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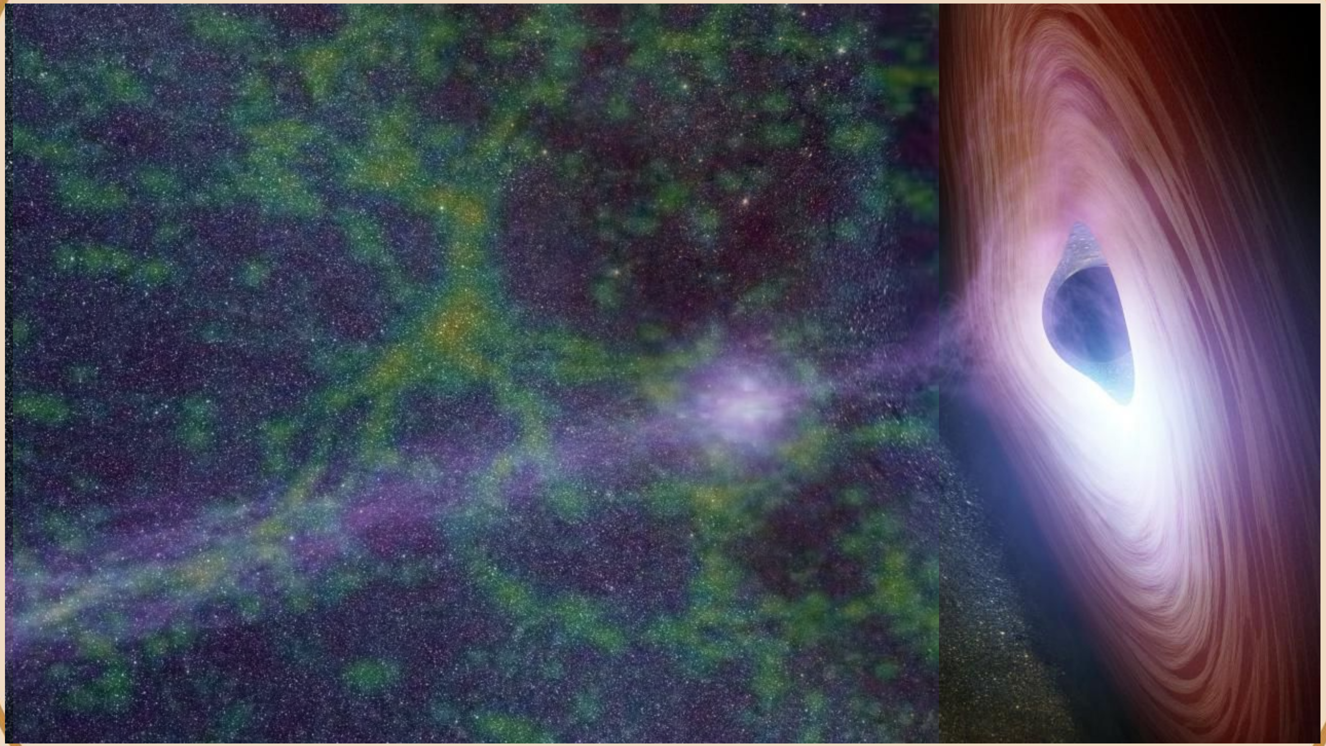
Probing the cosmic magnetism with gamma-ray observations of extragalactic sources



Paolo Da Vela

INAF OAS Bolgna, paolo.davela@inaf.it

Intergalactic Magnetic Field: a new probe of the Early Universe
Trieste, Italy, 9-14 February, 2025

About me

- Born in Empoli (Florence) 23 October 1982
- Graduated at the University of Florence
- PhD at the University of Siena

Probing the Intergalactic Magnetic field by means of high energy pair halos around extreme blazars

★ Postdoctoral fellowships:
  - INFN Pisa
  - University of Bari
  - University of Innsbruck

★ Currently PNRR not-permanent researcher at Istituto Nazionale di Astrofisica (INAF) OAS Bologna (**CTA+** project)

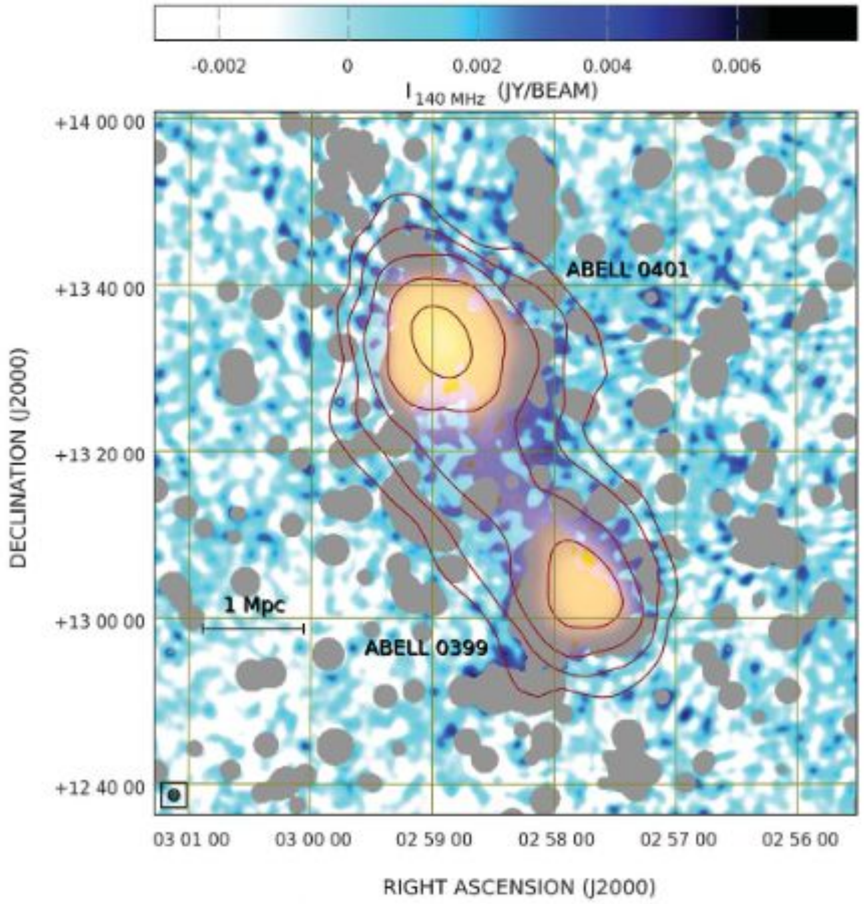
Magnetic Fields in galaxies

Borlaff et al. 2021

B < 1 μG

B ≃15 μG

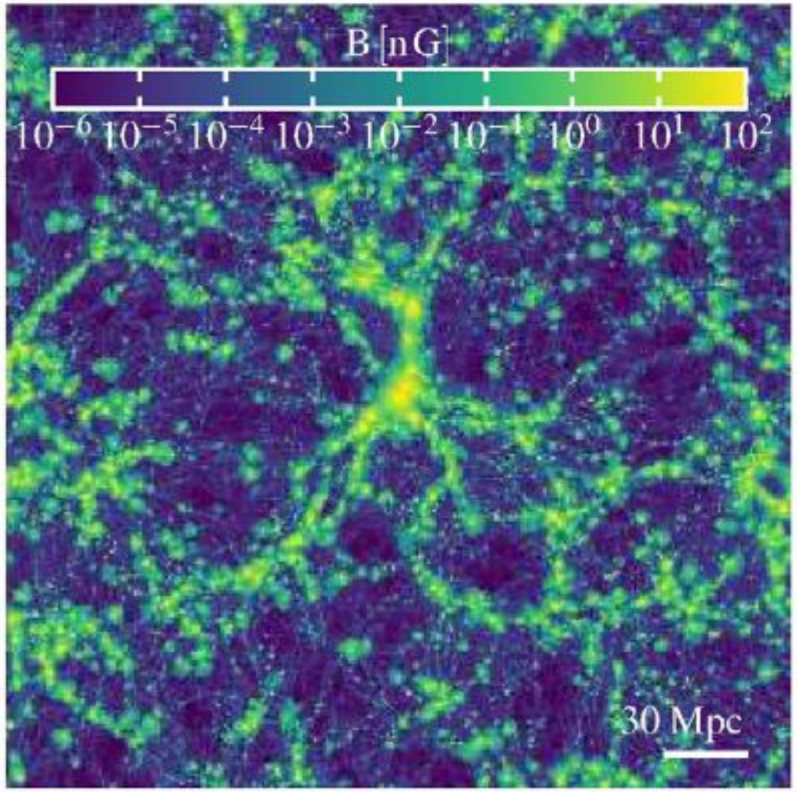
Most of the models that explain these magnetic fields assume a pre-existing magnetic field



Govoni et al. 2019

On the nature of the seed fields

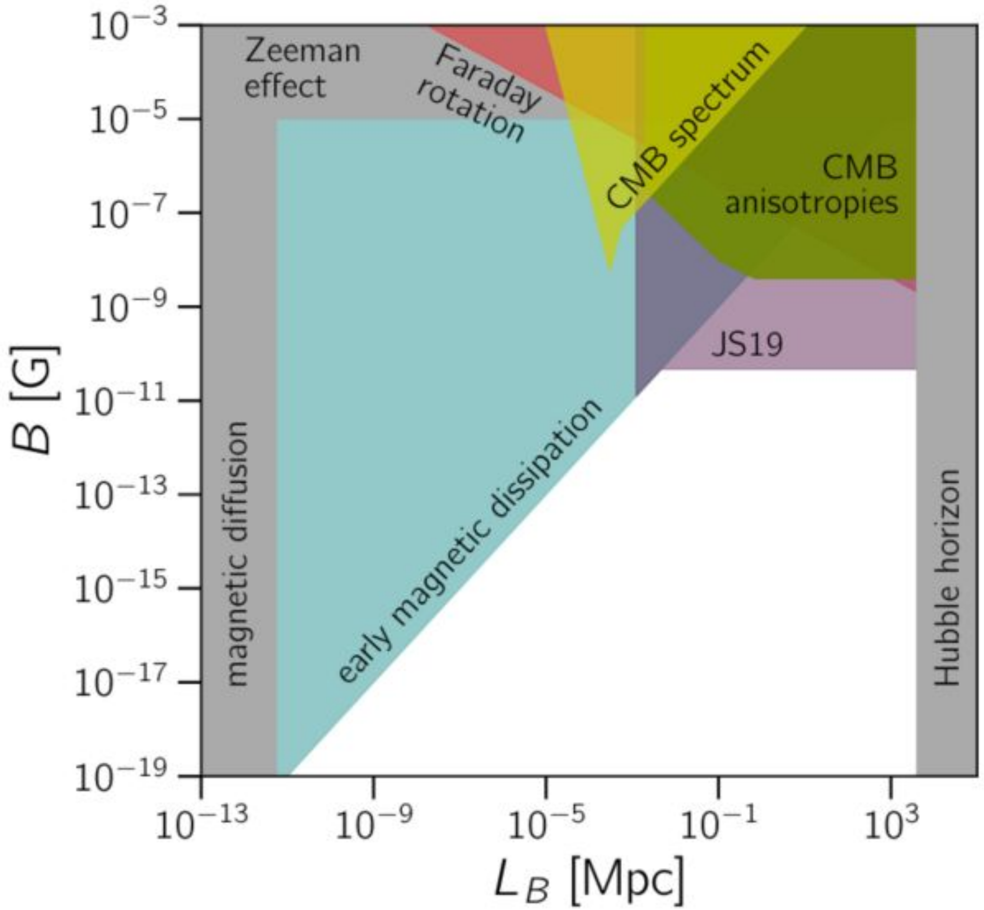
- The nature of the seed fields is largely unknown. Two main hypothesis exist:
  - the cosmological scenario
  - the astrophysical scenario
- Observationally we need measurement of magnetic fields in the intergalactic medium



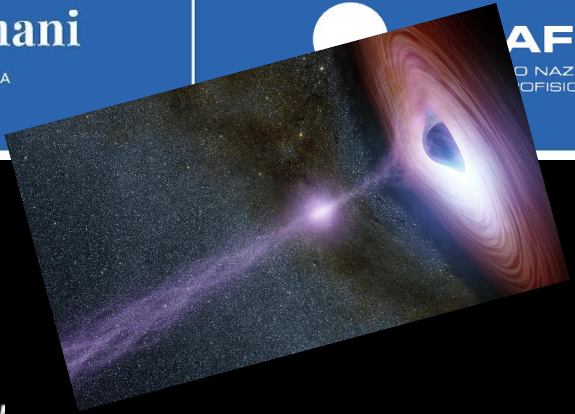
Marinacci et al. 2019

The Intergalactic magnetic field

- The IGMF is characterized by the field strength and the correlation length
- Standard techniques can constrain only a small portion of (B, λ_B) plane (the so called *exclusion plot*)
- We need a more sensitive technique



