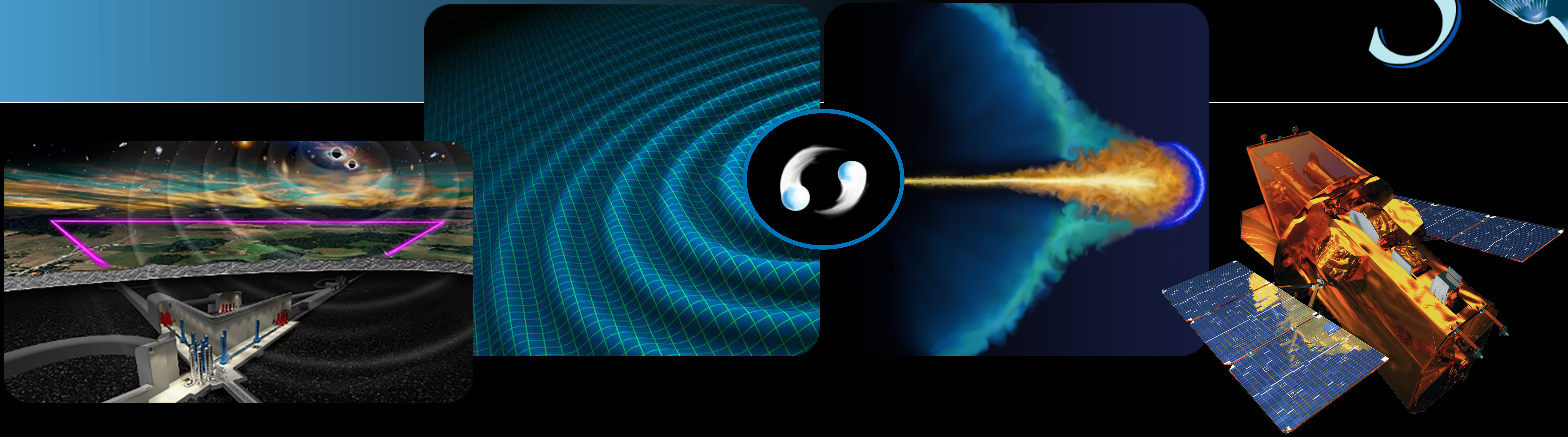
Past, present and future of multi-messenger observations of γ-ray bursts

- What we learned, work in progress and future prospects -

Samuele Ronchini

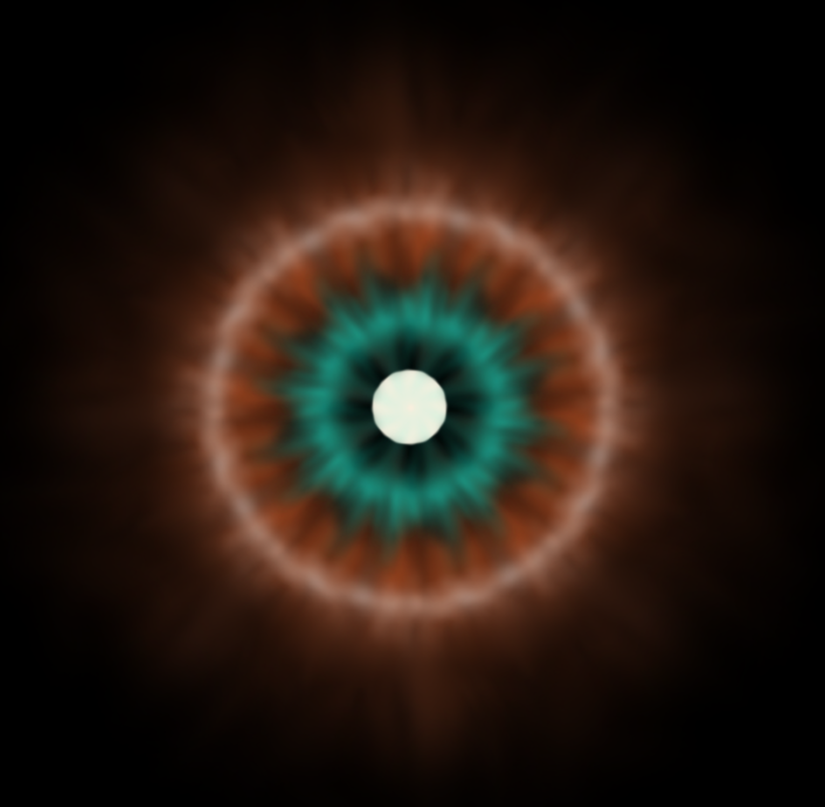
Post-doctoral scholar at the PennState University



The past

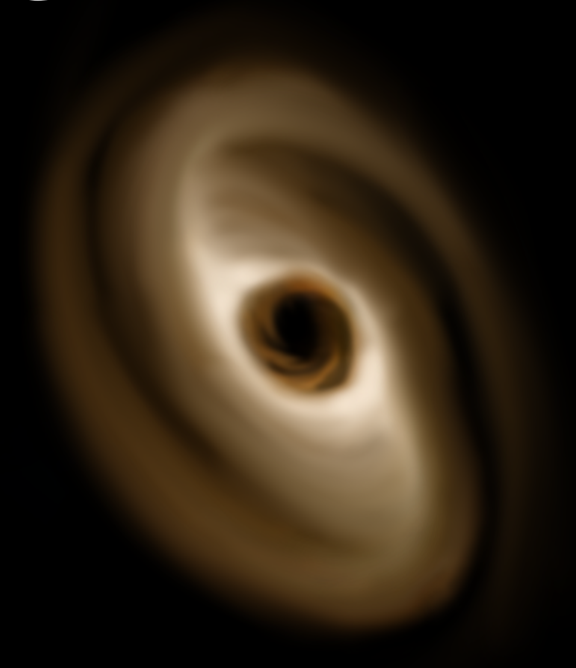
γ-ray bursts : the standard picture

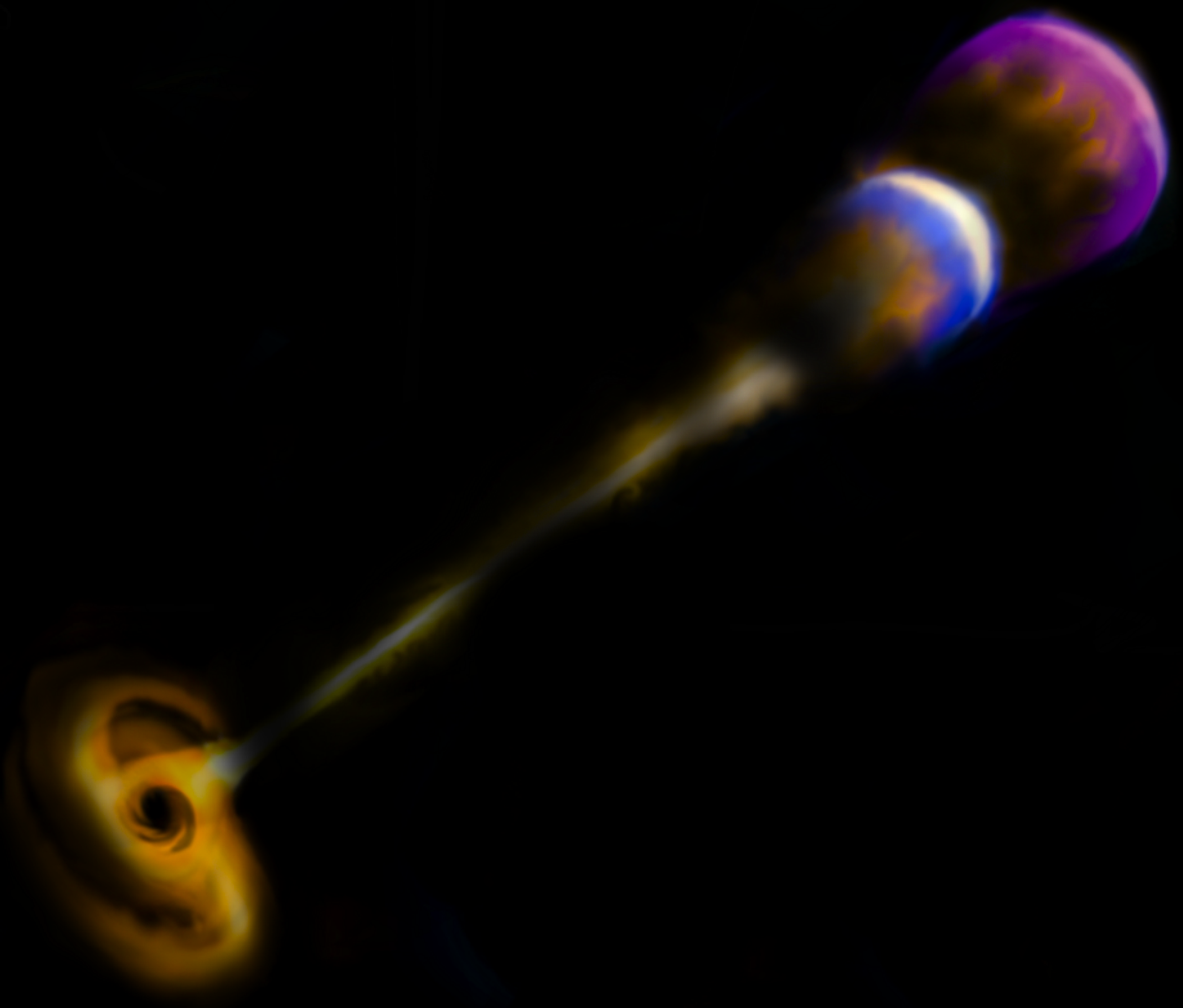
Massive star collapse



Compact binary merger, containing at least one neutron star

Central engine





Several prompt emission scenarios

γ-ray bursts : the standard picture

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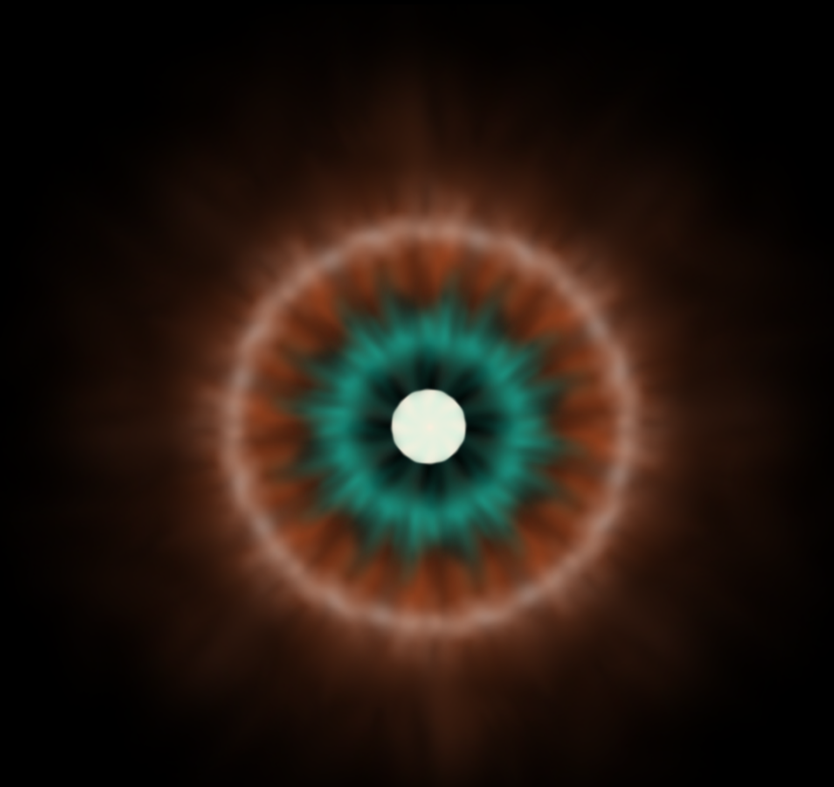

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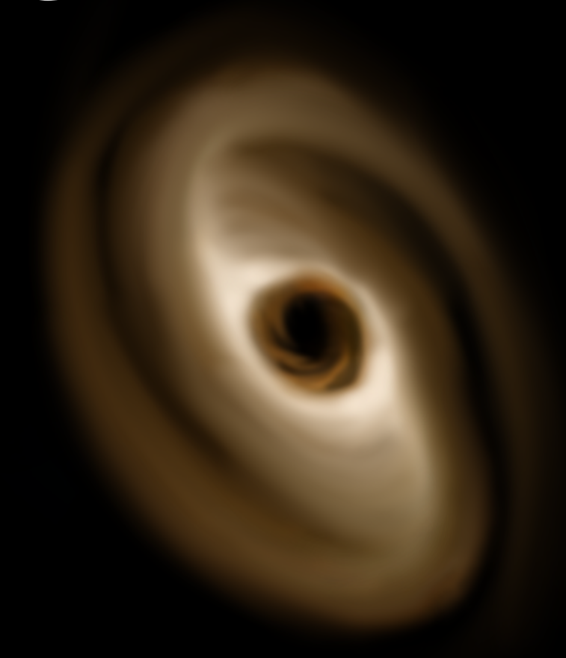

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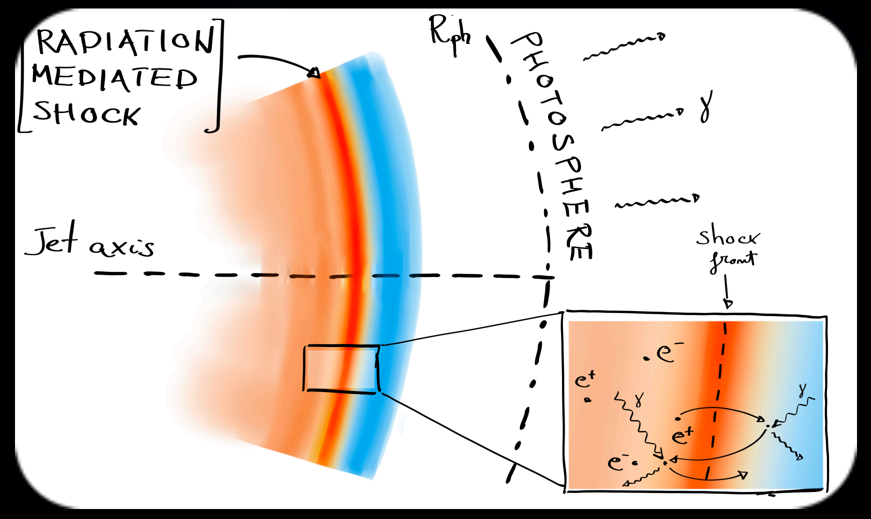
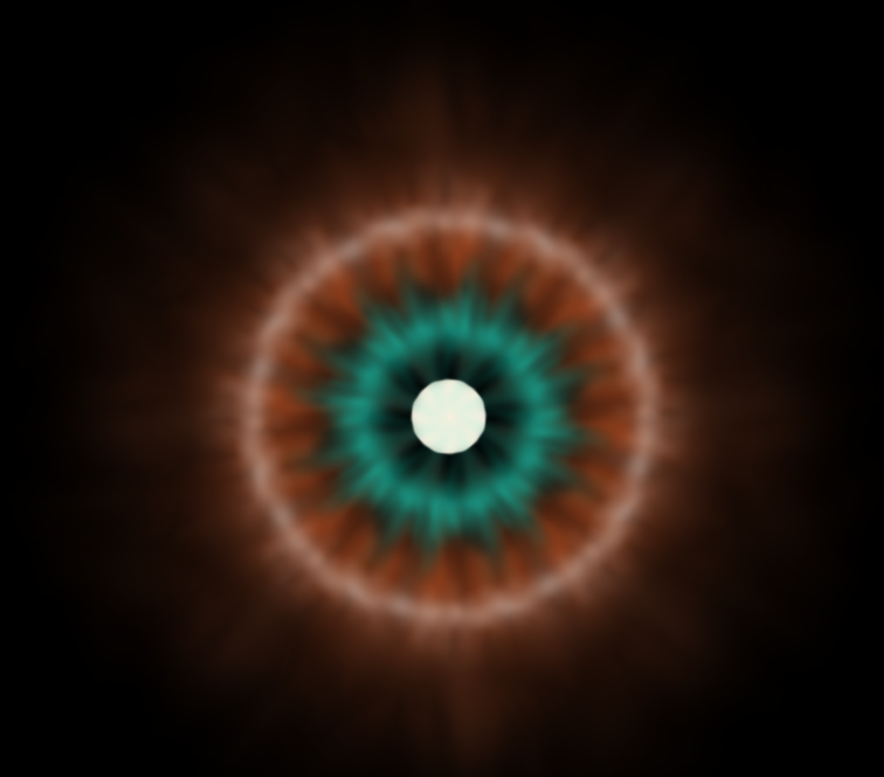


Photospheric emission

Eichler + 2000,
Ryde + 2005,
Pe'er + 2006

γ-ray bursts : the standard picture

Massive star
collapse



Compact binary merger, containing at
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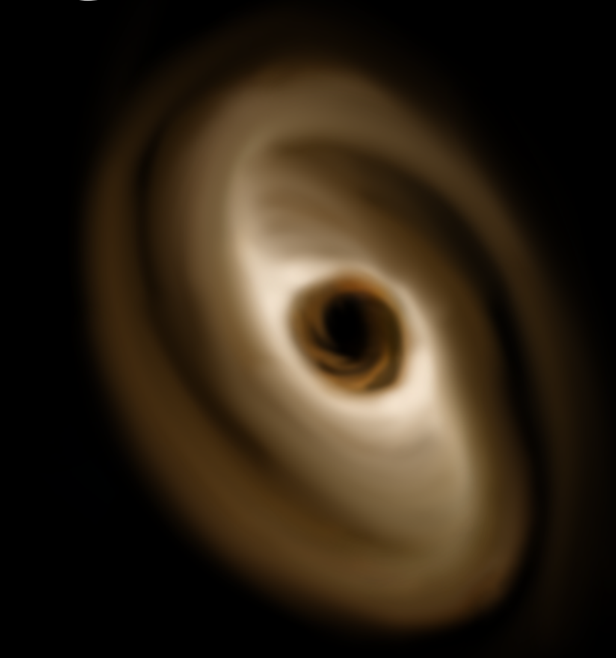
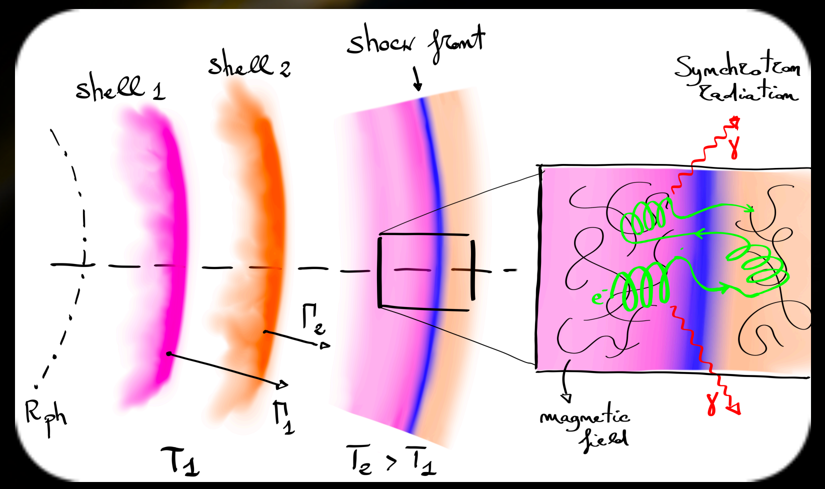
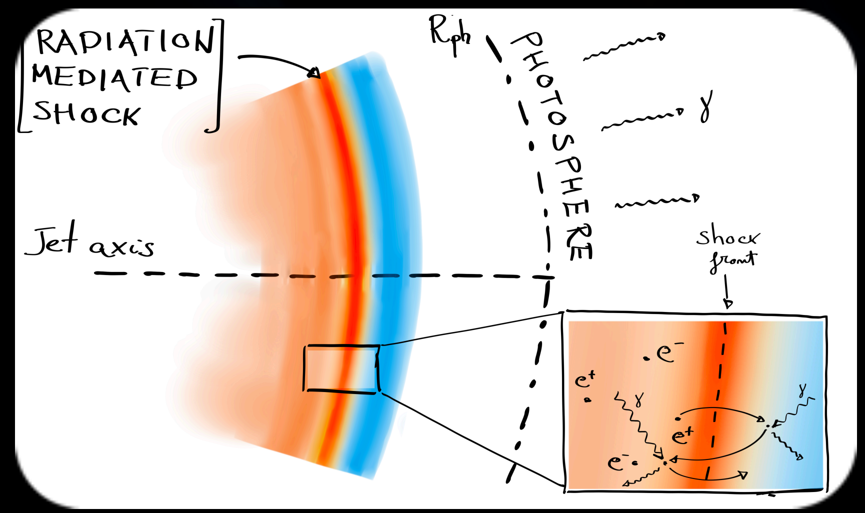


Several prompt
emission
scenarios



Internal shocks

Rees & Mezsaros 1994
Kobayashi + 1997
Daigne & Mochkovich 1998



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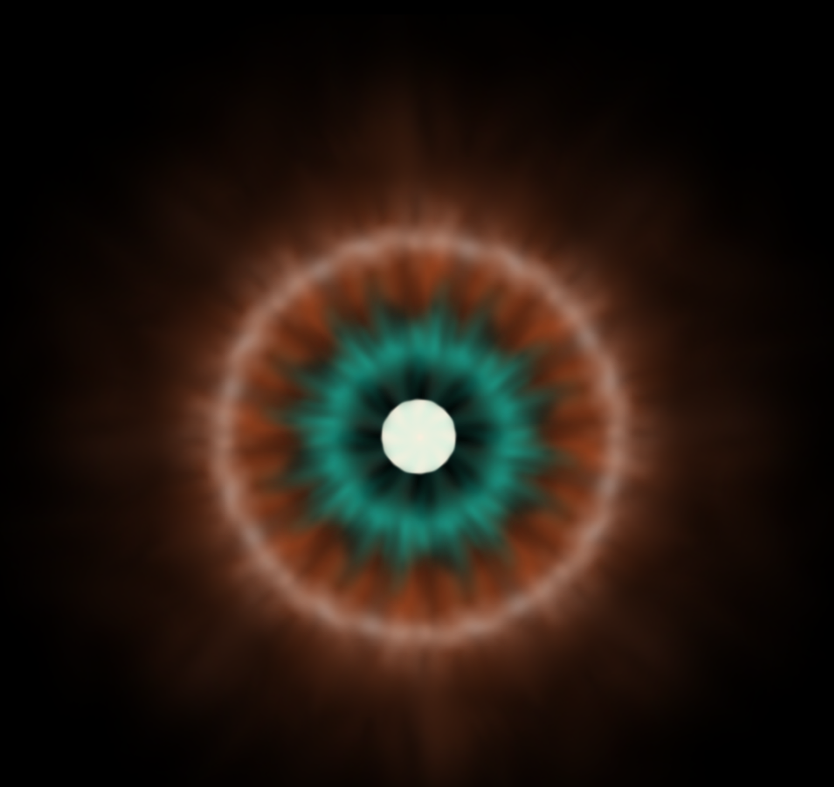

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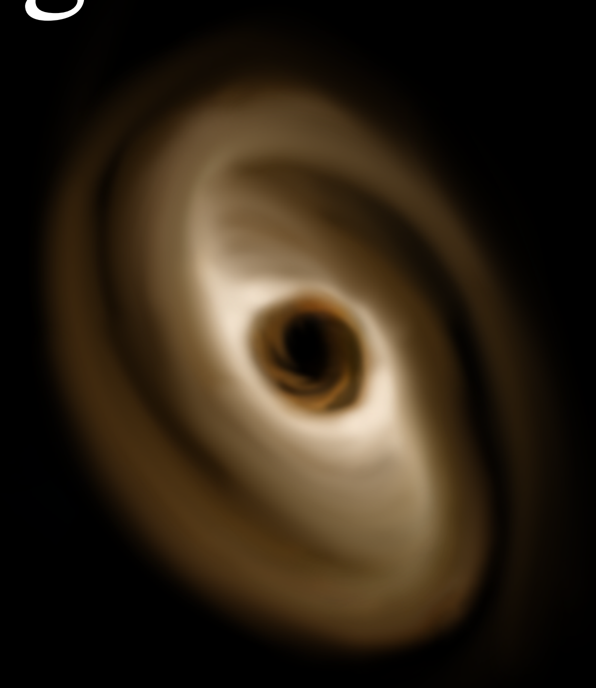
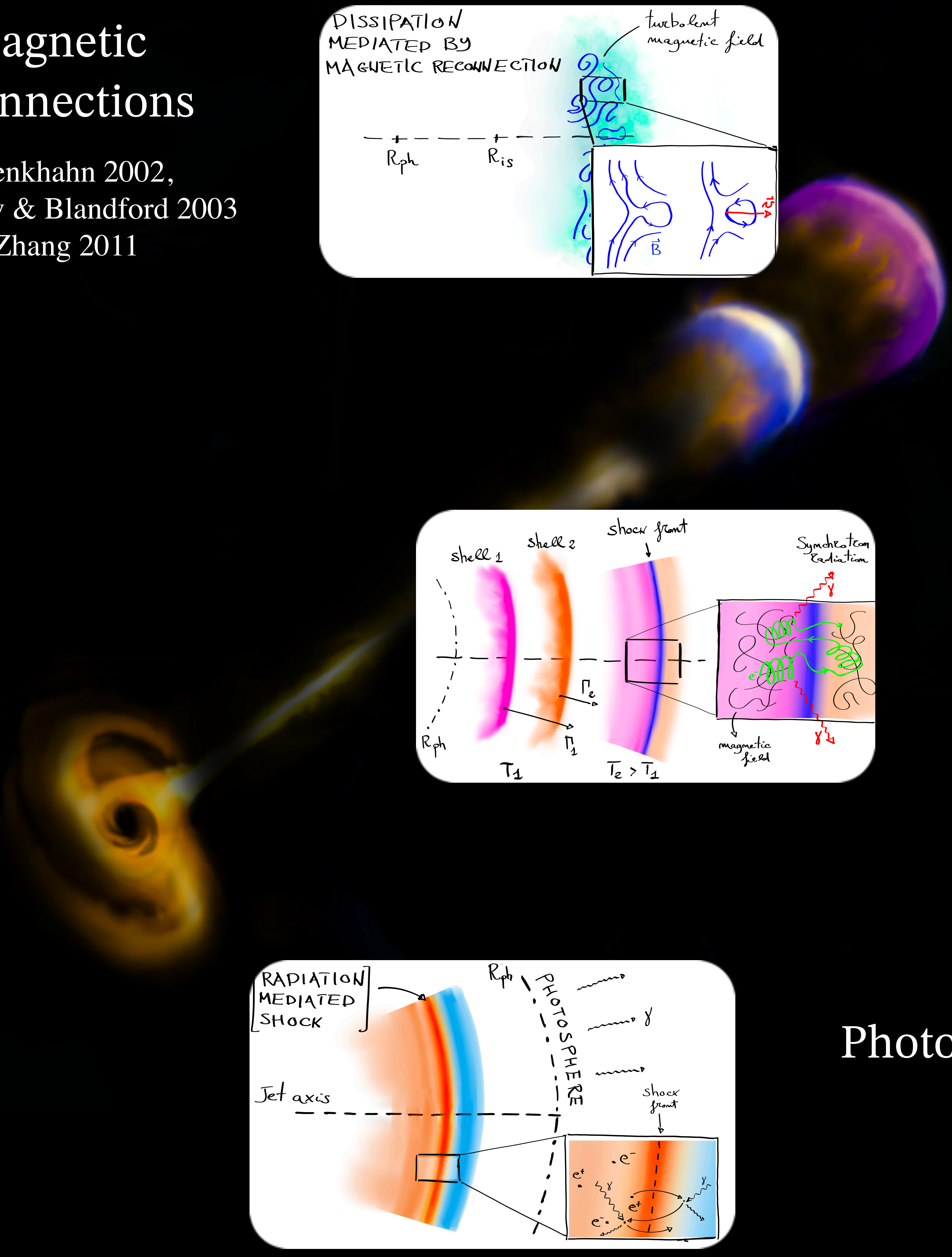


Compact binary merger, containing at least one neutron star

Magnetic reconnections

Drenkhahn 2002,
Lyutikov & Blandford 2003
Zhang 2011



Several prompt emission scenarios

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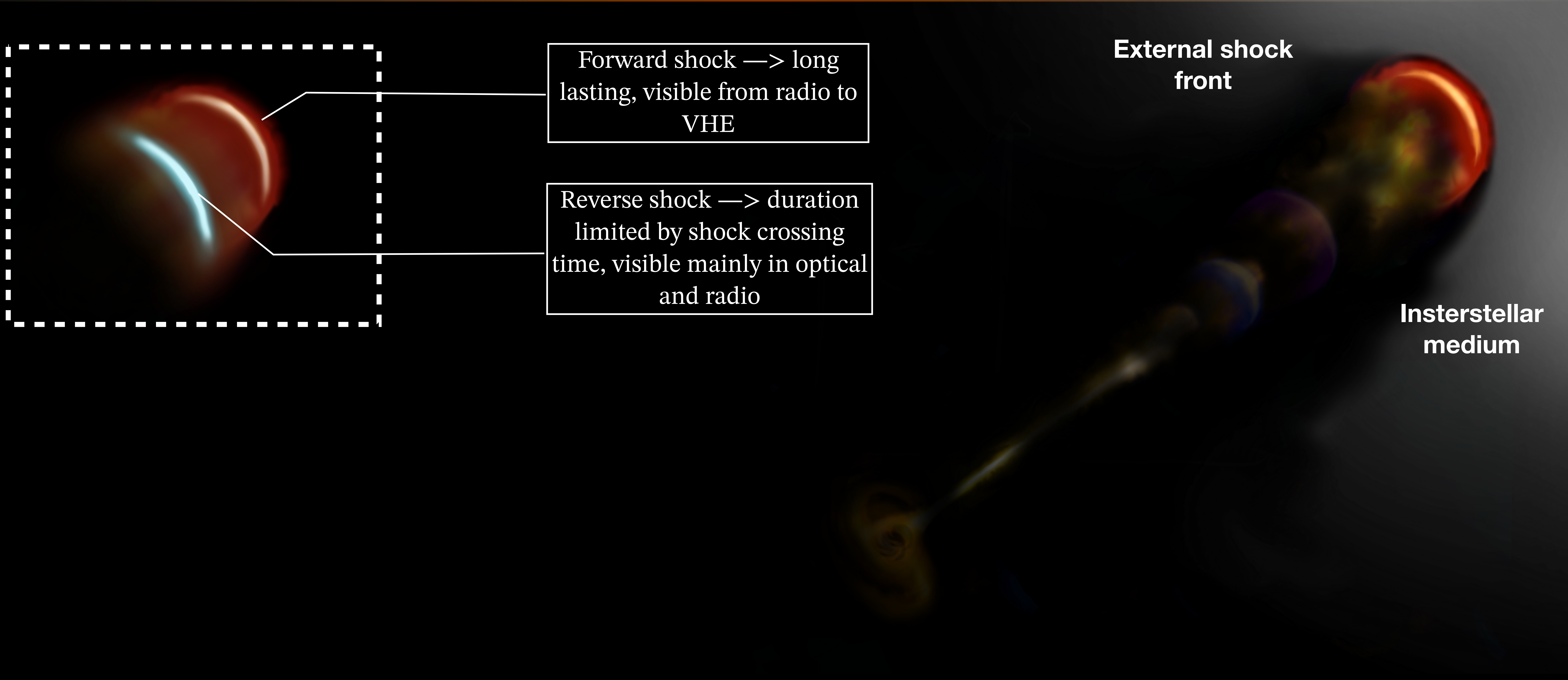
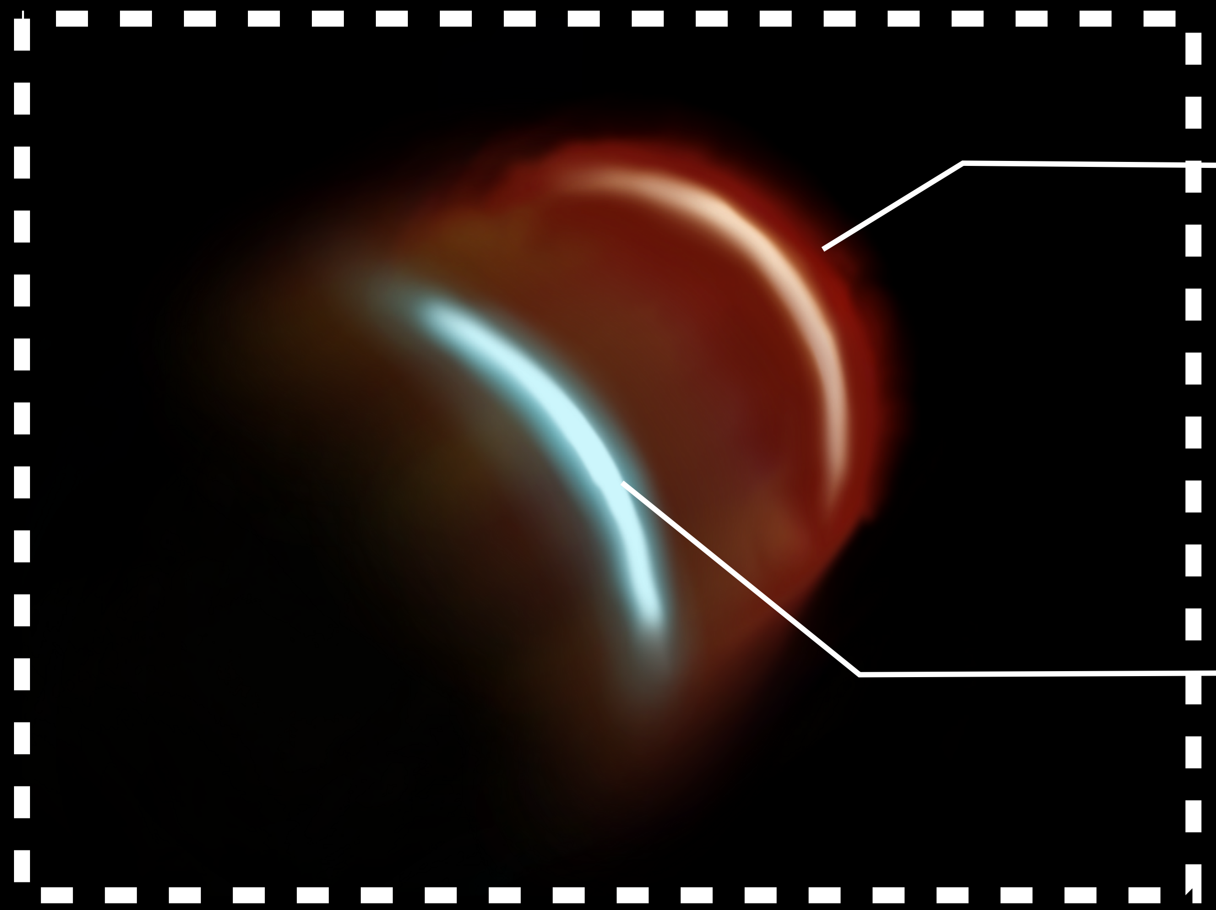
The standard picture



Forward shock —> long lasting, visible from radio to VHE

Reverse shock —> duration limited by shock crossing time, visible mainly in optical and radio

The standard picture



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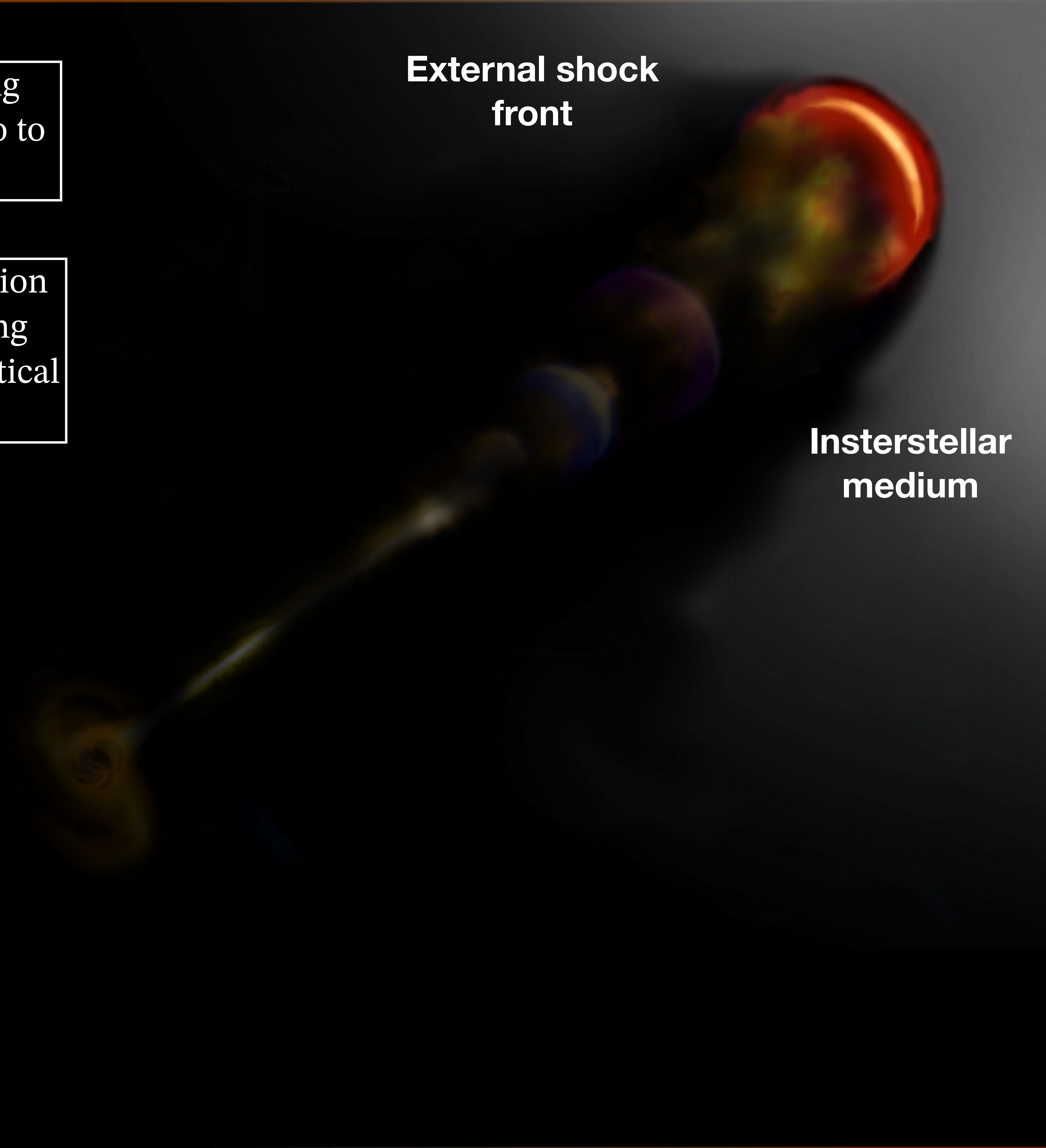
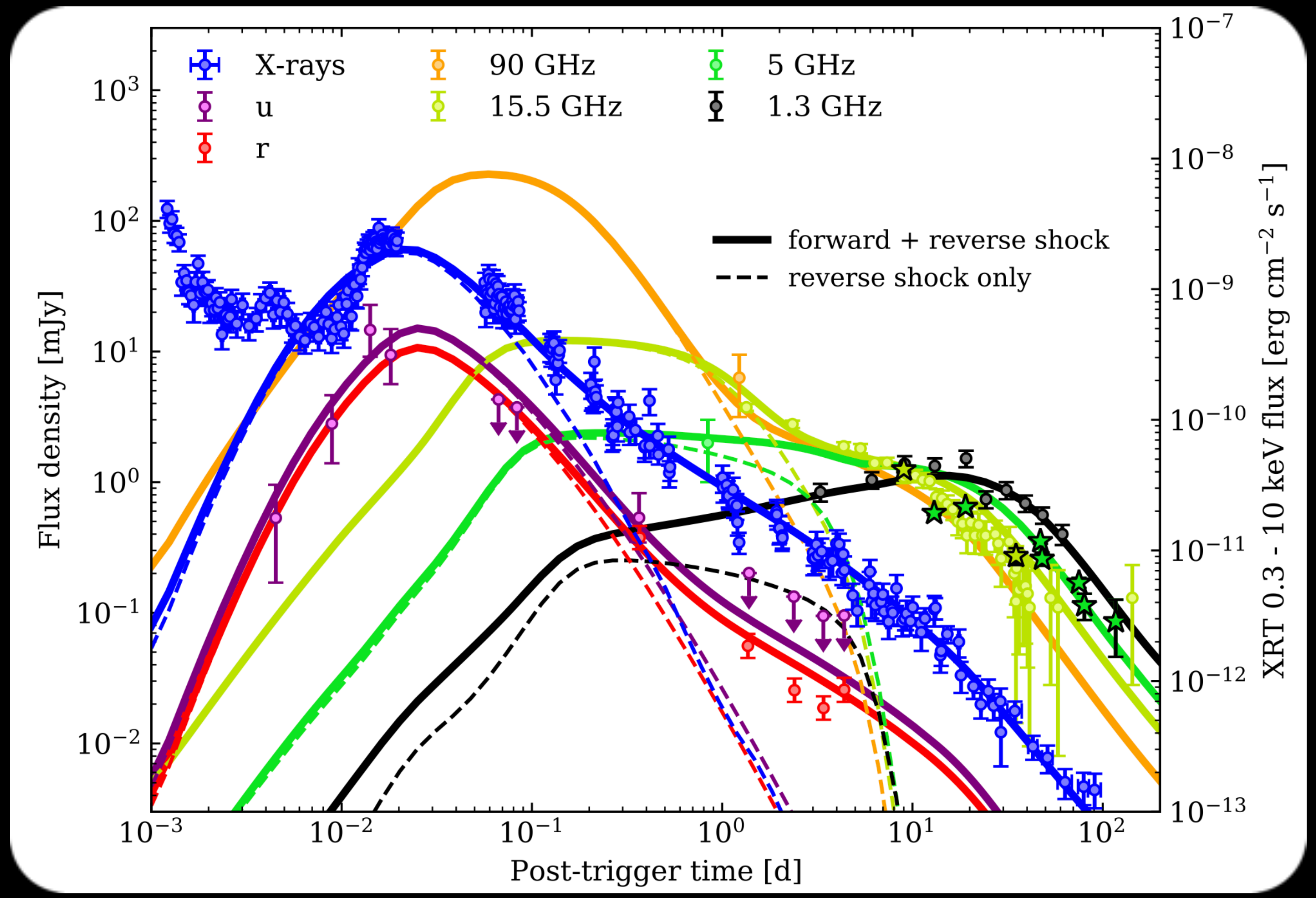
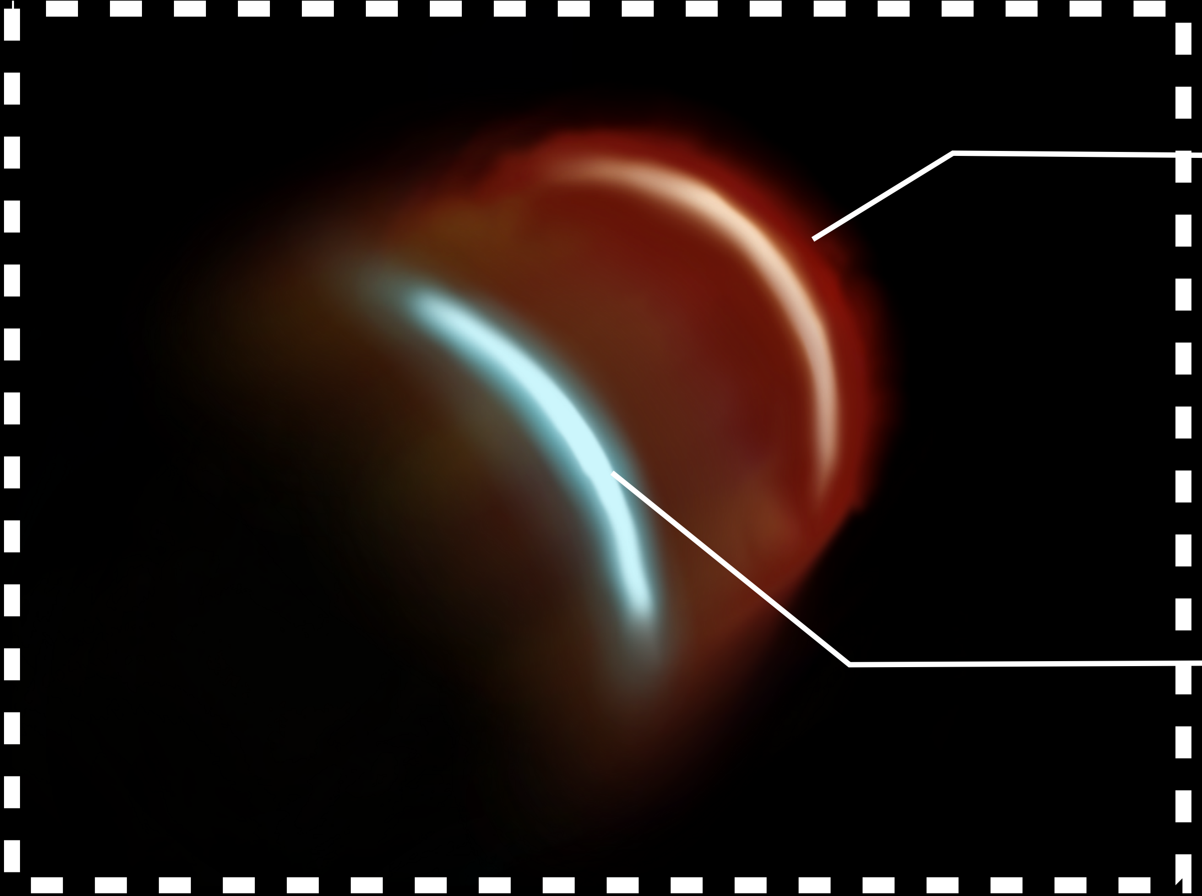


On-axis



e.g., Salafia 2022

The standard picture



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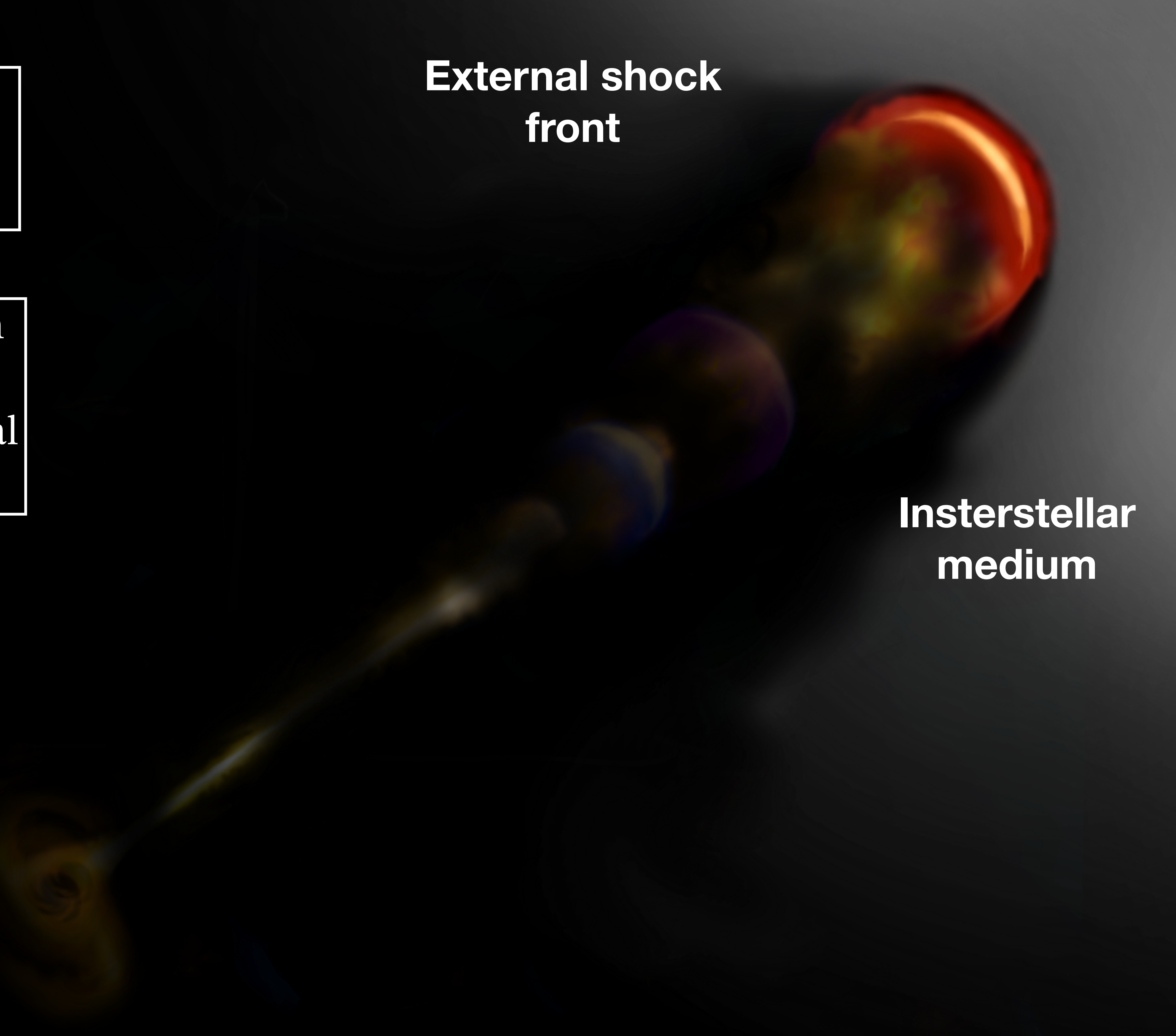
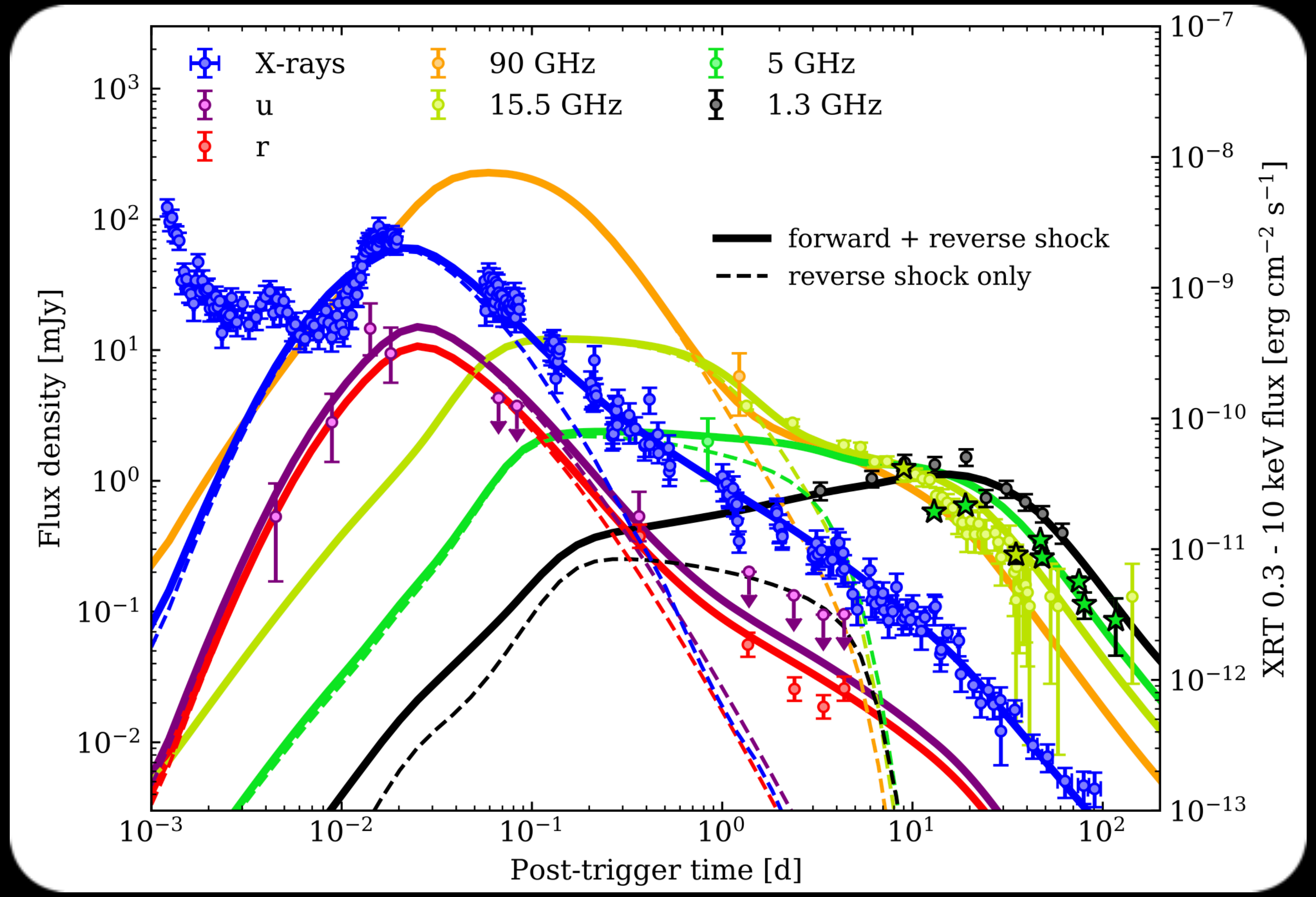


