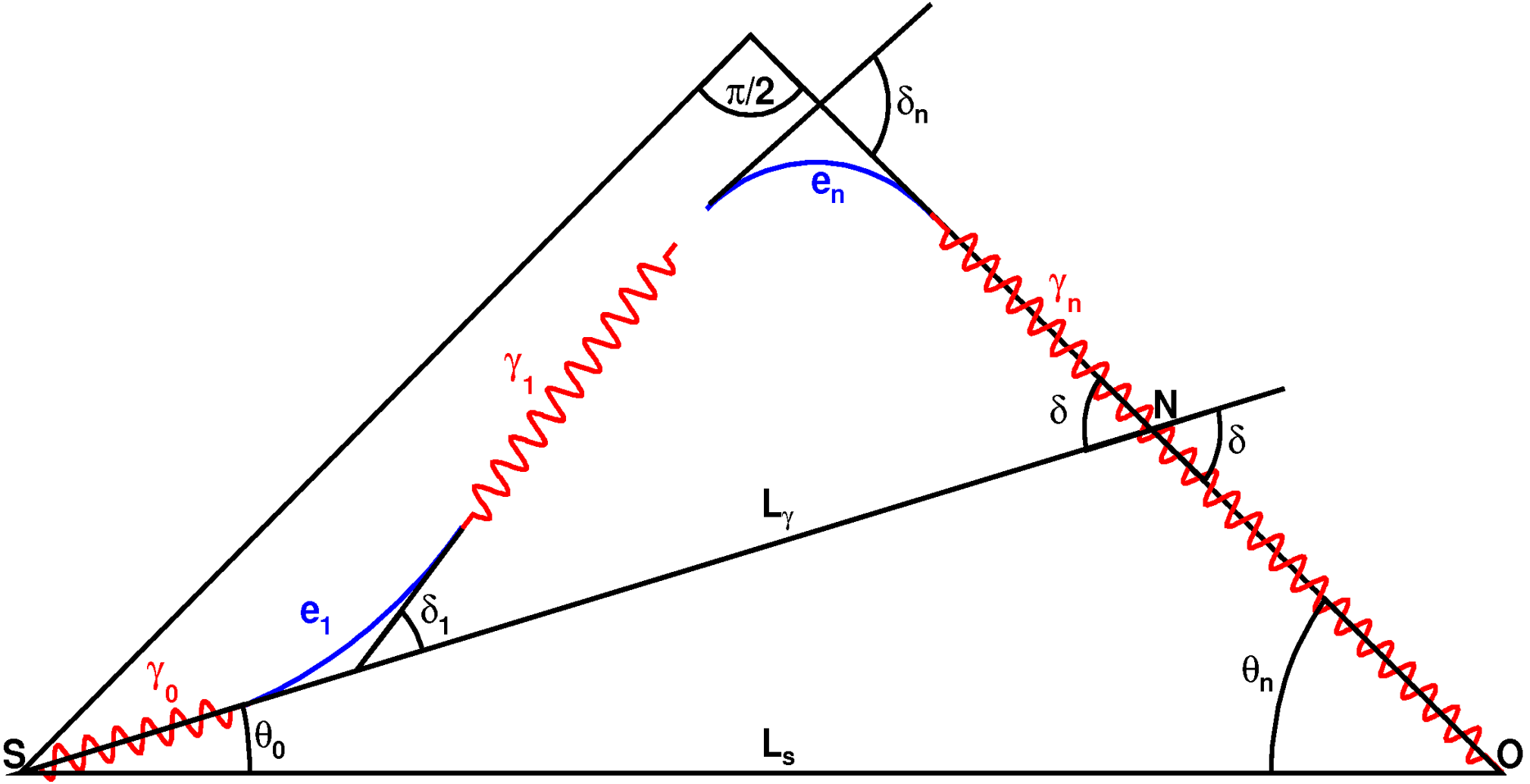
Intergalactic electromagnetic cascades in the magnetized Universe as a tool of astroparticle physics



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2018.05.31

This talk is mostly based on:

1. Dzhatdoev et al., A&A, **603**, A59 (2017)
2. Baklagin et al., Phys. Part. Nucl, **49**, 90 (2018)
3. Dzhatdoev et al., astro-ph/1711.08489 (2017)
(to appear in Phys. At. Nucl.)
4. Dzhatdoev et al., Bull. Rus. Acad. Sci., **81**, 443 (2017)
5. Dzhatdoev & Podlesnyi, in preparation (2018)
6. Dzhatdoev, talk at the program “The High Energy Universe: Gamma Ray, Neutrino, and Cosmic Ray Astronomy” (http://www.munich-iapp.de/programmes-topical-workshops/2018/the-high-energy-universe-gamma-ray-neutrino-and-cosmic-ray-astronomy/)

In this work we use for our simulations three MC codes:
Kachielriess et al., Comp. Phys. Comm., **183**, 1036 (2012)
Fitoussi et al., MNRAS, **466**, 3472 (2017)
and our own code ECS (from “electromagnetic cascade spectrum”)
(astro-ph/1705.05360)

Some abbreviations and definitions

$E_{\gamma 0}$ — primary energy of a γ-ray (source restframe)

E_{p0} — primary energy of a proton (source restframe)

z — redshift; τ — γγ pair production optical depth; γ — spectral power-law index (when γ is a number)

HE — high-energy (E>100 MeV); VHE — very high energy (E>100 GeV); UHE — ultra high energy (E>1 EeV)

EBL — extragalactic background light; EGMF — extragalactic magnetic field

CMB — cosmic microwave background

PP — pair production $\gamma\gamma \rightarrow e^+e^-$

IC — inverse Compton $e^-\gamma \rightarrow e^-\gamma'$ or $e^+\gamma \rightarrow e^+\gamma'$

AGN — active galactic nucleus

SED — spectral energy distribution

B06 — Berezinsky et al. Phys. Rev. D, **74**, 043005 (2006)

BK16 — Berezinsky & Kalashev, Phys. Rev. D, **94**, 023007 (2016)

G12 — Gilmore et al., MNRAS, **422**, 3189 (2012); HM12 — Horns & Meyer, JCAP, 033 (2012); H16 — Horns, astro-ph/1602.07499 (2016);

KD10 — Kneiske & Dole, A&A, **515**, A19 (2010)

NS09 — Neronov & Semikoz, Phys. Rev. D, **80**, 123012 (2009)

NV10 — Neronov & Vovk, Science, **328**, 73 (2010)

Topics to discuss

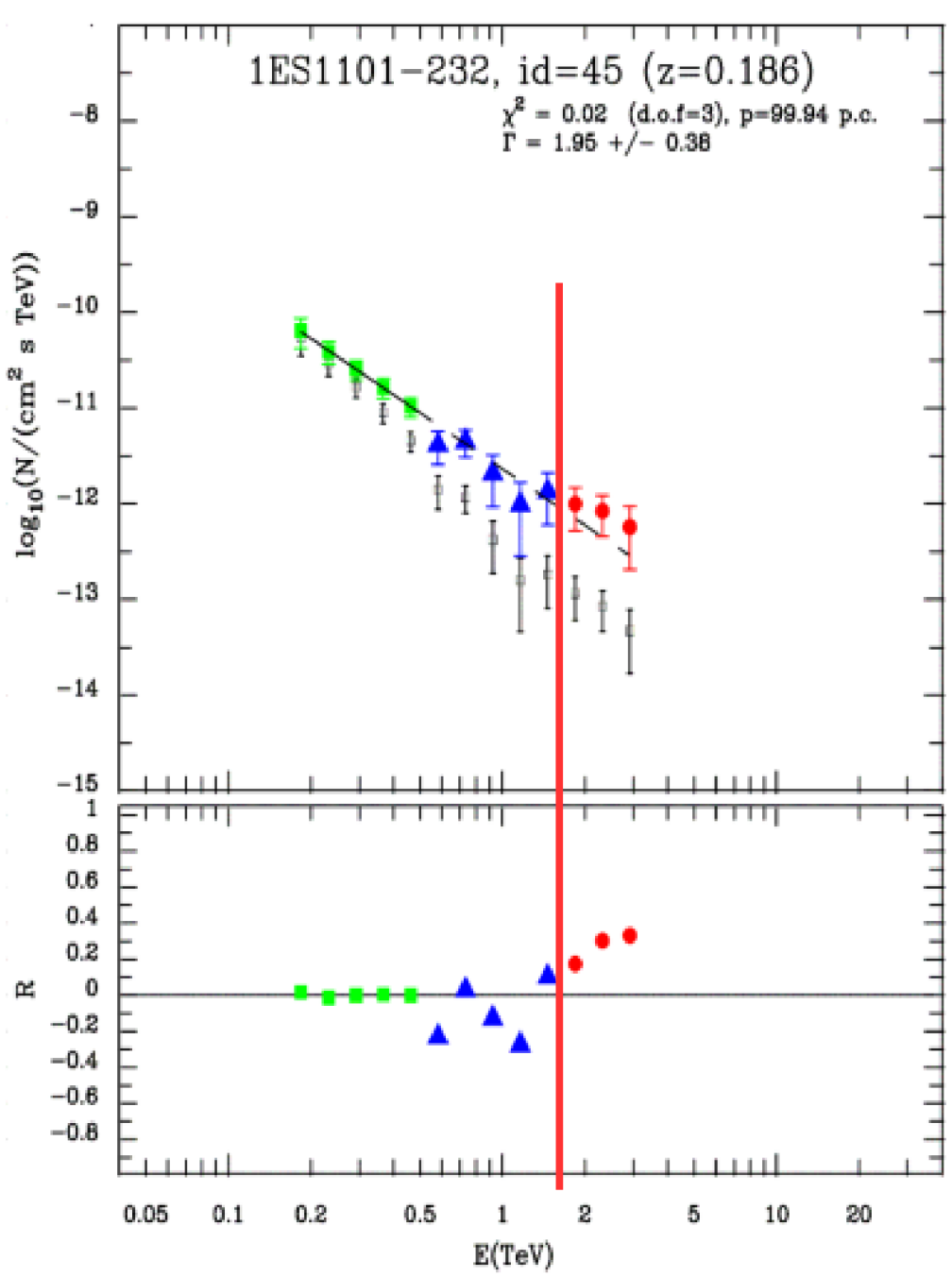
1. Secondary (cascade) γ-rays from UHE protons/nuclei emitted by blazars
2. Background for axion-like particle searches from (purely) EM cascades
3. EGMF parameter sensitivity for Fermi LAT and CTA
4. Spectrum and angular distribution of cascade γ-rays from nearby extragalactic sources in context of DM searches
5. What has changed after the recent Fermi LAT work (astro-ph/1804.08035)?

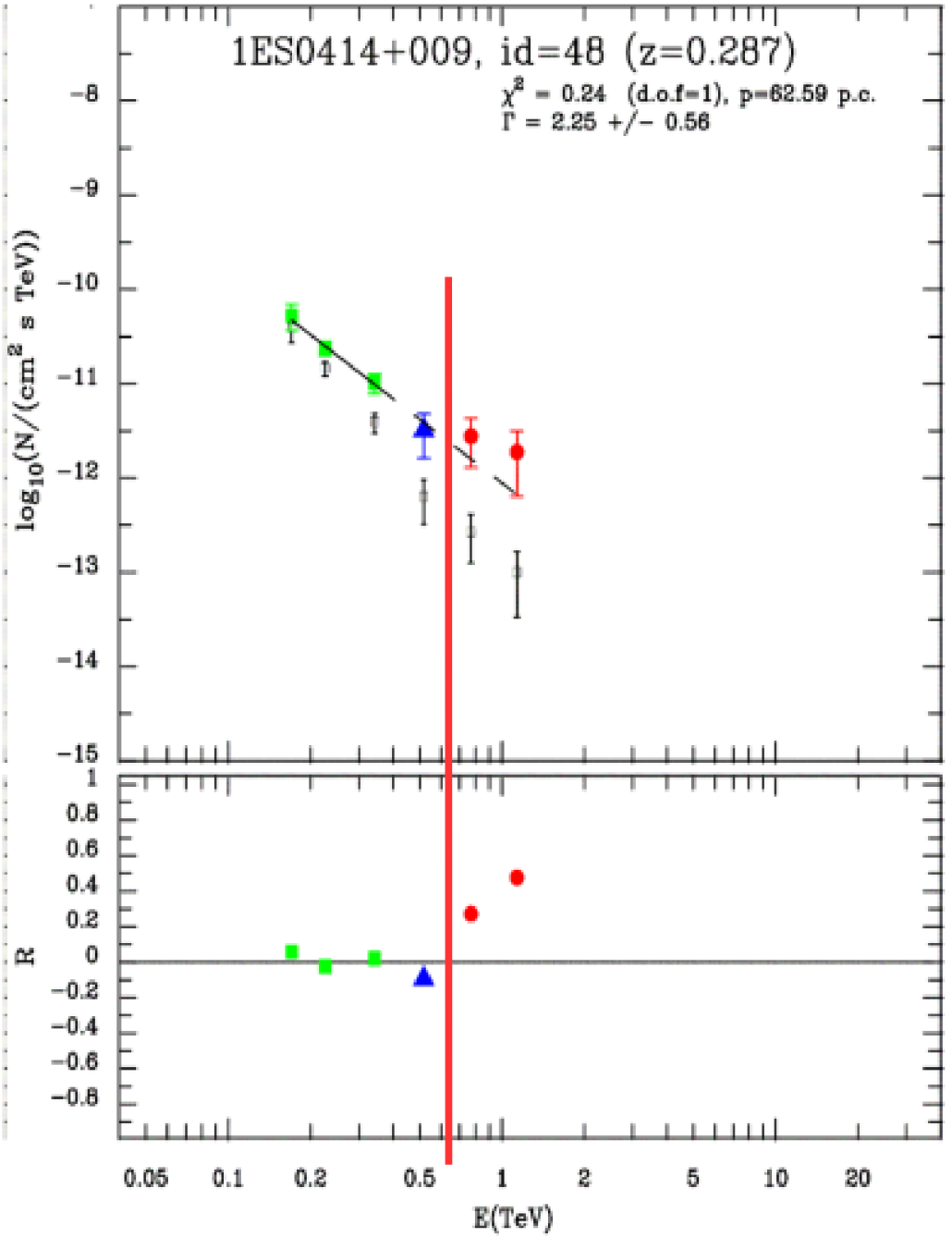
Note: we neglect "collective losses" ("plasma losses") of cascade electrons (Hayakawa Kitao, Prog. Theor. Phys. **16**, 139 (1956); Gould & Burbidge, Annales d'Astrophysique **28**, 171 (1965); Broderick et al., **752**, 22 (2012)) as their impact is highly uncertain (Vafin et al., ApJ, **857**, 43 (2018))

Synchrotron losses in voids are, as a rule, negligible given the contemporary upper limits on the EGMF (Pshirkov et al., Phys. Rev. Lett., **116**, 191302 (2016))

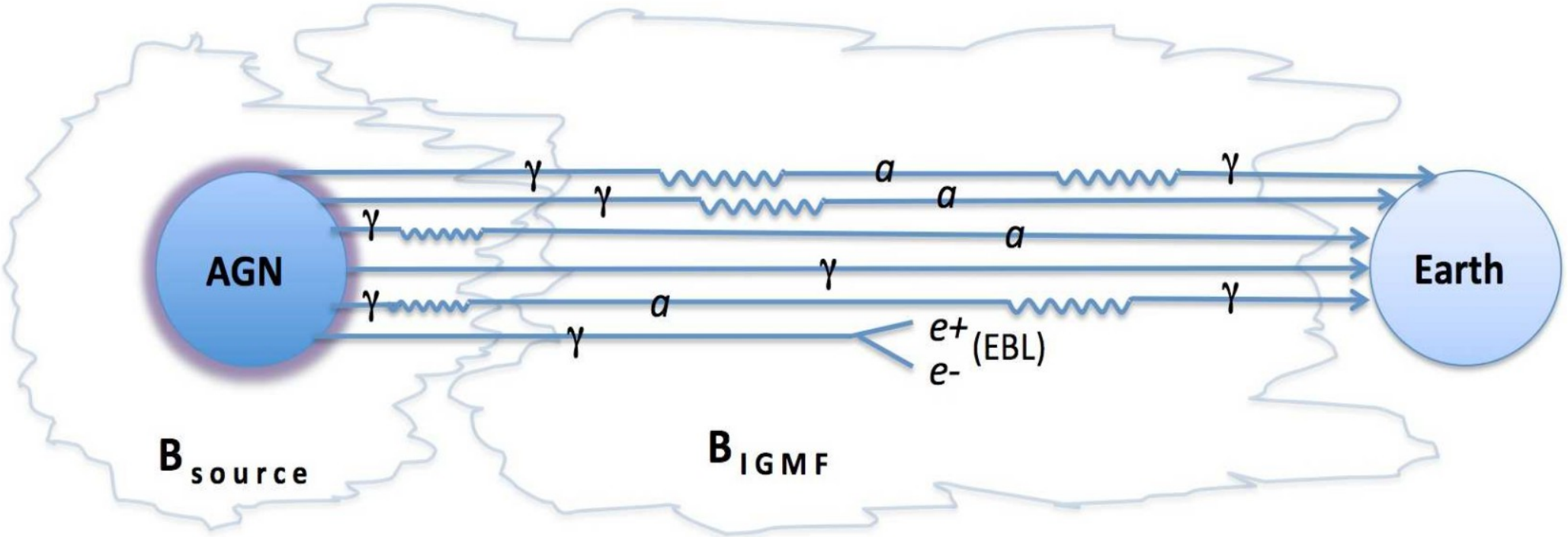
Our calculations where z is not indicated are for z= 0.186

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



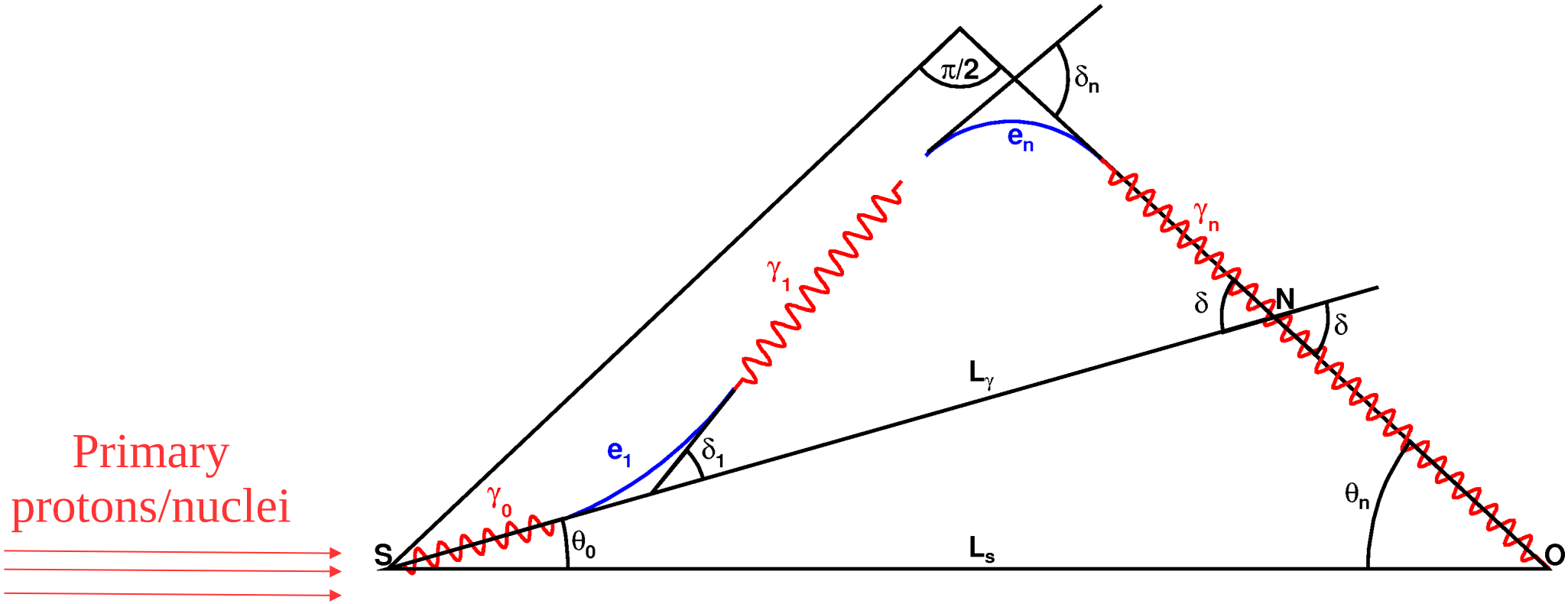
Raffelt & Stodolsky, Phys. Rev. D, **37**, 1237 (1988)
de Angelis et al., Phys. Rev. D, **76**, 121301 (2007)
Kartavtsev et al., JCAP, 01, 024 (2017)
Montanino et al., astro-ph/1703.07314 (2017)
The picture is from Sanchez-Conde et al.,
Phys. Rev. D, **79**, 123511 (2009)

1. Secondary (cascade) γ-rays from UHE protons/nuclei emitted by blazars

Motivation (e.g. Uryson, JETP, **86**, 213 (1998)):
Effectively moving the source of γ-rays closer to the observer

These secondary (cascade) γ-rays are the product of the GZK process / pair production on nuclei

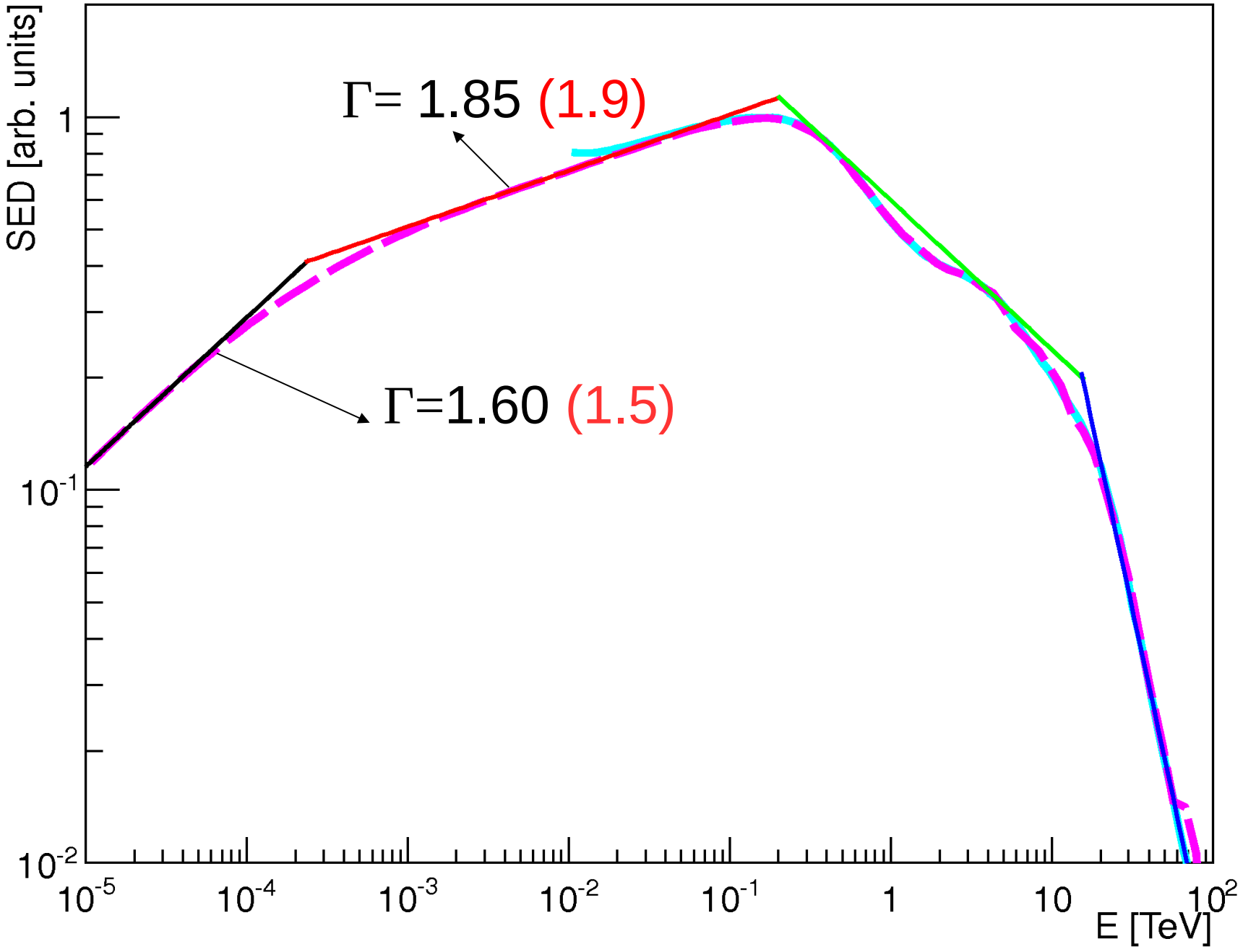
Intergalactic hadronic cascade model (HCM)



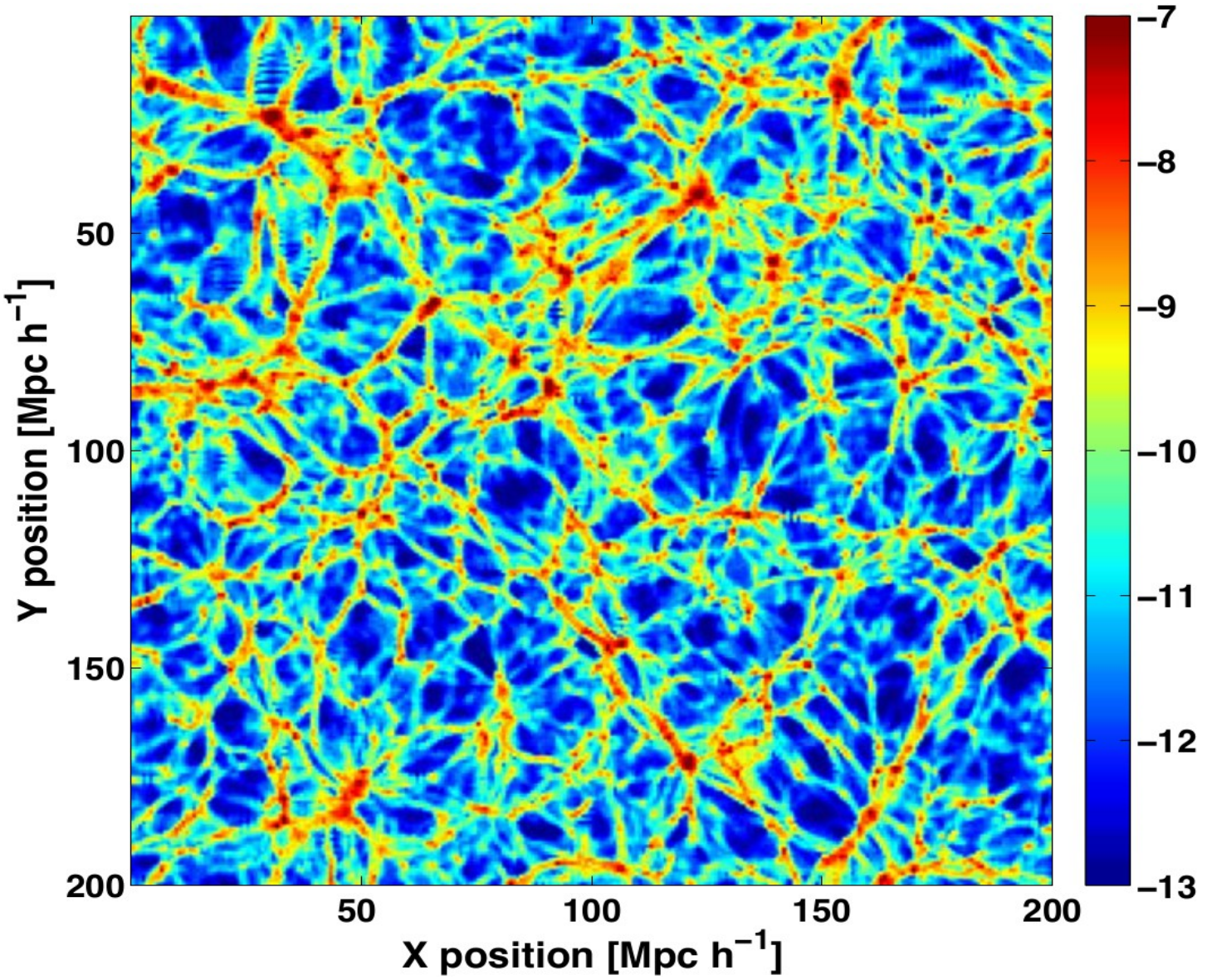
Uryson, JETP, **86**, 213 (1998); Essey & Kusenko, APh, **33**, 81 (2010); Essey et al., Phys. Rev. Lett., **104**, 141102 (2010); Essey et al., ApJ, **731**, 51 (2011) (E11); Murase et al., ApJ, **749**, 63 (2012); Takami et al., ApJ Lett., **771**, L32 (2013); Essey & Kusenko, APh, **57**, 30 (2014); Yan et al. (2015); Zheng et al., A&A, **585**, A8 (2016)

Most of these authors concluded that the hadronic cascade model can explain the high-energy anomaly

"Basic" HCM: all observable γ-rays are from protons/nuclei
and protons do not meet any obstacle on their way.
"Universal spectrum" (Berezinsky & Smirnov 1975, BK16)



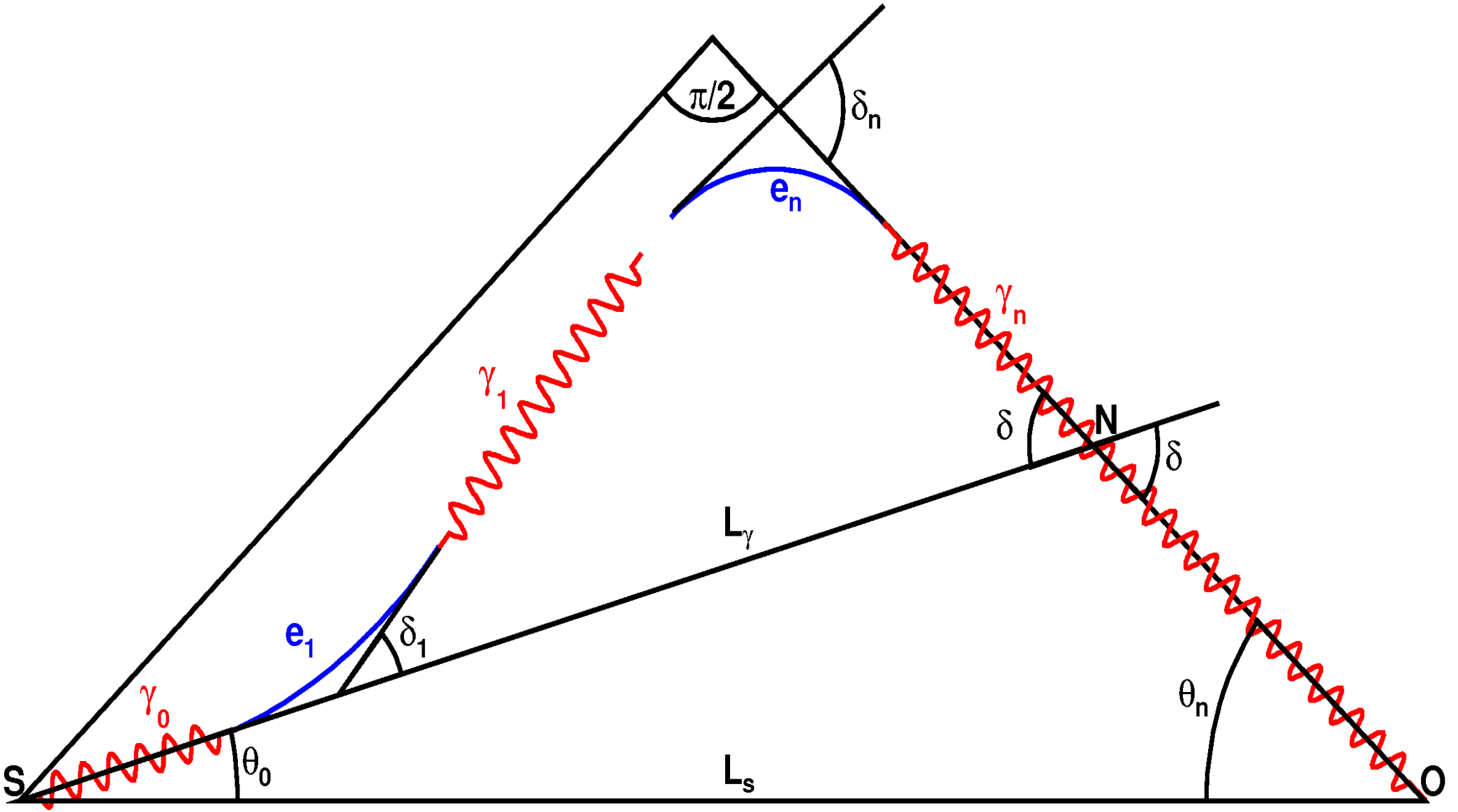
A slice of large-scale EGMF (~10 nG, 1 Mpc) at least every 50 Mpc!
(Oikonomou et al., 2014) → 10 deg deflection of protons



$$\delta \simeq \frac{BZe}{E}\sqrt{\frac{Ll_c}{2}} \simeq 1^\circ \frac{B}{\mathrm{nG}}\frac{40\ \mathrm{EeV}}{E/Z}\frac{\sqrt{Ll_c}}{\mathrm{Mpc}}$$

