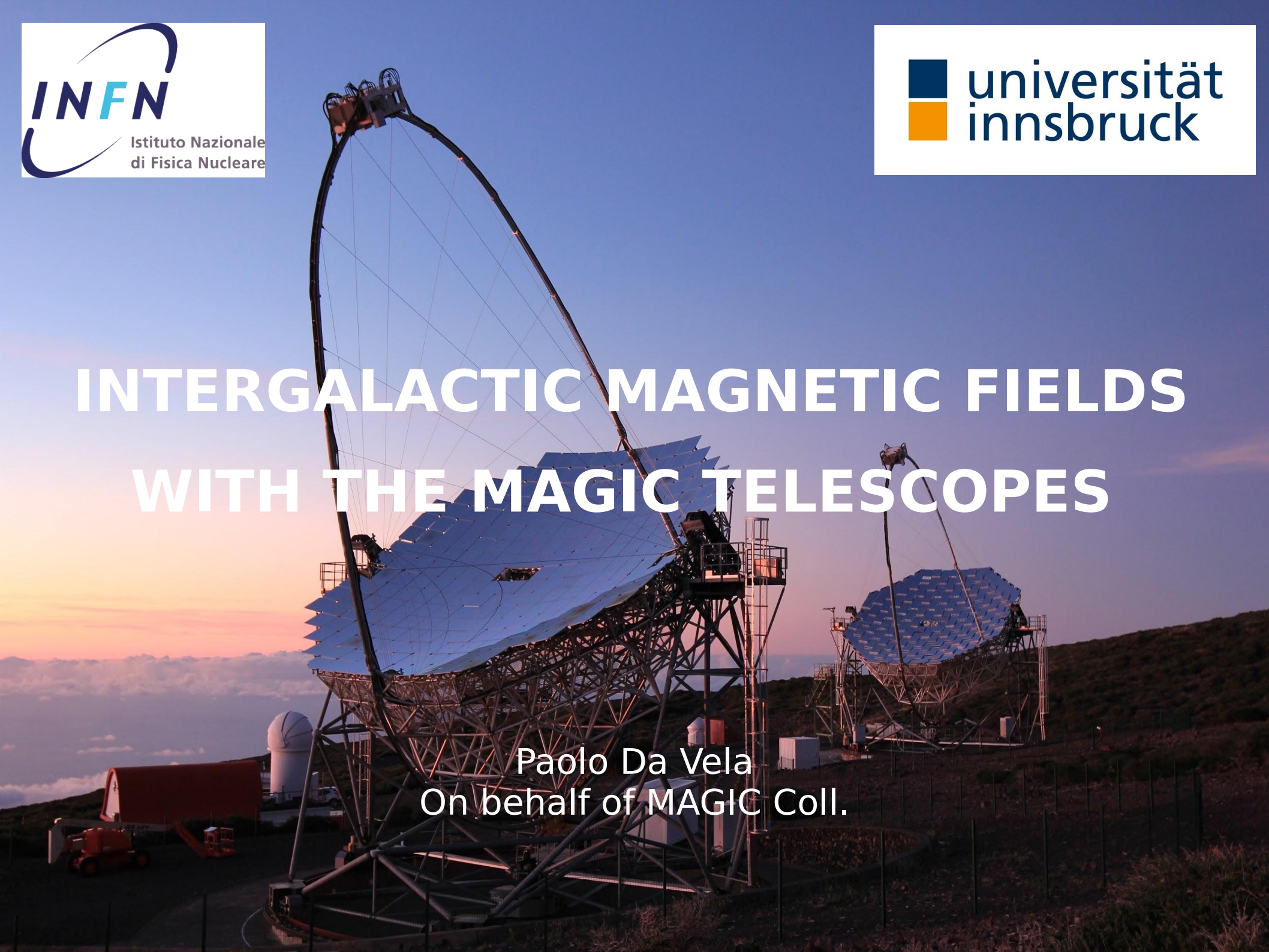
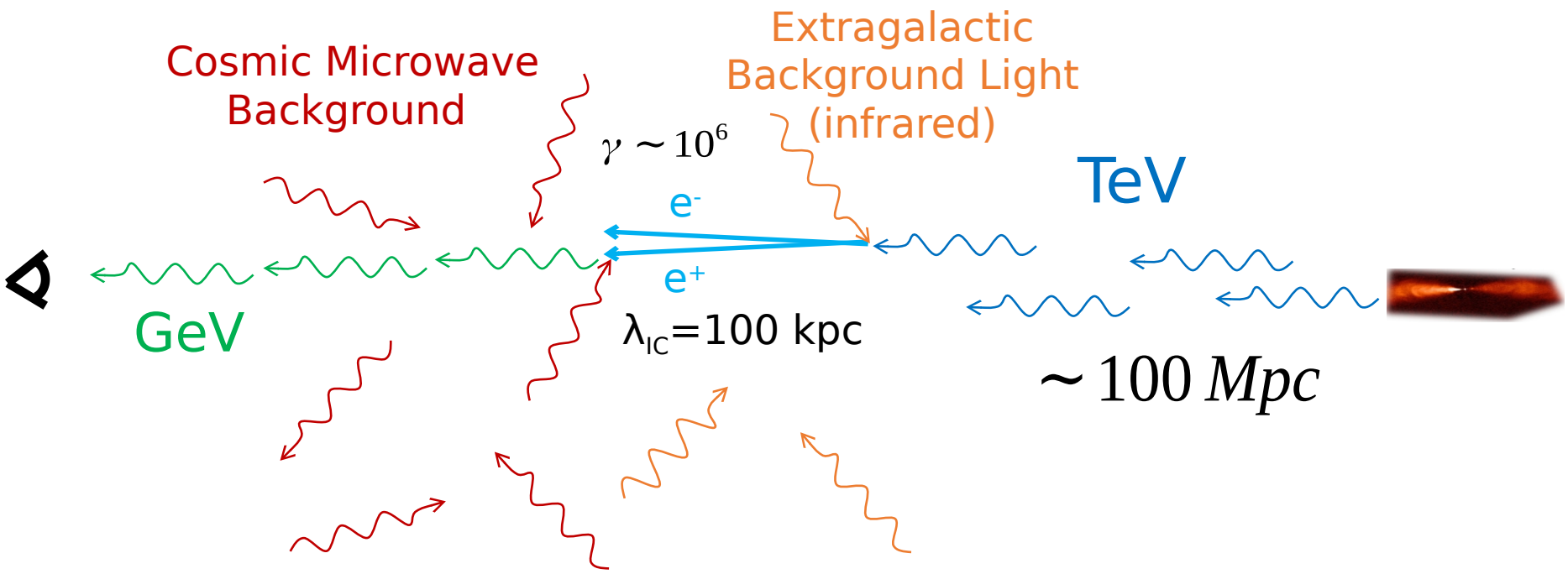

INFN
Istituto Nazionale
di Fisica Nucleare
universität
innsbruck
INTERGALACTIC MAGNETIC FIELDS
WITH THE MAGIC TELESCOPES
Paolo Da Vela
On behalf of MAGIC Coll.

