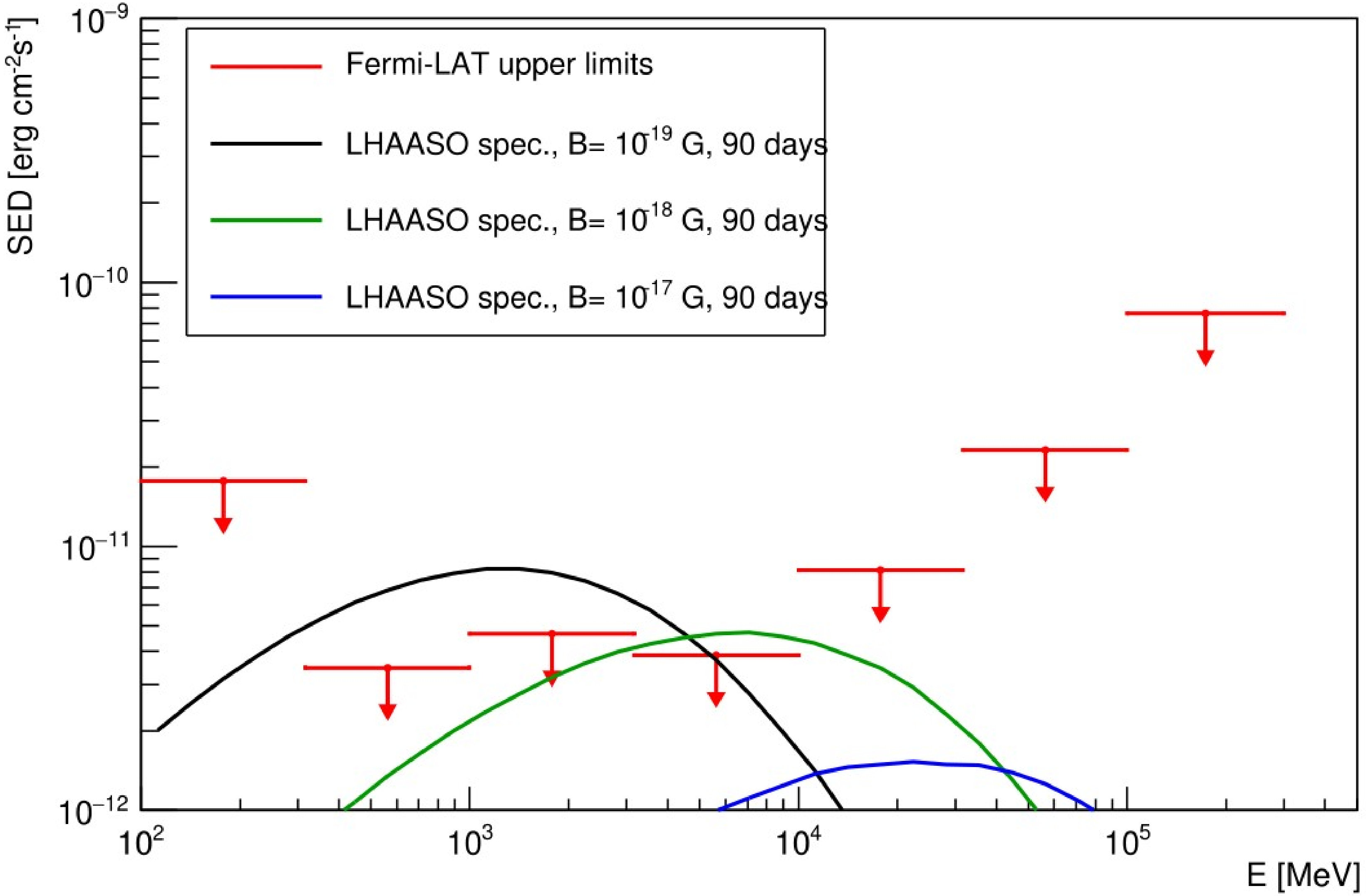
Constraints on the extragalactic magnetic field and the nature of multi-TeV γ-rays from the brightest of all time GRB 221009A



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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., Universe, **7**, 494 (2021) (semi-analytic approximation for the spectrum of electromagnetic cascades in the universal regime; it was applied there to extreme blazars, but might be useful for GRBs as well)
4. Dzhatdoev et al. (in preparation) (2024)

Basic “philosophy”:
an “unveiling” approach, not a front-end simulation

I) Intergalactic electromagnetic cascade echo from GRB 190114C
II) EGMF constraints from GRB 221009A; evidence for a cutoff in its primary γ-ray spectrum
III) An excess at E> several TeV above “conventional” models? A possible explanation: ~EeV neutrons escaping from the prompt emission zone interacting with star forming region (SFR) material
IV) 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 $(\gamma\gamma \rightarrow e^{+}e^{-})$

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 $e^{-}\gamma \rightarrow e^{-\prime}\gamma^{\prime}$ or $e^{+}\gamma \rightarrow e^{+\prime}\gamma^{\prime}$

Parameters of the observable γ-ray flux are sensitive to the EGMF strength and structure

