GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Gamma-ray Bursts prompt spectra in the high energies

Samanta Macera

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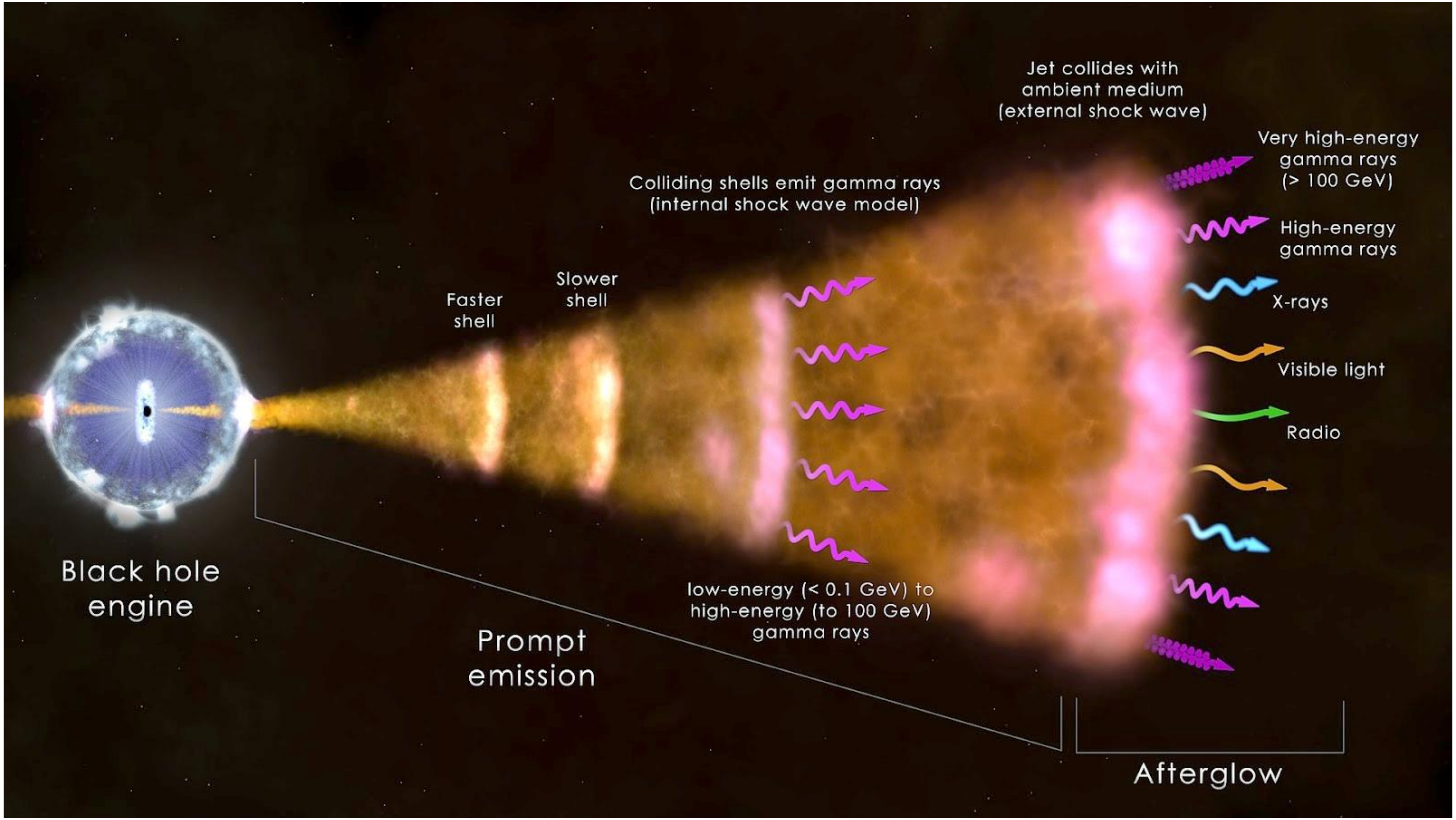
Istituto Nazionale di Fisica Nucleare

Outline

- What are Gamma-ray Bursts (GRBs)?
- Understanding the Prompt Emission: what do we really know?
- Early High-Energy (HE) Emission: prompt or early afterglow?
- GRBs at Very-High-Energies (VHE): open questions
- The BOAT GRB: why is it more informative?

What are Gamma-ray Bursts (GRBs)?

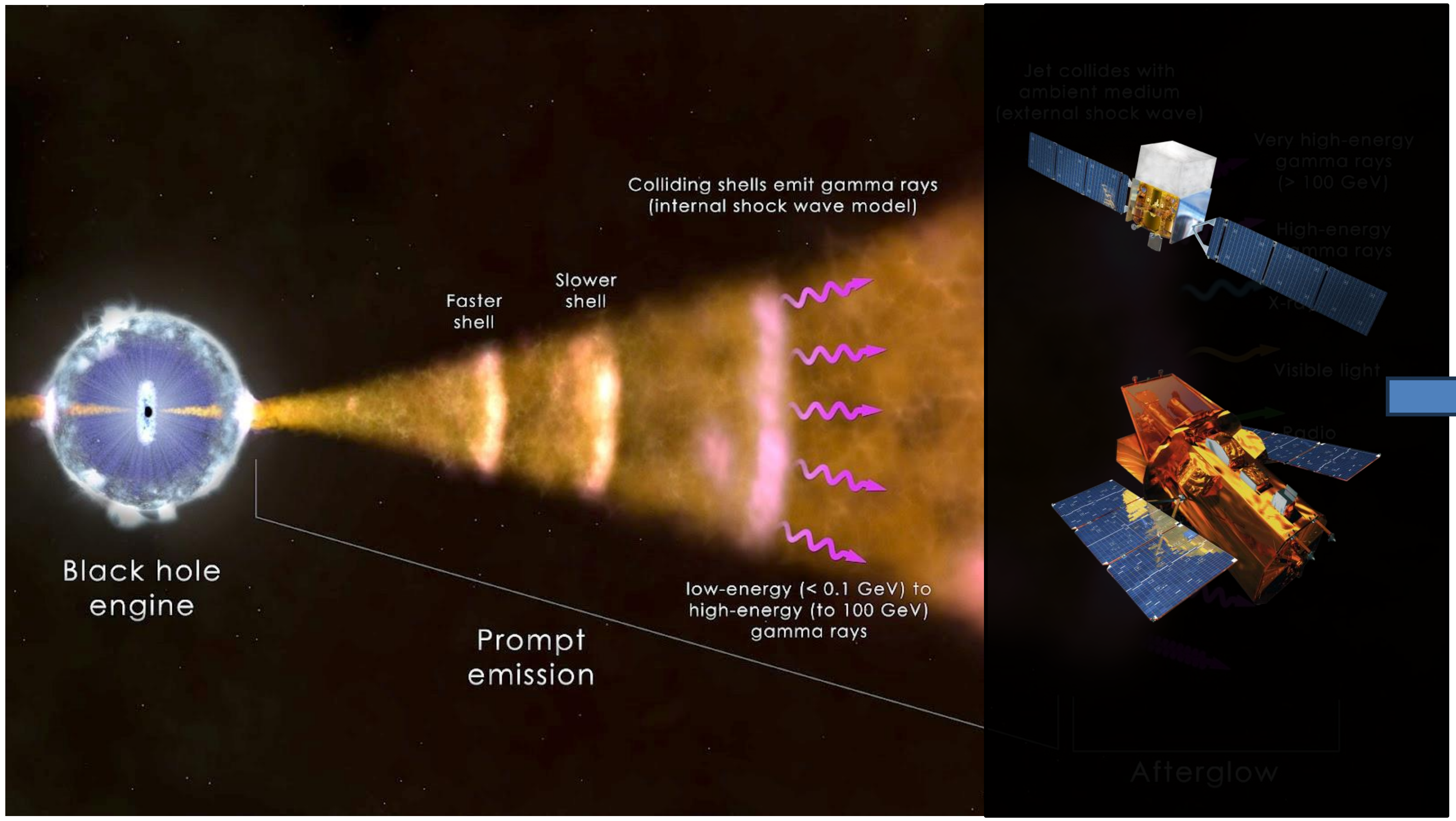


Jet Launching — A massive star collapses → forms a black hole → launches an ultra-relativistic jet.

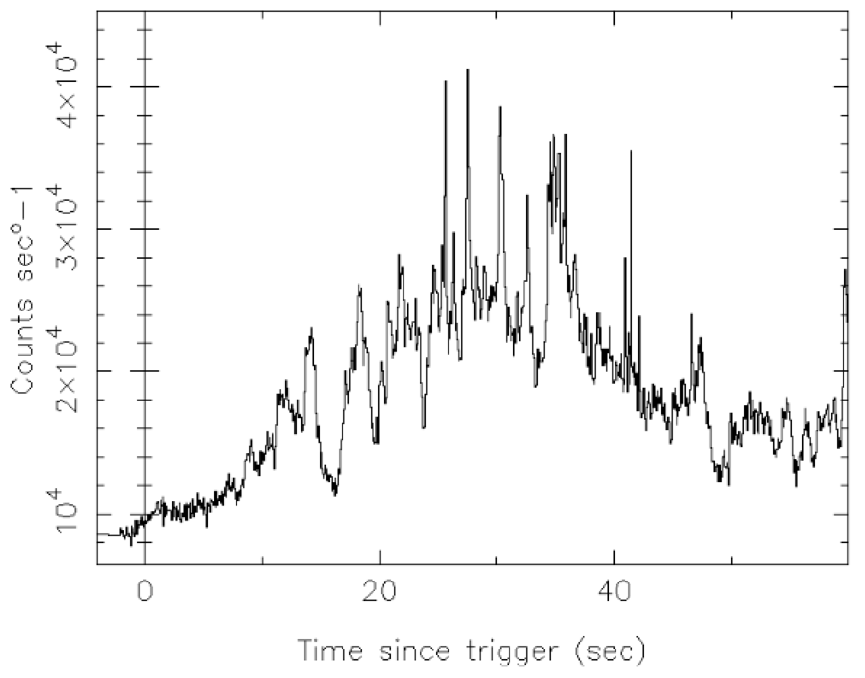
Dissipation — Energy inside the jet is dissipated

Particle Acceleration — The dissipated energy can be transferred to the particles, which are accelerated to non-thermal energies

Cooling → Prompt Emission — The accelerated particles cool, emitting photons



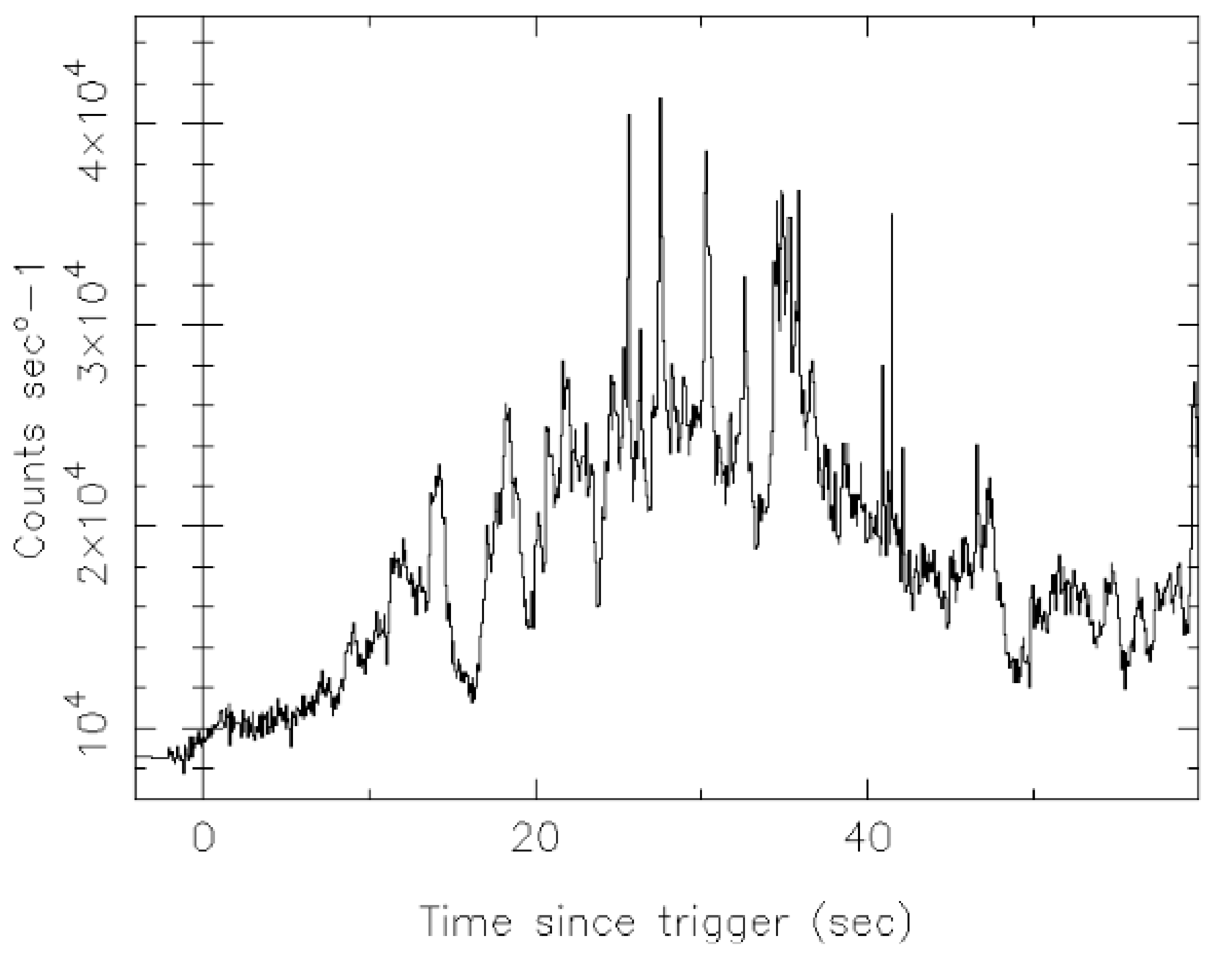
Space-based instruments are triggered by an increase in the count rate



GRB lightcurve

Prompt emission

Lightcurve



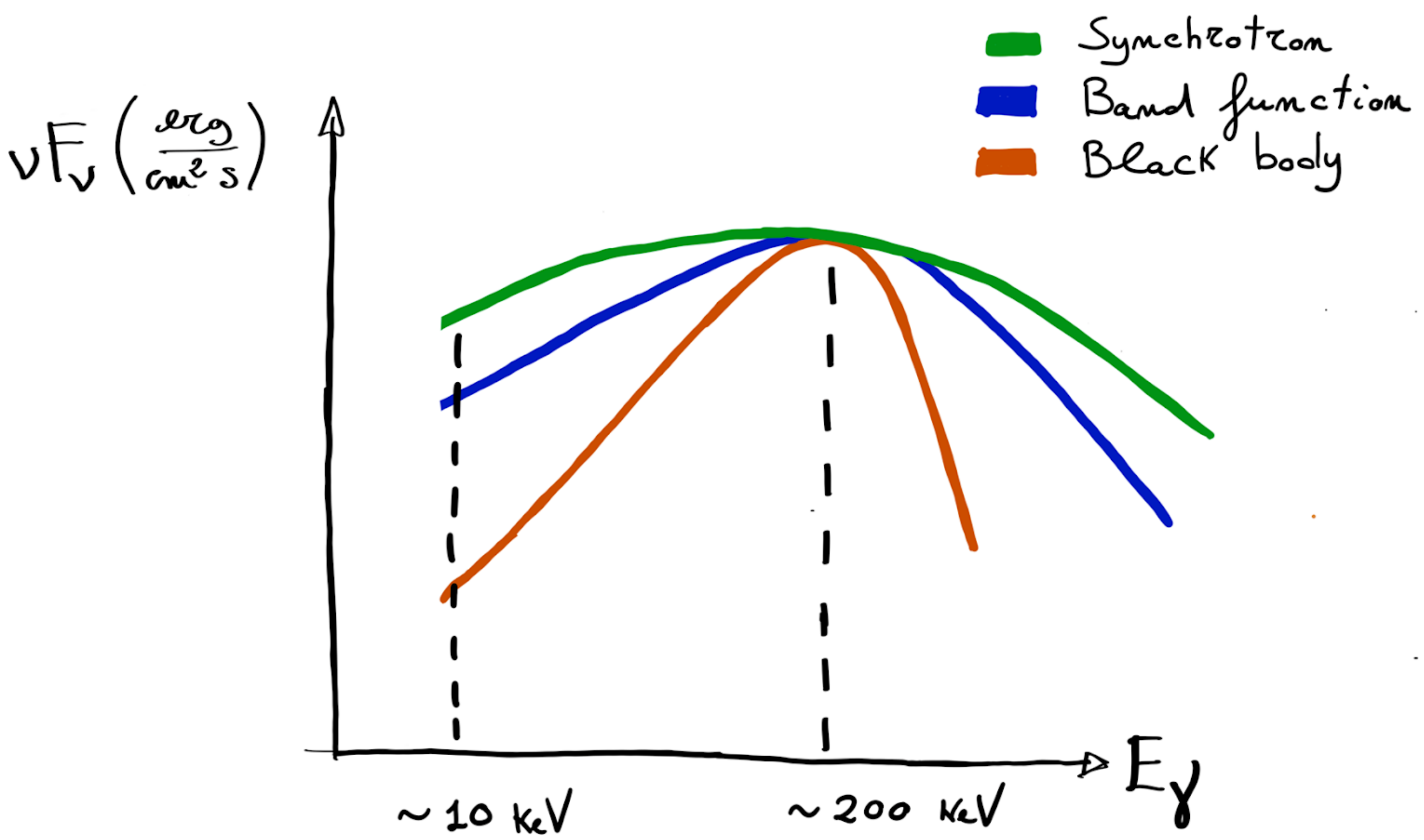
Sari and Piran, 1997

- Burst of MeV photons
- Energy $E_{iso}{\sim}10^{50} - 10^{54} erg$
- Duration 0.1 – 1000 s
- Variability 0.01 – 1 s

→ Internal dissipation of an ultrarelativistic jet

Prompt emission

Radiative process?



- Burst of MeV photons
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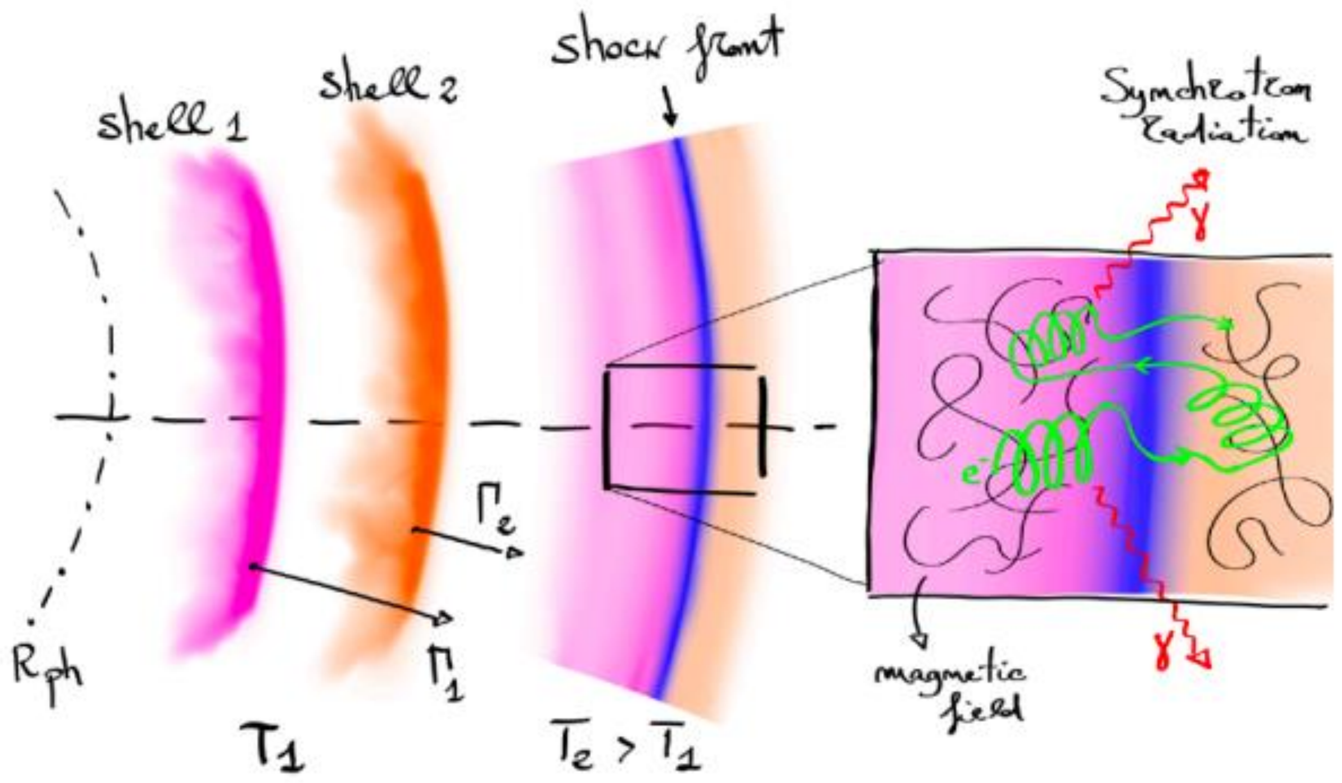
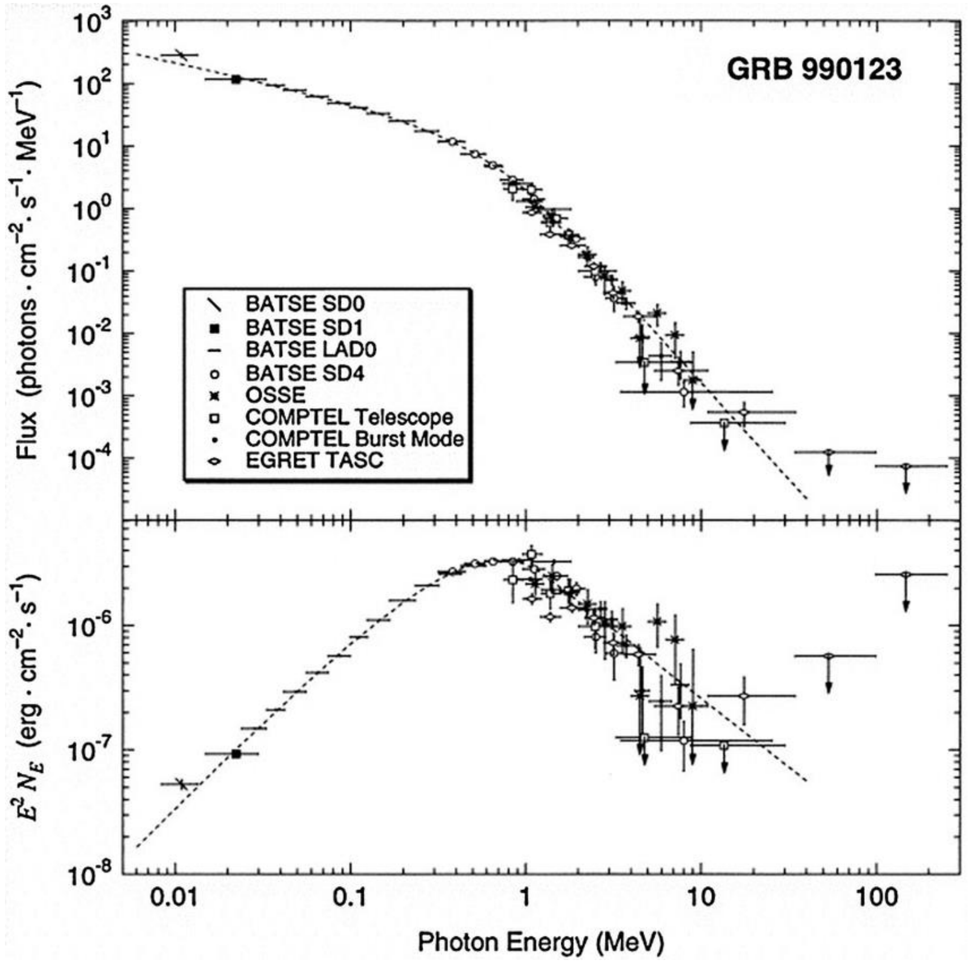


