Intergalactic electromagnetic cascades from extreme TeV blazars

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Based on:
Dzhatdoev et al., astro-ph/1810.06200 (2018)
Dzhatdoev et al., astro-ph/1808.06758 (2018)
Dzhatdoev et al., A&A, **603**, A59 (2017)
https://github.com/timur1606/Cascade-Masquerade/blob/master/Cascade-Masquerade-2017.zip
and some other papers

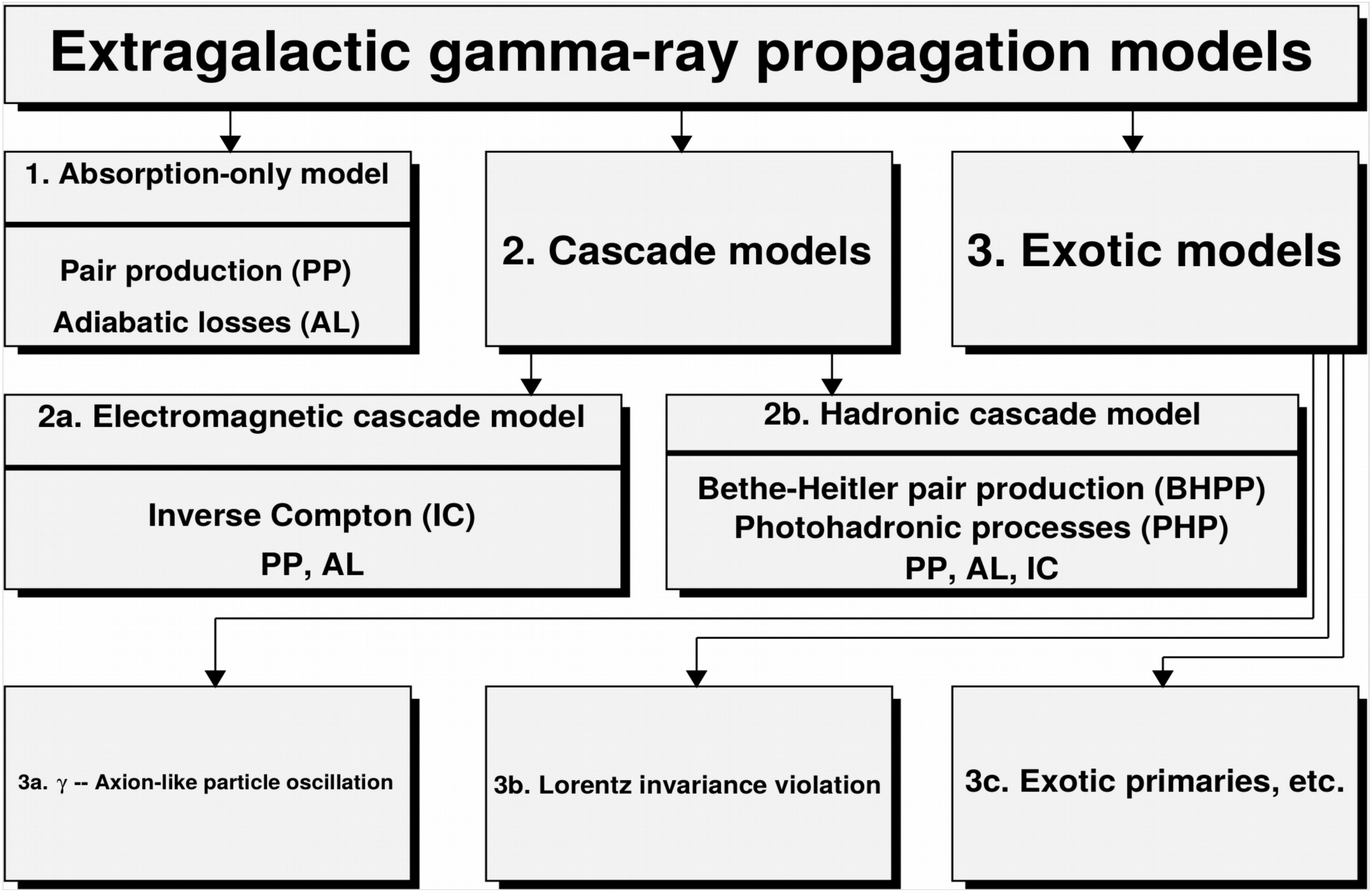
Rationale

Where the observable γ-rays were produced: inside the object (local magnetic fields/photon fields dominate) or outside the object (EGMF/(EBL+CMB) dominate)?

What are the signatures of intergalactic electromagnetic cascades in observable spectral, energy, and time distributions?

What to look for?
What had changed since the Torino conference (June 2018)?
For this talk z= 0.186 unless stated otherwise

Most cascade calculations were done with the following three codes:
1) ELMAG (Kachelriess et al., (2012))
2) ECS (Dzhatdoev (2017))
3) Fitoussi et al. (2017)


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.

“Extreme TeV blazars” (ETBs) are those that have the absorption-only model intrinsic (i.e., reconstructed) SED peaked at E>1 TeV

cf. “extreme Compton Bl Lacs” → ETB is a less interpretation-dependent definition

Our dataset

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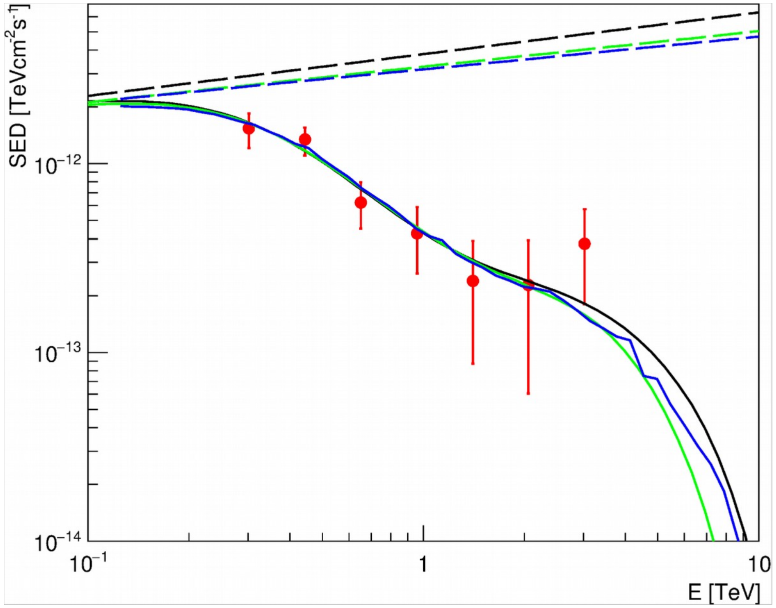
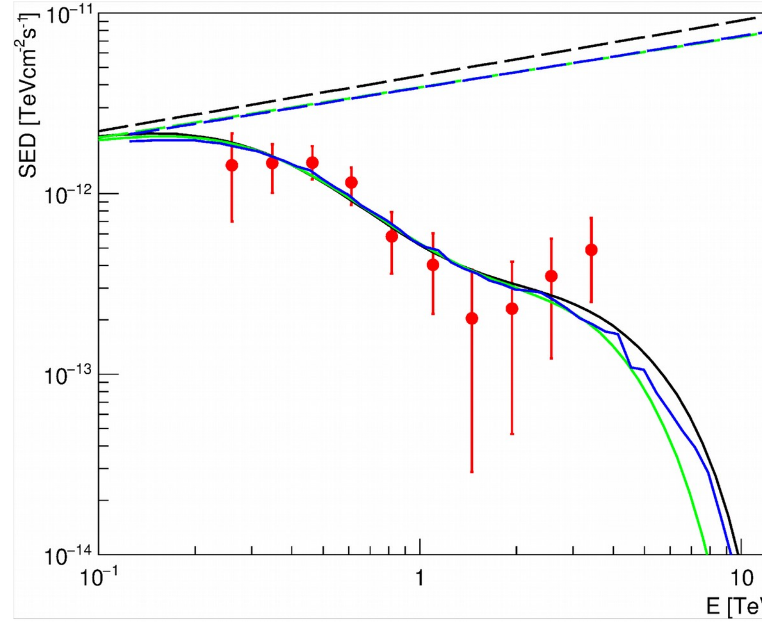
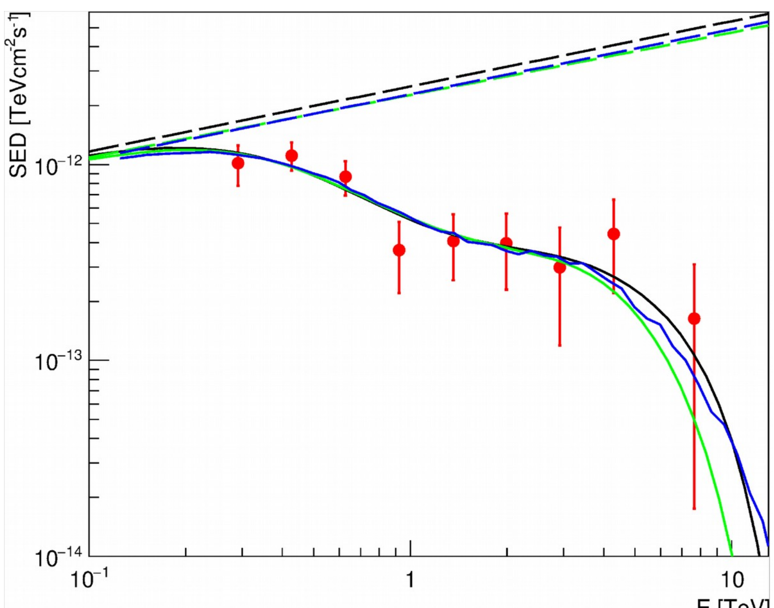
1ES 0347-121