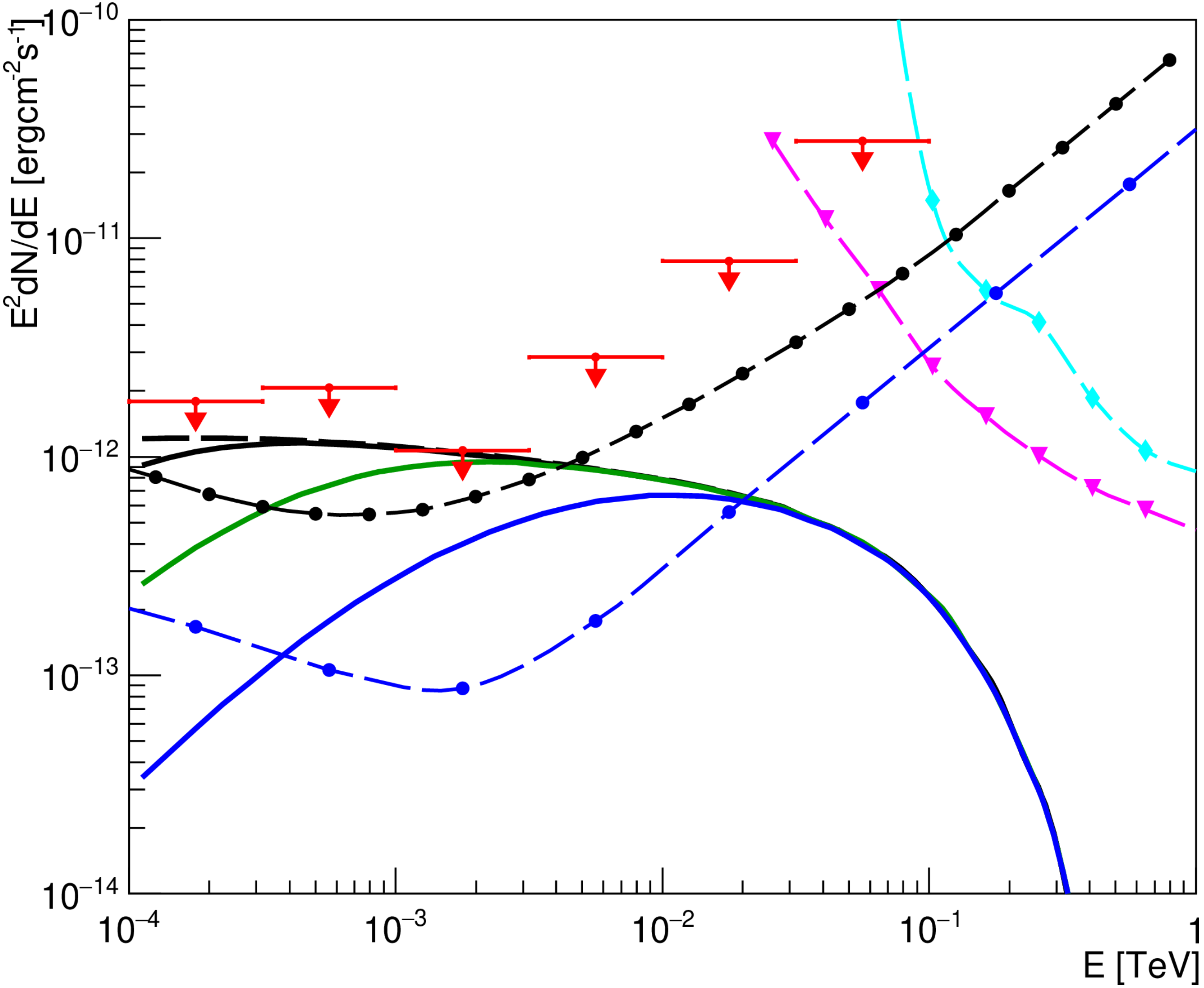
Calculations

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

EBL — 1) “original” 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

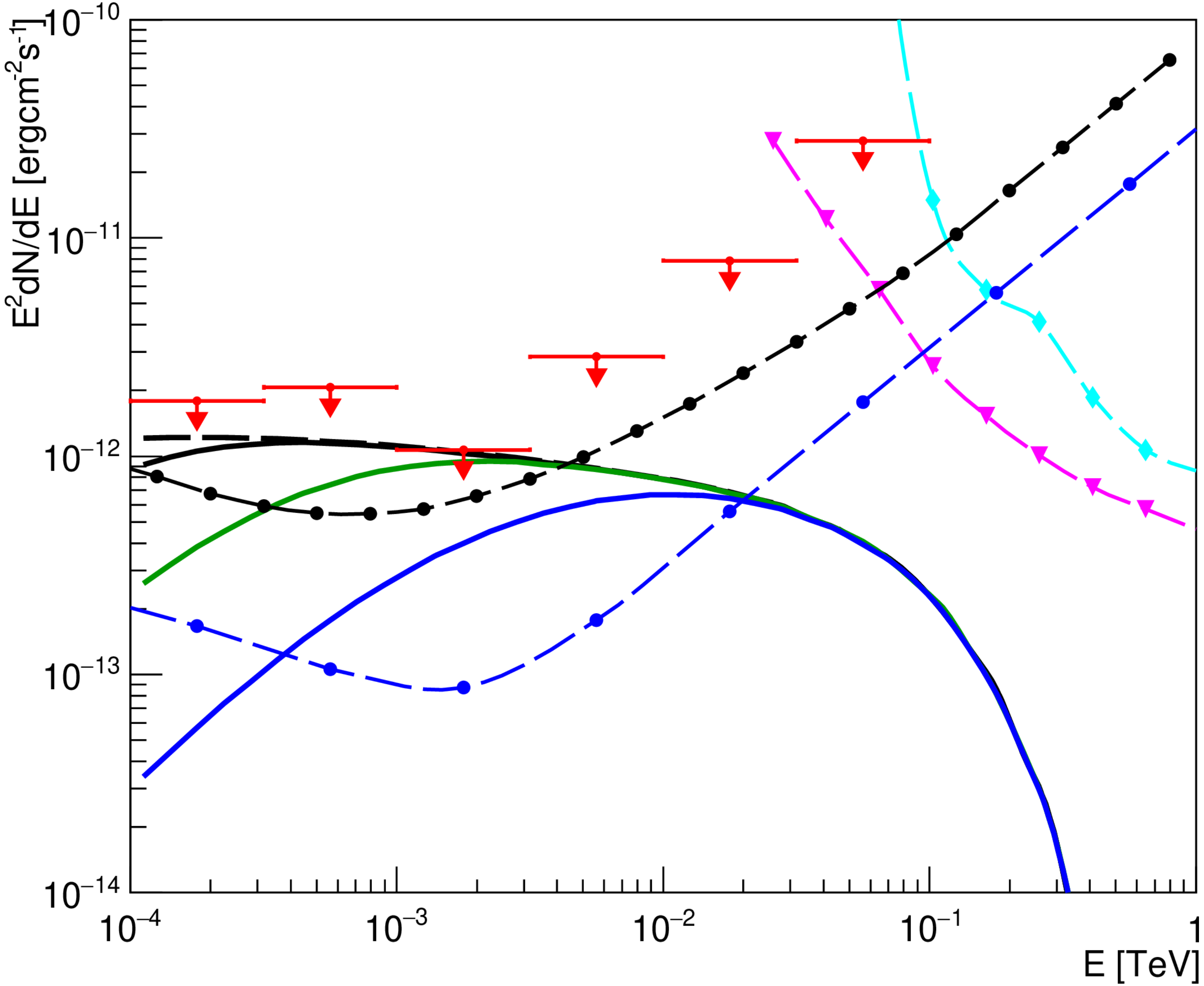
We obtain observable SEDs of intergalactic cascades over the time period of 1 month. Subtracting γ rays that have time delay less than 20000 s would decrease the observable intensity and thus (as we will show) would reinforce our conclusions.

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).



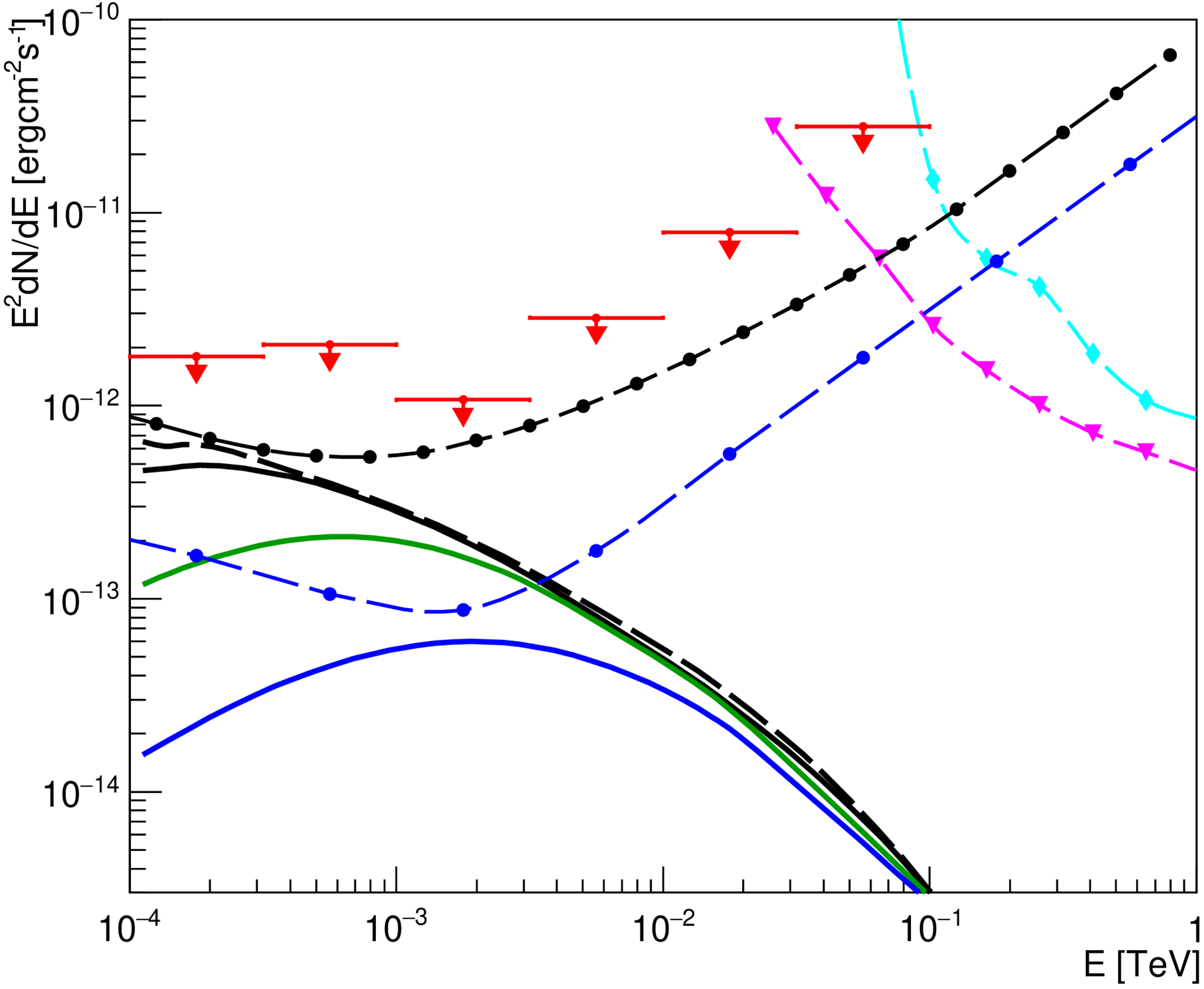
No constraints on B could be obtained from GRB 190114C

