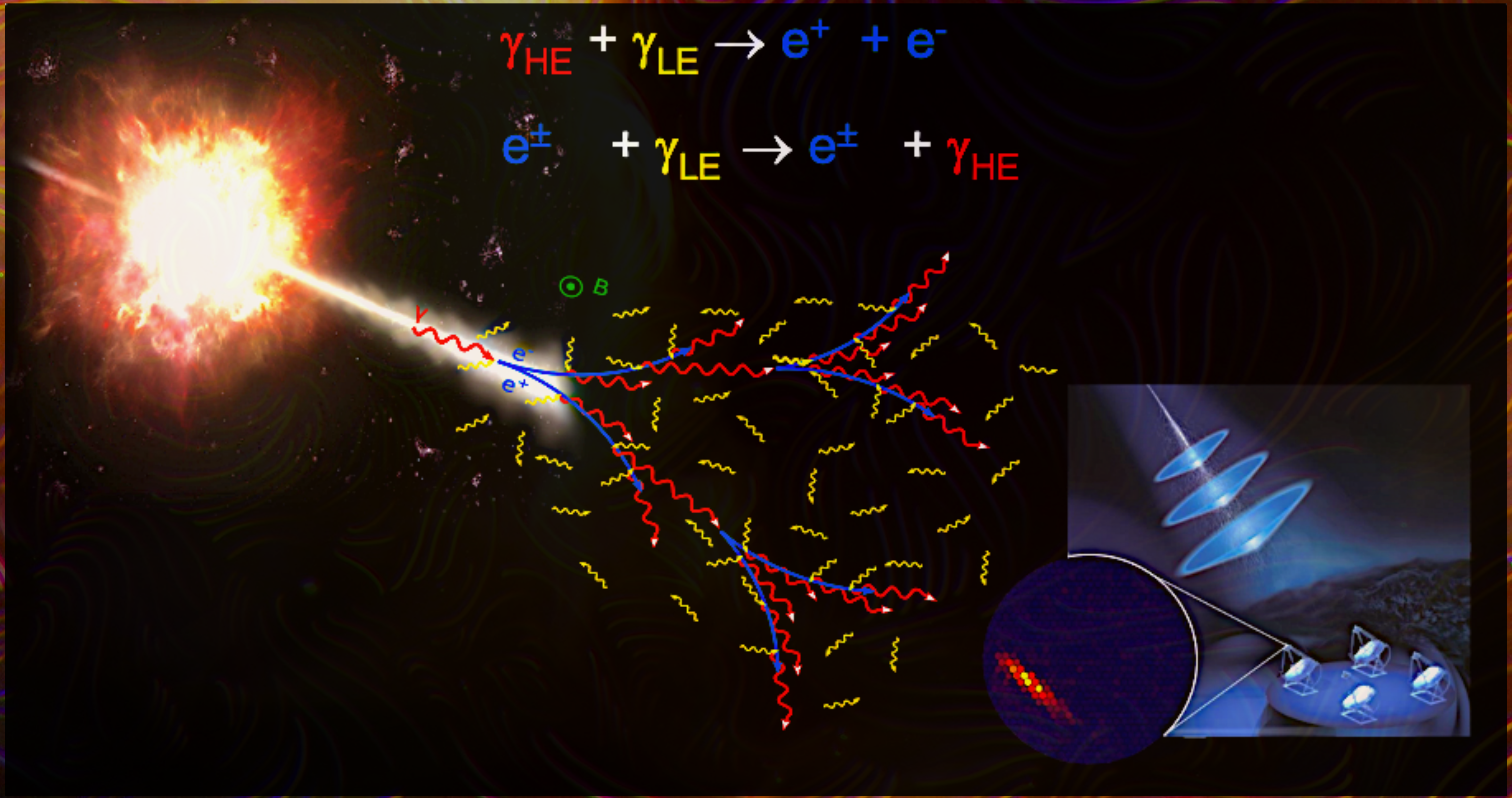
InterGalactic Magnetic Fields and Gamma-Ray Bursts with CTAO



Téneman Keita,

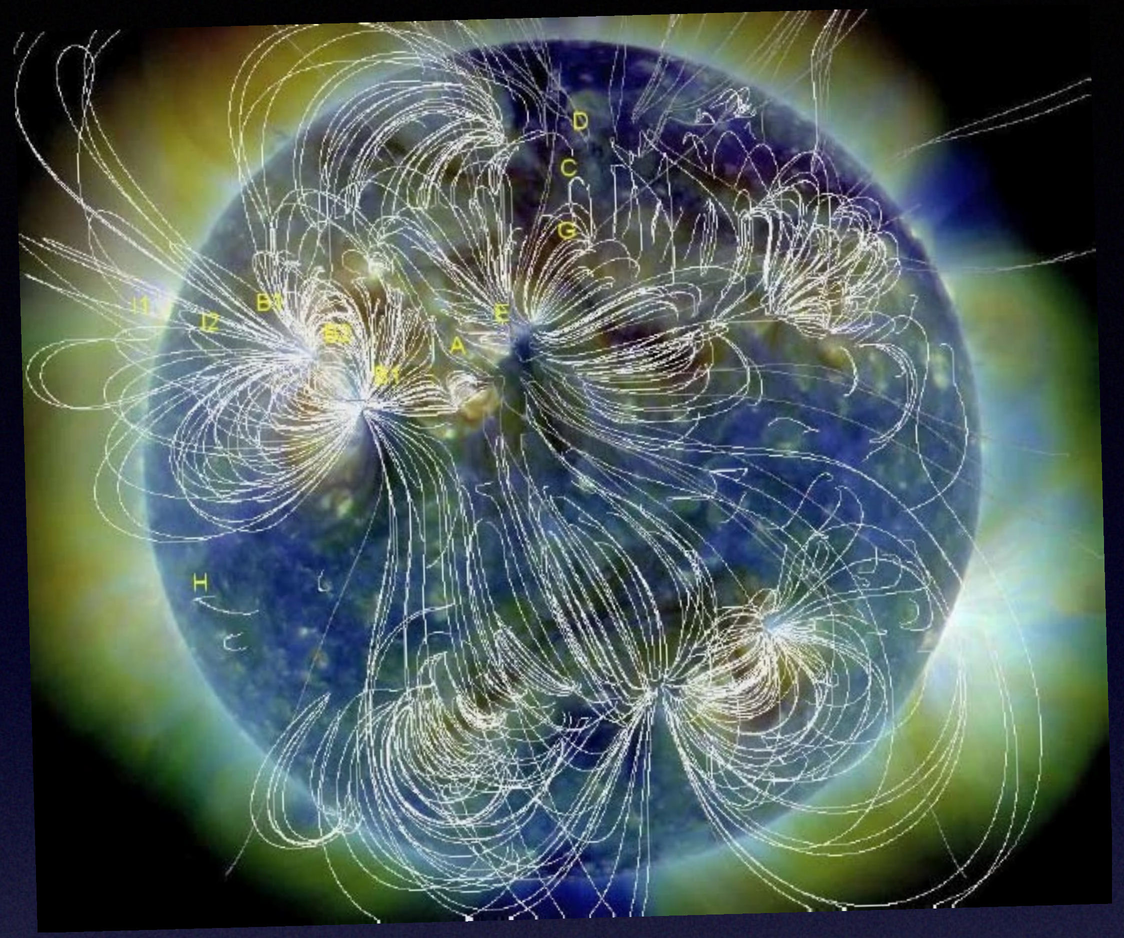
and R. Belmont, Th. Stolarczyk, T. Fitoussi, J. Malzac, A. Markowith

