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

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Fermi Gamma-ray Space Telescope

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Physics: Are magnetic fields of astrophysical or cosmological origin?

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Methods: Lower limits from blazars the only competitive approach in gamma-rays?

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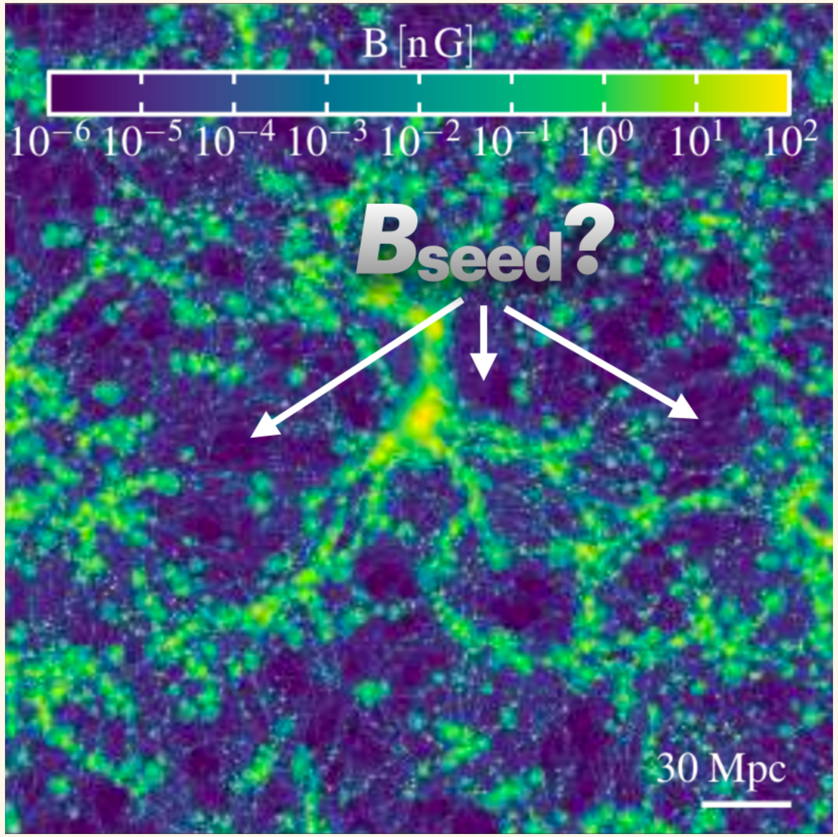
Searching for the intergalactic magnetic field

Context: See talk by Jonathan Biteau (Wednesday, Plenary)

Magnetic field: Origin, strength, orientation of seed fields unknown

A wide parameter space to constrain, with each method being subject to distinct challenges



