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Probing the intergalactic magnetic field through gamma-ray observations

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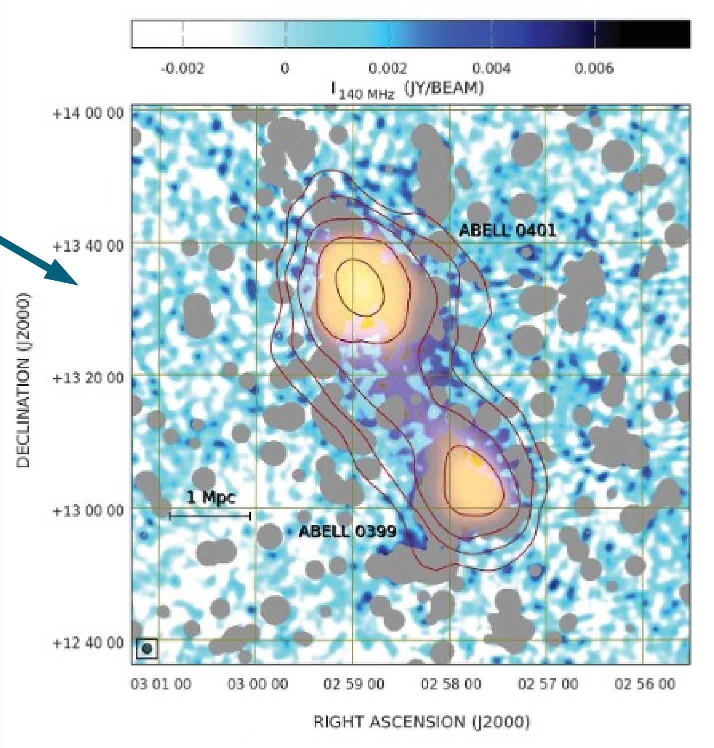
Magnetic Fields in galaxies

Borlaff et al. 2021

$B < 1\ \mu G$

$B \simeq 15\ \mu G$



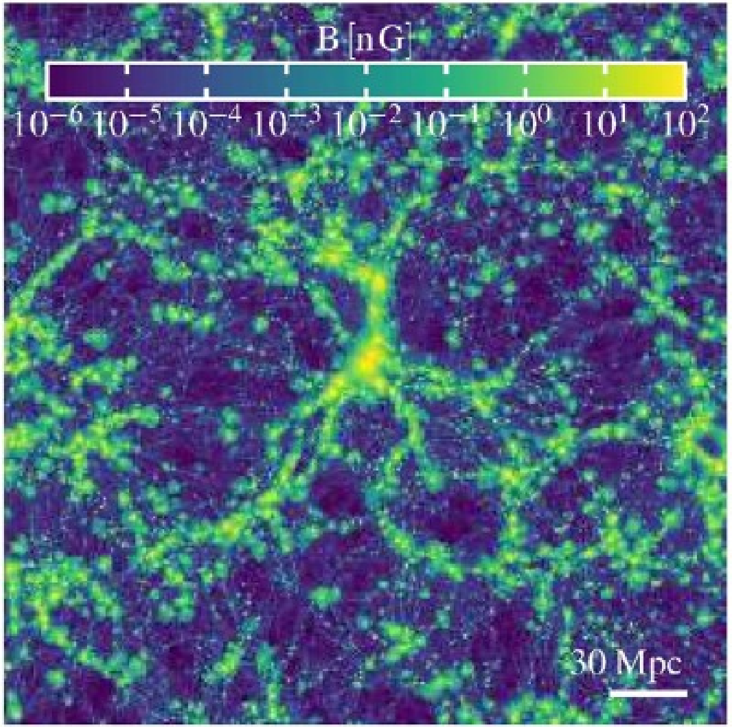
Govoni et al. 2019

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

On the nature of the seed fields

- The nature of the seed fields is largely unknown. Two main hypothesis on their origin:
  1. the astrophysical scenario
  2. The cosmological scenario

- Observationally we need measurements of magnetic fields in the intergalactic medium

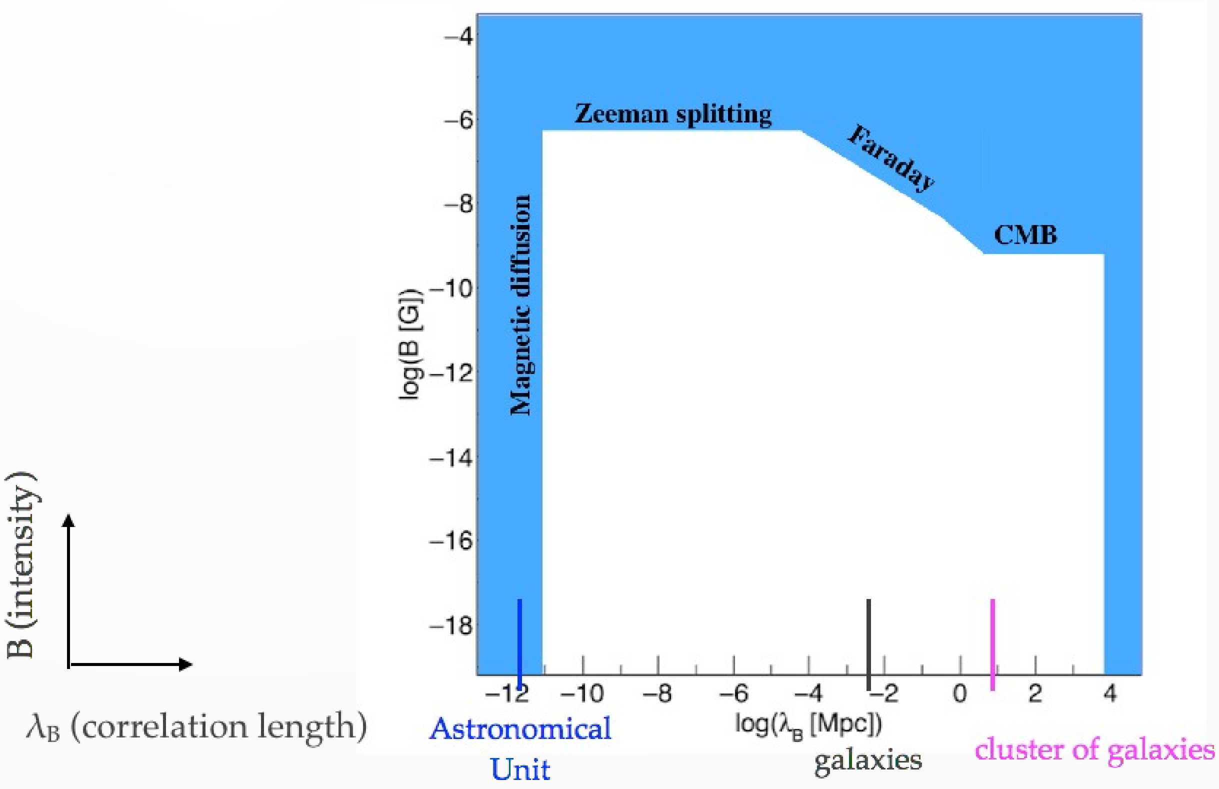


Marinacci et al. 2019

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

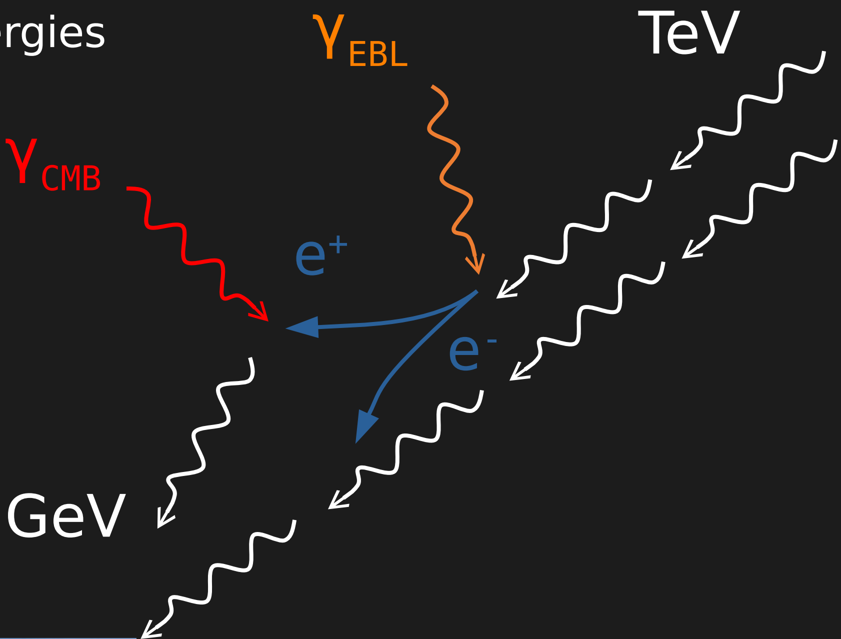
- We need a more sensitive technique

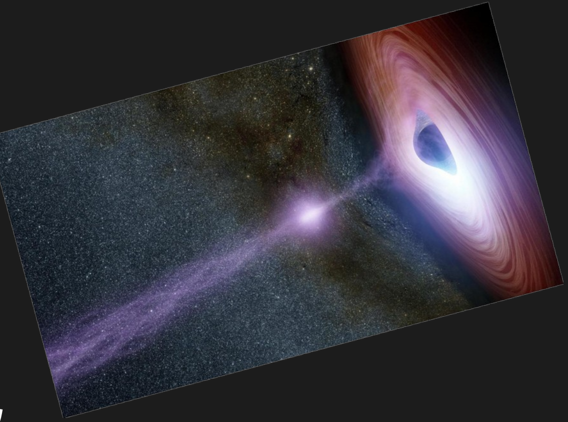


Physical process

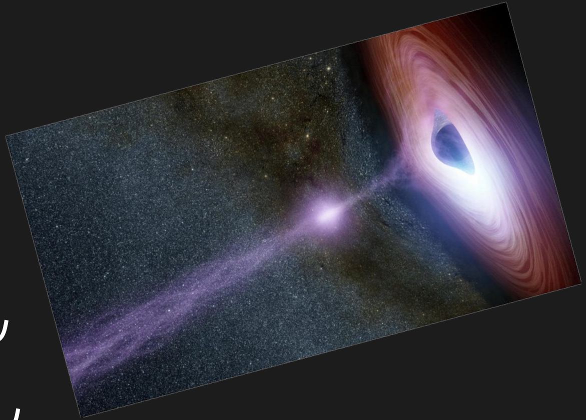
- Excess γ rays at lower energies

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





Physical process



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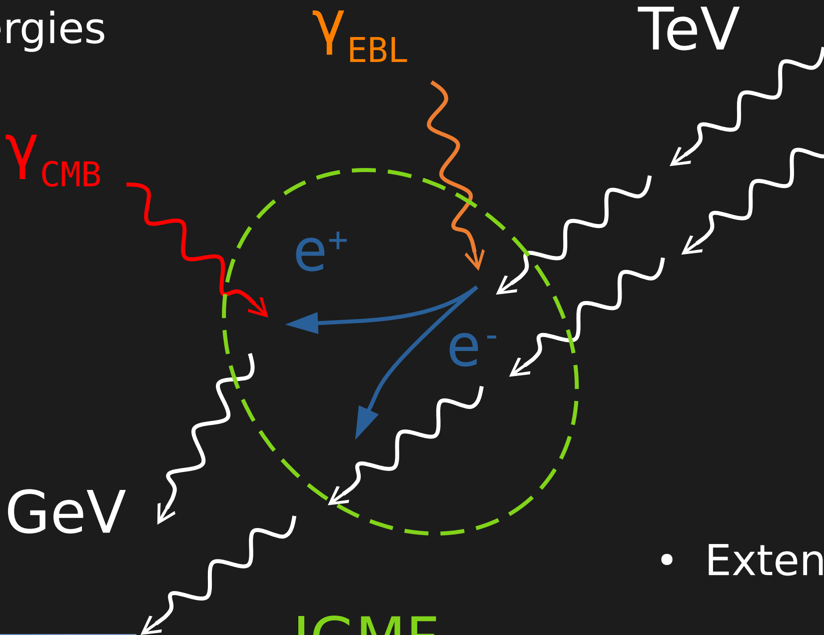
Indirect detection of the IGMF



γ_{EBL}

TeV

γ_{CMB}

e^+

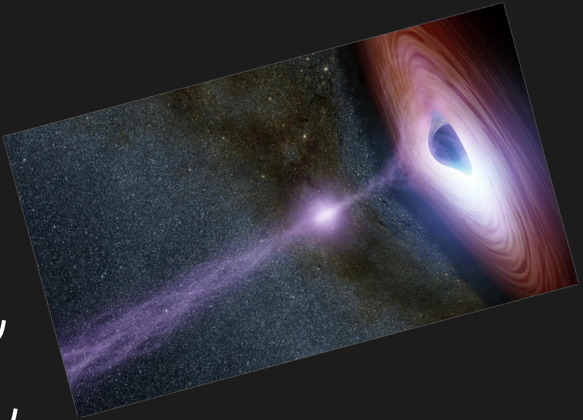
e^-

GeV

IGMF

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

Physical process



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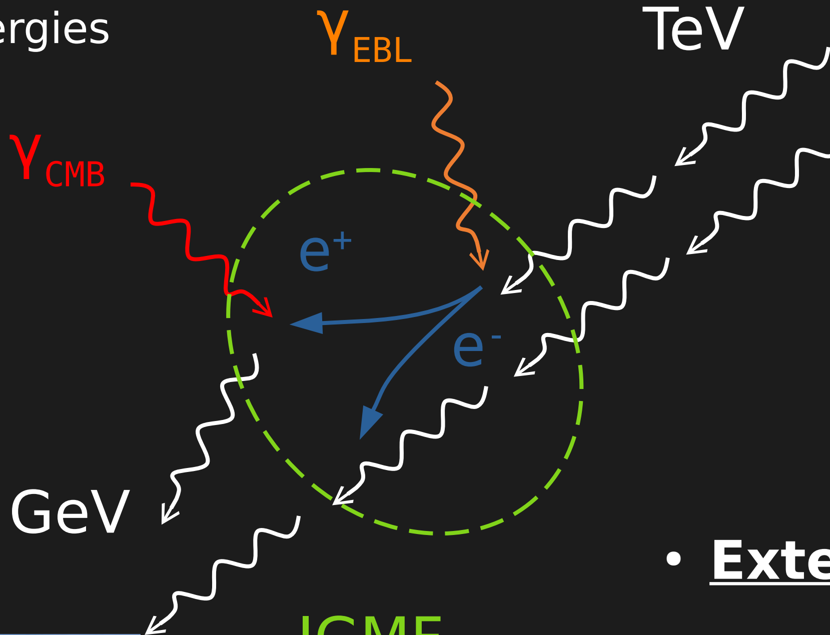
Indirect detection of the IGMF



