Probing the intergalactic magnetic field through gamma-ray observations

Paolo Da Vela

INAF OAS Bologna

1st VHEgam meeting, Bologna 15/1/24-17/1/24
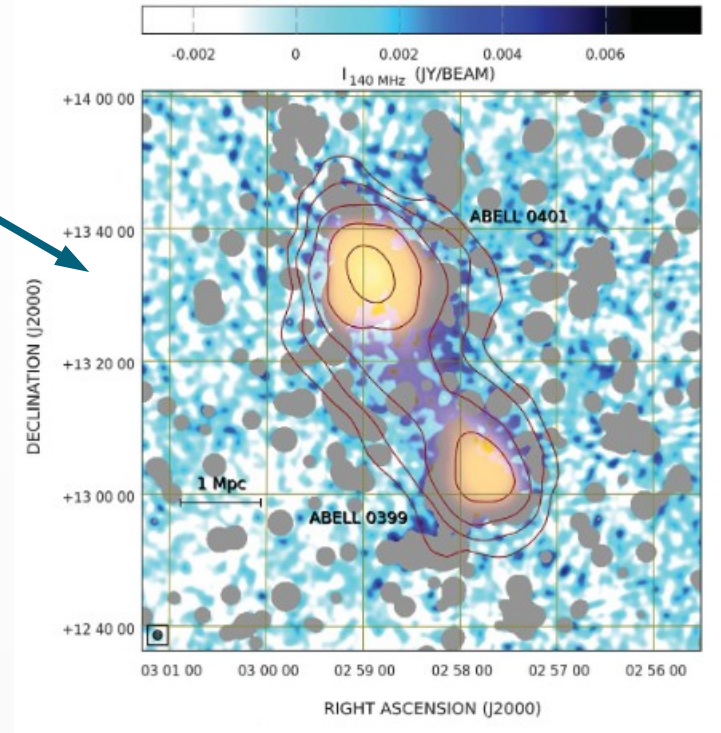
Magnetic Fields in galaxies

M51

Borlaff et al. 2021

$B < 1$ μG

$B \simeq 15$ μG

Govoni et al. 2019

Most of the models that explain these magnetic fields assume a pre-existing magnetic field

2

On the nature of the seed fields

- The nature of the seed fields is largely unknown. Two main hypothesis on their origin:

  I. The astrophysical scenario

  II. The cosmological scenario

- Observationally we need measurements of magnetic fields in the intergalactic medium
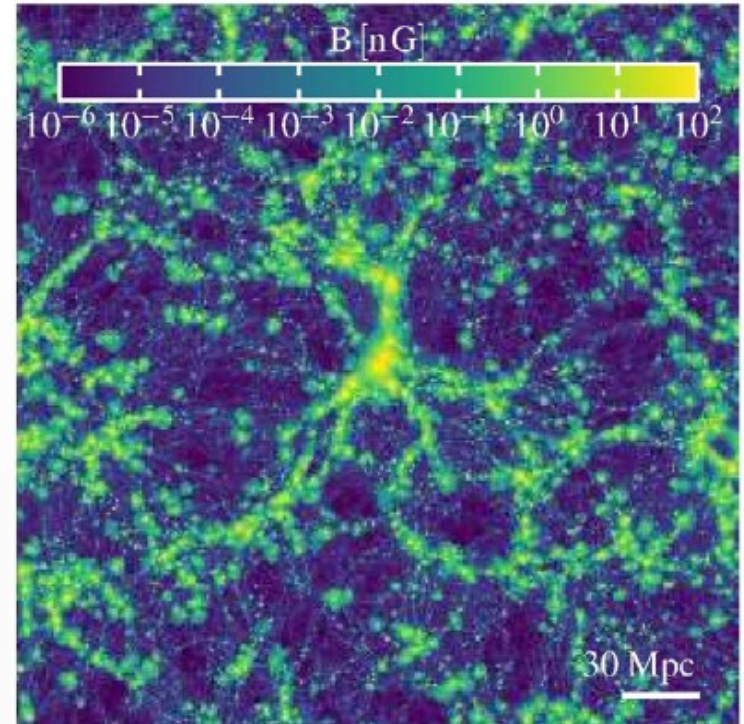
Marinacci et al. 2019

The Intergalactic Magnetic Field

- The IGMF is characterized by the fields strength and the correlation length

- Standard techniques can exclude only a small portion of the (B, λ_B) plane
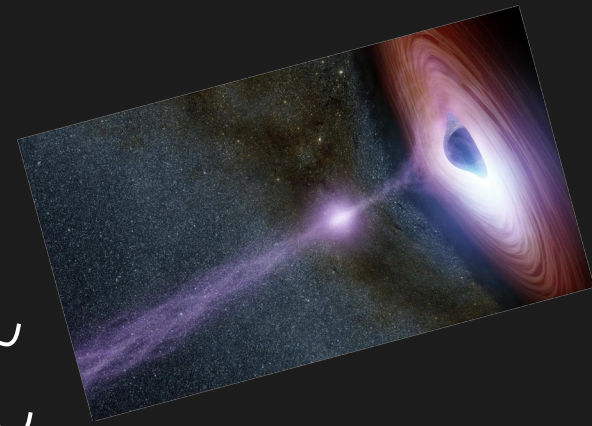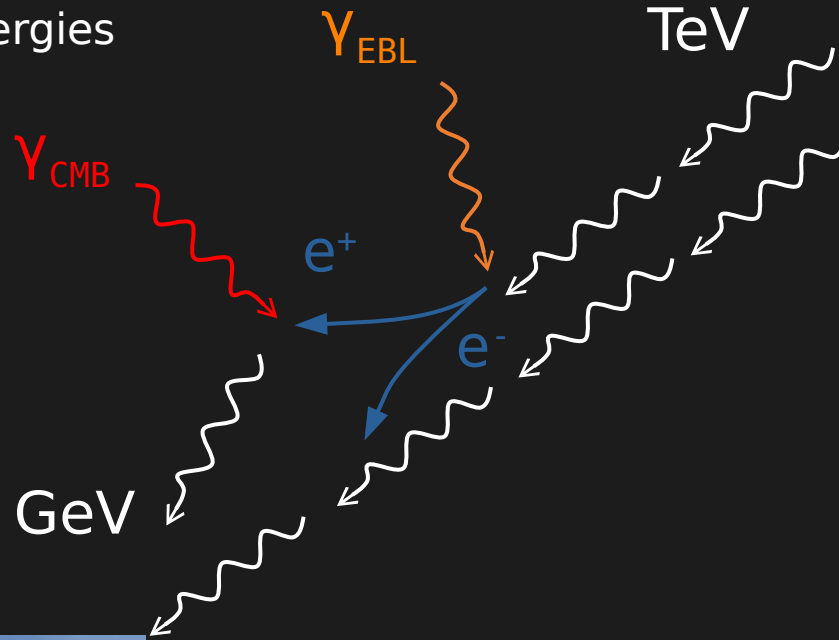
- We need a more sensitive technique
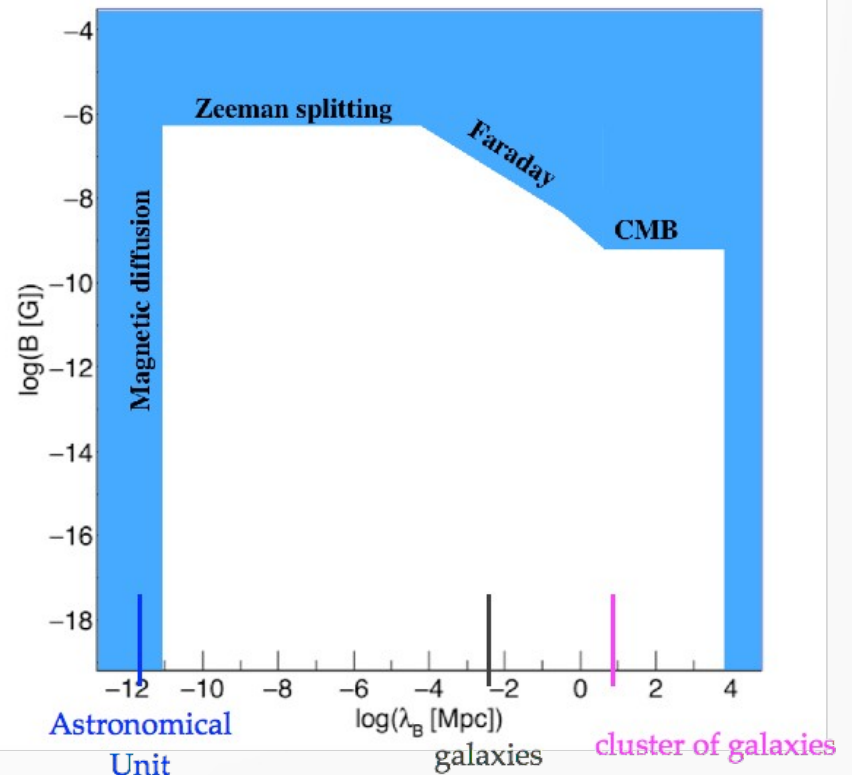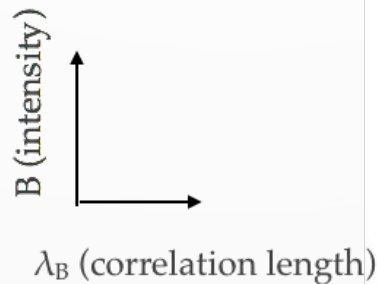
Physical process

- Excess γ rays at lower energies
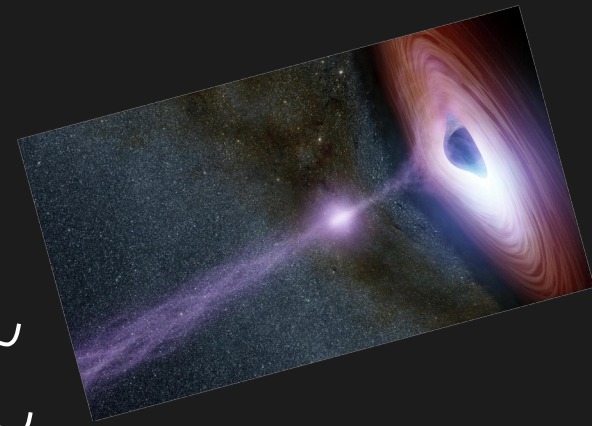
$$E \simeq 70 \left[\frac{E_0}{10\ TeV} \right]^2\ GeV$$

γ$_{EBL}$

γ$_{CMB}$

TeV

e$^+$

e$^-$

GeV

Physical process

- Excess γ rays at lower energies

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

Indirect detection of the IGMF

γ$_{EBL}$

γ$_{CMB}$

TeV

e^+

e^-

GeV

IGMF

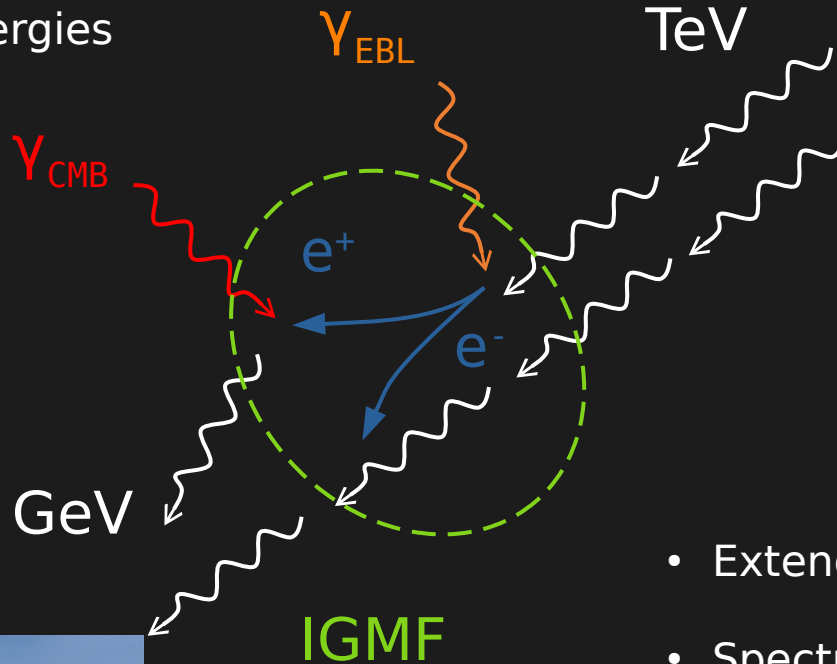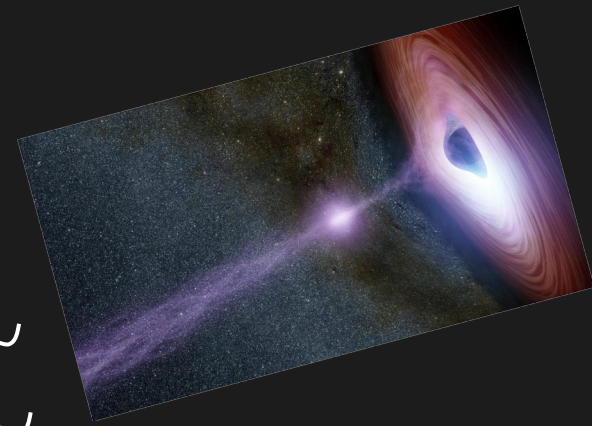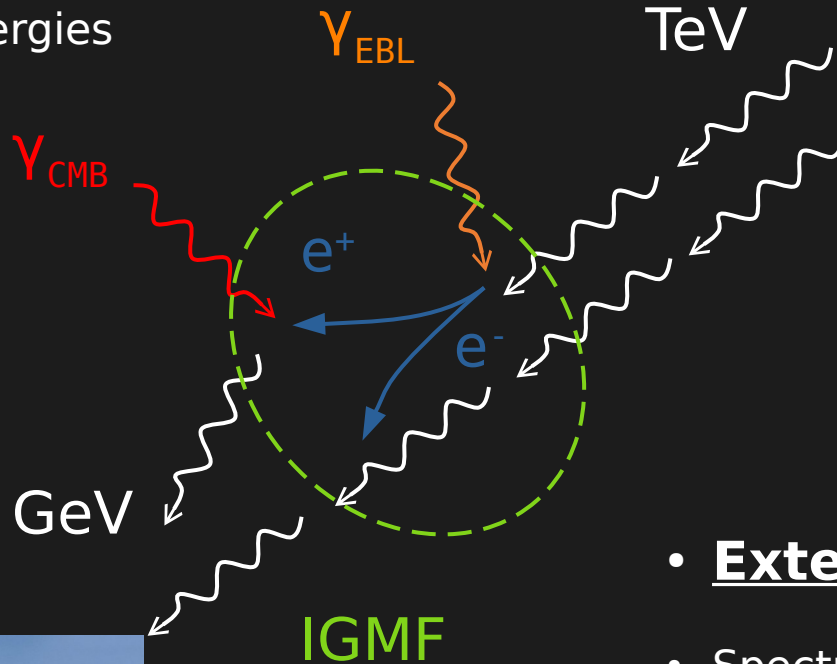- Extended γ rays halos
- Spectral features
- Time delayed γ-ray emission

Physical process

- Excess γ rays at lower energies

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

Indirect detection of the IGMF

γ$_{EBL}$ TeV

γ$_{CMB}$

e$^+$

e$^-$

GeV

IGMF

- **<u>Extended γ rays halos</u>**

- Spectral features
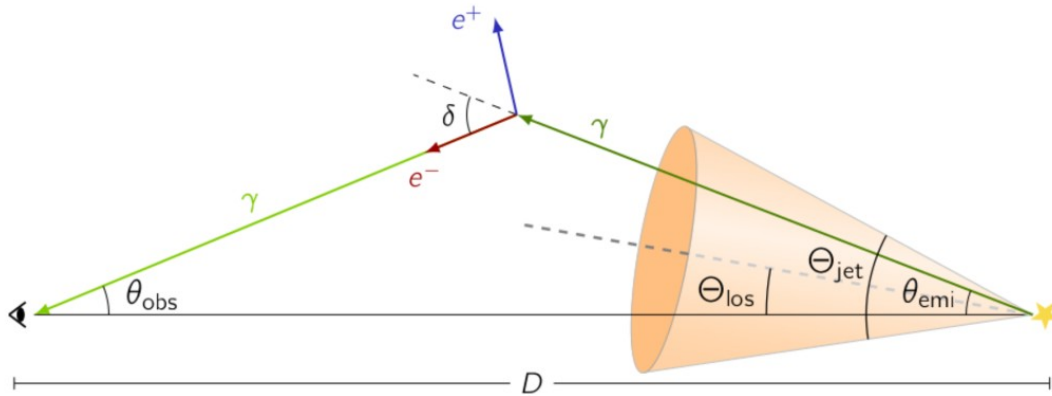
- Time delayed γ-ray emission

