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Prospect for detection of pair-echo emission from TeV gamma-ray bursts

Davide Miceli, Paolo Da Vela, Giancarlo Ghirlanda, Lara Nava, Elisa Prandini

17/04/2024

CTAO Science Symposium 2024, Bologna

Magnetic fields in the Universe

Magnetic field seeds origin

Cosmological

Astrophysical

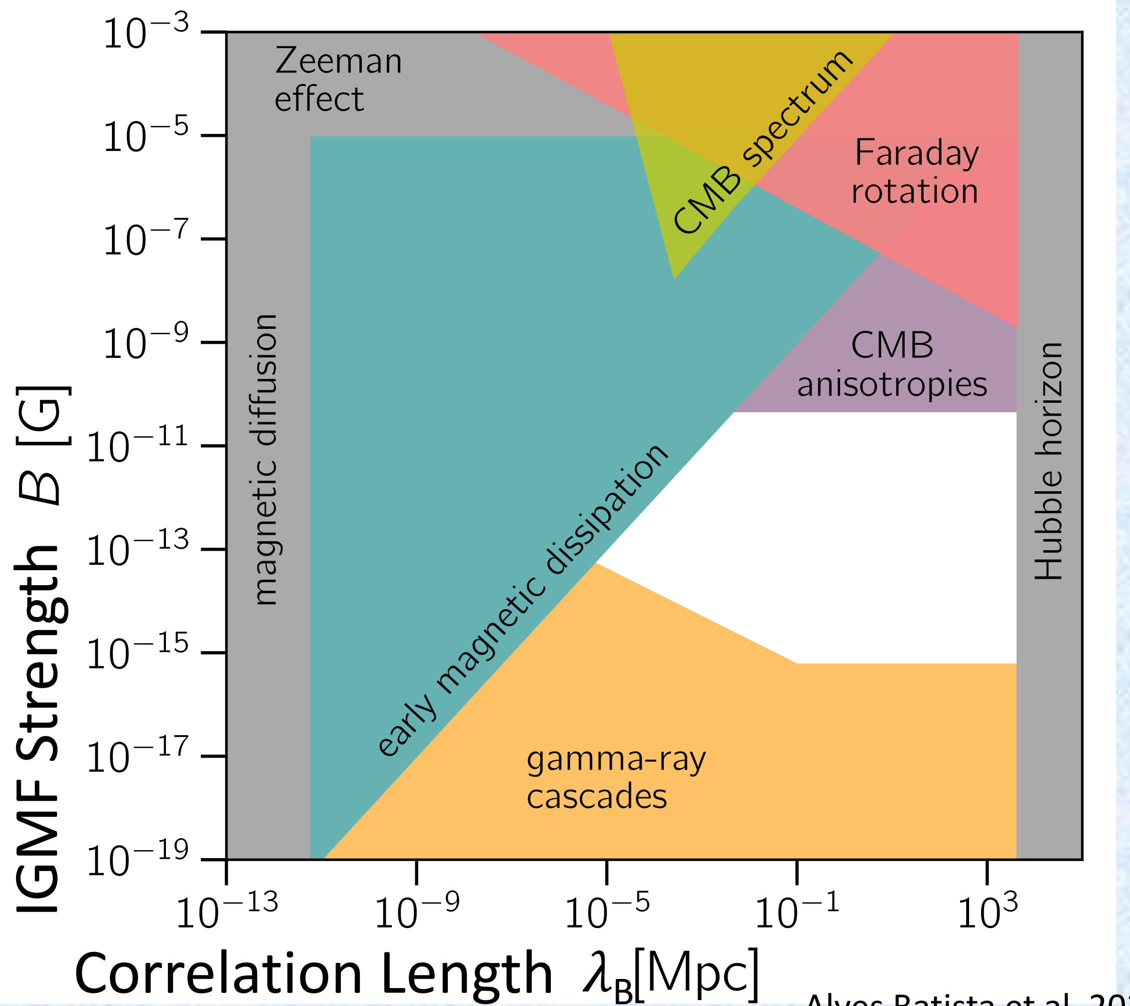
Amplification process

Dynamo amplification

Current B-fields detected

Modern μG magnetic fields in galaxy and galaxy clusters

Intergalactic Magnetic field (IGMF) studies



Alves Batista et al. 2022

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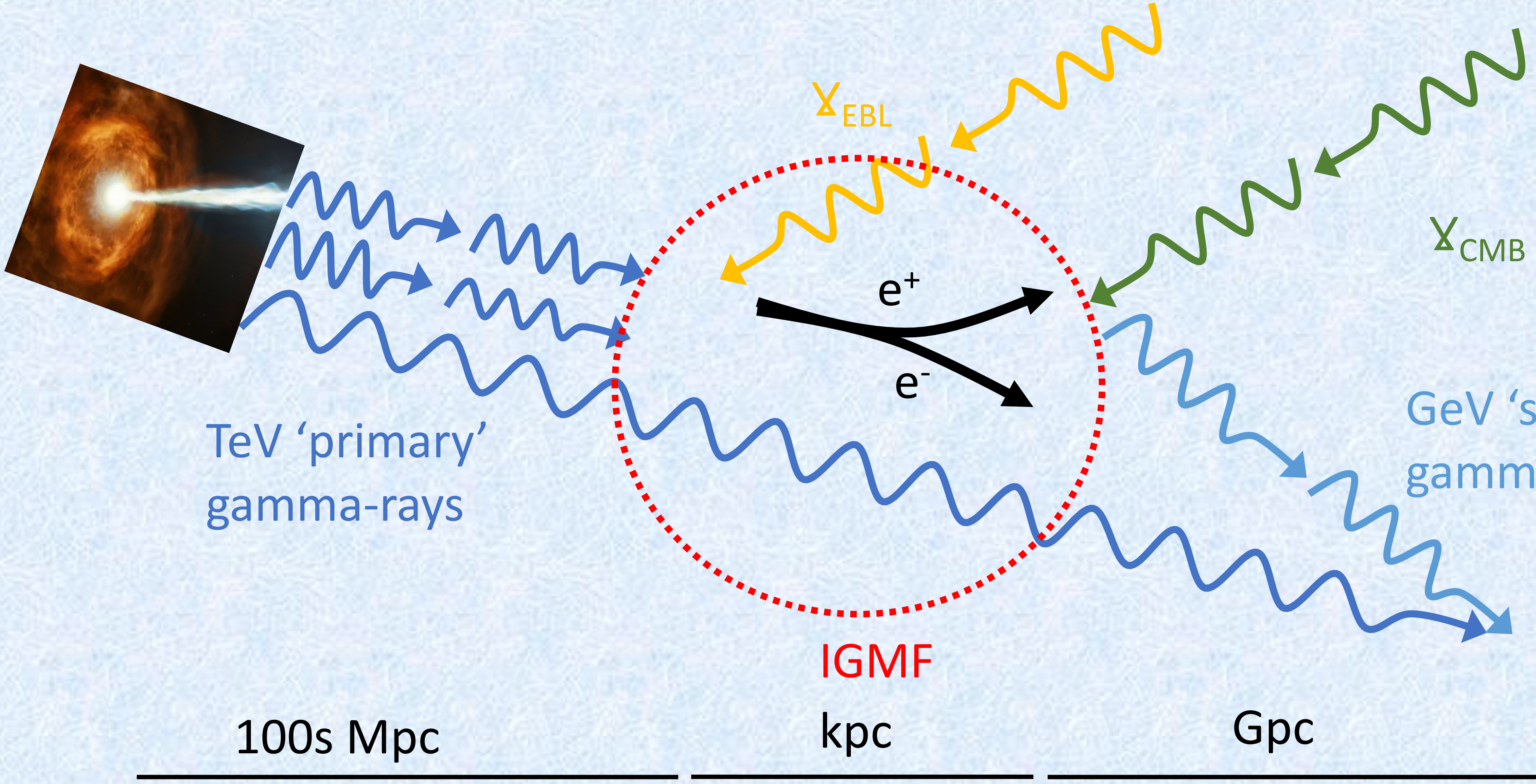
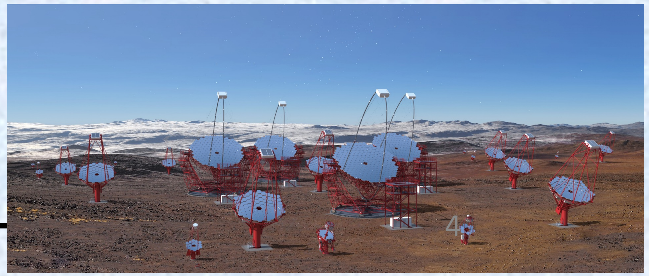
The IGMF studies in the gamma-ray domain



An **extended** and **time-delayed** component due to IGMF deflection + CMB reprocessing



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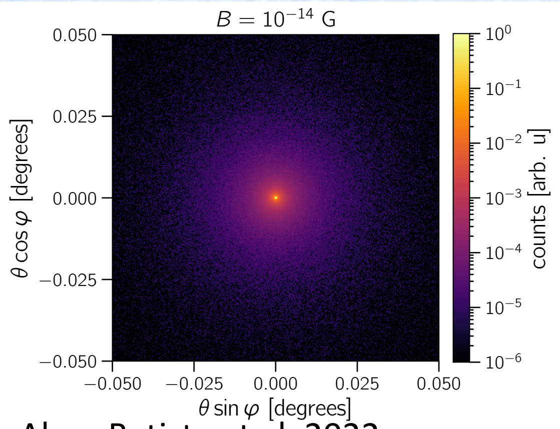
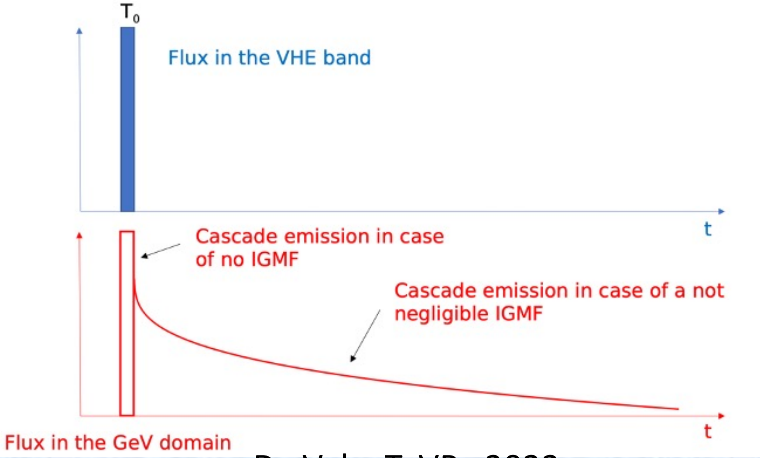
How can gamma-ray probe IGMF properties (B strength and correlation length λ_B)?