γ_{EBL}

TeV

γ_{CMB}

e^+

e^-

GeV

IGMF

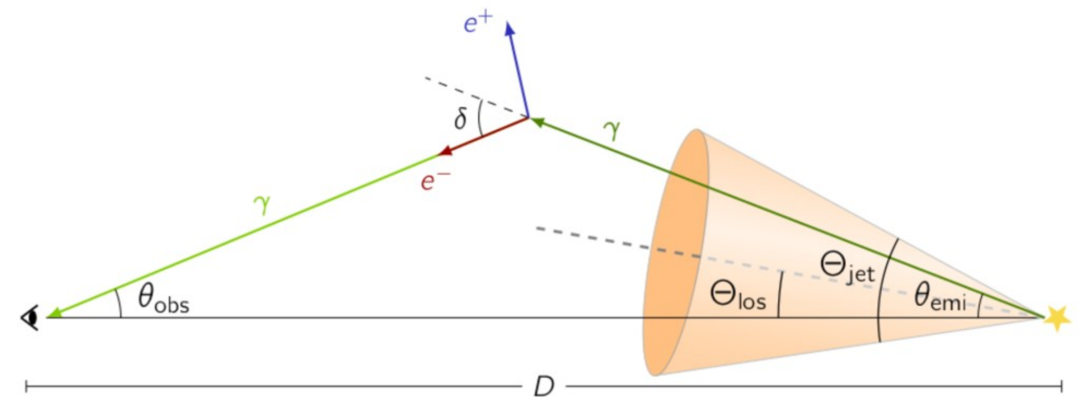
- **Extended γ rays halos**
- Spectral features
- Time delayed γ-ray emission

Extended emission

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

- Two regimes:

Alves Batista & Saveliev 2021



$\lambda_B \gg D_e$:

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

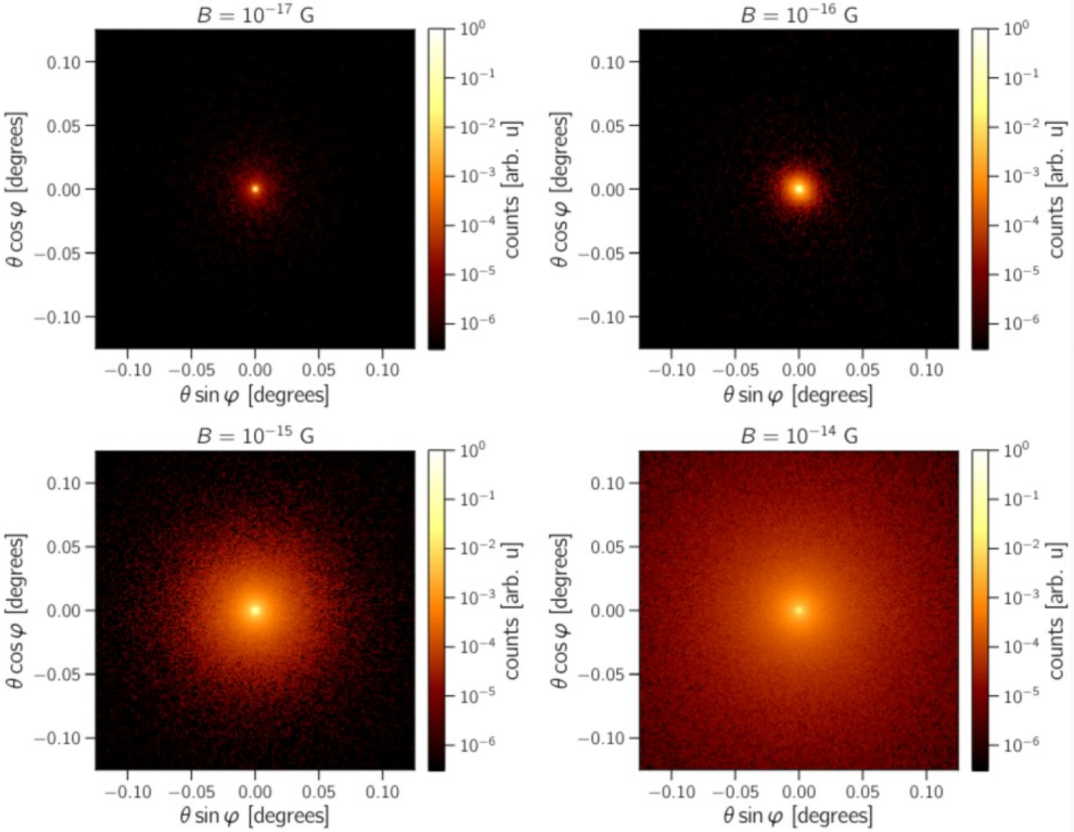
$\lambda_B \ll D_e$:

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

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

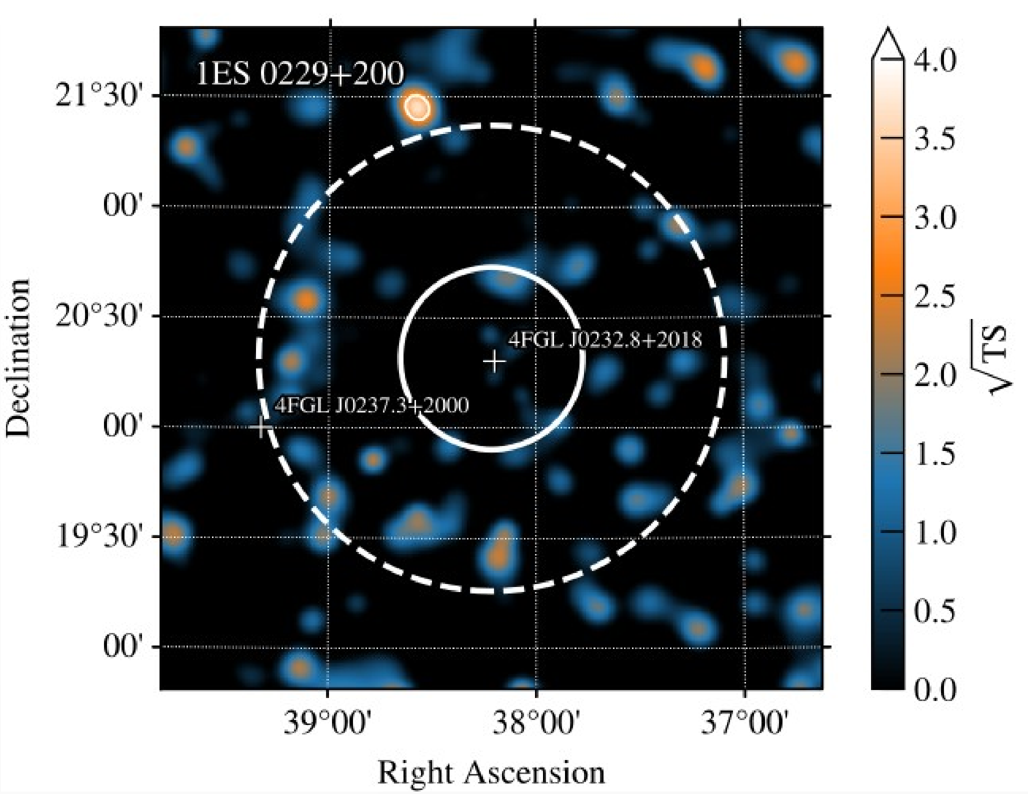


Alves Batista & Saveliev 2021

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

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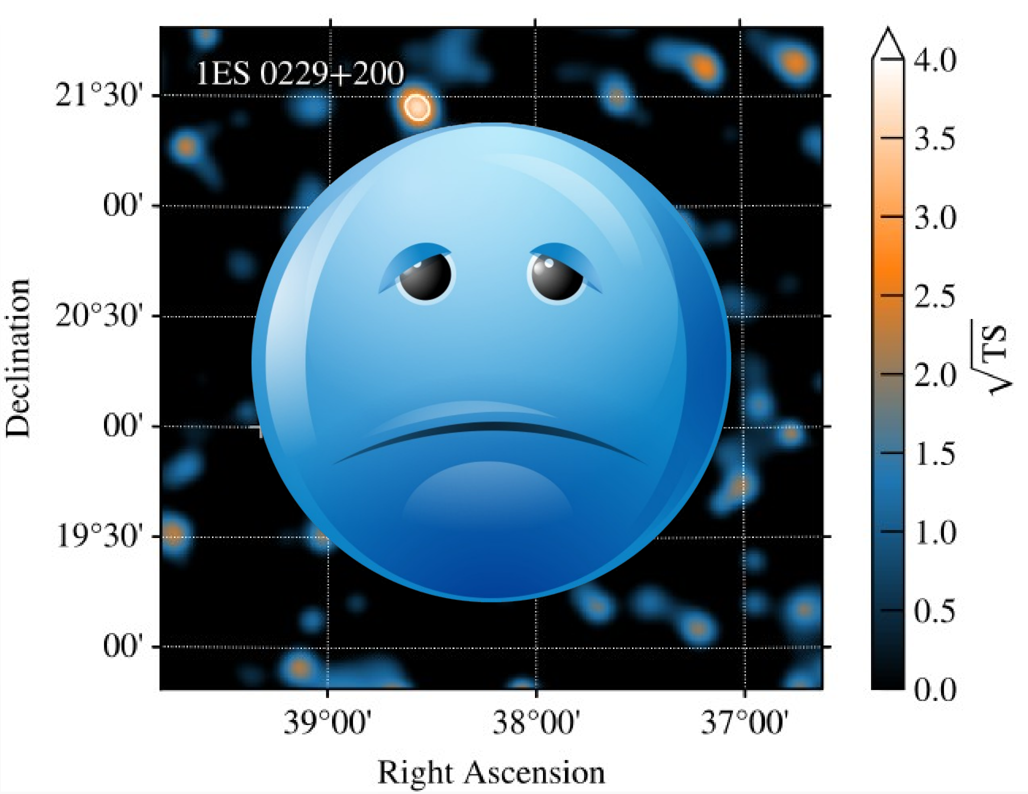
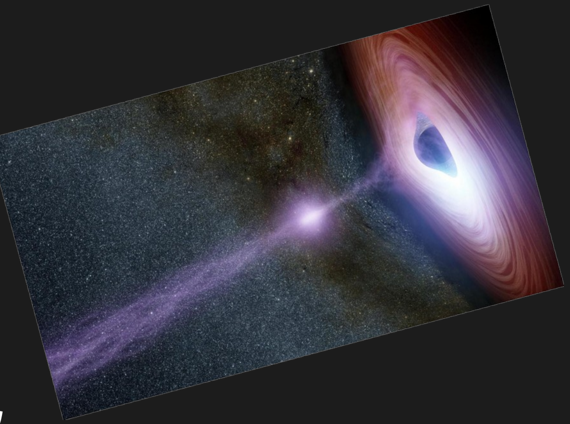


Aharonian et al. 2023

Physical process



- Excess γ rays at lower energies

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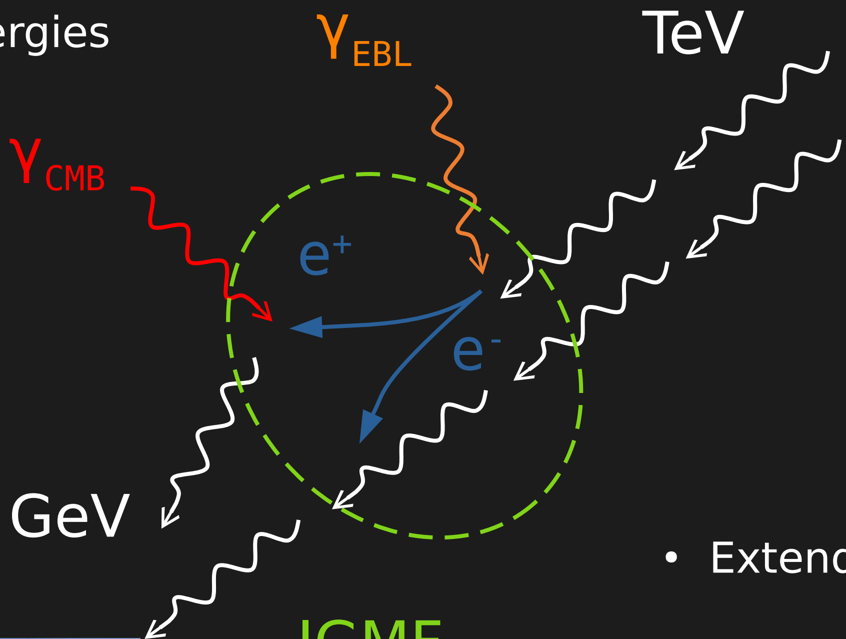
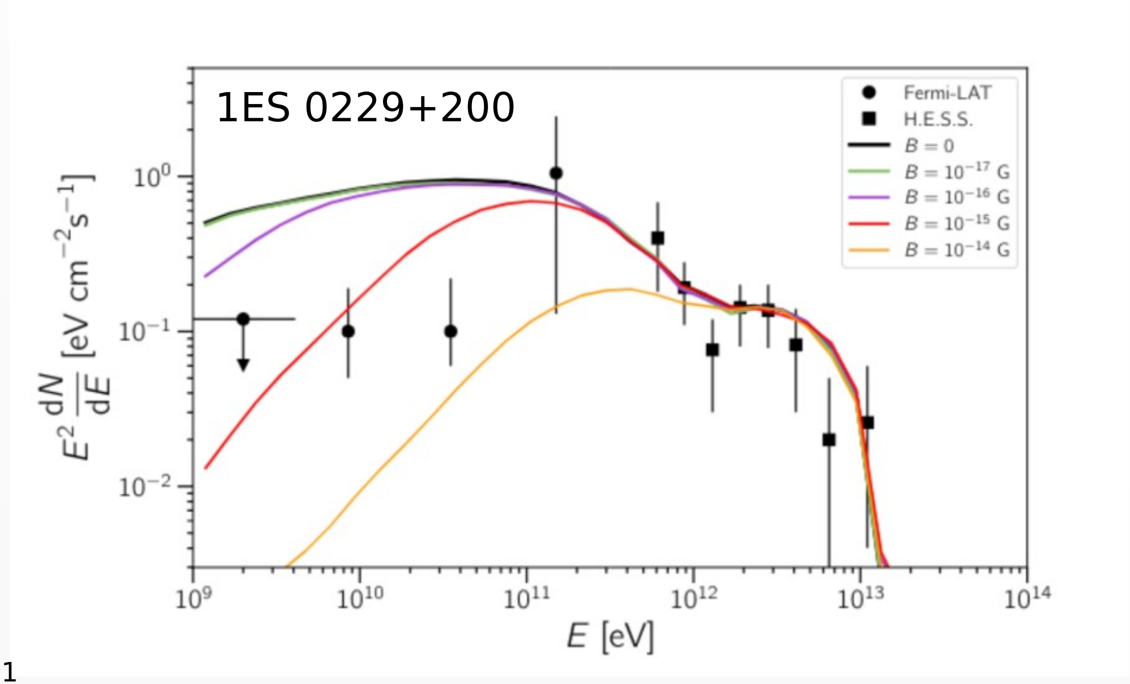
Indirect detection of the IGMF



