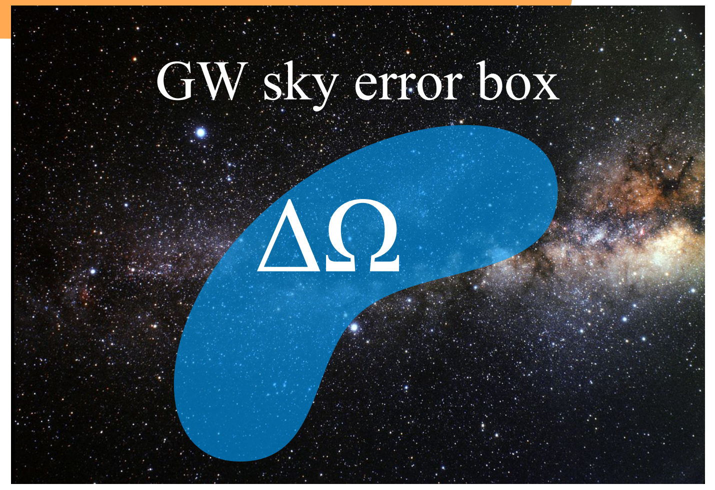
$$h \propto \frac{\cos(\theta_v)}{D_L} \longrightarrow$$ Degenerate parameters

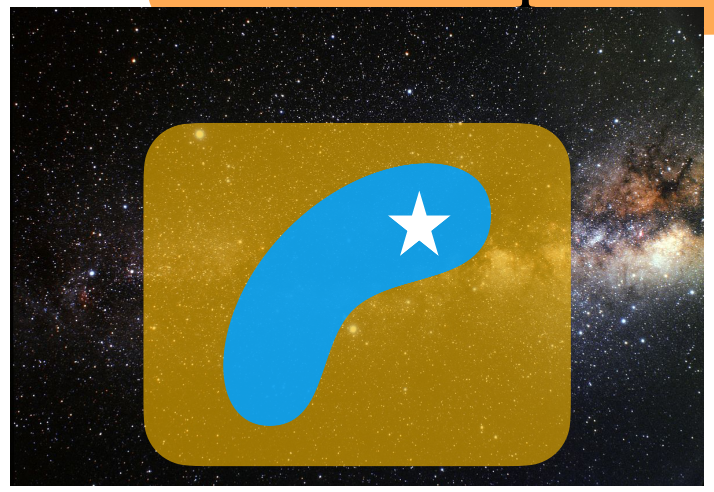
Detectability of the afterglow emission: survey vs pointing

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

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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

Caveats about the pointing strategy

	ET	ET+CE	ET+2CE
EP	9^{+5}_{-3}	294^{+80}_{-59}	359^{+168}_{-110}
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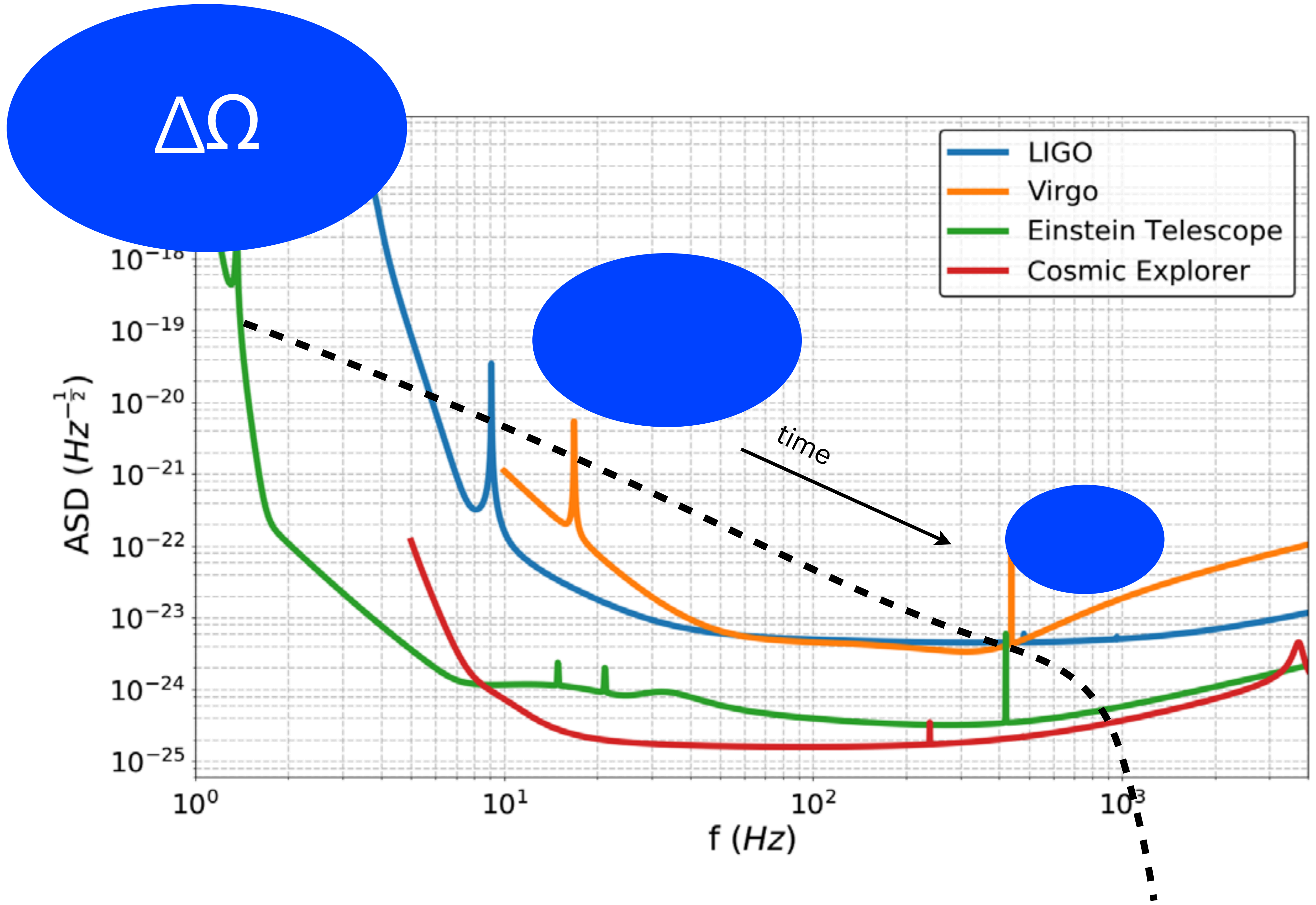
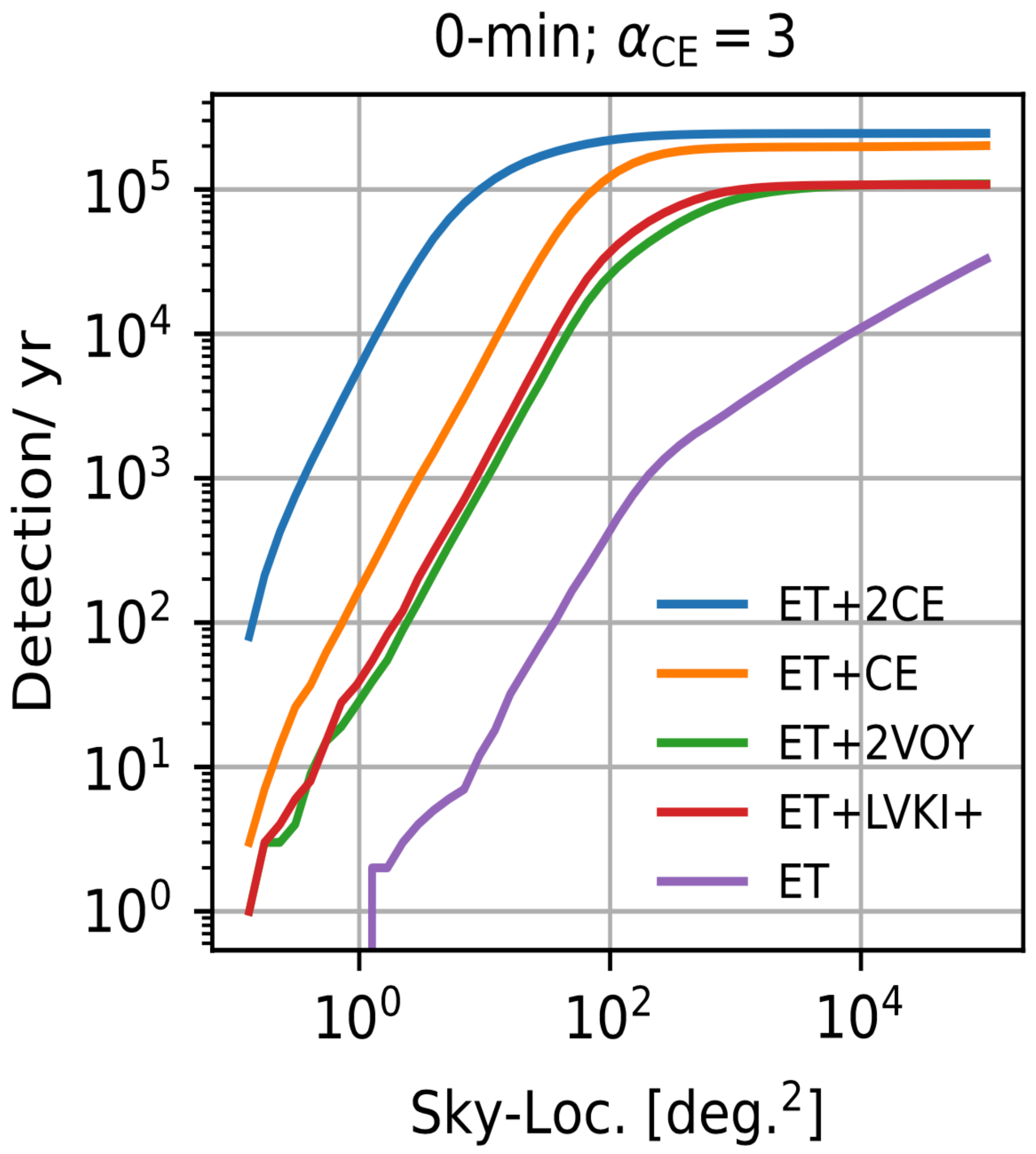
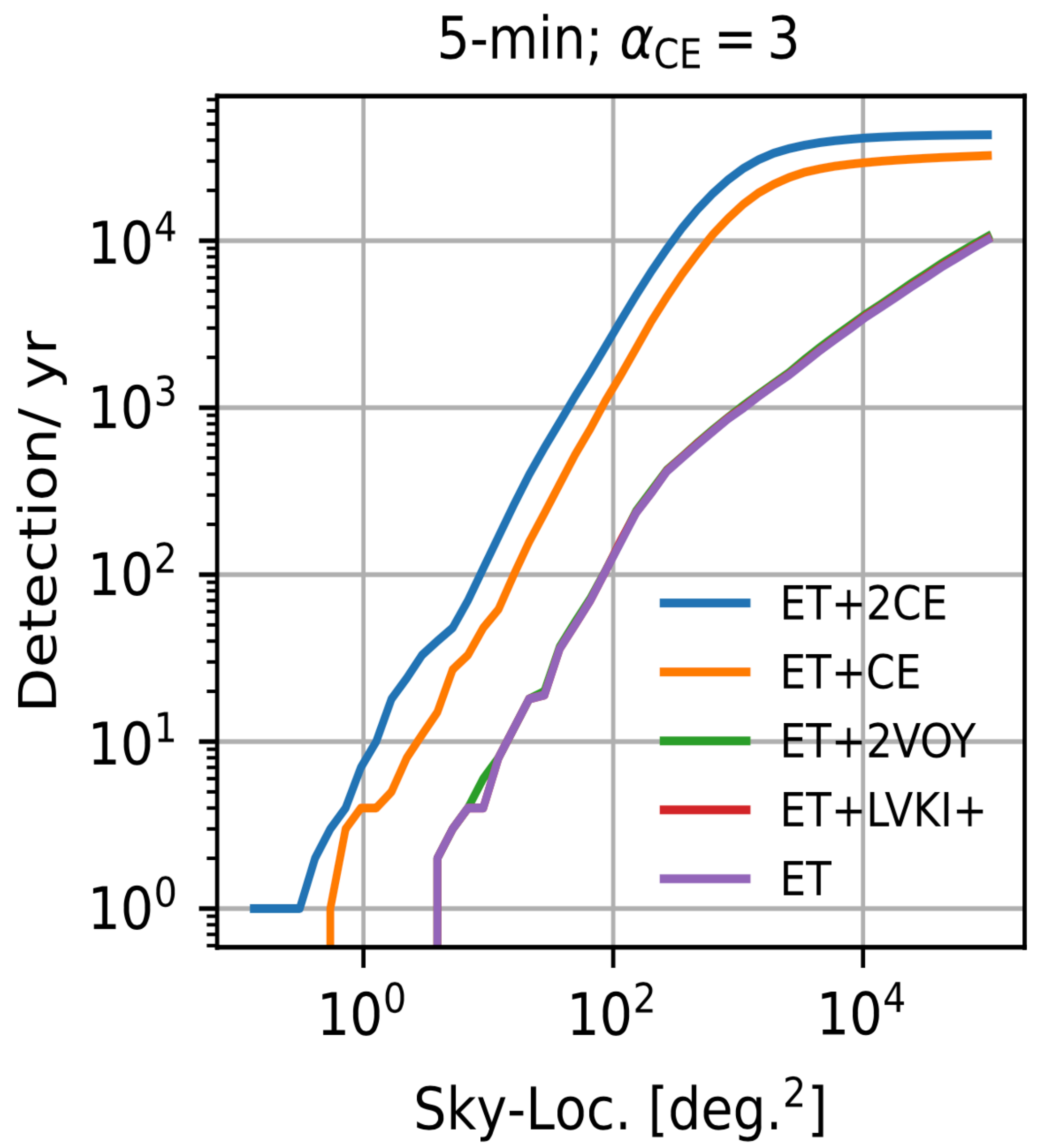
Pre-merger sky localisation

