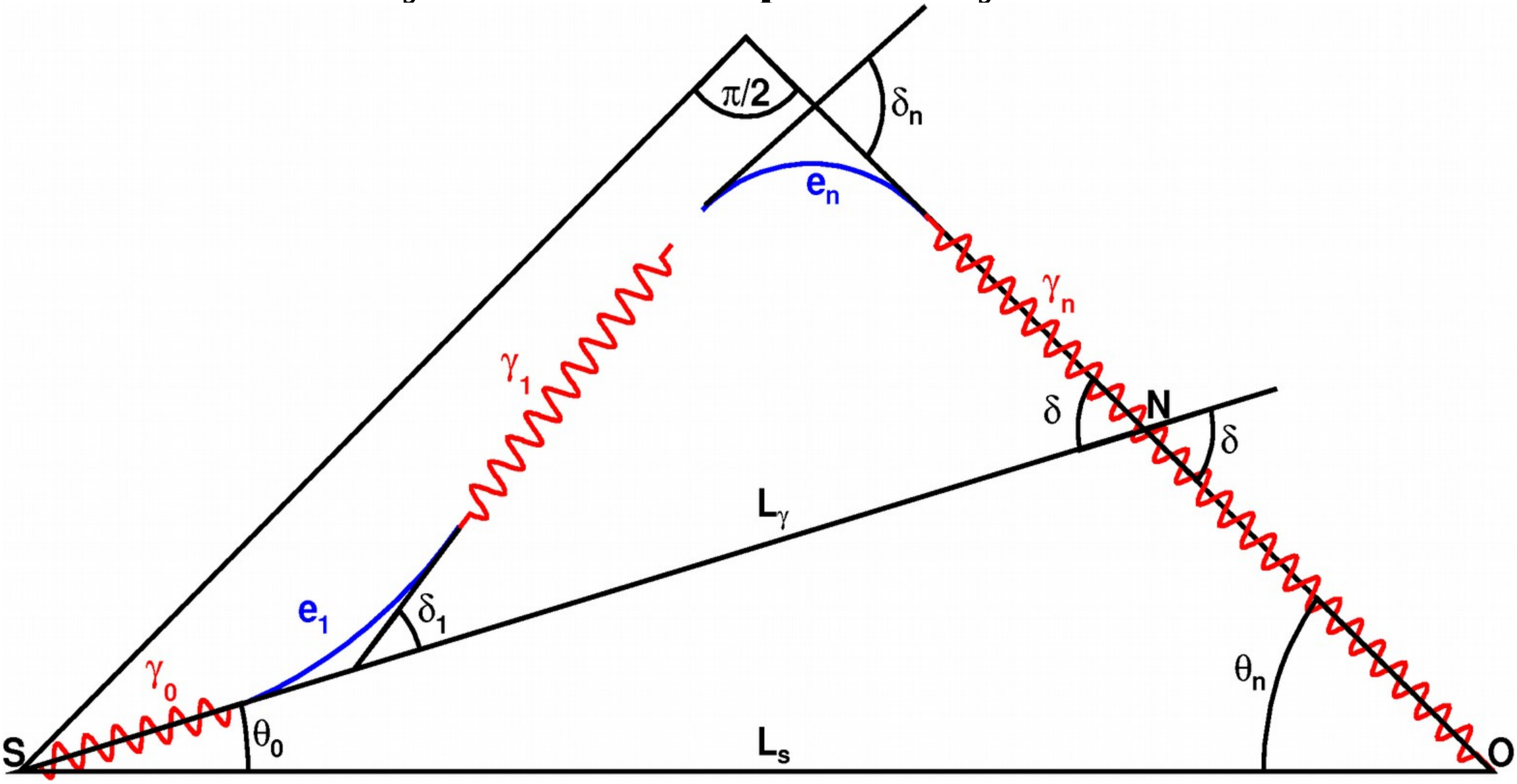
Extreme TeV blazars as probes of the intergalactic medium: beyond the absorption-only model



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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 $e^-\gamma \rightarrow e^{-\prime}\gamma'$ or $e^+\gamma \rightarrow e^{+\prime}\gamma'$

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)

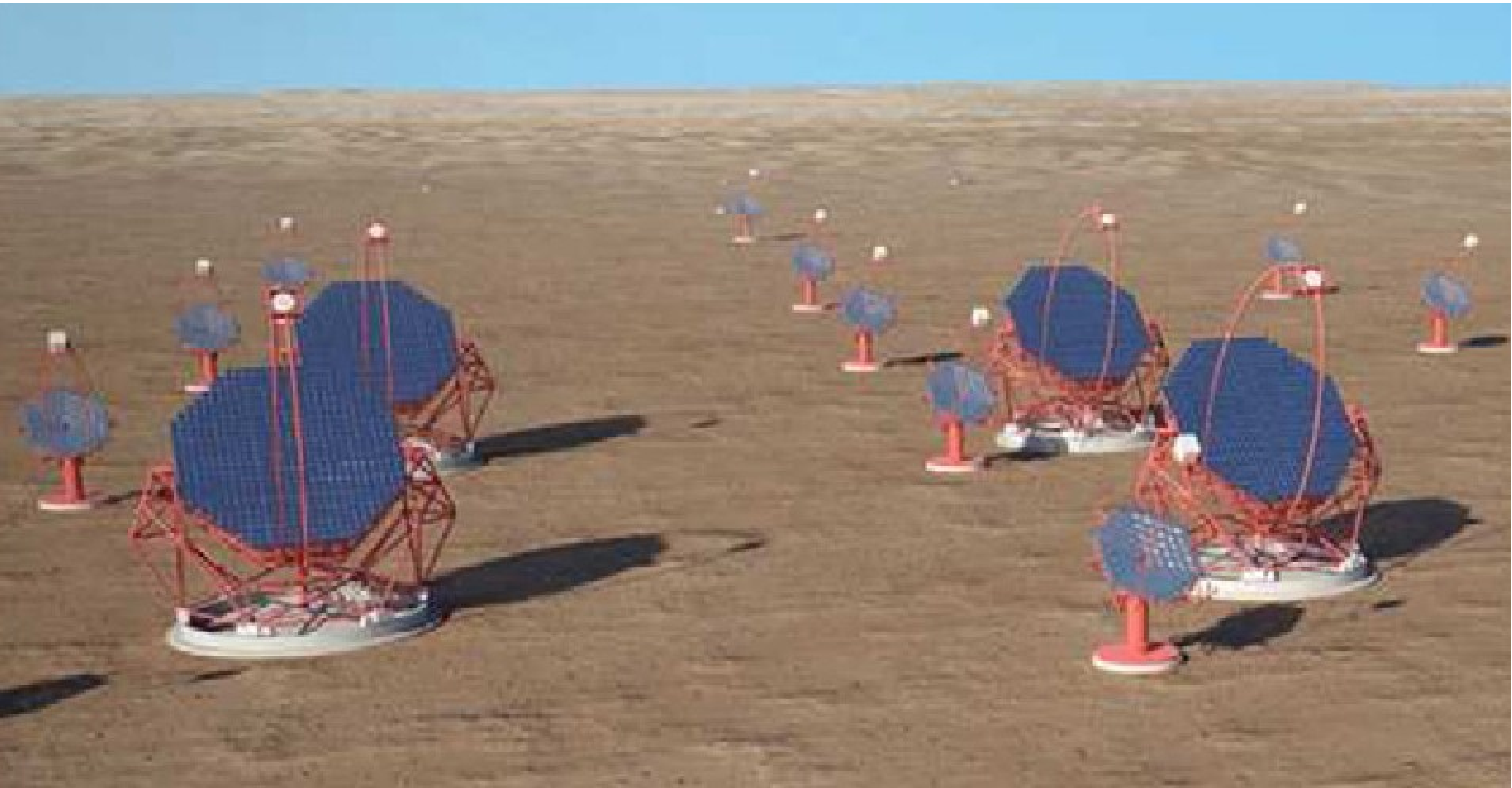
NV10 — Neronov & Vovk, Science, **328**, 73 (2010)

This talk is mostly based on:

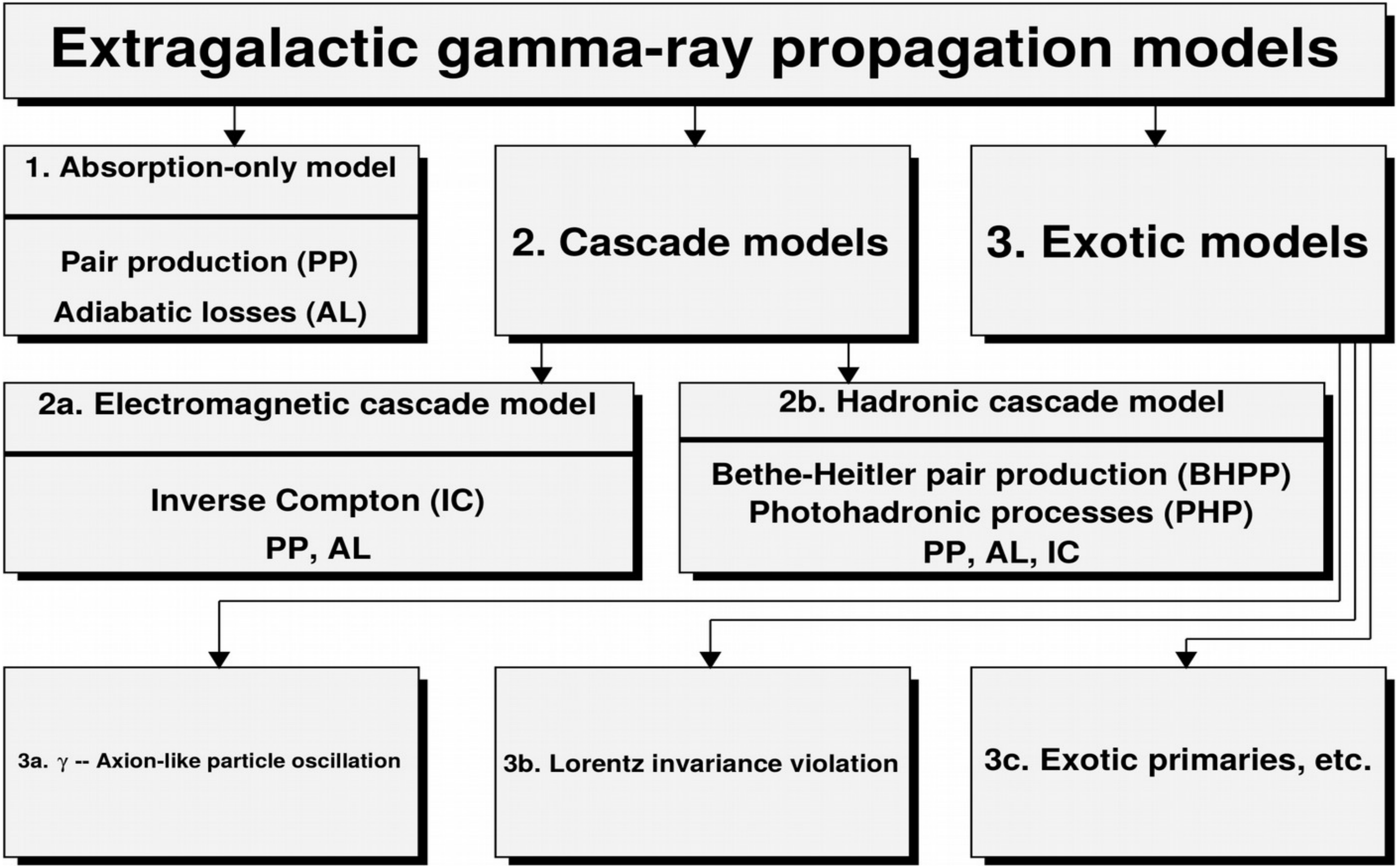
1. Dzhatdoev et al., A&A, **603**, A59 (2017)
2. Baklagin et al., Phys. Part. Nucl, **49**, 90 (2018)
3. Dzhatdoev et al., astro-ph/1711.08489 (2017) (to appear in Phys. At. Nucl.)
4. Dzhatdoev et al., Bull. Rus. Acad. Sci., **81**, 443 (2017)
5. Dzhatdoev & Podlesnyi, in preparation (2018) (EGMF)
6. 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)
For introduction on EBL/ γ-ray absorption: see talk by A. Dominguez
For introduction on extreme TeV blazars: see talk by E. Prandini

The Cherenkov Telescope Array (CTA): low threshold (20 GeV), improved sensitivity and angular resolution (Acharya et al., special APh issue (2013))



Our aim: to discuss the effects that could be introduced by electrons (and positrons) from pair-production acts