(Harari et al., 2016)

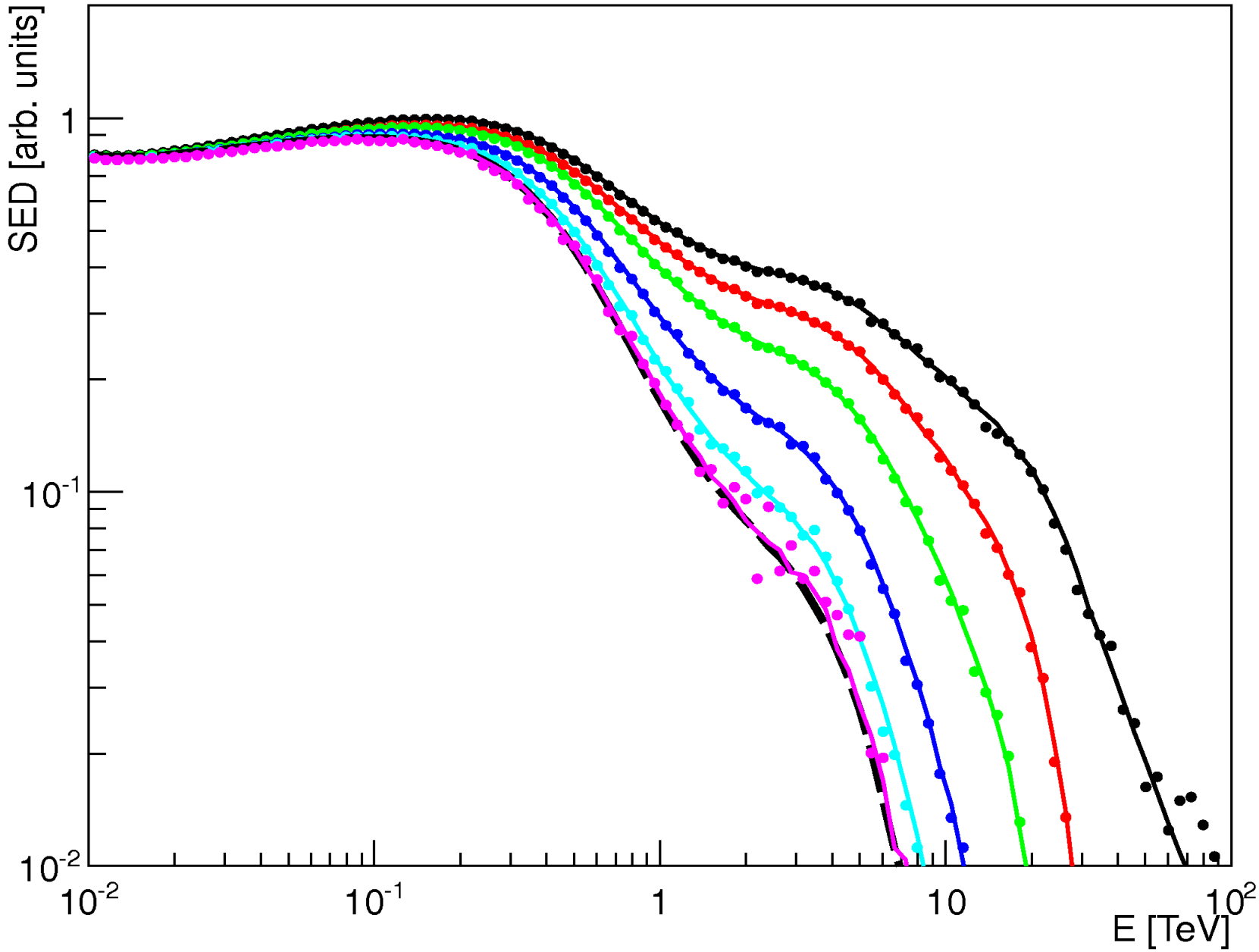
Towards a more realistic intergalactic hadronic cascade model!



$$sin(\theta_n) = sin(\delta)\frac{L_\gamma(E_{\gamma_{n-1}}, z_s)}{L_s}$$

Observable angles >1 deg, well beyond HESS/CTA PSF (~0.1 deg)!

"Intermediate" HCM: all observable γ-rays --- from protons/nuclei but the proton beam is terminated at z_c. Observable SEDscare for z_c = 0, 0.02, 0.05, 0.10, 0.15, 0.18



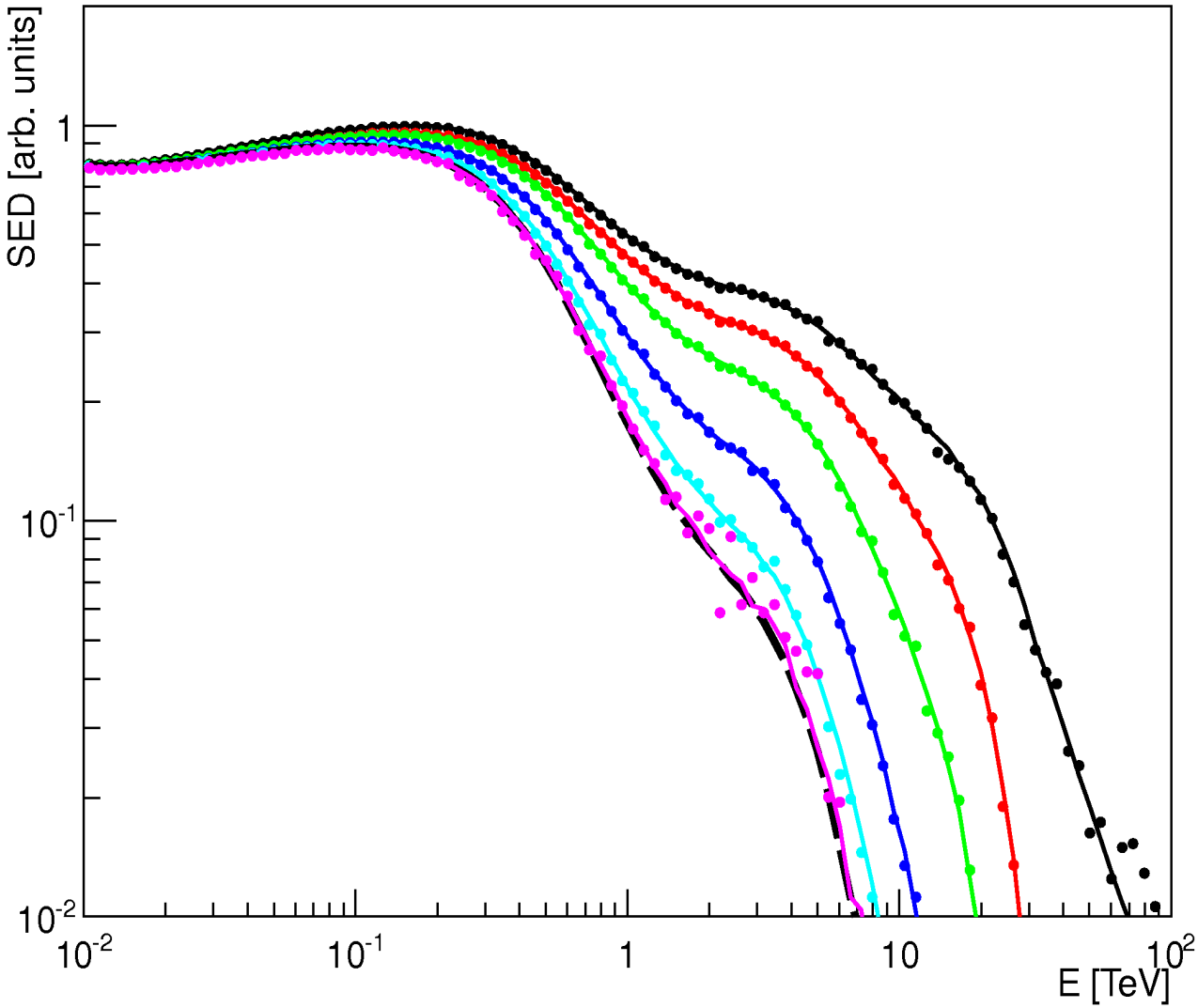
"Rule of thumb": take the universal spectrum of a purely electromagnetic cascade, but at a location L/2 closer to the observer

Effective opacity decrease is (25 Mpc) / (700-800 Mpc)= 0.03

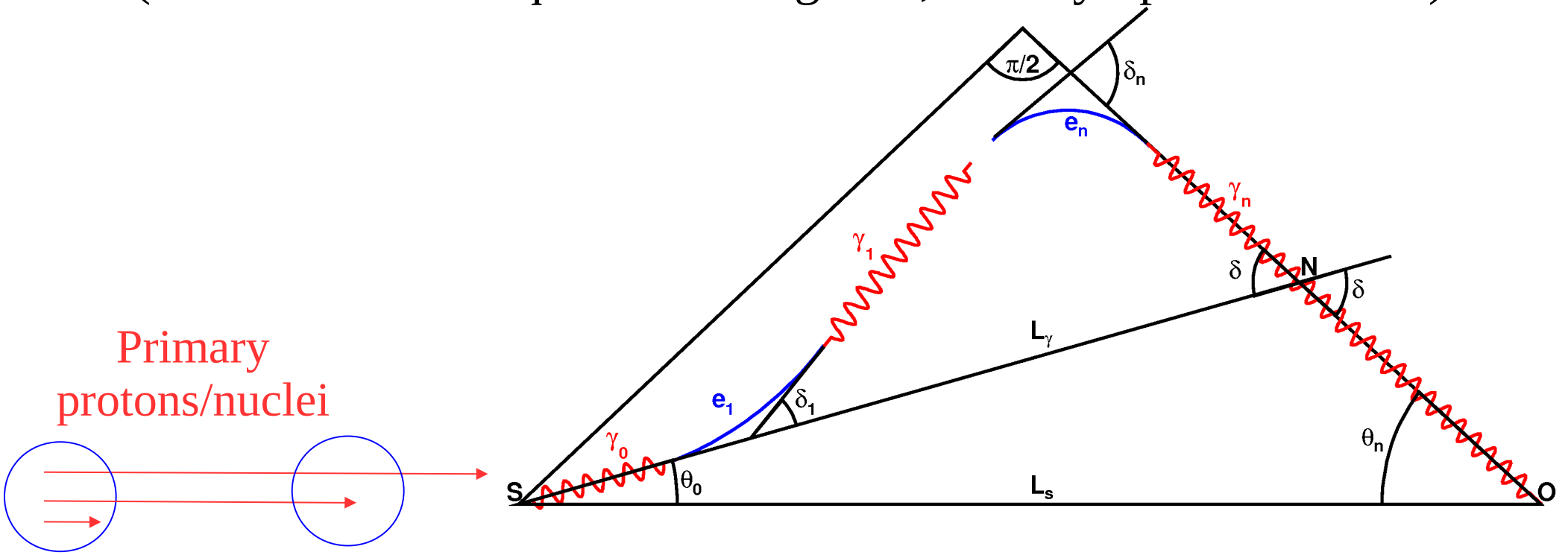
To compare with EBL intensity uncertainty: +-30 %

(e.g. Korochkin & Rubtsov, astro-ph/1712.06579)

Conclusion: the effective decrease of opacity is not significant



A more realistic hadronic cascade model
(calculation technique: following B06, test asymptotics: BK16)



Blue circles denote strong magnetic fields around the object and on the way to the observer.

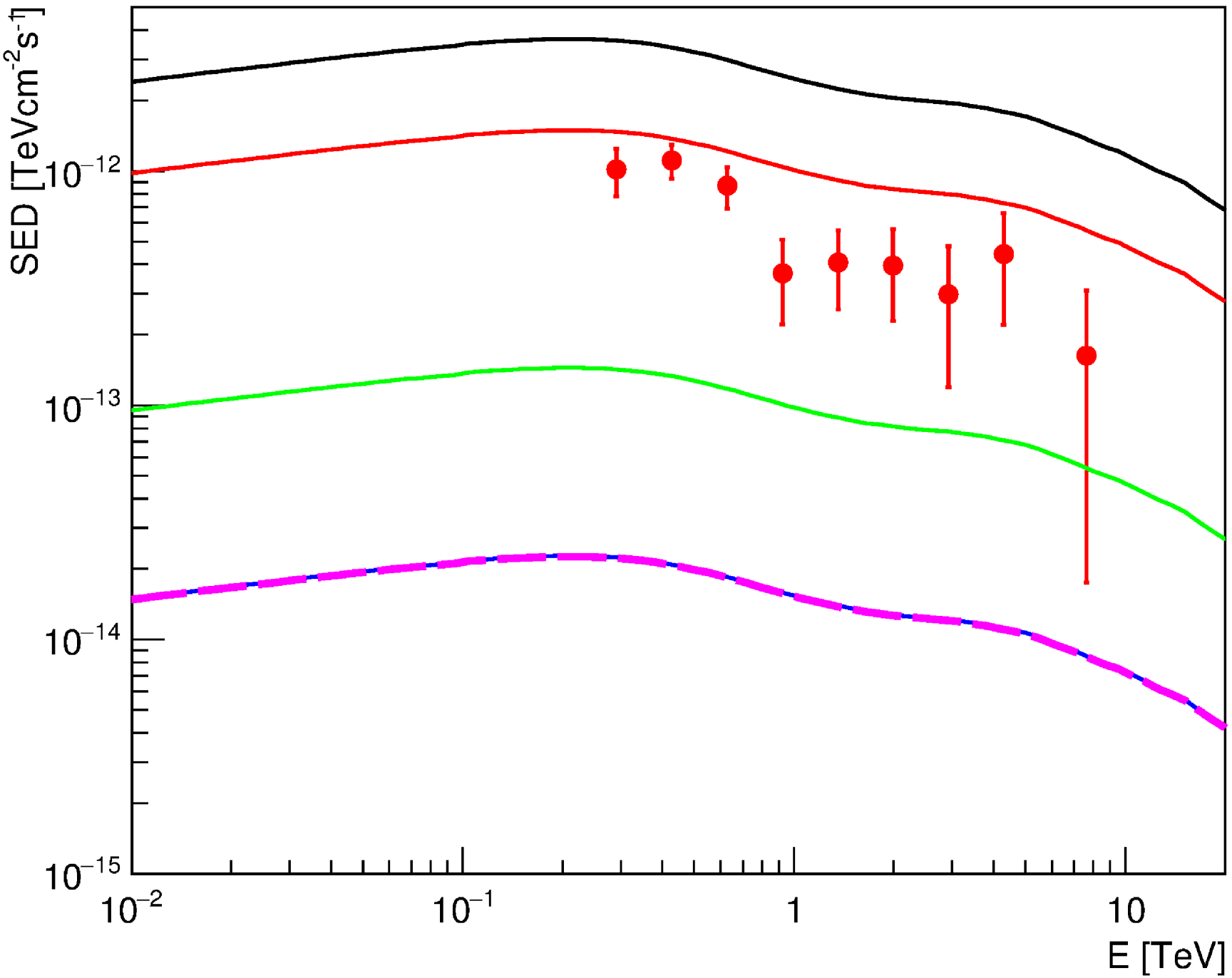
Primary luminosity and spectrum: Tavecchio, MNRAS, **438**, 3255 (2014)

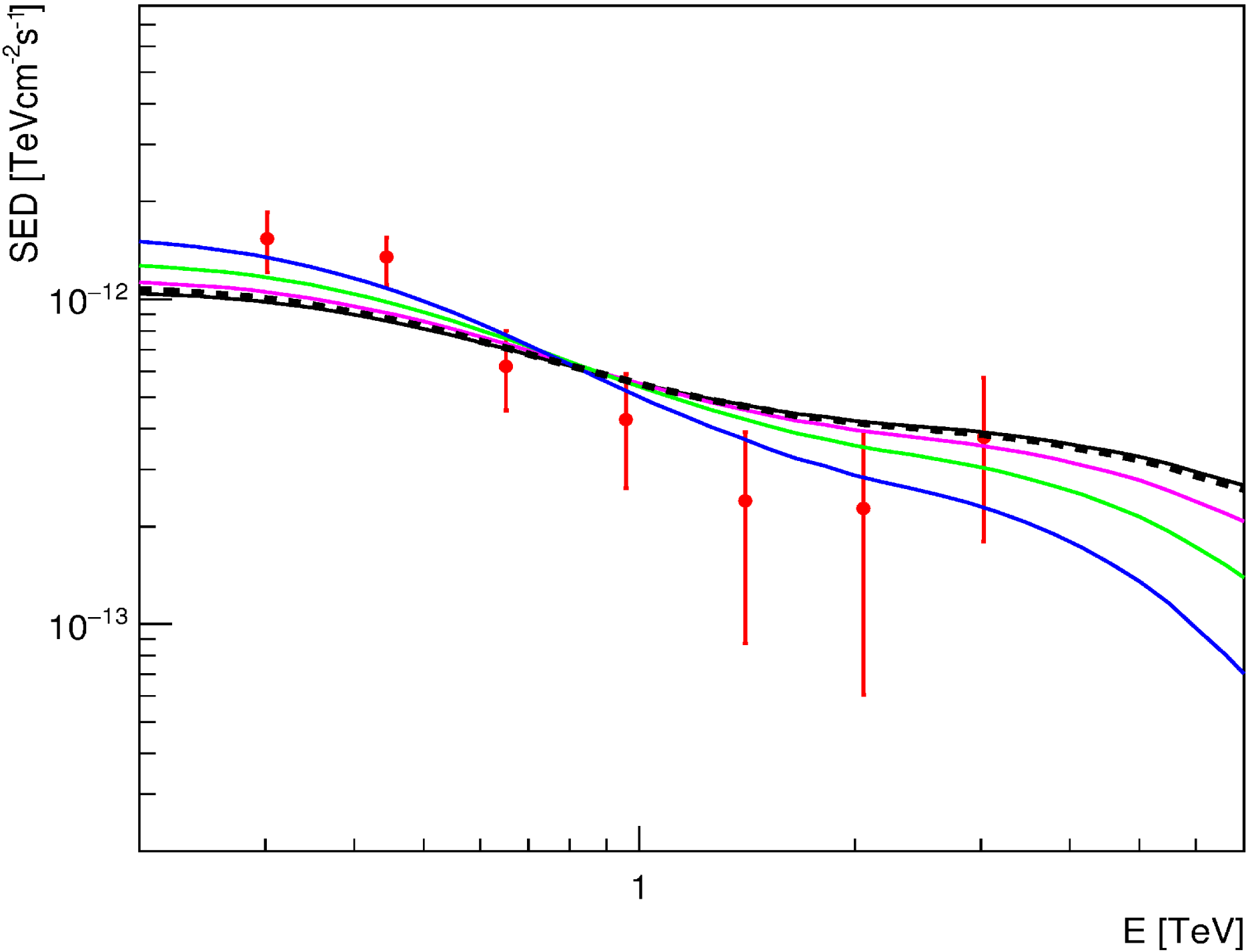
(primary proton luminosity is limited by magnetic field density)

The source is embedded in a galaxy cluster (Meyer et al., Phys. Rev. D, **87**, 035027 (2013)), central magnetic field B_0.

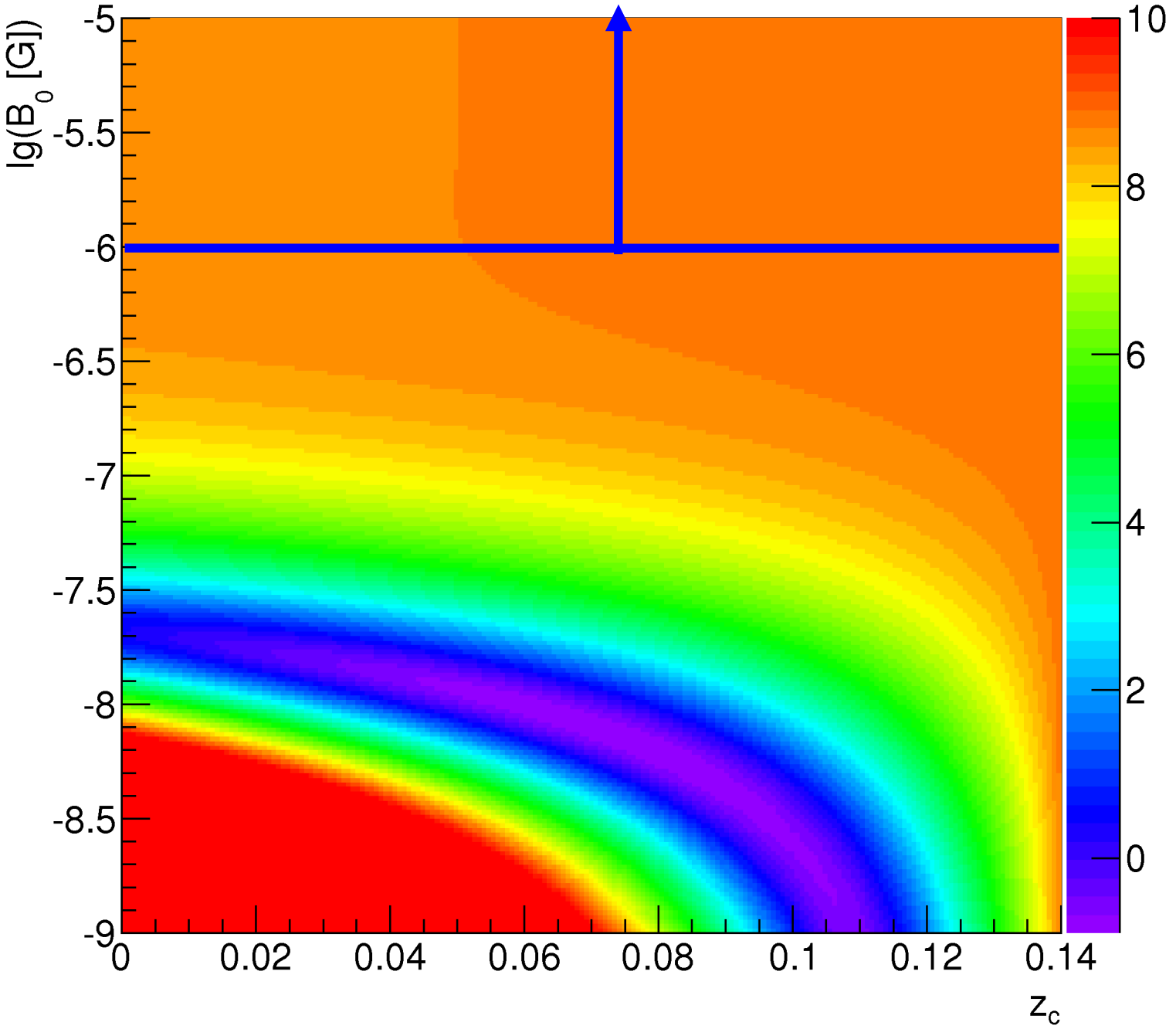
The proton beam may encounter another cluster at z_c

Observable intensity drops as B_0 grows from 1 nG (black)/10 nG (red) to 10 mkG (experimental data: Aliu et al., ApJ, **782**, 13 (2014); z= 0.14)




SED [TeVcm^{-2}s^{-1}]
10^{-12}
10^{-13}
1
E [TeV]

Constraints on hadronic cascade models (the case of 1ES 0229+200, z= 0.14). B_0= magnetic field strength in the center of the cluster, z_c= the termination redshift of the proton beam, in color: significance of exclusion

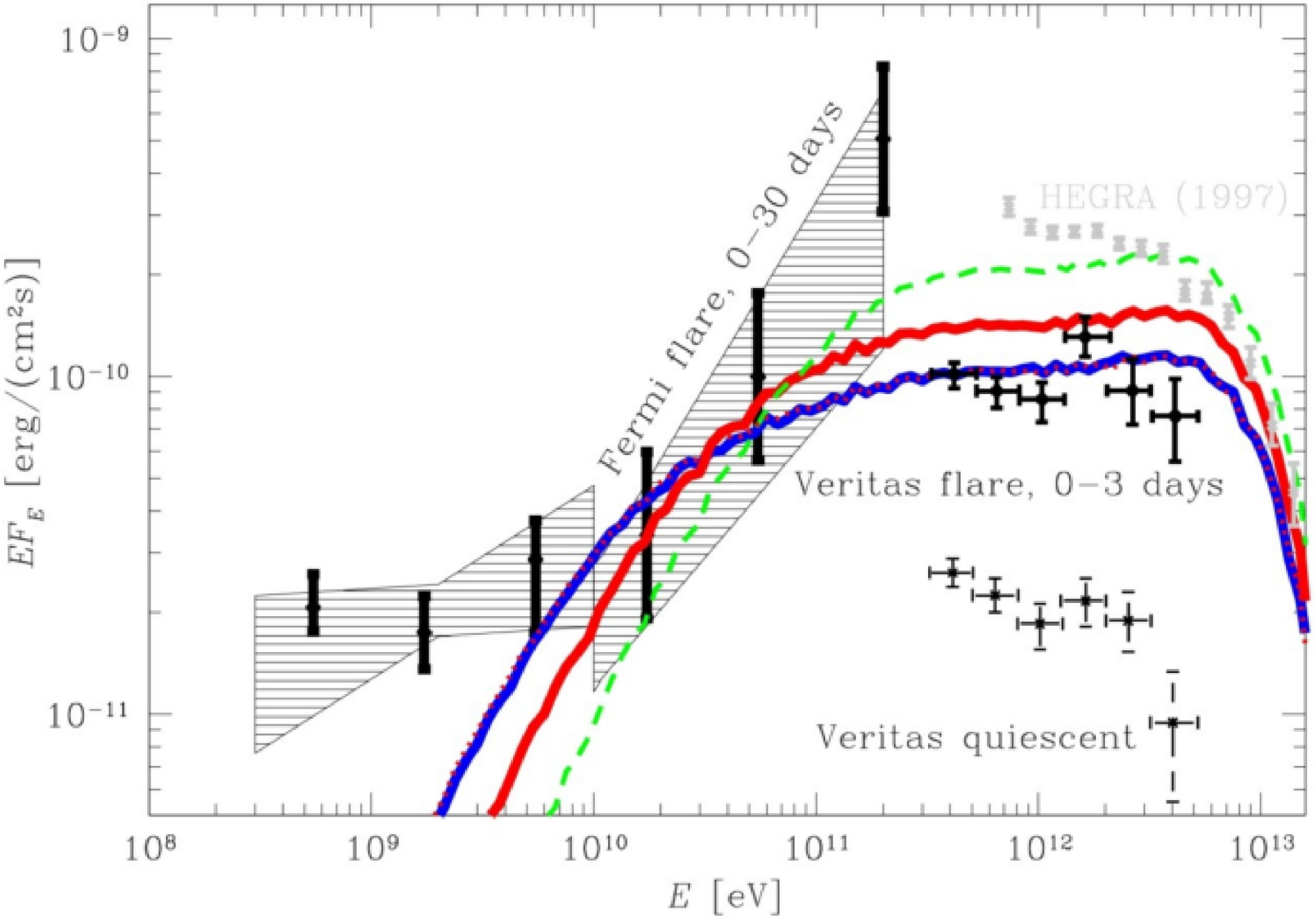


2. Background for axion-like particle searches from (purely) EM cascades

Motivation:
primary spectrum is not known, especially for the case of "extreme TeV blazars" --- active galactic nuclei with hard primary spectrum and low-amplitude slow variability!!

N	Source	z	Observational period	Reference
1	H 1426+428	0.129	1999-2000	Aharonian et al. (2003)
2	H 1426+428	0.129	1998-2000	Djannati-Atai et al. (2002)
3	H 1426+428	0.129	2001	Horan et al. (2002)
4	1ES 0229+200	0.140	2005-2006	Aharonian et al. (2007a)
5	1ES 0229+200	0.140	2010-2012	Aliu et al. (2014)
6	1ES 1218+304	0.182	2012-2013	Madhavan et al. (2013)
7	1ES 1101-232	0.186	2004-2005	Aharonian et al. (2007b)
8	1ES 1101-232	0.186	2004-2005	Aharonian et al. (2006)
9	1ES 0347-121	0.188	Aug.-Dec. 2006	Aharonian et al. (2007c)
10	1ES 0414+009	0.287	2005-2009	Abramowski A. et al. (2012)

Neronov et al, A&A, **541**, A31 (2012) (abnormal flare of Mkn 501): very hard intrinsic spectrum is sometimes possible even for fairly “normal” blazars. See also: Shukla et al. (2016): ~30 episodes of hard-spectra, high significance



Things to explain:

1) a possible high-energy anomaly (HM12 – 4.2 σ; Rubtsov & Troitsky, JETP. Lett., **100**, 355 (2014) ~12 σ)
Troitsky, Talk at the Mount Elbrus Conference (2017):
improved analysis, Z~9-10 σ even for Inoue et al. EBL model
Really strong anomaly, exotic solutions
such as ALPs are probably required

2) ~2-4 times higher flux of some blazars pointing towards the voids (indication for intergalactic EM cascade?) (Furniss. et al., MNRAS, **446**, 2267 (2015))

3) indication for ~20% magnetically broadened cascade (MBC) flux at ~1 degree scale at ~1 GeV (Chen et al., Phys. Rev. Lett., **115**, 211103 (2015))

If the anomaly at high energies can be explained by (purely) EM cascades?

