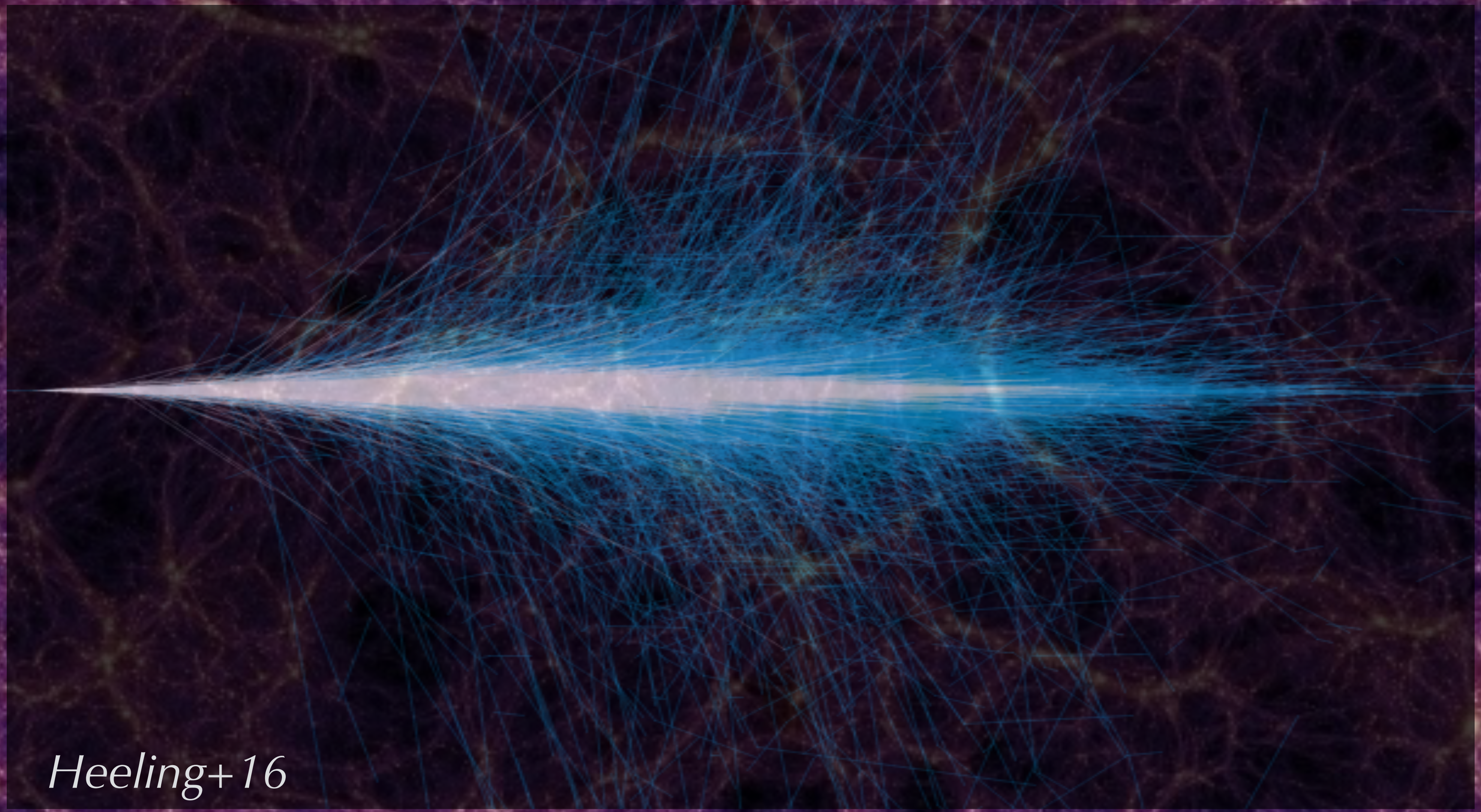
The InterGalactic Magnetic Field and γ-ray astronomy:

Prospects for GRBs and CTA


Nasa / Swift / Cruz deWilde


Heeling+16


FAE, CTA Consortium

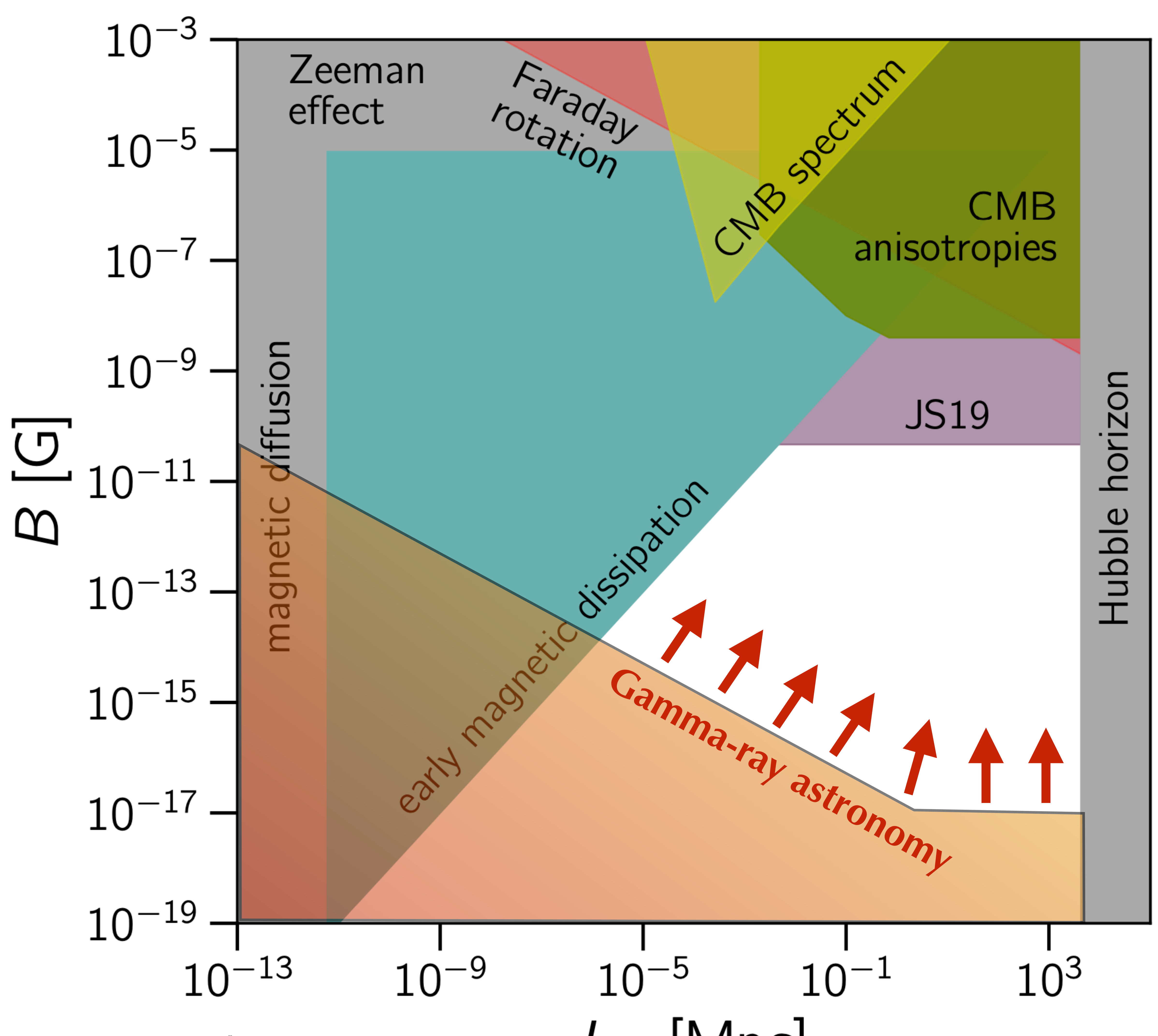
R. Belmont, T. Stolarczyk, Y. Faris, A. Huchet, (+ T. Keita)
J. Malzac, T. Fitoussi

Journées du PNHE 2023, Paris

Millenium simulation, Springel+2005

The InterGalactic Magnetic Field (IGMF)

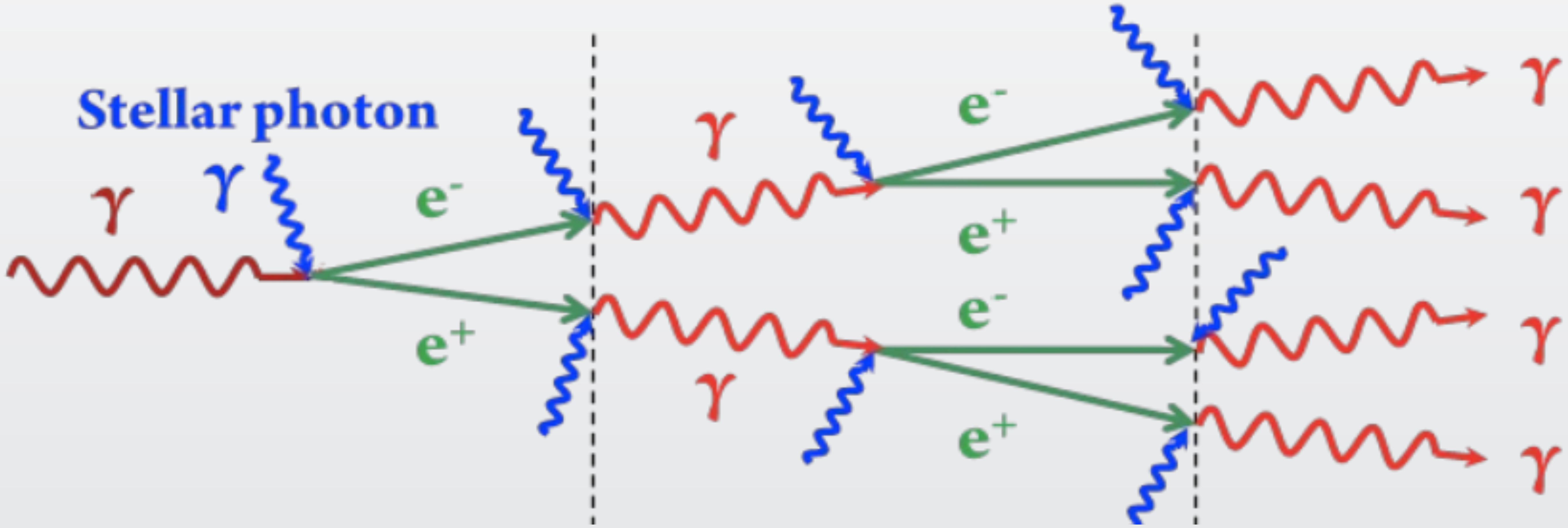
- **Magnetic fields are ubiquitous**
  - Stars, galaxies, clusters, filaments … Voids?
- **Origin?**
  - (Reviews: Durer&Neronov13, Subramanian+19, Batista&Saveliev21)
  - Astrophysical (Batteries, Plasma instabilities + amplification by dynamo)
  - Primordial (Inflation, post inflation, EW or QCD phase transitions…)
- **A turbulent Field:**
  - mean intensity B
  - coherence length L_B
- **Constraining (B,L_B) in the voids may help understanding its origin**