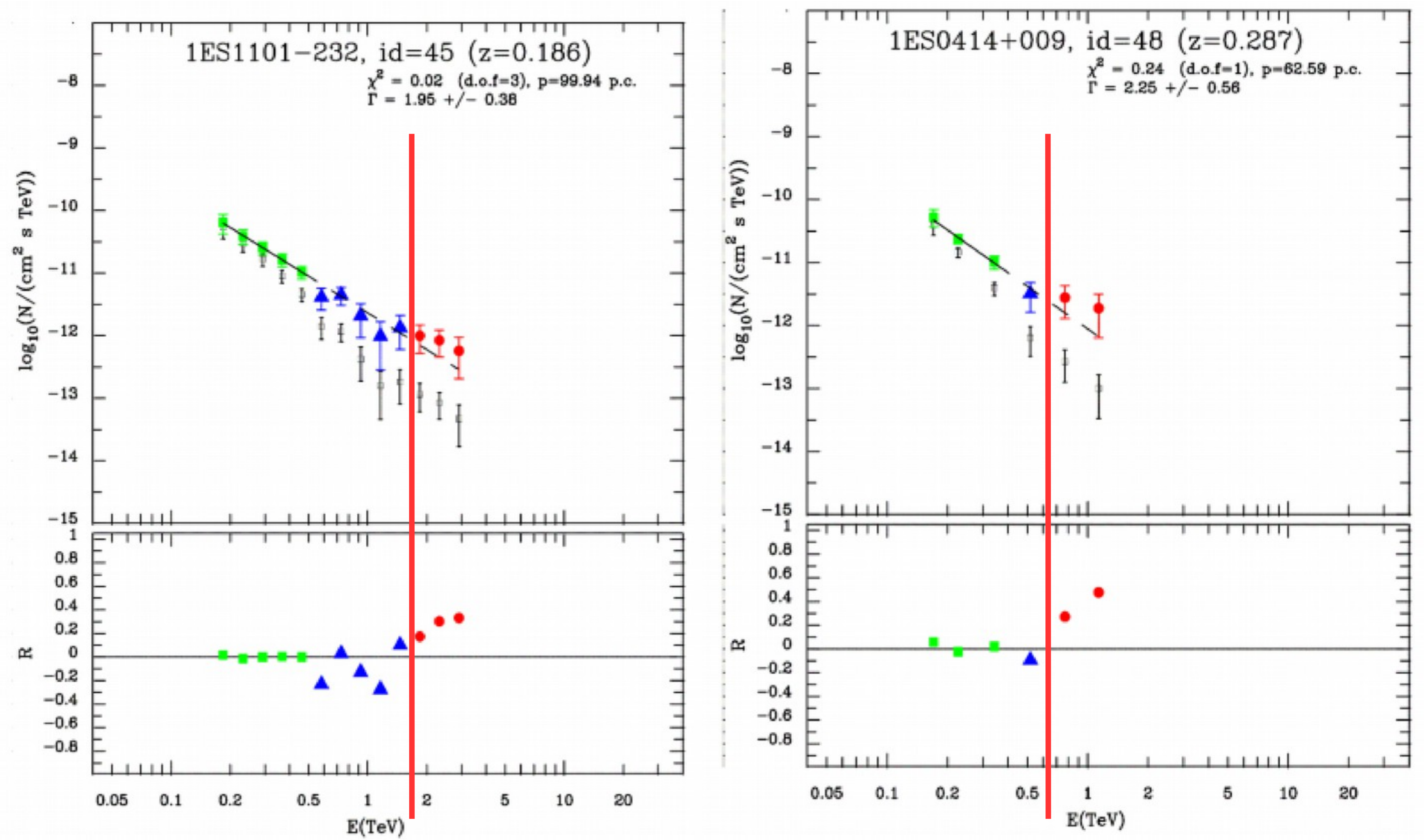
The absorption-only model of blazar spectra transformation is well-established classics.

Conceptually simple:
1) apply the absorption exponent
2) redshift

(S. Herbert, “Cats Galore: A Compendium of Cultured Cats”, image from http://www.dailymail.co.uk)

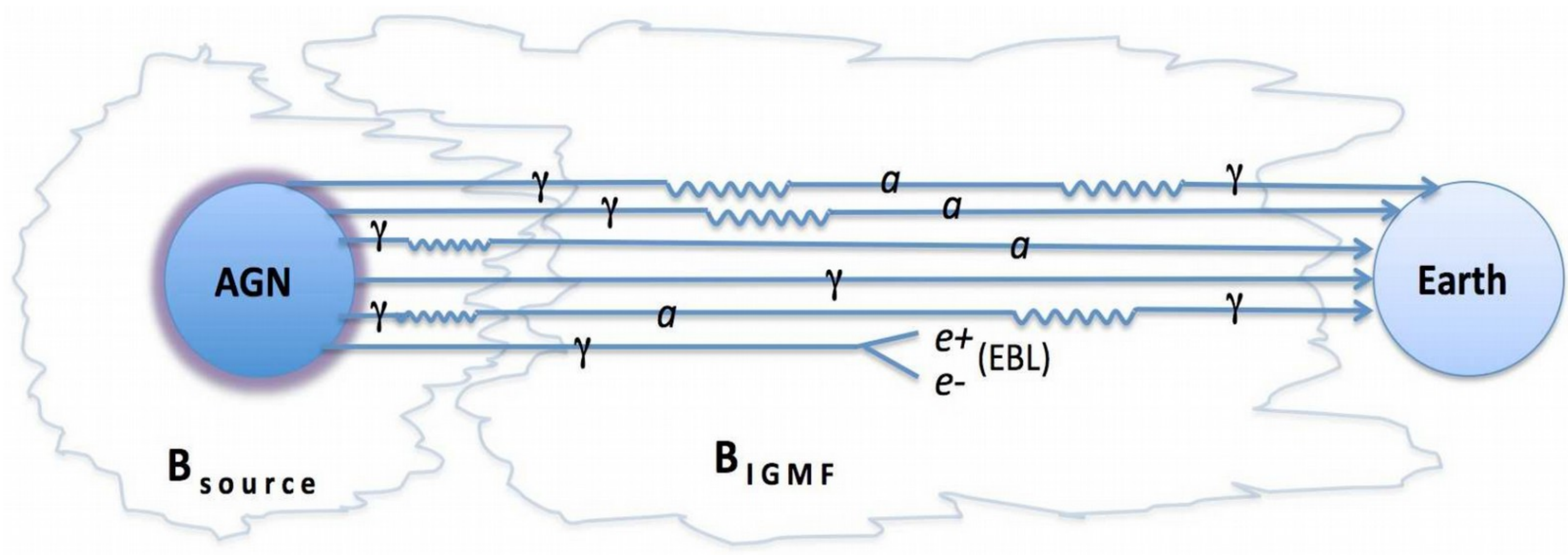
Any effects beyond this framework?

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)

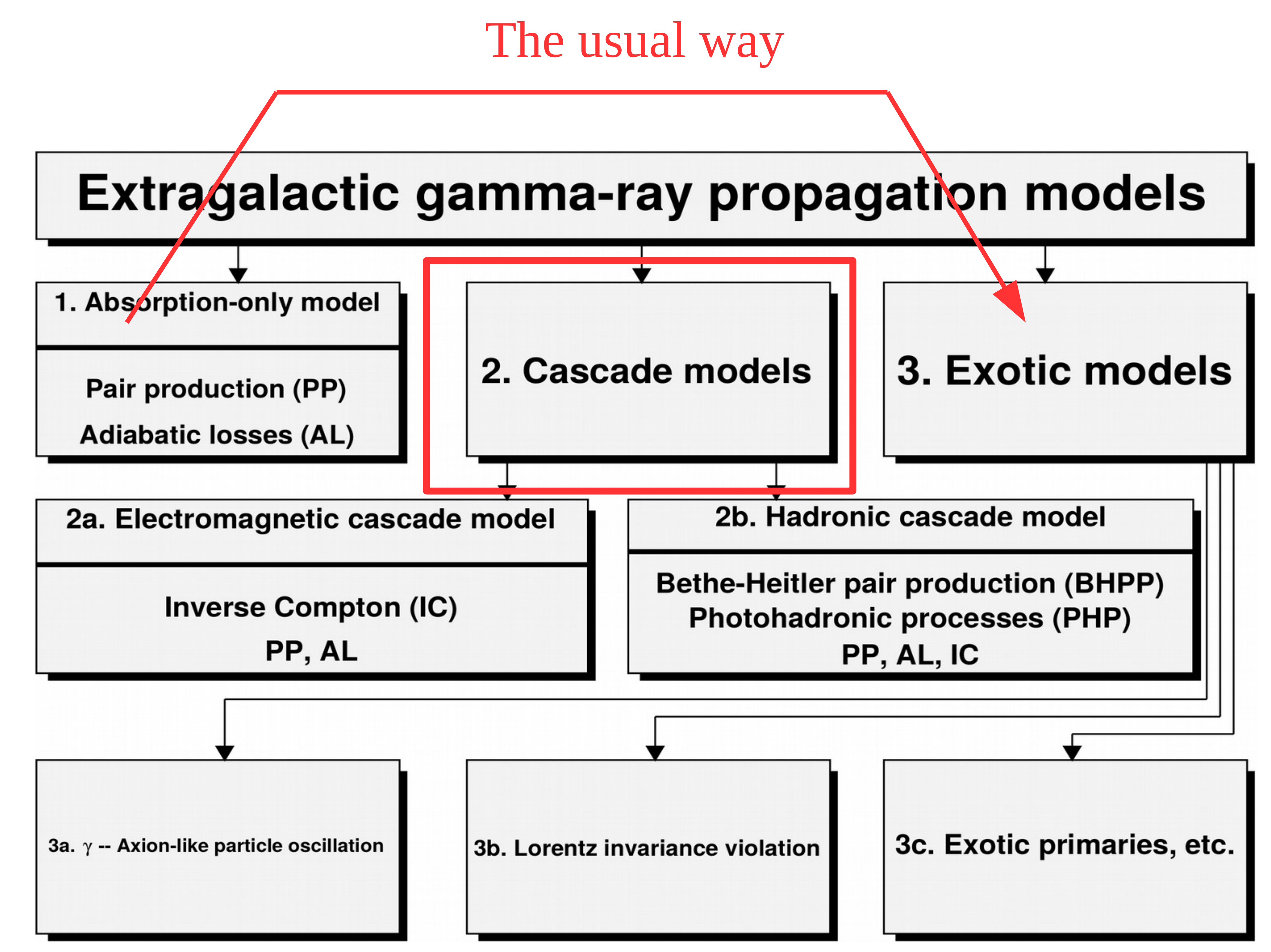


See, however, Biteau & Williams, ApJ, **200**, 58 (2015); Dominguez & Ajello, ApJ, **813**, L34 (2015)

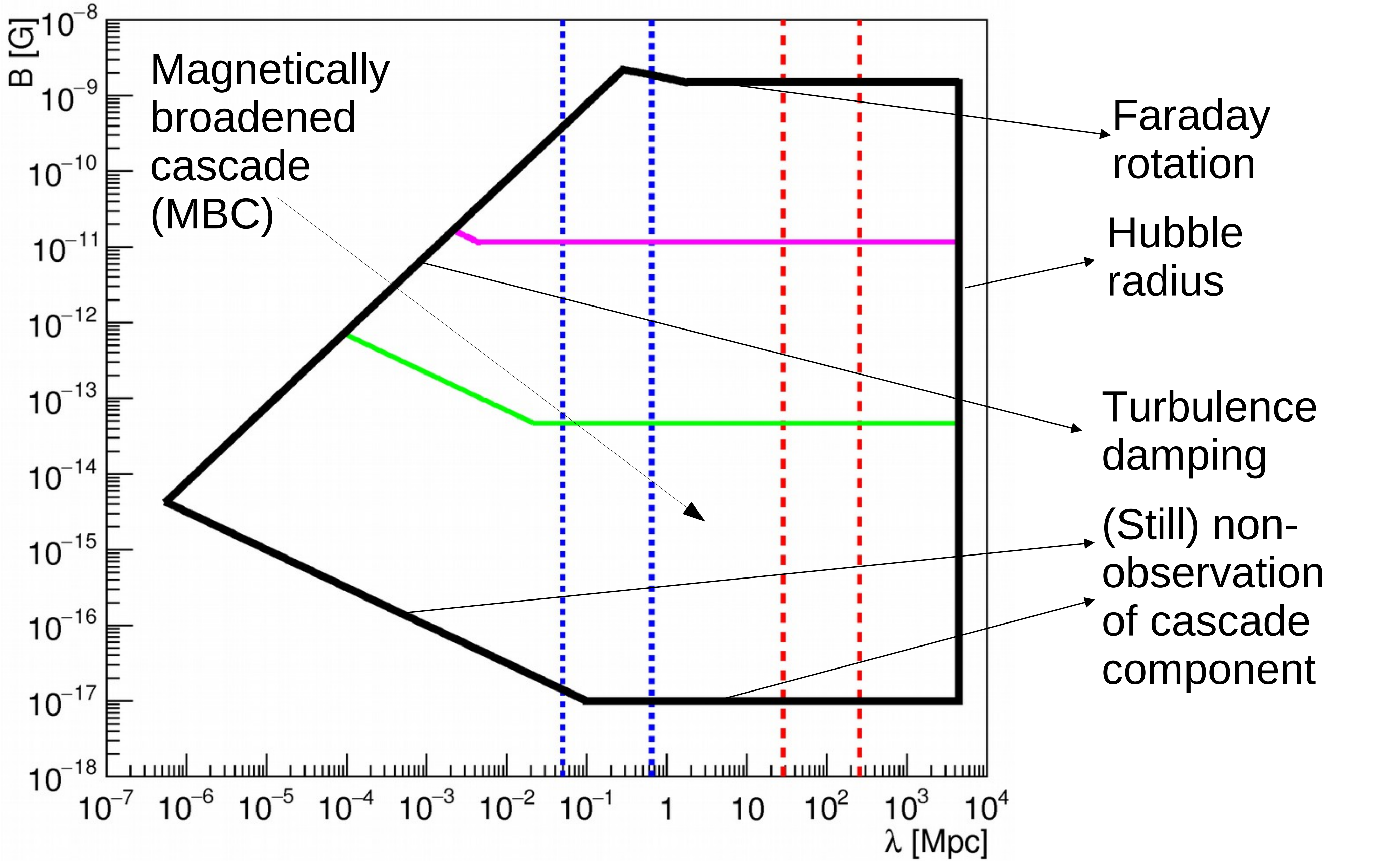
A possible explanation: γ-ALP conversion in magnetic field



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)

