Testing cascade models of extragalactic gamma-ray propagation using observations of extreme TeV blazars with imaging Cherenkov telescopes

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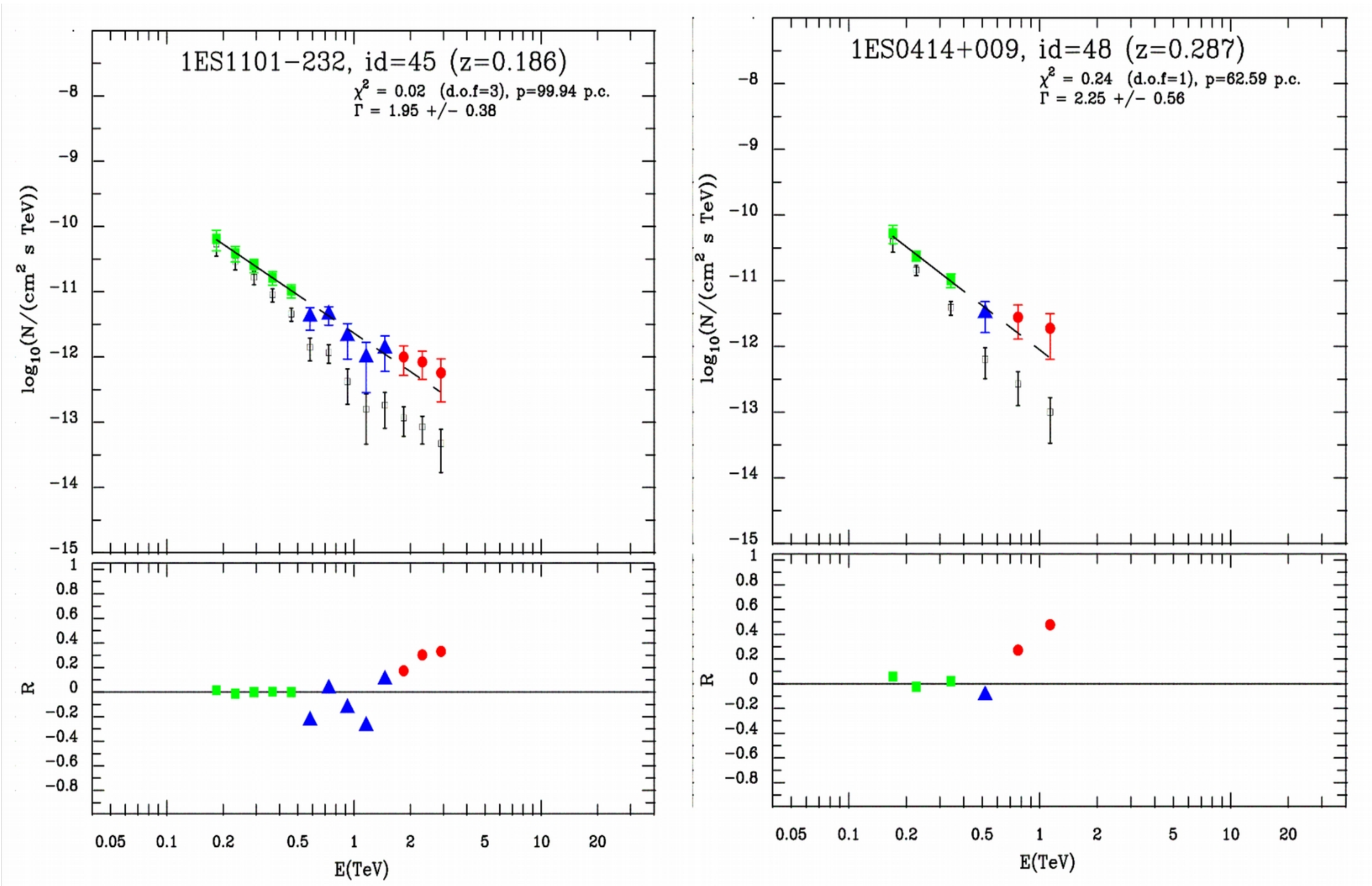
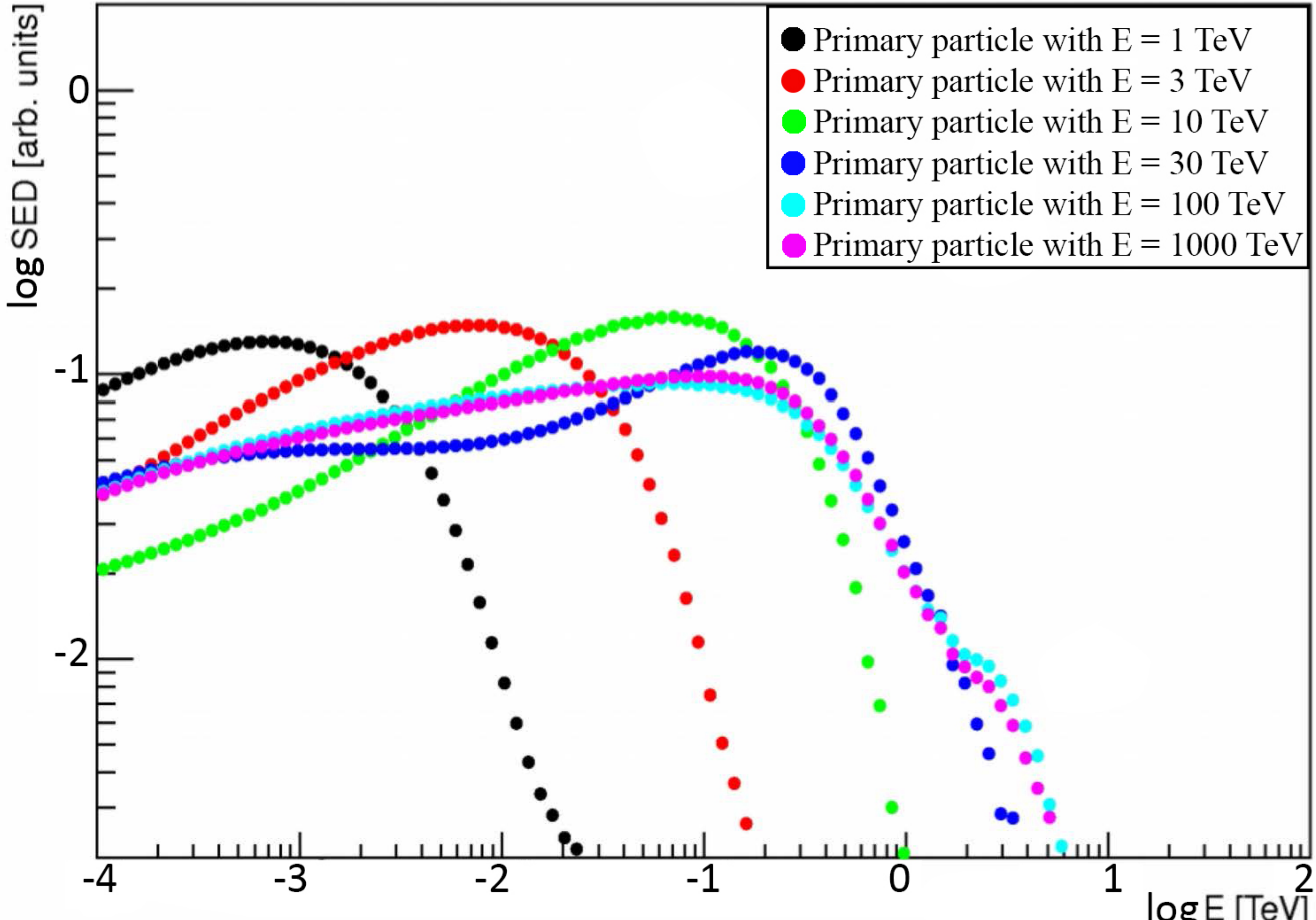
Most of the works that study gamma-ray propagation from extragalactic sources (mostly blazars) only consider the absorption of these gamma-rays on photons of the extragalactic background light.
Blazars are gamma-loud active galactic nuclei that emit particles in the form of jets presumably pointed towards the observer.
There are anomalies that cannot be explained by the "absorption-only model" - they are reviewed in our work (astro.ph/1609.01013).
For instance, for the high optical depth of pair-creation tau>2 there is an anomalous increase in the observed blazar spectrum in the TeV region.