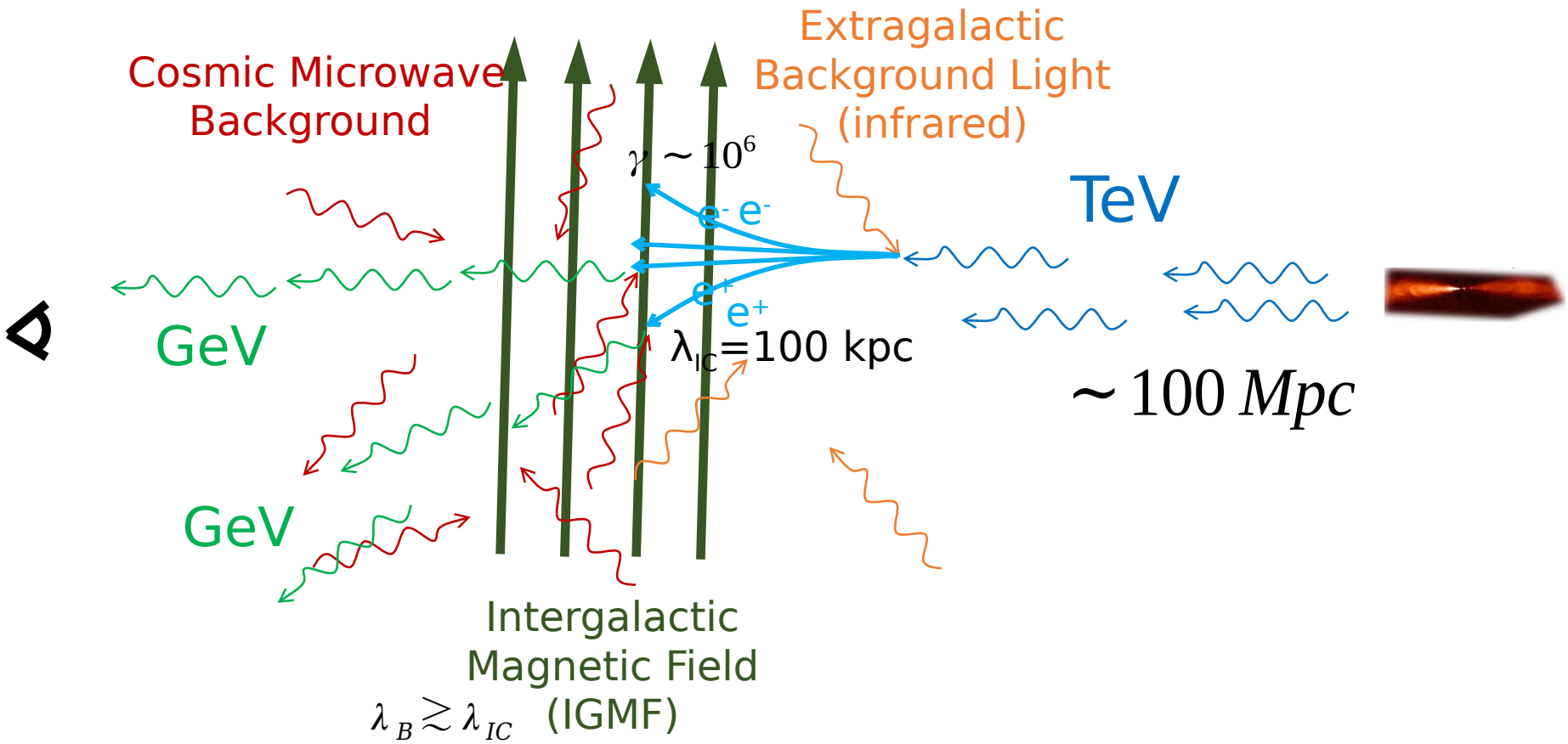
Summary

- IGMF studies with gamma ray sources
- Extreme High-frequency BL Lacs
- Existing lower bounds
- The MAGIC telescopes
- IGMF lower bounds with MAGIC
- Conclusions

Summary of a TeV γ-ray's life absent any other process

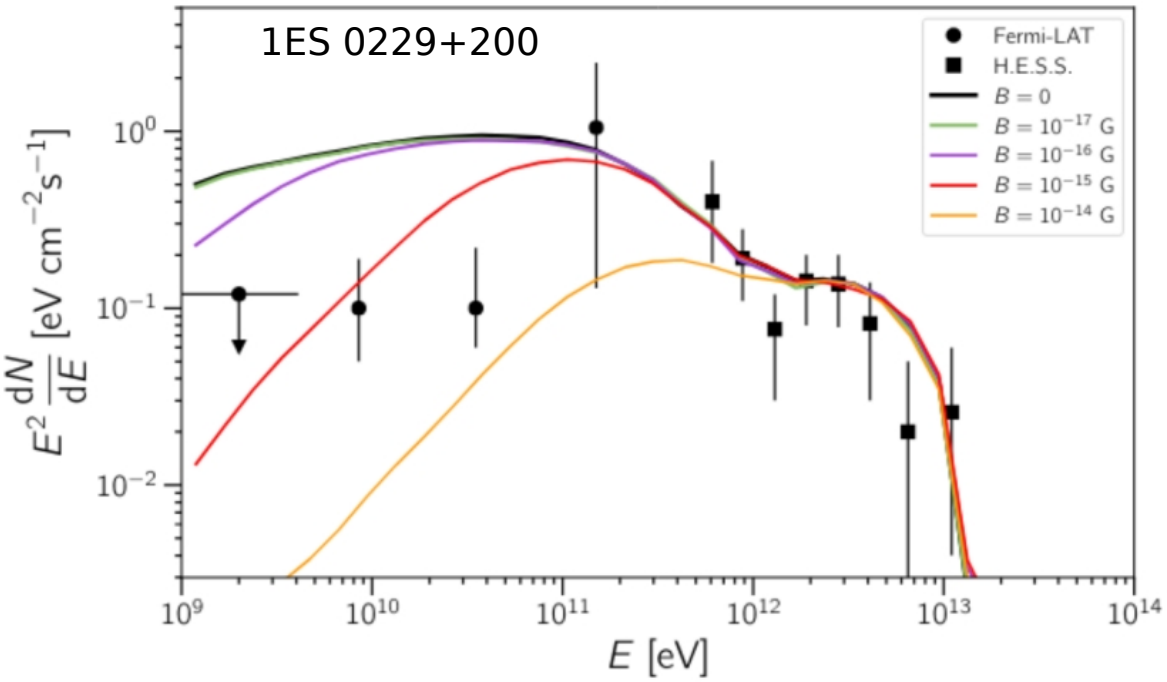


Summary of a TeV γ-ray's life with an IGMF



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

Cascade emission: “delay”

- Since the pairs are deviated the cascade signal is delayed (Neronov et al. 2009)

$\lambda_B >> \lambda_{IC}$

$$T_{delay} \simeq 7 \times 10^5 (1-\tau^{-1})(1+z)^{-5} \left[\frac{E}{0.1TeV}\right]^{-5/2} \left[\frac{B}{10^{-18}G}\right]^2 \quad s$$

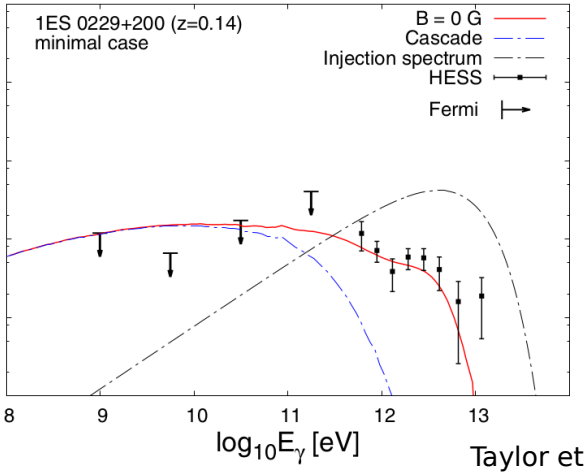
$\lambda_B << \lambda_{IC}$

$$T_{delay} \simeq 10^4 (1-\tau^{-1})(1+z)^{-2} \left[\frac{E}{0.1TeV}\right]^{-2} \left[\frac{B}{10^{-18}G}\right]^2 \left[\frac{\lambda_{B0}}{1kpc}\right] \quad s$$

