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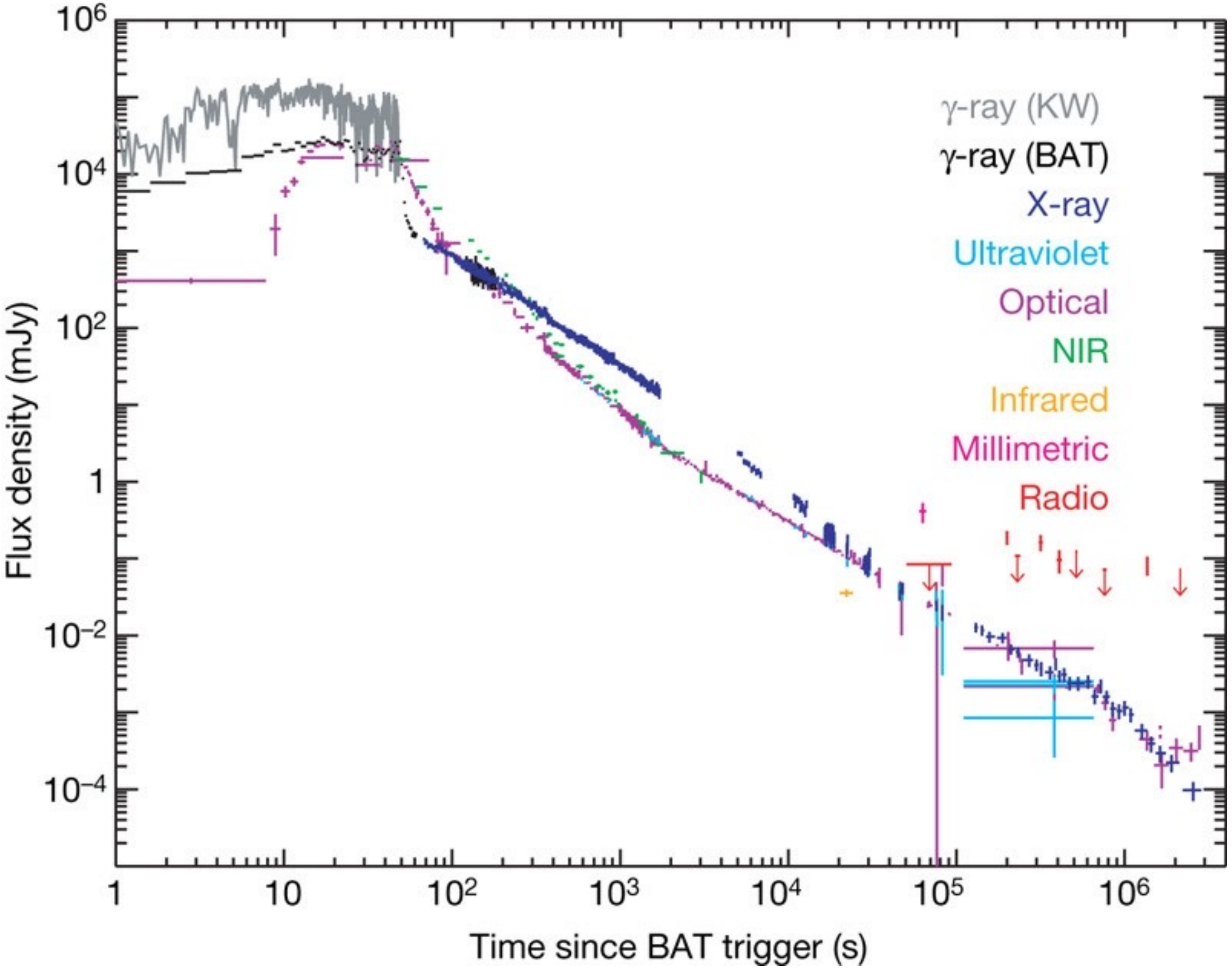
Gamma-ray Burst science with LST

Davide Miceli
INFN Padova

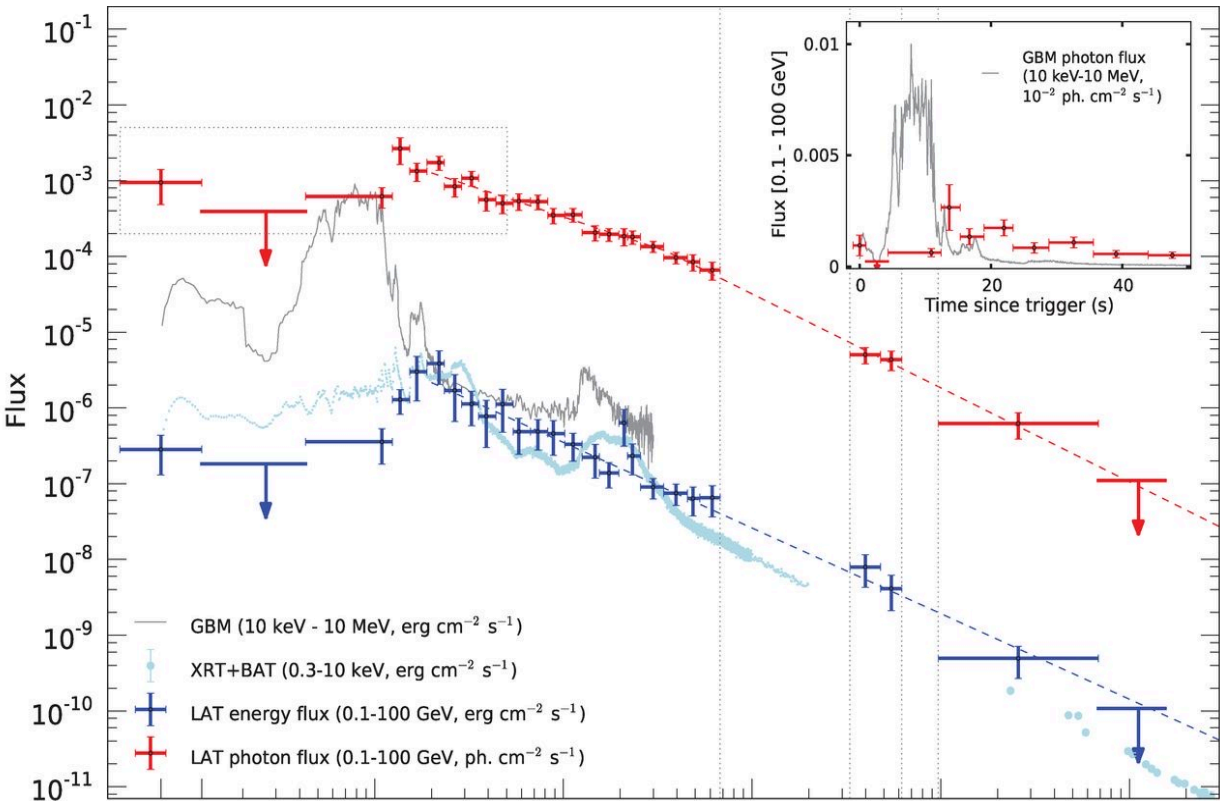
16/01/2024

1st VHEgam meeting, Bologna

Emission in Gamma-ray Bursts

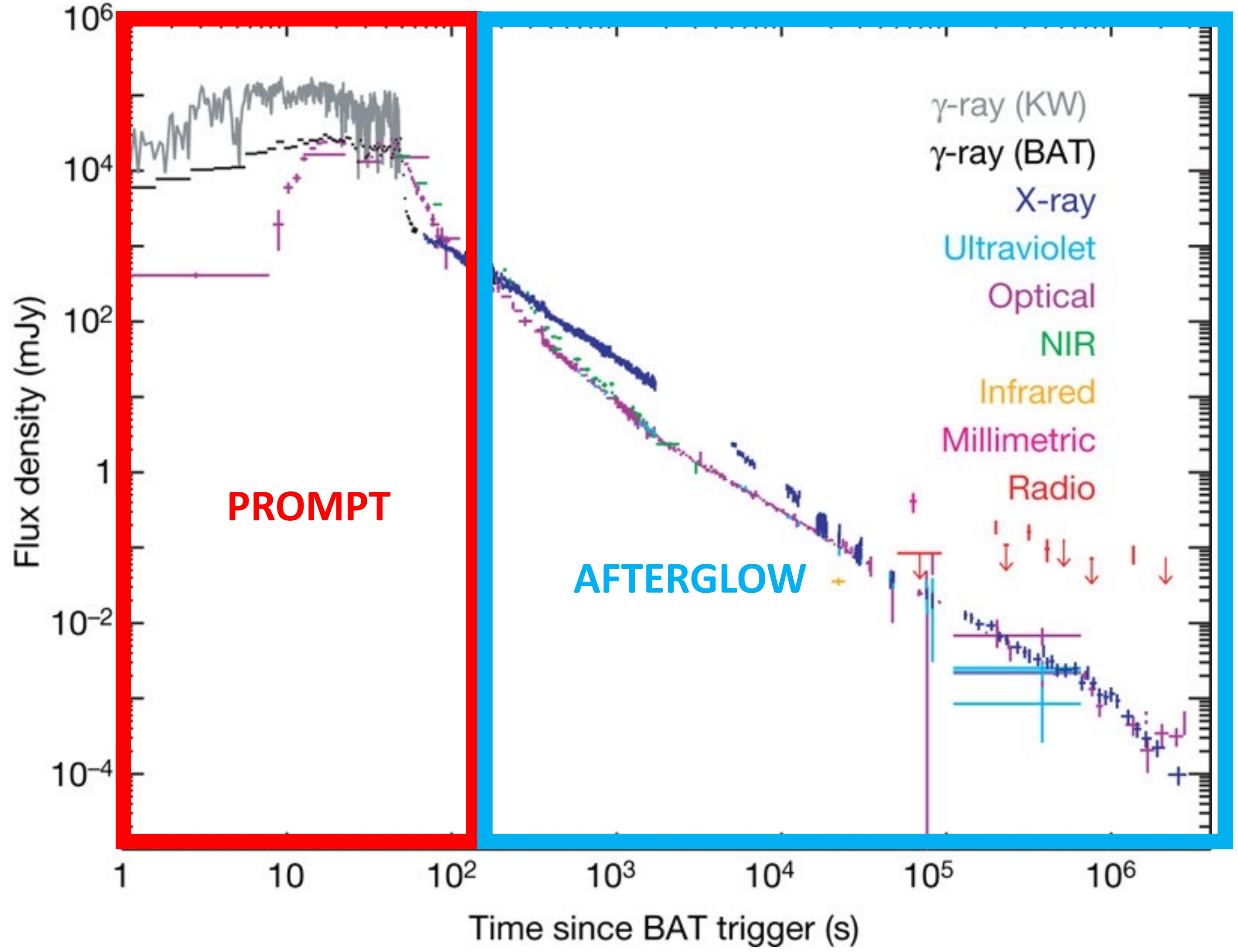


GRB080319B (Racusin et al., 2008)

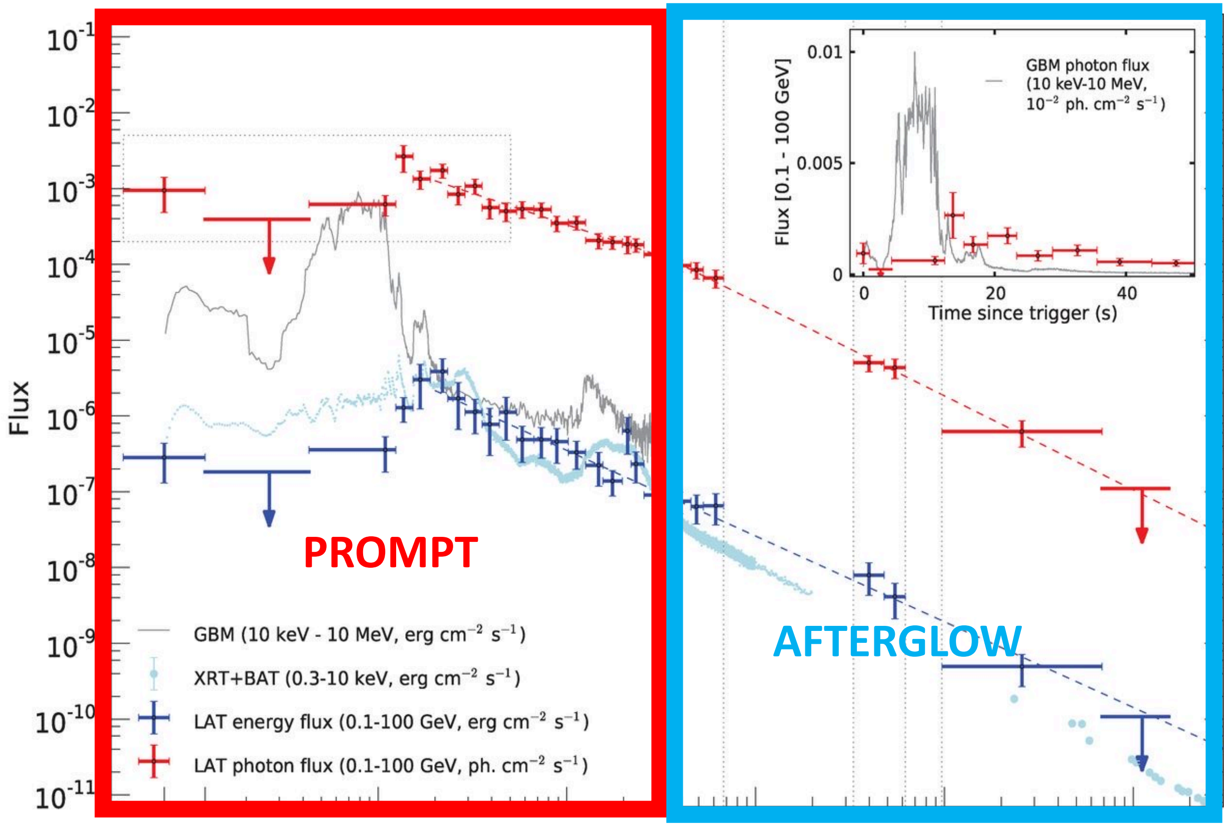


GRB130427A (Ackermann et al., 2013)

Emission in Gamma-ray Bursts

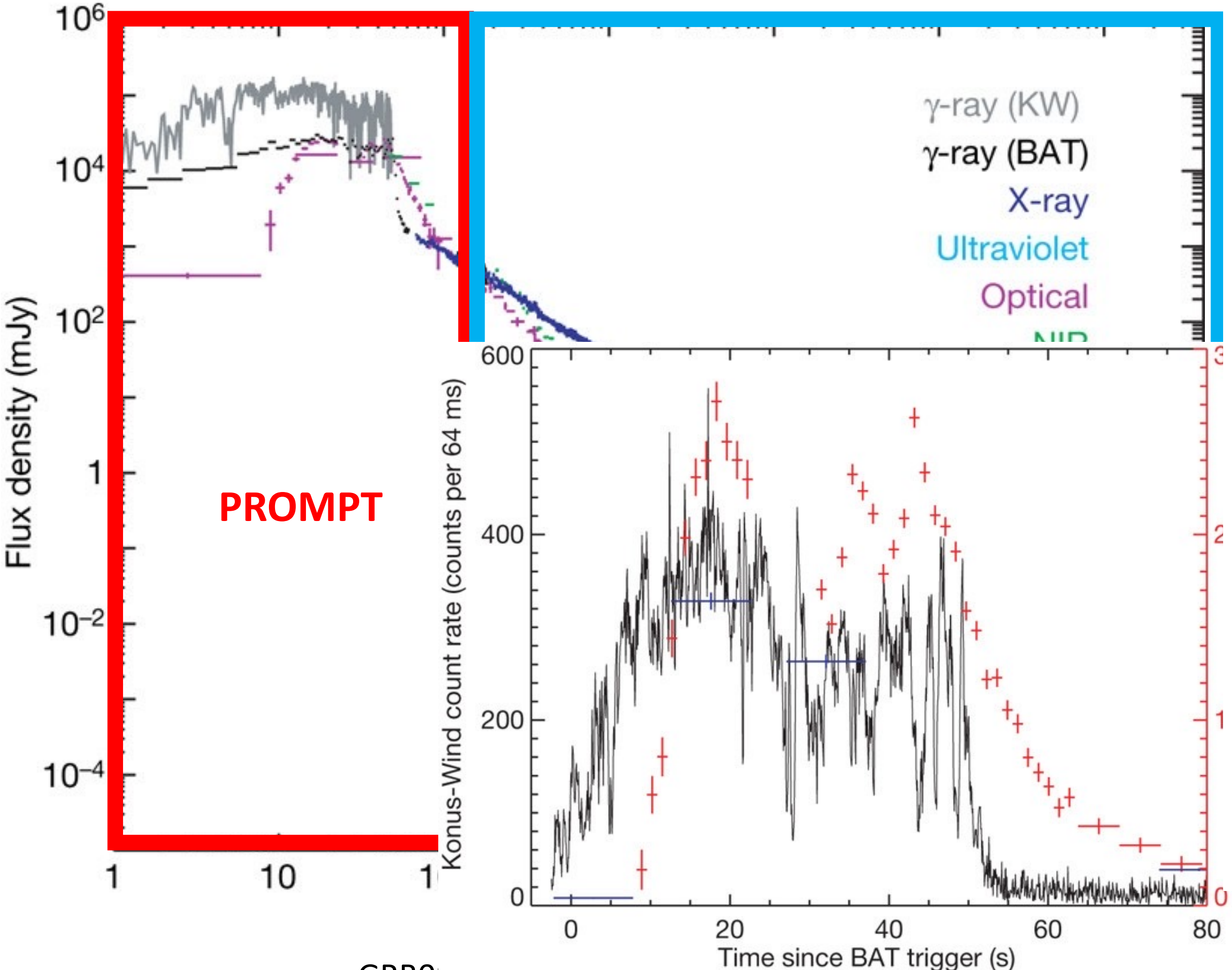


GRB080319B (Racusin et al., 2008)