Extended emission



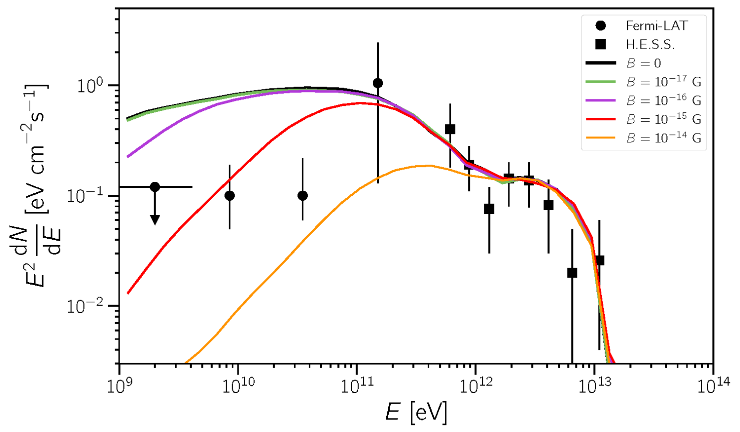
Alves Batista et al. 2022

Time-delayed ''pair-echo'' emission



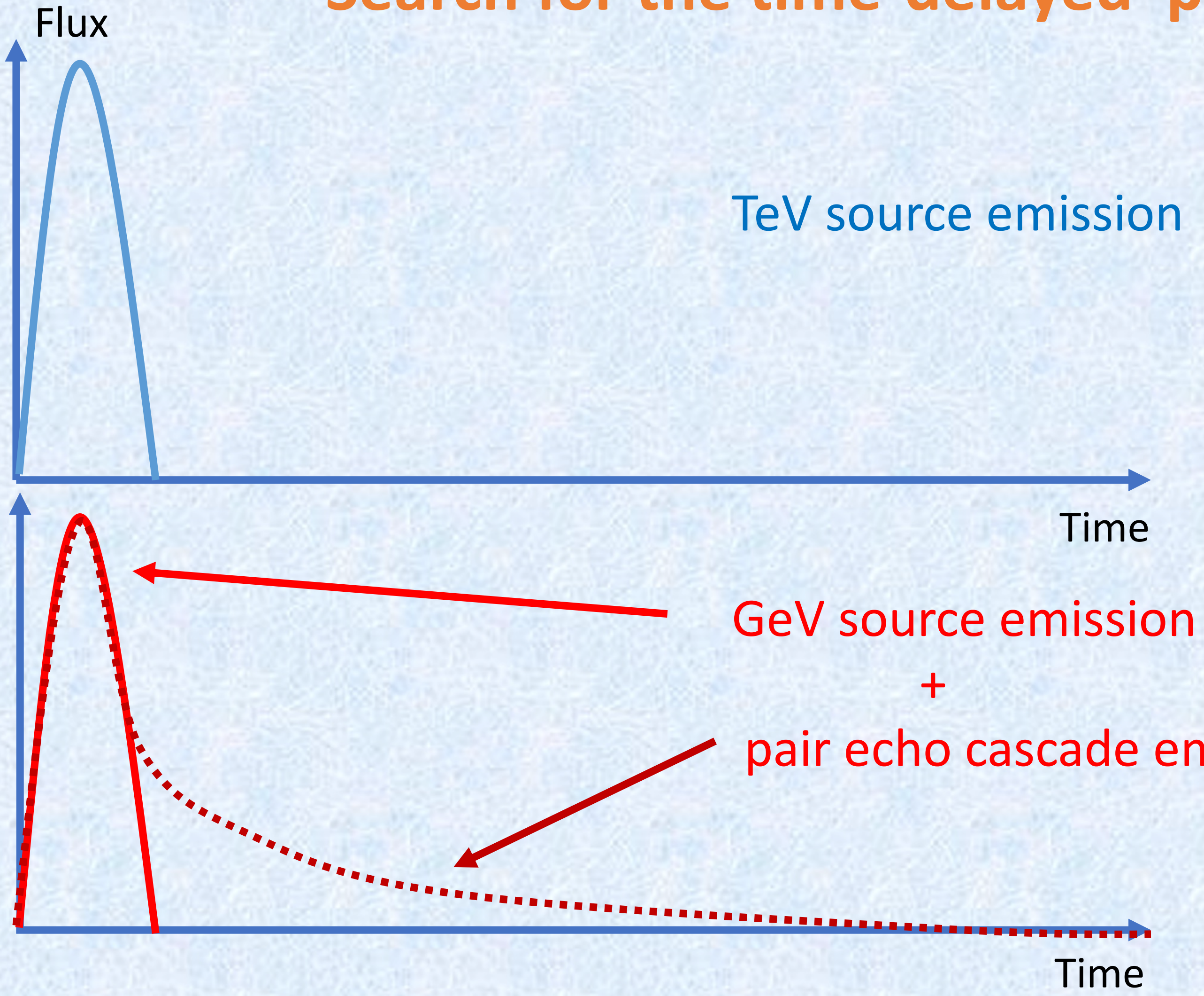
Da Vela, TeVPa 2022

SED signatures



Alves Batista & Saveliev, 2021

Search for the time-delayed 'pair-echo' cascade emission



Interesting for **AGN flares** or **transient** sources

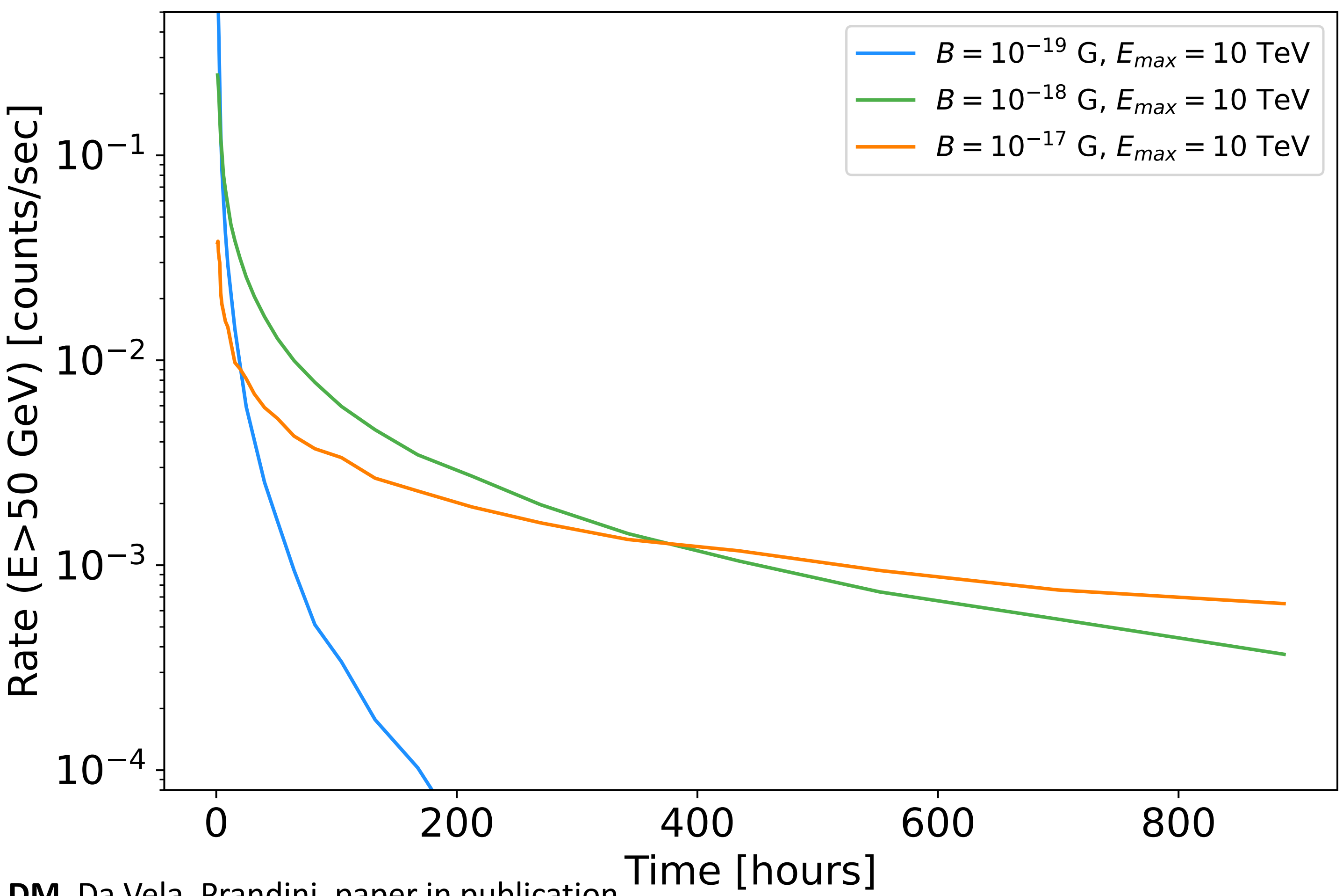
Search for the time-delayed 'pair-echo' cascade emission

$$E_{rep} \sim 0.32 \left(\frac{E\gamma}{20\,TeV}\right)^2 \text{TeV}$$

$$F_{delay} \sim F_0 \frac{T}{T_{delay}+T}$$

$T_{delay} \propto B^2 E_\gamma^{-5/2}$ $\lambda_B >> \lambda_{IC}$

$T_{delay} \propto B^2 E_\gamma^{-2} \lambda_B$ $\lambda_B << \lambda_{IC}$



DM, Da Vela, Prandini, paper in publication

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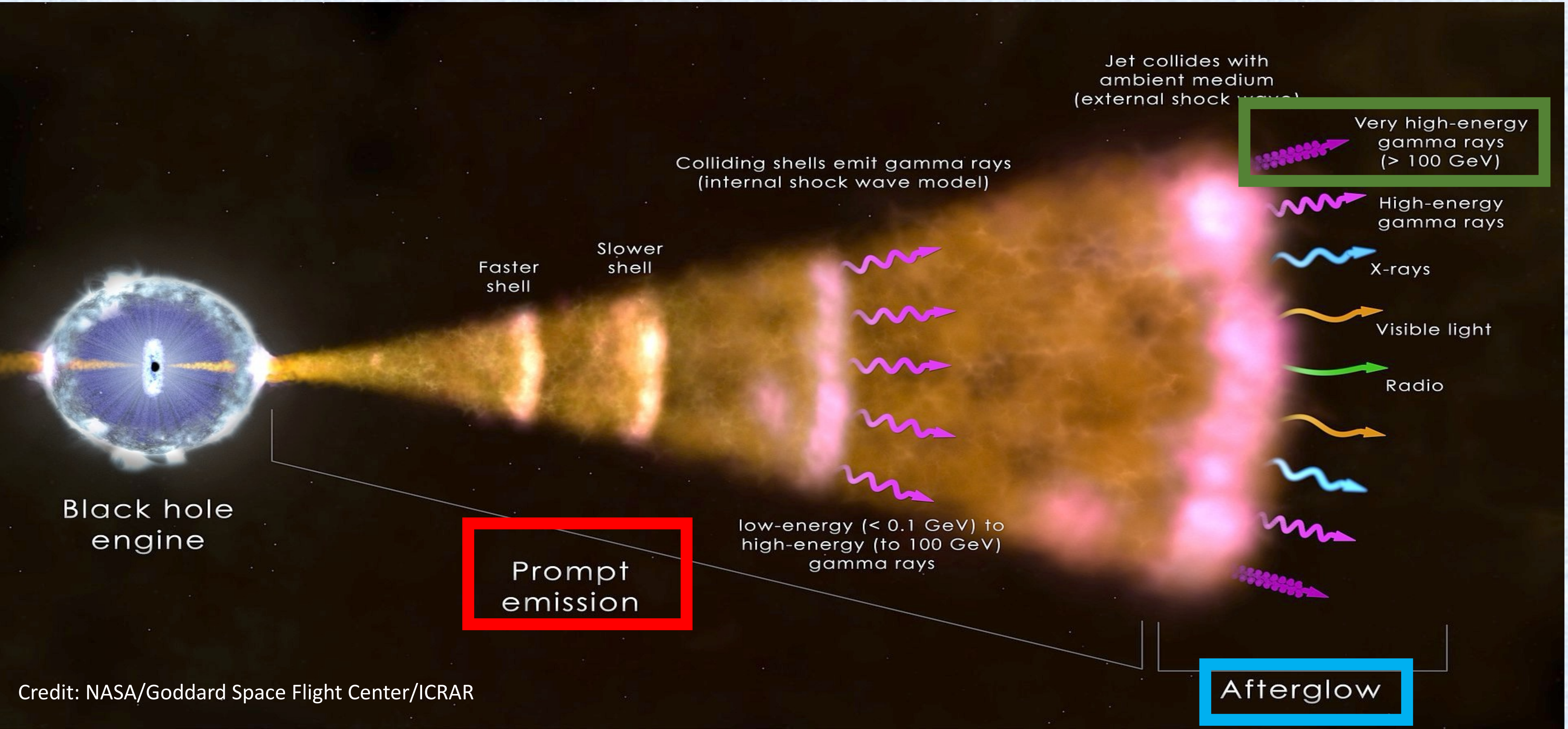
GRBs for IGMF studies: a hot new topic



Credit: NASA/Goddard Space Flight Center/ICRAR

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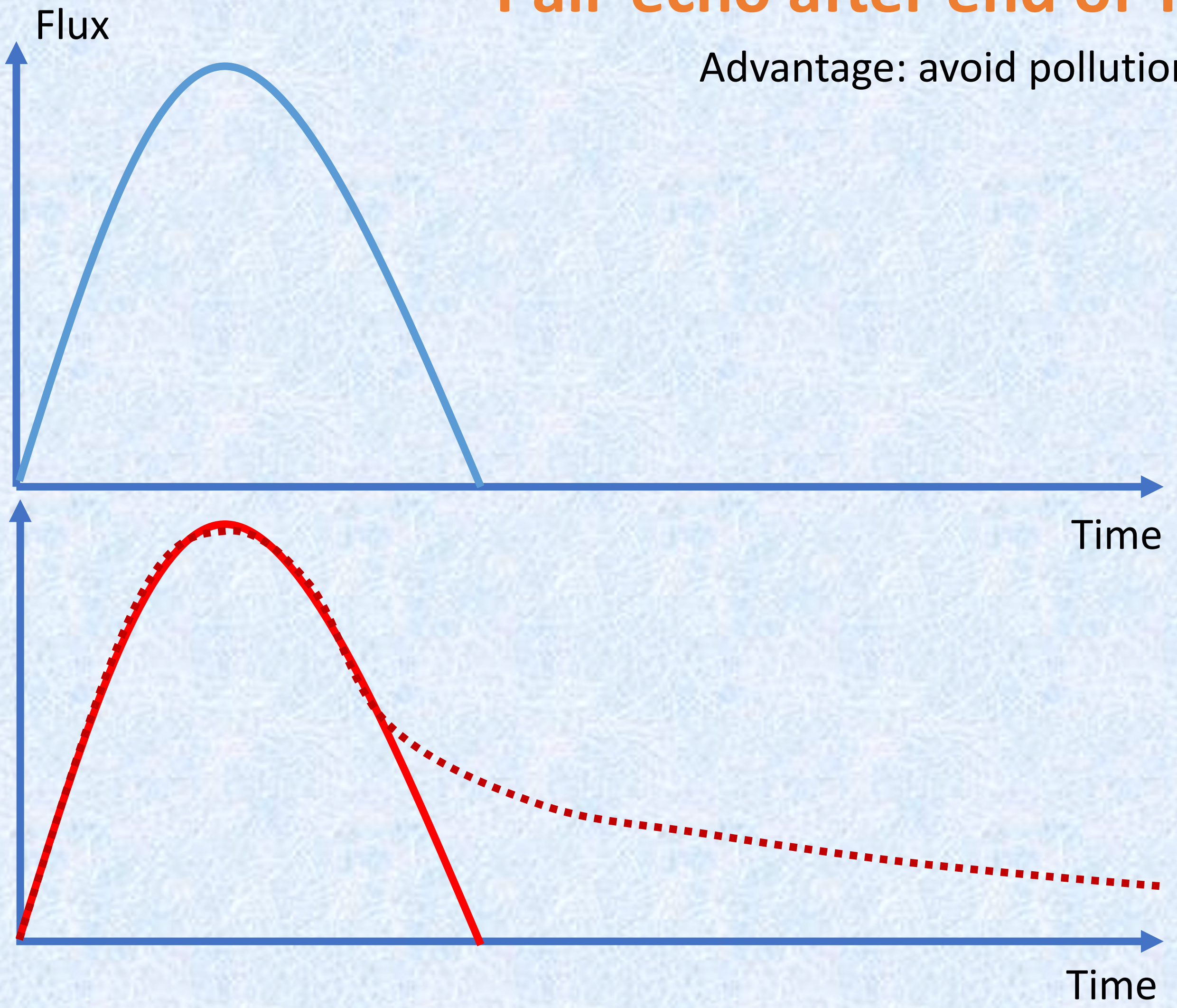
Pair-echo after end of TeV afterglow emission

