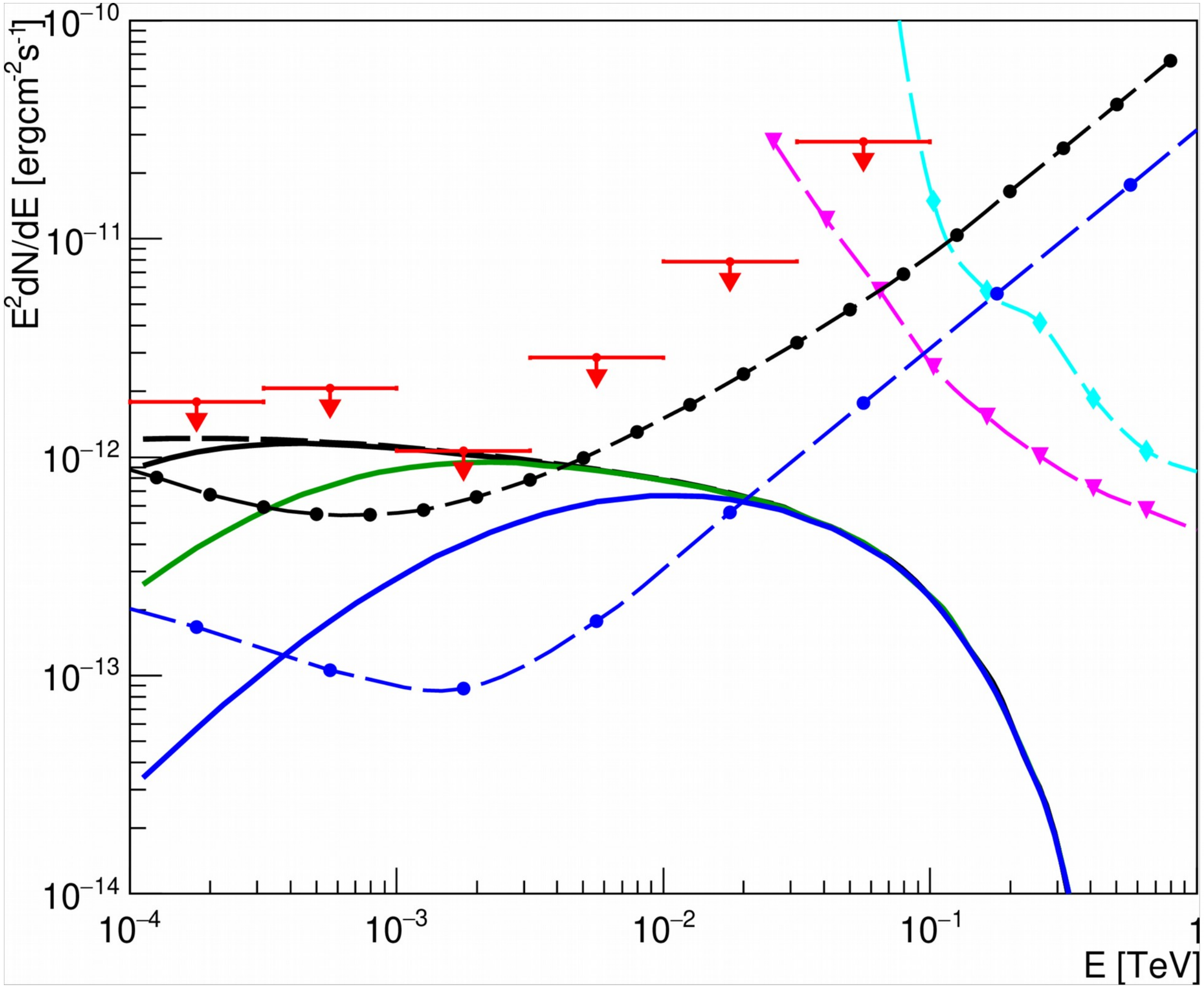
Intergalactic electromagnetic cascades: γ-ray bursts vs. blazars



Timur DZHATDOEV (Moscow State University) timur1606@gmail.com
Vladimir GALKIN, Emil KHALIKOV, Egor PODLESNYI, Igor VAIMAN

4 Dec. 2020

This talk is based on:

1) Dzhatdoev et al., astro-ph/2002.06918 (2020), accepted for publication in Phys. Rev. D

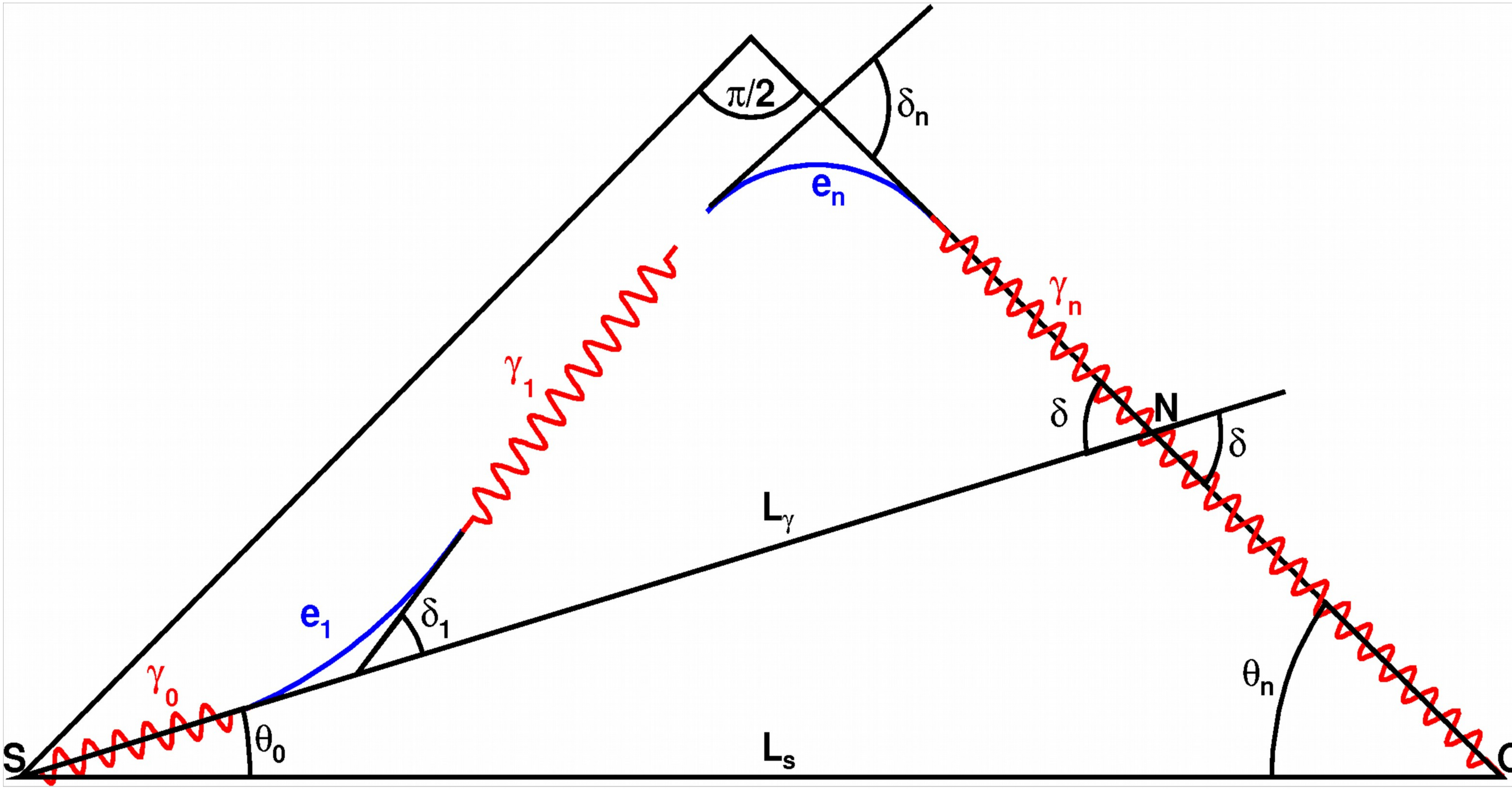
2) Khalikov & Dzhatdoev, astro-ph/1912.10570 (2019)

3) Dzhatdoev et al., A&A, **603**, A59 (2017) (https://github.com/timur1606/Cascade-Masquerade/blob/master/Cascade-Masquerade-2017.zip)

4) Dzhatdoev & Podlesnyi, APh, **112**, 1 (2019)

Primary γ-rays produce secondary electrons and positrons on extragalactic background light (EBL) photons
(for a review please see the talk of M. Ajello)

I consider the "fate" of these electrons



Deflection, time delay, and production of secondary (cascade) γ-rays via inverse Compton scattering

Why intergalactic electromagnetic cascades are important?

1. A probe of the extragalactic magnetic field (EGMF)!
2. A background for axion-like particle (ALP) searches!
3. Ultrahigh cosmic ray (UHECR) – γ-ray connection!
4. Some models represent an existential threat for precision γ-ray cosmology!!

(for instance primary UHECR → (photohadronic or Bethe-Heitler) → intergalactic cascade → observable γ-rays)

The objective of this talk:

I. Review the "core" papers (all of them are at least 8 years old)

II. How the status of the field has changed

III. Any robust results (even if negative)?

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8 "core papers" (1790 citations indexed in NASA ADS)

1) Plaga (1995)

2-4) Essey et al. (2010a,b; 2011) 5) Murase et al. (2012)

6) Neronov& Vovk (2010) 7) Tavecchio et al. (2010) 8) Dermer et al. (2011)

Any robust results (even if negative)?

The dark side (Lasciate ogni speranza, voi ch'entrate...)

Sisyphus trying to detect cascade γ-rays from GRBs

I. The probe of the EGMF with GRBs will be virtually ruined for the foreseeable future

II. One popular model of extreme blazars will be confronted with structure formation models and up-to date experimental data

"Always Look On The Bright Side Of Life" ©

I. The background for $\gamma \to$ ALP searches will be shown to be not too dangerous

II. Concerning the EGMF, almost all possibilities are still open!

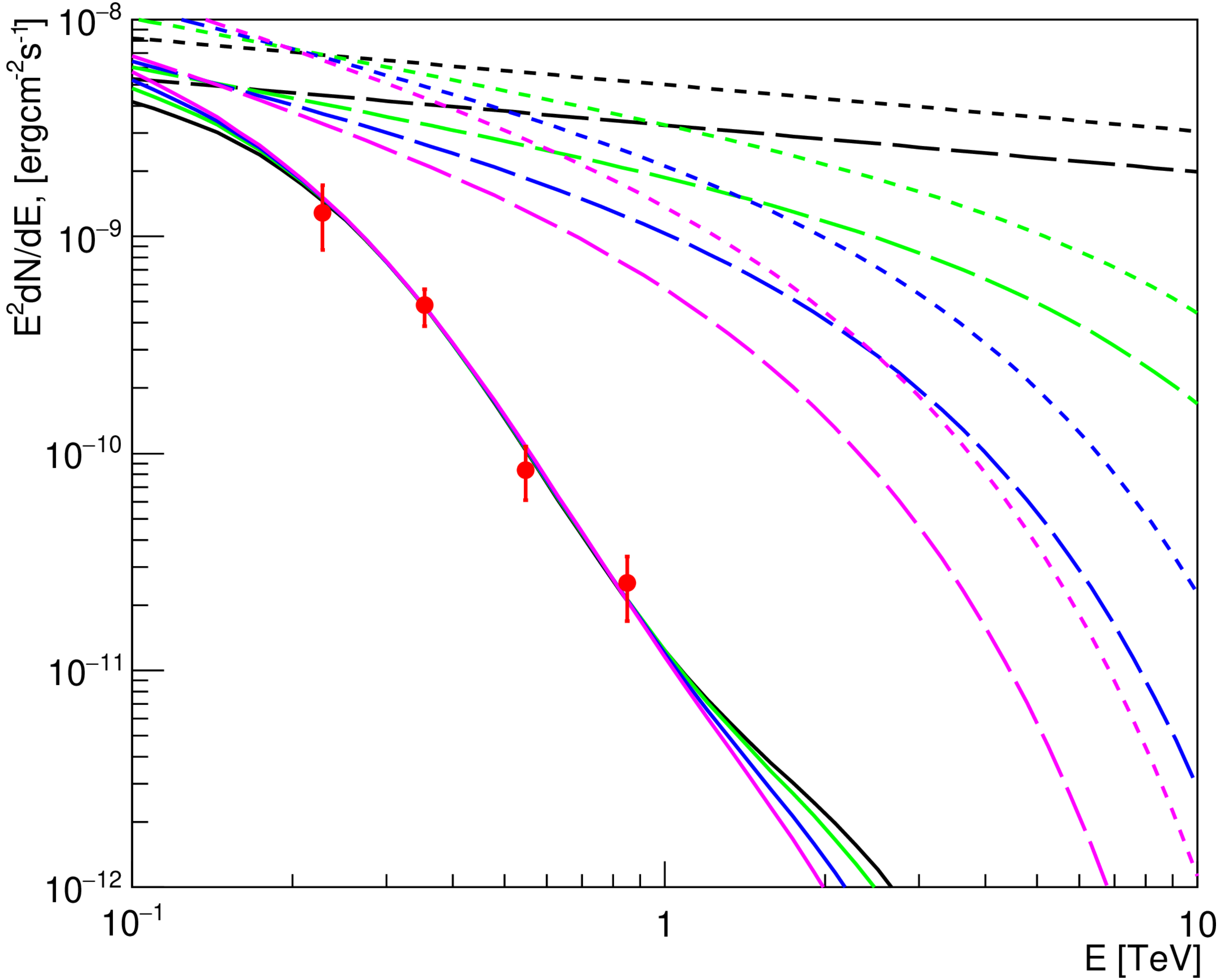
III. The mechanism beyond the peculiar behaviour of extreme TeV blazars will be unveiled

