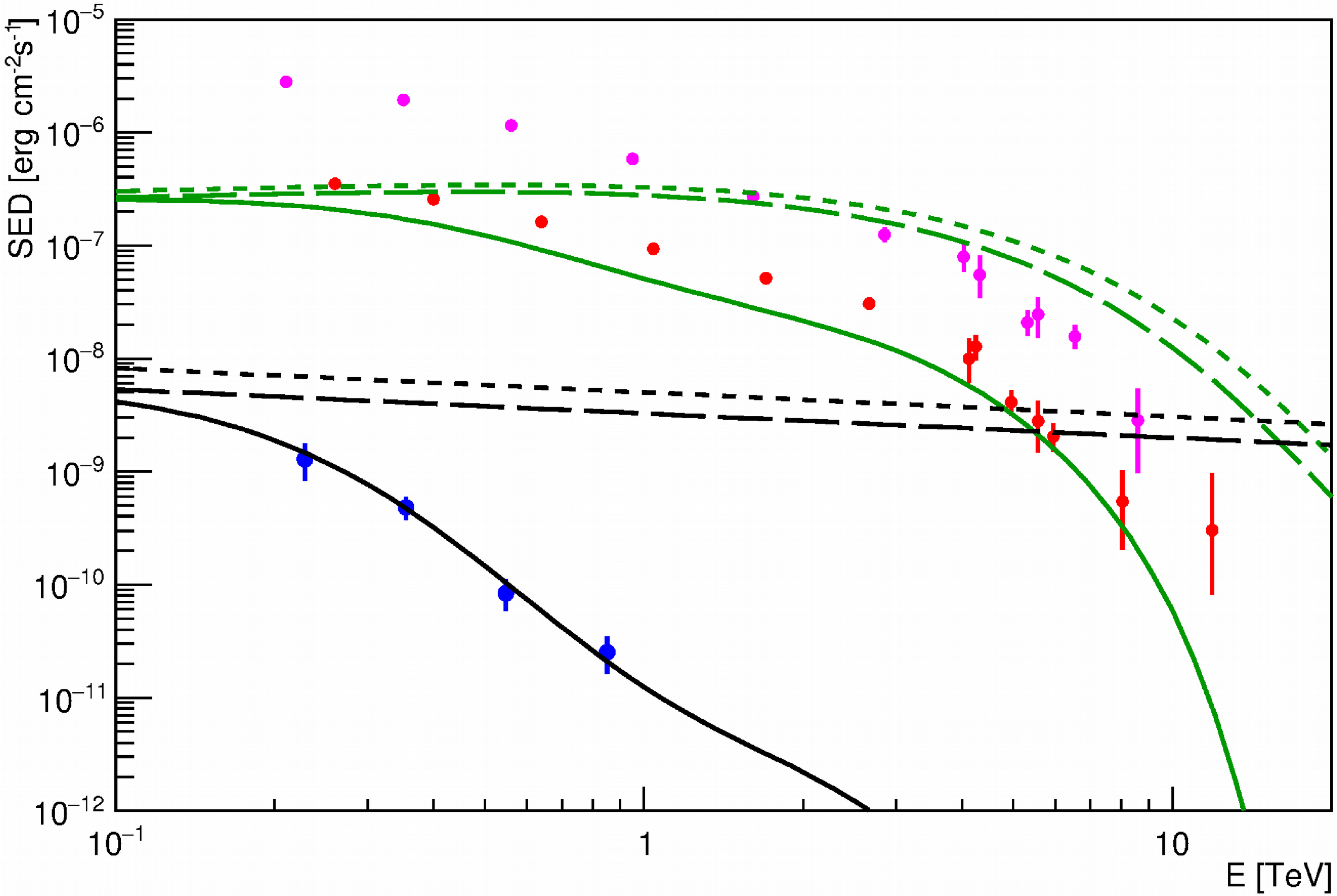
Probing the near and far environments of the brightest of all time GRB 221009A with γ-rays



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This talk is based on:

1. Dzhatdoev et al., MNRAS Lett., **527**, L95 (2024) (first constraints on the extragalactic magnetic field (EGMF) strength B from GRB 221009A)
2. Dzhatdoev et al., Phys. Rev. D, **102**, 123017 (2020) (no constraints on the EGMF strength from GRB 190114C)
3. Dzhatdoev et al. (in preparation) (2024)

A front-end simulation would be too difficult; we assume an “unveiling” approach: start from observations; then understand how the outermost “layer” of the problem works; then “peel it off”

I) Intergalactic electromagnetic cascade echo from GRB 190114C
II) Constraints on the EGMF strength from GRB 221009A:
exclusion of B < 1 aG= 10^{-18} G
III) Evidence for a cutoff in the primary γ-ray spectrum of GRB 221009A
IV) An excess at E> several TeV above “conventional” models and its possible explanation + hints from the “anomalous” 400 GeV Fermi-LAT γ-ray
V) Conclusions

I) Intergalactic electromagnetic cascade echo from GRB 190114C

Primary VHE ($E > 100$ GeV) γ-rays escaping from the source are partially absorbed on extragalactic background light (EBL) photons by means of the pair production (PP) process $\gamma\gamma \to e^+e^-$ [Nikishov, Sov. Phys. JETP, **14**, 393 (1962); Gould & Shreder, Phys. Rev., **155**, 1408 (1967)]
Secondary electrons and positrons (hereafter "electrons" for simplicity) get deflected in the EGMF and then produce cascade γ-rays by means of the inverse Compton (IC) process $e^-\gamma \to e^{-\prime}\gamma'$ or $e^+\gamma \to e^{+\prime}\gamma'$

Honda, ApJ, 339, 629 (1989); Plaga, Nature, 374, 430 (1995)
Neronov & Semikoz (2009)
Let's assume the EGMF coherence length = 1 Mpc. Various (attempts at) constraints on B from blazars (Neronov & Vovk (2010); Taylor et al. (2011); Abramowski et al. (2014); Finke et al. (2015); Ackermann et al. (2018); Podlesnyi et al. (2022); others): it is not certain if the ~1-10 aG area is excluded. Plasma (collective) losses(?) (Broderick et al., 2011)
The high-B domain (this is allowed by the intergalactic electromagnetic cascade constraints): B>10-100 fG

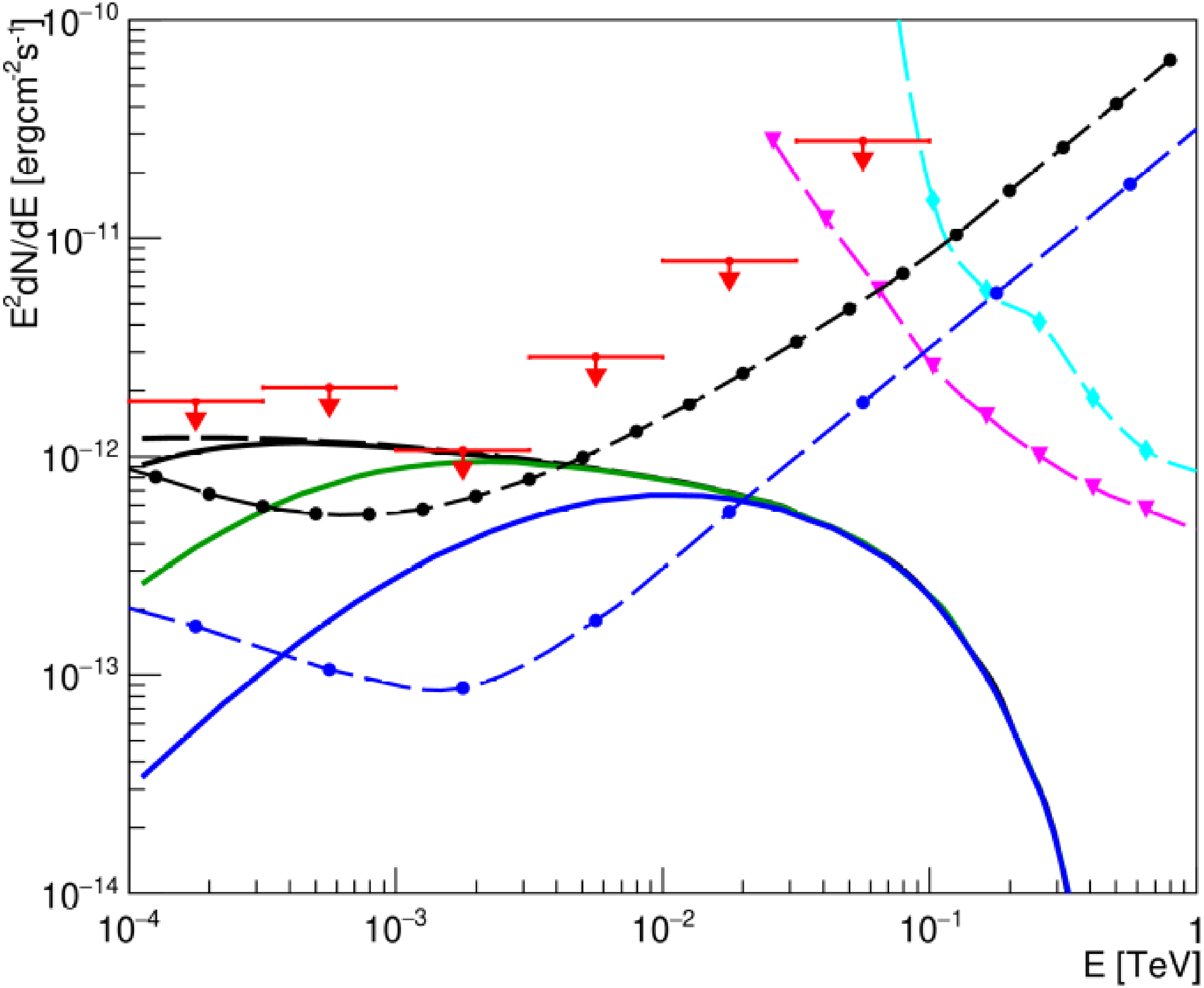
Calculations

we use the ELMAG 3.01 publicly-available code
[Blytt et al., Comput. Phys. Commun., **252**, 107163 (2020)]

EBL — 1) “nominal” model of Gilmore et al. (2012) (G12) 2) 70 % of the “original” G12 intensity
EGMF — isotropic random nonhelical turbulent field
Kolmogorov spectrum, Gaussian variance B
200 field modes
minimal spatial scale — 5×10^{-4} Mpc
maximal spatial scale — 5 Mpc
full three-dimensional propagation

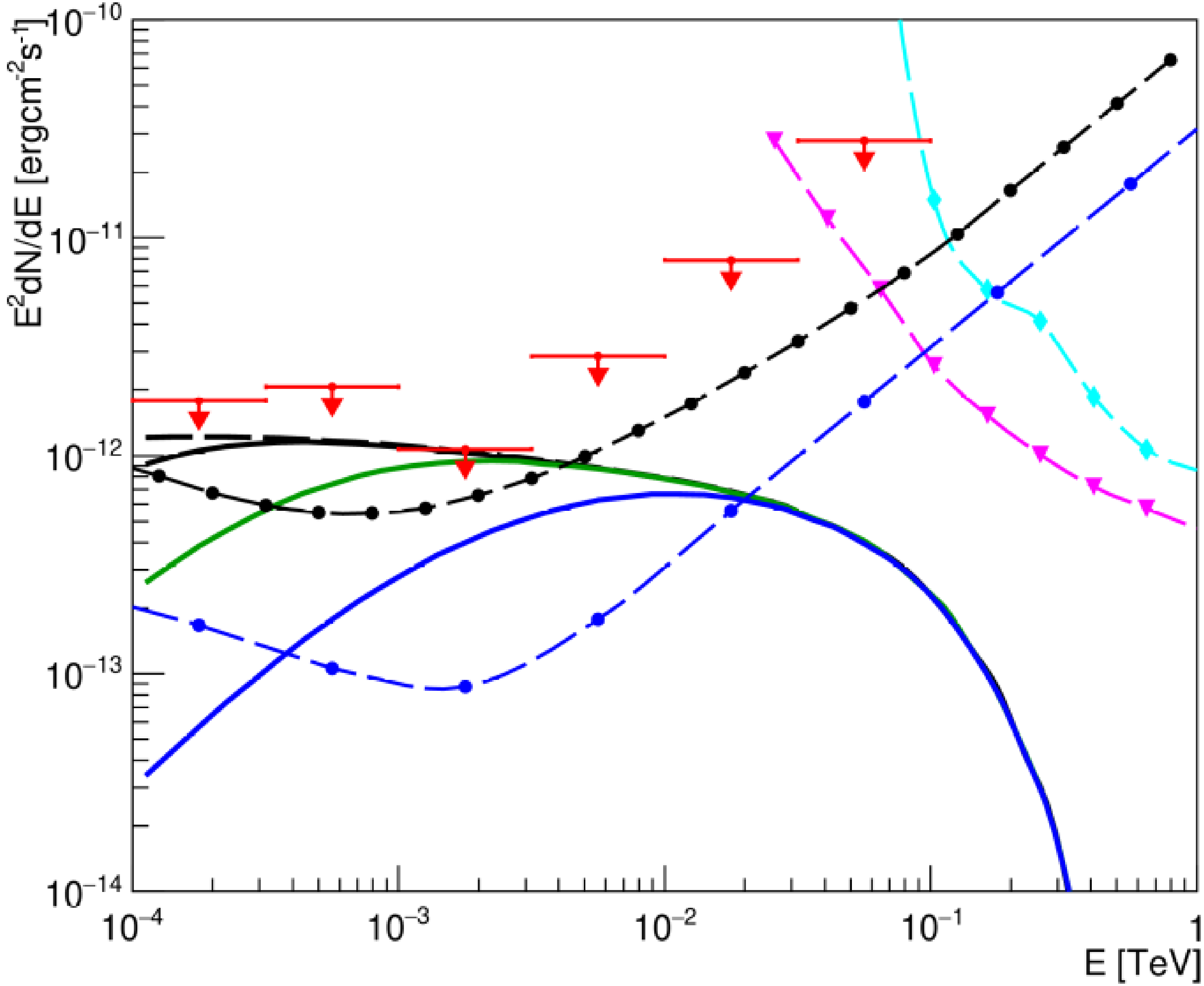
We obtain observable SEDs of intergalactic cascades over the time period of 1 month. Subtracting γ-rays that have time delay less than 20000 s would decrease the observable intensity and thus (as we will show) would reinforce our conclusions.

95 % Fermi-LAT upper limits on SED of GRB 190114C (20000 s – 1 month); observable cascade SEDs (B= 0 – dashed black, B= 10^{-20} G – solid black, B= 10^{-19} G, B= 10^{-18} G).