The absorption anomaly (Horns & Meyer 2012): Black open squares show differential spectra, colored filled markers show the measurements corrected for absorption

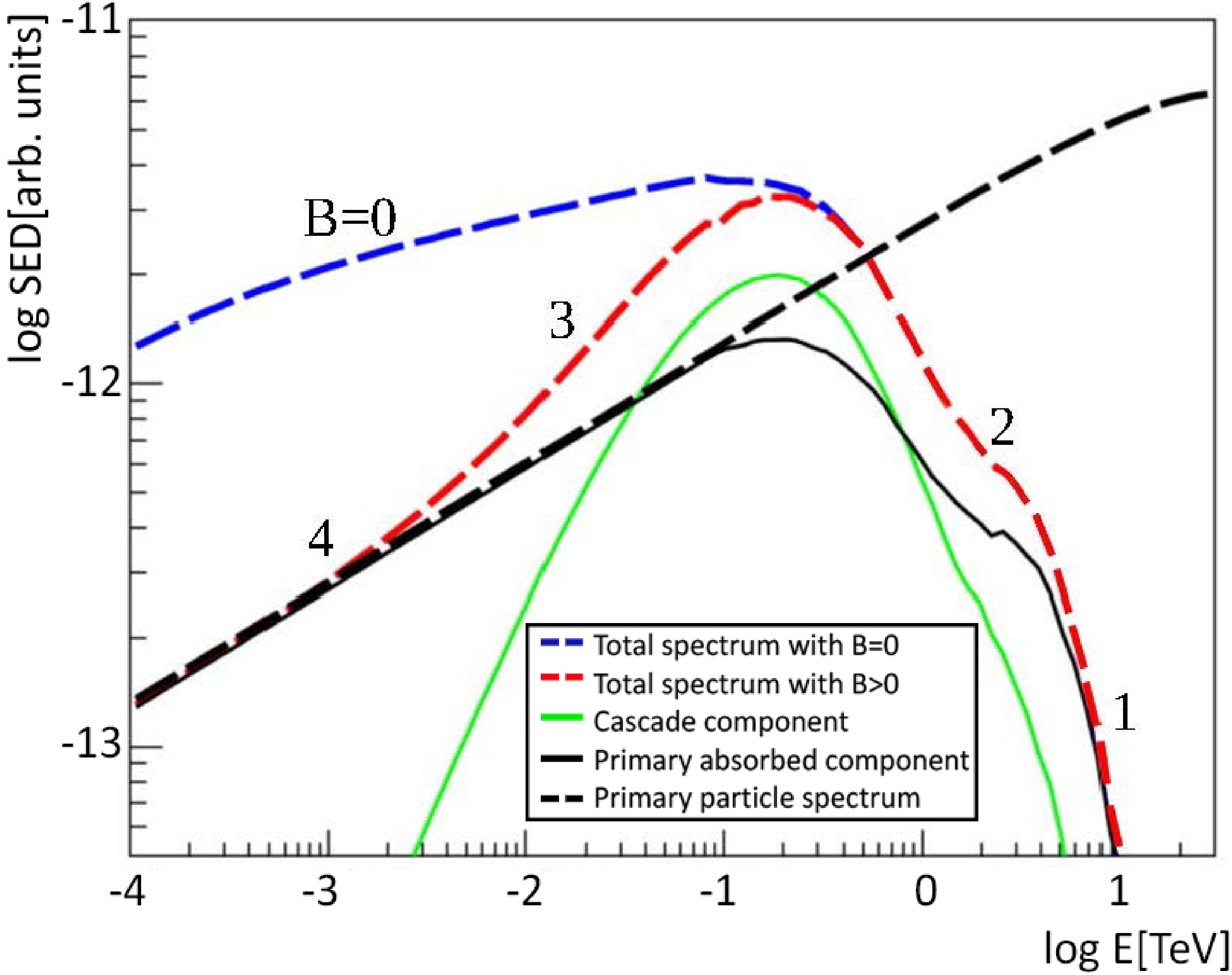


Electromagnetic cascades: one-generation and universal regimes (z= 0.186; calculations with ELMAG 2.02, Kachelriess et al. (2012))



All calculations of EM cascades hereafter with the ELMAG code (Kachelriess et al. (2012))

Signatures of the electromagnetic cascade model (z= 0.14)