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. EGMF constraints from GRB 221009A; evidence for a cutoff in its primary γ-ray spectrum

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

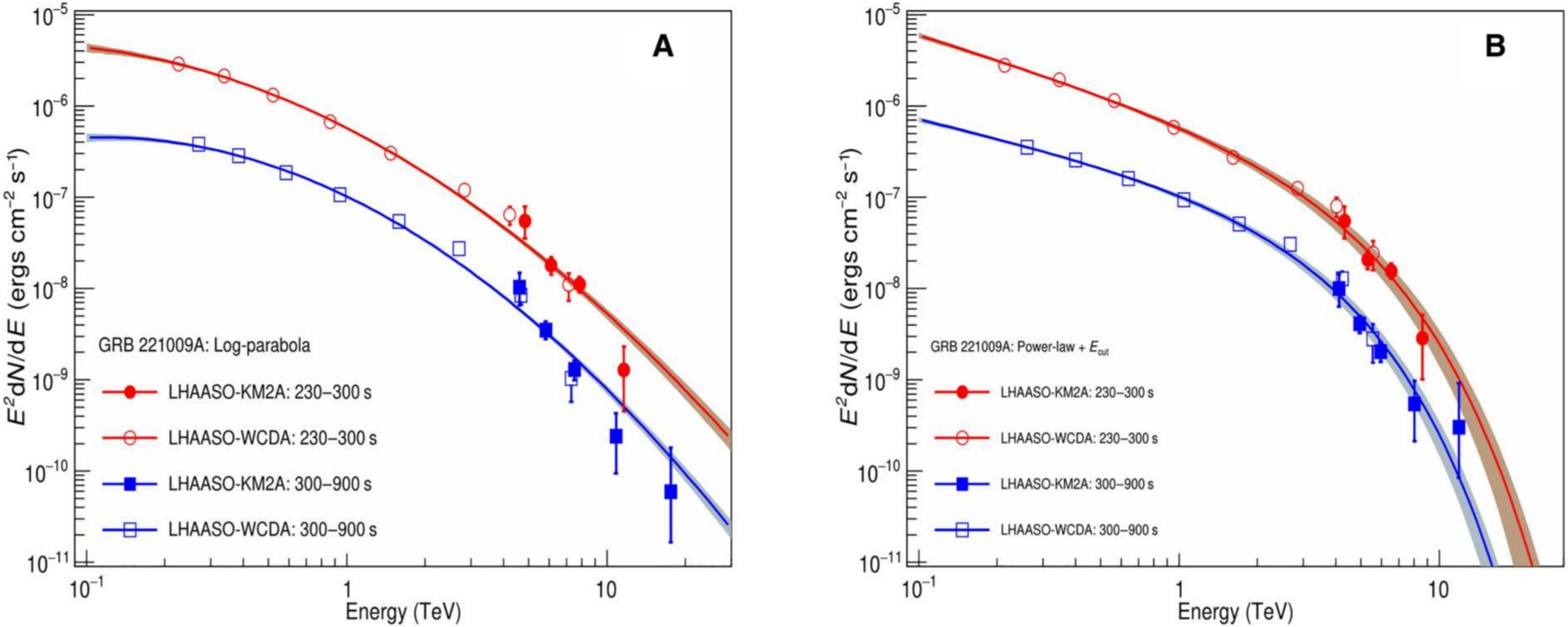
Note on the "intergalactic hadronic cascade model":
in realistic models of EGMF in filaments it is excluded by the time delay (typically >> 1 year) (detailed calculations of the primary proton deflection were performed in Khalikov & Dzhatdoev, MNRAS (2021))

Connoisseurs of the IHCM for GRB 221009A be like:

Q: Any time delay from the primary proton deflection on the intervening filaments (?!)

A: I don't know…
I never counted… I am not really a math guy, you know

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

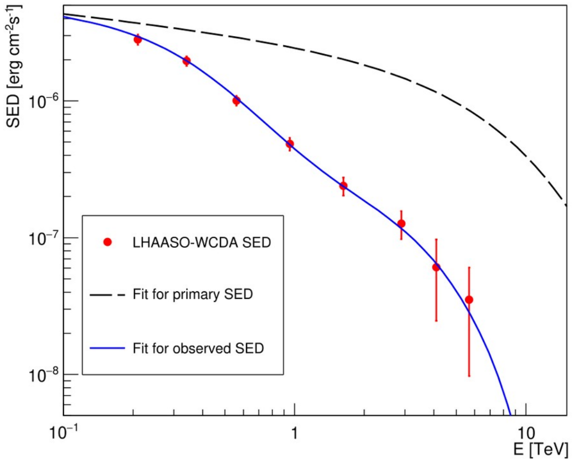


LHAASO-WCDA (Cao et al., 2023a) presented the spectra over five time intervals (all from 231 to 2000 s); these will be discussed in the next section

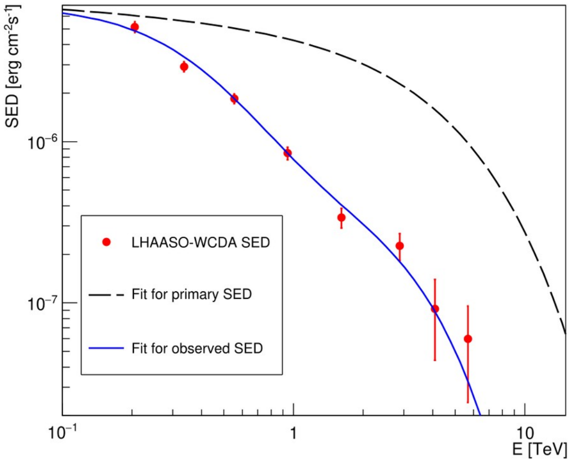
Before the publication of Cao et al., 2023a; Cao et al., 2023b there were many works discussing possible “new physics” (γ-ALP mixing, LIV, etc.). We do not discuss these efforts here due to limited time

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

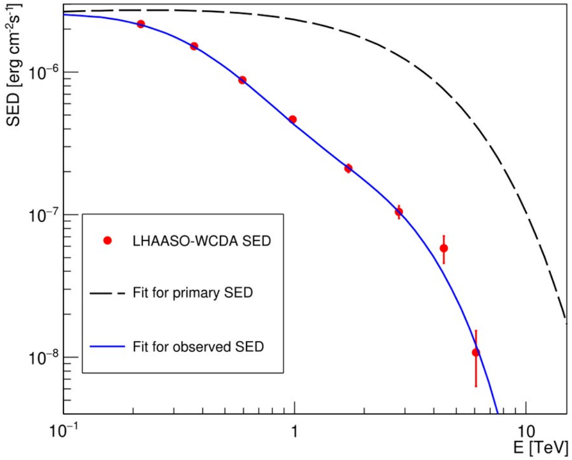
LHAASO-WCDA and LHAASO-KM2A spectra for various time intervals
[Cao et al., Science, **380**, 1390 (2023)]
[Cao et al., Science Advances, **9**, eadj2778 (2023)]