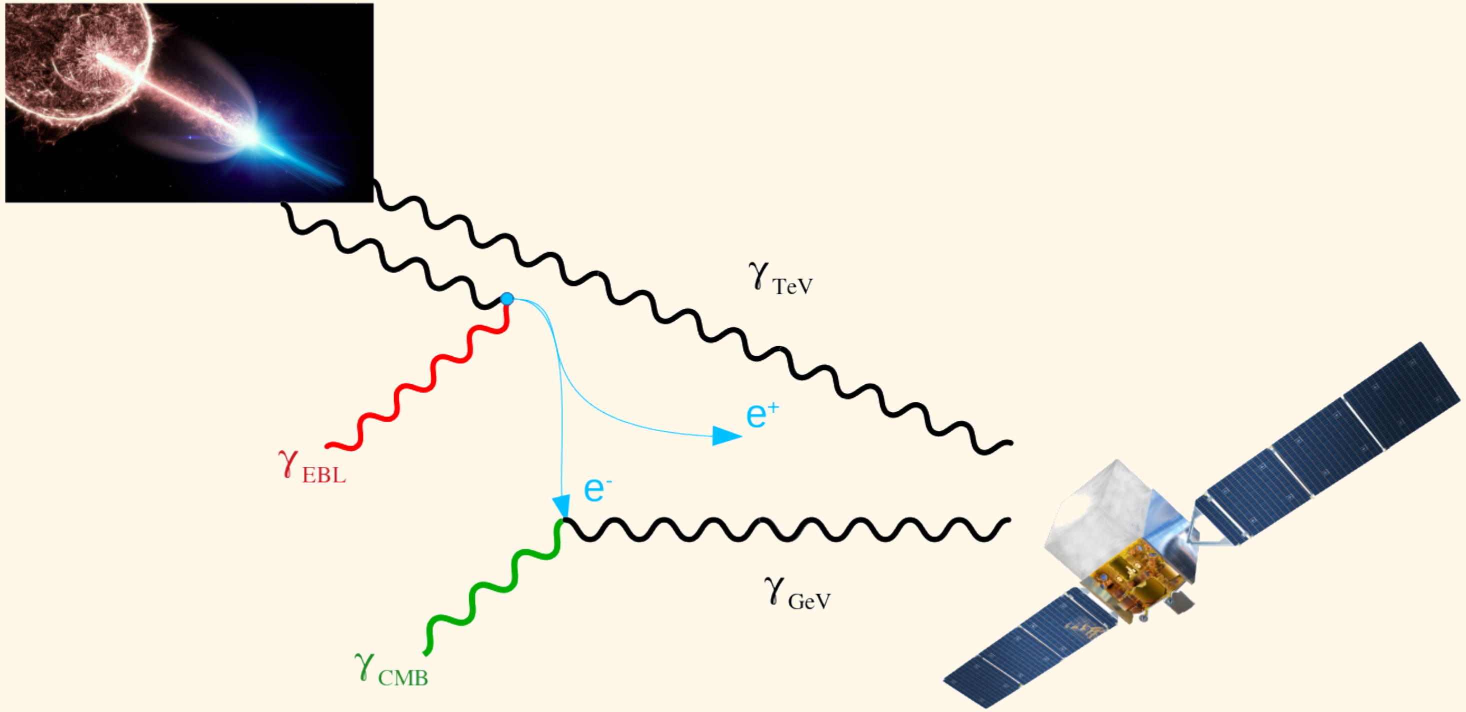
Credit: Marinacci et al. 2018

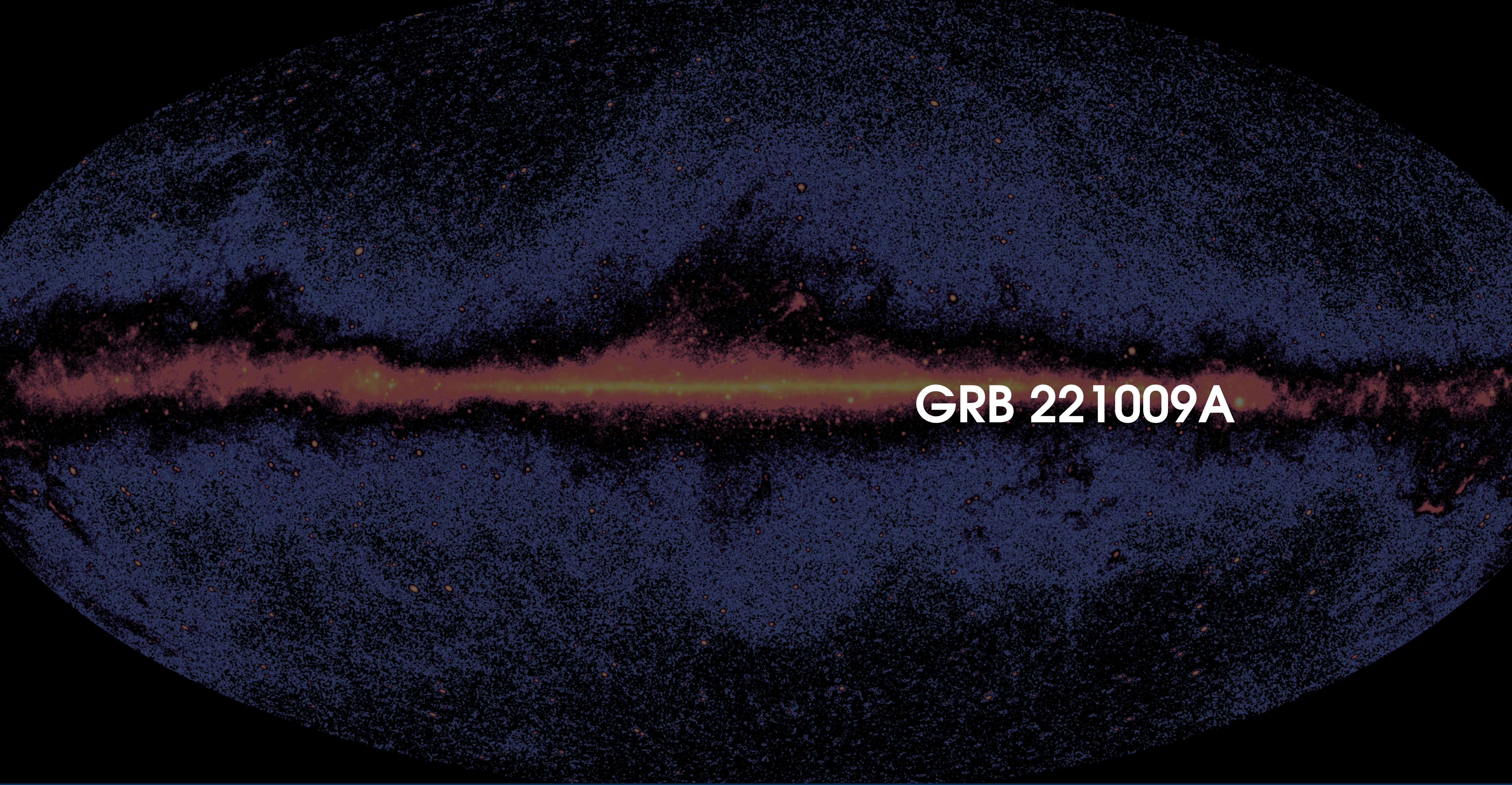
Limits using gamma-ray observations

$e^{-}e^{+}$ pairs produced by TeV photons interacting with EBL

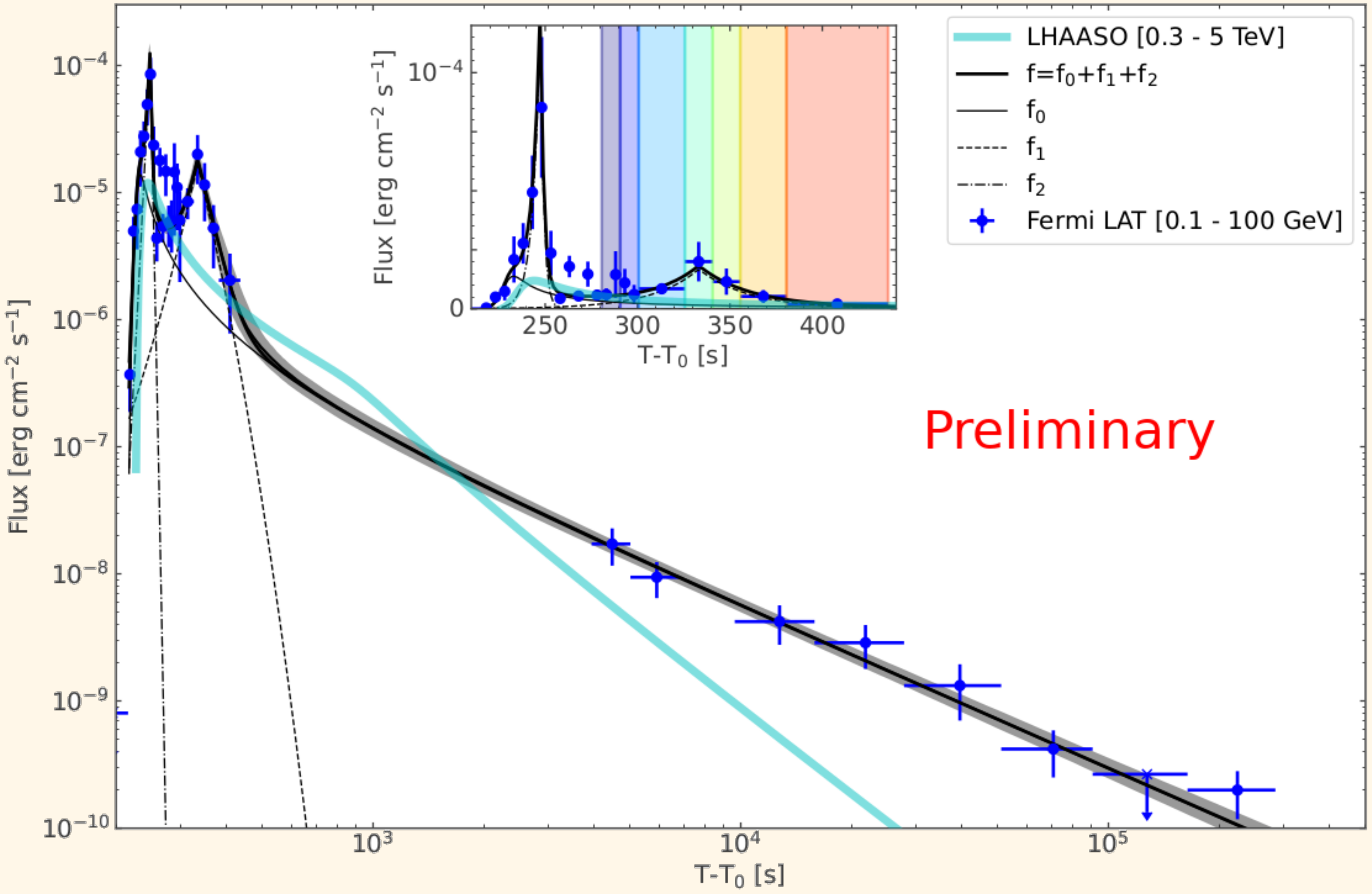
GeV photons produced by CMB scattering by the pairs

Delay of the additional GeV component with respect to the TeV




GRB 221009A

A LAT view on the BOAT



Fermi-LAT Collaboration, submitted

Pair echo modelling with CRPropa3

CRPropa 3 Monte Carlo Code used to generate 4D (spatial + energy + delay time) templates