- 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



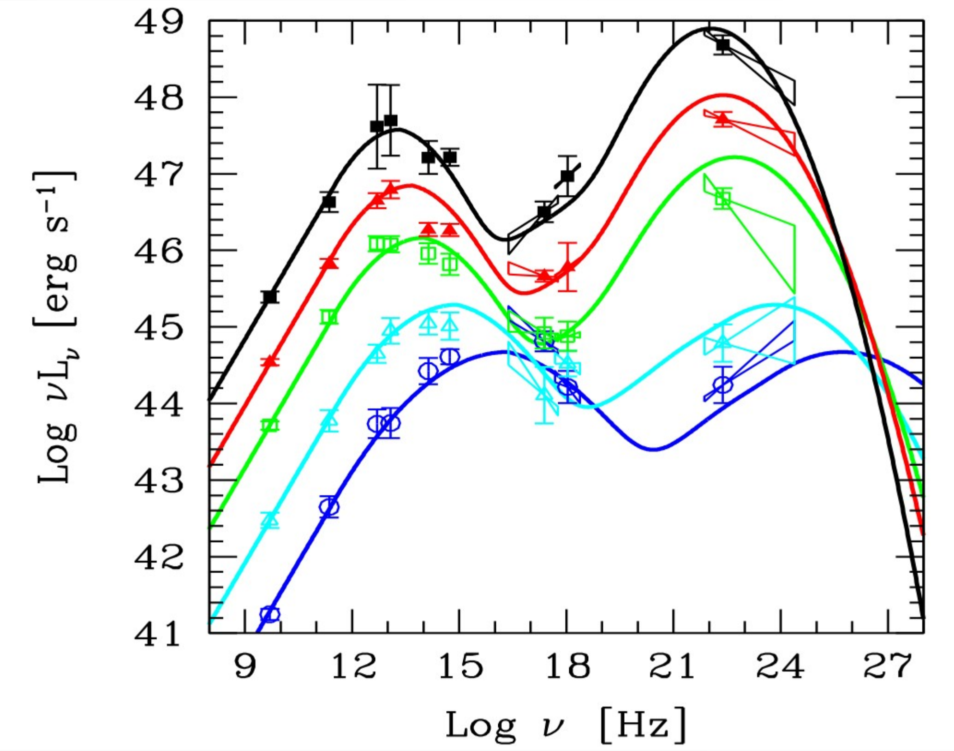
Alves Batista & Saveliev 2021

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)

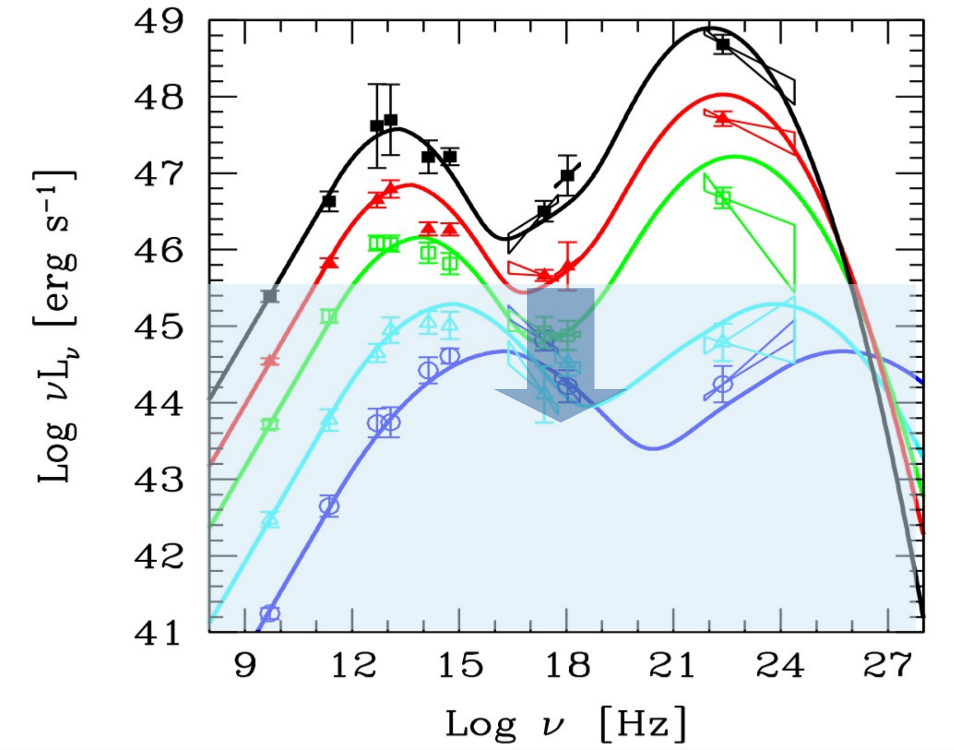
Blazar sequence and EHBL



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

Blazar sequence and EHBL



Fossati et al. 1998

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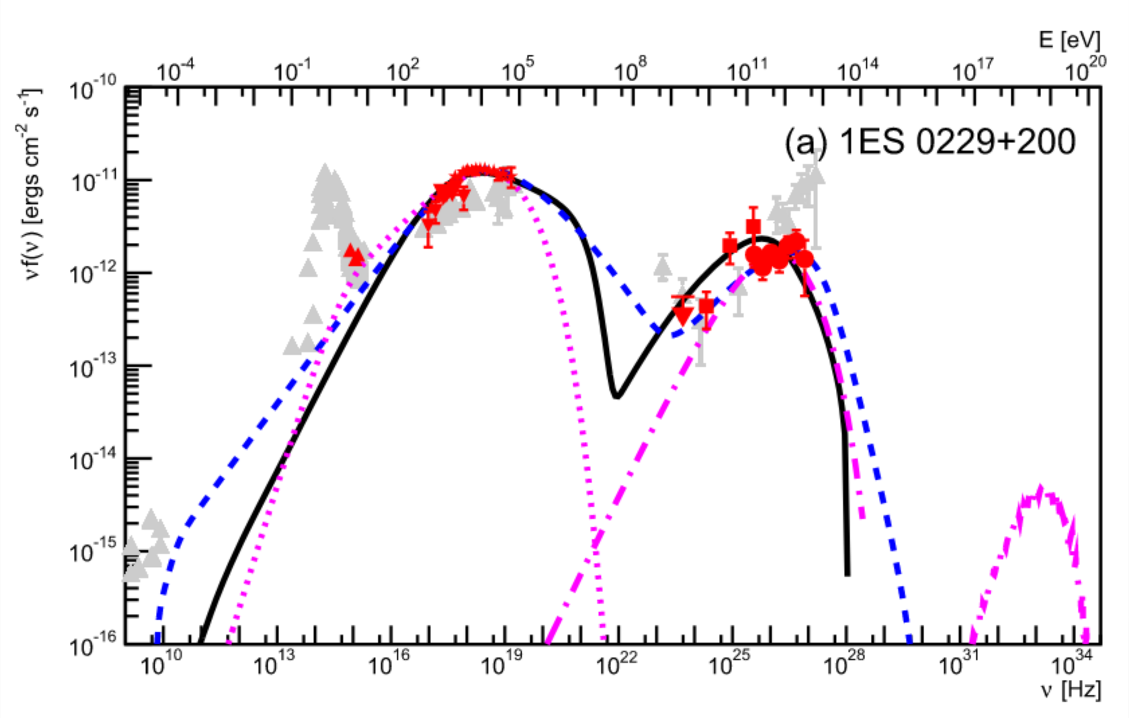
The case of 1ES 0229+200



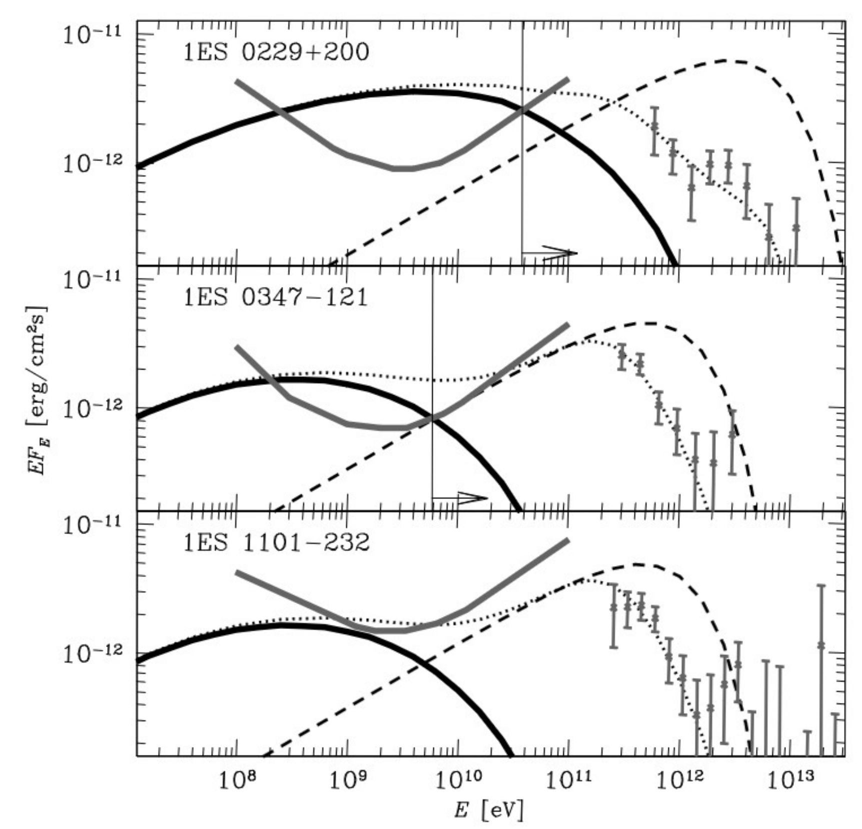
- VHE instrinsic spectrum with index ∽ 1.8 that extends above 1 TeV
- Redshift: z=0.14
- No evidence of cutoff in the VHE spectrum

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

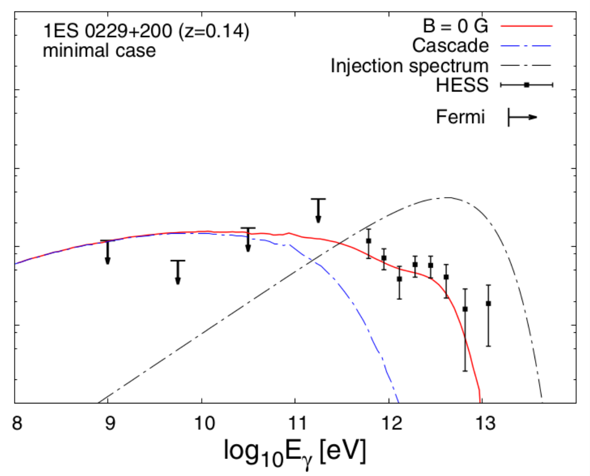
$$B \geq B_{PSF} \simeq 3 \times 10^{-16} G, \qquad \lambda_B \gg D_e$$

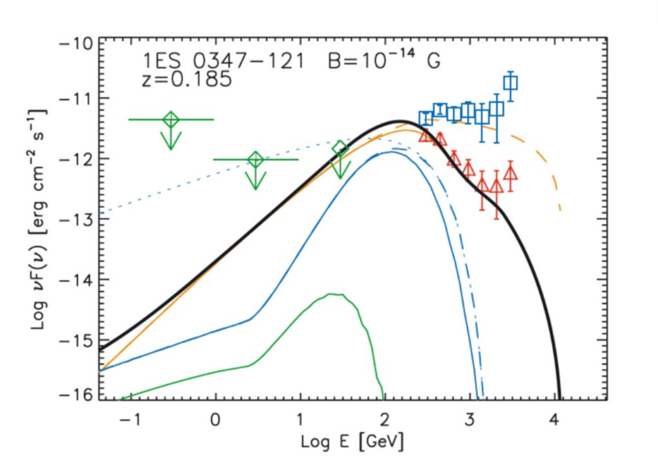


Neronov and Vovk 2010

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



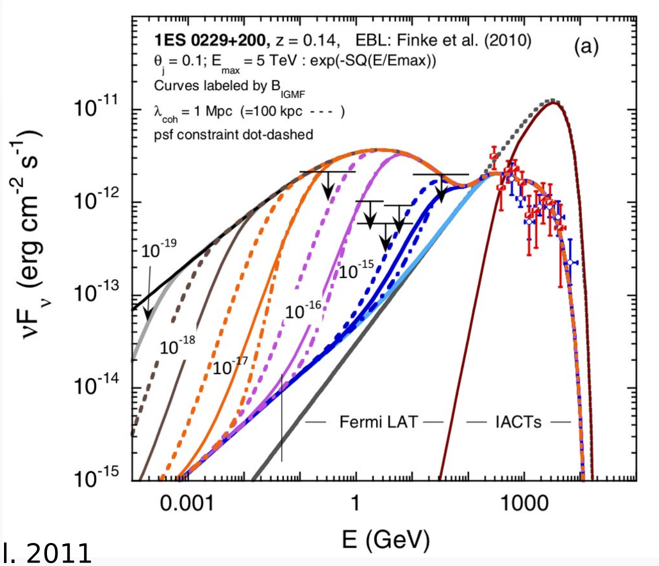


Taylor et al. 2011

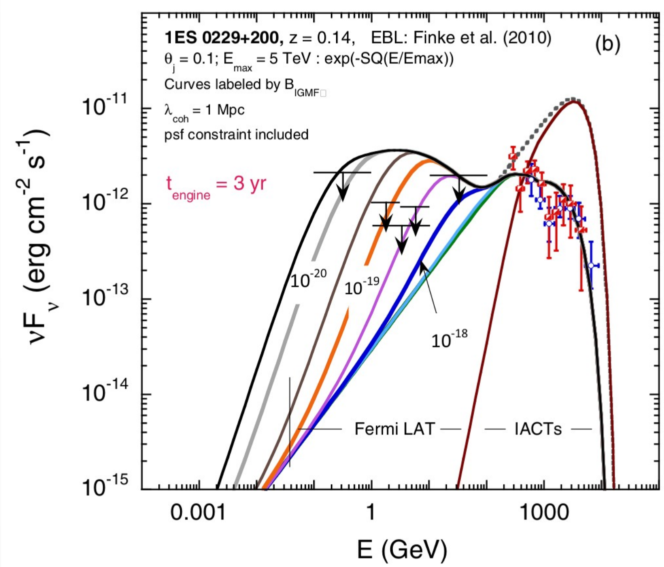
Tavecchio et al. 2011

The duty cycle of the source

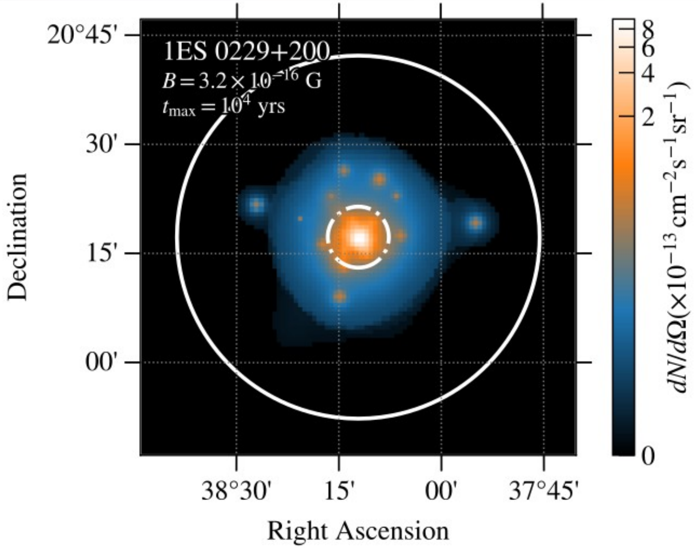
- The limits on IGMF depend on the assumption about the timesscale of the VHE lifecycle of the source (and on its flux level...)
  - ➔ Several studies suggest $t_{cycle}=10^6$-10^9
  - ➔ Safest approach: VHE time span