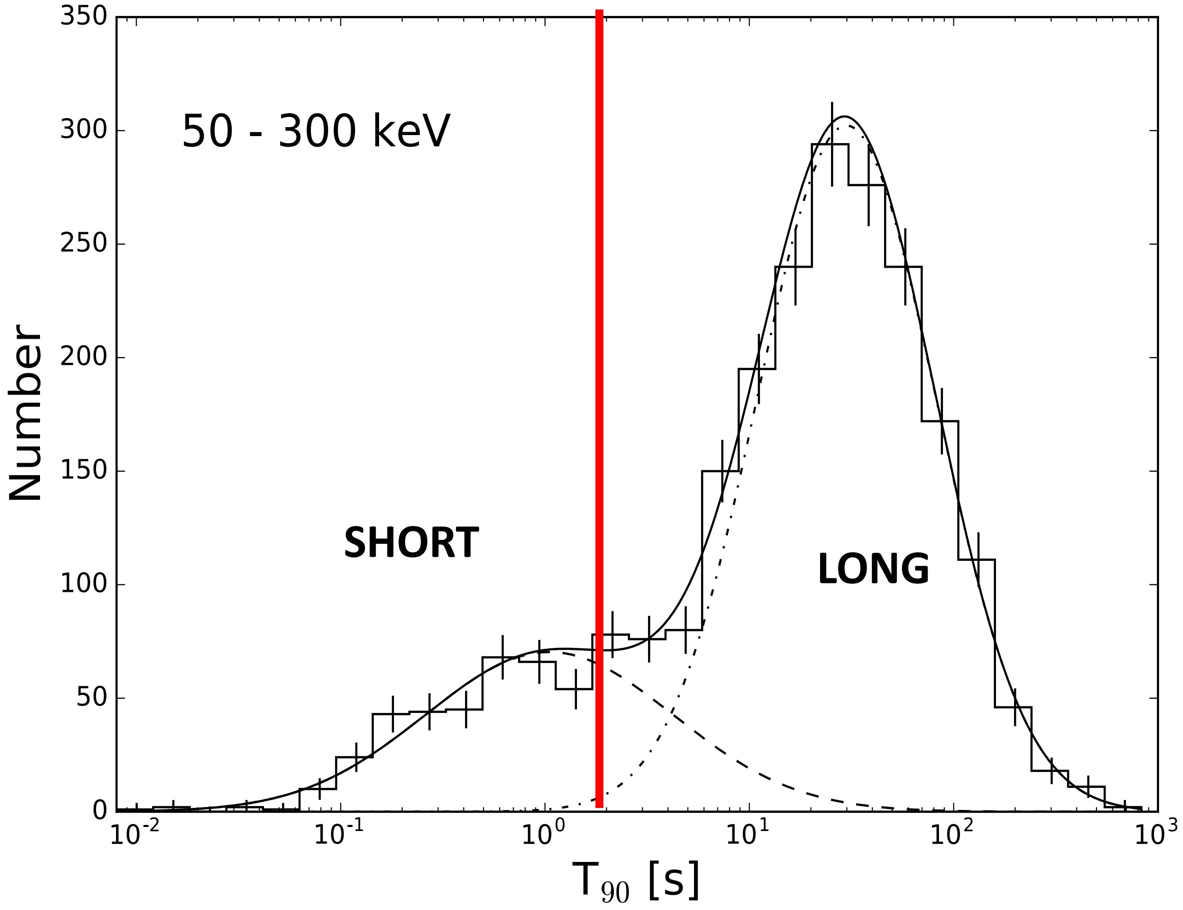


GRB130427A (Ackermann et al., 2013)

Prompt phase

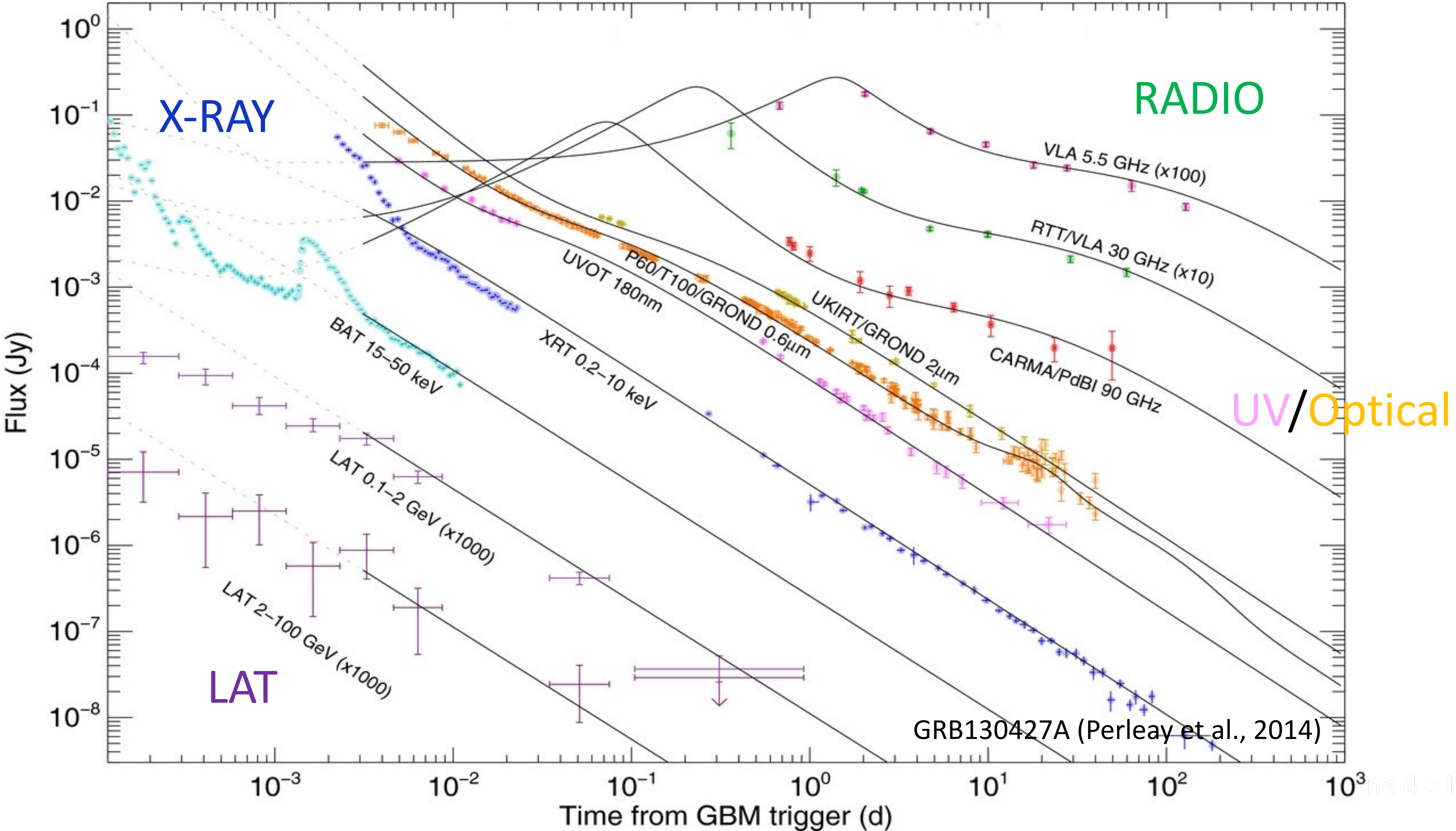


GRB080319B (Racusin et al., 2008)



(von Kienlin et al., 2020)

Afterglow phase



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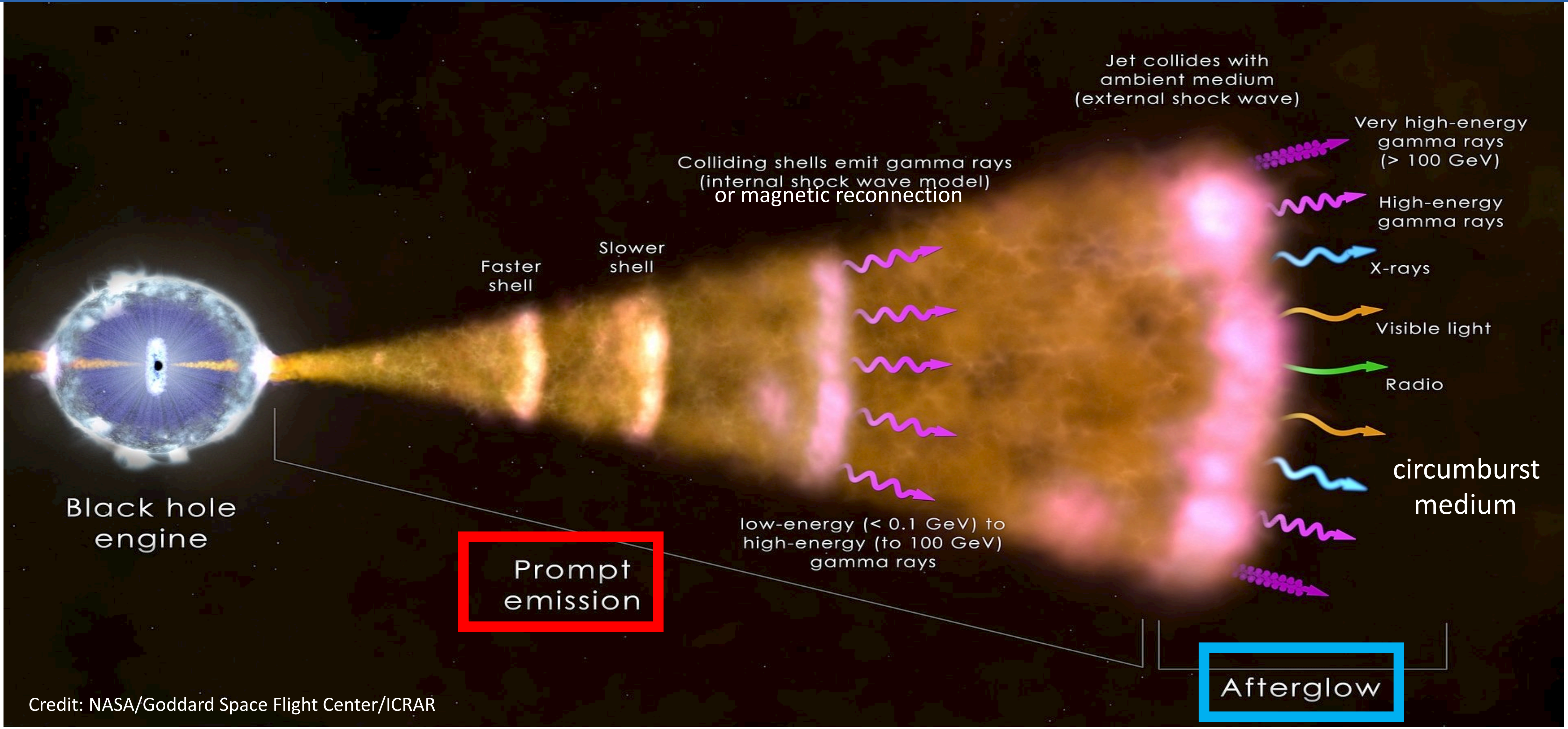
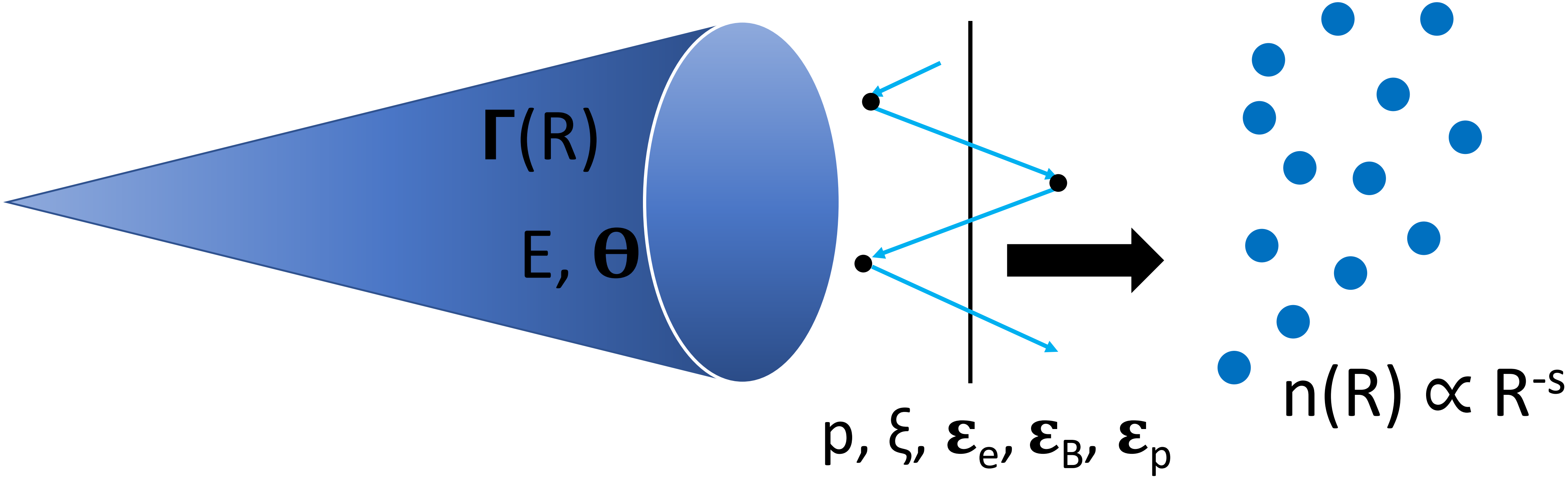


