Suppressing astrophysical backgrounds for gamma→ALP searches in extreme blazar spectra

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НИИЯФ
МГУ

TeVPA 2019
Sydney

Ingredients to our story

1. Once upon a time
2. The hero
3. The villain
4. The preparation
5. The fight
6. Happily ever after

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1. Once upon a time – intergalactic gamma-ray propagation models
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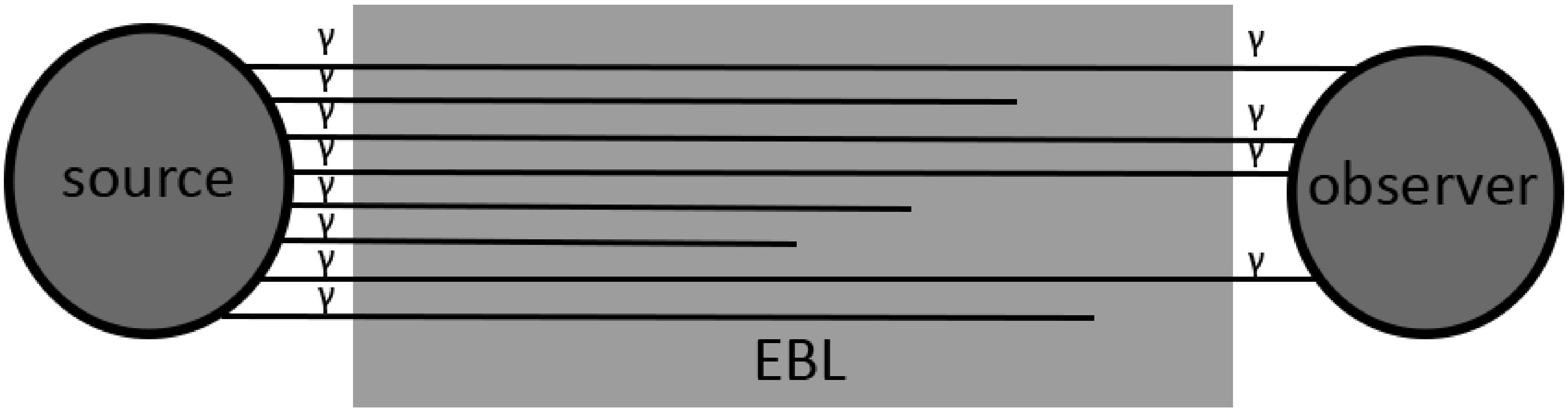
Absorption-only model



Beyond the absorption-only model

Korochkin, Rubtsov & Troitsky JCAP12(2019)002:
"we disfavour the absence of anomalous distance-dependent spectral features with the modest statistical significance of 1.9σ."

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))

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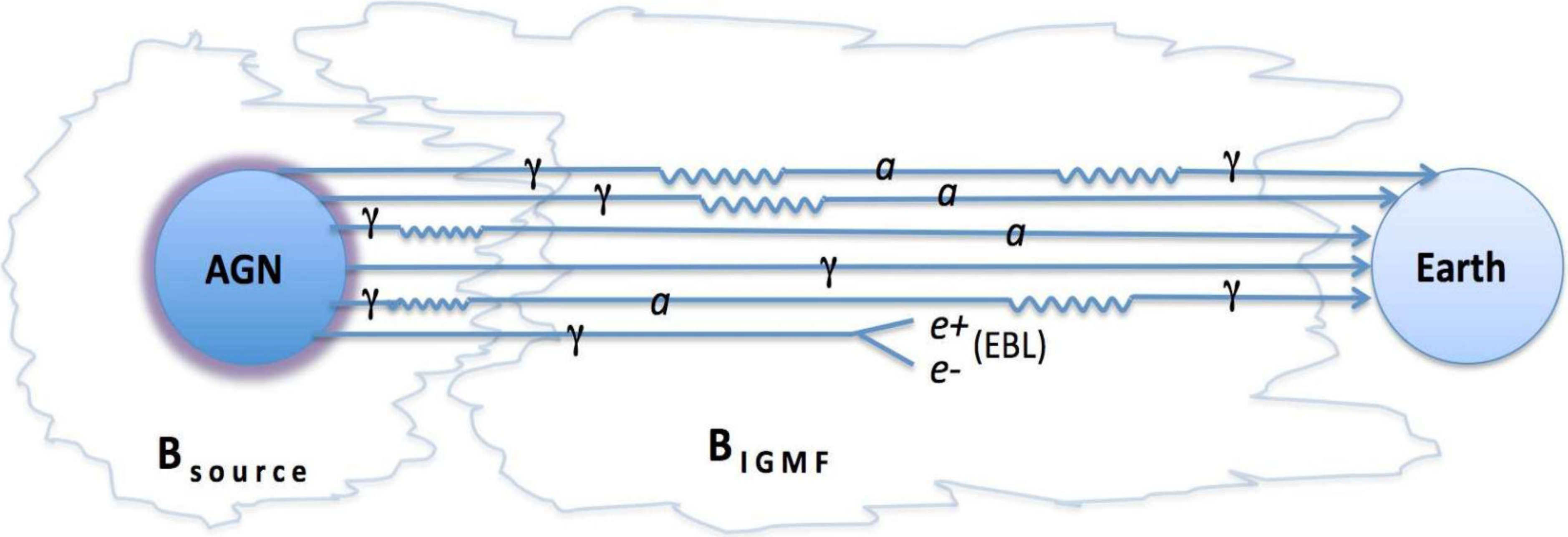
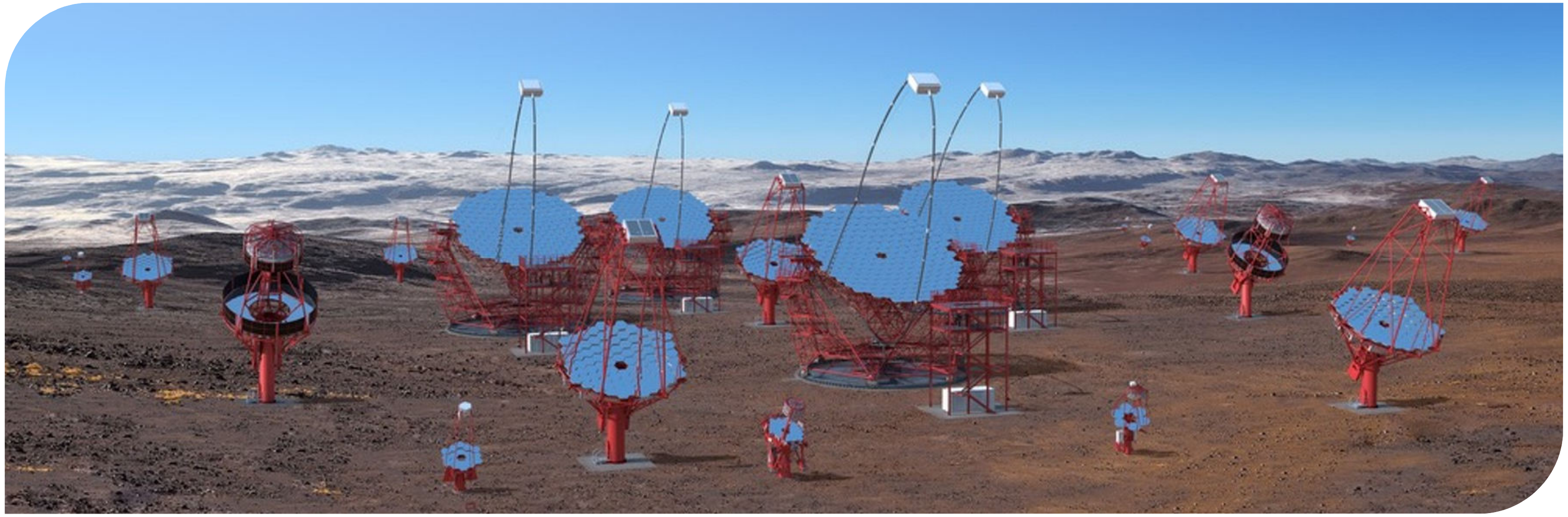
Reducing gamma-ray opacity with γ-ALP oscillations



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)

ALP search in the CTA experiment



cherenkov telescope array

Exploring Frontiers in Physics		
	3.1	What is the nature of Dark Matter? How is it distributed?
	3.2	Are there quantum gravitational effects on photon propagation?
	3.3	Do Axion-like particles exist?

Acharya et al., Aph, **43**, 3 (2013); Science with the Cherenkov Telescope Array (2019)

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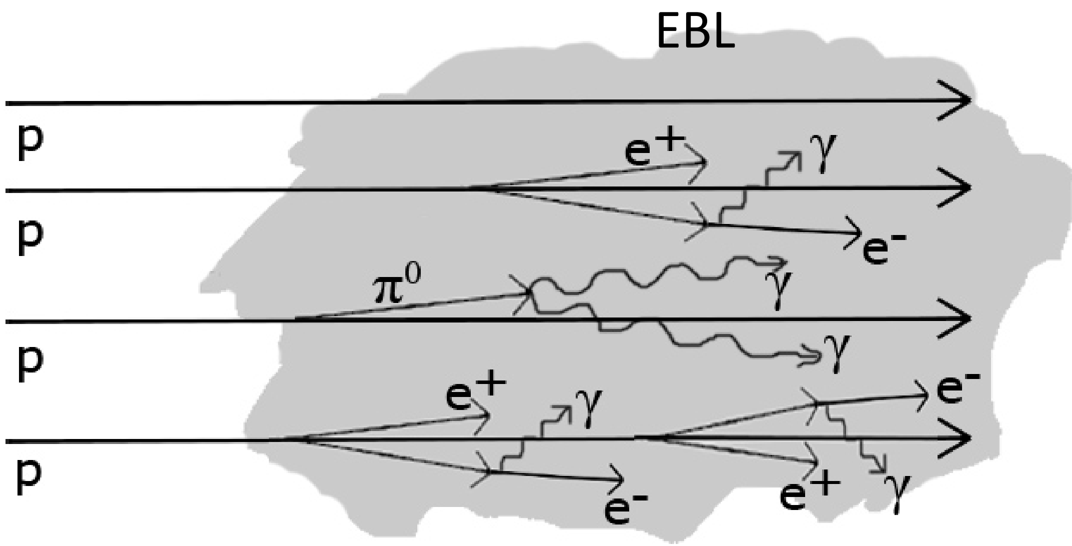
Intergalactic hadronic cascade model (IHCM)

Waxman & Coppi, ApJ, 464, L75 (1996); Uryson, JETP, 86, 213 (1998)

1. Part of observable spectrum from blazars is produced not inside the source, but as a result of EM cascade development in the intergalactic medium.

