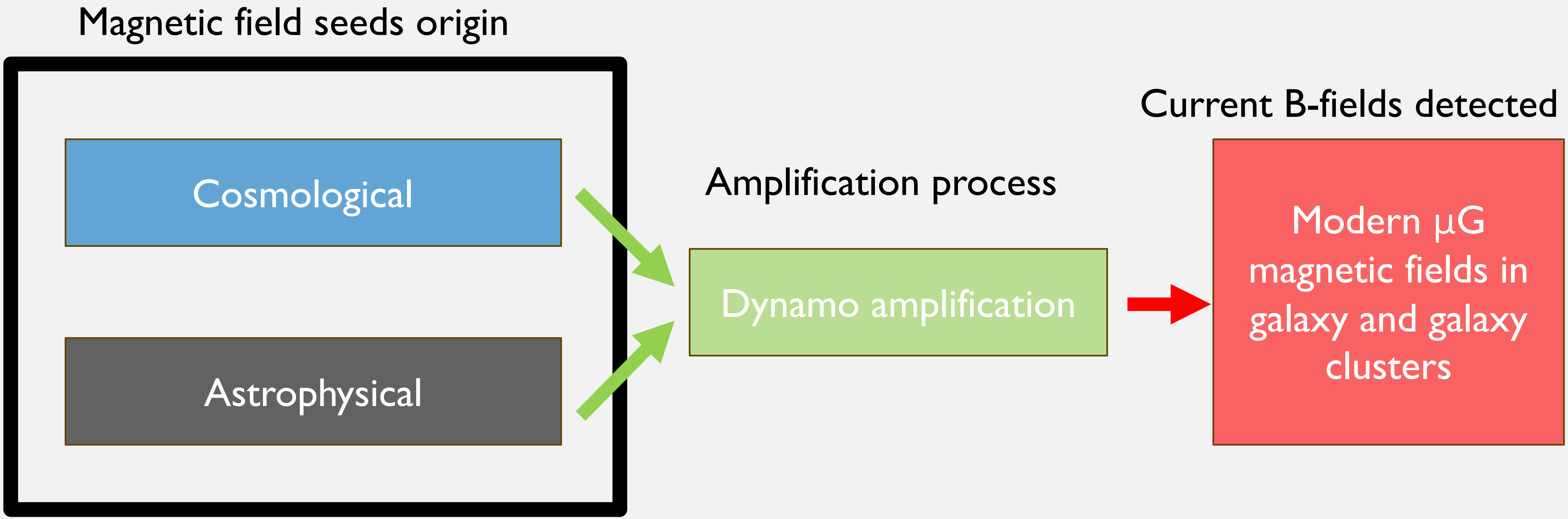
STATUS AND PERSPECTIVES OF INTERGALACTIC MAGNETIC FIELD STUDIES

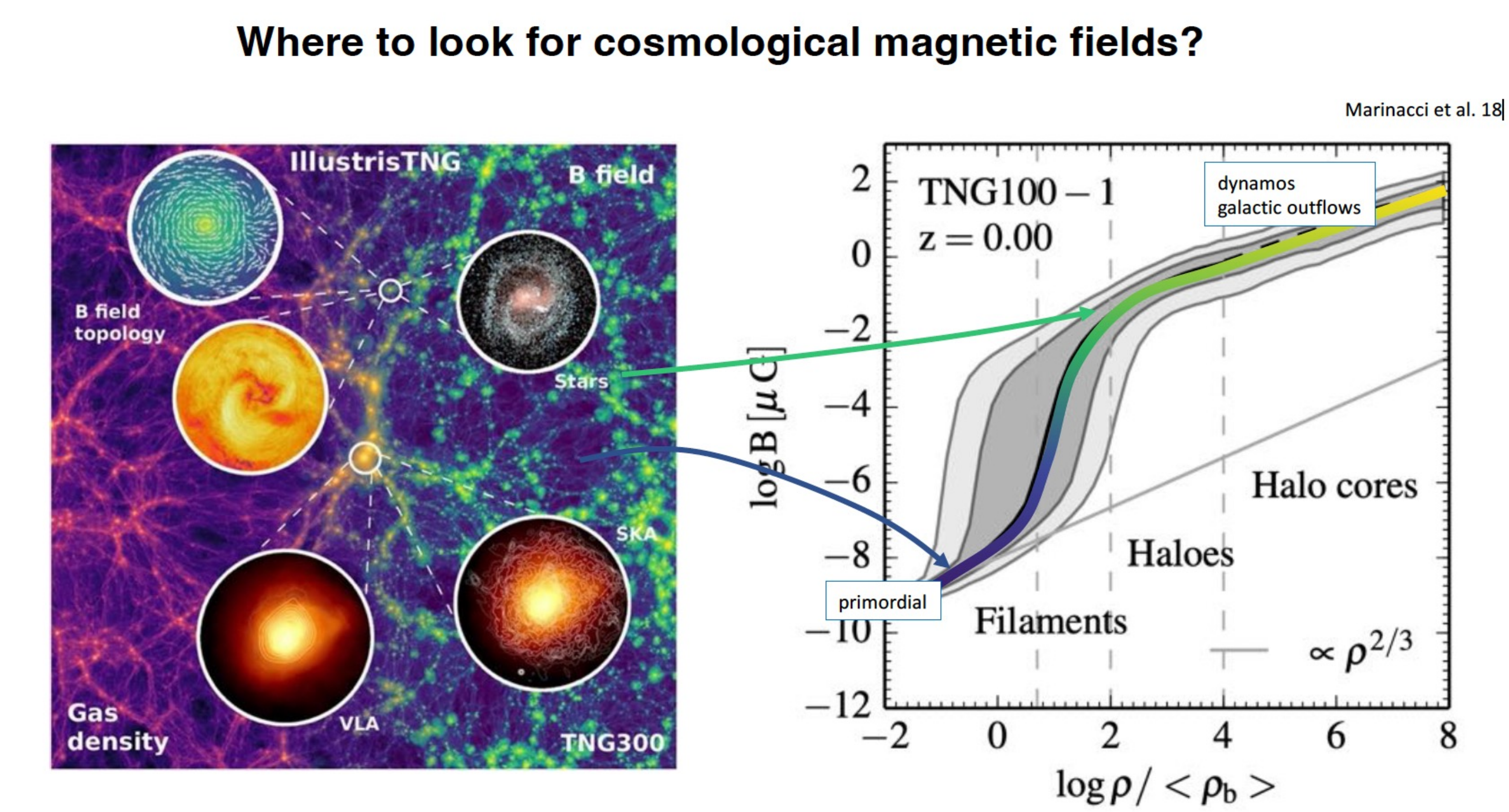
Davide Miceli

AVENGe, 31/05/2023

Magnetic Fields in the Universe

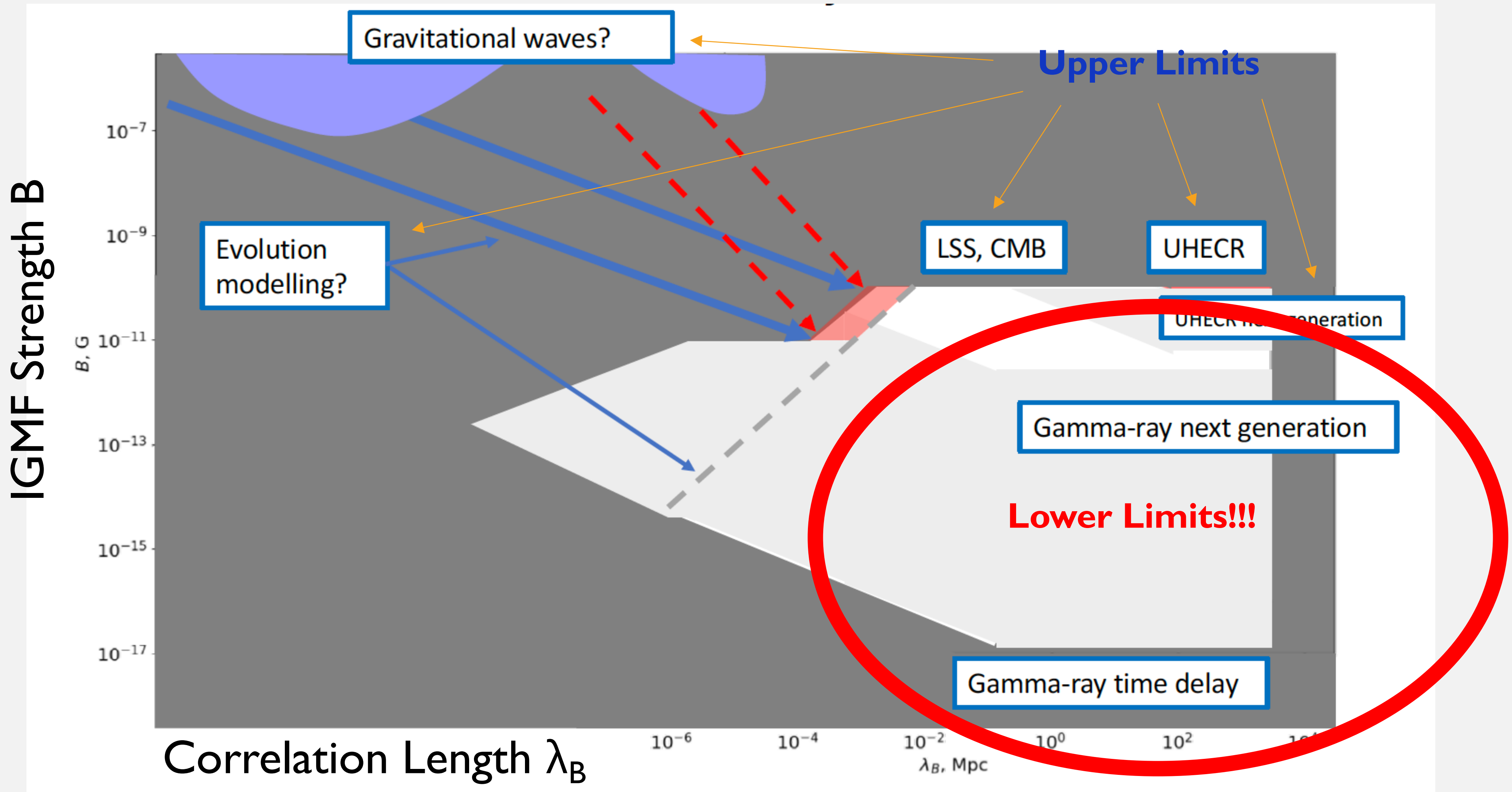


Magnetic Fields in the Universe



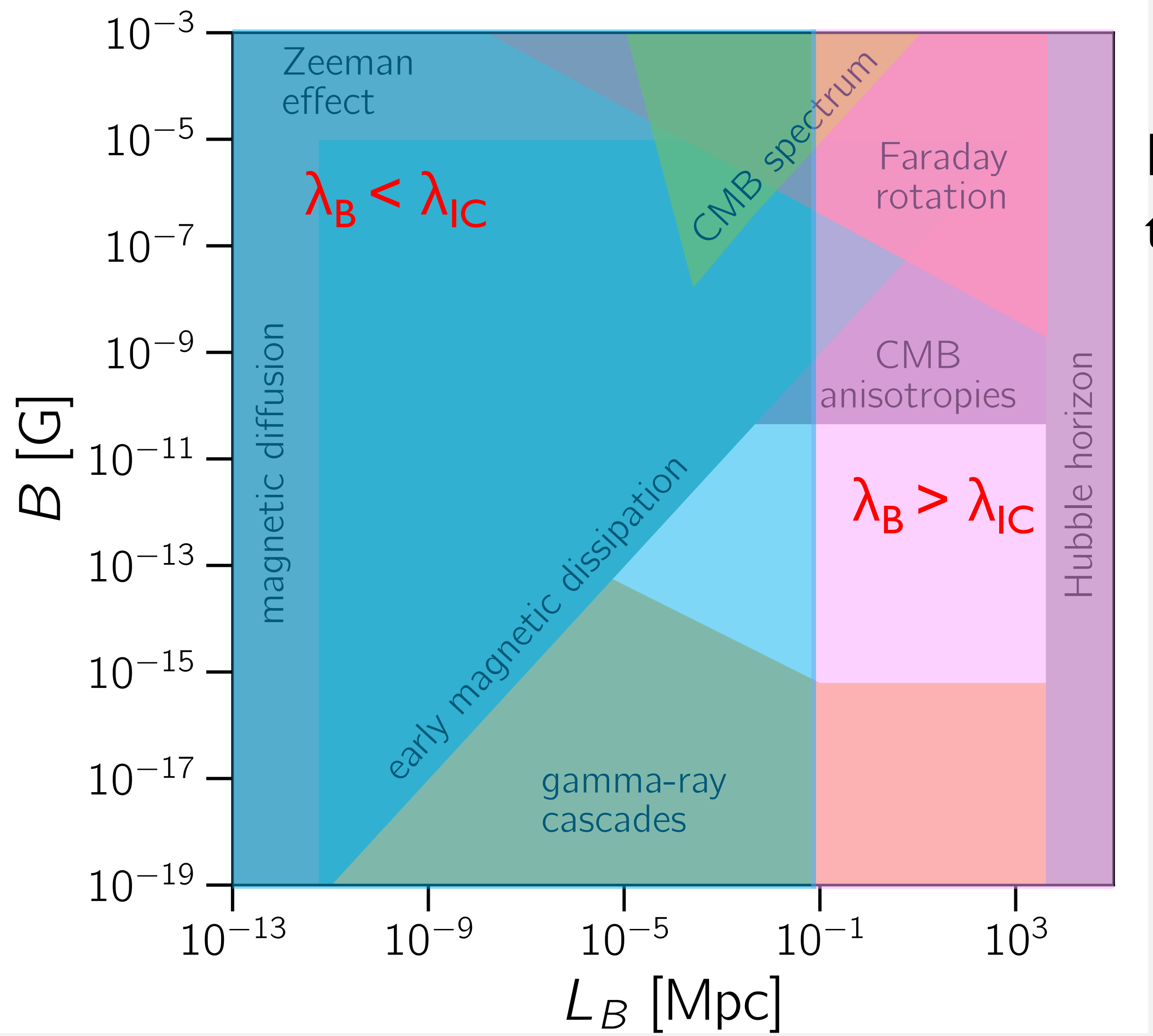
adapted from Andrii Neronov's slides, Bologna,'Cosmic magnetism in voids and filaments', 2023