Sketch by Samuele Ronchini

State-of-art

Band Model



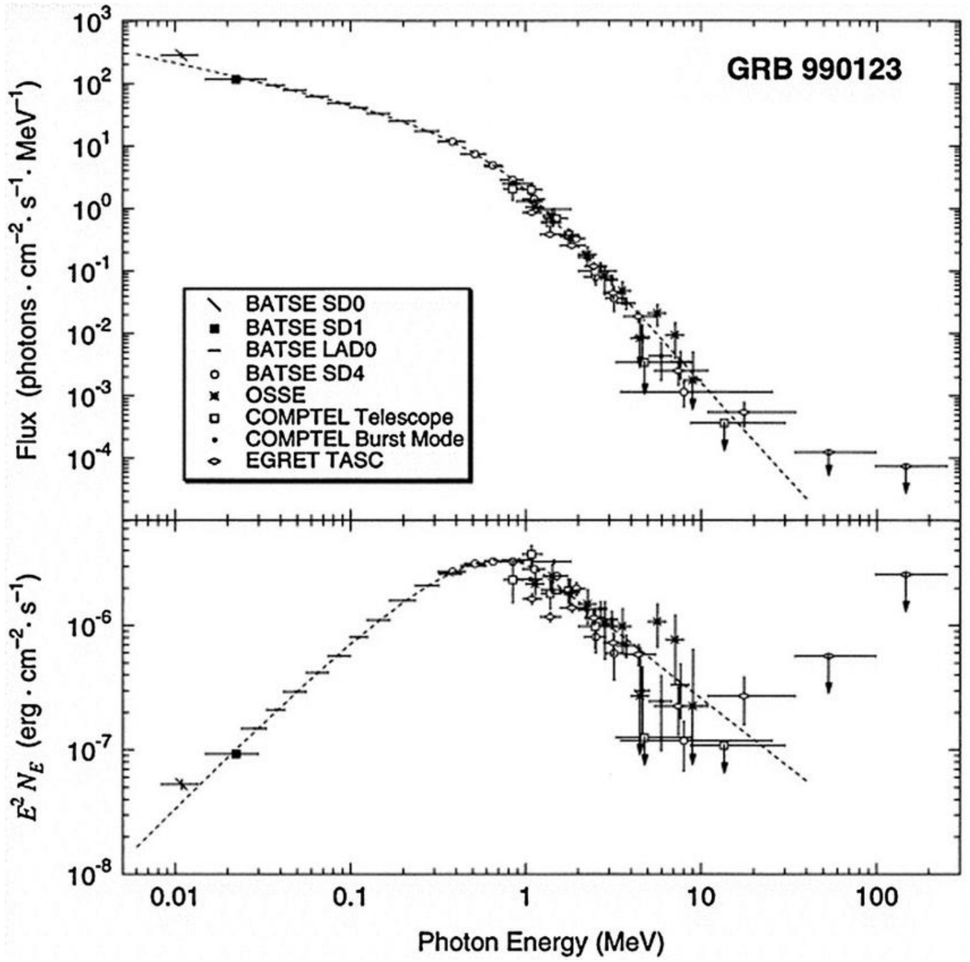
Briggs et al, 1999

Peak energy 100 keV – 1 MeV

State-of-art

Band Model

Spectral breaks



Briggs et al, 1999

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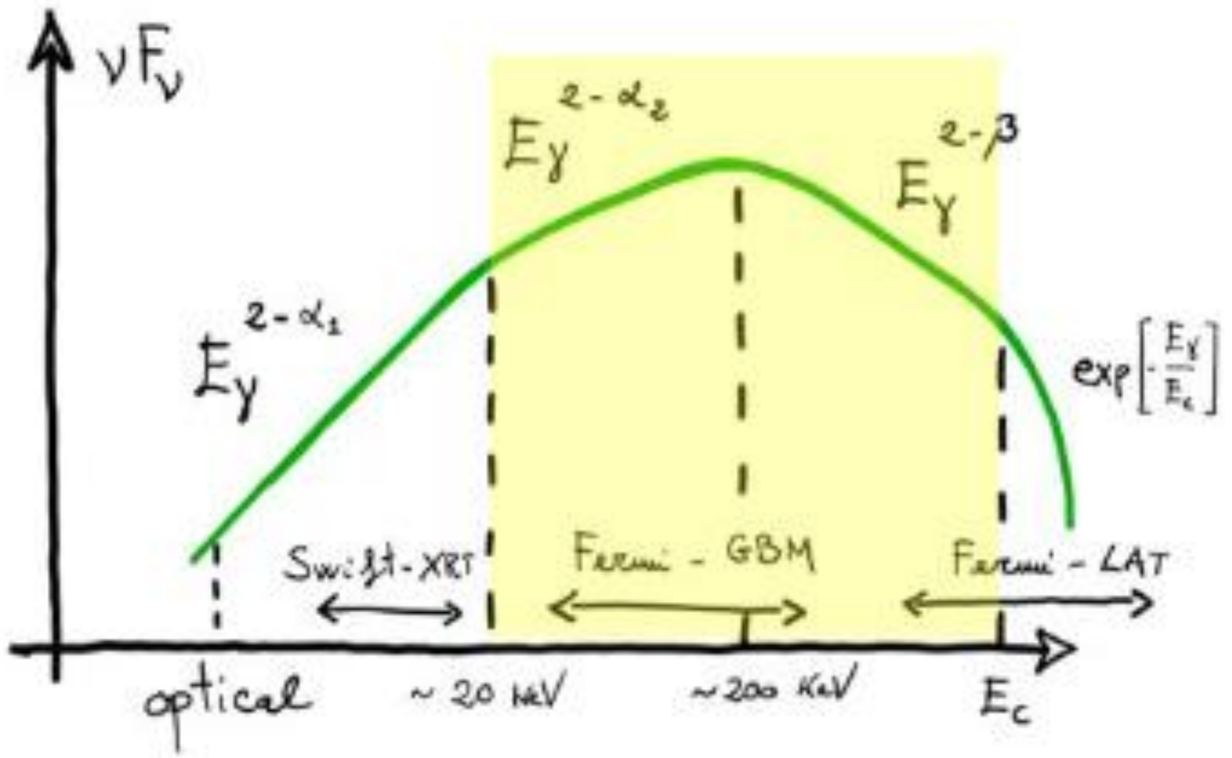
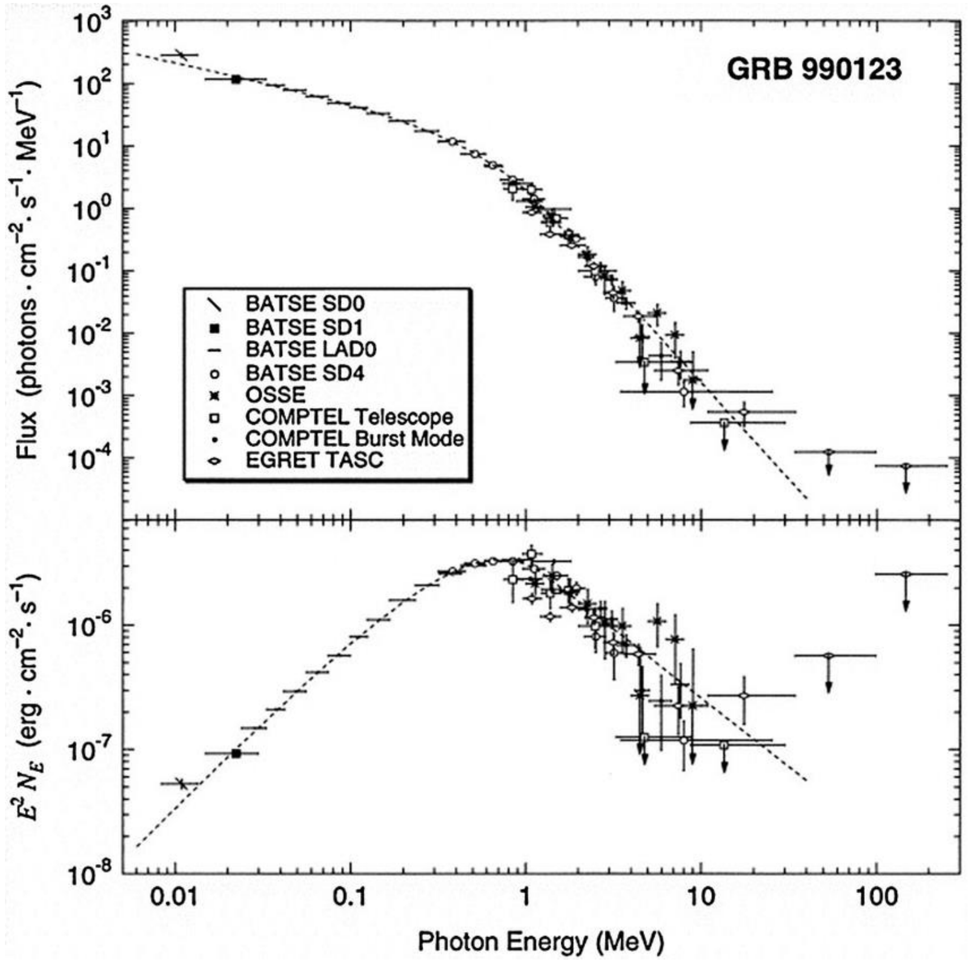


Including also lower and higher energies, energy breaks appear in the spectrum

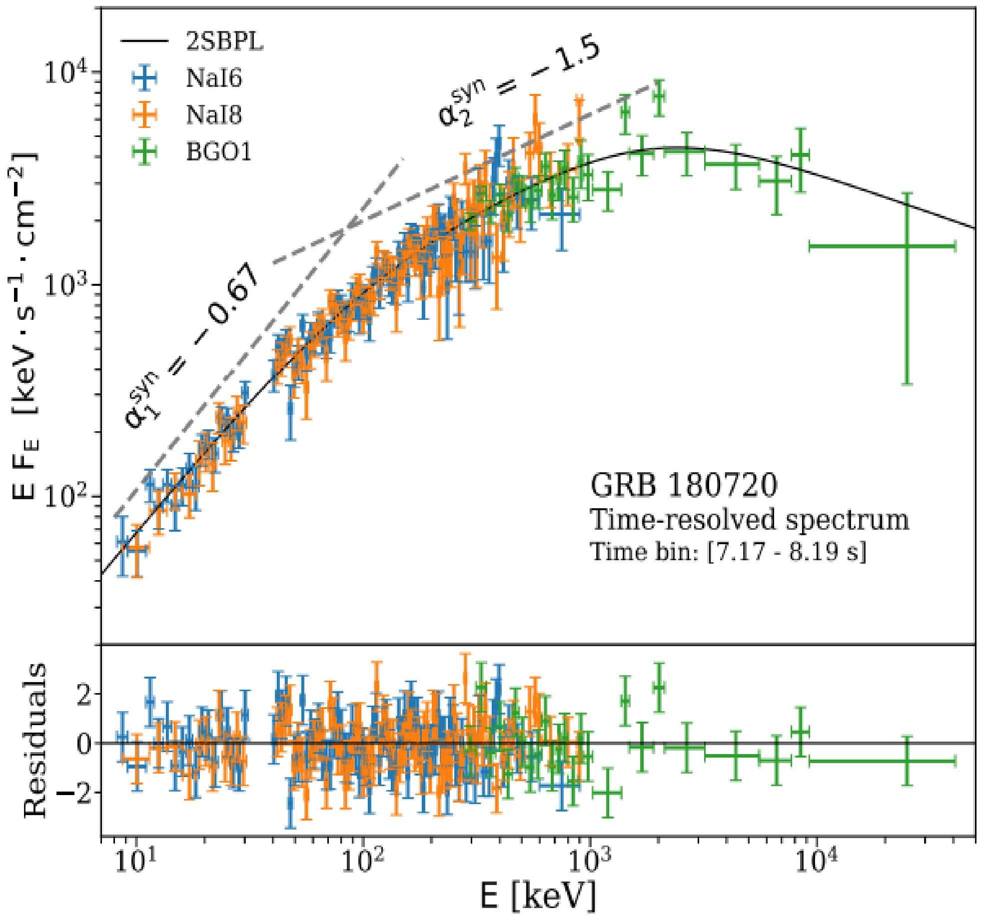
State-of-art

Band Model

Spectral breaks



Briggs et al, 1999



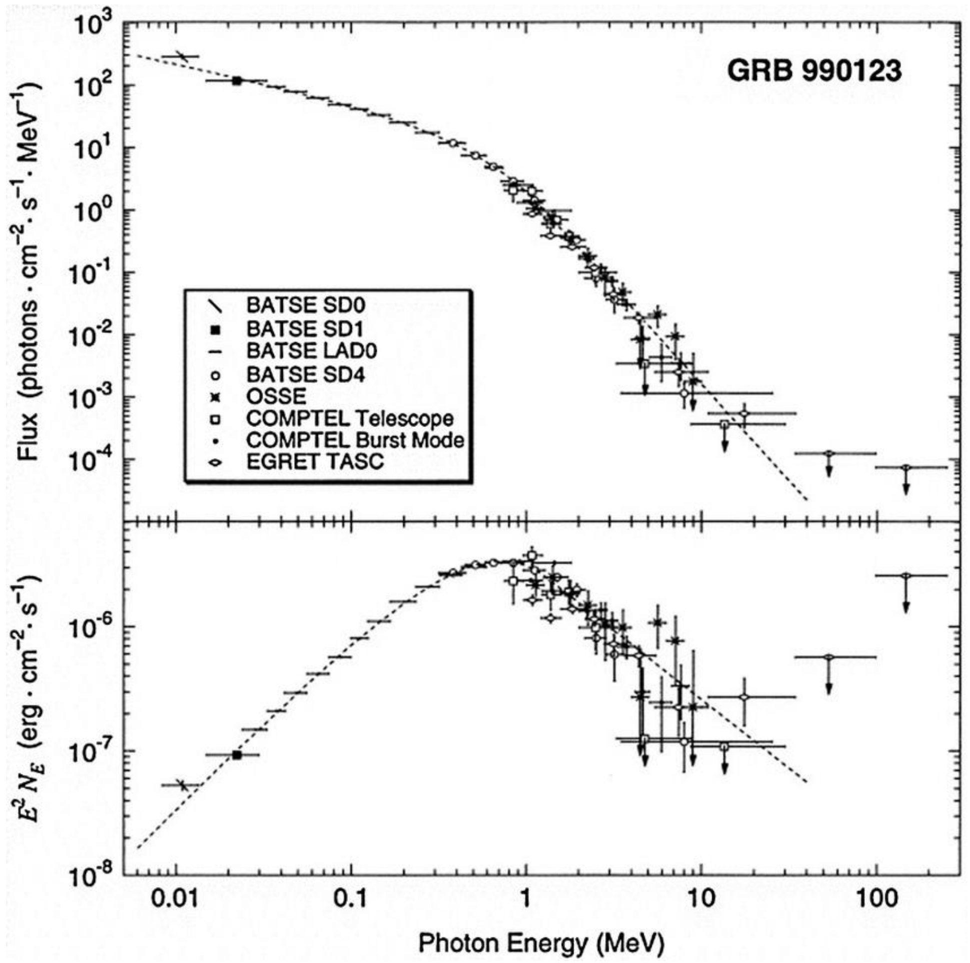
Oganesyan et al, 2017-2018
Ravasio et al, 2019

Peak energy 100 keV – 1 MeV

Low energy breaks empirically consistent with Synchrotron

State-of-art

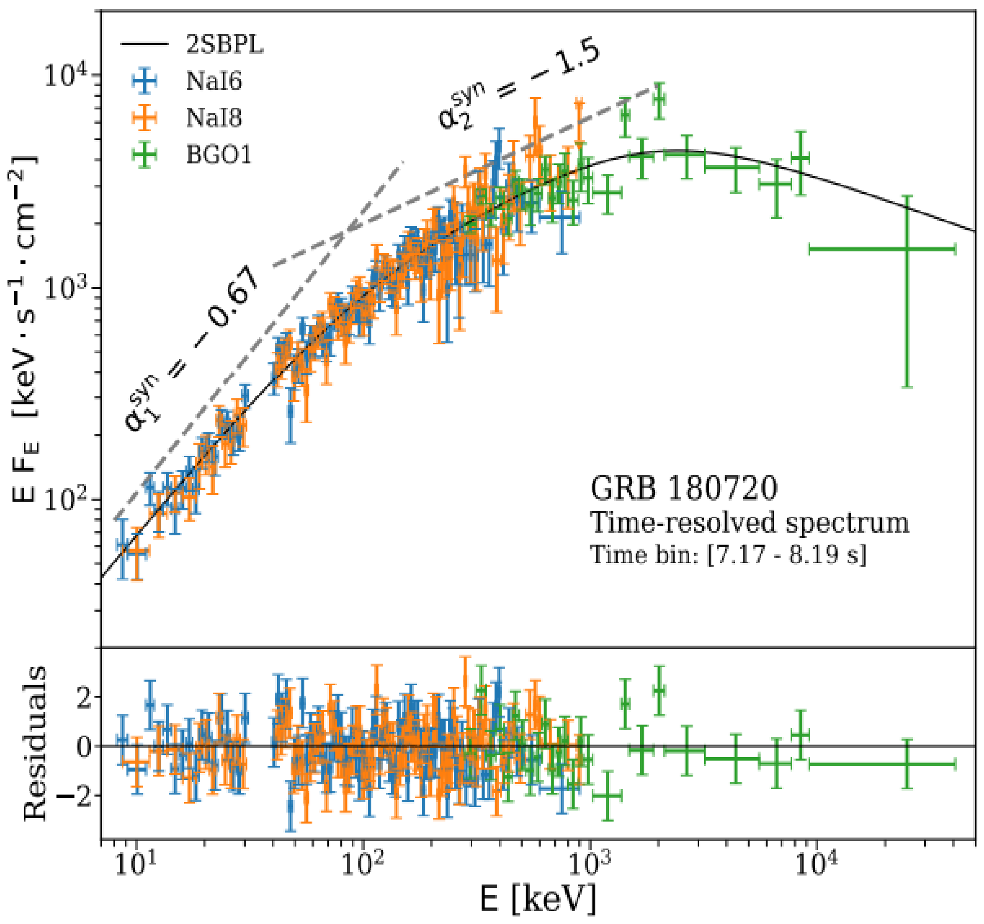
Band Model



Briggs et al, 1999

Peak energy 100 keV – 1 MeV

Spectral breaks

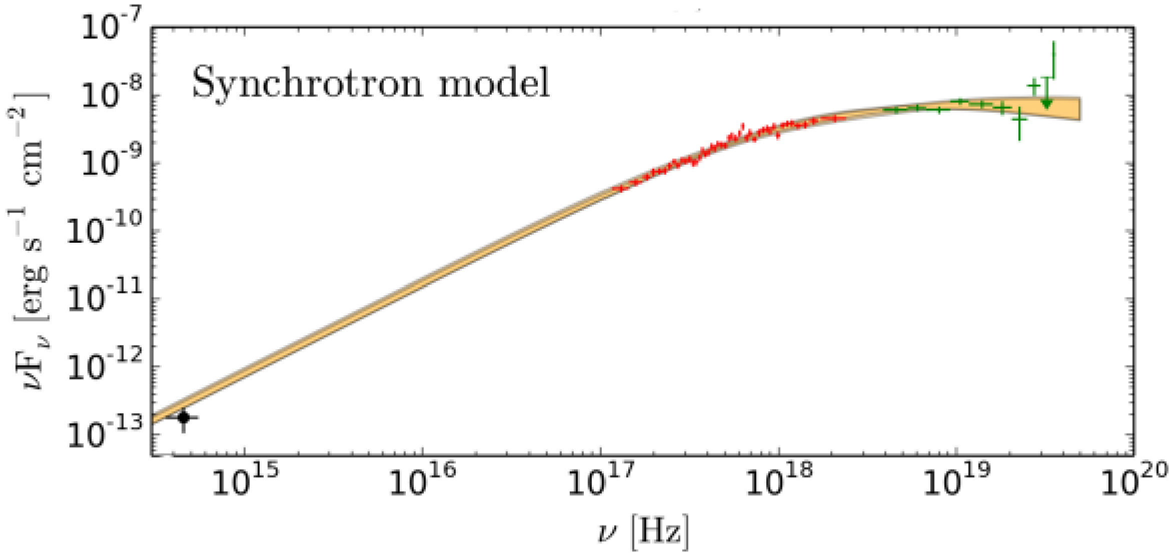


Oganesyan et al, 2017-2018

Ravasio et al, 2019

Low energy breaks empirically consistent with Synchrotron

Synchrotron



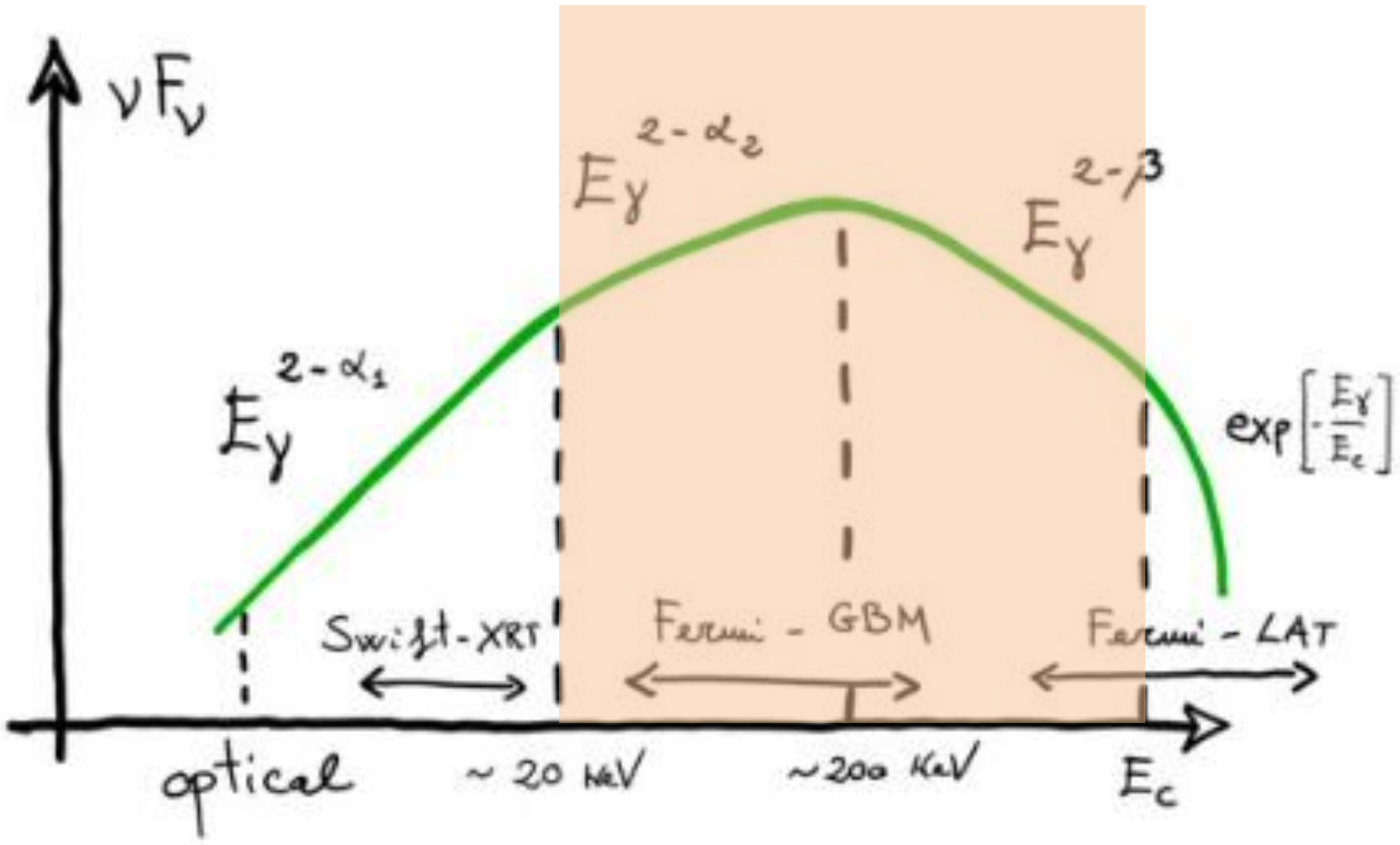
Oganesyan et al, 2019

From optical to MeV: synchrotron predicts the optical flux

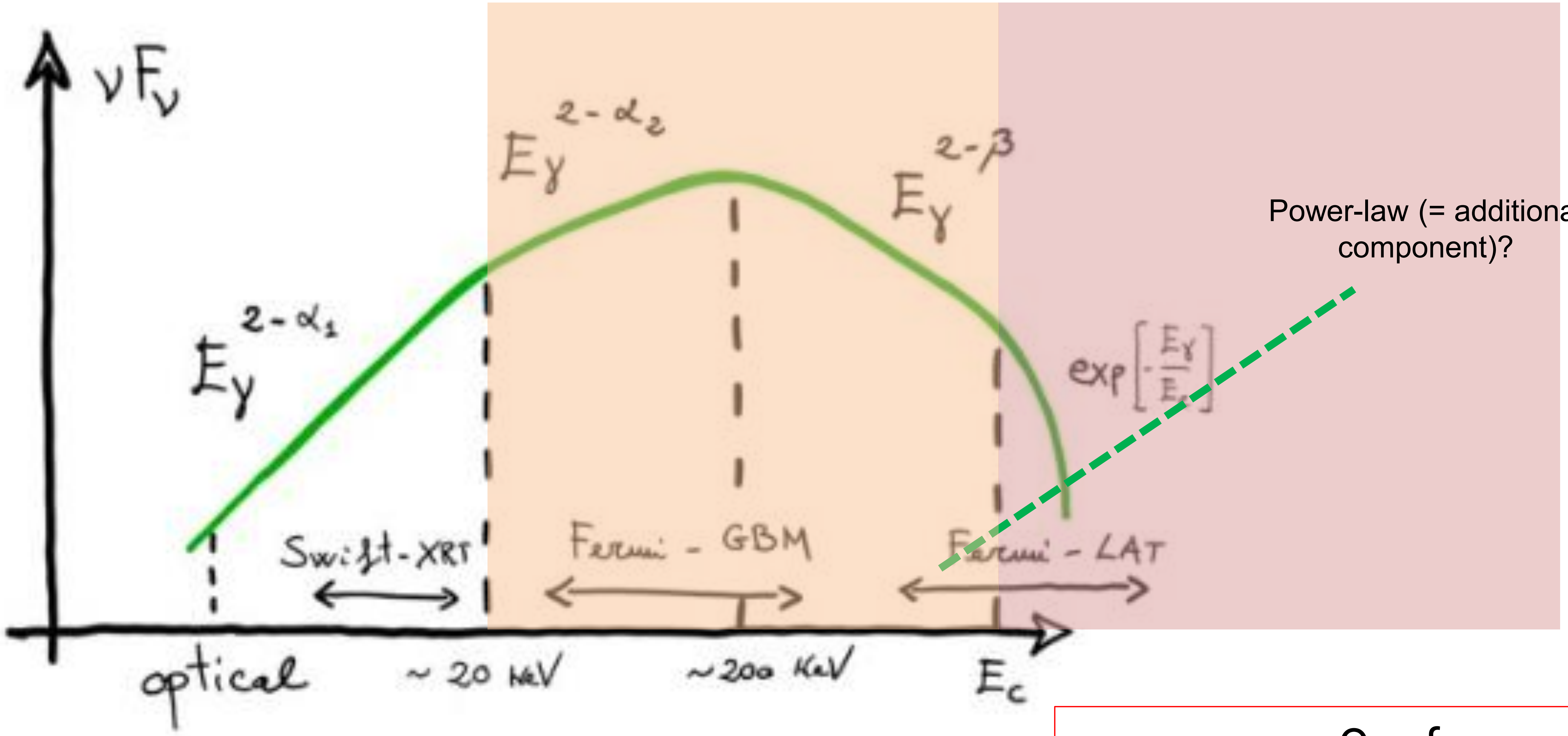
Burgess et al 2020

Zhang et al 2020, ...