- Magnetic field: Kolmogorov turbulence spectrum with $B_{\rm rms} = 10^{-20}$ G — 10^{-15} G
- Coherence length: ~ 6 Mpc
- EBL: Franceschini et al. (2008)
- Jet opening angle: 1.6° (LHAASO Collaboration 2023), jet aligned with the line of sight

The assumed intrinsic TeV spectrum

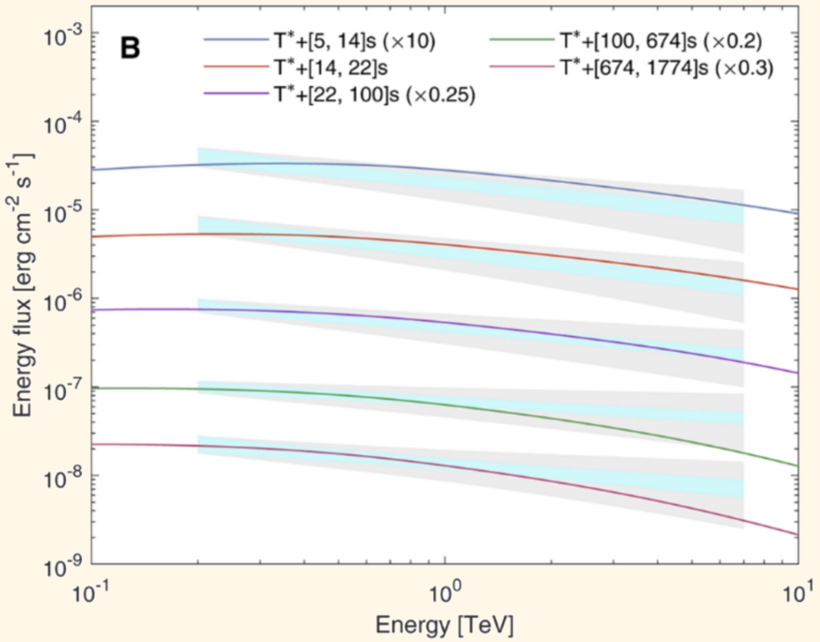
LHAASO Collaboration 2023: fitted physical GRB model to WCDA observations

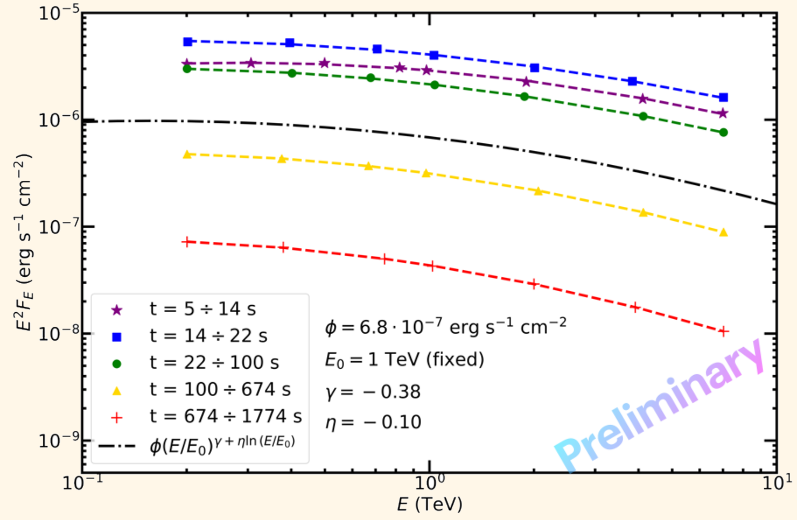
We parametrise and time-average that model with a log-parabola:

