Perspectives of gravitational-wave multi-messenger astronomy for current and future observatories

GSSI GW team

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Gran Sasso Science Institute, INFN/LNGS and INAF

GRAN SASSO SCIENCE INSTITUTE

SCHOOL OF ADVANCED STUDIES

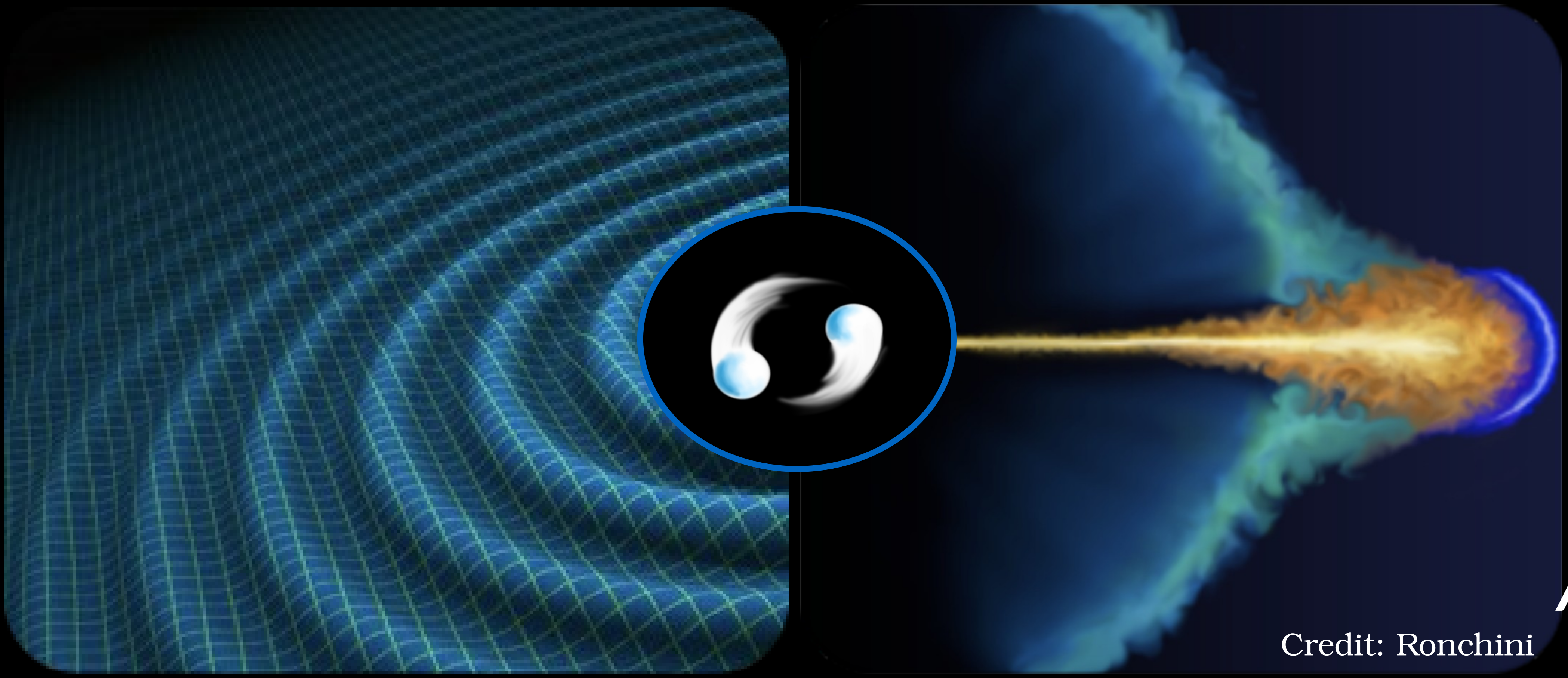
Scuola Universitaria Superiore

ISTITUTO NAZIONALE DI ASTROFISICA

INAF

INFN

Istituto Nazionale di Fisica Nucleare



Credit: Ronchini

AACOS- 2023

SINP

GSSI GW team

M. Branchesi, G. Oganesyan, J. Harms
A. Mei, U. Dupletsa, S. Ronchini,
O. S. Salafia, G. Ghirlanda, F. Aharonian,
E. Loffredo, N. Hazra,
S. Agarwal, P. Tiwari, A. Shukla+

Based on:

1. Mei, Banerjee, Oanesyan+, Nature 2022: ***2022Natur.612..236M***
2. Banerjee, Oganesyan, Branchesi+: ***arXiv:2212.14007***

MUR Ministero dell'Università e della Ricerca

PRIN 2020 grant 2020KB33TP

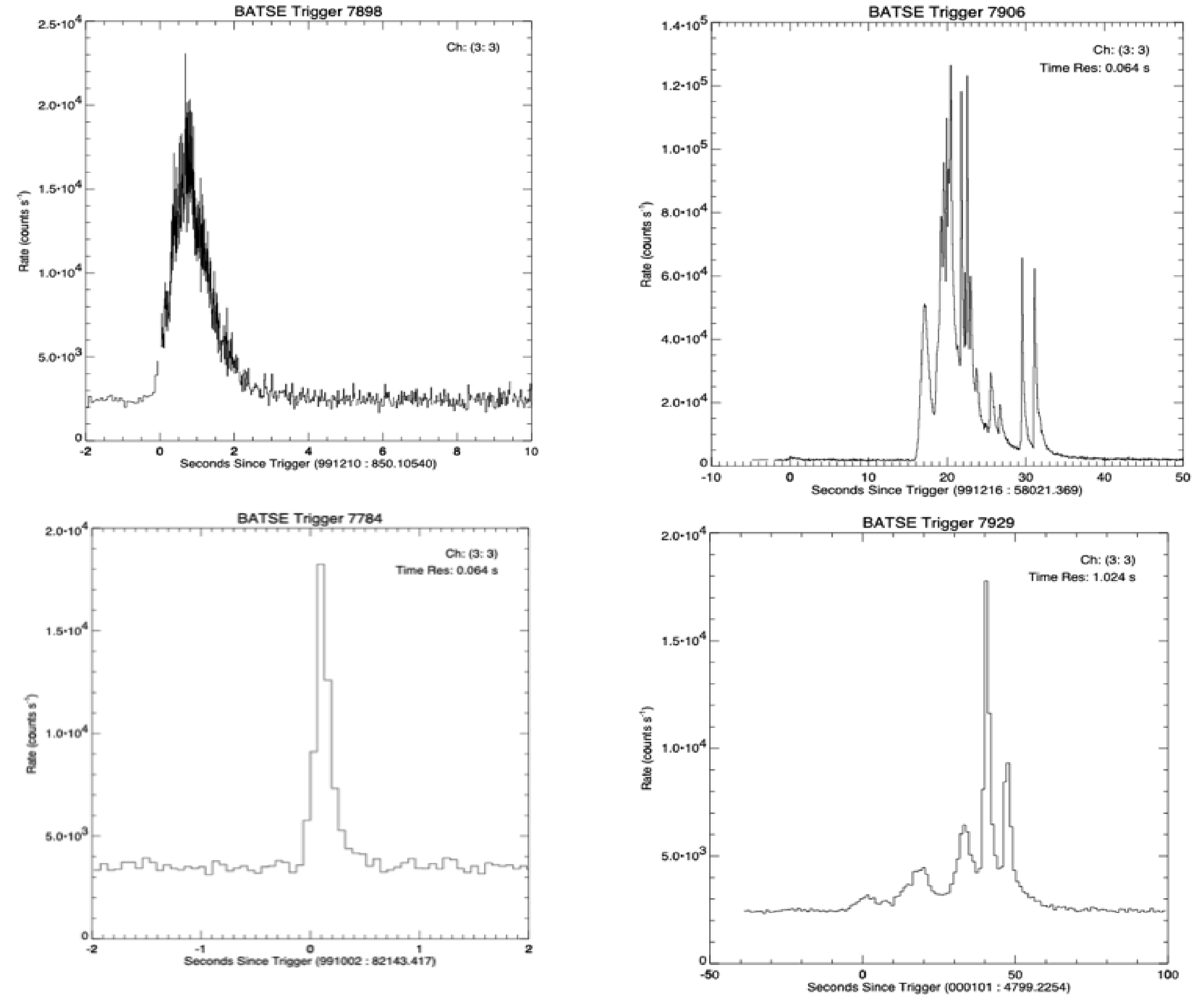
PRIN 2017 grant 20179ZF5KS

What are Gamma-ray bursts?

MWL era 2004-, ..

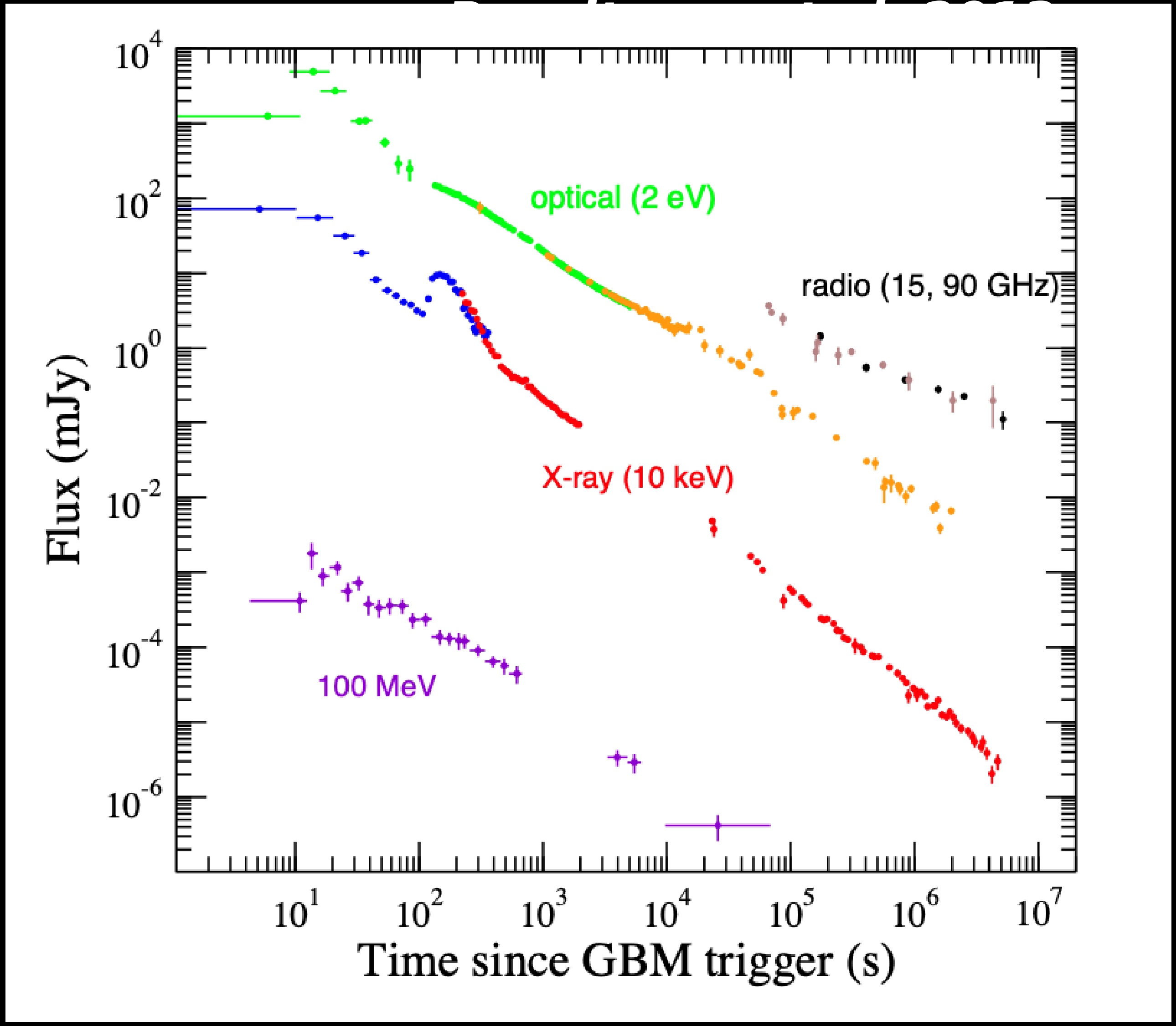
prompt emission

GRB LC (0.1-0.3 MeV) in BATSE



afterglow

GRB 130427A

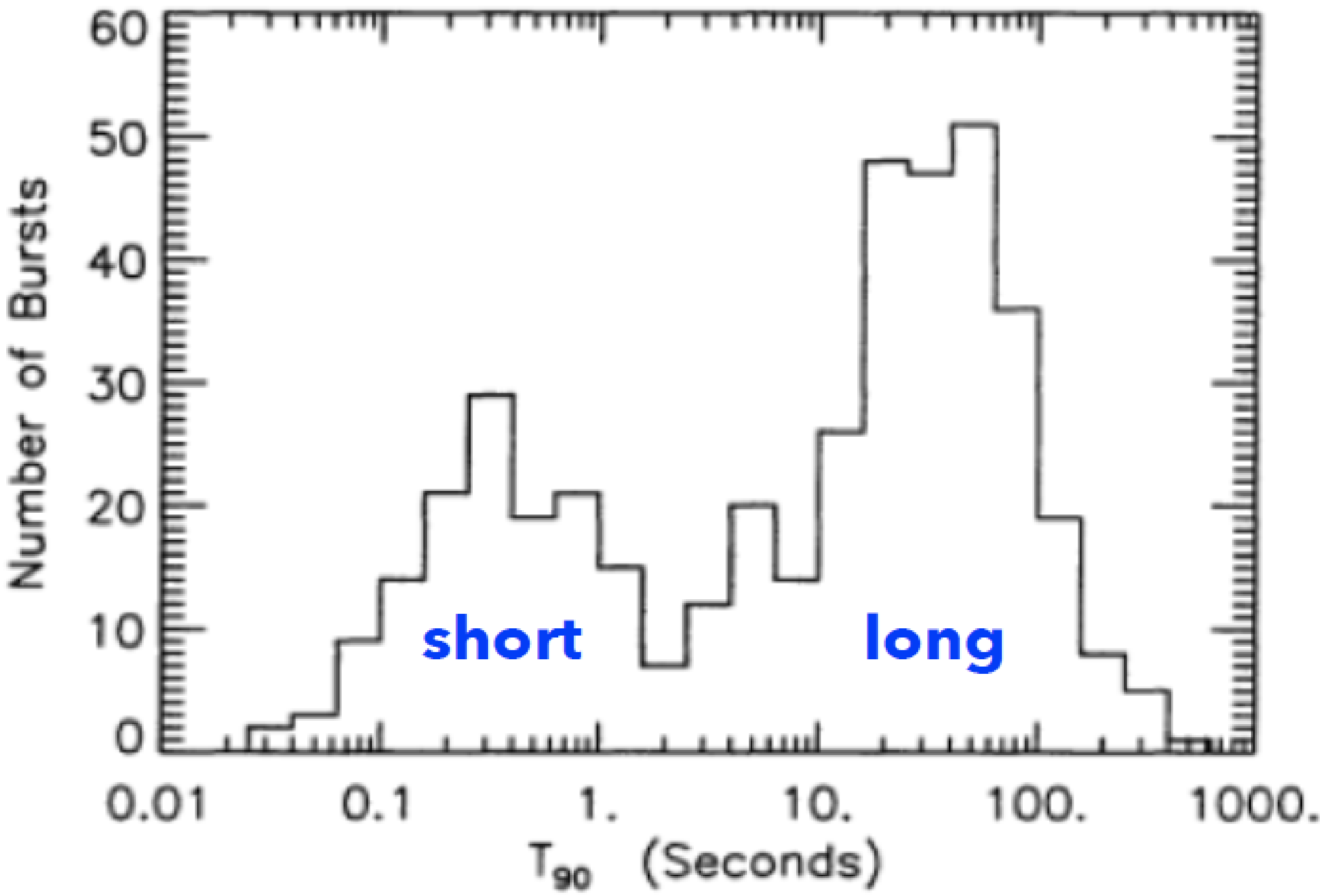


Energy: 10 keV - 10 MeV; Variability 0.01-1 s
Duration: 0.1 s – 1000s; Total energy: 10^{51}-10^{54} erg

What are Gamma-ray bursts?

MWL era 2004-, ..

short-hard vs. long-soft GRBs

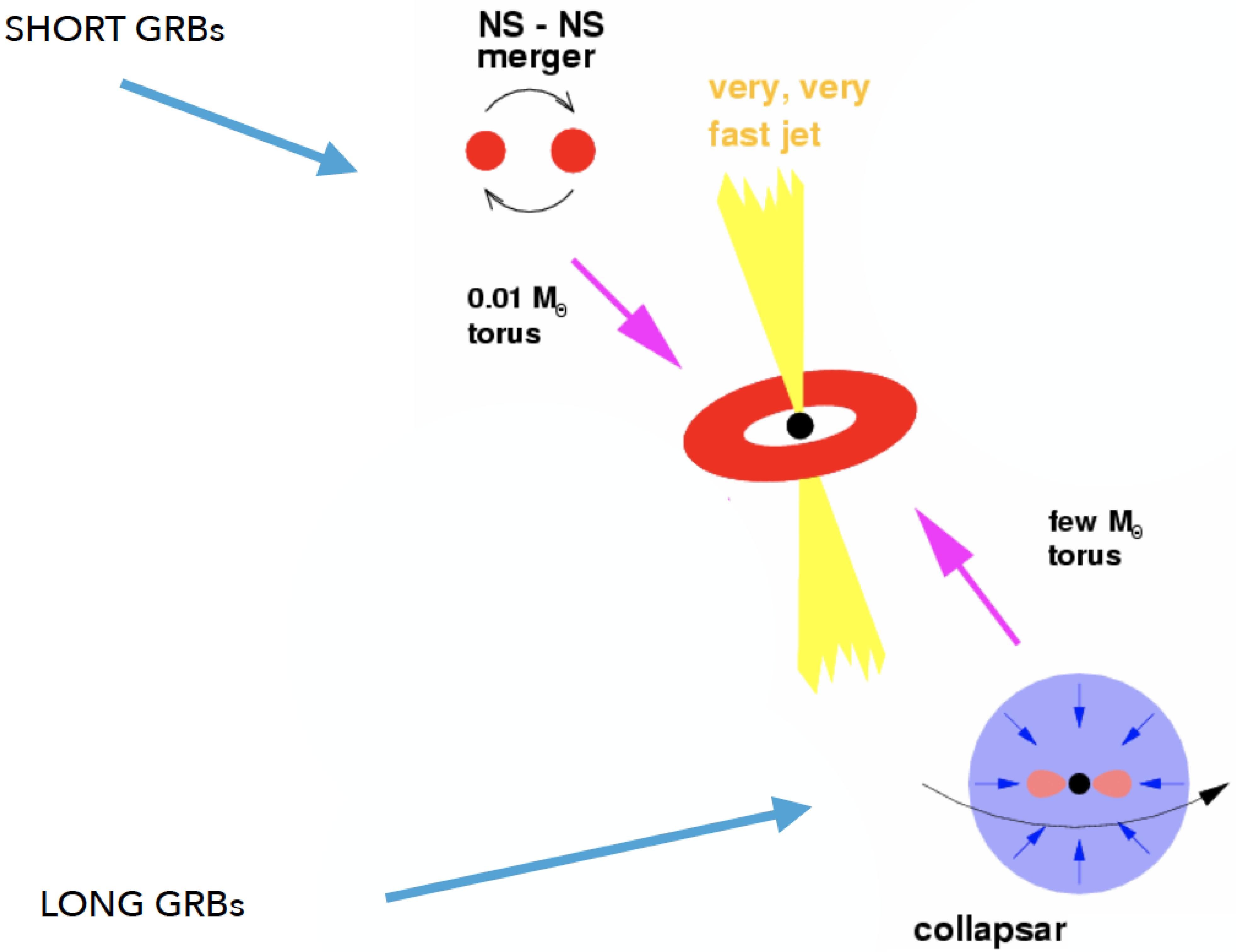


short (<2 s) and long (>2 s)

