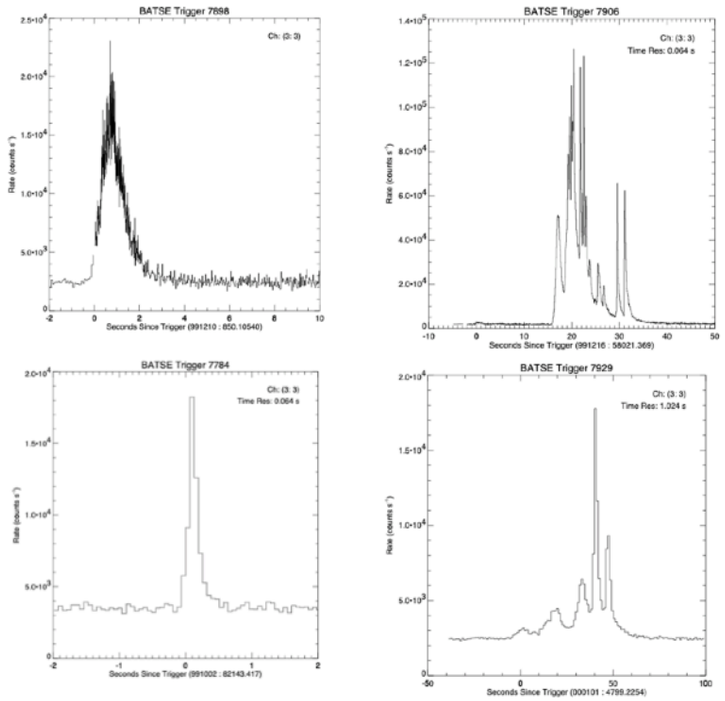
γ-ray bursts and gravitational waves

Gor Oganesyan

2nd LHAASO symposium, 24 March 2025

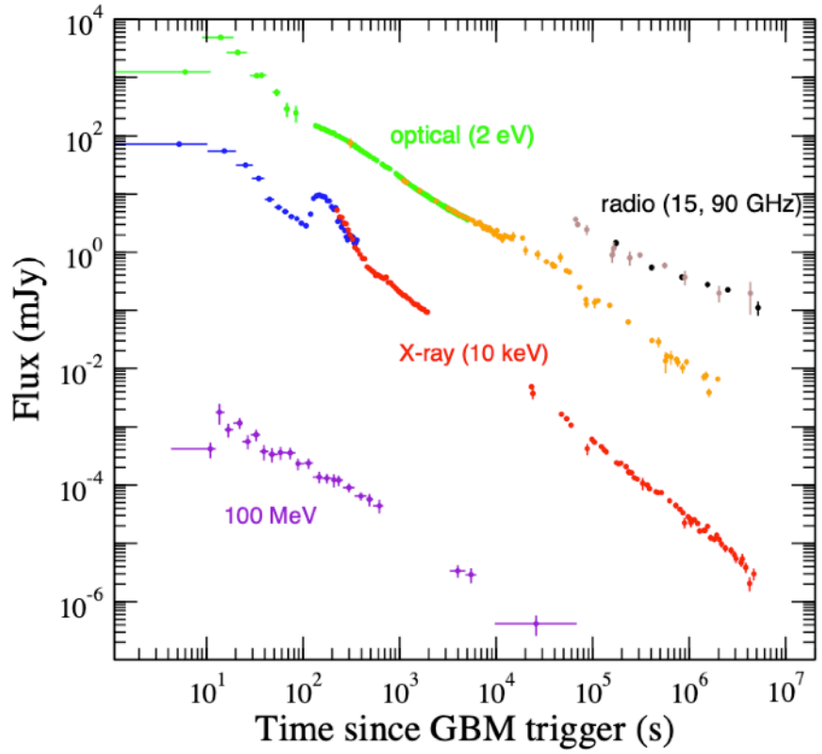
MeV burst



news

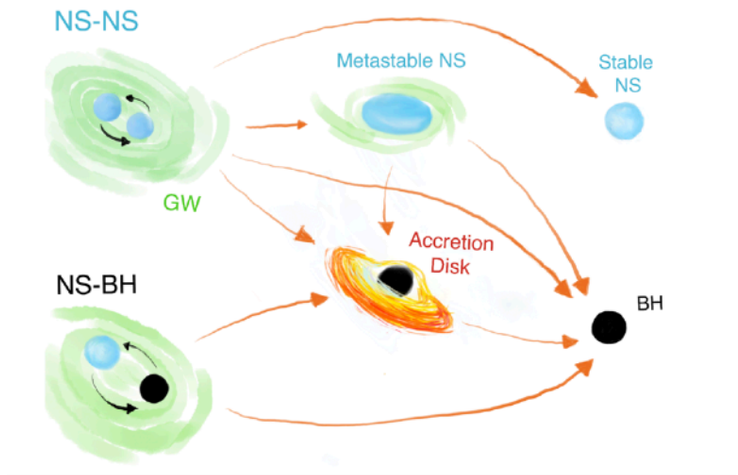
10 MeV line

Afterglow



TeV emission

Progenitors



news

oddballs

\+

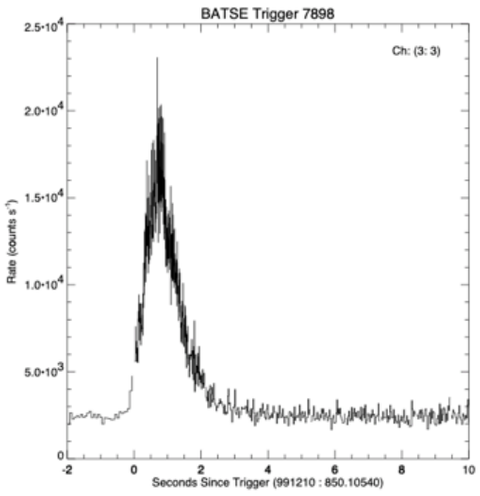
LVK status

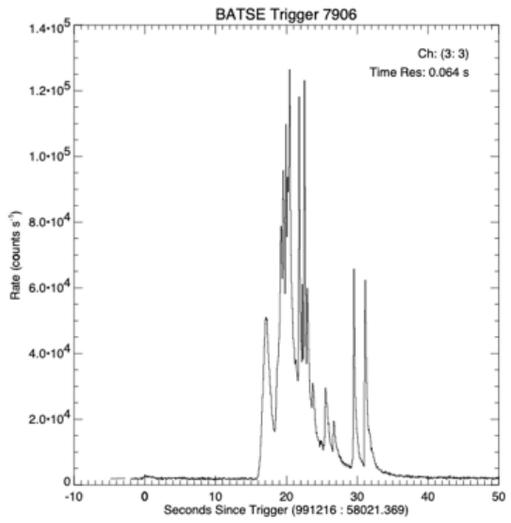
3G GW

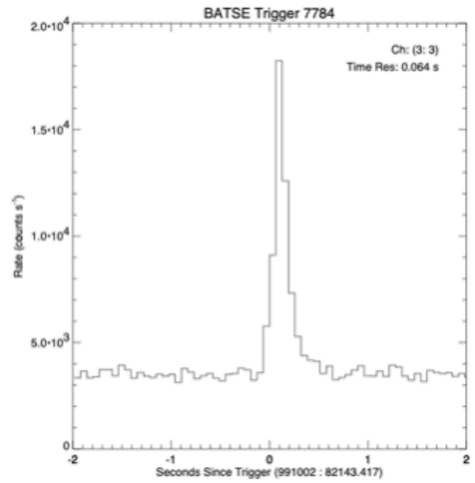
γ-ray bursts

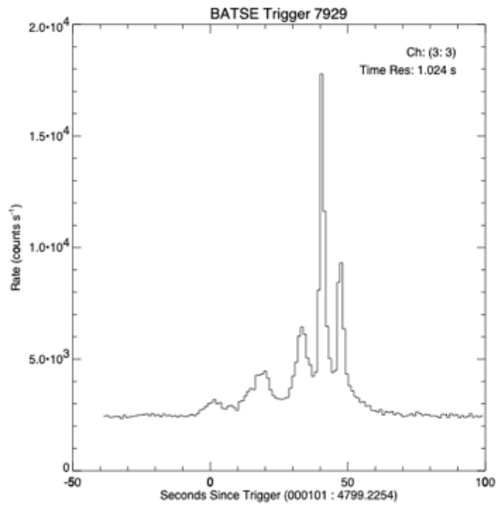
the prompt emission

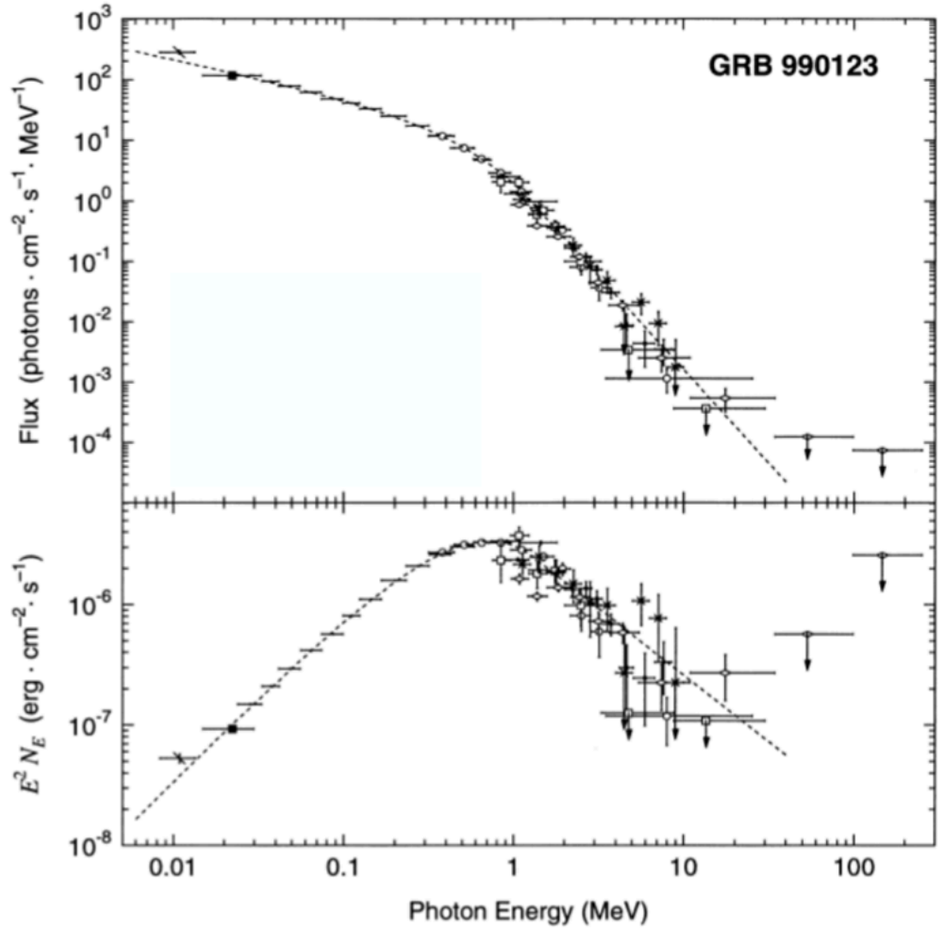
γ-ray bursts











Briggs et al. 1999

energy (iso) $\sim 10^{50} - 10^{54}\,\mathrm{erg}$

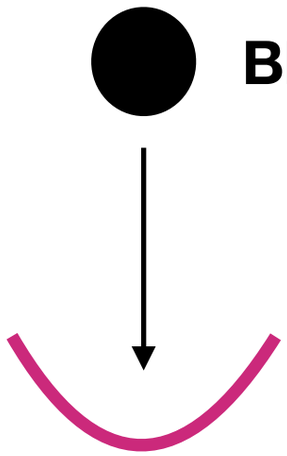
photons ~ MeV

$$E_{peak} \sim 100\,keV - 1\,MeV$$

variability 0.01-1 s

duration 0.1 - 1000 s

Pair fireball



BH $\sim 1 - 10 M_\odot$

$e^{\pm}, \gamma$

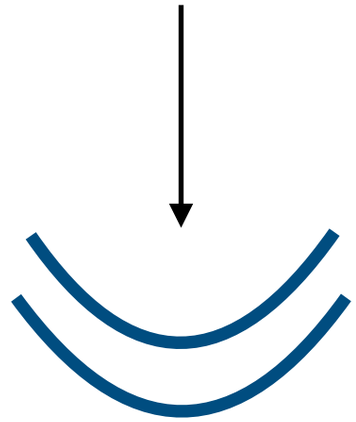
$L_\gamma >> 10^{10} L_{Edd}$

$T_{BB} \sim MeV$

Cavallo & Rees 1978
Paczýnski 1986
Goodman 1986

Baryon poisoning

Cavallo & Rees 1978
Paczýnski 1990
Shemi & Piran 1990



$R_{coll} \approx 2c\,\delta t\,\Gamma_s^2$

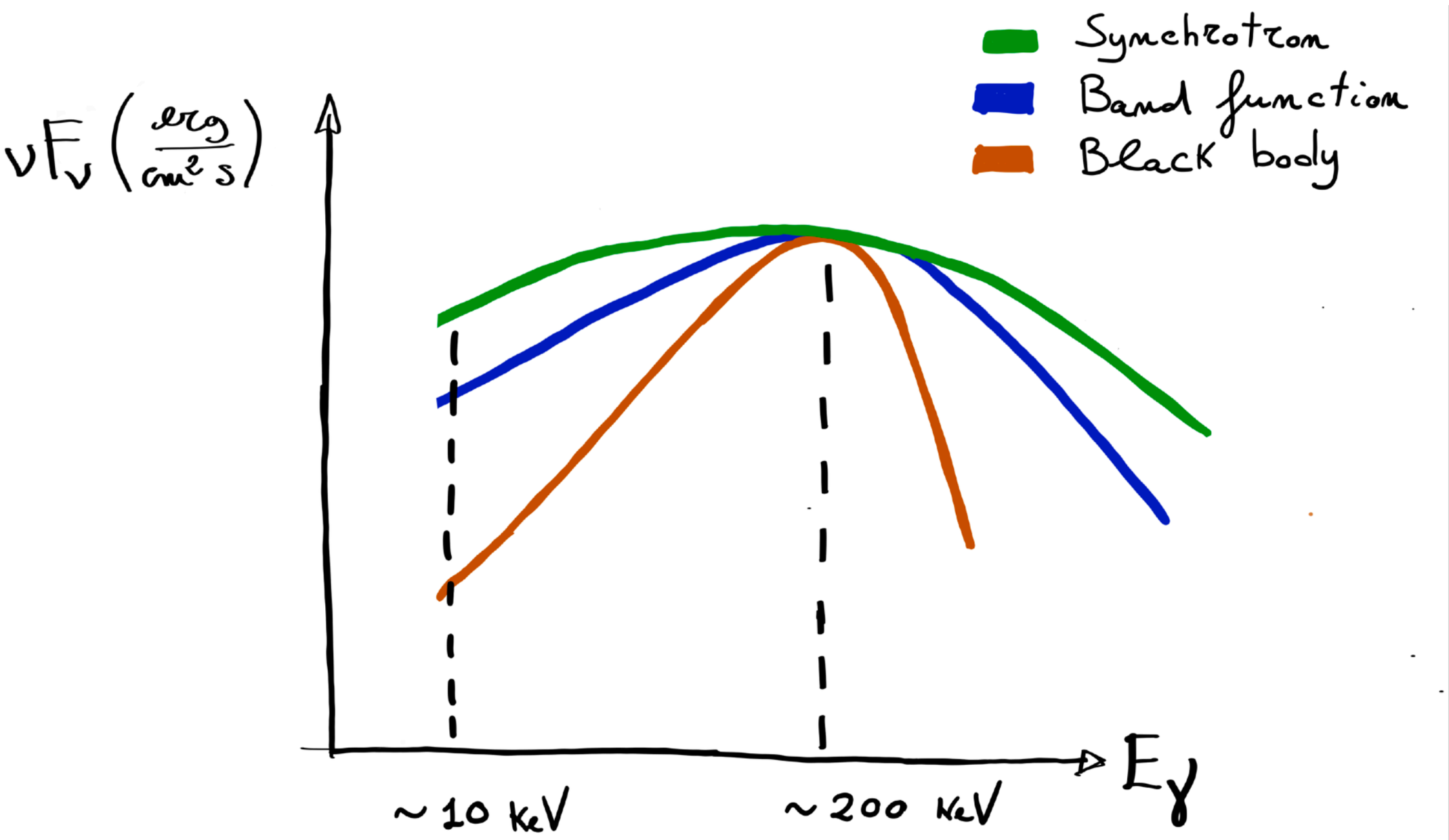
$T_{BB} \rightarrow L_k \rightarrow L_\gamma$

Rees & Mészáros 1994

(Narayan et al. 1992, Paczýnski & Xu 1994)