Extended emission

- Observable effect: extended emission around the point source. The angular extension grows with increasing IGMF

  - Two regimes:

Alves Batista & Saveliev 2021

$$\lambda_B \gg D_e :$$

$$\theta_{obs} \simeq 0.5° (1+z)^{-2} \left[\frac{\tau}{10}\right]^{-1} \left[\frac{E}{0.1\ TeV}\right]^{-1} \left[\frac{B}{10^{-14}\ G}\right]$$
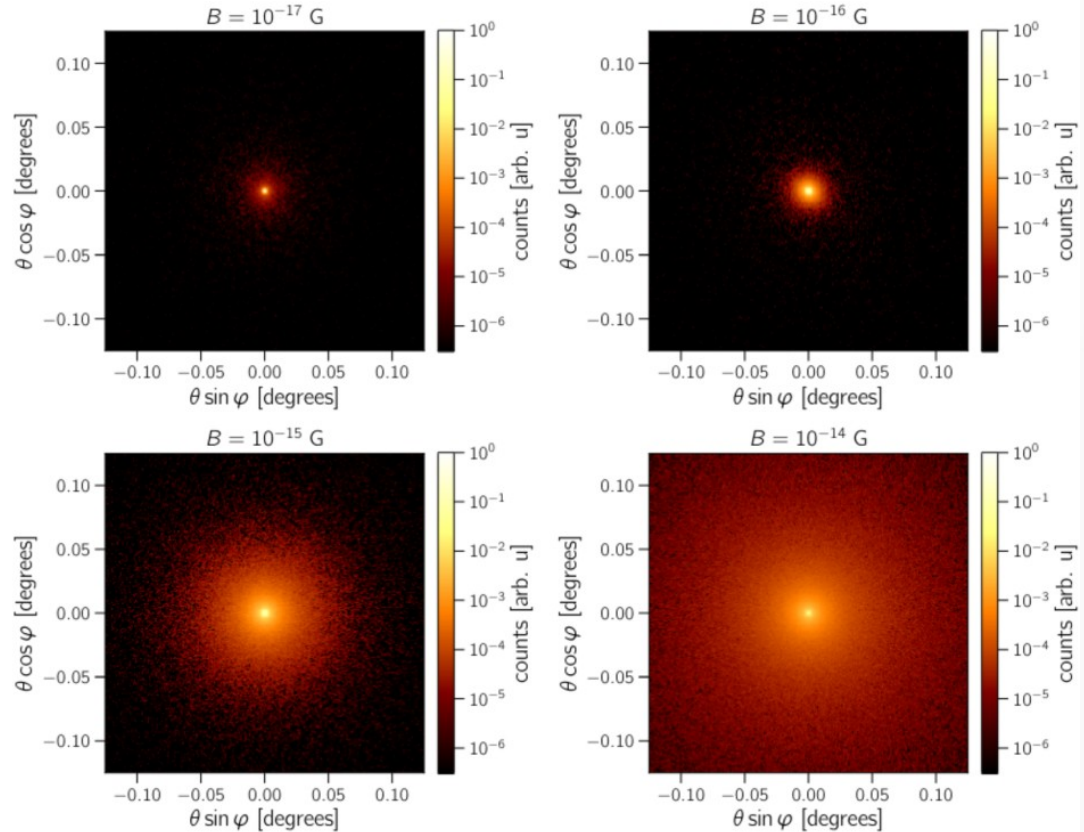
$$\lambda_B \ll D_e :$$

$$\theta_{obs} \simeq 0.07° (1+z)^{-1/2} \left[\frac{\tau}{10}\right]^{-1} \left[\frac{E}{0.1\ TeV}\right]^{-3/4} \left[\frac{B}{10^{-14}\ G}\right] \left[\frac{\lambda_B}{1\ kpc}\right]^{1/2}$$

The detection of the extended emission would allow a direct measure of the IGMF strength

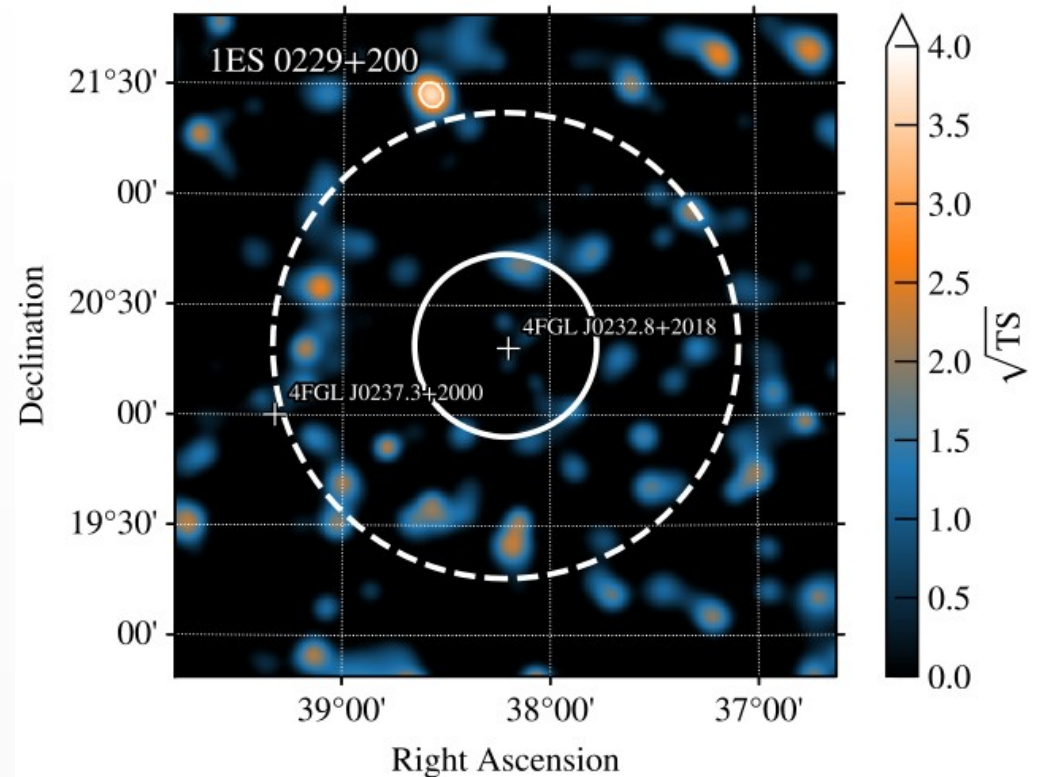# Extended emission: expectations

- Source: 1ES 0229+200 (blazar)

- Redshift: z=0.14

- Correlation length λ_B = 1Mpc

- Spectrum: powerlaw -1.5, E_{max}= 5 TeV

- E > 1 GeV

Alves Batista & Saveliev 2021

Extended emission: observations

- The extended emission can be searched in the GeV domain (Fermi/LAT) and in the VHE band (E > 50 GeV) with Cherenkov telescopes

- In spite of several attempts no detection has been claimed up to now in both energy bands
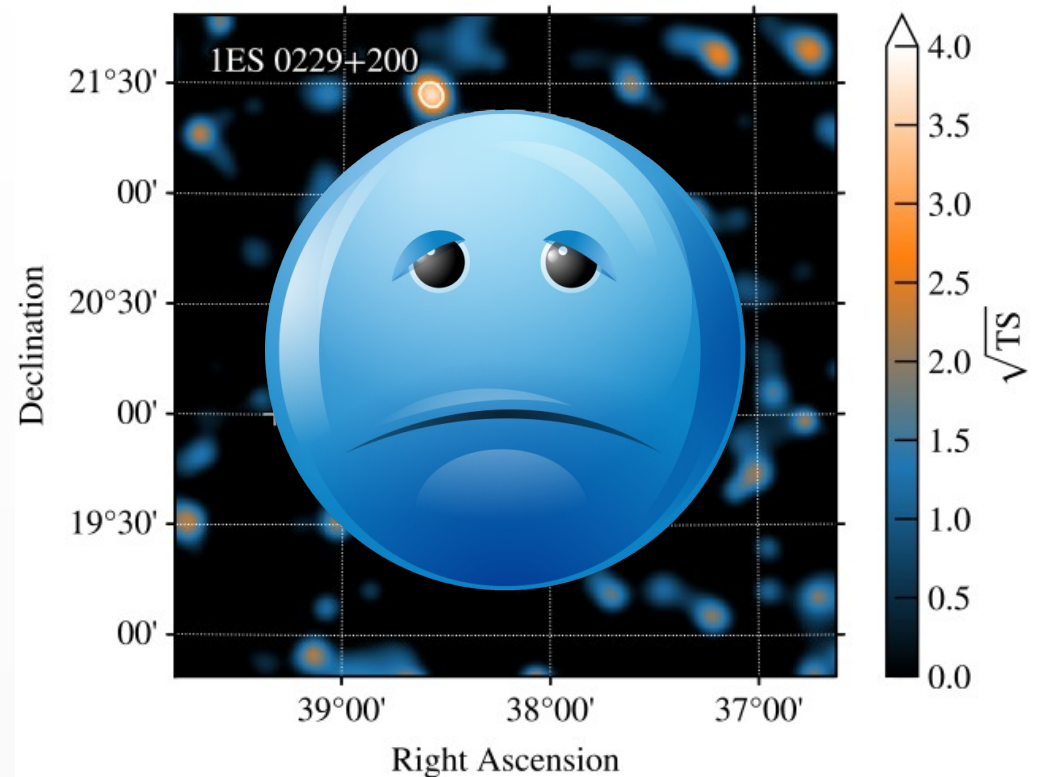
Aharonian et al. 2023

10

Extended emission: observations

- The extended emission can be searched in the GeV domain (Fermi/LAT) and in the VHE band (E > 50 GeV) with Cherenkov telescopes

- <u>In spite of several attempts no detection has been claimed up to now in both energy bands</u>
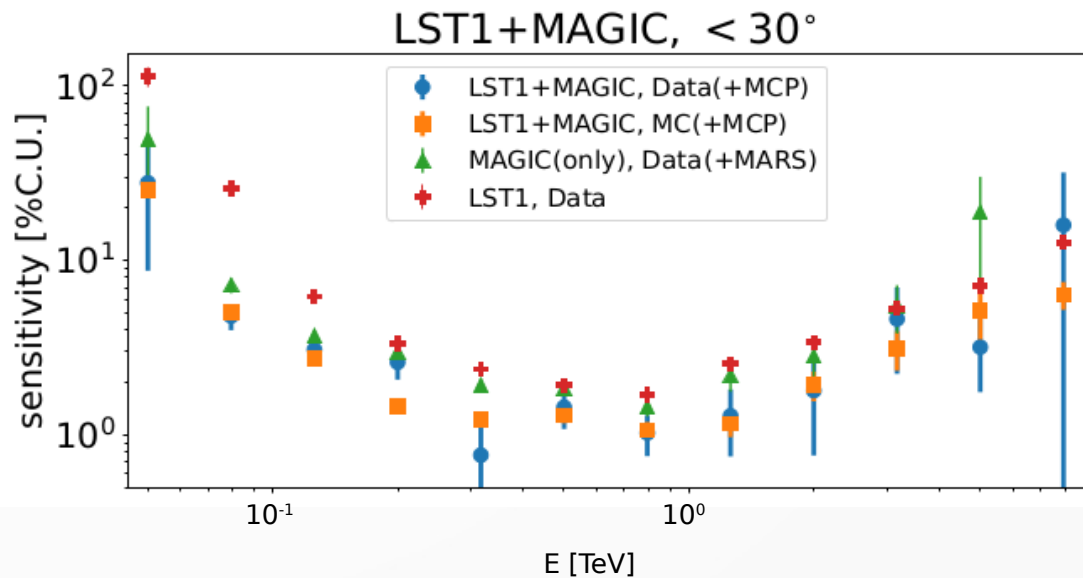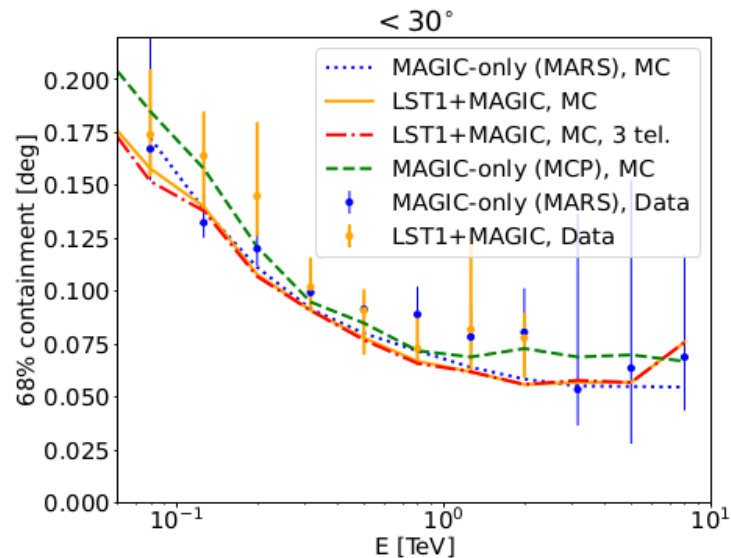

Aharonian et al. 2023

IGMF with joint MAGIC+LST1

MAGIC & LST coll. 2023

The improved angular resolution, sensitivity and energy threshold will allow the most sensitive emission search in the VHE band and pre-CTA era

12

Physical process

- Excess γ rays at lower energies

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

Indirect detection of the IGMF

γ$_{EBL}$ TeV

γ$_{CMB}$

e$^+$

e$^-$

GeV

IGMF

- Extended γ rays halos

- **Spectral features**

- Time delayed γ-ray emission

Spectral features

- Measuring the amount of absorbed flux of a TeV blazar we can predict the amount of cascade emission. Its suppression depends on the IGMF strength and correlation length
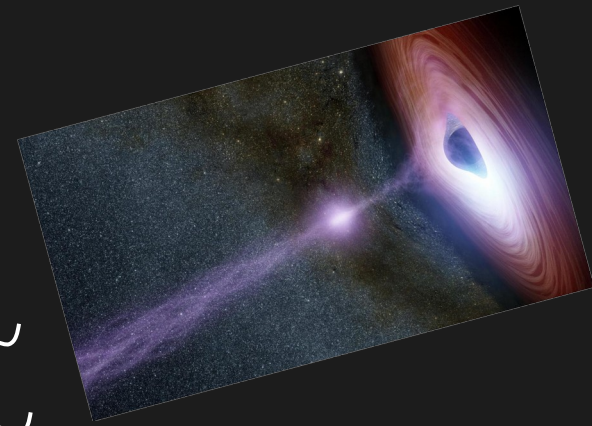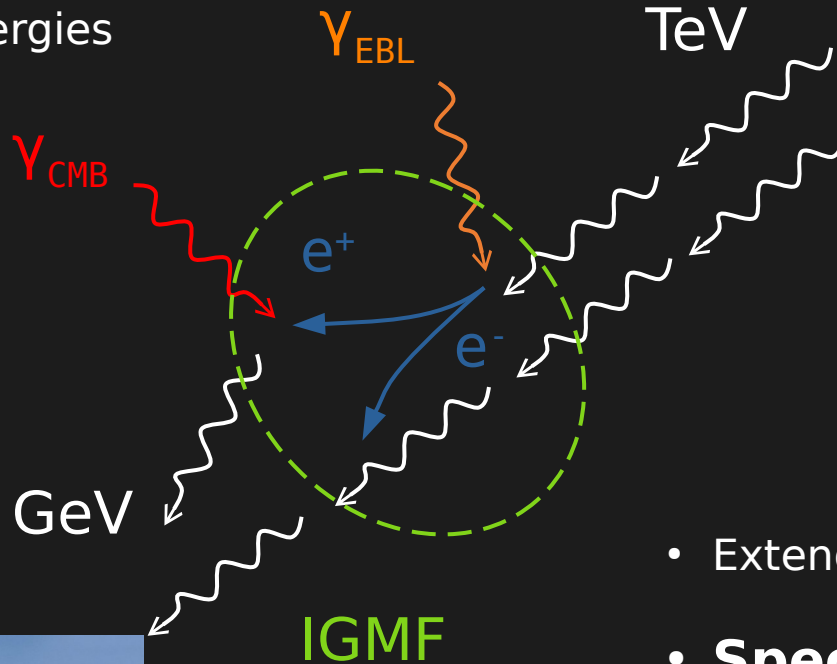
14

