emission models for extreme blazars


[redacted]

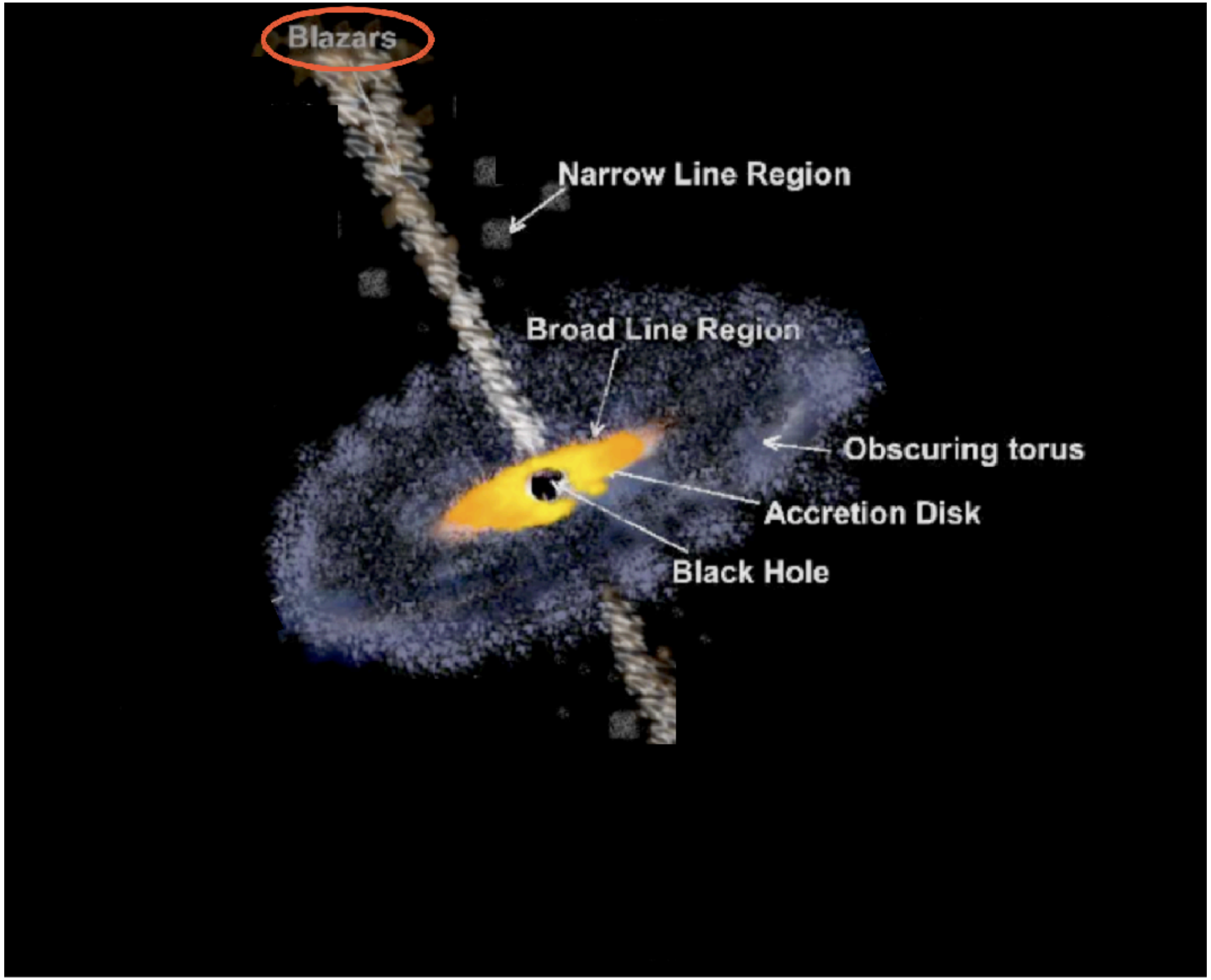
Andreas Zech

HEASA Conference 2024

LUTH Observatoire de Paris | PSL

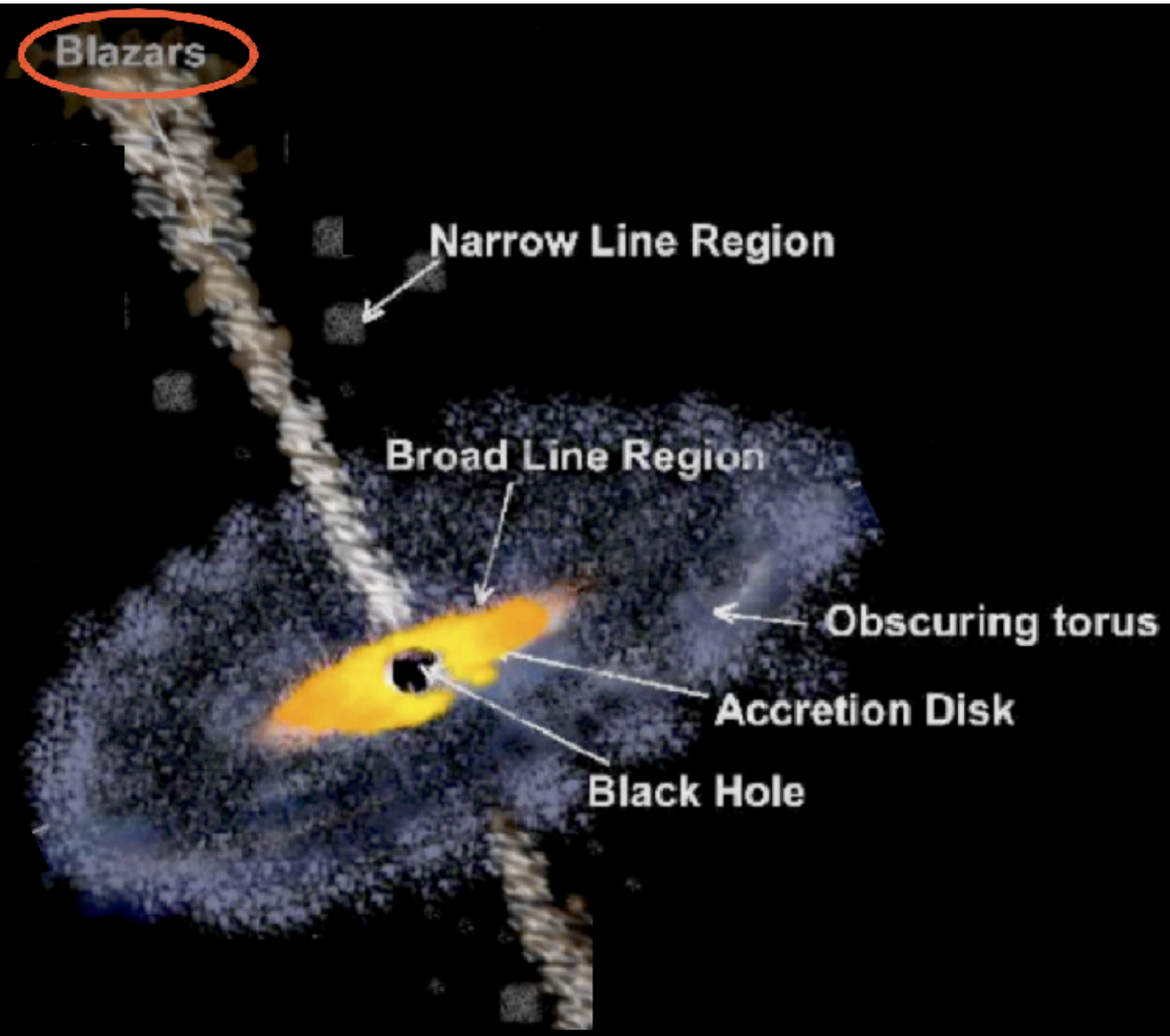
a short introduction to blazars

blazars



Blazars
Narrow Line Region
Broad Line Region
Obscuring torus
Accretion Disk
Black Hole