Intergalactic Magnetic Field (IGMF) Limits



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

Lower Limits (LL): the kingdom of gamma rays

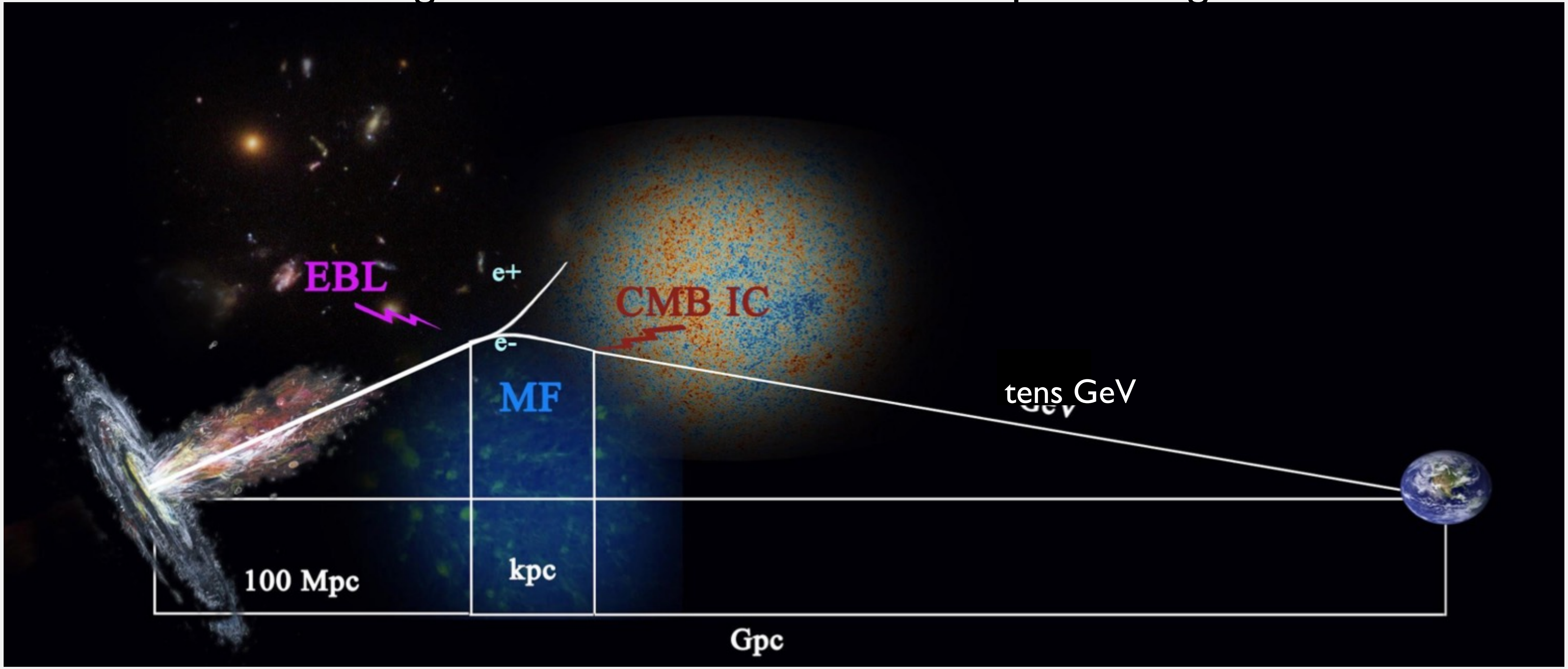


Results on IGMF are typically given considering two regimes:

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

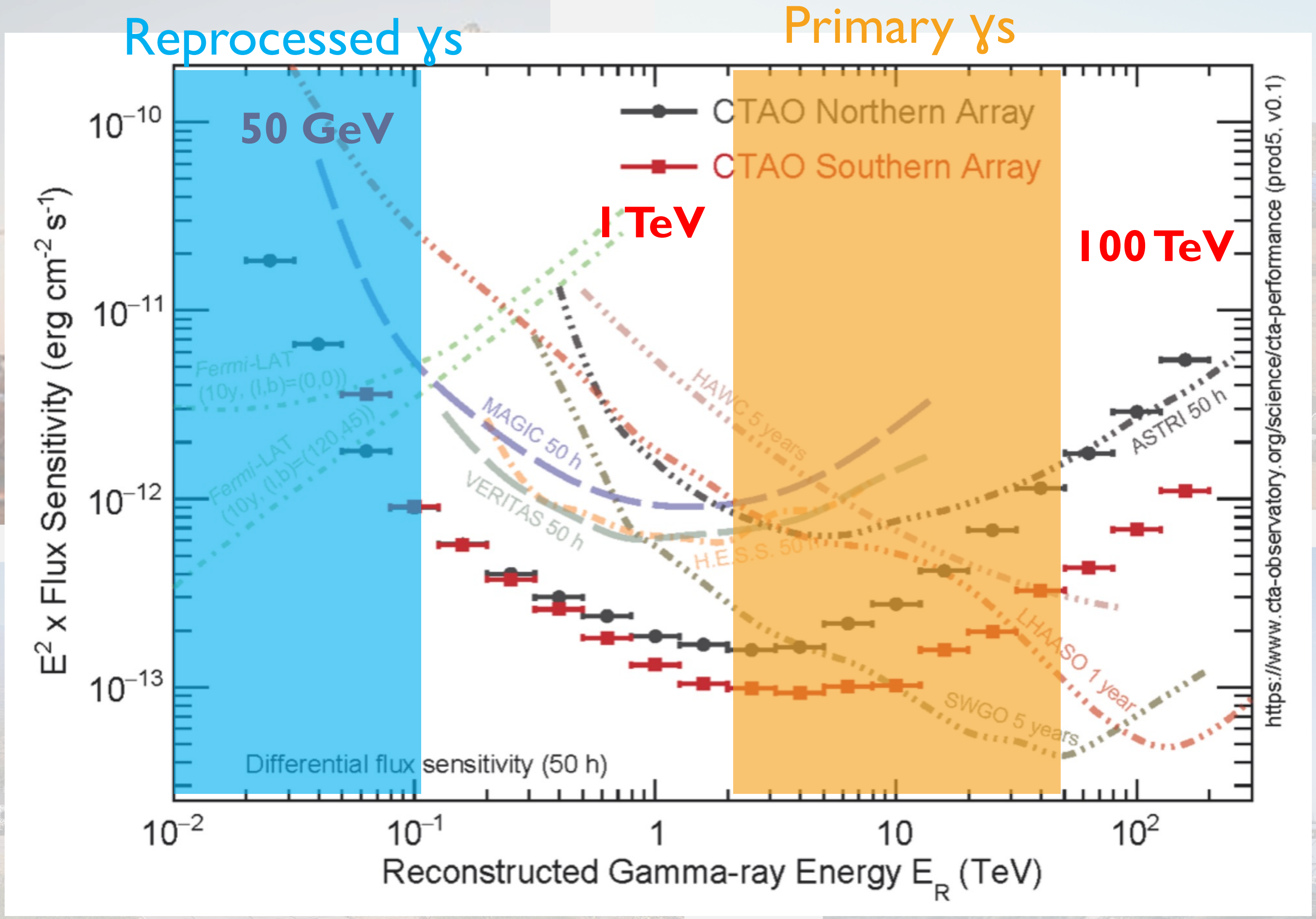
Probing IGMF in the GeV range

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



Adapted from Vachaspati et al. 2020

Gamma-ray window for IGMF

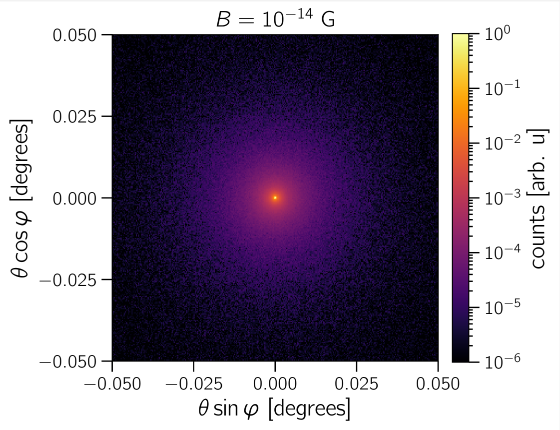


https://www.cta-observatory.org/science/ctao-performance/

Gamma-rays for IGMF studies: Methods

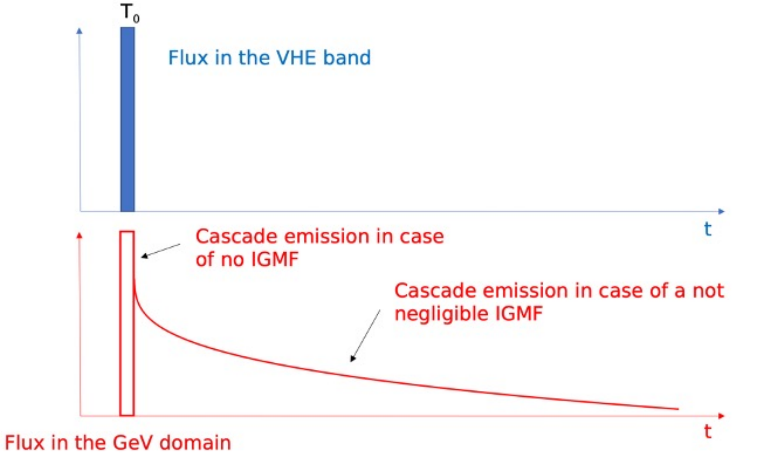
How gamma-ray can probe IGMF properties (B strength and correlation length λ_B)?

Extended emission

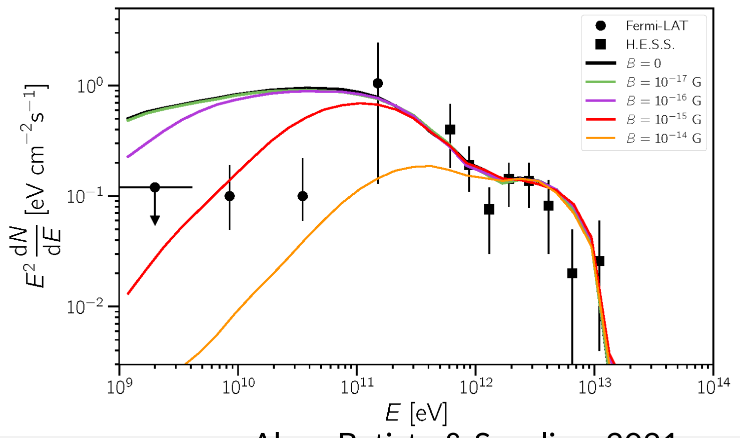


Alves Batista et al, 2022

Time-delayed "pair-echo" emission



SED signatures

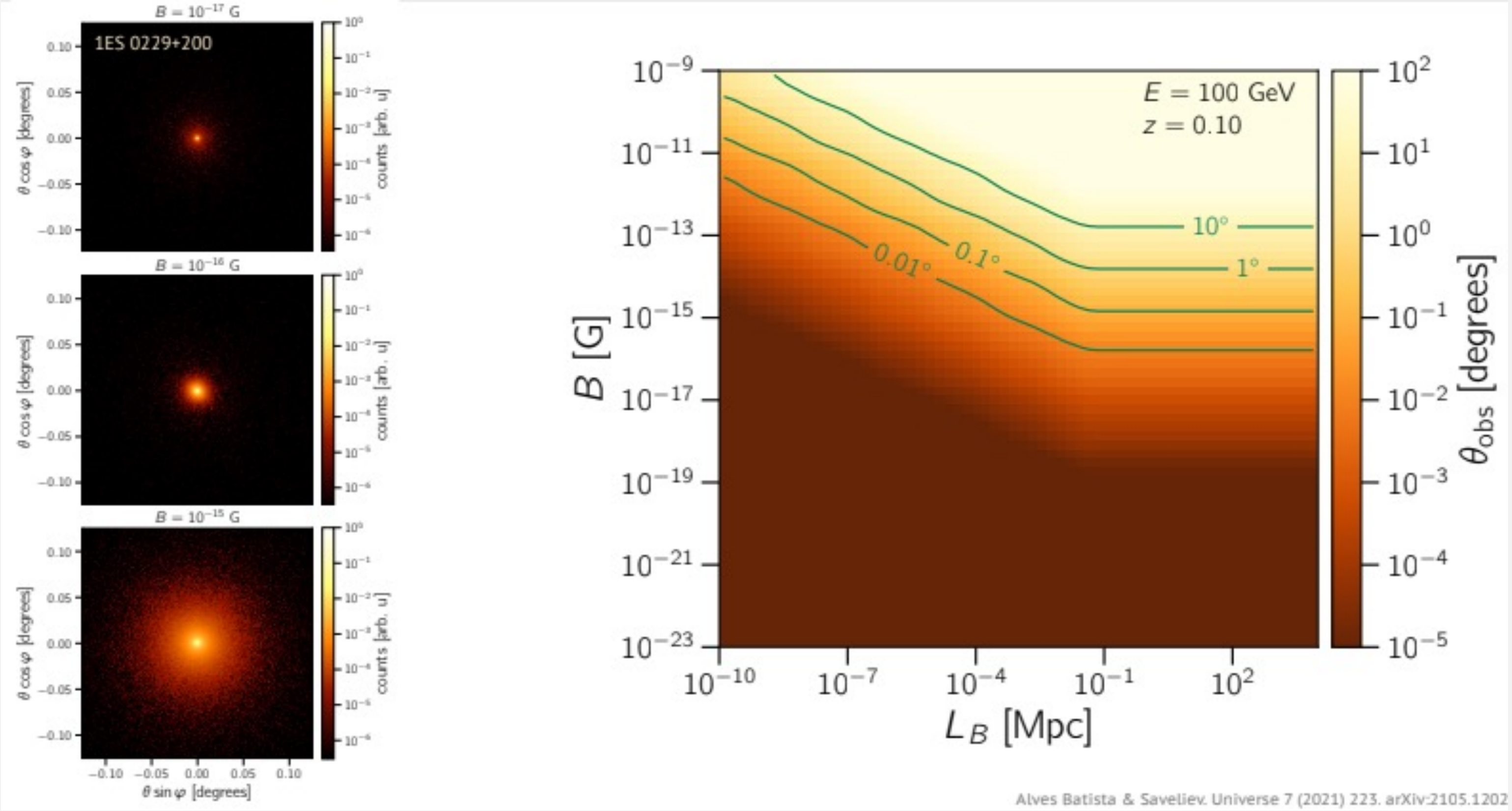


Alves Batista & Saveliev, 2021

Gamma-rays for IGMF studies: Methods

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

- Method I : search for extended emission



Alves Batista, 2021

- A "**smoking gun**" for IGMF discovery
- Size and shape depend on IGMF strength and source parameters (jet opening and orientation)