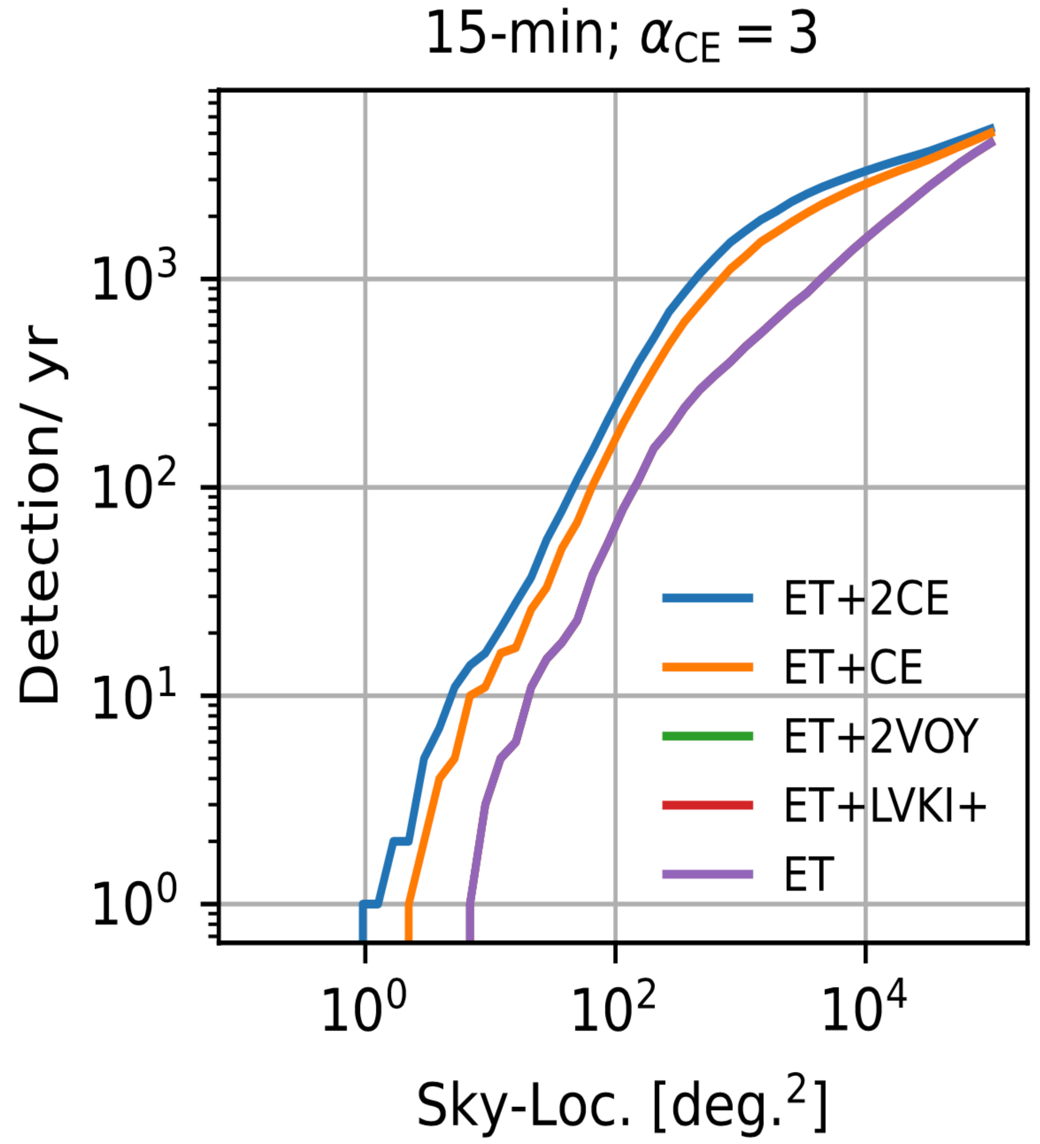


For some golden cases, enough SNR can be accumulated already **before the merger**

From Banerjee et al. (In preparation)

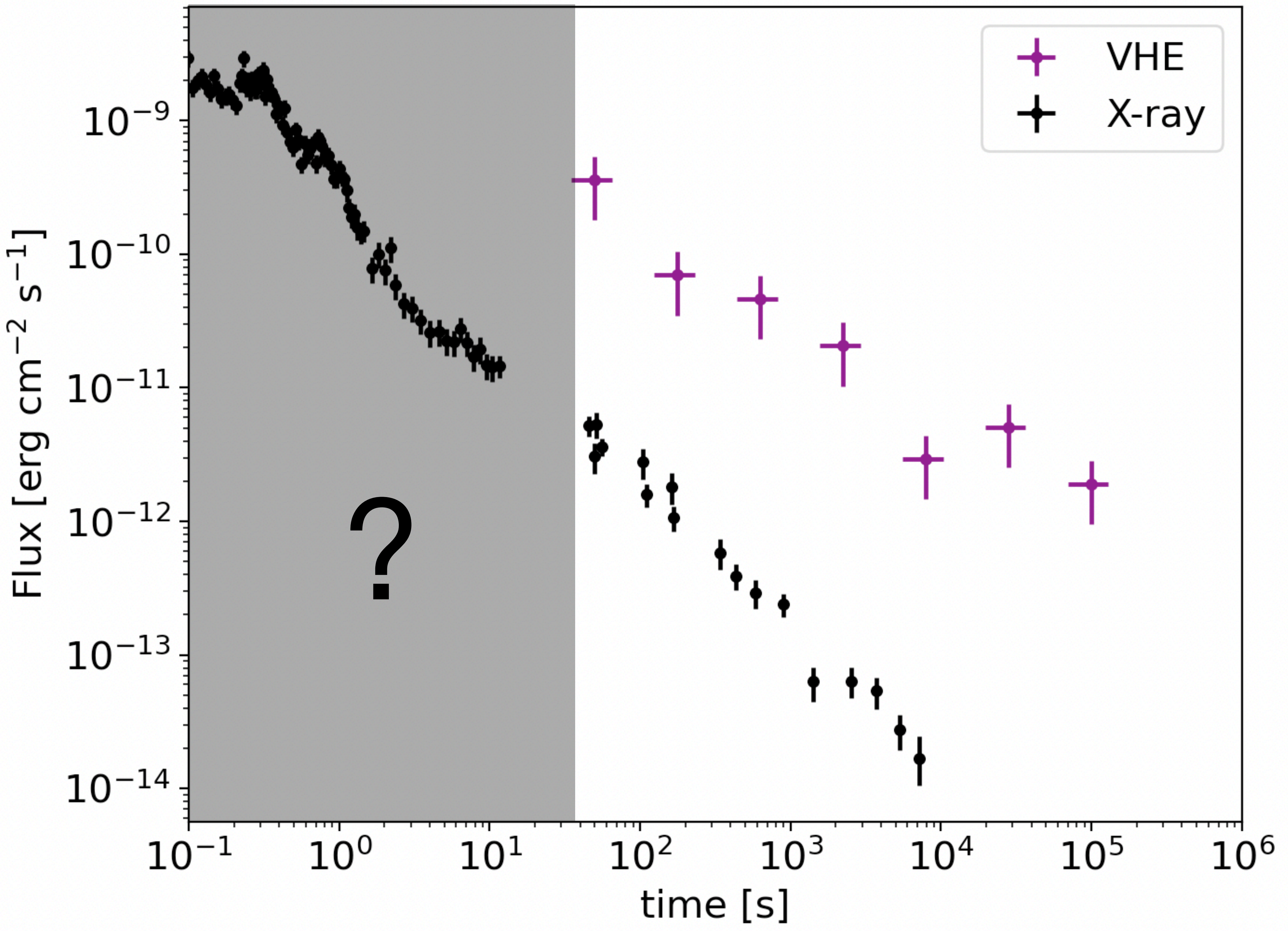


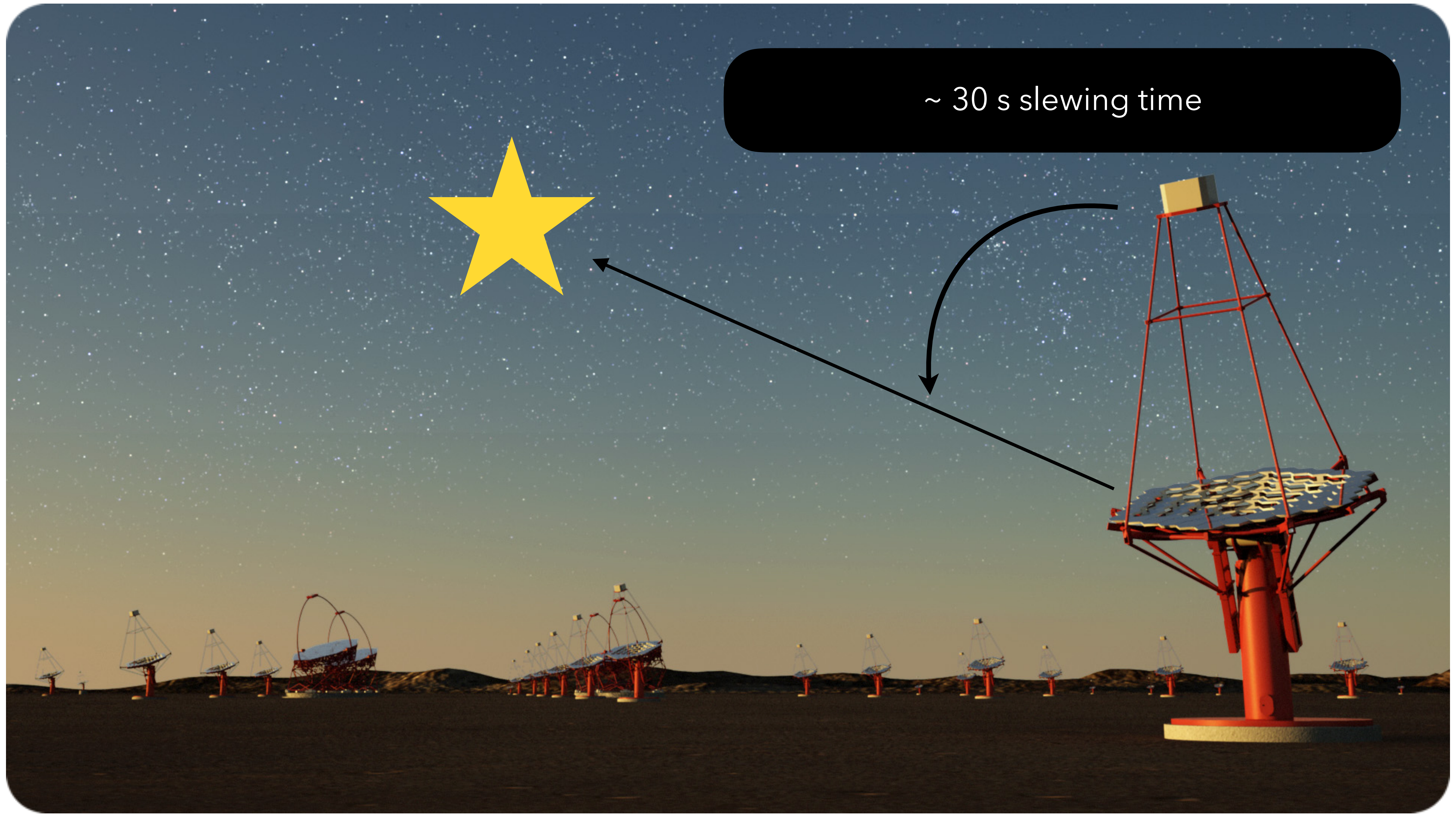




ET+2CE	$N_{det}(\Delta\Omega<100\ deg^2)$
t_m	$\sim 10^5$
t_m-5 min	$\sim 10^3$
t_m-15 min	$\sim 10^2$