External shock front

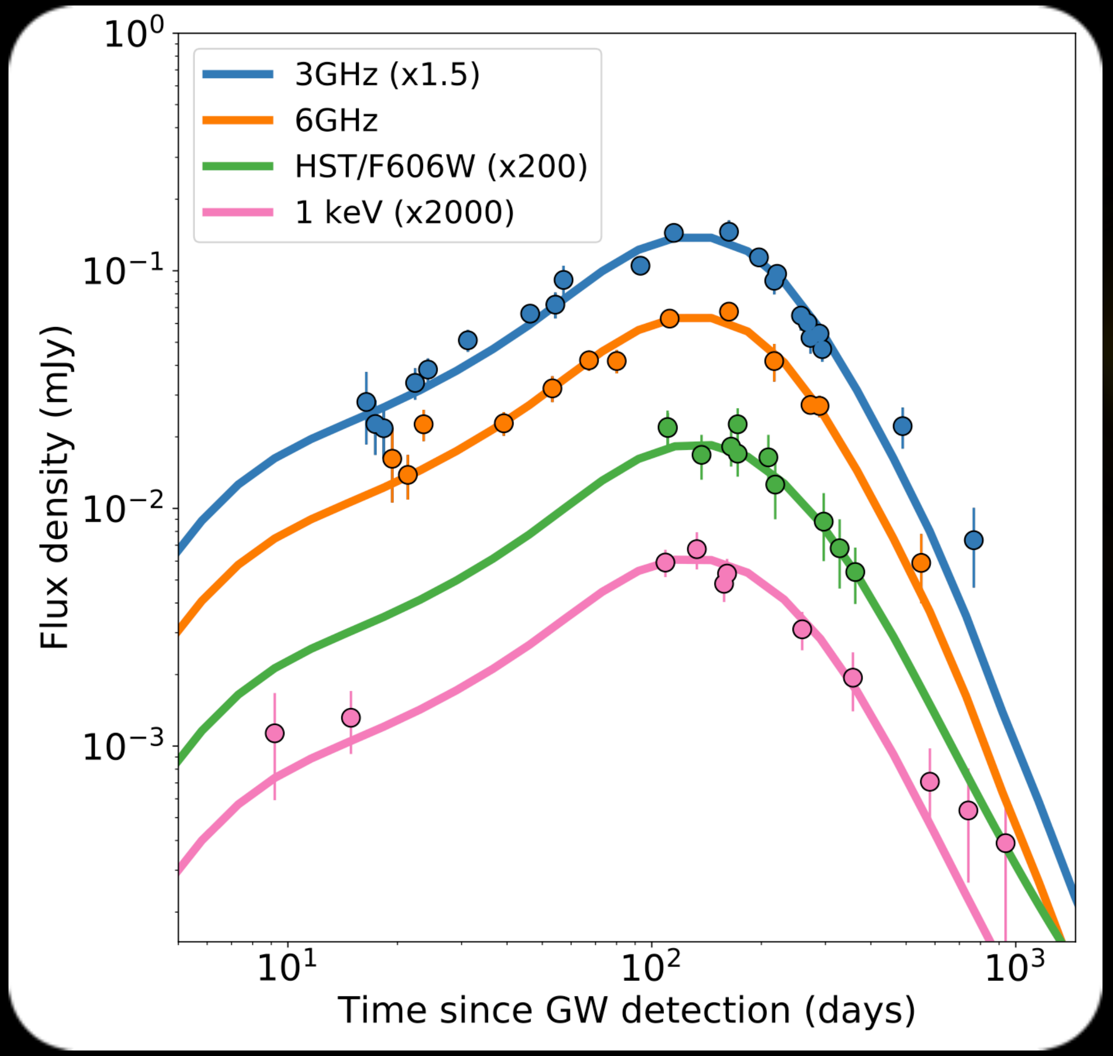
Interstellar medium

On-axis



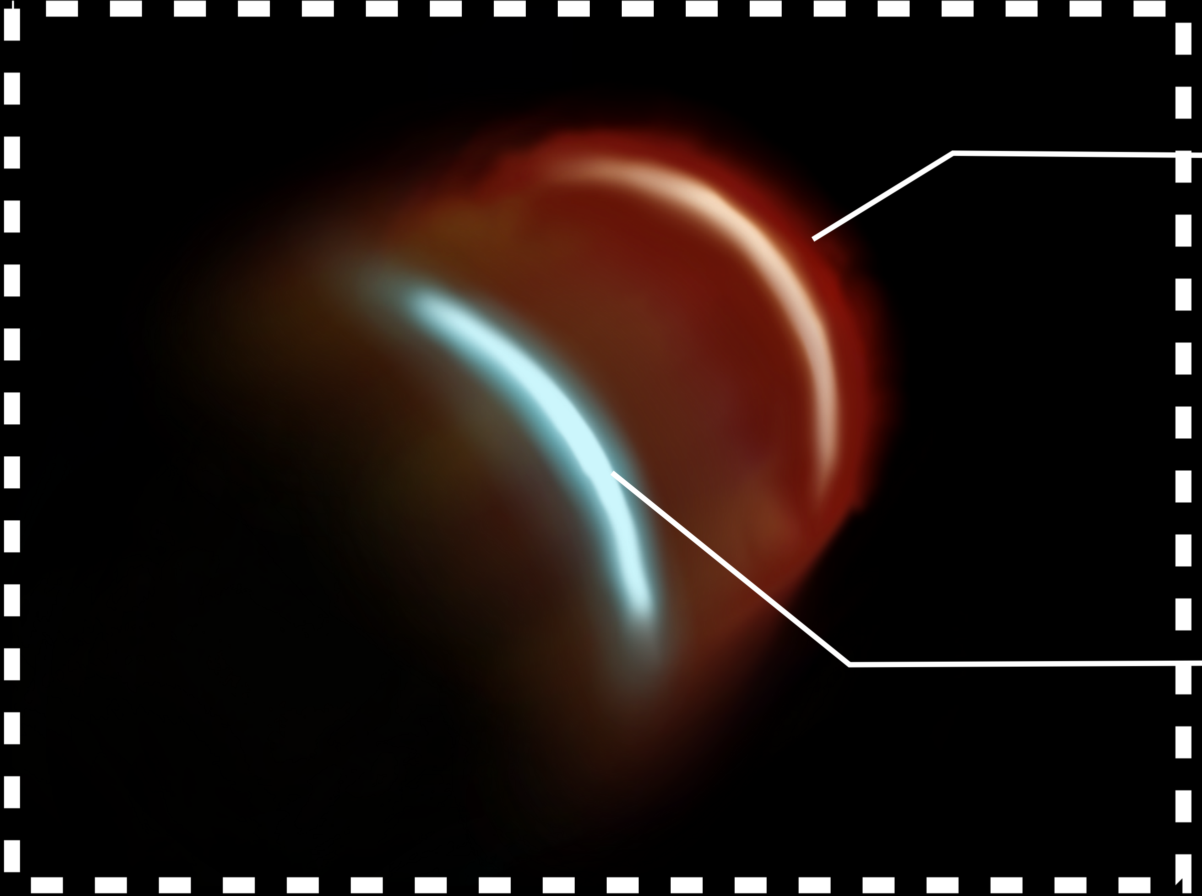
e.g., Salafia 2022

Off-axis



e.g., Makhathini 2021

The standard picture



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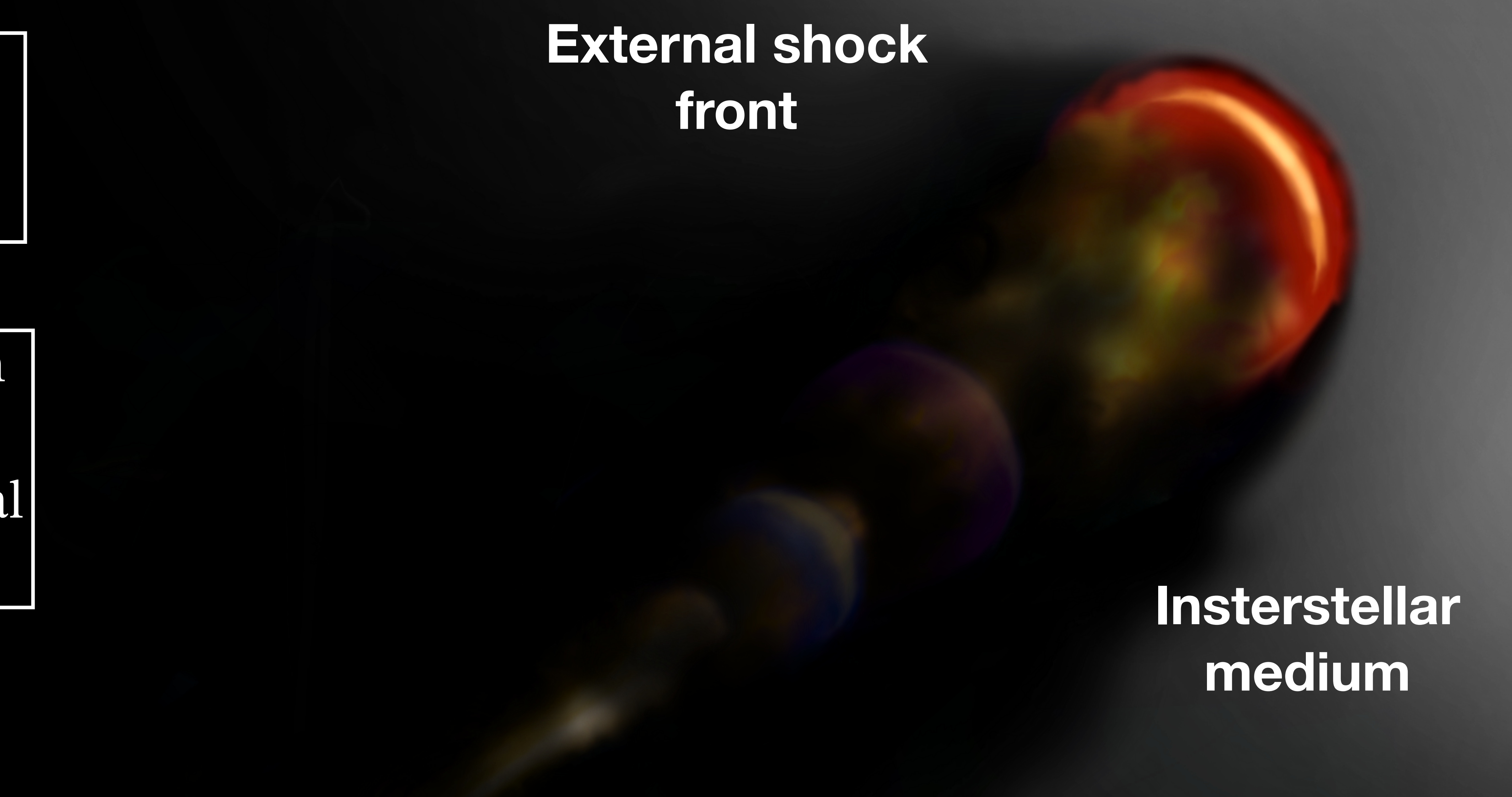
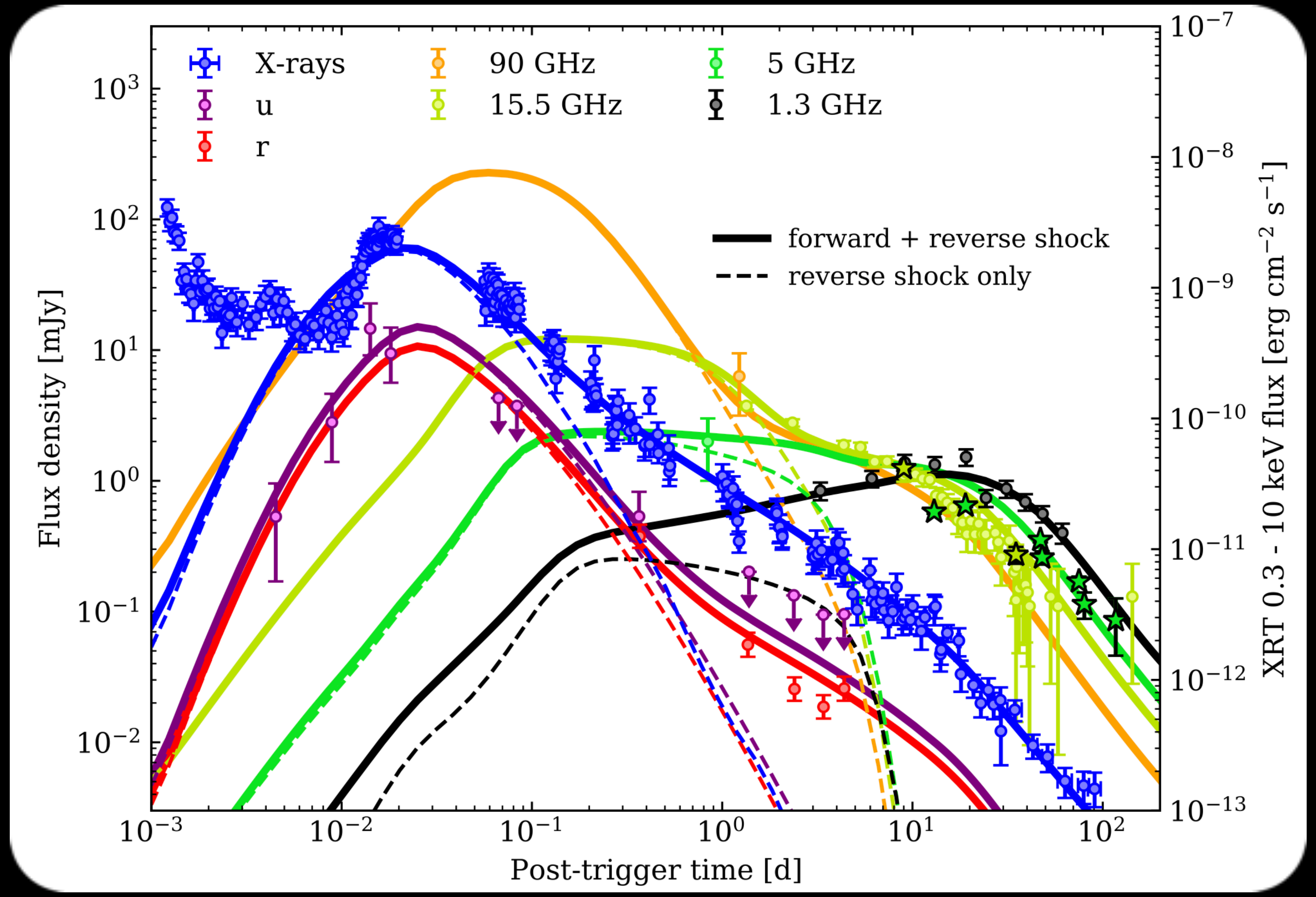


External shock front

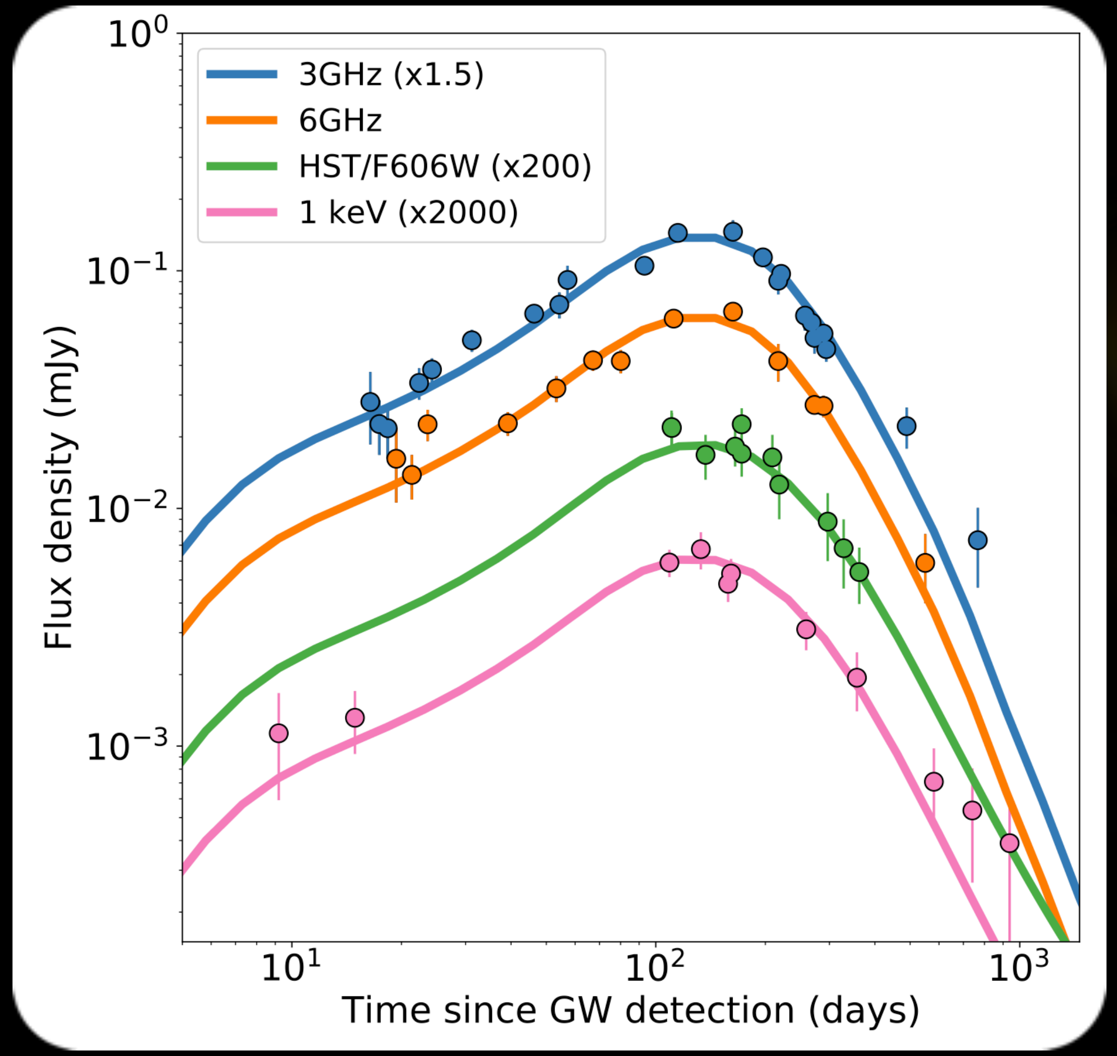
Insterstellar medium

On-axis



e.g., Salafia 2022

Off-axis

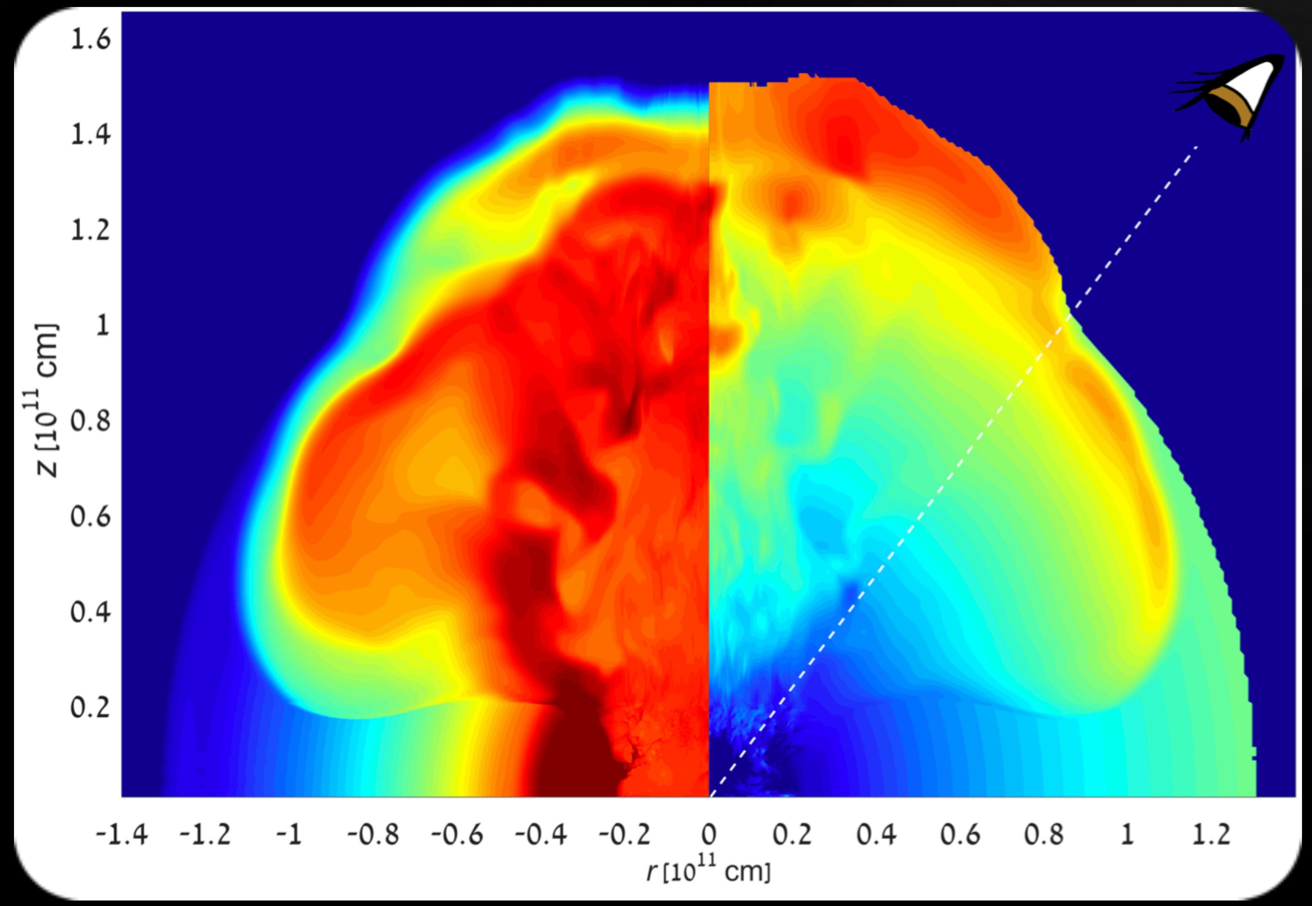


e.g., Makhathini 2021

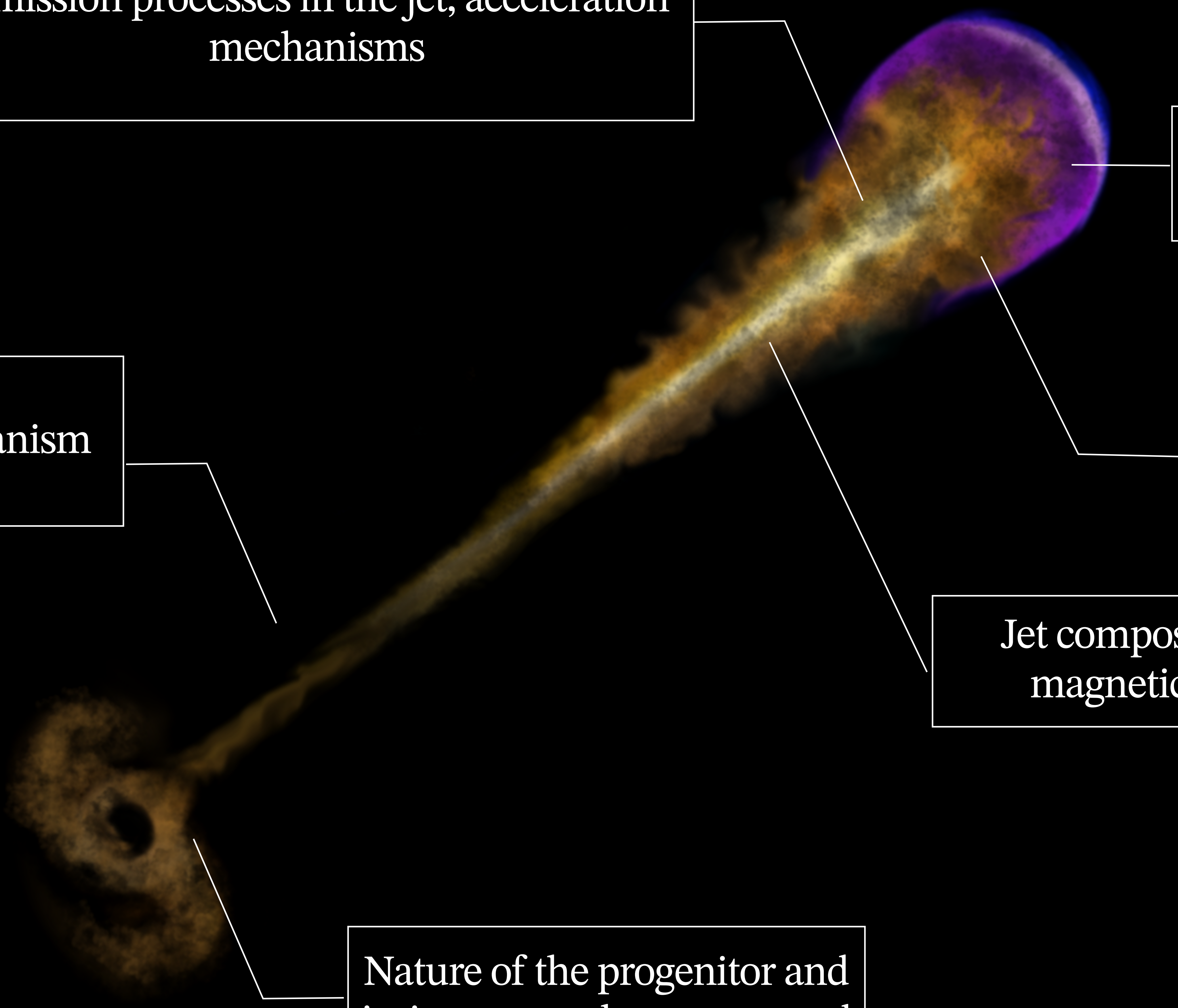
+ cocoon shock breakout

(Potentially visible at large viewing angles)

Nakar & Sari 2012, Nakar & Piran 2017



Open questions about γ-ray bursts physics



Emission processes in the jet, acceleration mechanisms

Origin of of very high-energy photons

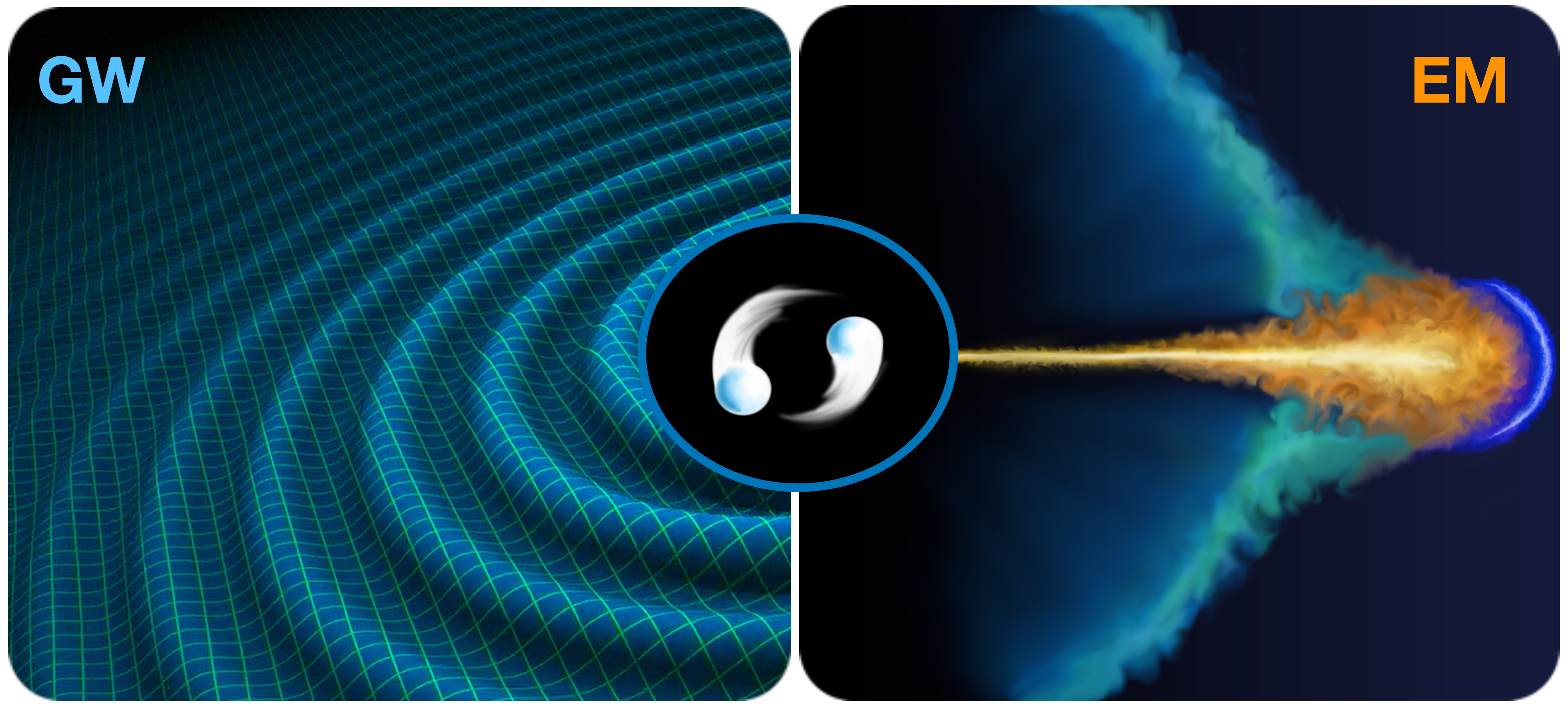
Formation of jet structure

Jet launching mechanism

Jet composition (dominated by magnetic or kinetic energy)

Nature of the progenitor and its impact on the prompt and afterglow features

The multi-messenger revolution: GW178017

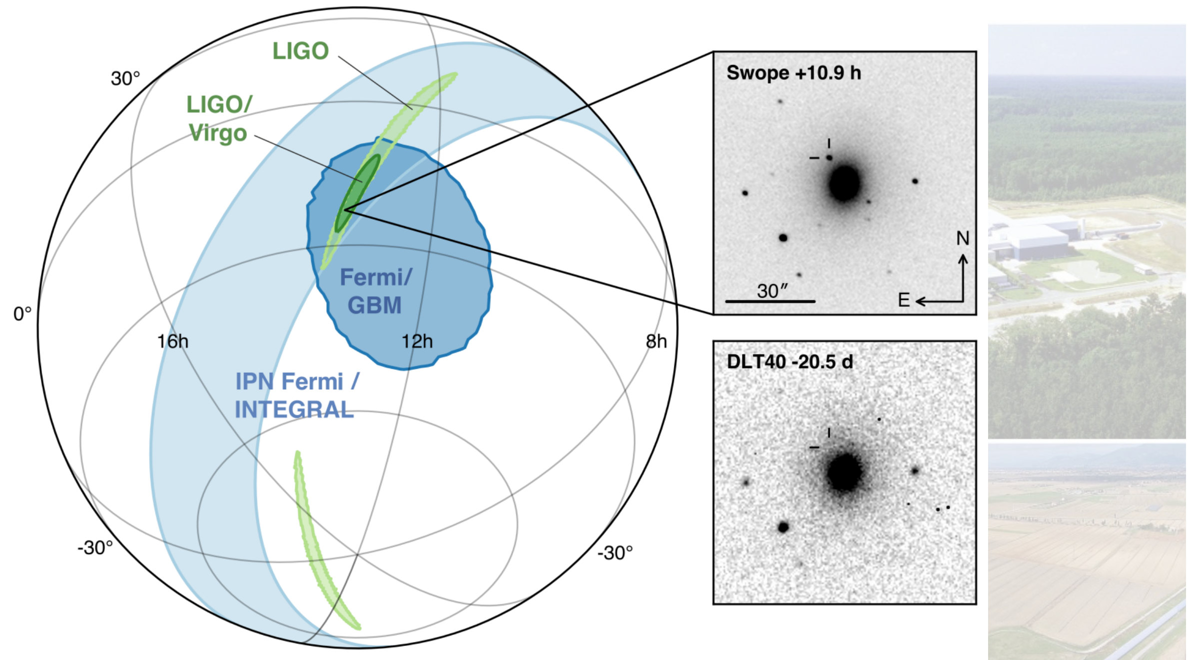


- First association between binary neutron star (**BNS**) mergers and **short GRBs**

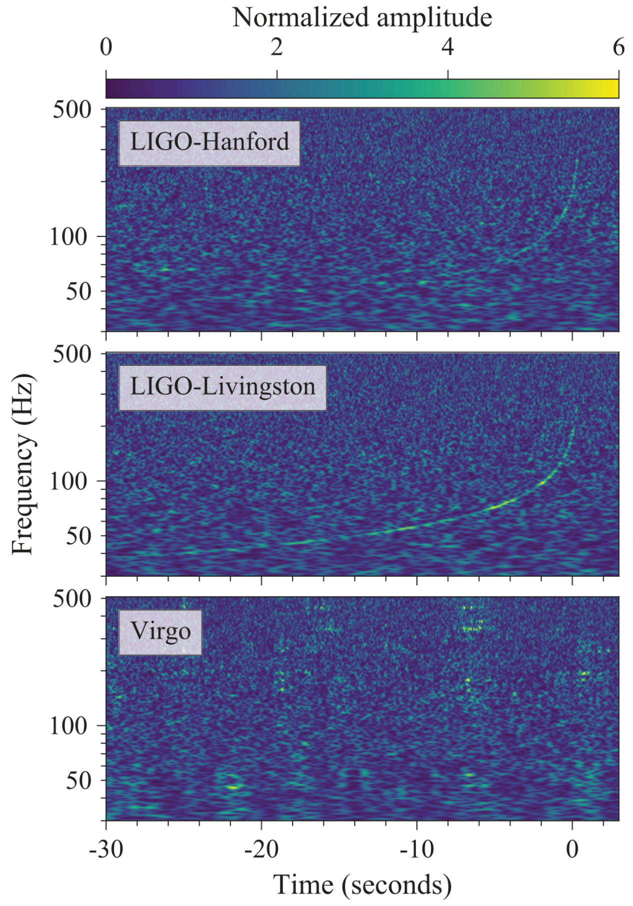
- Heavy elements are synthesized in the ejecta of BNS mergers —> their radioactive decay powers the **kilonova** (KN) emission (Li & Paczynski 1998)

- Evidence of a **relativistic jet with an angular structure**, observed **off-axis**

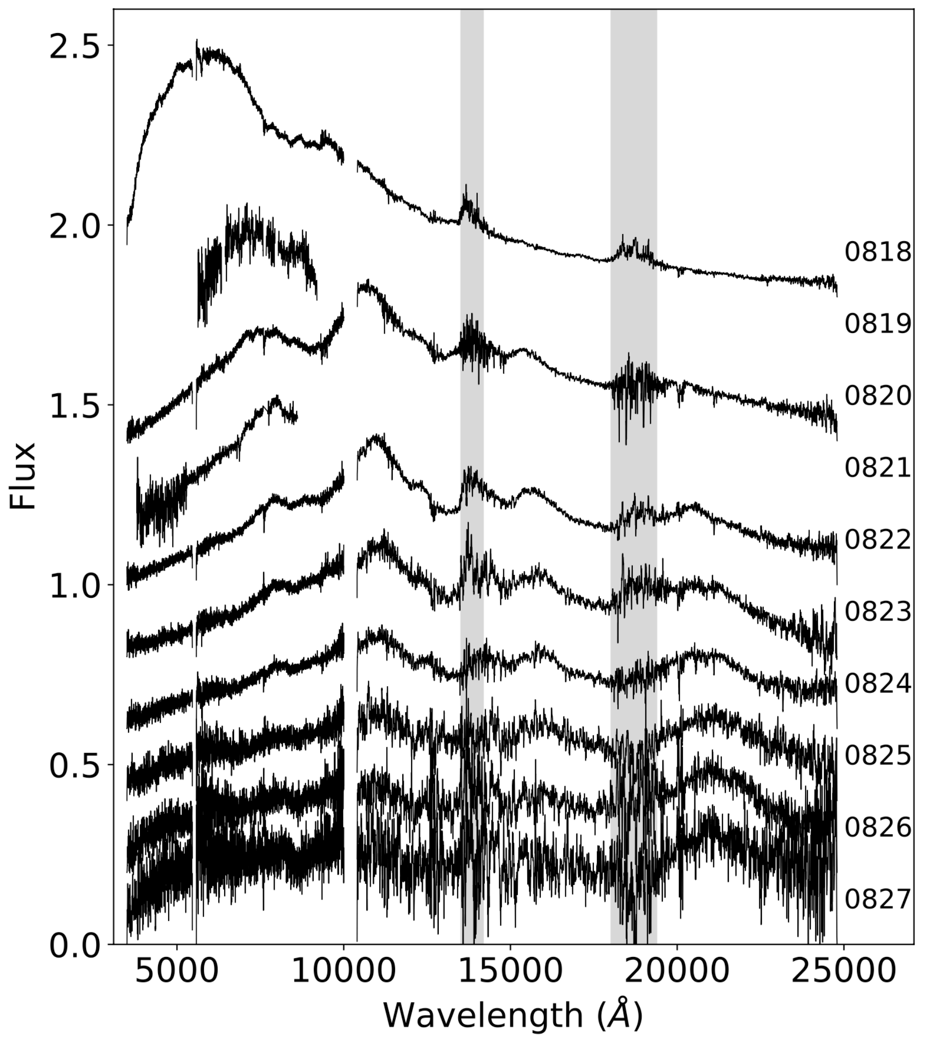
The **first smoking gun** of BNS merger / sGRB / KN association: GW170817, GRB 170817A and AT2017gfo



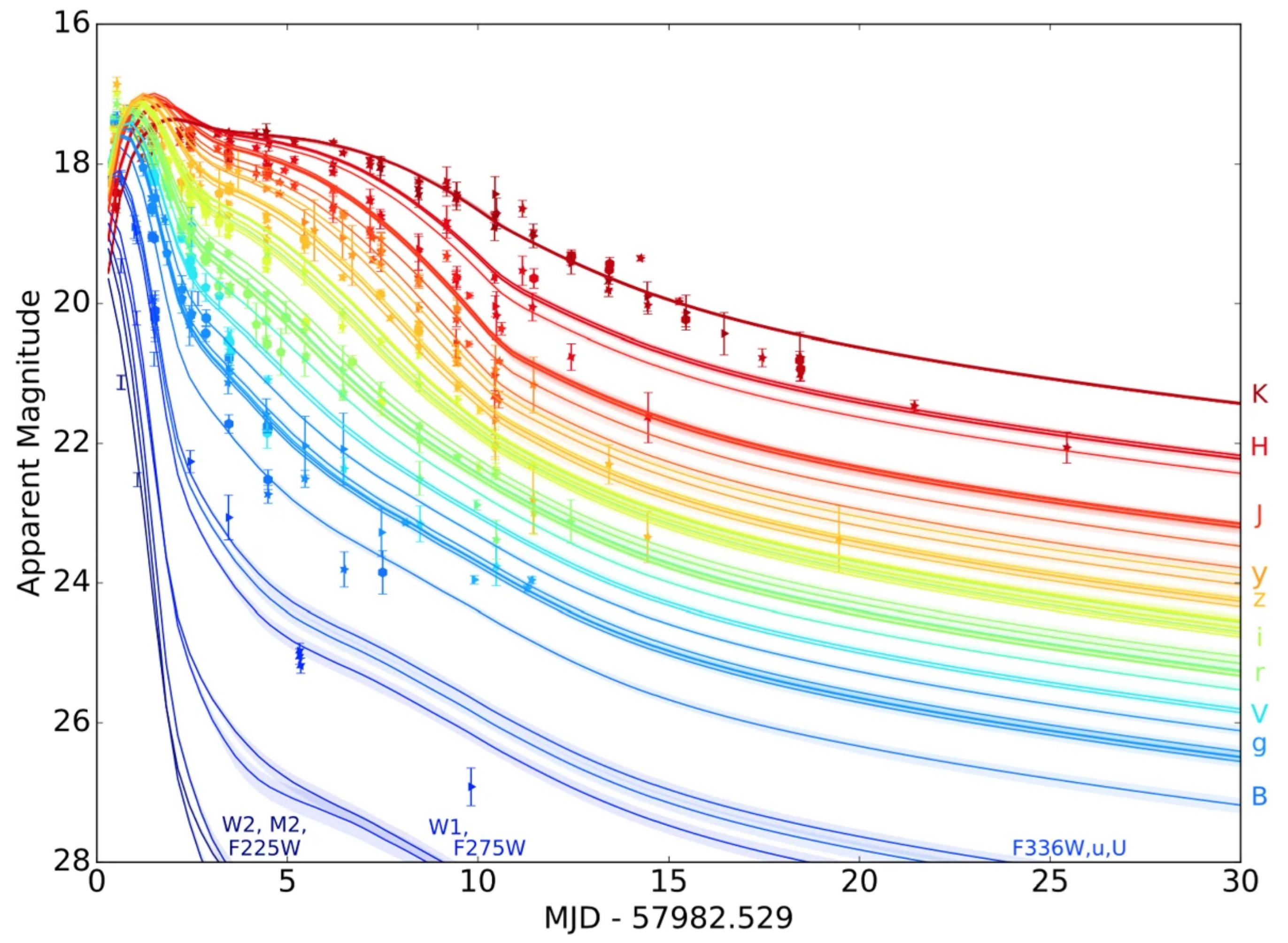
e.g. Abbott+ 2017, Goldstein+ 2017, Pian+ 2017, Smartt+ 2017, Villar + 2017, D'Avanzo+ 2018, Ghirlanda+ 2019