2. Primary particles are UHE CR and they continuously create secondary electrons and gamma through Bethe-Heitler pair production and photopion processes on EBL and CMB.



3. Primary protons cover more distance than primary gamma-rays and continue creating cascades even near the observer!

Electromagnetic cascade models (ECM) are studied by us in Dzhatdoev, et al., A&A, 603, A59, 2017.

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Intergalactic hadronic cascade model (IHCM)

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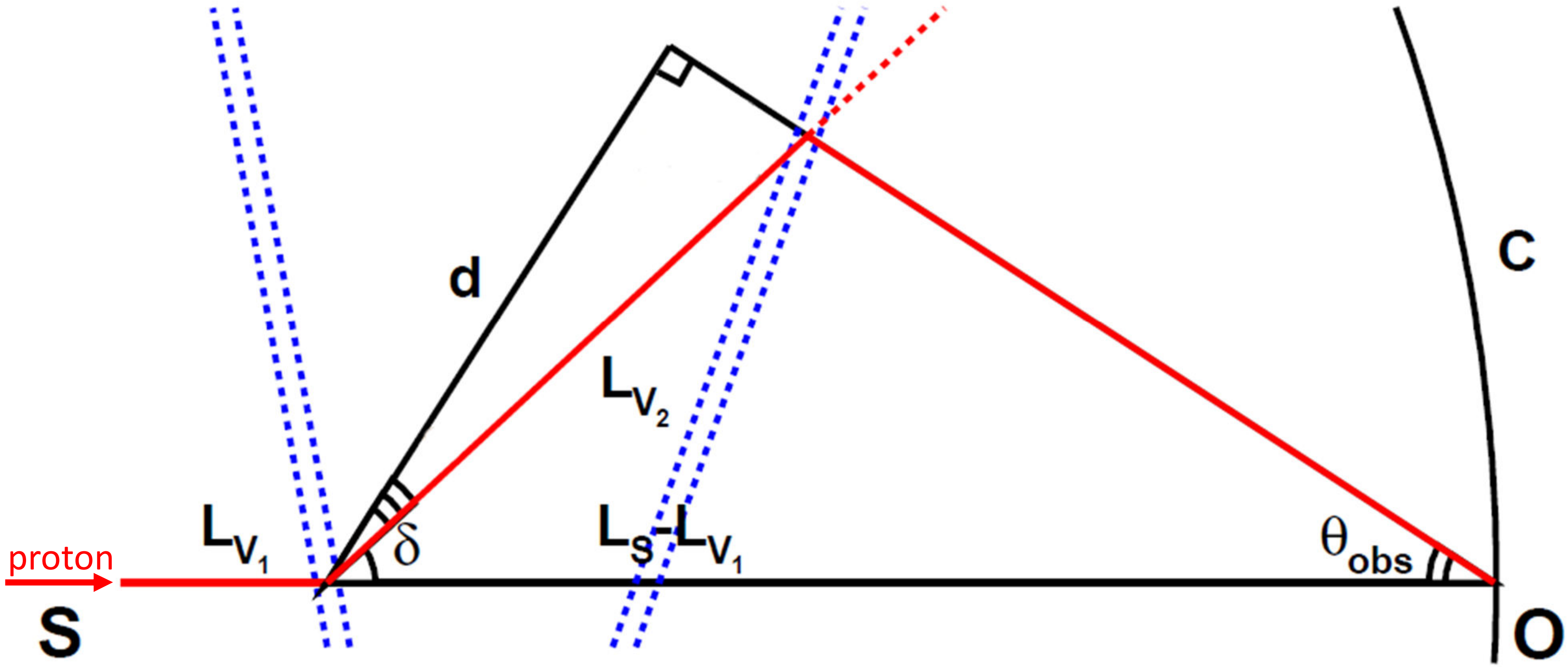
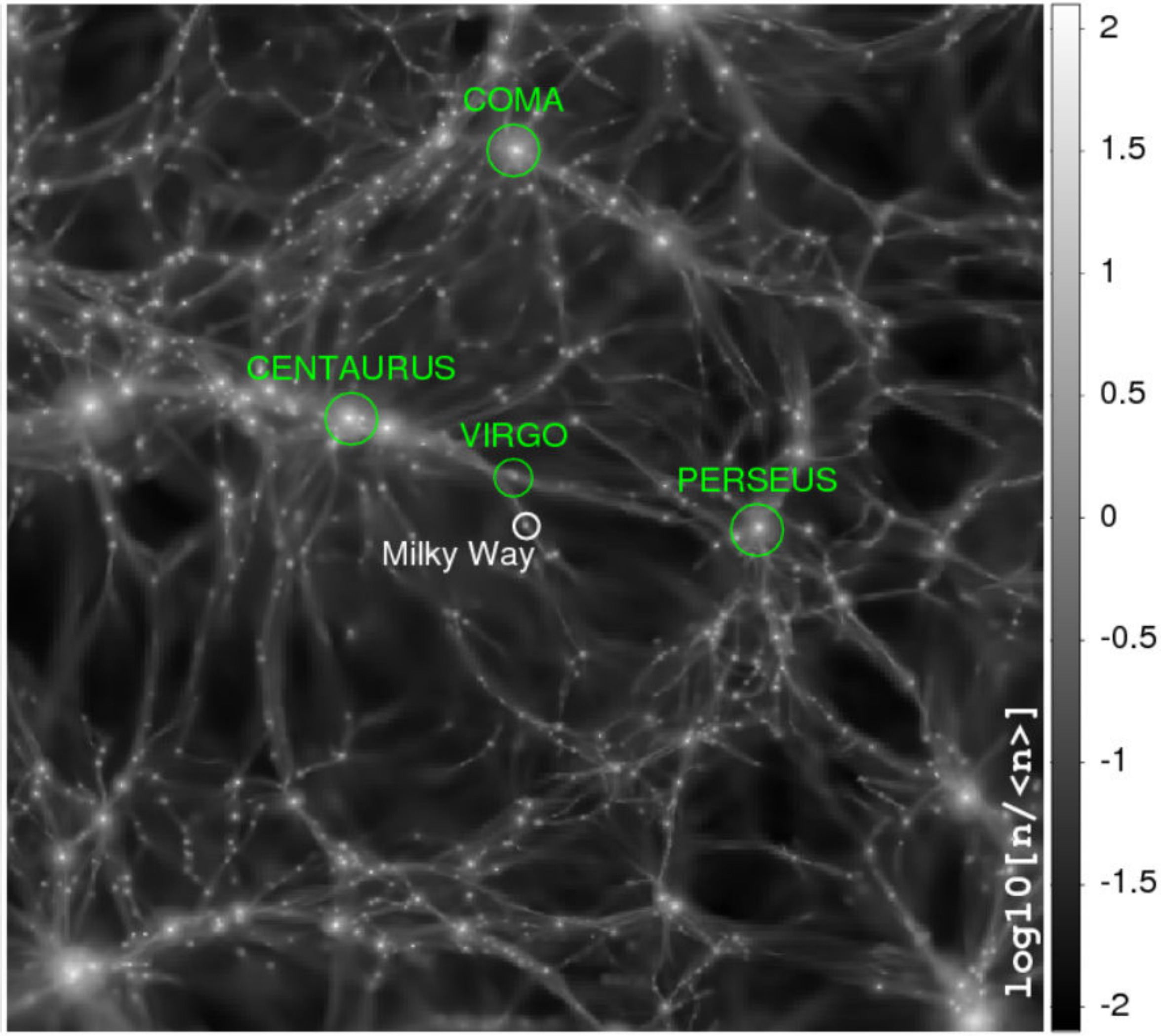


Structure of the EGMF



Inhomogeneous,

with strong fields in clusters B~1-10 μG,

filaments B~1-100 nG,

and comparatively weak fields B<1 nG in voids.

There might be 1 or more filaments every 50 Mpc of the way.

The picture of the EGMF is taken from Hackstein, MNRAS, 475, 2519 (2018)

IHCM: Estimates

1 filament

$$\delta \approx 1^\circ \frac{B}{1nG} \frac{40EeV}{E_p/Z} \frac{\sqrt{L_B l_c}}{1Mpc},$$

$$\sin(\theta_{obs}) = \sin(\delta)\frac{L_V}{L_S}.$$

2 filaments

$$\theta_{obs} \approx \frac{\delta L_{V_2}}{L_S - L_{V_1} - L_{V_2}}.$$

n>>2 filaments

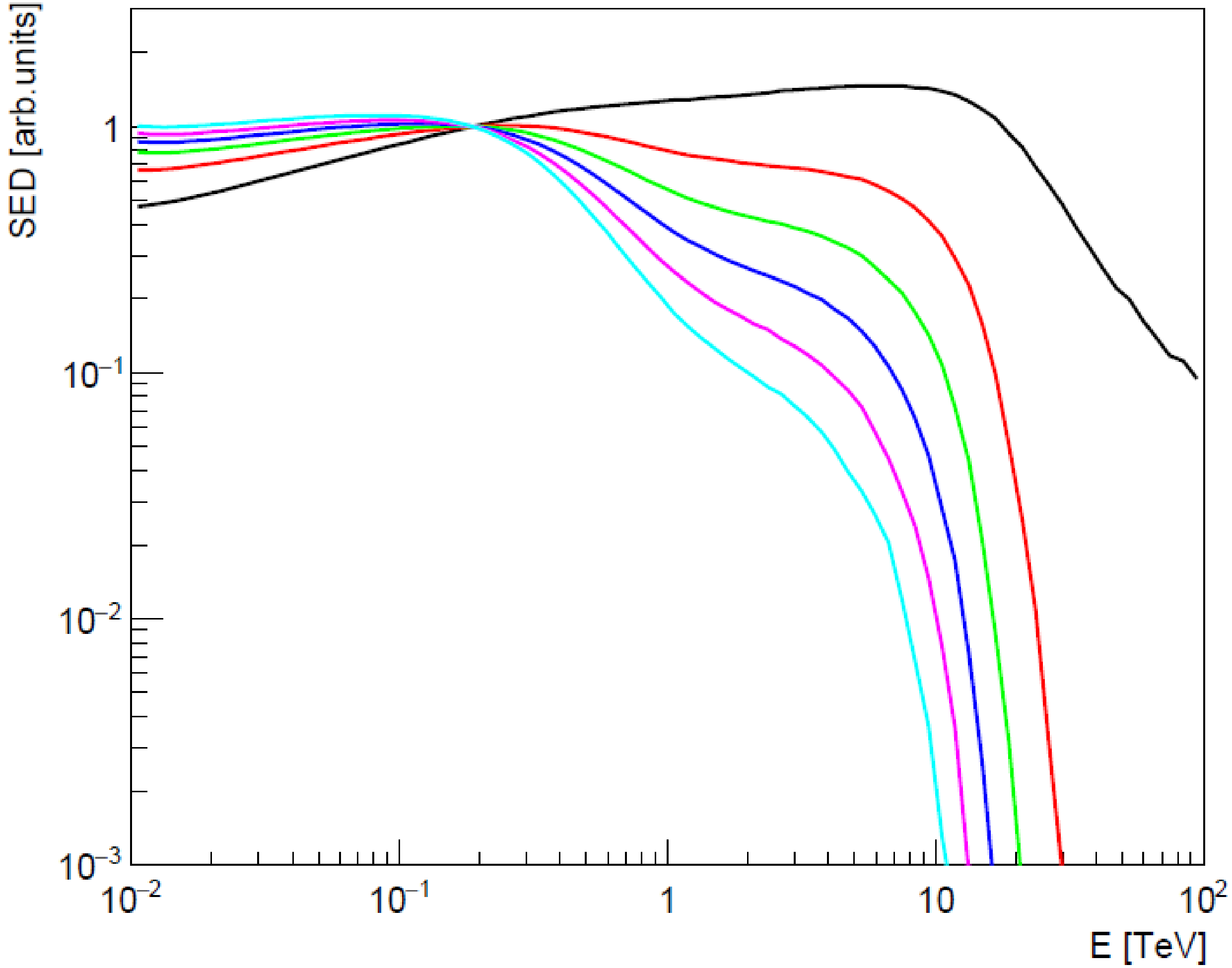
$$\theta_{obs} \sim \delta_n \sqrt{\frac{L}{L_V}\frac{L}{L_S}} = \delta\left(\frac{L}{L_S}\right)^{3/2}.$$