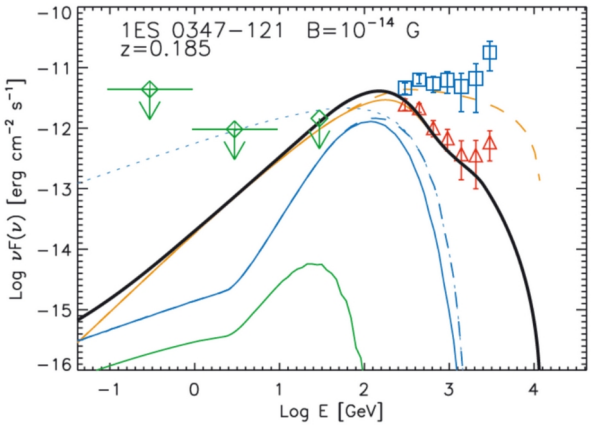
The time delay depends on the IGMF strength and correlation length

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



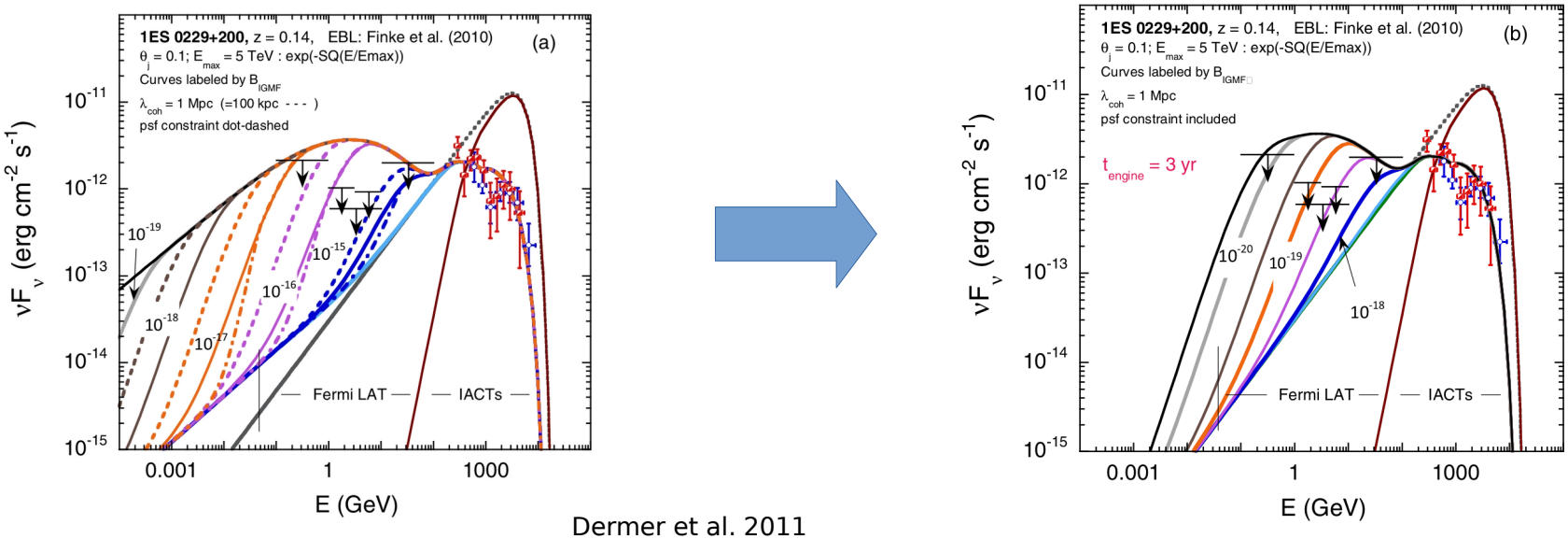
Taylor et al. 2011



Tavecchio et al. 2011

The duty cycle of the source

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



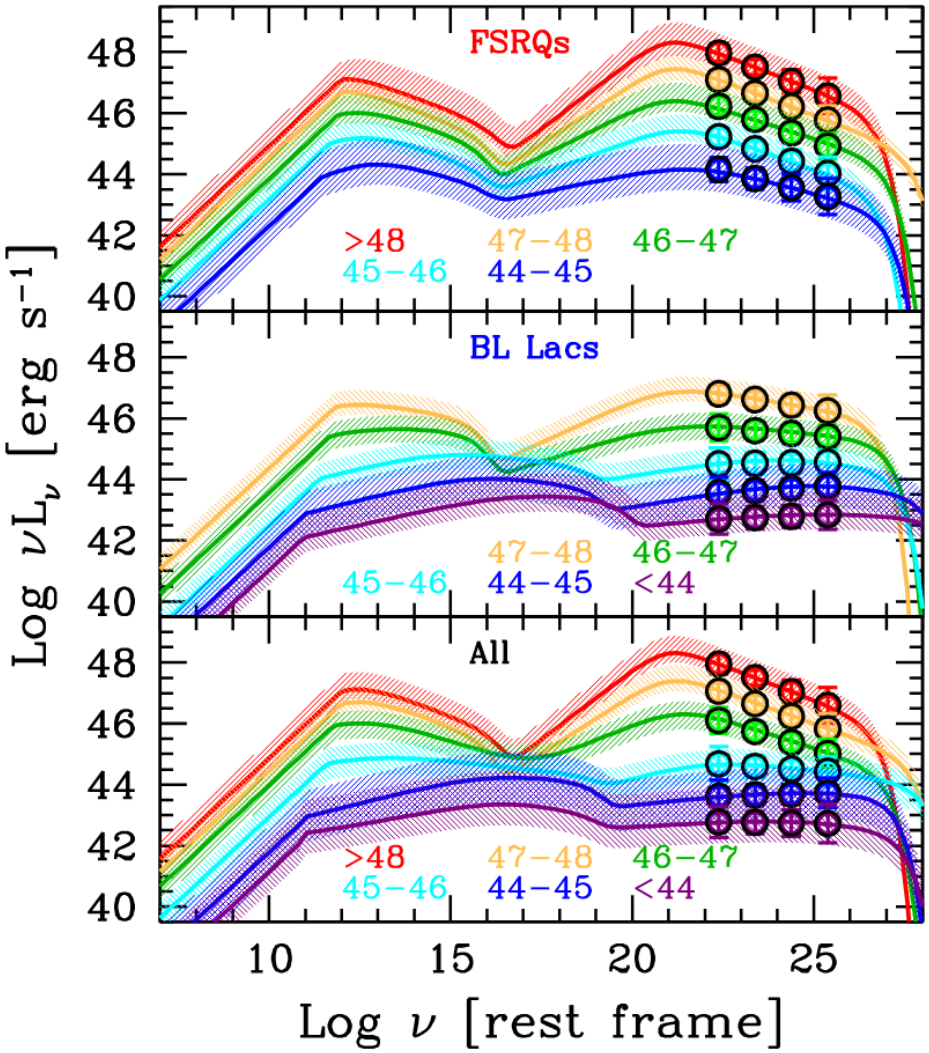
Dermer et al. 2011

What are the most promising sources?