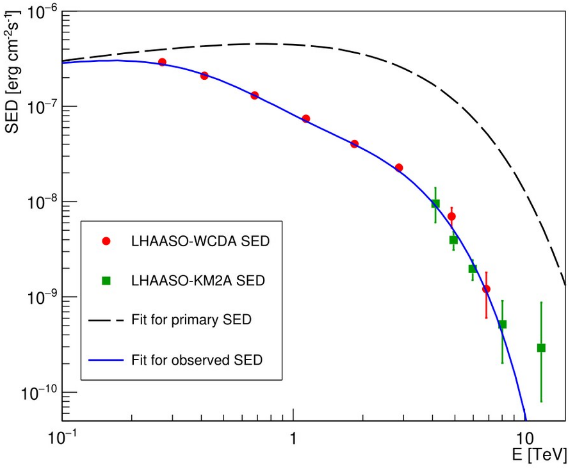
(a) 231 – 240 s



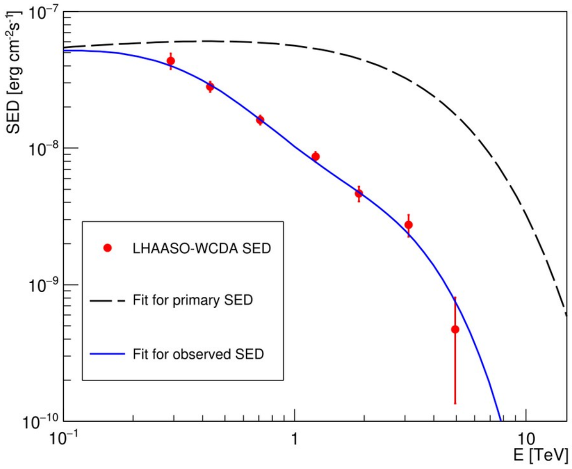
(b) 240 – 248 s



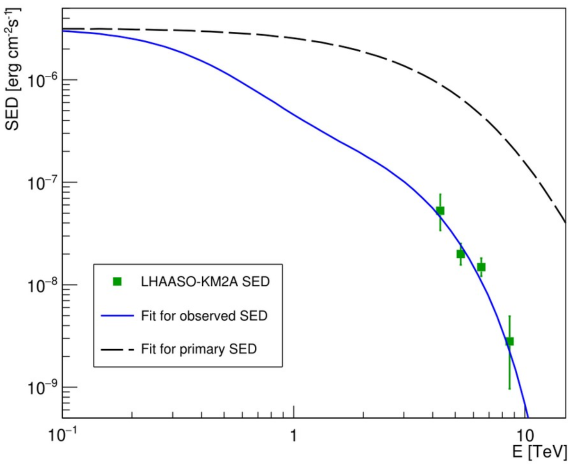
(c) 248 – 326 s



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

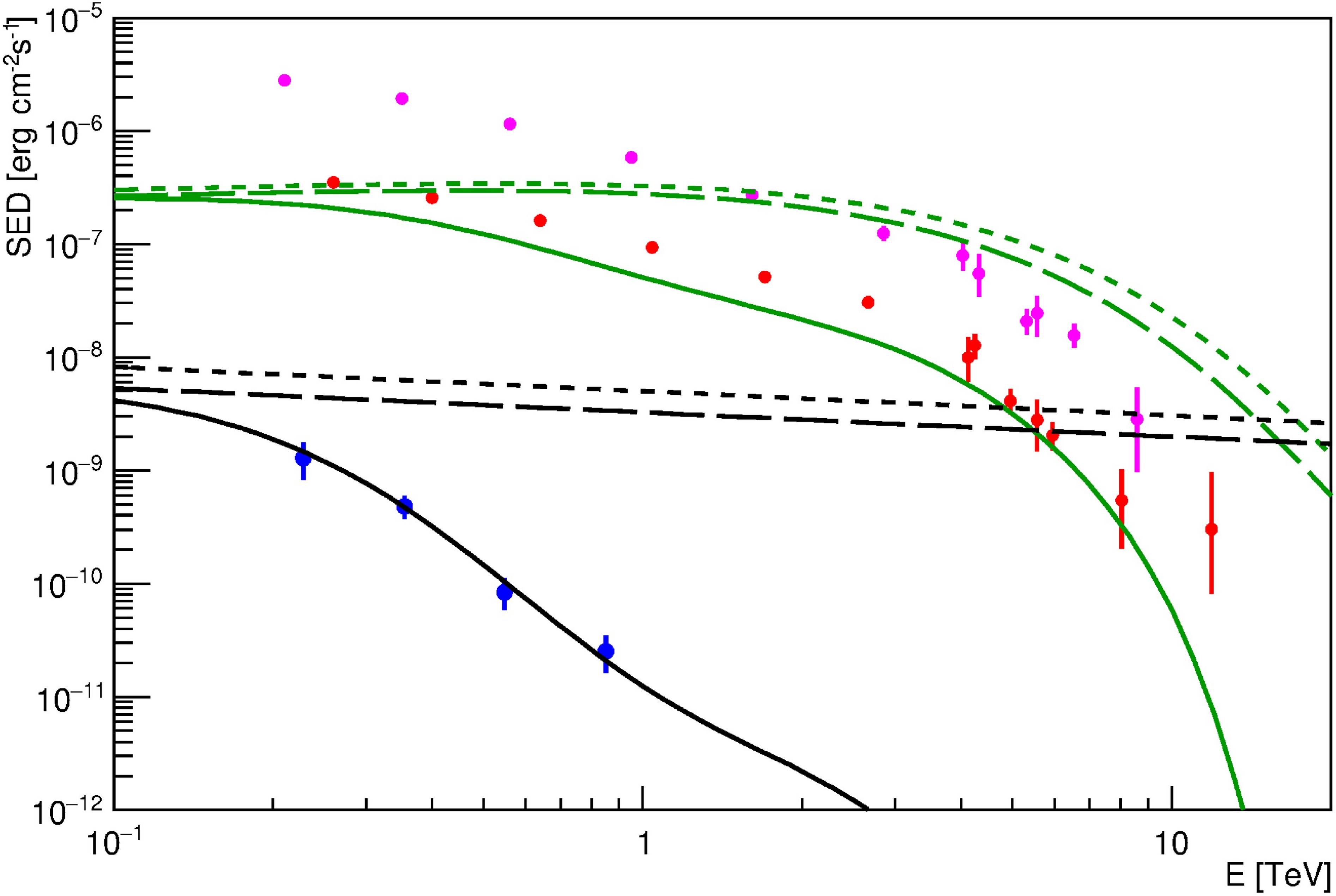


(e) 900 – 2000 s



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

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



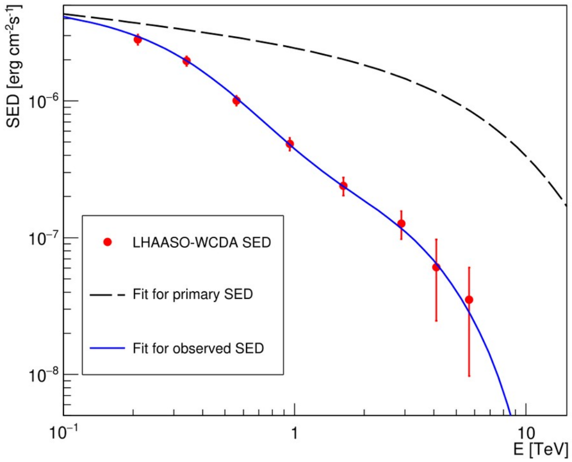
A possible cutoff is present in the intrinsic spectrum of GRB 221009A

LHAASO-WCDA and LHAASO-KM2A spectra for various time intervals

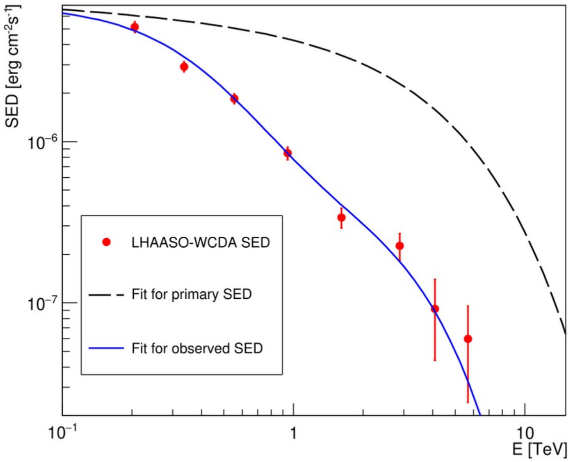
The intrinsic spectra reveal a clear high-energy cutoff

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

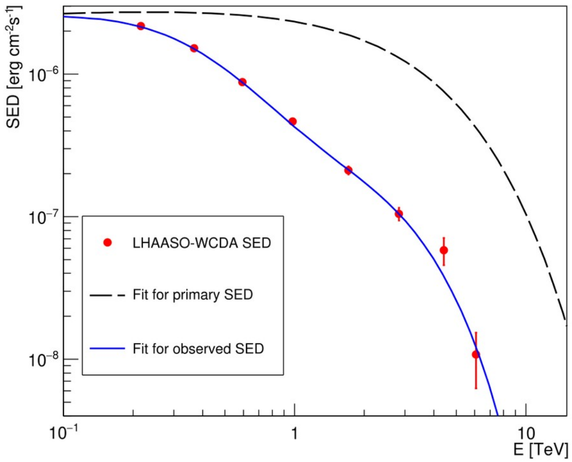
S21, spectrum N4:
K = 1.0: p= $2.42\cdot10^{-8}$
K = 1.2: p= $5.46\cdot10^{-7}$
K = 1.4: p= $2.81\cdot10^{-6}$
Caveat: systematic uncertainties are not known well enough