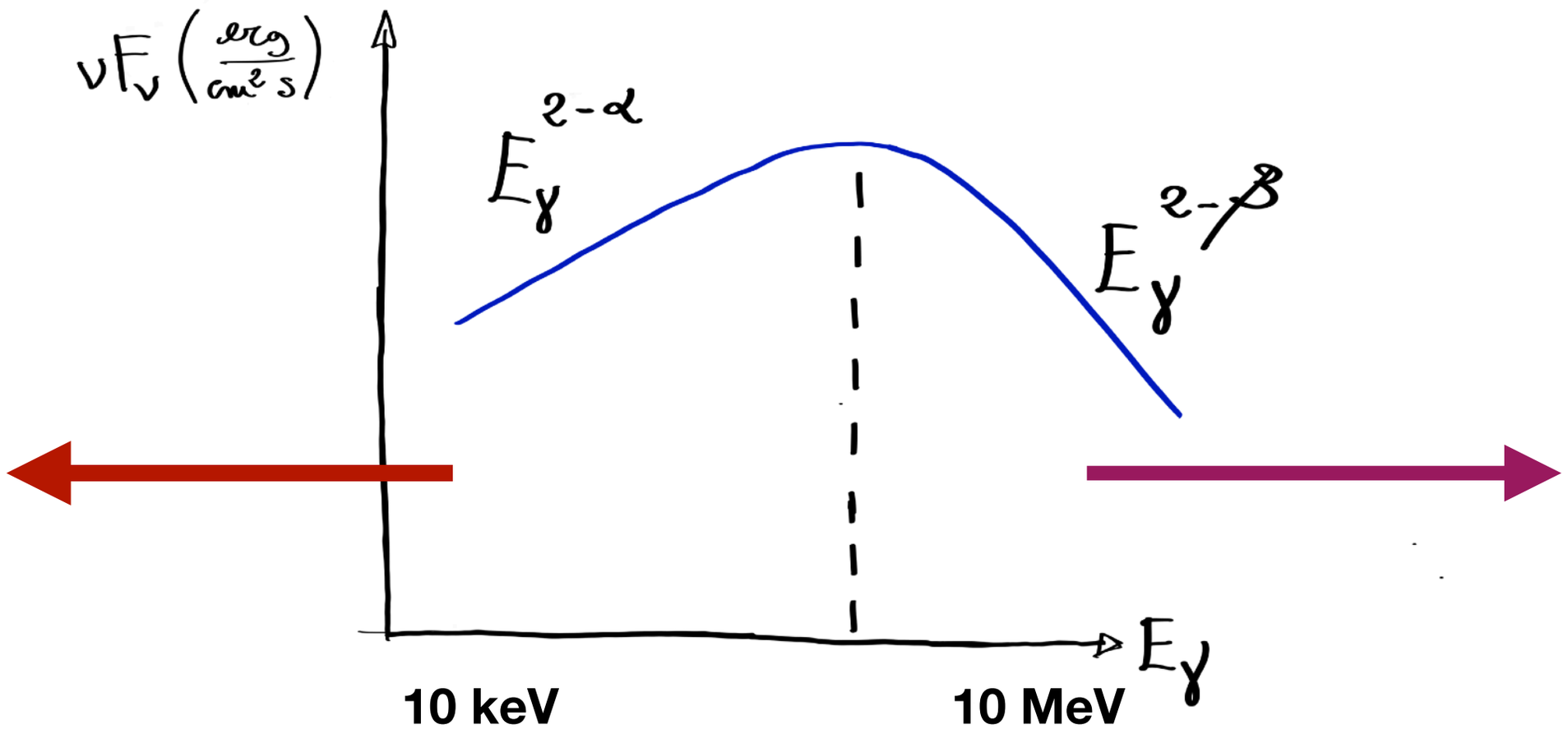
Daigne & Mochkovitch 1998

Synchrotron vs Thermal emission



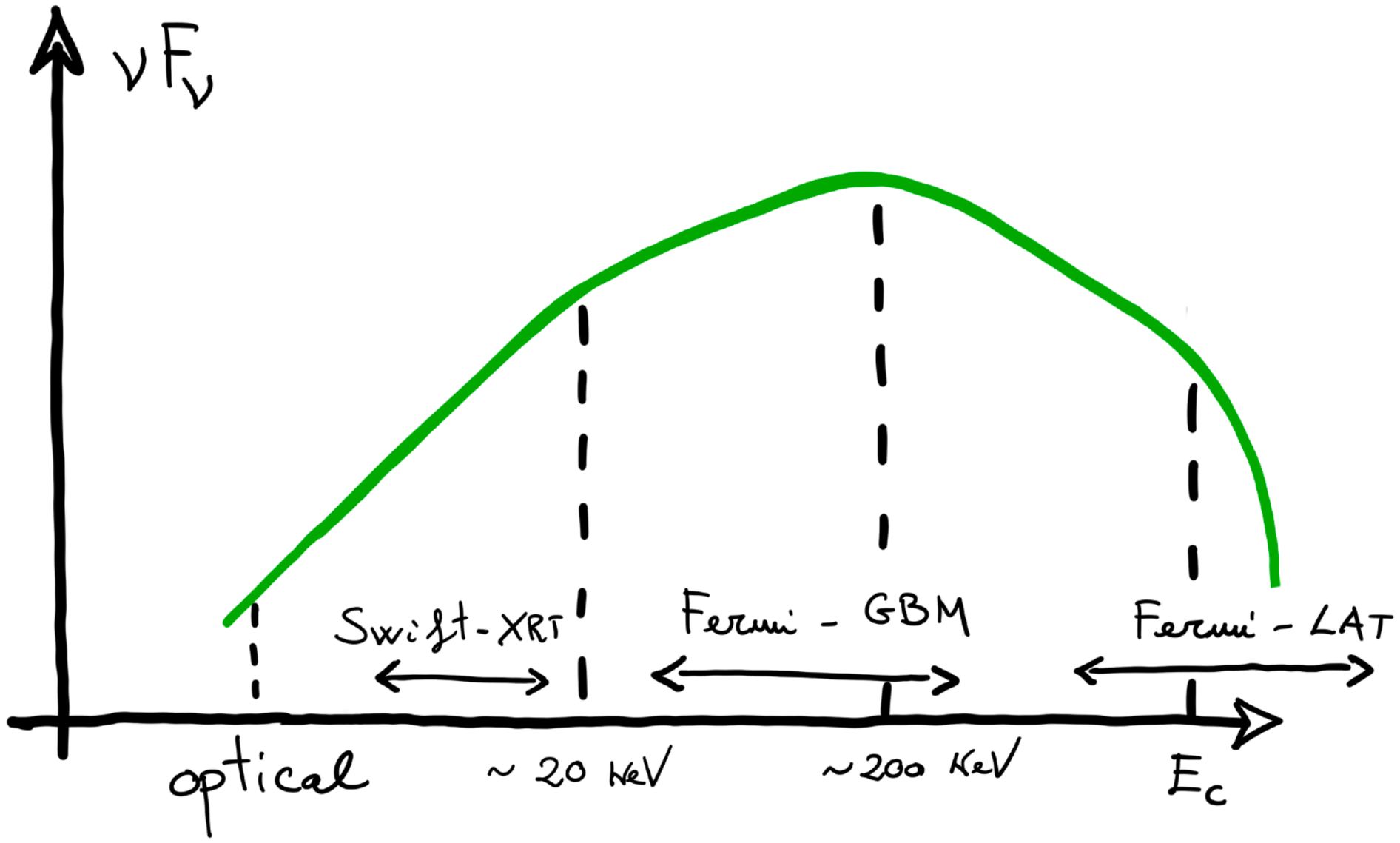
Ghisellini et al. 2000

Multi-wavelength observations



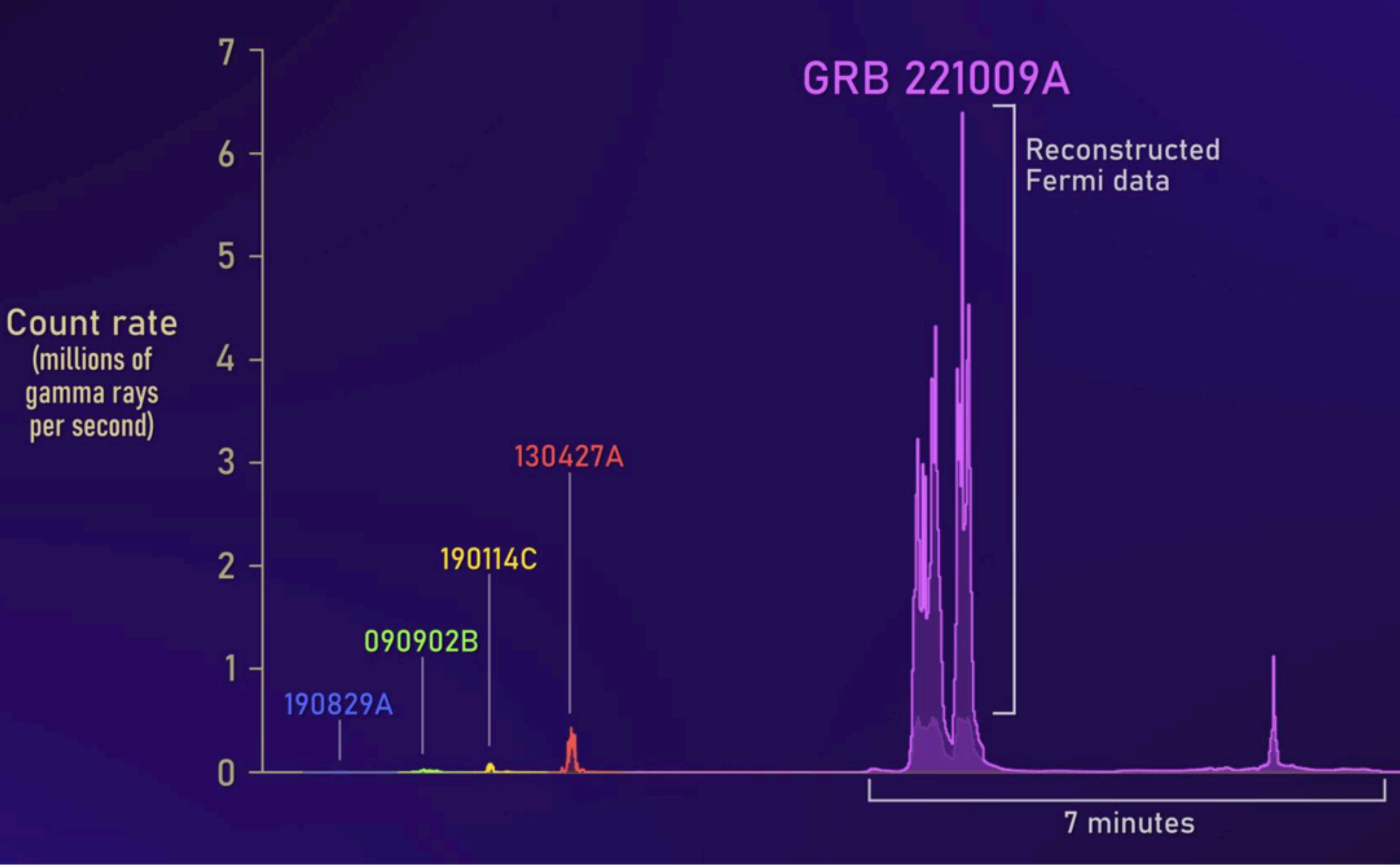
γ-ray bursts

the prompt emission



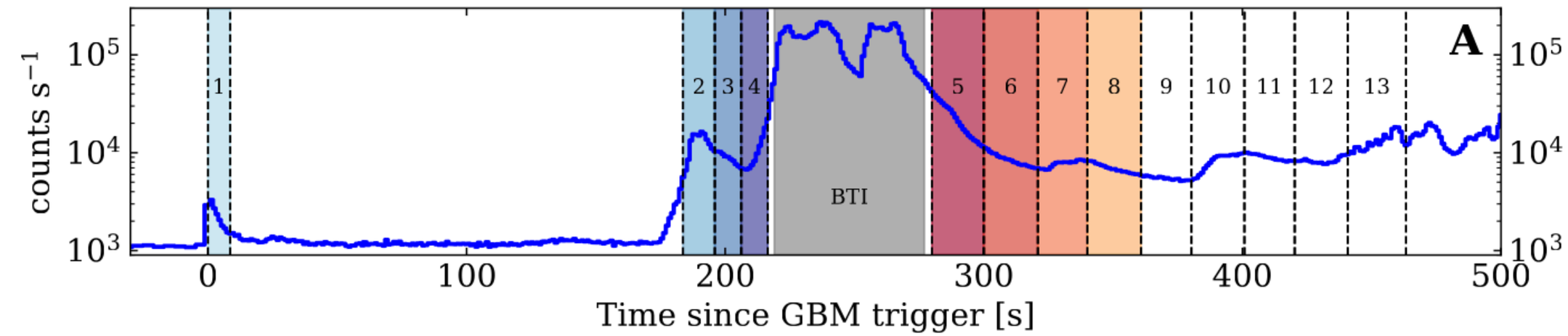
GO+ 2017, Ravasio et al. 2018

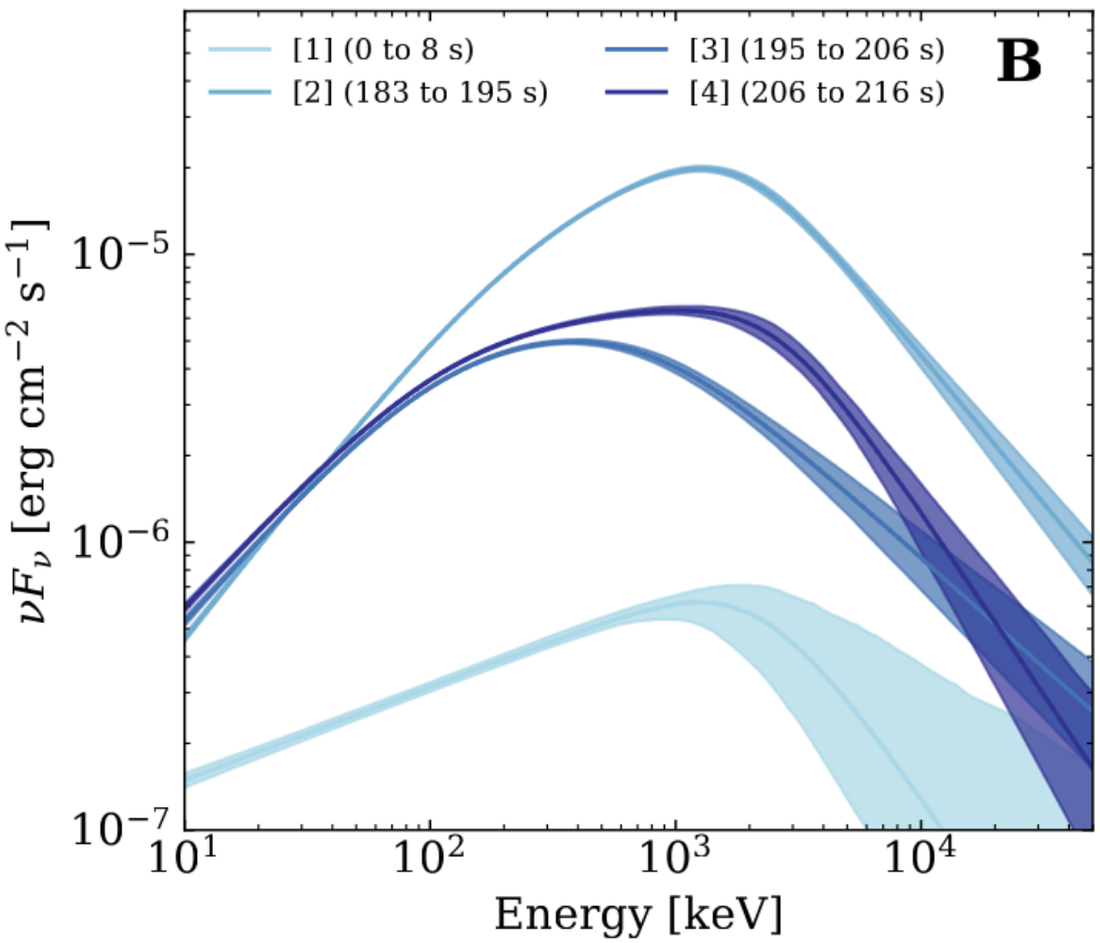
anything new?

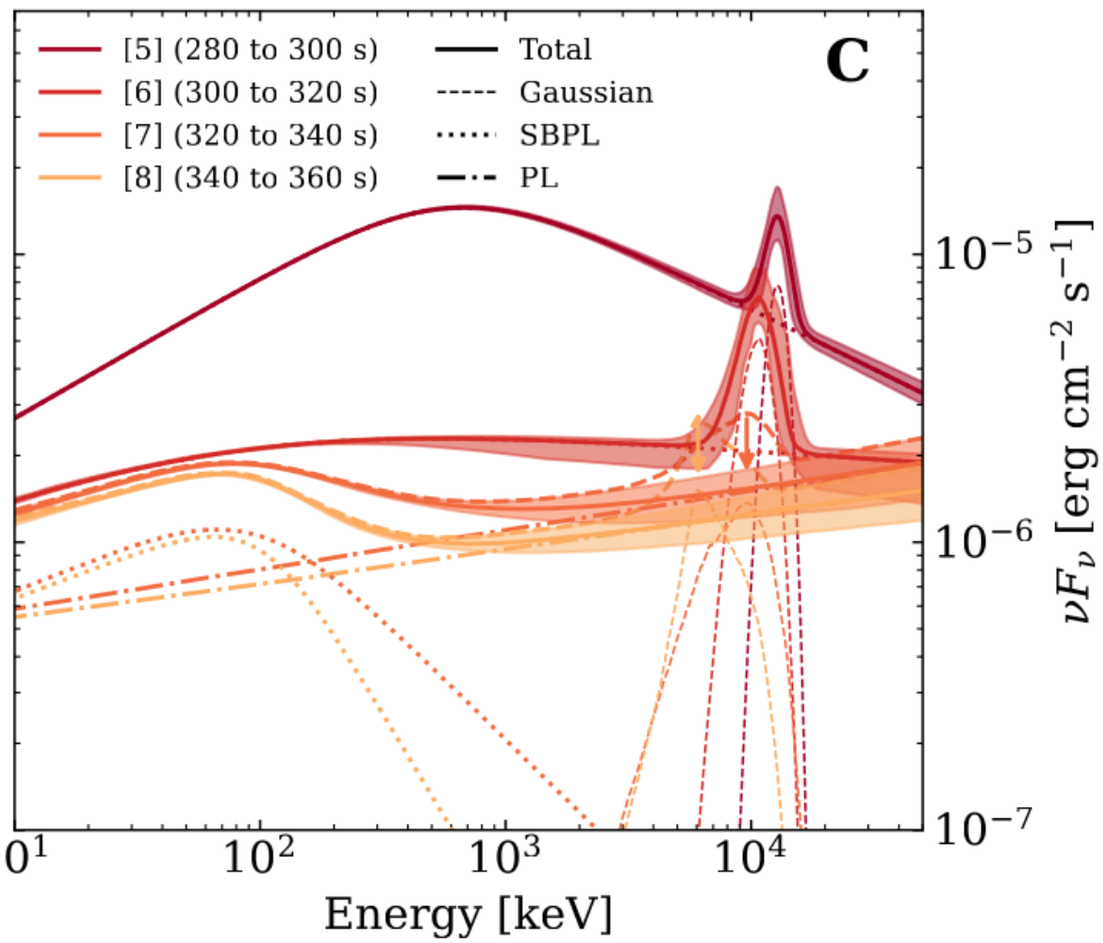


NASA Goddard Space Flight Center, Adam Goldstein (USRA)

Discovery of the ~ 10 MeV line

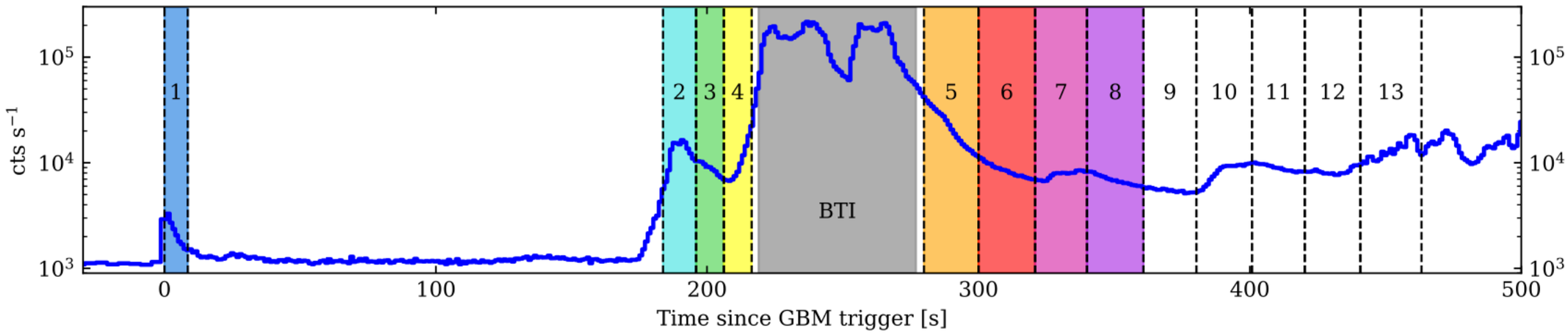


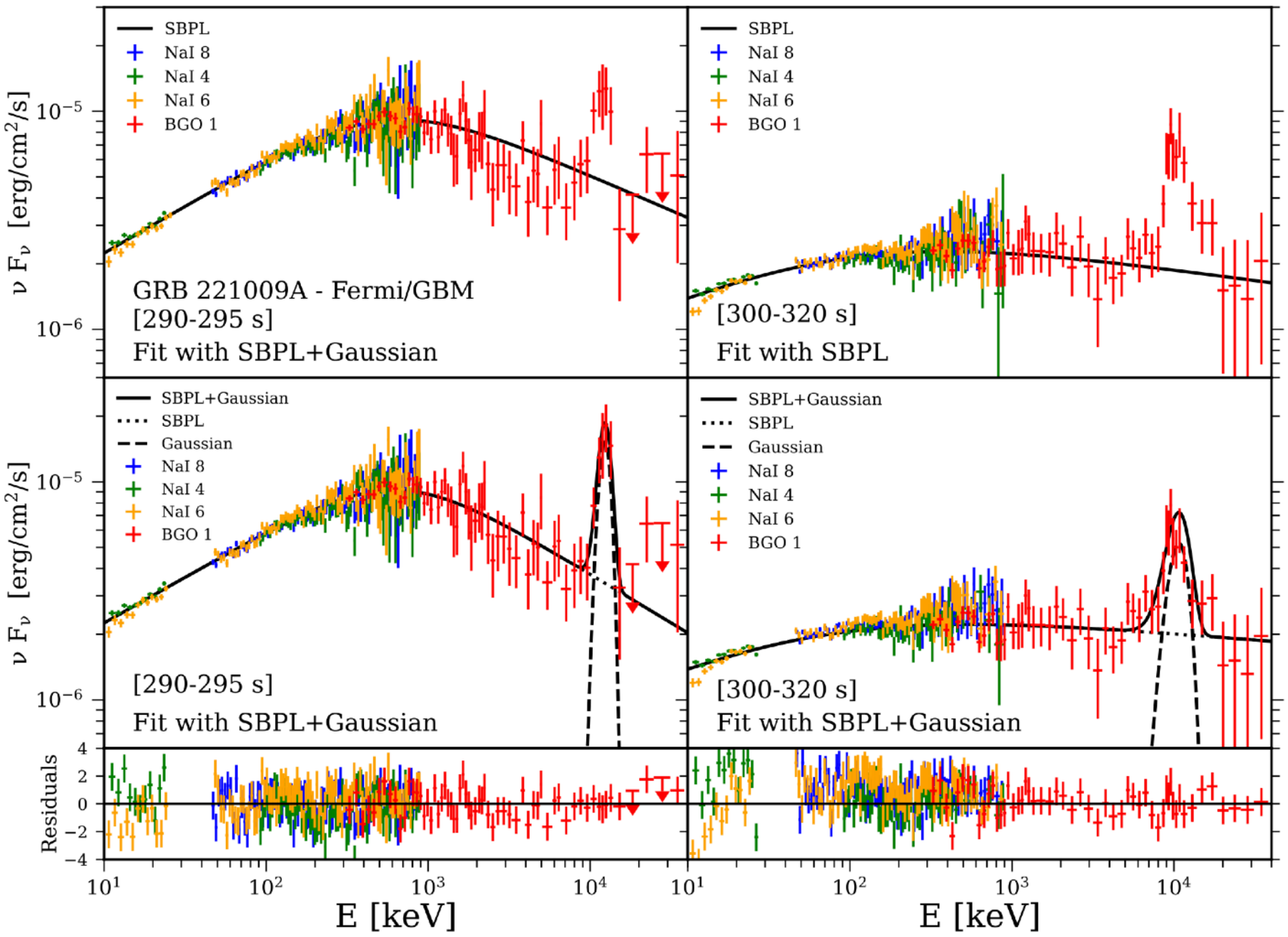




Ravasio et al. 2024, Science

GRB 221009A - BOAT 10 MeV line Ravasio et al. 2024, Science



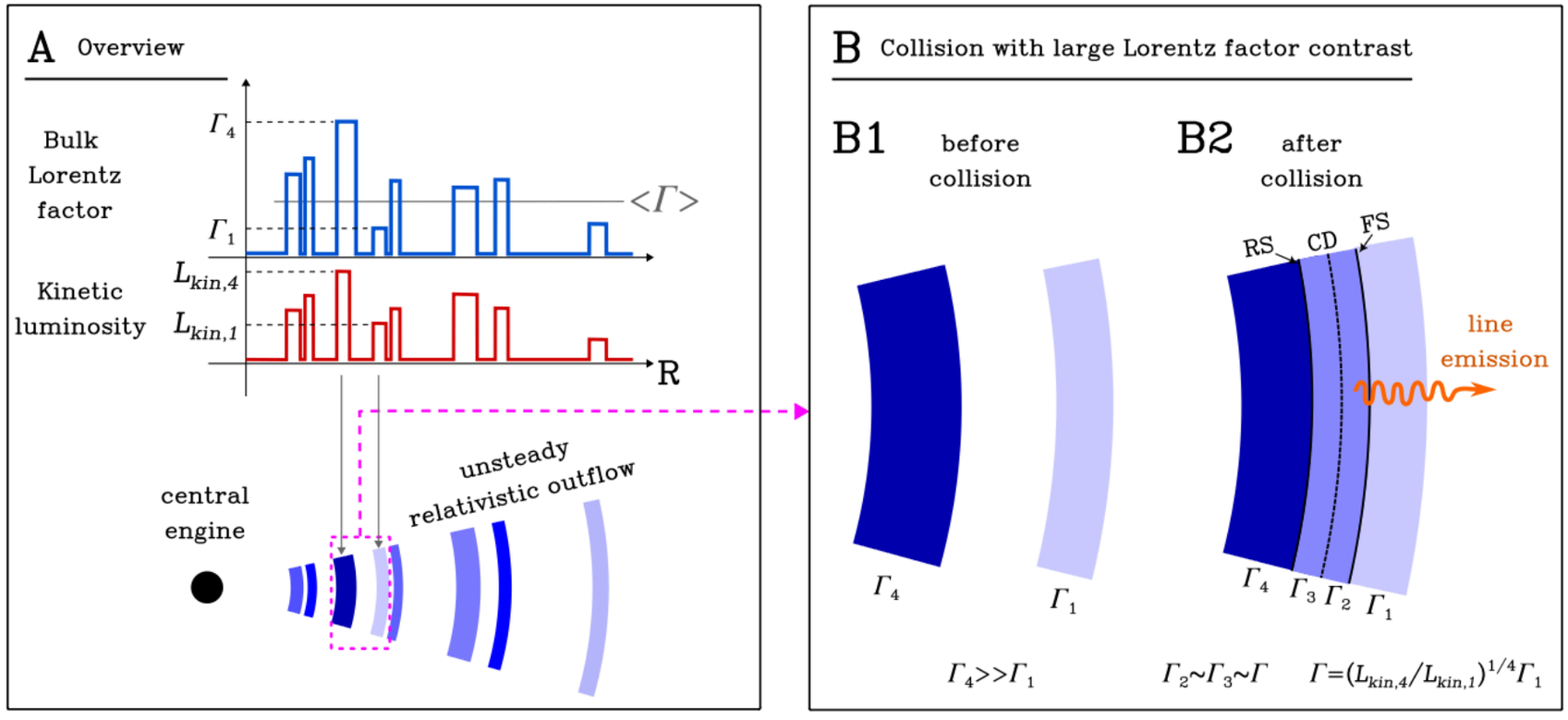


Origin of the MeV line

1. Take a keV line and boost it to MeV —-> too fast SN ejecta

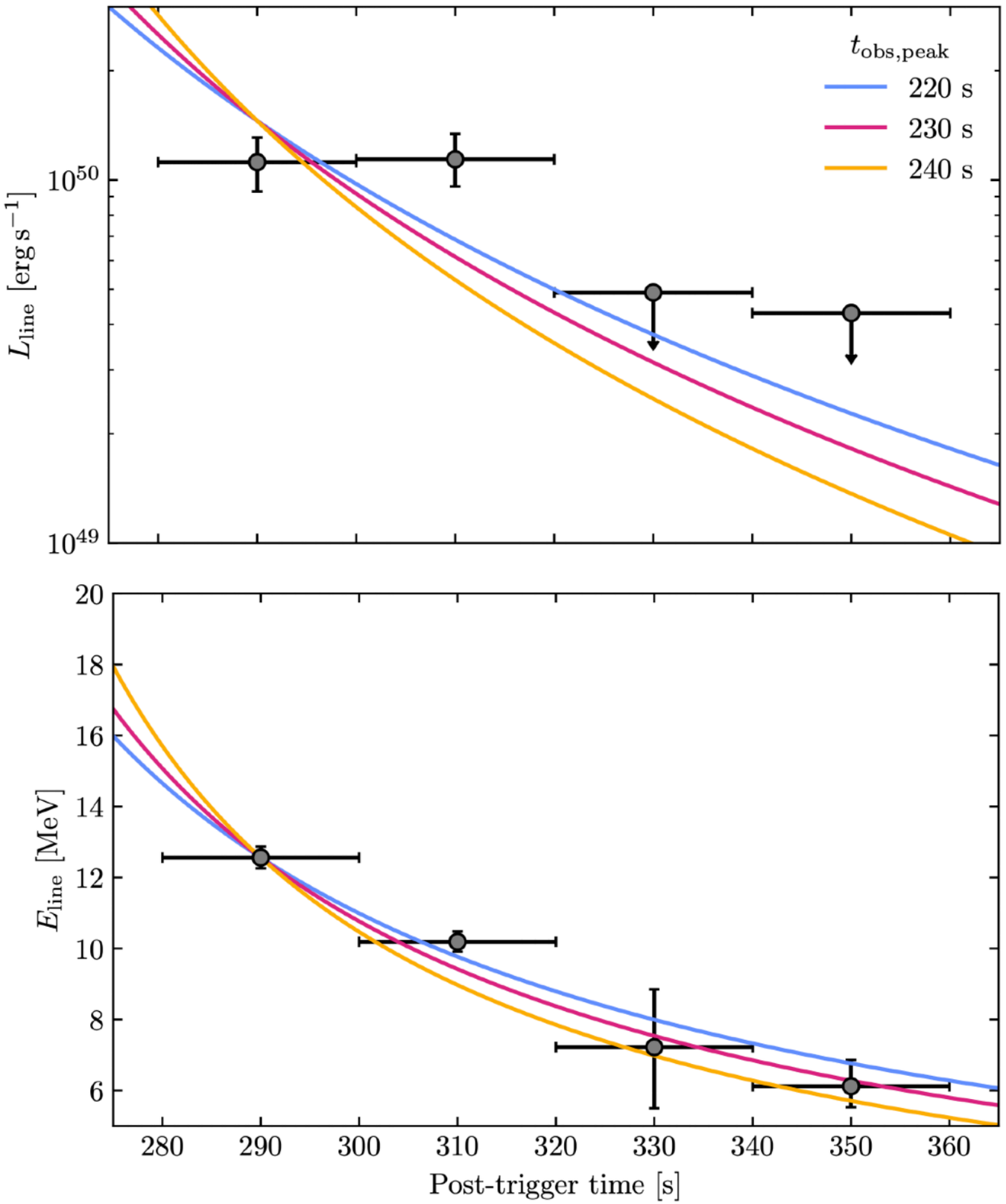
2. Take an annihilation line and boost it to MeV —-> small bulk LF