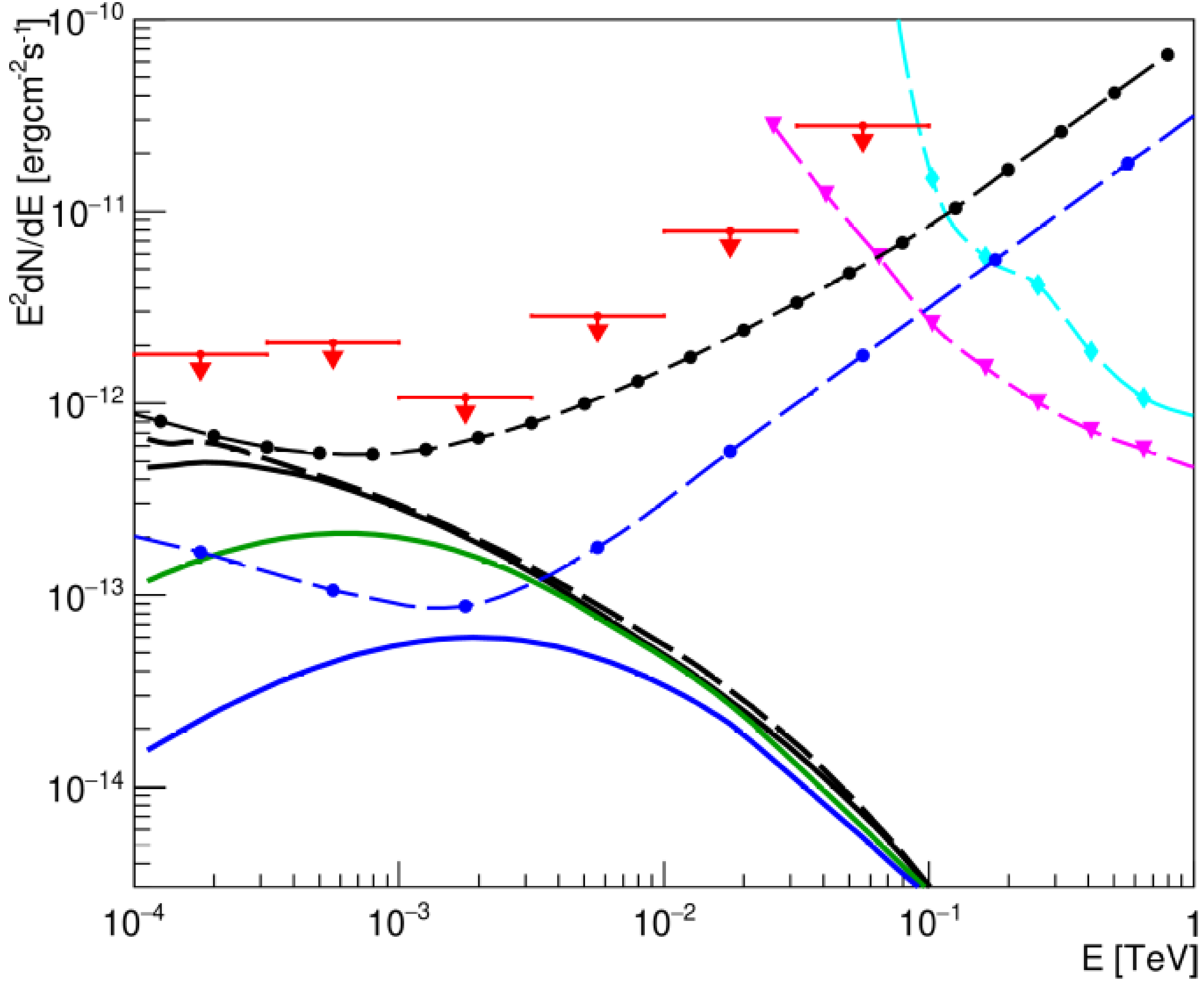
No constraints on B could be obtained from GRB 190114C

CTA: 5 hours of observation, 5σ (20 deg, 60 deg)
MAST project (“Massive Argon Space Telescope”, Dzhatdoev & Podlesnyi, 2019): circles; 2σ, 5σ



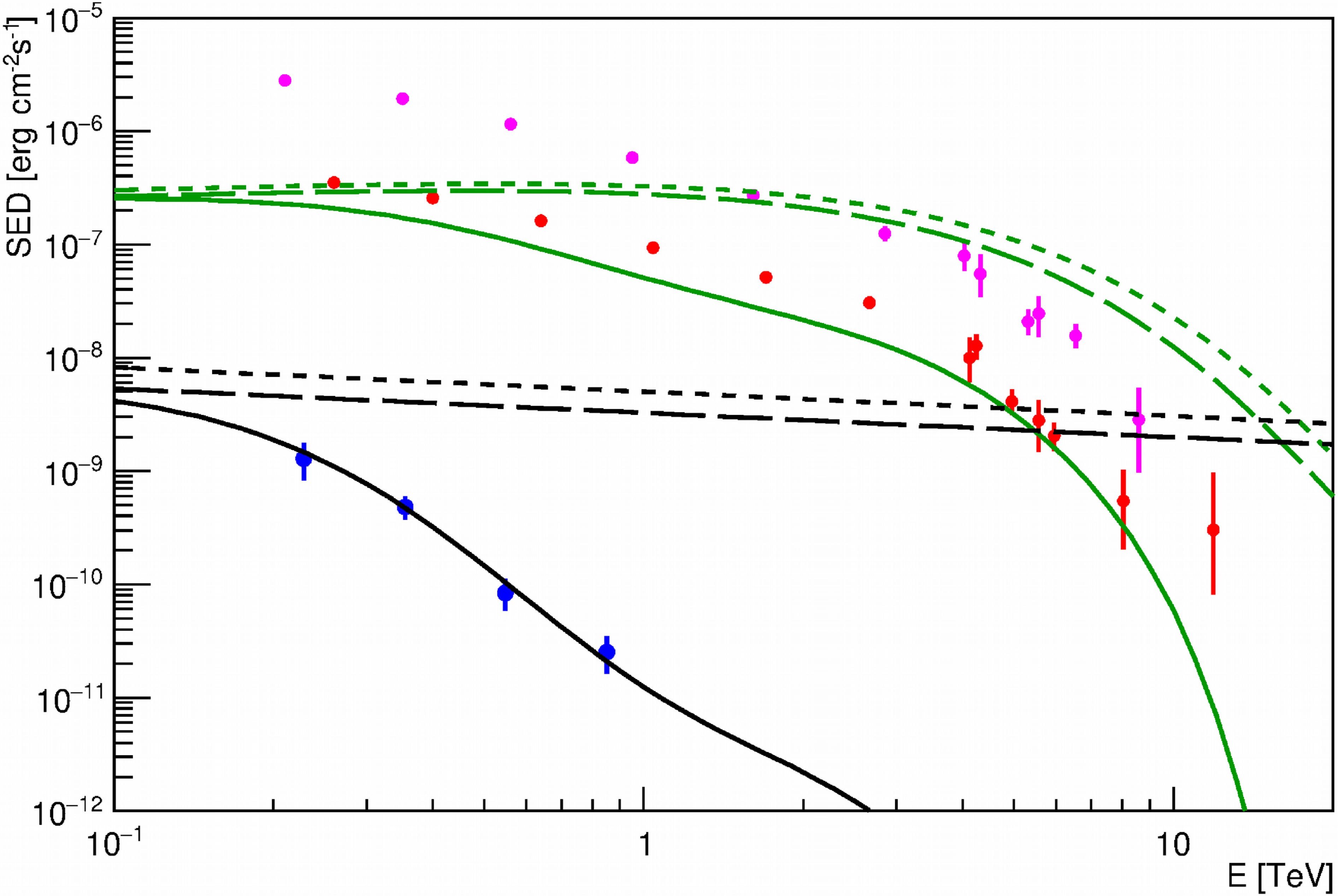
The same for the 70 % G12 EBL

The cascade signal is not detectable even for B=0



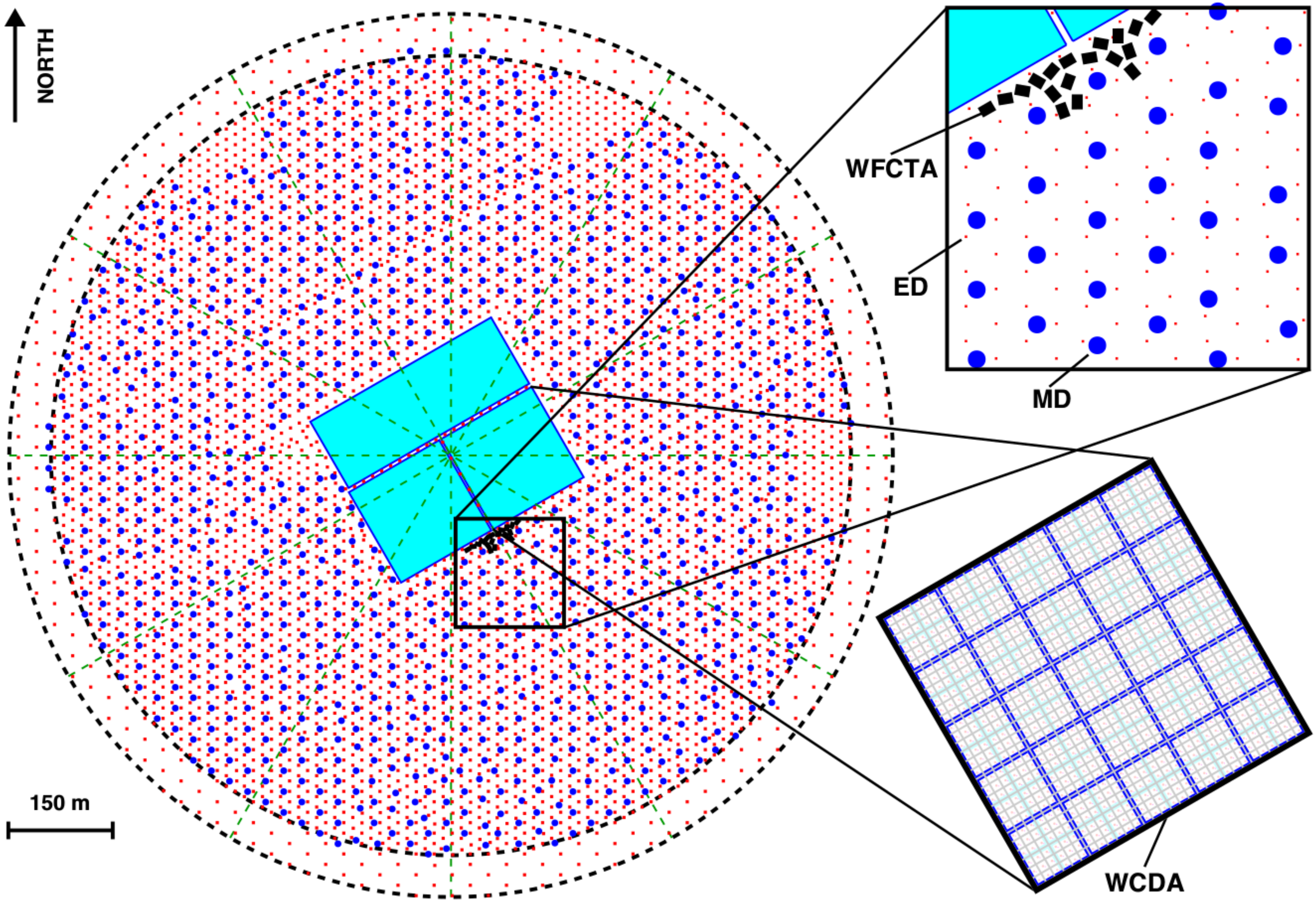
II) Constraints on the EGMF strength from GRB 221009A

GRB 221009A (230-300 s; 300-900 s; average fit for 0-2000 s)
vs. GRB 190114C (MAGIC, 2019): comparison of VHE spectra

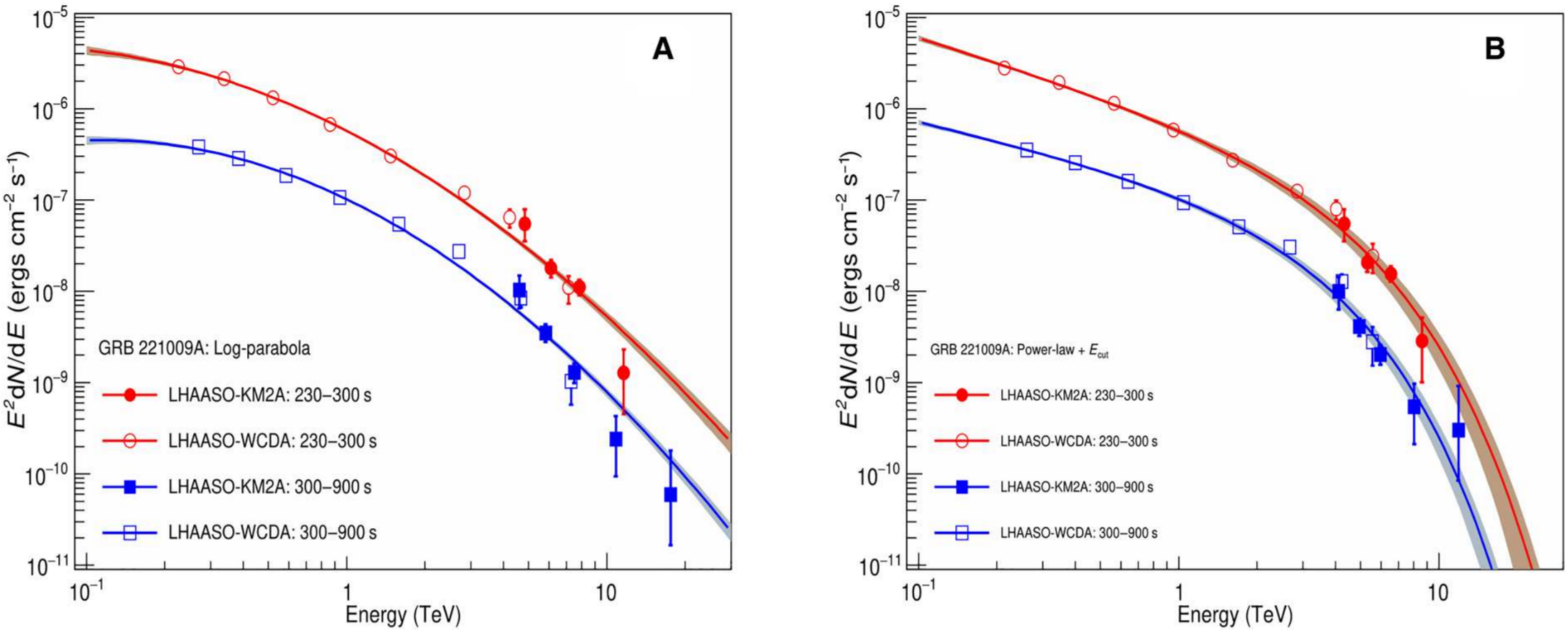


A possible cutoff is present in the intrinsic spectrum of GRB 221009A

The layout of LHAASO (Cao et al., 2021)

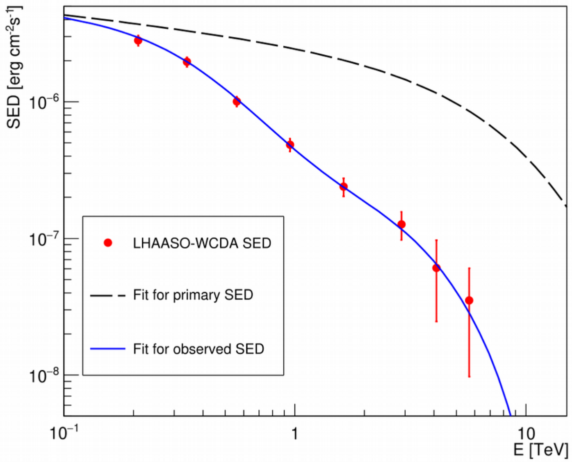


LHAASO-(WCDA+KM2A) spectra (Cao et al., 2023b)

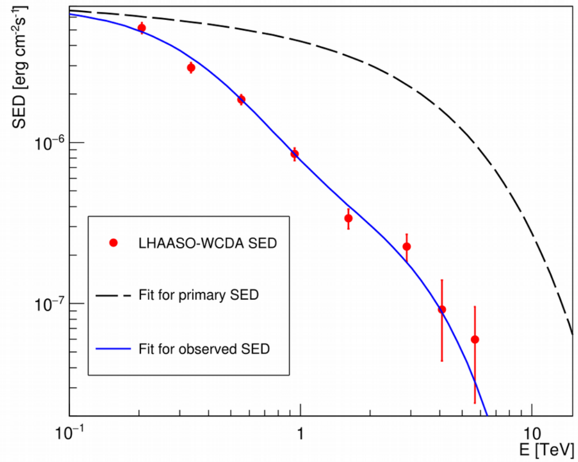


LHAASO-WCDA (Cao et al., 2023a) presented the spectra over five time intervals (all from 231 to 2000 s); these will be discussed below

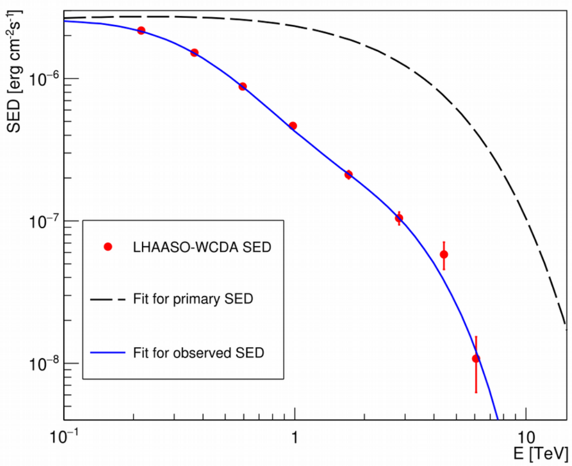
Before the publication of Cao et al., 2023a; Cao et al., 2023b there were many works discussing possible “new physics” effects (γ-ALP mixing, LIV, etc.). We do not discuss these efforts here due to limited time