Physical process

- Excess γ rays at lower energies

$$E \simeq 70 \left[\frac{E_0}{10\ TeV} \right]^2\ GeV$$
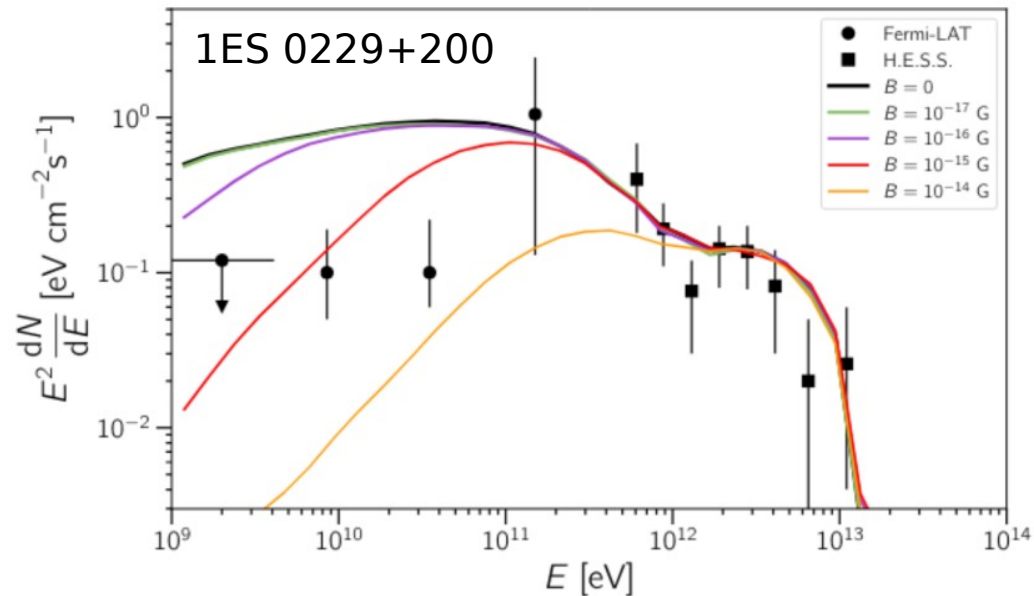
Indirect detection of the IGMF

γ$_{EBL}$

γ$_{CMB}$

TeV

e^+

e^-

GeV

IGMF

- Extended γ rays halos

- Spectral features

- **Time delayed γ-ray emission**

Flux in the VHE band

T_0

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

Cascade emission in case of no IGMF

Cascade emission in case of a not negligible IGMF

Flux in the GeV domain

t

t

16

GRB 190114C

MAGIC coll. 2019
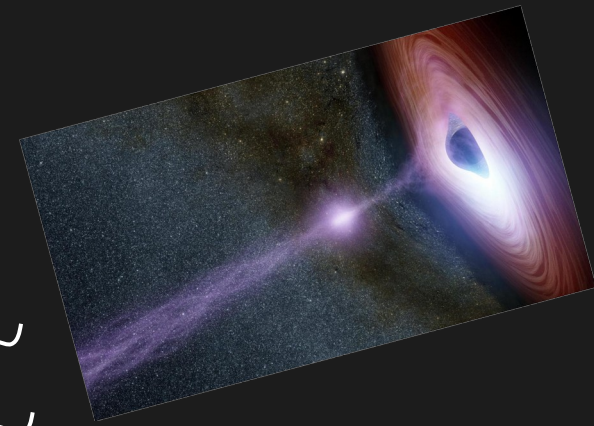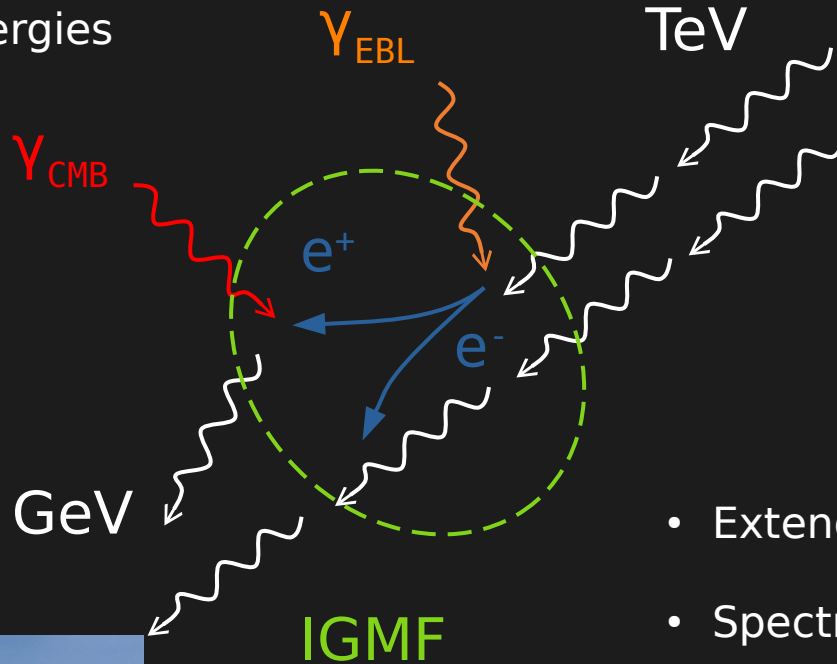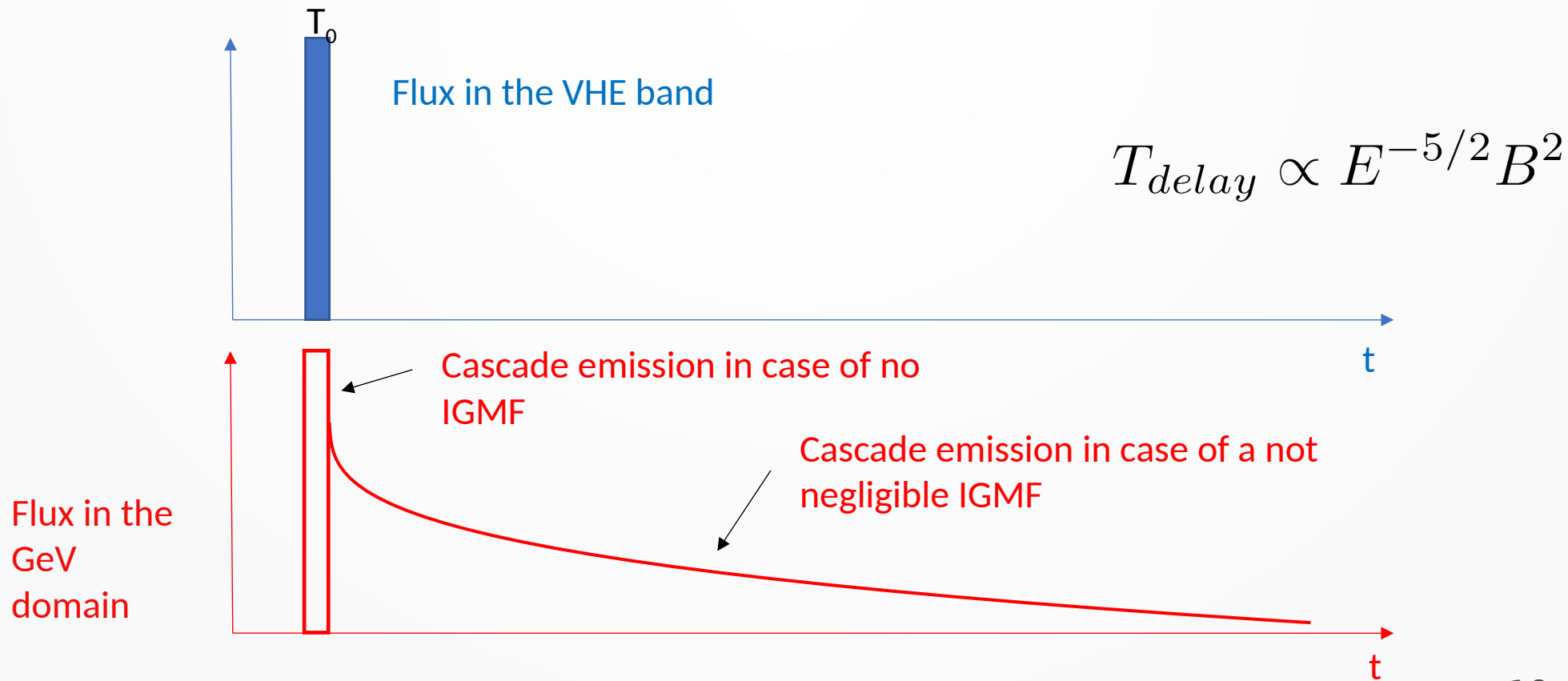
- GRB 190114C was triggered by Swift-BAT on 14 January at T_0=20:57:03 UT

- Most of the prompt emission within ~ 25 s

- Afterglow onset at ~ 6 s after T_0 (Ravasio et al. 2019)

- $E_{\gamma,iso} \simeq 2 \times 10^{53}$ erg in the E=1-10^4 keV

- $Z \simeq 0.42$

- $T_{activity, VHE} \simeq 40$ m

Primary spectrum
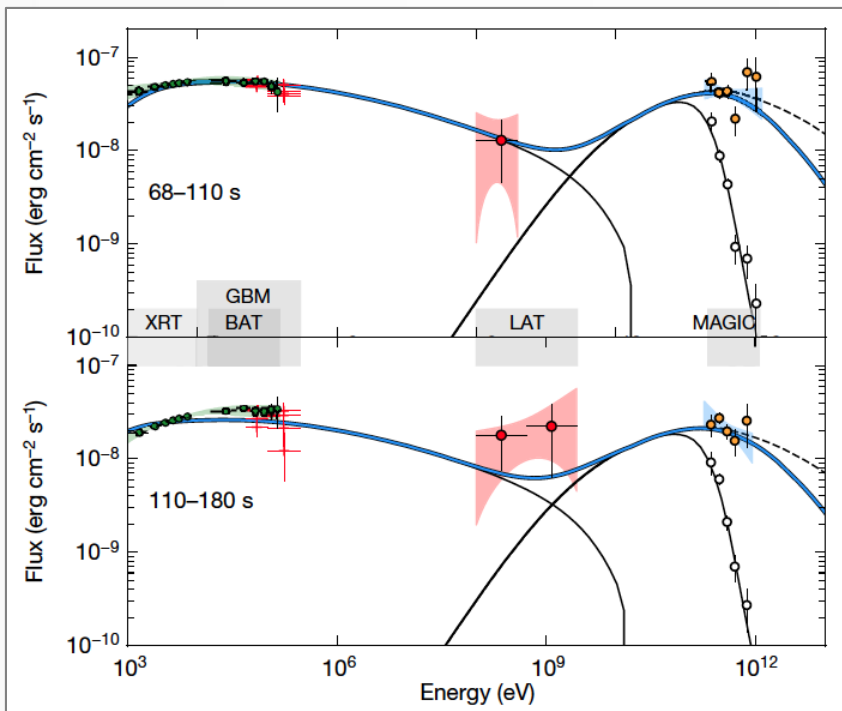
MAGIC coll. 2019

- We used the GRB 190114C model in the MAGIC band (200GeV<E<10 TeV) in the first temporal bin (68-110 s) approximated it with a log-parabola

$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-2.5 - 0.2\log(E/E_0)}$$

- The normalization has been fixed extrapolating the flux up to the first 6 s after T_0

$$\langle F \rangle_{6-2454} = \frac{\int_6^{2454} F(t)dt}{\Delta t}$$
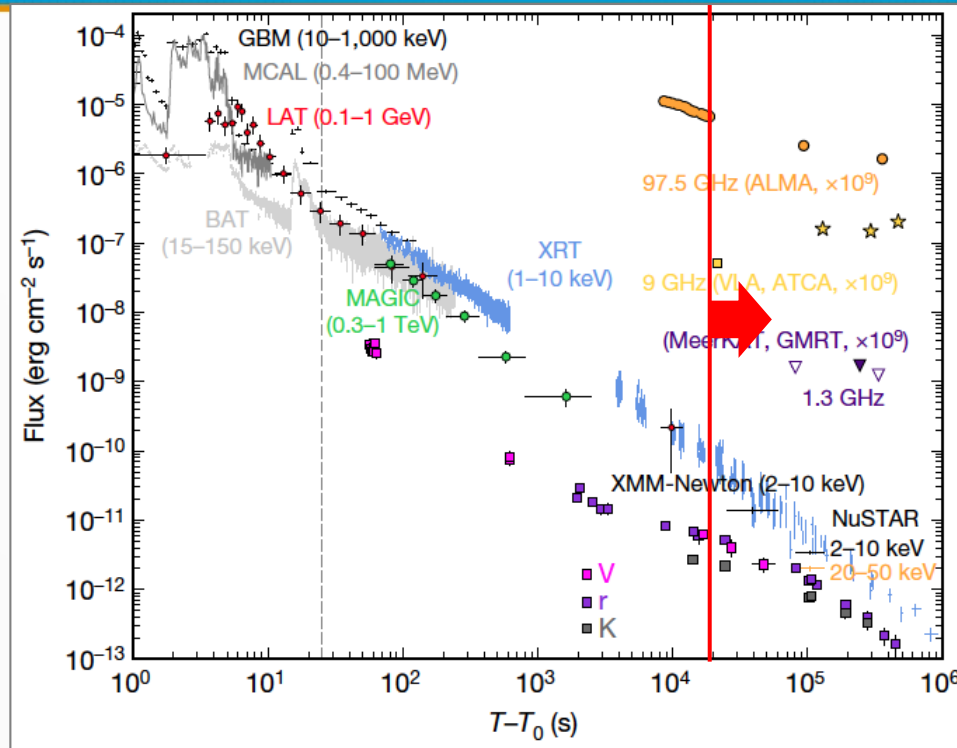
- We started to count the cascade photons at $T-T_0 = 2 \times 10^4$ s to avoid possible contamination of the primary emission coming from the source

CRPropa simulations: settings

- Source:
  - Point source
  - Z=0.42
  - Logparabola spectrum between 200 GeV and 10 TeV, 10^6 primary photons
  - Minimum energy of cascade photons: 0.05 GeV
  - Emission cone: 10°
- Magnetic Field:
  - Turbulent magnetic field with a Kolmogorov spectrum and different B_{rms}
  - Correlation length: > 1 Mpc
- Observer:
  - Sphere with radius 1.6 Gpc with the source at the center

