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

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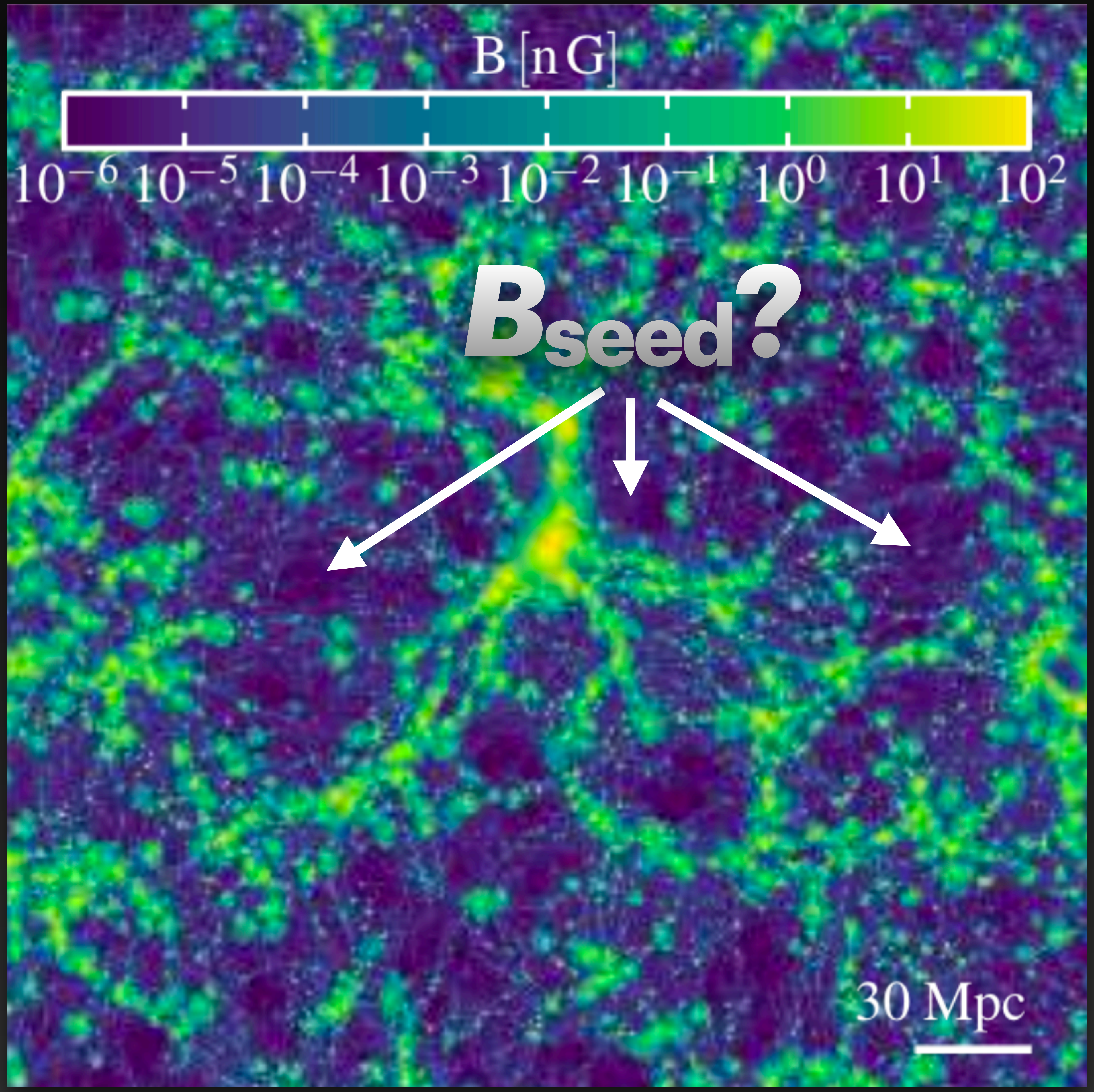
The Intergalactic magnetic field

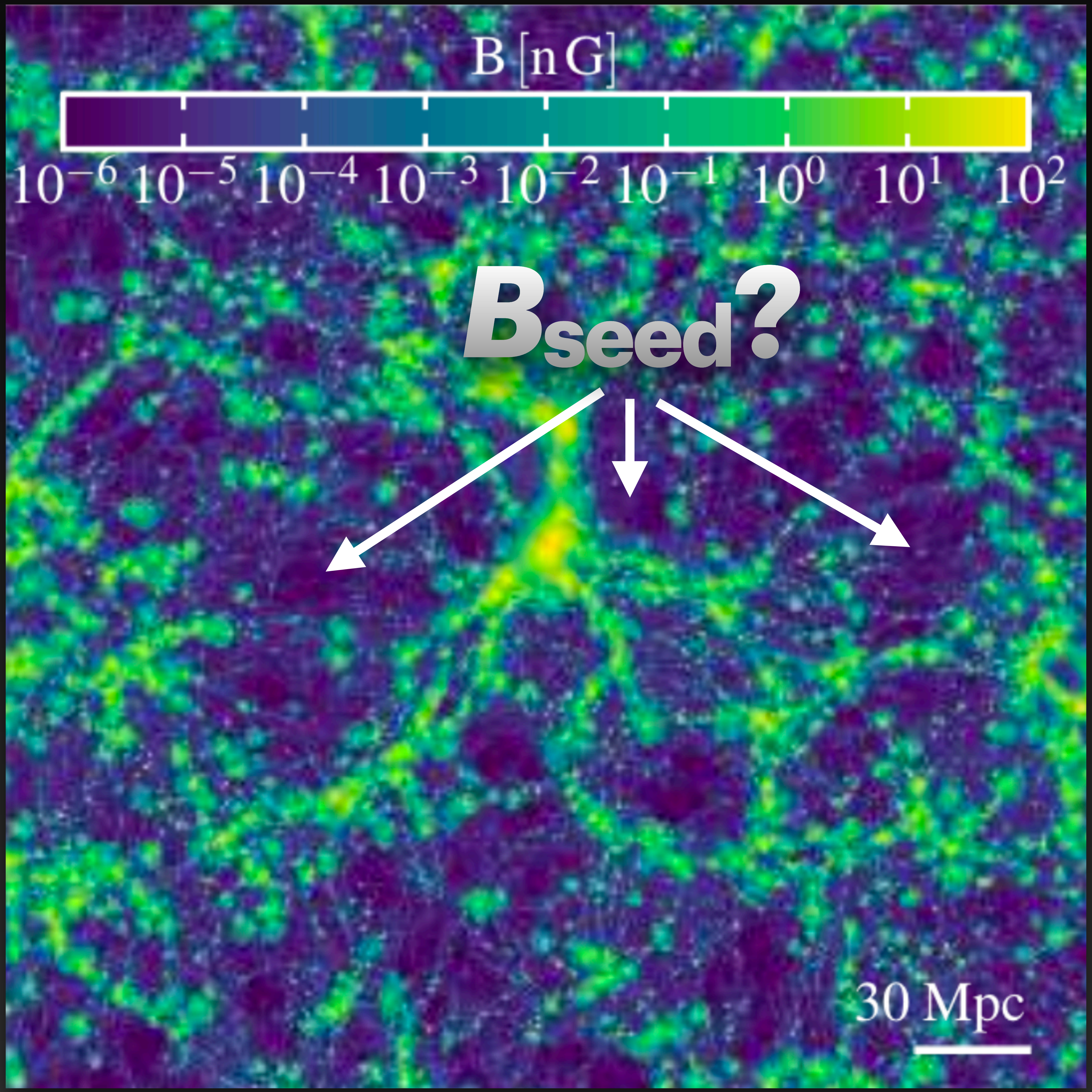
IllustrisTNG simulation — Marinacci et al. (2018)



The Intergalactic magnetic field

- B-fields in galaxies and galaxy clusters originate from amplified seed field
- Origin, strength, orientation of seed fields unknown
- Extremely difficult to measure directly

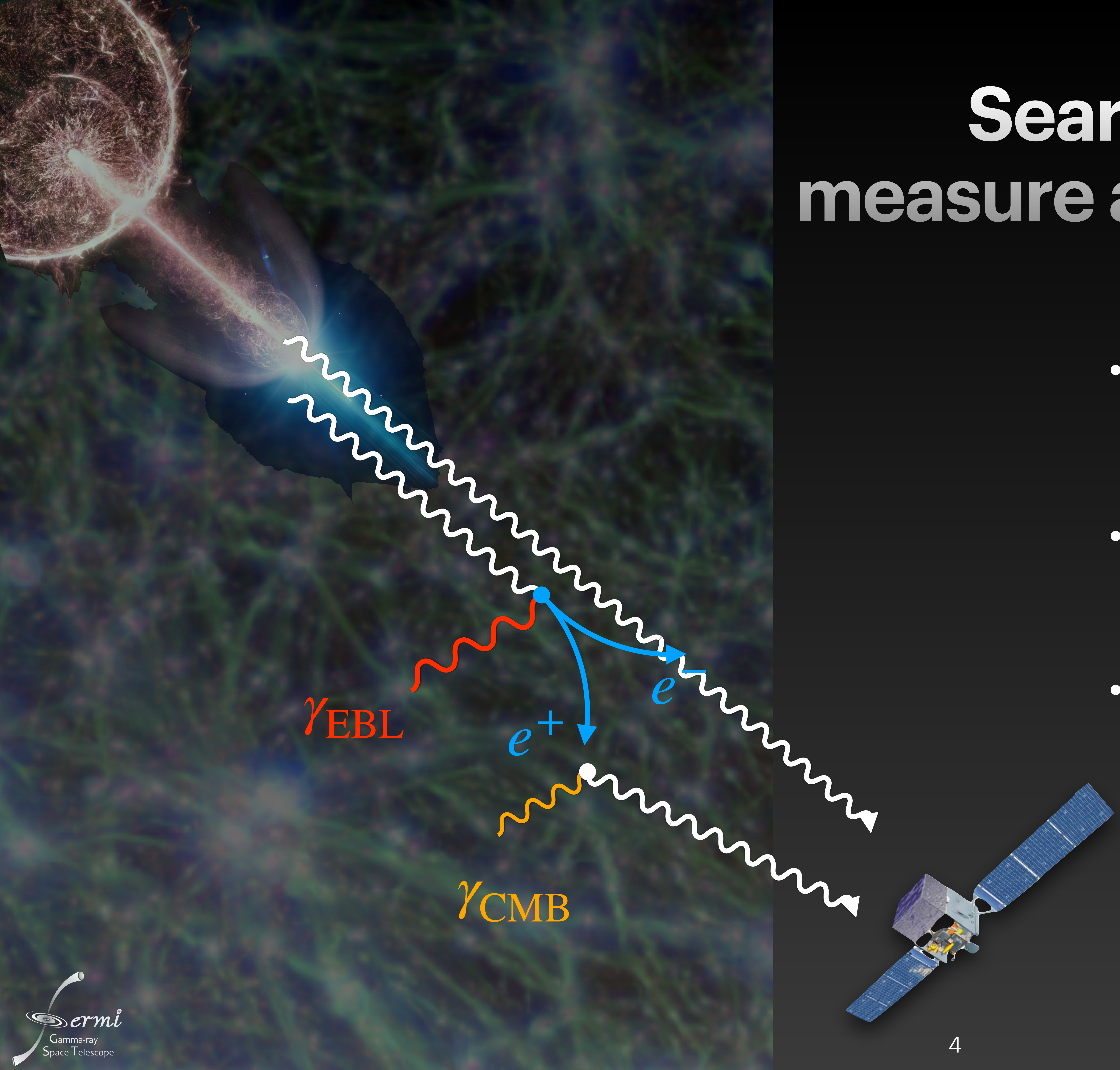
IllustrisTNG simulation — Marinacci et al. (2018)



Fermi Gamma-ray Space Telescope

Searching for a pair echo to measure and constrain the IGMF

[Plaga 1995]