Afterglow: the external forward shock scenario

Decelerating blastwave interacting with the circumburst external medium

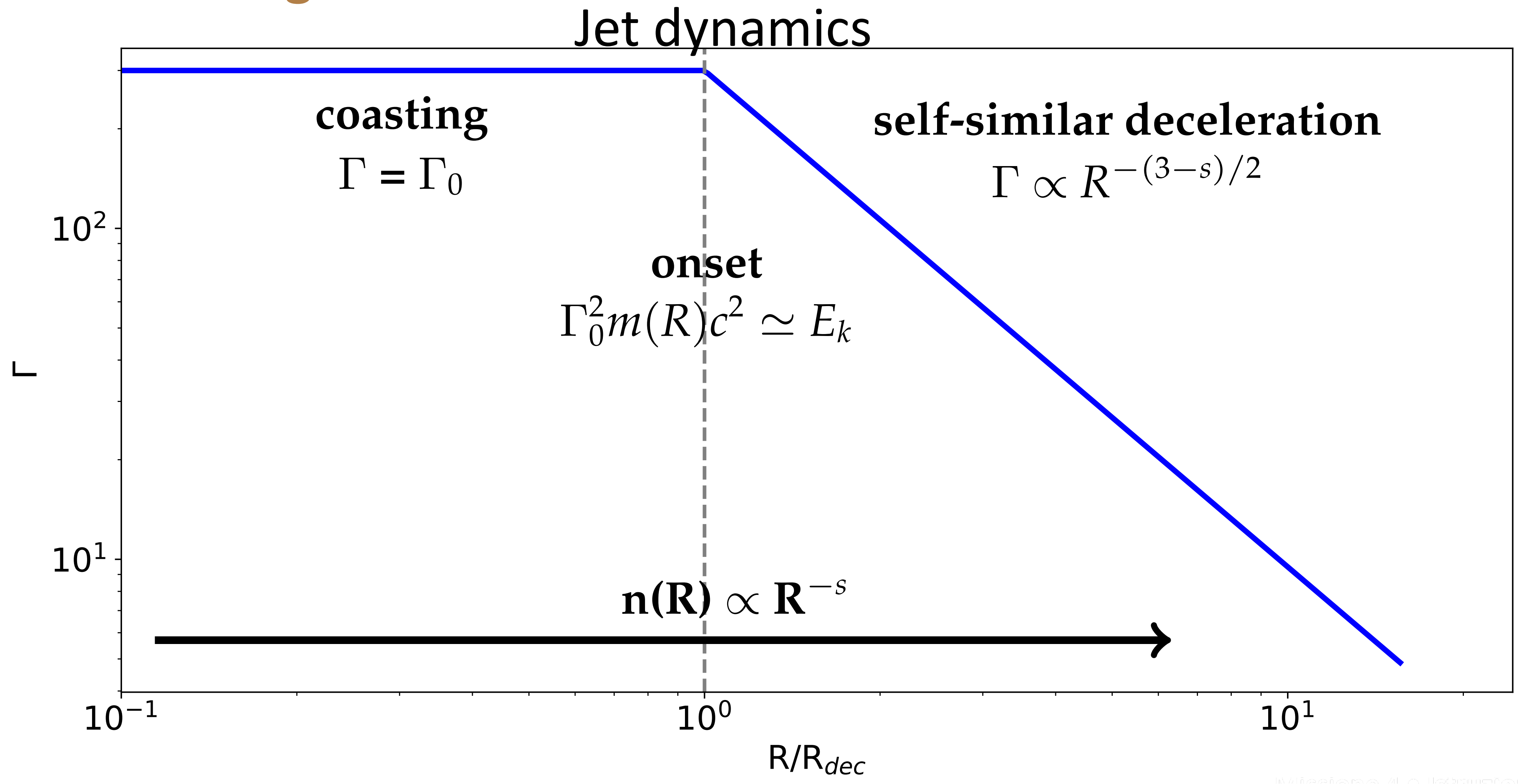


Jet structure and dynamics

Relativistic shock acceleration

External circumburst medium

Afterglow: the external forward shock scenario



See Blandford & Mckee, 1976; Nava et al., 2014

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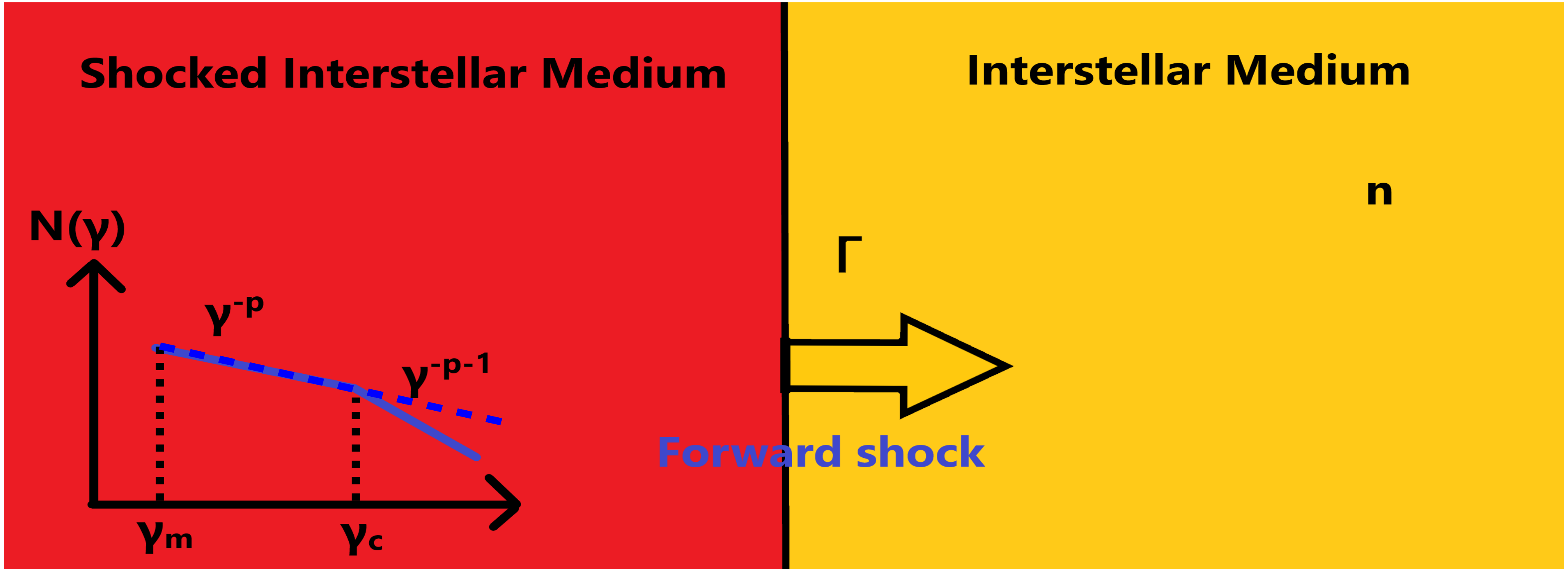
Afterglow: the external forward shock scenario

Relativistic shocks in GRB afterglow



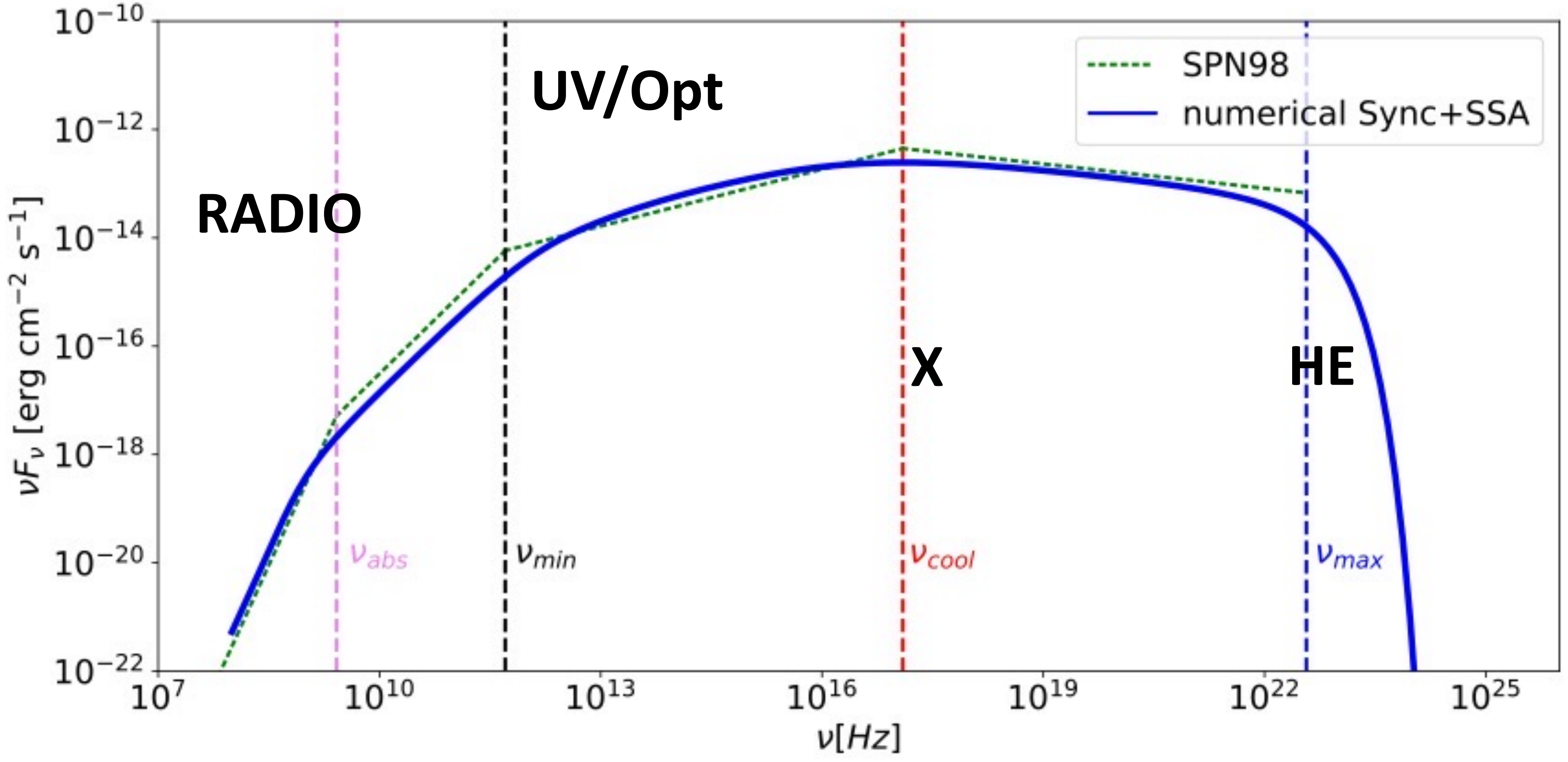
$$u' = (\Gamma - 1)n' m_p c^2$$

$$u'_e = \varepsilon_e u' \quad u'_P = \varepsilon_P u'$$

$$u'_B = \varepsilon_B u' = B^2/8\pi$$

Afterglow: the external forward shock scenario

Radiative output: Synchrotron radiation



See Sari et al, 1998; Panaitescu et al. 2000; Granot et al. 2002

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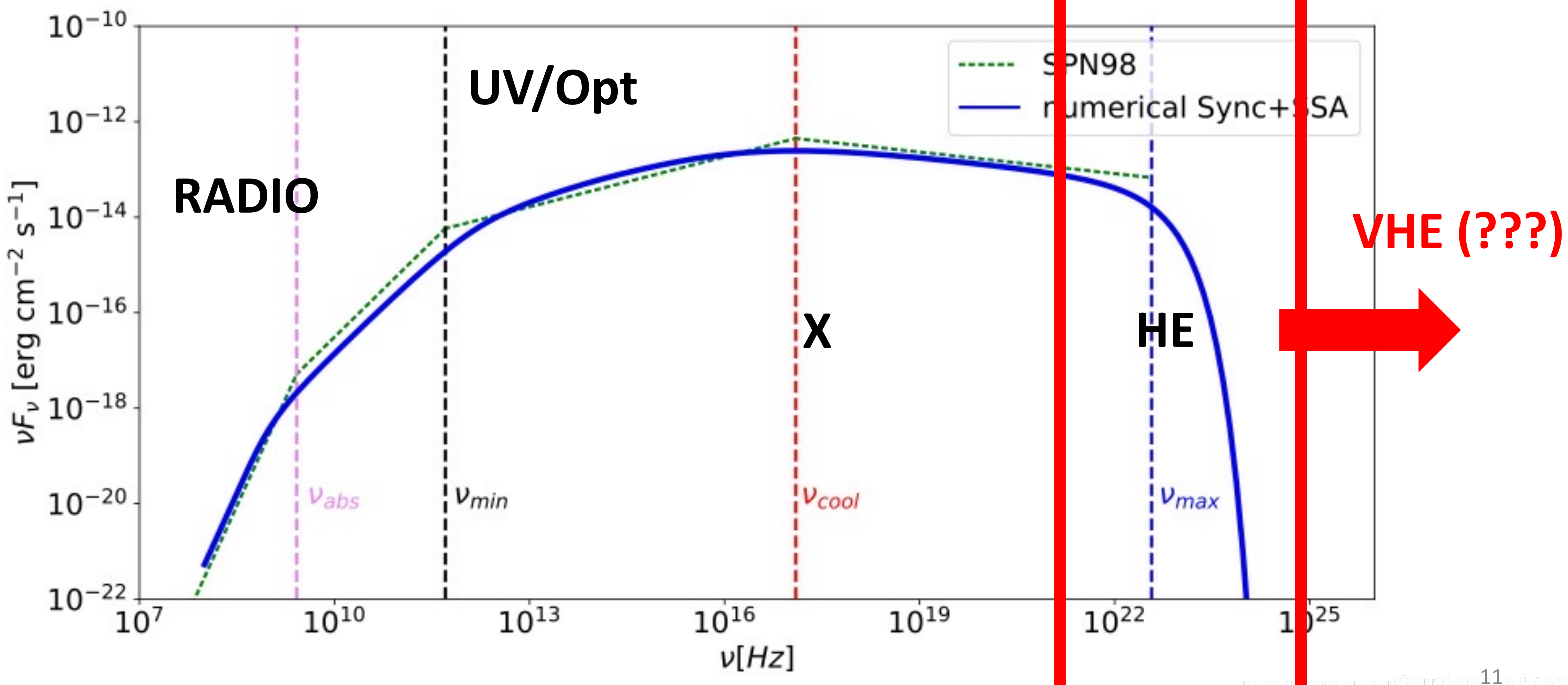
Afterglow: the external forward shock scenario

Radiative output: Synchrotron radiation



See Sari et al, 1998; Panaitescu et al. 2000; Granot et al. 2002

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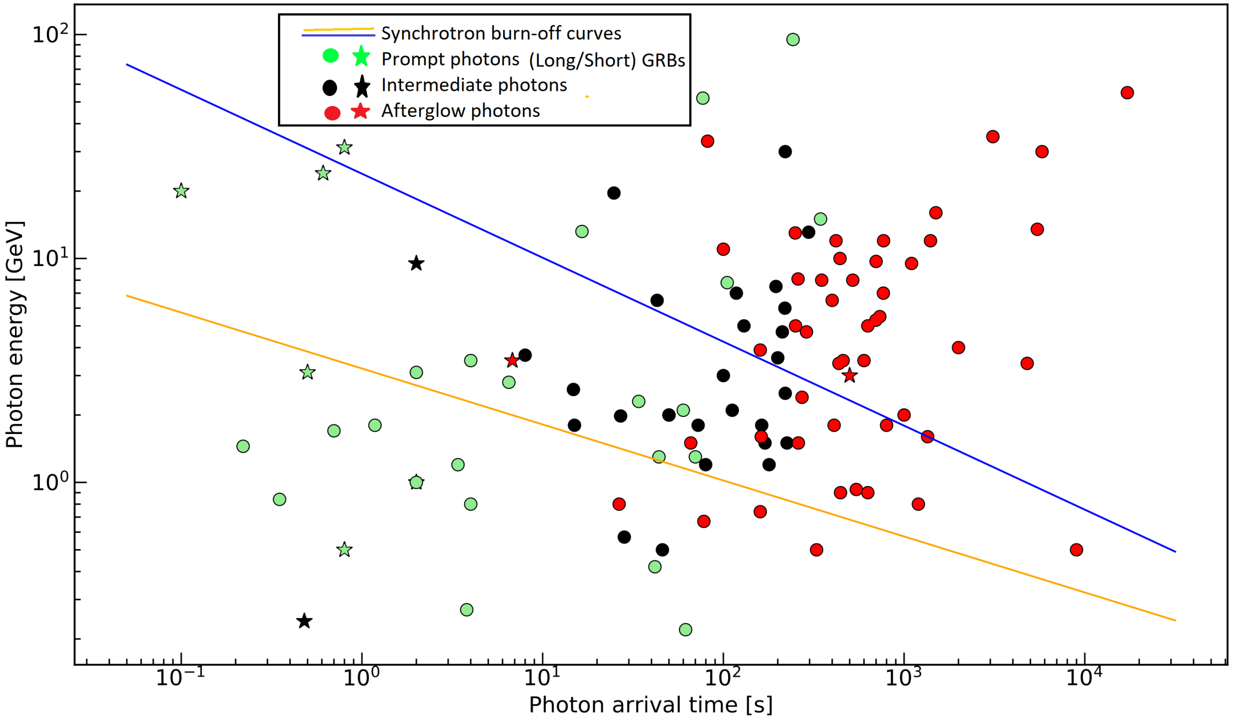
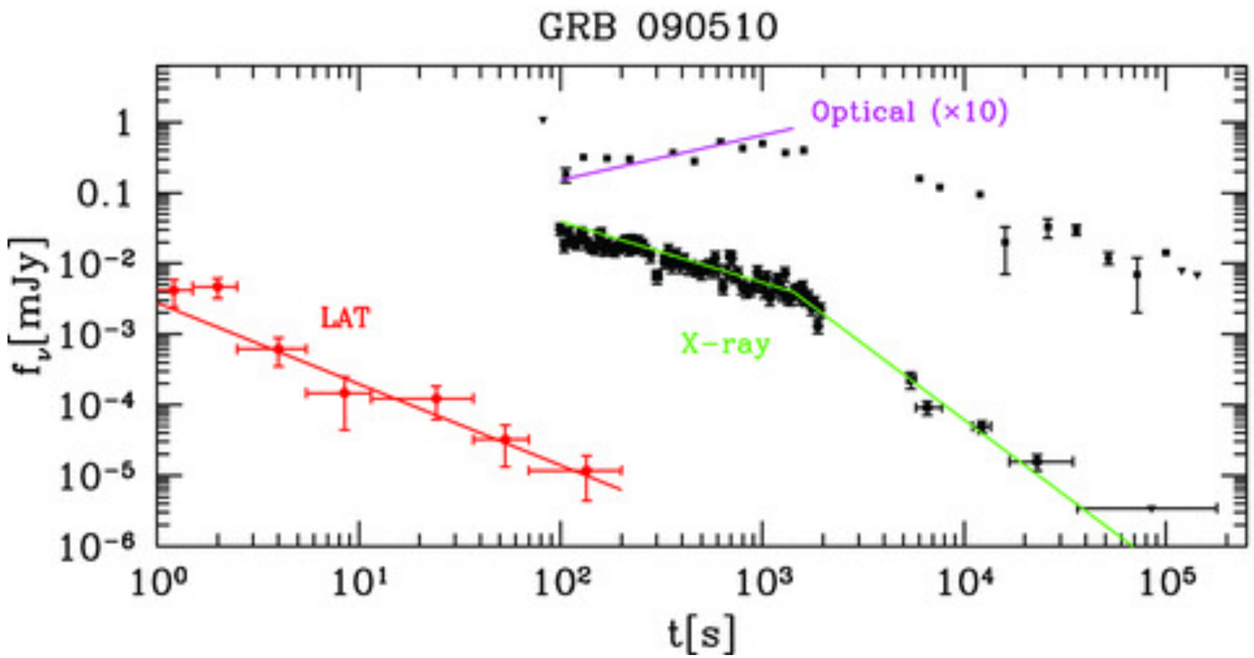
Open issue: the HE and VHE radiation

HE emission

- Almost consistent with synchrotron radiation (synchrotron burnoff limit)
- No spectral cut-off identified (shock microphysics uncertainties, non-uniform magnetic fields)