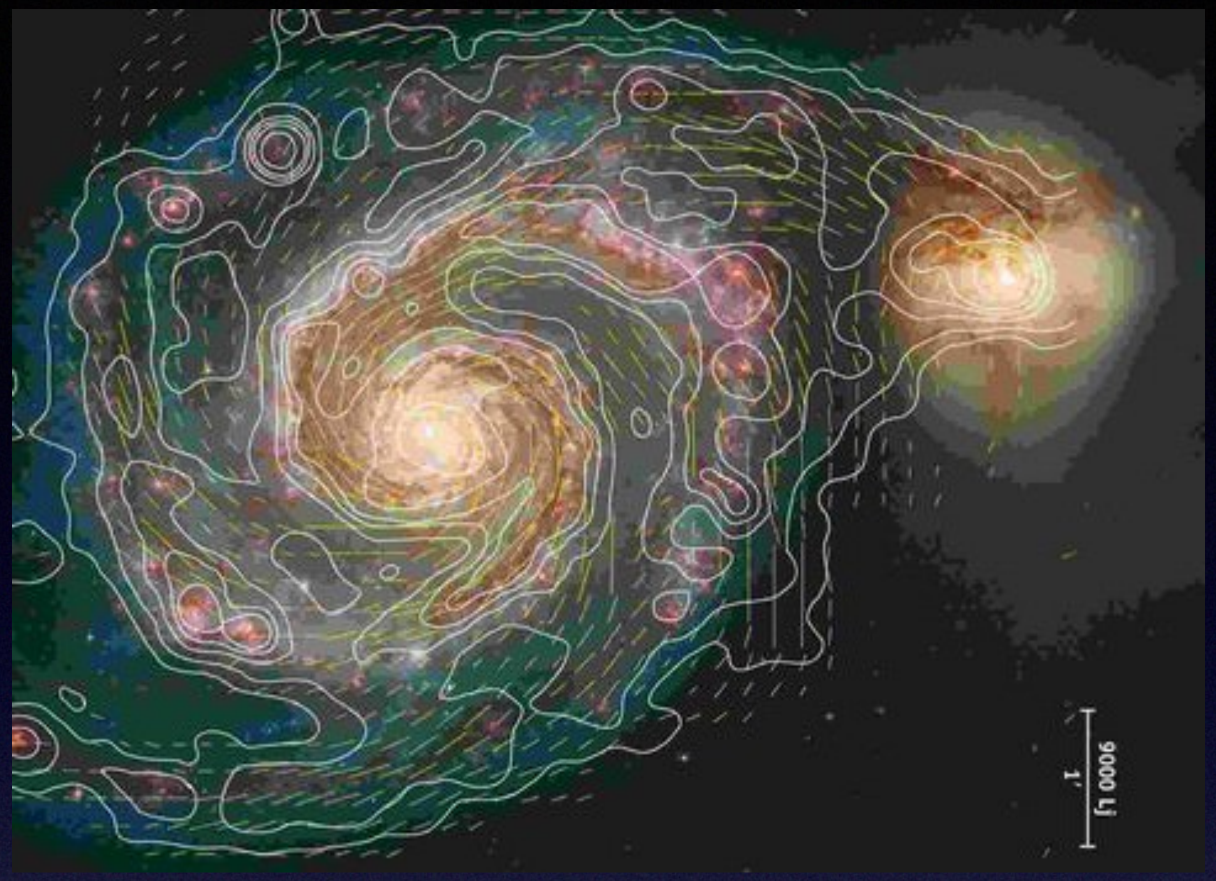
Journées ATPEM : 02/10/2025

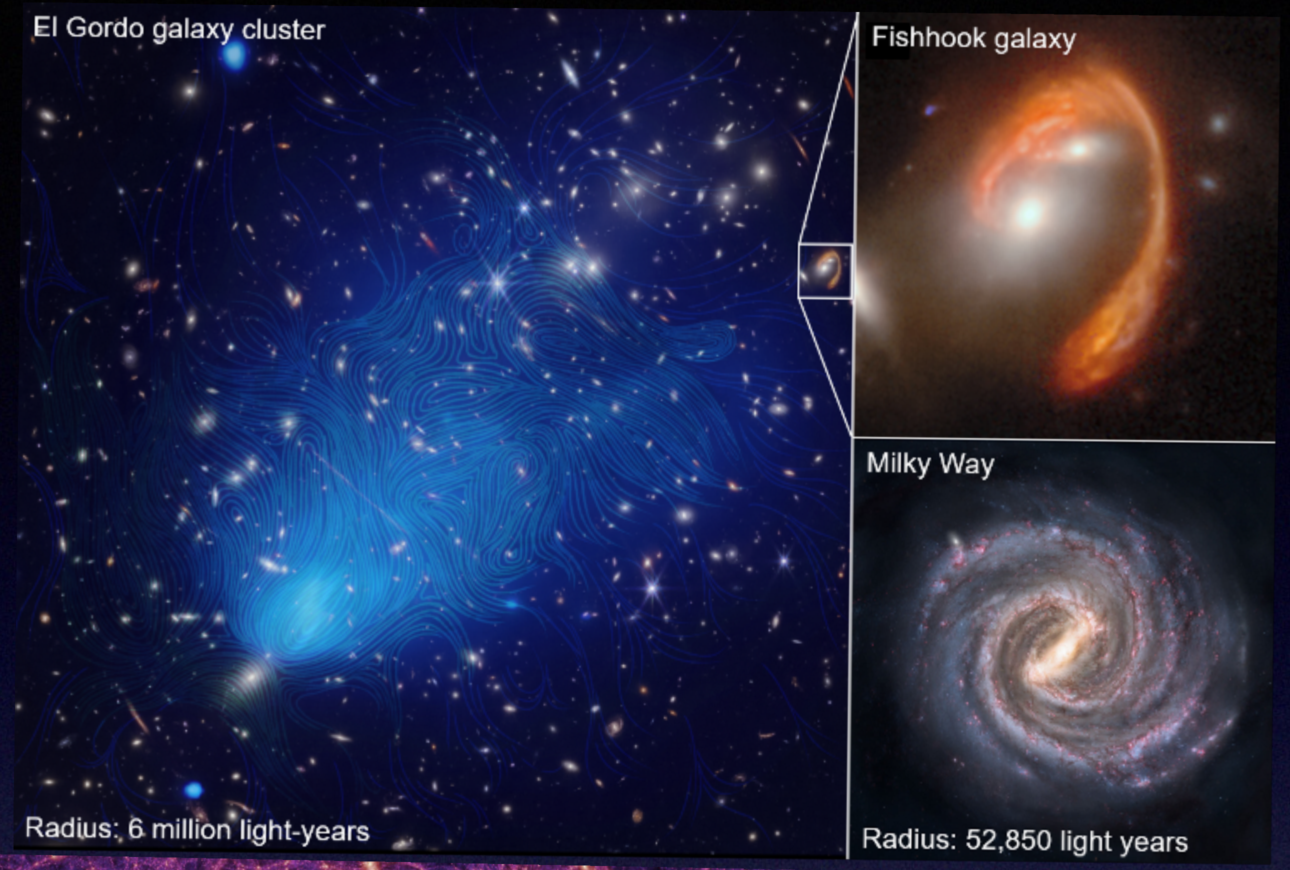
Pauline Voß for Quanta Magazine

InterGalactic Magnetic Fields

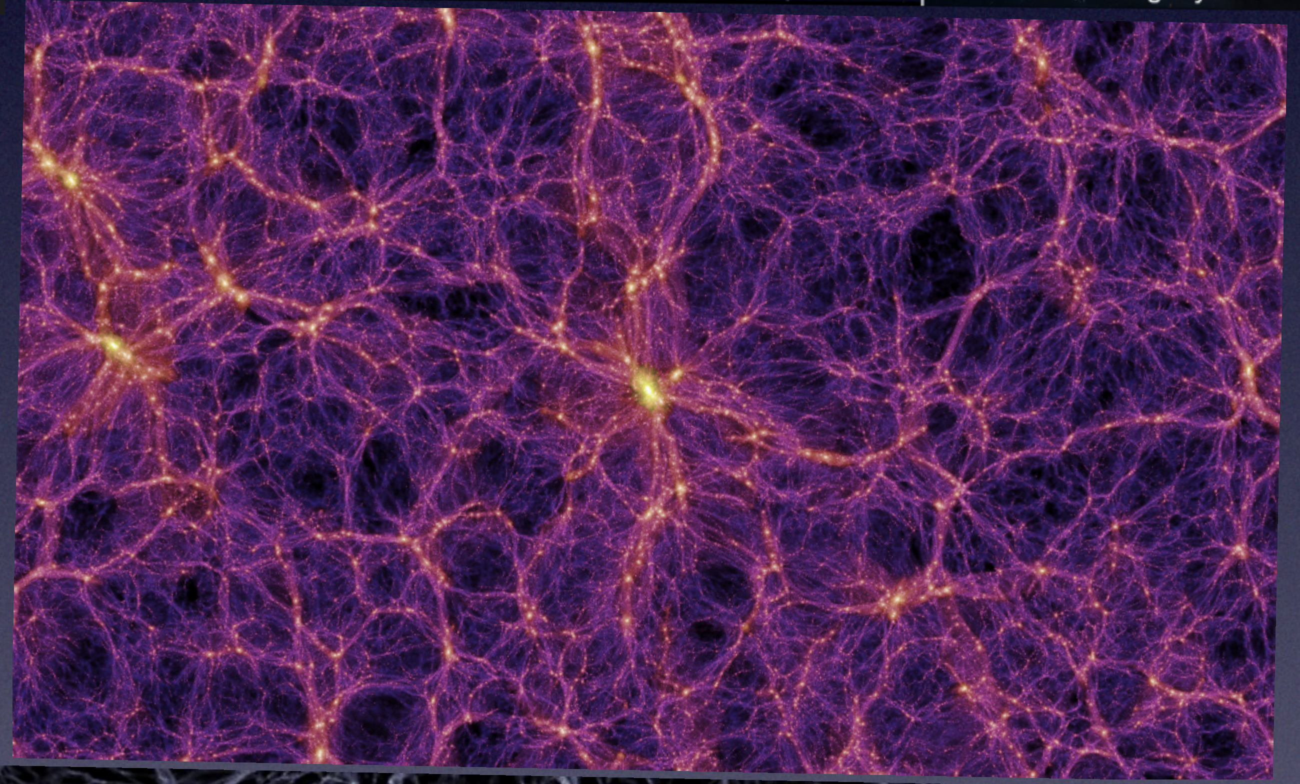
Magnetic fields universality







Refs in appendix



100 G — Magnets

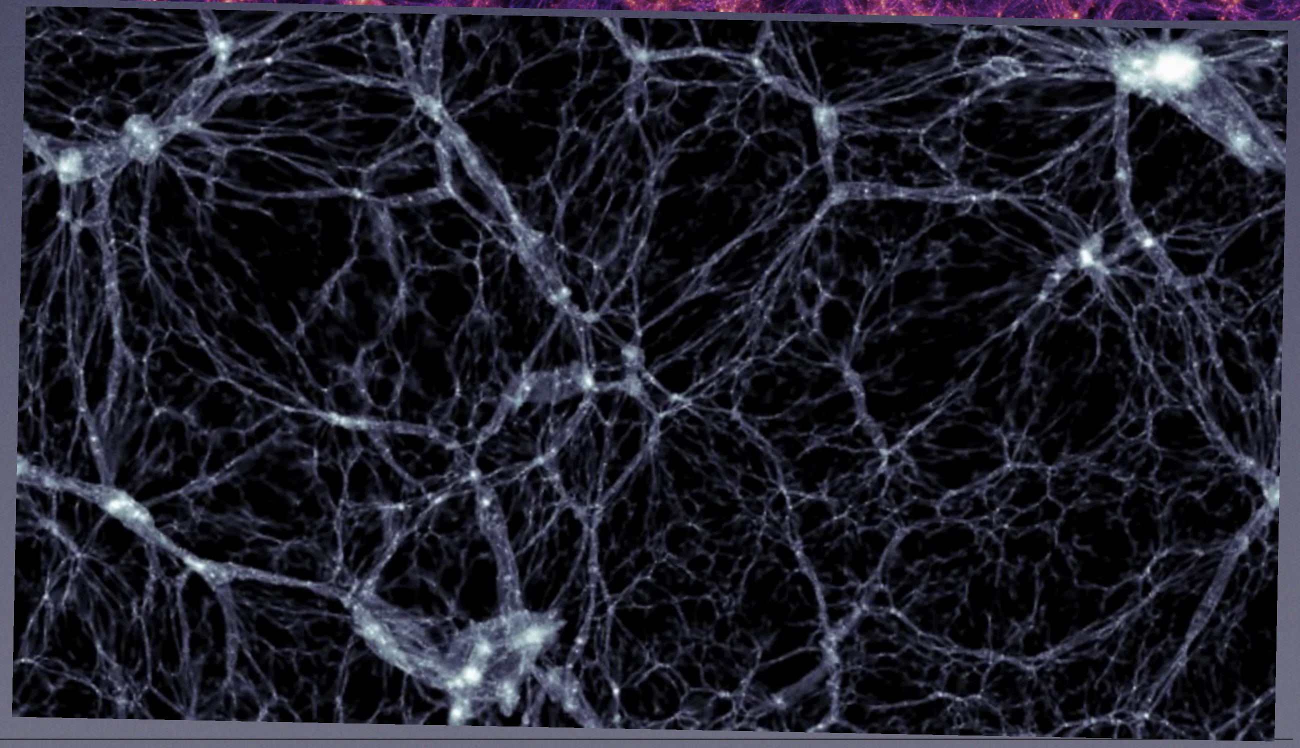
1 G — Stars

10 μG — Galaxies

30 nG — Clusters

?? fG — Cosmological: Filaments, Voids

Magnetic intensity (G)

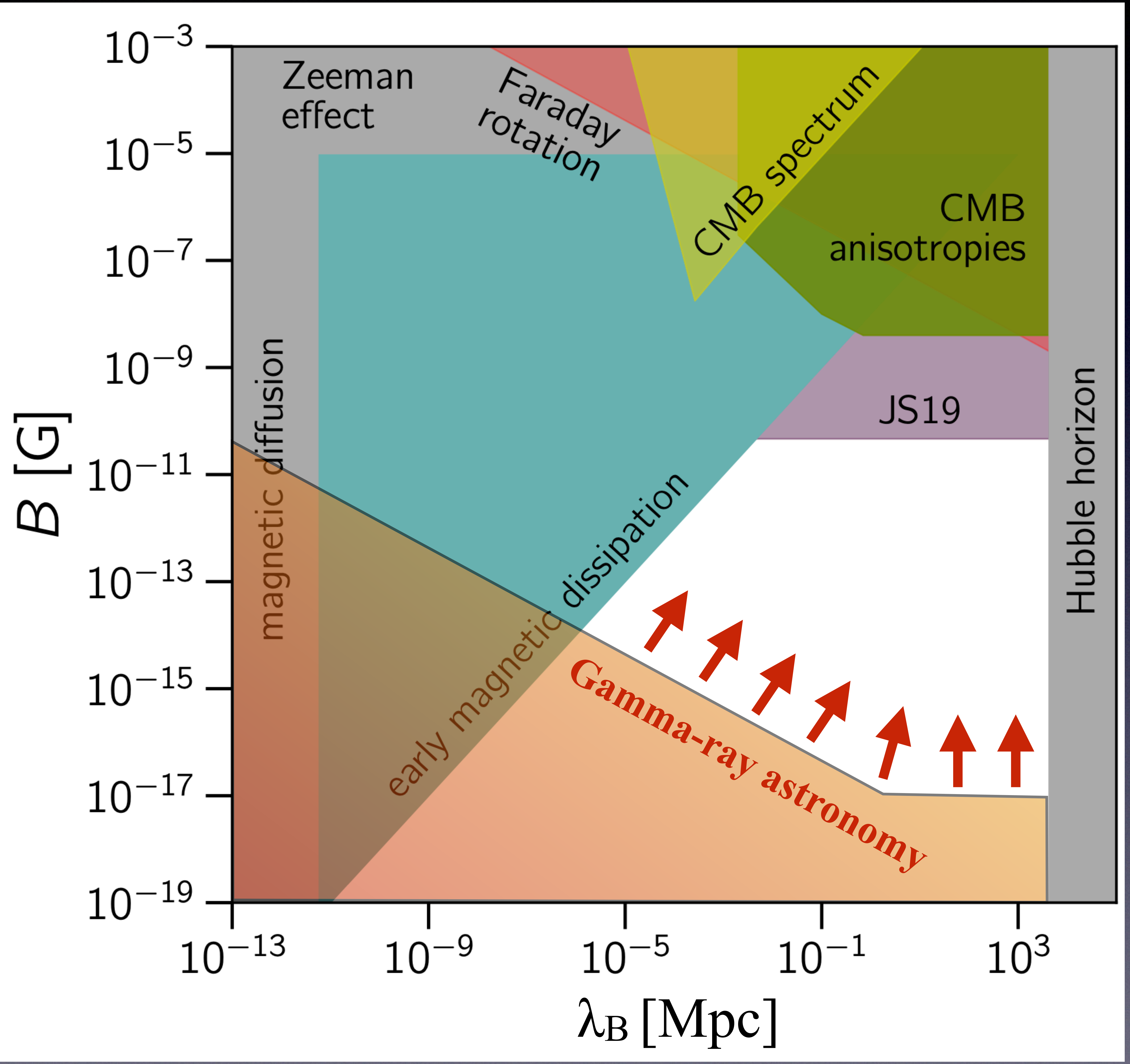


- **Magnetic fields exist at every scale**
- **What is the origin of cosmological magnetic fields ?**
  - ➡ **The InterGalactic Magnetic Field (IGMF)**

The InterGalactic Magnetic Field (IGMF)

- A relic from the Big Bang
- A turbulent field:
  - mean intensity B
  - correlation length λ_B
- Too weak for a direct detection
- Constraining the IGMF in cosmic voids might provide insights into its origin

Only lower limits with Gamma-ray astronomy
→ can be increased



Observational constraints

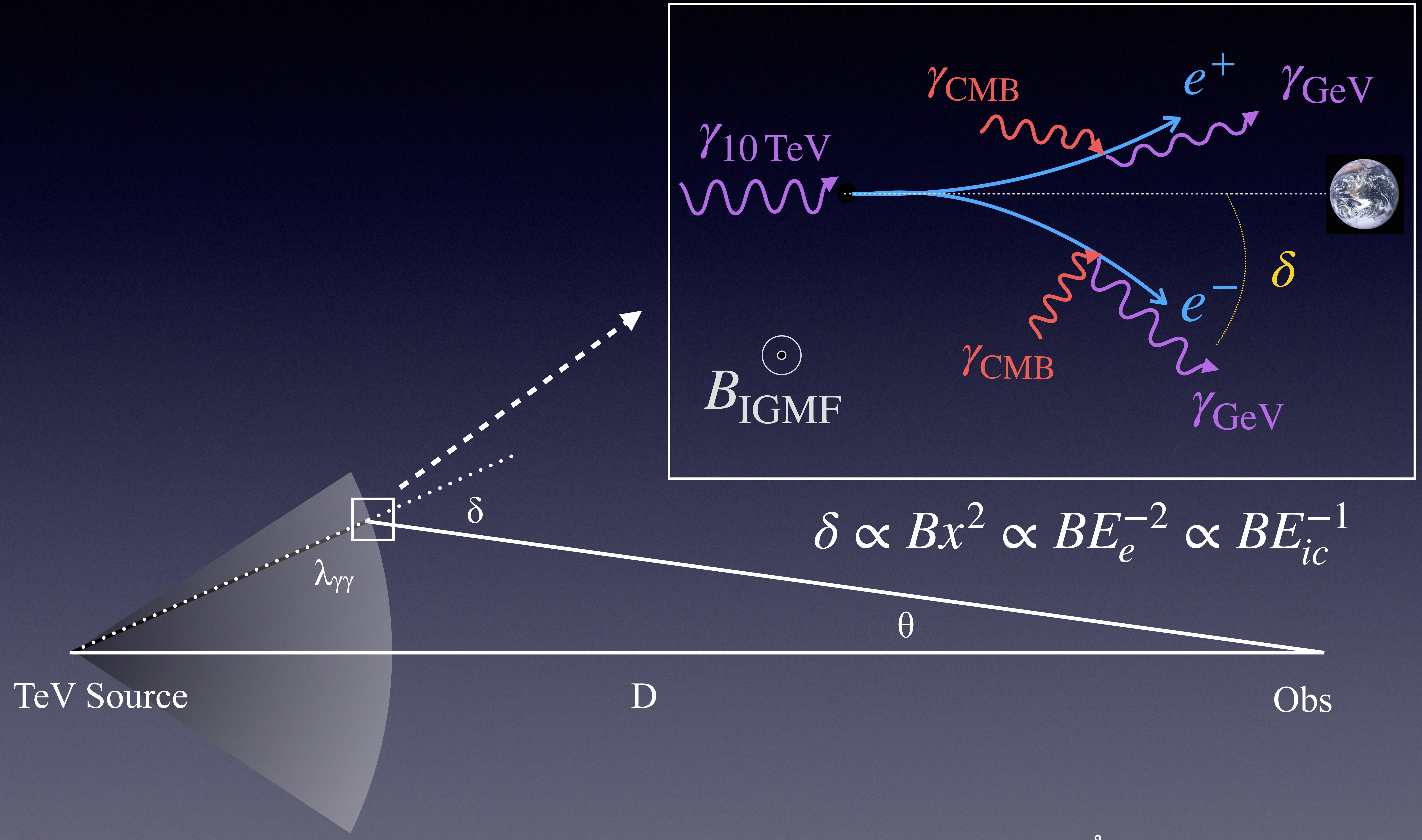
Batista et al., 2021

Expected IGMF signatures

IGMF-induced deflection on the pairs in the cascade

- **<u>Angular effect:</u>** (traditional)
  - Stable, long living sources: **AGN**
  - $B > 10^{-17}$ G to $B > 10^{-14}$ G [1]
  - Various assumptions (no plasma instability, large AGN lifetime)