Pre-merger sky localisation and VHE from sGRBs

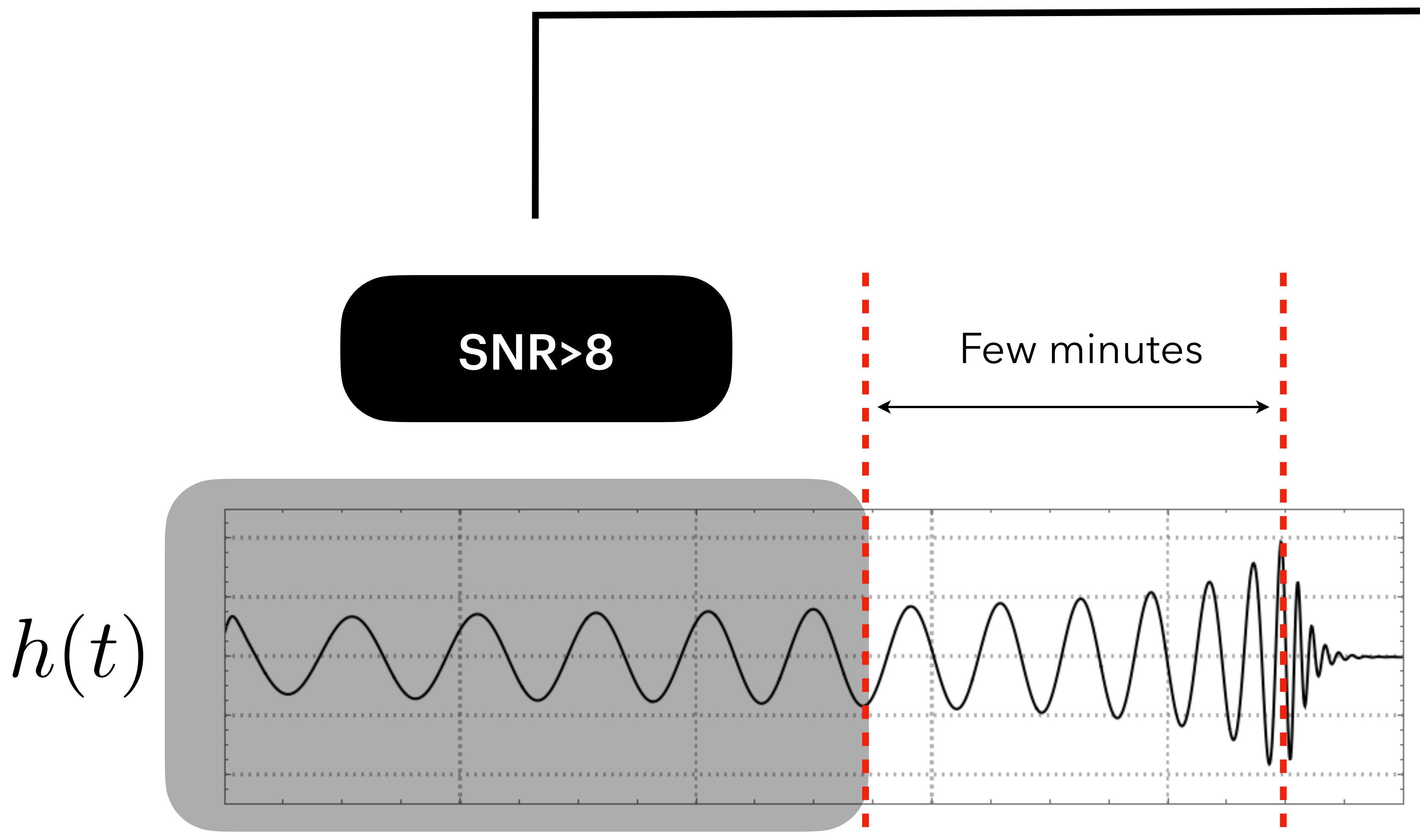


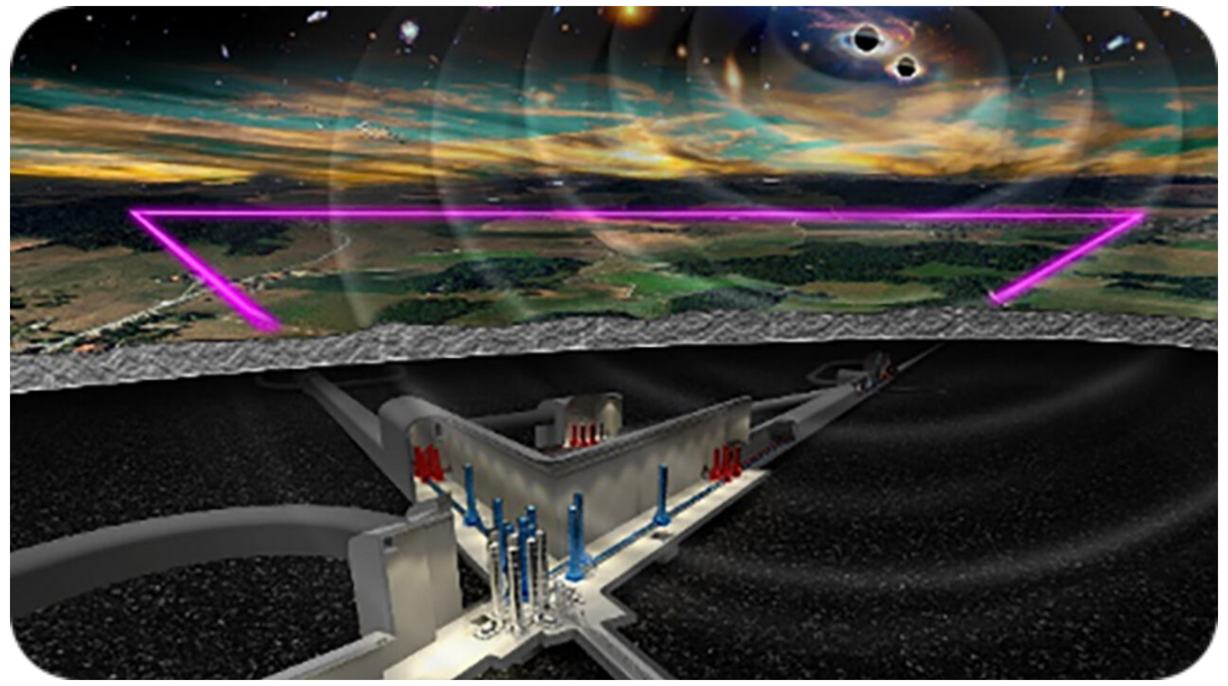


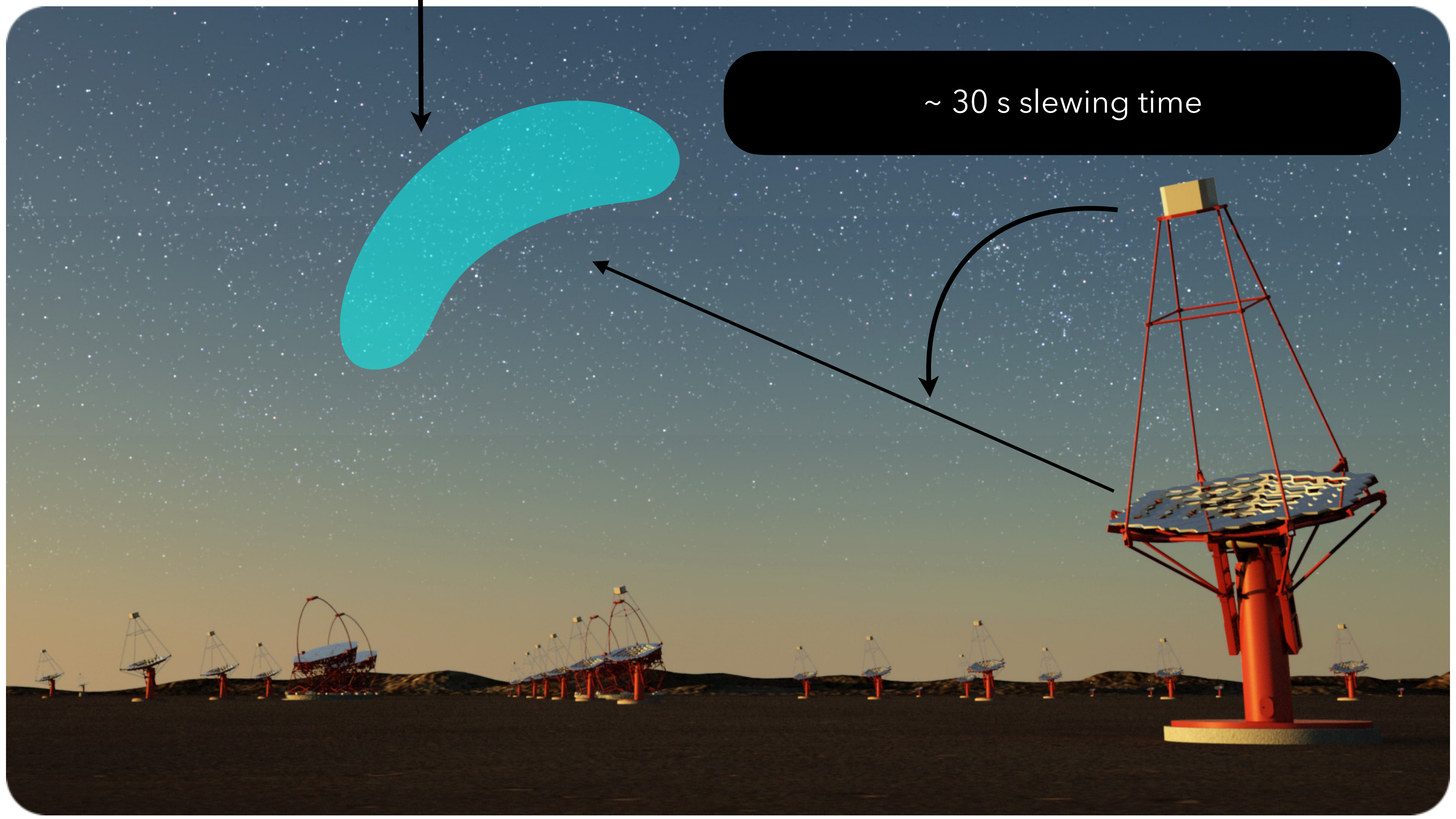
MAGIC and HESS detected VHE during GRB afterglows → **what about the prompt emission?**

During the activity of 3G GW detectors, **CTA** should be operative as well

Pre-merger sky localisation and VHE from sGRBs







In this way, CTA will be able to point in the direction of the GRB at the moment of the merger, allowing to **detect possible VHE emission during the prompt phase**

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}
TAP-WFI	8^{+5}_{-3}	182^{+43}_{-31}	225^{+76}_{-72}

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}

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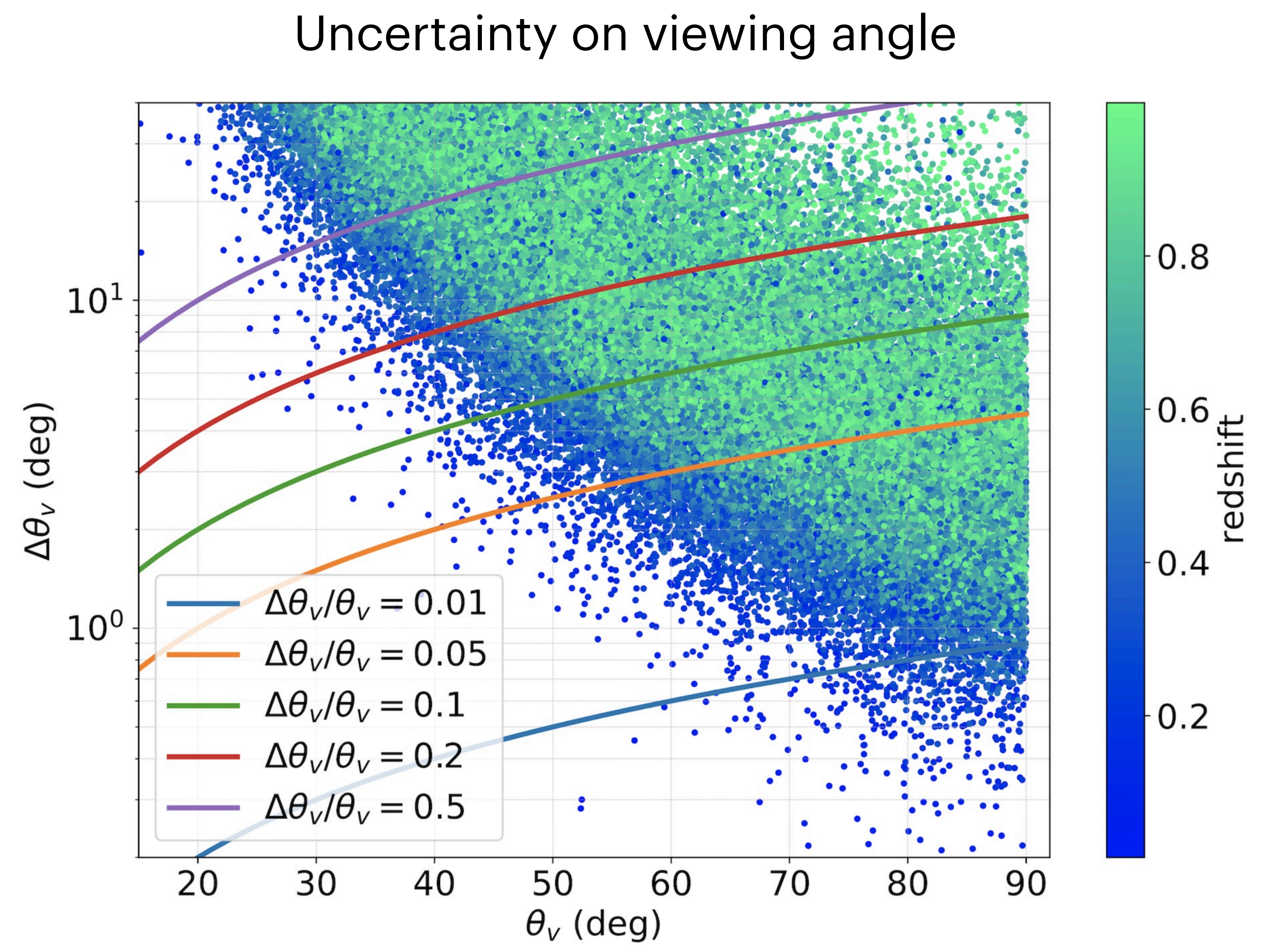
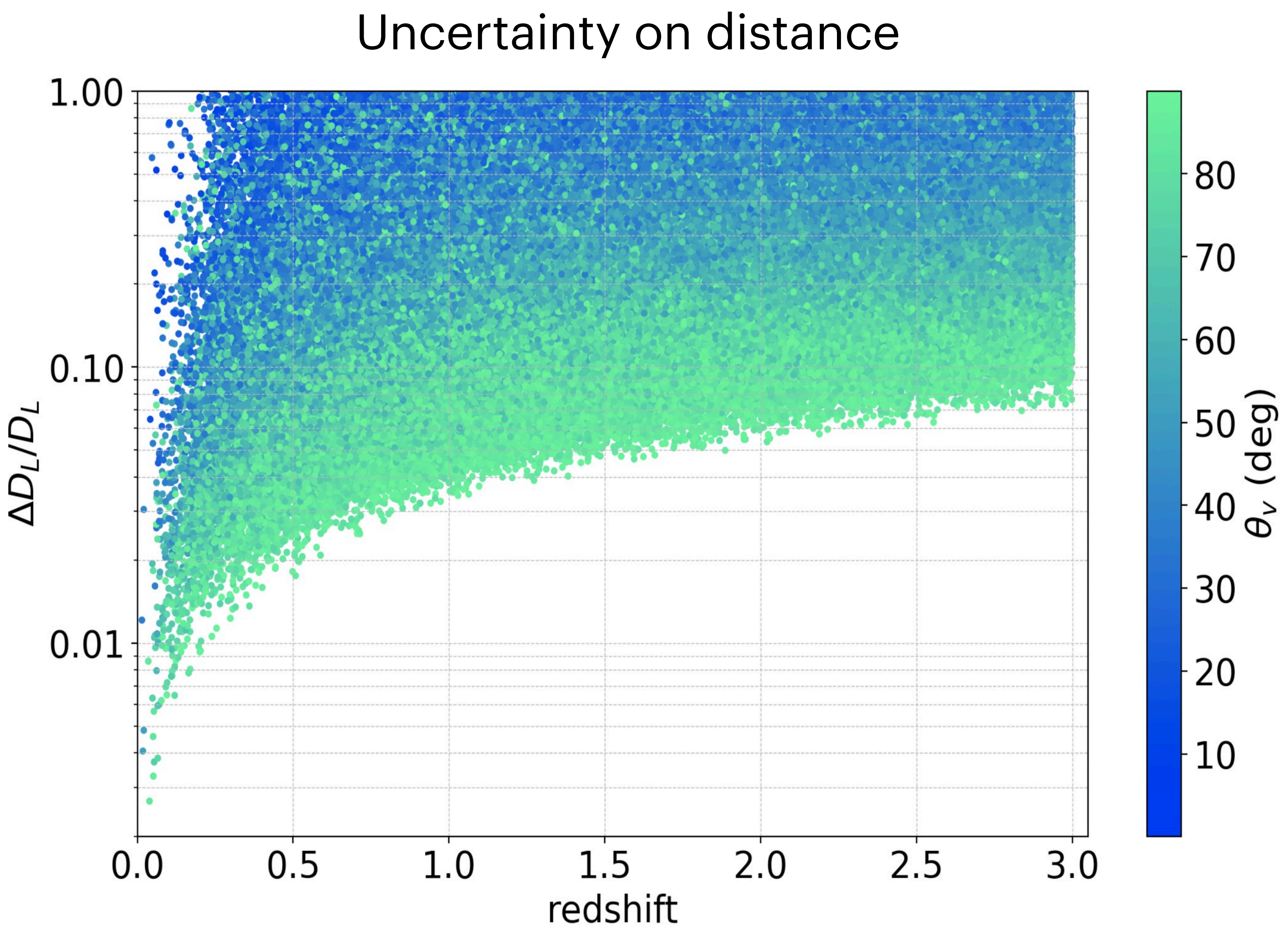
How to exploit the GW information





