PROBING TRACES OF INTERGALACTIC MAGNETIC FIELD FROM GAMMA-RAY BURTS WITH VERY-HIGH ENERGY GAMMA-RAY DETECTORS

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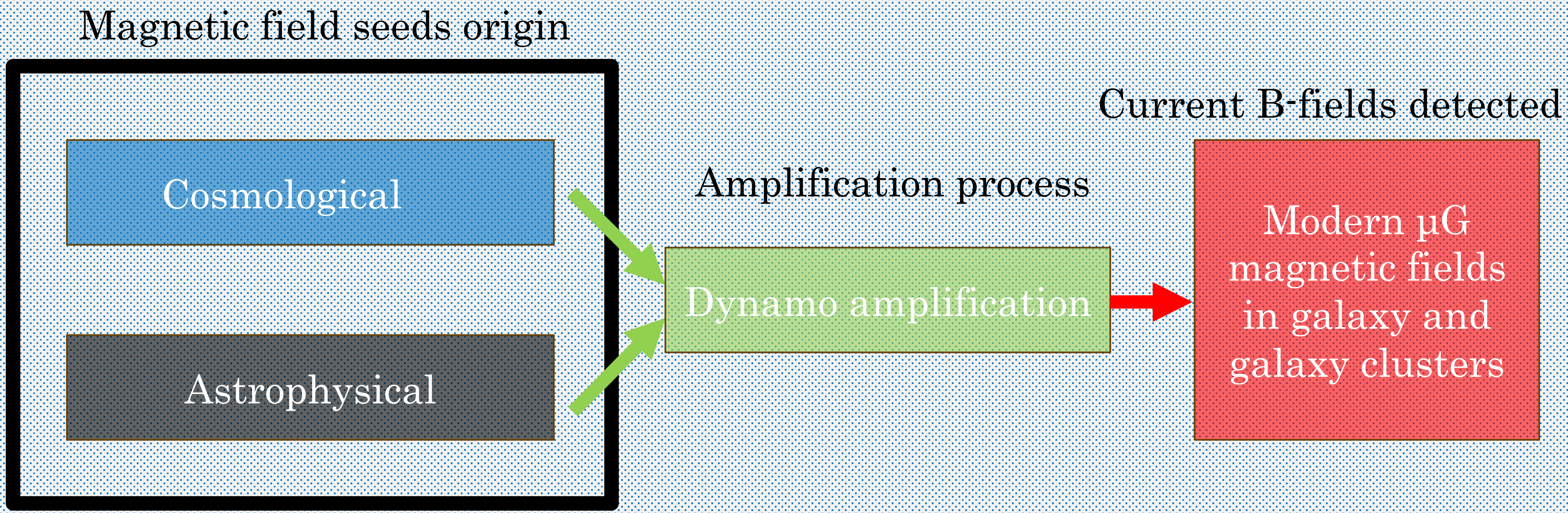
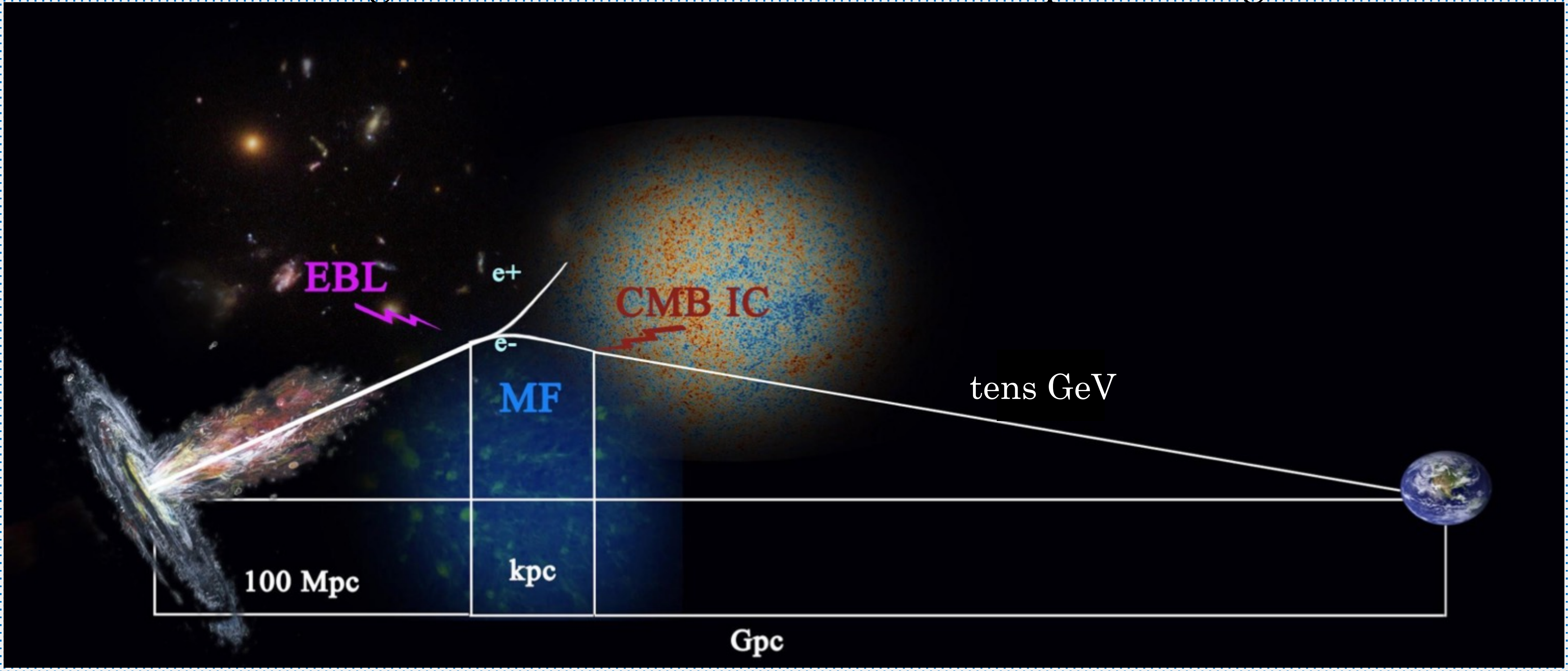
TAUP, 29/08/2023

Magnetic Fields in the Universe



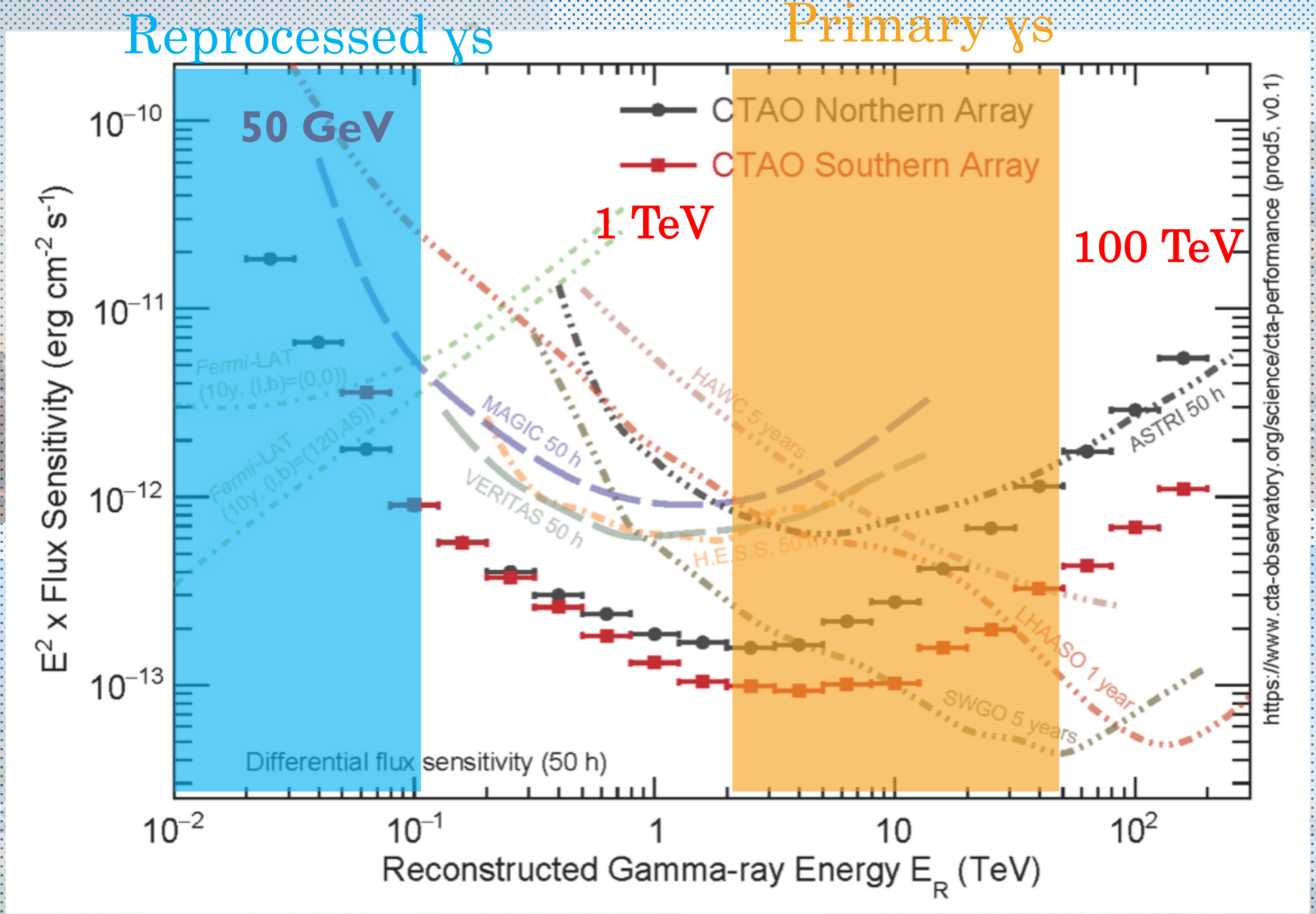
Probing Intergalactic Magnetic Field (IGMF) in the GeV range

IGMF can generate an ***extended*** *and* ***time-delayed*** emission at GeV energies due to magnetic field deflection + CMB reprocessing



Adapted from Vachaspati et al. 2020

Imaging Atmospheric Cherenkov Telescopes (IACTs)