Typical arguments:

1. Secondary electrons acquire energy $E_e = E_{\gamma 0}/2$
2. These electrons interact mainly on dense CMB
3. Therefore, cascade photon energy $\approx 4/3 \Gamma_e^2 E_{CMB} << E_{\gamma 0}$

(example: 100 GeV for $E_{\gamma 0}$ = 10 TeV)

4. Therefore, intergalactic EM cascade can not explain the anomaly at high energy

Electromagnetic cascade model of blazar emission

Aharonian et al., A&A, **349**, 11 (1999)

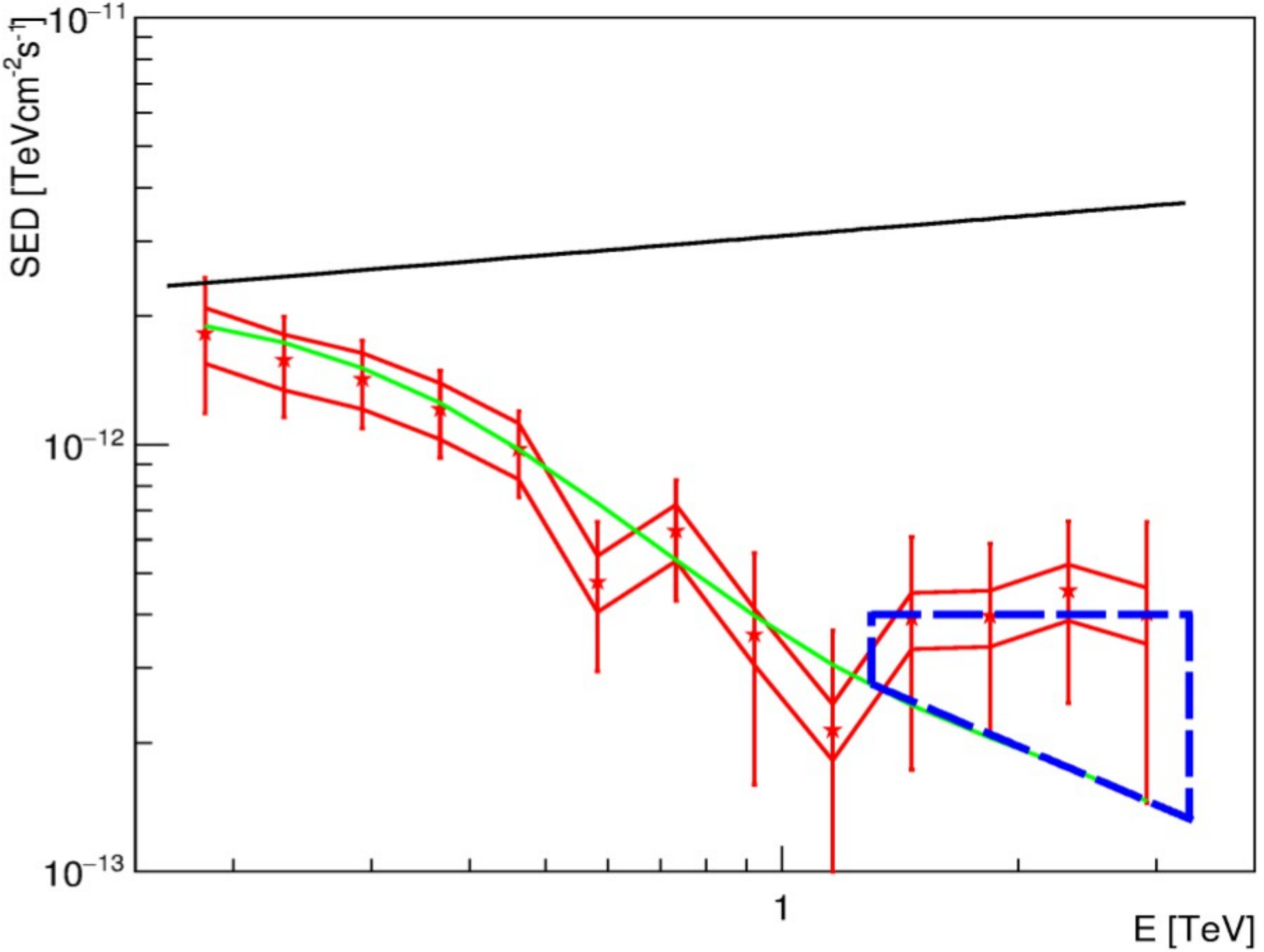
Aharonian et al., A&A, **384**, 834 (2002)

d'Avezac et al., A&A, **469**, 857 (2007)

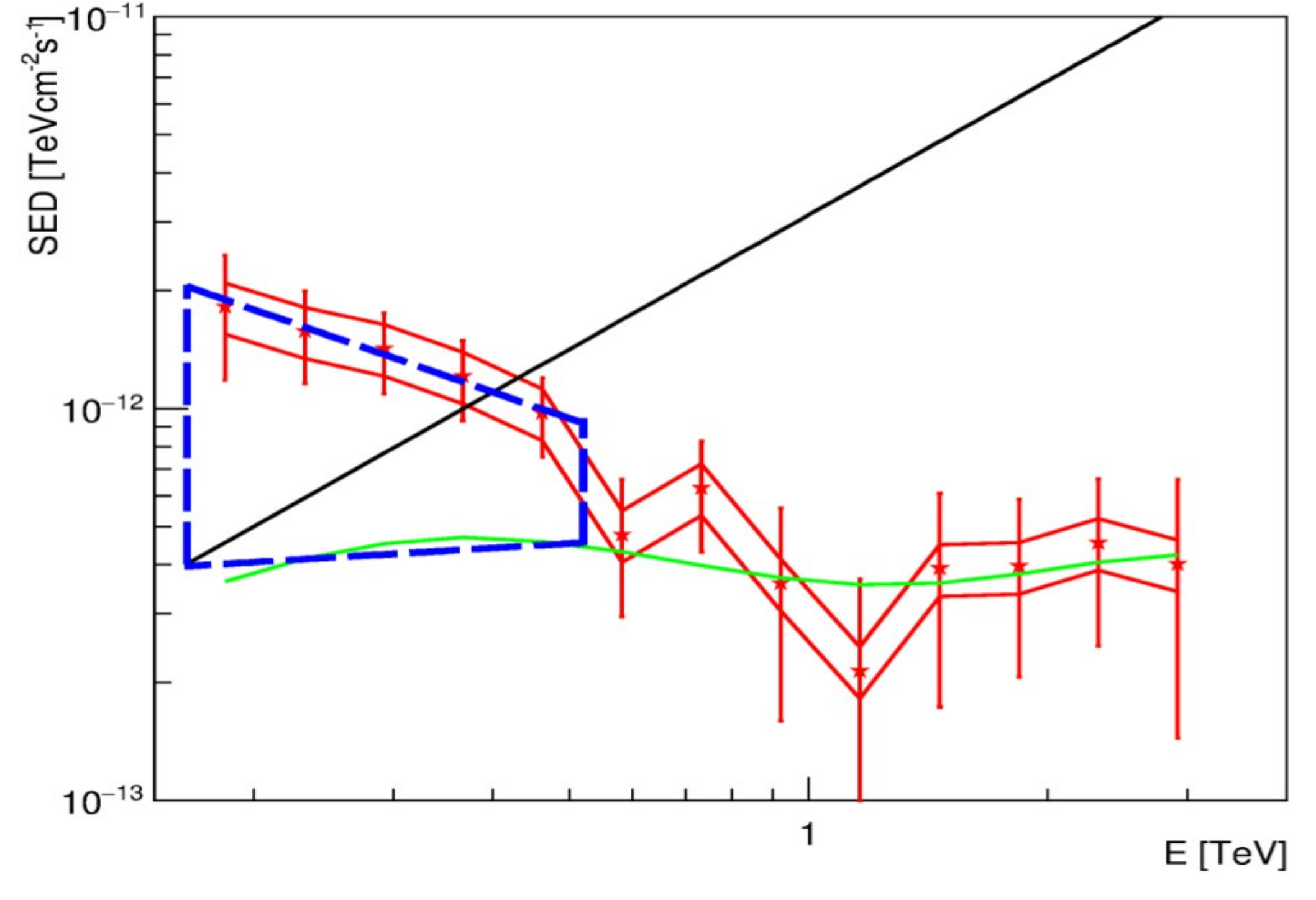
Murase et al., ApJ, **749**, 63 (2012)

Takami et al., ApJ Lett., **771**, L32 (2013)

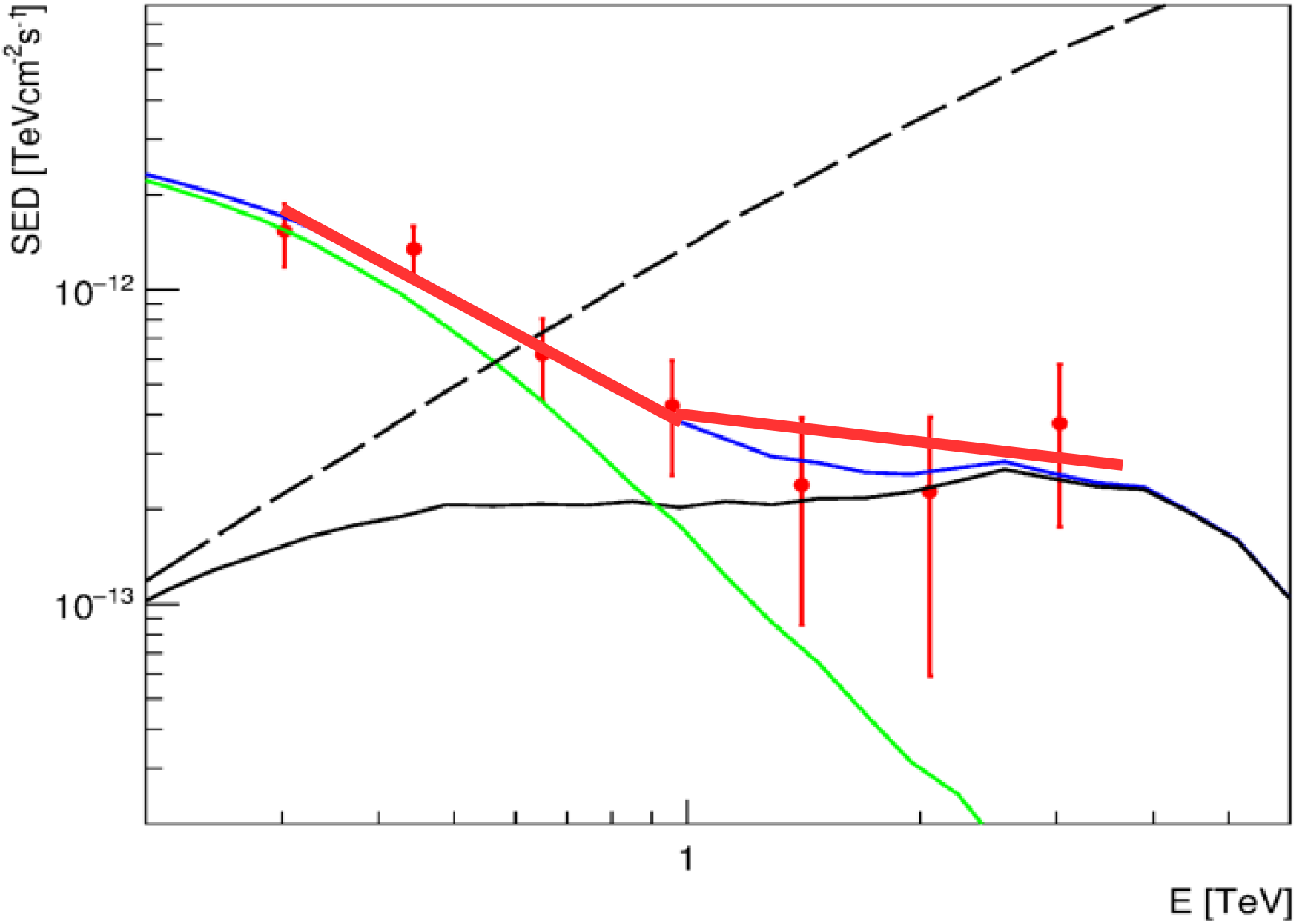
The high-energy excess option



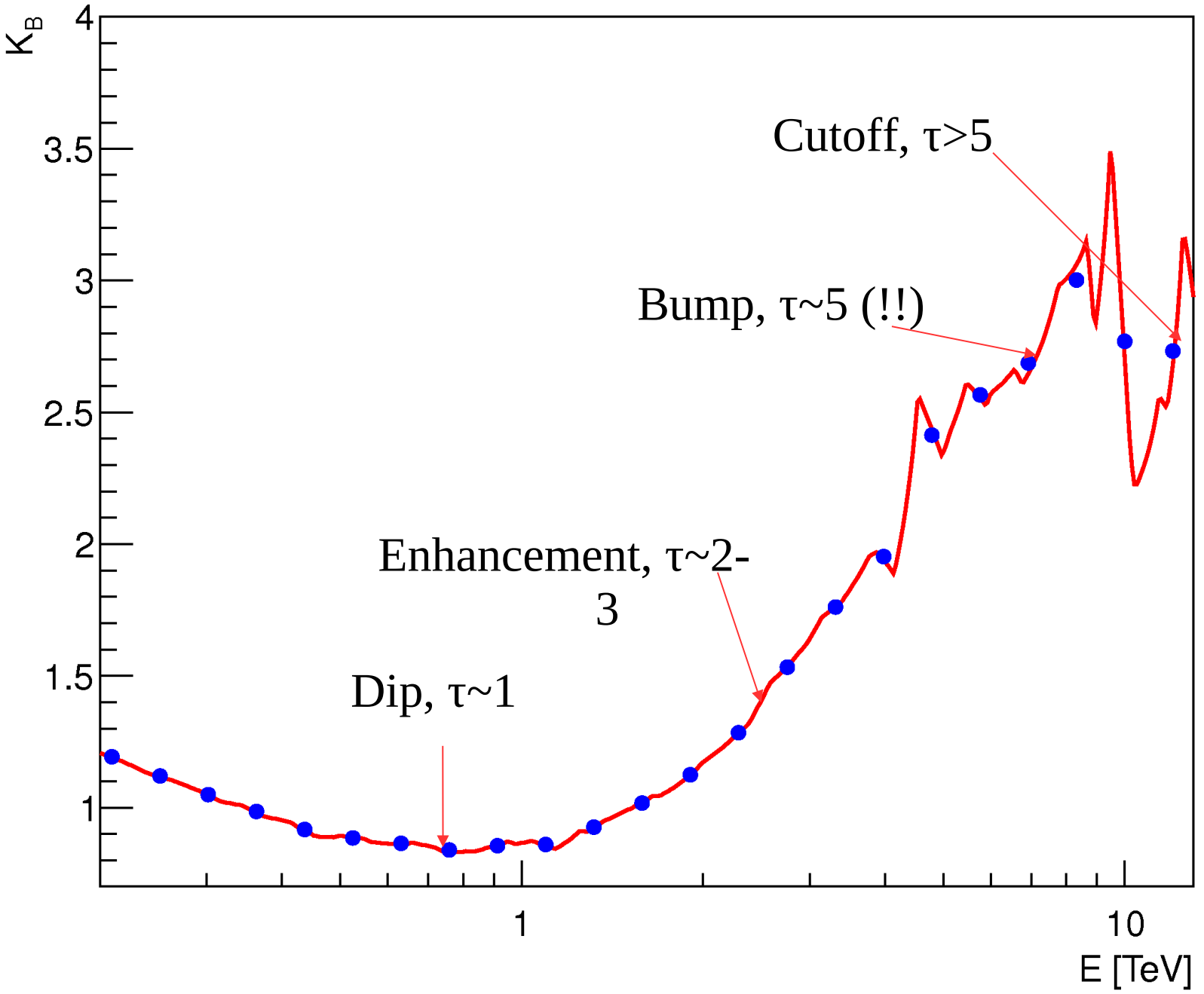
The low-energy excess option



Electromagnetic cascade model (z= 0.188). SED shape at low energy is concealed by the cascade component (“EM cascade masquerade”).

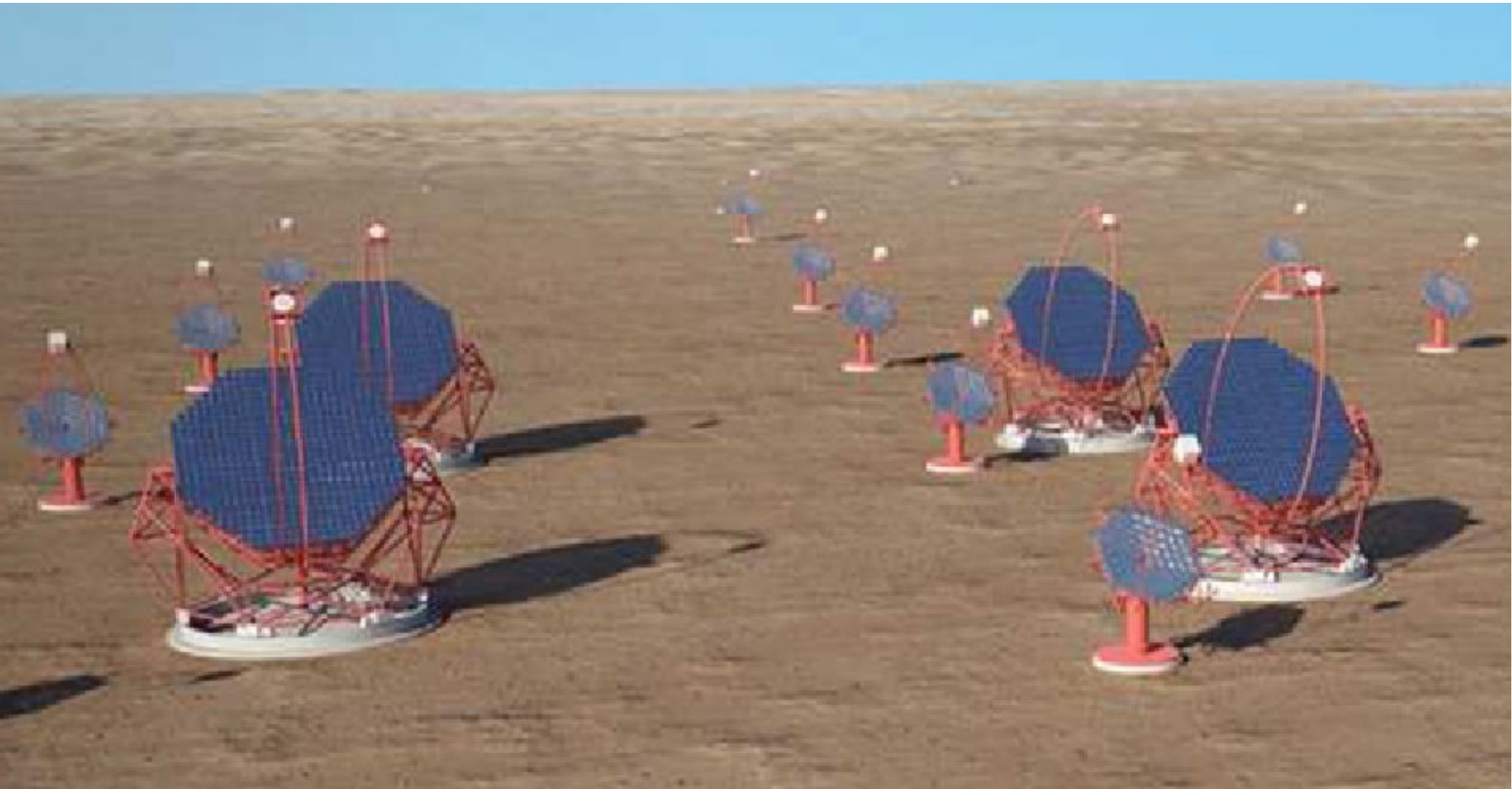


The ratio of best-fit model spectra for electromagnetic cascade model and the absorption-only model. Electromagnetic cascade model predicts up to 3 times more flux at E=8 TeV

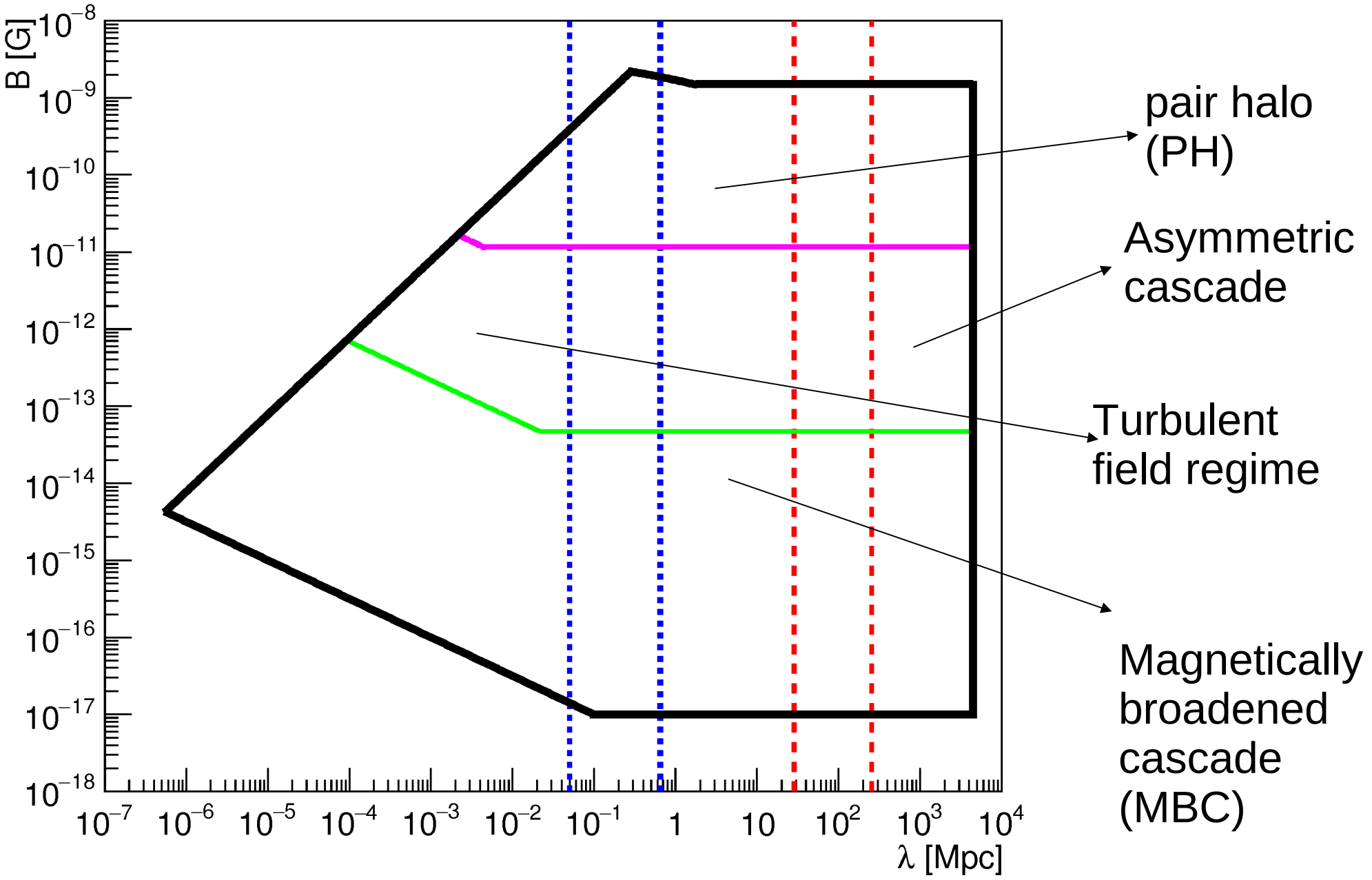


3. EGMF parameter sensitivity for Fermi LAT and CTA
(cf. Meyer et al. (2016), see section 5
for their assumptions)

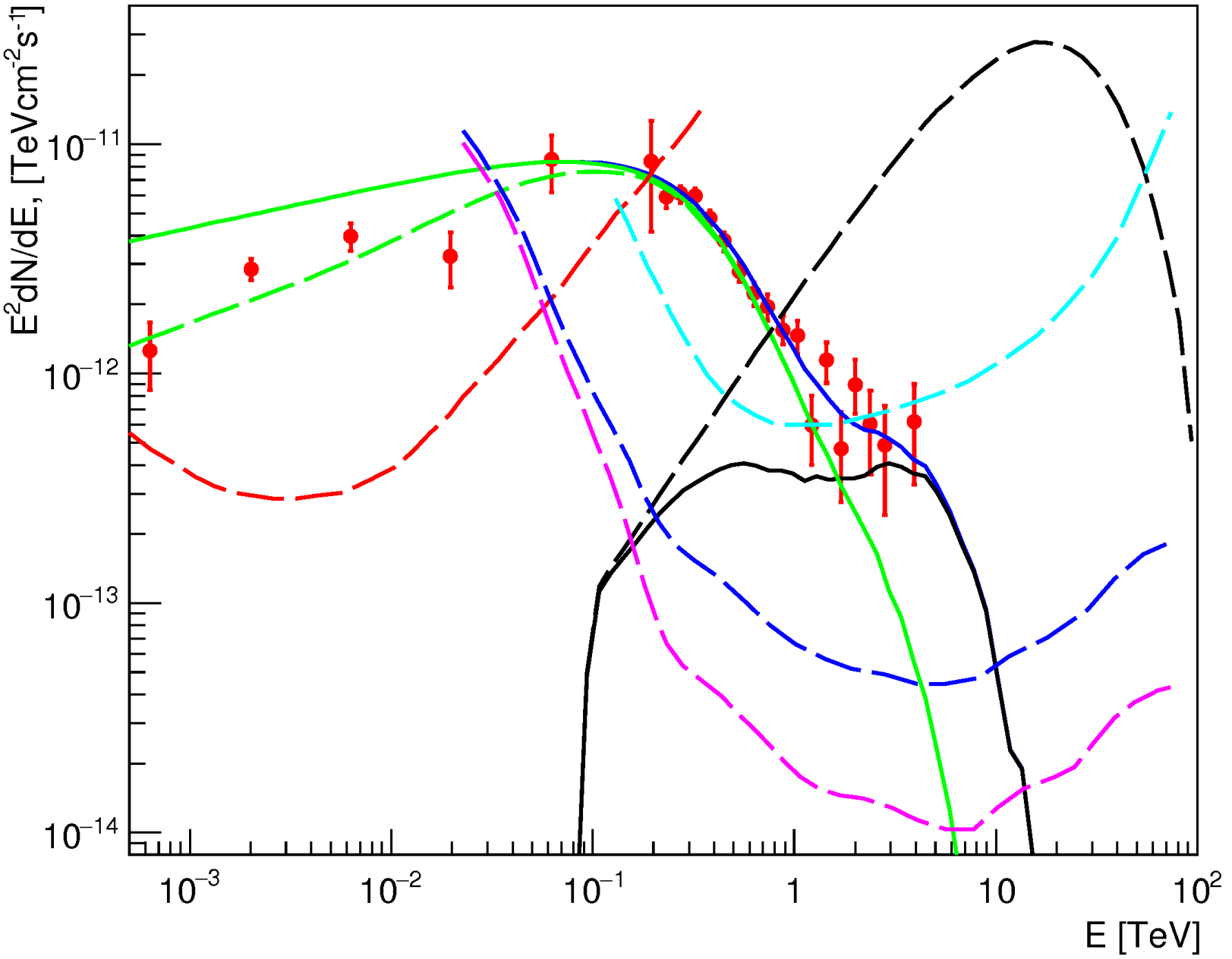
The Cherenkov Telescope Array (CTA): low threshold (20 GeV), improved sensitivity and angular resolution



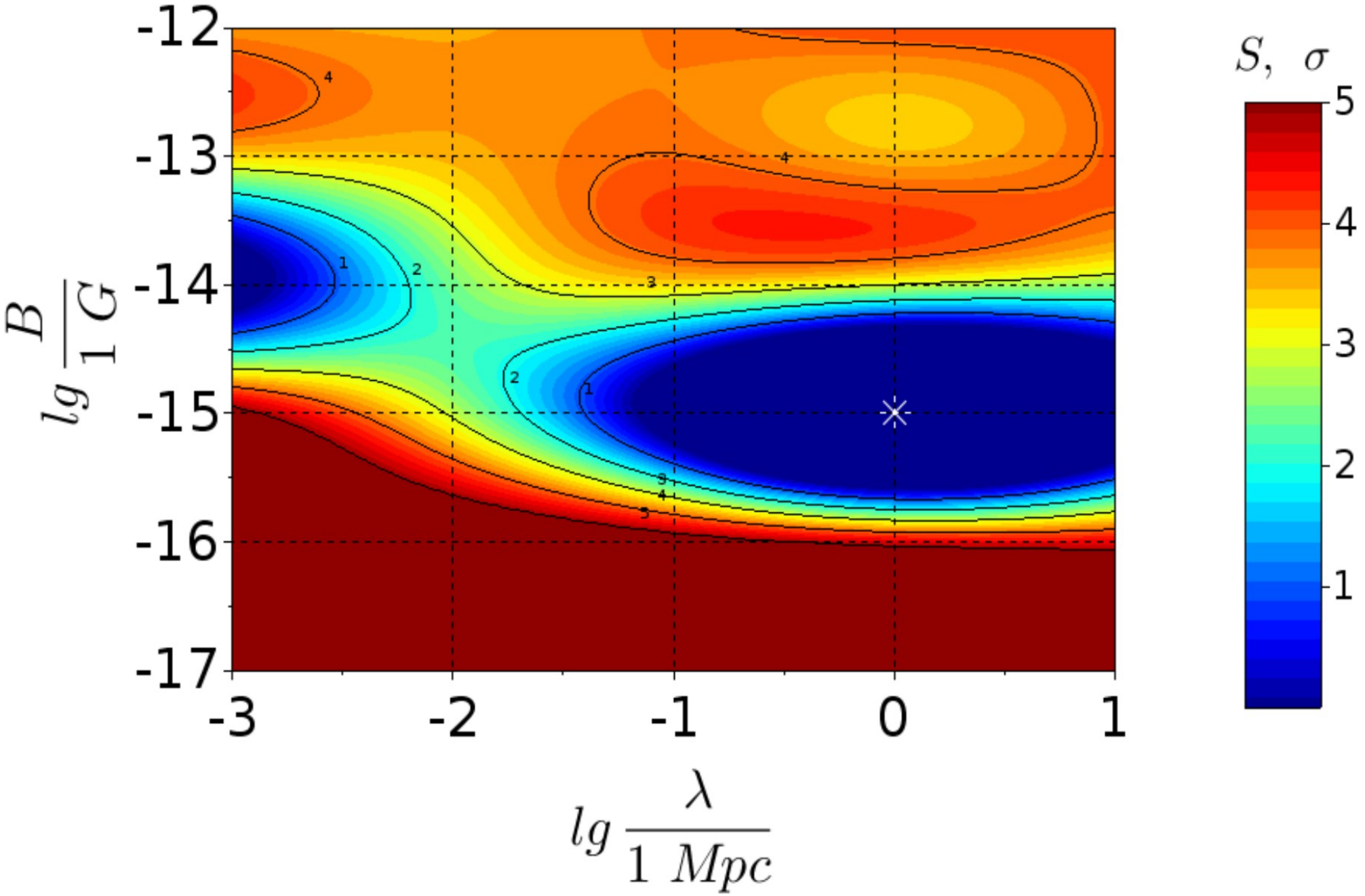
EGMF constraints following NS09 and the main regimes of intergalactic EM cascade development



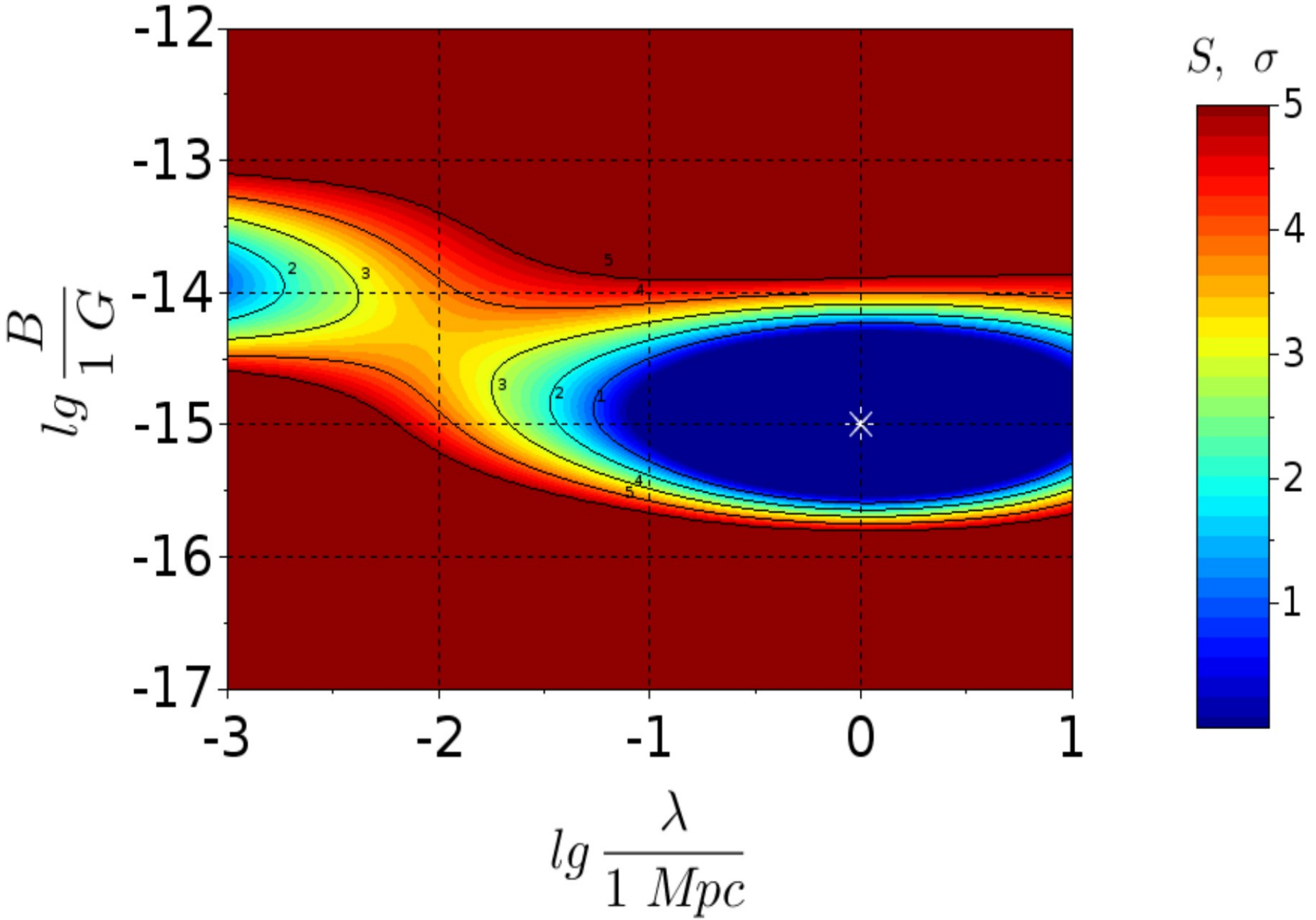
"Magnetic cutoff" (cf. -1 spectrum of Neronov et al.). 1ES 1218+304, B= 1 fG, L= 1 Mpc. The PSF radius depends on energy! Variability studies are extremely important!



