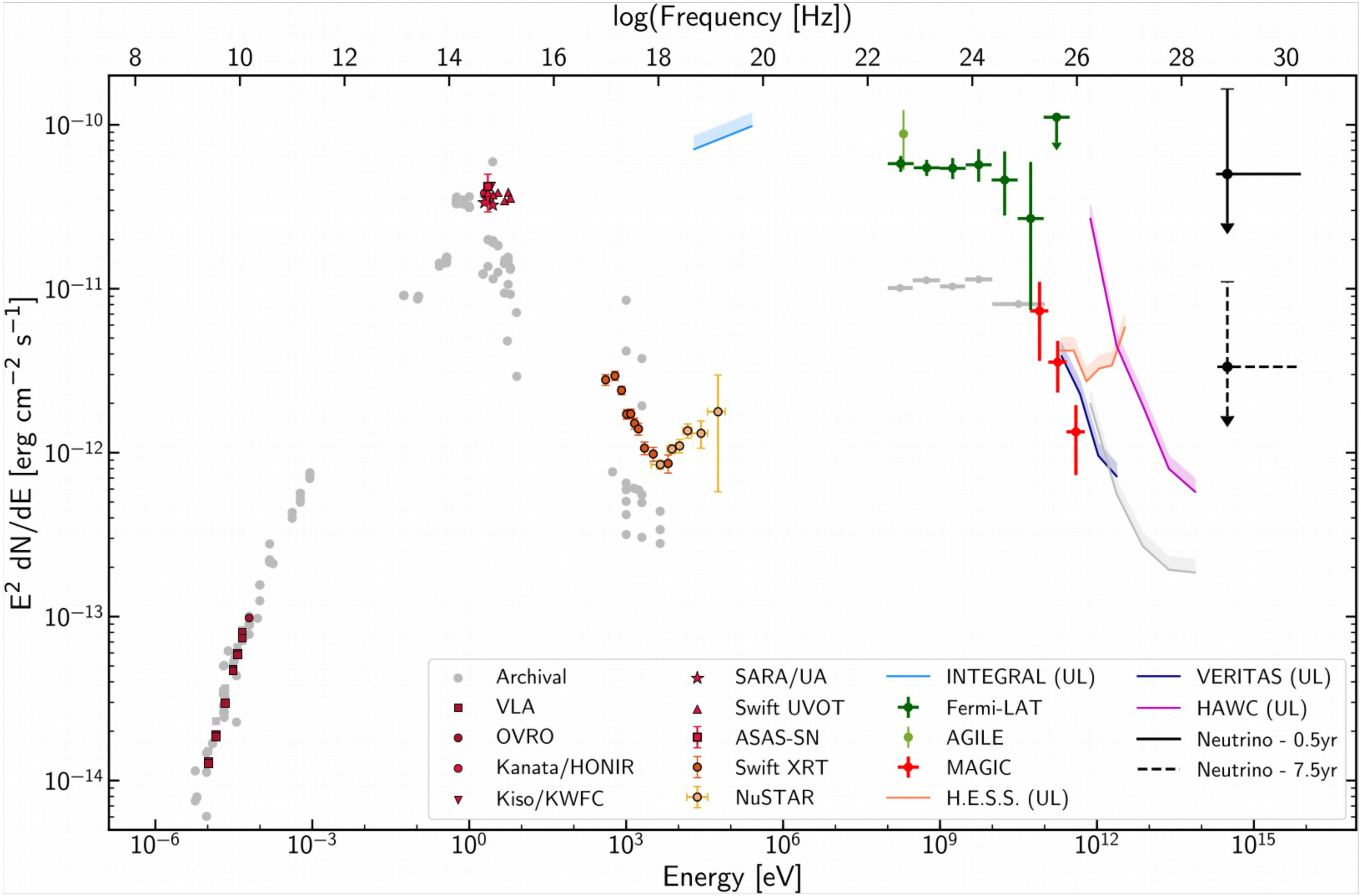
A mixed origin of neutrinos from TXS 0506+056

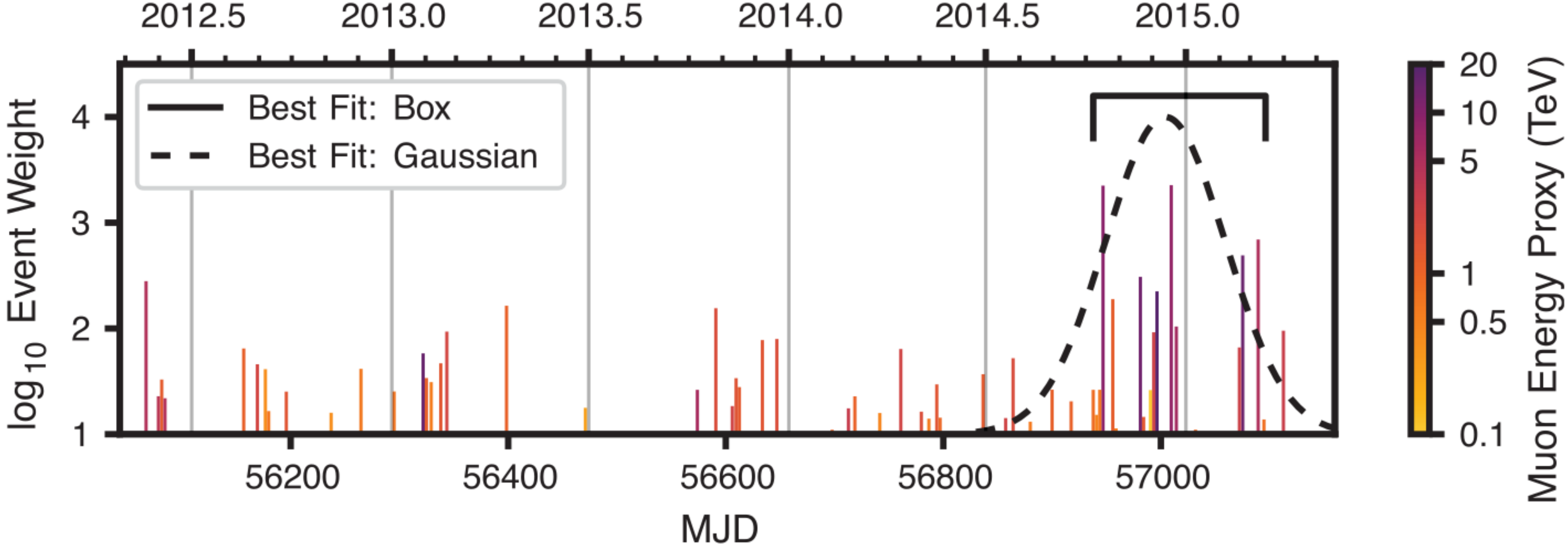
Timur DZHATDOEV (timur1606@gmail.com),
Egor PODLESNYI

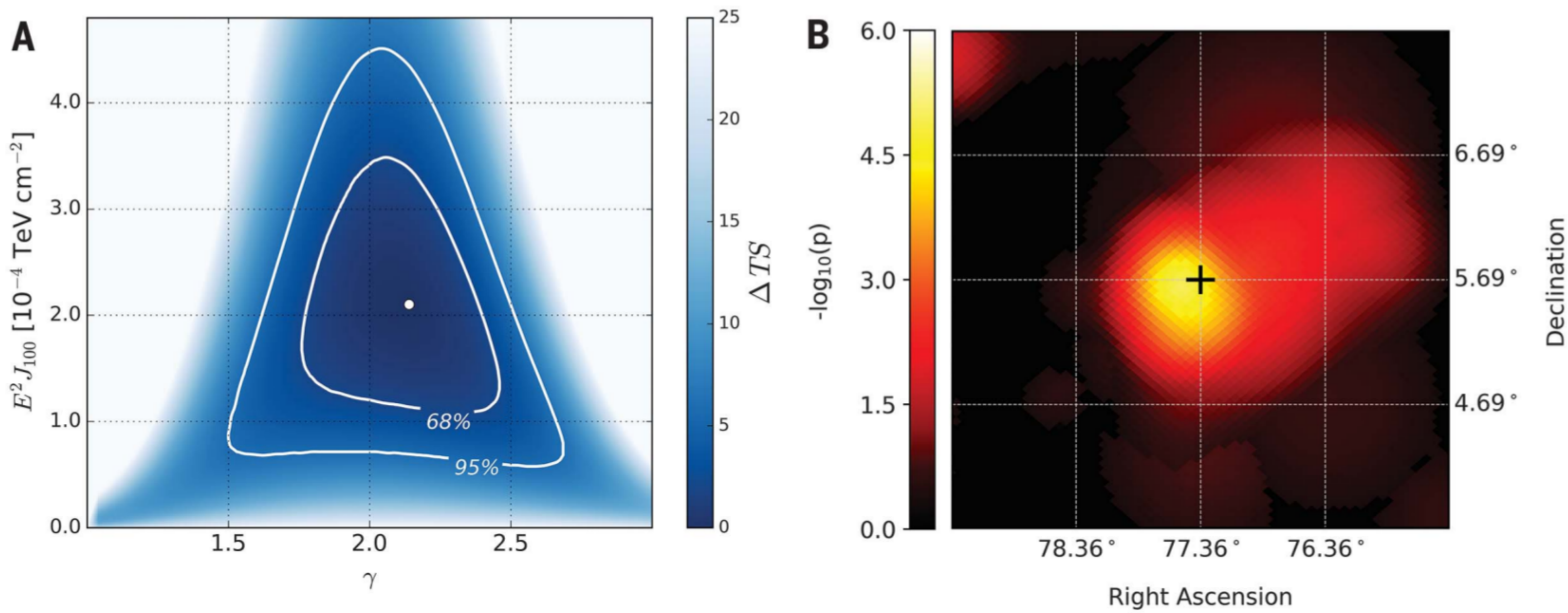
Moscow State University

Multiwavelength/multimessenger (MWL/MM) observation of a "flare" from TXS 0506+056 (Sept. 2017) (IceCube Collaboration et al., Science, **361**, eaat1378 (2018))