Advantage: avoid pollution by source GeV emission



Source intrinsic properties

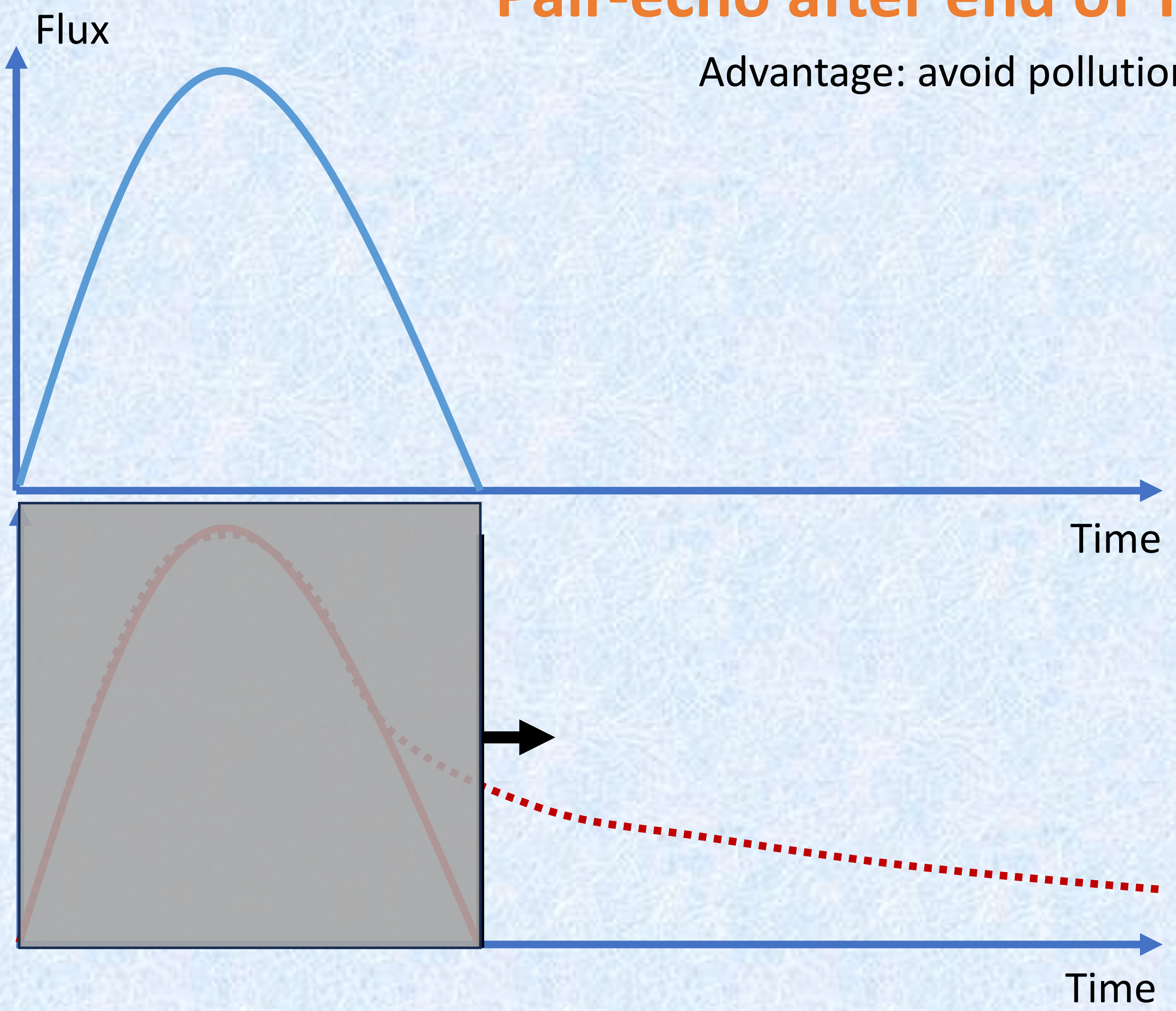
GeV source emission

+

pair echo emission with non-negligible IGMF

Pair-echo after end of TeV afterglow emission

Advantage: avoid pollution by source GeV emission



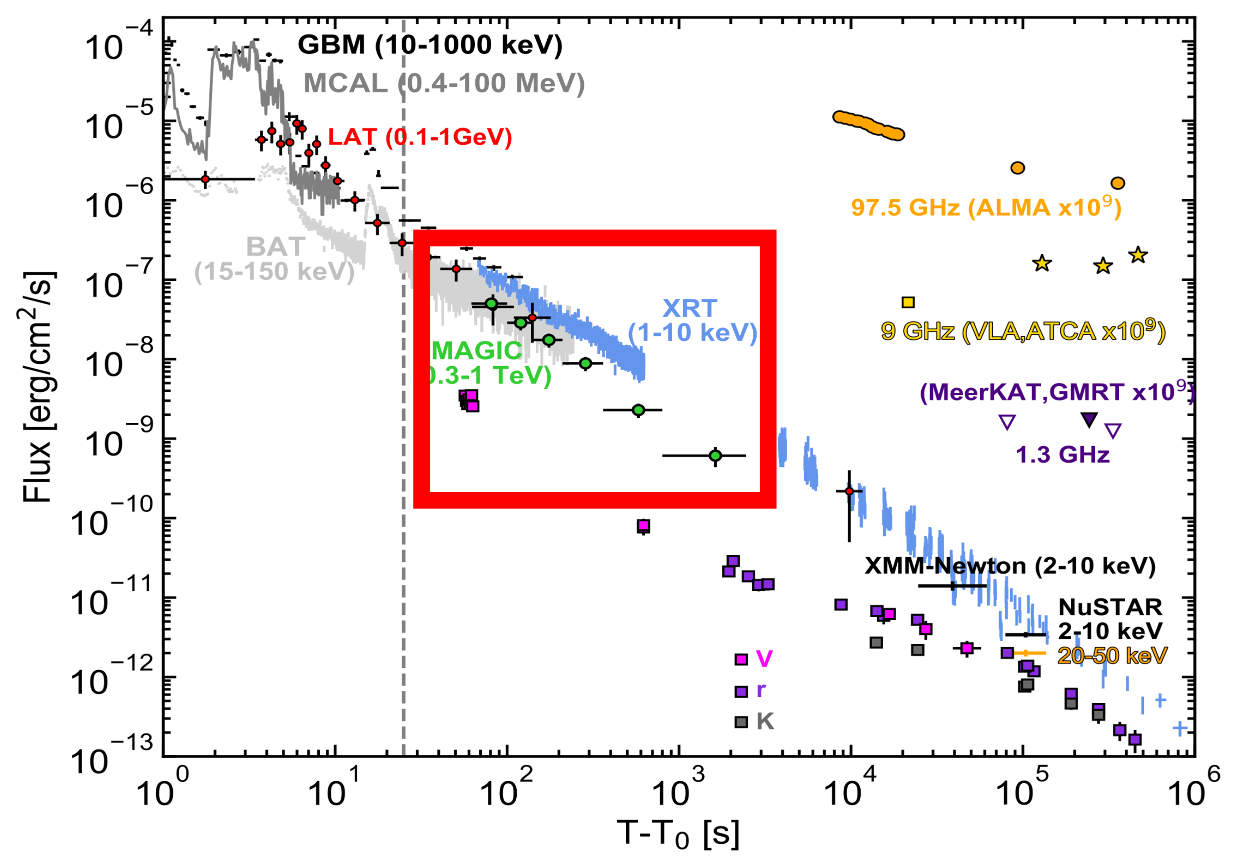
Source intrinsic properties

~~GeV source emission~~

+

pair echo emission with non-negligible IGMF

Pair-echo after end of TeV afterglow emission



MAGIC Coll. et al., 2019

Purpose: calculate the pair-echo emission with ***CRPropa*** when GRB TeV afterglow is not detected anymore

- For the case of GRB190114C (z=0.42)
- For a generic GRB190114C-like source at different distance (z=1.0 and z=0.2)
- For GRB221009A (z = 0.15)
- For a generic GRB221009A-like source at larger distance (z = 1.0)

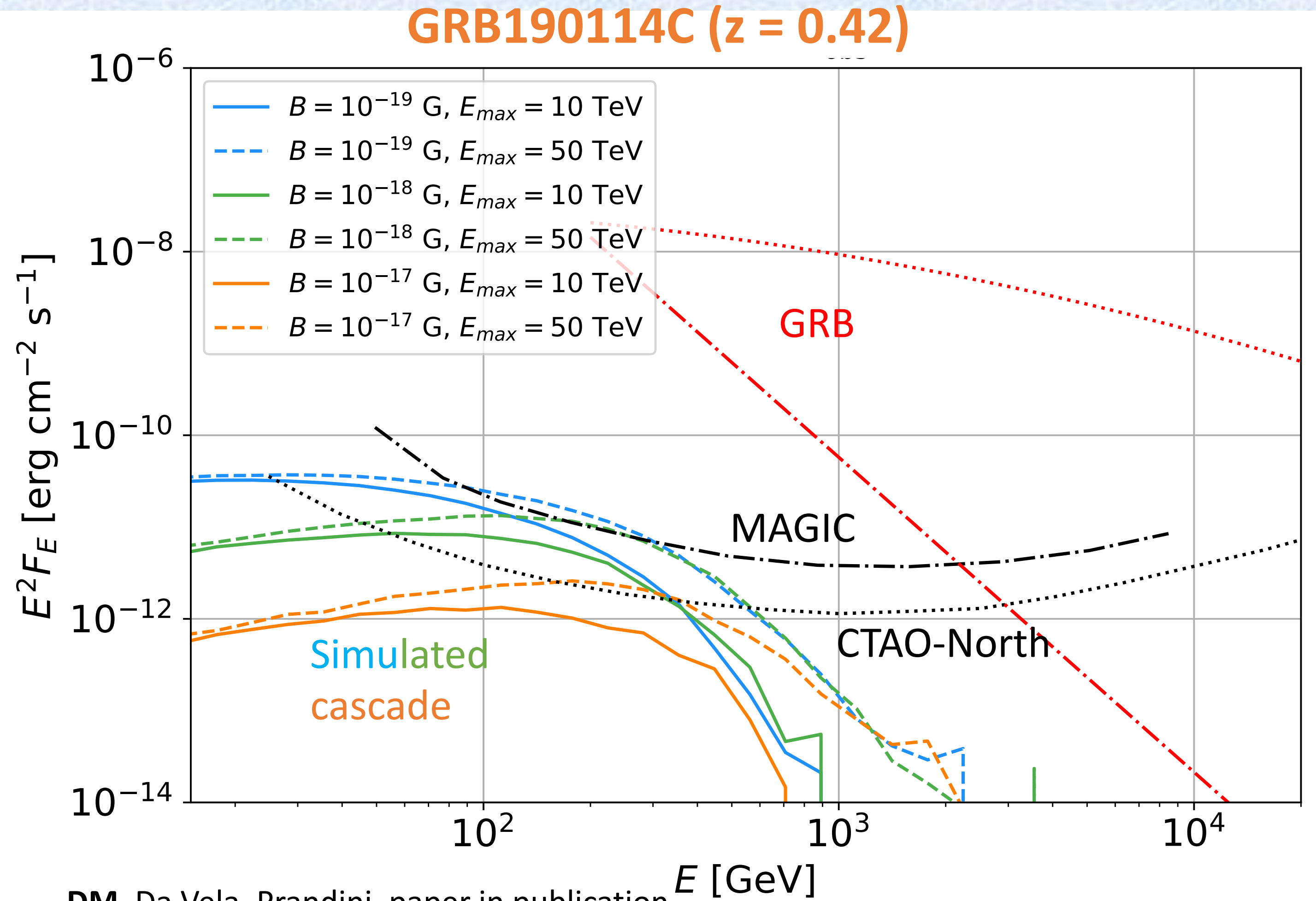
Pair-echo after end of TeV afterglow emission

We estimated the pair-echo SEDs for:

- 3 IGMF strength values (10^{-19} G, 10^{-18} G, 10^{-17} G)
- 2 maximum energies for source photons (10 TeV and 50 TeV)
- 3 observational times compatible with IACTs capabilities (3, 6 and 9 hrs)

Comparison of pair-echo SEDs with MAGIC and CTAO-North sensitivities

Pair-echo after end of TeV afterglow emission



DM, Da Vela, Prandini, paper in publication

Spectral energy distribution

- Primary GRB emission
- Secondary emission
- Observational time: **3 hours** starting from 2400 s after trigger burst
- MAGIC and CTAO sensitivity derived and rescaled in time (S ∝ (1/√t))