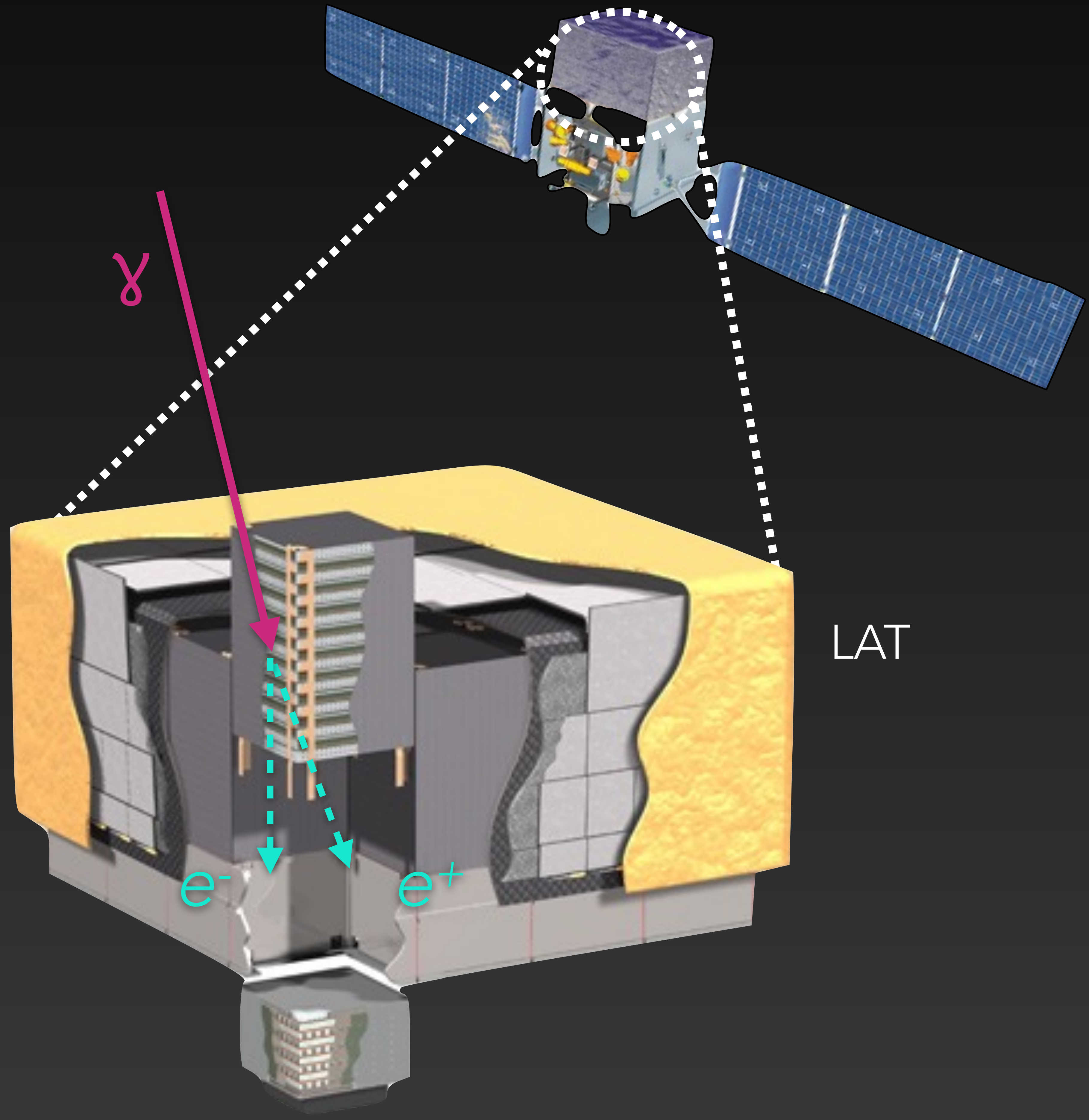
- Primary γ rays from GRB produce e^+e^- pairs
- Pairs up scatter CMB photons to γ-ray energies → cascade
- Cascade photons arrive with delay due to deflection in IGMF

The *Fermi* Large Area Telescope (LAT)

Observing the gamma-ray sky since June 11, 2008

Energy range	20 MeV - over 300 GeV
Effective Area (E > 1 GeV)	~ 1 m^2
Point spread function (PSF)	0.8° @ 1 GeV
Field of view	2.4 sr (~20% of the sky)
Orbital period	91 minutes
Altitude	565 km

- **Survey mode**: full sky observed every 3 hours
- **Public data**, available within 12 hours



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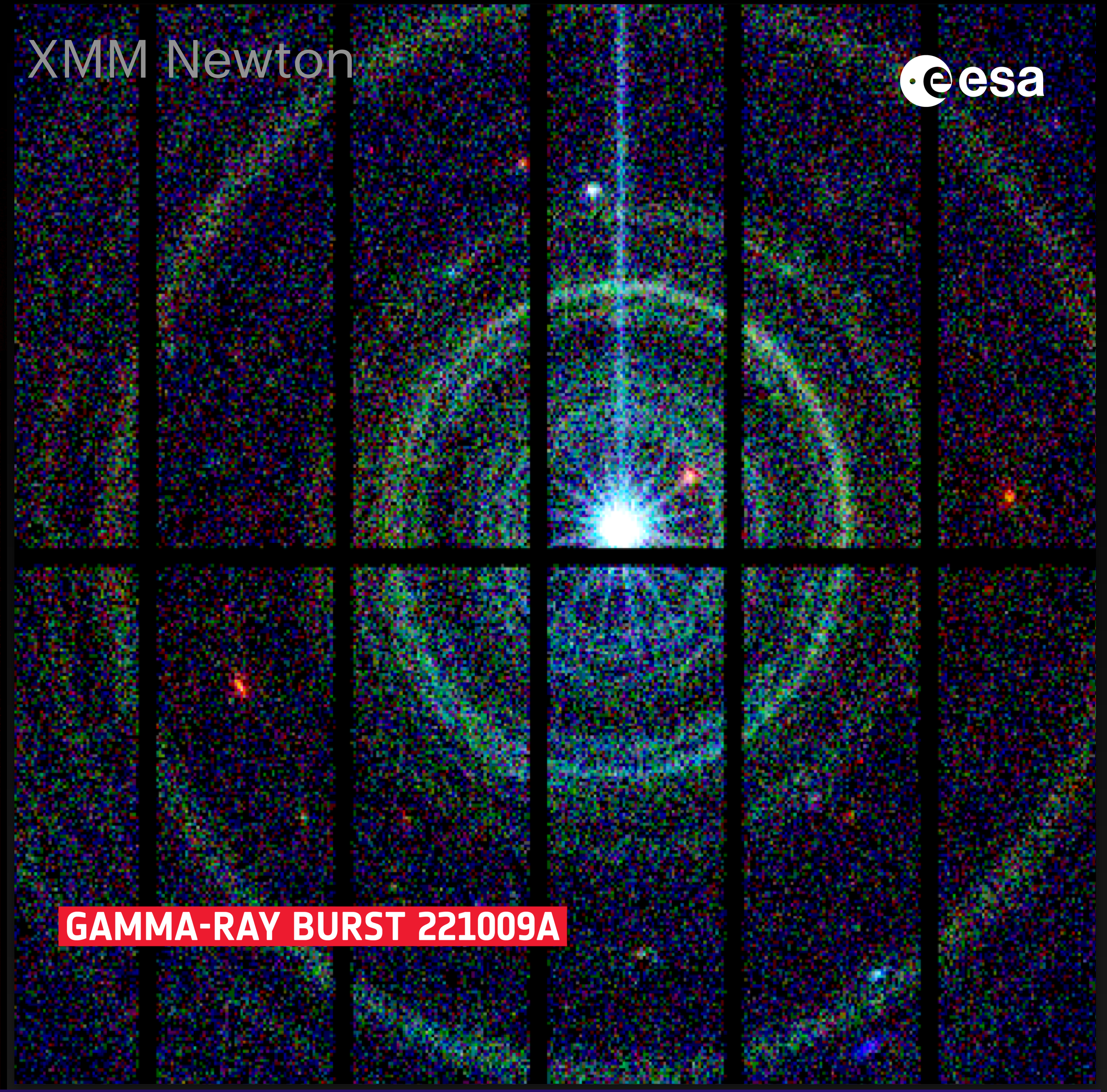
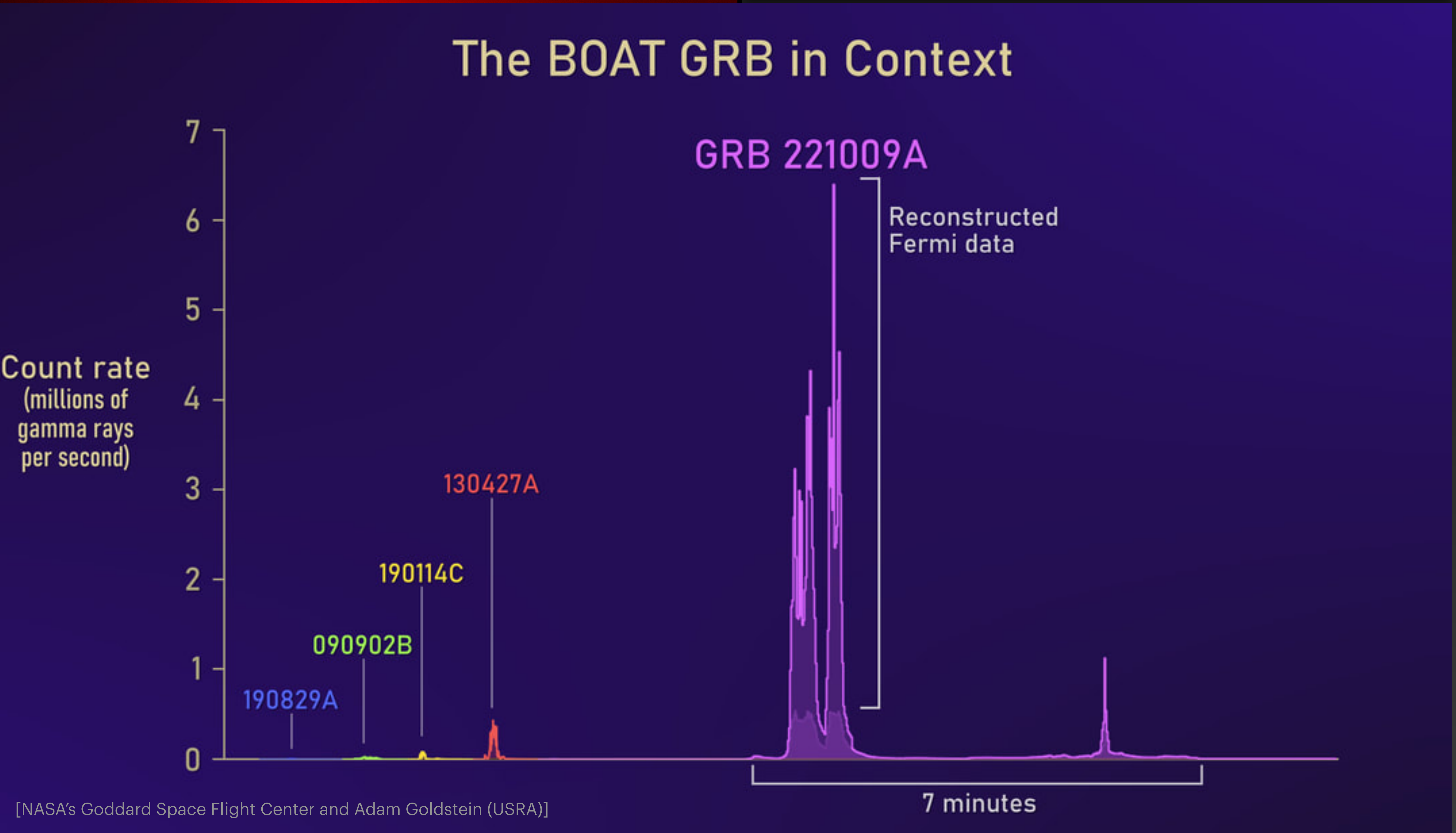
[Atwood et al. 2009]



