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photo by W.Zakrzewski, 2004

Constraints on the extragalactic magnetic field from gamma-ray observations of GRB 221009A

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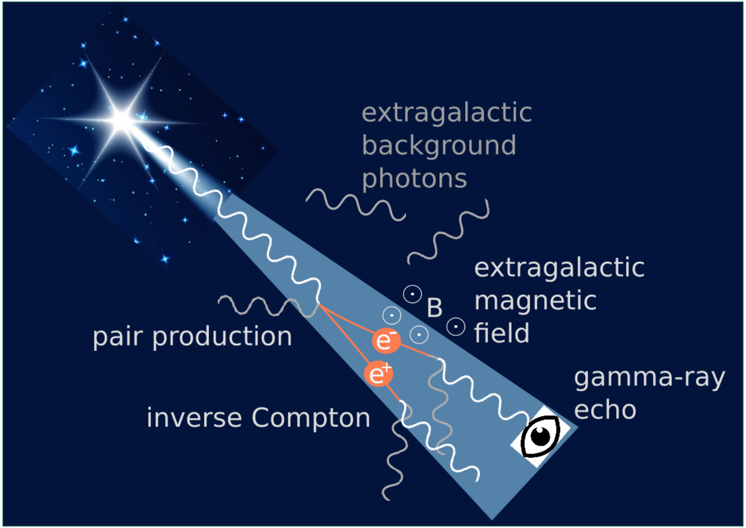
Introduction: gamma-ray echo



Gamma-ray echo – delayed radiation shifted to lower energies

Gamma-ray echo may allow to probe the extragalactic magnetic field (EGMF)

Plaga, Nature (1995)

Ichiki et al. ApJ (2008)

Neronov, Semikoz, PRD (2009)

Earlier observations of bright GRBs

- GRB 130427A
  - brightest GRB in gamma-ray band at the moment of observation
  - has possibly enough flux at TeV to constrain extragalactic magnetic fields (EGMF) Veres at al., ApJ (2017)
  - has not been detected at TeV energies
- GRB 190114C
  - 0.2 - 1 TeV emission has been observed by MAGIC

    MAGIC Collaboration, Nature 575 (2019)
  - no photon echo constraints on EGMF may be set since the expected flux is too small to be observable with Fermi LAT

    Dzhatdoev et al., PRD 102 (2020)

GRB 221009A

- GRB 221009A
  - exceptionally bright gamma-ray burst
  - z=0.151 (700 Mpc)
  - $\alpha_{J2000} = 288.264^\circ, \delta_{J2000} = 19.773^\circ$
  - Registered by Swift, Fermi GBM and Fermi LAT

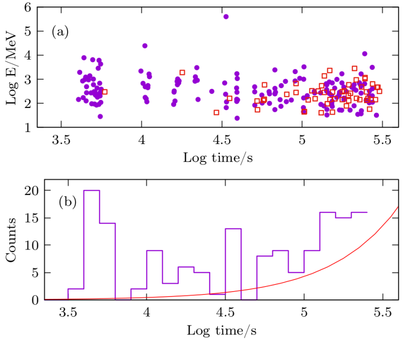
    GCN #32635, #32636, #32637
  - Fermi LAT afterglow duration is longer than 10^5 seconds

    talk by B. Stern, this session
  - LHAASO has observed burst for 2000 seconds since Fermi GBM trigger, including photons with energies greater that 10 TeV

    GCN #32677
  - Carpet-2 has registered air shower consistent with being initiated with photon of 251 TeV, 4556 s after the GBM trigger