C. Kouveliotou et al. 1993, Meegan et al 1996, Sakamoto et al. 2011, Paciesas et al 2012

Progenitors of short and long GRBs

Ascenzi et al. 2020



A new window into the Universe

O1

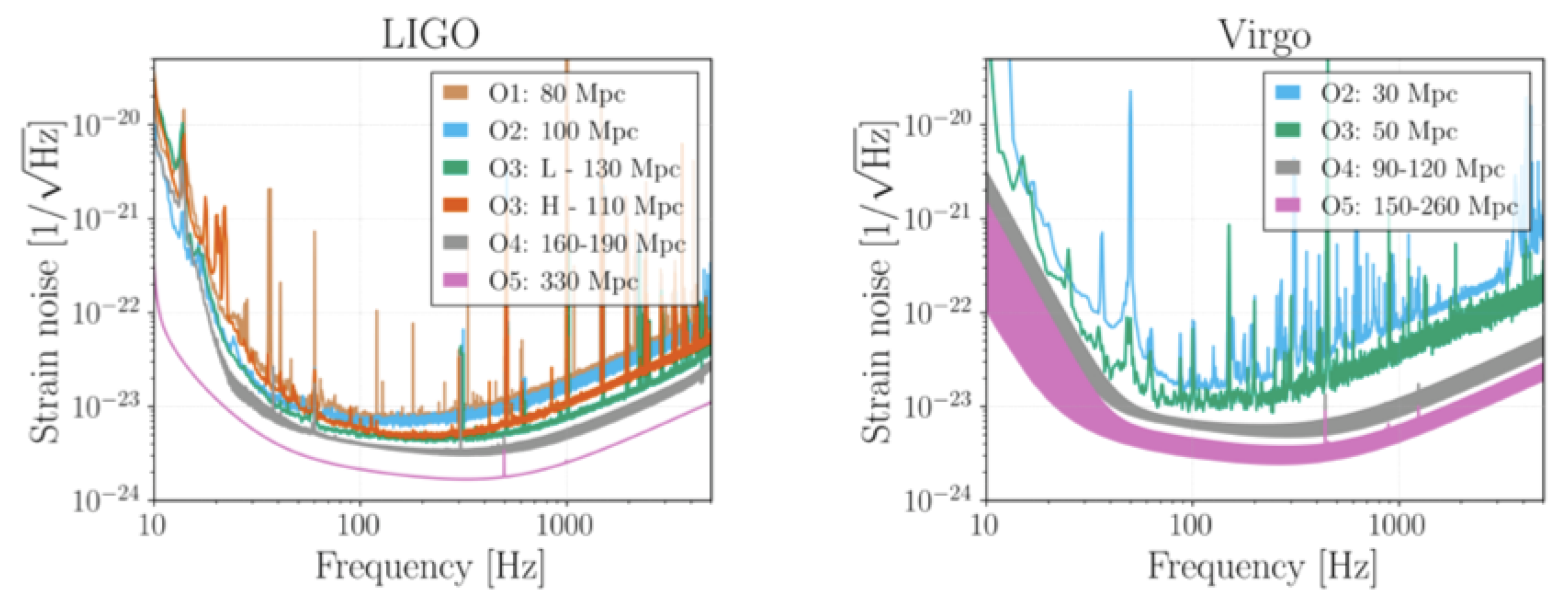
Sep ‘15 - Jan ‘16

O2

Nov ‘16 - Aug ‘17

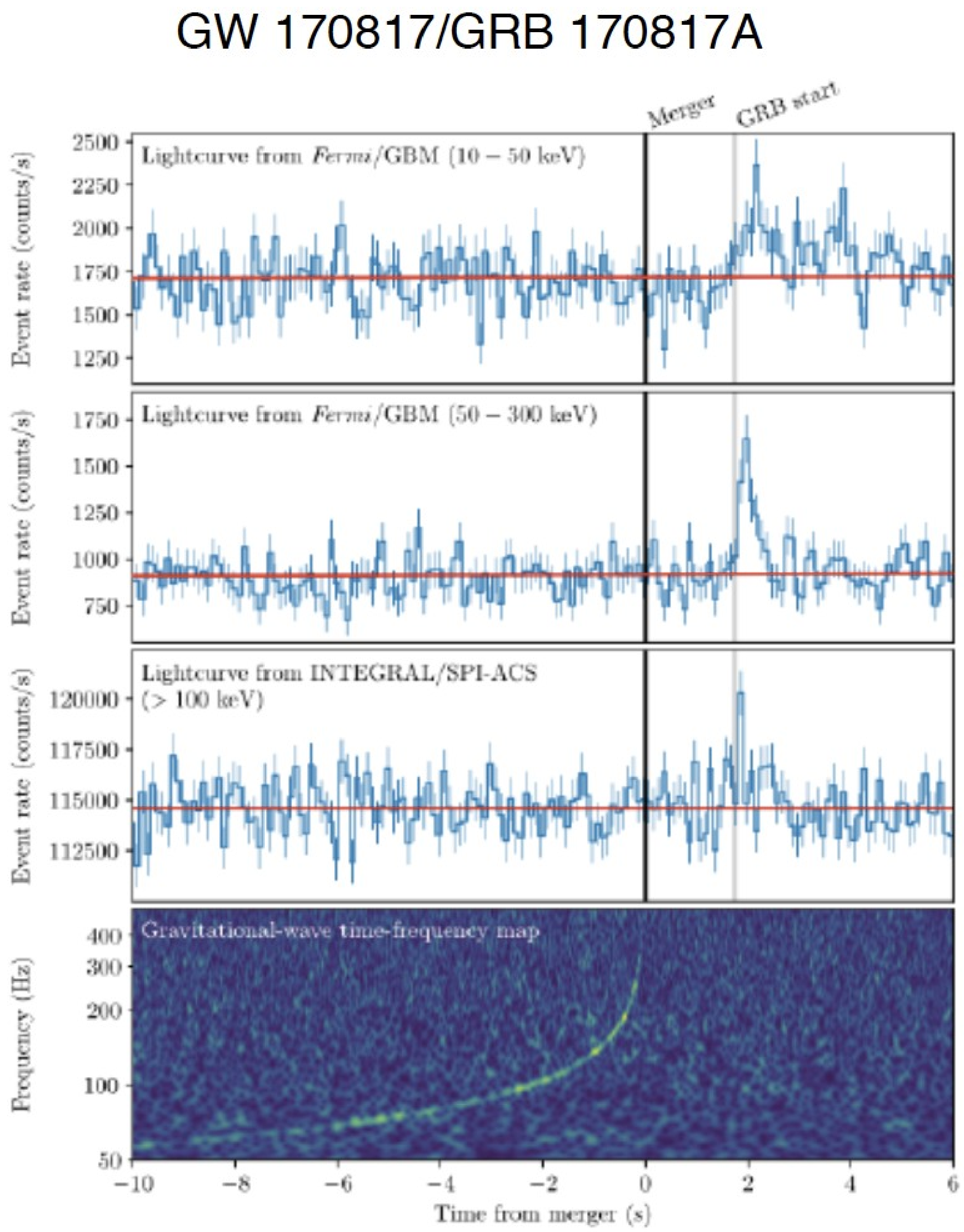
O3

Apr ‘19 - Mar ‘20



Abbott et al. 2020, LRR

GWs + KN jointly with short GRB 170817A



GW 170817/GRB 170817A

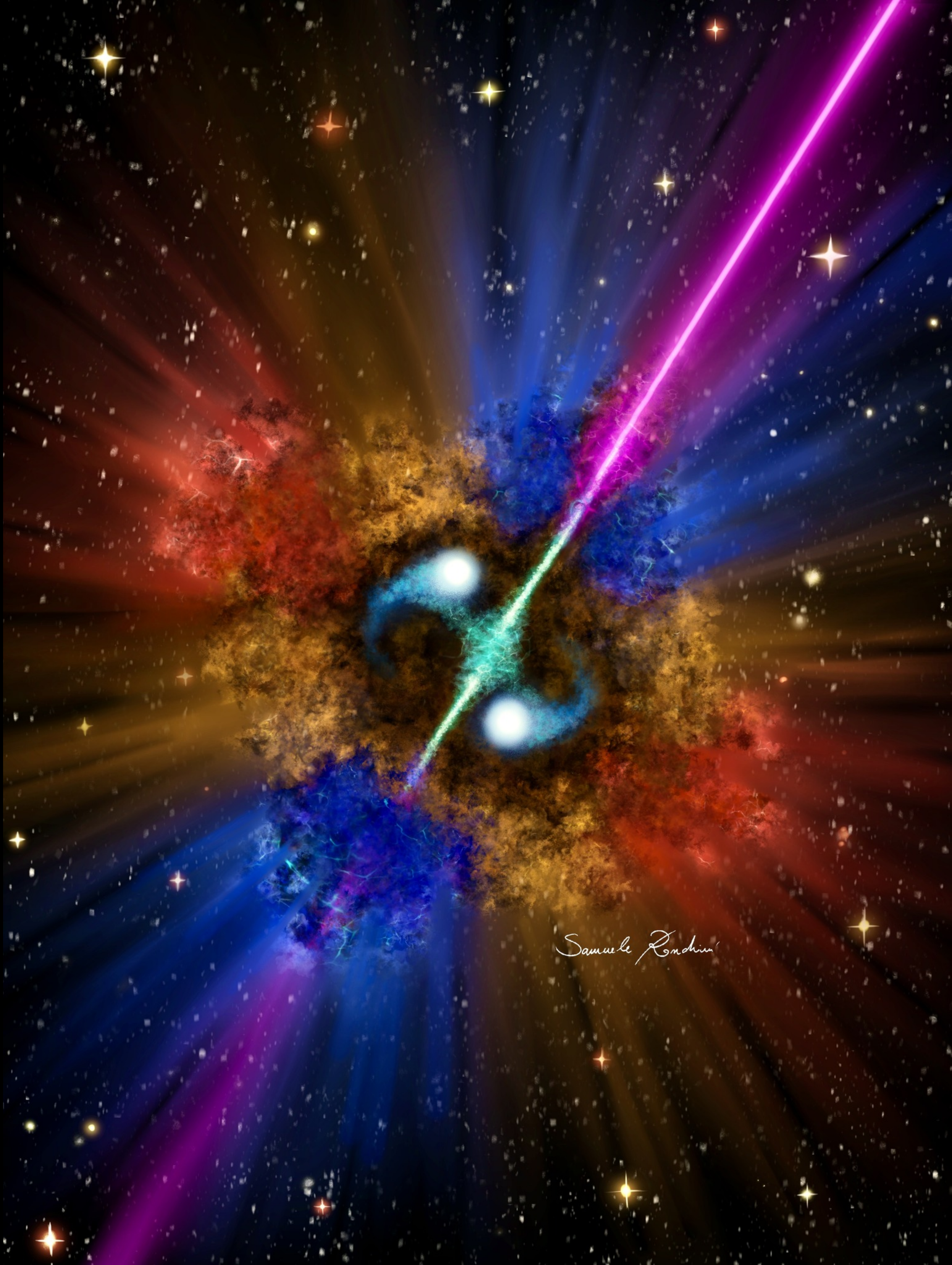
short GRBs

NS-NS

Abbott et al 2017

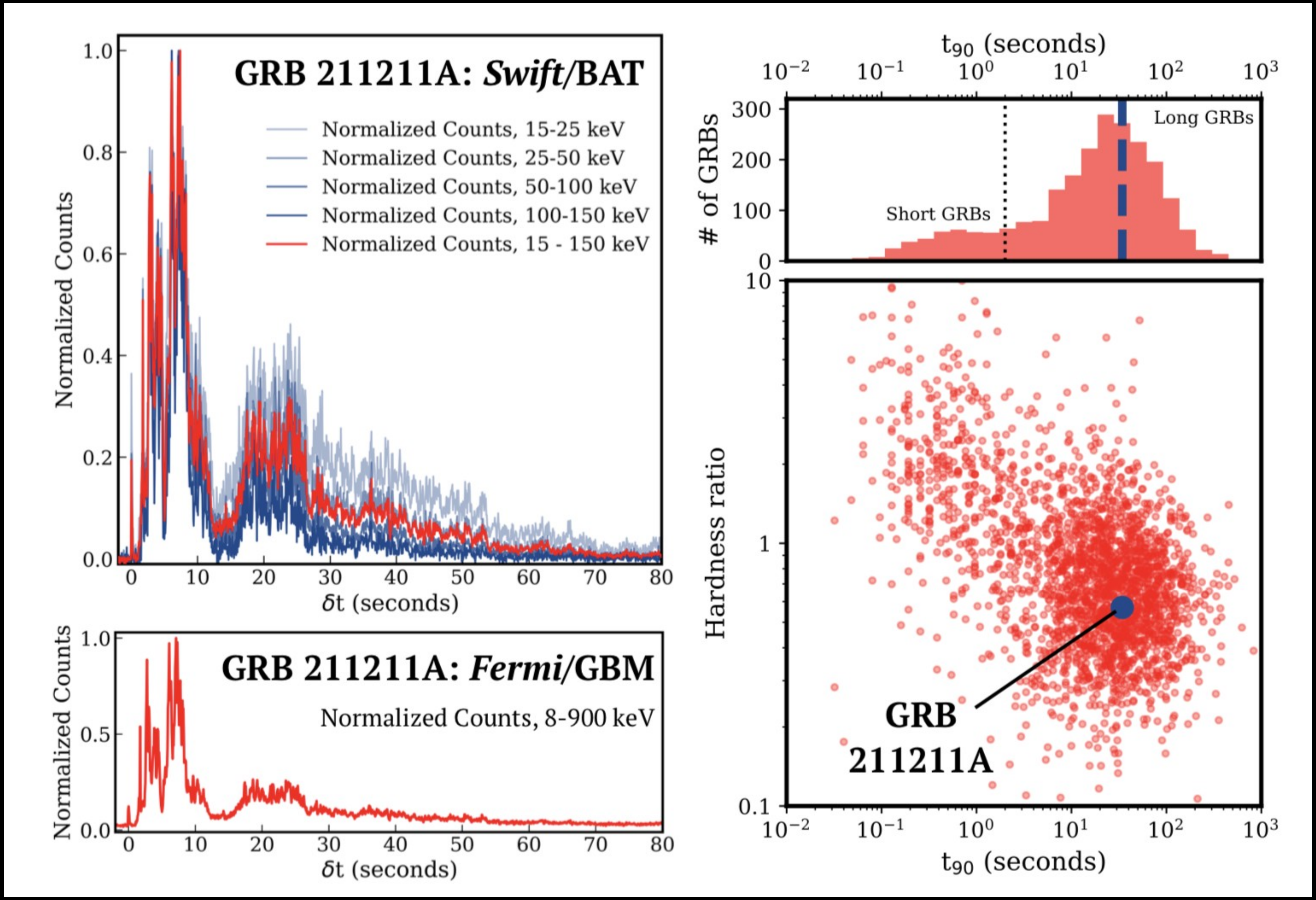
Beginning of the MM era

GRB 211211A



GRB 211211A: long GRB/ KILONOVA

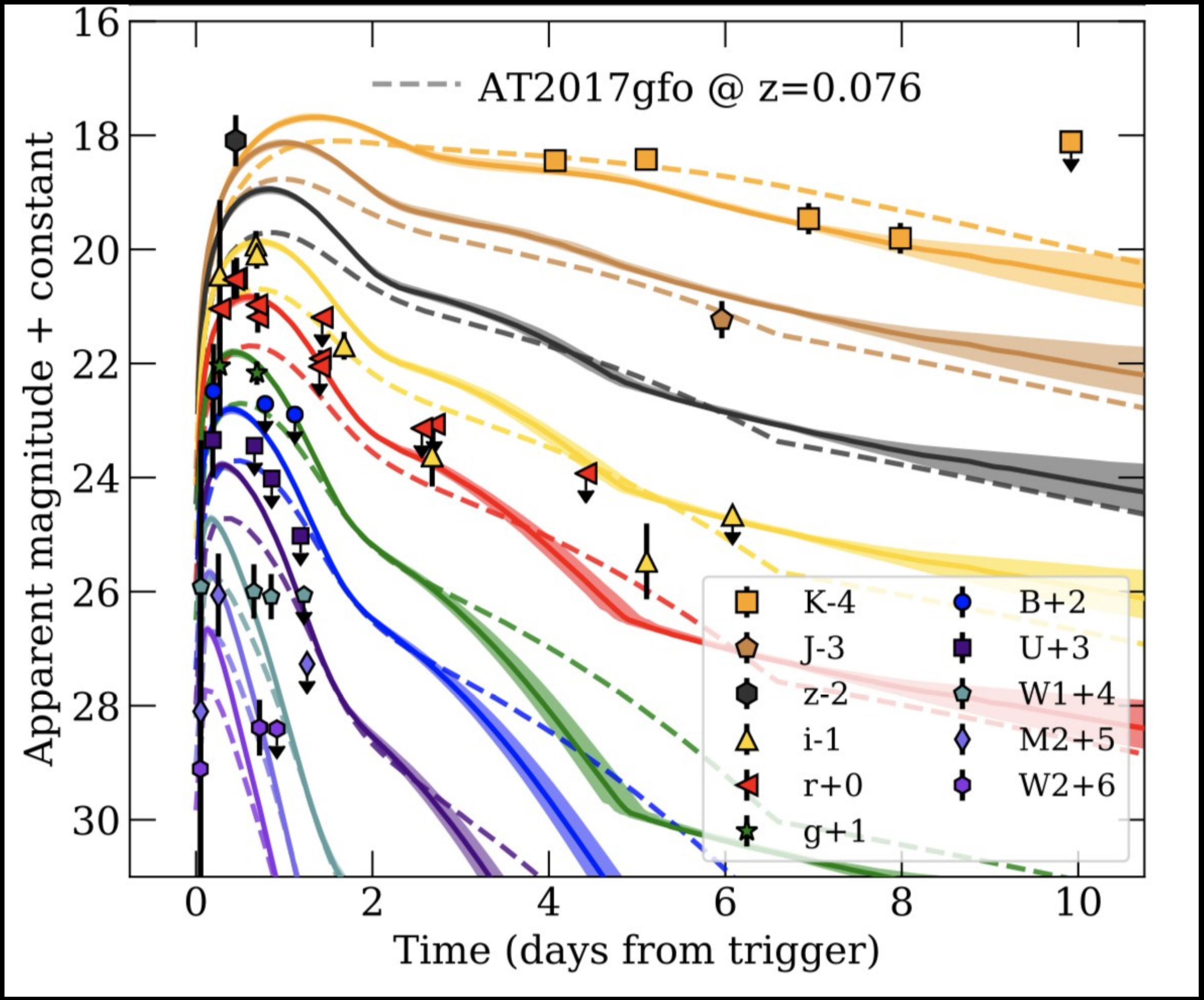
Rastinejad, J. C. et al. 2022 Nature



Minute-duration GRB, prompt and bright spikes lasted >12 s

Nearby GRB at 350 Mpc and 8 kpc from the galaxy center

GRB 211211A: long GRB/ KILONOVA



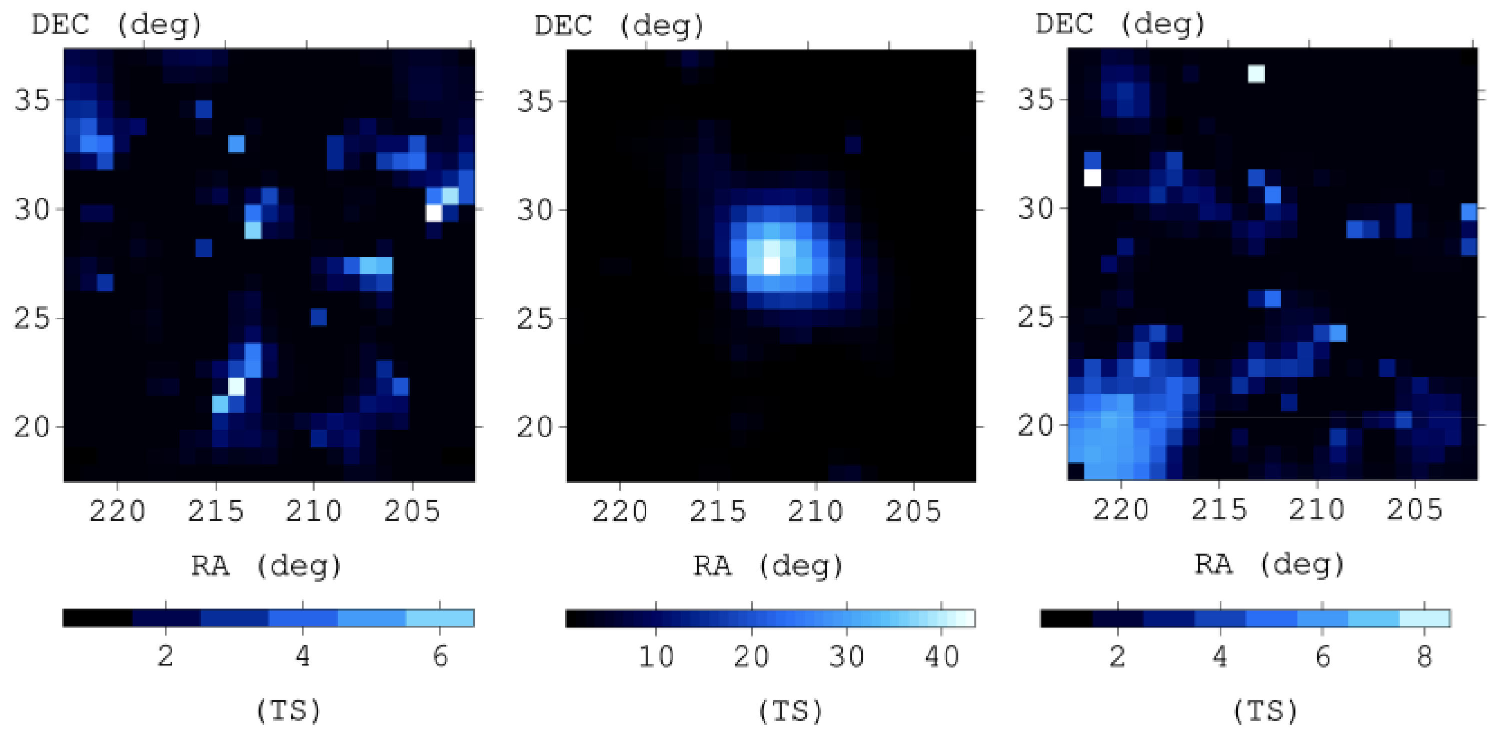
Rastinejad, J. C. et al. arXiv:2204.10864

10% local long GRB population may come from mergers

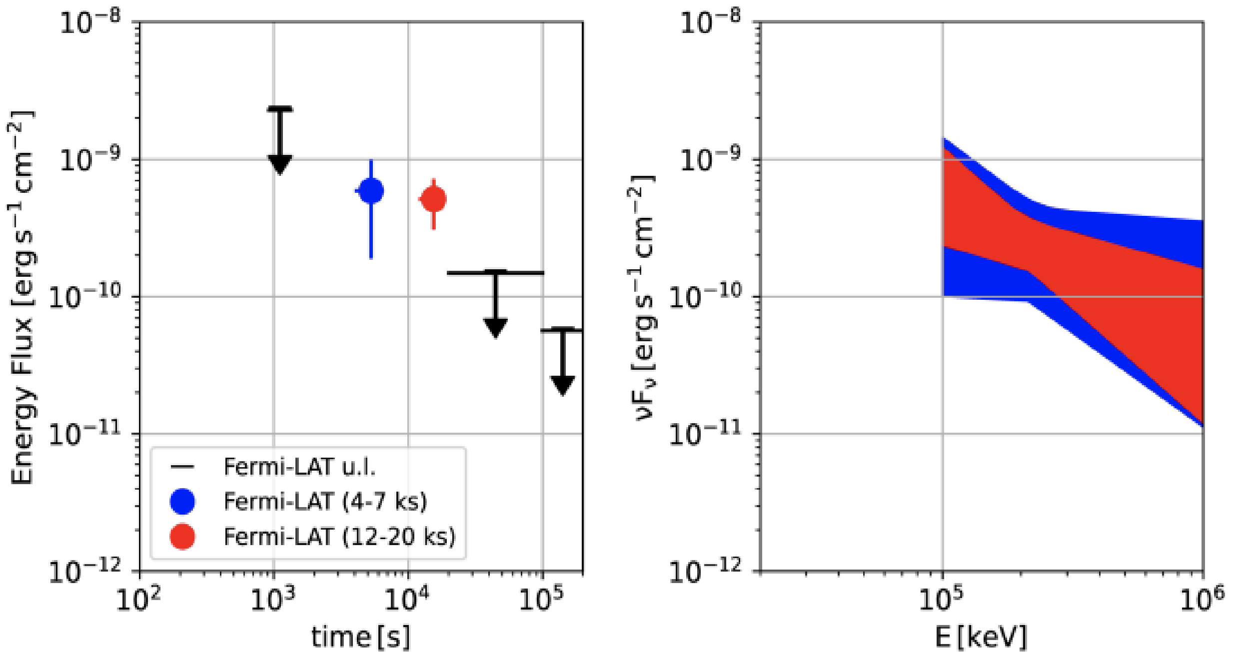
GW170817-like events are within reach

See also Troja et al. 2022 Nature, Xiao, S. et al. 2022 Nature

GRB 211211A: GeV emission



(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



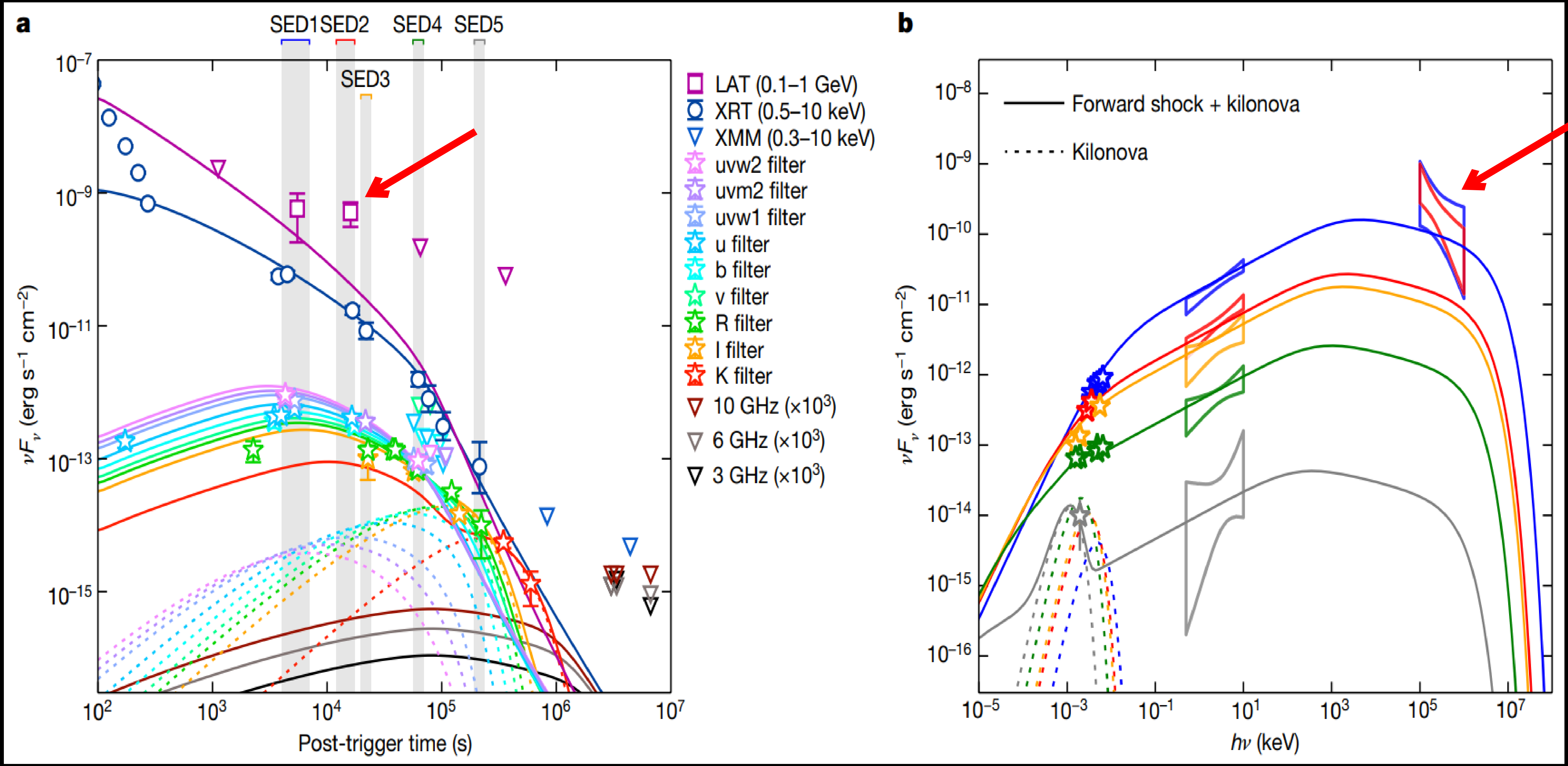
(d) t_0 to t_0+2 d

Mei, BB+ 2022, Nature

GRB 211211A: GeV excess

Light curve

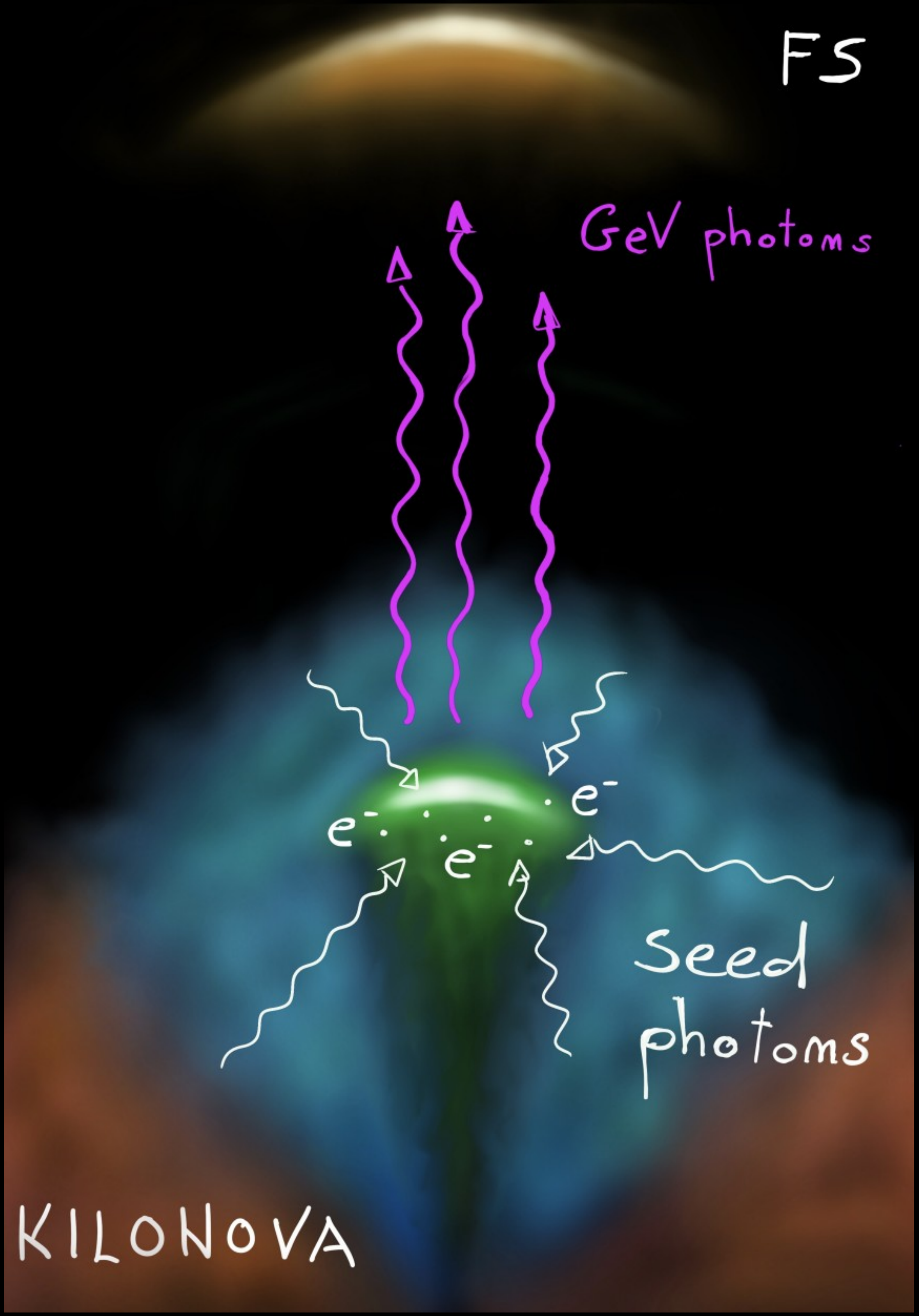
Spectrum



The GeV emision is in EXCESS with respect to synchrotron emission from standard forward shock of the relativisic jet explaining the afterglow emission in the other bands

Mei, BB+ 2022, Nature

GeV emission from a compact binary merger



- External Inverse Compton

- Kilonova seed photons for the EIC

- Electrons nearby the kilonova photosphere at $t = 10^4$ s

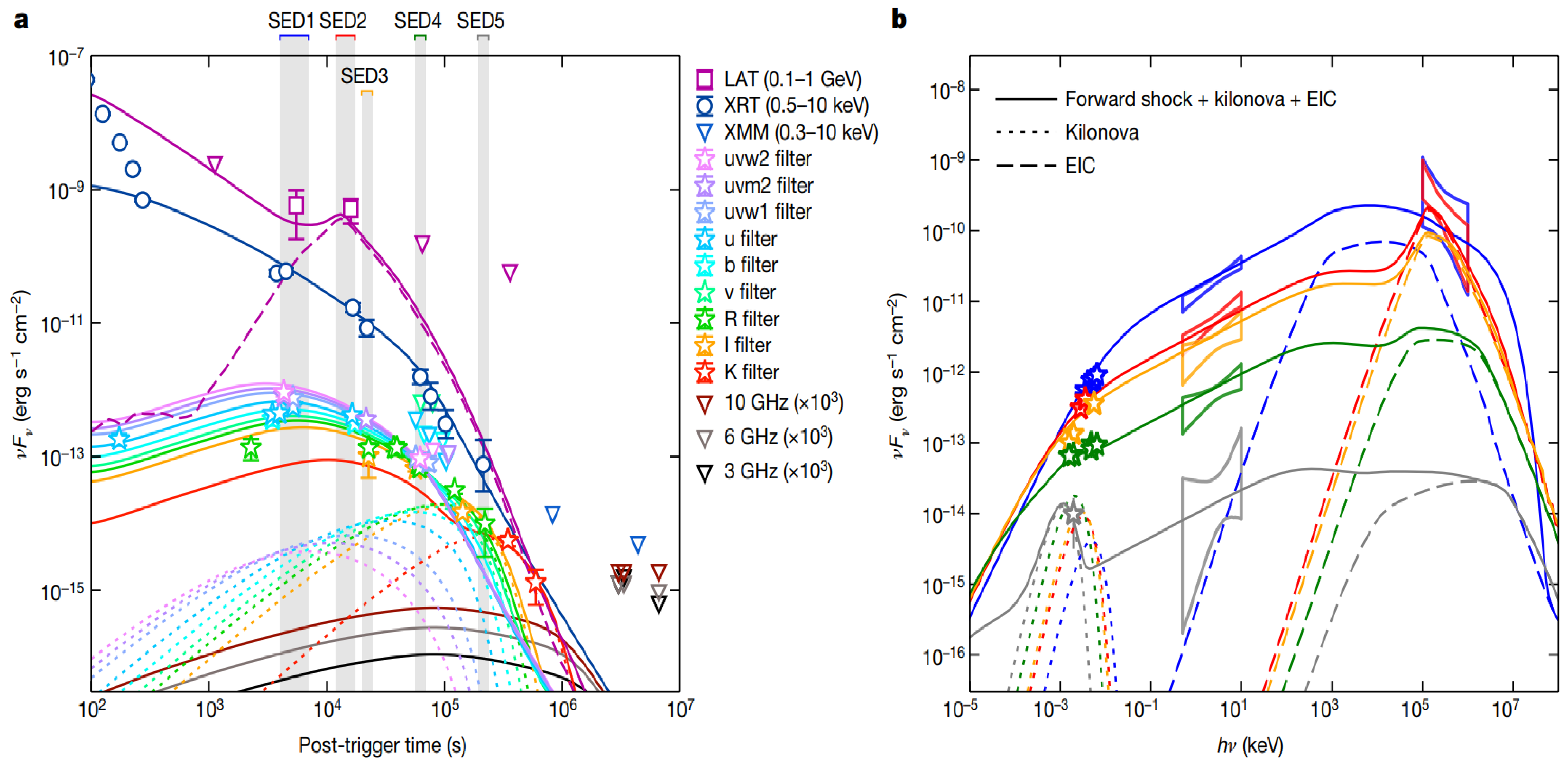
- Presence of a late-time low-power jet

Mei, BB+ 2022, Nature

External Inverse Compton of Kilonova photons

Light curve

Spectrum



Mei, BB+ 2022, Nature

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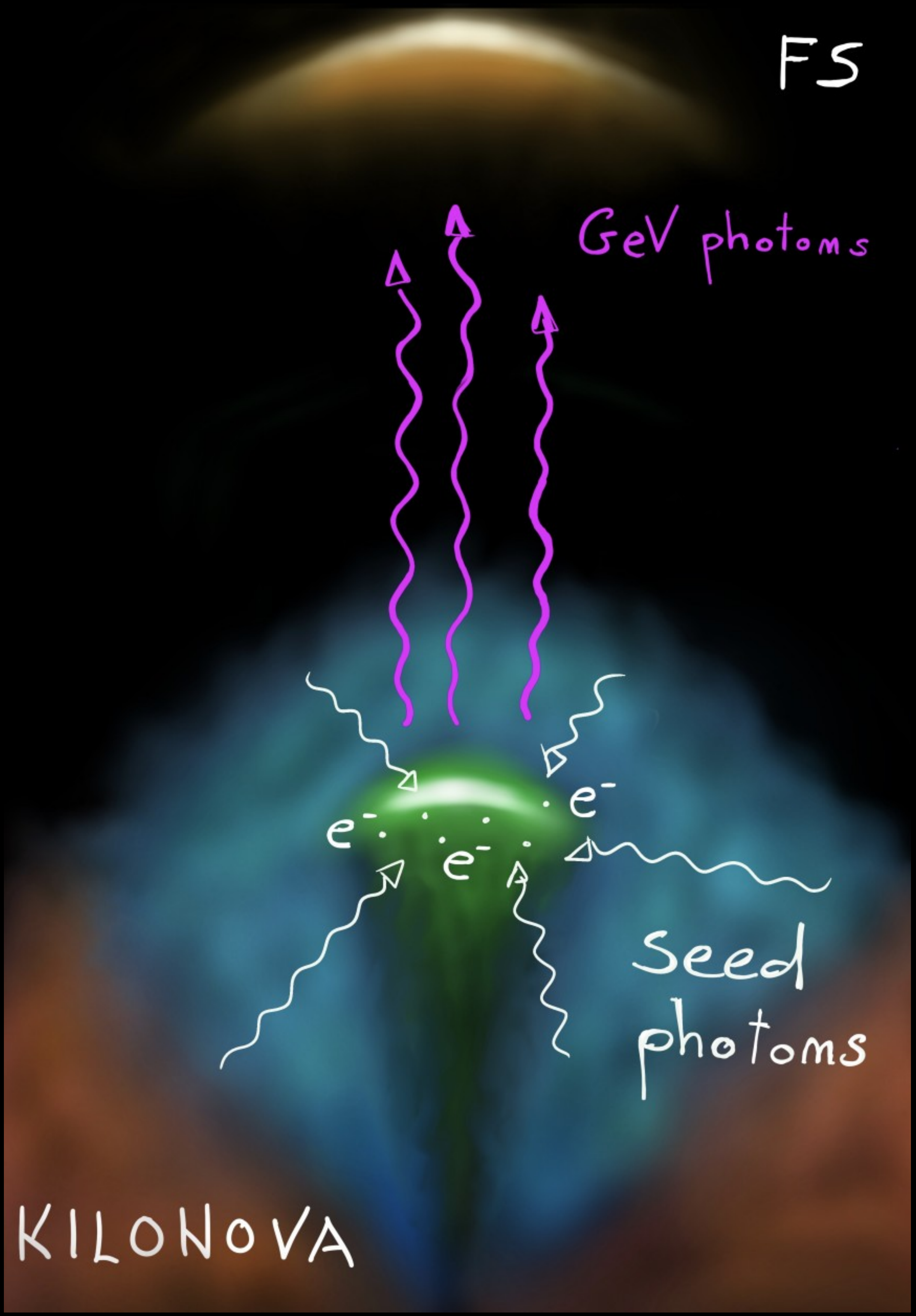
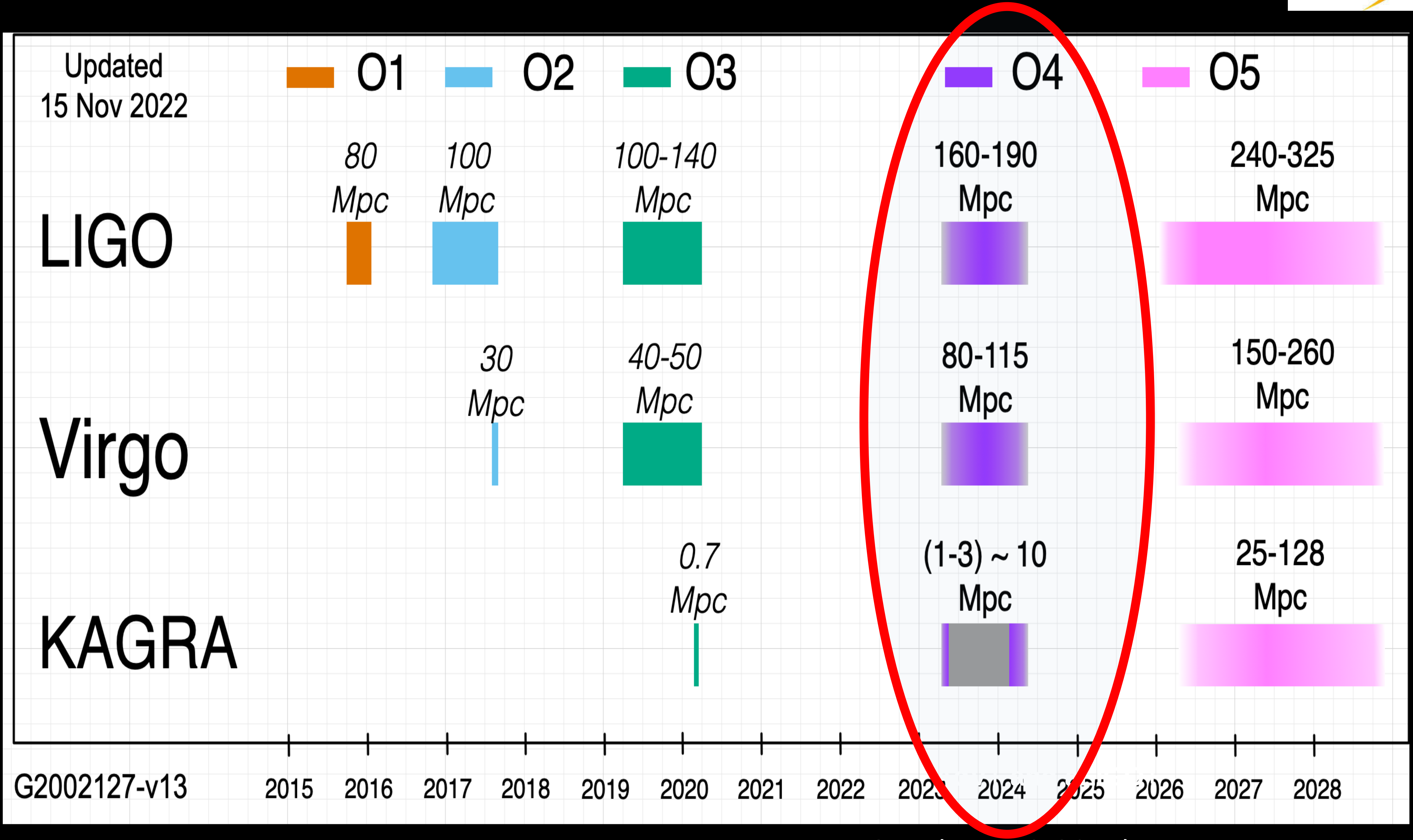


New counterpart for GW signals

GeV gamma-rays can probe central engine activity and kilonova ejecta

Mei, BB+ 2022, Nature

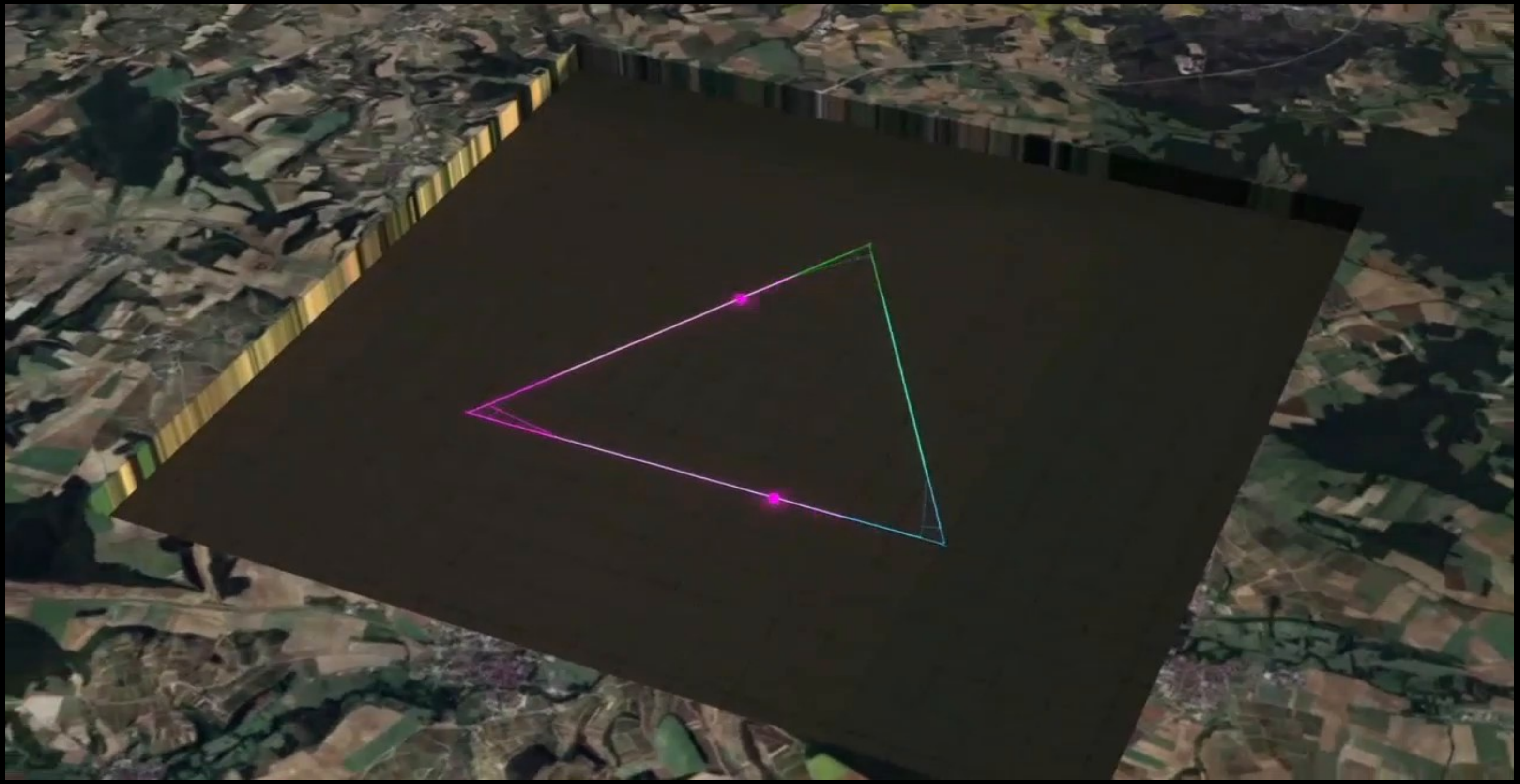
Observing run timeline & BNS range



Abbott et al. 2020, LRR

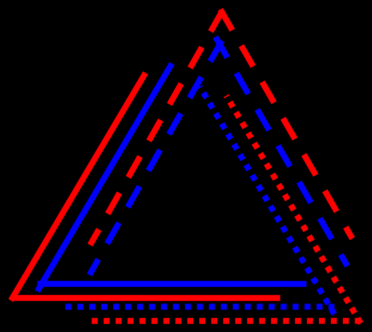
O4 volume ~ 3*O3 volume
O5 volume ~10*O3 volume