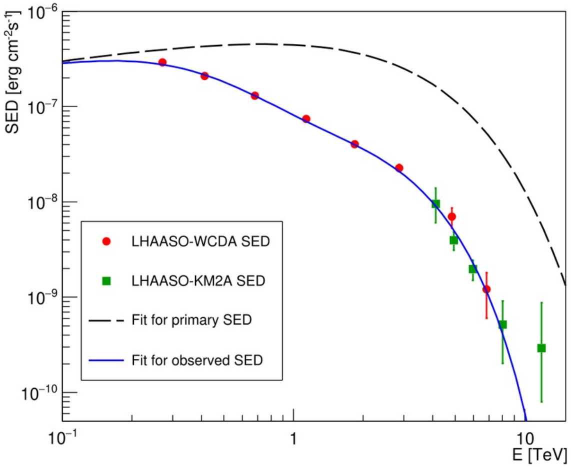
(a) 231 – 240 s



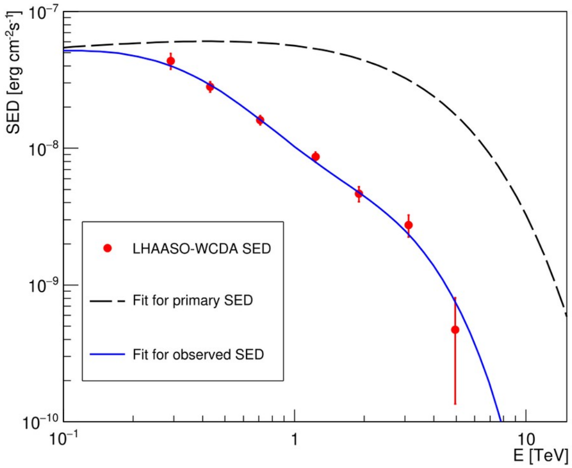
(b) 240 – 248 s



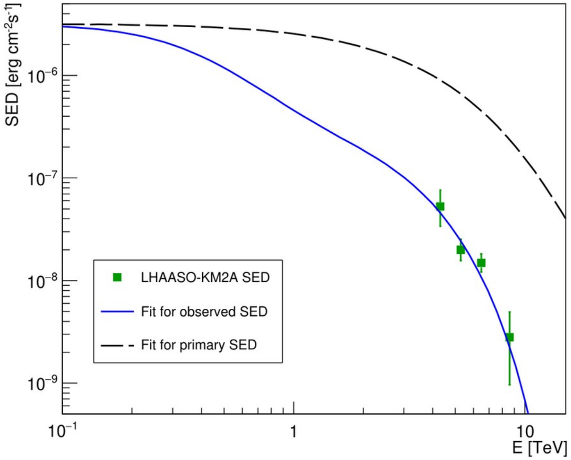
(c) 248 – 326 s



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



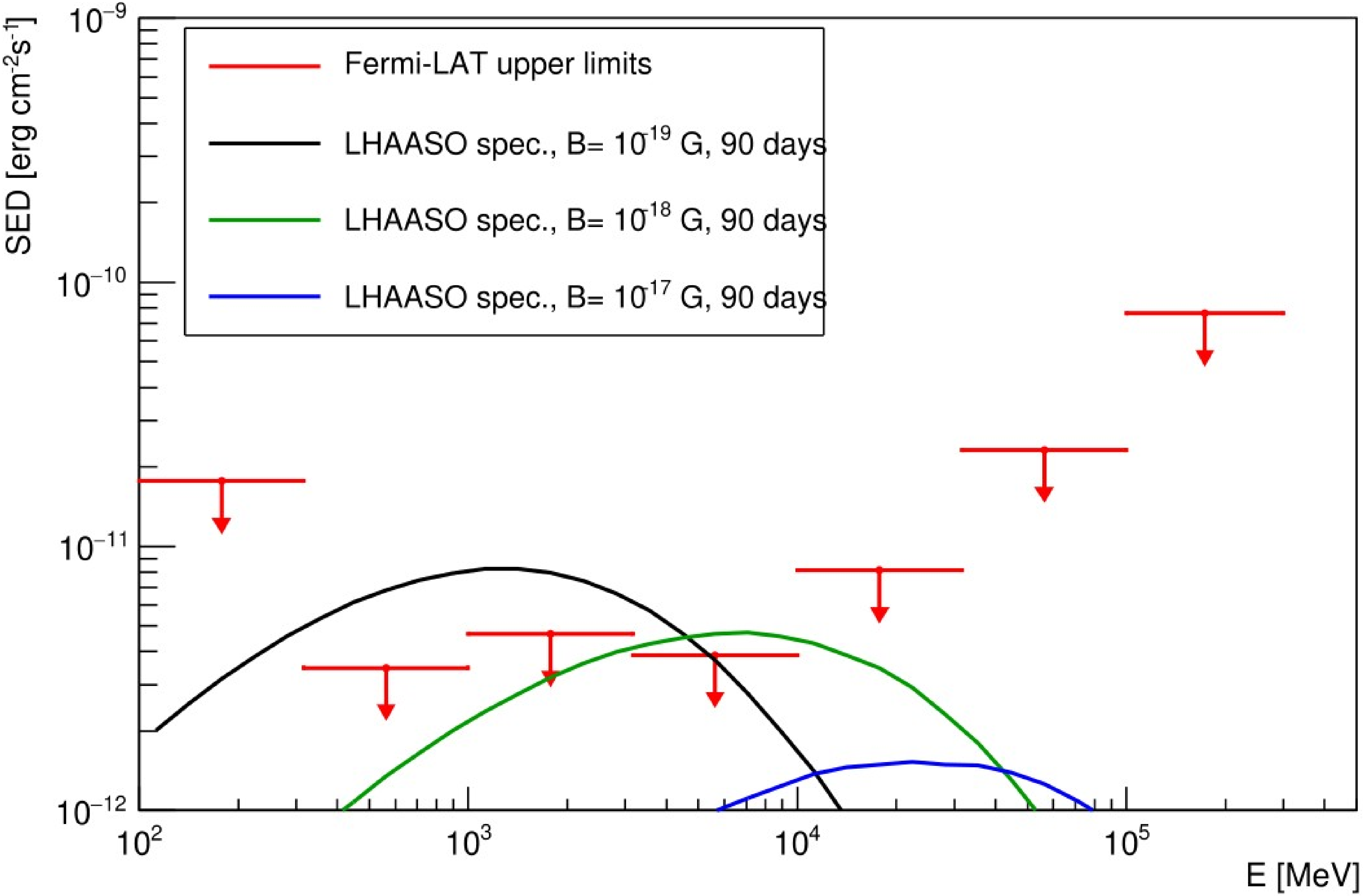