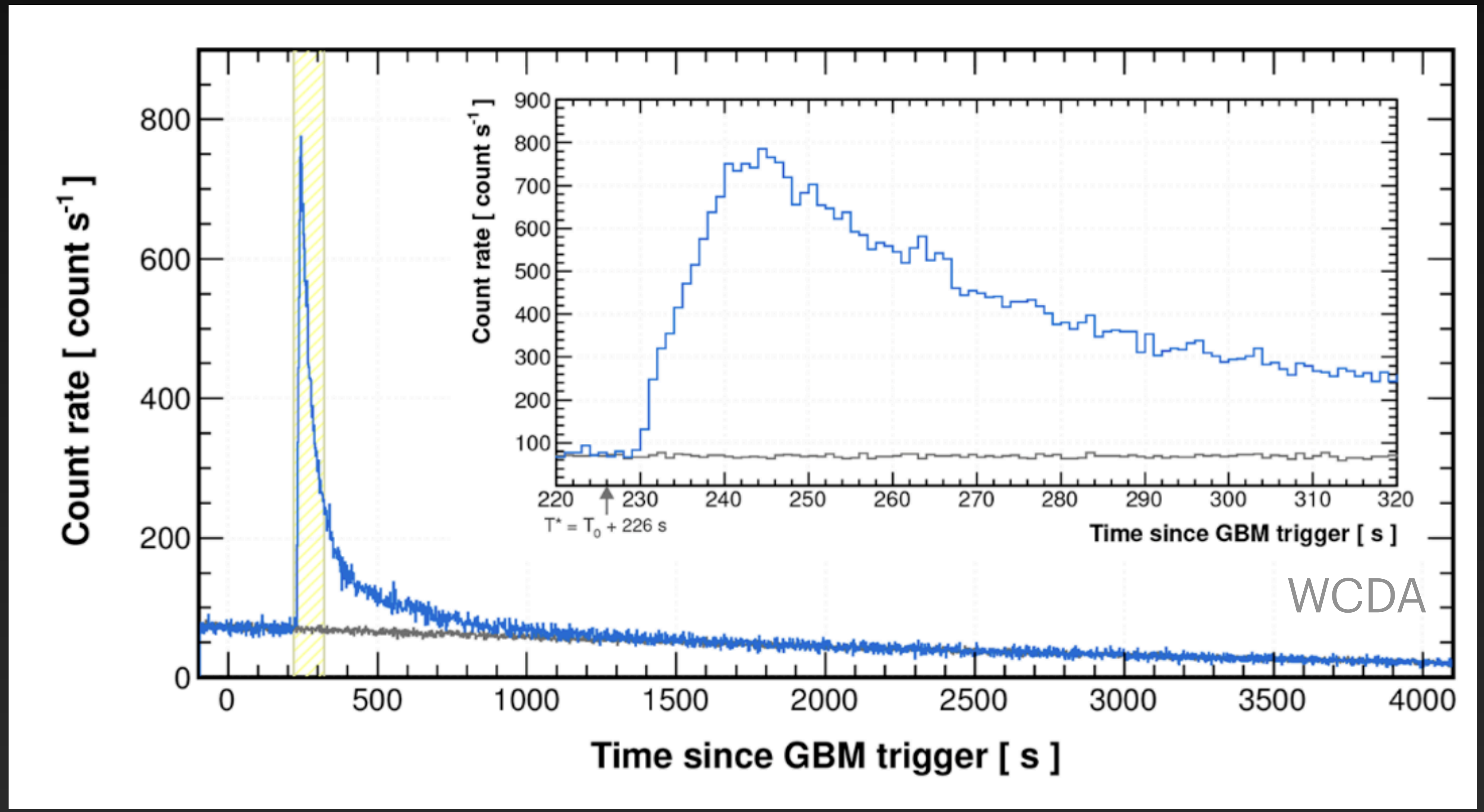


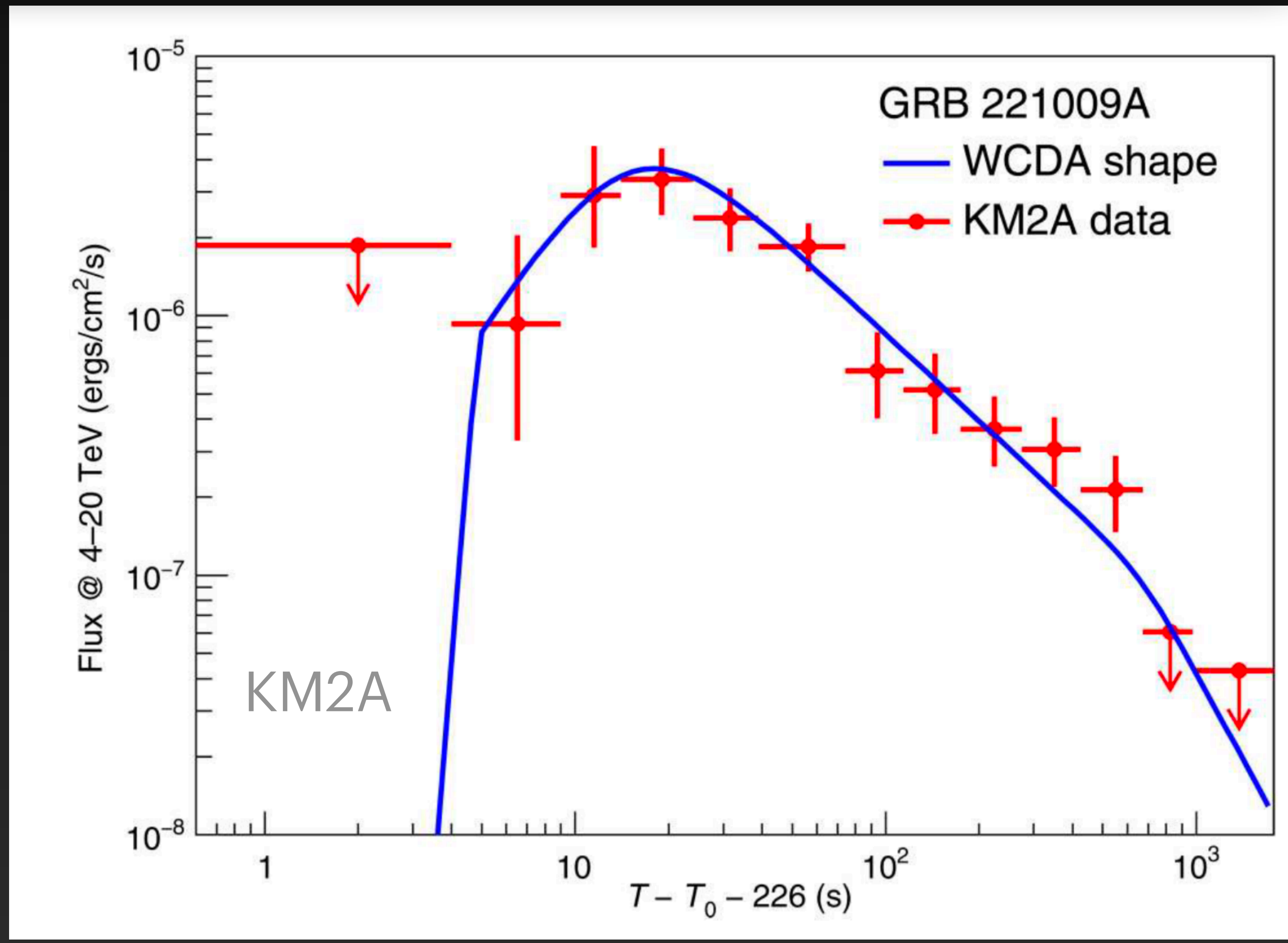
GRB221009A — BOAT

- Brightest GRB ever observed
- Redshift $z = 0.1505$ (VLT X-Shooter, GTC) from CaI, II absorption lines
- *Fermi* LAT detected 99.4 GeV photon (new record from GRB) at $T_0 + 240\,\mathrm{s}$
- LAT also detected 400 GeV photon at $T_0 + 33\,\mathrm{ks}$ (preliminary: 4σ association with GRB)
- Detected at very high energies with LHAASO

Fermi Gamma-ray Space Telescope

VHE photons seen with LHAASO

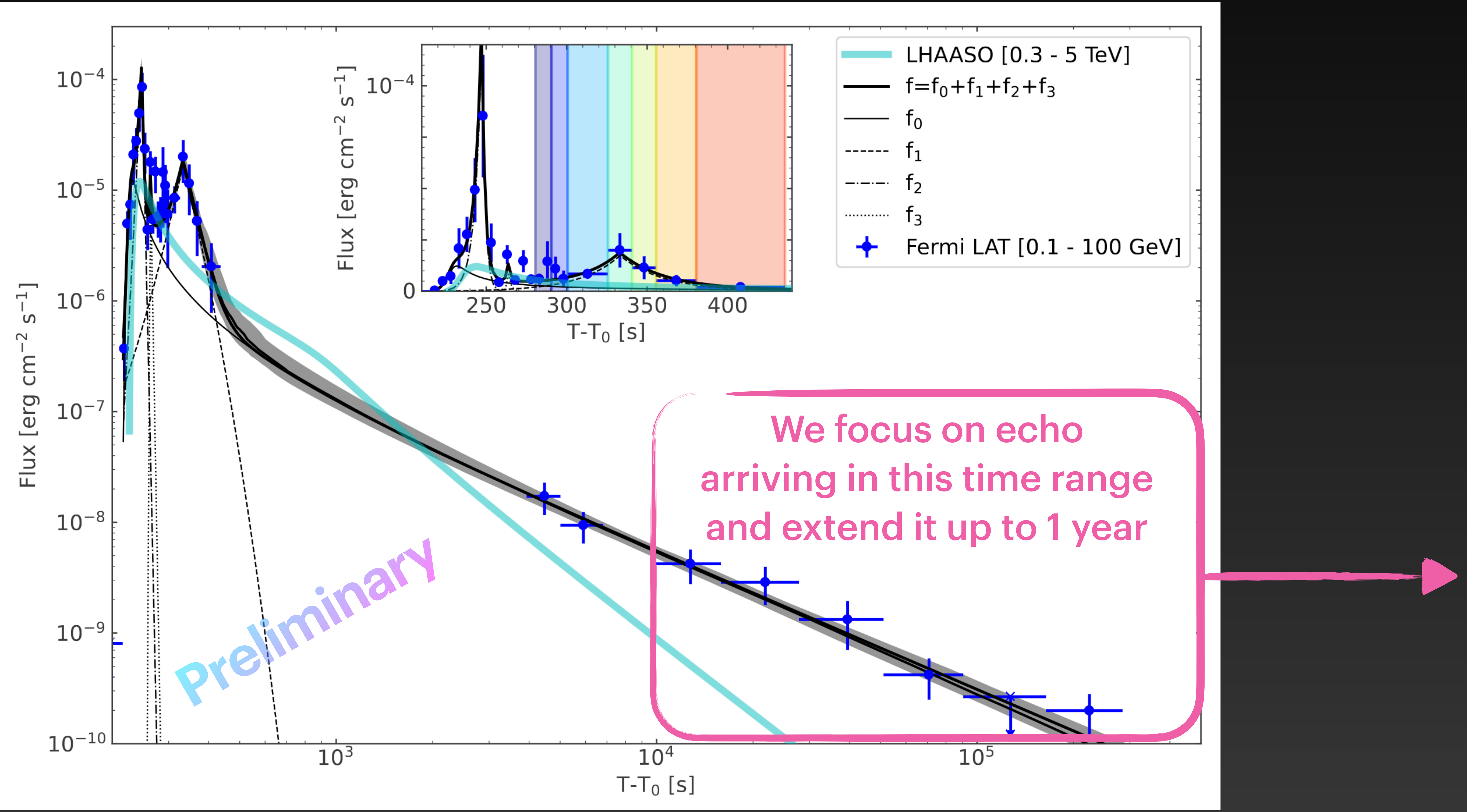




- WCDA: > 64,000 gamma rays between 0.2 TeV and 7 TeV in ~3000s
- KM2A: 140 gamma rays between 3 and 13 TeV in ~900s
- Light curve suggests jet opening angle of 1.6º
- Distance and highest energies: strong absorption on EBL

[LHAASO Collaboration Science 2023, Sci. Adv. 2023]

Composite LAT and LHAASO light curves



[Fermi-LAT collaboration, in prep.]