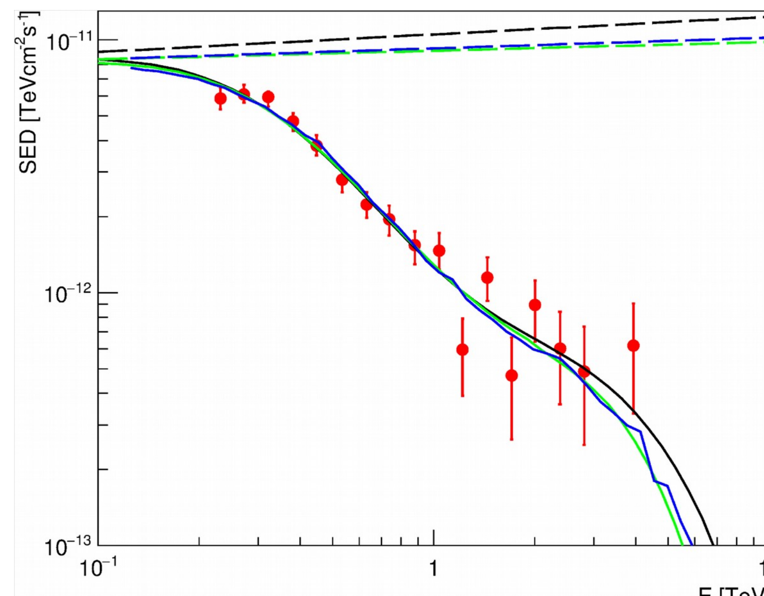
1ES 1101-232



1ES 0229+200



1ES 1218+304

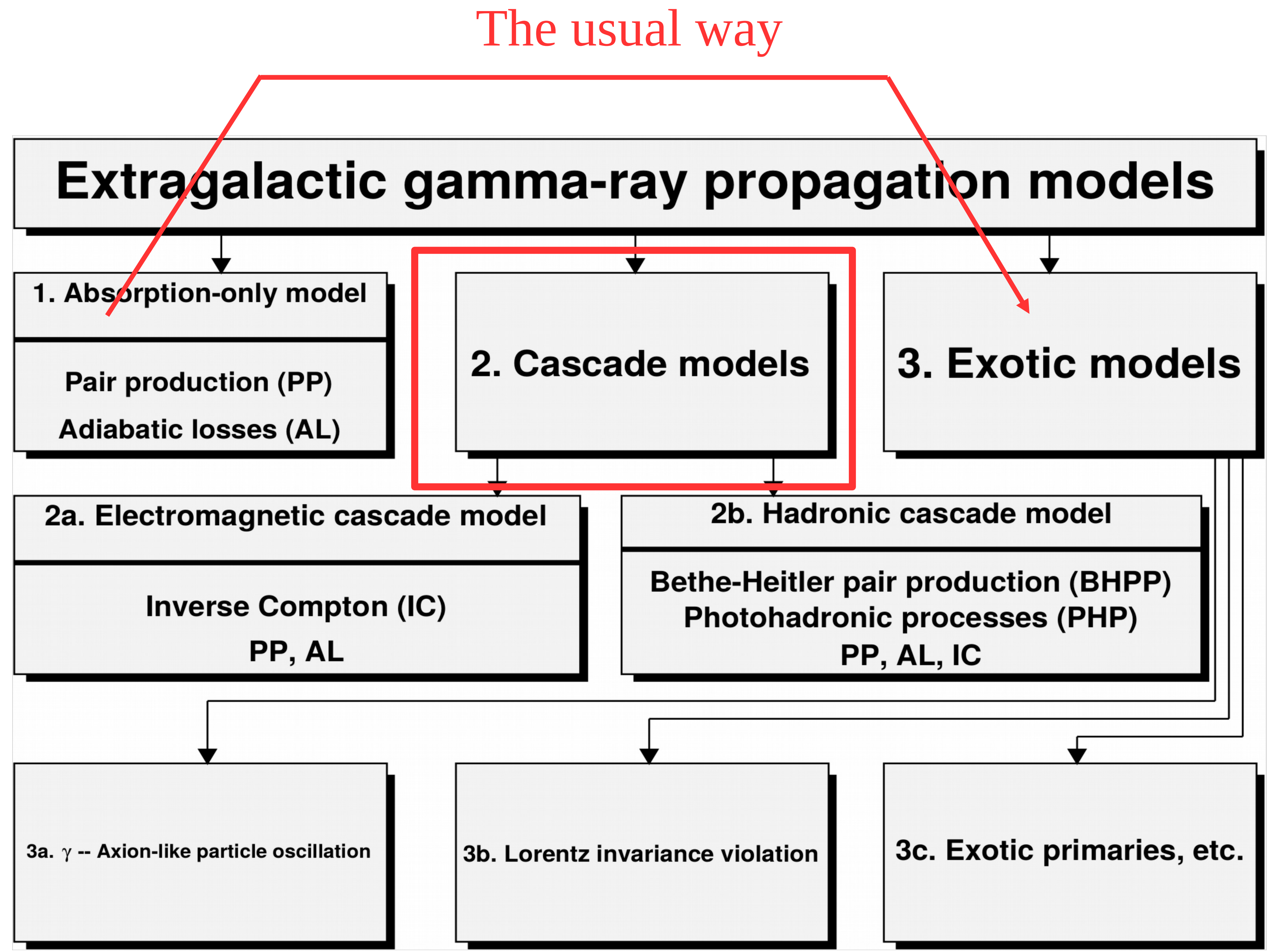


EBL models: Gilmore et al. (2012) (black); Franceschini et al. (2008) (green); Kneiske & Dole (2010) as implemented in the ELMAG code (blue)

Is the absorption-only model sufficient?

Korochkin et al., astro-ph/1810.03443 (2018):
“The result of the present study **supports** previous claims of distance-dependent hardenings in spectra of VHE gamma-ray blazars, corrected for the pair-production attenuation with conservative EBL models. Absence of these hardenings is excluded with the statistical significance of 4.5σ.”
cf. Horns & Meyer (2012); Rubtsov & Troitsky (2014)
but see Biteau&Williams (2015); Dominguez&Ajello (2015)
Note that e.g. the two-hump EBL SED structure is accounted for in all these studies!

Other “anomalies”: Chen et al. (2018) (2015); Furniss et al. (2015)) may be explained by the appearance of EM cascade component at GeV energy



The usual way
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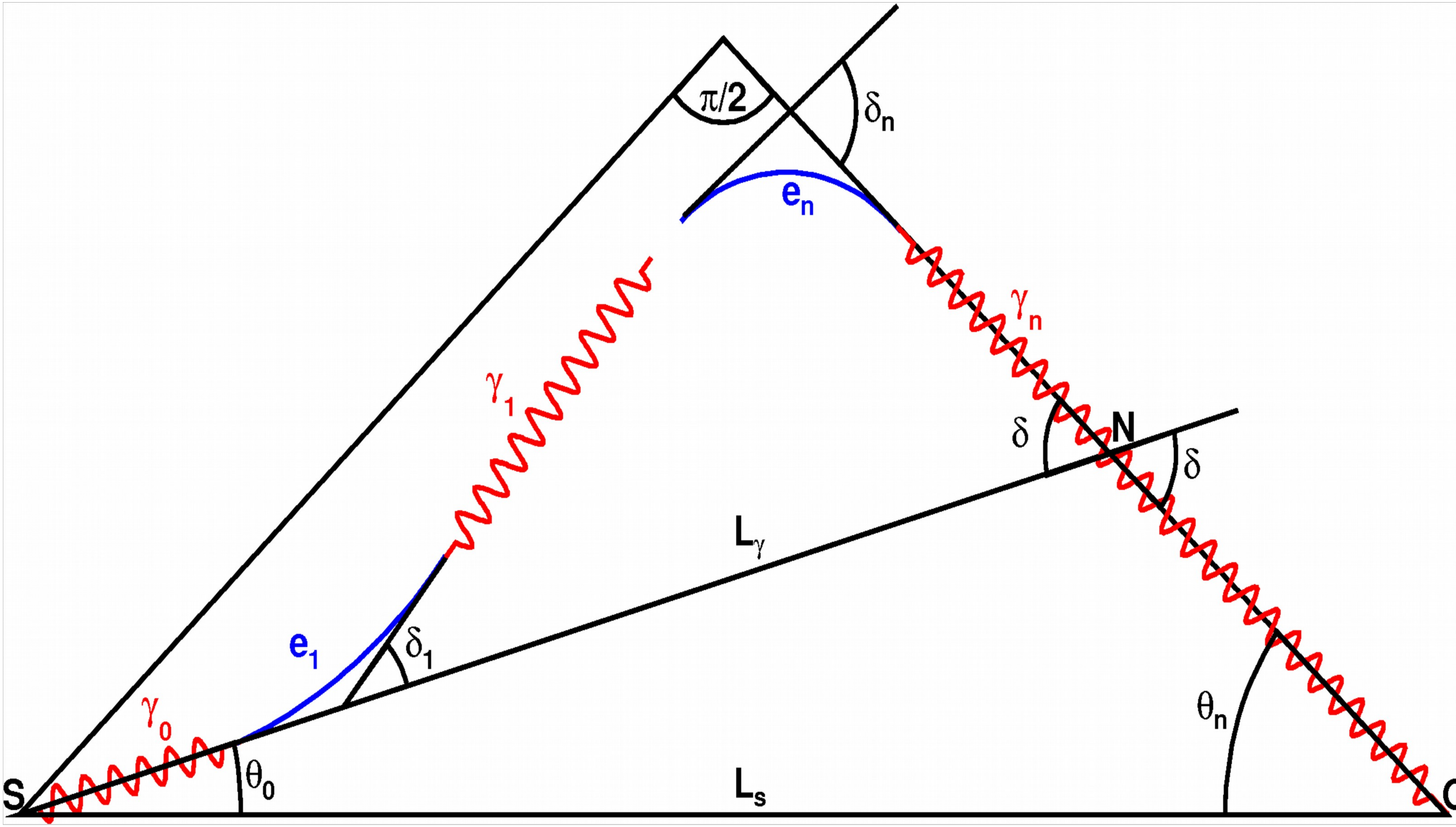
Time delay (~time variability). Isolated flares are not very helpful!