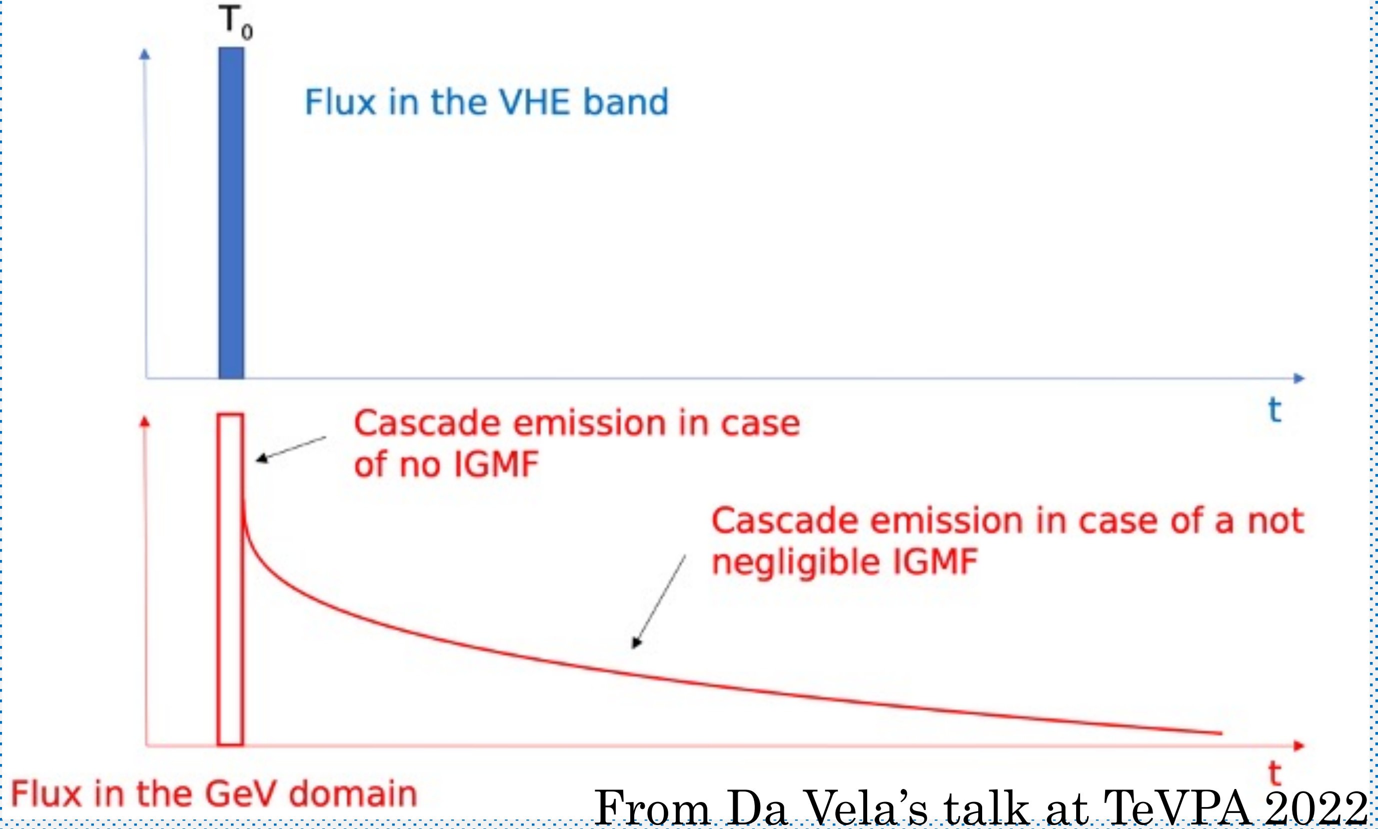


https://www.cta-observatory.org/science/ctao-performance/

Gamma-rays for Intergalactic Magnetic Field (IGMF) studies

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

- Method: search for **time-delayed '*pair-echo*' emission**



From Da Vela's talk at TeVPA 2022

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

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

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

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

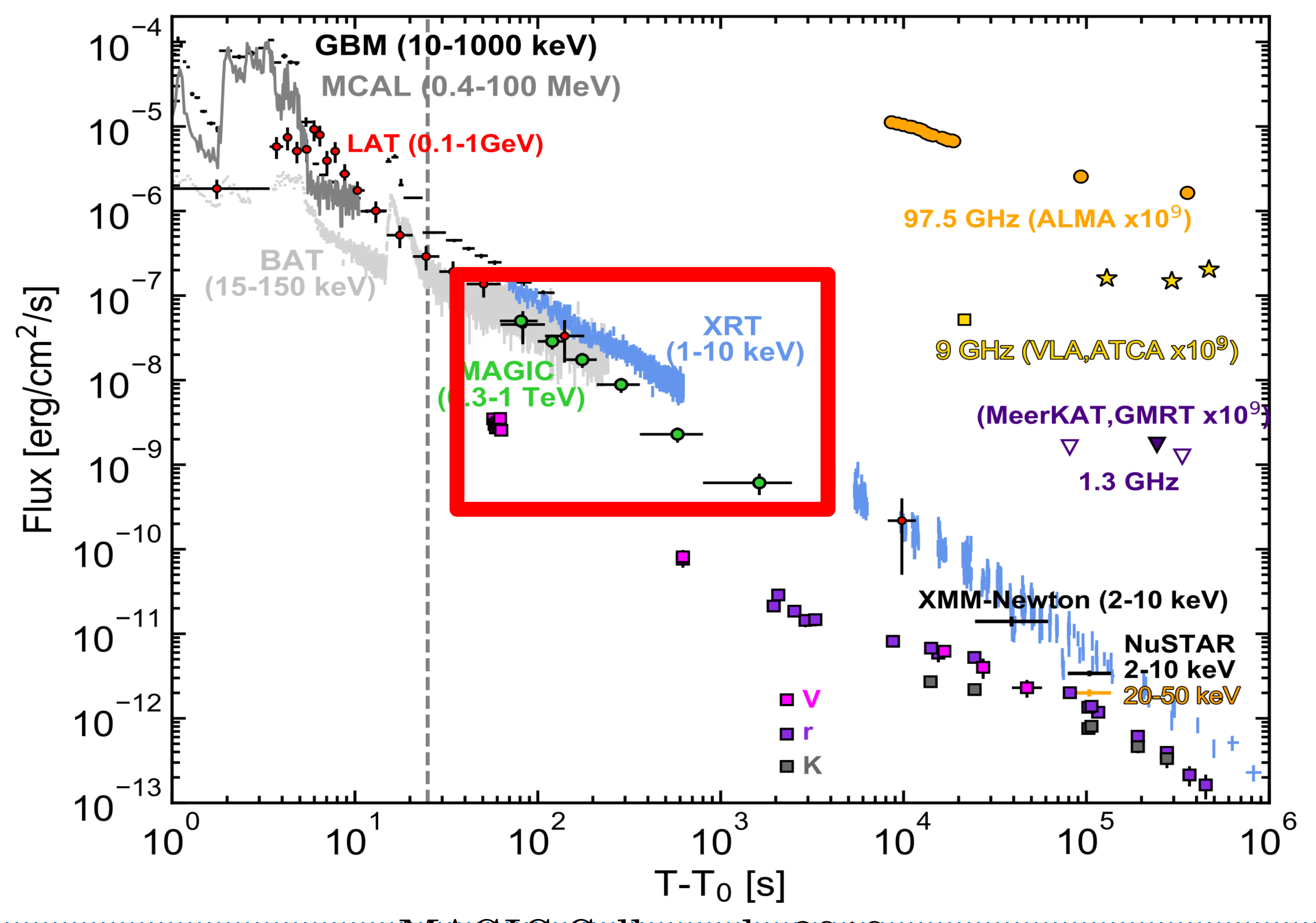
GRB190114C

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

TeV detection info (MAGIC):

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

Multi-wavelength light curve



MAGIC Coll. et al., 2019

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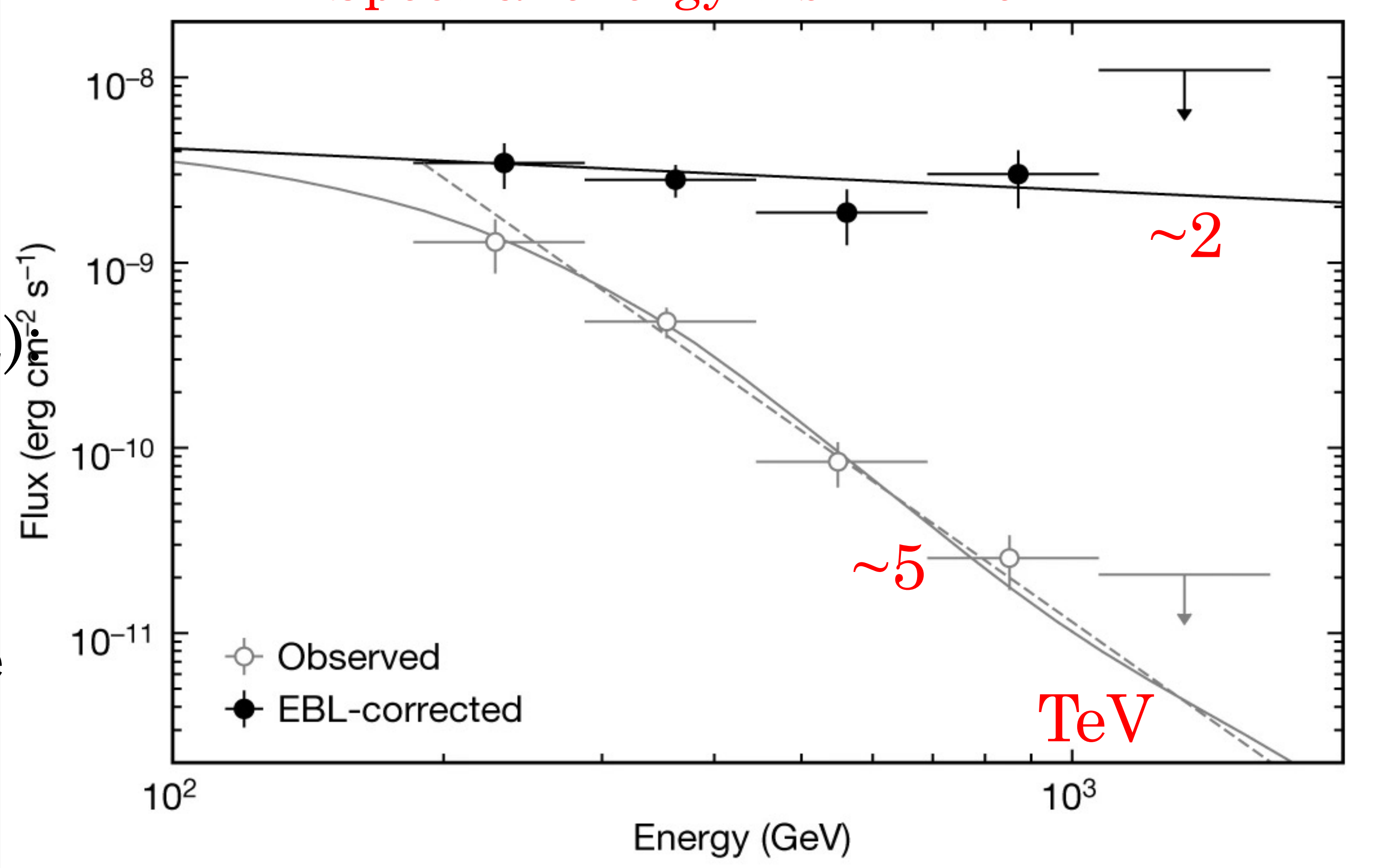
Spectral energy distribution



MAGIC Coll. et al., 2019

GRB190114C: Simulated echo emission

Purpose: calculate the simulated secondary cascade with ***CRPropa***

- For the case of GRB190114C (z=042)
- For a generic GRB190114C-like source at different distance (z=1.0 and z=0.2)

- Details of CRPropa (Source; Magnetic Field; Observer)

- Assumptions:

  - Starting time for photon cascade counting: 3000 s
  - Source time activity: MAGIC detection interval (40 min)
  - No spectral variability with time (consistent with MAGIC results)
  - Average flux emitted in afterglow phase

GRB190114C: Simulated echo emission

Estimate the average flux emitted in the afterglow phase in TeV range

- Afterglow starting phase → ~ 6 s (Ravasio et al. 2019)

MAGIC LC fit in [0.3 – 1] TeV from 68 s up to 2400 s

↓

Flux extrapolated from 6 s up to 2400 s

GRB190114C: Simulated echo emission

Estimate the average flux emitted in the afterglow phase in TeV range

Assumed photon (EBL-deabsorbed) spectrum in [0.2 - 10] TeV:

- Power-law spectrum

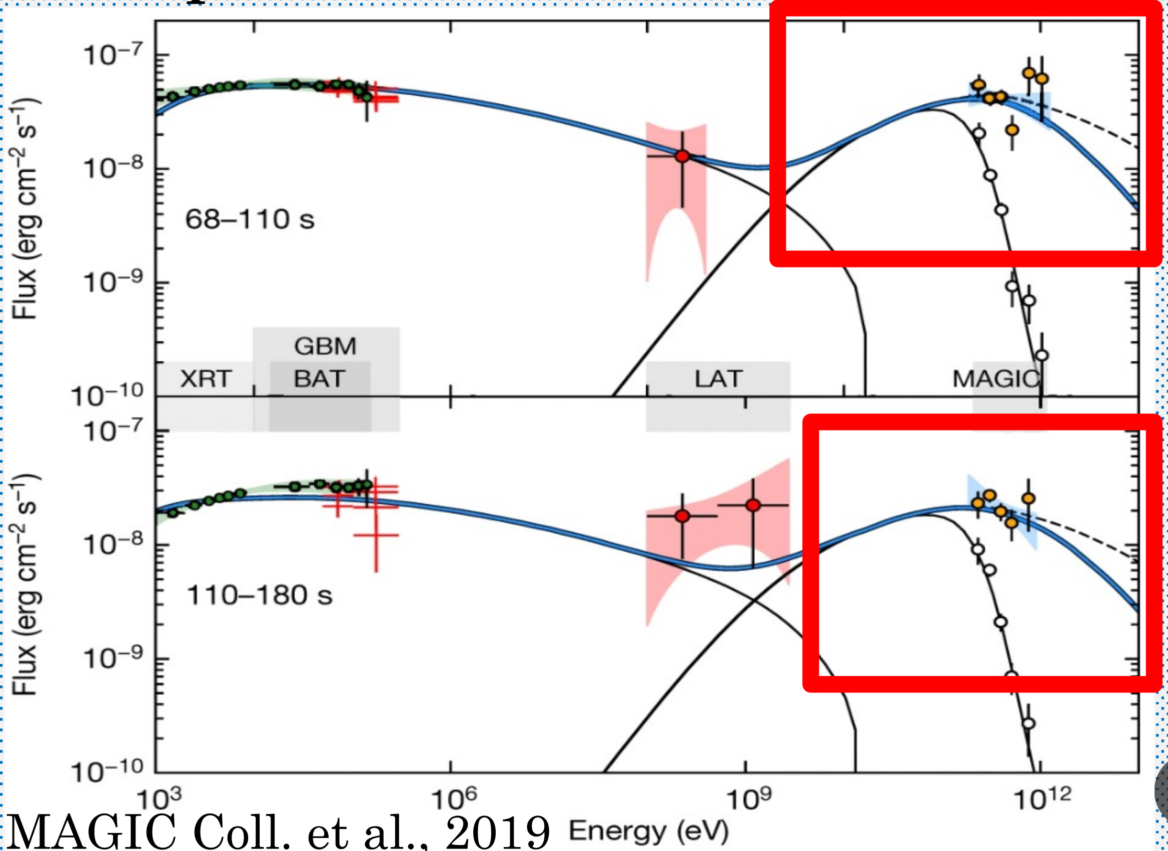
↓

too optimistic assumption

- Log-parabola spectrum

↓

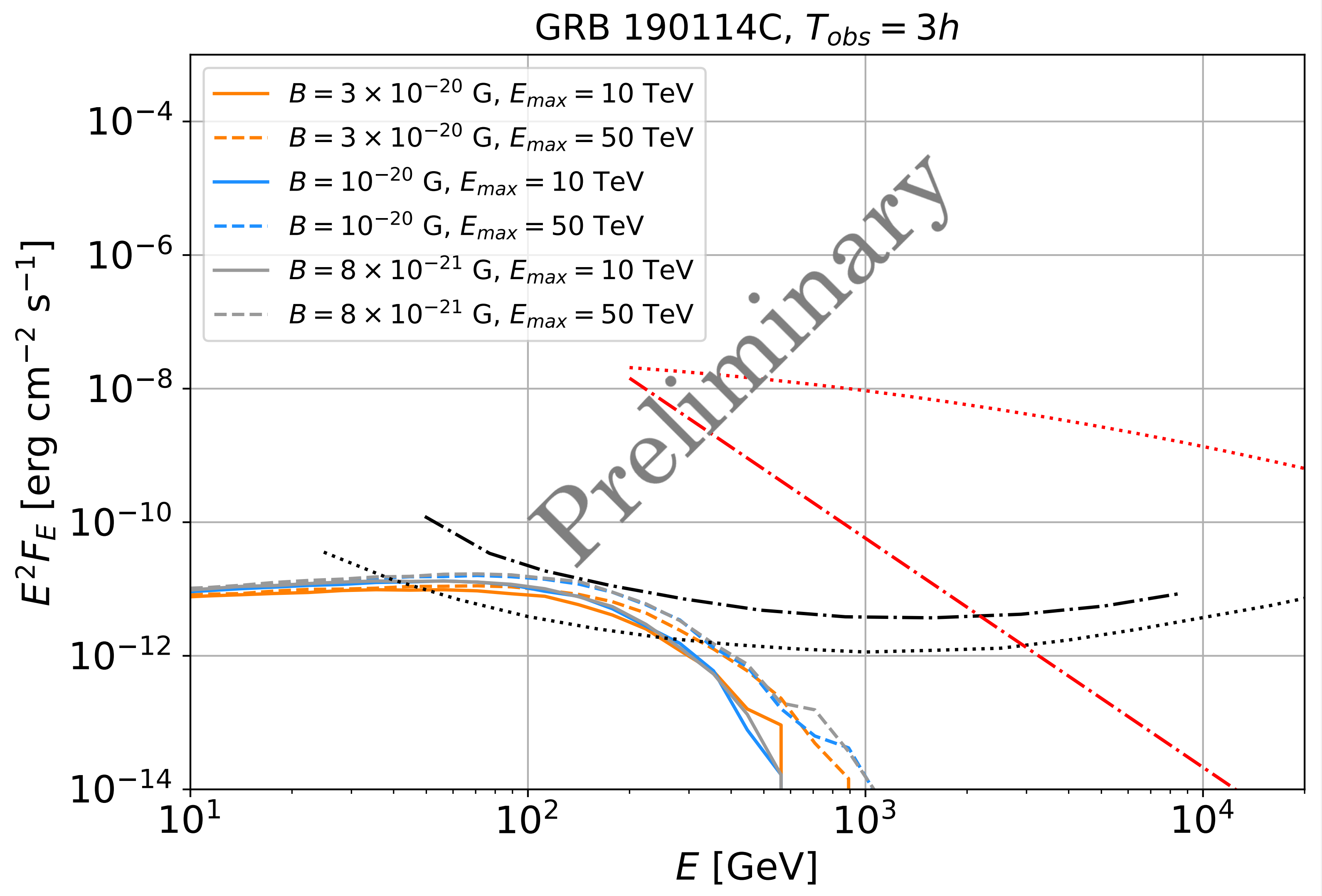
consistent with data modeling theoretical expectations



MAGIC Coll. et al., 2019

GRB190114C (z = 0.42)

Comparison with MAGIC and CTA sensitivities

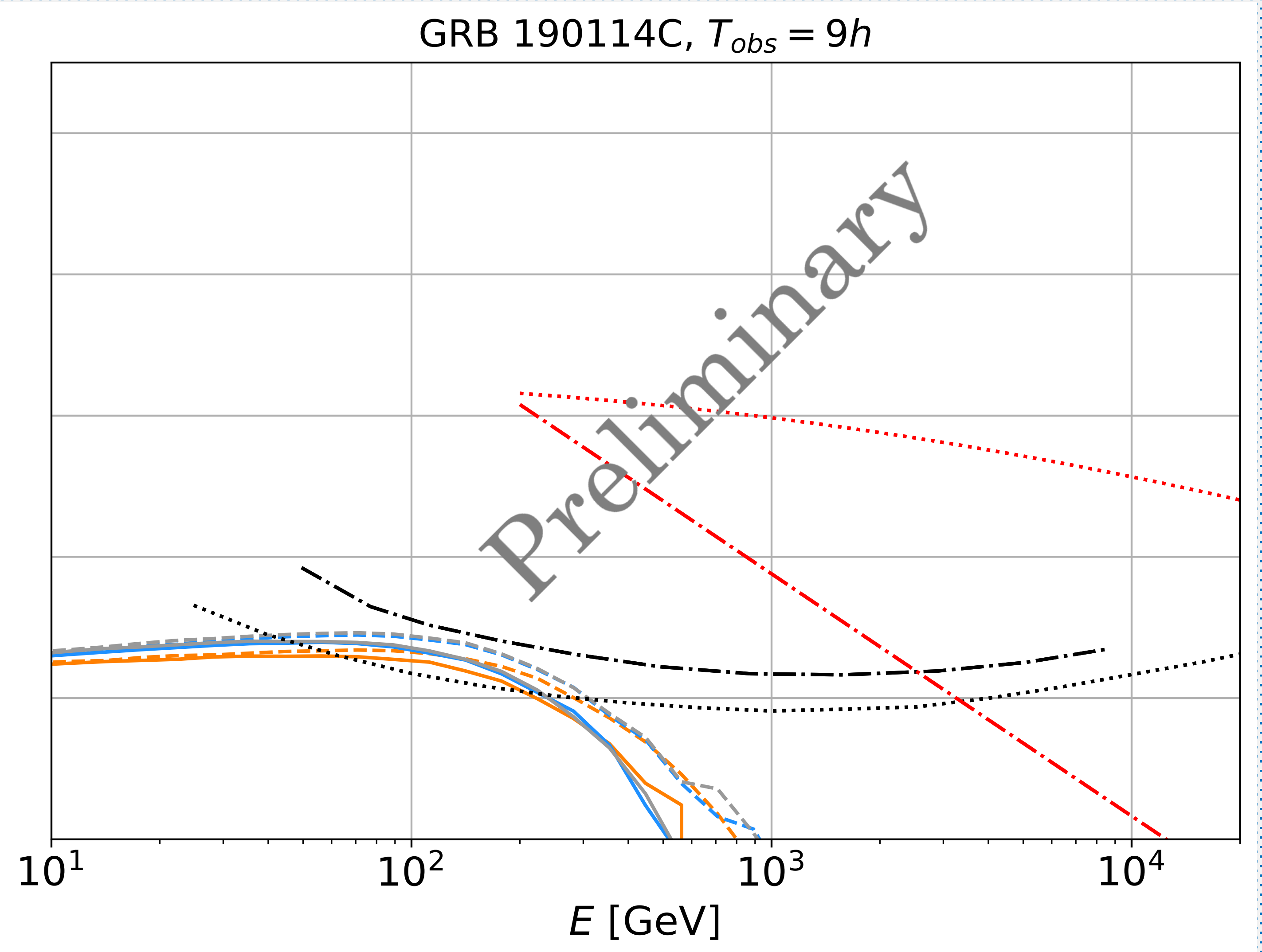


Spectral energy distribution

- Primary GRB emission
- Secondary emission
- Observational time: **3 hours** starting from 2400 s after trigger burst
- MAGIC and CTA sensitivity derived from CTA website and rescaled in time

GRB190114C (z = 0.42)

Comparison with MAGIC and CTA-North sensitivities

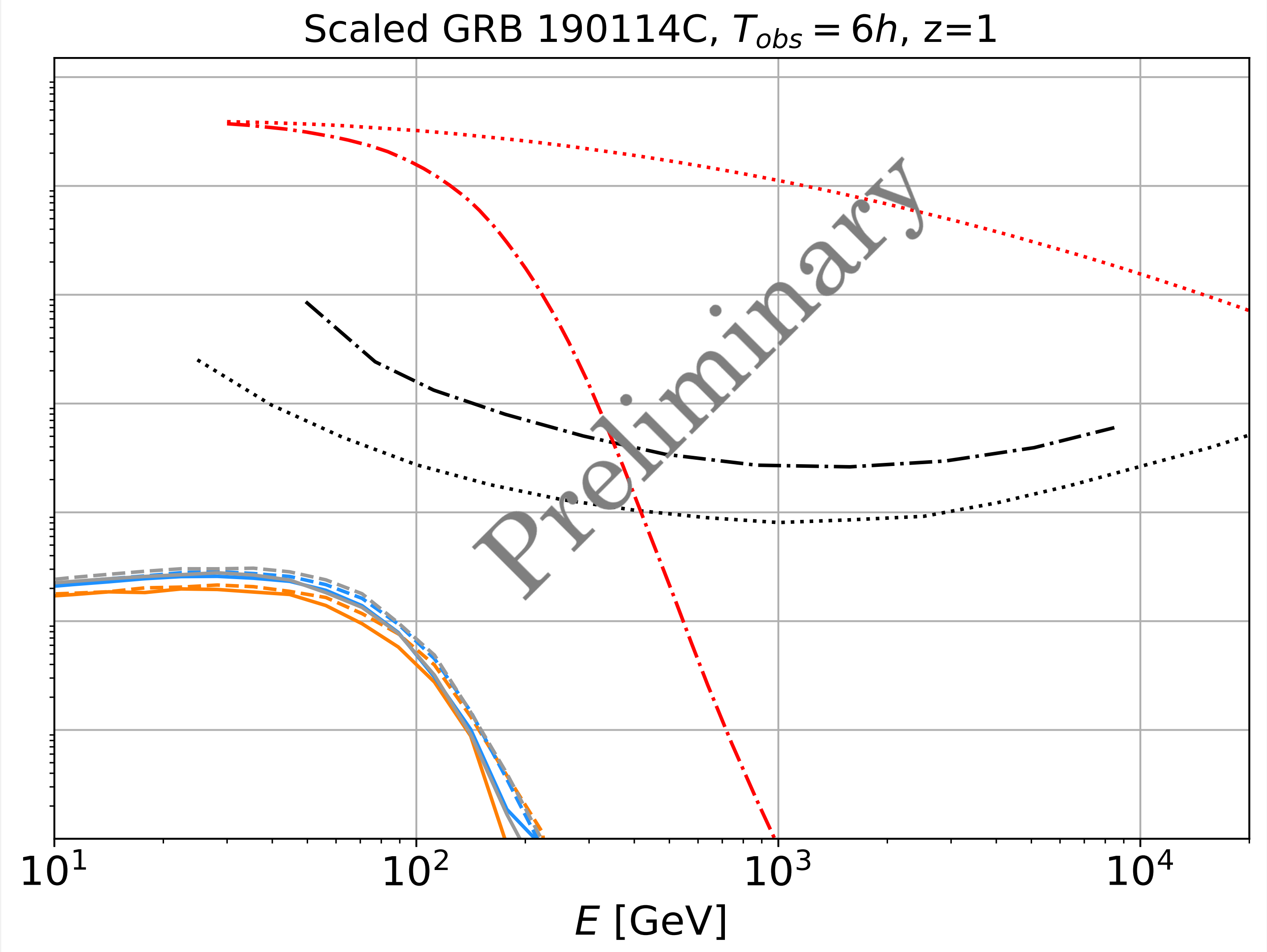


Spectral energy distribution

- Primary GRB emission
- Secondary emission
- Observational time: **9 hours** starting from 2400 s after trigger burst
- MAGIC and CTA-North sensitivity derived from CTA website and rescaled in time (S ∝ (1/√t))

GRB190114C-like with higher redshift (z = 1.0)