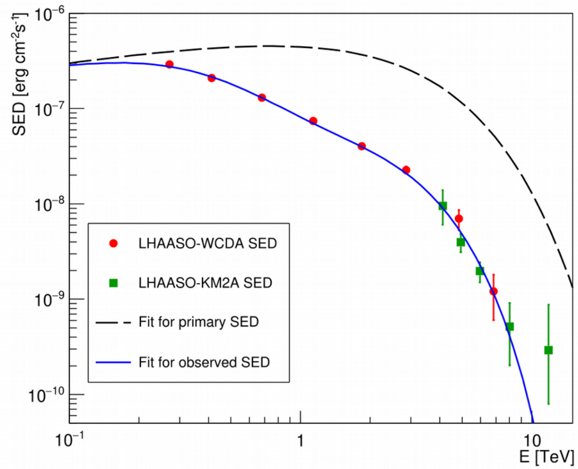
(a) 231 – 240 s



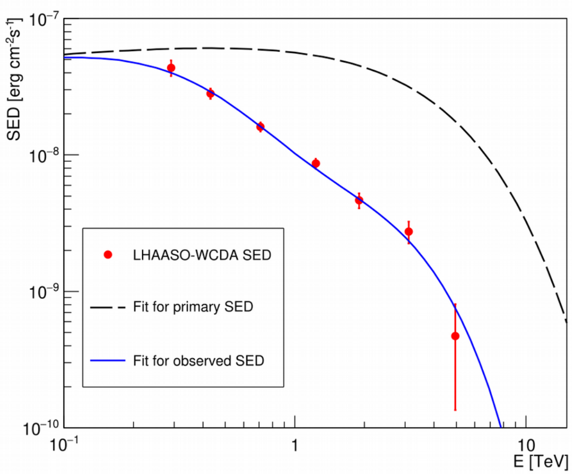
(b) 240 – 248 s



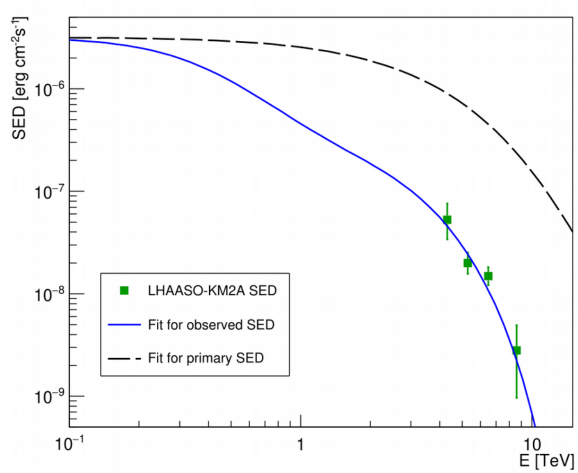
(c) 248 – 326 s



(d) Circles: 326 – 900 s; squares: 300 – 900 s re-scaled to 326 – 900 s



(e) 900 – 2000 s



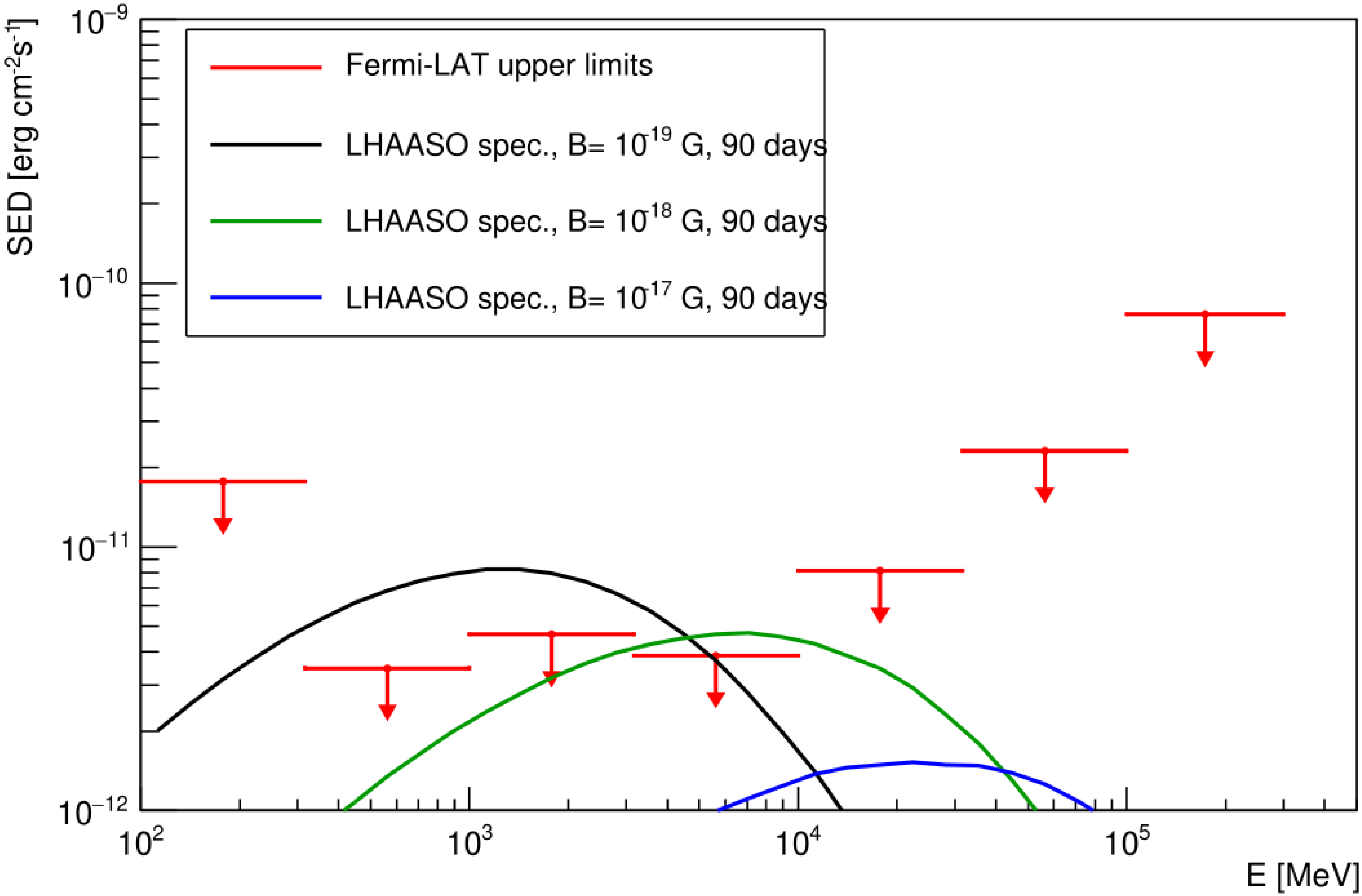
(f) Squares: 230 – 300 s, re-scaled to 231 – 326 s, for which the curves are plotted

GRB 221009A
SEDs= E^2dN/dE:

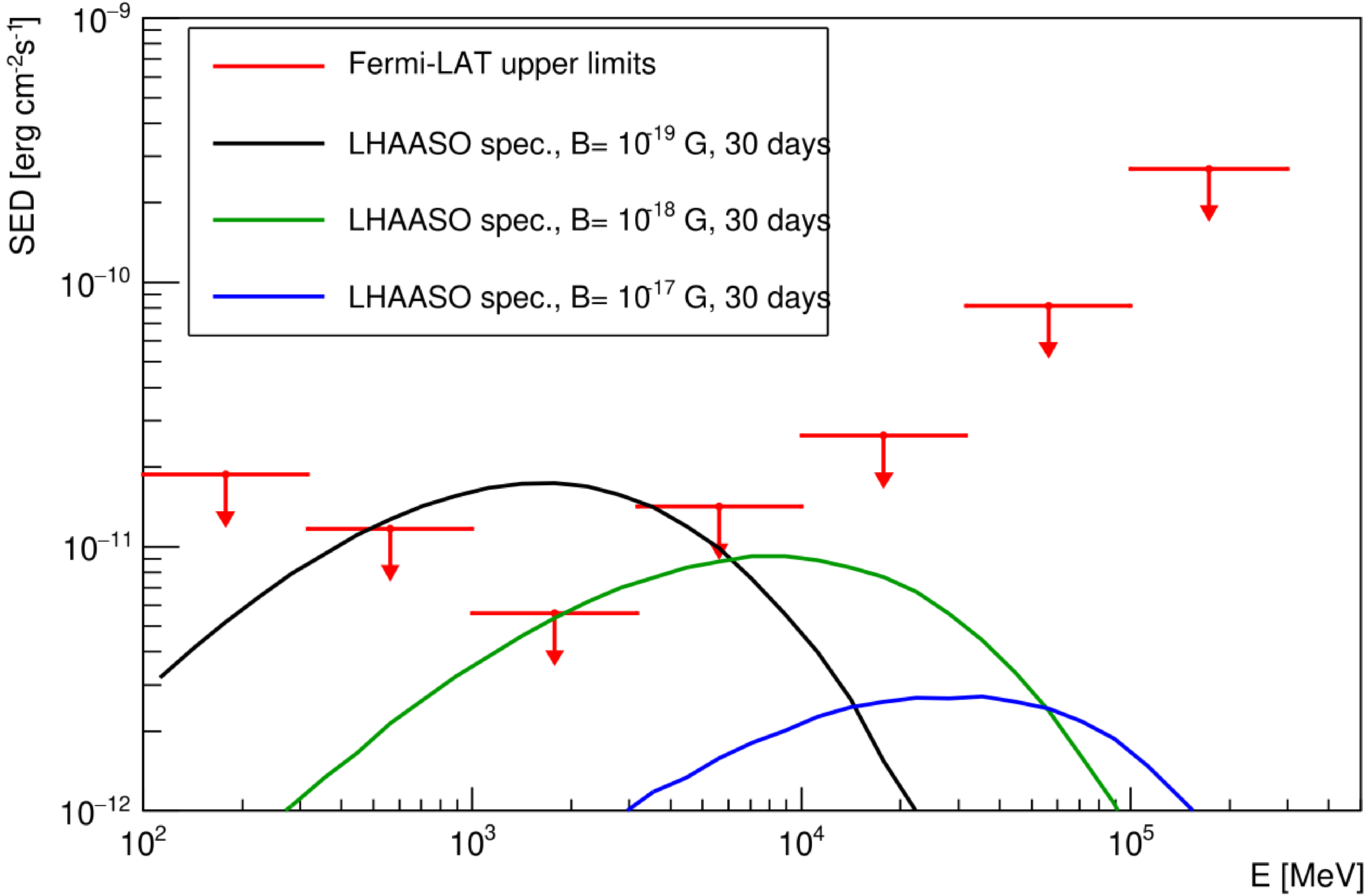
LHAASO-WCDA and LHAASO-KM2A spectra for various time intervals
[Cao et al., Science, **380**, 1390 (2023)]
[Cao et al., Science Advances, **9**, eadj2778 (2023)]

GRB 221009A for the “nominal” G12 EBL model:

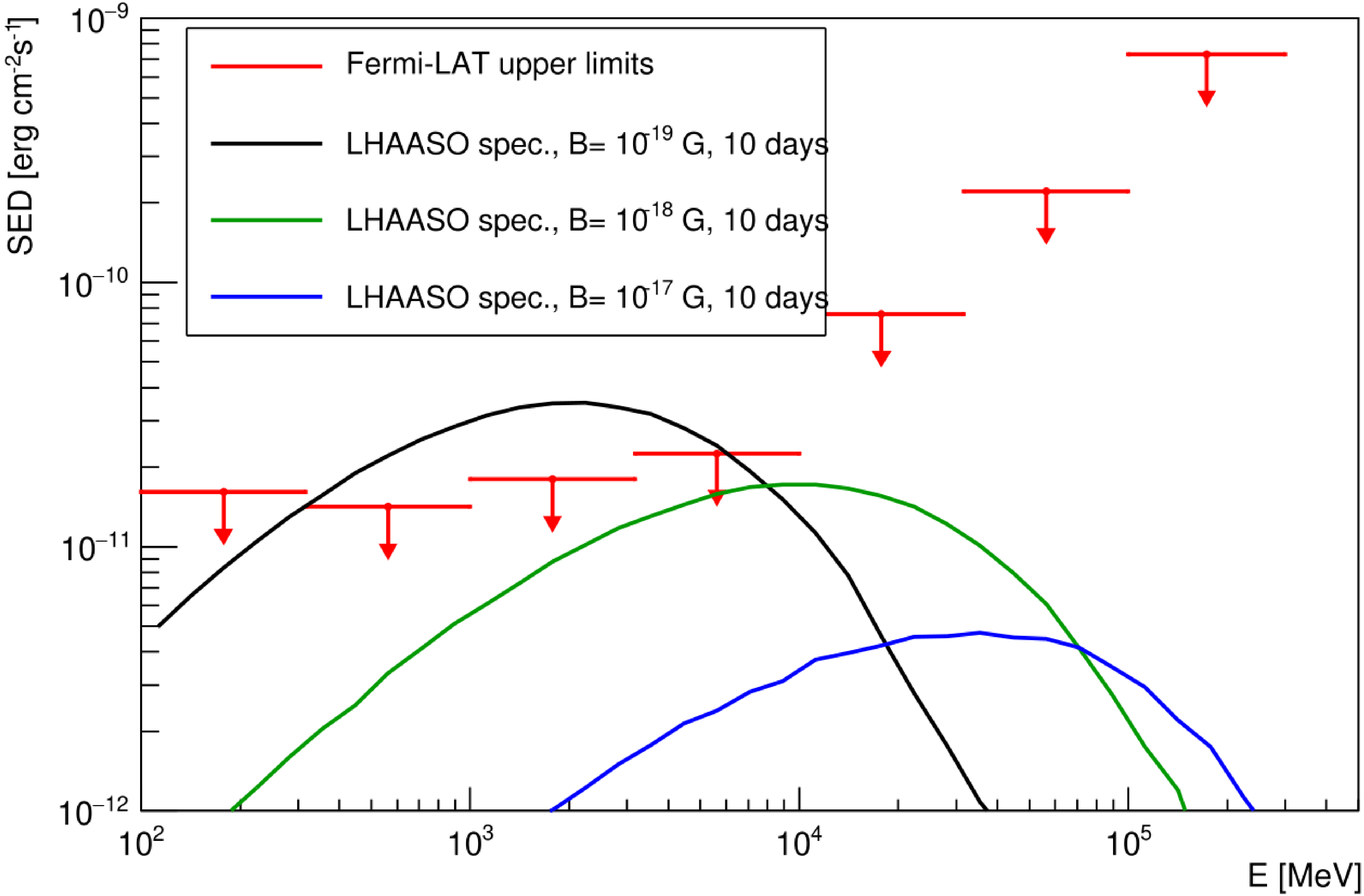
B= 1 aG is excluded!

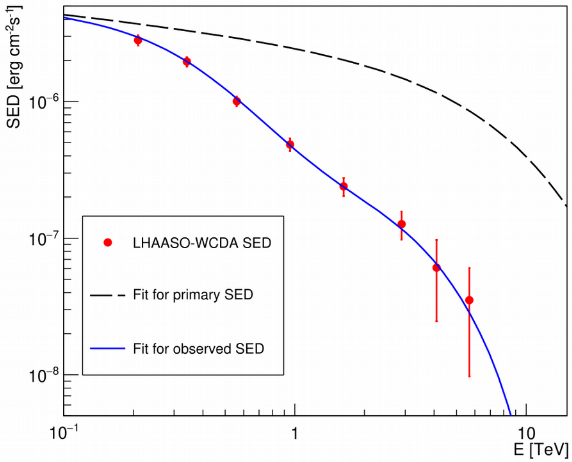


The same for the time window of 30 days



The same for the time window of 10 days





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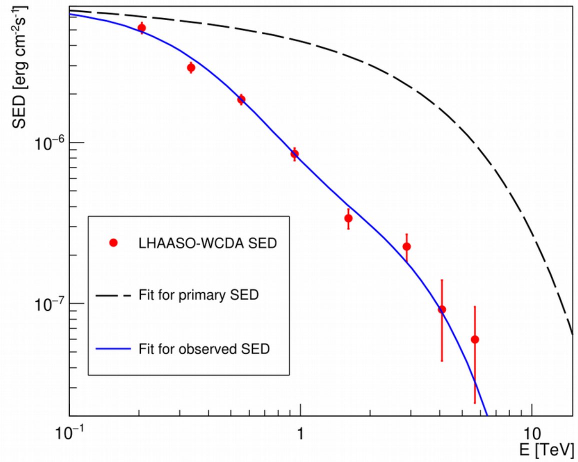
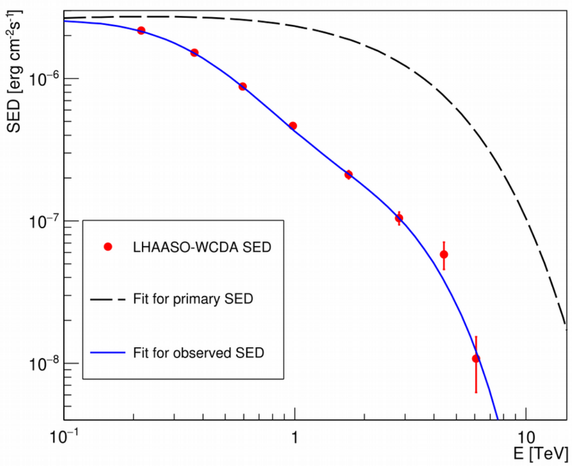