blazars



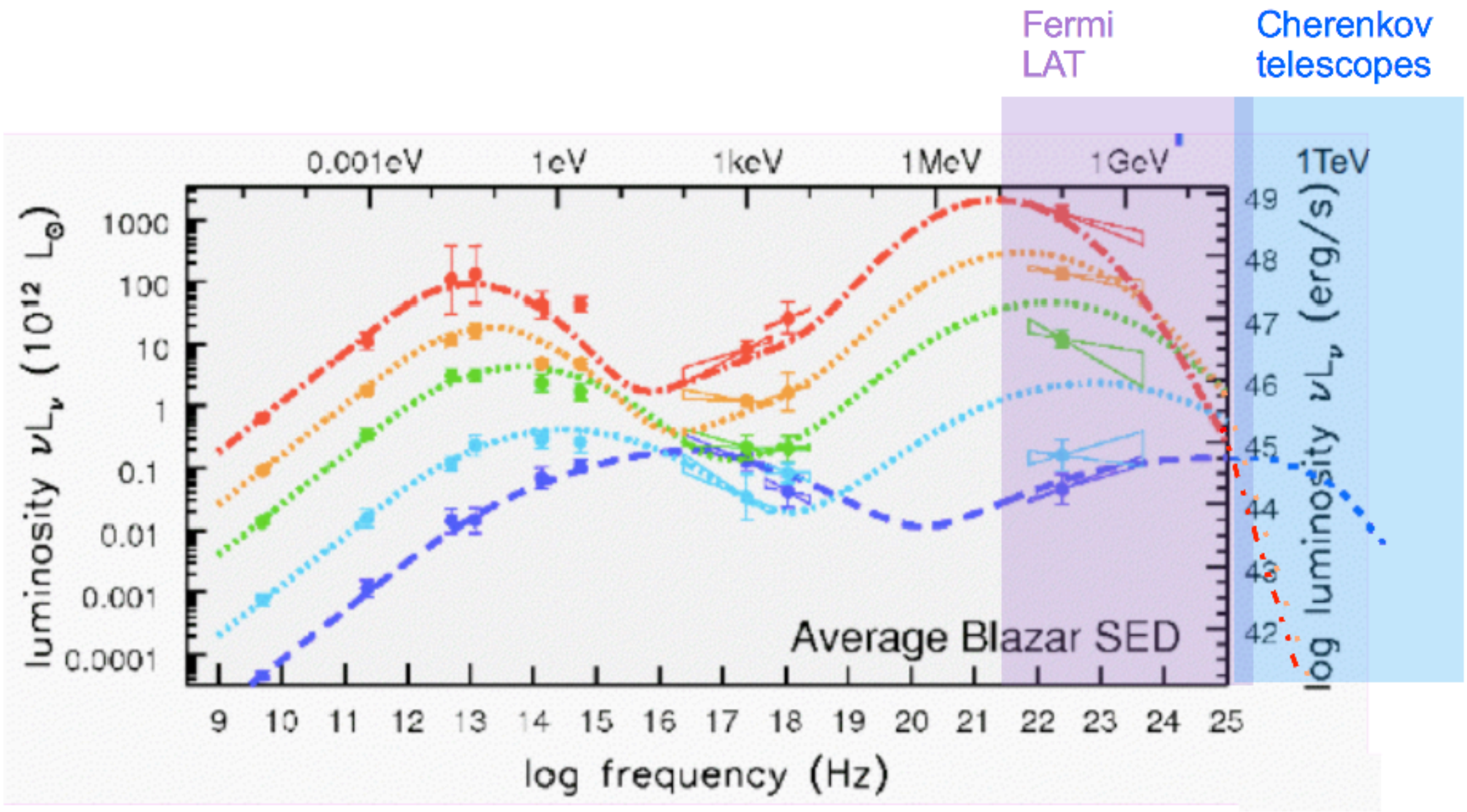
relativistic beaming

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

$$I_\nu(\nu) = \delta^3 I'_\nu(\nu')$$
$$\Delta t = \Delta t' / \delta$$

the "blazar sequence"

FSRQs (flat-spectrum radio quasars)
- high jet luminosity & low peak frequencies
- high disk luminosity (radiatively efficient accretion disk) -> strong photon fields (disk, corona, torus, BLR)



(*Fossati et al. 1998*)

BL Lac objects (LBLs, IBLs, HBLs, UHBLs)
- low jet luminosity & high peak frequencies
- low disk luminosity (ADAF?) -> low photon fields

the "blazar sequence"

FSRQs (flat-spectrum radio quasars)
- high jet luminosity & low peak frequencies
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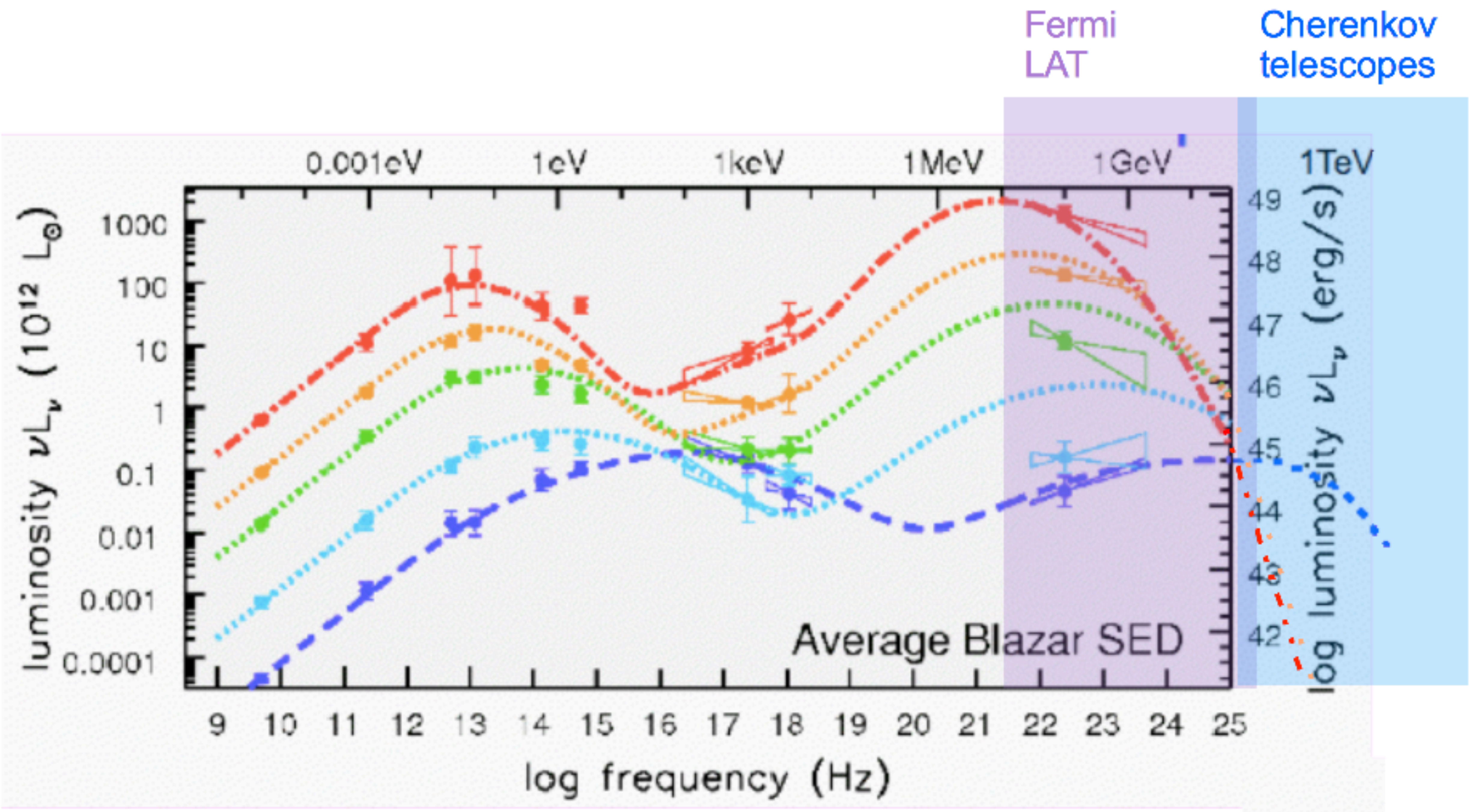
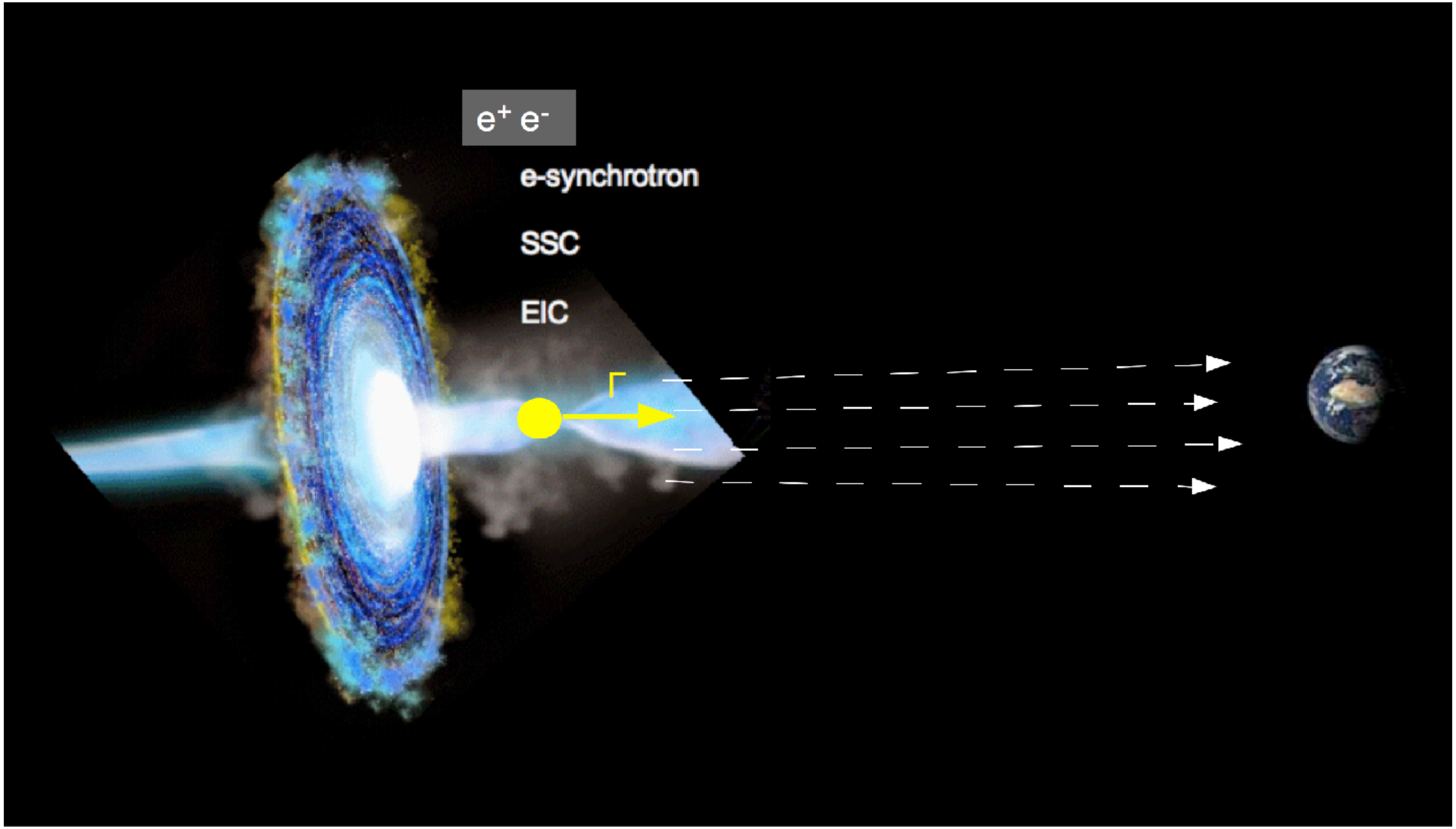