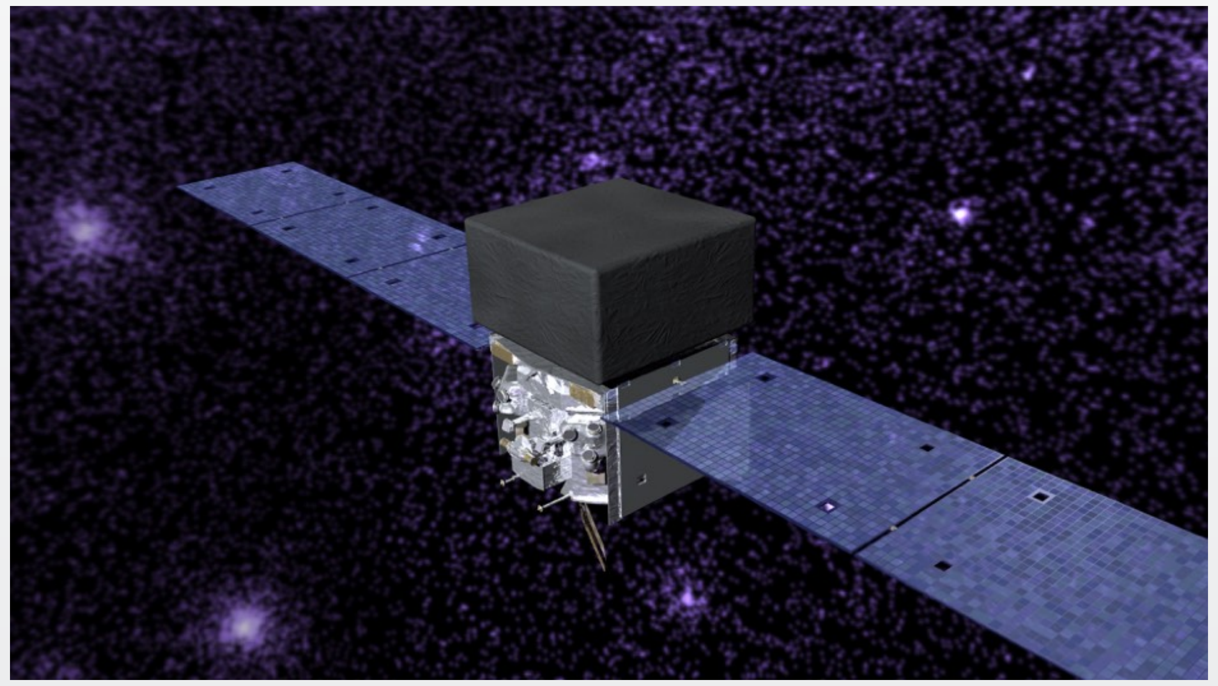


Batista&Saveliev21

Electromagnetic cascades

- **Absorbed energy redistributed into many secondary particles**
  - VHE gamma-ray absorption + Compton up-scattering
- **Secondary emission expected in the GeV-TeV band**
  - No unambiguous detection so far…
  - => **lower limits on the IGMF**





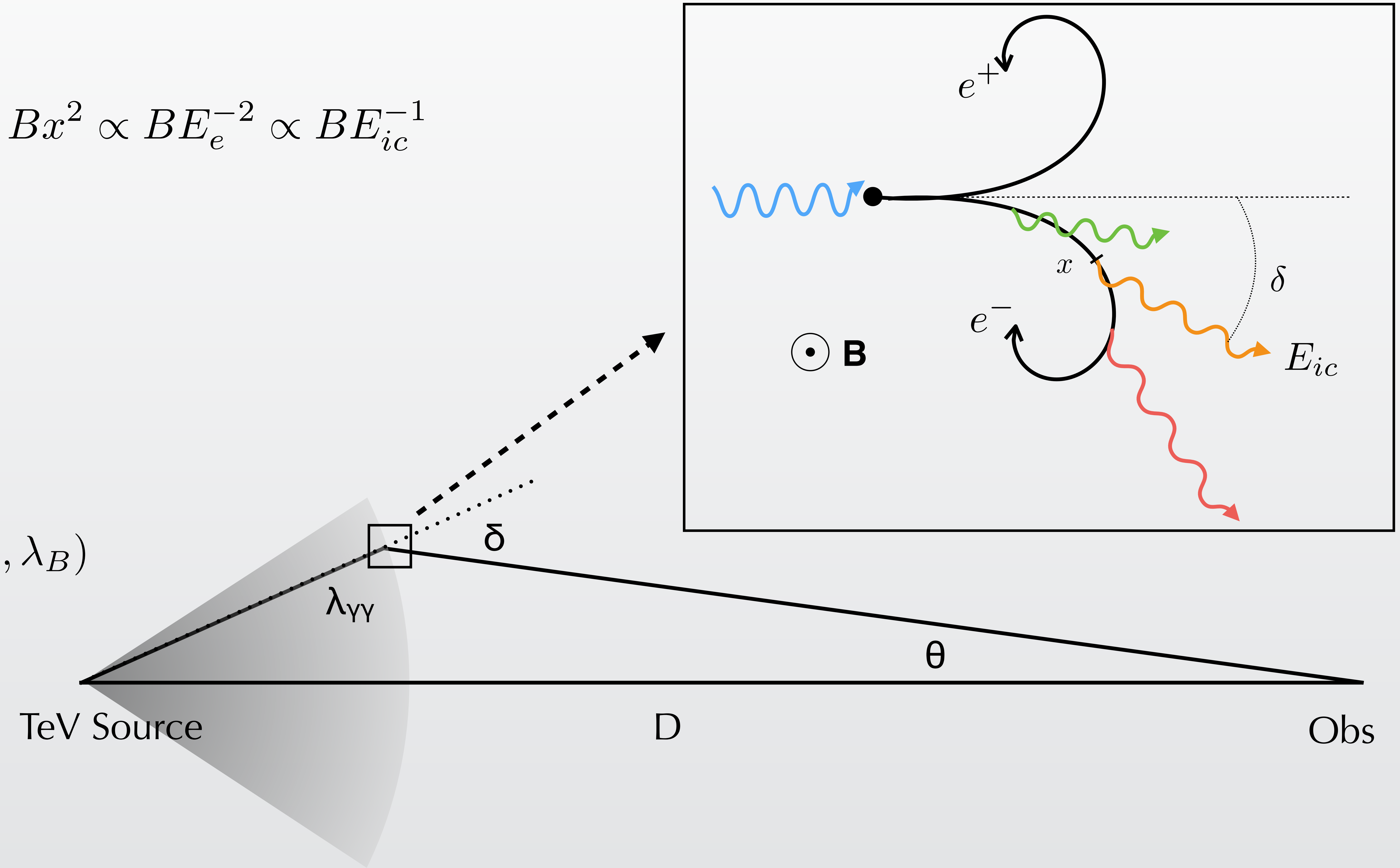
E_0 = 100 TeV → E_1 <30 TeV → E_2 < 3 TeV → E_3 < 30 GeV 2-3 generations

E_0 = 10 TeV → E_1 < 300 GeV → —— Only 1 generation ——

E_0 = 1 TeV → E_1 < 3 GeV → —— Only 1 generation ——

Expected IGMF signatures

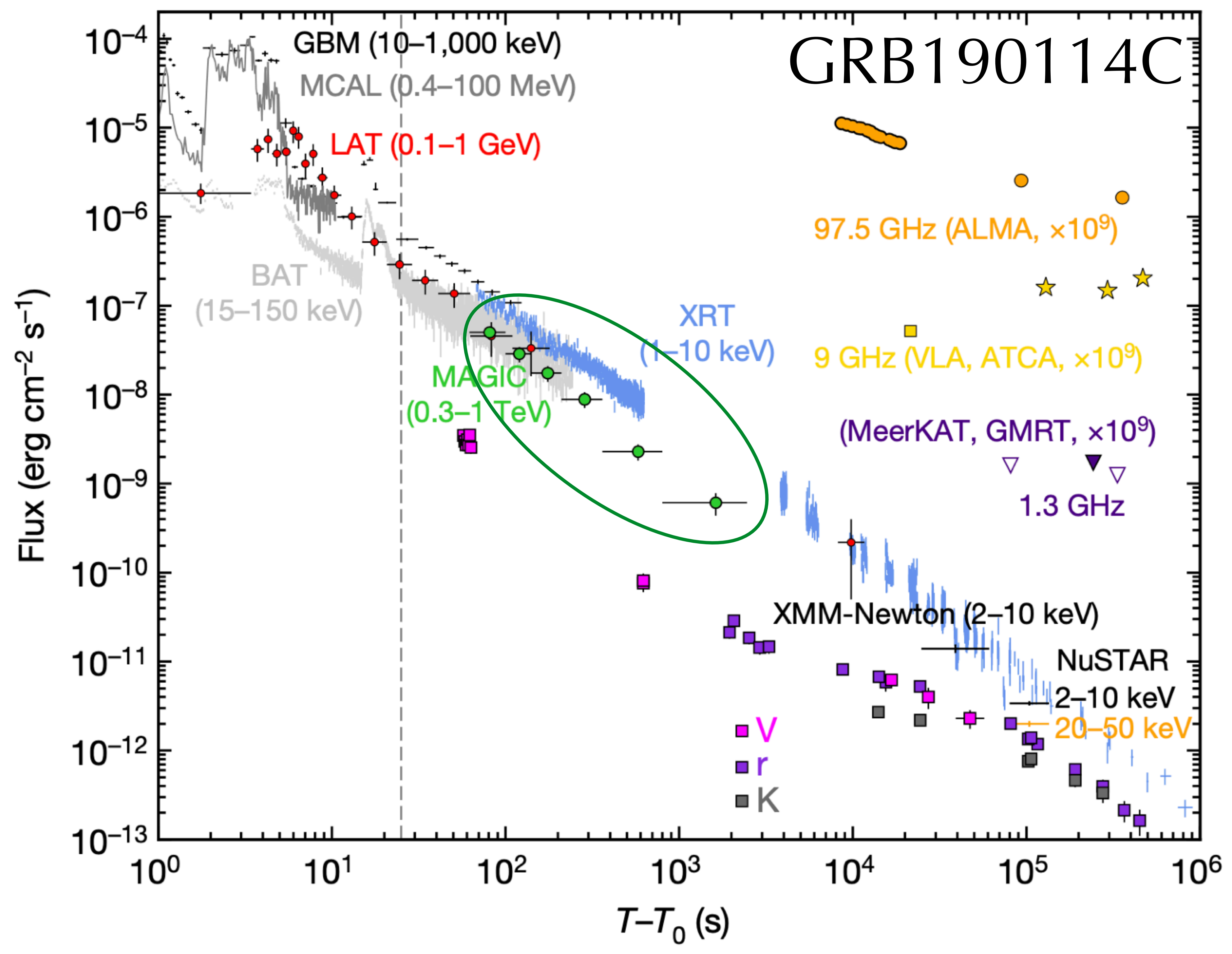
- **The Extragalactic Magnetic Field deflects pairs in the cascade**
  - For large correlation length (uniform field): $\delta \propto Bx^2 \propto BE_e^{-2} \propto BE_{ic}^{-1}$
- **Angular effect:** $\theta \approx \frac{\lambda_{\gamma\gamma}}{D}\,\delta(E_{ic}, B, \lambda_B)$
  - Require stable, long living sources: **AGN**
  - Probe up to **B=10^{-16} - 10^{-13} G** depending on the method/assumptions
- **Temporal effect (Plaga95):** $c\Delta t \approx \frac{\lambda_{\gamma\gamma}}{2}\,\delta^2(E_{ic}, B, \lambda_B)$
  - Need for transient sources: **GRBs**
  - (Ishiki+08, Takahashi+08,11, Veres+17, Wang+20,Dzhatdoev+20,23,Huang+23,Vela+23,Vovk+23a,b,Miceli+23,Xia+23)
  - Time delays could probe up to **B=10^{-16}G**