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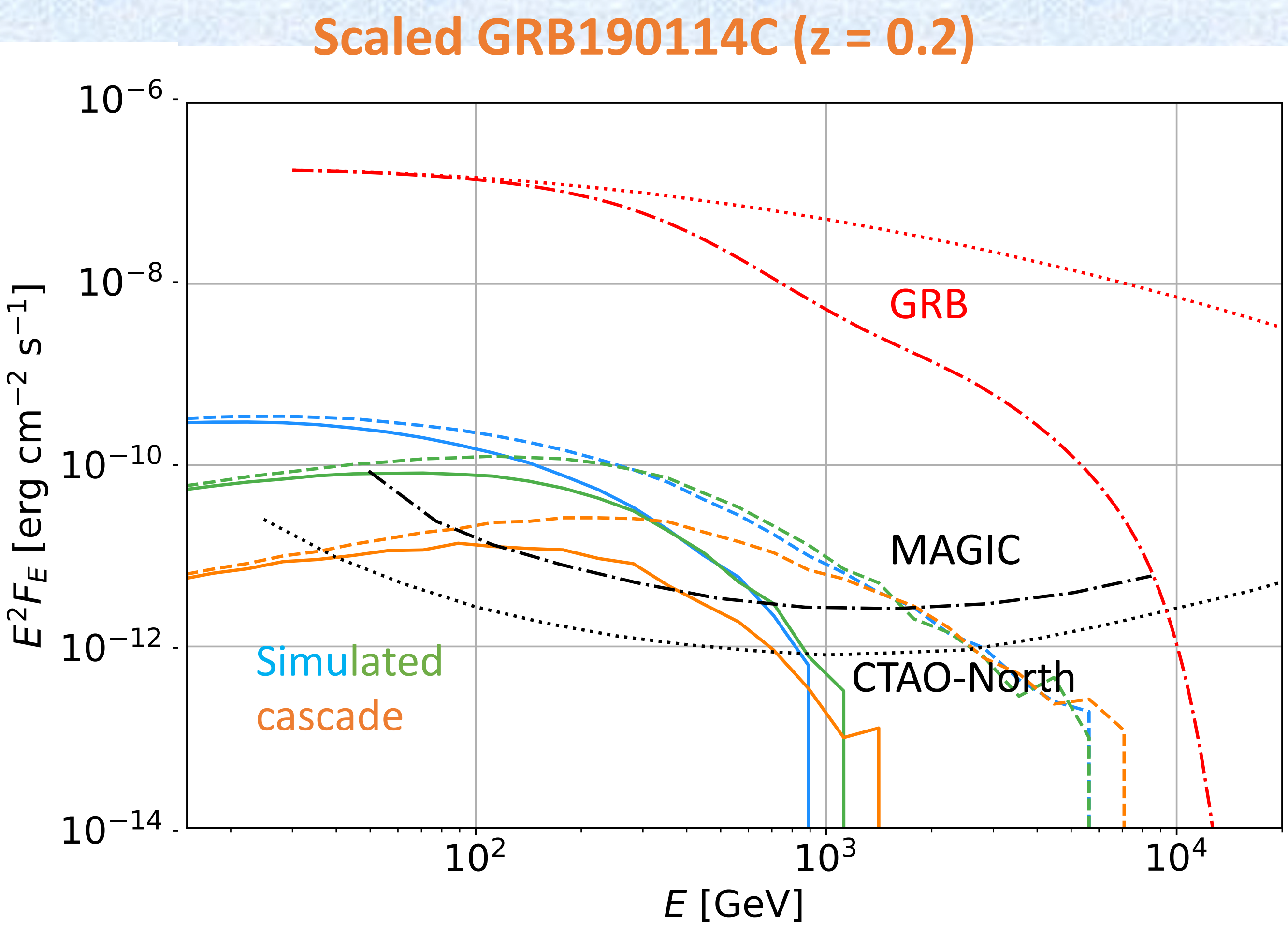
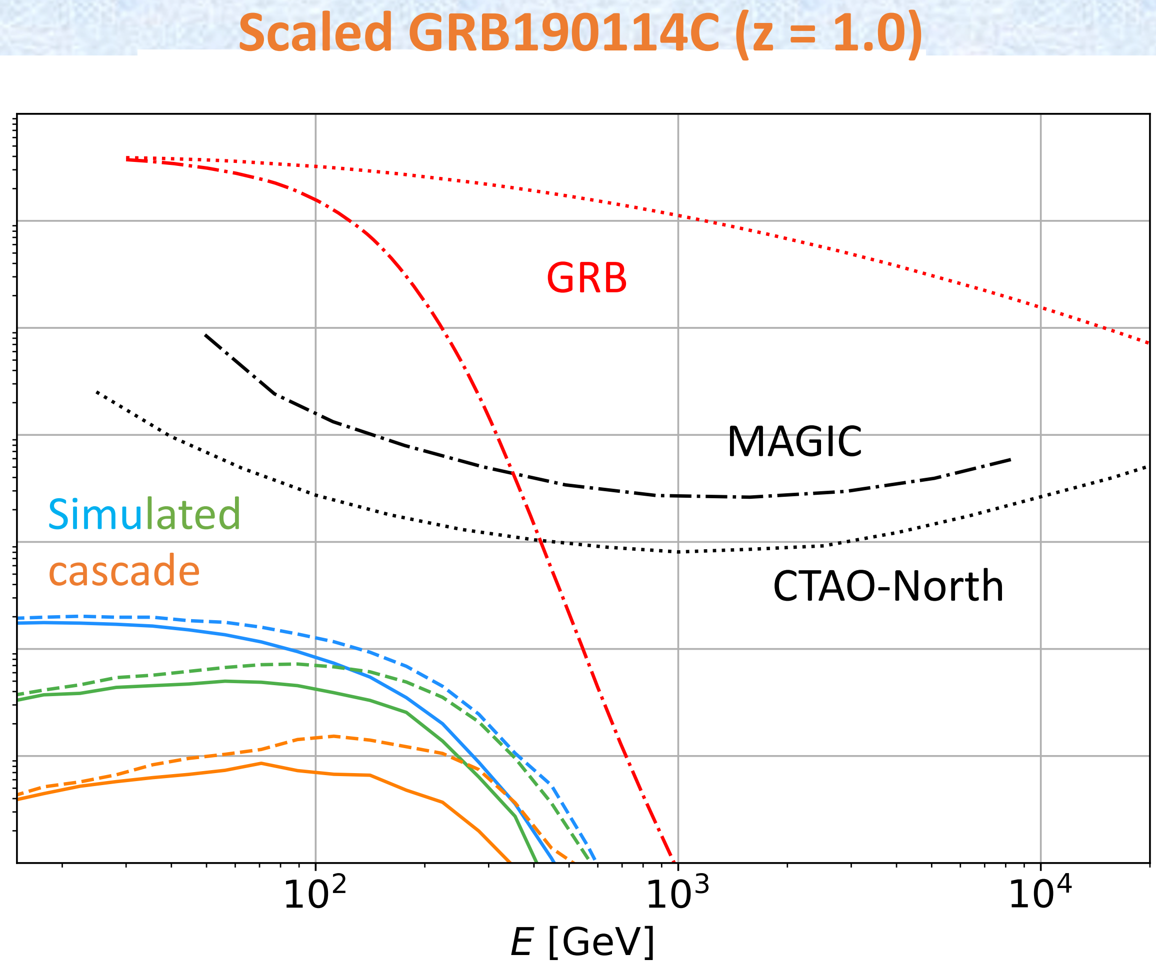
Pair-echo after end of TeV afterglow emission

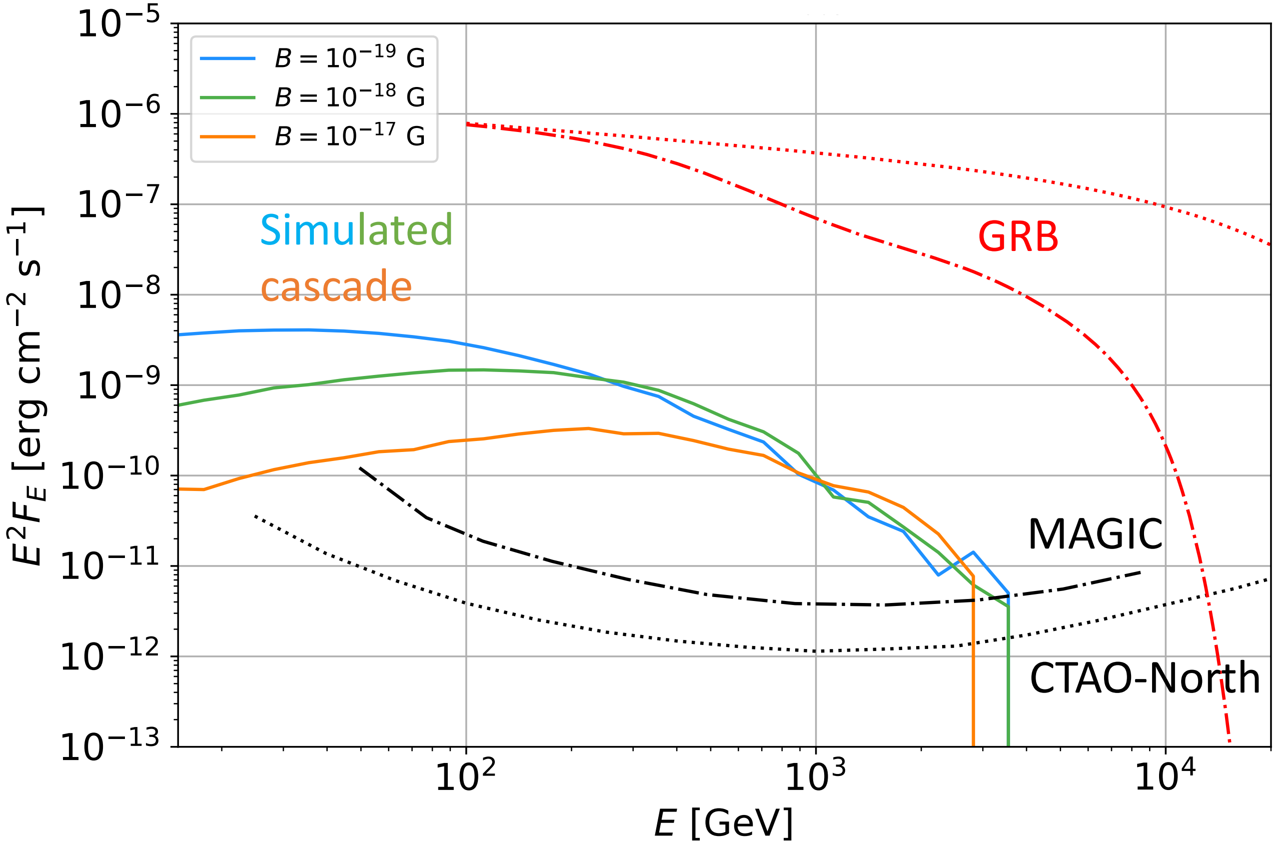




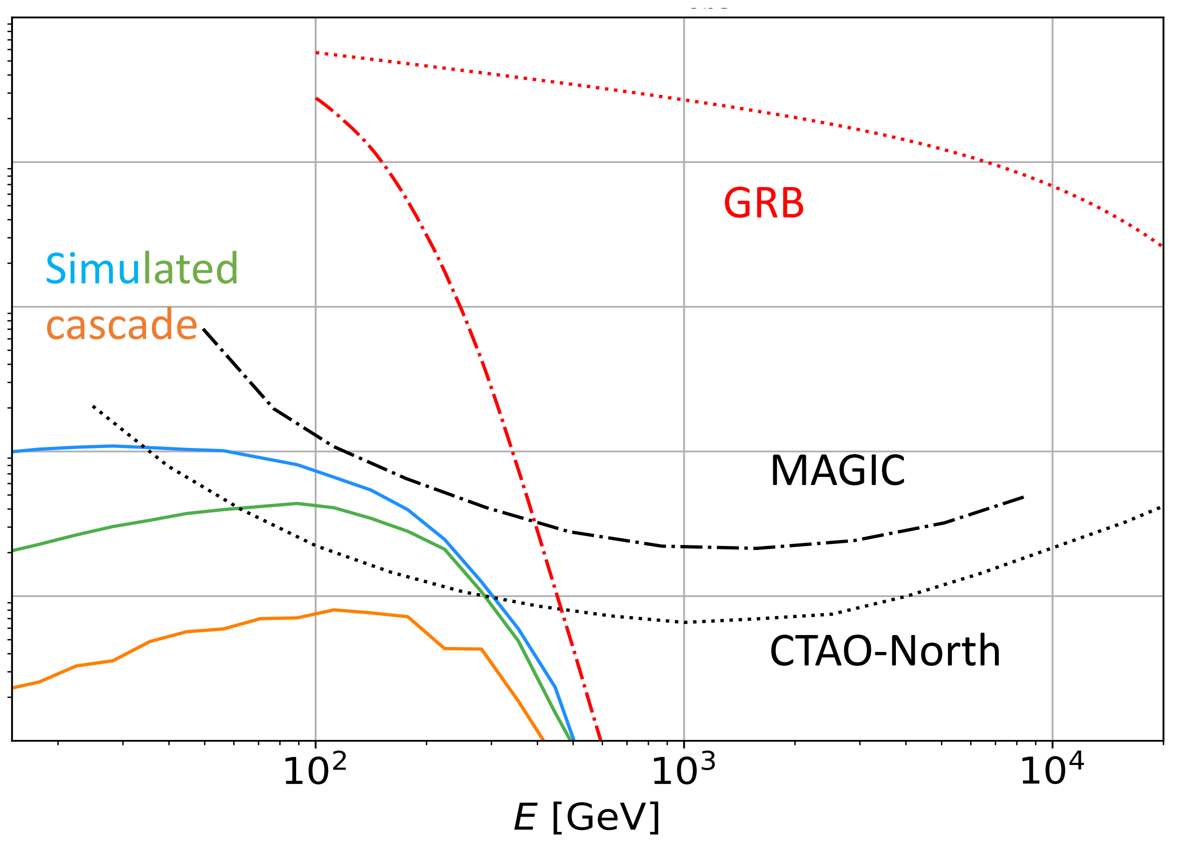
DM, Da Vela, Prandini, paper in publication

Pair-echo after end of TeV afterglow emission

GRB221009A (z = 0.151)



Scaled GRB221009A (z = 1.0)



DM, Da Vela, Prandini, paper in publication

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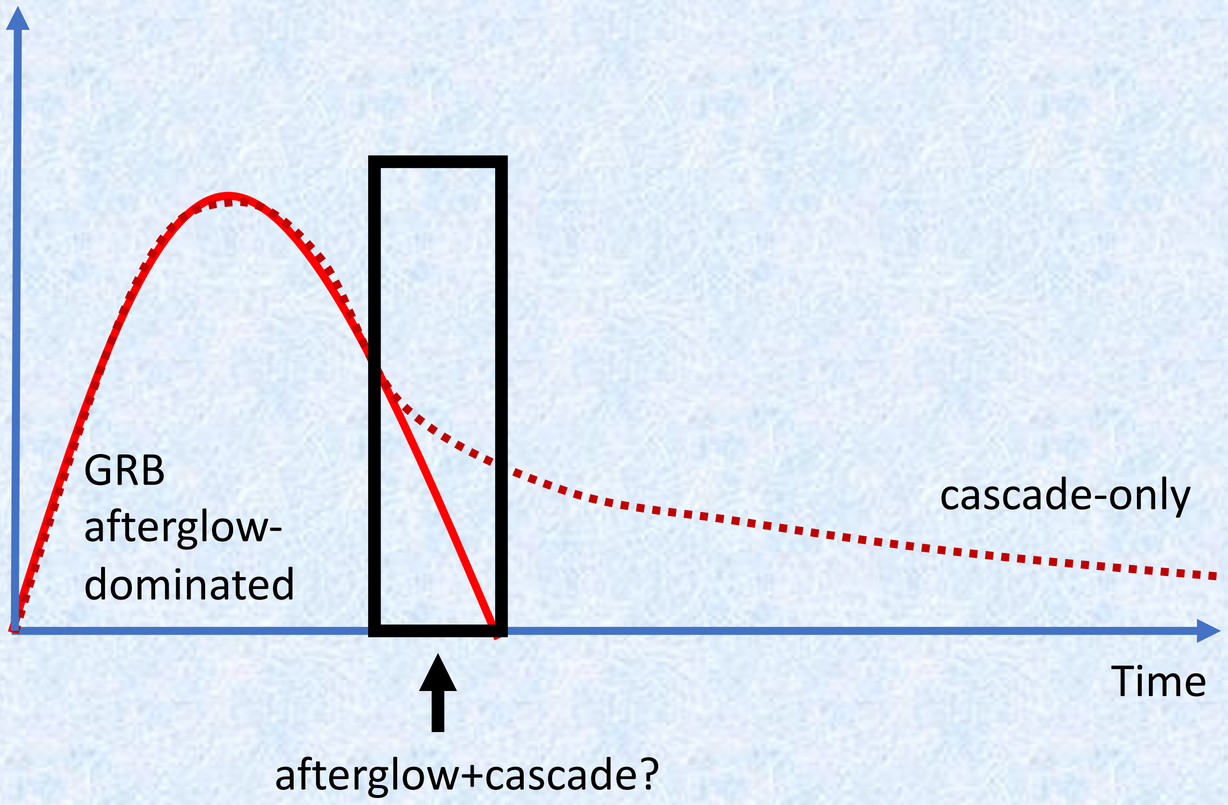
Pair-echo emission + GRB afterglow convolution