(*Fossati et al. 1998*)

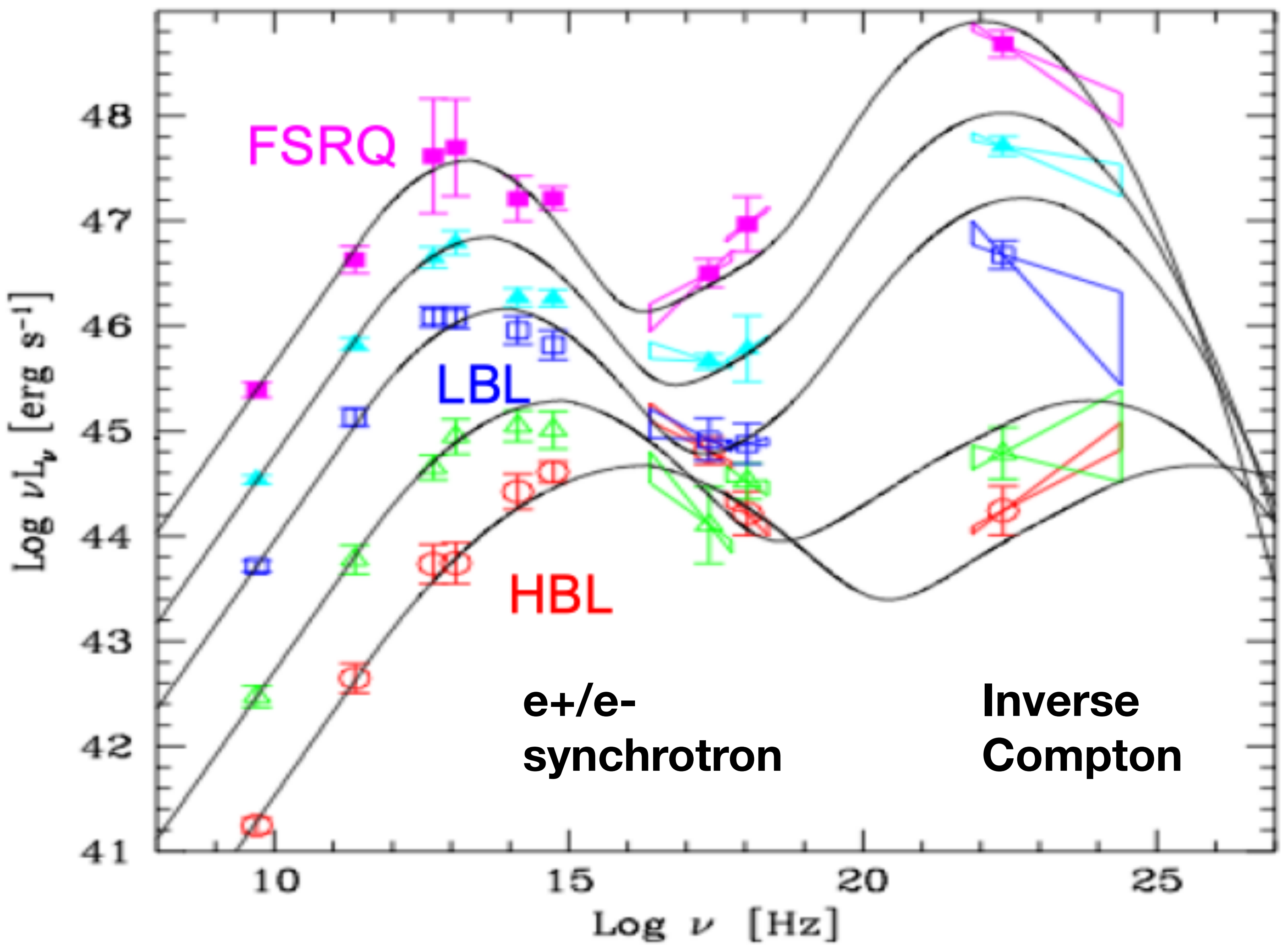
extreme blazars

BL Lac objects (LBLs, IBLs, HBLs, UHBLs)
- low jet luminosity & high peak frequencies
- low disk luminosity (ADAF?) -> low photon fields