Neutrino "cluster" (2014-2015); sparse MWL data (IceCube Collaboration, Science, **361**, 147 (2018))





We assume:
1) that the “flare” and the “cluster” are not statistical fluctuations, and that they are indeed from TXS 0506+056
2) the absorption-only model for extragalactic γ-ray propagation – account only γγ pair production and adiabatic losses (redshift) (for intergalactic cascade models see Dzhatdoev et al., A&A, **603**, A59 (2017); application to TXS 0506+056: Halzen et al., ApJ Lett., **874**, L9 (2019))
3) the approximation of Jones, Phys. Rev. D., **167**, 1159 (1968), eq. 9 for inverse Compton (IC)
4) classical theory for synchrotron radiation, ultra-relativistic approximation
5) photohadronic processes: Kelner & Aharonian (2008), pp: Kelner et al. (2006)
6) model-dependent confidence levels for the neutrino “flare” flux from Strotjohann et al., A&A, **622**, L9 (2019), Table 1, the “FSRQ-standard candle” model
(they accounted for the Eddington bias!)

Some models of neutrino emission from active galactic nuclei: Stecker et al. (1991); Mannheim (1993); Nellen et al. (1993); Kalashev et al. (2015)

Some models of ν/γ-ray emission from TXS 0506+056:

1) Gao et al. (2019) (Doppler factor D around 20-30); 2) Cerruti et al. (2018) – γ-rays mainly from synchrotron-self-Compton (SSC) of a "blob";

3) Keivani et al. (2018);

4) Ansoldi et al. (2018) (external Compton spine-sheath scenario);

5) Liu et al. (2019); 6) Sahakyan (2018) – pp scenarious for the "flare"

7) Wang et al. (2018) – pp scenario for the "cluster"

Constraints on photohadronic models: Reimer et al. (2018); Rodriguez et al. (2019)

The origin of external photon fields from collision of two jets/blobs: Britzen et al. (2019)

External Compton emission may have significantly sharper beaming pattern ($\sim D^6$) than the SSC component ($\sim D^4$) (Dermer 1995 and the followers)

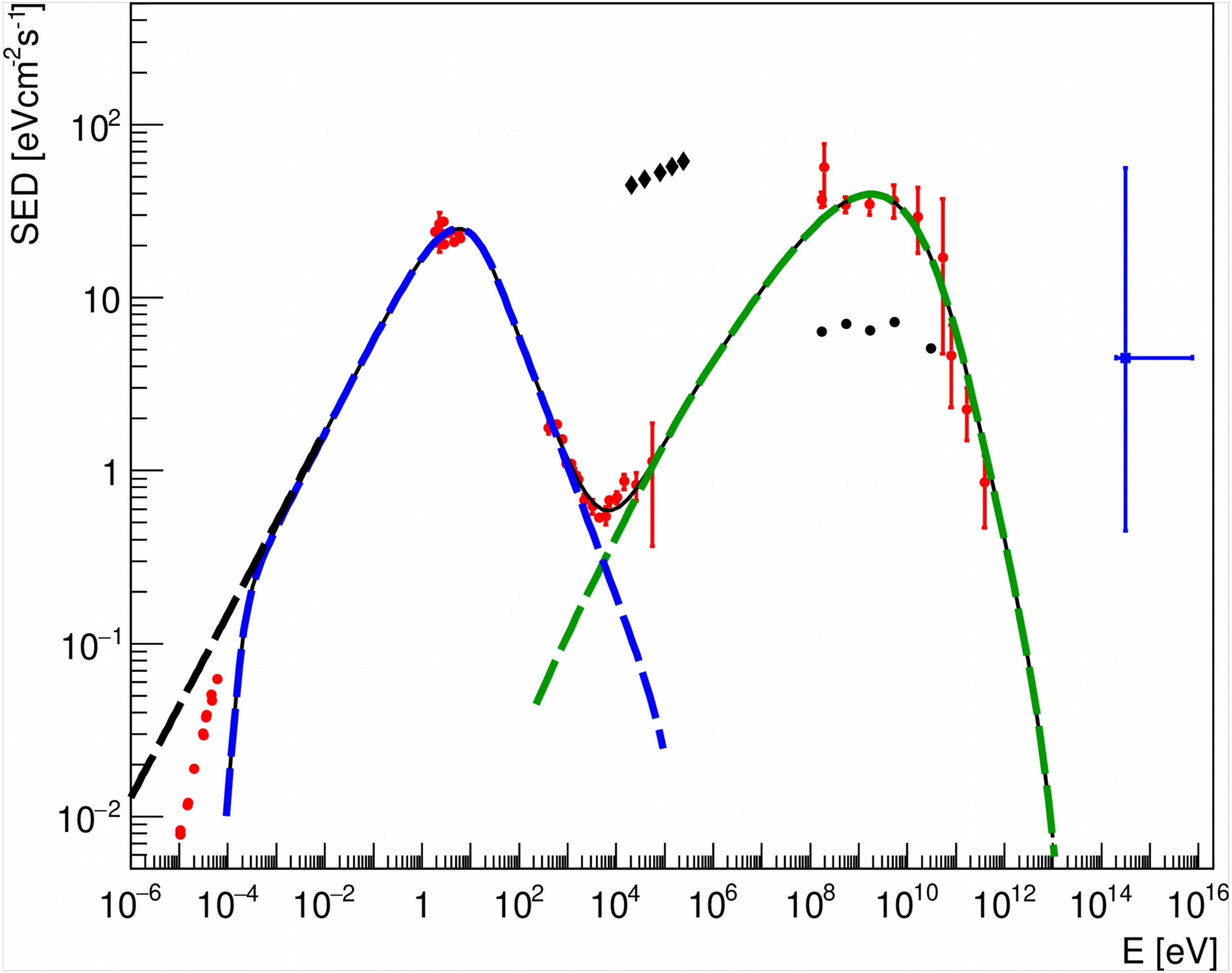
Here we present some preliminary results on a mixed model: a pγ model for the 2017 "flare", and a pp model for the 2014-2015 "cluster"

The 2017 neutrino event and associated photon emission (“the flare”)

technically, we consider emission from a “blob” (Doppler factor D= 30)