- Hard VHE (E>100 GeV) spectra
- VHE 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)

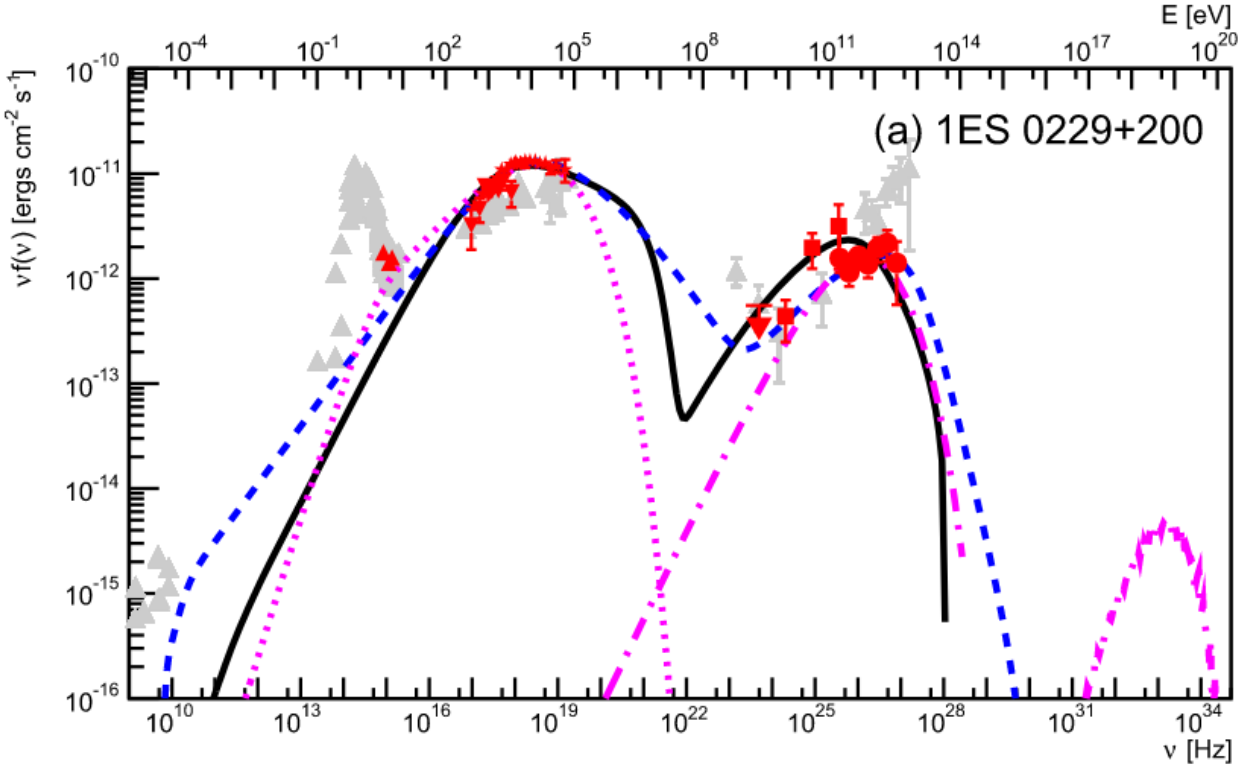
Extreme High frequency BL-Lac (EHBL)



- EHBLs populate the low luminosity branch of the blazar sequence
- Observationally they are characterized by high X-ray to radio flux ratio
- They come in two different flavors:
  - *i. Extreme-synchrotron* : $h\nu_x > 1$ keV (2.5×10^{17} Hz)
  - *ii. Extreme-TeV* : $h\nu_\gamma > 1$ TeV (2.4×10^{26} Hz)

Ghisellini et al. 2017

The case of 1ES 0229+200



Acciari et al. 2020

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

Ideal source for IGMF studies!

Lower bounds on IGMF from Fermi coll.

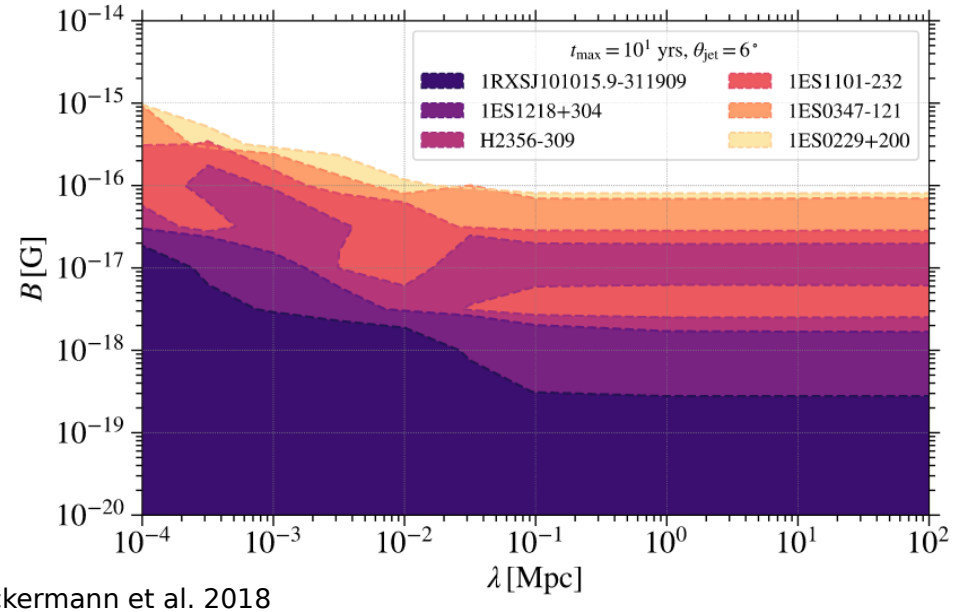
Source	z	R.A. (deg)	Decl. (deg)	3FGL name	3FGL var. index	Experiment	Obs. Period
1ES 1312–423	0.105	198.76	−42.61	J1314.7-4237	45.0	H.E.S.S.	2004-2010
RGB J0710+591	0.125	107.63	59.14	J0710.3+5908	55.5	VERITAS	2008-2009
1ES 0229+200	0.14	38.20	20.29	J0232.8+2016	49.2	H.E.S.S.	2005-2006
						VERITAS	2009-2012
1RXS J101015.9–311909	0.143	152.57	−31.32	J1010.2-3120	86.3	H.E.S.S.	2006-2010
						VERITAS	2009-2012
H 2356–309	0.165	359.78	−30.63	J2359.3-3038	41.0	H.E.S.S.	2004
						H.E.S.S.	2005
						H.E.S.S.	2006
1ES 1218+304	0.182	185.34	30.18	J1221.3+3010	92.5	VERITAS	2007
						VERITAS	2008-2009
1ES 1101–232	0.186	165.91	−23.49	J1103.5-2329	36.5	H.E.S.S.	2004-2005
1ES 0347–121	0.185	57.35	−11.99	J0349.2-1158	44.3	H.E.S.S.	2006
1ES 0414+009	0.287	64.22	1.09	J0416.8+0104	55.8	H.E.S.S.	2005-2009
						VERITAS	2008-2011