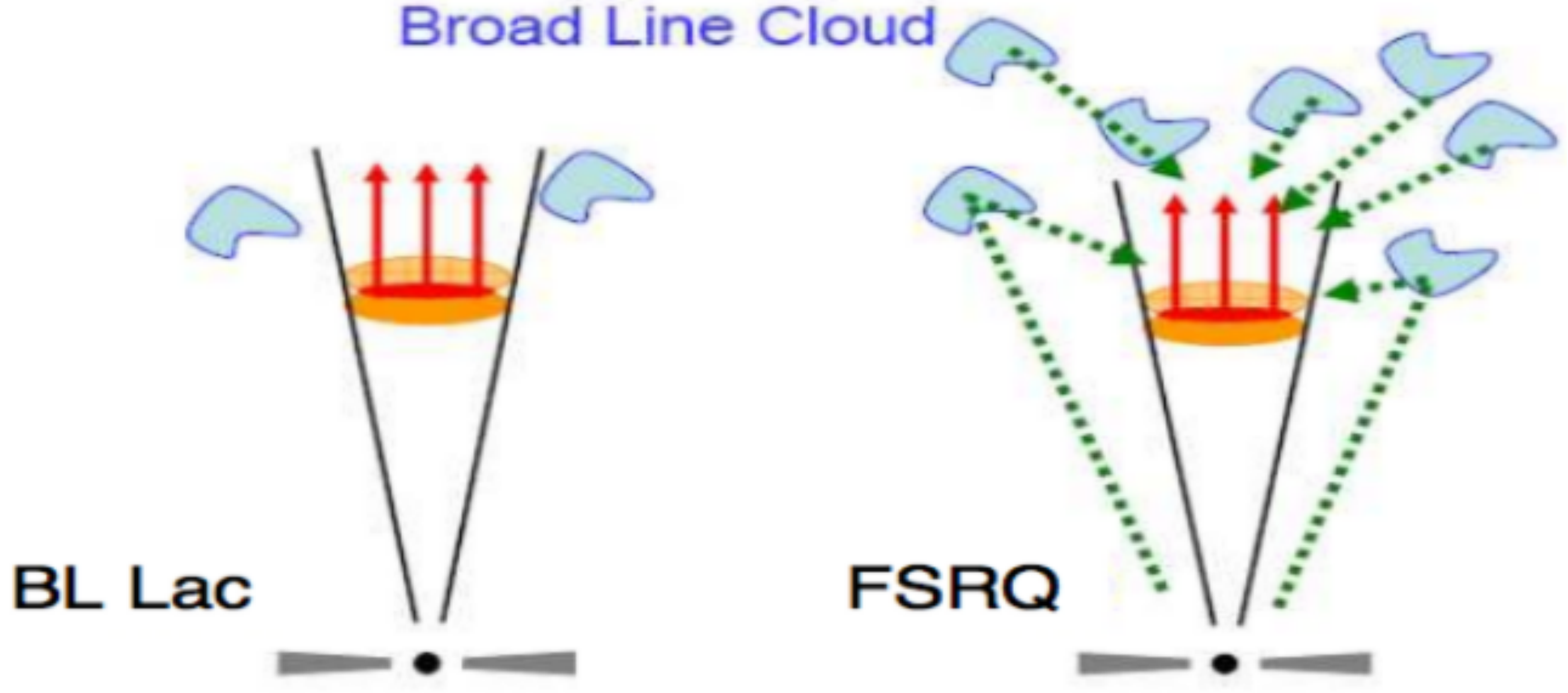
leptonic emission models



blazar emission in the leptonic scenario



Donato et al. (2002), based on Fossati et al. (1998)



B. Lott, Cospar 02/10

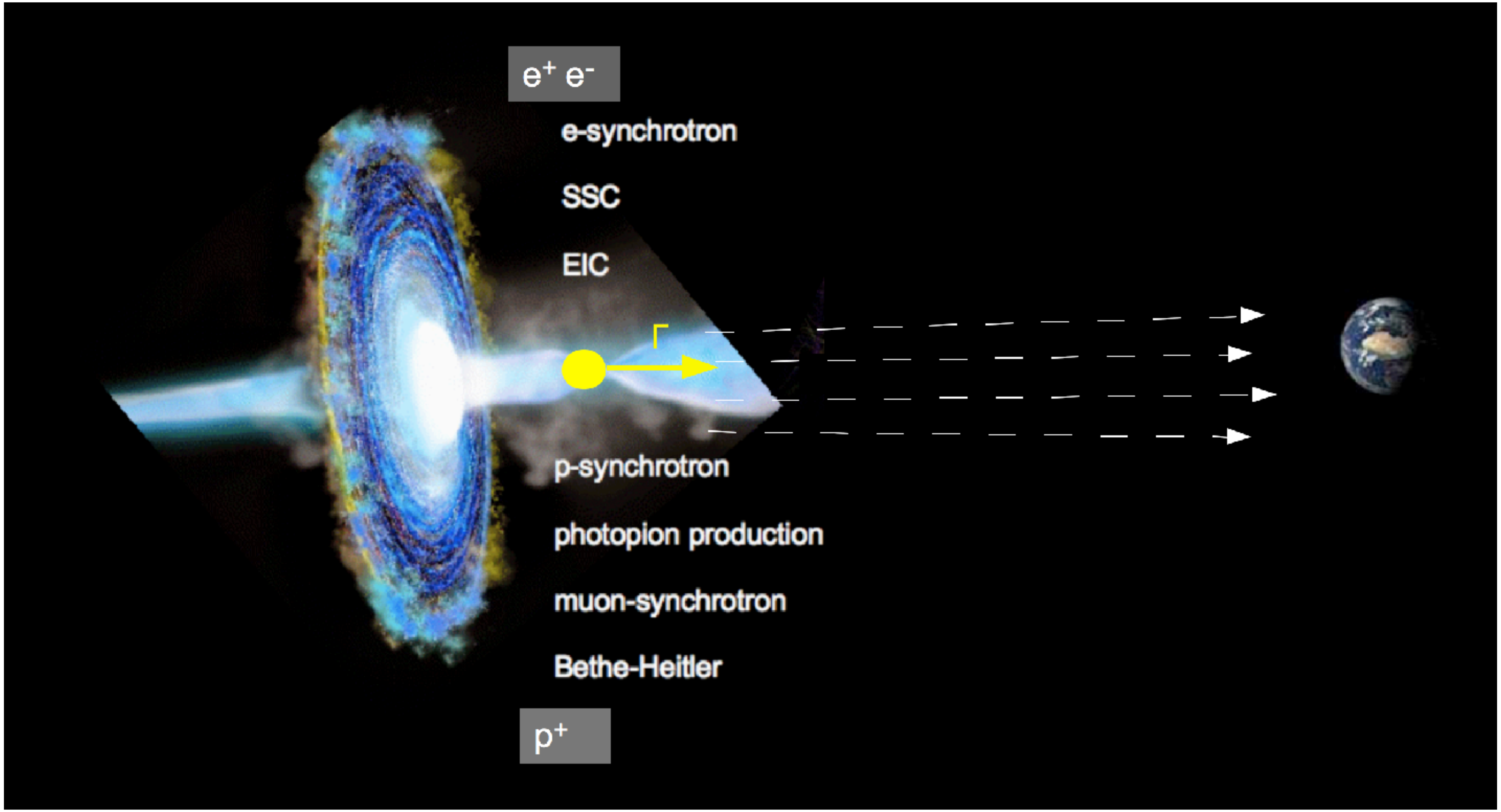
- weak emission from disk and broad line region

- γ-rays due to Synchrotron Self-Compton

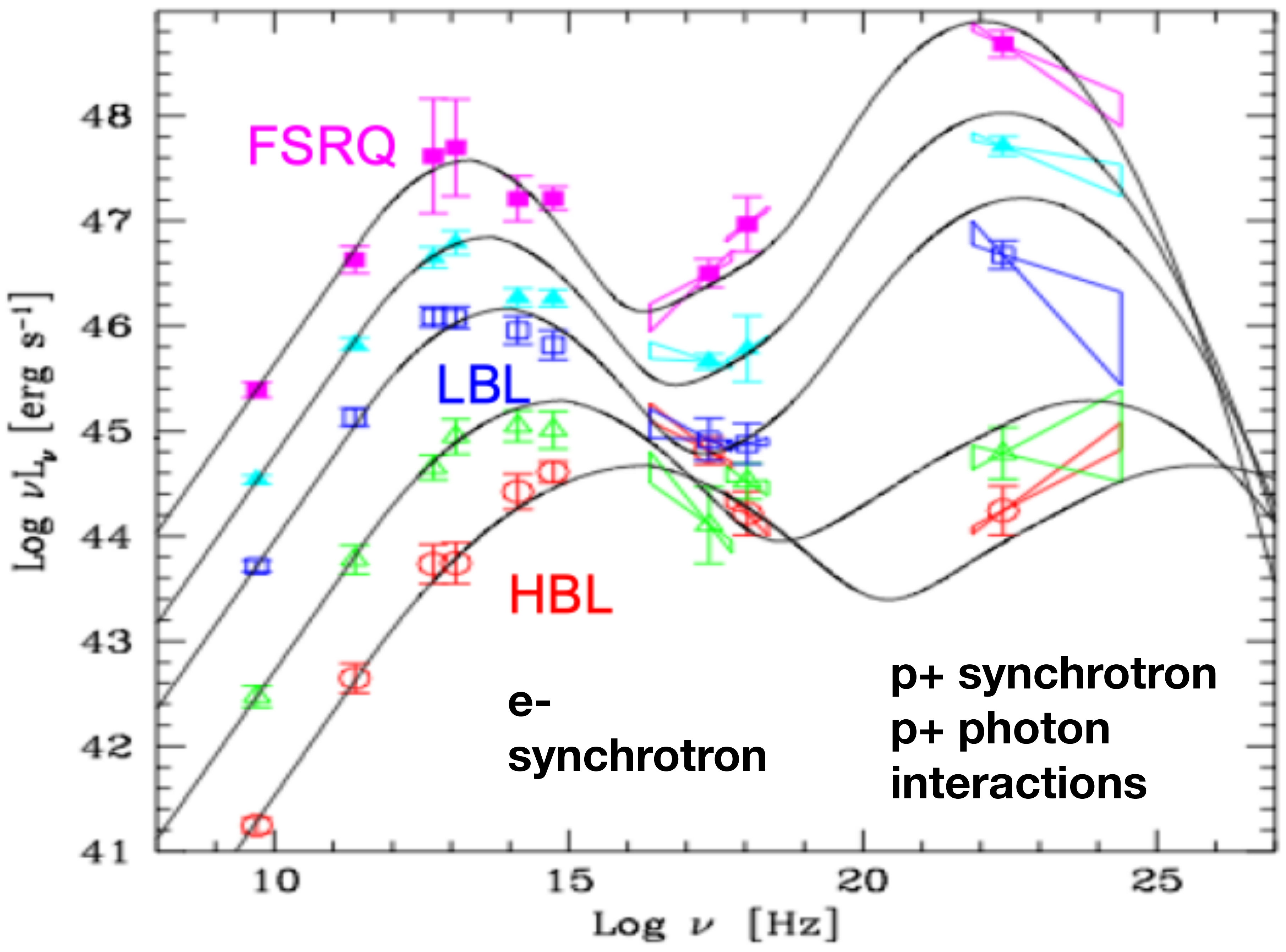
- strong emission from disk and broad line region