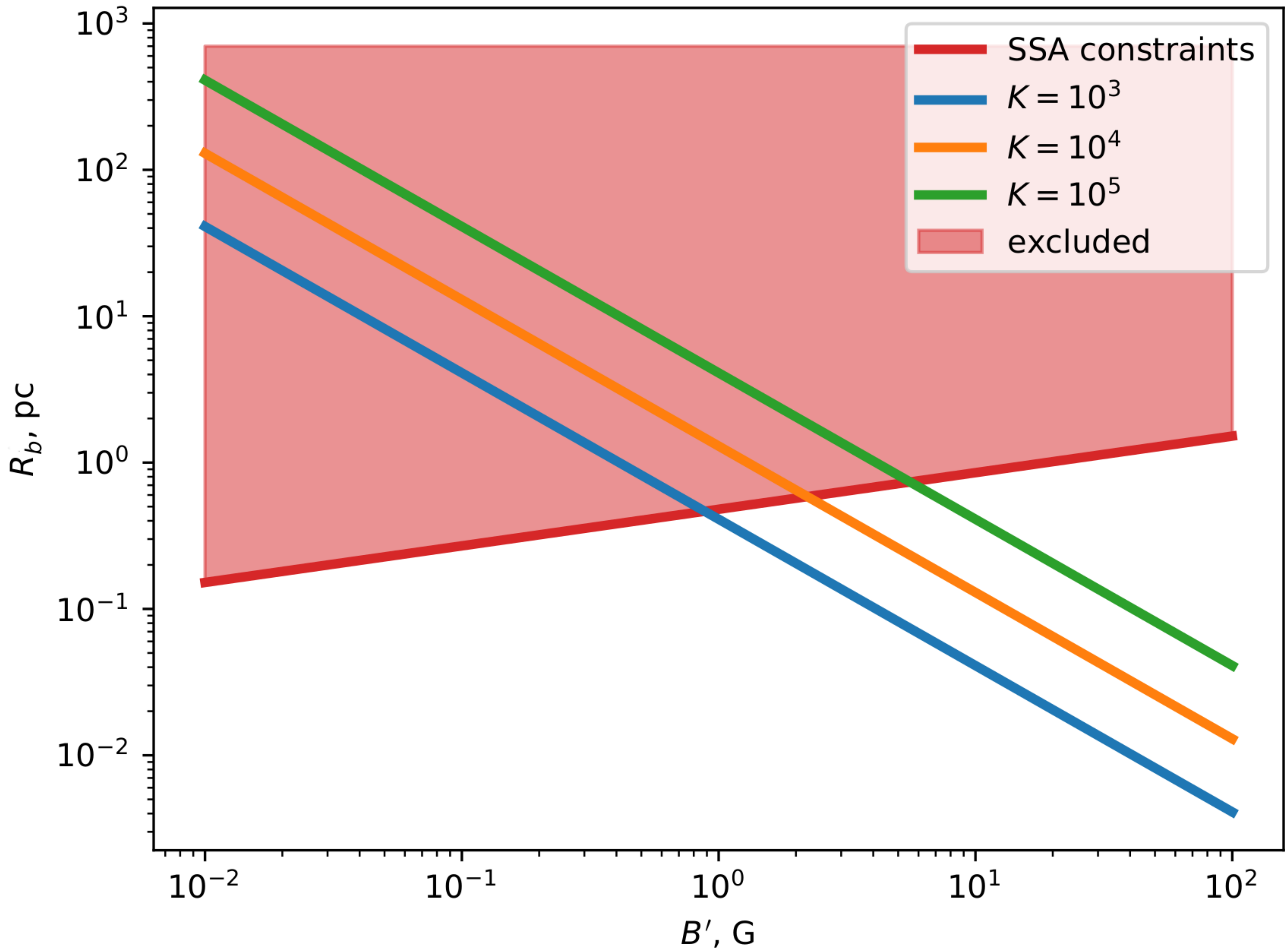
Primed quantities are measured in the blob rest frame

Relevant photon data: red, archival: black circles, INTEGRAL upper limit: black diamonds. SSC model for photons (R_b= 0.03 pc, B'= 0.05 G); neutrino (blue cross) production on the synchrotron spectrum "tail": any problem?

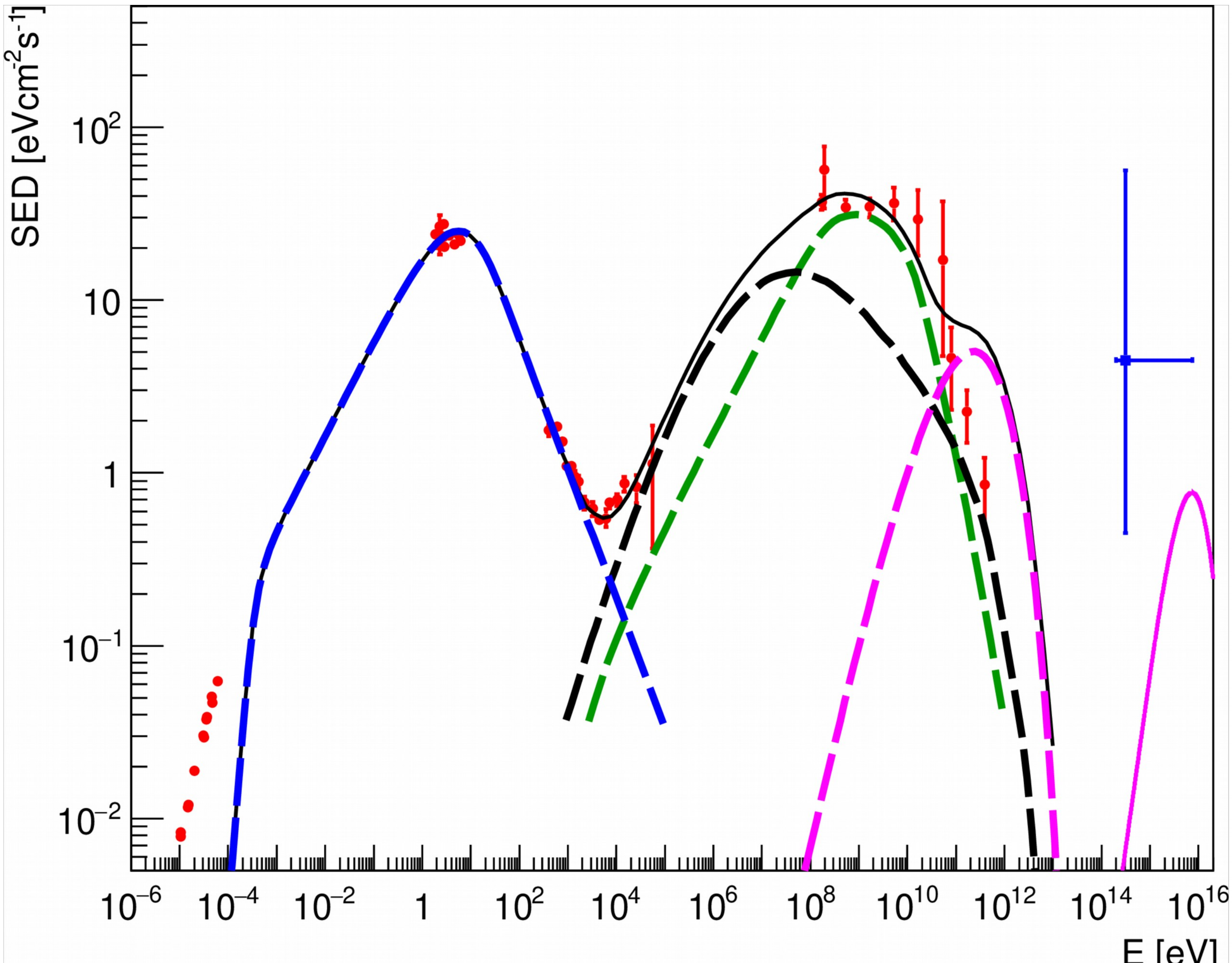


Energy density $u_p < u_B$ + synchrotron self absorption constraints

$K = L_p/L_e$



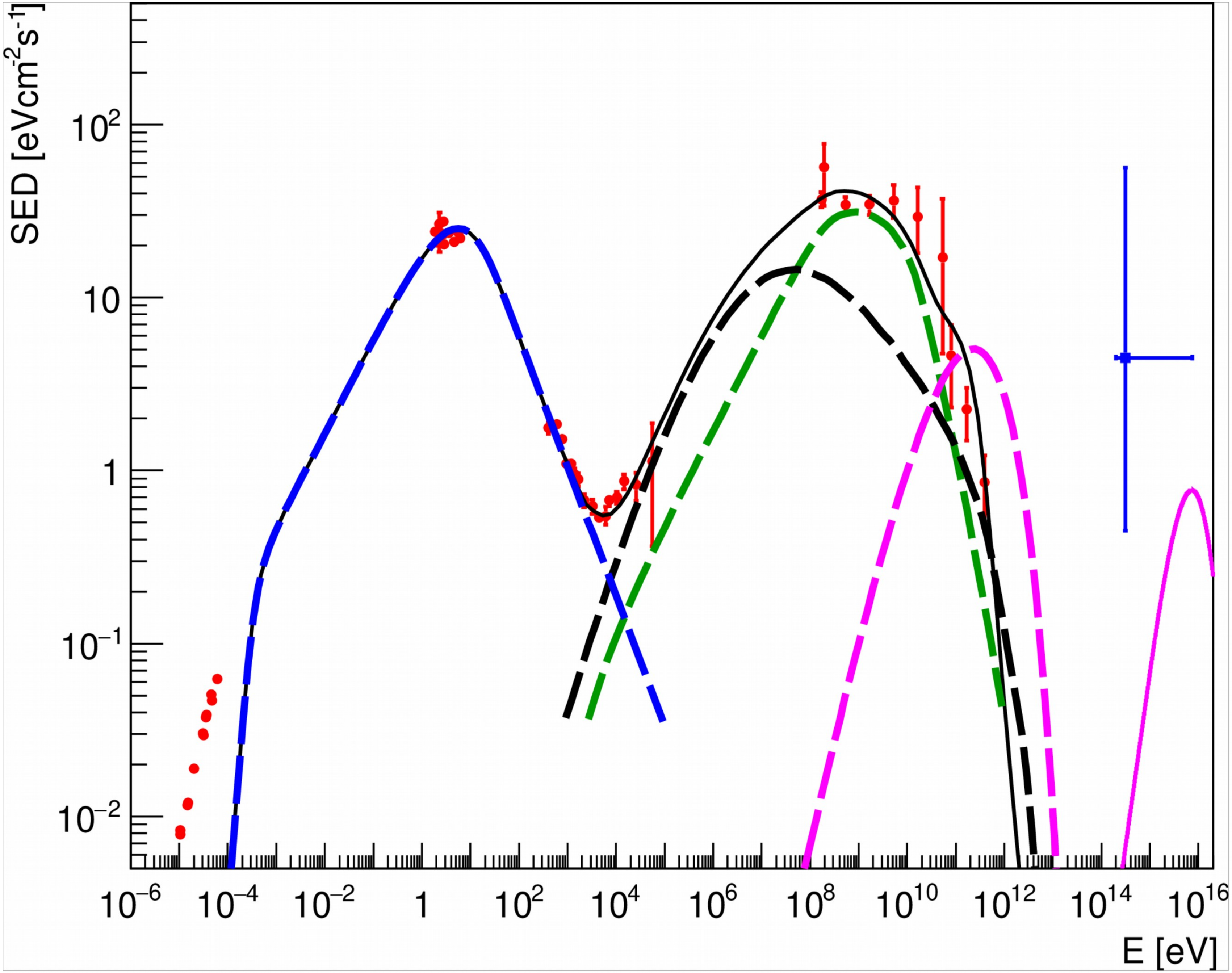
Hybrid EC multiple synchrotron/hadroleptonic model (B'= 1 G) (external Compton – green, synchrotron from BH electrons – black, synchrotron from “hadronic electrons” – magenta dashed, muon neutrinos – magenta solid)