(b) 240 – 248 s



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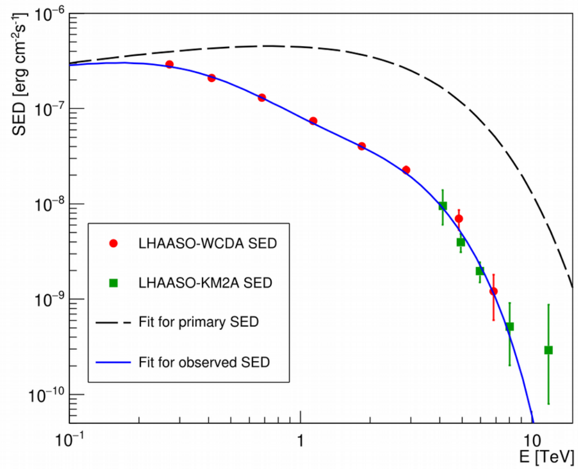

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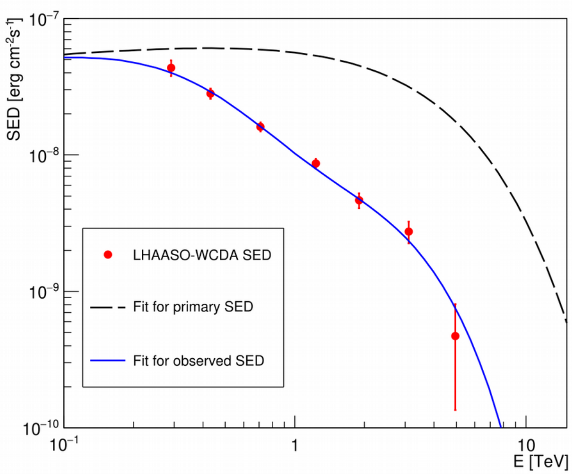
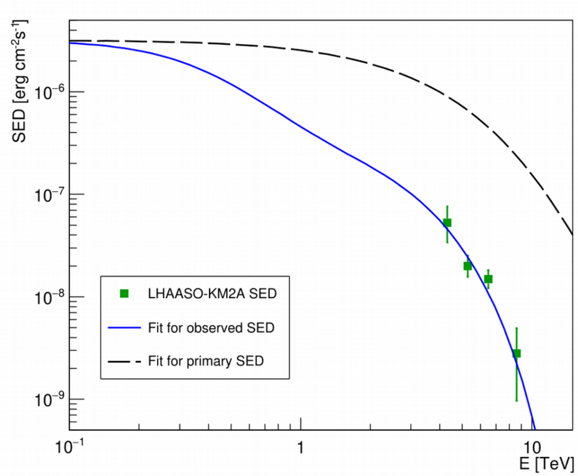


(e) 900 – 2000 s



(f) Squares: 230 – 300 s, re-scaled to 231 – 326 s, for which the curves are plotted

III) The primary γ-ray spectrum of GRB 221009A

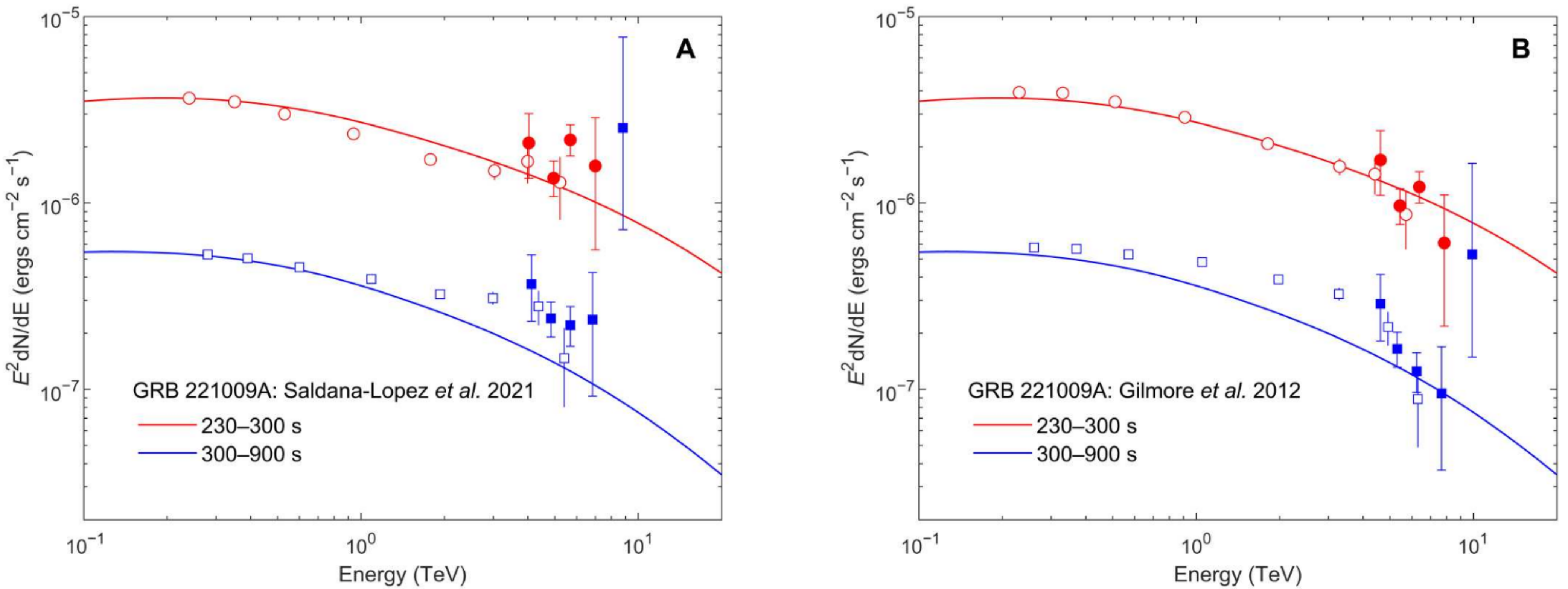
The intrinsic spectra reveal a clear high-energy cutoff

Here the Gilmore et al. (2012) (G12) model was utilised. The same conclusion holds for the Saldana-Lopez et al. (2021) (S21) EBL model

S21, spectrum N4:
K = 1.0: p= $2.42\cdot10^{-8}$
K = 1.2: p= $5.46\cdot10^{-7}$
K = 1.4: p= $2.81\cdot10^{-6}$
Caveat: systematic uncertainties are not known well enough

There is a good agreement with the model for the first time period (for at least one EBL model option); excess of observed γ-rays at several TeV (or 10 TeV, depending on the EBL model option) for the second time period

The Klein-Nishina effect is appreciable at E = 100 GeV – 1 TeV already
We note that the excess appears only after 300 s
Possible explanations:
1) the need to correct the EBL model
2) γ-ALP oscillations
3) "conservative" GRB physics (without beyond-the-SM physics!)



An excess at E> several TeV above "conventional" models?
A possible explanation: ~EeV neutrons escaping from the prompt emission zone interacting with the star forming region material

A mechanism for the escape of cosmic rays from dense supernova envelopes

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Institute for Nuclear Research, USSR Academy of Sciences, Moscow and Institute for Space Research, USSR Academy of Sciences, Moscow

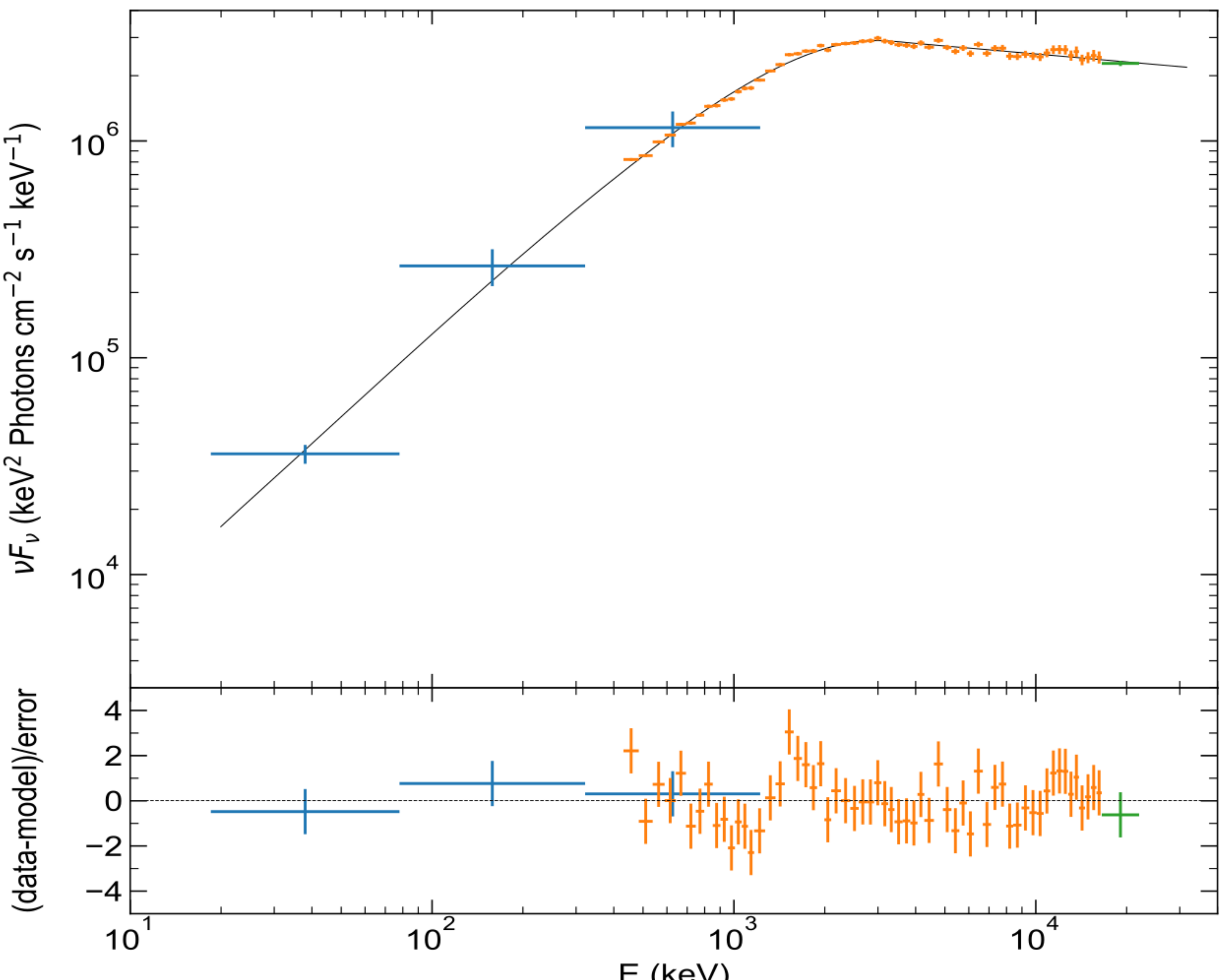
(Submitted February 7, 1977)

Pis'ma Astron. Zh. **3**, 267–270 (June 1977)

Accelerated protons can escape from a dense supernova envelope surrounding a young pulsar if nuclear collisions convert them into neutrons, which then will not be confined by the magnetic fields. If a supernova were to explode in the Galaxy, the flux of neutrons emanating from its envelope at energies $E > 10^{18}$ eV could be detected by means of extensive air showers.

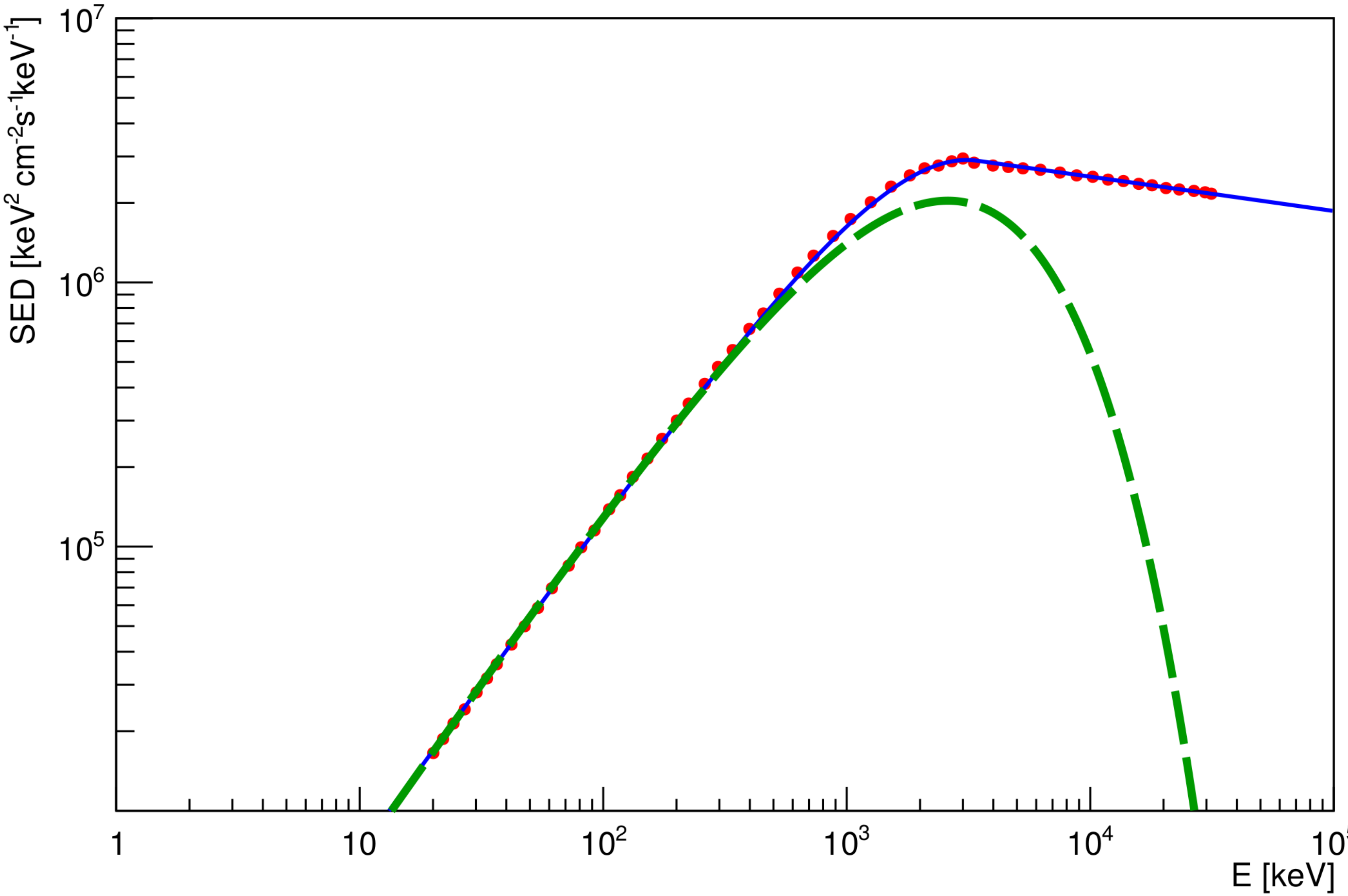
Eichler, Nature, **274**, 38 (1978)
Kirk & Mastichiadis, A&A, **213**, 75 (1989)
Tkaczyk, ApJ Suppl., **92**, 611 (1994)
Atoyan & Dermer, ApJ, **586**, 79 (2003)
Dermer & Atoyan, A&A, **418**, L5 (2004)

Konus-WIND and SRG/ART-XC observations (225-233 s; Frederiks et al., 2023); low-energy $dN/dE = K \cdot E^{-0.76}$