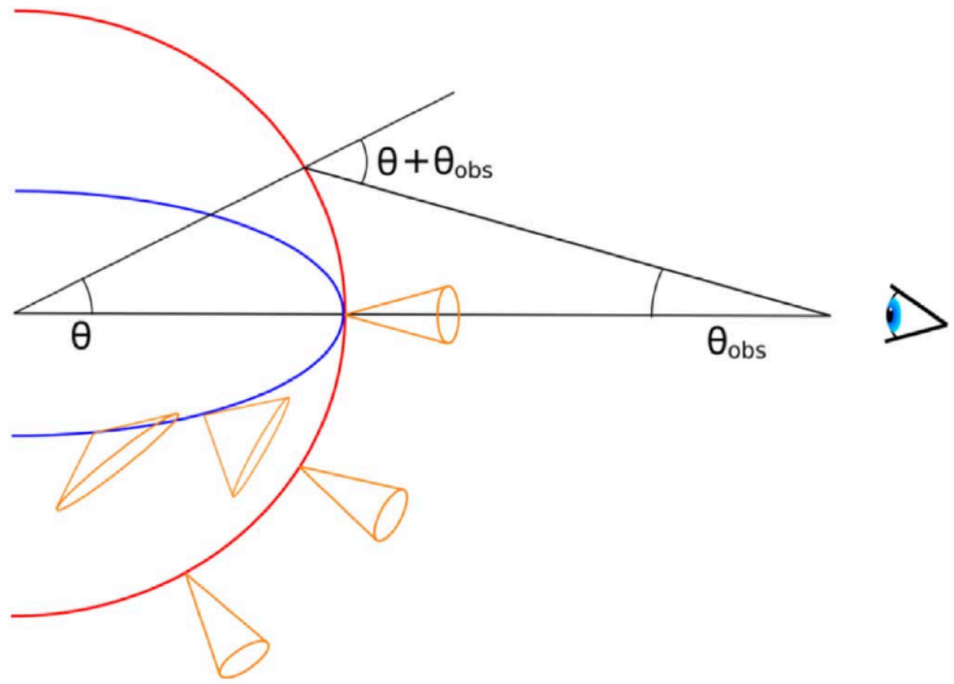
2.1 Slow shells in the internal shocks model



Ravasio et al. 2024, Science

2.2 Fast or a slow shell observed later on



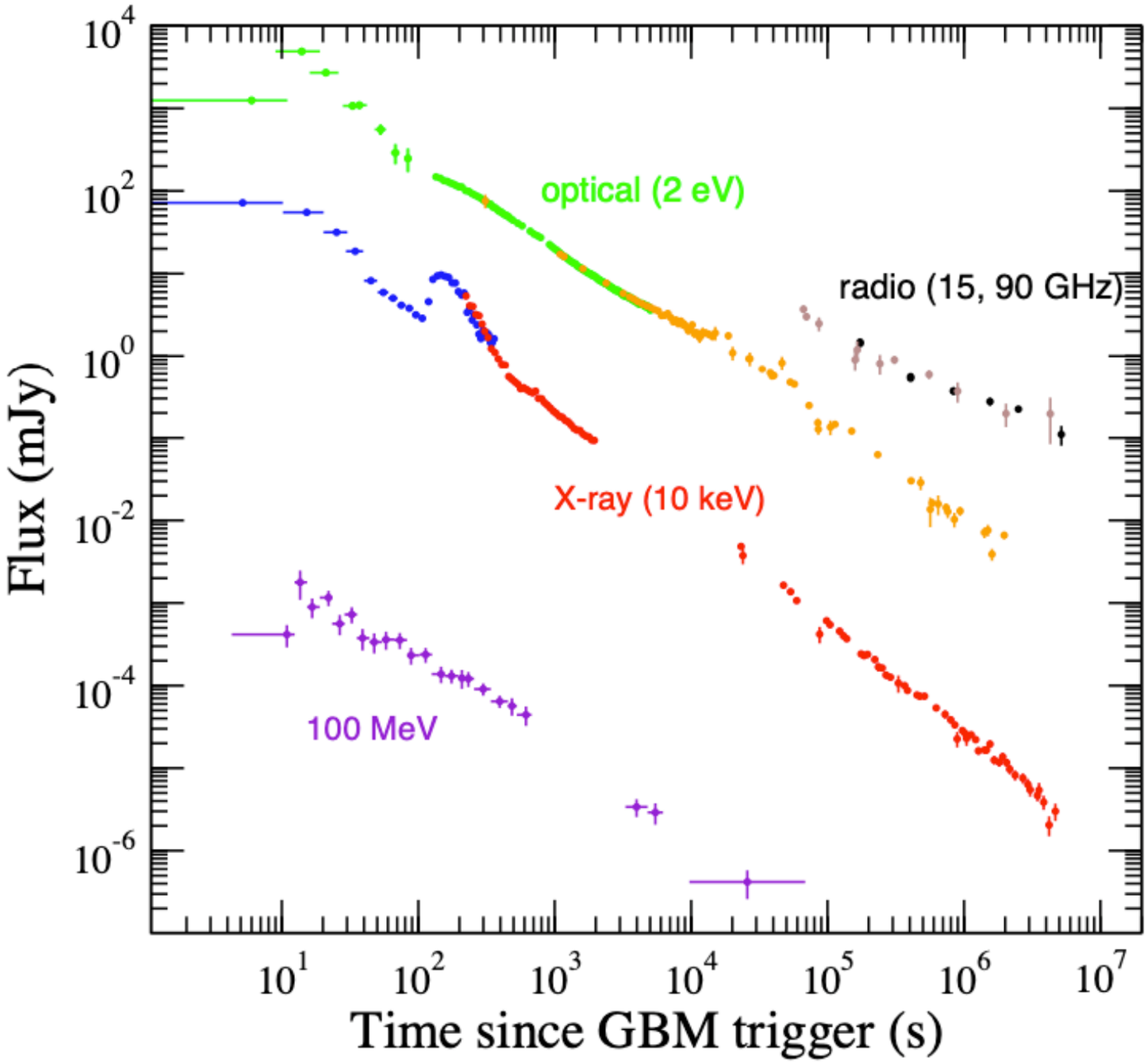


Ravasio et al. 2024, Science

γ-ray bursts

the afterglow

Afterglow



example GRB 130427A Panaitescu et. al. 2013

discovered

Costa et al. 1997

predicted

Paczýnski & Rhoads 1993

Mészáros & Rees 1997

dynamics

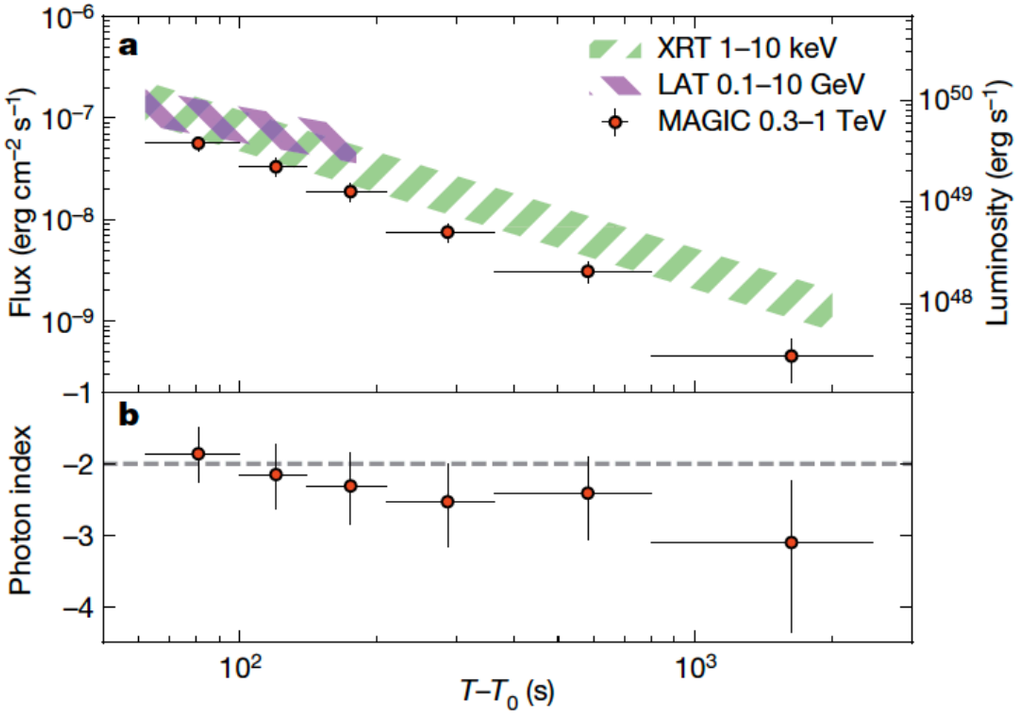
Blandford & McKee 1976

phenomenology

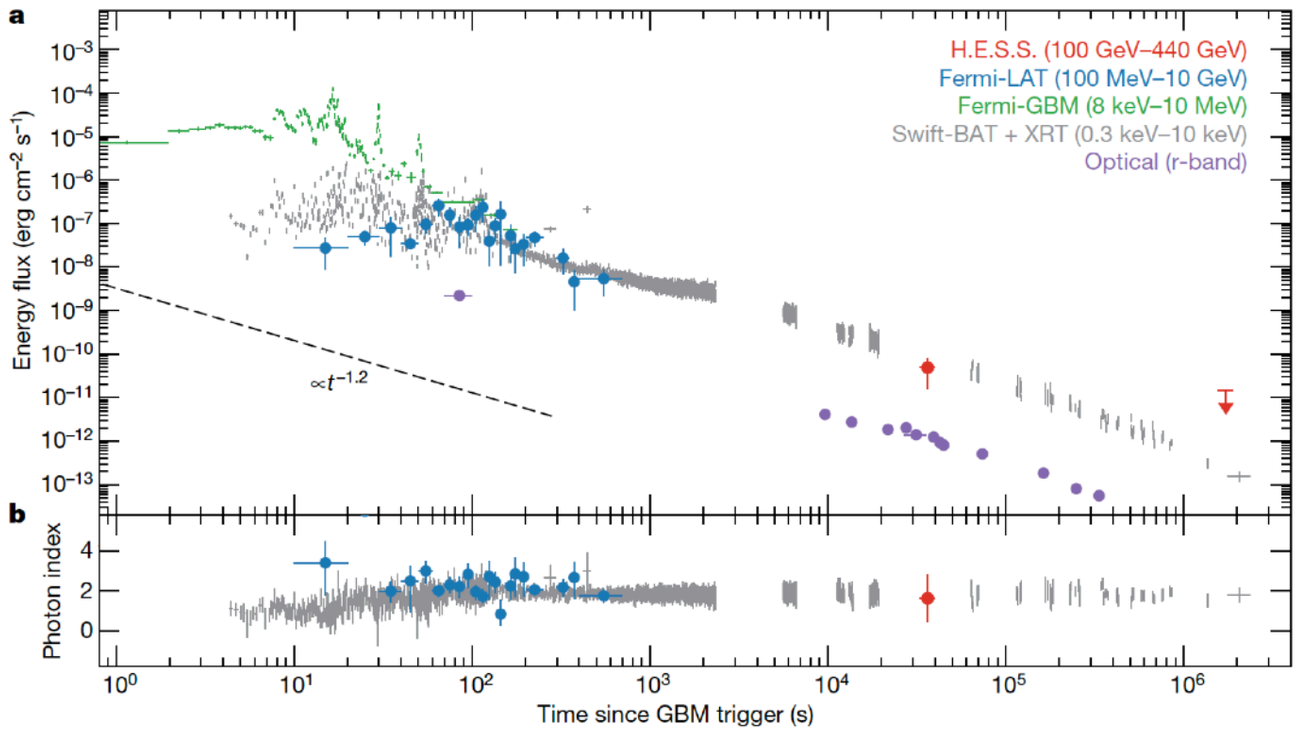
Sari et al. 1998

GRBs at Very High Energies - the discoveries of 2019

MAGIC and H.E.S.S. collaborations

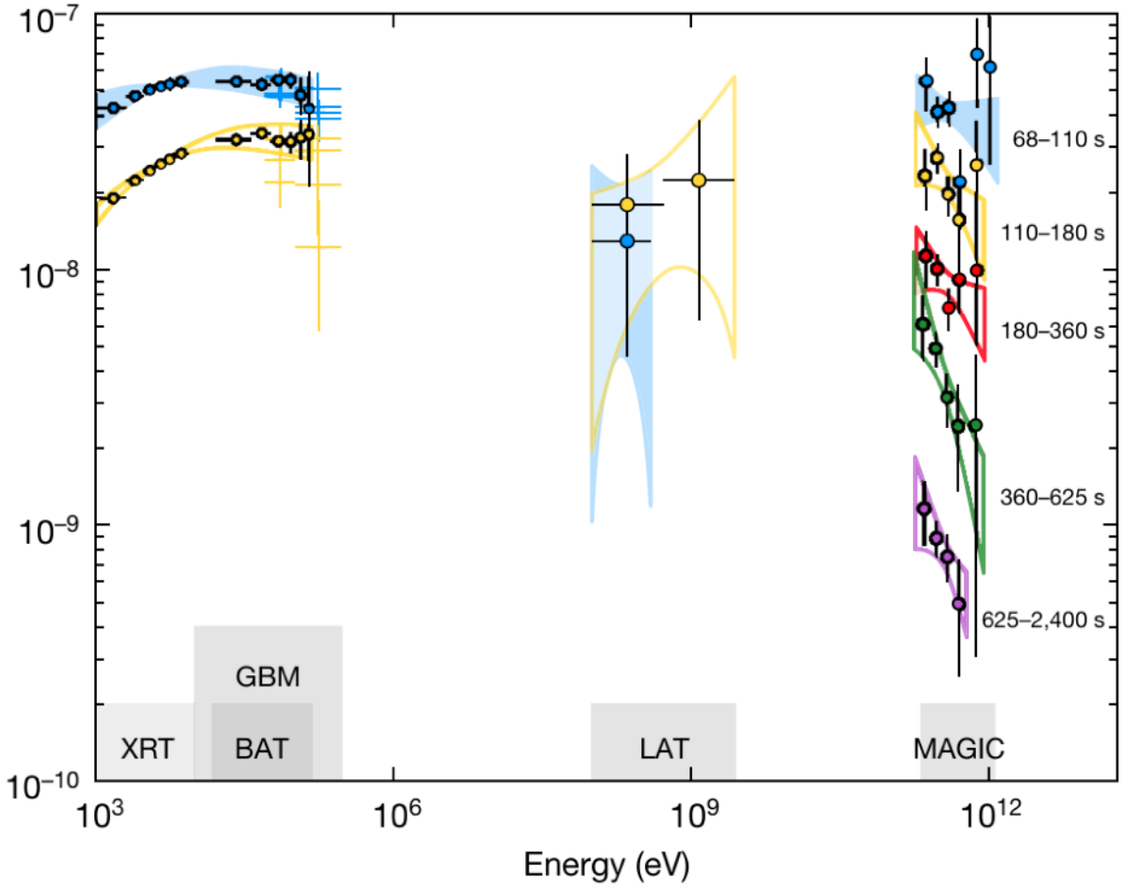


MAGIC collaboration
Nature 2019



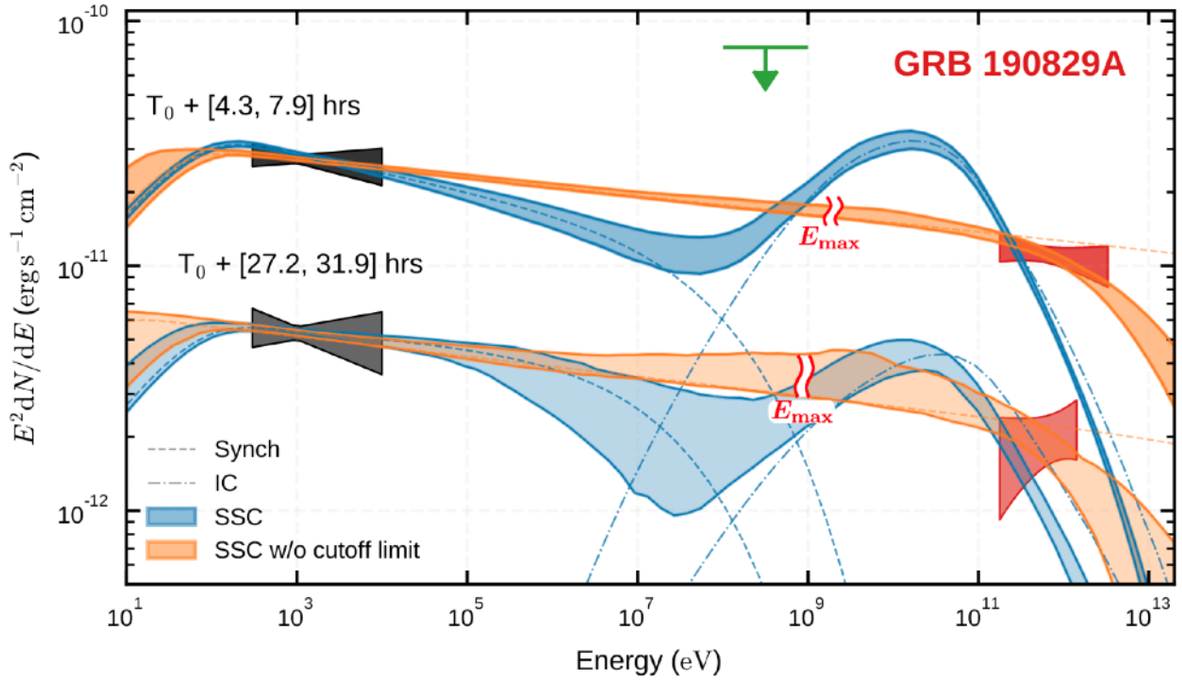
H.E.S.S. collaboration
Nature 2019

GRB 190114C



MAGIC collaboration
Nature 2019

GRB 190829A



H.E.S.S. collaboration
Science 2021

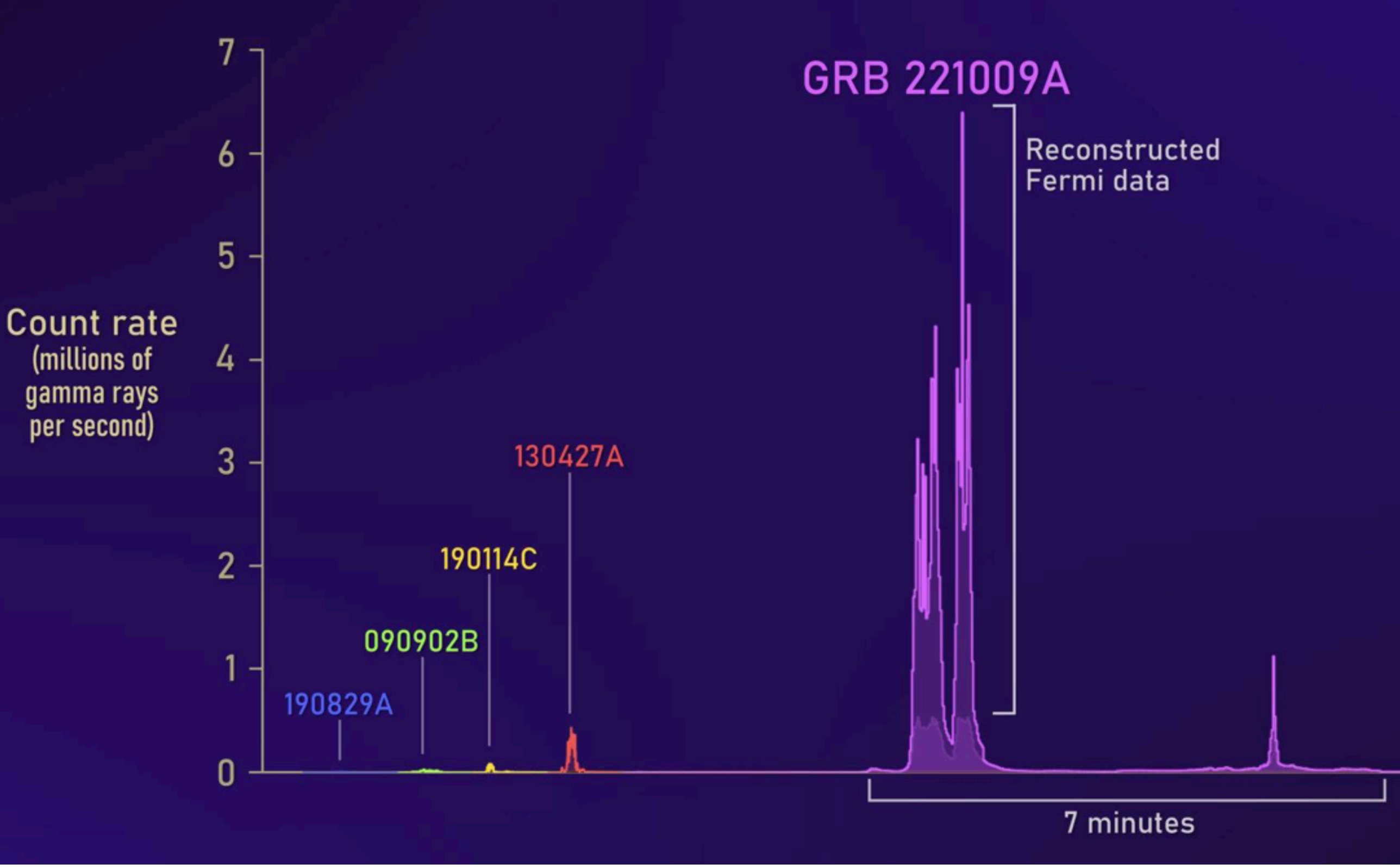
If SSC, why syn ~ SSC?