Table 1. Estimates of the observable angle θ_{obs} [°] for models with different number of filaments.

$L_V/L_{V_2}/L$	50 Mpc	100 Mpc	200 Mpc	500 Mpc
one filament	0.064	0.13	0.25	0.64
two filaments	0.073	0.16	0.37	2.1
n>>2 filaments	0.016	0.045	0.13	0.51

The formula for deflection angle δ is provided by Harari, et al., PhysRevD, 93 (2016);
Some of the estimates are presented in Dzhatdoev, et al., J. Phys.: Conf. Ser. 1181 012049 (2019).

EM cascade spectral features



- Black line denotes the interval 0.0 < z0 < 0.03, red - 0.03 < z0 < 0.06, green - 0.06 < z0 < 0.09, blue - 0.09 < z0 < 0.12, magenta - 0.12 <z0 < 0.15, cyan - 0.15 < z0 < 0.18.
- The observable spectrum becomes harder with the falling redshift of the source, but at the same time the angular distribution becomes broader.

This simulation was done using the code ELMAG 2.03 (Kachelrieß, et al., Comput. Phys. Commun.,183, 1036 (2012))

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Simulation of proton propagation

For our simulation we used the following codes and models:

- CRPropa3 code (Alves Batista, et al., JCAP, 2016, 038) to calculate deflections of protons in the Dolag (Dolag, et al., JCAP, 2005, 009) model of EGMF;
- ELMAG 2.03 code (Kachelrieß, et al., Comput. Phys. Commun.,183, 1036 (2012)) to calculate cascade spectra;
- our own hybrid code to propagate protons through photon fields accounting for adiabatic and interaction losses;
- Gilmore model of EBL (Gilmore, st al., MNRAS, 422, 3189 (2012)).

The source

1ES 1101-232

SIMBAD

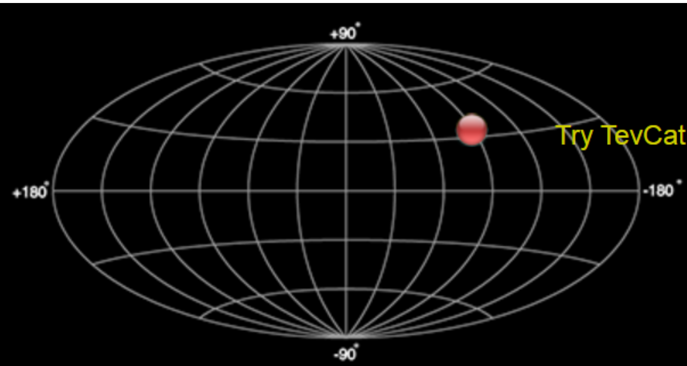
Canonical Name:	1ES 1101-232
TeVCat Name:	TeV J1103-234
Other Names:	1H 1100-230, HESS J1103-234
Source Type:	HBL
R.A.:	11 03 36.5 (hh mm ss)
Dec.:	-23 29 45 (dd mm ss)
Gal Long:	273.19 (deg)
Gal Lat:	33.07 (deg)
Distance:	z=0.186
Flux:	0.02 (Crab Units)
Energy Threshold:	100 GeV
Spectral Index:	2.94
Extended:	No
Discovery Date:	2006-04
Discovered By:	H.E.S.S.
TeVCat SubCat:	Default Catalog

Source Notes:

Source position and its uncertainty:
From Aharonian et al. (2007):
- RA (J2000): 11h03m36.5s +/- 2.5s(stat)
- Dec (J2000): −23d29'45" +/- 26"(stat)

Spectral Index:
From Aharonian et al. (2007):
- 2.94 +/- 0.20(stat)

Seen by: H.E.S.S.



Try TevCat 2.0 Beta!

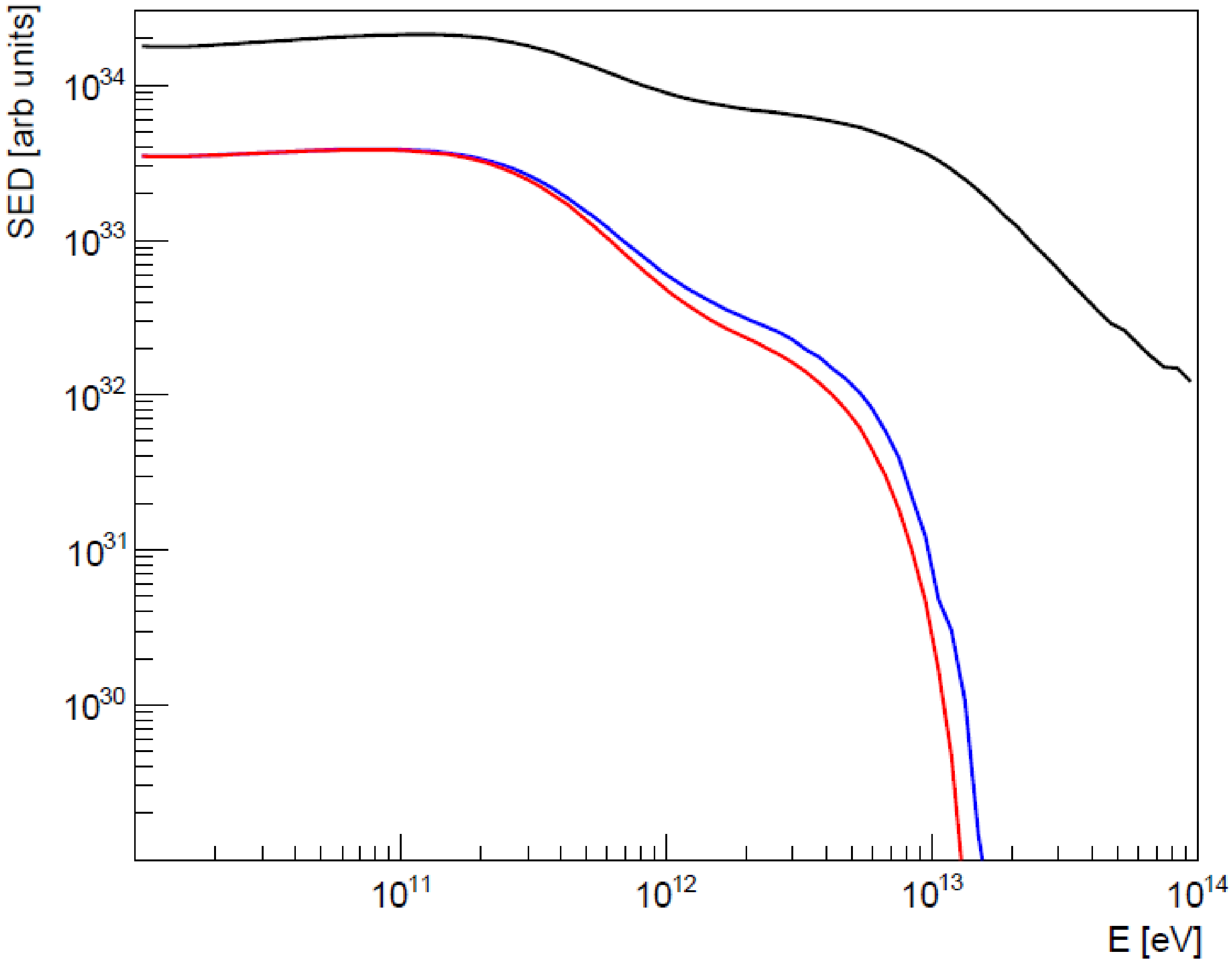
Observation Date (UT) | Observation Lat
7-11-2019 | ARGO-YBJ (30.11)
Vis-Plot this Source! | Vis-Plot Full Year