Pair echo SEDs vs observation time
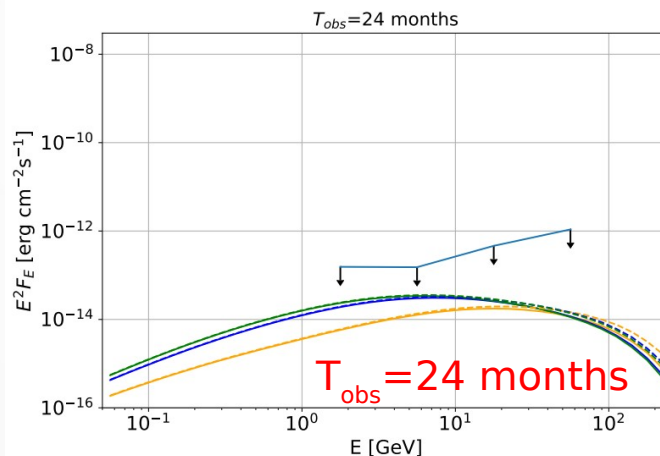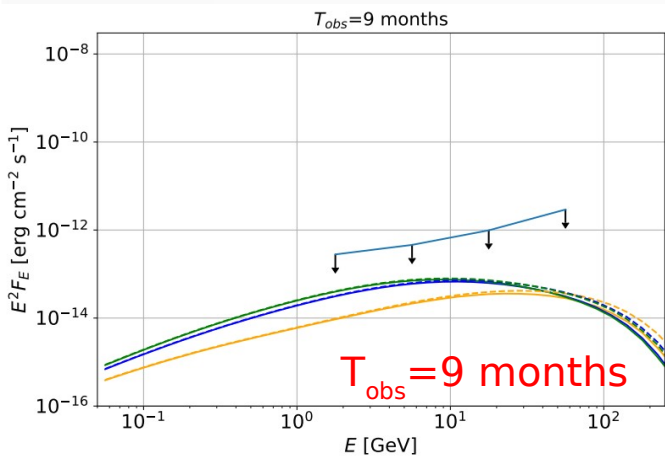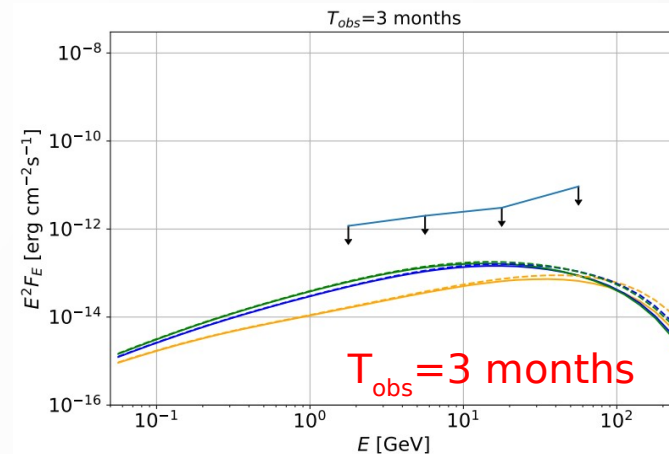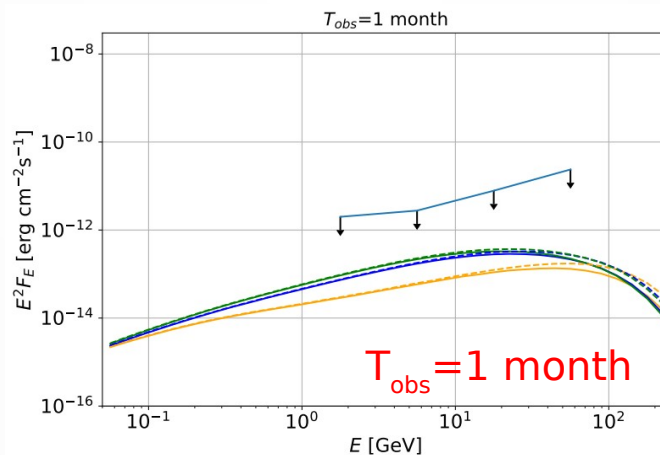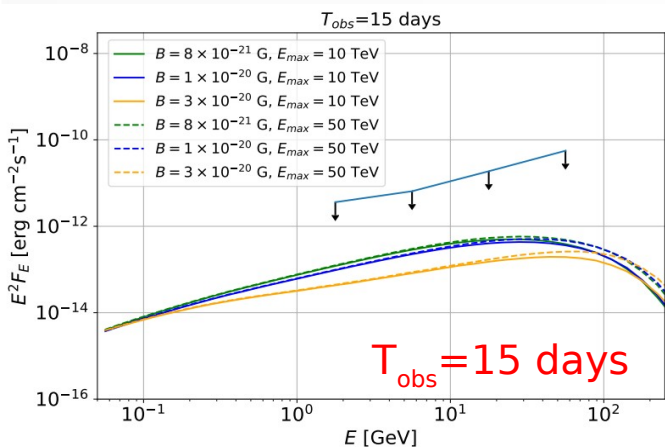
Da Vela et al. 2023

No constraints on IGMF can be inferred...

What about if we want to use Cherenkov telescopes?

GRB 190114C, $T_{obs} = 3h$

Preliminary

Legend:
- $B = 3 \times 10^{-20}$ G, $E_{max} = 10$ TeV
- $B = 3 \times 10^{-20}$ G, $E_{max} = 50$ TeV
- $B = 10^{-20}$ G, $E_{max} = 10$ TeV
- $B = 10^{-20}$ G, $E_{max} = 50$ TeV
- $B = 8 \times 10^{-21}$ G, $E_{max} = 10$ TeV
- $B = 8 \times 10^{-21}$ G, $E_{max} = 50$ TeV

$E^2 F_E$ [erg cm^{-2} s^{-1}]

E [GeV]

MAGIC

CTA North

GRB 190114C, $T_{obs} = 6h$

Preliminary

Legend:
- $B = 3 \times 10^{-20}$ G, $E_{max} = 10$ TeV
- $B = 3 \times 10^{-20}$ G, $E_{max} = 50$ TeV
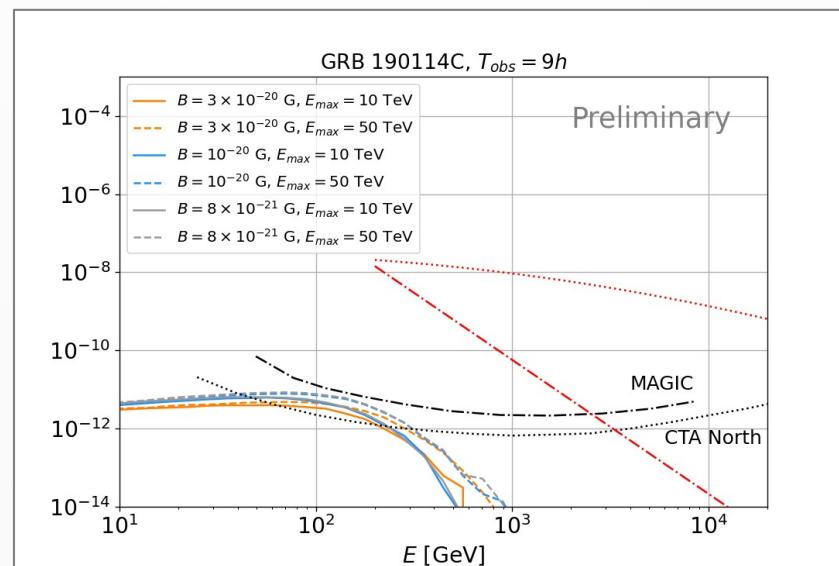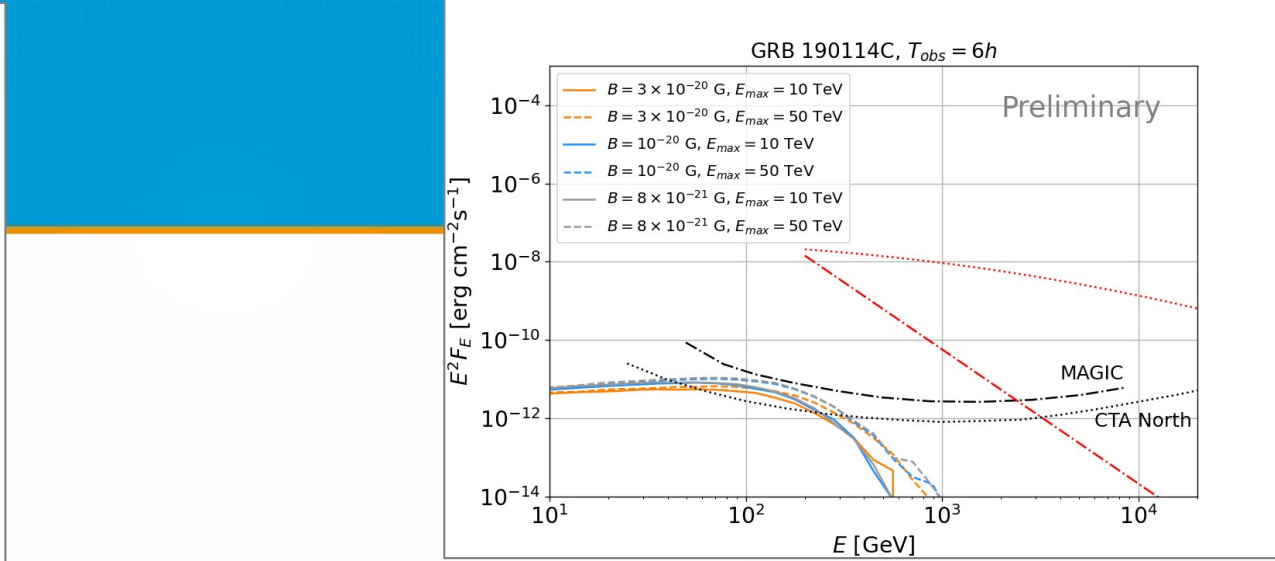- $B = 10^{-20}$ G, $E_{max} = 10$ TeV
- $B = 10^{-20}$ G, $E_{max} = 50$ TeV
- $B = 8 \times 10^{-21}$ G, $E_{max} = 10$ TeV
- $B = 8 \times 10^{-21}$ G, $E_{max} = 50$ TeV

$E^2 F_E$ [erg cm^{-2} s^{-1}]

E [GeV]

MAGIC

CTA North

GRB 190114C, $T_{obs} = 9h$

Preliminary

Legend:
- $B = 3 \times 10^{-20}$ G, $E_{max} = 10$ TeV
- $B = 3 \times 10^{-20}$ G, $E_{max} = 50$ TeV
- $B = 10^{-20}$ G, $E_{max} = 10$ TeV
- $B = 10^{-20}$ G, $E_{max} = 50$ TeV
- $B = 8 \times 10^{-21}$ G, $E_{max} = 10$ TeV
- $B = 8 \times 10^{-21}$ G, $E_{max} = 50$ TeV

E [GeV]

MAGIC

CTA North

These IGMF strengths can be excluded (or detected) with CTA North, T_{obs}=3 hours

23

Conclusions and Outlook

- The study of the IGMF through gamma-ray emission from extragalactic sources is a powerful instrument

- Plasma instabilities: the presence of plasma instabilities can suppress the production the cascade emission.

- <u>Pair echo from GRBs</u>:
  - the time activity (in the VHE band) and the time evolution of the VHE emission of the prompt play an important role and need to be considered
  - VHE emission characterization is crucial to proper model the afterglow and to look for the pair echo

- <u>Extended emission:</u> no detection so far but with LST and later CTA…
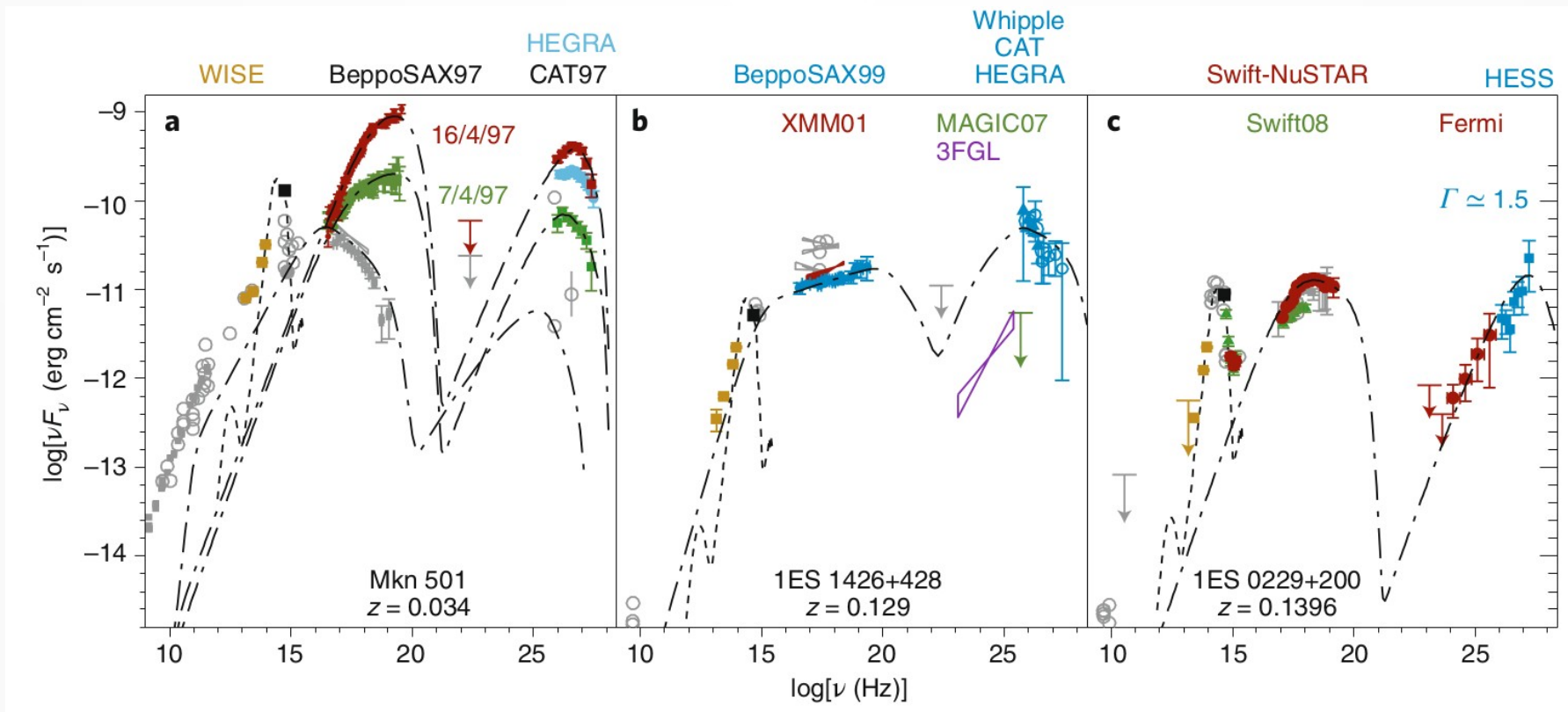
Back up

$\theta_{obs} = 0°$ $\theta_{obs} = 3°$ $\theta_{obs} = 6°$ $\theta_{obs} = 9°$

0.001   0.01   0.1   1

Neronov et al. 2010
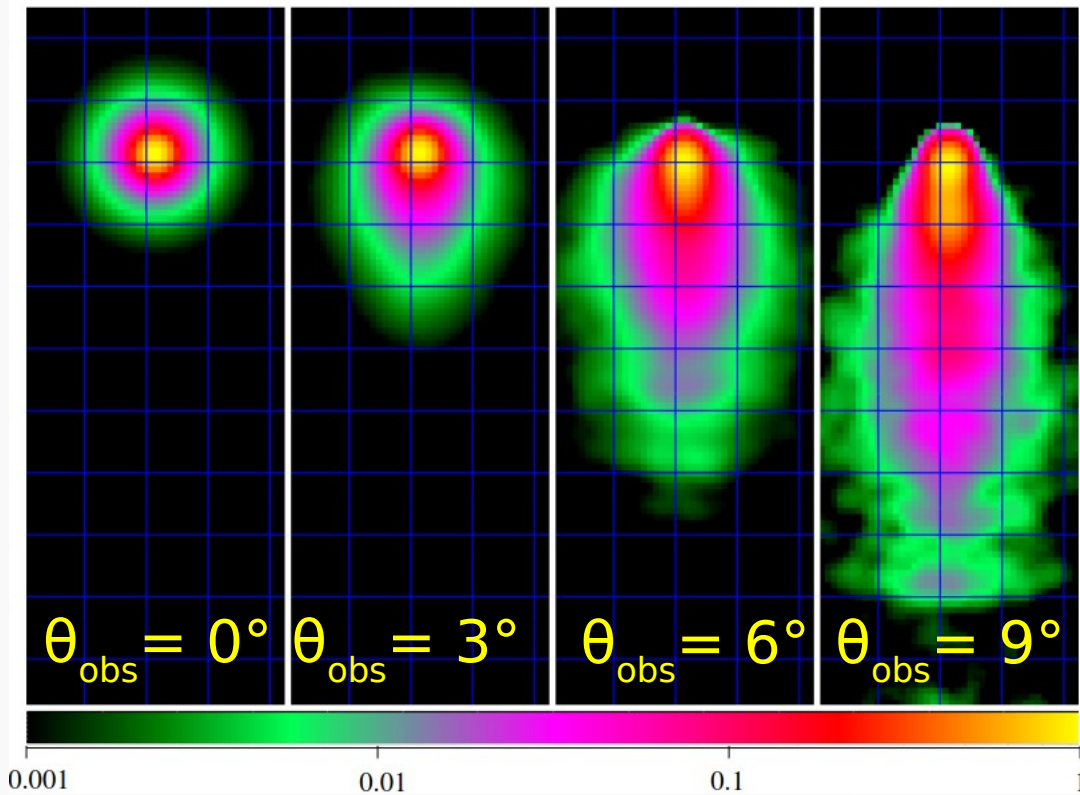
- The shape of the halo depends also on the inclination of the jet:

  - Monchromatic photons E=1 TeV

  - Redshift: z≈0.1

  - Jet opening angle: $\theta_{jet}=3°$

  - Correlation length $\lambda_B > 1$ Mpc

  - IGMF strength: $B = 10^{-16}$ G

26

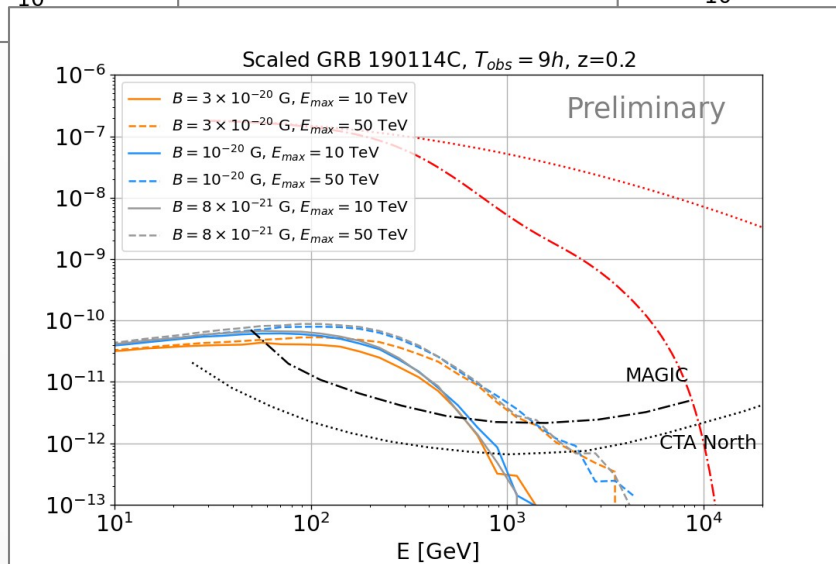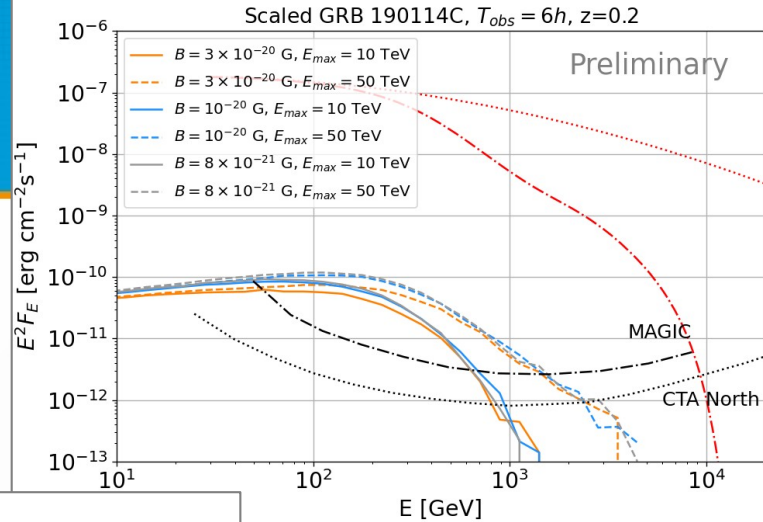# Extreme High frequency BL-Lac (EHBL)

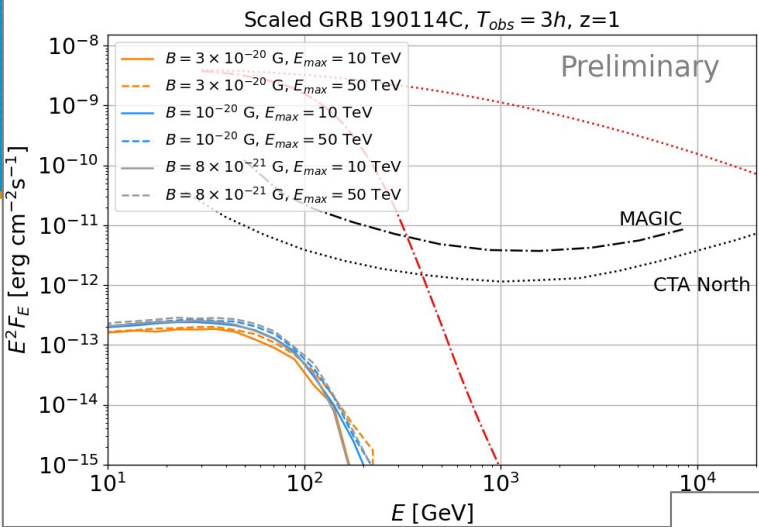# Pair echo emission detection vs GRB distance

- We assumed the same intrinsic properties as GRB 190114C:

  - VHE spectral shape
  - $L_{\gamma,\,iso}$

- We repeated the same procedure assuming z=0.2, 1

Scaled GRB 190114C, T_{obs} = 3h, z=0.2

z=0.2

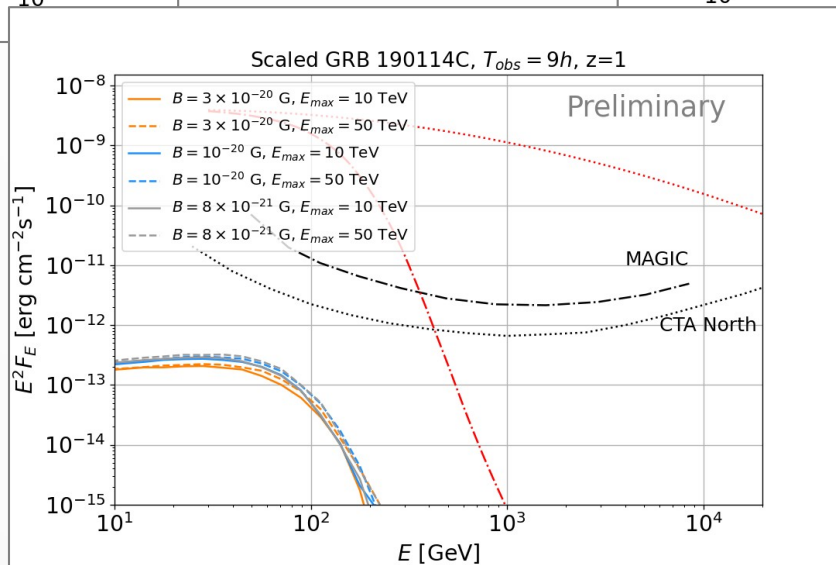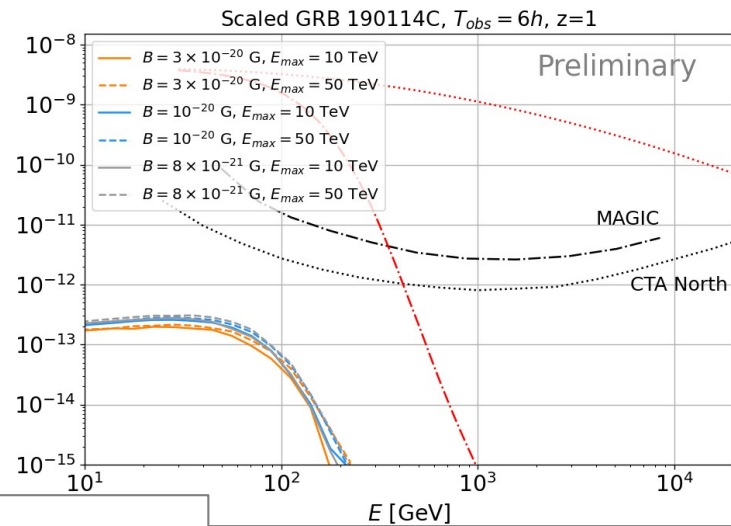Scaled GRB 190114C, T_{obs} = 6h, z=0.2
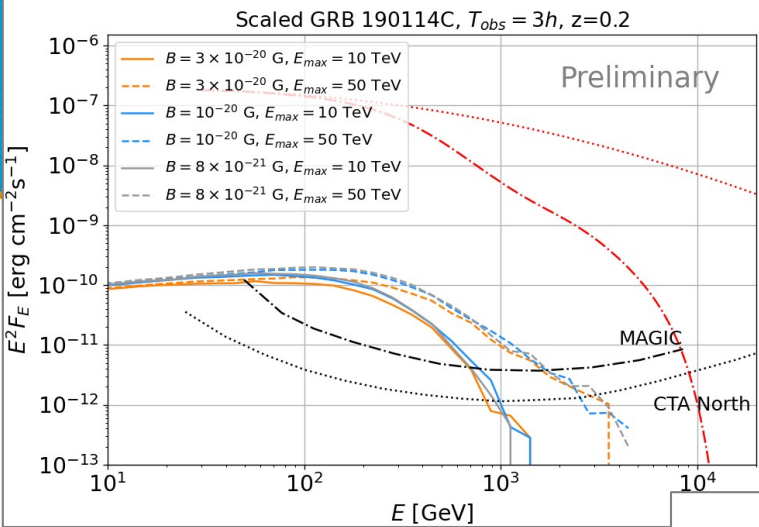
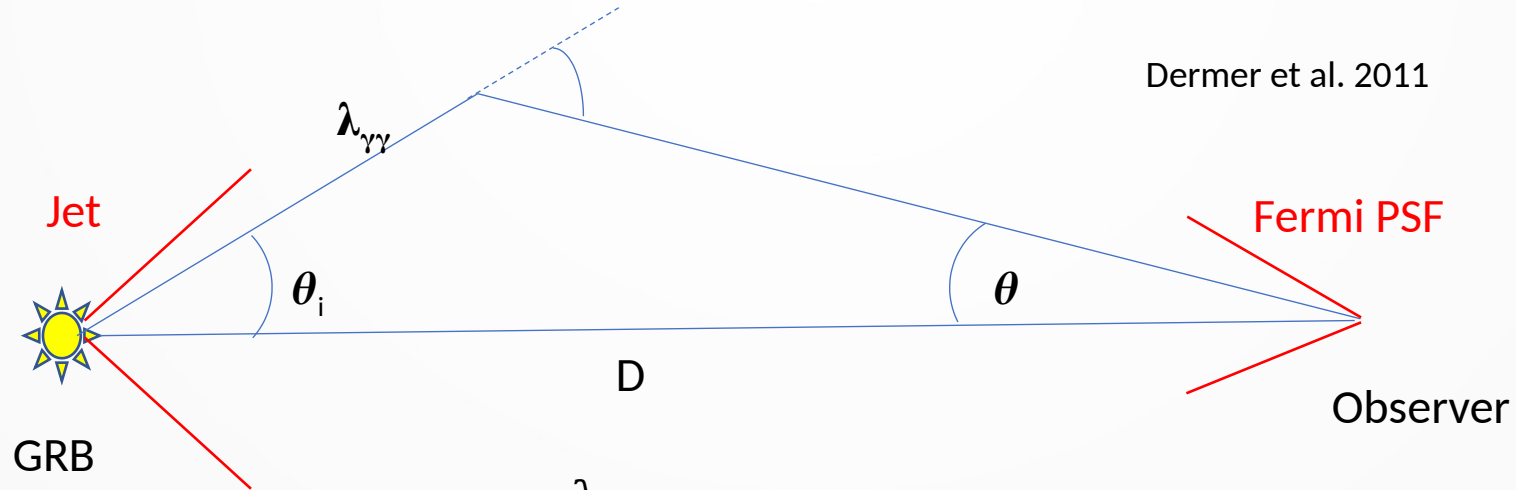Scaled GRB 190114C, T_{obs} = 9h, z=0.2

z=1

The distance is more important than the cascade power

- So far the cascade emission has always been studied in the GeV domain
- Extending the observation of GRBs in the VHE (e.g. CTA North) band for at least 3 hours could lead to the detection of the pair echo or to exclude some IGMF configurations
- Assuming the same intrinsic properties of GRB 190114C and considering different distances we proved that the distance plays a more crucial role than the cascade power
- Next steps:
  - role of other parameters
  - Pair echo emission from a suitable GRB sample for CTA
  - Accurate predictions for CTA

Dermer et al. 2011

Jet

$\boldsymbol{\lambda}_{\gamma\gamma}$

$\boldsymbol{\theta}_i$

D

Fermi PSF

$\boldsymbol{\theta}$

Observer

GRB

$$\sin\theta = \frac{\lambda_{\gamma\gamma}}{D}\sin\delta$$

$$\frac{dN}{dSdtdE} = \frac{F^{MAGIC}_{meas}}{F_{sim}}\frac{\Delta N_{cascade}\left(\theta < PSF_{Fermi}\right)}{\Delta A\,\Delta T_{obs}\,\Delta E}$$
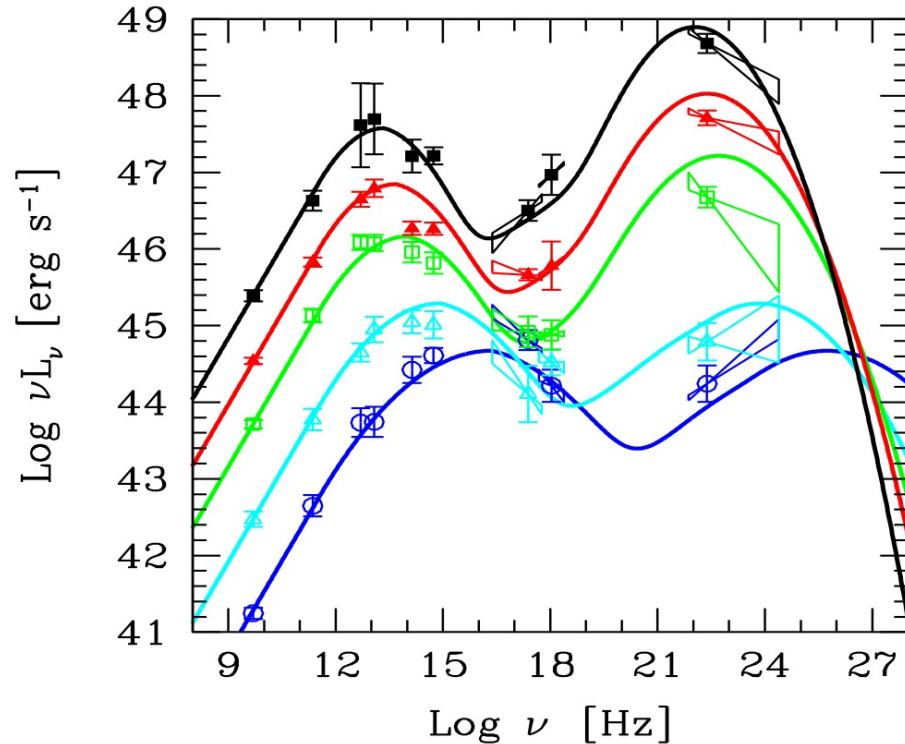
Cascade spectrum

What are the most promising sources?

