Gamma-Ray Bursts pair echoes as probes of the Intergalactic Magnetic Field in the CTAO era

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From nine to forty: the SST telescopes and gamma-ray science with ASTRI and CTAO
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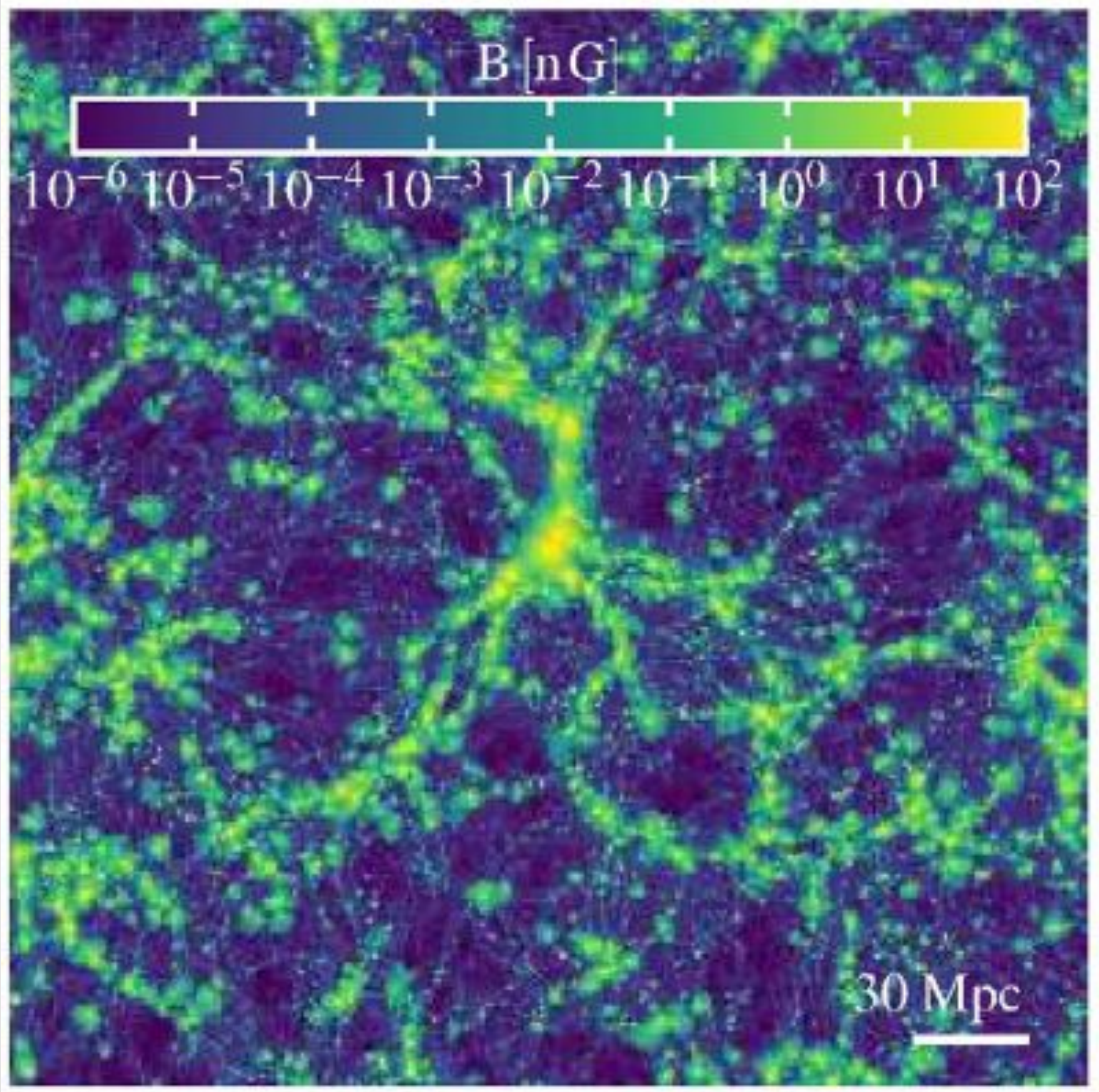
The Intergalactic Magnetic Field

- ❖ B-Fields in galaxies and cluster of galaxies originate from amplified seed fields -> their origin is unkown



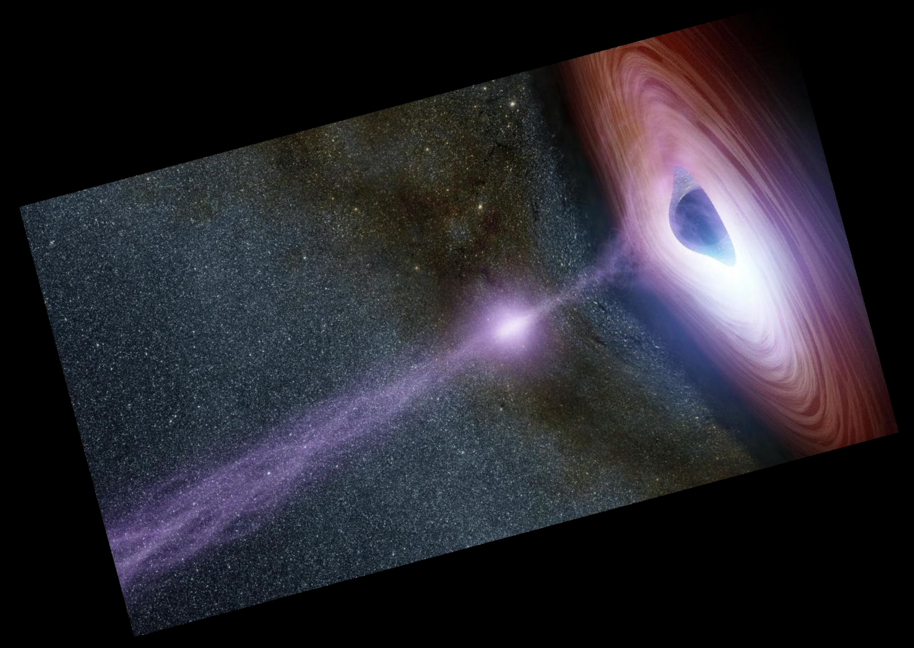
Marinacci et al. 2019

- ❖ The **cosmological scenario:**
  - ➢ Inflation
  - ➢ Post-inflationary
  - ➢ Electroweak phase transition
  - ➢ QCD phase transition

- ❖ The **astrophysical scenario:**
  - ➢ Biermann battery
  - ➢ Galactic outflows
  - ➢ Photoionization during the reionization era
  - ➢ Primordial vorticity

➔ Observationally we need measurements of magnetic fields in the intergalactic medium