Energy range



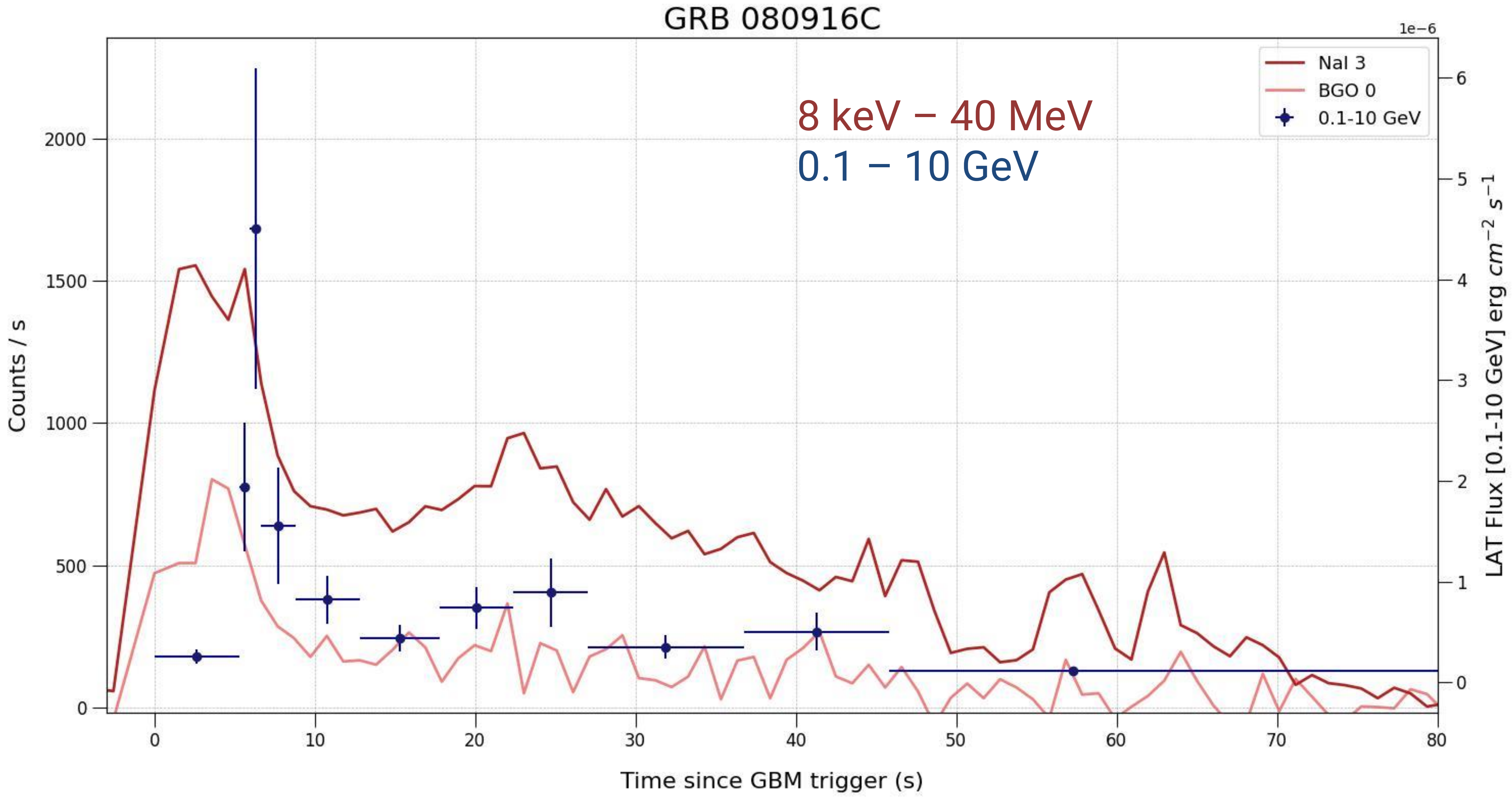
Energy range



… what happens at HE and VHE?

Our focus:

Study of the high-energy (HE) and very-high-energy (VHE) emission during the prompt phase



Macera S. et al 2025

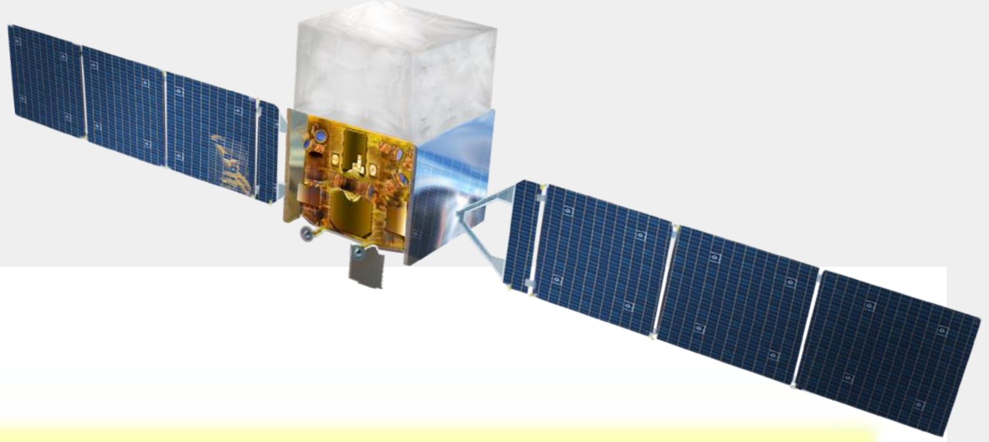
- High energy emission is delayed
  [Tajima et al. 2009 for GRB080916C]
  [Abdo et al. 2009 for GRB090902B]
- For some GRBs early GeV emission follows variability of prompt
  [Zhang et al. 2011]
- Early Afterglow or Prompt origin?
  [Ghisellini et al. 2009, Kumar & Barniol Duran, 2009, Maxham et al 2011]
- What is the contribution of the keV-MeV prompt?

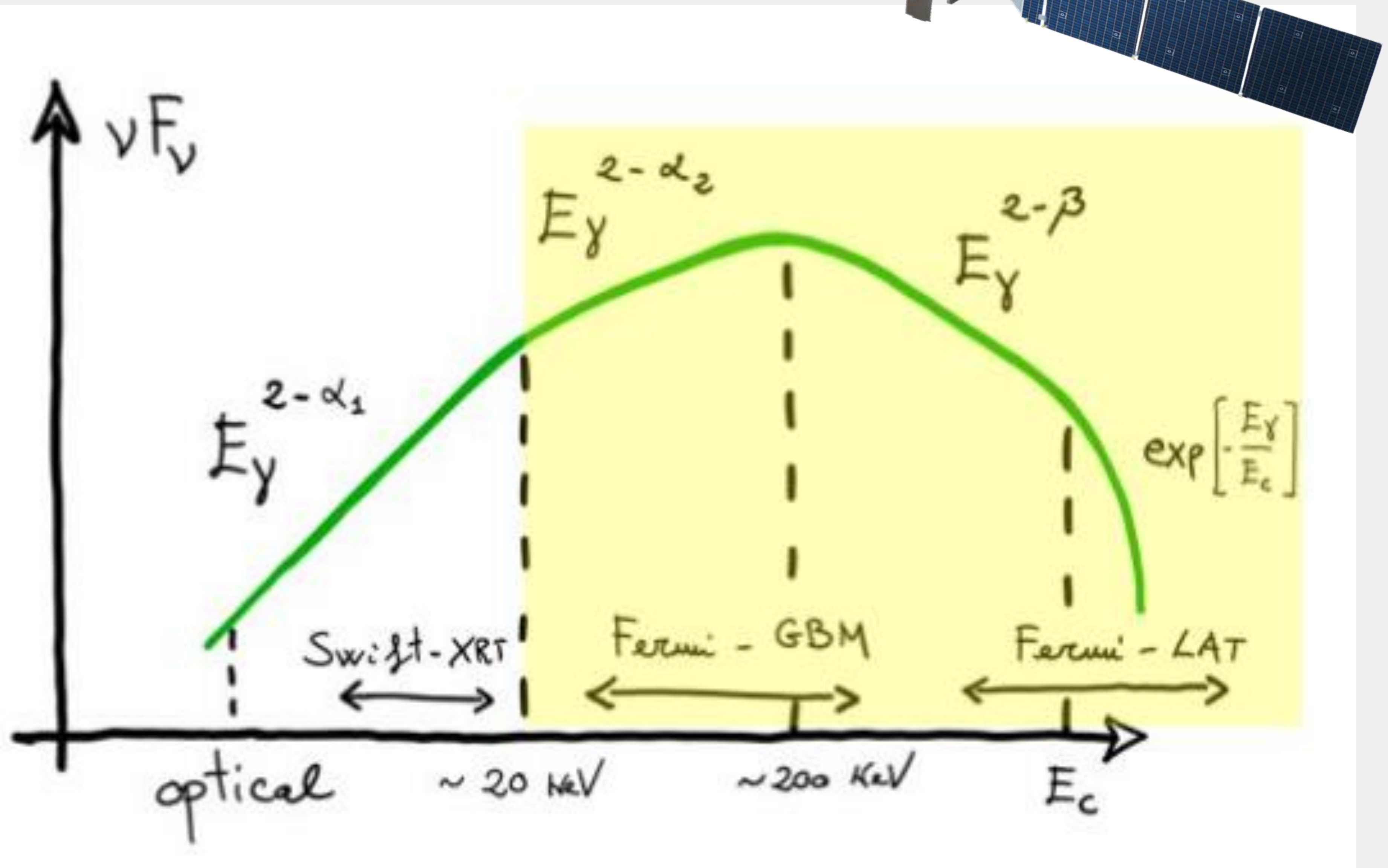
Prompt emission at higher energies

High energy emission simultaneous with the prompt phase

Prompt emission at high energies

Extension of the spectrum up to GeV





Fermi/GBM	LLE (LAT-low-energy)	Fermi/LAT
8 keV – 40 MeV	30 MeV – 100 MeV	100 MeV to > 300 GeV

Sample Selection

At least three significant temporal bins (>5 σ detection) simultaneous with Fermi-GBM

GRBs with and without redshift up to year 2023

At least 20 photons within 10° of region of interest around the GRB location

Sample 1

Time resolved spectral analysis of 13 GRBs, 68 spectra

Sample Selection

GRBs with and without redshift up to year 2023

At least three significant temporal bins simultaneous Fermi/GBM – Fermi/LAT

At least 20 photons within 10° of region of interest

Sample 1

Time resolved spectral analysis of 13 GRBs, 68 spectra

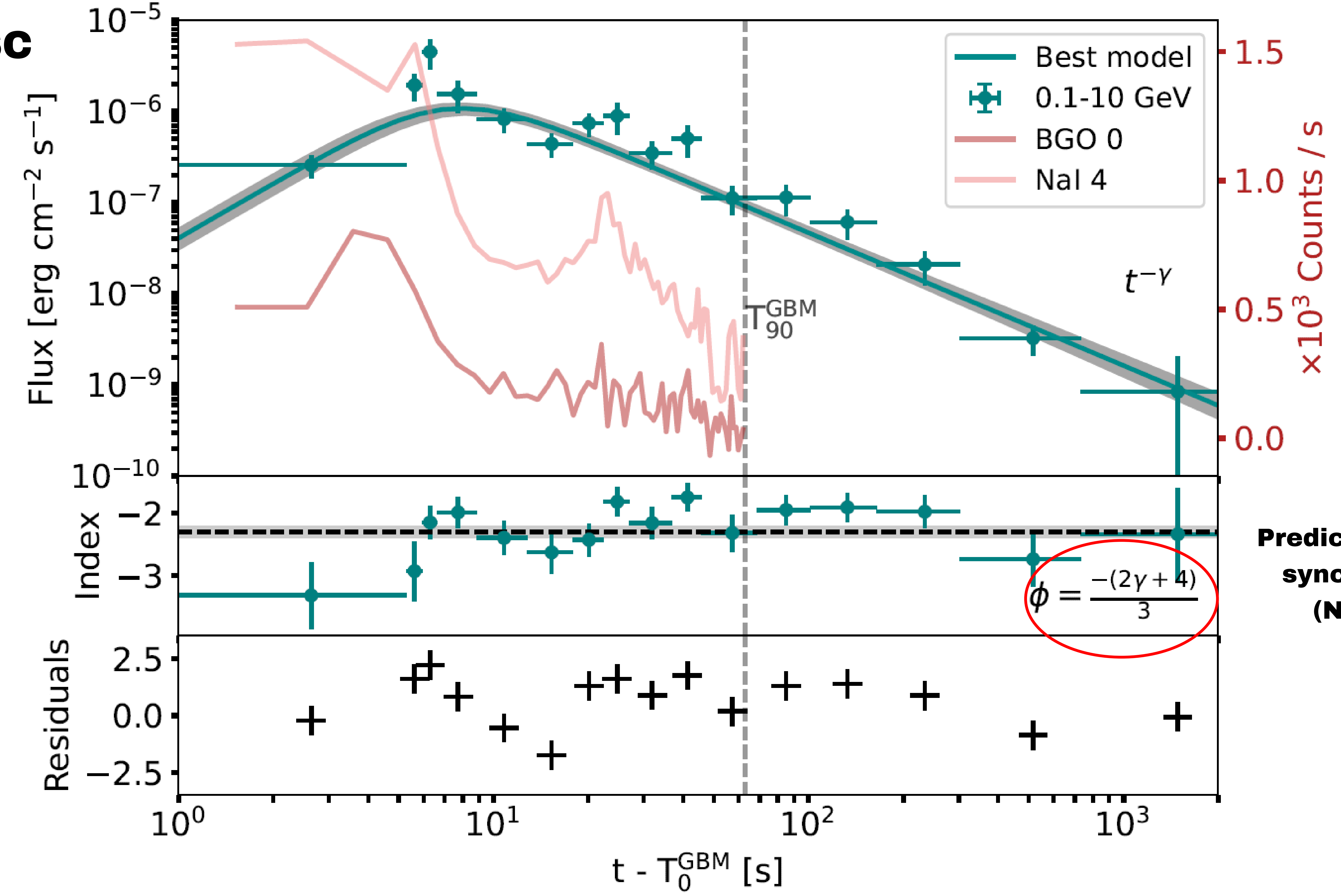
At least one significant temporal bin simultaneous Fermi/GBM – Fermi/LAT

Sample 2

Spectral analysis of 21 GRBs

Timing analysis (Sample 1)

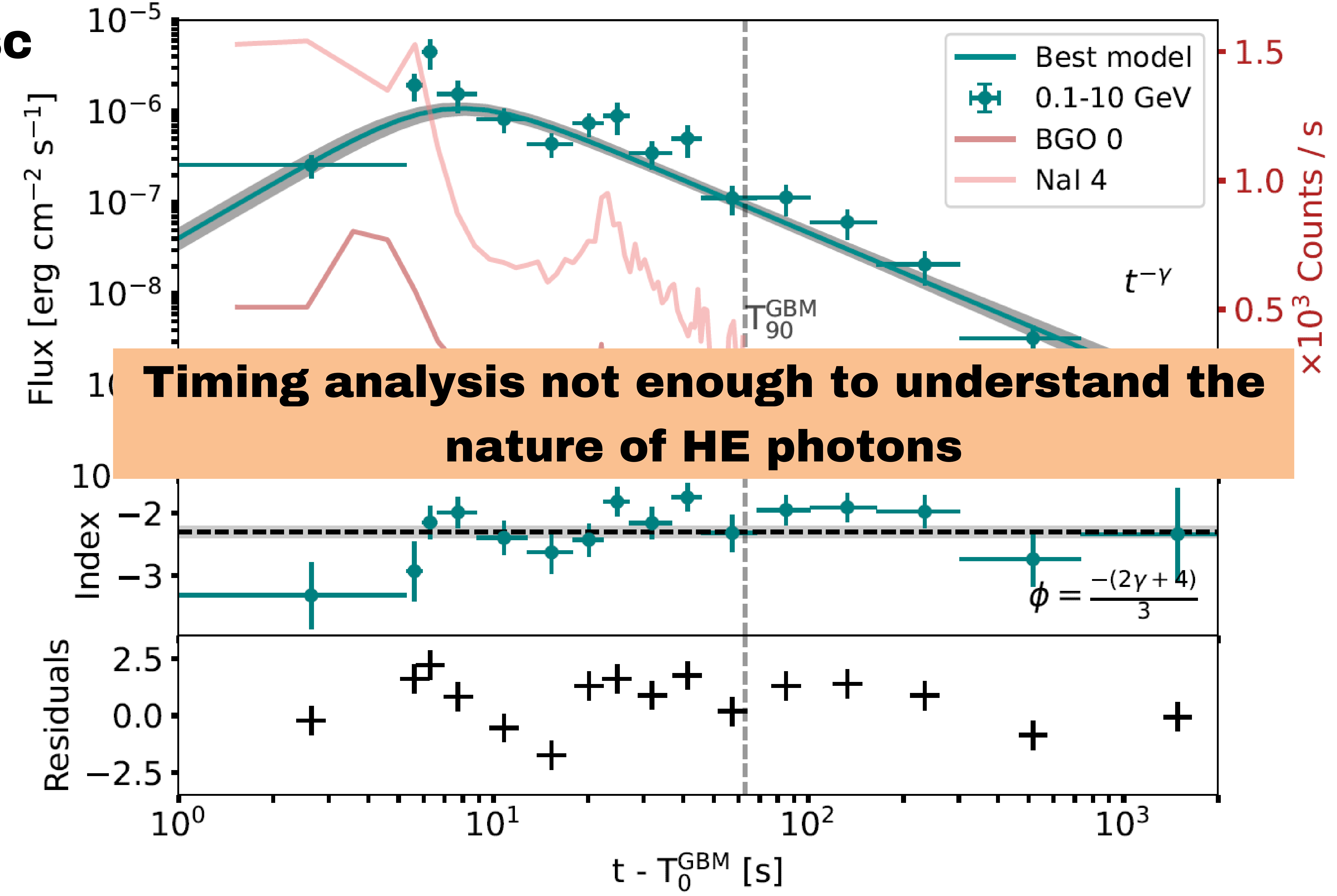
GRB 080916C



Predicted value assuming synchrotron afterglow (Nava et al, 2017)

Timing analysis (Sample 1)

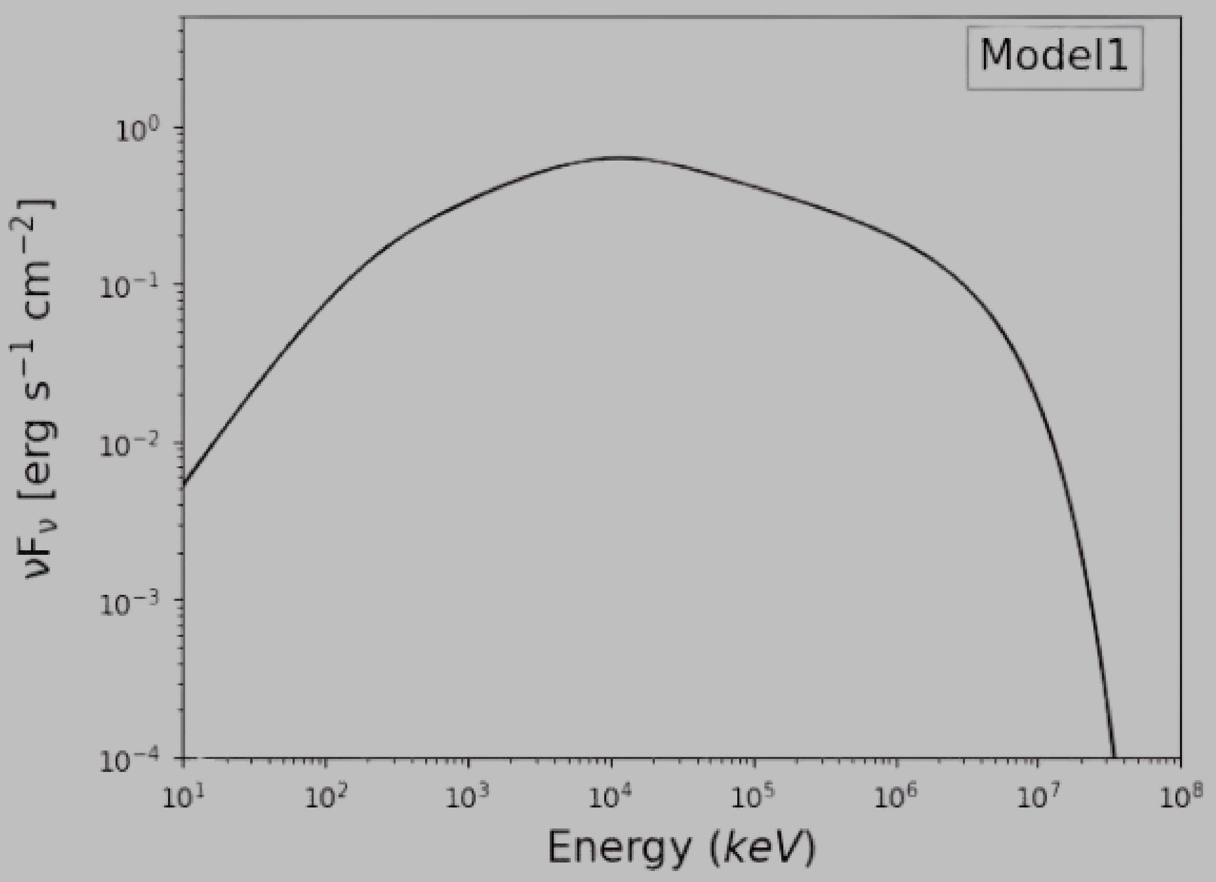
GRB 080916C



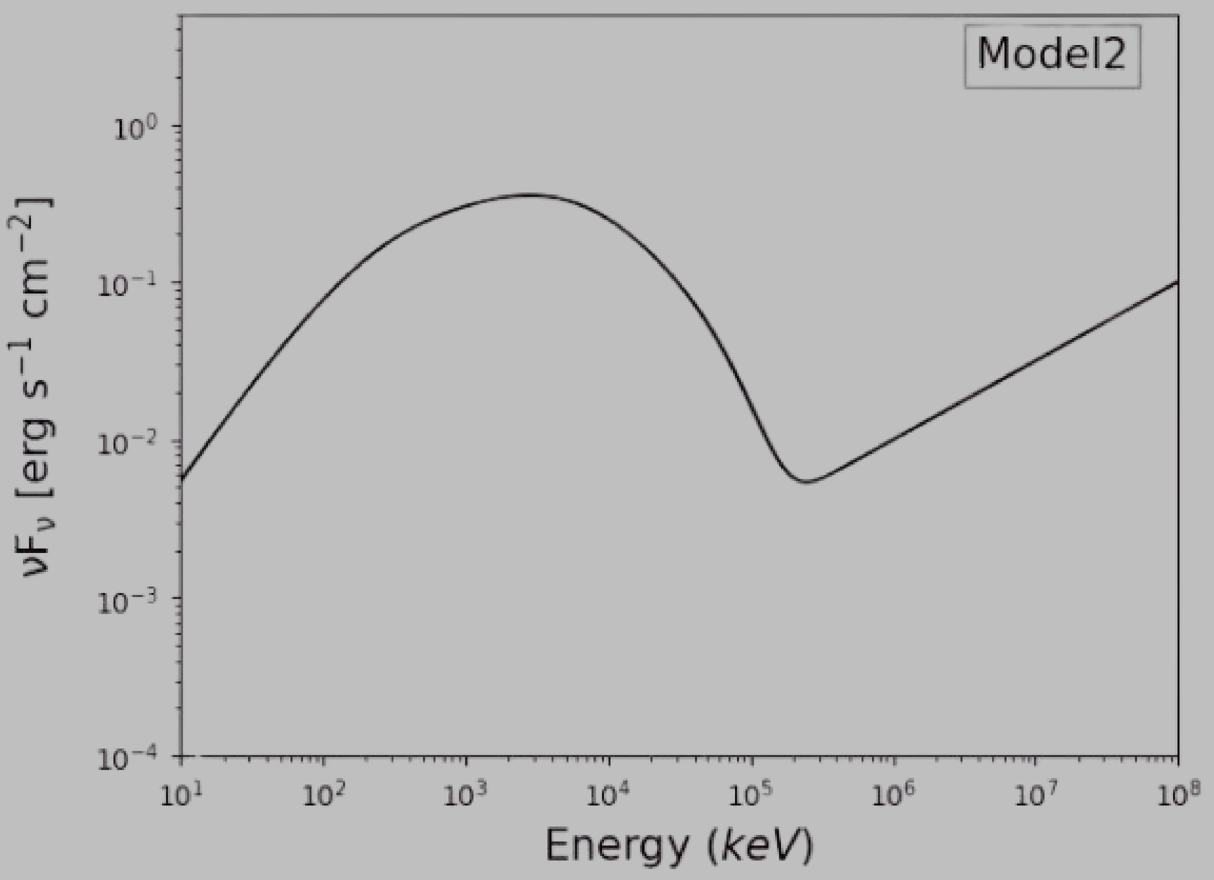
Timing analysis not enough to understand the nature of HE photons