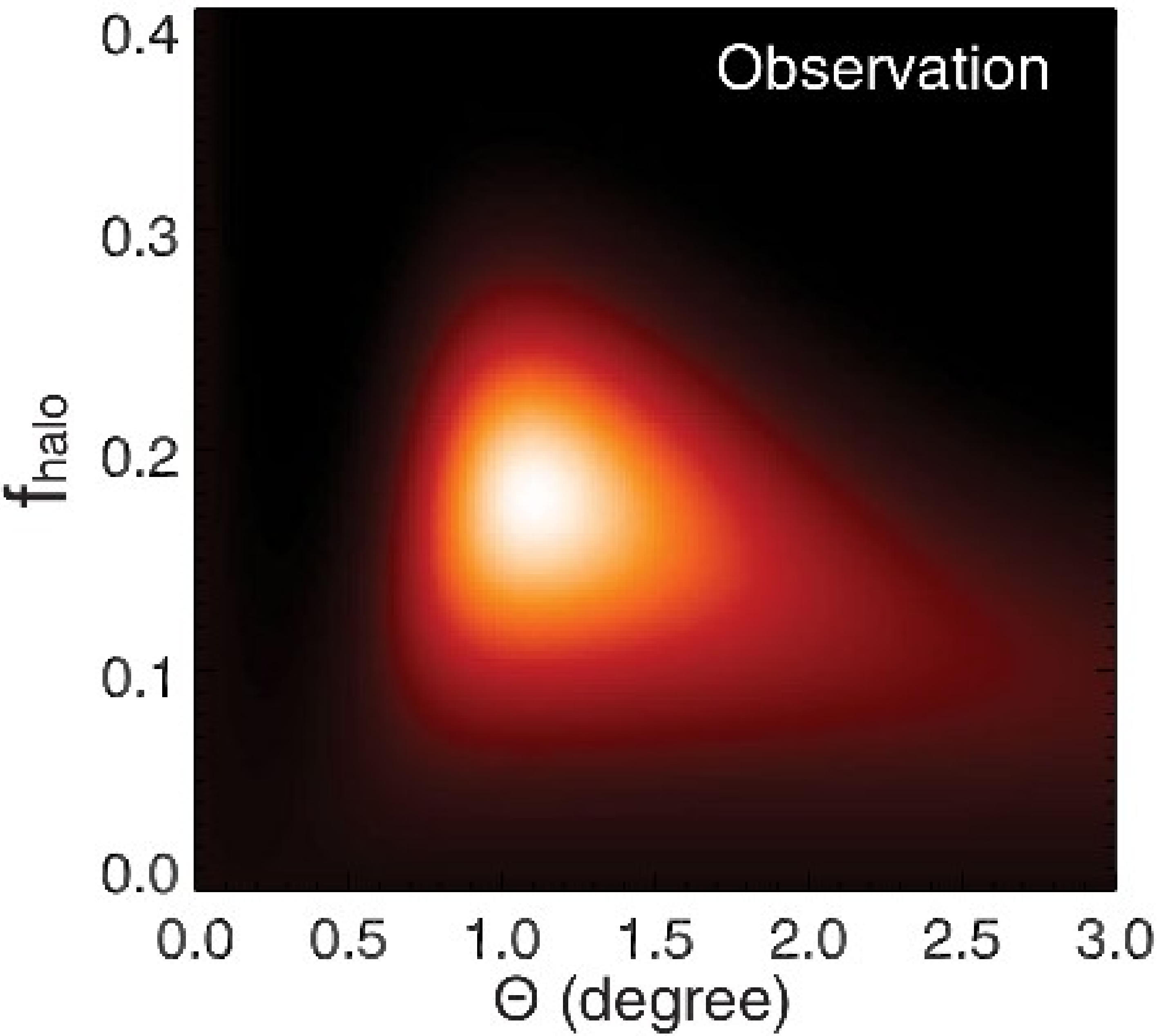

The usual way
Extragalactic gamma-ray propagation models
1. Absorption-only model
Pair production (PP)
Adiabatic losses (AL)
2. Cascade models
3. Exotic models
2a. Electromagnetic cascade model
Inverse Compton (IC)
PP, AL
2b. Hadronic cascade model
Bethe-Heitler pair production (BHPP)
Photohadronic processes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

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

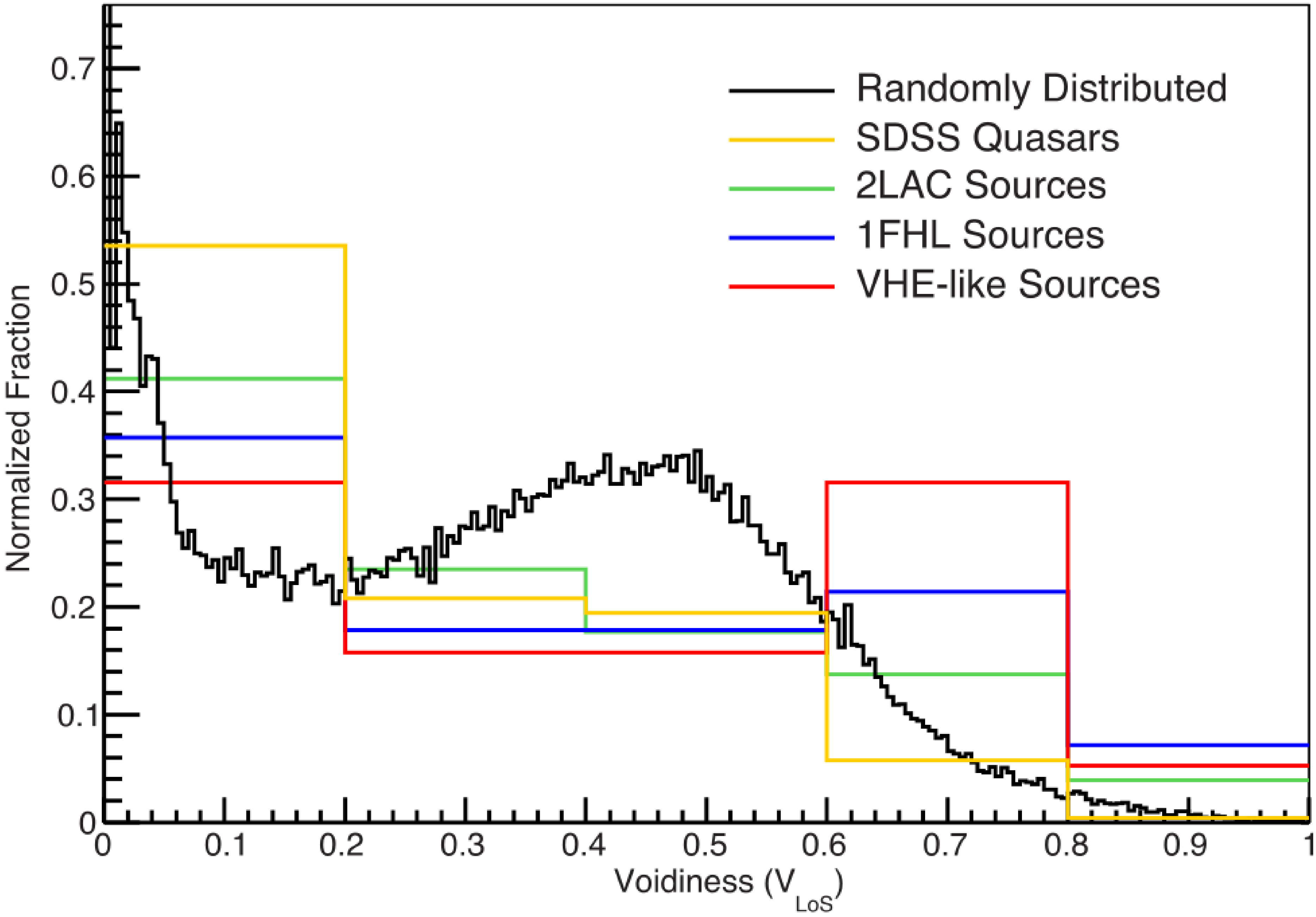


Many claims of strong constraints/detection inside the black frame

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)



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

Their results on the EGMF:

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

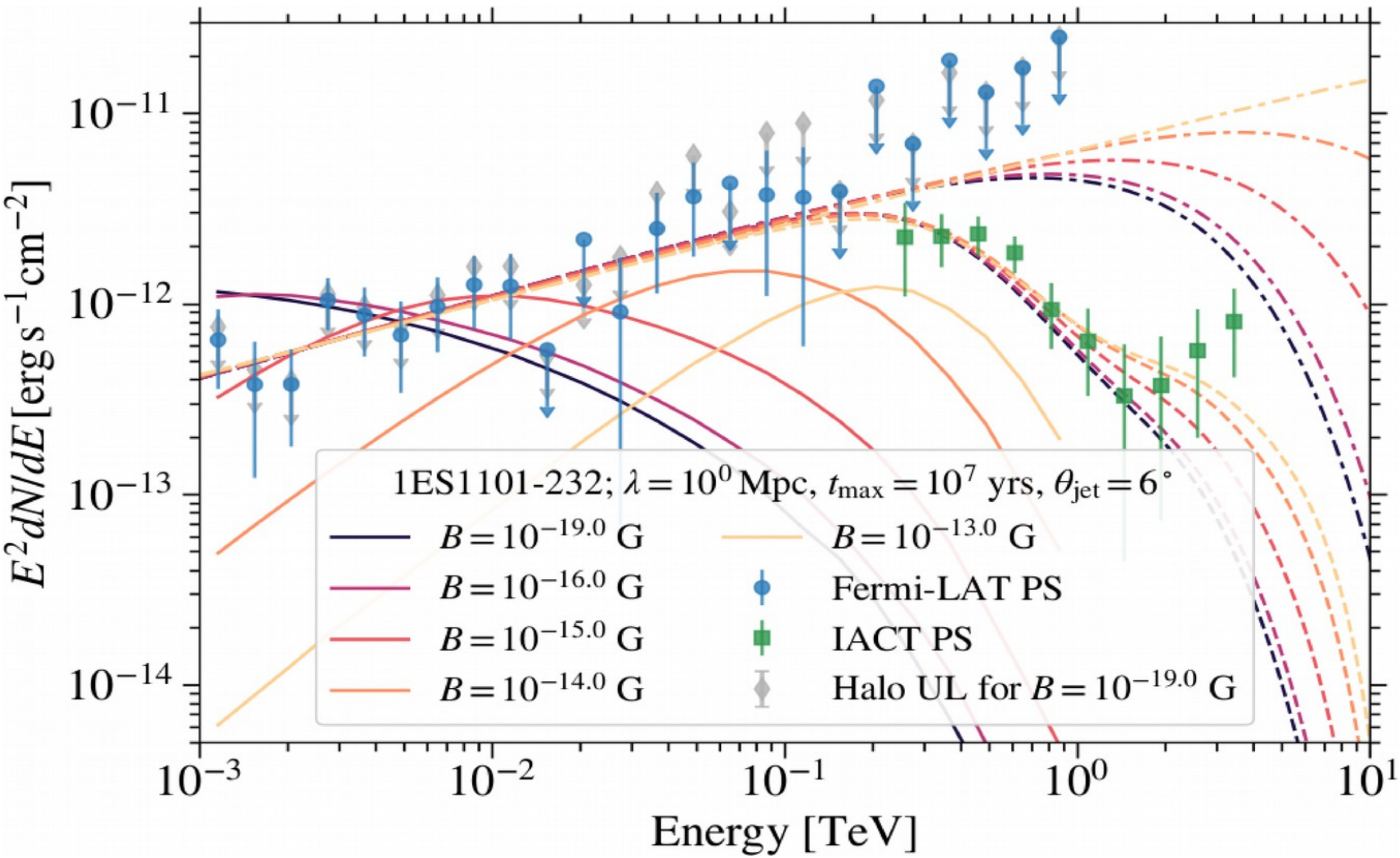
Their conclusion: "This improves previous limits by several orders of magnitude."

No MBC/PH was found

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

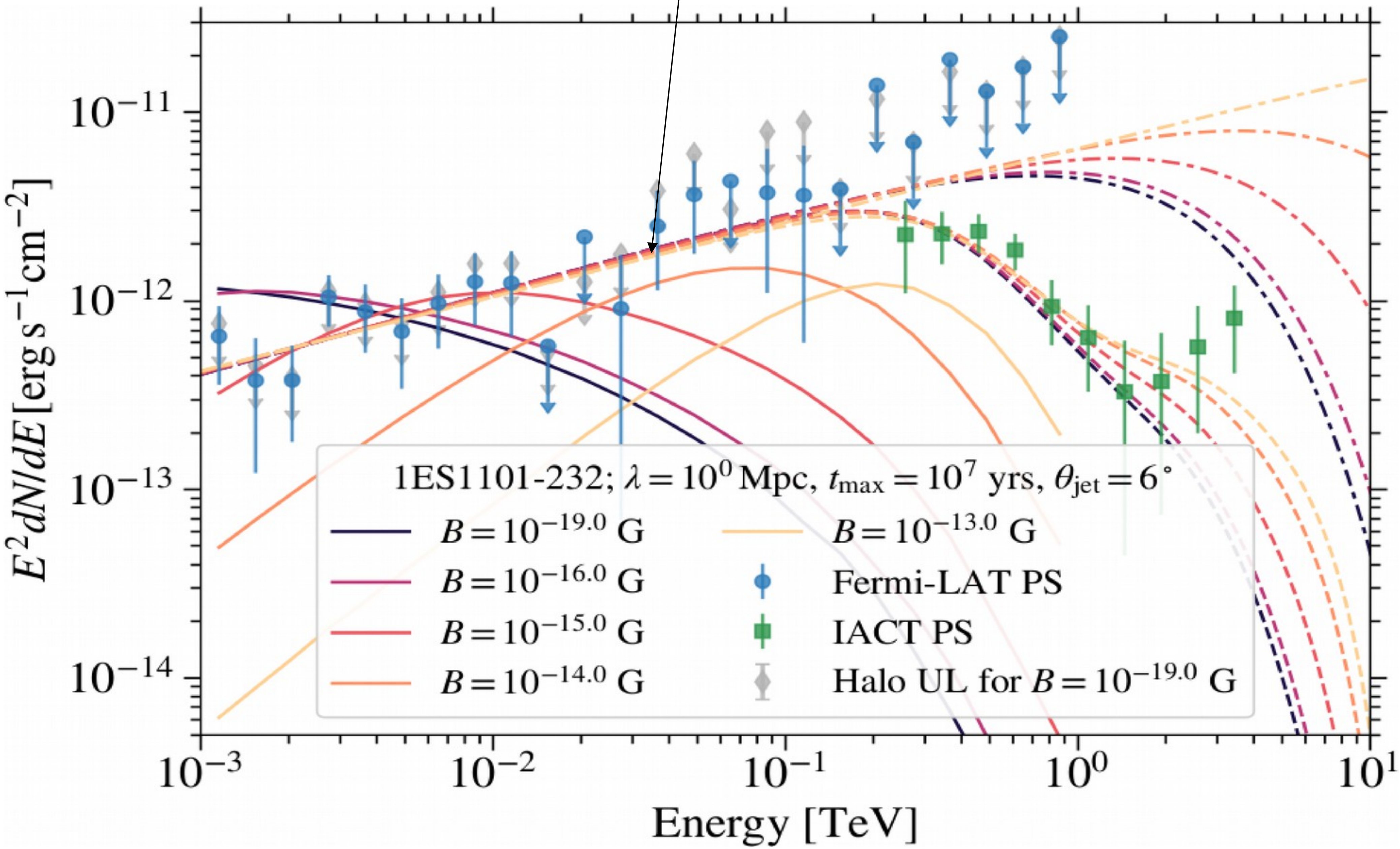
It is rather noted that systematics does not allow to prove the existence of the MBC/PH