Nava, 2018



Kumar et al., 2010

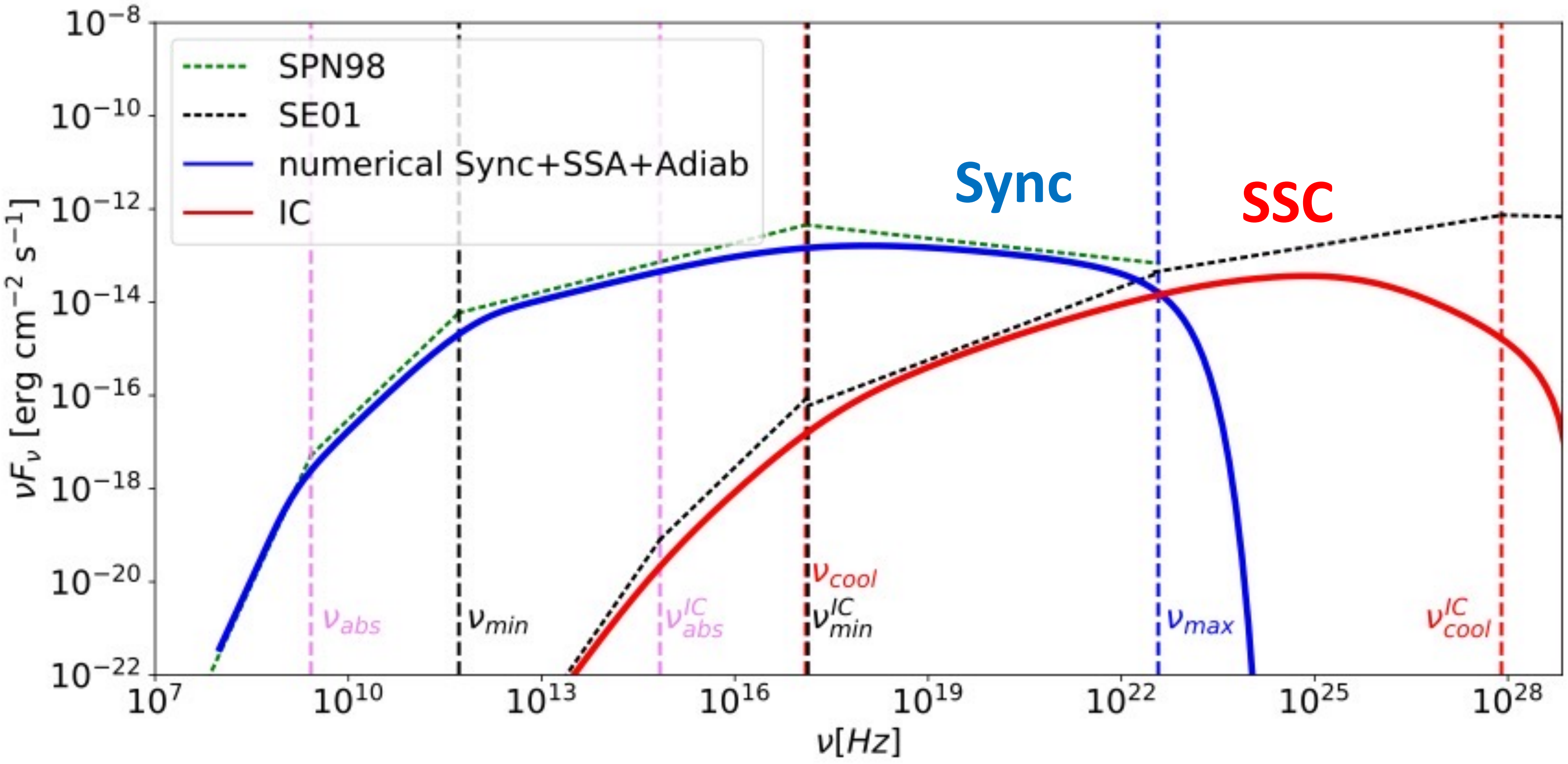
Open issue: the HE and VHE radiation

VHE emission

Possible radiation processes

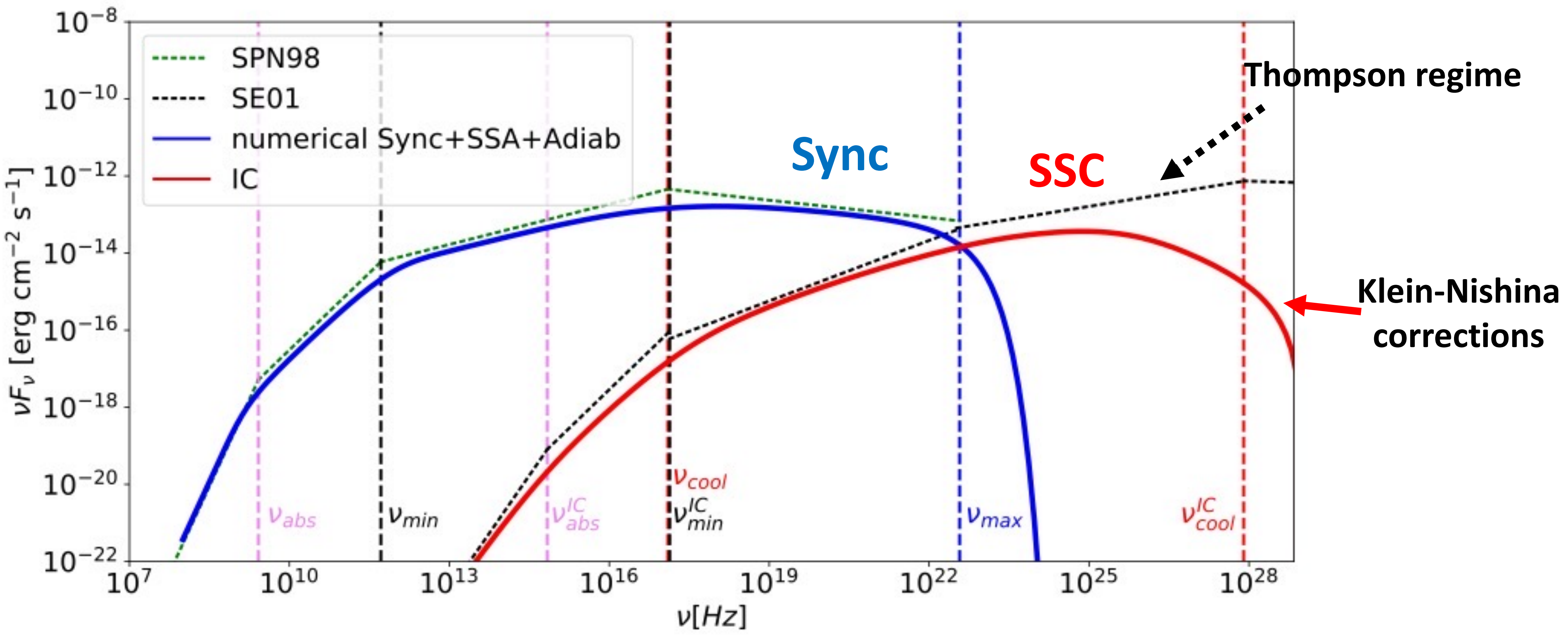
- Synchrotron emission from e^- — Limited by burnoff limit, microphysics conditions, particle acceleration assumptions
- Synchrotron emission from *p* — Requires high radiative efficiency
- Synchrotron Self Compton (SSC) emission — Natural candidate (Sari et al., 2001; Nakar et al. 2009)

VHE emission



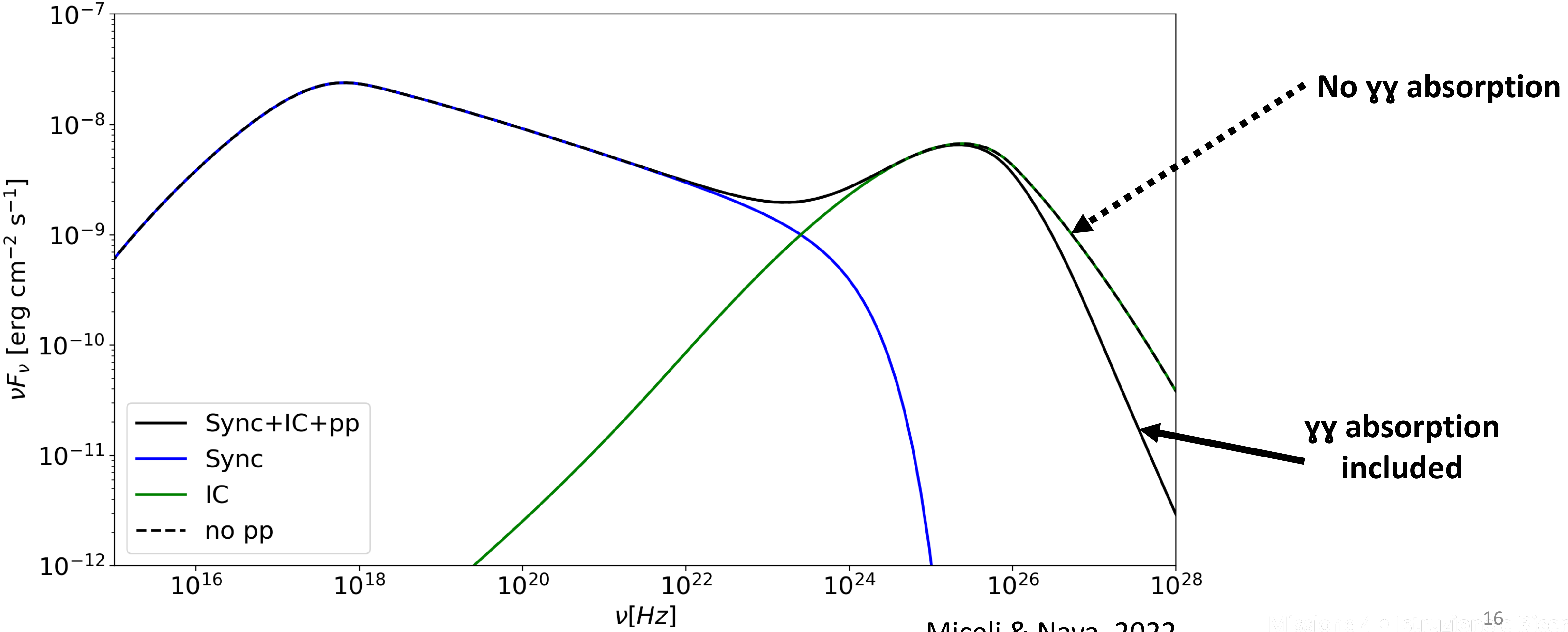
Miceli & Nava, 2022

Shaping the VHE spectrum



Miceli & Nava, 2022

Shaping the VHE spectrum: γγ absorption



Miceli & Nava, 2022

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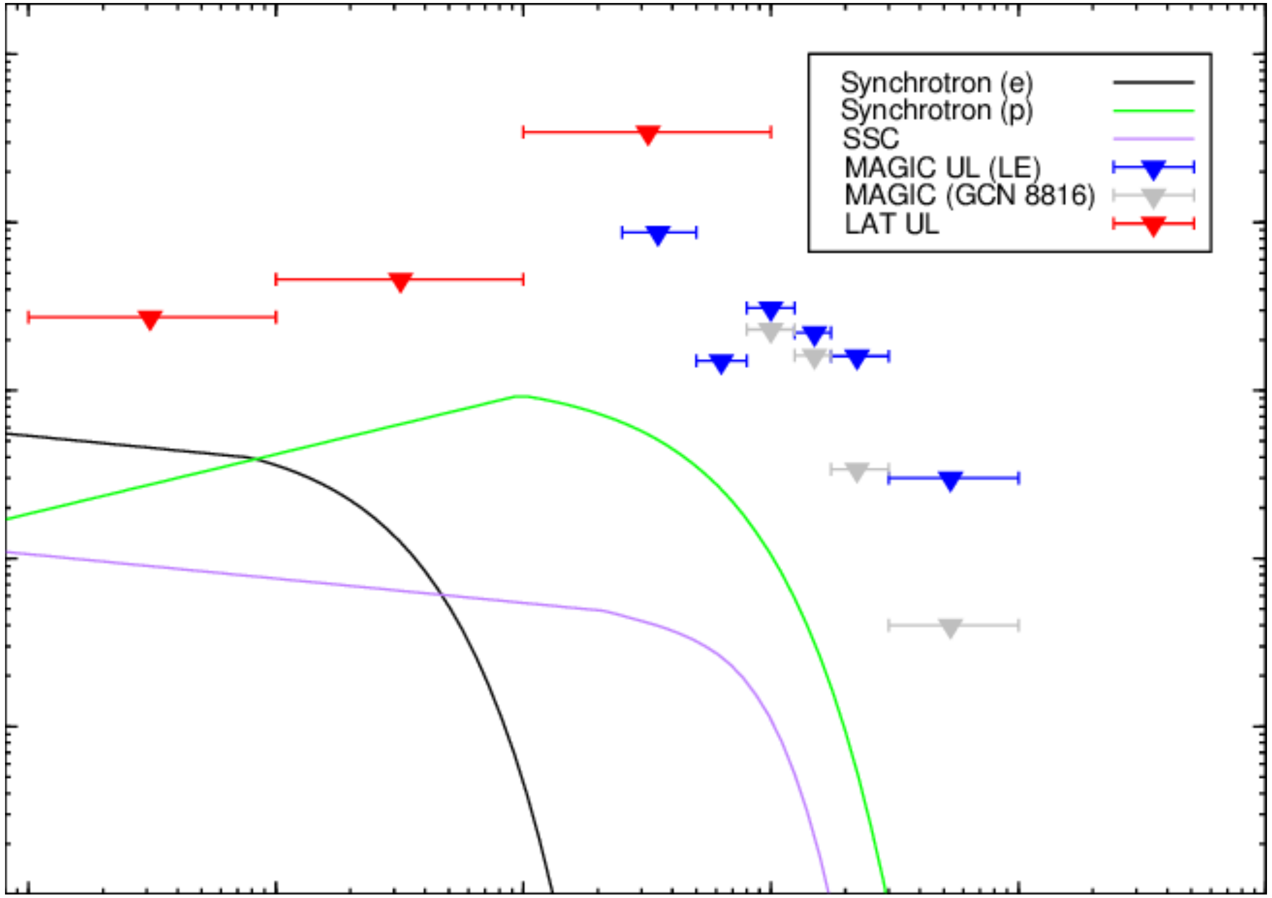
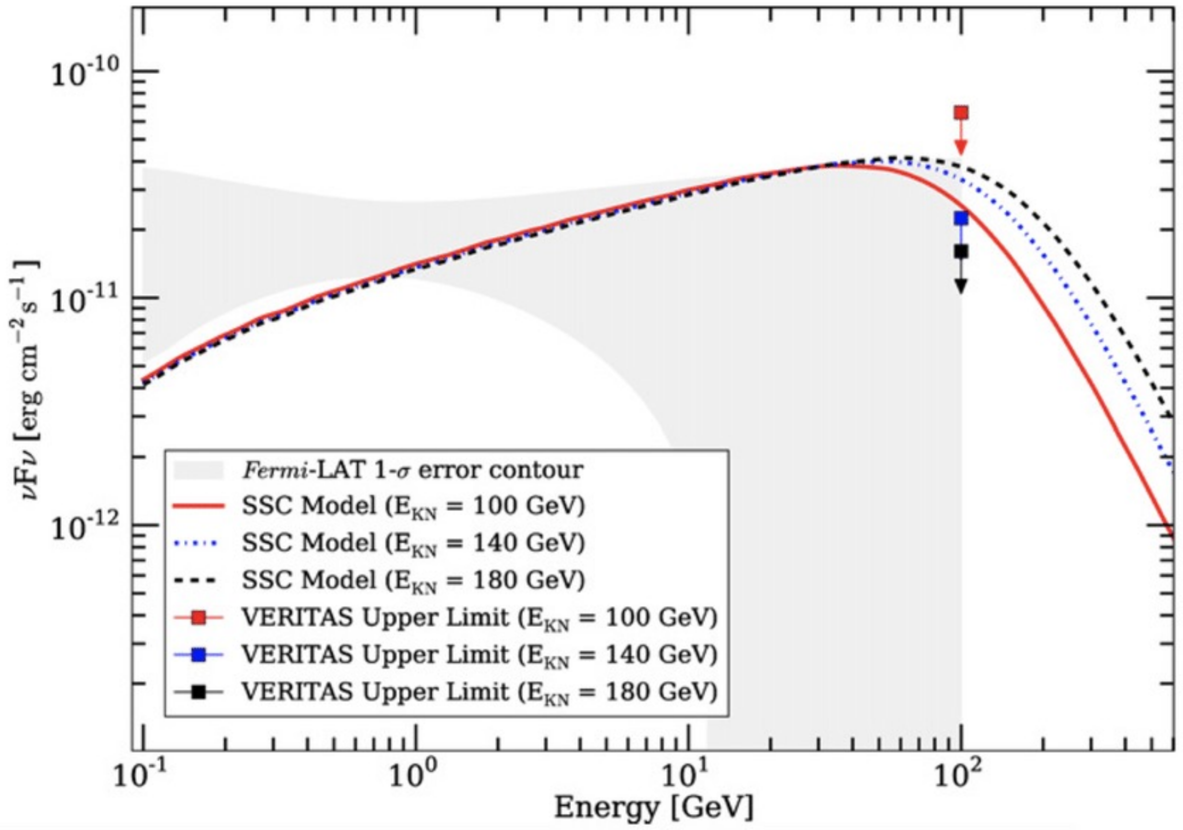
Gamma-ray Bursts in the VHE domain

Cherenkov telescope observations: only upper limits until 2019



Aleksic et al. 2014



Aliu et al., 2014

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Gamma-ray Bursts in the VHE domain

	T_{90} s	$E_{\gamma,iso}$ erg	z	T_{delay} s	E_{range} TeV	IACT (sign.)
160821B	0.48	1.2×10^{49}	0.162	24	0.5-5	MAGIC (3.1σ)
180720B	48.9	6.0×10^{53}	0.654	3.64×10^4	0.1-0.44	H.E.S.S. (5.3σ)
190114C	362	2.5×10^{53}	0.424	57	0.3-1	MAGIC ($> 50\sigma$)
190829A	58.2	2.0×10^{50}	0.079	1.55×10^4	0.18-3.3	H.E.S.S. (21.7σ)
201015A	9.78	1.1×10^{50}	0.42	33	0.14	MAGIC (3.5σ)
201216C	48	4.7×10^{53}	1.1	56	0.1	MAGIC (6.0σ)
221009A	289	1.0×10^{55}	0.151	0-2400	0.5-18	LHAASO