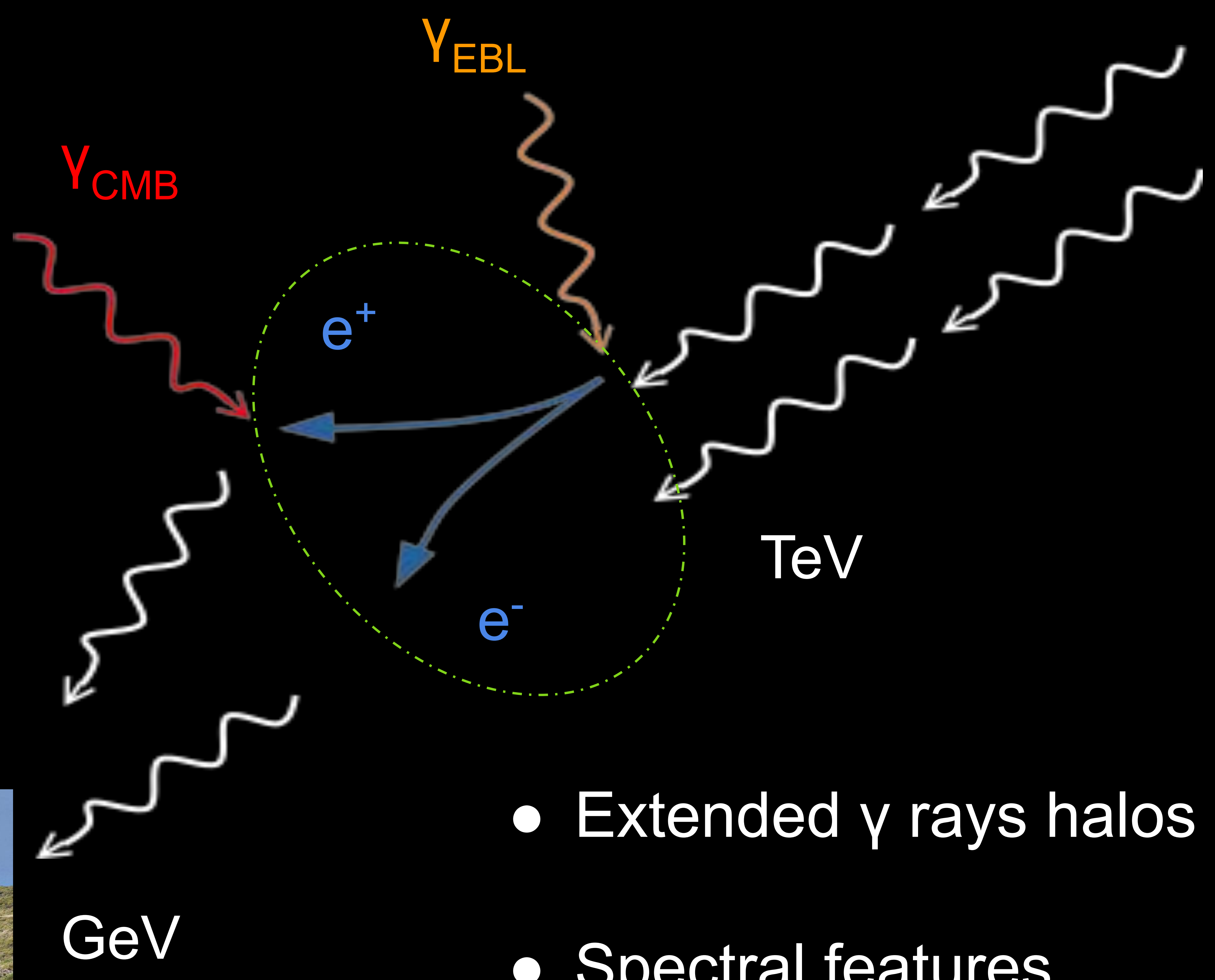
Physical process



Excess at lower energies

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

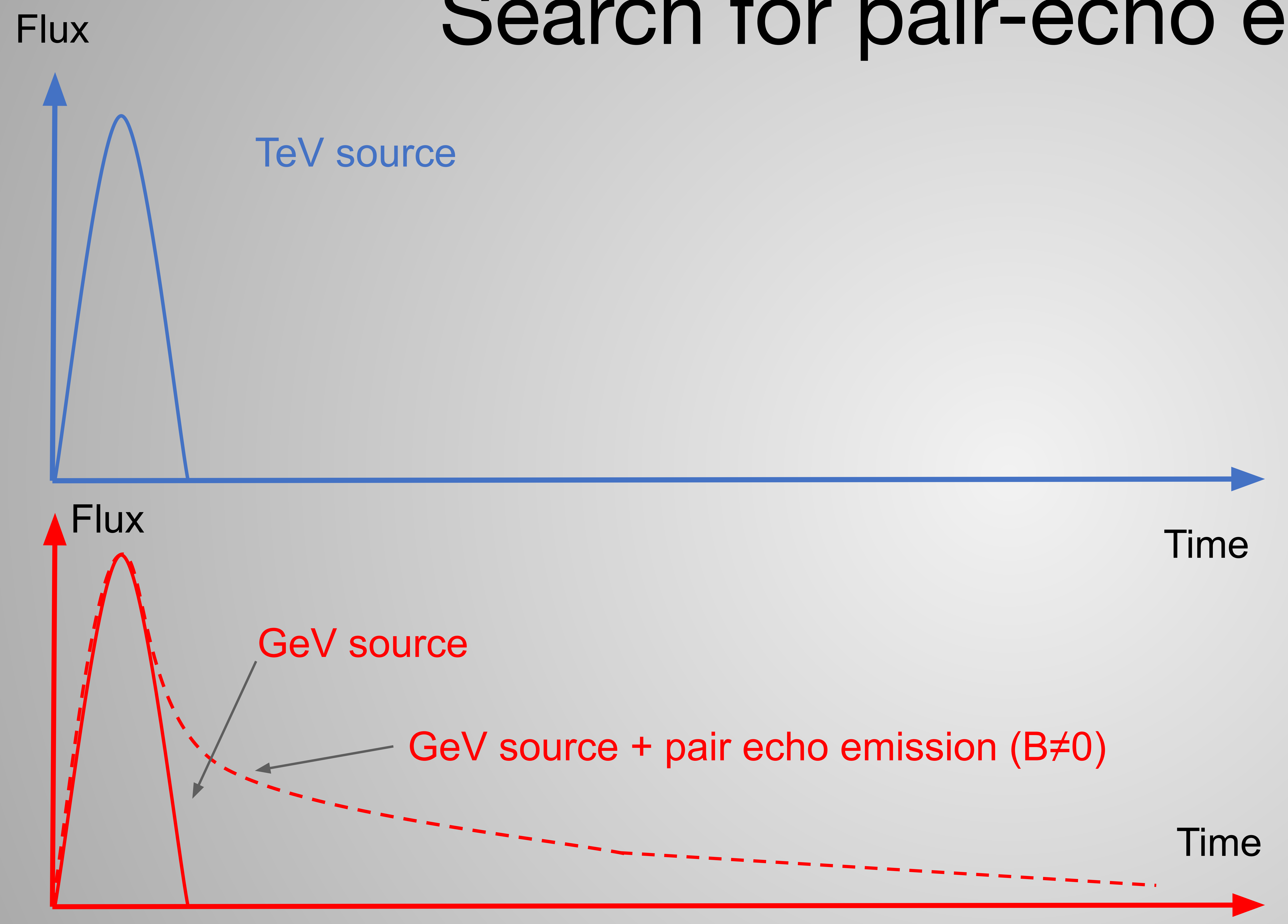
Neronov et al. 2009



Indirect detection of IGMF

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

Search for pair-echo emission



- The cascade emission is delayed -> tail in the GeV lightcurve

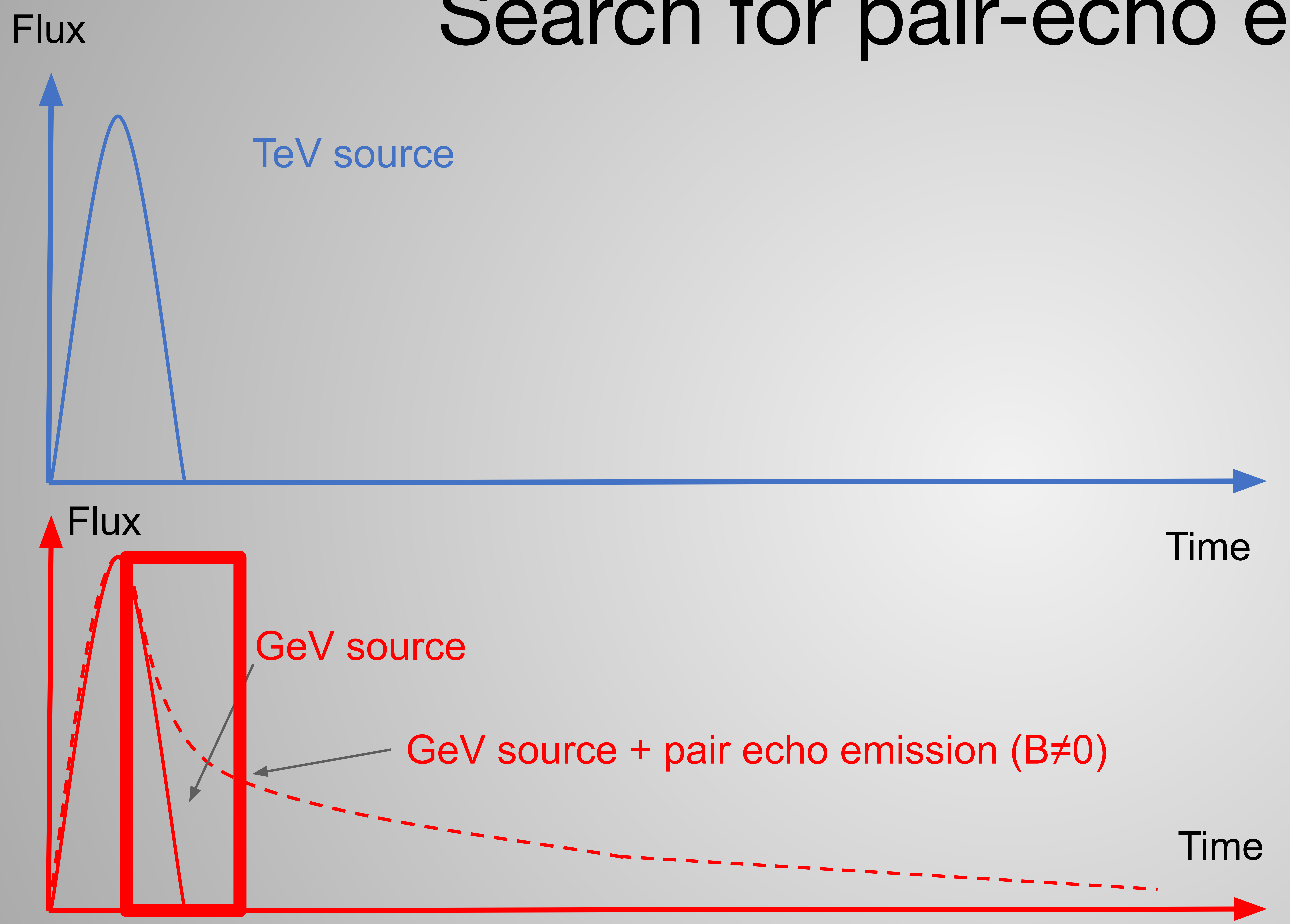
- The pair-echo is diluted in time and the dilution depends on the IGMF strength