- **<u>Temporal effect:</u>** (recent)
  - Transient sources: **GRBs**
  - More robust constraints
  - $B > 10^{-19}$ G (Fermi, LHAASO) [2]
  - Predicted future constraints up to $B > 10^{-17}$ G with CTAO [3]



$$\delta \propto Bx^2 \propto BE_e^{-2} \propto BE_{ic}^{-1}$$

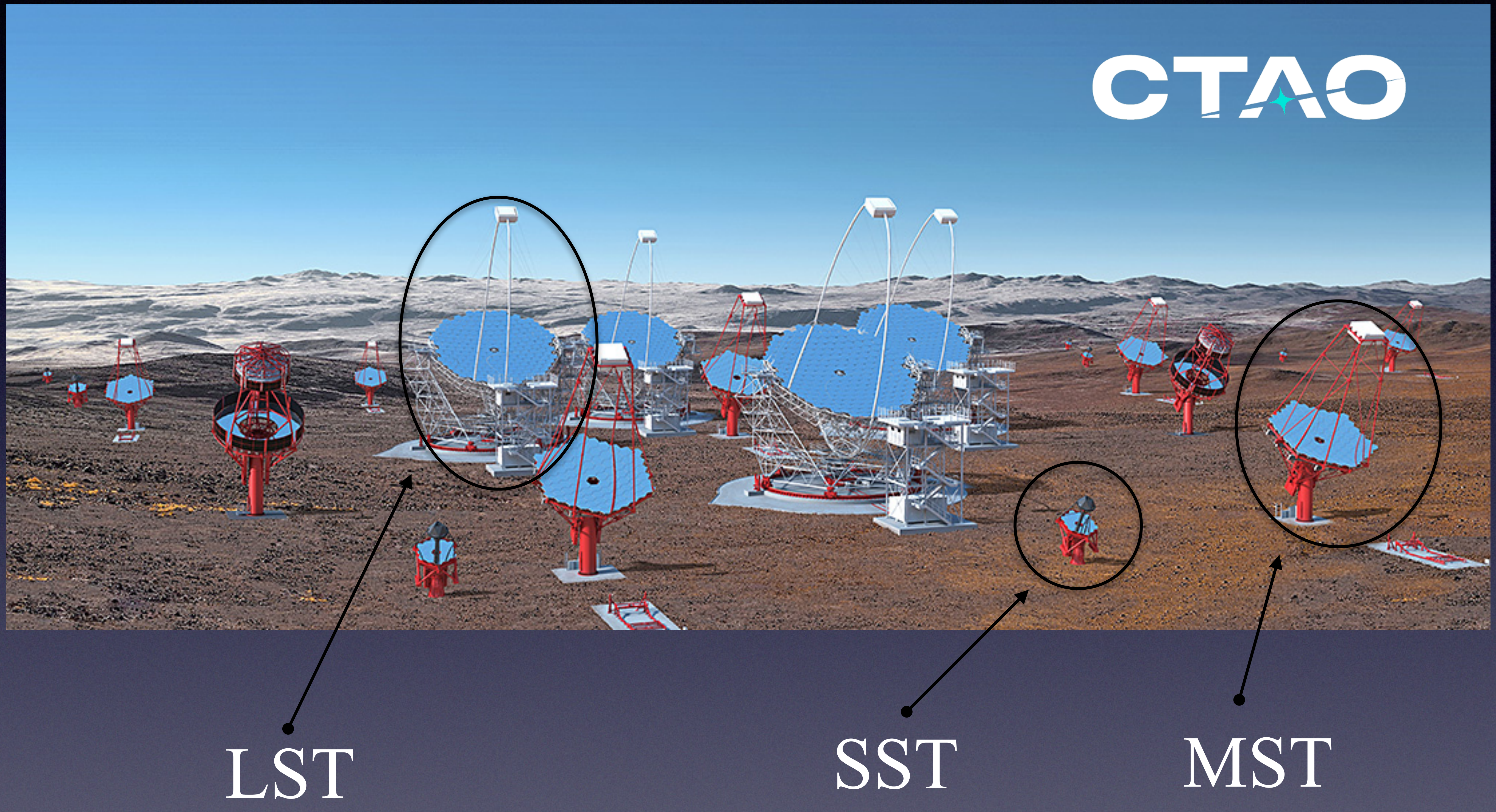
$$\Delta t \sim 1 \text{ hour} \Rightarrow \theta \sim 0.00002^{\circ}$$

$$\theta \sim 0.1^{\circ} \Rightarrow \Delta t \sim 50000 \text{ years}$$

Separated effects

Cherenkov Telescope Array Observatory

- **3 types of telescopes:**
  - Large Sized Telescope (LST): [20 - 200 GeV]
  - Medium Sized Telescope (MST): [0.1 - 10 TeV]
  - Small Sized Telescope (SST): [1 - 300 TeV]
- **Alpha configuration:**
  - North: 4 LST, 9 MST —> 30s slewing time
  - South: 14 MST, 37 SST —> 90s slewing time
- **Construction schedule:**
  - 1st LST already operational
  - 2nd LST expected this year
  - Alpha configuration prototype in 2027
  - Full construction in 2030
- **GRB observations prospects:**
  - 2 VHE GRBs per year above 5σ
  - 1 very bright GRB every two years above 50σ



CTAO southern site (3 km wide)

Simulation & Results

Methodology

- **Full 3D Monte Carlo code (CascadEl, *Fitoussi et al. 2017*) + post-processing**

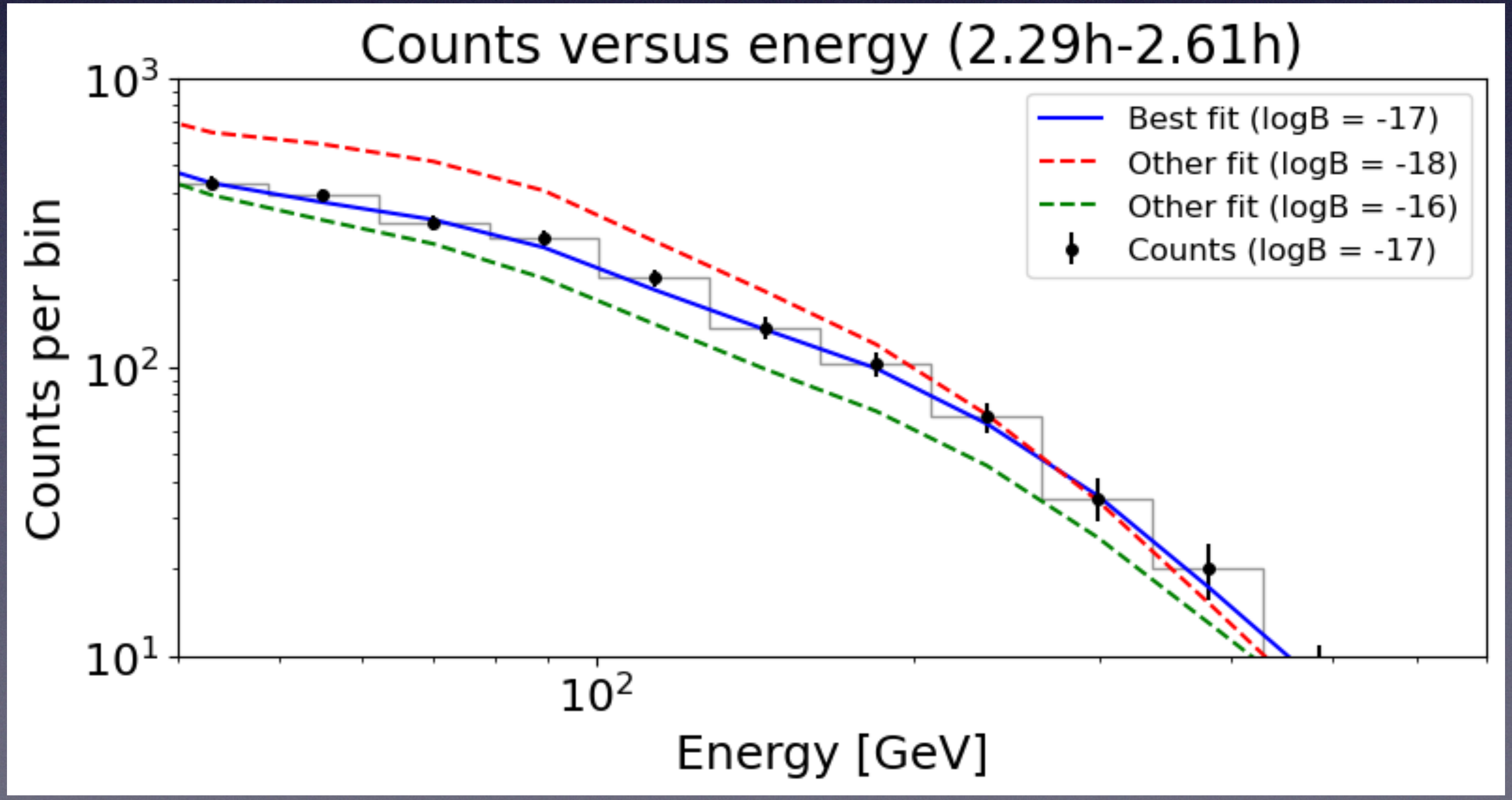
- **Input: B, λ_B, z, $\Phi_{\mathrm{int}}(\mathbf{E},\mathbf{t})$**
  - **Mean over 100 IGMF realizations**
  - **Full intrinsic evolution in time**
  - **GRB typically modeled with a Power-Law**

$$\Phi(E, t > t_{\min}) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma} \left(\frac{t}{t_0}\right)^{-\alpha} \mathrm{e}^{-E/E_{\mathrm{cut}}}$$

- **Output: $\Phi_{\mathrm{cascade}}(\mathbf{E},\mathbf{t})$**

- **Data generated with CTAO**
  - **GRBs 190114C and 221009A**
  - **North + South analysis**
  - **Publicly available IRFs**
  - **Realistic observation window**

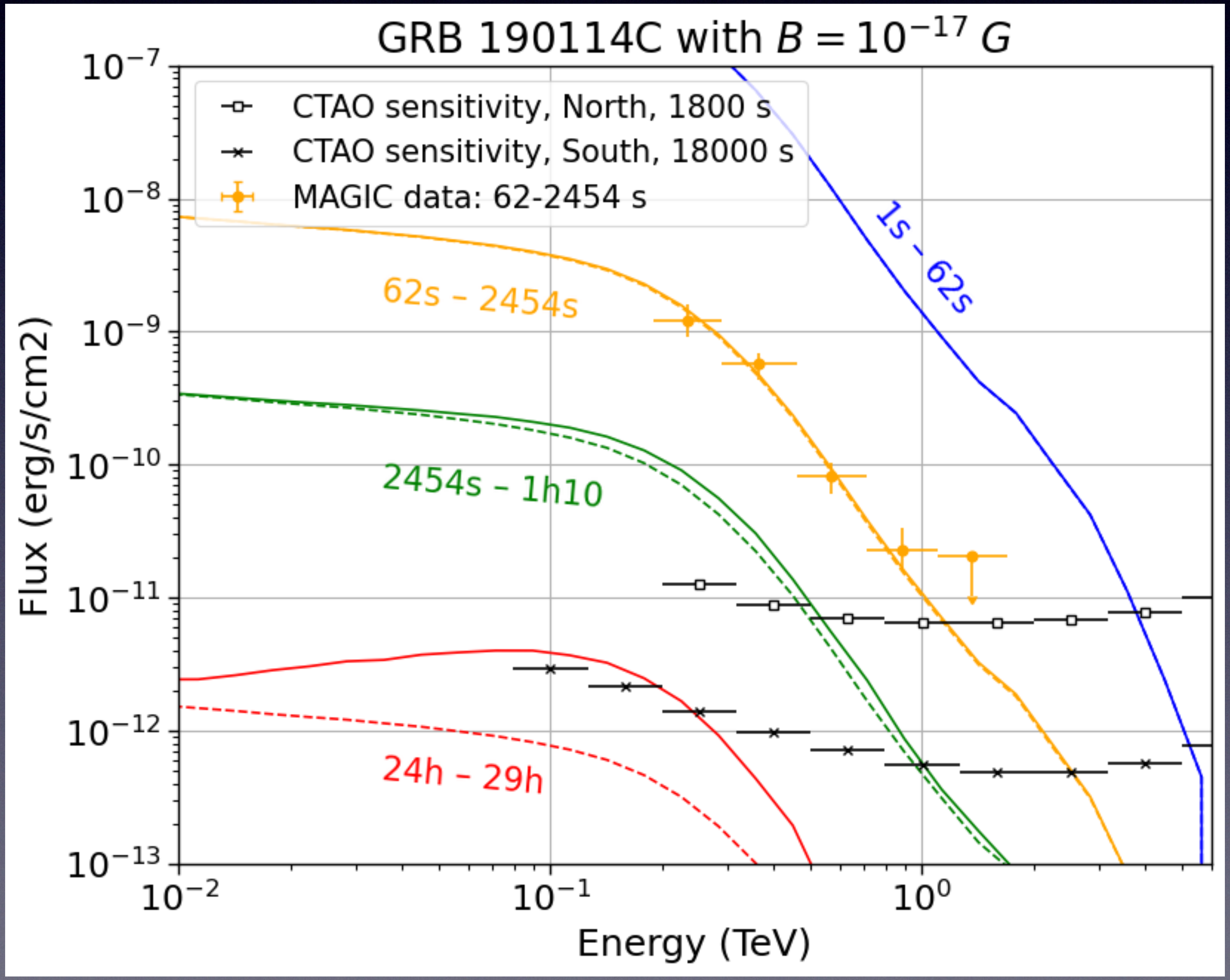
- **Spectral-temporal fit with Gammapy**