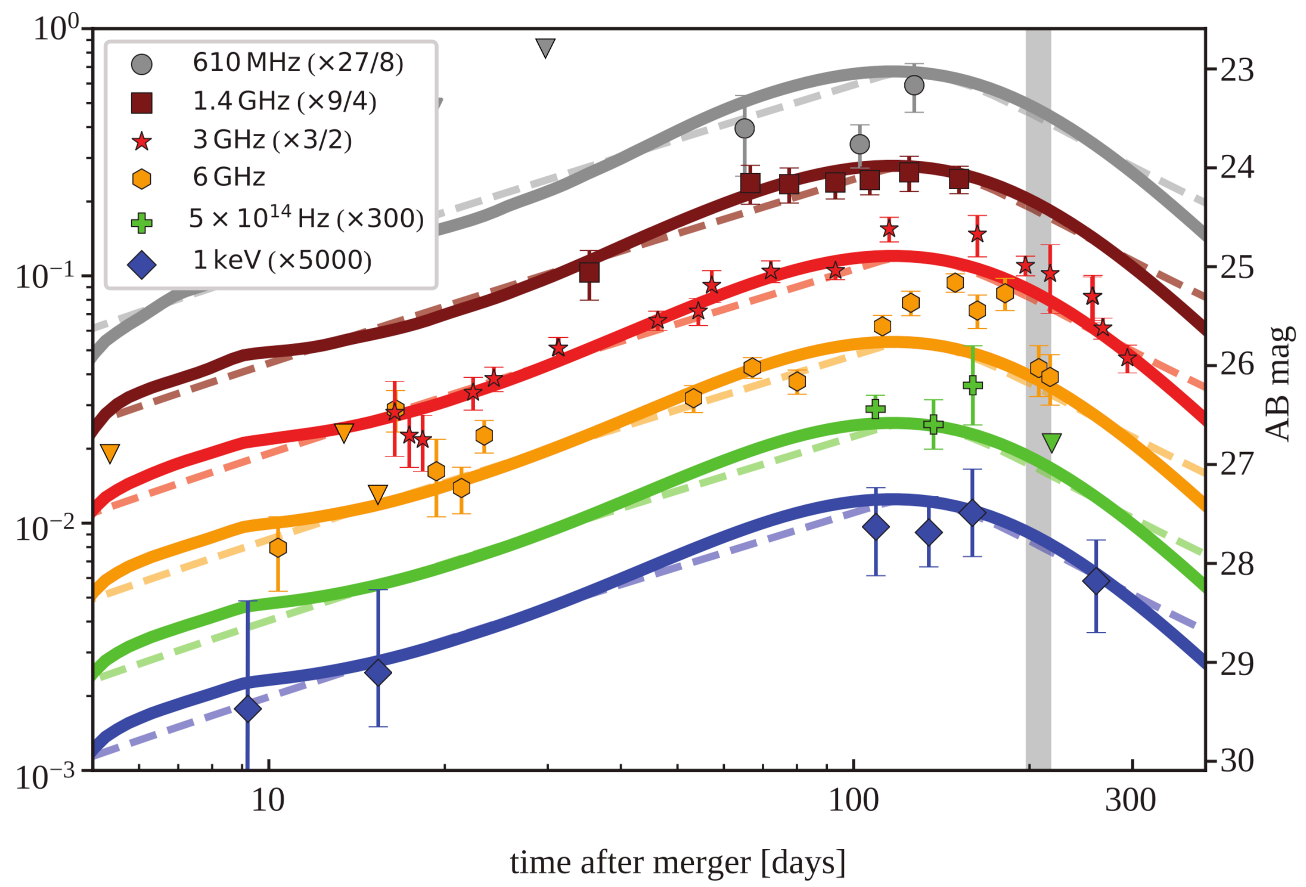
KN spectra



KN light curve

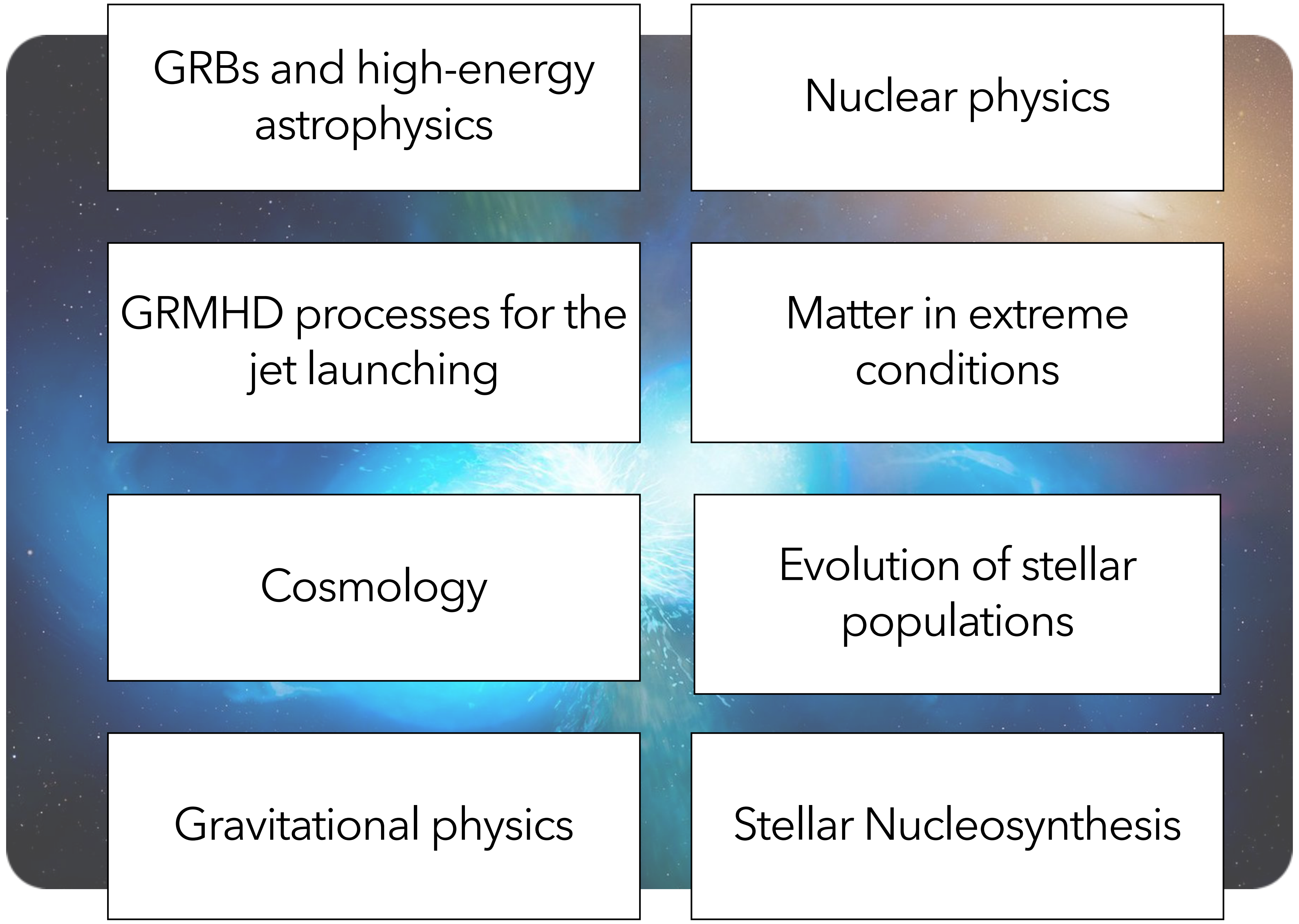


Radio to X-ray afterglow

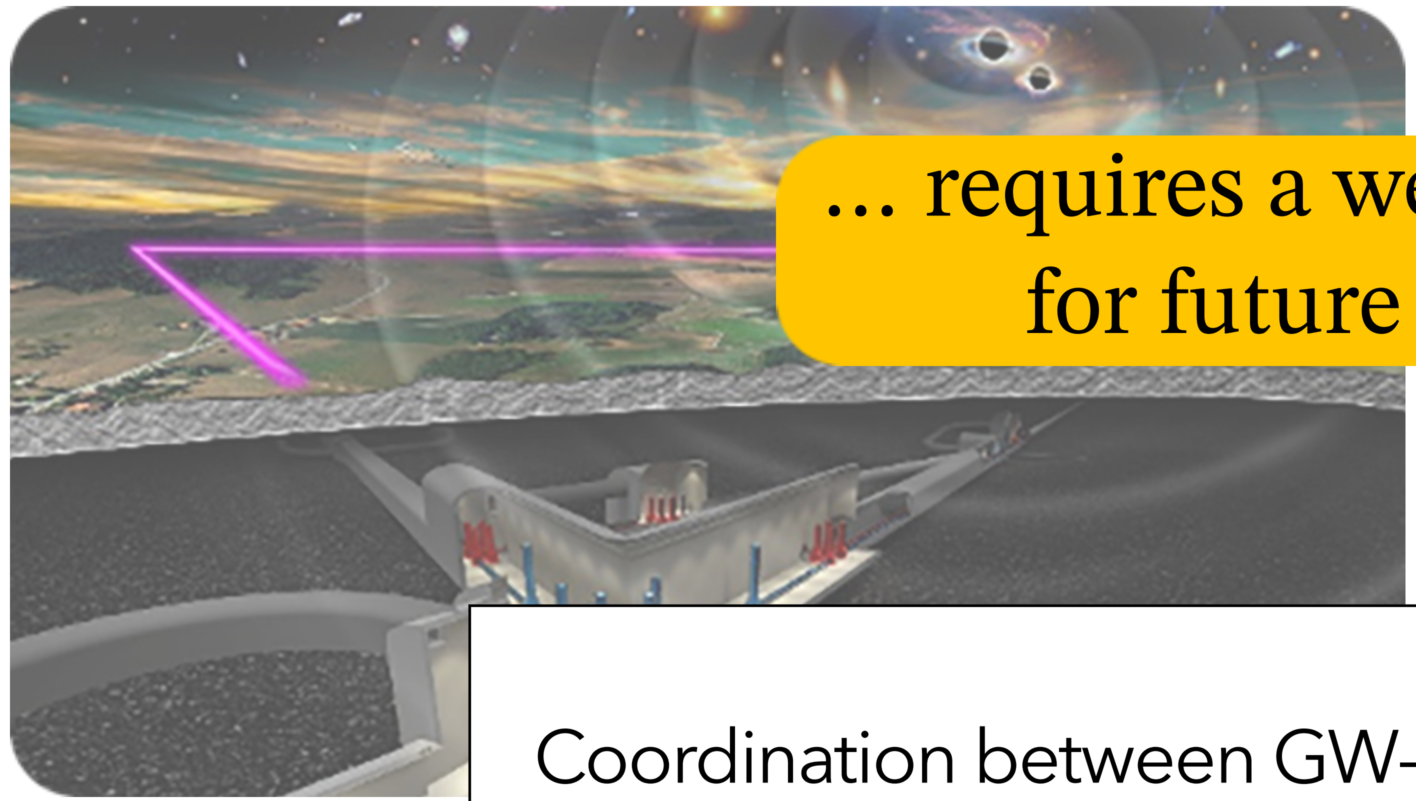


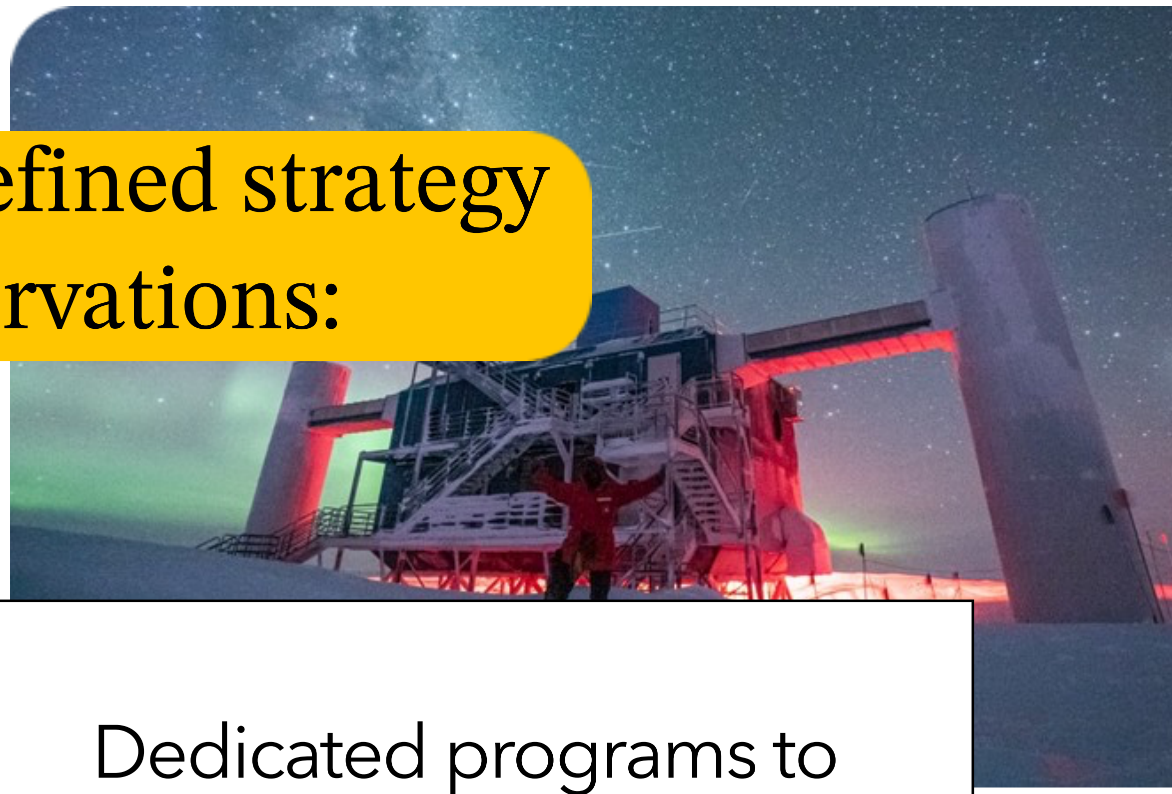
MM discoveries: their impact and new challenges

Such a wide,
multi-disciplinary impact …



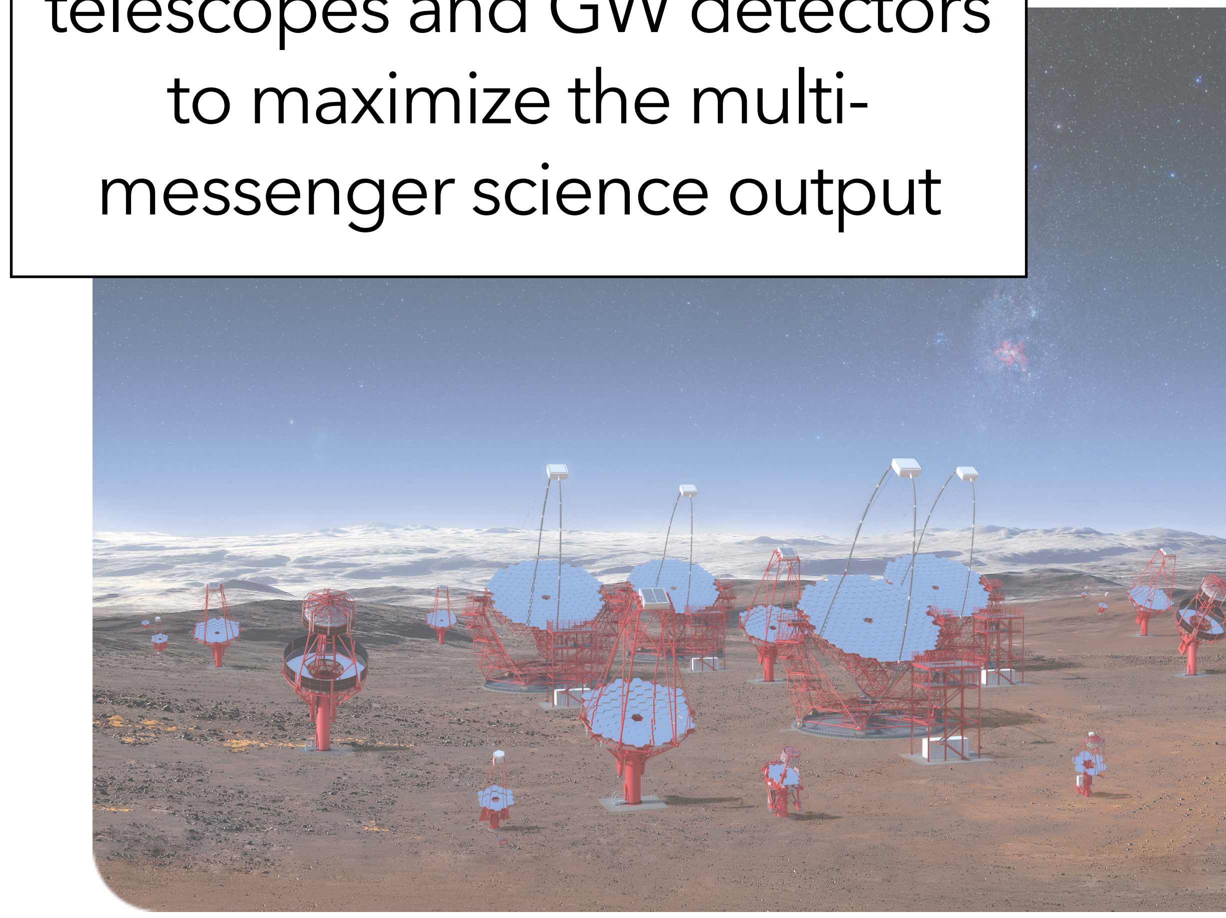
- GRBs and high-energy astrophysics
- Nuclear physics
- GRMHD processes for the jet launching
- Matter in extreme conditions
- Cosmology
- Evolution of stellar populations
- Gravitational physics
- Stellar Nucleosynthesis





… requires a well defined strategy
for future observations:

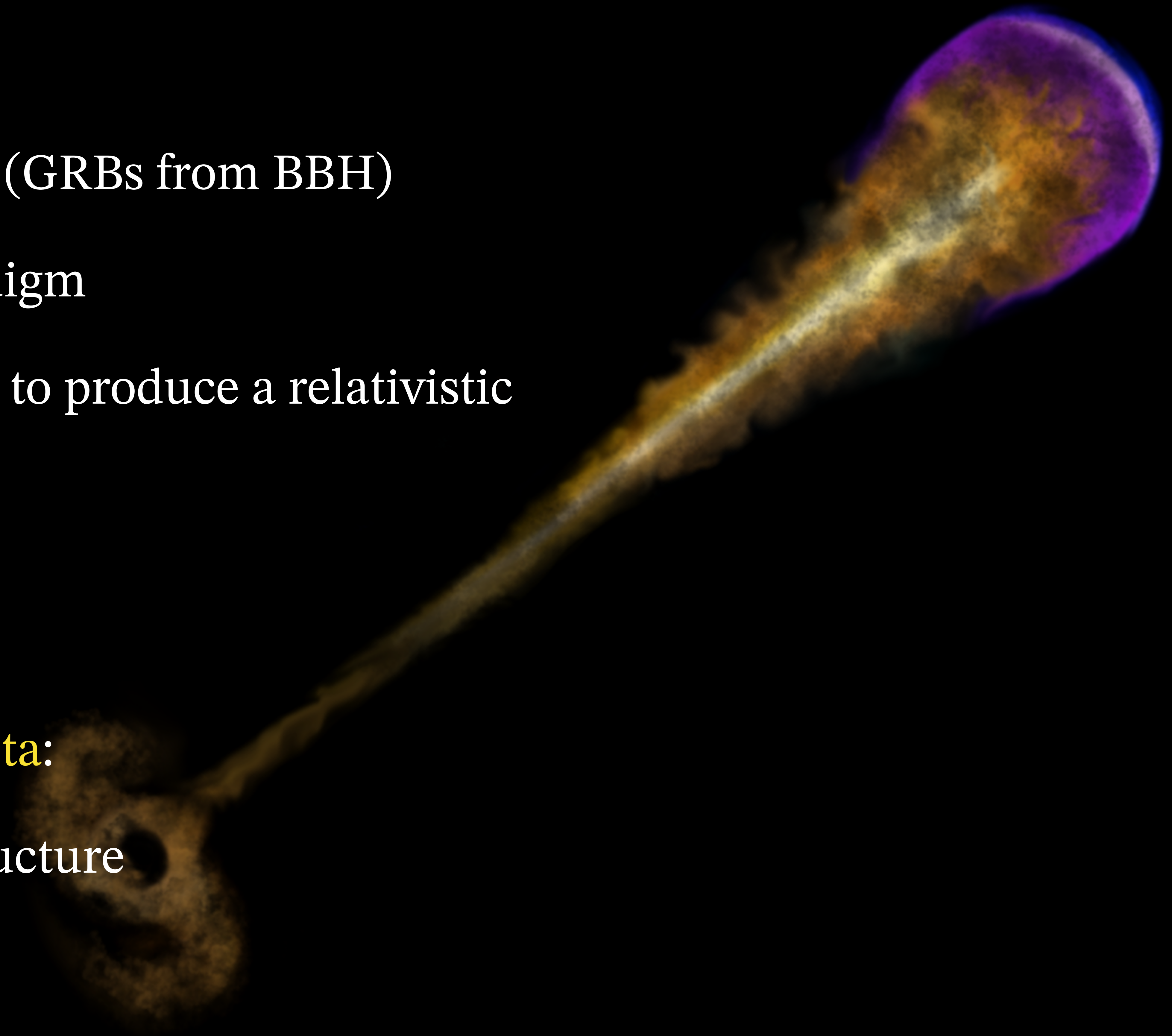
- Coordination between GW-EM community
- Dedicated programs to follow-up the GW events
- Optimized observational strategies
- Design next generation telescopes and GW detectors to maximize the multi-messenger science output



What are the questions still open in the MM field?

What GW data can tell about the remnant and the GRB progenitor:

1. NS-NS or NS-BH?
2. constraints on exotic scenarios (GRBs from BBH)
3. central engine: BH vs NS paradigm
4. fraction of binary mergers able to produce a relativistic jet



Properties of the KN ejecta:

1. geometrical and dynamical structure
2. neutron richness
3. Heavy elements nucleosynthesis
4. Probe the Jet-KN interaction

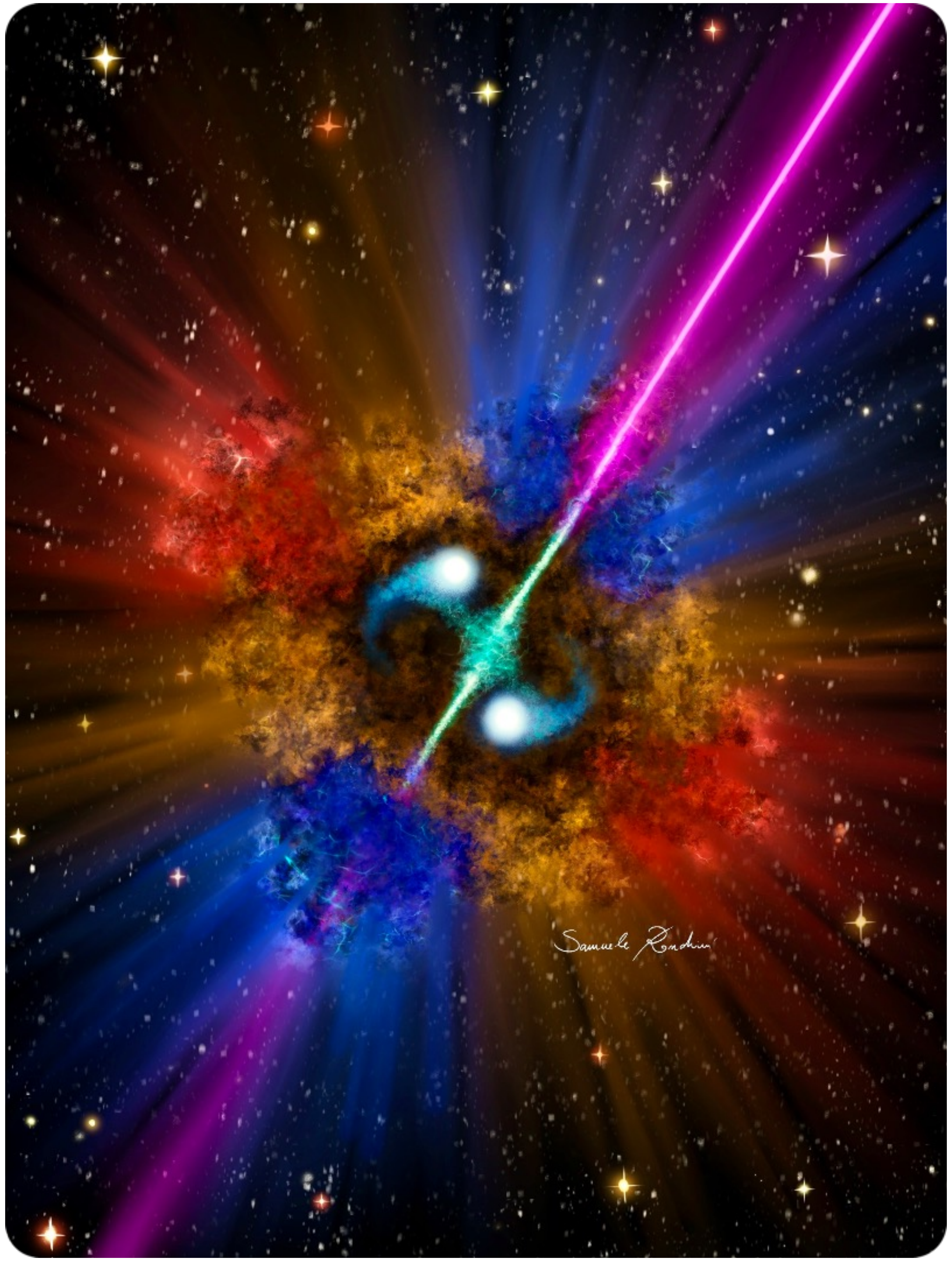
Joint GW+EM detection:

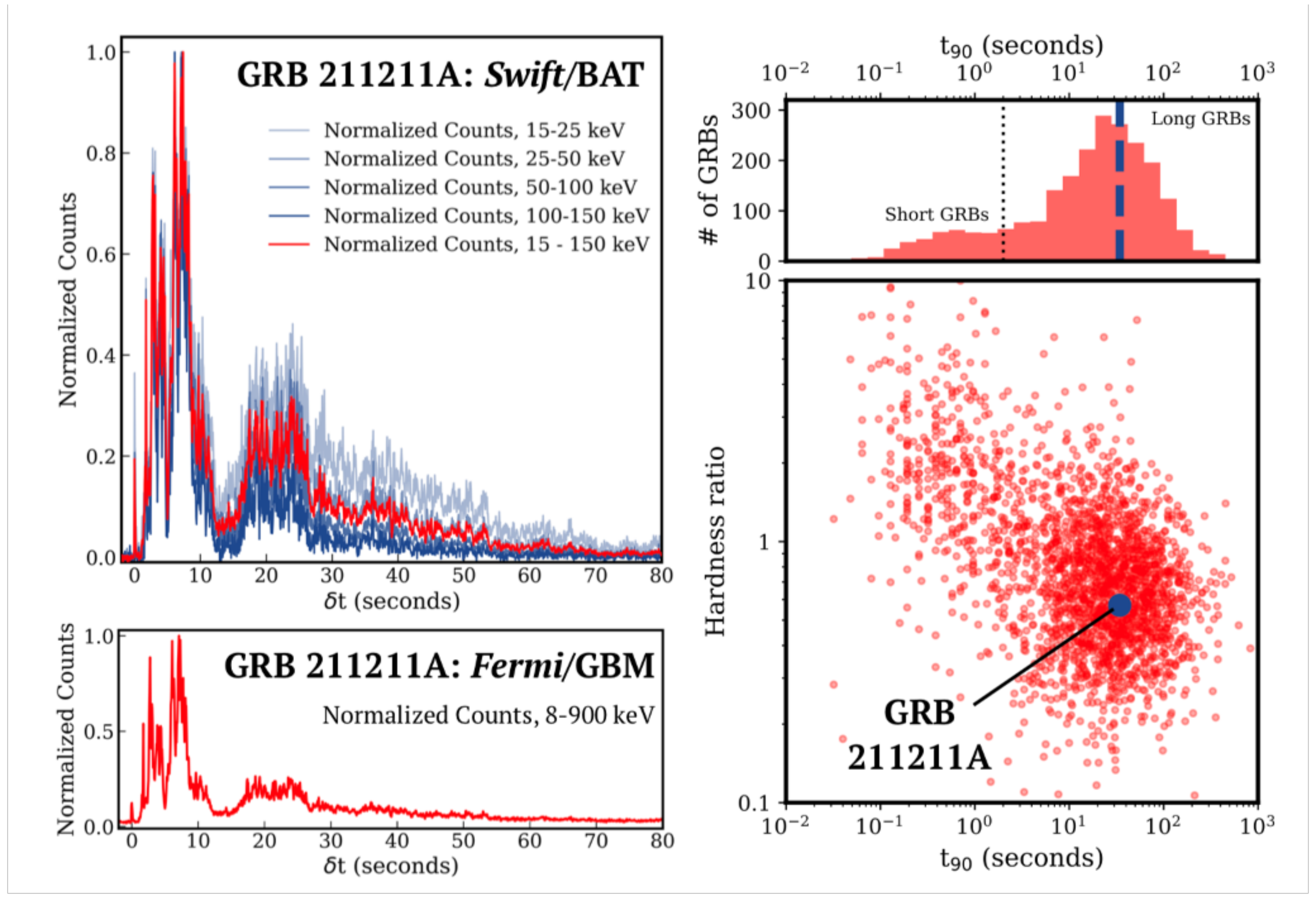
1. a fundamental tool to test alternative theories of gravity, through speed of gravity/light comparison
2. critical to probe the physics of the launching mechanism and the jet break-out through the circum-burst ejecta
3. Bright siren measurement of Hubble constant

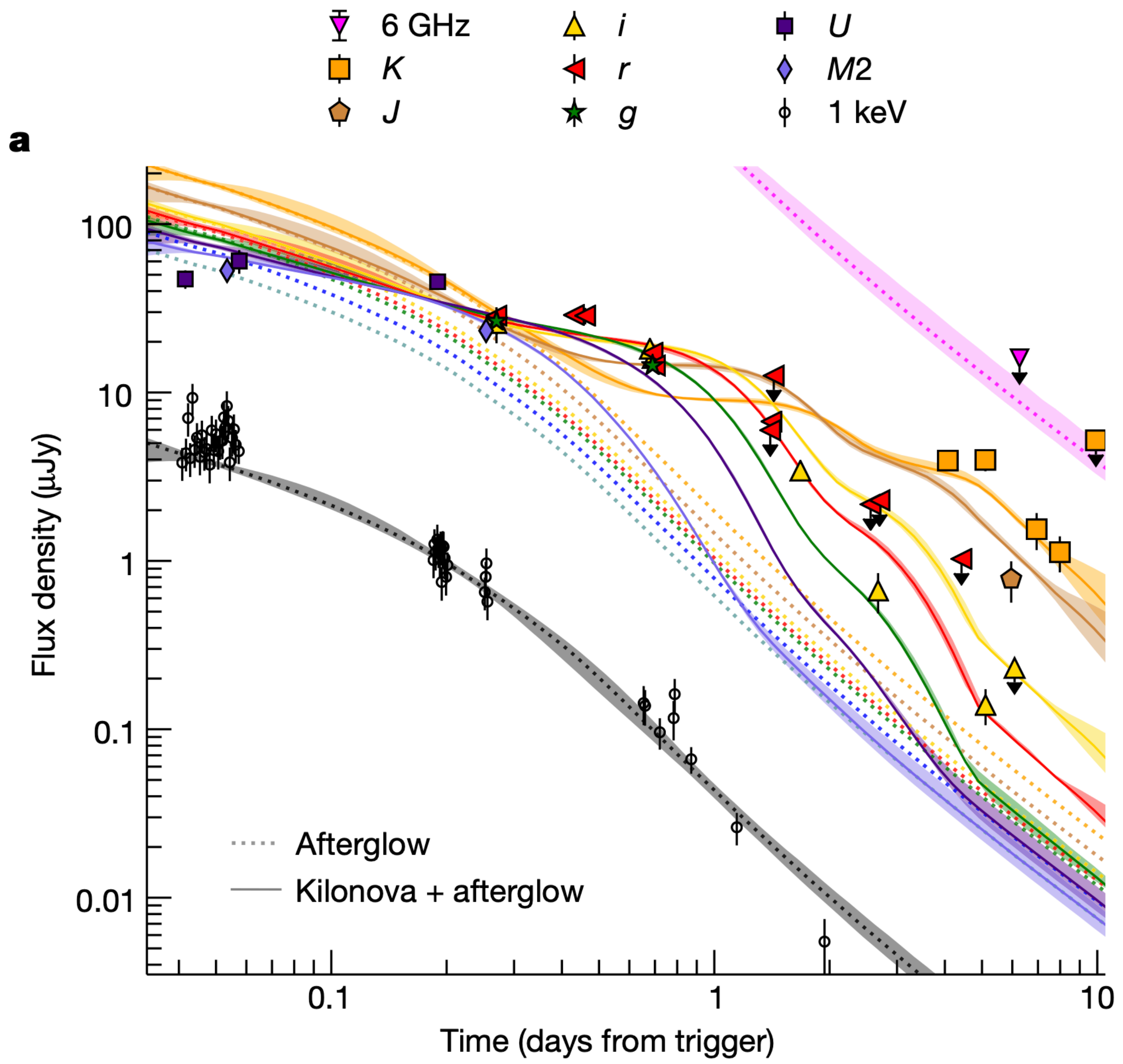
The missing messenger:

1. Where are high-energy neutrinos from CBMs?
2. Can GRBs contribute to the flux of high-energy neutrinos observed by IceCube

Other recent peculiarities in the MM field: GRB 211211A







First long GRB associated with a binary merger

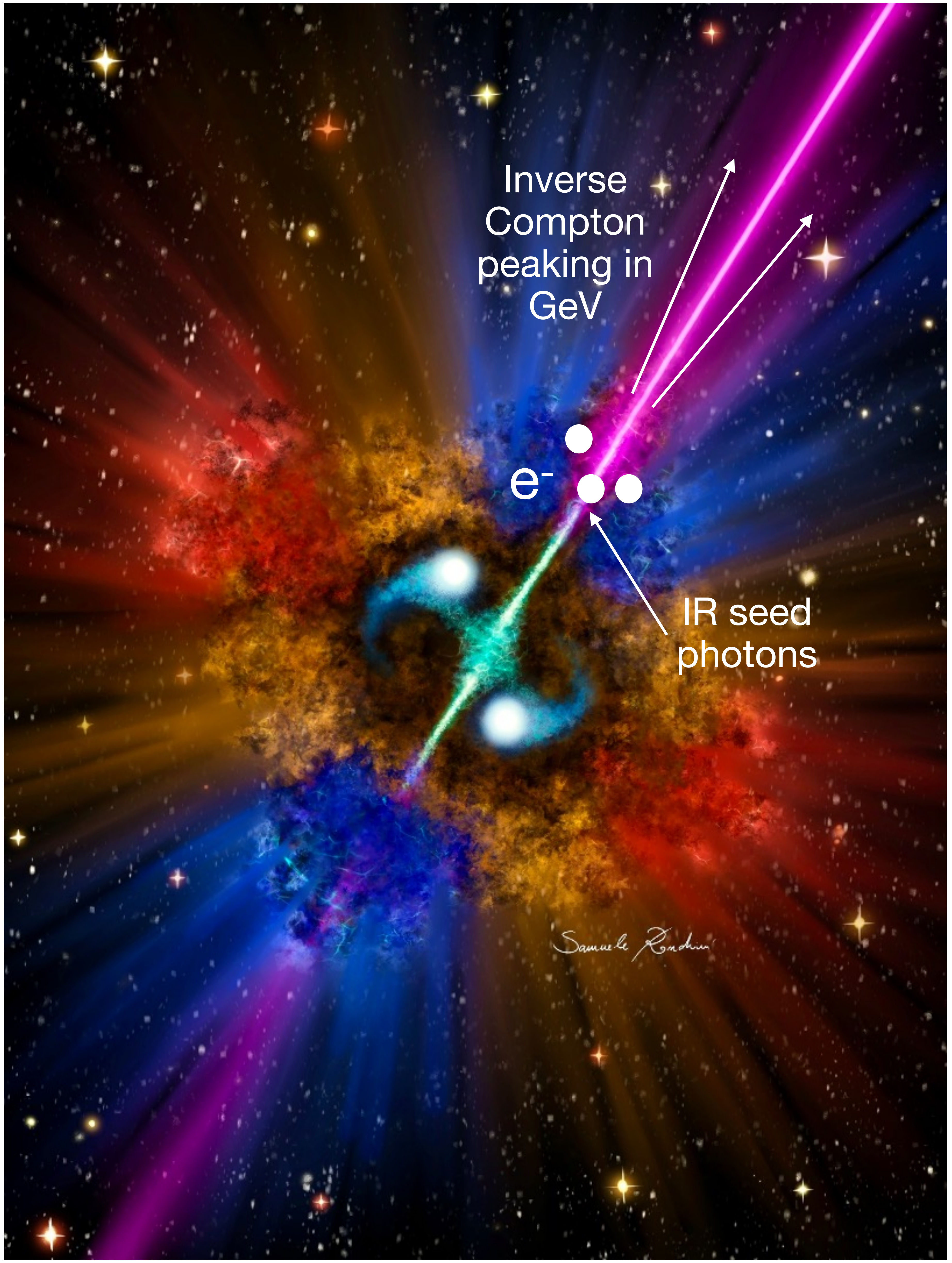
D = 350 Mpc

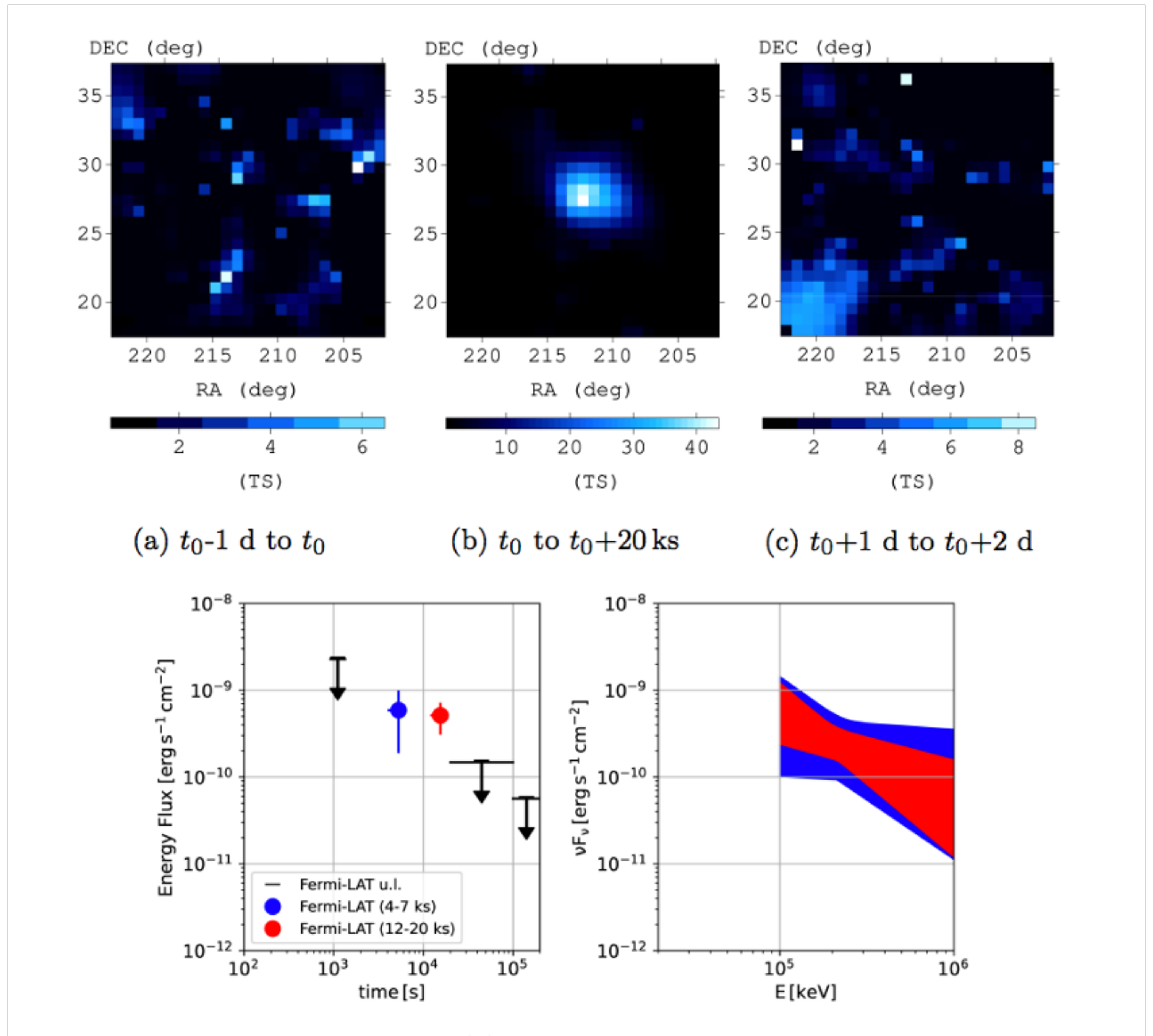
If NSBH, detectable by LVK? —> YES, at high SNR

If BNS, detectable by LVK? —> YES, at SNR~10, because we know that is face-on

Rastinejad et al. 2022, Mei et al. 2022, Troja et al. 2022, Yang et al. 2022

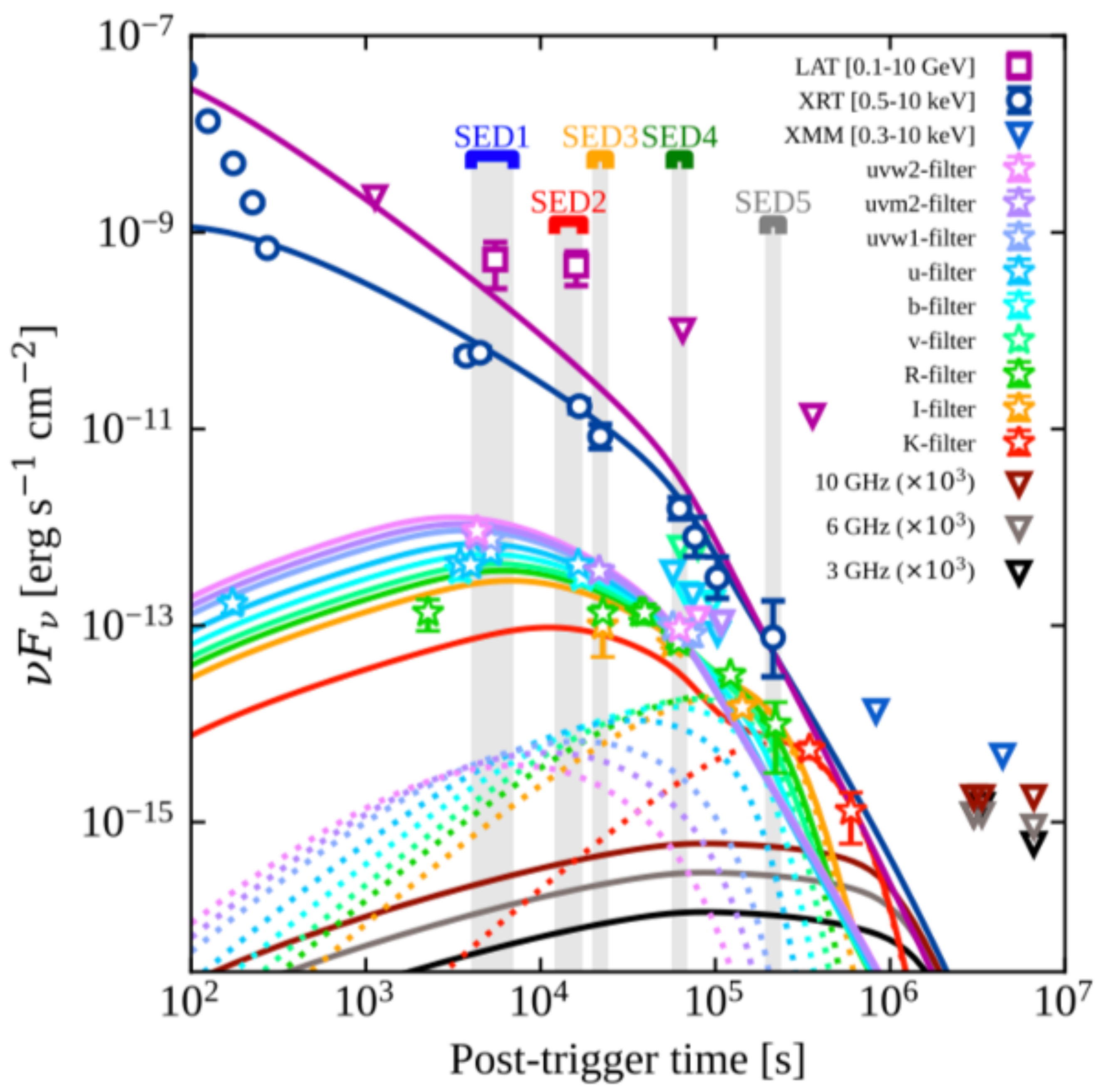
Other recent peculiarities in the MM field: GRB 211211A





(a) t_0-1 d to t_0 (b) t_0 to t_0+20 ks (c) t_0+1 d to t_0+2 d

(d) t_0 to t_0+2 d

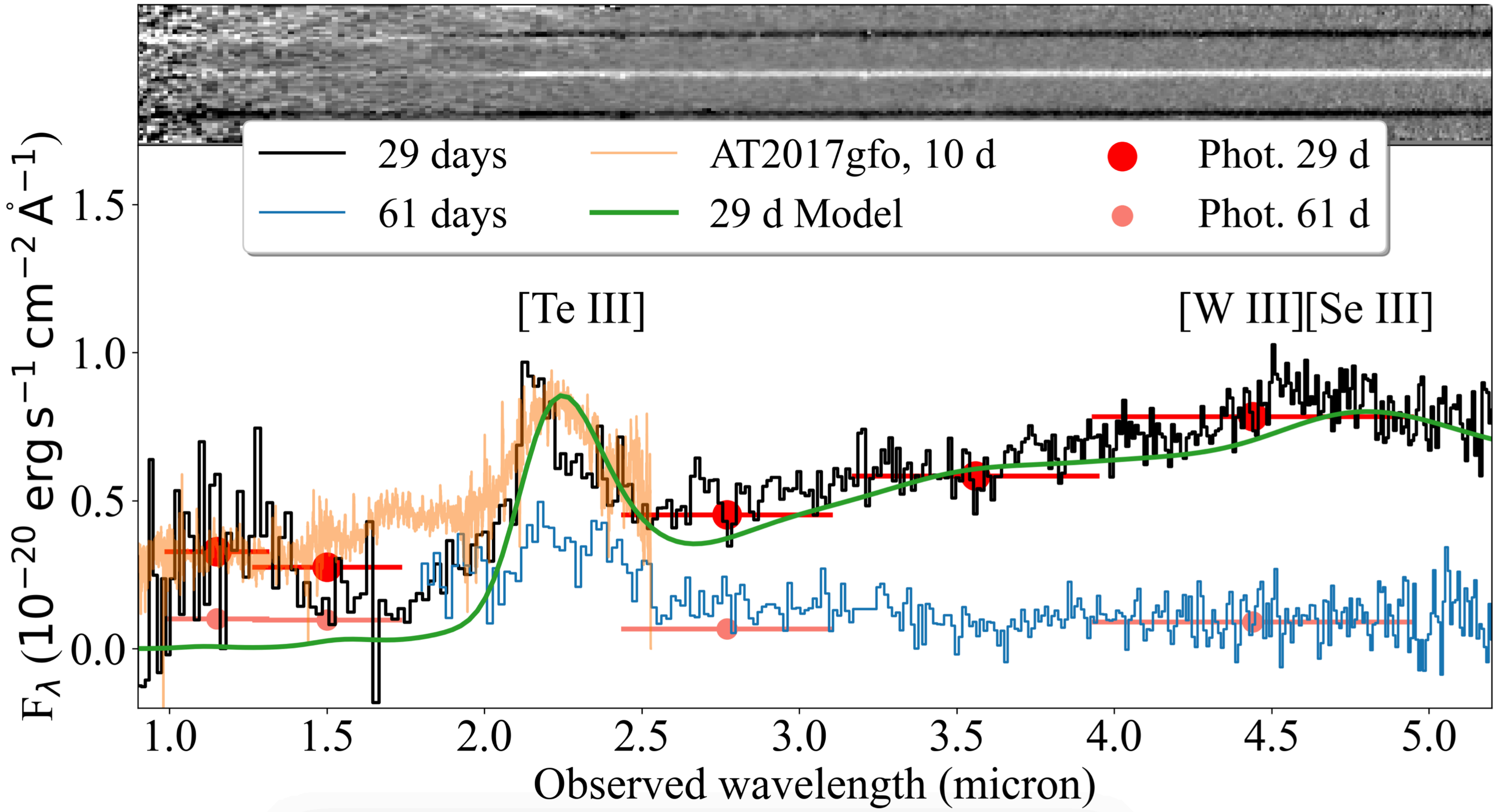


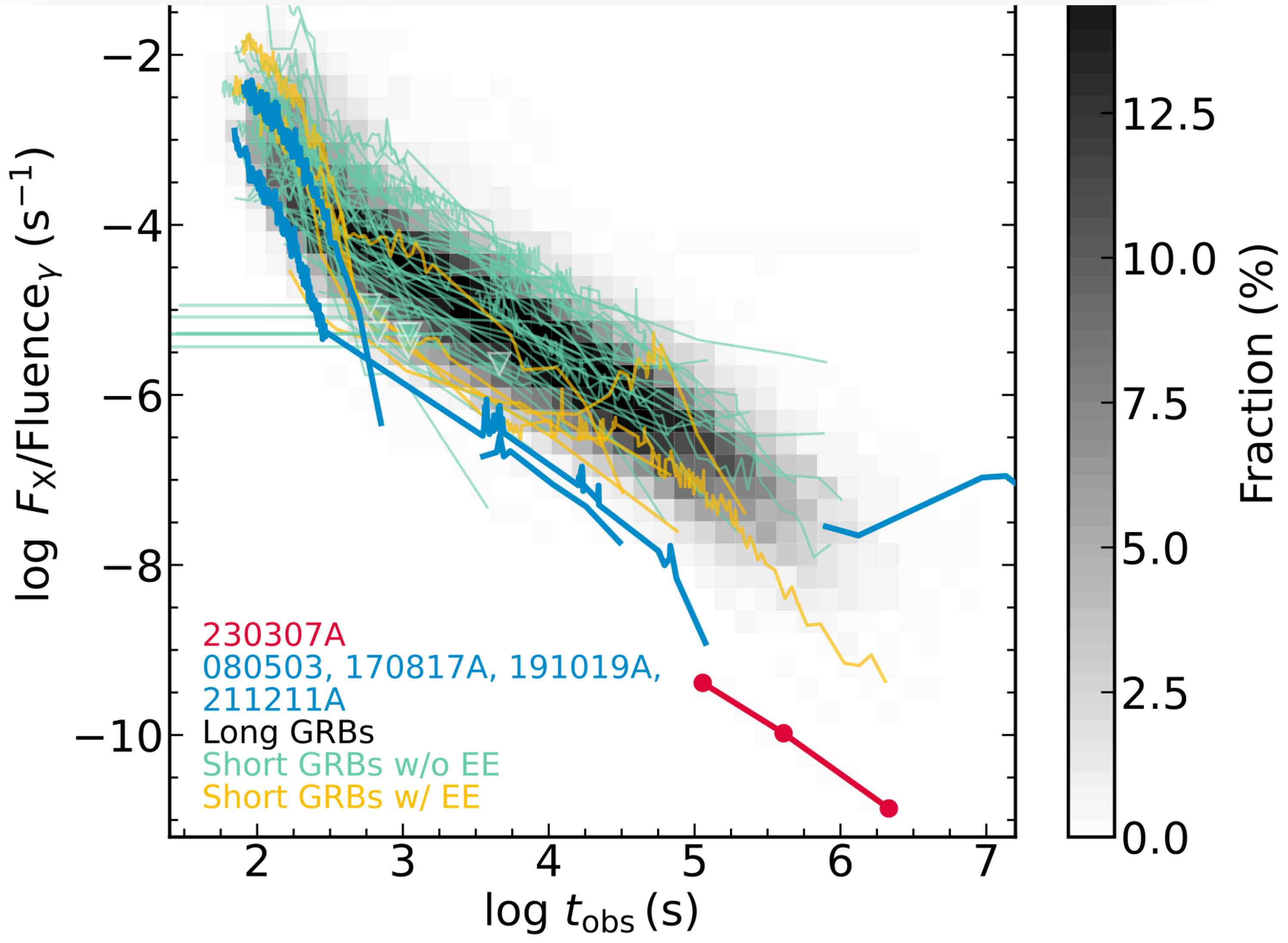
First GeV emission associated with a binary merger

Late-time low-power jet, which drills through the KN ejecta

Mei et al. 2022

Other recent peculiarities in the MM field: GRB 230307A





First detection by JWST of a merger driven GRB

Levan et al. 2023

- Second brightest GRB ever detected
- Sub-luminous X-ray afterglow
- D = 300 Mpc —> **detectable by LVK**
- KN emission detected by JWST at 30d from GRB
- Color evolution remarkably similar to the KN of 211211A and AT2017gfo

Proposal of a unified scenario

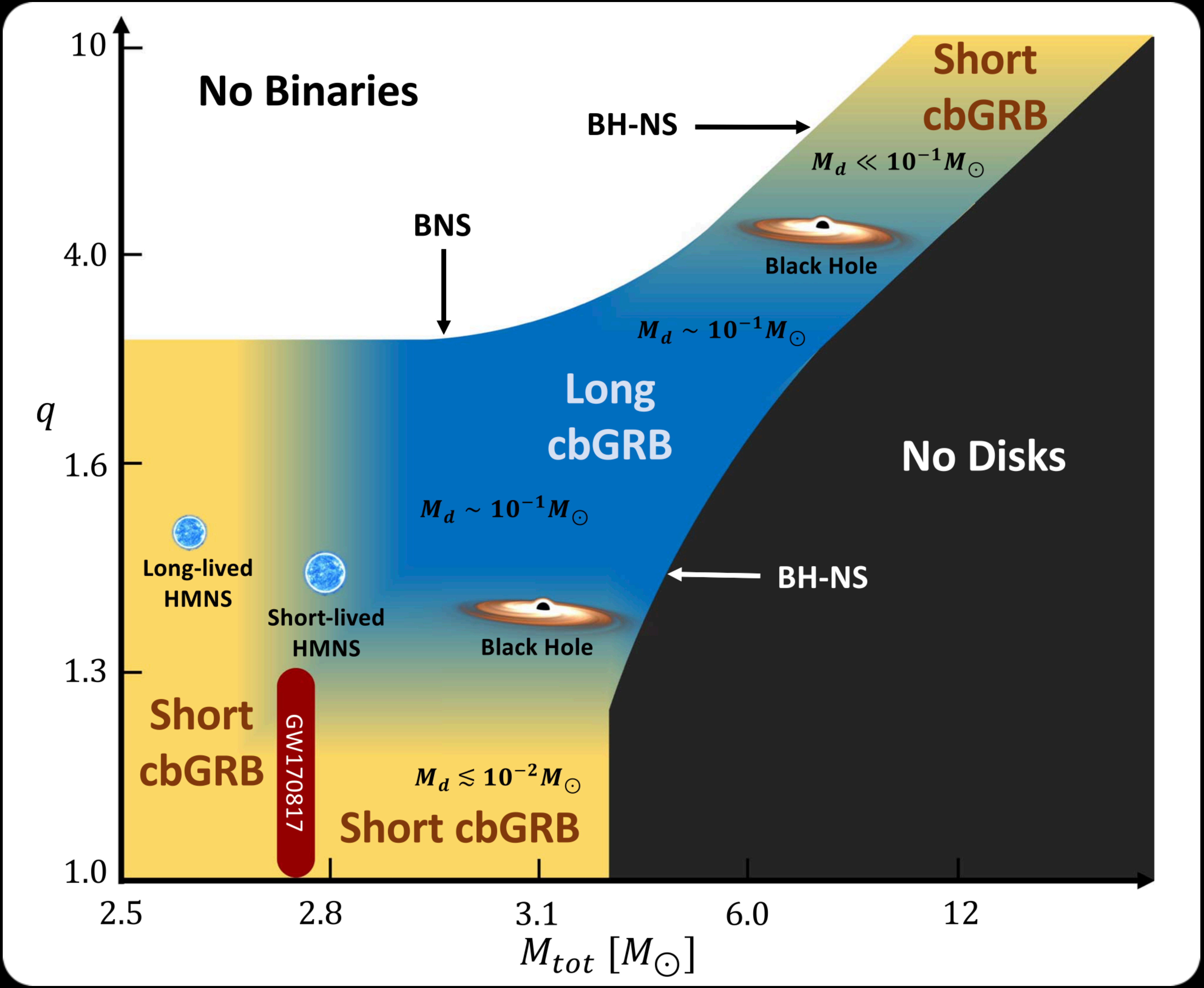
Gottlieb et al. 2023

GRB 211211A is:

- NS-BH? —>Seems in contrast with the blue component of the KN
- HMNS?—>more plausible

230307A

- ???