Alves Batista & Saveliev 2021

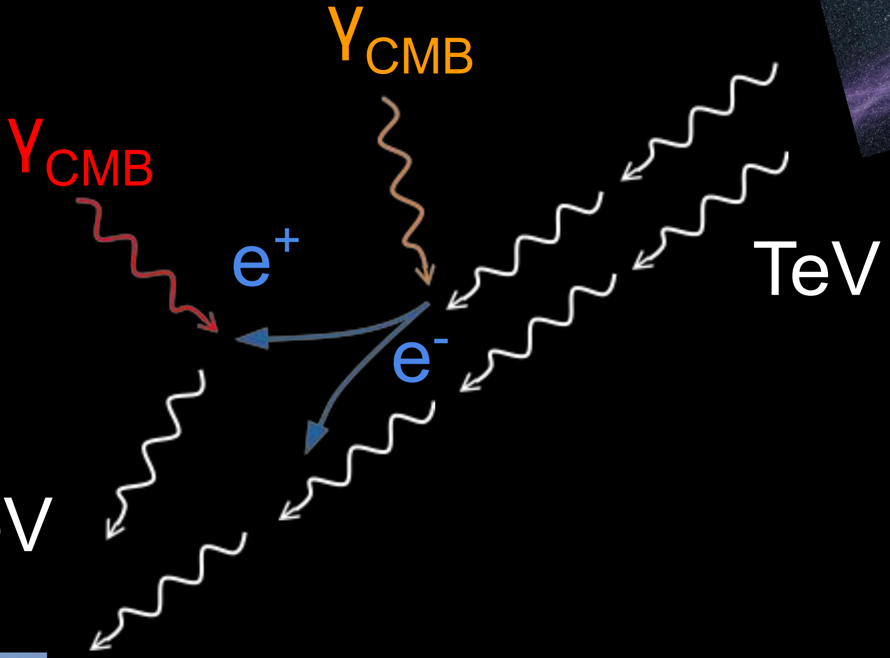


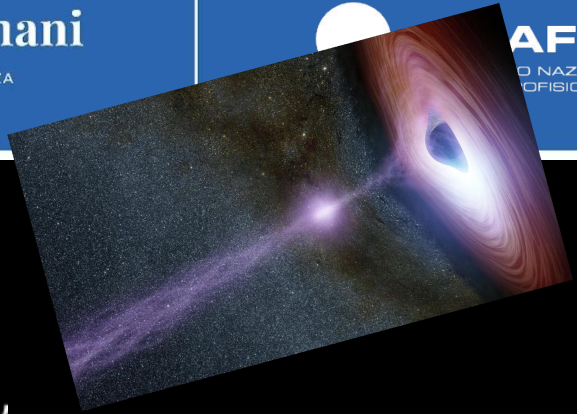
Physical process

Excess at lower energies

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

Neronov et al. 2009





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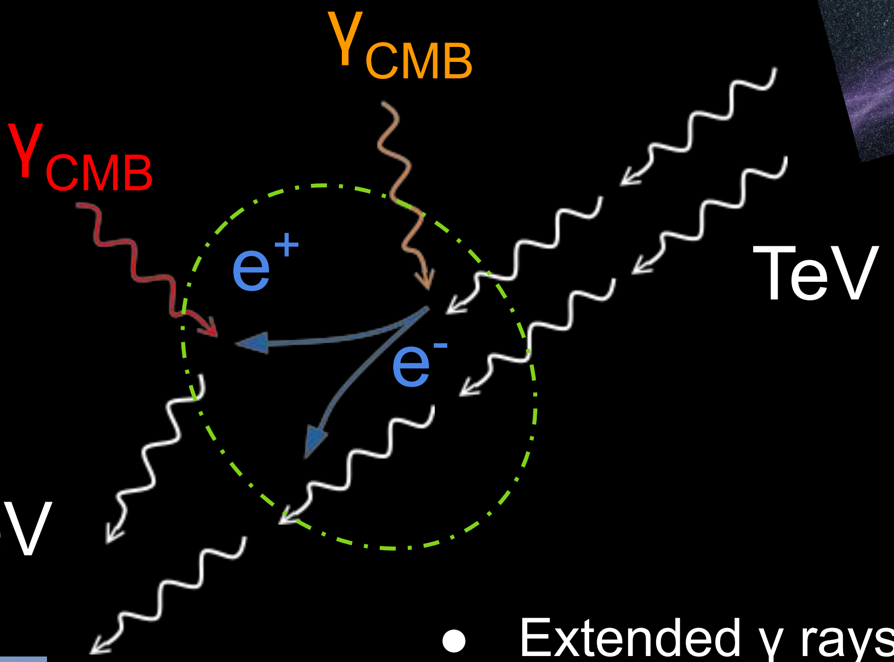
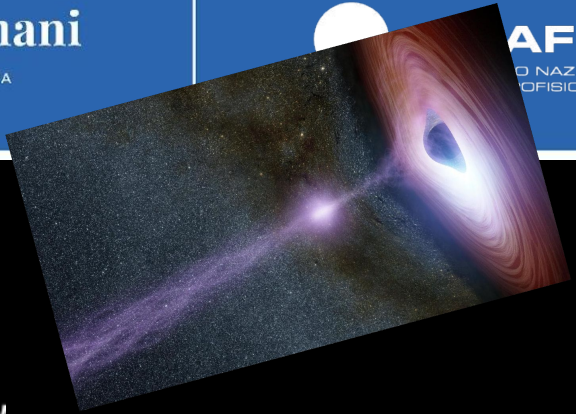


Indirect detection of the IGMF

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



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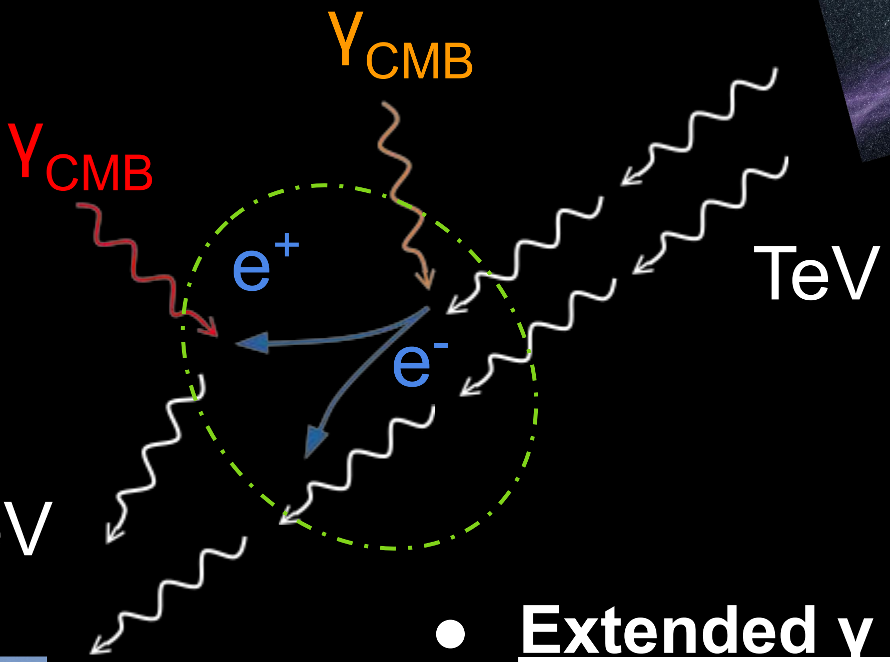


Indirect detection of the IGMF

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

About me

★ Background and expertise
  - Gamma ray Cherenkov telescopes: member of CTAO, MAGIC and LST.
  - Blazars: emission mechanisms
  - IGMF with gamma ray observations of extragalactic sources

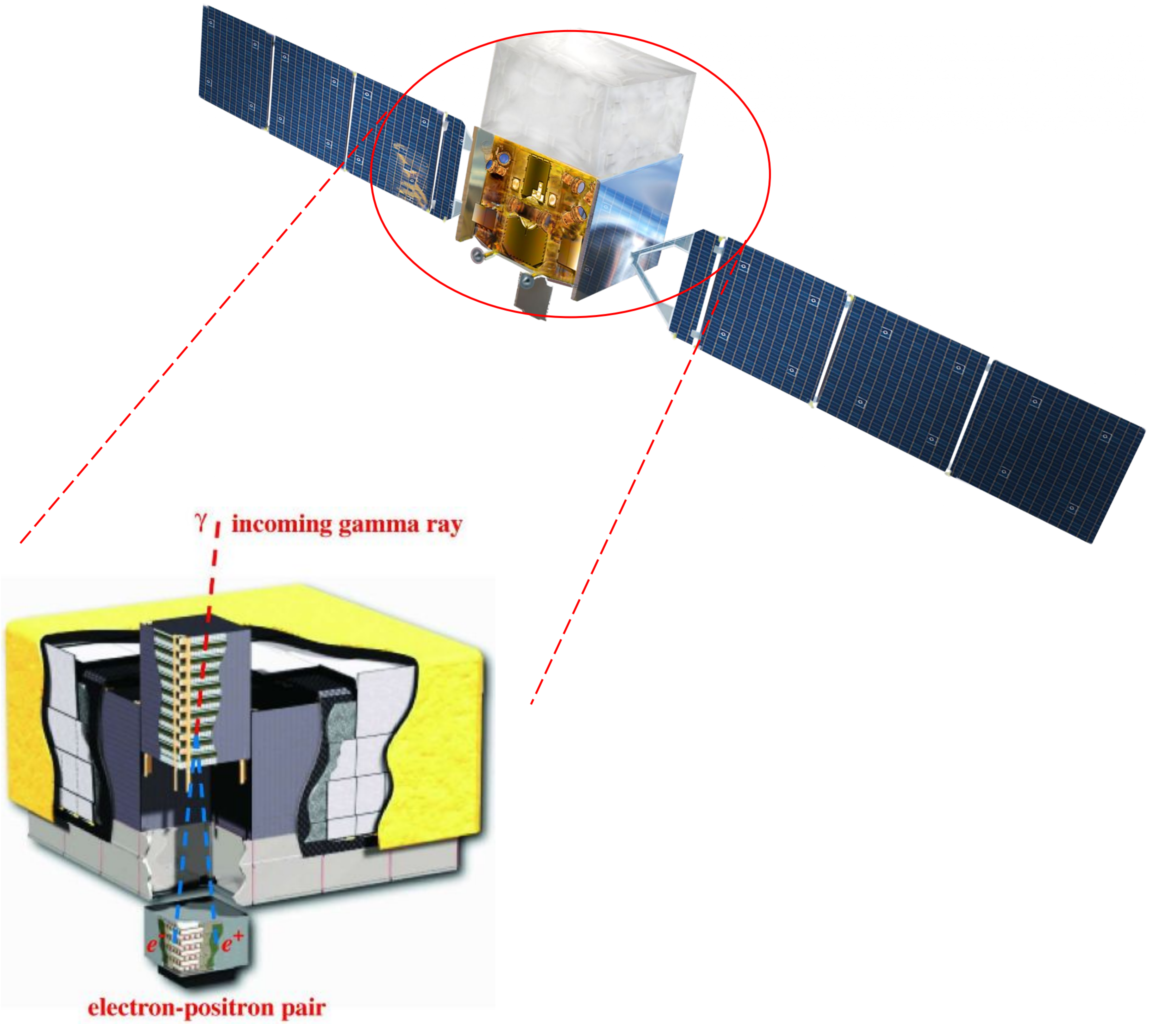
★ Research activities
  - IGMF constraints from GRBs
  - Search for halo emission from VHE blazars
  - Characterization of VHE Emission from HBL and EHBL

★ Collaborators: A. Stamerra, E. Prandini, C. Nanci, P. Veres, D, Miceli, L. Nava, G. Ghirlanda, G. Martì-Devesa, F. Saturni, F. Longo, M. Meyer

The *Fermi* Large Area Telescope

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



Imaging Air Cherenkov Telescopes: the present

VERITAS, MAGIC and H.E.S.S.

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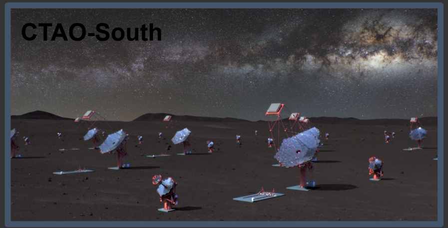
The MAGIC telescopes

Energy range	∽ 50 GeV - tens of TeV
Field of view	3.5°
Angular resolution	~0.06° @ E > 300 GeV
Energy resolution	~16% @ E > 300 GeV
Sensitivity (5 σ in 50 hours)	~ 0.8% Crab Nebula flux (E > 250 GeV)

Imaging Air Cherenkov Telescopes: the present

VERITAS, MAGIC and H.E.S.S. and CTAO

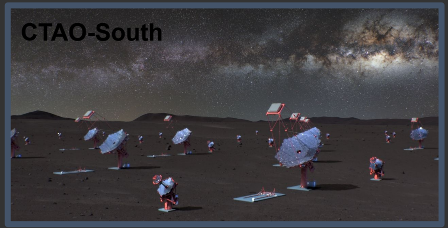


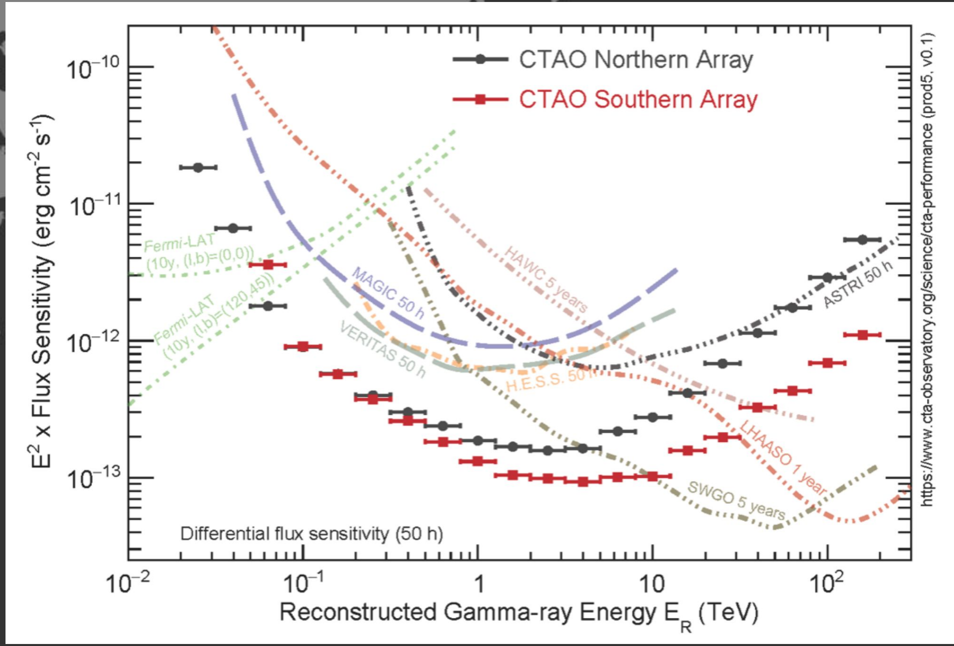
CTAO North (Alpha configuration): 4 LSTs (23m), 9 MSTs (12m)