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

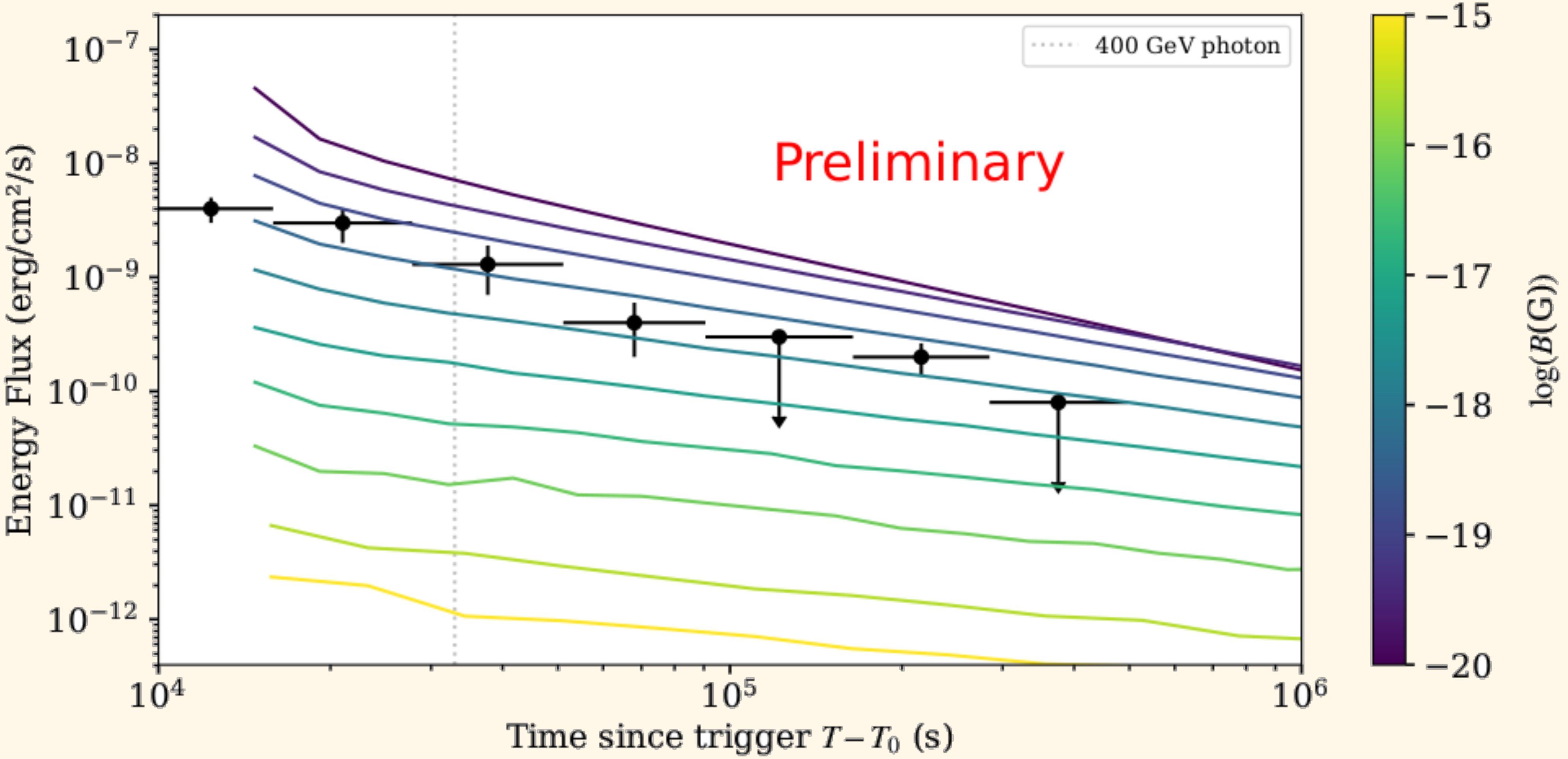
Additionally, we test a model with an additional cut-off at 7 TeV