Spectral Analysis

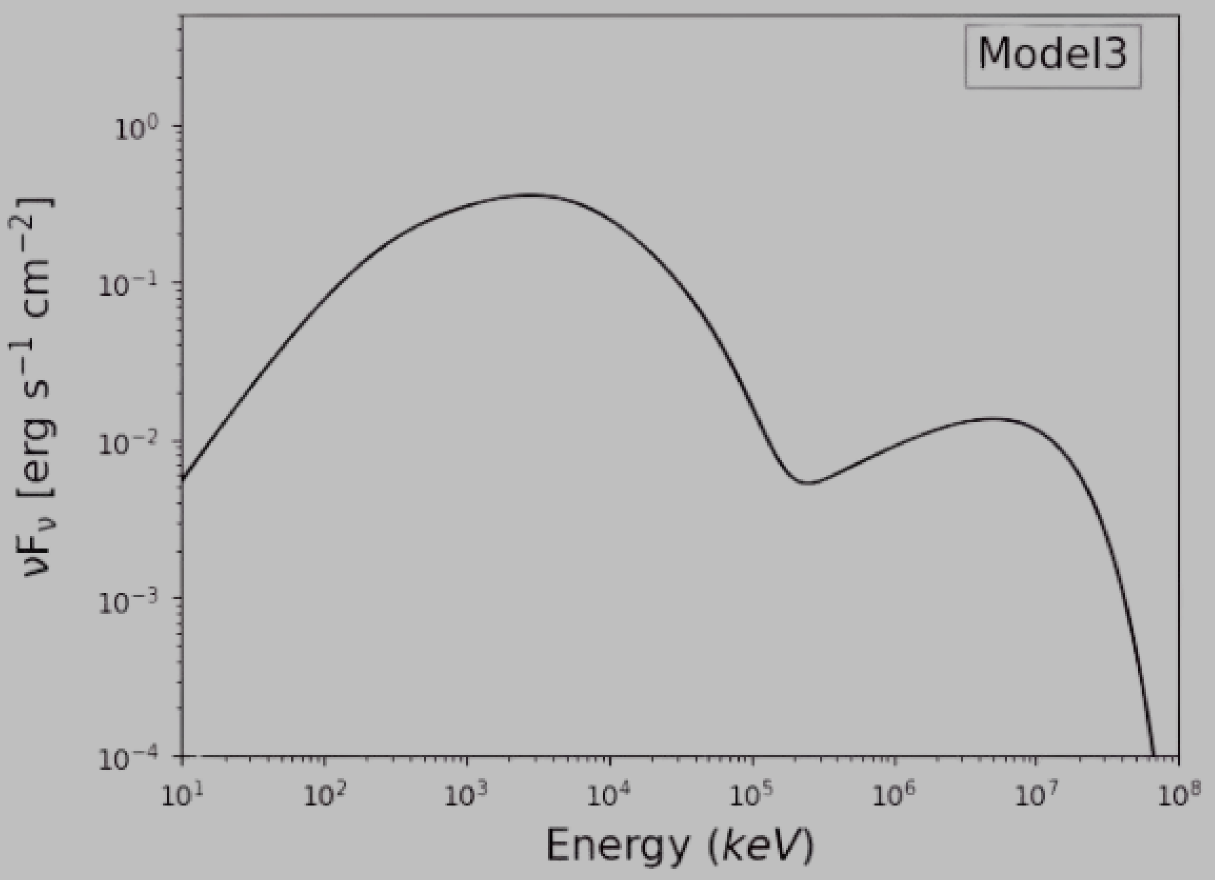
Models Tested



Synchrotron with high energy cutoff



Synchrotron with a power law



Synchrotron with a cutoff power law

35 GRBs analyzed, 89 Spectra

01 70 spectra and 32 GRBs best fitted with pure synchrotron

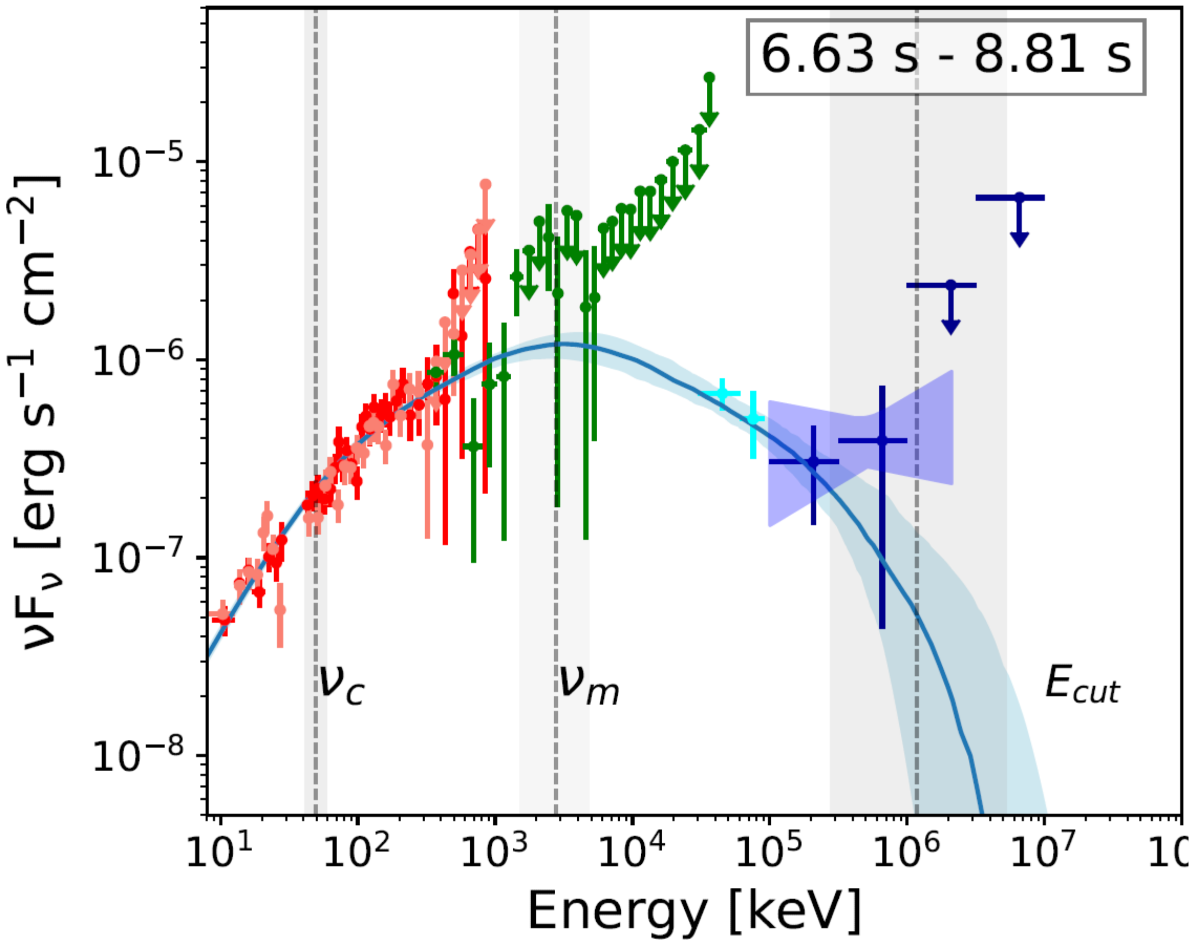
02 18 spectra and 3 GRBs best fitted with synchrotron + power-law

03 1 spectrum best fitted with synchrotron + cutoff power-law

Spectral Analysis

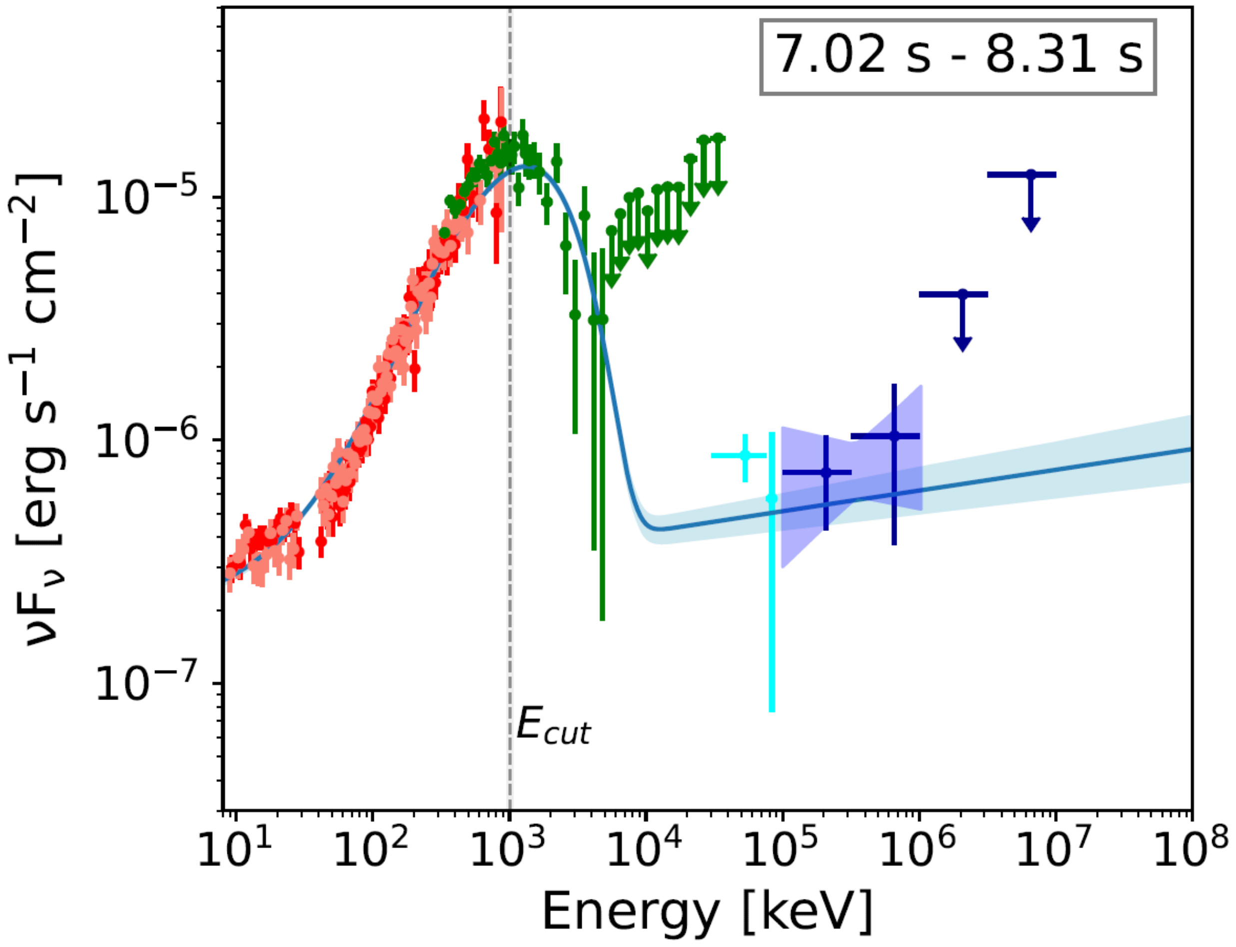
Model 1

GRB 080916C



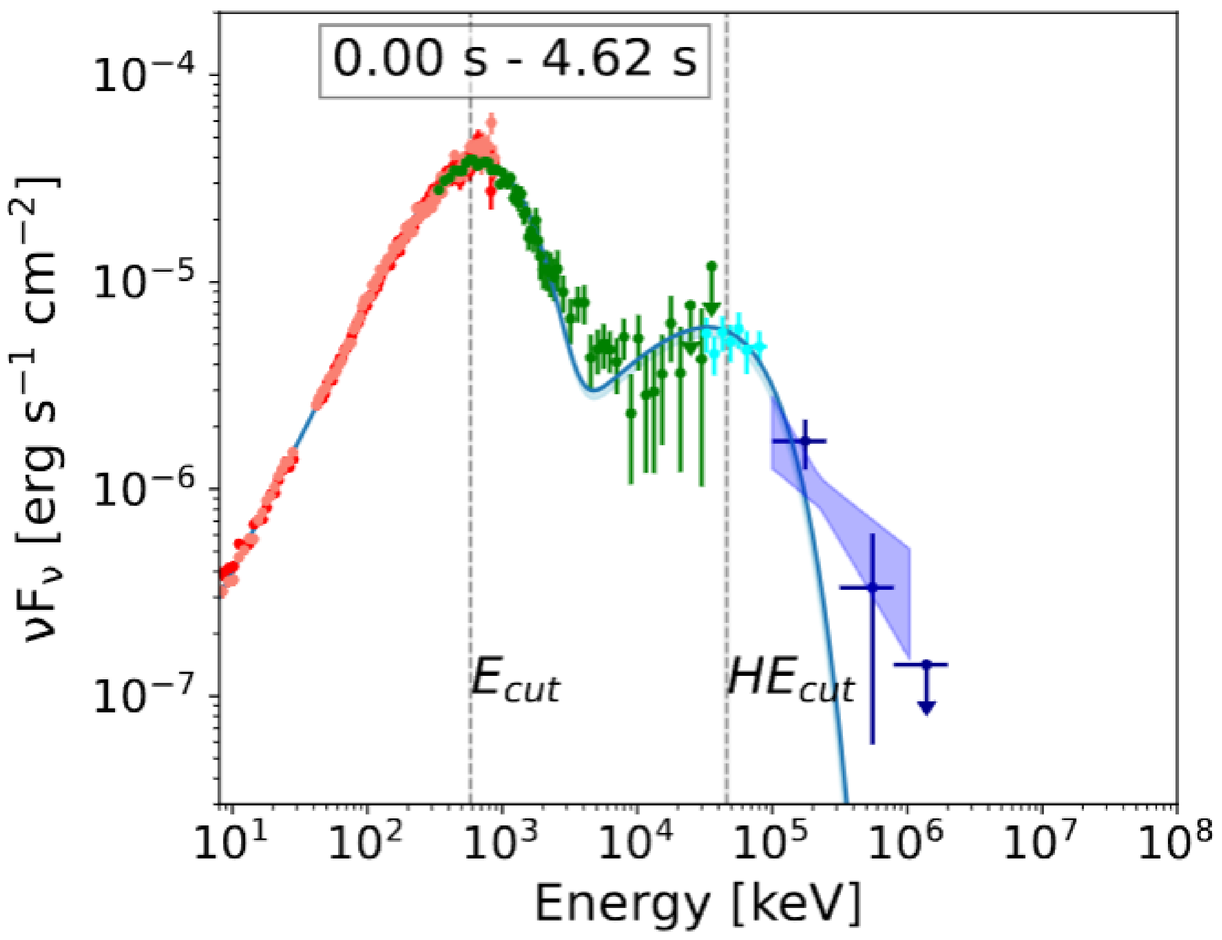
Model 2

GRB 090902B



Model 3

GRB 190114C

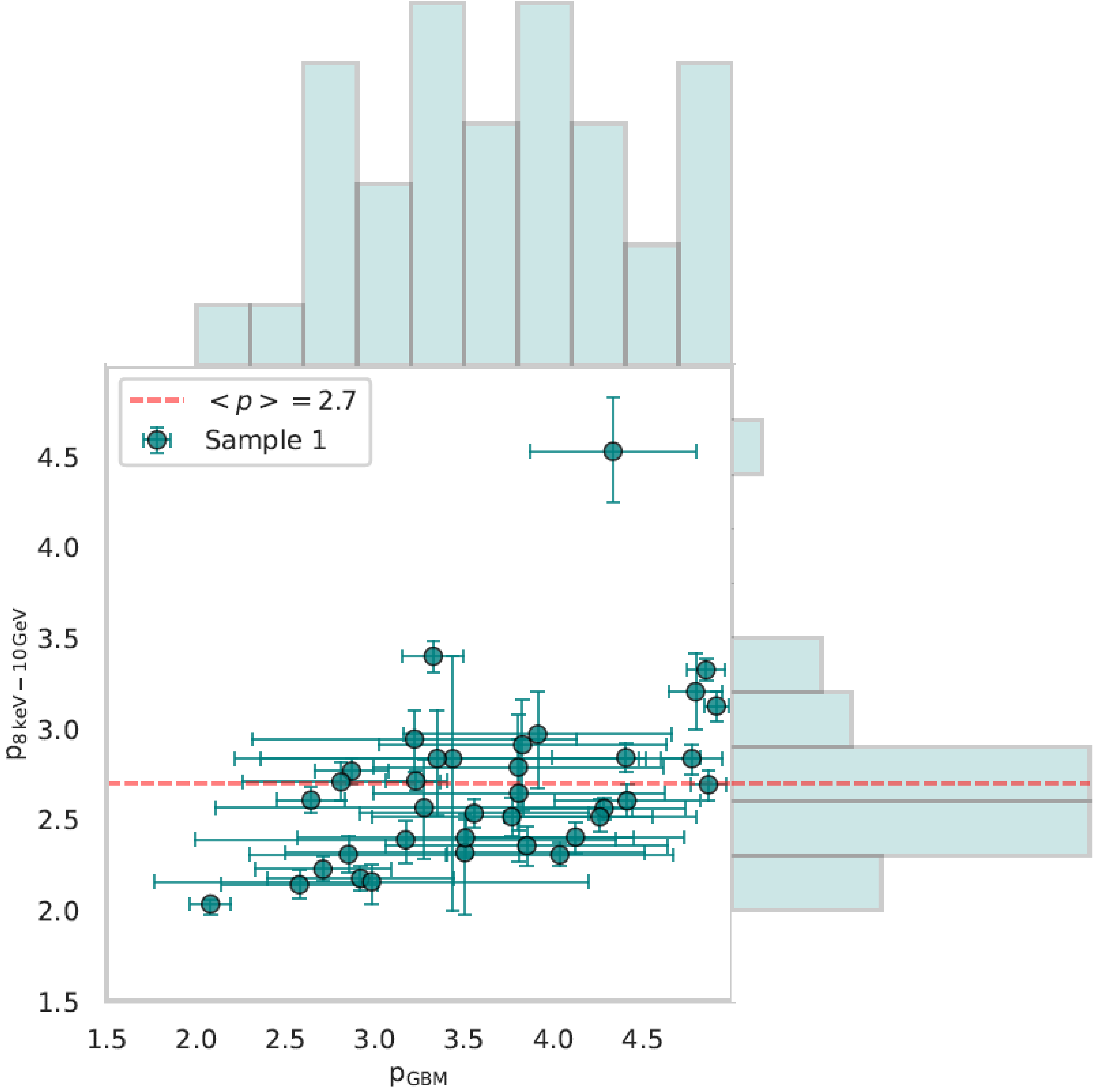


Spectral index distribution

Distribution of p index $\frac{dN}{d\gamma} \propto \gamma^{-p}$

p ≃ 2.7 → consistent with theoretical predictions for shock acceleration and reconnection processes (Sironi et al. 2015).

→ The inclusion of Fermi/LLE and Fermi/LAT data significantly improves the constraints on p compared to fits limited to the Fermi/GBM range.



In summary

- ❑ Prompt emission can be explained as synchrotron in the majority of the cases studied.
- ❑ Synchrotron prompt spectra are broad, covering the energy range 8 kev-10 GeV → A possible second component (if present) should appear at VHE
- ❑ Second power law component is very rare; with Fermi/LAT data it is difficult to resolve in time
  → VHE can help in understanding the nature and the physics of this component
- ❑ High-energy data help in constraining the slope of the particle distribution function, (i.e. the acceleration mechanism)

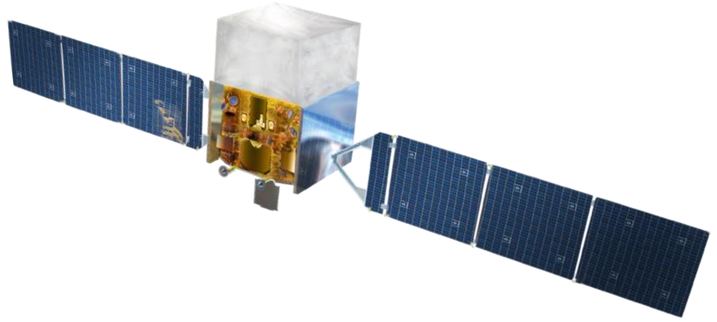
→ MS, Banerjee B., Mei A., Tiwari P., Oganesyan G., Branchesi M., accepted for publication A&A (arxiv: 2501.10507)

... what about VHE (~TeV) detections?