ET: The European 3G GW observatory concept



- Triangular shape
- Arms: 10 km
- Underground
- Cryogenic
- Increase laser power
- Xylophone

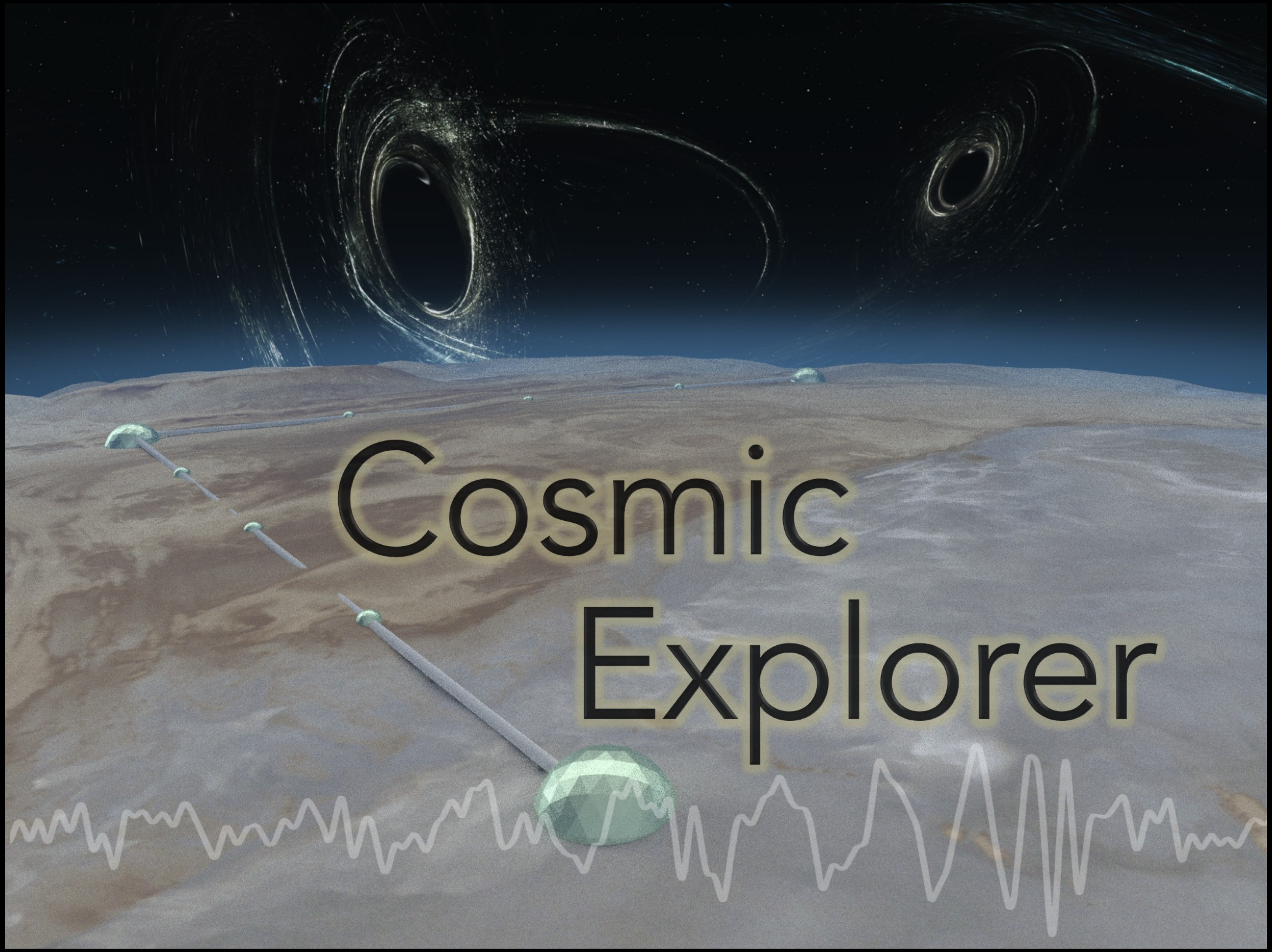
...



INCLUDED IN ESFRI ROADMAP in 2021

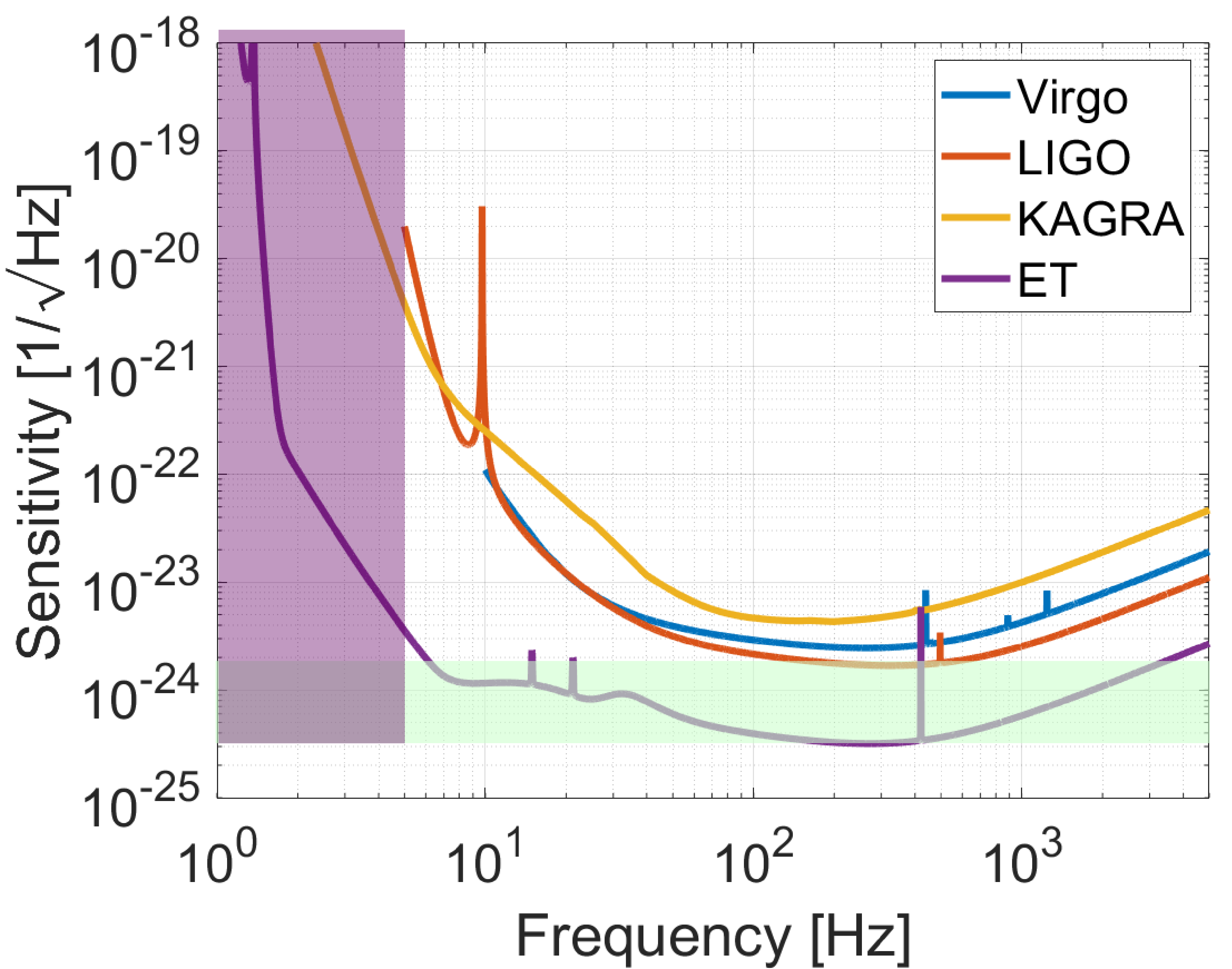
See GWIC roadmap, Bailes et al. 2021, Nature Reviews Physics
Maggiore et al 2020, JCAP; Evans et al. 2021 arXiv:2109.09882

3G effort worldwide



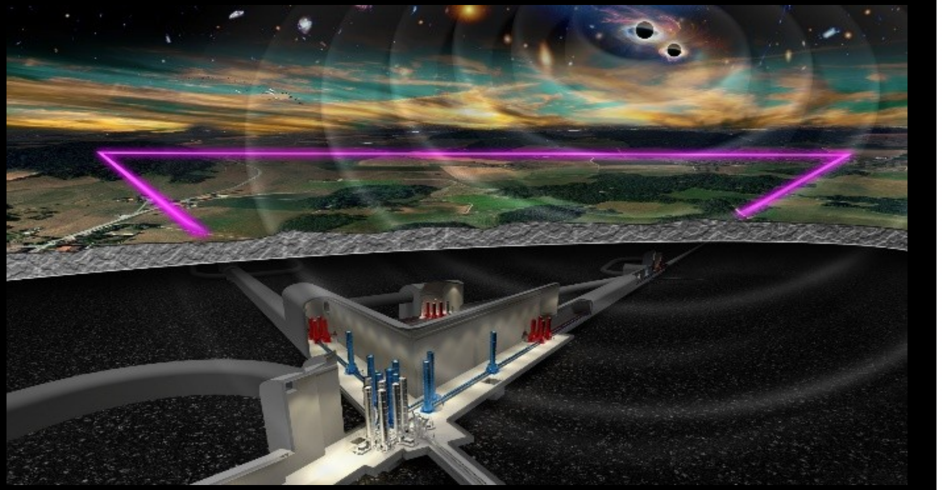
Cosmic Explorer: L shaped detectors, two sites
(40km, 20 km [option])

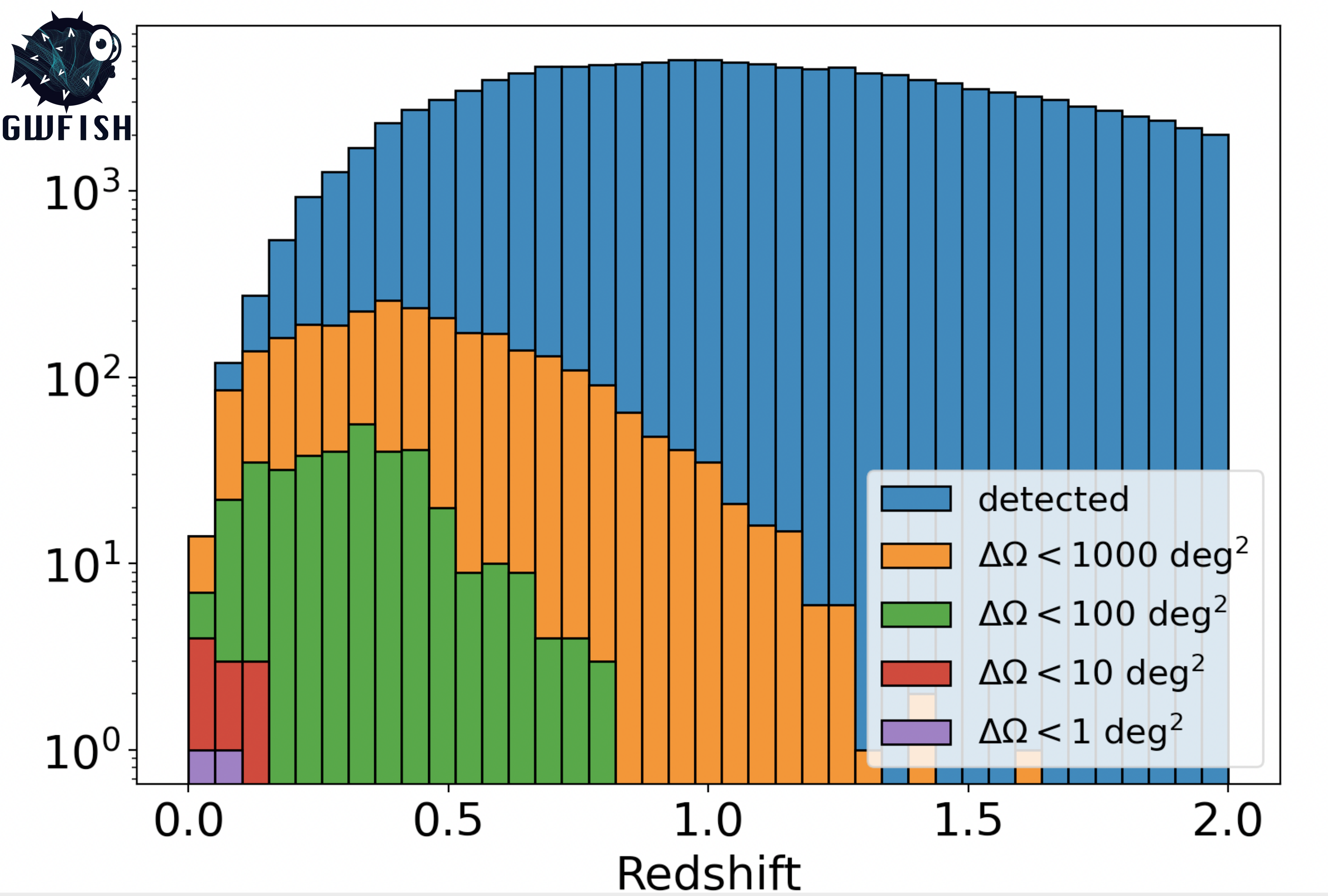
EXPECTED SENSITIVITY



ET sky-localization capabilities

GWFISH:
Dupesta, Harms, ***BB***+ 2022





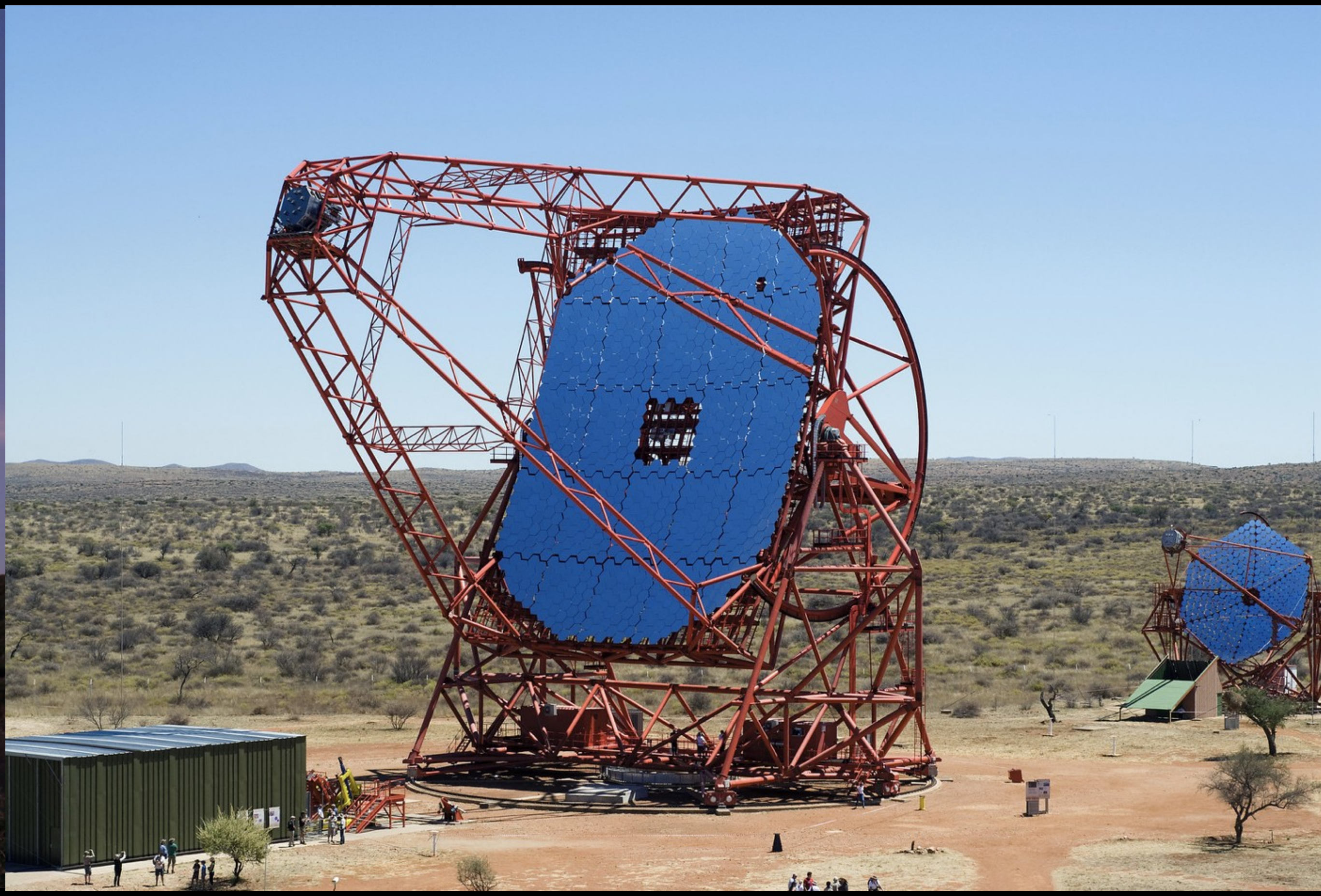
ET low frequency sensitivity makes it possibile to localize BNS!

- O(100) detections/ yr with sky-localization (90% c.r.) < 100 sq. deg
- Early warning alerts!

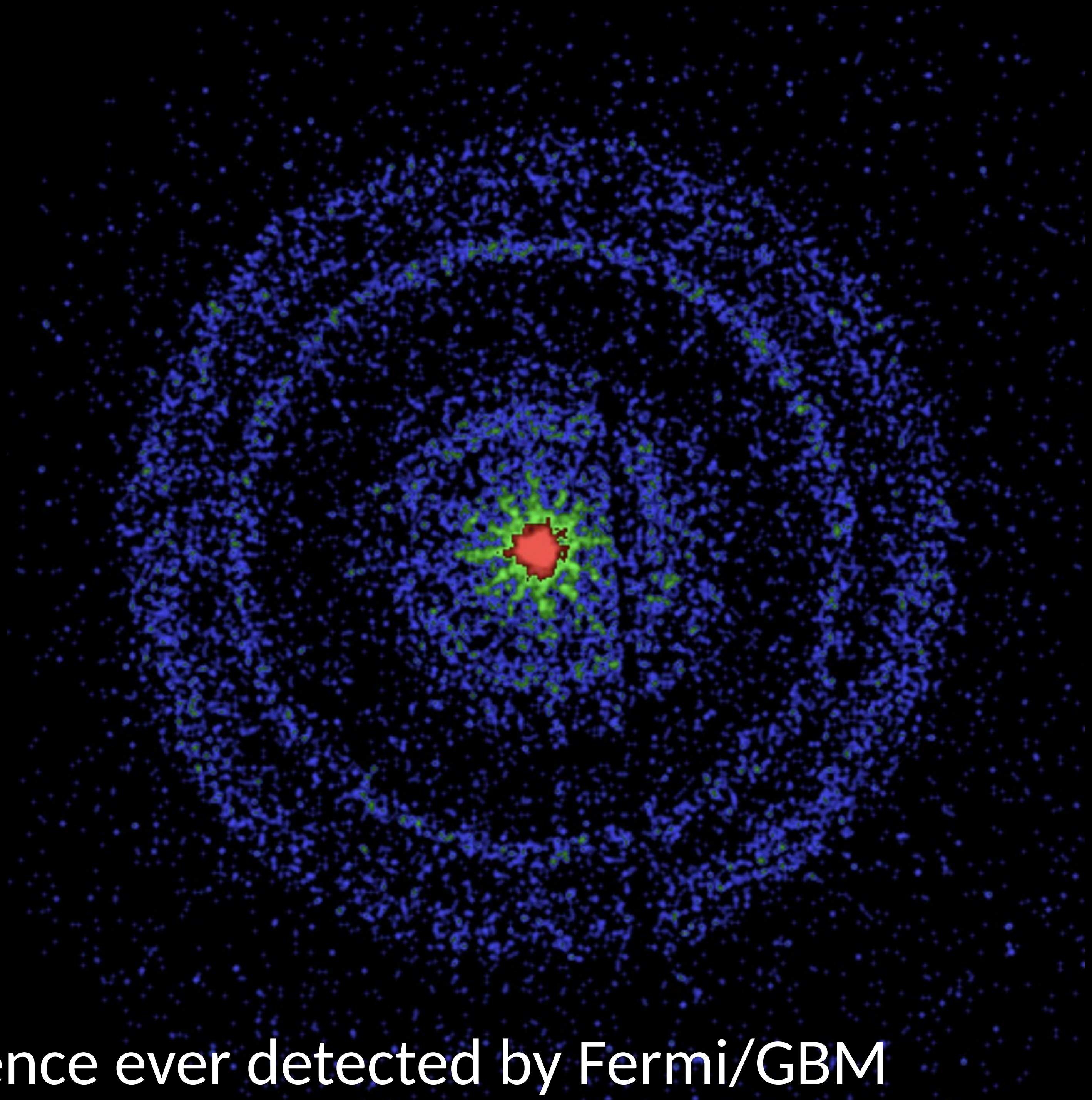
GRBs at very-high-energies (TeV)

The discoveries of 2019

MAGIC and H.E.S.S.

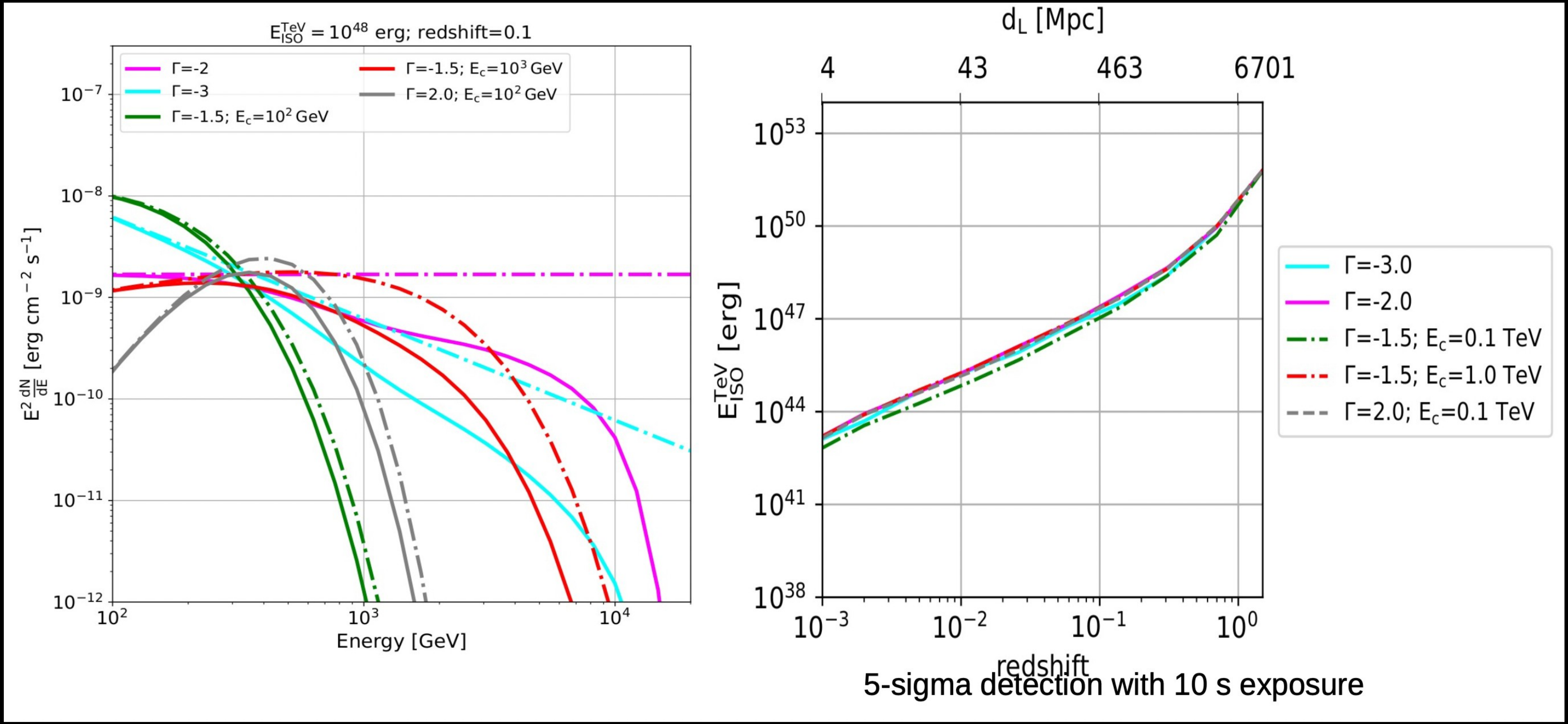


GRB 221009A the GRB of the century!



- highest fluence ever detected by Fermi/GBM
- high-energy counterpart starting after about 200 s from the Fermi/GBM trigger time
- LHAASO reported the detection of more than 5000 VHE photons (up to 18 TeV) within 2 ks from the trigger-time

VHE gamma-ray emission



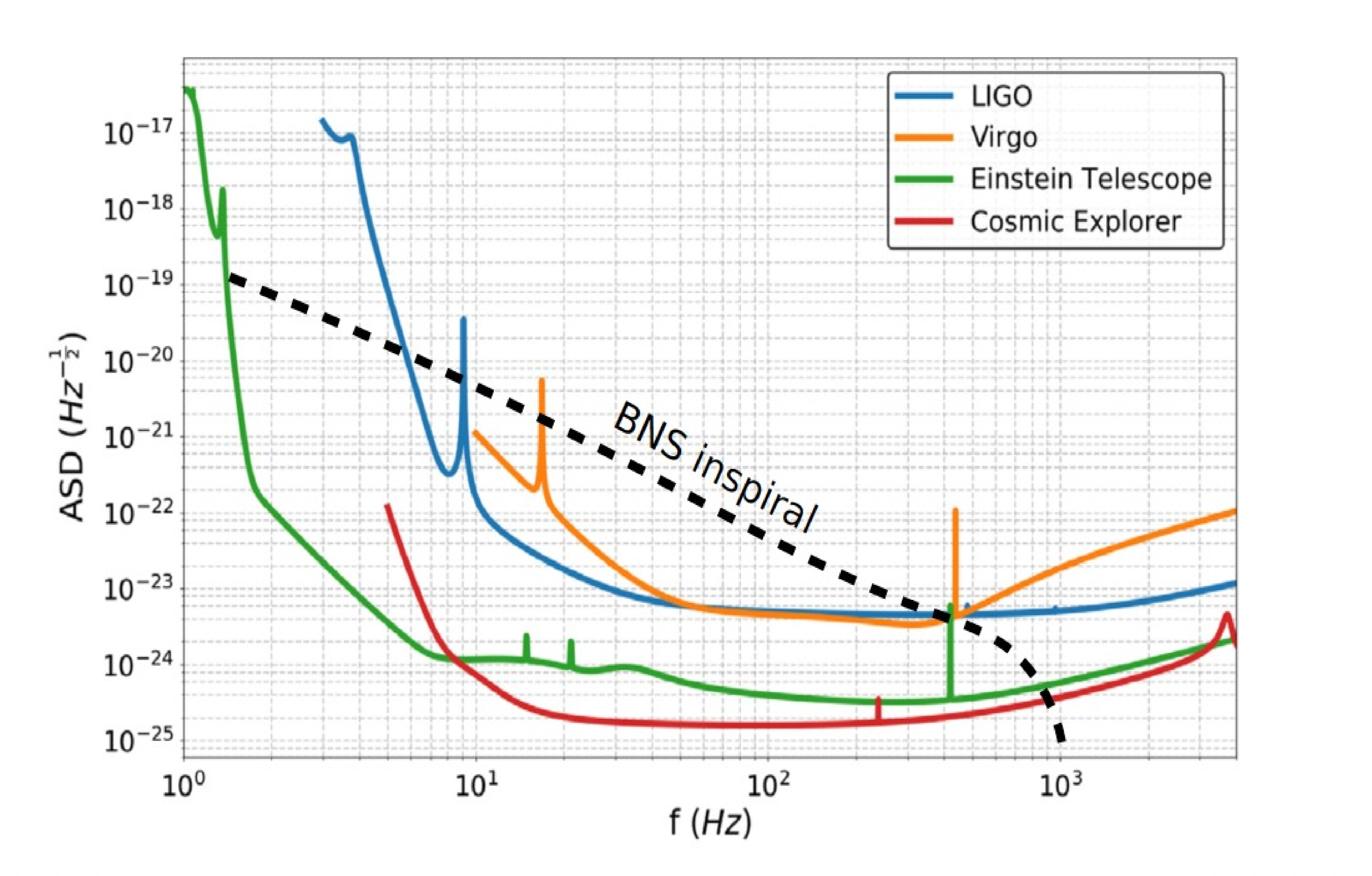
5-sigma detection with 10 s exposure

Banerjee et al. 2022, arXiv:2212.14007

Synthetic VHE prompt SED from BNS, possible with CTA

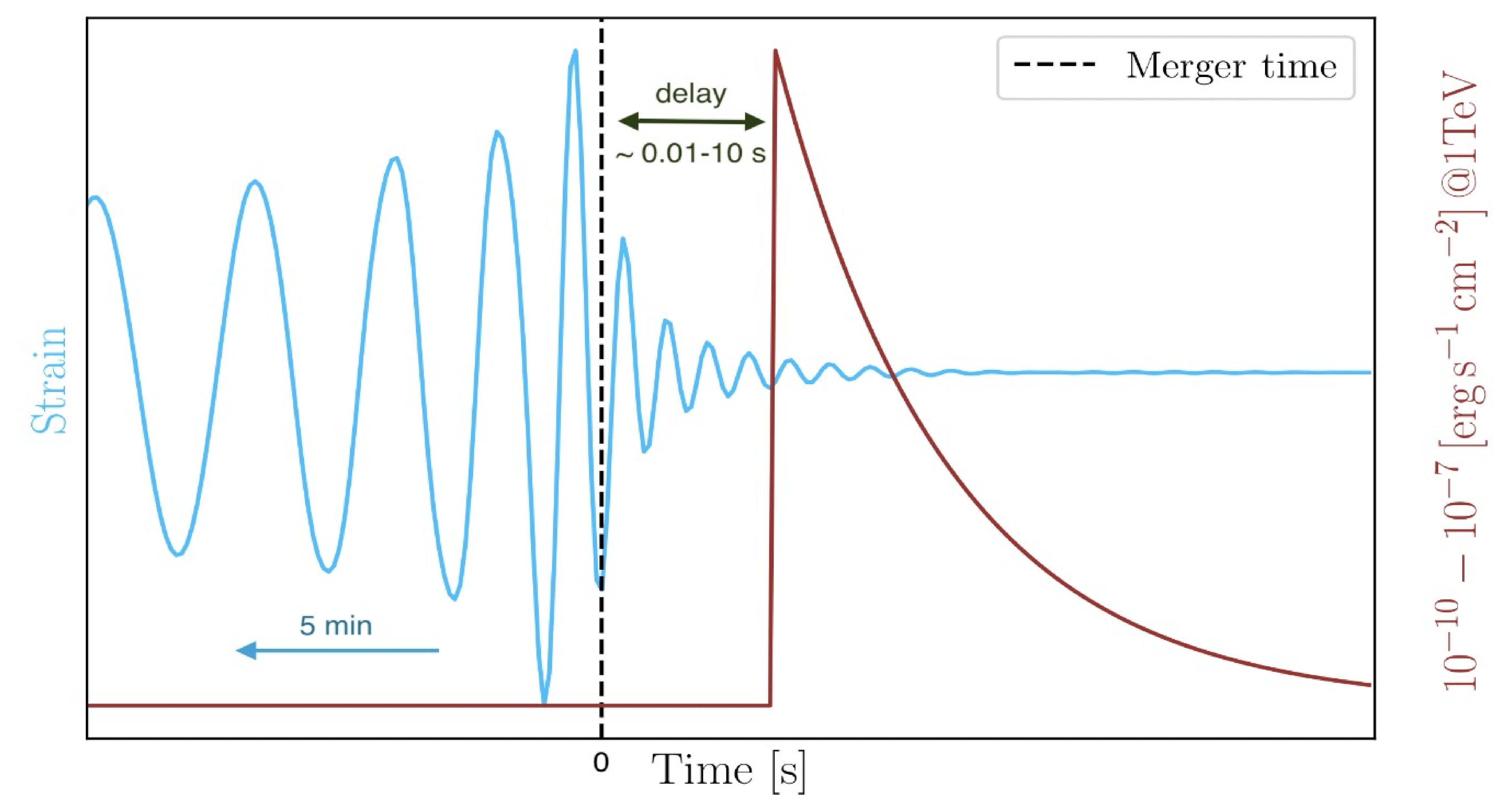
But, sky-loc.?