The MeV-GeV gap

GRBs	Time ($t-T_0$)	0.3 keV	10 keV	100 keV	1 MeV	100 MeV	10 GeV	100 GeV	1 TeV
GRB 180720B	~10 hr	?	?	?	?			H.E.S.S.	
GRB 190114C	68–110 s	XRT	GBM / BAT	?	LAT (~3σ)			MAGIC@20	
	110–180 s	XRT	GBM / BAT	?	LAT (~5σ)				
GRB 190829A	4.3–7.9 hr	XRT	?	?	LAT (U.L.)			H.E.S.S.	
	27.2–31.9 hr	XRT	?	?	LAT (U.L.)				
GRB 201216A	60–1.2 ks	XRT	?	?	LAT (U.L.)			MAGIC@20	

XRT | BAT | GBM | LAT | IACTs

MAGIC Collaboration:
Nature v. 575, p. 455–458 (2019) and
Nature v. 575, p. 459–463 (2019)
H.E.S.S. collaboration, Nature, 2019
H.E.S.S. collaboration, Science, 2021
MAGIC Collaboration, MNRAS, 2024



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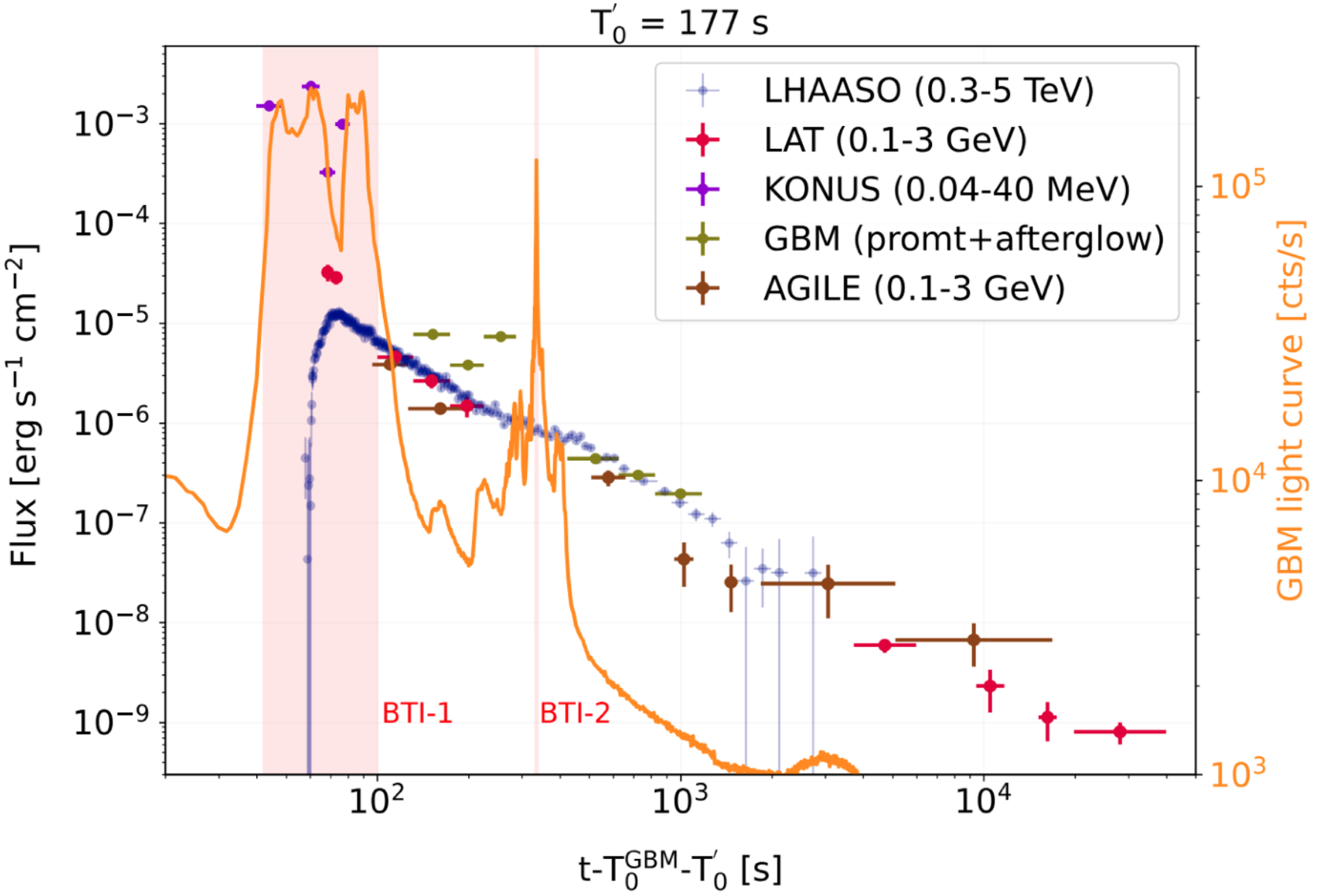
GRB 221009A - BOAT



Banerjee et al. 2024,
arXiv 2405.15855

LHAASO Collaboration, Science (2023)

Tavani et al 2023
ApJL 956 L23, 2023

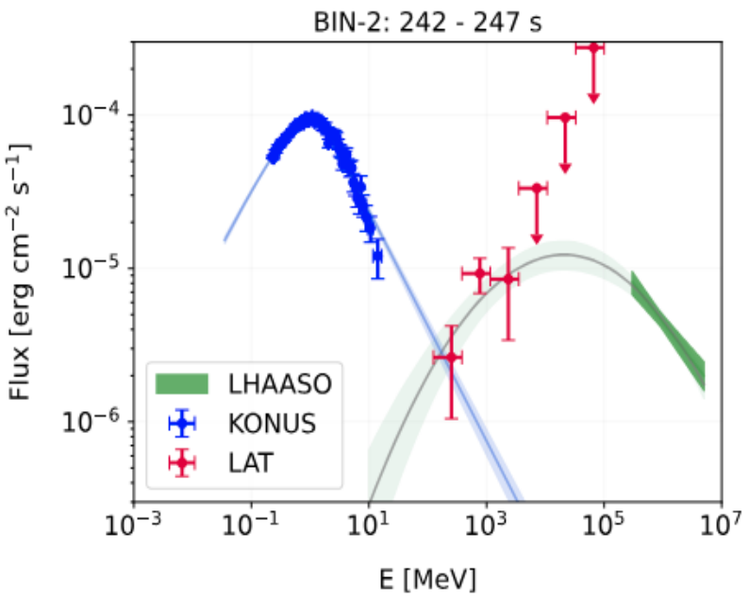
Bissaldi et al 2023

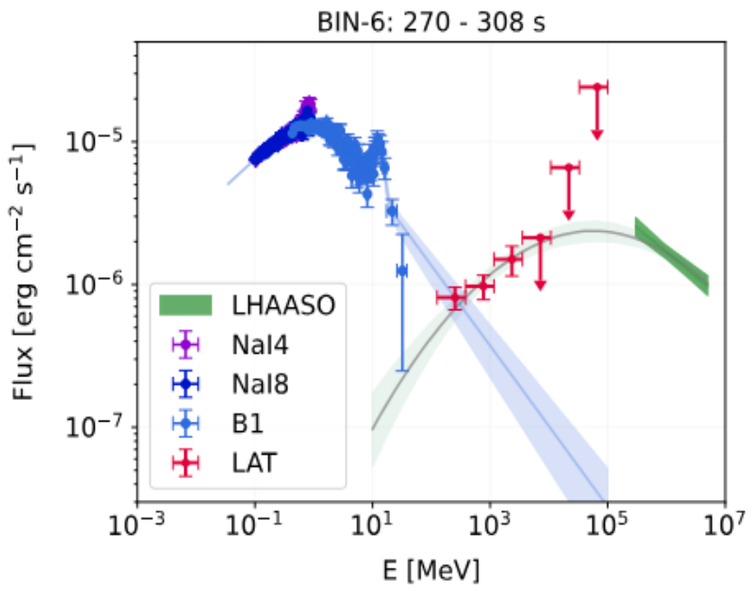
Frederiks et al 2023
ApJL, 949, L7 (2023)