Modeling the temporal and spectral cascade structure with CRPropa3

- CRPropa 3 Monte Carlo Code used to generate 4D (spatial + energy + delay time) templates
- Assumed magnetic field:
  - **Kolmogorov turbulence spectrum**
  - $B_{\mathrm{rms}} = 10^{-20}\,\mathrm{G}, \ldots, 10^{-15}\,\mathrm{G}$
  - Coherence length: $\ell_B \approx 6\,\mathrm{Mpc}$
- EBL model of Franceschini et al. (2008)
- Jet opening angle: 1.6º, jet aligned with line of sight

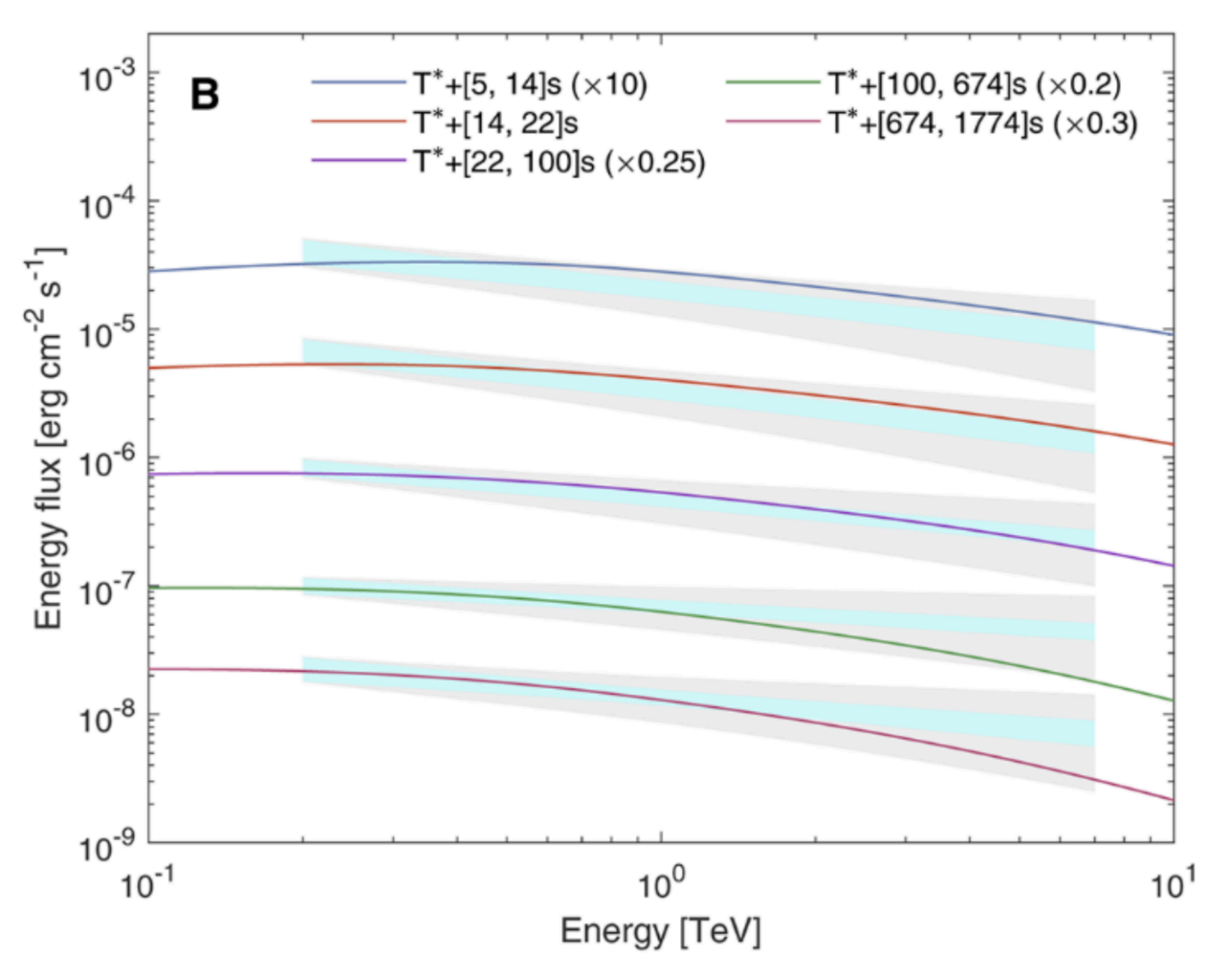
Assumed Intrinsic spectrum

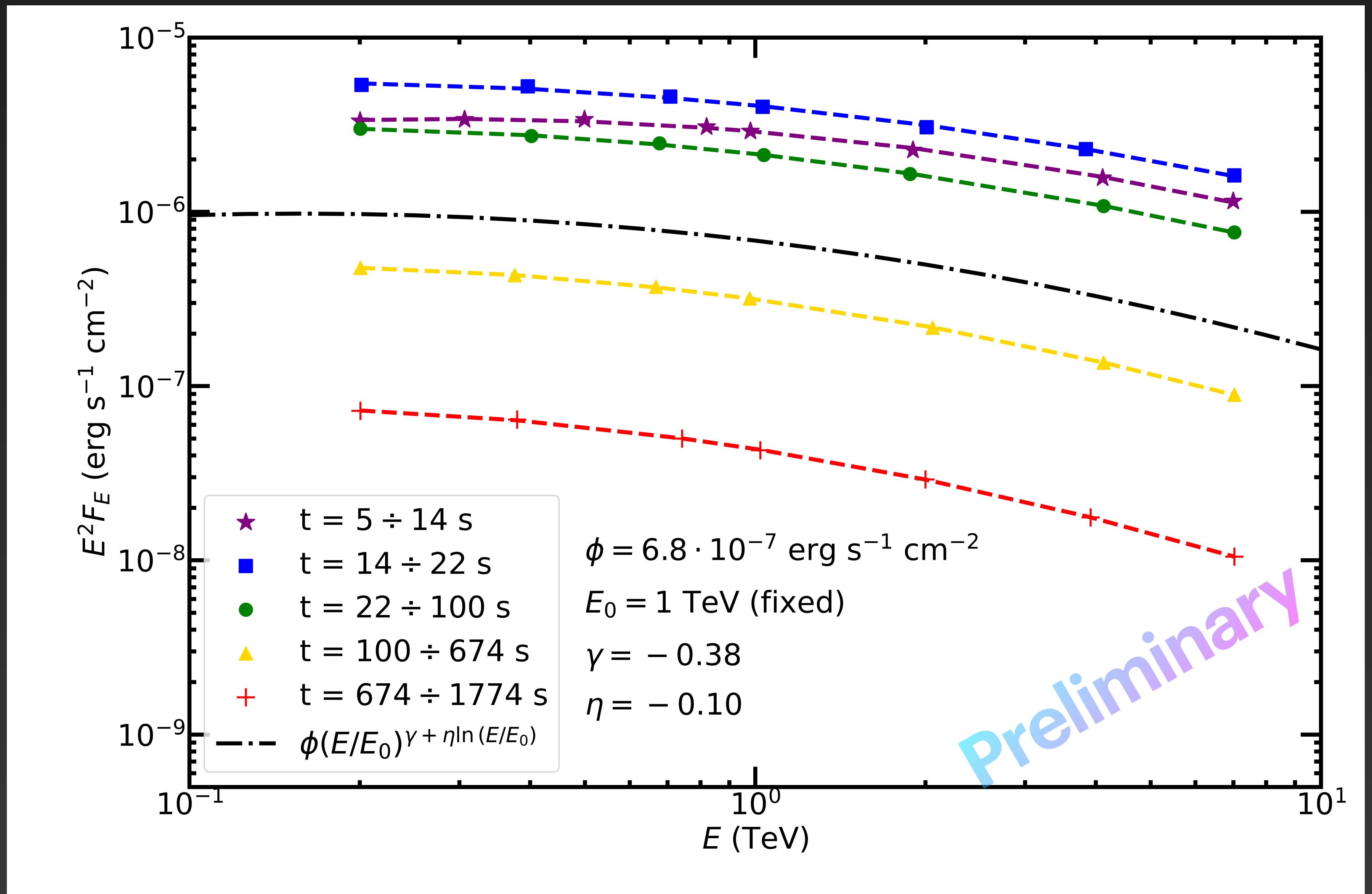
Taken from LHAASO WCDA

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

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

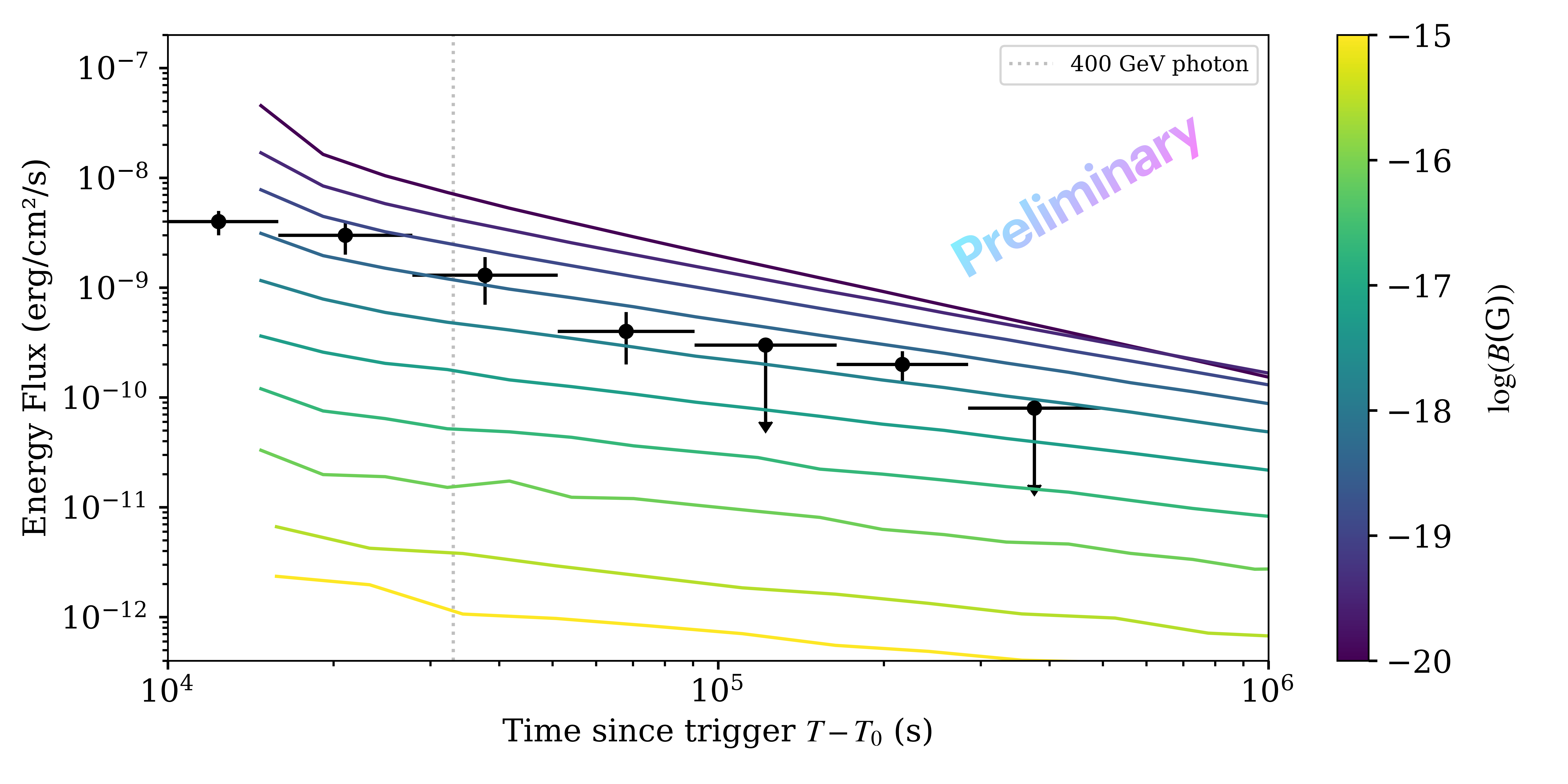
- Additionally multiplied with exponential cutoff at 7 TeV
- Assumed emission time: 3000s