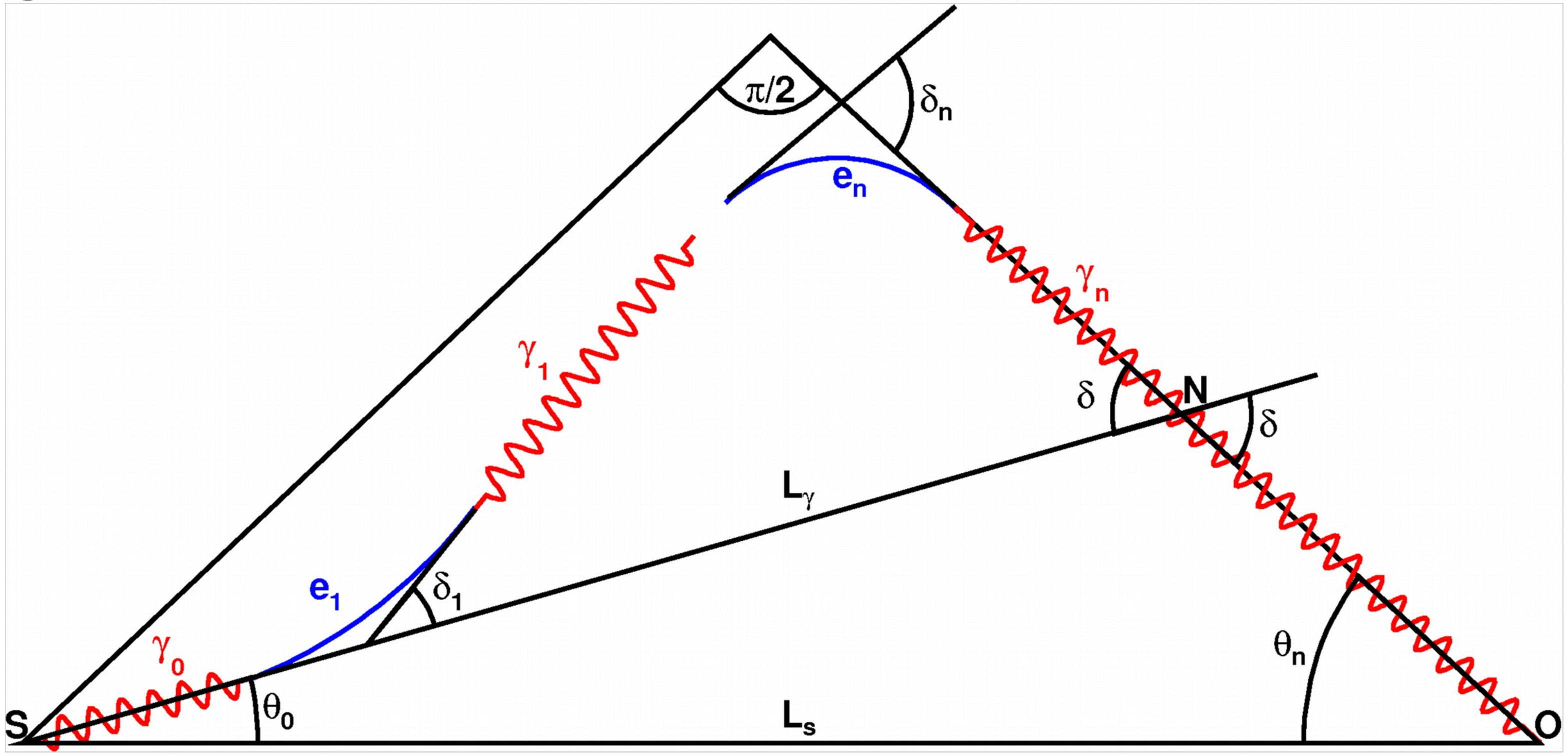


$$\delta t \approx \frac{L_\gamma}{2c}\left(1 - \frac{L_\gamma}{L_s}\right) sin^2\delta$$

Electron deflection angle
~300X(B/1 [aG])X(E[TeV])$^{-1}$ μrad
Time delay ~months-years

Intergalactic hadronic cascade model (HCM)

Primary
protons/nuclei

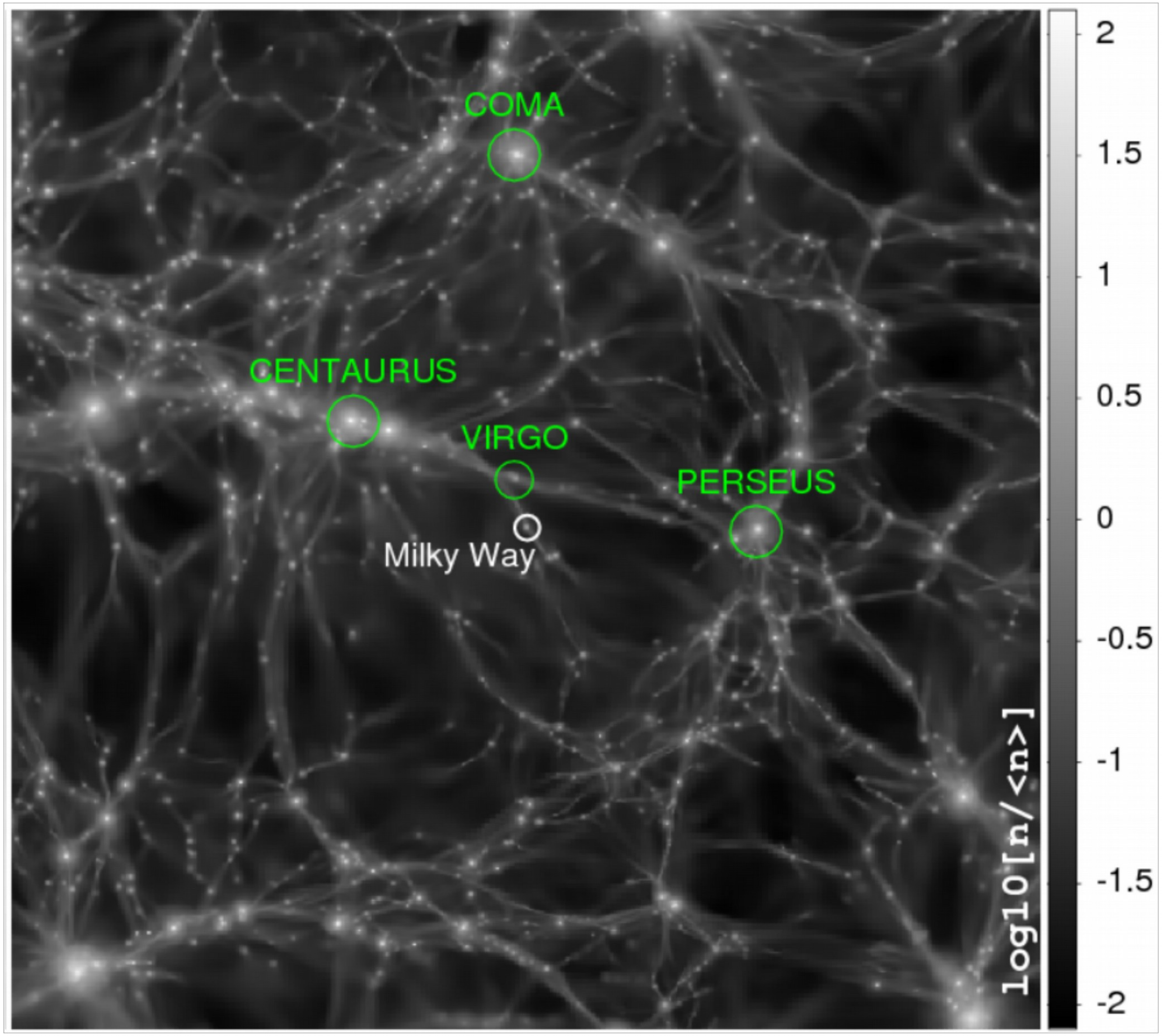


Waxman & Coppi, ApJ Lett., **464**, L75 (1996); Uryson, JETP, **86**, 213 (1998); Essey & Kusenko, APh, **33**, 81 (2010); Essey et al., Phys. Rev. Lett., **104**, 141102 (2010); Essey et al., ApJ, **731**, 51 (2011) (E11); Murase et al., ApJ, **749**, 63 (2012); Takami et al., ApJ Lett., **771**, L32 (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 induce the high-energy anomaly

A slice of large-scale EGMF at least every 50 Mpc!