(e) 900 – 2000 s



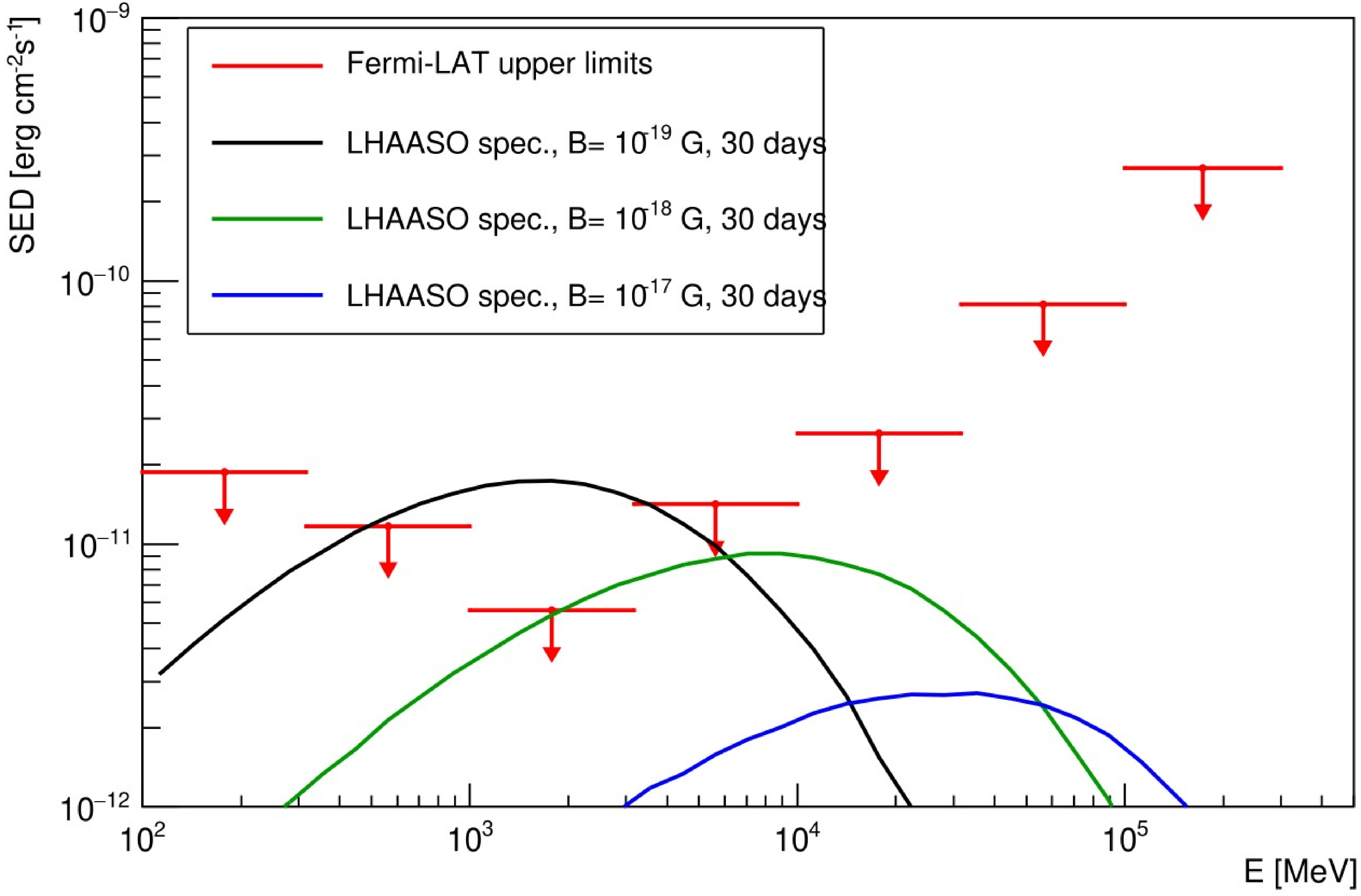
(f) Squares: 230 – 300 s, re-scaled to 231 – 326 s, for which the curves are plotted

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

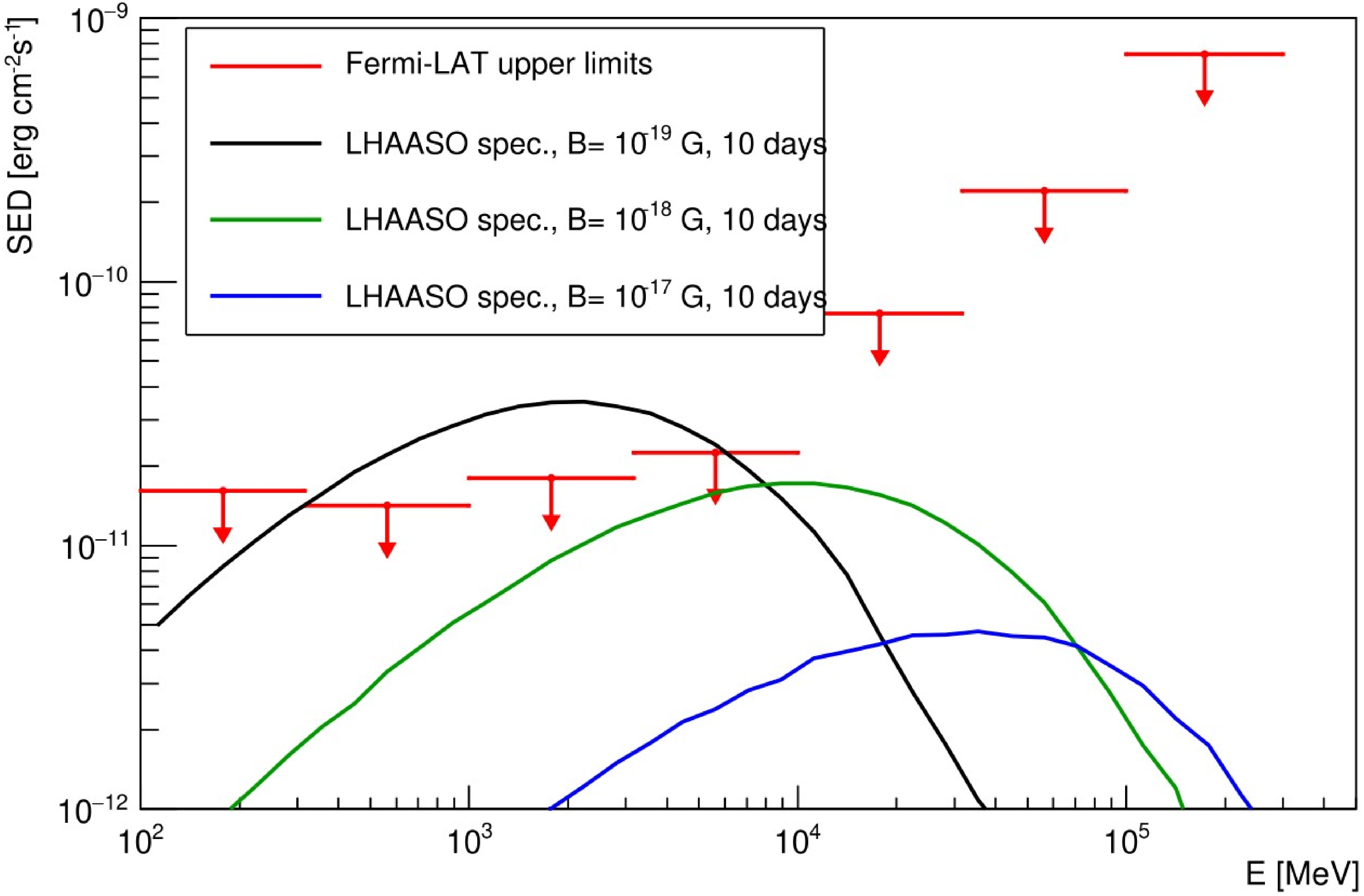
B= 1 aG is excluded!