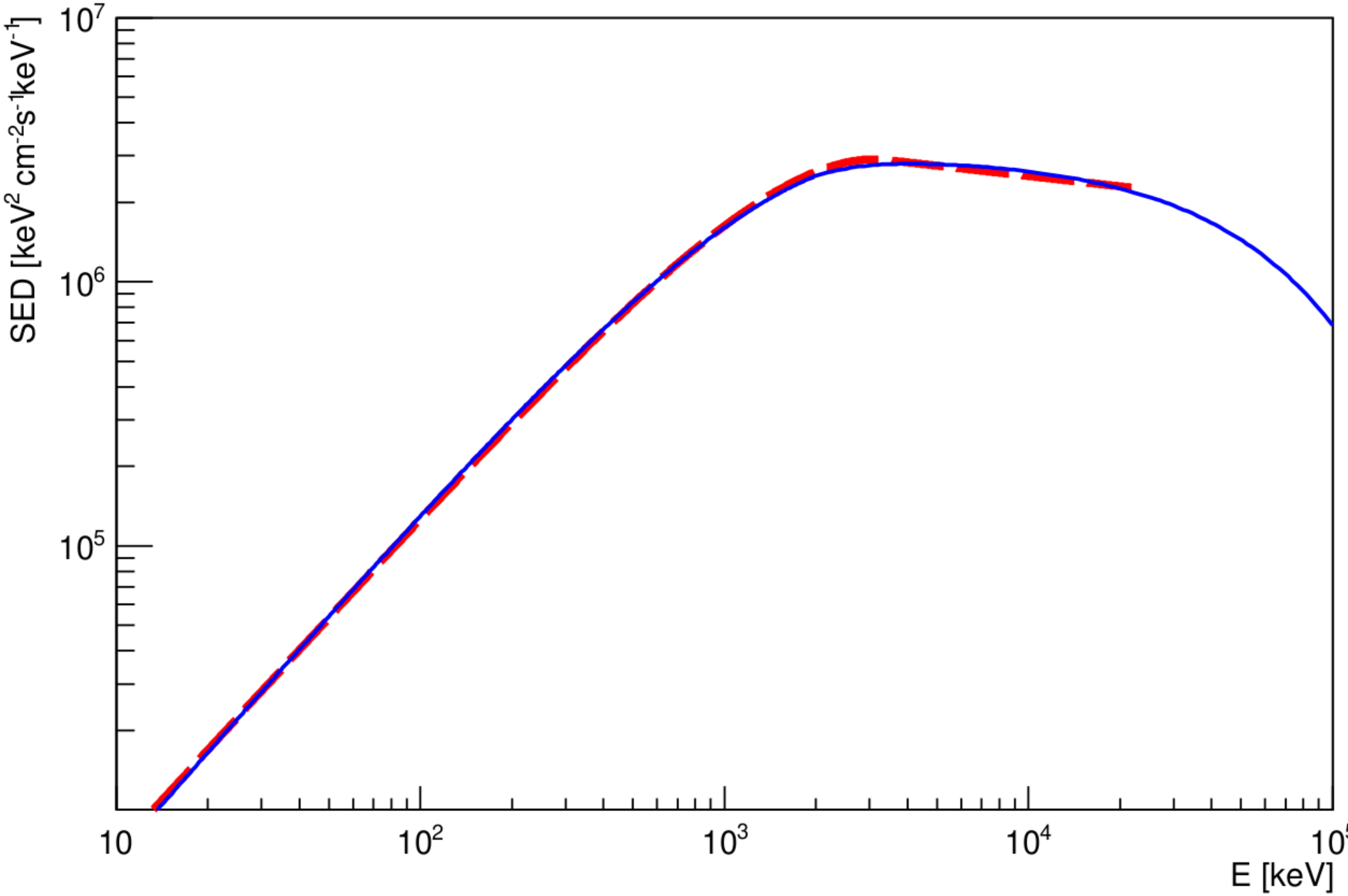


Low-energy part of the spectrum Konus-WIND and SRG/ART-XC observations (225-233 s; Frederiks et al., 2023); approximation below is from Derishev & Aharonian (2019)

$$\left(\frac{d\dot{N}}{d\omega}\right)_t = \frac{\alpha}{3}\frac{1}{\gamma^2}\left(1 + \frac{1}{x^{2/3}}\right)\exp\left(-2x^{2/3}\right), \text{ where } x = \frac{\omega}{\omega_0};\ \omega_0 = \frac{4}{3}\gamma^2\frac{eB_0}{m_e c}$$



The main episode of the prompt emission (duration 8.2 s, start at 225 s):
measured (main episode, approximation; Frederiks et al., 2023);
internal electromagnetic cascade model + cutoff at 100 MeV



The synchrotron scenario is viable if there is a minimal energy of the radiating electrons ~ 1 GeV and there is an electron re-acceleration process in operation

The multimessenger connection (photohadronic interactions)
see e.g. Troitsky, Phys.-Usp., **64**, 1261 (2021)

$\pi^0 \to \gamma\gamma$

$\pi^+ \to \mu^+ \nu_\mu$

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

Near the threshold: $\approx 1/2\ \pi^0$, $\approx 1/2\ \pi^+$

π^- are almost absent

the fractions of the total energy $F_\gamma / F_\nu \approx 7/5$

often the factor 4/3 is assumed

Neutrino constraints (Abbasi et al., 2023) allow for at least 1/3 of the observed prompt emission to be produced in hadron-initiated cascades for the Lorentz factor > 1200.

Inelasticity of the photopion process is $\approx$15 %; f $\approx$9 % of the proton energy is transferred to cascade γ-rays. $\approx(1/2)\cdot 85$ % = 42.5 % of the proton energy is carried by neutrons. The pp inelastic cross section at 100 PeV is $\approx$70 mb; the corresponding optical depth is $N_H/(1.4\cdot 10^{25}) = 0.01$ for $N_H = 1.4\cdot 10^{23}$ nucleon/cm^2; electrons carry $\approx$20 % of the neutron energy

The multimessenger connection (photohadronic interactions)
see e.g. Troitsky, Phys.-Usp., **64**, 1261 (2021)

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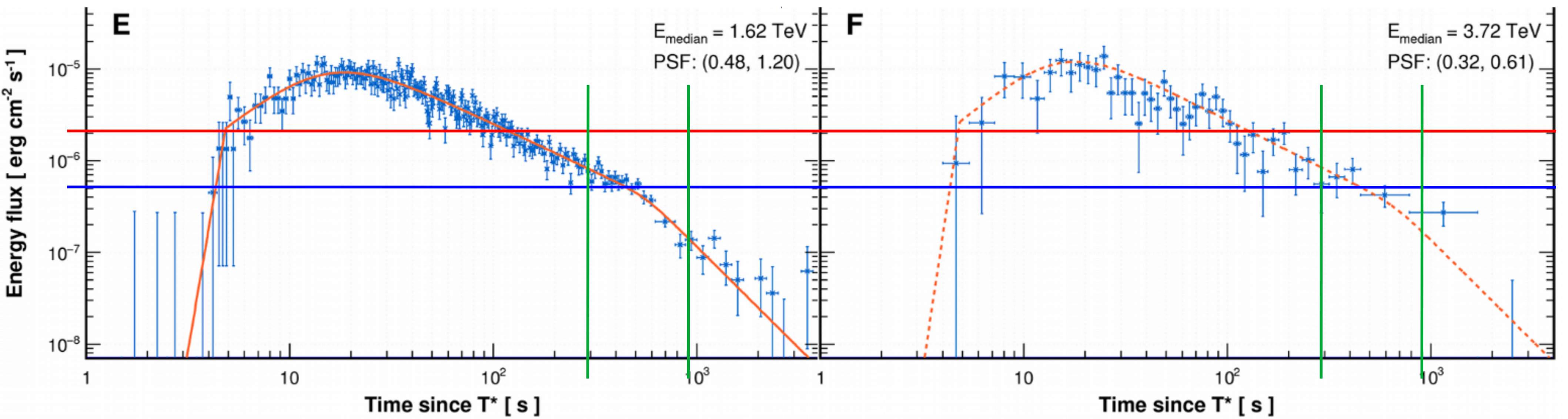
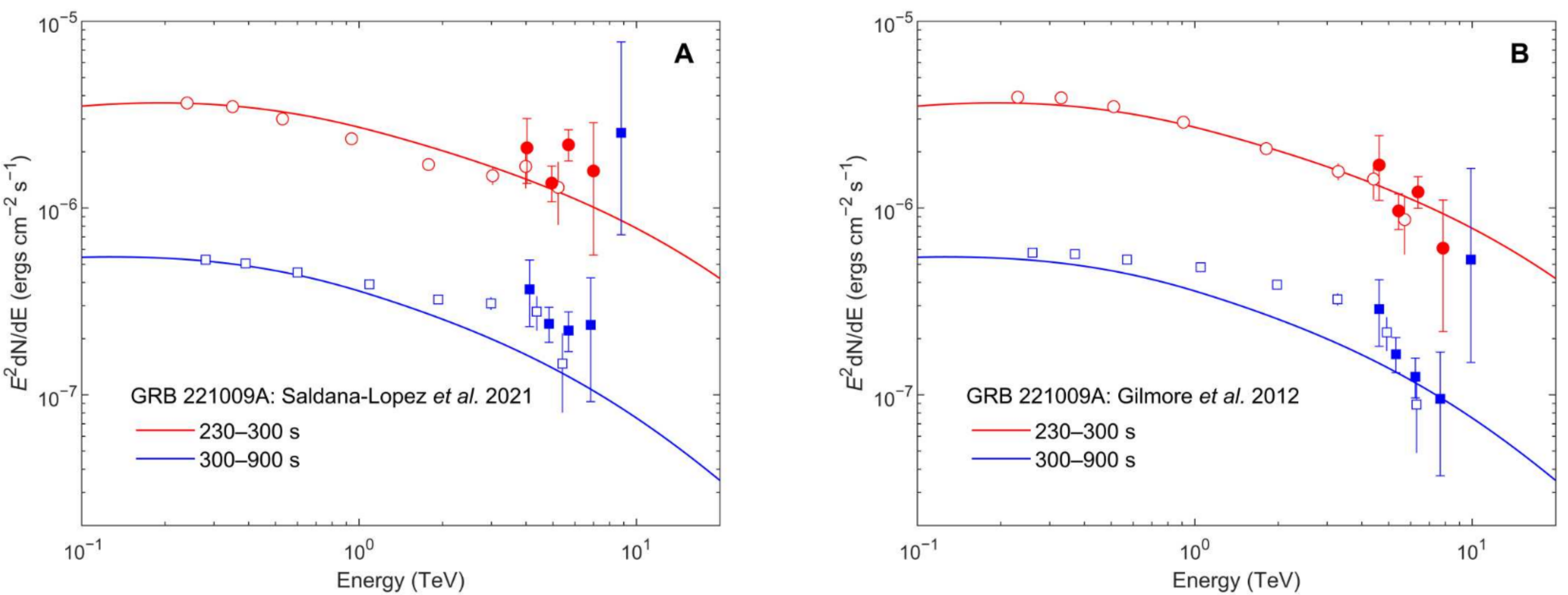
$f = 8.5 \cdot 10^{-4}$ of the primary proton energy is transferred to electrons and radiated as synchrotron photons (we assume $B_{SFR} = 1$ mG). The fluence of the "hard" γ-ray component is $9.4 \cdot 10^{-3}$ ($\approx$1 %) $\rightarrow$ $1.2 \cdot 10^{-3}$ erg/cm^2 of the hadronic prompt emission fluence (0.13 erg/cm^2 for the main prompt emission episode). Over 600 s this gives the flux of $2 \cdot 10^{-6}$ erg/(cm^{2}s)



upper line: 100 % (lower line: 25 %) of the prompt emission is of a hadronic nature

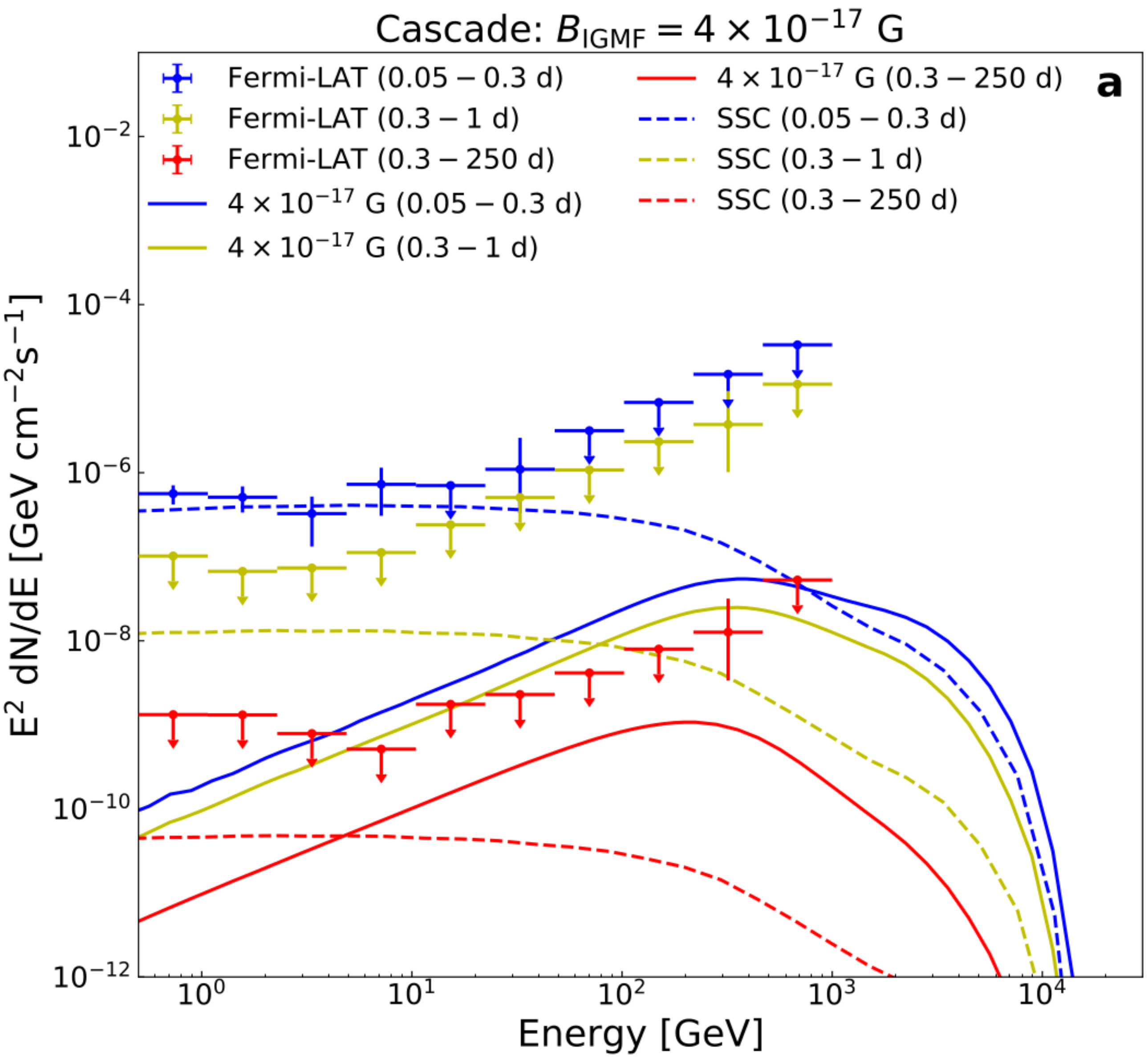
typical energy of synchrotron γ-rays ≈15 TeV·$(E_{p\text{-}max}/10\ \mathrm{EeV})^2$

pulse width ≈600s·$(R/1.8\cdot10^{17}$ cm); $1.8\cdot10^{17}$ cm ≈ the expected size of the SFR bubble



A 400 GeV γ-ray-like delayed event (33 ks after the Fermi-GBM trigger) [Xia et al., Nature Communications, 2024]

A viable scenario here: the afterglow-generating region enters a denser (~10^3–10^5 $1/cm^3$) matter (Ramirez-Ruiz et al., 2001) → external photon field (reflected photons) → a new Compton component with a very narrow angular distribution



Conclusions

I. The first meaningful constraint on the EGMF strength from any GRB was obtained: $B > 1$ aG

II. The intrinsic spectrum of GRB 221009A probably has a cutoff at E= several TeV

III. No evidence for new physics from intergalactic γ-ray propagation

IV. A hard additional γ-ray component could be produced by neutrons escaping from the fireball and then interacting with the SFR matter; the produced electrons radiate observable 1-10 TeV synchrotron photons

V. A delayed (~0.4 day) VHE emission could be caused by the afterglow-generating region entering a denser ($>10^3$–10^5 1/cm^3) matter from the star wind bubble (external Compton on reflected photons?)