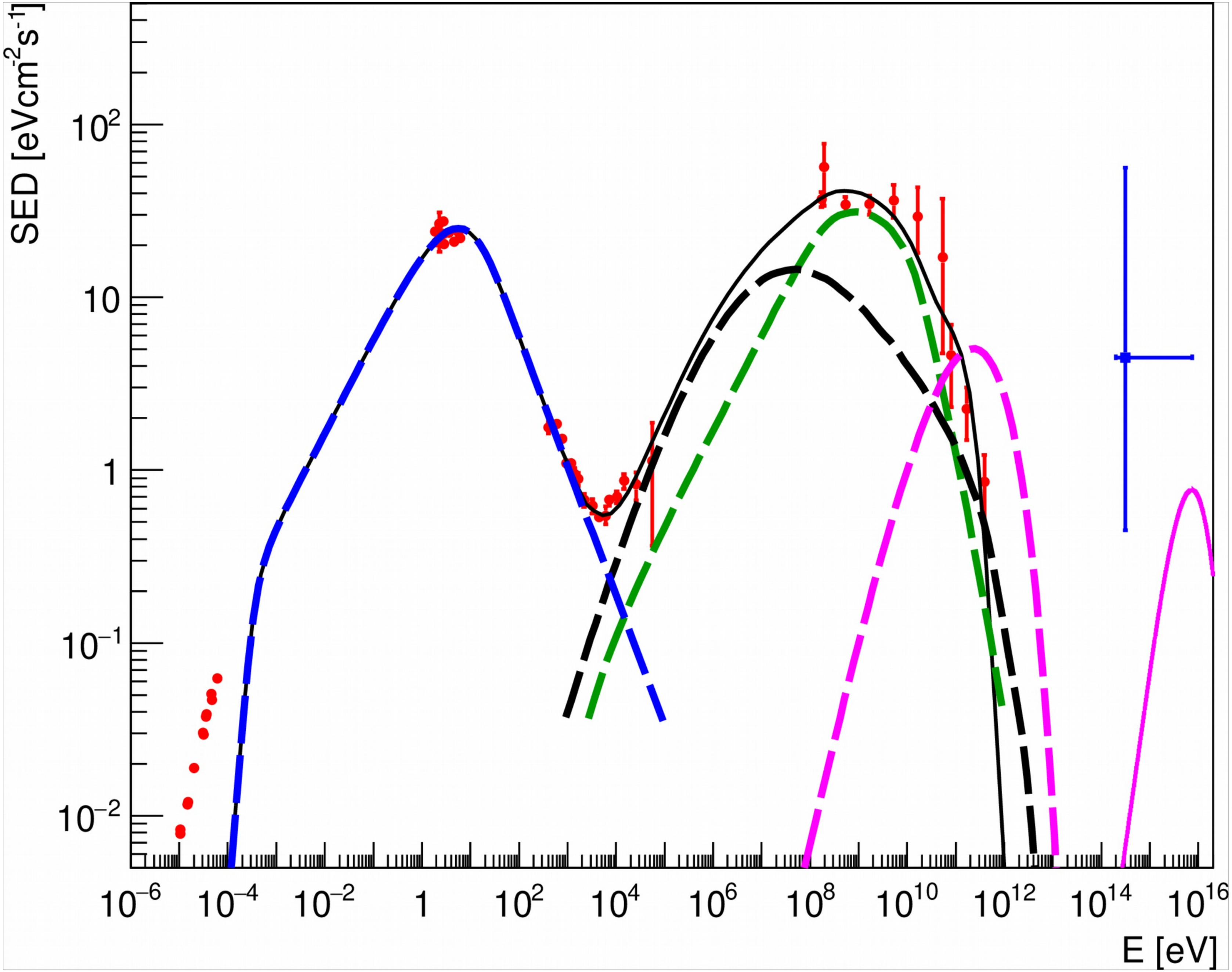
Ansoldi et al. (2018): “The absorption of gamma-rays during their propagation to the observer caused by γγ interactions with the extragalactic background light is modeled following Domínguez et al. (2011), and is expected to be minor at the measured redshift of TXS 0506+056 at energies below 400 GeV (∼10% at 400 GeV and ∼50% at 4 TeV).”

In fact, at E= 1 TeV $\tau>2$ for $z>0.2$ (Gilmore et al., 2012). Intergalactic γγ absorption is still more important for z= 0.33! See also Franceschini et al. (2008), (2017); Finke et al. (2009); Kneiske & Dole (2010), Stecker et al. (2016), etc.

Hybrid multiple synchrotron/hadroleptonic model
(Gilmore et al, 2012 – “nominal” absorption)



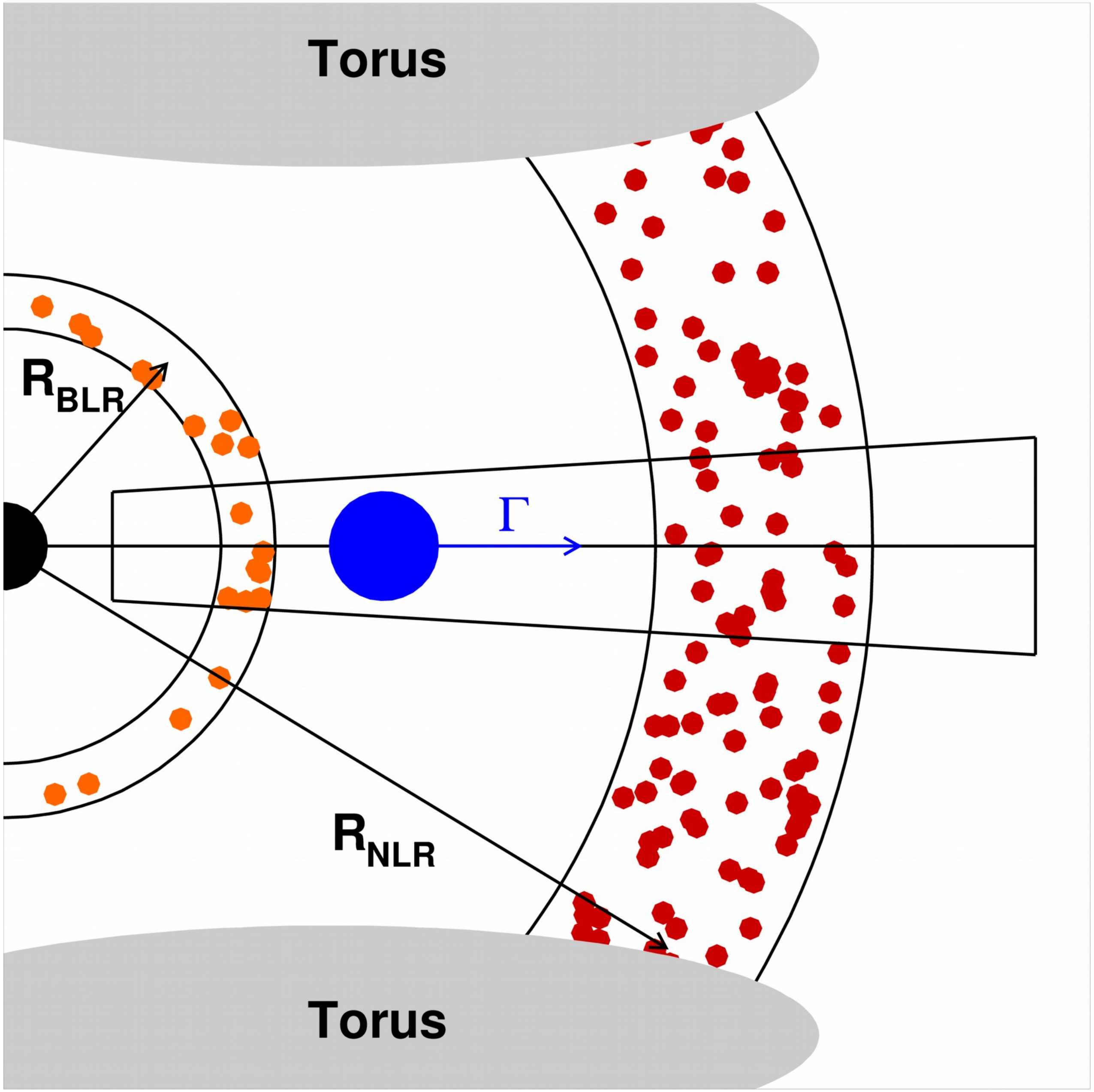
Hybrid multiple synchrotron/hadroleptonic model
(Gilmore et al, 2012 – 150 % absorption)