- 9 TeV blazars
- Elmag code (Blytt et al. 2020) to simulate the cascade emission

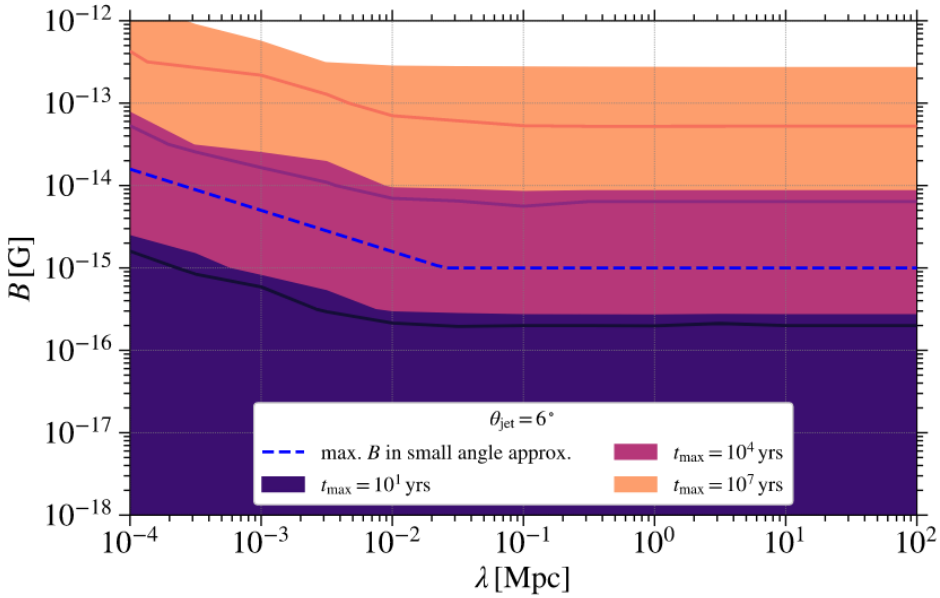
Ackermann et al. 2018

- Marginalization over the VHE intrinsic spectral shape
- θ_{jet} = 1°, 3°, 6° and 10°
- Stability of the TeV flux over the time activity
- Stacking analysis

Lower bounds on IGMF from Fermi coll.



Ackermann et al. 2018



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

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

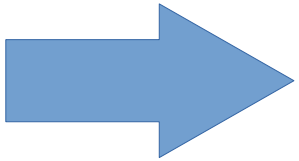
Stacking analysis, $T_{activity}$=10, 10^4 and 10^7 years, θ_{jet}=6°:

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

Can we do better?

- 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

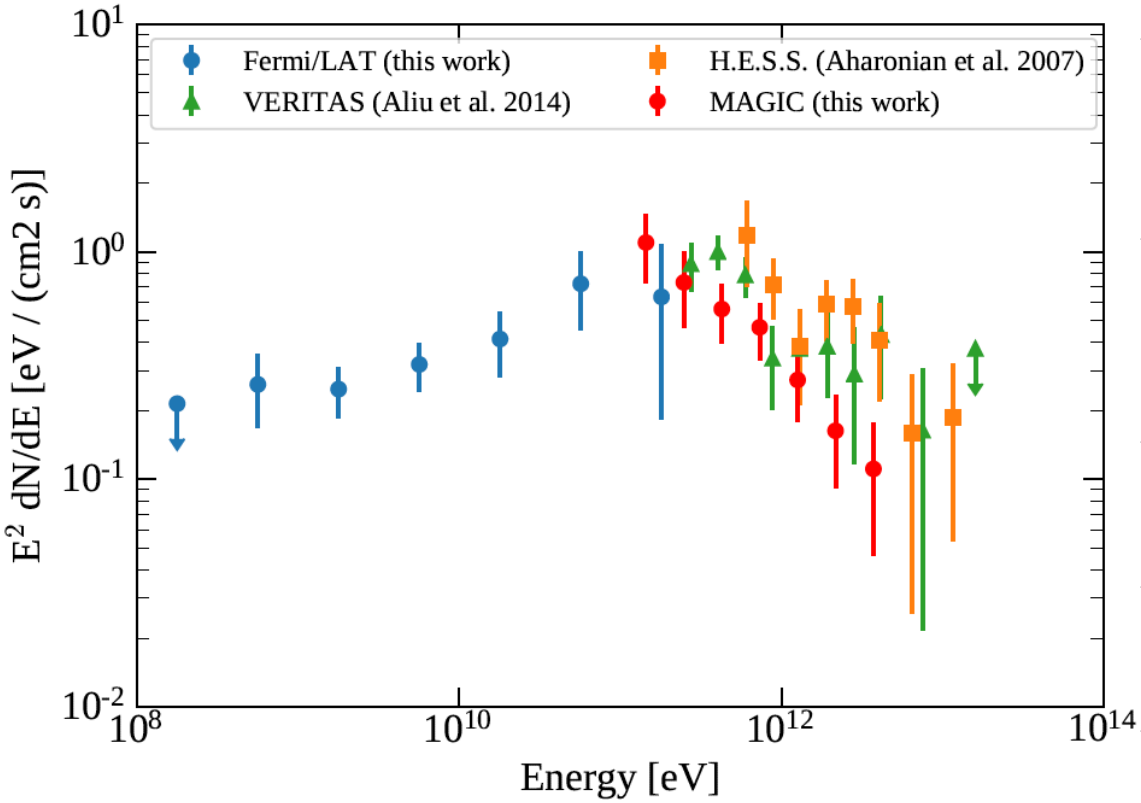


A more reliable lower bound can be obtained taking into account the variability pattern of the source in the VHE band that can be inferred from the observations

The MAGIC telescopes

- Energy resolution ~50 GeV
- FOV 3.5°
- Energy Resolution ~16% (E>300 GeV)
- Angular resolution ~0.06° (E>300 GeV)
- Sensitivity (5σ in 50 hours) ~0.8% Crab Nebula flux (>250 GeV)

