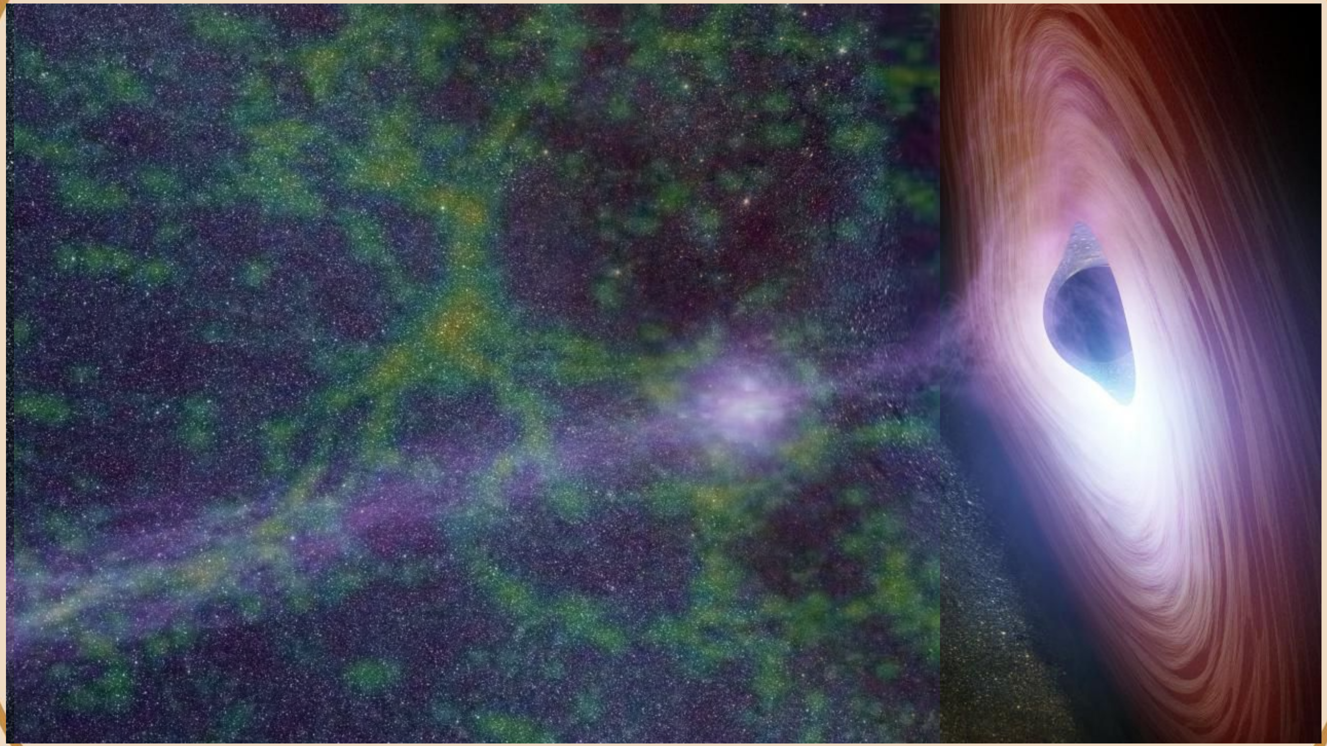
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Constraints on the intergalactic magnetic field from Fermi-LAT observations of GRB 221009A



Paolo Da Vela, Guillem Martì Devesa, Manuel Meyer, Lea Burmeister, Francesco Saturni, Antonio Stamerra, Peter Veres, Francesco Longo on behalf of the *Fermi*-LAT coll.

11th International Fermi Symposium
College Park, MD, 9-13 September, 2024

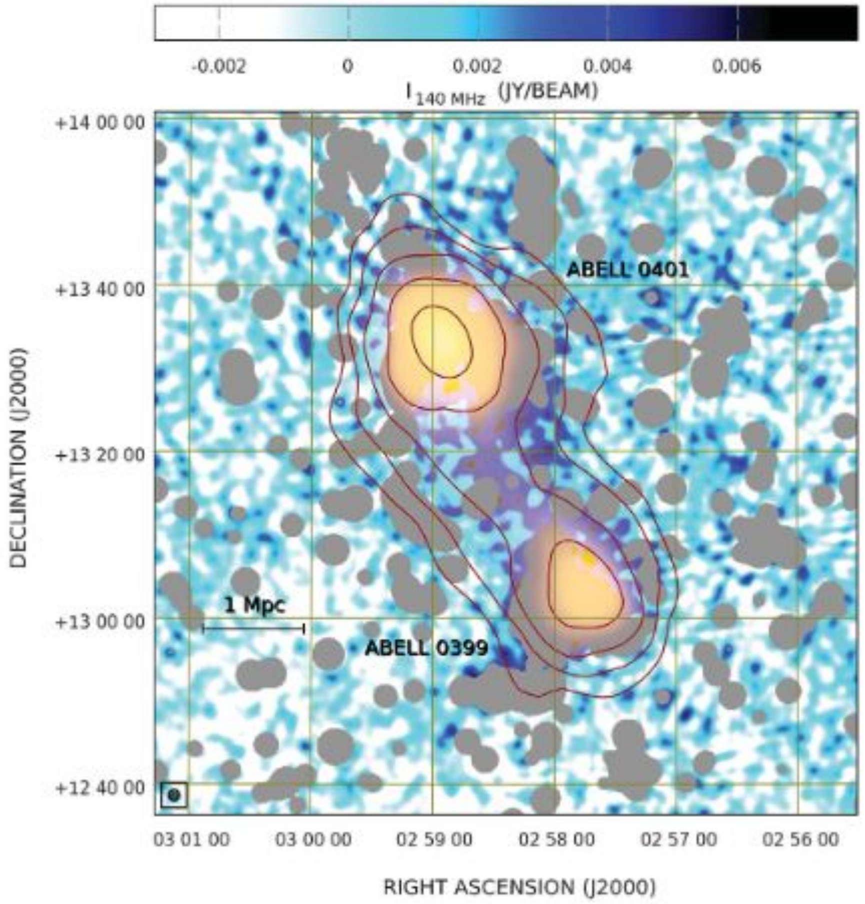
Magnetic Fields in galaxies

Borlaff et al. 2021

B < 1 μG

B ≈15 μG

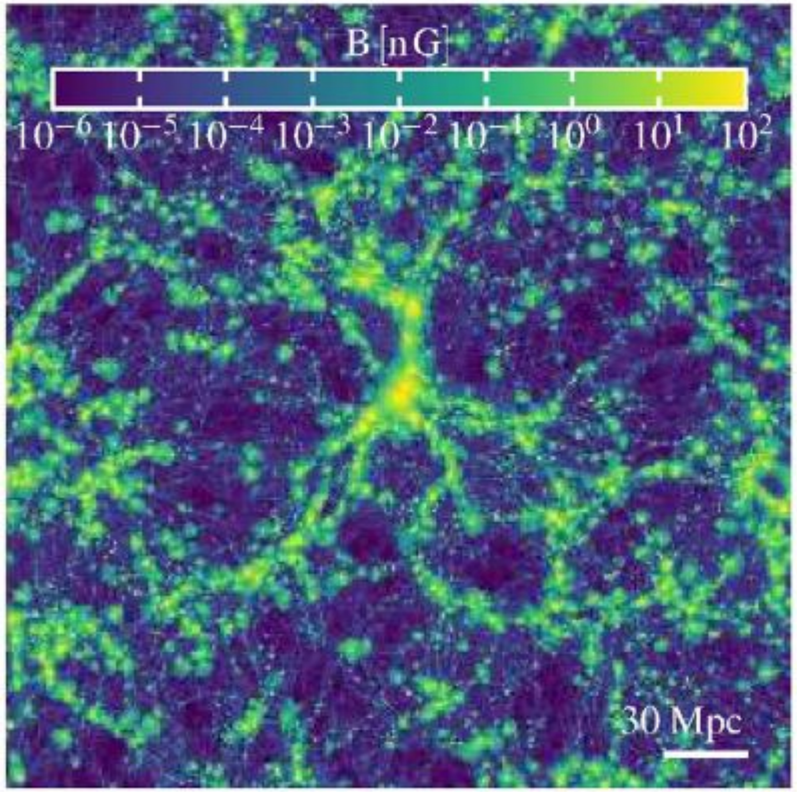
Most of the models that explain these magnetic fields assume a pre-existing magnetic field