This work was supported
by the Russian Science Foundation, grant no. 22-12-00253

Additional slides

Abbasi et al. (IceCube) (2023)

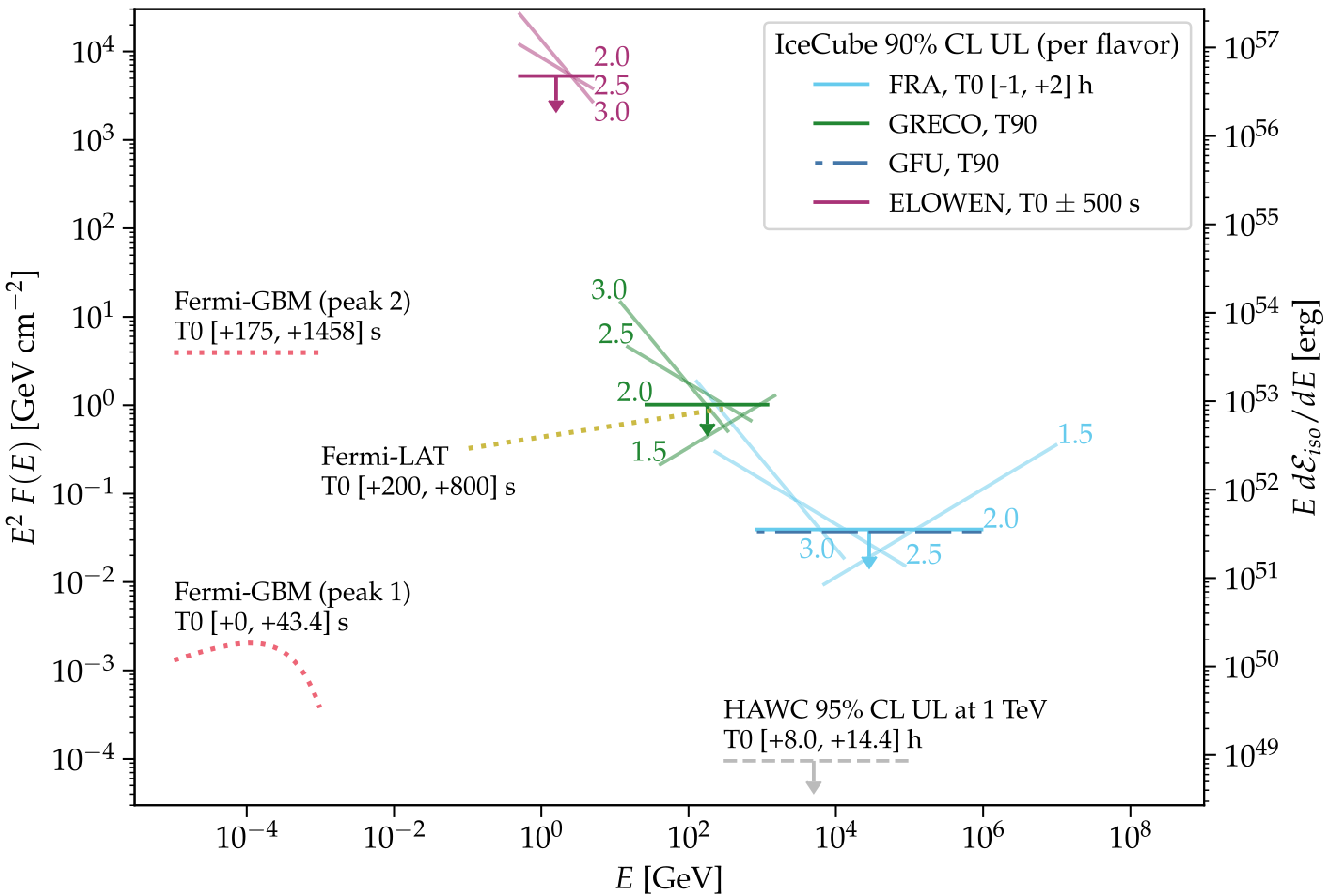


Table 1
Models for the Time-integrated Neutrino Flux $F(E)$ and Energy Ranges Probed by Different Data Sets

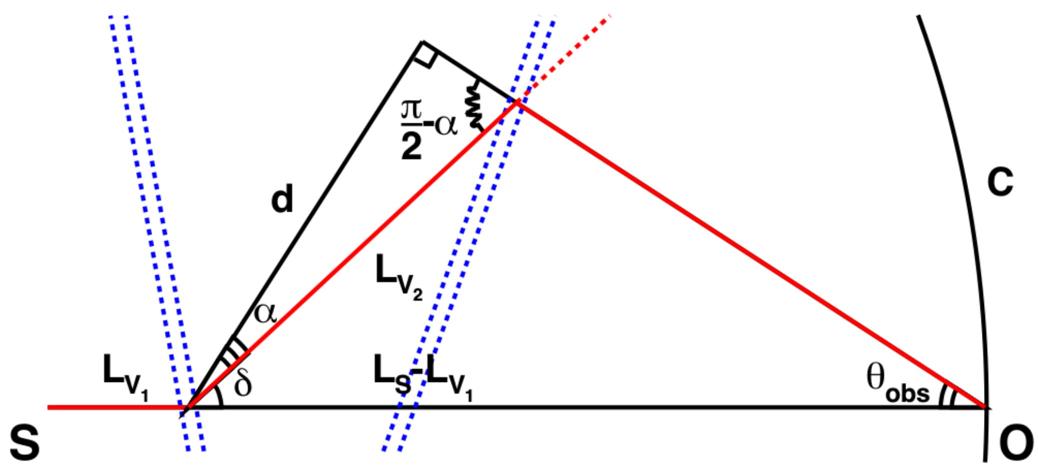
Data Set	Time-integrated Neutrino Flux Model		
	Power Law: $F(E) \propto E^{-\gamma}$ for $E_{\min} \leqslant E \leqslant E_{\max}$		
	γ	$E_{\min}$	$E_{\max}$
GFU[a]	1.5	6.8 TeV	9.9 PeV
	2.0	0.83 TeV	0.96 PeV
	2.5	0.23 TeV	0.086 PeV
	3.0	0.13 TeV	0.013 PeV
GRECO[a]	1.5	40 GeV	1.5 TeV
	2.0	26 GeV	1.2 TeV
	2.5	15 GeV	0.70 TeV
	3.0	11 GeV	0.35 TeV
ELOWEN	2.0–3.0	0.5 GeV	5.0 GeV
SNDAQ	Quasi-thermal : $F_{\bar{\nu}_e}(E) \propto E^2 \exp(-3E/\langle E \rangle)$ $E \simeq \langle E \rangle \simeq (10\text{–}20)$ MeV		

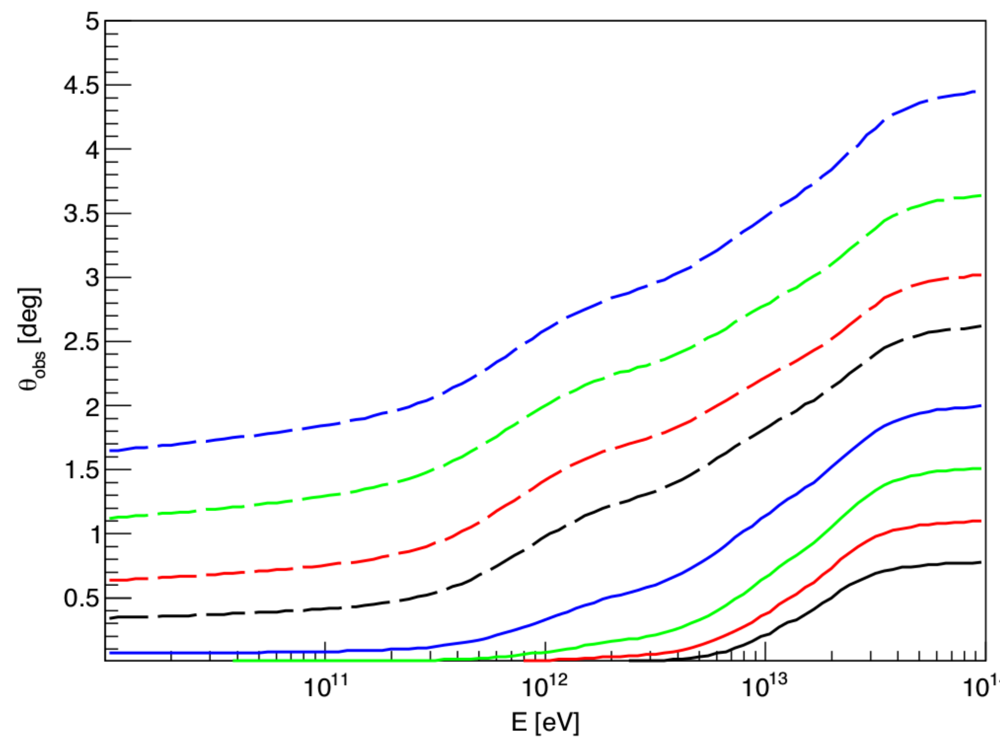
II) Constraints on the EGMF strength from GRB 221009A

Here the "intergalactic electromagnetic cascade model" is assumed (i.e. it is assumed that the primary particles are γ-rays).

Note on the "intergalactic hadronic cascade model":

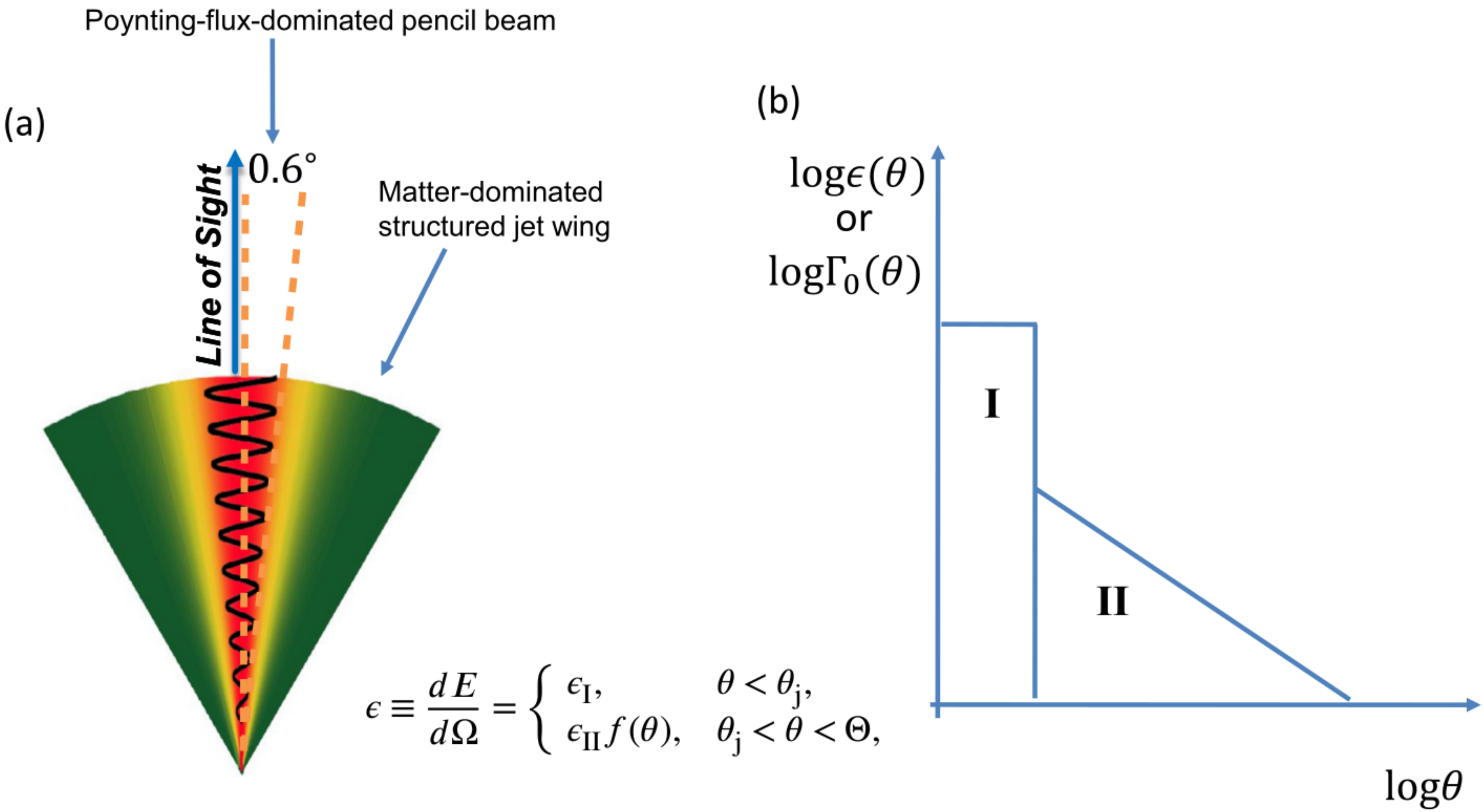
in realistic models of EGMF in filaments it is disfavored by the time delay (typically >> 2000 s) (pictures below were published in Khalikov & Dzhatdoev, MNRAS (2021); Dolag et al., JCAP (2005) EGMF was assumed)





For z= 0.186, K > 0.95 of the simulated trajectories experience these relatively strong deflections; for z= 0.15 the value of K is not far from 0.95

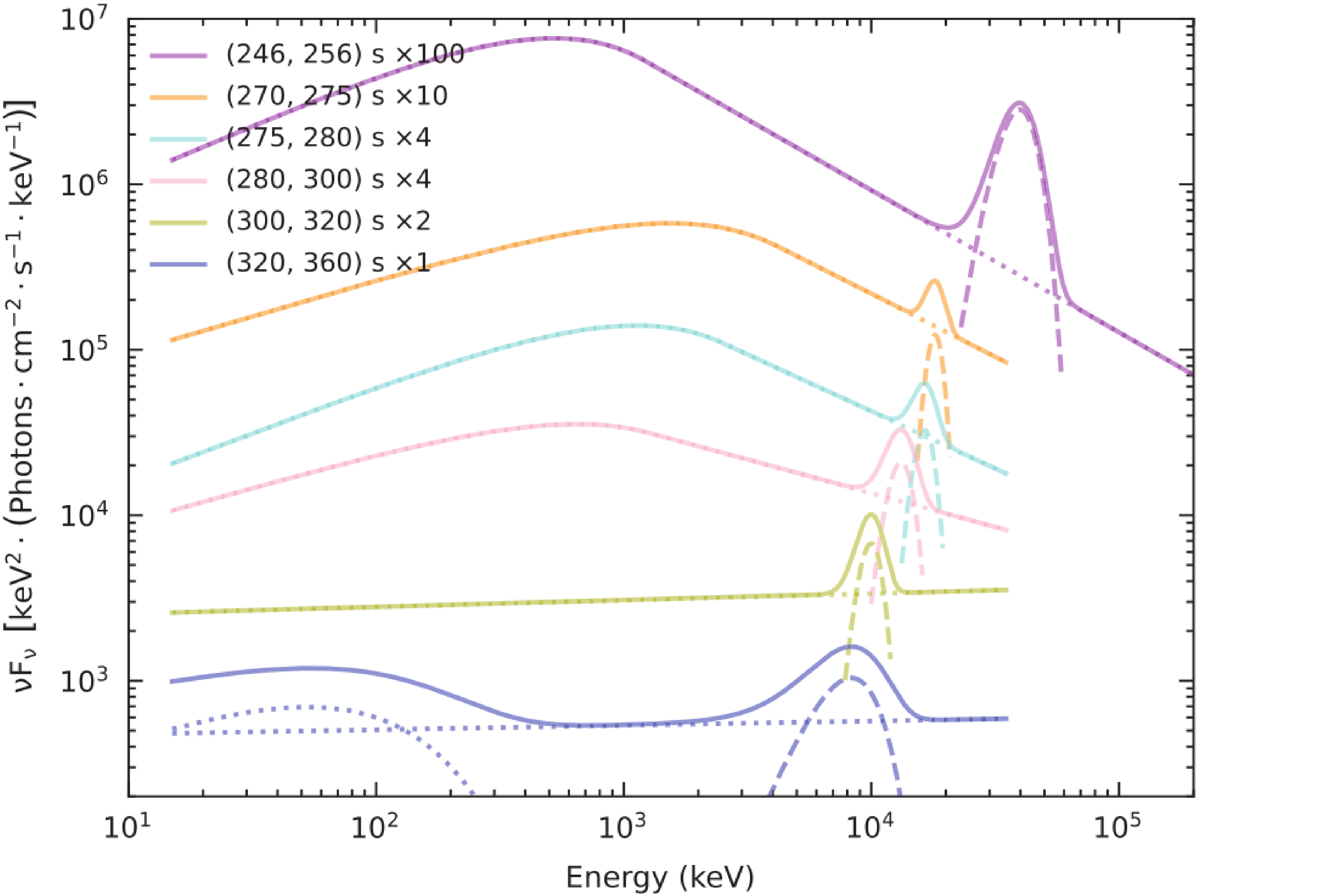
The "structured jet" ("spine-sheath") geometry (Zhang et al., JHEAP, 2024)