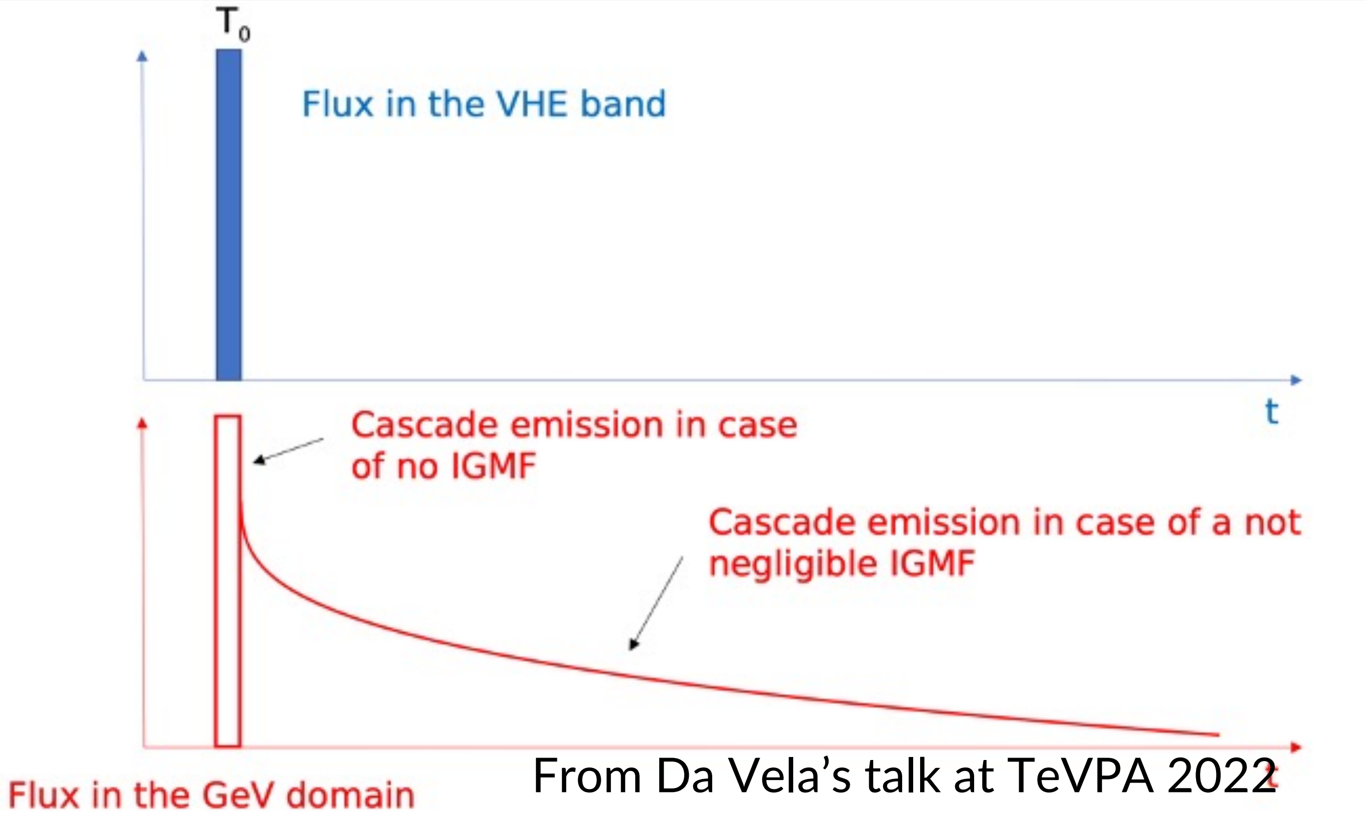
$\theta_{ext} \propto B\, E_\gamma^{-1}$ $\quad \lambda_B >> \lambda_{IC}$

$\theta_{ext} \propto B\, E_\gamma^{-3/4}\, \lambda_B^{1/2}$ $\quad \lambda_B << \lambda_{IC}$

Gamma-rays for IGMF studies: Methods

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

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



From Da Vela's talk at TeVPA 2022

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

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

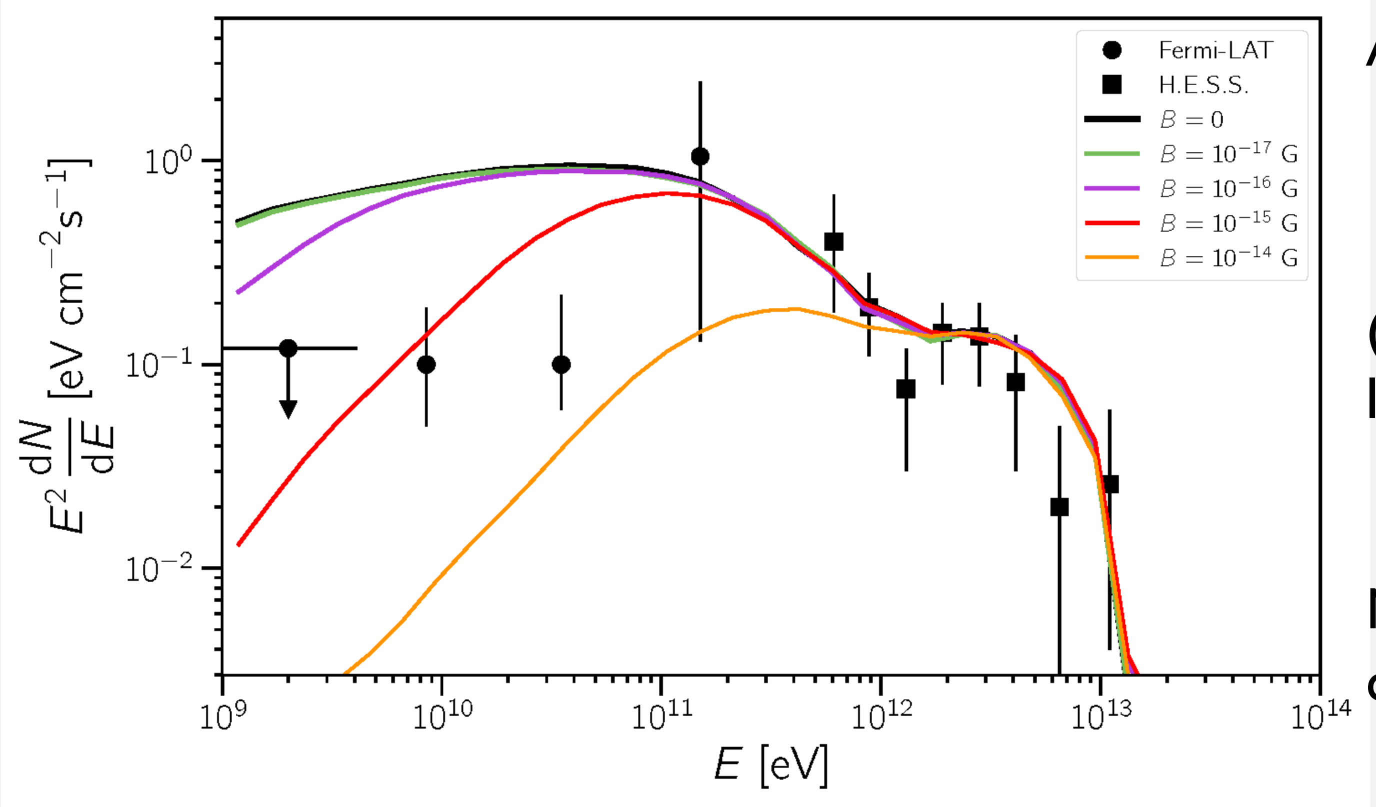
$T_{delay} \propto B^2 E_\gamma^{-2} \lambda_B$ $\lambda_B << \lambda_{IC}$

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

Gamma-rays for IGMF studies: Methods

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

- Method III: search for SED signatures



Alves Batista & Saveliev, 2021

Absorbed flux of a TeV source due to EBL

Aumont of cascade secondary emission (depends on the IGMF strength, correlation length, intrinsic source properties)

Non-detection: minimal cascade power and calculate LL on B

IGMF studies: source features

What properties do we need?

- Hard spectrum in the VHE domain
- VHE Emission extending above few TeV
- Redshift $z > 0.1$

IGMF studies: sources

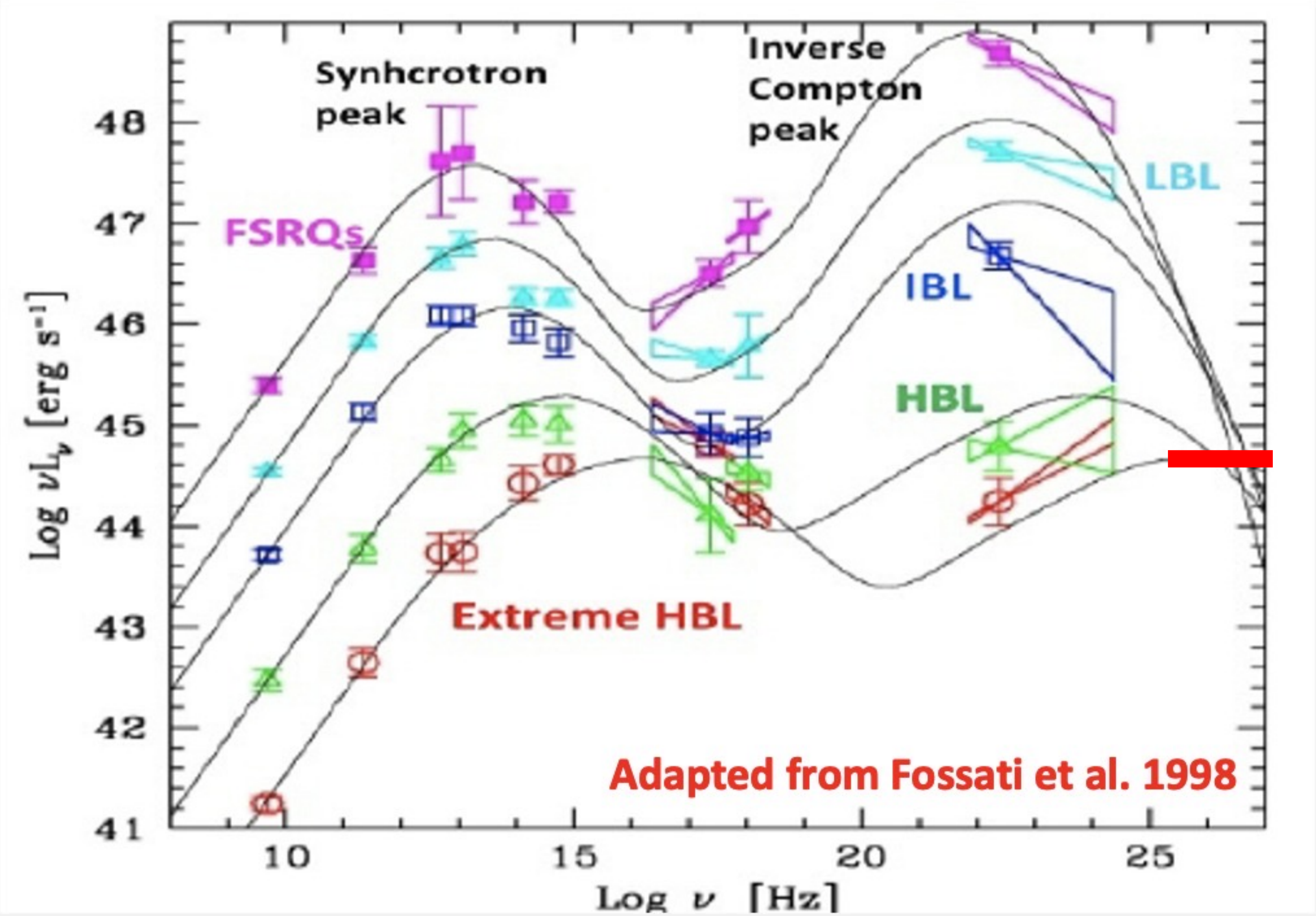
Blazars

Features:

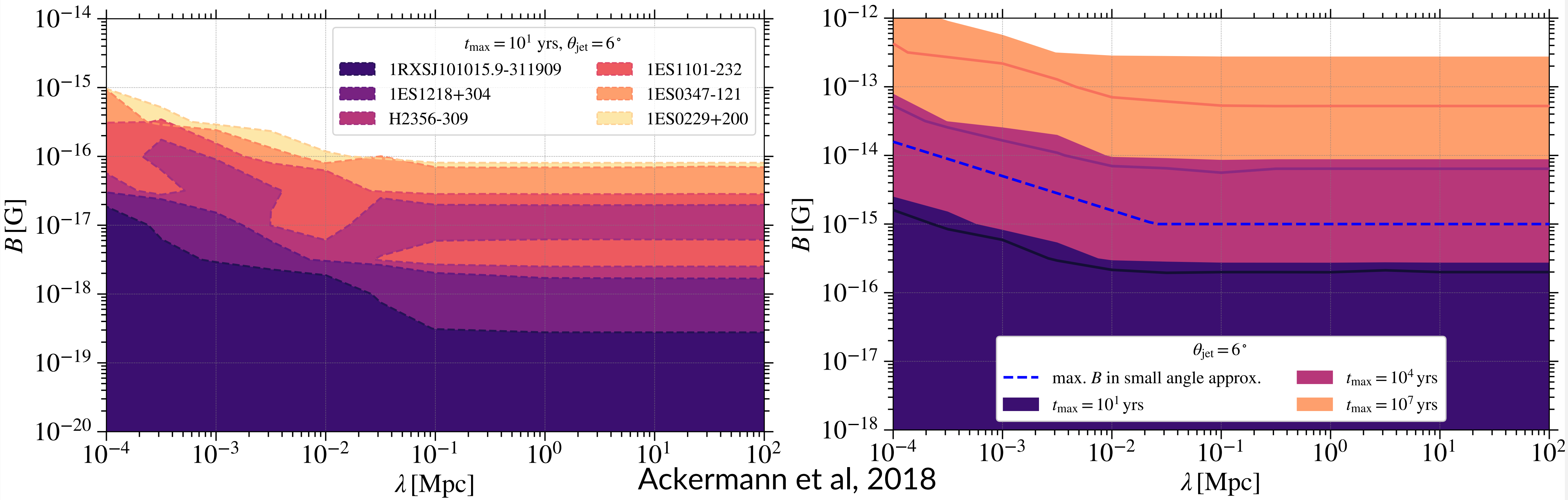
- Persistent sources of TeV radiation
- Subclass with Hard-TeV spectrum
- Population of ~ 80 sources as TeV emitters