VHE detection in GRBs

Space-based

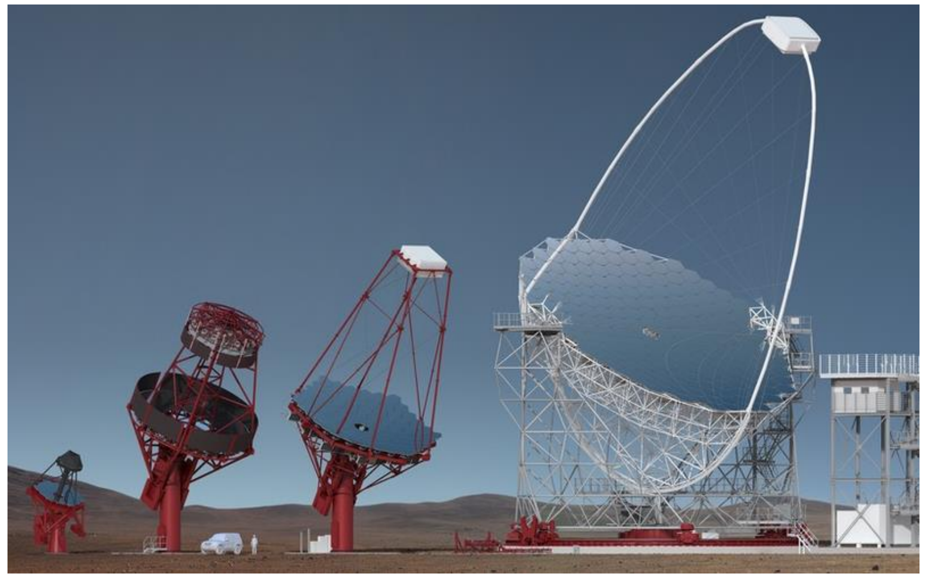
Fermi/LAT
100 MeV to > 300 GeV



Ground-based

Cherenkov Telescopes

MAGIC
100 MeV to > 300 GeV



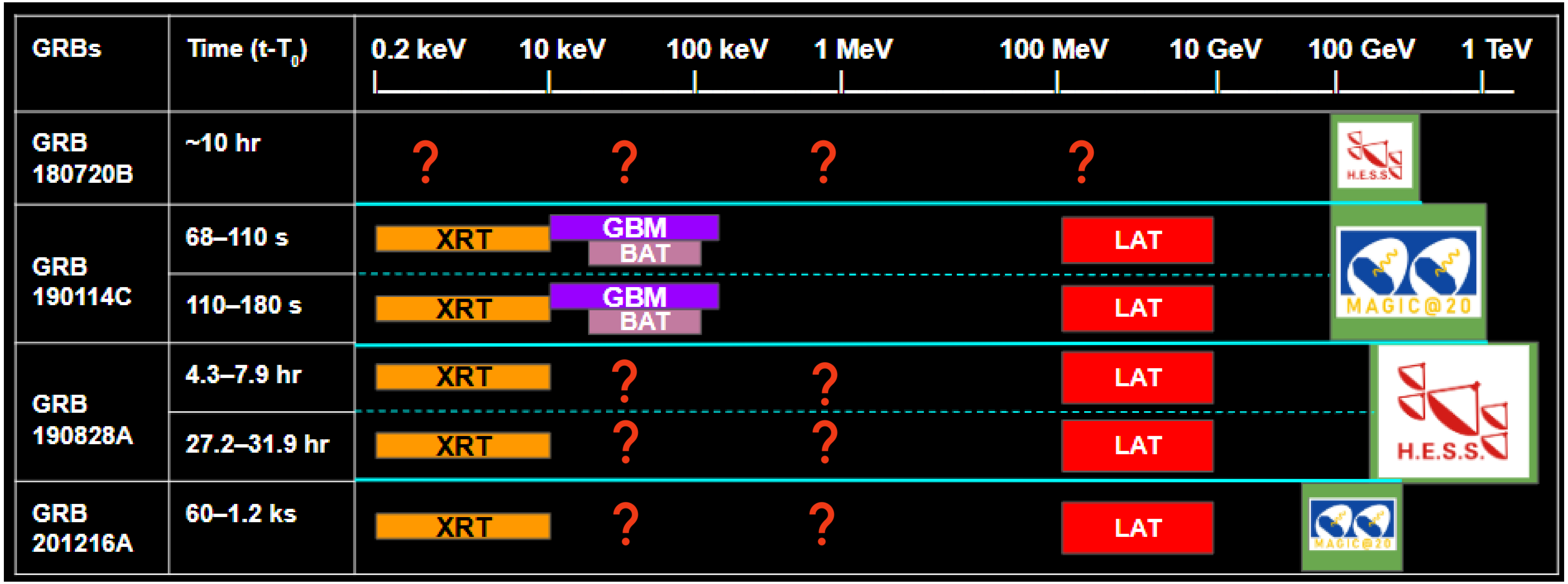
CTAO
100 MeV to > 300 GeV

Water-tanks

LHAASO
100 MeV to > 300 GeV

VHE detection in GRBs

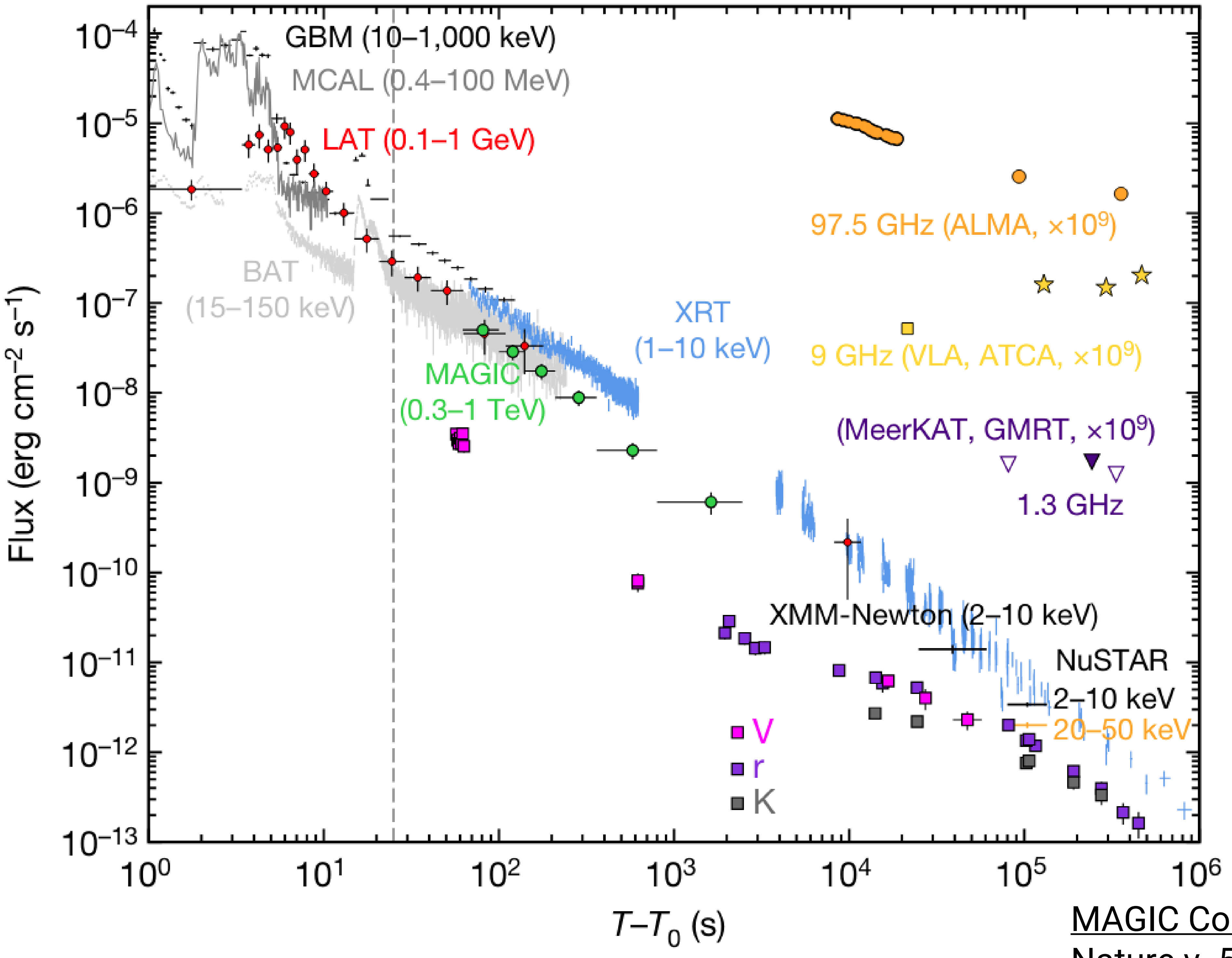
TeV GRBs

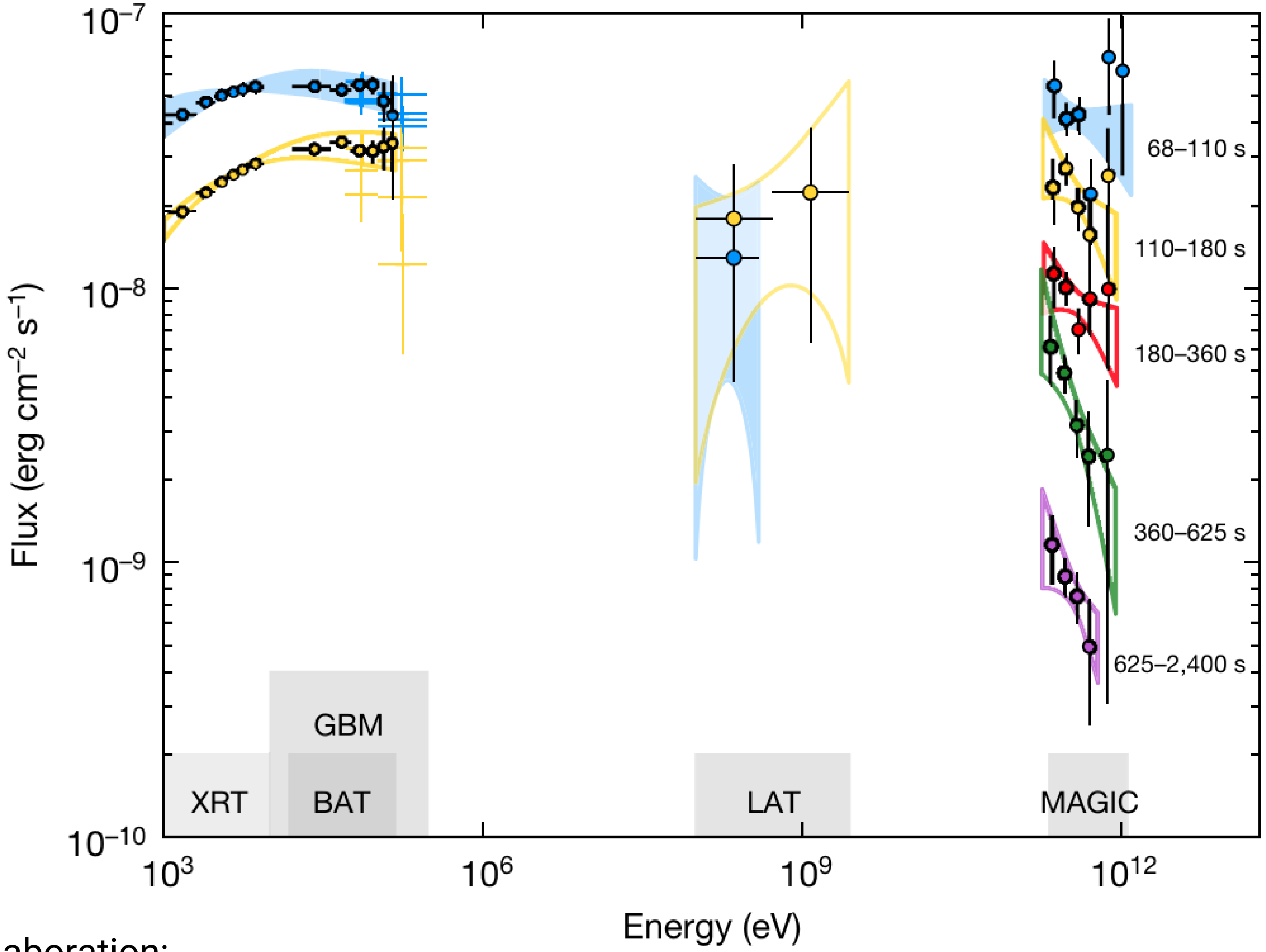


MAGIC Collaboration:
Nature v. 575, p. 455–458 (2019) and
Nature v. 575, p. 459–463 (2019)
H.E.S.S. collaboration, Nature, 2019
H.E.S.S. collaboration, Science, 2021
MAGIC Collaboration, MNRAS, 2024

VHE detection in GRBs

GRB 190114C (z = 0.42)

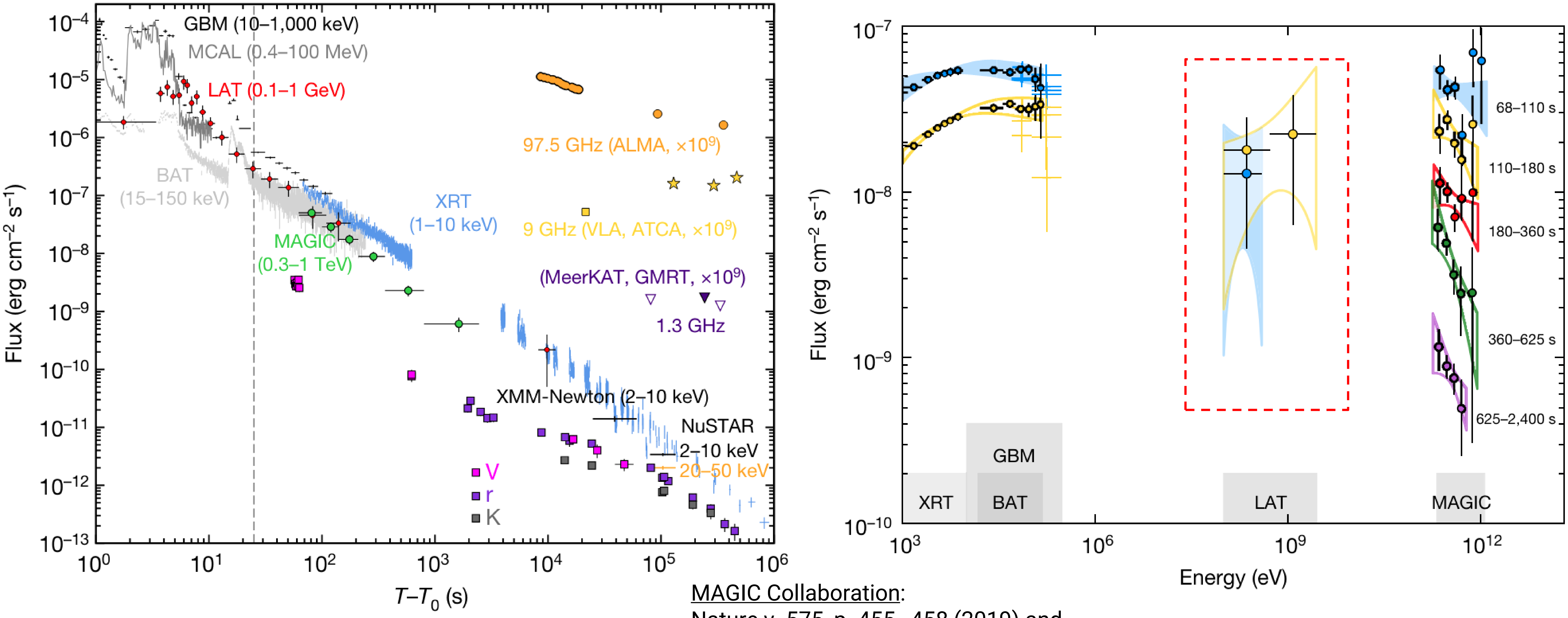




<u>MAGIC Collaboration</u>:
Nature v. 575, p. 455−458 (2019) and
Nature v. 575, p. 459−463 (2019)

VHE detection in GRBs

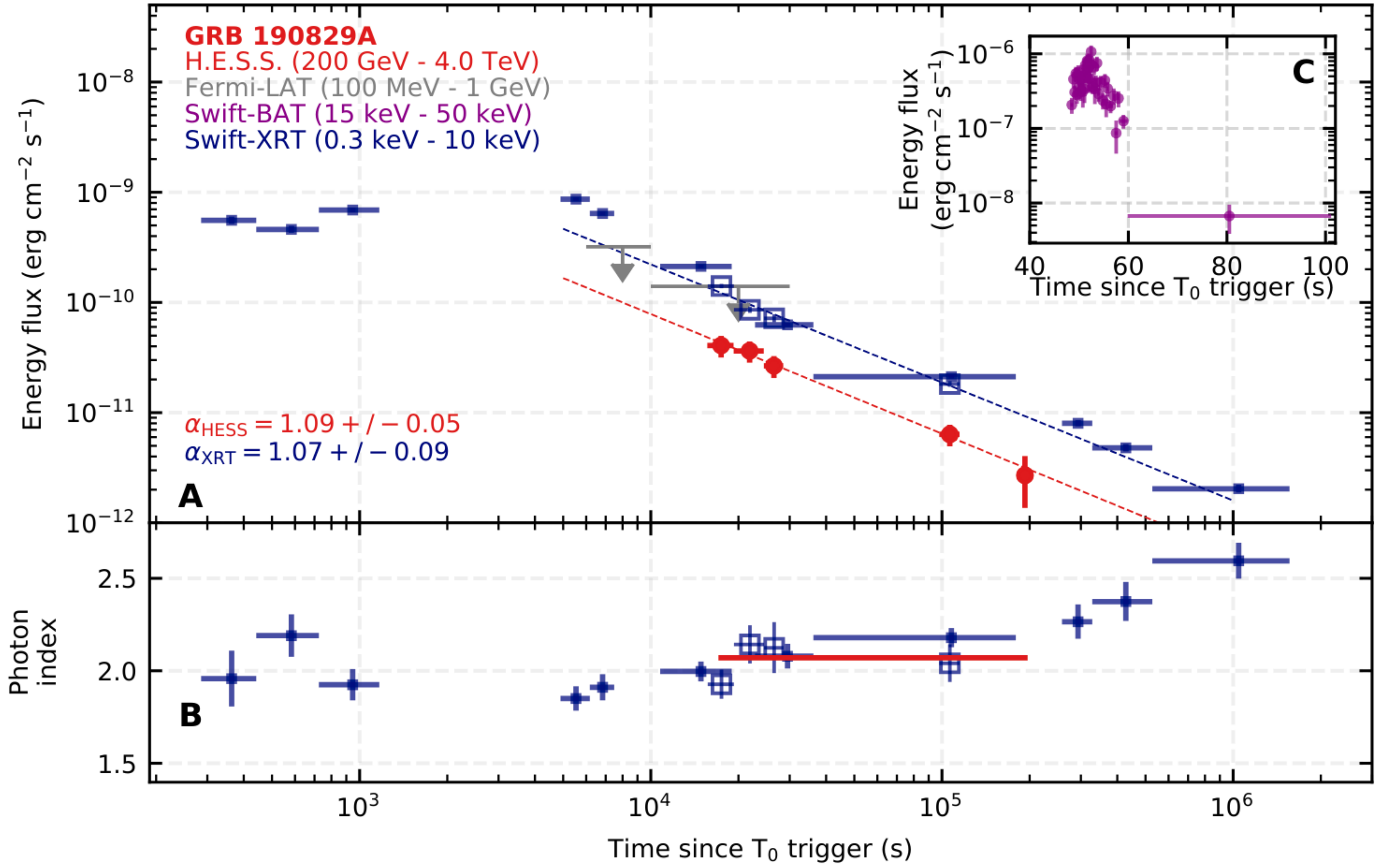
GRB 190114C (z = 0.42)

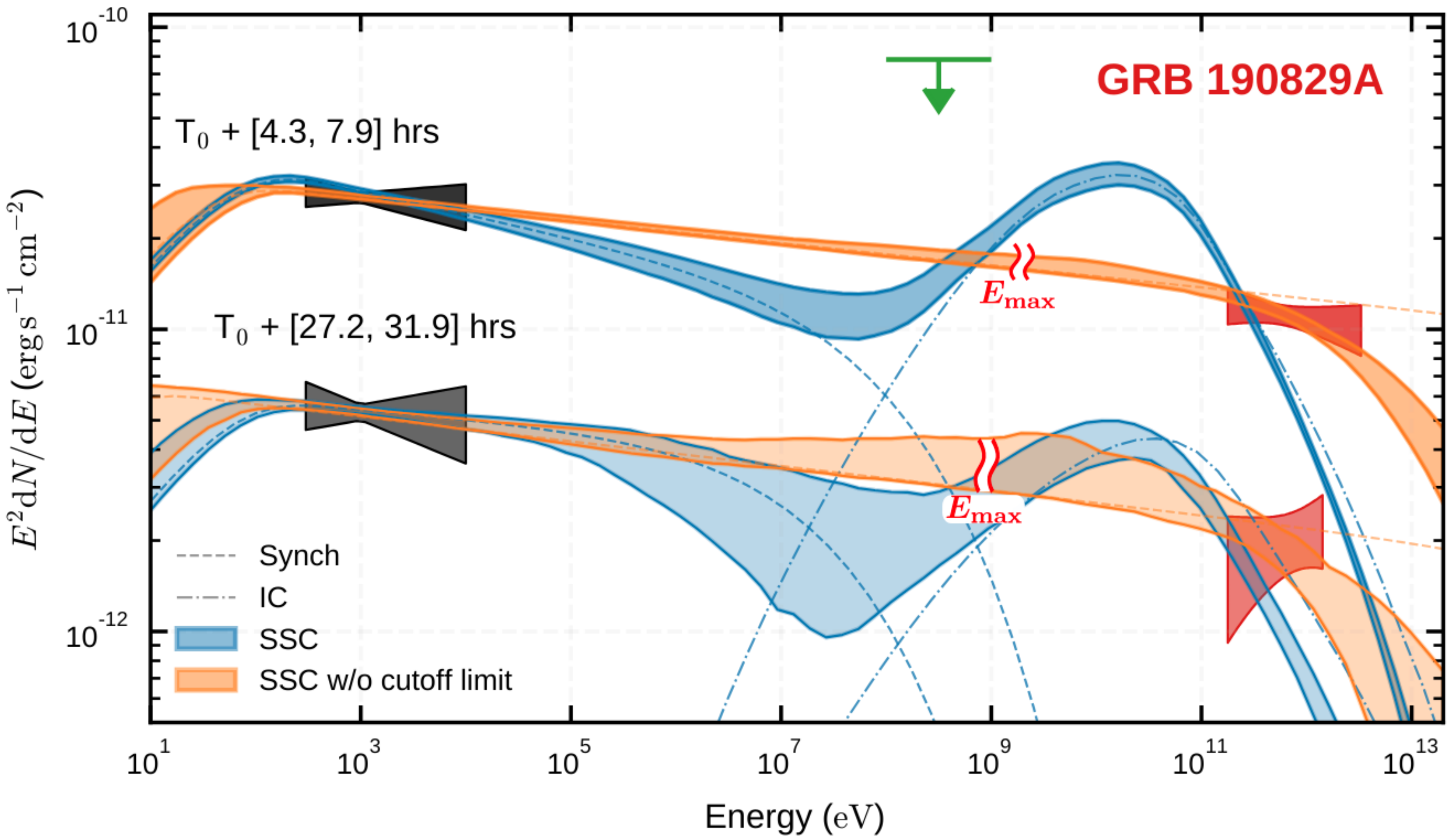


MAGIC Collaboration:
Nature v. 575, p. 455–458 (2019) and
Nature v. 575, p. 459–463 (2019)

VHE detection in GRBs

GRB 190829A (z = 0.08)