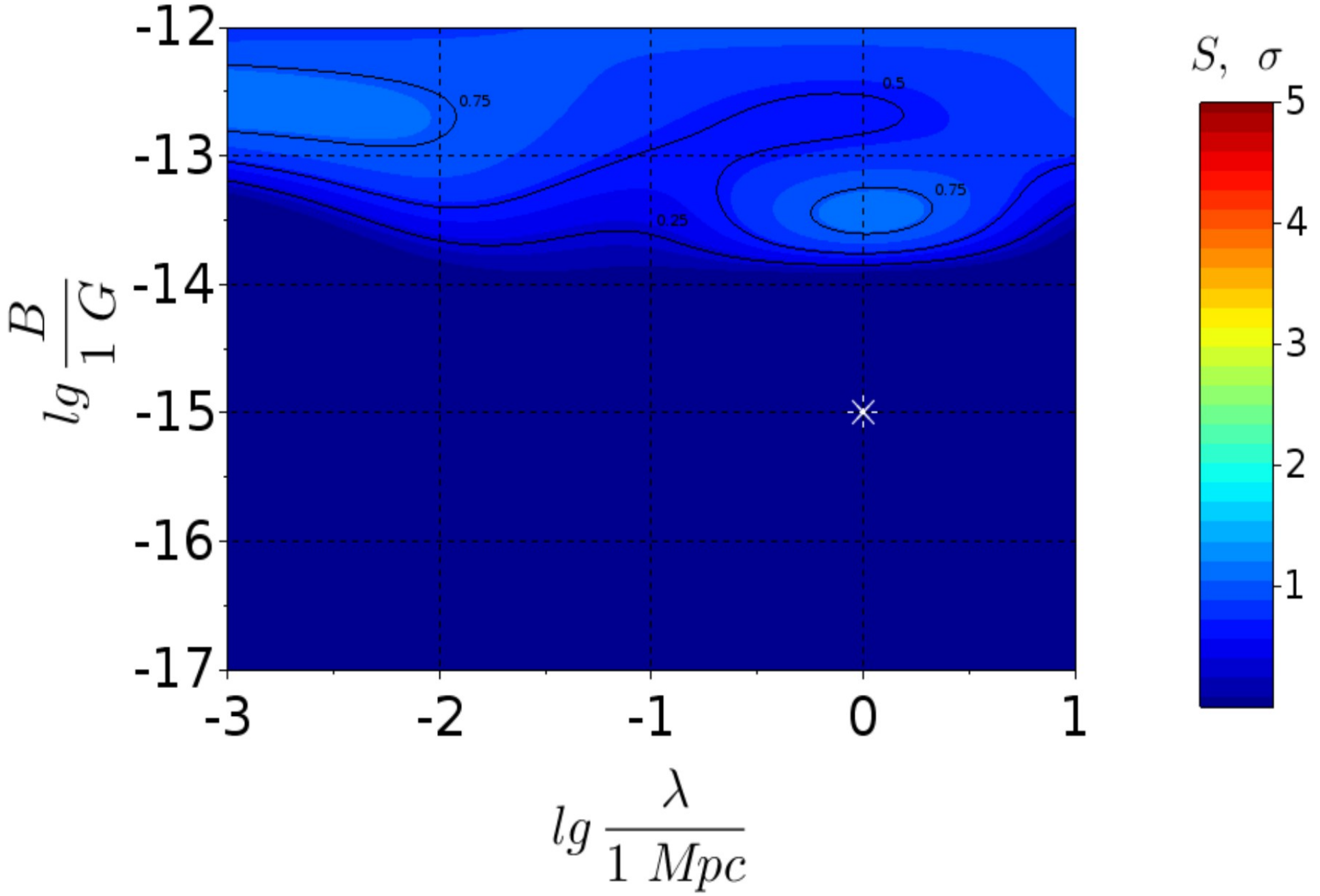
Sensitivity to the EGMF parameters: “magnetic cutoff” method, CTA+ Fermi LAT. 1ES 1218+304, (B= 1 fG, L= 1 Mpc).



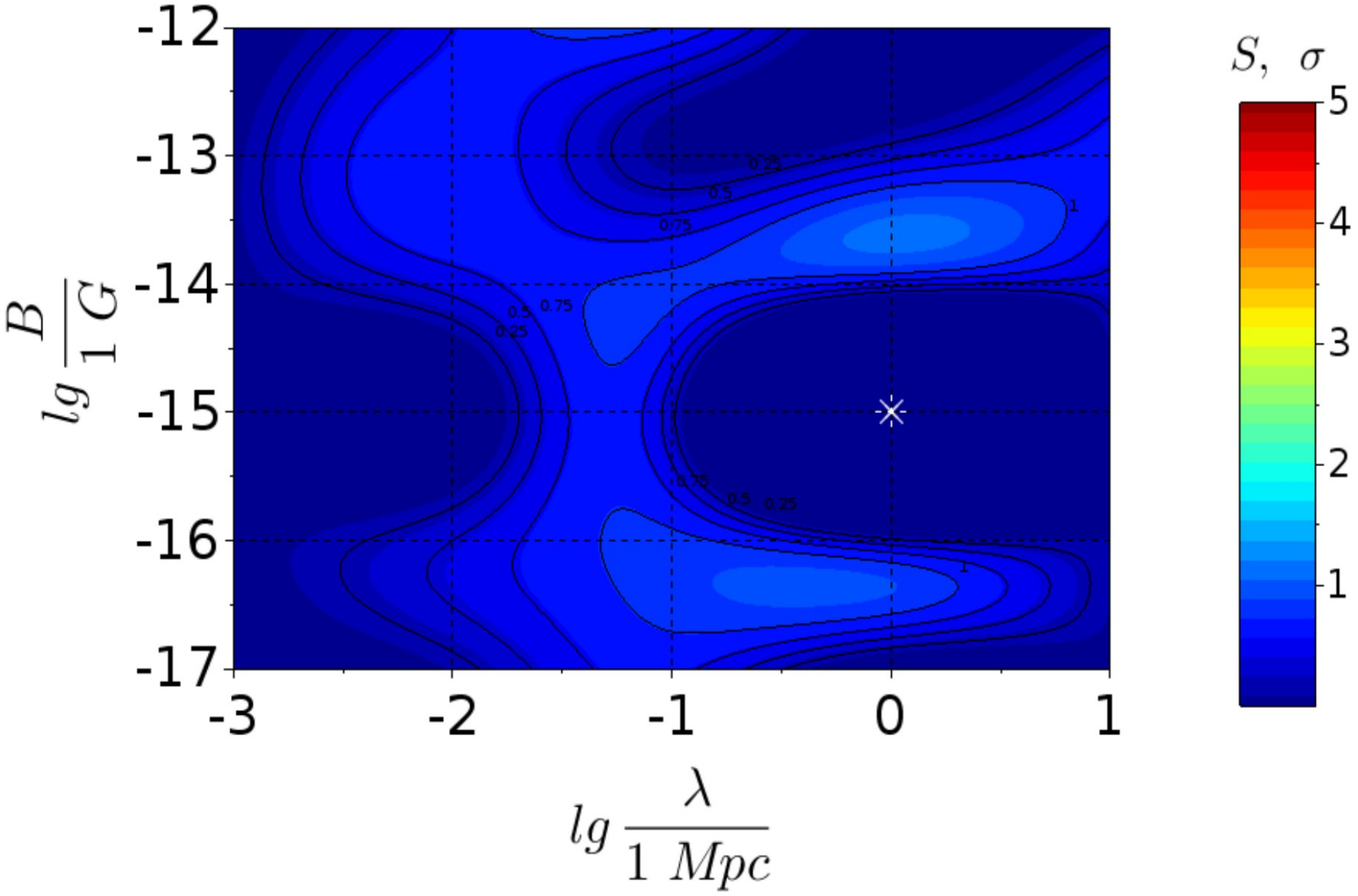
Sensitivity to the EGMF parameters: MBC method, CTA+ Fermi LAT



Sensitivity to the EGMF parameters: “magnetic cutoff” method, only CTA



Sensitivity to the EGMF parameters: MBC method, only CTA. Conclusion: a space telescope is needed

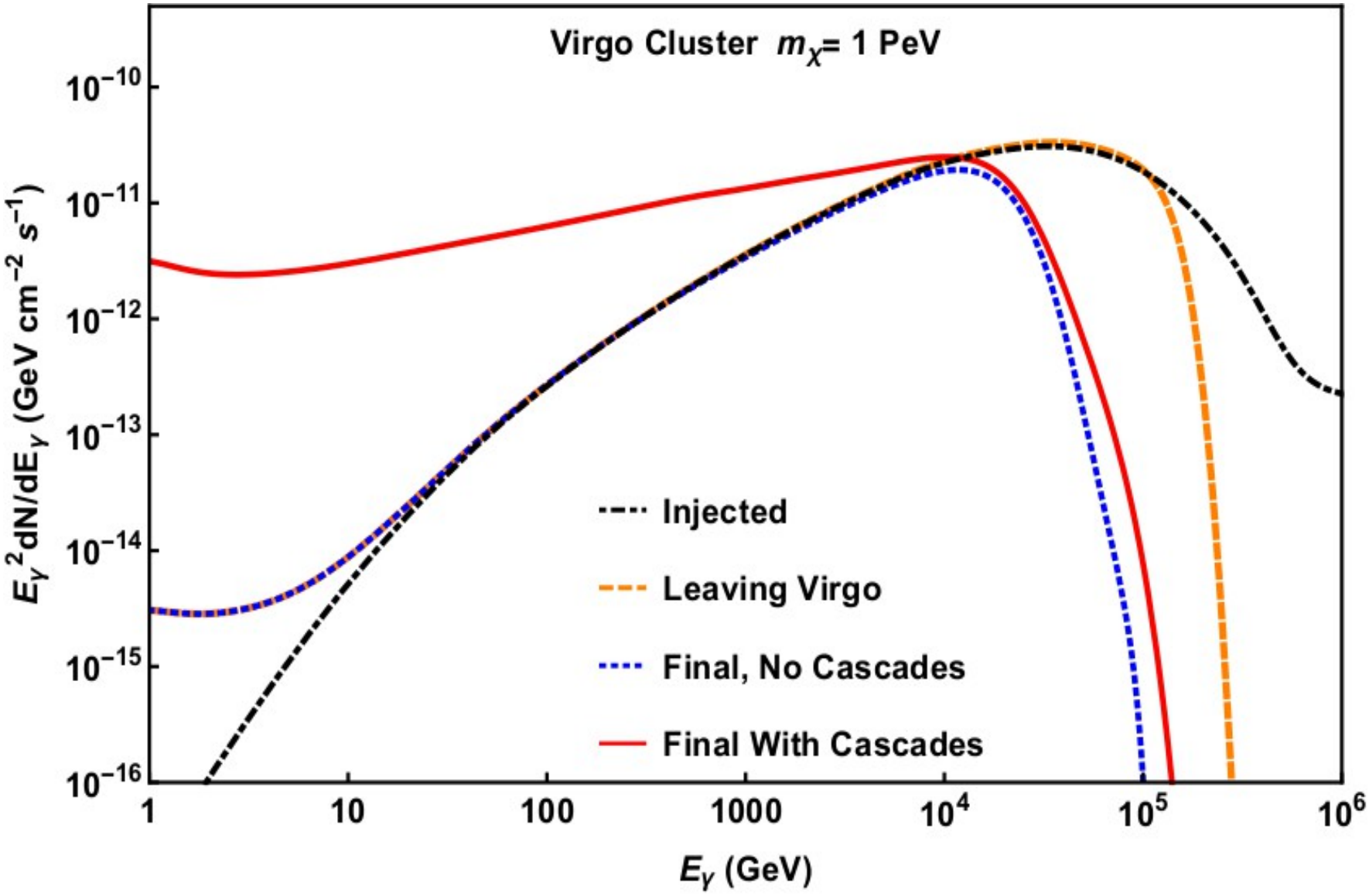


4. Spectrum and angular distribution of cascade γ-rays from nearby extragalactic sources in context of DM searches

Their motivation: “the streetlight effect” (эффект Ходжи Насреддина) (Esmaili et al. JCAP, 12, 054 (2014))

Blanco et al., JCAP, 04, 060 (2018): highly non-standard scenarious with very heavy (>100 TeV) annihilating dark matter (ovecoming usual upper bounds on mass).
Our work: applicable to any source of gamma-rays in nearby extragalactic objects

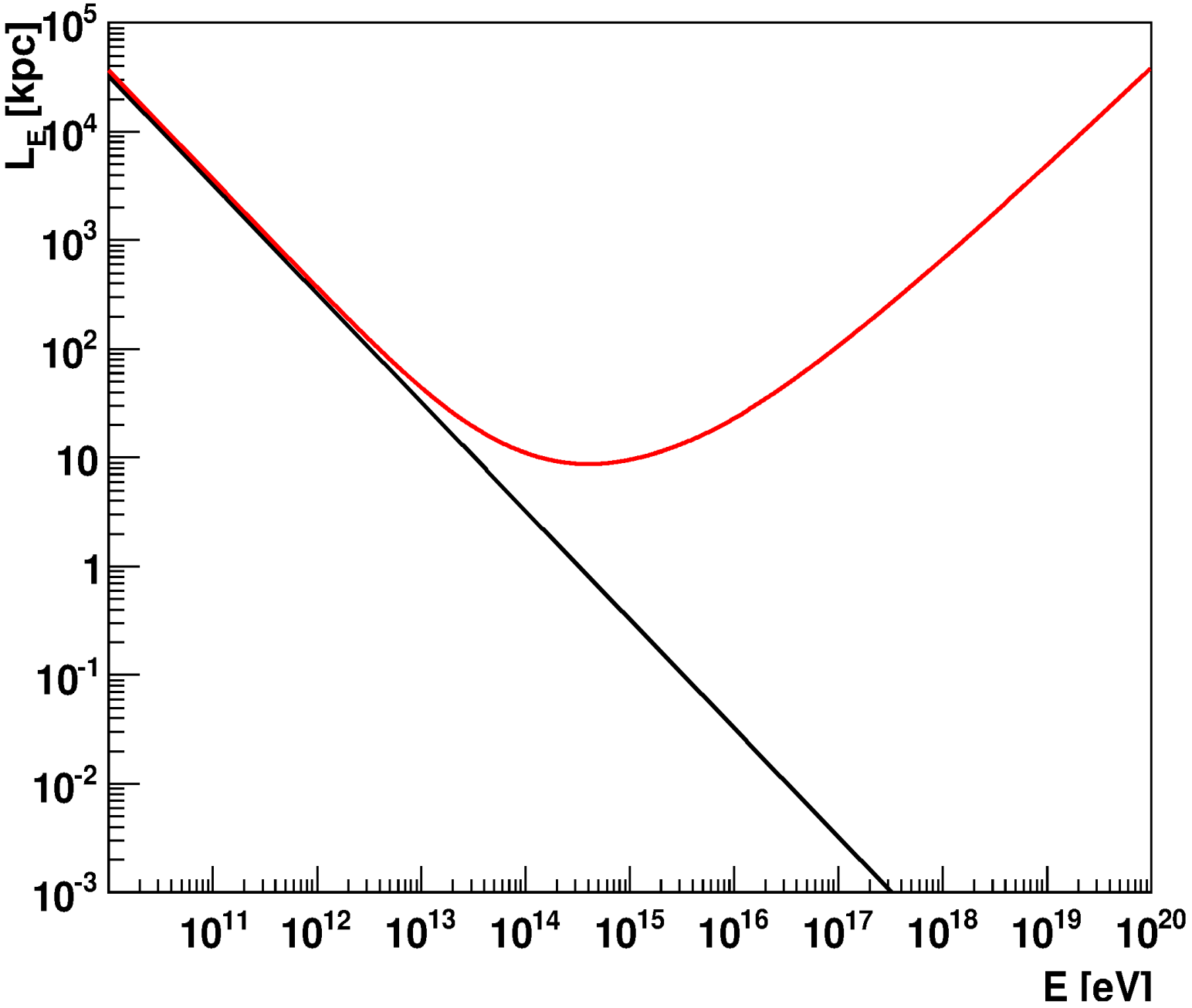
Example: Blanco et al. (2018)



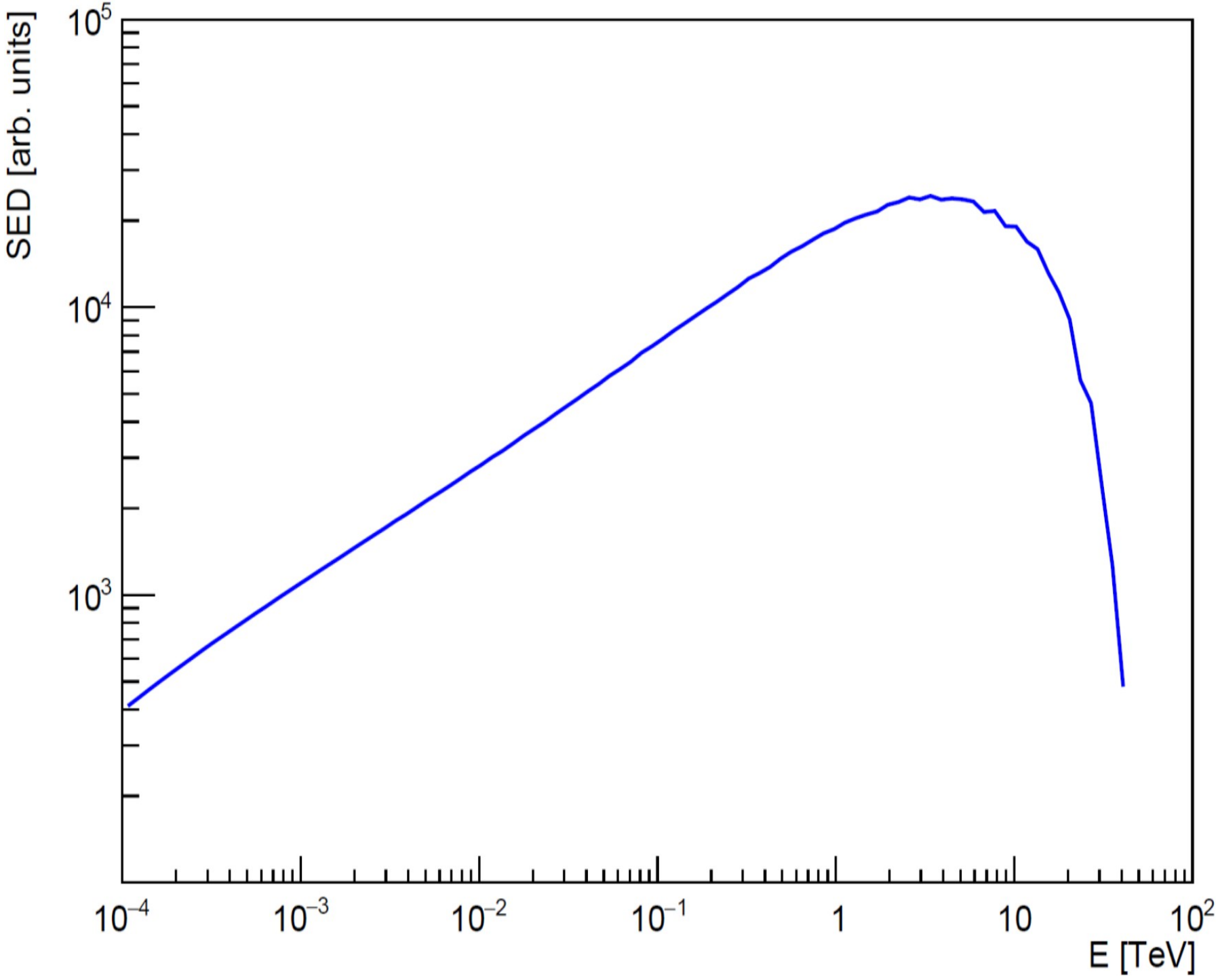
$$\sin\Theta \simeq l/r_l \sim 0.3 \left(\frac{B}{10^{-11}\,\mathrm{G}}\right)\left(\frac{100\ \mathrm{TeV}}{E_e}\right)^2$$

The (l/r) ratio was severely underestimated!! → no MBC observable

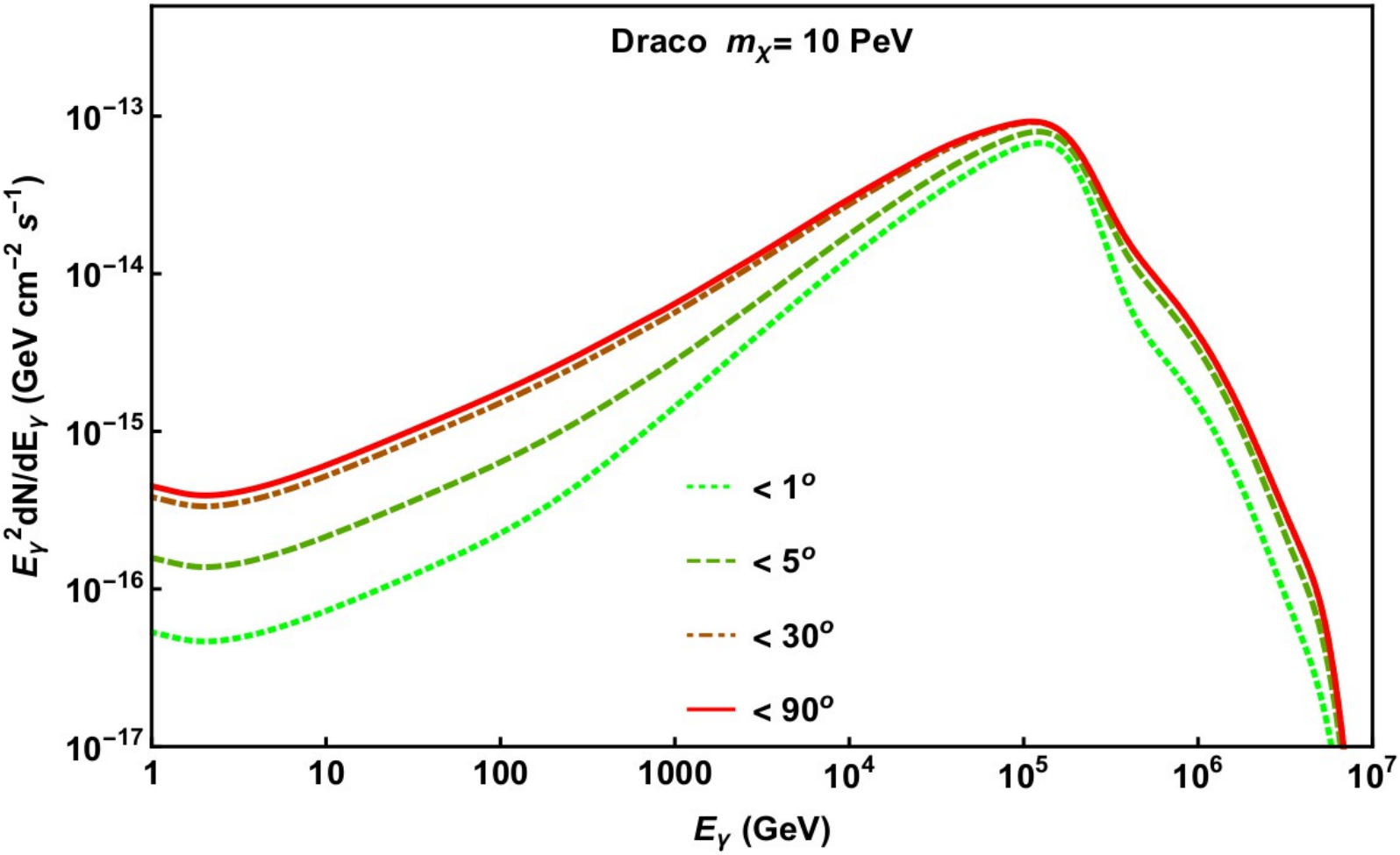
(Black: Thomson regime approximation, red: approximation of Khangulyan et al. (2014))



Observable spectrum: $E_{\gamma 0}$= 100 TeV, L= 16.8 Mpc



Distribution on deflection angle (Blanco et al. (2018))



In fact, the "pair halo regime" is realised (instead of the MBC regime). If $E_{\gamma 0}$~1-3 PeV, the observer can see a cloud of angular extension ~(8 kpc+10 kpc)/(80 kpc)= 0.2 rad. For Virgo, if $E_{\gamma 0}$= 100 TeV, ~(1 Mpc)/(16.8 Mpc)= 0.06 rad.

5. Any room for intergalactic cascade models after astro-ph/1804.08035?

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

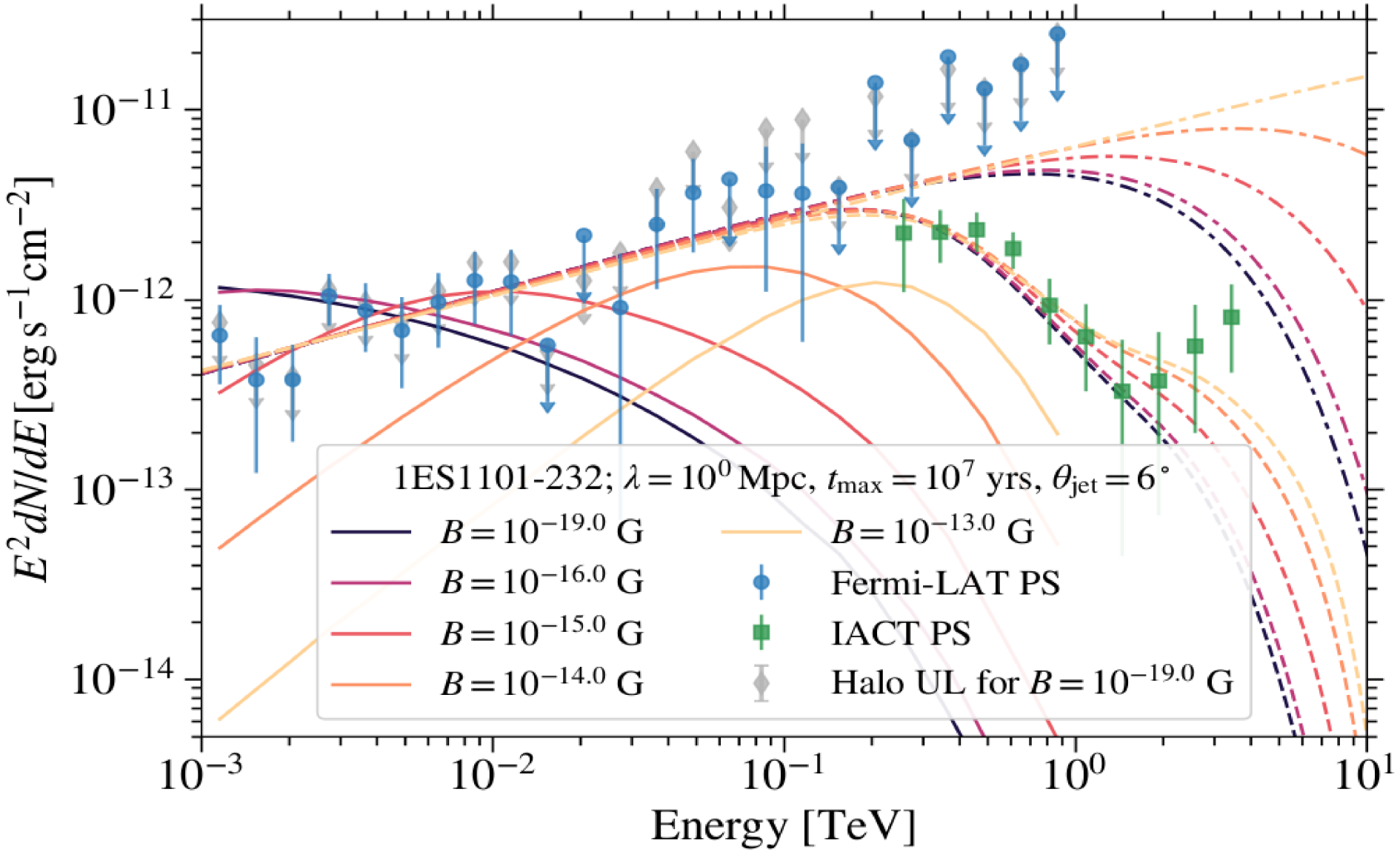
Their conclusion: “This improves previous limits by several orders of magnitude.”