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”

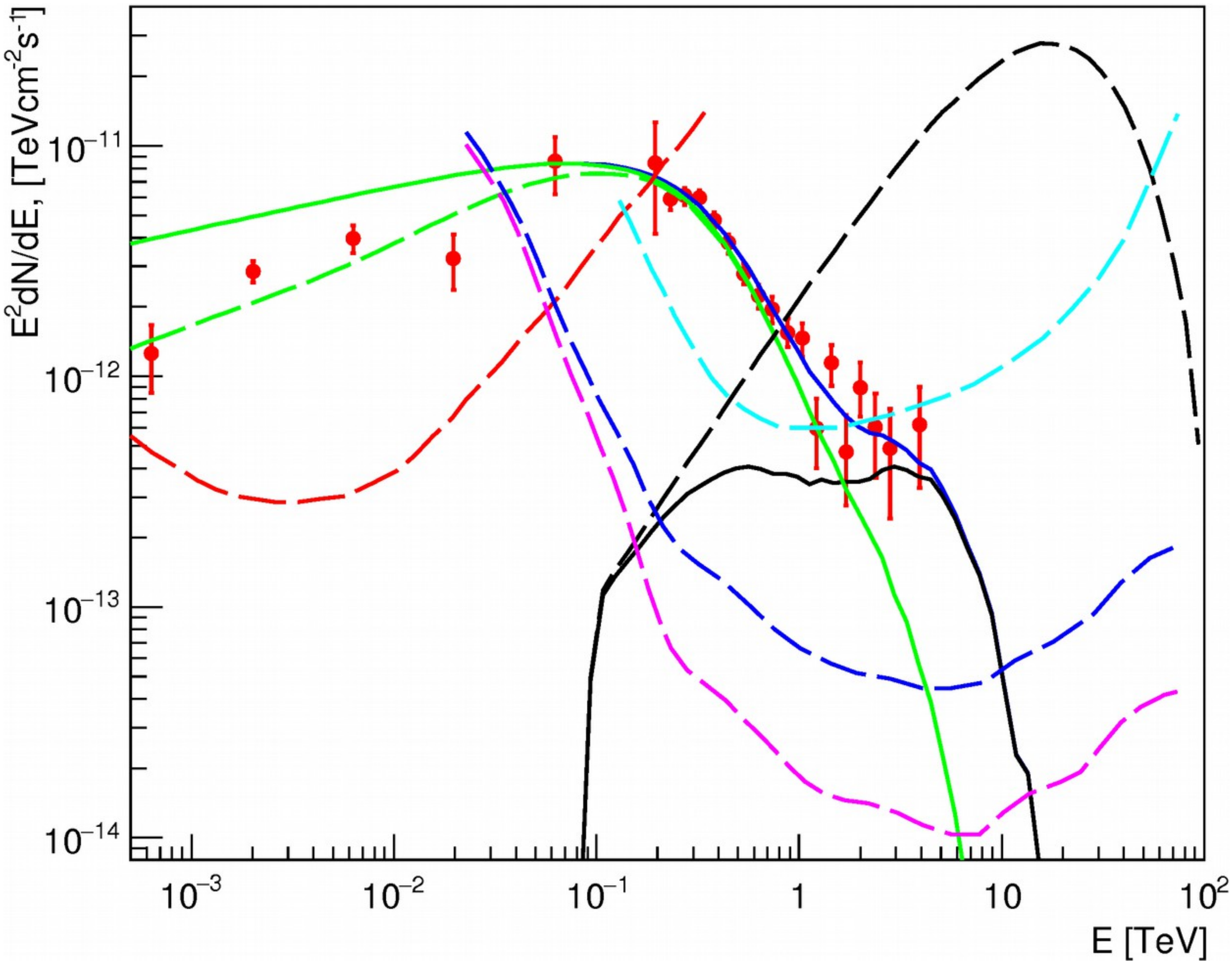


There is no room for the cascade component in their fit!

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



“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!

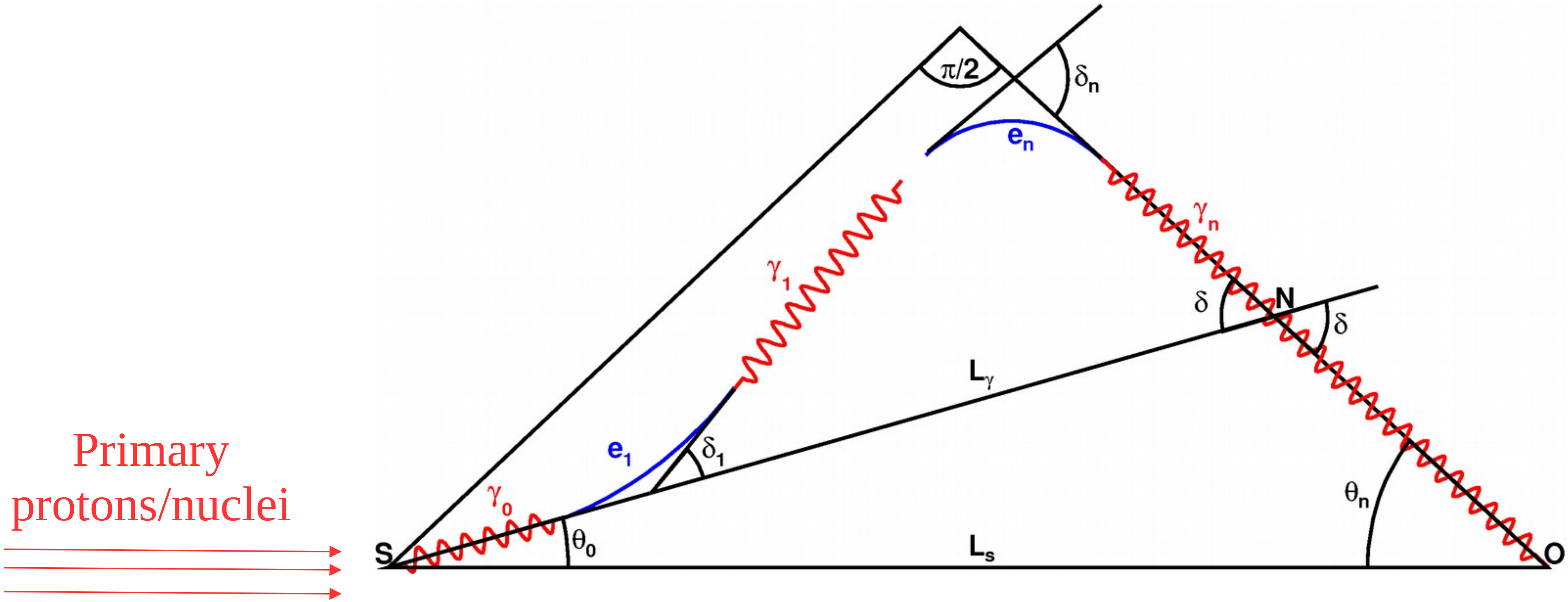


Secondary (cascade) γ-rays from UHE protons/nuclei emitted by blazars

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 (Greisen, Phys. Rev. Lett., **16**, 748 (1966); Zatsepin & Kuzmin, JETP Lett., **4**, 78 (1966))

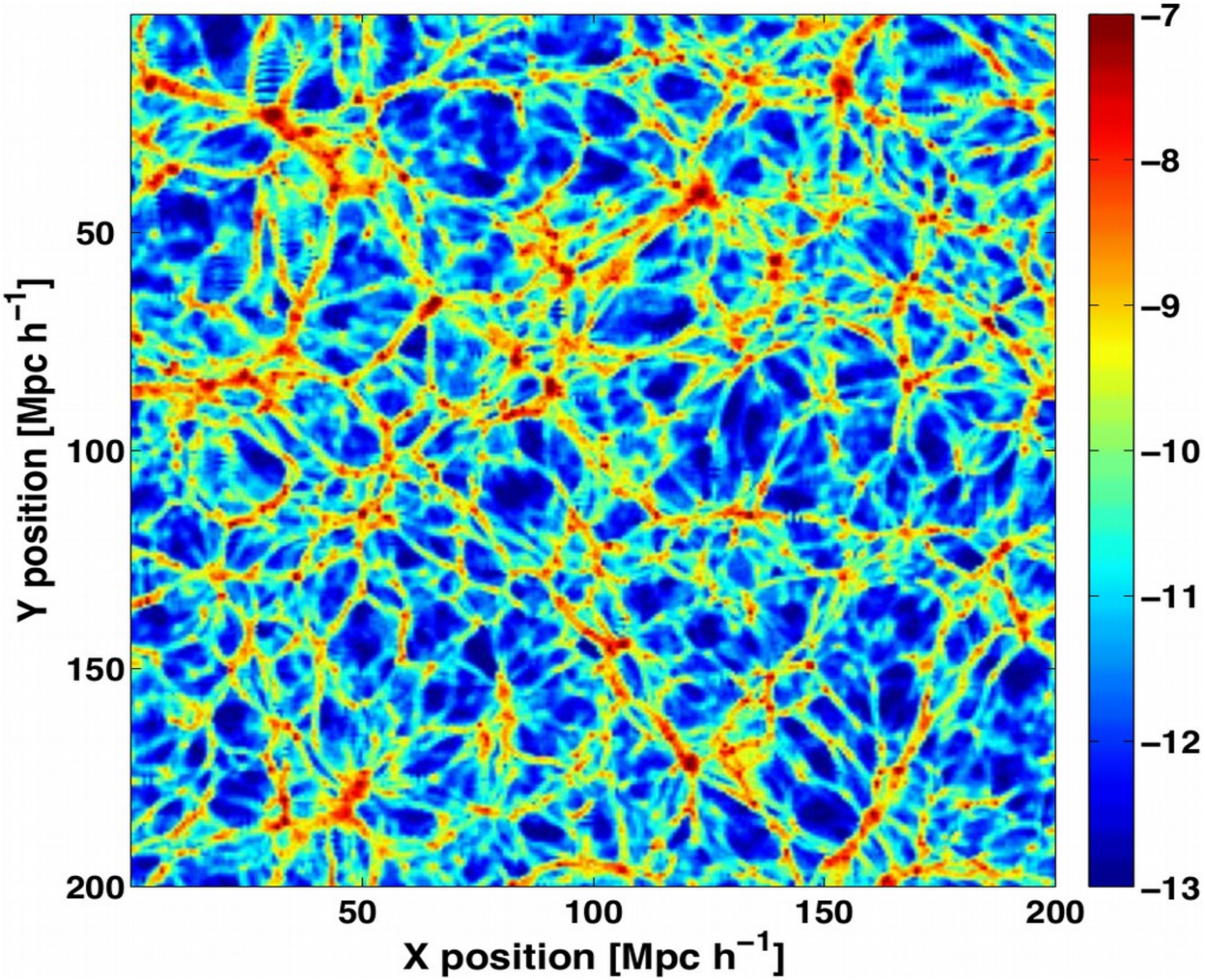
Intergalactic hadronic cascade model (HCM)



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); Cerruti et al., A&A, **606**, A68 (2017)

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

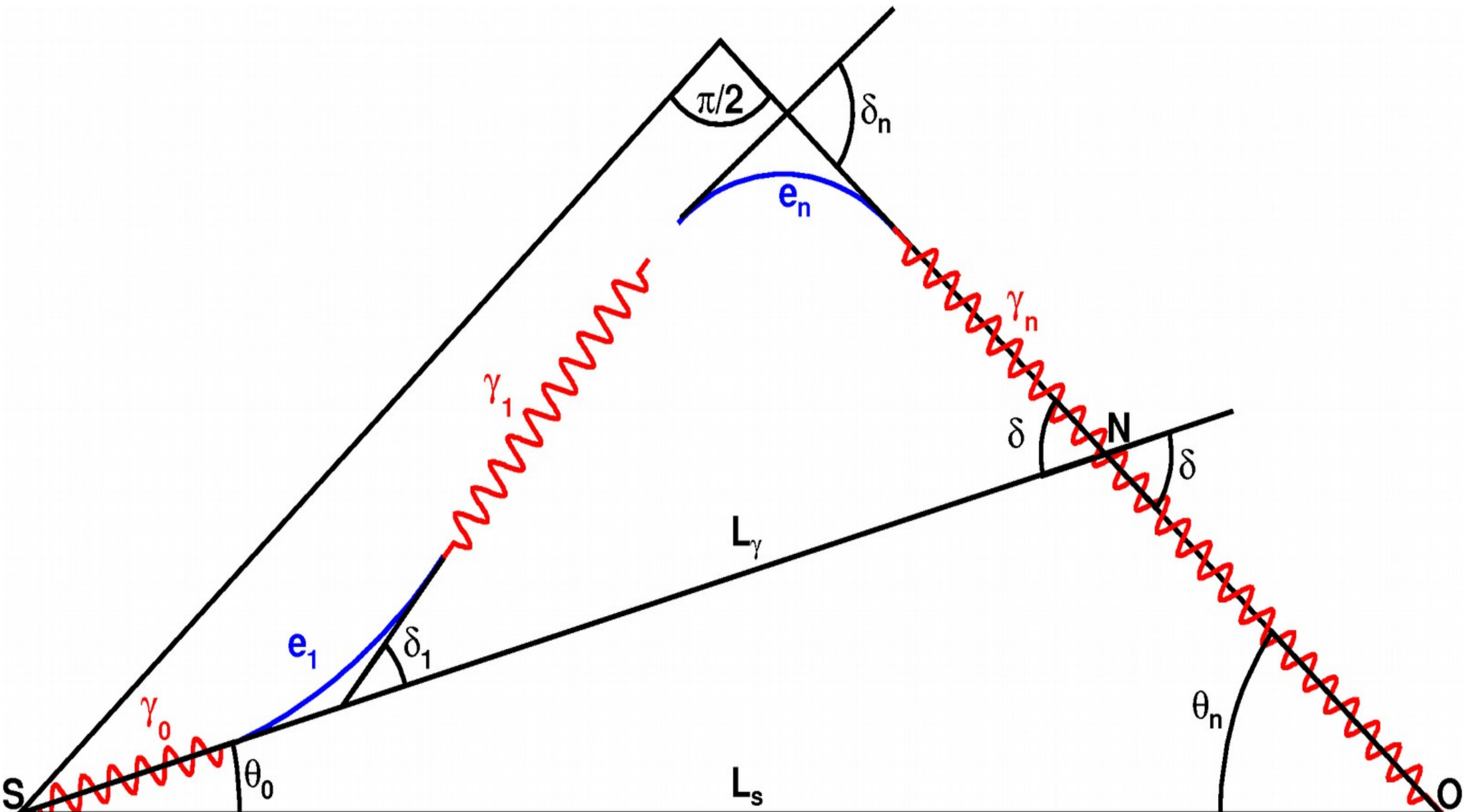
A slice of large-scale EGMF (~10 nG, 1 Mpc) at least every 50 Mpc!
(Oikonomou et al., 2014) → 10 deg deflection of protons