The 2014-2015 neutrino events and associated photon emission ("the cluster")

We were not able to propose any reasonable photohadronic model for this episode so far. Given that TXS 0506+056 is likely a flat-spectrum radio quasar (FSRQ), and not a Bl Lacertae (Bl Lac) object, we consider hadronuclear (pp) models instead. We build on the model of Dar & Laor (1997).

Broad line region (BLR), dusty torus (DT), narrow line region (NLR): an additional source of photon fields and gas clouds



R_{BLR}= 0.03 pc

R_{DT}= 1 pc

N_{BLR}= 10^{24} 1/cm^2

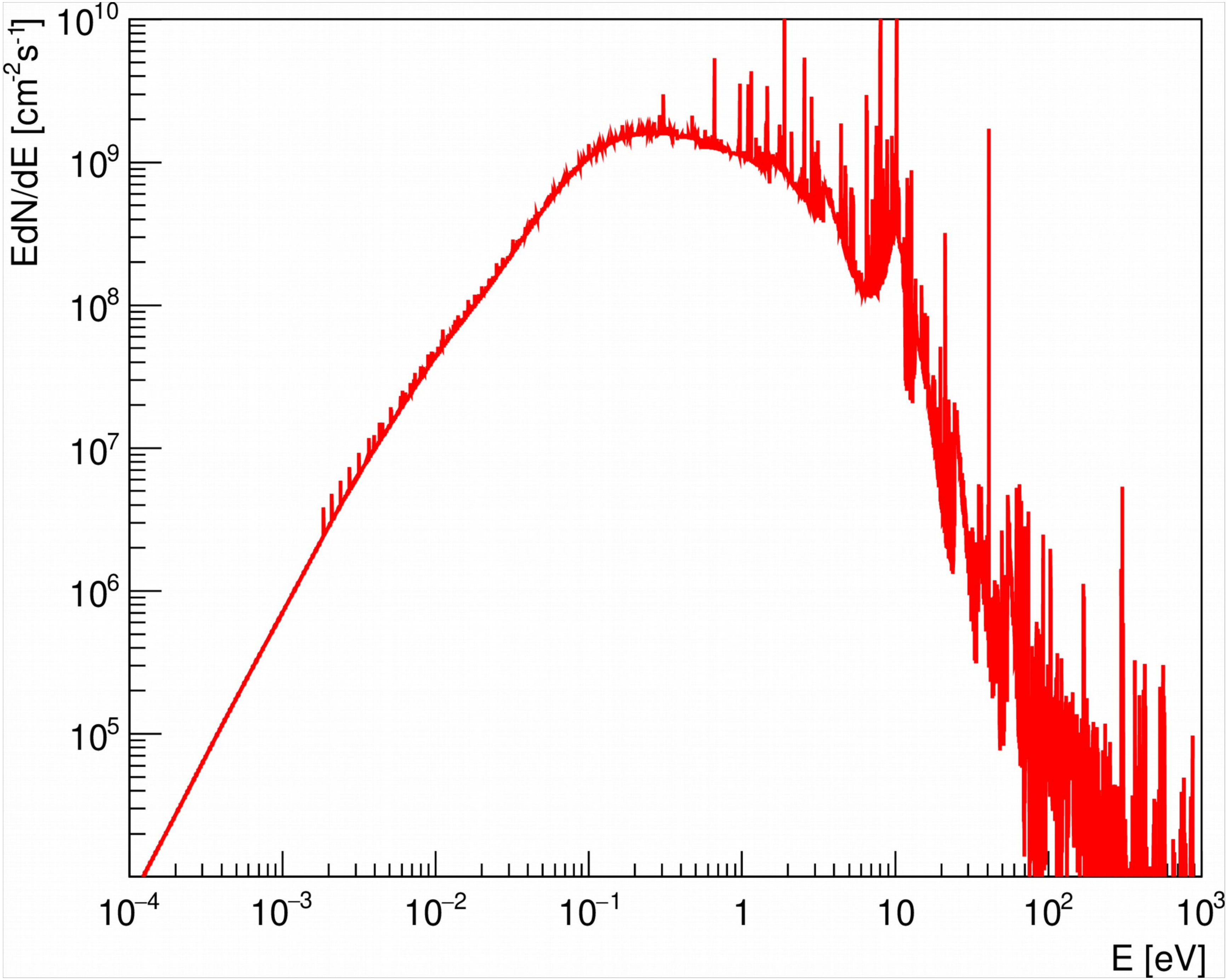
N_{NLR}= 10^{23} 1/cm^2

C= 0.1

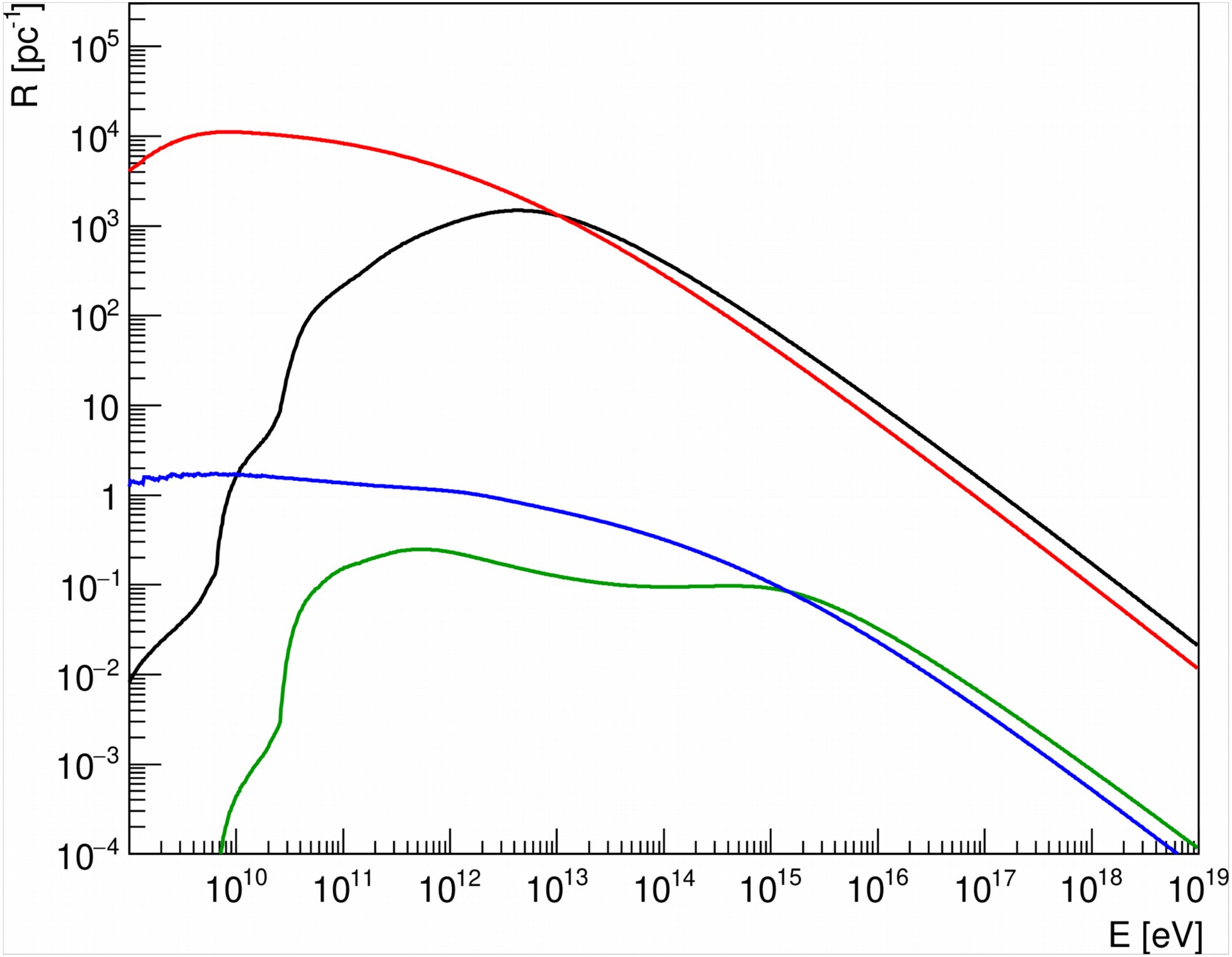
T= 10^5 K

L= 10^{45} erg/s

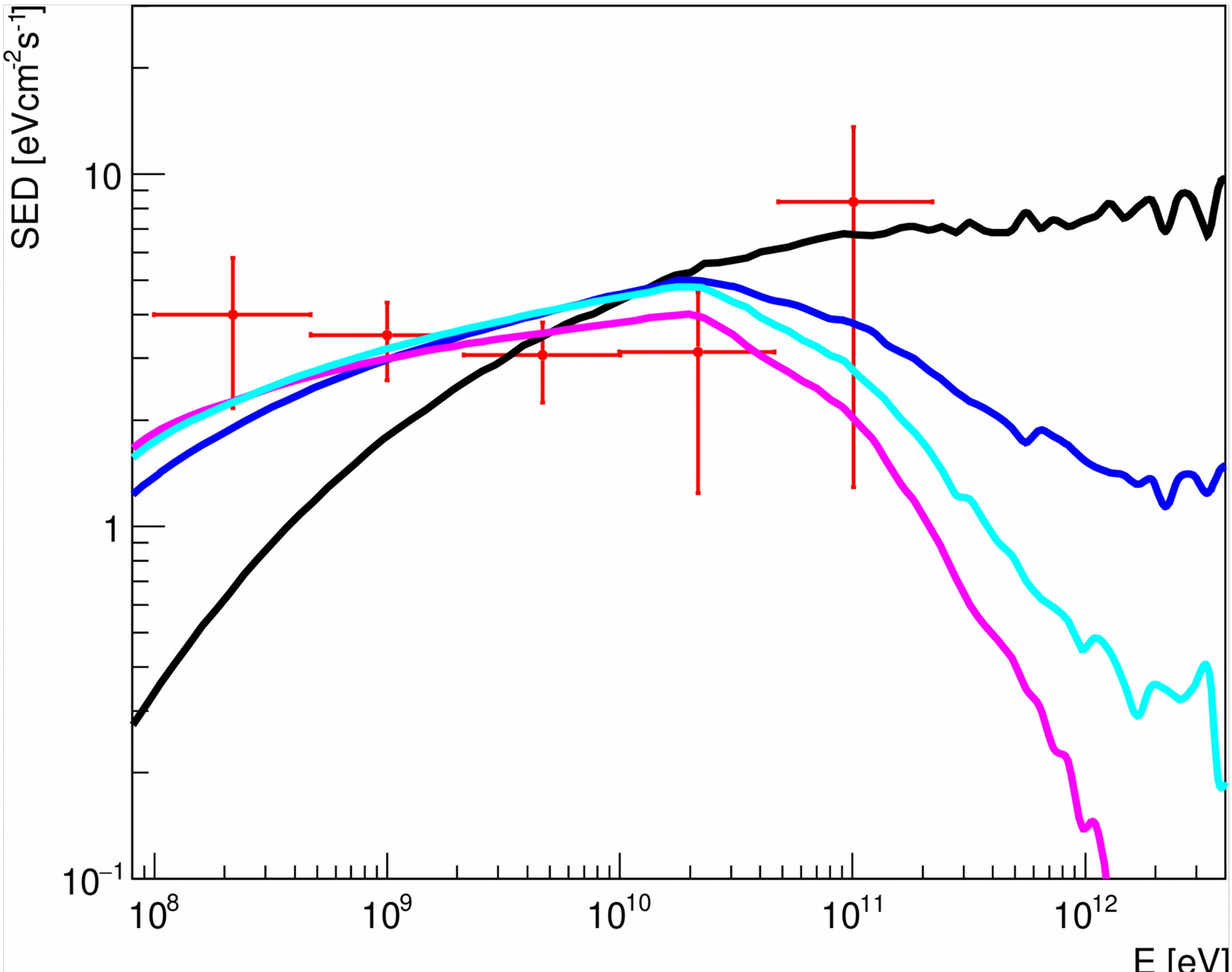
BLR flux calculated with the CLOUDY publicly-available code (Ferland et al. (2013))



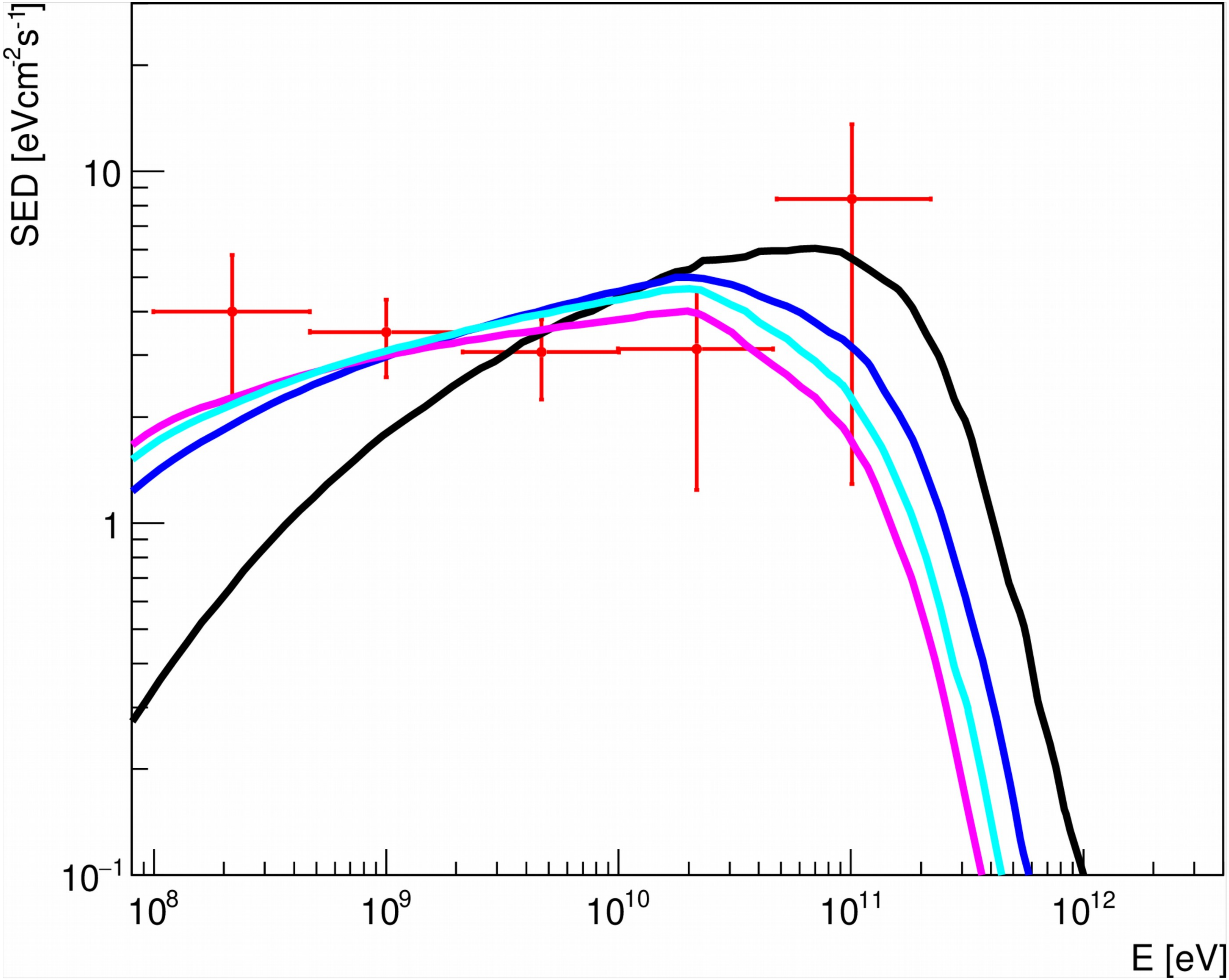
Interaction rates on the BLR for γ-rays (black) and electrons (red, secondary photon energy> 3 MeV) and DT/NLR photon fields (γ-rays: green, electrons: blue)