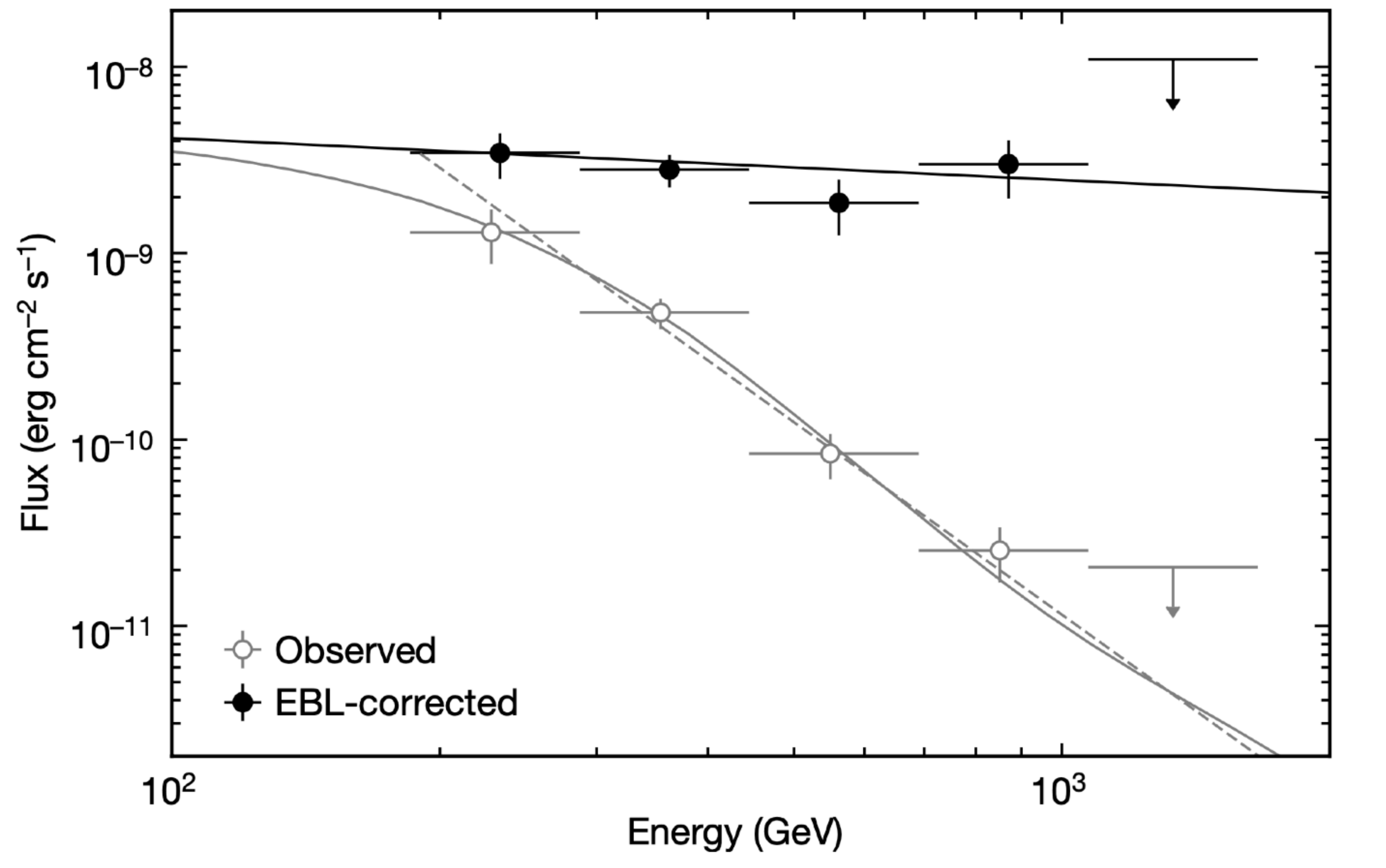


- **Time- and angular effects are well separated and complementary**

$$\Delta t \approx 5\times 10^4 \left(\frac{D}{1\mathrm{Gpc}}\right)^2 \left(\frac{\lambda_{\gamma\gamma}}{100\mathrm{Mpc}}\right)^{-1} \left(\frac{\theta}{0.1^o}\right)^2 \mathrm{yr}$$

GRBs in the VHE band





MAGIC coll. 2020a,b

- **Observed up to a couple of days**
- **Consistent with power-laws:**

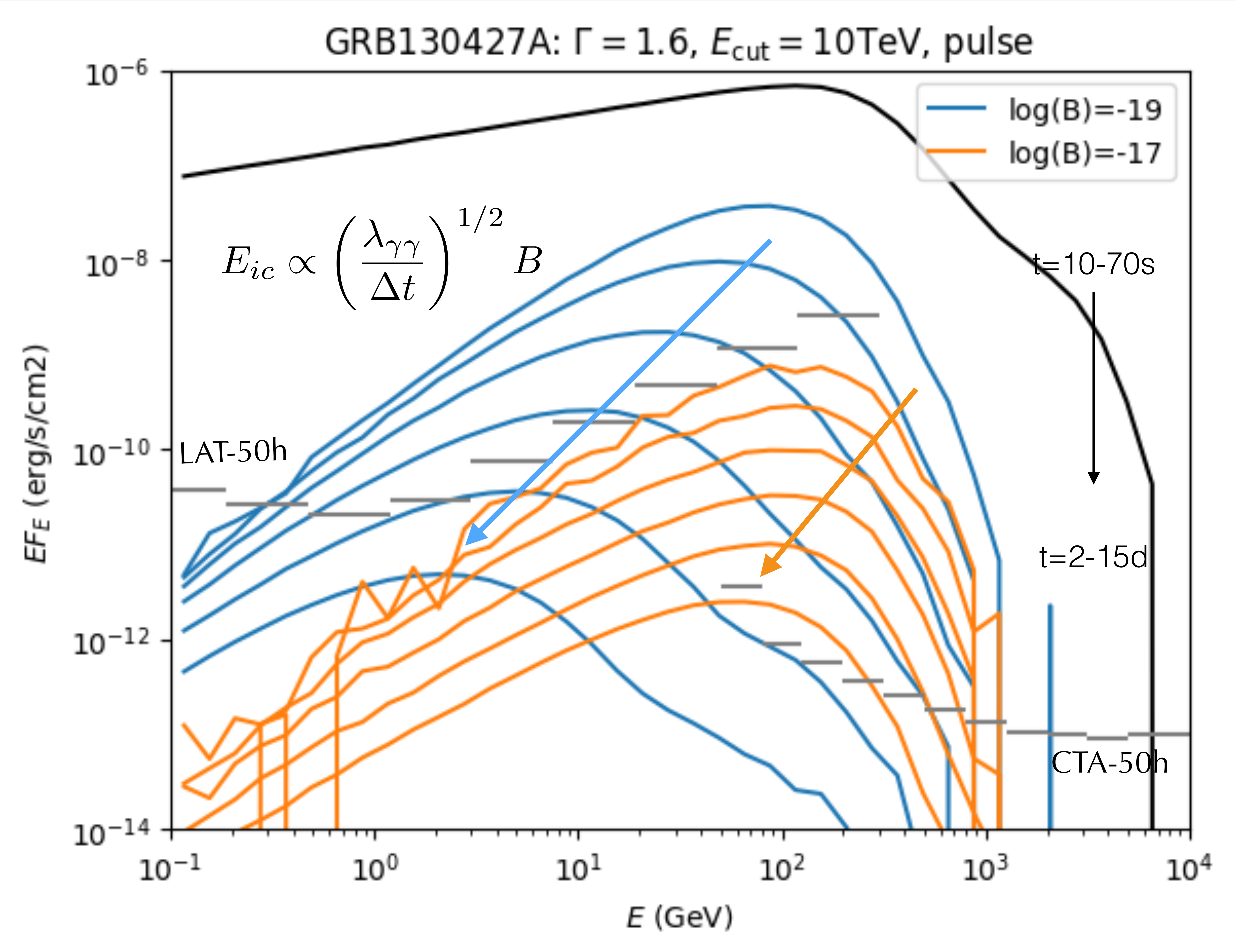
$$N_E(t) \propto t^{-\alpha} E^{-\Gamma}$$

- **Unknown cutoff energy: E_{cut}**

	IACT	z	t_{max}	$\Gamma_{(EBL\ corr)}$	α	Highest E
GRB130427C	*(LAT)*	*0.34*	*20h*	*1.66*	*1.17*	----
GRB160921B	MAGIC	0.16				0.5 TeV
GRB180720B	HESS	0.65	12h	**1.6**	?	0.4 TeV
GRB190114C	MAGIC	0.42	40min	2.22	1.6	1 TeV
GRB190829A	HESS	0.08	**56h**	2.07	1.09	4TeV
GRB201216C	MAGIC	1.1	2h			----
GRB221009A	Lhaaso	0.15	1h	2.3	1.1/2.2	**7 TeV** (18TeV?)

Time delays with GRBs: standard approach

- **All studies assume an instantaneous primary emission:**



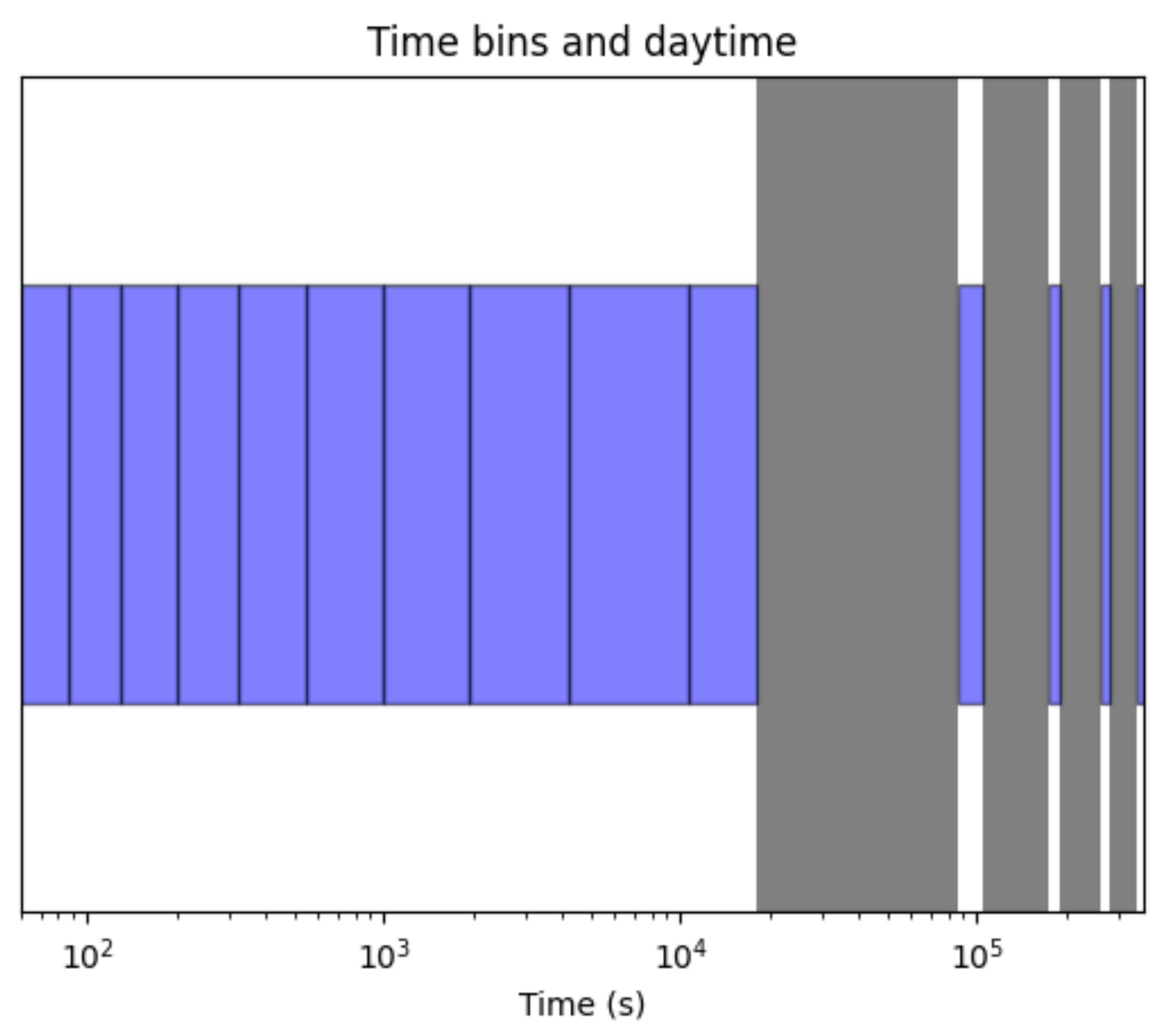
- **The probed intensities depend on:**
  - The instrument energy range
  - The instrument sensitivity
  - The absorbed intrinsic flux