1= high-energy cutoff; 2= ankle; 3= magnetic cutoff; 4= second ankle

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

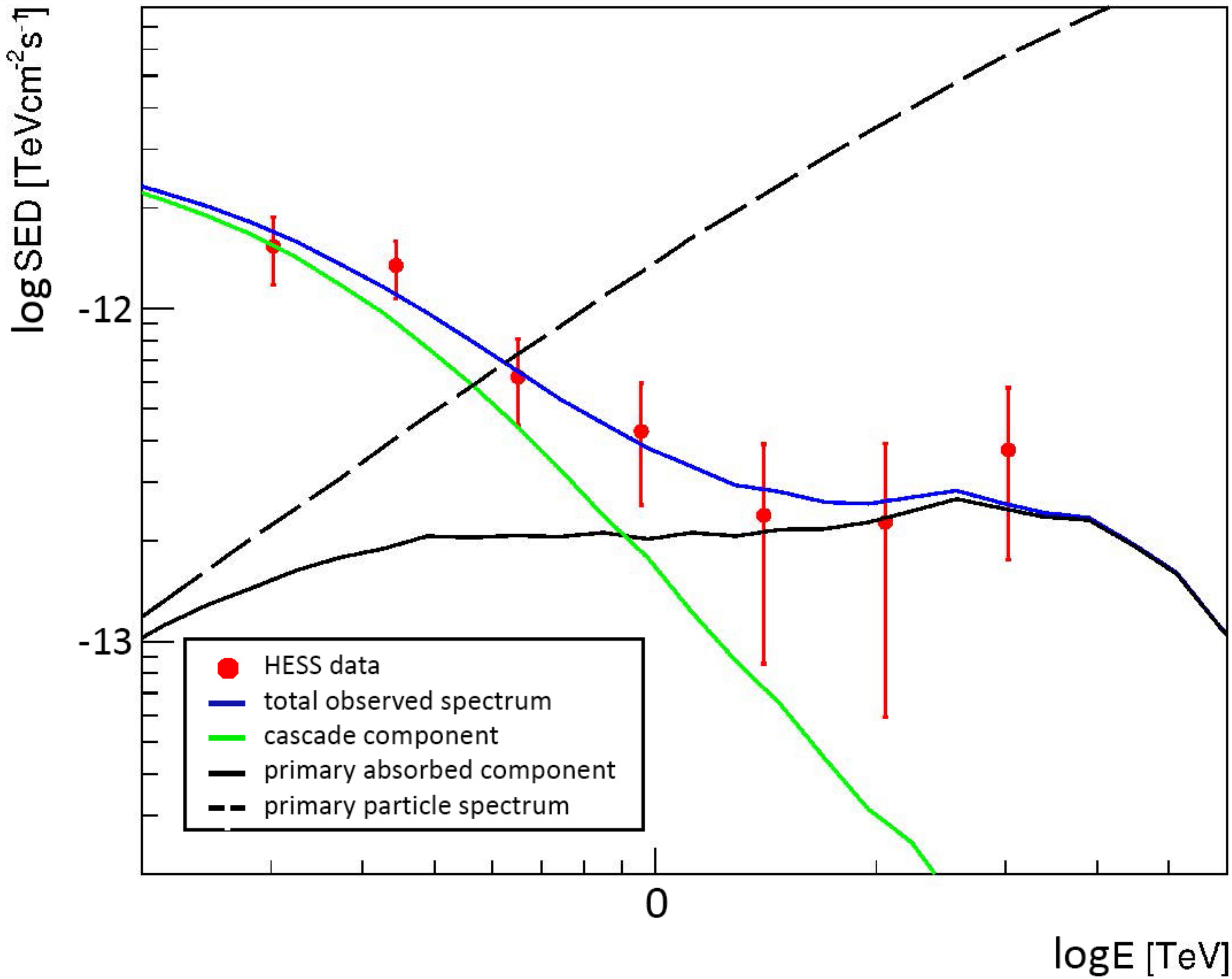