CTAO South (Alpha configuration + CTA+): 2 LSTs, 14 MSTs, 37+5 SSTs

Imaging Air Cherenkov Telescopes: the present

VERITAS, MAGIC and H.E.S.S. and CTAO





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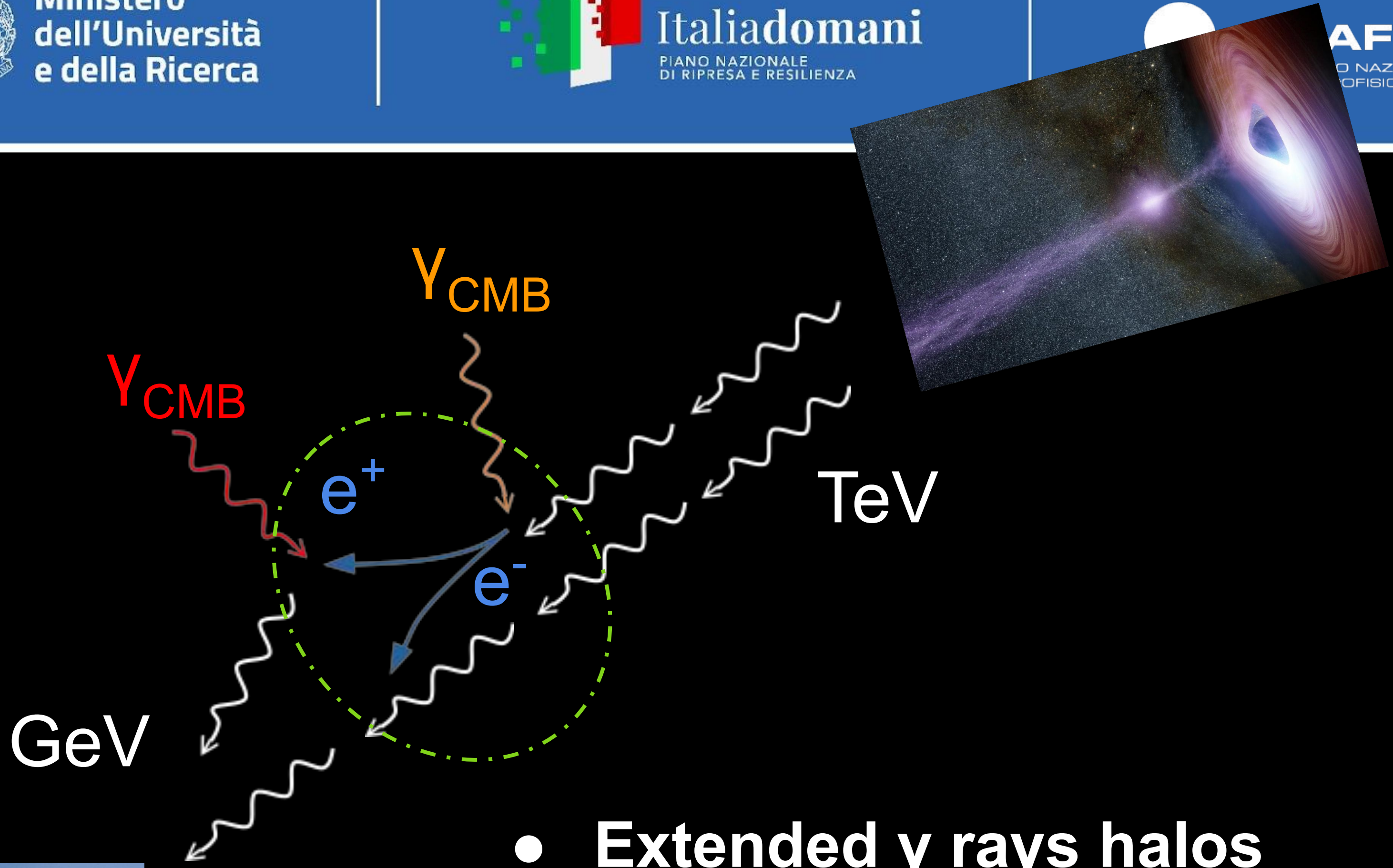
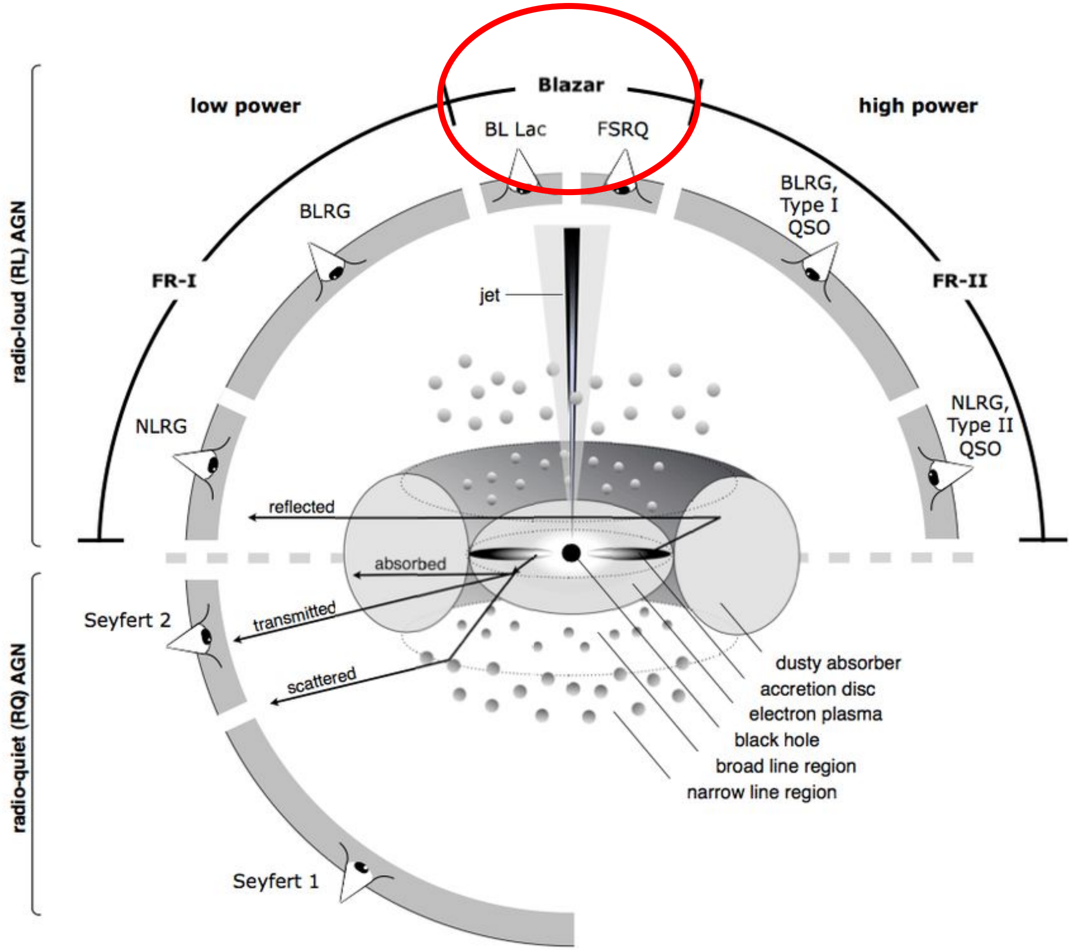


Indirect detection of the IGMF

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

Blazars



- Blazars represent the most extreme flavor of AGN
  - Emission dominated by the non thermal continuum produced within the jet
  - Variable sources
  - Well known gamma-ray emitters

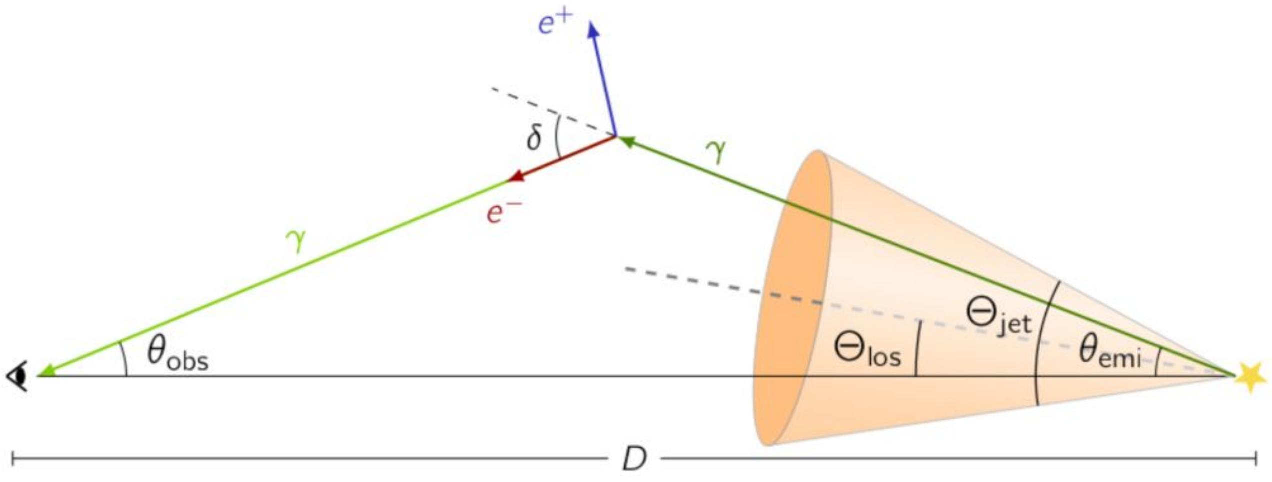
What are the most promising sources?

- We need hard VHE spectra (E > 50 GeV)
- Spectra that reach the highest energies
- “Proper” redshift z > 0.1

Among the different classes of blazars the most promising sources are the High Frequency BL Lac object (HBL)

Extended emission

Observable effect: extended emission around the point source. The angular extension grows with increasing IGMF



$\lambda_B \gg \lambda_{IC}$:

$$\theta_{obs} \simeq 0.5^\circ (1+z)^{-2} \left[\frac{\tau}{10}\right]^{-1} \left[\frac{E}{0.1TeV}\right]^{-2} \left[\frac{B}{10^{-14}G}\right]$$

$\lambda_B \ll \lambda_{IC}$:

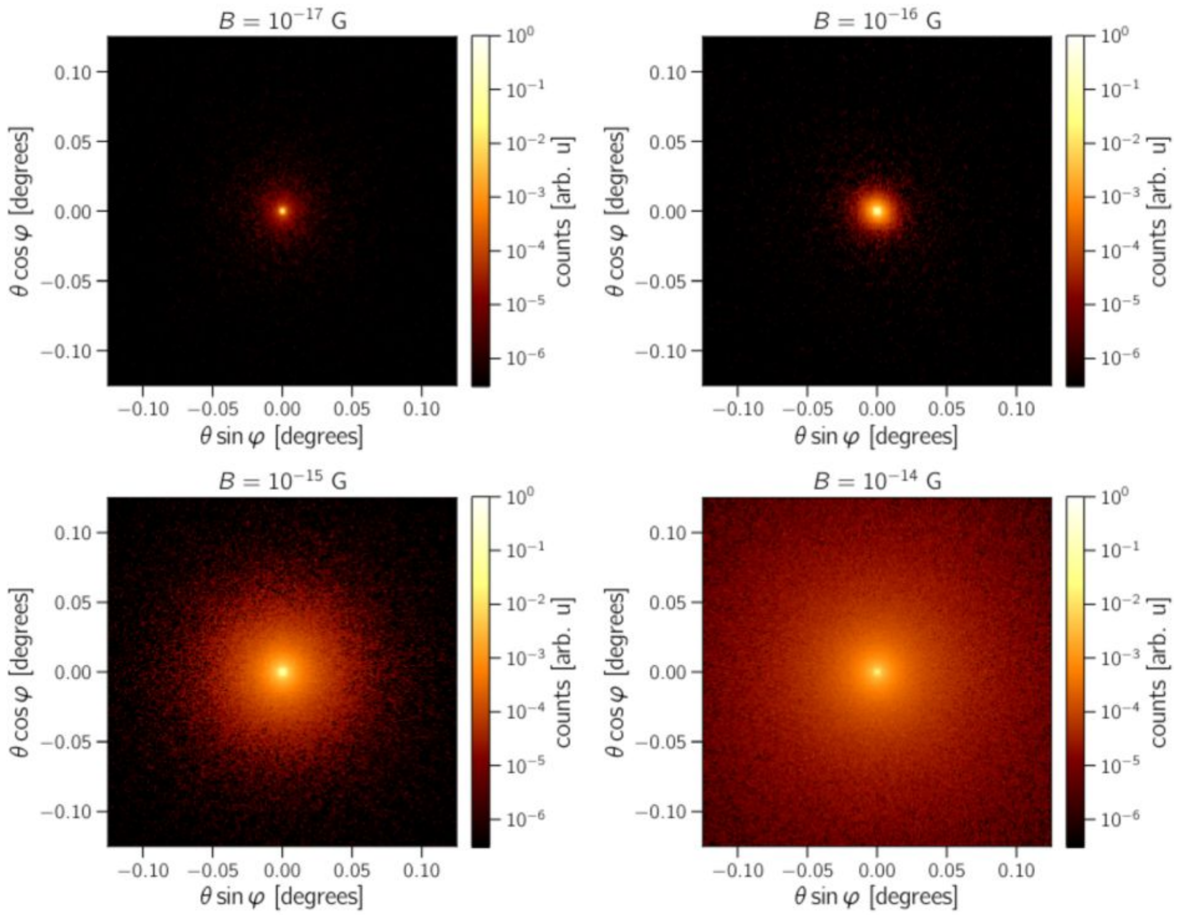
$$\theta_{obs} \simeq 0.07^\circ (1+z)^{-1/2} \left[\frac{\tau}{10}\right]^{-1} \left[\frac{E}{0.1TeV}\right]^{-3/4} \left[\frac{B}{10^{-14}G}\right] \left[\frac{\lambda_B}{1kpc}\right]^{1/2}$$