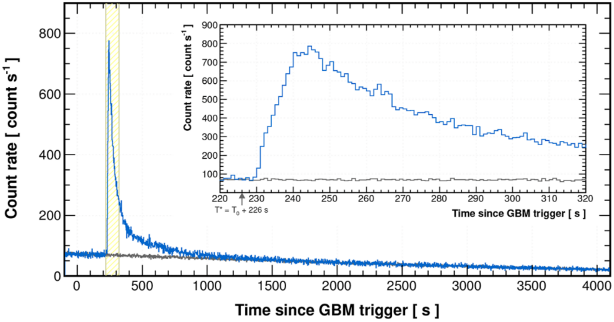
    ATel #15669

GRB 221009A light curve



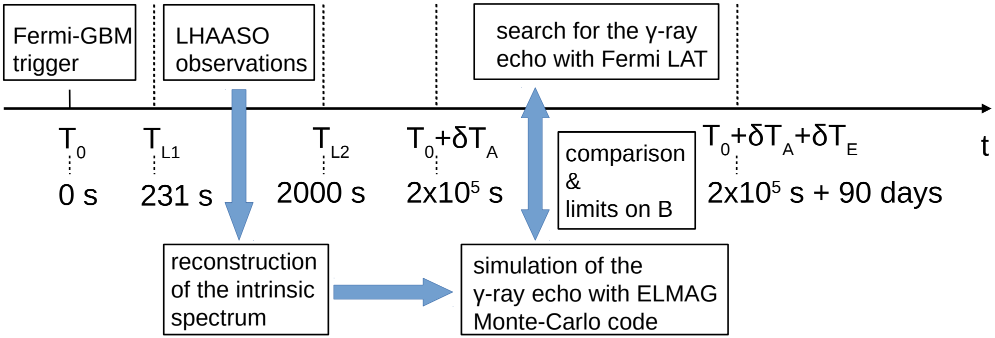
Fermi LAT photons after and before Fermi GBM trigger starting at 1000 s

Stern,Tkachev, arXiv:2303.03855



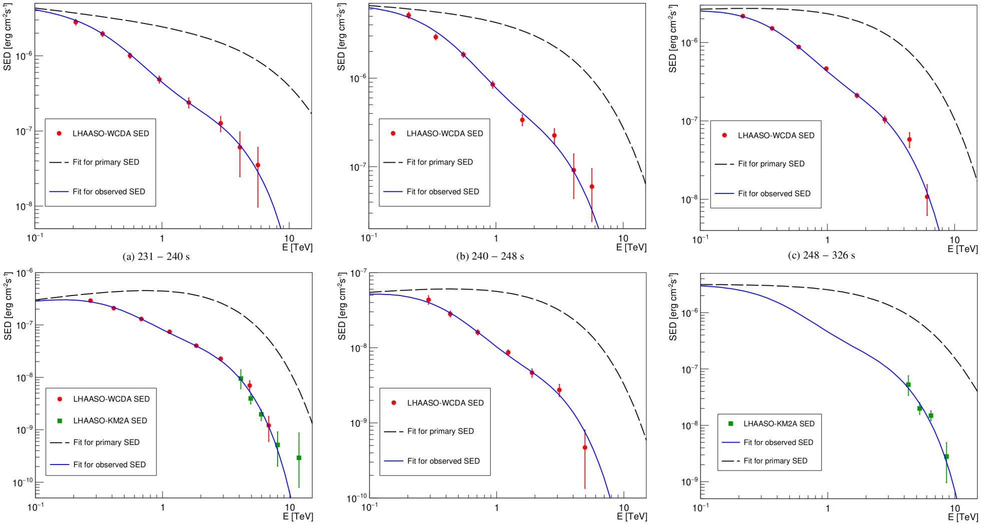
LHAASO, Science, 380 (2023)

Analysis: general scheme



The general scheme follows Dzhatdoev et al., PRD 102 (2020)

LHAASO spectral energy distribution fit



(a) 231 – 240 s

(b) 240 – 248 s

(c) 248 – 326 s

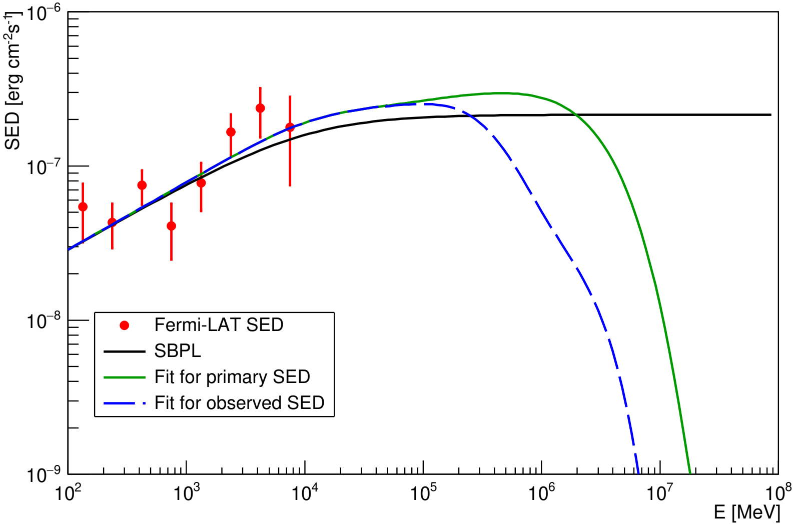
(d) Circles: 326 – 900 s; squares: 300 – 900 s re-scaled to 326 – 900 s