Duration mostly driven by M_{disk}

Long merger driven GRB powered by

- NS-BH with moderate mass ratio
- BNS with $M_{\rm tot} \gtrsim 2.8 M_\odot$

Short merger driven GRB powered by:

- BNS with $M_{\rm tot} \lesssim 2.8 M_\odot$

Proposal of a unified scenario

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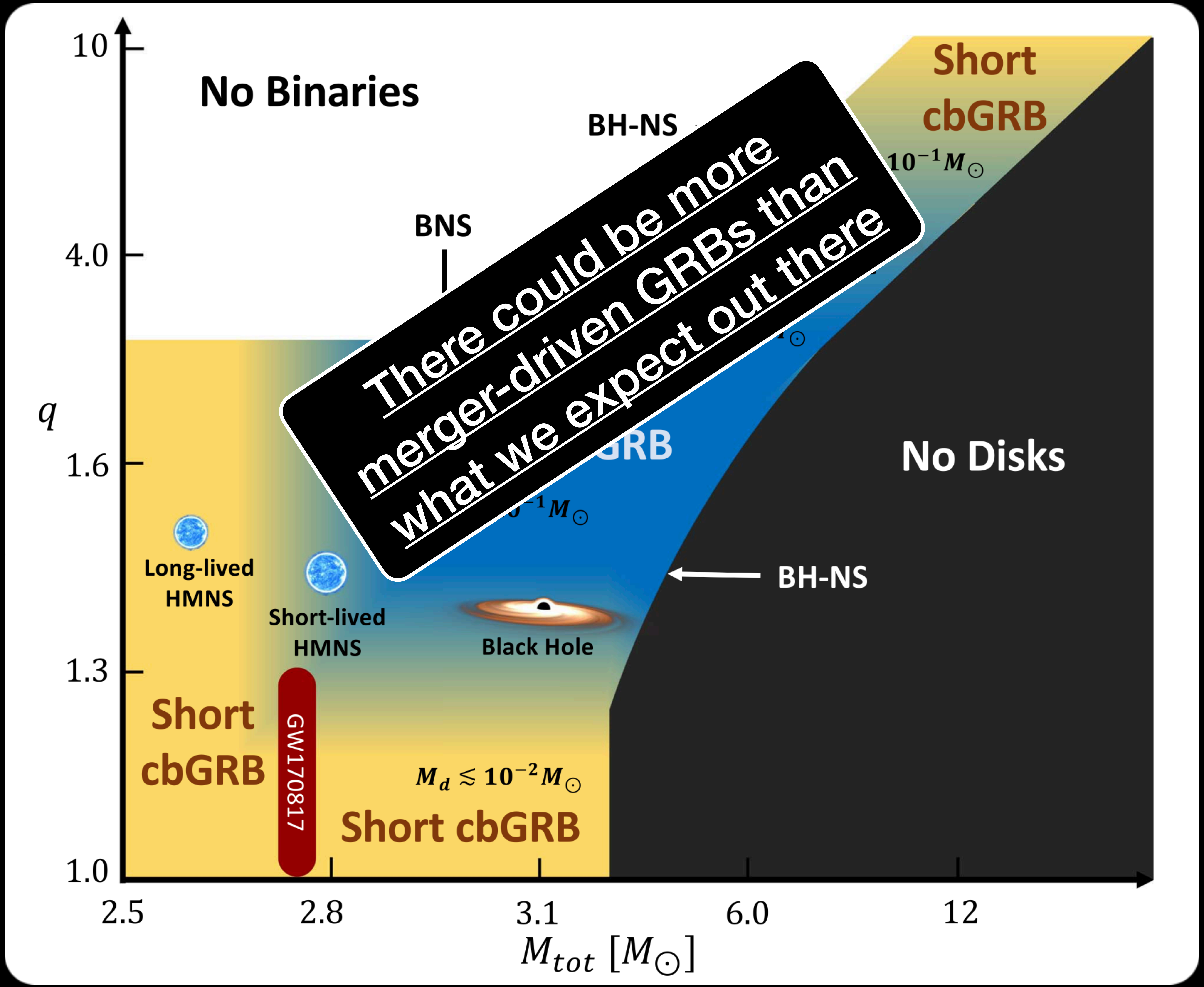
Gottlieb et al. 2023



There could be more merger-driven GRBs than what we expect out there

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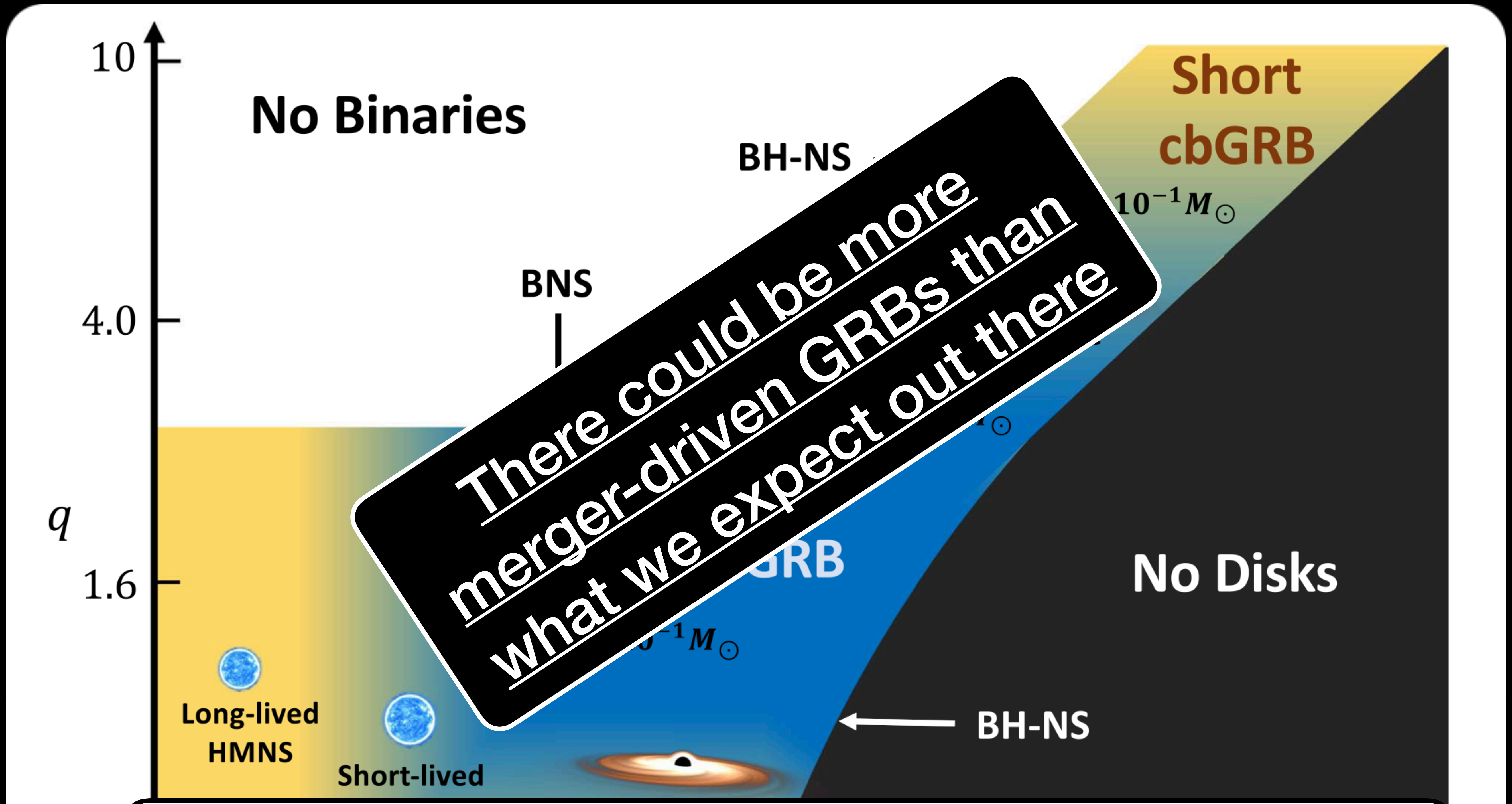

There could be more merger-driven GRBs than what we expect out there

What we could gain with future MM observations?

GW:

M1 and M2

EM:

- GRB duration and spectrum
- KN properties

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Short merger driven GRB powered by:

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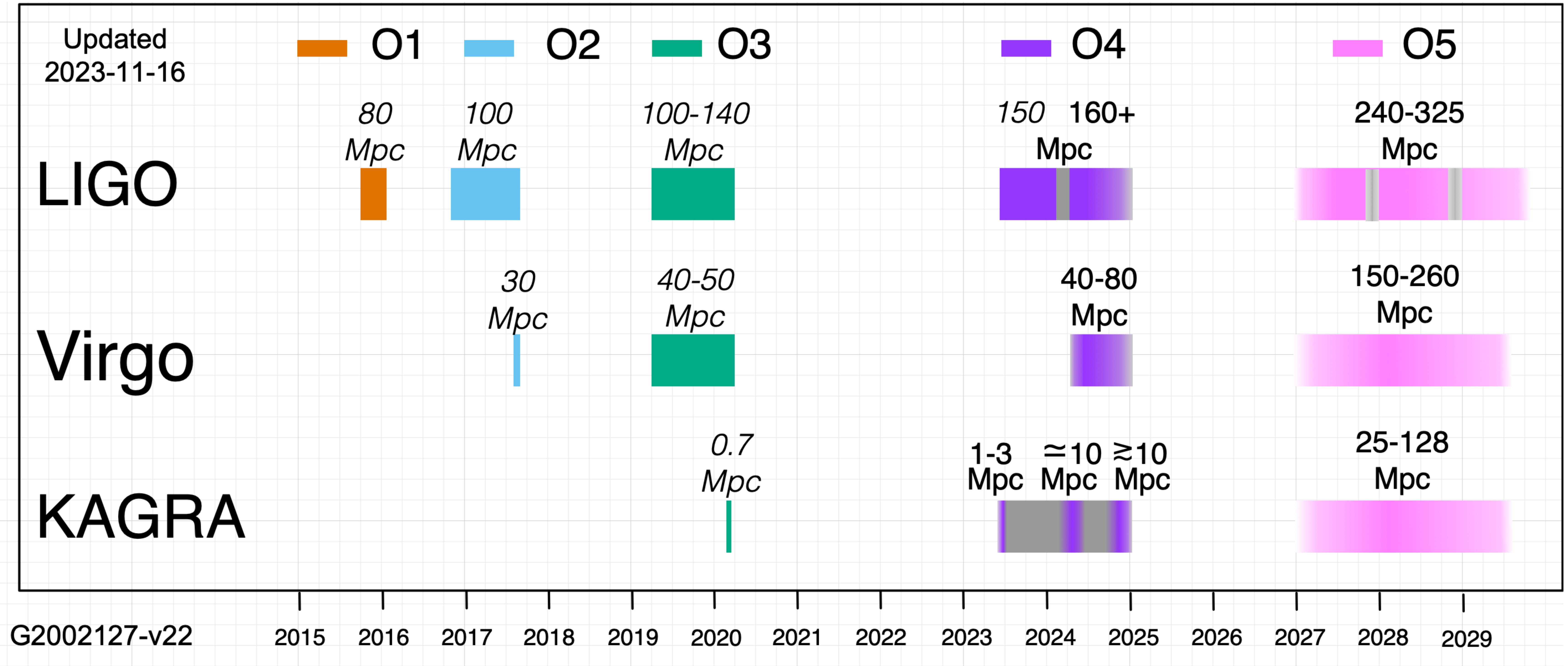
The present

Masses in the Stellar Graveyard



- O4: 18 months of active observing time, started end of May

- So far, only LIGOs

71 in O4

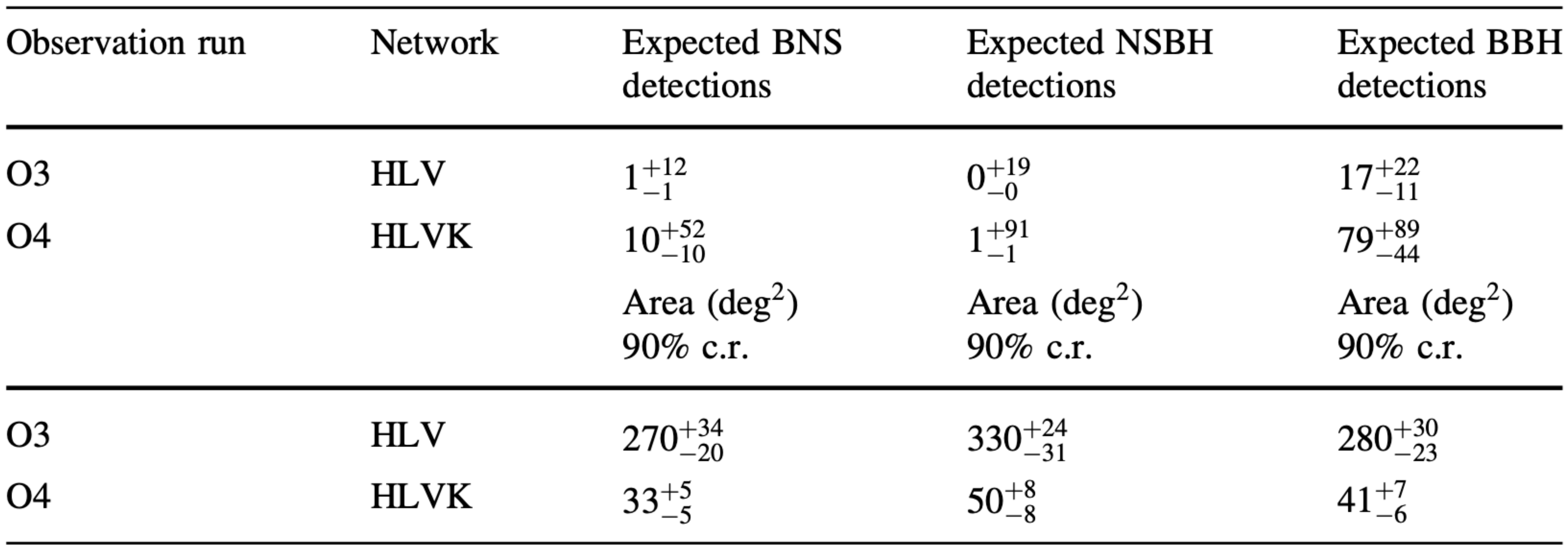
Significant events:

1. CBC events: FAR threshold 1/month (post trials)
2. Burst events: FAR threshold 1/year (post trials)

1456 in O4

Low-significance events:
Sent with a max FAR of 2/day

Abbott et al. 2020, Living Reviews in relativity



Observation run	Network	Expected BNS detections	Expected NSBH detections	Expected BBH detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}

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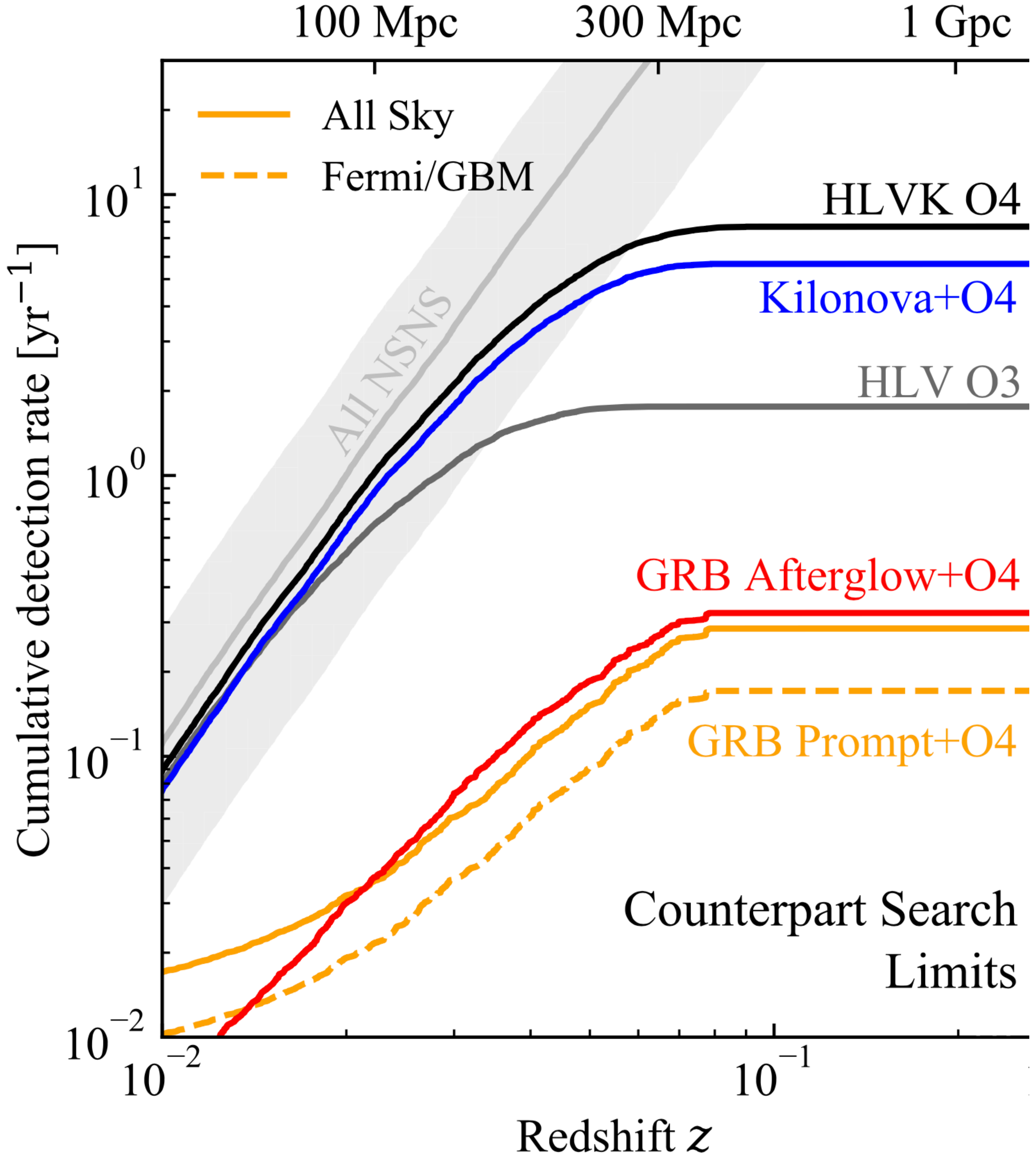
Sent with a max FAR of 2/day

O4 multimessenger prospects for BNS and NSBH



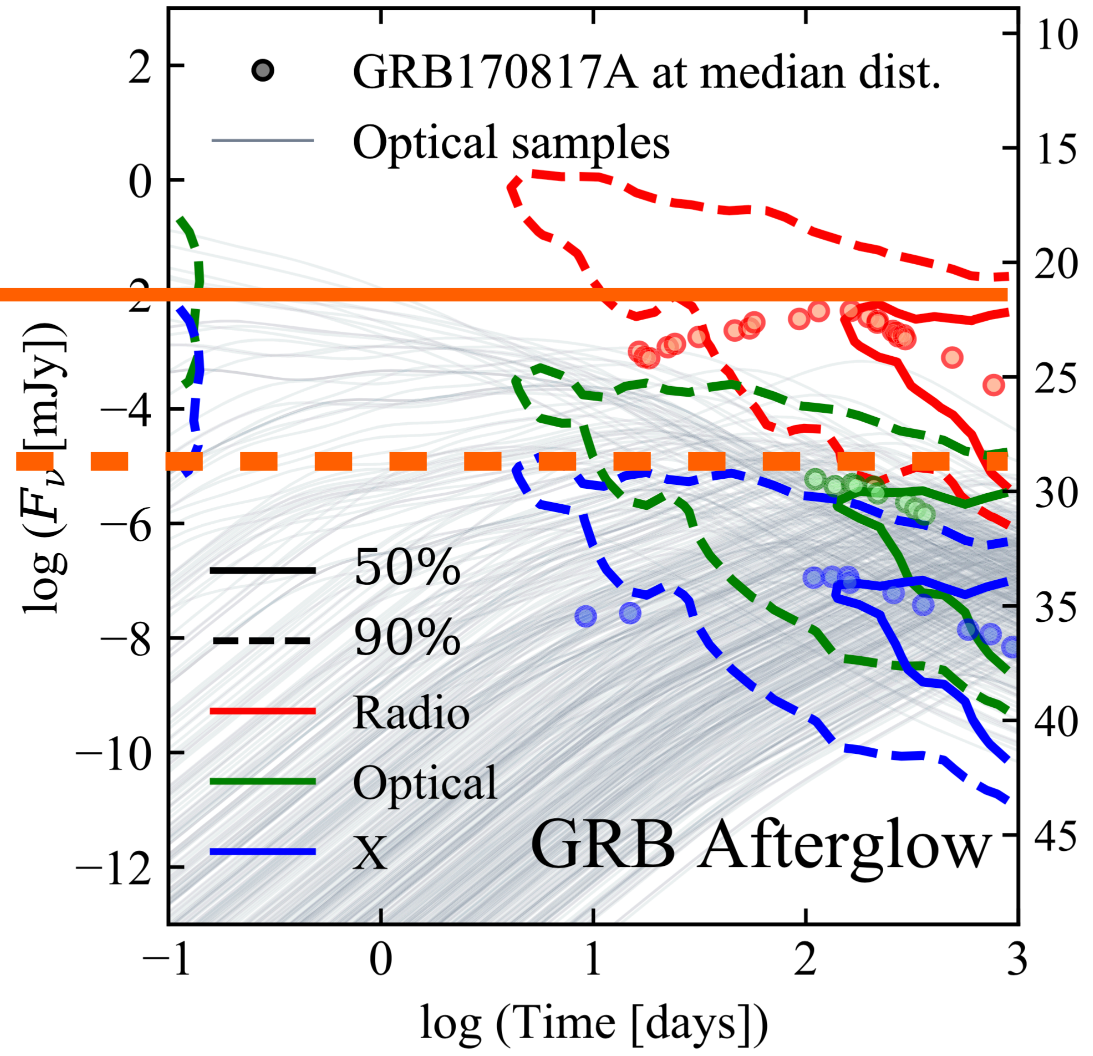
Colombo et al. 2022

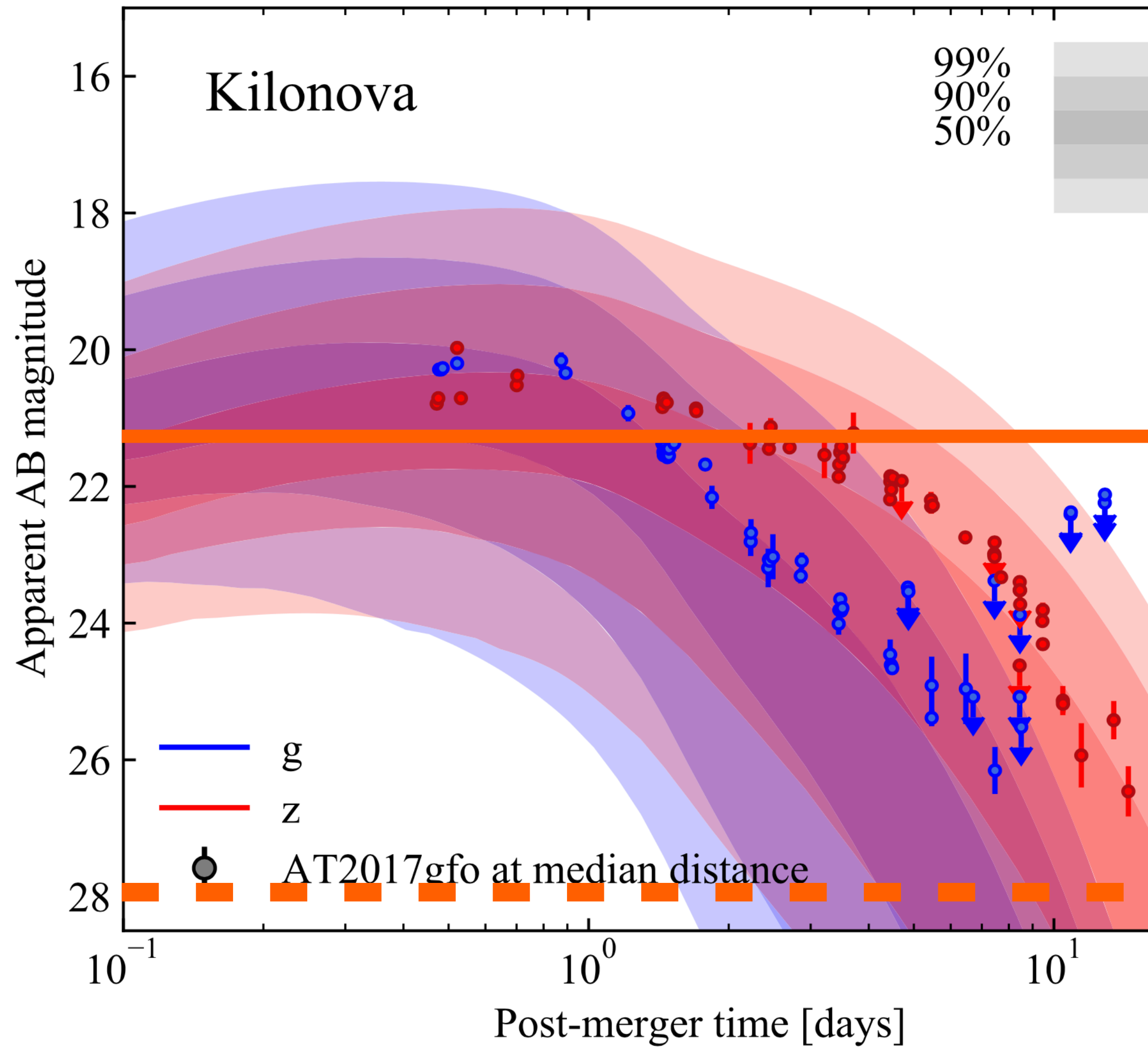
BNS

Candidate search limit

Candidate monitoring limit

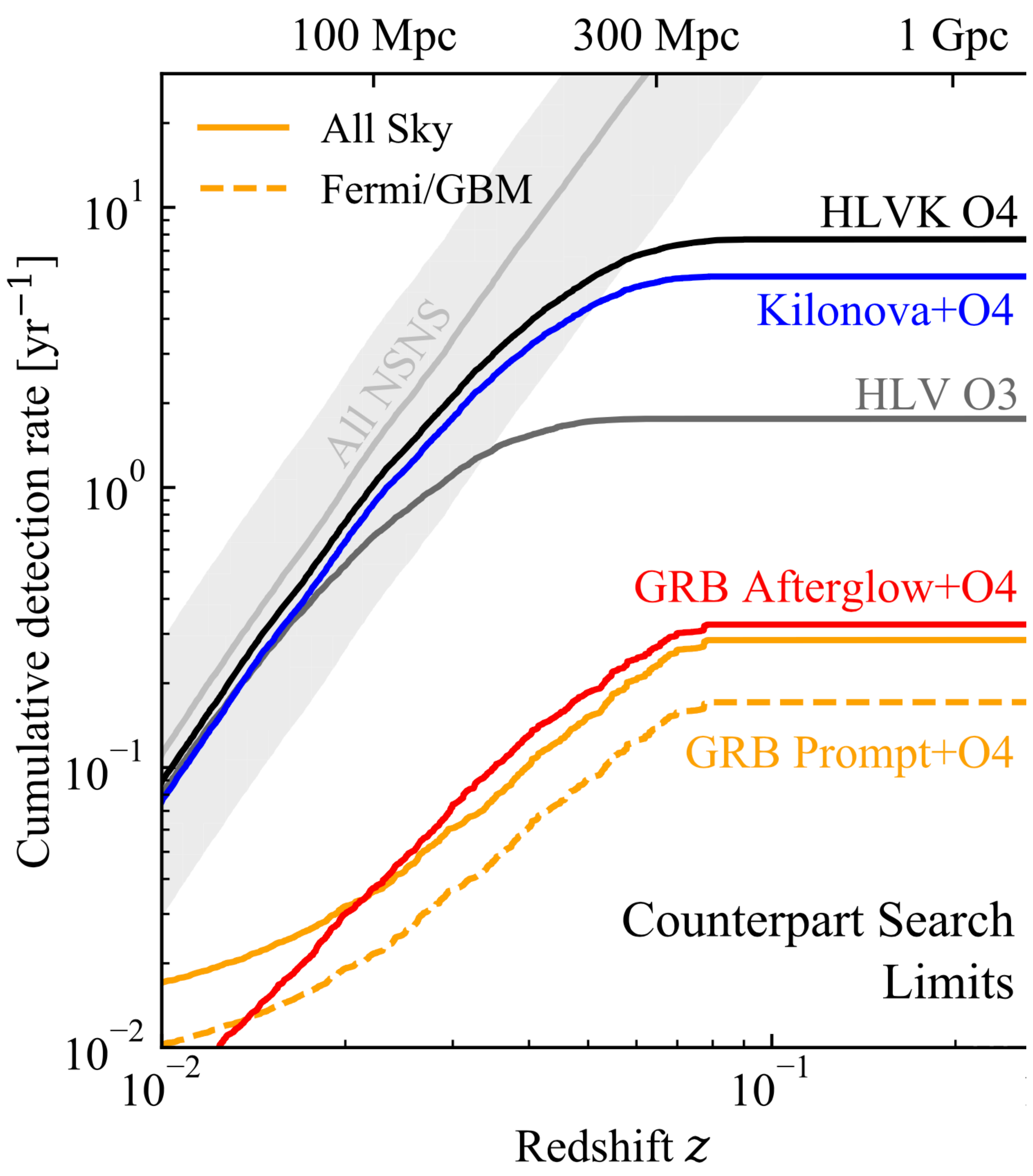
The candidate monitoring increases just the probability of detecting an off-axis afterglow





	GW		KN + GW O4			GRB Afterglow + GW O4			GRB Prompt + GW O4	
	HLV O3	HLVK O4	J	z	g	Radio	Optical	X-rays	Swift/BAT	Fermi/GBM
Counterpart search										
Limit	12	12	21	22	22	0.1	22	10^{-13}	3.5	4
Rate	$1.8^{+2.7}_{-1.3}$	$7.7^{+11.9}_{-5.7}$	$2.4^{+3.6}_{-1.8}$	$5.1^{+7.8}_{-3.8}$	$5.7^{+8.7}_{-4.2}$	$0.29^{+0.44}_{-0.22}$	$0.06^{+0.09}_{-0.04}$	$0.32^{+0.51}_{-0.23}$	$0.03^{+0.04}_{-0.02}$	$0.17^{+0.26}_{-0.13}$
(% of O4 GW)	(23%)	(100%)	(36%)	(67%)	(74%)	(4%)	(0.8%)	(4%)	(0.4%)	(2%)

O4 multimessenger prospects for BNS and NSBH



Colombo et al. 2022

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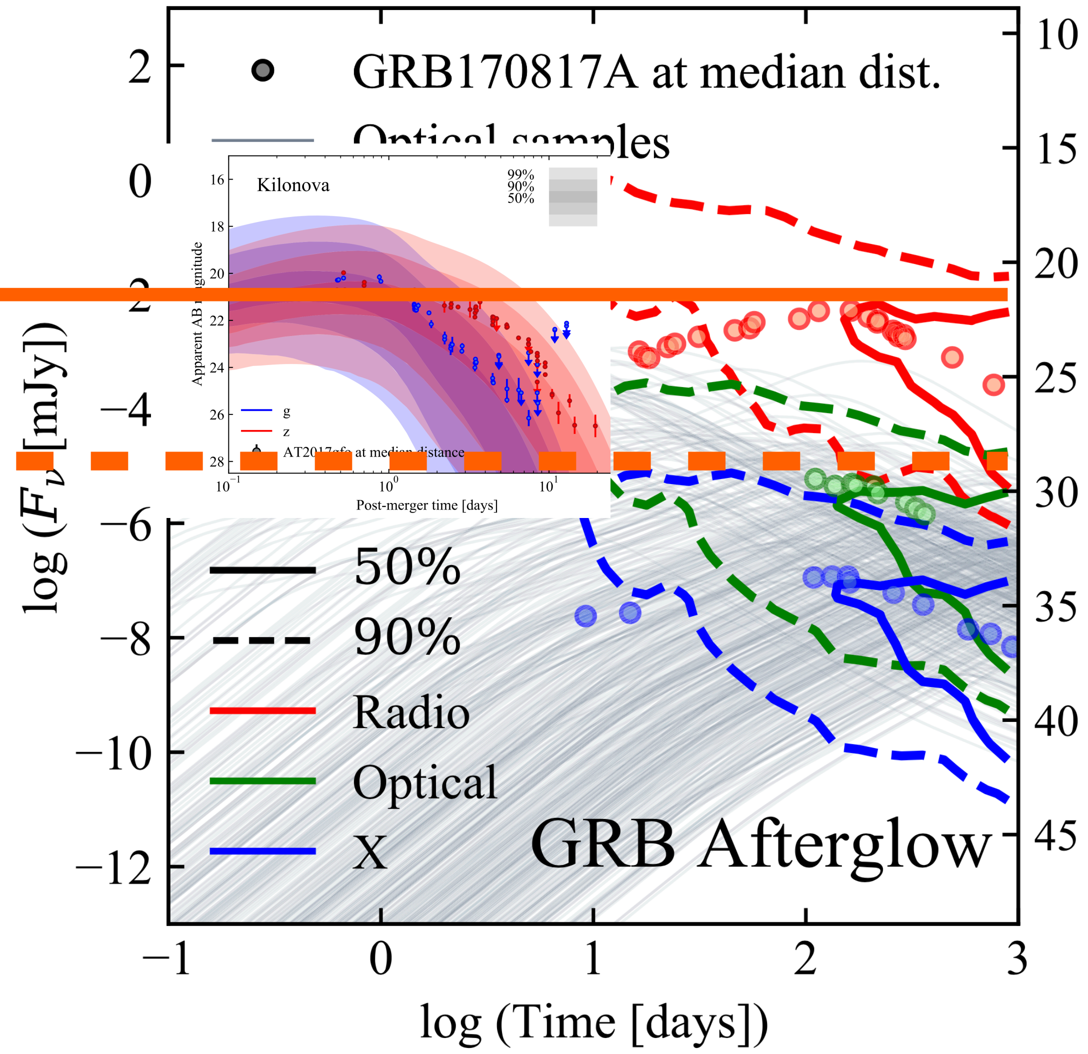

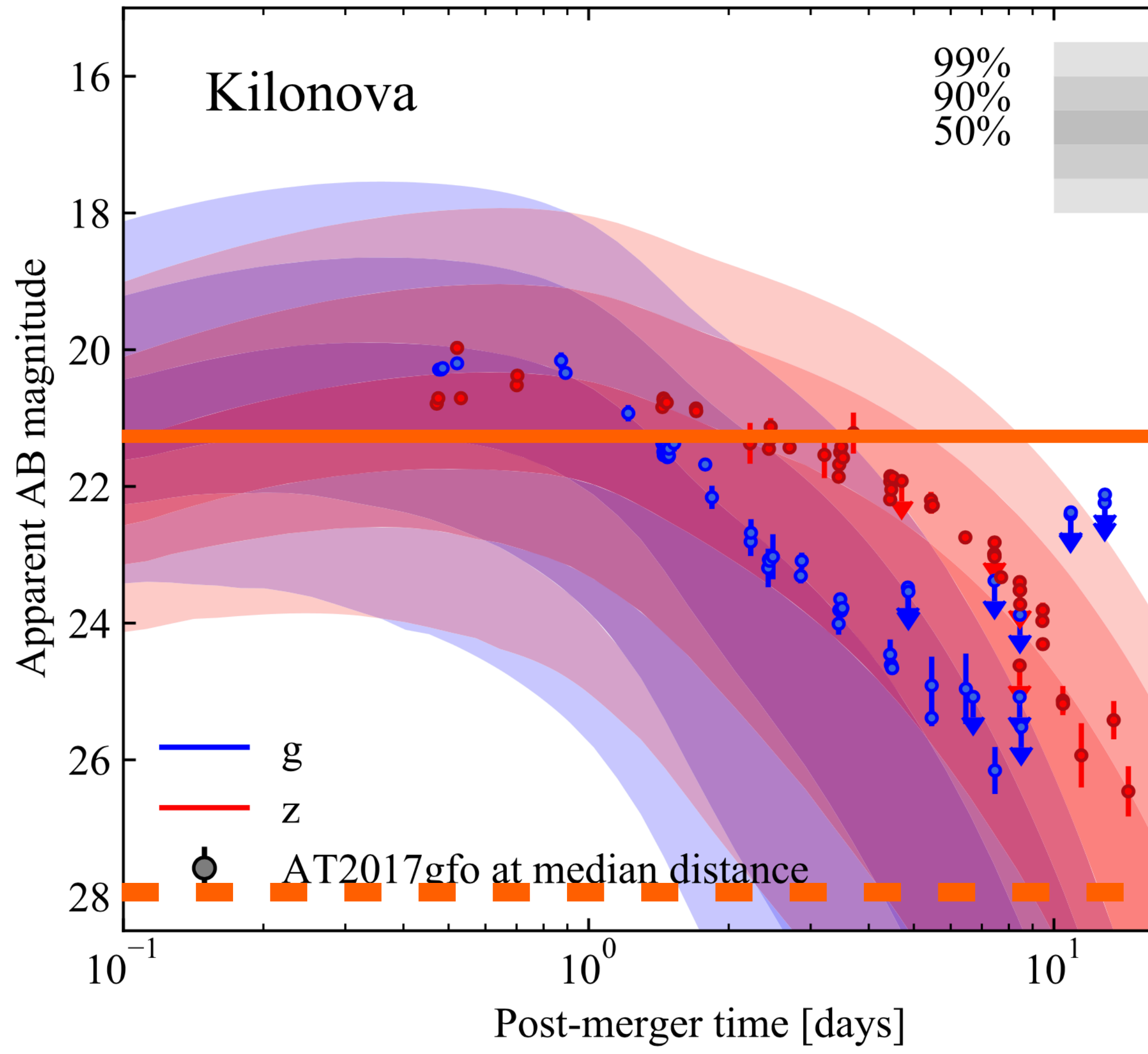

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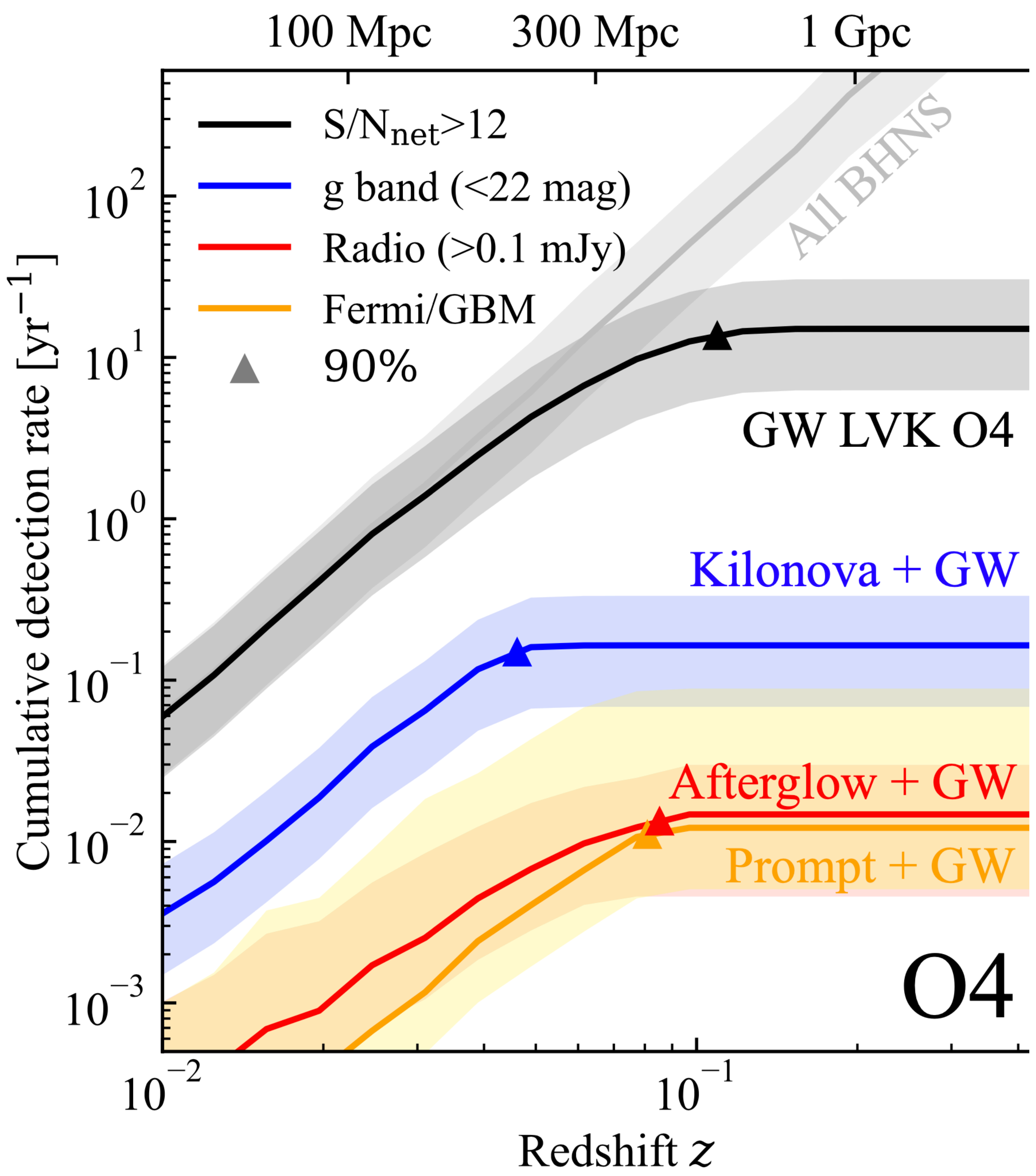
O4 multimessenger prospects for BNS and NSBH

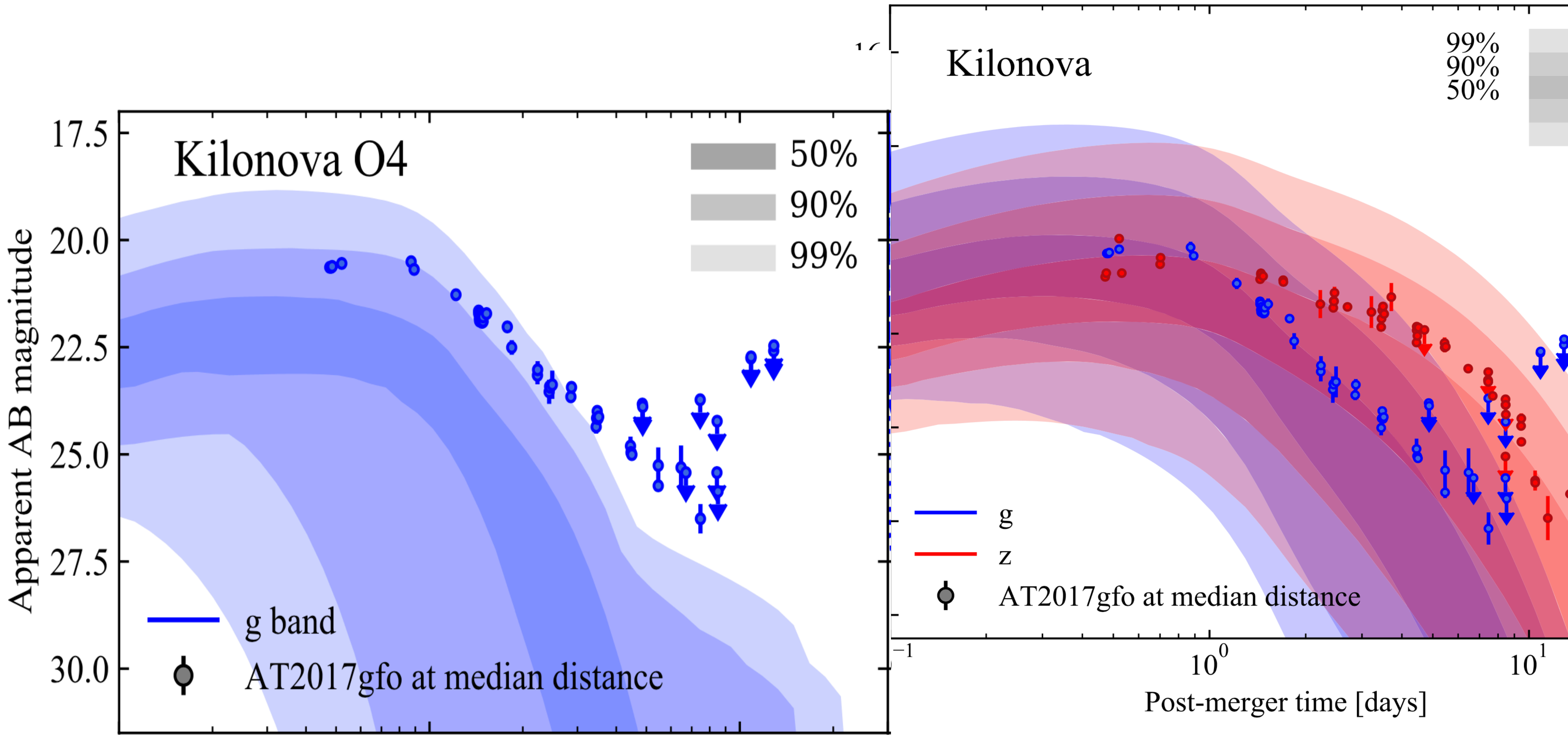


Colombo et al. 2023

NSBH

Independently of the local NS-BH rate, it is challenging to detect the EM emission, since:

1. Only for some combinations of mass ratios and spins a massive disk is formed and a jet launched
2. If formed, wider jets are expected, hence less luminous
3. The KN is less bright than BNS case

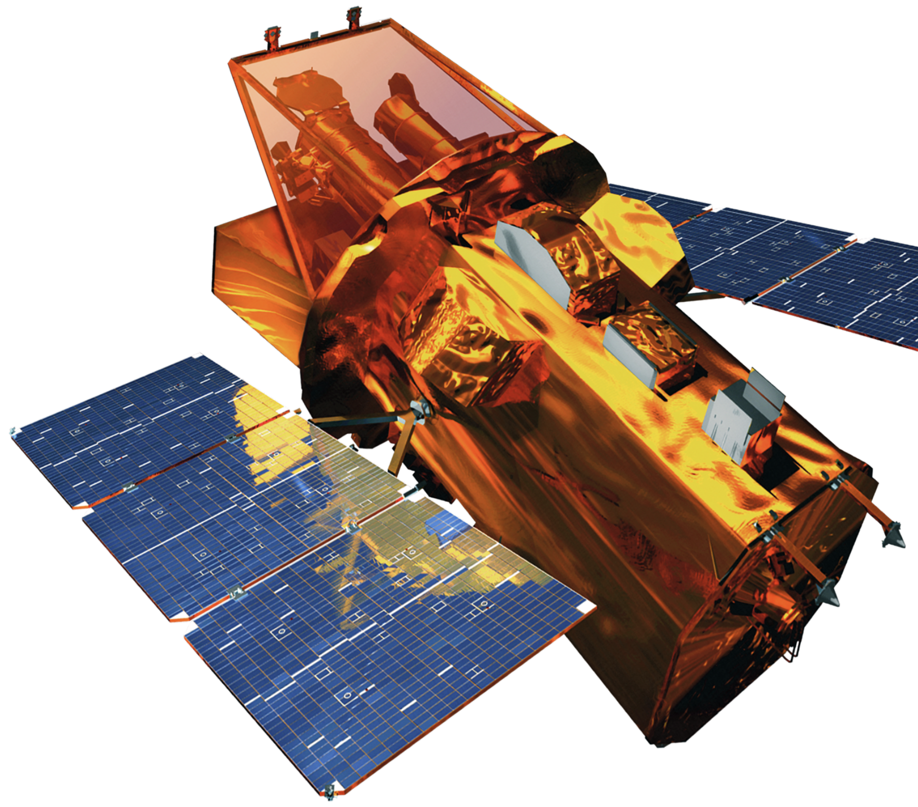


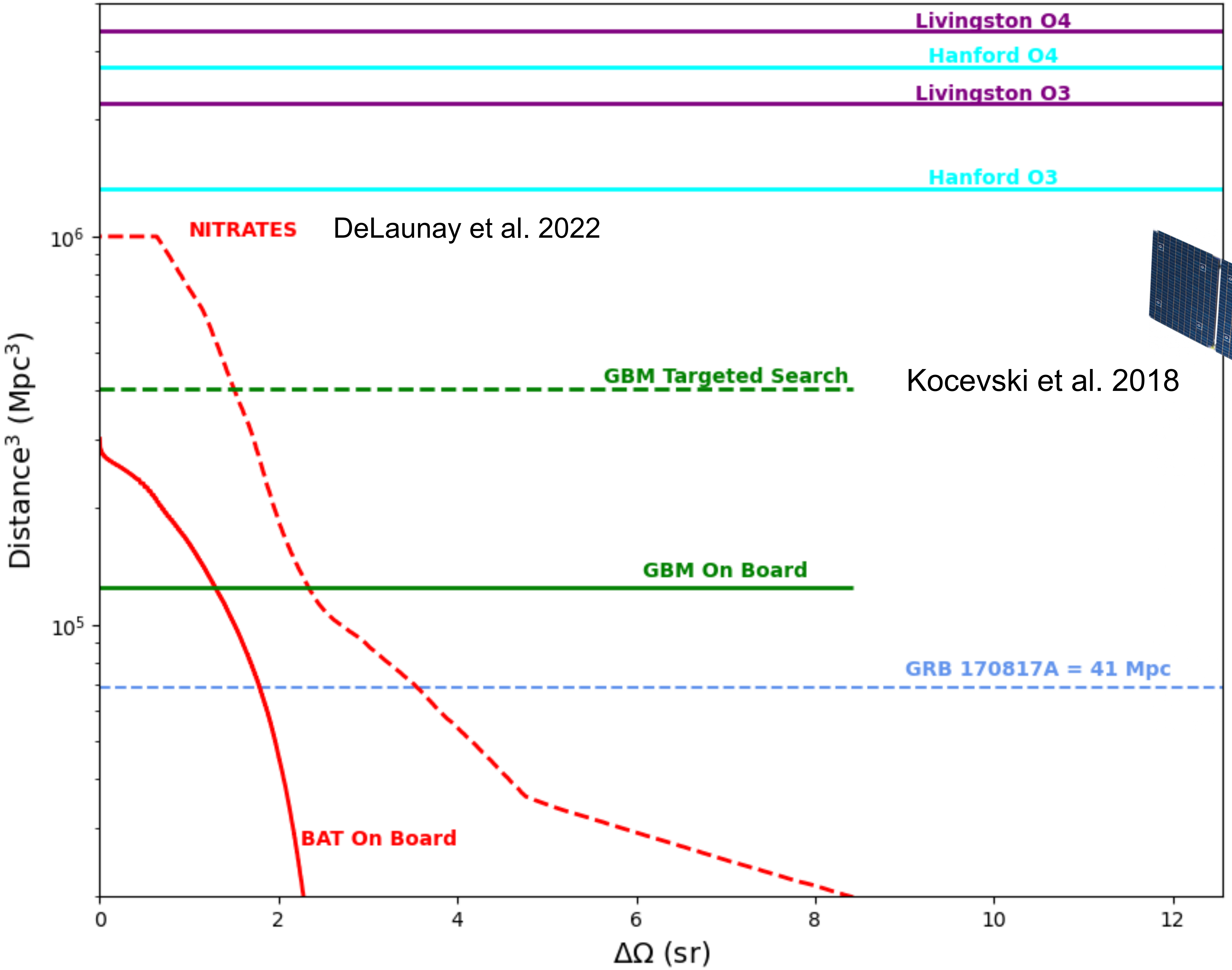
	GW	KN + GW			GRB Afterglow + GW			GRB Prompt + GW	
		J	*z*	*g*	Radio	Optical	X-rays	*Swift*/BAT	*Fermi*/GBM
LVK O4									
Rate DD2, $\chi_{\rm BH} = 0$	$19.0^{+19.5}_{-11.1}$	$0.30^{+0.31}_{-0.18}$	$0.56^{+0.57}_{-0.33}$	$0.54^{+0.56}_{-0.32}$	$0.03^{+0.04}_{-0.02}$	$0.007^{+0.007}_{-0.004}$	$0.04^{+0.04}_{-0.02}$	$0.003^{+0.003}_{-0.002}$	$0.02^{+0.02}_{-0.01}$