Adapted from Miceli & Nava, 2022

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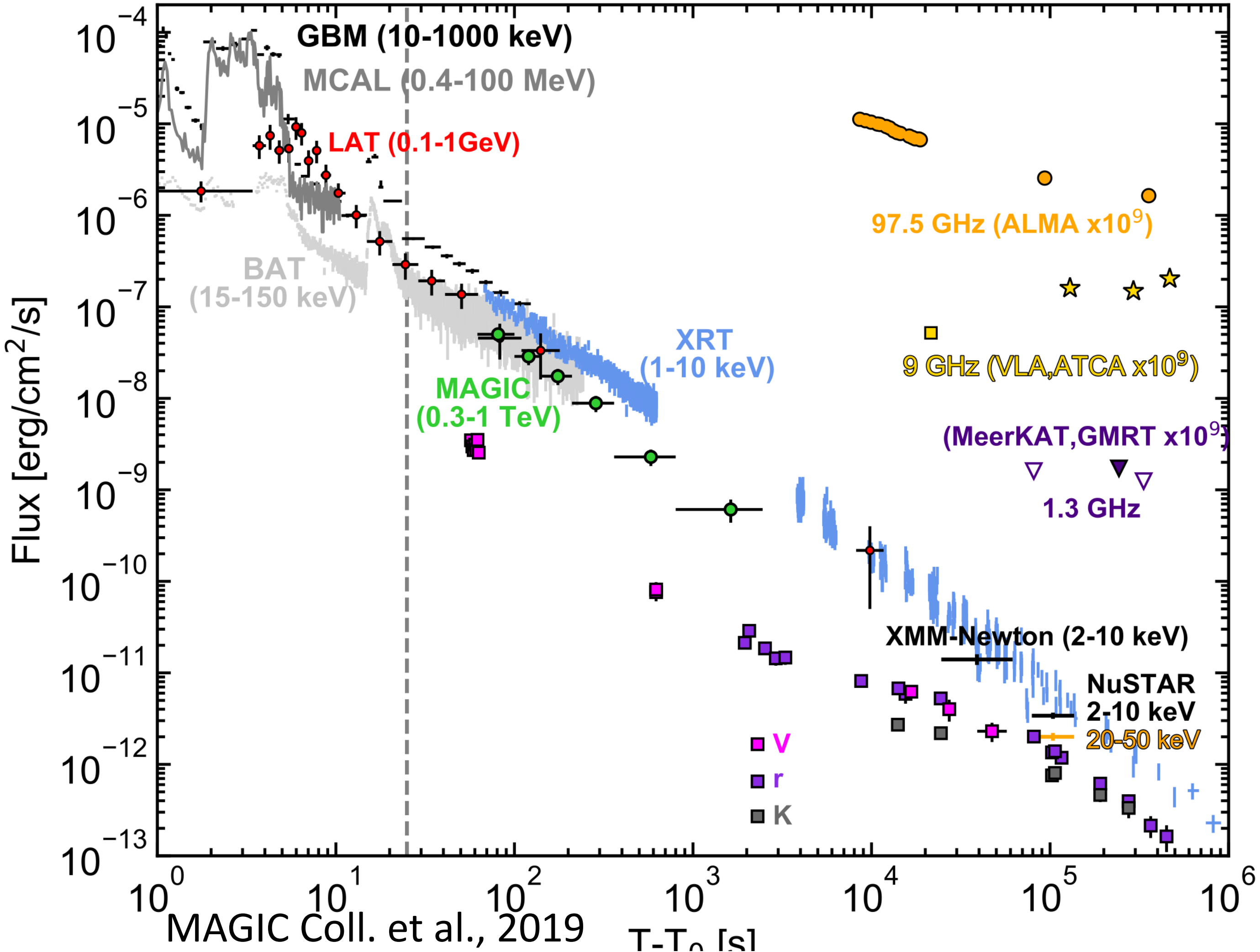
GRB190114C

- Long GRB
- $E_{\gamma,iso} \sim 2.5 \times 10^{53}$ erg
- z = 0.42

MAGIC detection info:

- $T_{delay} \sim 57$ s
- > 50σ in 20 minutes
- detection up to 40 min
- 0.3 - 1 TeV energy range
- moon conditions and Zd>50



MAGIC Coll. et al., 2019

GRB190114C

X-ray + GeV + TeV

↓

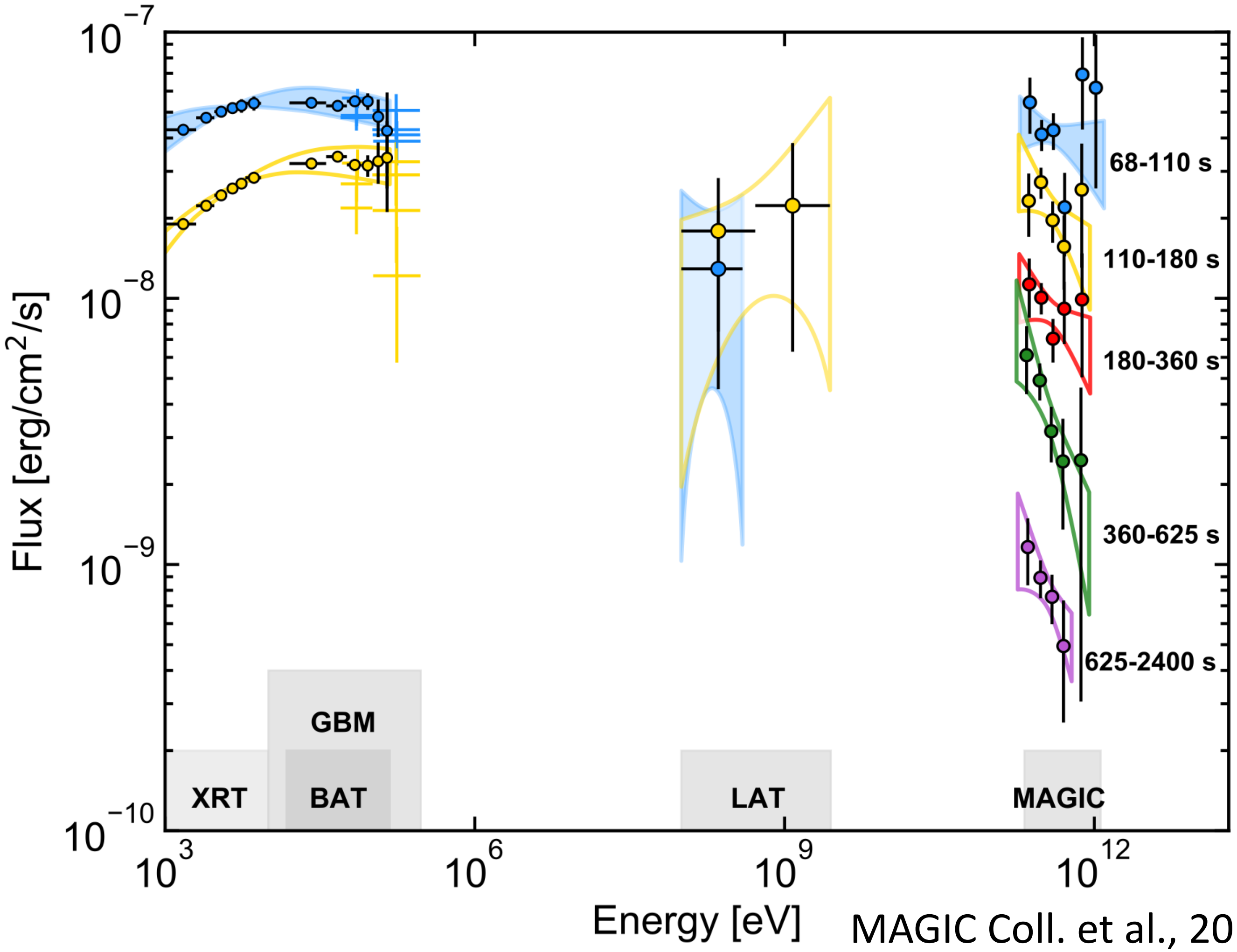
Spectral hardening for E > 0.2 TeV

↓

Can't be extention of Synchrotron component

↓

New emission component at VHE



MAGIC Coll. et al., 2019

GRB190114C

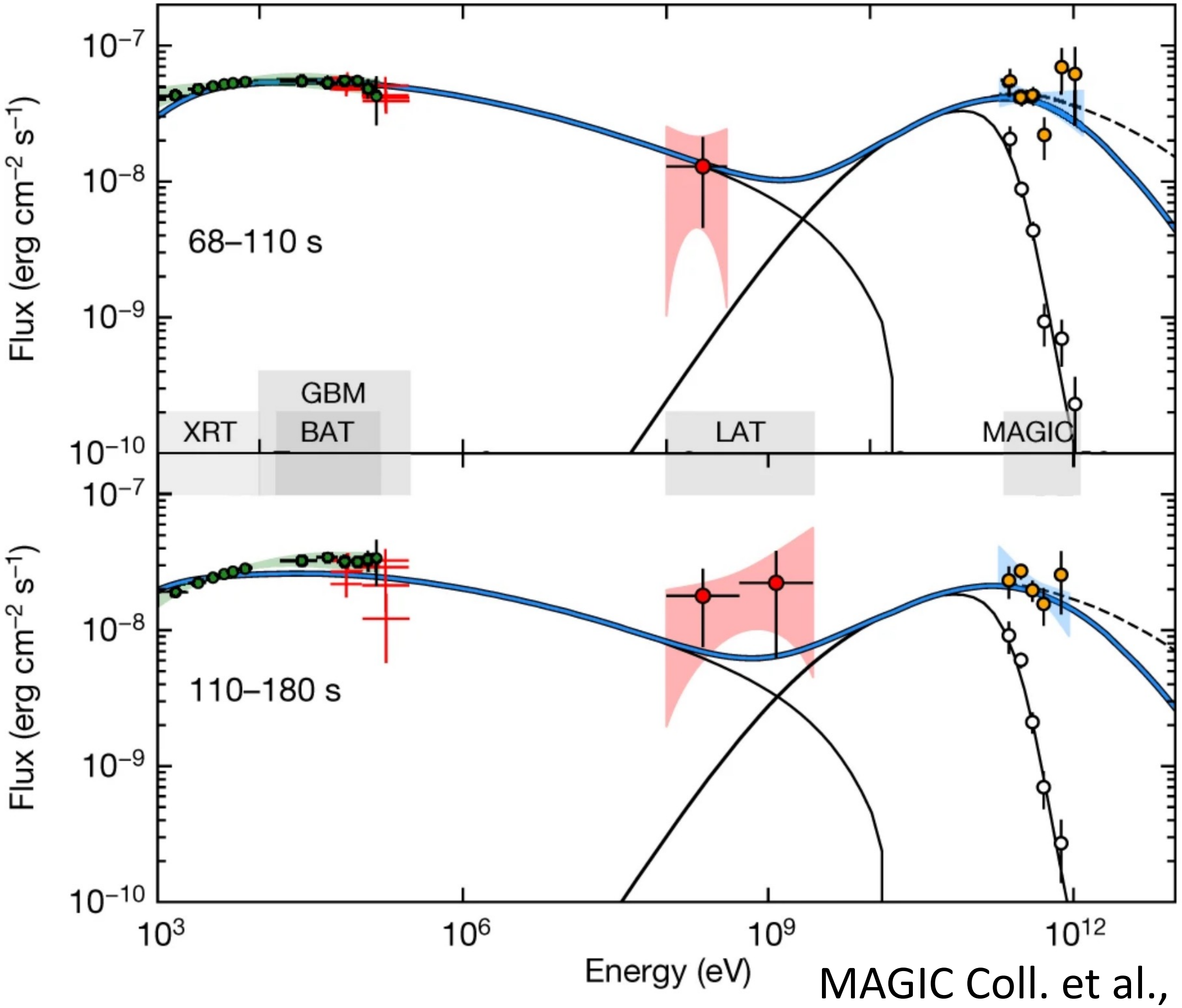
- Observed
- No γ-γ opacity
- EBL-deabsorbed

MAGIC soft spectrum:

- Klein-Nishina
- γ-γ internal absorption

GRB afterglow parameters:

$E_k \gtrsim 3 \times 10^{53}$ erg
$\varepsilon_e \approx 0.05\text{-}0.15$
$\varepsilon_b \approx 0.05\text{-}1 \times 10^{-3}$
$n \approx 0.5\text{-}5\ \text{cm}^{-3}$
$p \approx 2.4\text{-}2.6$



MAGIC Coll. et al., 2019

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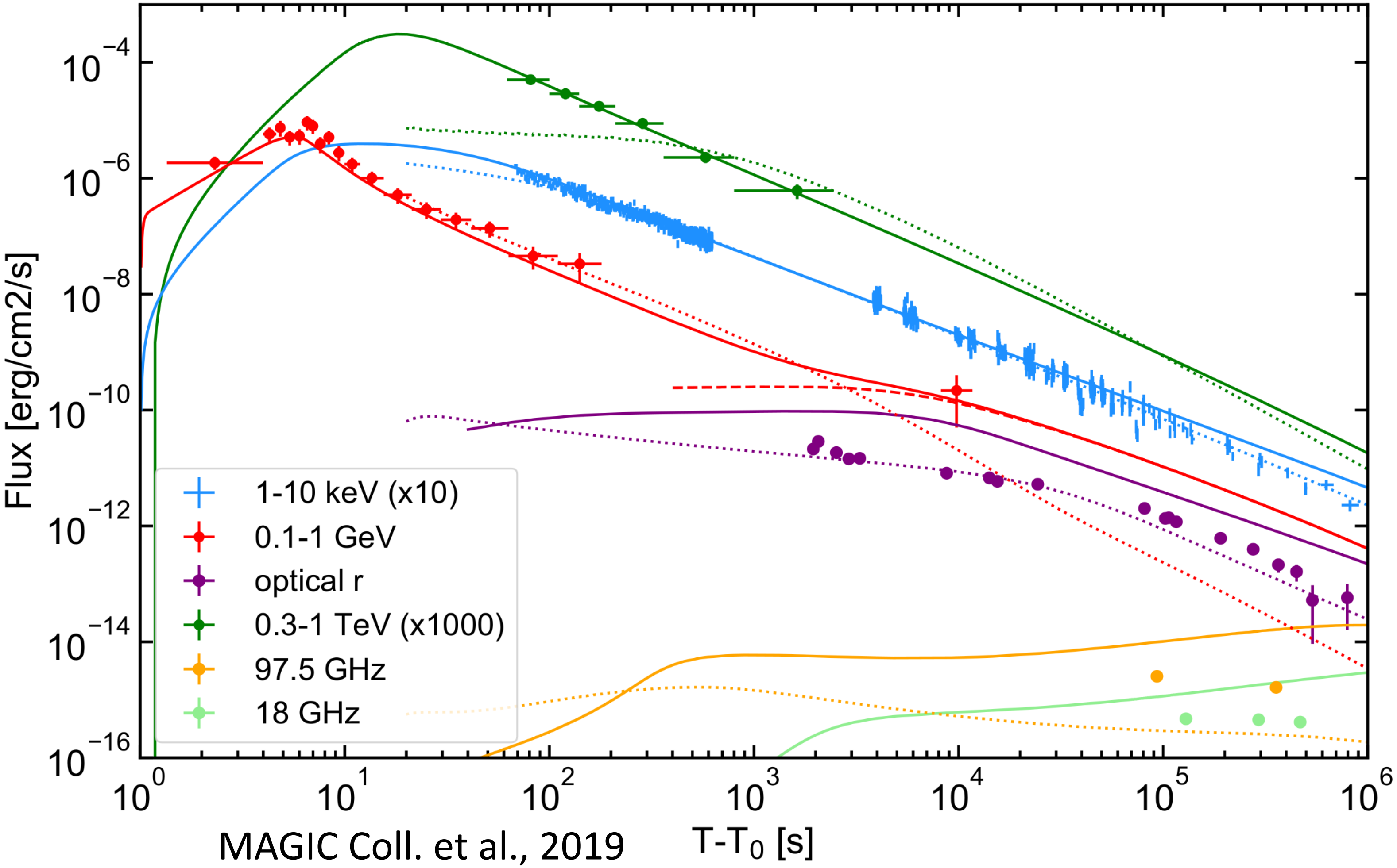
MWL LIGHT CURVES

GRB190114C

- Sync+SSC external forward scenario
- Two modeling displayed:
  - X to TeV (solid lines)
  - Radio-optical (dotted lines)
  - SSC contribution (dashed lines)
- Indication of time-dependent afterglow parameters