VHE gamma-ray emission



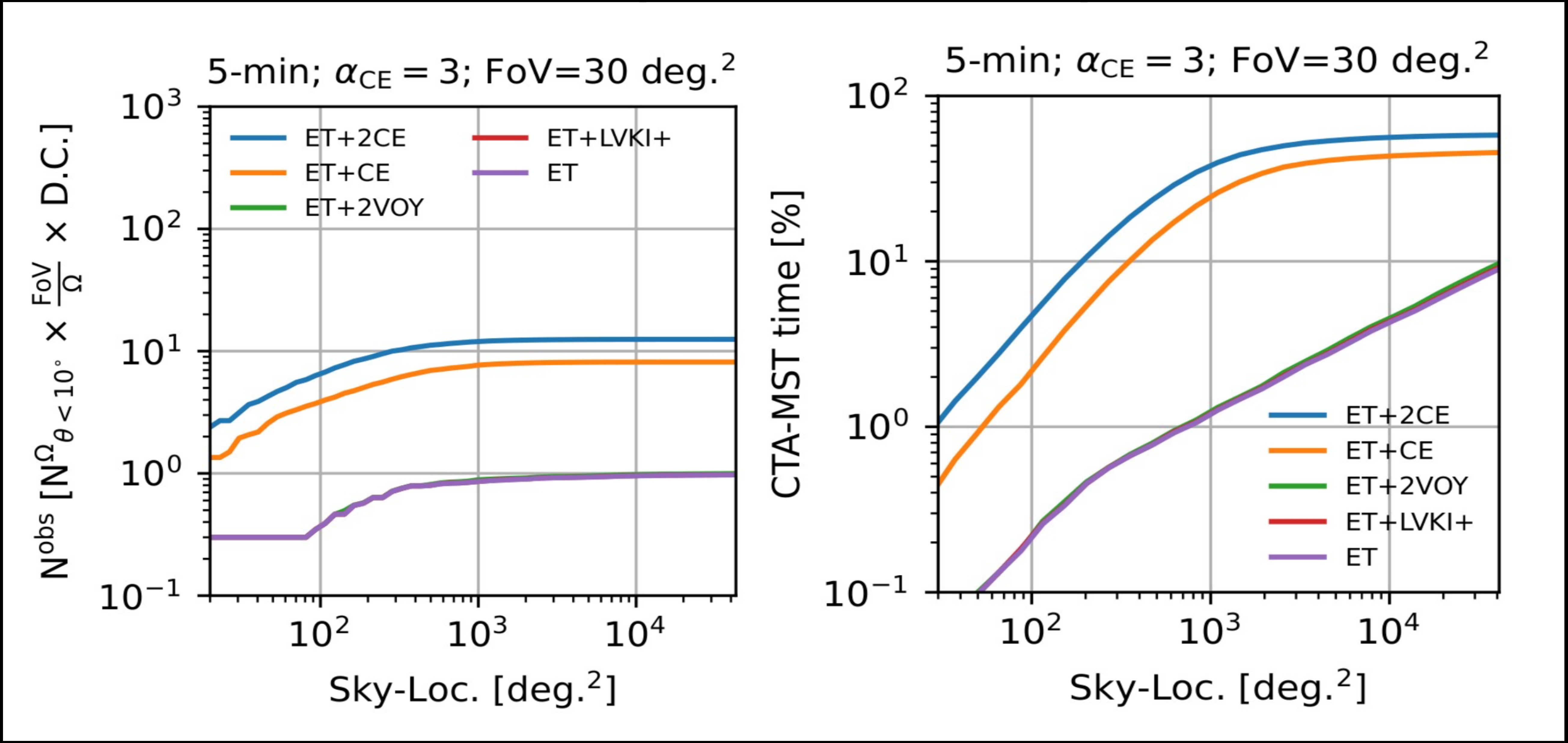
Banerjee et al. 2022, arXiv:2212.14007

VHE gamma-ray emission



Banerjee et al. 2022, arXiv:2212.14007

VHE gamma-ray emission



Banerjee et al. 2022, arXiv:2212.14007

Summary

1. GW 170817/ GRB 170817A has opened the new era of MM astronomy

2. GRB 211211A has raised series of questions and possibilities. GeV is a possible window to look for the counterparts: large FoV, all-sky!

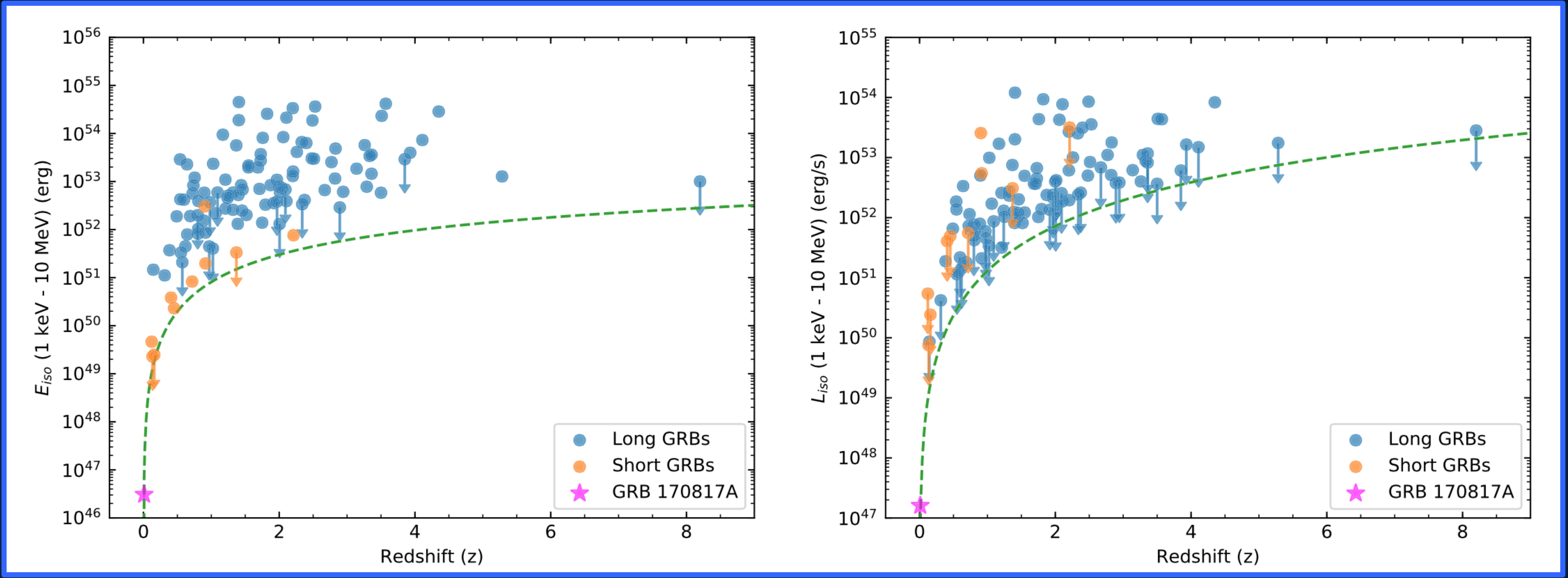
3. Late spring 2023, we wait for the 04 run of LVK with as many telescopes as possible. **GMRT proposal submitted**!

4. GeV and TeV counterparts of GWs are yet to be explored by observations.

5. BNS merger pre-alert is powerful tool for early EM detections (e.g. CTA) in the third generation of GW detectors.

GRB 170817A

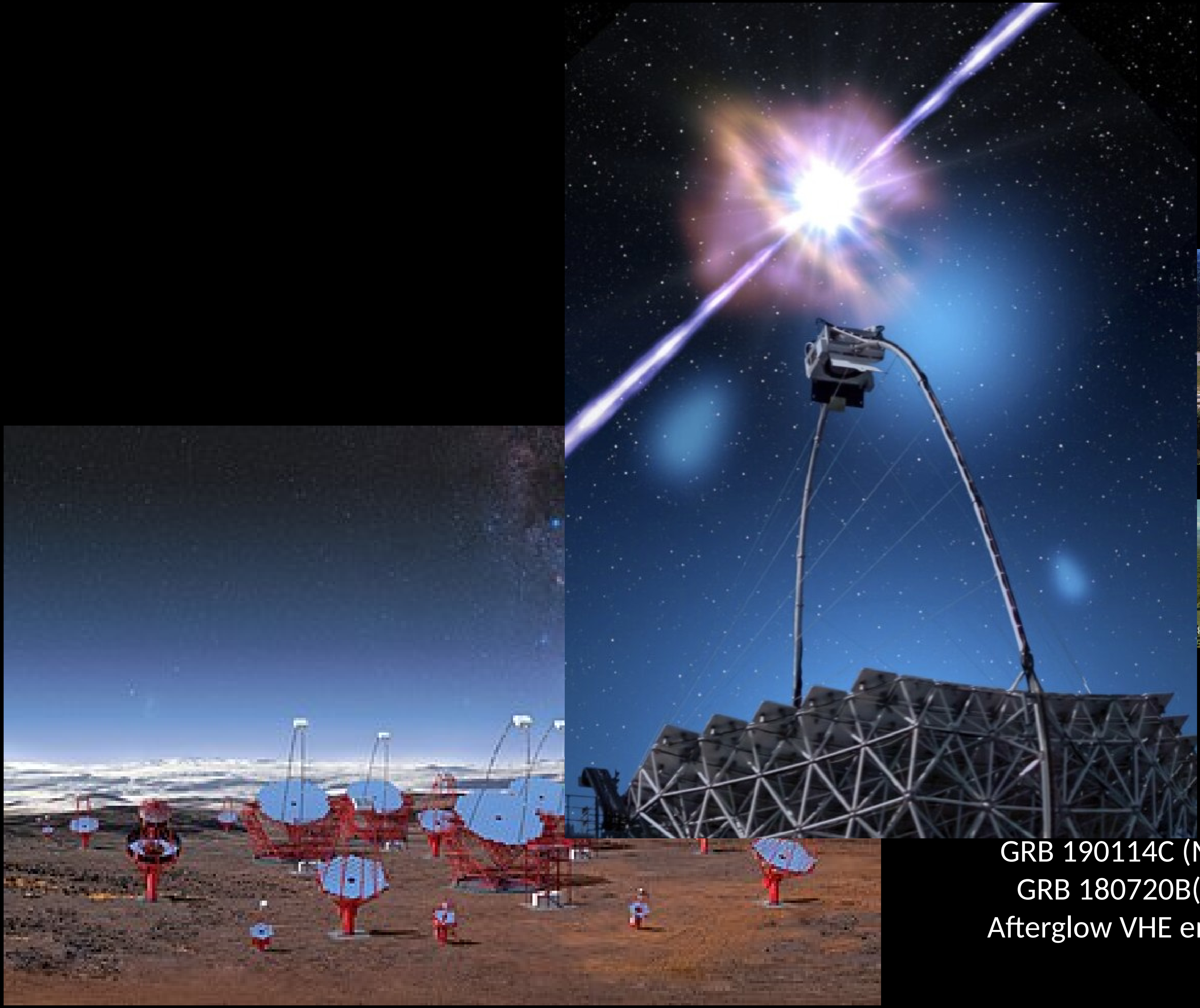
- 100 times closer than typical GRBs observed by Fermi-GBM
- "Subluminous" compared to the population of long/short GRBs
- 10^2 – 10^6 less energetic than other short GRBs

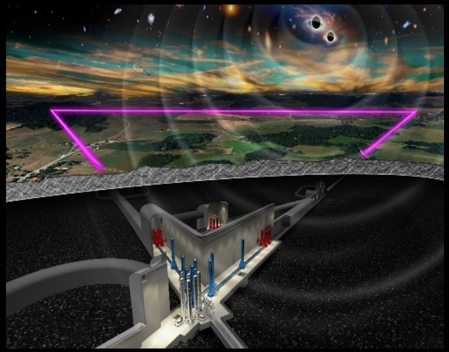


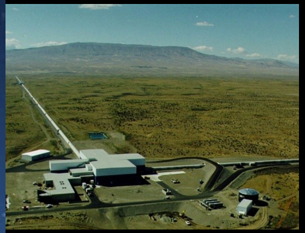
Abbott et al. 2017, APJL, 848, L13

First short GRB viewed off-axis?

CTA and GW DETECTOR synergies

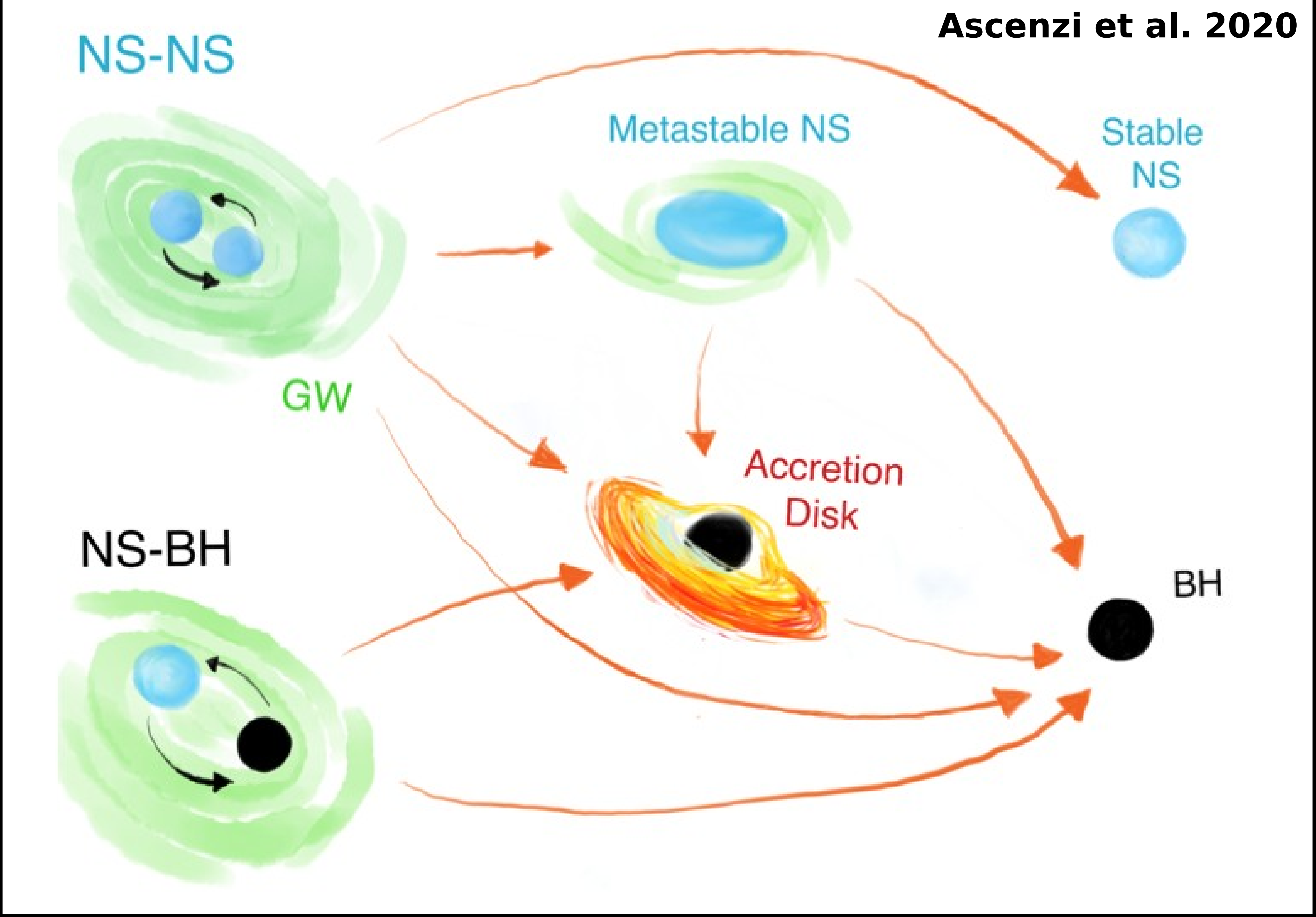






GRB 190114C (MAGIC)
GRB 180720B(HESS)
Afterglow VHE emission!

NSNS/ NSBH channels to produce short GRB jets



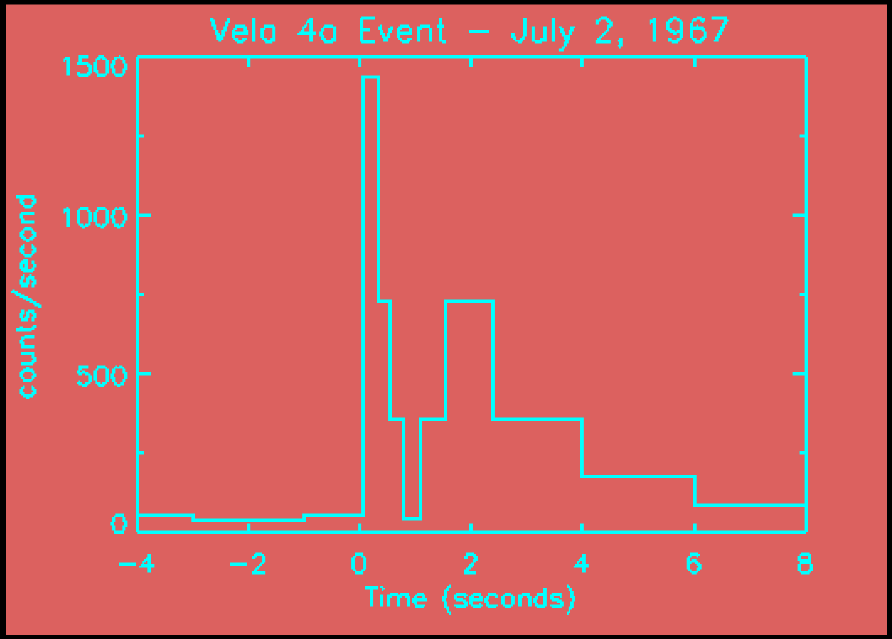
Ascenzi et al. 2020

Unnecessary,
yet
sometimes life saving
slides

Gamma-ray bursts

Discovery	Dark ages	Afterglow-era	MWL-era	MM-era	VHE-era
1967	1970- 1990	1997- ...	2004- ...	2017- ...	2019- ...

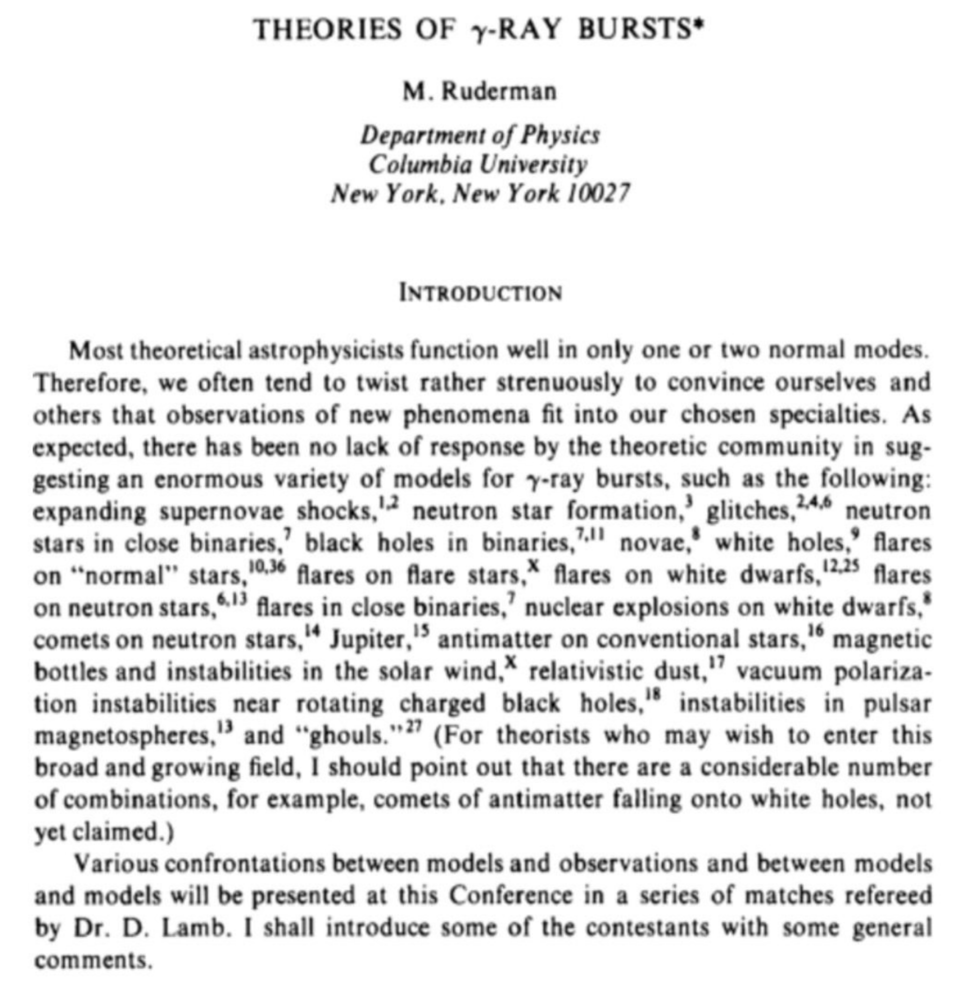
0.2 - 1.5 MeV



Klebesadel et al. 1973

Dark ages 1970-1990

it can be almost anything



THEORIES OF γ-RAY BURSTS*

M. Ruderman

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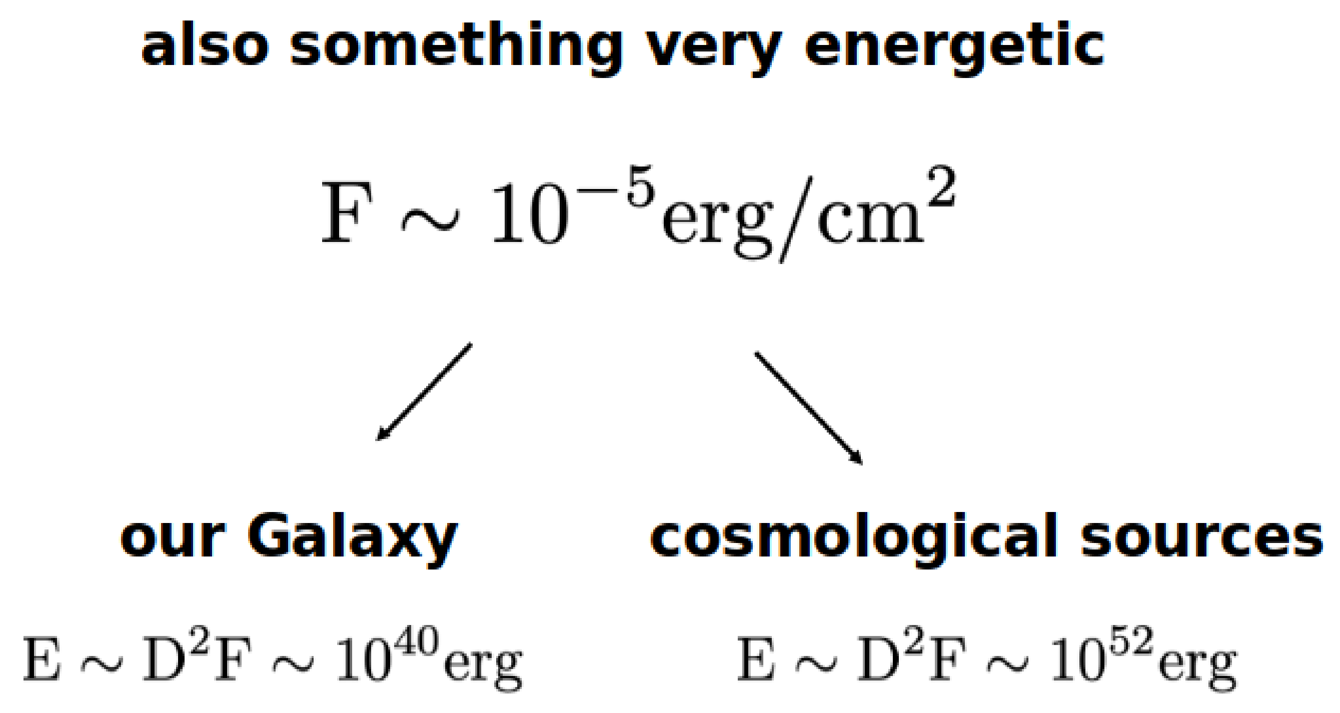
INTRODUCTION

Most theoretical astrophysicists function well in only one or two normal modes. Therefore, we often tend to twist rather strenuously to convince ourselves and others that observations of new phenomena fit into our chosen specialties. As expected, there has been no lack of response by the theoretic community in suggesting an enormous variety of models for γ-ray bursts, such as the following: expanding supernovae shocks,[1,2] neutron star formation,[3] glitches,[2,4,6] neutron stars in close binaries,[7] black holes in binaries,[7,11] novae,[8] white holes,[9] flares on "normal" stars,[10,36] flares on flare stars,[X] flares on white dwarfs,[12,25] flares on neutron stars,[6,13] flares in close binaries,[7] nuclear explosions on white dwarfs,[8] comets on neutron stars,[14] Jupiter,[15] antimatter on conventional stars,[16] magnetic bottles and instabilities in the solar wind,[X] relativistic dust,[17] vacuum polarization instabilities near rotating charged black holes,[18] instabilities in pulsar magnetospheres,[13] and "ghouls."[27] (For theorists who may wish to enter this broad and growing field, I should point out that there are a considerable number of combinations, for example, comets of antimatter falling onto white holes, not yet claimed.)

Various confrontations between models and observations and between models and models will be presented at this Conference in a series of matches refereed by Dr. D. Lamb. I shall introduce some of the contestants with some general comments.

also something very energetic



also something very energetic

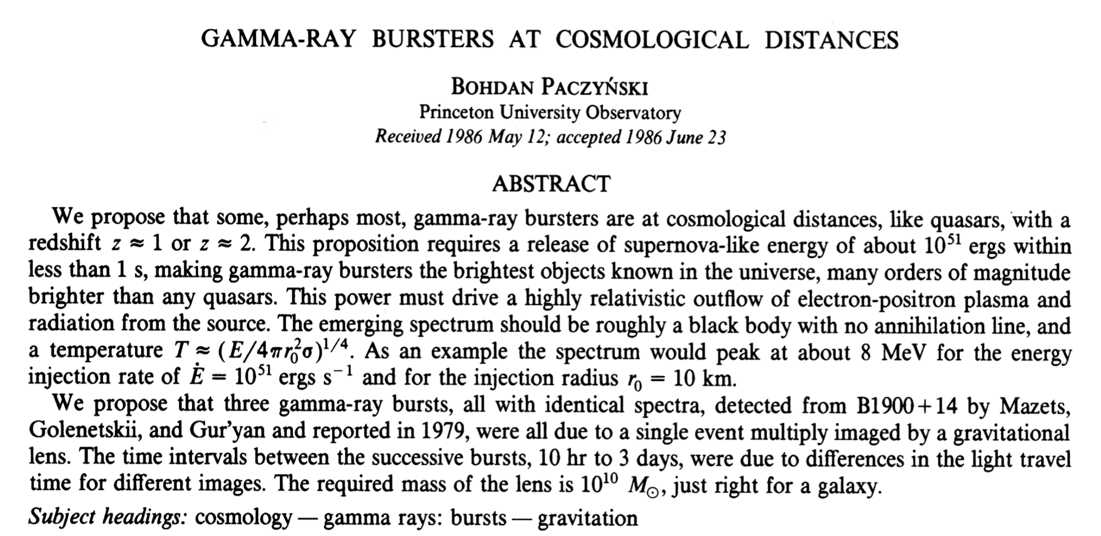
$$F \sim 10^{-5} \mathrm{erg/cm^2}$$

our Galaxy

$$E \sim D^2 F \sim 10^{40} \mathrm{erg}$$

cosmological sources

$$E \sim D^2 F \sim 10^{52} \mathrm{erg}$$



GAMMA-RAY BURSTERS AT COSMOLOGICAL DISTANCES

BOHDAN PACZYŃSKI
Princeton University Observatory

Received 1986 May 12; accepted 1986 June 23

ABSTRACT

We propose that some, perhaps most, gamma-ray bursters are at cosmological distances, like quasars, with a redshift $z \approx 1$ or $z \approx 2$. This proposition requires a release of supernova-like energy of about 10^{51} ergs within less than 1 s, making gamma-ray bursters the brightest objects known in the universe, many orders of magnitude brighter than any quasars. This power must drive a highly relativistic outflow of electron-positron plasma and radiation from the source. The emerging spectrum should be roughly a black body with no annihilation line, and a temperature $T \approx (E/4\pi r_0^2 \sigma)^{1/4}$. As an example the spectrum would peak at about 8 MeV for the energy injection rate of $\dot{E} = 10^{51}$ ergs s^{-1} and for the injection radius $r_0 = 10$ km.

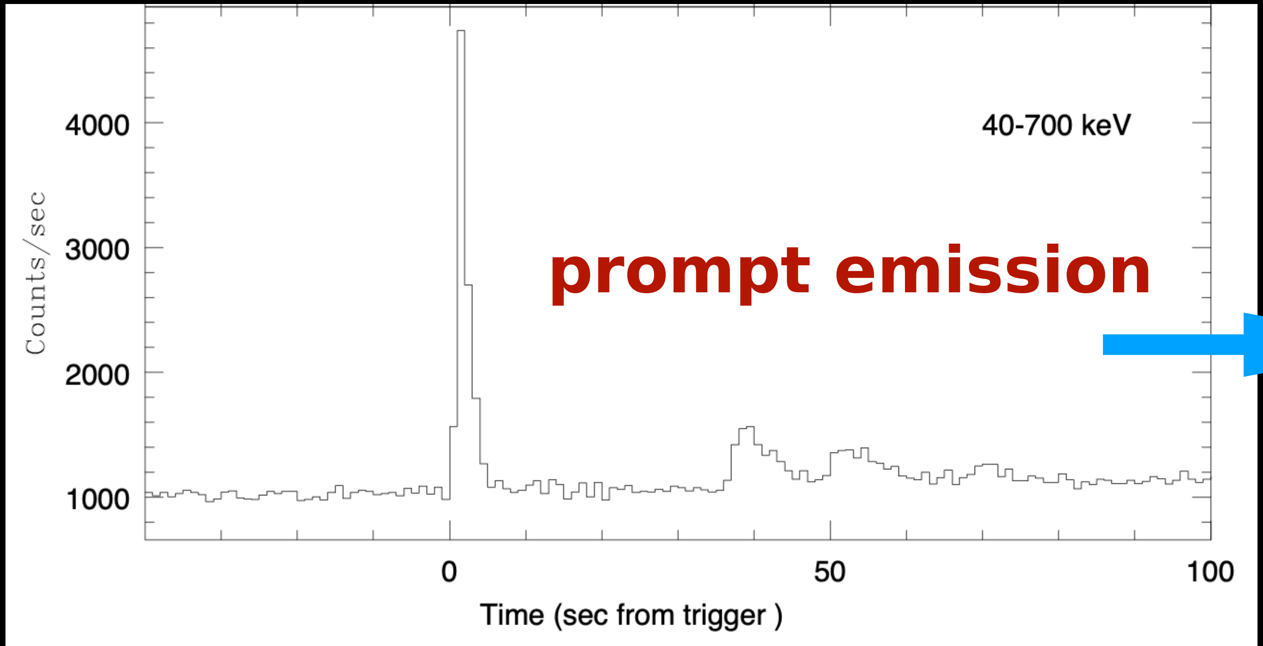
We propose that three gamma-ray bursts, all with identical spectra, detected from B1900+14 by Mazets, Golenetskii, and Gur'yan and reported in 1979, were all due to a single event multiply imaged by a gravitational lens. The time intervals between the successive bursts, 10 hr to 3 days, were due to differences in the light travel time for different images. The required mass of the lens is 10^{10} $M_\odot$, just right for a galaxy.