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

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

Neronov et al. 2009

Search for pair-echo emission



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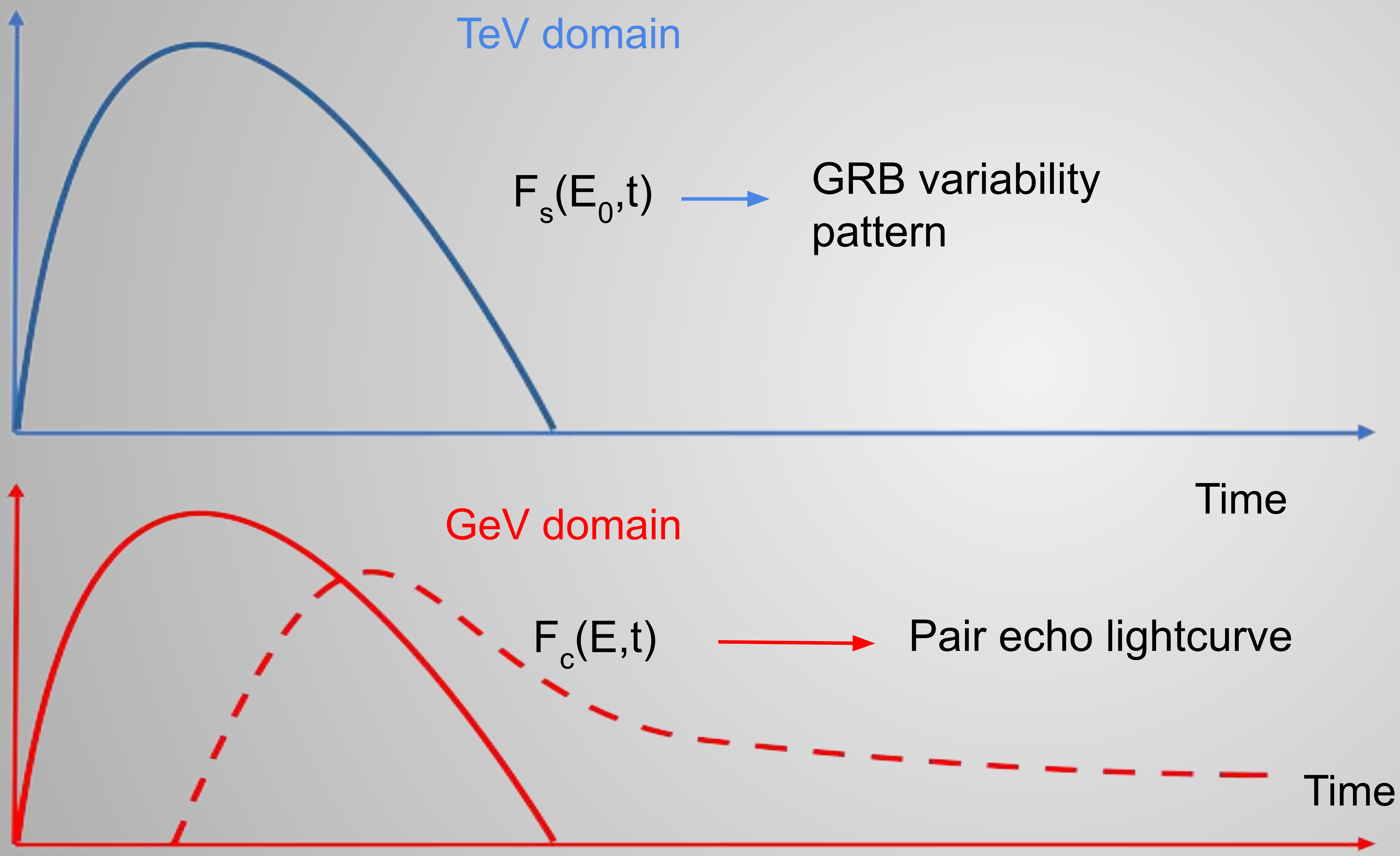
Time evolution of the pair echo emission from a GRB



- The time evolution of the pair echo needs to be modeled:
  - The VHE variability pattern reshapes the pair echo lightcurve
  - The detection of the pair echo strongly depends on the properties of the GRB (in addition to the IGMF strength): jet break, energetics and redshift

Pair echo emission "during" the GRB afterglow

- MC simulations provides the pair echo response to an impulse in the VHE band

$$G(E_0, E, \tau) \rightarrow$$

Kernel function describing the distribution of the pair echo photons in energy and time

- Possible approach: convolution of the kernel with the variability pattern of the GRB in the VHE band

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

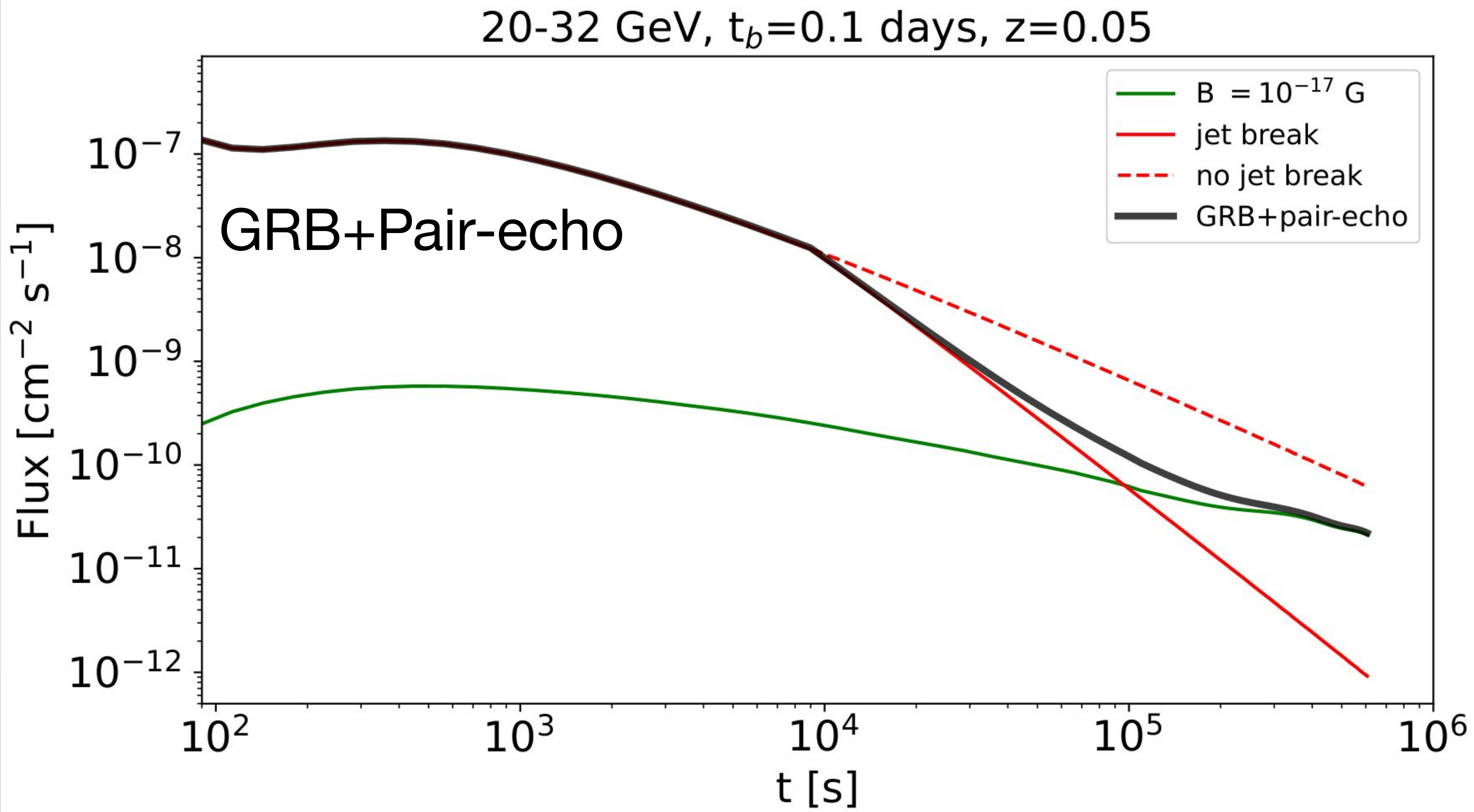
Pair-echo emission during the afterglow fading phase: lightcurve computation