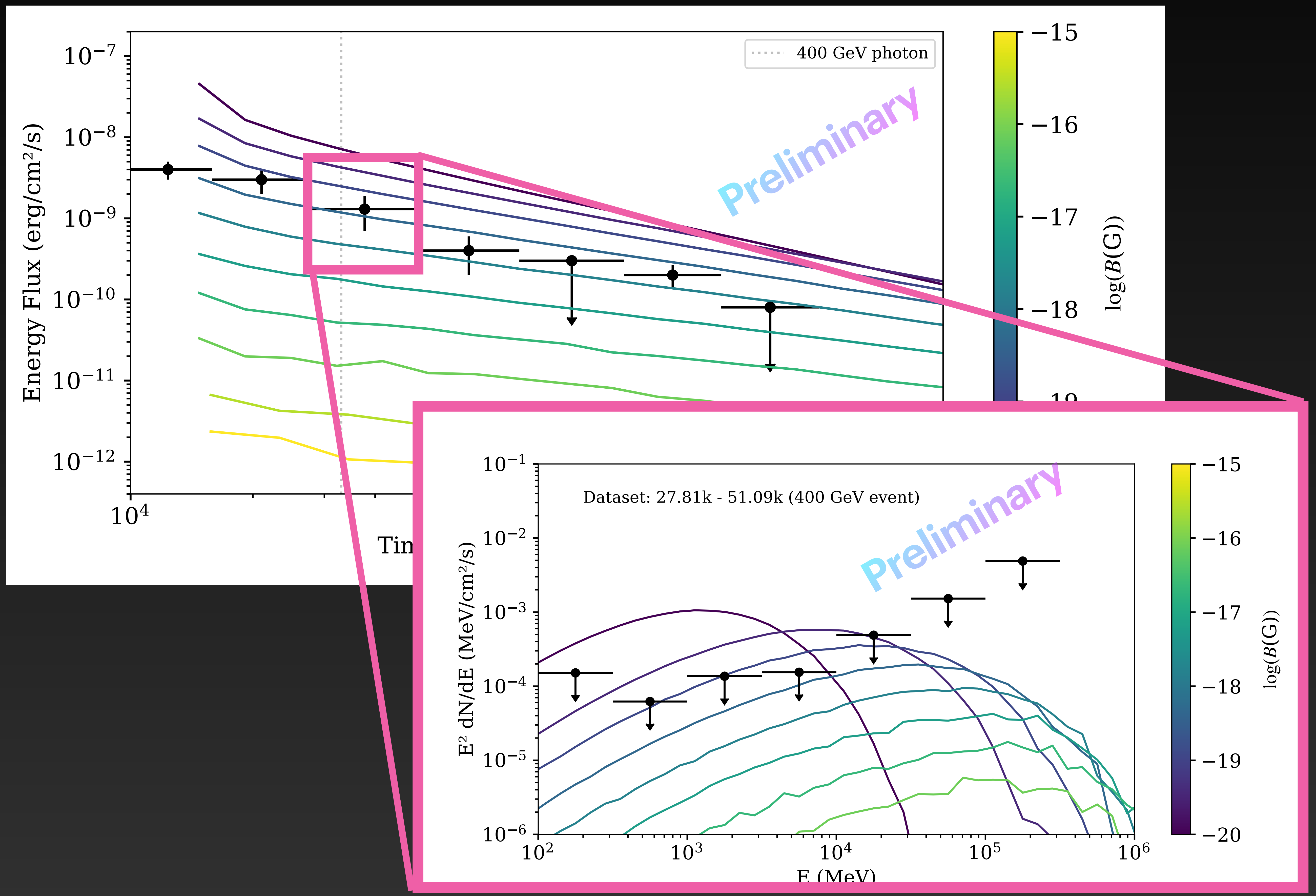
[LHAASO Collaboration Science 2023]

Fermi-LAT light curve vs pair echo predictions



Fermi Gamma-ray Space Telescope

Statistical analysis: spectral and temporal likelihood



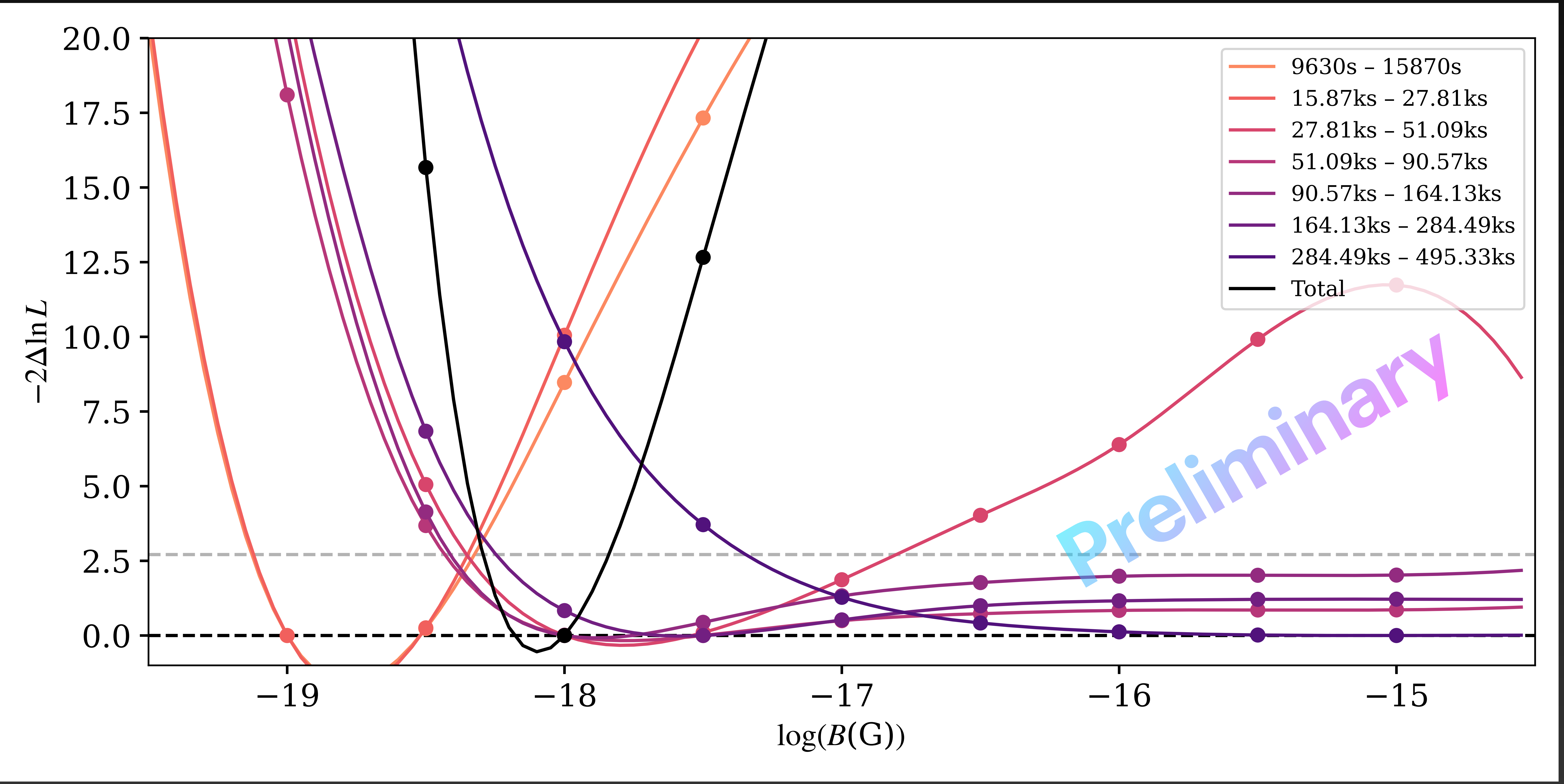
Cascade SED with additional afterglow emission (not shown)

- For each time bin i:
  - Add cascade prediction for fixed $B_{\rm rms}$
  - Compute log likelihood summed over energy bins j:
    $$\ln \mathscr{L}_i \equiv \sum_j \ln \mathscr{L}(B_{\rm rms}, \hat{\boldsymbol{\theta}} \,|\, D_{ij})$$
  - $\hat{\boldsymbol{\theta}}$: optimized nuisance parameters
- Consider two cases for $T < T_0 + 3$ days:
  - No afterglow emission
  - Afterglow emission modeled with power law with index $\Gamma = 2$

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 be present



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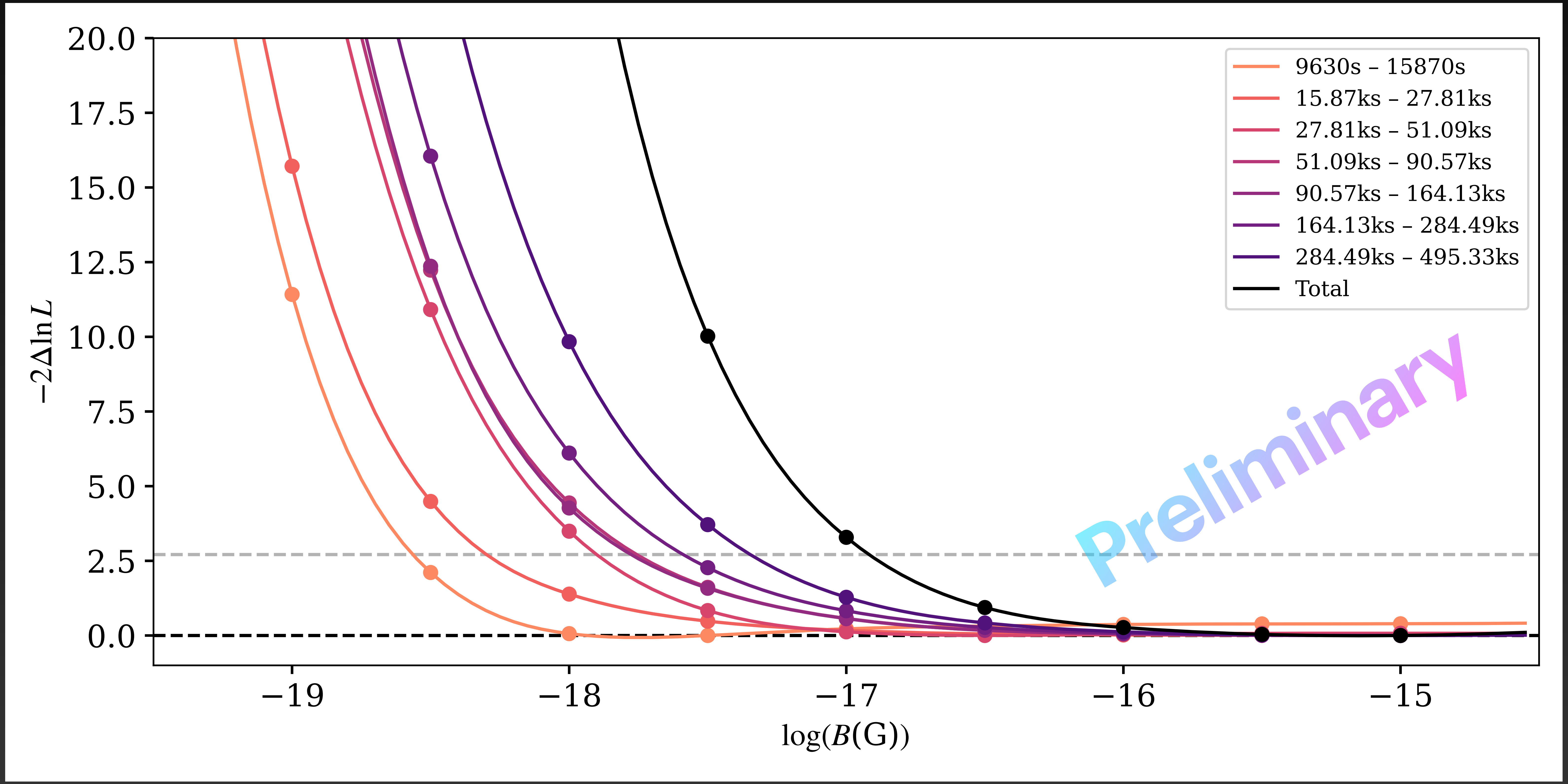
Likelihood profiles