Assumed emission time: 3000 s





LAT data vs pair echo predictions



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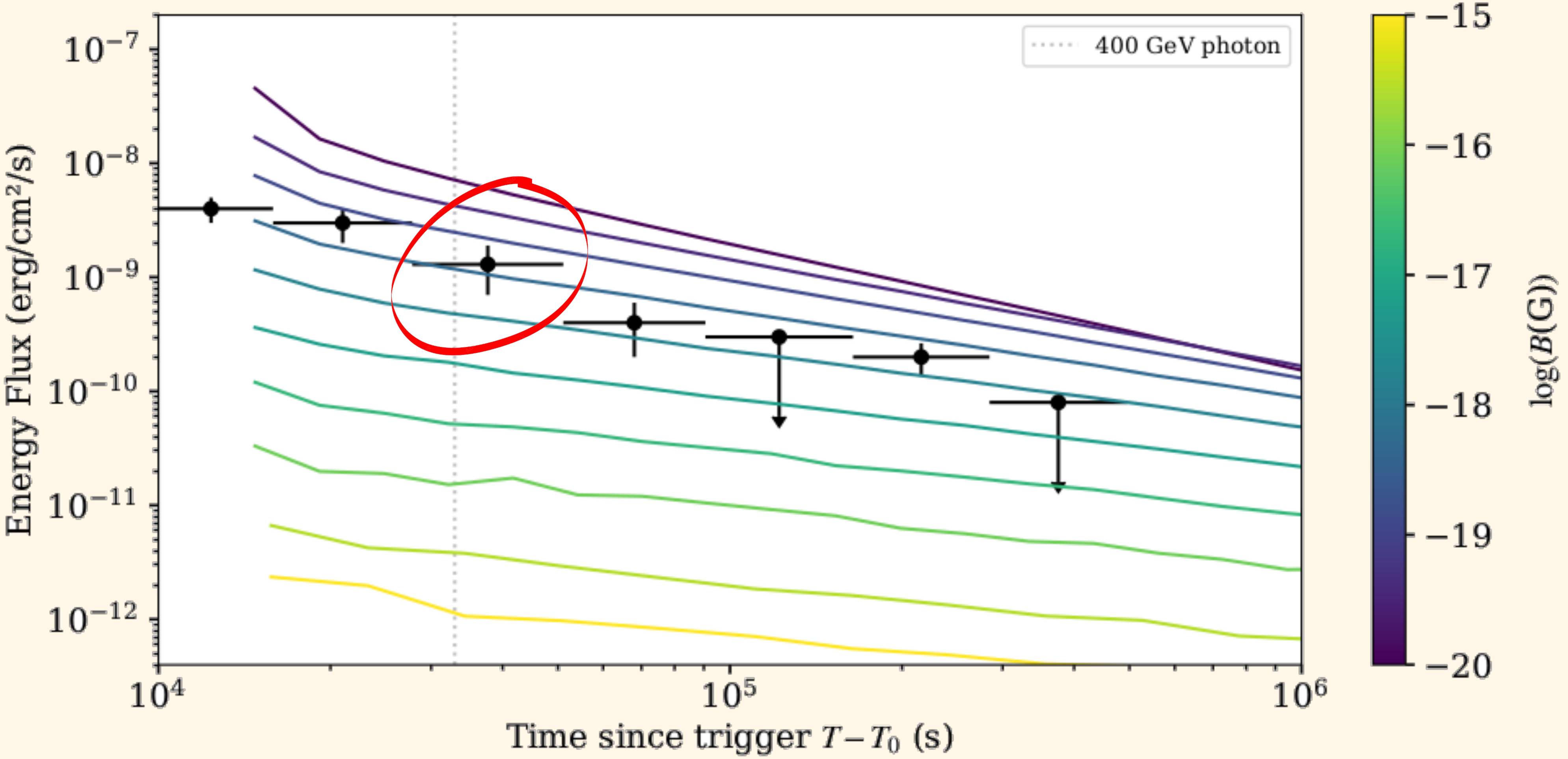


Analysis: spectral and temporal likelihood

For each time bin i:

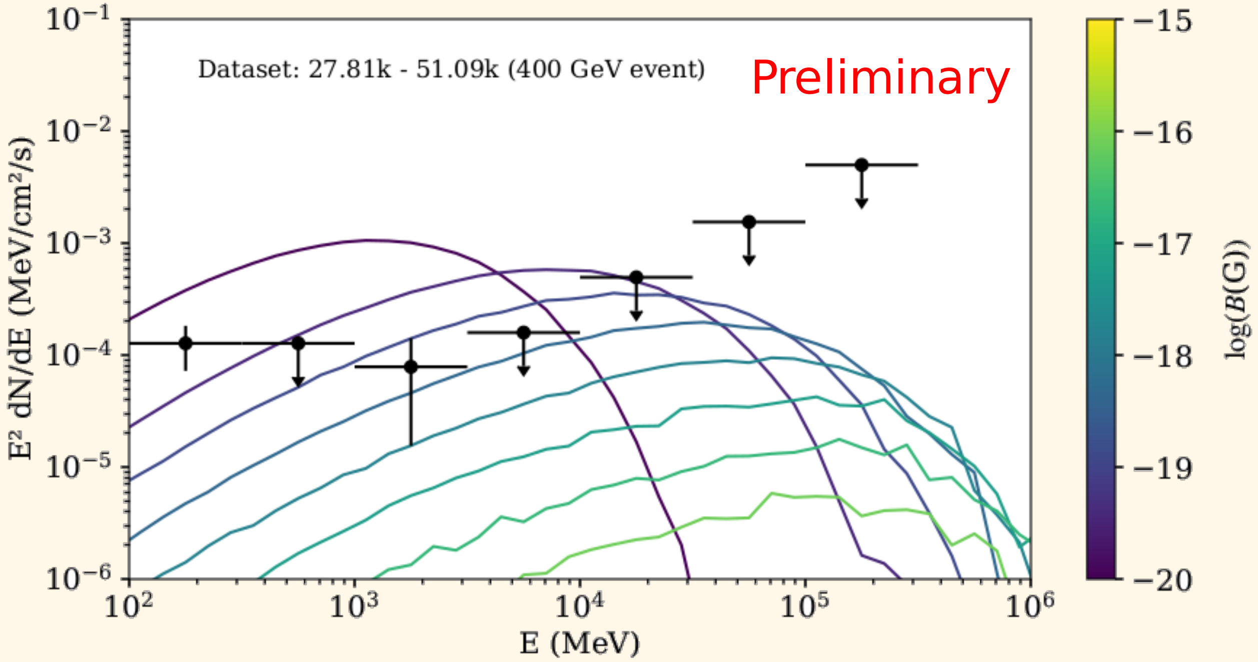
- Add cascade prediction for fixed $B_{\rm rms}$
- Compute log likelihood summer over energy bins j

$$\ln L_i \equiv \sum_j \ln L(B_{\rm rms}, \hat{\theta} | D_{ij})$$

- Optimize nuisance parameters $\hat{\theta}$

Two scenarios for $T < T_0 + 3$ days:

- No afterglow
- Afterglow emission modelled as power law with index $\Gamma = 2$



Only background

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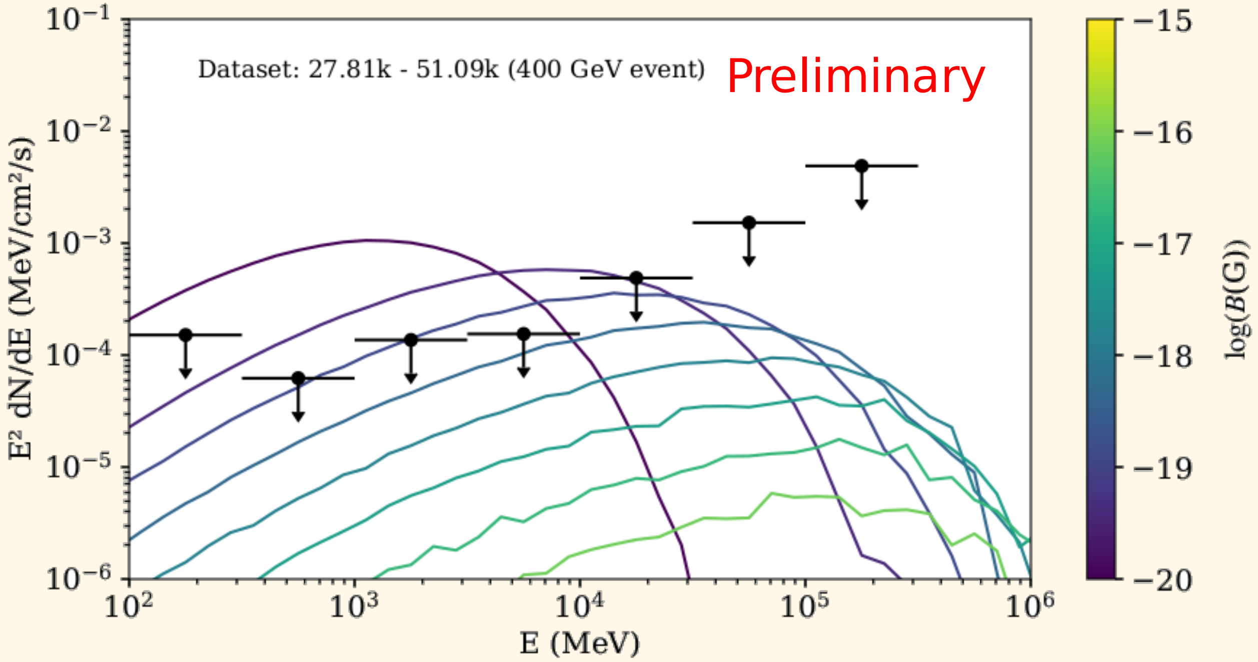
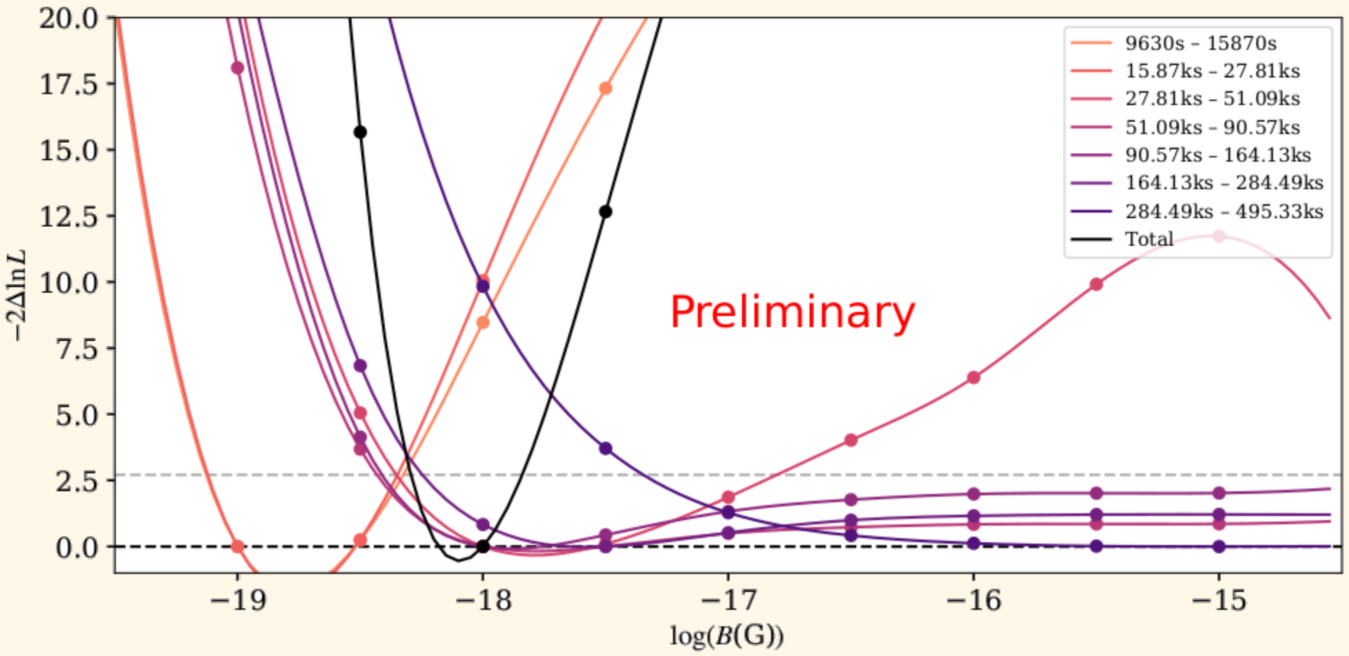