- Simulated GRB:
  - Emission Model: Synchrotron Self Compton (SSC)
  - $E_{iso} = 10^{53}$ erg
  - Redshift: 0.05

- Intrinsic VHE spectrum (for the simulations): we computed the average VHE spectrum over the whole time window

- We built the Kernel function G using the montecarlo code CRPropa 3 (Alves Batista et al. 2022) for different IGMF strengths and computed the pair echo lightcurves

Pair-echo emission during the afterglow fading phase



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Observational signature: **flattening of the lightcurve for late times**

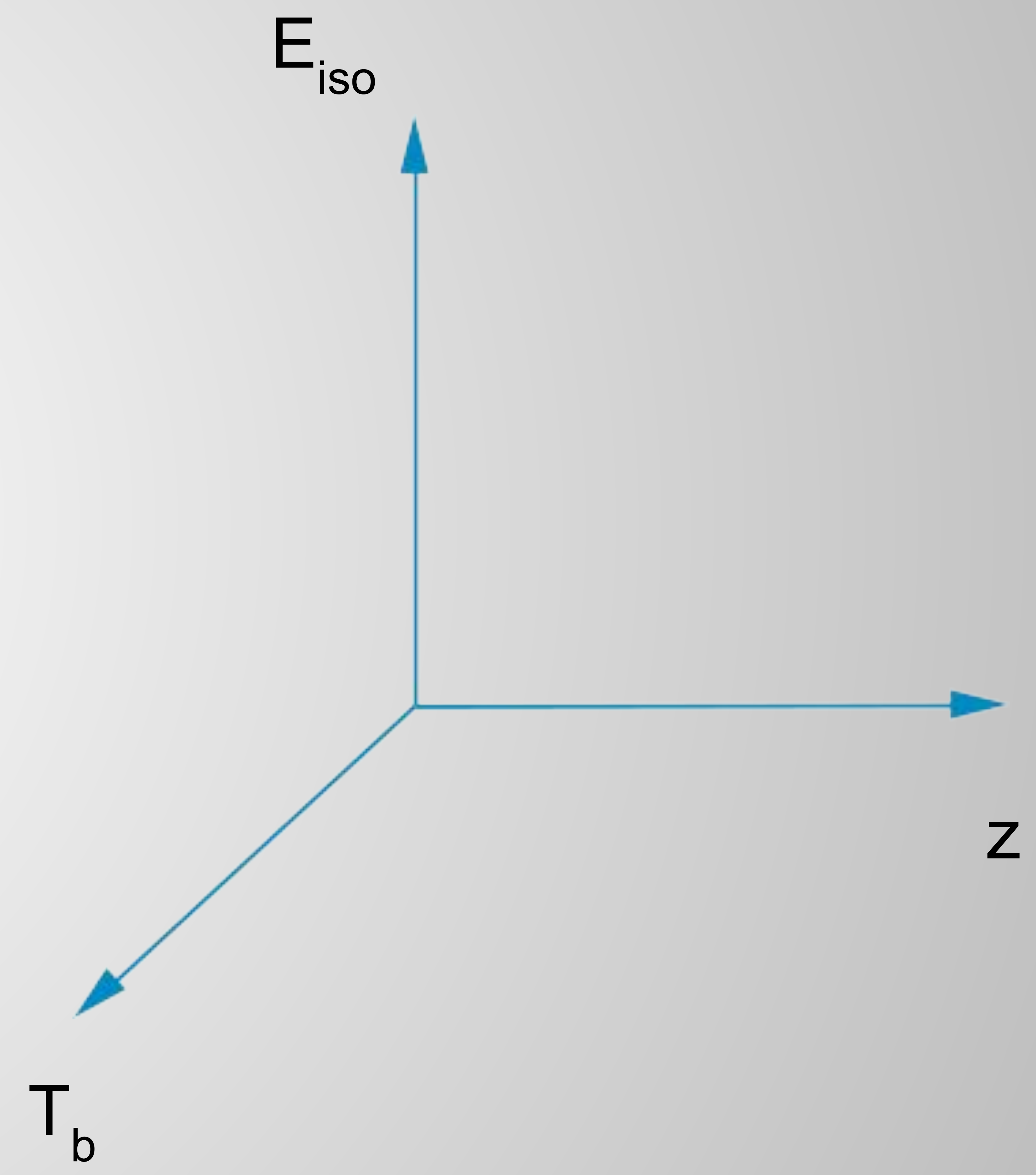
Simulation grid

GRB sample: 208 events, 16 redshift x 13 E_{iso}

- redshift, z: **16 values** in the range 0.03-1
- E_{iso}[erg]: **13** values between log(E_{iso}[erg])=49 and log(E_{iso}[erg])=55

Pair echo simulations: for each event we computed the cascade flux in two different the energy ranges [20-32] GeV, [80-125] GeV and 4 B x 5 jet break:

- B, **4 values:** log(B[G])=-19, -18, -17, -16
- Jetbreak, **5 values:** no jetbreak, log(T_b[days])=-1, -0.5, 0, 0.5