- We need hard VHE (E>50 GeV) spectra

- Spectra that reach the highest energies

- "Proper" redshift (z > 0.1)

Among the different classes of blazars the most promising sources are the Extreme High frequency BL Lac Objects (EHBL)

Blazar sequence and EHBL

Fossati et al. 1998

- EHBL populate the low luminosity branch of the blazar sequence

- Observationally they are characterized by a high X-ray to radio flux ratio

- They come in two different flavors: *extreme-synchrotron* and *extreme-TeV* sources

34

Blazar sequence and EHBL

Fossati et al. 1998

- EHBL populate the low luminosity branch of the blazar sequence

- Observationally they are characterized by a high X-ray to radio flux ratio

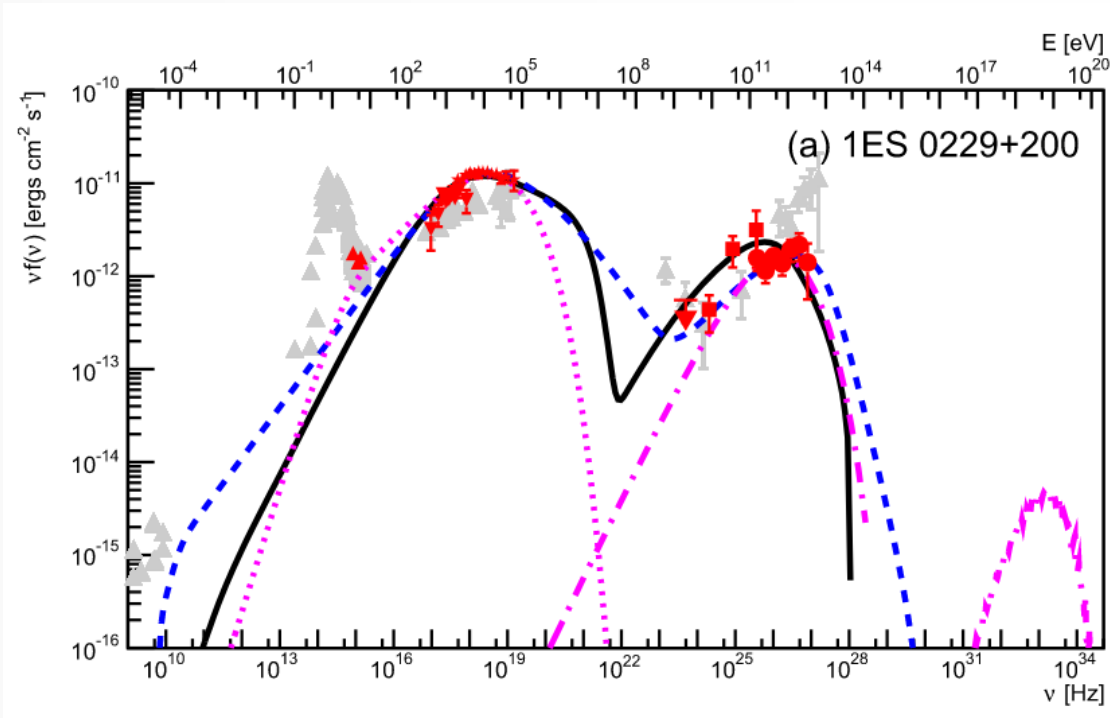- They come in two different flavors: *extreme-synchrotron* and *extreme-TeV* sources

35
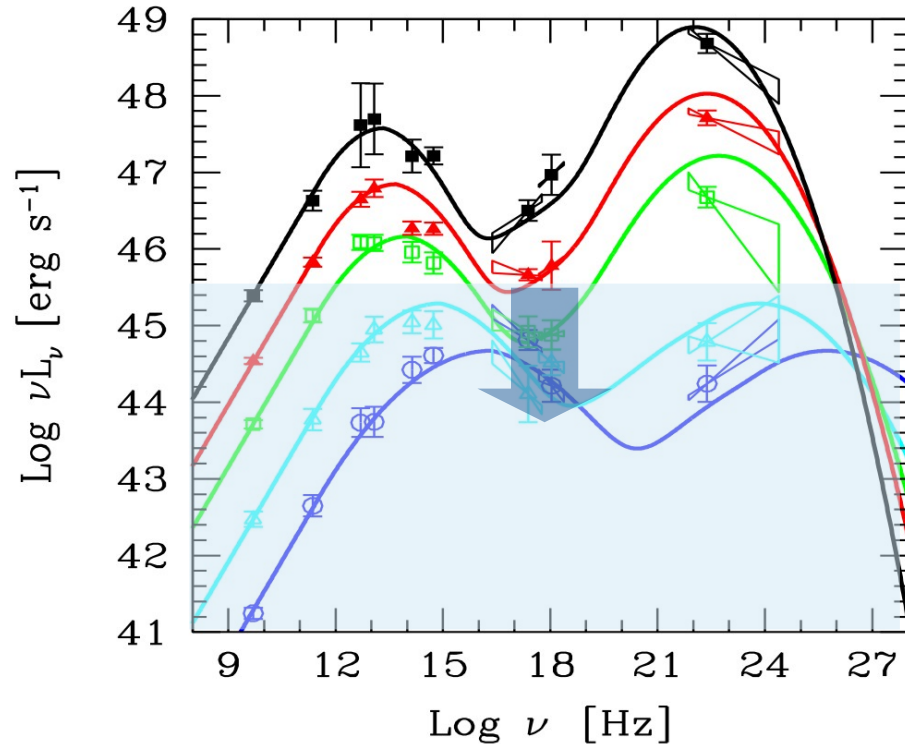
The case of 1ES 0229+200

(a) 1ES 0229+200

- VHE instrinsic spectrum with index ⌣ 1.8 that extends above 1 TeV

- Redshift: z=0.14

- No evidence of cutoff in the VHE spectrum

MAGIC coll. 2020

Spectral features

- First attempt performed by Neronov and Vovk 2010:

  - 4 blazars selected from the first year of Fermi/LAT operation

  - Redshift: z > 0.1

  - Hard TeV spectra

$$B \geq B_{PSF} \simeq 3 \times 10^{-16} G, \quad \lambda_B \gg D_e$$
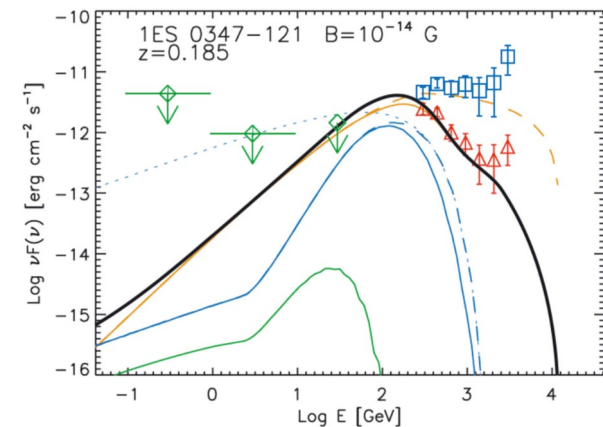
Neronov and Vovk 2010
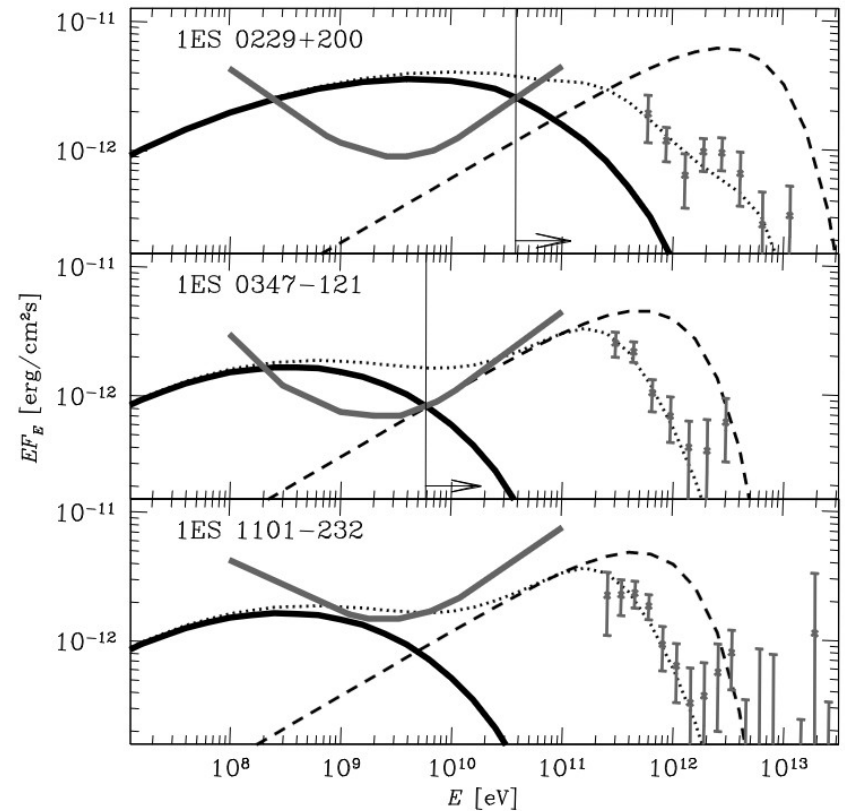
The intrinsic VHE spectrum

- In order to predict the cascade spectrum the choice of the intrinsic VHE spectrum is crucial
  - Minimal expected cascade estimate
  - SED modeling
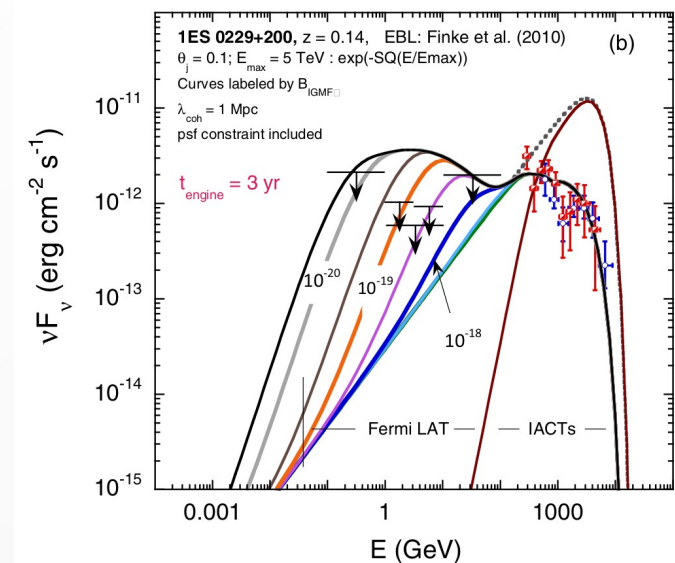 - Marginalization over all possible VHE spectra
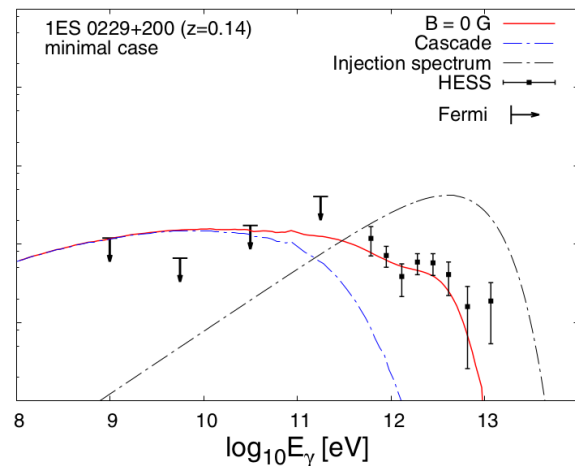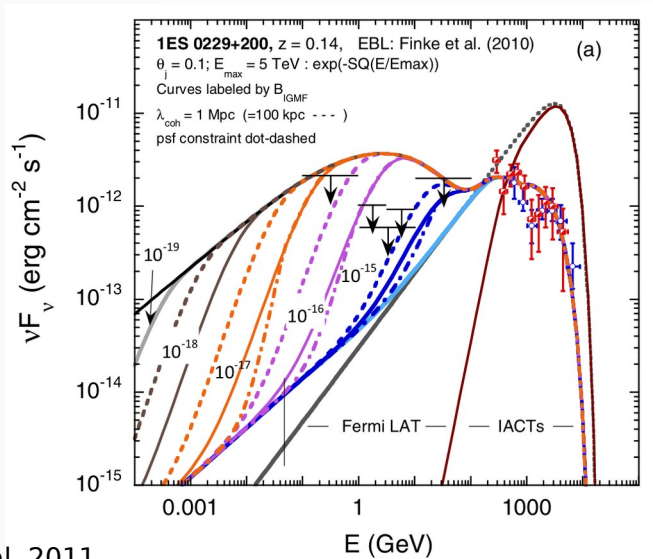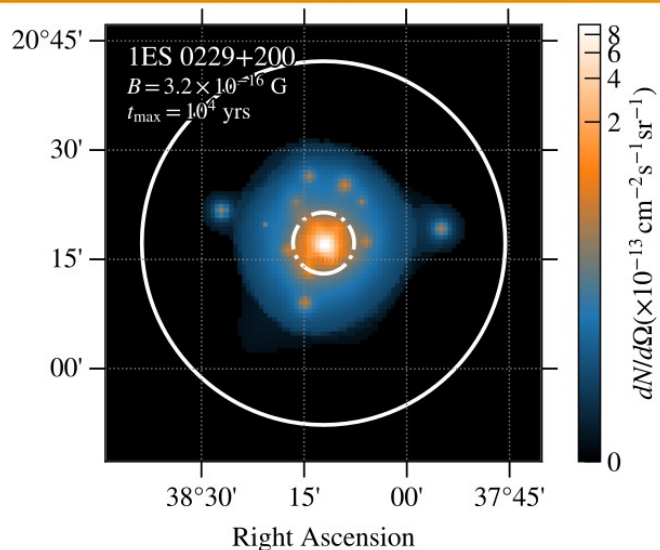

Taylor et al. 2011

Tavecchio et al. 2011

The duty cycle of the source

- The limits on IGMF depend on the assumption about the timesscale of the VHE lifecycle of the source (and on its flux level…)

  → Several studies suggest $t_{cycle}=10^6-10^9$
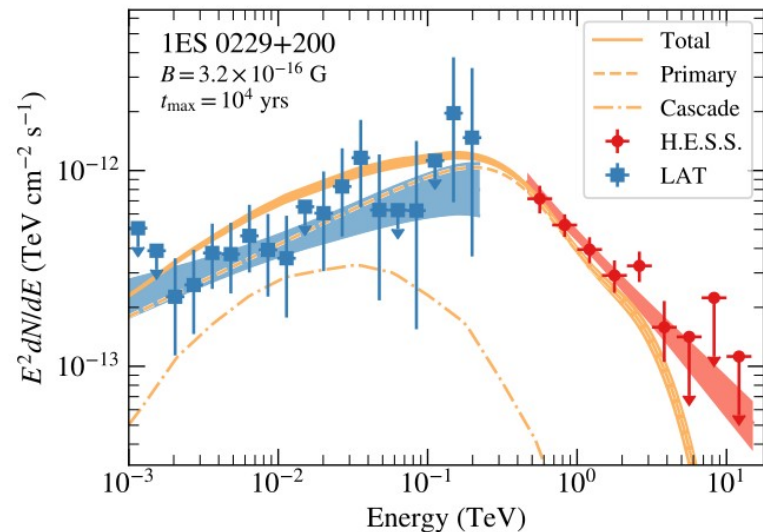
  → Safest approach: VHE time span

Dermer et al. 2011

IGMF constraints from Fermi/LAT and HESS observations

CRPropa simulations:

- Powerlaw with an exponential cutoff
- $\Theta_{los}=0°$
- $\lambda_B=1$ Mpc
- $T_{cycle}=10$, 10^4 and 10^7 yr
- $B=10^{-16}$, $10^{-15.5}$...10^{-13} G