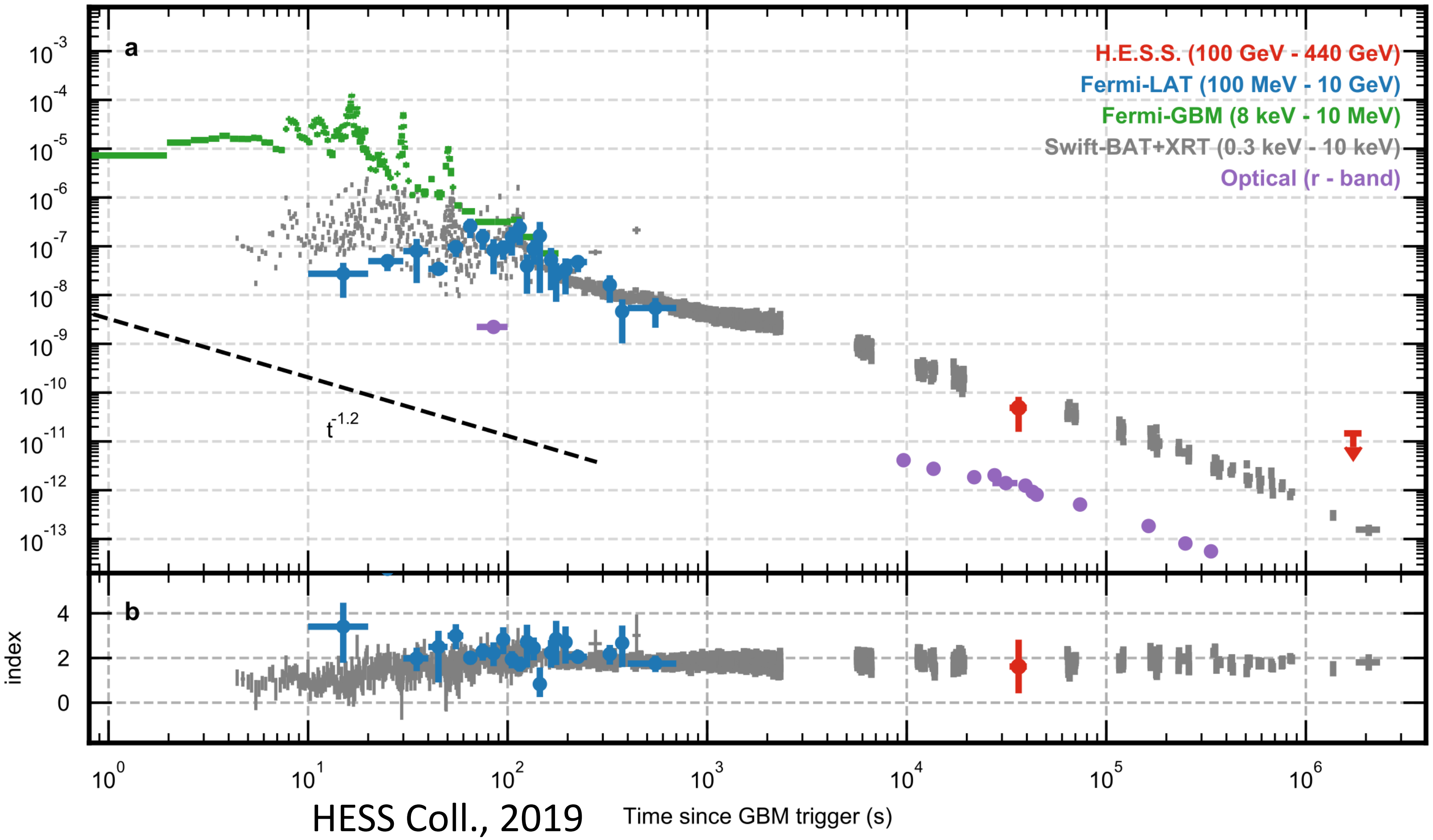
MAGIC Coll. et al., 2019

GRB180720B

- Long GRB
- $E_{\gamma,iso} \sim 6.0 \times 10^{53}$ erg
- z = 0.654

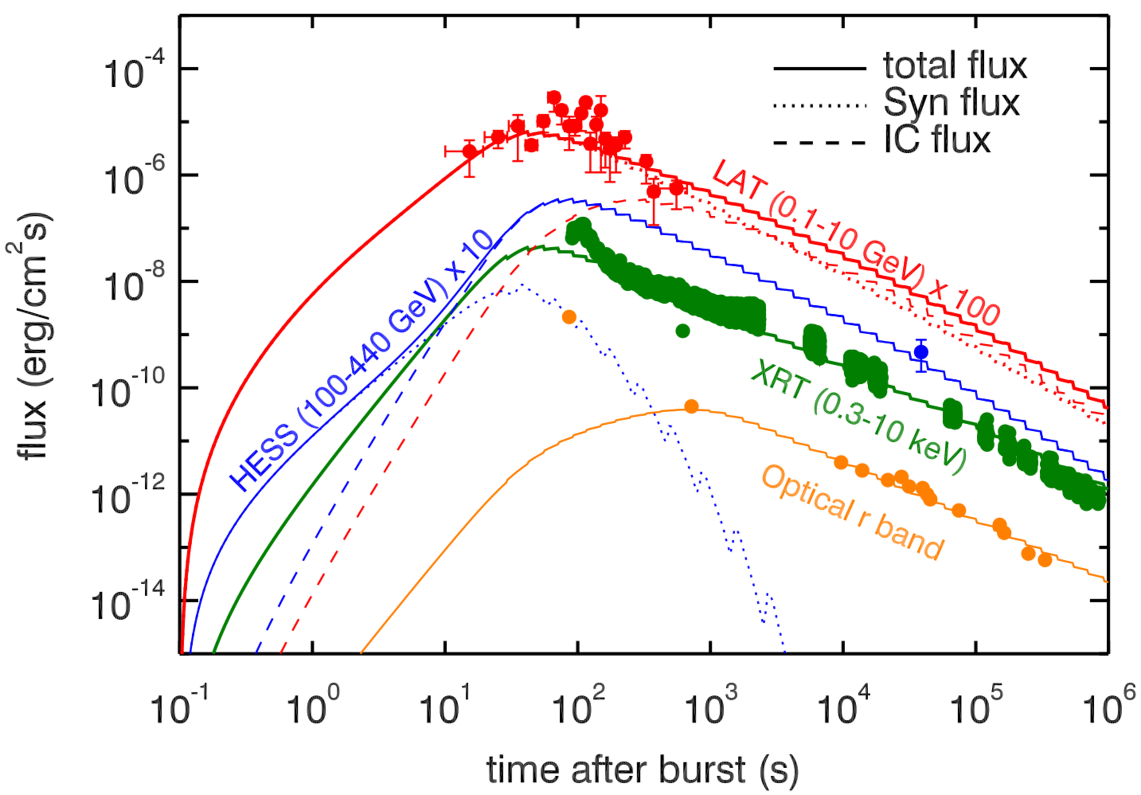
H.E.S.S. detection info:

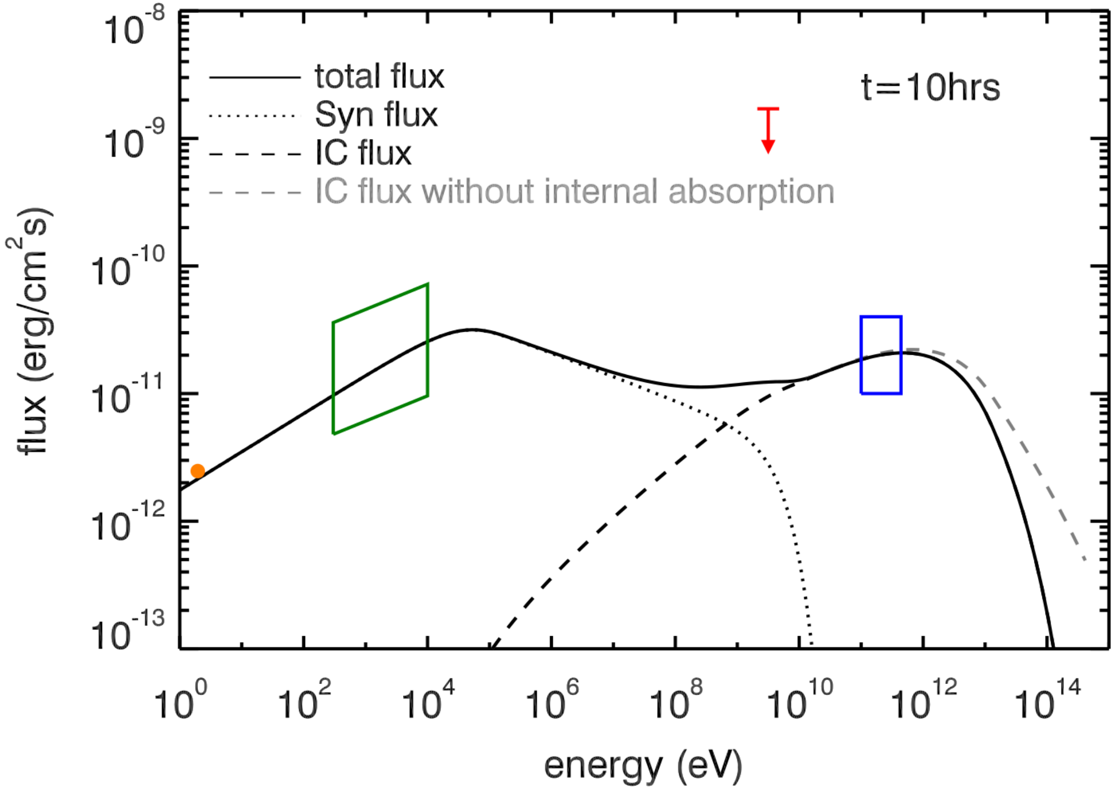
- Tdelay ~ 10 hrs
- > 5.3σ in 2 hrs
- 0.1 – 0.44 TeV energy range



HESS Coll., 2019

GRB180720B





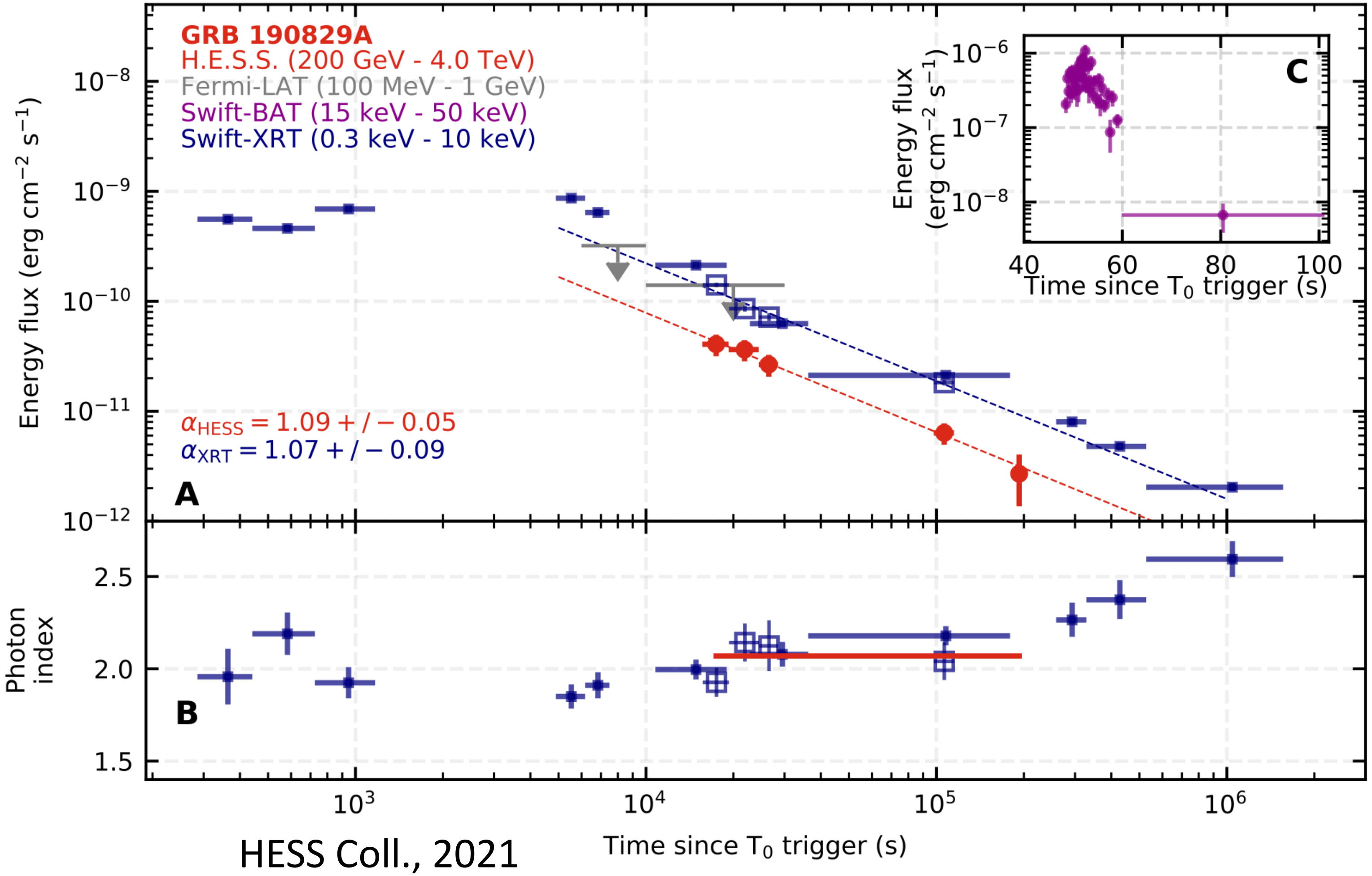
Wang et al.,2019

GRB190829A

- Long GRB
- $E_{\gamma,iso}$ ~ 2.0 x 10^{50} erg
- z = 0.079

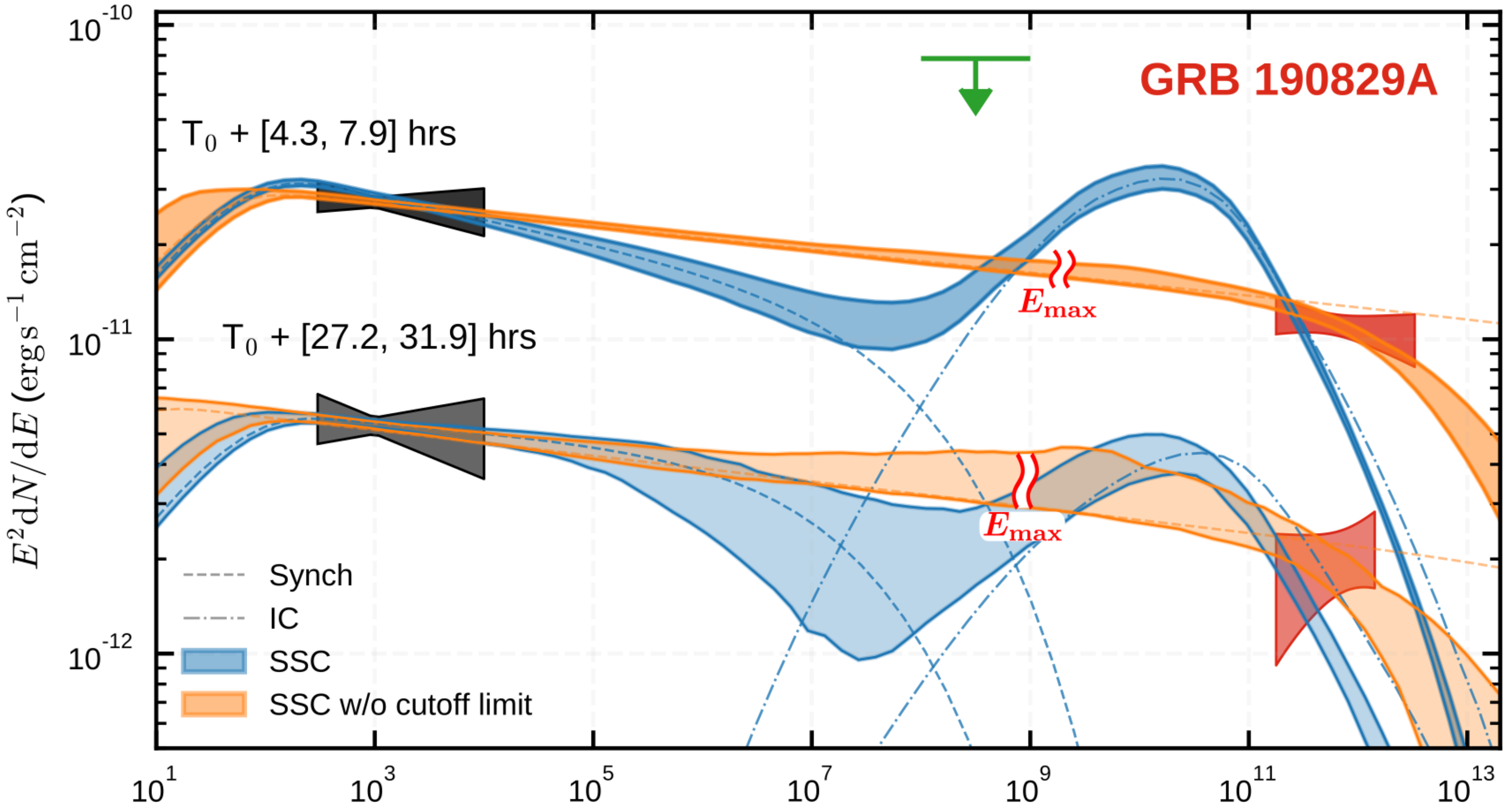
H.E.S.S. detection info:

- T_{obs} ~ 4.3 - 55.9 hrs
- 21.7σ, 5.5σ, 2.4σ,
- 0.18 – 3.3 TeV energy range



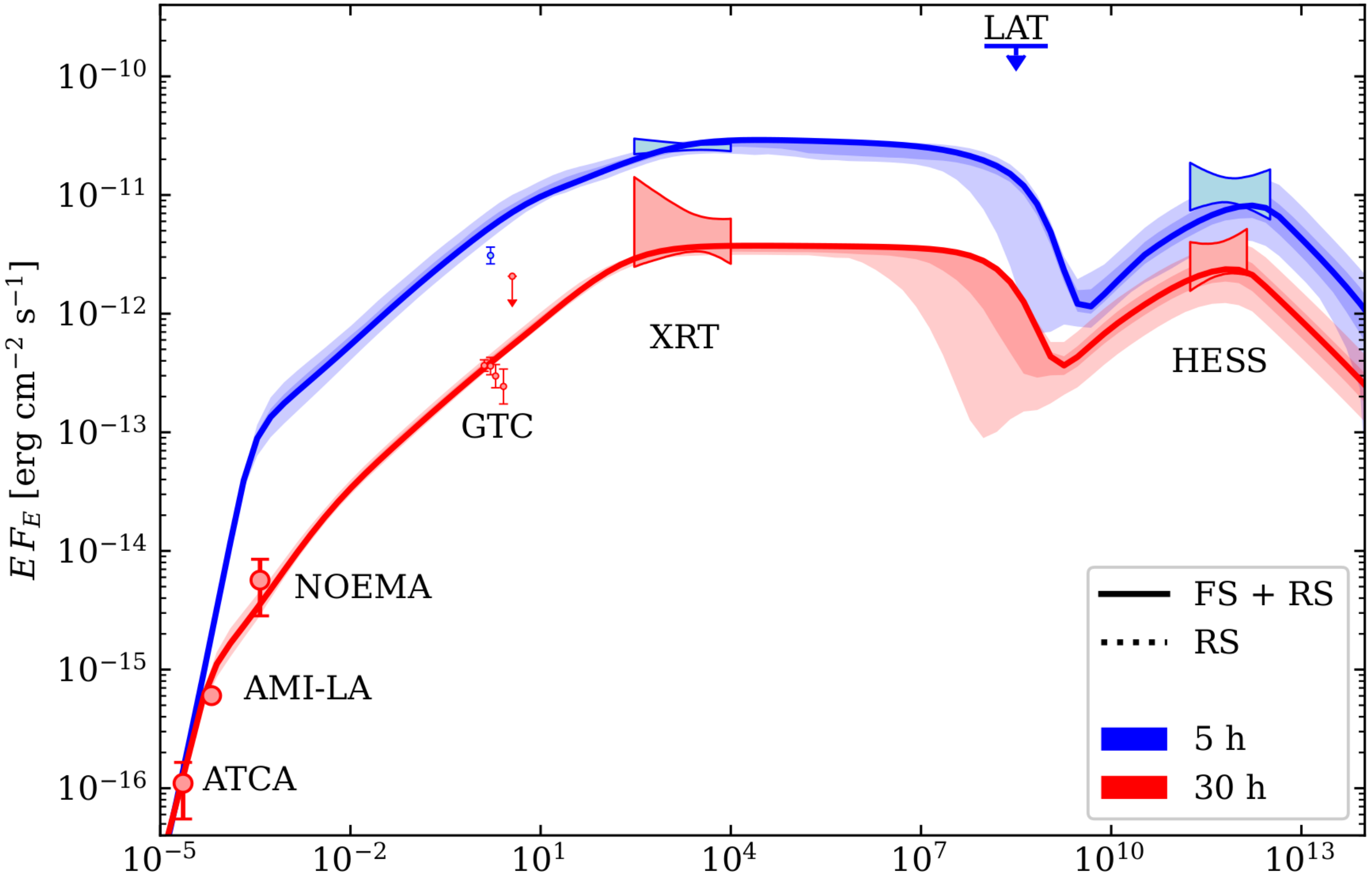
HESS Coll., 2021

GRB190829A



HESS Coll., 2021

GRB190829A



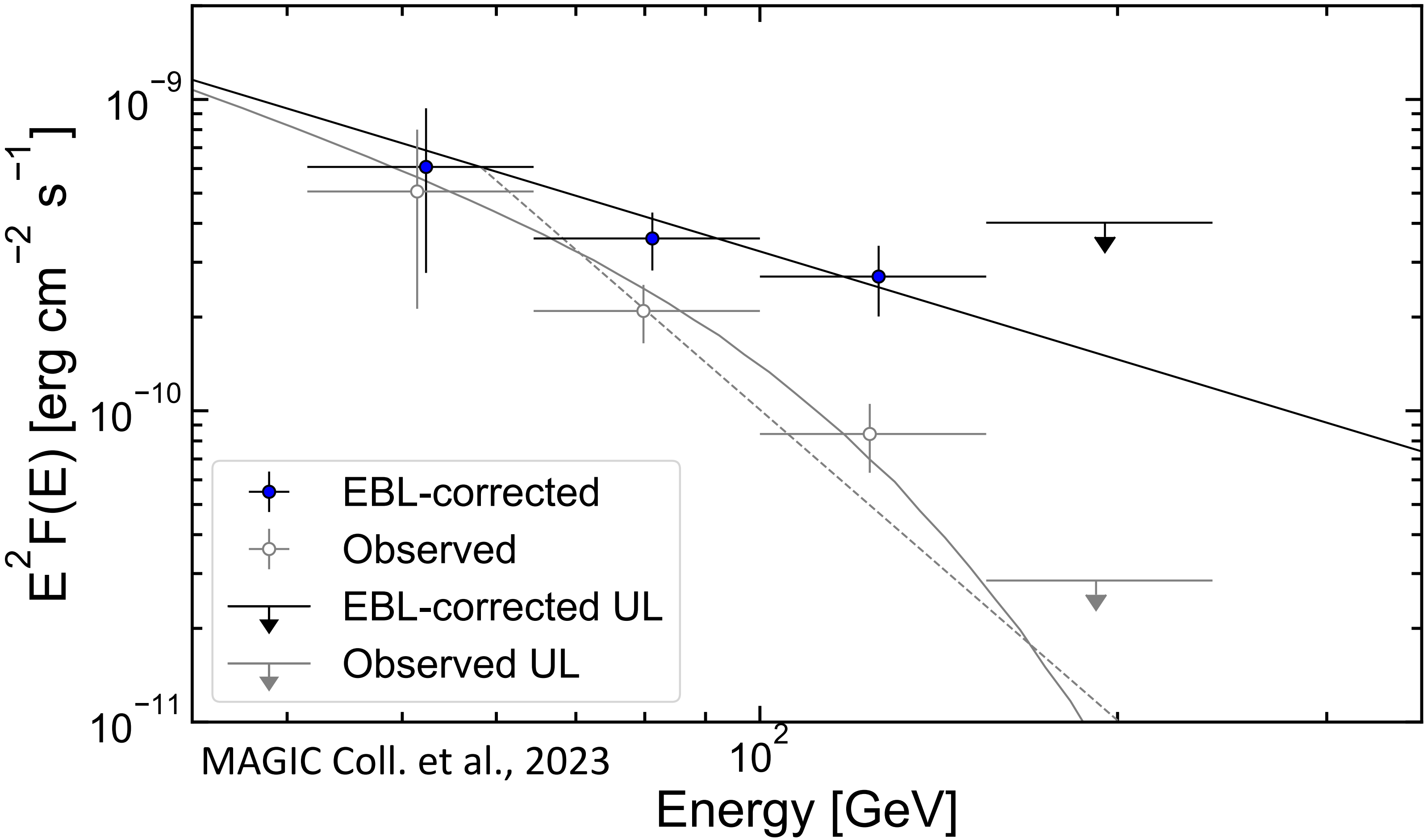
Salafia et al., 2021

GRB201216C

- Long GRB
- $E_{\gamma,iso}$ ~ 4.7 x 10^{53} erg
- z = 1.1

MAGIC detection info:

- Tdelay ~ 56 s
- 6σ in 20 minutes
- 0.07 – 0.2 TeV energy range



MAGIC Coll. et al., 2023

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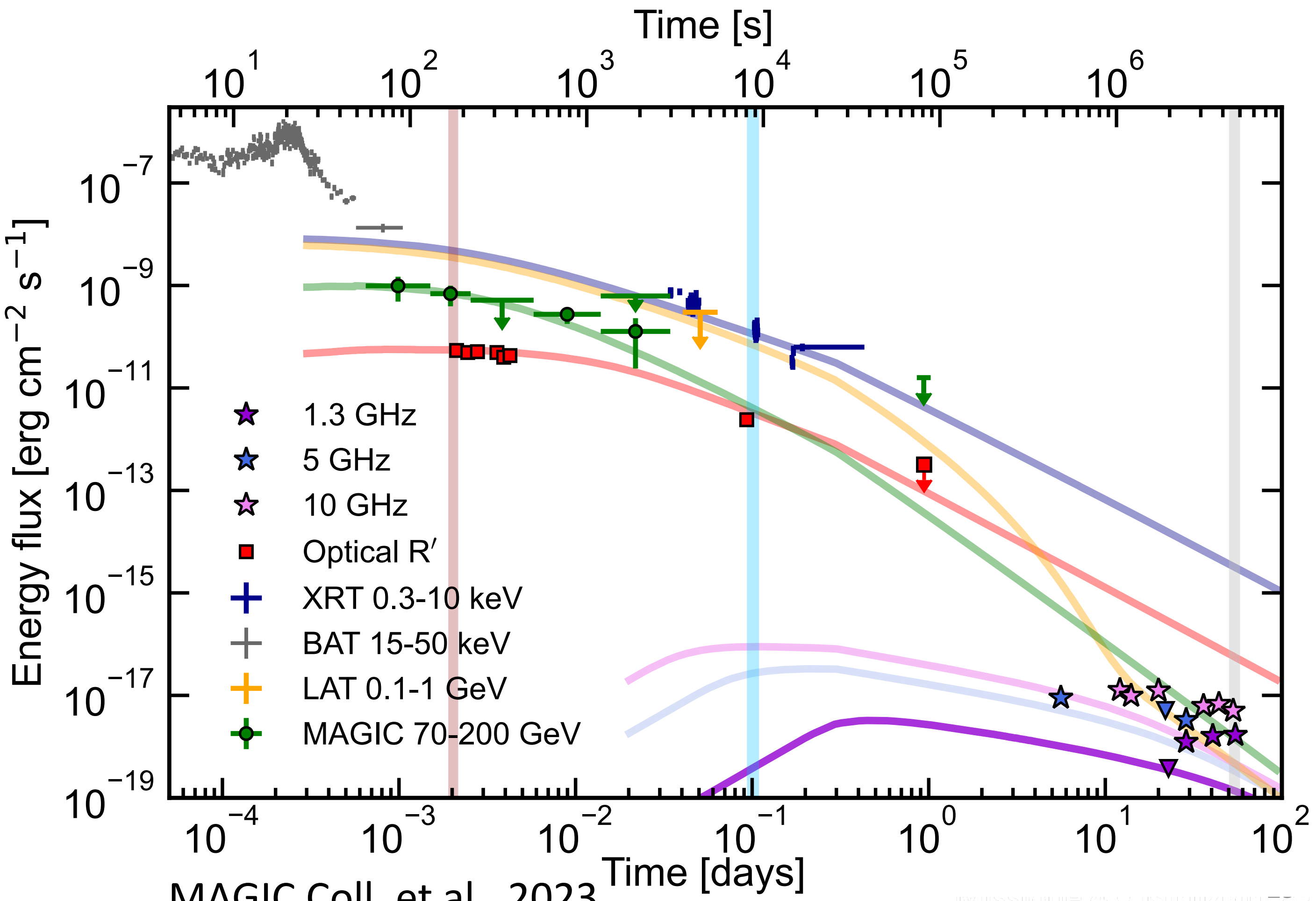
GRB201216C

Parameter	Range	Best fit value
E_k [erg]	$10^{50} - 10^{54}$	4×10^{53}
θ_{jet} [degrees]	$0.5 - 3$	1
Γ_0	80-300	180
n_0 [cm^{-3}] ($s = 0$)	$10^{-2} - 10^{2}$	-
$A_\star$ ($s = 2$)	$10^{-2} - 10^{2}$	2.5×10^{-2}
p	2.05 - 2.6	2.1
ϵ_e	0.01-0.9	0.08
ϵ_B	$10^{-7} - 10^{-1}$	2.5×10^{-3}

Strong indication in favour of a wind-like medium



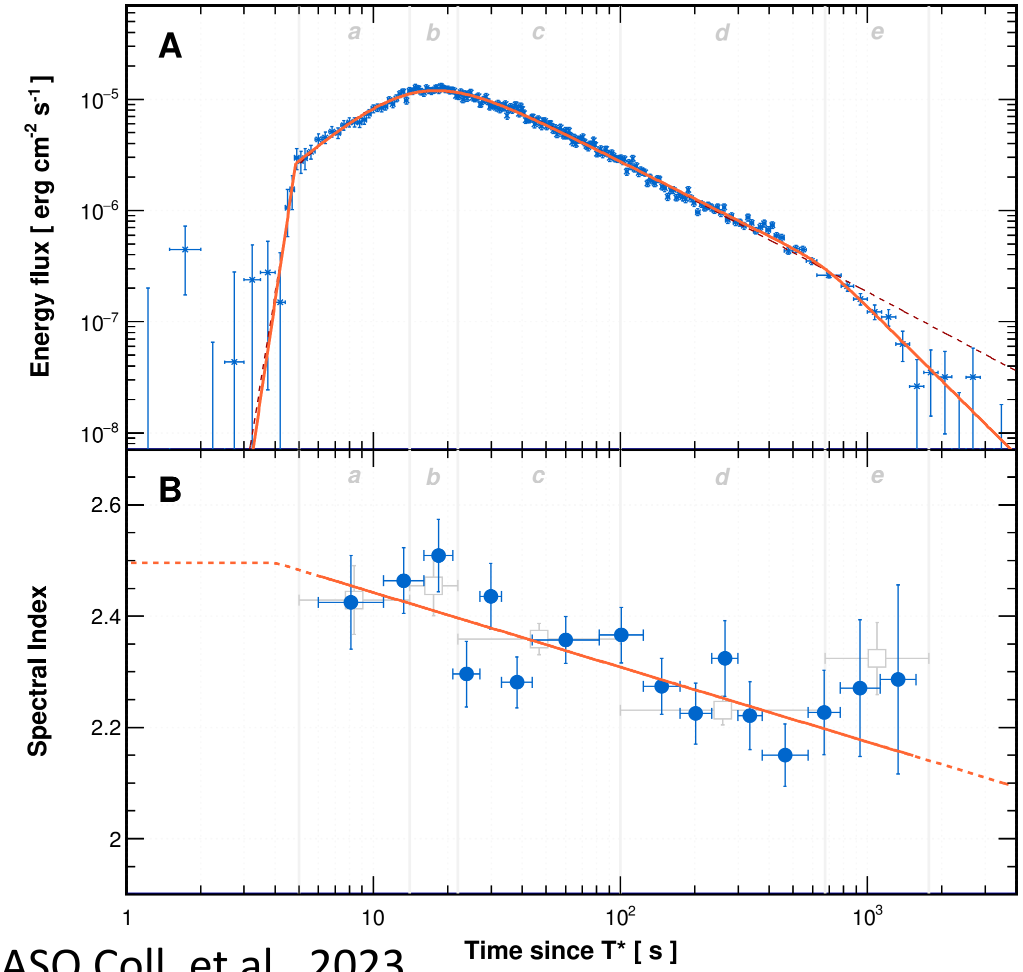
MAGIC Coll. et al., 2023

GRB221009A

- Long GRB: The BOAT
- $E_{\gamma,iso}$ > 3 x 10^{54} erg
- z = 0.15

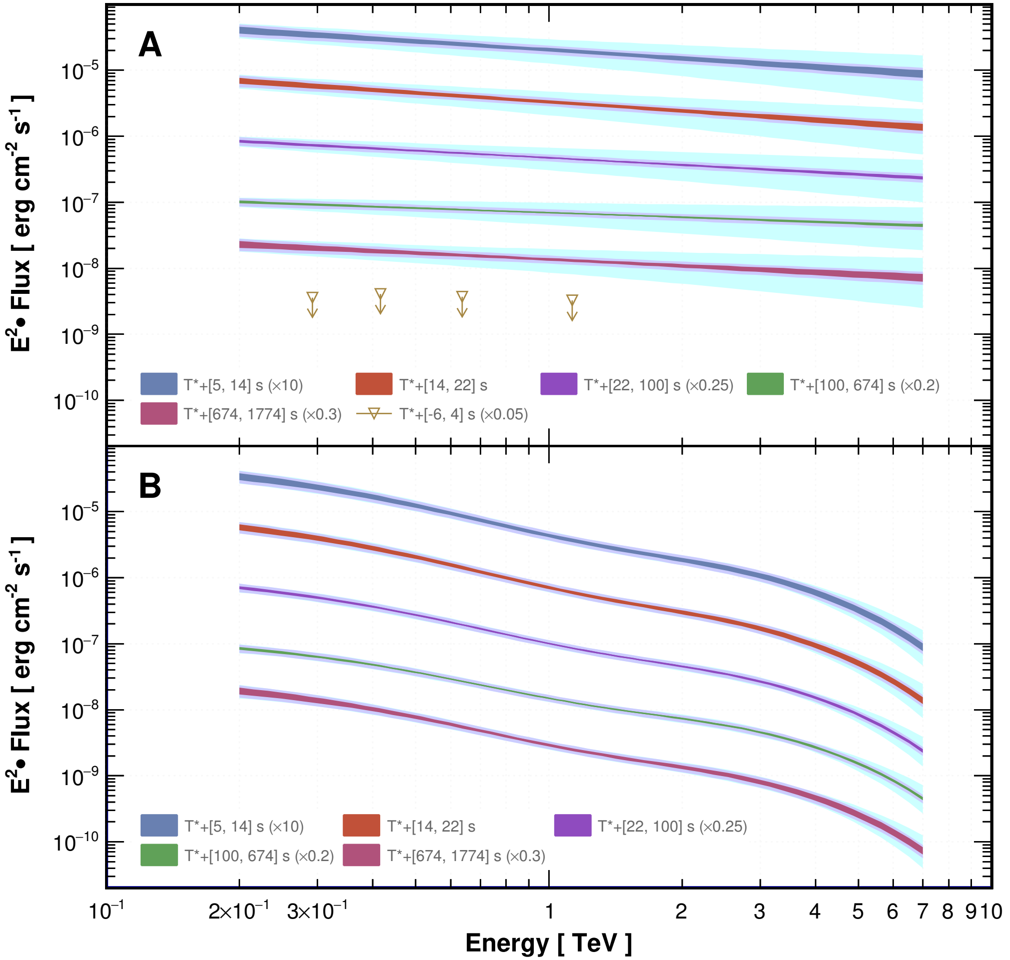
LHAASO detection info:

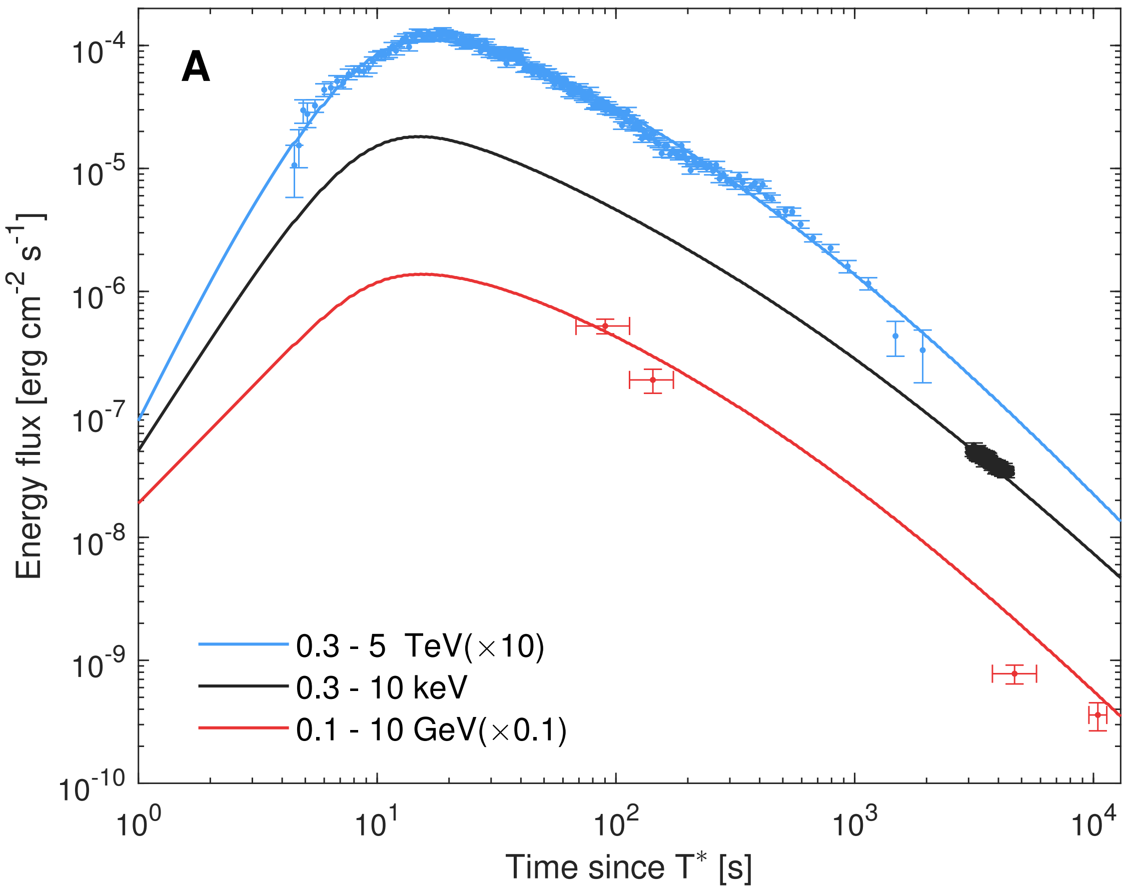
- > 250σ in 230 – 3000 s
- 0.3 – 13 TeV energy range



LHAASO Coll. et al., 2023

GRB221009A





LHAASO Coll. et al., 2023

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Population of GRBs at VHE: What we thought vs what we discovered

IACT Capabilities

"Mandatory" requirements:

- low zenith angles
- dark nights
- small delays
- low *z*
- highly energetic events

GRB190114C: zenith >55°, Moon conditions

GRB160821B: Moon conditions

GRB180720B, GRB190829A: T_{delay} ~ hrs/days

GRB201216C: $z = 1.1$

GRB190829A, GRB201015A, GRB160821B: $E_{\gamma,iso} \sim 10^{49} - 10^{50}$ erg

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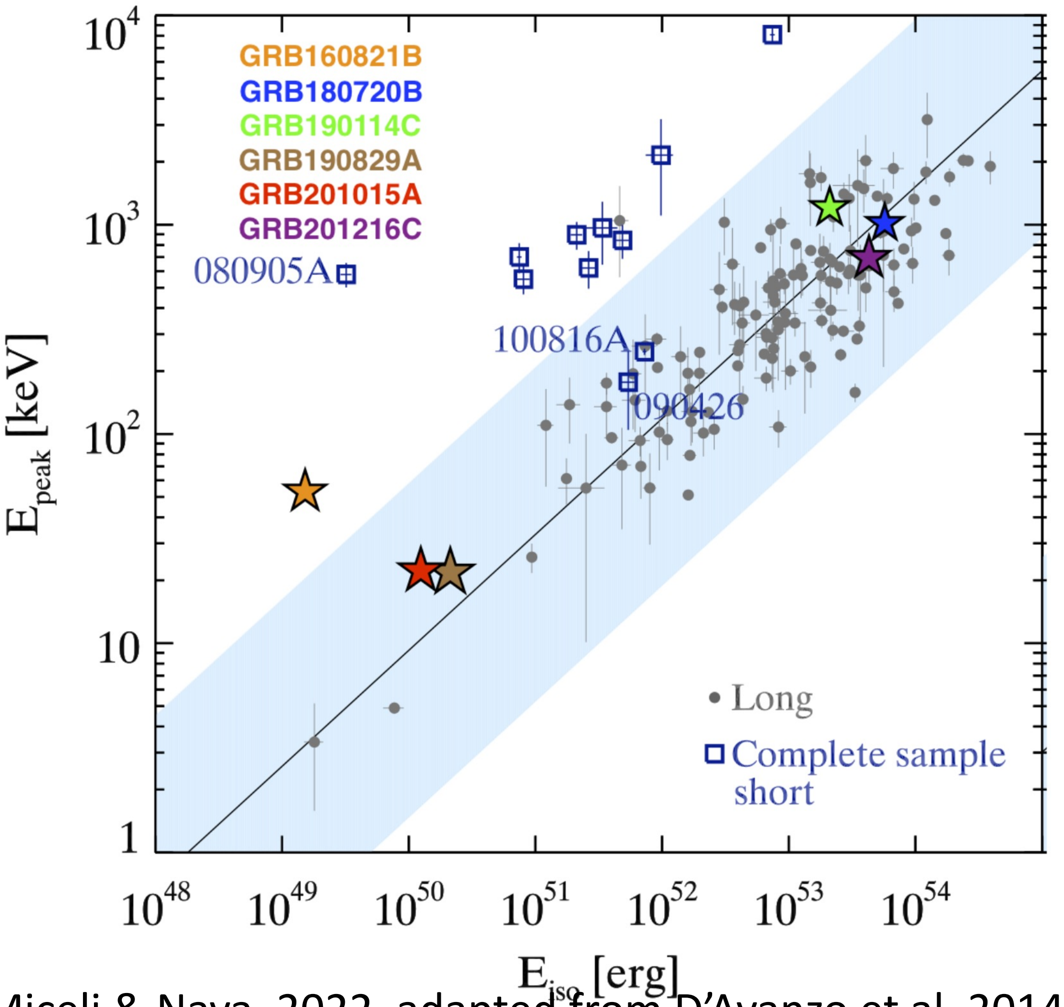
Population of GRBs at VHE

- Broadband intrinsic properties:
  - span more than 3 orders of magnitude in $E_{\gamma,iso}$
  - Span 2 orders of magnitude in terms of L_{VHE}
  - ranging in redshift between 0.079–1.1
- X-ray – TeV connection:
  - similar fluxes and decay slopes
  - similar amount of radiated power
- Data modeling:
  - SSC suggested (not conclusive)
  - no preferences on constant/wind-like medium
  - $\varepsilon_e \sim 0.1$, $\varepsilon_B \sim 10^{-5}$–$10^{-3}$, $\xi<1$



Miceli & Nava, 2022, adapted from D'Avanzo et al. 2014

Population of GRBs at VHE

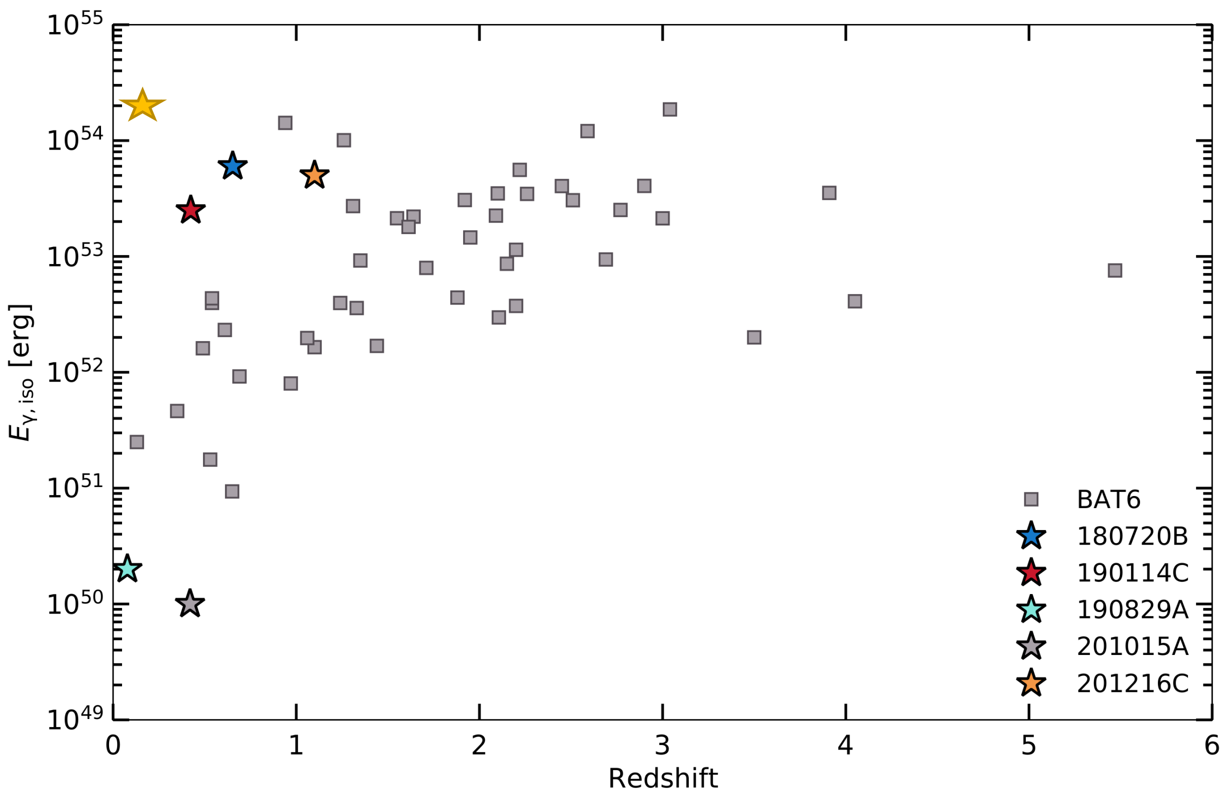
	E_k erg	ϵ_e	ϵ_B	n cm^{-3}	p	ξ_e	θ_j rad
Hess Coll. (SSC)	2.0×10^{50}	0.91	$5.9 - 7.7 \times 10^{-2}$	1.	2.06-2.15	1.	/
Hess Coll. (Sync)	2.0×10^{50}	0.03-0.08	≈ 1	1.	2.1	1.	/
Salafia + 2021	$1.2 - 4.4 \times 10^{53}$	0.01-0.06	$1.2 - 6.0 \times 10^{-5}$	0.12-0.58	2.01	$< 6.5 \times 10^{-2}$	0.25-0.29
Zhang + 2021	9.8×10^{51}	0.39	8.7×10^{-5}	0.09	2.1	0.34	0.1

	E_k erg	ϵ_e	ϵ_B	n cm^{-3}	p	ξ_e
MAGIC Coll.	$\gtrsim 3 \times 10^{53}$	0.05-0.15	$0.05\text{-}1 \times 10^{-3}$	0.5-5	2.4-2.6	1
Wang + 2019	6×10^{53}	0.07	4×10^{-5}	0.3	2.5	1
Asano + 2020	10^{54}	0.06	9×10^{-4}	1	2.3	0.3
Asano + 2020	10^{54}	0.08	1.2×10^{-3}	0.1 (wind)	2.35	0.3
Joshi + 2021	4×10^{54}	0.03	0.012	2×10^{-2} (wind)	2.2	1
Derishev + 2021	3×10^{53}	0.1	$2 - 6 \times 10^{-3}$	2	2.5	1

	E_k erg	$\log(\epsilon_e)$	$\log(\epsilon_B)$	log(n) cm^{-3}	p	ξ_e	θ_j rad
MAGIC Coll.	$10^{51} - 10^{52}$	[-1 ; -0.1]	[-5.5 ; -0.8]	[-4.85 ; -0.24]	2.2-2.35	1	/
Troja + 2019	$10^{50} - 10^{51}$	[-0.39 ; -0.05]	[-3.1 ; -1.1]	[-4.2 ; -1.7]	2.26-2.39	1	0.08-0.50
Zhang + 2021 (SSC)	3×10^{51}	-0.52	-5	-1.3	2.3	0.5	0.15
Zhang + 2021 (EIC)	2×10^{51}	-0.3	-6	-1	2.5	0.1	0.1

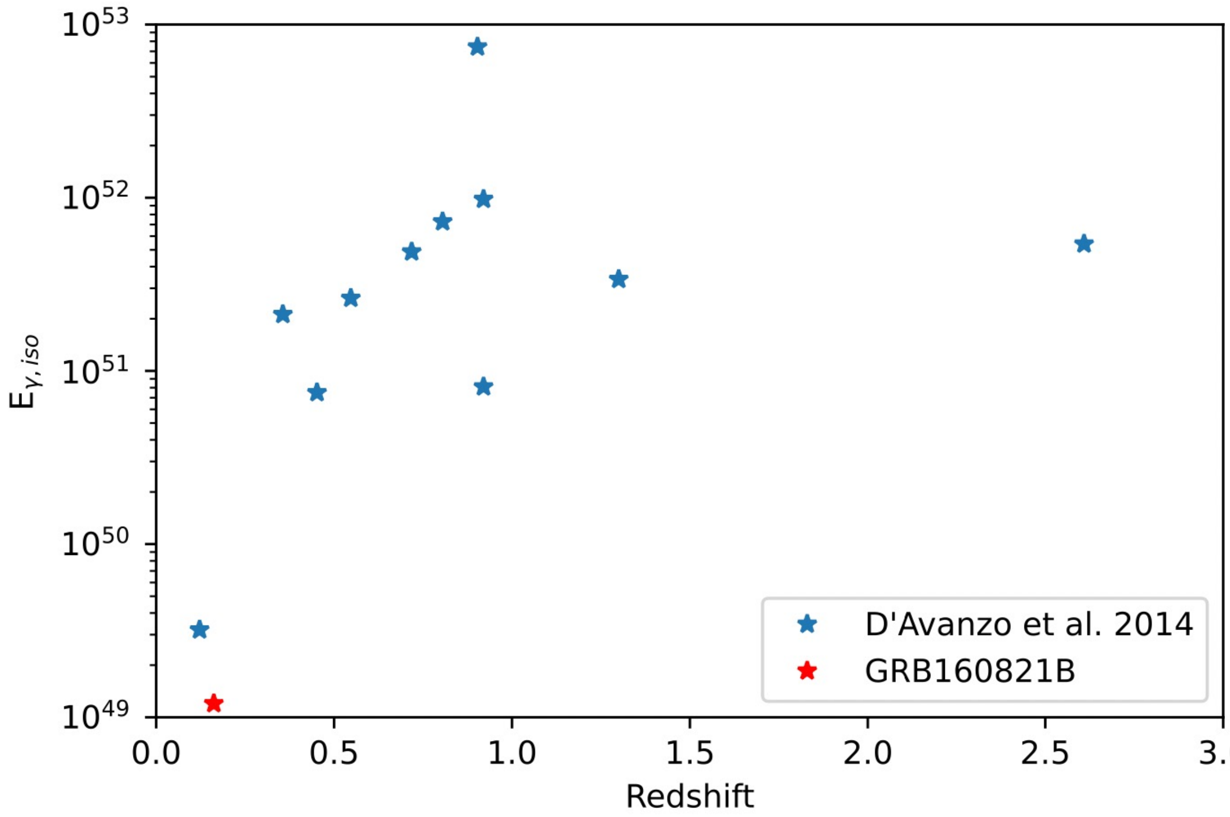
Population of GRBs at VHE

long GRBs



Nava, 2021

short GRBs



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LST in the game: open issues (a not exhaustive list…)

- Are we looking at a sub-class of GRBs? Is it VHE emission universal?

- Low energy threshold ($E < 100$ GeV): how is it crucial for IACTs?

- Afterglow VHE radiation mechanism: still not conclusive answer
    - Responsible radiation mechanisms
    - absence of synchrotron spectral cutoff (Can LST provide new info?)
    - particle acceleration mechanisms
    - magnetic fields

LST in the game: open issues (a not exhaustive list…)

- VHE emission in prompt phase?
- VHE emission from short GRBs
- Flares, plateaus not included in the external fwd shock scenario
- GRB environmental conditions (external medium profile: ISM? wind-like?)
- Shock microphysical parameters (unconstrained, time-dependent)
- Jet dynamics and structure (off-axis GRBs and GW connection)

LSTs can provide renovate and boost studies on GRB physics