(Hackstein et al., 2018) → one or several degree deflection of UHE protons

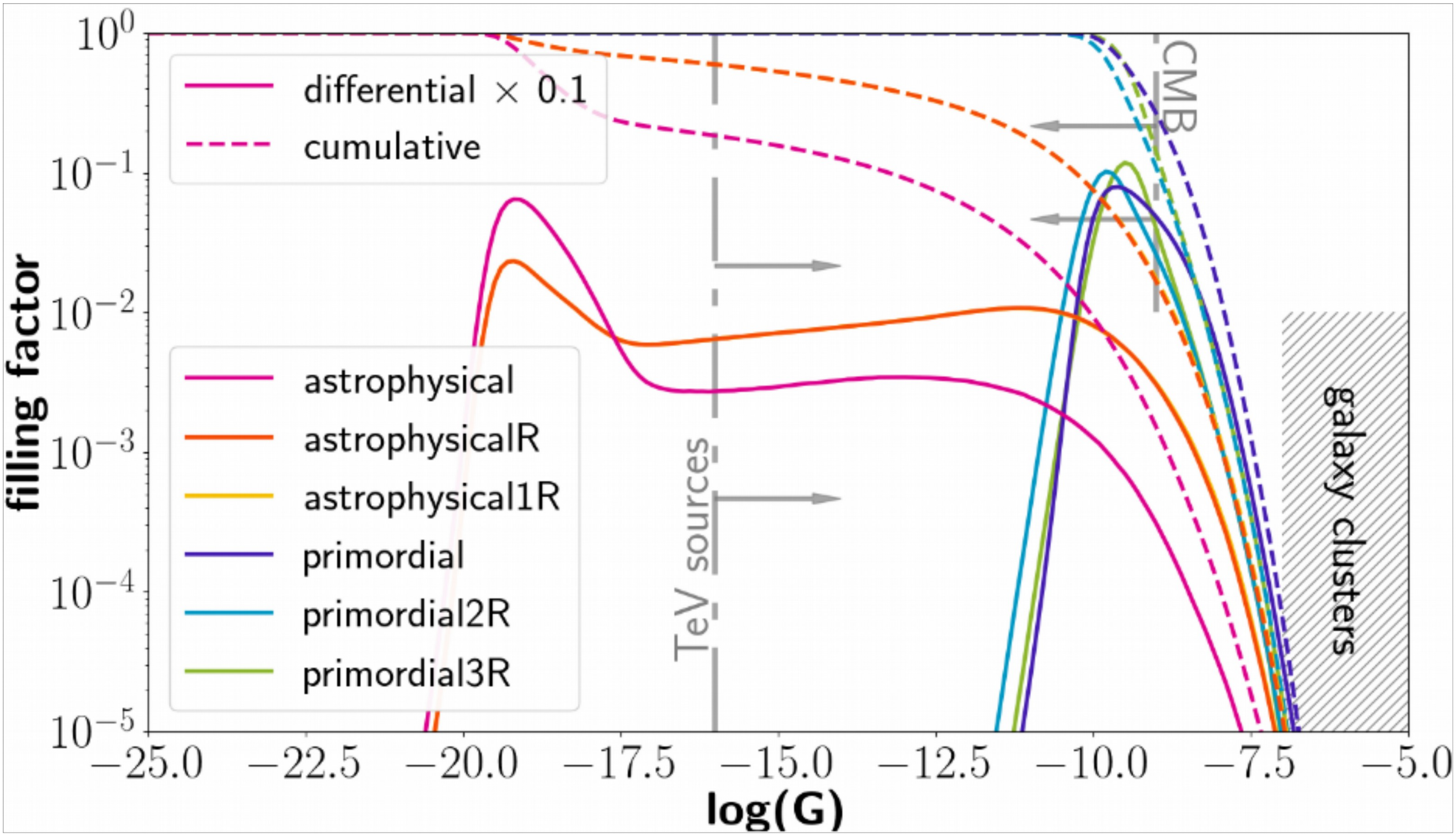


$$\delta \simeq \frac{BZe}{E}\sqrt{\frac{Ll_c}{2}} \simeq 1^\circ \frac{B}{\mathrm{nG}} \frac{40\ \mathrm{EeV}}{E/Z} \frac{\sqrt{Ll_c}}{\mathrm{Mpc}}$$

(Harari et al., 2016)

EGMF volume filling factor
(Hackstein et al., MNRAS, **475**, 2519 (2018))

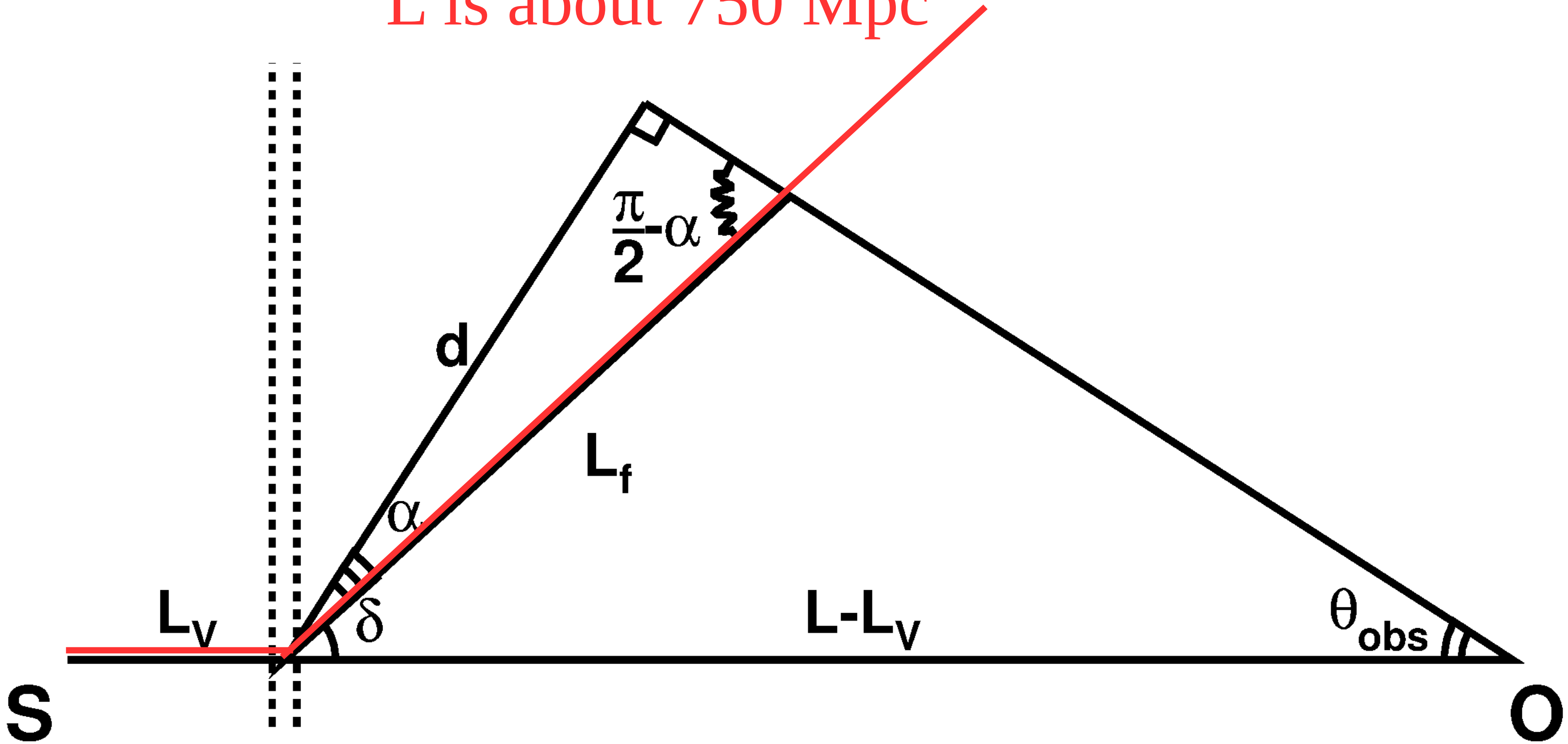
cf. Dolag et. al. (2005); Sigl et al. (2003)



The width of the observable angular distribution

(Dzhatdoev et al., astro-ph/1810.06200 (2018));

L is about 750 Mpc



$$\theta_{obs} \approx \frac{\delta \cdot L_f}{L - L_f - L_V} = \delta \frac{L_{int} - L_V}{L - L_{int}}$$

L_{int} = 100 Mpc → 0.08 deg.