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

(Harari et al., 2016)

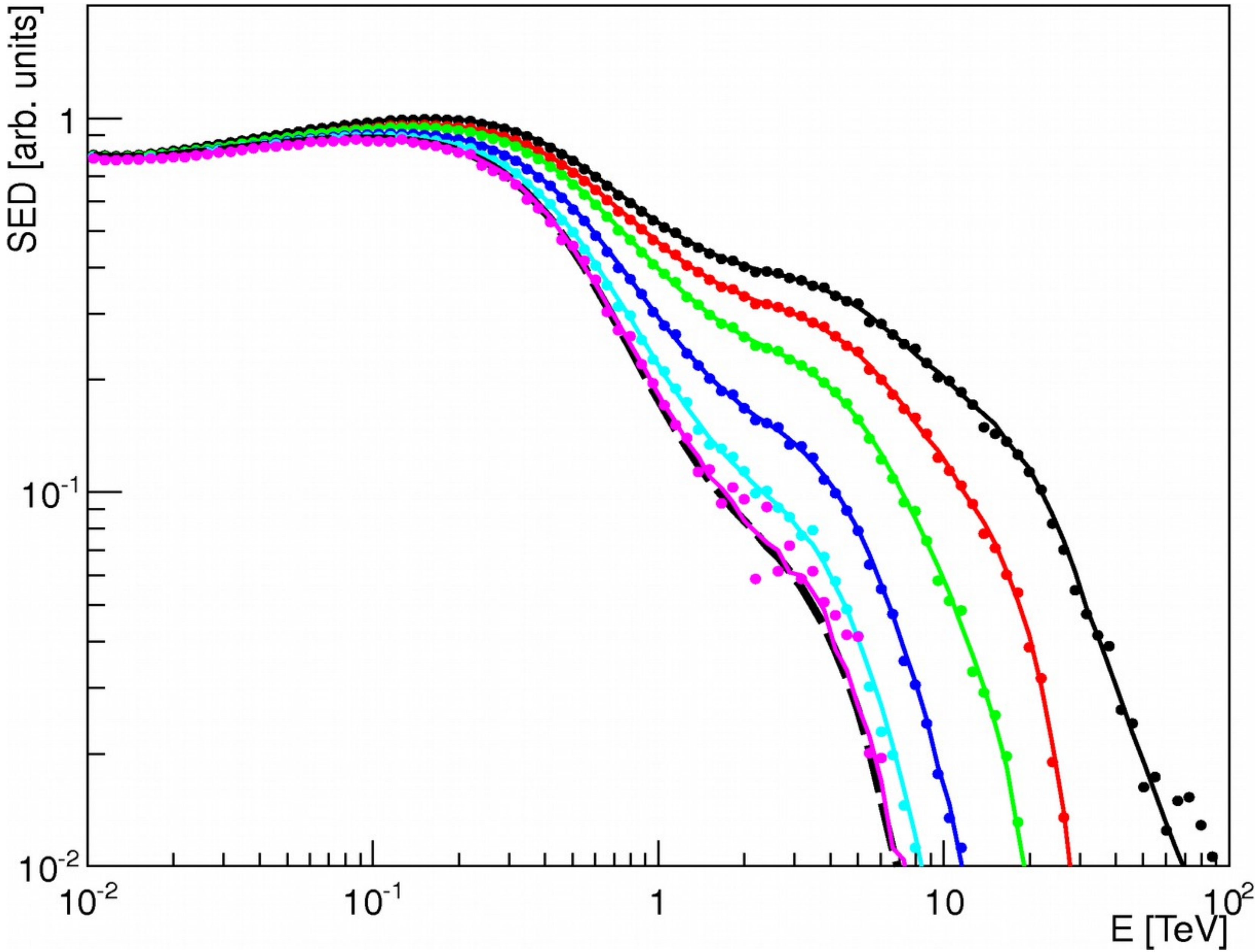
Towards a more realistic intergalactic hadronic cascade model!



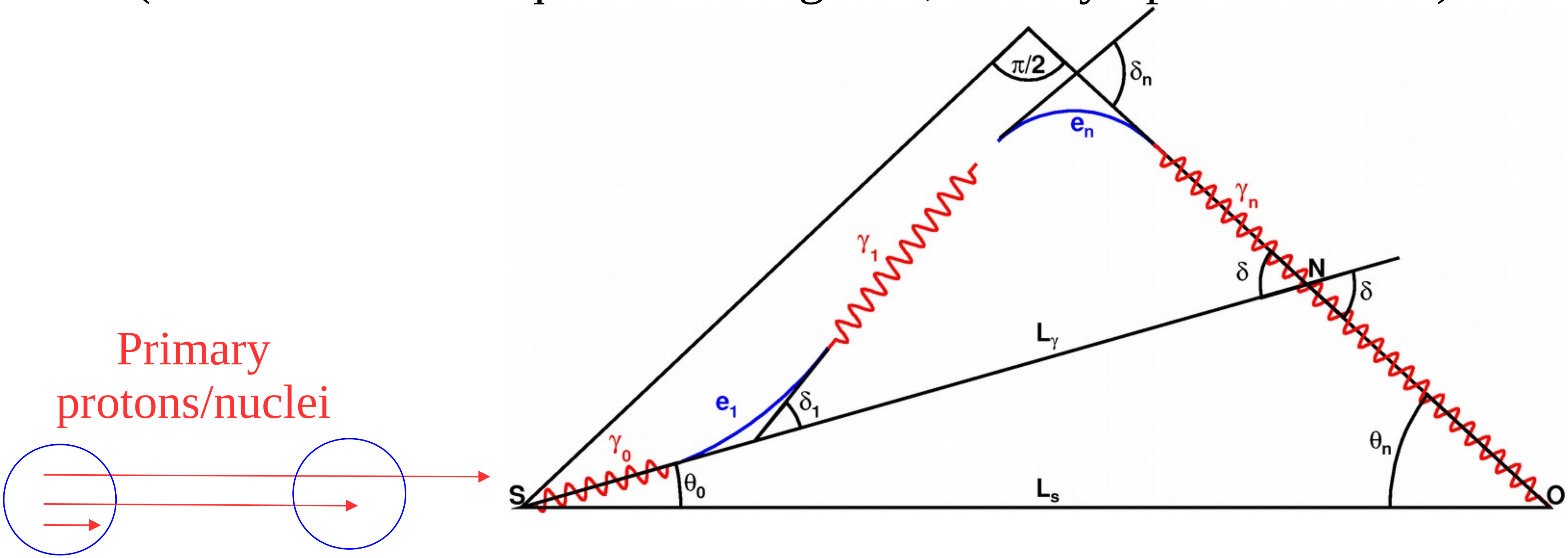
$$sin(\theta_n) = sin(\delta)\frac{L_\gamma(E_{\gamma_{n-1}}, z_s)}{L_s}$$

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 SEDs for z_c= 0, 0.02, 0.05, 0.10, 0.15, 0.18



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.

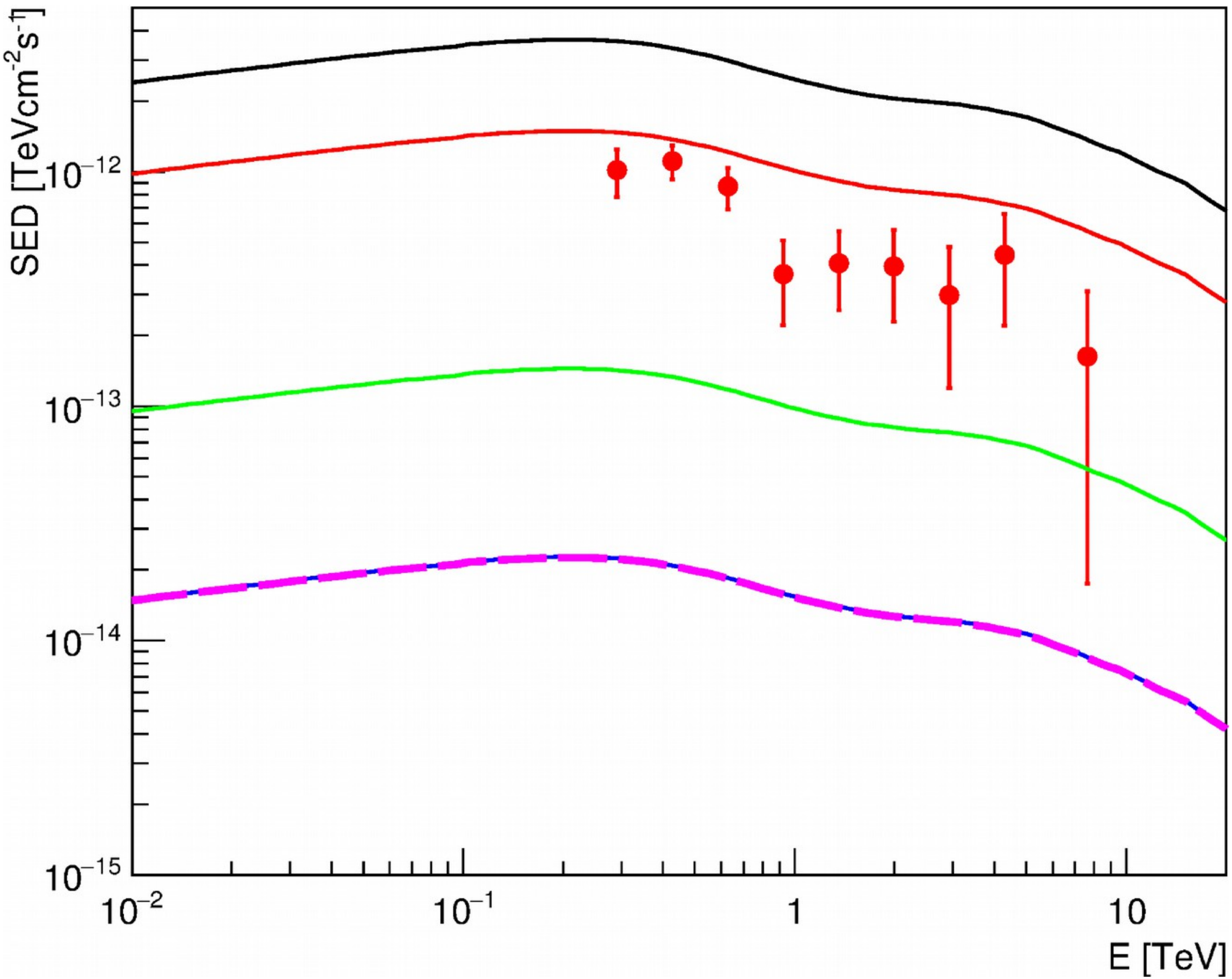
Primary luminosity and spectrum: Tavecchio, MNRAS, **438**, 3255 (2014)

(primary proton luminosity is limited by magnetic field density)

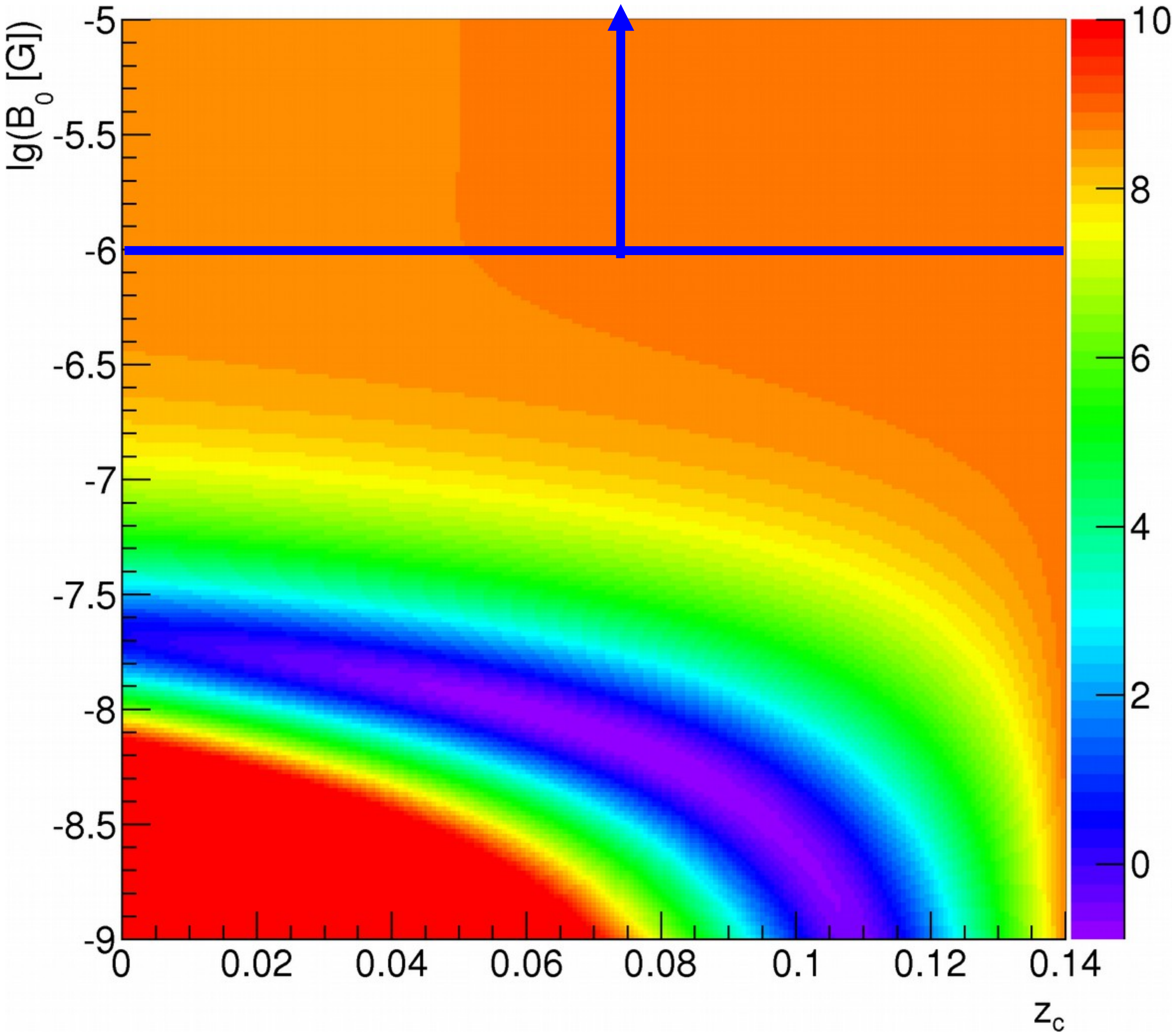
The source is embedded in a galaxy cluster (Meyer et al., Phys. Rev. D, **87**, 035027 (2013)), central magnetic field B_0.