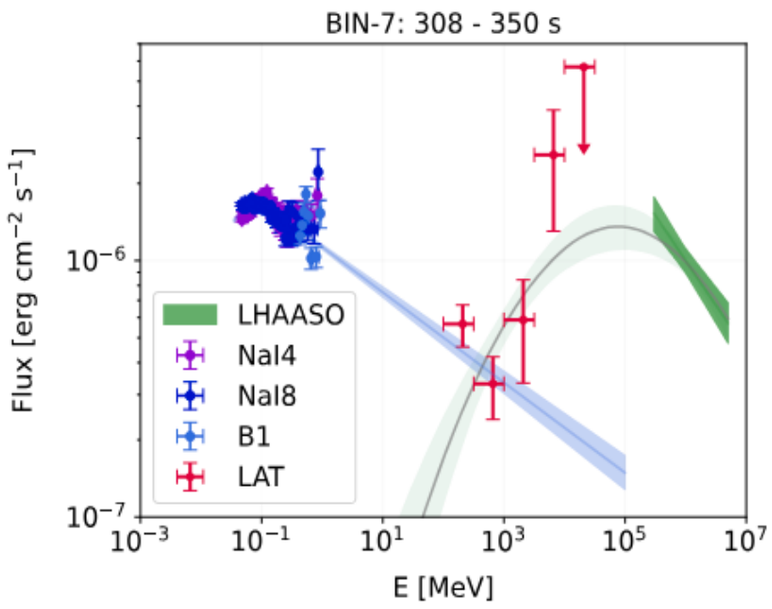
Lesage et al 2023,
ApJL 952 L42

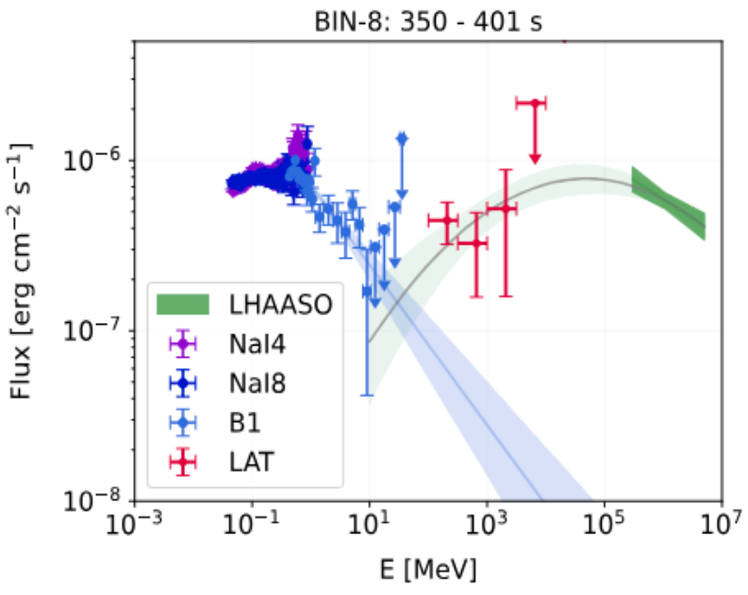
Burns et al 2023,
ApJL 946 L31

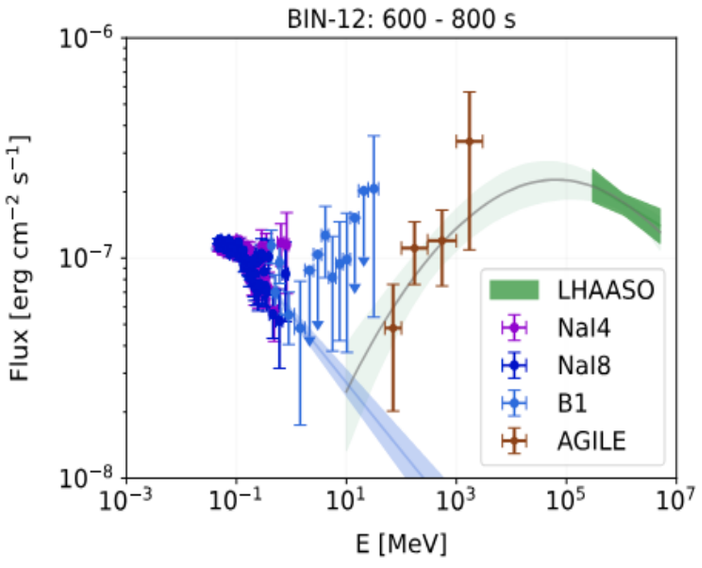
GRB 221009A - BOAT

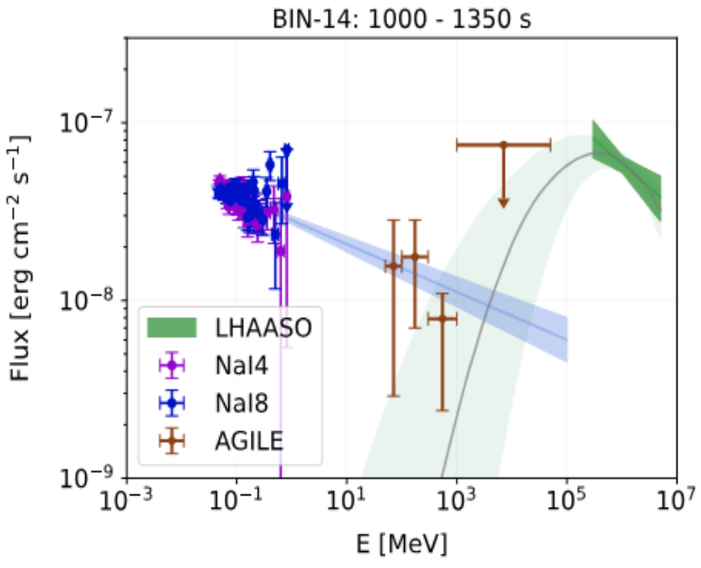






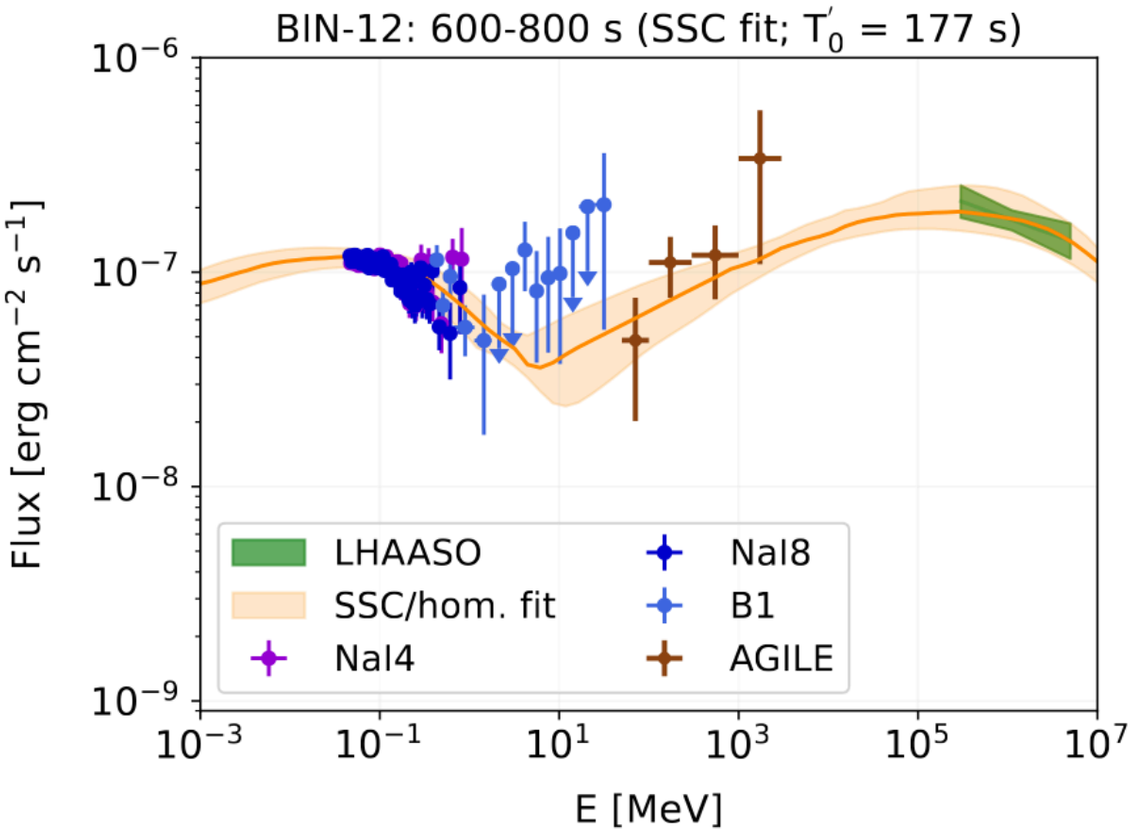


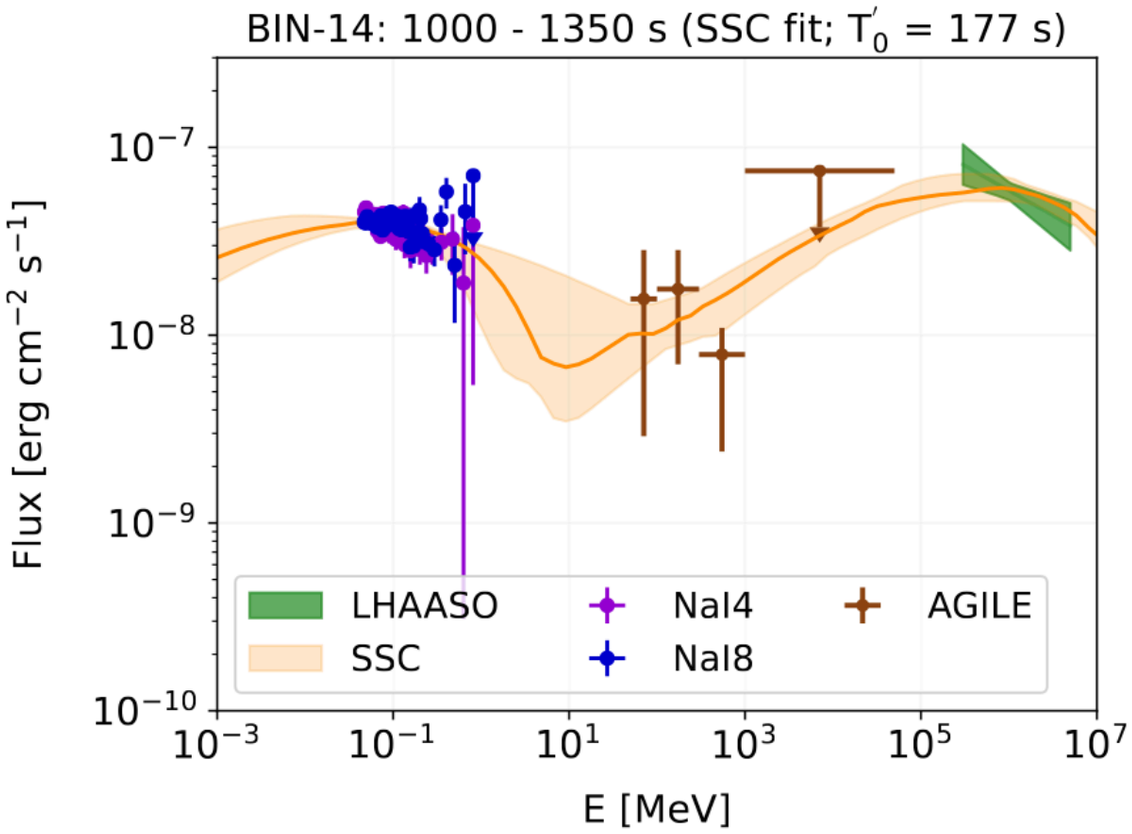




Banerjee et al. 2024,
arXiv 2405.15855

Afterglow spectra





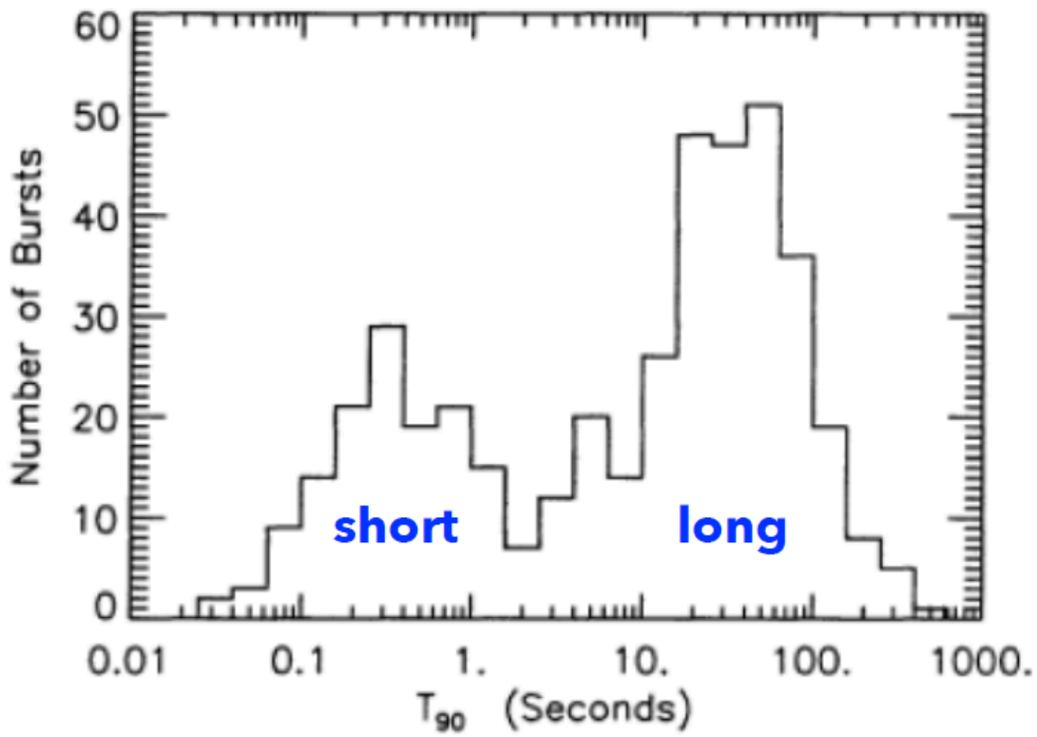
$$\mathrm{B} \approx 0.1\,\mathrm{G}$$

Banerjee et al. 2024,
arXiv 2405.15855

γ-ray bursts

progenitors

Standard classification

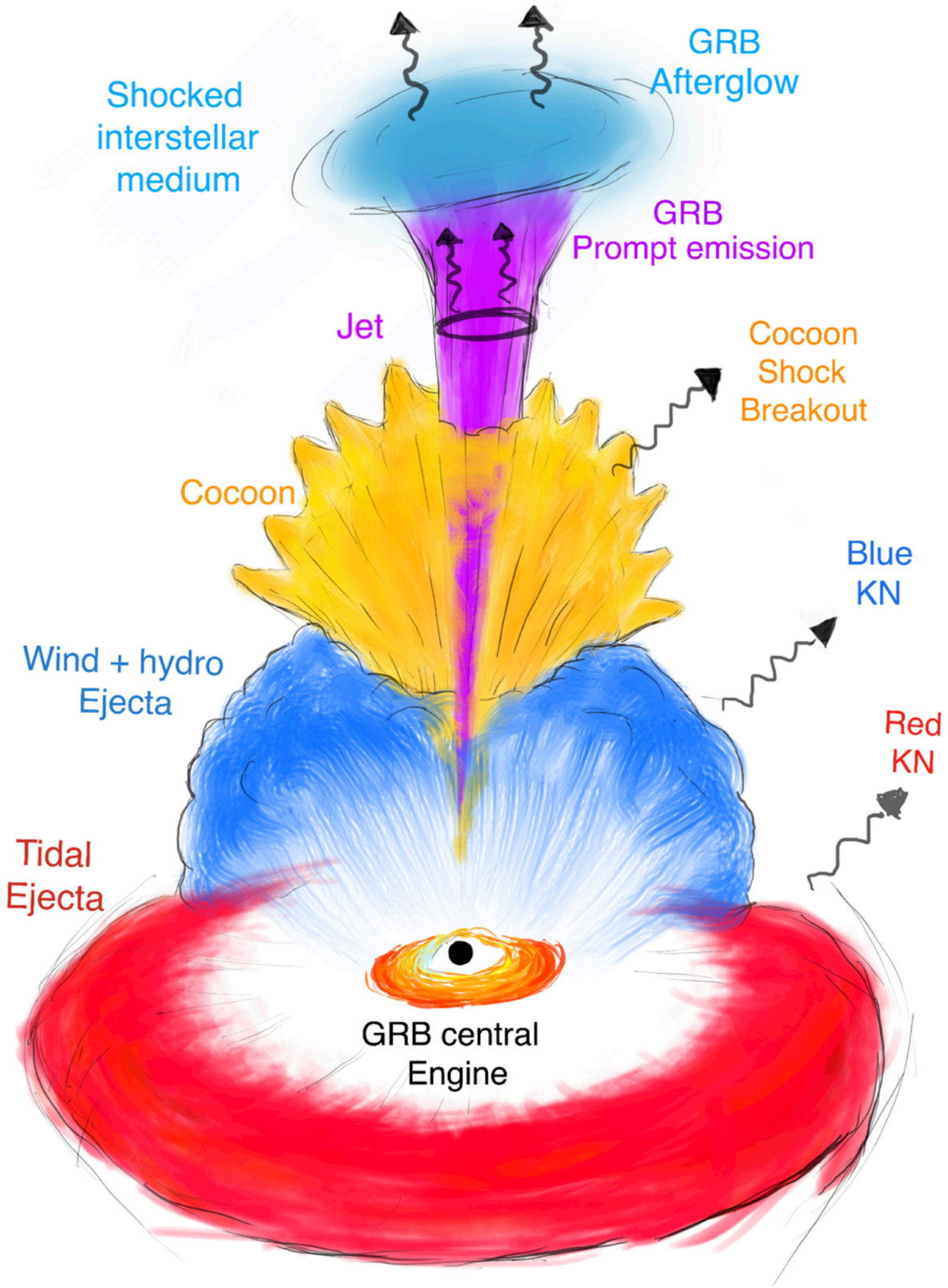


short (<2 s) and long (>2 s)

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

short-hard vs long-soft GRBs

Compact Binaries Coalescence (NS+NS and NS+BH)

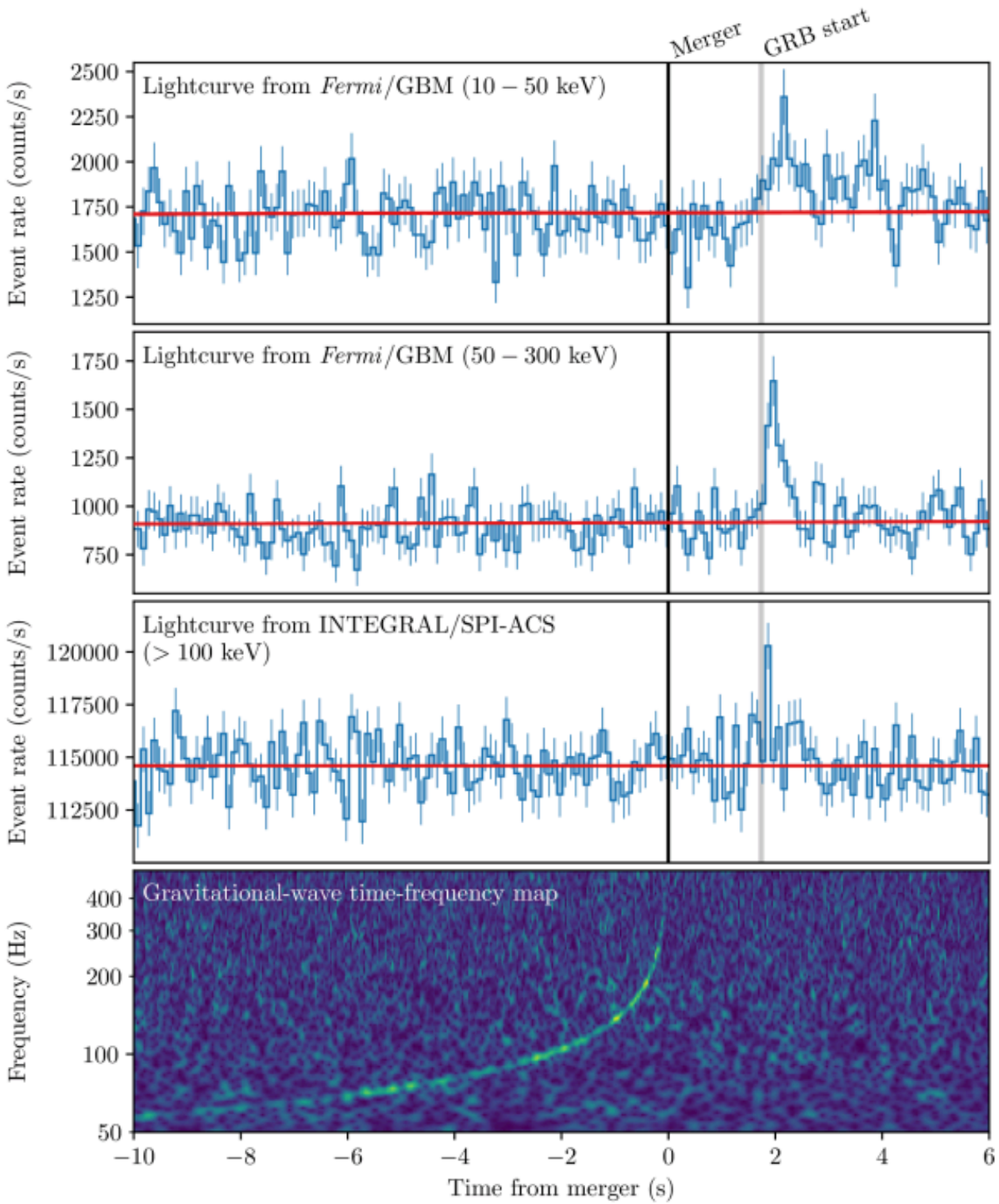


Credit: Stefano Ascenzi

The only GW-GRB joint detection

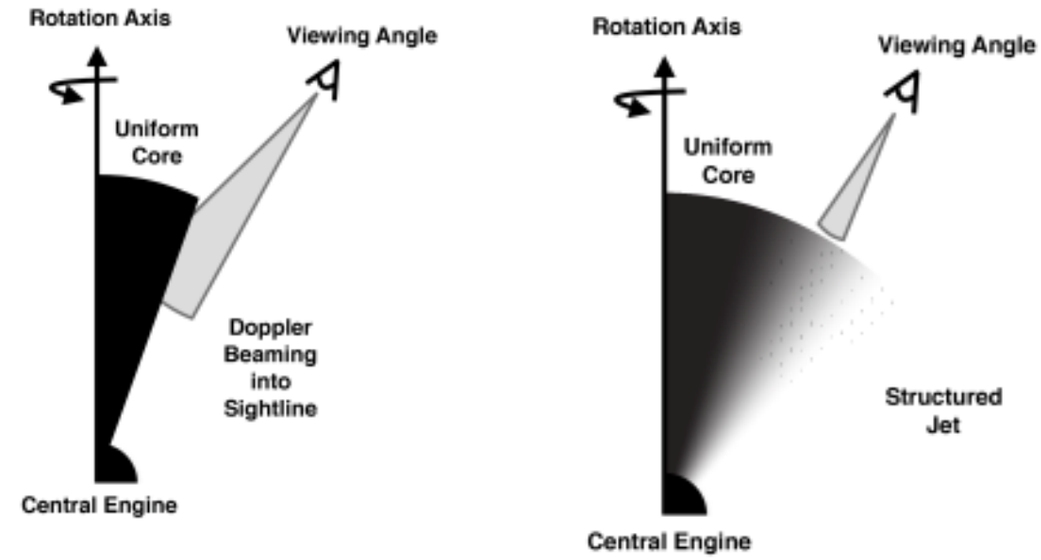
Jet structure: Lipunov et al. 2001; Dai & Gou 2001; Rossi et al. 2002; Zhang & Meszaros 2002

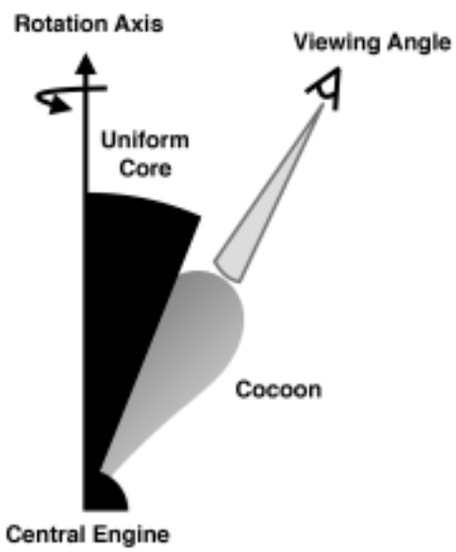
GRB 170817/GW 170817



Abbott et al. 2017

What is it?



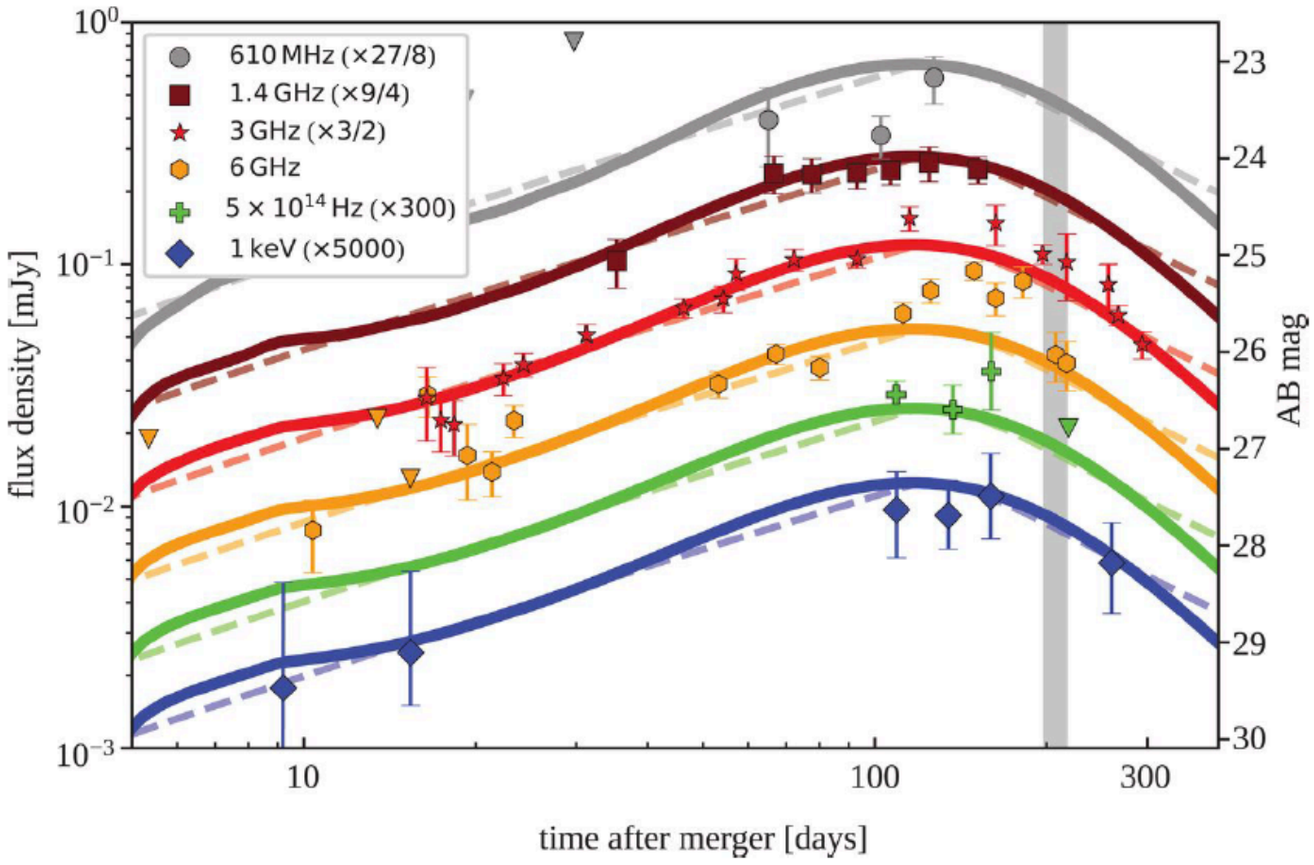


Kasliwal et al. 2017
Ioka&Nakamura 2018
Salafia et al. 2018
Lazzati 2018
Bromberg et al. 2018
Matsumoto et al 2018
....

observations - the off-axis afterglow

GRB 170817/GW 170817

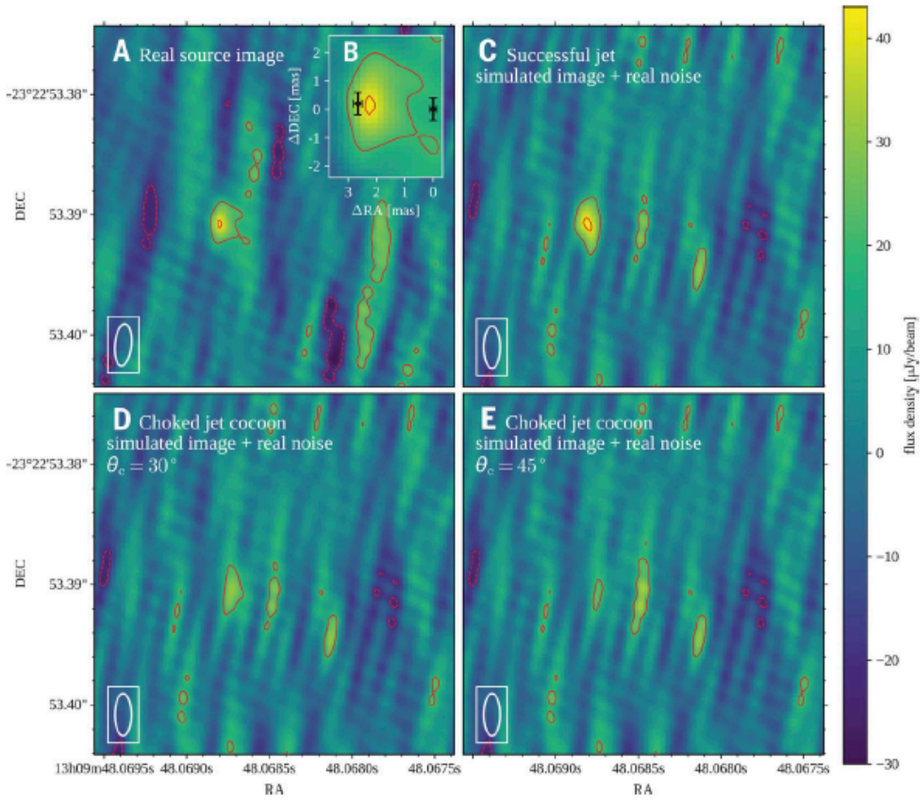
multi-wavelength LCs of the afterglow



D'Avanzo et al. 2018
Dobie et al. 2018
Alexander et al. 2018
Troja et al. 2018
.....

Ghirlanda et al. 2019

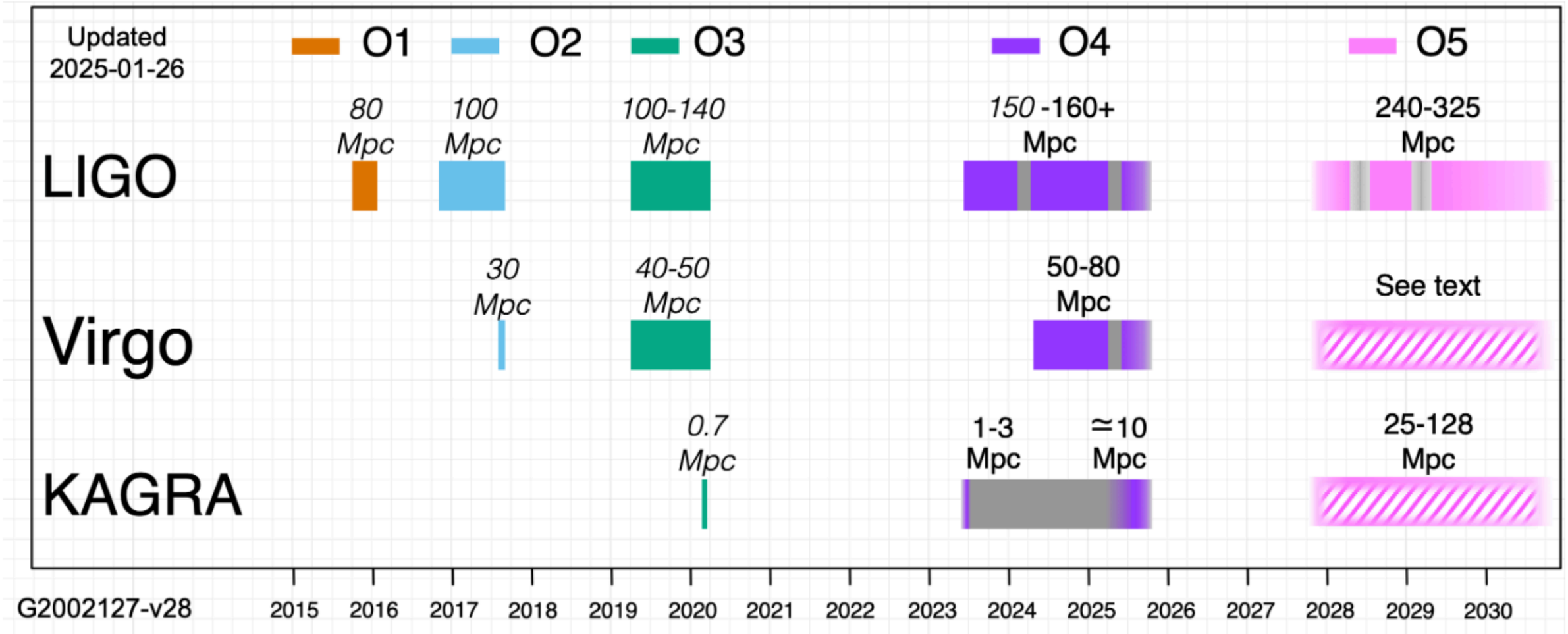
apparent size is 2.5 milli–arc seconds at > 200 days