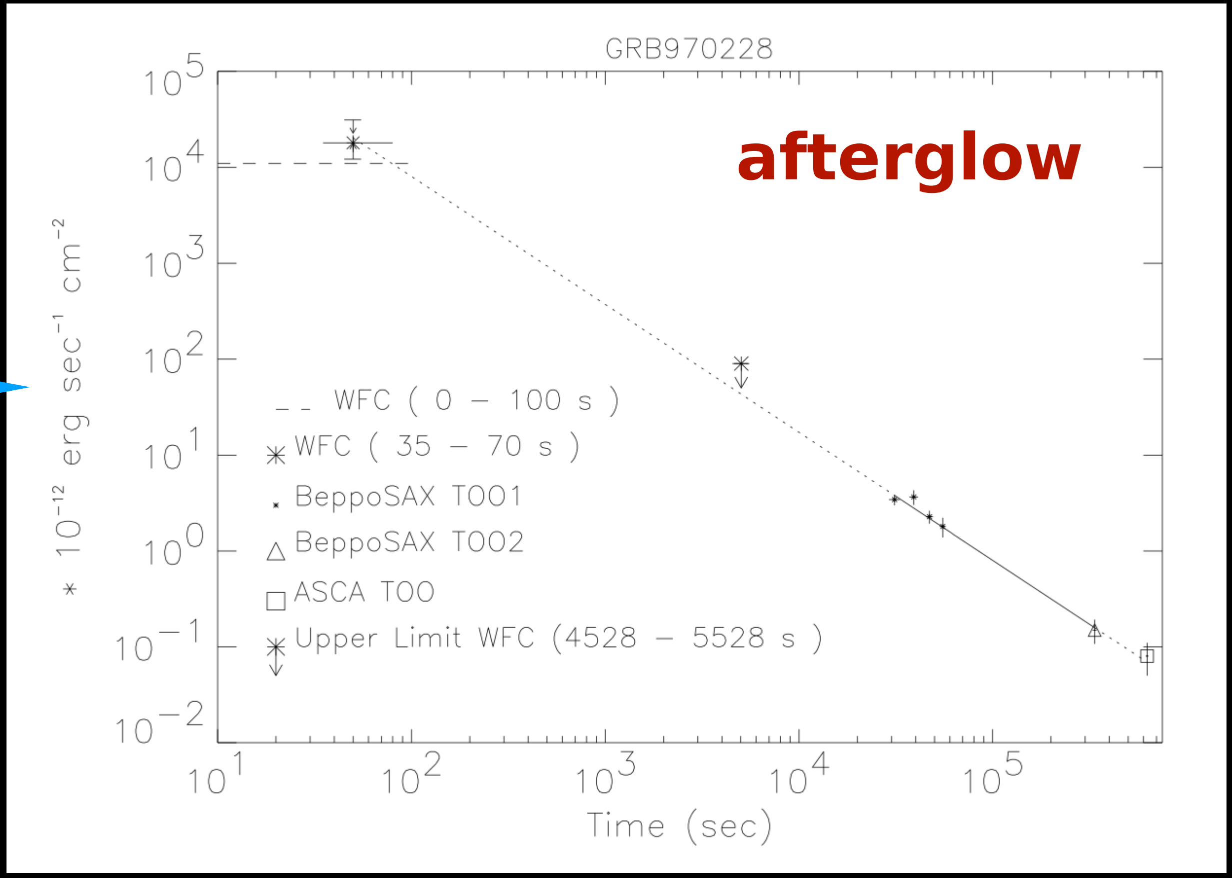
Subject headings: cosmology — gamma rays: bursts — gravitation

Afterglow era

BeppoSAX-Wide Field (20x20 deg^2) X-ray camera onboard (2-30 keV)

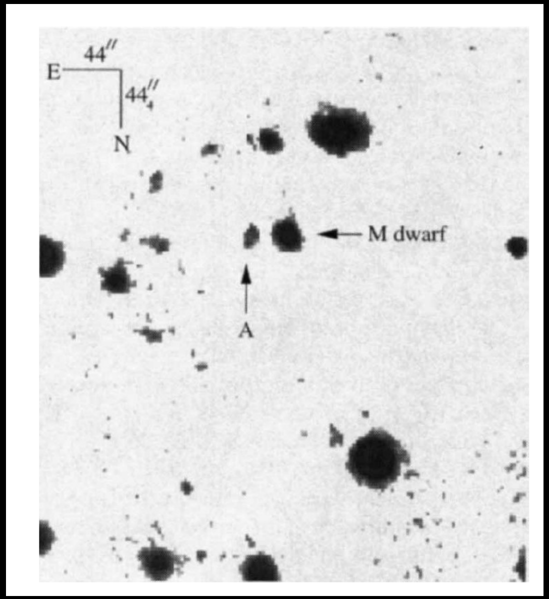
Costa et al. 1997

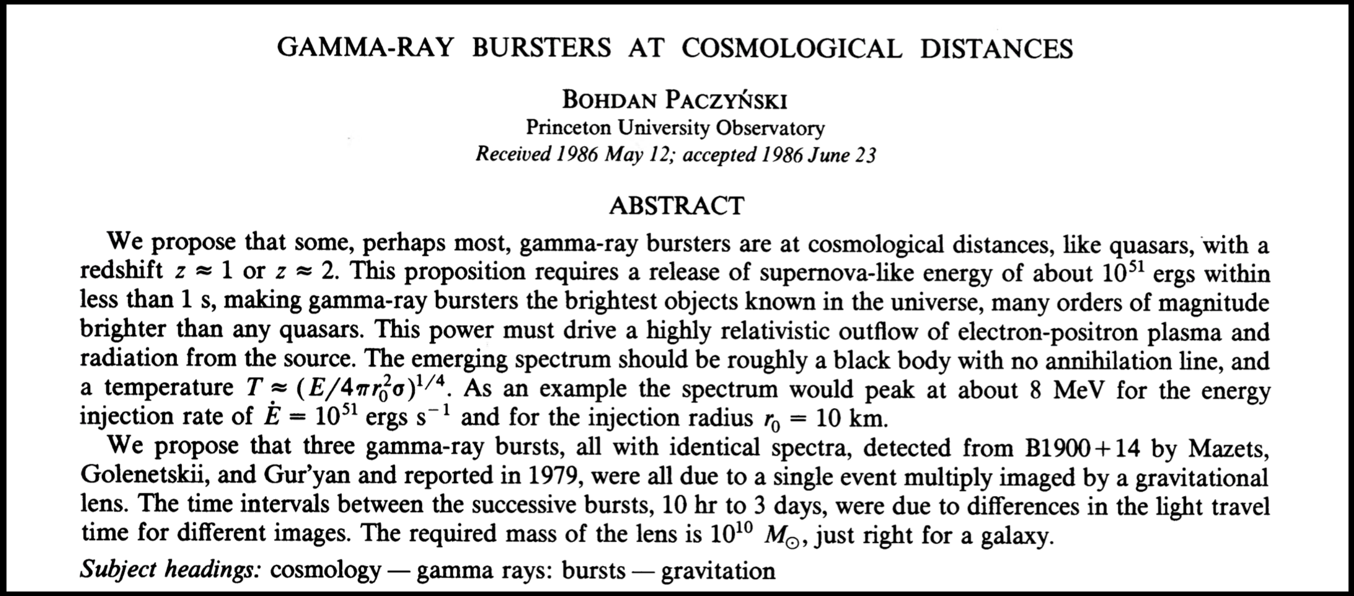




van Paradijs et al. 1997

z~ 0.2-2





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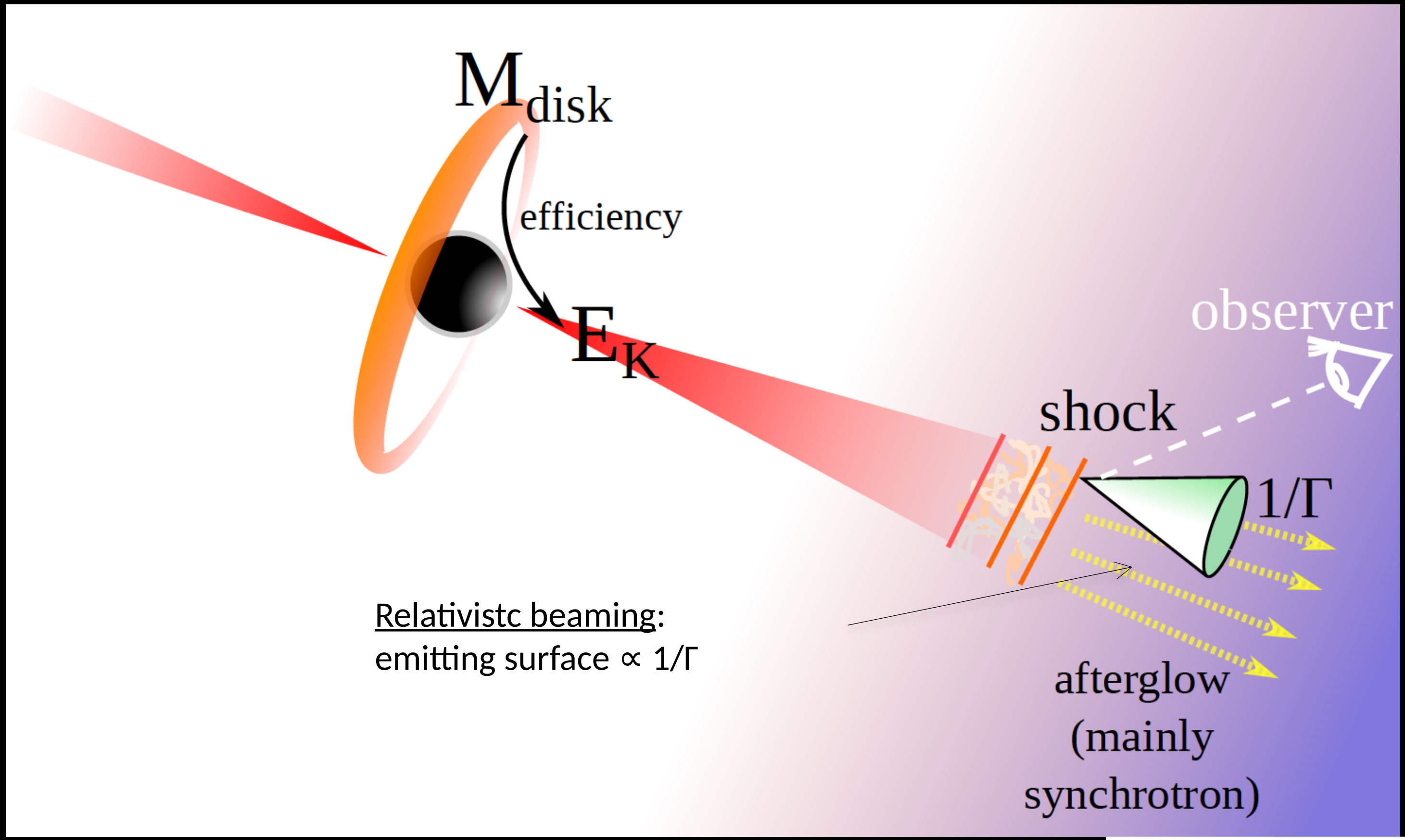
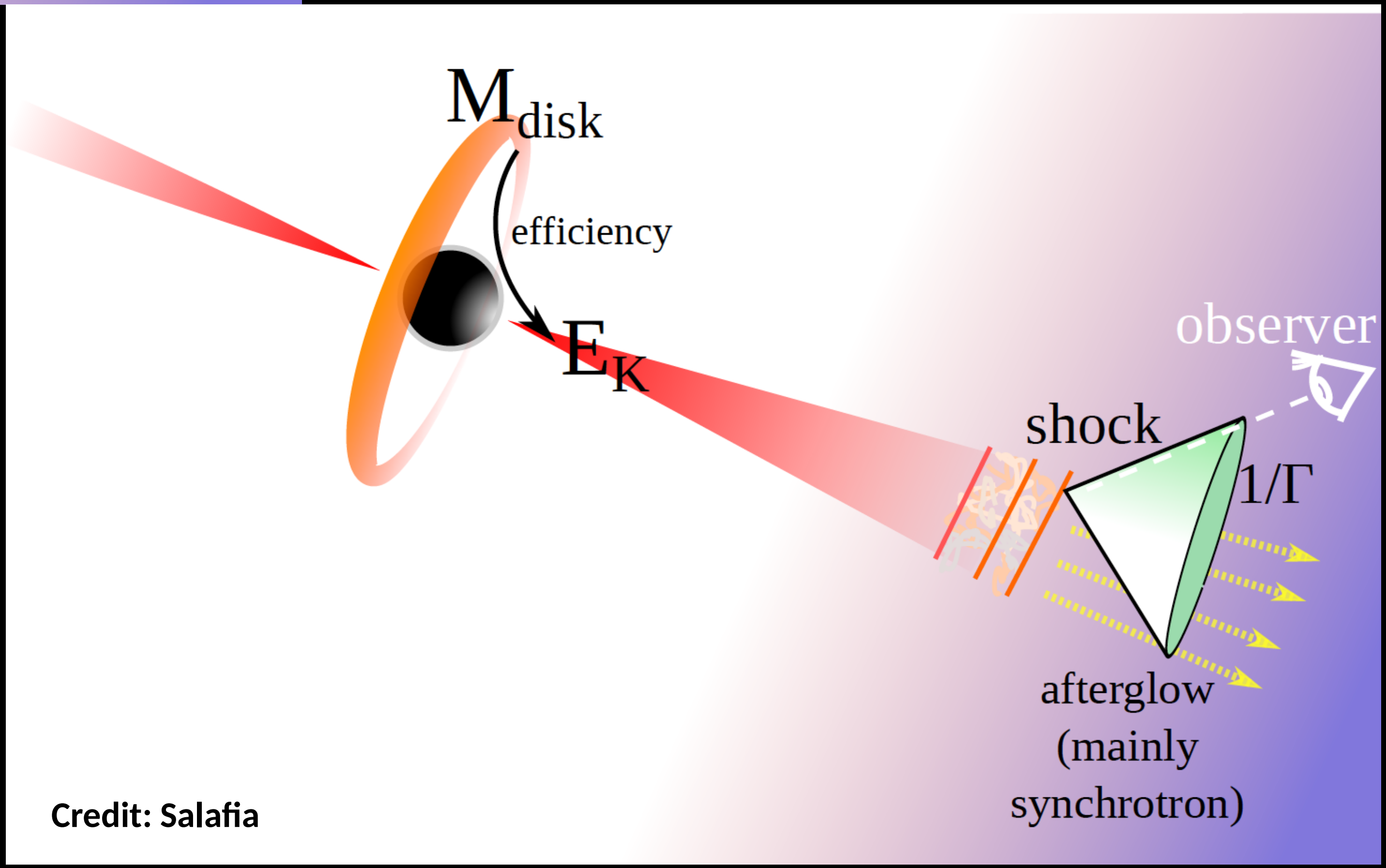


EM emission
detectable also by
off-axis observers

Early EM emission
detectable only by
on-axis observers

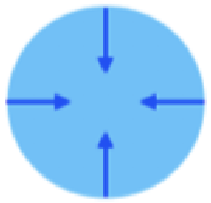


Credit: Salafia

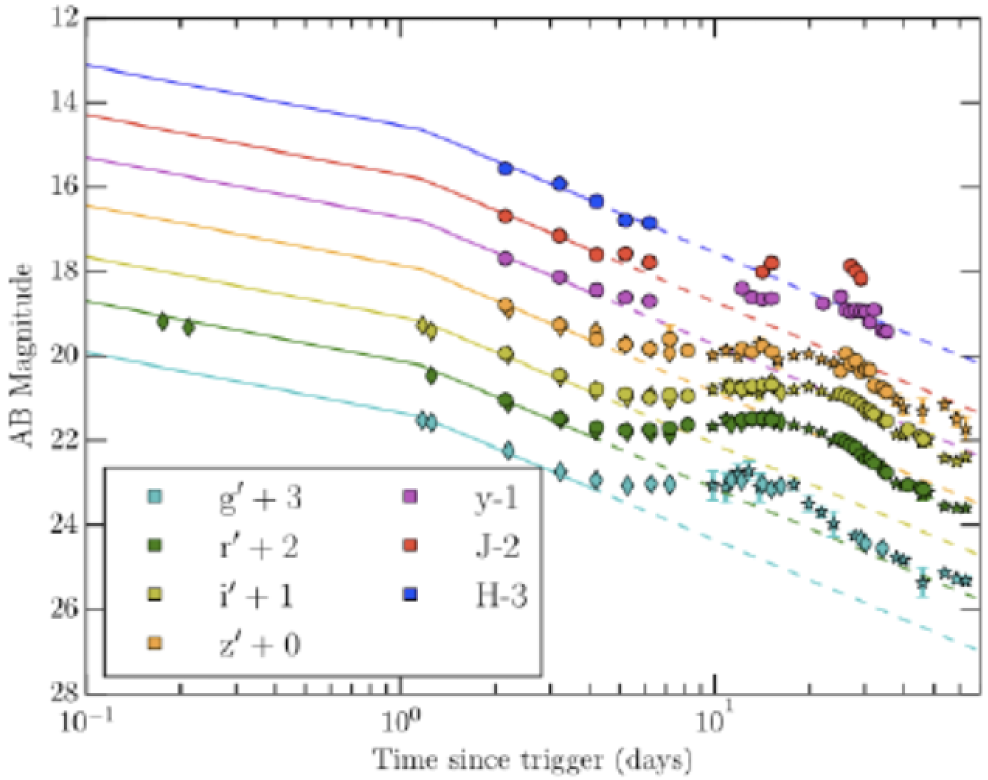
Discovery of SNe associated with long GRBs:
SN 1998bw, historically first

massive stars

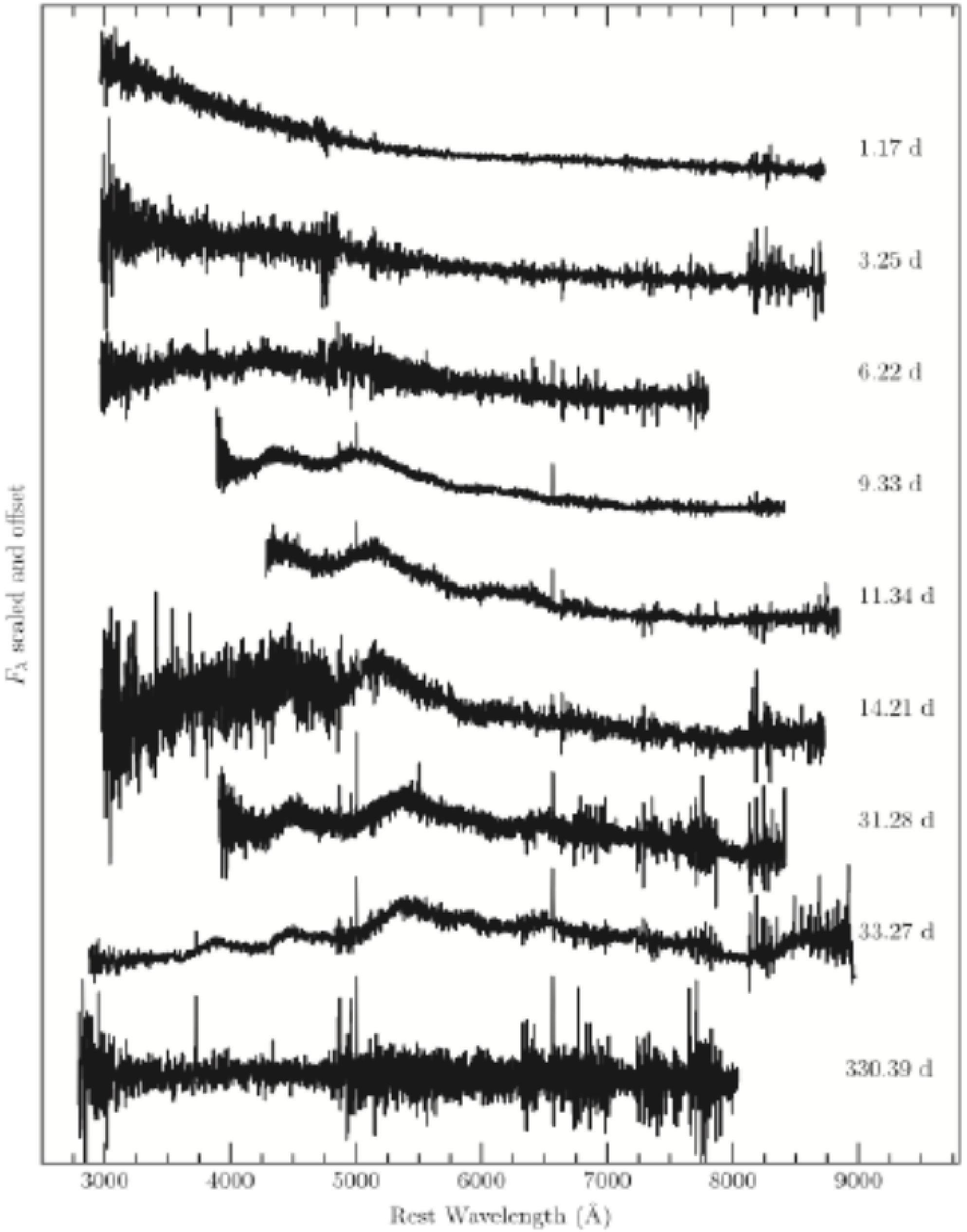
long GRBs (>2 s)