Unfortunately, the Nature is cruel in this case → the **most promising cases** for high-energy detection are the **on-axis ones**, which also correspond to the ones with **larger uncertainty on viewing angle and distance**

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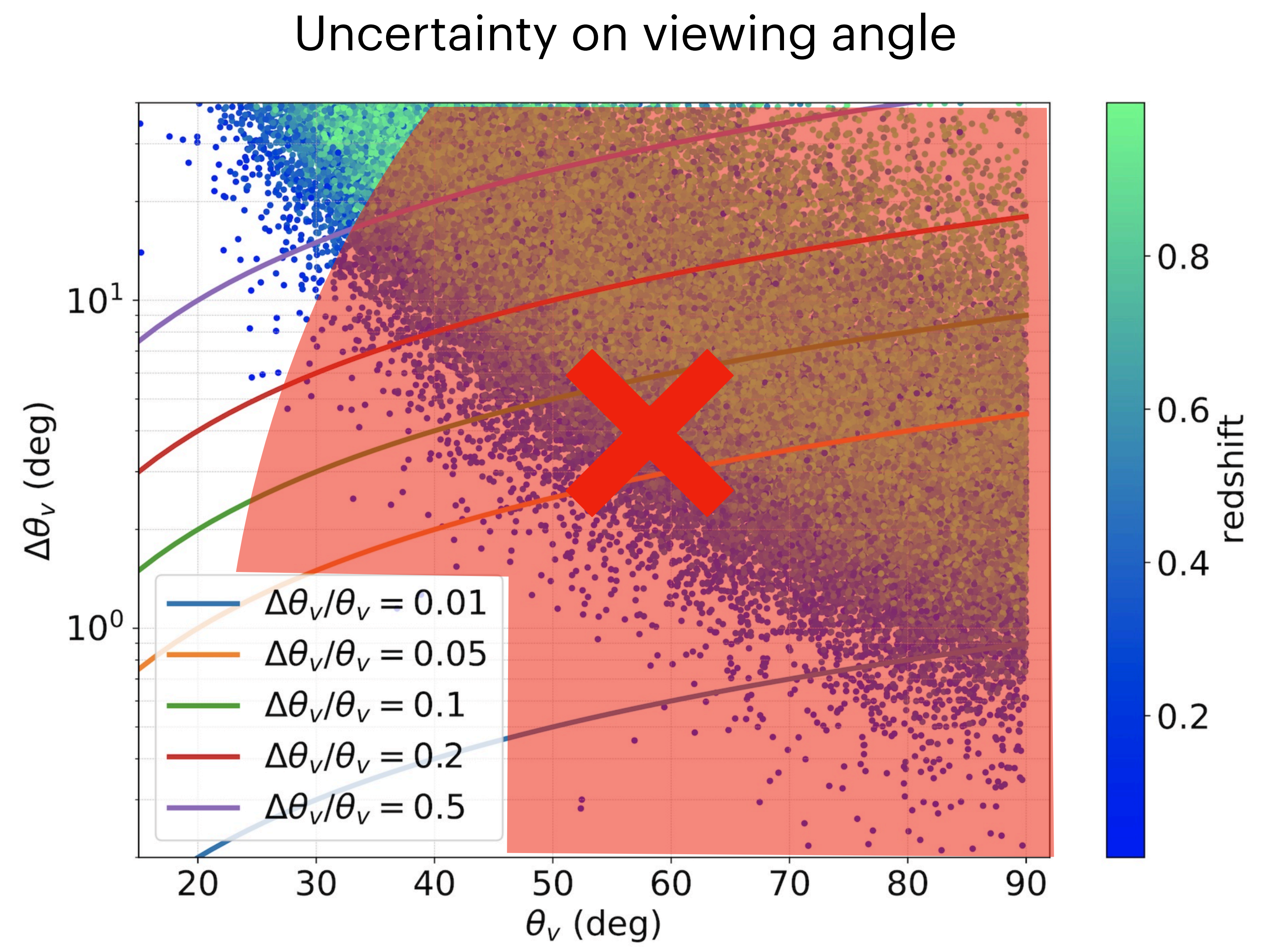

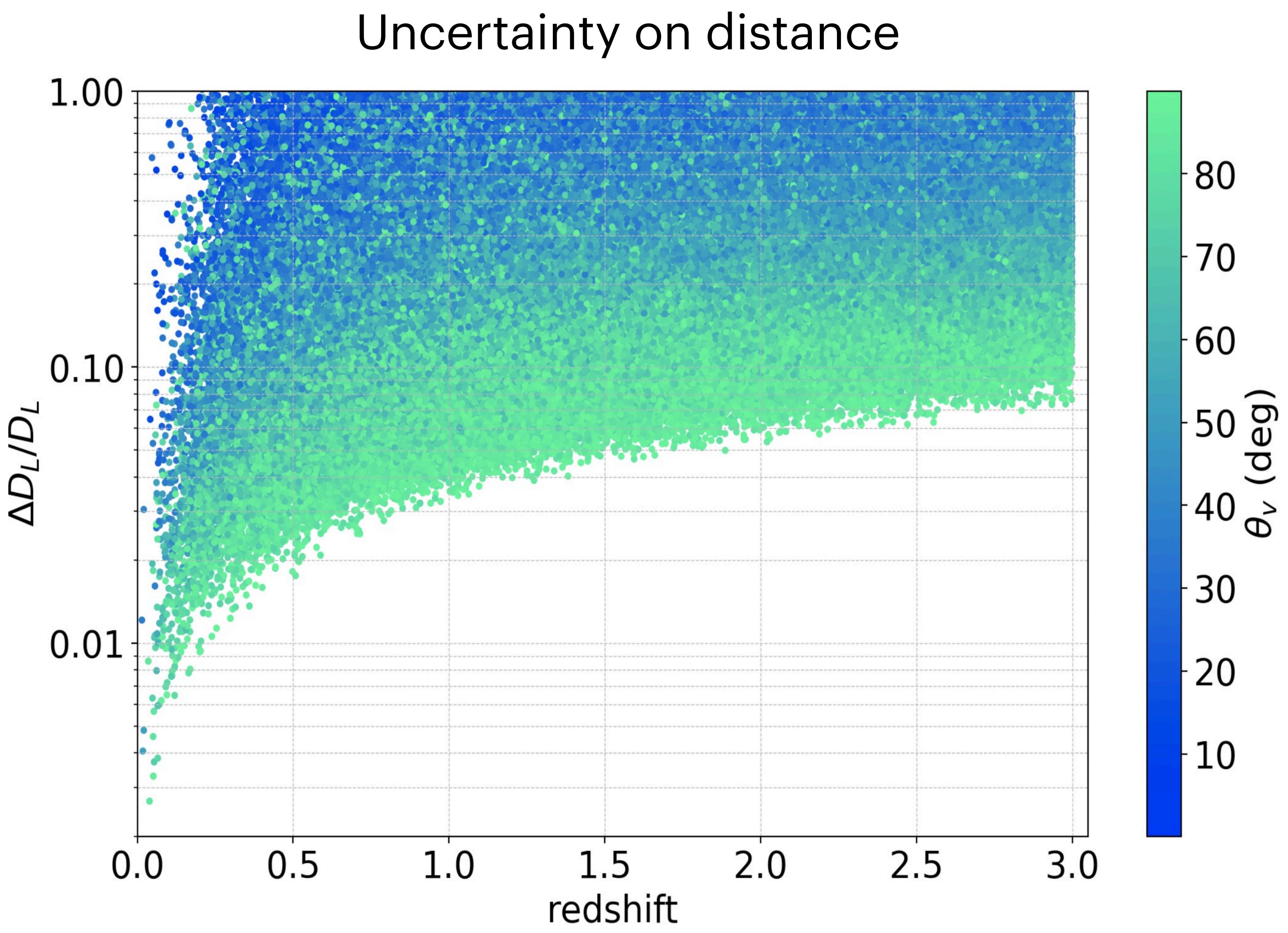

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$$\mathrm{SNR} > 100, \Delta\Omega < 100\,\mathrm{deg}^2, \theta_\mathrm{v} \pm \Delta\theta_\mathrm{v} < 20^\circ$$