Why we need:

1. To consider low-significance GW candidates
2. Circulate their info in low latency

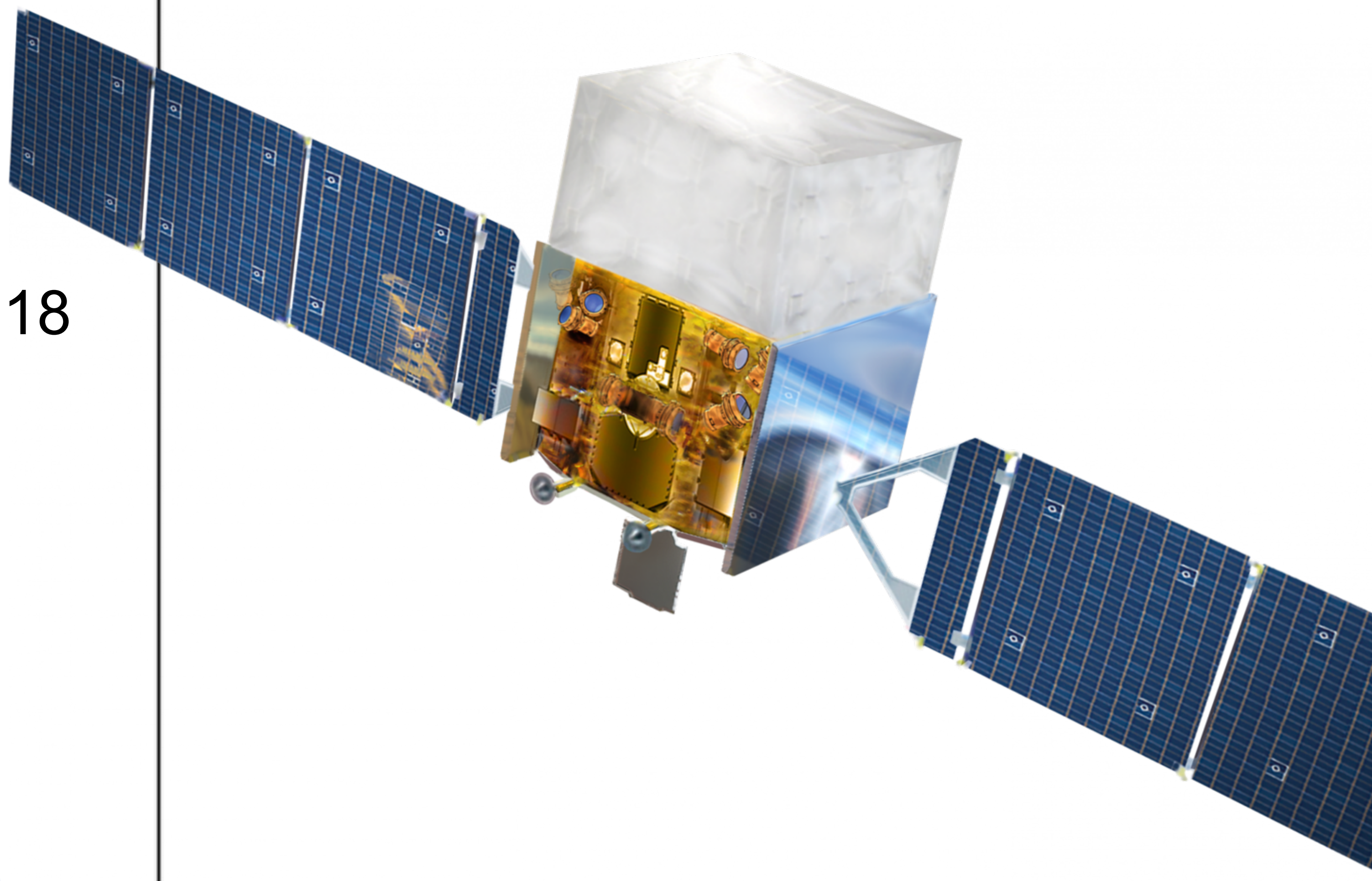
Subthreshold searches



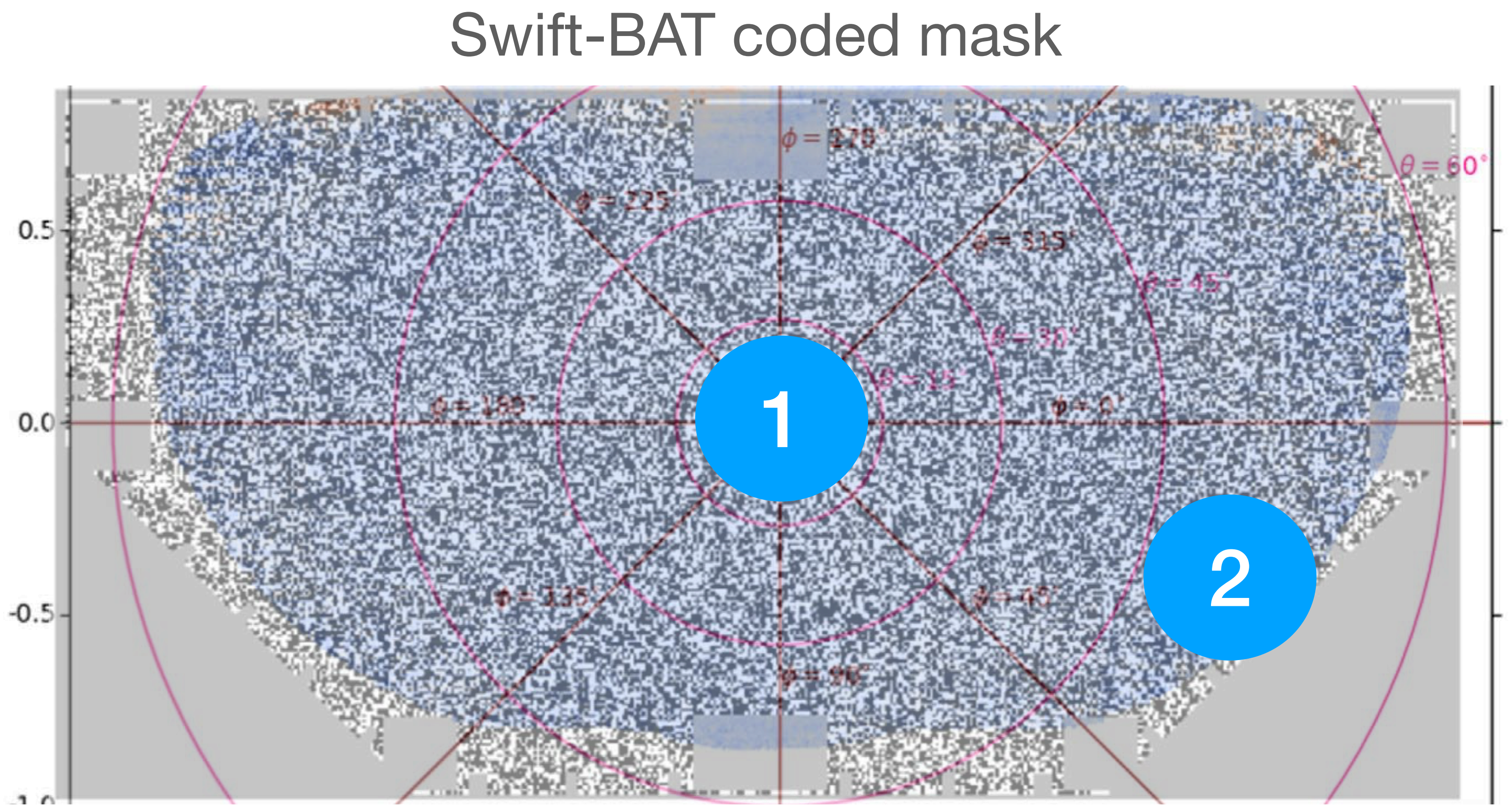


DeLaunay et al. 2022

Kocevski et al. 2018



What is Swift/BAT-GUANO



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

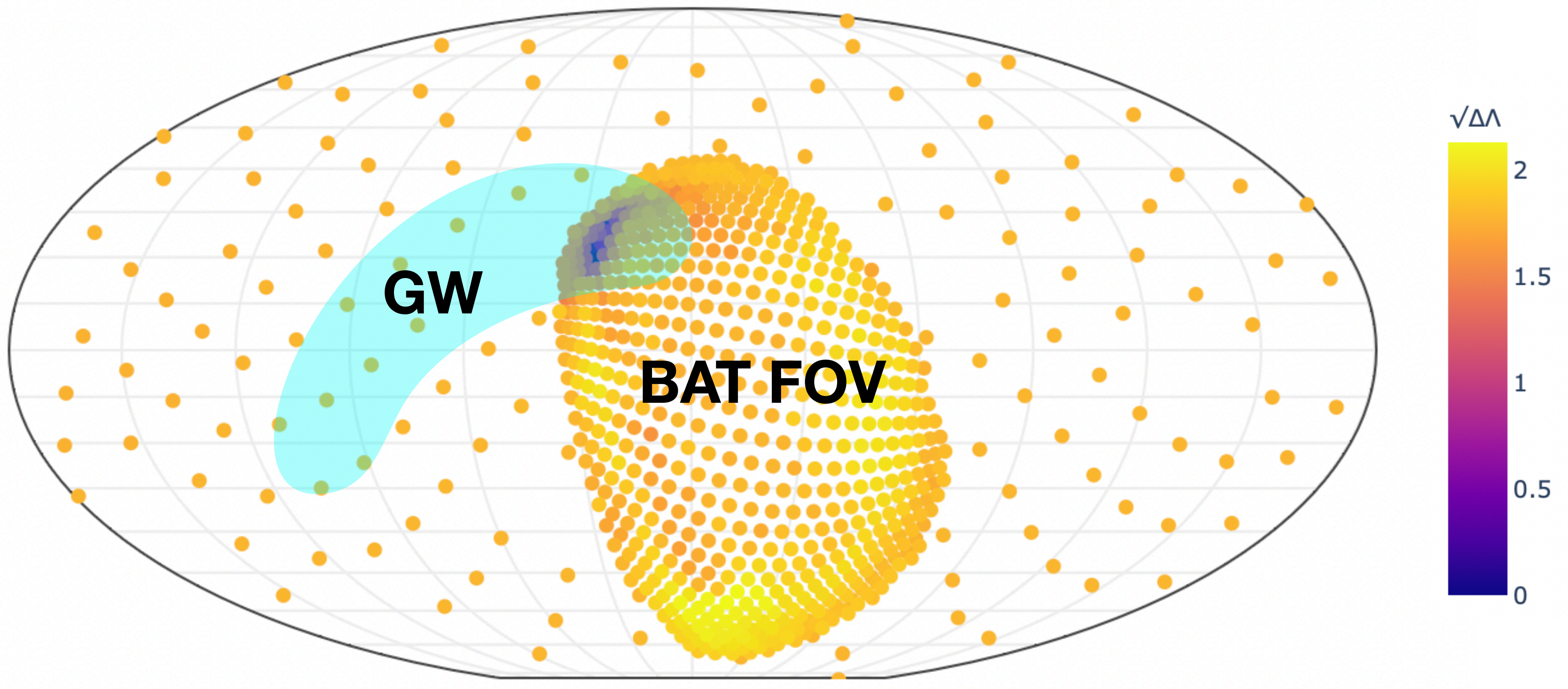
Tohuvavohu et al. 2020

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

NITRATES workflow and results

External trigger: info on trigger time and sky position

Dump BAT data around trigger time

Max likelihood analysis, on a full sky grid

No significant candidate

P(IN/OUT FoV)

IN

Arcmin localization provided

OUT

Coarse constraints about localization, but we can stil claim a detection

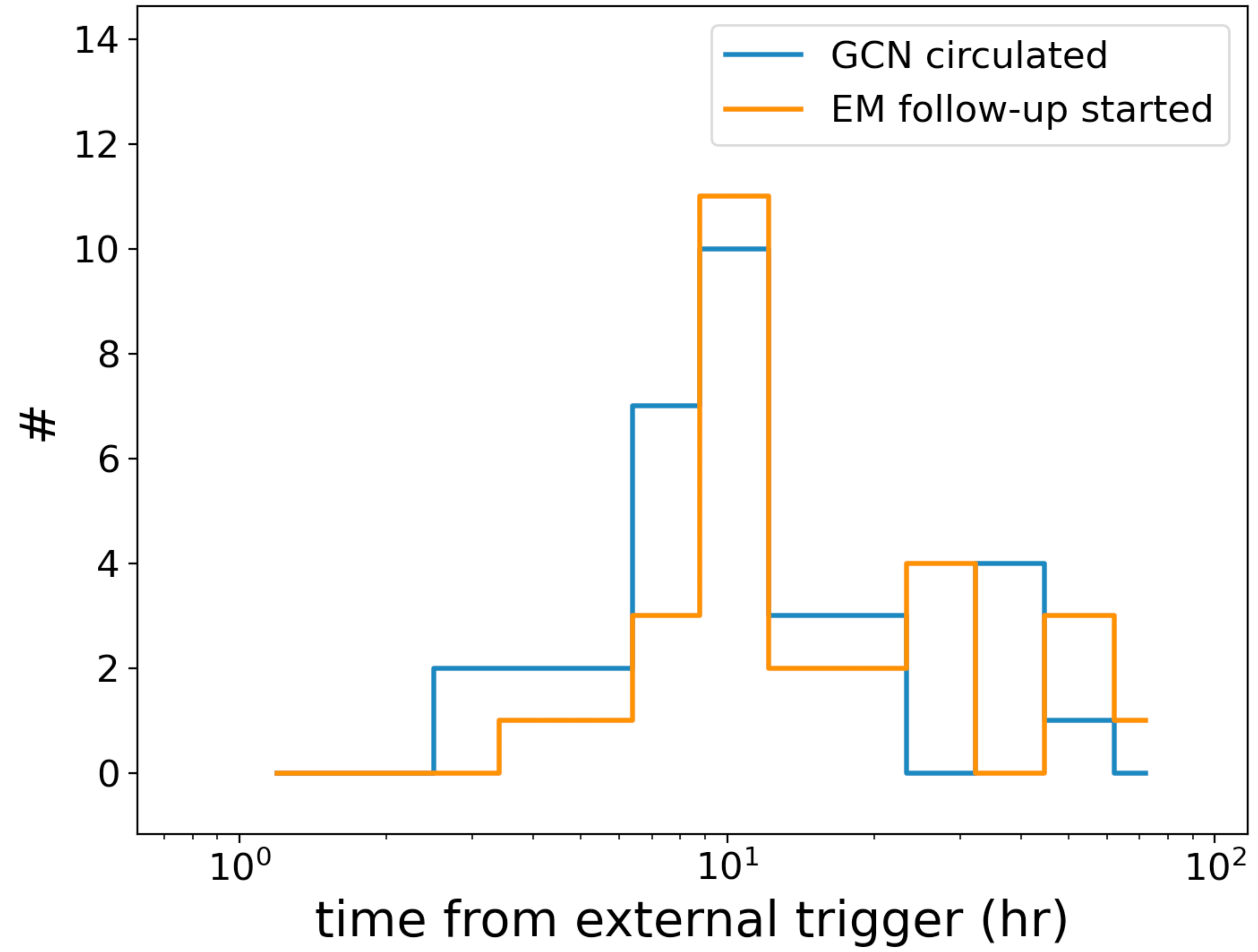
Location promptly circulated via GCN

Multi-wavelength follow up, search of host galaxy, redshift

Few hours

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

Currently running 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)

GUANO workflow and results

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

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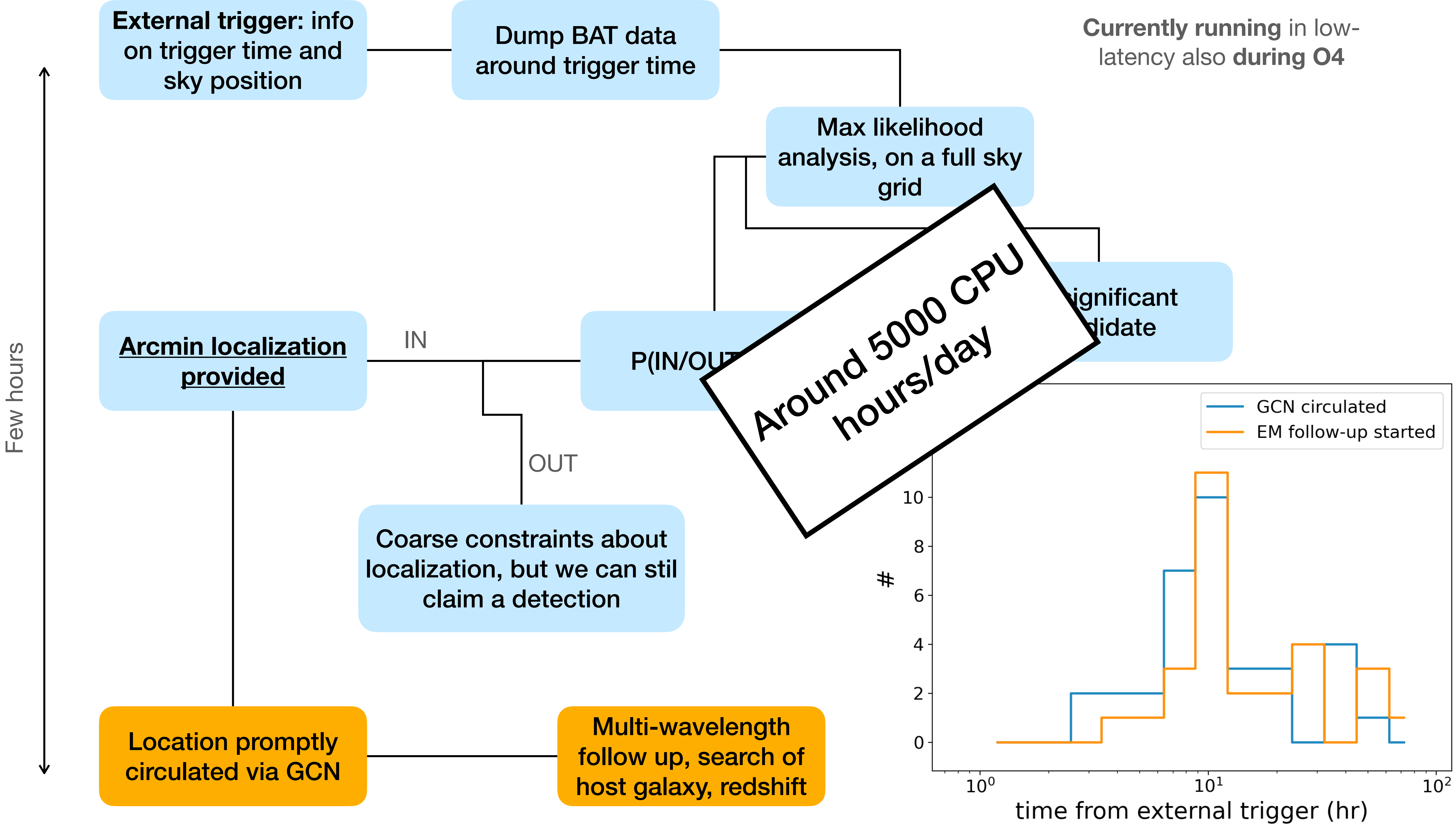

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didate

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Multi-wavelength follow up, search of host galaxy, redshift

Around 5000 CPU hours/day

Ingested external triggers:

- Fermi/GBM, Integral, Calet, GECAM
- **GWs**
- IceCube
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Why we need a well localized EM counterpart

Possible scenarios for a joint GW-gamma-ray detection:

1: poorly localized gamma-ray bursts (~100 deg^2)

We can study:

- the GW-EM delay
- jet properties,
- masses-jet connection in terms of spectrum, duration…
- jet structure from knowledge of inclination angle

2: well localized gamma-ray bursts (~10 deg^2)

We may (or may not) find the host galaxy and determine the redshift, but it may require hours/days

We can study:

- D_L-redshift relation for cosmology
- speed of gravity tests
- spectral and photometric evolution of KN emission

3: arcmin localized gamma-ray bursts

The source is identified after few seconds and in addition to case 2 we can study:

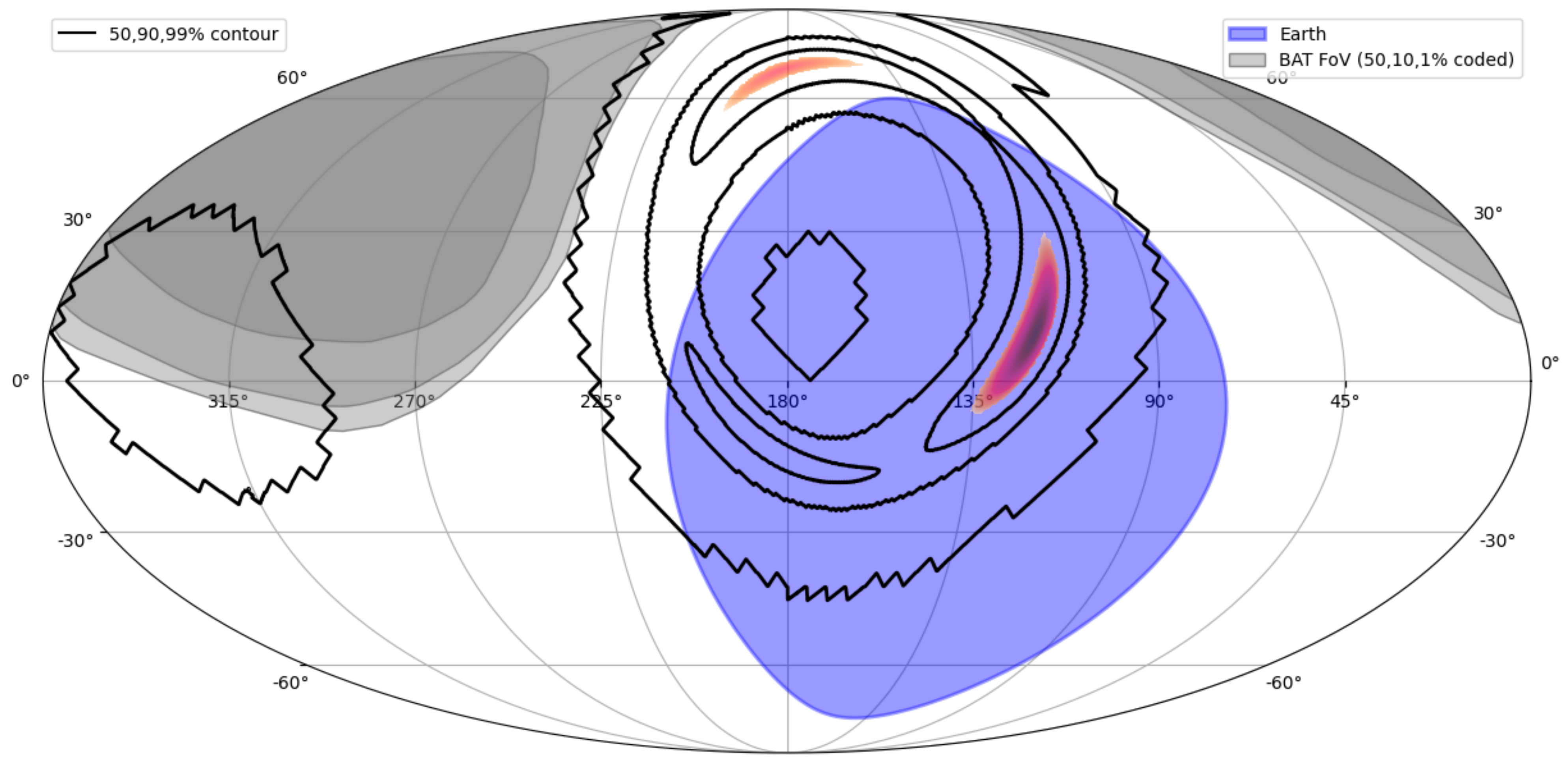
- full evolution in X-rays (plateau ?) and optical up to the appearance of KN component
- possible UV early emission due to free neutron decay

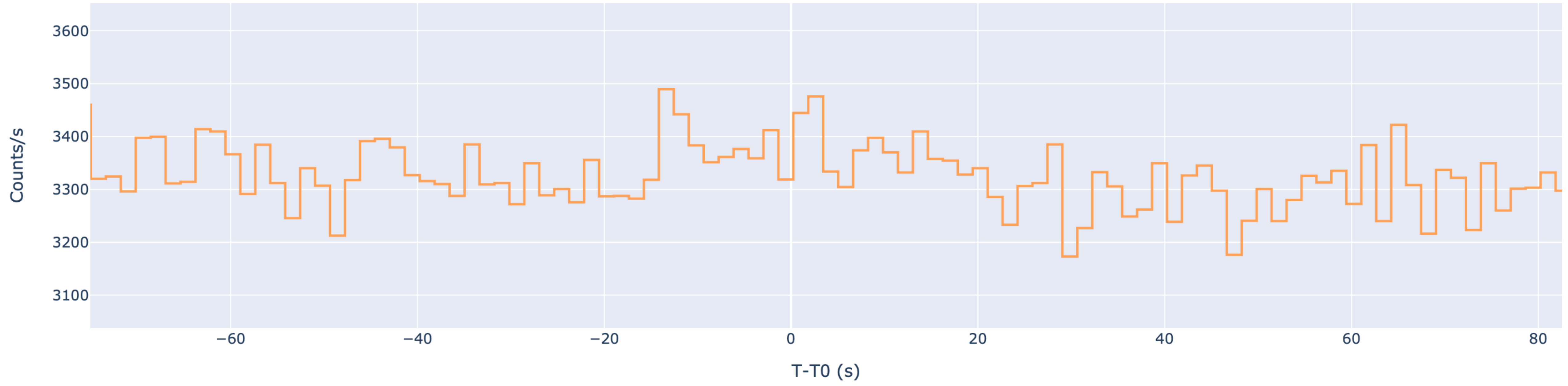
What if we don’t have an arcmin localized burst?

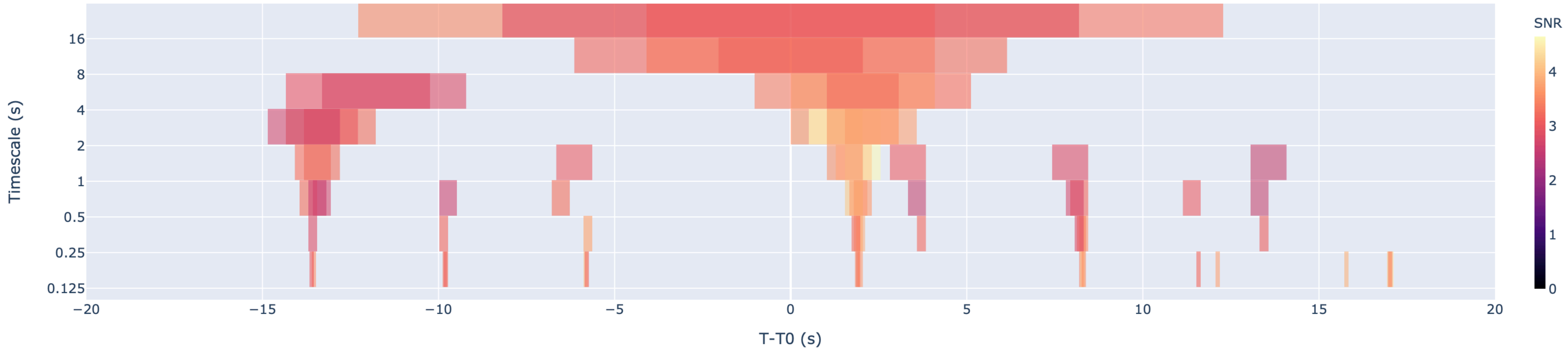
What if we don’t have an arcmin localized burst?

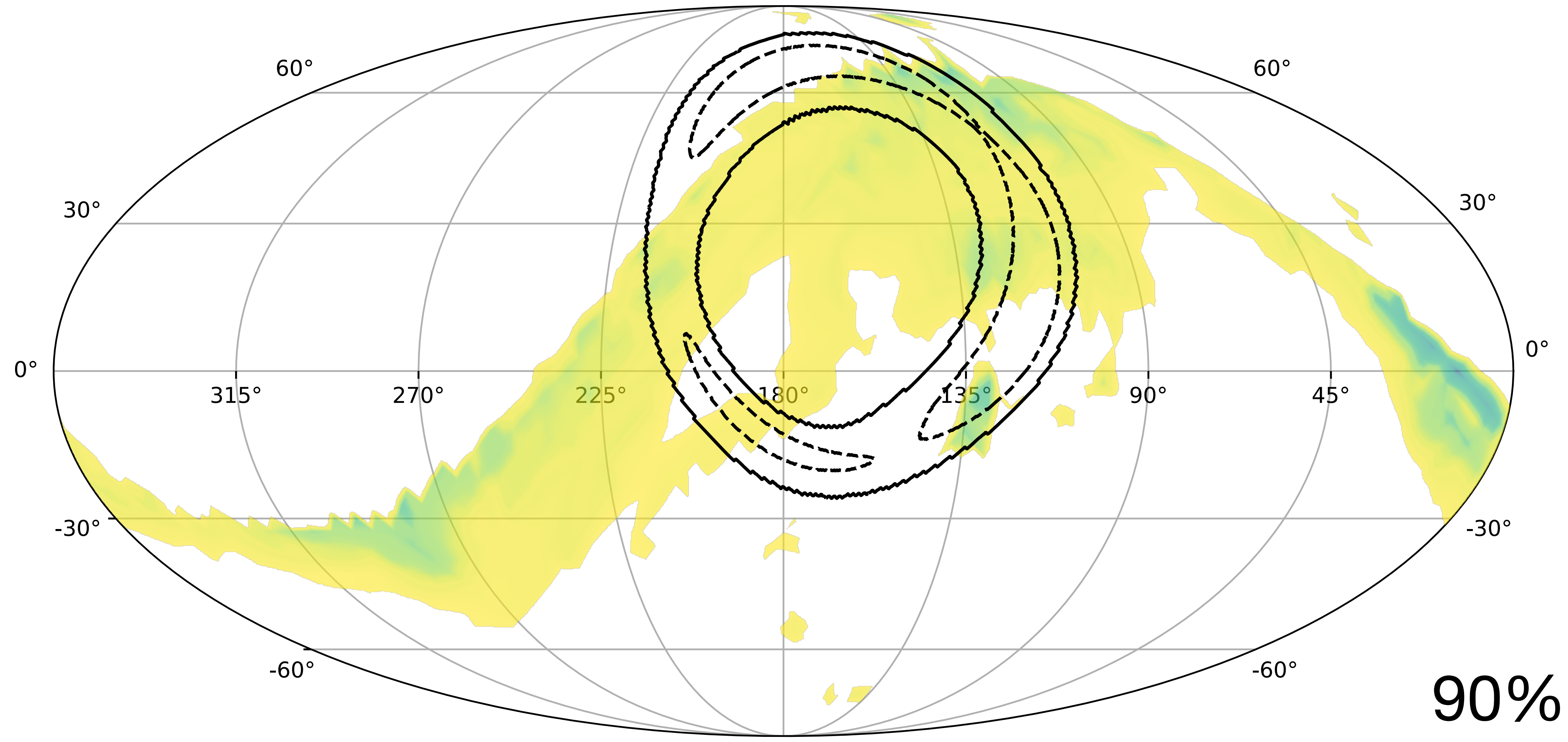
Combine maps!

Example: S230701z, P(NSBH)=0.12, max TS=8.0









TS	Delta LLH Out	Delta LLH Peak
8.0	10.07	0.68
7.36	12.26	1.49
7.3	12.73	0.4
7.02	10.7	0.58

90% area: solid
50% area: dashed

With the inclusion of Earth

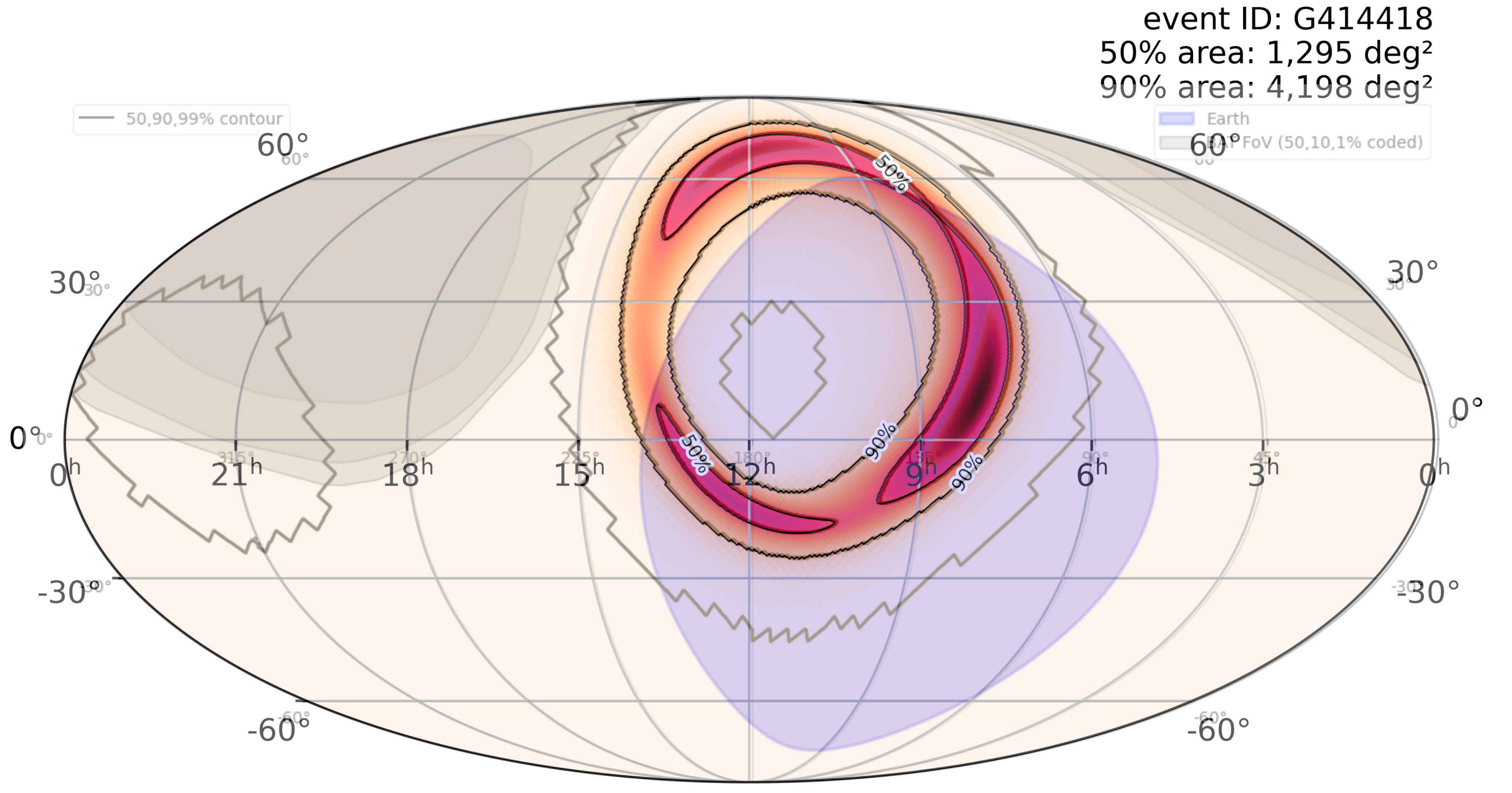
The BAT sky map is renormalized considering a probability identical to zero in correspondence of the region occulted by Earth. This is done imposing:

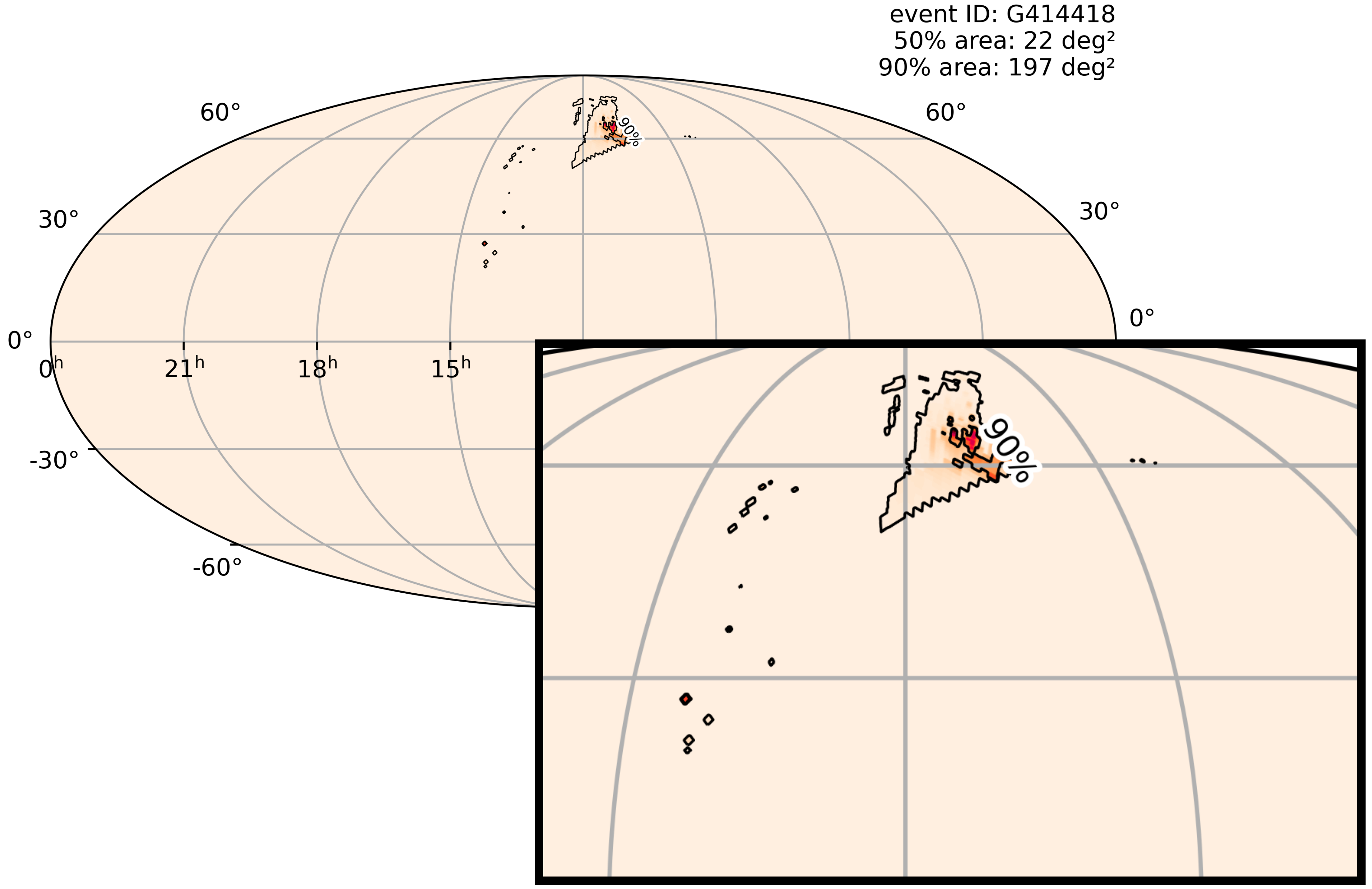
$$1 = P_\oplus + (1 - P_\oplus)\sum_{i\notin\oplus} P_{BAT}(x_i, y_i)\Delta\Omega_i$$

$$P_\oplus = \frac{\Delta\Omega_\oplus}{4\pi}$$

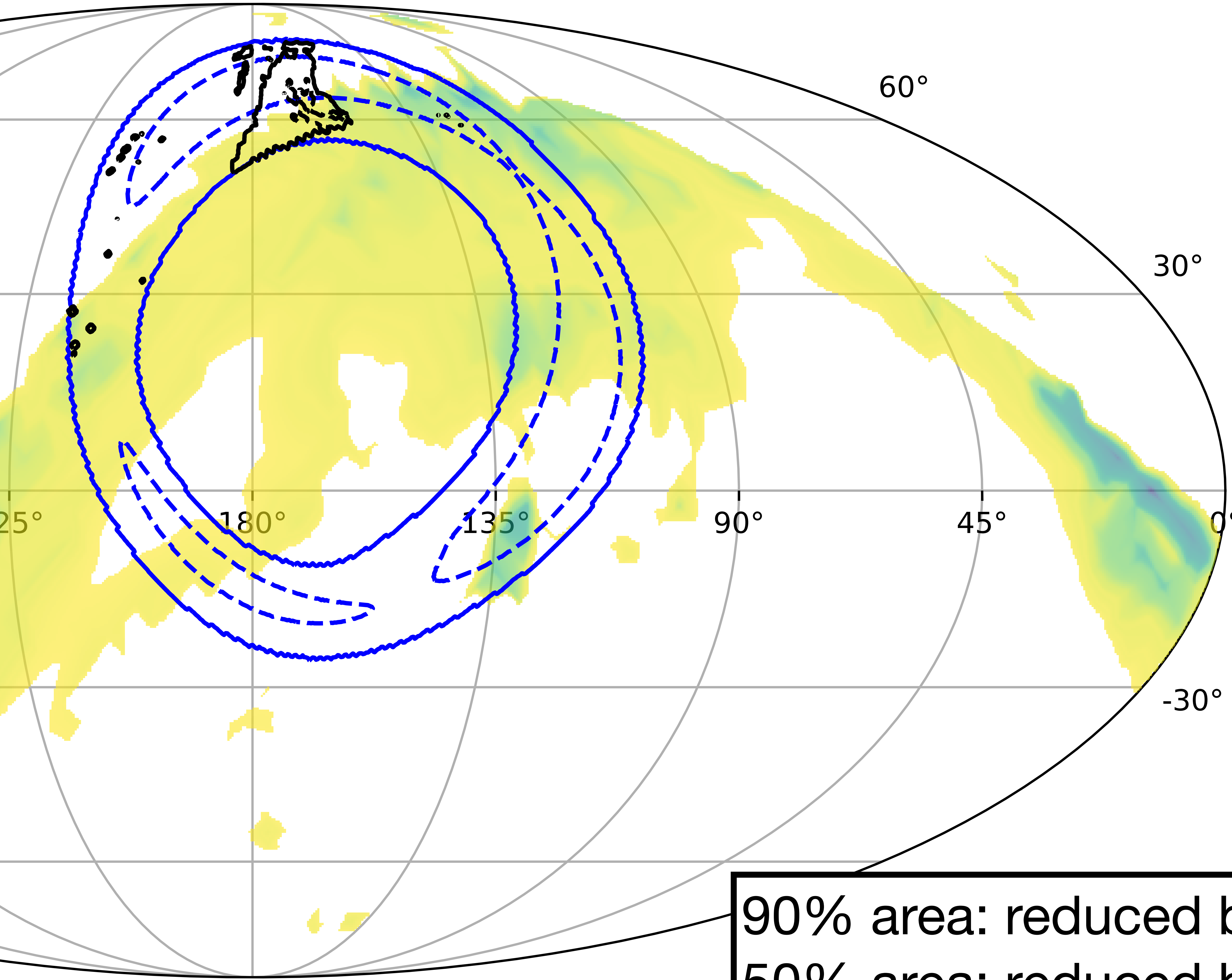
The resulting convoluted map is

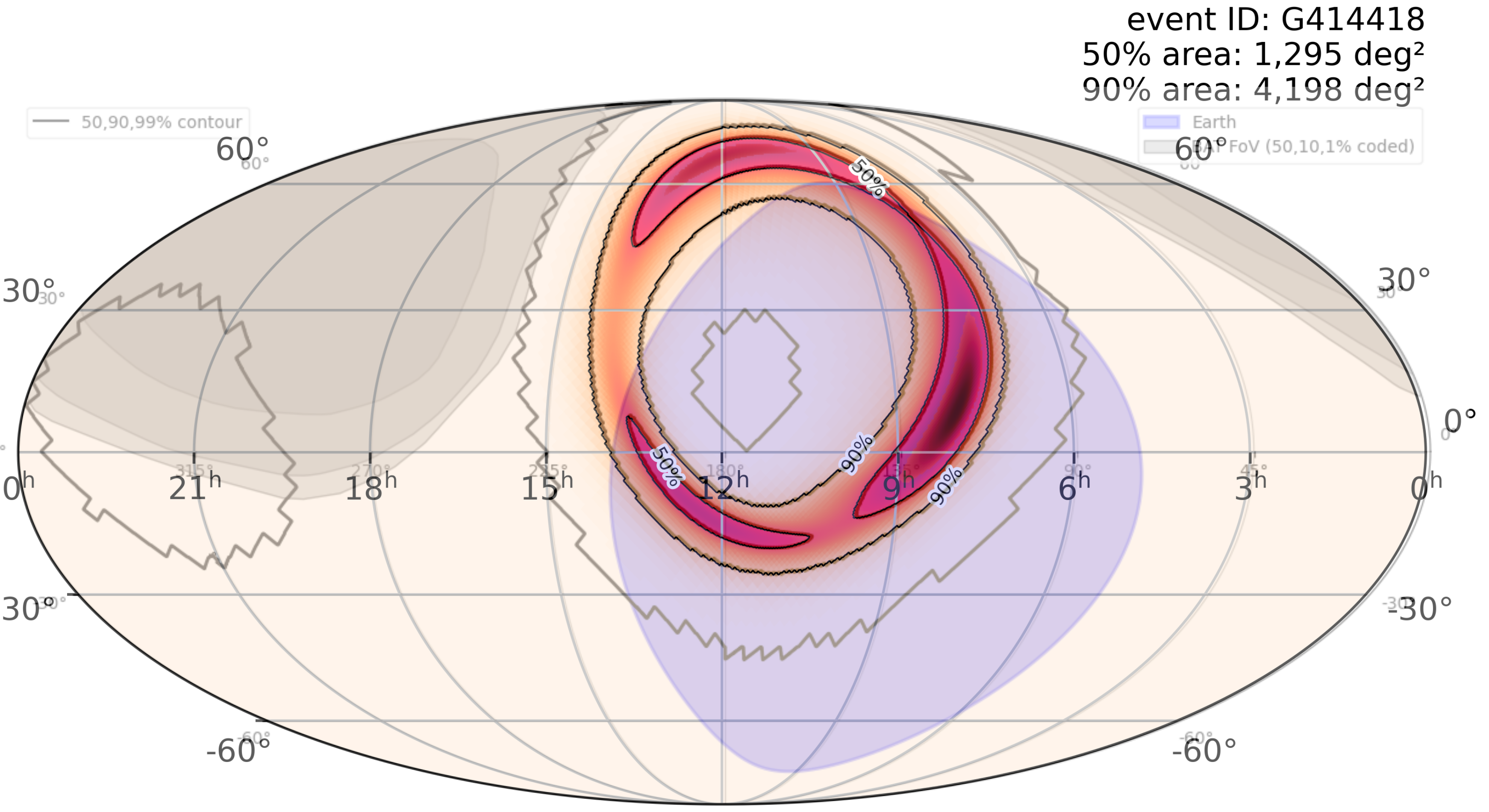
$$P_{joint}(x_i, y_i) = P_{GW}(x_i, y_i)\times\begin{cases}0, & (x_i, y_i) \in \oplus \\ P_{BAT}(x_i, y_i), & (x_i, y_i) \notin \oplus\end{cases}$$