(e) 900 – 2000 s

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

LHAASO-WCDA (LHAASO, 2023, Science, 380, 1390), LHAASO-K2MA(Wang, ICRC'2023)

LHAASO spectral energy distribution fit result



Simulation of the pair echo

- Electromagnetic cascades have been simulated with the Monte-Carlo code ELMAG version 3.03

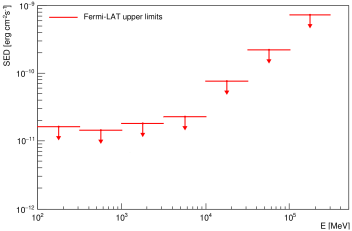
  Blytt, Kachelriess, Ostapchenko, Comput.Phys.Commun (2020)

- EGMF – turbulent field with a Kolmogorov spectrum and field strength variance B; 200 field modes in simulation; coherence length 1 Mpc
- Extragalactic background light model by Gilmore at al. (2012)
- Time range: $T_0 + \delta T_A < t < T_0 + \delta T_A + \delta T_E$, where T_0 is Fermi-GBM trigger time, $\delta T_A = 2 \times 10^5$ s, δT_E = 10,30,90 days
- Jet opening angle 1°

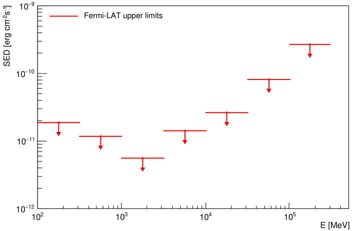
Fermi-LAT analysis

- We use Fermi-LAT data within 20° circle centered at the position of GRB. Fermi Tools version 2.20 with P8R3_SOURCE_V3 instrument response functions.
- Include all point and diffuse sources from 4FGL within the 17° from the center of GRB, galactic and isotropic backgrounds
- We reconstruct Fermi-LAT SED for the first 2000 s after the T_0 and derive 95% CL upper limits in the time range: $T_0 + \delta T_A < t < T_0 + \delta T_A + \delta T_E$, where T_0 is Fermi-GBM trigger time, $\delta T_A = 2 \times 10^5$ s, δT_E = 10,30,90 days

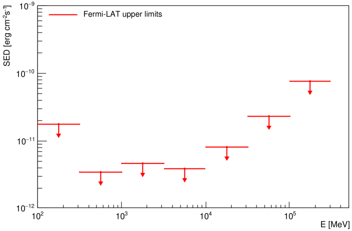
δT_E =10 days



30 days



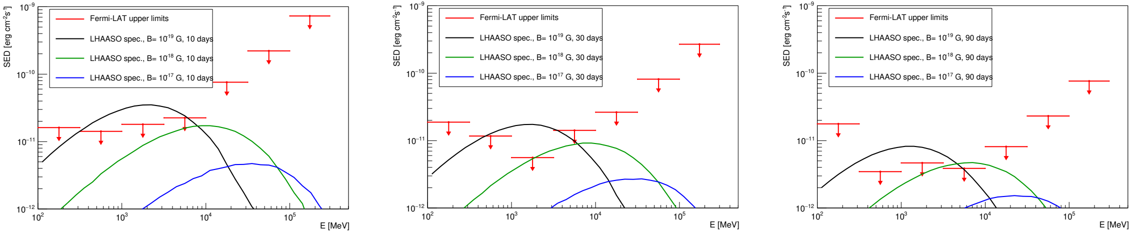
90 days



Results

- We have compared the predicted gamma-ray echo spectral energy distribution with the Fermi LAT upper limits.
- Time range: $T_0 + \delta T_A < t < T_0 + \delta T_A + \delta T_E$, where T_0 is Fermi-GBM trigger time, $\delta T_A = 2 \times 10^5$ s, δT_E = 10,30,90 days