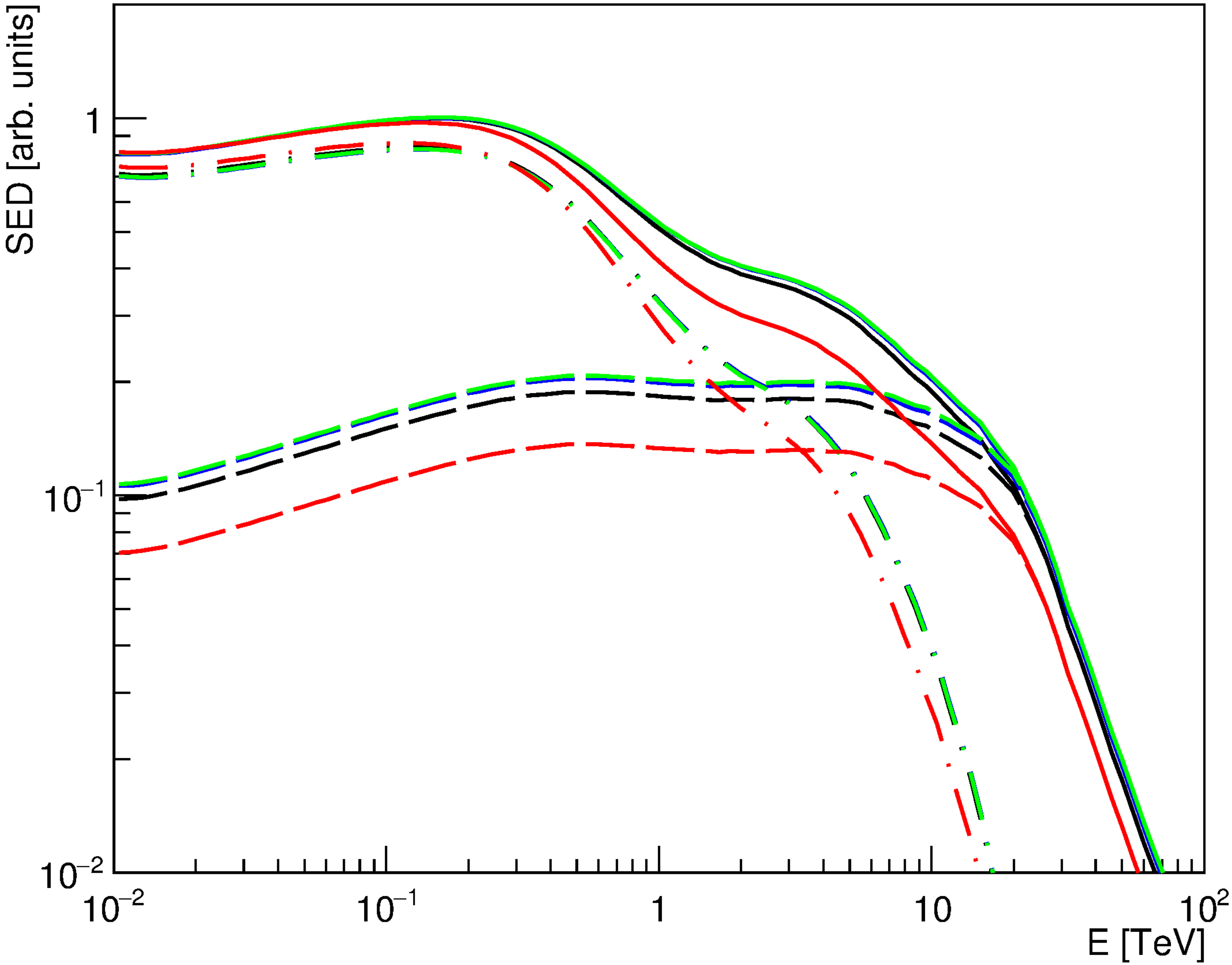
L_{int} = 200 Mpc → 0.27 deg

L_{int} = 500 Mpc → 1.8 deg

To compare: 0.1 deg (IACT PSF)

HCM: breakdown of the spectra on production z: z<0.03 (hard spectra); z<0.03 (soft spectra); also shown is the sum of the two components