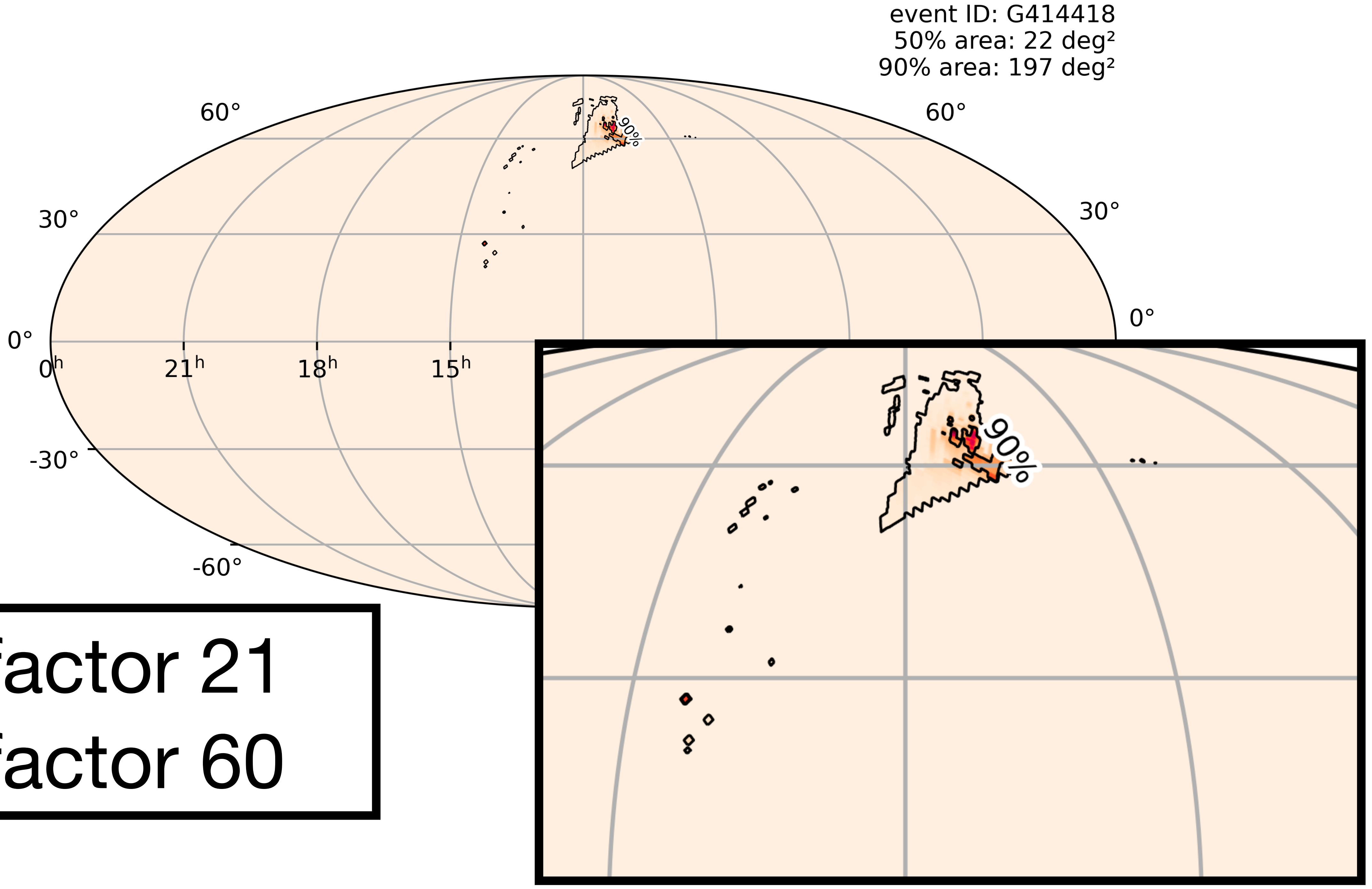




With the inclusion of Earth

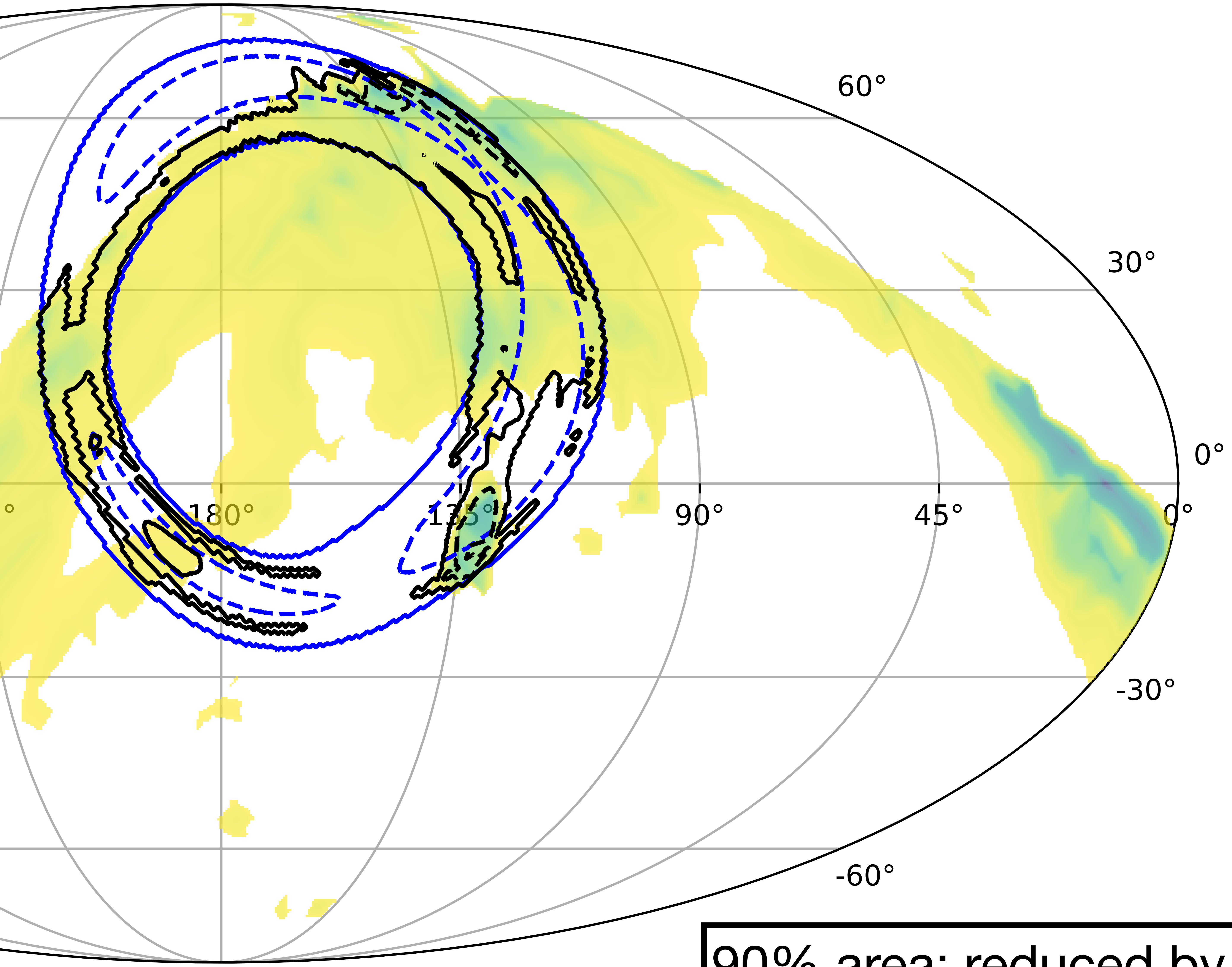


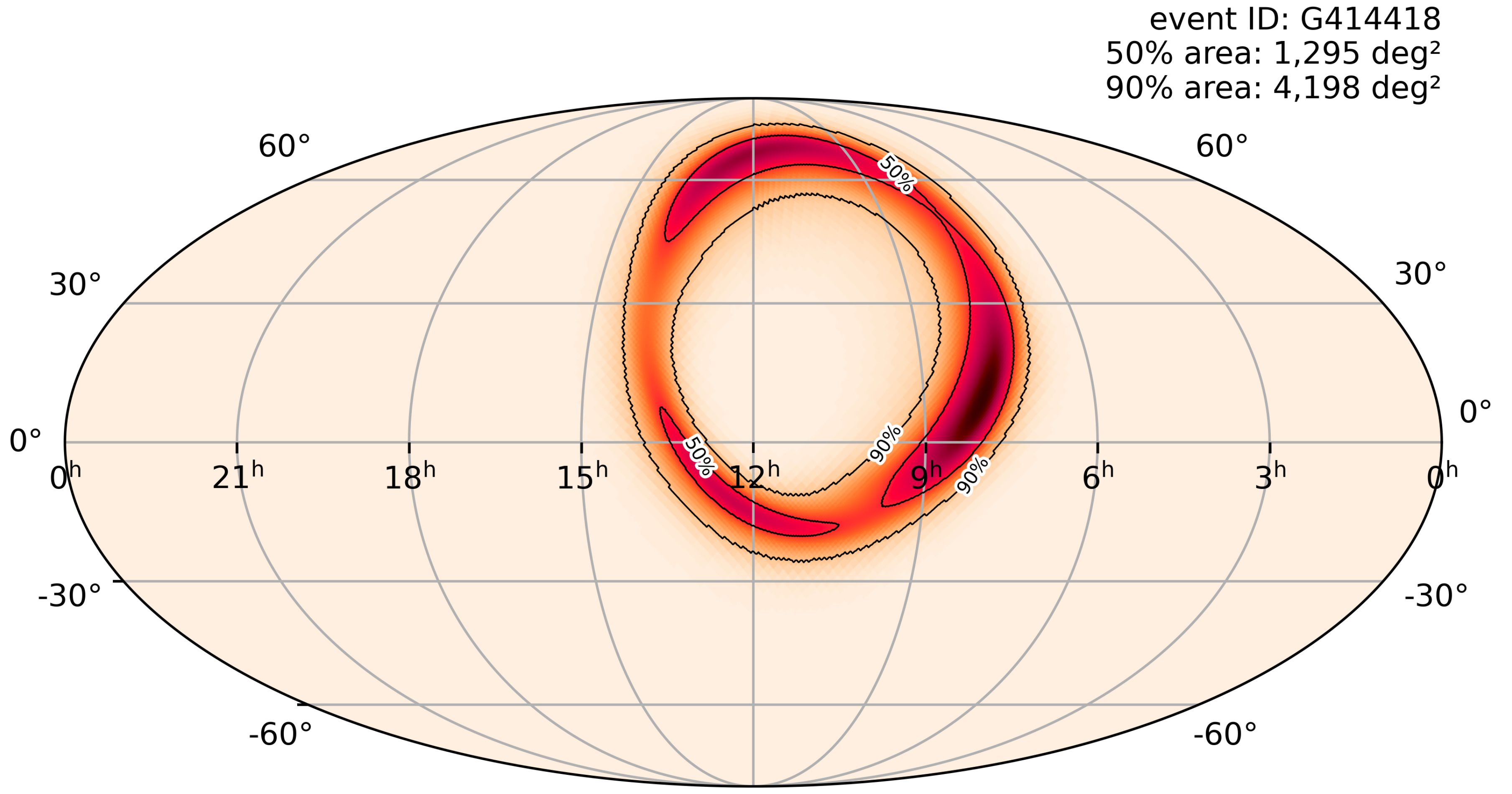


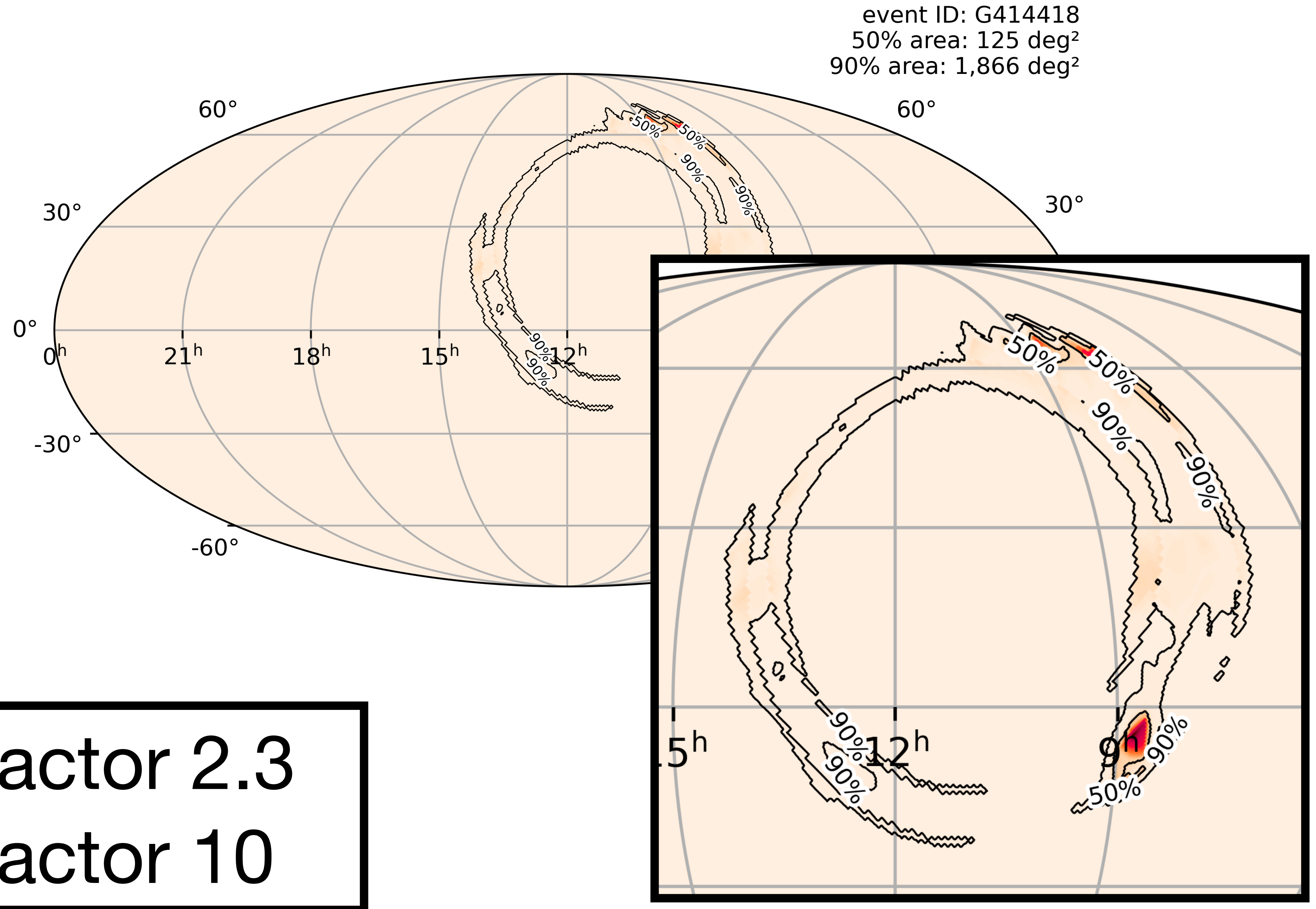


90% area: reduced by factor 21
50% area: reduced by factor 60

Without the inclusion of Earth



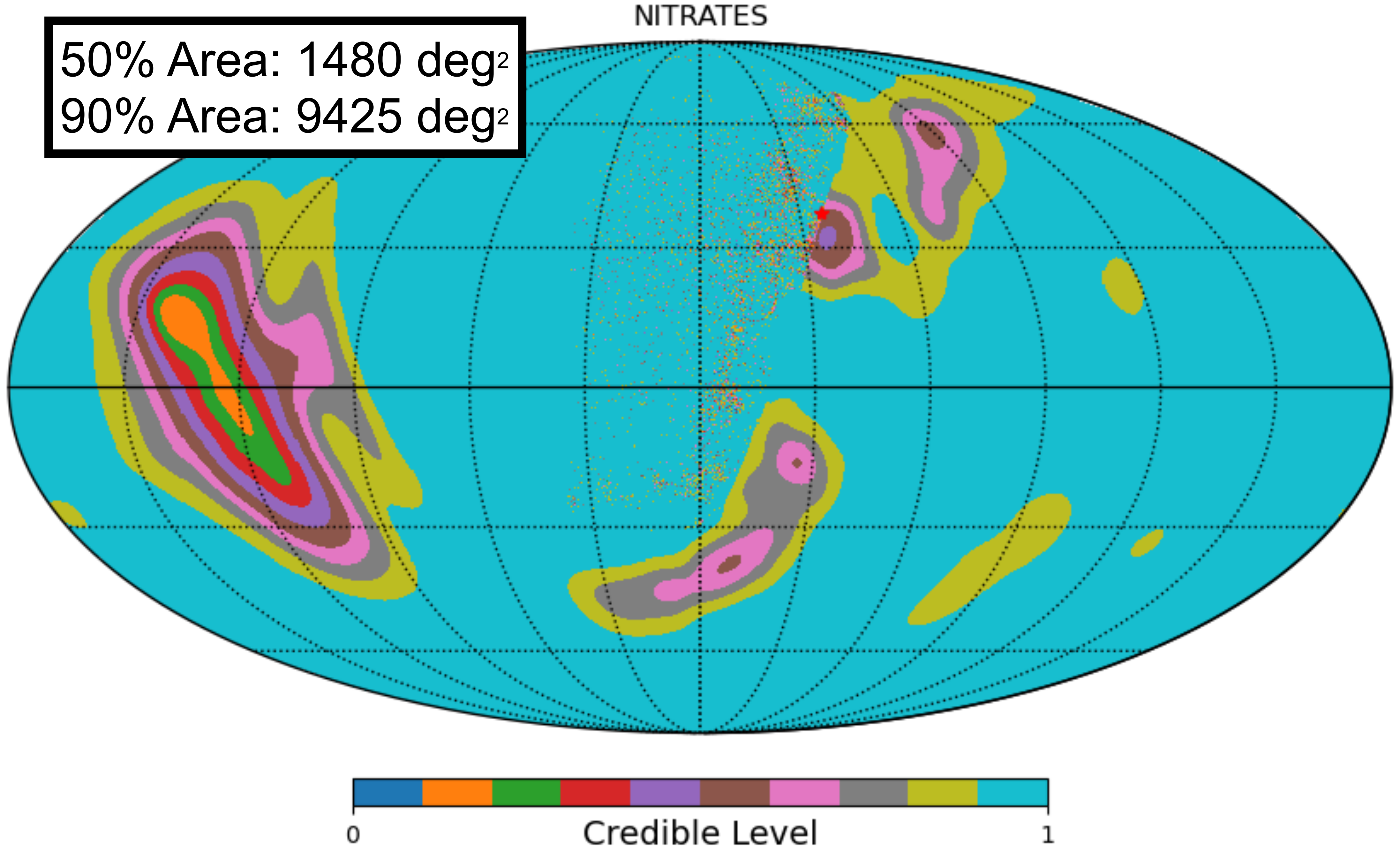




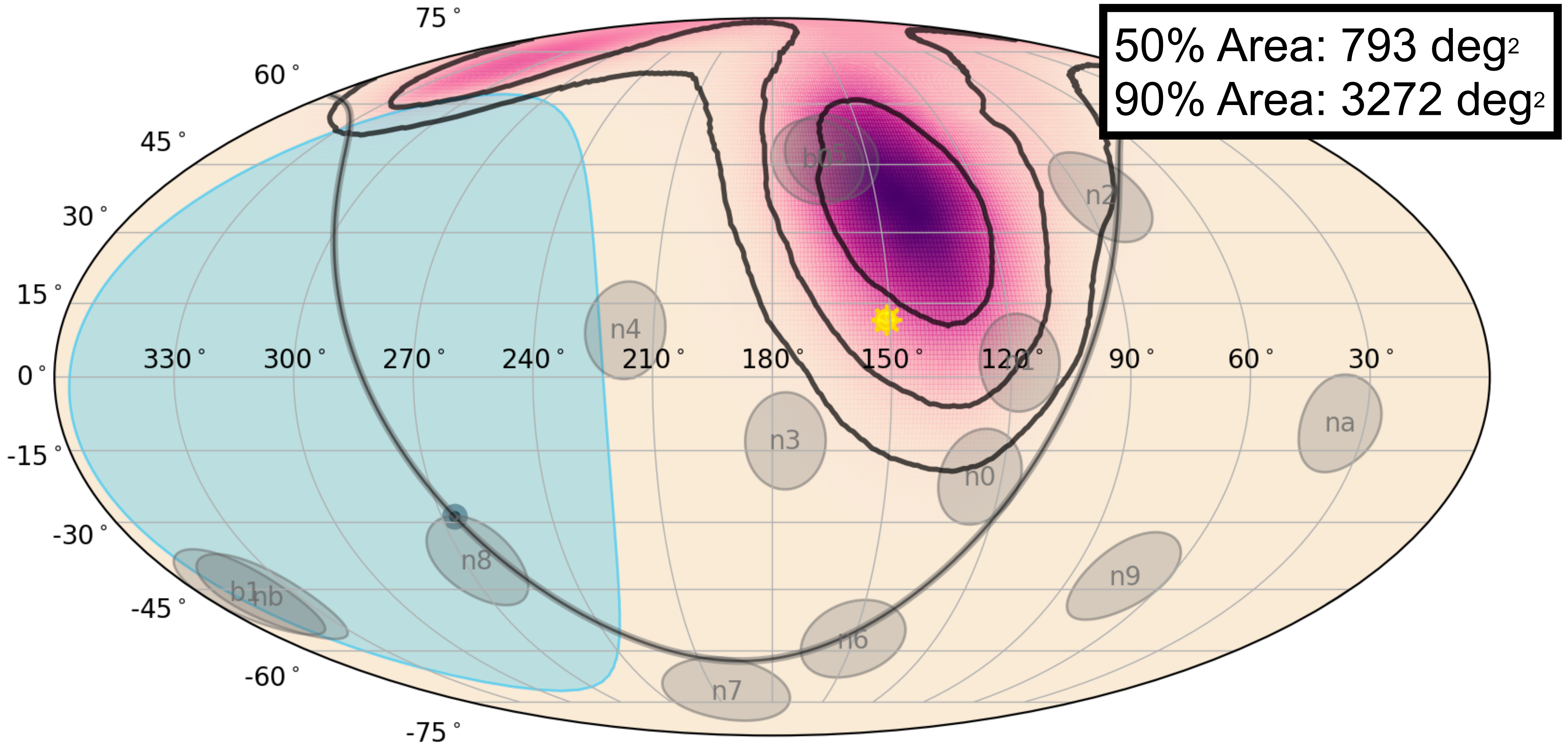
90% area: reduced by factor 2.3

50% area: reduced by factor 10

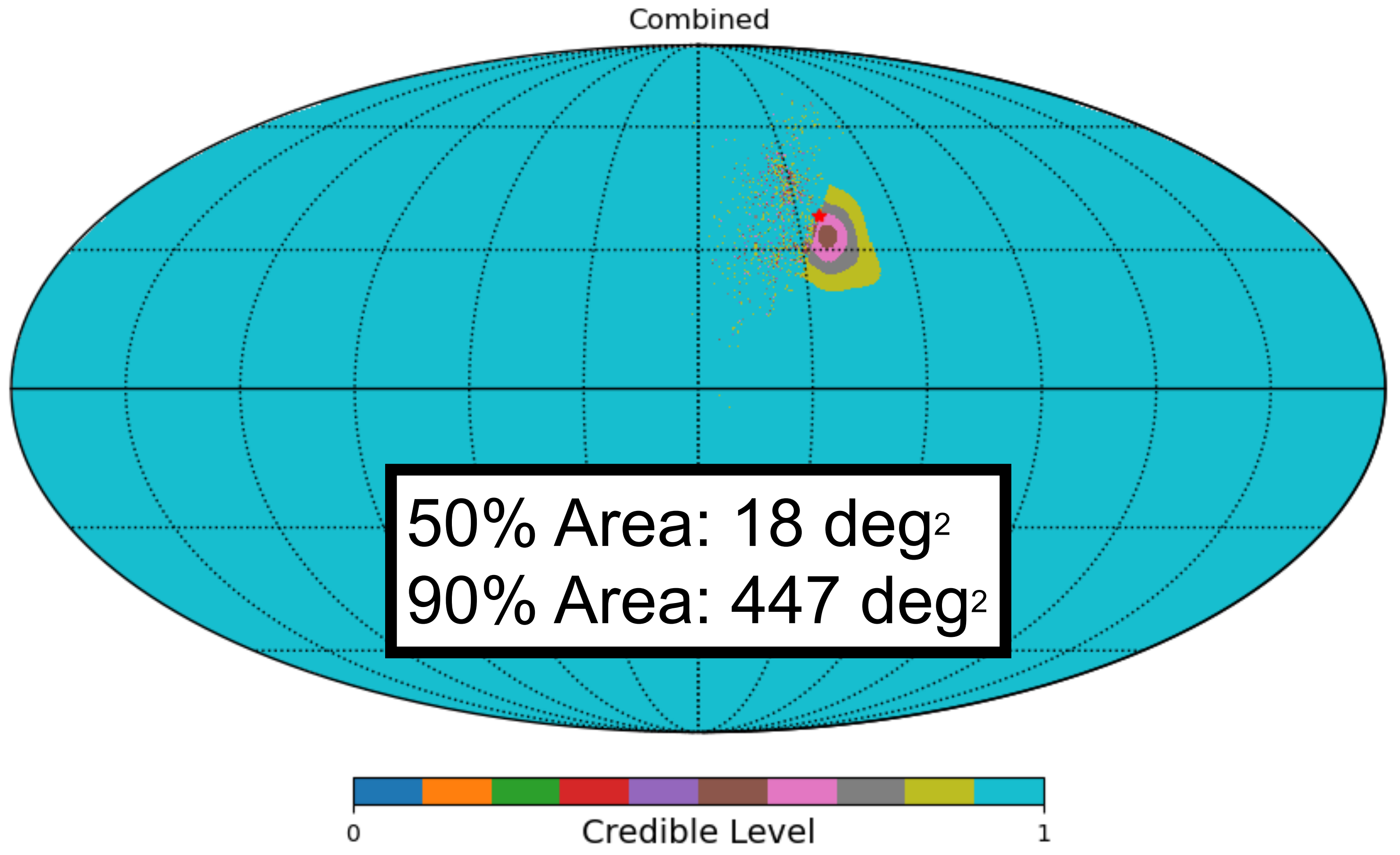
GRB 230822A - Weak Short GRB



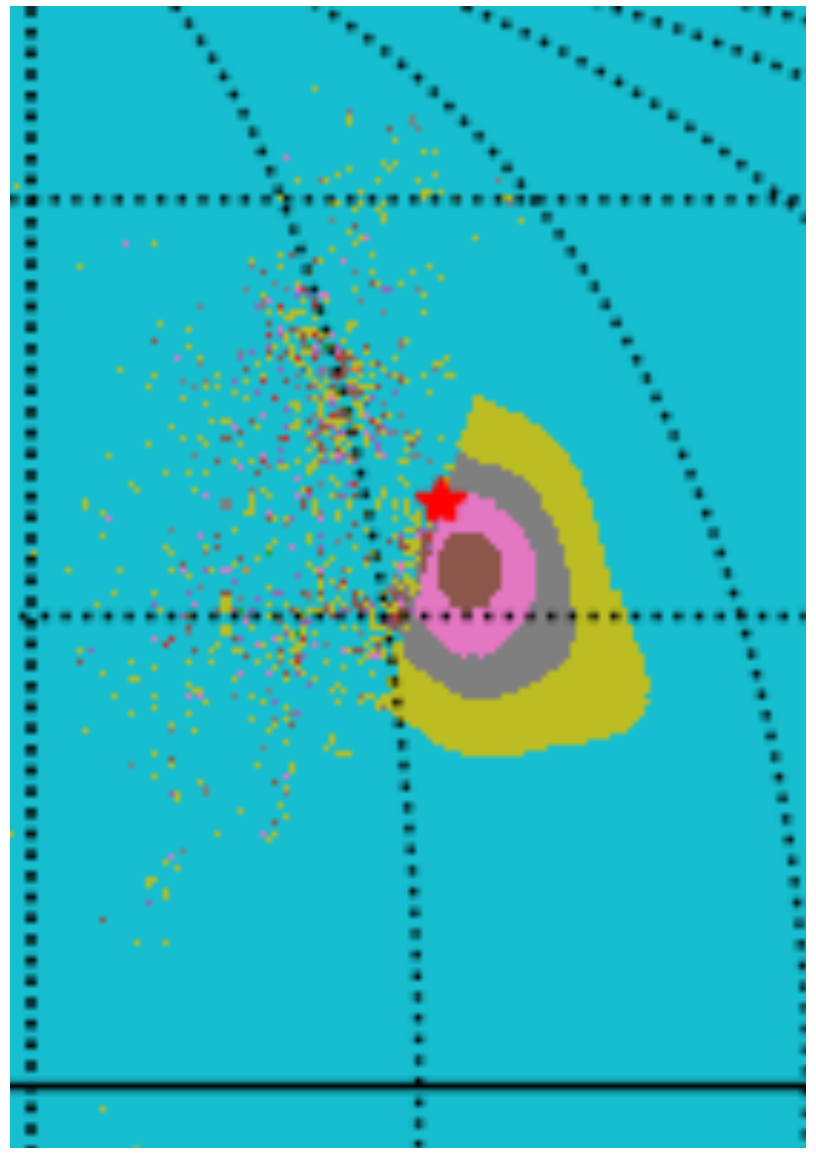
50% Area: 1480 deg^2
90% Area: 9425 deg^2

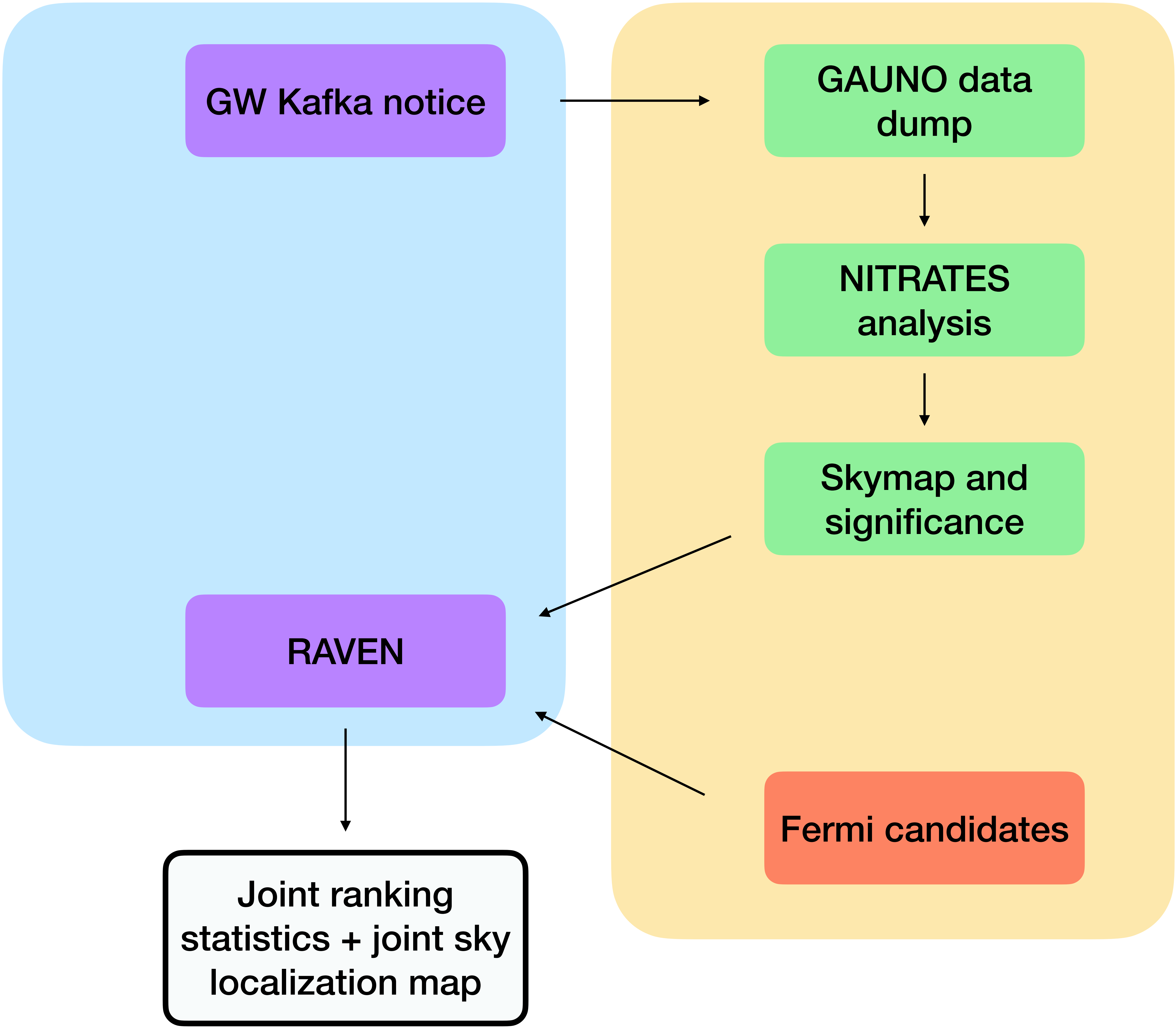


50% Area: 793 deg^2
90% Area: 3272 deg^2



50% Area: 18 deg^2
90% Area: 447 deg^2





GW Kafka notice

GAUNO data dump

NITRATES analysis

Skymap and significance

RAVEN

Fermi candidates

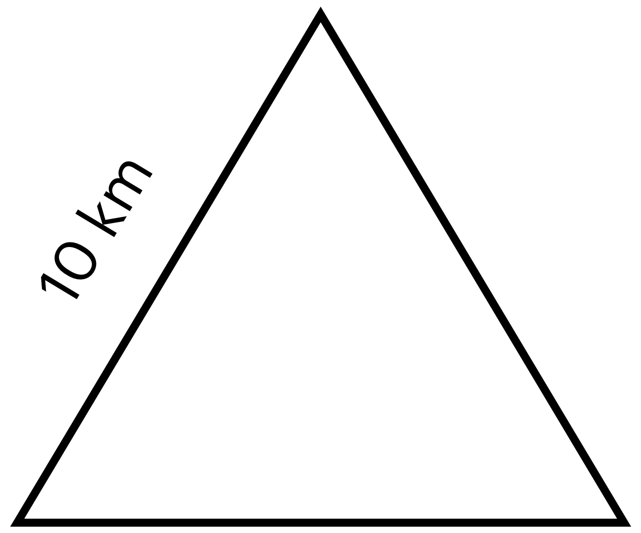
Joint ranking statistics + joint sky localization map

Possible scenarios, in descending order of goodness:

1. The candidate is localized inside the Swift-BAT field of view, with arcmin precision
2. The candidate is outside the FOV, but with the skymap we can exclude a large portion of the sky
3. The skymap is non-informative (low-significance candidate) and we can just exclude the area covered by Earth

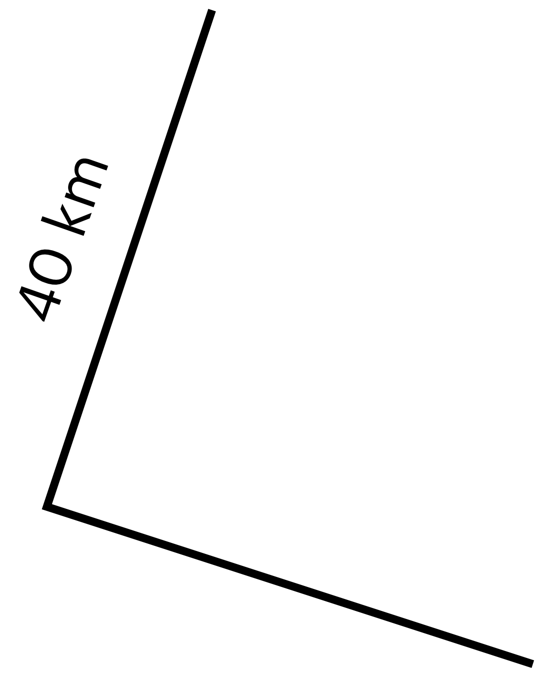
The future

The 3rd generation of GW detectors: steps forwards



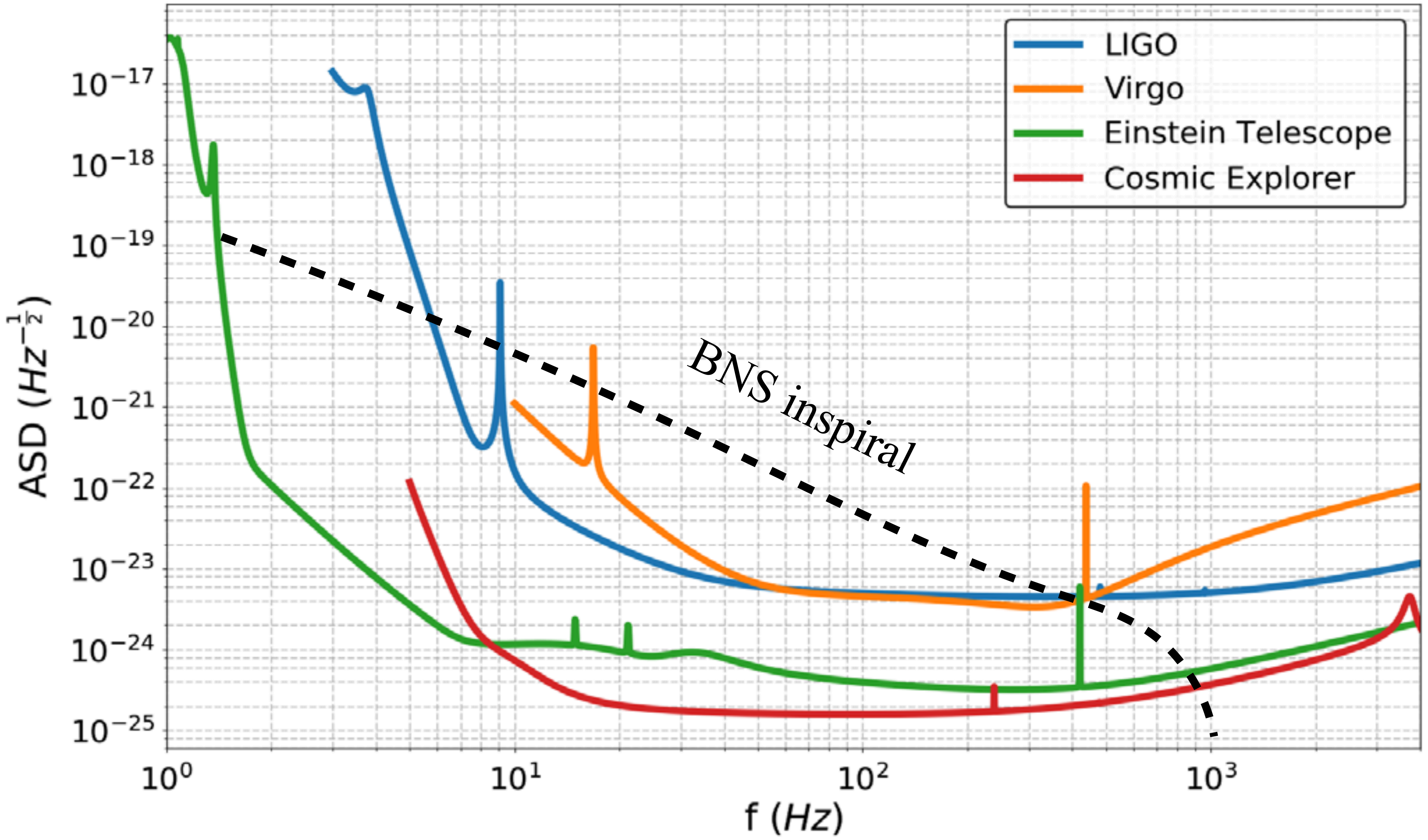
Einstein Telescope
(ET)

- **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

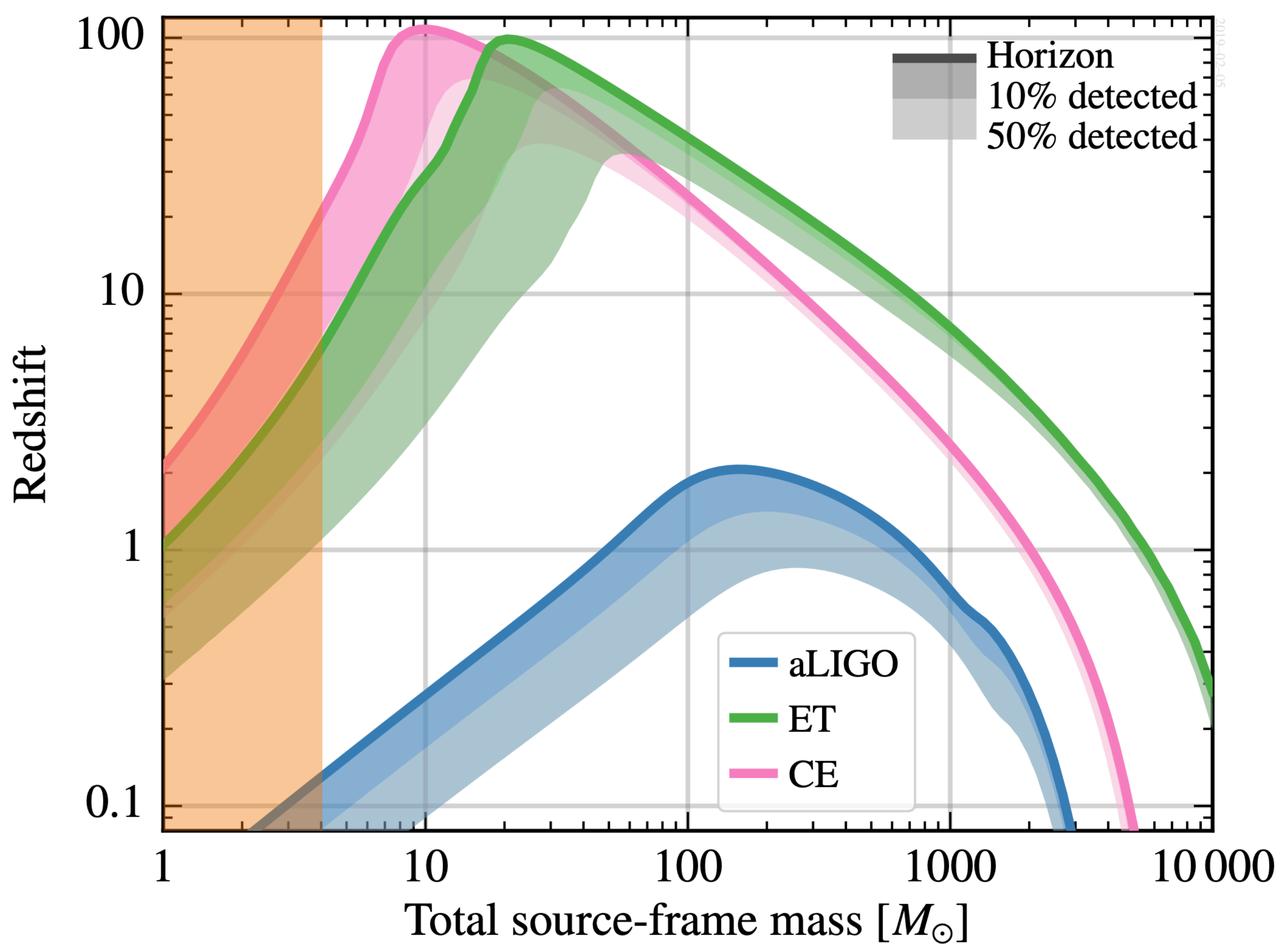
- 10^5-10^6 detections / yr of stellar mass BH mergers up to z~100

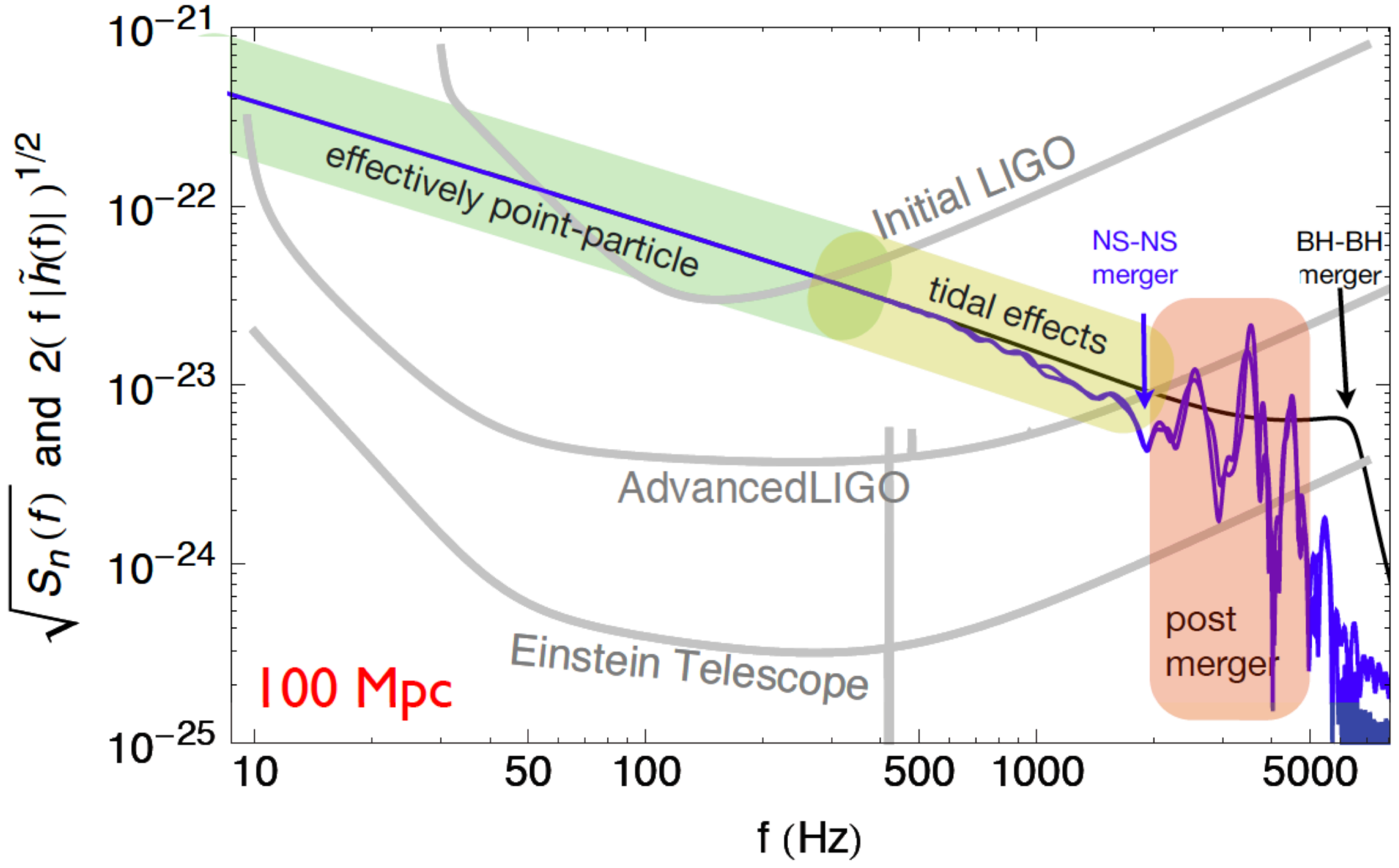
- Detection of primordial BH

- 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**

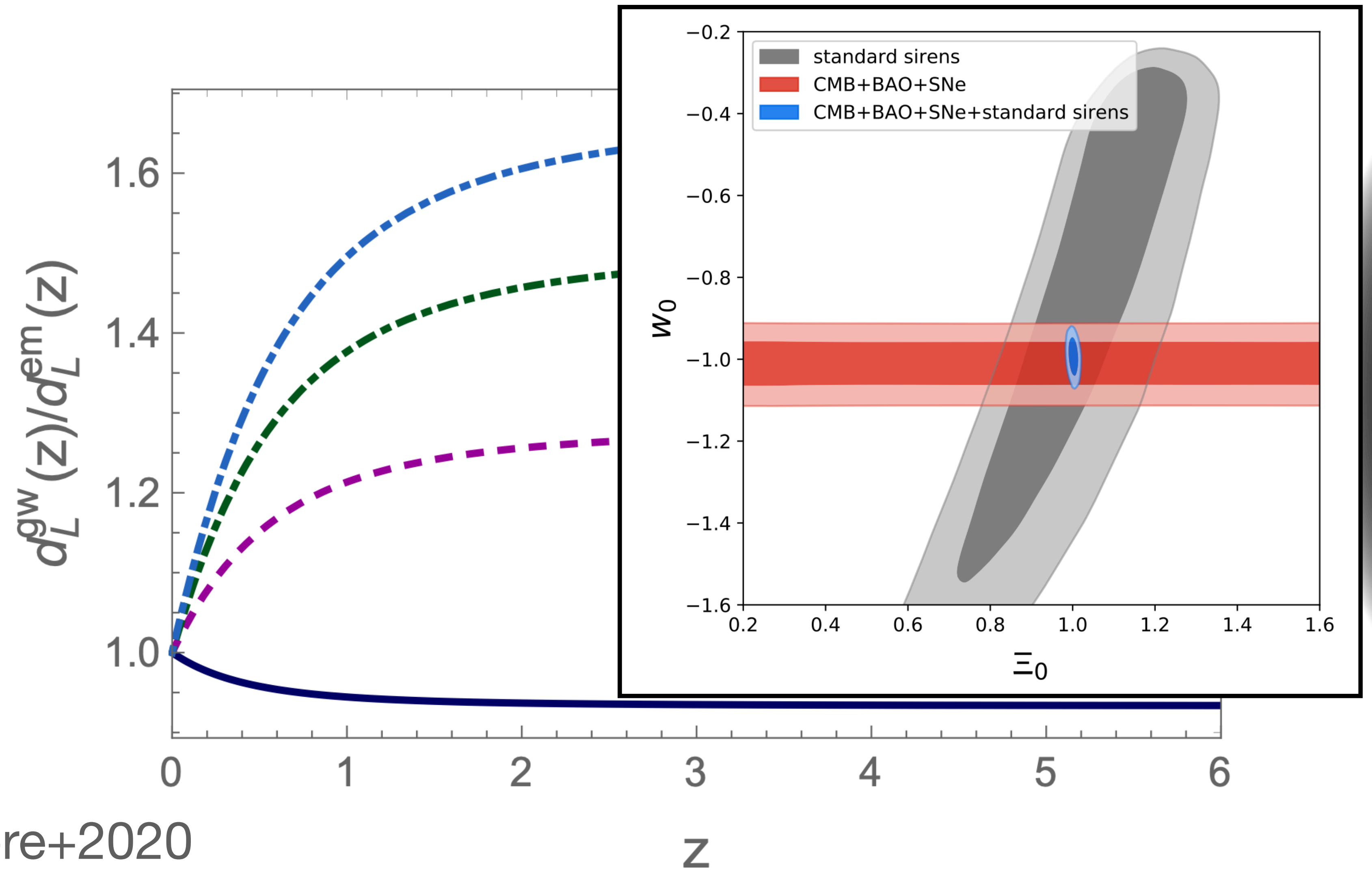
- Test of GR during the inspiral and in the post-merger (e.g. BH ringdown)