Black: (100TeV, cloud embedded by f= 0.05 of the BLR radius); blue: (100TeV, 0.2); magenta: (10 TeV, 0.2); cyan: (30 TeV, 0.2). Fermi-LAT data are taken from Garrappa et al. (2019)

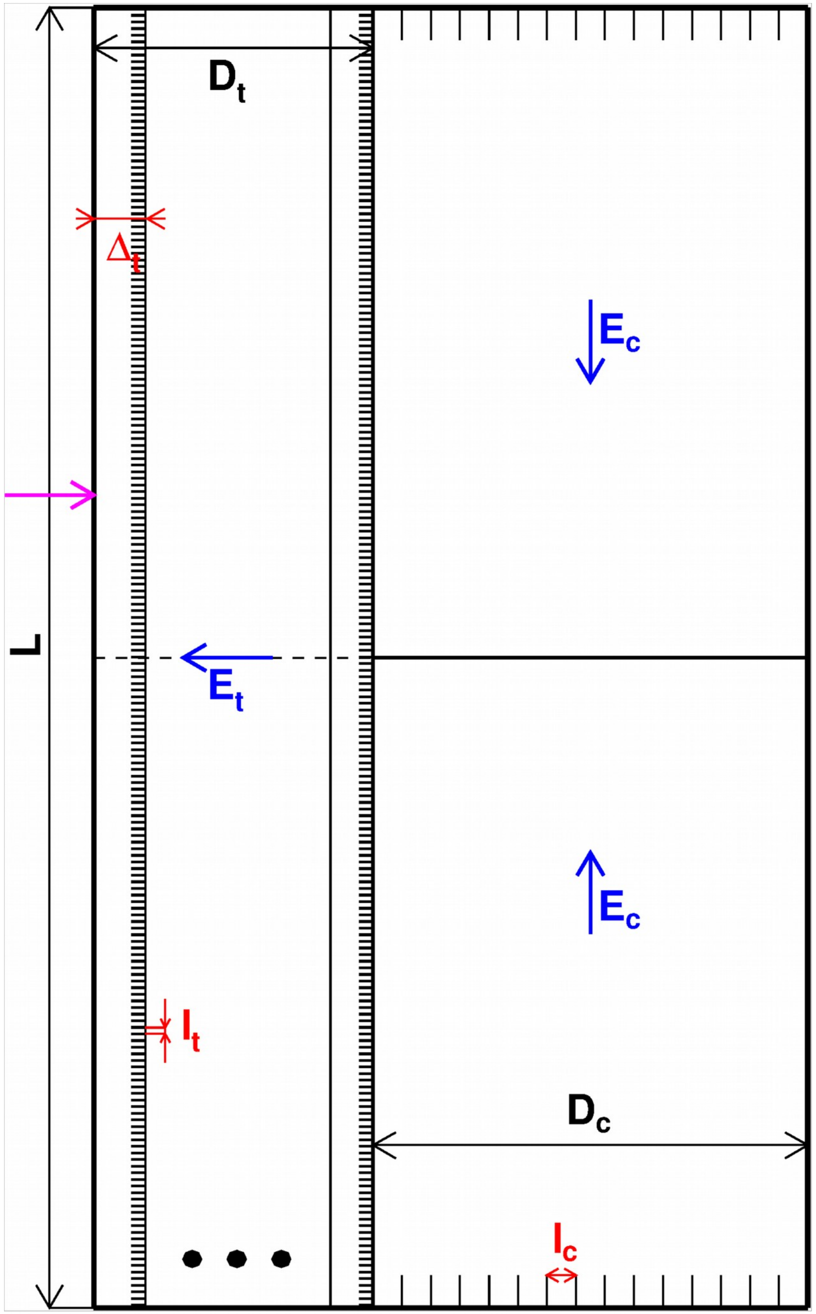


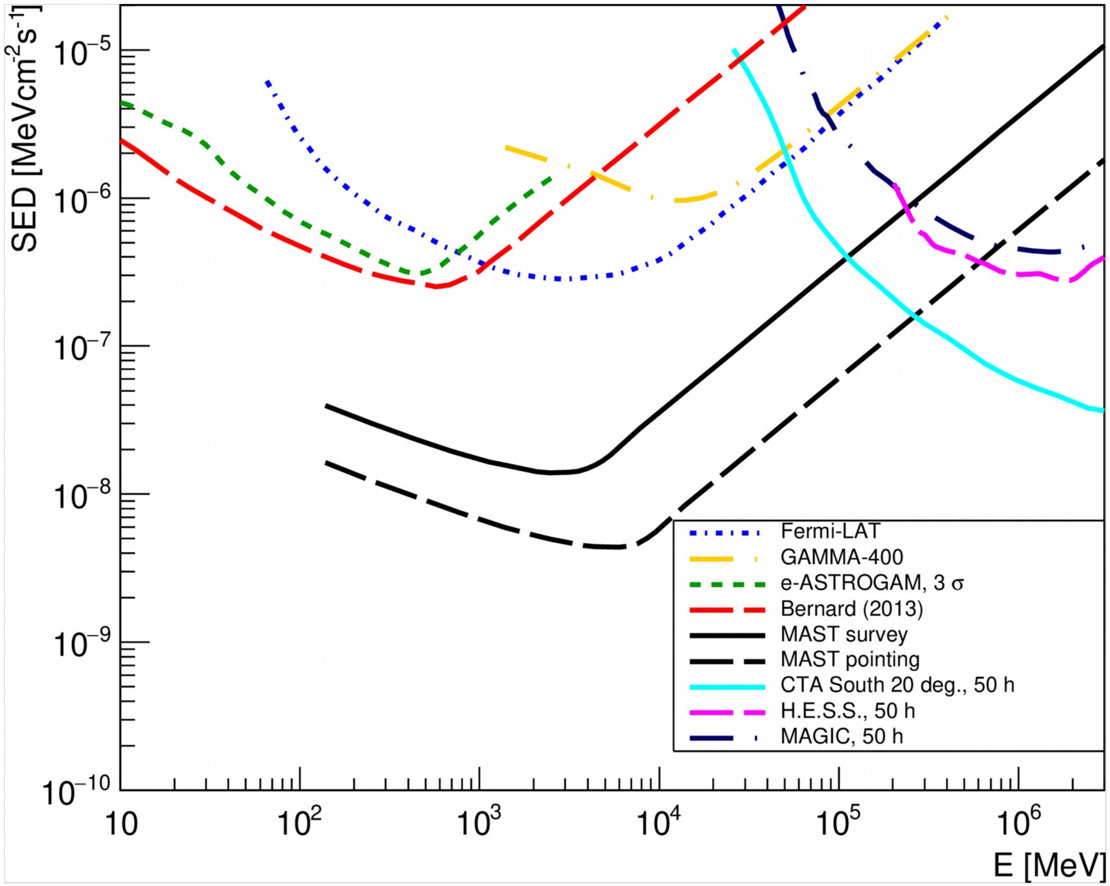
The same with intergalactic absorption included



The future: does Fermi-LAT need a successor?