1ES1101-232

Z = 0.186

This screenshot is taken from http://tevcat.uchicago.edu/?mode=1;id=97

IHCM Spectral energy distribution



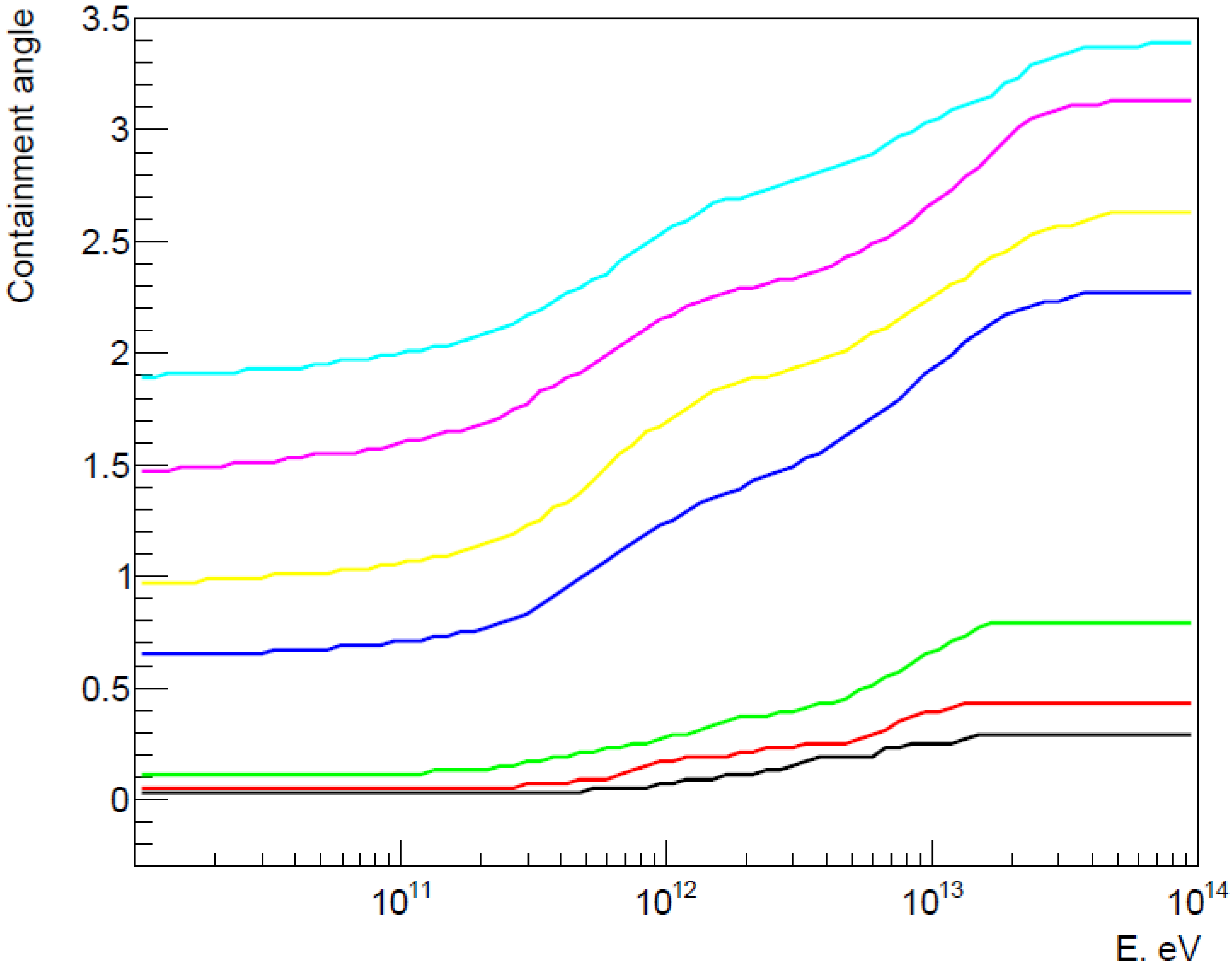
Primary energy of protons = 30 EeV.

Black curve denotes integral SED,

blue – observable spectrum inside a PSF of 0.1 degree,

red – universal spectrum of the source in ECM.

IHCM containment angle (in degrees)



- Black curve denotes a 5% containment angle,
- red curve - 10%,
- green curve - 20%,
- blue curve - 68%,
- yellow curve - 80%,
- magenta curve - 90%, and
- cyan curve - 95%.

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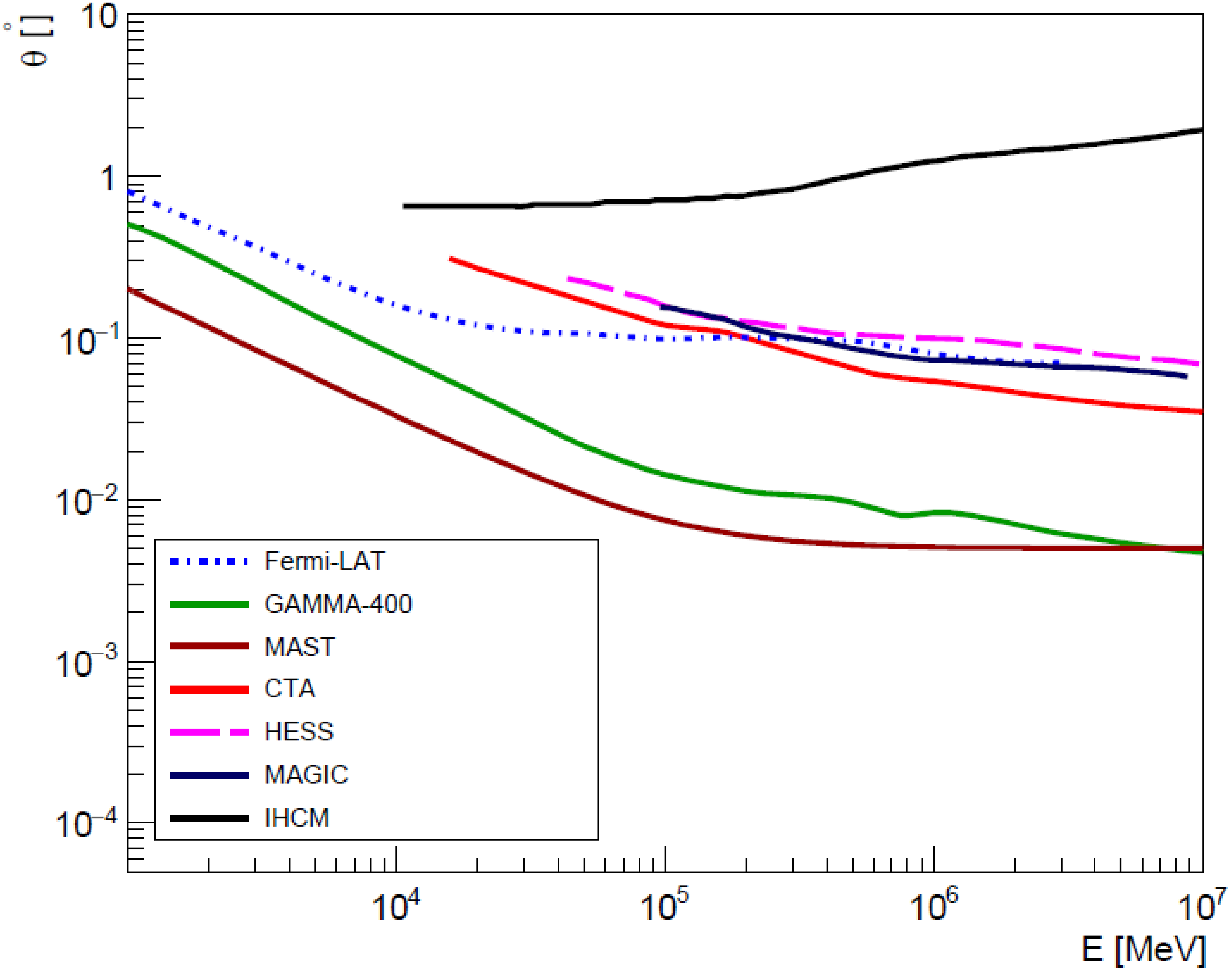
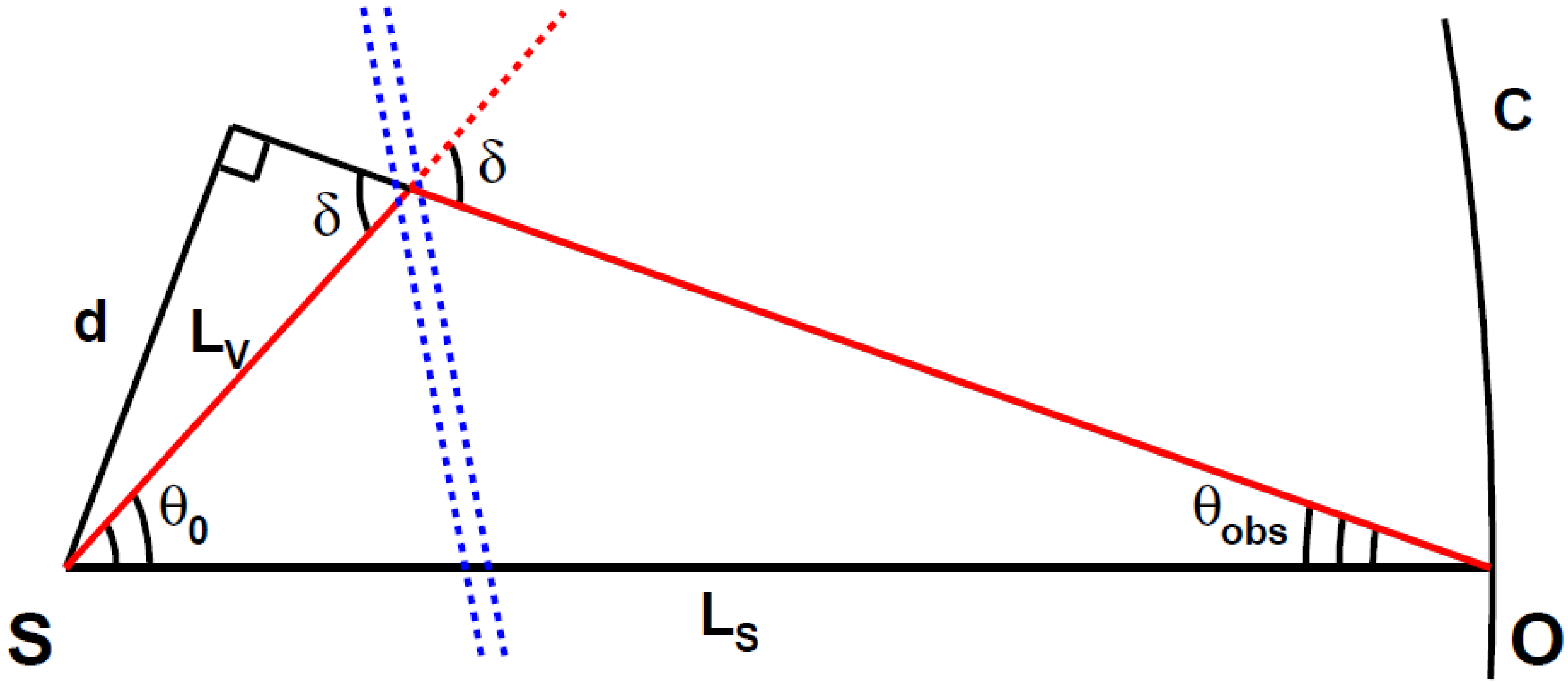
Observational prospects