Govoni et al. 2019

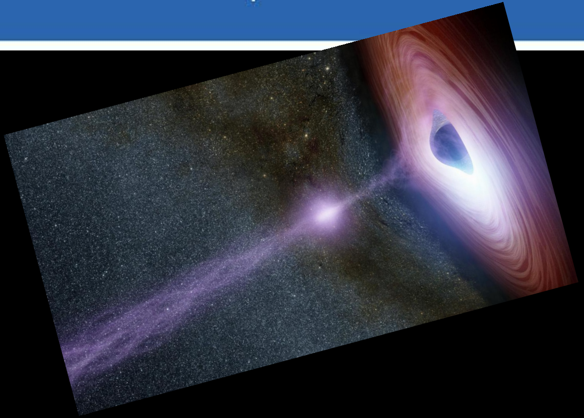
On the nature of the seed fields

- The nature of the seed fields is largely unknown. Two main hypothesis exist:
  - the cosmological scenario
  - the astrophysical scenario
- Observationally we need measurement of magnetic fields in the intergalactic medium



Marinacci et al. 2019

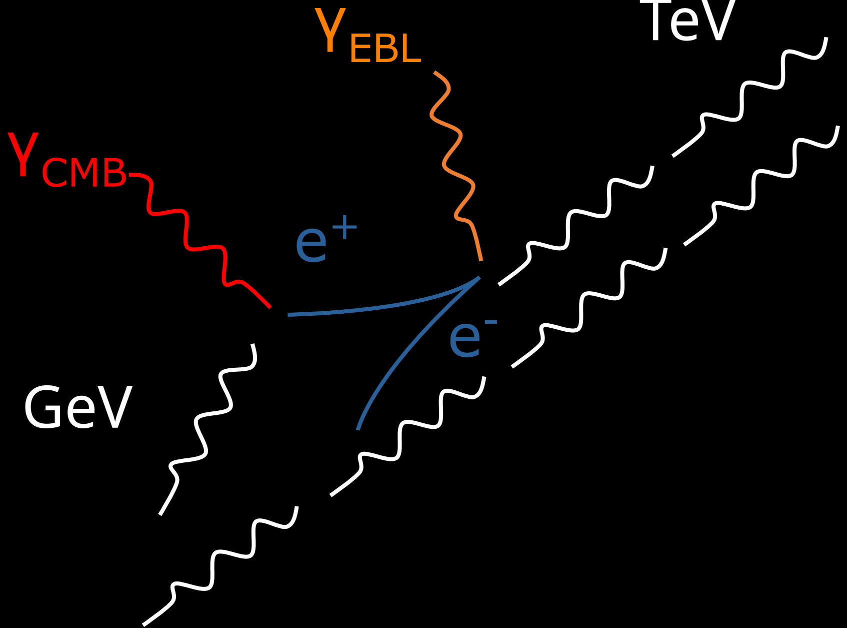
Physical process



Excess at lower energies

$$E \simeq 70 \left[\frac{E_0}{10\ TeV}\right]^2 \quad GeV$$

Neronov et al. 2009



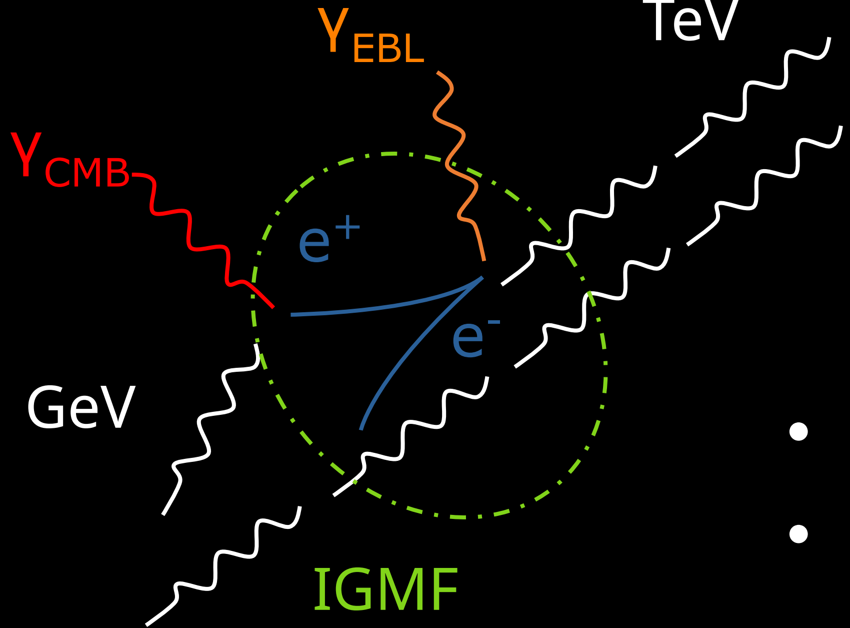
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Physical process