Comparison with MAGIC and CTA-North sensitivities

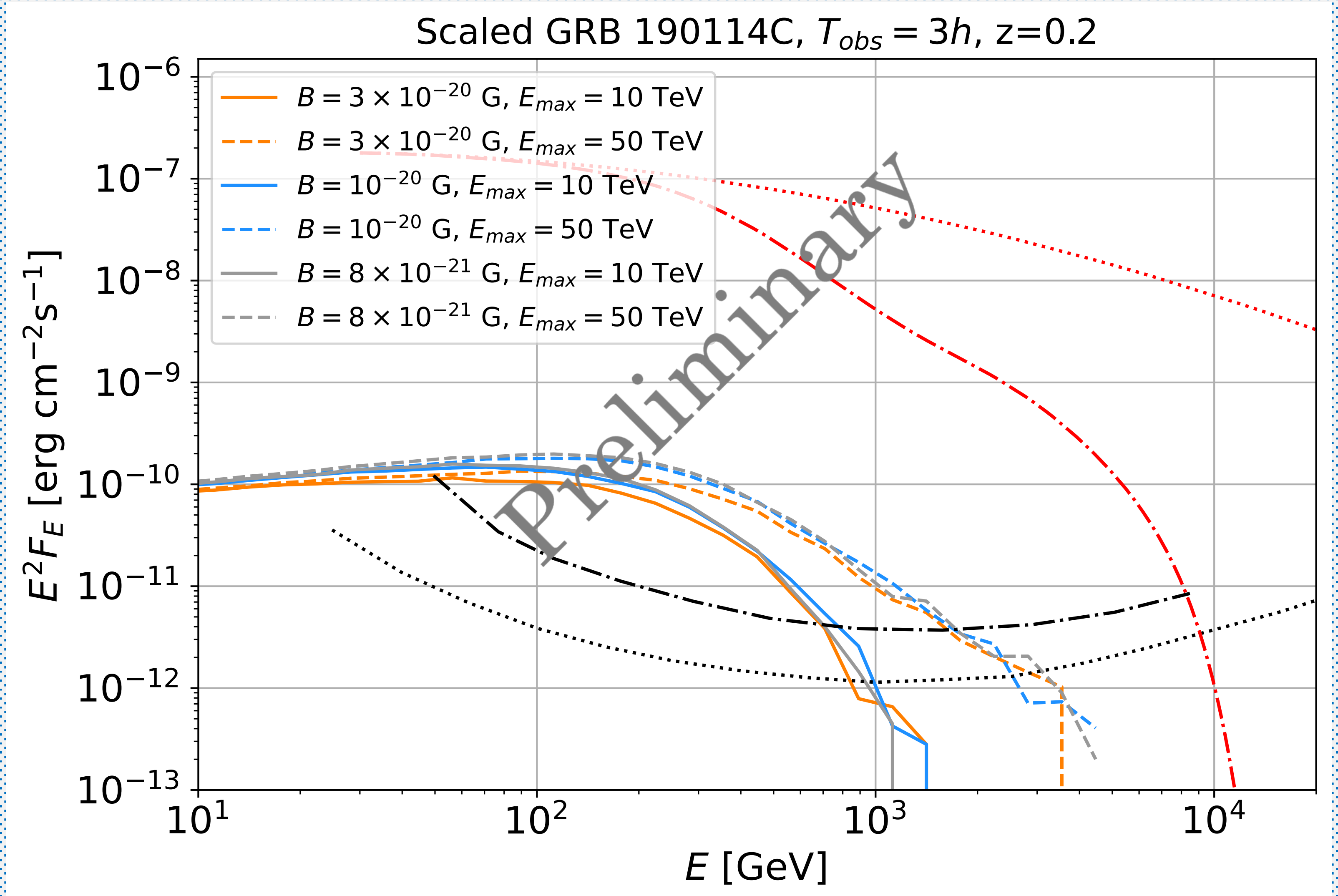


Spectral energy distribution

- Primary GRB emission
- Secondary emission
- Observational time: **6 hours** starting from 2400 s after trigger burst
- MAGIC and CTA-North sensitivity derived from [CTA website] and rescaled in time (S ∝ (1/√t))

GRB190114C-like with lower redshift (z = 0.2)

Comparison with MAGIC and CTA-North sensitivities



Spectral energy distribution

- Primary GRB emission
- Secondary emission
- Observational time: **3 hours** starting from 2400 s after trigger burst
- MAGIC and CTA-North sensitivity derived from CTA website and rescaled in time ($S \propto (1/\sqrt{t})$)

Conclusions

- Gamma-Ray Bursts are promising sources for IGMF studies
- Current and future IACTs can probe the "weakest" IGMFs **extending observational time** (3-6-9 h) after GRB emission is not visible anymore
- Impact of intrinsic source features is greater than secondary reprocessing due to distance → bright and nearby GRBs are the most interesting objects
- Next steps:
  - Provide accurate predictions for CTA full array
  - Explore the role of other parameters

BACKUP SLIDES

GRB221009A (z = 0.151)

TITLE: GCN CIRCULAR
NUMBER:
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE:
FROM: Judith Racusin at GSFC <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen, Min Zha, Cheng Liu, Zhiguo Y
Zhen Cao report on behalf of the LHAASO experiment

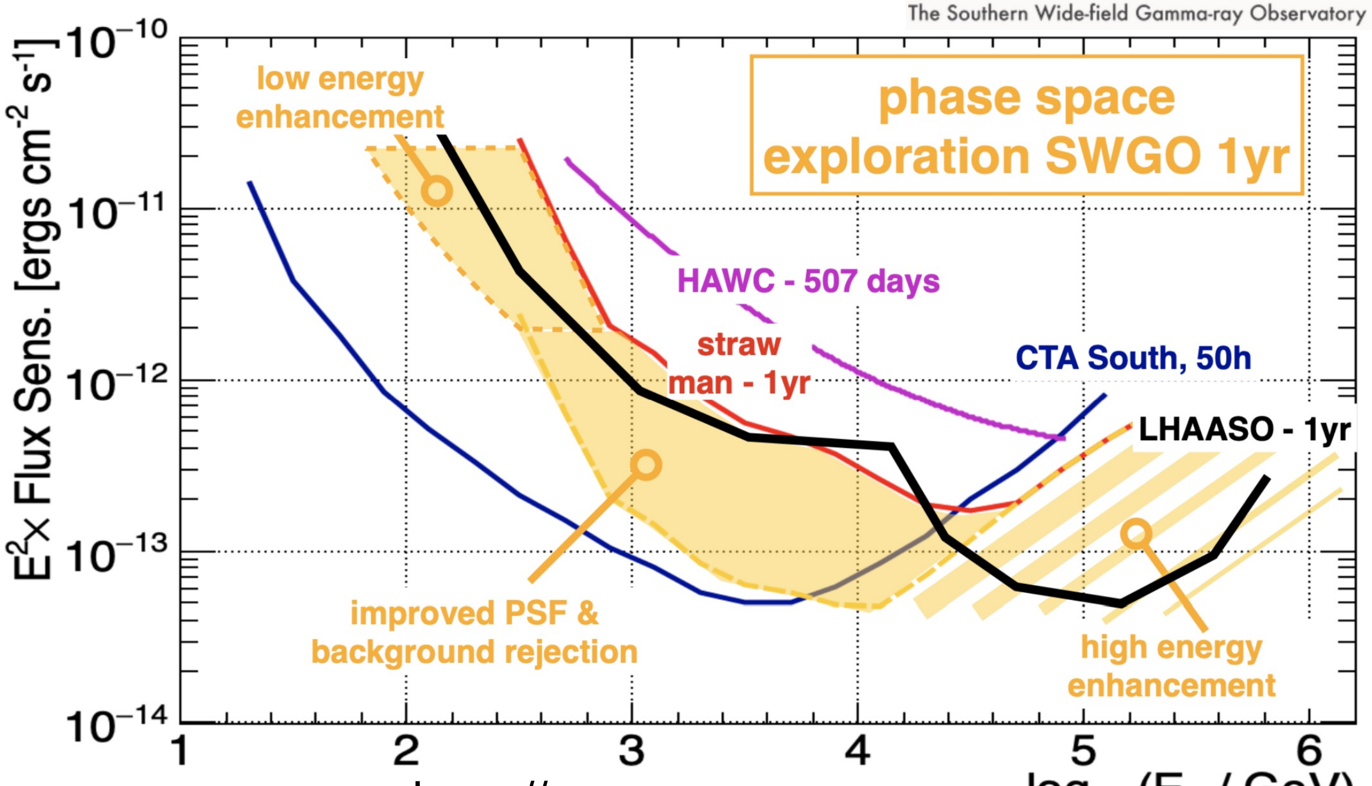
We report the observation of GRB 221009A, which was detected by Swif
et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al
Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #326

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, cent
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the signif
100 s.d., and is observed as well by LHAASO-KM2A with the significan
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRB

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in
band between 10^11 and 10^15 eV) and cosmic ray measurements.

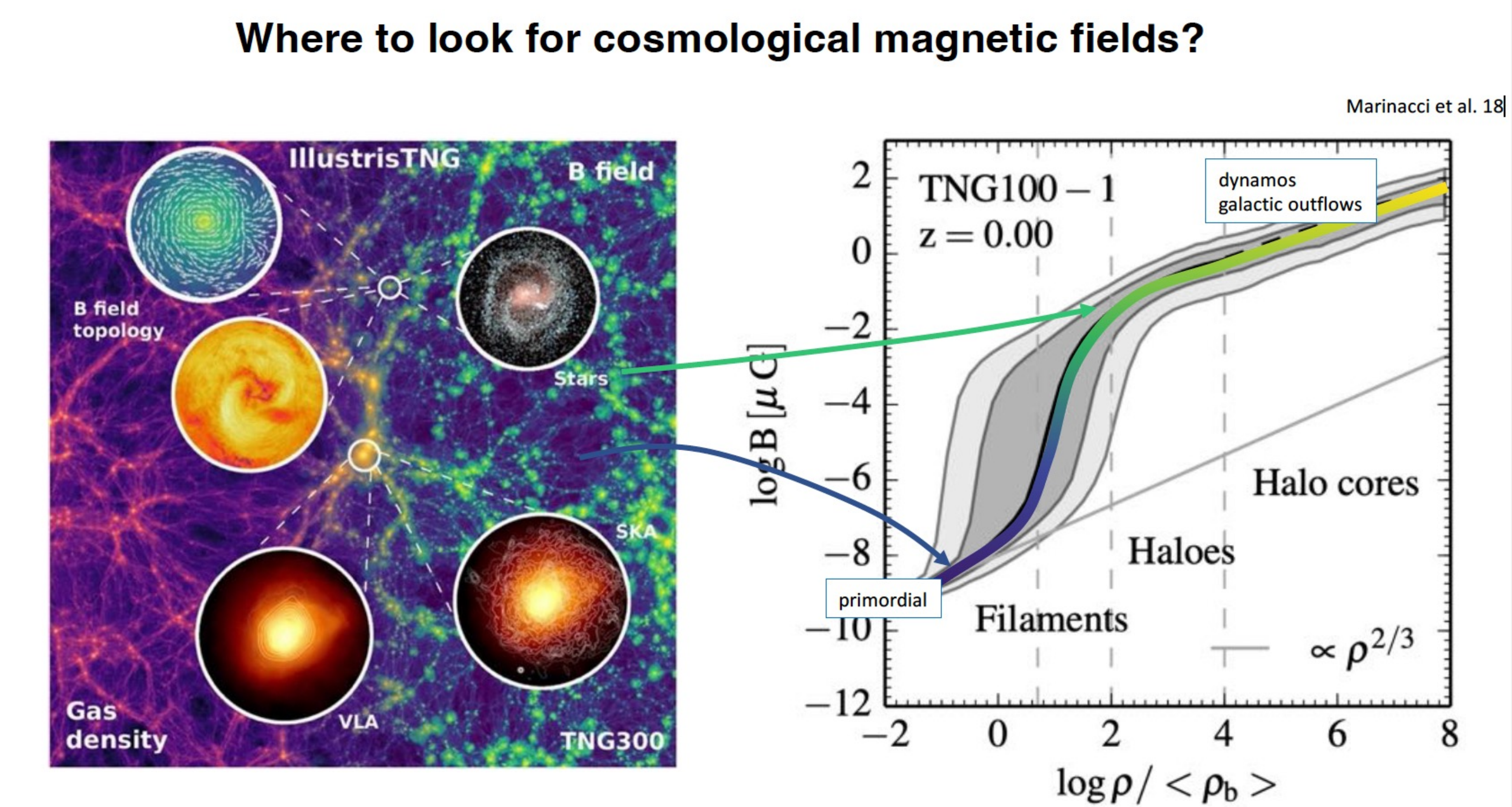
The Southern Wide-field Gamma-ray Observatory