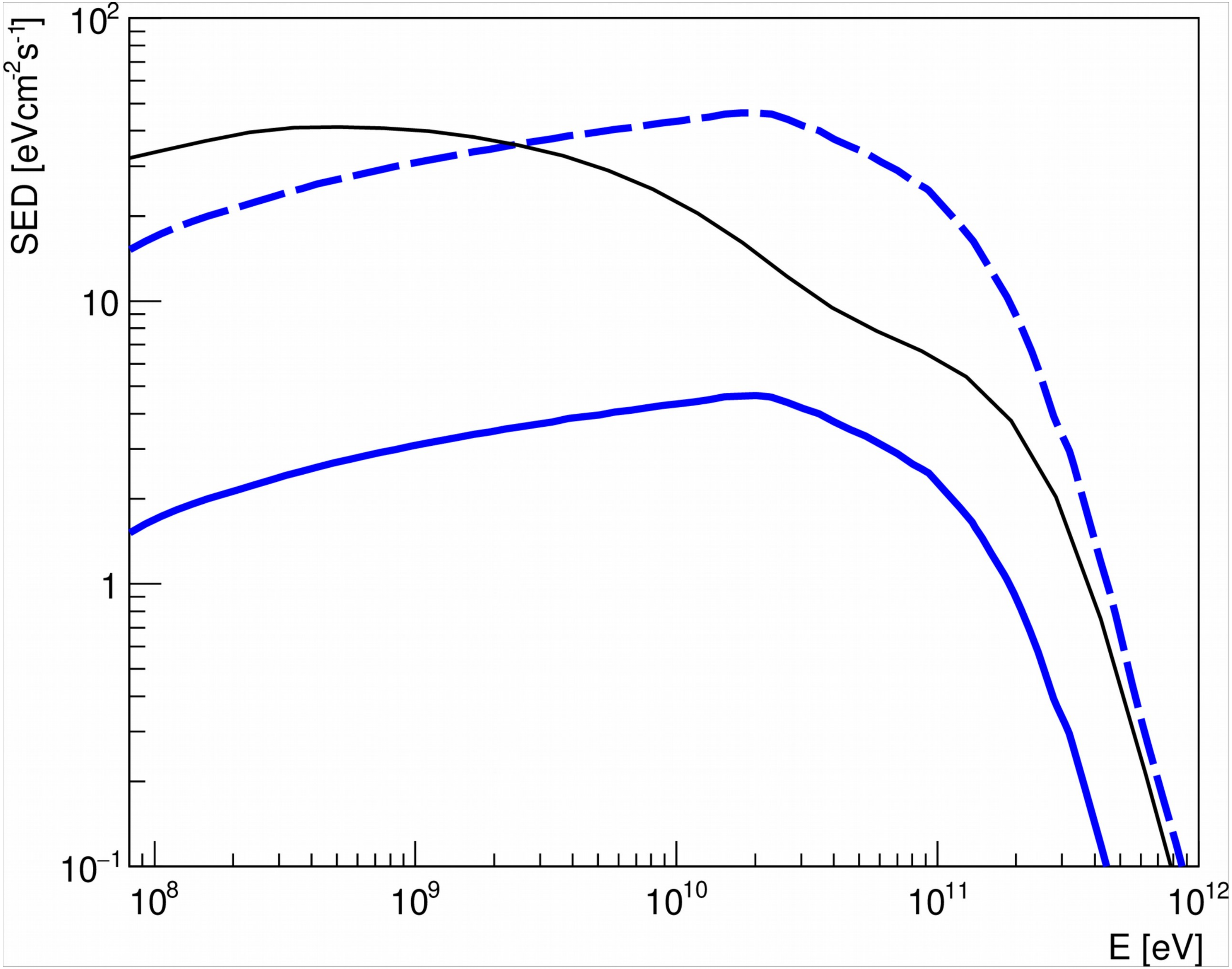
We propose heavy TPC (~30-40 t) called MAST
Dzhatdoev& Podlesnyi, Aph, **112**, 1 (2019)





Excellent performance (~1-2 orders of magnitude better sensitivity than for the case of Fermi LAT)

MAST will be able to discriminate between the models!
(a more detailed sensitivity study is in progress!)



Conclusions

Notwithstanding the small number of detected neutrinos, constraints on the models are already quite strong.

1) External photon fields are required at least for neutrino production.

2) Hybrid external Compton model can fit the data for the 2017 episode ("the flare"). The colliding blobs/jets scenario (Britzen et al., 2019) could explain the origin of the external photon field.

3) Intergalactic absorption is important for the blazar TXS 0506+056 at very high energies.

4) Here we present, for the first time, a detailed calculation of EM cascade inside FSRQ with realistic photon fields inside the BLR/DT/NLR complex; the corresponding model well fits the γ-ray spectrum for the 2014-2015 episode ("the cluster") assuming the hadronuclear origin of primary γ-rays and neutrinos.

5) Next-generation gamma-ray telescopes such as MAST will be able to classify the γ-ray episodes by their spectral shape.

6) Diffuse neutrino flux: "an ankle" at the intersection of the photohadronic (pp) and the hadronuclear (pγ) components?

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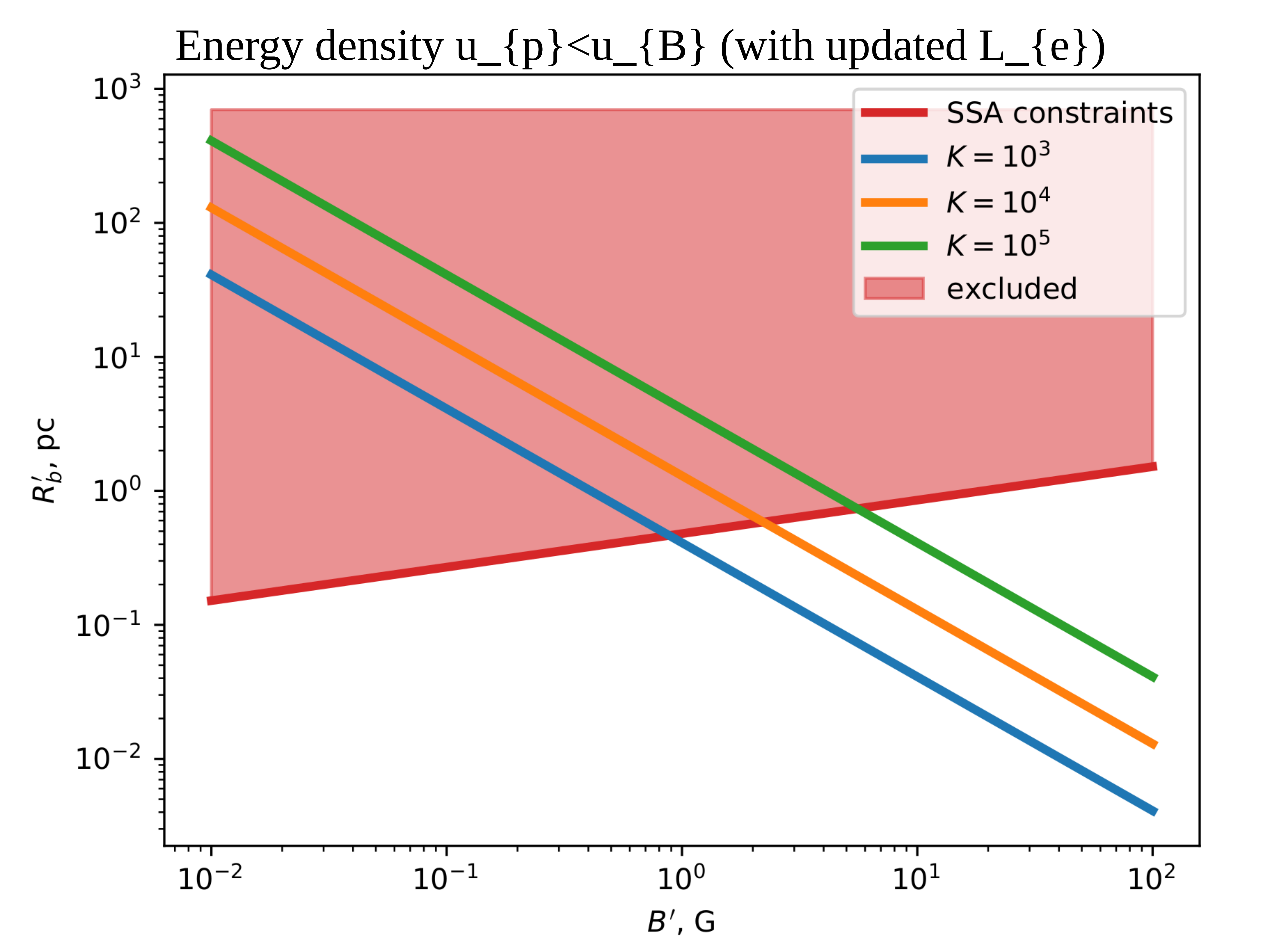
Additional slides

Accounting for the Eddington bias: Table 1 of Strotjohann et al., 2019 (see table below)

Source class	Source density (at $z = 0$) (Mpc^{-3})	#Sources (within $z < 4$)	lumi. variations width of gaussian (dex)	Flux of source det. with one event 5% perc.	Flux of source det. with one event median	Flux of source det. with one event 95% perc.	Eff. density (Mpc^{-3})
FSRQs	6×10^{-10}	530	0 (standard candle)	4×10^{-3}	0.04	0.5	6×10^{-10}
Ajello et al. (2014)			1 (lognorm. $\sigma = 1$)	6×10^{-3}	0.11	1.1	10^{-10}
BL Lac objects	2×10^{-7}	1.2×10^{4}	0	1.9×10^{-4}	6×10^{-3}	0.2	8×10^{-9}
Ajello et al. (2014)			1	3×10^{-4}	0.03	0.7	9×10^{-10}
Galaxy clusters	3×10^{-5}	1.9×10^{6}	0	1.1×10^{-6}	3×10^{-5}	6×10^{-3}	2×10^{-6}
Zandanel et al. (2015)			1	3×10^{-6}	5×10^{-4}	0.2	1.4×10^{-7}
Starburst galaxies	3×10^{-5}	1.8×10^{7}	0	1.3×10^{-7}	1.7×10^{-6}	3×10^{-4}	4×10^{-5}
Gruppioni et al. (2013)			1	2×10^{-7}	3×10^{-5}	1.4×10^{-2}	2×10^{-6}


Energy density u_{p}<u_{B} (with updated L_{e})
SSA constraints
$K = 10^3$
$K = 10^4$
$K = 10^5$
excluded
R'_b, pc
B', G
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3

Semi-analytic model of EM cascade in the universal regime