Drawbacks:

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



IGMF bounds from Blazars



Individual source analysis, $T_{activity}$=10 years, θ_{jet}=6°

Stacking analysis, $T_{activity}$=10, 10^4 and 10^7 years, θ_{jet}=6°

$B > 8 \times 10^{-17}$ G

$B > 3 \times 10^{-16}$ G

IGMF bounds from Blazars

Cascade Fraction Limits → IGMF Limits

IGMF strength B = 1 x 10^{-16} - 1 x 10^{-13} G, 13 values

Generate toys at different cascade fractions (f_c)

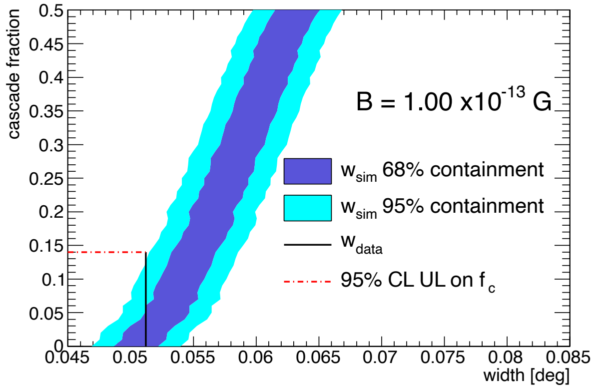
from simulated point source

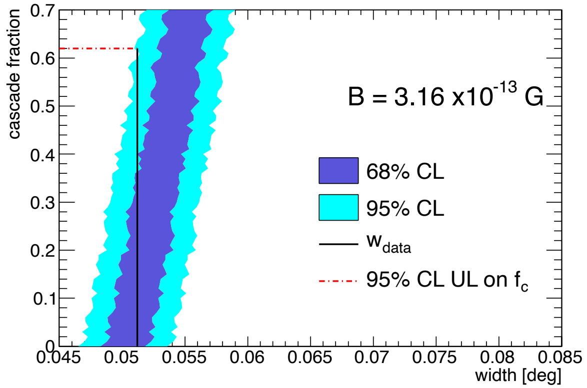
Primary emission + Cascade emission

$(1 - f_c)$ PSF + f_c (PSF conv. w. cascade model)

from cascade sims

Set 95% CL upper limits on f_c





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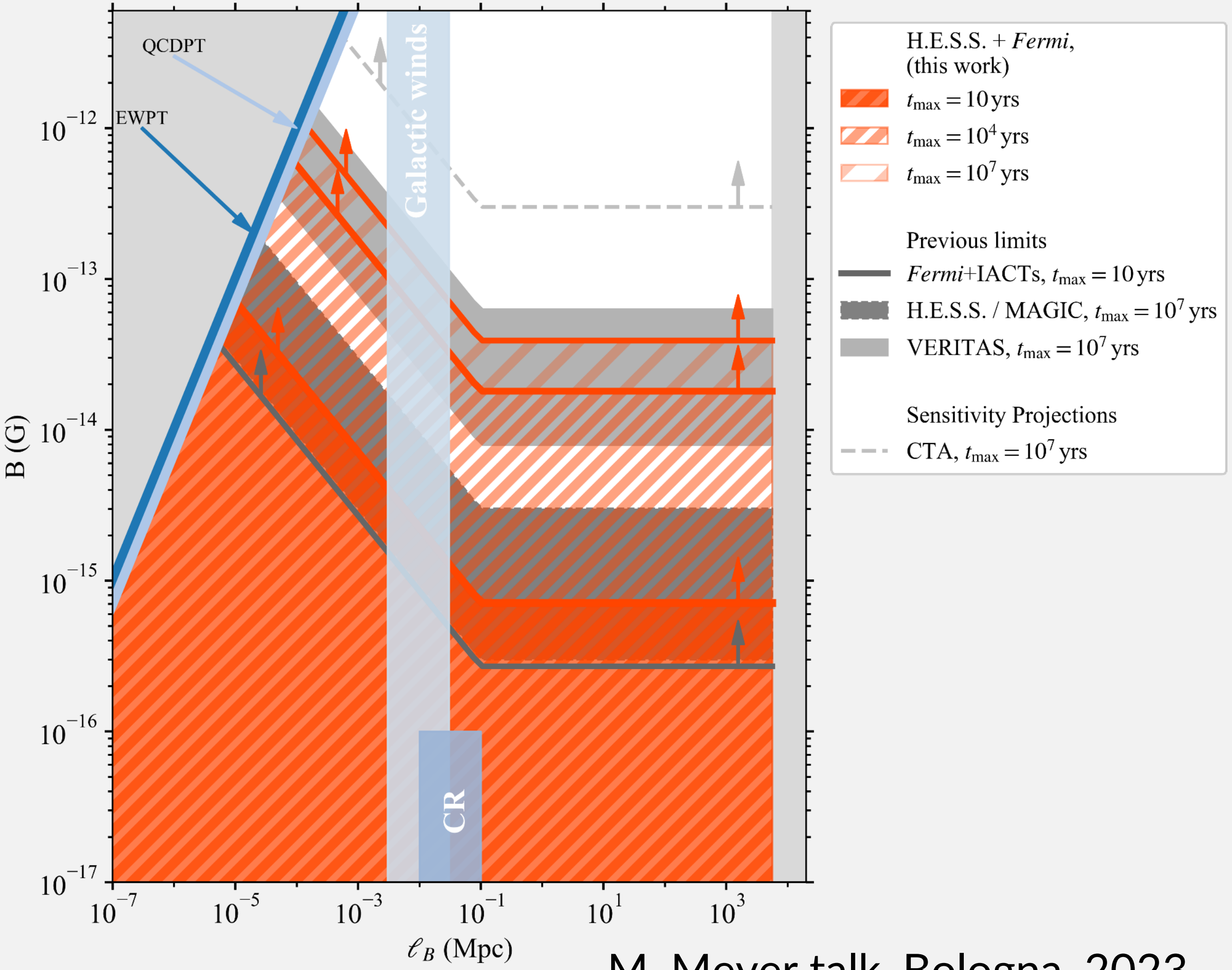
E. Pueschel talk, Bologna, 2023

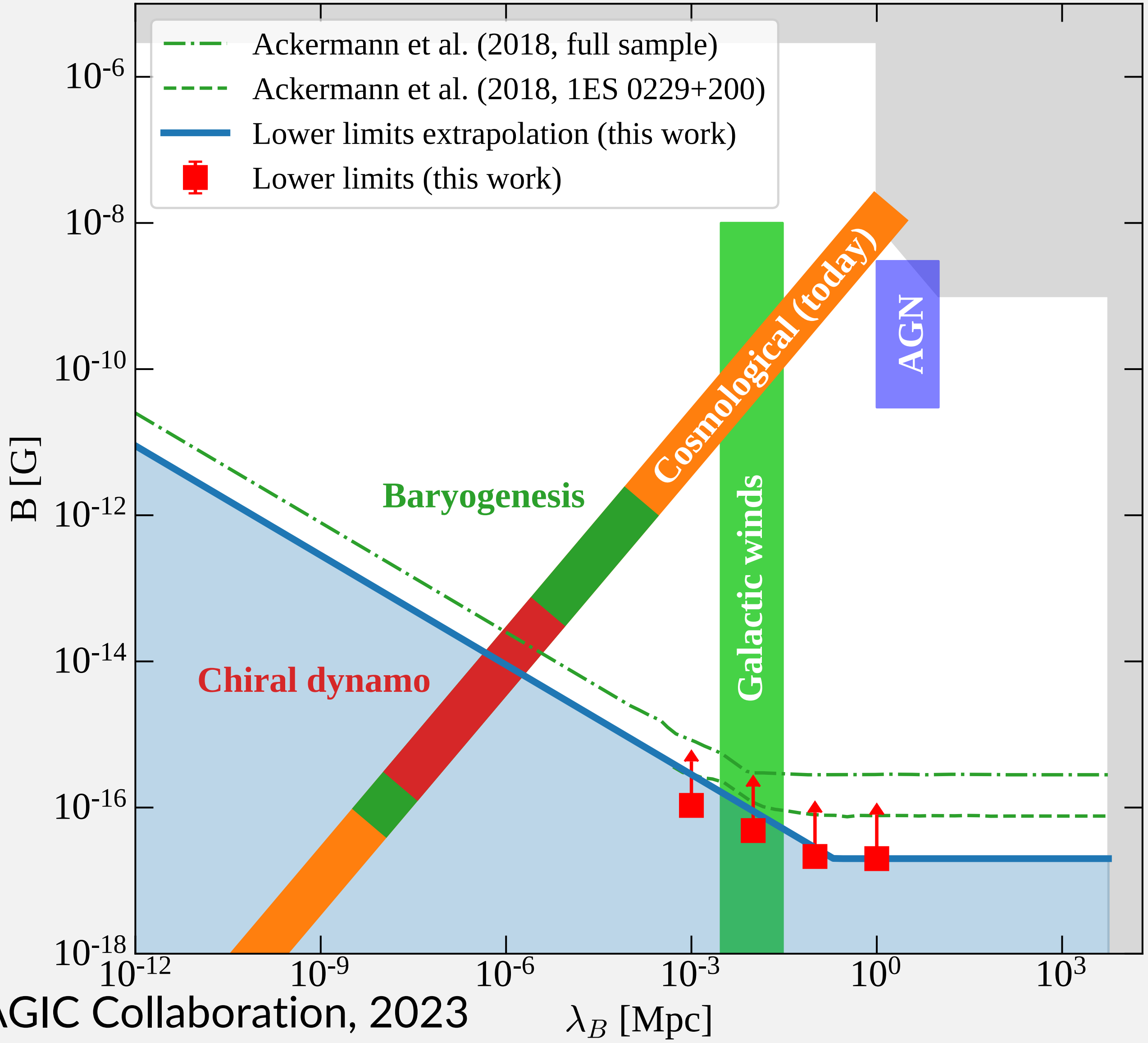
IGMF bounds from Blazars



M. Meyer talk, Bologna, 2023

- Source stacking following selection criteria from 4LAC-DR2 catalog (pwl intrinsic spectrum, known redshift, HBL behaviour)
- Building cascade halo template with CRPropa3 simulations
- Combine Fermi-LAT+HESS data and compare with Intrinsic+halo flux sources
- Provide LL for different duty cycle values (10, 10^4, 10^7 yrs)

IGMF bounds from Blazars



MAGIC Collaboration, 2023

- 1ES0229+200 (z = 0.14), 140 hours of MAGIC observations
- Published HESS, VERITAS data +. Fermi-LAT and new MAGIC data used for validation of results
- VHE spectrum: power-law with exponential cutoff minimizing the cascade power: $\Gamma \approx 1.72$, $E_{cut} \approx 6.9$ TeV
- The variability pattern is taken into account and inferred from the VHE lightcurves
- Scan performed in the (B, λ_B) space in order to look for the IGMF configurations rejected by the data

$B > 1.8 \times 10^{-17}$ G $\quad \lambda_B > 0.2$ Mpc

$B > 1.8 \times 10^{-17} (\lambda_B / 0.2\ \text{Mpc})^{-1/2}$ G $\quad \lambda_B < 0.2$ Mpc