Alves Batista & Saveliev 2021

Extended emission: expectations

- Source: 1ES 0229+200
- Redshift: 0.14
- Correlation length: 1 Mpc
- Spectrum: powerlaw -1.5, E_{max}=5 TeV
- E > 1 GeV

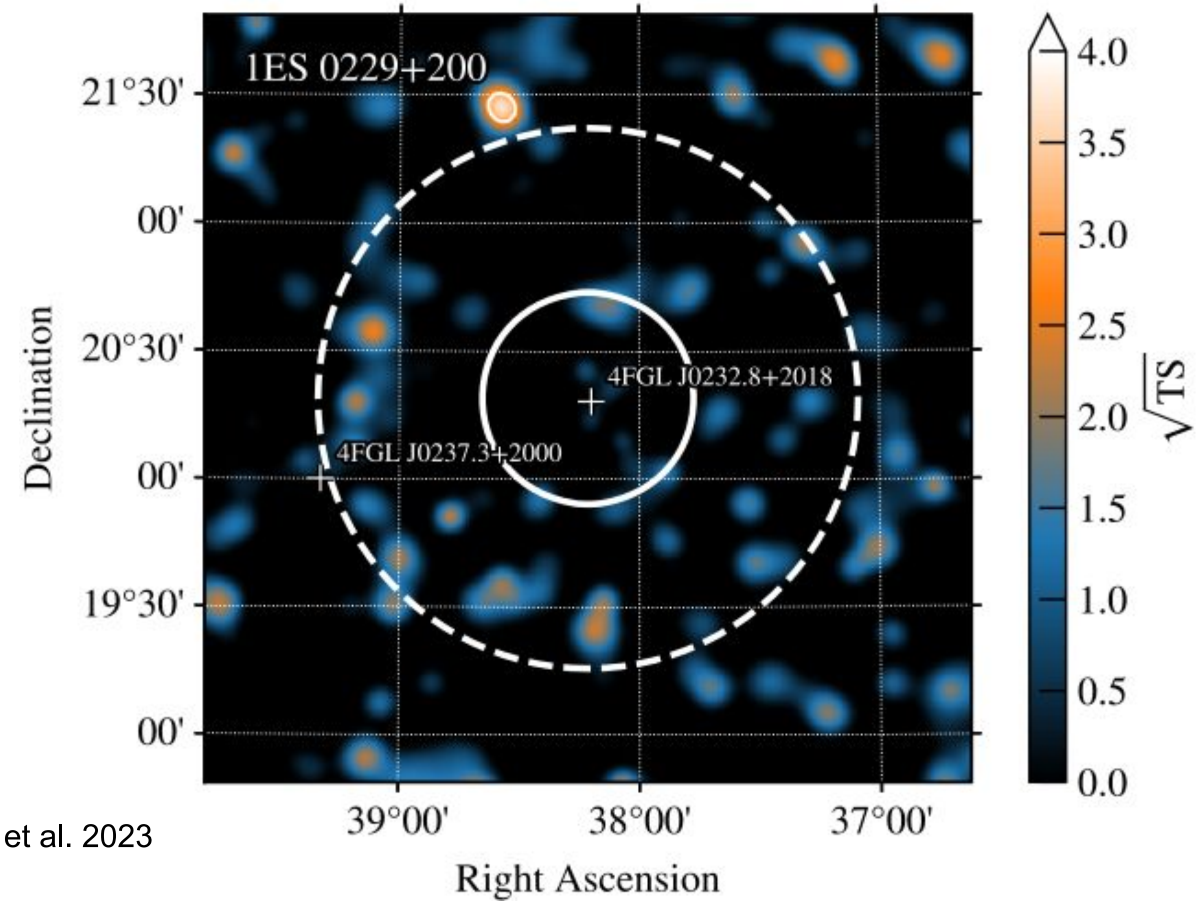
Alves Batista & Saveliev 2021



Extended emission: observations

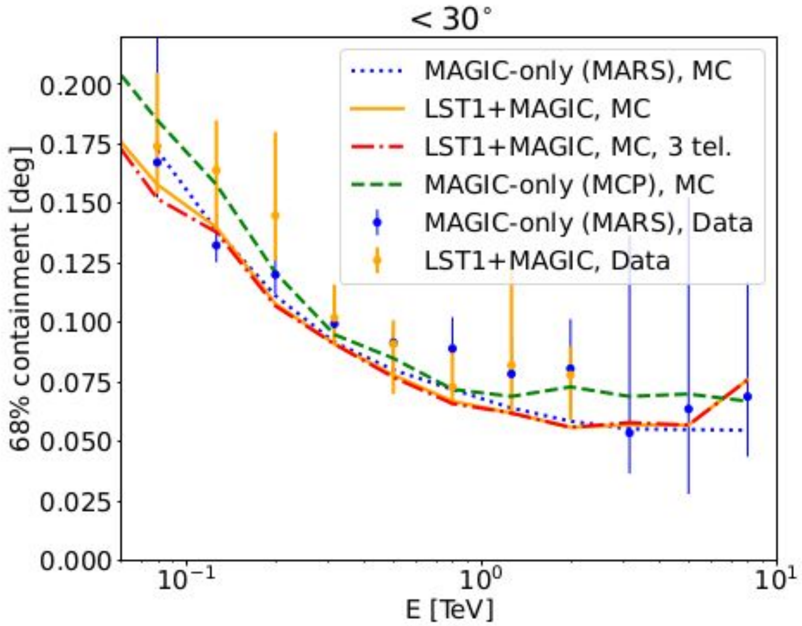
- The extended emission can be searched in the GeV domain (Fermi/LAT) and in the VHE band (E > 50 GeV) with Cherenkov telescopes

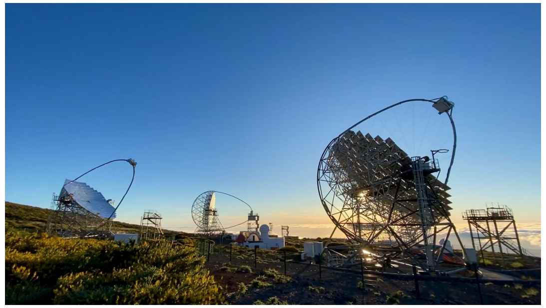
- In spite of several attempts no detection has been claimed up to now in both energy bands

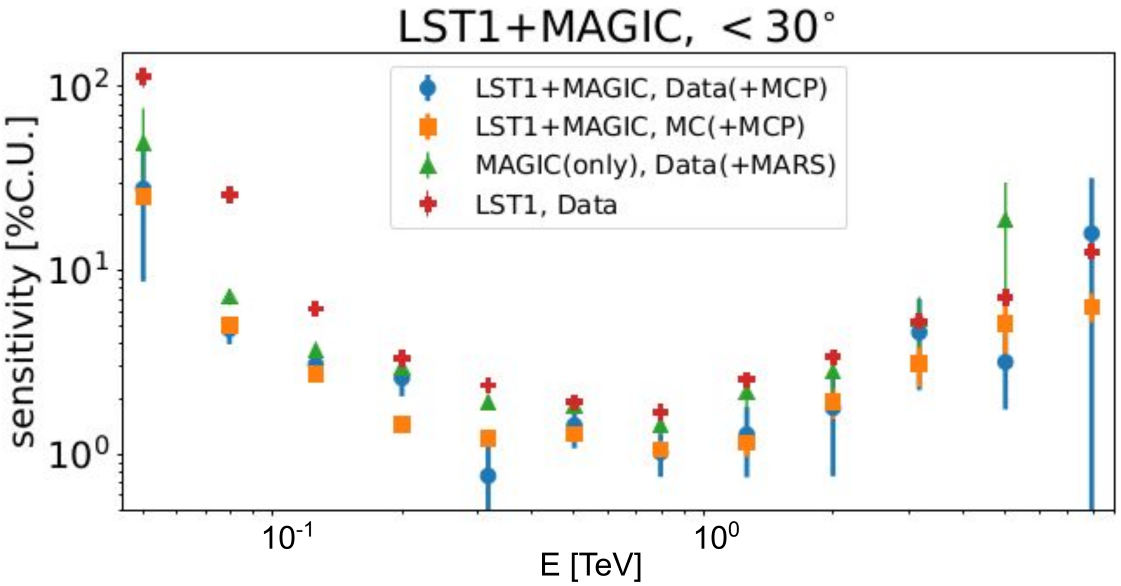


Aharonian et al. 2023

MAGIC + CTAO/LST1 observations of 1ES 0229+200







Most sensitive extended emission search in the VHE band and pre-CTAO era

Goal: derive a range of IGMF strengths excluded by the data assuming different source lifecycles

MAGIC+LST1 map of 1ES 0229+200

Simulations the 2D cascade distribution for different IGMF strengths (B_i)

Fit of the excess map with the PSF model

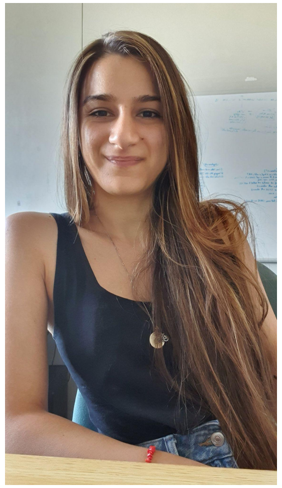
Convolution of the simulation output with the PSF of MAGIC+LST system:
$halo_{conv}(B_i) = halo(B_i) \otimes PSF$

Repeat the procedure scanning different IGMF strengths (B_i)

Add the halo component to the fit:
$F(B_i) = PSF + halo_{conv}(B_i)$

Evaluate the significance of the halo component
→ exclude this IGMF configuration if required

MAGIC + CTAO/LST1 observations of 1ES 0229+200



- The project is led by **Cristina Nanci**. We want to address the following questions:
  - which magnetic field configurations can be excluded in the VHE band? (prepare the ground for CTAO)
  - How do the lifecycle and the variability of the source can affect the results?
- Caveats:
  - realistic halo templates: jet misalignment, opening angle
  - realistic magnetic field models

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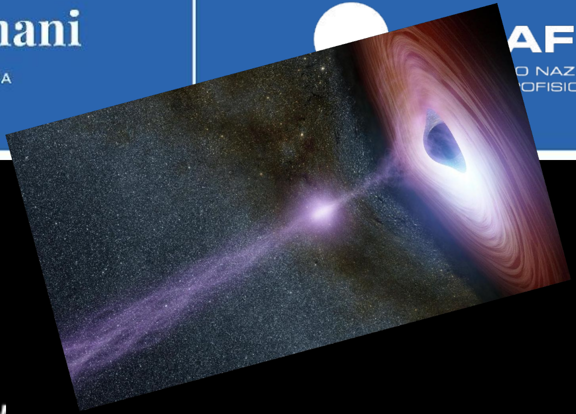