e.g., ET+2CE + THESEUS-SXI: $\sim 10^5 \to 450 \to 4^{+3}_{-2}\,\mathrm{det/yr}$

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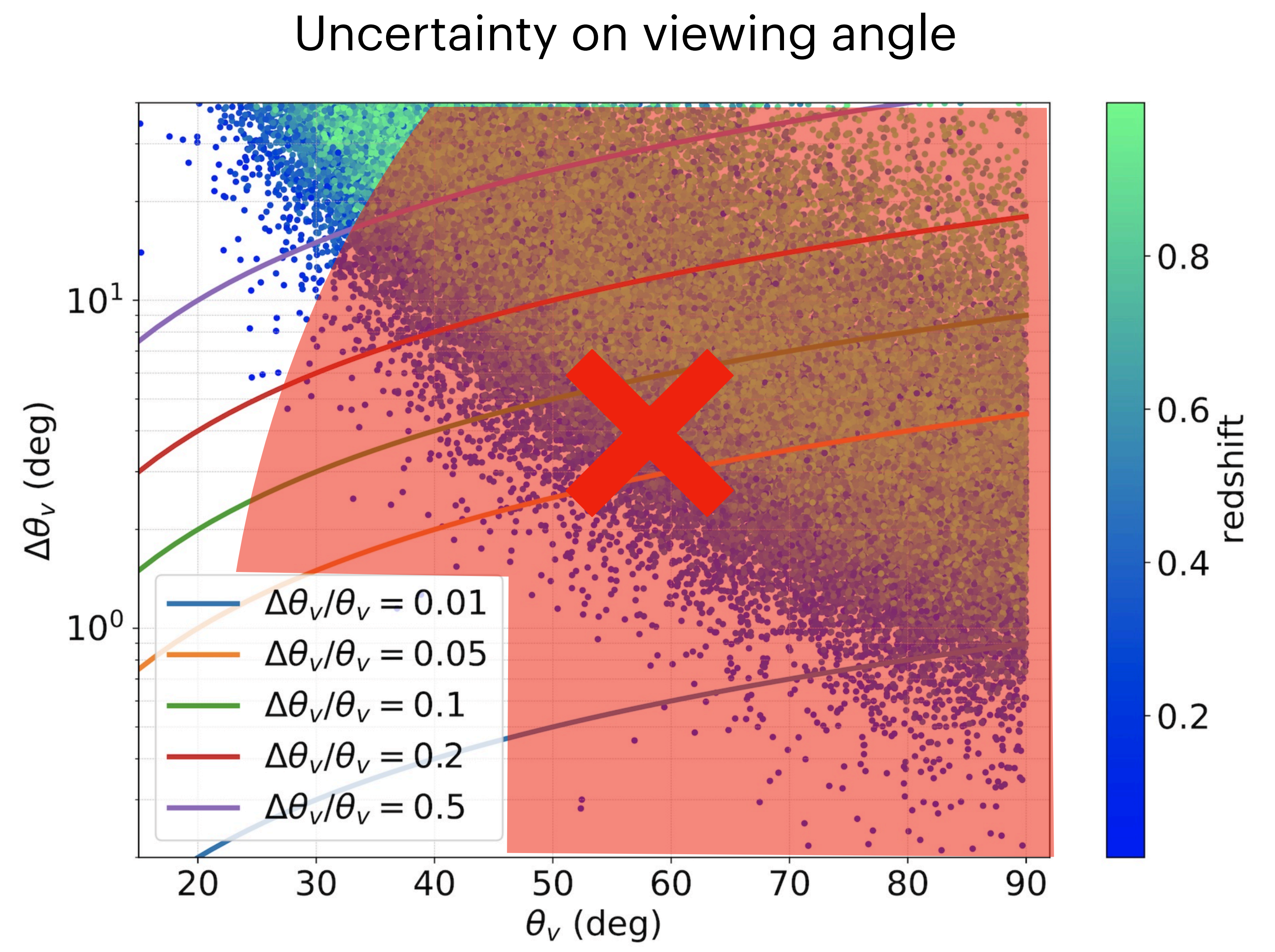

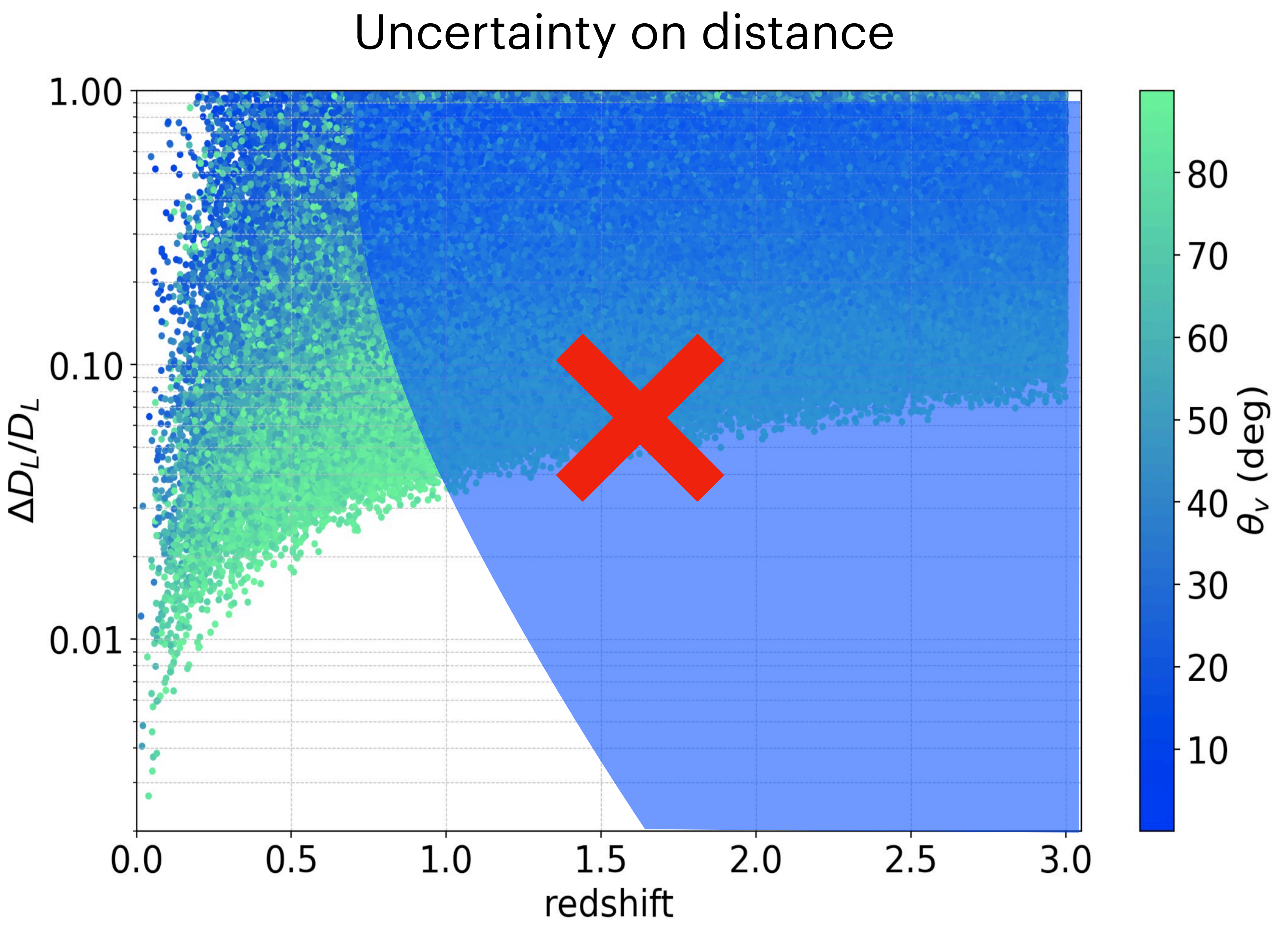

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$$\Delta V = \Delta\Omega D_L^2 \Delta D_L < V_{max} \Rightarrow \frac{\Delta D_L}{D_L} < \frac{V_{max}}{\Delta\Omega D_L^3}$$

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$$V_{max} = 10\,\mathrm{Mpc}^3$$

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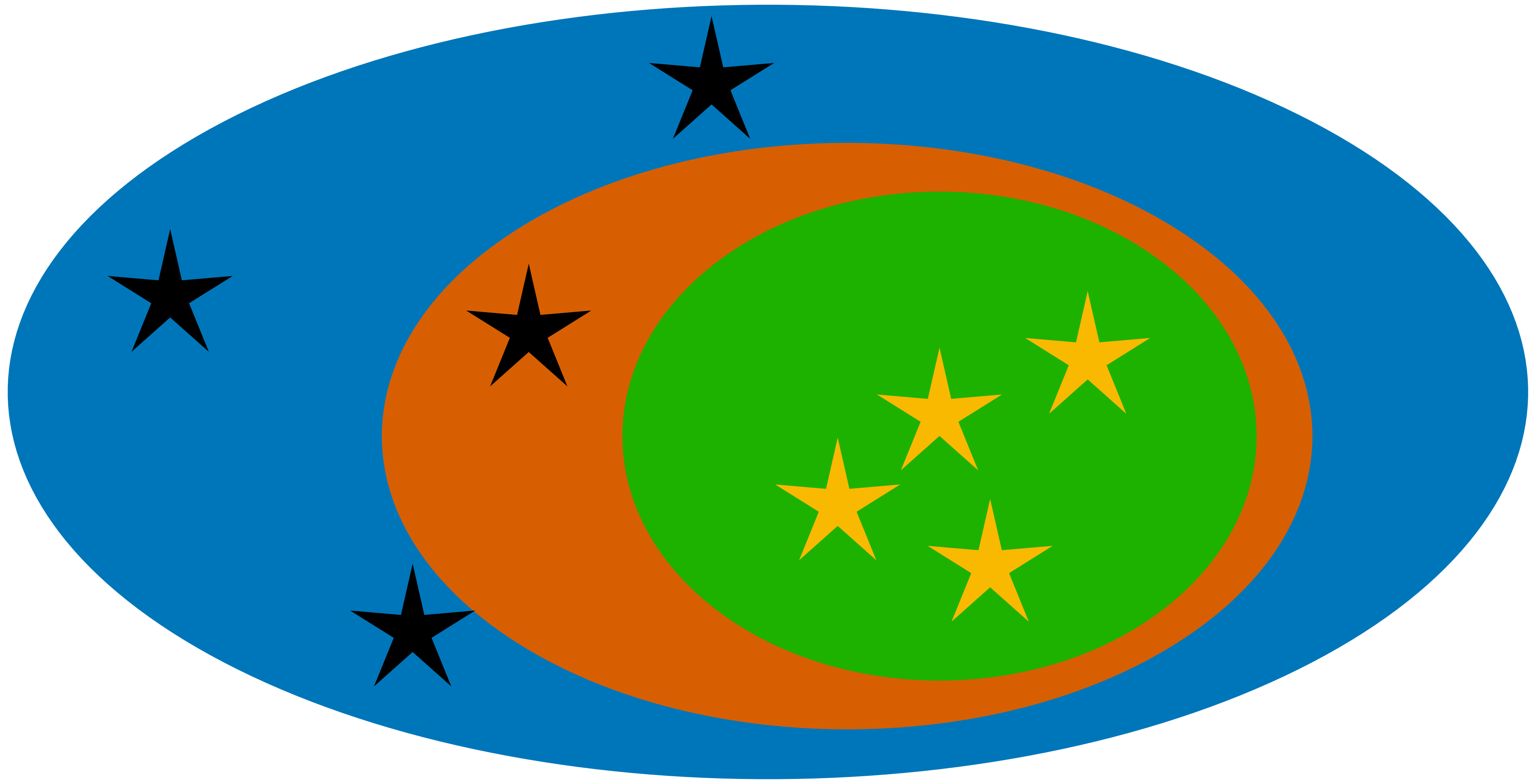