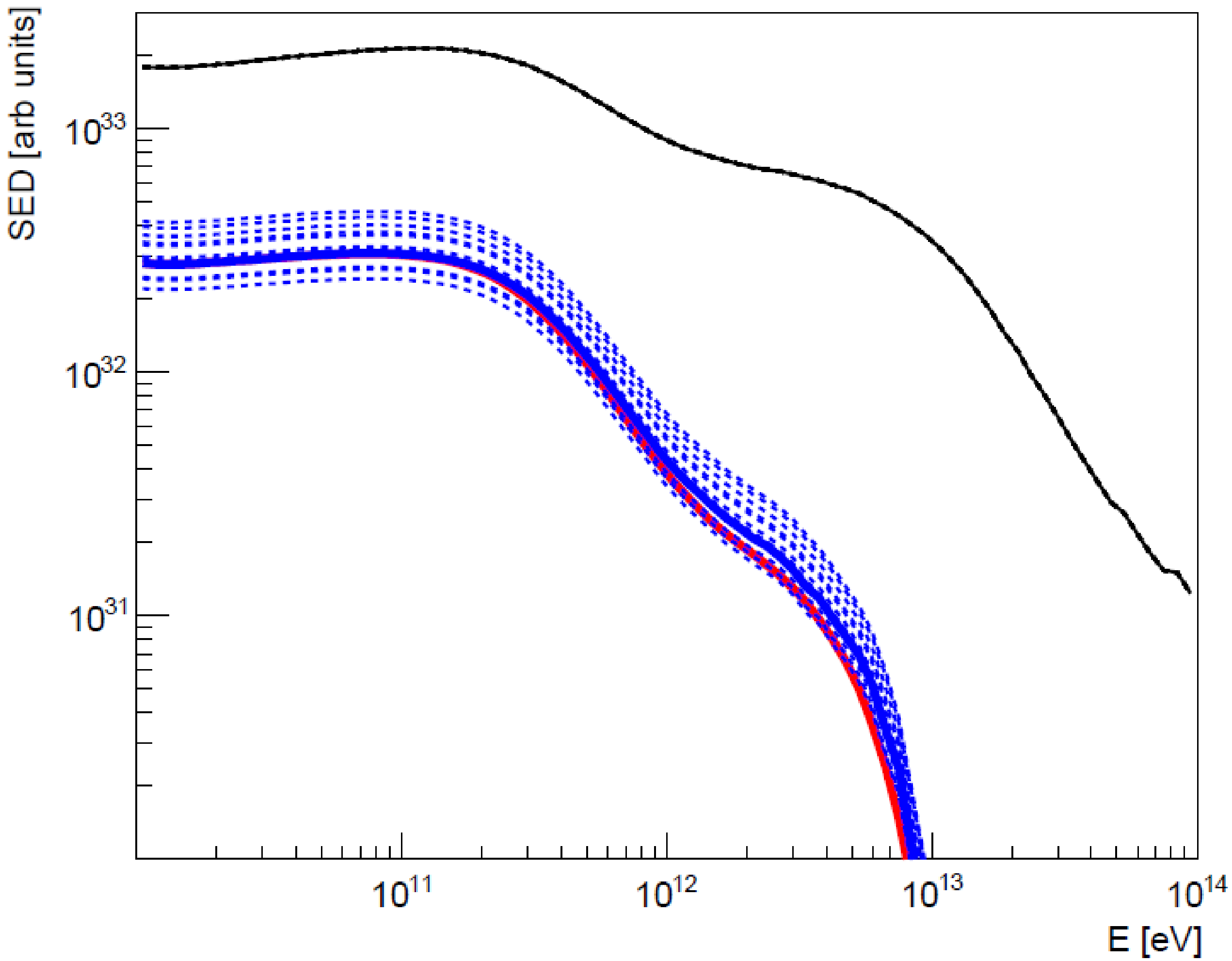
Conclusions

- Emission from primary UHECR of extreme TeV blazars has recognizable features in the form of a high-energy cutoff in the observable SEDs and a broad angular distribution.
- Broad angular distribution of these blazars in the IHCM (with 68% containment angle value at about 1-2 degrees) make them identifiable not as point sources but rather as extended ones.
- The account of IHCM spectral signatures could facilitate future gamma→ALP oscillation searches in the optically thick region of blazar spectra with existing and future gamma-ray instruments such as Fermi-LAT, H.E.S.S., MAGIC, VERITAS, CTA, HAWC, and LHAASO.
- There is still background from electromagnetic cascade models that needs to be studied further (see Dzhatdoev, et al., A&A, 603, A59, 2017).

backup



C
δ
δ
d
L_V
θ_0
θ_{obs}
S
L_S
O


SED [arb units]
10^{33}
10^{32}
10^{31}
10^{11}
10^{12}
10^{13}
10^{14}
E [eV]

Active/passive losses ratio vs redshift

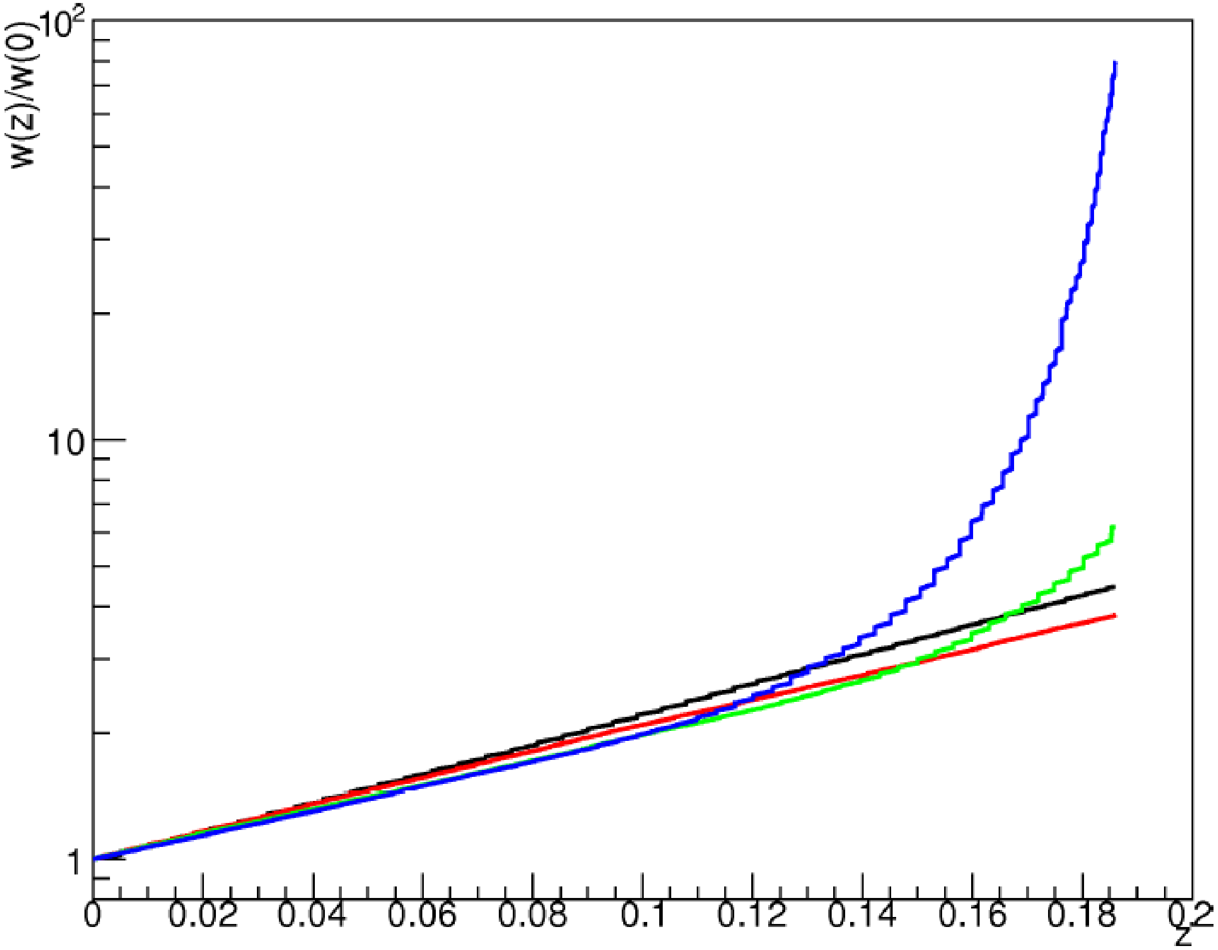
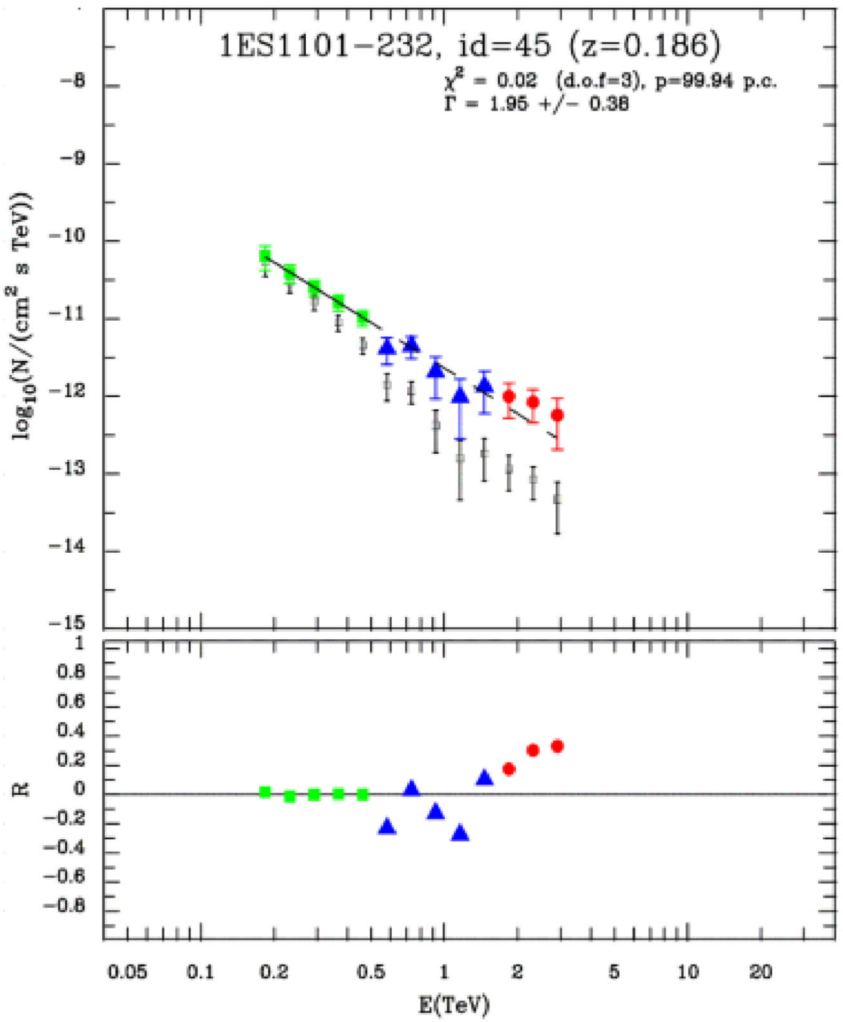
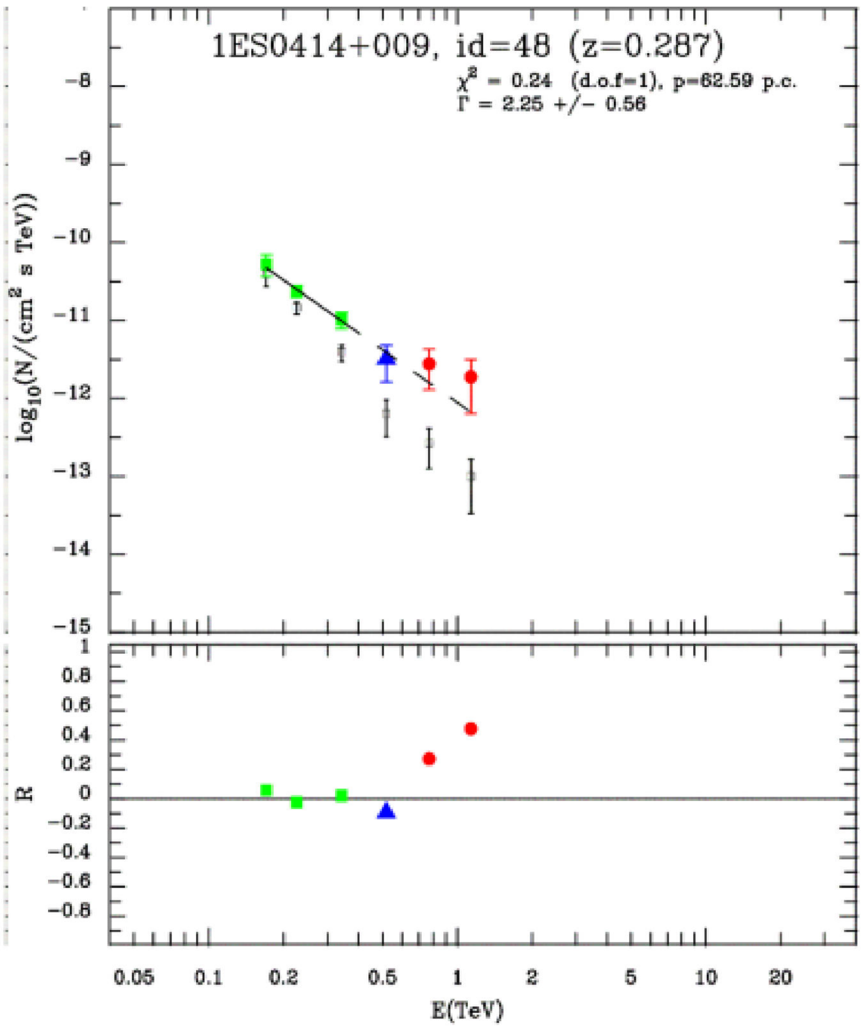