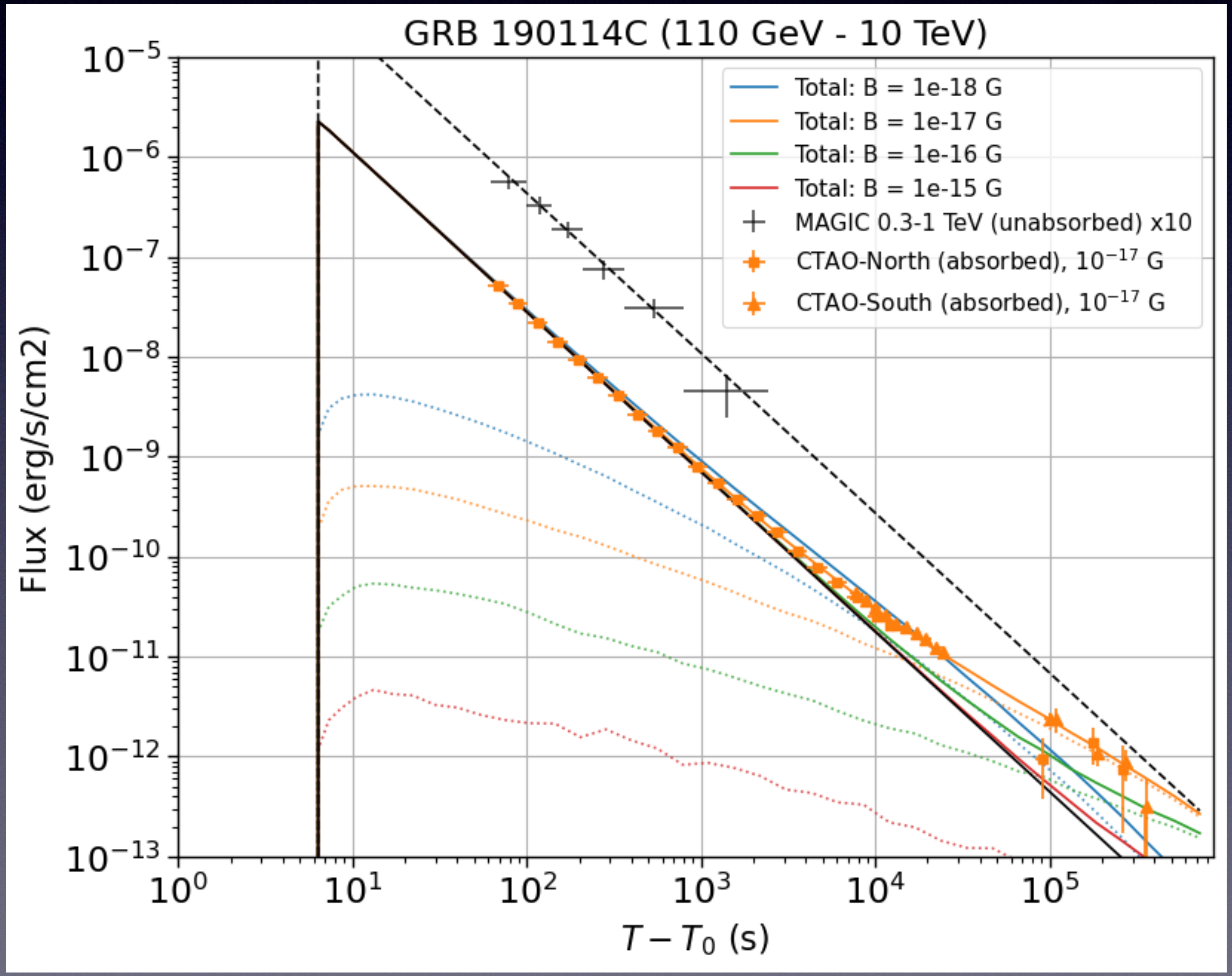


Test case: GRB 190114C

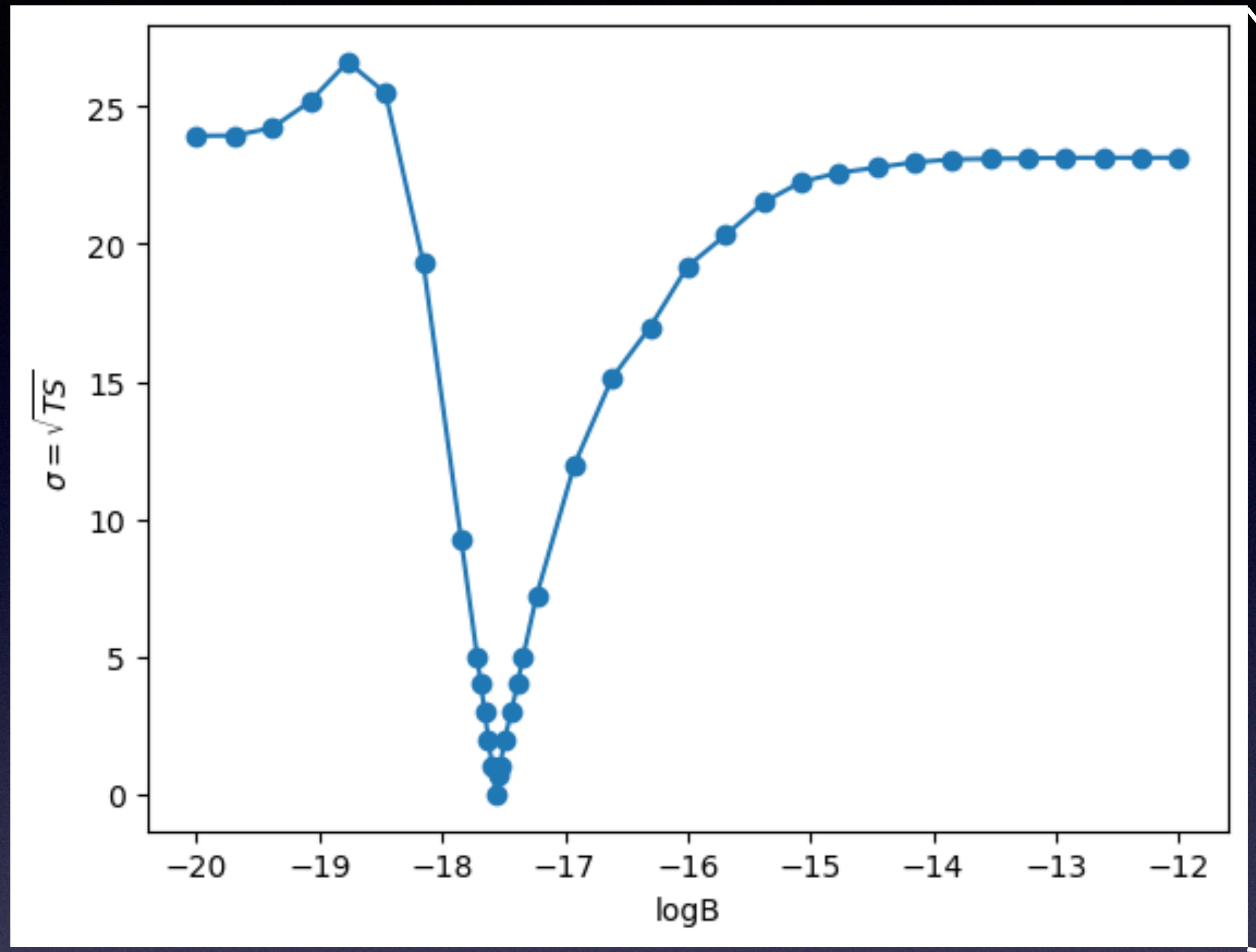
$z = 0.425$
$\lambda_B = 1$ Mpc

$$\Phi(E, t > 6\text{ s}) = \Phi_0 \left(\frac{E}{1\text{ TeV}}\right)^{-2.22} \left(\frac{t}{100\text{ s}}\right)^{-1.60} \exp\left(\frac{-E}{10\text{ TeV}}\right)$$