- A significant cascade contribution can be present also during fading phase of GRB afterglow emission
- Afterglow emission can vary of several order of magnitudes
- Model to estimate simultaneous afterglow+cascade contribution

Pair-echo emission + GRB afterglow convolution

$$F_c(E,t) = \int_0^\infty \int_E^\infty G(E_0, E, t-\tau, \tau) F_s(E_0, t-\tau) dE_0 d\tau$$

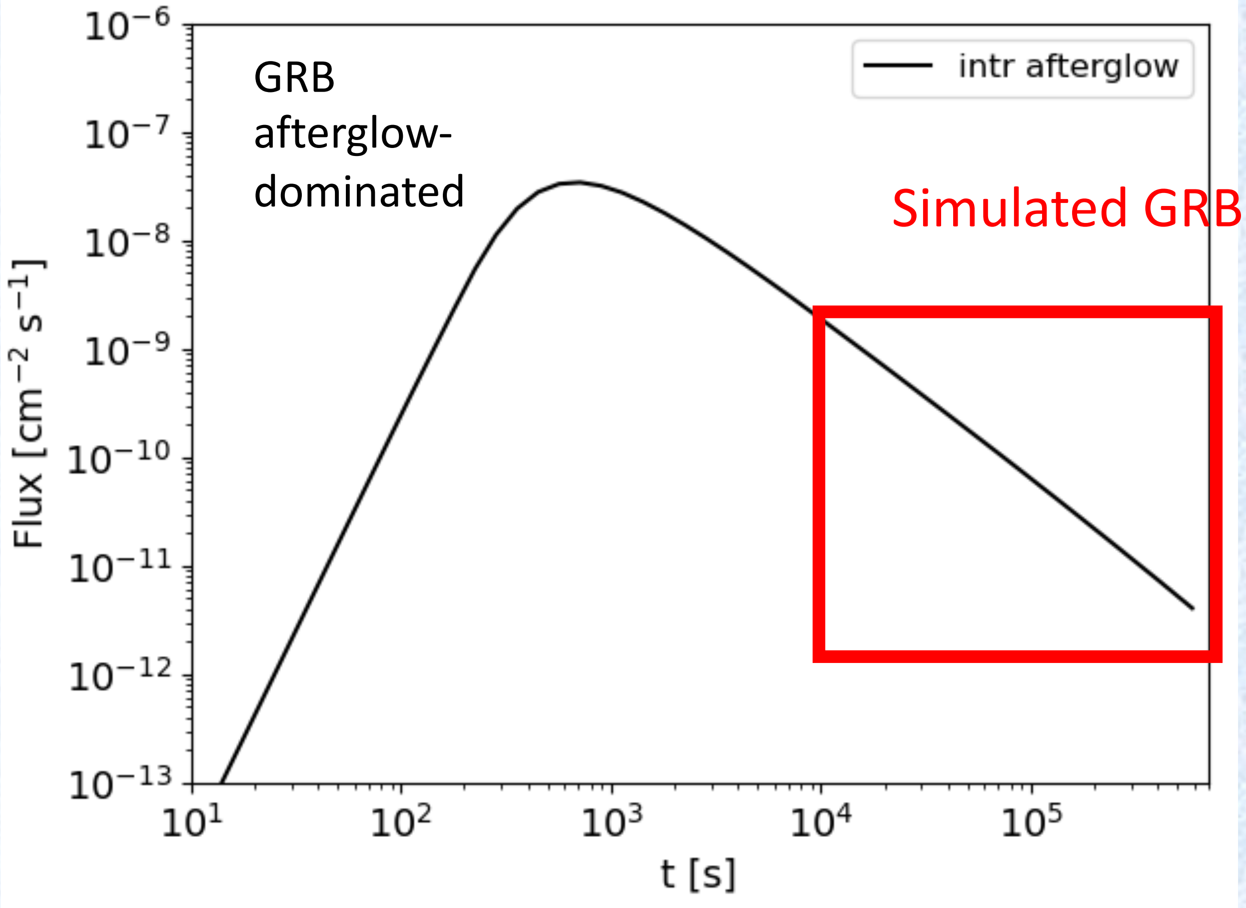
Cascade Flux

Kernel describing the distribution in energy and time of the cascade signal

"Variability pattern" (Source intrinsic properties and time evolution)

Pair-echo emission + GRB afterglow convolution

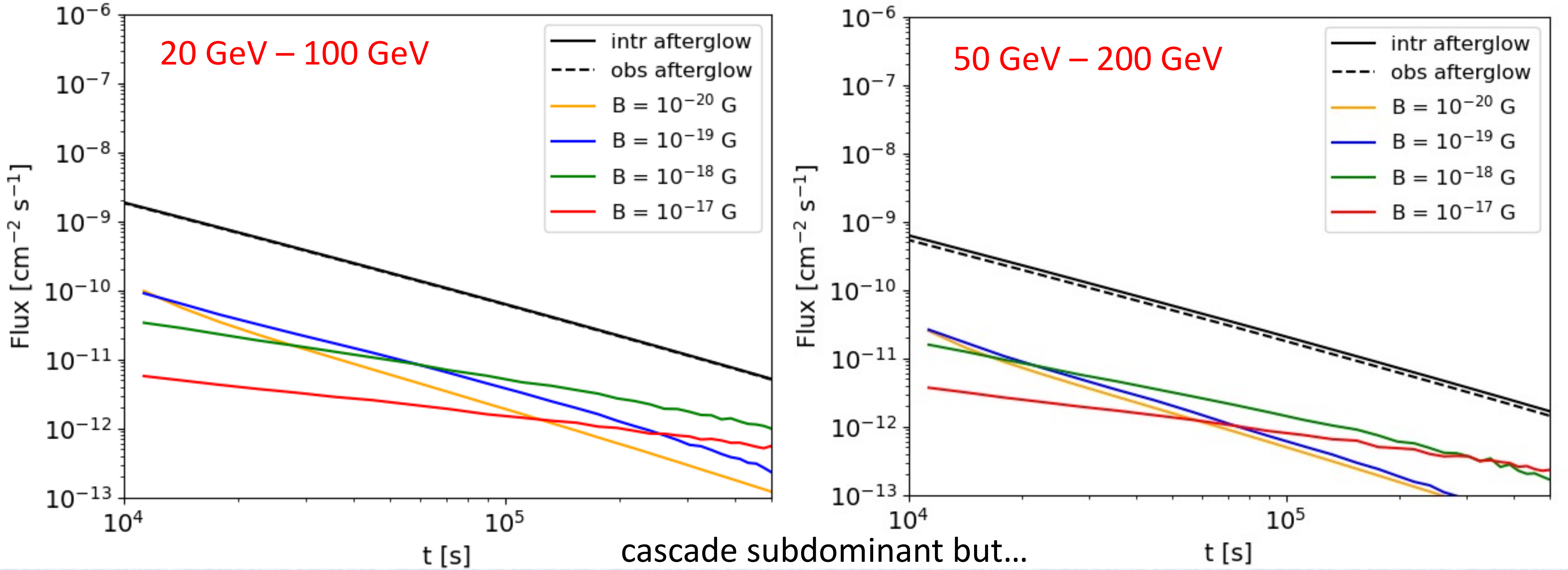
Extrapolate GRB properties (spectrum and time evolution)



Simulated GRB LCs (z= 0.47)

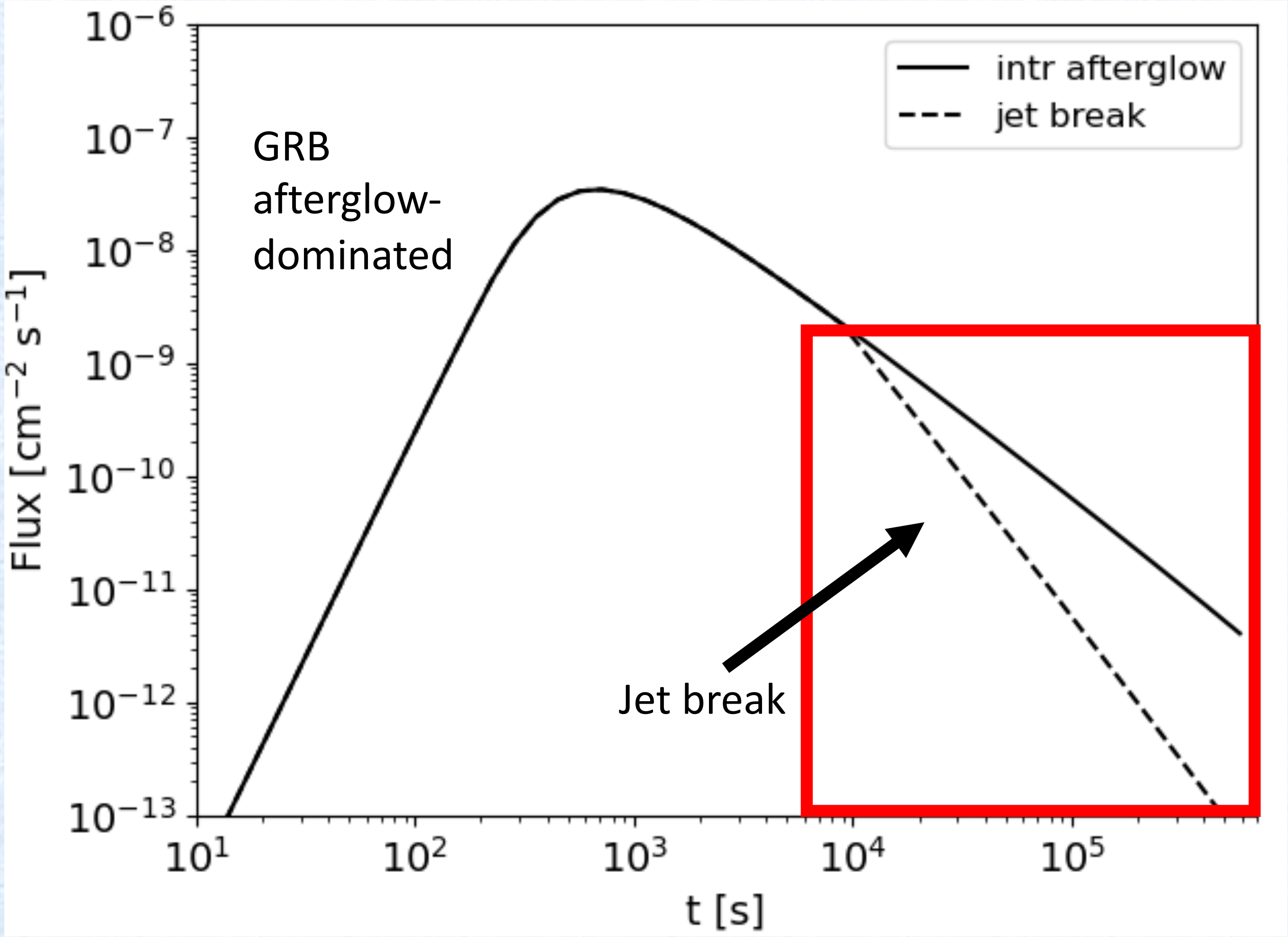
Pair-echo emission + GRB afterglow convolution

- We estimated the pair-echo LCs from a simulated GRB produced for the CTAO GRB Consortium Paper



cascade subdominant but…

Pair-echo emission + GRB afterglow convolution



- Assuming a smaller redshift (z=0.15) with same GRB properties
- Add a “jet break” at 10^4 s (light curve steeping of a factor $\propto t^{-1}$)

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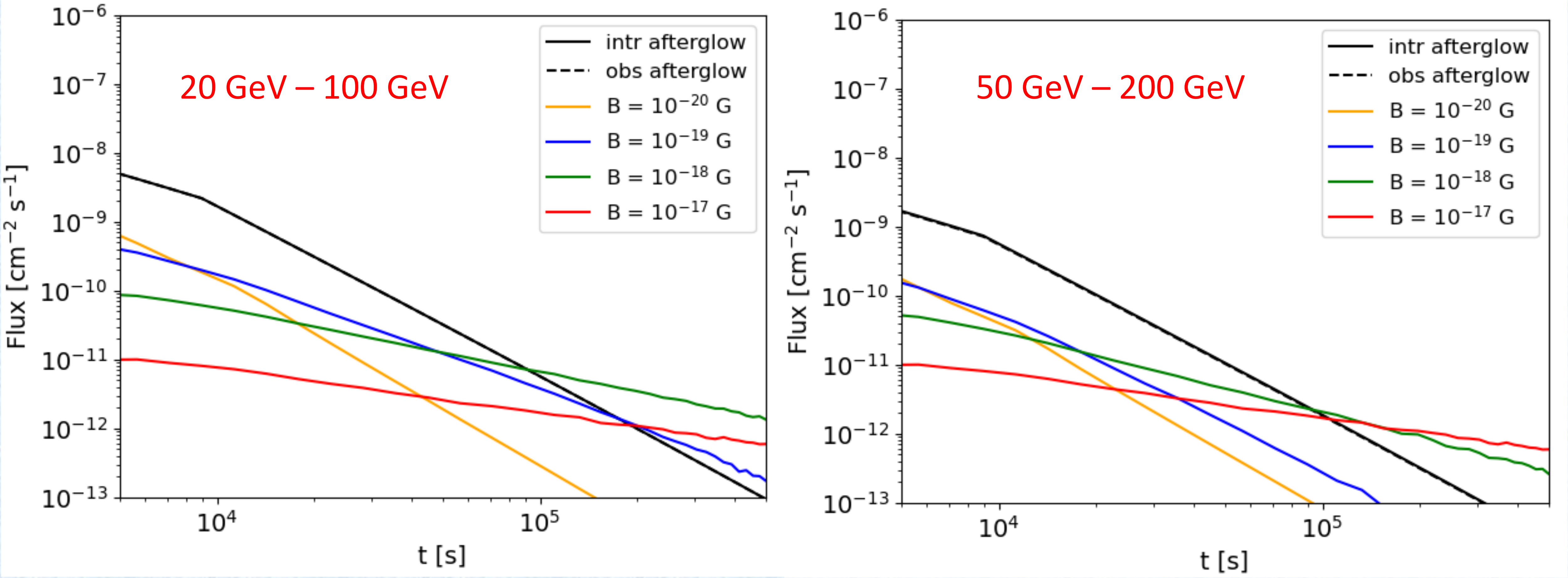
Pair-echo emission + GRB afterglow convolution