Fig. 4. $w(z)/w(0)$ dependence. Black line – E_{p0} = 10 EeV, red – 30 EeV, green – 50 EeV, blue – 100 EeV.

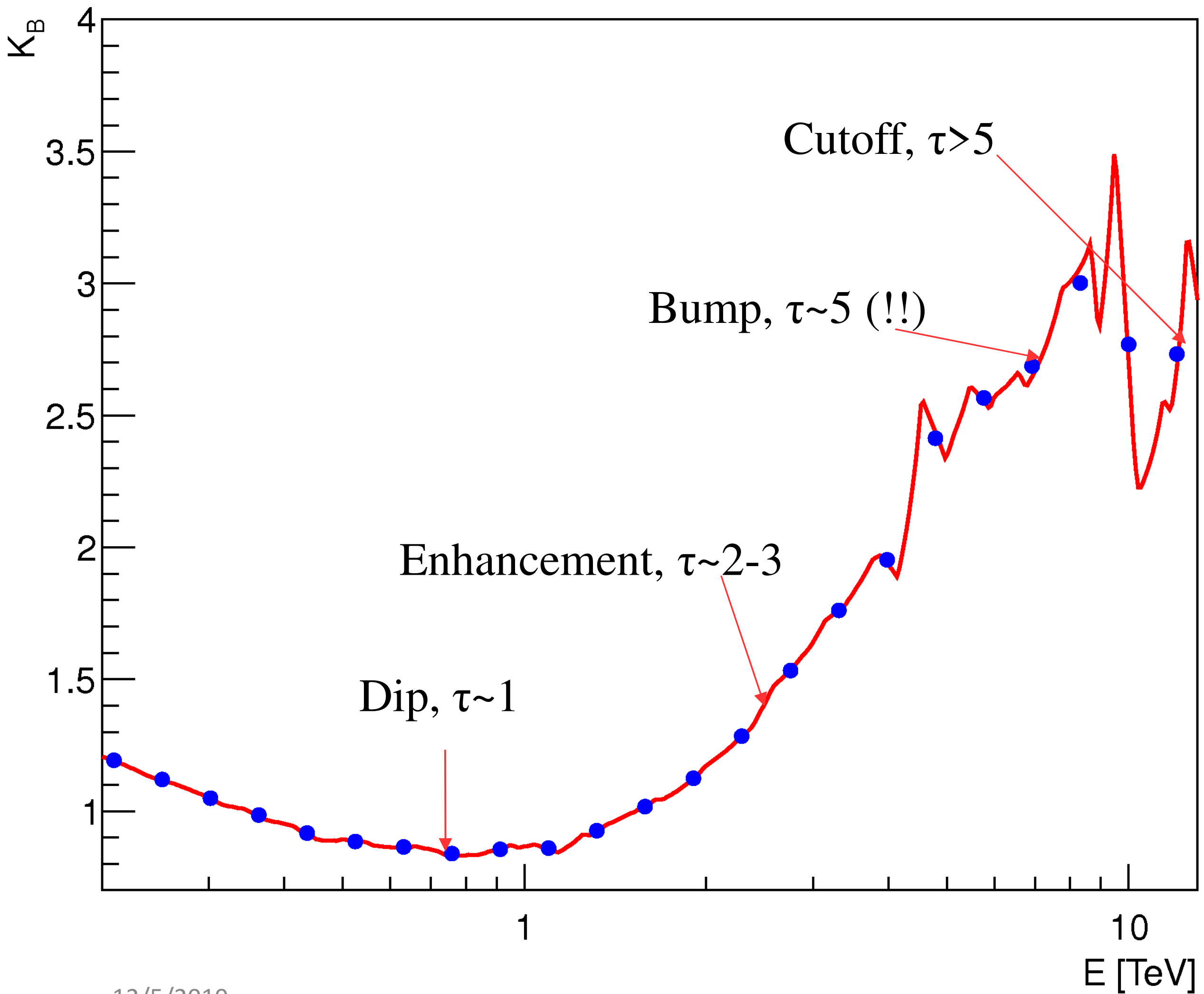
Dzhatdoev, et al., A&A, 603, A59 (2017)

High-energy anomaly: Horns & Meyer, JCAP, 033 (2012)