No MBC/PH was found

Still the result of Chen et al. (2015) on MBC is not excluded directly

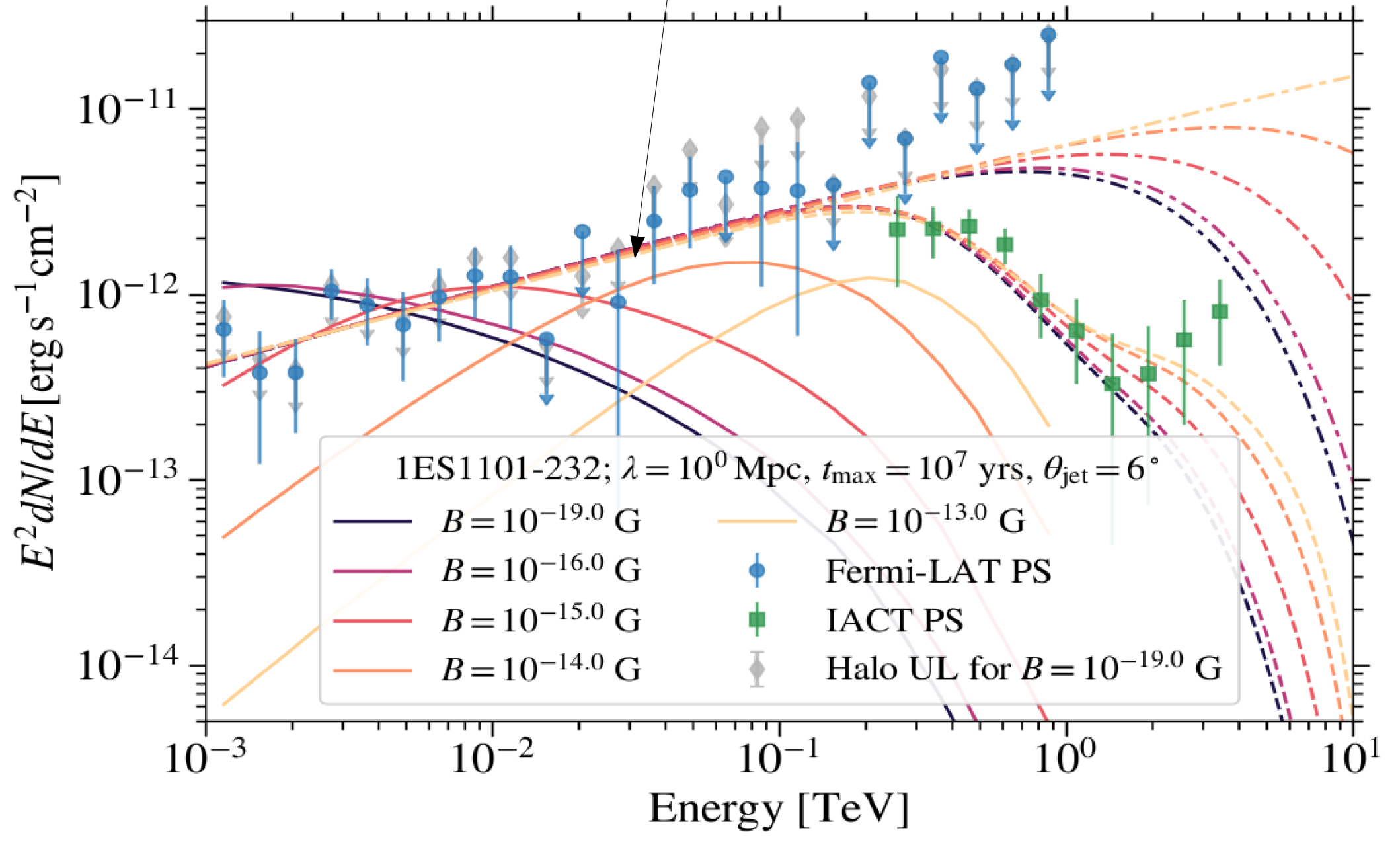
It is rather noted that systematics does not allow to prove the existence of the MBC/PH

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!!



Conclusions (1)

1. For intergalactic hadronic cascade models of blazar emission, it is very important to account for realistic structure of the EGMF "strong component". For realistic models of this component the development of EM cascades from primary protons/nuclei does not modify the effective opacity of the Universe significantly.

2. The development of EM cascades from primary γ-rays may, in principle, qualitatively explain all known "anomalies". A very strong anomaly, however, could not be produced by this mechanism.

The most severe test of the intergalactic electromagnetic cascade model is variability.

Conclusions (2)

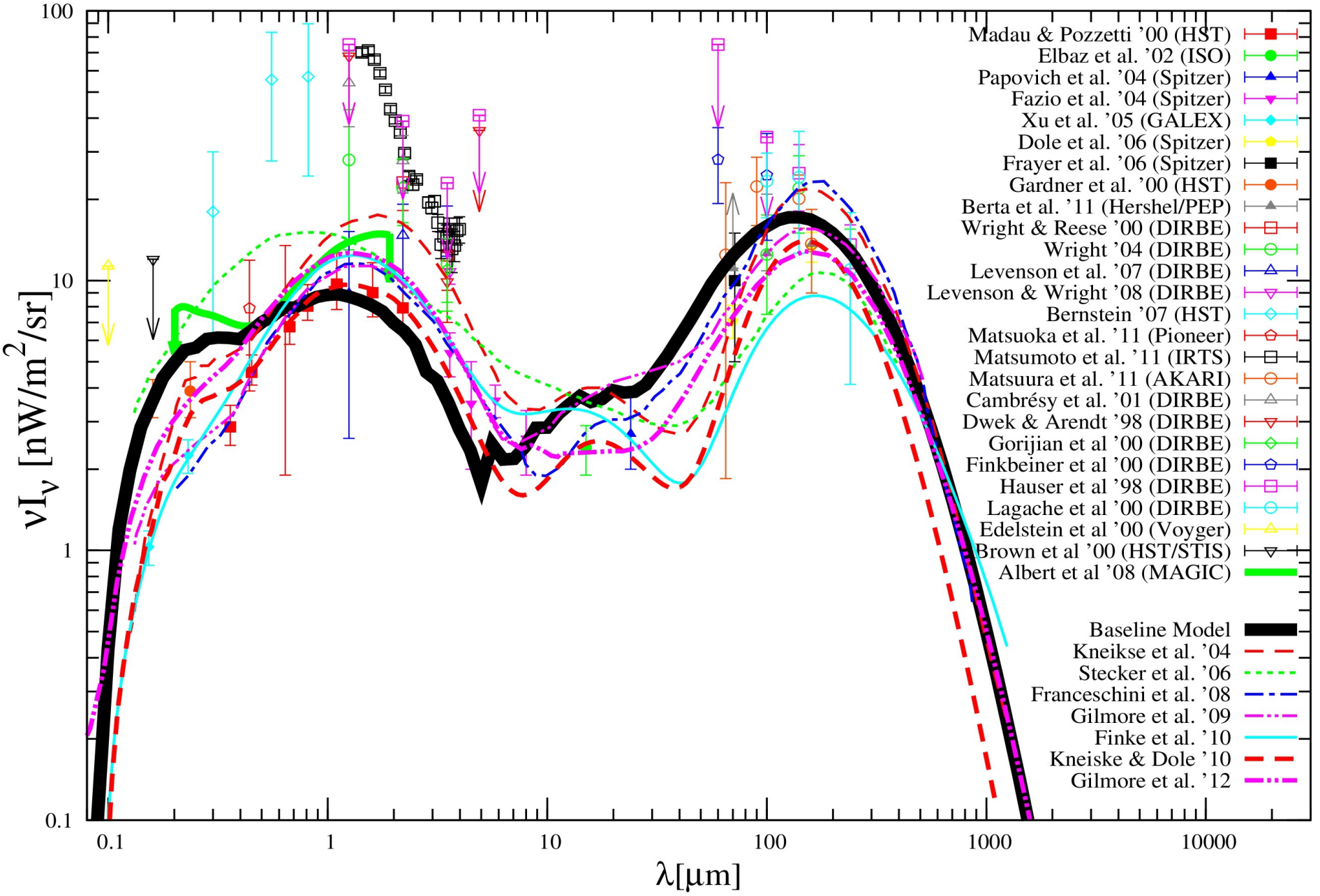
3. While measuring EGMF, CTA should be supplemented by a space-based telescope such as Fermi LAT.

4. MBC/PH boundary (on magnetic field) moves up for the case of nearby extragalactic objects due to higher electron energy. Thomson regime formulas are not applicable in this case!

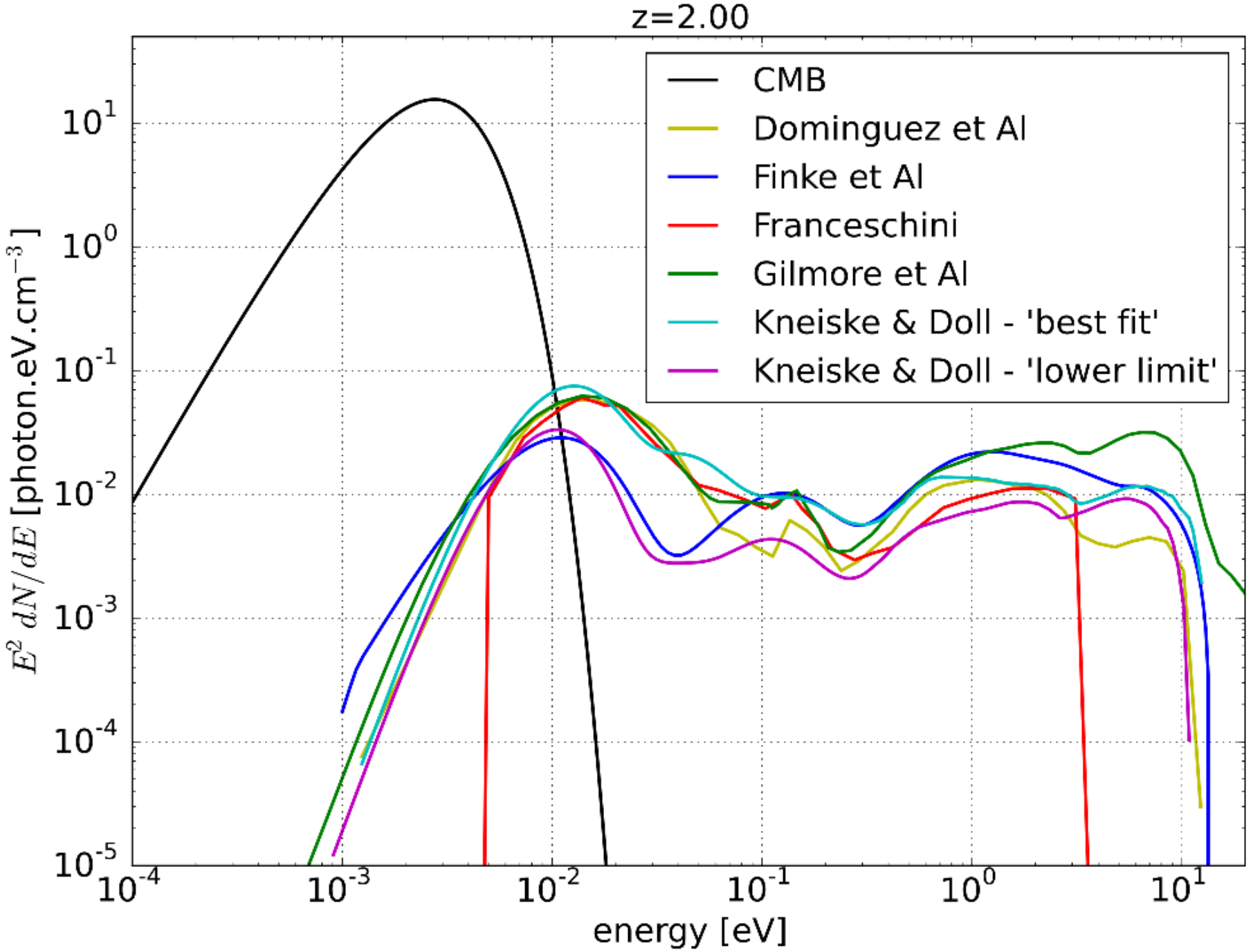
5. No evidence for strong (0.1 pG) EGMF in voids from Fermi LAT so far, even for stable sources.

Additional slides

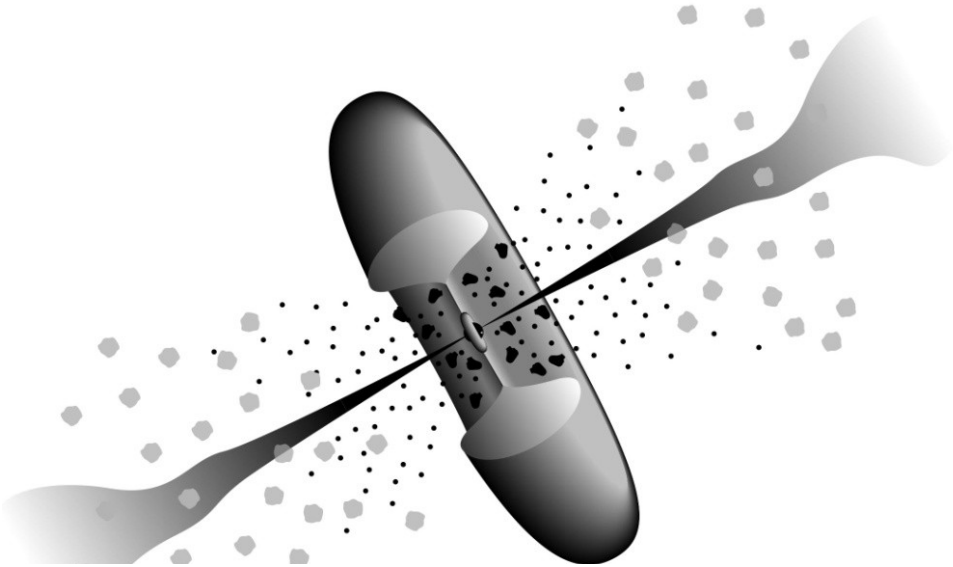
We consider point-like extragalactic sources (for the most part beamed). Primary γ-rays absorb on EBL (and for $E_{\gamma 0} > 100$ TeV/(1+z) --- on CMB) photons (model SEDs of EBL: Inoue et al., ApJ, **768**, 197 (2013)

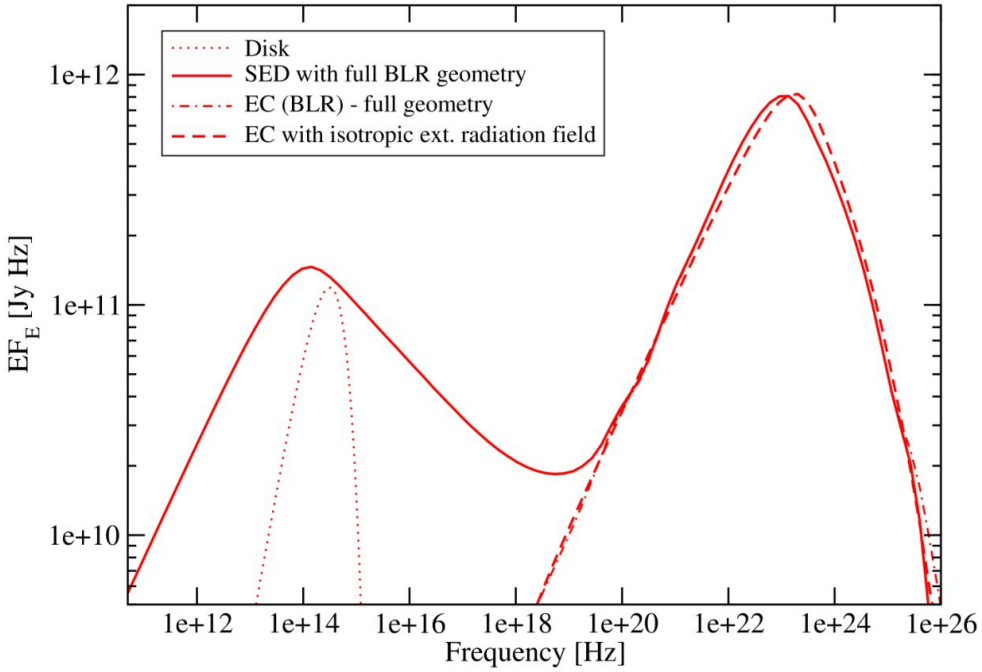


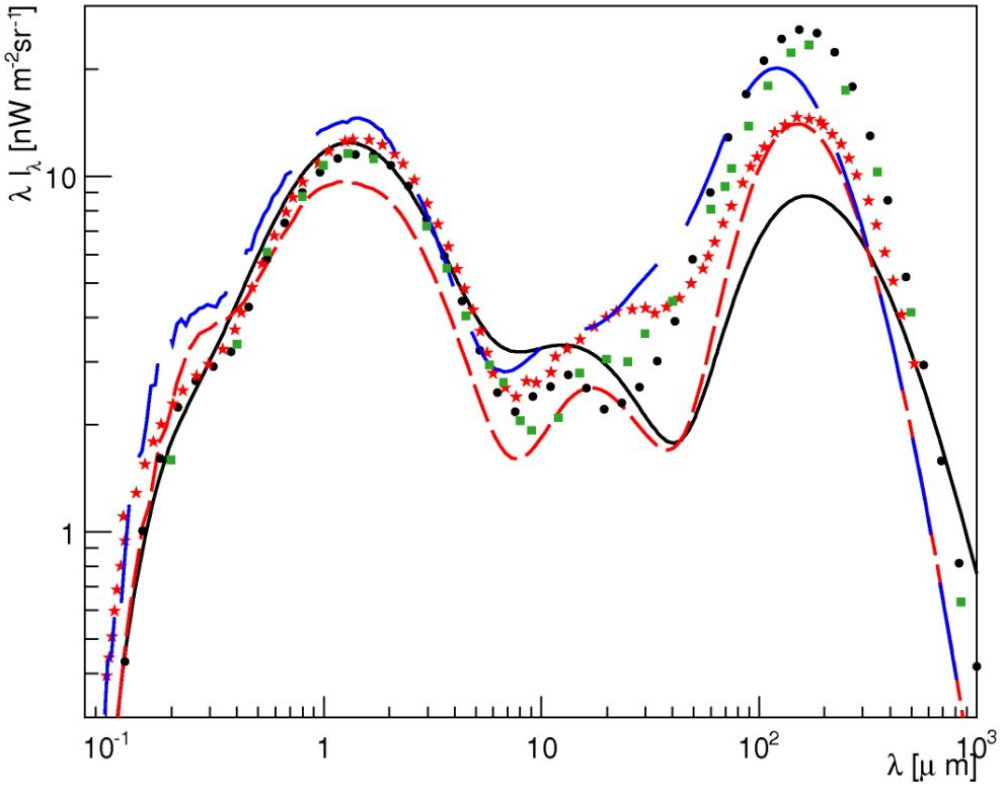
SED of EBL at z=2 (according to F17).
Caveat: large systematic uncertainty of EBL models at high z



Typical AGN geometry (left, [1]) and SED of a MeV-GeV blazar (right, [2]); SED of EBL for several models (bottom, [3])







[1] Urry & Padovani, PASP, **107**, 803 (1995); more details in: Antonucci, ARA&A, **31**, 473 (1993)

[2] Boettcher et al., ApJ, **768**, 54 (2013)

[3] EBL model KD10 is shown by red dashed line

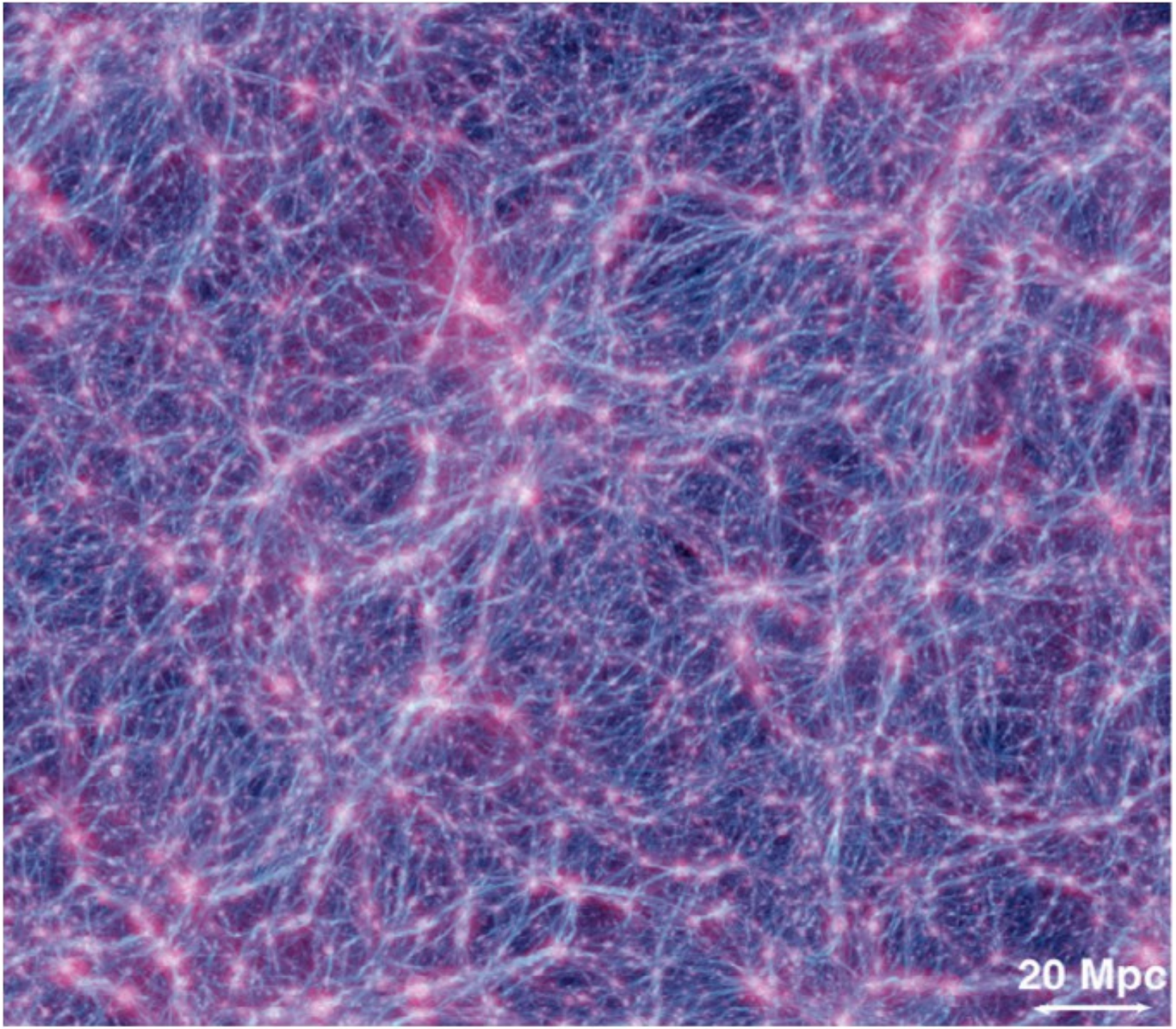
Extreme TeV blazars: high-energy peak in the SED at E>1 TeV, usually weak variability

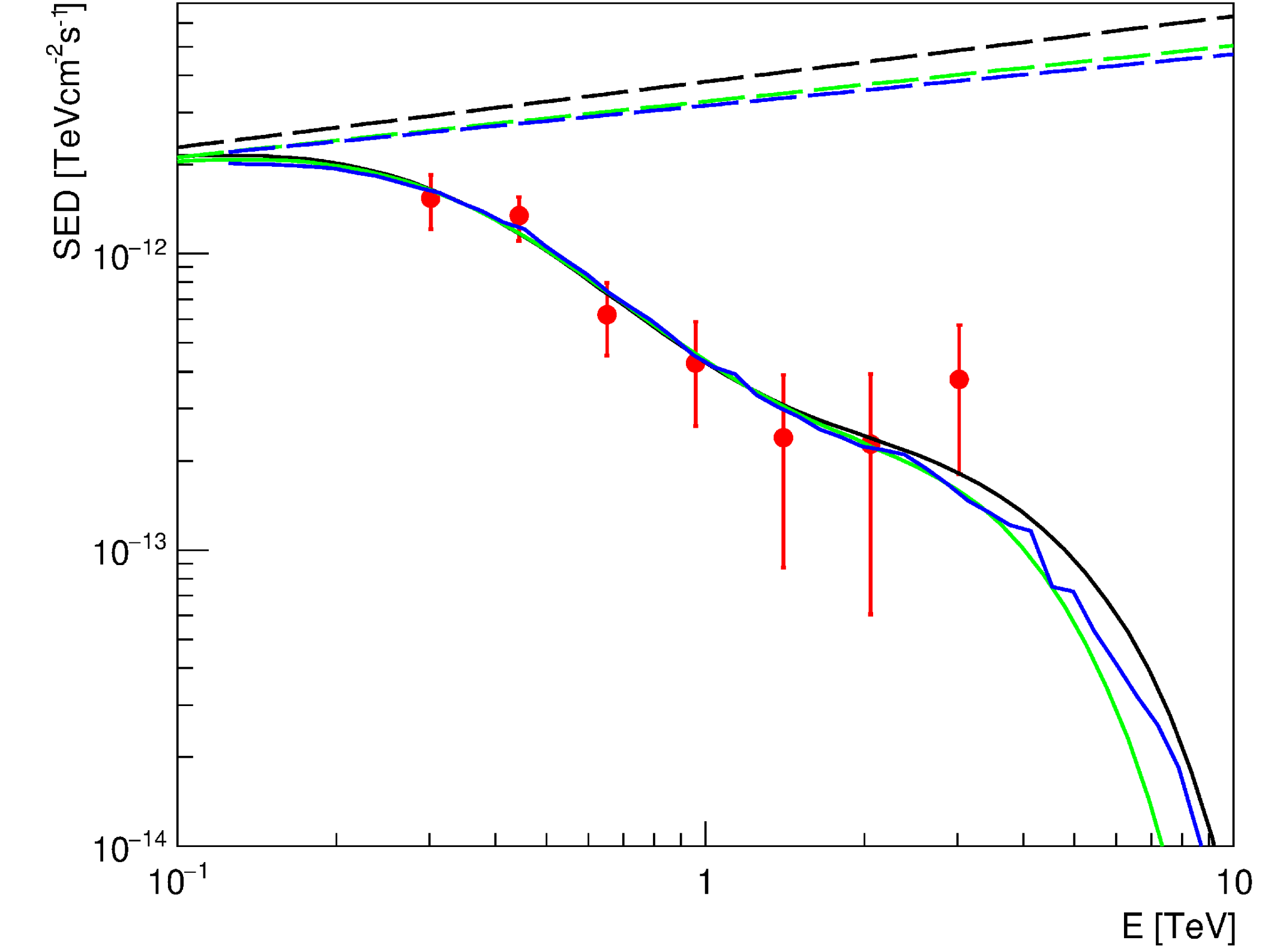
Extragalactic gamma-ray propagation models (more conservative first)

1. Absorption-only model: pair production+adiabatic losses
2. Electromagnetic cascade model: +IC
3. Hadronic cascade model: +EM cascades from UHE (>1 EeV) protons and nuclei
4. gamma-axion-like particle (ALP) oscillation
5. Other "exotic" models (exotic primaries, etc.), for for instance: Aharonian et al., ApJ, **543**, L39 (2000) "Rejection of the Hypothesis That Markarian 501 TeV Photons Are Pure Bose-Einstein Condensates"

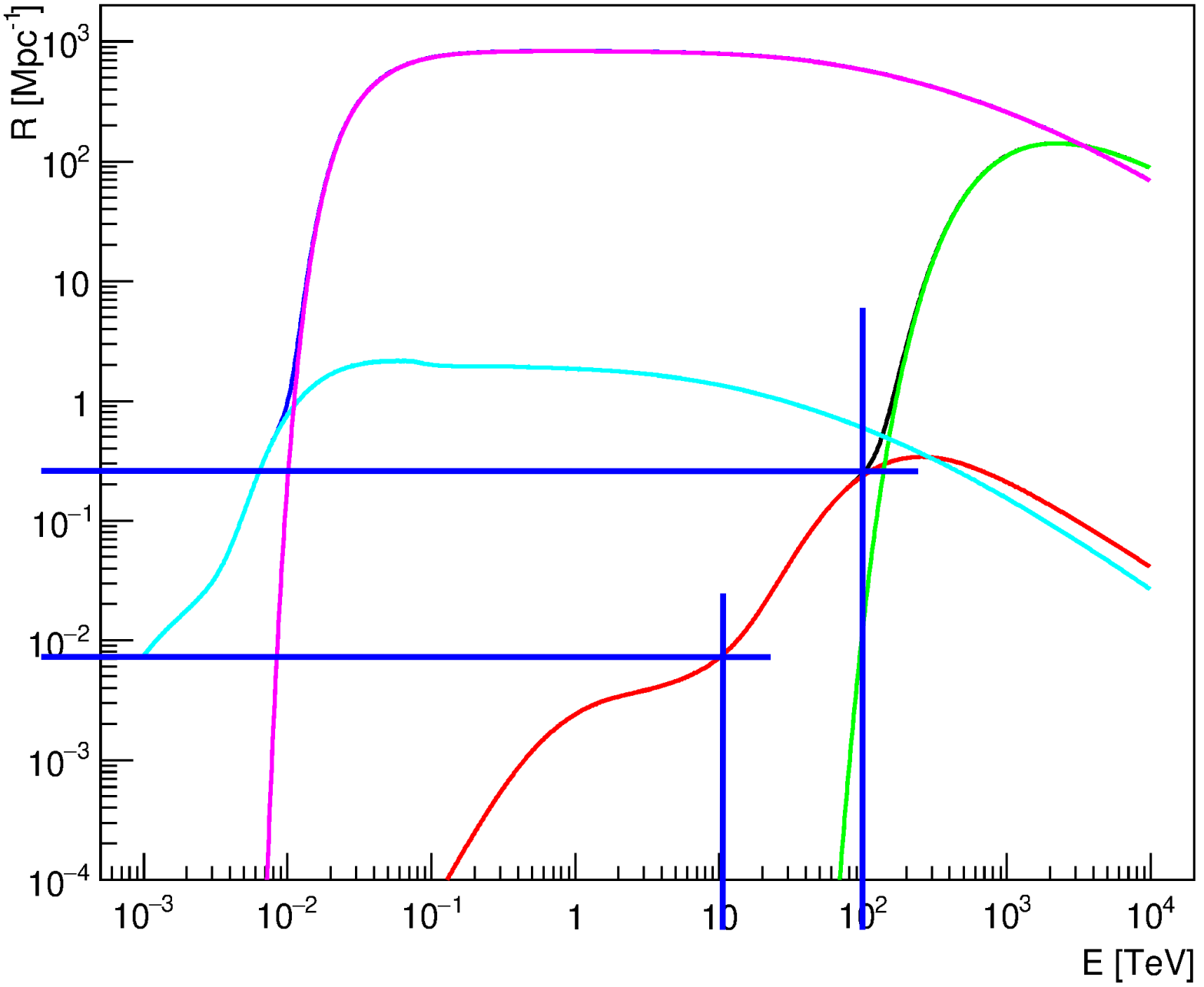
General idea: BEC (superposition of several photons) usually develop a shower in the atmosphere earlier wrt normal photons; this affects the parameters of the images and was ruled out experimentally

EGMF simulations: Vazza et al., Class. Quantum Grav., **34**, 234001 (2017)




SED [TeVcm^{-2}s^{-1}]
10^{-12}
10^{-13}
10^{-14}
10^{-1}
1
10
E [TeV]