- **Fermi observations can probe B in the 10^{-21}-10^{-18}G range**
  - GRB130427A: B>10^{-19}G (LAT only, Veres+17)
  - GRB190114C: B>$10^{-19.5}$G (Wang+20), no constraint (Dhzatdoev+20, Da Vela+23,Vovk+23a)
  - GRB221009A: B>$10^{-18.5}$G (Huang+23,Vovk+23b), B=$10^{-17.5}$ (Xia+23, one cascade photon?)

- **CTA:**
  - Higher energy
  - More sensitive on short time scales
  - => will probe higher B (10^{-18}-10^{-16}G)

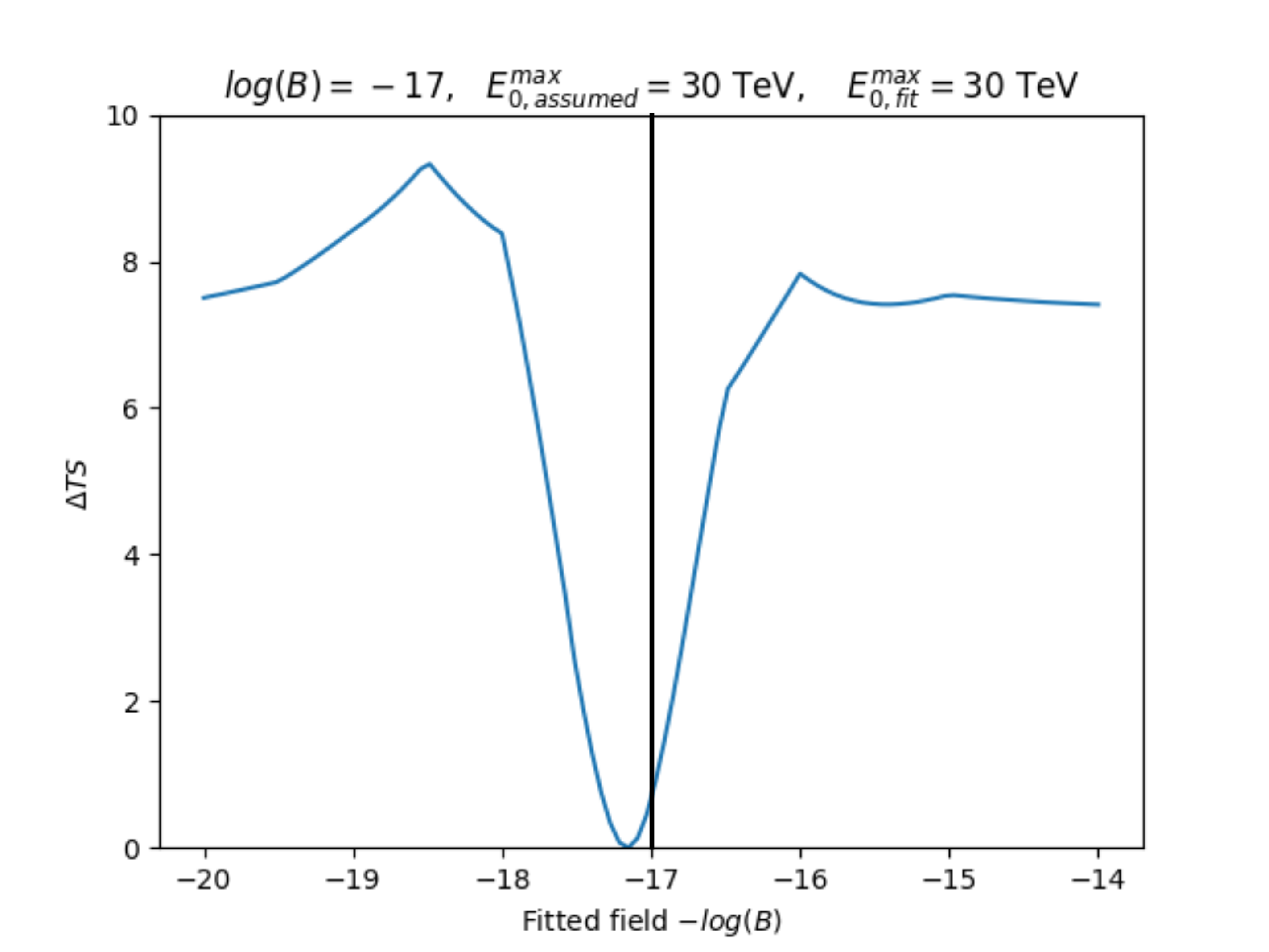
Constraints with CTA: Time dependent fitting

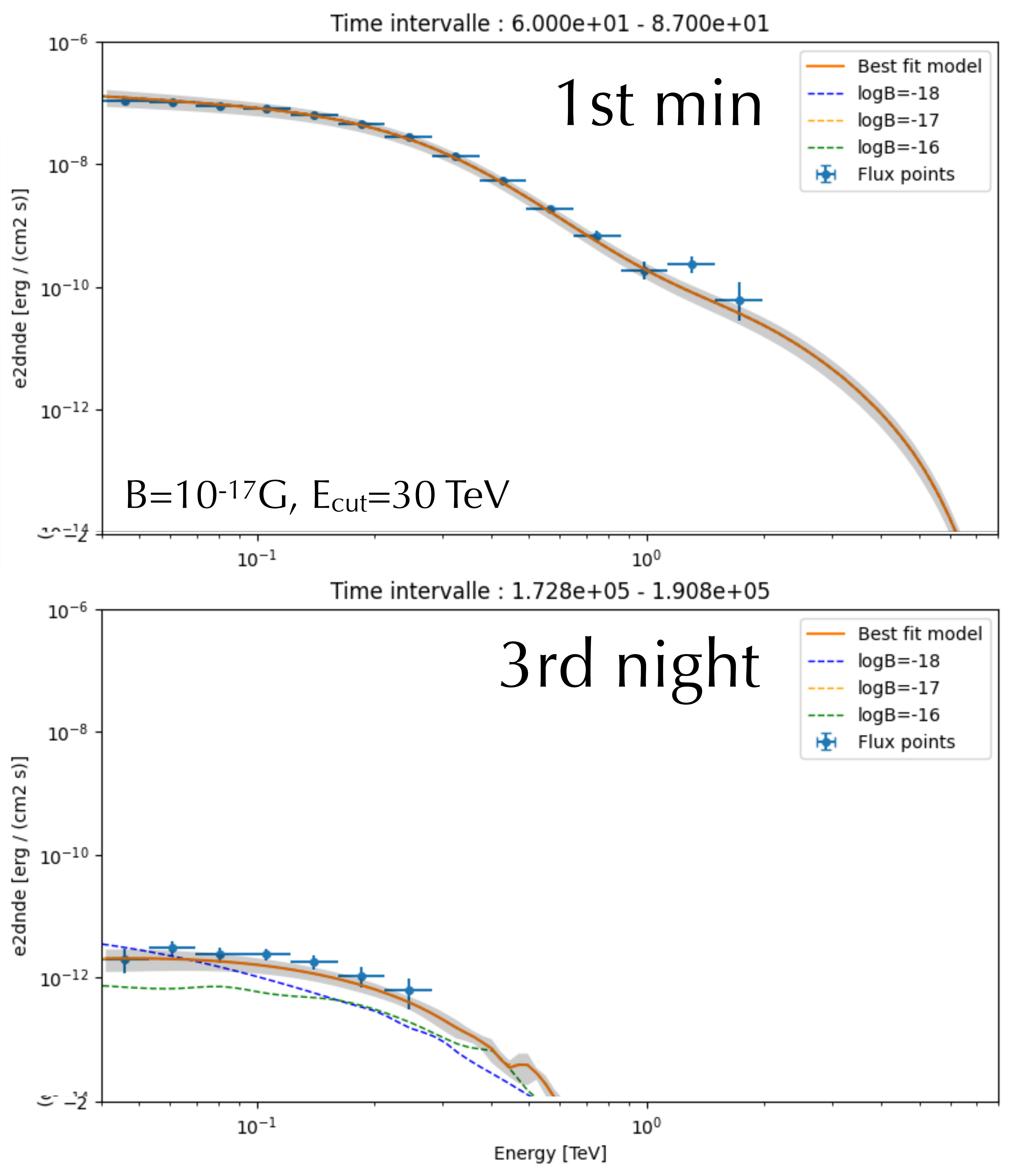
- **Problem: Intrinsic decay occurs on a finite time**
  - More secondary photons can be produced
  - The cascade can be hidden by the late primary emission: degeneracy between intrinsic and secondary emission
- **Solution:**
  - Model the time evolution of the primary emission
  - include the specific time evolution of the cascade emission in a time dependent fitting
- **Production of CTA synthetic data corresponding to GRB190114C:**
  - Assume GRB intrinsic properties, including fluence, **spectral** (Γ=2.2), and **temporal** (α=1.6) behaviour. $N_E(t) \propto t^{-\alpha} E^{-\Gamma}$
  - Monte Carlo simulations of cascade contributions (code Fitoussi+17 upgraded) + weighting + time convolution
  - Data including both the intrinsic + secondary emissions
  - Use of CTA-North IFRs at 40°
  - Data produced for different **time bins** (consistent with at most 4h-long nights, up to 5 days)



Constraints with CTA: Time dependent fitting

- **Fitting synthetic data:**
  - Using gammapy
  - Same model with 4 free parameters (**norm, Γ, α, B**)
  - Production of a table model (Γ5 x α5 x B16)
  - IRF cut at 100 GeV
  - Add systematic to account for uncertainty on the intrinsic model (150%)
  - **Joint fit of all time bins**