see also **Mooley et al. 2018**

LIGO Virgo KAGRA schedule

All sky sensitivity to BNS mergers



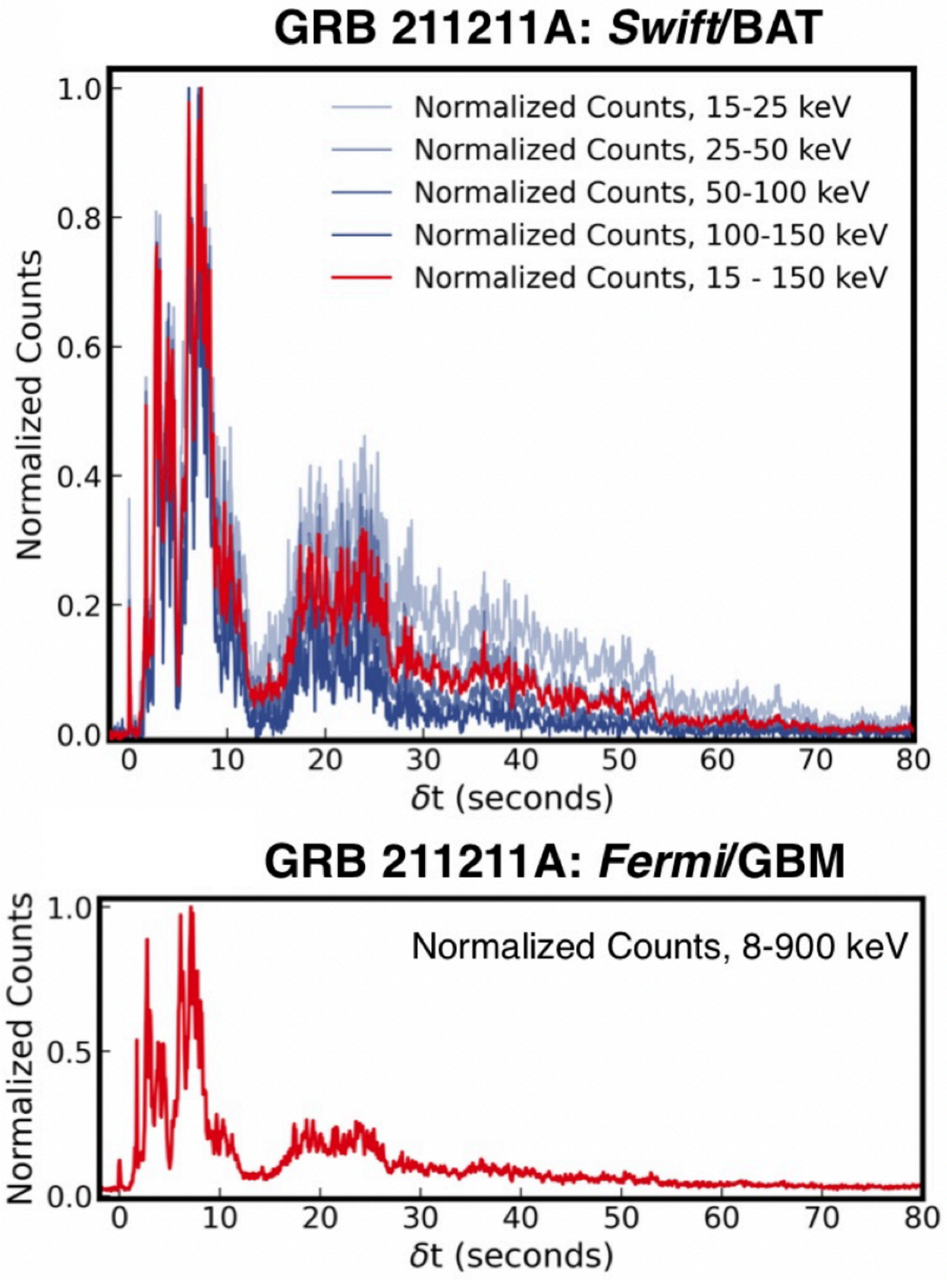
Offline GW search from GRBs

O2 Abbott et al. 2019, ApJ

O3a Abbott et al. 2021, ApJ

O3b Abbott et al. 2022, ApJ

it is not just waiting for new BNS

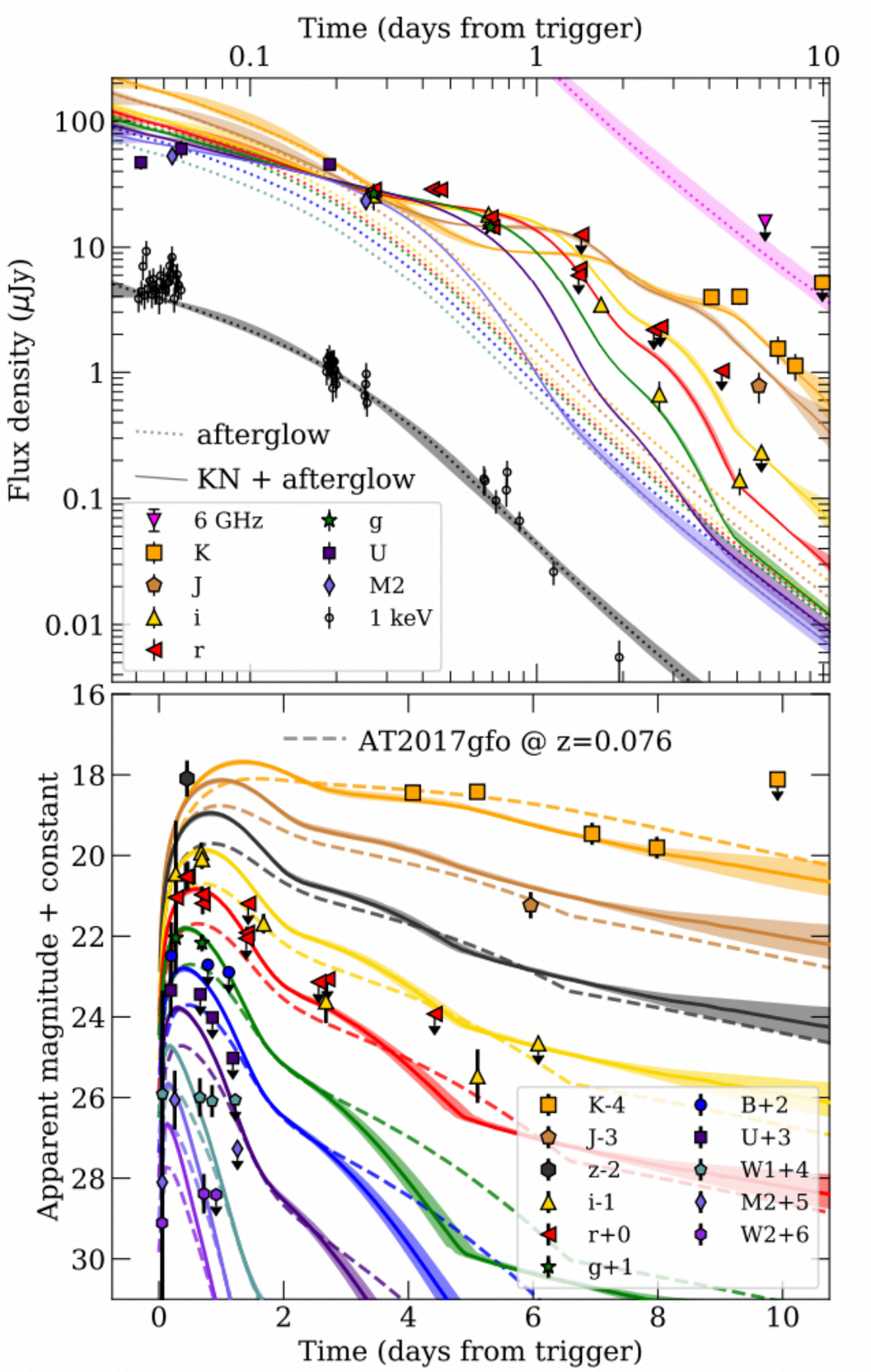


GRB 211211A

T90 ~ 34 s

350 Mpc

Rastinejad et al. 2022, Nature



GRB 211211A

350 Mpc

Three-component kilonova fit

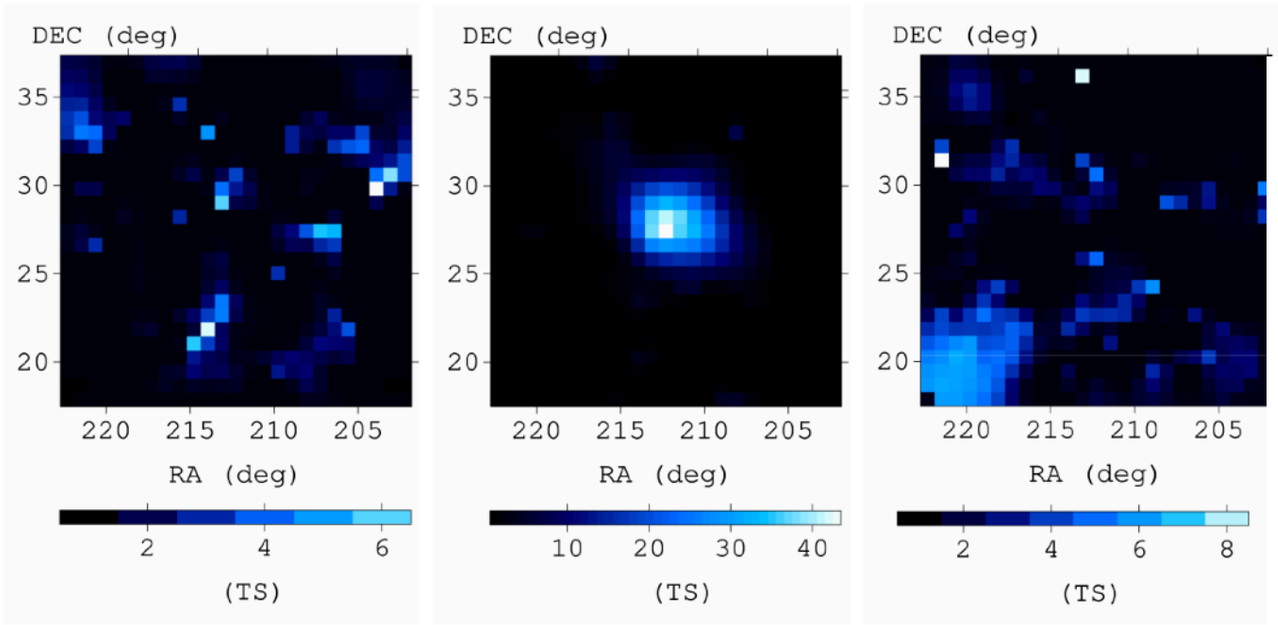
- $M_{ej} = 0.04 \pm 0.02\ M_{\odot}$, almost all lanthanide-rich, in reasonable agreement with at2017gfo.
- $v_{ej} \simeq 0.25 - 0.3\ c$
- Associated to compact object merger in a binary system, likely BNS

Rastinejad et al. 2022, Nature

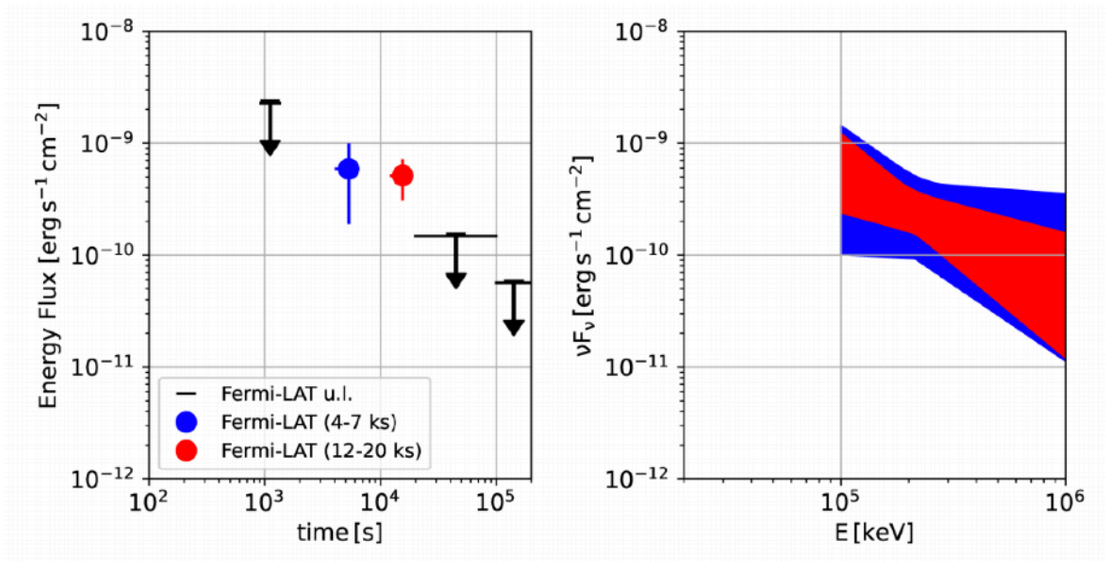
see Troja et al. 2022, Yang et al. 2022

GRB 211211A

GeV emission



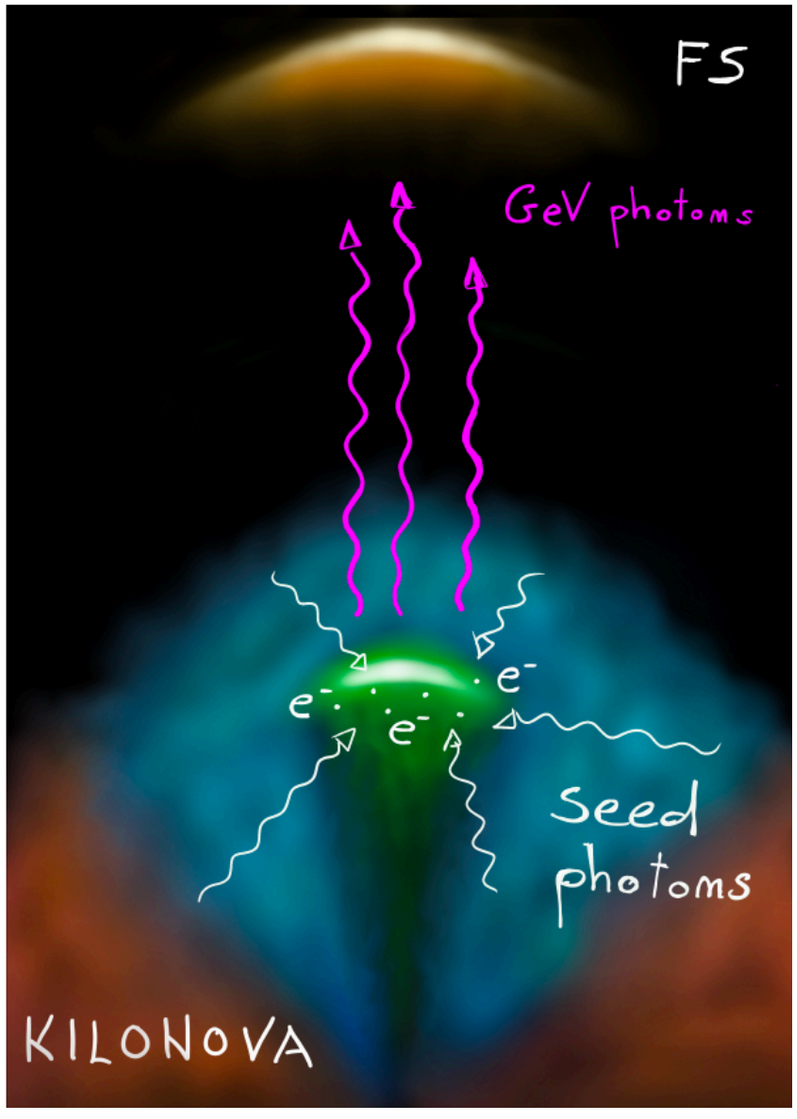
(a) t_0-1 d to t_0 (b) t_0 to t_0+20 ks (c) t_0+1 d to t_0+2 d