I. To measure the EGMF with GRB observations?

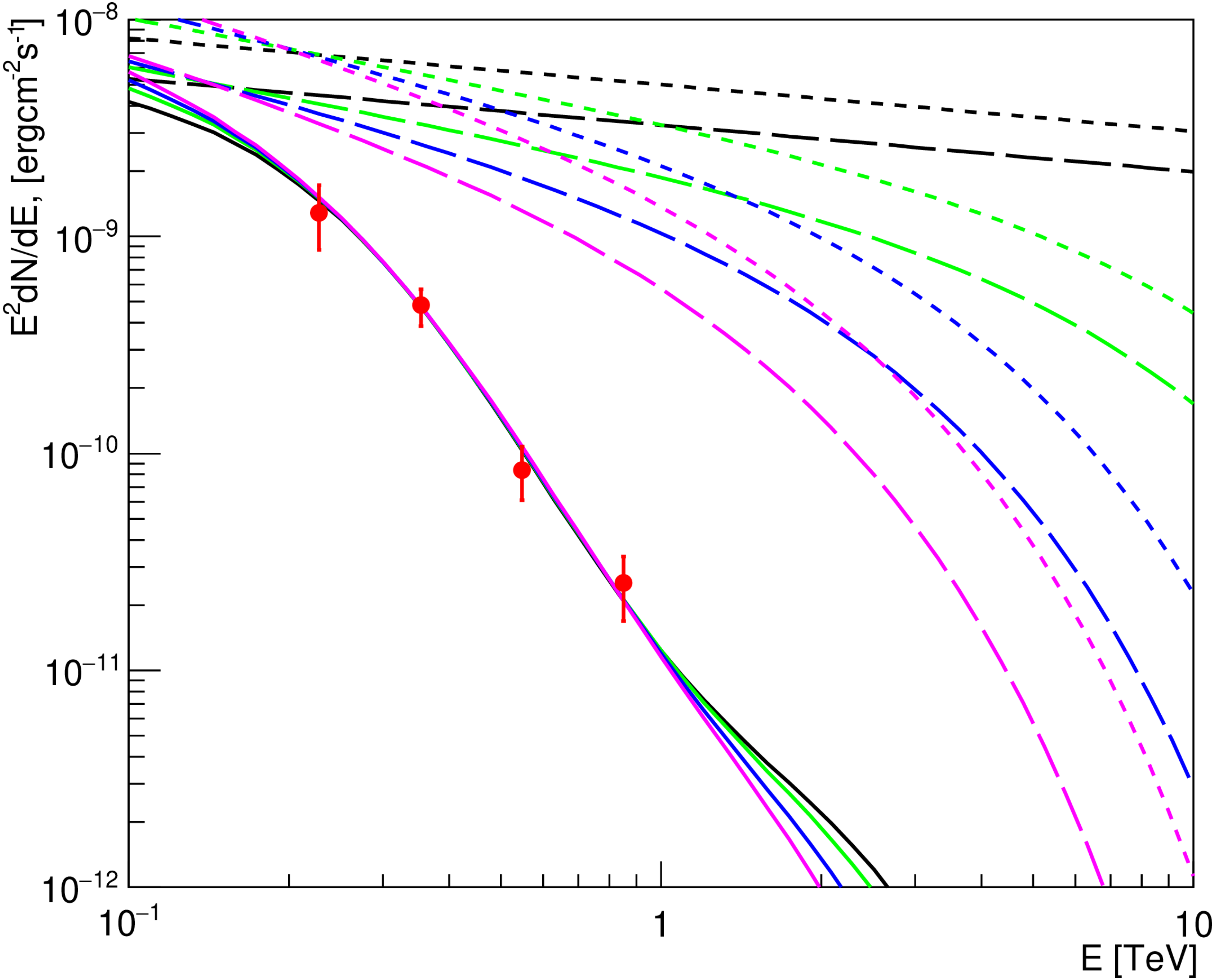
Plaga, Nature, **374**, 430 (1995)

“Here I propose a highly sensitive method IGMFs by exploiting their effect on the arrival times of γ-rays from extragalactic sources. The delay in arrival owing to the action of intergalactic magnetic fields on electron cascades caused by scattering of the γ-ray photons might be used to measure fields as weak as 10^{-24} gauss. I suggest that this effect may already have been seen in the arrival times of high-energy photons after the main burst of a γ-ray burster.”

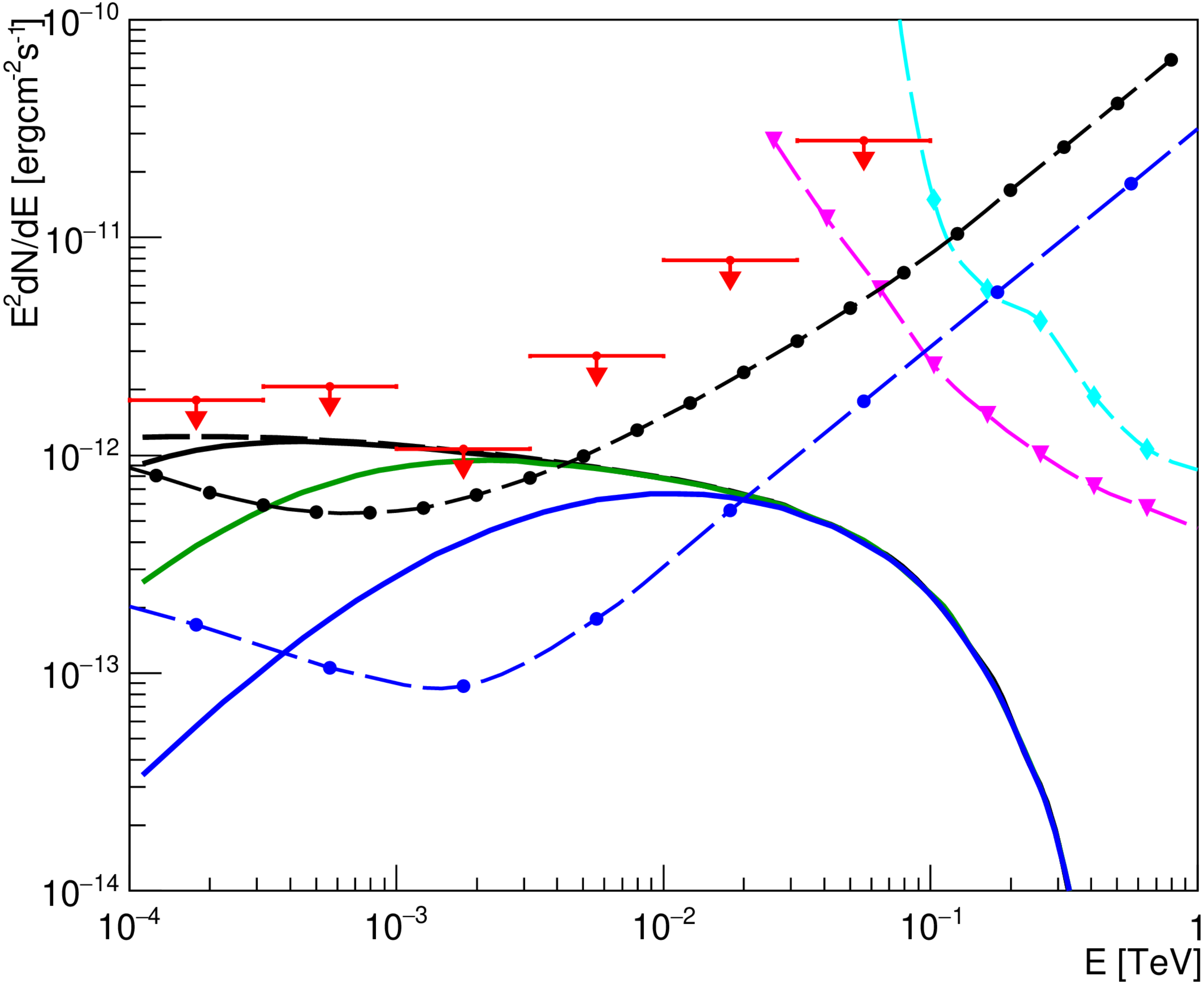
Spectral energy distribution (SED) of GRB 190114C measured with MAGIC;
fits assuming “nominal” Gilmore at al. EBL (black), 90 %, 80 %, 70 %;
primary spectra leaving the source: short-dashed



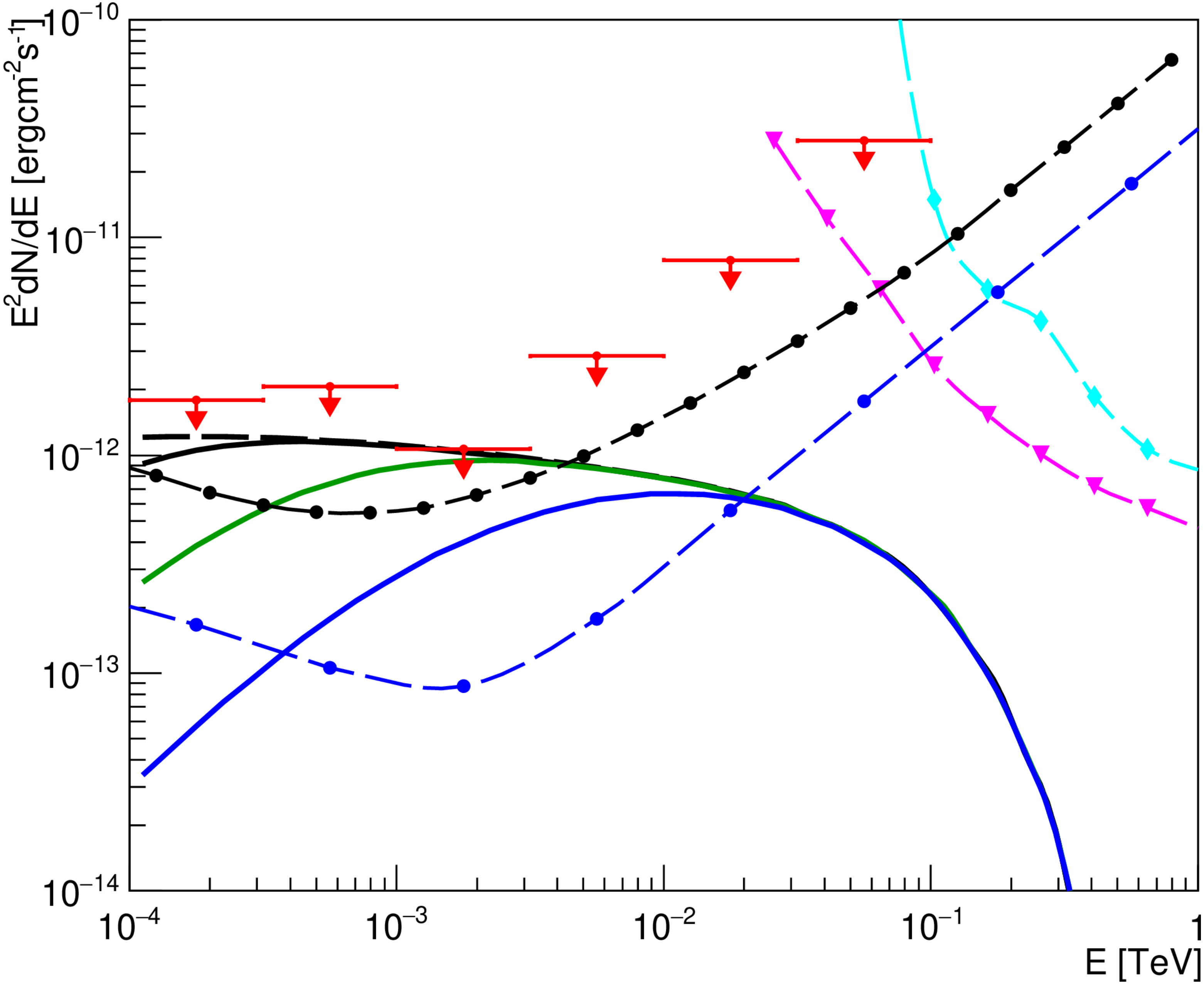
At E>1 TeV, for the 70 % EBL the primary intensity is much smaller than for the "nominal" (100 %) EBL normalization!



Fermi-LAT upper limits on the SED of GRB 190114C (20 000 s – 1 month); observable cascade SEDs (B= 0 – dashed black, B= 10^{-20} G – solid black, B= 10^{-19} G, B= 10^{-18} G).

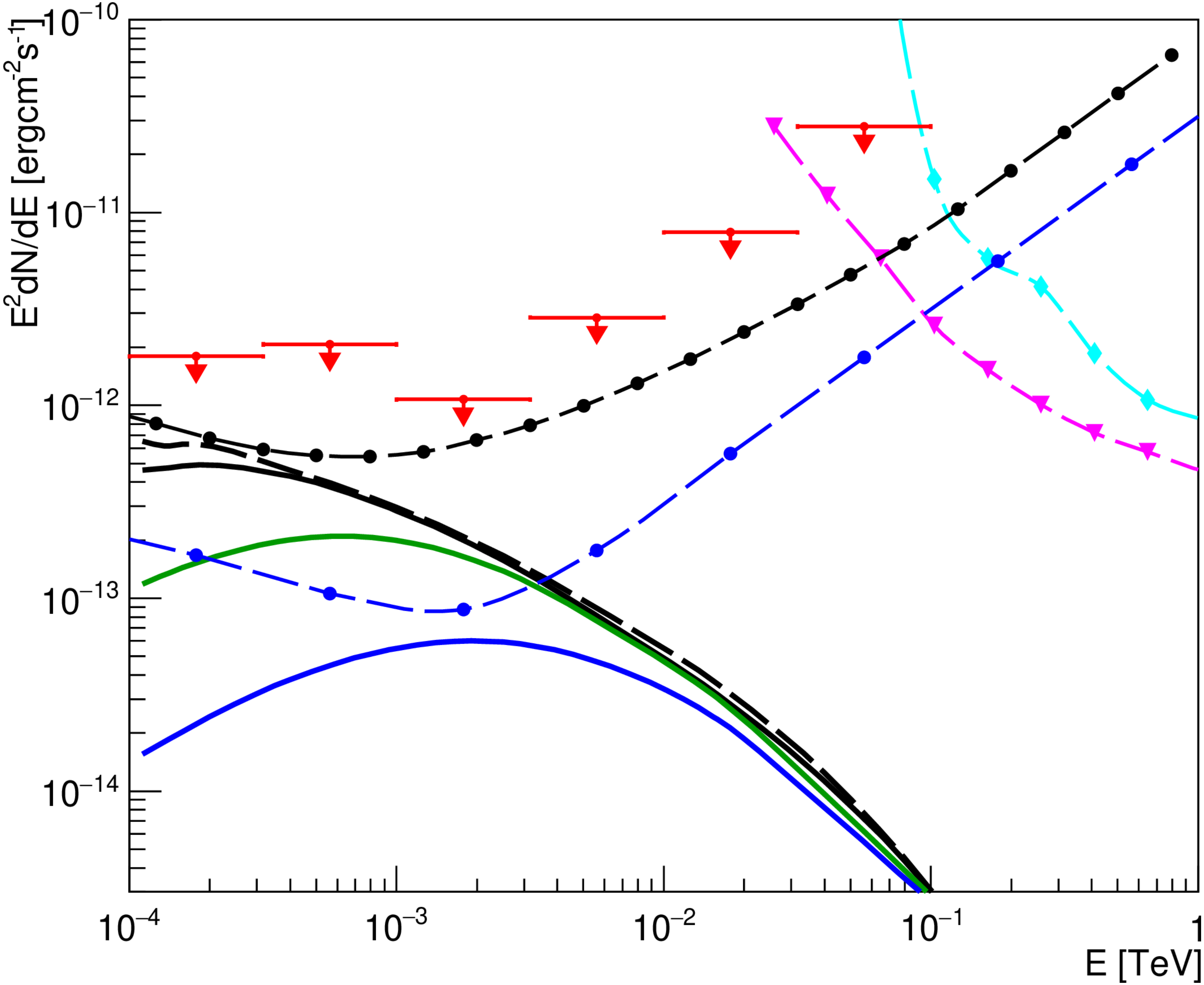


CTA: 5 hours (20 deg, 60 deg)
MAST project ("Massive Argon Space Telescope",
Dzhatdoev & Podlesnyi, APh, 112, 1 (2019)): circles; 2σ, 5σ