- **Results:**
  - Any B in the **10^{-18}-10^{-16}G** range can be measured
  - Any larger field leads to lower limits at **B=10^{-16}G**

Conclusions

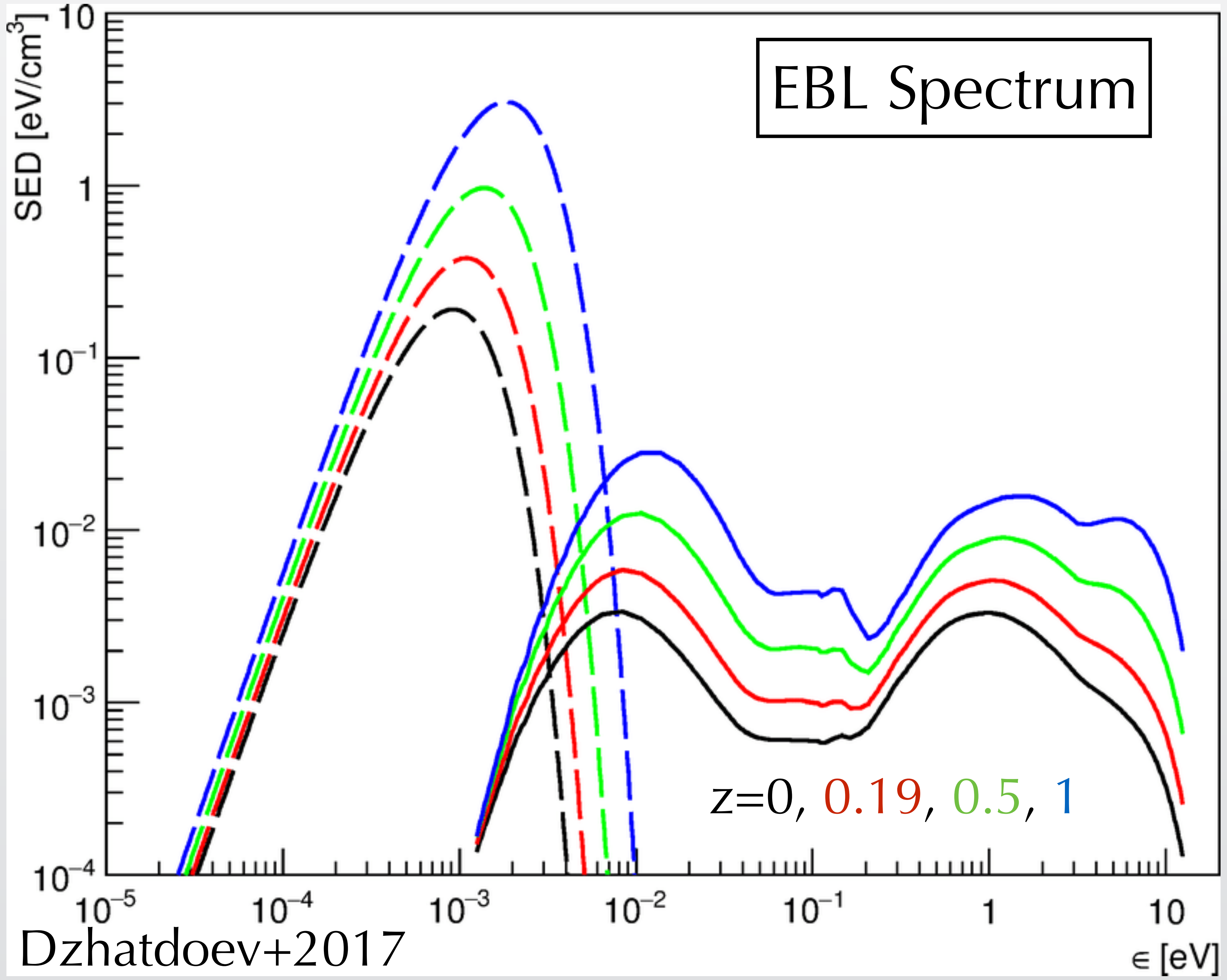
- **VHE GRBs open the possibility to measure times delays, complementary to searches based on halos**
- **CTA will detect GRB emission for several days**
- **Modelling requires**
  - precise MC simulations
  - description of the intrinsic time evolution
- **On a simple example (GRB190114C), our preliminary results show that with CTA it will be possible to**
  - Perform time dependent spectral fitting
  - Probe larger intensities than Fermi
  - Measure any B in the 10^{-18}-10^{-16}G range
  - Put lower limits at B=10^{-16}G for any larger field
- **This result must be extended:**
  - E_{cut}, spectral shape, systematics
  - Coherence length
  - Other individual sources, Multiple source fitting
  - Use of a synthetic GRB population

MERCI!

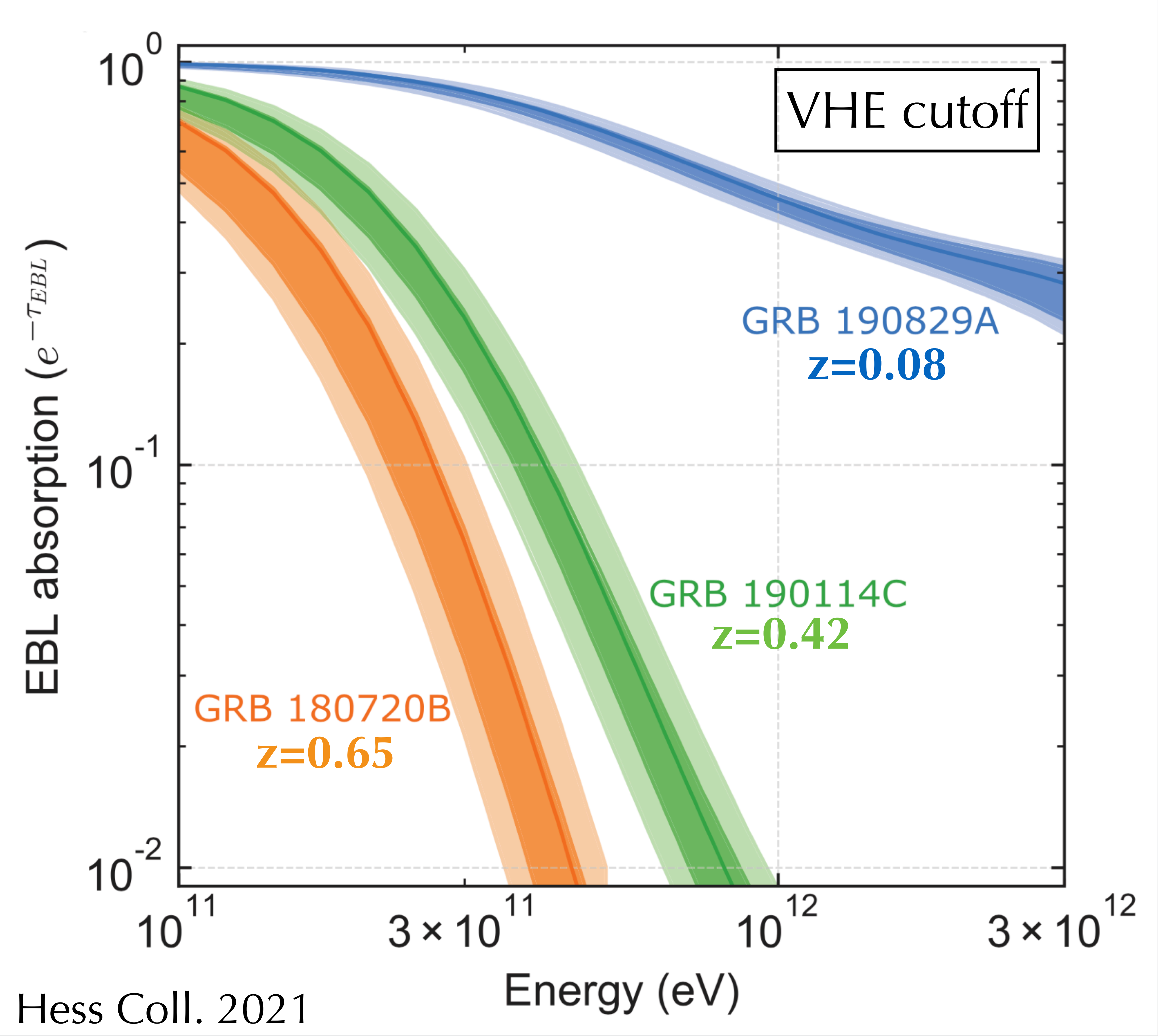
Supplementary slides

EBL absorption

- **Gamma-ray absorption by low energy, background photons**
- **Extragalactic Background light**
  - stars + dust
  - Not well constrained (at z>1)