- γ-rays due to Synchrotron Self-Compton & External Inverse Compton -> high Compton dominance

lepto-hadronic emission models



blazar emission in the lepto-hadronic scenario



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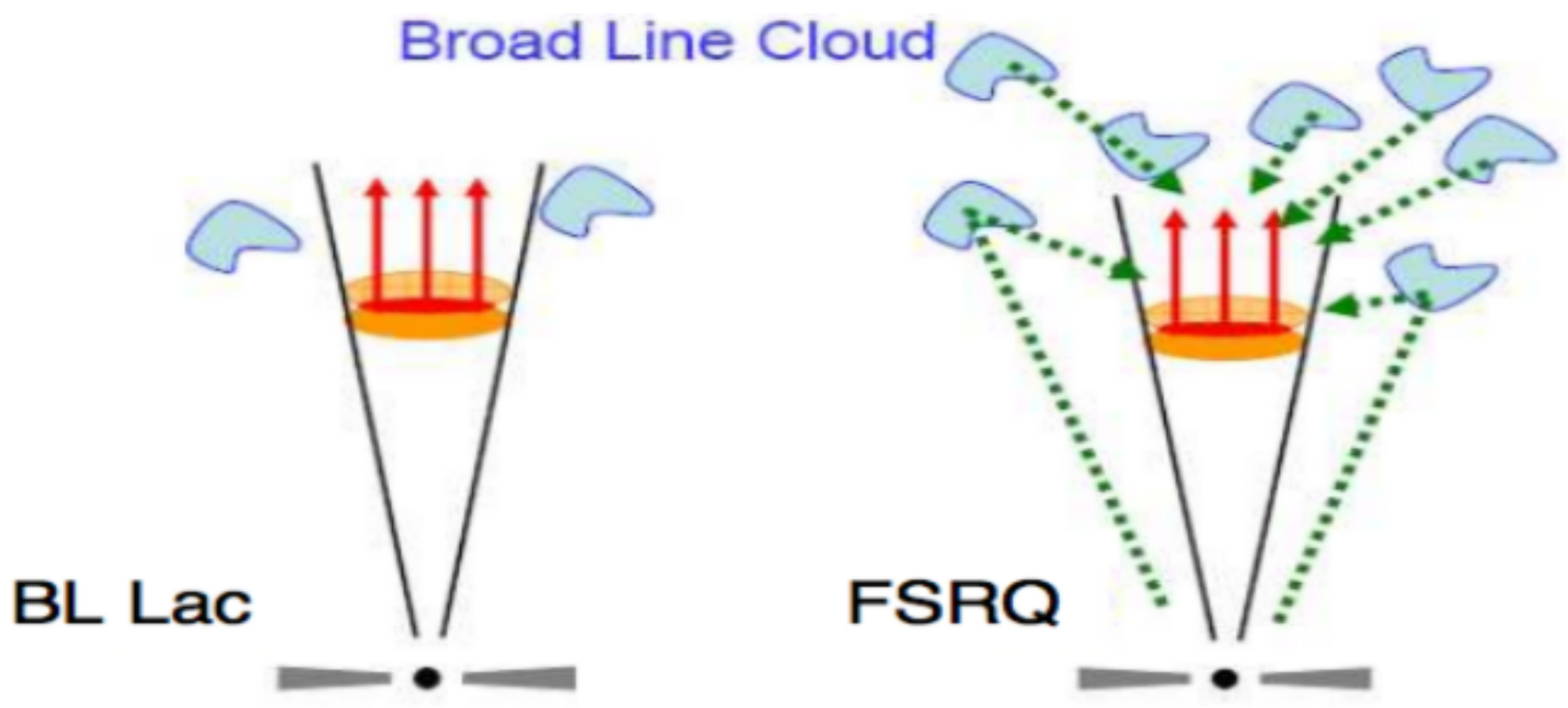


B. Lott, Cospar 02/10

- weak emission from disk and broad line region

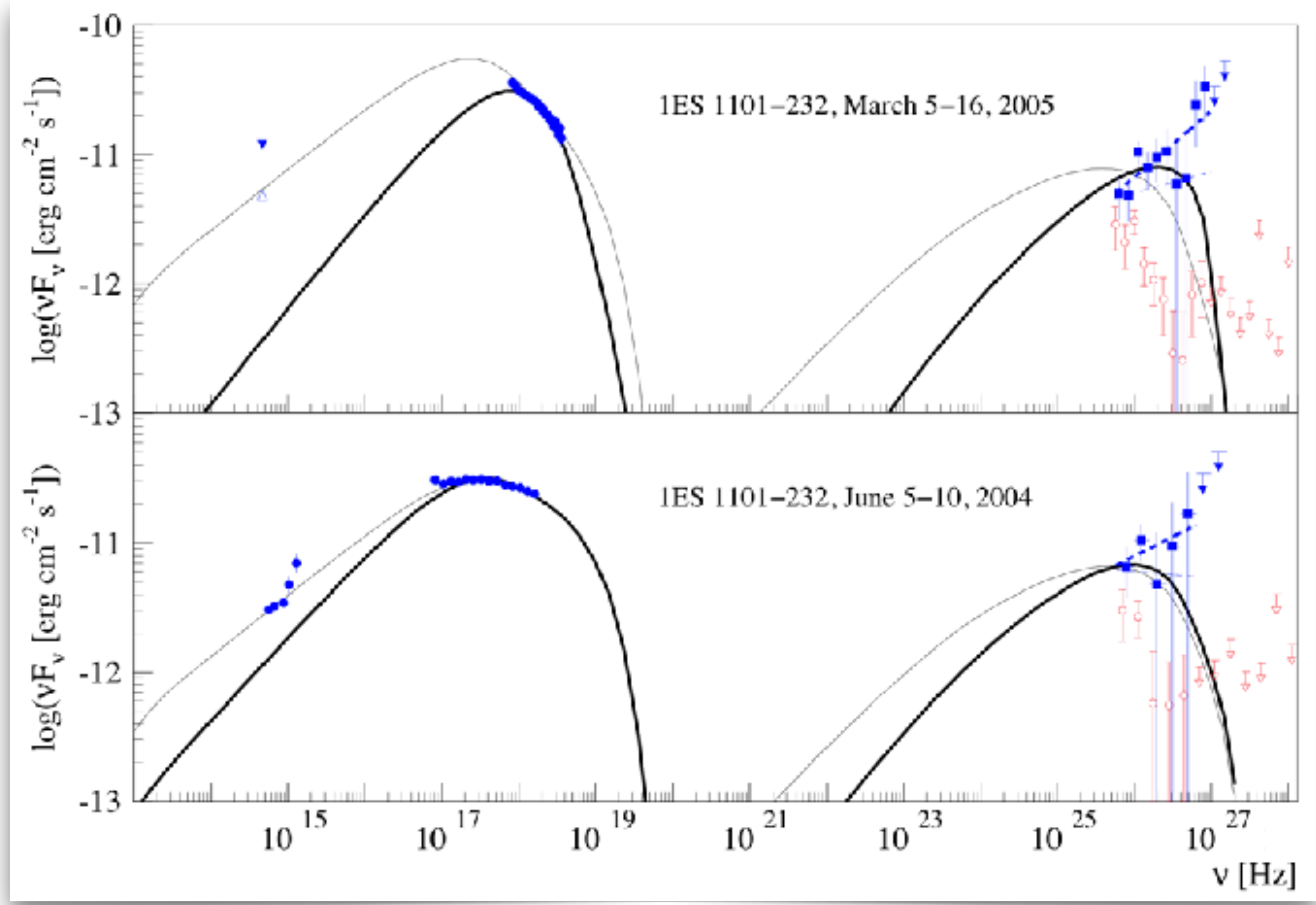
- γ-rays mostly due to proton synchrotron ?