Excess at lower energies

$$E \simeq 70 \left[\frac{E_0}{10\ TeV}\right]^2 \quad GeV$$

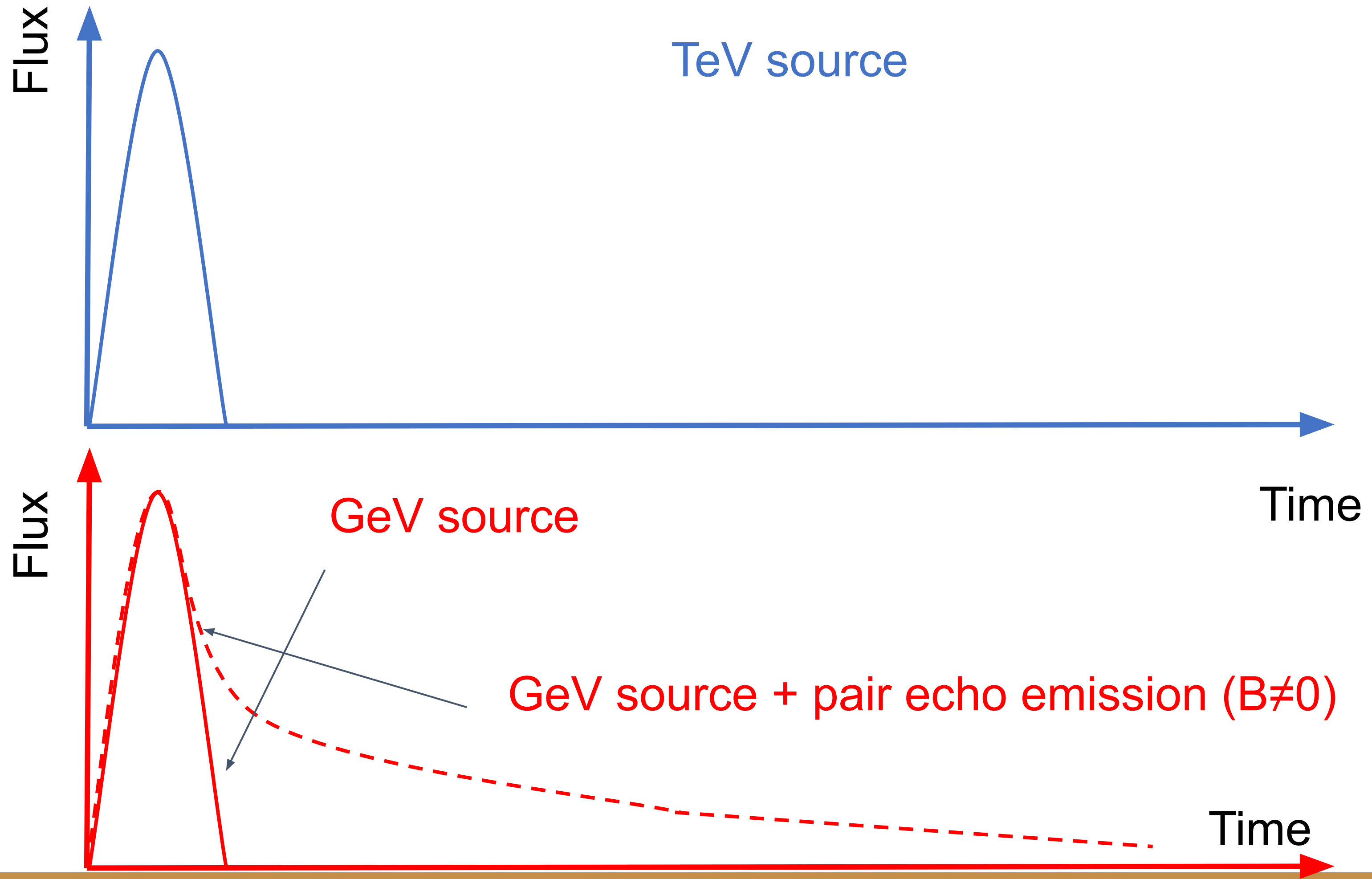
Neronov et al. 2009



Indirect detection of the IGMF

- Extended γ rays halos
- Spectral features
- **Time delayed γ-ray emission**

Search for the “pair-echo” emission

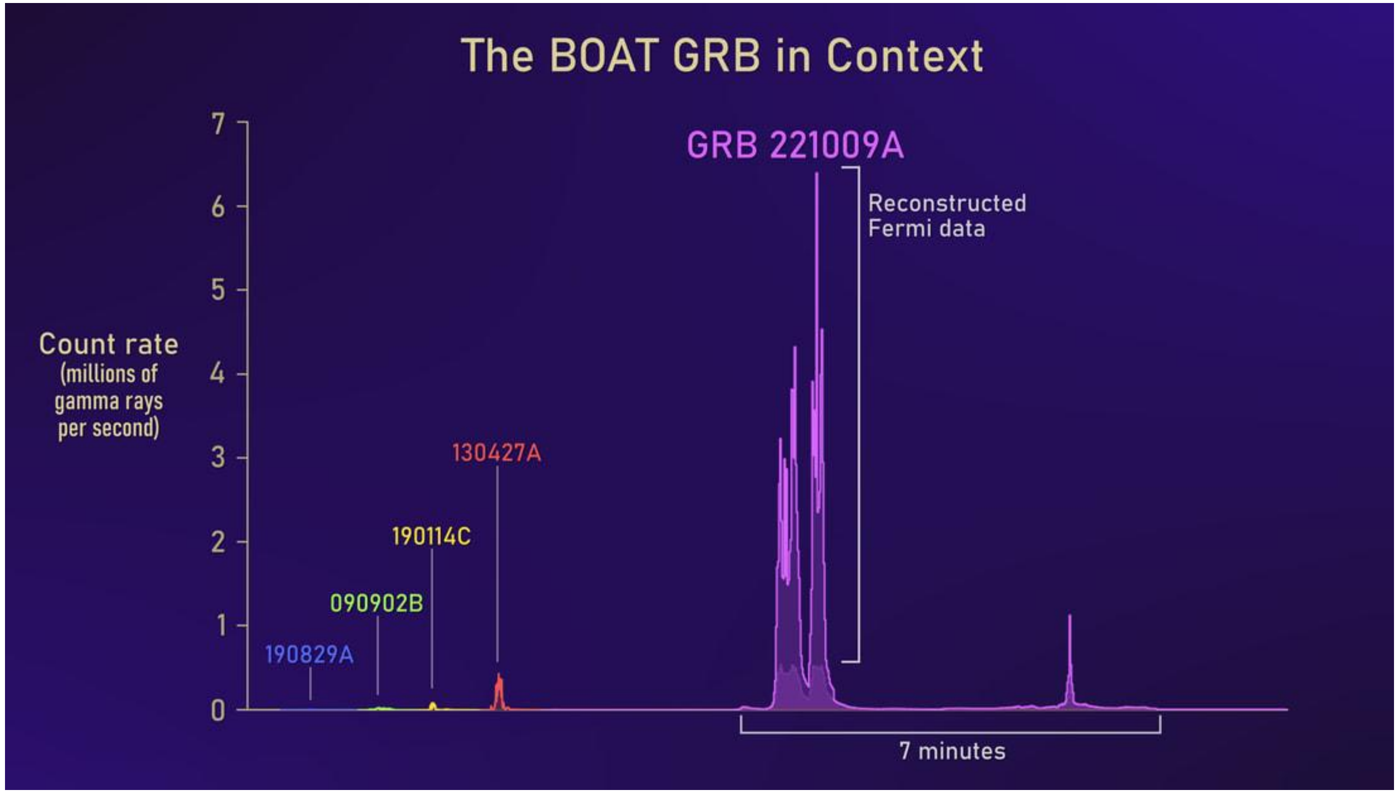


$$T_{delay} \propto E^{-5/2} B^2$$

Neronov et al. 2009

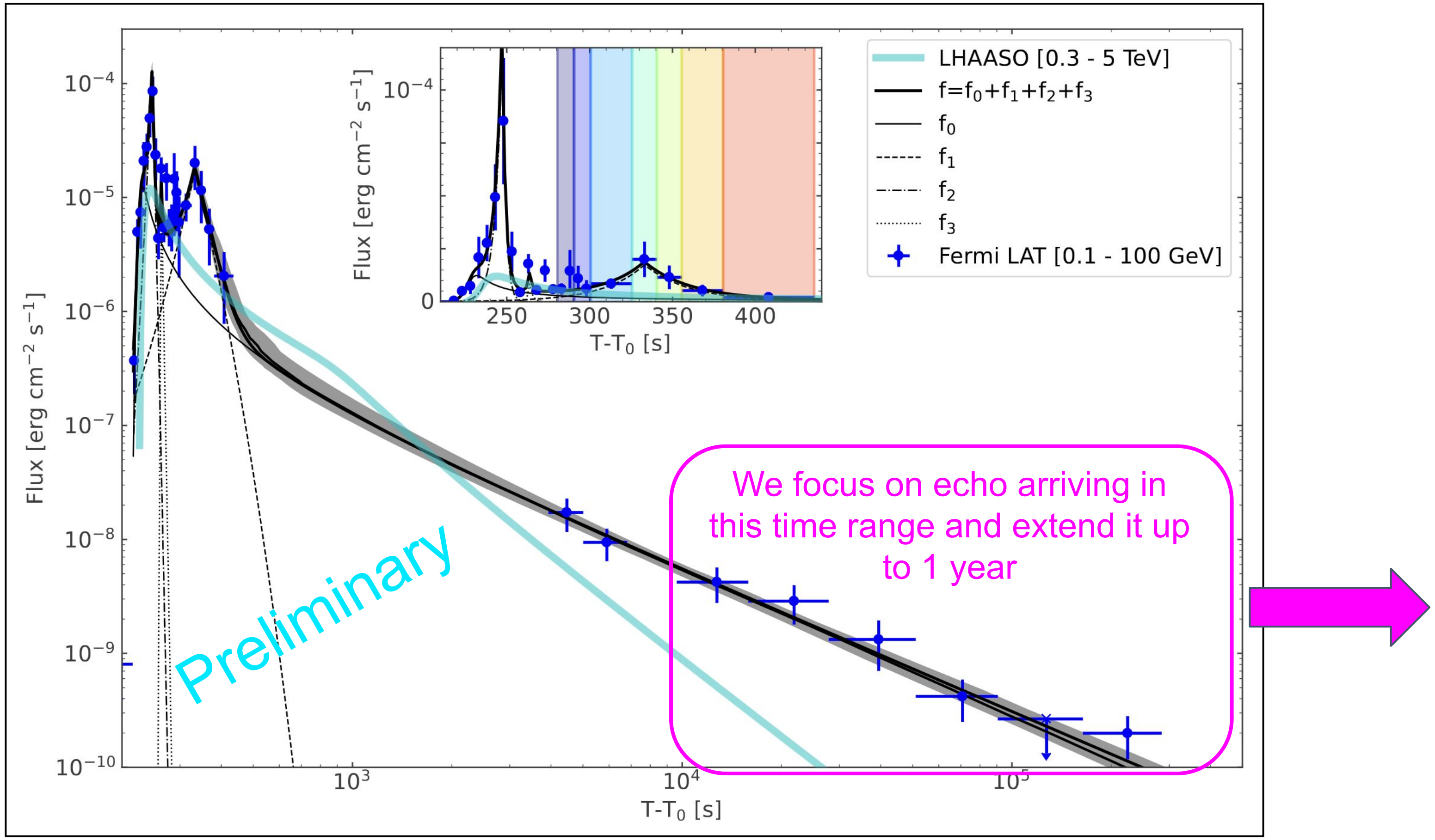
Interesting for transient events, particularly for GRB

GRB 221009A: BOAT



- Brightest GRB ever observed
- Redshift from CaI, II absorption lines: z=0.1505
- *Fermi*-LAT detected 99.4 GeV photon (new record from GRB) at T_0+240s
- LAT also detected 400 GeV photon at T_0+33 ks (preliminary: 4σ association with GRB)
- Detected at very high energies with LHAASO:
  - WCDA: between 0.2 and 7 TeV in ~3000 s
  - KM2A: between 3 and 13 TeV in ~900 s

Composite LAT and LHAASO lightcurves