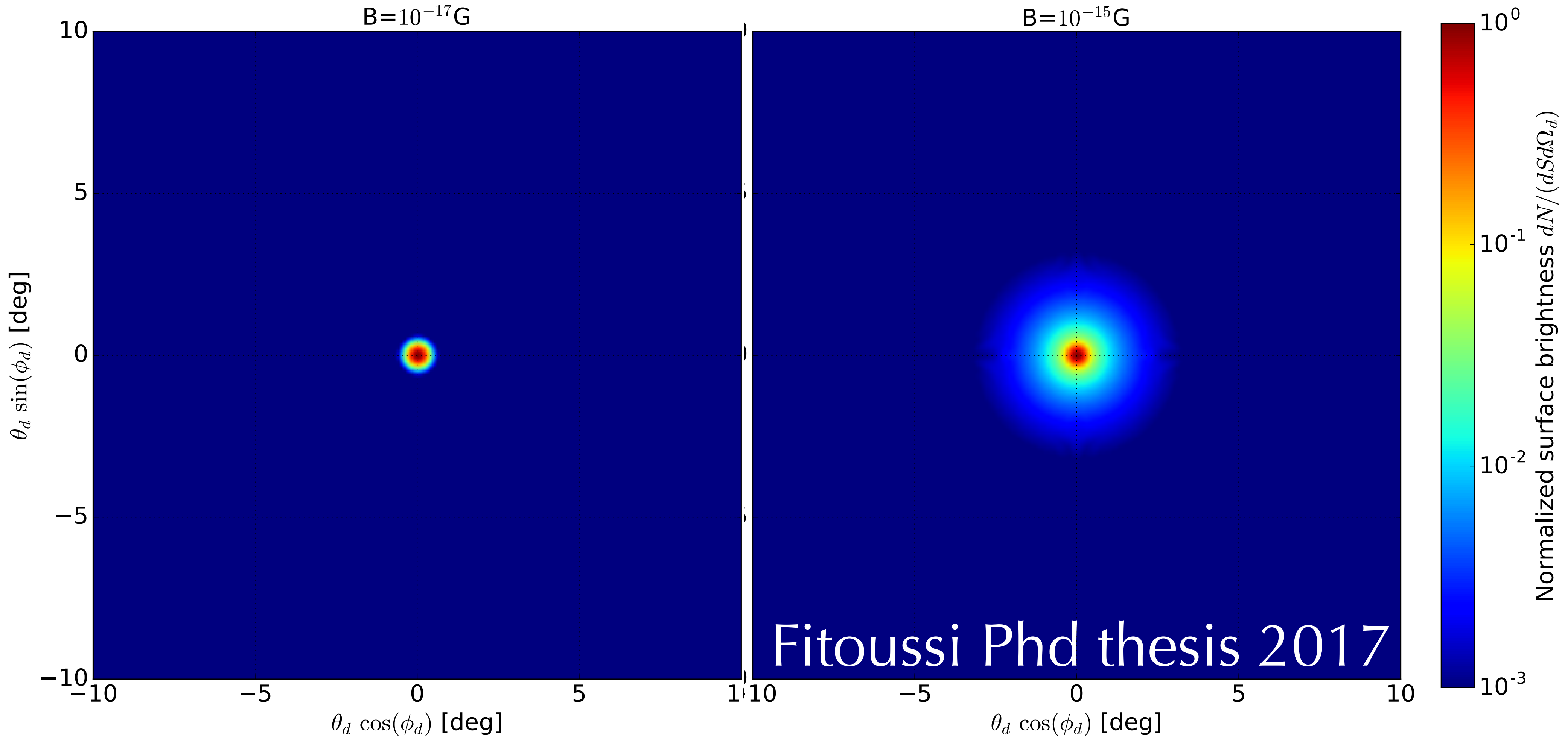


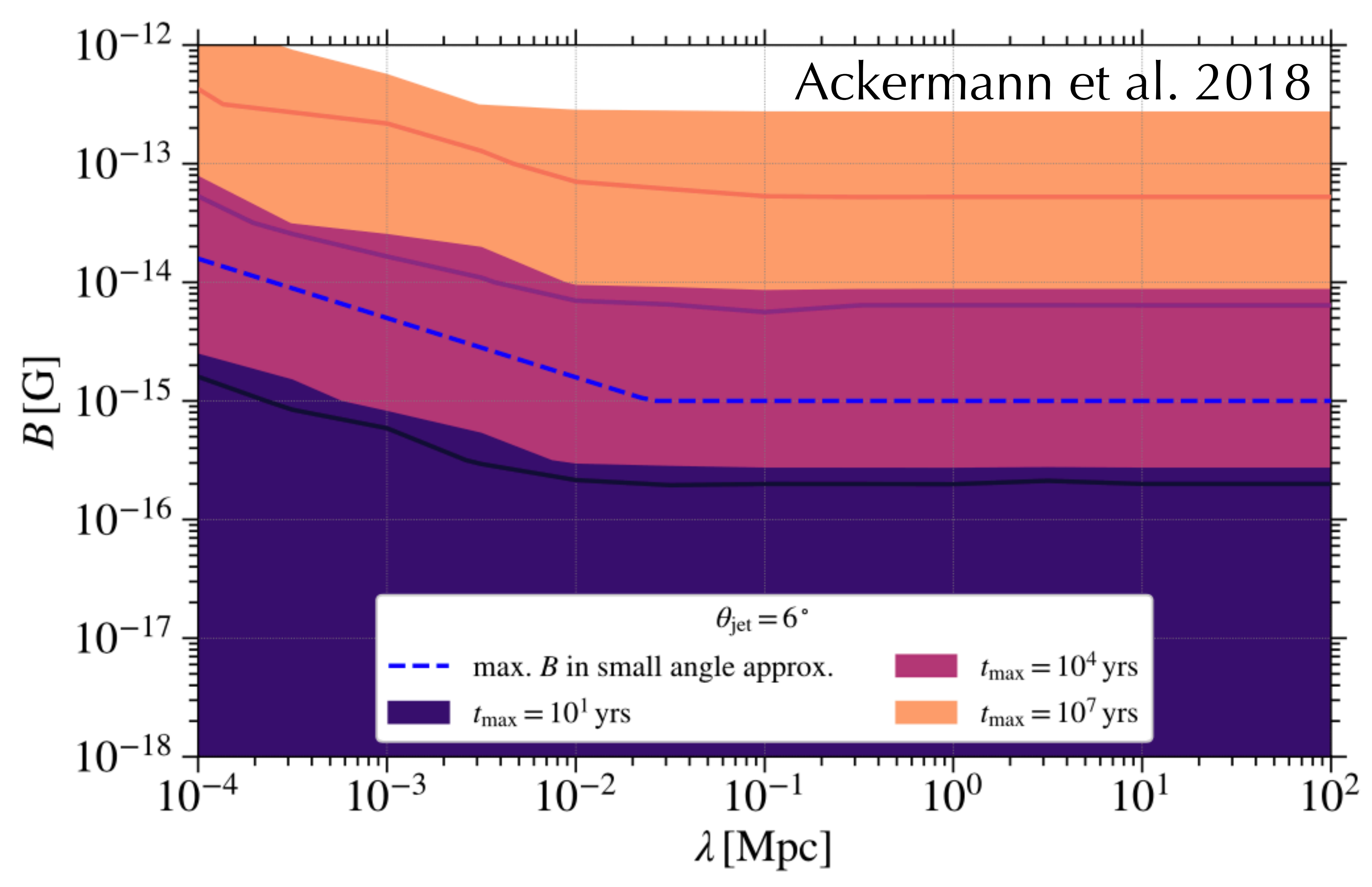
=> Spectral cutoff at TeV energies



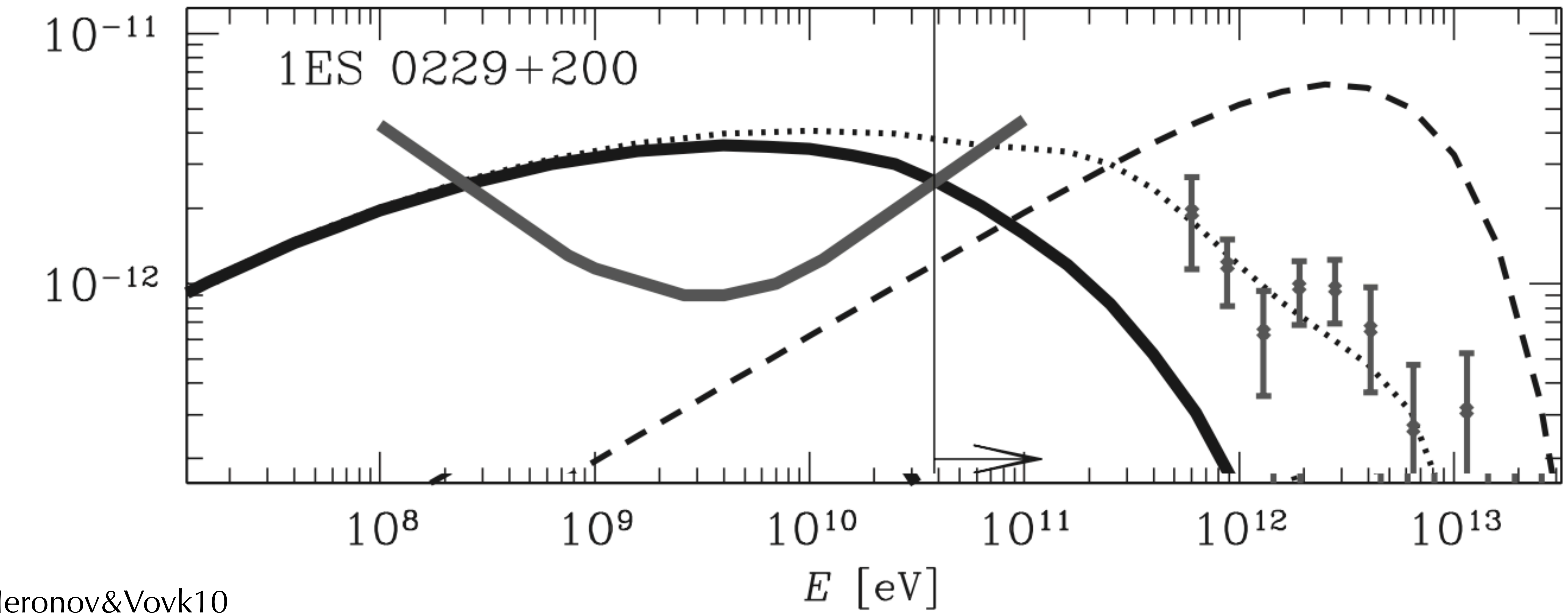
Spatial Extension with AGN

- **Need for very stable, long living sources: AGN!**
- **Different angular-scales/energies probe different IGMF:**
  - For large coherence length: $B \propto \frac{D}{\lambda_{\gamma\gamma}} E_{ic}\, \theta$
- **From pure geometrical arguments** (e.g. Neronov&Semikoz09)**:**
  - Upper limits on the secondary emission within the PSF due to large spatial extension (Neronov&Vovk10, Dermer+11, Vovk+12) can probe fields up to:
  $$B \approx 3 \times 10^{15} \left(\frac{D/\lambda_{\gamma\gamma}}{10}\right)\left(\frac{E_{ic}}{100\mathrm{GeV}}\right)\left(\frac{\theta}{0.1^o}\right) \mathrm{G}$$
  - Search for pair halos (Aharonian+01,Aleksic+10, Ackerman+13, Abramovski+14, Chen+15,18, Prokhorov+16, Archambault+17, Ackerman+18) can probe fields up to:
  $$B \approx 10^{13} \left(\frac{D/\lambda_{\gamma\gamma}}{10}\right)\left(\frac{E_{ic}}{100\mathrm{GeV}}\right)\left(\frac{\theta}{3^o}\right) \mathrm{G}$$
- **However, other limitations prevent from reaching theses intensities** (EBL, PSF, weak sources, E_{max}, confusion with intrinsic, **activity time, instabilities**…)
- **Recent data analysis use precise MC simulations + several sources**
  - Most optimistic limits: $B>10^{-13}$G
  - Most robust limits: **$B>10^{-16}$G**





Angular effects



Neronov&Vovk10

The hunt for IGMF signatures

- **In any case:**
  - No secondary emission detection interpreted as space- or time dilution because of a strong IGMF
  - => Lower limits for B
- **Two complementary methods:**