IGMF studies: sources

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

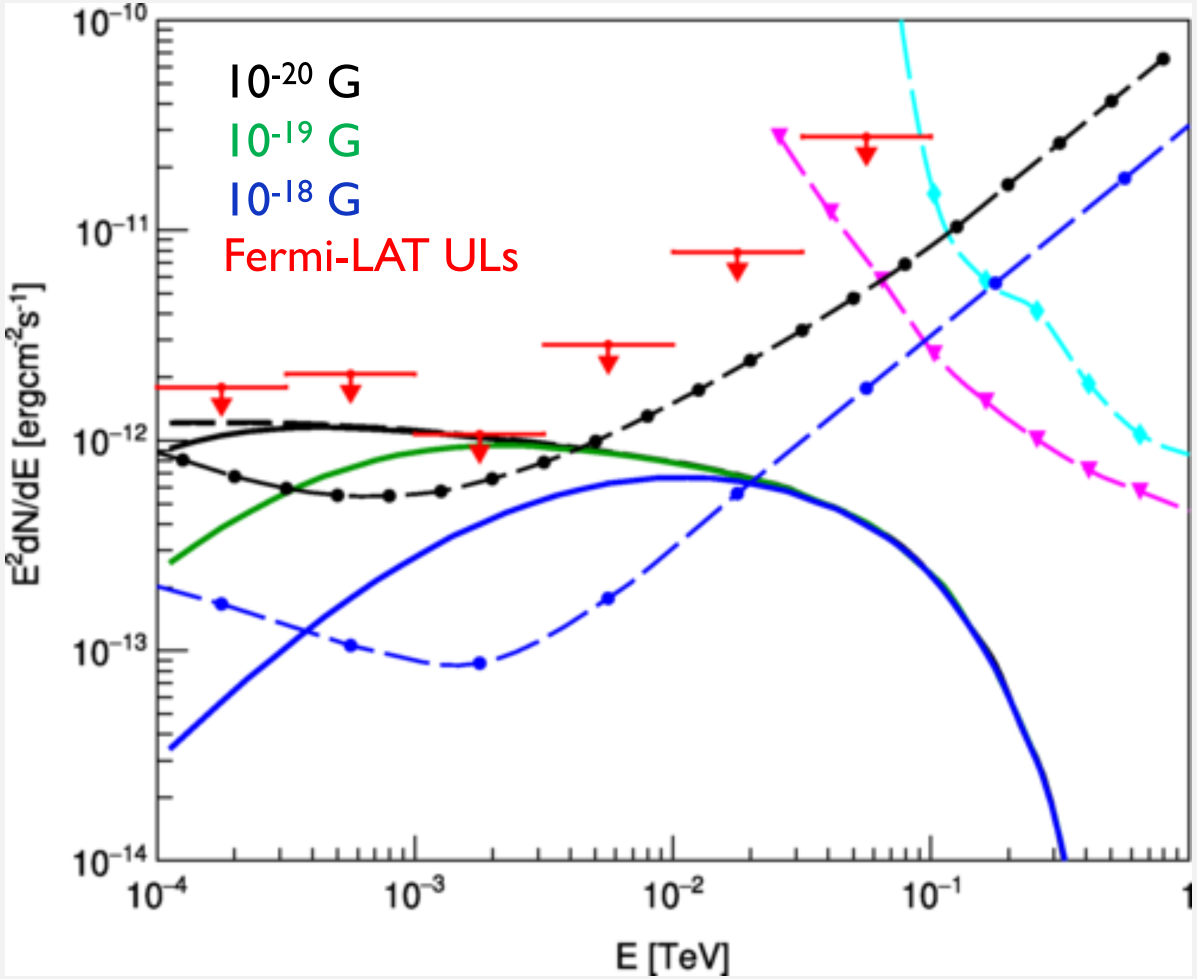
GRBs at Very High Energy

	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

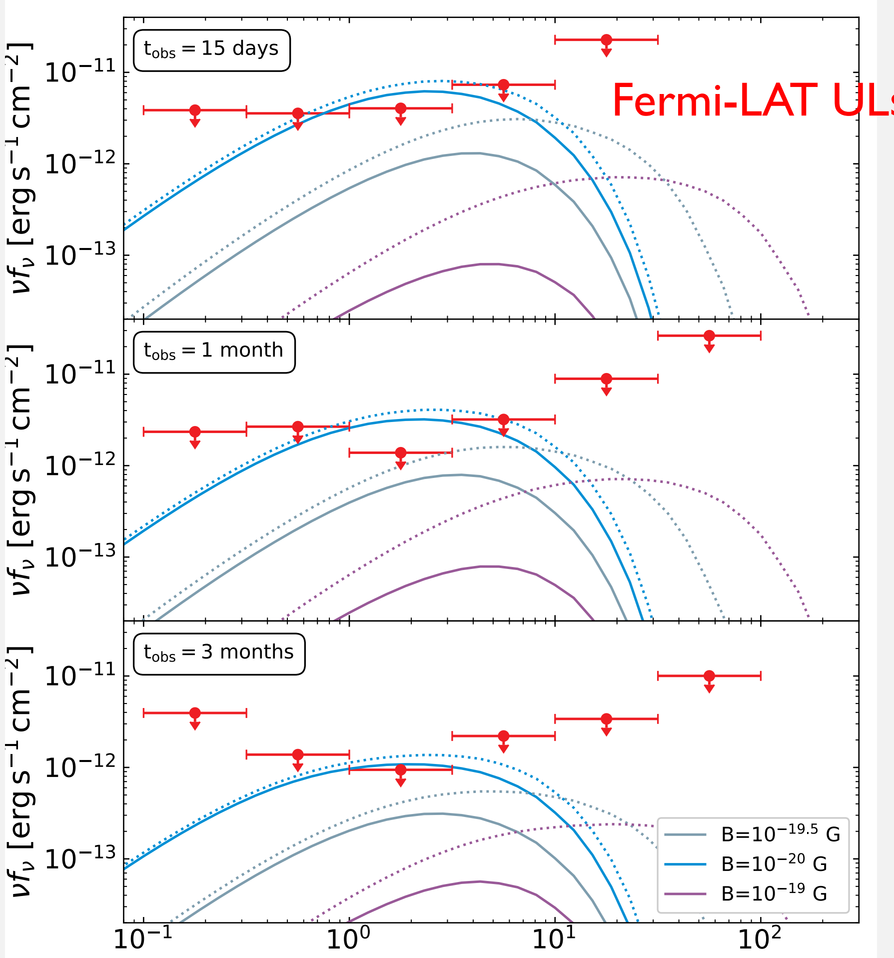
Adapted from Miceli & Nava, 2022

IGMF bounds from GRBs

The case of GRB190114C



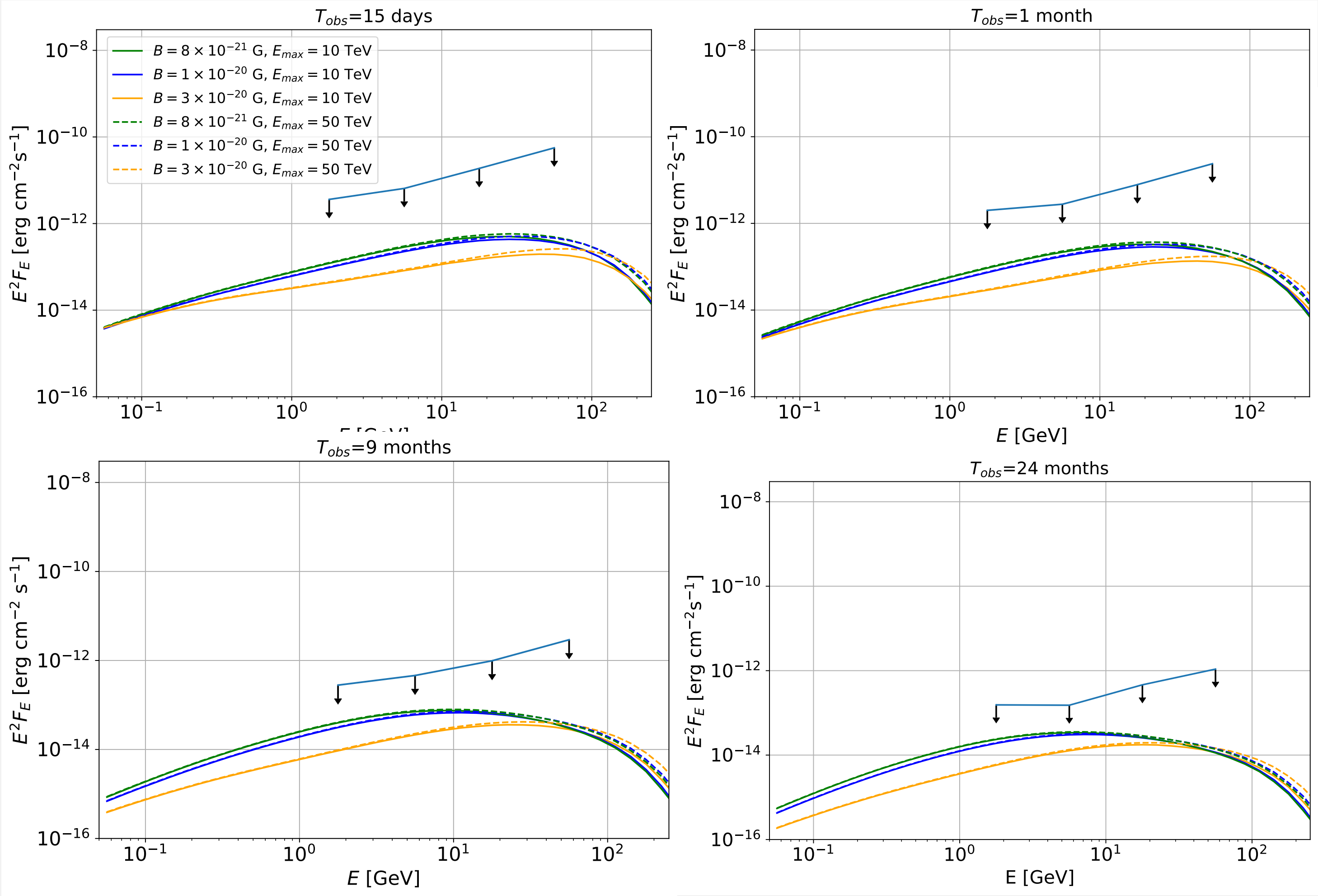
Dzhatdoev et al. 2020



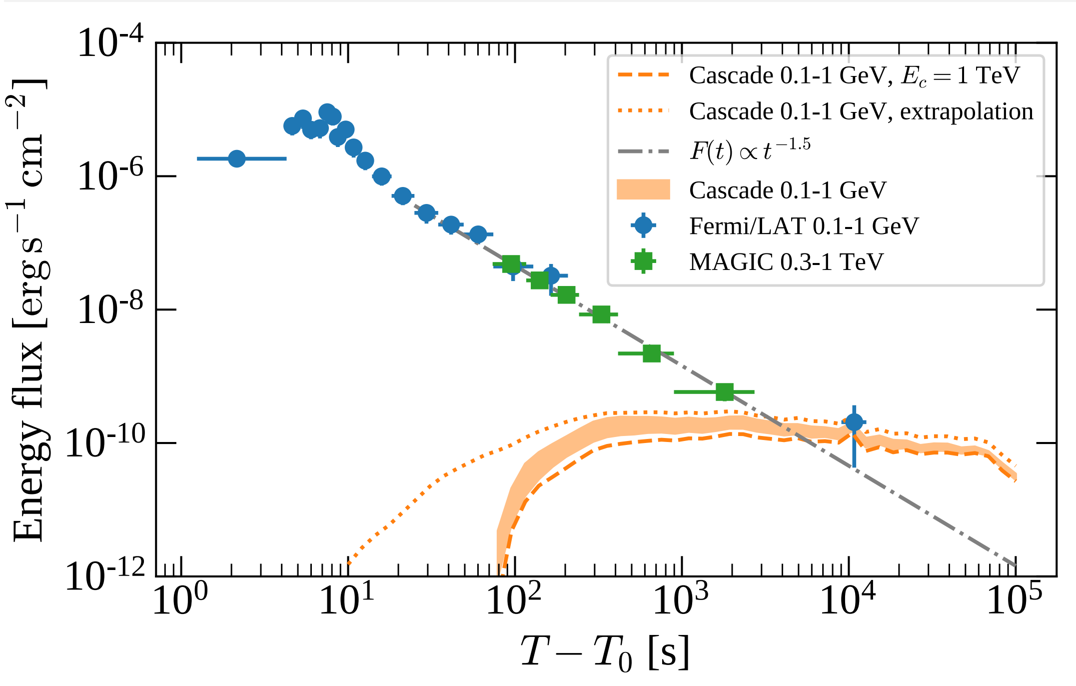
Wang et al. 2020

IGMF bounds from GRBs

The case of GRB190114C



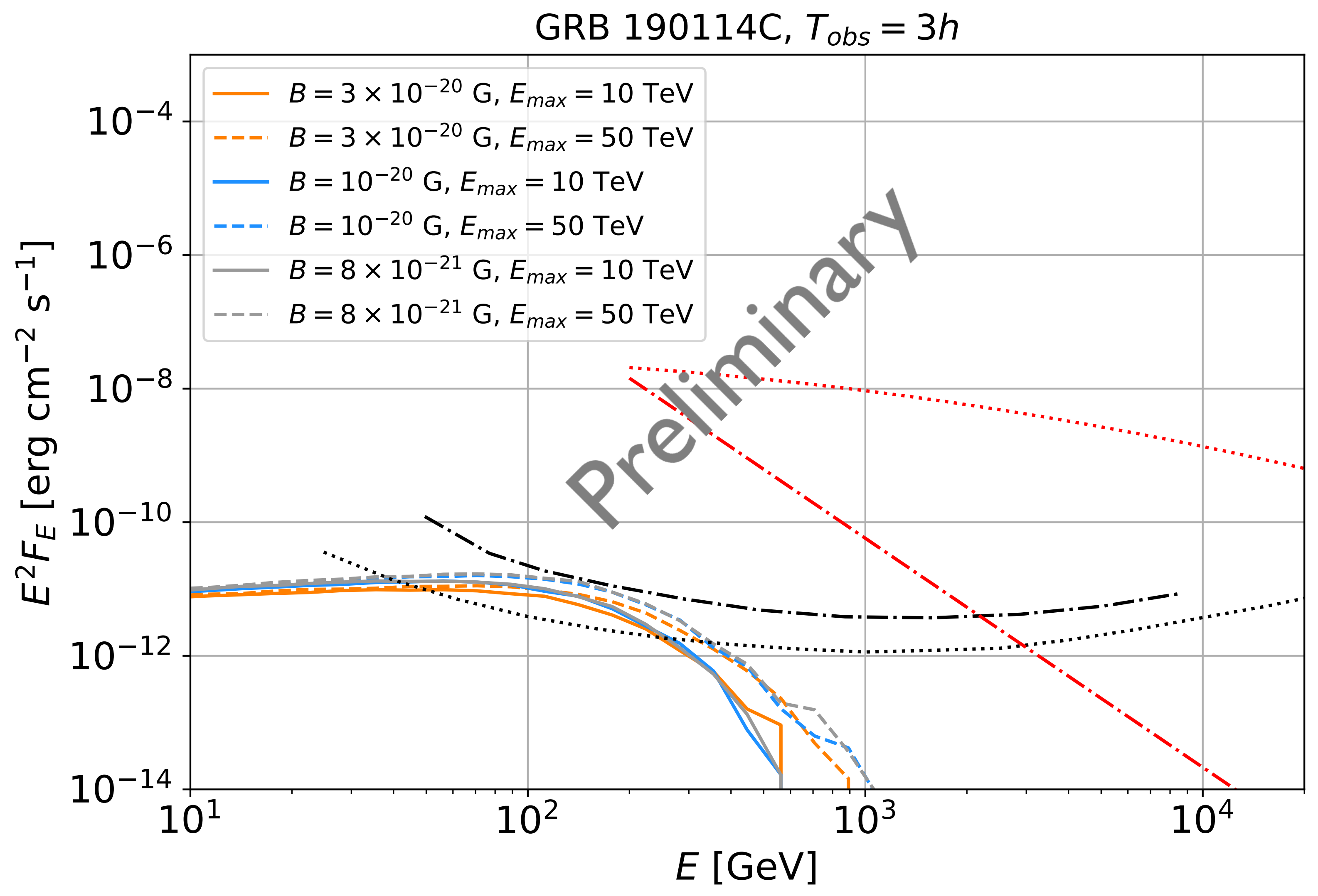
Da Vela et al. 2023



Vovk, 2023

GRB190114C (z = 0.42)