- strong emission from disk and broad line region

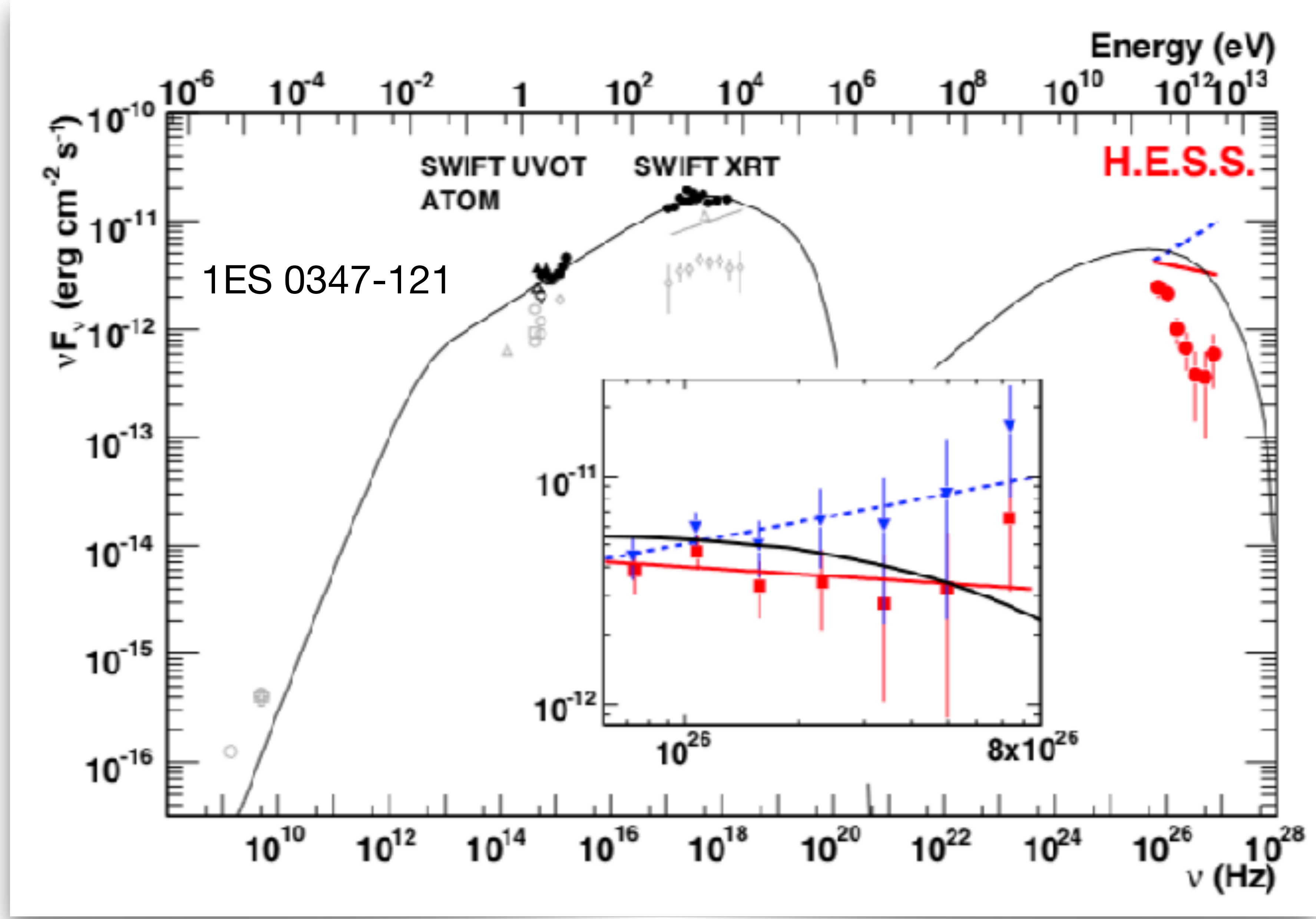
- γ-rays due to proton synchrotron and proton-photon interactions ?

extreme blazars

lessons from the first extreme blazar SEDs



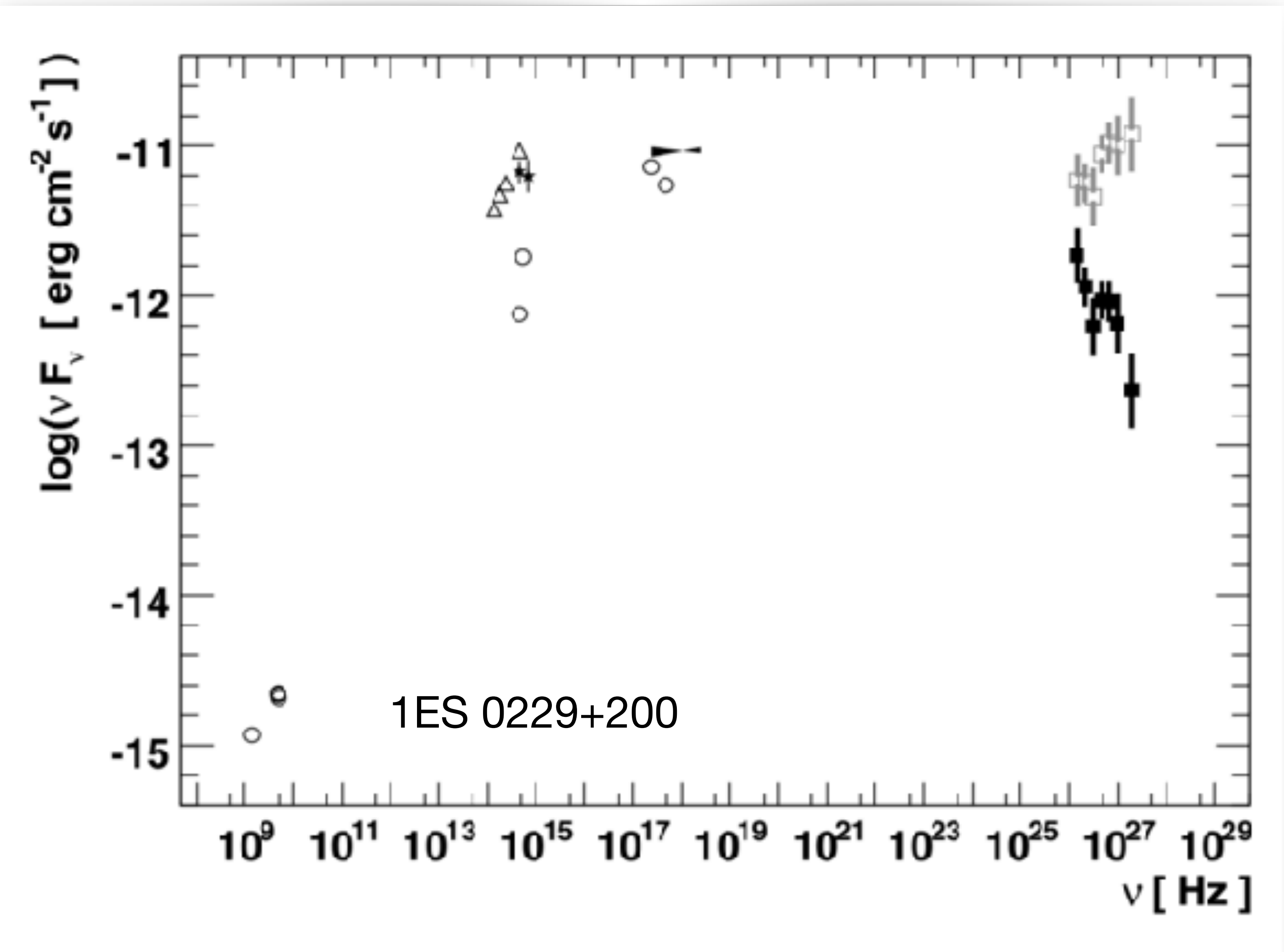
Aharonian et al. 2007a



Aharonian et al. 2007b

In 2007, three H.E.S.S. publications on extreme blazars.

-> very hard intrinsic TeV spectra, difficult to reconcile with one-zone SSC models, even with hard particle spectra.