Physical process

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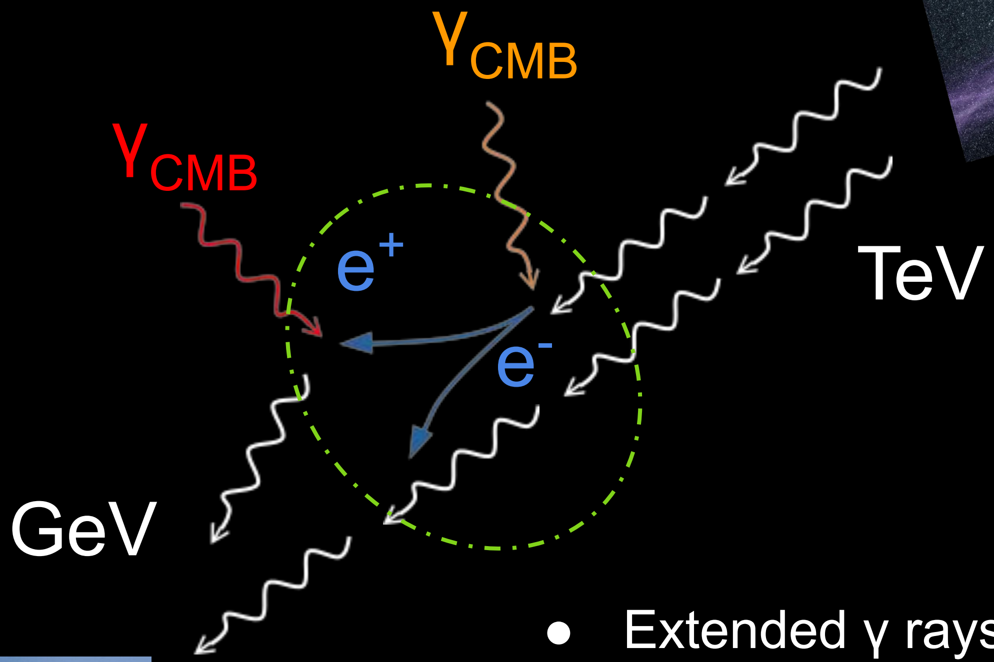
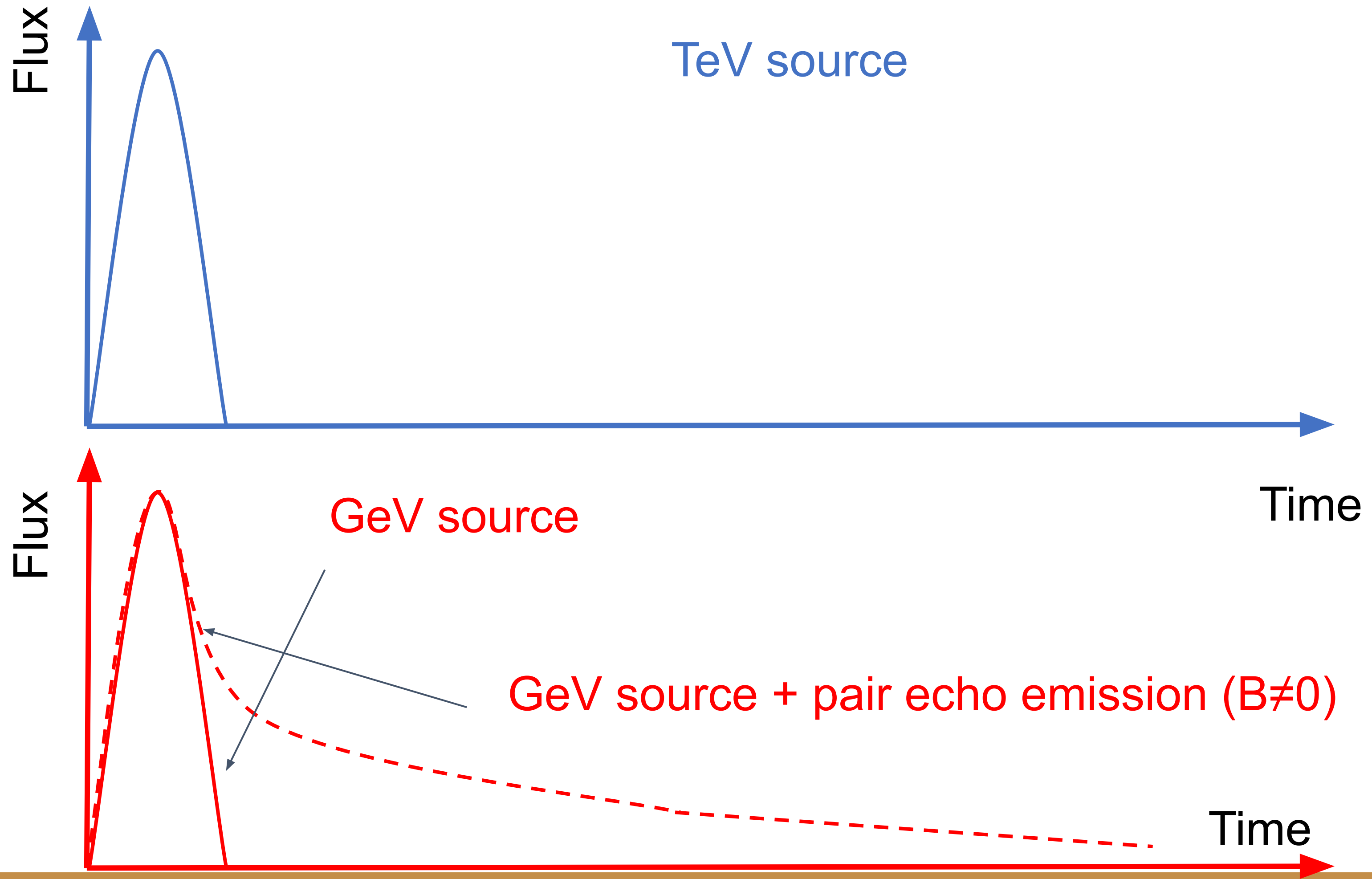
Neronov et al. 2009



Indirect detection of the IGMF

- Extended γ rays halos
- Spectral features
- **<u>Time delayed γ-ray emission</u>**

Search for the “pair-echo” emission



- ❖ The cascade emission is delayed -> tail in the GeV lightcurve
- ❖ The pair-echo is diluted in time and the dilution depends on the IGMF strength

$$F_{delay}(E) \sim \frac{T}{T_{delay} + T} F(E_0)$$

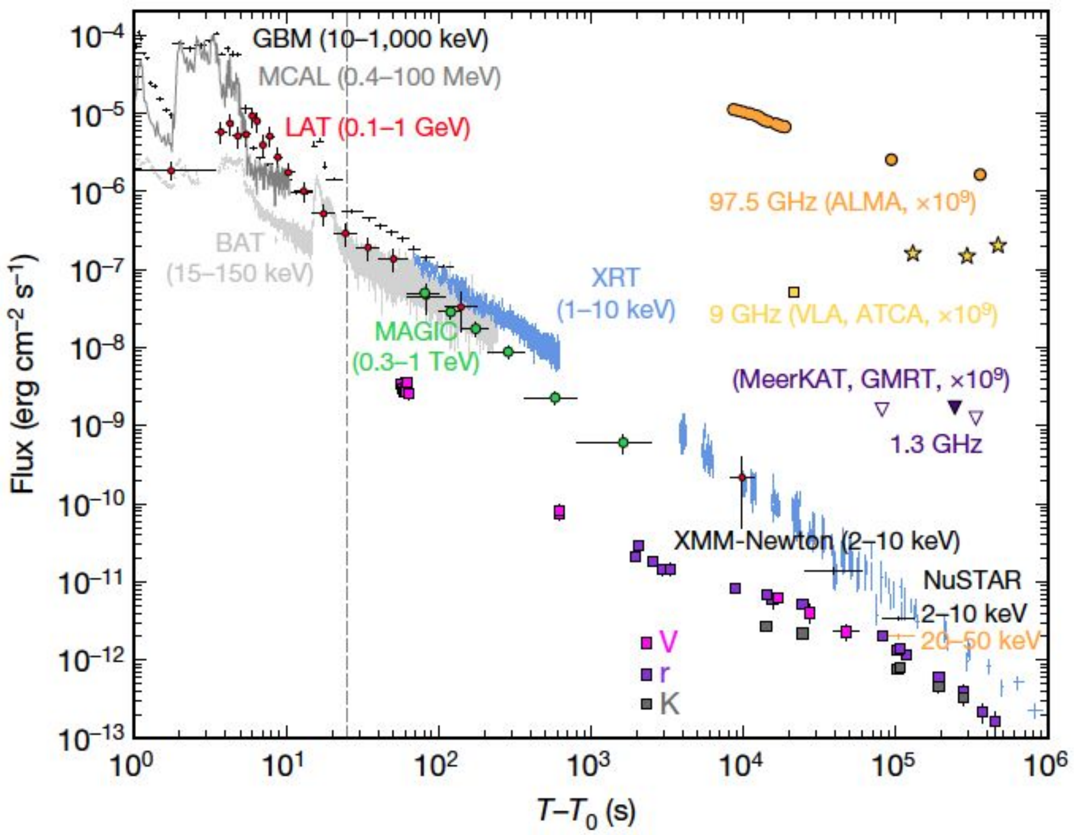
$$T_{delay} \propto E^{-5/2} B^2$$

Neronov et al. 2009

Search for the pair-echo emission from GRBs

- Together with my team we studied the pair echo emission from a couple of GRBs focusing on the following points:
  - physically motivated model of the GRB -> important impact on the amount of cascade power
  - Long delay -> strong dilution -> stronger IGMF strength can be excluded
- How does the properties of the GRB can impact the detection of the pair echo? (see Davide's talk)

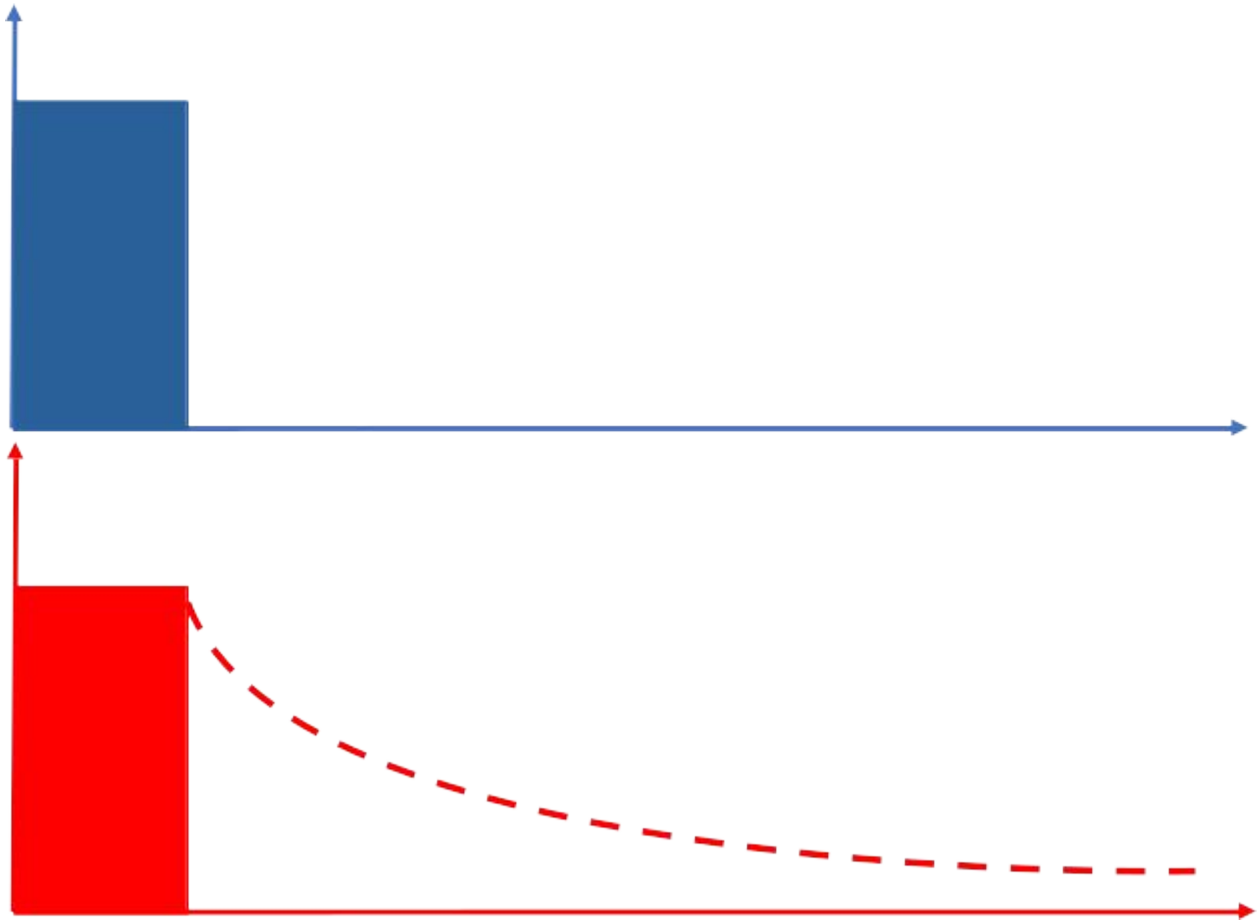
GRB 190114C



MAGIC coll. 2019

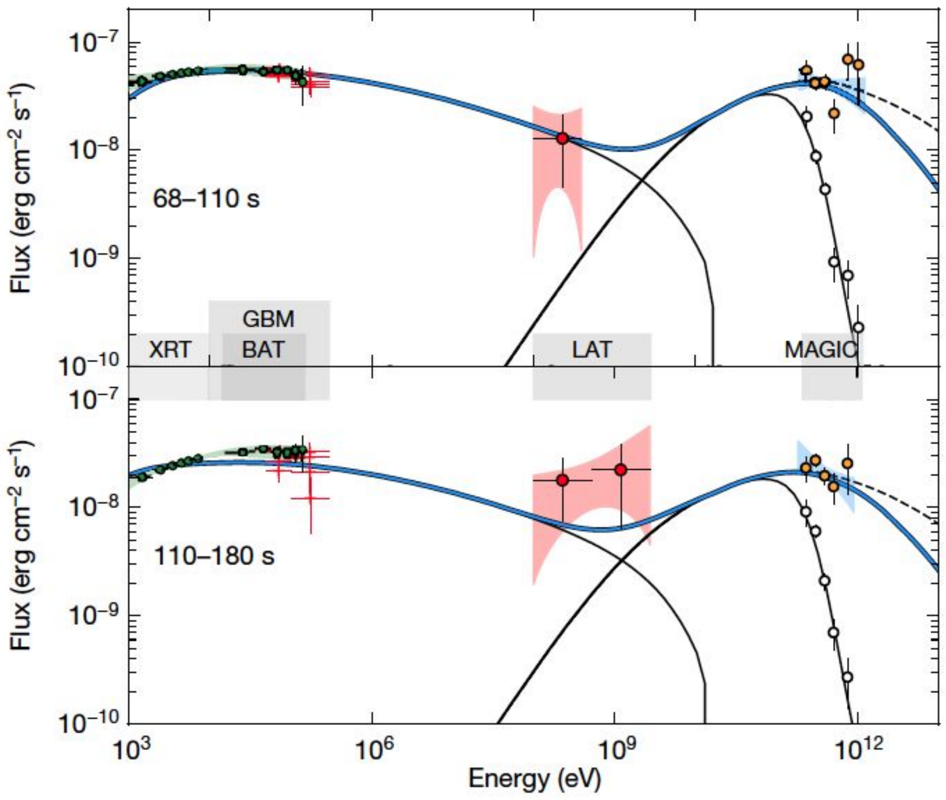
- GRB 190114C was triggered by Swift-BAT on 14 January at T0=20:57:03 UT
- Most of the prompt emission within ~ 25 s
- Afterglow onset at ~ 6 s after T0 (Ravasio et al. 2019)
- $E_{\gamma,iso} \simeq 2\times10^{53}$ erg in the E=1-10^4 keV
- **z=0.42**
- **$T_{activity, VHE}$=40 minutes**