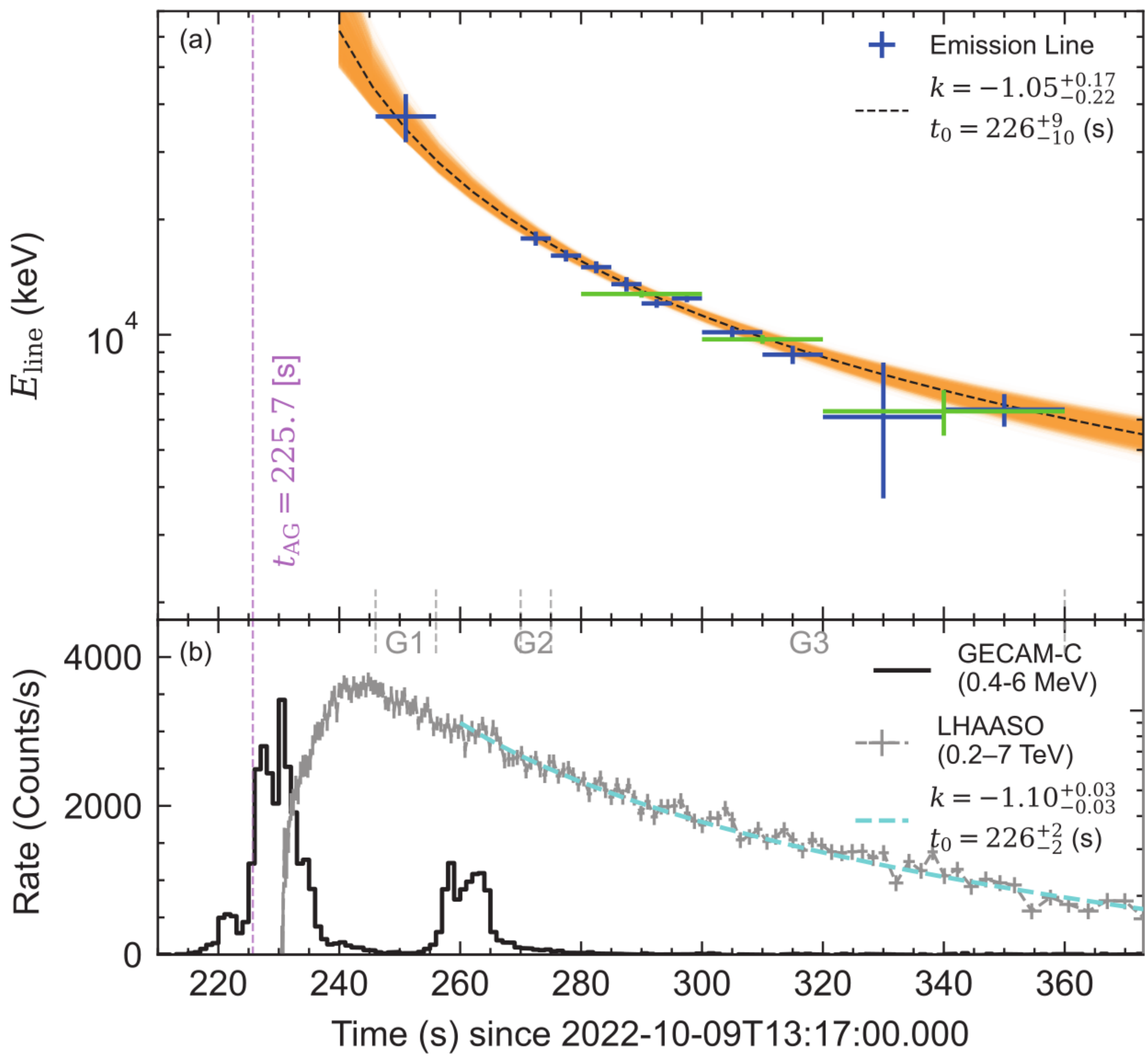
$$\epsilon \equiv \frac{dE}{d\Omega} = \begin{cases} \epsilon_{\rm I}, & \theta < \theta_{\rm j}, \\ \epsilon_{\rm II} f(\theta), & \theta_{\rm j} < \theta < \Theta, \end{cases}$$

The concept itself is not new (e.g. Lipunov et al., 2001; Rossi et al., 2002), but some implications could be quite unexpected given the unique γ-ray dataset from GRB 221009A (MeV line; delayed VHE event, etc.). This scenario was discussed in e.g. O'Connor et al., Sci. Adv., (2023): "The prediction for the [non structured jet] post-jet-break decay is $t^{-p} \approx t^{-2.2}$, which is inconsistent with the x-ray slope of −1.66 measured after $t_{b,X}$."

The MeV line (Zhang et al., 2024; see also Ravasio et al., 2023)
One viable scenario: annihilation line from the "sheath"
of the spine-sheath structure



Zhang et al., 2024; see also Ravasio et al., 2023



A bird's-eye view of observations

1. Fermi-GBM + Fermi-LAT low-energy dataset
2. Prompt emission spectrum (Konus-WIND and SRG/ART-XC)
3. LHAASO-WCDA light curve
4. LHAASO-(WCDA+KM2A) spectra

Fermi-GBM and LHAASO-WCDA light curves (Cao et al., 2023a)

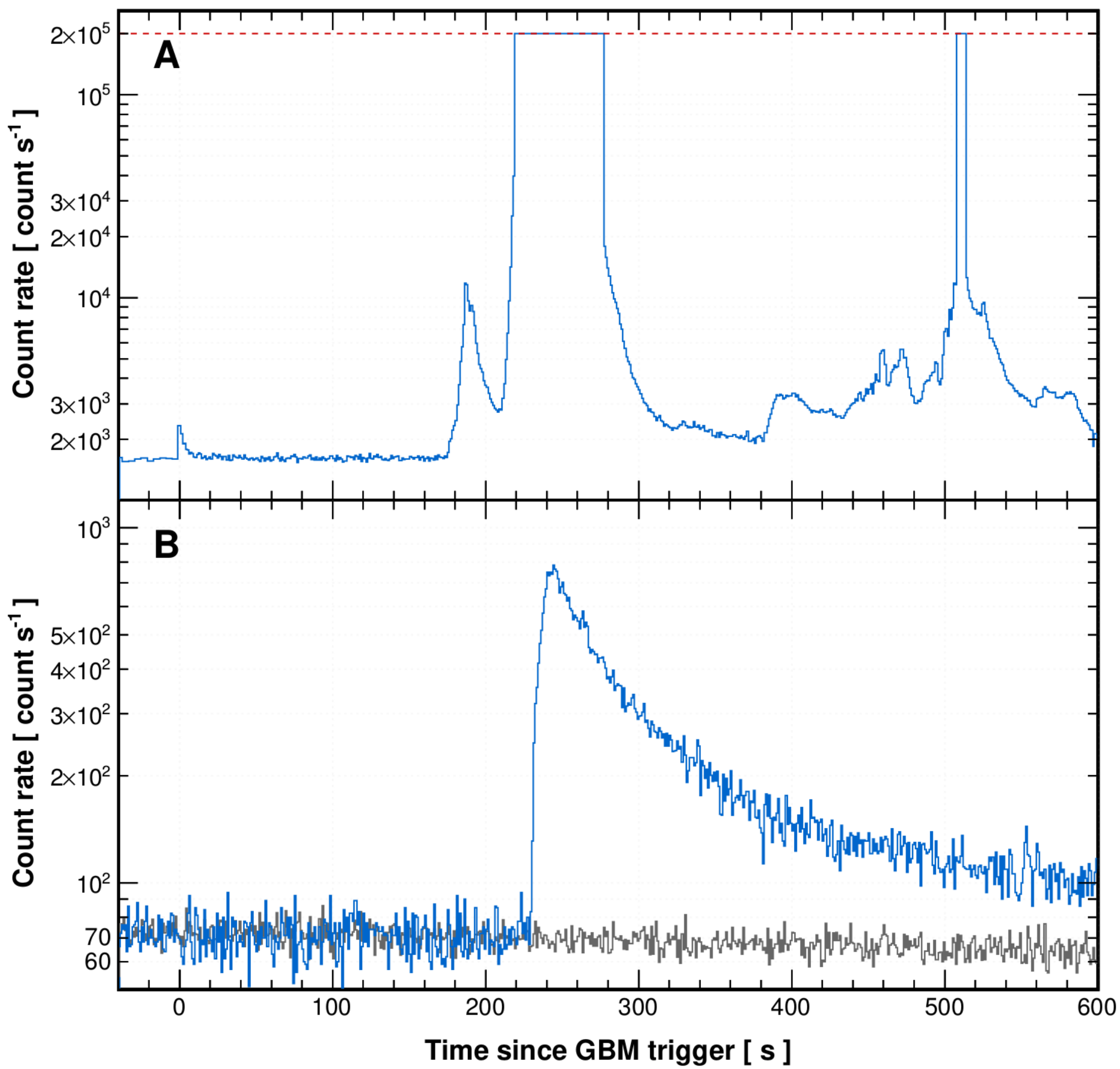
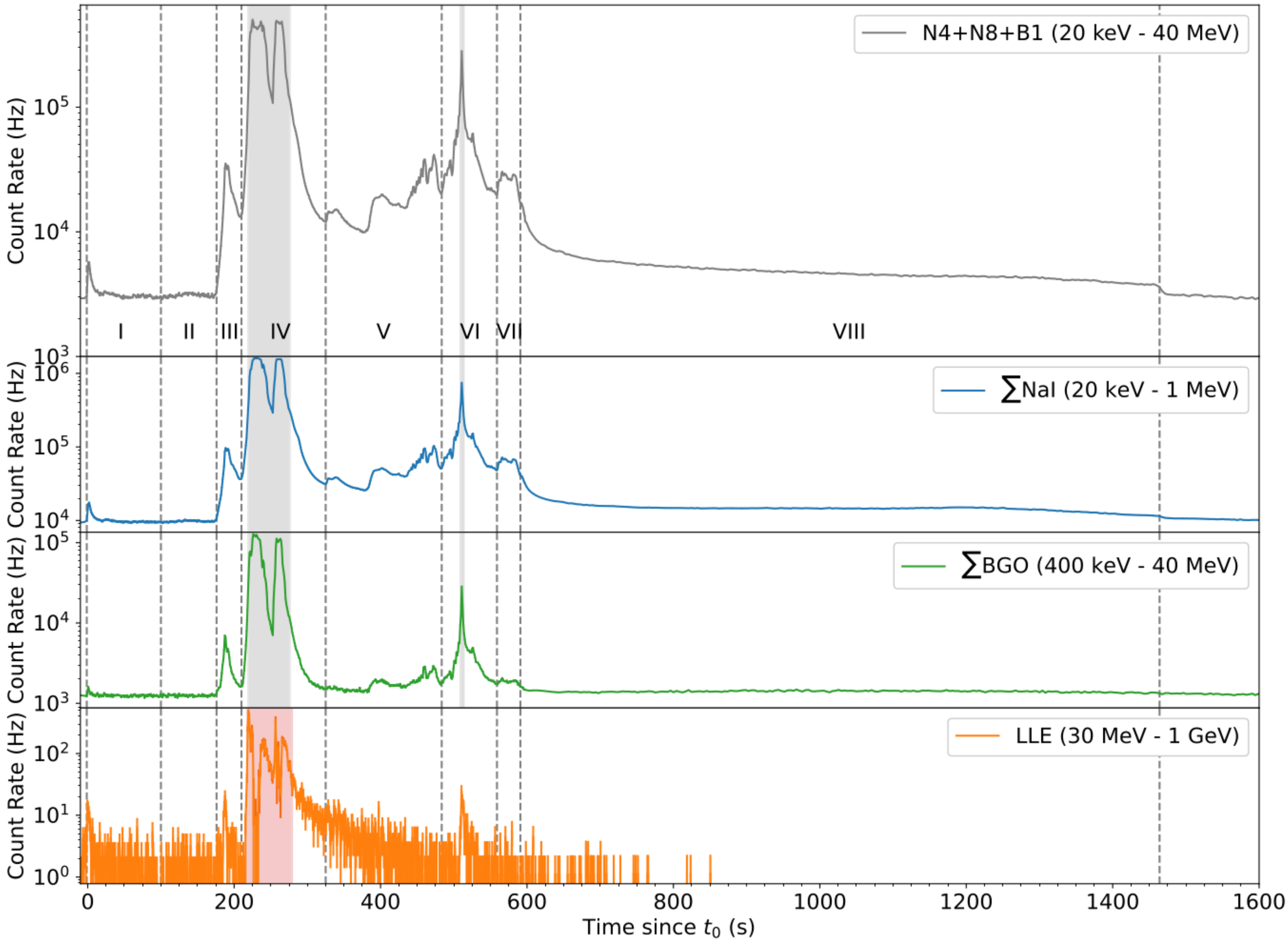
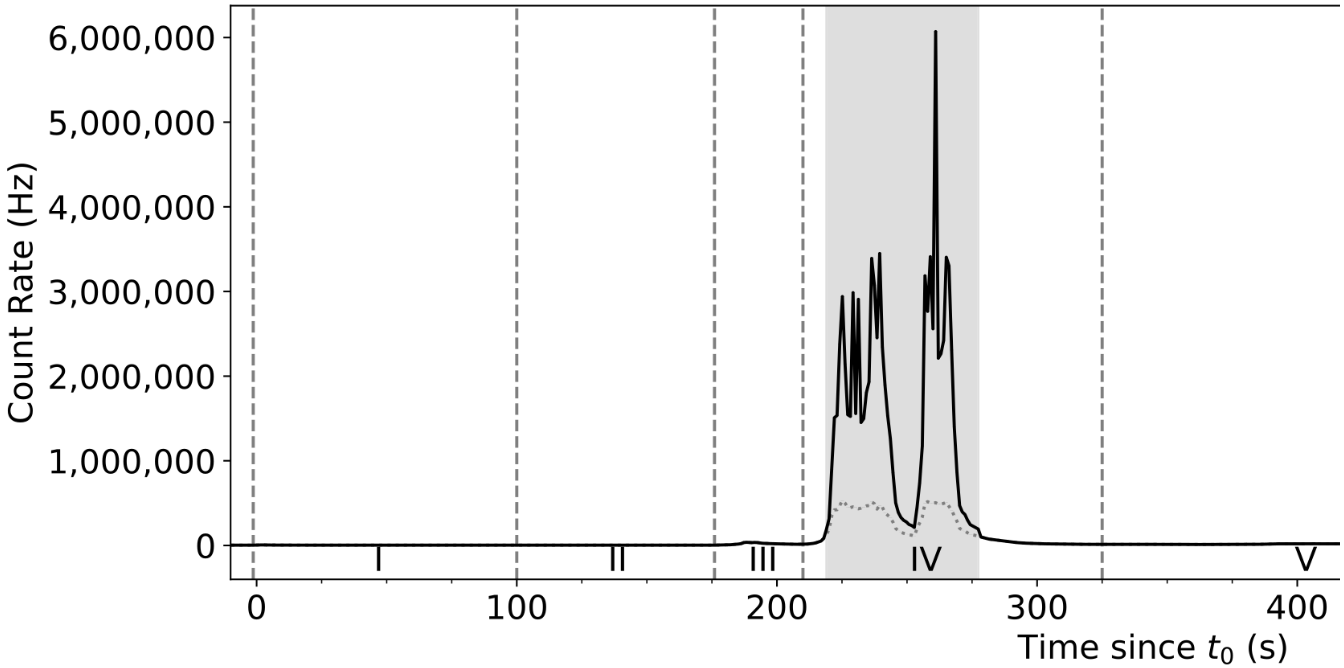


Figure S10: **Comparison between the keV–MeV light curve measured by Fermi/GBM and the TeV light curve measured by LHAASO-WCDA.** (A) the count-rate light curve of 200 keV–40 MeV emission measured by Fermi/GBM (BGO detector). The red horizontal dashed line indicates the level at which the detector became saturated during two periods: 219–277 and 508–514 seconds after the GBM trigger. (B) the count-rate light curve (in blue) of GRB 221009A with $N_{\rm hit} \geq 30$ (energy range 0.2–7 TeV) detected by LHAASO-WCDA in the first ~ 600 seconds, while the black curve shows the background rates.