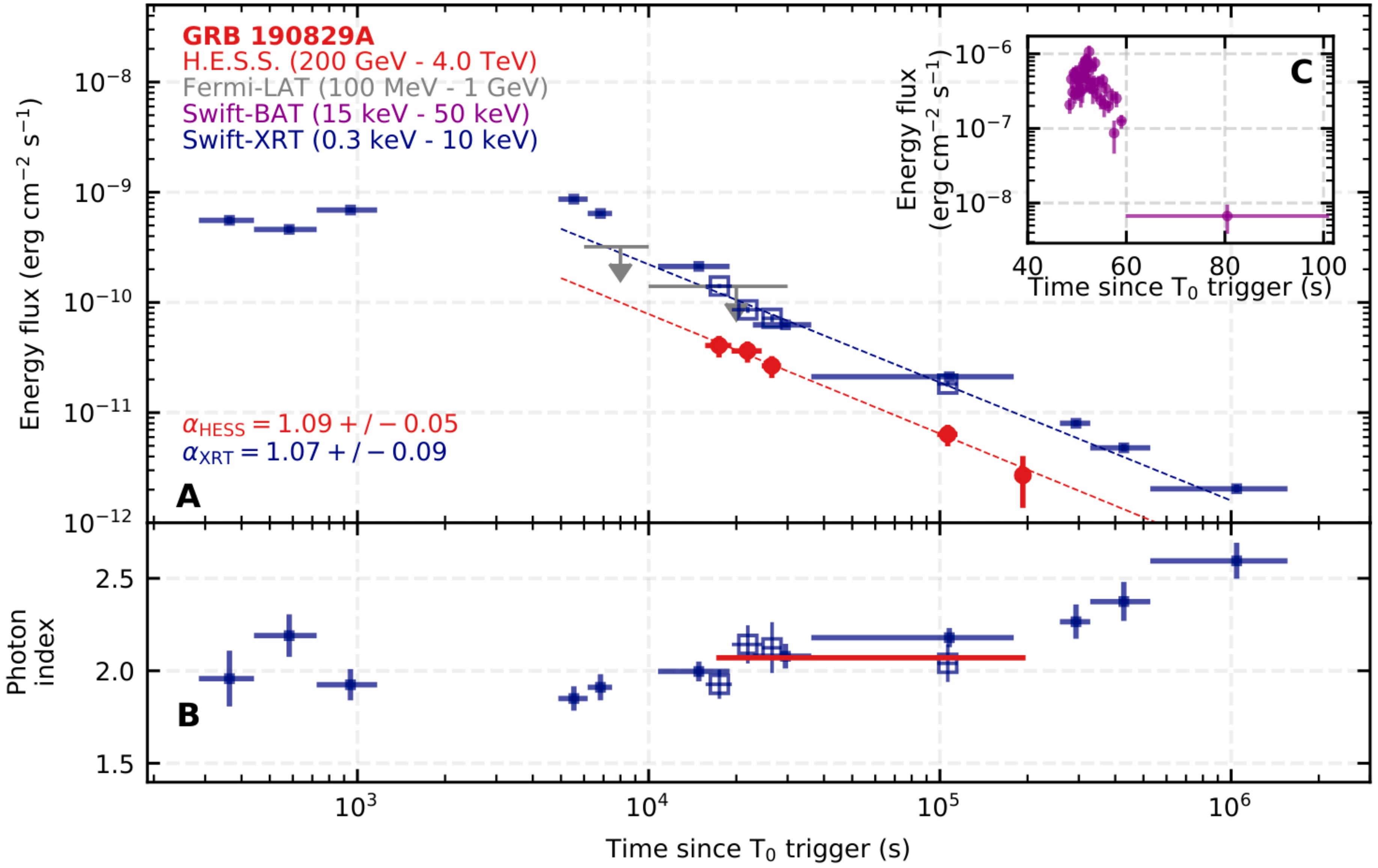




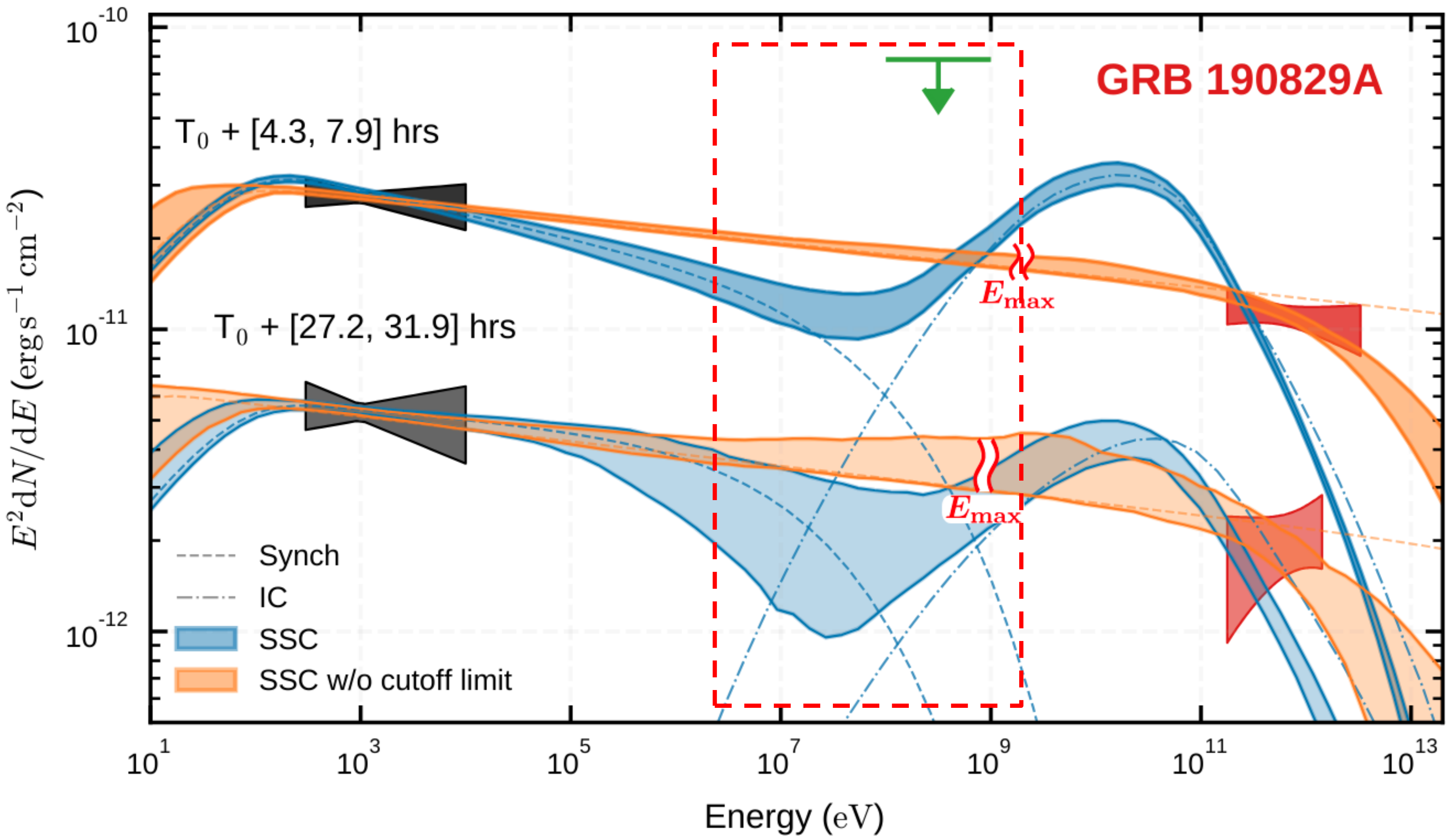
H.E.S.S. Collaboration 2021

VHE detection in GRBs

GRB 190829A (z = 0.08)



Synchrotron-self Compton (SSC) or single component?

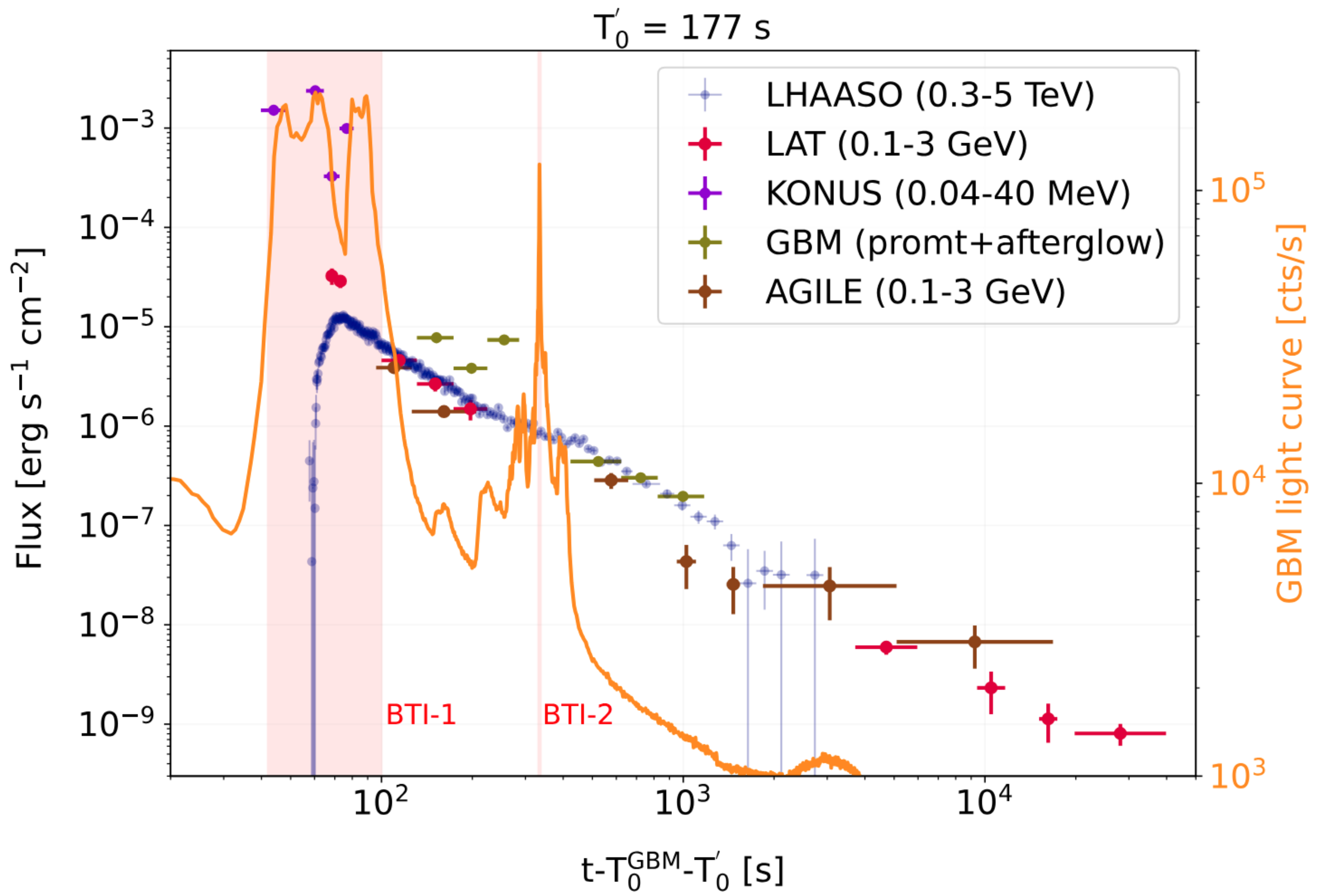


Difficult to constrain the spectral turnover from X-ray to TeV energies

H.E.S.S. Collaboration 2021

The BOAT GRB

GRB 221009A; BOAT (Brightest Of All Time*),   z = 0.15



Banerjee B., **MS**, et al 2025, submitted ([arXiv: 2405.15855](https://arxiv.org/abs/2405.15855))

Focus on early emission (20 min),
keV-TeV spectra

LHAASO Collaboration, Science (2023)

Tavani et al 2023, ApJL 956 L23, 2023

Bissaldi et al 2023: https://pos.sissa.it/444/847/

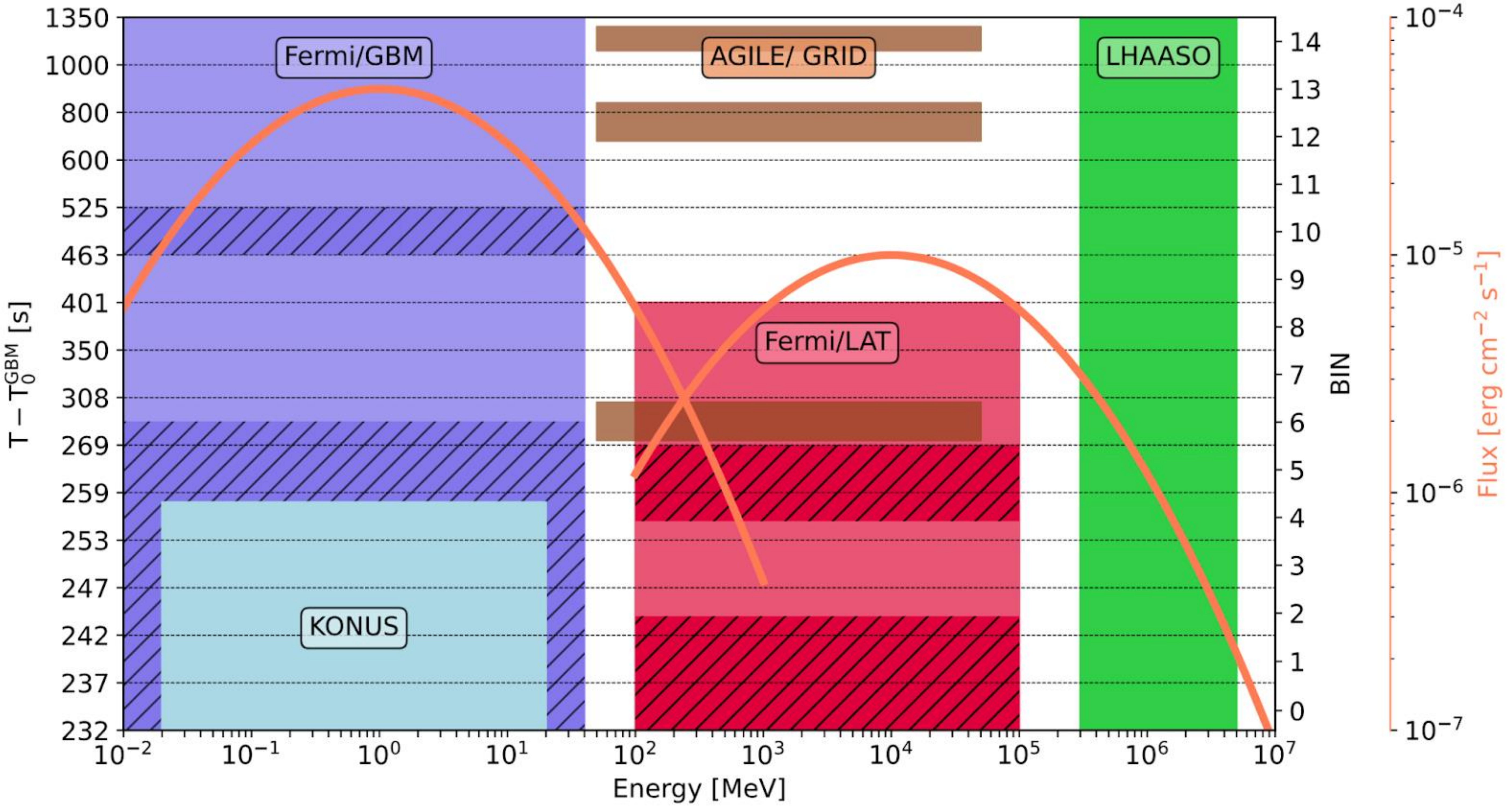
Frederiks et al 2023, ApJL, 949, L7 (2023)

Lesage et al 2023, ApJL 952 L42

*Burns et al 2023 ApJL 946 L31

VHE emission in the BOAT

Available period of instrument coverage from X-rays (keV) to TeV energies

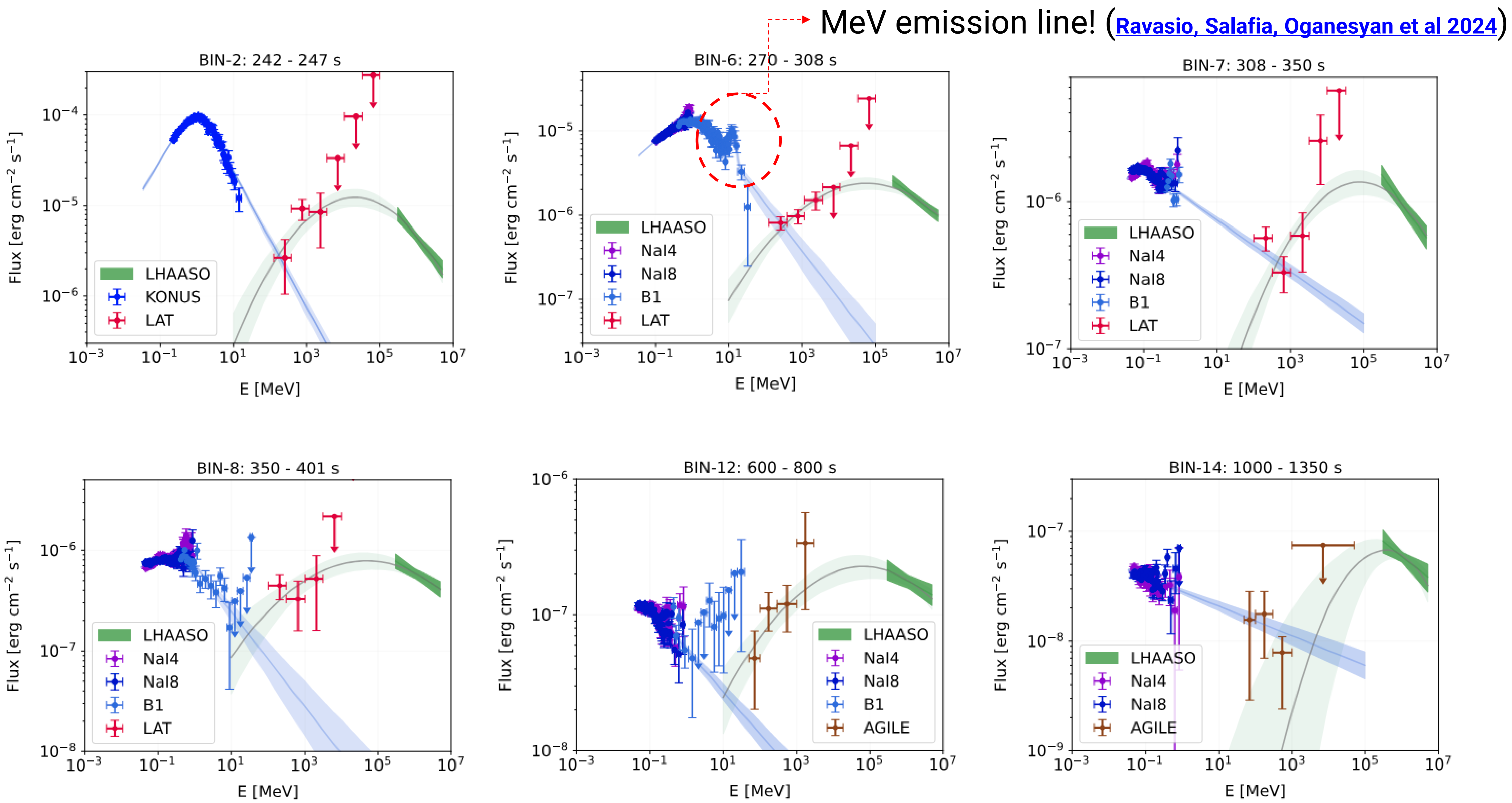


6 time-bins selected

VHE emission in the BOAT

keV-MeV: Band Function

GeV-TeV: Log Parabula



Modelling of the VHE component

At later time, the emission is dominated by the SSC afterglow.

→ estimate the SSC spectra and the light-curve of the GeV and TeV emission of early epoch by rescaling the SSC parameters of late epoch (**self-similarity** the relativistic blast-wave dynamics in the cold medium (Blandford & McKee 1976))

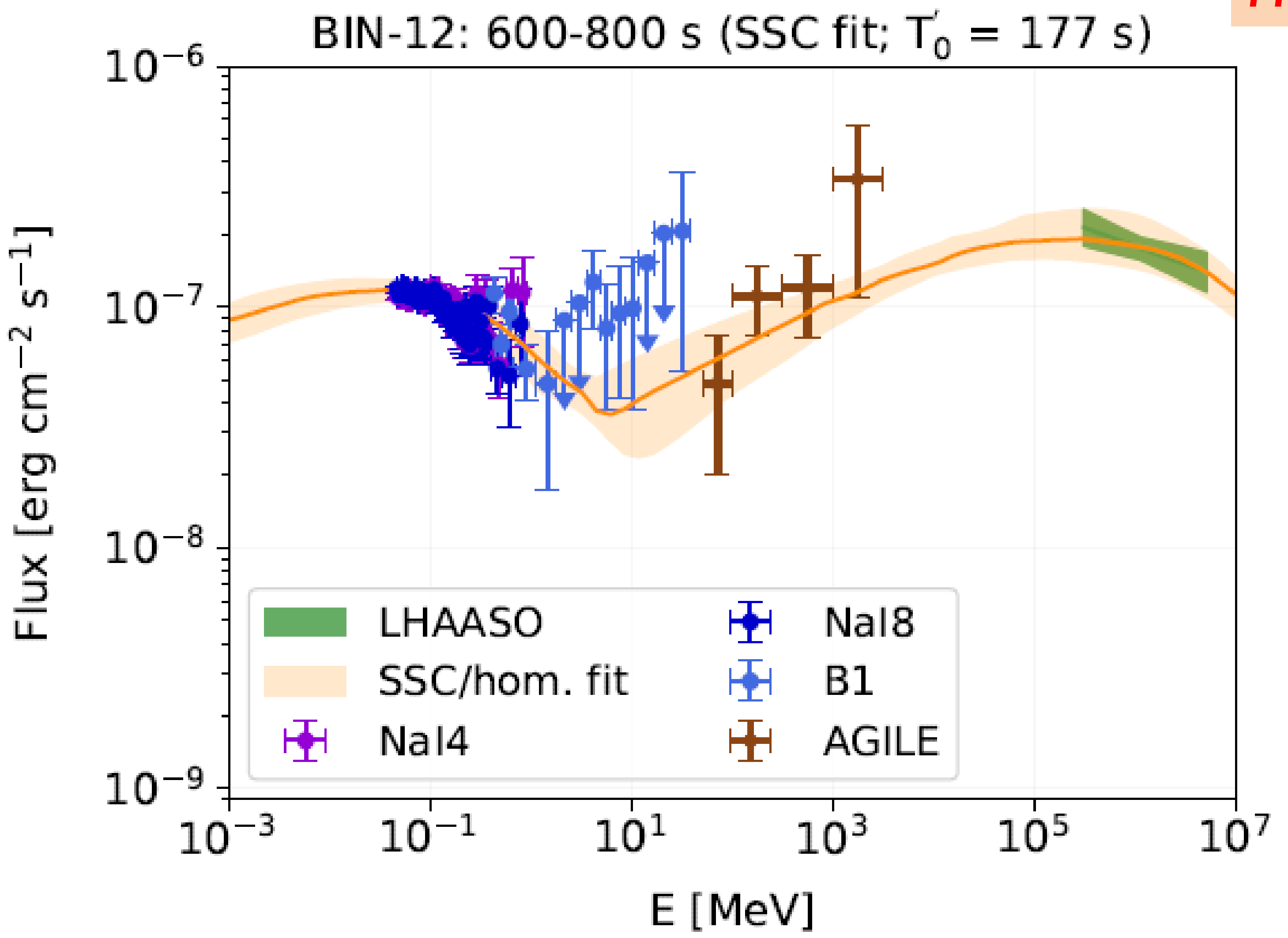
- Use the Lepto-Hadronic Modeling Code (LeHaMoC; Stathopoulos et al. 2024) to model the SSC.
- Estimate the 6 free parameters: **B, γ_{min}, γ_{max}, p, l_e, D**

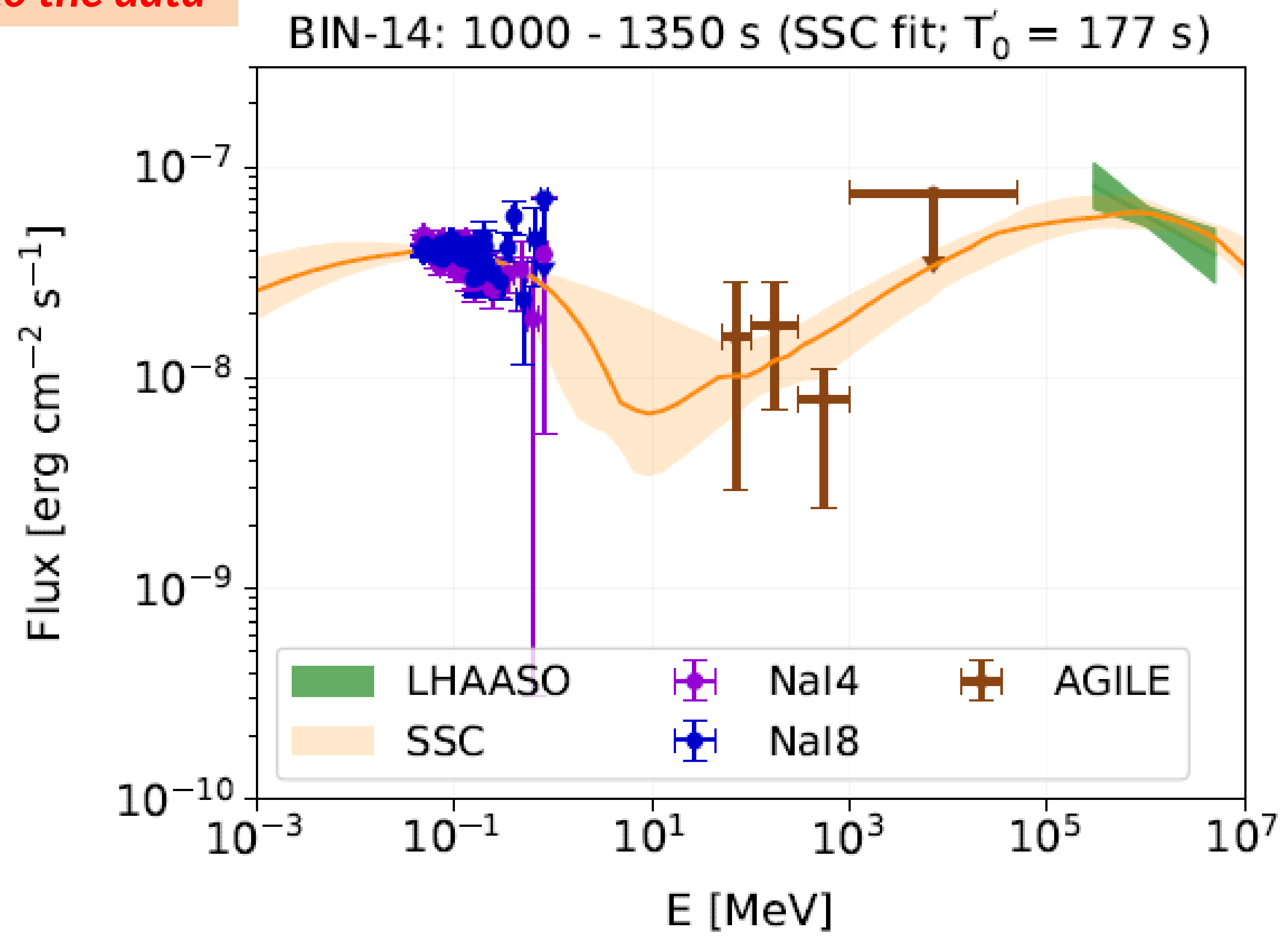
Possible origin of the VHE emission

- Extract microphysical parameters from BIN-14 (SSC model)
- Extrapolate at earlier bins