https://www.swgo.org

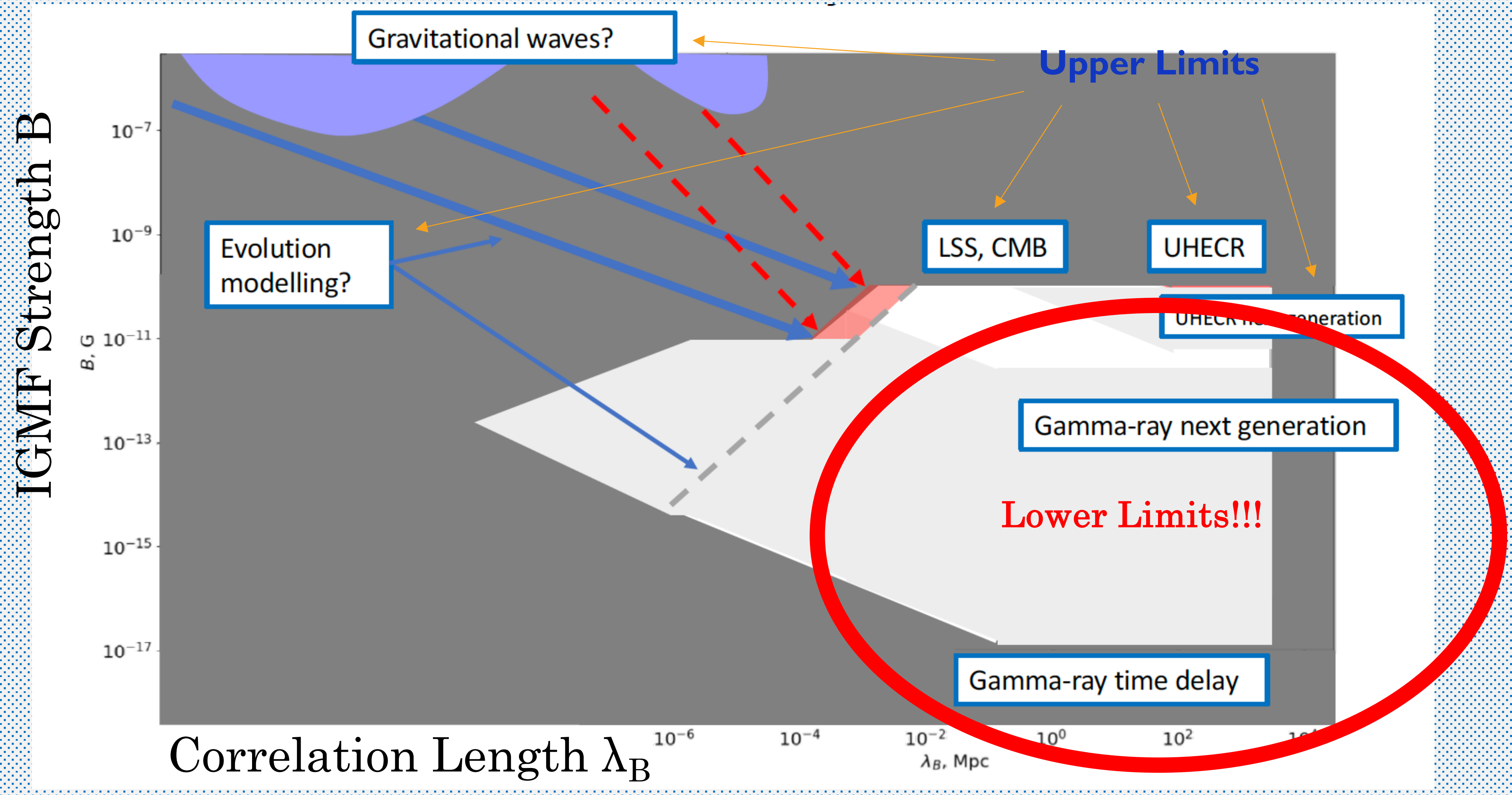
Current and future Extended Air Shower (EAS) can provide useful results

Magnetic Fields in the Universe



adapted from Andrii Neronov's slides, Bologna,'Cosmic magnetism in voids and filaments', 2023

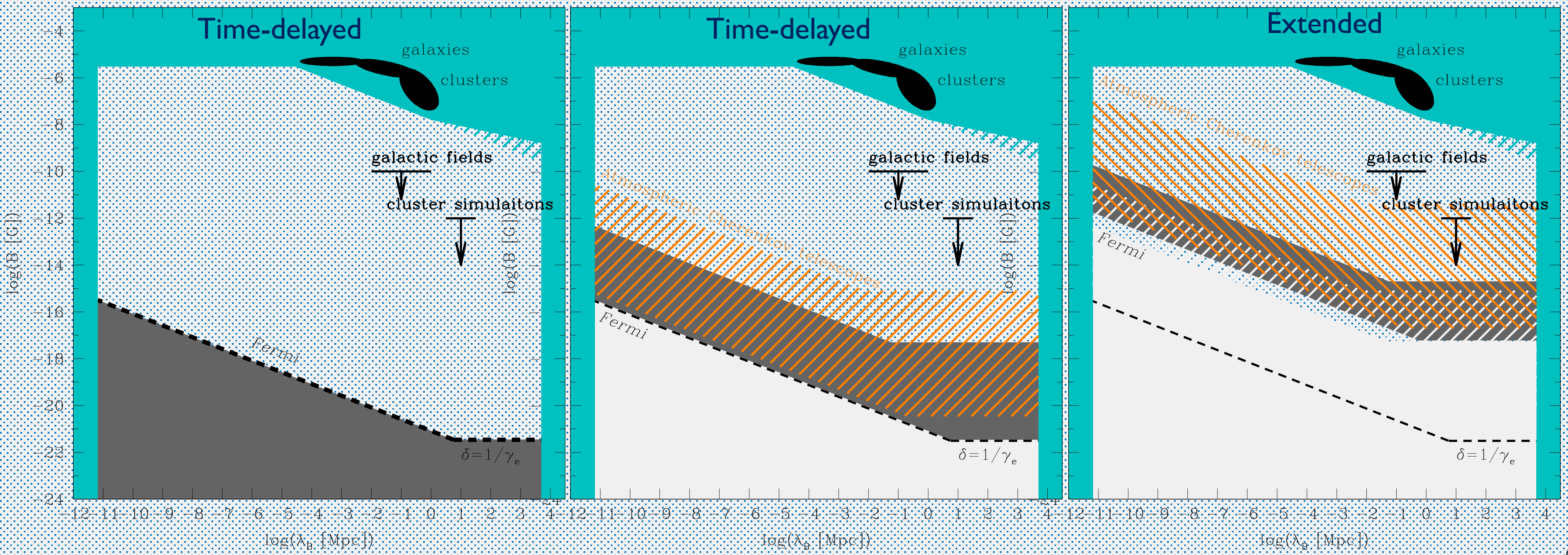
Intergalactic Magnetic Field (IGMF) Limits



adapted from Andrii Neronov's slides, Bologna, 'Cosmic magnetism in voids and filaments', 2023

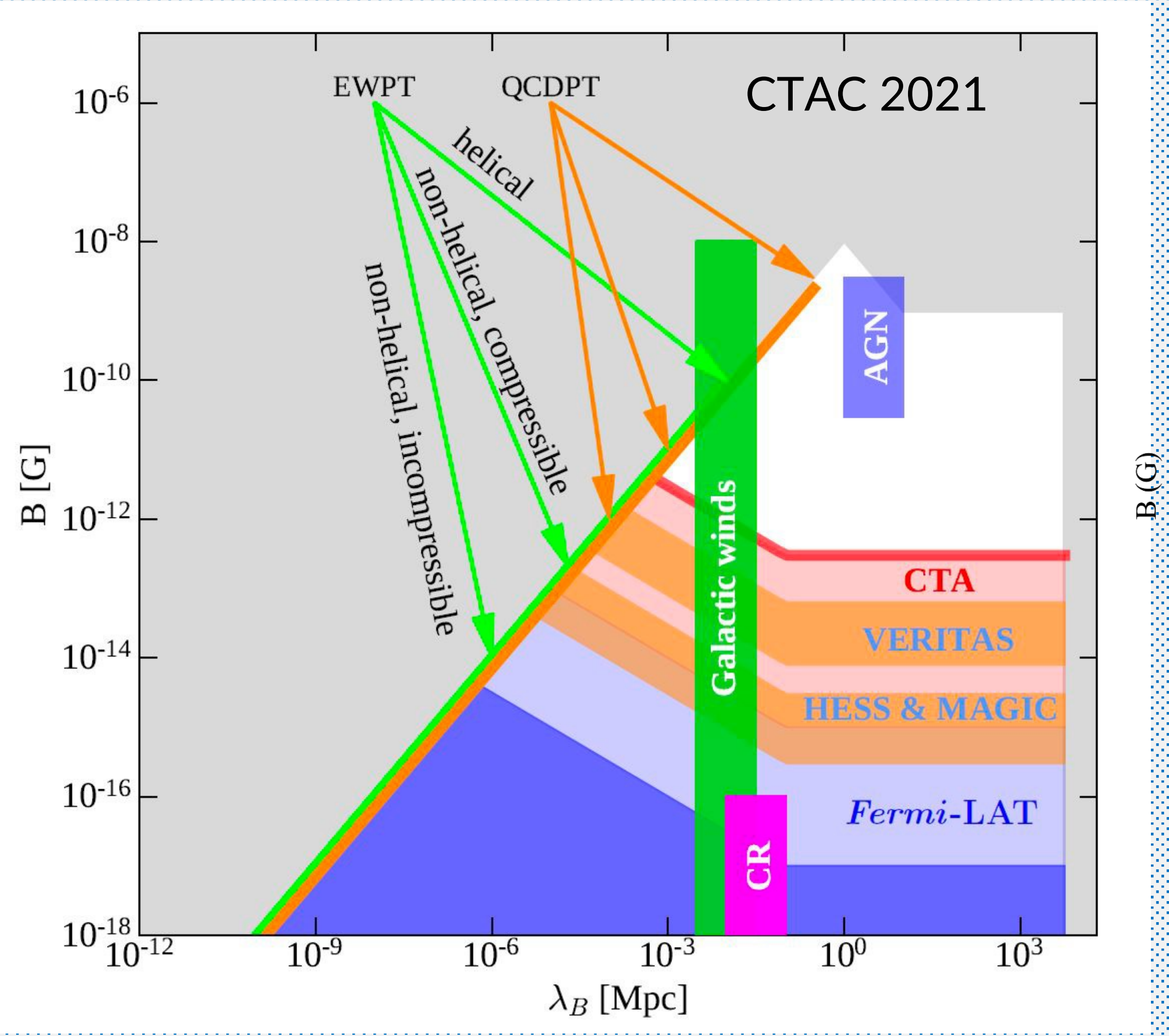
Probing IGMF in the GeV range

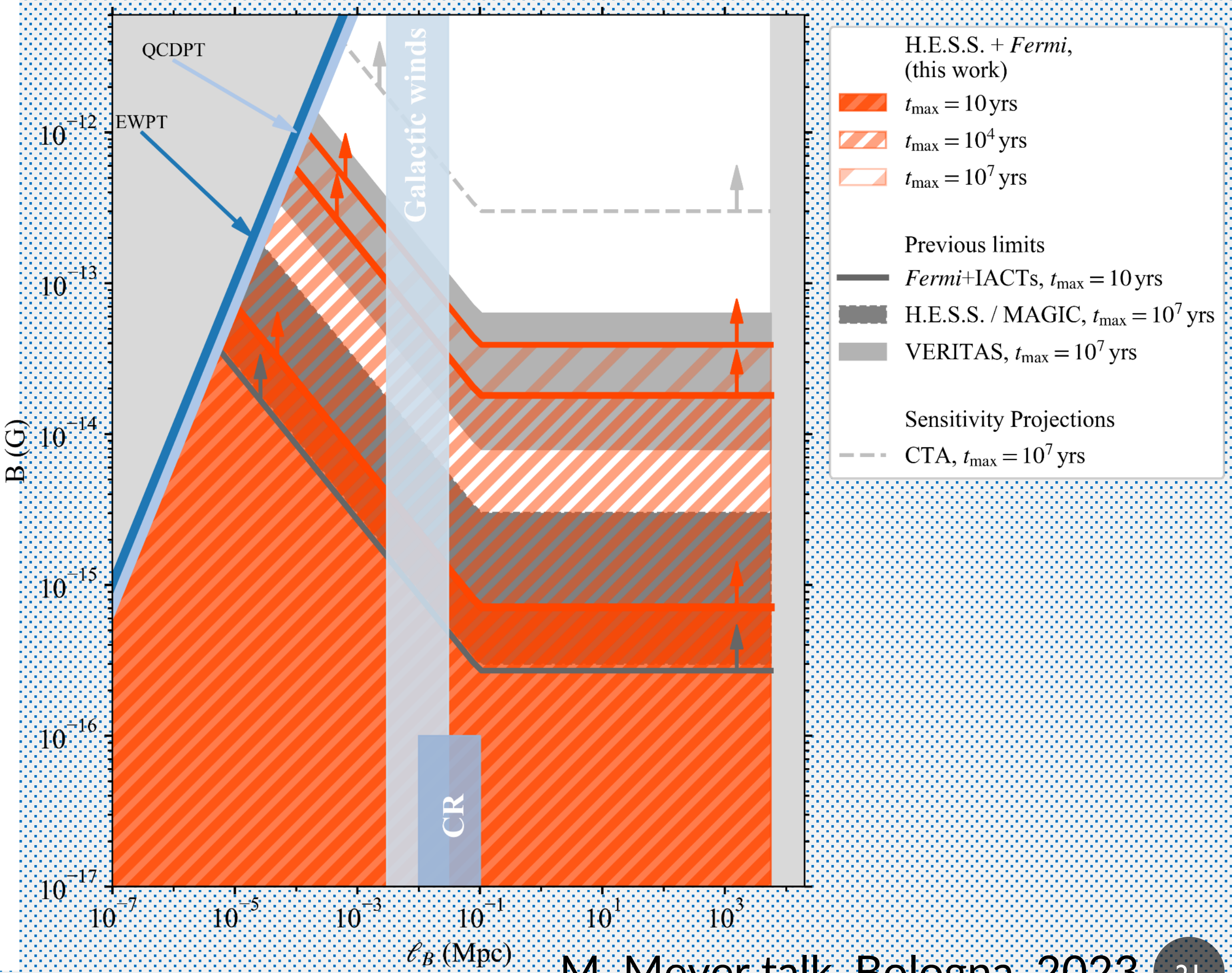
IGMF can generate an ***extended*** *and* ***time-delayed*** emission at GeV energies due to magnetic field deflection + CMB reprocessing