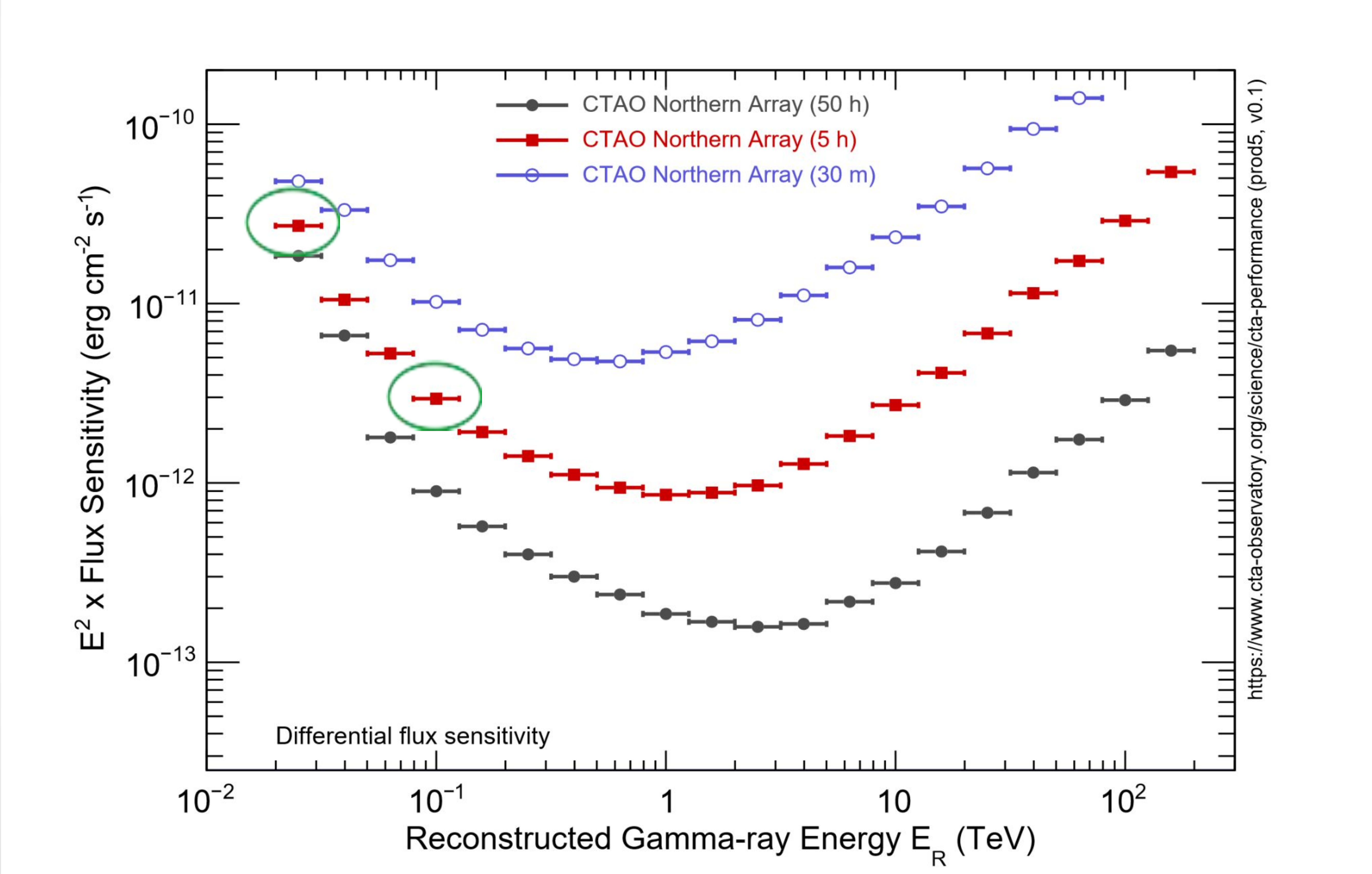
Simulations: results

To study the pair-echo flux dependence on the different parameters we built the following histograms:

- $F_{pair\text{-}echo} / F_{GRB}$ vs E_{iso}, T for different redshift and B

- We plot also the contours $T(F_{pair\text{-}echo} = k * F_{GRB}, k=1,2..,5)$

- We require that $F_{pair\text{-}echo} > F_{CTAO}$



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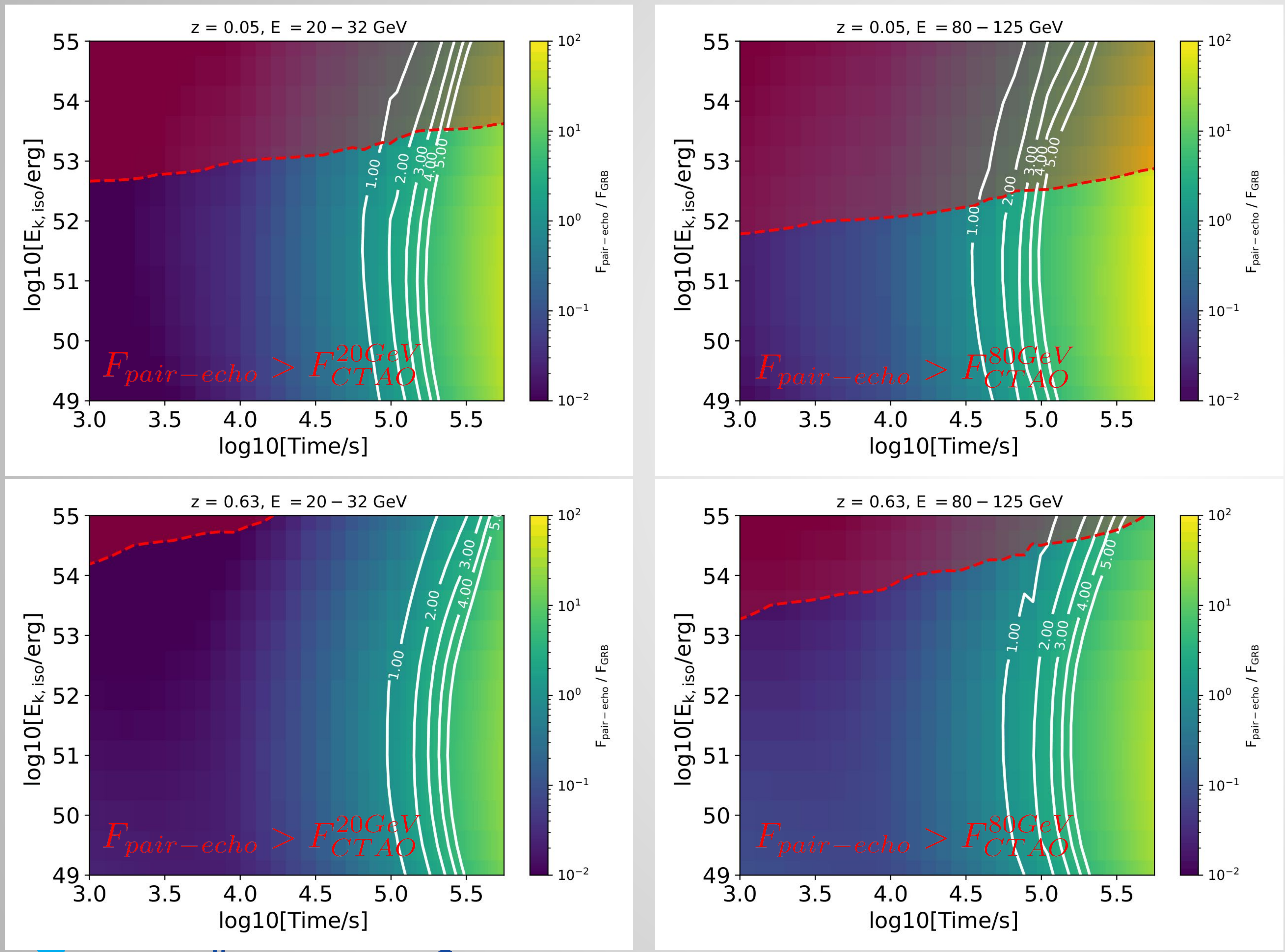
Results: the dependence on the energy and redshift



log(B[G])=-17, T_{break}=0.1 days:

- ❖ mild dependence on time
- ❖ the pair echo component tends to overtake the afterglow at earlier times at higher energies

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

- ❖ Increasing the redshift the counotur lines shift to longer delay -> the time at which the cascade becomes dominant occurs later for more distant GRBs.