Background with an additional component for the afterglow

Likelihood profiles: no afterglow model

"Detection" of pair echo emissions at early times

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

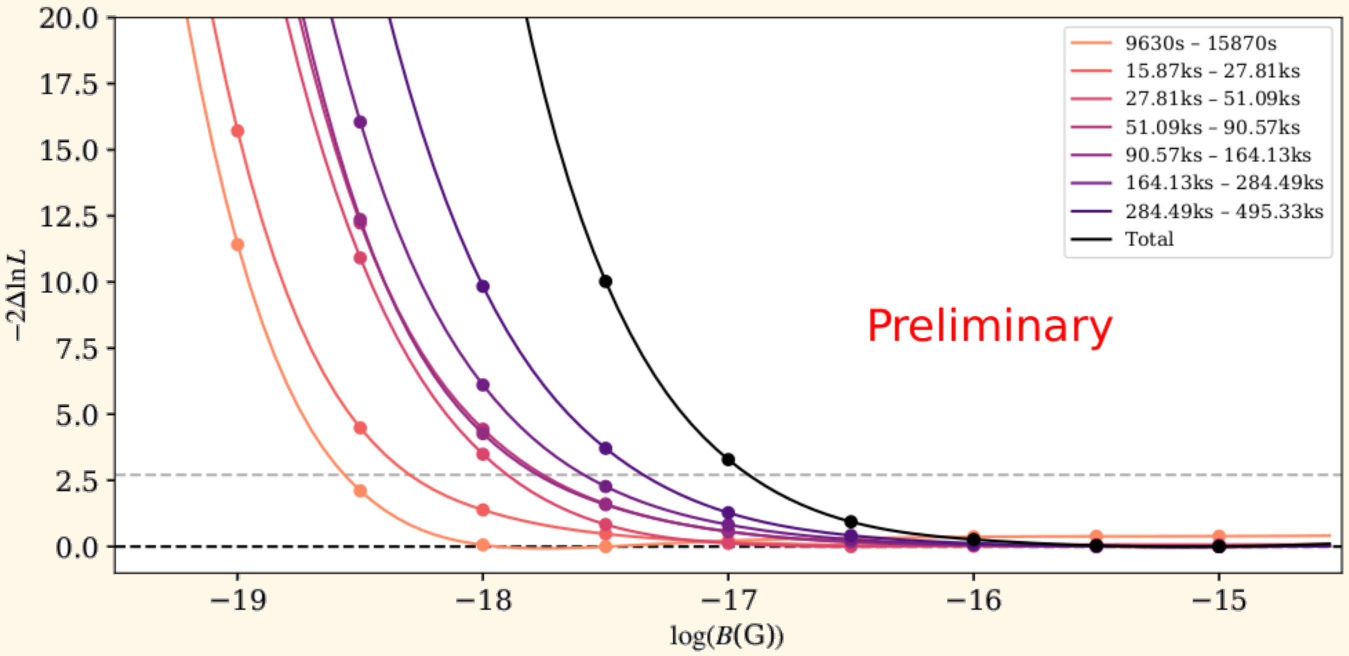


Likelihood profiles: afterglow and beyond

With added afterglow: "detection" disappears

We can rule out magnetic fields where summed log-likelihood is > 2.71

For $T \in [T_0 + 3\ \mathrm{days}\ , \mathrm{T}_0 + 365\ \mathrm{days}\ ]$: $B_{\mathrm{rms}} > 4 \cdot 10^{-17}$ G (95% confidence)