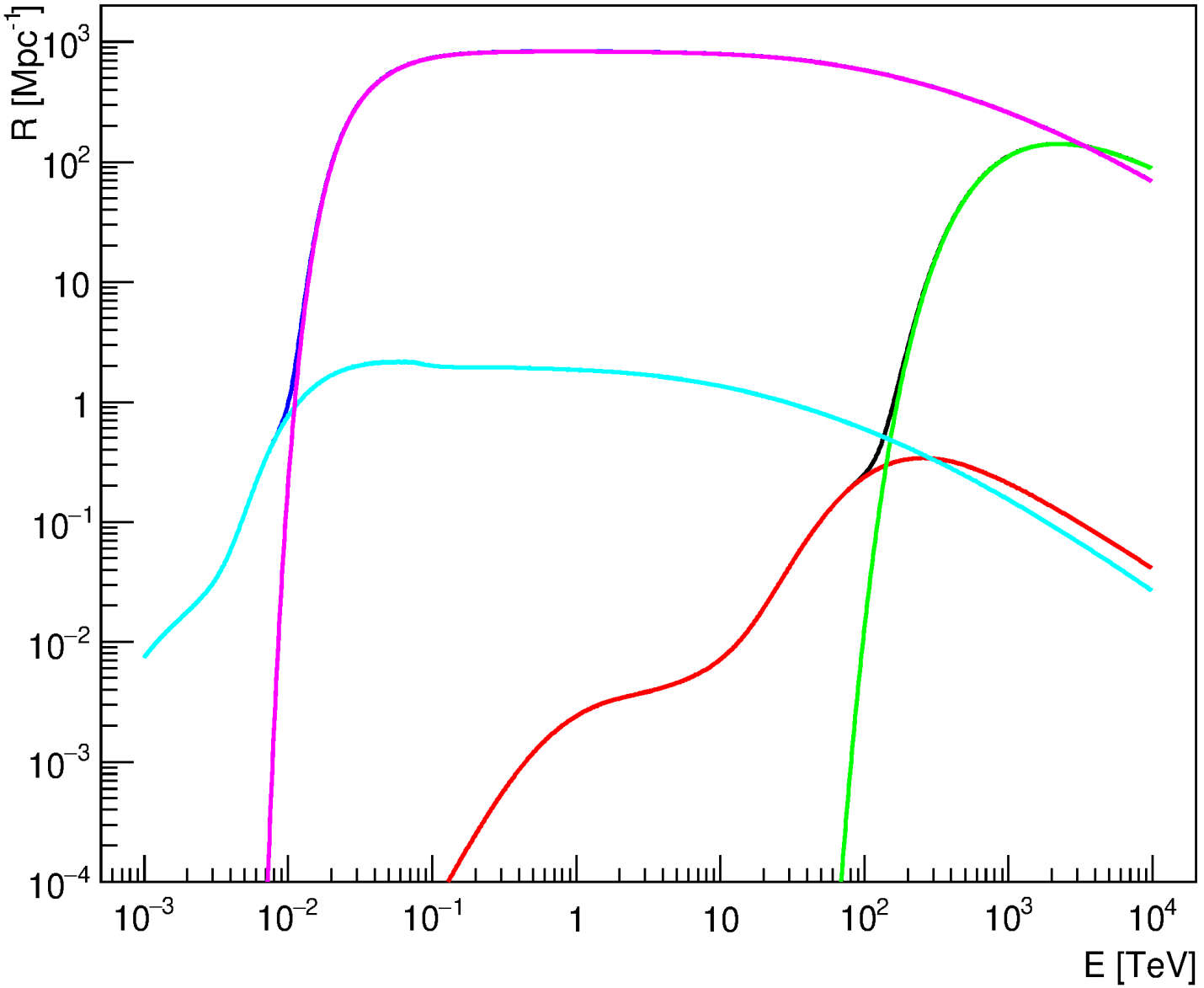
Interaction rates for z= 0 (different components). Black --- gamma (total); red --- gamma (EBL); green --- gamma (CMB); blue --- e (CMB); cyan --- e (EBL); magenta --- e (total)



E_0<100 TeV → gamma-rays escape to voids

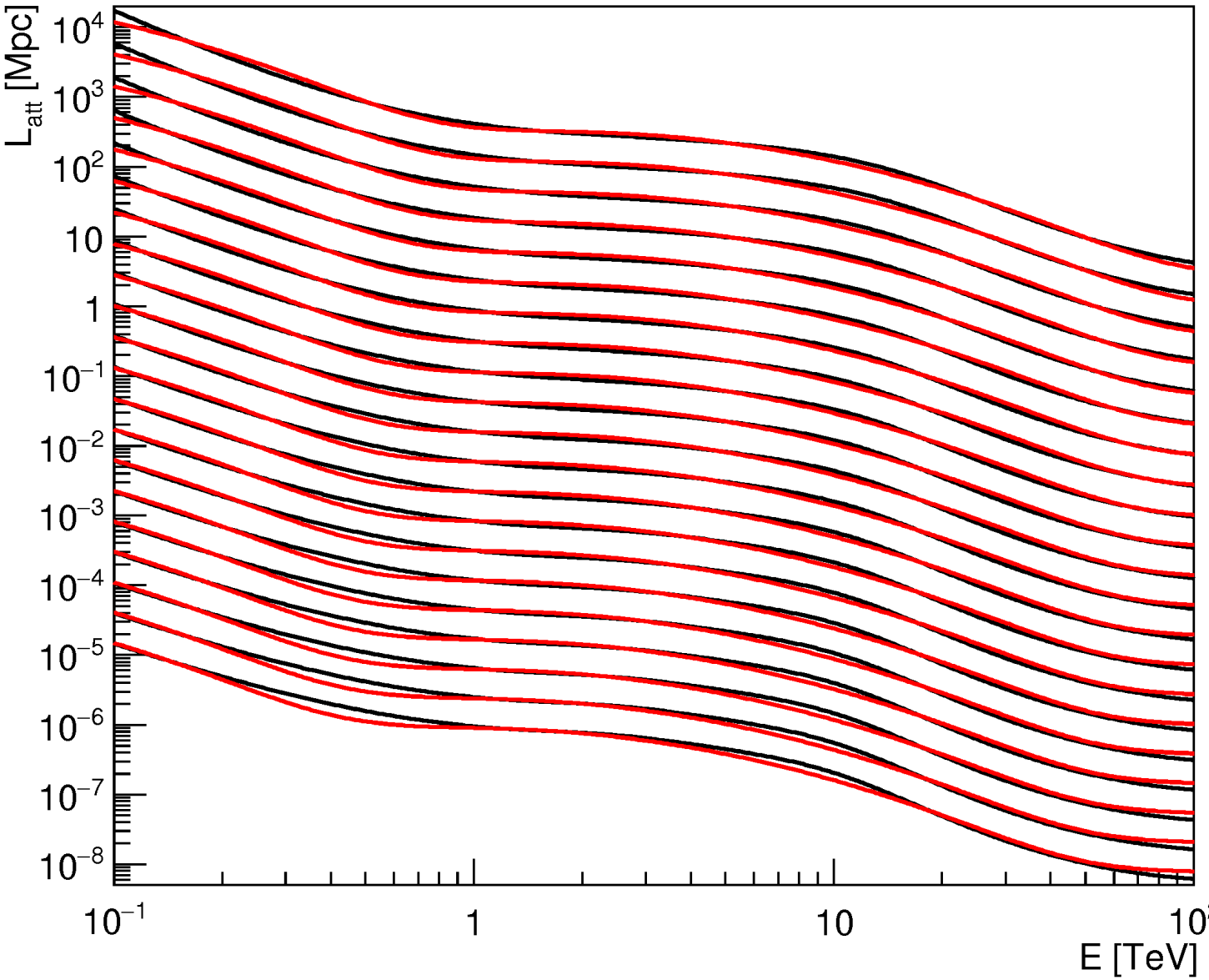
E_0= 10 TeV → E_{0e}~5 TeV; electrons produce cascade photons almost “in situ”

E_{casc}~$(E_{0e}/m_e)^2 E_{CMB}$~100 GeV → cascade photons travel practically without absorption; **voidiness<1 is not an issue**

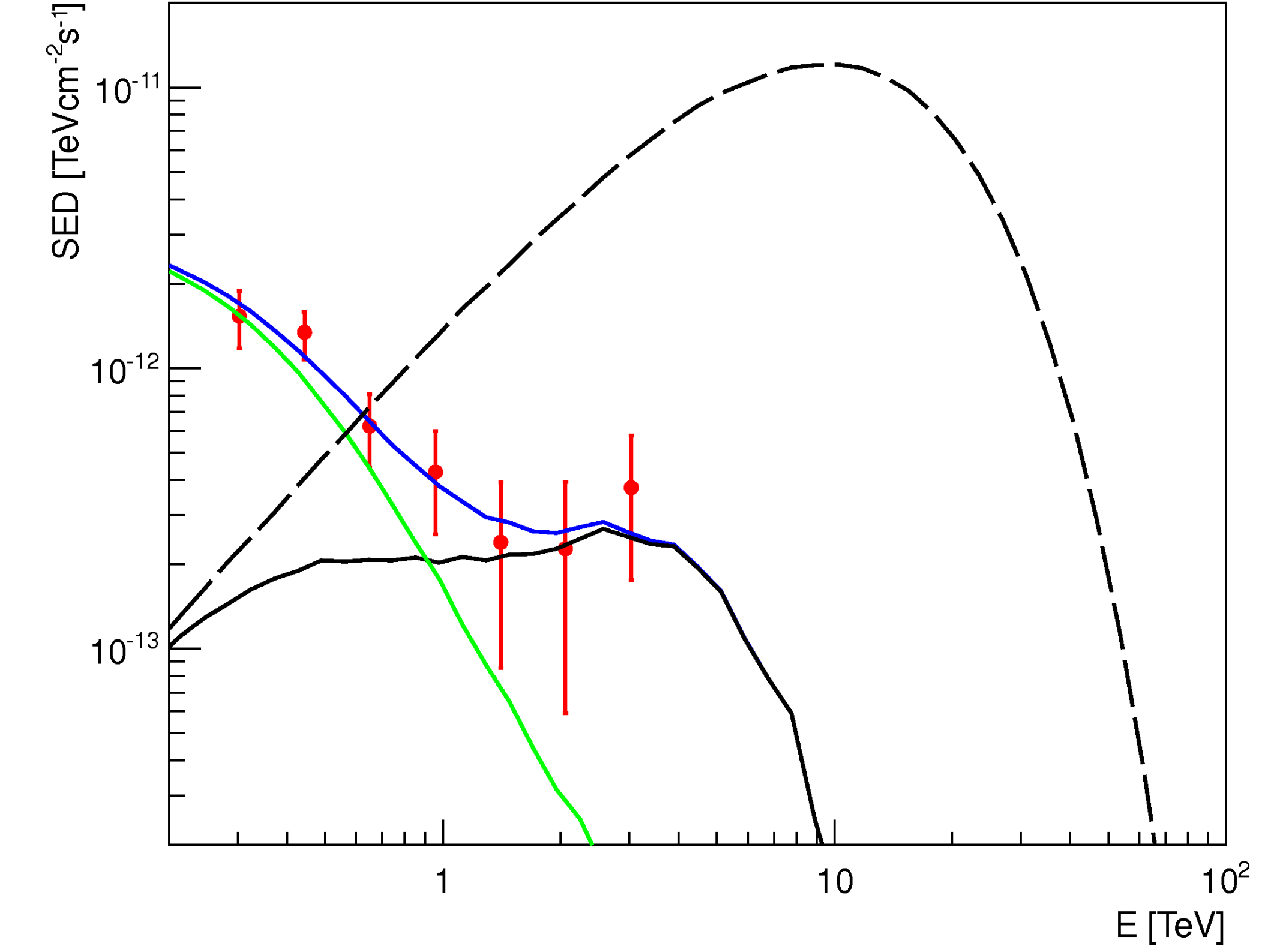


$$D_\gamma(E'_{\gamma_0}, z) = 40 \frac{\kappa}{(1+z)^2} \left[\frac{E'_{\gamma_0}}{20 \text{ TeV}} \right]^{-1} \text{ Mpc},$$

$$L_{att}(E, z) = C \cdot L_t \frac{E_t}{(1+z)^\alpha E} [1 + k \cdot sin(a \cdot lg[(1+z)^\beta E] - b)]$$



γ-ray attenuation length: "original" and "refined" NS09 approximation (z from 0 to 1) black: numerical calculation, red: fit (both downscaled for z>0)

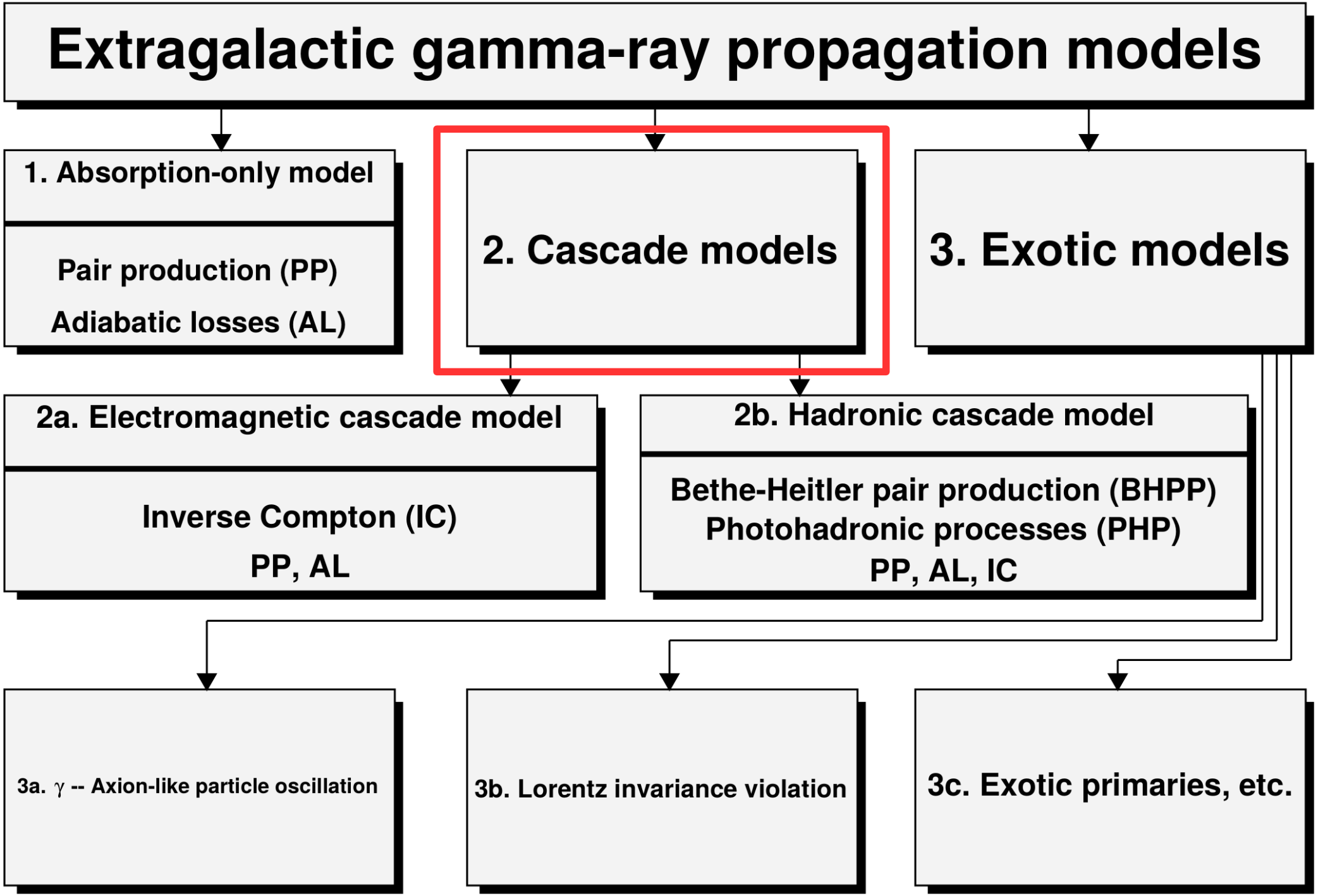

SED [TeVcm^{-2}s^{-1}]
10^{-11}
10^{-12}
10^{-13}
1
10
10^{2}
E [TeV]

Blazars are the brightest distant (z>0.03) extragalactic HE gamma-ray emitters (Ackermann et al., astro-ph/1702.00664 (2017)).

VHE primary gamma rays are strongly absorbed (if E_0>1 TeV at z>0.1) on EBL photons (Nikishov, Sov. Phys. JETP, **14**, 393 (1962); Gould & Shreder, Phys. Rev., **155**, 1408 (1967); Stecker & de Jager, ApJ, **415**, 71 (1993); de Jager et al., Nature, **369**, 294 (1994); Mazin & Raue, A&A, **471**, 439 (2007); Ackermann et al., Science, **338**, 11 (2012); Abramowski et al., A&A, 550, A4 (2013))

and cascade down through the IC process to the GeV energy region

Synchrotron losses are not an issue; we do not account for any collective effects in e^+e^- beams


Extragalactic gamma-ray propagation models
1. Absorption-only model
Pair production (PP)
Adiabatic losses (AL)
2. Cascade models
3. Exotic models
2a. Electromagnetic cascade model
Inverse Compton (IC)
PP, AL
2b. Hadronic cascade model
Bethe-Heitler pair production (BHPP)
Photohadronic processes (PHP)
PP, AL, IC
3a. γ -- Axion-like particle oscillation
3b. Lorentz invariance violation
3c. Exotic primaries, etc.

The “absorption-only model”

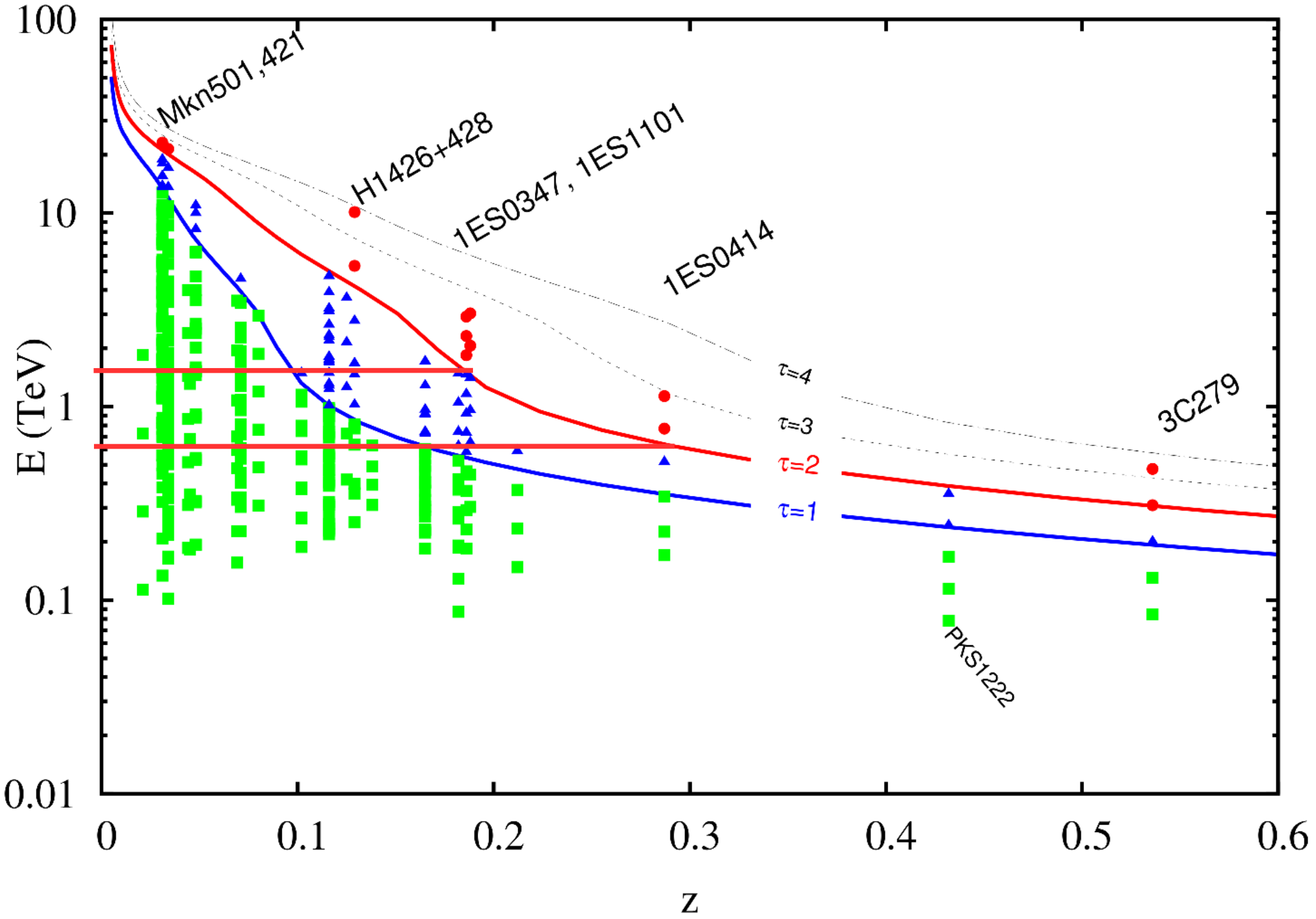
Account for only the absorption (PP) of primary γ-rays and adiabatic losses

Nikishov, Sov. Phys. JETP, **14**, 393 (1962)
Gould & Shreder, Phys. Rev. Lett., **16**, 252 (1966)
Jelley, Phys. Rev. Lett., **16**, 479 (1966)
Stecker & de Jager, ApJ, **415**, 71 (1993)
de Jager et al., Nature, **369**, 294 (1994)
Mazin & Raue, A&A, **471**, 439 (2007)
Biteau & Williams, ApJ, **200**, 58 (2015)

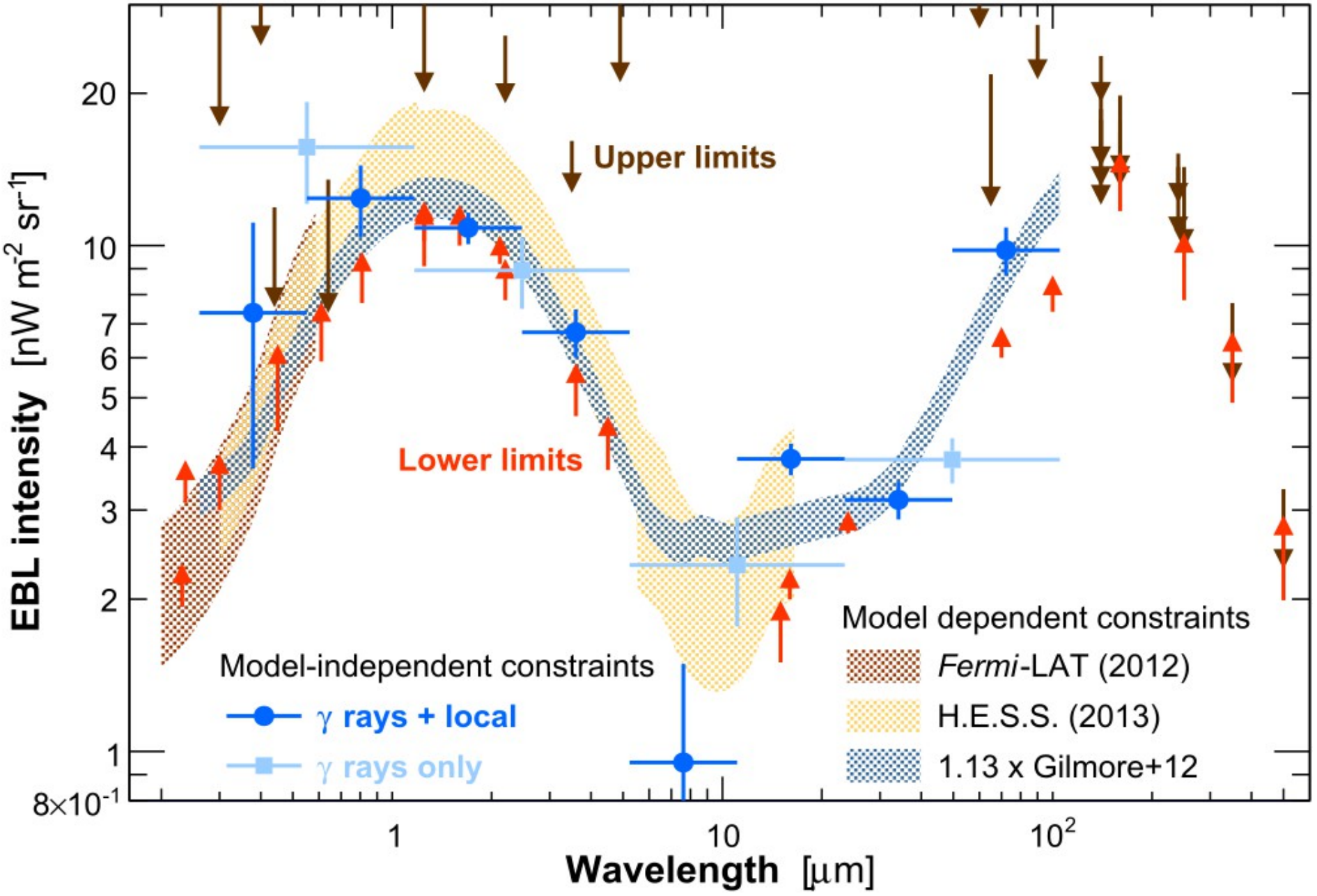
The PP process signatures in blazar spectra were convincingly detected in:

Ackermann et al., Science, **338**, 11 (2012);
Abramowski et al., A&A, **550**, A4 (2013)
Abdalla et al., A&A, **606**, A59 (2017)

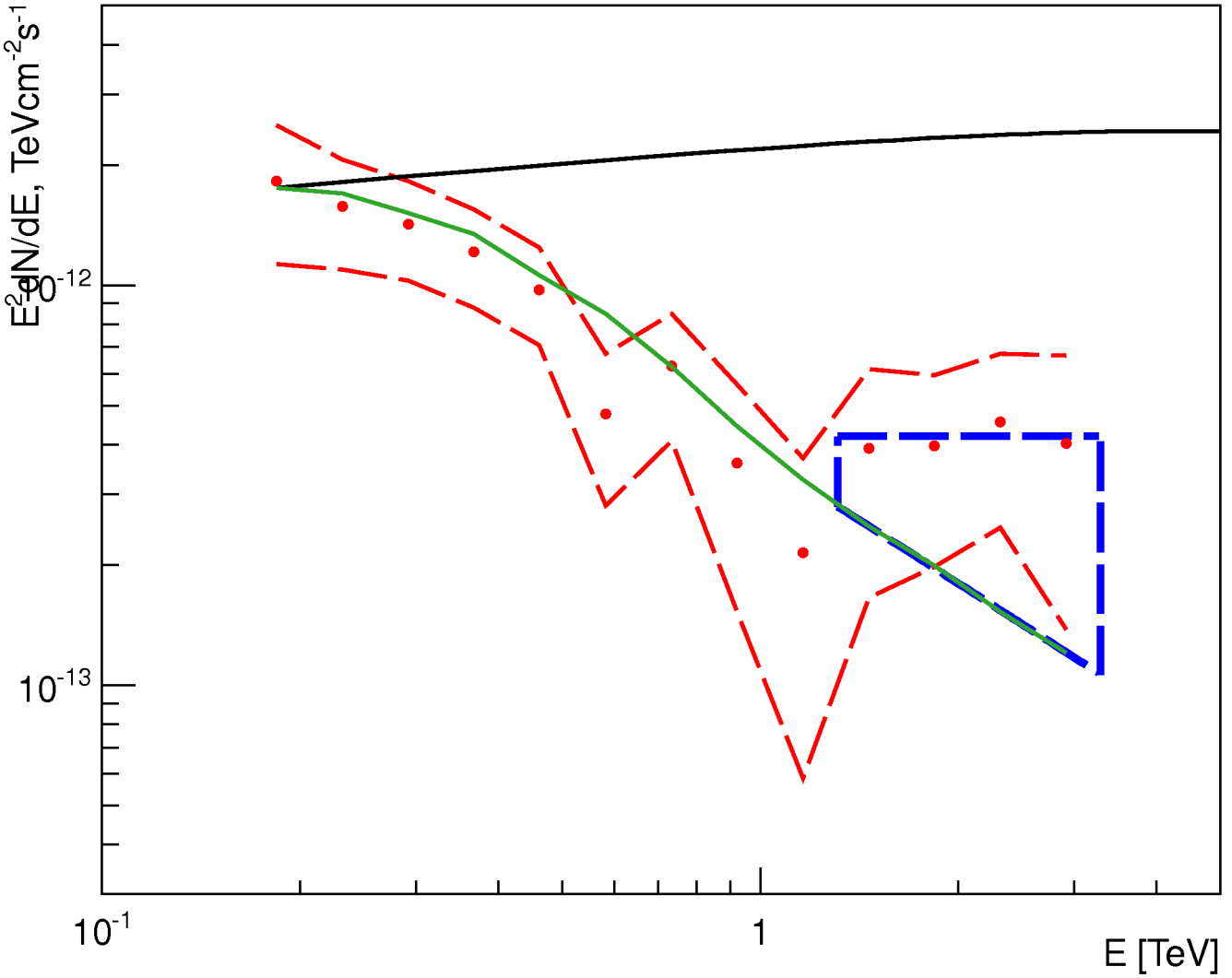
Gamma-ray horizon (from HM12, EBL model: KD10)



Biteau & Williams, ApJ, **200**, 58 (2015) did not find any anomaly.
Their EBL model comes directly from VHE data



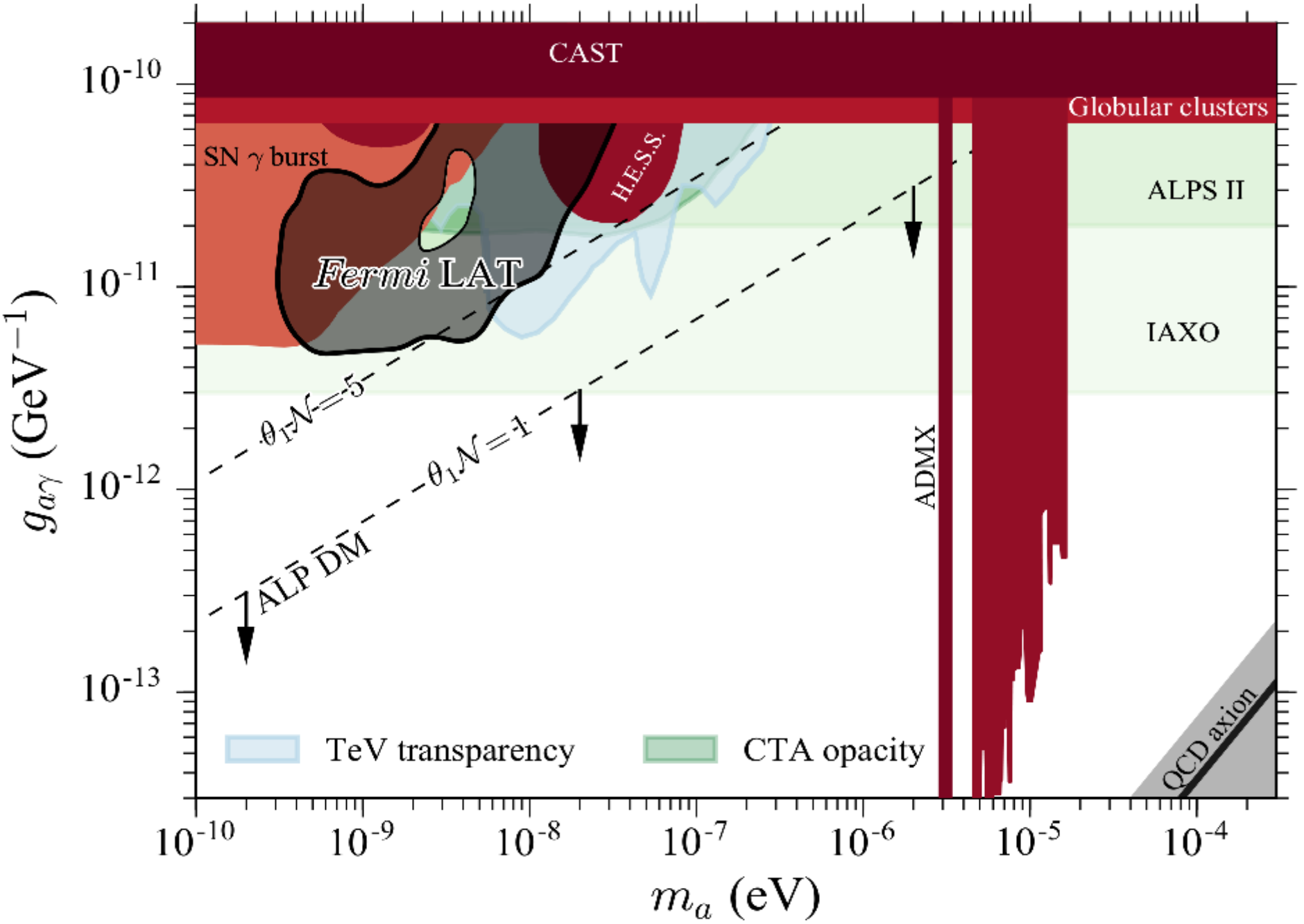
Our own very modest contribution (z= 0.186, 1ES 1101-232 observations from Aharonian et al., Nature, 440, 1018 2006)