Pair-echo emission "after" the GRB



- Easiest approach:
  - Average VHE spectrum
  - Duration $T_{activity}$
  - All cascade photons within $T_{activity}$ are neglected
  - Production of SEDs for different exposures and IGMF strengths

The primary VHE spectrum



MAGIC coll. 2019

- The GRB 190114C model can be used to infer a physically motivated choice for VHE spectrum to be used to compute the pair-echo SEDs

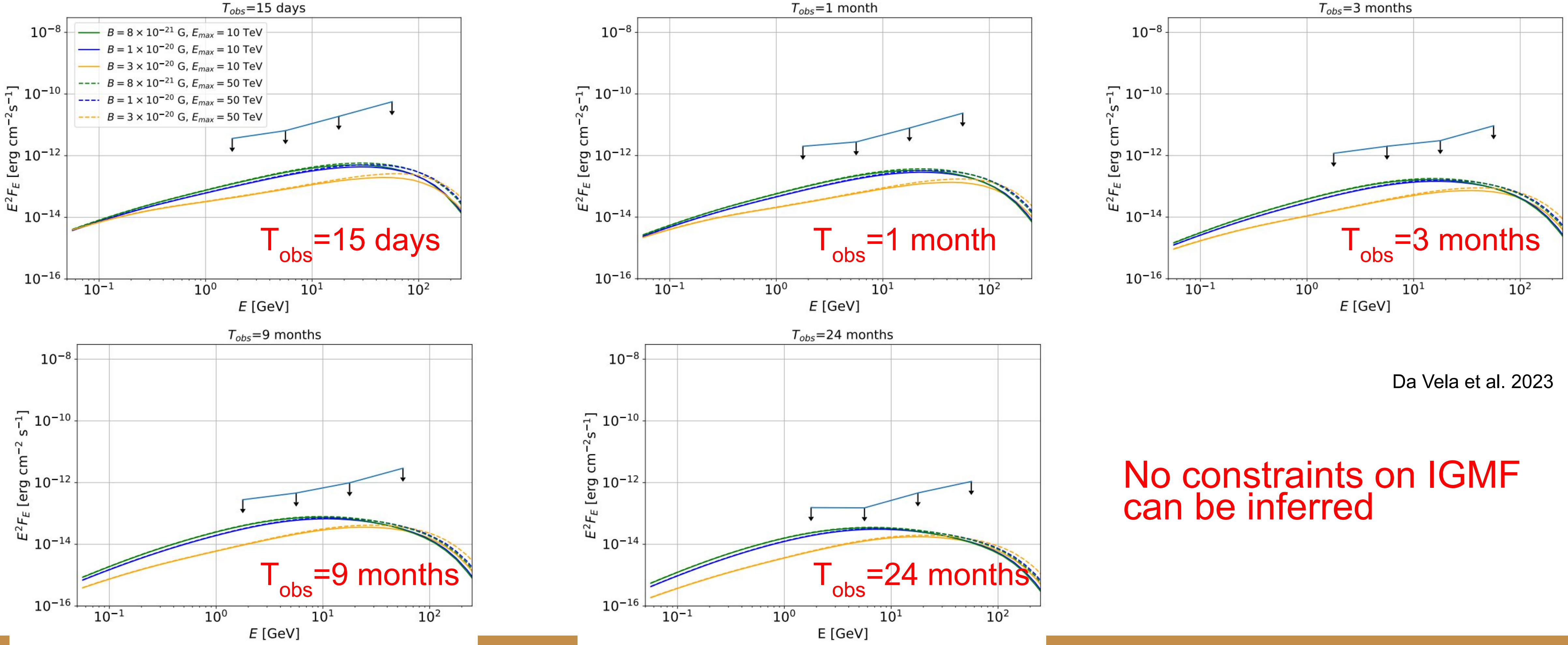
$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-2.5-0.2\log(E/E_0)}$$

- The logparabola shape gives less cascade power than the powerlaw due to the lower lux at the higher energies

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
  - $B_{rms} = 8\times10^{-21}$ G, …, 3×10^{-20} G
  - Coherence length: $\ell_B \simeq 6$ Mpc
- EBL model of Franceschini et al. (2008)
- Jet opening angle: 10° jet aligned with the line of sight

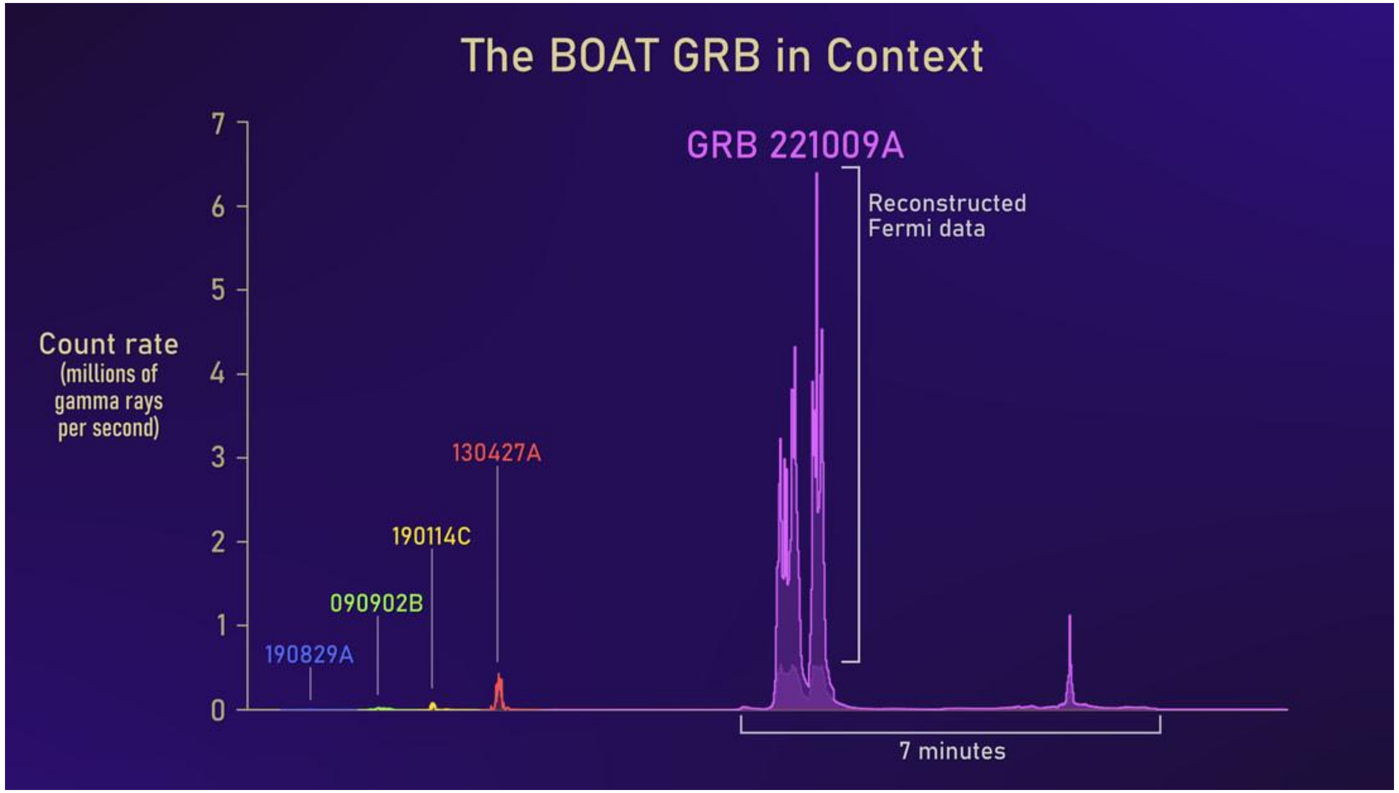
GRB 190114C



Da Vela et al. 2023

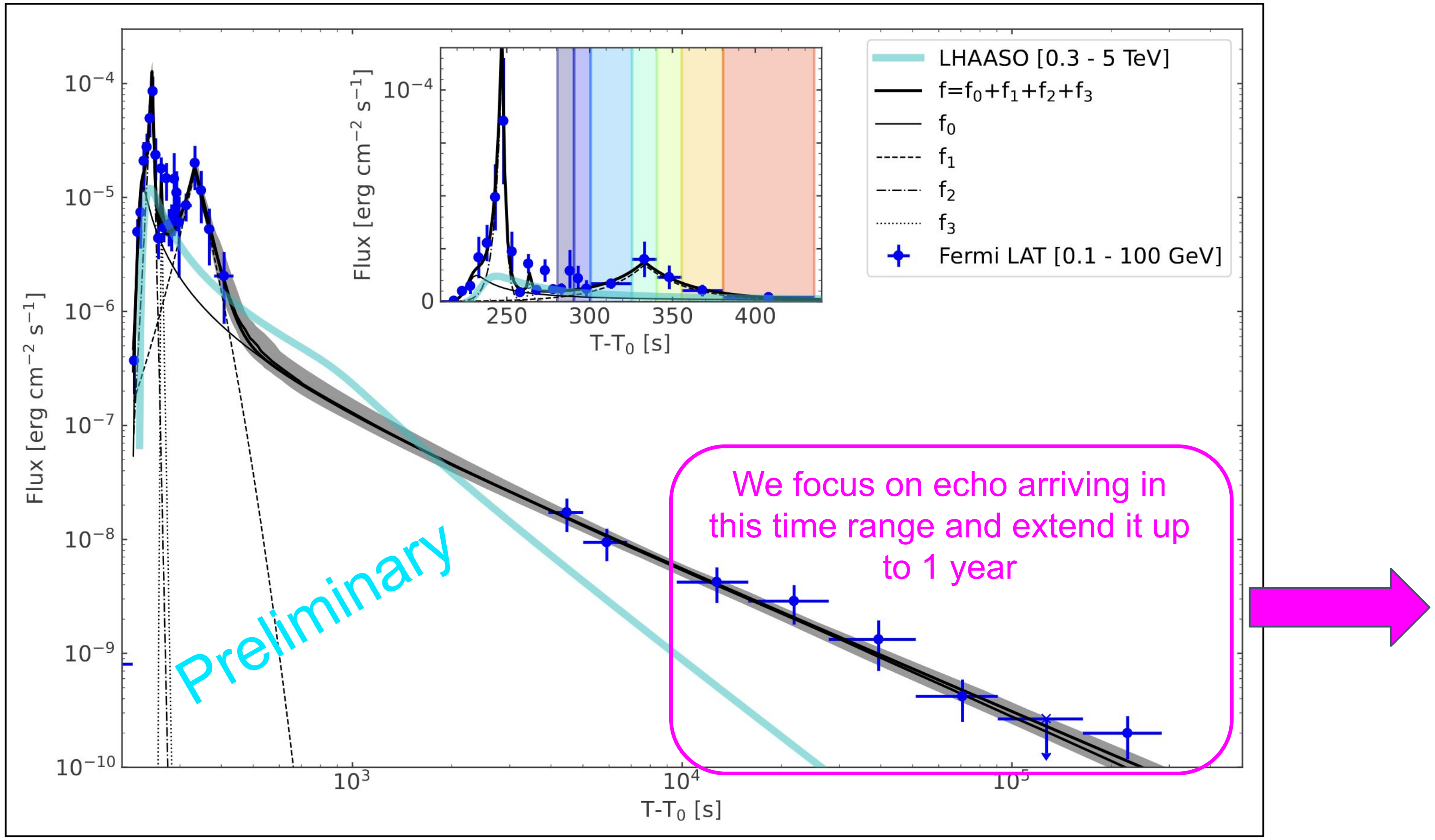
No constraints on IGMF can be inferred

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. 2024

Modeling the temporal and spectral cascade structure with CRPropa3

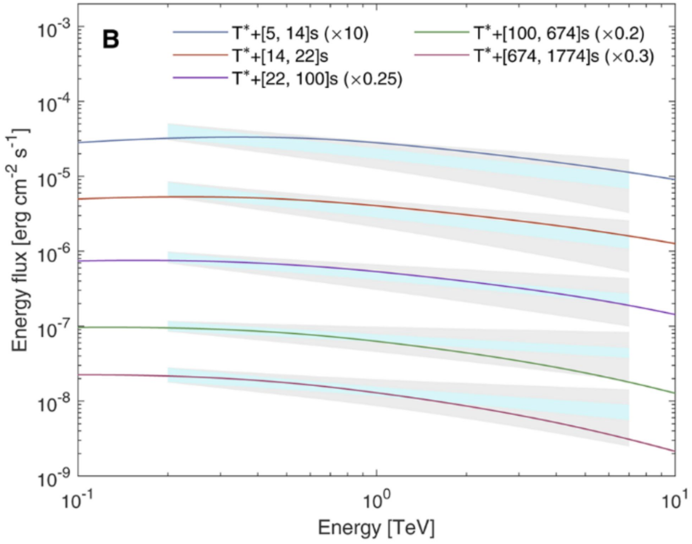
- CRPropa3 Monte Carlo Code used to generate 4D (spatial + energy + delay time) templates
- IGMF:
  - Kolmogorov turbulent spectrum
  - $B_{rms} = 10^{-20}$ G, …, 10^{-15} G
  - Coherence length: $\ell_B \simeq 6$ Mpc
- EBL model of Franceschini et al. (2008)
- Jet opening angle: 1.6° (from LHAASO coll.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