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)



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



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) (for Mkn 501)

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

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

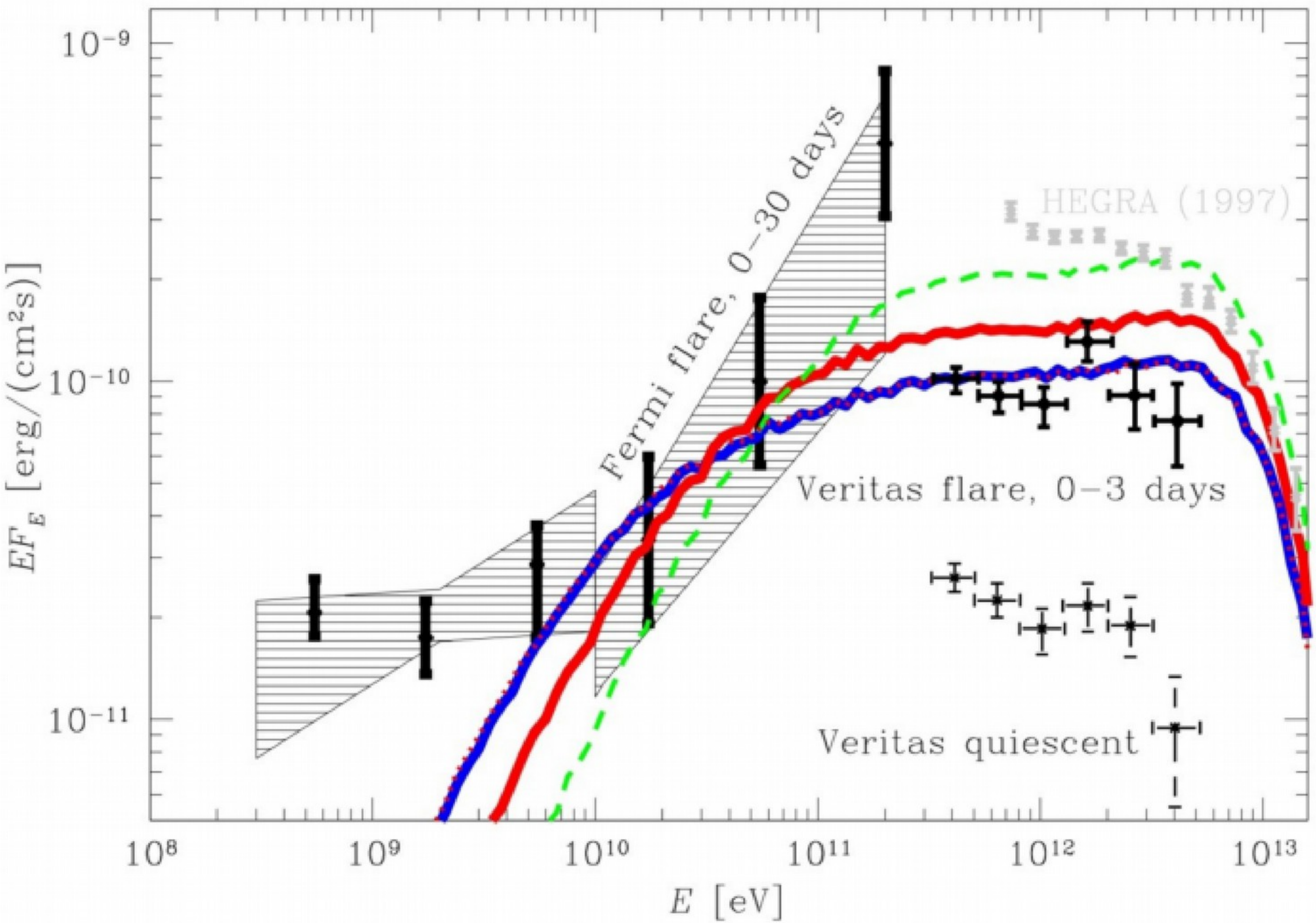
Takami et al., ApJ Lett., **771**, L32 (2013)

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

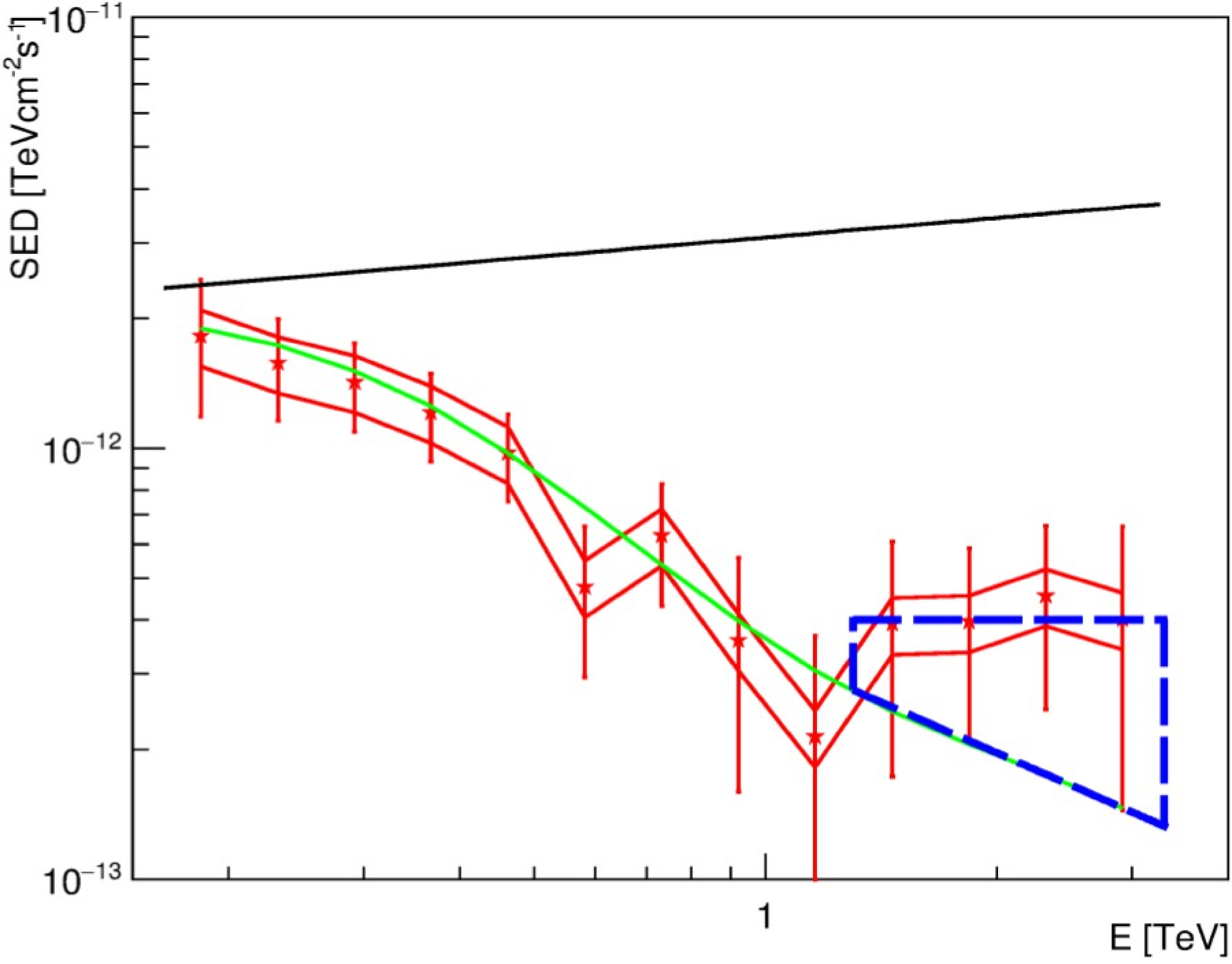
Motivation:
primary spectrum is not known, especially for the case of "extreme TeV blazars" --- active galactic nuclei with hard primary spectrum and low-amplitude slow variability!!

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): >20 episodes of hard-spectra; high significance