Neronov et al, 2009

Lower Limits (LL): the kingdom of gamma rays

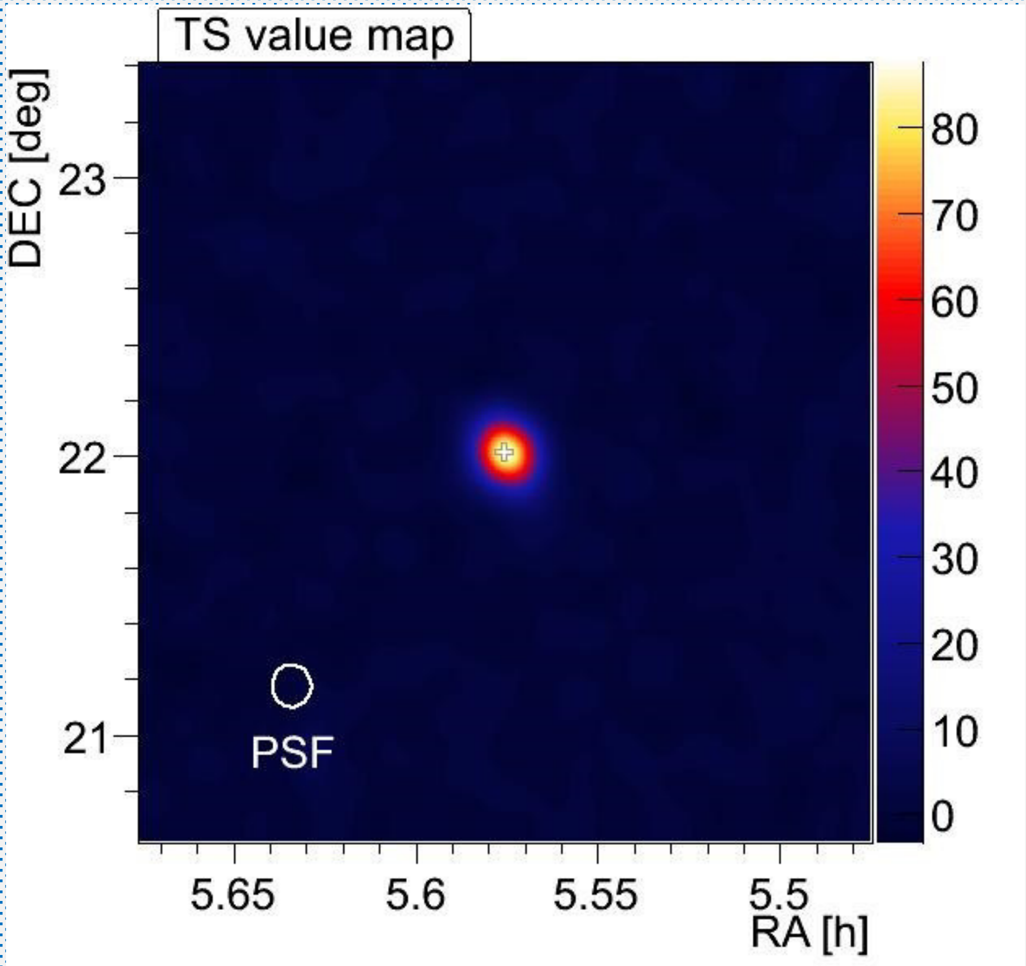




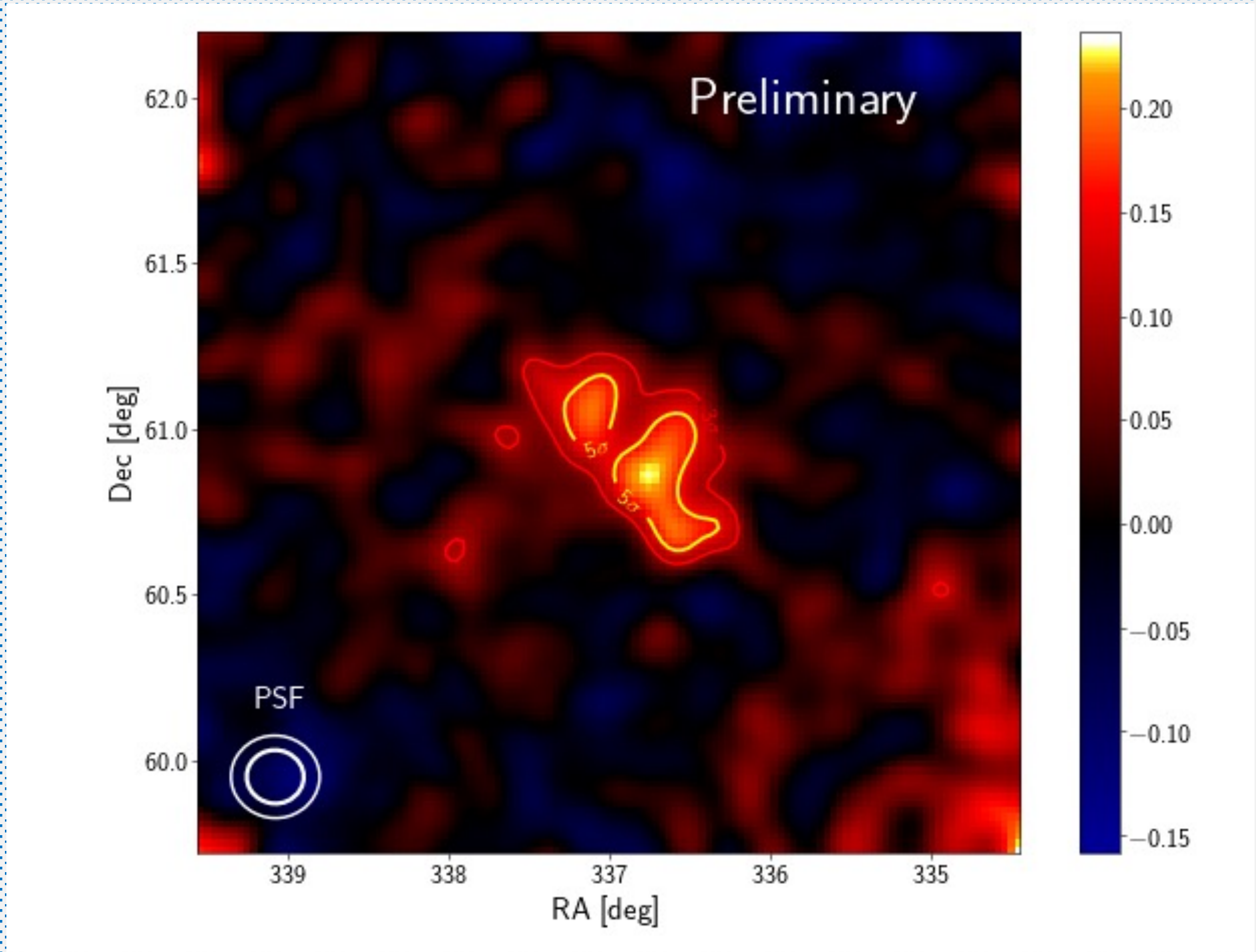
M. Meyer talk, Bologna, 2023

IGMF: Extended emission

Point-like source

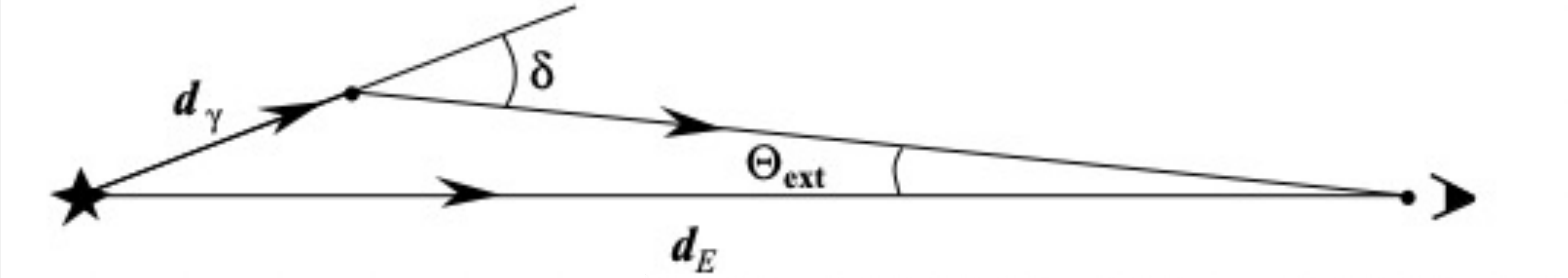


Extended source



IGMF: Extended emission

Deflection angle ($\boldsymbol{\delta}$) and angular extention ($\boldsymbol{\Theta}_{ext}$) are sensitive to magnetic field B, energy of reprocessed photons (E_γ) and source distance (z)



$$\begin{aligned}\delta &= \frac{D_e}{R_L} \simeq 3\times 10^{-6}(1+z_{\gamma\gamma})^{-4}\left[\frac{B'}{10^{-18}\ \mathrm{G}}\right]\left[\frac{E'_e}{10\ \mathrm{TeV}}\right]^{-2} \\ &\simeq 3\times 10^{-6}(1+z_{\gamma\gamma})^{-2}\left[\frac{B_0}{10^{-18}\ \mathrm{G}}\right]\left[\frac{E'_e}{10\ \mathrm{TeV}}\right]^{-2} \qquad (30)\end{aligned}$$

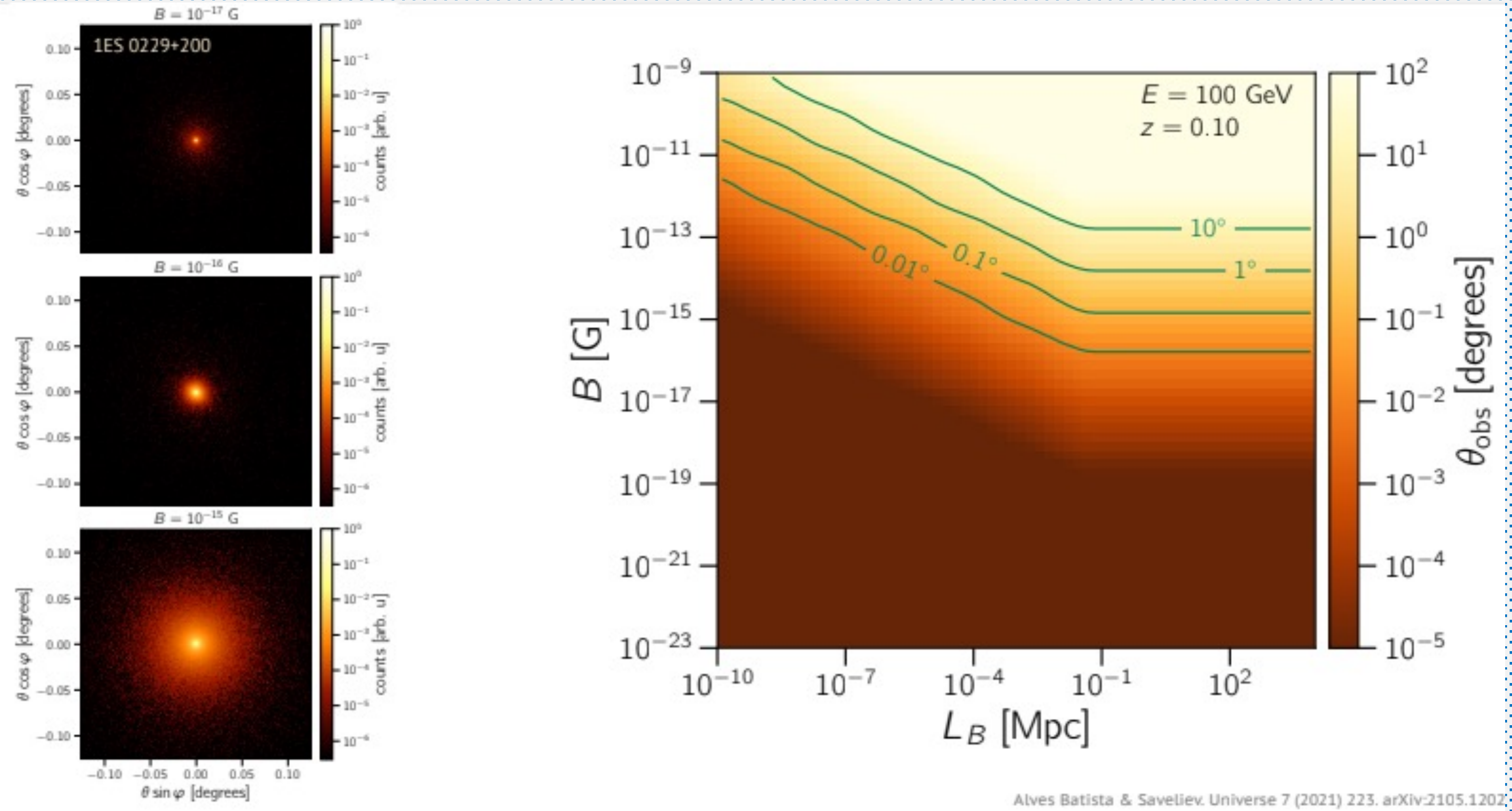
$$\Theta_{ext} \simeq \begin{cases} 0.5^\circ(1+z)^{-2}\left[\frac{\tau_\theta}{10}\right]^{-1} \left[\frac{E_\gamma}{0.1\ \mathrm{TeV}}\right]^{-1}\left[\frac{B_0}{10^{-14}\ \mathrm{G}}\right], & \lambda'_B \gg D_e \\ 0.07^\circ(1+z)^{-1/2}\left[\frac{\tau_\theta}{10}\right]^{-1} \left[\frac{E_\gamma}{0.1\ \mathrm{TeV}}\right]^{-3/4}\left[\frac{B_0}{10^{-14}\ \mathrm{G}}\right]\left[\frac{\lambda_{B0}}{1\ \mathrm{kpc}}\right]^{1/2}, & \lambda'_B \ll D_e \end{cases}$$