Dermer et al. 2011

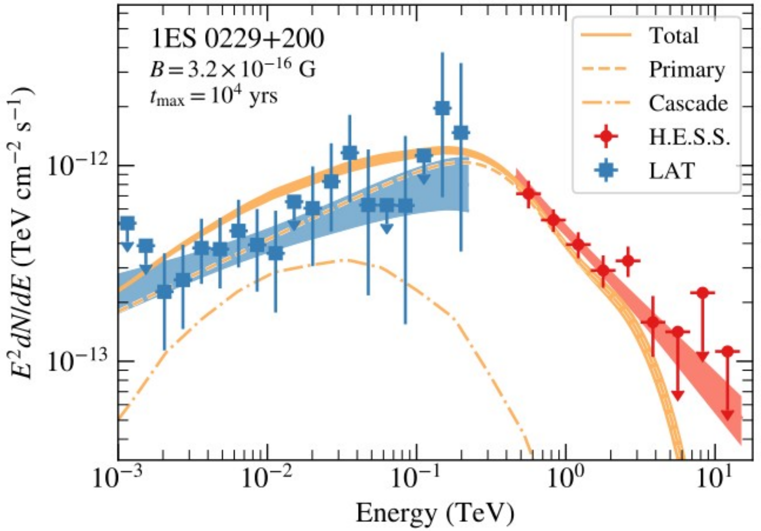


IGMF constraints from Fermi/LAT and HESS observations



CRPropa simulations:

- Powerlaw with an exponential cutoff
- $\Theta_{los}=0°$
- $\lambda_B=1$ Mpc
- $T_{cycle}=10$, 10^4 and 10^7 yr
- $B=10^{-16}$, $10^{-15.5}\dots10^{-13}$ G



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

- Total likelihood:

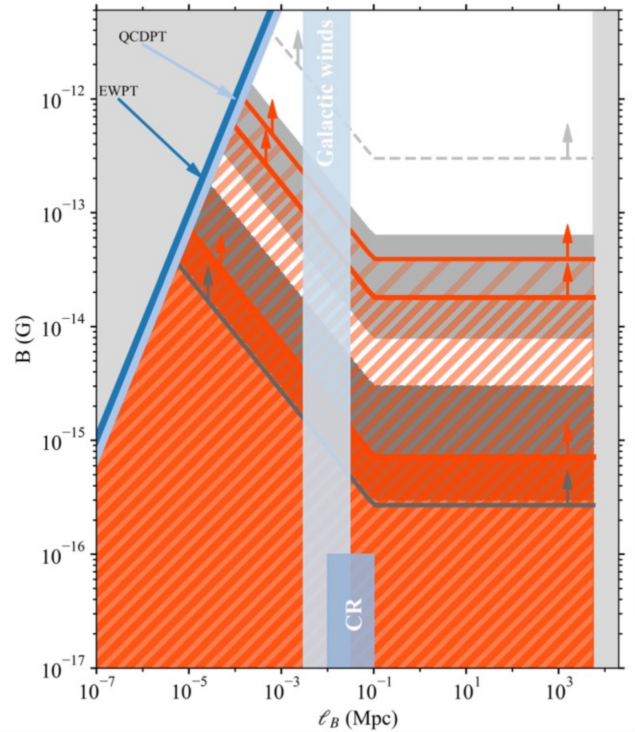
$$\mathscr{L}(B,\theta_i|\mathcal{D}_i) = \mathscr{L}(B,\theta_i|\mathcal{D}_{i,LAT}) * \mathscr{L}(B,\theta_i|\mathcal{D}_{i,HESS})$$

Scanning all the parameter the best fit is evaluated → the presence of cascade is not preferred with respect to the case of “no cascade”

IGMF constraints from Fermi/LAT and HESS observations

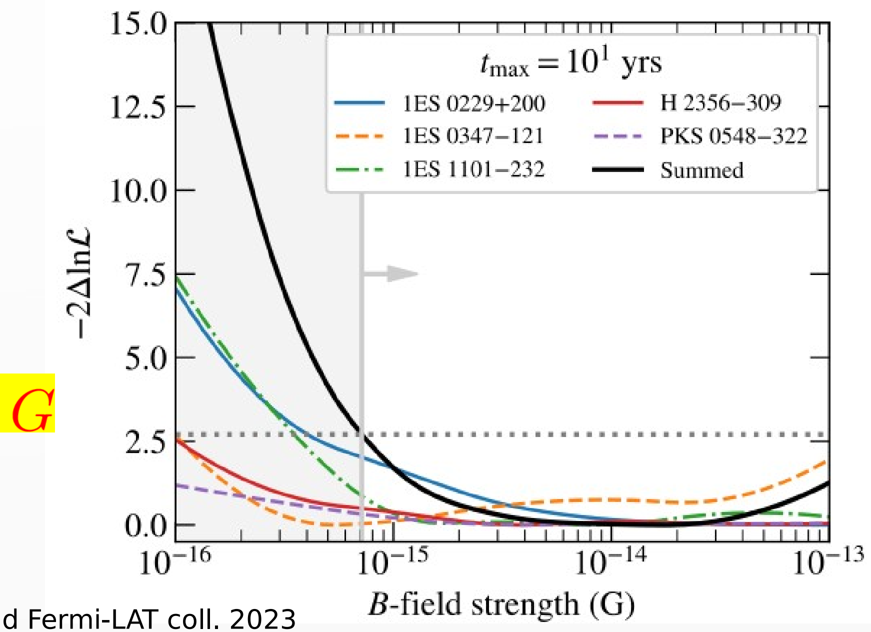
- Loglikelihood ratio test:

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



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

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



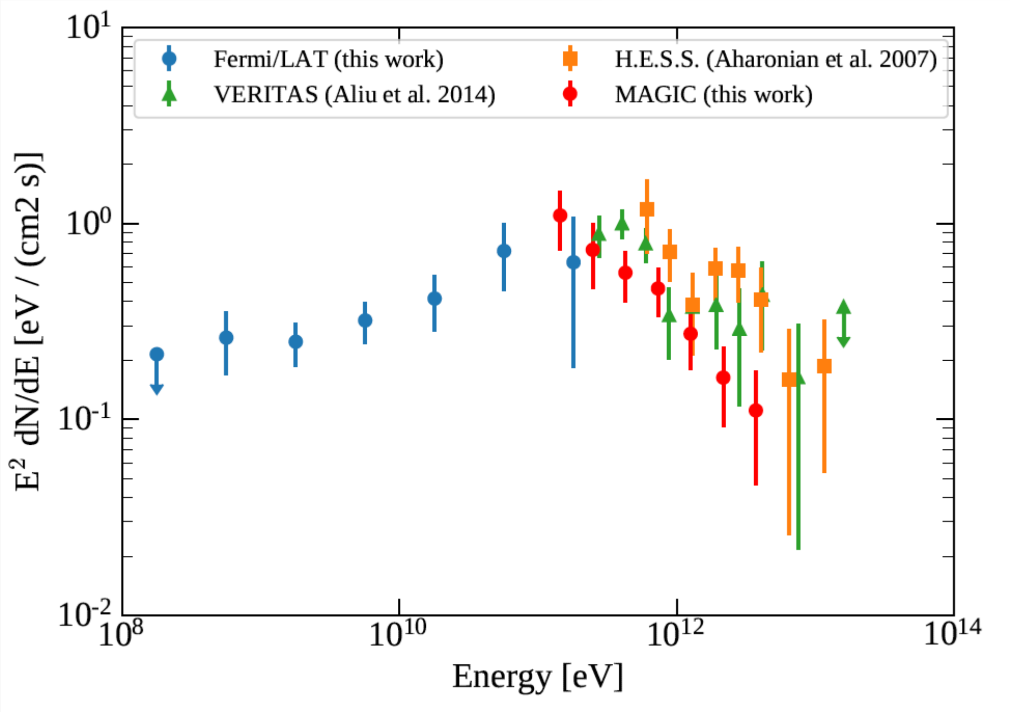
H.E.S.S. and Fermi-LAT coll. 2023

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

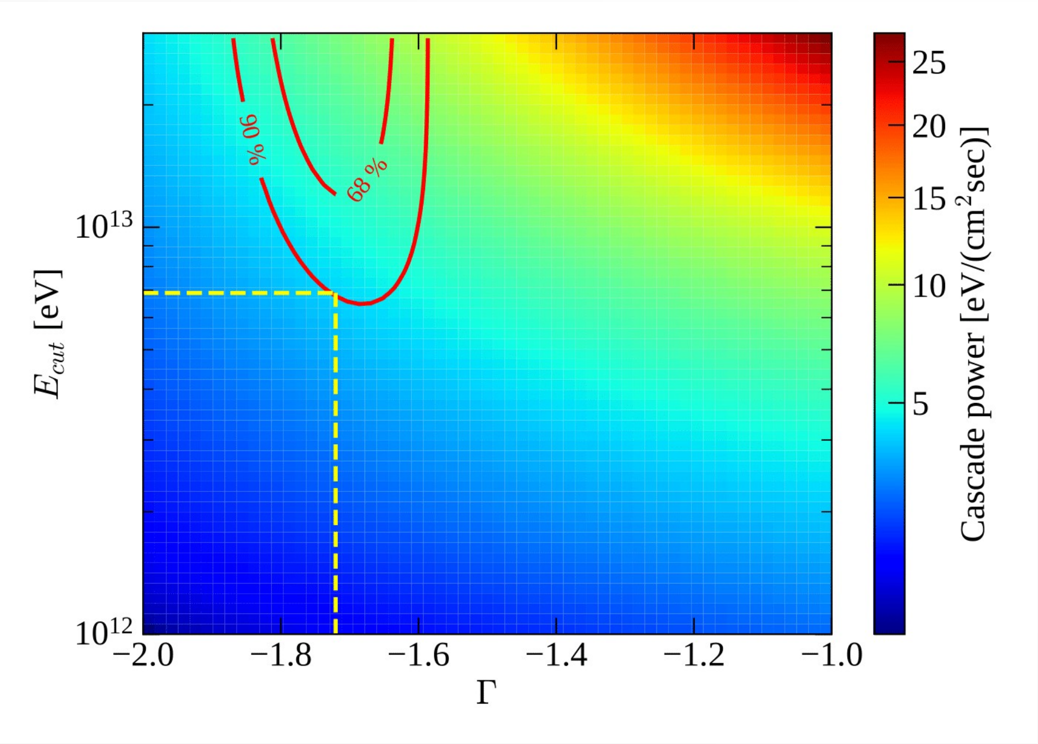
A lower bound on IGMF from the variability of 1ES 0229+200



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

VHE spectrum: minimal expected cascade estimate



MAGIC coll. 2023

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

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

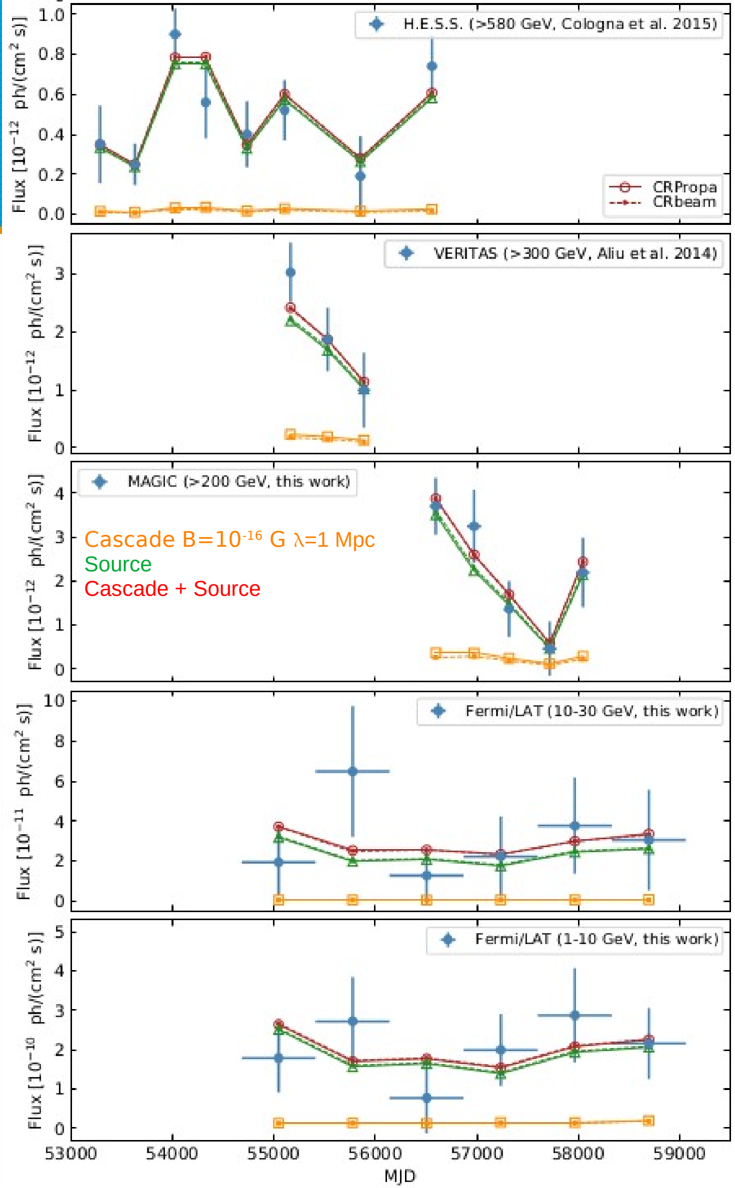
- We took the values of E_{cut} and Γ that lie in the 90% of confidence contour and that give the minimum cascade power: Γ1.72, E_{cut}6.9 TeV

Numerical modeling of cascade emission

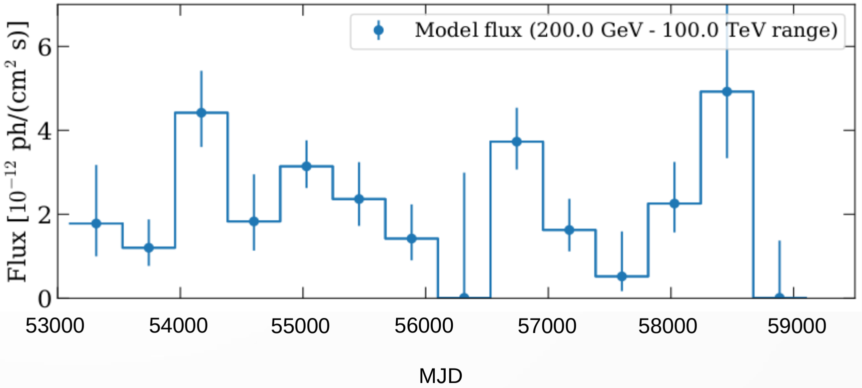
- We used CRPropa to trace the development of the cascade in the intergalactic medium.
- Source model: Powerlaw with exponential cutoff, jet emission within a cone of 10 deg
- $G(E_0,E,t,B,\lambda)$ Green function, $F_s(E_0,t)$ variability pattern of the source in the VHE band. The cascade signal $F_c(E,t)$ 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