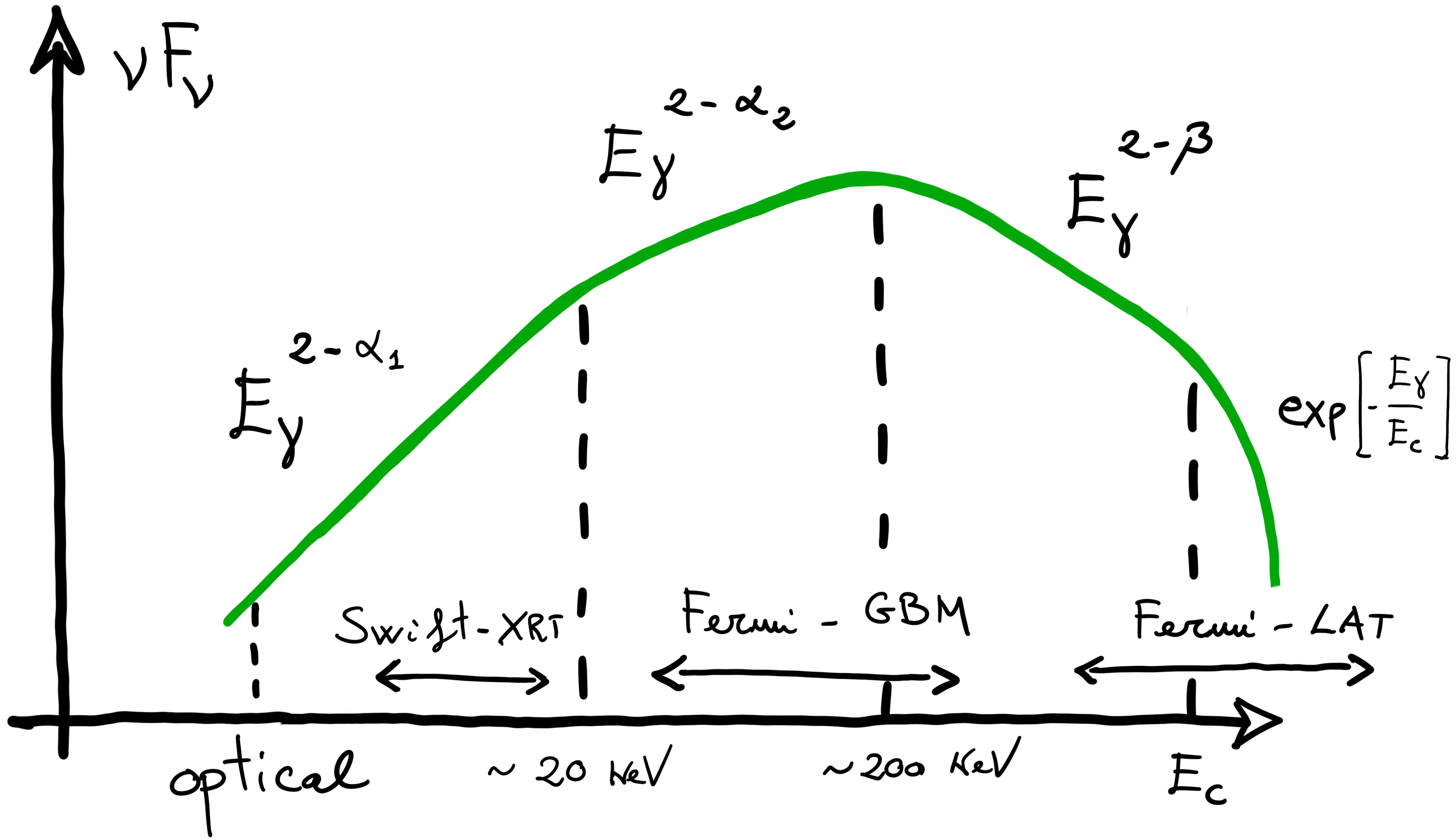
collapse



Toy et al 2016



Prompt emission



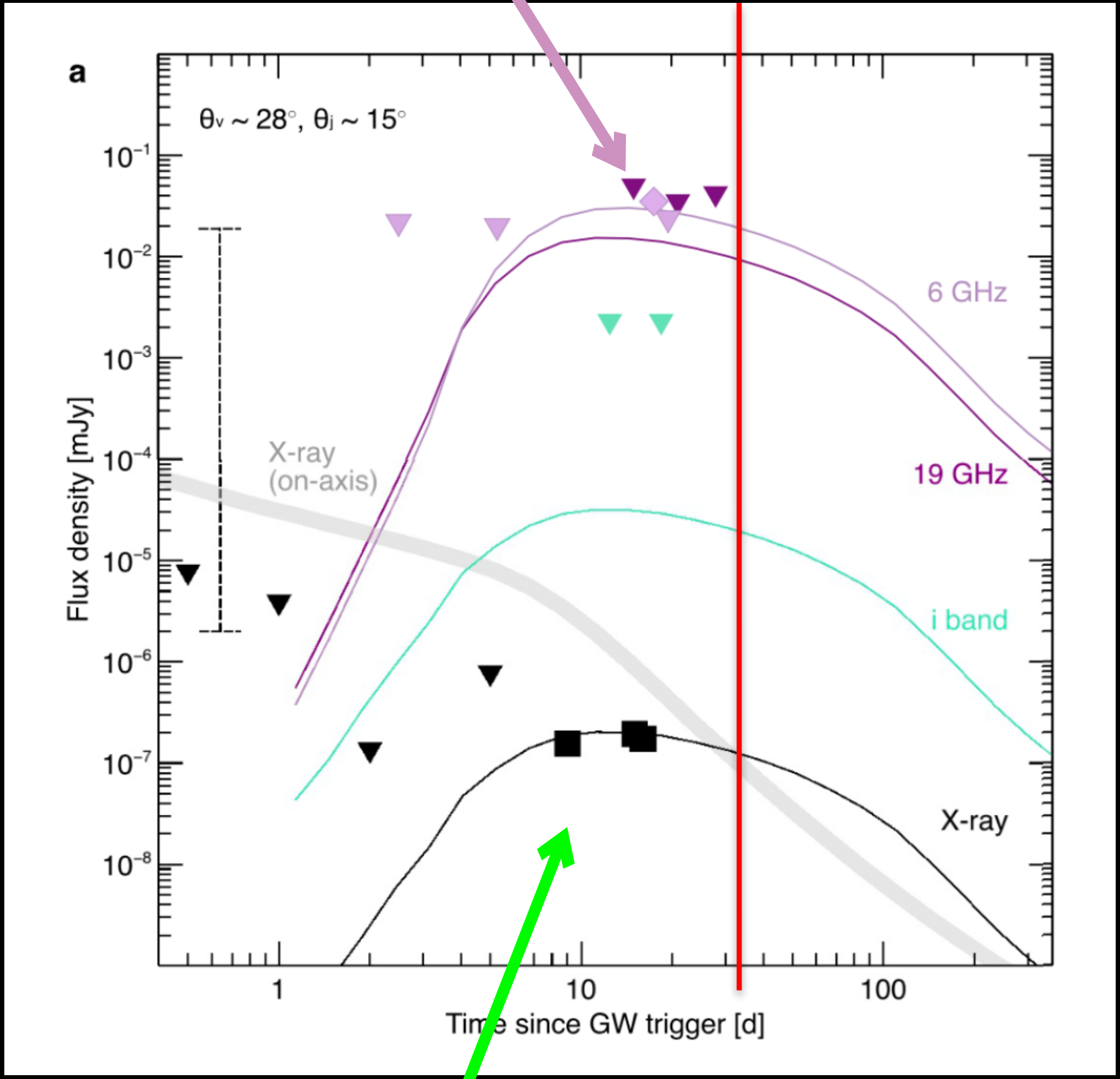
GW 170817

Forward shock
from a
structured jet

Credits: Ronchini

Radio emissions 16 days after the merger

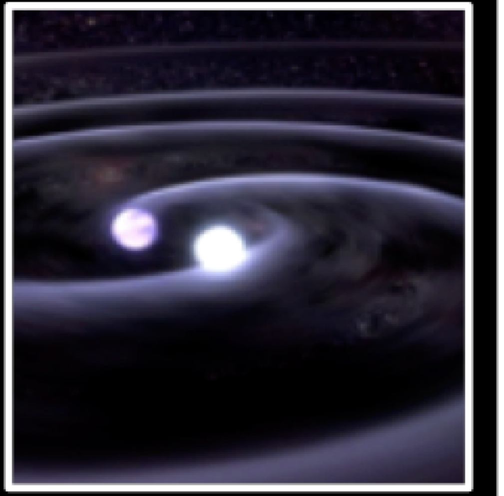
Hallinan et al. 2017 Science



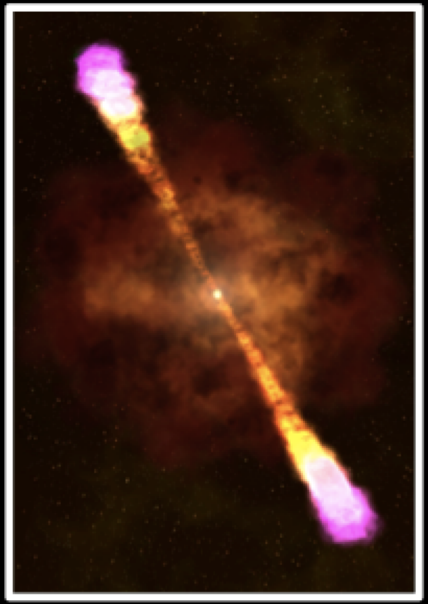
Troja et al. 2017 Nature

**X-ray emission
9 days after the merger**

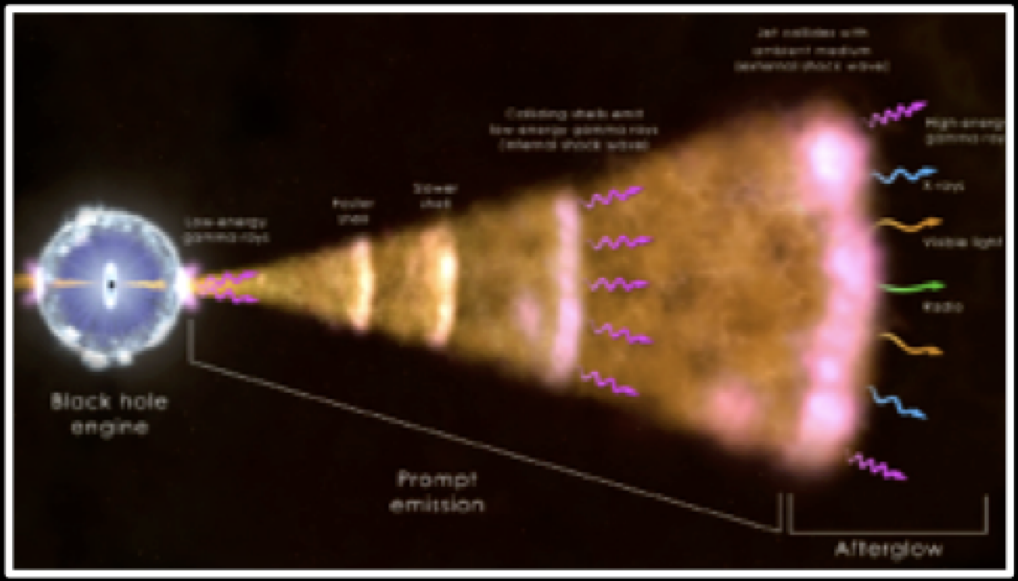
GW170817 BINARY NS MERGER



NS merger



Short GRB



X-ray

Radio afterglow

t0

1.7s

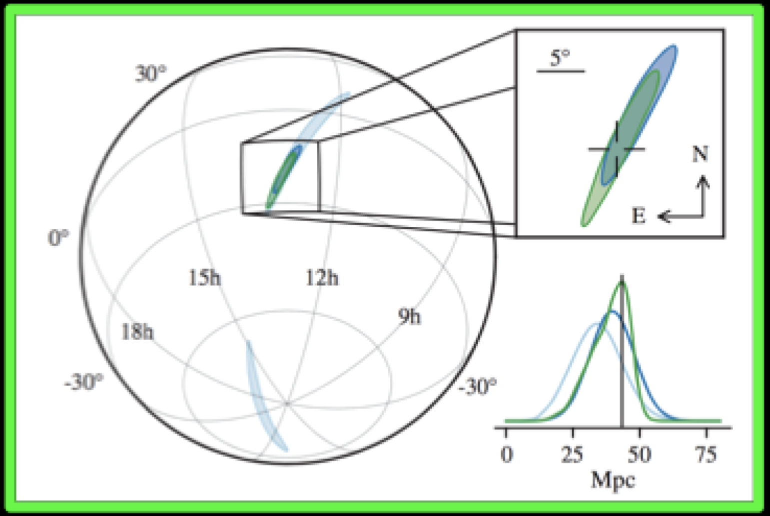
+5.23hrs

+10.87 hrs

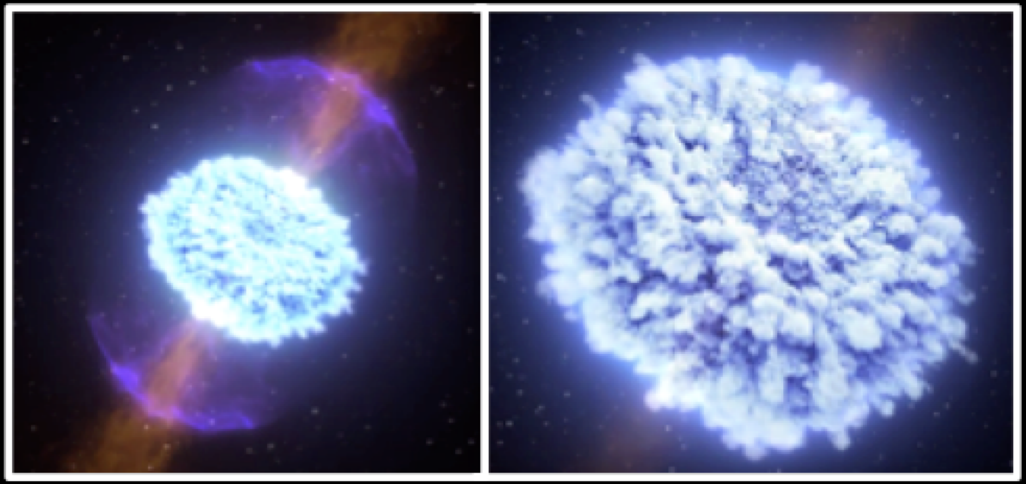
+9 days

+16 days

LHV sky localization

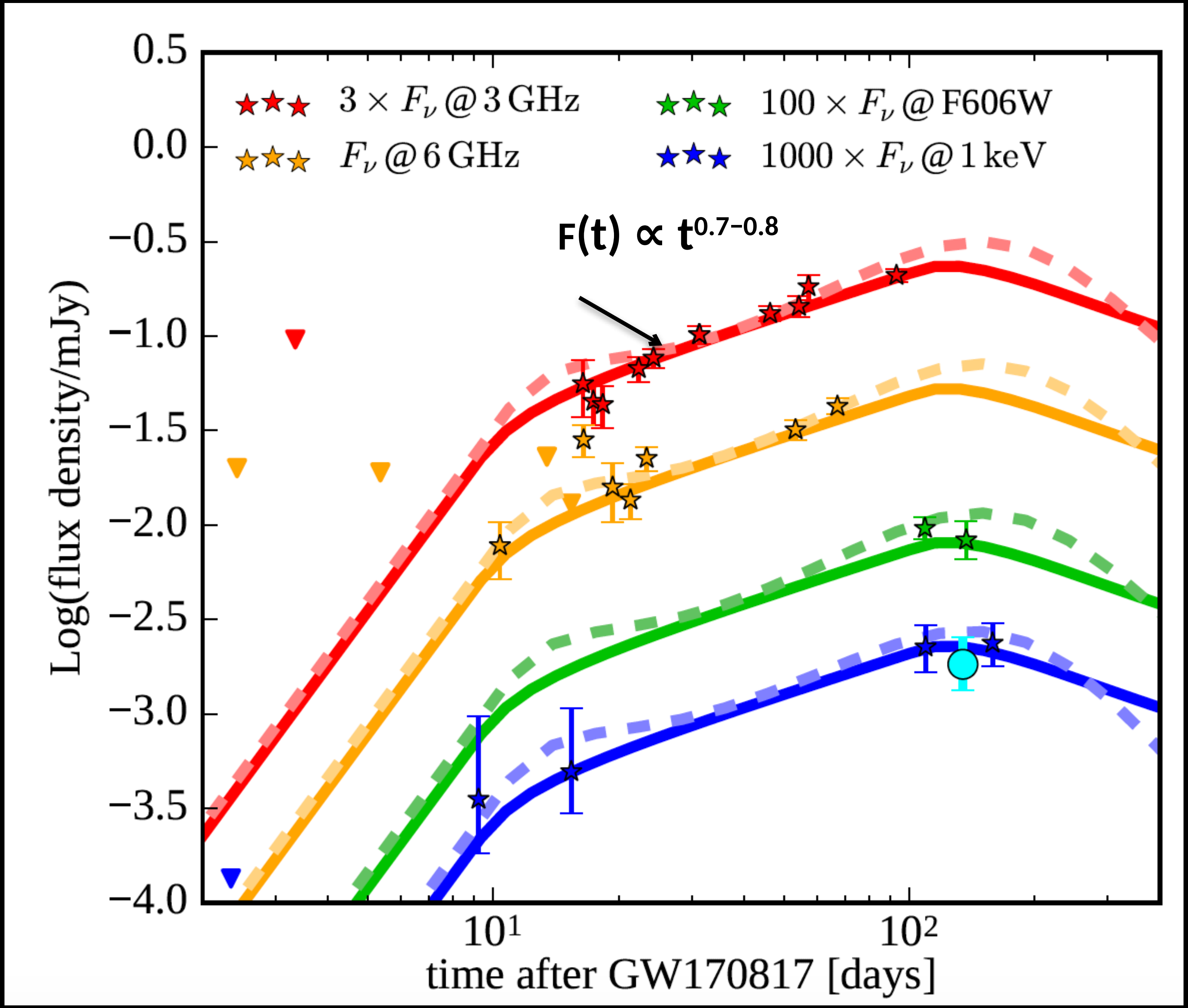


UV/Optical/NIR Kilonova



LVC + astronomers, ApJL, 848, L12

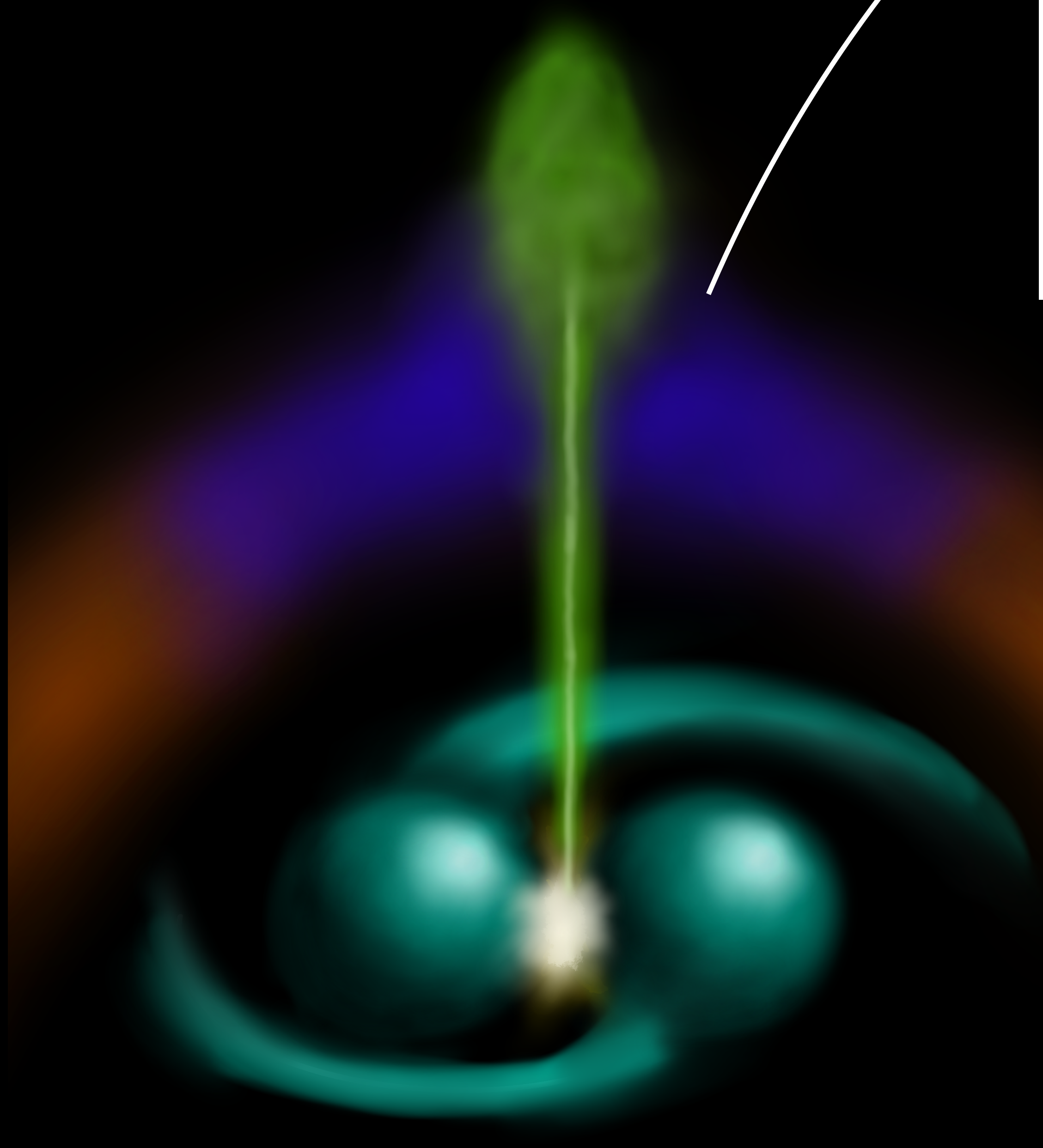
After 150 days from the BNS merger…

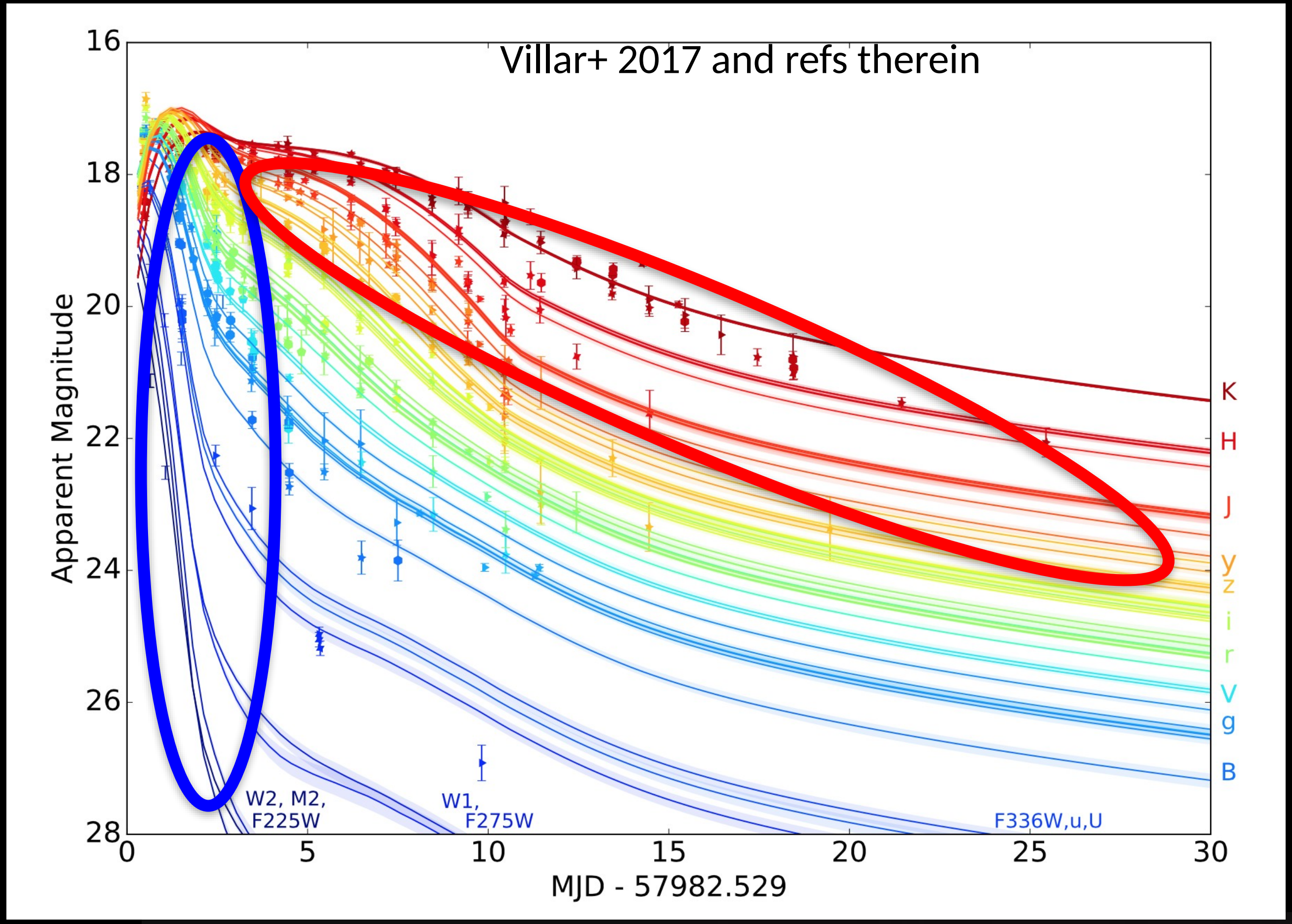


D’Avanzo et al. 2017, A&A

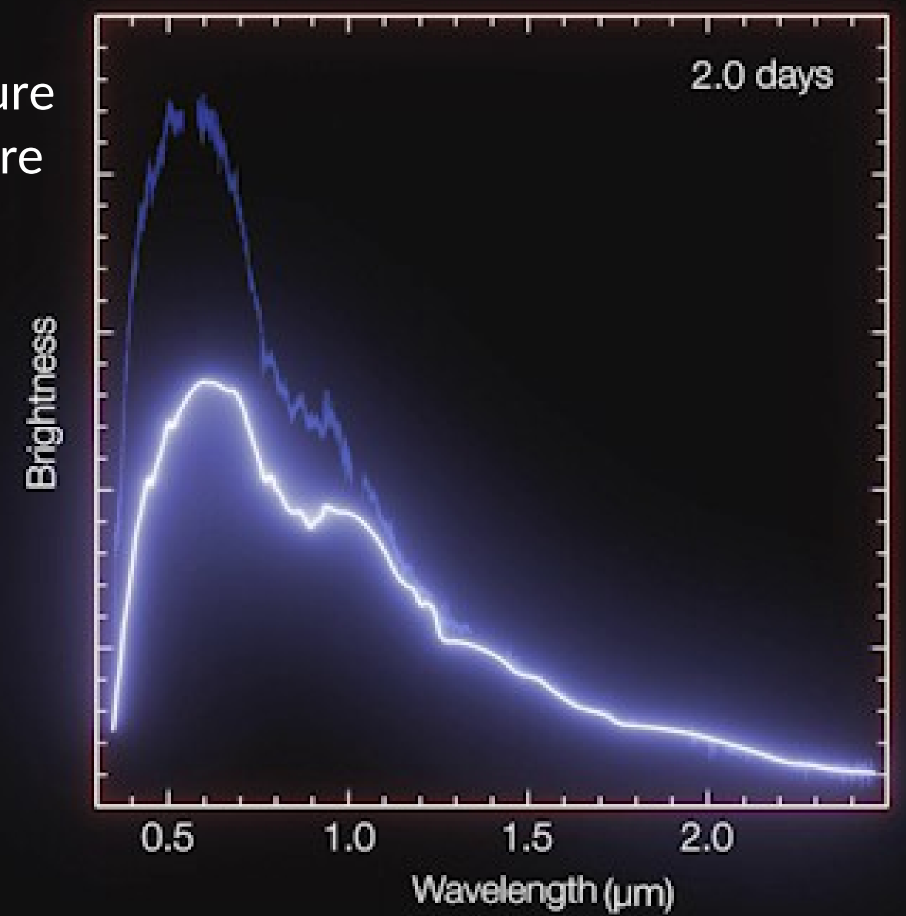
..unexpected slow achromatic flux–rise until ∼ 150 days!

GW 170817



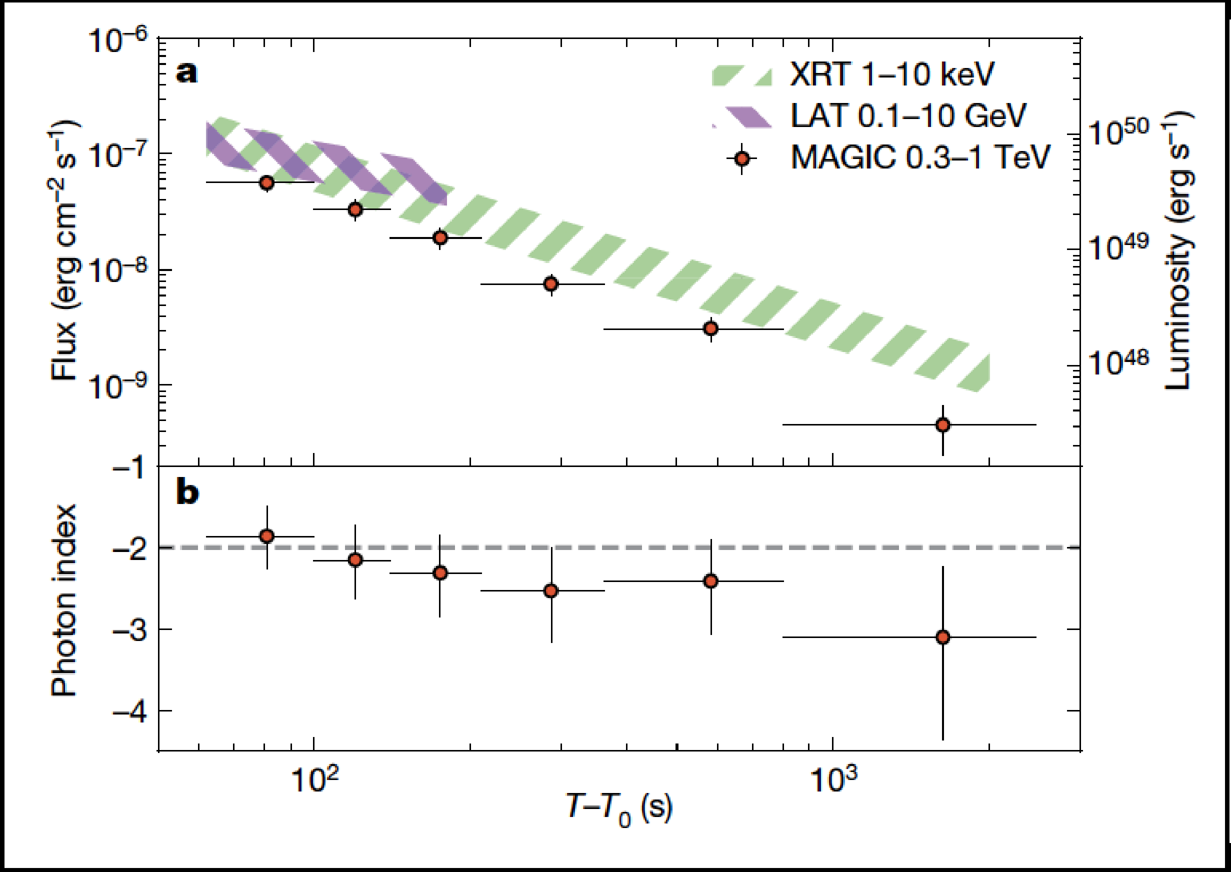


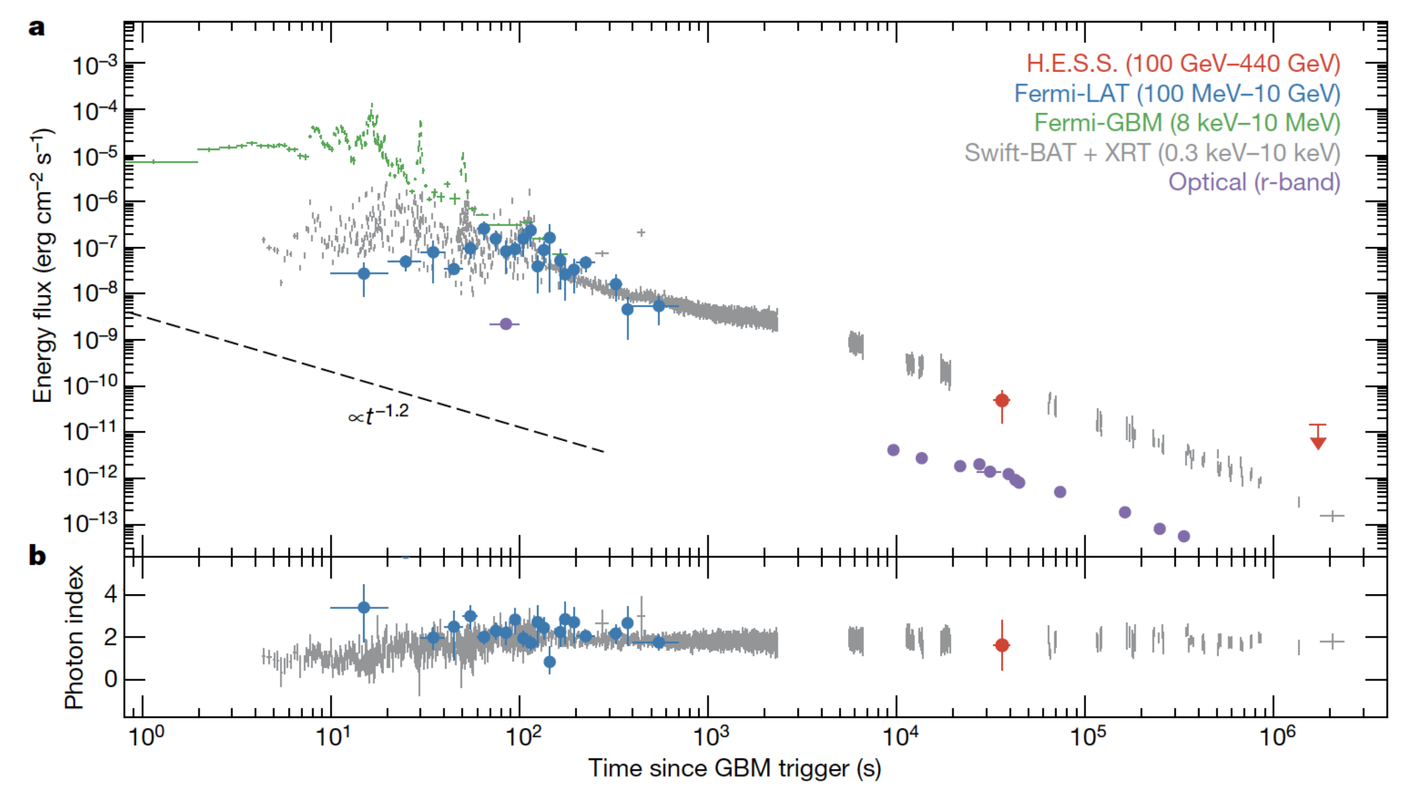
Pian et al. 2017 Nature
Smartt et al. 2017 Nature



GRBs at very-high-energies (TeV)
The discoveries of 2019

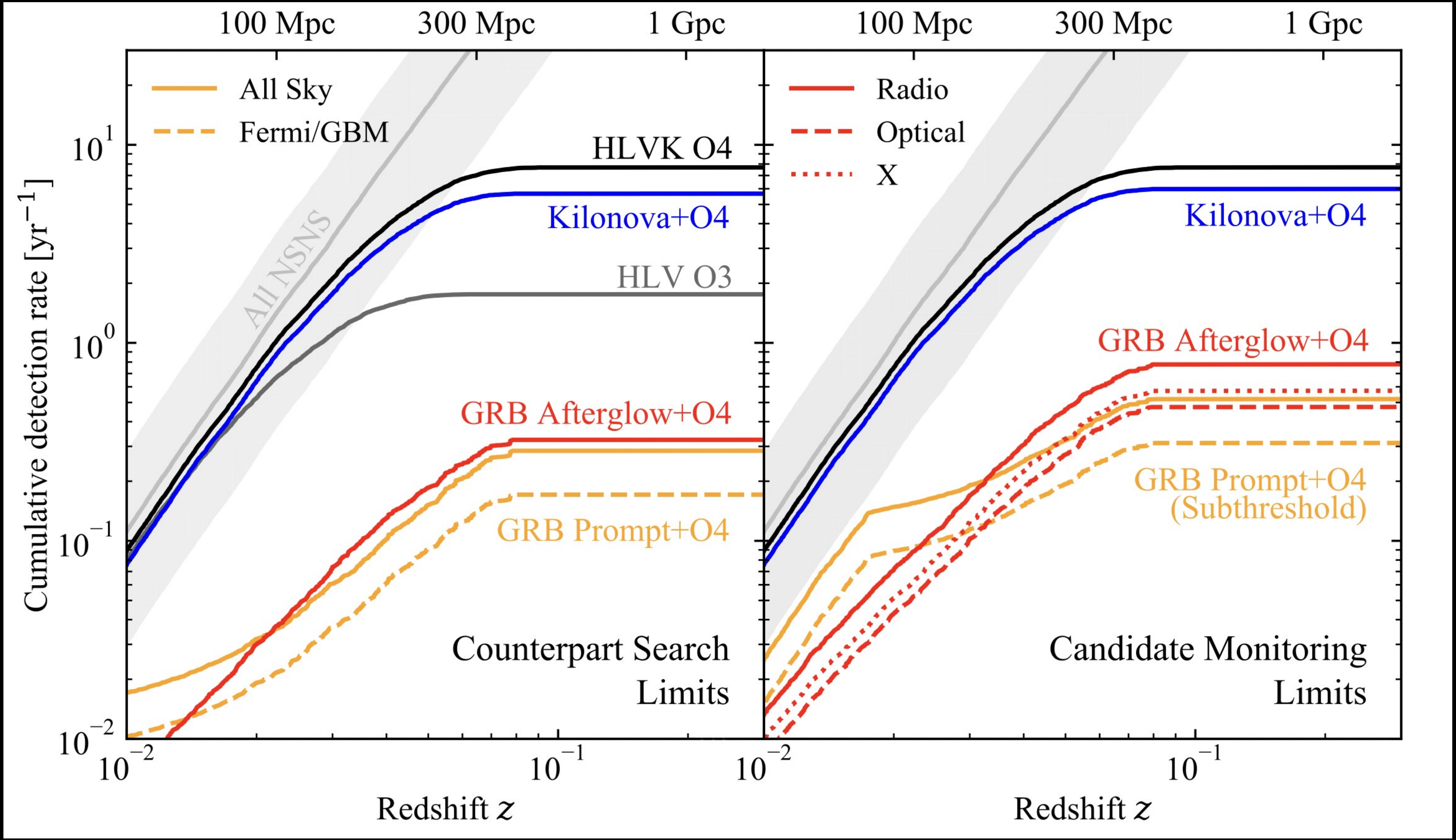
MAGIC and H.E.S.S.





Acciari et al. 2019, Abdalla et al. 2019 & 2021; Acciari et al. 2021

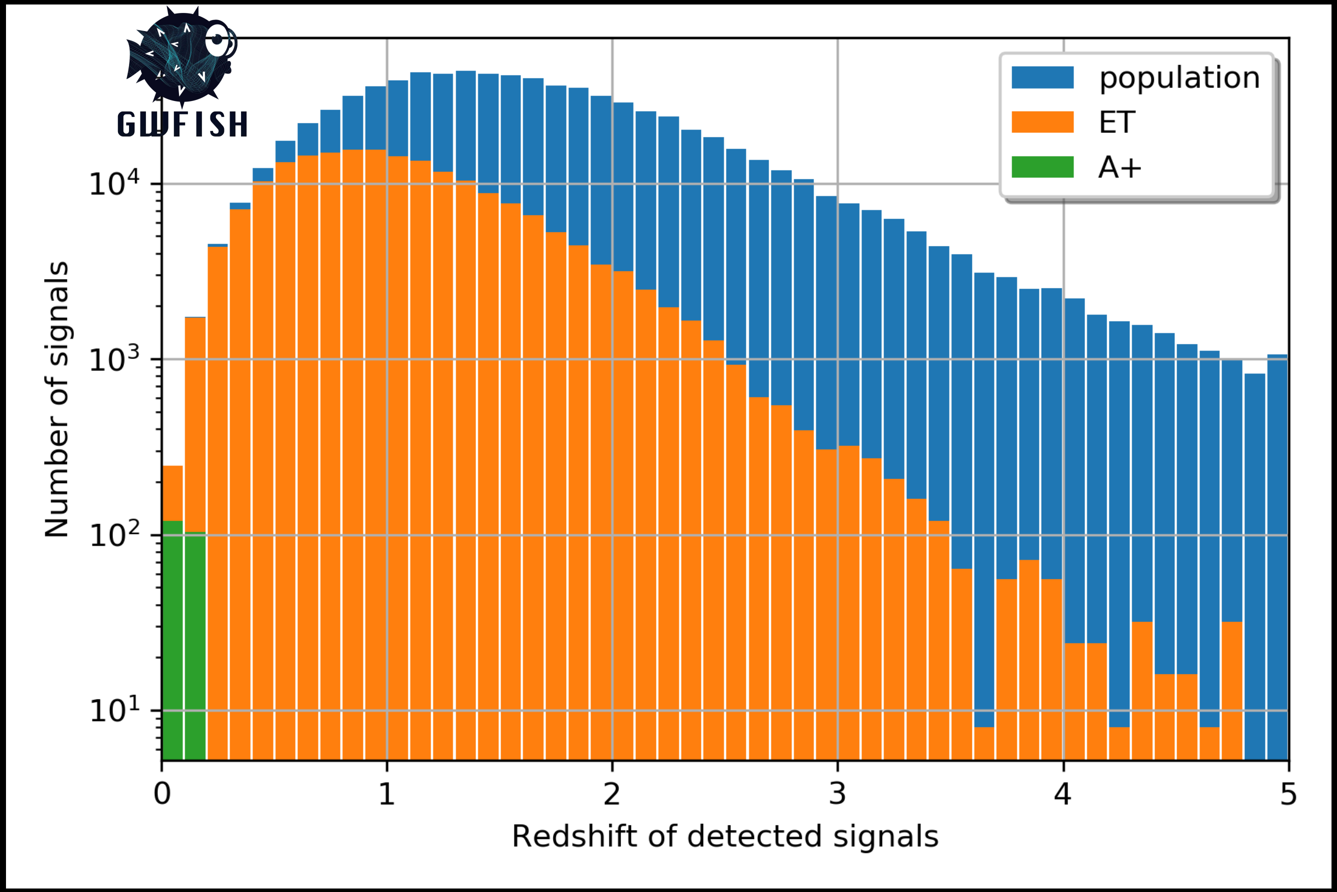
LVK 04



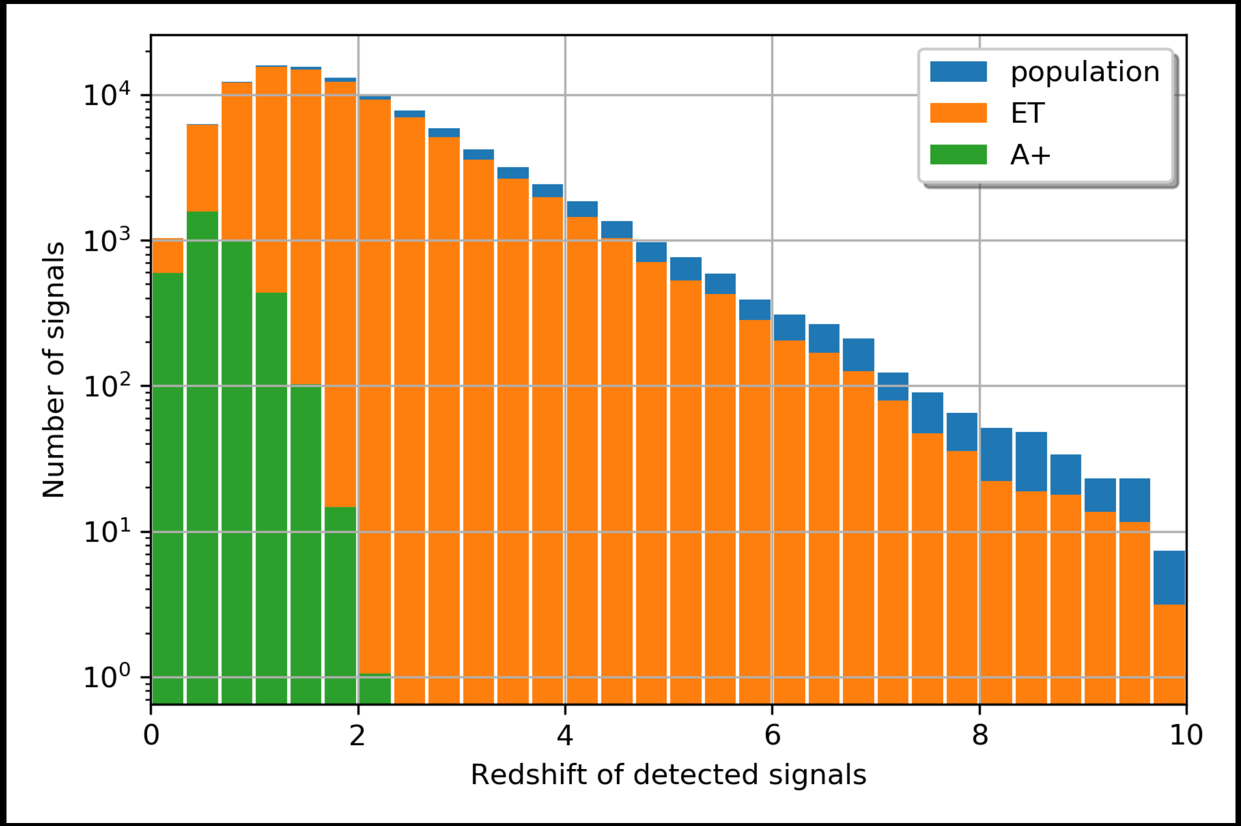
Colombo et al. 2022

COMPACT OBJECT BINARY POPULATIONS

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS



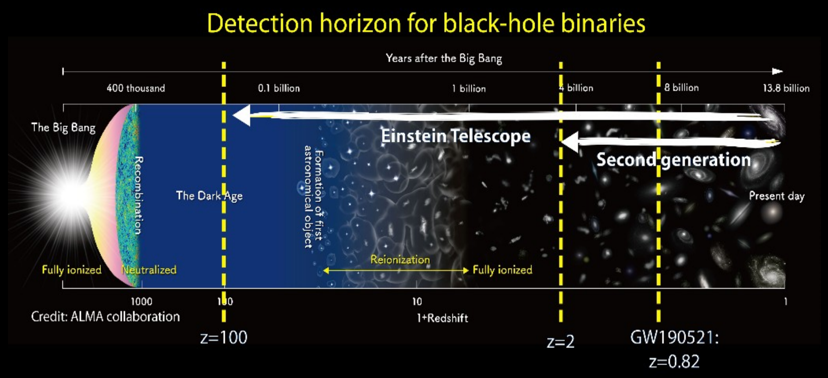
Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