(d) t_0 to t_0+2 d

Mei et al. 2022, Nature

GeV emission from a BNS merger



- not present in GW/GRB 170817
- new component from KN-jet interaction

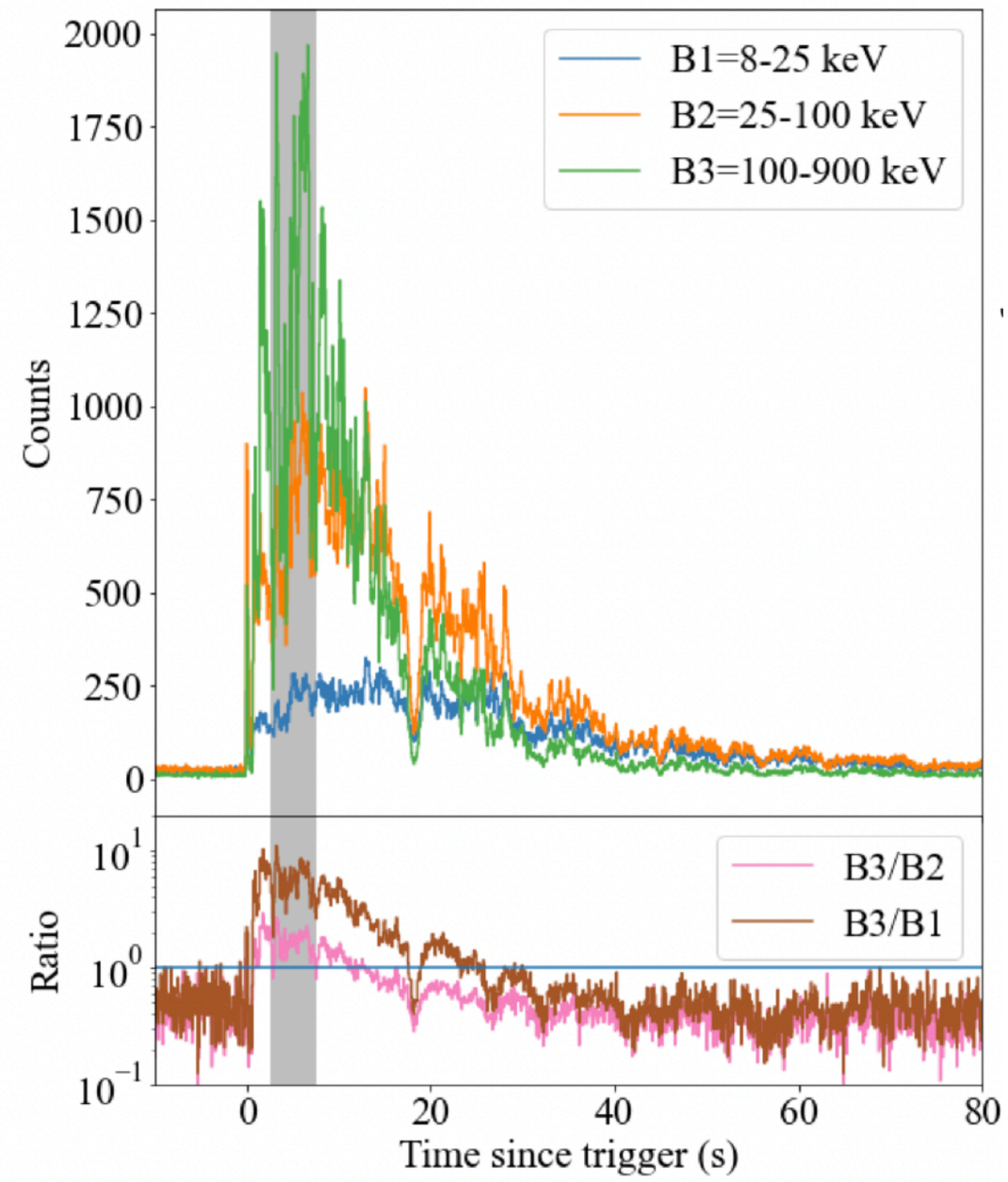
Mei et al. 2022, Nature

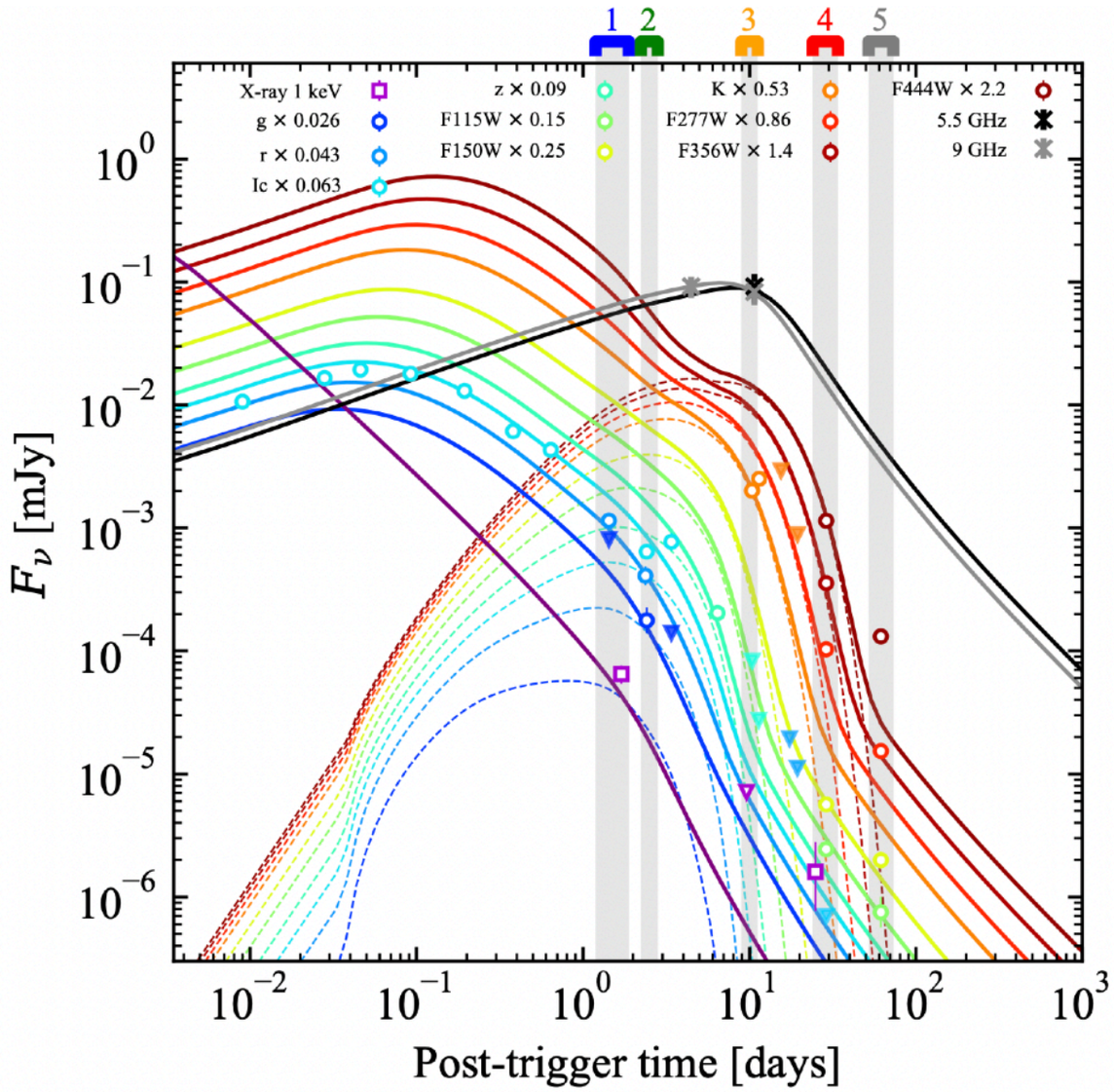
The most recent example

GRB 230307A

T90 ~ 30 s

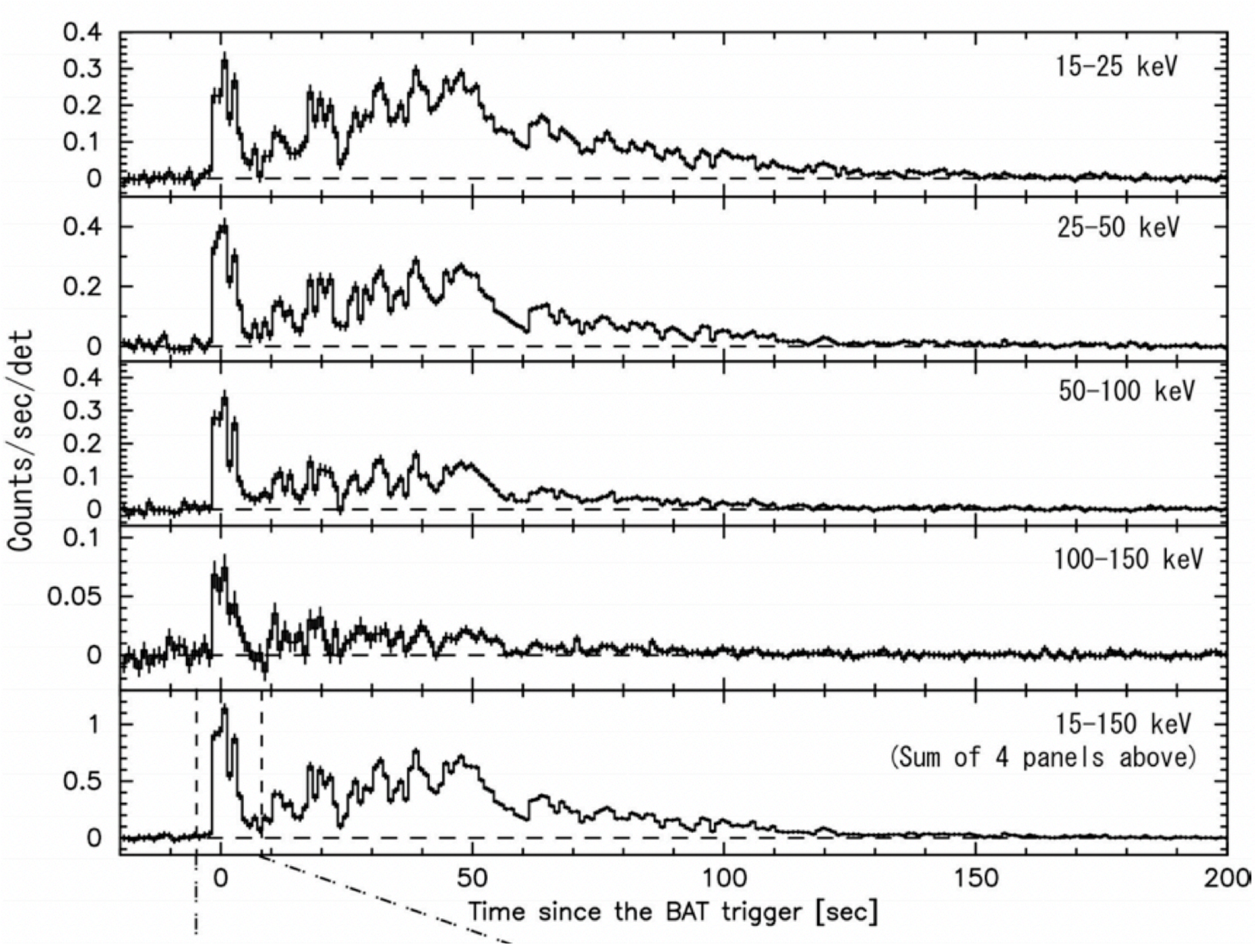
z = 0.065





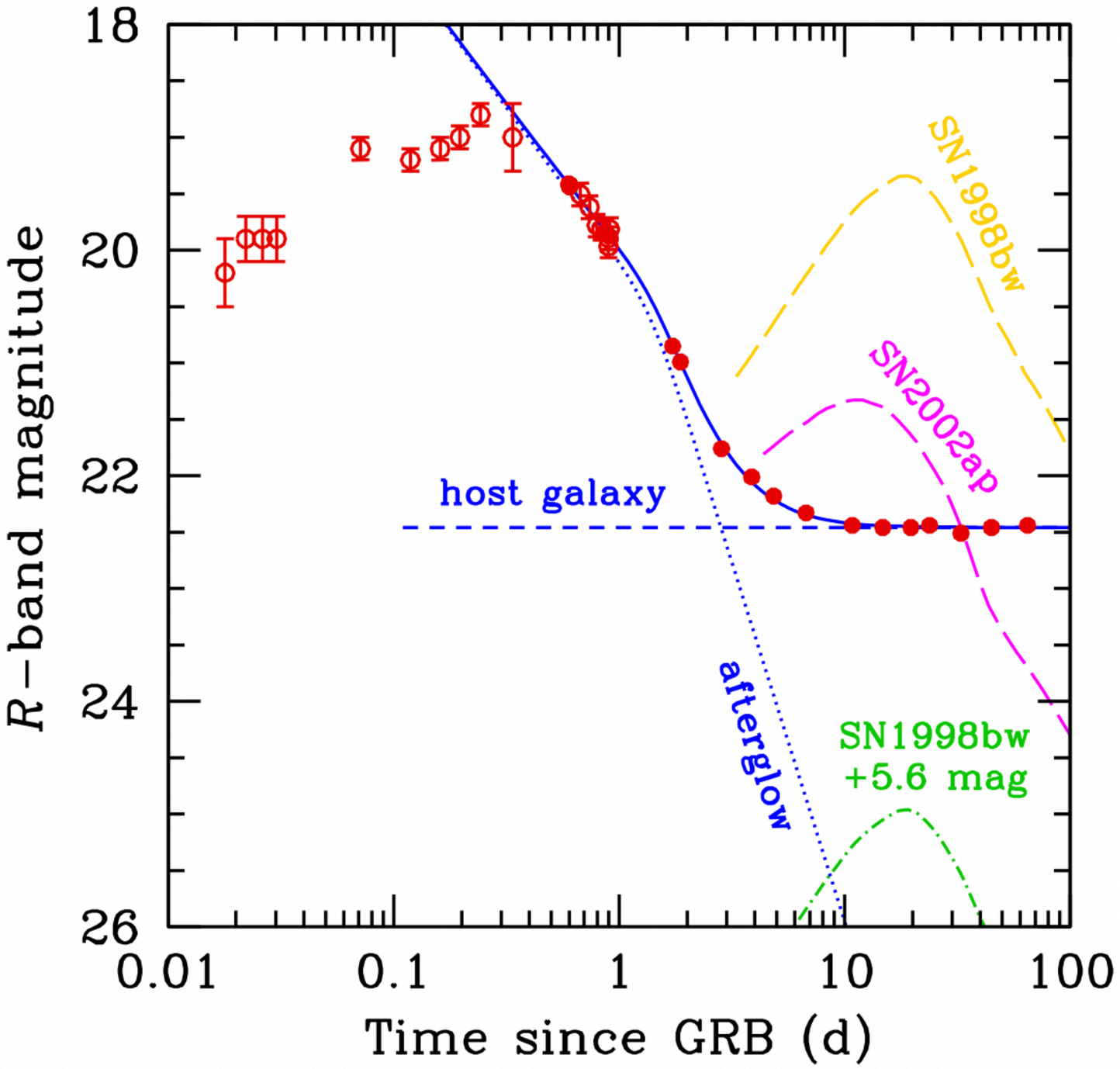
Levan et al. 2024, Nature

Unusual (oddball) GRBs Historical example #1 GRB 060614



Gehrels et al. 2006, Nature

Historical example #1 GRB 060614



any SN should be x100 fainter

Della Valle et al. 2006, Nature

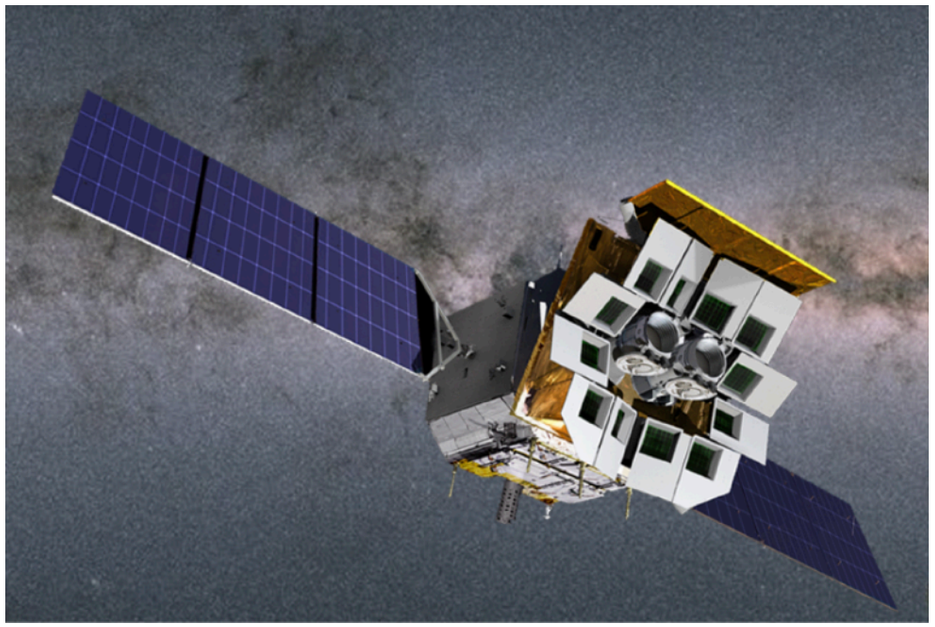
Gal-Yam et al. 2006, Nature 2006

γ-ray bursts and GWs

Future

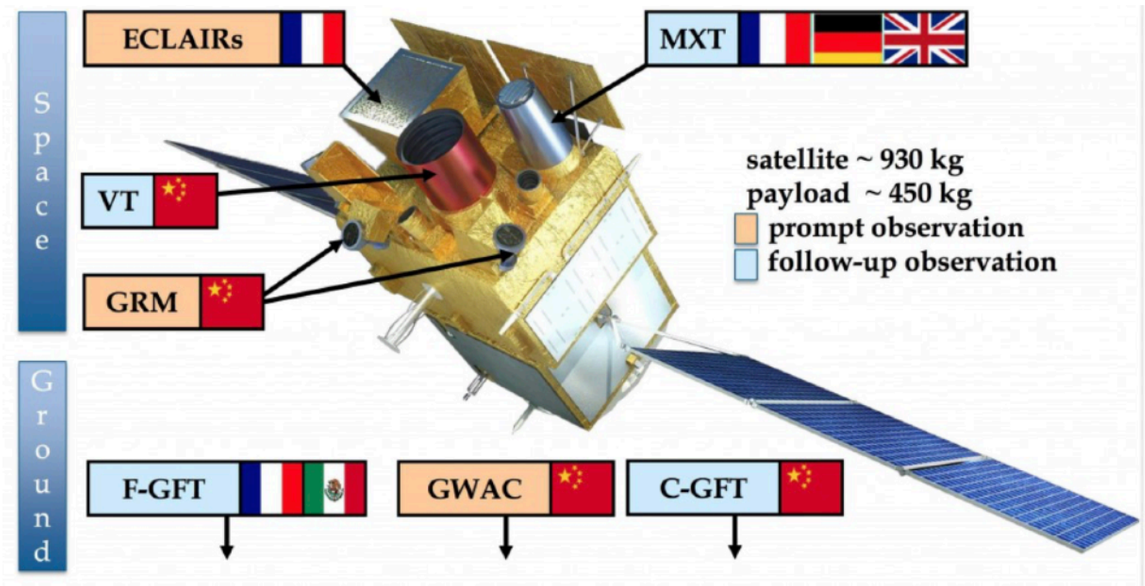
Future/now

Einstein Probe



0.5-4 keV

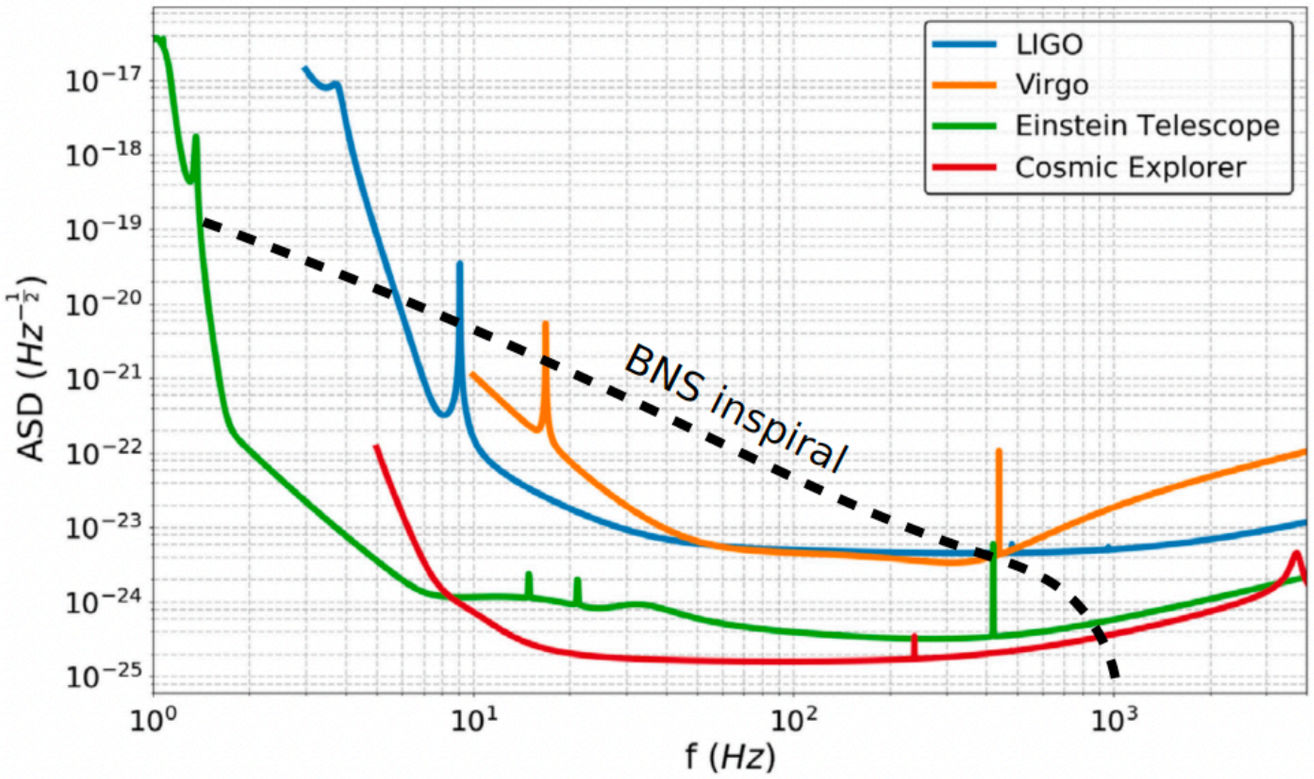
SVOM

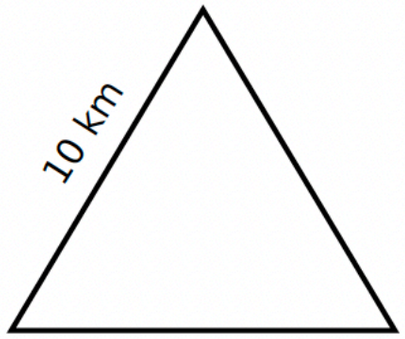


ECLAIRs > 4 keV

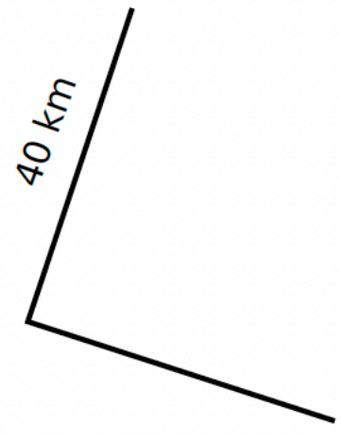
Lobster-eye Angel 1979

3rd gen GW interferometers





Einstein Telescope (ET)



Cosmic Explorer (CE)

GW Parameter estimation

GWFISH

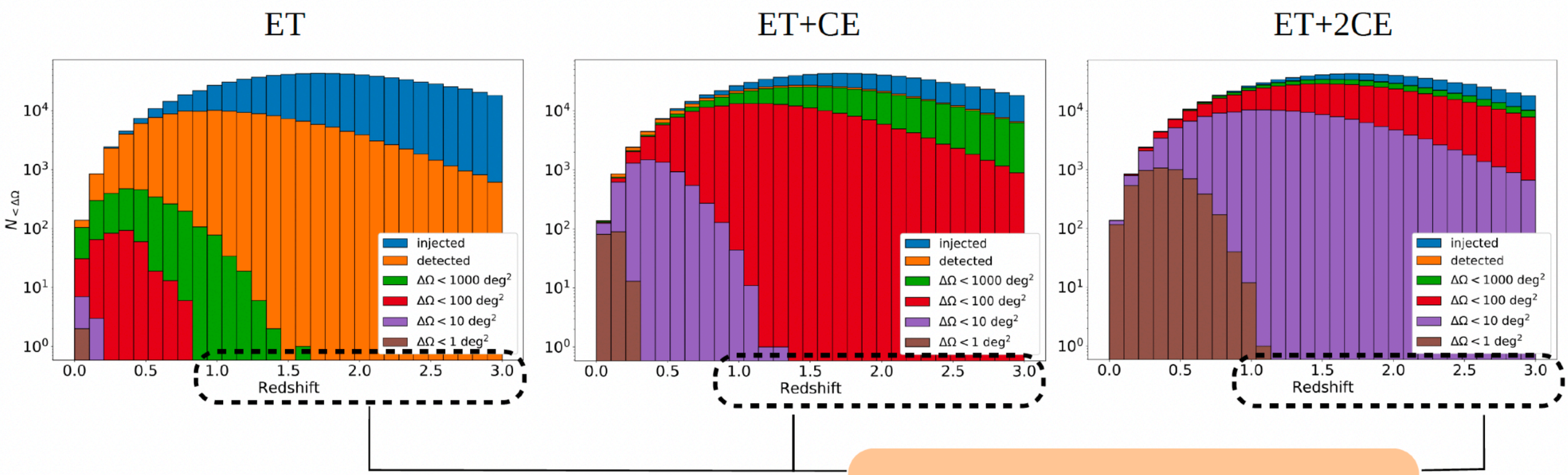
Harms et al. 2022
arXiv:2205.02499

EINSTEIN TELESCOPE

arXiv 2503.12263

3rd gen GW interferometers

localisation

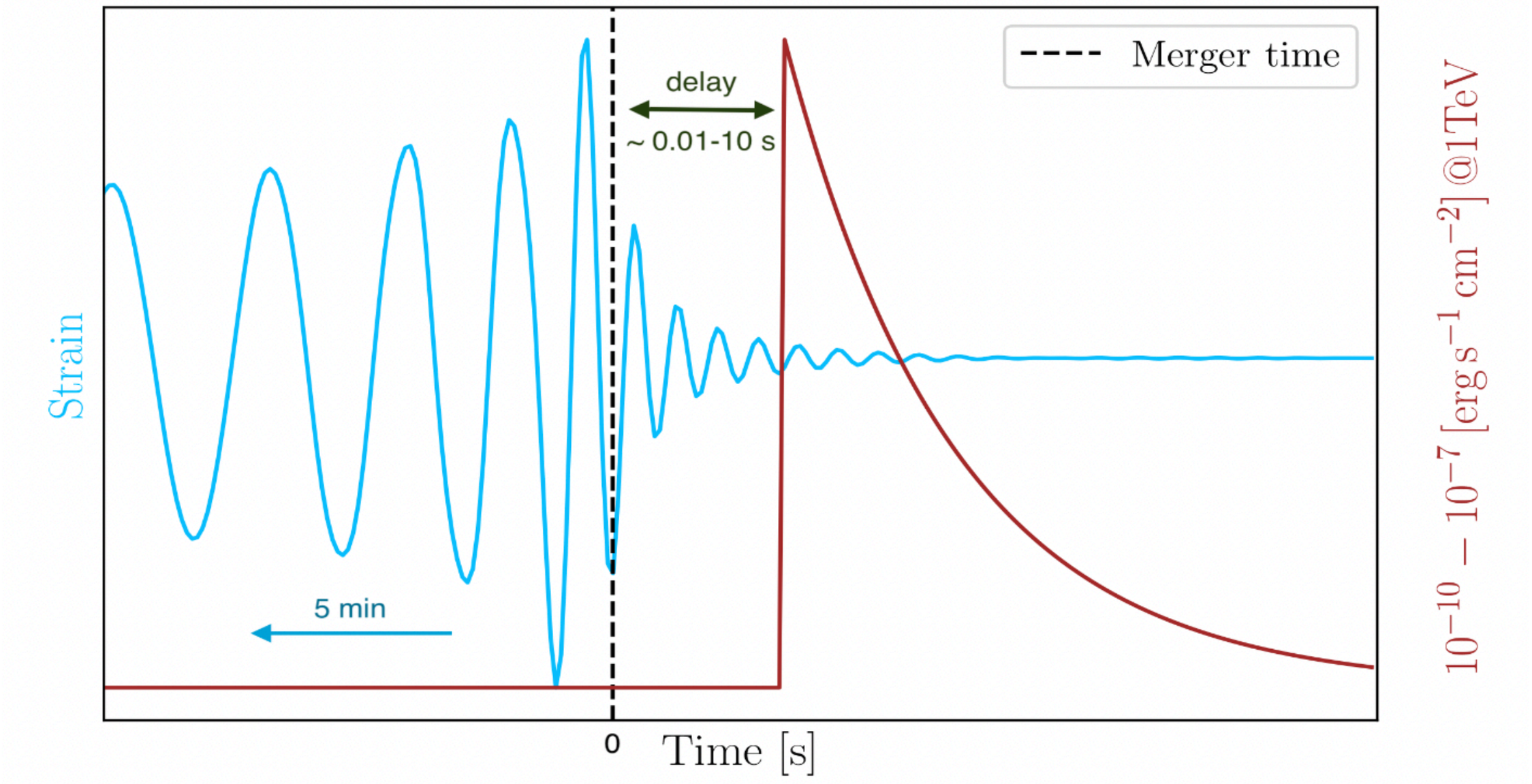


	ET	ET+CE	ET+2CE
$N_{\rm det}$	143970	458801	592565
$N_{\rm det}(\Delta\Omega < 1\ {\rm deg}^2)$	2	184	5009
$N_{\rm det}(\Delta\Omega < 10\ {\rm deg}^2)$	10	6797	154167
$N_{\rm det}(\Delta\Omega < 100\ {\rm deg}^2)$	370	192468	493819
$N_{\rm det}(\Delta\Omega < 1000\ {\rm deg}^2)$	2791	428484	585317

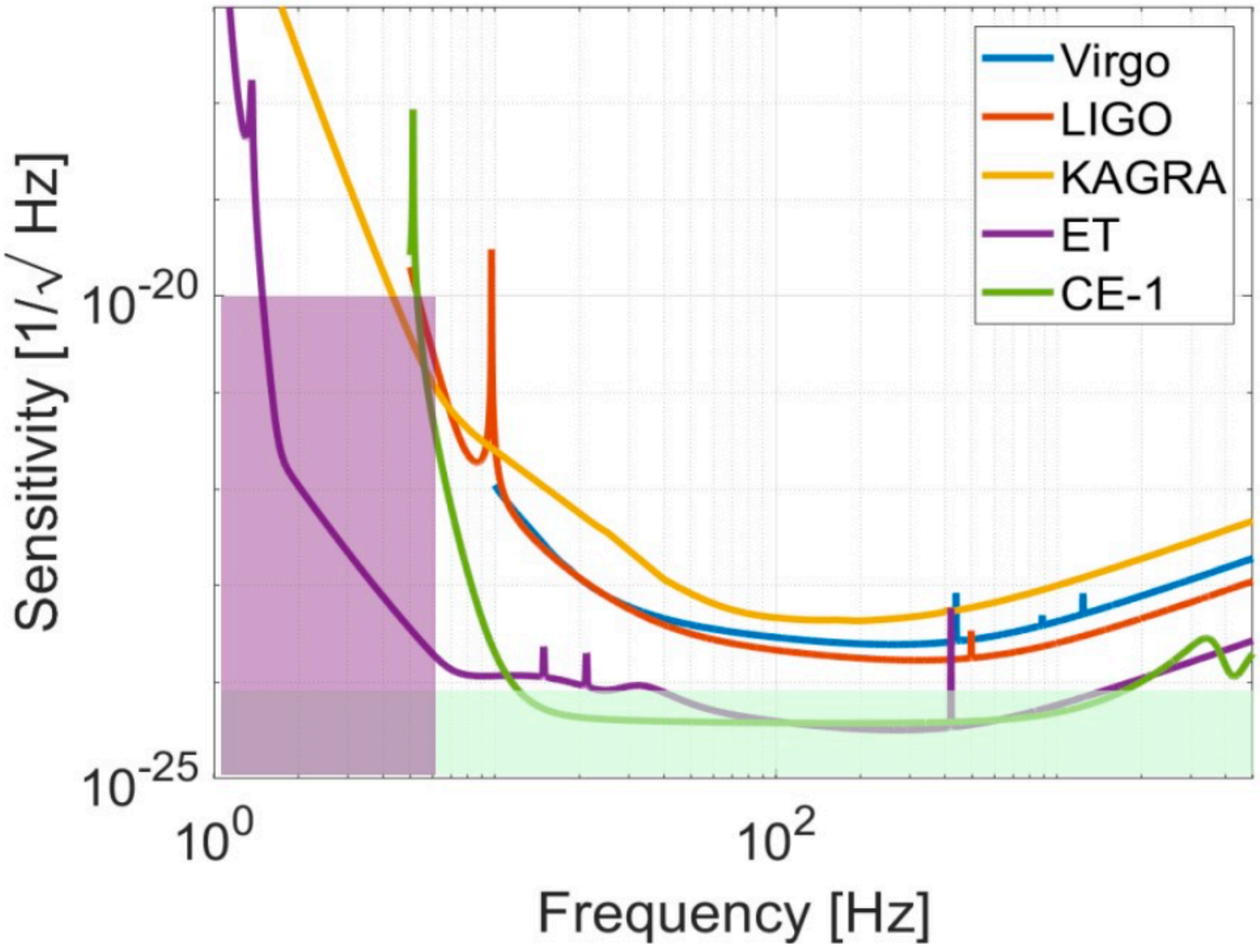
High-z GW source localisation is given by counterparts detected by **wide field X-ray and γ-ray telescopes** with arcmin localisation capabilities