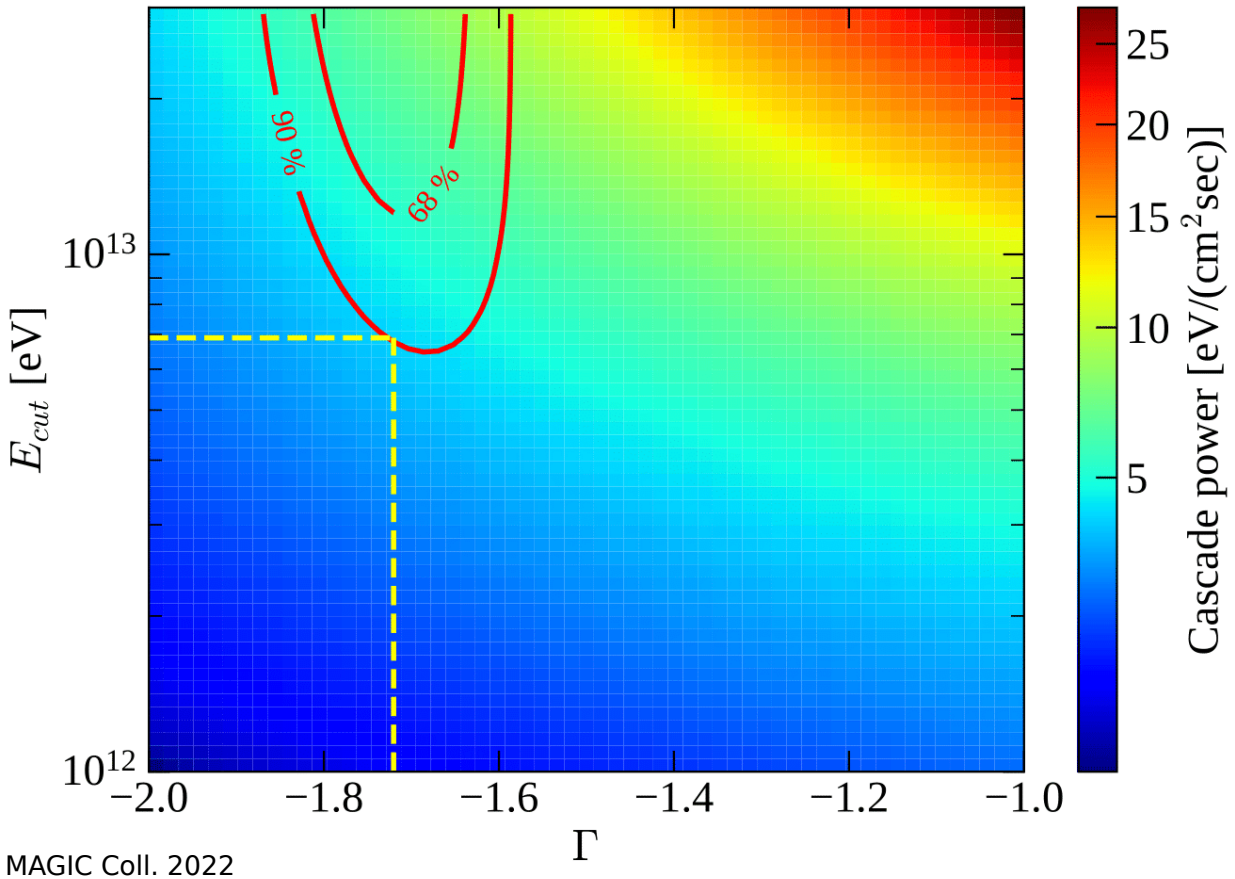
1ES 0229+200: γ-ray spectrum



MAGIC Coll. 2022

- Data sample: September 2013 – December 2017. Totally we collected about 140 hours of data
- The joint spectrum is described by a simple EBL absorbed powerlaw 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 4.8σ level
- Variability timescale of ~500 days

Minimal expected cascade estimate and source modeling



MAGIC Coll. 2022

- Following the approach of Neronov et al. 2010 we looked for the softest spectrum 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: $\Gamma \approx 1.72$, $E_{cut} \approx 6.9$ TeV

Numerical modeling of cascade emission

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

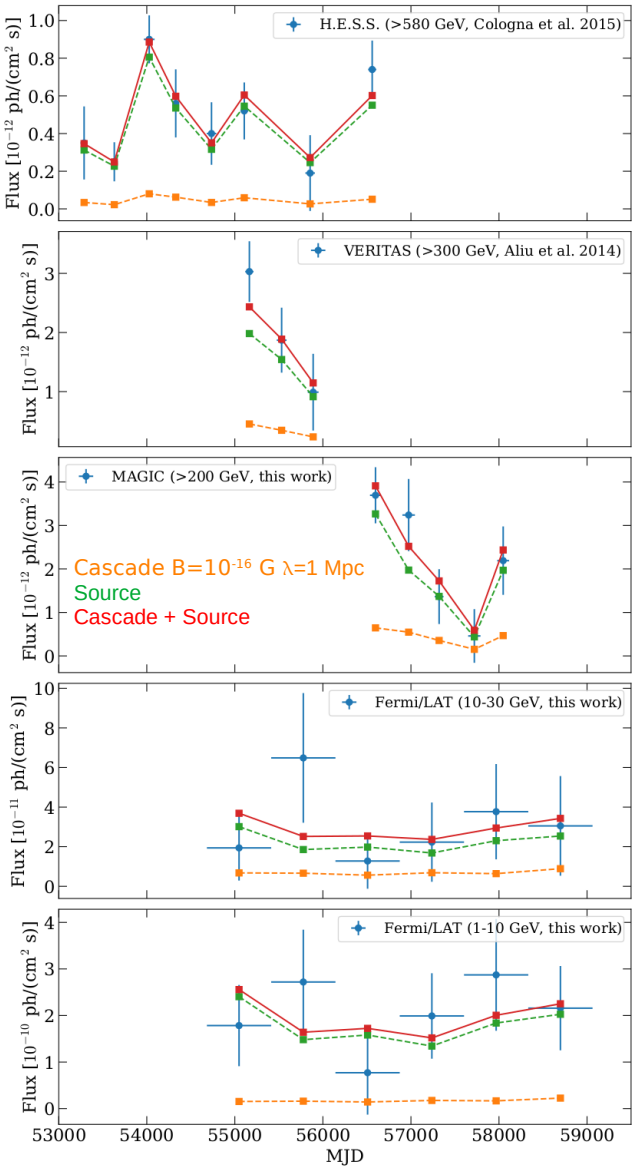
- Source model: Powerlaw with exponential cutoff, jet emission within a con of 10 deg

- $G(E_0,E,t,B,\lambda)$ 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

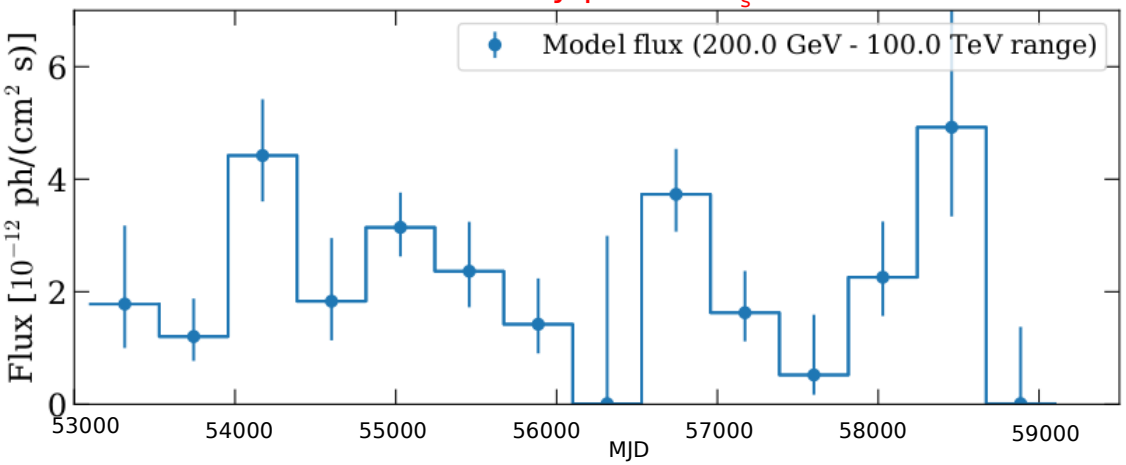
$$F_c(E,t) = \int_0^\infty \int_E^\infty G(E_0, E, t-\tau, \tau) F_s(E_0, \tau) dE_0 d\tau$$