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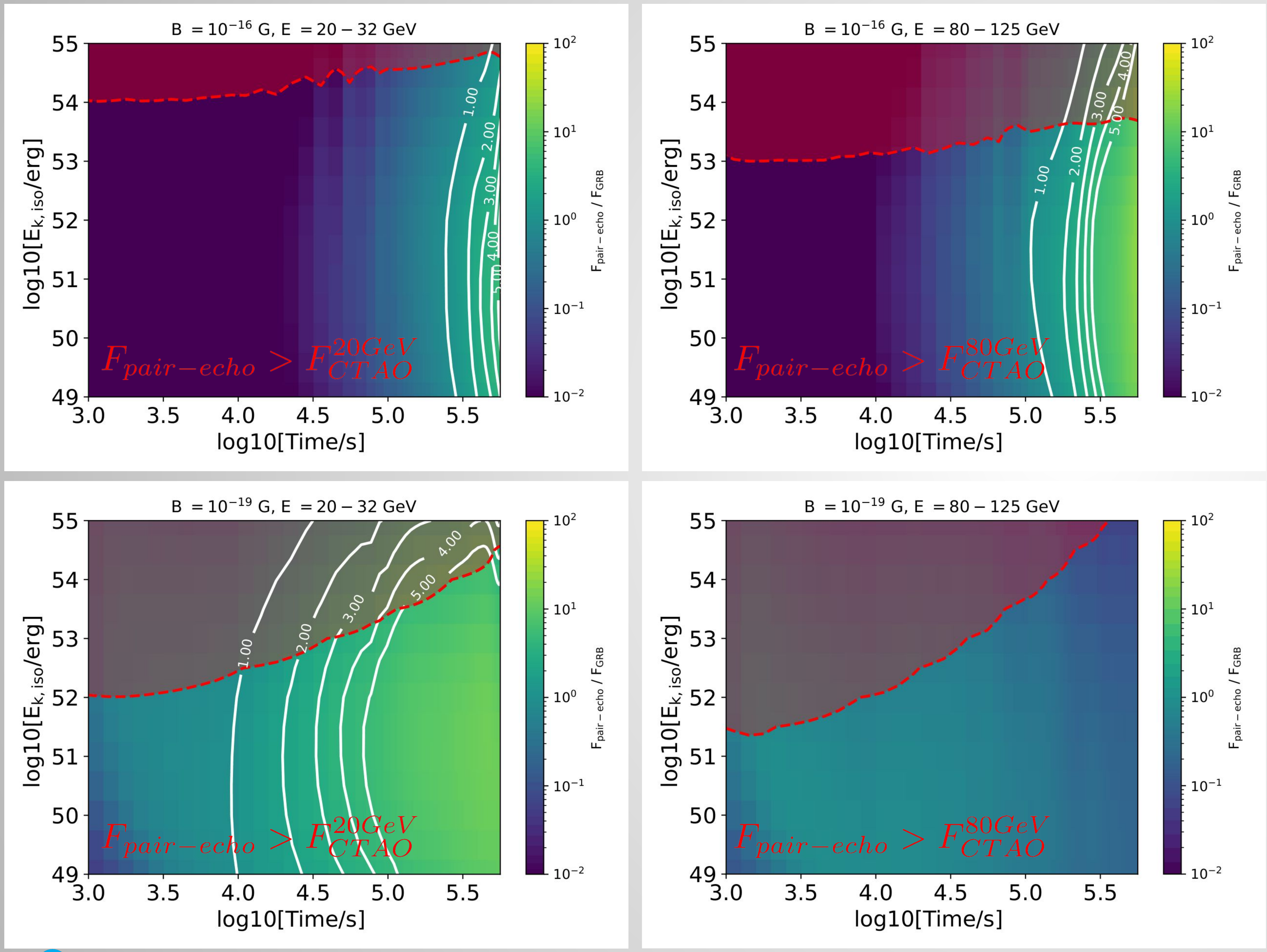
Results: the dependence on the energy and IGMF strength



z=0.1, T_{break}=0.1 days:

- In the 80 - 125 GeV band the pair-echo emission for weak magnetic fields peaks at short delays -> the cascade never becomes comparable to or dominant over the afterglow.

- In the 20 - 32 GeV band, for the weakest tested magnetic field there exist regions of the parameter space where the pair echo could be detectable by CTAO.

- Conversely the case B = 10^{-16} G is more favorable in the 80 - 125 GeV band

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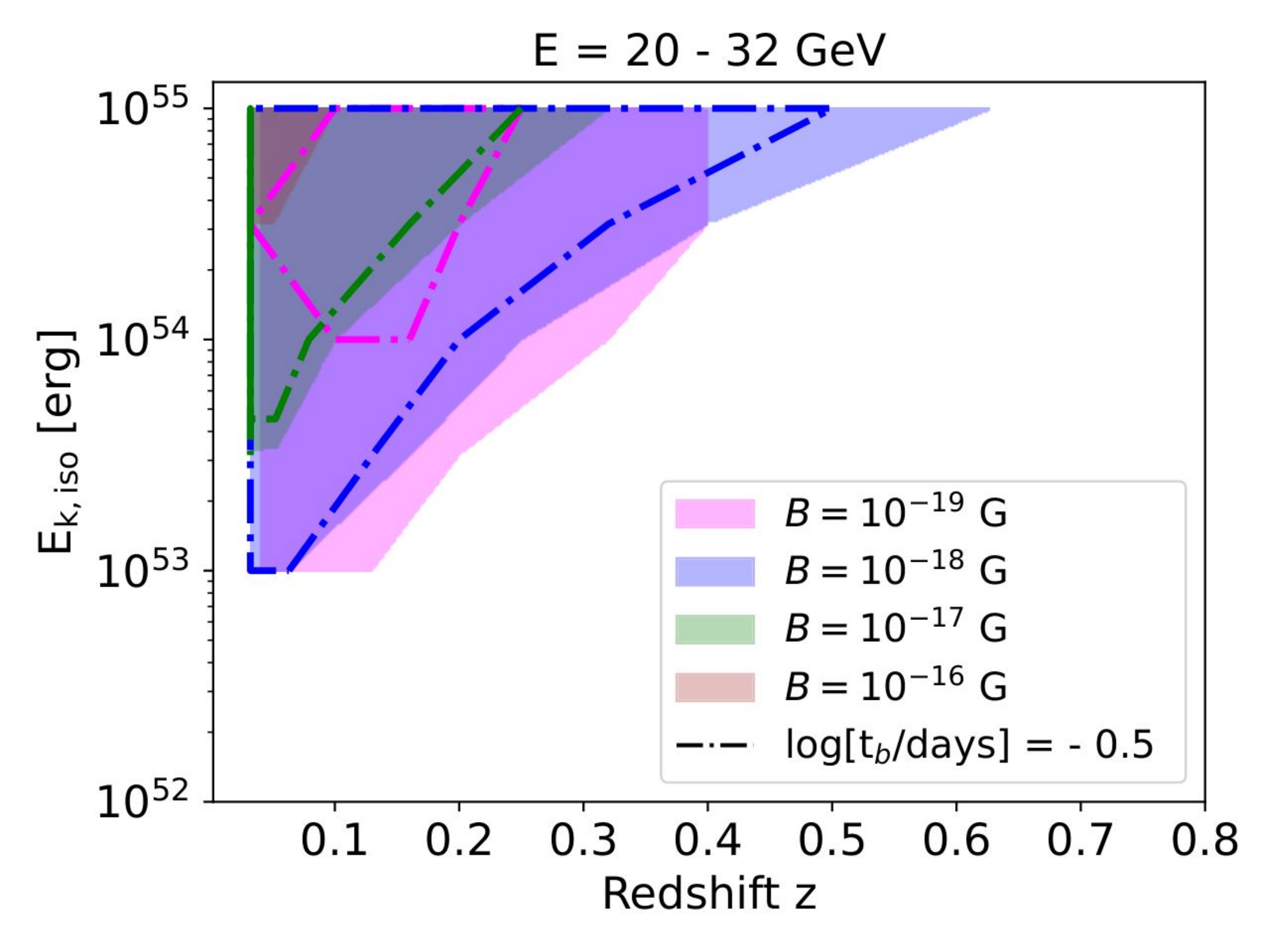
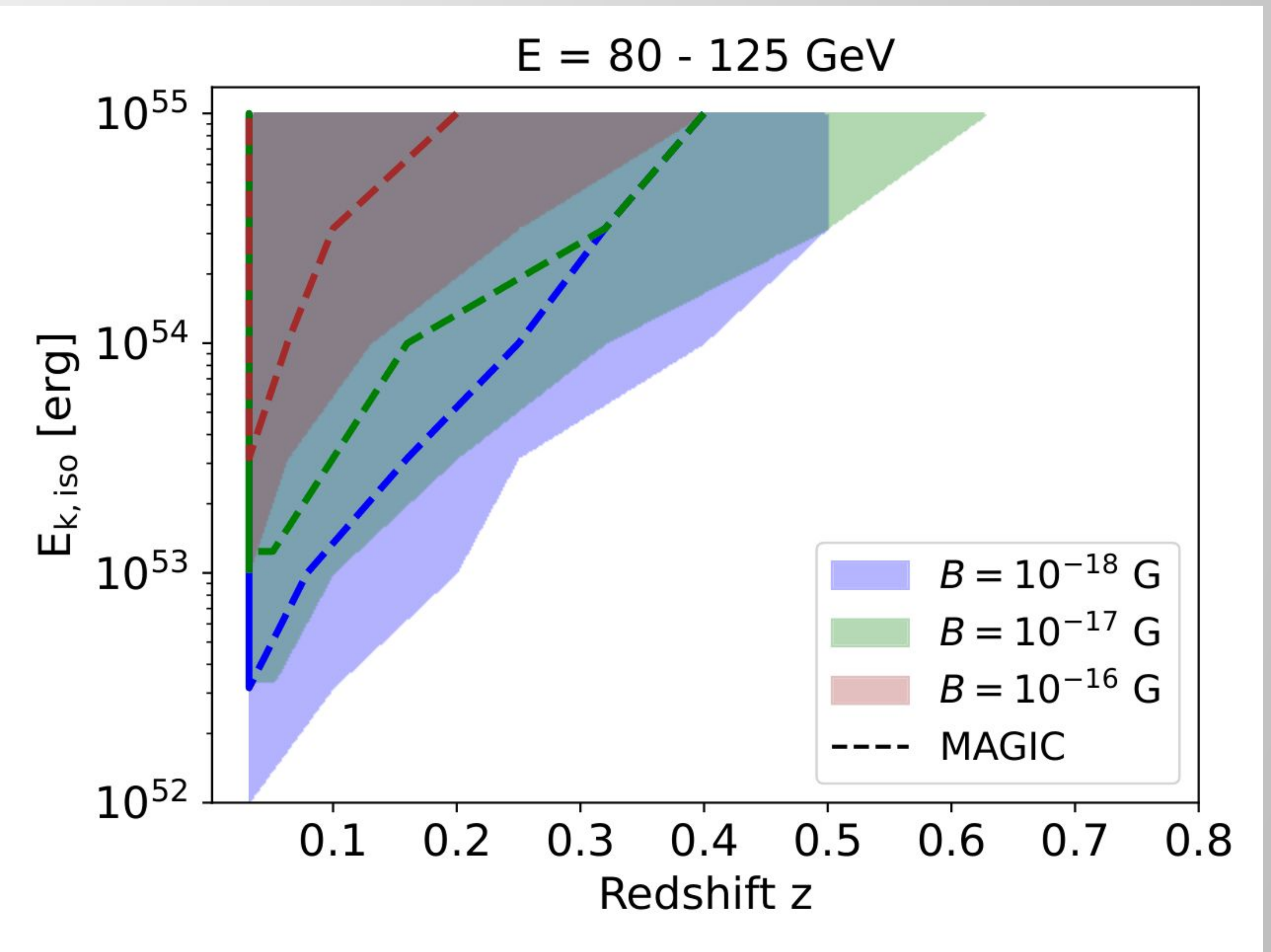
Results: detectability of pair-echo