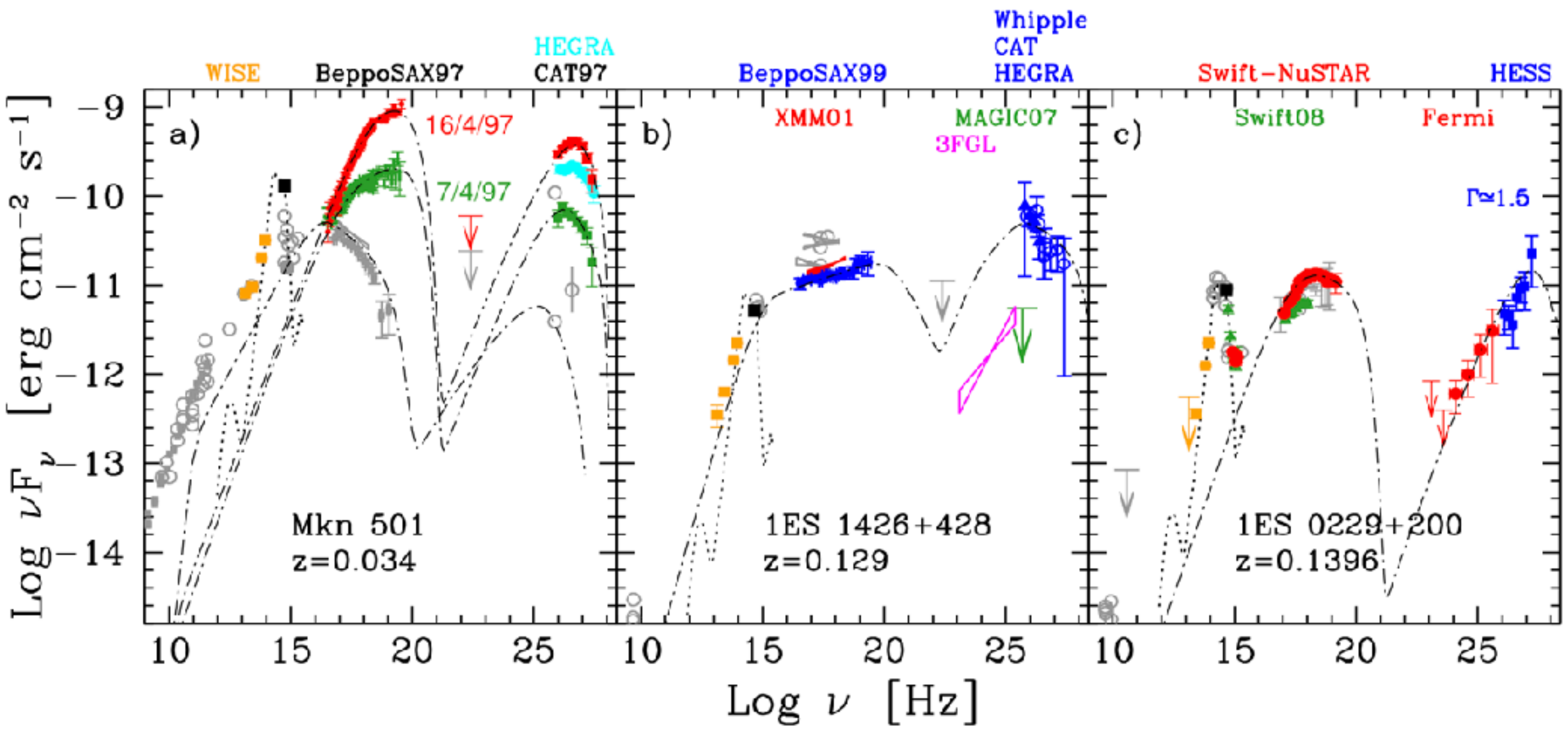


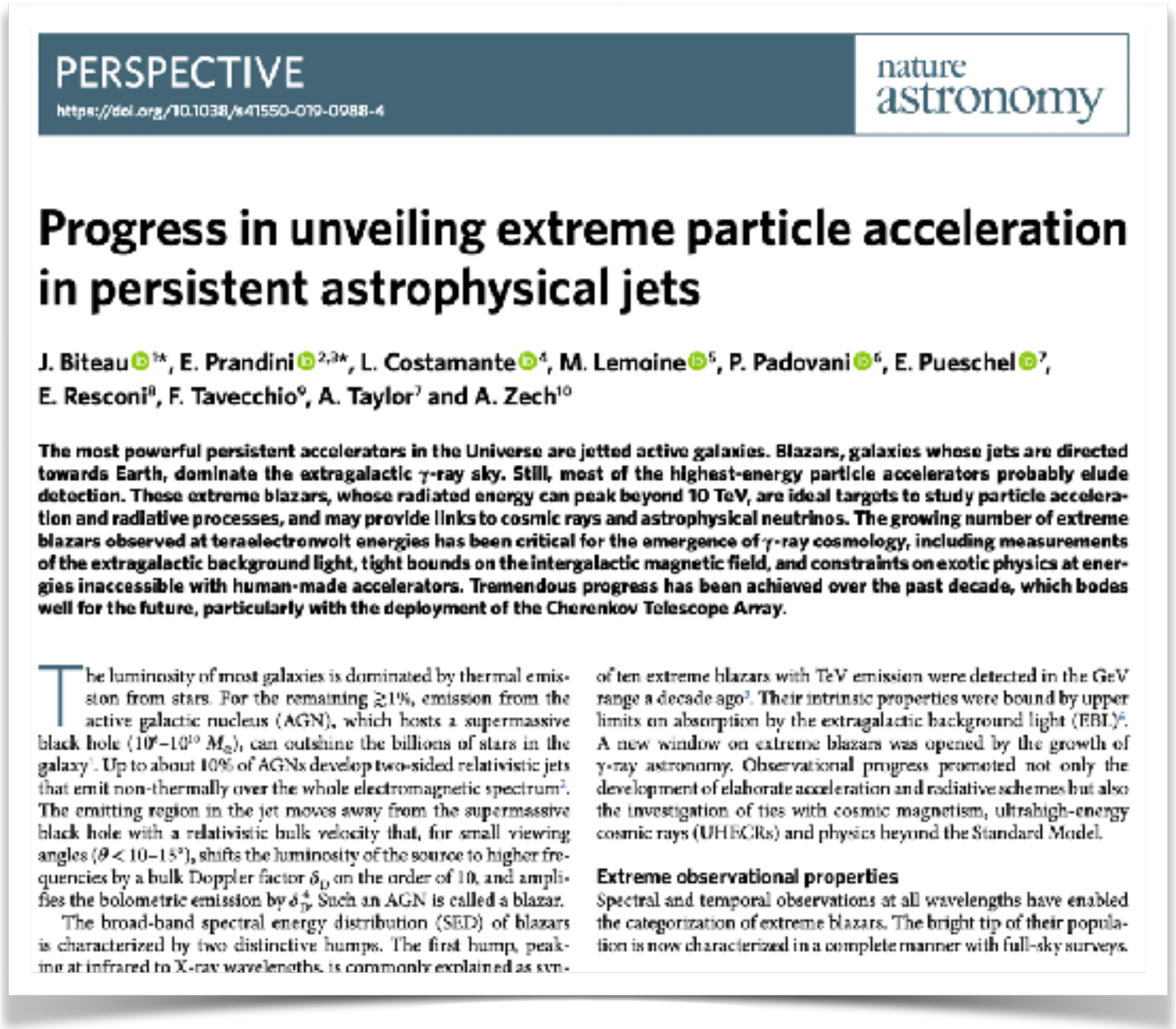
Aharonian et al. 2007c

characterization of extreme blazars

definition of two extreme blazar types in a review in 2020:
- **extreme synchrotron** blazars ($h\nu_X \gtrsim 1\,\mathrm{keV}$) (*b*)
- **extreme TeV** blazars ($h\nu_\gamma \gtrsim 1\,\mathrm{TeV}$) (*c*)
  -> usually also show extreme synchrotron behaviour

Other characteristics:
No or **little flux variability**, but certain blazars become extreme only during flares (*a*).