Neronov et al, 2009

Gamma-rays for Intergalactic Magnetic Field (IGMF) studies

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

- Method I : search for extended emission

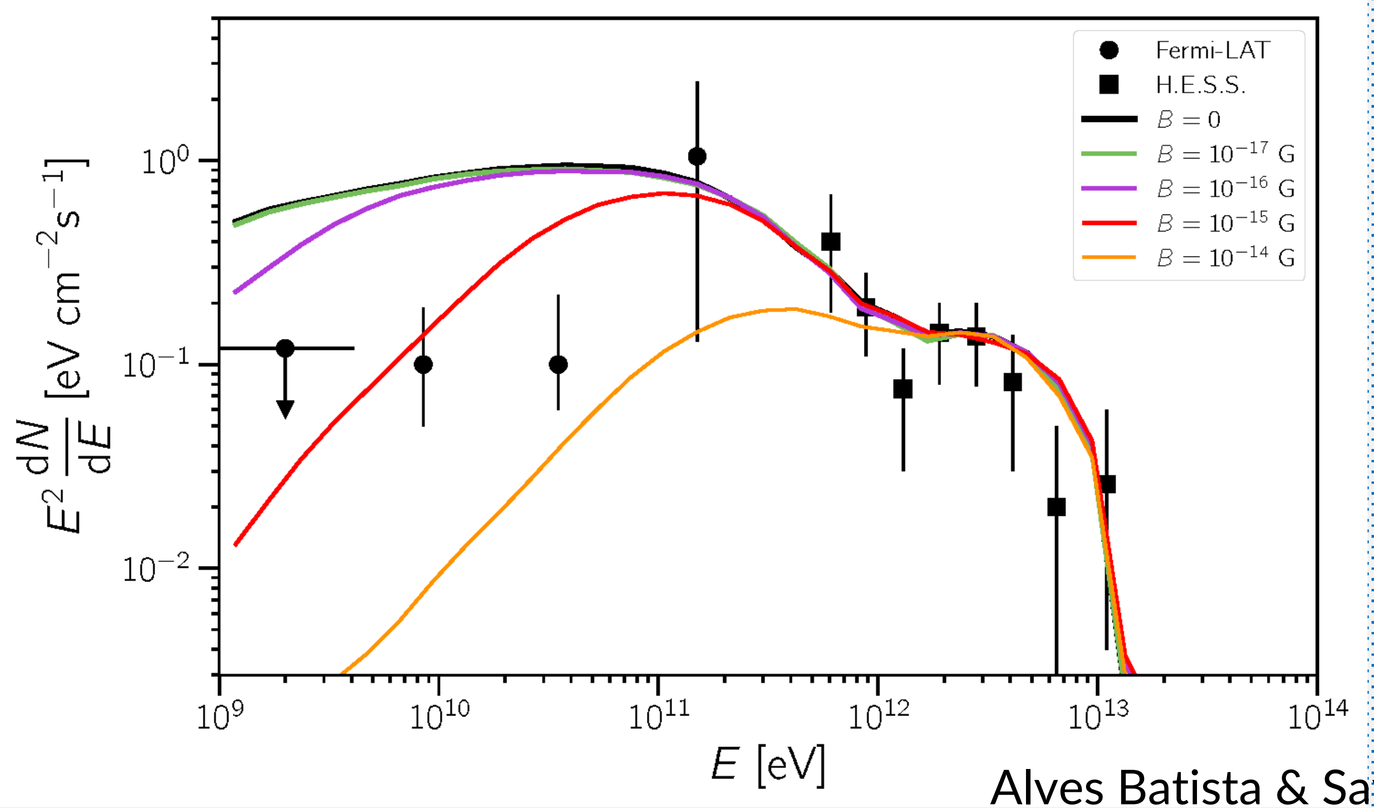


Alves Batista, 2021

Gamma-rays for Intergalactic Magnetic Field (IGMF) studies

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

- Method III: search for SED signatures



Alves Batista & Saveliev, 2021

IGMF studies

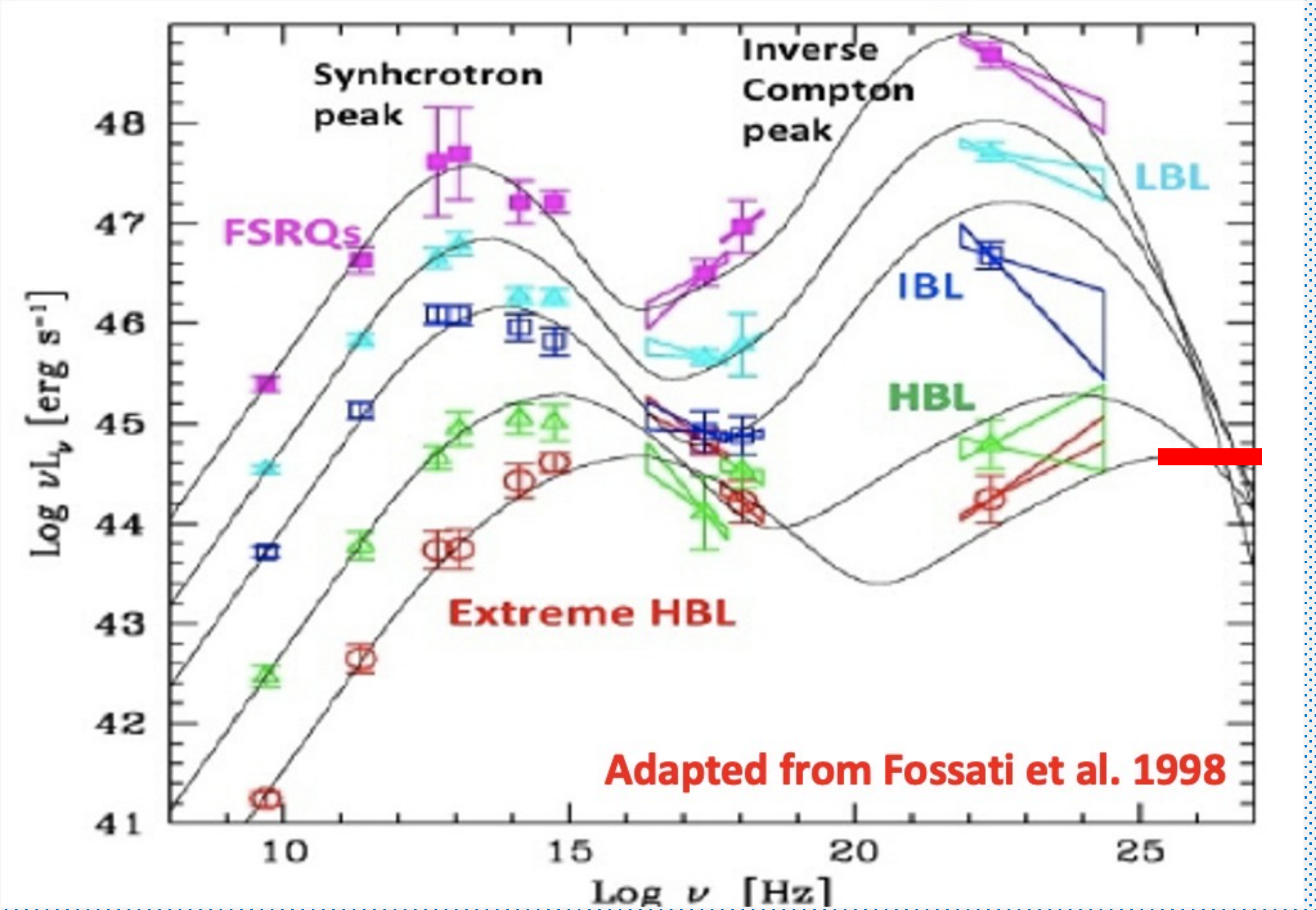
Blazars

Features:

- Persistent sources of TeV radiation
- Subclass with Hard-TeV spectrum
- Population of ~ 80 sources as TeV emitters

Drawbacks:

- Source temporal (min-yrs) and spectral variability
- Pollution by primary GeV emission
- Unknown duty cycle



IGMF studies

GRBs

Features:

- Cosmological sources
- Bright transient events (L up to ~ 10^{53} erg s^{-1})

Advantages:

- ~~Pollution by primary GeV emission~~
- ~~Unknown duty cycle~~

Drawbacks:

- Limited number of events (4 events at TeV + 2 hints of TeV emission)
- Source spectrum and spectral variability

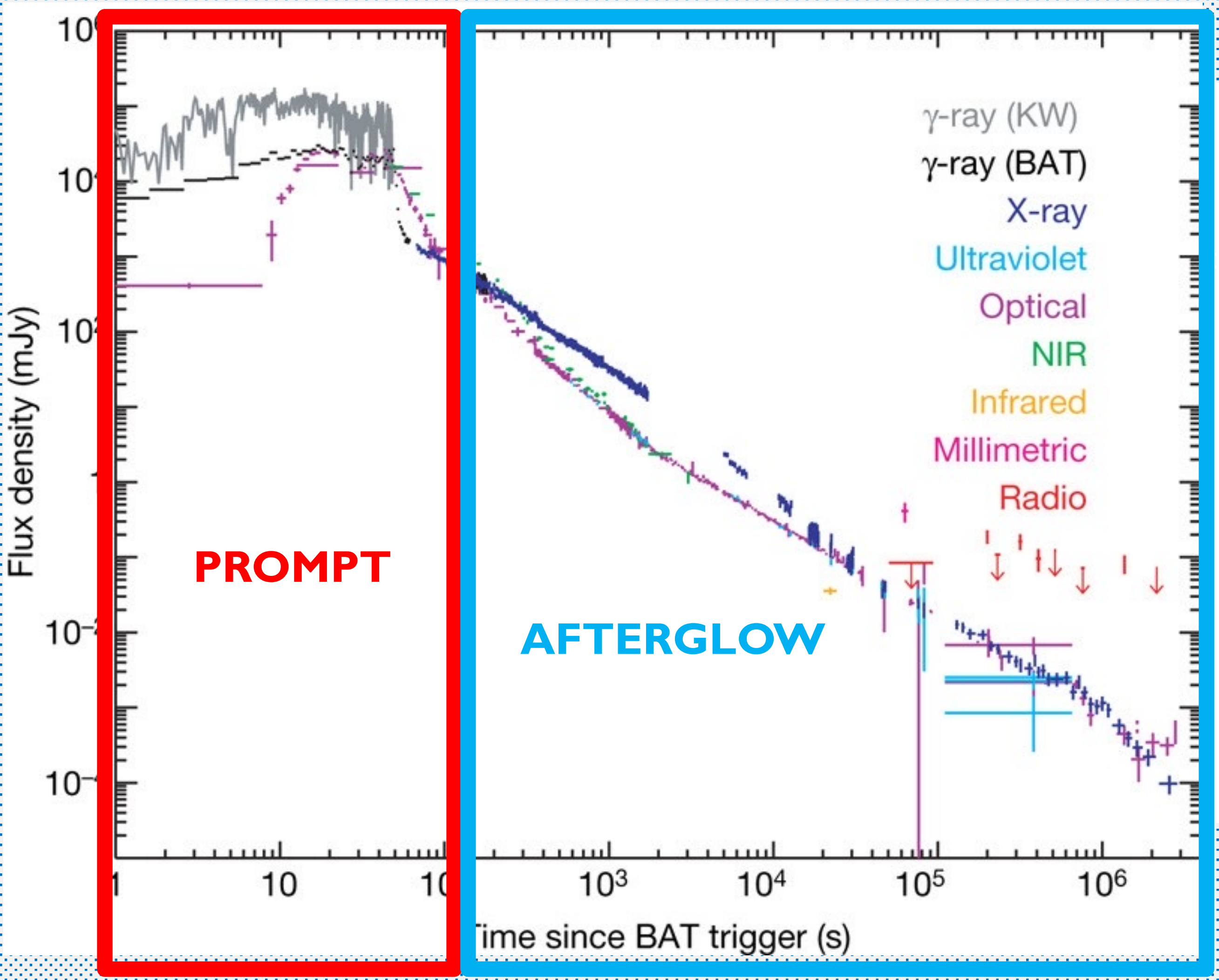
Gamma-Ray Bursts (GRBs)