We require that $F_{pair\text{-}echo} / F_{GRB} = 2$ **and** $F_{pair\text{-}echo} > F_{CTAO}$

- Weak magnetic fields are better probed at the lowest energies, whereas strong magnetic fields can be more effectively investigated at higher energies
- The parameter space in which the cascade might be detectable is generally larger at the higher tested energies -> **the better sensitivity of CTAO in the 80 - 125 GeV band plays a more significant role in determining the detectability of the emission**





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Conclusions

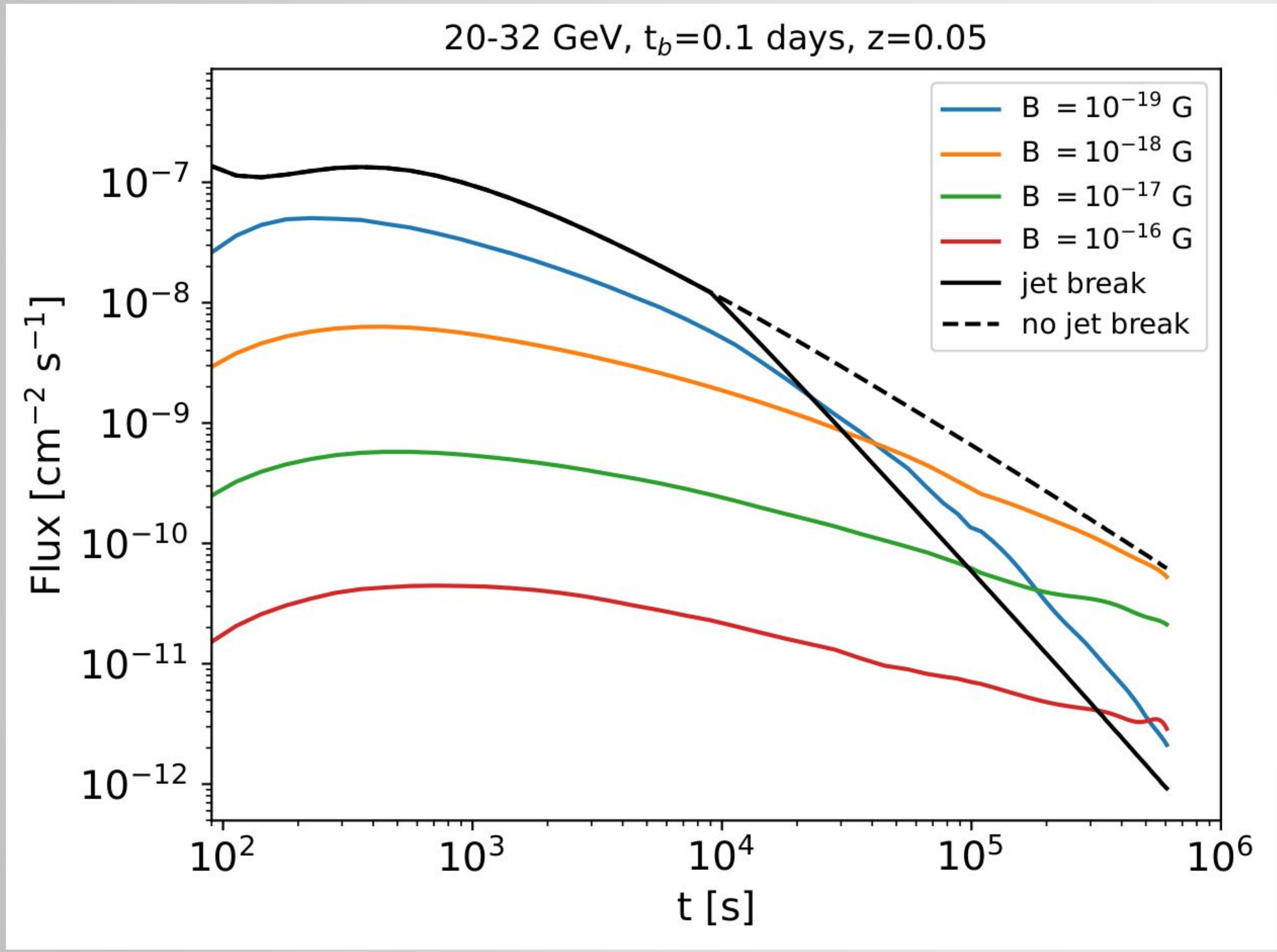
- We present a comprehensive study on IGMF signatures from GRBs in the tens to hundreds of GeV energy range exploring the capability of CTAO to detect the time-delayed pair-echo signature

- This investigation explores the detectability of the pair-echo signal as a function of key GRB parameters and demonstrates that a detection is possible for a subclass of events:
  - GRBs with isotropic kinetic energies $E_{k,iso} \gtrsim 10^{52} - 10^{53}$ erg are suitable for IGMF studies
  - The redshift range that can be probed depends on the kinetic energy $E_{k,iso}$: only the highest tested isotropic energies allows to reach $z \simeq 0.5$-0.6
  - The broader region of the ($E_{k,iso}$, z) is covered in the energy range 80-125 GeV due the better sensitivity of CTAO with respect to the energy range 20-32 GeV

- <u>Next step:</u> the estimate of the detection performances (e.g. detection rate) of CTAO requires the implementation of a realistic GRB cosmic population and additional features such as the jet orientation with respect to the line of sight.