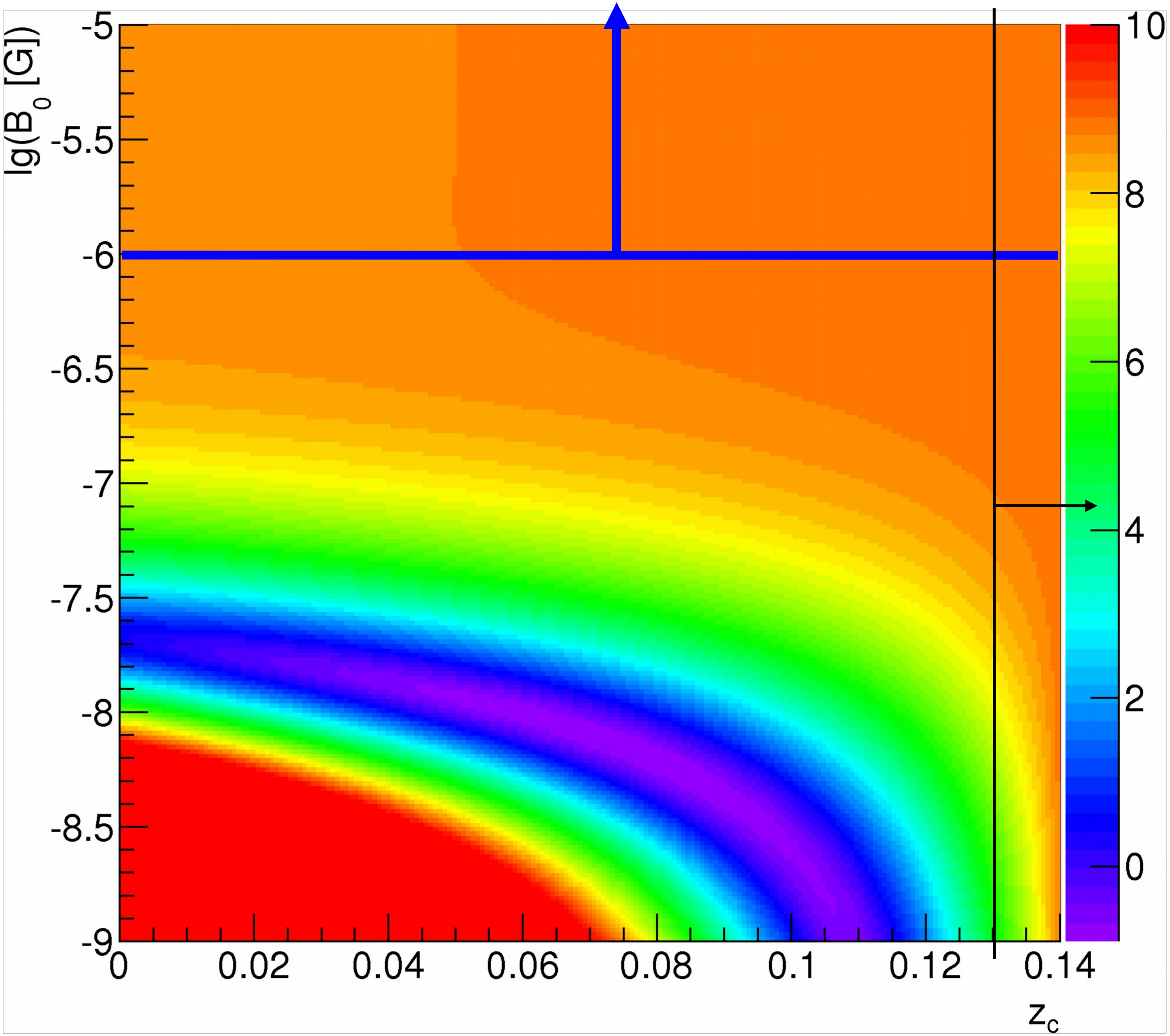
E_0= 10 PeV, 30 PeV, 50 PeV, 100 PeV



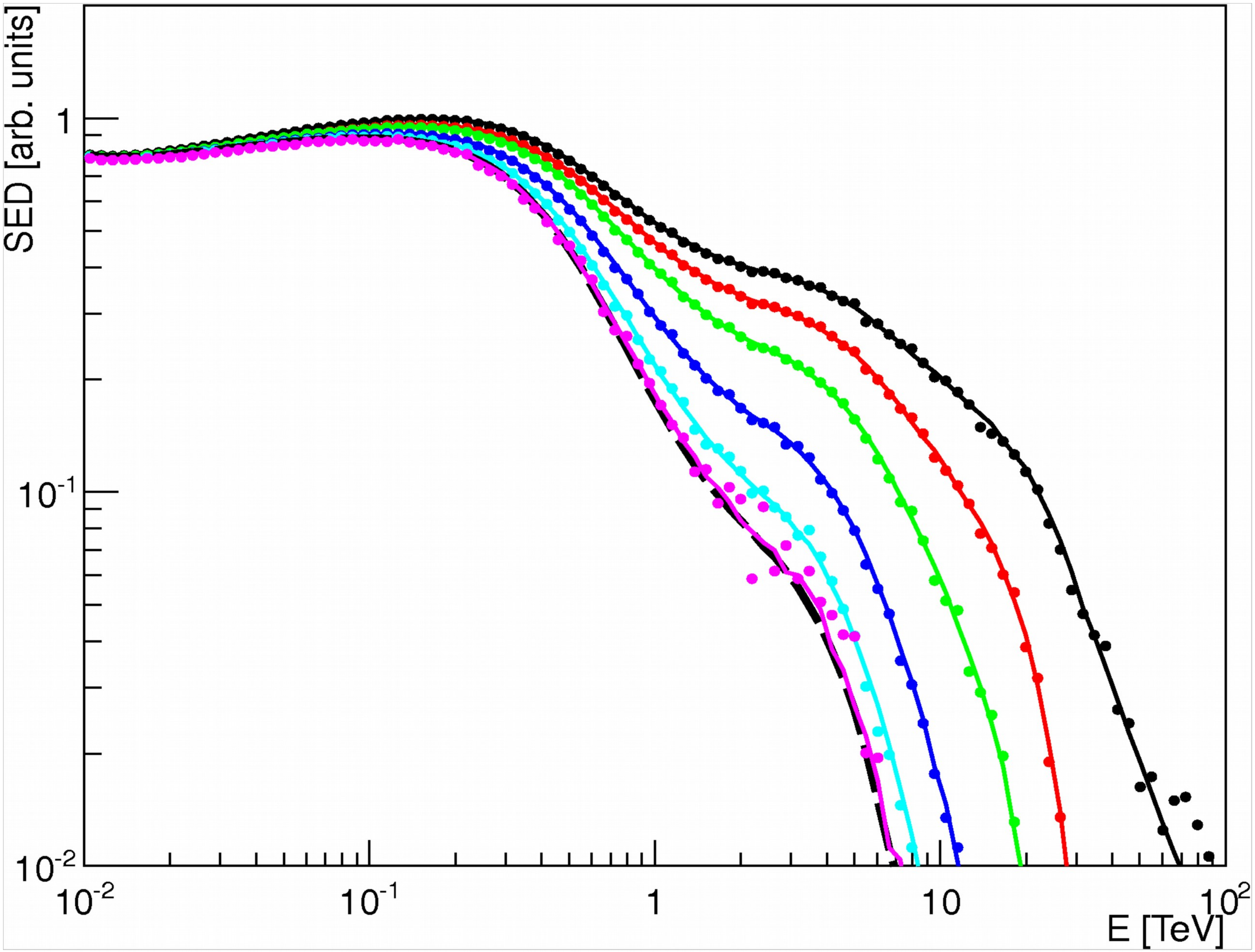
The hard component is twenty or more times as wide as the PSF(!!)

If this is a robust result (?!?!)
1. Heavy primary nuclei → still stronger deflections
2. Plasma losses (Broderick et al. (2012)) → suppression of cascade flux → still harder to observe
3. Synchroton losses → suppression of cascade flux → still harder to observe
4. Additional intrinsic component → the normalisation of the cascade component is still lower → still harder to observe
5. Blandford-Znajek process (Blandford & Znajek (1977)) → huge internal flux of curvature and synchrotron photons → the normalisation of the cascade component is still lower → still harder to observe
6. Internal magnetic fields → defocusing of the proton/nuclei beam → still harder to observe
7. Neutron production inside the source → huge internal flux of photohadronic γ-rays and electrons → the normalisation of the cascade component is still lower → still harder to observe
Etc., etc., etc.

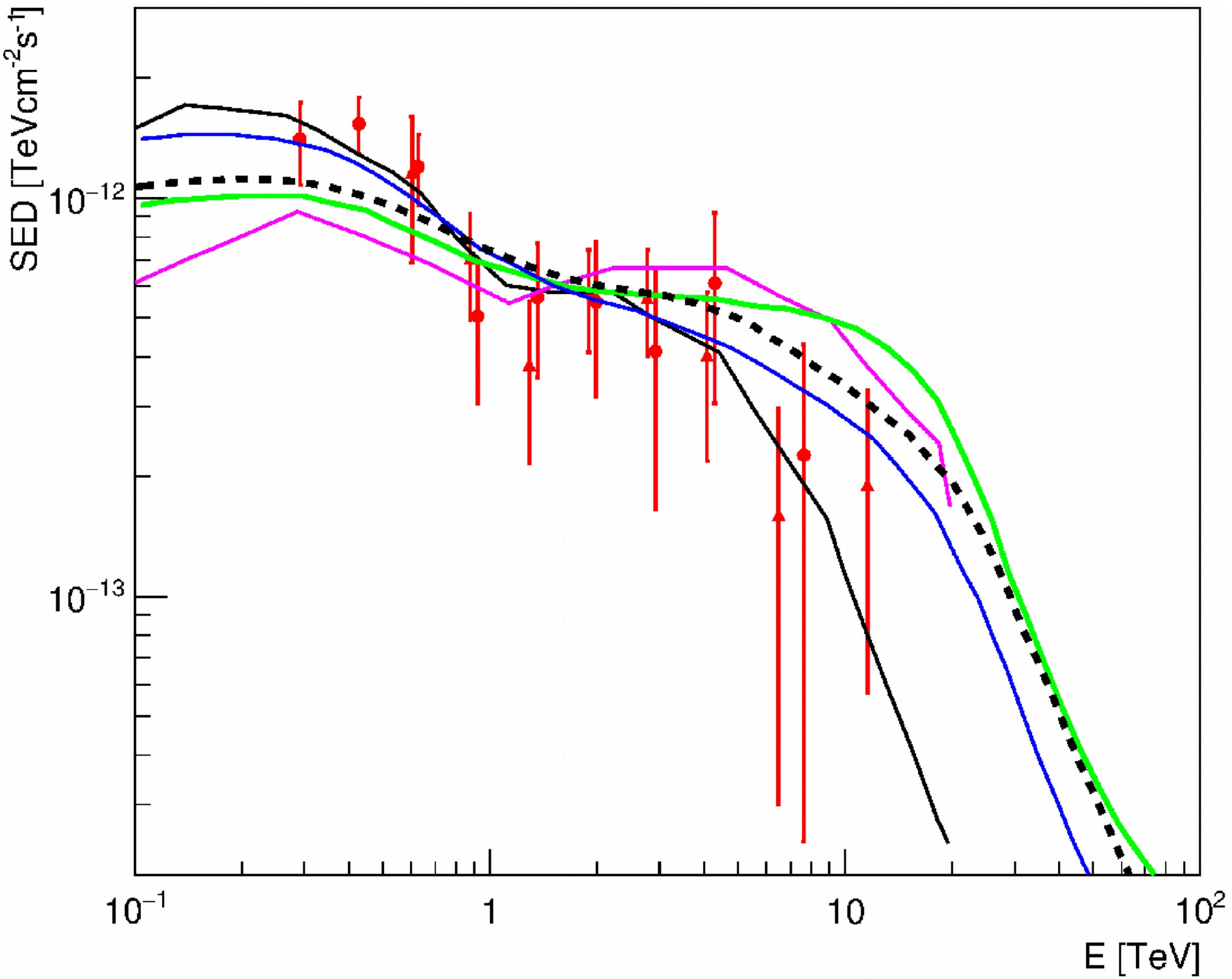
Constraints on hadronic cascade models (the case of 1ES 0229+200, z= 0.14). B_0= magnetic field strength in the center of the cluster, z_c= the termination redshift of the proton beam, in color: significance of exclusion



“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.



Comparison of simulations: Dzhatdoev et al. (2017) (dashed black) with Essey et al. (2011) (magenta, black; ~three times difference on the EBL intensity!) and Murase et al. (2012) (green,blue). With the state-of art EBL models the dependence on the EBL model would be minor (~10-20 %)



Any background for γ-ALP oscillation from (purely) EM cascades??!!