The same for the 70 % G12 EBL

The cascade signal is not detectable even for B=0



II. UHECR-γ-ray connection?

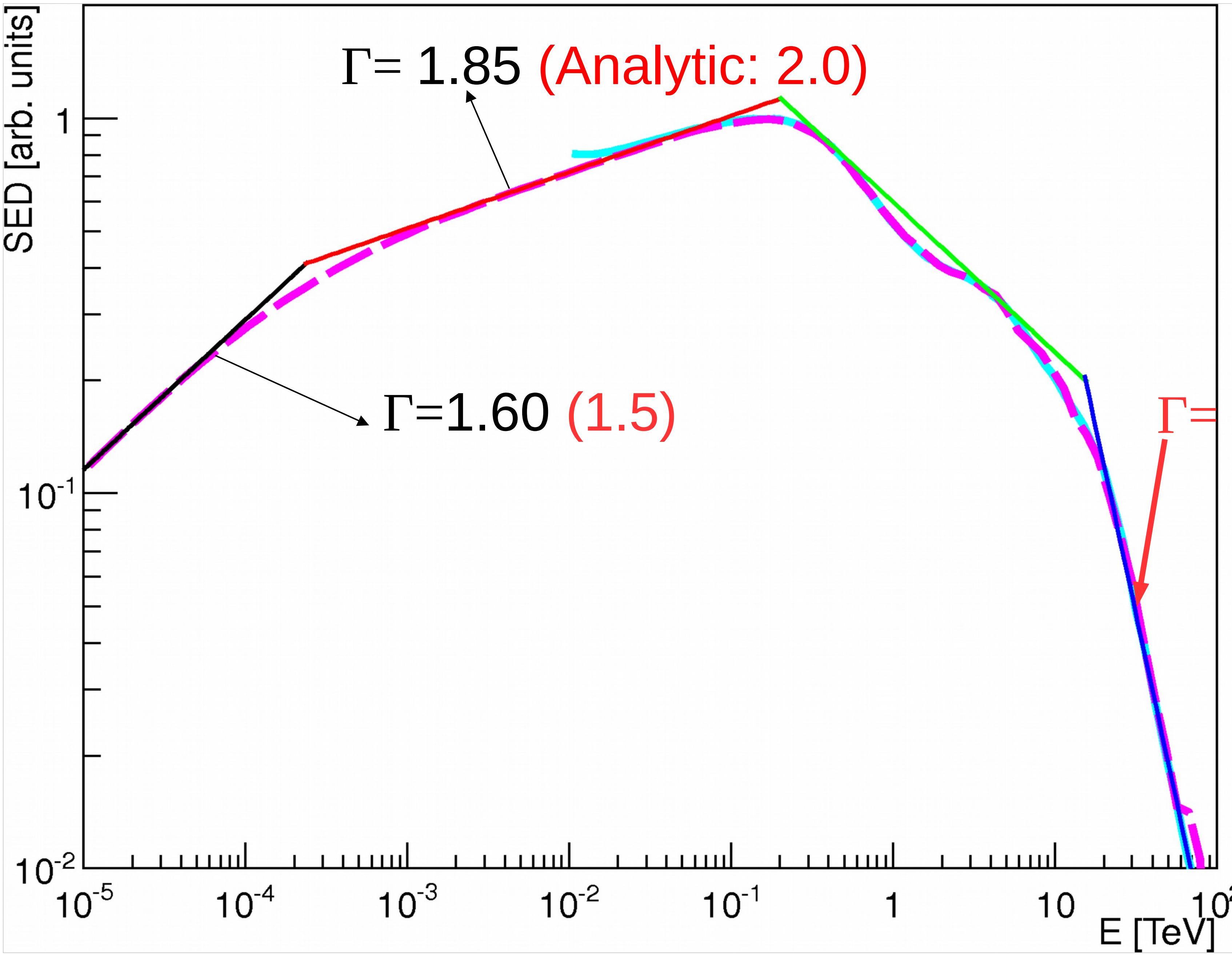
Essey & Kusenko, APh, 33, 81 (2010)

"Gamma-ray telescopes have reported some surprising observations of multi-TeV photons from distant active galactic nuclei (AGN), which show no significant attenuation. (...) We suggest a new interpretation of these observations (...) Cosmic rays with energies below 50 EeV, produced by AGN, can cross cosmological distances, interact with EBL relatively close to Earth, and generate the secondary photons observed by γ-ray telescopes. We calculate the spectrum of the secondary photons and find that it agrees with the γ-ray data."

Essey et al. (2011)

"The observed high-energy gamma-ray signals from distant blazars may be dominated by secondary gamma rays produced along the line of sight by the interactions of cosmic-ray protons with background photons. This explains the surprisingly low attenuation observed for distant blazars (...) Thus, the observed spectrum in the TeV range does not depend on the intrinsic gamma-ray spectrum, while it depends on the output of the source in cosmic rays. We apply this hypothesis to a number of sources and, in every case, we obtain an excellent fit, strengthening the interpretation of the observed spectra as being due to secondary gamma rays."

“Basic” intergalactic hadronic cascade model: all observable γ-rays are from protons/nuclei and protons do not meet any obstacle on their way.



EGMF in extragalactic filaments is already detected (Govoni et al., Science, **364**, 981 (2019))!

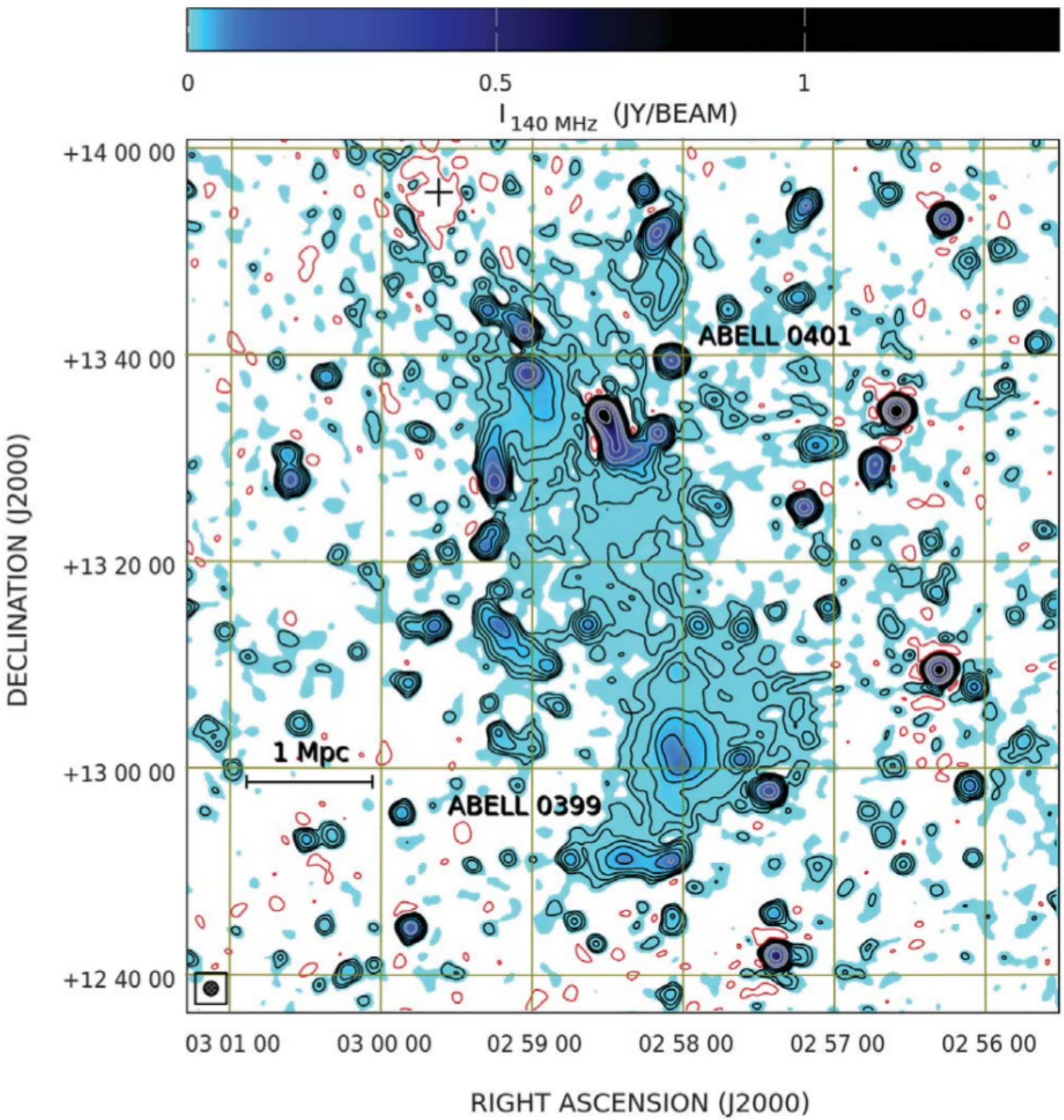
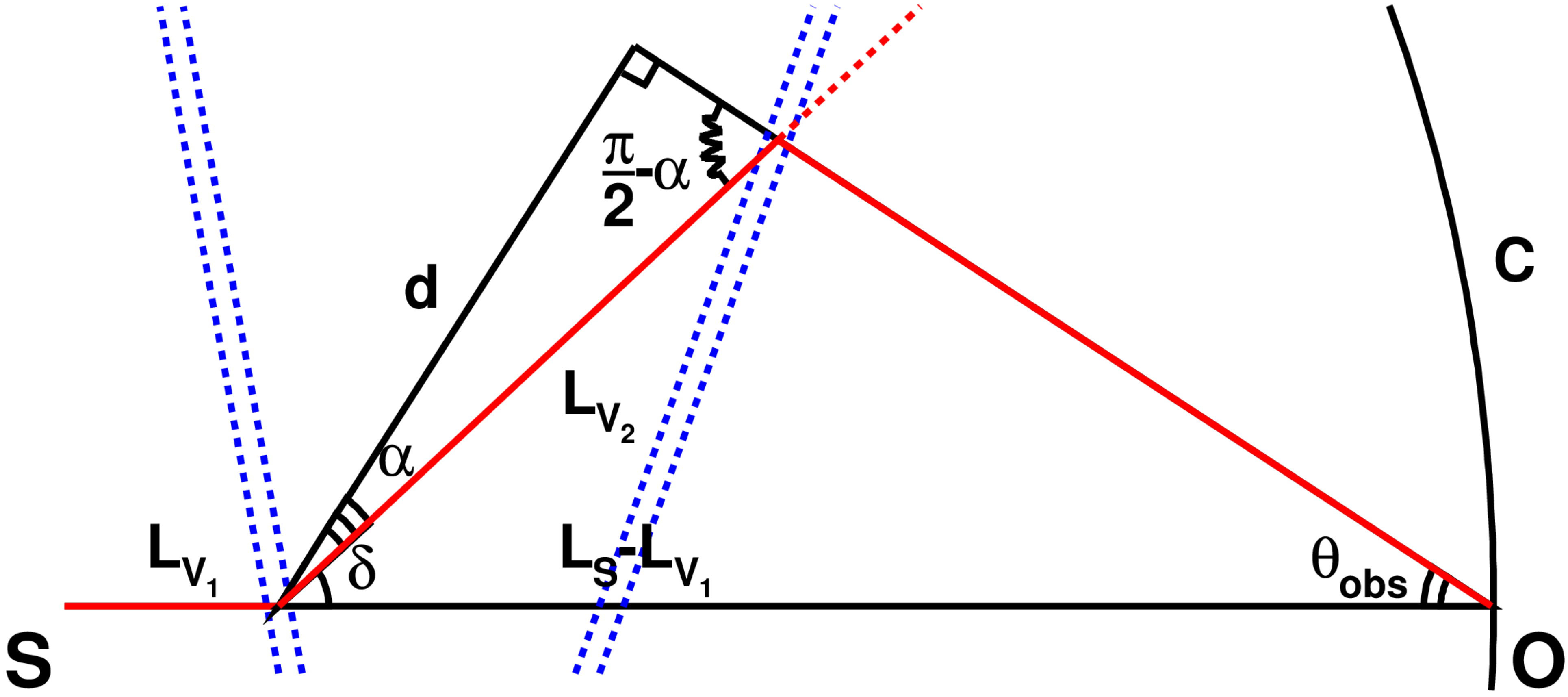


Fig. 1. LOFAR image of the 1.4° × 1.4° region centered on the Abell 0399–Abell 0401 system. Color and contours show the radio emission at 140 MHz with a resolution of 80 arc sec and RMS sensitivity of 1 mJy beam^{-1}. The beam size and shape are indicated by the inset at the bottom left. Contour levels start at 3 mJy beam^{-1} and increase by factors of 2. One negative contour (red) is drawn at −3 mJy beam^{-1}. The black cross (right ascension 02h 59m 38s, declination +13° 54′ 55″, J2000 equinox) indicates the location of a strong radio source that was removed from the image.