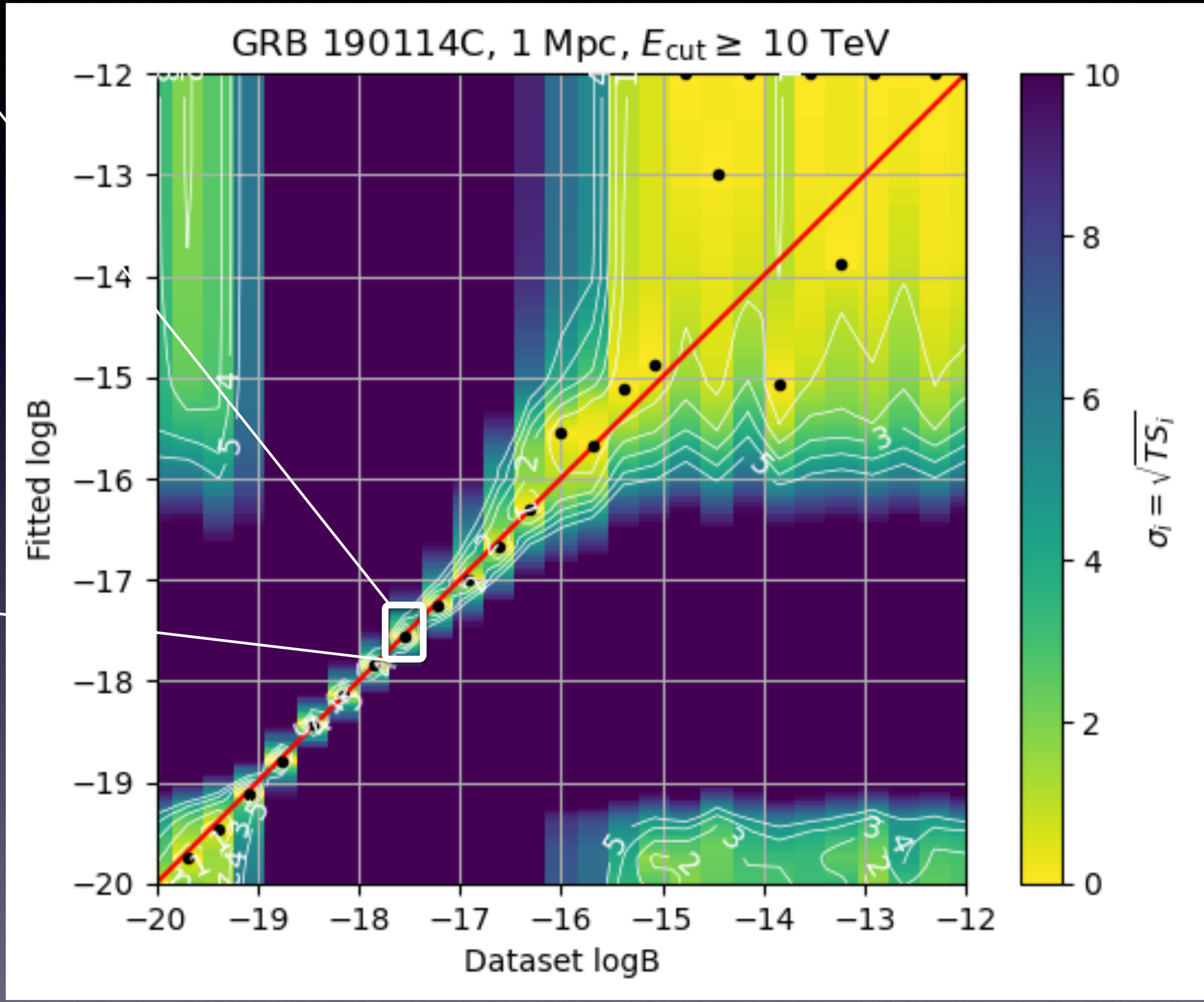




Spectral-temporal fit



Profile for $B = 10^{-17.5}$ G

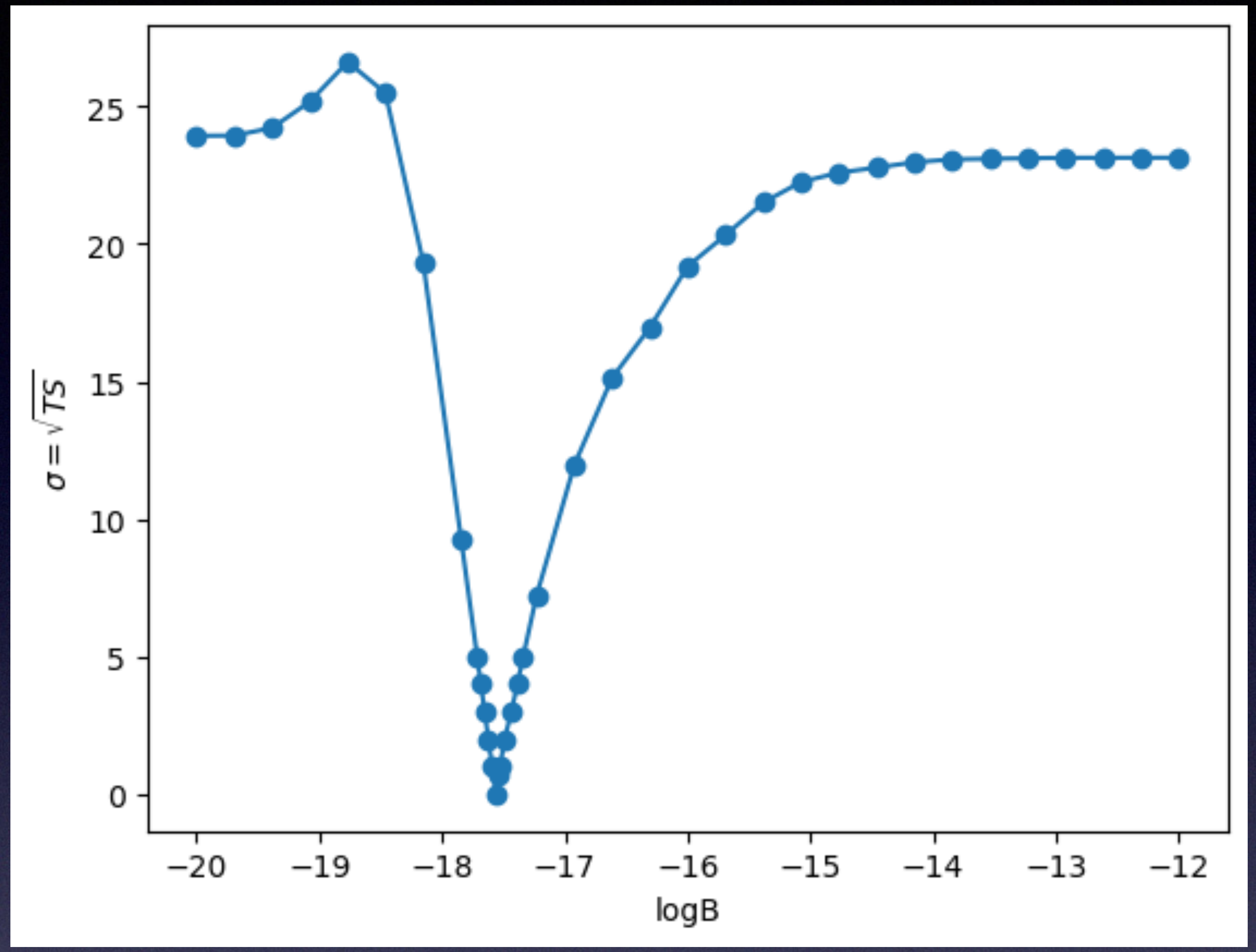


Fitted B
vs
Assumed B

Observation criteria:
- ✓ **Night**
- ✓ **Altitude above 24°**

North: 60° zenith ⇒ 110 GeV - 30 TeV
South: 20° zenith ⇒ 60 GeV - 30 TeV

Spectral-temporal fit



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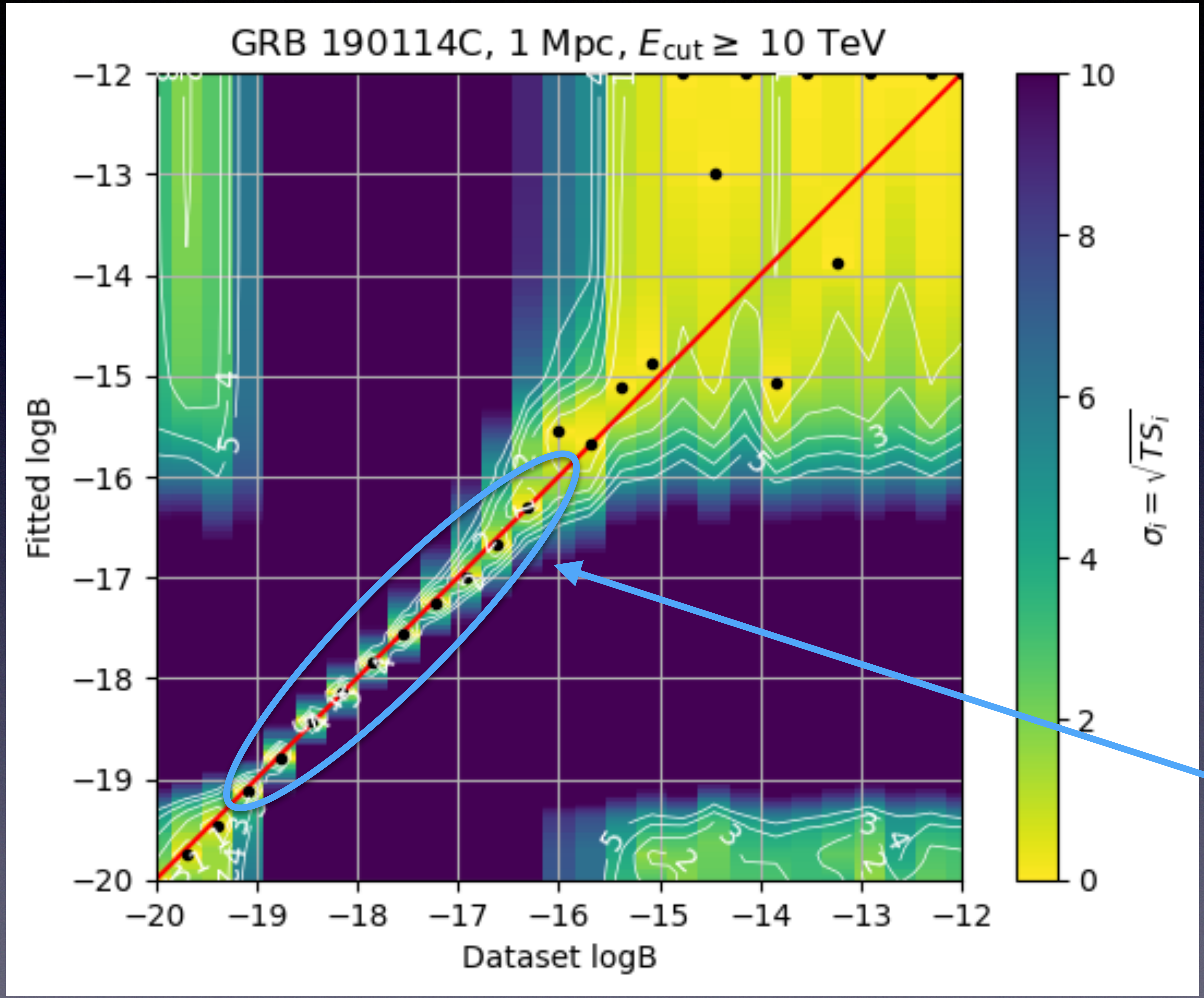
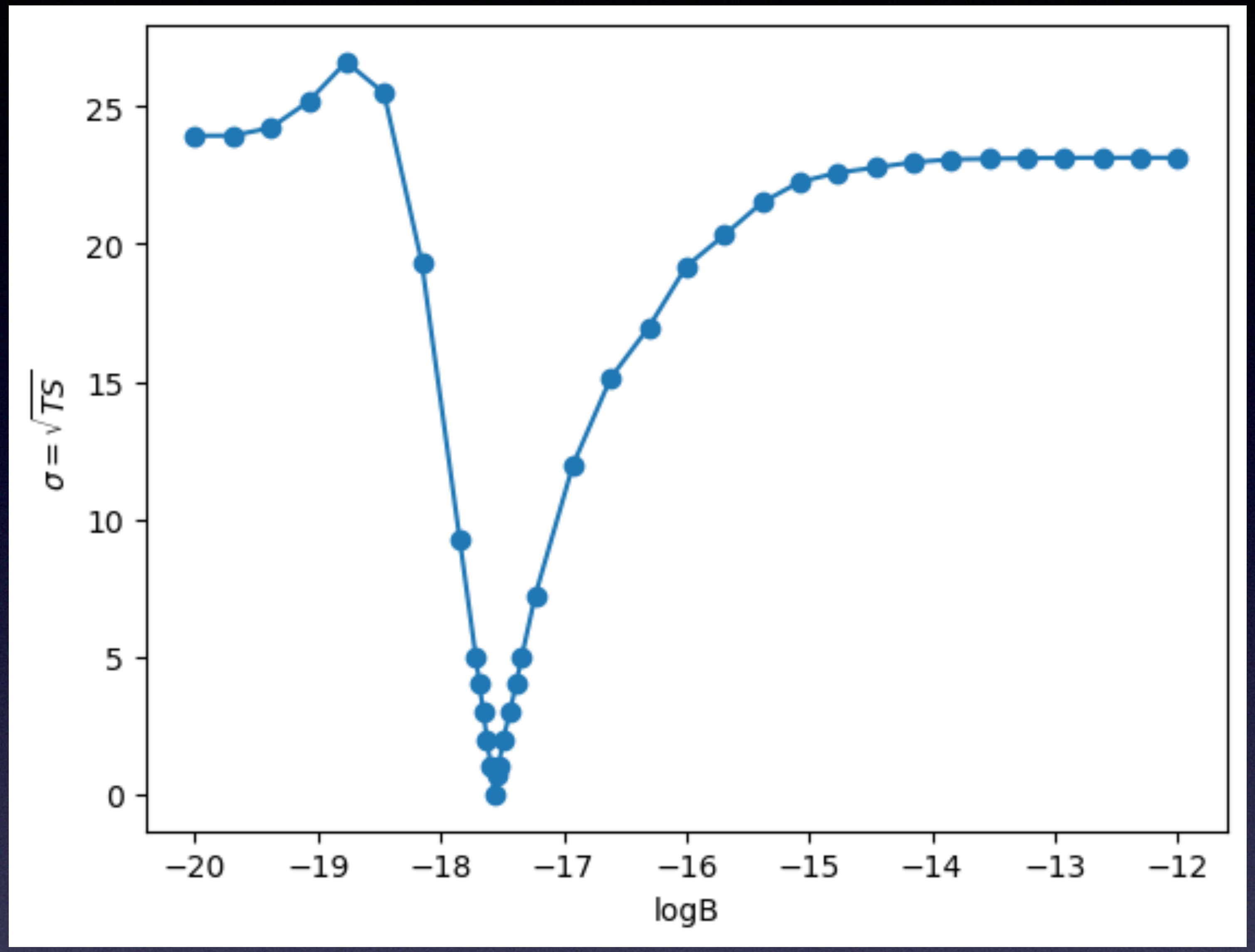


Fitted B vs Assumed B

Detectable cascade

Spectral-temporal fit



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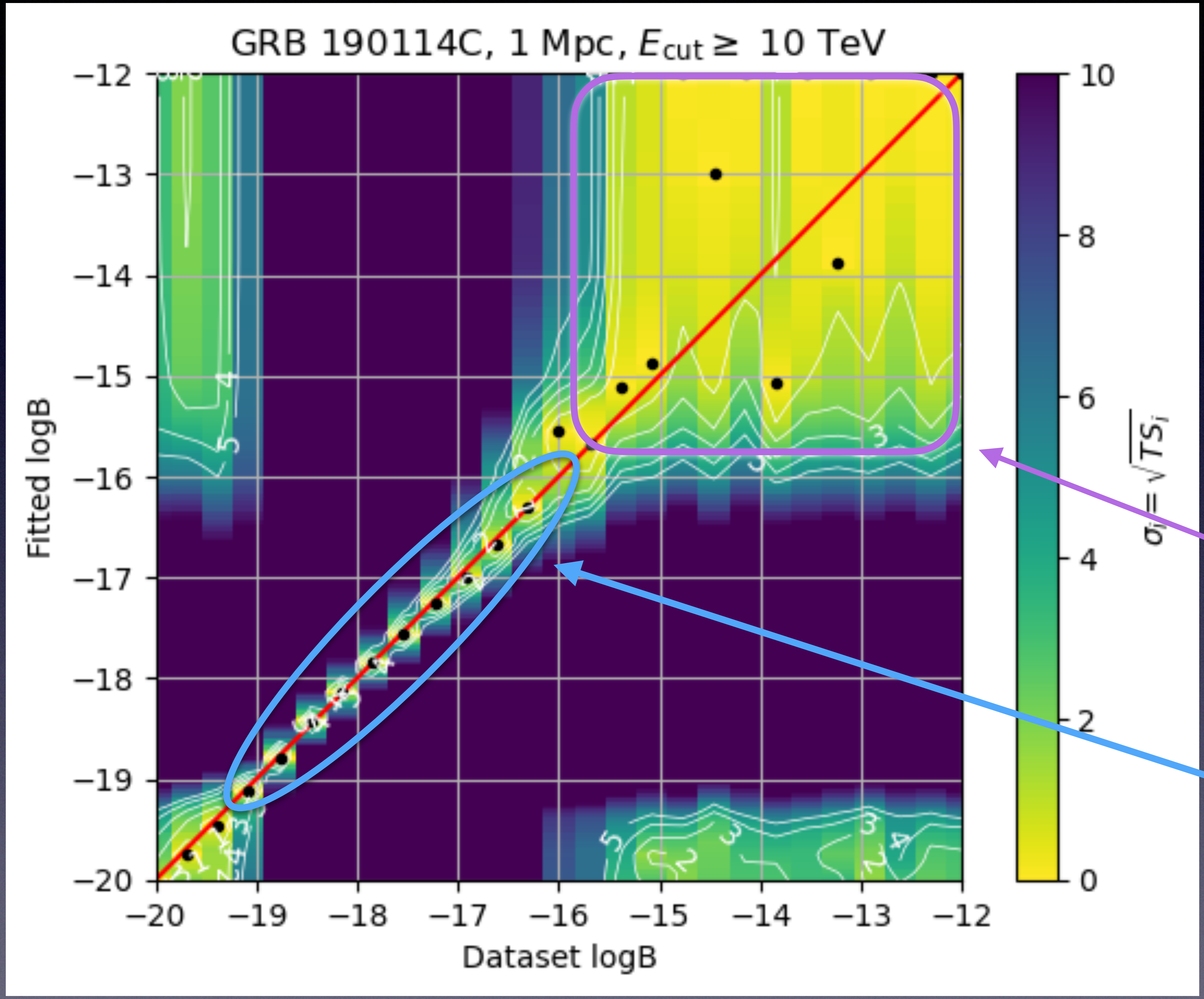
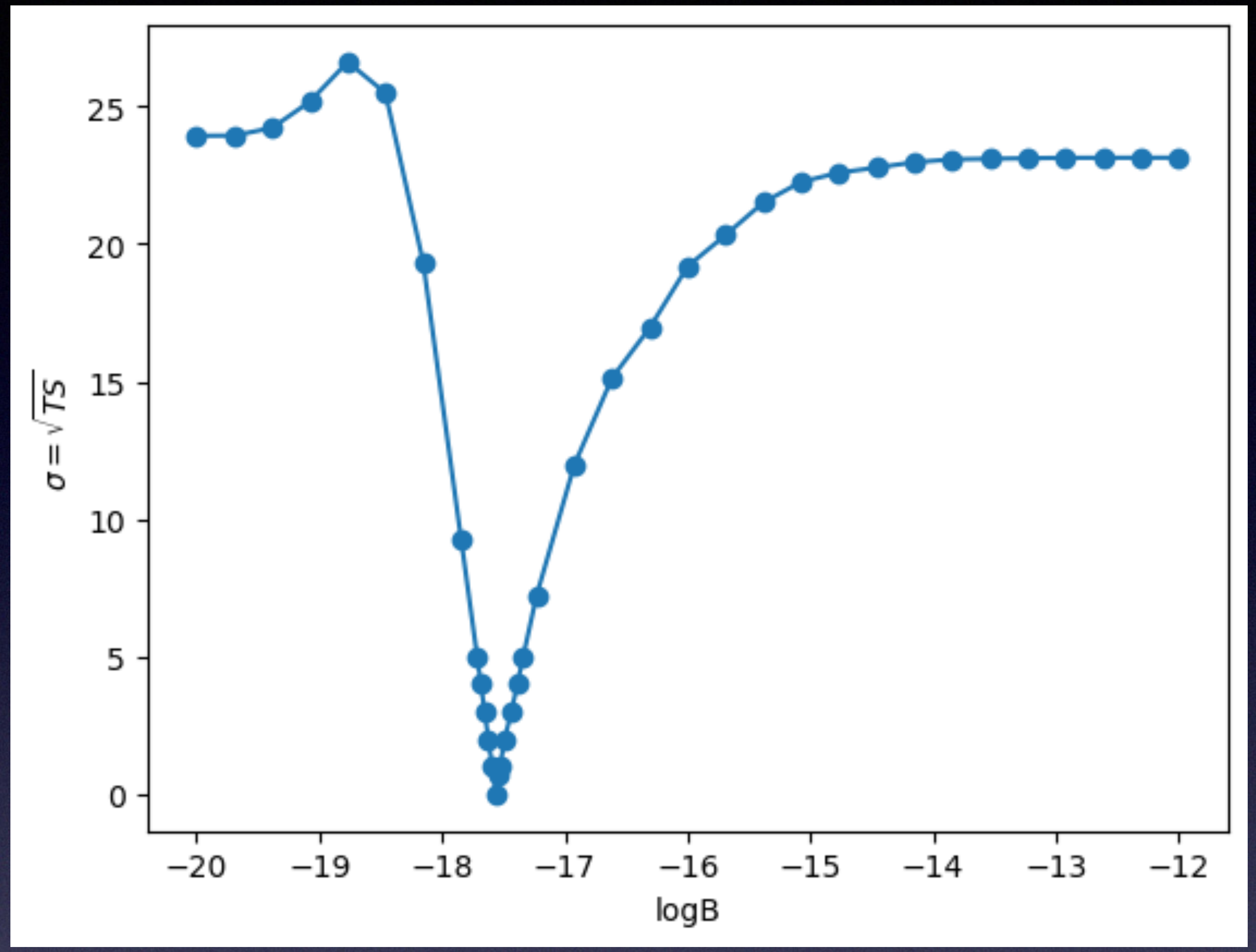


Fitted B
vs
Assumed B

Undetectable cascade

Detectable cascade

Spectral-temporal fit



Profile for $B = 10^{-17.5}$ G

Observation criteria:
- ✓ **Night**
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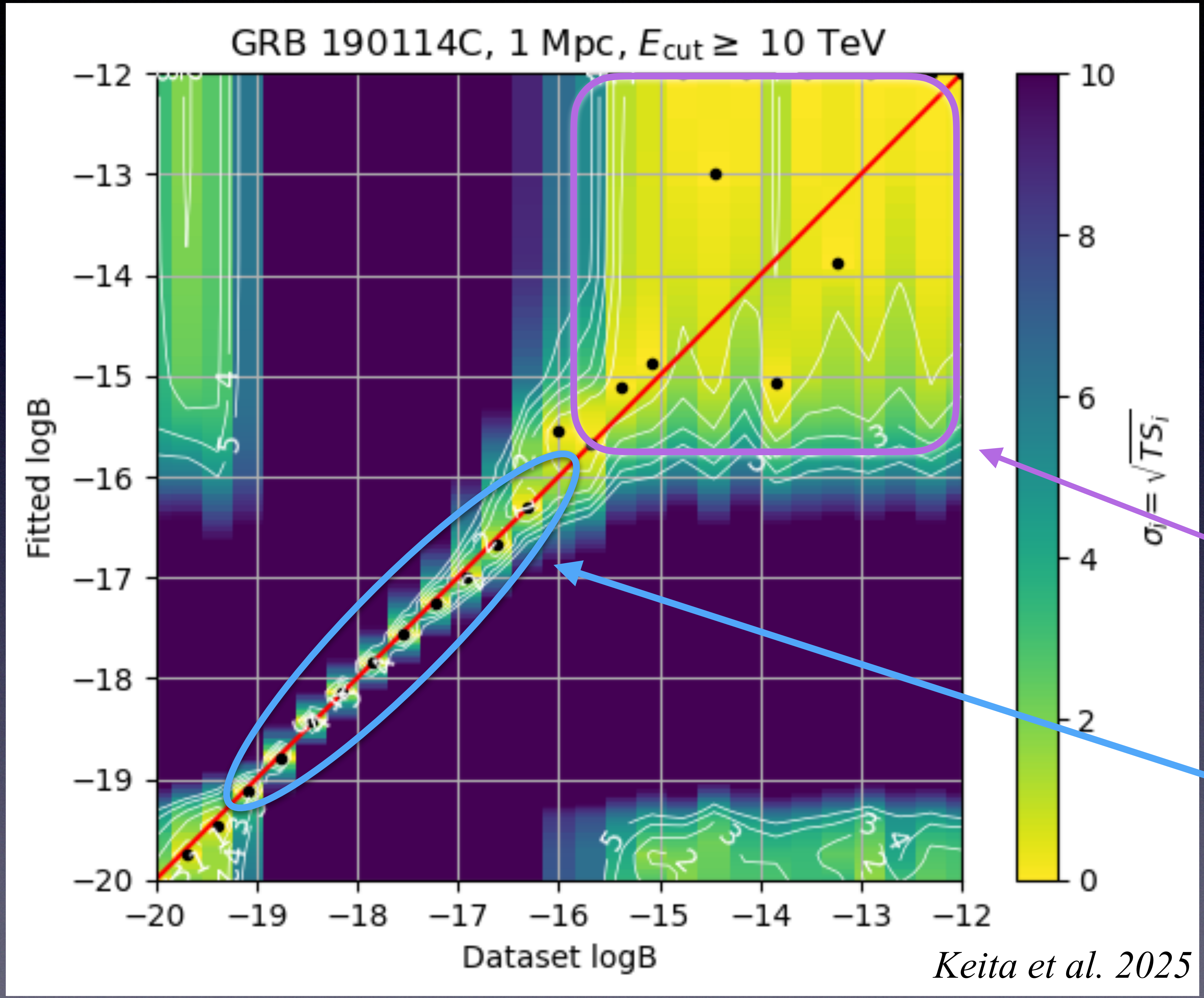
North: 60° zenith ⇒ 110 GeV - 30 TeV
South: 20° zenith ⇒ 60 GeV - 30 TeV