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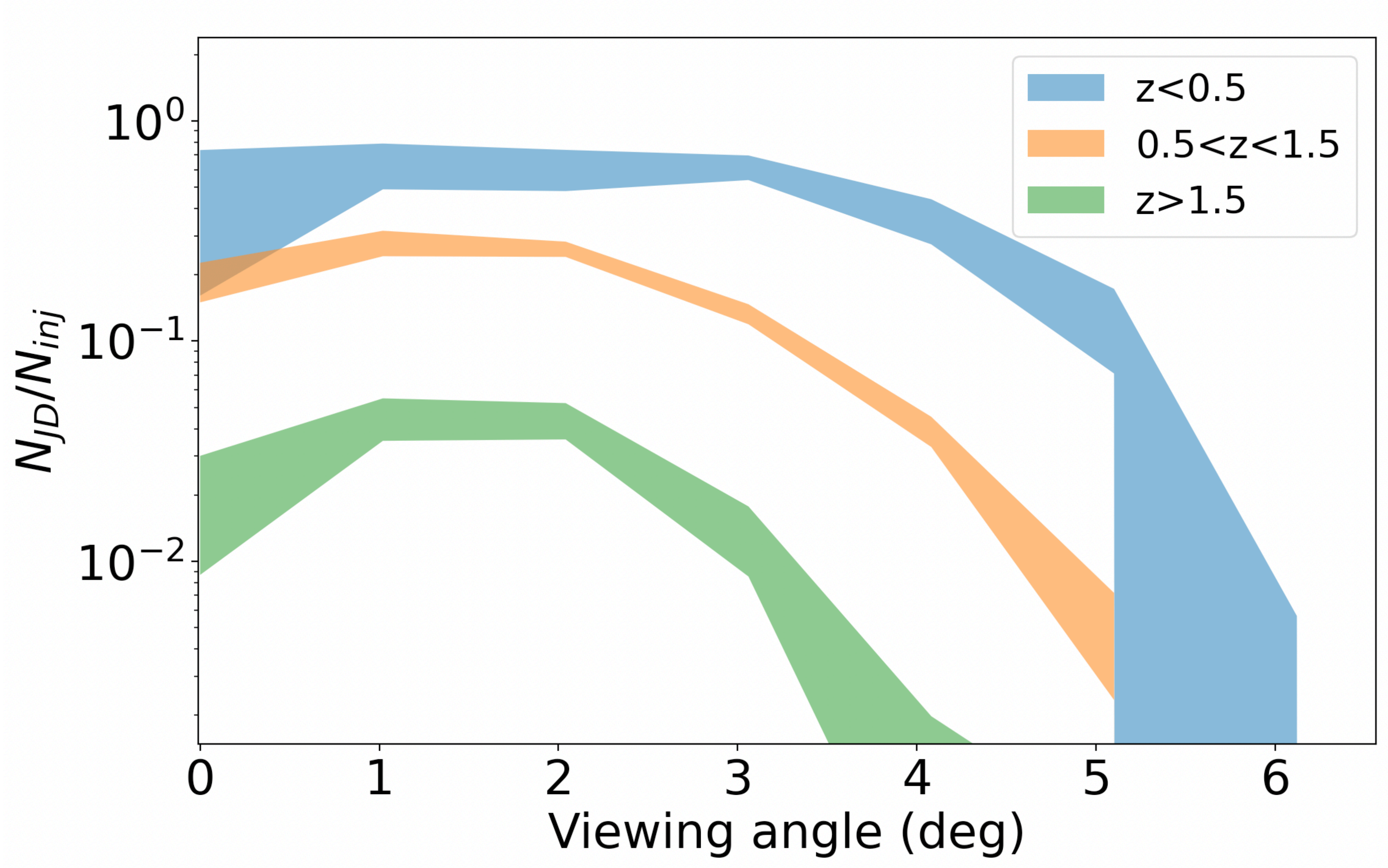
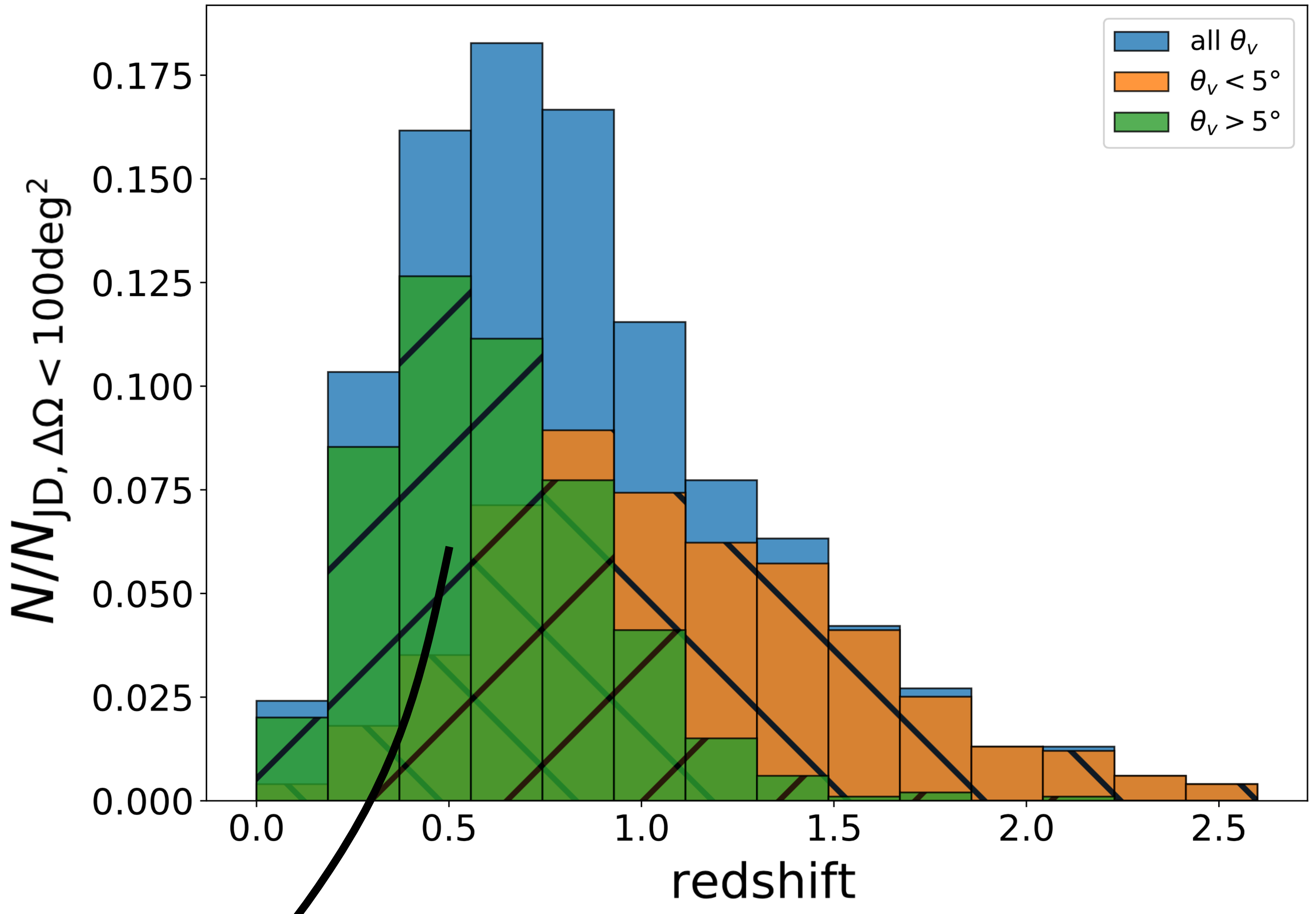
The importance of WFX-ray telescopes

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



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



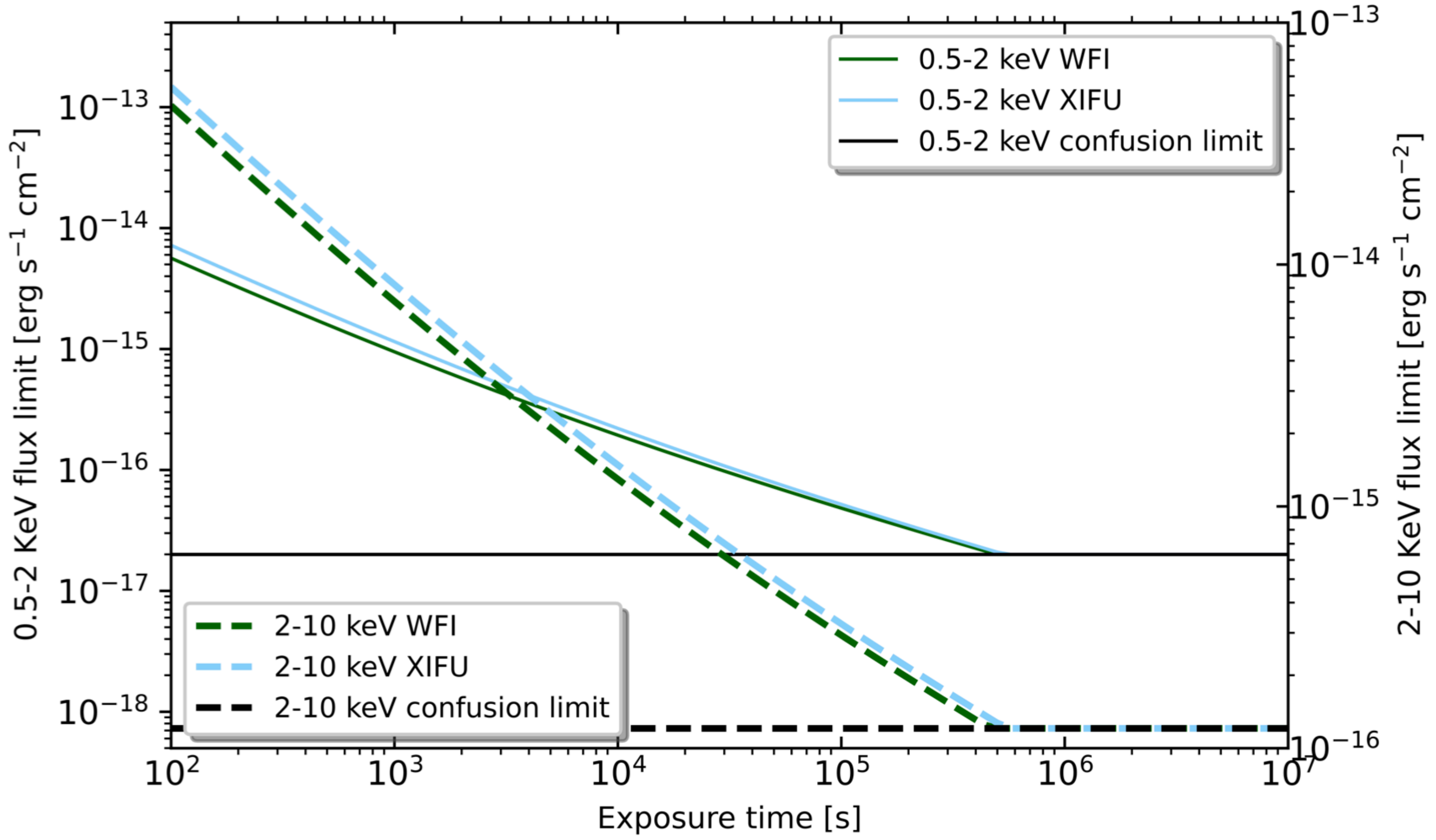
Too off-axis to have a detectable γ-ray emission

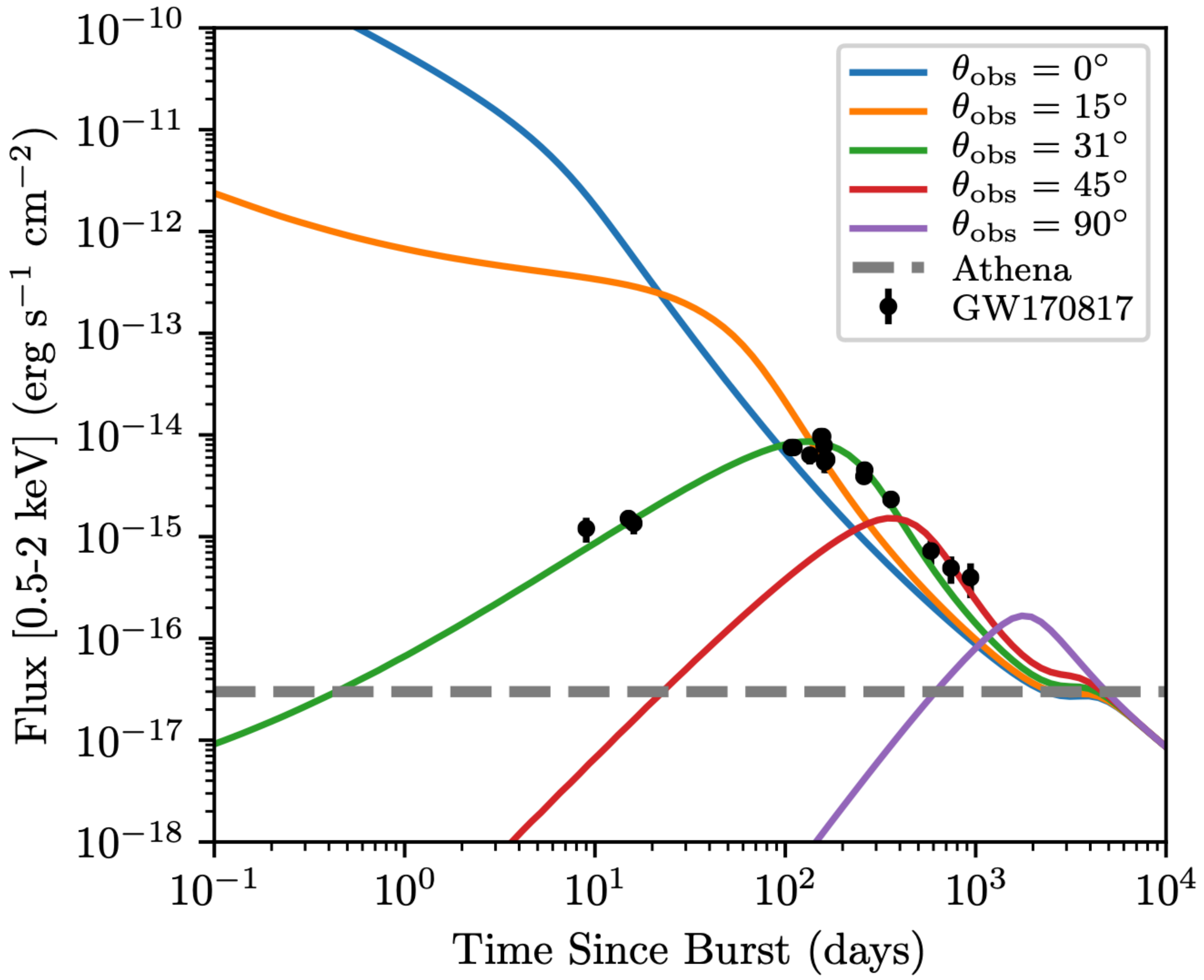
WFX-ray telescopes can significantly **enhance the probability of a joint detection**