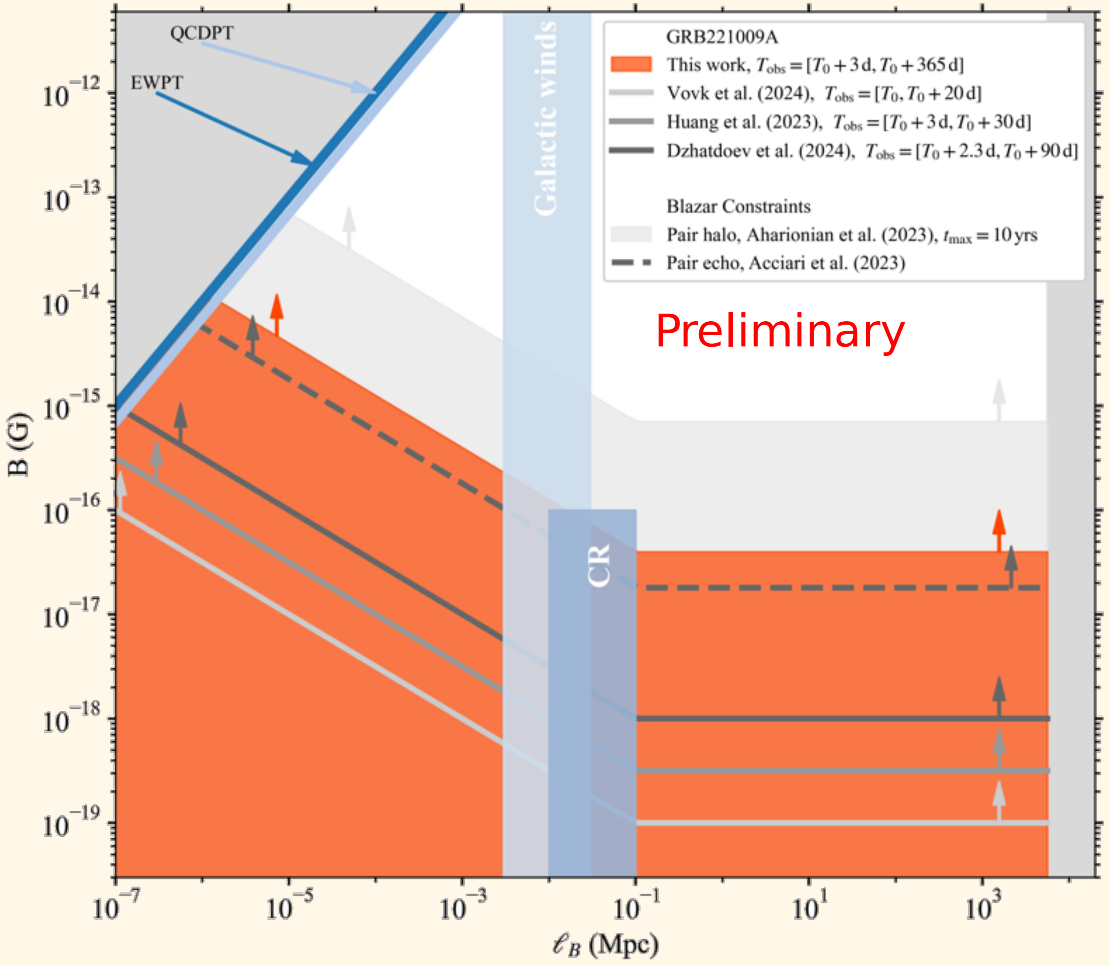
Comparison with previous works

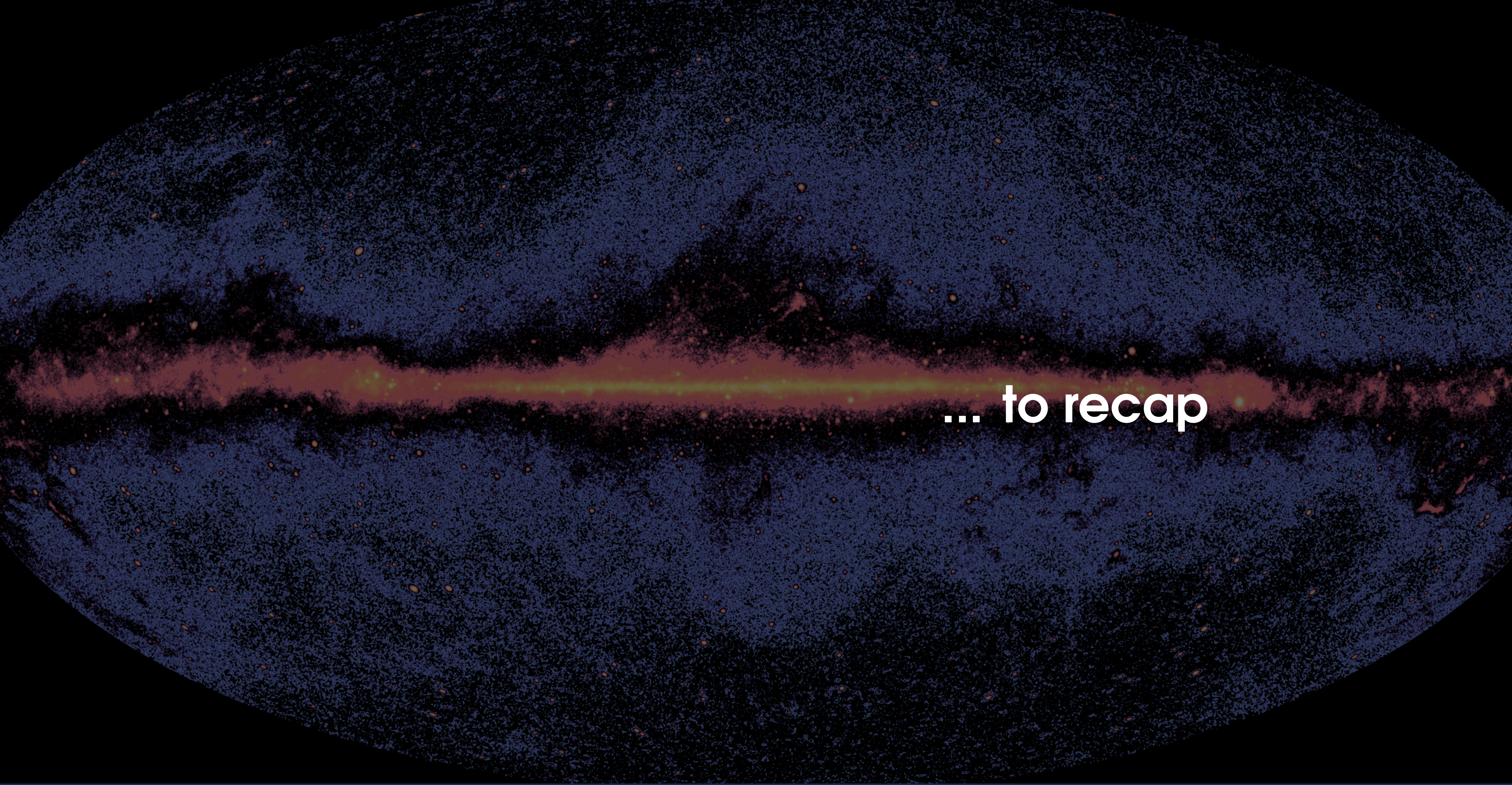
Compared with previous works ...

- We include more data
- Robust statistical analysis
- We include the astrophysical afterglow

Compared to pair halo searches ...

- No assumption on activity time required
- Plasma instabilities suppressing the cascade probably not relevant




... to recap

Summary

GRB 221009A offers the best constraints so far with the pair echo technique, leading to $B_{\rm rms} > 4 \cdot 10^{-17}$ G

- Results depend only mildly on assumptions such as the EBL
- Outlook: use a physically motivated model for the GRB afterglow instead of subtracting the emission detected ($\Gamma = 2$)