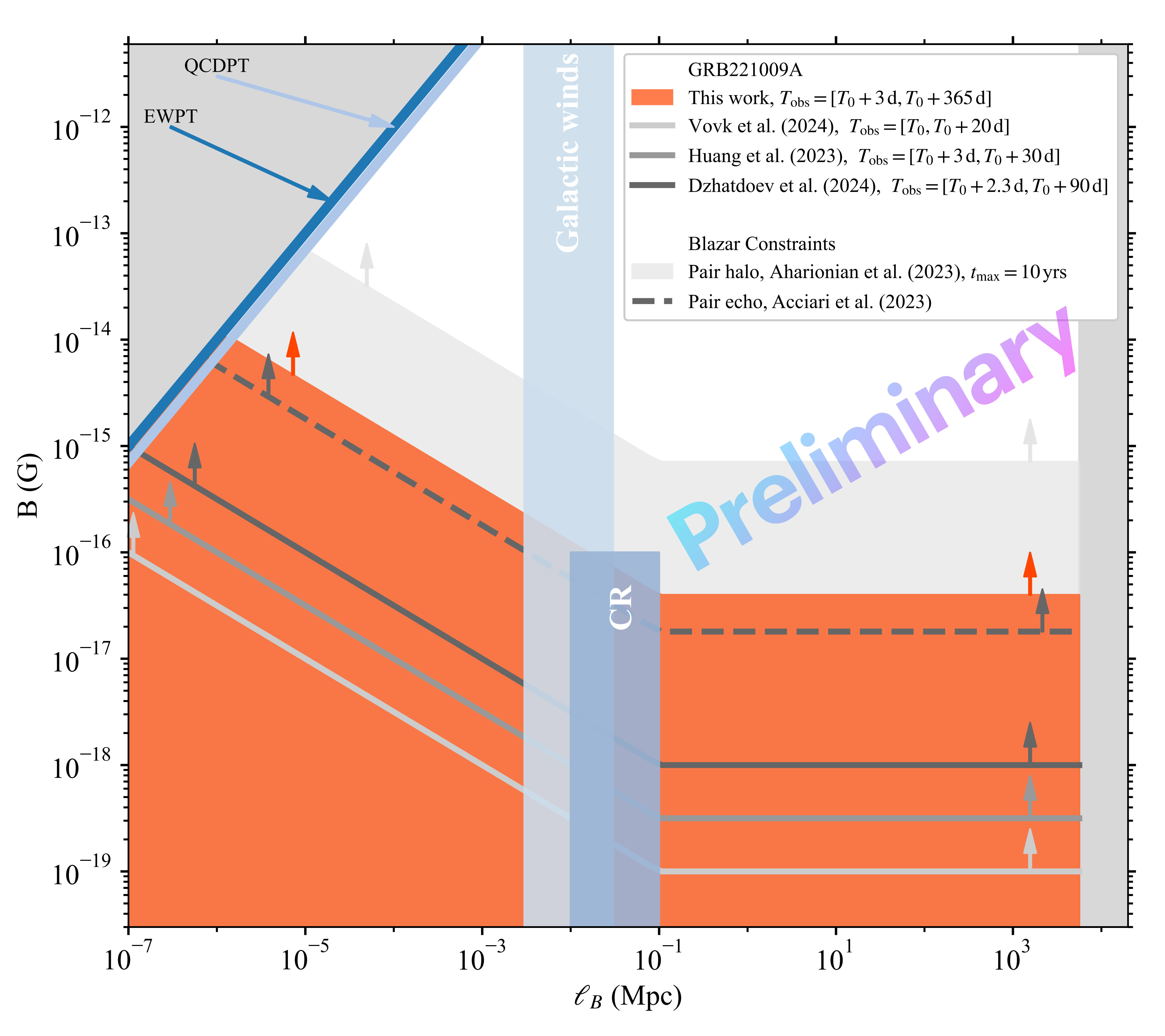
With afterglow emission added

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



Comparison with previous constraints

- Best constraints so far on IGMF with pair echo technique
- Compared with previous constraints also using GRB221009A:
  - We include more data
  - Robust statistical analysis
  - Include astrophysical afterglow
- Compared to pair halo searches:
  - No assumptions on activity time necessary
  - Plasma instabilities that could suppress cascade probably not relevant here



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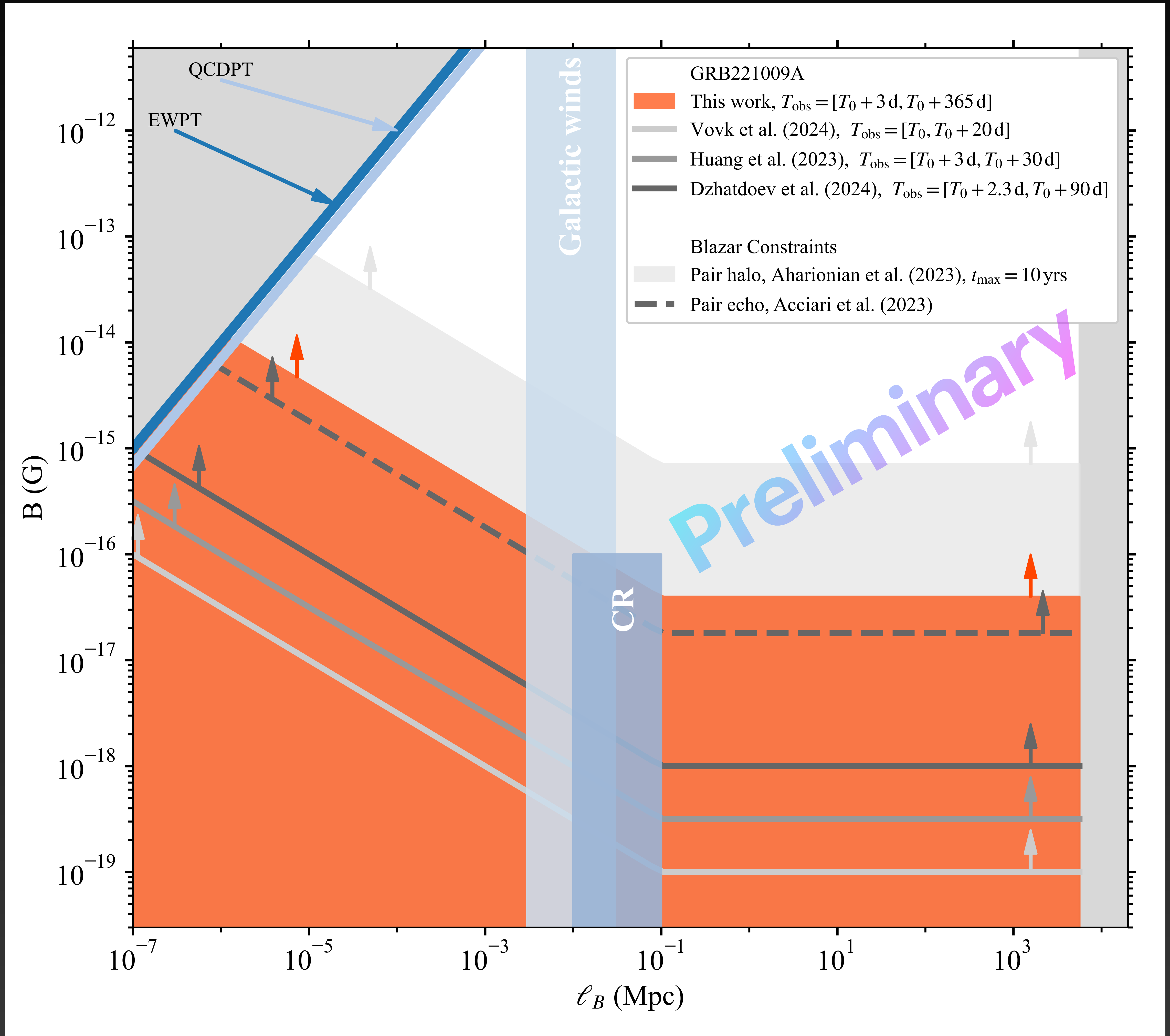
Summary and Conclusions

- GRB221009A offers wealth of opportunities to study GRB physics and photon propagation
- We have derived new constraints on IGMF with $B_{\rm rms} \gtrsim 4 \times 10^{-17}\,{\rm G}$
- Best constraints so far from pair echo technique
- Constraints depend mildly on chosen EBL model
- Outlook: use predictions from GRB afterglow model instead of power law with $\Gamma = 2$



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Back up

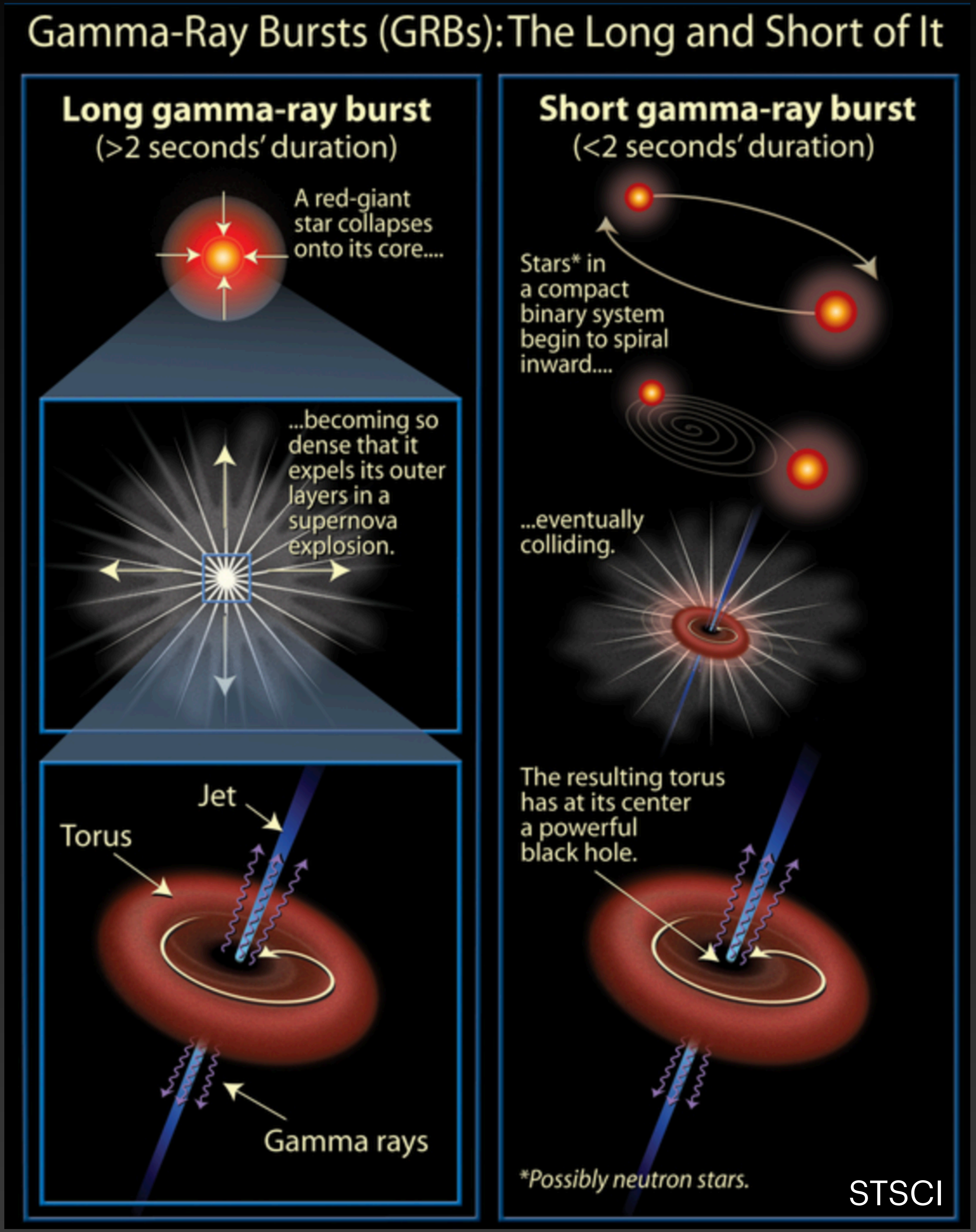
Fermi-LAT data selection

- All point sources within 15º from 4FGL catalog included in ROI
- Galactic diffuse and isotropic diffuse backgrounds included
- After initial optimization: spectral parameters of point sources within 3º from GRB re-fitted