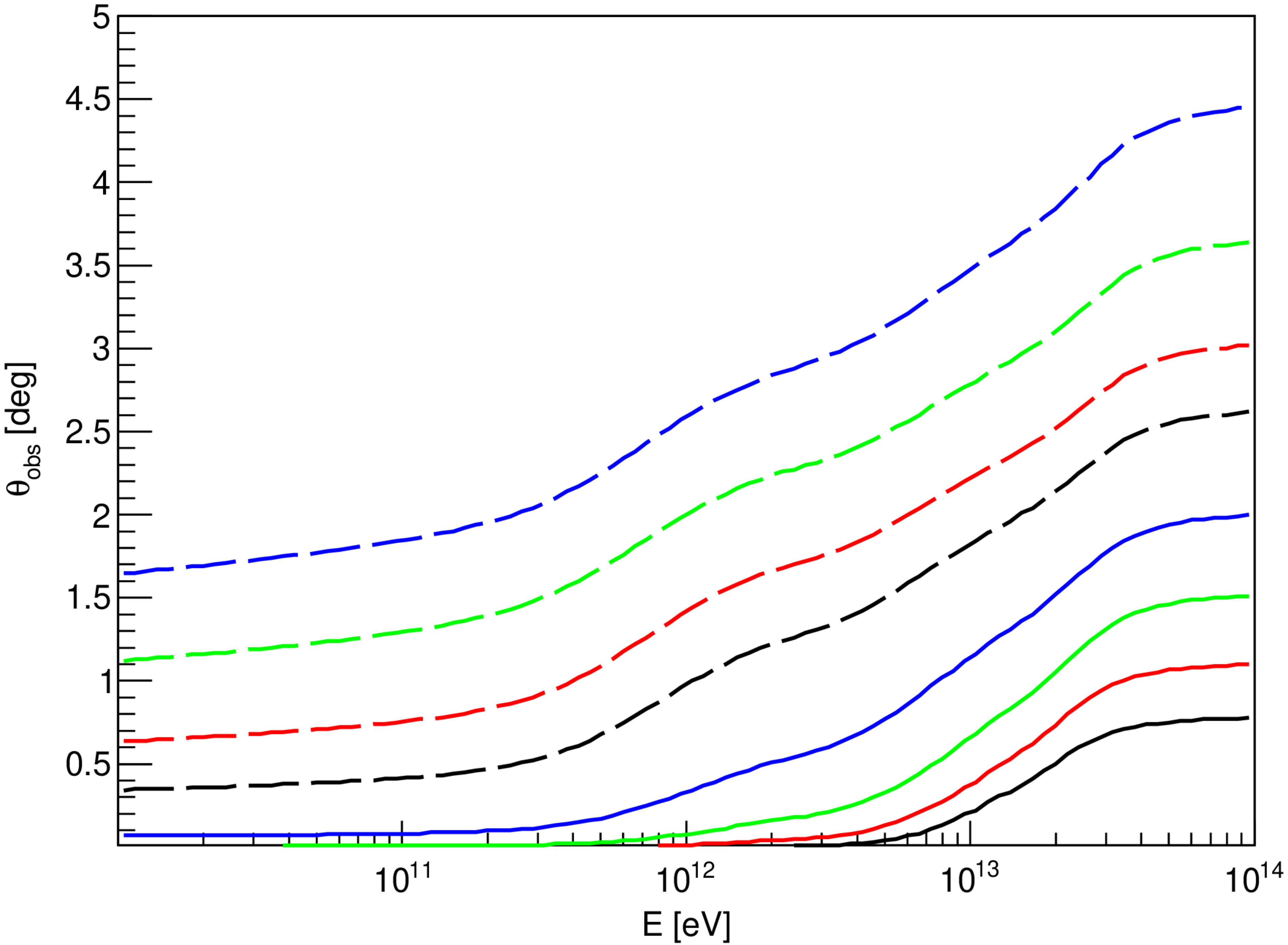
Filaments; primary proton path; observer (O)

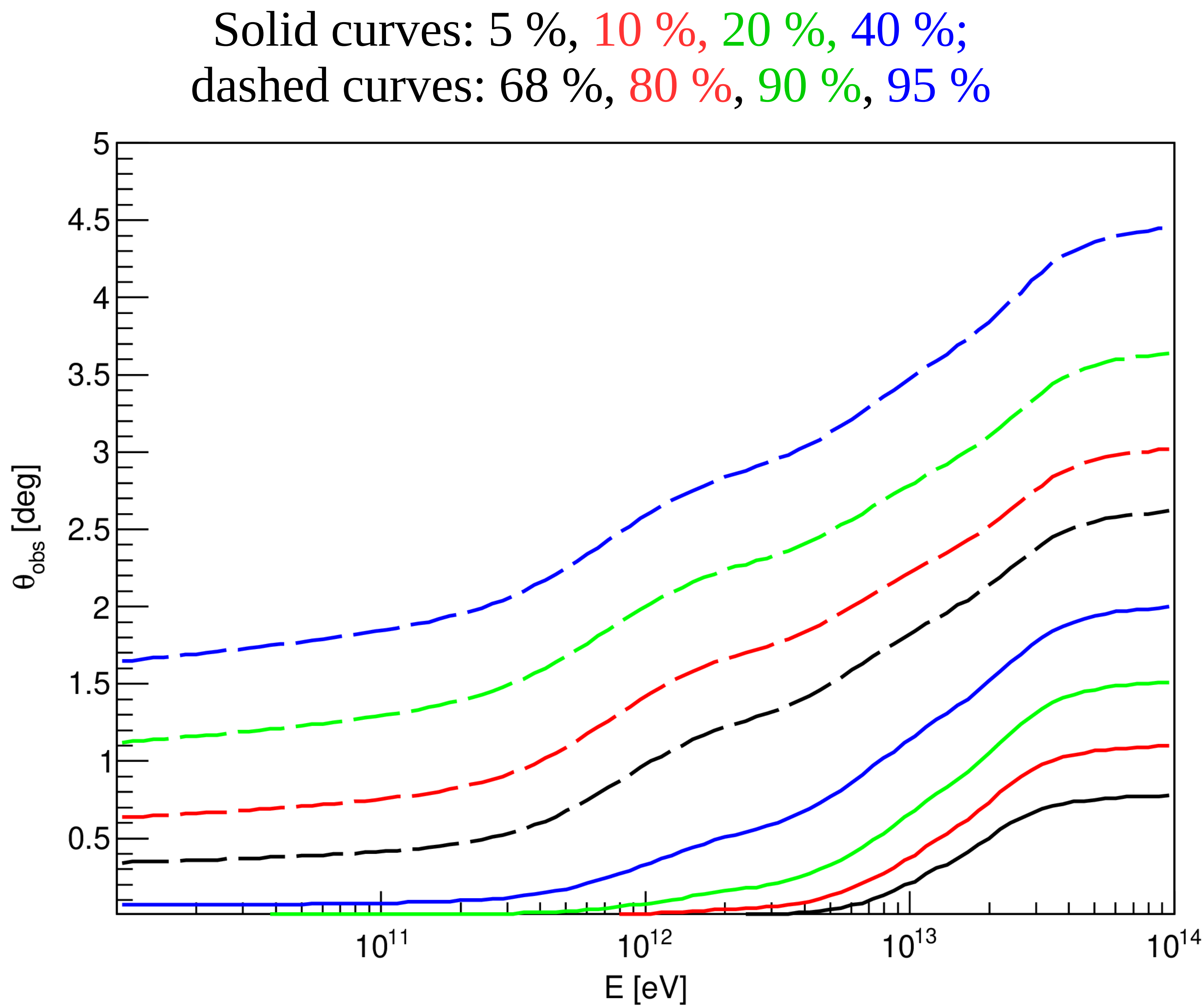


The source is extended!

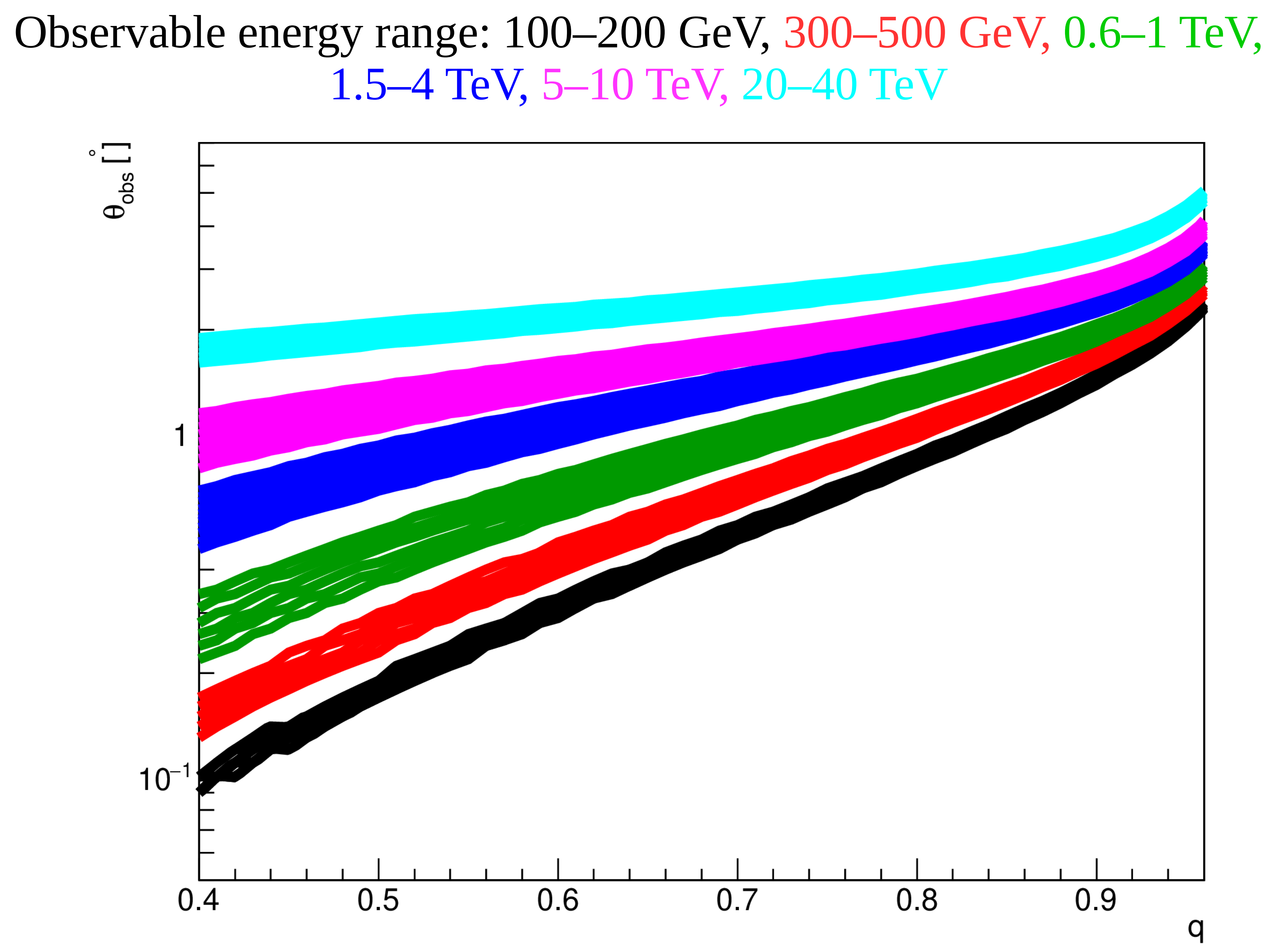
Let us assume the EGMF model of Dolag et al. (2005) (in filaments and voids)

Observable angular distribution



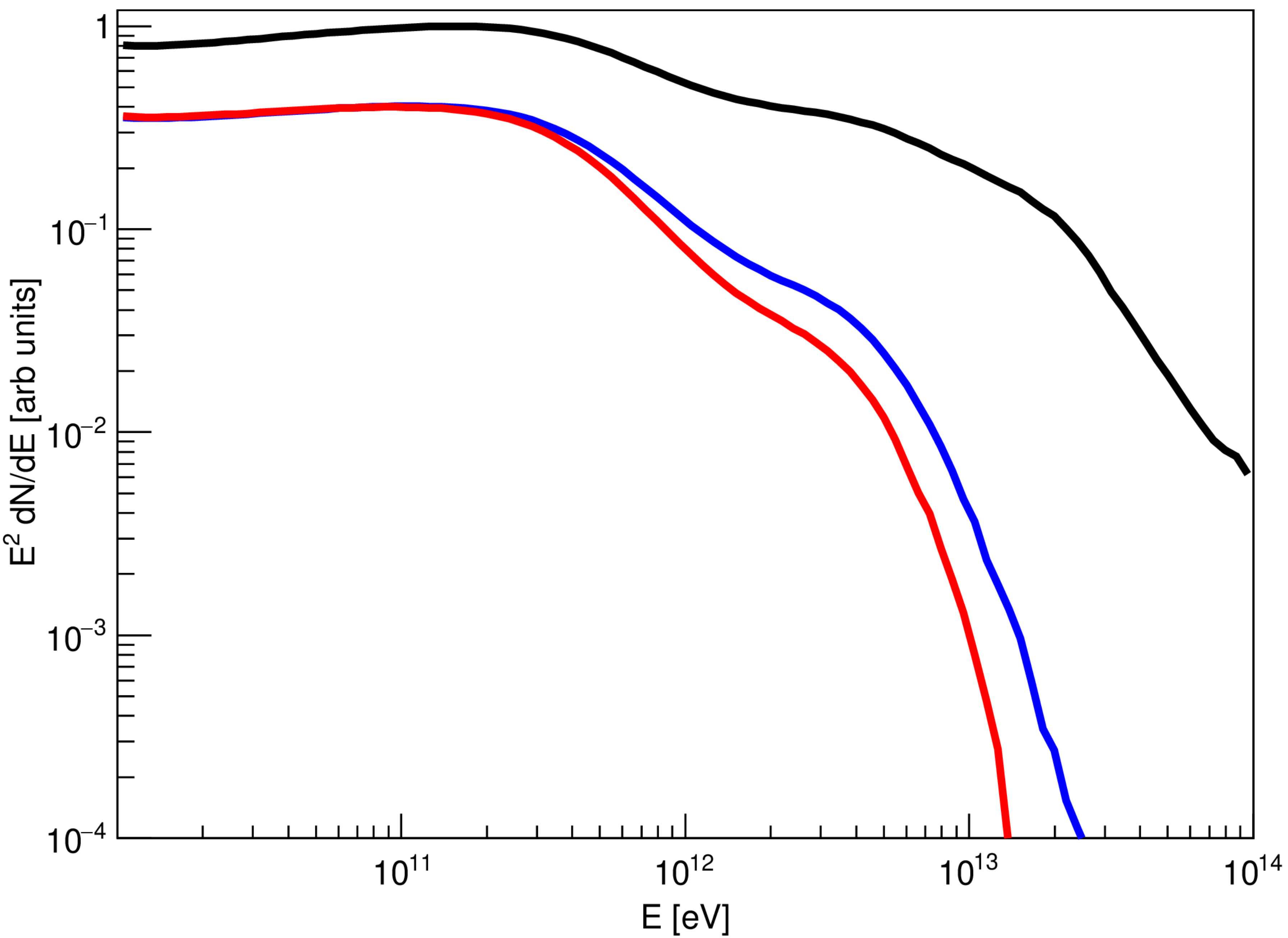


Solid curves: 5 %, 10 %, 20 %, 40 %;
dashed curves: 68 %, 80 %, 90 %, 95 %
θ_{obs} [deg]
E [eV]
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10^{11}
10^{12}
10^{13}
10^{14}