Fermi-LAT coll., submitted

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | INAF ISTITUTO NAZIONALE DI ASTROFISICA

Modeling the temporal and spectral cascade structure with CRPropa3

- CRPropa3 Monte Carlo Code used to generate 4D (spatial + energy + delay time) templates
- IGMF:
  - Kolmogorov turbulent spectrum
  - $B_{rms} = 10^{-20}$ G, …, 10^{-15} G
  - Coherence length: $\ell_B \simeq 6$ Mpc
- EBL model of Franceschini et al. (2008)
- Jet opening angle: 1.6° (from LHAASO coll. 2023), jet aligned with the line of sight

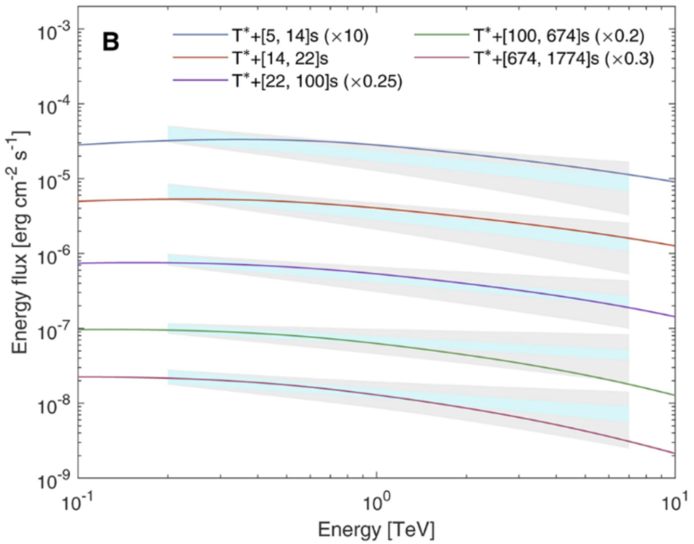
Finanziato dall'Unione europea
NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA
INAF
ISTITUTO NAZIONALE DI ASTROFISICA

Assumed Intrinsic spectrum: from LHAASO WCDA

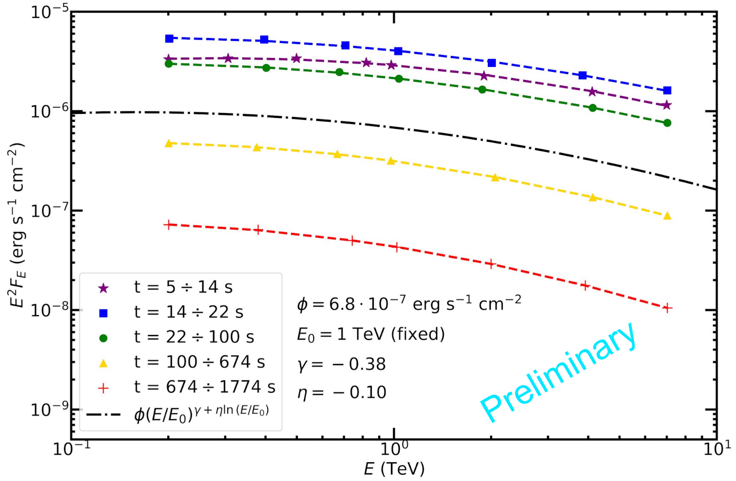
- LHAASO Collaboration fitted physical GRB model to their observations
- We approximated this model with a logparabola and derived time averaged spectrum:

$$E^2 F_E = \phi_0 \left(\frac{E}{E_0} \right)^{\gamma + \eta \ln(E/E_0)}$$

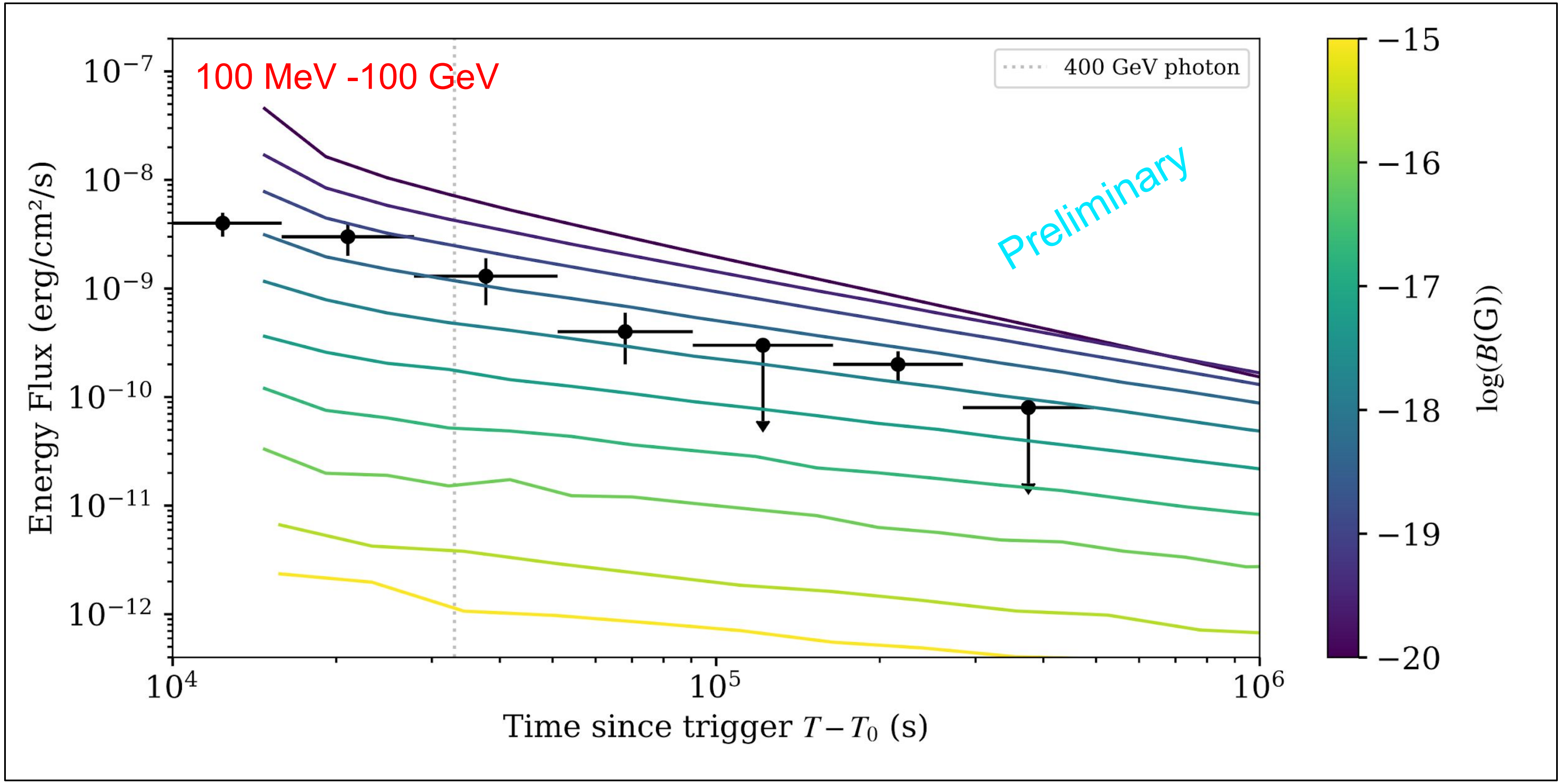
- Additionally multiplied with exponential cutoff at 7 TeV
- Assumed emission time: 3000s