Ronchini et al. 2022, A&A

Very High Energy Emission

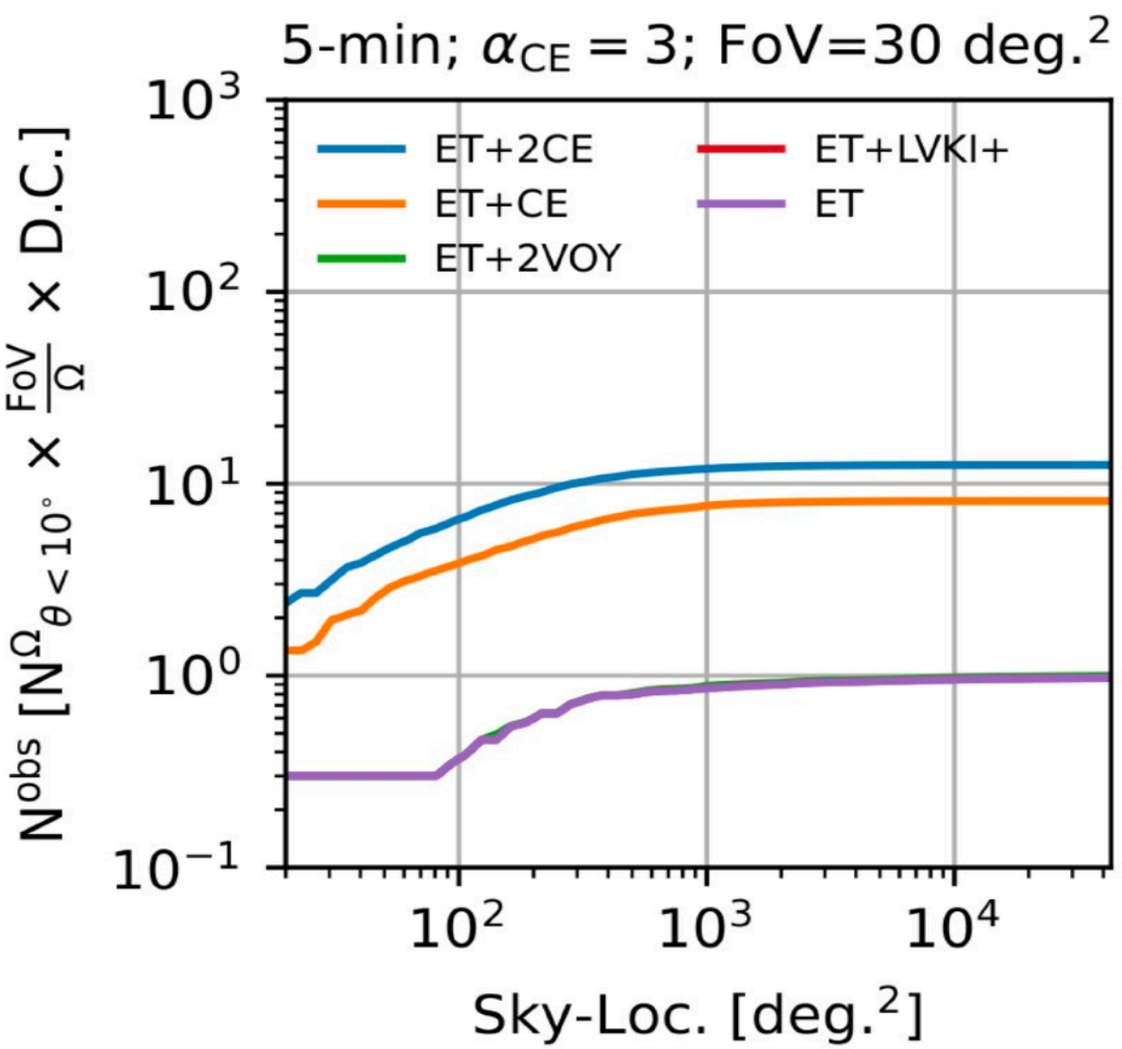


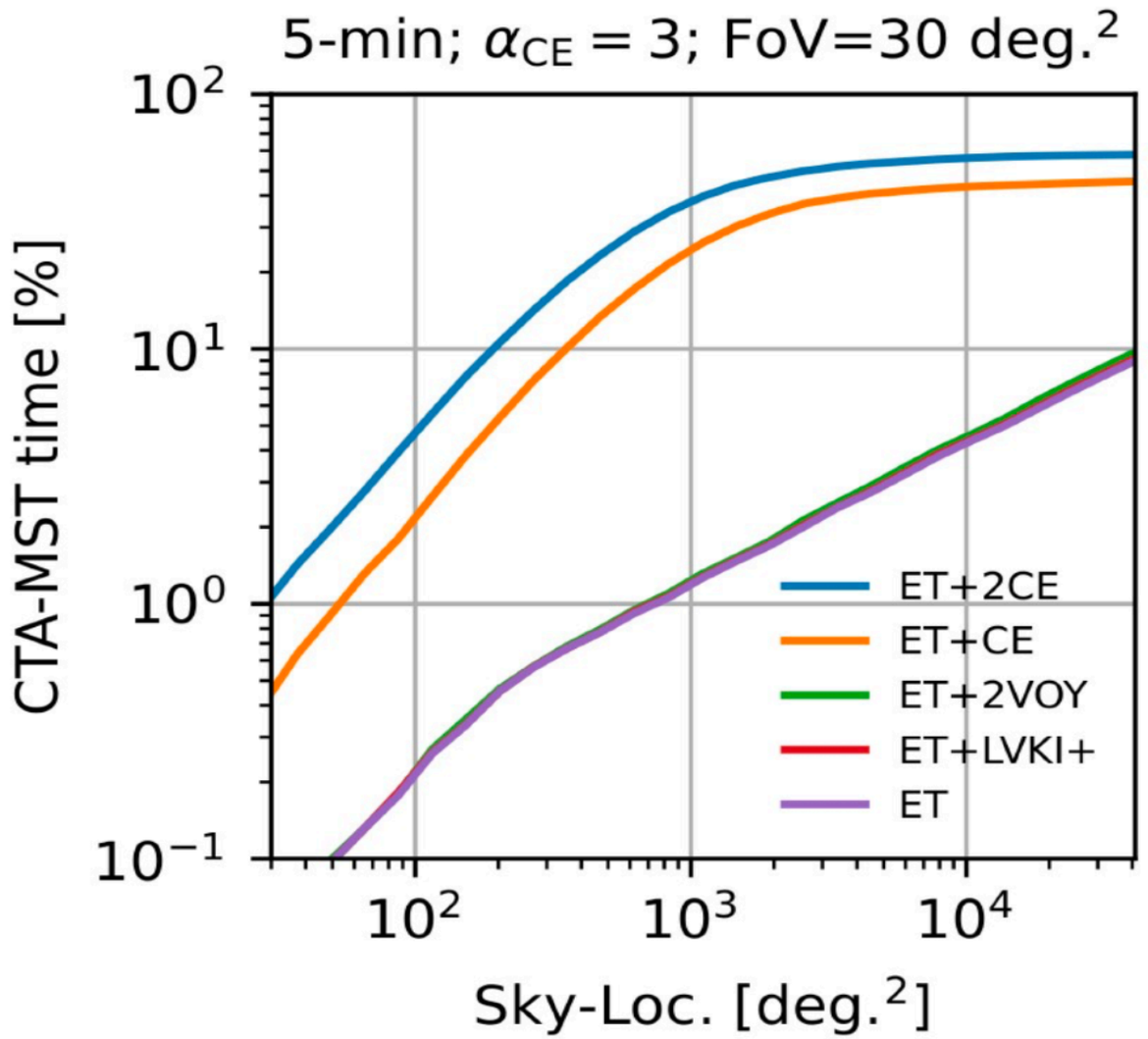
Banerjee et al. 2023, A&A



Banerjee et al. 2023, A&A

Very High Energy Emission





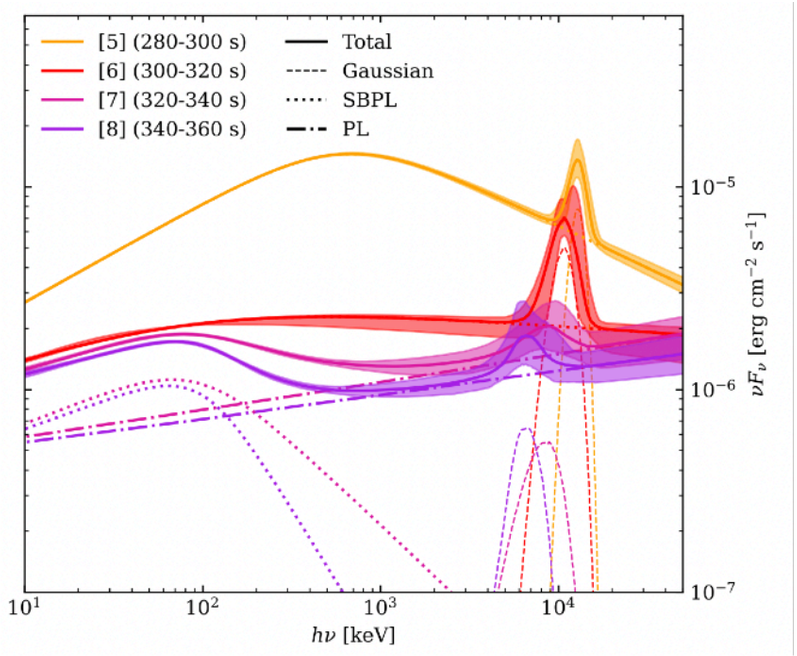
Banerjee et al. 2023, A&A

γ-ray bursts and GWs

summary

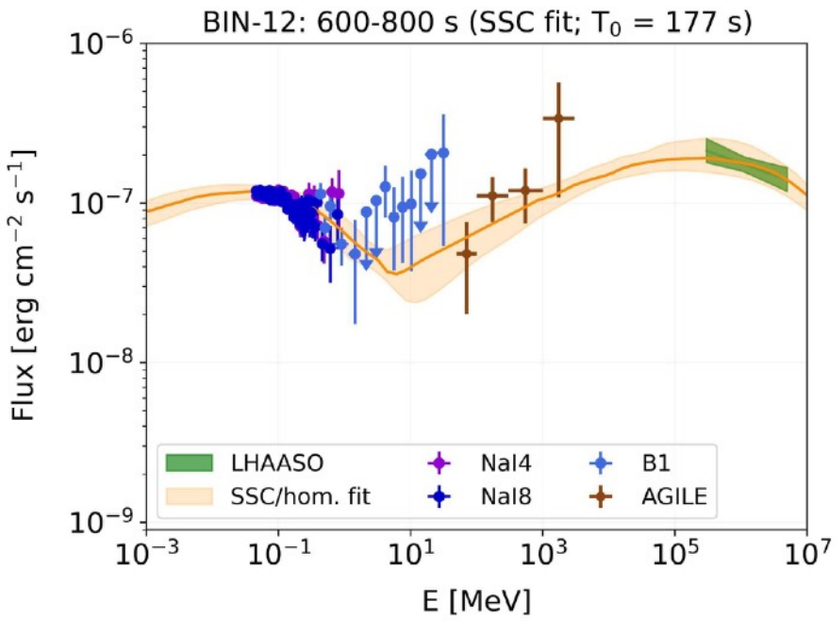
γ-ray burst

MeV line



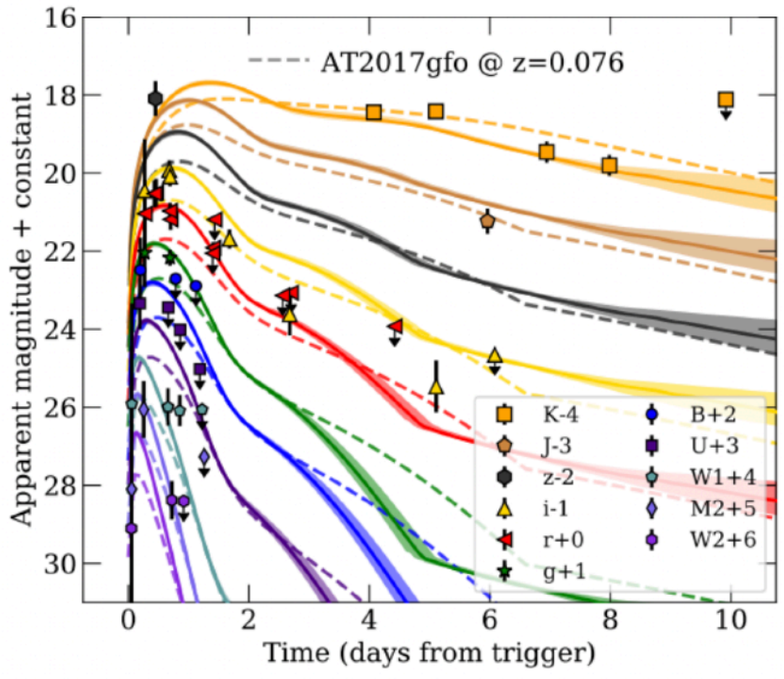
afterglow

laboratory for relativistic shocks



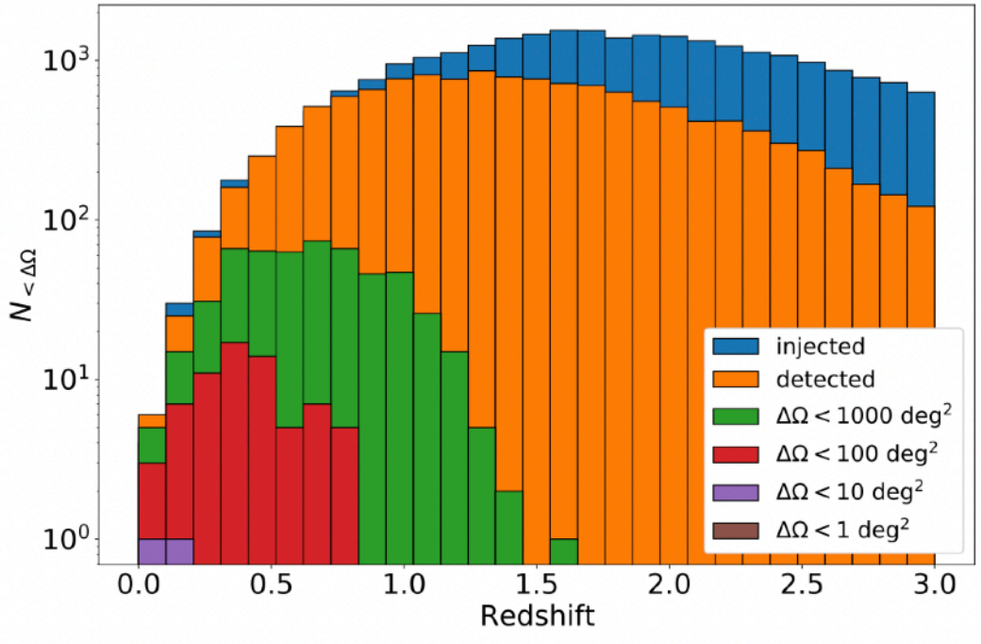
progenitors

odd GRBs



gravitational waves

future 3 gen. GW ET



Thank you!

BH

Possible dissipation models

collisional heating

Beloborodov 2010, Vurm et al. 2011

RMS

Levinson & Nakar 2020 review

$10^{12} - 10^{13}\,\mathrm{cm}$

photosphere

magnetic dissipation

Drenkhahn & Spruit 2002

Giannios & Spruit 2005
Thompson 2006
Giannios 2008

standard internal shocks

Rees & Mészáros 1994

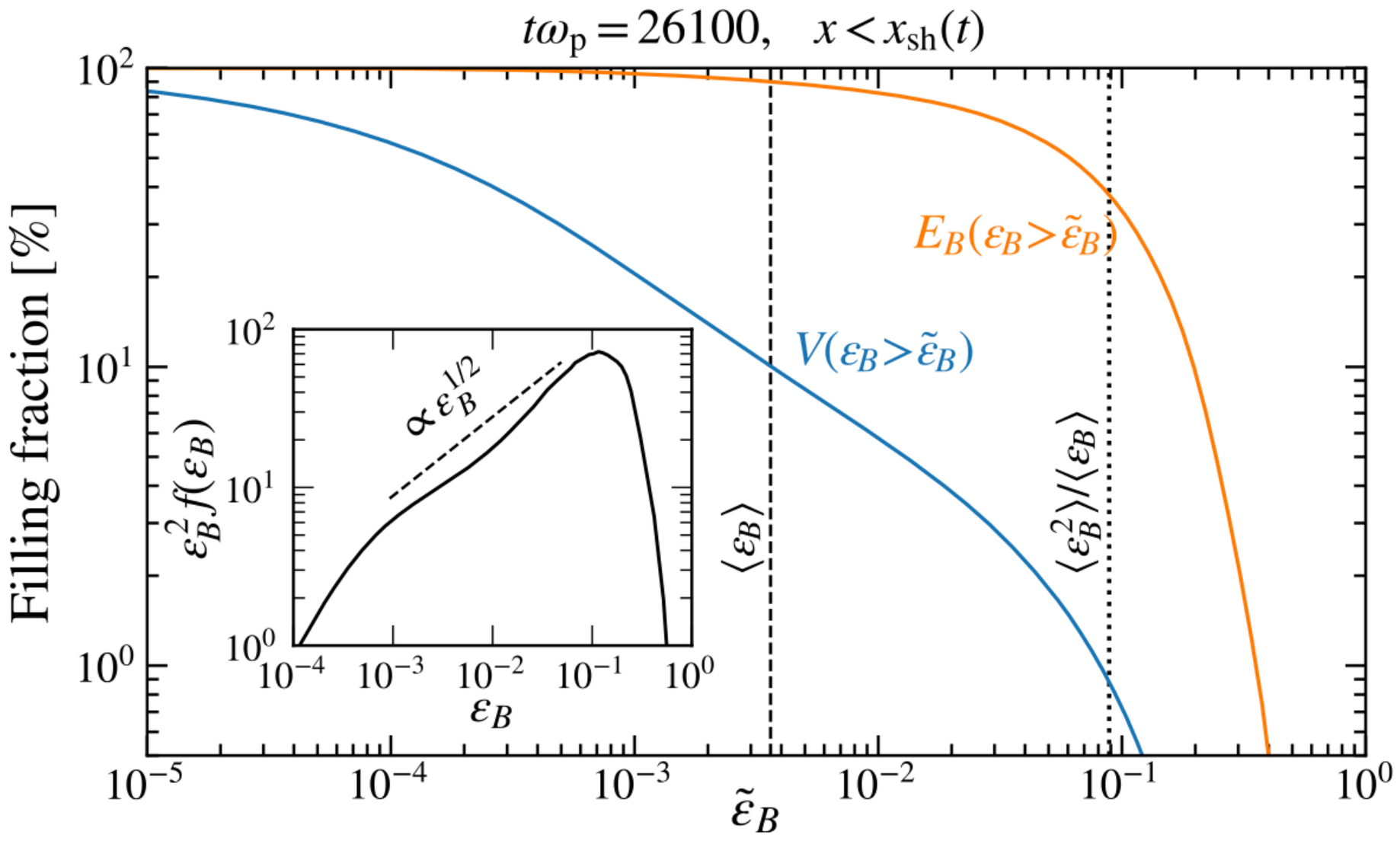
ICMART

Zhang et al. 2011

$10^{16} - 10^{17}\,\mathrm{cm}$

external dissipation

We expect more complexity

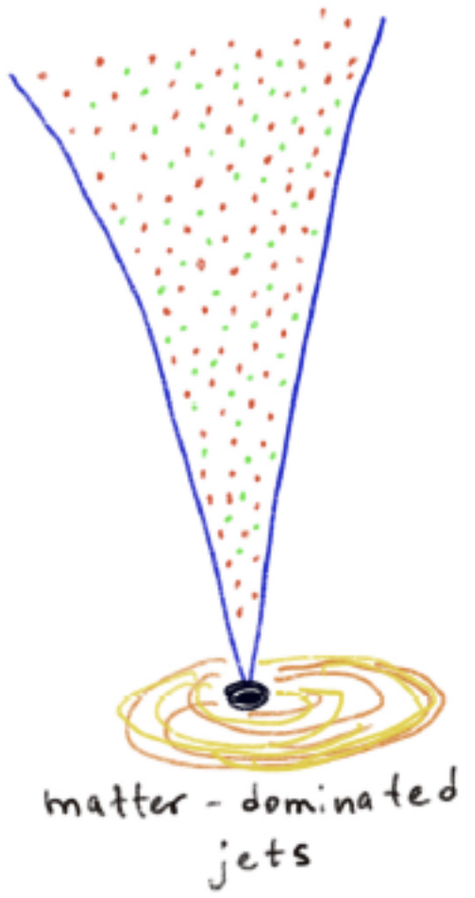


Grošelj et al. 2024, ApJL

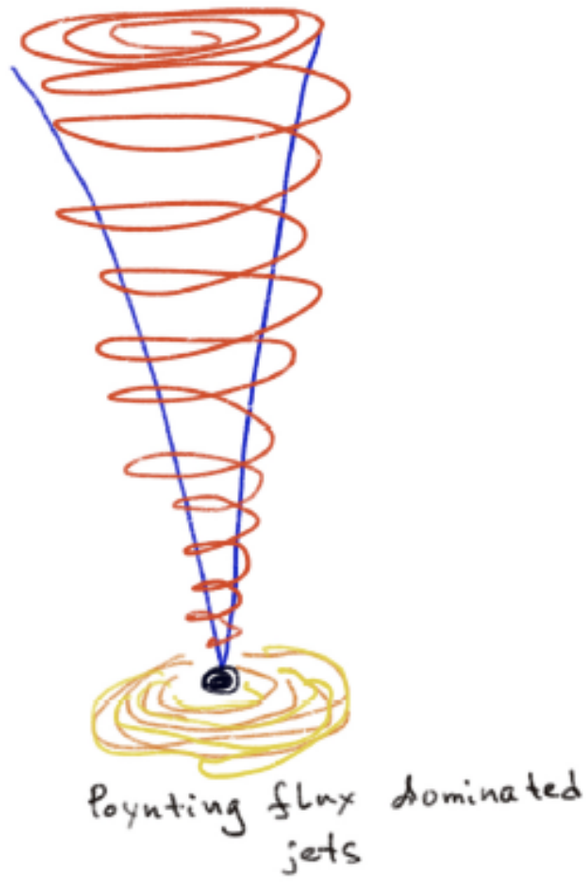
see Khangulyan et al. 2023, ApJ for two zone model

GRB	band	$T_{90}(s)$	$T_{50}(s)$	$D_L(Mpc)$	kilonova
060614	15-350 keV	106	43	590	hint (Yang et al. 2015)
060505	15-350 keV	4		409	hint? (Jin et al. 2021, arXiv)
111005A	15-350 keV	26	11	57	-
191019A	15-350 keV	64	30	1260	-
211211A	50-300 KeV	34	15	350	yes (Rastinejad et al. 2022)
230707A	50-300 KeV	30	13	294	yes (Levan et al. 2024)

GRB jet mystery



Cavallo & Rees 1978
Paczýnski 1986
Goodman 1986
Shemi & Piran 1990



Usov 1992
Thompson 1994
Mészáros & Rees 1997
Lyutikov & Blandford 2003