Keita et al. 2025

Fitted B vs Assumed B

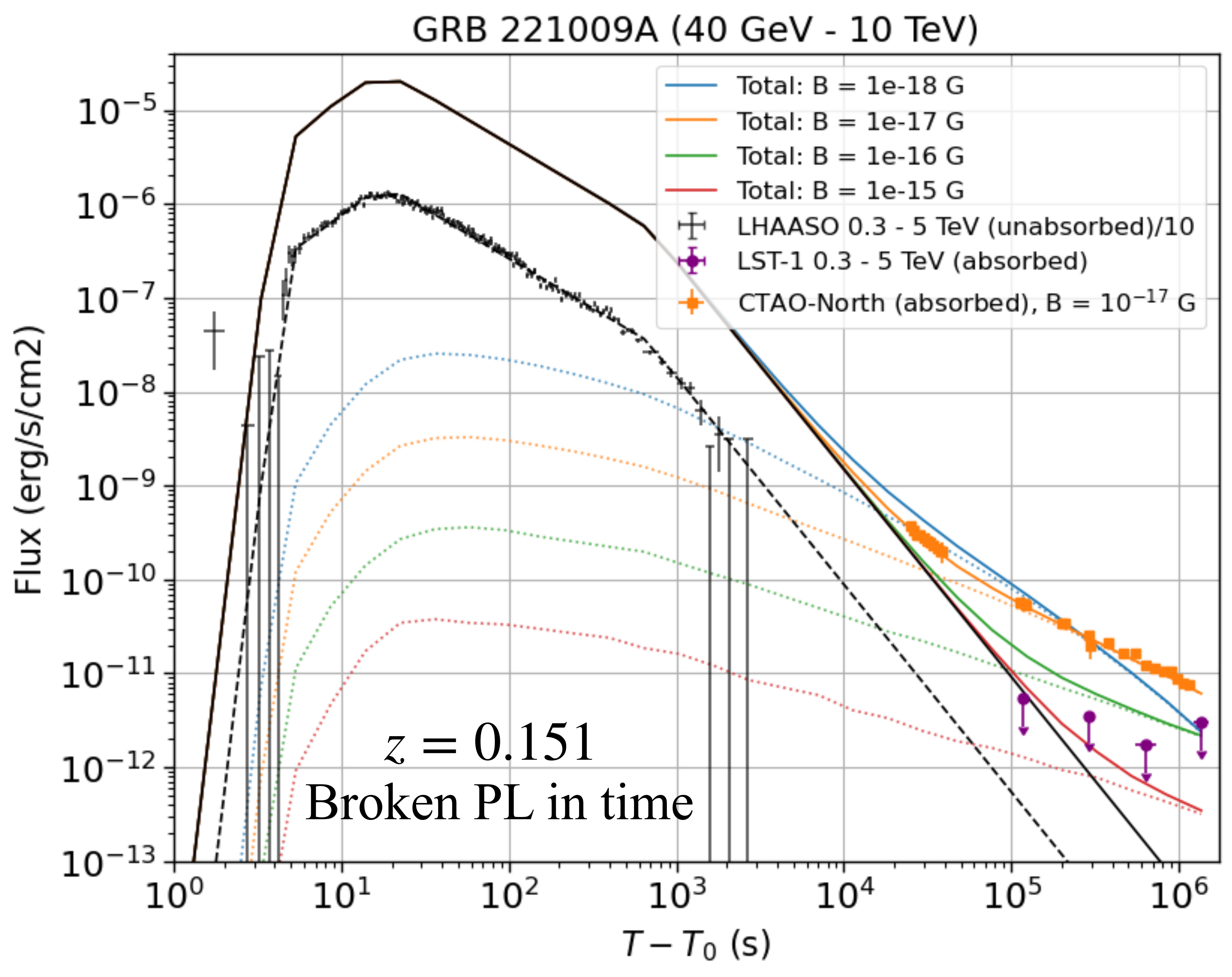
Undetectable cascade

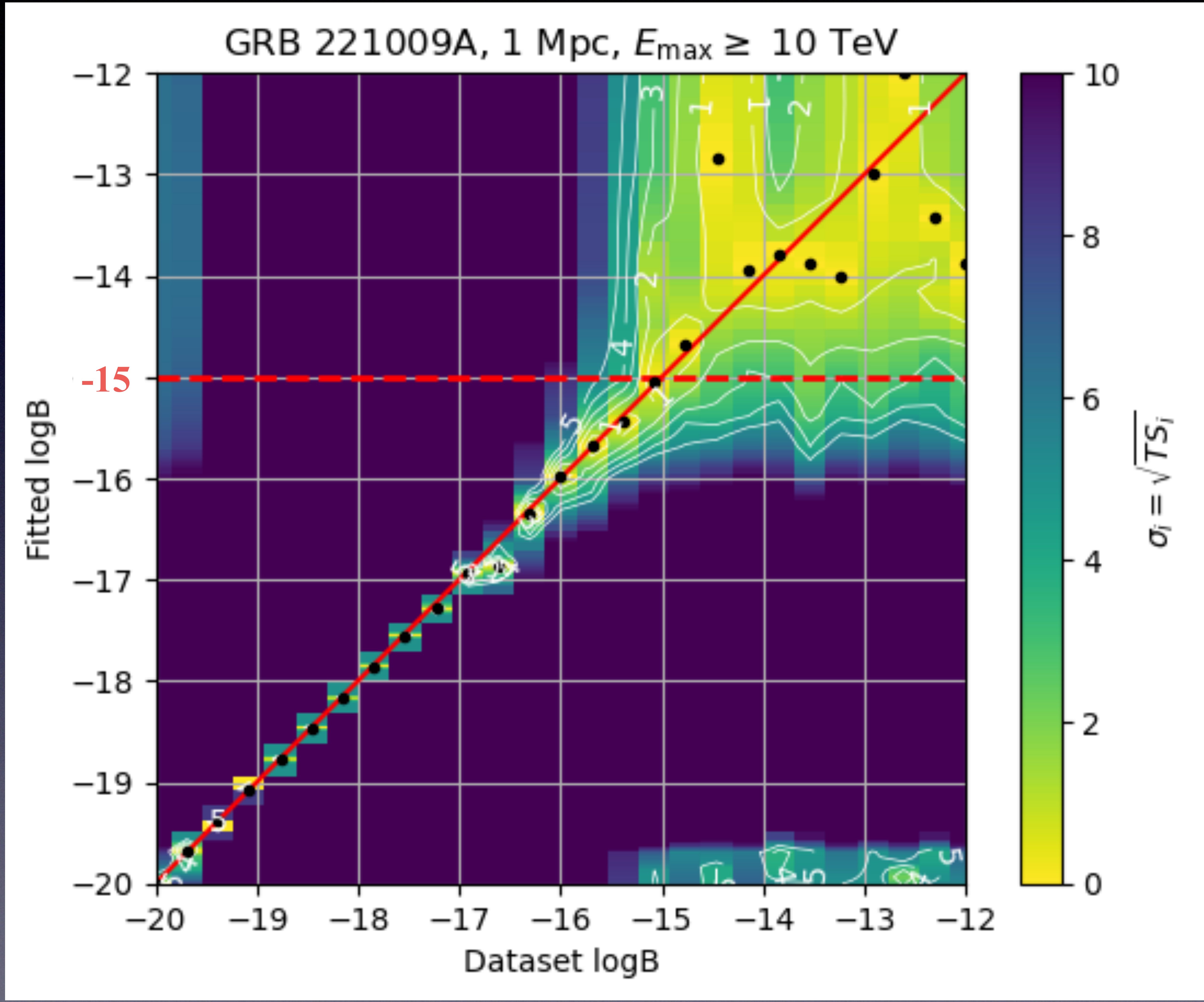
Detectable cascade

CTAO constraints for $B \in \left[10^{-19}\ \mathrm{G},\ 10^{-16}\ \mathrm{G}\right]$ range

Improvement!

Extreme case: GRB 221009A





- LST-1 data from 2nd to 19th nights [4]
  - ➡ $B \leq 3 \times 10^{-17}$ G **excluded**
  - ➡ 4.1σ **point compatible with** $B = 3 \times 10^{-17}$ G
- $B \leq 10^{-15}$ G **excluded if full array**

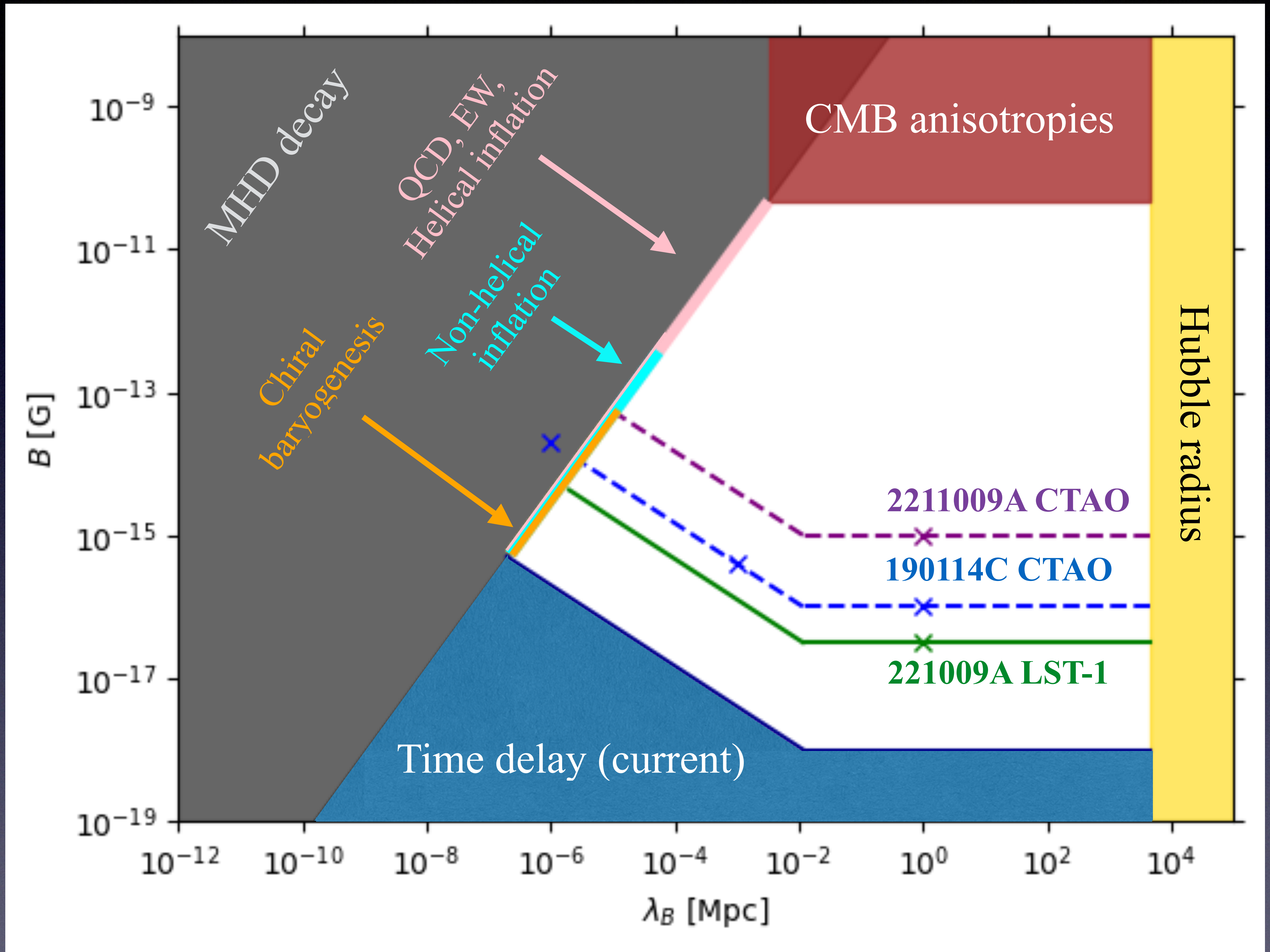
Conclusion

- **Complete framework for IGMF-modified cosmological cascade**

- **Preliminary results with GRBs (paper under review)**
  - Detectable for several nights with CTAO
  - LST-1: $B \geq 3 \times 10^{-17}$ G
    Consistent with $B = 3 \times 10^{-17}$ G
  - Expected full array: $B \geq 10^{-15}$ G

- **Relevant quantities:**
  - Absorbed TeV flux (redshift, hardness and cutoff)
  - Ratio primary-secondary at late times (time decay)
  - Ideal intrinsic model: $0.1 < z < 0.6$, hard spectrum, large cutoff, short temporal decay

- Favourable observation conditions:
  - Early data (intrinsic flux characterisation)
  - High zenith angle (weak magnetic fields or large redshifts)



New constraints and predictions

Now: <u>statistical generalisation (synthetic population)</u>

Appendix

Slide 3 figures references (left to right, up to down)

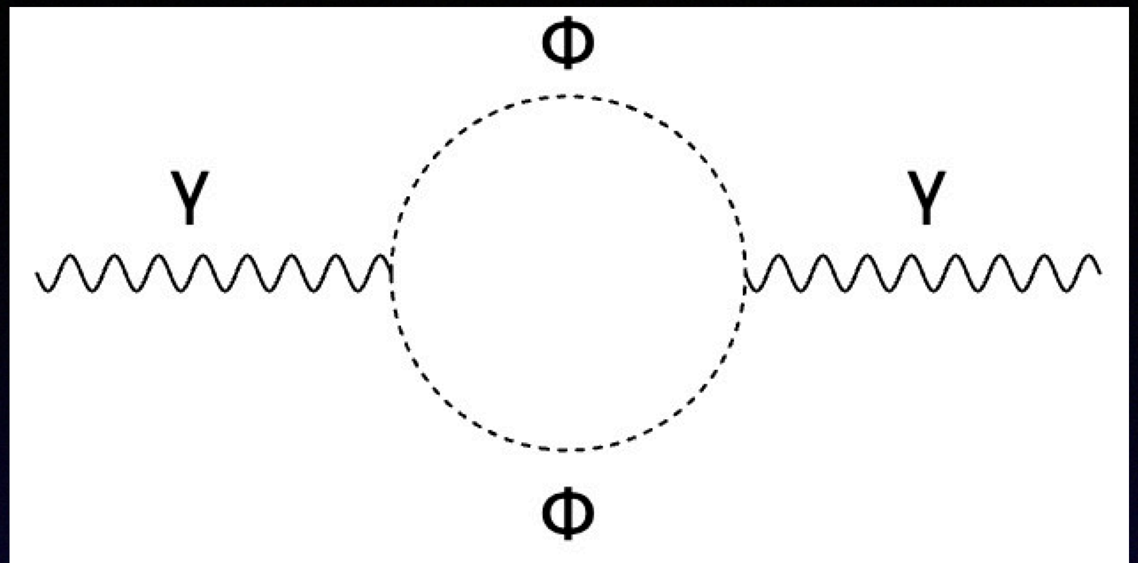
- My fridge, **Keita, September 17, 2024.**
- Sun magnetosphere, **Schriver and Title, 2011.**
- M51 (Hubble telescope) intensity contours, **Effelsberg and VLA, MPIfR Bonn**
- Left: El Gordo cluster (Chandra X-ray observatory & Ground-based telescopes), Right: Fishhook galaxy and Milky-Way galaxy, **NASA/ESA/CSA**
- An image from the millenium simulation, **Springel+2005**
- Dark matter distribution, **Markus Haider/Illustris collaboration**