Comparison with MAGIC and CTA sensitivities

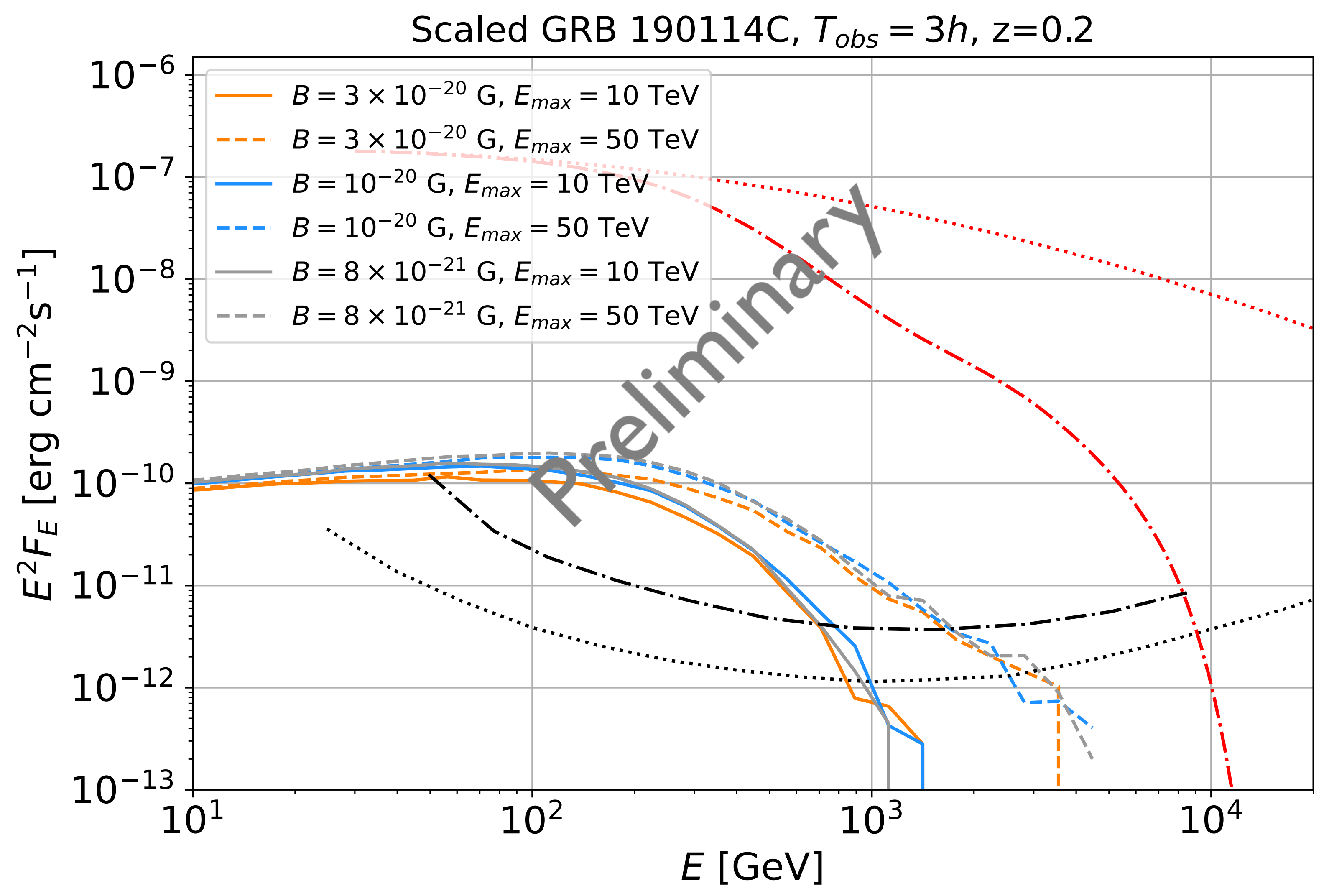


Spectral energy distribution

- 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-like with lower redhshift (z = 0.2)

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

GRB221009A (z = 0.151)

GRB221009A is certainly the best transient source for IGMF studies so far but…

lack of IACT data in the 1-100 GeV band…

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TITLE:    GCN CIRCULAR
NUMBER:   32677
SUBJECT:  LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE:     [illegible]
FROM:     Judith Racusin at GSFC  <judith.racusin@nasa.gov>

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

We report the observation of GRB 221009A, which was detected by Swift (Kennea
et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642),
Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above
100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d.,
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

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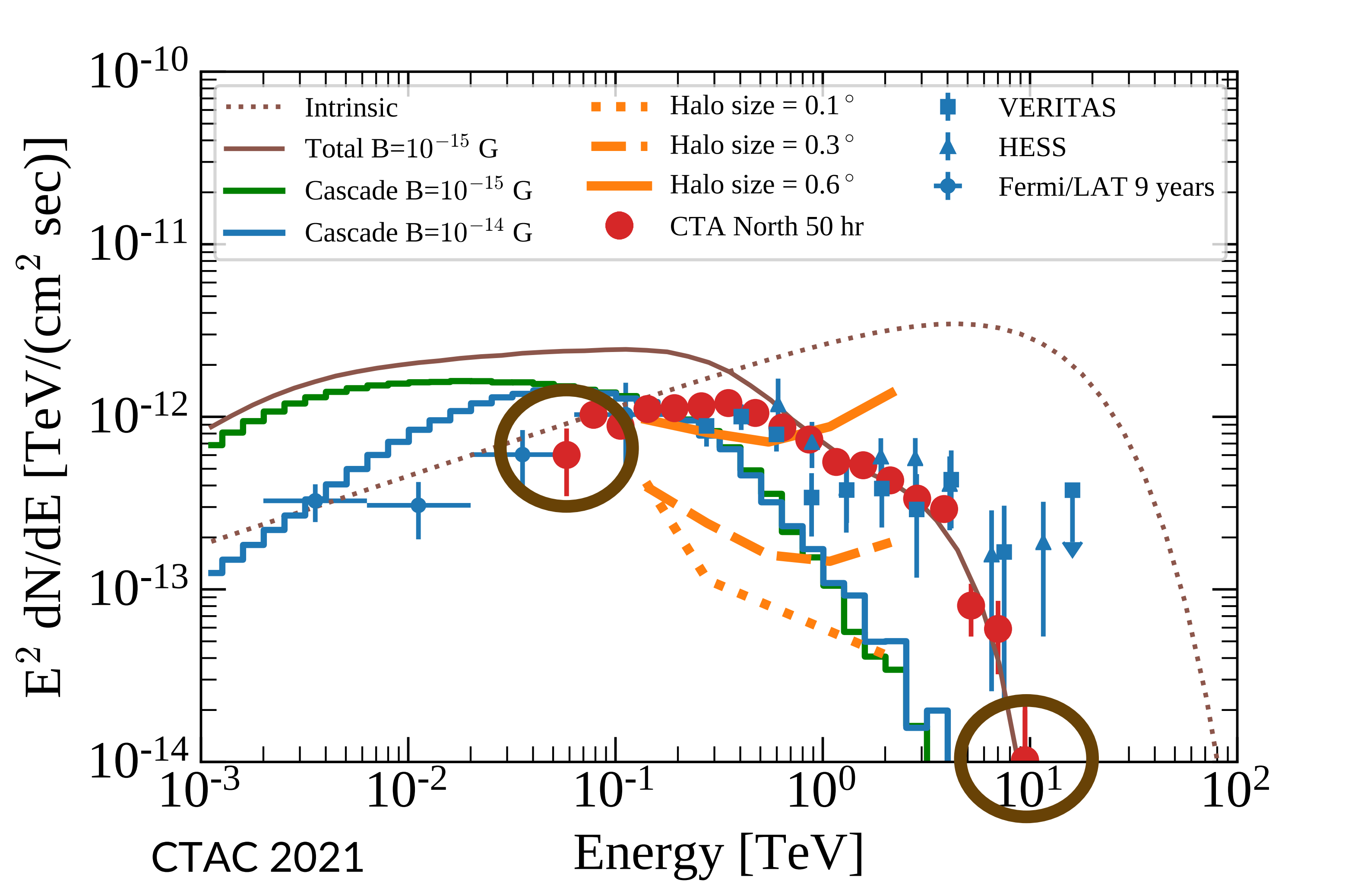
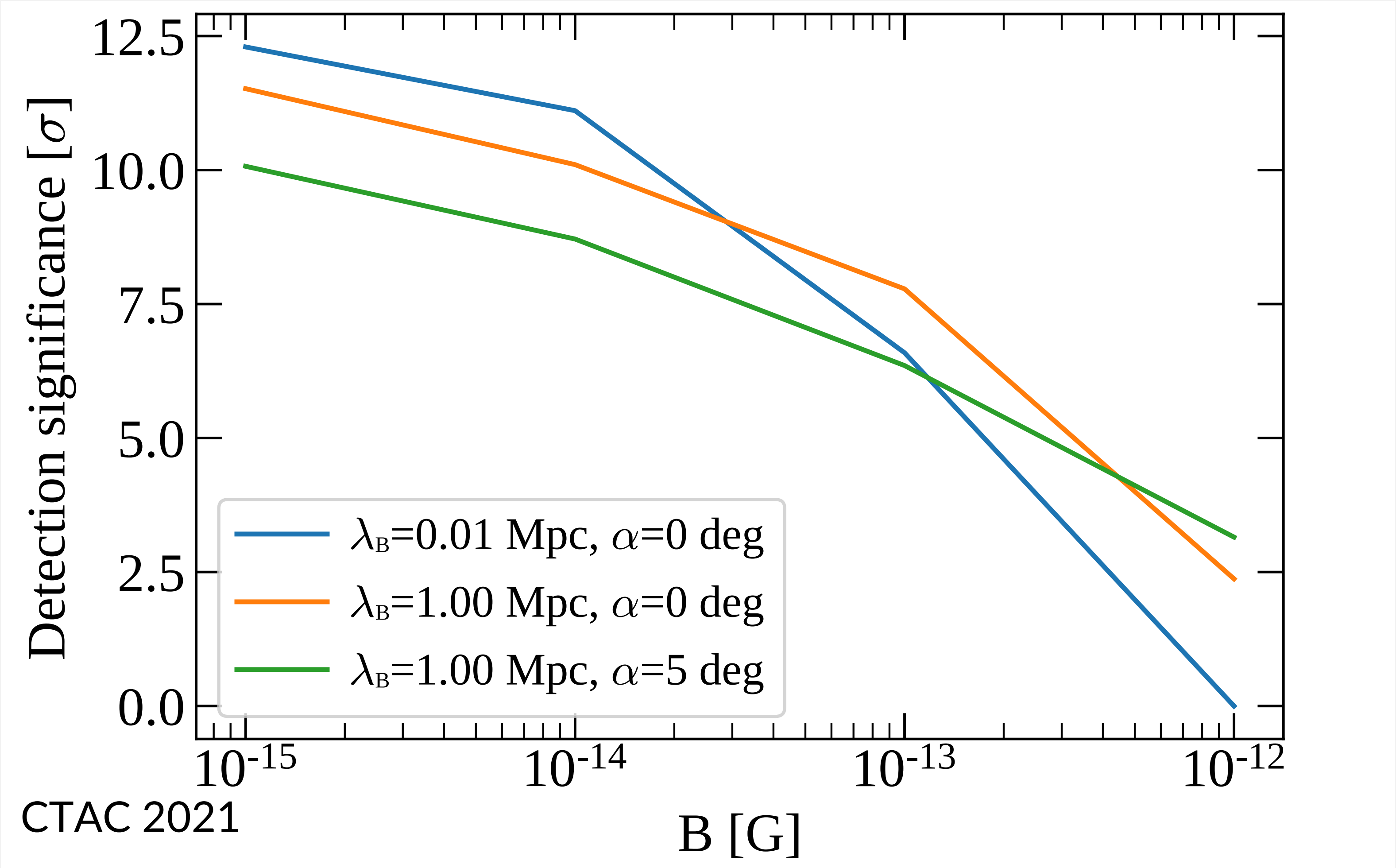
CTA prospects for IGMF studies



Single source test:

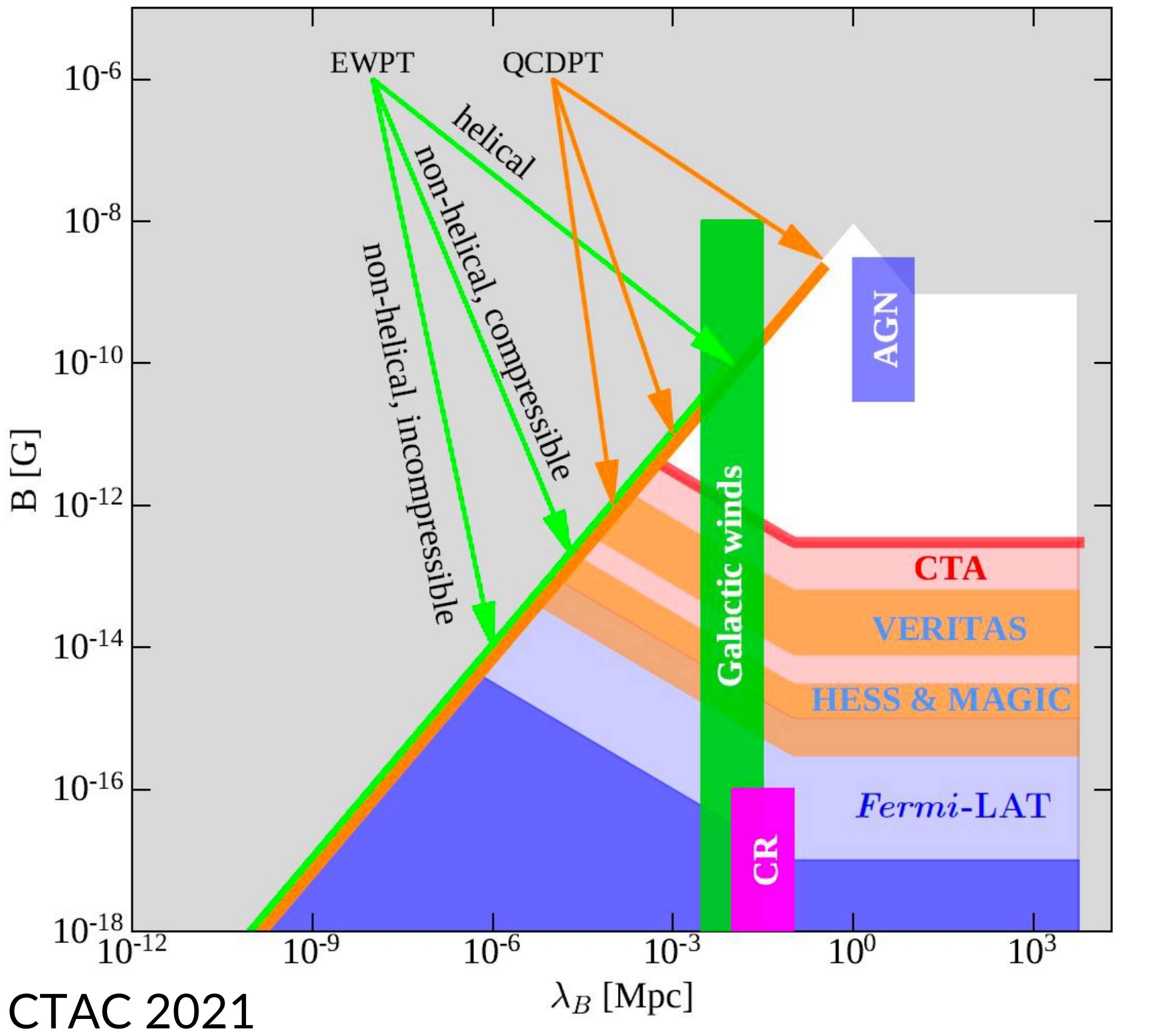
- simulate 50-hour observation of 1ES 0229+200
- Assume a disk-like halo brightness profile
- Emission = "point-like component + halo cascade component"
- Sensitivity = "minimal halo flux of fixed extension resulting in a 3σ detection of the extended component"

CTA prospects for IGMF studies



Several unknown parameters impact the results (IGMF coherence length, jet orientation, AGN activity evolution,…?)