(*)https://github.com/CRPropa

Lightcurves: fit results



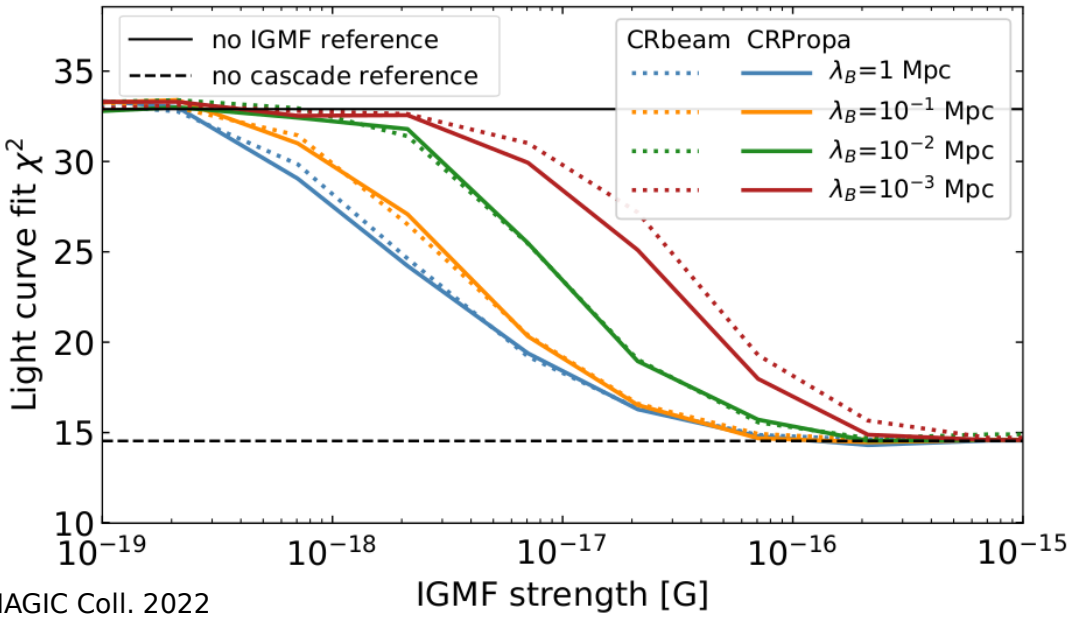
Variability pattern F_s



- The variability pattern is inferred from the VHE lightcurves
- The suppression of the signal is entirely due to the dilution in time (the signal is well within the PSF)
- For $B=10^{-16}$ G and $\lambda=1$ Mpc the cascade is almost suppressed in all energy bands so that we cannot exclude this particular IGMF configuration

Lightcurves: fit results

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



MAGIC Coll. 2022

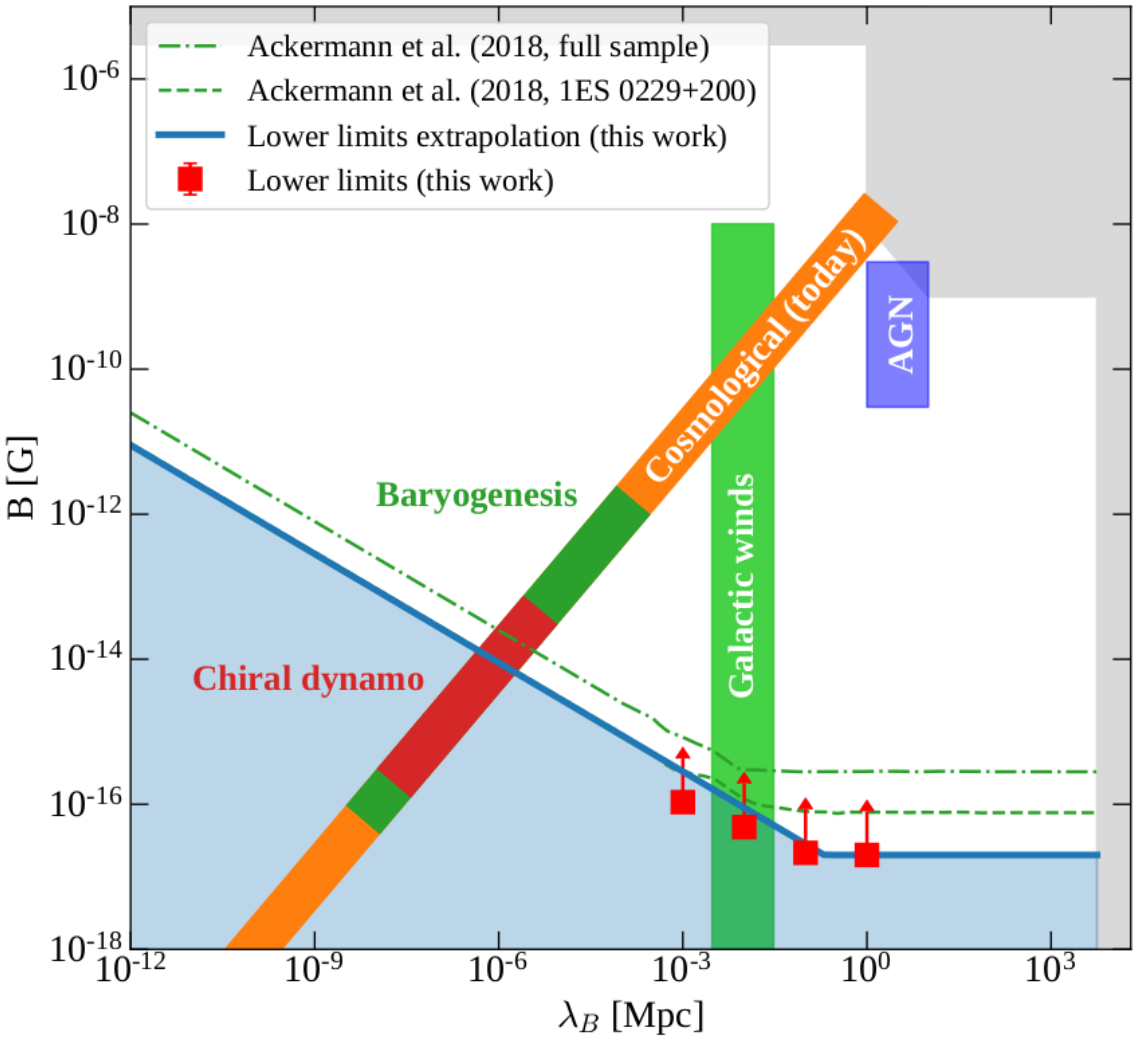
- The energy band in which we are most sensitive to the delayed emission is 1-10 GeV

$$\lambda_{IC}(E = 1\ GeV) \simeq 0.2\ Mpc$$

$$B \gtrsim \begin{cases} 1.8 \times 10^{-17}\ \mathrm{G} & , \lambda_B > 0.2\ \mathrm{Mpc} \\ 1.8 \times 10^{-17}\,(\lambda_B/0.2\ \mathrm{Mpc})^{-1/2}\ \mathrm{G} & , \lambda_B < 0.2\ \mathrm{Mpc} \end{cases}$$

95% confidence level

Conclusions



- The derived lower bound is weaker but more robust than the one reported by Fermi coll. Because we take into account the variability of the source in the VHE band
- In the case of cosmological fields our limit is at the level of $B_{cosmological} \geq 10^{-14}$ G
- The detection of ~10 yr delayed signal for z~0.1 requires systematic monitoring in both TeV and 1-100 GeV bands