Motivation:

primary spectrum is not known (Abdo et al. (2011); Neronov et al. (2012); Shukla et al. (2016)), especially for the case of “extreme TeV blazars”

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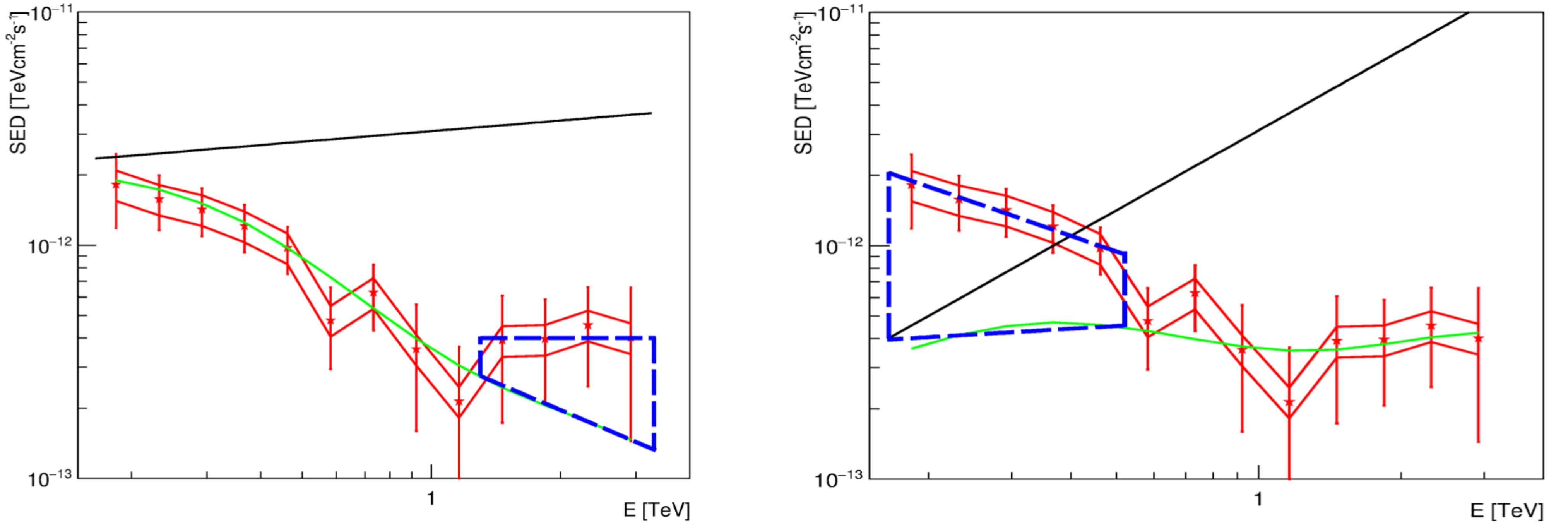
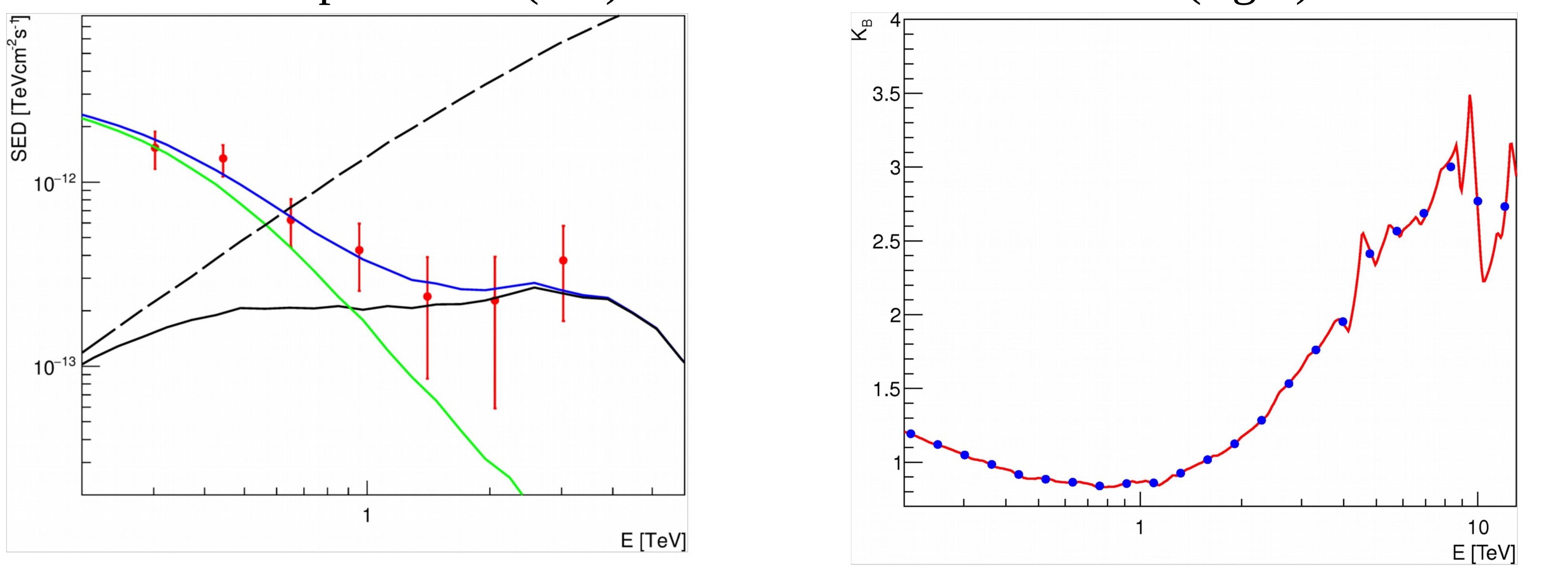
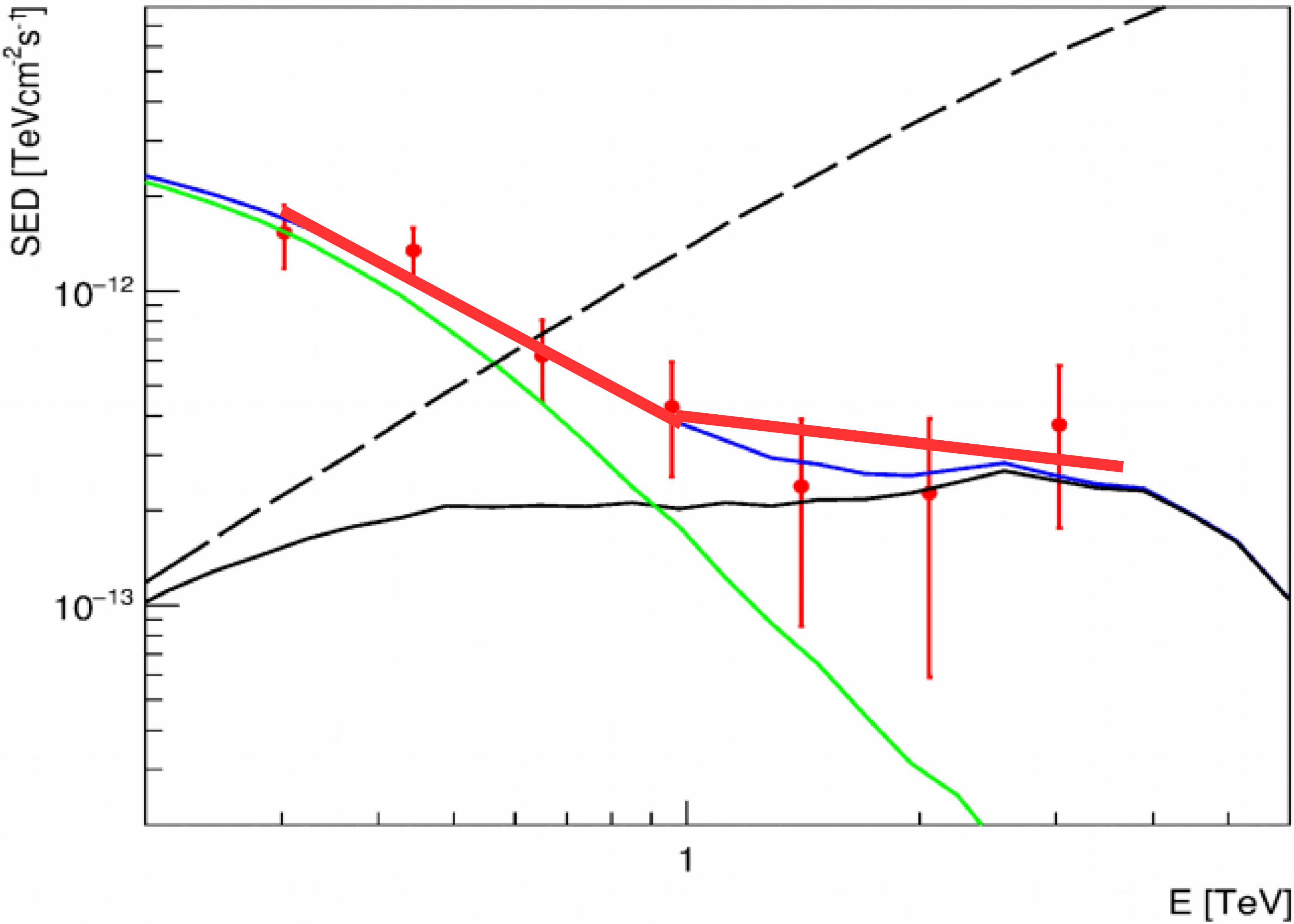
The high-energy (left) and low-energy (right) excess options