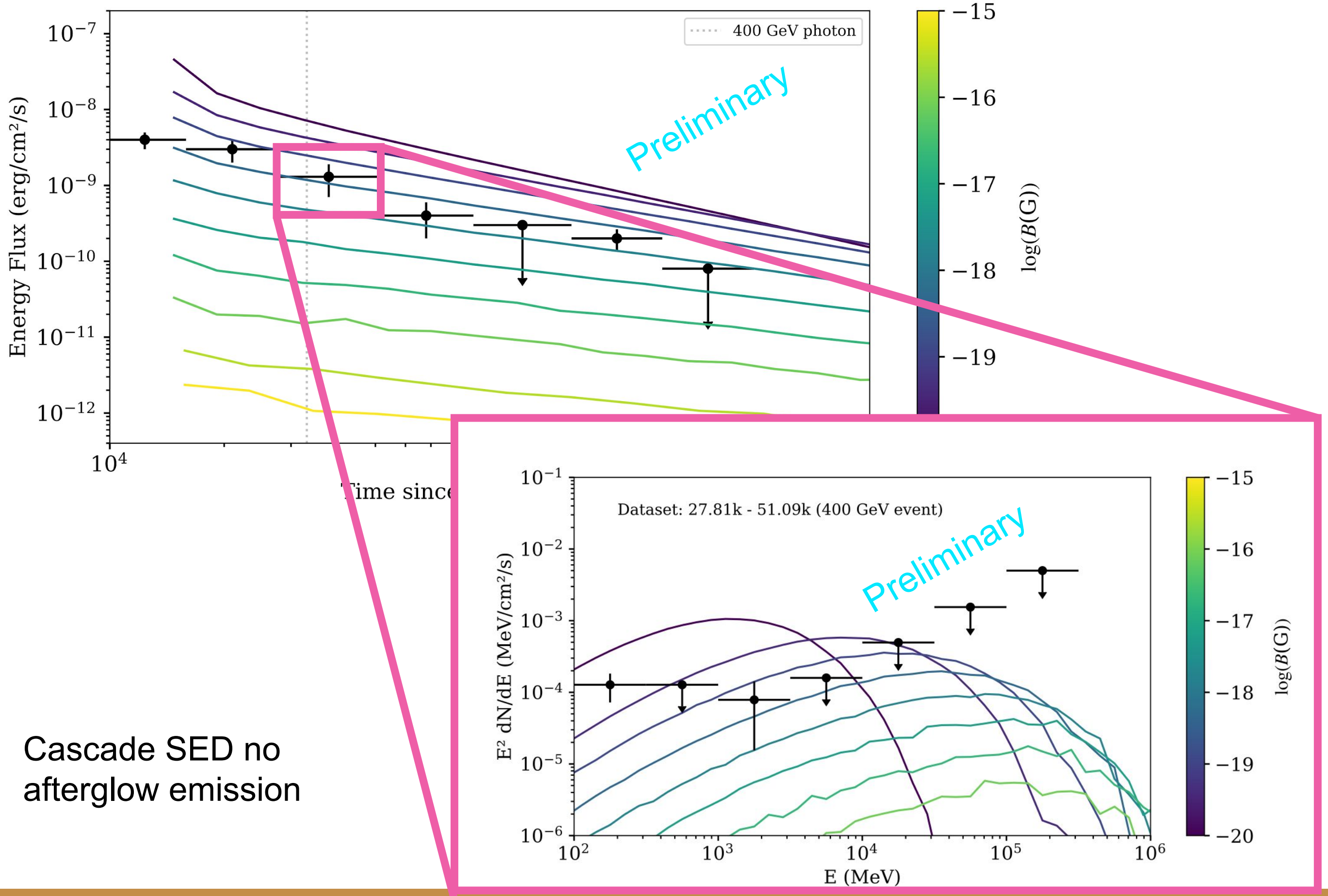
LHAASO Coll. Science 2023



Fermi-LAT LAT lightcurve vs pair echo predictions



Statistical analysis: spectral and temporal likelihood



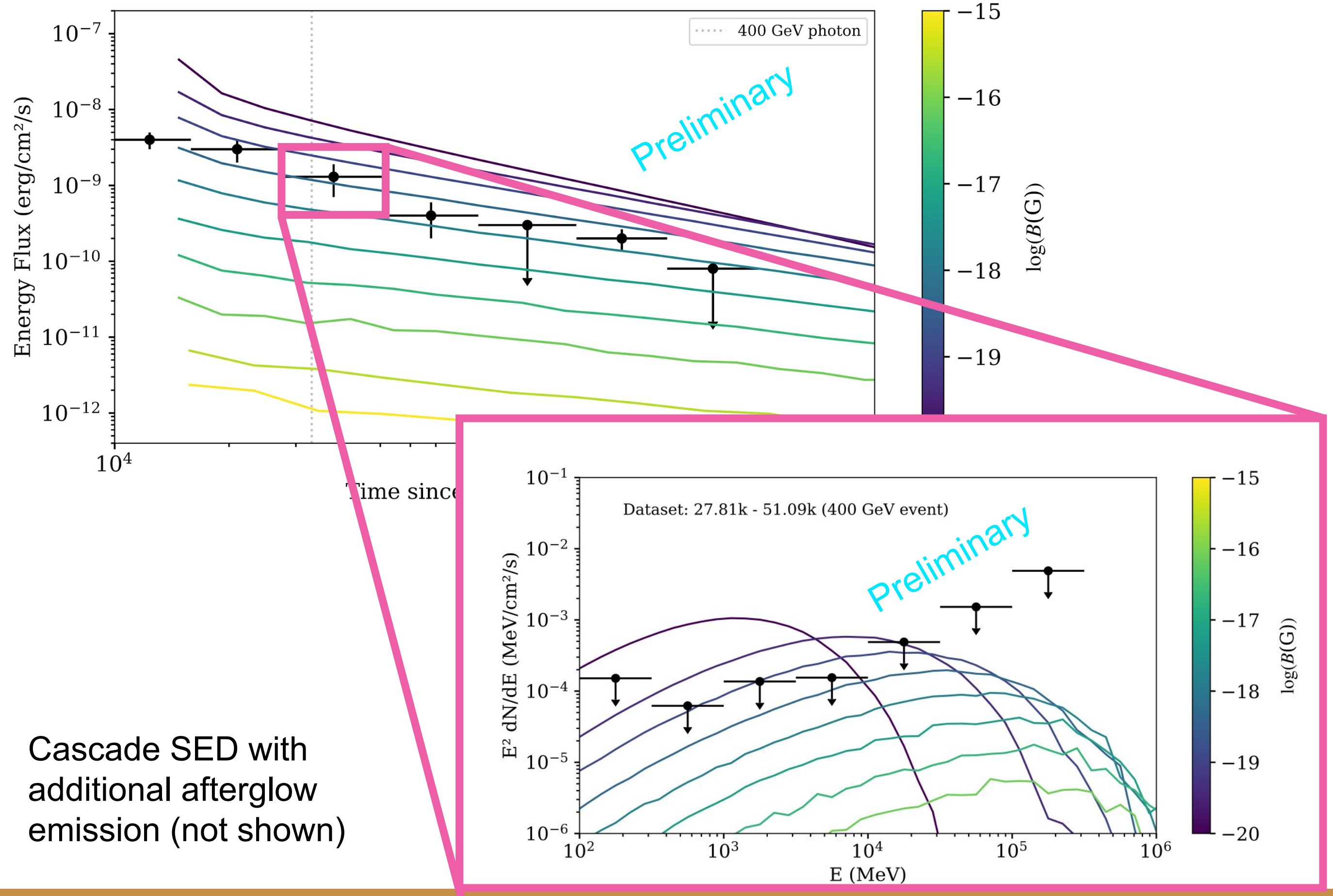
Cascade SED no afterglow emission

- For each time bin *i*:
  - Add cascade prediction for fixed B_{rms}
  - Compute log likelihood summed over energy bins *j*:

$$\ln \mathbf{L}_i = \sum_j \ln \mathbf{L}\left(B_{rms}, \hat{\theta}\,|D_{ij}\right)$$

  - θ: optimized nuisance parameters
- Consider two cases for $T<T_0+3$ days:
  - No afterglow emission
  - Afterglow emission modeled with powerlaw with index Γ=2

Statistical analysis: spectral and temporal likelihood



Cascade SED with additional afterglow emission (not shown)

- For each time bin *i*:
  - Add cascade prediction for fixed B_{rms}
  - Compute log likelihood summed over energy bins *j*:

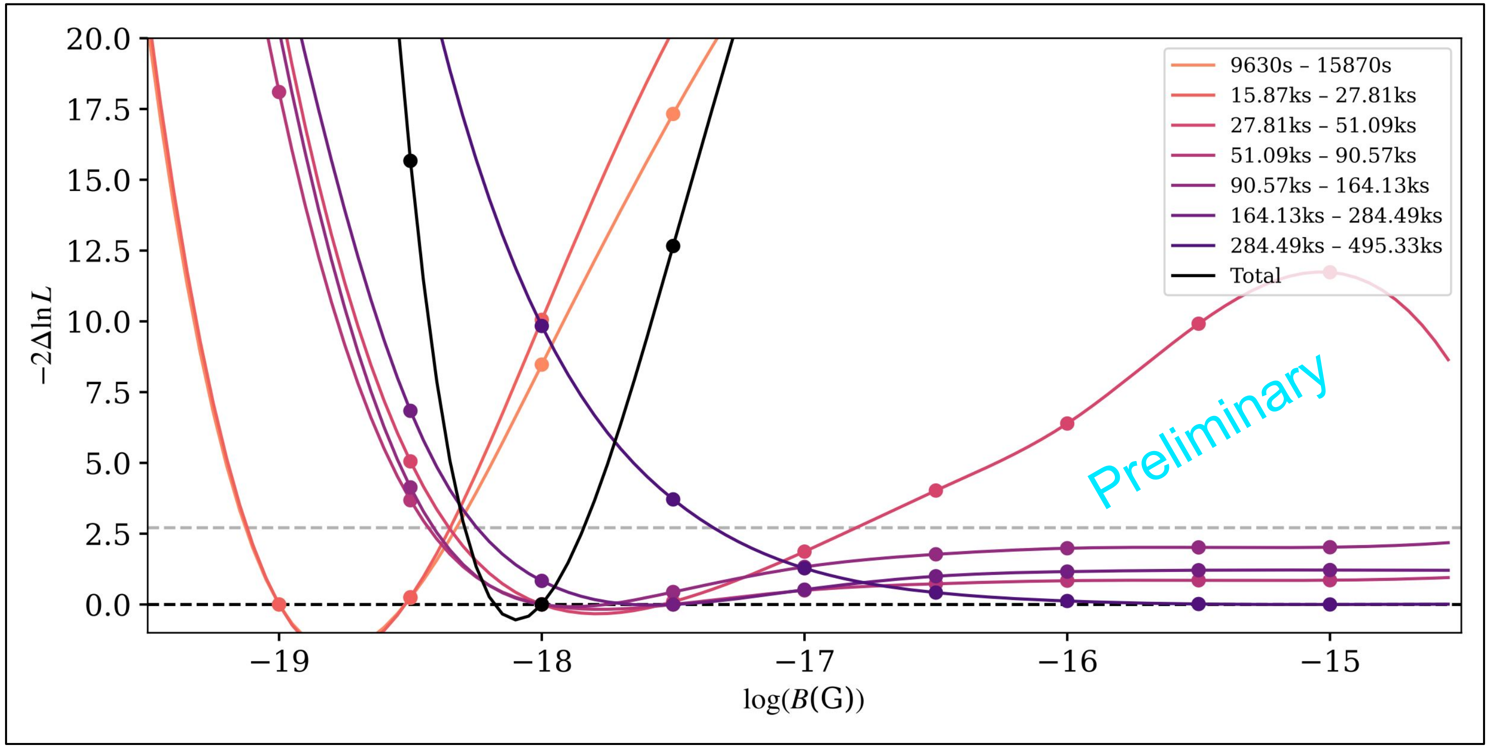
$$\ln \mathbf{L}_i = \sum_j \ln \mathbf{L}\left(B_{rms}, \hat{\theta} \,|\, D_{ij}\right)$$