- Pair-echo emission becomes competitive with GRB afterglow at late times for B > 10^{-19} G

Conclusions and future perspectives

- Gamma-Ray Bursts are promising sources for IGMF studies

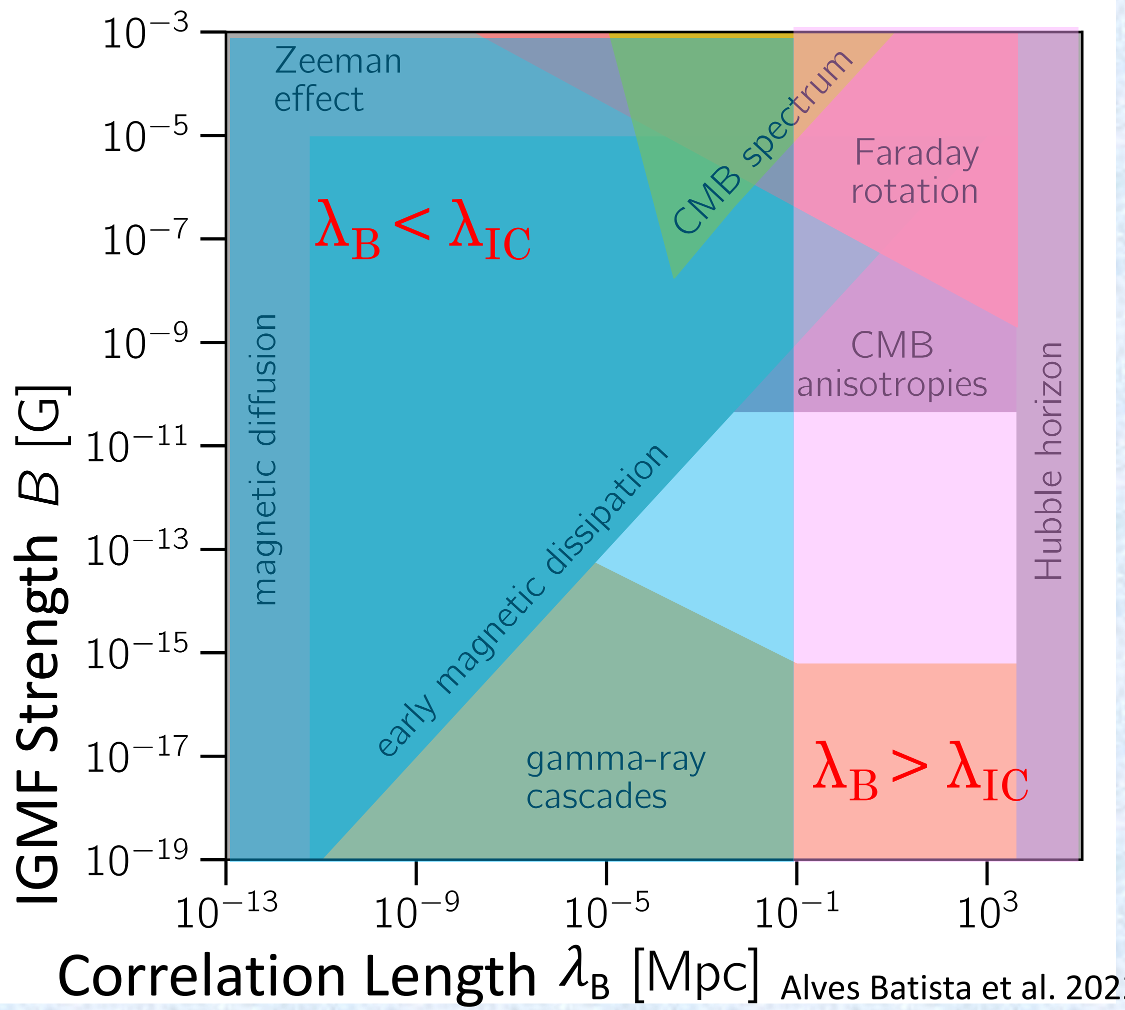
- Pair-echo after end of TeV afterglow emission:
  - Extend observations for at least 3 hours after GRB detection
  - GRBs observations can probe IGMF strengths in the $10^{-17} – 10^{-19}$ G → competitive with AGN studies!

- A new approach: pair-echo emission + GRB afterglow convolution:
  - Cascade seems to be competitive with afterglow at late-times (fading afterglow phase, jet break, ..)
  - Impact of intrinsic source features (distance, brightness, intrinsic spectrum shape and features, time evolution, jet break) to be investigated

- Future perspectives: investigate results with this approach on more GRBs and explore CTAO capabilities

BACKUP SLIDES

Intergalactic Magnetic field (IGMF) studies



Alves Batista et al. 2022

Results on IGMF are typically given considering two regimes:

- Long correlation length ($\lambda_B >> \lambda_{IC}$) (motion in homogeneous B, ballistic $e^{\pm}$)
- Short correlation length ($\lambda_B << \lambda_{IC}$) (diffusion in angle, diffusive $e^{\pm}$)

Search for the time-delayed 'pair-echo' emission

$$E_{rep} \sim 0.32 \left(\frac{E\gamma}{20\,TeV}\right)^2 \text{TeV}$$

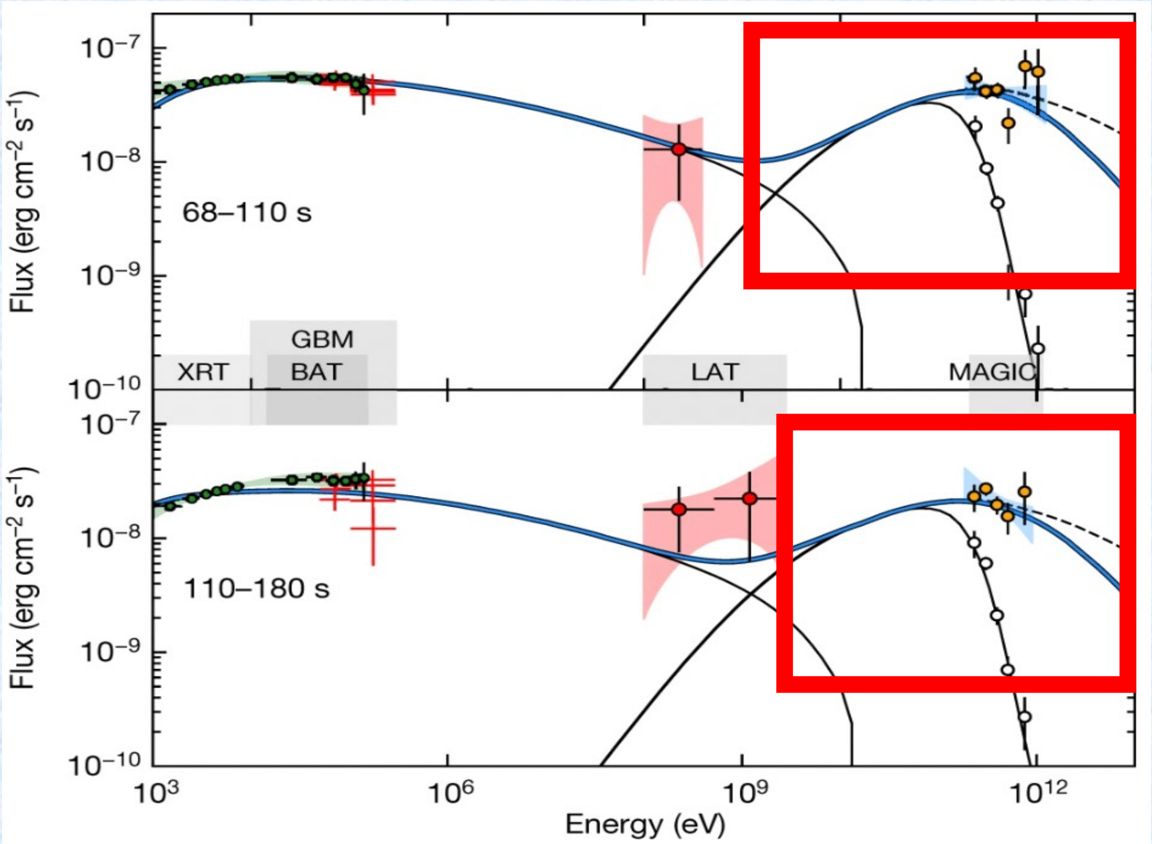
$$F_{delay} \sim F_0 \frac{T}{T_{delay}+T}$$

$$T_{delay} \propto B^2 E_\gamma^{-5/2} \qquad \lambda_B >> \lambda_{IC}$$

$$T_{delay} \propto B^2 E_\gamma^{-2} \lambda_B \qquad \lambda_B << \lambda_{IC}$$

- 100s GeV photons experience shorter delays than GeV photons
- Weak B field (10^{-17} – 10^{-21} G) are compatible short delays
- Stronger B are compatible with longer delays (and a more diluted cascade)

Pair-echo emission after GRB afterglow



MAGIC Coll. et al., 2019

Assumptions:

- Starting time for photon cascade counting: 3000 s
- Source time activity: MAGIC detection interval (40 min) for 14C and LHAASO detection interval for 09A (3000 s)
- No spectral variability with time
- Average flux emitted in afterglow phase
  - Log-parabola for 14C (MAGIC modeling)
  - Power-law with exponential cut-off for 09A (LHAASO results)

Gamma-ray Bursts in the VHE domain

	T_{90} s	$E_{\gamma,iso}$ erg	z	T_{delay} s	E_{range} TeV	IACT (sign.)
160821B	0.48	1.2×10^{49}	0.162	24	0.5-5	MAGIC (3.1σ)
180720B	48.9	6.0×10^{53}	0.654	3.64×10^{4}	0.1-0.44	H.E.S.S. (5.3σ)
190114C	362	2.5×10^{53}	0.424	57	0.3-1	MAGIC ($> 50\sigma$)
190829A	58.2	2.0×10^{50}	0.079	1.55×10^{4}	0.18-3.3	H.E.S.S. (21.7σ)
201015A	9.78	1.1×10^{50}	0.42	33	0.14	MAGIC (3.5σ)
201216C	48	4.7×10^{53}	1.1	56	0.1	MAGIC (6.0σ)
221009A	289	1.0×10^{55}	0.151	0-2400	0.5-18	LHAASO

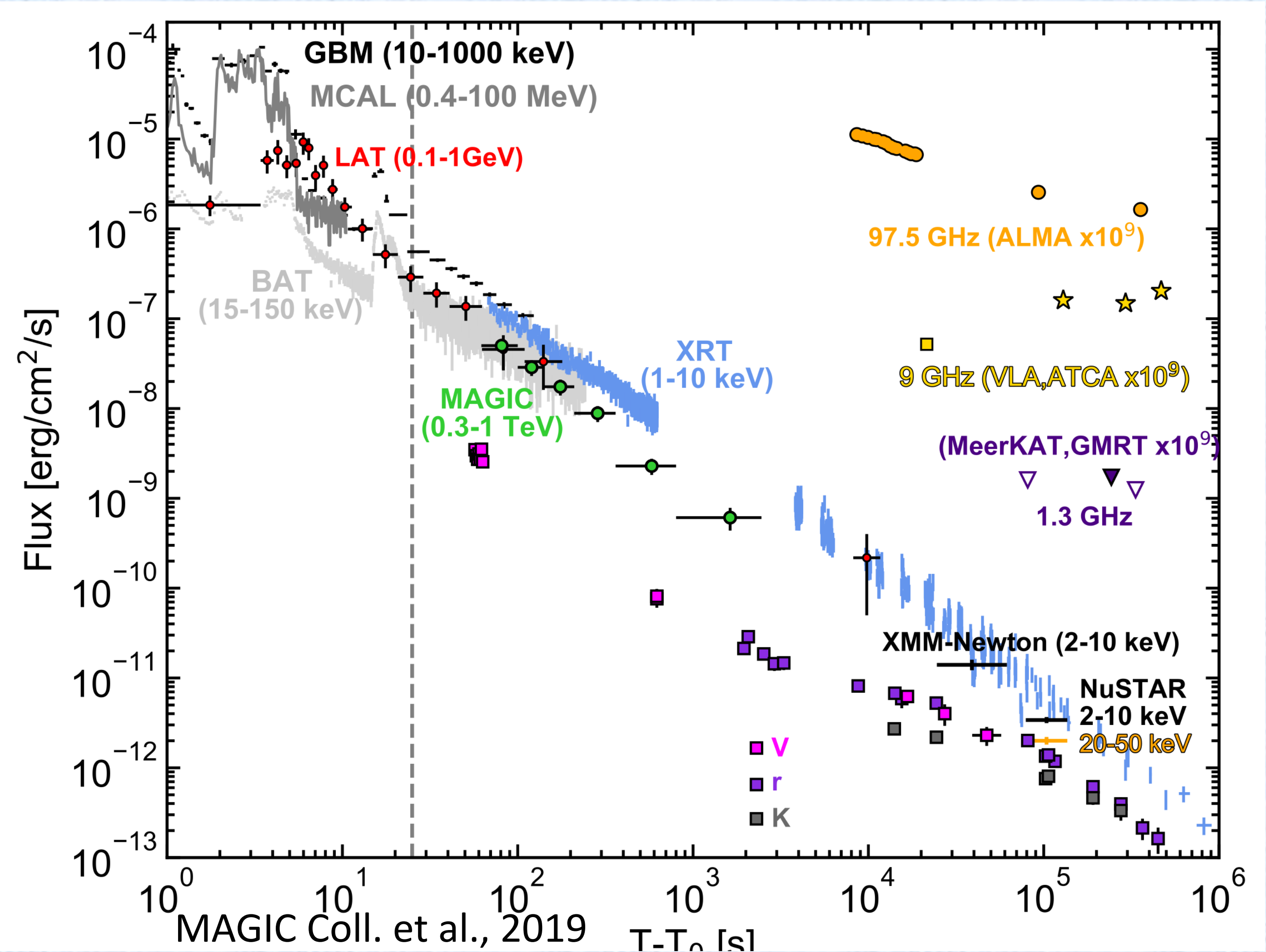
Adapted from Miceli & Nava, 2022

GRB190114C

- Long GRB
- $E_{\gamma,iso} \sim 2.5 \times 10^{53}$ erg
- $z = 0.42$

MAGIC detection info:

- $T_{delay} \sim 57$ s
- > 50σ in 20 minutes
- detection up to 40 min
- 0.3 - 1 TeV energy range
- moon conditions and Zd>50



MAGIC Coll. et al., 2019

GRB190114C

X-ray + GeV + TeV

↓

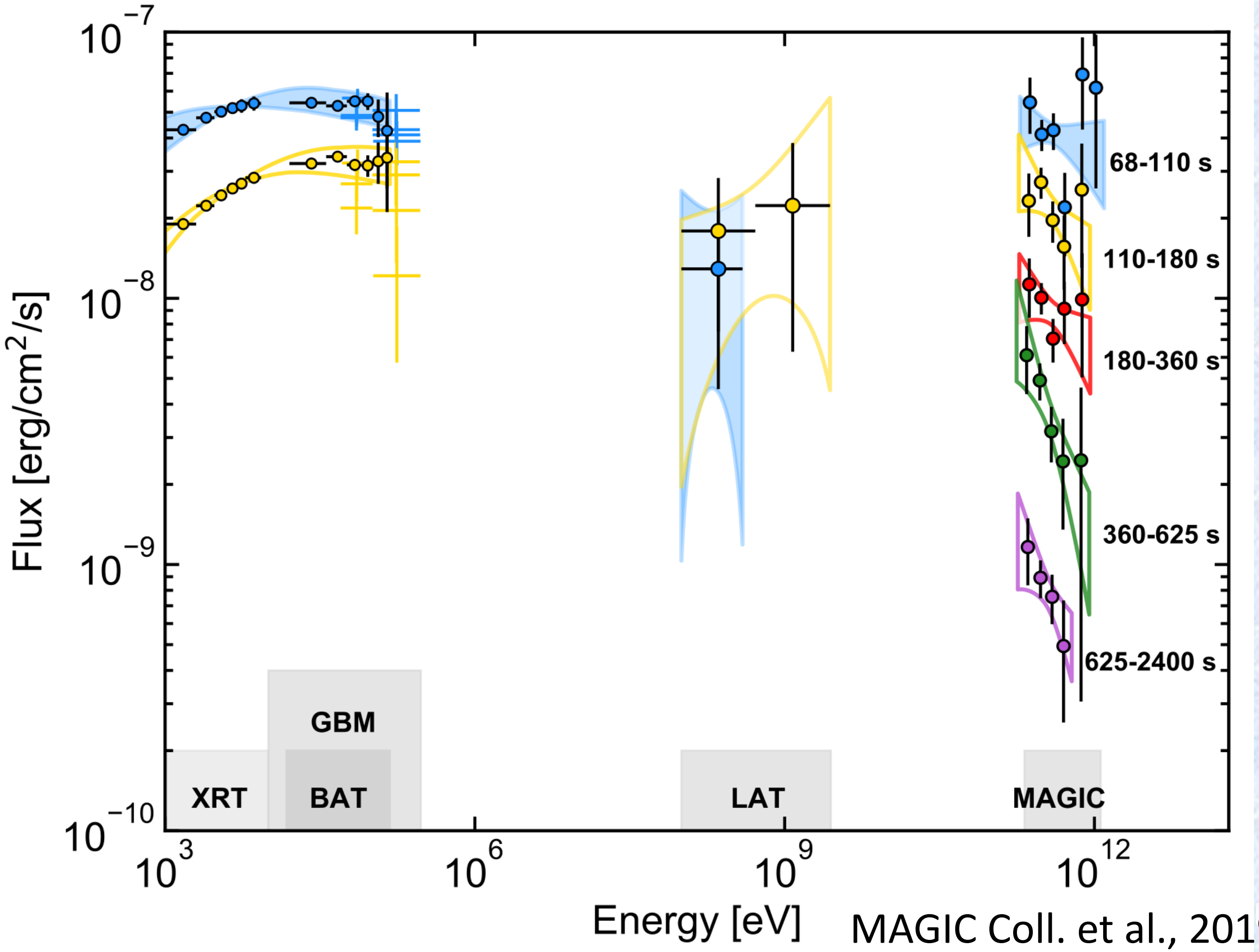
Spectral hardening for E > 0.2 TeV

↓

Can't be extention of Synchrotron component

↓

New emission component at VHE



MAGIC Coll. et al., 2019

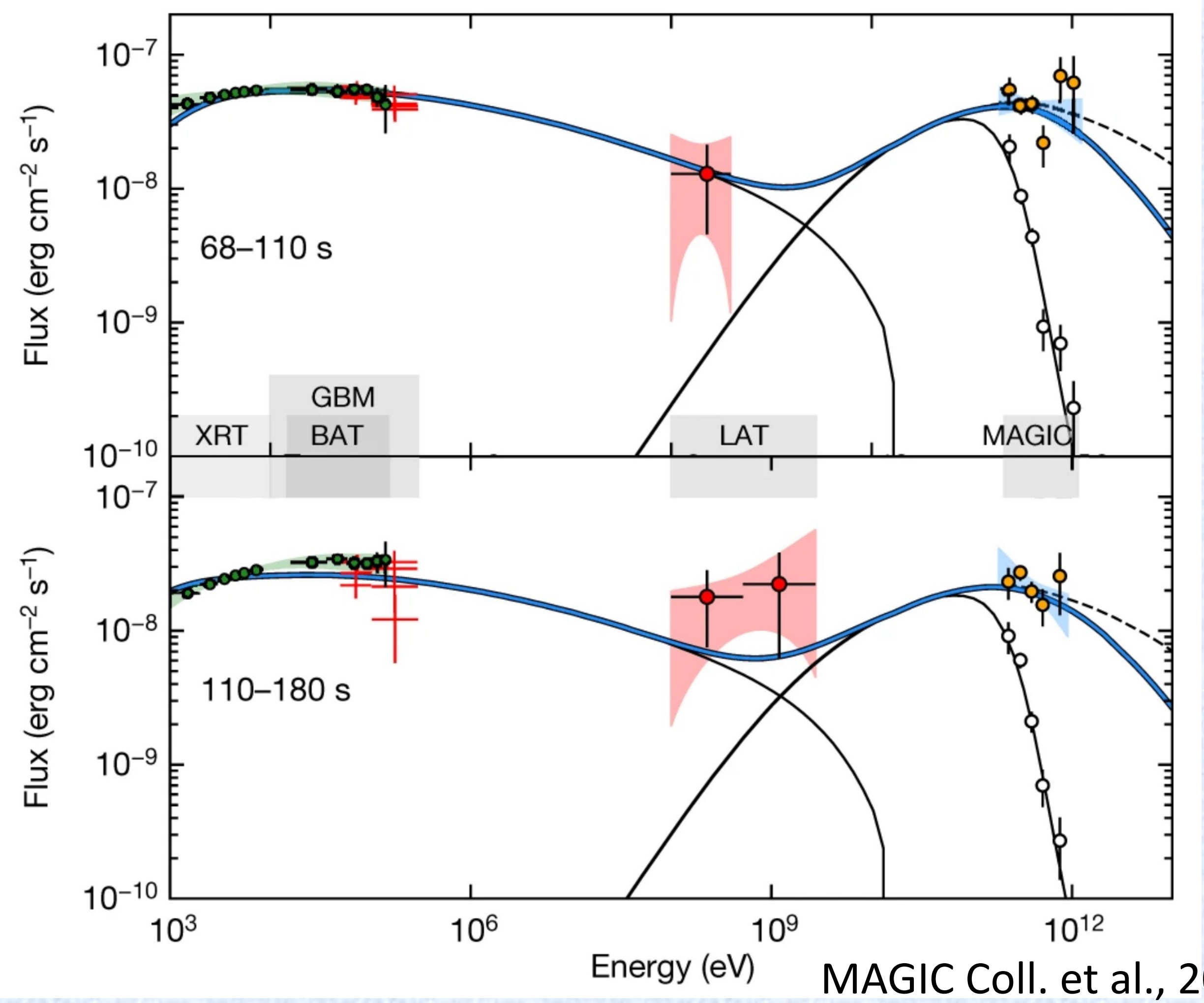
GRB190114C

Observed (solid black line)
No γ-γ opacity (dashed line)
EBL-deabsorbed (blue line)

MAGIC soft spectrum:

- Klein-Nishina
- γ-γ internal absorption

GRB afterglow parameters:
$E_k \gtrsim 3 \times 10^{53}$ erg
$\varepsilon_e \approx 0.05\text{-}0.15$
$\varepsilon_b \approx 0.05\text{-}1 \times 10^{-3}$
$n \approx 0.5\text{-}5$ cm^{-3}
$p \approx 2.4\text{-}2.6$



MAGIC Coll. et al., 2019

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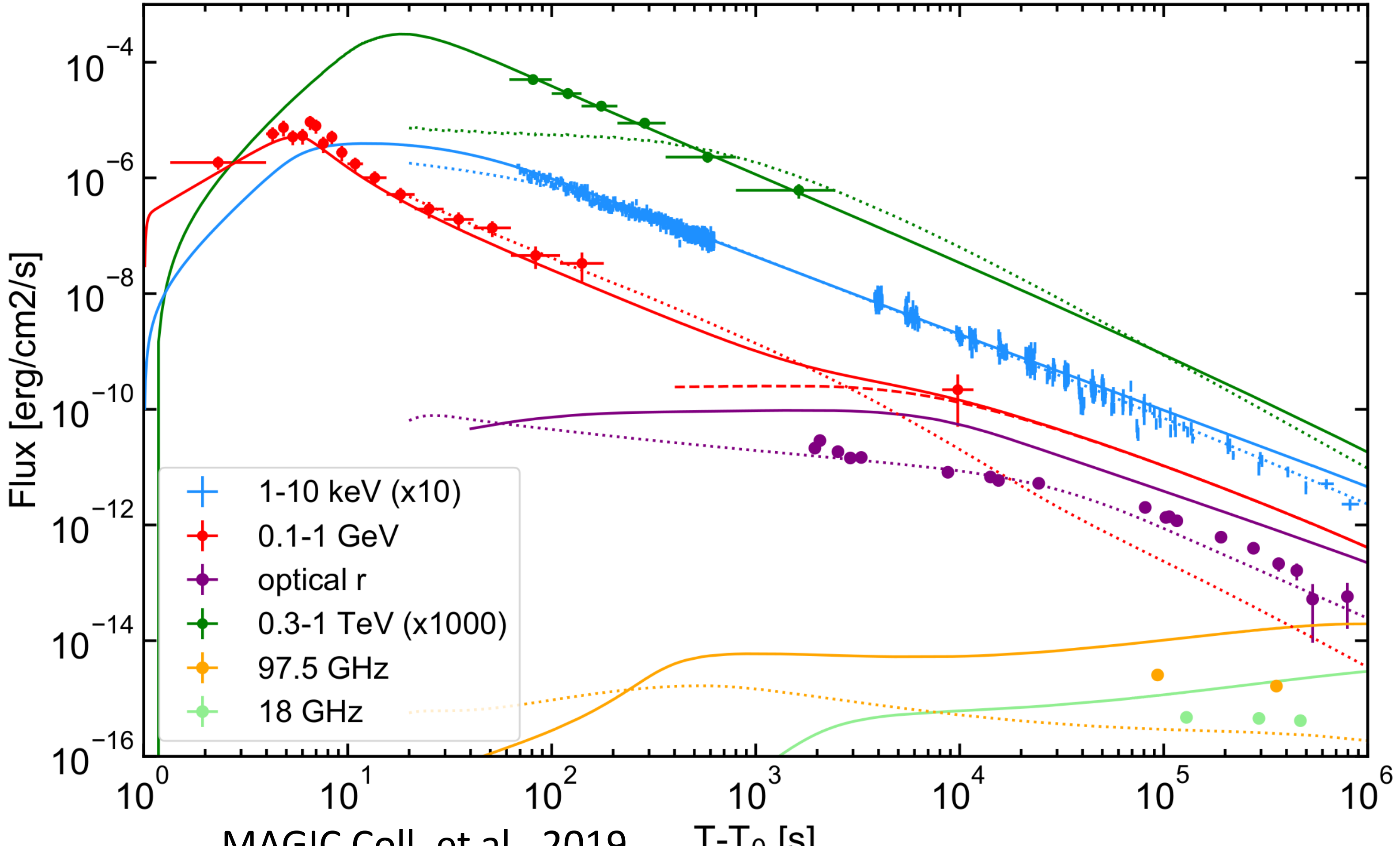
MWL LIGHT CURVES

GRB190114C

- Sync+SSC external forward scenario
- Two modeling displayed:
  - X to TeV (solid lines)
  - Radio-optical (dotted lines)
  - SSC contribution (dashed lines)
- Indication of time-dependent afterglow parameters