Variability pattern F_s

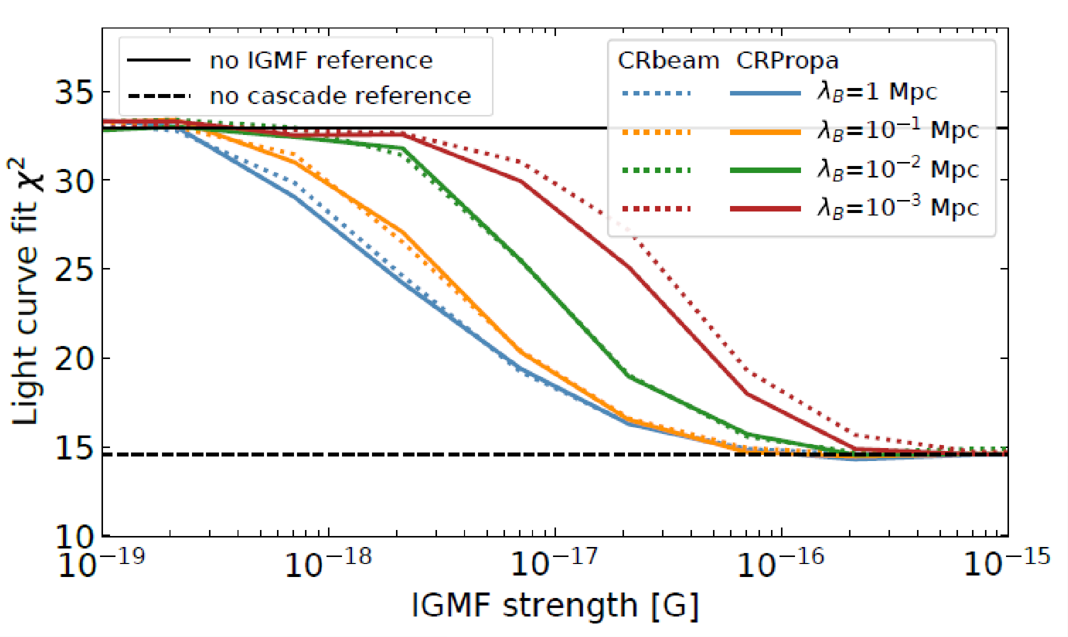


MAGIC coll. 2023

- 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

Lightcuves: fit results

MAGIC coll. 2023

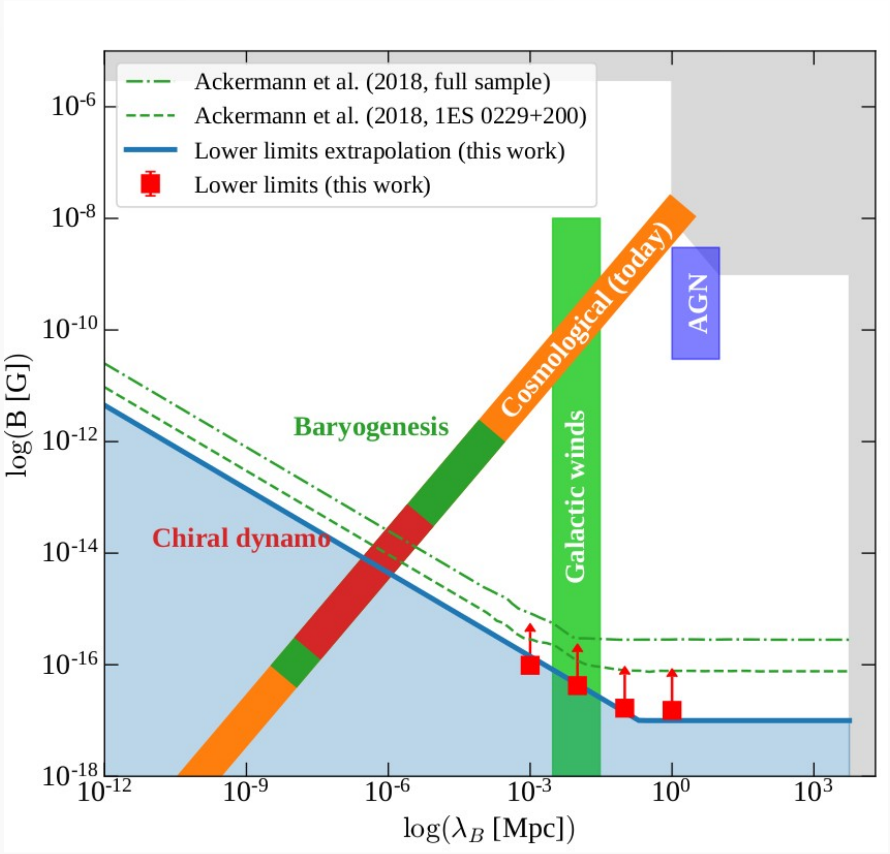


$$B > 1.8 \times 10^{-17}\ G$$

- 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

95 % confidence level

Results



MAGIC coll. 2023

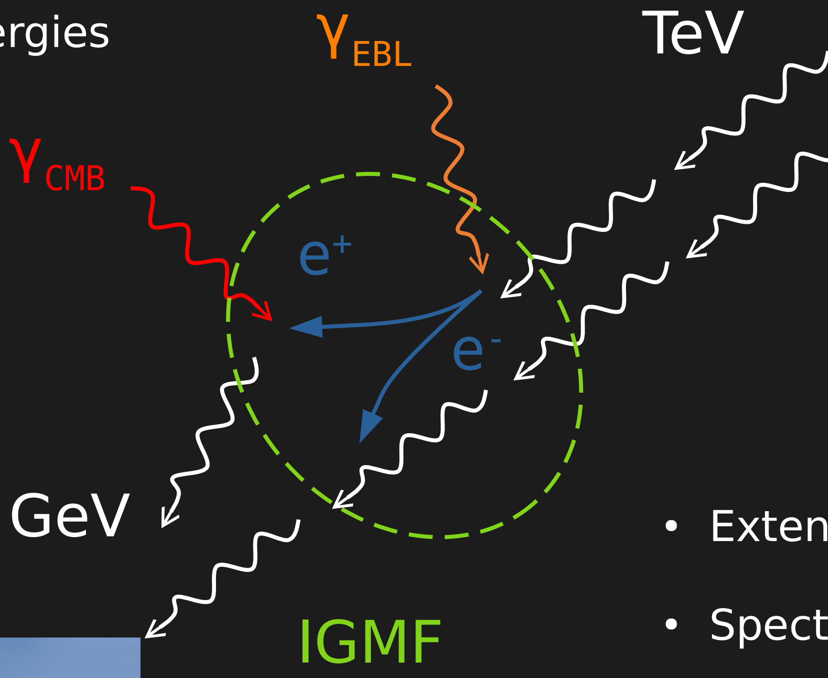
- The derived lower bound is weaker than the one reported by H.E.S.S. and Fermi LAT coll.
- **VHE variability of the source is taken into account**
- The detection of 10 yr delayed signal for z∽0.1 requires systematic monitoring in both TeV and 1-100 GeV bands

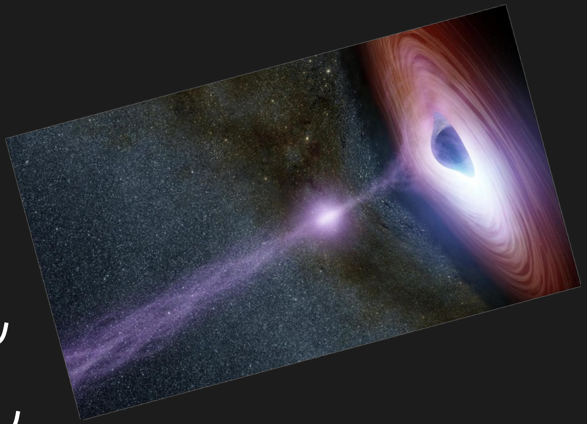
Physical process

- Excess γ rays at lower energies

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

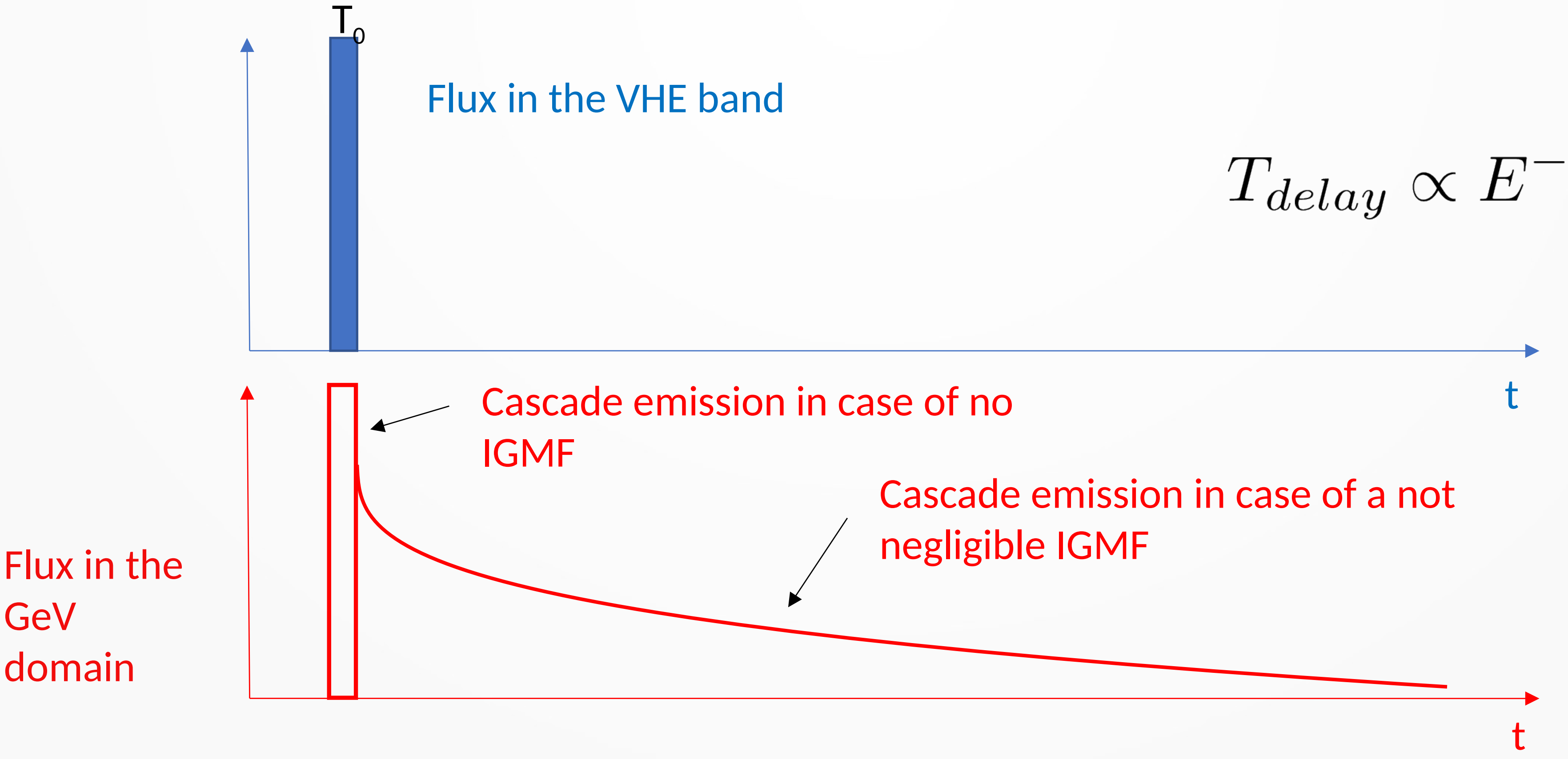
Indirect detection of the IGMF





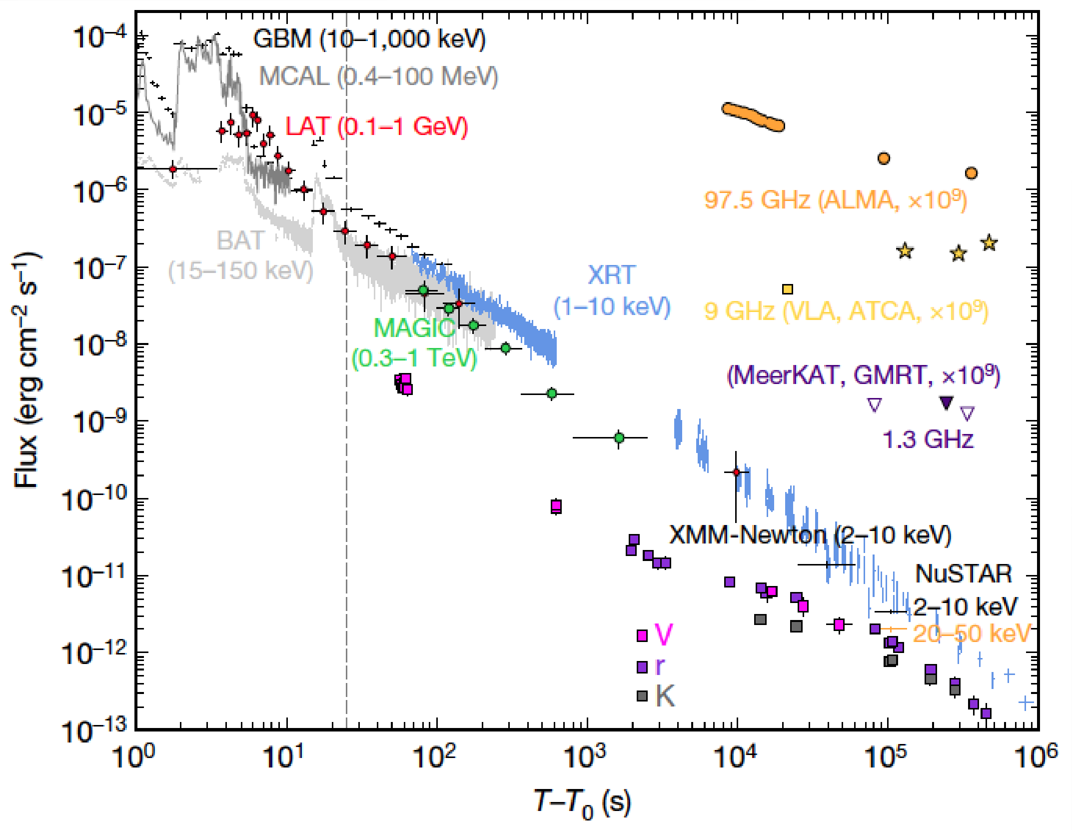
- Extended γ rays halos
- Spectral features
- **<u>Time delayed γ-ray emission</u>**

Pair echo emission from GRB



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

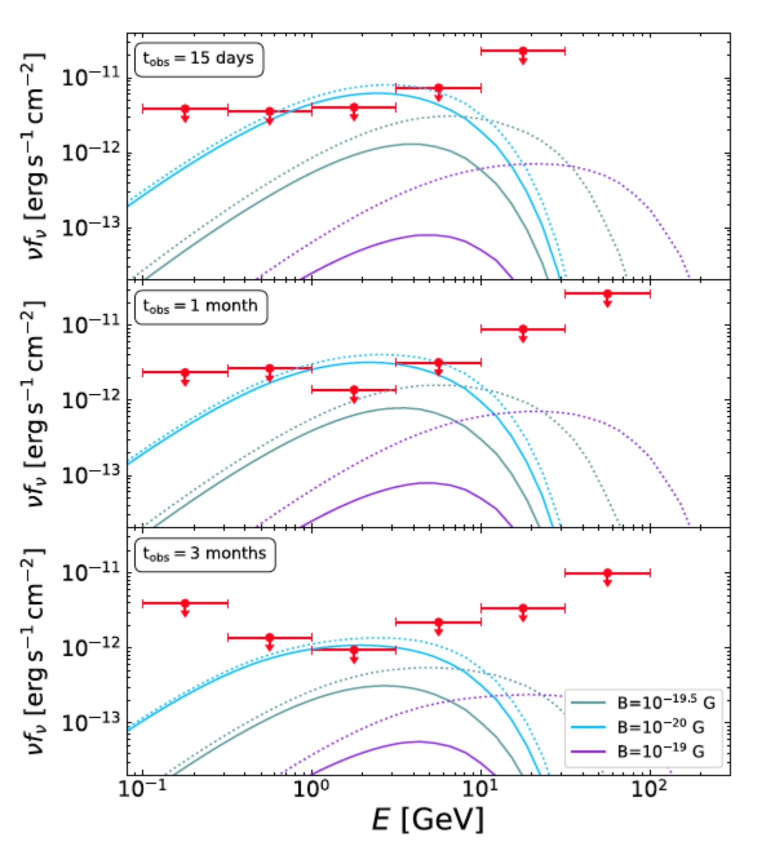
GRB 190114C



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)
- $E_{\gamma,iso} \simeq 2\times10^{53}$ erg in the E=1-10^4 keV
- Z≃ 0.42
- $T_{\text{activity, VHE}} \simeq$ 40 m