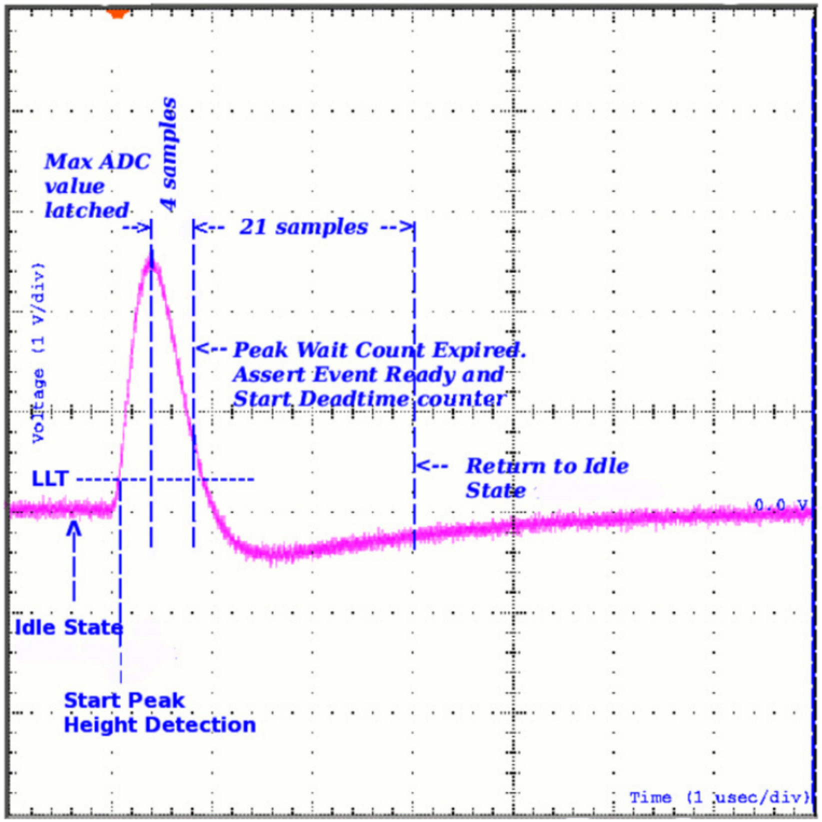
Uncorrected light curve as seen by Fermi-GBM (Lesage et al., 2023)
(+ low-energy Fermi-LAT data)



Minimal observable variability timescale $\delta t \approx 0.1$ s

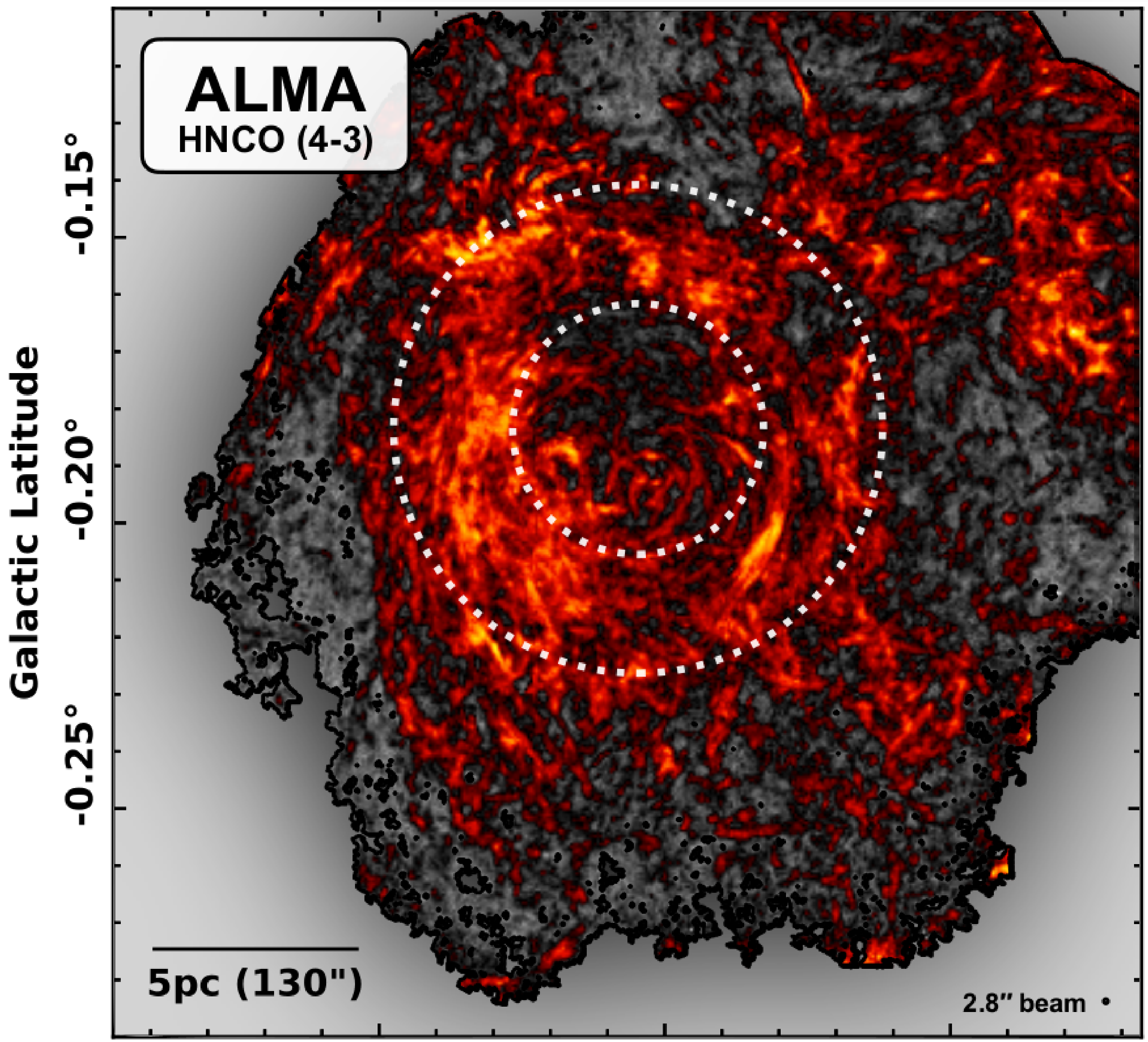


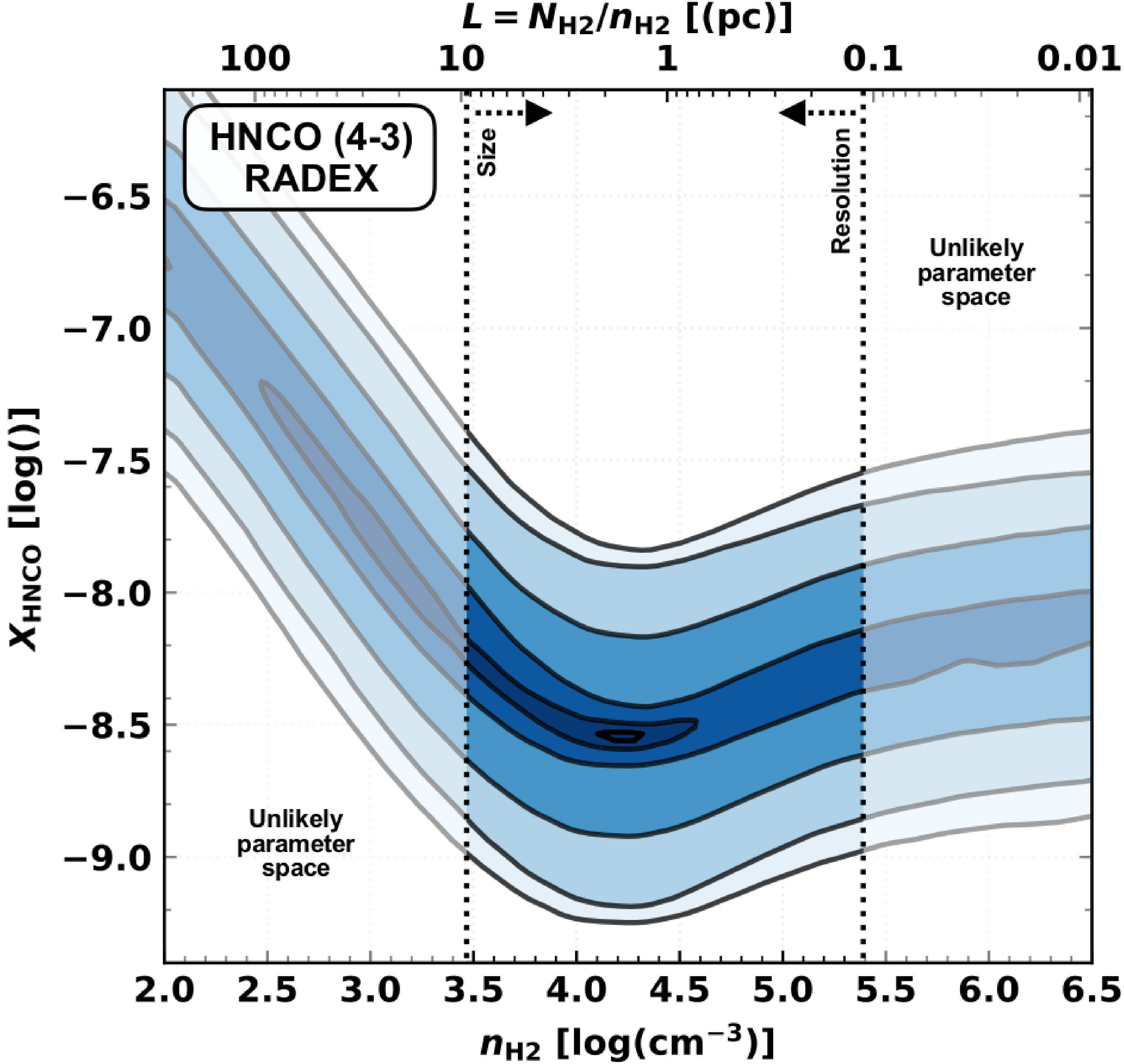
Uncorrected and corrected Fermi-GBM light curves (Lesage et al., 2023)



Typical pulse shape in Fermi-GBM (Meegan et al., 2009)

Disruption of a galactic molecular cloud by a supernova?
(Nonhebel et al., 2024)





L = N_H2/n_H2 [(pc)]
100
10
1
0.1
0.01
HNCO (4-3)
RADEX
Size
Resolution
Unlikely
parameter
space
Unlikely
parameter
space
−6.5
−7.0
−7.5
−8.0
−8.5
−9.0
X_HNCO [log()]
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
n_H2 [log(cm^−3)]

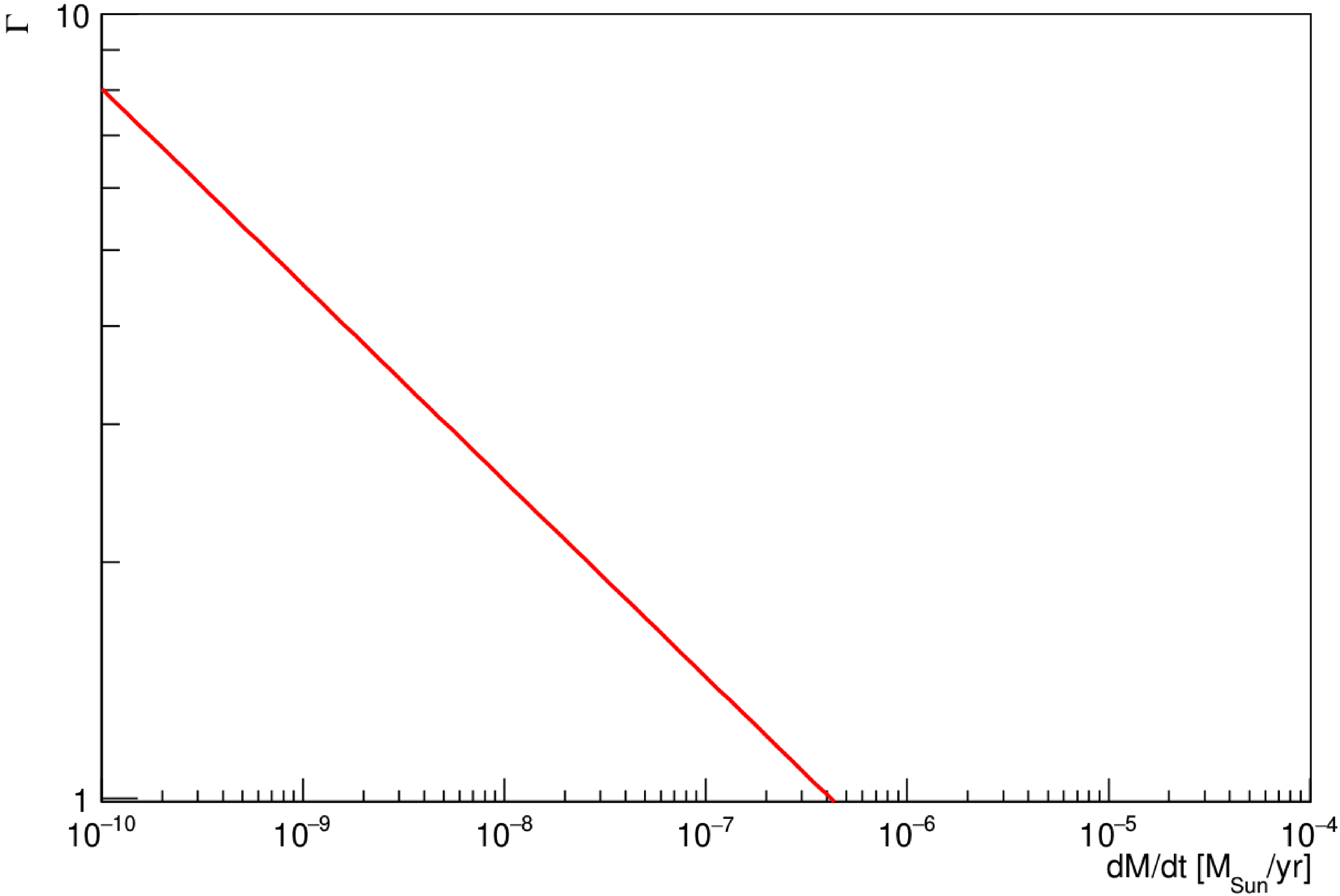


Figure 1. The bulk Lorentz factor Γ vs. $\dot{M}$.

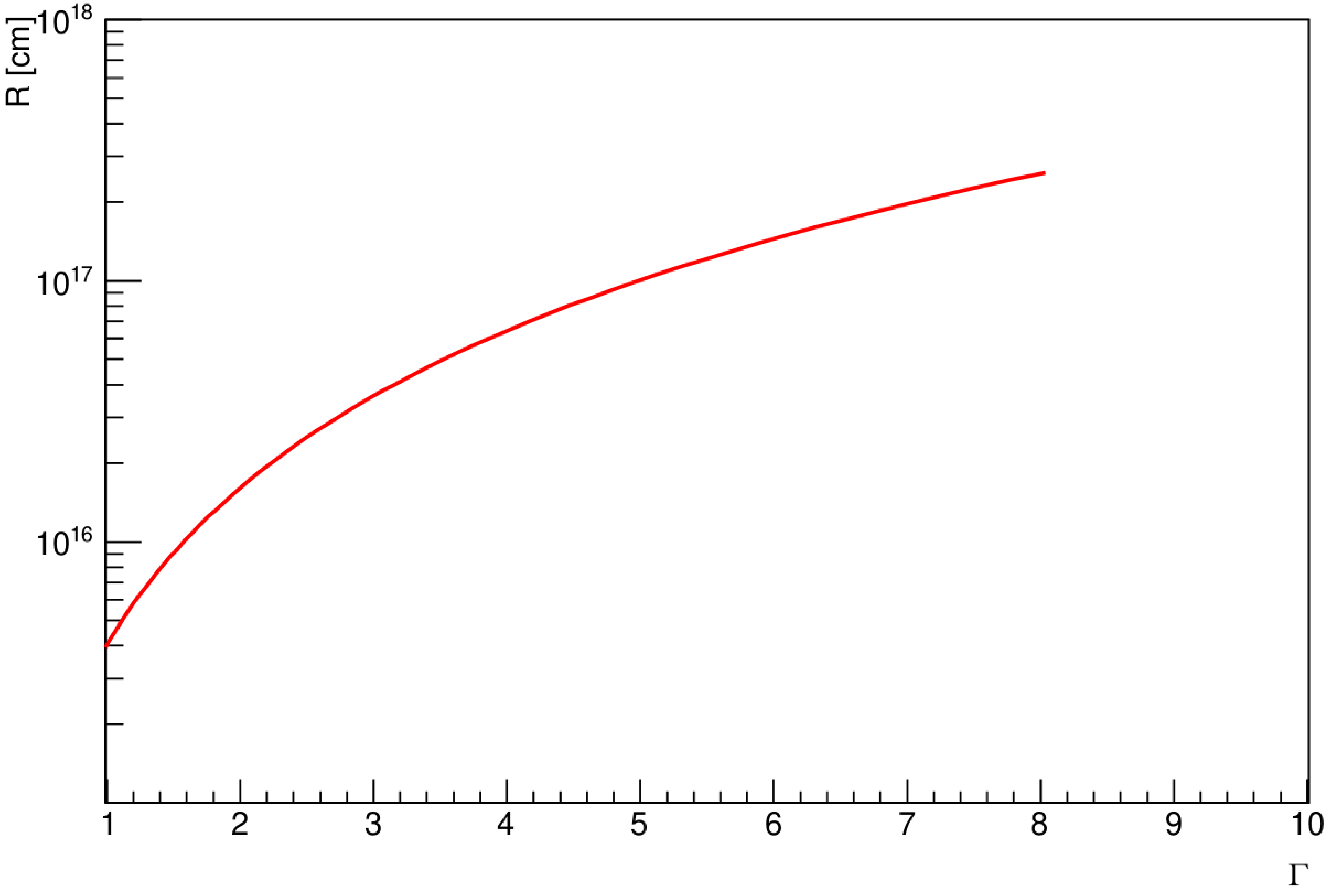


Figure 2. The radius of the bubble R vs. Γ.

Derishev & Piran (2019)

$$\Gamma = \left(\frac{E_{iso} v_w}{4\dot{M} c^3 t} \right)^{1/4}$$

$$R = 4\Gamma^2 ct$$