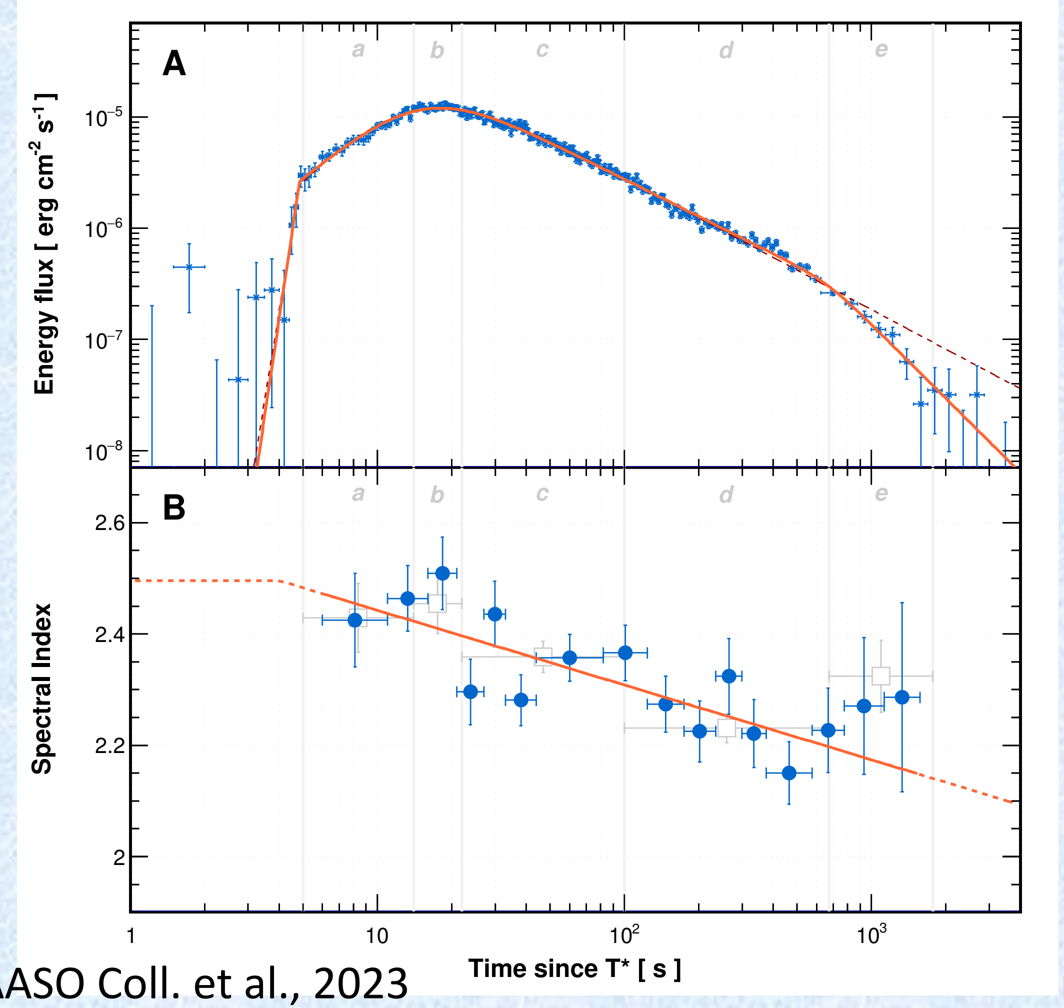
MAGIC Coll. et al., 2019

GRB221009A

- Long GRB: The BOAT
- $E_{\gamma,iso}$ > 3 x 10^{54} erg
- z = 0.15

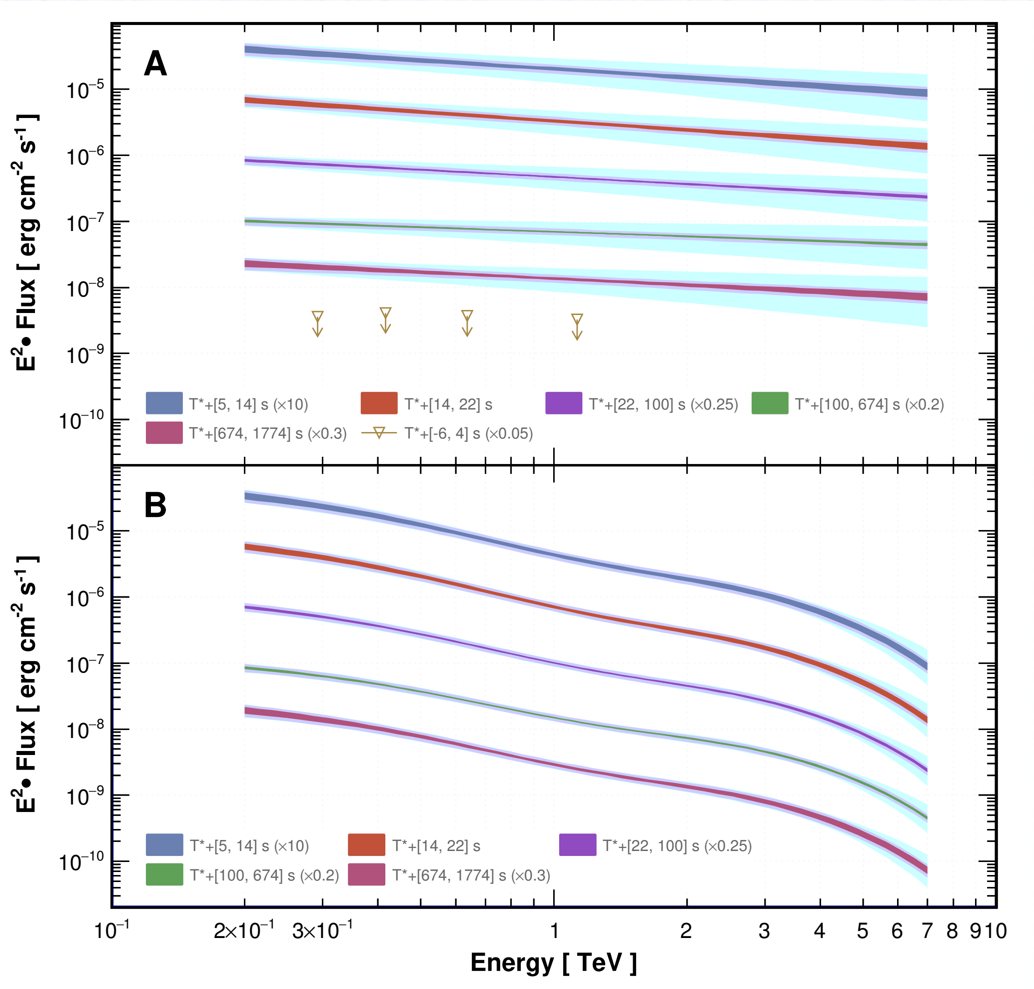
LHAASO detection info:

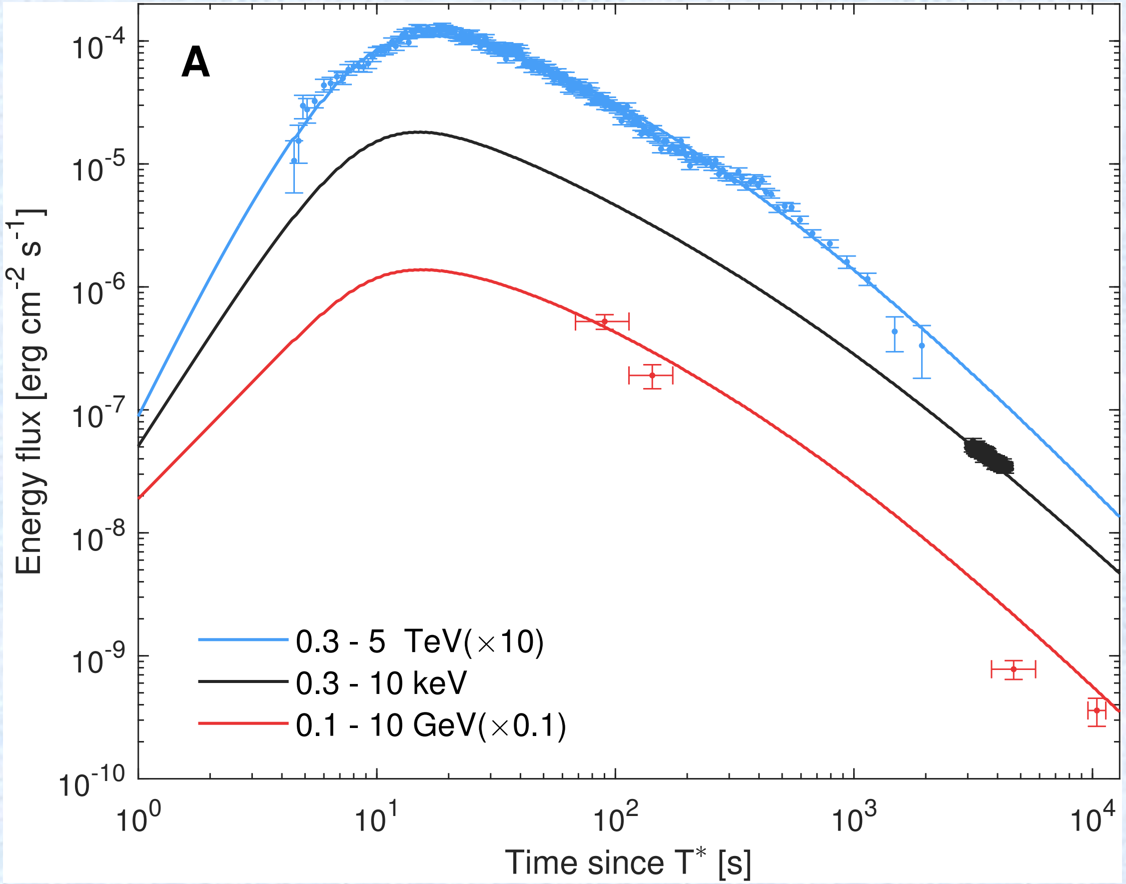
- > 250σ in 230 – 3000 s
- 0.3 – 13 TeV energy range



LHAASO Coll. et al., 2023

GRB221009A





LHAASO Coll. et al., 2023

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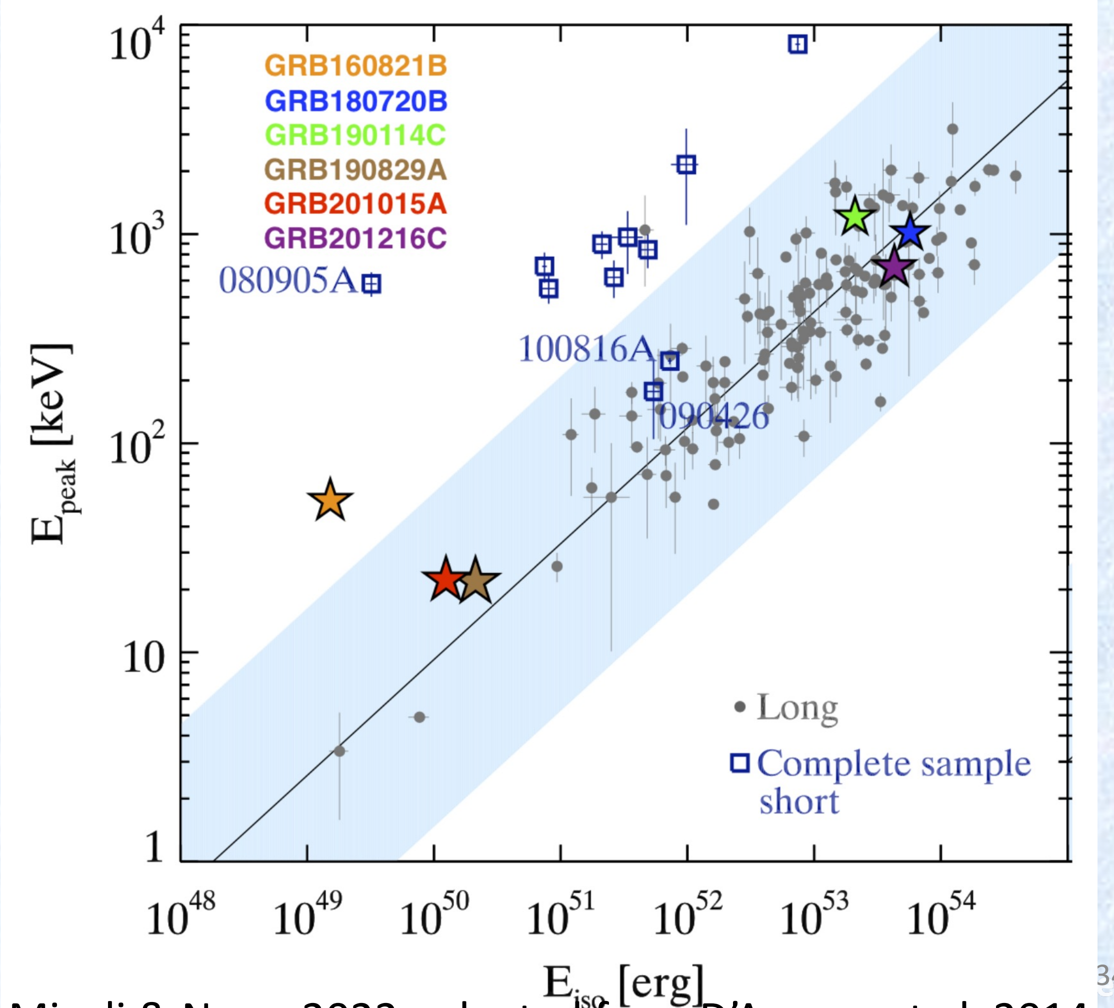
Population of GRBs at VHE

- Broadband intrinsic properties:
  - span more than 3 orders of magnitude in $E_{\gamma,iso}$
  - Span 2 orders of magnitude in terms of L_{VHE}
  - ranging in redshift between 0.079–1.1
- X-ray – TeV connection:
  - similar fluxes and decay slopes
  - similar amount of radiated power
- Data modeling:
  - SSC suggested (not conclusive)
  - no preferences on constant/wind-like medium
  - $\varepsilon_e \sim 0.1$, $\varepsilon_B \sim 10^{-5}$–$10^{-3}$, $\xi<1$



Miceli & Nava, 2022, adapted from D'Avanzo et al. 2014