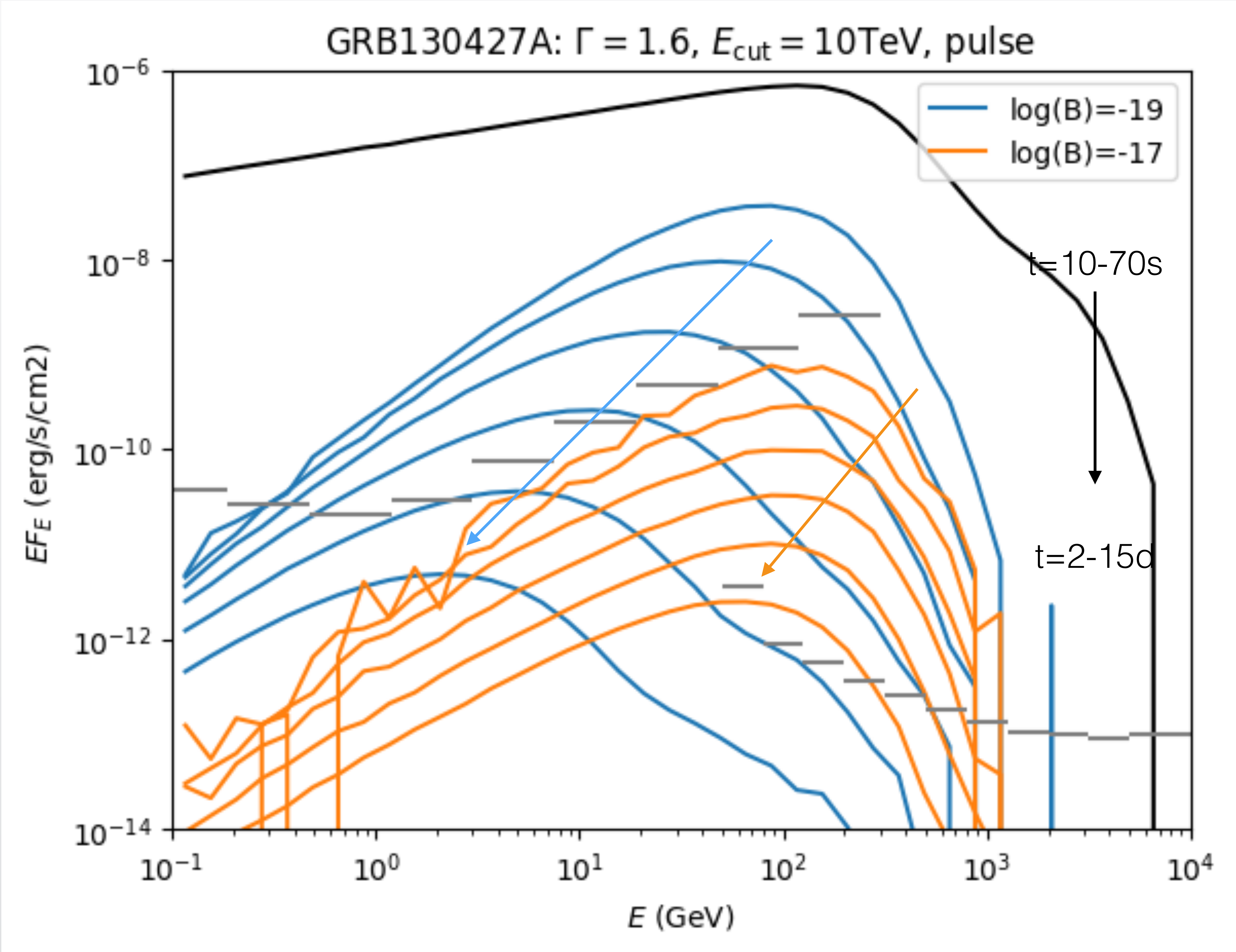
	Extension AGN	Time delay GRBs
PSF	X	V
Confusion with primaries	X	X
Cutoff energy	X	$E_{cut}>10$TeV
Jet opening angle	X	V
Violation of small angle approx	X/V	V
Activity duration	X	V
Source variability	X	X
Plasma instabilities	X	V?

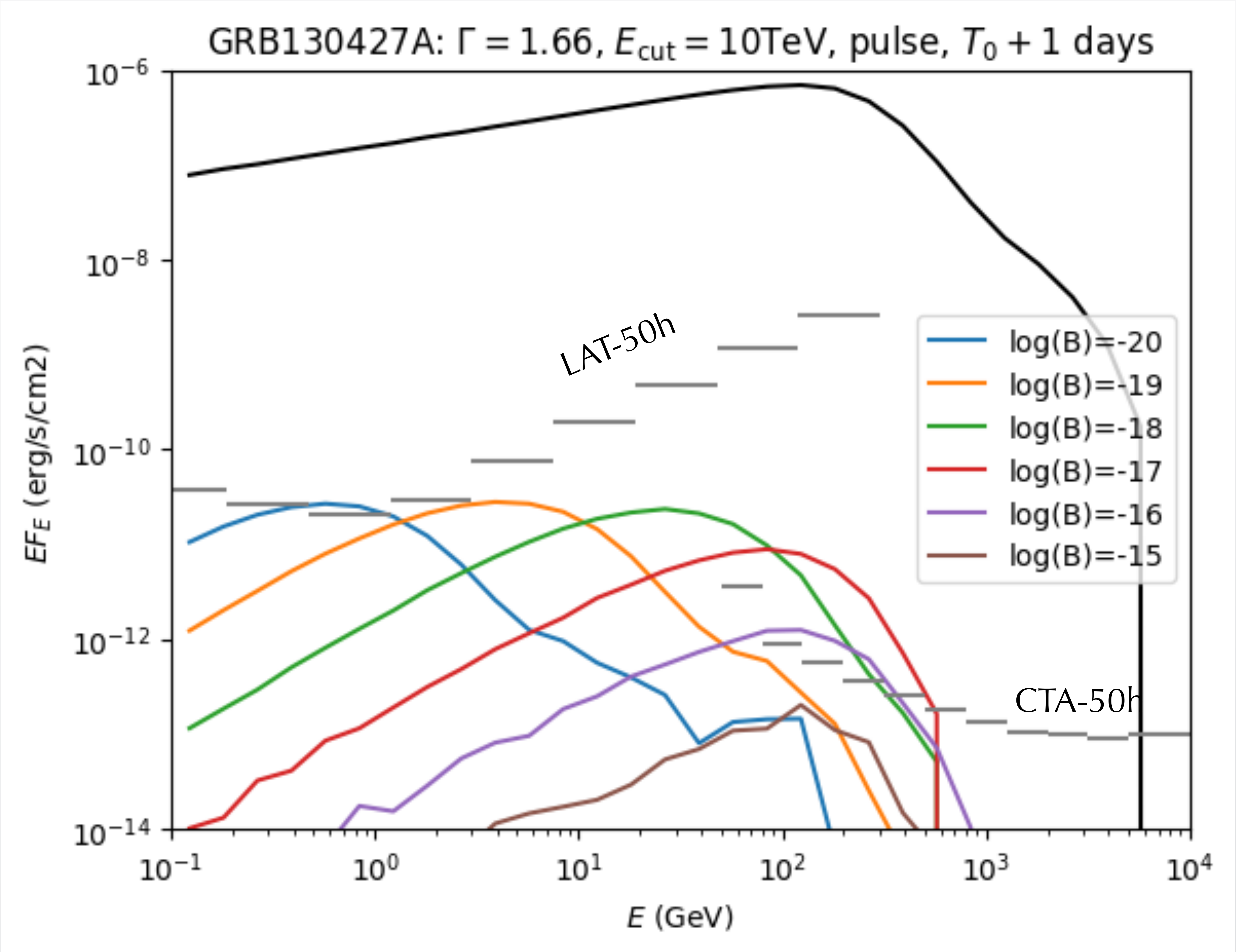
- **Angular effects:**
  - Require stable, long living sources: **AGN**
  - Probe up to **$B=10^{-16}$ - 10^{-13} G** depending on the method/assumptions
- **Time delays:**
  - Need for transient sources:
    - AGN flares/variability
      - (Batista&Saveliev20, Acciari+23)
    - **GRBs**
      - (Ishiki+08, Takahashi+08,11, Veres+17, Wang+20,Dzhatdoev+20,23,Huang+23,Vela+23,Vovk+23a,b,Miceli+23,Xia+23)
  - Time delays could probe up to **$B=10^{-16}$G**