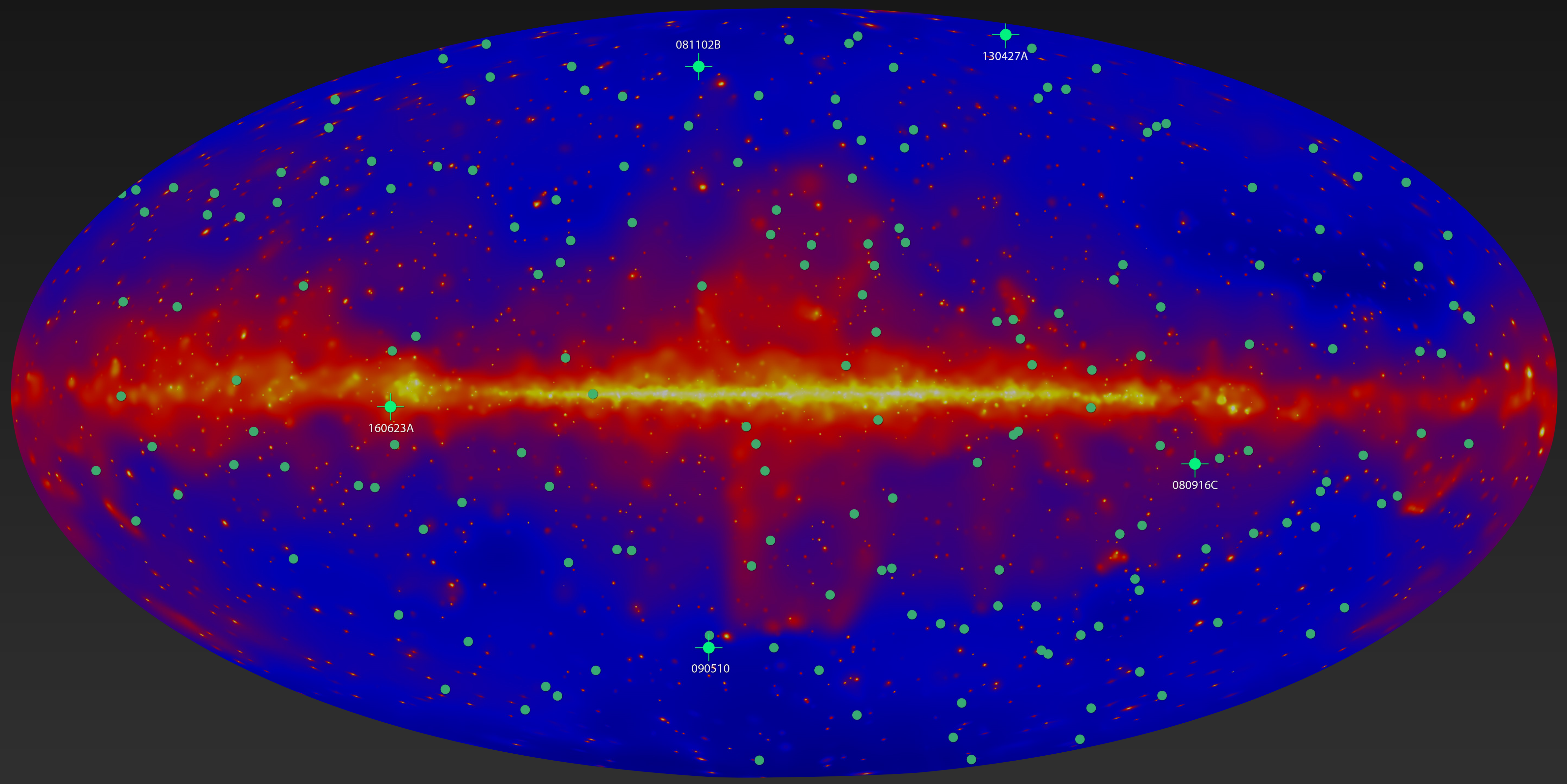
Parameter	Selection
Time range	Up to 1 year after T_0
Energy Range	100 MeV — 0.1 TeV
ROI size	10º x 10º
Max. Zenith angle	90º
Filter	DATA_QUAL>0 && LAT_CONFIG==1
Spatial binning	0.1º / pixel
Energy binning	8 bins per decade
Event Class / IRFs	P8R3_SOURCE_V3, inflight PSF

Fermi Gamma-ray Space Telescope

One slide on GRBs



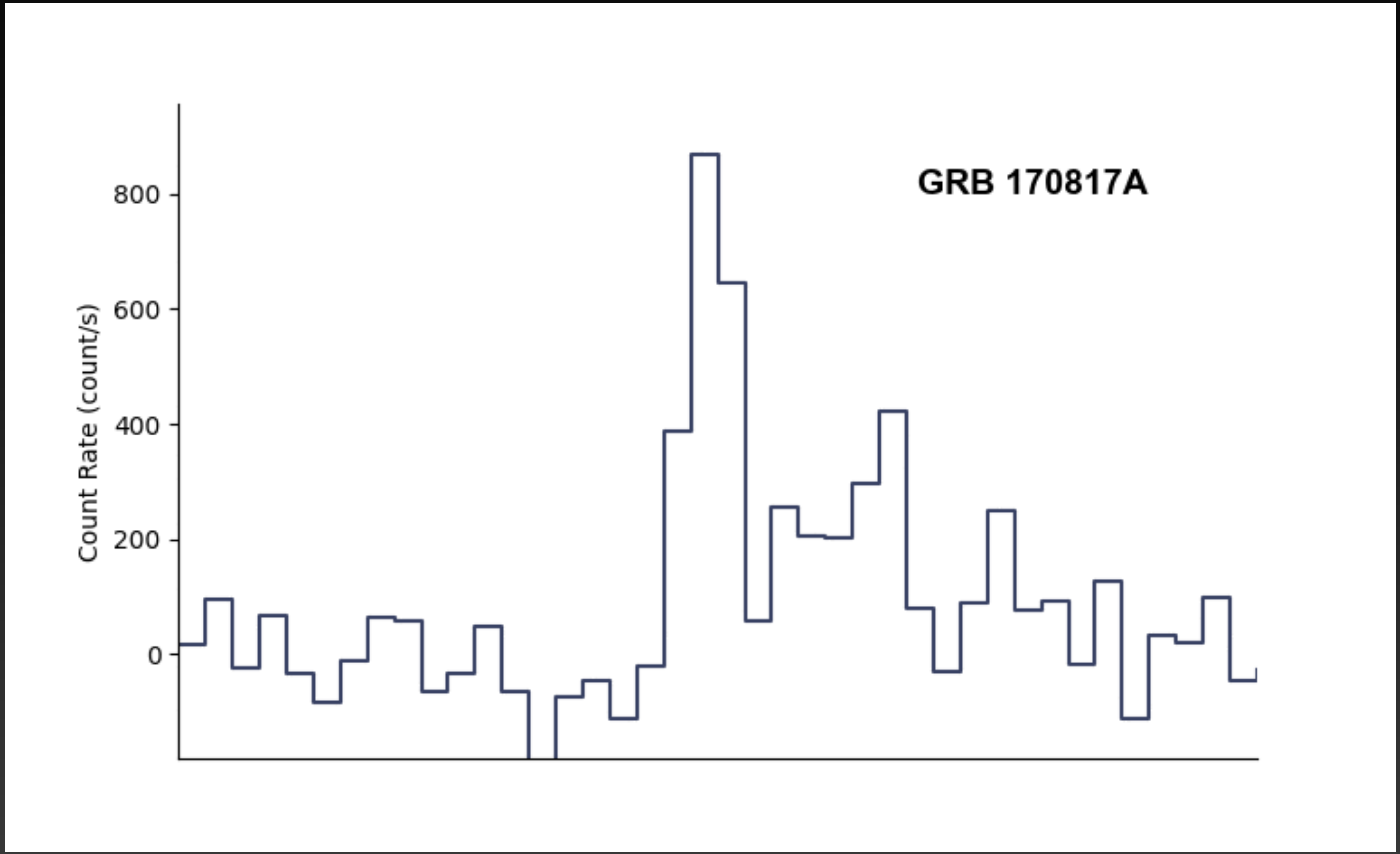
17 short GRBs, 169 long GRBs detected in 10 years with the LAT



2FLGC, Ajello et al. (2019)