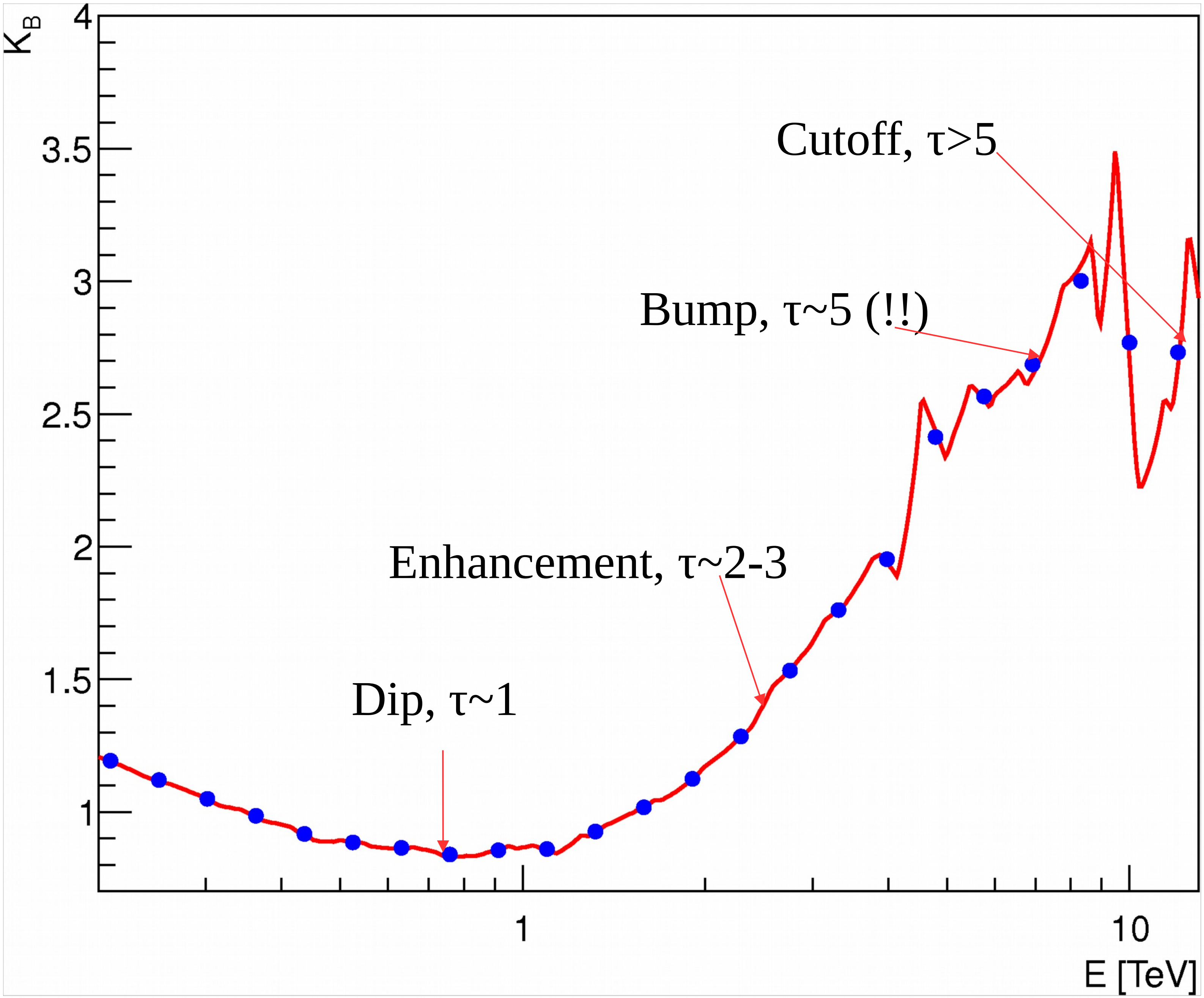
The spectral fit (left) and the modification factor (right)



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 (1000 h): stat. uncertainty 10 % at 3 TeV, 40 % at 6 TeV



Conclusions

1. What to look for if we want to find signatures of intergalactic EM cascades in extreme TeV blazar observations? A probable answer: look to the observable angular distribution (and the spectrum, of course!).

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

3. If the anomaly is present, redshifts and EBL models are correct, and no new physics is in operation , then it is a signature of low EGMF in voids (<0.1-1 fG) together with very hard intrinsic spectra. In this case the previously neglected effect --- "electromagnetic cascade masquerade" --- is in operation.

4. On the bright side: great promise for axion-like particle search with the CTA experiment!

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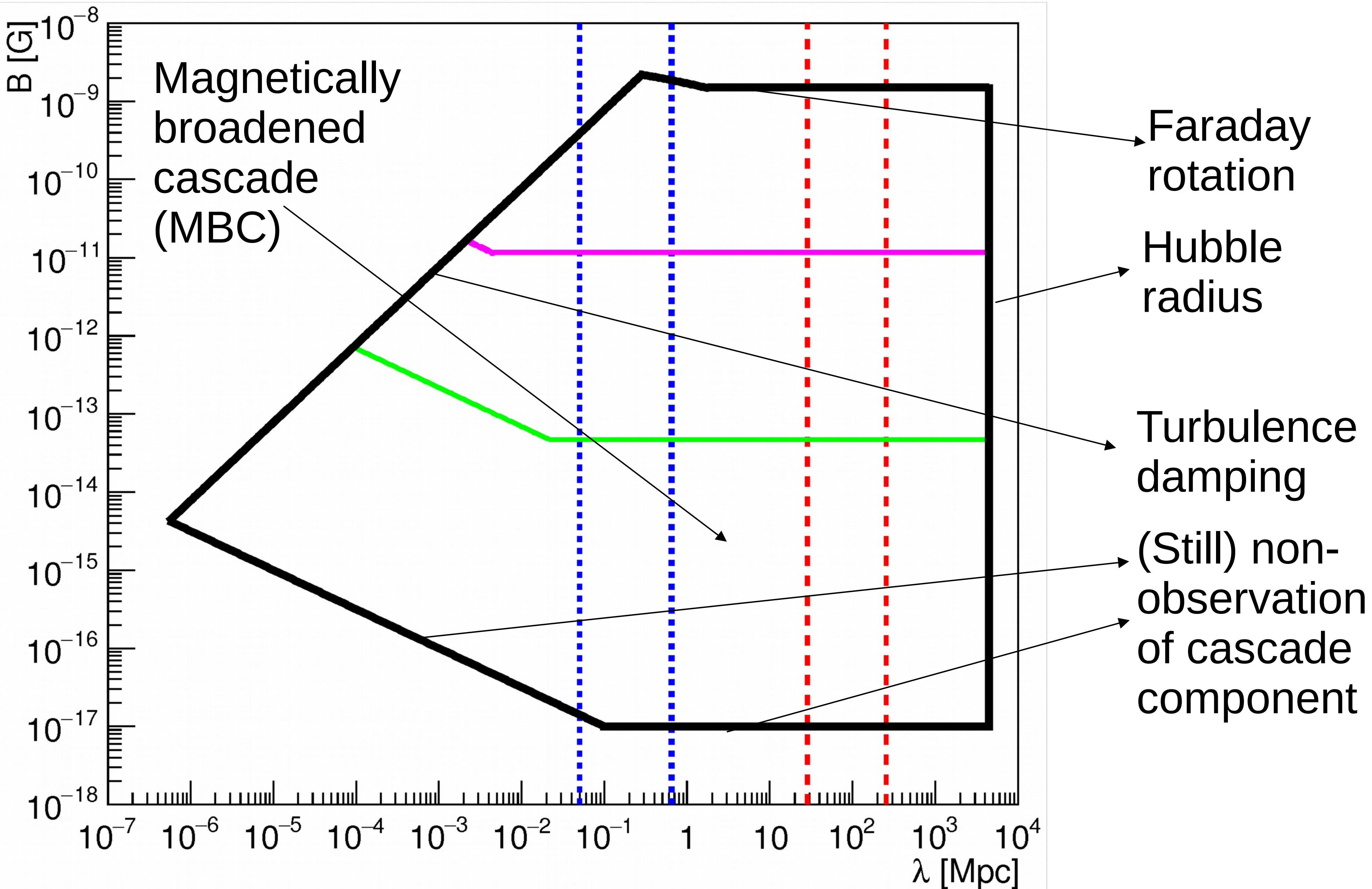
This work was supported by the Russian Science Foundation (project No 18-72-00083)

Additional slides

EGMF constraints following Durrer & Neronov (2013) and the main regimes of intergalactic EM cascade development



Many claims of strong constraints/detection inside the black frame

Some works that consider constraints on the EGMF

Blasi et al. 1999; Pshirkov et al. 2016 --- Faraday rotation

Dolag et al. 2005 --- galaxy cluster simulations

Neronov & Vovk 2010; Dermer et al. 2011; Taylor et al. 2011; Vovk et al. 2012; Abramowski et al. 2014; Takahashi et al. 2012, 2013; Finke et al. (2015); Arlen et al. (2014); Tashiro & Vachaspati (2015) --- intergalactic EM cascades

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: Abdo et al. (2011). Shukla et al. (2016): ~20 episodes of hard-spectra, high significance