IGMF lower bounds from GRB 190114C

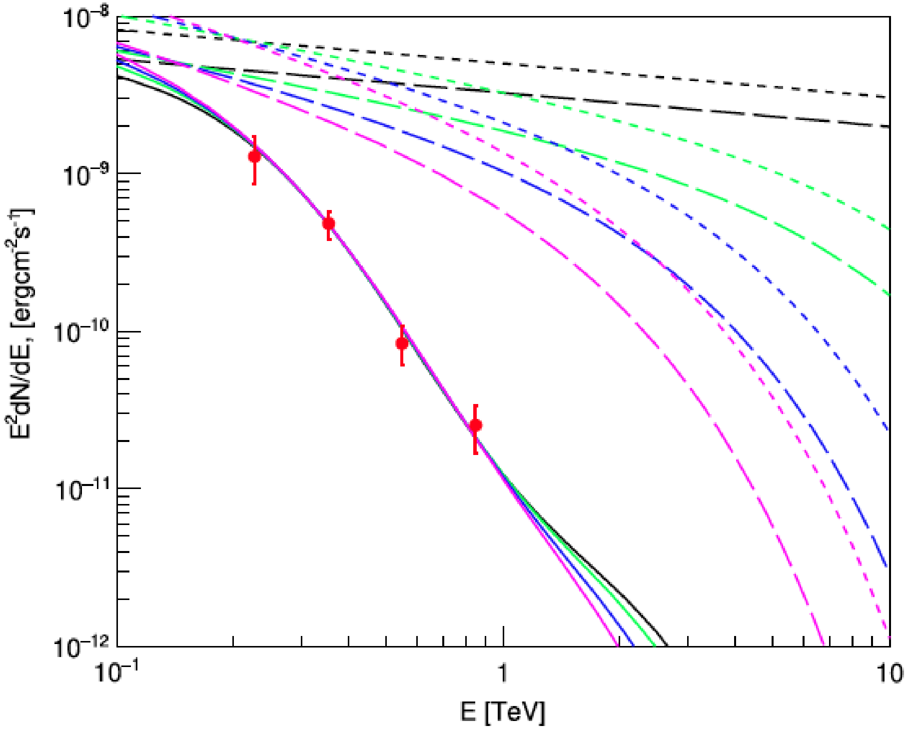


Wang et al. 2020

- 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: **$B \gtrsim 3\times10^{-20}$ G for $\lambda_B \lesssim 1$ Mpc**

IGMF lower bounds from GRB 190114C

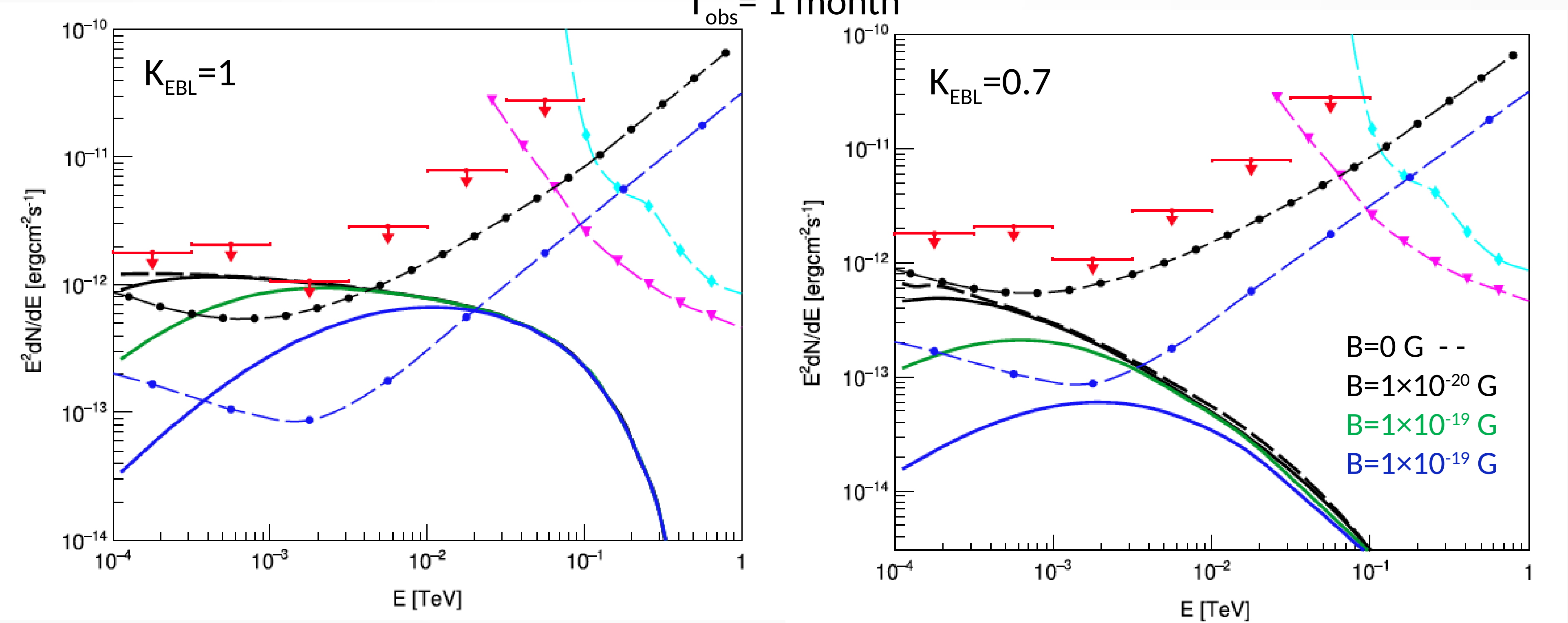
- Reconstruction of the VHE intrinsic spectrum fitting the data
- Assumed model: powerlaw with an exponential cutoff
- Different EBL normalization assumed: 70%, 80%, 90%
- EBL: Gilmore et al. 2012
- Elmag3 used to trace the development of the cascade emission



Dzhatdoev et al. 2020

IGMF lower bounds from GRB 190114C

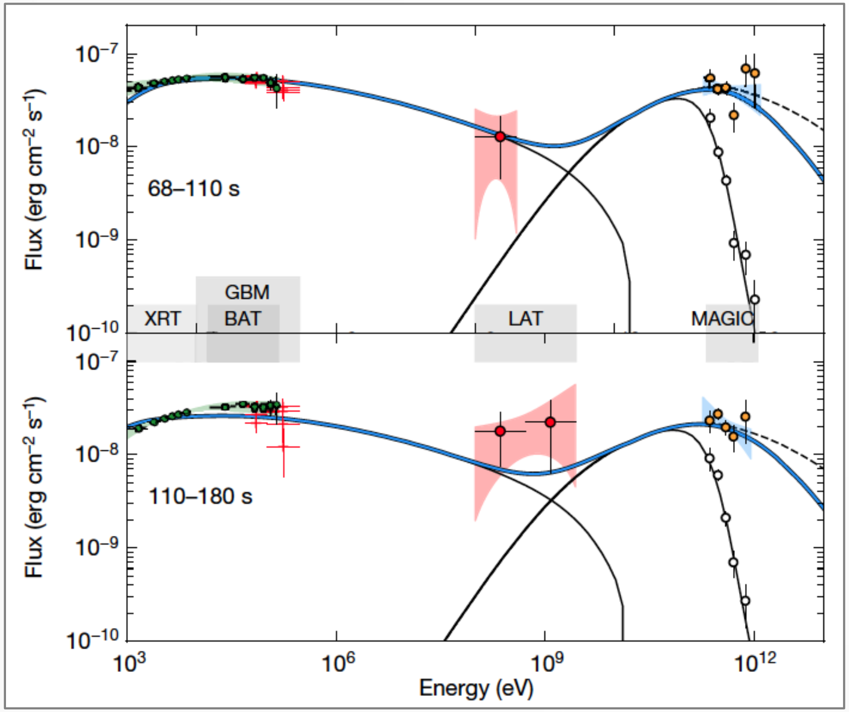
T_{obs}= 1 month



Dzhatdoev et al. 2020

No constraints on IGMF can be derived

Primary spectrum



MAGIC coll. 2019

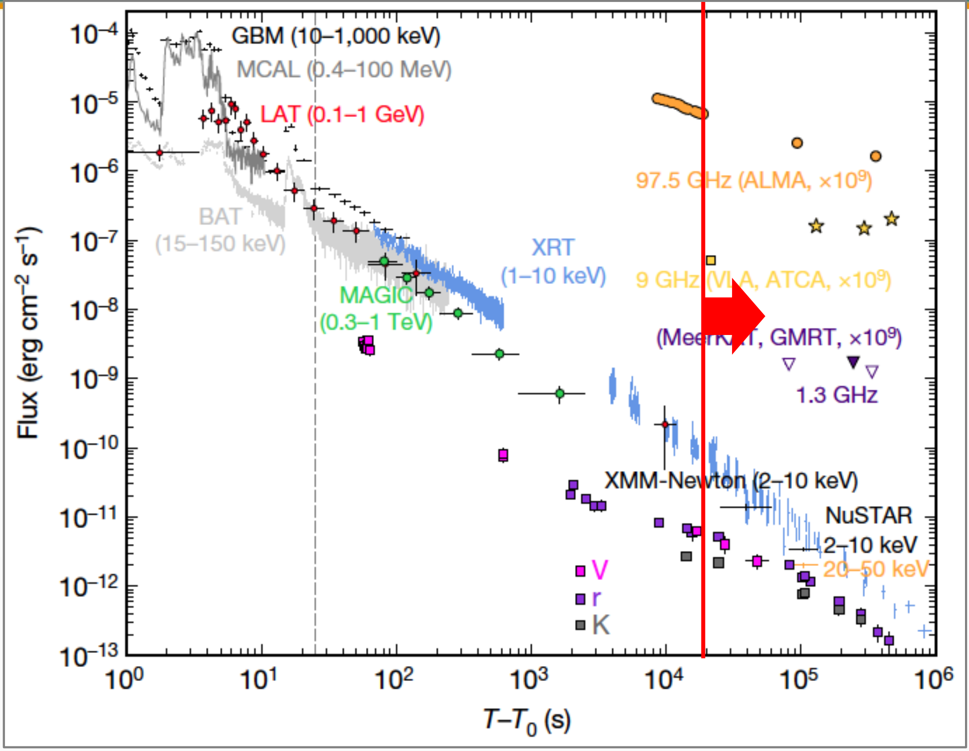
- We used the GRB 190114C model in the MAGIC band (200GeV<E<10 TeV) in the first temporal bin (68-110 s) approximated it with a log-parabola

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

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

$$\langle F\rangle_{6-2454} = \frac{\int_6^{2454} F(t)dt}{\Delta t}$$

Starting time

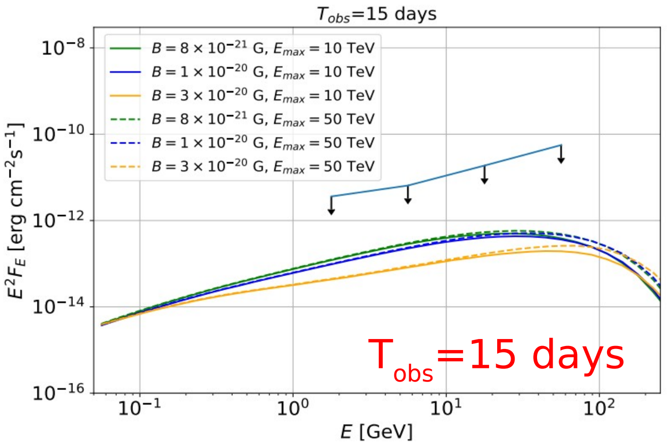


- We started to count the cascade photons at T-T$_0$=2×10^4 s to avoid possible contamination of the primary emission coming from the source