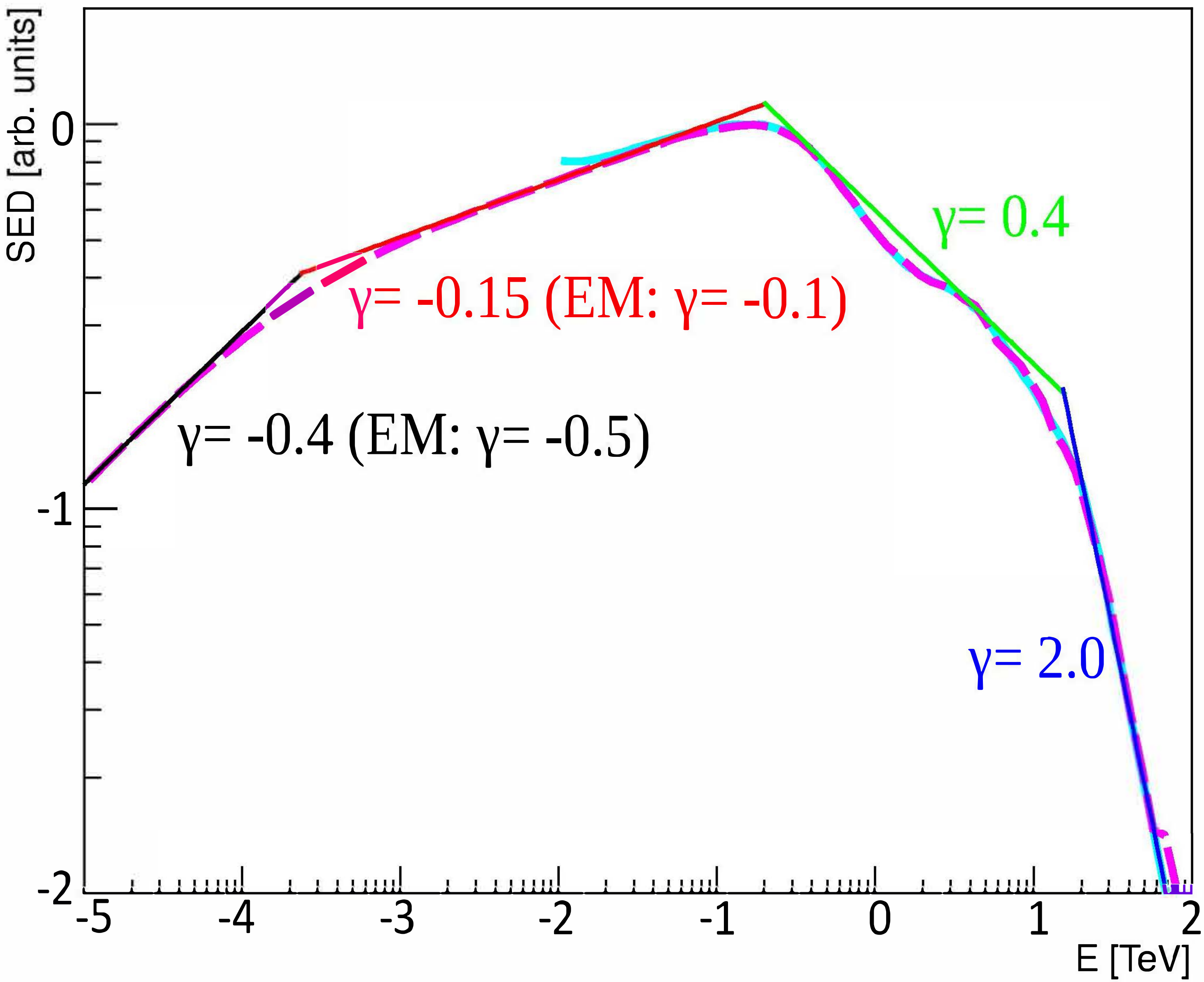
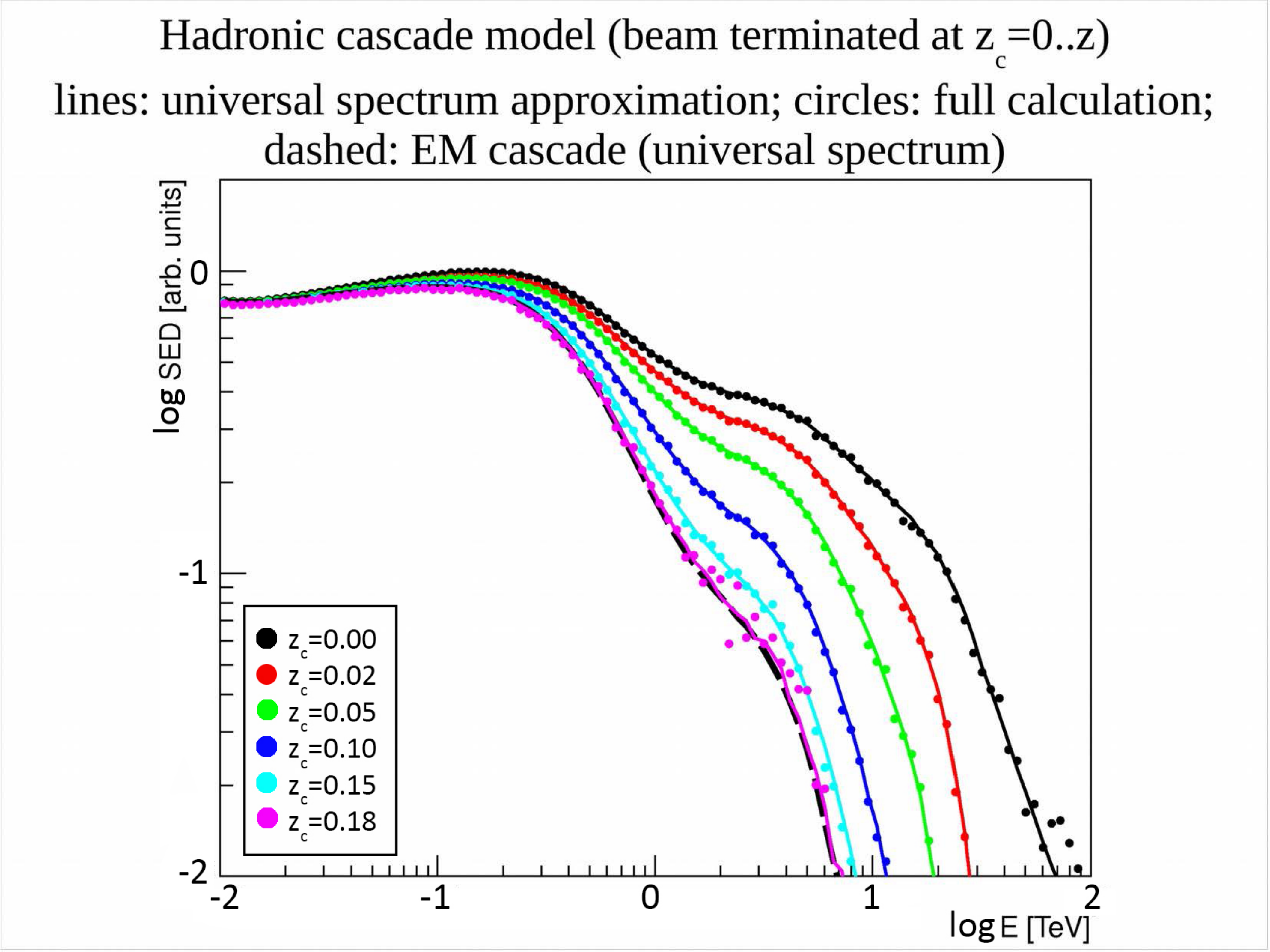