Parameters	Priors	Posteriors
$\log_{10}(B)$ [G]	(-5; 2)	$-1.0^{+0.3}_{-0.4}$
$\log_{10}(\gamma_m)$	(0; 5)	$2.4^{+1.1}_{-1.5}$
$\log_{10}(\gamma_{max})$	(4; 8)	$6.7^{1.0}_{-0.3}$
$\log_{10} l_e$	(-7; -1)	$-3.3^{+0.4}_{-0.5}$
p	(2; 3)	$2.4^{+0.1}_{-0.3}$
$\log_{10}D$	(1; 4)	$2.2^{+0.1}$ [illegible]

FIT to the data

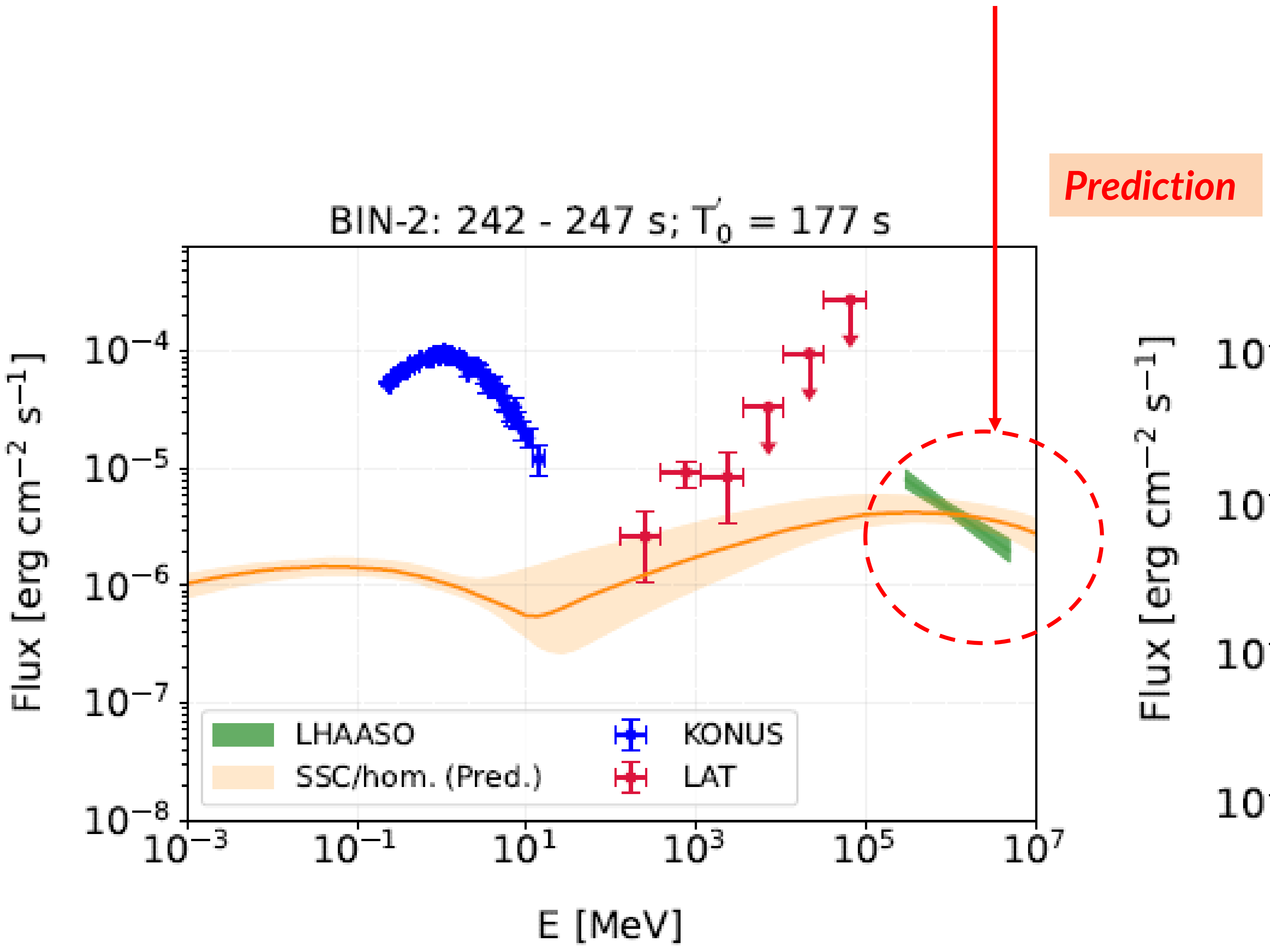


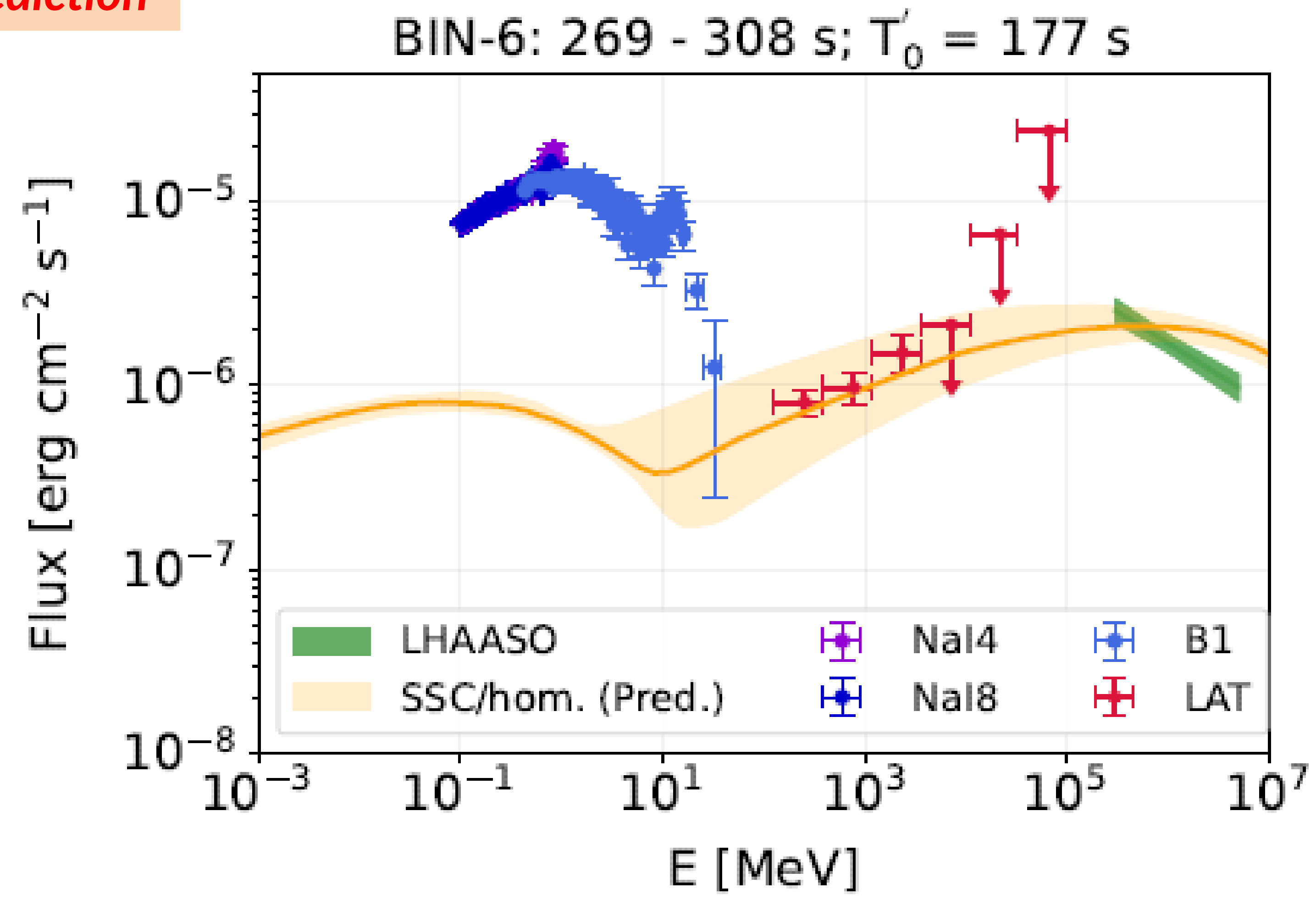


Possible origin of the VHE emission

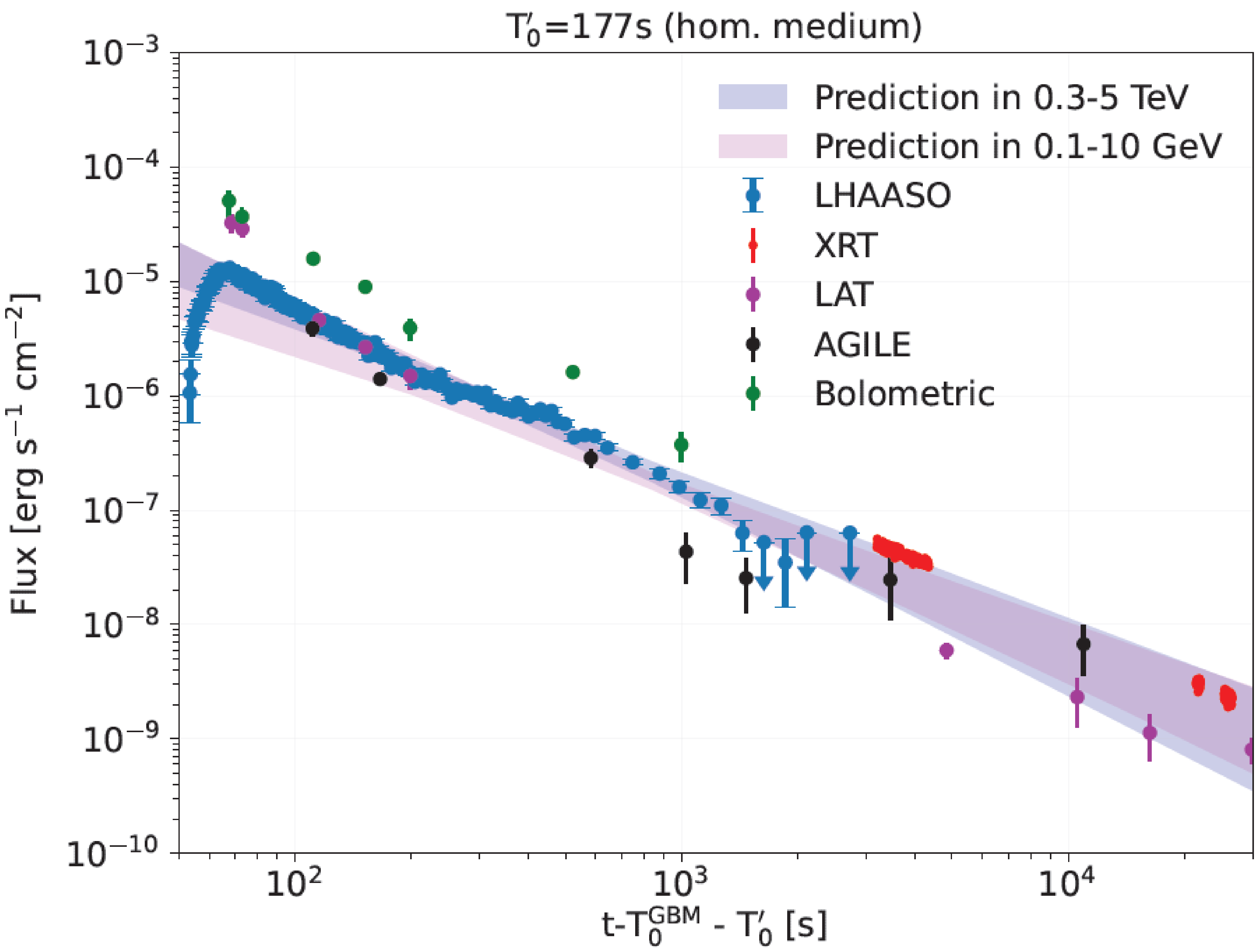
- Also during the prompt phase, SSC prediction can explain the second spectral component
- Softening of LHAASO might be explained with MeV photons from the bright prompt

$\gamma - \gamma$ attenuation,
MeV suppression,
….





Possible origin of the VHE emission



- Computed GeV-TeV ligthcurve in the SSC scenario, in good agreement with LHAASO

- Early GeV excess can be explained wit interaction of MeV-prompt photons (additional External Inverse Compton photons)

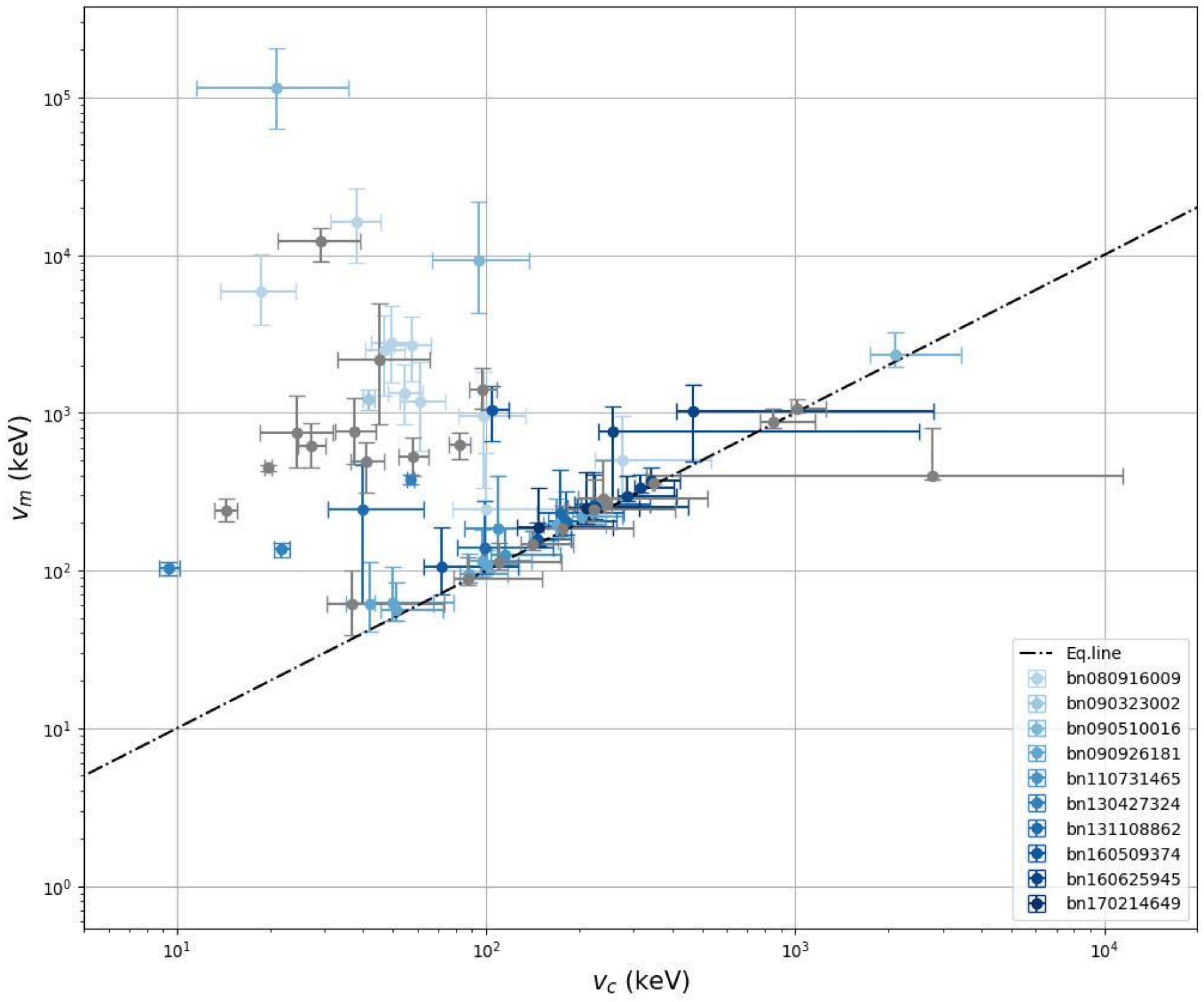
CONCLUSIONS

- ❑ Analyzing the multi-wave band afterglow emission, we identified two distinct spectral components during the initial 30 minutes.
- ❑ The second spectral component peaks at ∼100 GeV
- ❑ Performing broad-band spectral modeling, we provide constraints on the magnetic field (∼ 0.1 G) and the energies of the accelerated electrons in the external relativistic shock.
- ❑ GeV detections (LAT and AGILE) were crucial to establish the presence of the second component
- ❑ Important to catch and characterize early GeV/TeV emission → observational proposals are in place!

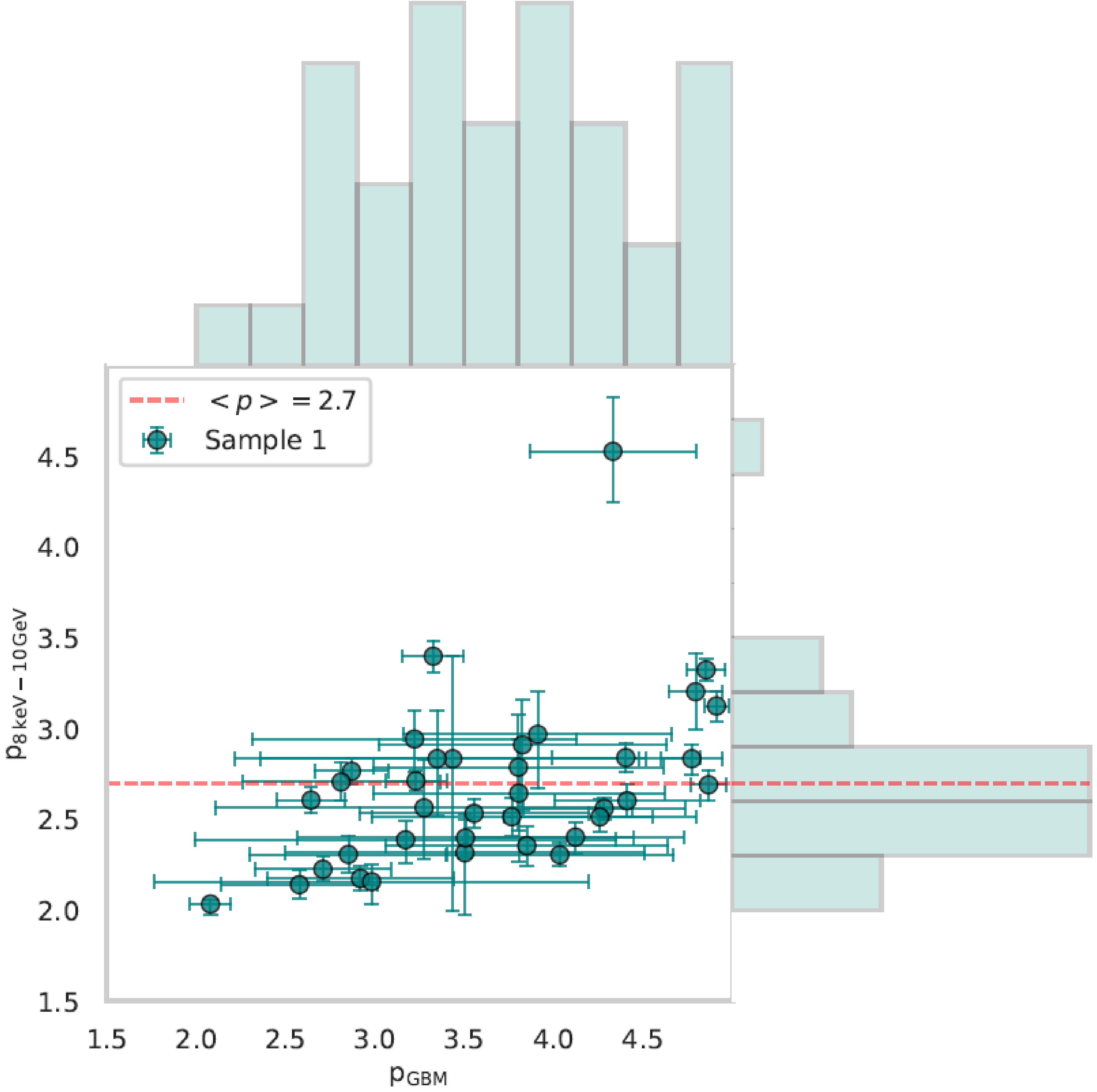
THANK YOU!

Parameter space

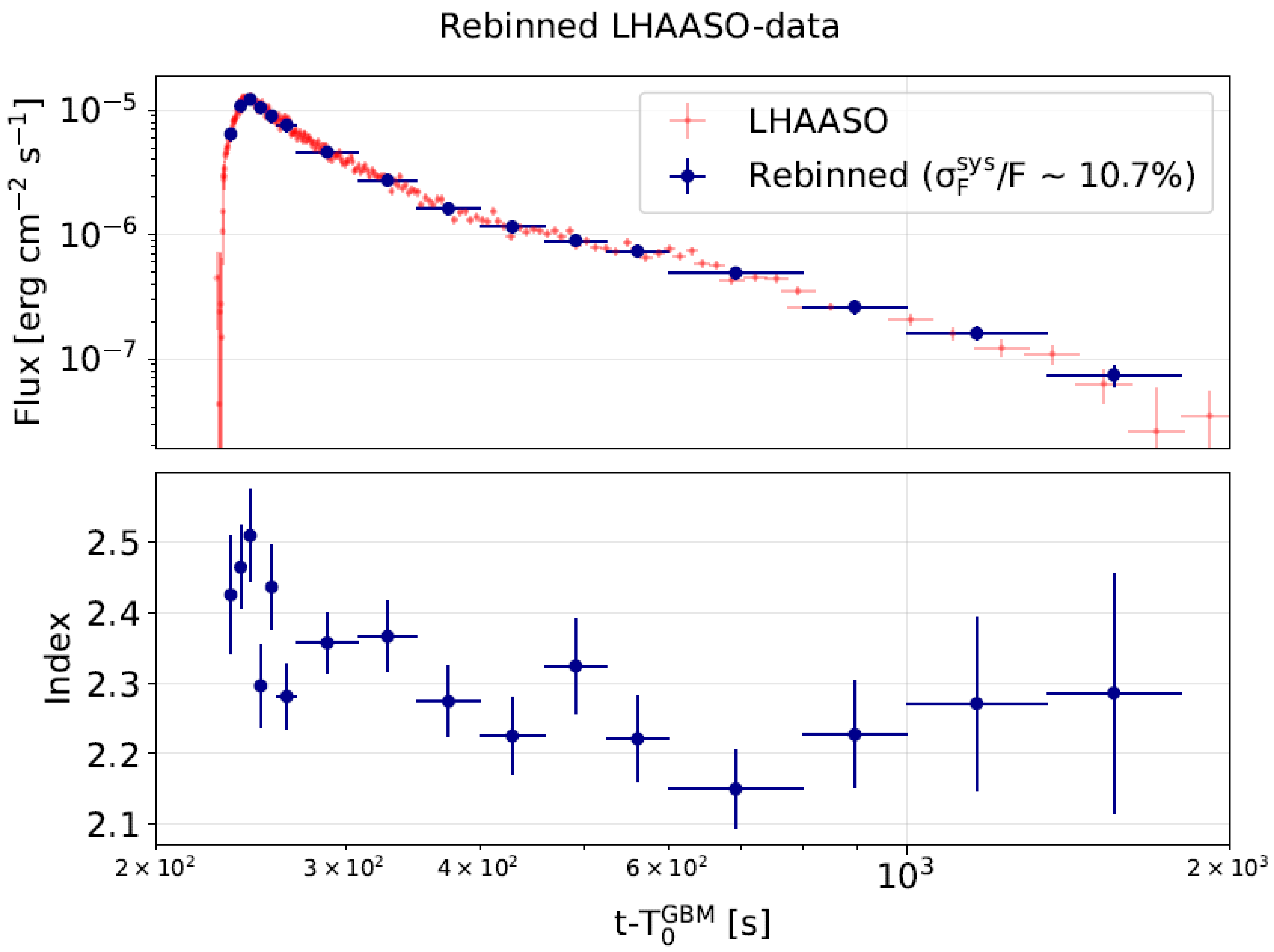
ν_c vs ν_m



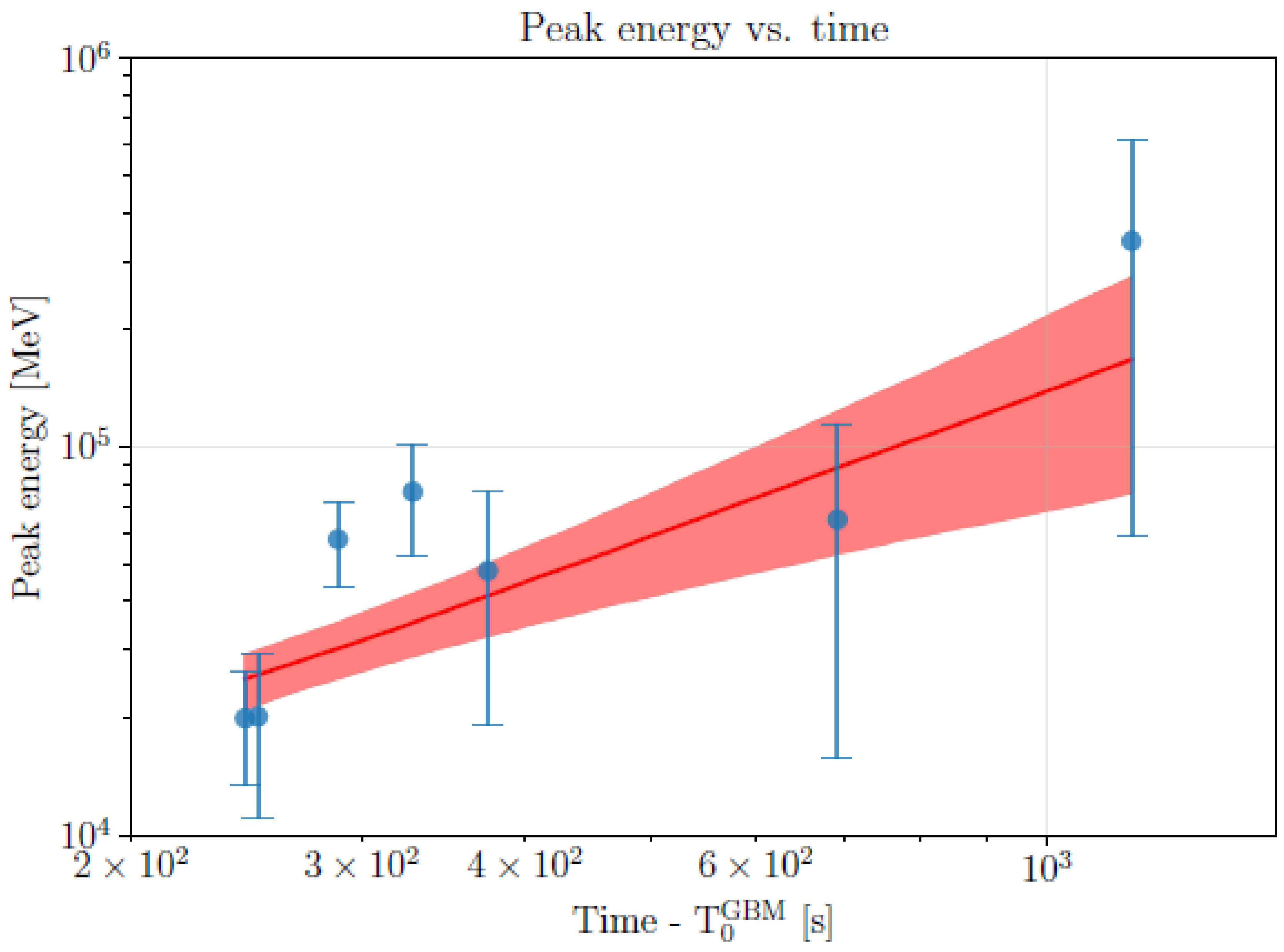
Fast cooling / intermediate fast cooling regime