Time delays with GRBs

- **Secondary contribution for an <u>instantaneous</u> primary emission:**

$$E_{ic} \propto \left(\frac{\lambda_{\gamma\gamma}}{\Delta t}\right)^{1/2} B$$

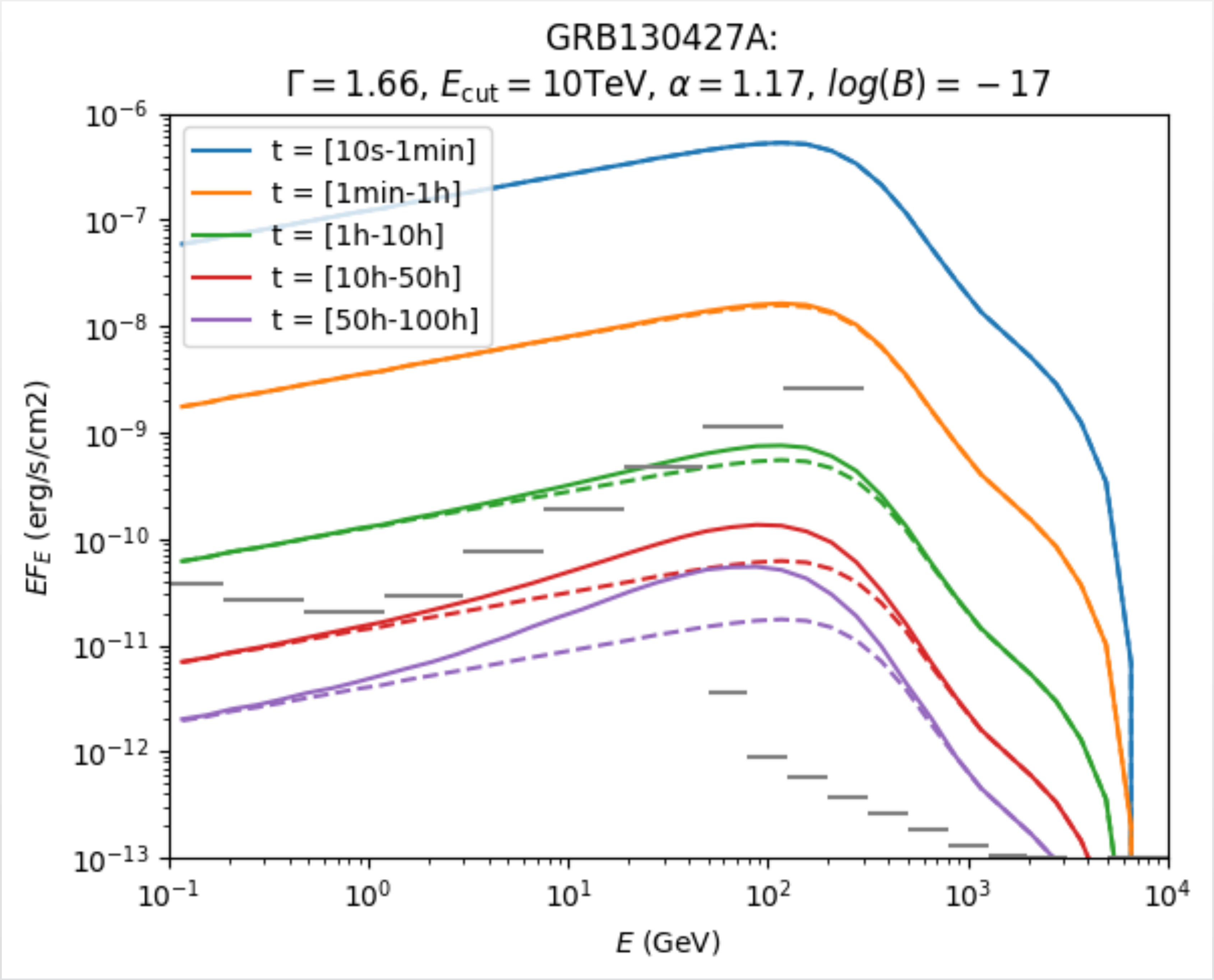


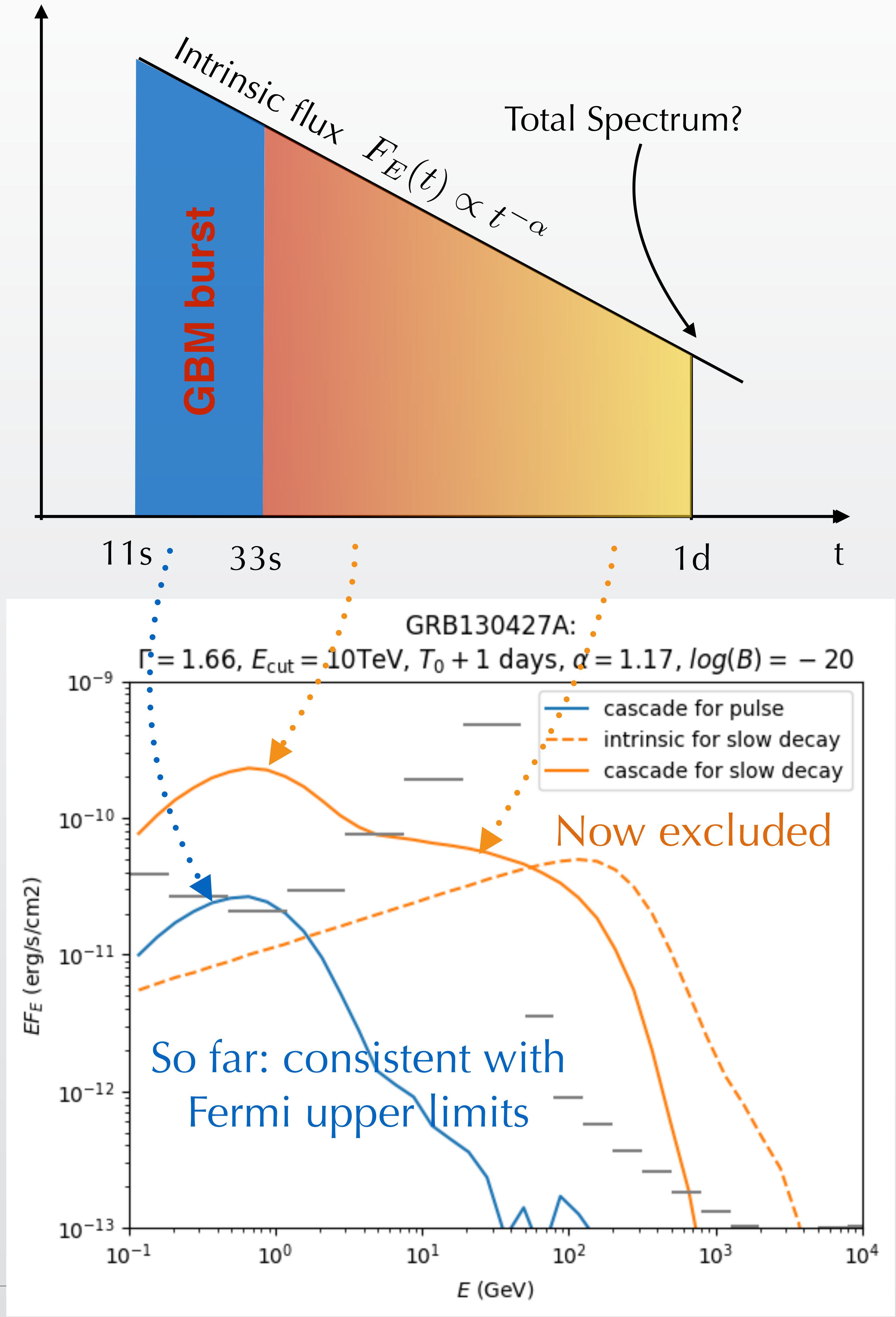


Adapted from Veres+2017

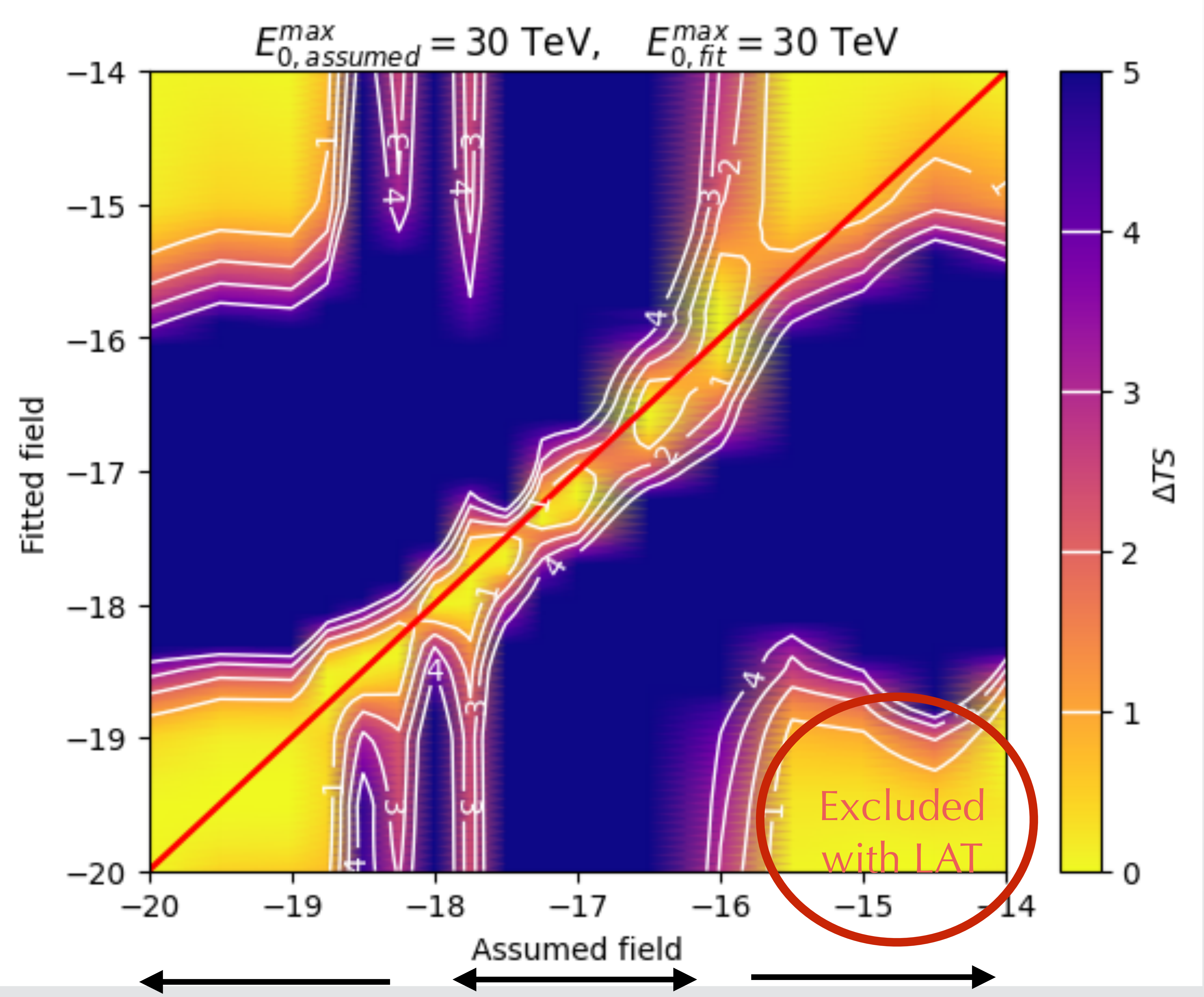
Taking into account the late intrinsic emission

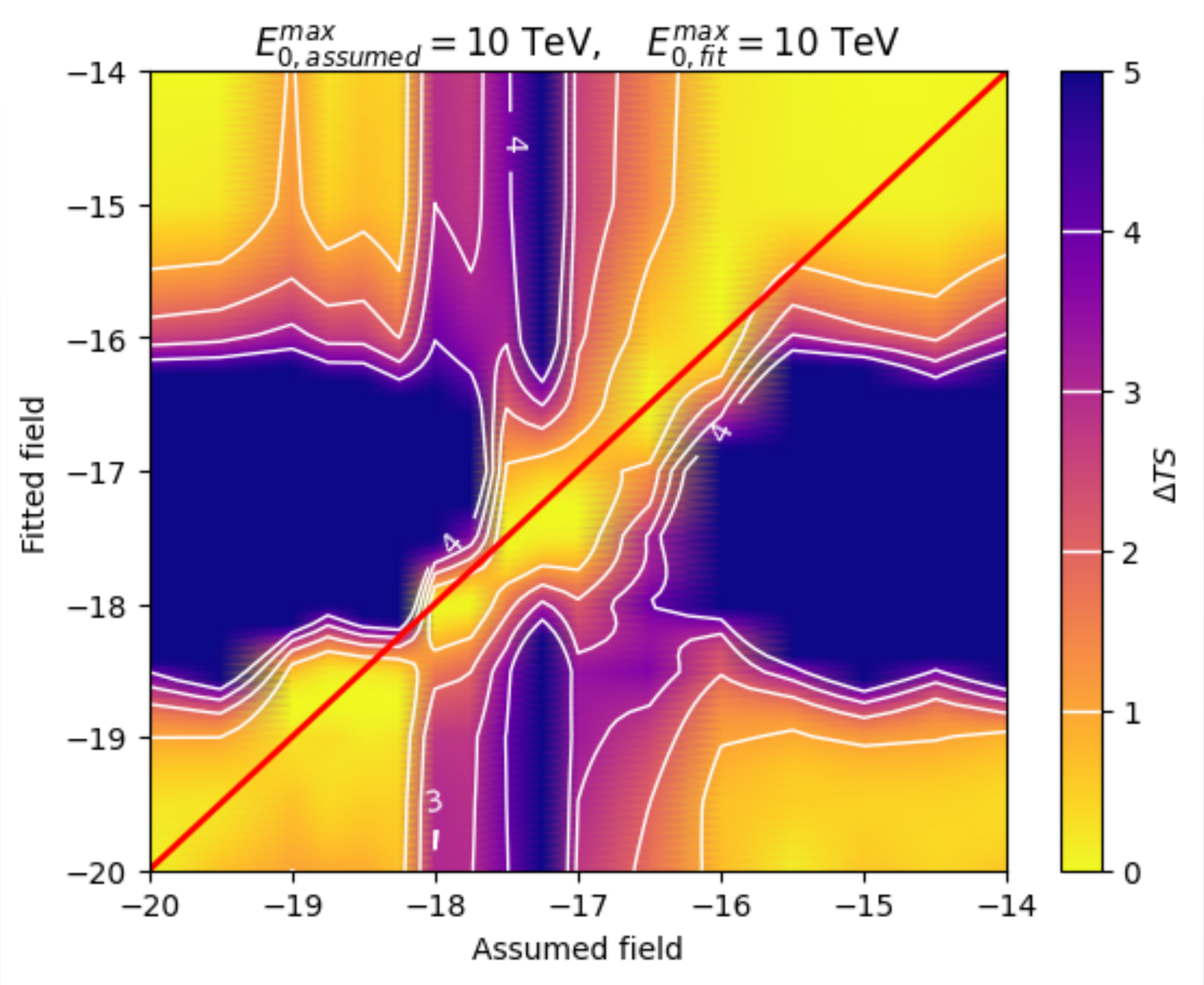
- **Intrinsic decay occurs on a finite time**
- **a) The late, intrinsic emission can hide the secondary emission** ✗
  - The cascade flux decreases slower than the intrinsic flux
- **b) The late, intrinsic emission keeps producing new secondaries** ✓
  - Stronger emission + plateau => betters constraints





Supplementary material





The cascade has gone below the CTA band

The cascade contributes at late times in the CTA band =>B is measured

The cascade is too weak