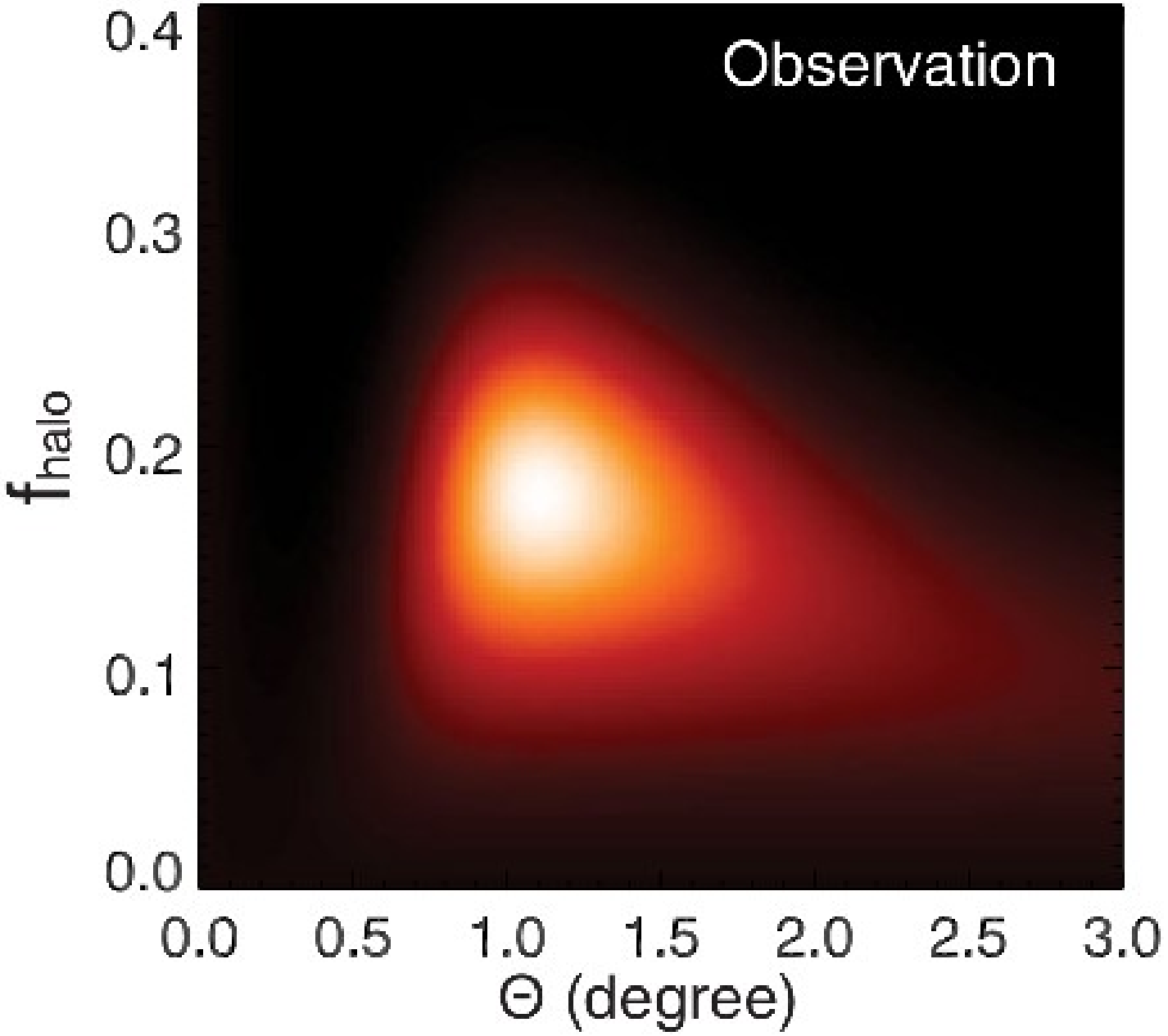
~3σ indication (systematics included) for the anomaly was found (6 sources); almost all excess is due to extreme TeV blazars, and not to classical blazars such as Mkn421, Mkn 501

(Dzhatdoev, J. Phys. Conf. Ser., **632**, 012035 (2015))

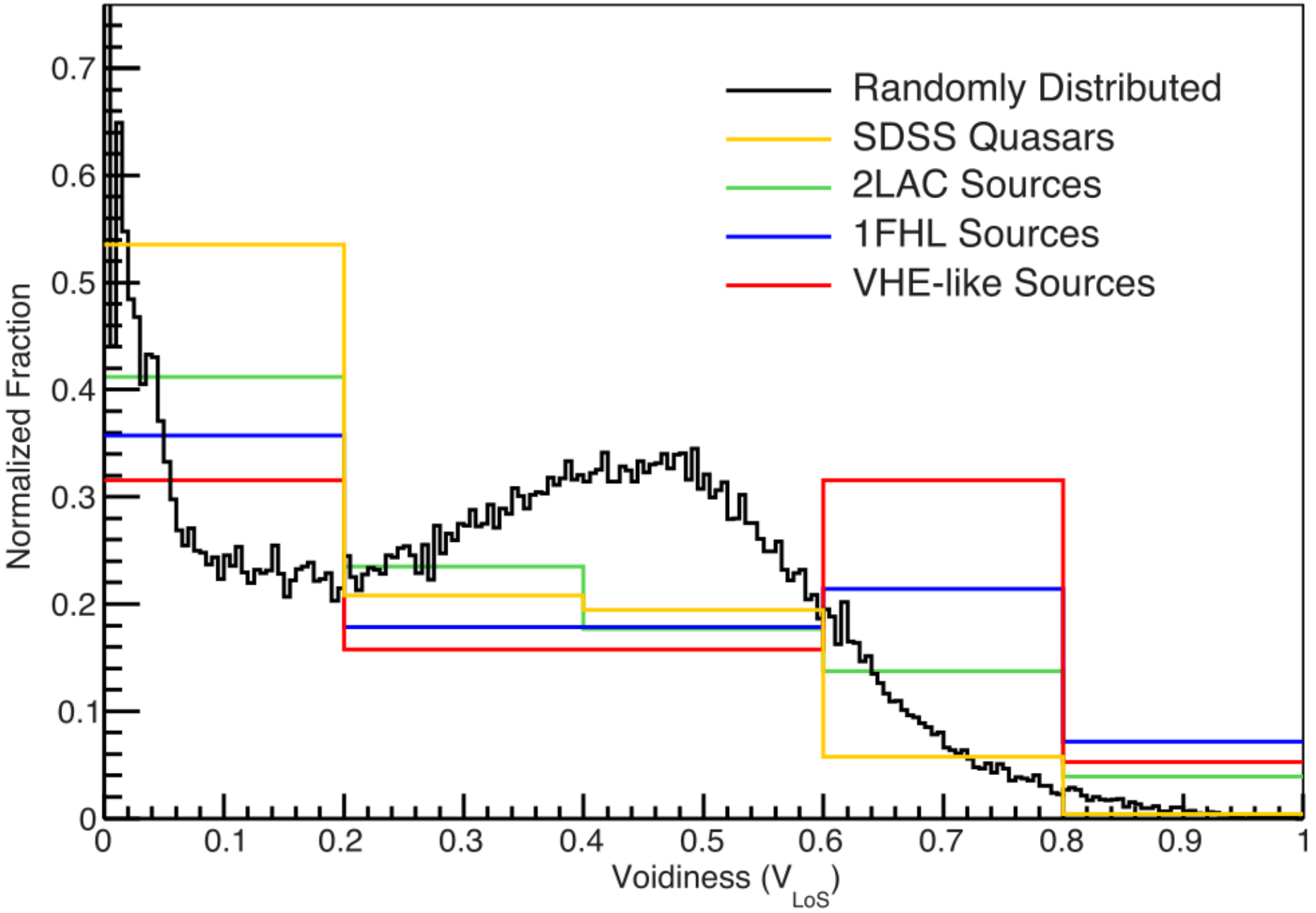
Constraints on gamma-ALP mixing (Ajello et al., Phys. Rev. Lett., 116, 161101 (2016))



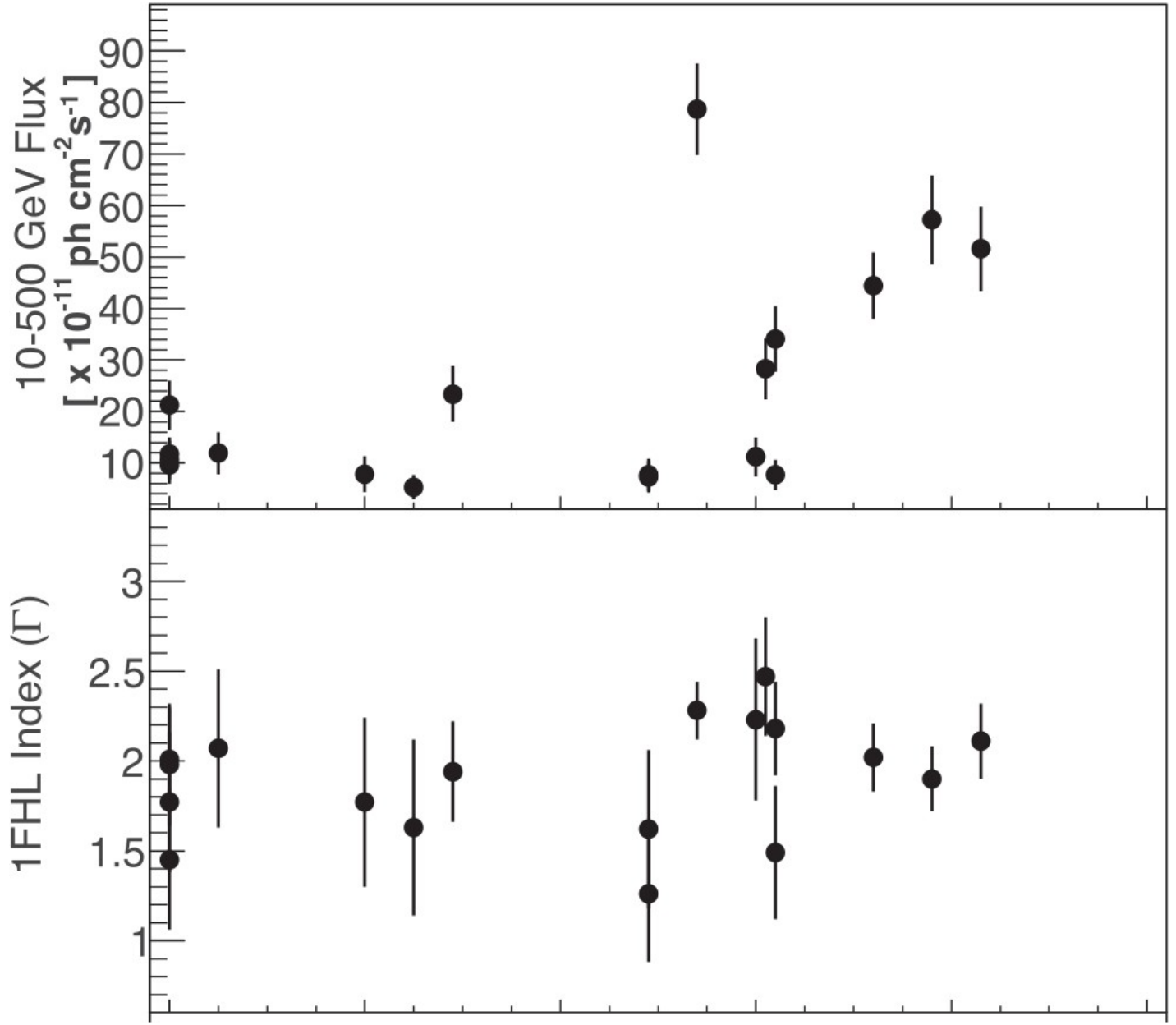
Color: the ratio of the likelihood of the extended-emission hypothesis to that of the null hypothesis (the PSF) (Chen et al., Phys. Rev. Lett., **115**, 211103 (2015), p-value~ 0.01), EGMF: B= 0.01-1 fG



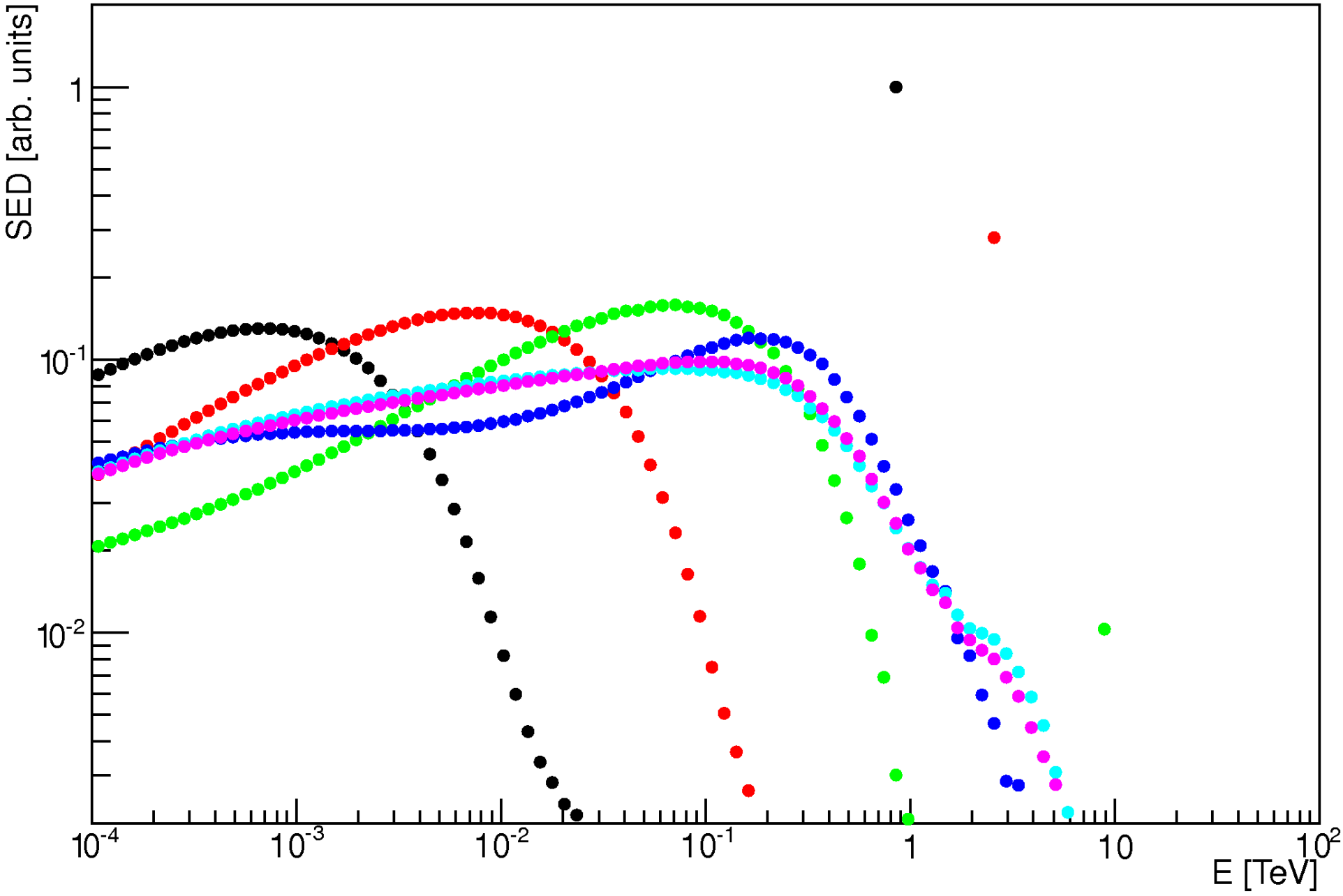
Hard-spectra Fermi LAT blazars tend to be located towards the voids in the large scale structure (Furniss. et al., MNRAS, **446**, 2267 (2015) (F15), significance ~2.5 σ)



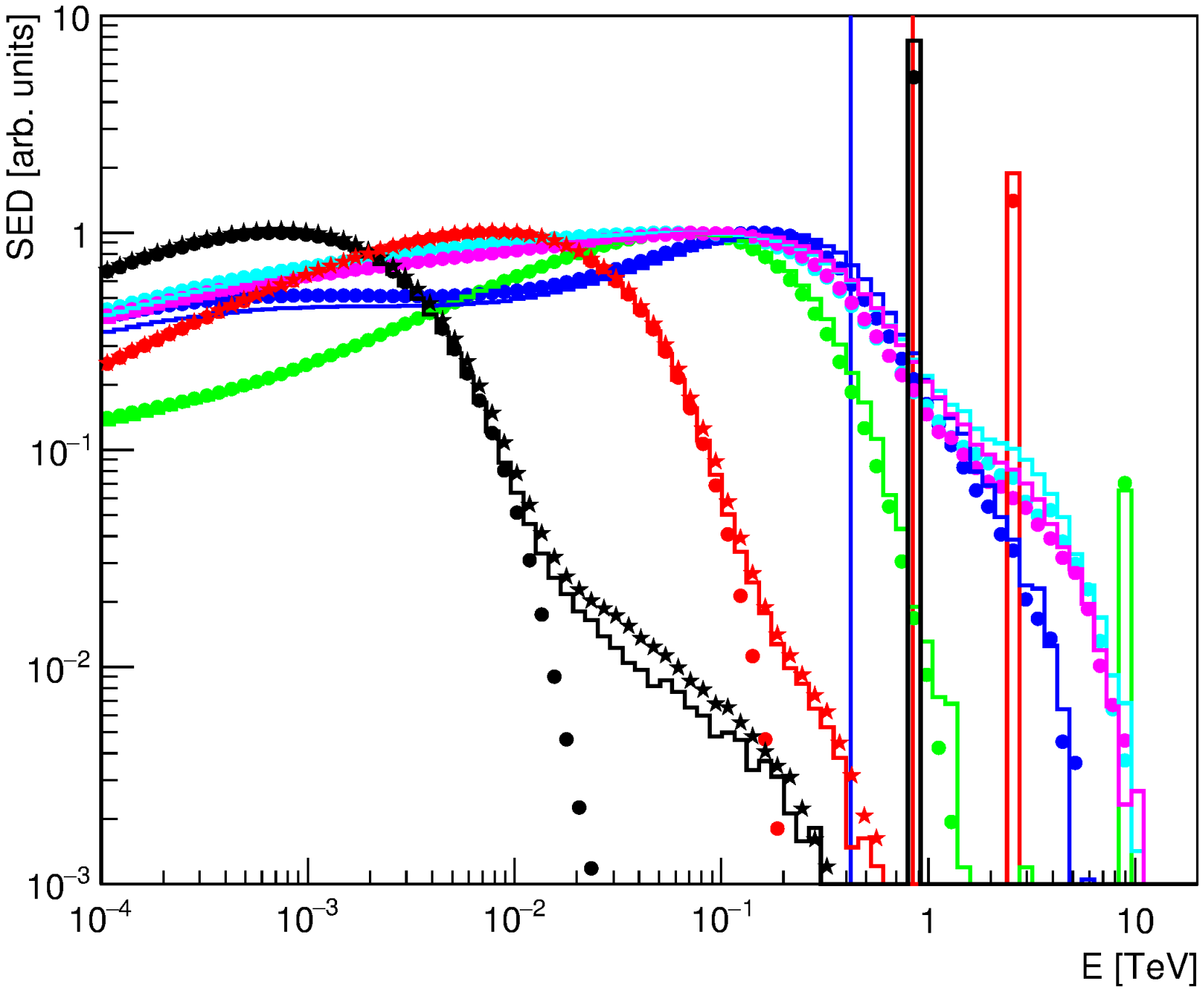
In these cases, observed flux is usually much higher (F15, significance ~2.5 σ);
x: voidiness runs from 0 to 1. EGMF-dependent effects?



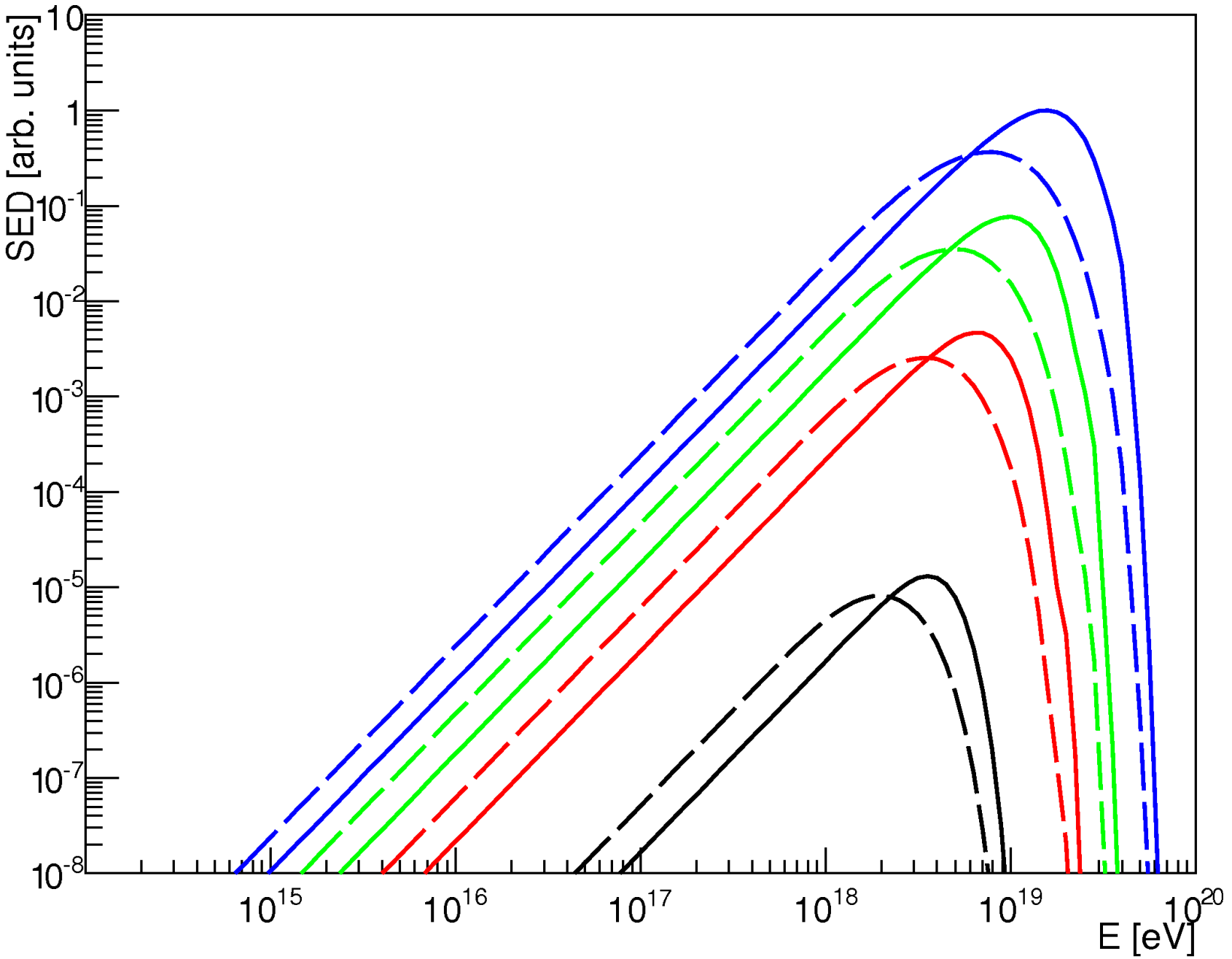
"Delta-plot" (z= 0.186, ELMAG 2.02): observable spectra for one-generation (E_0= 1 TeV, 3 TeV, 10 TeV) and universal regime (100 TeV, 1 PeV); transition regime (30 TeV)

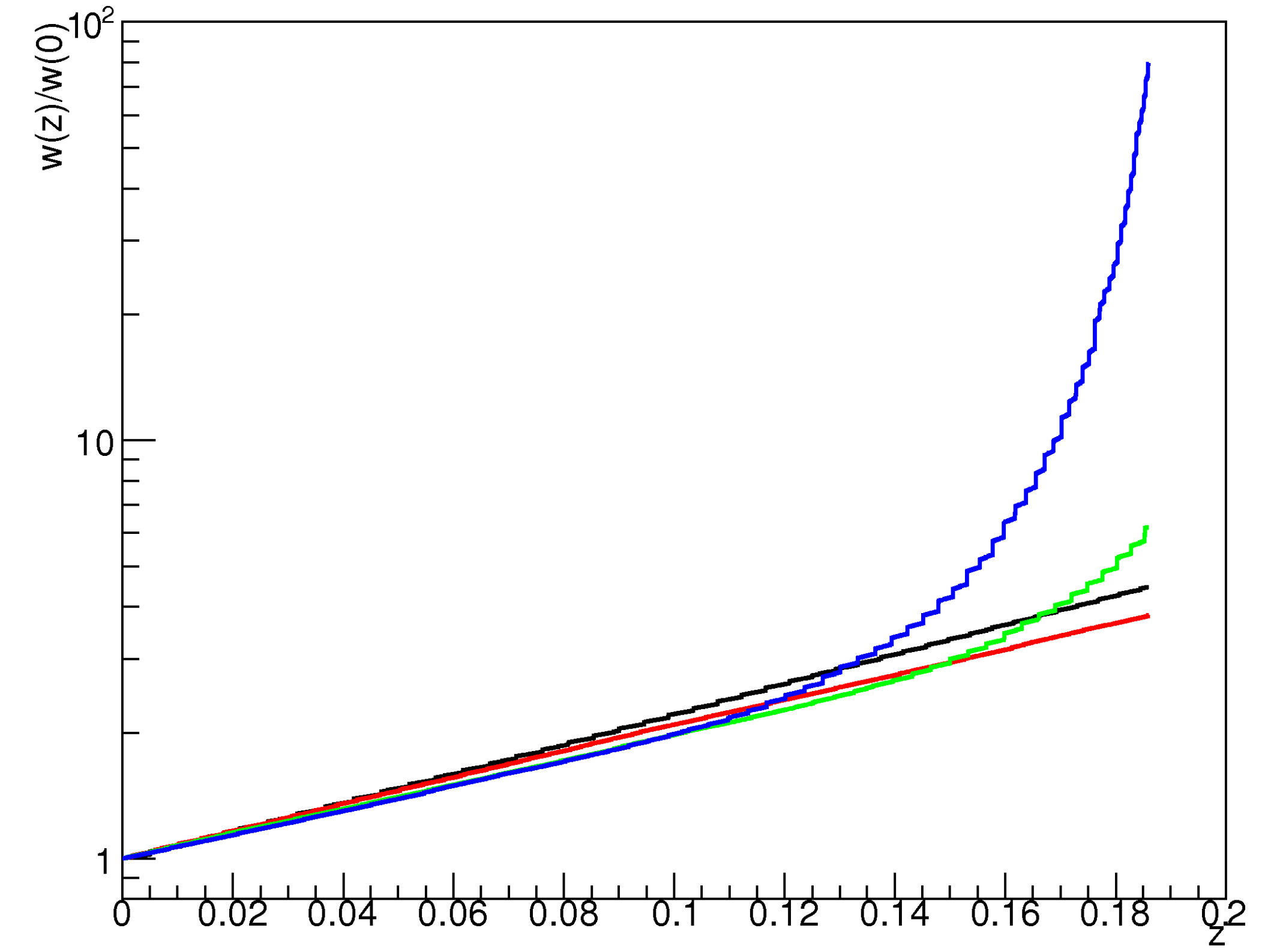


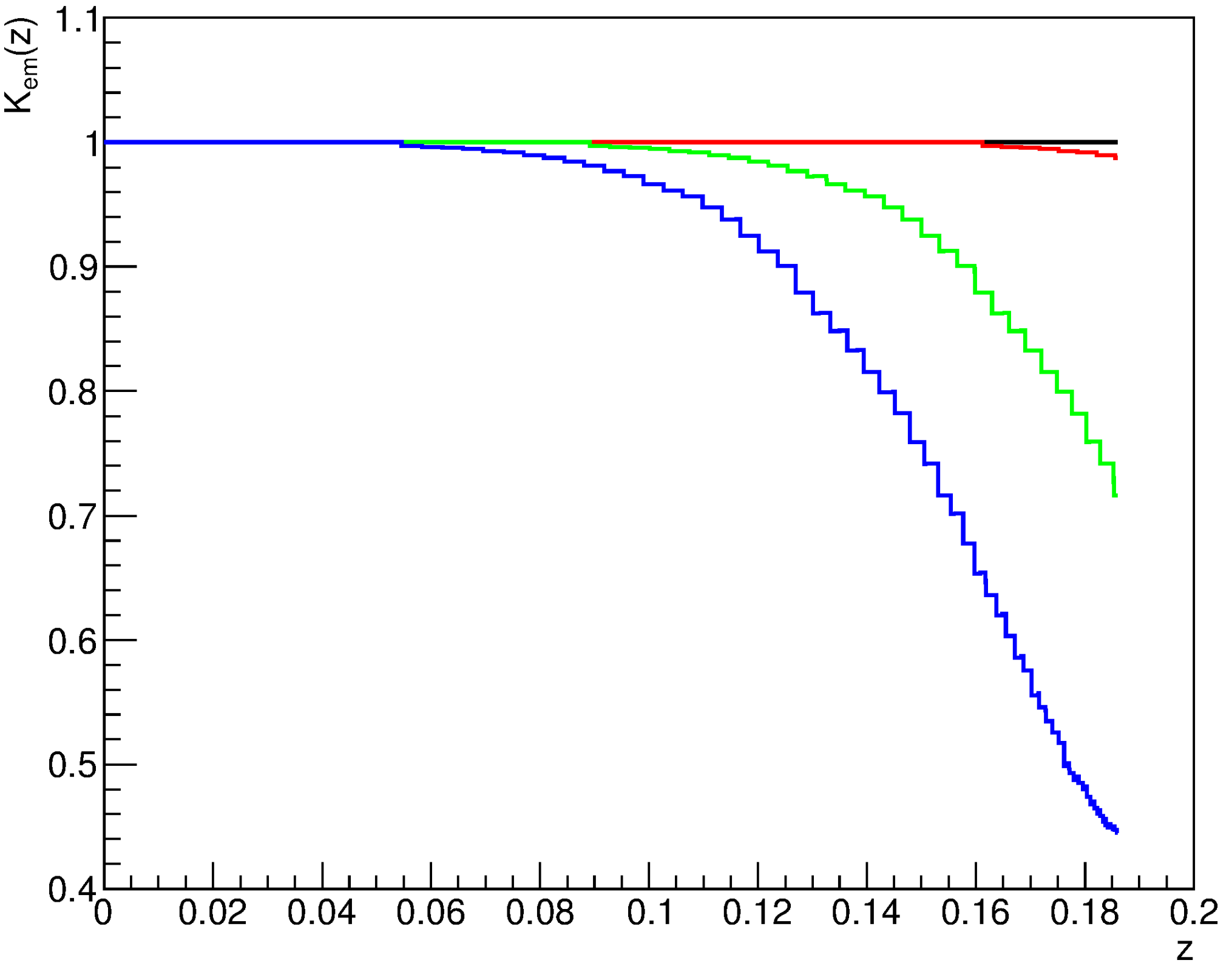
“Delta-plot”, cascade spectra for primary monoenergetic emission (histograms: ELMAG (KD10 EBL), symbols: ECS (G12 EBL))