10^5 BNS detections per year
10^5 BBH detections per year

Harms et al. arXiv:2205.02499

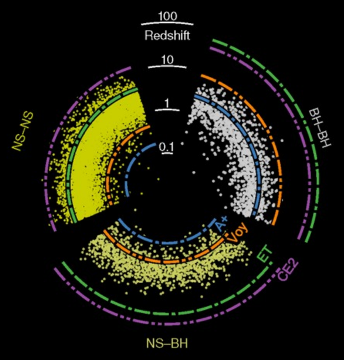
The ET sensitivity will make it possible:

- EARLY UNIVERSE

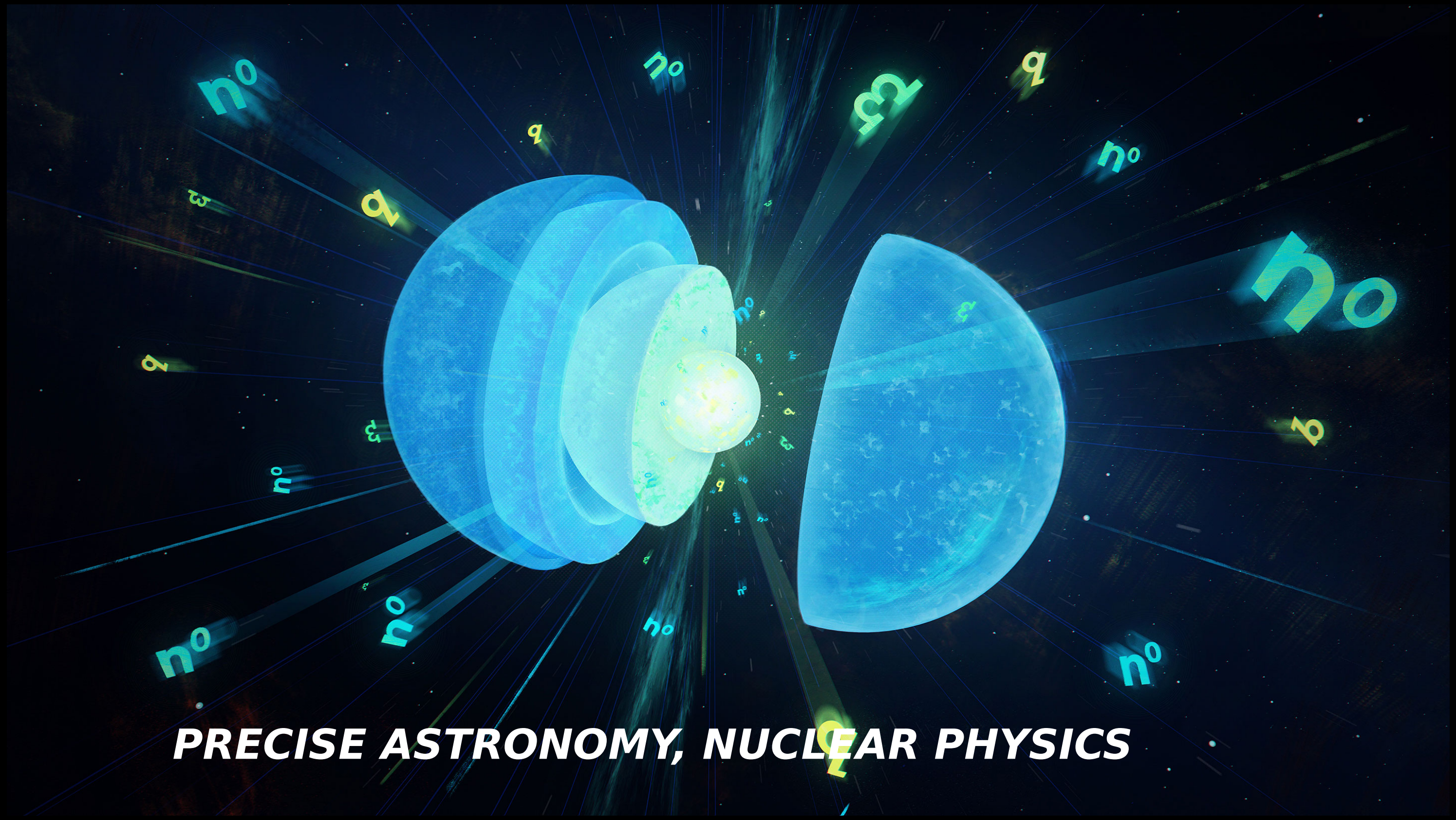


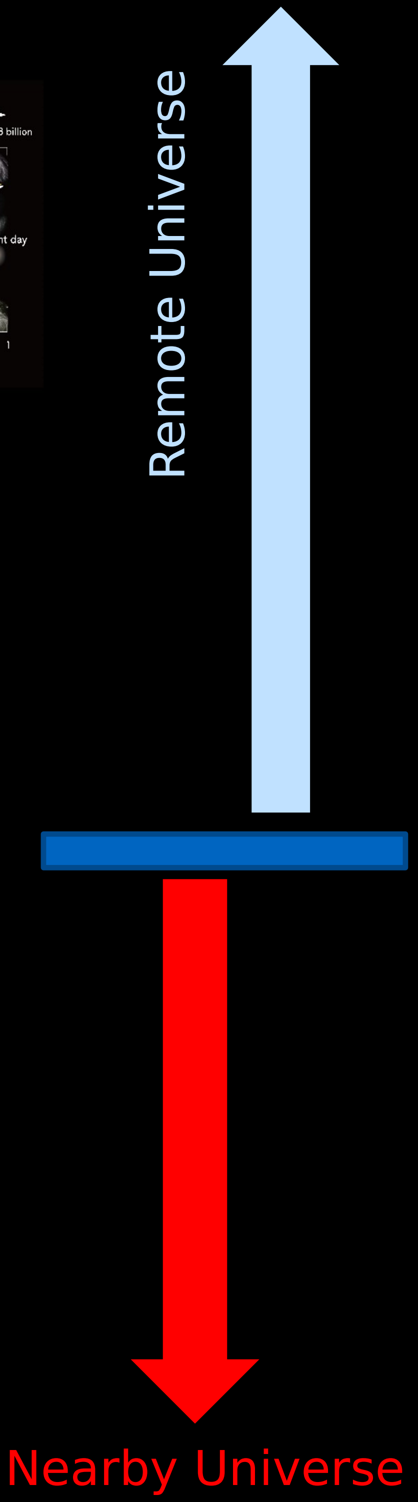
Credit: ALMA collaboration

  - POPULATION



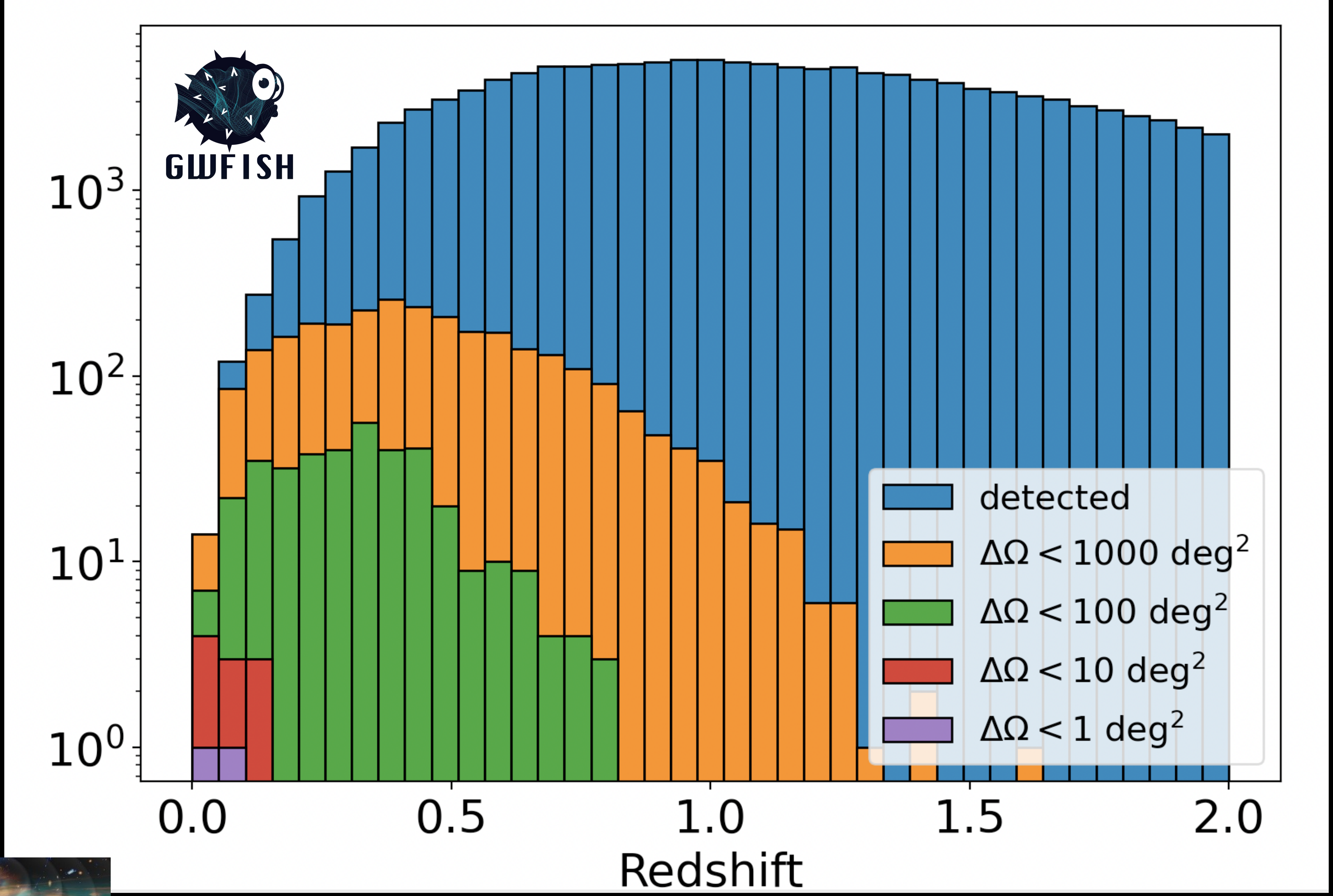
- PRECISION GW ASTRONOMY: exceptional parameter estimation accuracy for very high SNR events

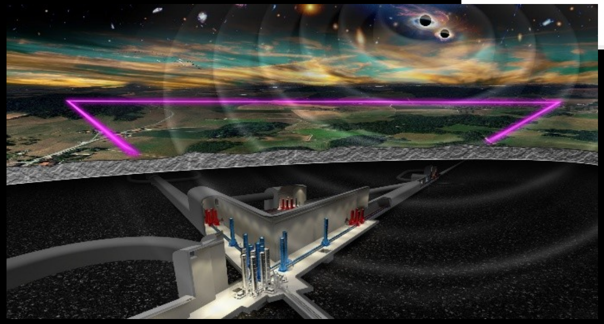




Multi-messenger in the ET era

ET sky-localization capabilities

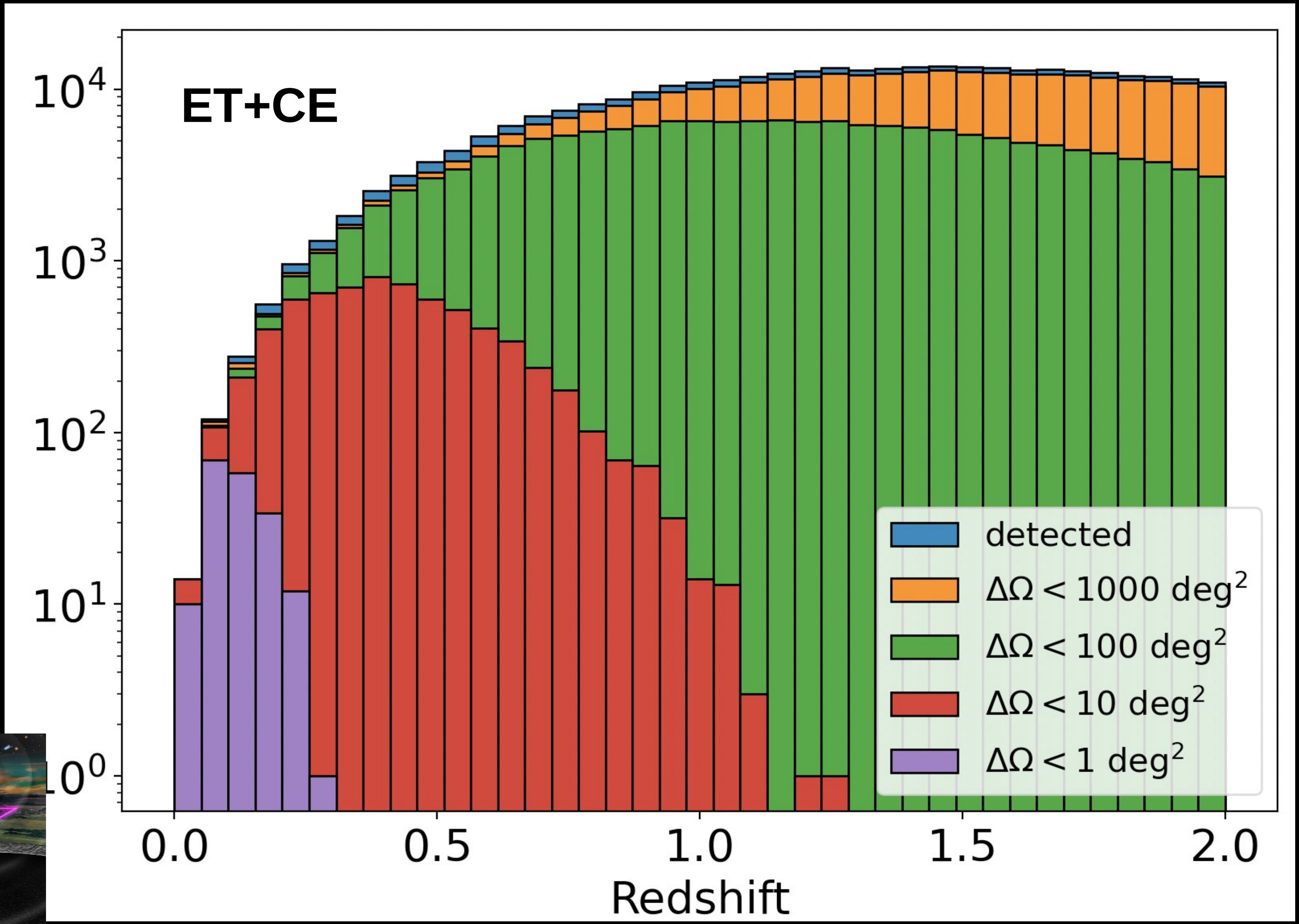


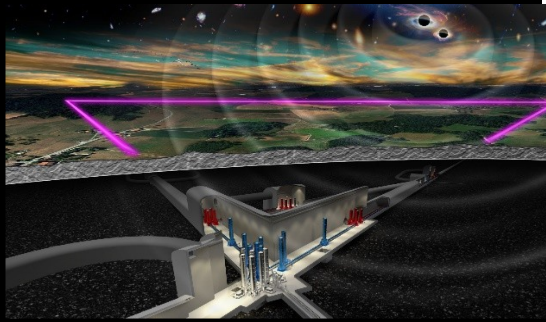


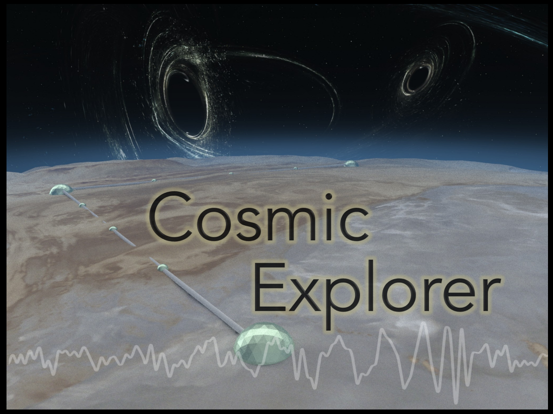
ET low frequency sensitivity make it possibile
To localize BNS!

- O(100) detections per year with sky-localization (90% c.r.) < 100 sq. deg
- Early warning alerts!

Network sky-localization capabilities

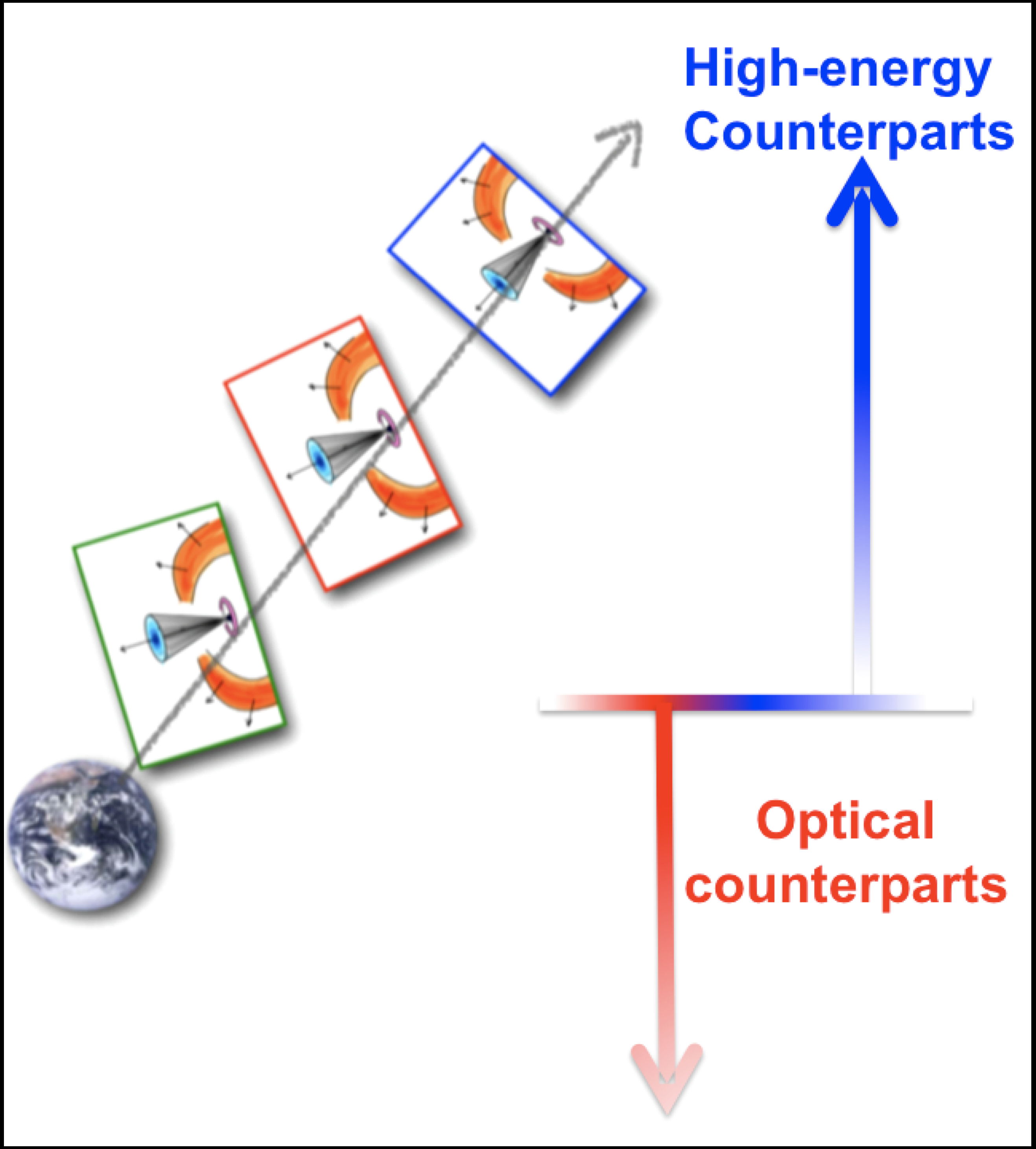






- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Harms et al. arXiv:2205.02499, Ronchini et al. arXiv:2204.01746



Hundred of MM events per year!

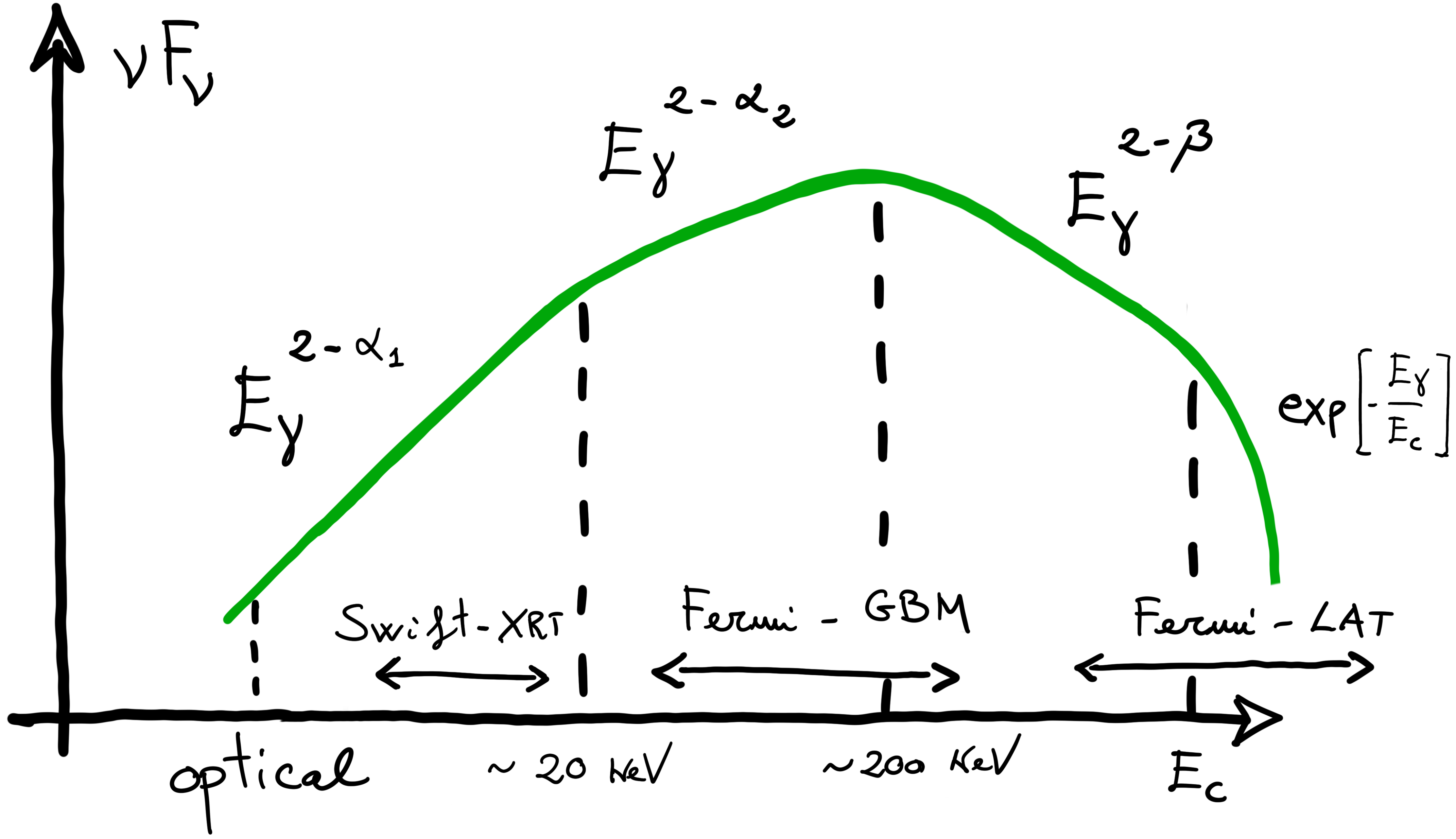
RELATIVISTIC JET PHYSICS,
GRB EMISSION MECHANISMS, COSMOLOGY and MODIFIED GRAVITY

Credit: Ronchini

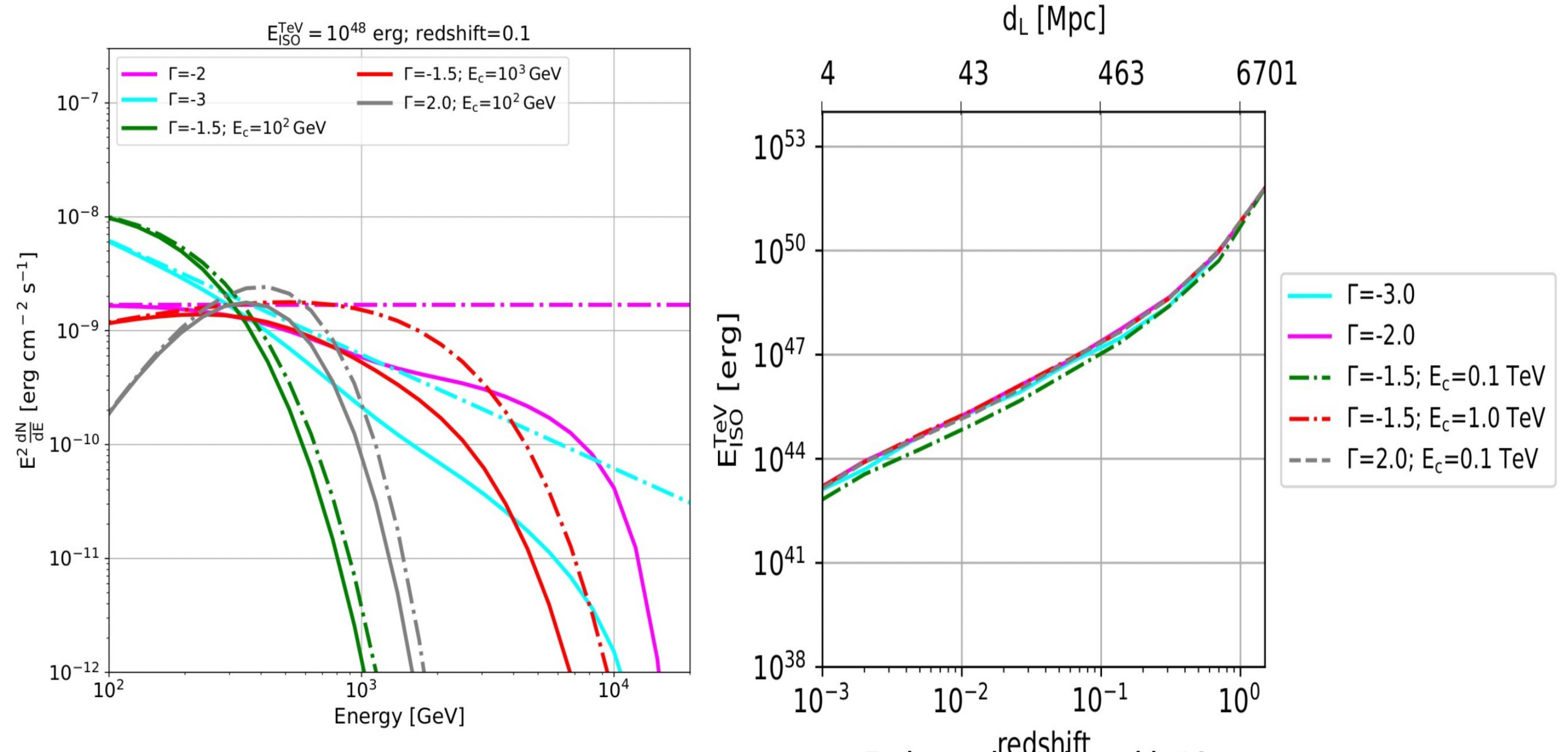
KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and H0 ESTIMATE

Image credit: NASA Goddard Space Flight Center

Prompt emission



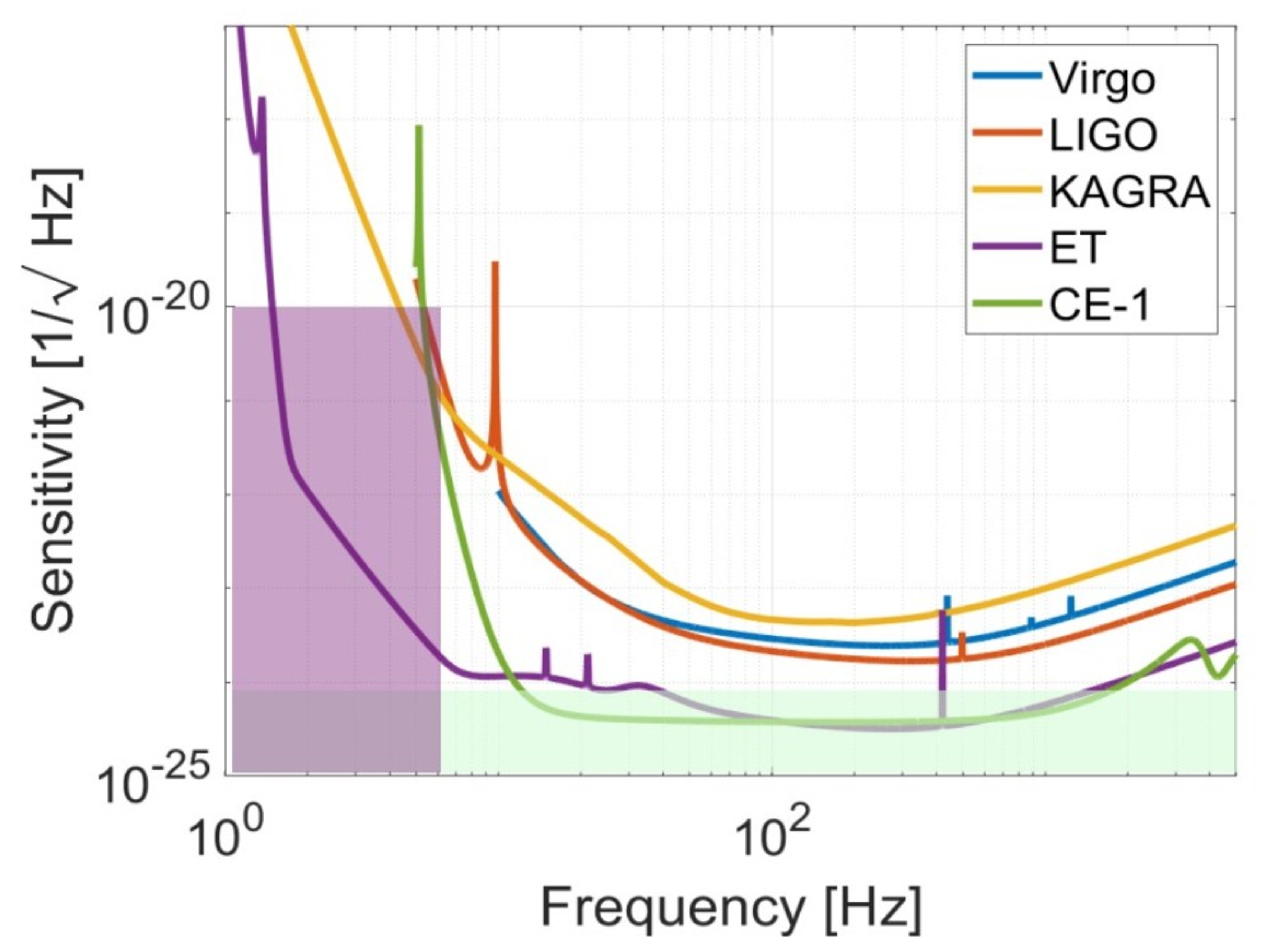
Very High Energy Emission



5-sigma detection with 10 s exposure

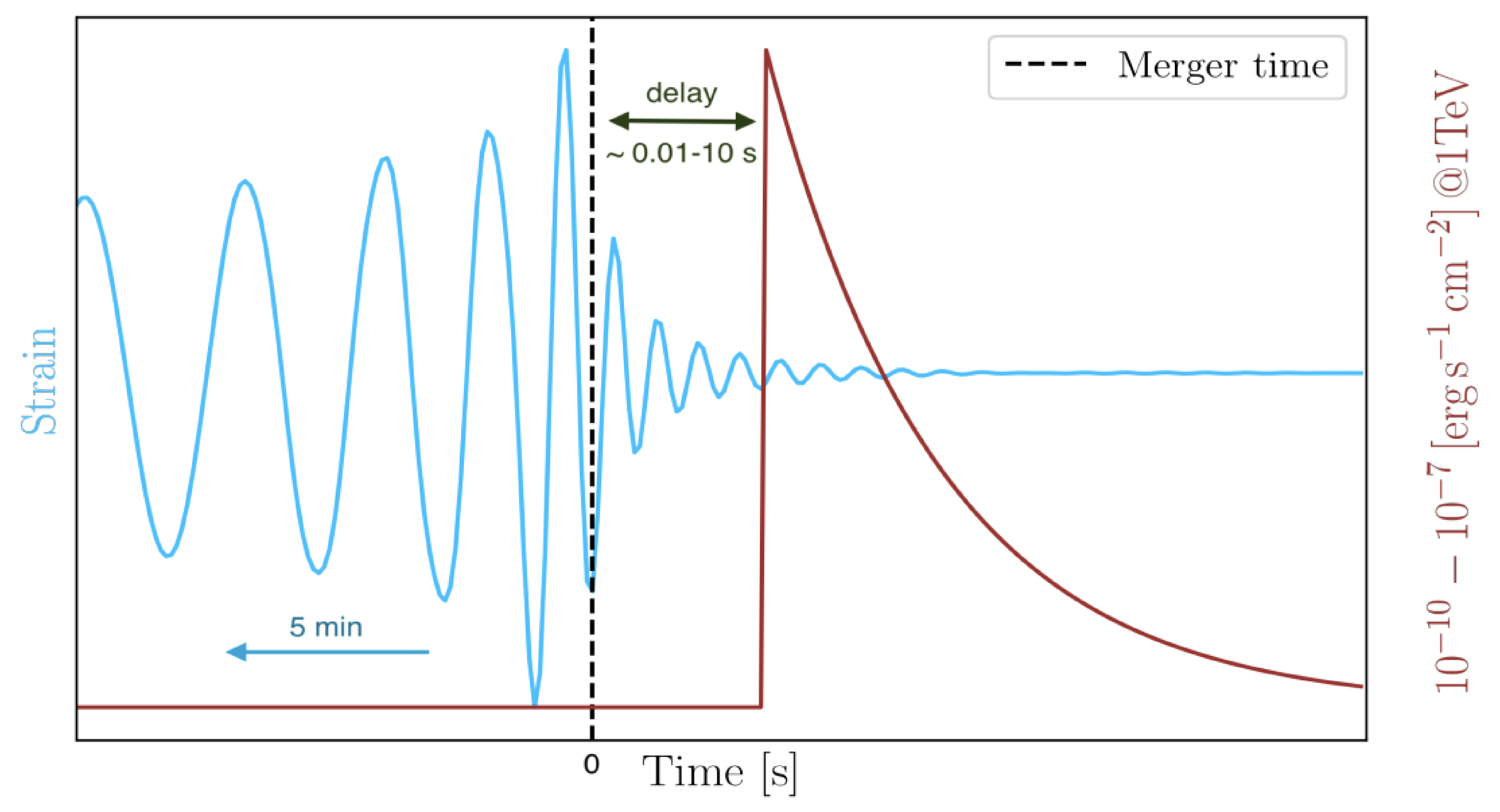
Banerjee et al. 2023, arXiv

Very High Energy Emission



Banerjee et al. 2023, arXiv

Detection of VHE prompt emission from BNS?