The role of sensitive X-ray instruments

Piro et al. 2021

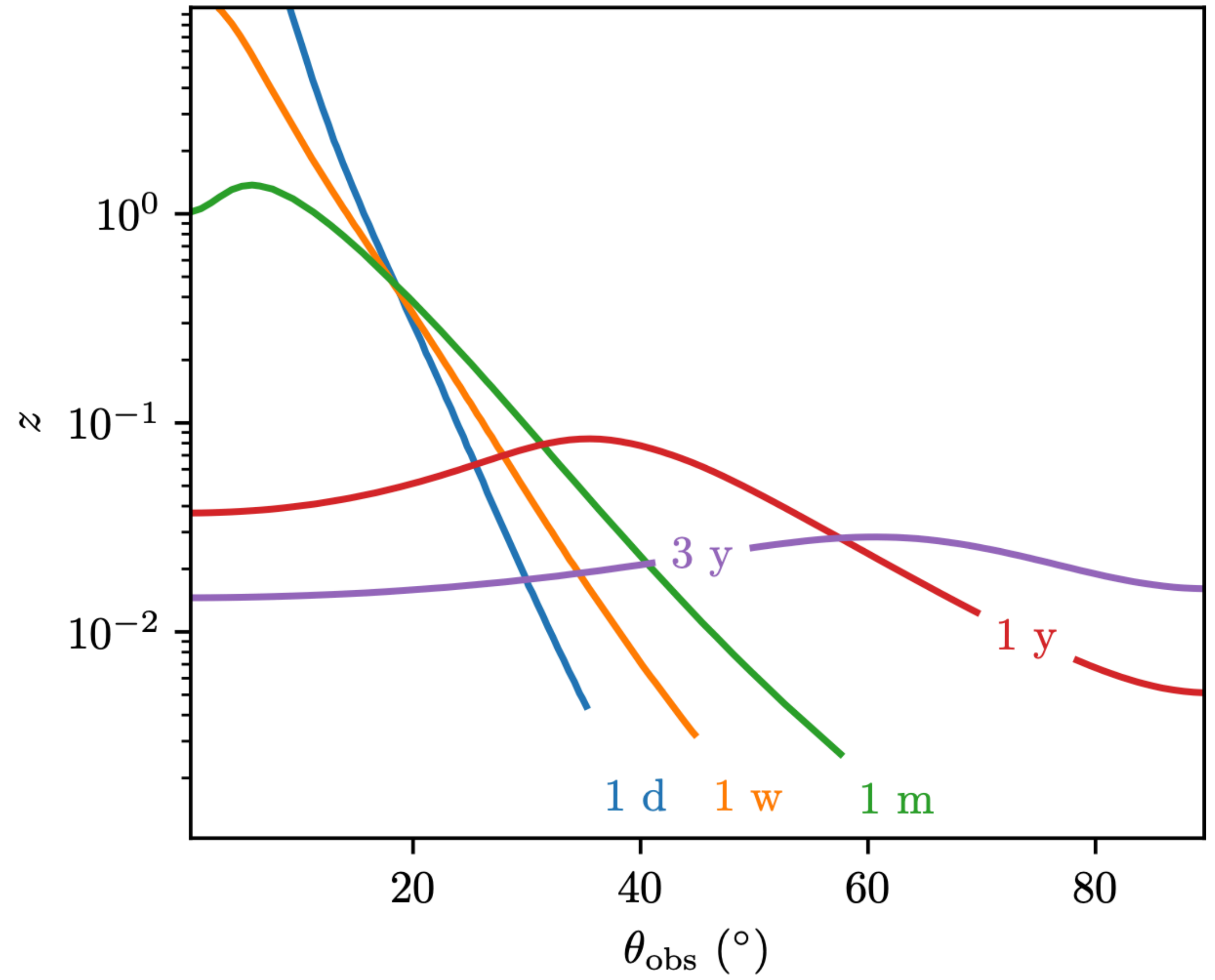
Unprecedented sensitivity in the soft X-rays





GW170817-like events are detectable:

- Months/years after the merger
- Up to large inclination angles

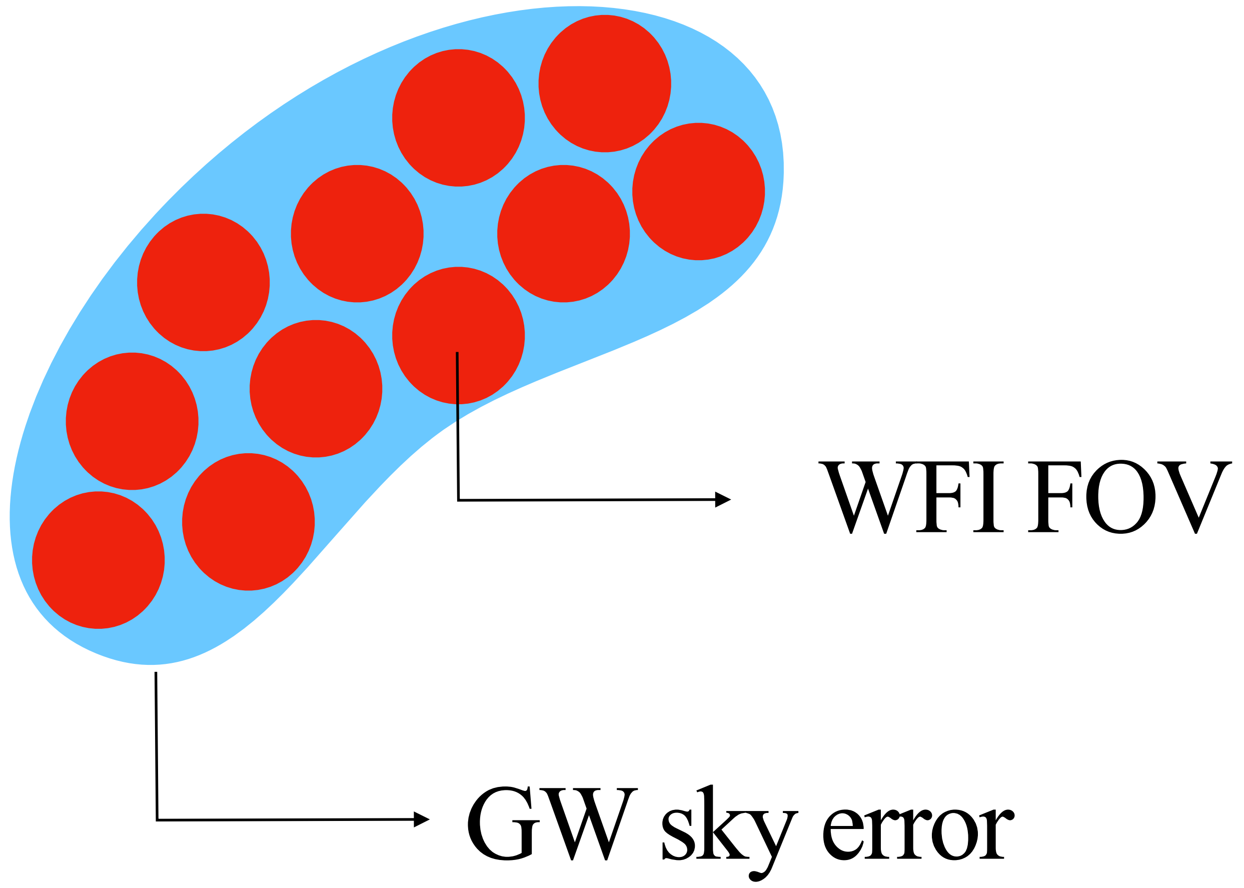


The role of sensitive X-ray instruments

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**

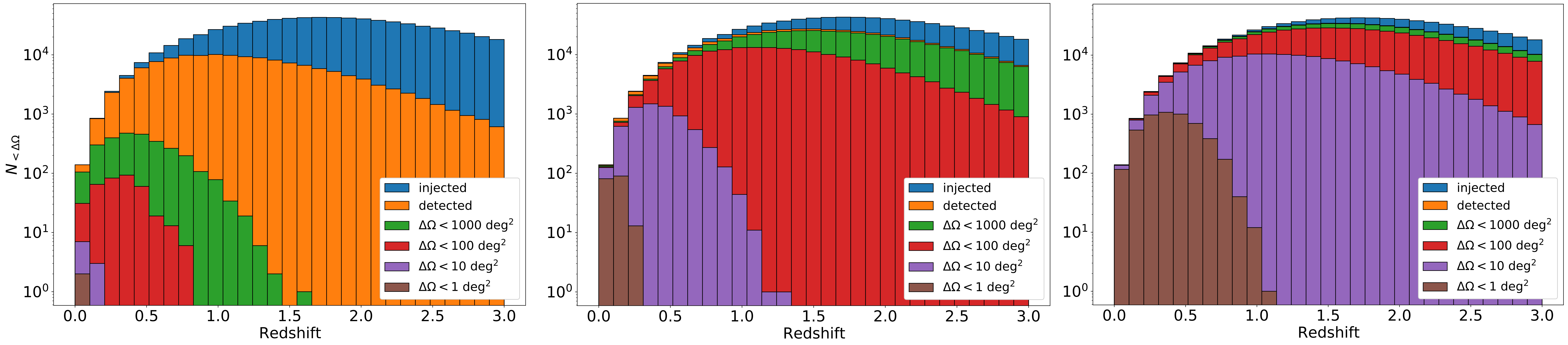
- It is necessary to define an **optimal strategy to select GW events** for which the detection of EM signal is higher

Thank you!

Backup slides

GW sky localisation

ET | ET+CE | ET+2CE



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$N_{\rm det}$	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

	ET	ET+CE	ET+2CE
$N_{\rm det}(\Delta\Omega < 1\,{\rm deg}^2)/{\rm N_{det}}$	$< 0.1\%$	$< 0.1\%$	0.8 %
$N_{\rm det}(\Delta\Omega < 10\,{\rm deg}^2)/{\rm N_{det}}$	$< 0.1\%$	2 %	26 %
$N_{\rm det}(\Delta\Omega < 100\,{\rm deg}^2)/{\rm N_{det}}$	0.3 %	42 %	83 %
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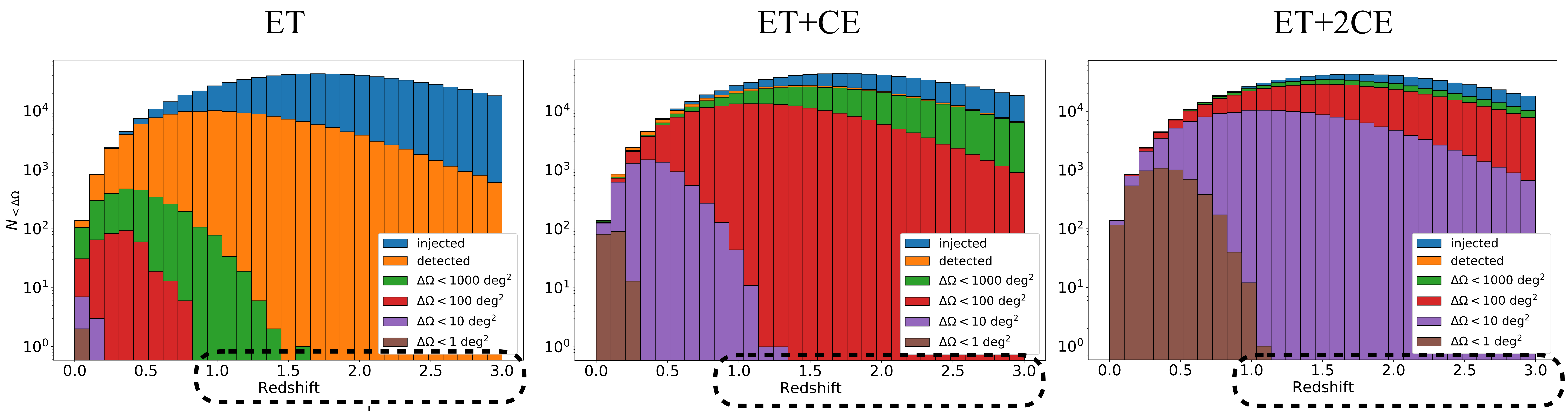
GW sky localisation