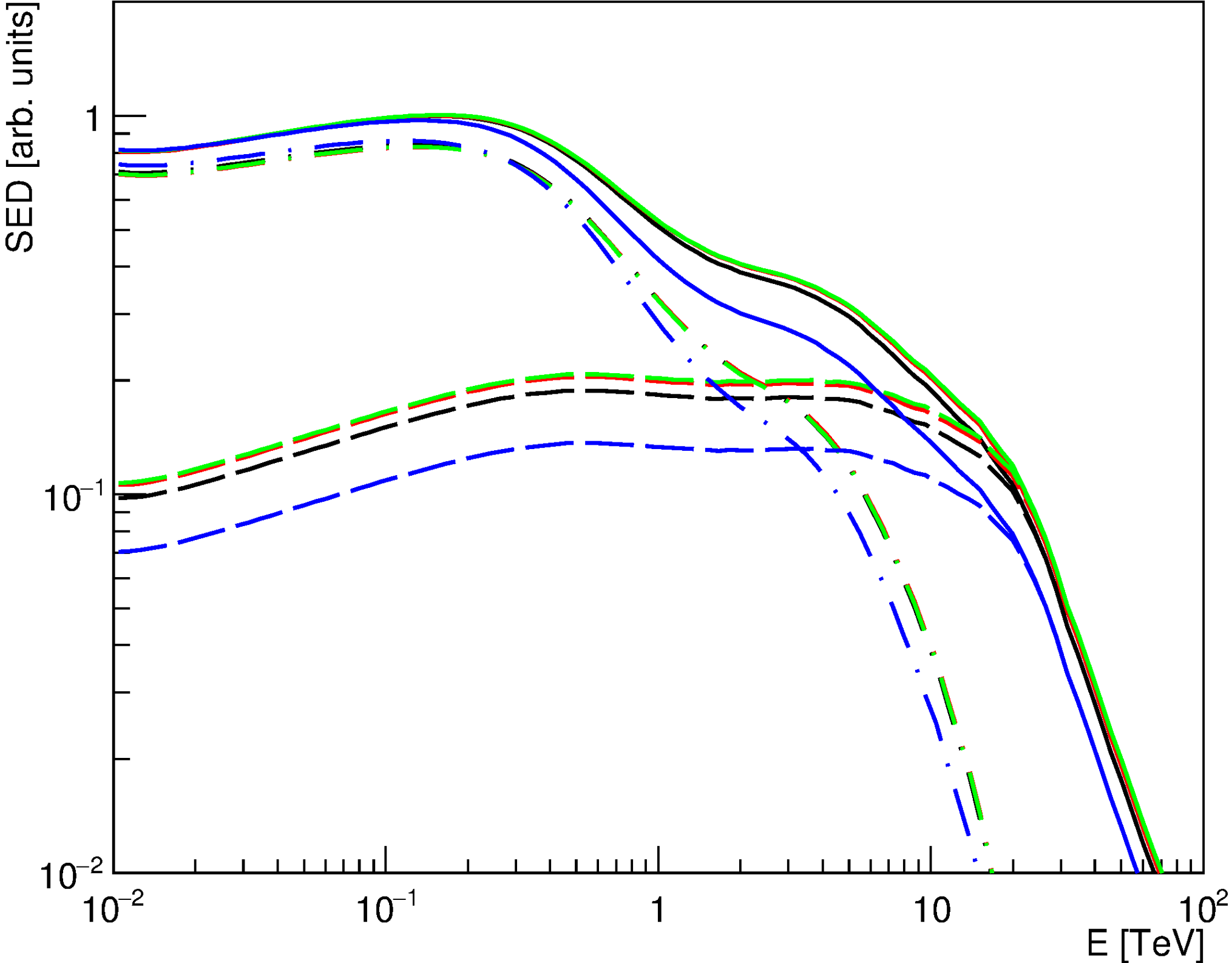


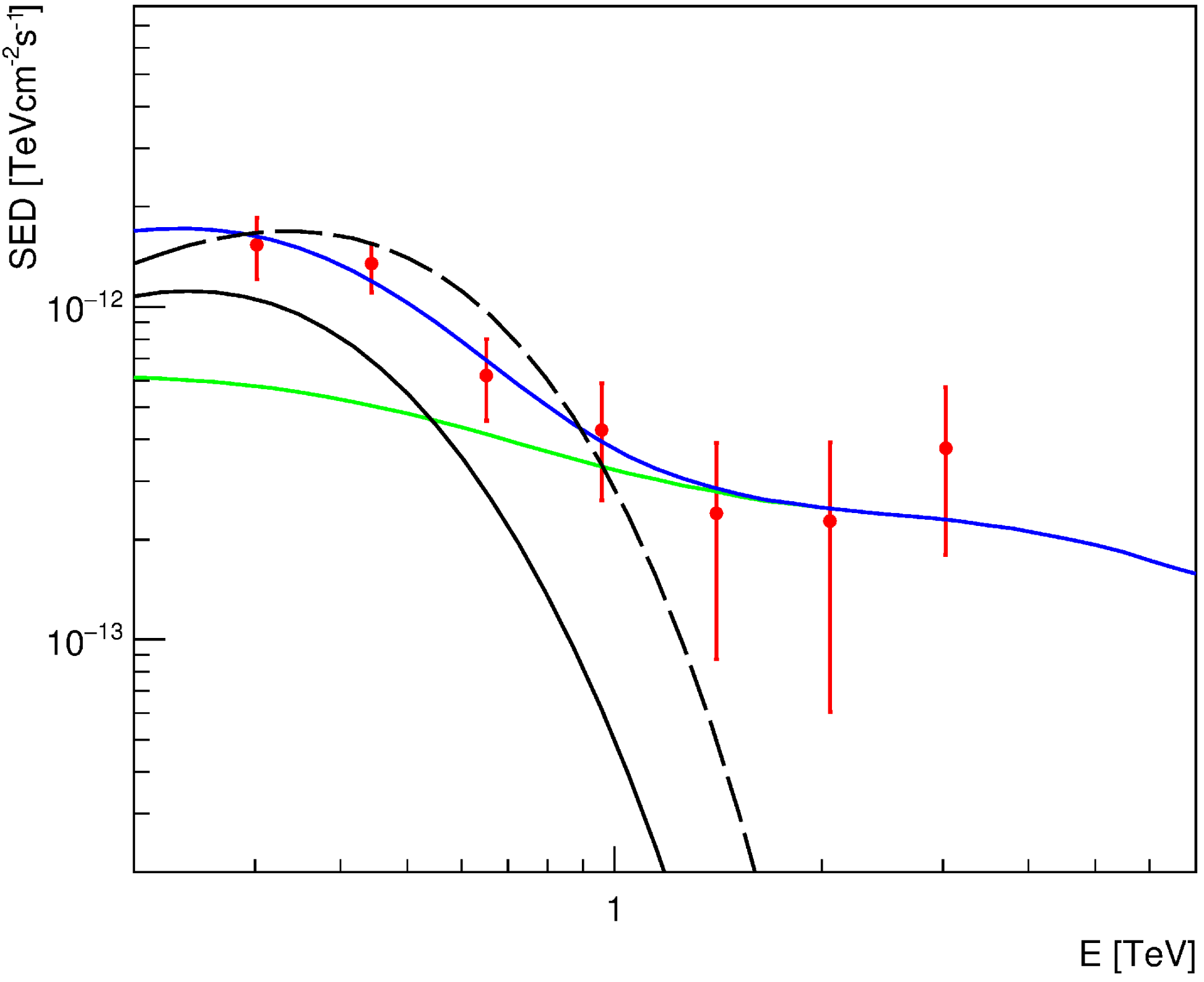
Gamma-ray (solid) and positron (dashed) SEDs (KA08, E_{p0}= 30 EeV, 50 EeV, 70 EeV, 100 EeV); relevant neutrino fluxes were accounted for (Kelner & Aharonian (2008))



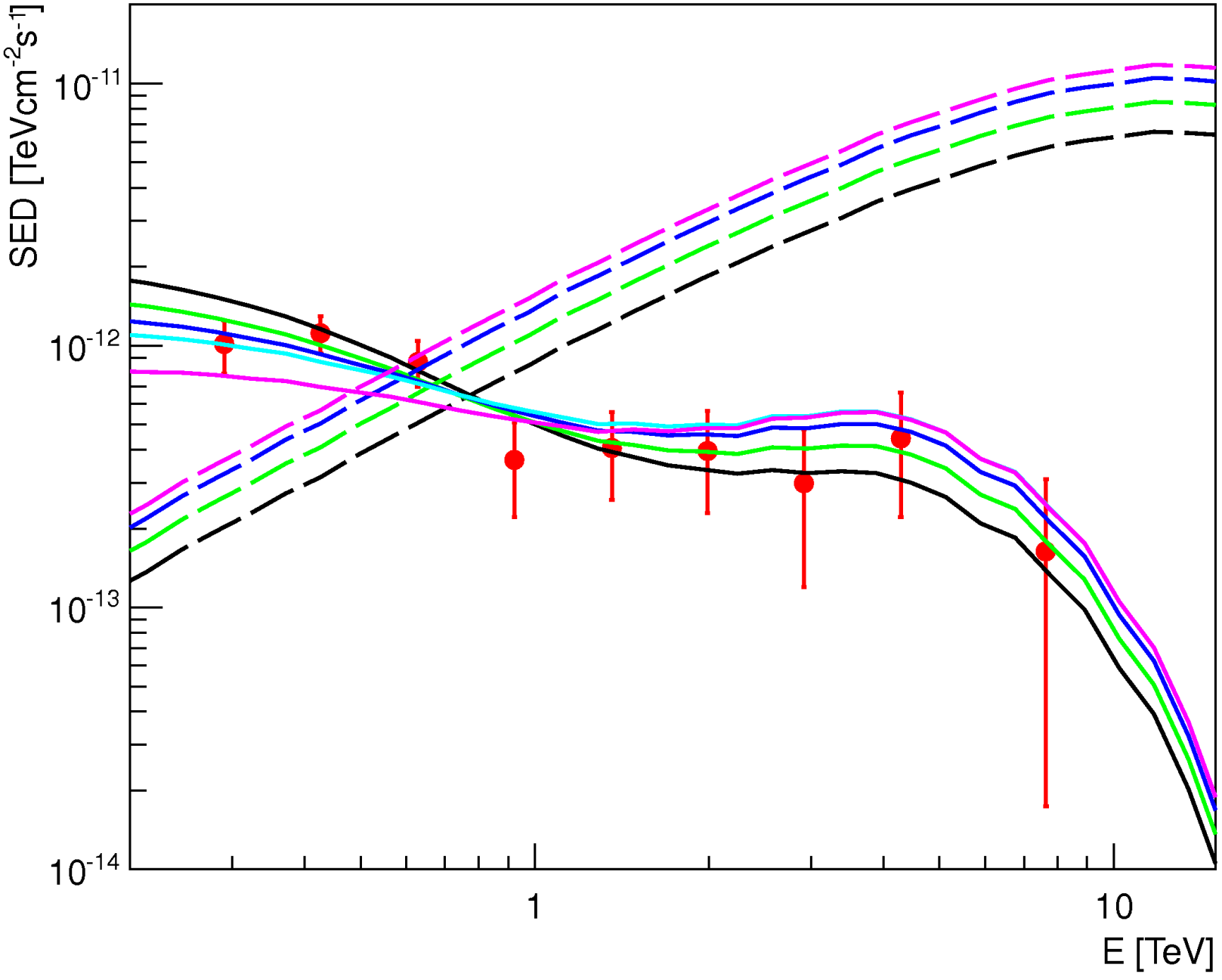

w(z)/w(0)
10^2
10
1
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
z


$K_{em}(z)$
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
z

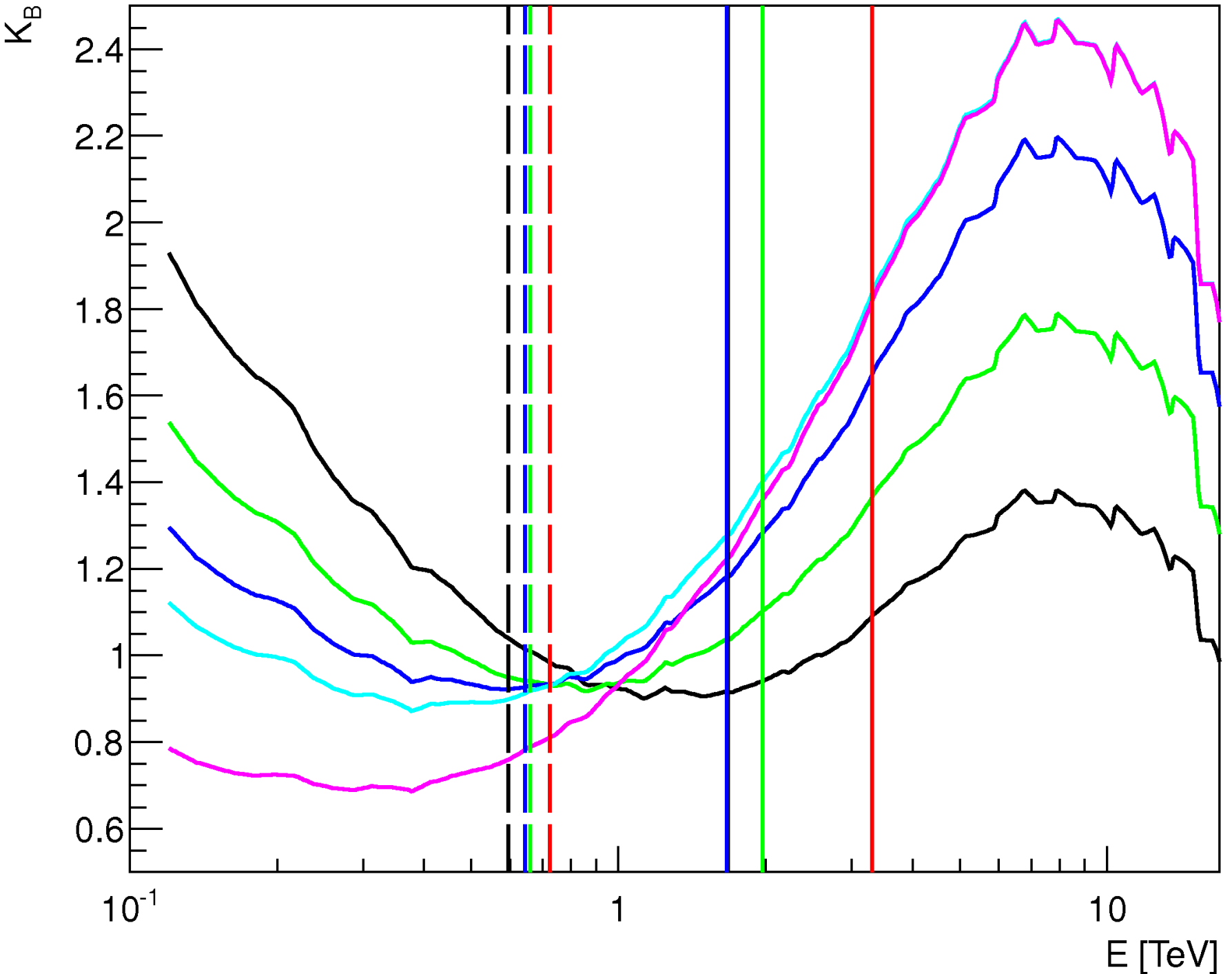

SED [arb. units]
1
10^{-1}
10^{-2}
10^{-2}
10^{-1}
1
10
10^{2}
E [TeV]


SED [TeVcm^{-2}s^{-1}]
10^{-12}
10^{-13}
1
E [TeV]

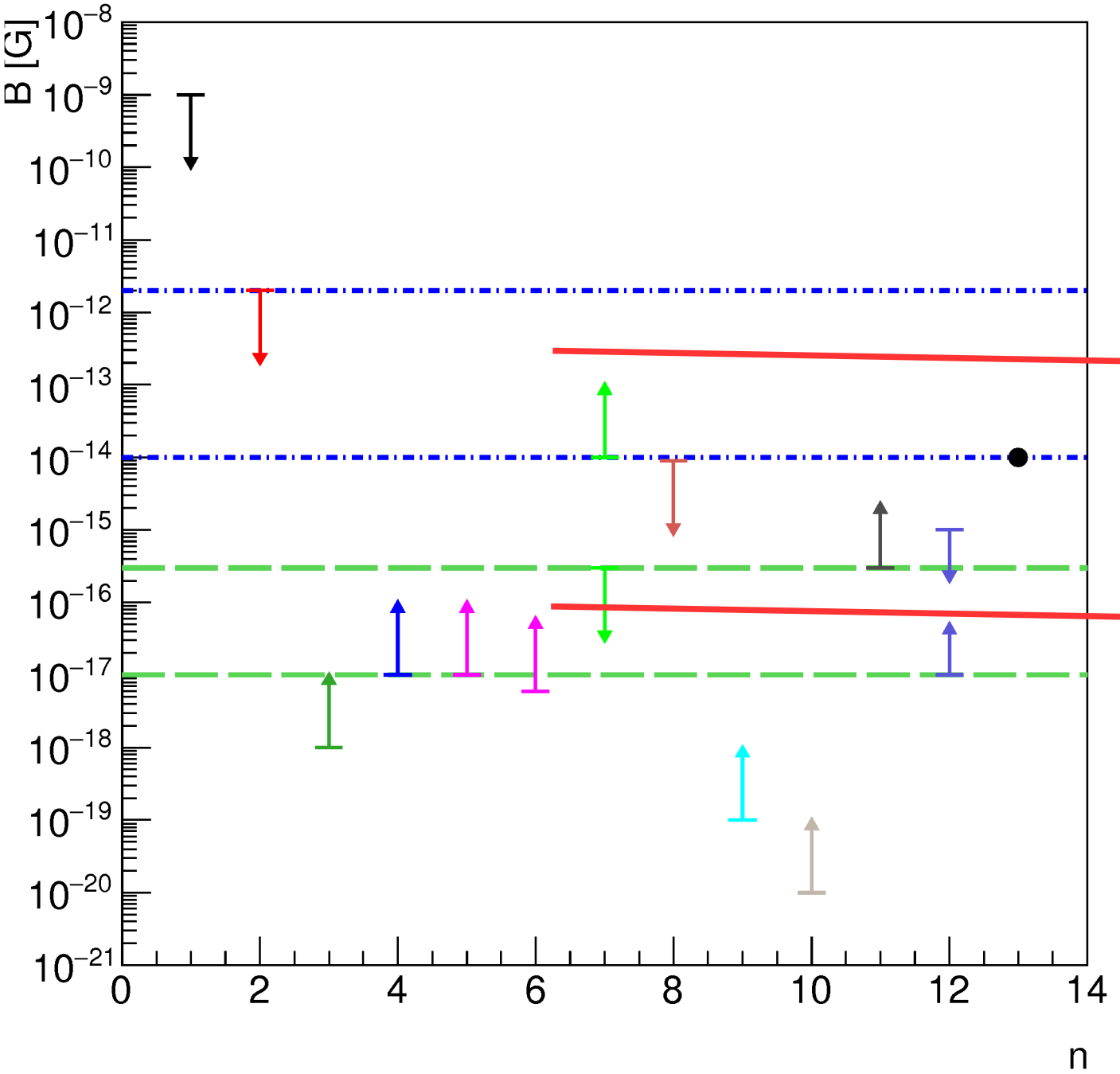
Impact of voidiness (K= 1.0, 0.6, 0.4, 0.3, 0.2).The source is 1ES 0229+200 (z= 0.188). The high-energy part is better fitted for K<0.6, the low-energy part — for K from 0.3 to 0.6.



The ratio of best-fit model spectra for electromagnetic cascade model and the absorption-only model



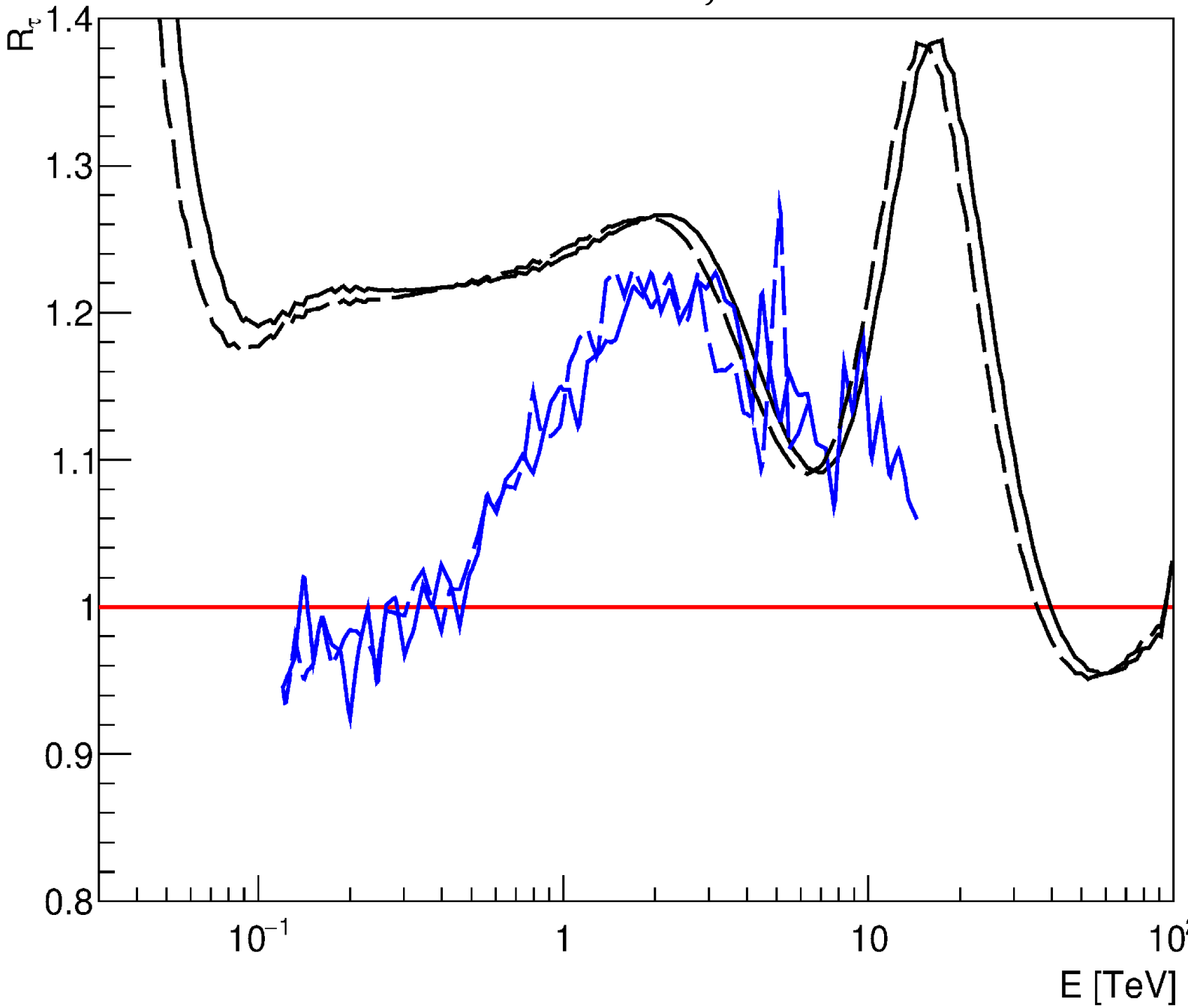
Constraints on the EGMF



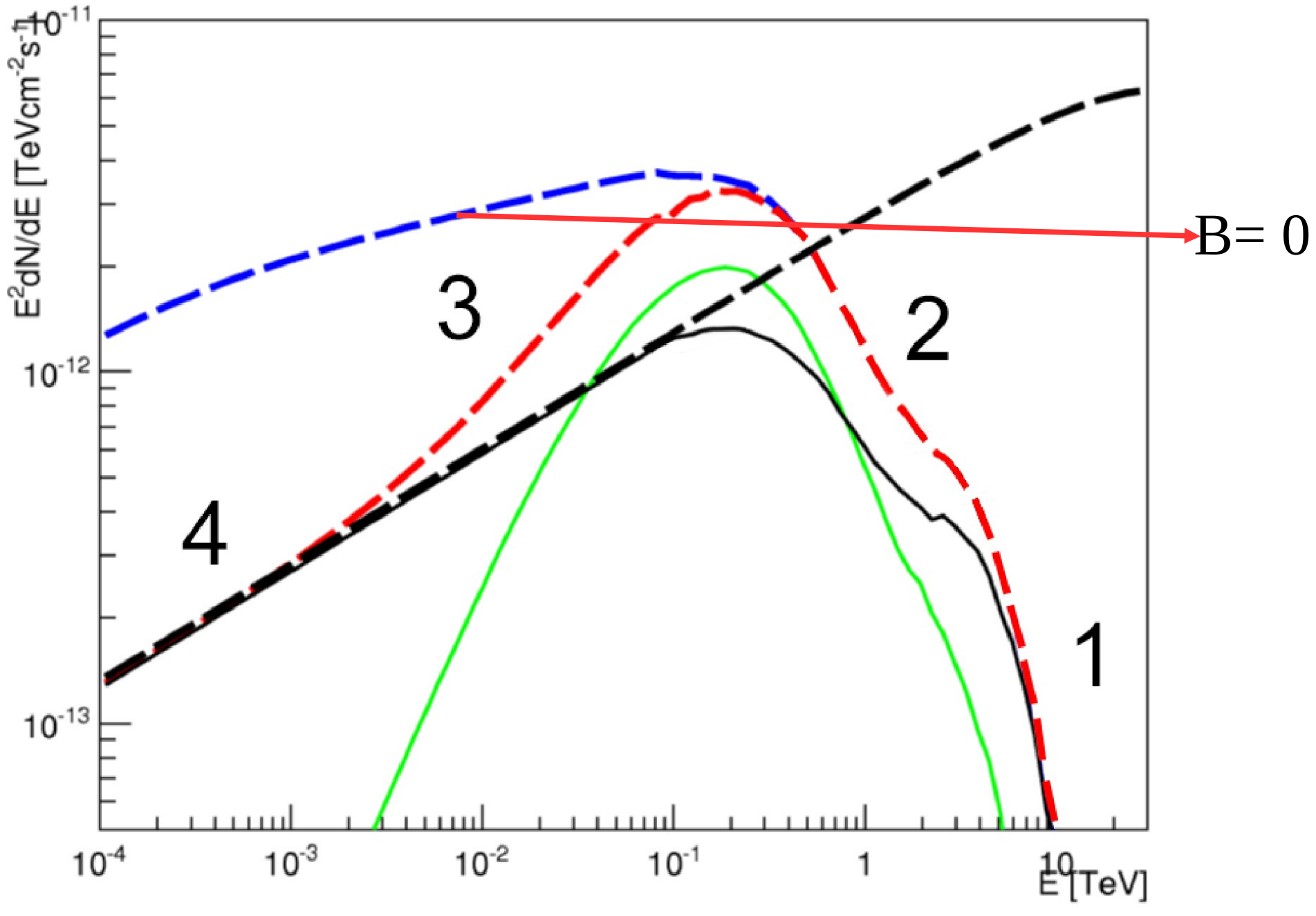
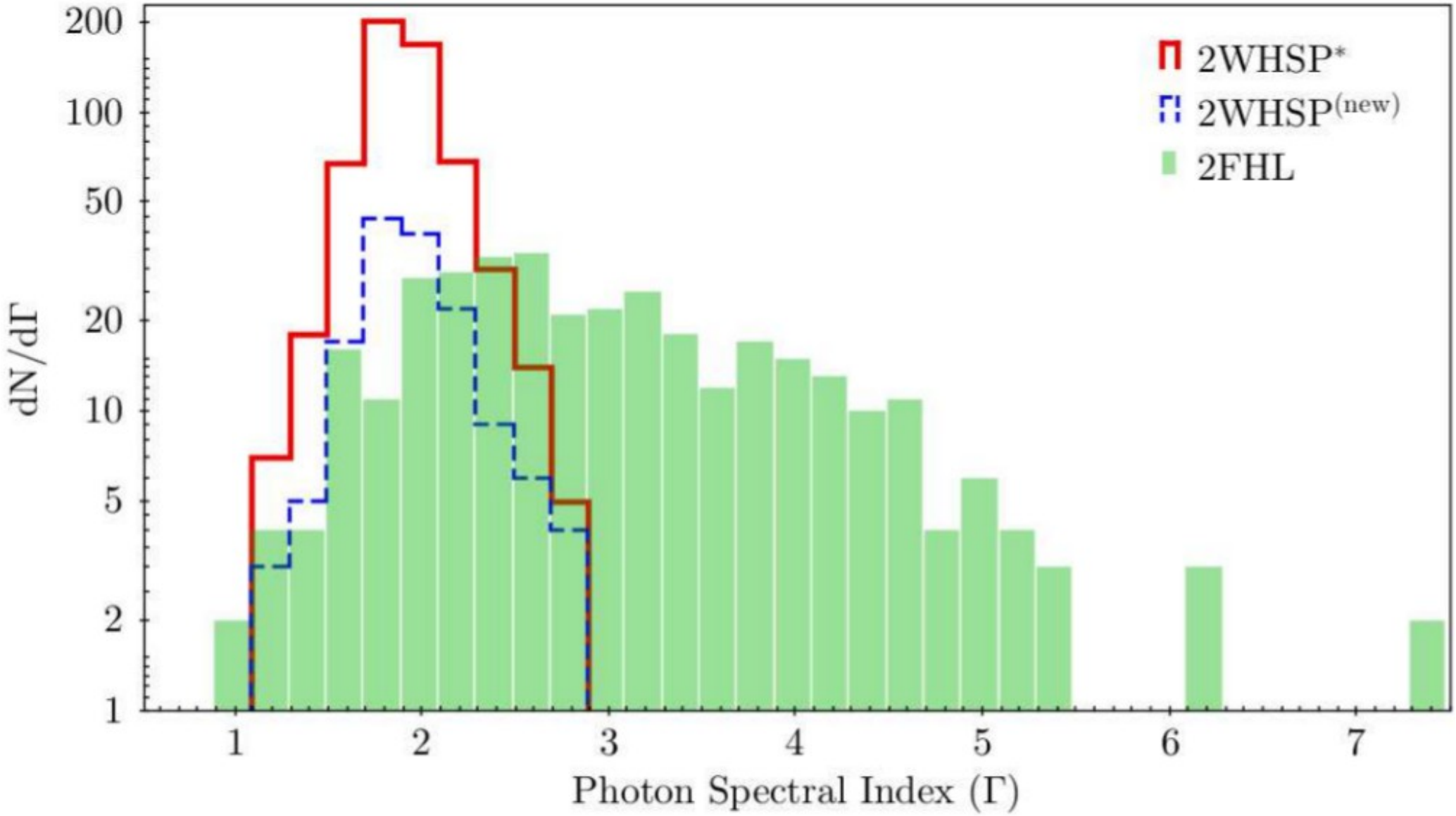
No MBC, but it is still possible to observe pair-halo (PH)

The MBC solution

The ratio of the optical depth (blue — KD10 as implemented in ELMAG 2.02, black — G12 model) to the one for the original KD10 model. Solid — z= 0.186, dashed — z= 0.287.



Spectral signatures of the electromagnetic cascade model: 1) high-energy cutoff, 2) “ankle” 3) “magnetic cutoff” 4) second ankle.



Arsioli & Chang A&A **598**, A134 (2017) found a plenty of blazars with hard primary spectra in Fermi LAT data (of course, TS is usually lower than in the official Fermi LAT catalogues)