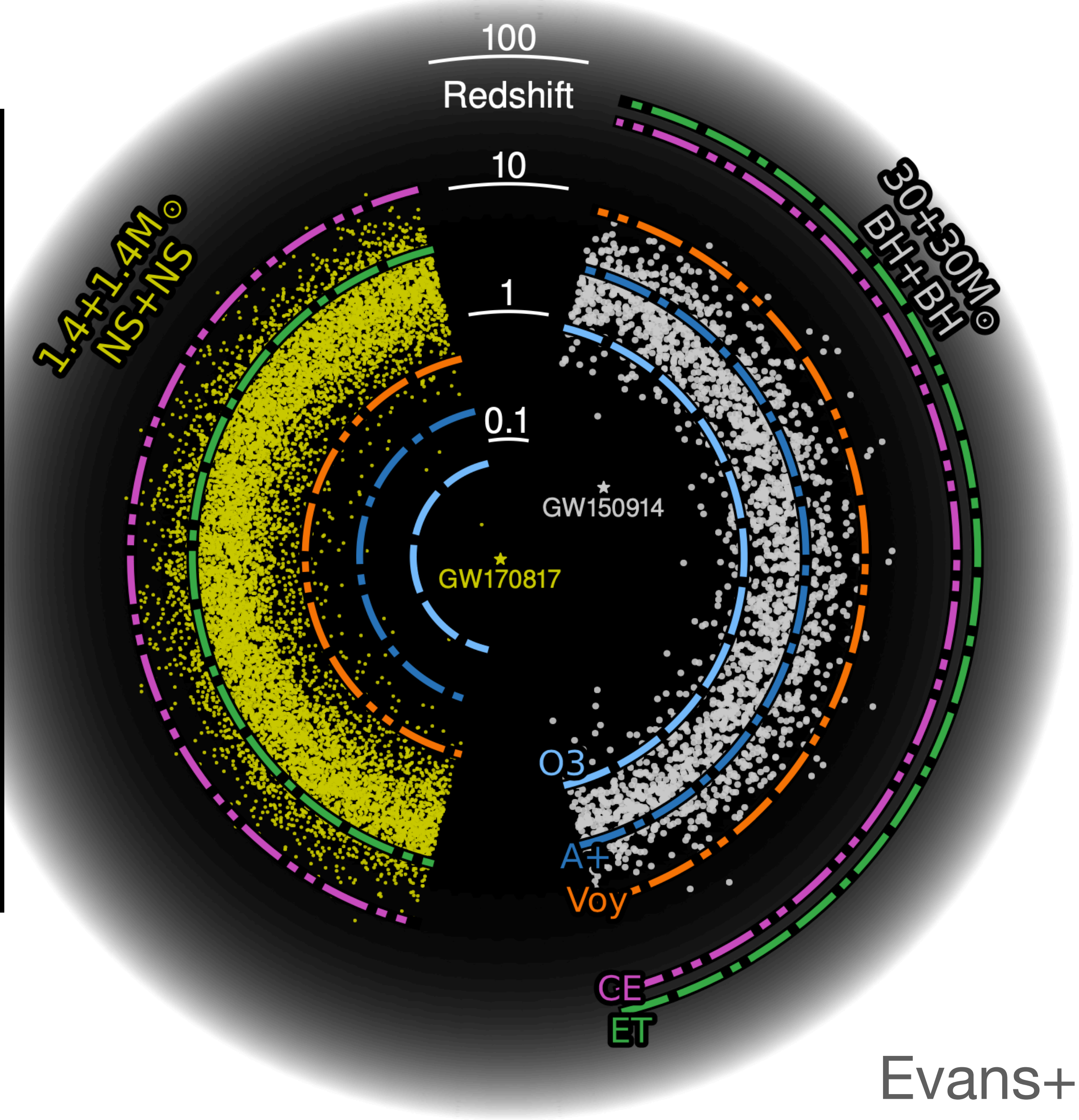
- Nature of dark energy and modifications of GR at cosmological distances





Maggiore+2020





Evans+2021

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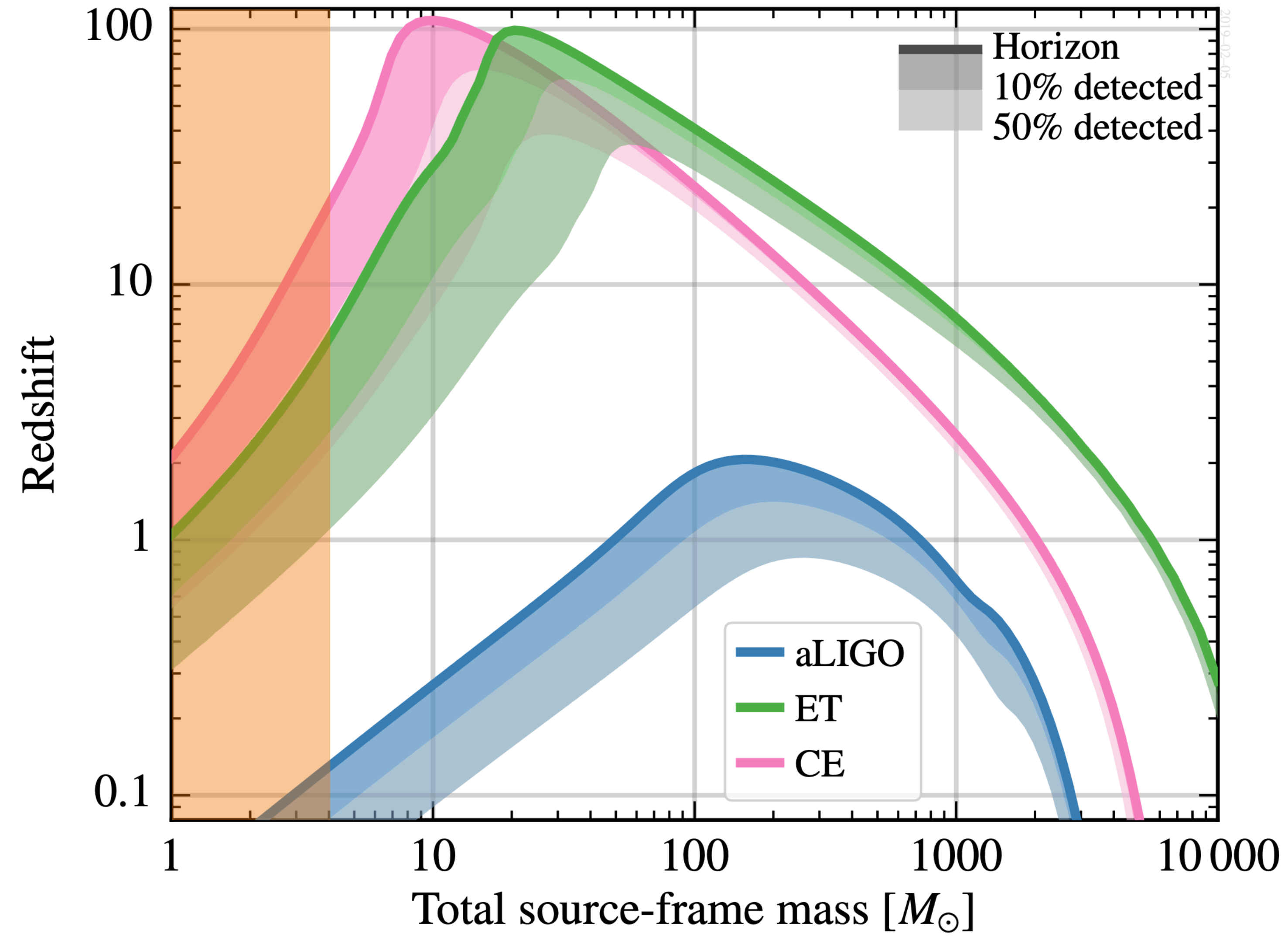
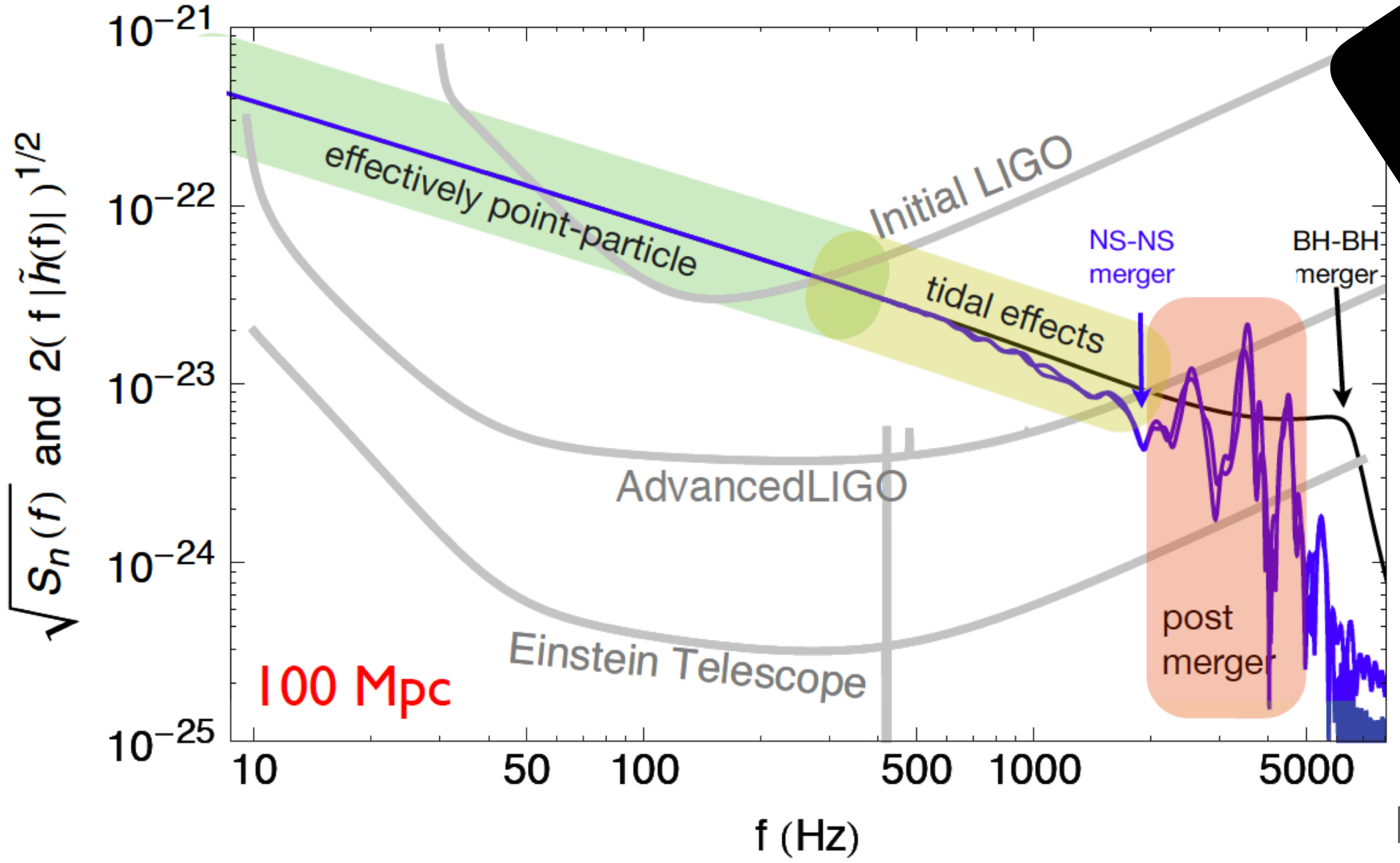
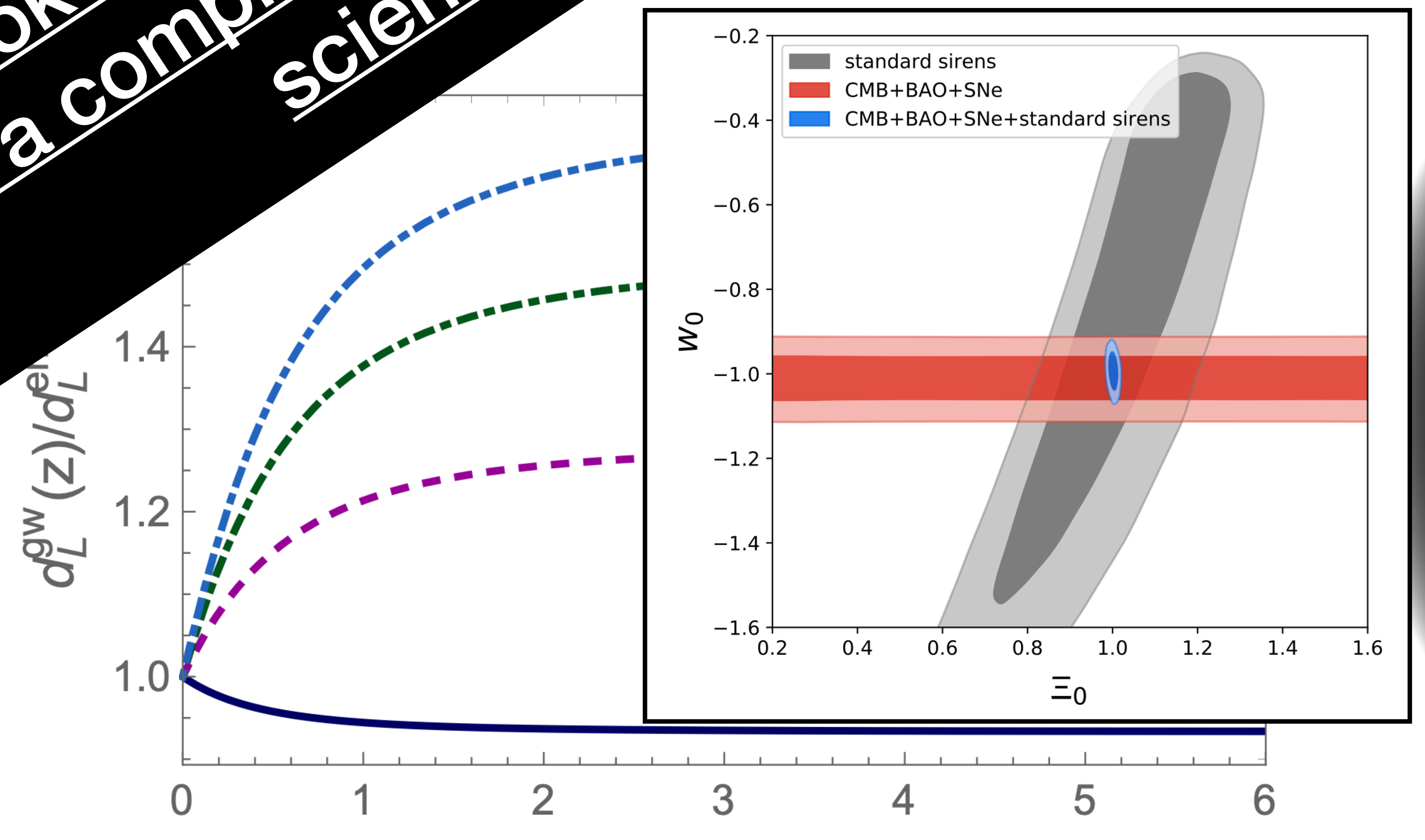
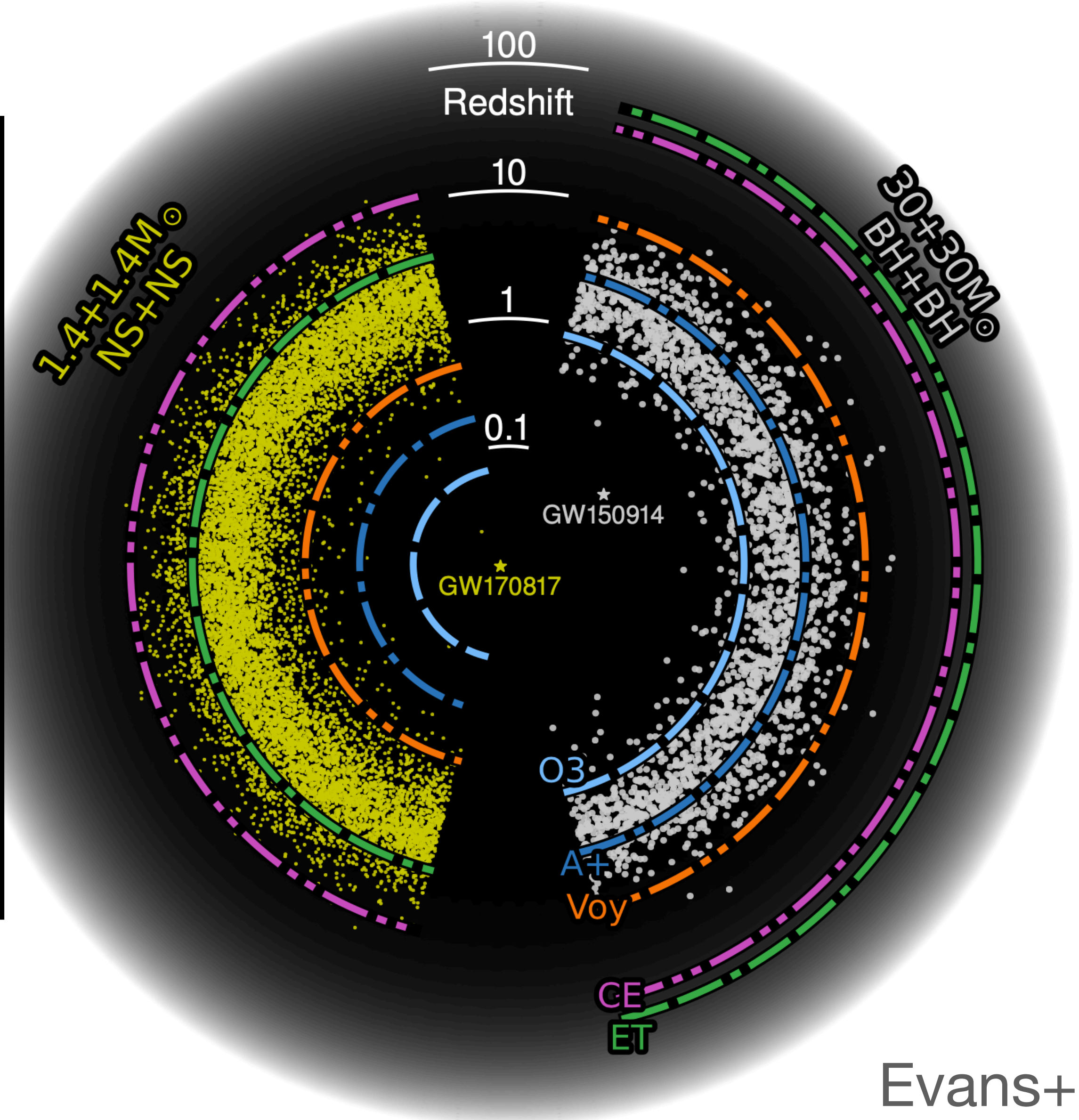
Look at Branchesi et al. 2023
For a complete overview of the ET science case







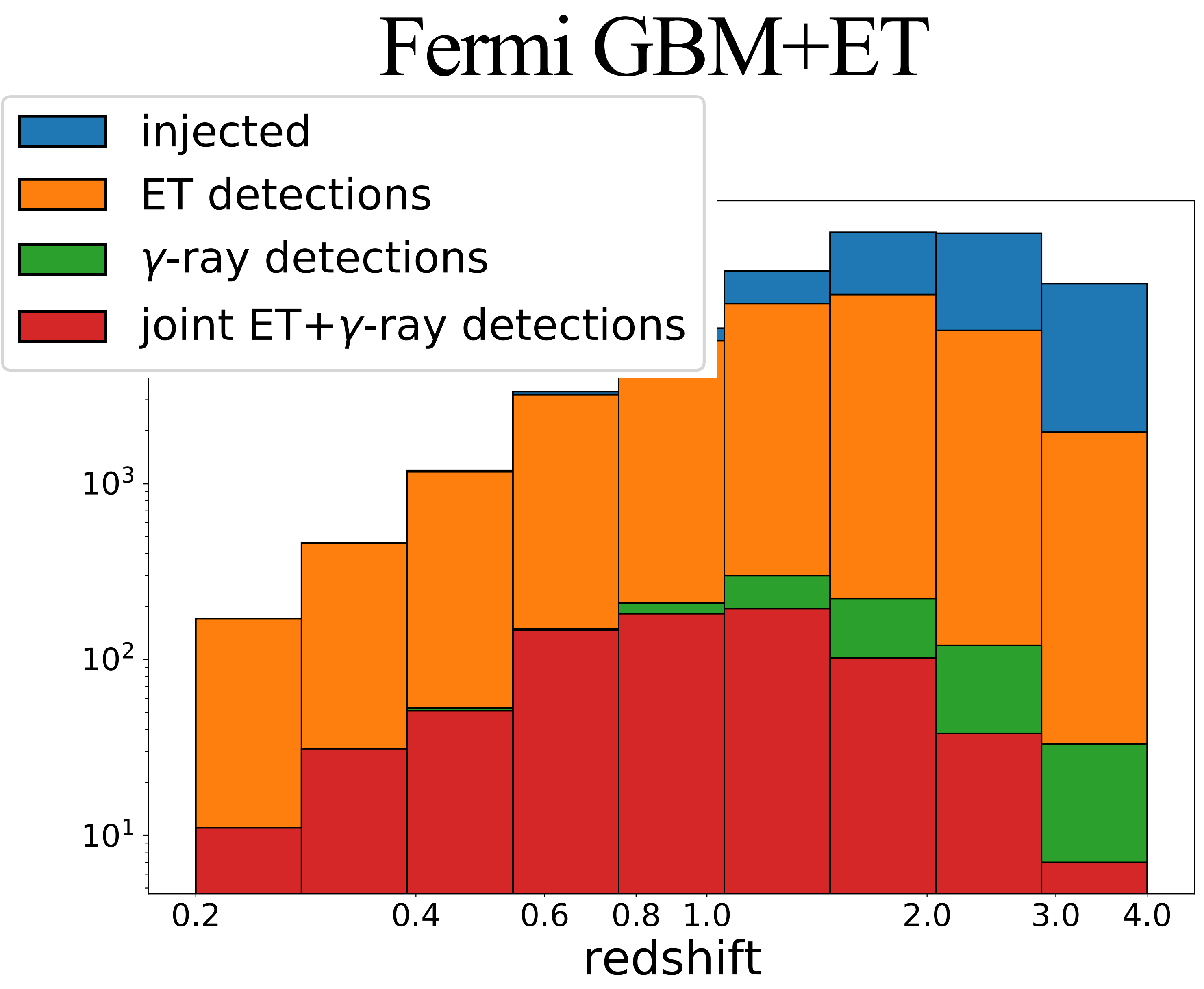
Maggiore+2020



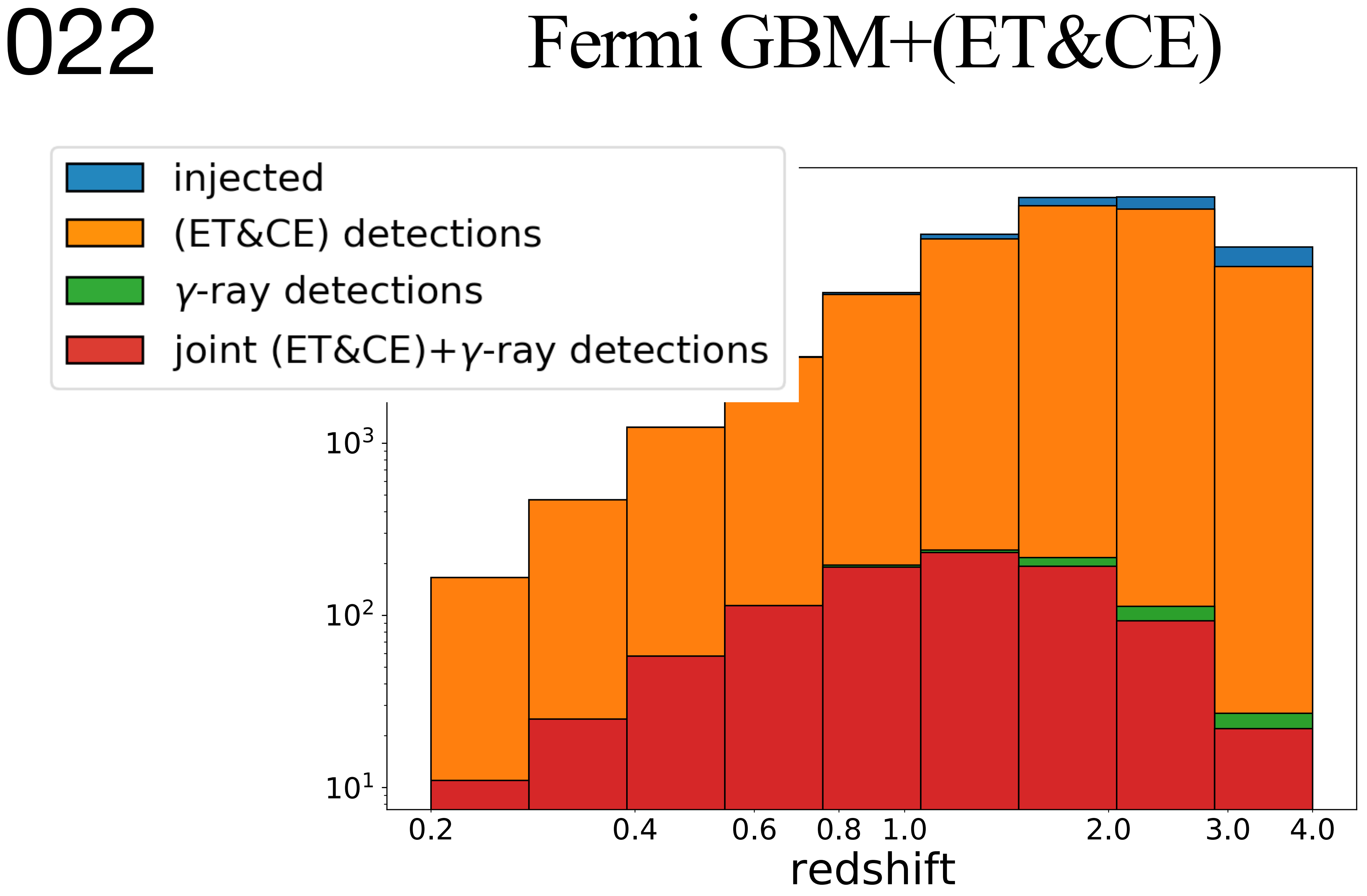
Evans+2021

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

Ronchini et al. 2022


Fermi GBM+(ET&CE)

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(*	[illegible]	5 deg (^{a})	33^{+14}_{-11}	$68^{+13}_{-18}\%$	47^{+14}_{-14}	$95^{+5}_{-7}\%$
Swift-BAT	0.015 - 0.15	[illegible]	[illegible]	-3 arcmin	10^{+3}_{-3}	$62^{+11}_{-14}\%$	13^{+5}_{-4}	$94^{+6}_{-7}\%$
SVOM-ECLAIRs	0.004 - 0.25	[illegible]	[illegible]	10 arcmin	3^{+1}_{-1}	$69^{+10}_{-9}\%$	4^{+1}_{-1}	$95^{+5}_{-4}\%$
SVOM-GRM	0.0	[illegible]	[illegible]	~ 5 deg	9^{+4}_{-3}	$59^{+6}_{-6}\%$	14^{+6}_{-4}	$92^{+3}_{-3}\%$
THESEUS-XGIS	[illegible]	[illegible]	0.16	< 15 arcmin	10^{+5}_{-4}	$63^{+13}_{-13}\%$	15^{+6}_{-4}	$94^{+6}_{-7}\%$
HERMES	[illegible]	[illegible]	1.0	1 deg	84^{+42}_{-30}	$61^{+10}_{-11}\%$	139^{+54}_{-36}	$94^{+6}_{-6}\%$
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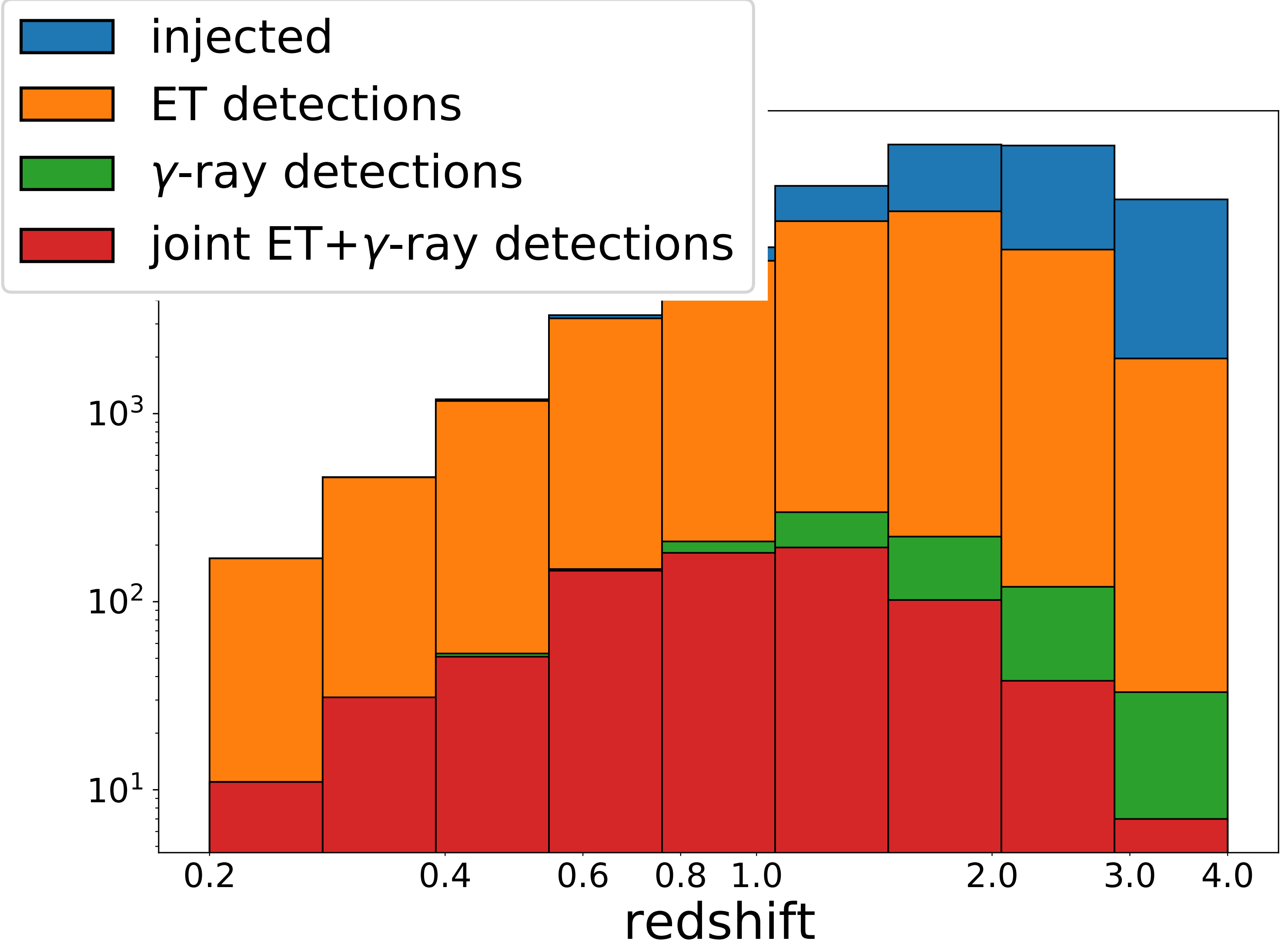
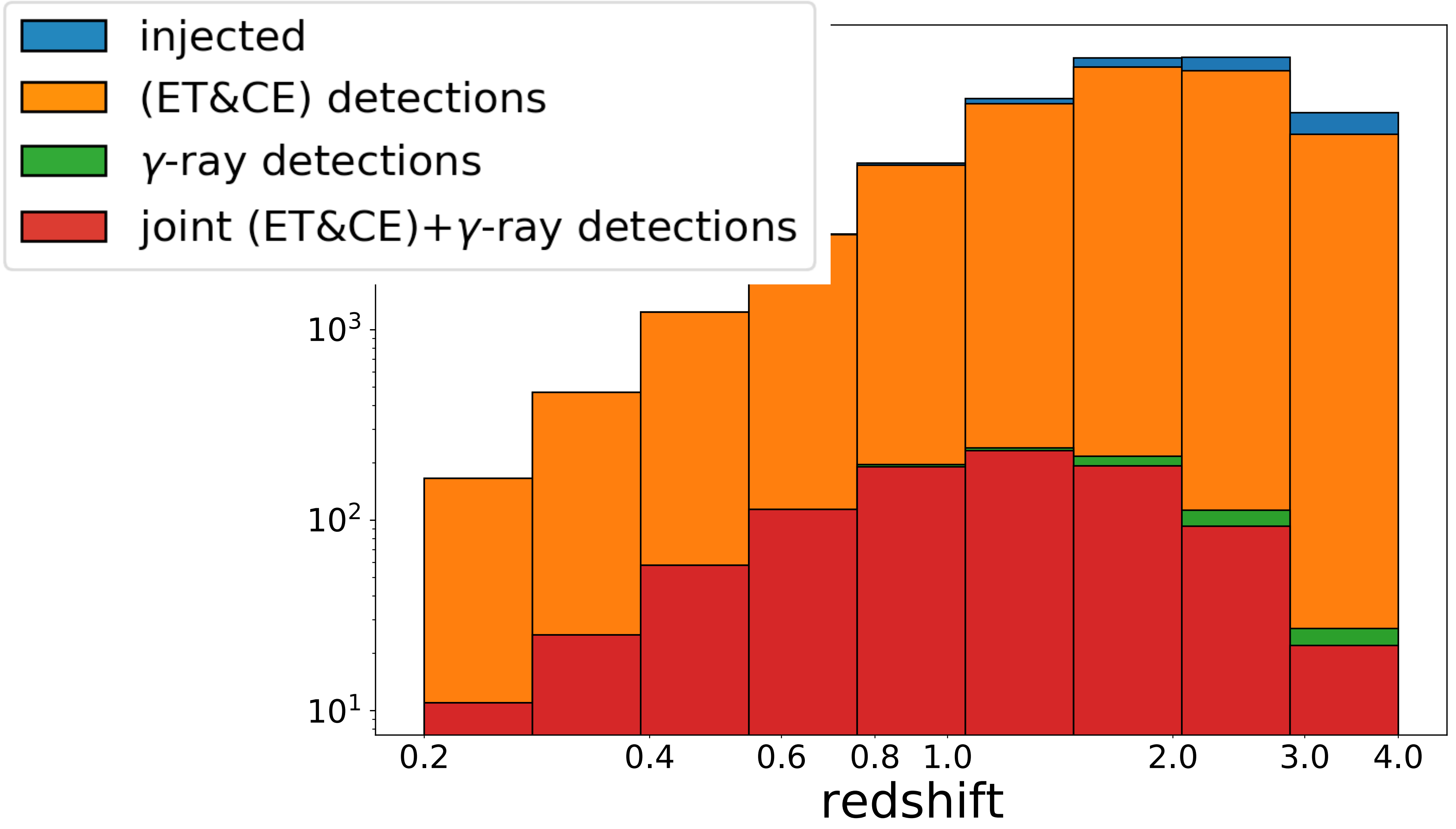
~ 60-70 % of short GRBs will have a GW detectable emission with ET and close to 100% with ET+CE

Ronchini et al. 2022

Fermi GBM+ET



Fermi GBM+(ET&CE)



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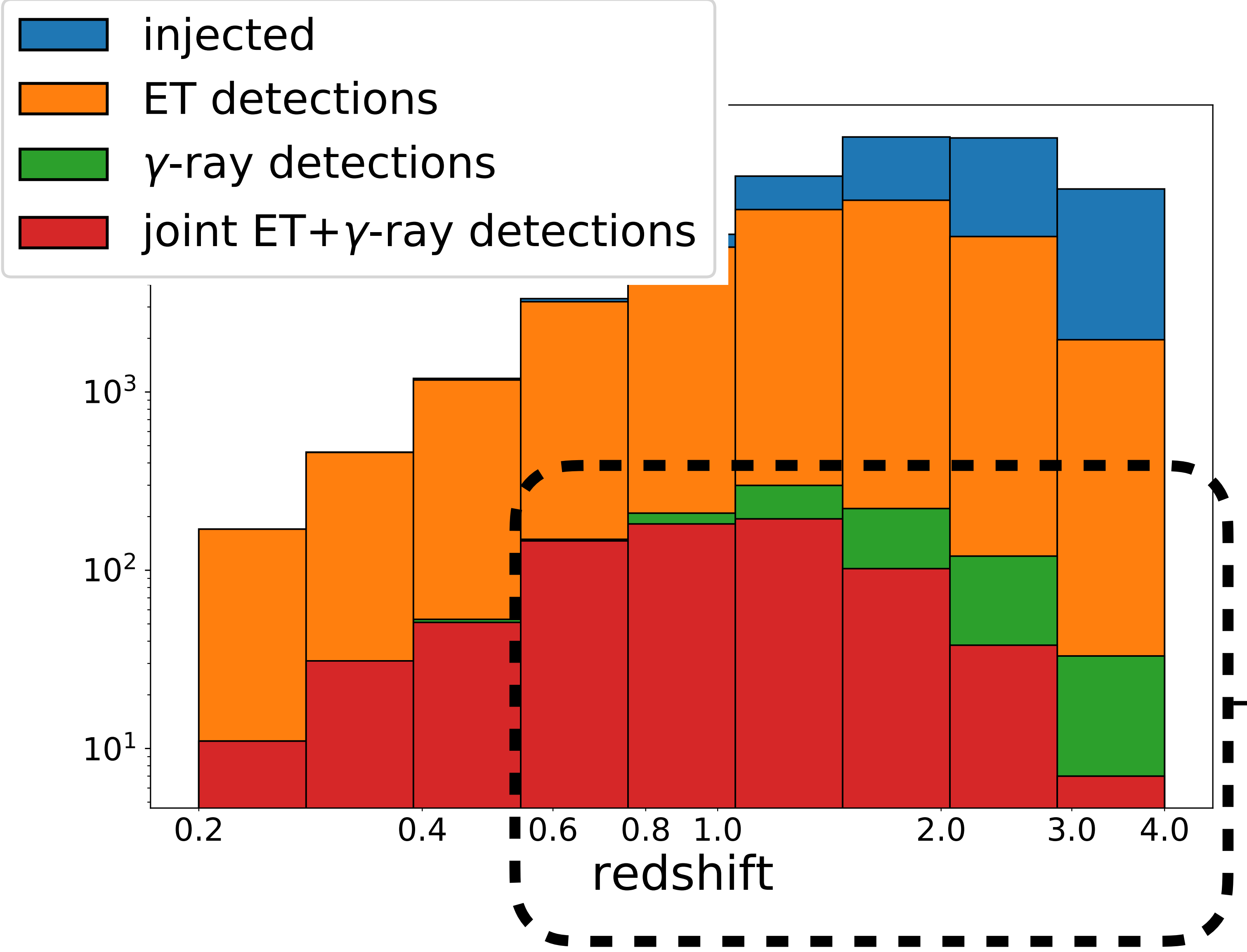
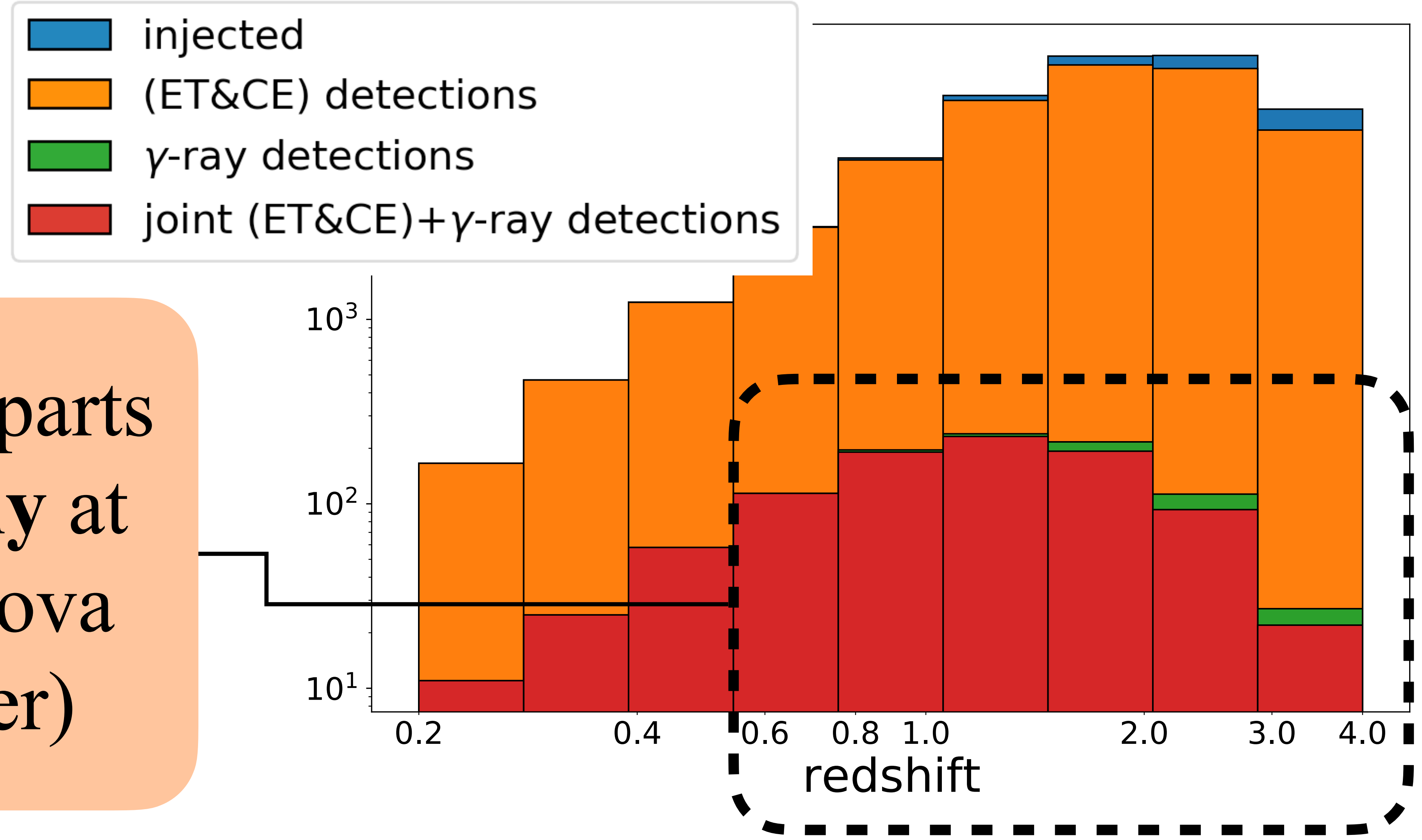
Ronchini et al. 2022

Fermi GBM+ET



Fermi GBM+(ET&CE)



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

Joint detection of γ-ray emission and GWs

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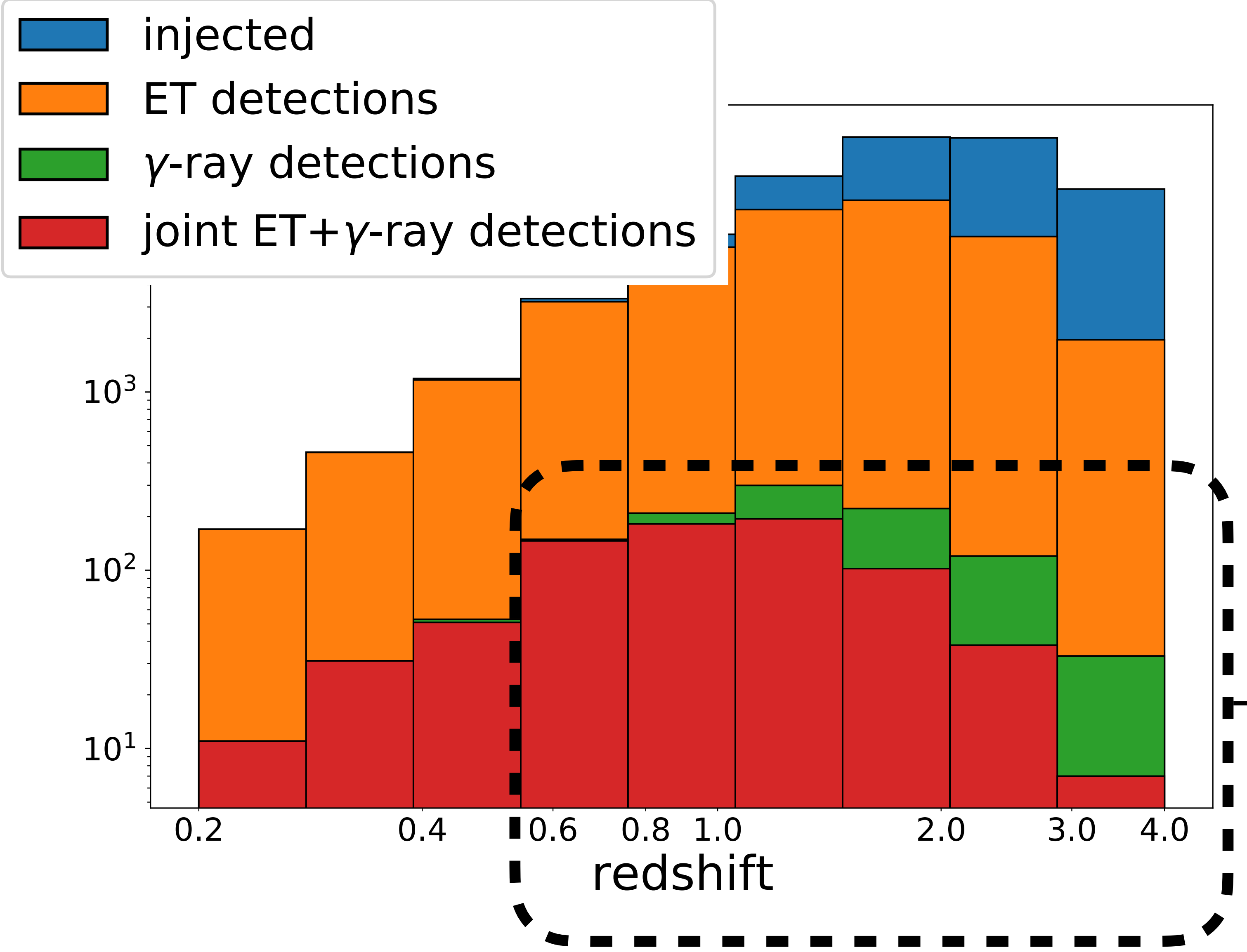
~ 60-70 % of short GRBs will have a GW detectable emission with ET and close to 100% with ET+CE

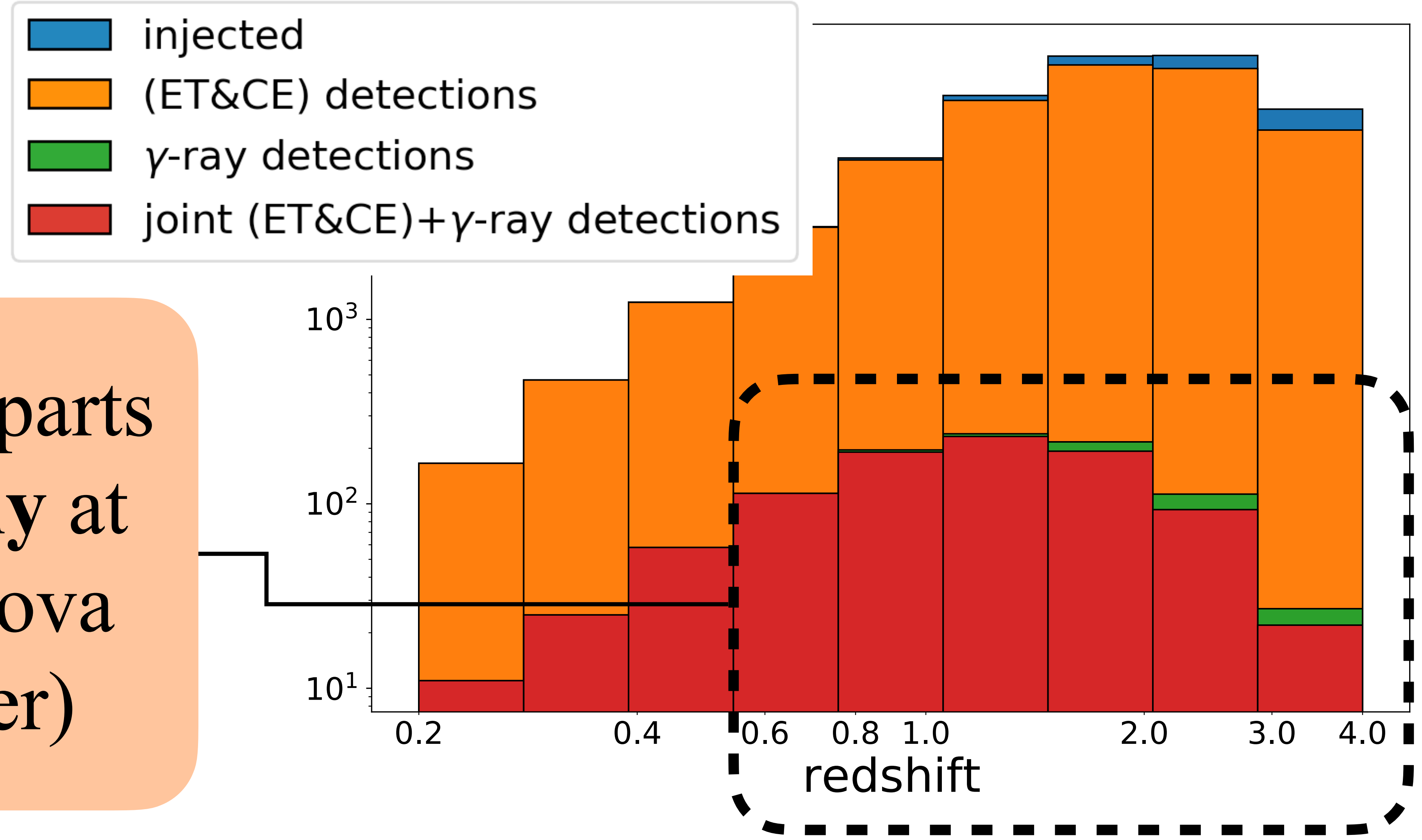
Few but **well localised** events

Ronchini et al. 2022

Fermi GBM+ET



Fermi GBM+(ET&CE)



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

Two kinds of joint detections

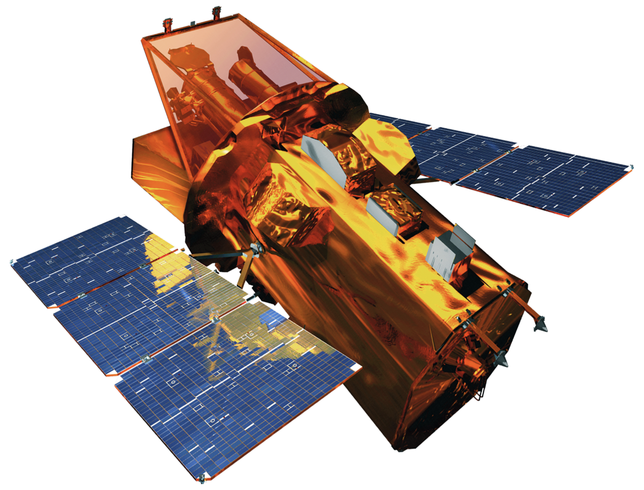
Fermi-like telescopes

- ~ **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
- High number of joint detections ⇒ **statistical studies**