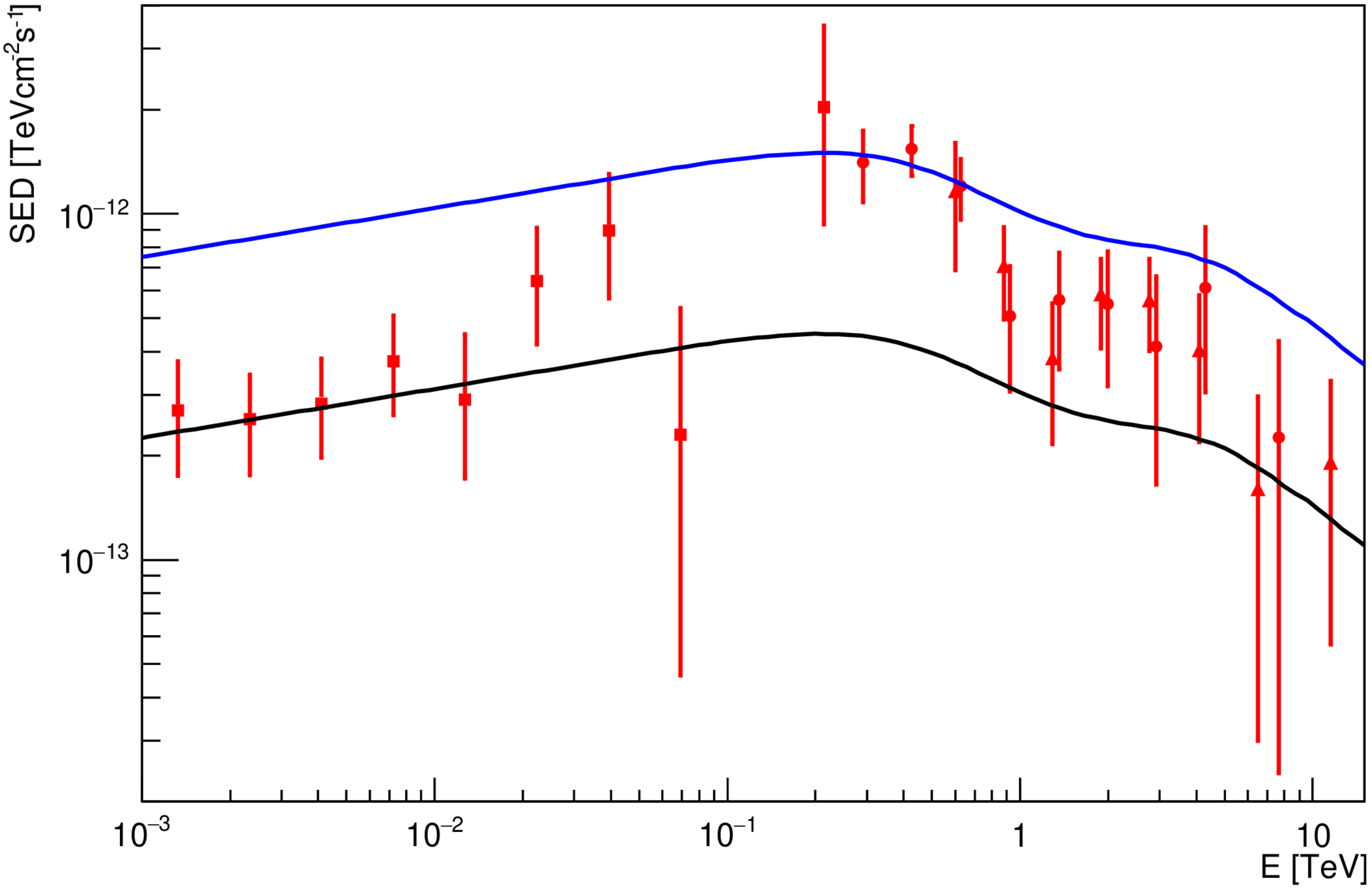


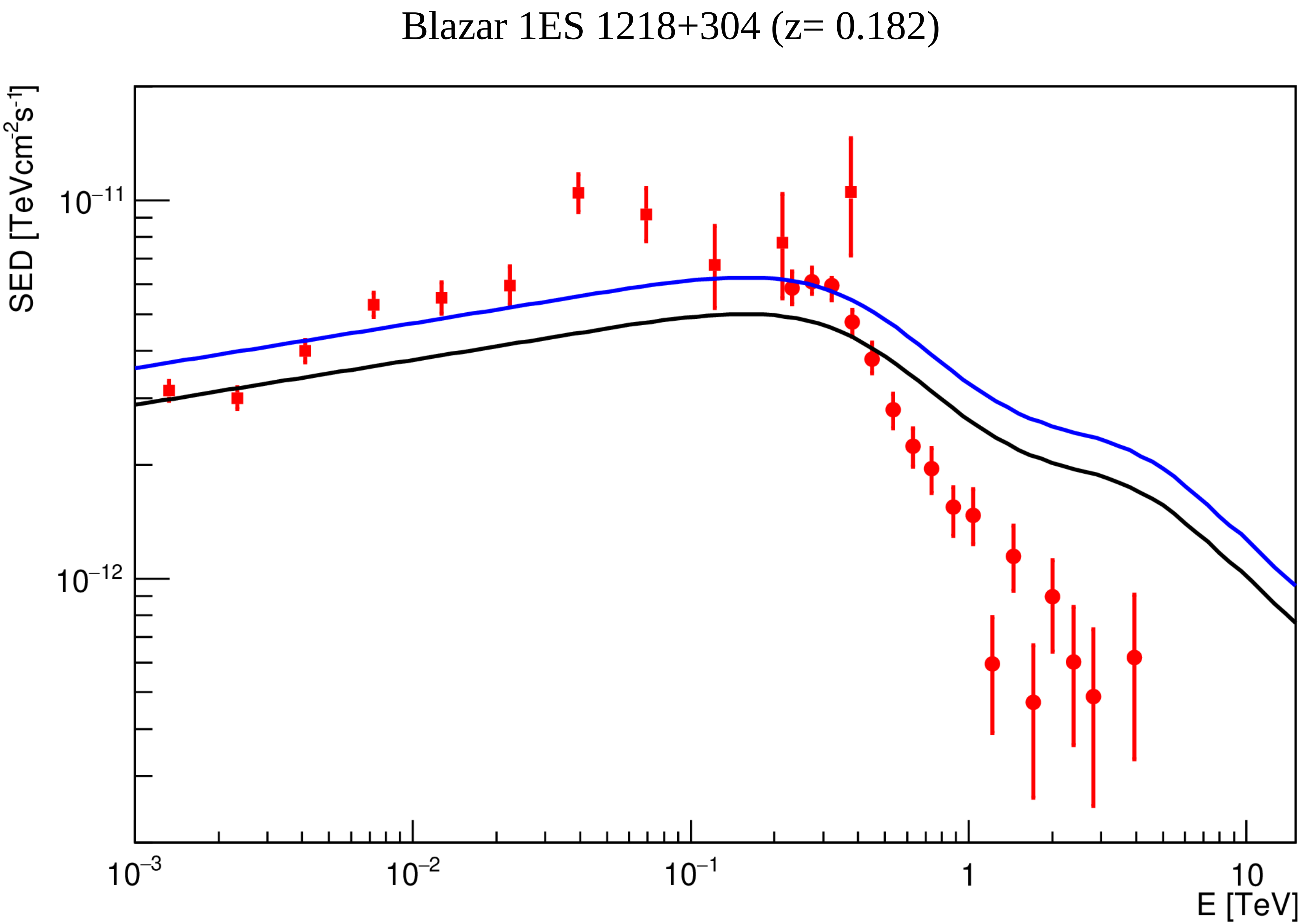
Observable energy range: 100–200 GeV, 300–500 GeV, 0.6–1 TeV,
1.5–4 TeV, 5–10 TeV, 20–40 TeV
θ_obs [°]
1
10^−1
0.4
0.5
0.6
0.7
0.8
0.9
q

“Basic model” (B=0); purely electromagnetic cascade;
“modified” model (the EGMF according to Dolag et al.)

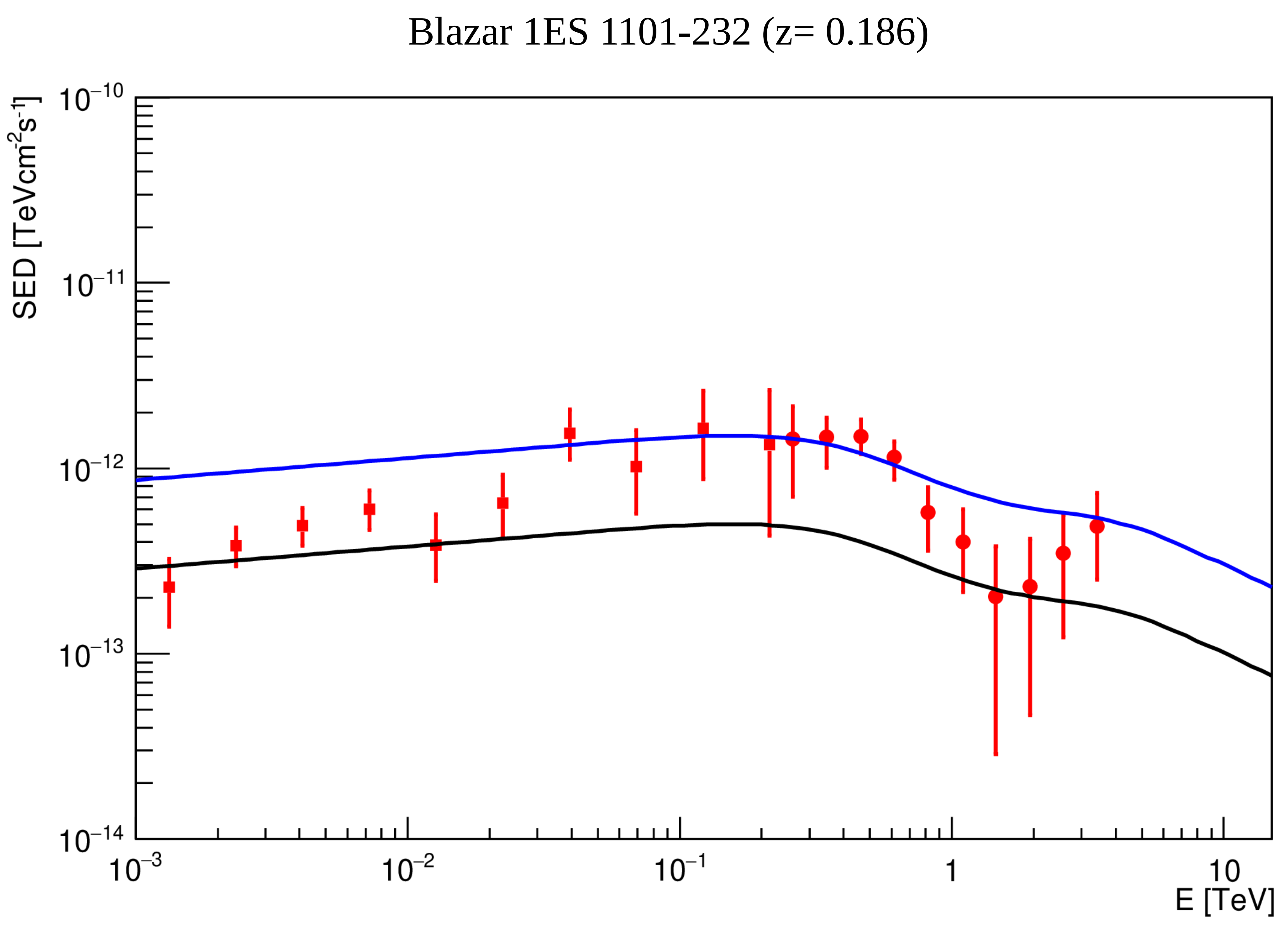


OK, let us set B=0. Is the agreement of the model with Fermi-LAT and imaging atmospheric Cherenkov telescope (IACT) data for the blazar 1ES 0229+200 (z= 0.14) any good? No, the agreement is not very good