  - θ: optimized nuisance parameters
- Consider two cases for $T<T_0+3$ days:
  - No afterglow emission
  - Afterglow emission modeled with powerlaw with index Γ=2

Likelihood profiles: no astrophysical afterglow emission added

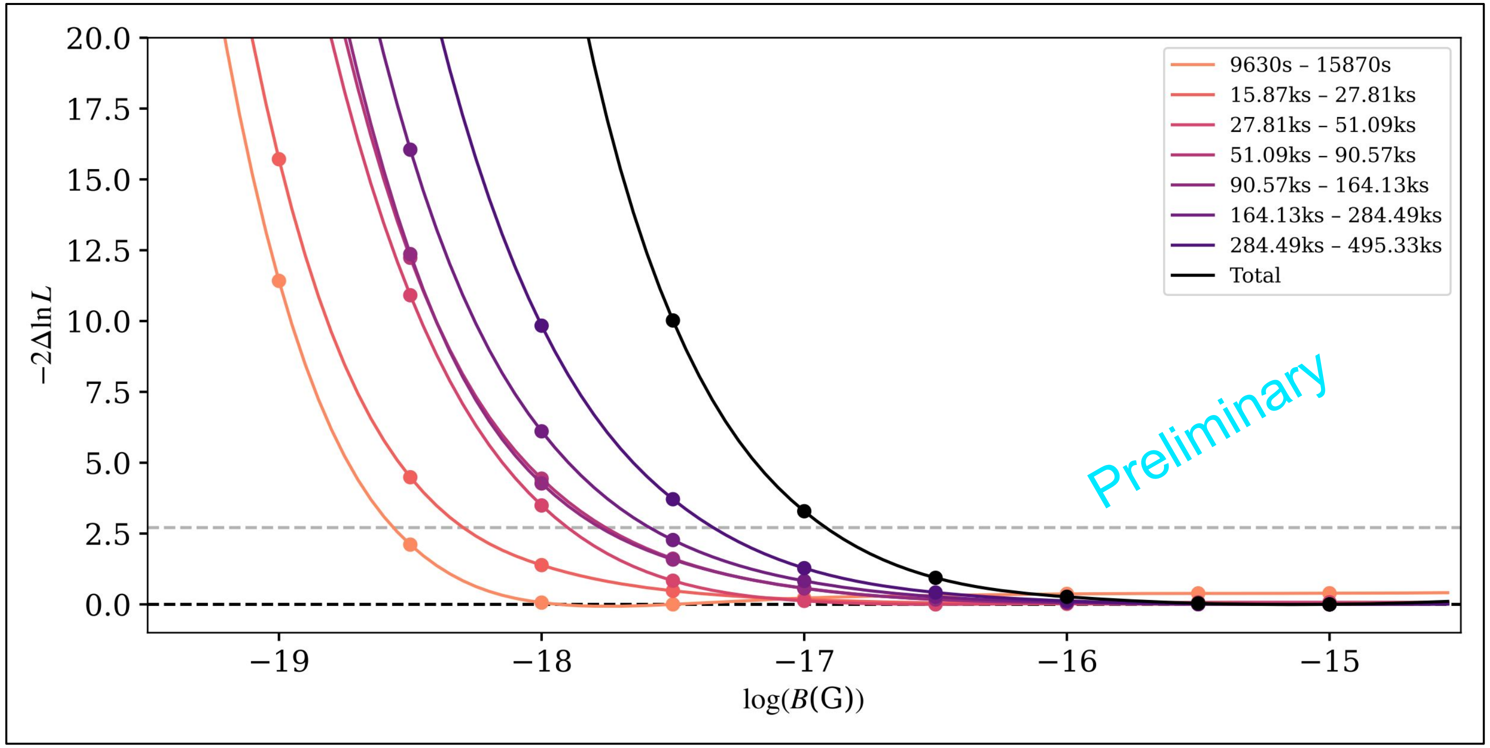
- "Detection" of pair echo emissions at early times

- Pair echo takes role of astrophysical afterglow, which is expected to present



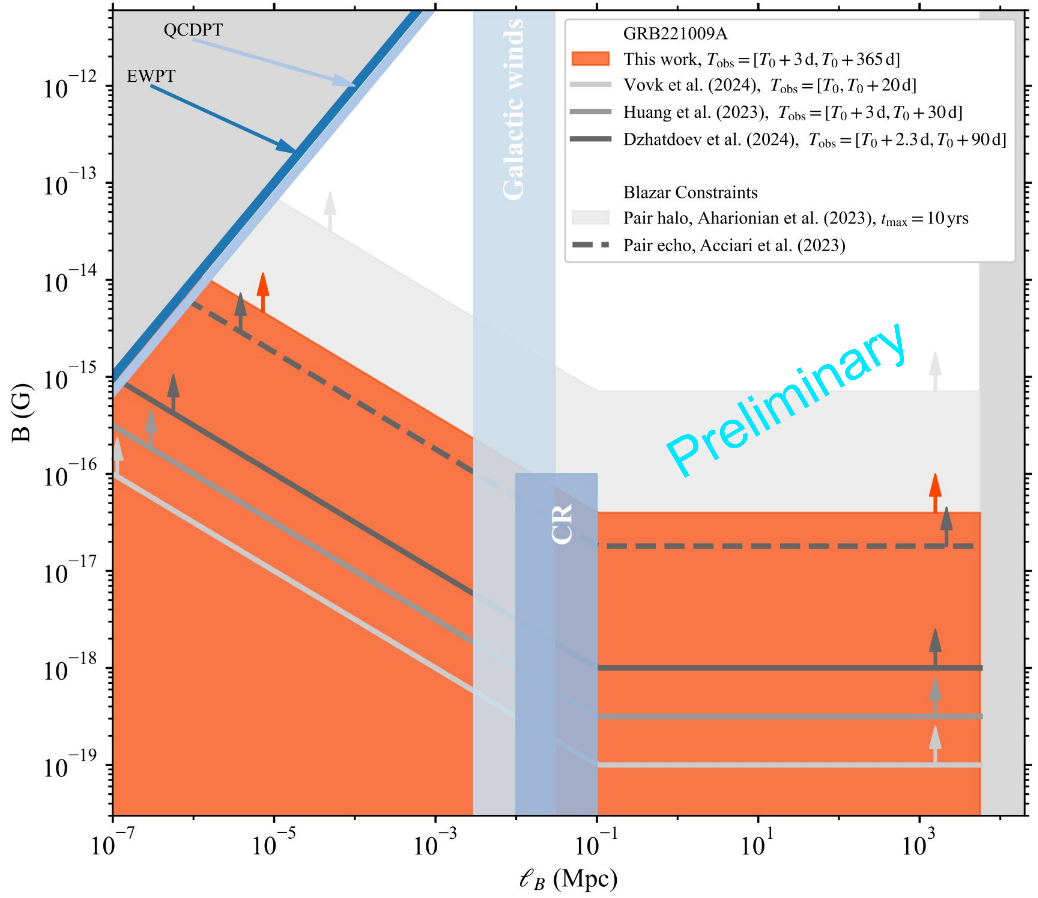
Likelihood profiles: no astrophysical afterglow emission added