Fermi
Gamma-ray Space Telescope

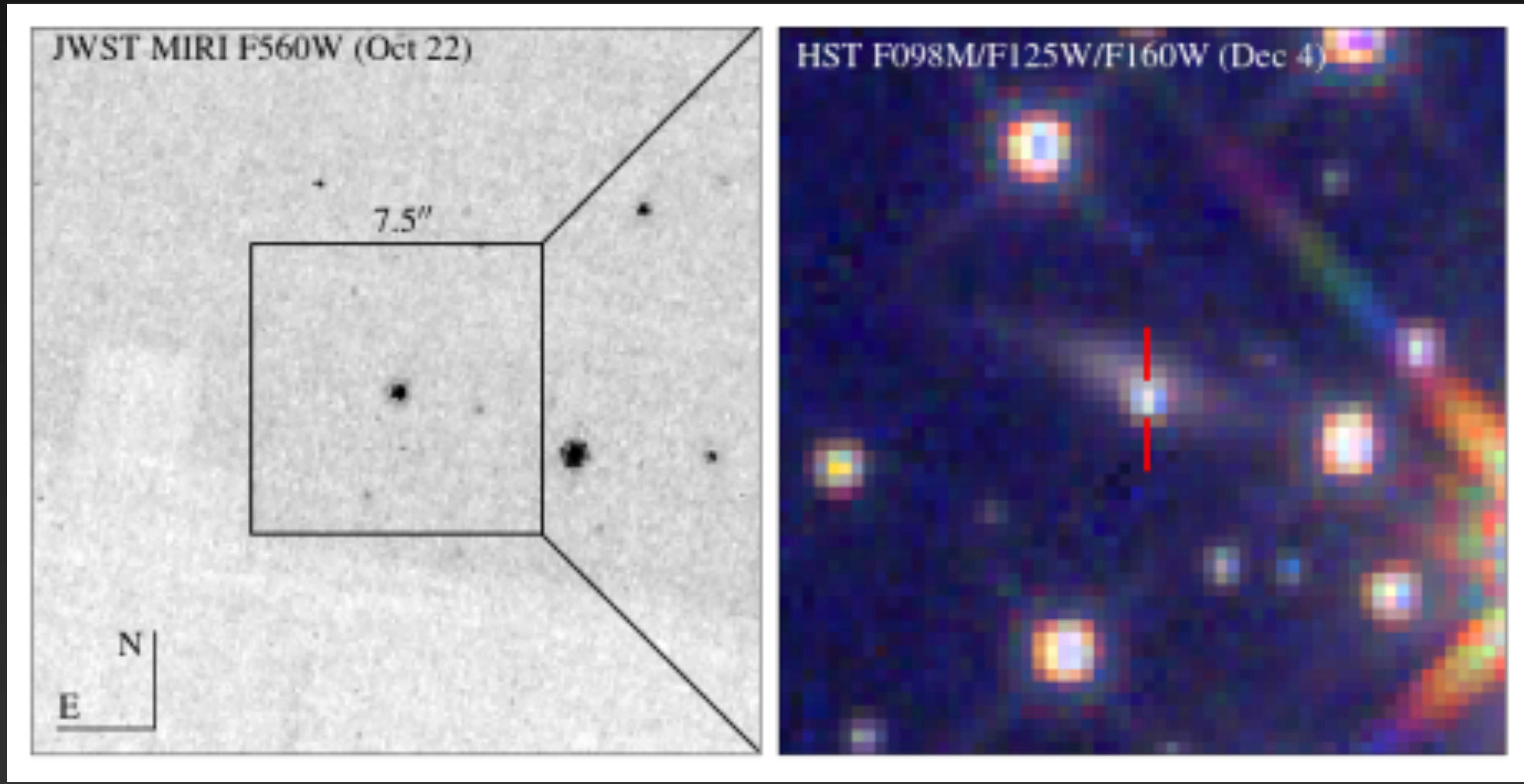
GRB221009A in perspective



Credit: Adam Goldstein

Host galaxy of GRB221009A

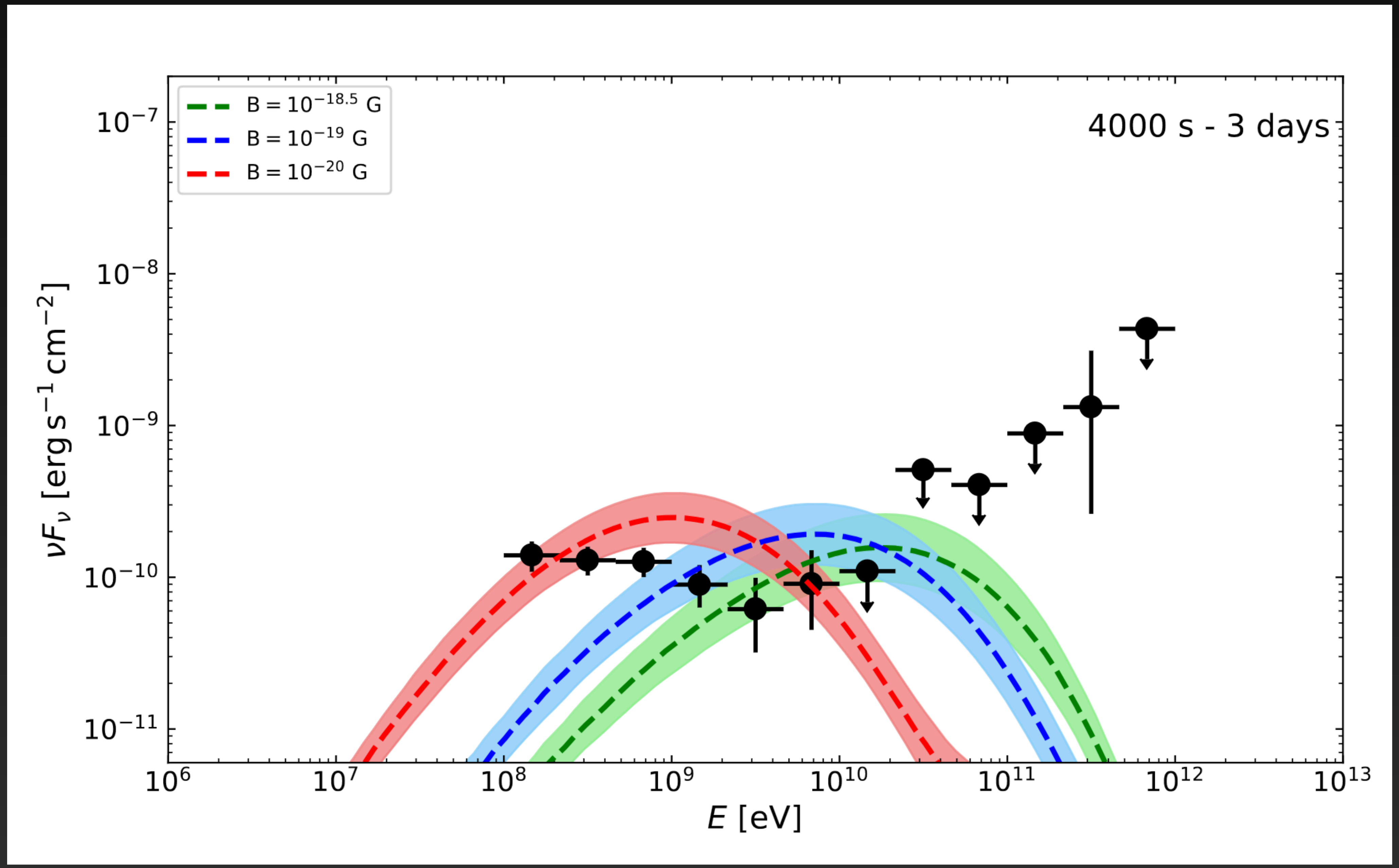
- Observed with JWST and HST
- Appears to be ordinary spiral galaxy
- Observed edge-on
- Strong B field unlikely

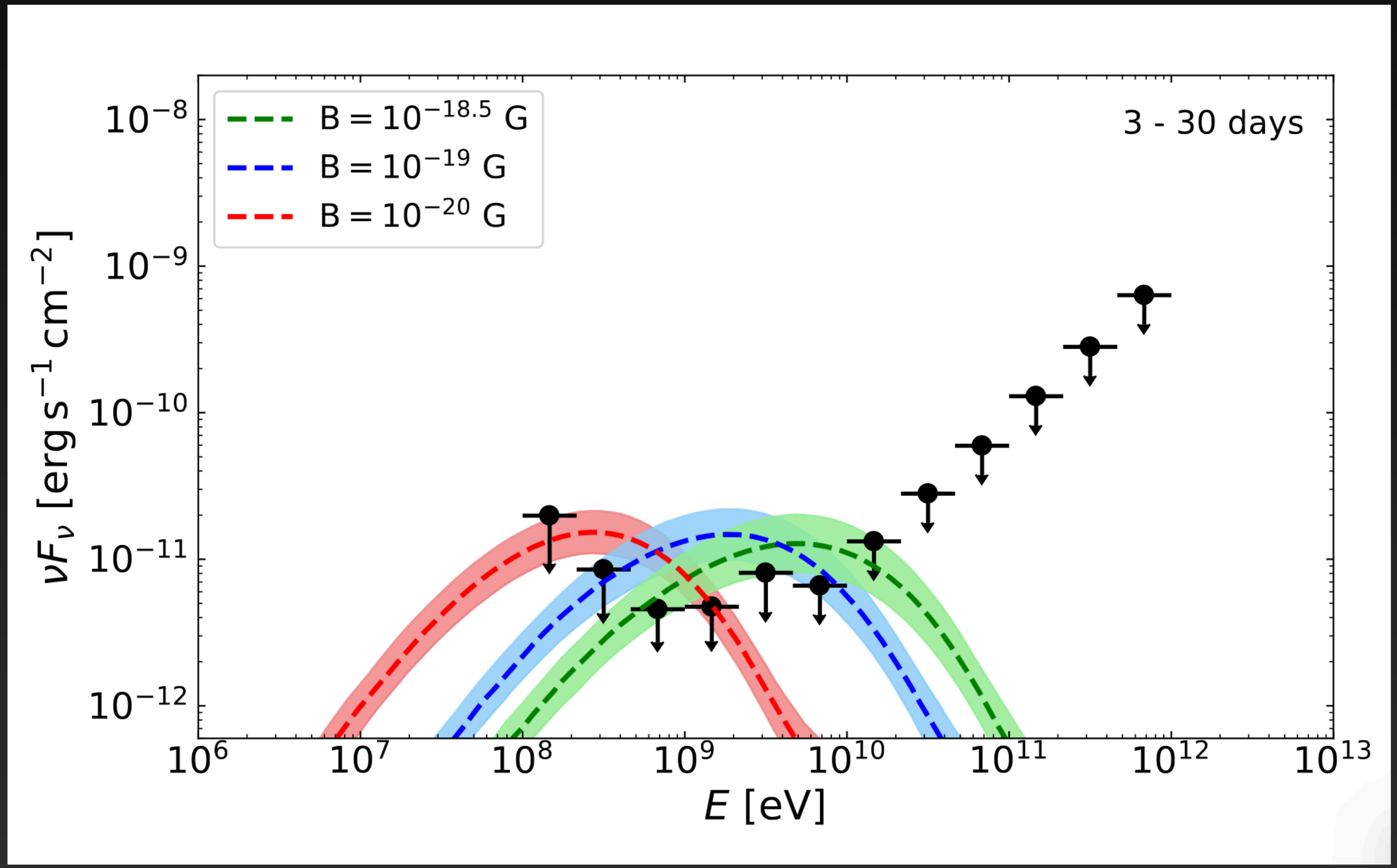


https://arxiv.org/pdf/2302.07761.pdf

Constraints on the IGMF from other authors

Using GRB221009A





Time resolved SEDs from Huang et al. (2023)

[Huang et al. (2023), Volk et al. (2024), Dzhatdoev et al. (2024)]

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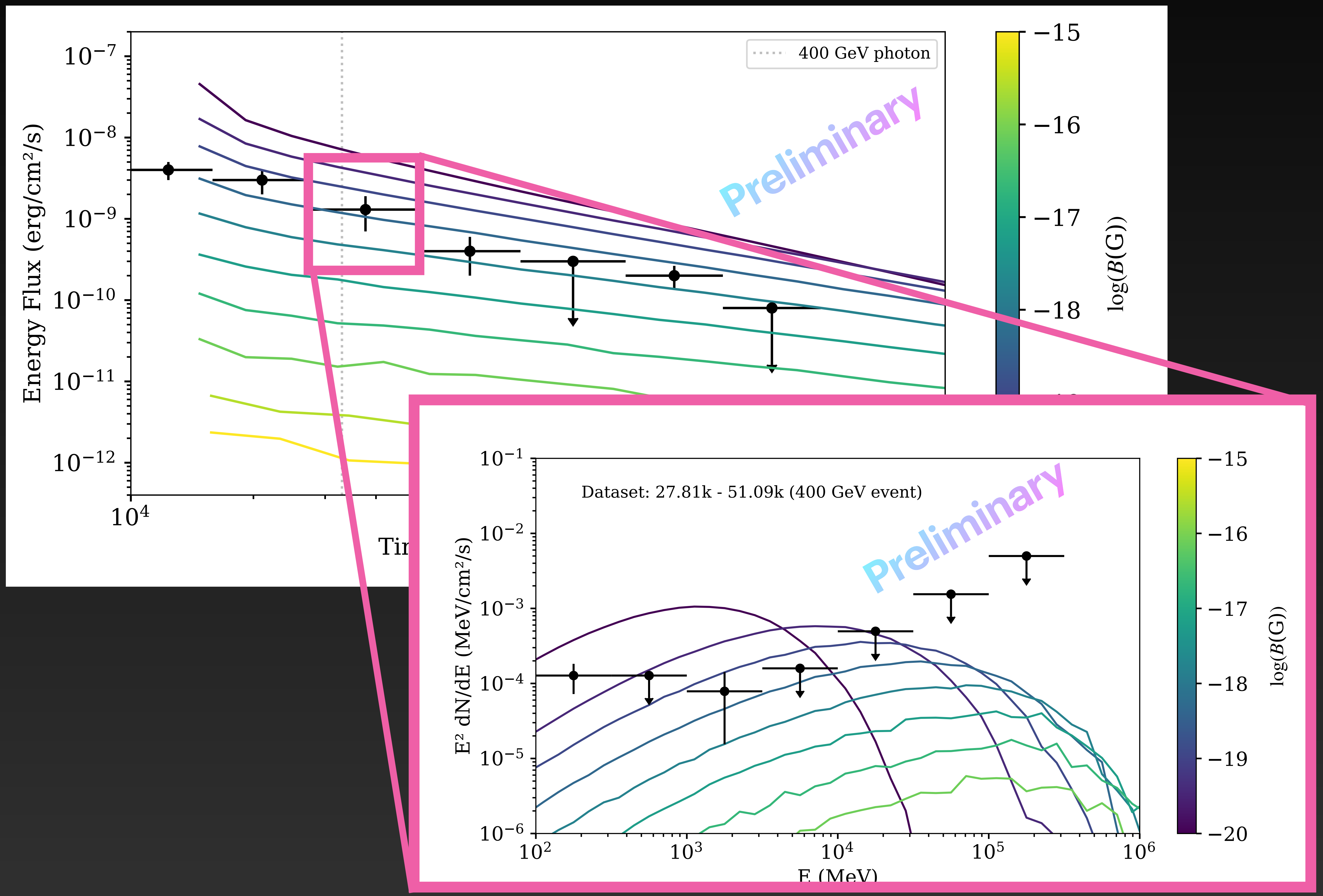

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