Bibliography

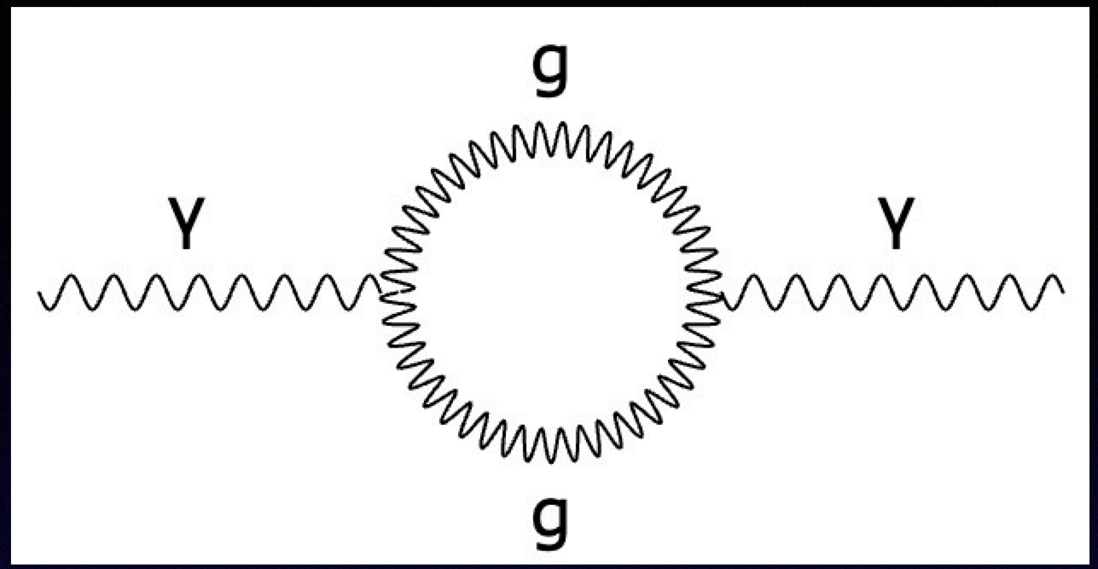
- [1]: **The Gamma-ray Window to Intergalactic Magnetism**, *Alves Batista and Saveliev*, July 2021.
- [2]: **Constraint on intergalactic magnetic field from Fermi/LAT observations of the "pair echo" of GRB 221009A**, *Volk et al.*, June 2023.
- [3]: **Prospects for detection of the pair-echo emission from TeV gamma-ray bursts**, *Miceli et al.*, May 2024.
- [4]: **GRB 221009A observations with LST-1 at VHE gamma rays**, *Aguasca-Cabot et al.*, October 2023.

Two main methods

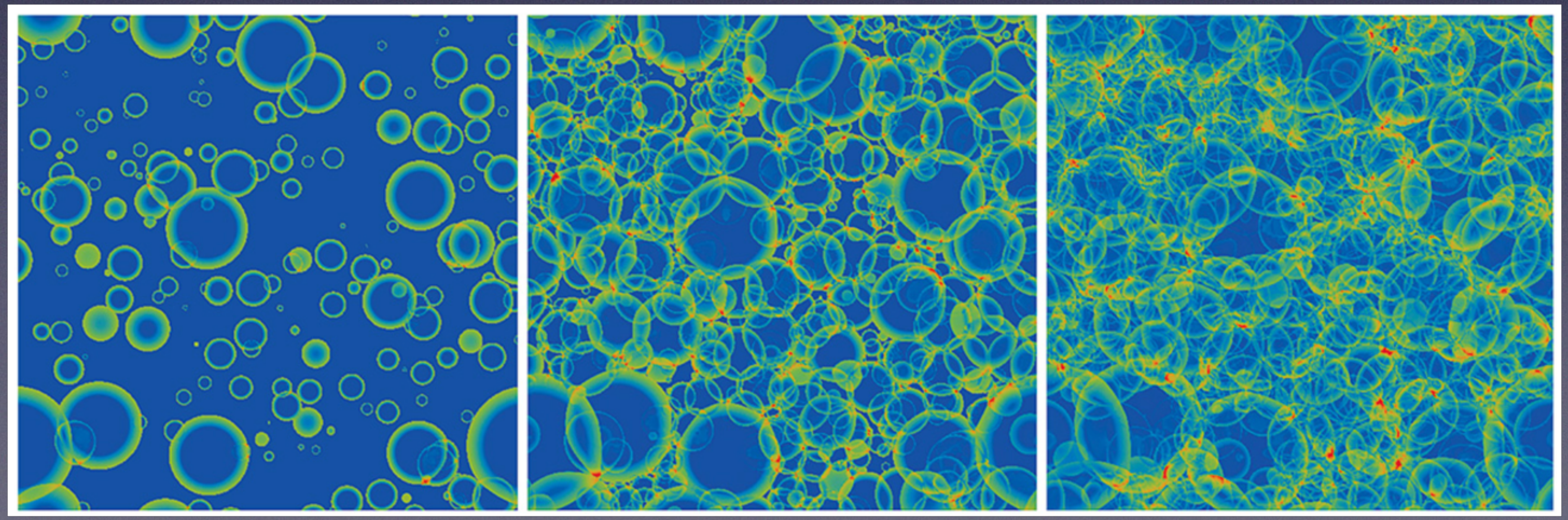
- **Inflationary coupling** $\mathscr{L} \Rightarrow A_\mu \Rightarrow P_B \Rightarrow \rho_B \Rightarrow (B, \lambda_B)$
  - **Simple inflation coupling**
  - **Helical inflation coupling**
  - **Curvature coupling**
- **1st order phase transitions** *Leptogenesis sector*
  - **Electroweak phase transition**
  - **Quantum chromodynamics phase transition**



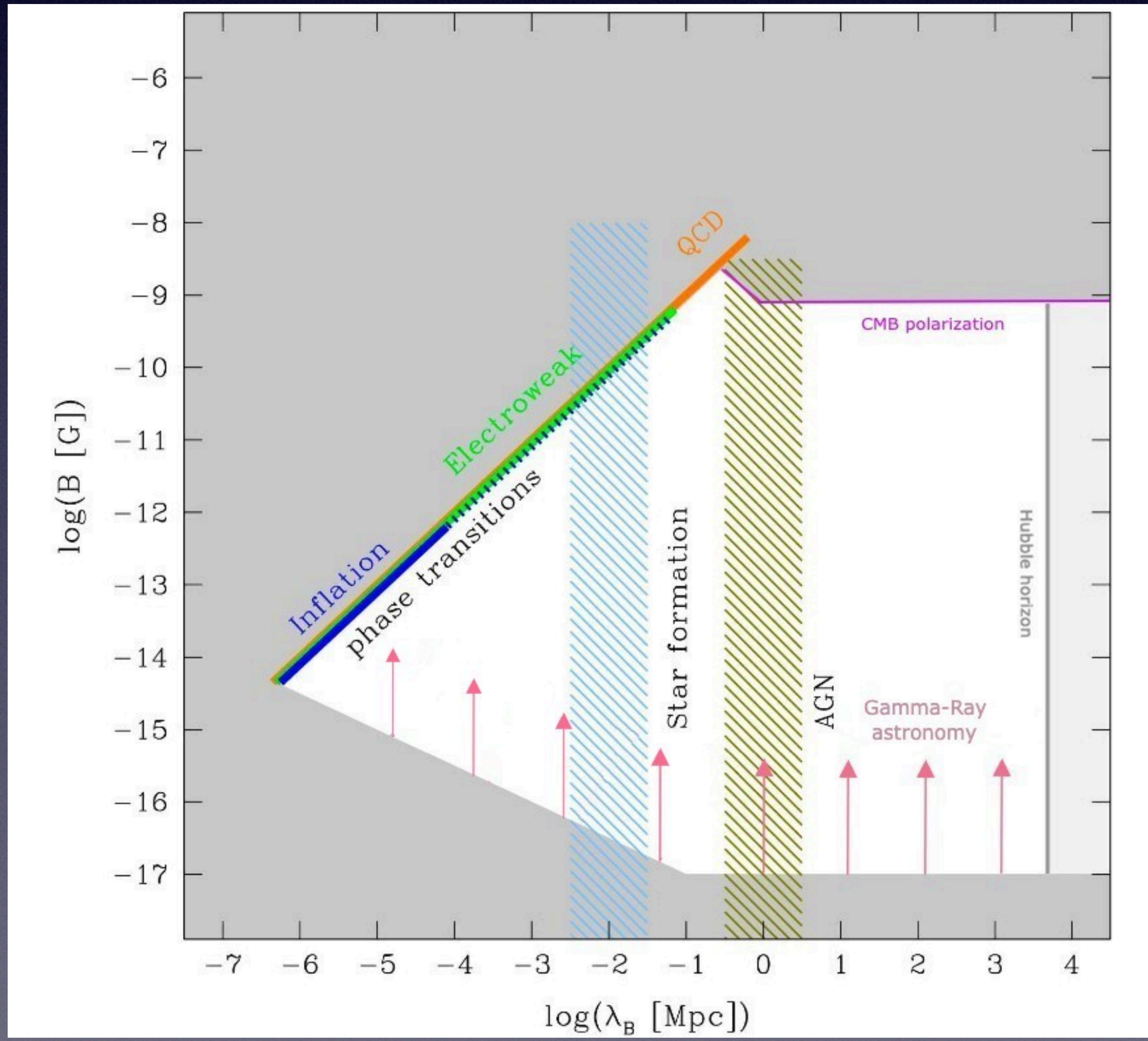
Inflationary interacting photons



Gravitationally interacting photons



Bubble nucleation



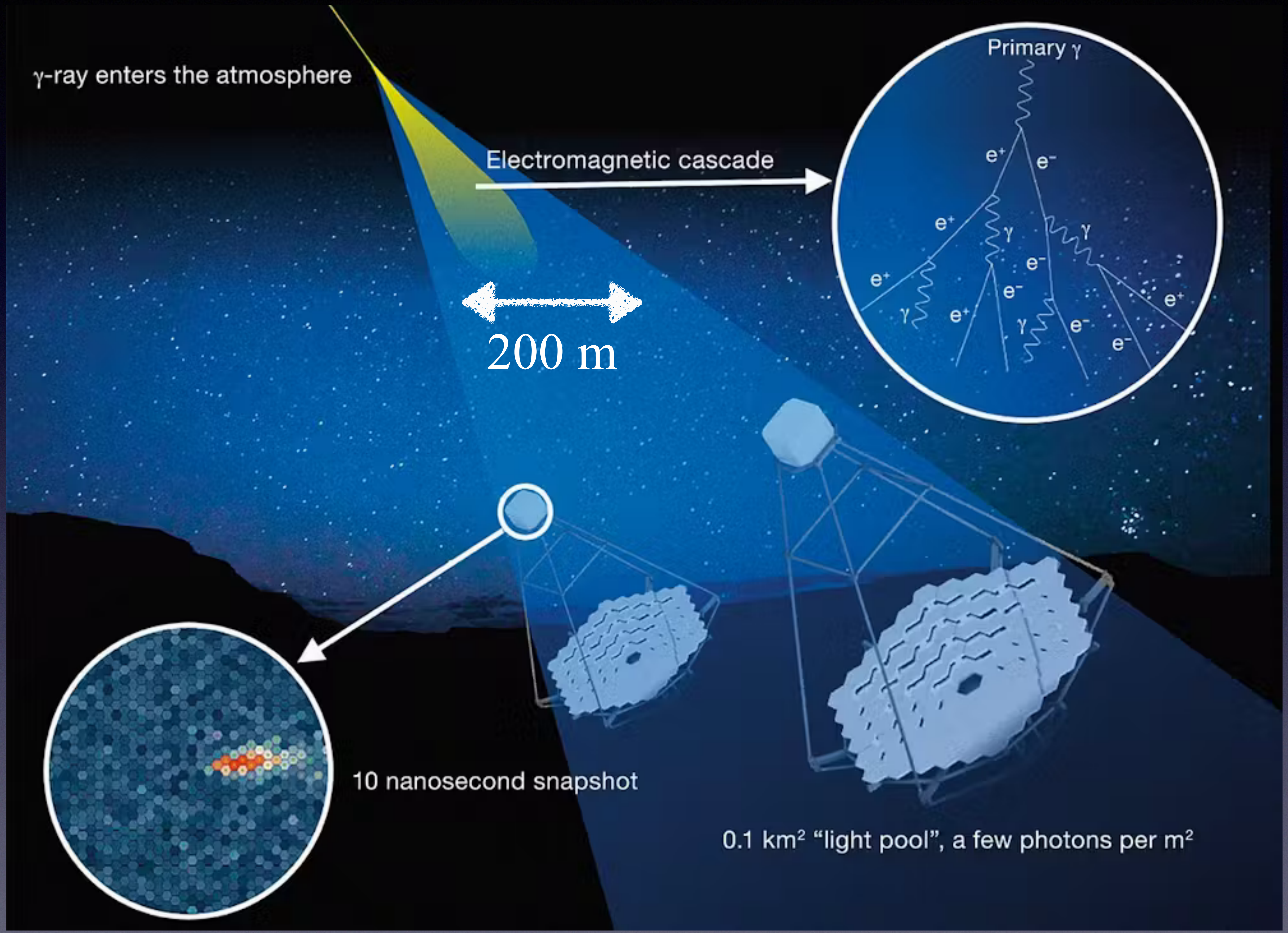
Complete map of constraints for the IGMF