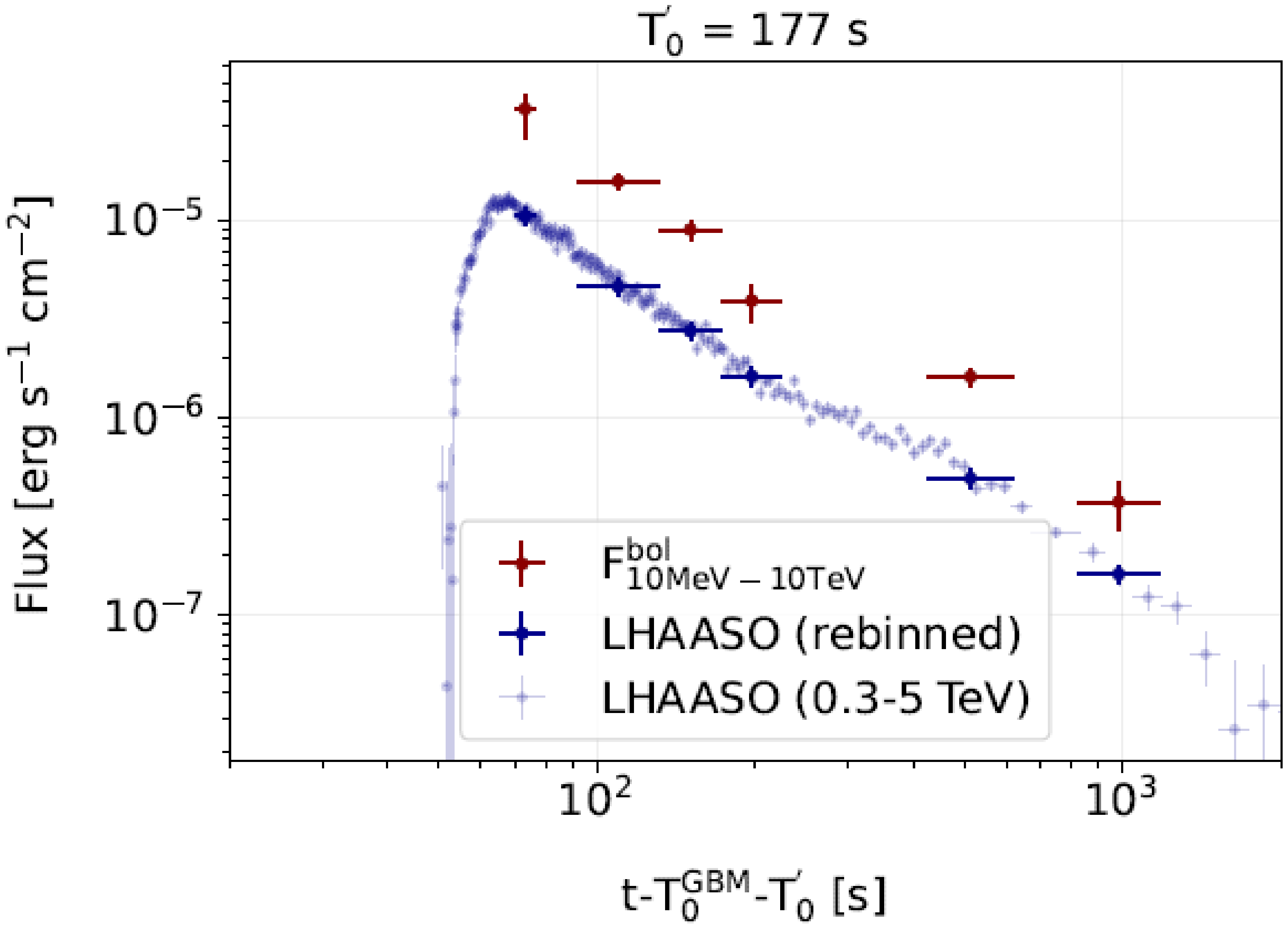


VHE emission in the BOAT



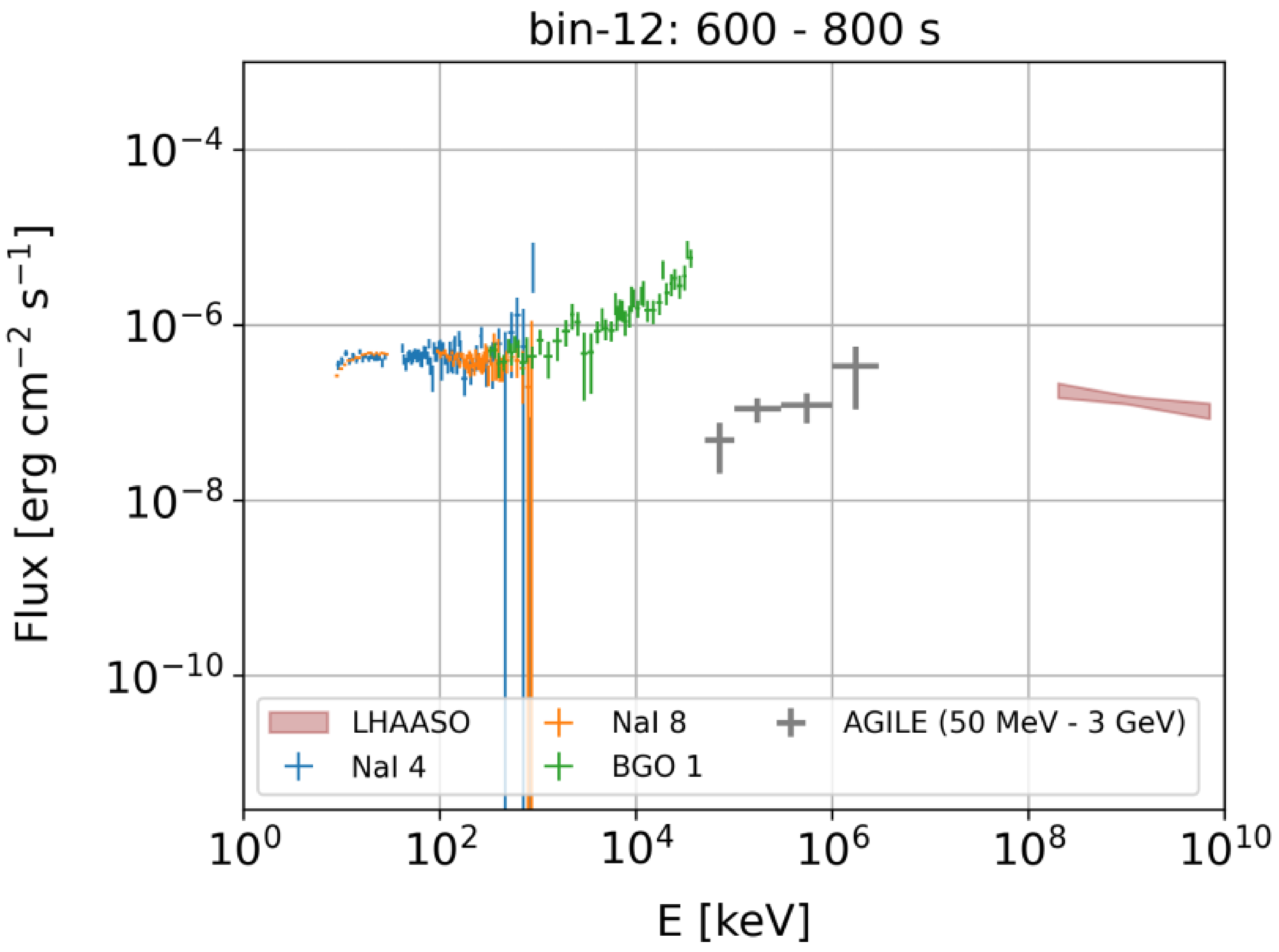
VHE emission in the BOAT

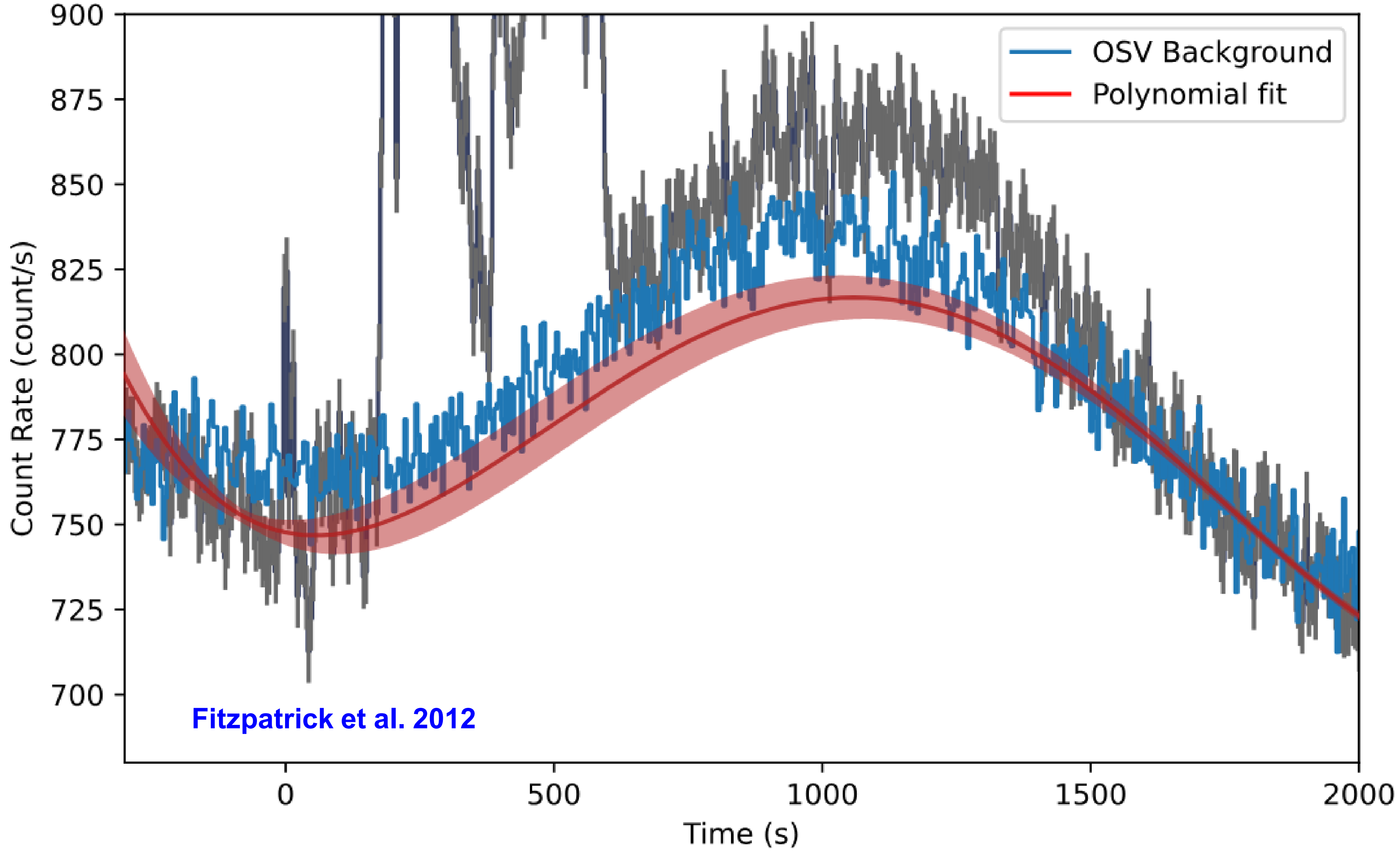




VHE emission in the BOAT

Non standard GBM analysis:





Modelling of the VHE component

→ estimate the SSC spectra and the light-curve of the GeV and TeV emission of early and late epoch by rescaling the SSC parameters (**self-similarity** the relativistic blast-wave dynamics in the cold medium (Blandford & McKee 1976))

$$R_e \sim 2\,c\,t\,\Gamma$$

$$L'_e \sim 4\,\pi\,R_e\,m_e\,c^3\,l_e\,/\,\sigma_{TH}$$

Homo. Medium

$$\gamma'_{min} \sim \gamma_{min}\,(t_{pred.}\,/\,t_{obs})^{3/8}$$

$$\gamma'_{max} \sim \gamma_{max}\,(t_{pred.}\,/\,t_{obs})^{-3/4}$$

$$L'_e \sim l_e\,(t_{pred.}\,/\,t_{obs})^{-1/2}$$

$$R'_e \sim R_e\,(t_{pred.}\,/\,t_{obs})^{-5/8}$$

$$B' \sim B\,(t_{pred.}\,/\,t_{obs})^{3/8}$$

Wind Medium

$$\gamma'_{min} \sim \gamma_{min}\,(t_{pred.}\,/\,t_{obs})^{1/4}$$

$$\gamma'_{max} \sim \gamma_{max}\,(t_{pred.}\,/\,t_{obs})^{-3/8}$$

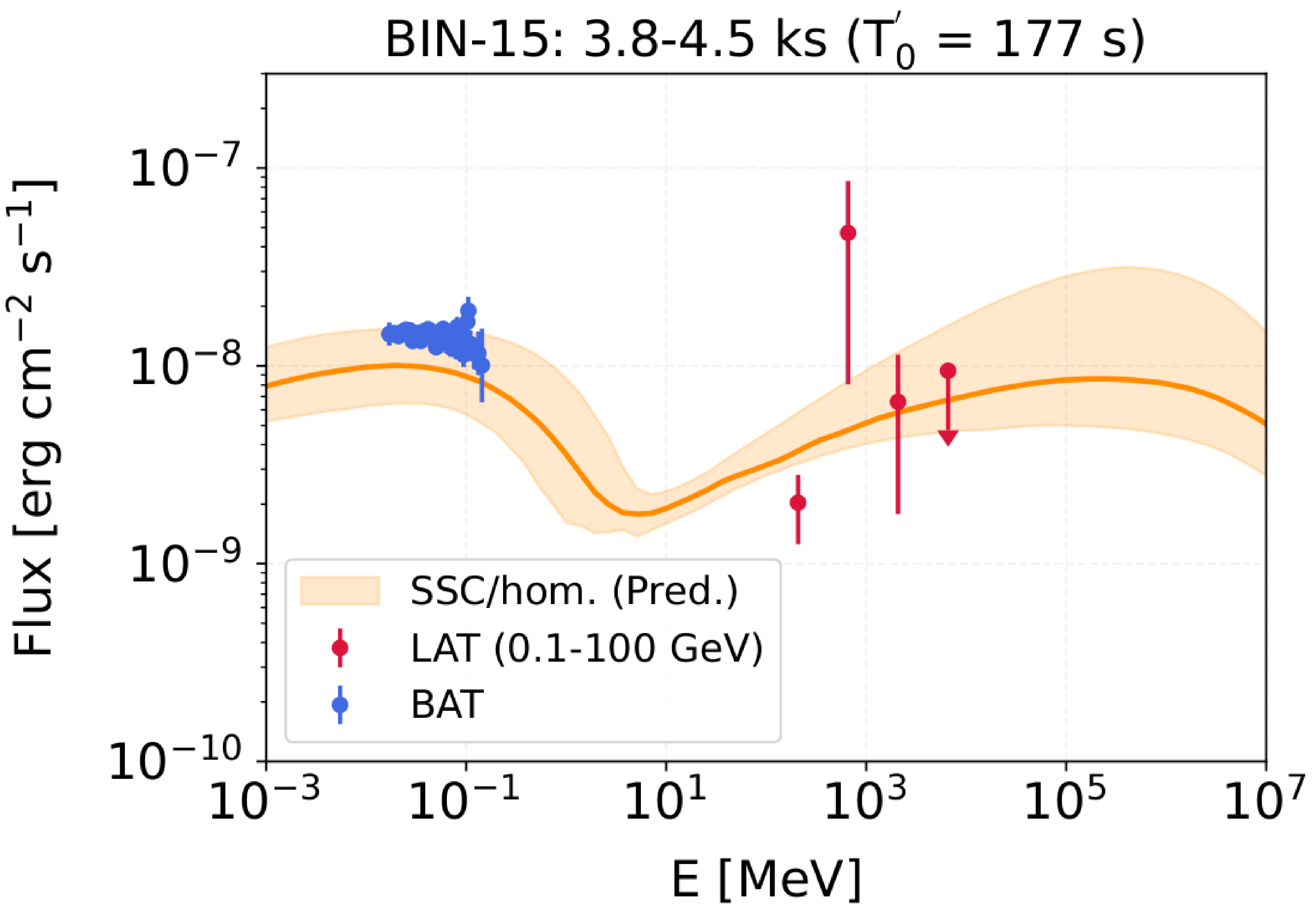
$$L'_e \sim l_e\,(t_{pred.}\,/\,t_{obs})^{-1}$$

$$R'_e \sim R_e\,(t_{pred.}\,/\,t_{obs})^{-3/4}$$

$$B' \sim B\,(t_{pred.}\,/\,t_{obs})^{3/4}$$

Modelling of the VHE component

→ estimate the SSC spectra and the light-curve of the GeV and TeV emission of early and late epoch by rescaling the SSC parameters (**self-similarity** the relativistic blast-wave dynamics in the cold medium (Blandford & McKee 1976))



→ Produce another bin (BIN-15) for which we have LAT and X-ray data, extrapolate the model and compare data and prediction and data

MeV line

1. Precursor evacuate the medium, radiate and makes a blastwave

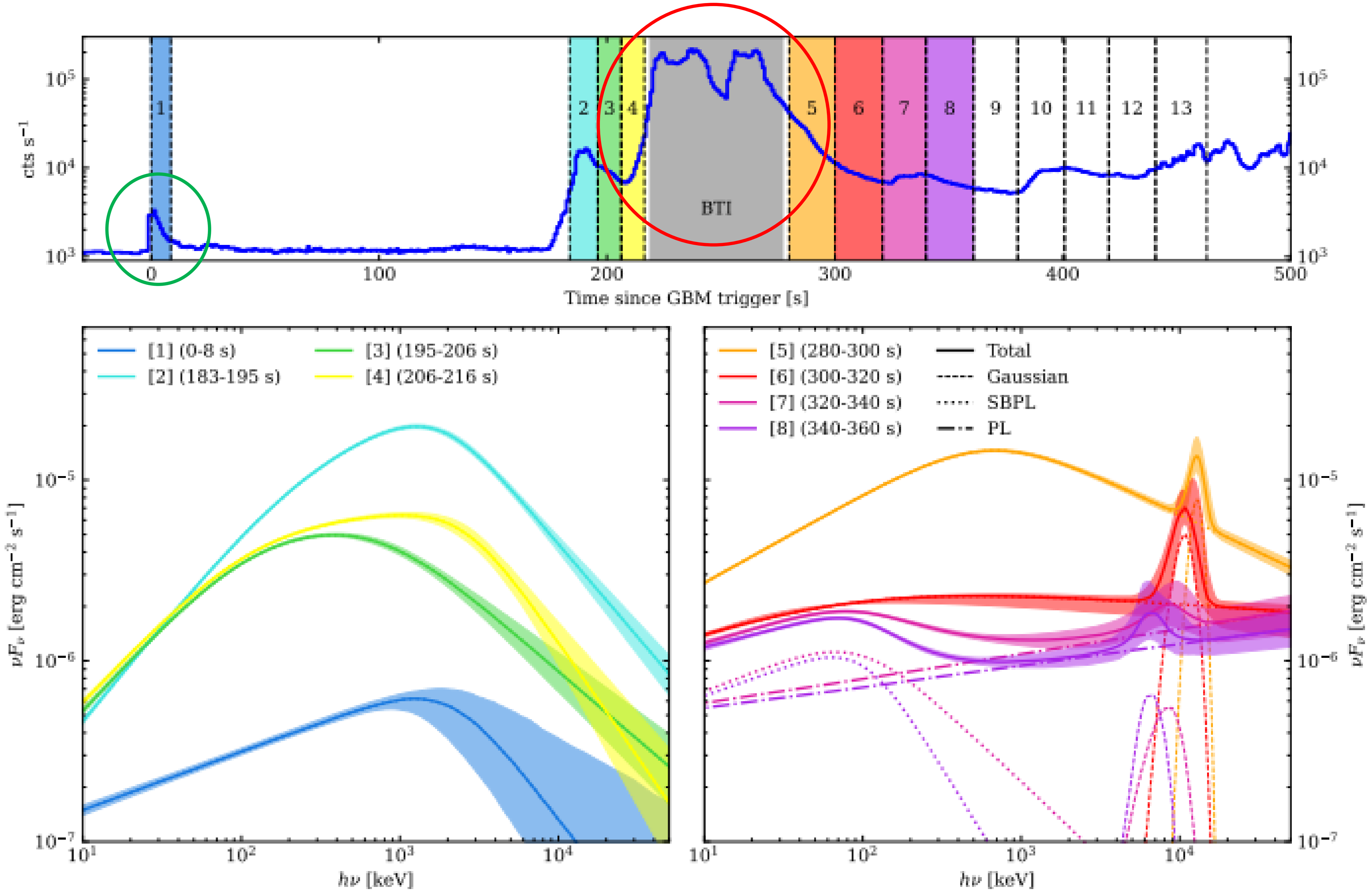
2. The main event illuminates the blastwave, producing pairs $e^- e^+$

3. $e^- e^+$ annihilation line Doppler shifted

$$L \sim \frac{10^{50} erg}{s}$$
$$h\nu \sim 10\ MeV$$

4. Evolution: High Latitude Emission (HLE)

$$\delta = \Gamma^{-1}(1-\beta\cos\theta)^{-1}$$



Ravasio, Salafia, Oganesyan et al 2024