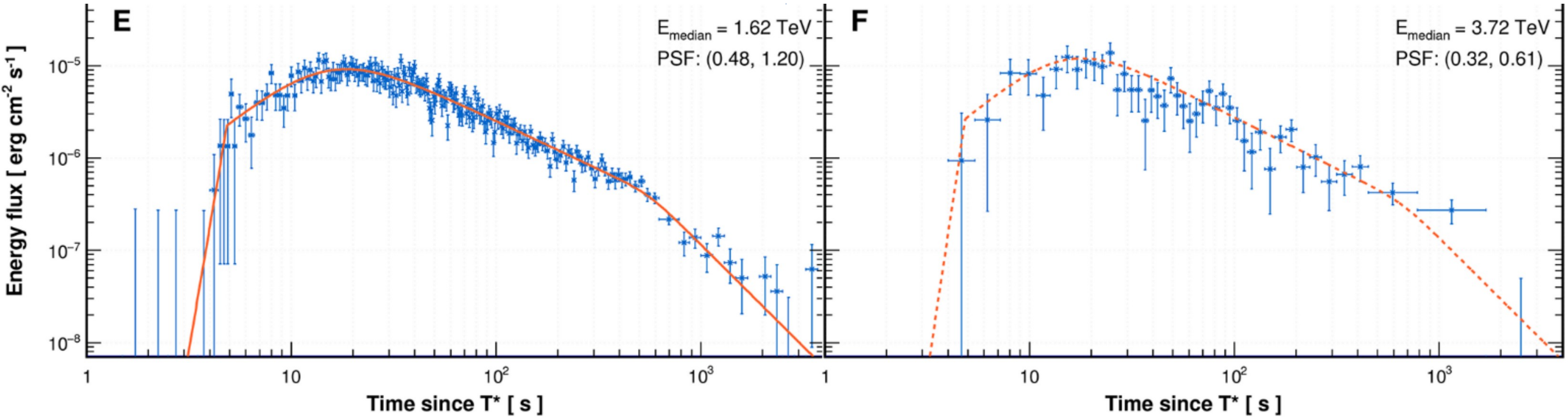


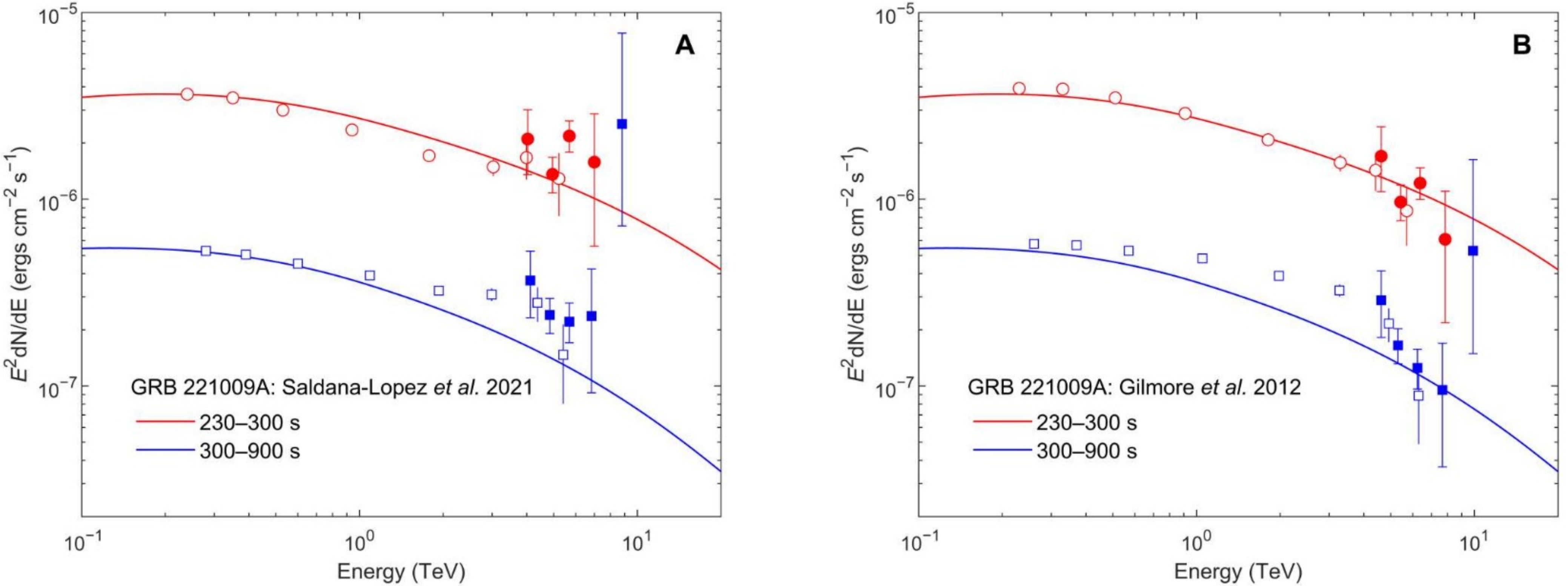
The same for the time window of 30 days



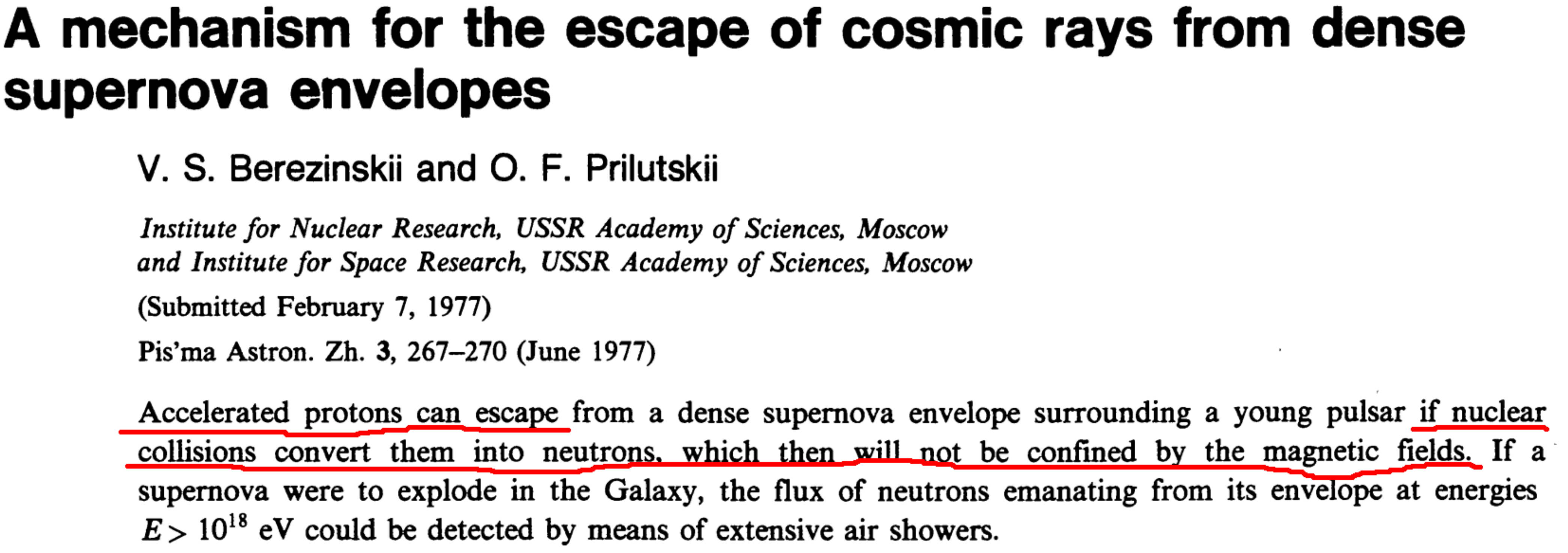
The same for the time window of 10 days




E
E_median = 1.62 TeV
PSF: (0.48, 1.20)
F
E_median = 3.72 TeV
PSF: (0.32, 0.61)
Energy flux [erg cm^-2 s^-1]
10^-5
10^-6
10^-7
10^-8
1
10
10^2
10^3
Time since T* [s]


A
B
E^2dN/dE (ergs cm^-2 s^-1)
10^-5
10^-6
10^-7
10^-1
10^0
10^1
Energy (TeV)
GRB 221009A: Saldana-Lopez et al. 2021
GRB 221009A: Gilmore et al. 2012
230–300 s
300–900 s

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



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

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

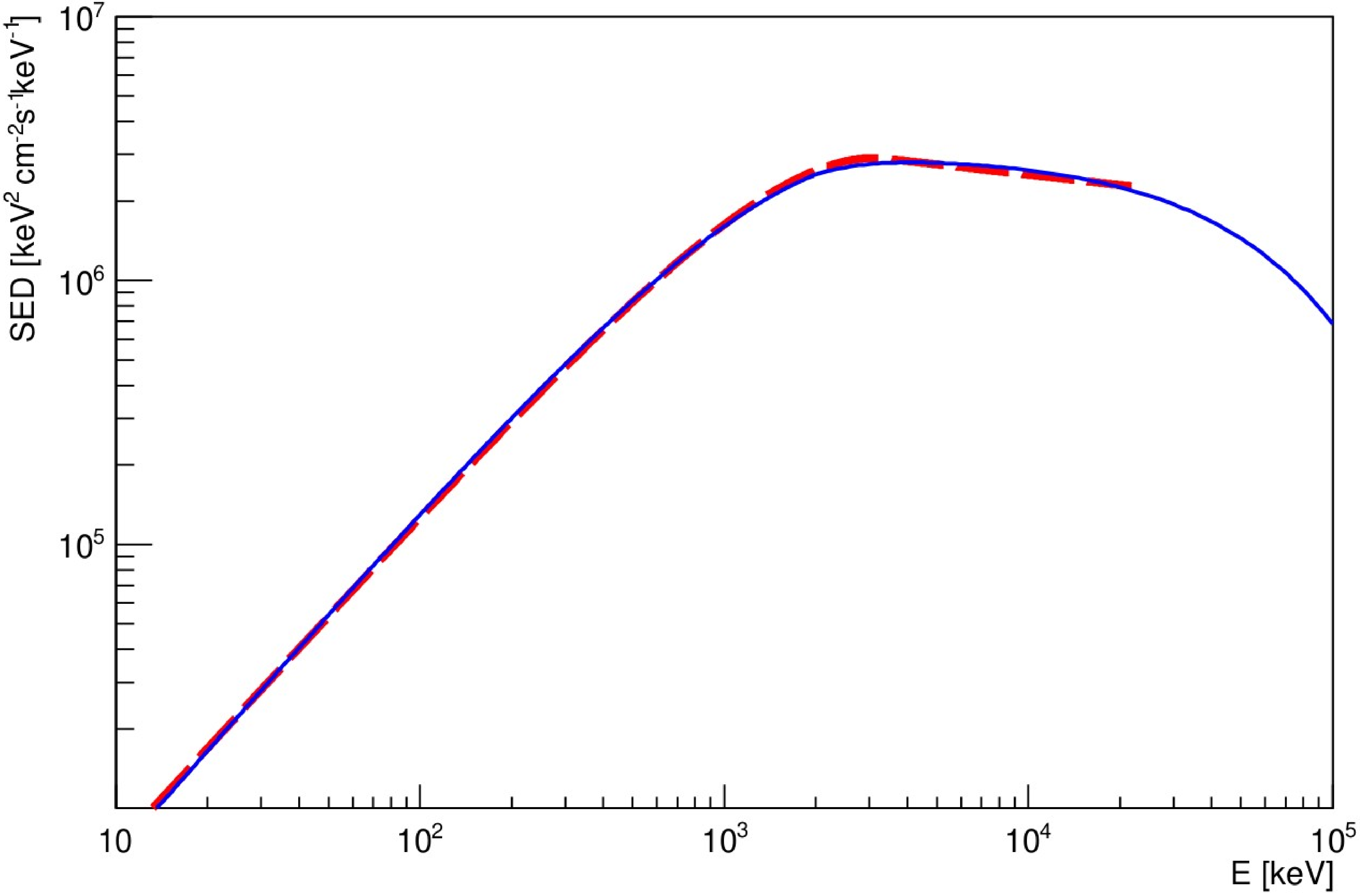
(Submitted February 7, 1977)