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

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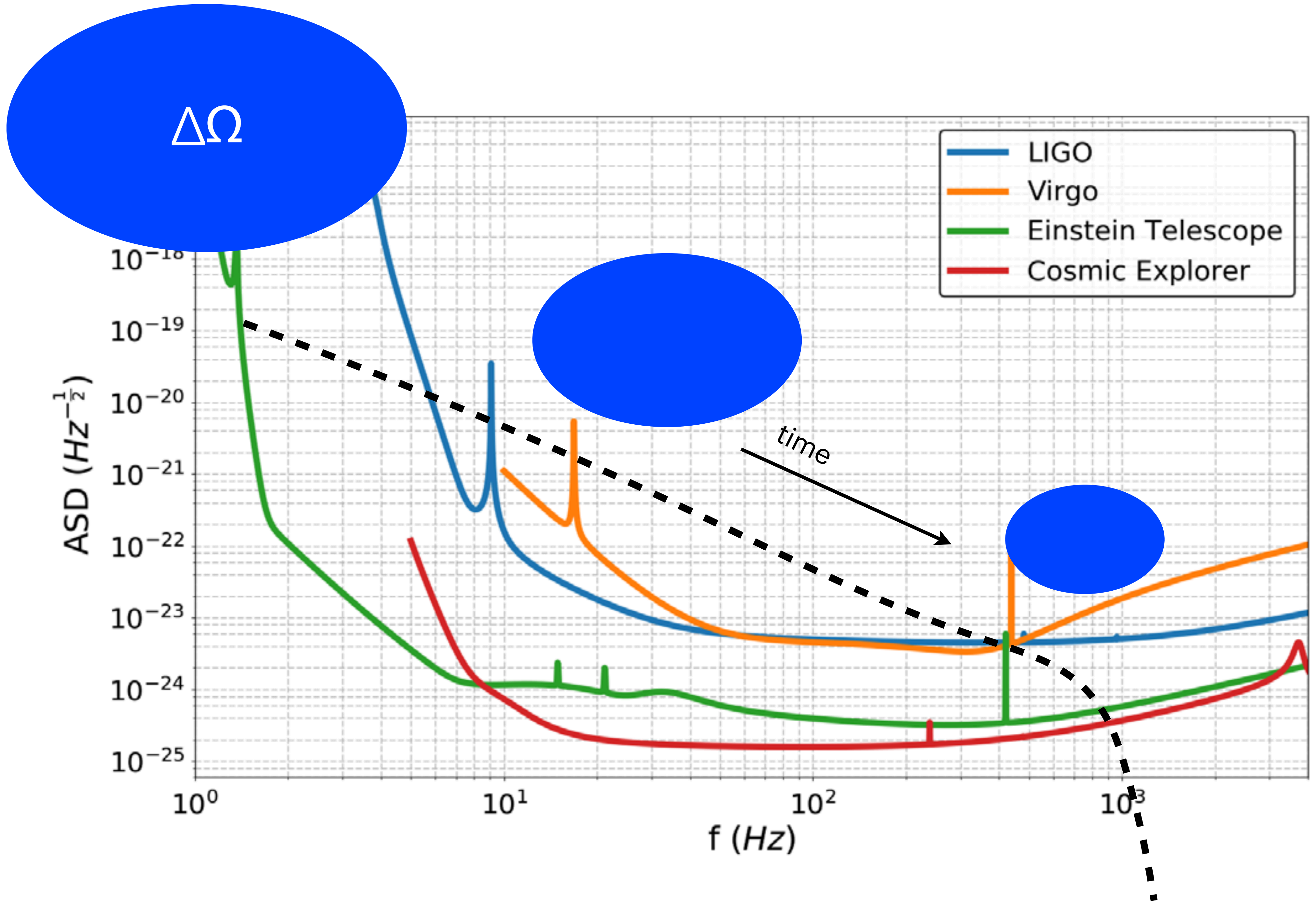
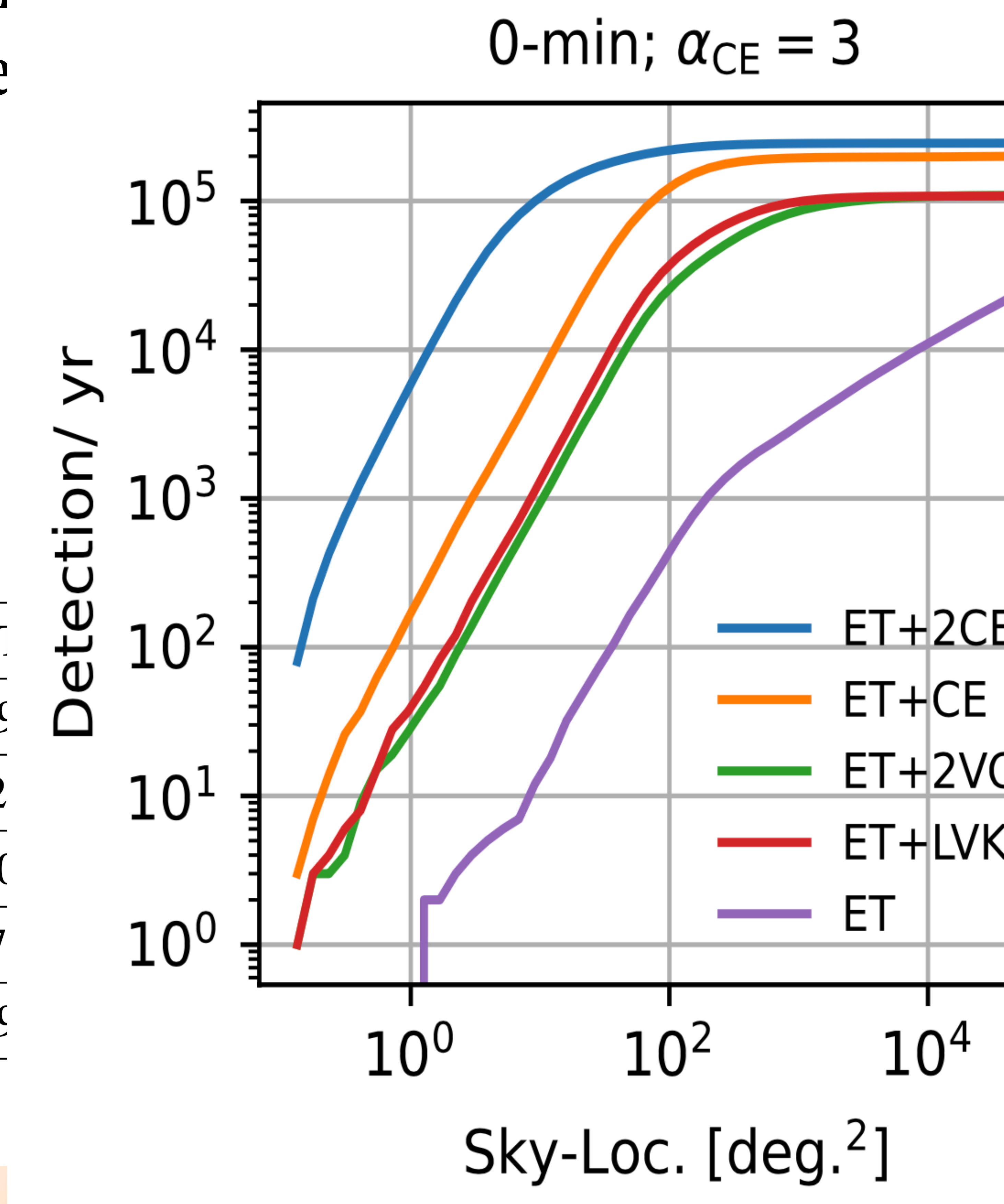


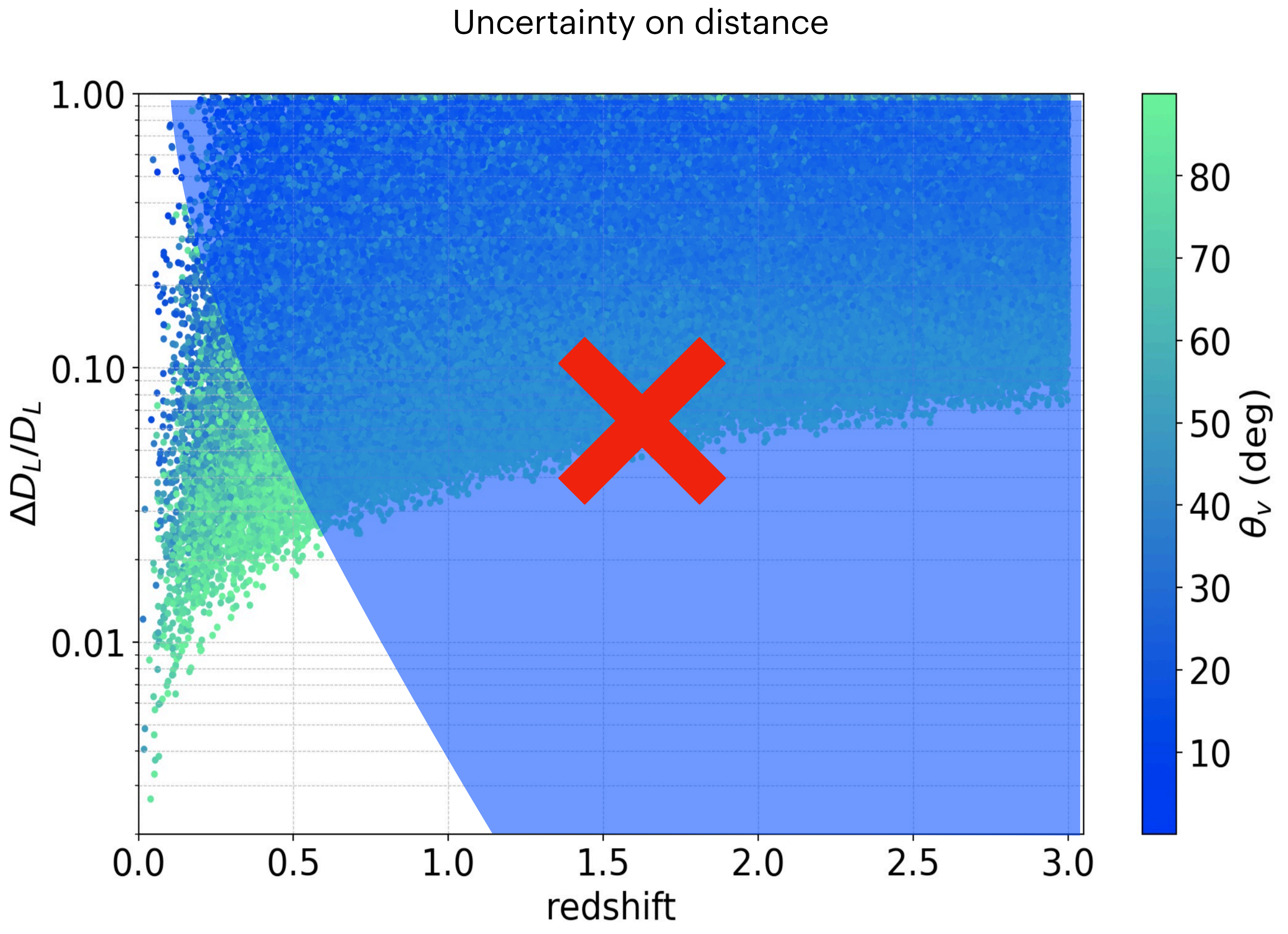
	$N_{\Delta\Omega<1000\,\mathrm{deg}^2,t_{\mathrm{pre}}}/N_{\Delta\Omega<100\,\mathrm{deg}^2,t_{\mathrm{merger}}}$			
	SNR> 8		SNR> 7	
t_{pre}	10 min	20 min	10 min	20 min
ET	63%	29%	68%	37%
ET+CE	5%	0.5%	5%	0.7%
ET+2CE	6%	0.5%	6%	0.6%

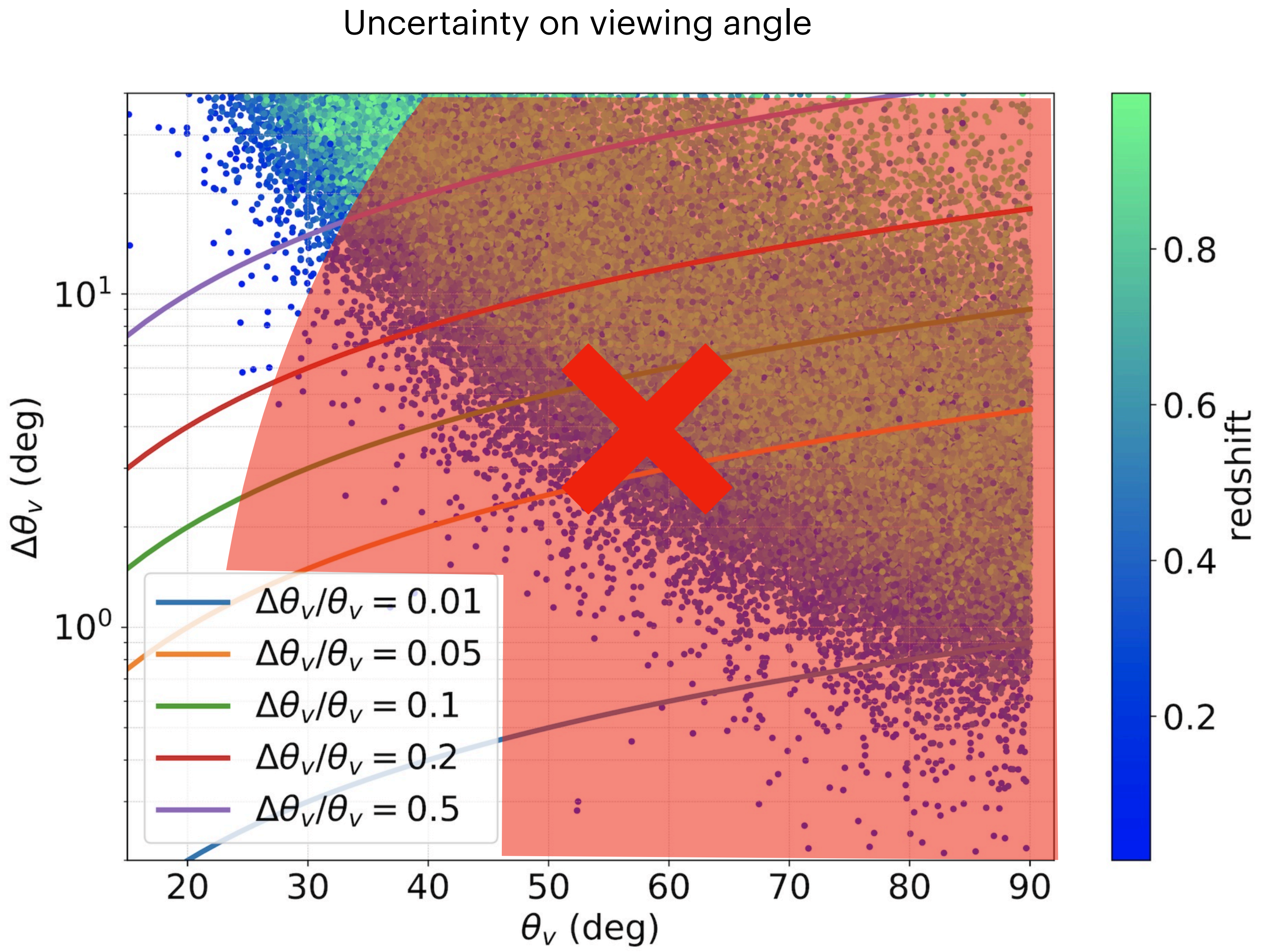
For some golden cases, enough SNR can be accumulated already **before the**

	ET
N_{det}	1439
$N_{\mathrm{det}}(\Delta\Omega < 1\ \mathrm{deg}^2)$	2
$N_{\mathrm{det}}(\Delta\Omega < 10\ \mathrm{deg}^2)$	10
$N_{\mathrm{det}}(\Delta\Omega < 100\ \mathrm{deg}^2)$	37
$N_{\mathrm{det}}(\Delta\Omega < 1000\ \mathrm{deg}^2)$	279



How to exploit the GW information





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Scenario 1: selection on viewing angle and SNR

SXI

$$\mathrm{SNR} > 100, \Delta\Omega < 100\,\mathrm{deg}^2, \theta_\mathrm{v} \pm \Delta\theta_\mathrm{v} < 20^\circ \qquad \sim 10^5 \rightarrow 450 \rightarrow 4^{+3}_{-2}\,\mathrm{det/yr}$$

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