CTA prospects for IGMF studies

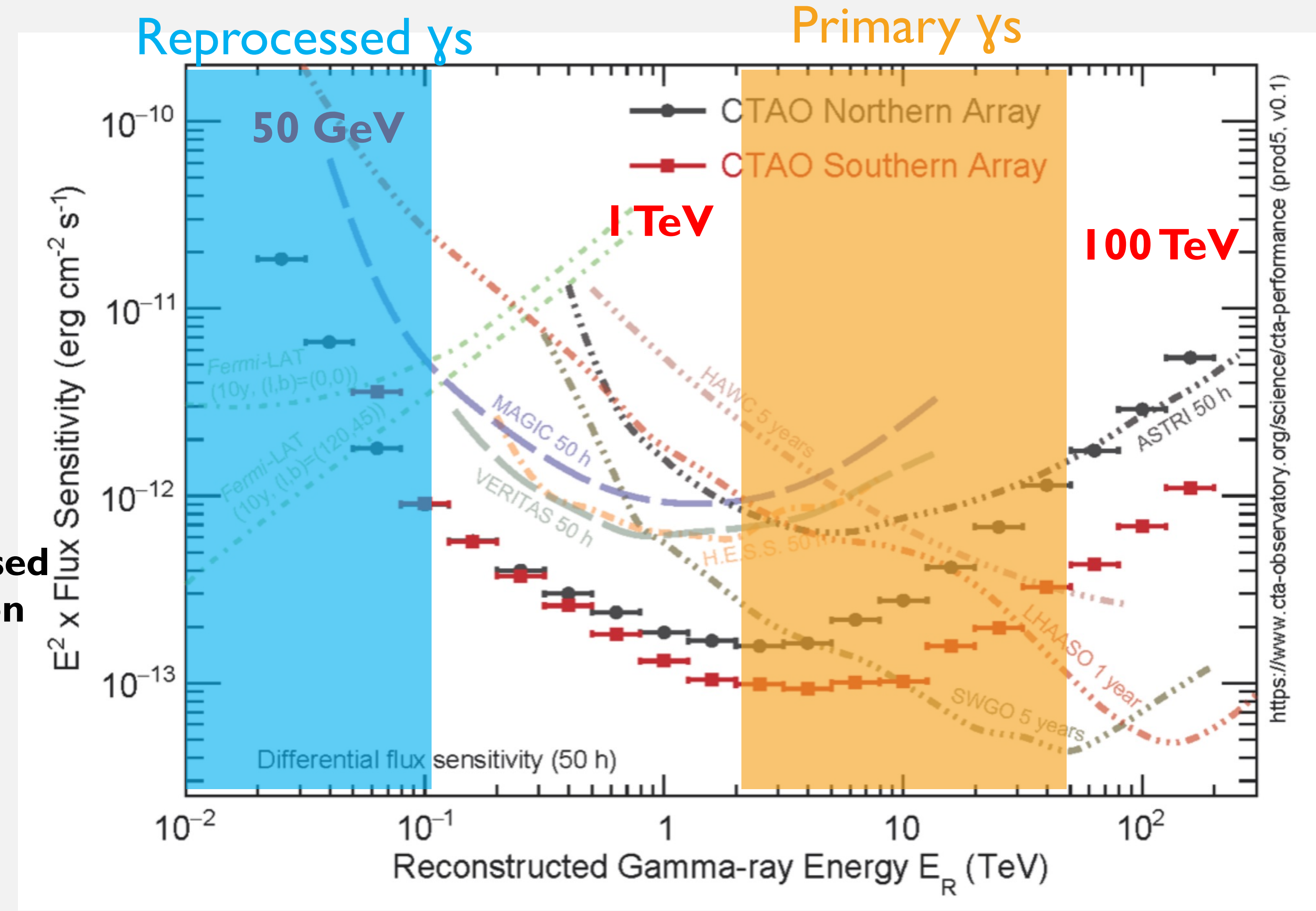


CTAC 2021

The contribution of CTA+ to IGMF

LSTs
Better sensitivity, angular resolution for E< 100 GeV

Study reprocessed cascade emission



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

SSTs
Intrinsic VHE spectrum above TeV

Study intrinsic source properties (photon index, cut-offs?)

Conclusions

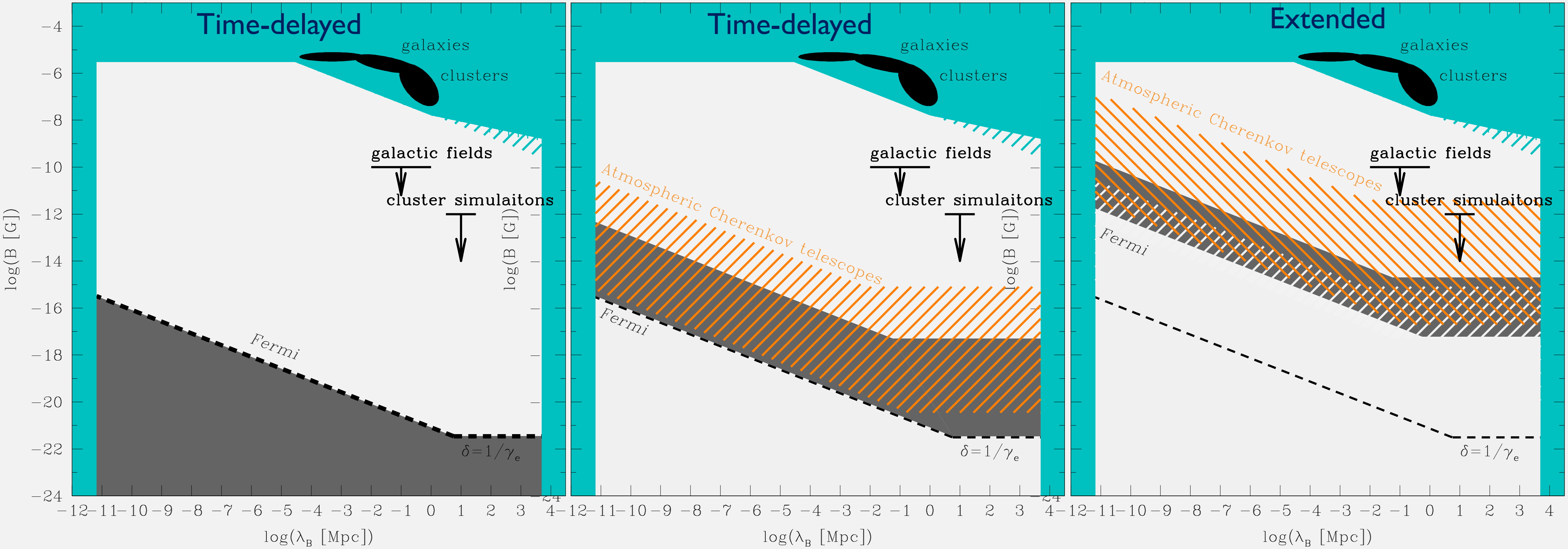
- IGMF current hot interdisciplinary topic (cosmology, astroparticle and astrophysics involved)
- VHE can provide unique results to this field → detection? LL?
- Recent studies and discoveries on AGNs and GRBs increase the "hype" on IGMF → for bright AGN flares or GRBs it may be worth to revise the observational strategies
- CTA (+synergies with LHAASO,SWGO, ASTRI-MA, Fermi-LAT) will be able to play a relevant role → is the cascade emission there or are there relevant effects that we are missing?
- CTA+ can provide a significant upgrade on IGMF studies both of secondary and primary gamma-ray emission

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

Probing IGMF in the GeV range

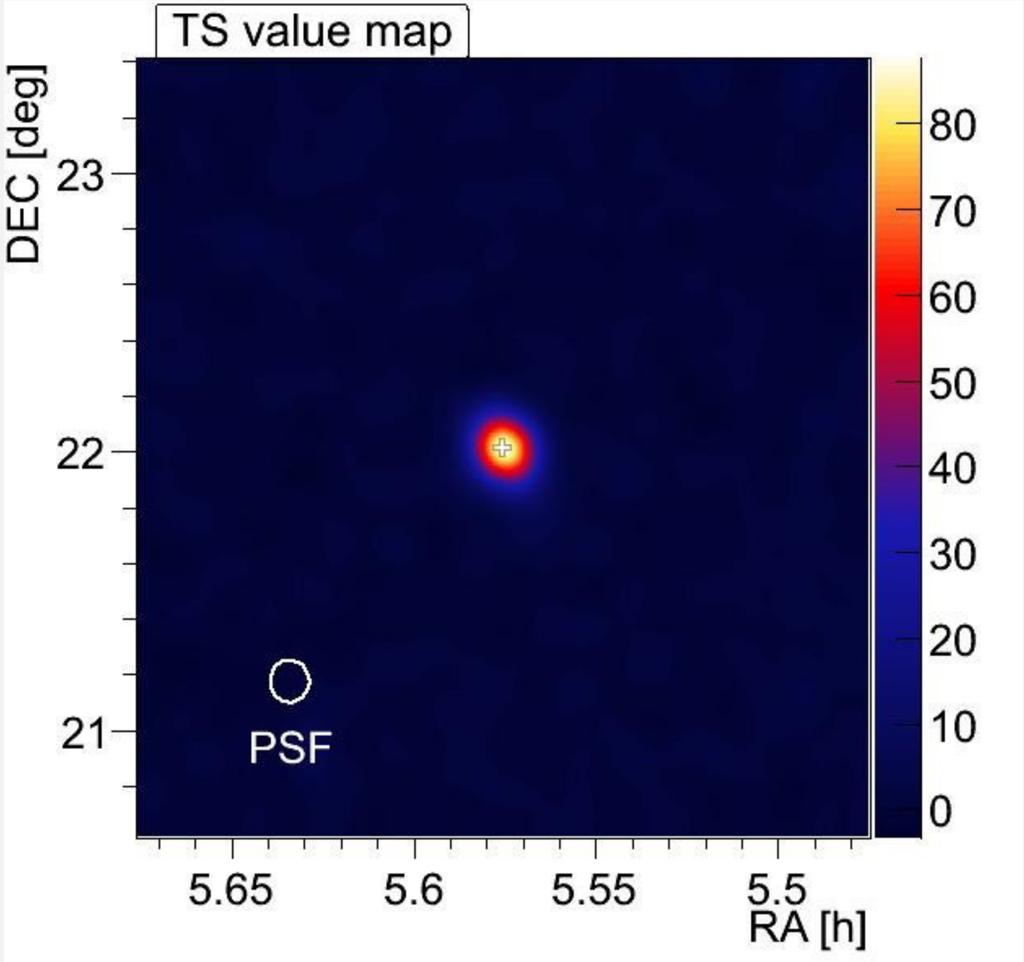
IGMF can generate an ***extended*** *and* ***time-delayed*** emission at GeV energies due to magnetic field deflection + CMB reprocessing