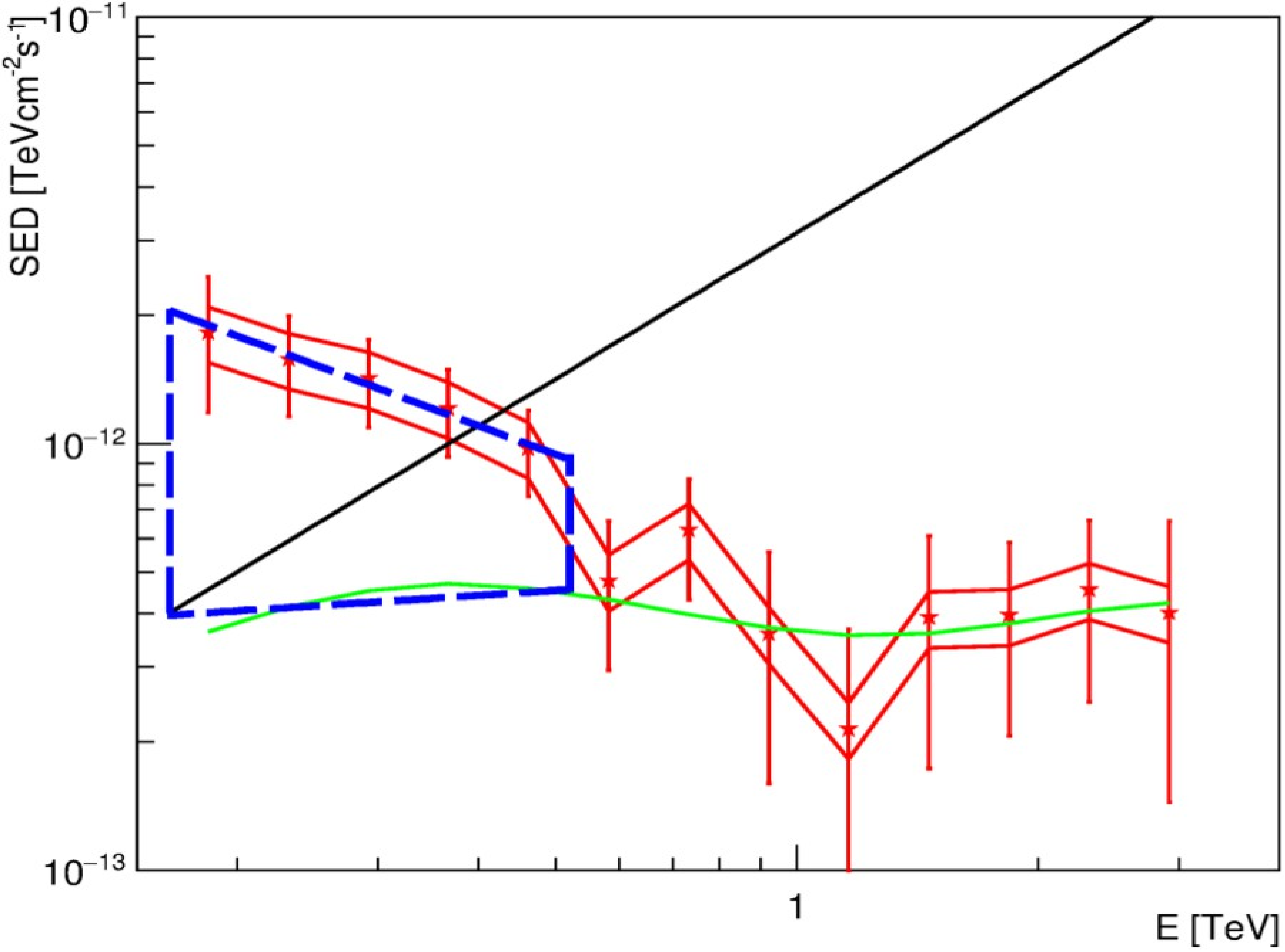


The high-energy excess option

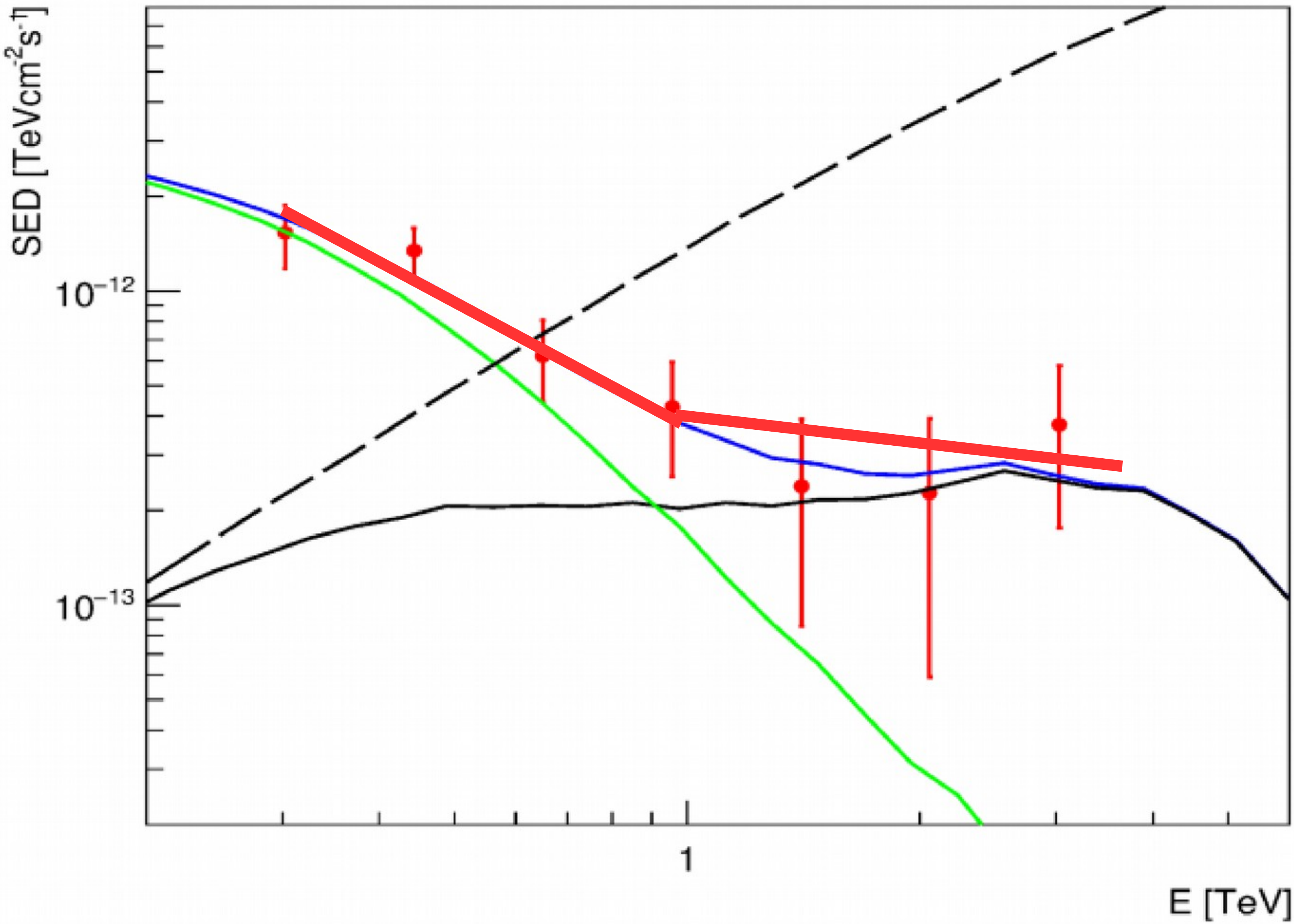


The low-energy excess option.

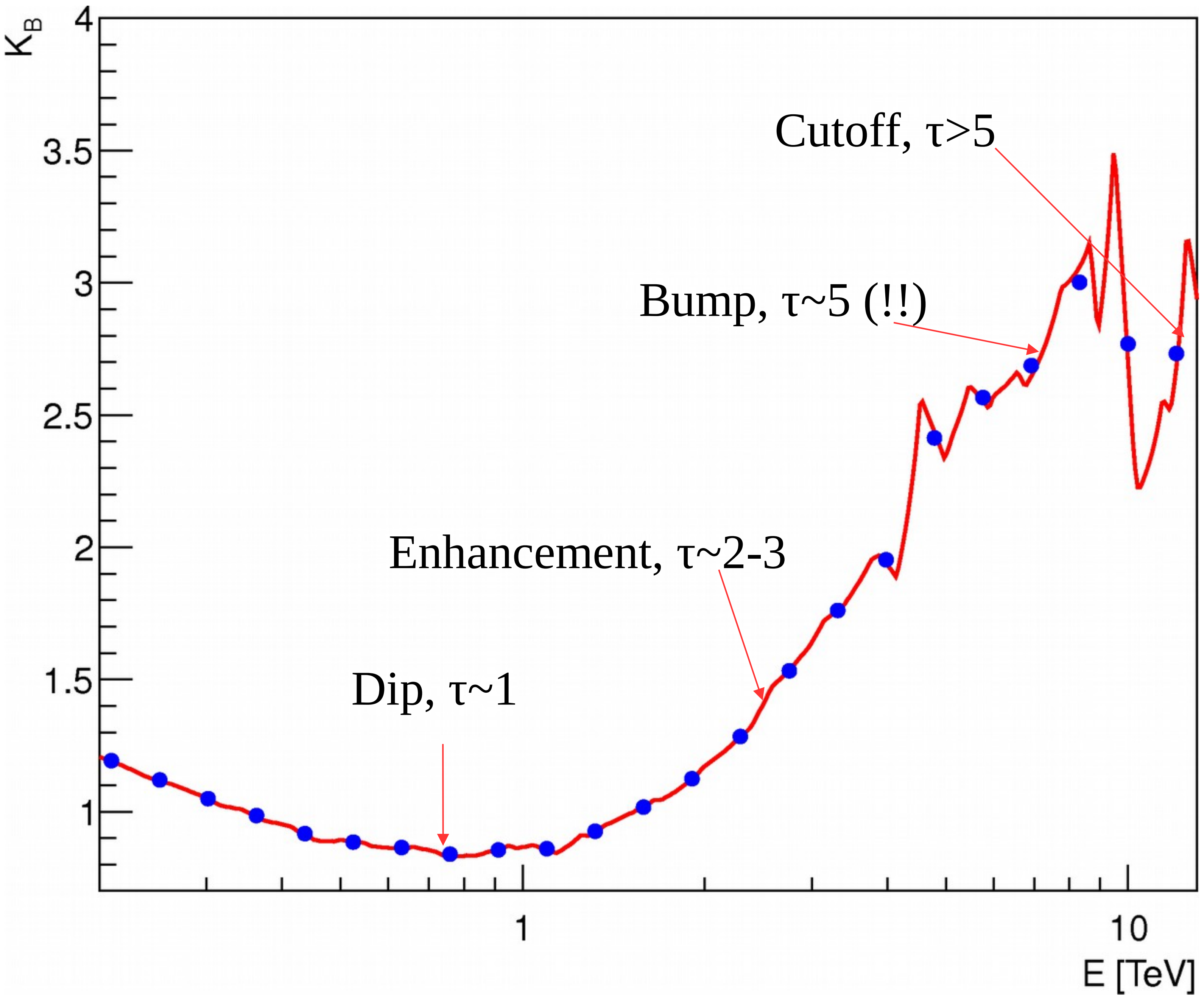
All known anomalies are explained in a unified way!



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



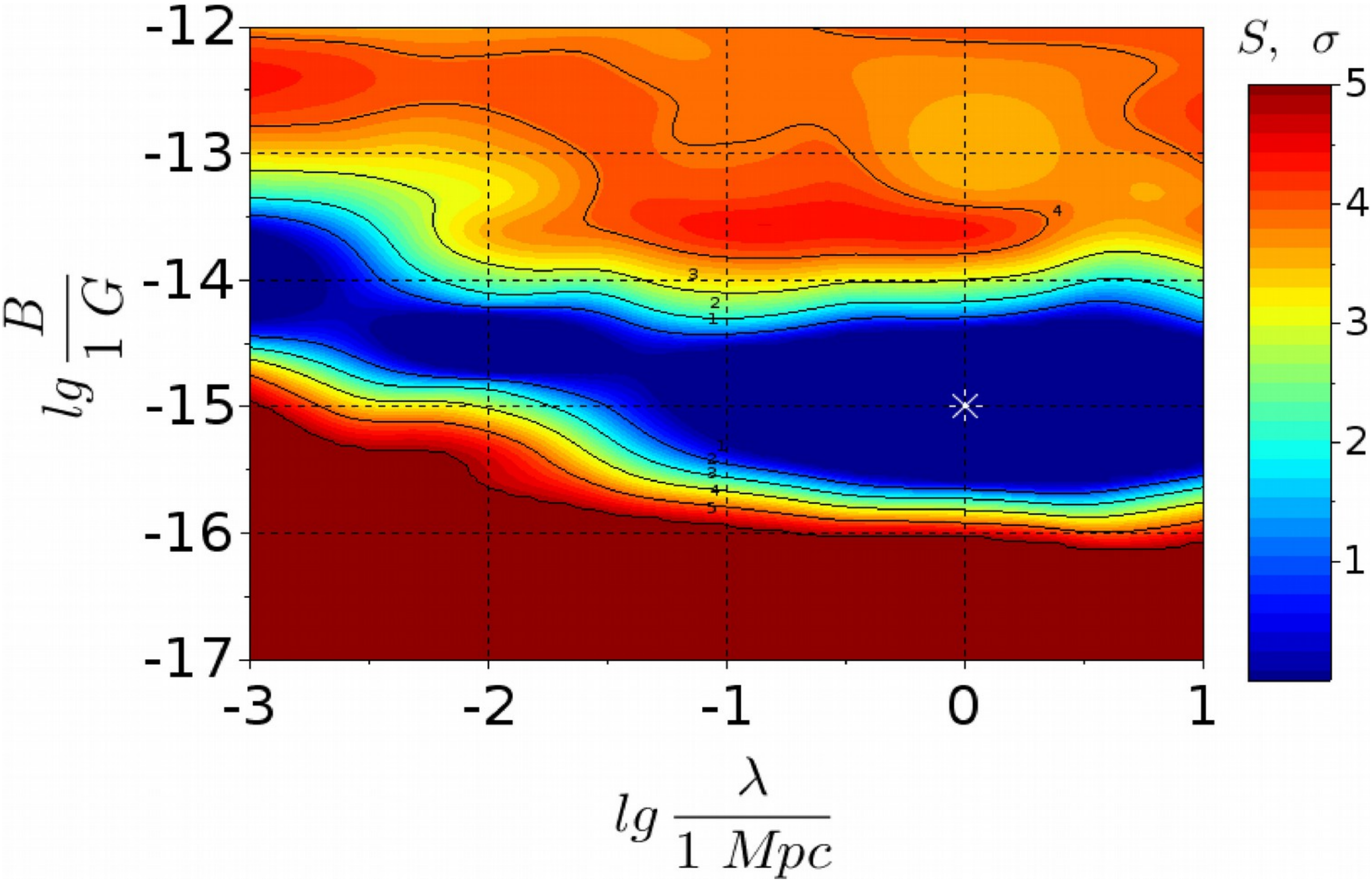
The ratio of best-fit model spectra for electromagnetic cascade model and the absorption-only model. Prospects for CTA: stat. Uncertainty 10 % at 3 TeV, 40 % at 6 TeV



EGMF parameter sensitivity for Fermi LAT and CTA
(cf. Meyer et al. (2016))

We use 1ES 1218+304 as our source

Sensitivity to the EGMF parameters: “magnetic cutoff” method, CTA+ Fermi LAT

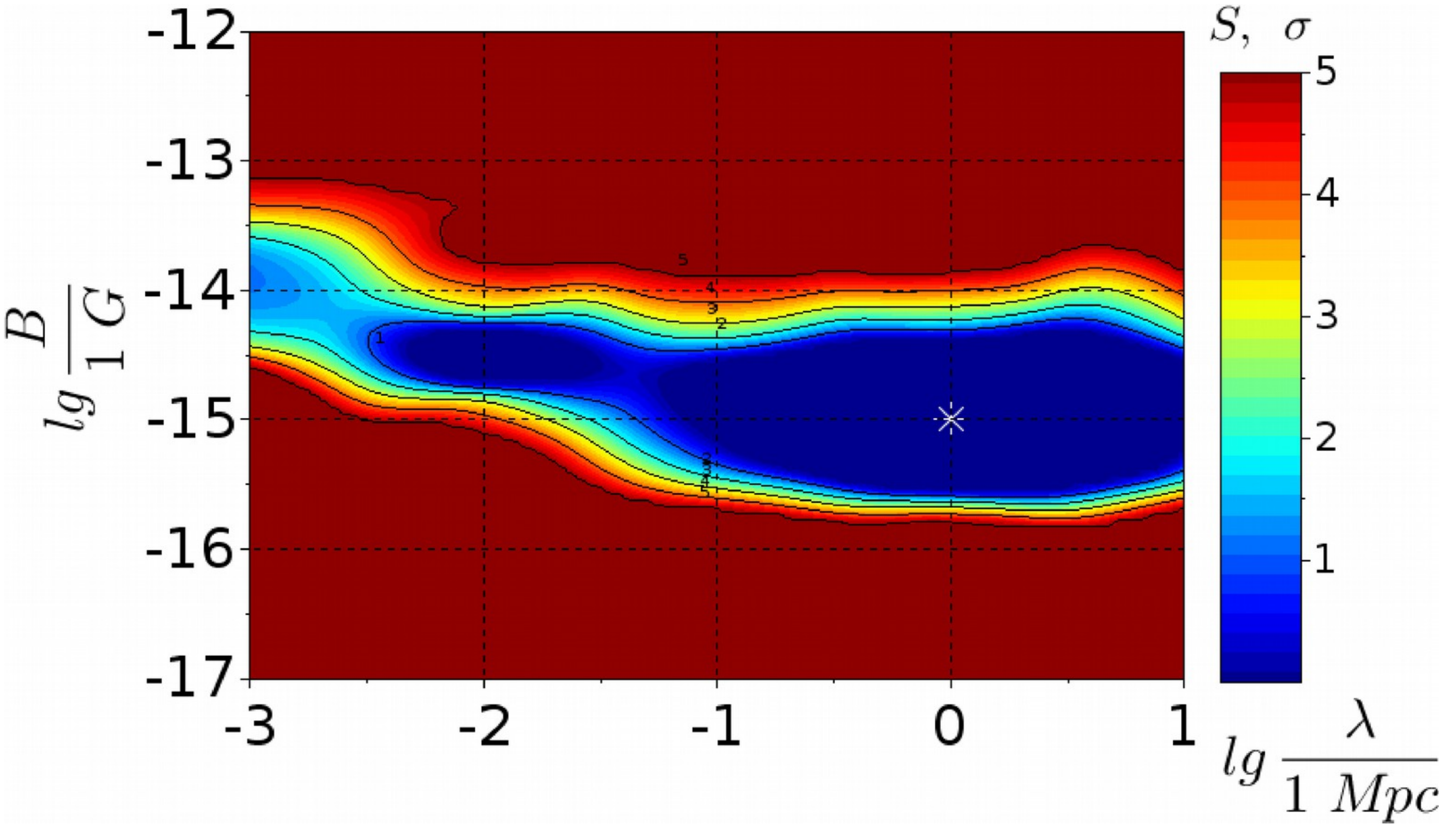


Sensitivity to the EGMF parameters: MBC method, CTA+ Fermi LAT

1) Limited sensitivity to correlation length

2) Angular information is significant!