H.E.S.S. and Fermi-LAT coll. 2023

- **Total likelihood:**

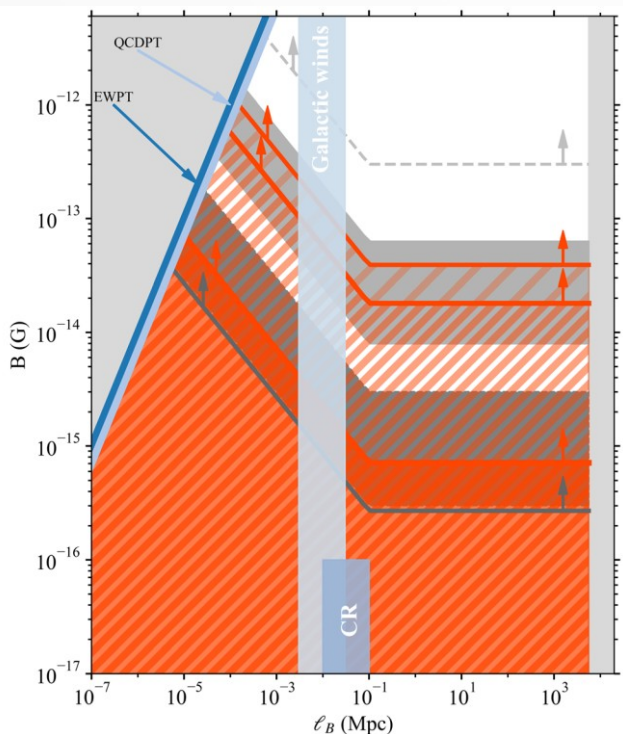$$\mathscr{L}(B,\theta_i|\mathcal{D}_i) = \mathscr{L}(B,\theta_i|\mathcal{D}_{i,LAT}) * \mathscr{L}(B,\theta_i|\mathcal{D}_{i,HESS})$$

Scanning all the parameter the best fit is evaluated → the presence of cascade is not preferred with respect to the case of "no cascade"
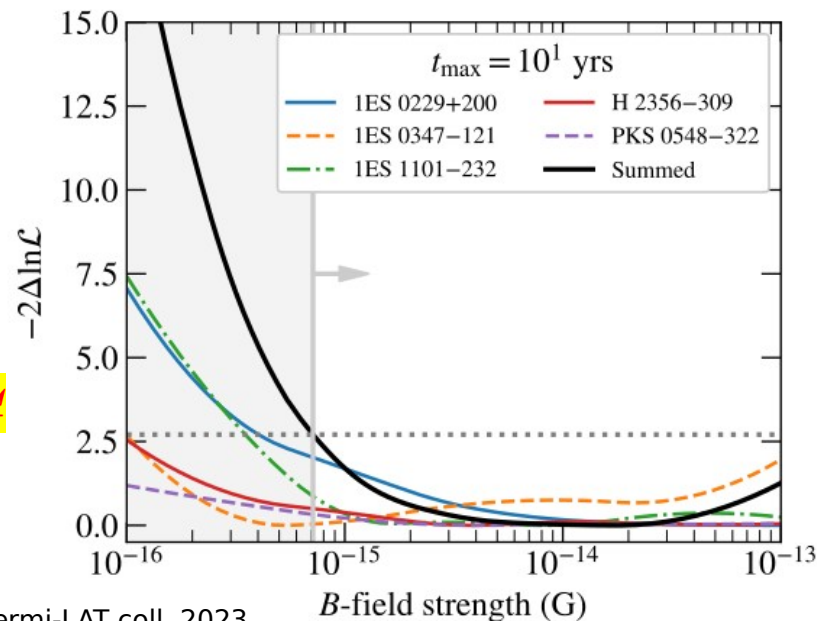
- **Loglikelihood ratio test:**

$$\lambda(B) = -2 \sum_i \ln\left(\frac{\mathscr{L}(B, \hat{\theta}_i | \mathcal{D}_i)}{\mathscr{L}(\hat{B}, \hat{\theta}_i | \mathcal{D}_i)}\right)$$

Most safest scenario
(T_{cycle}=10 yr):

$B > 7.1 \times 10^{-16} \ G$

H.E.S.S. and Fermi-LAT coll. 2023

41

What about the variability of the source?

- The lower bound derived by Fermi coll. relies on an (unverified) assumption of stability of the TeV band flux on decade time span

- Blazars are variable sources
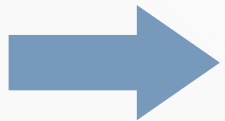
A more reliable lower bound can be obtained taking into account the variability pattern of the source in the VHE band that can be inferred from the observations

MAGIC coll. 2023

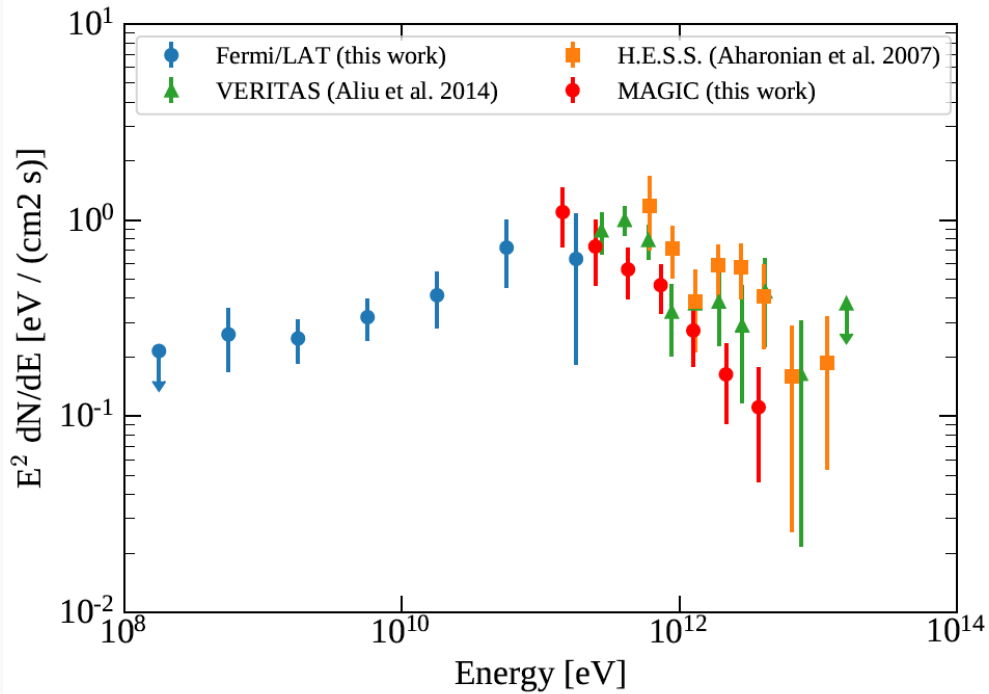- MAGIC data sample: September 2013 – December 2017. Totally we collected about 140 hours of data

- The joint spectrum is described by a simple EBL absorbed power with $\Gamma=1.74\pm0.05$ and $E_{cut} > 10$ TeV

- No variability found below 100 GeV using 12 years of data (Fermi/LAT)

- Joint VHE lightcurve: the constant flux fit is discarded at 4.8 σ level

- Variability time scale of 500 days

- Following the approach of Neronov et al. 2010 we looked for the softest spectrum and with the lowest E_{cut}

$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{cut}}\right)$$

- We took the values of E_{cut} and Γ that lie in the 90% of confidence contour and that give the minimum cascade power: Γ1.72, E_{cut}6.9 TeV
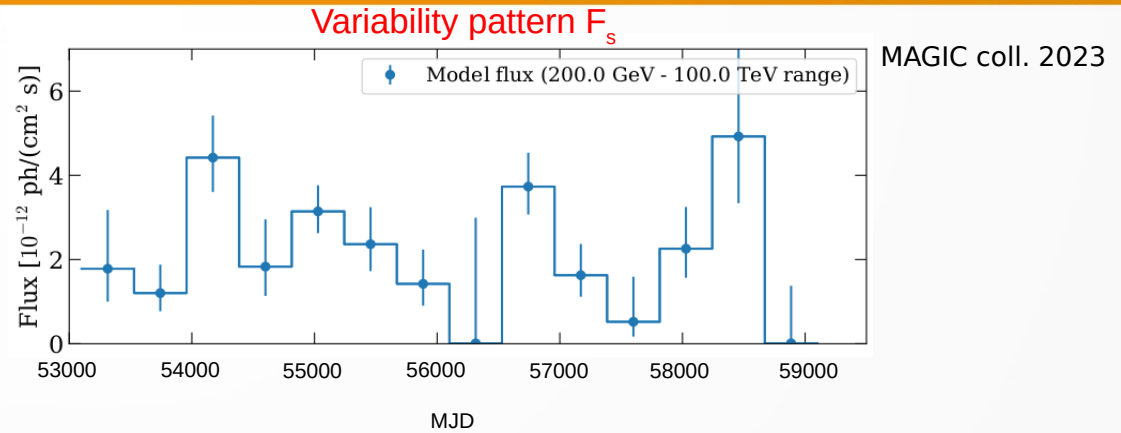
MAGIC coll. 2023

Numerical modeling of cascade emission

- We used CRPropa to trace the development of the cascade in the intergalactic medium.

- Source model: Powerlaw with exponential cutoff, jet emission within a cone of 10 deg

- $G(E_0,E,t,B,\lambda)$ Green function, $F_s(E_0,t)$ variability pattern of the source in the VHE band. The cascade signal $F_c(E,t)$ above a certain energy E is given by:

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

Lightcurves: fit results

H.E.S.S. (>580 GeV, Cologna et al. 2015)

CRPropa
CRbeam

VERITAS (>300 GeV, Aliu et al. 2014)

MAGIC (>200 GeV, this work)

Cascade B=10^{-16} G λ=1 Mpc
Source
Cascade + Source

Fermi/LAT (10-30 GeV, this work)

Fermi/LAT (1-10 GeV, this work)

Variability pattern F_s

MAGIC coll. 2023

Model flux (200.0 GeV - 100.0 TeV range)
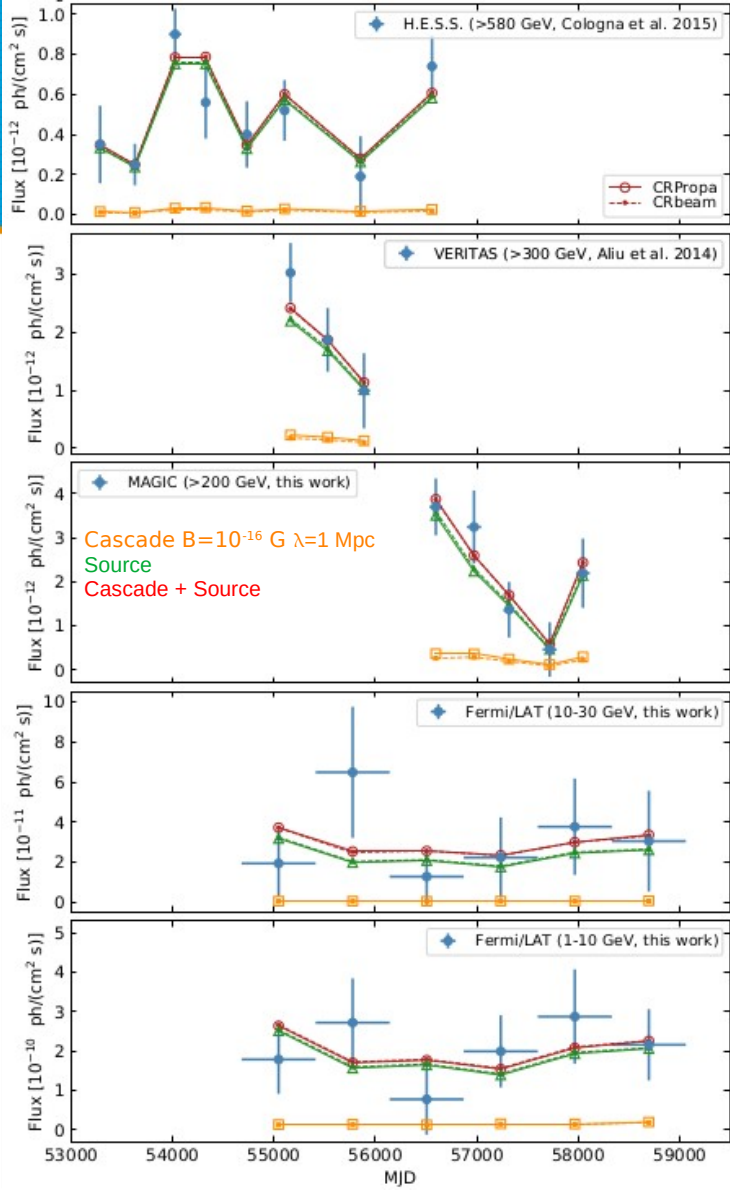
- The variability pattern F_s is inferred from the VHE lightcurves

- The suppression of the signal is entirely due to the diluition in time (the signal is well within the PSF)

- For B=10^{-16} G and λ=1 Mpc the cascade is almost suppressed in all energy bands so that we cannot exclude this particular IGMF configuration
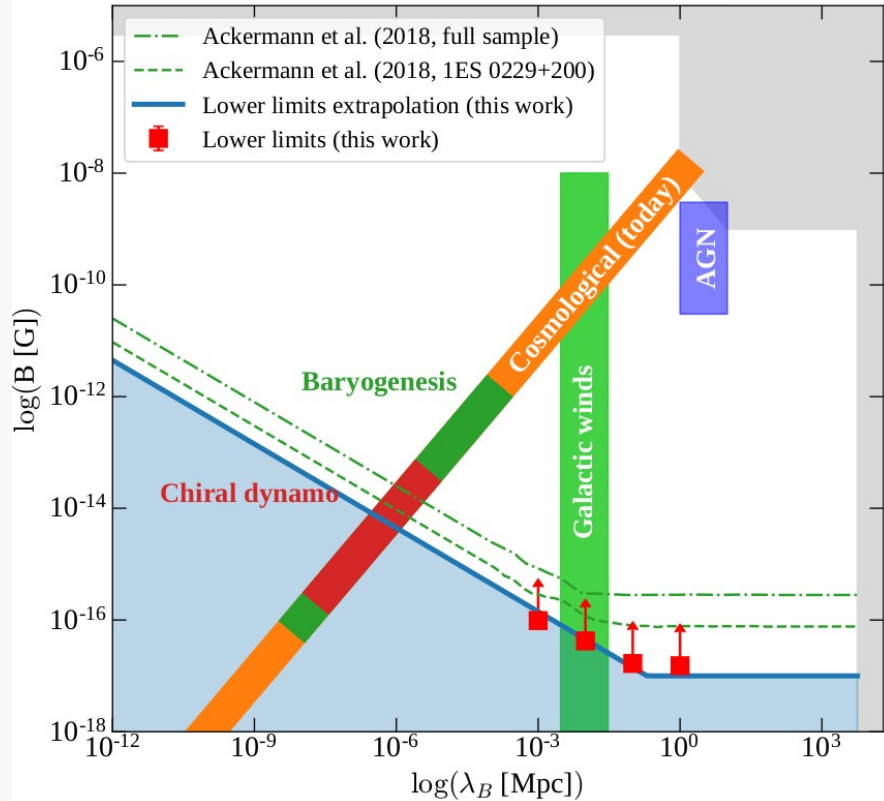
46

Lightcuves: fit results

MAGIC coll. 2023
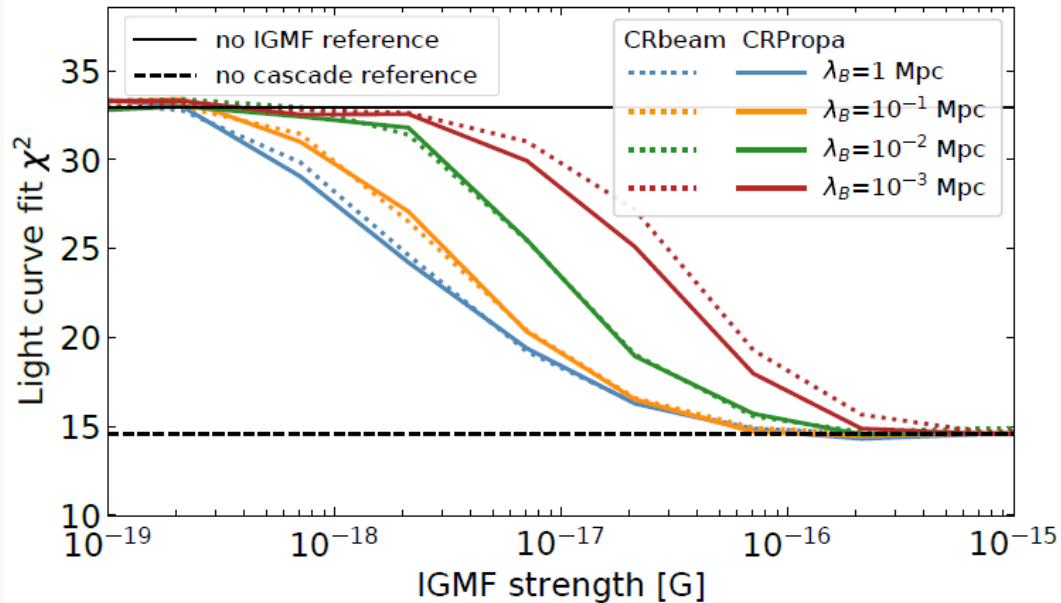
- We performed a scan in the (B, λ_B) space in order to look for the IGMF configurations rejected by the data.