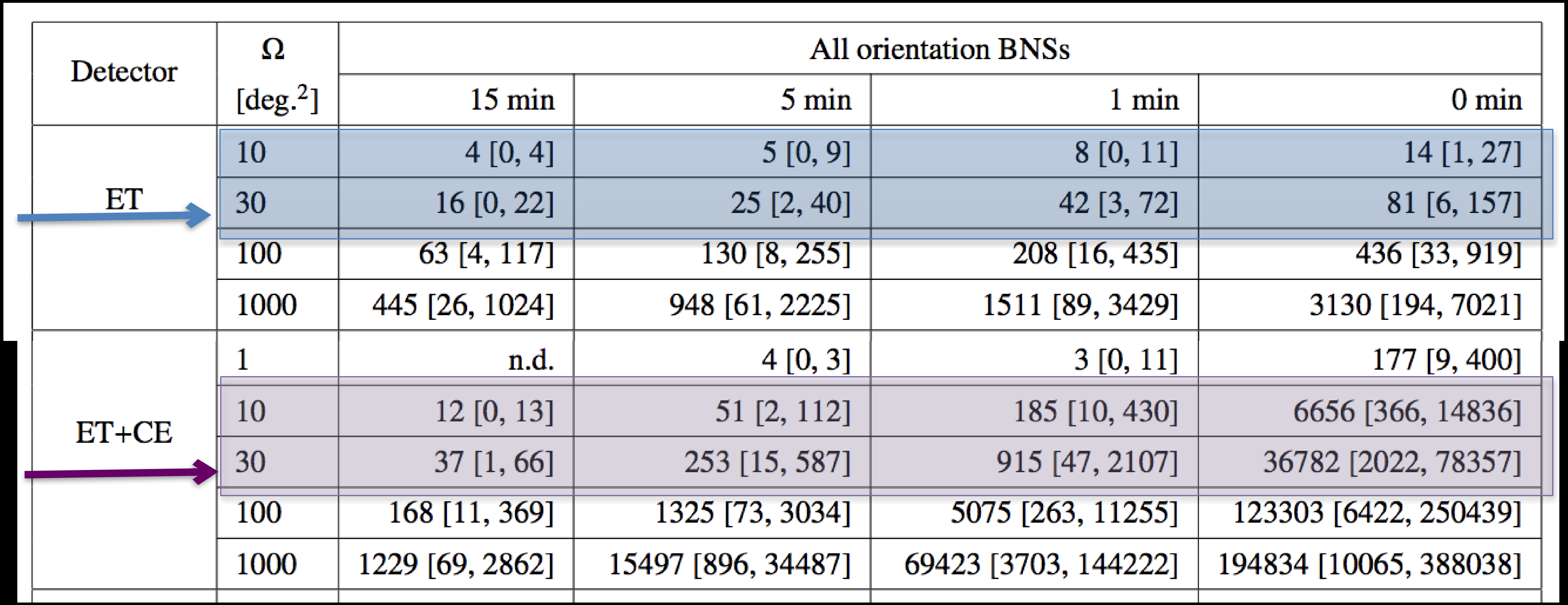


USE OF EARLY WARNING ALERTS FROM ET!

Banerjee et al. 2022, in prep.

SKY-LOCALIZATION PRE-MERGERS

BNS Events per year up to z=1.5

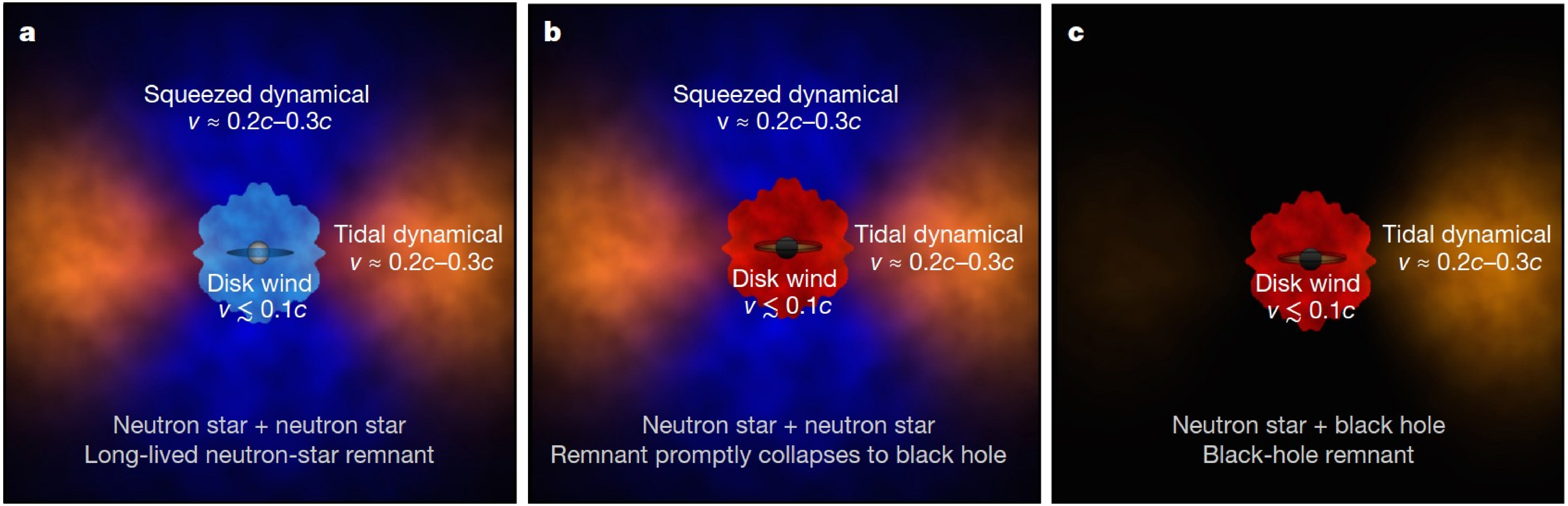


Detector	Ω [deg.^{2}]	All orientation BNSs			
		15 min	5 min	1 min	0 min
ET	10	4 [0, 4]	5 [0, 9]	8 [0, 11]	14 [1, 27]
	30	16 [0, 22]	25 [2, 40]	42 [3, 72]	81 [6, 157]
	100	63 [4, 117]	130 [8, 255]	208 [16, 435]	436 [33, 919]
	1000	445 [26, 1024]	948 [61, 2225]	1511 [89, 3429]	3130 [194, 7021]
ET+CE	1	n.d.	4 [0, 3]	3 [0, 11]	177 [9, 400]
	10	12 [0, 13]	51 [2, 112]	185 [10, 430]	6656 [366, 14836]
	30	37 [1, 66]	253 [15, 587]	915 [47, 2107]	36782 [2022, 78357]
	100	168 [11, 369]	1325 [73, 3034]	5075 [263, 11255]	123303 [6422, 250439]
	1000	1229 [69, 2862]	15497 [896, 34487]	69423 [3703, 144222]	194834 [10065, 388038]

Banerjee et al. 2022, in prep.

Kilonova emission

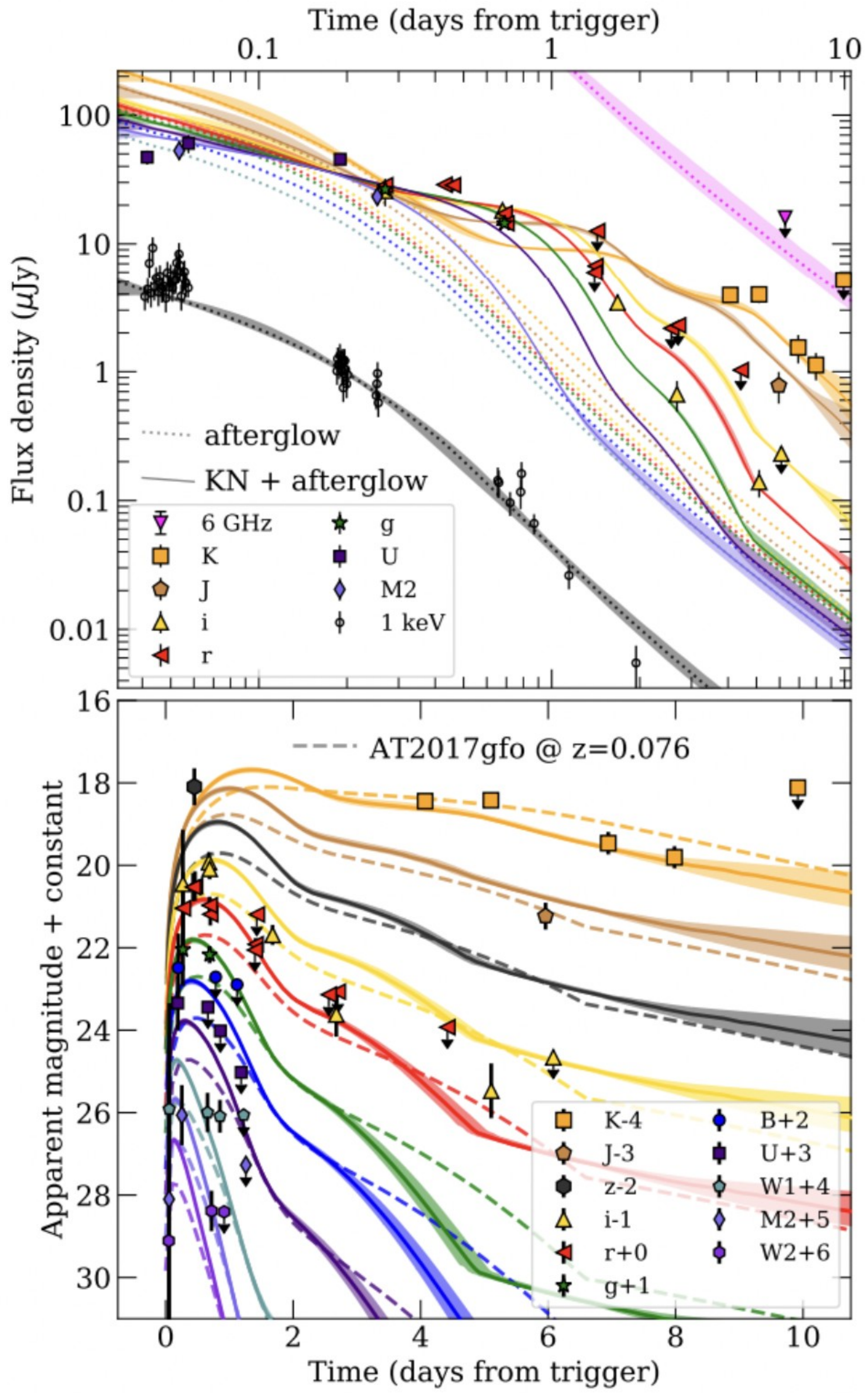
Li & Paczyński 1998:
Transient events from neutron star mergers



Daniel Kazen et al. 2017

Metzger 2019 for the review

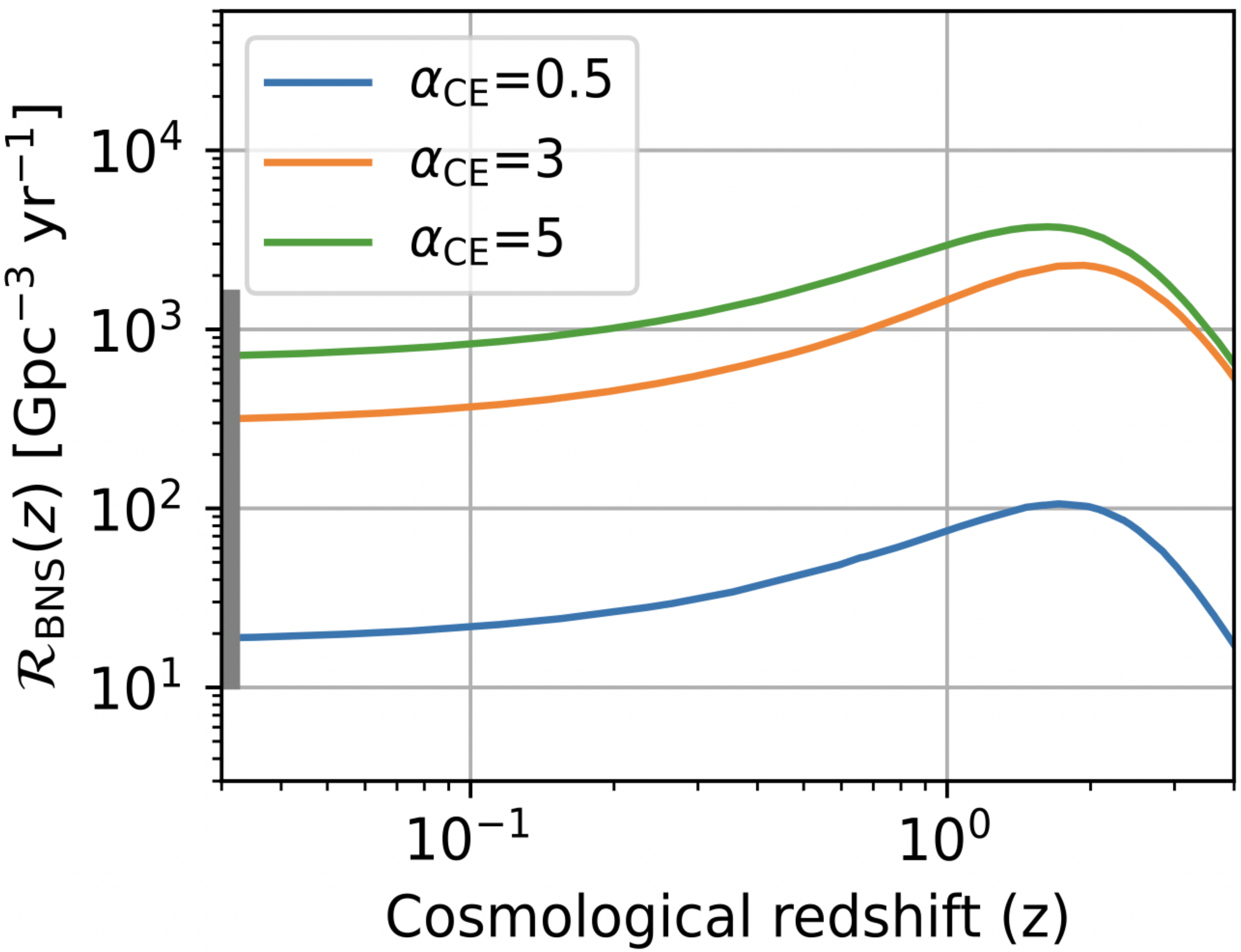
GRB 211211A



Three-component kilonova fit

- $M_{ej} = 0.04 \pm 0.02\ M_{\odot}$, almost all lanthanide-rich, in reasonable agreement with at2017gfo.
- $v_{ej} \simeq 0.25 - 0.3\ c$
- Associated to compact object merger in a binary system, likely BNS

Rastinejad et al. 2022, Nature



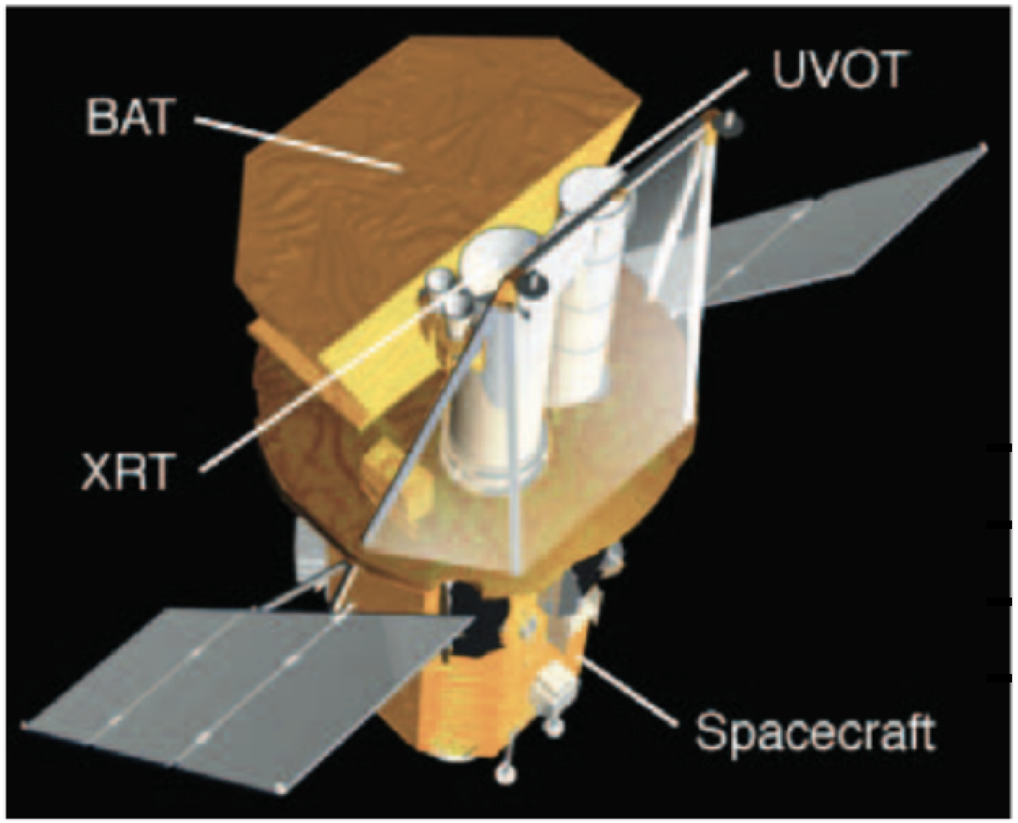
α_{CE}=0.5
α_{CE}=3
α_{CE}=5
$\mathcal{R}_{\mathrm{BNS}}(z)$ [Gpc^{-3} yr^{-1}]
10^4
10^3
10^2
10^1
10^{-1}
10^0
Cosmological redshift (z)

The Neil Gehrels Swift Observatory - from 2004

15 keV Swift/BAT 150 keV

FOV 1.4 sr

Swift/UVOT



- **70 GRBs/yr**
- **almost all with X-ray afterglow**
- **~60% optical afterglow**
- **~30 radio afterglow**

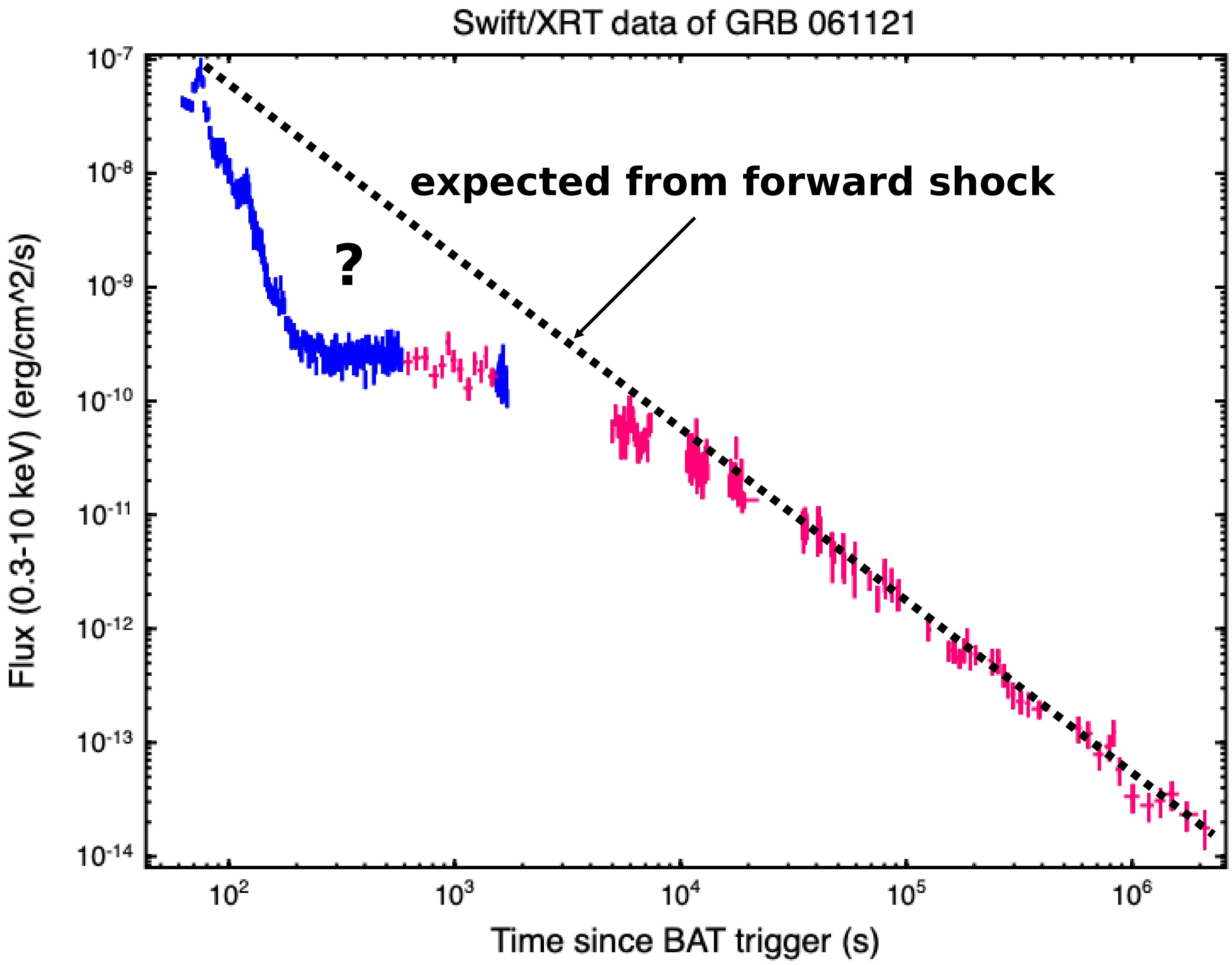
0.5-10 keV

Swift/XRT

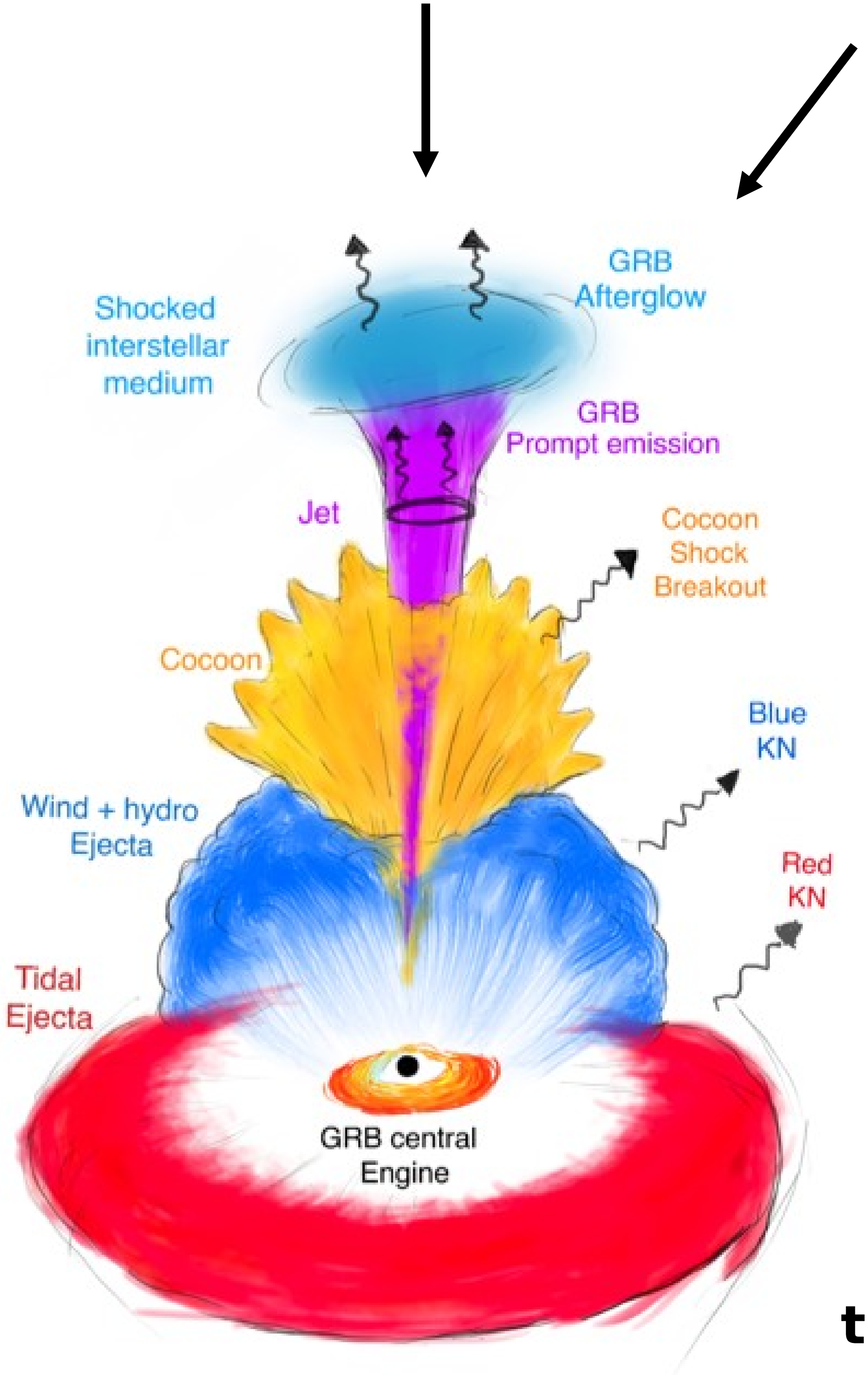
FOV 23.6 arcmin sq

XRT average slewing time ~ 90 s

The mystery of X-ray afterglows observed by Swift



NS-NS(BH) channels to produce short GRB jets



on-axis view

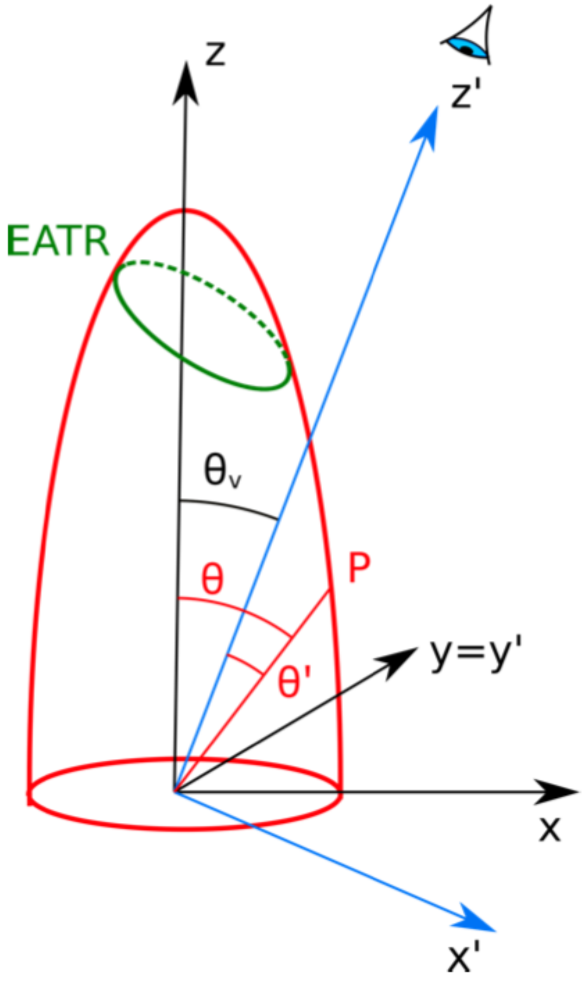
off-axis view

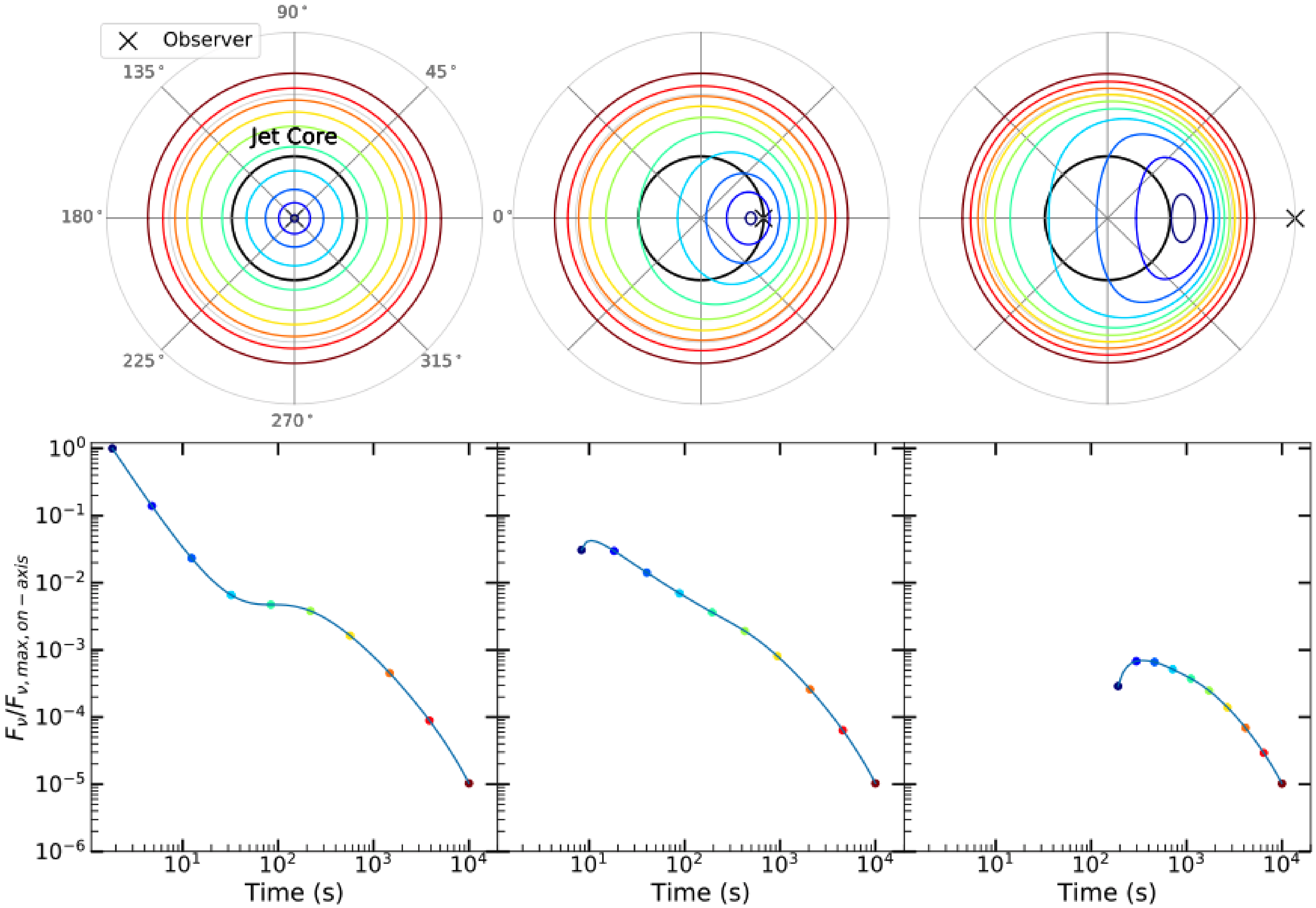
on axis transients
GWs,GRB, afterglow, kilonova

off axis transients
GWs, ?, afterglow, kilonova

taken from Ascenzi et al. 2020

Off-axis X-ray emission from GRBs





Ascenzi et al. 2020