- With added afterglow: “detection” disappears
- We can rule out magnetic fields where summed log-likelihood is > 2.71
- For T ∈ [T_0+3 days, T_0+365 days]: $B_{rms} \gtrsim 4 \times 10^{-17}$ G (95% confidence)



Comparisons with previous constraints

- ★ Best constraints so far on IGMF with pair echo technique
- ★ Compared with previous constraints also using GRB 221009A:
  - we include more data
  - Robust statistical analysis
  - Include astrophysical afterglow
- ★ Compared to pair halo searches:
  - No assumptions on activity time necessary
  - Plasma instabilities that coils suppress cascade probably not relevant here



Summary and Conclusions

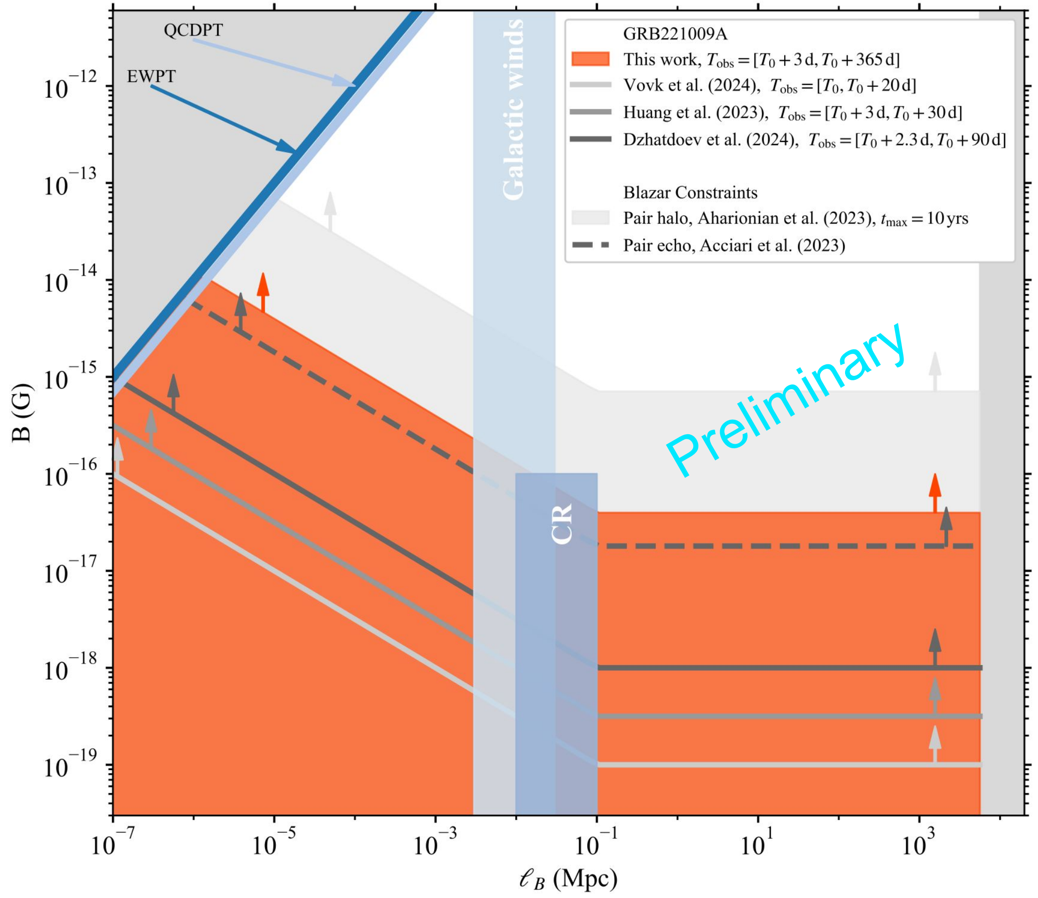
★ GRB 221009A offers a wealth of opportunities to study GRB physics and photon propagation

★ We have derived new constraints on IGMF with $B_{rms} \gtrsim 4 \times 10^{-17}$ G

★ Best constraints so far from pair echo technique

★ Constraints depend mildly on chosen EBL model

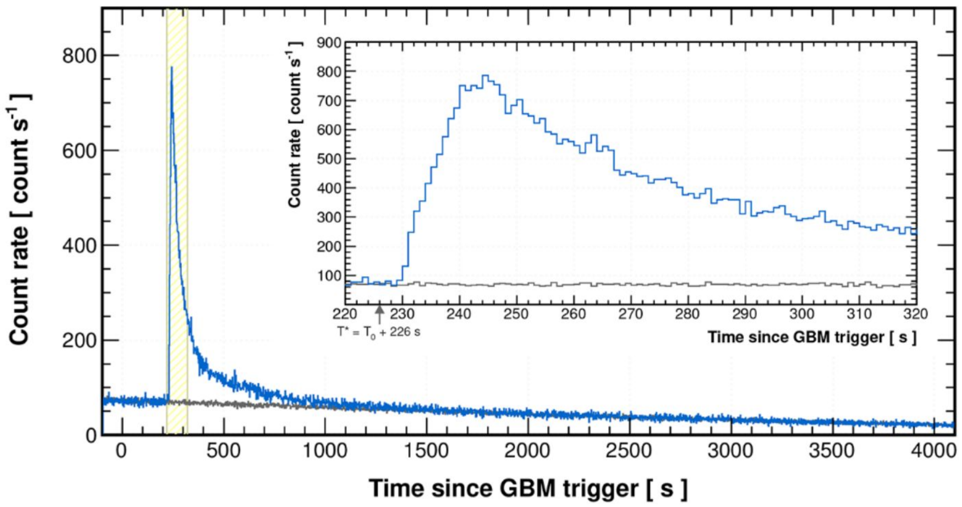
★ Outlook: use predictions from GRB afterglow model instead of powerlaw with Γ=2

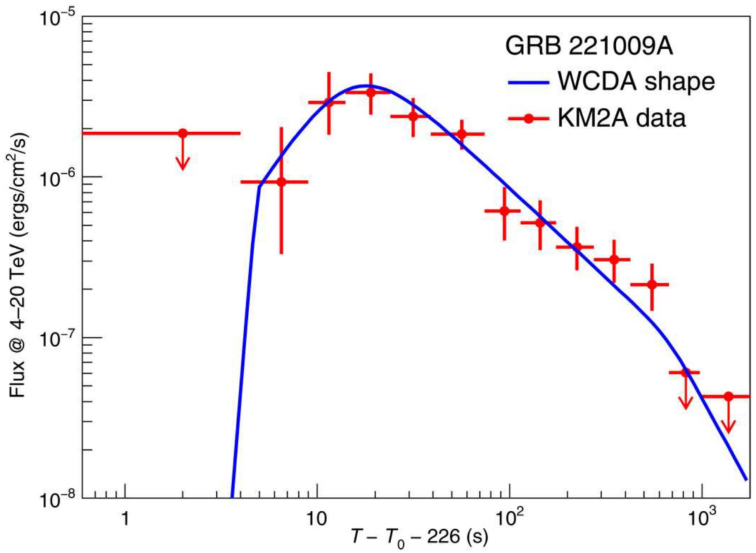


Back up

VHE photons seen with LHAASO

- WCDA: > 64,000 gamma rays between 0.2 and 7 TeV in ~3000 s
- KM2A: 140 gamma rays between 3 and 13 TeV in ~900 s
- Lightcurve suggests jet opening angle of 1.6°
- Distance and highest energies: strong absorption on EBL





LHAASO Coll. Science 2023