Figure is taken from T. Dzhatdoev et al (2016) (Preprint astro.ph/1609.01013). For other options see Aharonian et al. (2002), d'Avezac et al. (2007), Murase et al.

Hadronic cascade model: spectral signatures
(primary proton energy $E_{p0} = 3 \cdot 10^{19}$ eV= 30 EeV B=0)

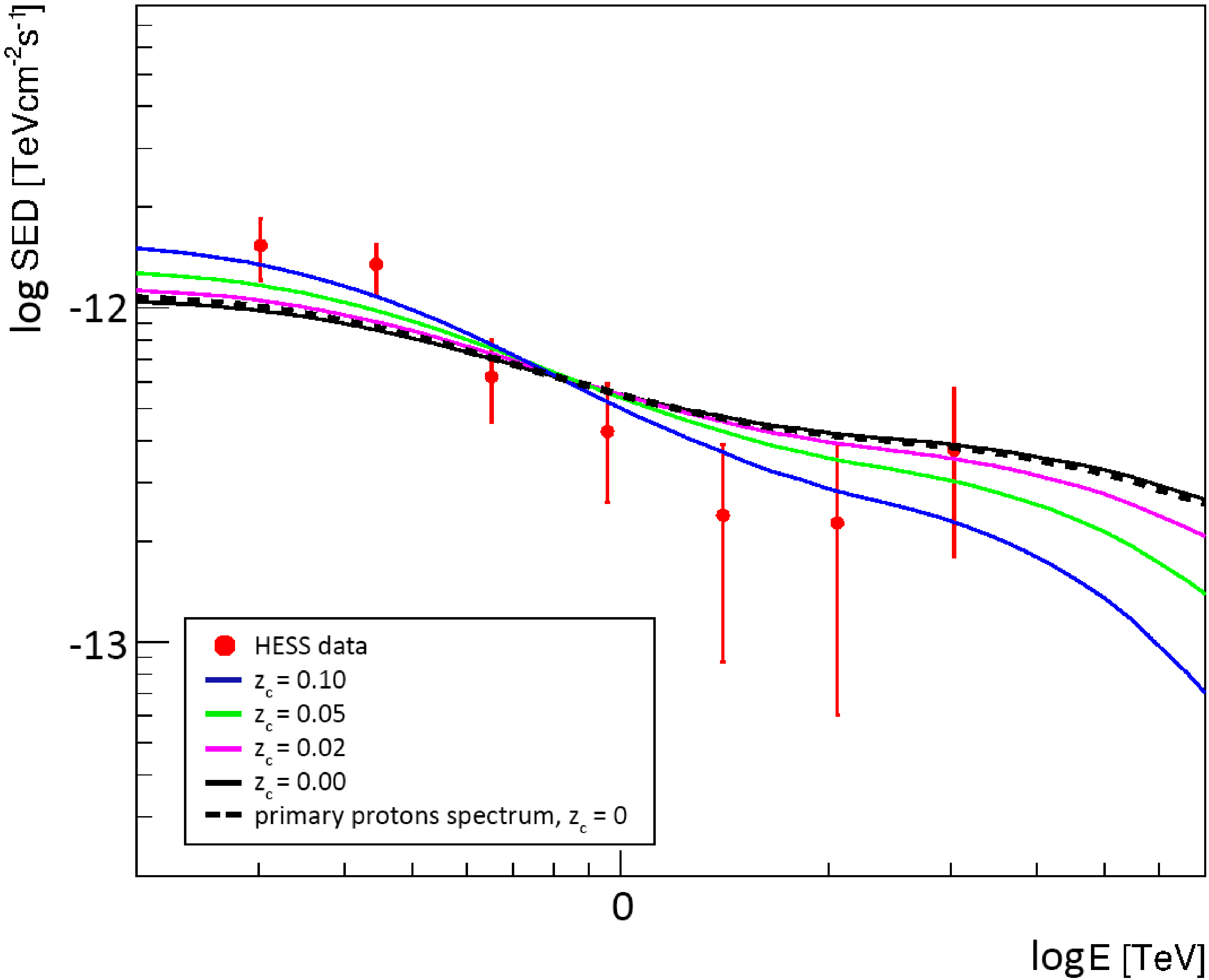


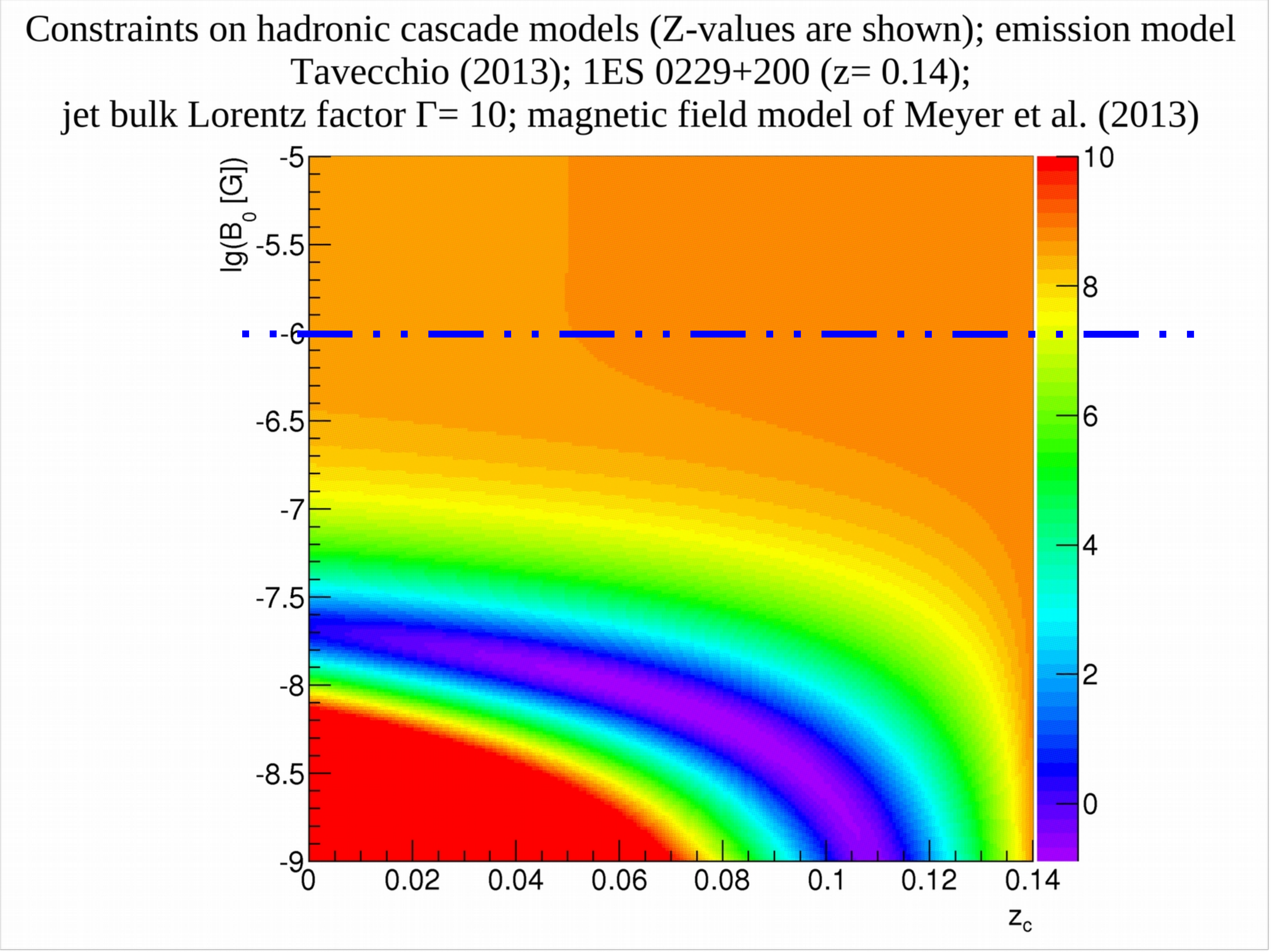
EM (universal regime): numbers from Berezinsky& Kalashev (2016)



Hadronic cascade model (beam terminated at z_c=0..z)
lines: universal spectrum approximation; circles: full calculation;
dashed: EM cascade (universal spectrum)
log SED [arb. units]
0
-1
-2
-2
-1
0
1
2
log E [TeV]
z_c=0.00
z_c=0.02
z_c=0.05
z_c=0.10
z_c=0.15
z_c=0.18

Hadronic Cascade Model (z=0.188)




Constraints on hadronic cascade models (Z-values are shown); emission model Tavecchio (2013); 1ES 0229+200 (z= 0.14); jet bulk Lorentz factor Γ= 10; magnetic field model of Meyer et al. (2013)
lg(B0 [G])
-5
-5.5
-6
-6.5
-7
-7.5
-8
-8.5
-9
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
zc
10
8
6
4
2
0

Conclusions

There are many indications for EM cascades in blazar spectra!

If primary spectra are hard enough, the absorption anomaly may be somewhat relaxed (the “EM cascade masquerade effect”).

One can easily distinguish between electromagnetic and hadronic cascade models by comparing the high-energy cutoff region in their observed spectra

If blazars are embedded in galaxy clusters with central magnetic field more than 100 nG, simplest hadronic cascade models experience significant difficulties.

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