δT_E =10 days — 30 days — 90 days



- The values 10^{-20} G $\leq B \leq 10^{-18}$ G are excluded

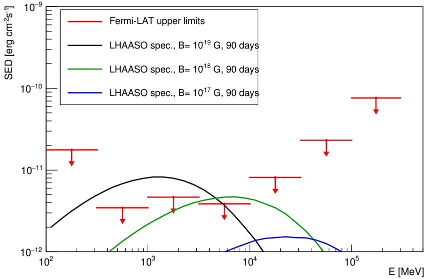
Dzhatdoev,Podlesnyi,GR, arXiv:2306.05347, accepted to MNRAS Letters

Comparison to the results of other authors

- Two papers appeared after our first version have been submitted to arXiv:
  - Huang et al., Astrophys.J.Lett. 955 (2023) 1, L10, arXiv:2306.05970
    - similar approach
    - exclude $B \leq 10^{-18.5}$ G
    - different EBL model Saldana-Lopez et al. (2021) and different time intervals
  - Vovk et al., arXiv: 2306.07672
    - different approach: compare Fermi-LAT light curve integrated over the spectrum in the time interval until 10 days since T_0
    - exclude $B \leq 10^{-19}$ G

Conclusions

- We have obtained for the first time the constraints on the EGMF strength from GRB emission using the Fermi-LAT and LHAASO observations of GRB 221009A
- The values 10^{-20} G $\leq B \leq 10^{-18}$ G are excluded



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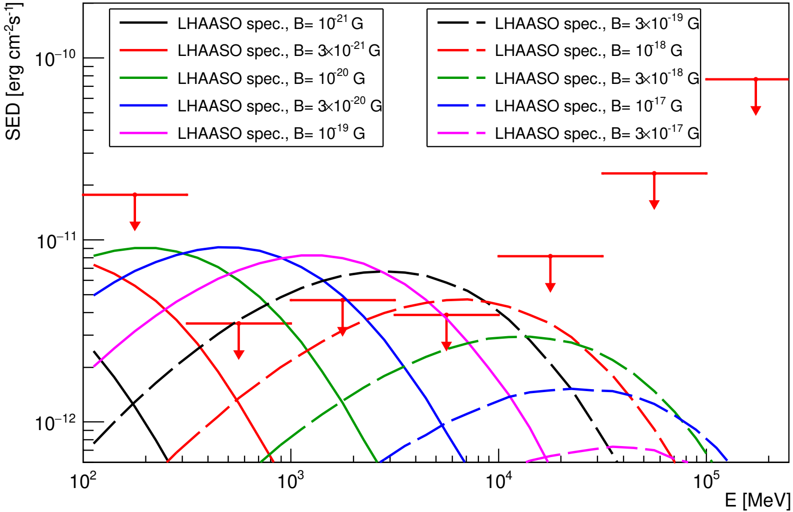
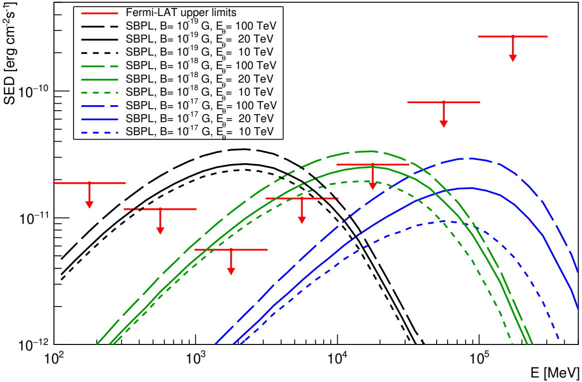
RSF | Russian Science Foundation

Backup slides

Wider range of the magnetic field strength



Pre-publication fit of the LHAASO spectrum



$$E^2 \frac{dN}{dE} = K_s \left(\frac{E}{E_s}\right)^2 \left(\frac{E}{E_s}\right)^{-\gamma_1} \left[1 + \left(\frac{E}{E_b}\right)^{\epsilon}\right]^{-(\gamma_2-\gamma_1)/\epsilon} \theta(E_\theta - E),$$

$K_s = 5.38 \times 10^{-8}\,\mathrm{erg\,cm^{-1}\,s^{-1}}$, $\gamma_1 = 1.56$, $\gamma_2 = 2$, $E_b = 10$ GeV, $\epsilon = 1$,
$E_s = 422$ MeV