GRBs at Very High Energy

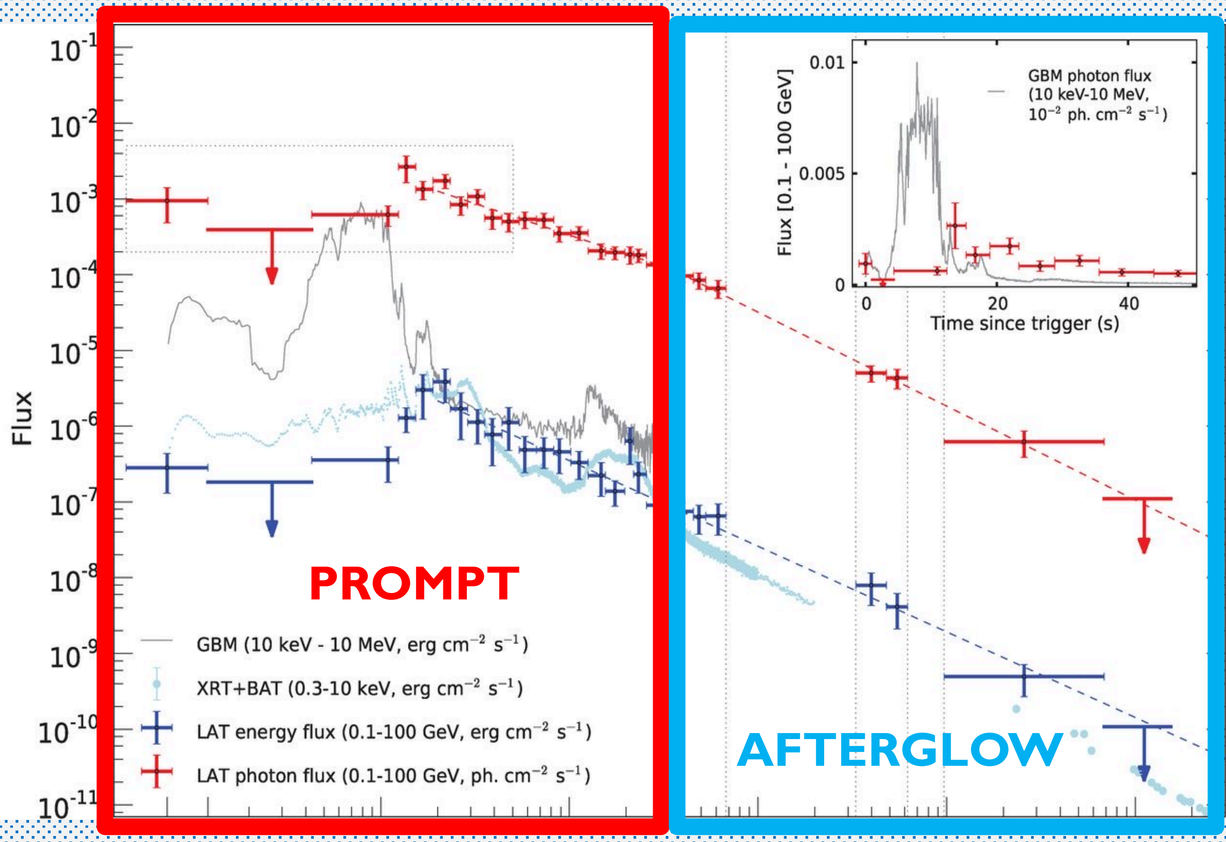
		T_{90} s	$E_{\gamma,iso}$ erg	z	T_{delay} s	E_{range} TeV	IACT (sign.)
Short	160821B	0.48	1.2×10^{49}	0.162	24	0.5-5	MAGIC (3.1σ)
Long	180720B	48.9	6.0×10^{53}	0.654	3.64×10^{4}	0.1-0.44	H.E.S.S. (5.3σ)
Long	190114C	362	2.5×10^{53}	0.424	57	0.3-1	MAGIC ($> 50\sigma$)
Long	190829A	58.2	2.0×10^{50}	0.079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

Miceli & Nava, 2022

Gamma-Ray Bursts (GRBs)

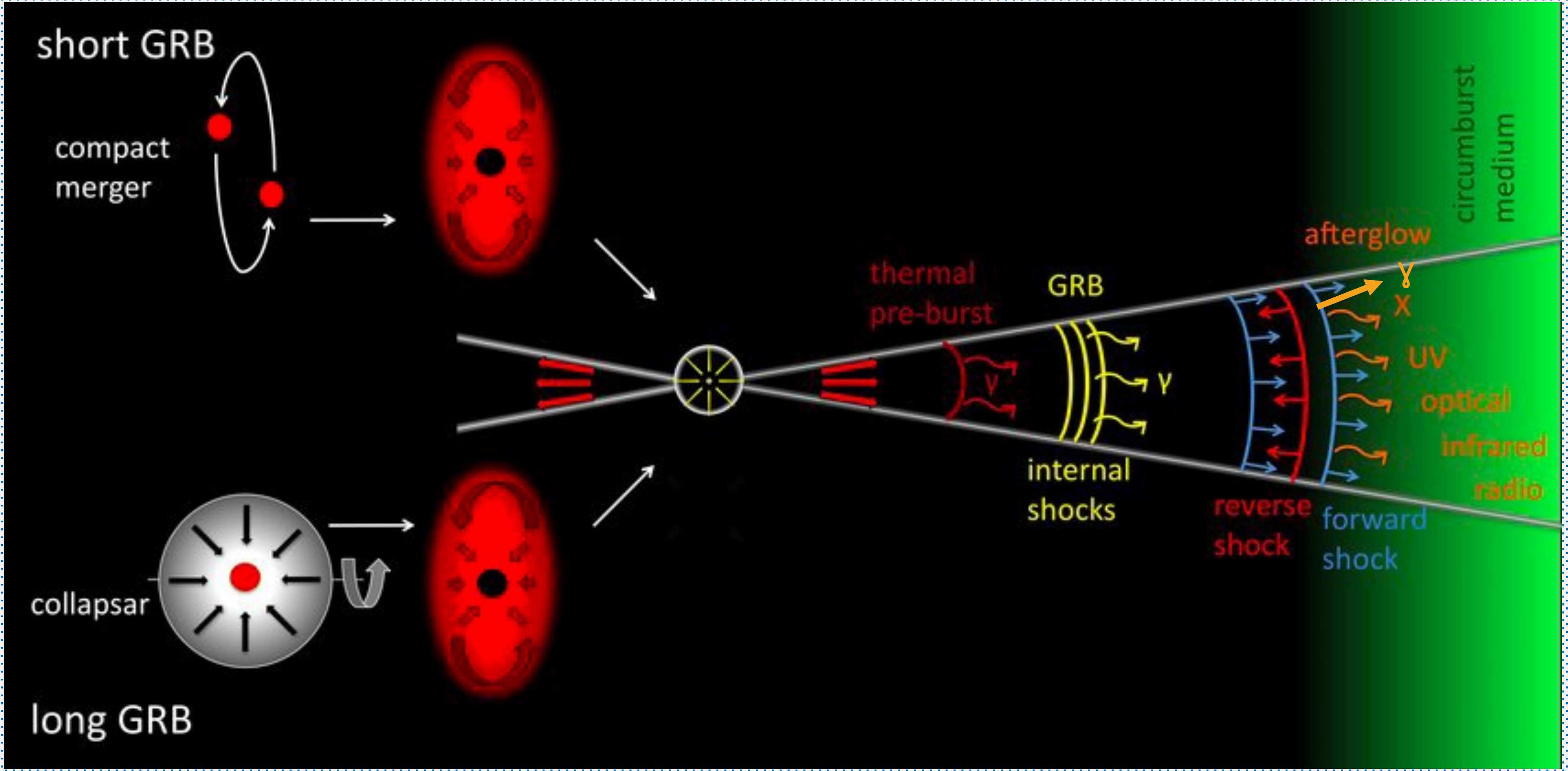


GRB080319B (Racusin et al., 2008)



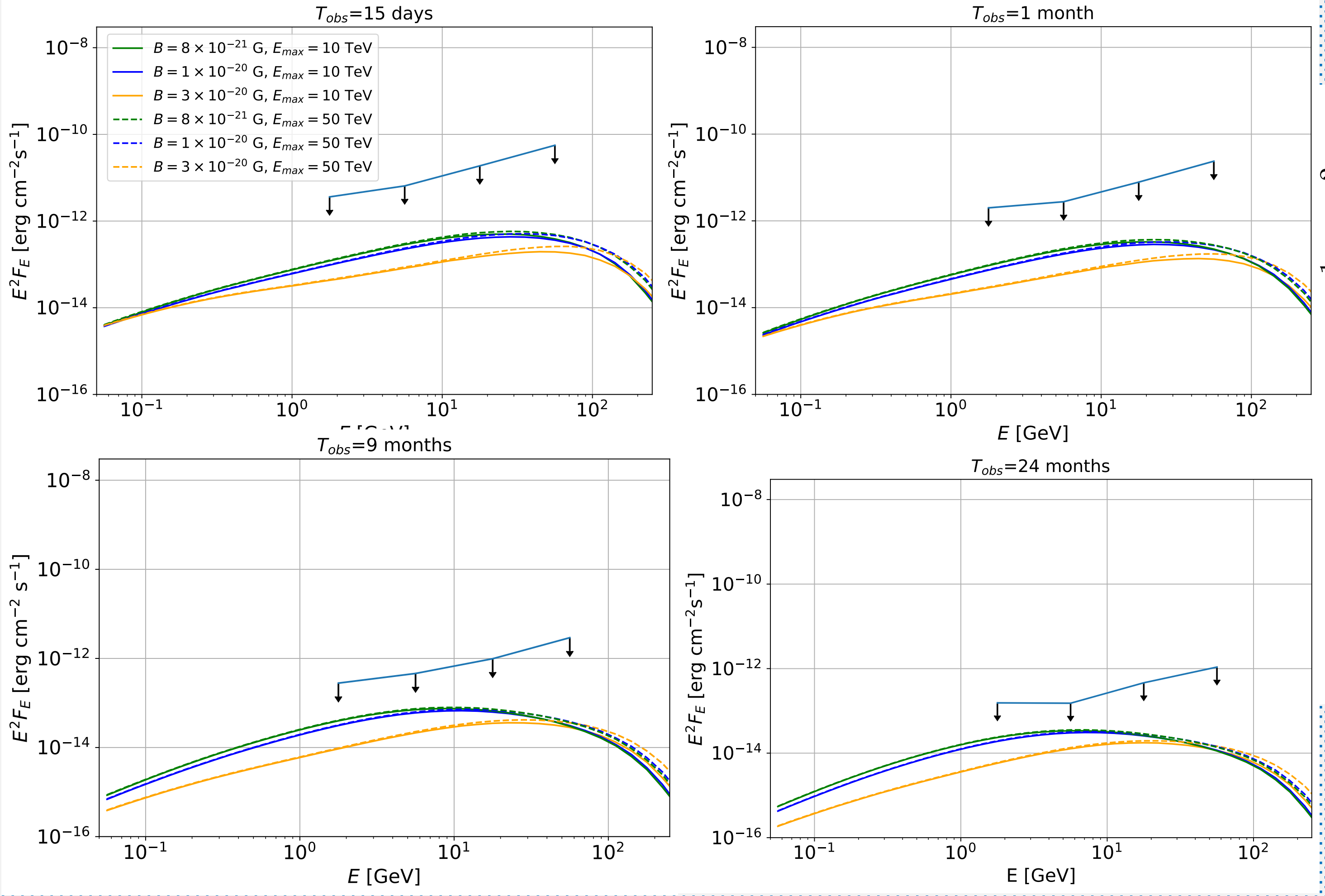
GRB130427A (Ackermann et al., 2013)

Gamma-Ray Bursts (GRBs)

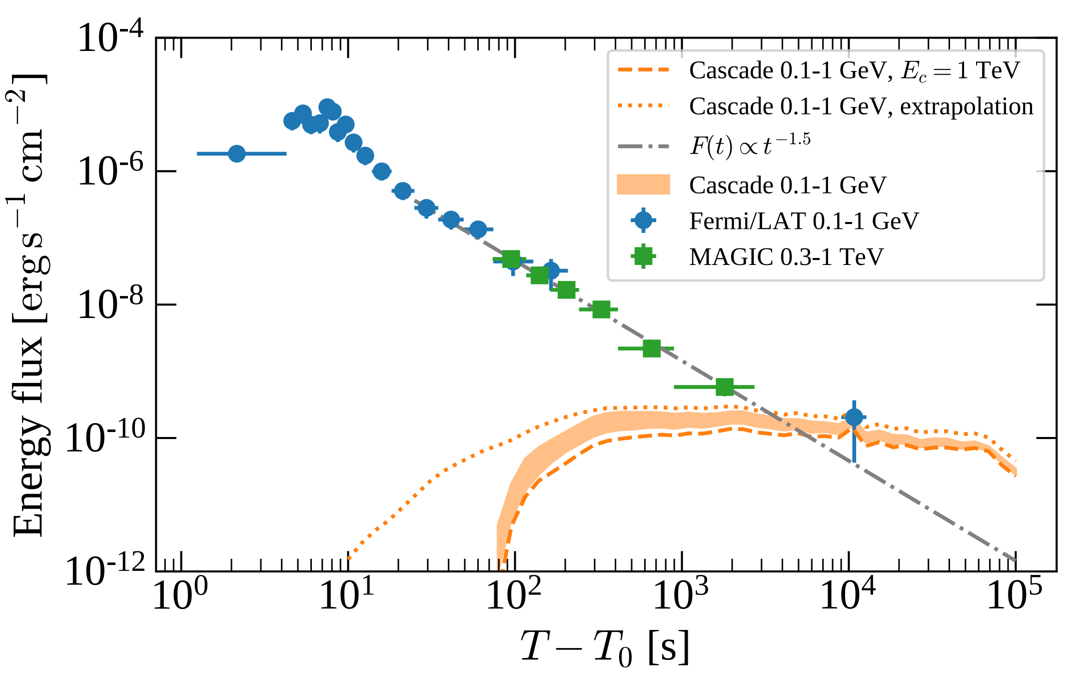


IGMF bounds from GRBs

The case of GRB190114C



Da Vela et al. 2023



Vovk, 2023