Assumed Intrinsic spectrum: from LHAASO WCDA

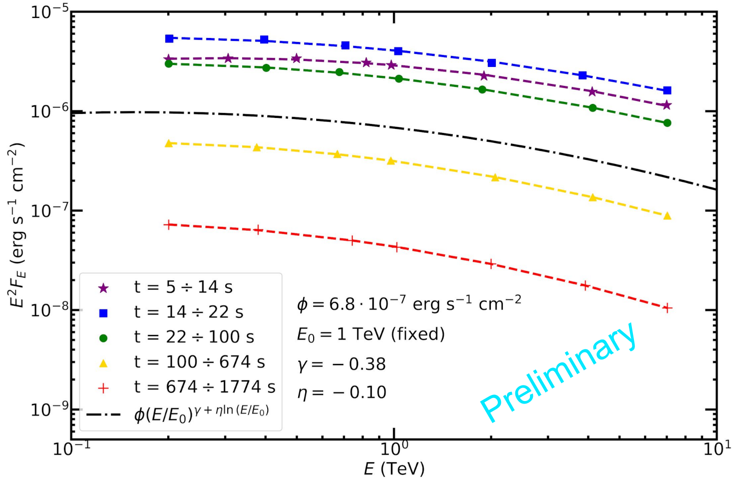
- LHAASO Collaboration fitted physical GRB model to their observations
- We approximated this model with a logparabola and derived time averaged spectrum:

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

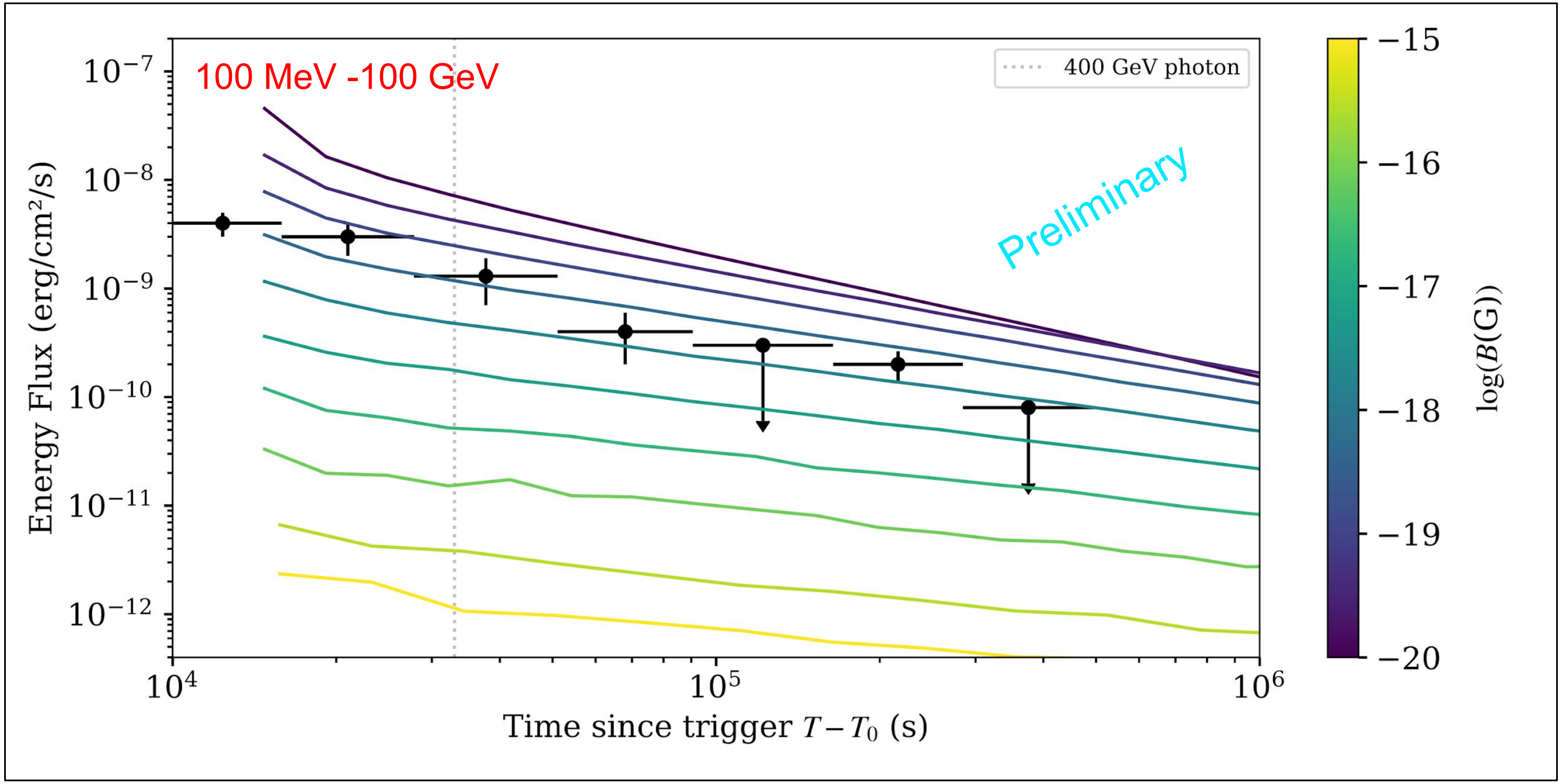
- Additionally multiplied with exponential cutoff at 7 TeV
- Assumed emission time: 3000s



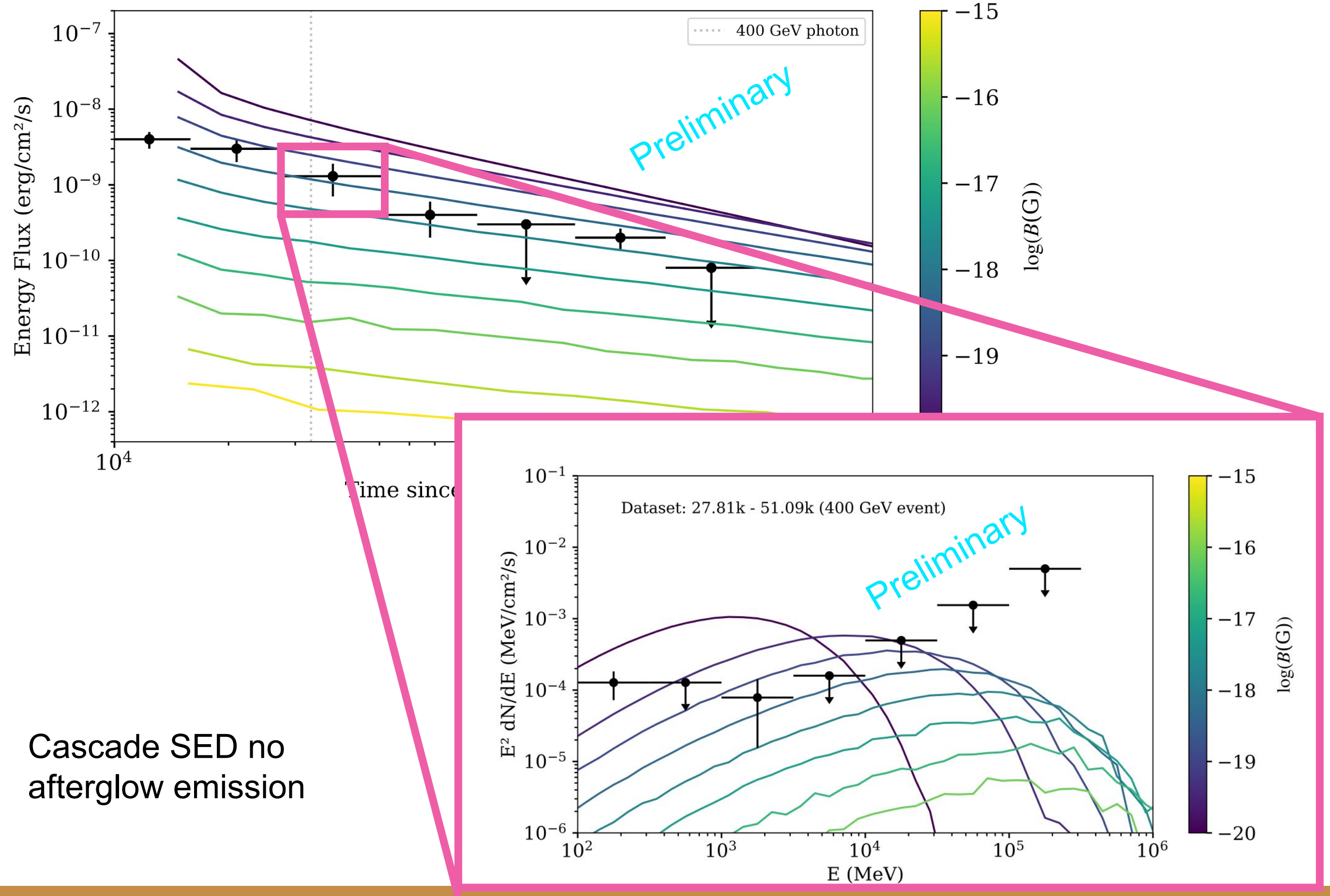
LHAASO Coll. Science 2023



Fermi-LAT LAT lightcurve vs pair echo predictions



Statistical analysis: spectral and temporal likelihood



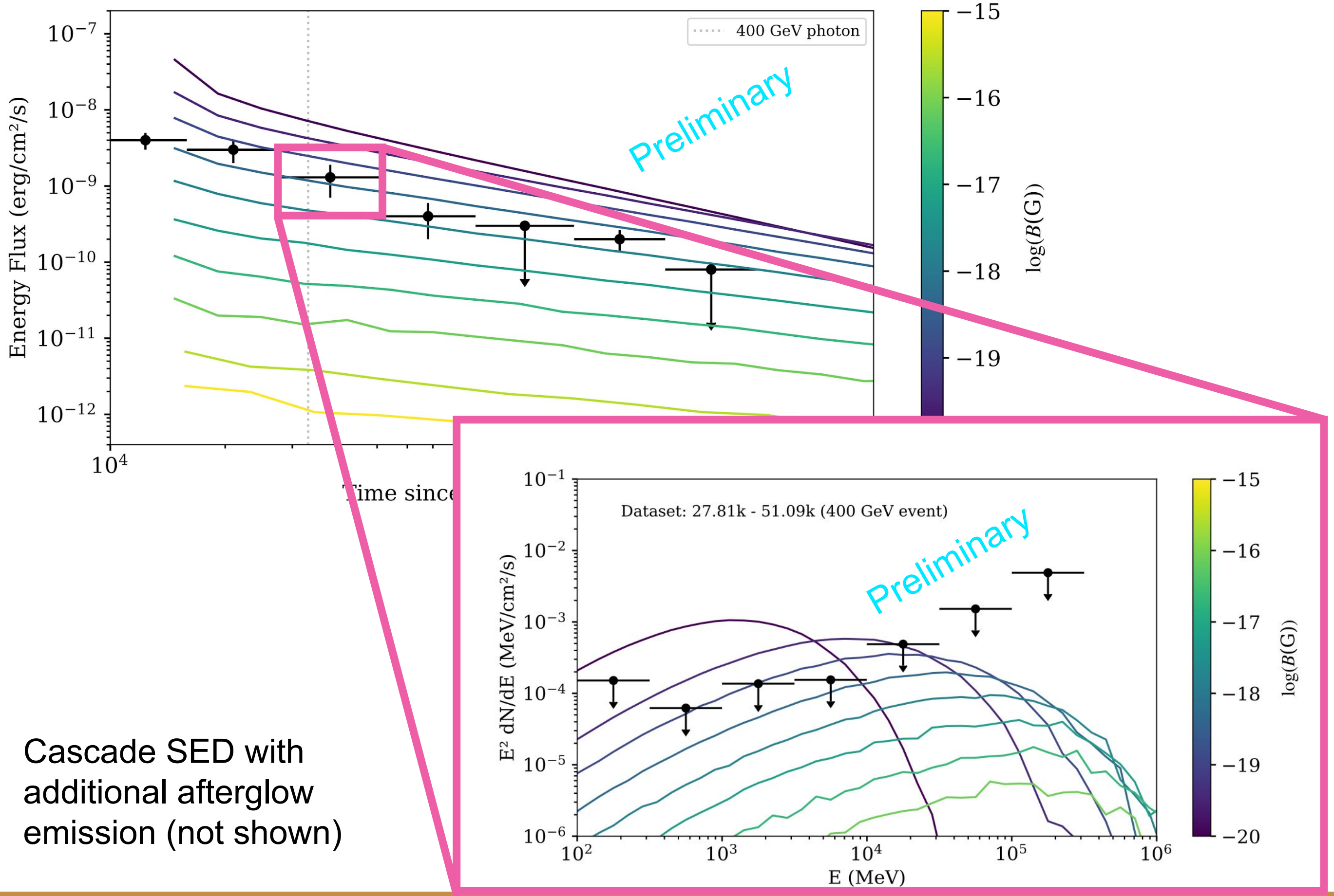
Cascade SED no afterglow emission

- 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)