Gamma-Ray Burst

Physics of the Cherenkov telescopes

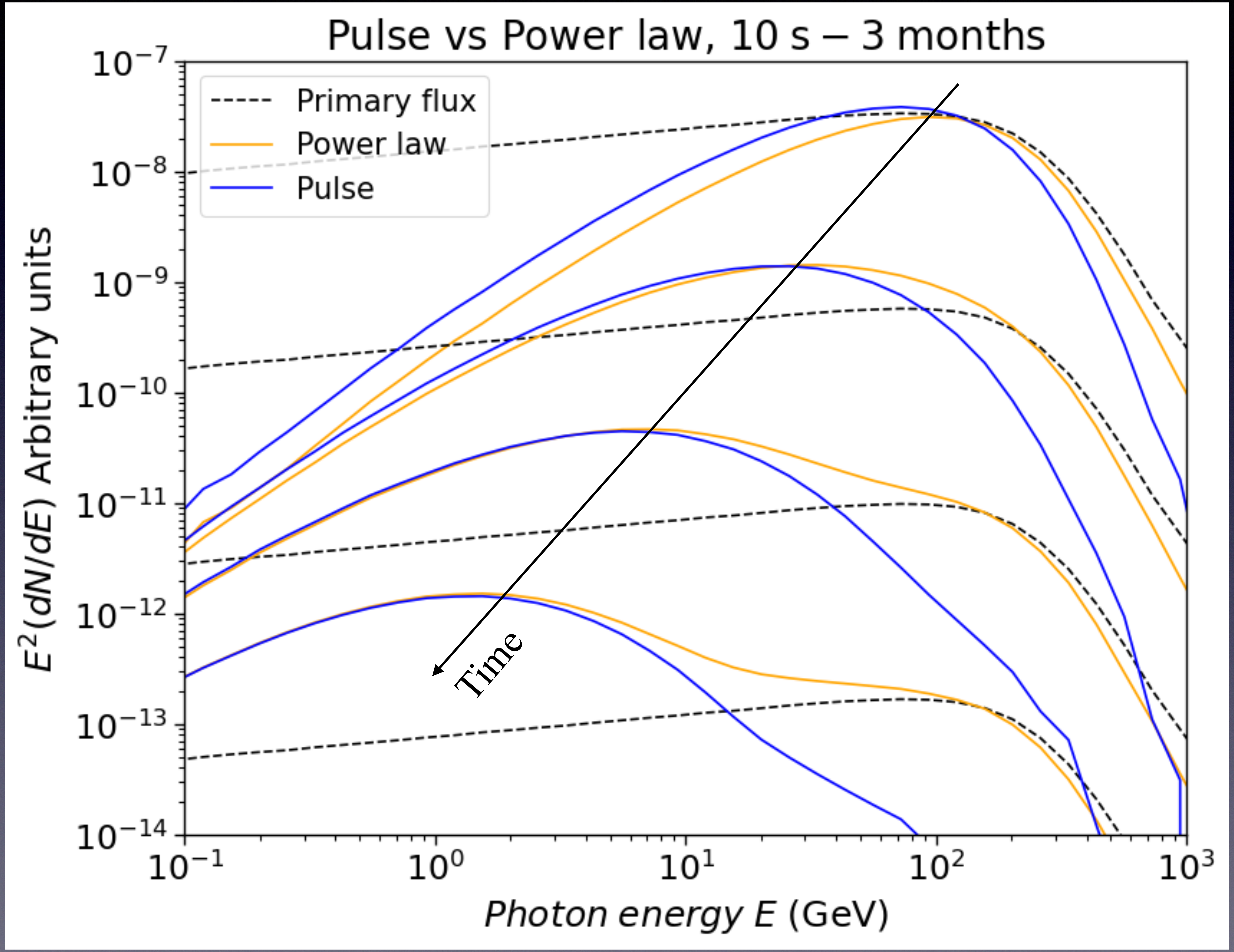
- **Cherenkov light:**
  - VHE photon scattering on atmospheric atoms
  - Faster-than-light leptons —> Cherenkov light
  - Photomultipliers and snapshot image
  - Primary reconstruction with triangulation

- **3 main criteria for a Gamma-Ray Burst observation:**
  - The night
  - An altitude above 24°
  - An affordable moonlight

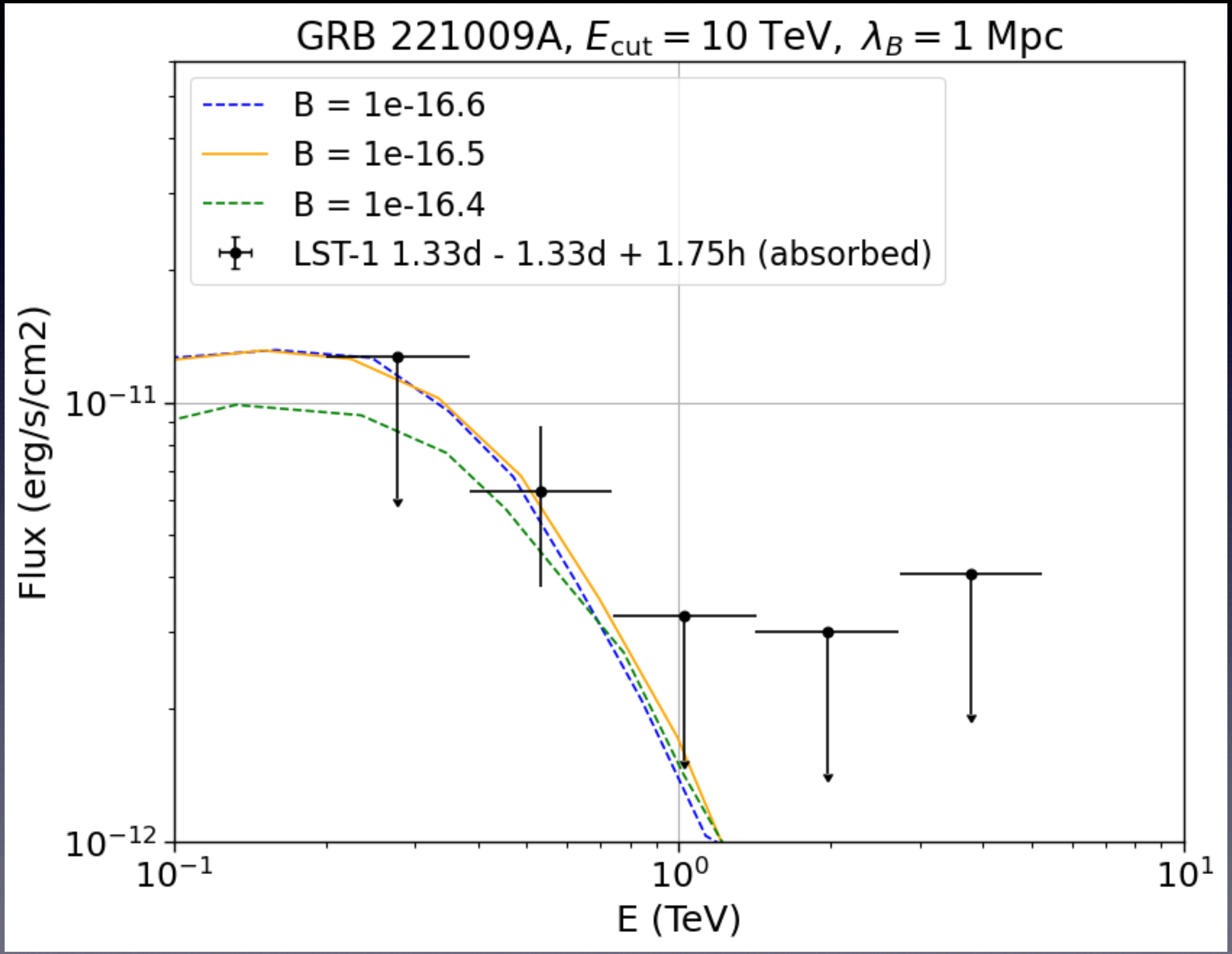


Cherenkov telescope mechanism

Late time cascade



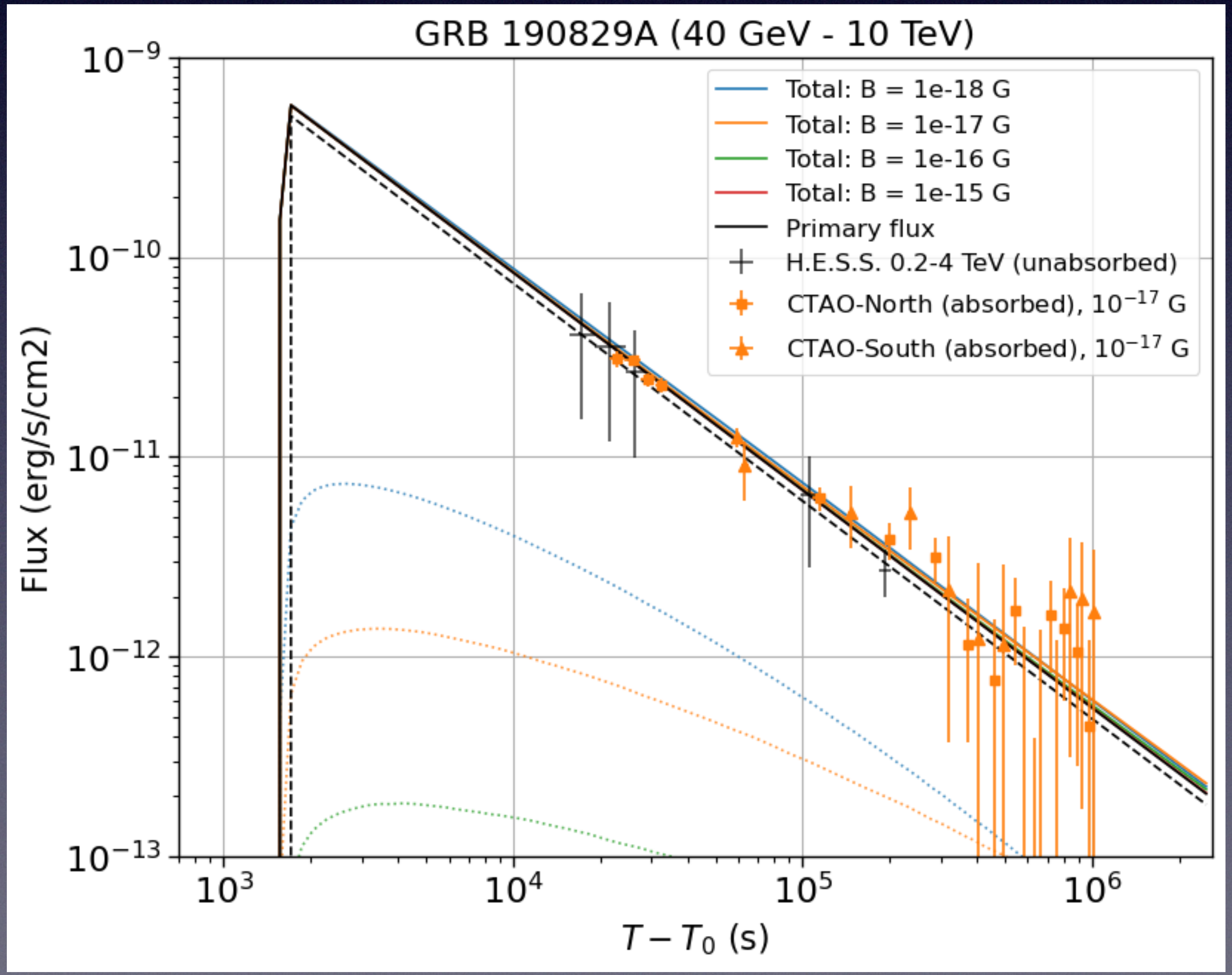
LST-1 detection



Other GRBs

$$\Phi(E,t) = \Phi_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-2.07} \left(\frac{t}{4\ \mathrm{h}}\right)^{-1.09} \qquad z = 0.08$$

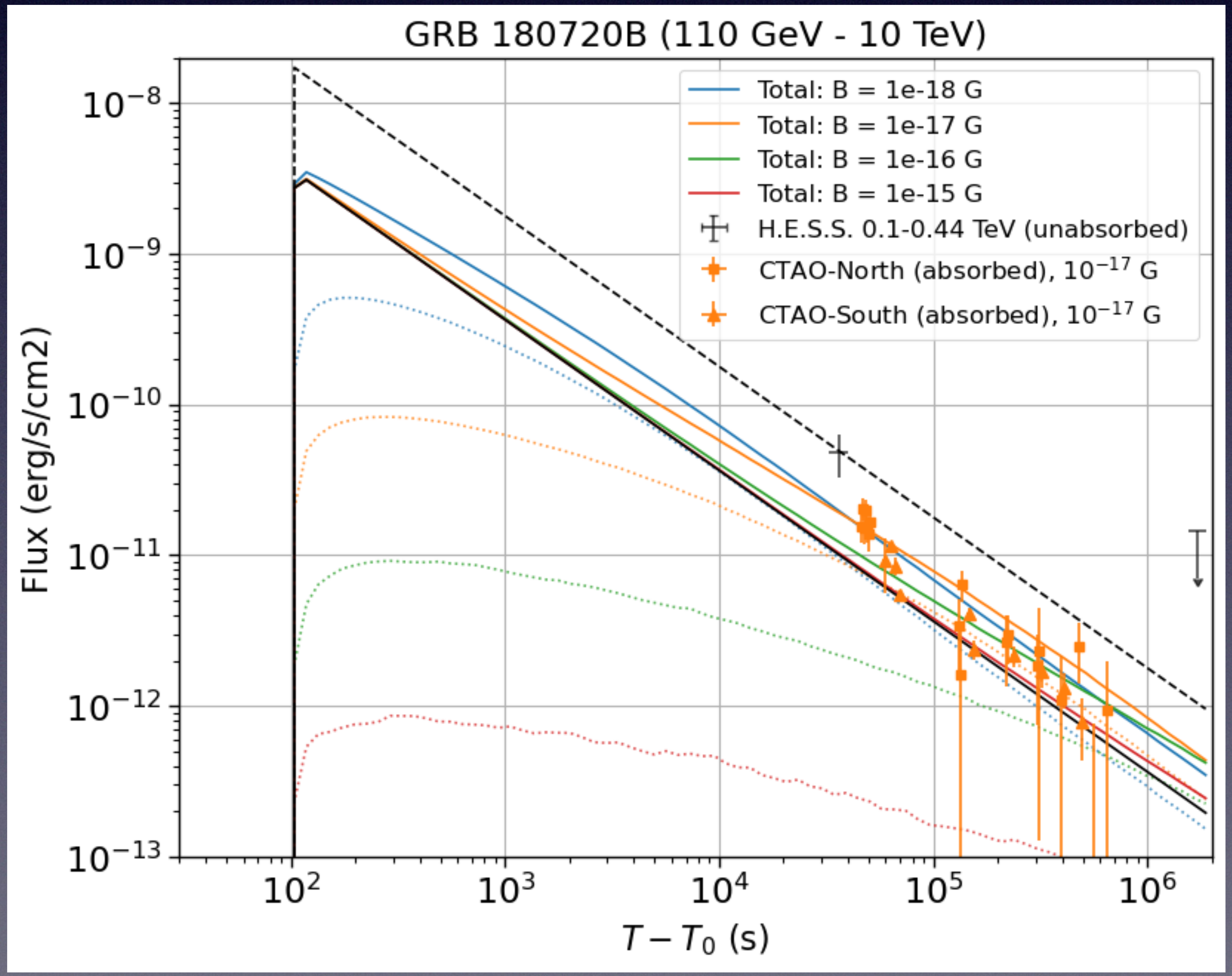
- Low redshift and soft spectrum
- No detectable secondary flux



$$\Phi(E,t) = \Phi_0 \left(\frac{E}{154\ \mathrm{GeV}}\right)^{-1.6} \left(\frac{t}{2\ \mathrm{h}}\right)^{-1.0} \qquad z = 0.653$$

- Large redshift and hard spectrum
- No detectable primary flux

(Conservative assumption on temporal index)



No IGMF detection