Backup

Pair-echo emission during the afterglow fading phase: lightcurve computation



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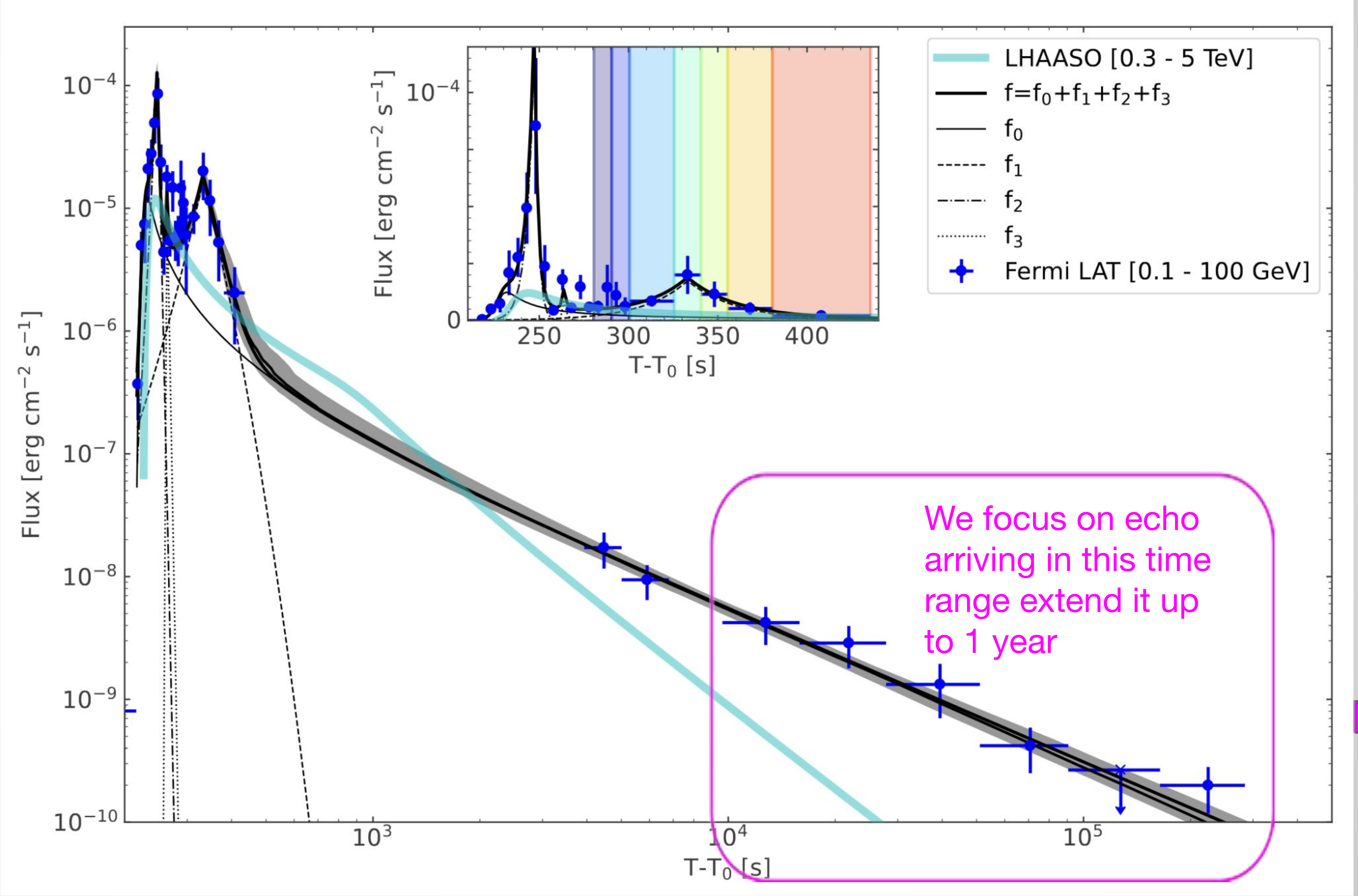
- ❖ The jet break plays a crucial role: the pair-echo can rise over the afterglow easier in case of jetbreak
- ❖ As expected for low IGMF strengths the pair-echo lightcurves are more peaked at low time delays
- ❖ As soon as the IGMF strength increases the pair echo is more diluted in time and can rise over the afterglow for late times

The case of GRB 221009A



Fermi LAT coll., 2025

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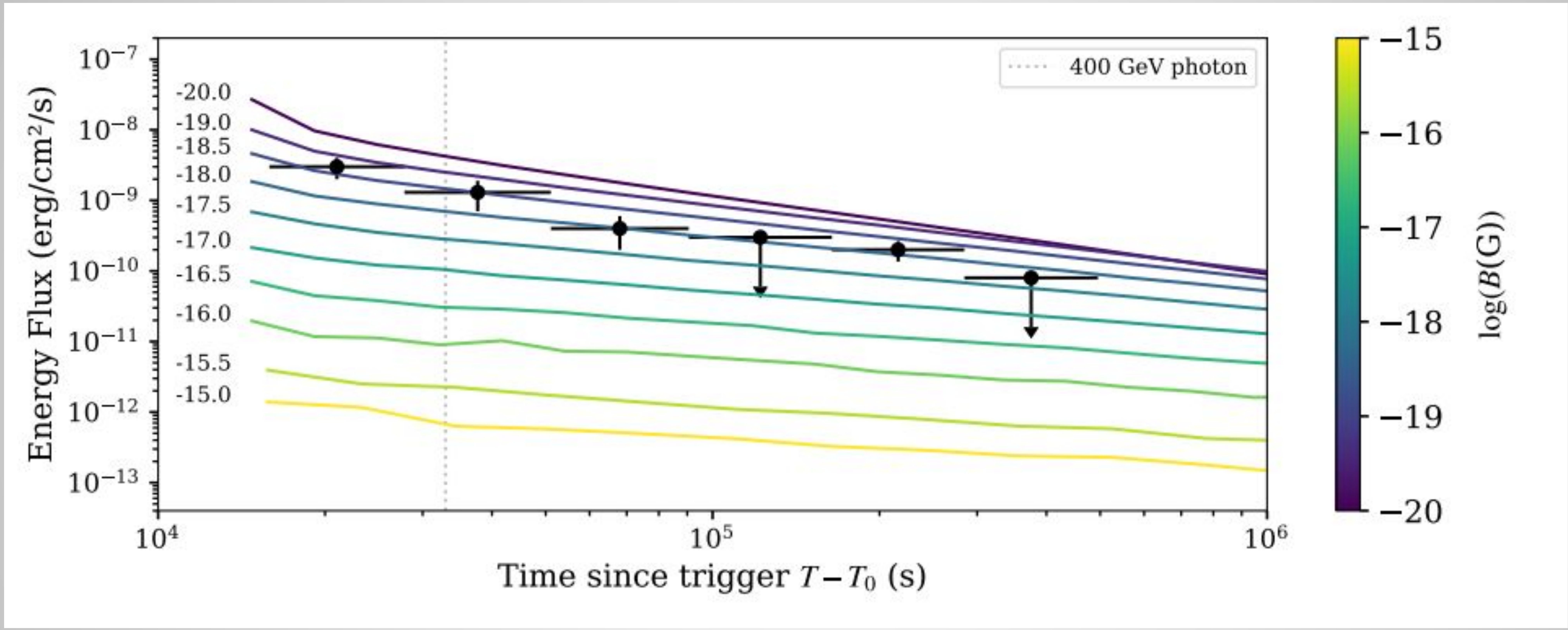

Burmeister L., **Da Vela P.,** et al. 2026

➔ Combining all time and energy bins we obtain: **B > 2.5 ✕ 10^{-17} G**

GRB model used in the simulations

- Synchrotron Self Compton (SSC) model:
  - afterglow emission from radio band to GeV -> synchrotron radiation emitted by electrons accelerated at the external shock running into the GRB surrounding medium
  - **VHE radiation** -> Inverse Compton from the same electron population scattering off the synchrotron photons

- Electron non thermal population described by a powerlaw energy spectrum:

$$\frac{dN}{dE} \propto \gamma^{-p}$$

- The SSC parameters (n, ξ_e, ε_e, ε_B and p) have been fixed to the values obtained with the procedure illustrated in Ghirlanda et al. 2015: they reproduce the X-ray, optical, radio and VHE fluxes of the observed GRBs:

  n=0.5 cm^{-3}, ε_e=0.04, ε_B=5×10^{-5}, ξ_e=0.2, p=2.3