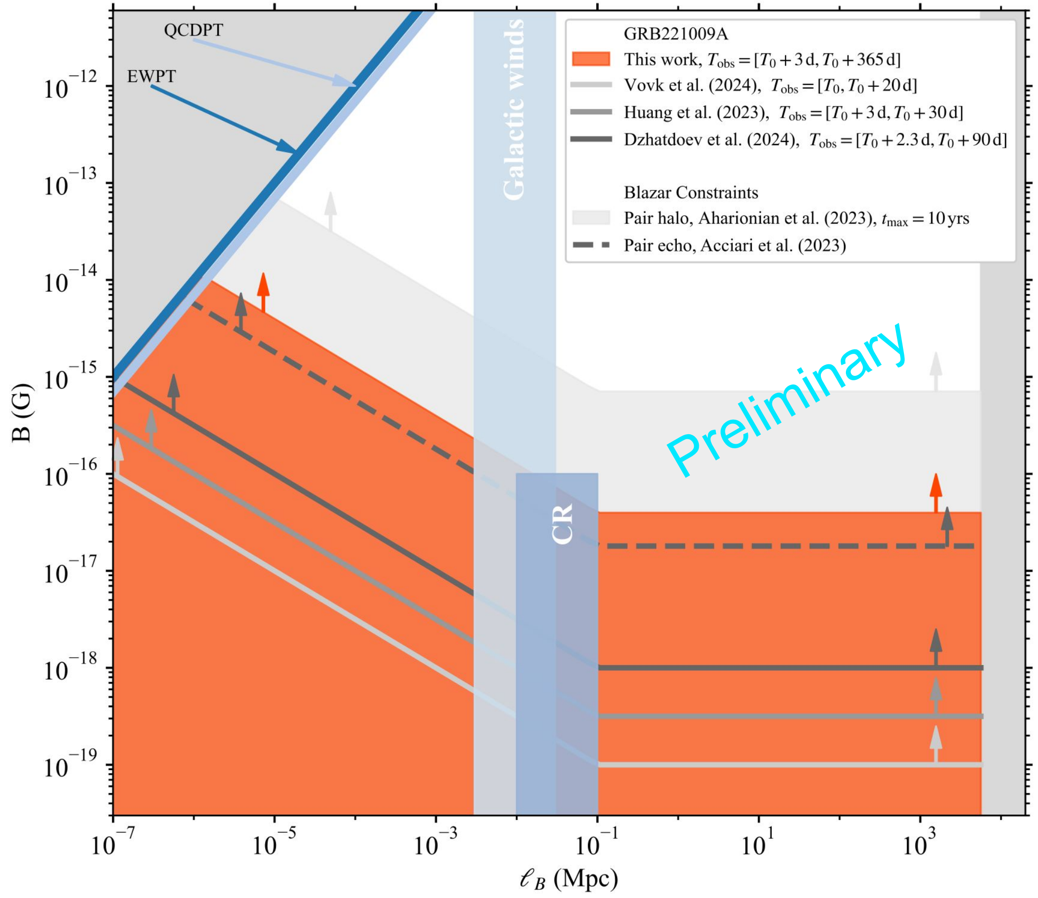
- For each time bin *i*:
  - Add cascade prediction for fixed B_{rms}
  - Compute log likelihood summed over energy bins *j*:

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

  - 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

Summary

- ★ 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
- ★ We also used predictions from GRB afterglow model instead of powerlaw with Γ=2



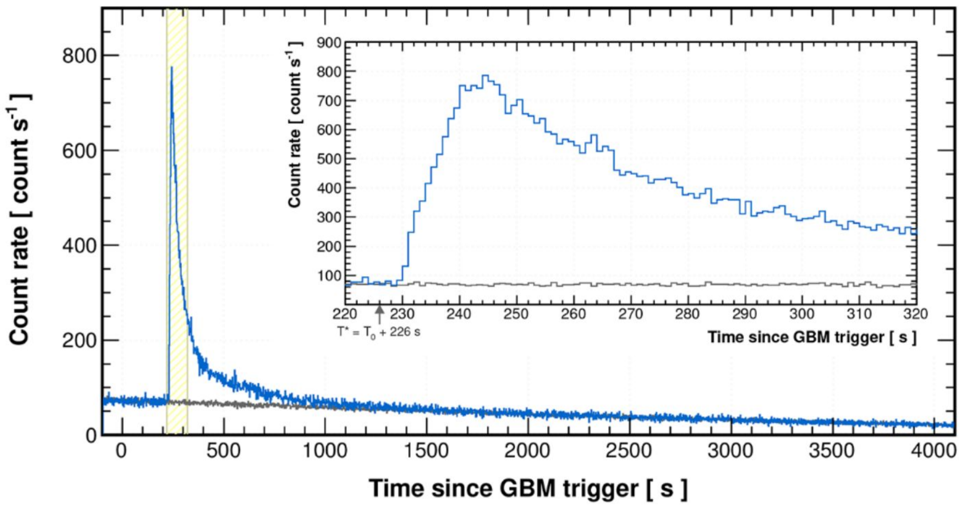
IGMF from GRBs: pros and opens questions

- Pros:
  - The duration of a transient in the VHE band is measured → no assumptions about the lifecycle need to be done
  - The variability pattern and the evolution of the VHE spectra in time is measured
- Open questions:
  - For small time delays, most codes suffer from a lack of precision in the calculation of time delay
  - In addition, at low time delays, other factors can contribute significantly -> intrinsic aperture of the pairs
  - Plasma instabilities: they should not play an important role but dedicated studies are needed
  - What are the most suitable GRBs for this kind of studies? (See Davide's talk)
  - Application to blazars?

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



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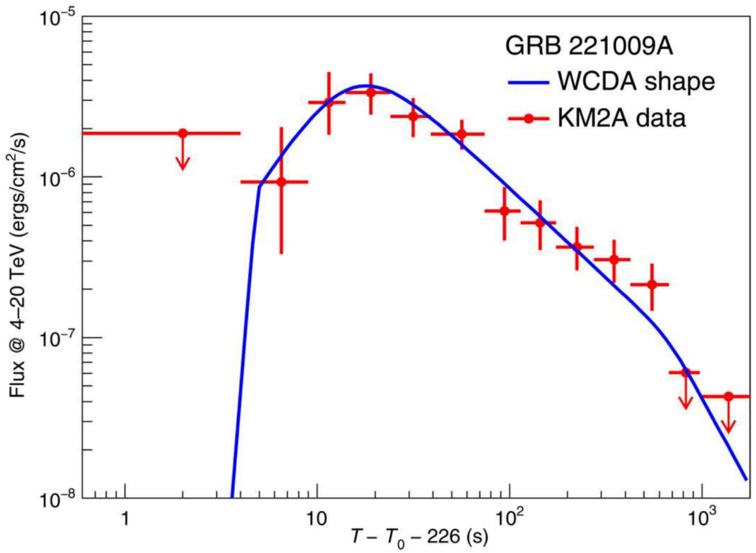
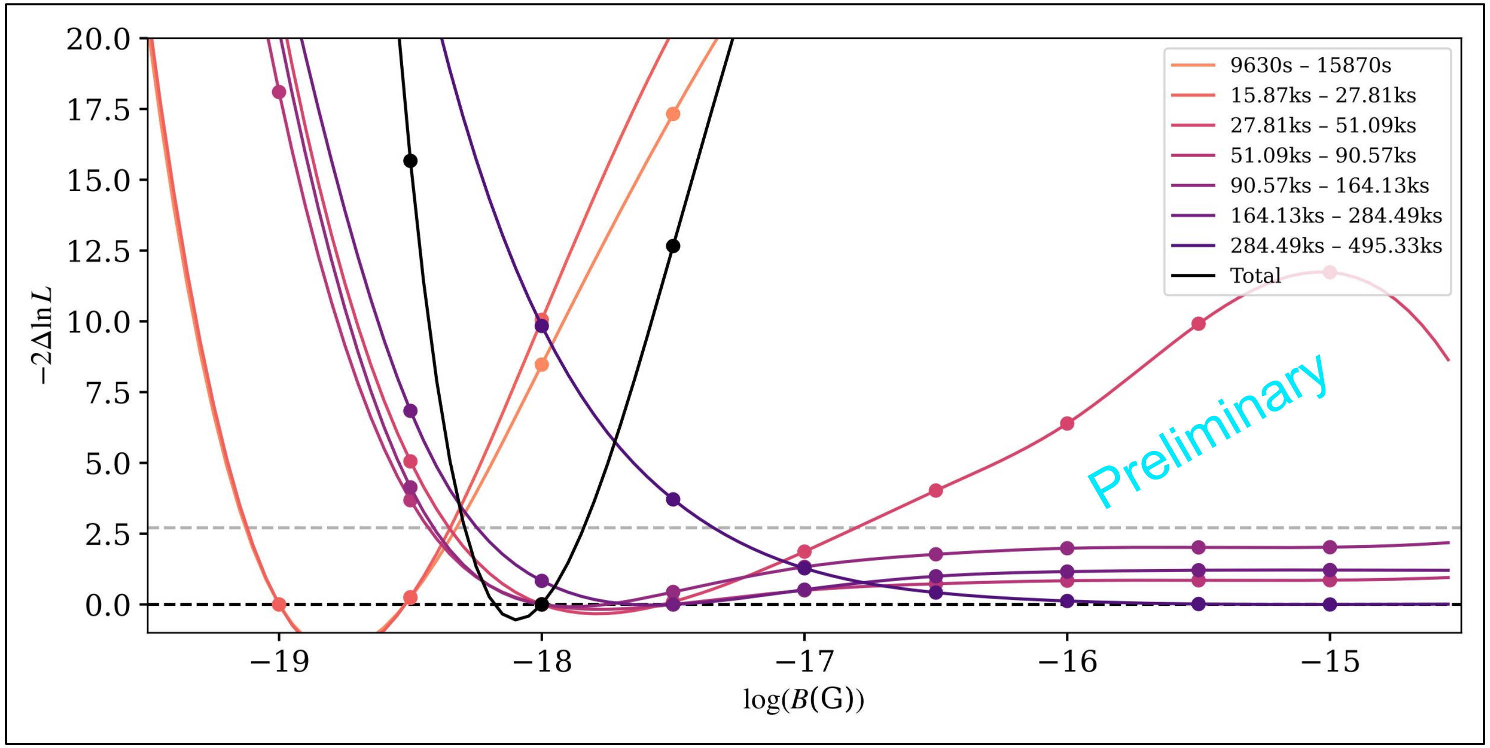


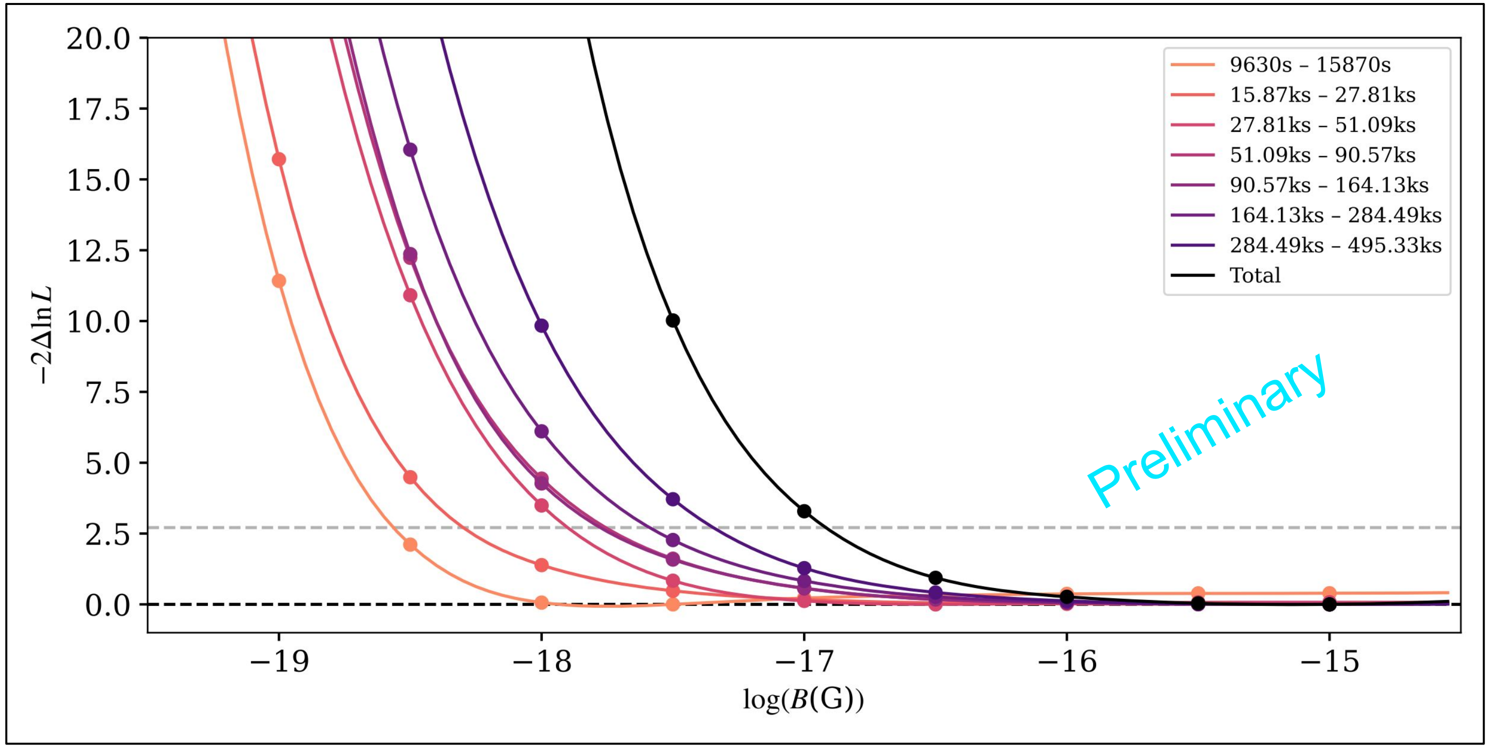
Likelihood profiles: no astrophysical afterglow emission added

- "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 $T \in [T_0+3 \text{ days}, T_0+365 \text{ days}]$: $B_{rms} \gtrsim 4 \times 10^{-17}$ 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