Caveats and future perspectives

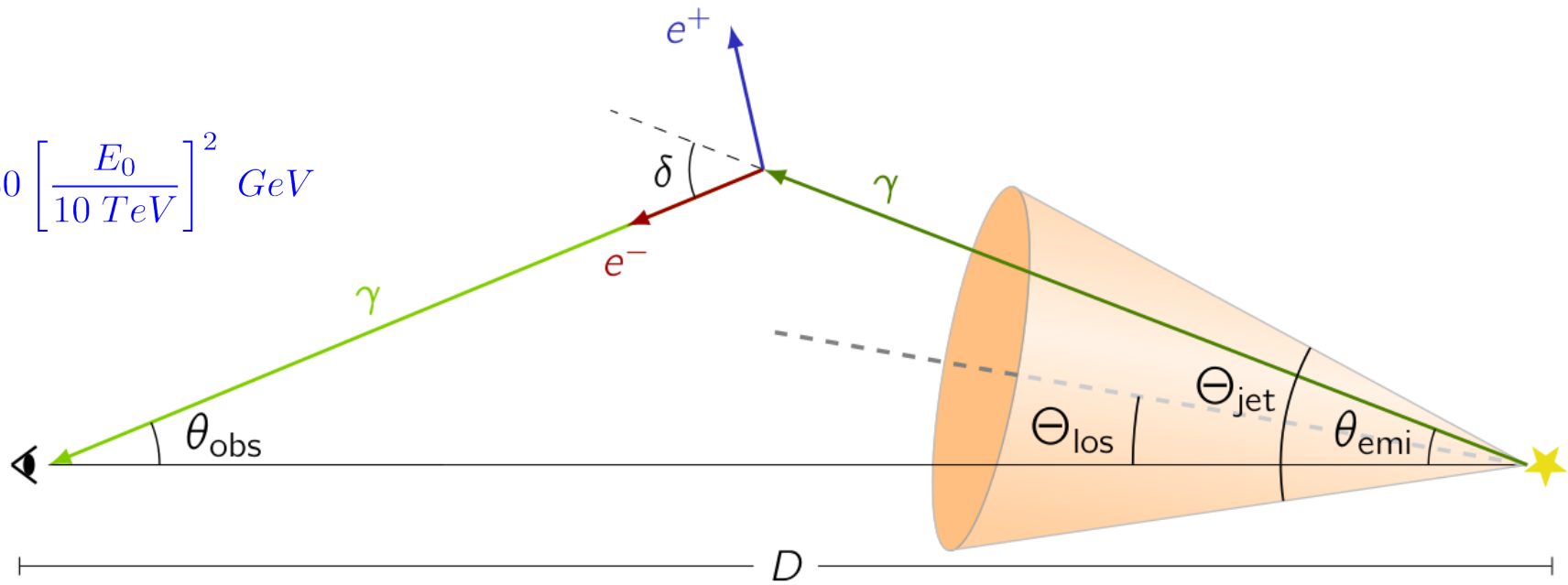
- We need more sources 1ES 0229 like → CTA ?
- The monitoring of Extreme TeV sources in the VHE band is crucial.
- Extended emission? No detection up to now…
- What about variable sources?
  - GRBs…(-→ see the talks by Guillem Martì-Devesa and Davide Miceli)
  - Can we exploit the huge archive of VHE flares from blazars?
- In spite of a very big effort in the last 10 years, the cascade emission has never been detected:
  - Plasma instabilities?

Back up

Cascade emission: modeling

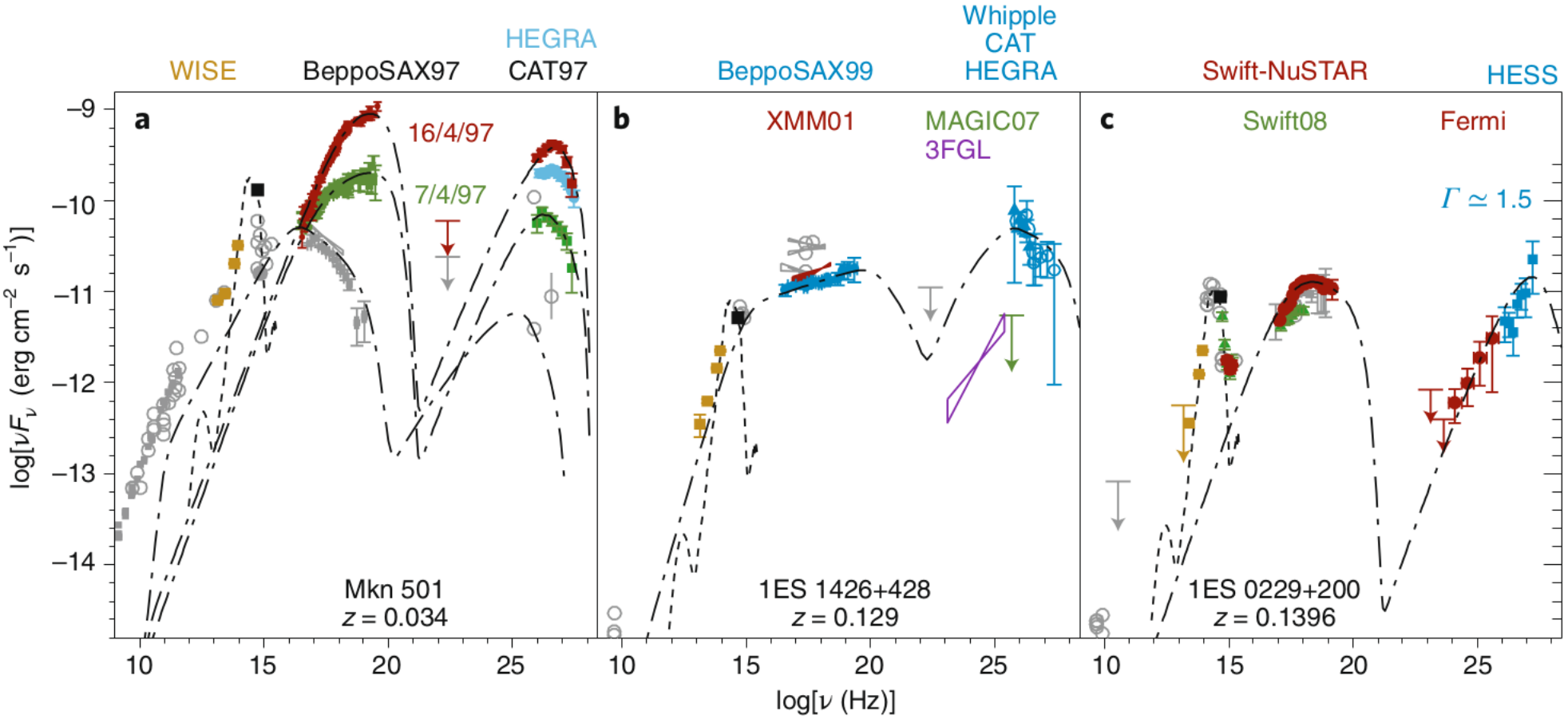
- Given a particular VHE intrinsic spectrum the cascade emission can be modeled

$$E \simeq 80 \left[\frac{E_0}{10\ TeV}\right]^2\ GeV$$



Alves Batista & Saveliev 2021

Extreme High frquency BL-Lac (EHBL)



Prandini et al. 2020

1ES 0229+200: MAGIC observations

- MAGIC observed the source during the period September 2013 – December 2017. Totally we collected about 140 hours of data