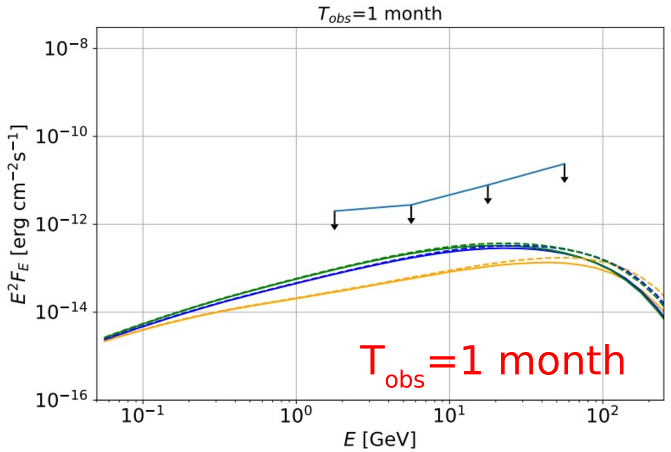
CRPropa simulations: settings

- 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

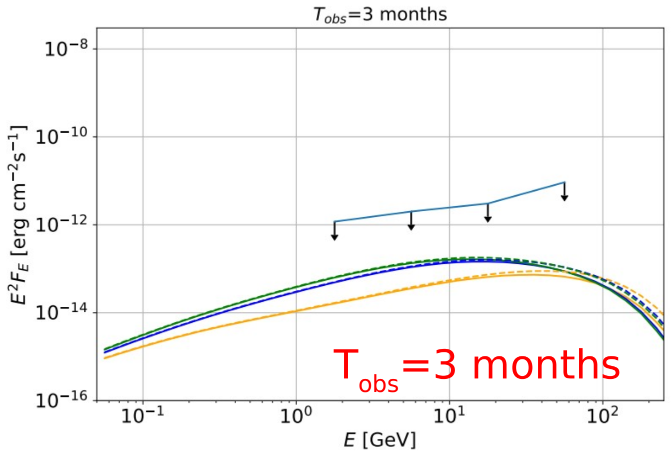
Pair echo SEDs vs observation time



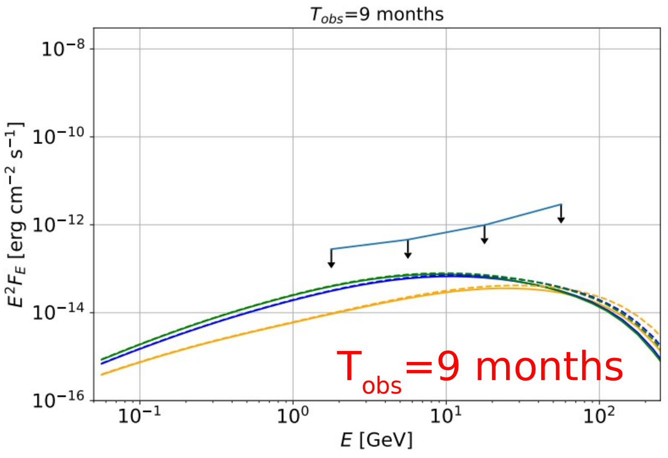
T_{obs}=15 days



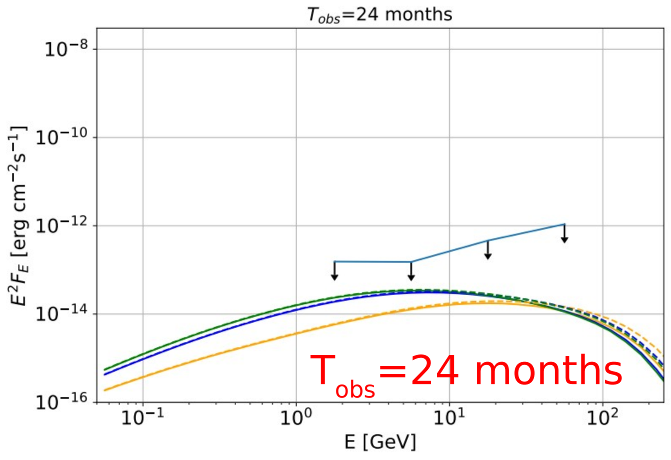
T_{obs}=1 month



T_{obs}=3 months



T_{obs}=9 months

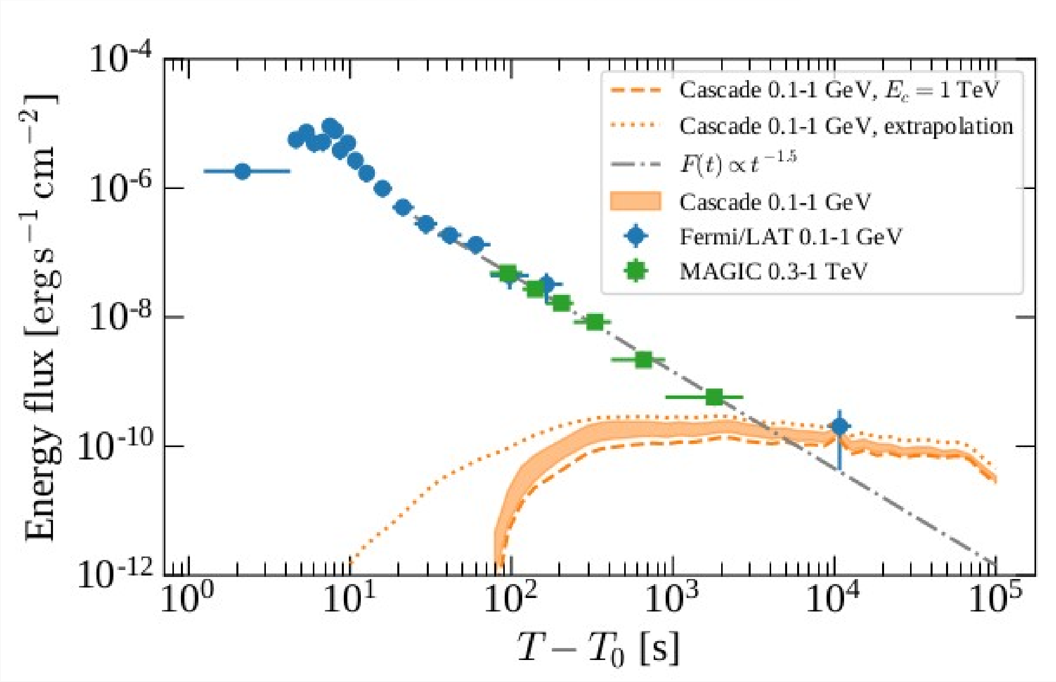


T_{obs}=24 months

Da Vela et al. 2023

No constraints on IGMF can be inferred…

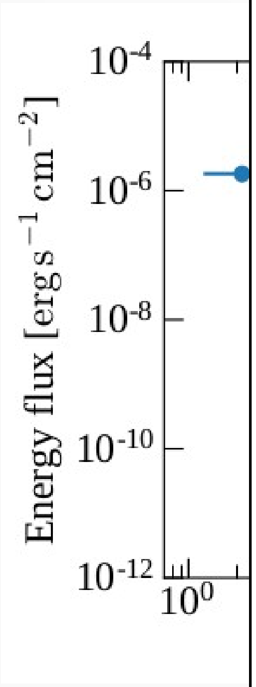
Can we study the lowest delays…?



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 ($B \simeq 10^{-21}$ G)**
- VHE spectrum: Powerlaw up to 10 TeV has been assumed
- The cascade lightcurve for $B < 10^{-21}$ G is compatible with the data…

Can we study the lowest delays …?



Vovk 2023

- 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
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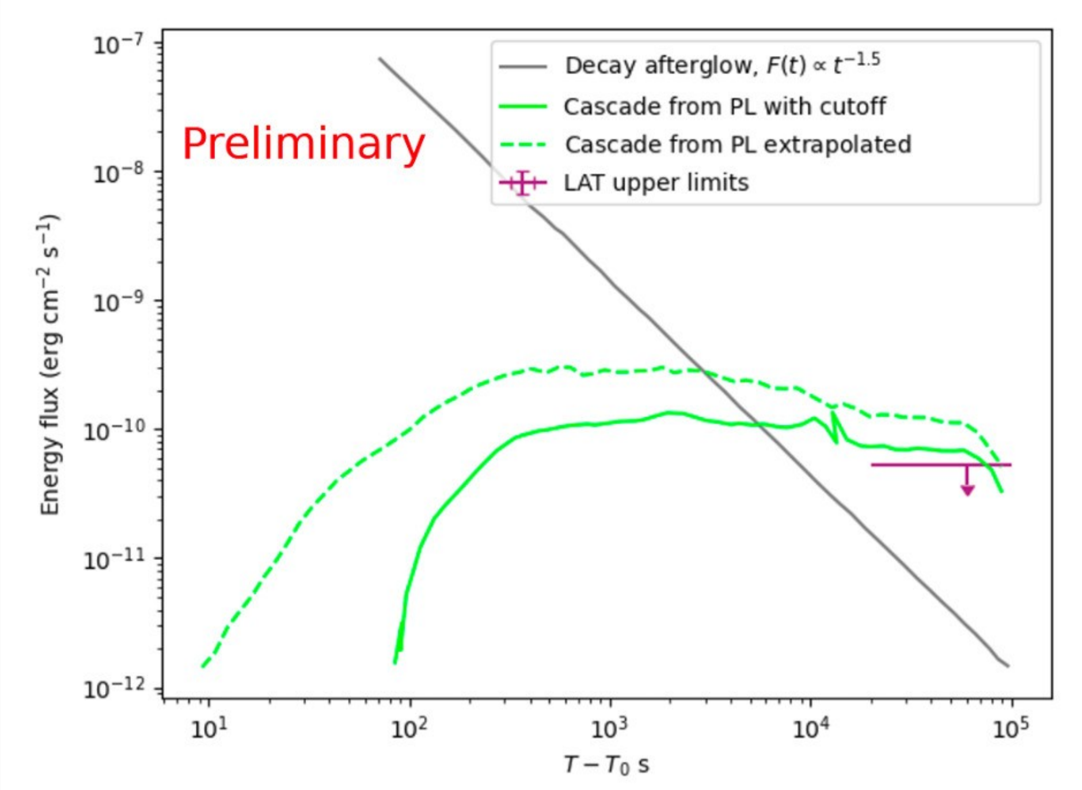
ver than their
G)

p to 10 TeV has

$B<10^{-21}$ G is

However…

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



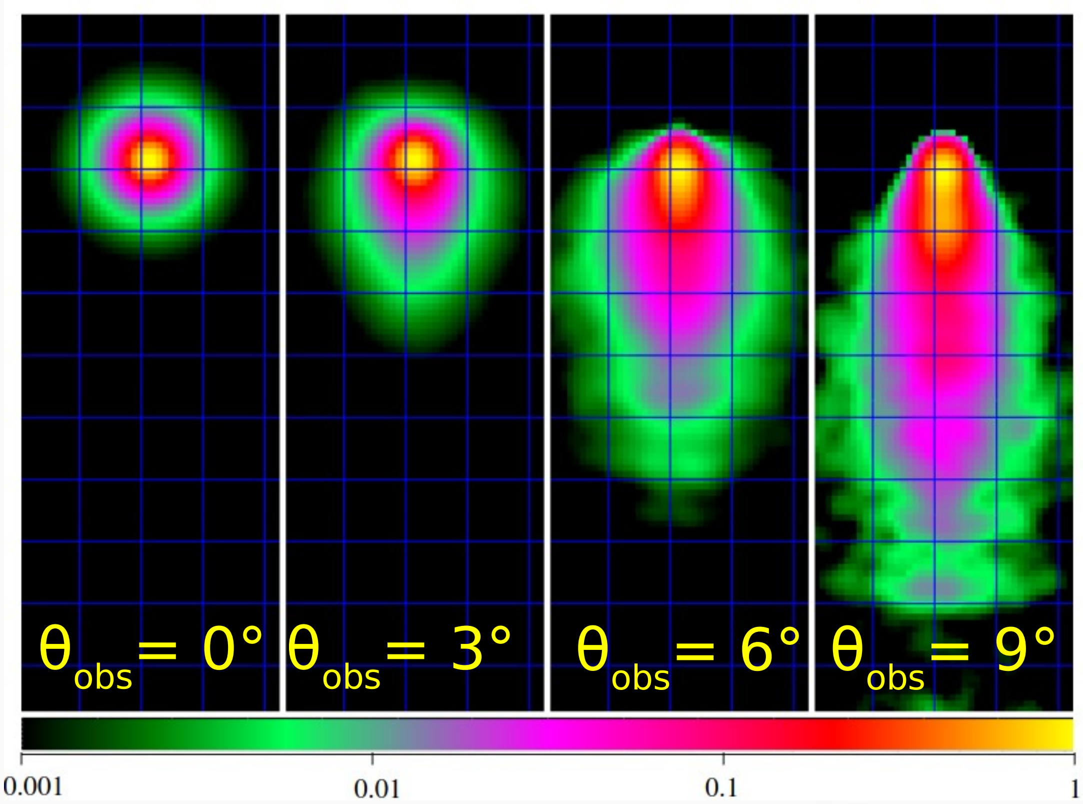
Performing the Fermi LAT analysis after T-T_0 this prediction is not compatible with the upper limit → this extreme scenario seems to be disfavored

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.
- Spectral features: some assumptions on the features of the selected blazars are crucial:
  - Lifcycle of the source
  - Variability
  - Choice of the VHE spectrum
- Pair echo from GRBs: 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
- Extended emission: no detection so far
- Future perspectives:
  - Lahaso GRB…
  - CTA: new EHBL candidates, better angular resolution

Back up

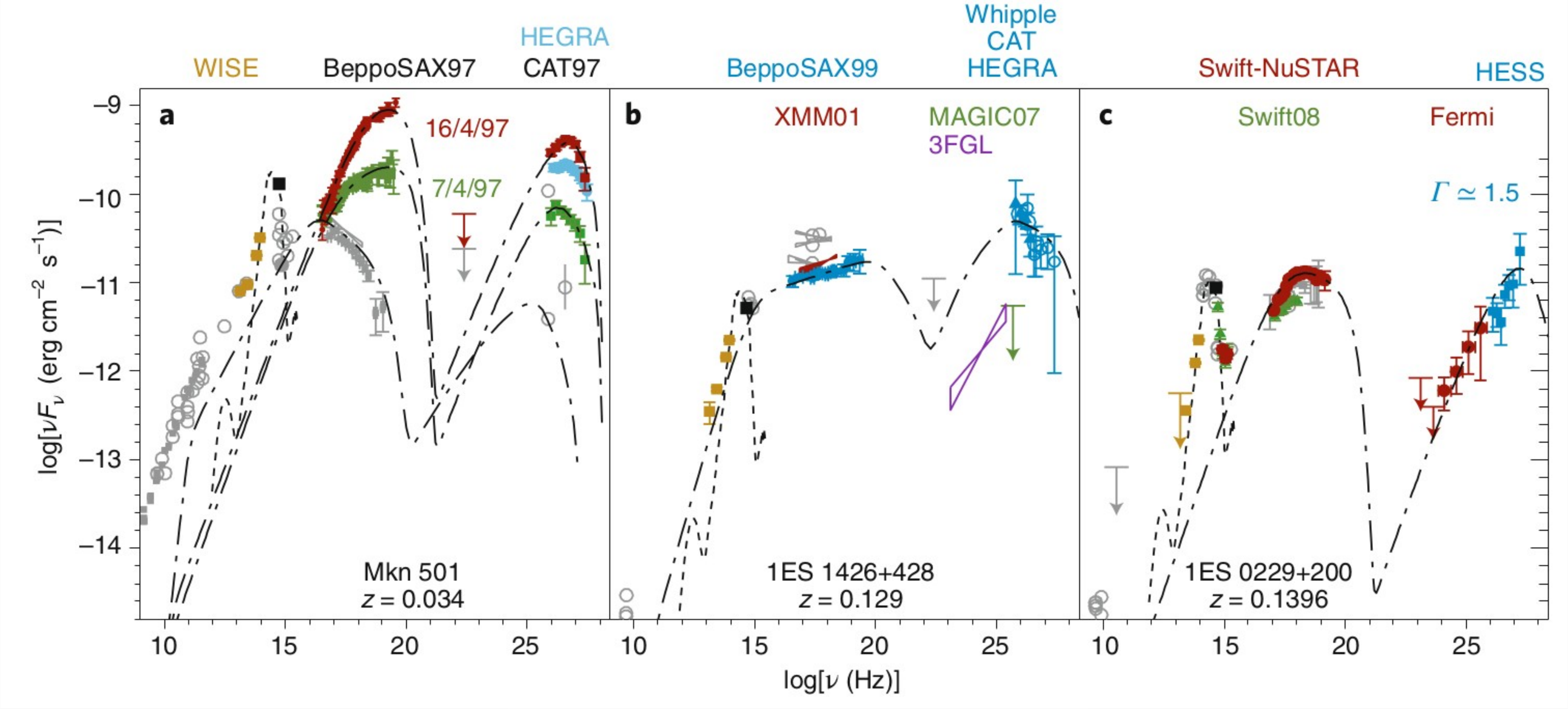
Extended emission: expectations



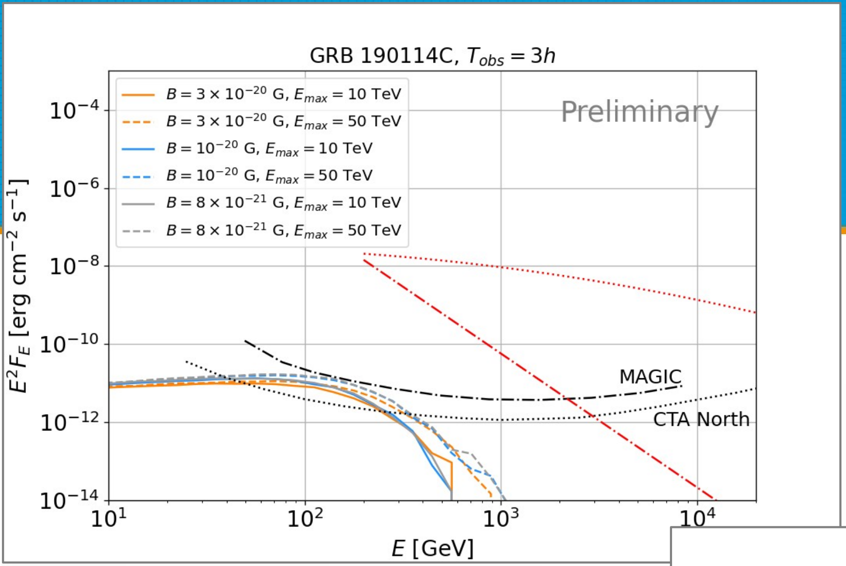
Neronov et al. 2010

- The shape of the halo depends also on the inclination of the jet:
  - Monchromatic photons E=1 TeV
  - Redshift: $z \simeq 0.1$
  - Jet opening angle: $\Theta_{jet}=3°$
  - Correlation length λ_B > 1 Mpc
  - IGMF strength: $B = 10^{-16}$ G