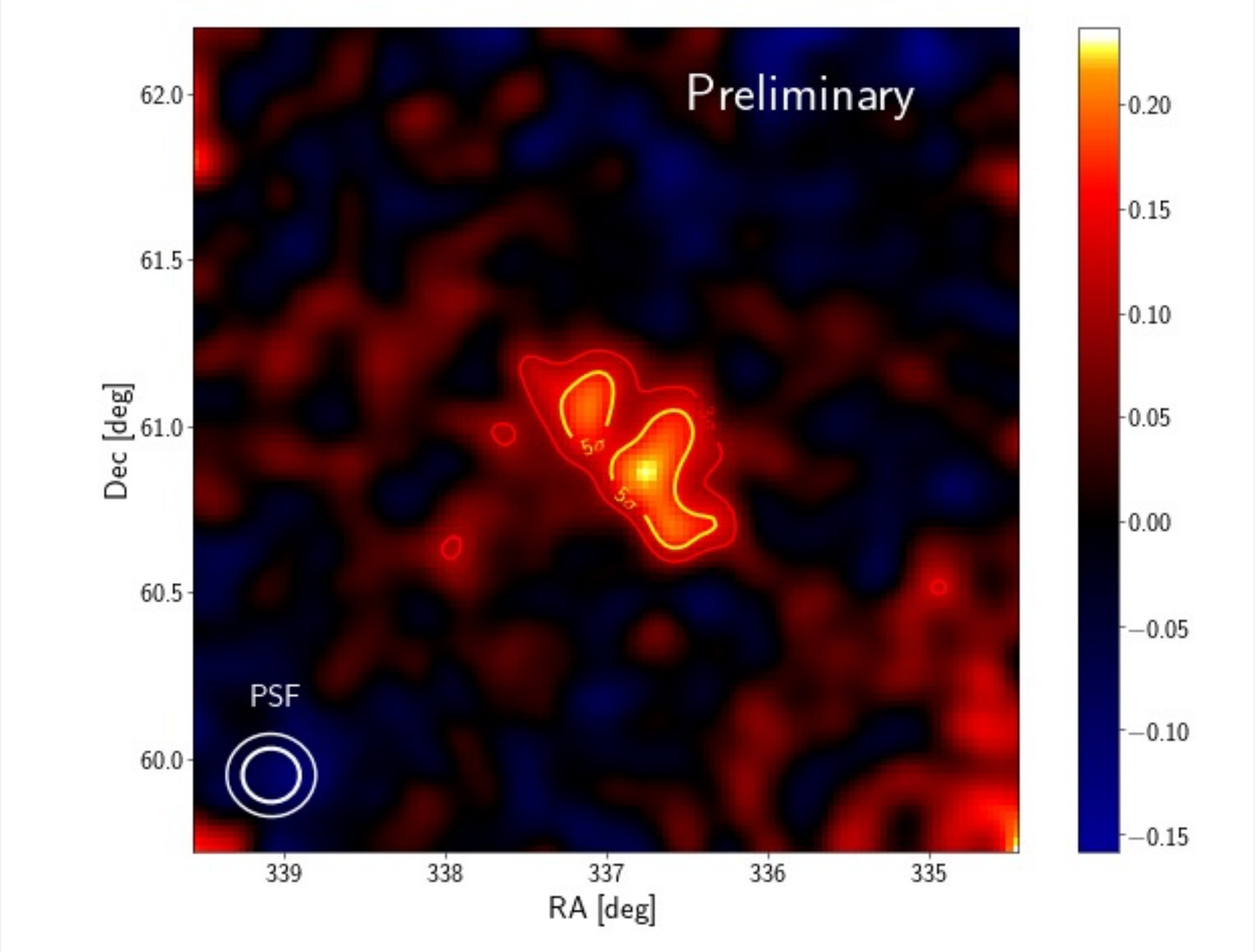
Neronov et al, 2009

IGMF: Extended emission

Point-like source

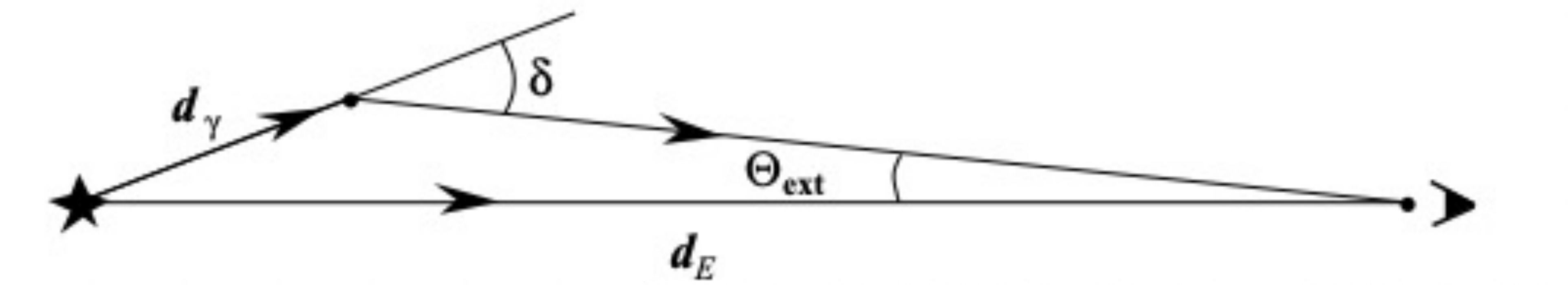


Extended source



IGMF: Extended emission

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

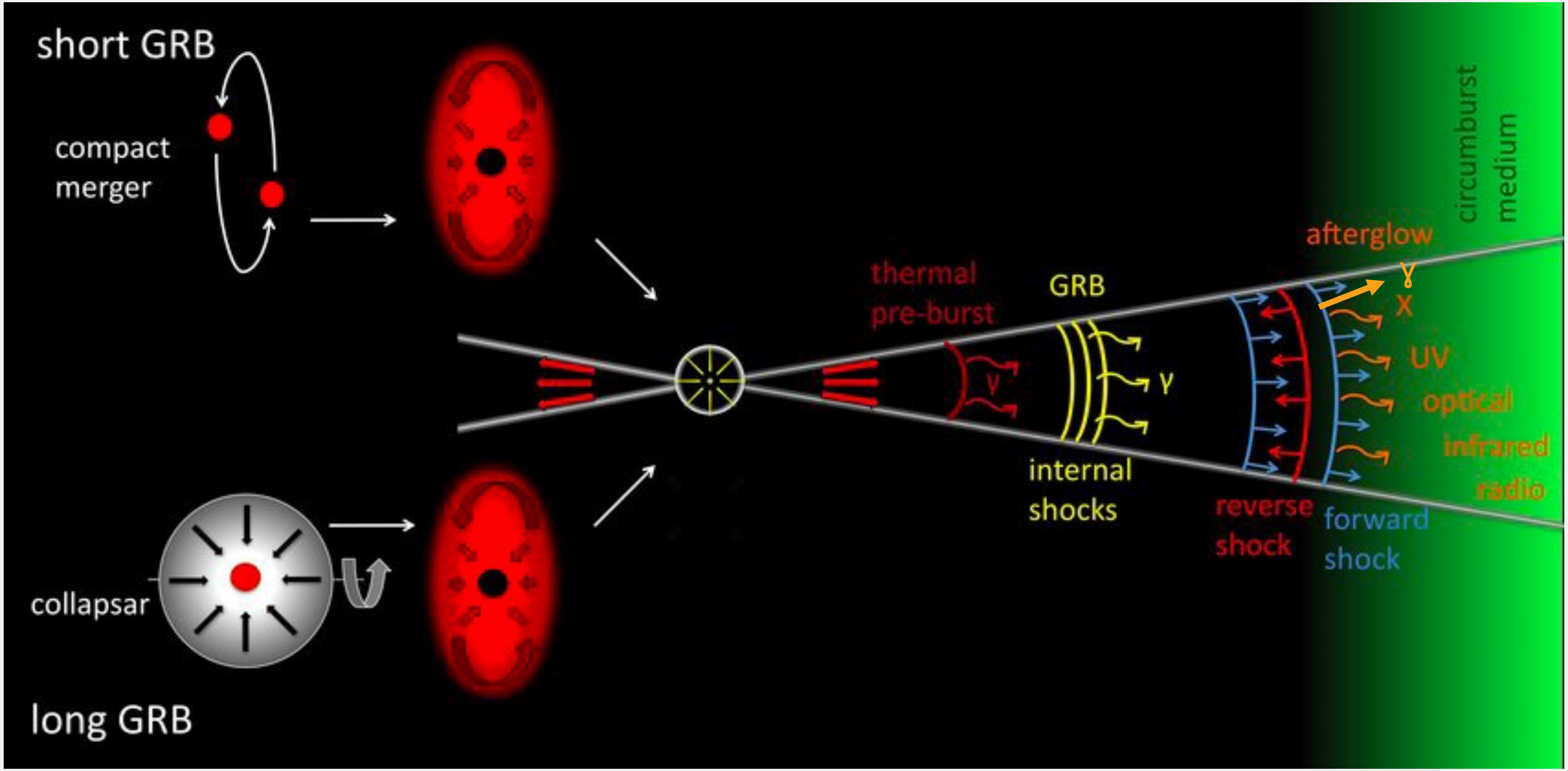


$$\delta = \frac{D_e}{R_L} \simeq 3\times10^{-6}(1+z_{\gamma\gamma})^{-4}\left[\frac{B'}{10^{-18}\text{ G}}\right]\left[\frac{E'_e}{10\text{ TeV}}\right]^{-2}$$
$$\simeq 3\times10^{-6}(1+z_{\gamma\gamma})^{-2}\left[\frac{B_0}{10^{-18}\text{ G}}\right]\left[\frac{E'_e}{10\text{ TeV}}\right]^{-2} \qquad (30)$$

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

Neronov et al, 2009

Gamma-Ray Bursts (GRBs)



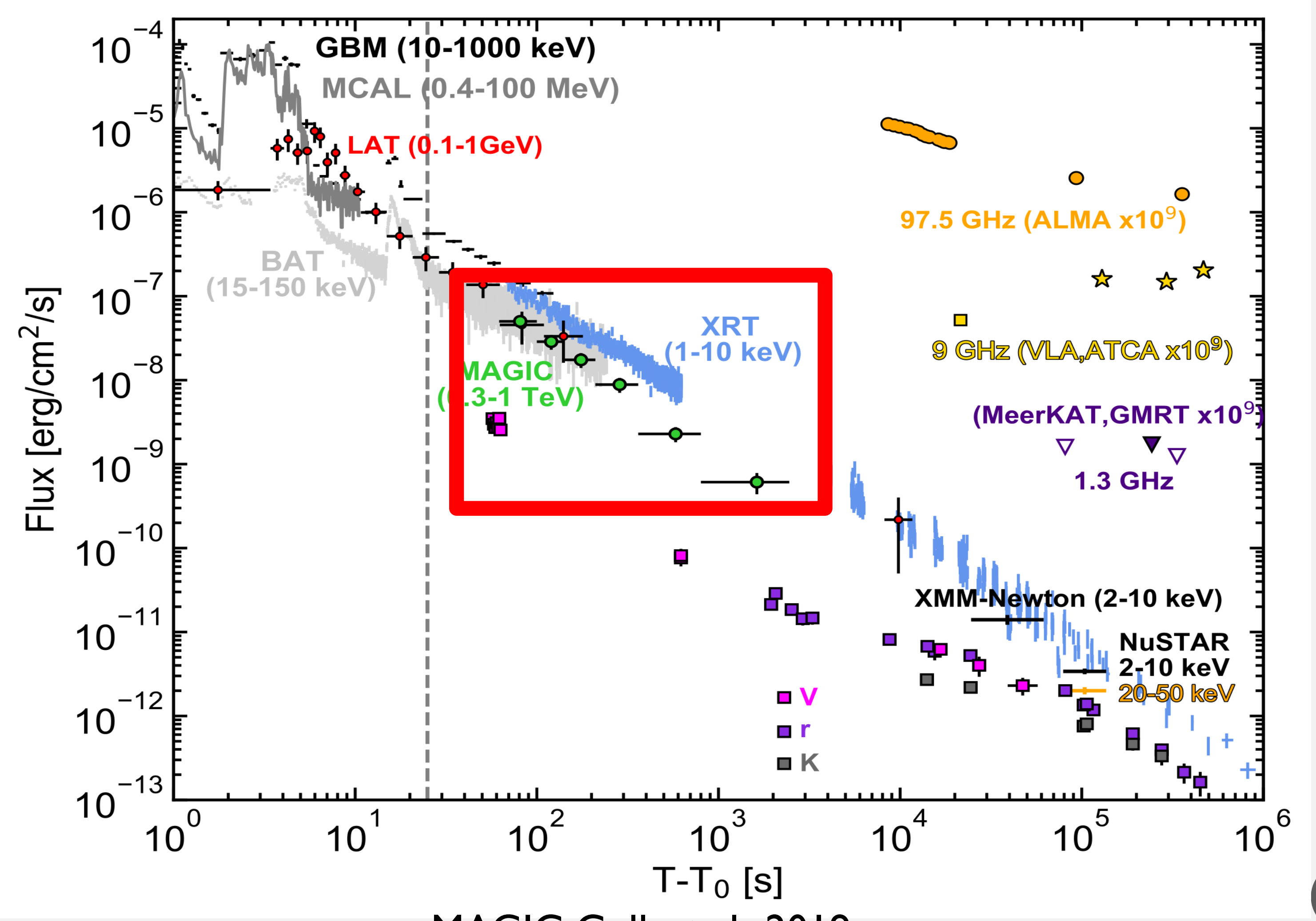
GRB190114C

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

TeV detection info (MAGIC):

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

Multi-wavelength light curve



MAGIC Coll. et al., 2019

GRB190114C

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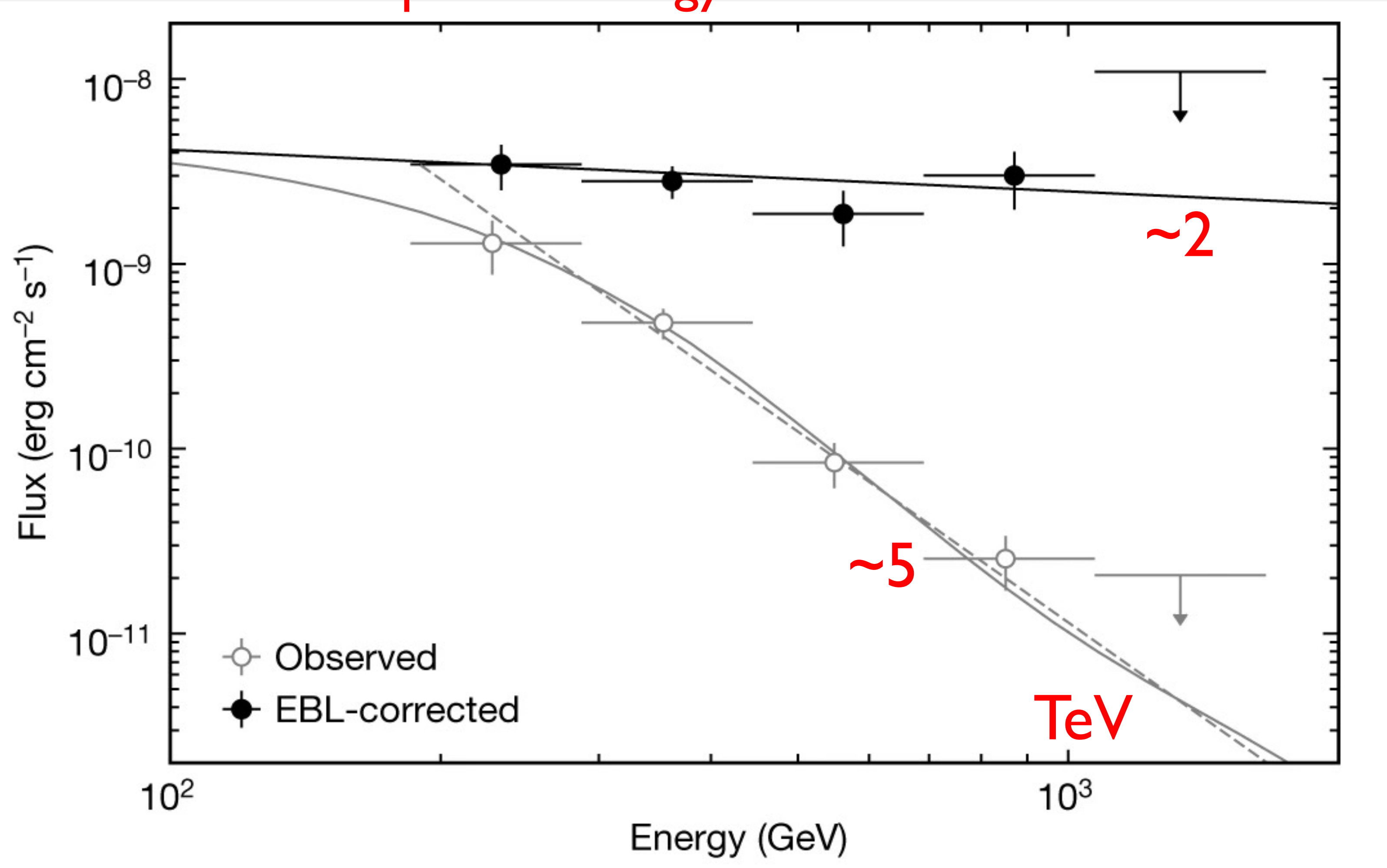

MAGIC Coll. et al., 2019