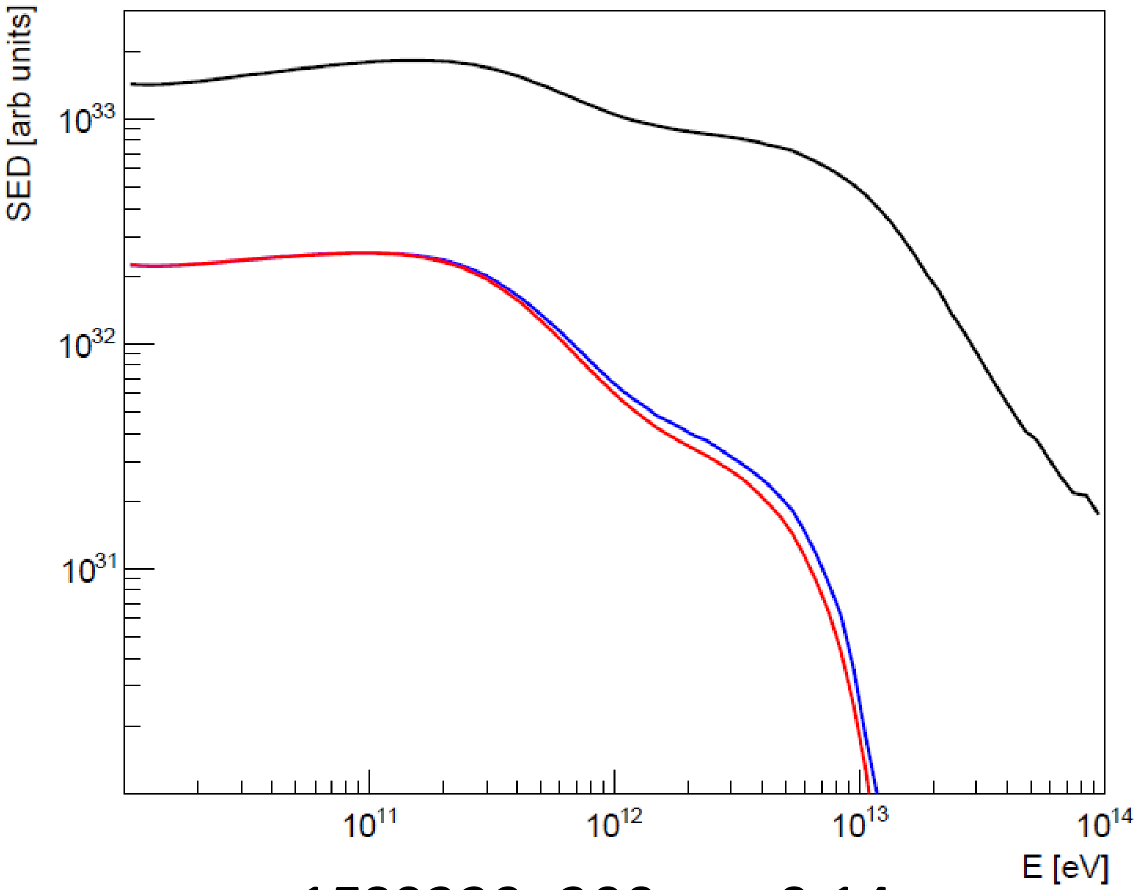
Modification factor



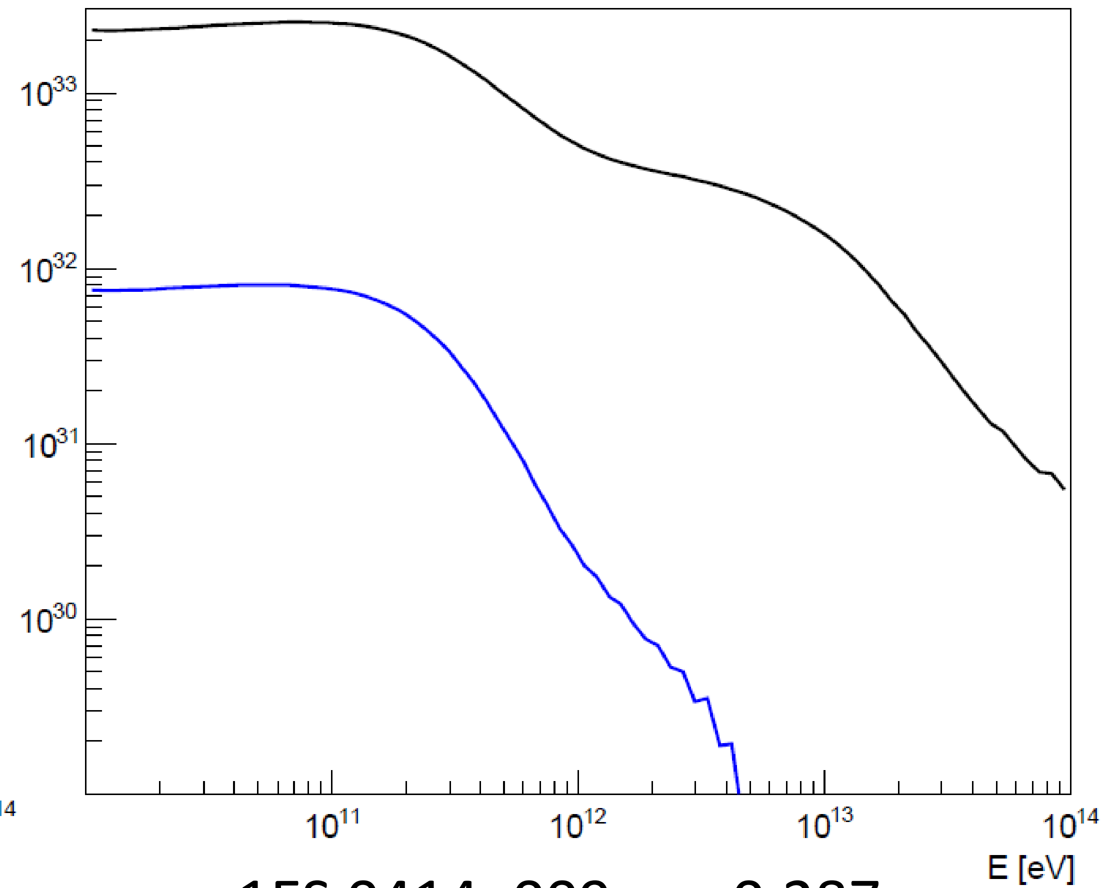
The ratio of best-fit model spectra for electromagnetic cascade model and the absorption-only model.