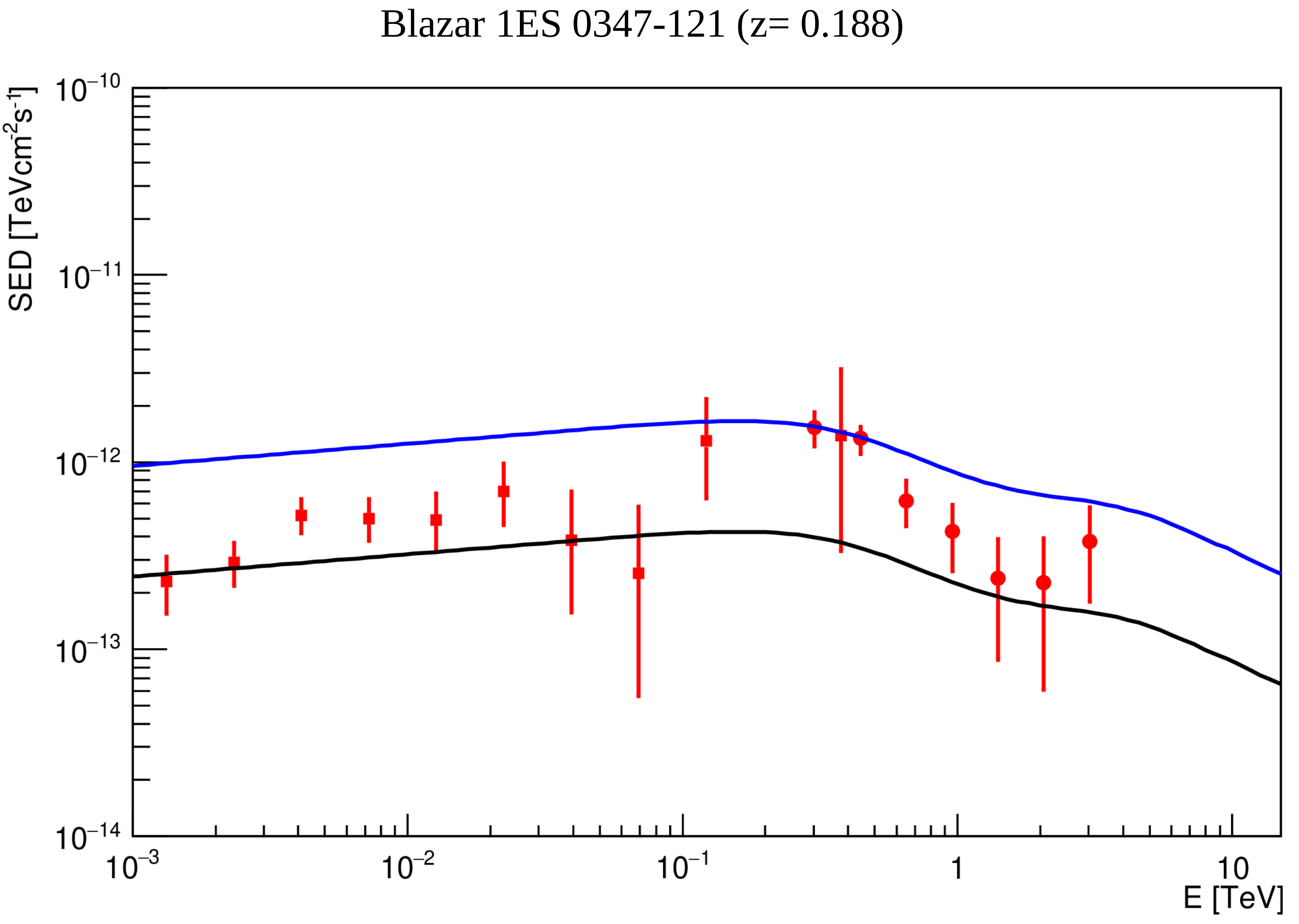




Blazar 1ES 1218+304 (z= 0.182)
SED [TeVcm^{-2}s^{-1}]
10^{-11}
10^{-12}
10^{-3}
10^{-2}
10^{-1}
1
10
E [TeV]



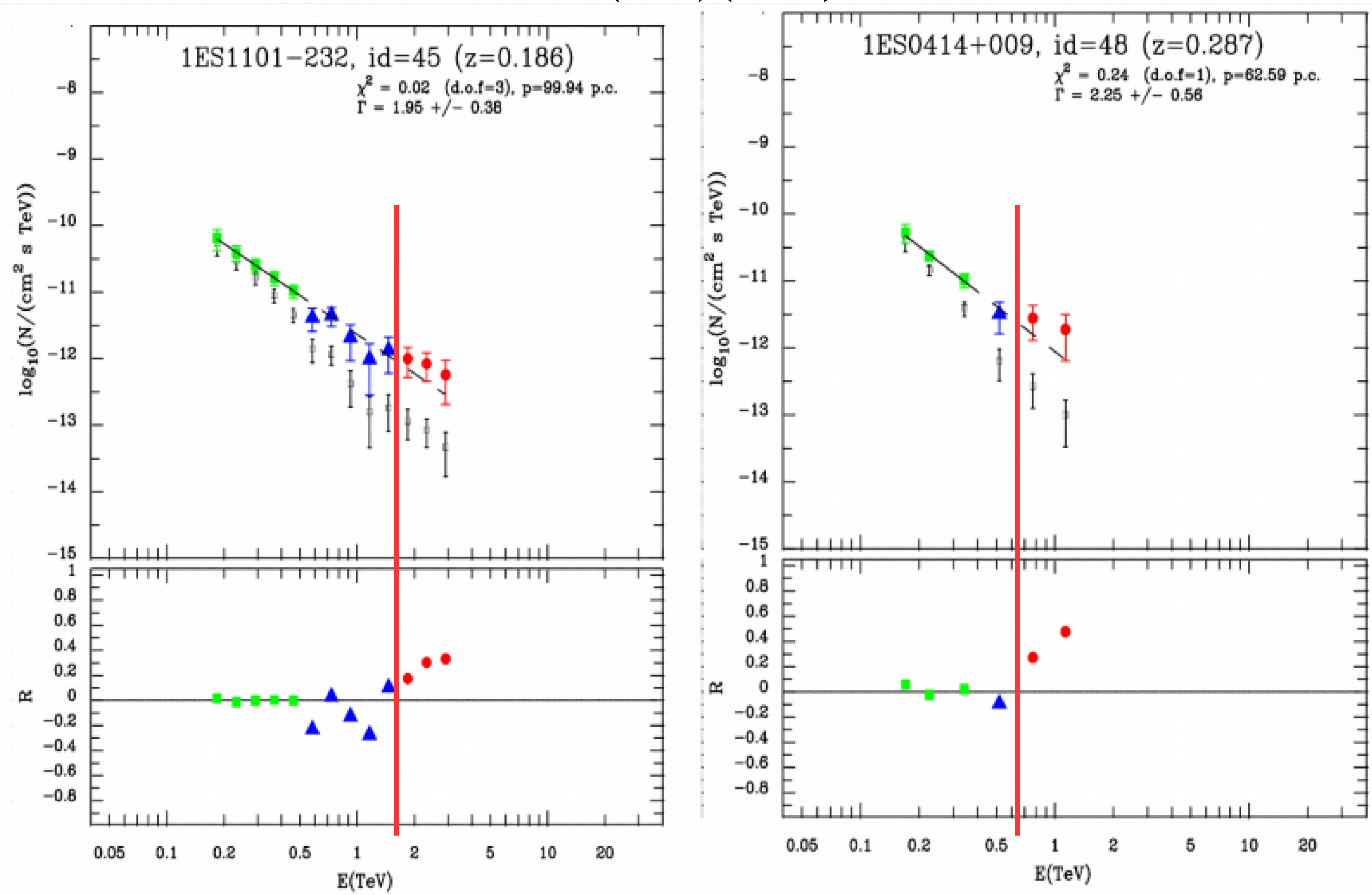
Blazar 1ES 1101-232 (z= 0.186)
SED [TeVcm^{-2}s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-3}
10^{-2}
10^{-1}
1
10
E [TeV]



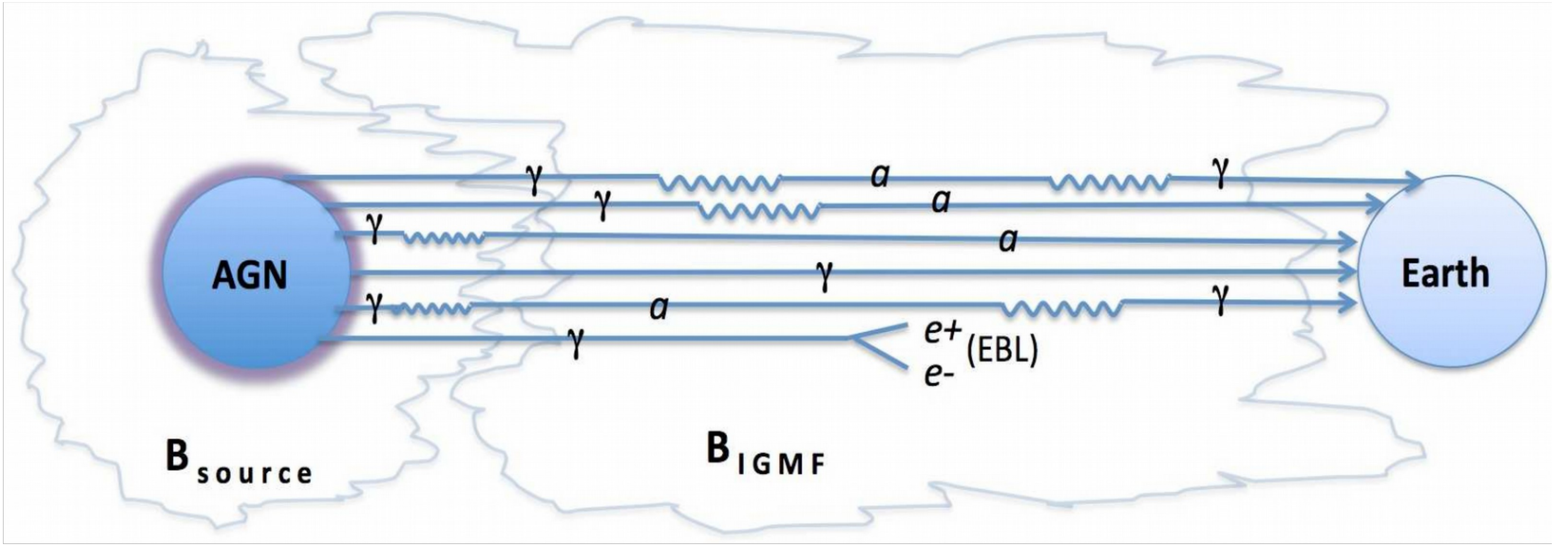
Blazar 1ES 0347-121 (z= 0.188)
SED [TeVcm^{-2}s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-3}
10^{-2}
10^{-1}
1
10
E [TeV]

III. High-energy excess in extreme blazar spectra→ a paved road to new physics (axion-like particles, etc.)?

High-energy anomaly (HM12, H16): colored symbols denote absorption-corrected data (significance: originally 4.2 σ). A similar effect: Rubtsov & Troitsky, JETP. Lett., **100**, 355 (2014) (~12 σ)