3) For weak EGMF (~1 fG; 1 Mpc) Fermi LAT data are significant!



Conclusions (1)

1. No evidence for strong (0.1 pG) EGMF in voids from Fermi LAT so far, even for stable sources. Intergalactic cascade models are still alive!

2. The development of EM cascades from primary protons/nuclei does not modify the effective opacity of the Universe significantly.

3. The development of EM cascades from primary γ-rays may, in principle, qualitatively explain all known “anomalies”. “Extreme” versions of this model are testable with CTA!

Conclusions (2)

4. While measuring EGMF:
a) Constraining the correlation length is difficult
b) Angular information is significant
c) For weak EGMF (~1 fG) CTA should be supplemented by a space-based telescope such as Fermi LAT.

Additional slides

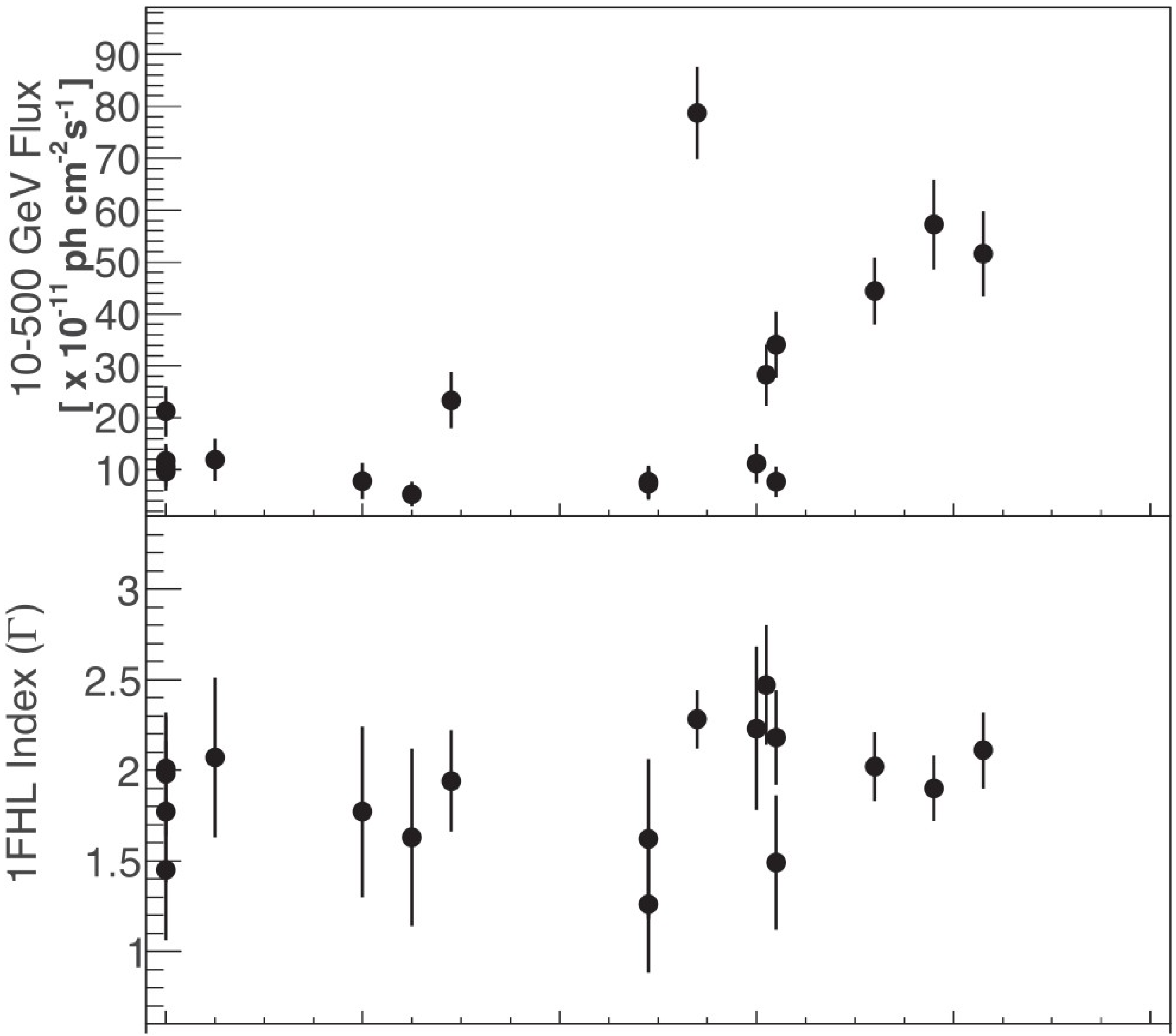
Things to explain:

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

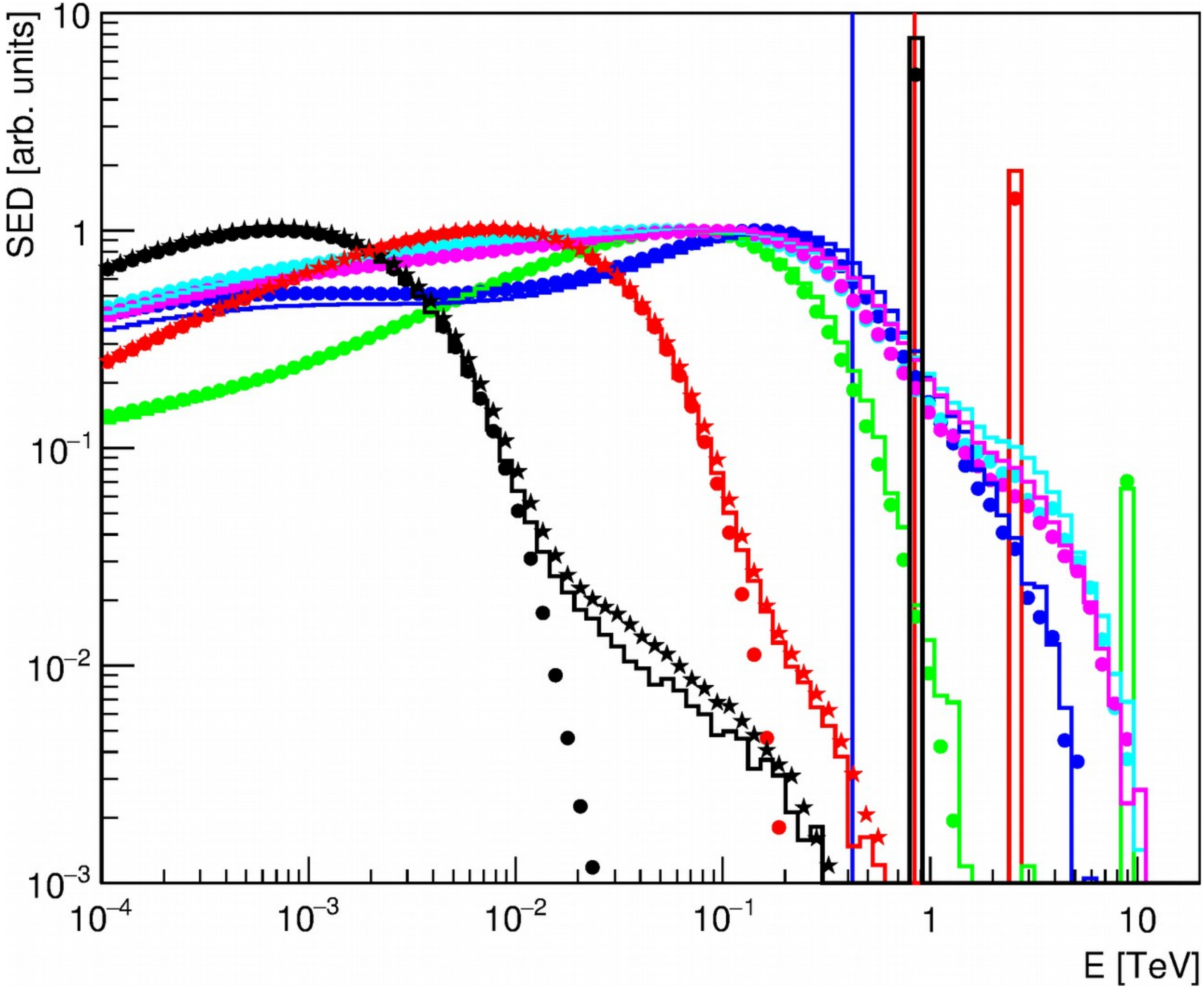
2) ~2-4 times higher flux of some blazars pointing towards the voids (indication for intergalactic EM cascade?) (Furniss. et al., MNRAS, **446**, 2267 (2015))

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))

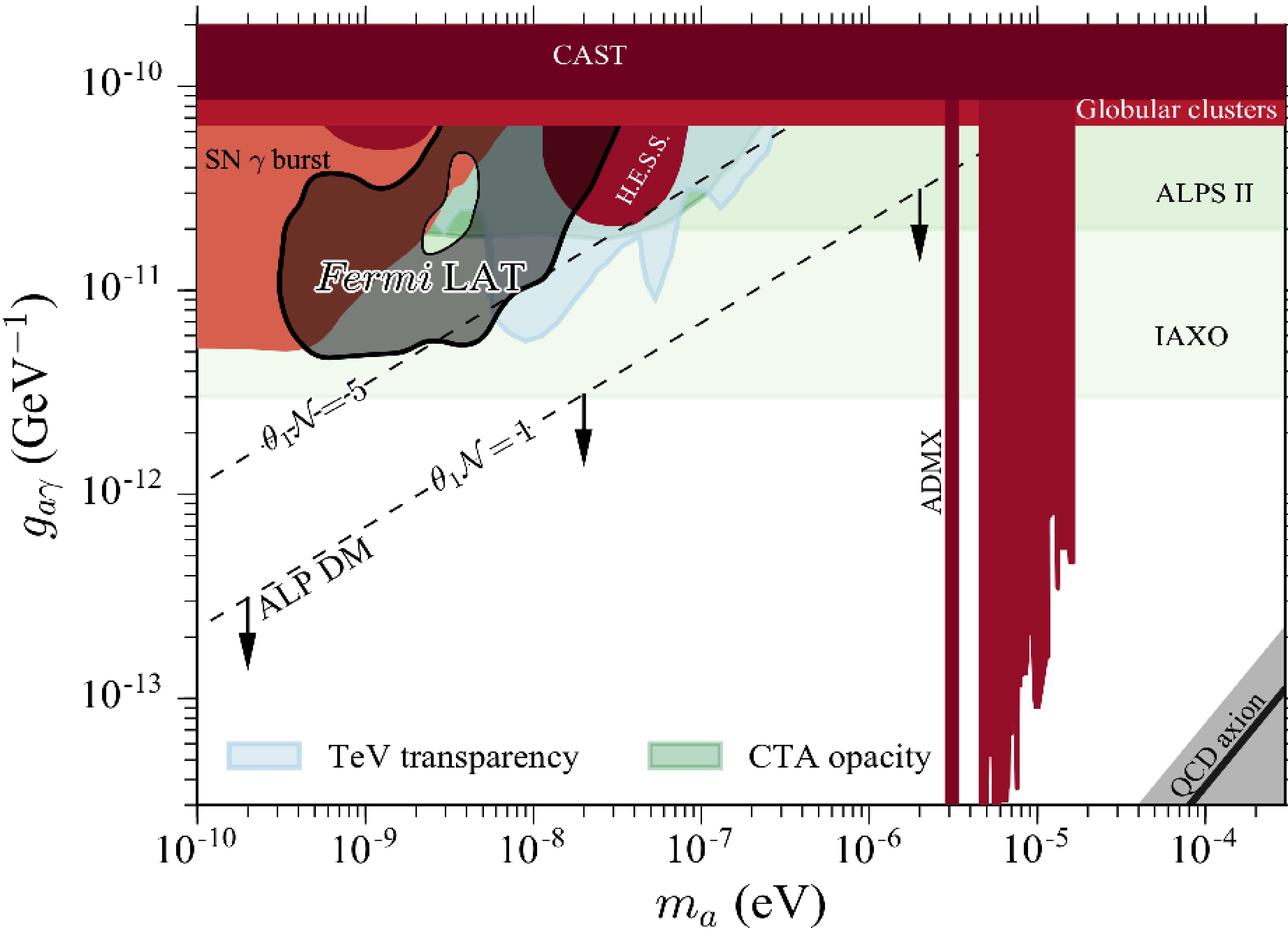
In these cases, observed flux is usually much higher (F15, significance ~2.5 σ); x: voidiness runs from 0 to 1. EGMF-dependent effects?



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



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



Point spread function (PSF) width for various instruments