- The energy band in which we are most sensitive to the delayed emission is 1-10 GeV
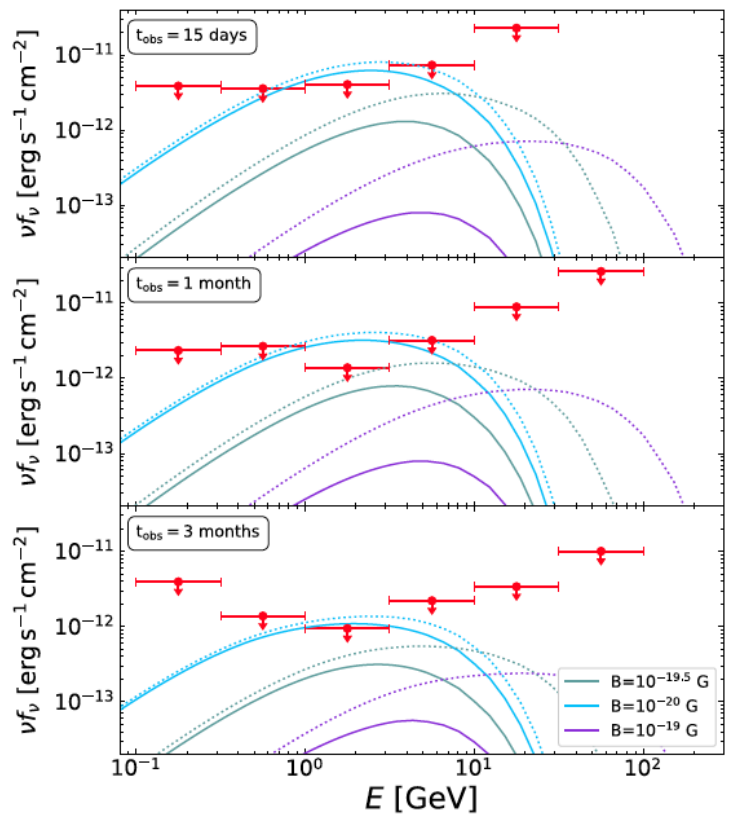
$$B > 1.8 \times 10^{-17} \, G$$

95 % confidence level

Results

- The derived lower bound is weaker than the one reported by H.E.S.S. and Fermi LAT coll.

- **VHE variability of the source is taken into account**

- The detection of 10 yr delayed signal for z~0.1 requires systematic monitoring in both TeV and 1-100 GeV bands

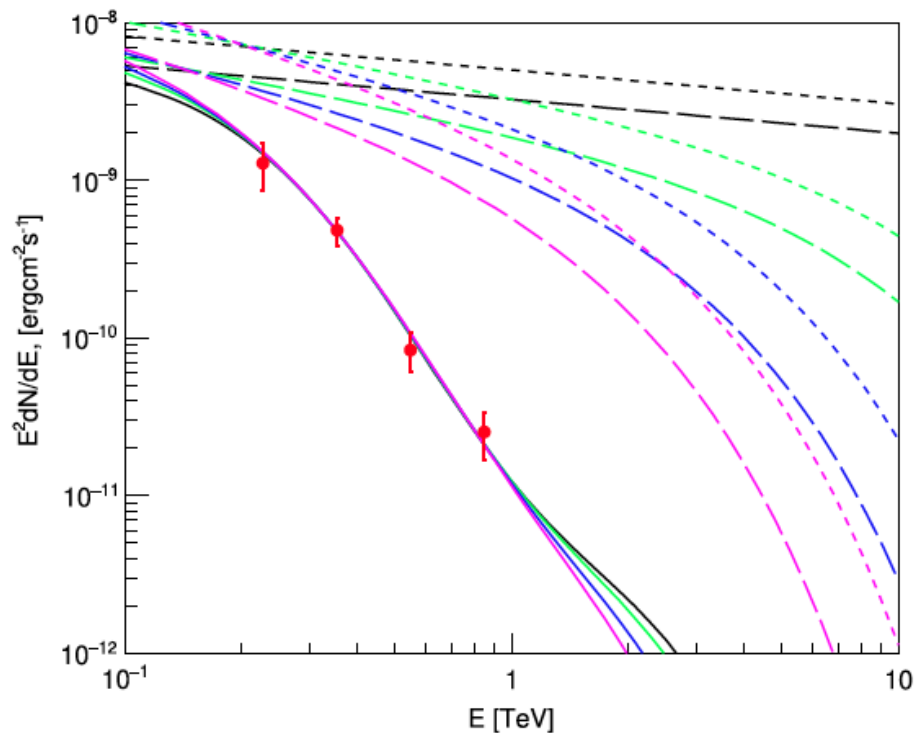MAGIC coll. 2023

IGMF lower bounds from GRB 190114C

Wang et al. 2020

- Analytic approach

- EBL models tested: Finke et al. 2010, Dominguez et al. 2011, Gilmore et al. 2012 → results do not change much

- Intrinsic spectral shape in the VHE band: power law index 2 up to 1 TeV and 15 TeV

- Flux above 200 GeV extrapolated up to T_0=6s (about factor of 5 the flux measured by MAGIC from T_0=64 s)

- Result: **B ≳ 3×10⁻²⁰ G for λ_B ≲ 1 Mpc**
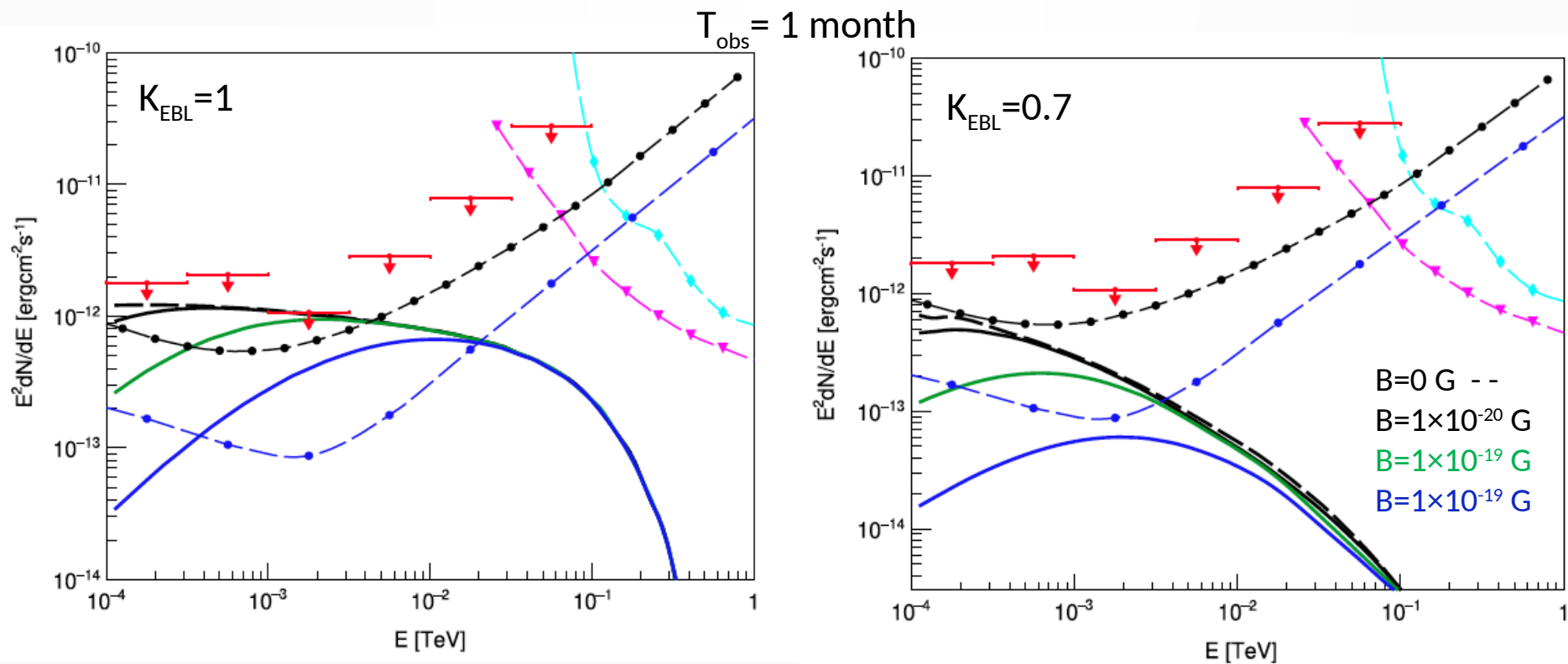
- Reconstruction of the VHE intrinsic spectrum fitting the data

- Assumed model: powerlaw with an exponential cutoff

- Different EBL normalization assumed: 70%, 80%, 90%

- EBL: Gilmore et al. 2012

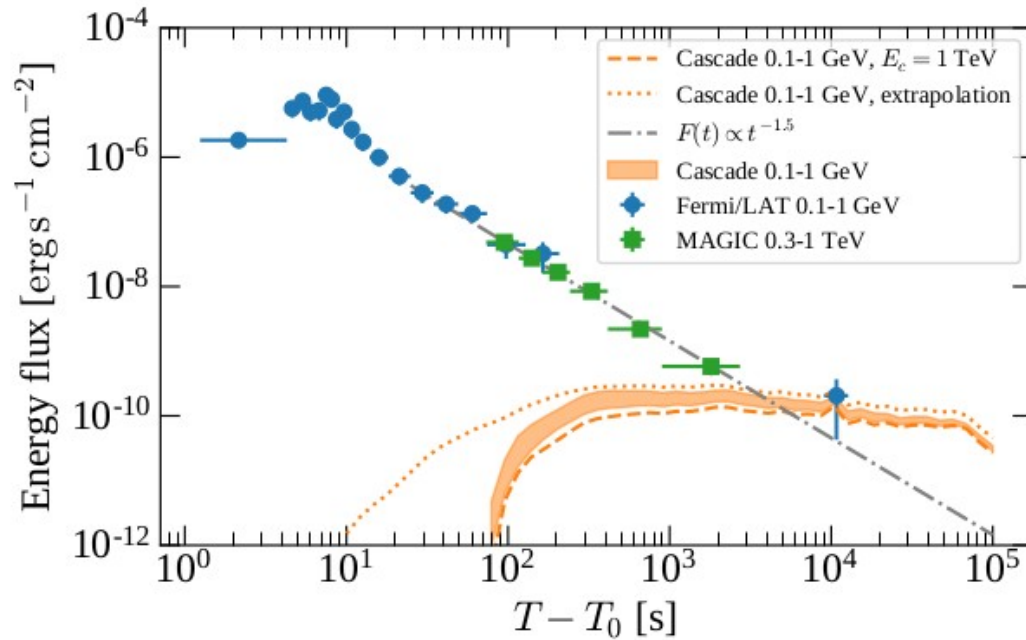- Elmag3 used to trace the development of the cascade emission

Dzhatdoev et al. 2020

T_{obs} = 1 month

K_{EBL}=1

K_{EBL}=0.7

B=0 G - -
B=1×10^{-20} G
B=1×10^{-19} G
B=1×10^{-19} G

Dzhatdoev et al. 2020

No constraints on IGMF can be derived

Can we study the lowest delays…?

Vovk 2023

- Vovk (2023) studied the evolution of the cascade

- The lowest magnetic field that can be tested is **the one which induces angular deflections on the pairs lower than their intrinsic aperture (B≃10^-21 G)**

- VHE spectrum: Powerlaw up to 10 TeV has been assumed

- The cascade lightcurve for B<10^-21 G is compatible with the data…

➢ This study would imply B<10^{-21} G

➢ This limit is contradiction with the limits derived with the blazars

➢ "(...) Such a detection would indicate a fast evolution of IGMF with redshift (...)"

→ This scenario can be easily crosschecked as soon as the time delays induced by the intrinsic aperture of the pairs is implemented in CRPropa ;-)
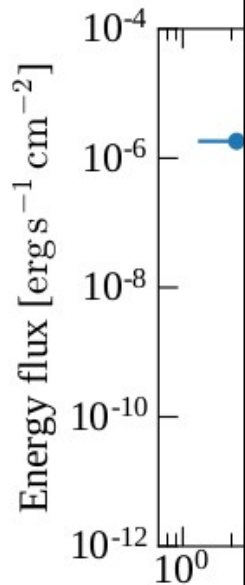
olution of the

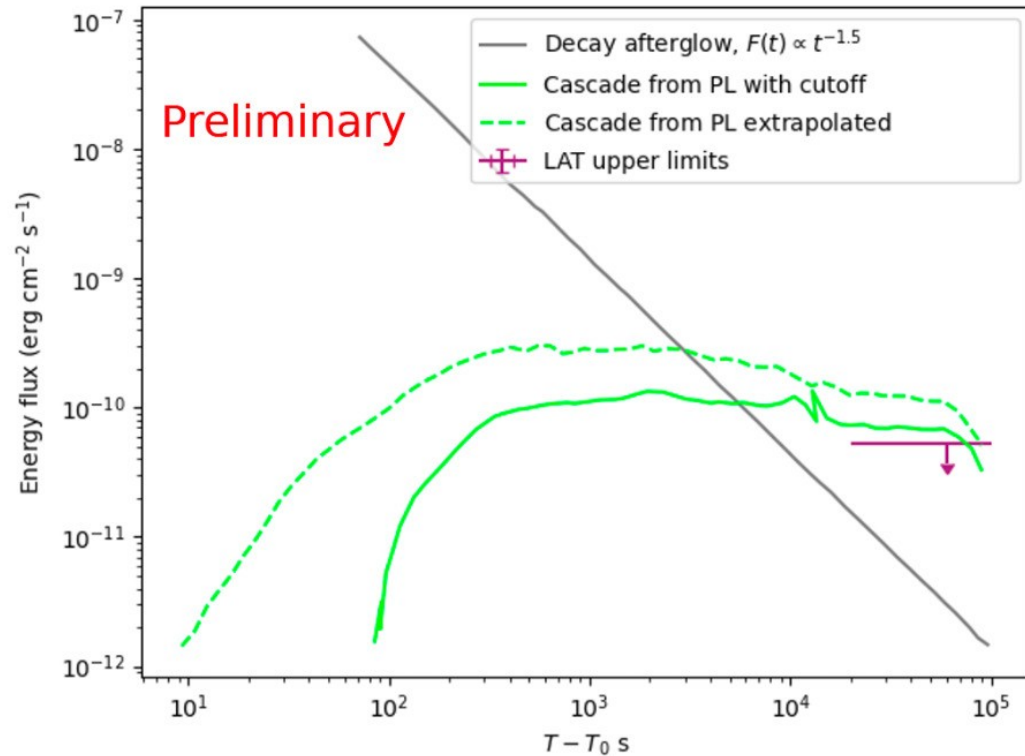that can be
uce angular
ver than their
G)

p to 10 TeV has

B<10^{-21} G is

Vovk 2023

However...

- What happens when $T-T_0 > 10^4$ s ?

Performing the Fermi LAT analysis after $T-T_0$ this prediction is not compatible with the upper limit → this extreme scenario seems to be disfavored