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

IHCM SEDs for other sources

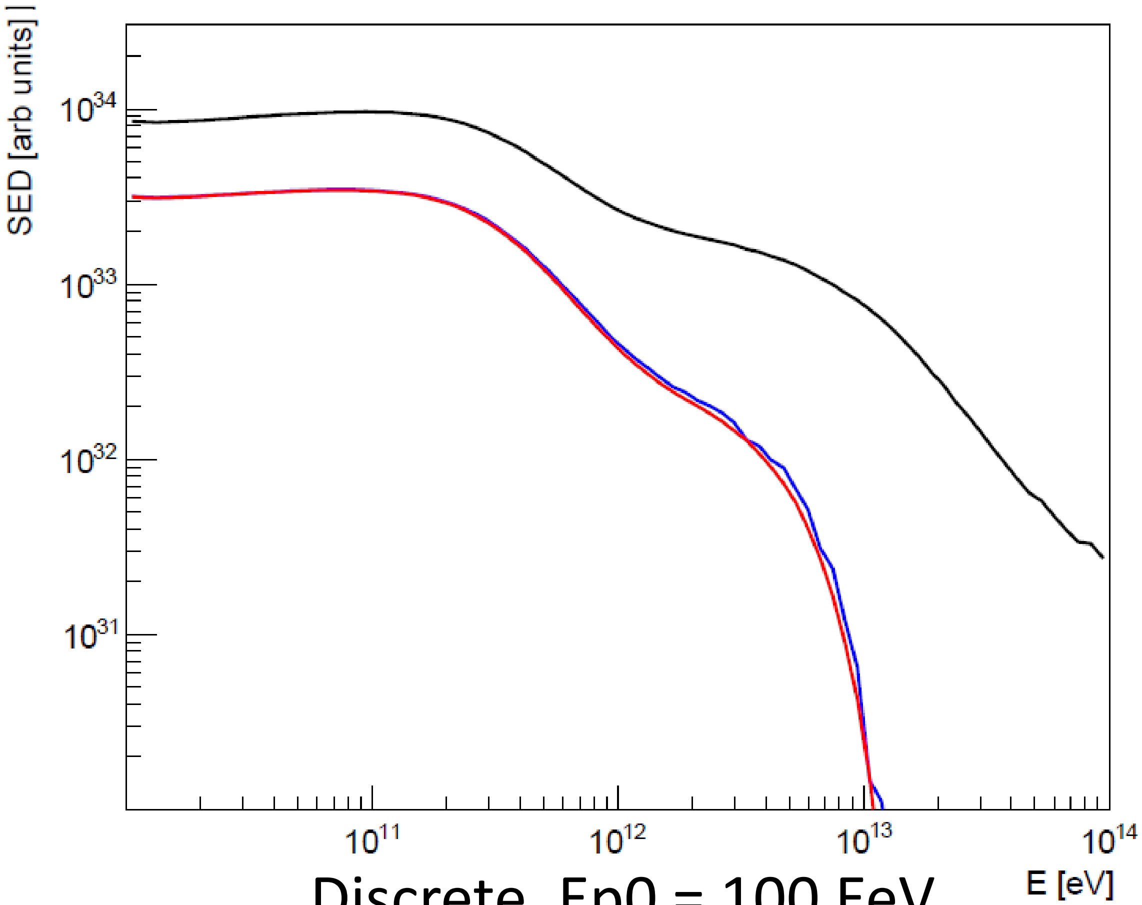


1ES0229+200, z = 0.14

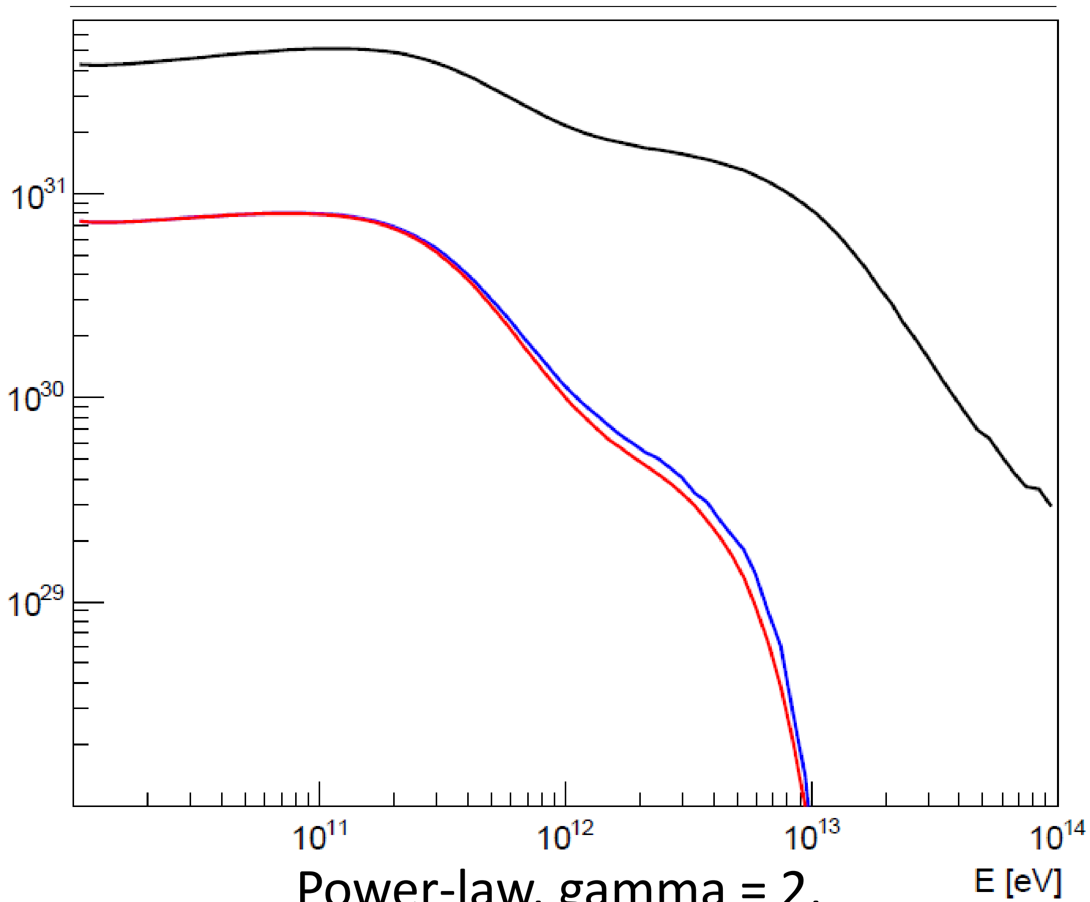


1ES 0414+009, z = 0.287

IHCM SEDs for other primary spectra

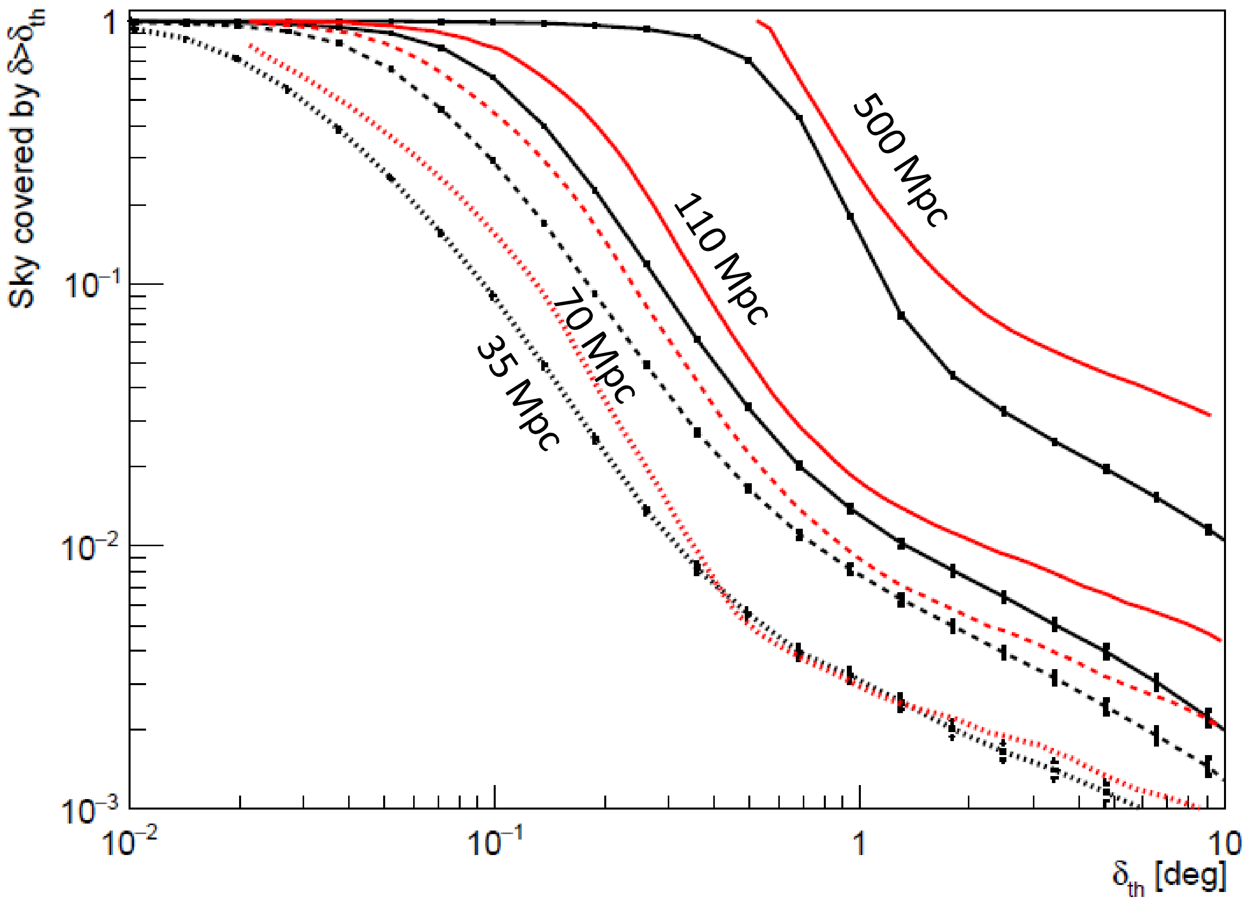


Discrete, Ep0 = 100 EeV



Power-law, gamma = 2,
Emin = 1 EeV, Emax = 100 EeV

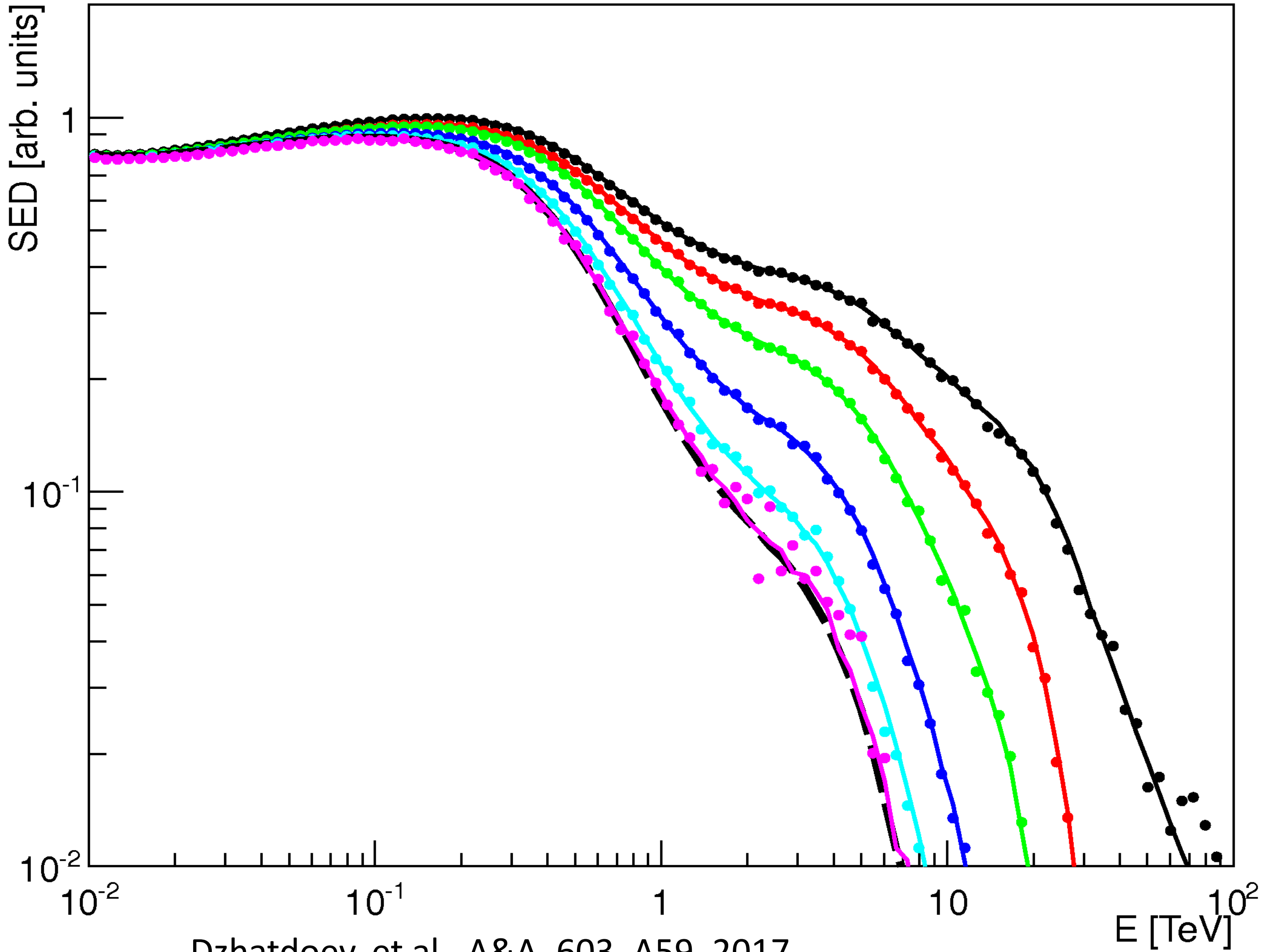
Simulation of proton propagation



This simulation was done using the code CRPropa3 (Alves Batista, et al., JCAP, 2016, 038)
We consider a Dolag model of EGMF (Dolag, et al., JCAP, 2005, 009)

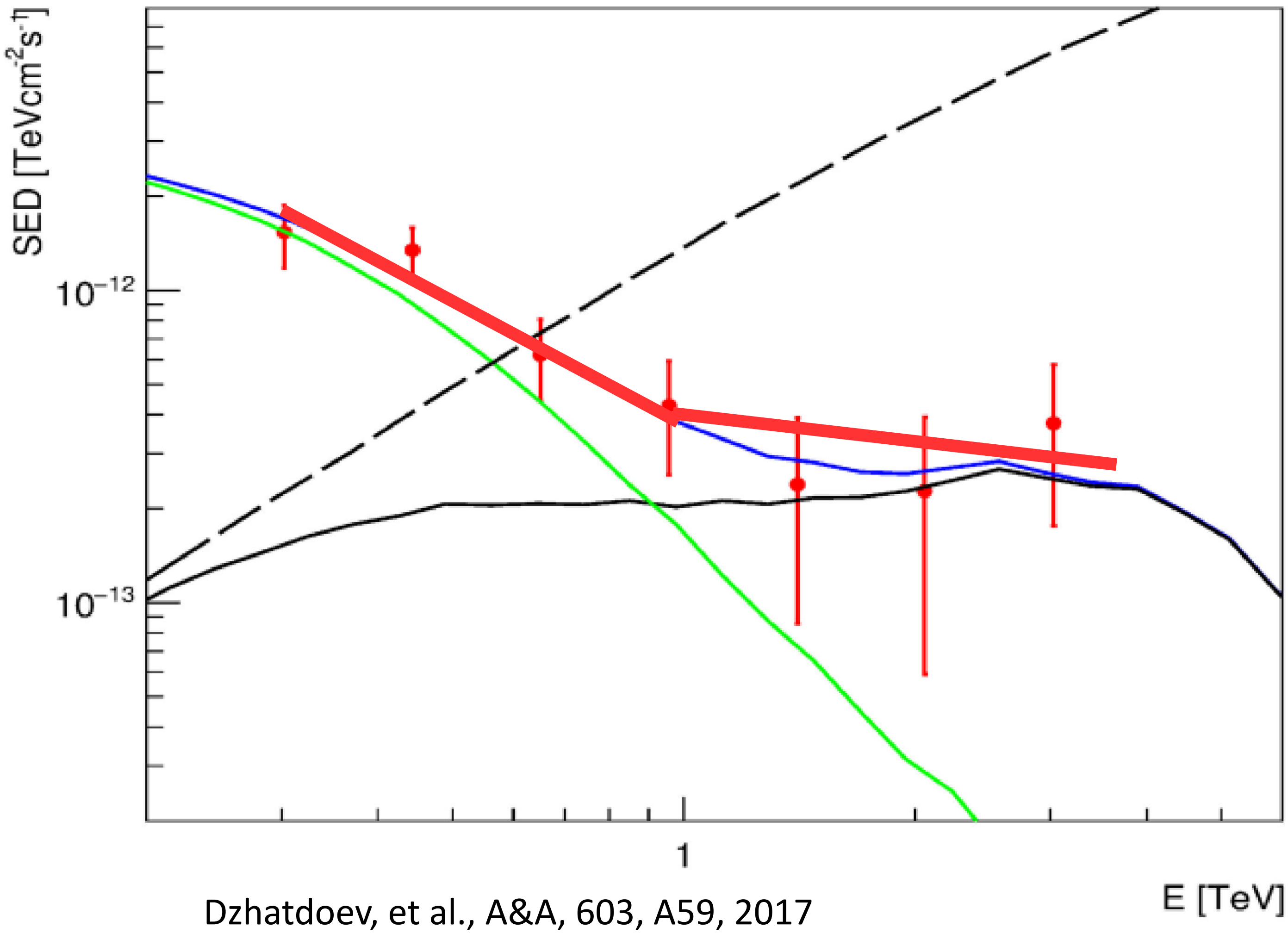
"Intermediate" HCM: proton beam is terminated at z_c

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



Dzhatdoev, et al., A&A, 603, A59, 2017

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



Dzhatdoev, et al., A&A, 603, A59, 2017