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)

The prompt emission: measured (main episode, approximation; Frederiks et al., 2023); internal electromagnetic cascade model



The multimessenger connection (photohadronic interactions)

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^+ \rightarrow \mu^+\nu_\mu$$

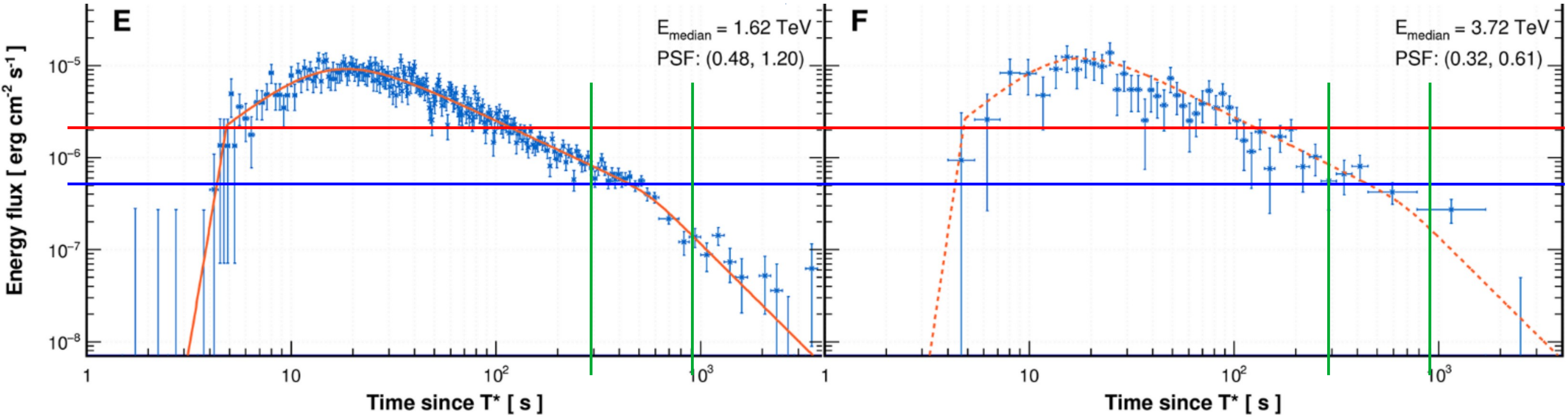
$$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$

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

Inelasticity is ≈15 %; therefore, ≈9 % of the proton energy is transferred to cascade γ-rays. ≈1/2·85 % = 42.5 % of the proton energy is carried by neutrons.

The proton-proton inelastic cross section at 100 PeV is ≈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}; for this value of N_H, assuming that ≈20 % of the neutron energy goes to electrons+positrons, we get $8.5 \cdot 10^{-4}$ of the primary proton energy transferred to electrons+positrons; almost all this energy could be radiated as synchrotron photons (we assume B_{SFR}= 1 mG). Therefore, the fluence of the “hard” γ-ray component is $9.4 \cdot 10^{-3}$ (≈1 %) → $1.2 \cdot 10^{-3}$ 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).

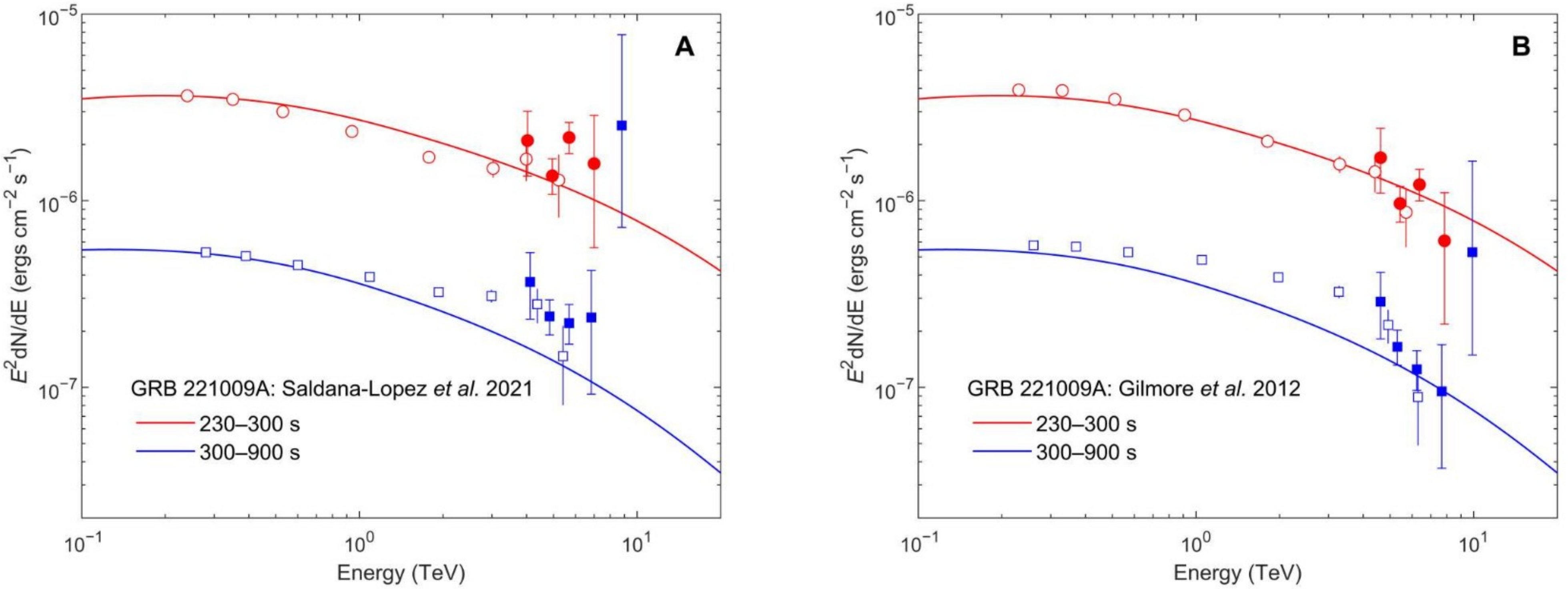
Neutrino constraints (Abbasi et al., 2023) allow at least 1/3 of the observed prompt emission to be produced in hadron-initiated cascades for the Lorentz factor> 1200 (even more for high magnetic field inside the prompt emission zone, B>100-200 kG).



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

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

pulse width ≈600s·(R/1.8·10^{17} cm); 1.8·10^{17} cm ≈ the expected size of the SFR bubble



Conclusions

I. First meaningful constraint on the EGMF strength from GRBs 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; produced electrons radiate 1-10 TeV synchrotron photons that may have an appreciable intensity

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