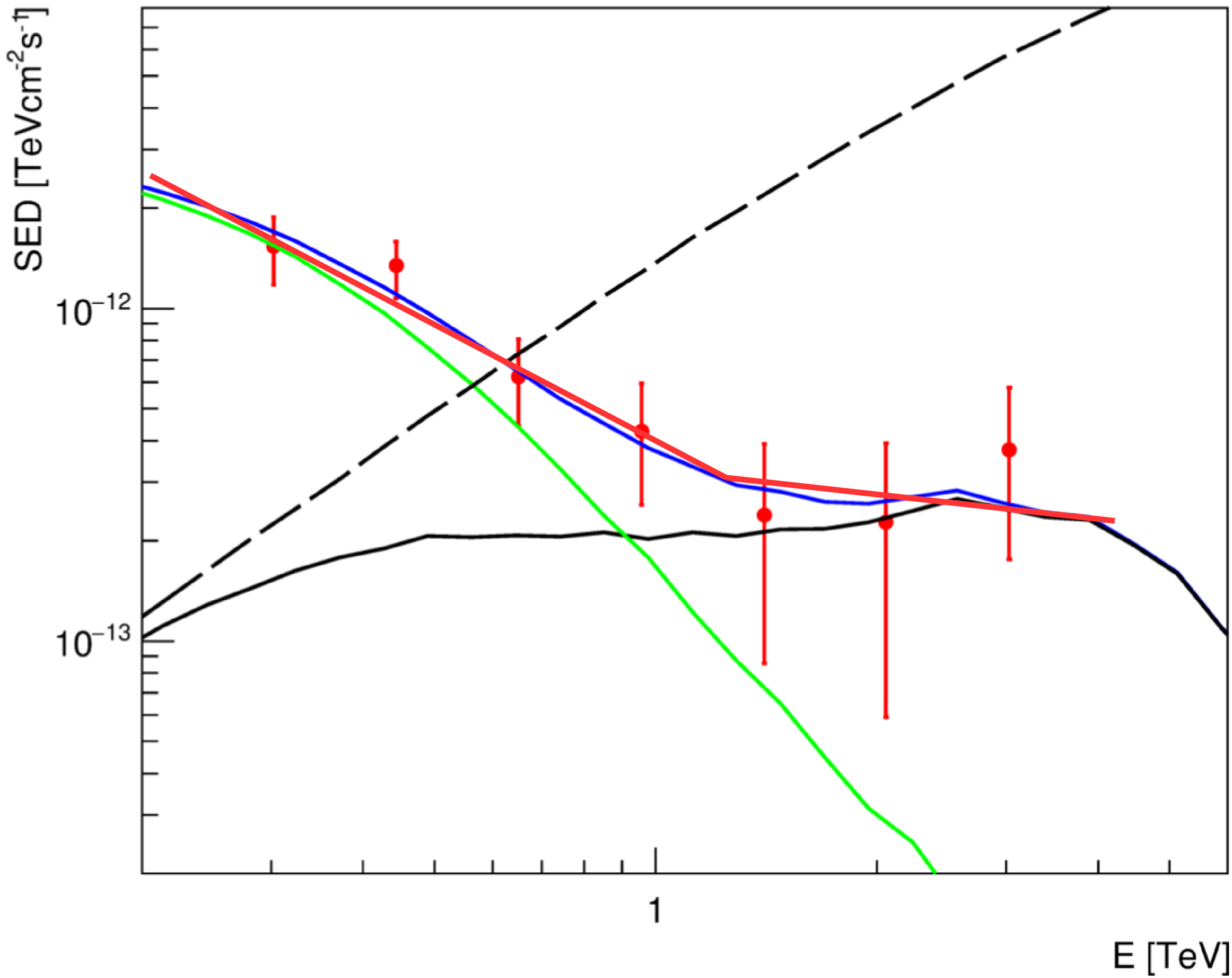


A possible explanation: γ-ALP conversion in magnetic field

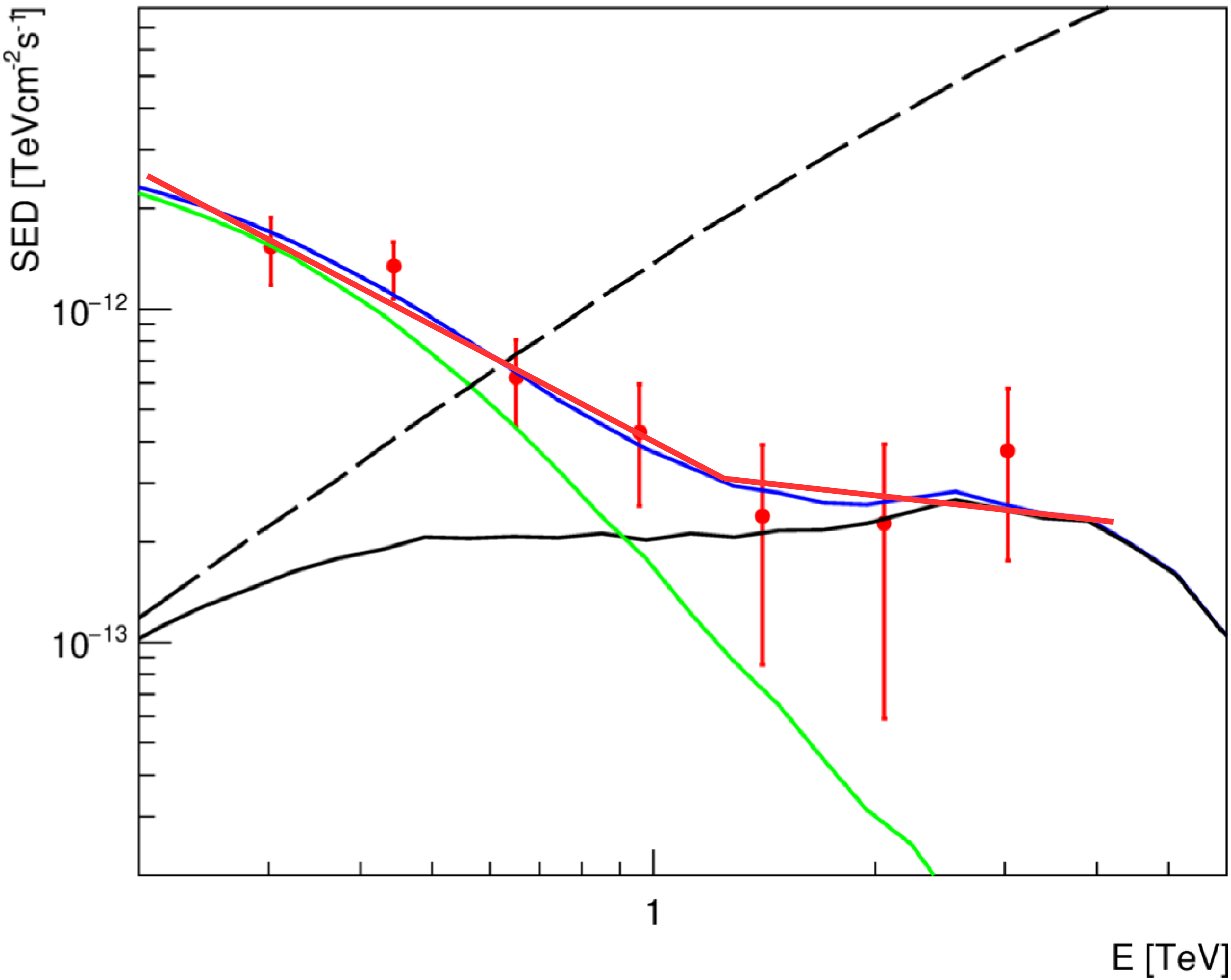


Raffelt & Stodolsky, Phys. Rev. D, **37**, 1237 (1988)
de Angelis et al., Phys. Rev. D, **76**, 121301 (2007)
Kartavtsev et al., JCAP, 01, 024 (2017)
Montanino et al., astro-ph/1703.07314 (2017)
The picture is from Sanchez-Conde et al., Phys. Rev. D, **79**, 123511 (2009)

Primary component (solid black); cascade component



“Electromagnetic cascade masquerade”



IV. Strong ($B>10^{-14}$ G) EGMF from blazar observations?

Neronov & Vovk, Science, **328**, 73 (2010)

"We report a lower bound $B \geq 3\times10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera–electron volt gamma rays in intergalactic medium."

Tavecchio et al., MNRAS Lett., **406**, L70 (2010)

"we constrain the value of the intergalactic magnetic field to be larger than $B \simeq 5\times10^{-15}$ G, depending on the model of extragalactic background light."

Dermer et al., ApJ., **733**, L21 (2011)

"Restricting TeV activity of 1ES 0229+200 to ≈3–4 years during which the source has been observed leads to a more robust lower limit" of B> 1 aG

M. Ackermann et al., ApJ Suppl., **237**, 32 (2018)

"We do not find evidence for extension in individual sources or in stacked source samples. This enables us to place limits on the flux of the extended source components, which are then used to constrain the intergalactic magnetic field to be stronger than 3×10^{-16} G for a coherence length $\lambda>10$ kpc, even when conservative assumptions on the source duty cycle are made."

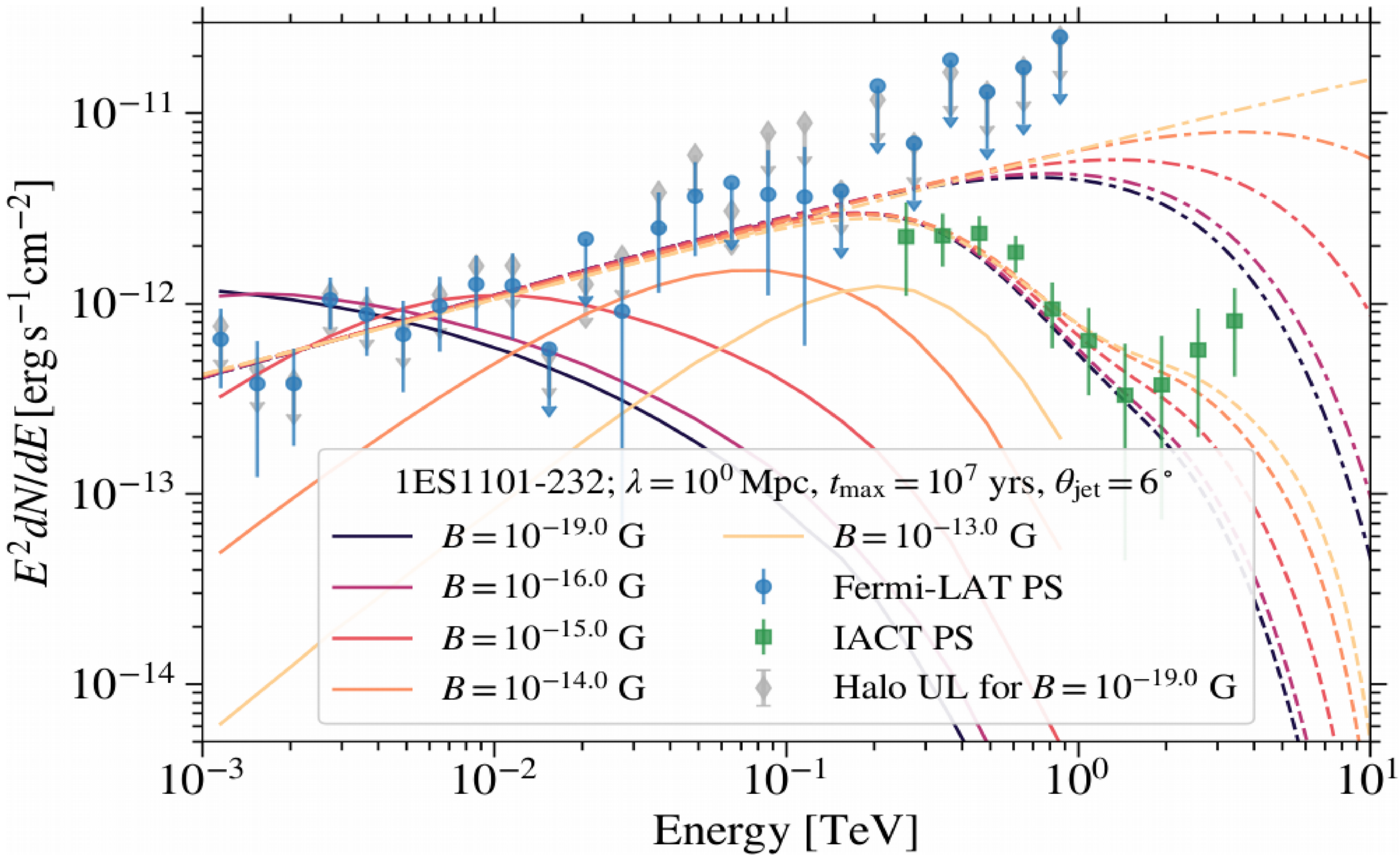
Any room for intergalactic cascade models left after Ackermann et al., ApJ Suppl., **237**, 32 (2018)?

Their results on the EGMF:

1. $B > 3\times10^{-16}$ G for $\lambda > 10$ kpc even for highly variable sources,
2. $B > 3\times10^{-13}$ G for $\lambda > 10$ kpc and stable sources

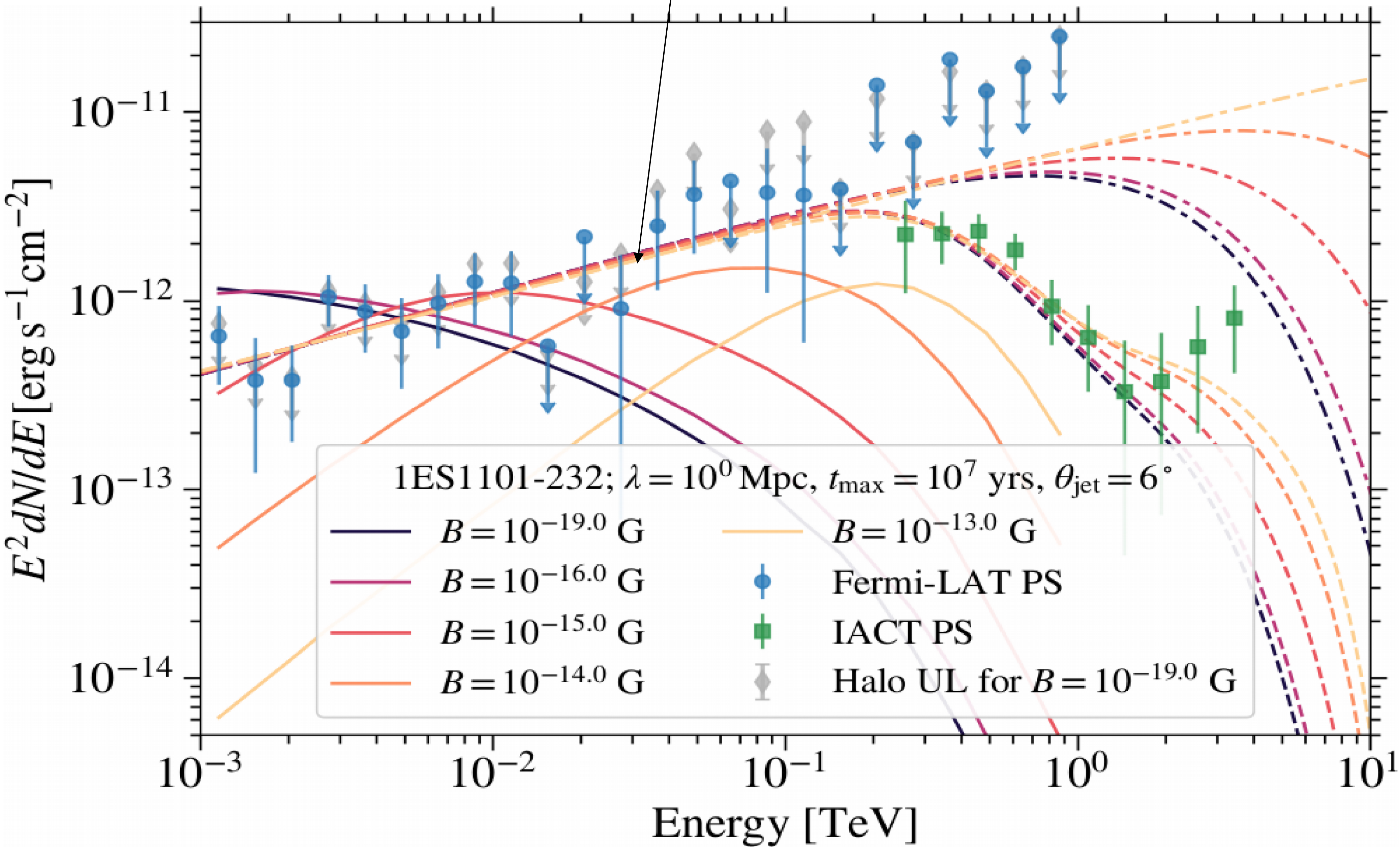
Their conclusion: "This improves previous limits by several orders of magnitude."