Swift-like telescopes

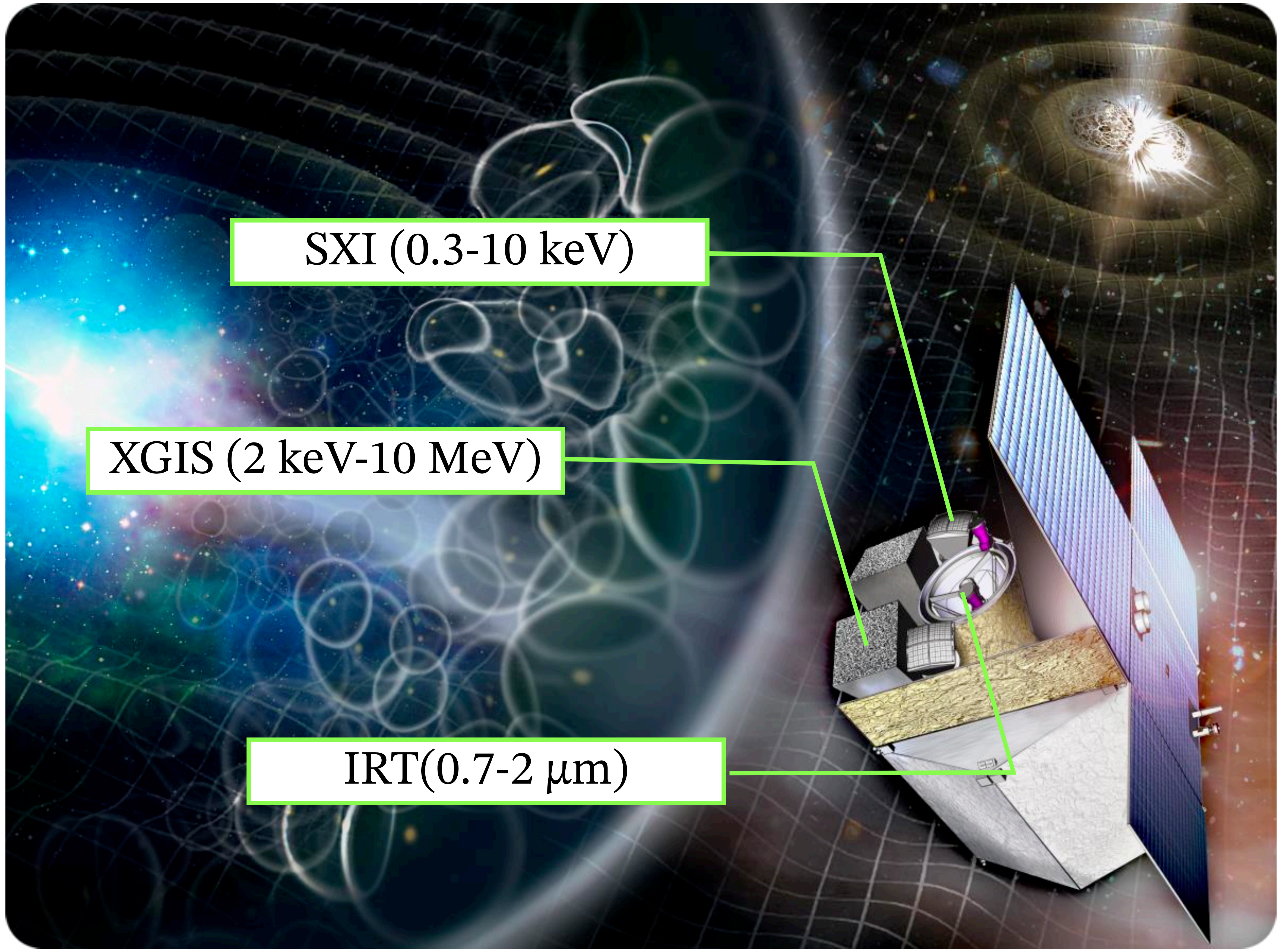


- Good sky coverage
- **Arcmin location accuracy**
- Possibility to promptly follow up with ground-based telescopes

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**

THESEUS: Transient High-Energy Sky and Early Universe Surveyor

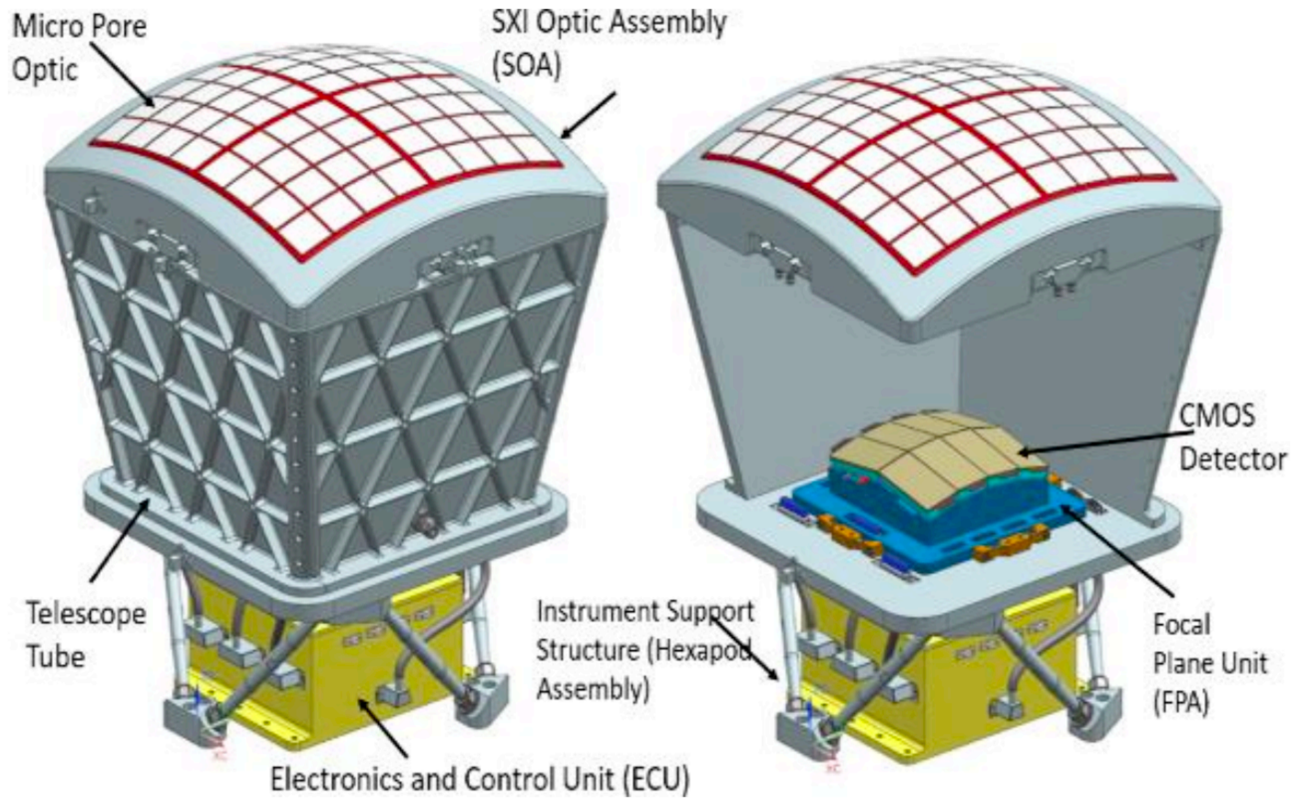


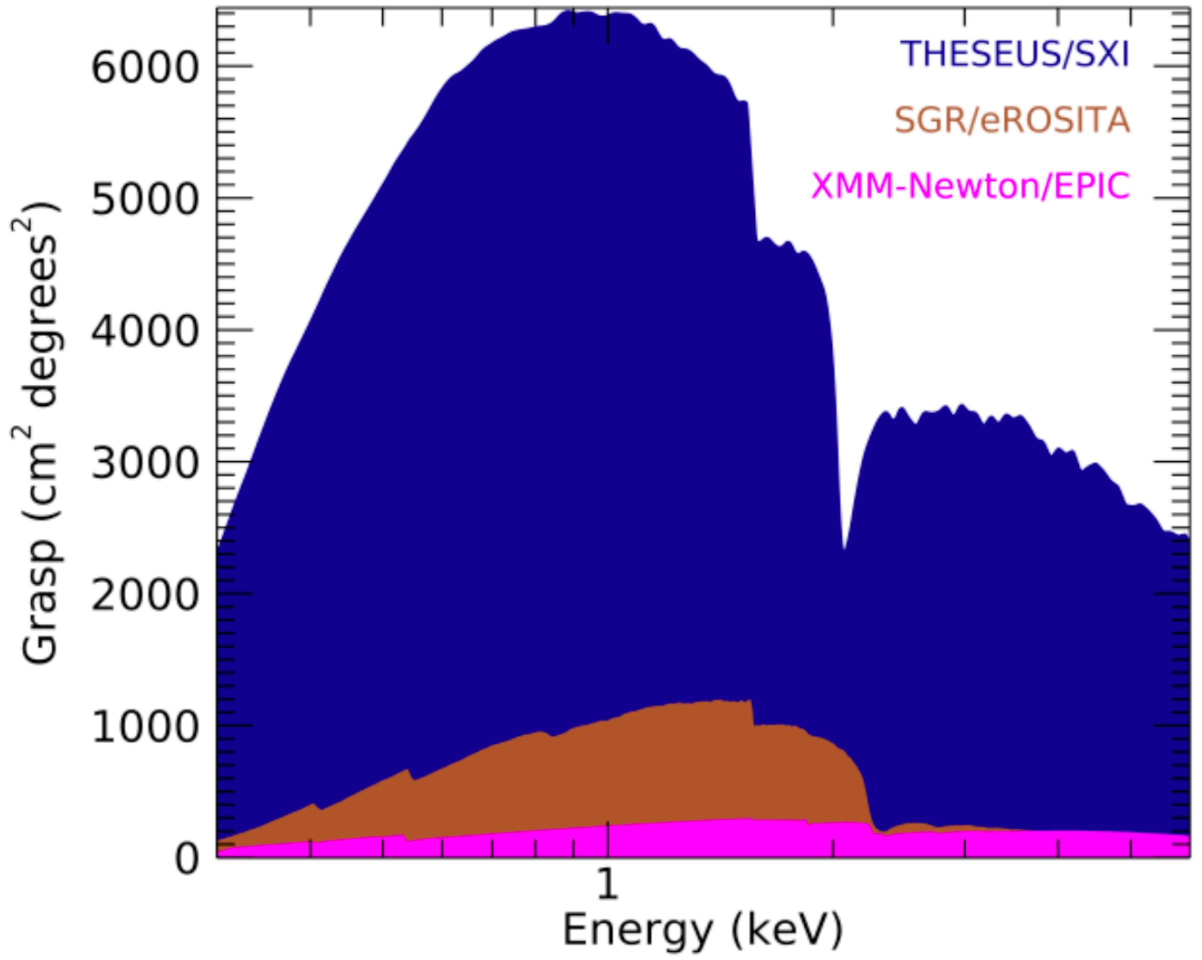
Mission concept optimized for:

1. Multi-messenger studies, follow up and identification of EM counterpart of GW and neutrino events
2. Detection and characterization of GRBs up to redshifts close to the re-ionization epoch of the Universe
3. Systematic survey of the transient sky in the high-energy

THESEUS: Transient High-Energy Sky and Early Universe Surveyor

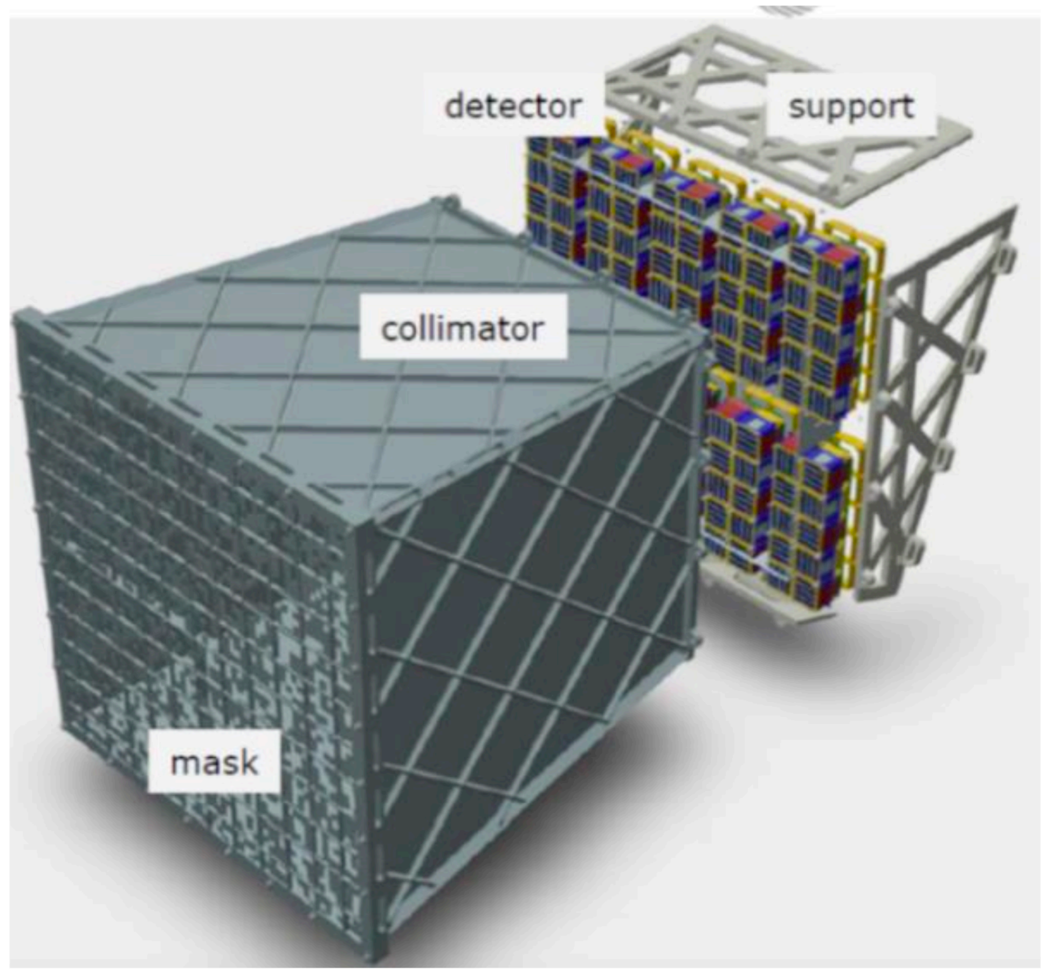
Soft X-ray Imager (SXI)

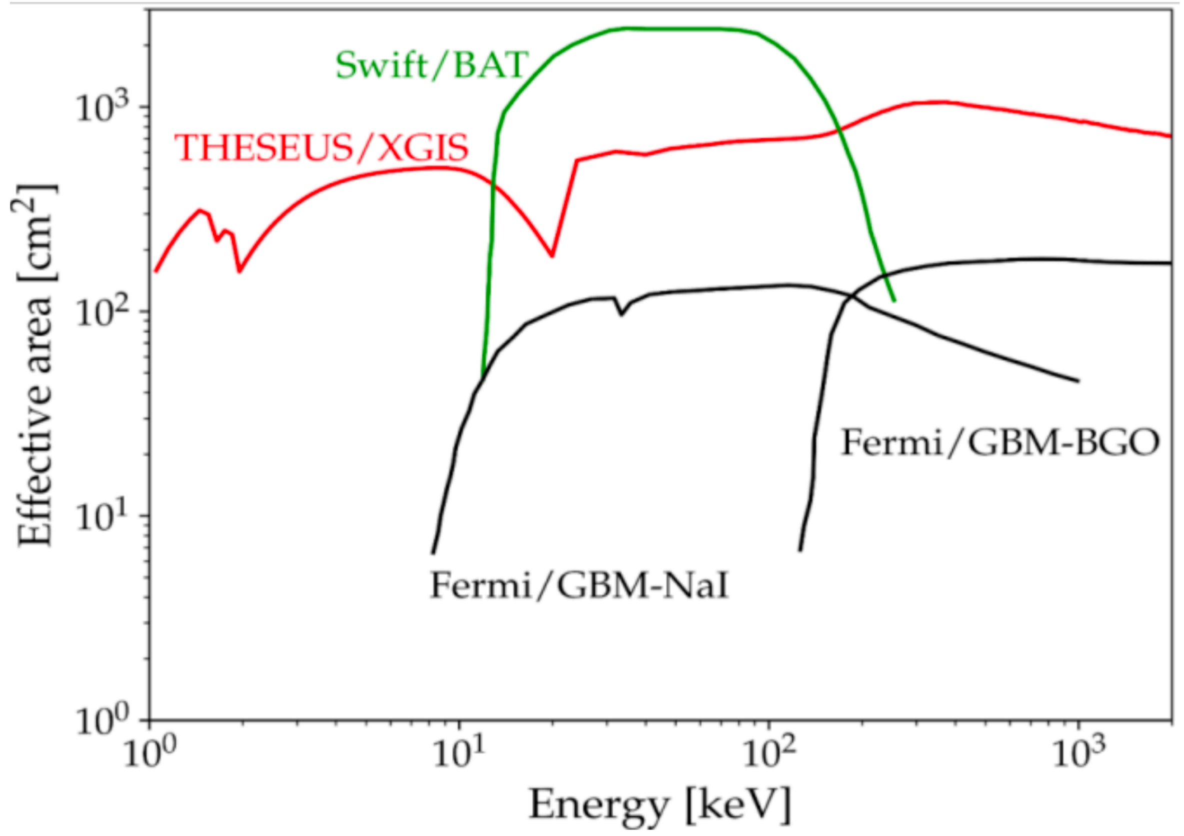




Large Grasp

X/gamma-ray Imaging spectrometer (XGIS)





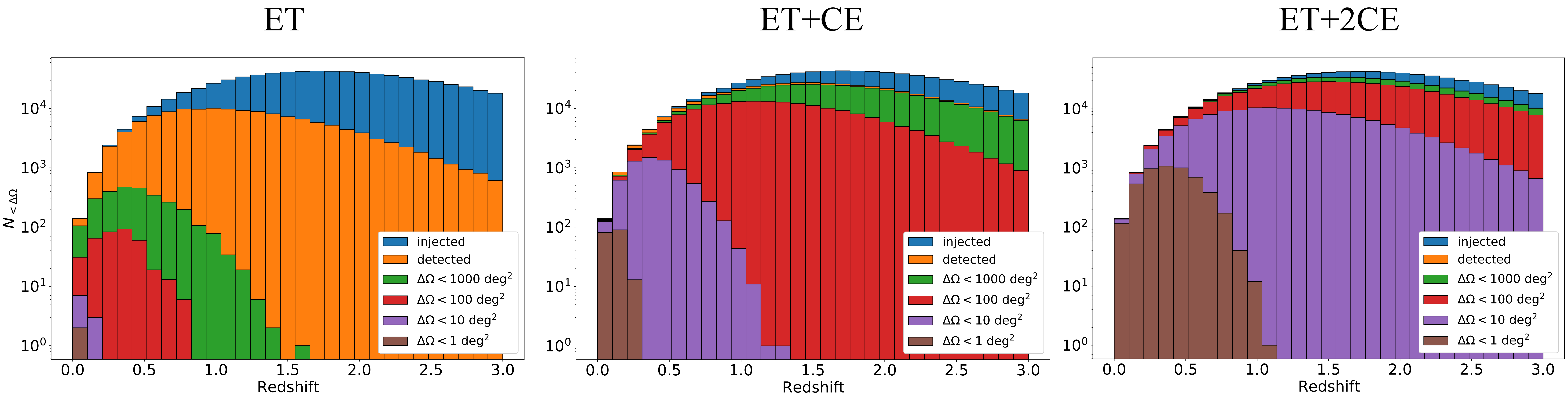
Very wide spectral coverage

Key advantages:

1. Wide coverage of the sky
2. Very extended energy range, from 0.3 keV to 10 MeV
3. Arcmin localisation

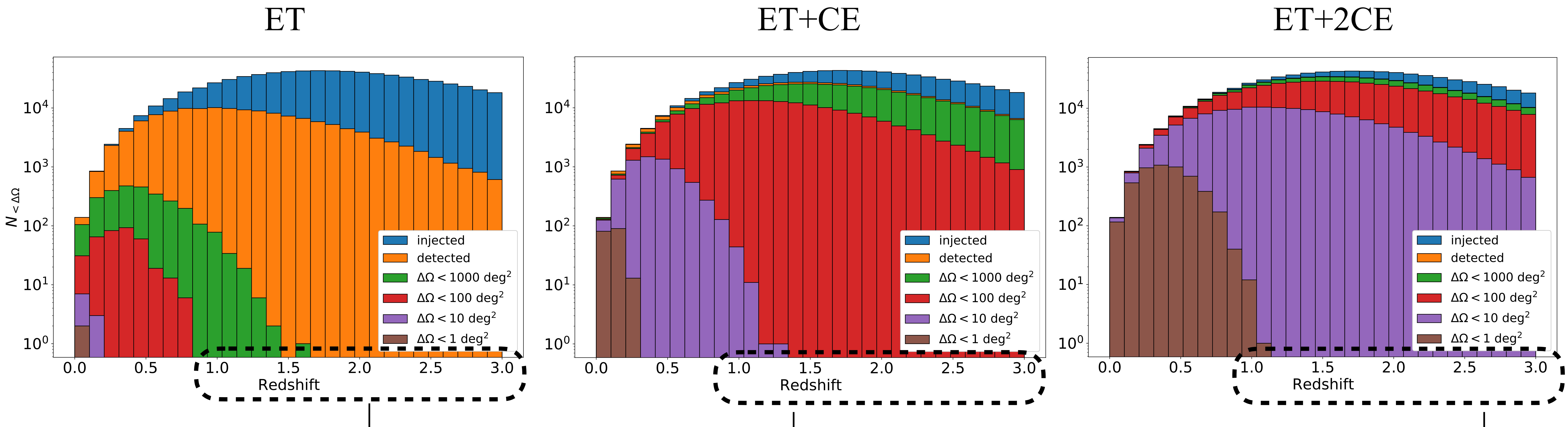
	FOV	Position accuracy
SXI	0.5 sr	< 2 arcmin
XGIS	2 sr (2 - 150 keV) 4 sr (>150 keV)	< 15 arcmin
IRT	15’ x 15’	< 1 arcsec

GW sky localisation



	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



ET

ET+CE

ET+2CE

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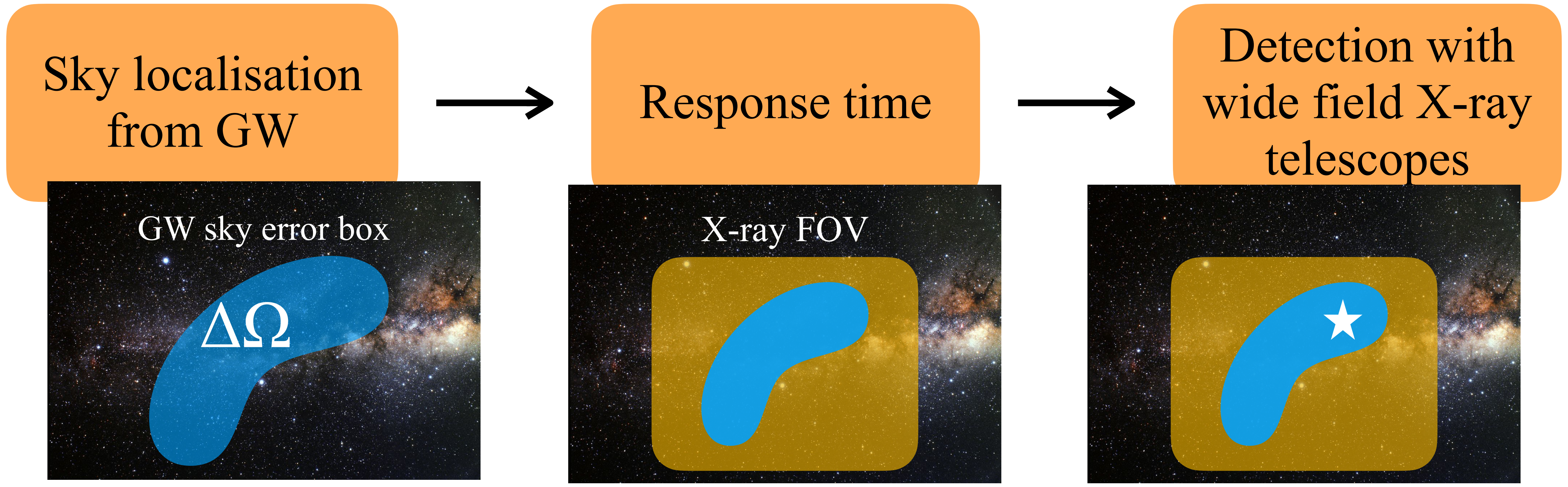
High-z GW source localisation is given by counterparts detected by **wide field X-ray and γ-ray telescopes** with arcmin localisation capabilities

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

	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}

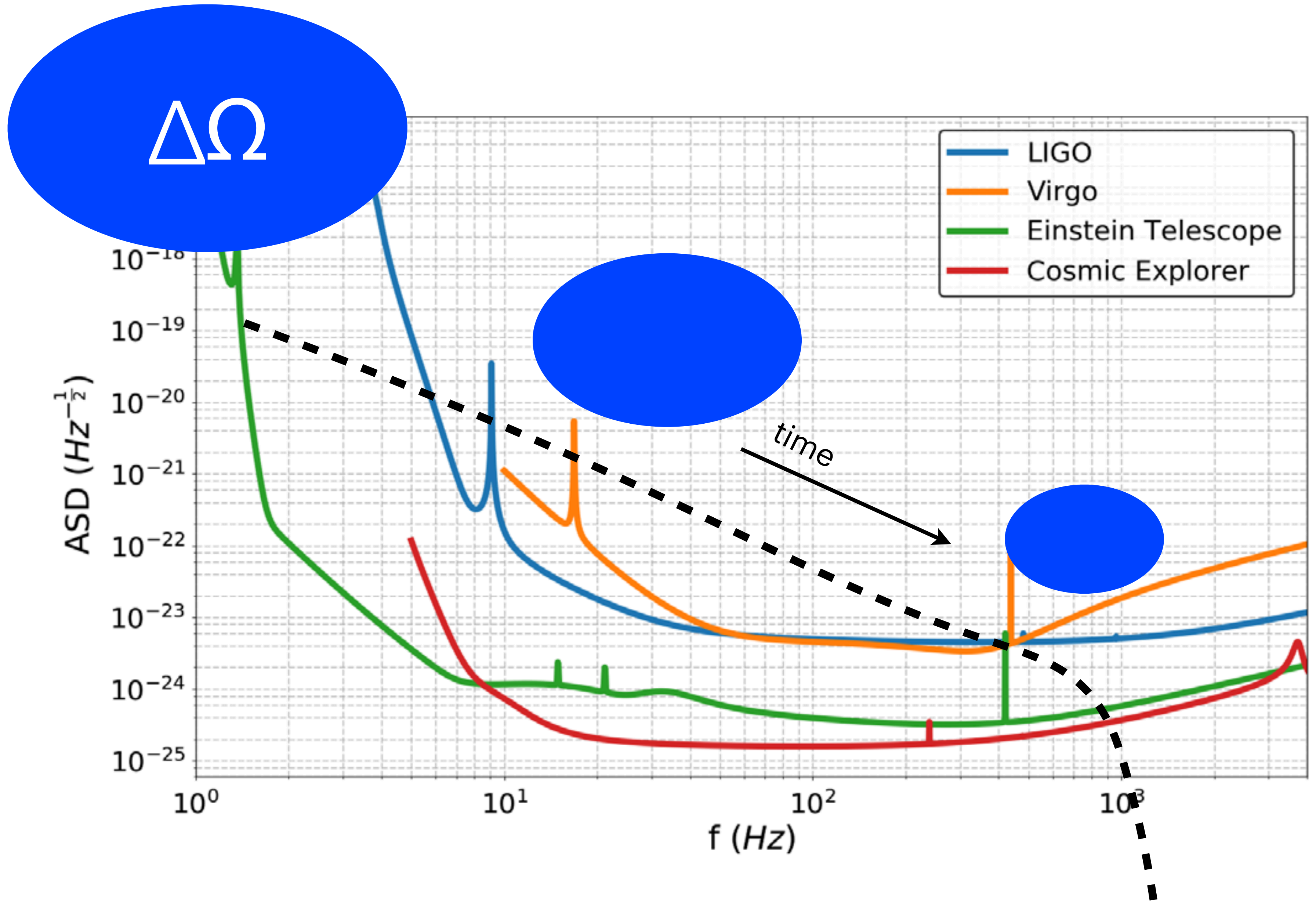
A **rapid response** is necessary to catch the brighter phase of the afterglow

Following-up all the sources with $\Delta\Omega < 100$ deg^2 is **unfeasible**

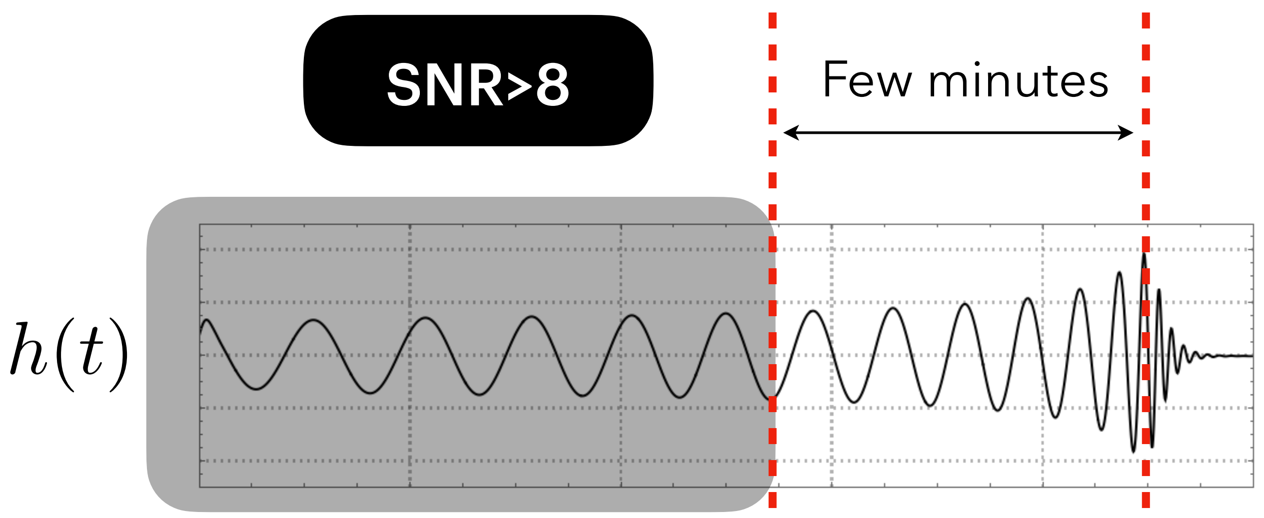
Other GW parameters should be exploited to restrict the selection:

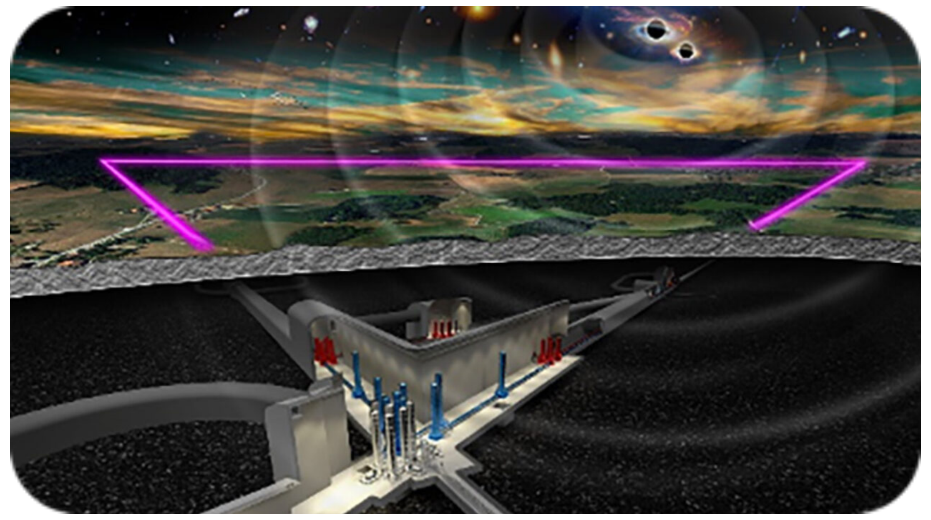
- **SNR**
- **Viewing angle** and relative error
- **Luminosity distance** and relative error

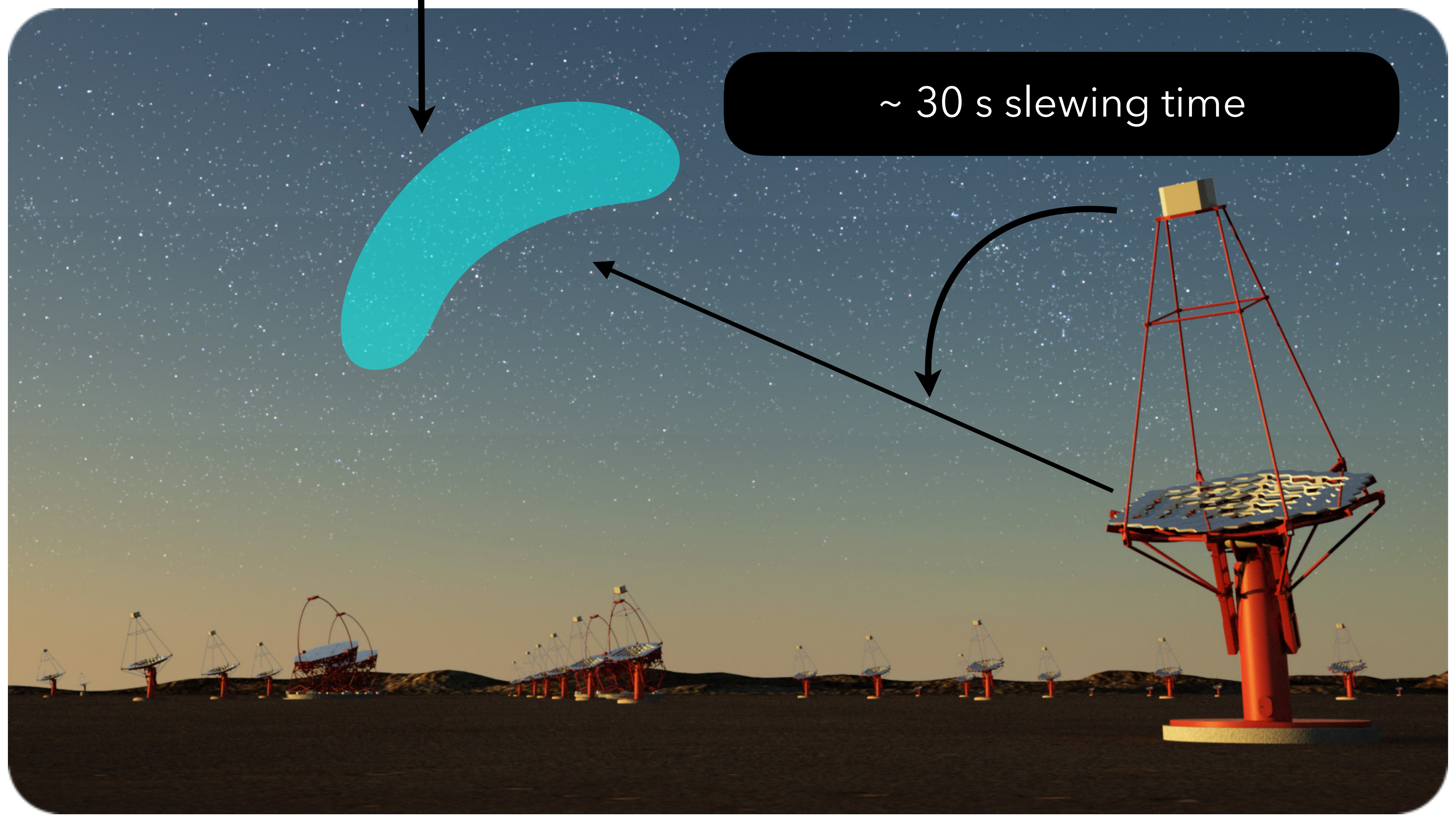
Pre-merger sky localisation



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



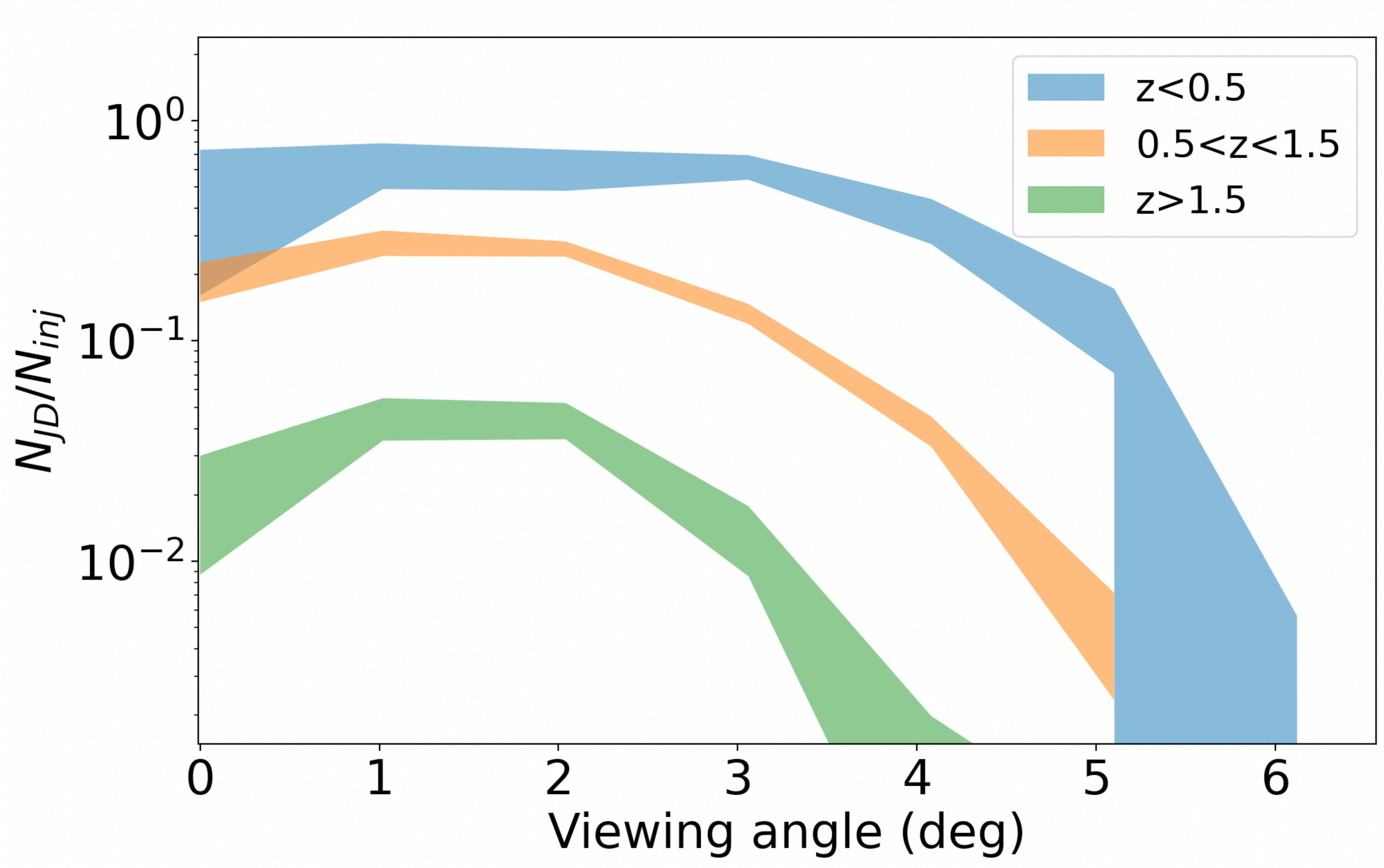




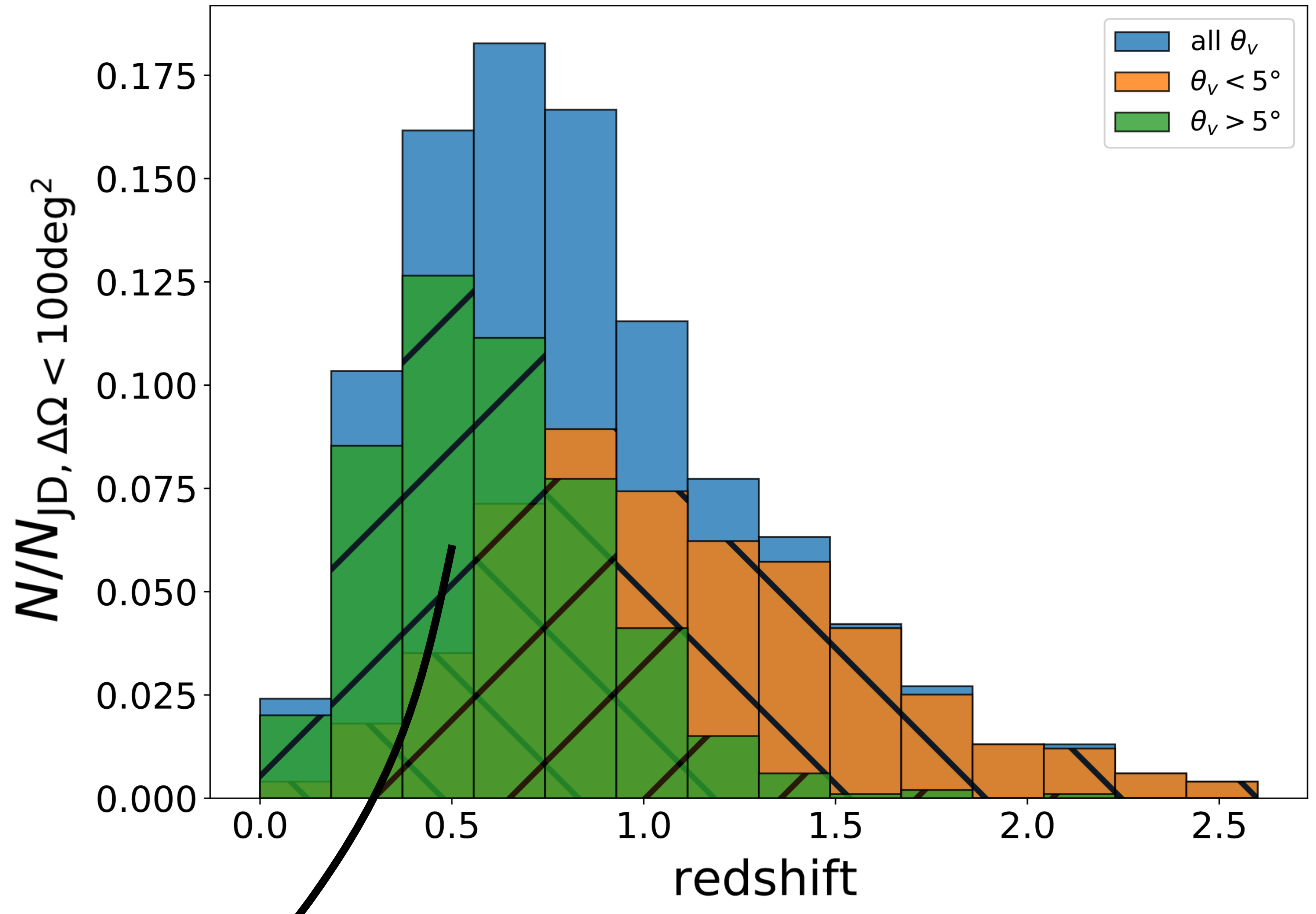
Future Cherenkov telescopes, like CTA, will be able to point in the direction of the GRB at the moment of the merger, allowing to **detect possible very-high energy emission during the prompt phase**

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

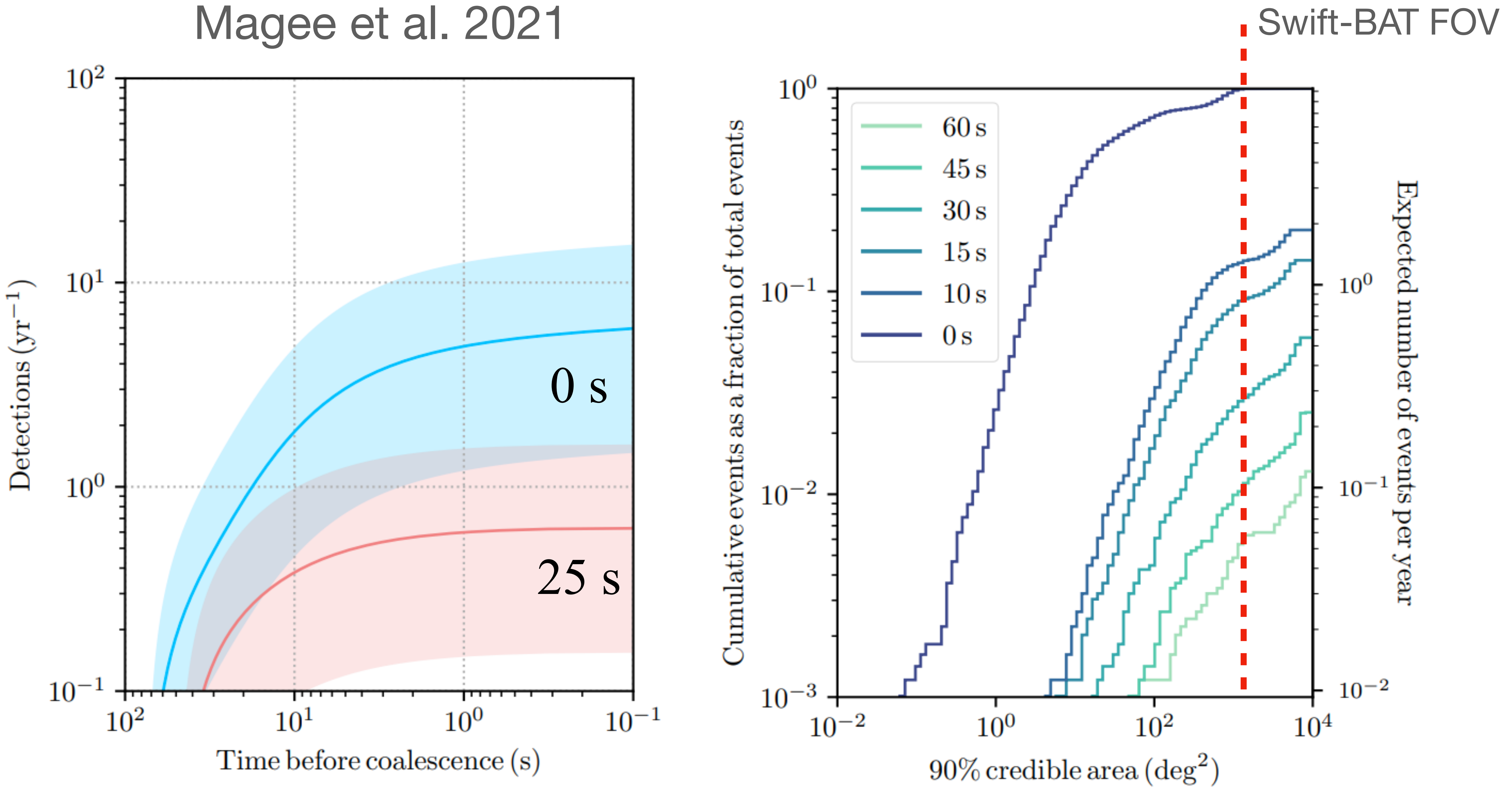


Too off-axis to have a detectable γ-ray emission

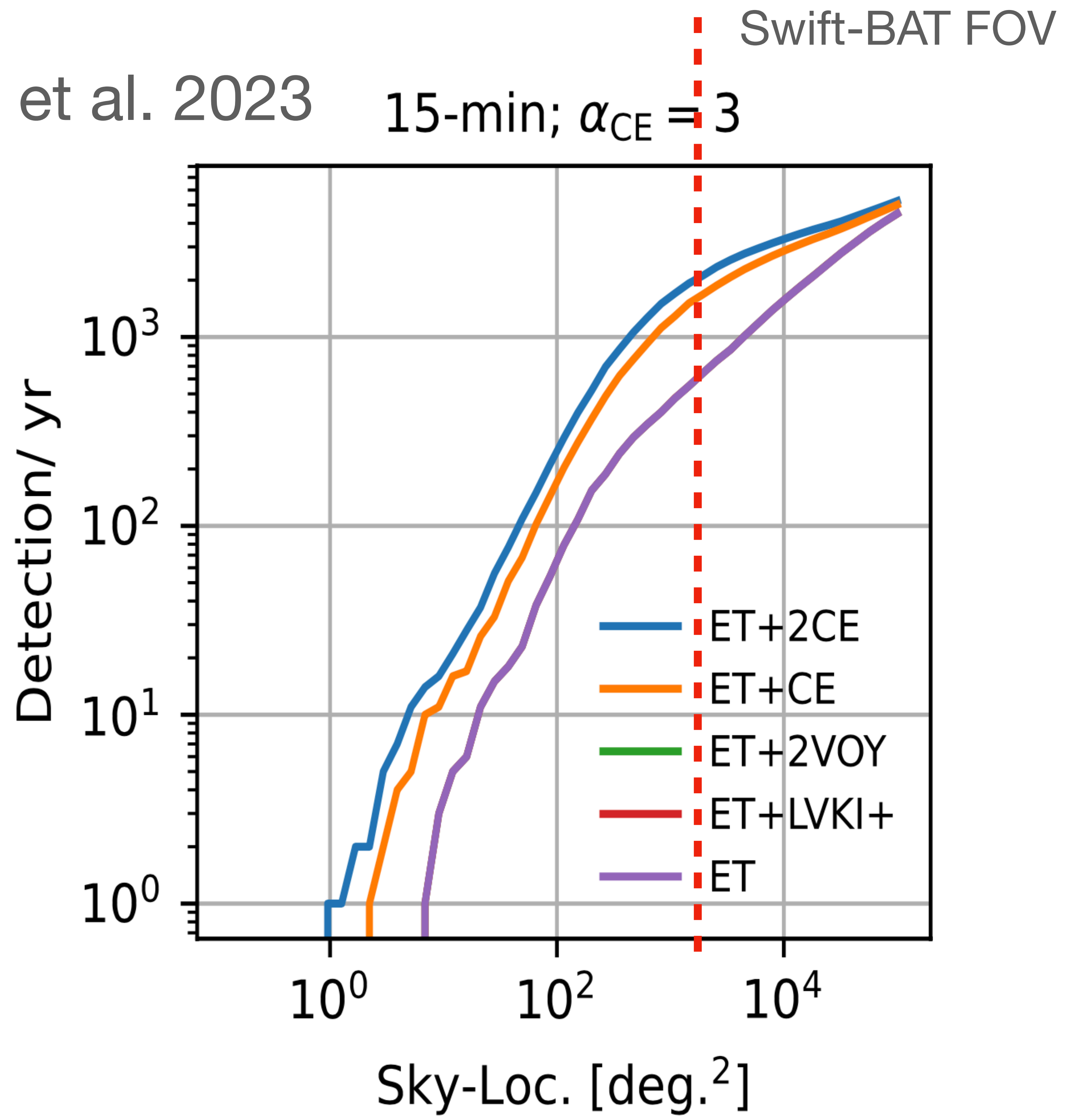
WFX-ray telescopes can significantly **enhance the probability of a joint detection**

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

Magee et al. 2021



Banerjee et al. 2023



In O4: < ~ 1 BNS pre-merger detections

In the ET era: ~ **1000 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

Thank you!