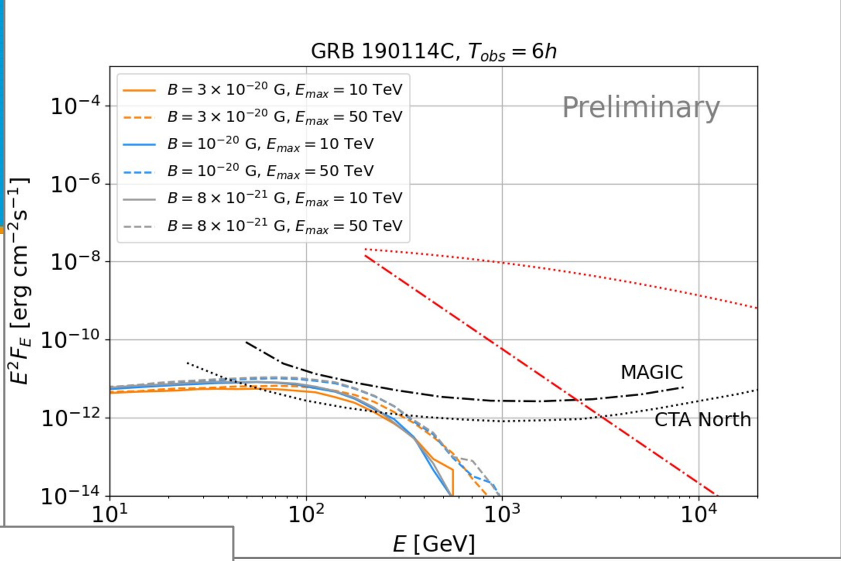
Extreme High frequency BL-Lac (EHBL)

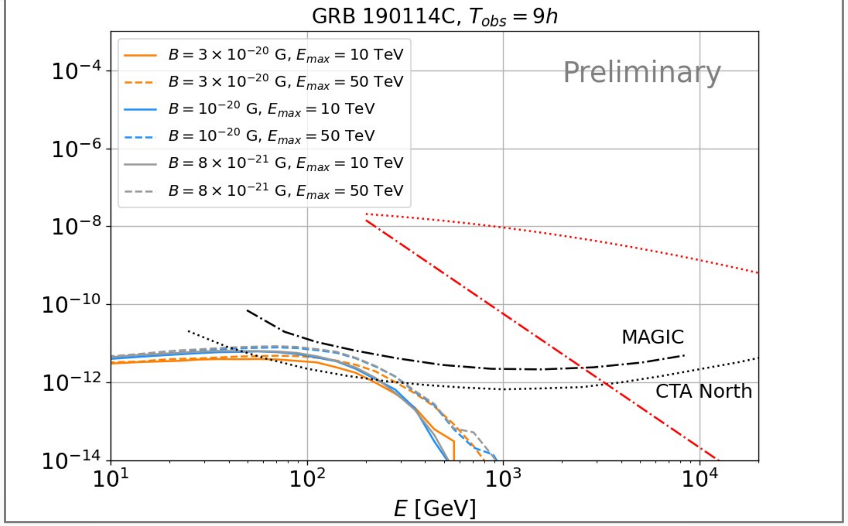


Prandini et al. 2020


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

z=0.42


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

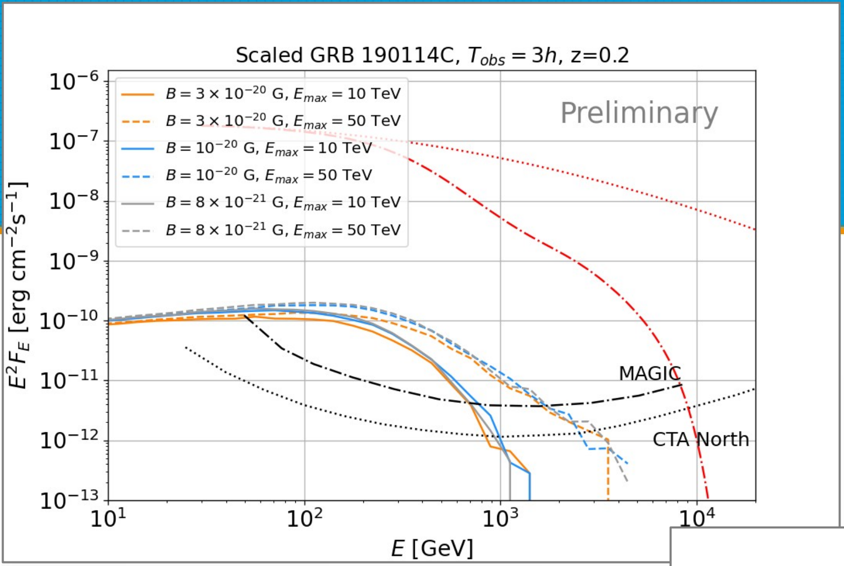

GRB 190114C, $T_{obs} = 9h$

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

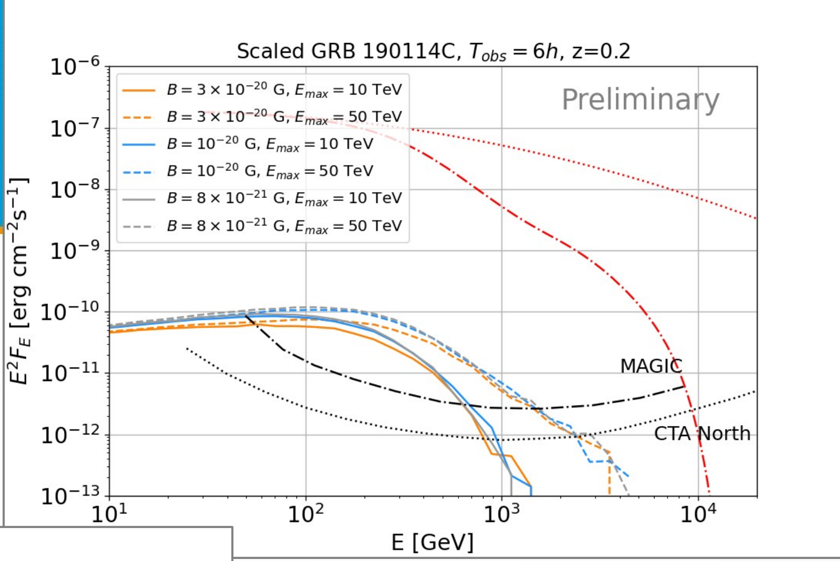
Pair echo emission detection vs GRB distance

- We assumed the same intrinsic properties as GRB 190114C:
  - VHE spectral shape
  - $L_{\gamma,\,\mathrm{iso}}$
- We repeated the same procedure assuming z=0.2, 1

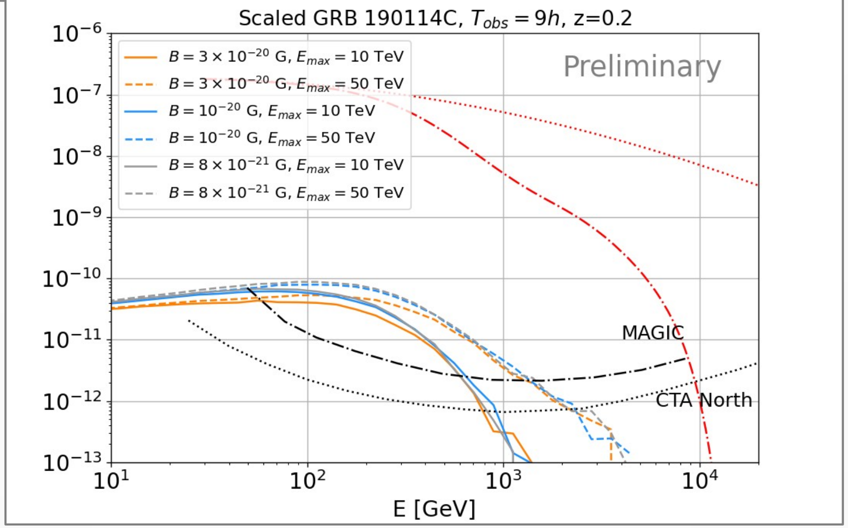
Z=0.2



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

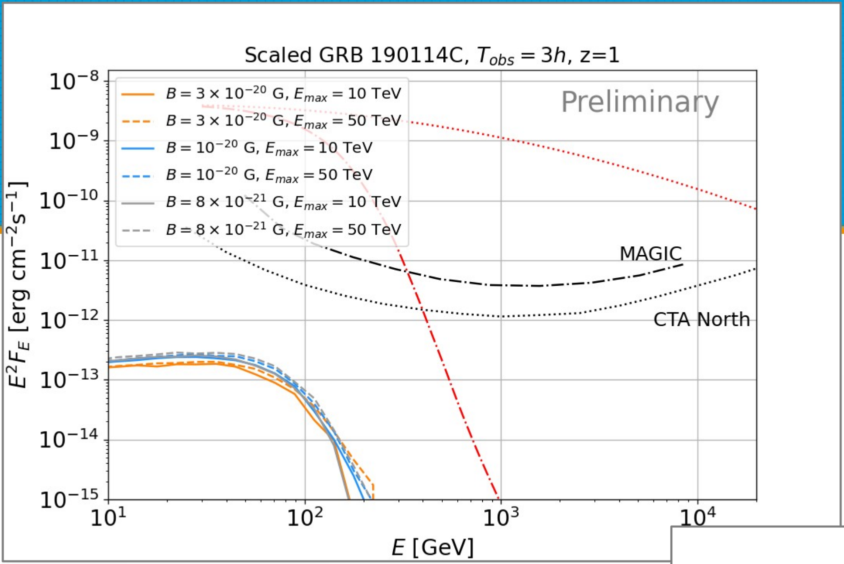


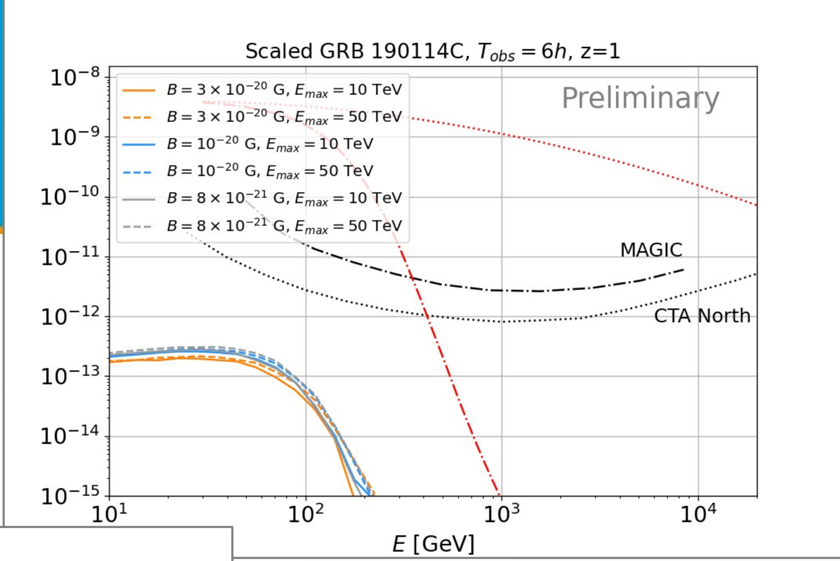
Scaled GRB 190114C, $T_{obs} = 6h$, z=0.2

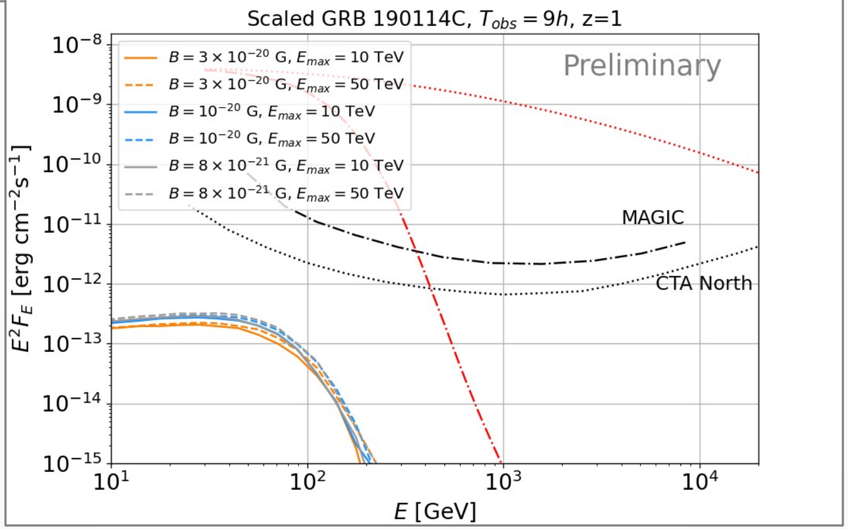


Scaled GRB 190114C, $T_{obs} = 9h$, z=0.2

Z=1



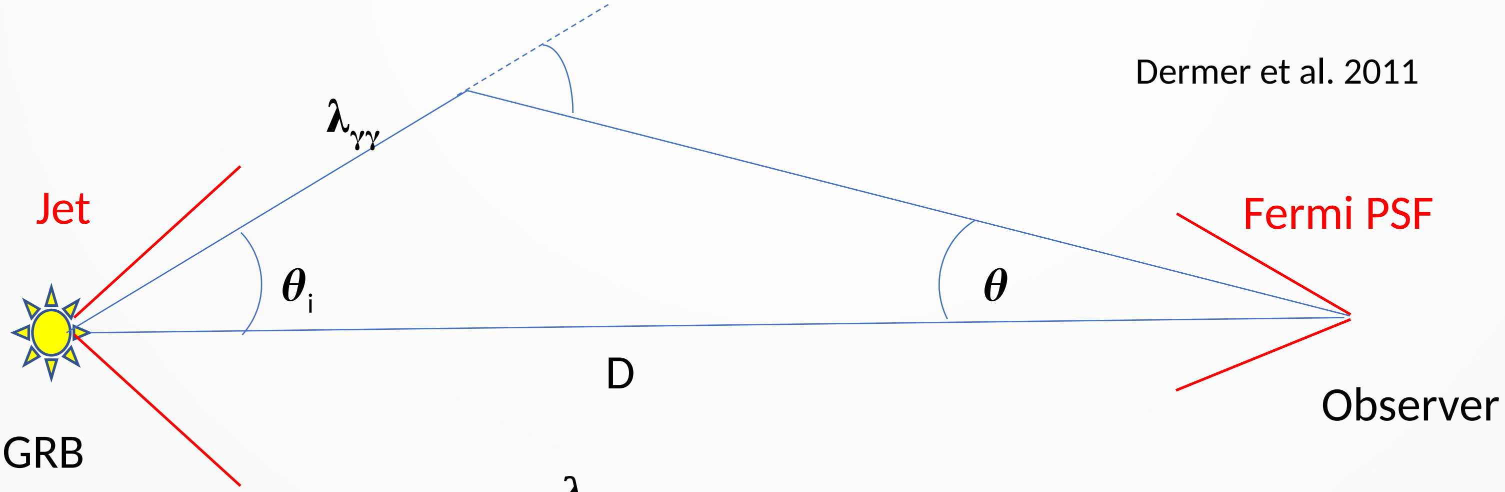




The distance is more important than the cascade power

- 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

Normalization and PSF



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

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

Cascade spectrum