One of their assumptions: “Accounting for the cascade contribution does not change the best-fit spectrum of the central point source in the entire Fermi-LAT energy band by more than 5 σ”

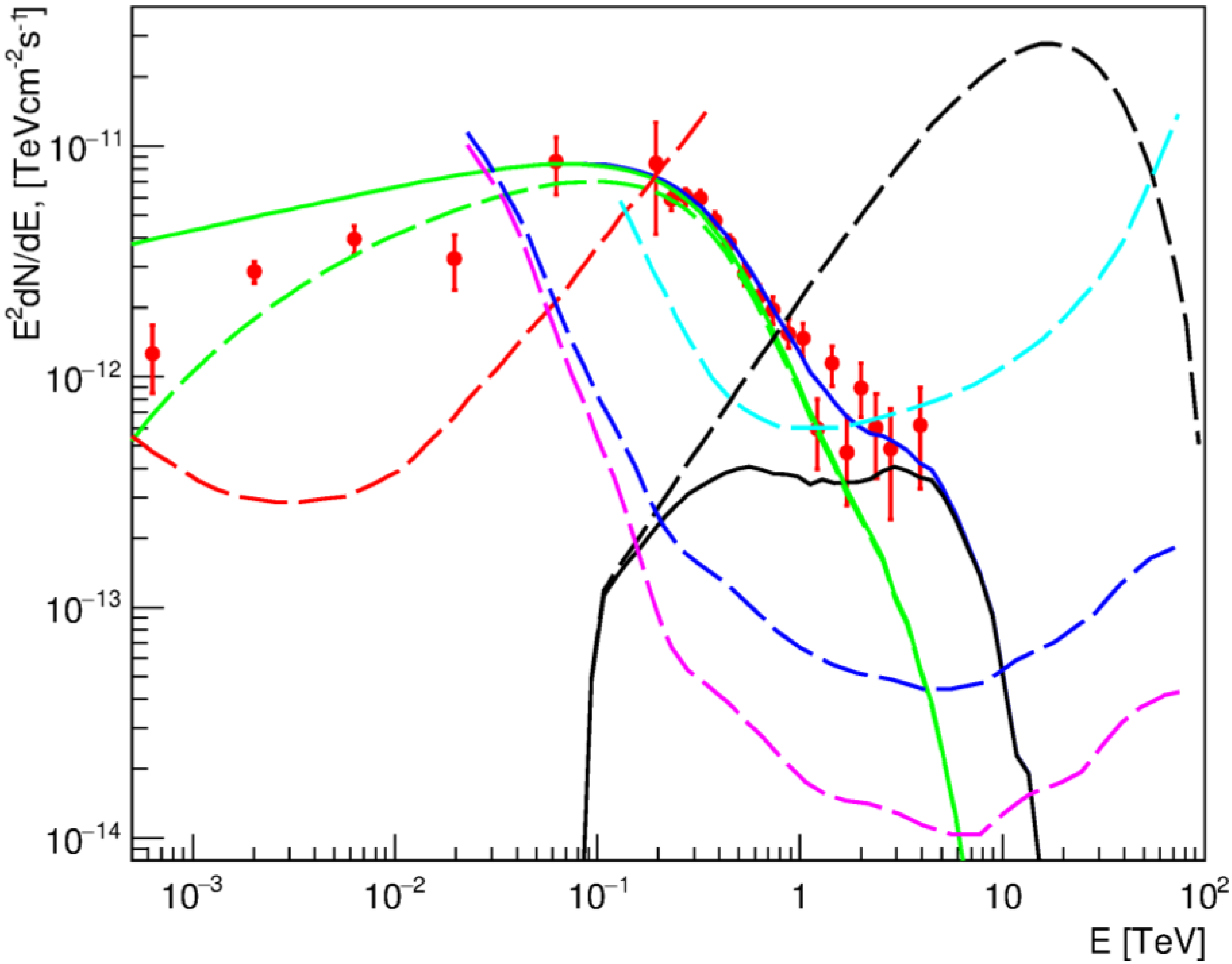


There is no room for the cascade component in their fit!

Conclusion: their results are mainly driven by their assumptions!!



astro-ph/1705.05360: 1ES 1218+304 (B= 10^{-16} G) Conclusion: there IS some room left for the cascade component in the spectrum!! Final decision will come from the analysis of the angular distribution



Conclusions

I. No EGMF constraints from GRB observations in the foreseeable future. Only an observation of signal in the lightcurve (“appearance mode”) or a detection of a nerby ($z<0.1$) and very bright GRB would help

II. Strictly speaking, there is no need for the “intergalactic hadronic cascade model”. But still, CTA and LHAASO could search for a ~-4 power-law spectrum above 15-20 TeV

III. There IS background for $\gamma \rightarrow$ ALP searches from intergalactic electromagnetic cascades, but (if we assume the EGMF in cluysters and filaments according to Dolag et al. or stronger) it is not so dangerous!

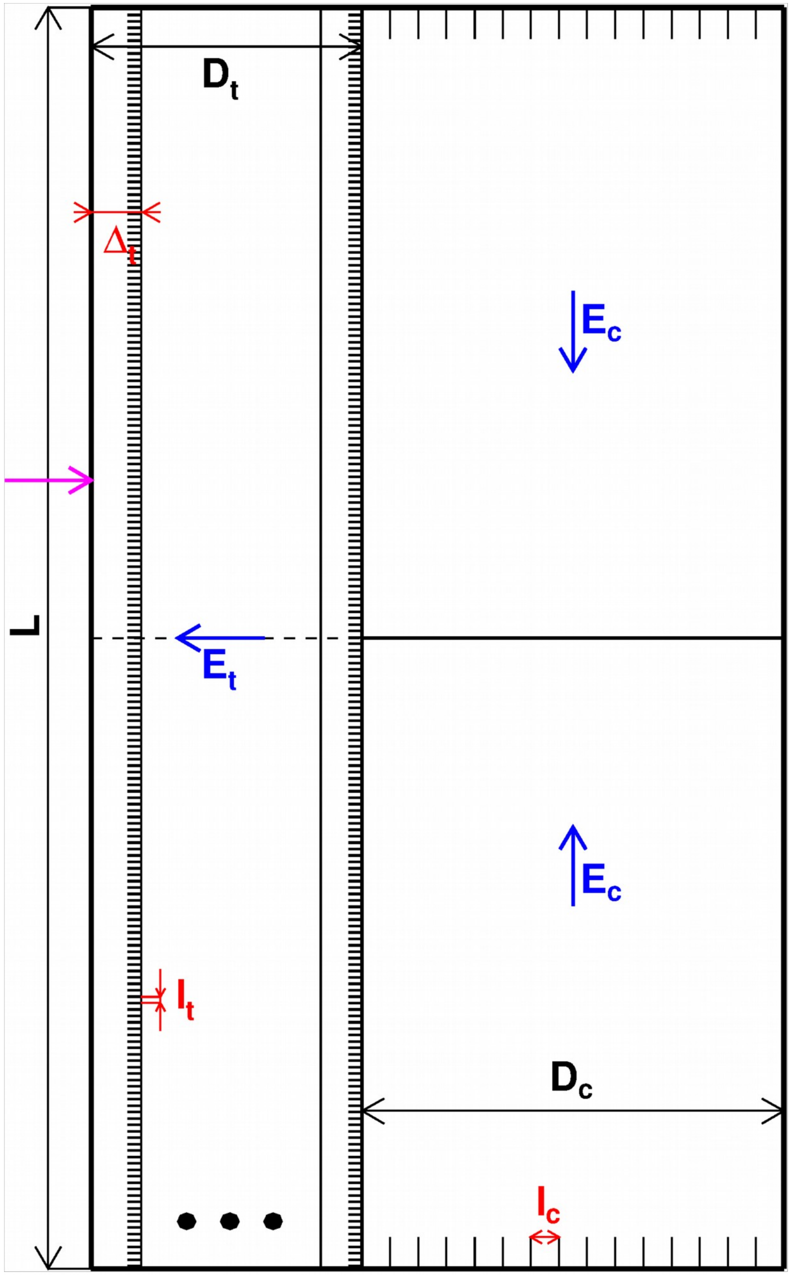
IV. The spectral analysis does not exclude a ~0.1 fG EGMF even for steady sources. The angular analysis is in progress; results will be reported elsewhere.

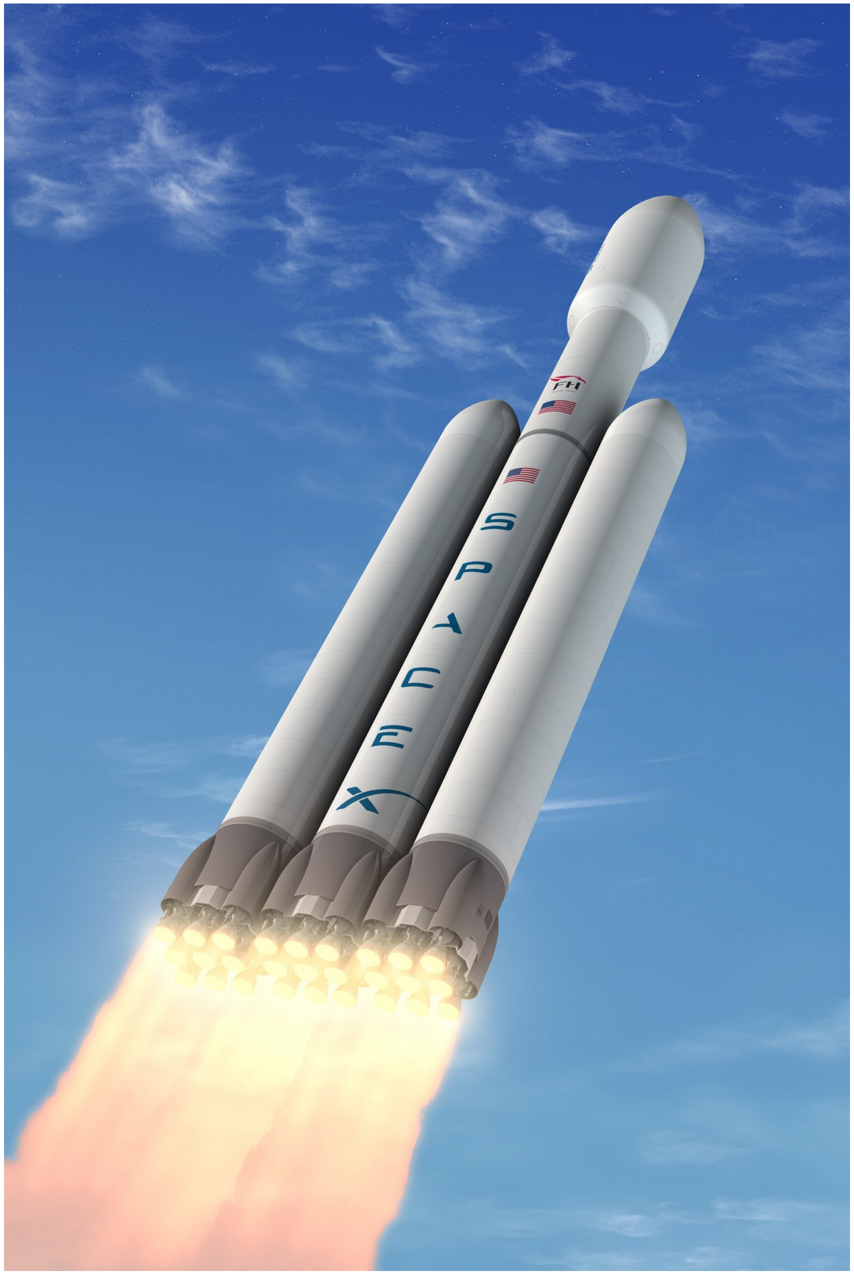
Acknowledgments

The reported study was funded by RFBR, Russia, project number 20-32-70169.

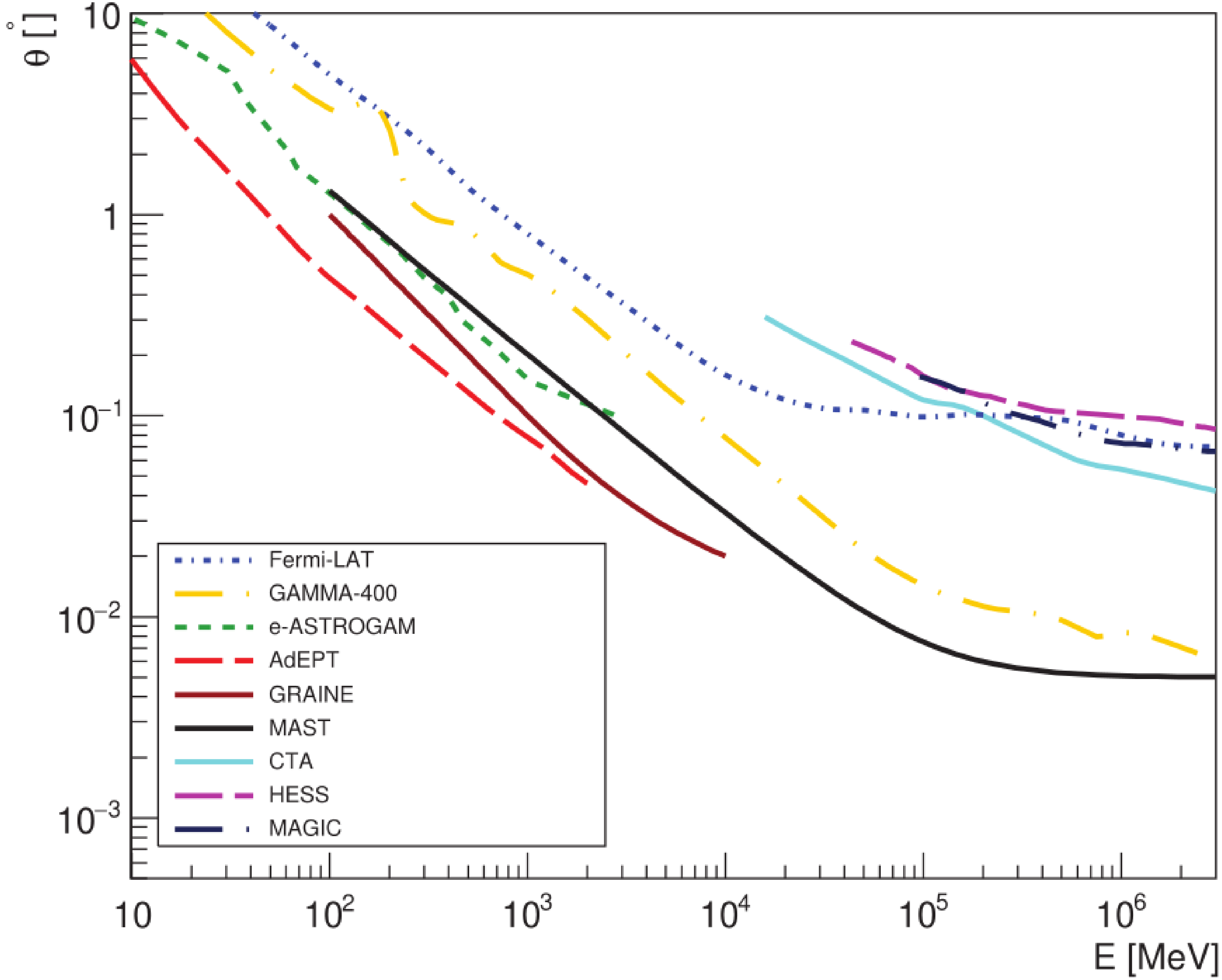
Additional slides

The Falcon Heavy launcher: 64 t for (R= 185 km); about 40 t for R= 565 km. We propose a new space instrument called Massive Argon Space Telescope (MAST) based on the time projection chamber concept





Angular resolution vs. energy: CTA, other IACT arrays (H.E.S.S., MAGIC); operating and projected space telescopes



Differential sensitivity for point-like sources: angular resolution is important at low energy! We propose a heavy (~40 t) time projection chamber filled with liquid Argon for Falcon Heavy launcher

background-dominated regime

statistics-dominated regime