PERSPECTIVE
https://doi.org/10.1038/s41550-019-0988-4
nature astronomy

Progress in unveiling extreme particle acceleration in persistent astrophysical jets

J. Biteau[1*], E. Prandini[2,3*], L. Costamante[4], M. Lemoine[5], P. Padovani[6], E. Pueschel[7], E. Resconi[8], F. Tavecchio[9], A. Taylor[7] and A. Zech[10]

The most powerful persistent accelerators in the Universe are jetted active galaxies. Blazars, galaxies whose jets are directed towards Earth, dominate the extragalactic γ-ray sky. Still, most of the highest-energy particle accelerators probably elude detection. These extreme blazars, whose radiated energy can peak beyond 10 TeV, are ideal targets to study particle acceleration and radiative processes, and may provide links to cosmic rays and astrophysical neutrinos. The growing number of extreme blazars observed at teraelectronvolt energies has been critical for the emergence of γ-ray cosmology, including measurements of the extragalactic background light, tight bounds on the intergalactic magnetic field, and constraints on exotic physics at energies inaccessible with human-made accelerators. Tremendous progress has been achieved over the past decade, which bodes well for the future, particularly with the deployment of the Cherenkov Telescope Array.

The luminosity of most galaxies is dominated by thermal emission from stars. For the remaining ≳1%, emission from the active galactic nucleus (AGN), which hosts a supermassive black hole (10^6–10^{10} $M_\odot$), can outshine the billions of stars in the galaxy[1]. Up to about 10% of AGNs develop two-sided relativistic jets that emit non-thermally over the whole electromagnetic spectrum[2]. The emitting region in the jet moves away from the supermassive black hole with a relativistic bulk velocity that, for small viewing angles ($\theta < 10$–$15°$), shifts the luminosity of the source to higher frequencies by a bulk Doppler factor δ_D on the order of 10, and amplifies the bolometric emission by δ_D^4. Such an AGN is called a blazar.

The broad-band spectral energy distribution (SED) of blazars is characterized by two distinctive humps. The first hump, peaking at infrared to X-ray wavelengths, is commonly explained as syn-

of ten extreme blazars with TeV emission were detected in the GeV range a decade ago[3]. Their intrinsic properties were bound by upper limits on absorption by the extragalactic background light (EBL)[4]. A new window on extreme blazars was opened by the growth of γ-ray astronomy. Observational progress promoted not only the development of elaborate acceleration and radiative schemes but also the investigation of ties with cosmic magnetism, ultrahigh-energy cosmic rays (UHECRs) and physics beyond the Standard Model.

Extreme observational properties

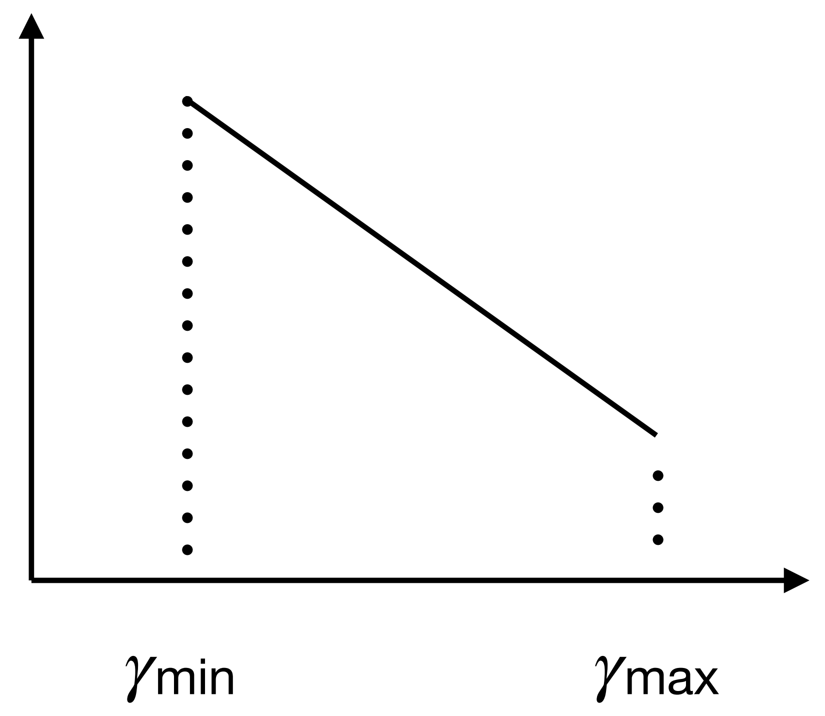
Spectral and temporal observations at all wavelengths have enabled the categorization of extreme blazars. The bright tip of their population is now characterized in a complete manner with full-sky surveys.

Extreme-synchrotron blazars make up ~1% of BL Lac objects.

About 200 extreme-synchrotron blazars detectable over the whole sky.

the problem with very hard TeV spectra

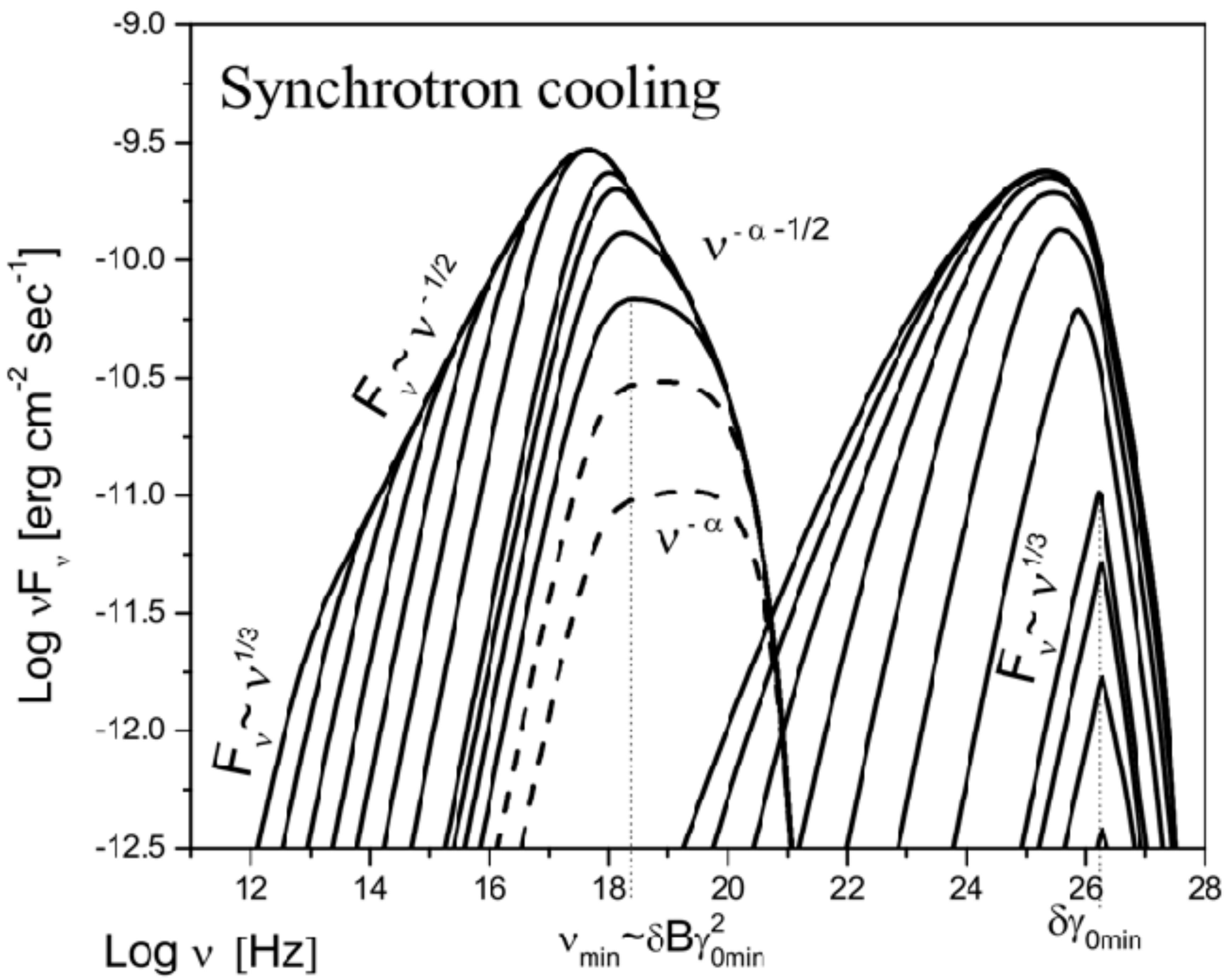
- standard shock acceleration predicts particle spectra $dN/d\gamma \sim \gamma^{-2}$ => $\alpha = (n - 1)/2 = 1/2$



- radiative (synchrotron) cooling softens initially hard particle spectra

-> expect steady-state radiation spectrum $F_\nu \sim \nu^{-1/2}$

- in addition, at TeV energies, flux reduction is expected, since high electron energies lead to scattering partly in the **Klein-Nishina** regime



Effect of synchrotron cooling on the emission from a constantly injected very narrow electron distribution. (Lefa et al. 2011)

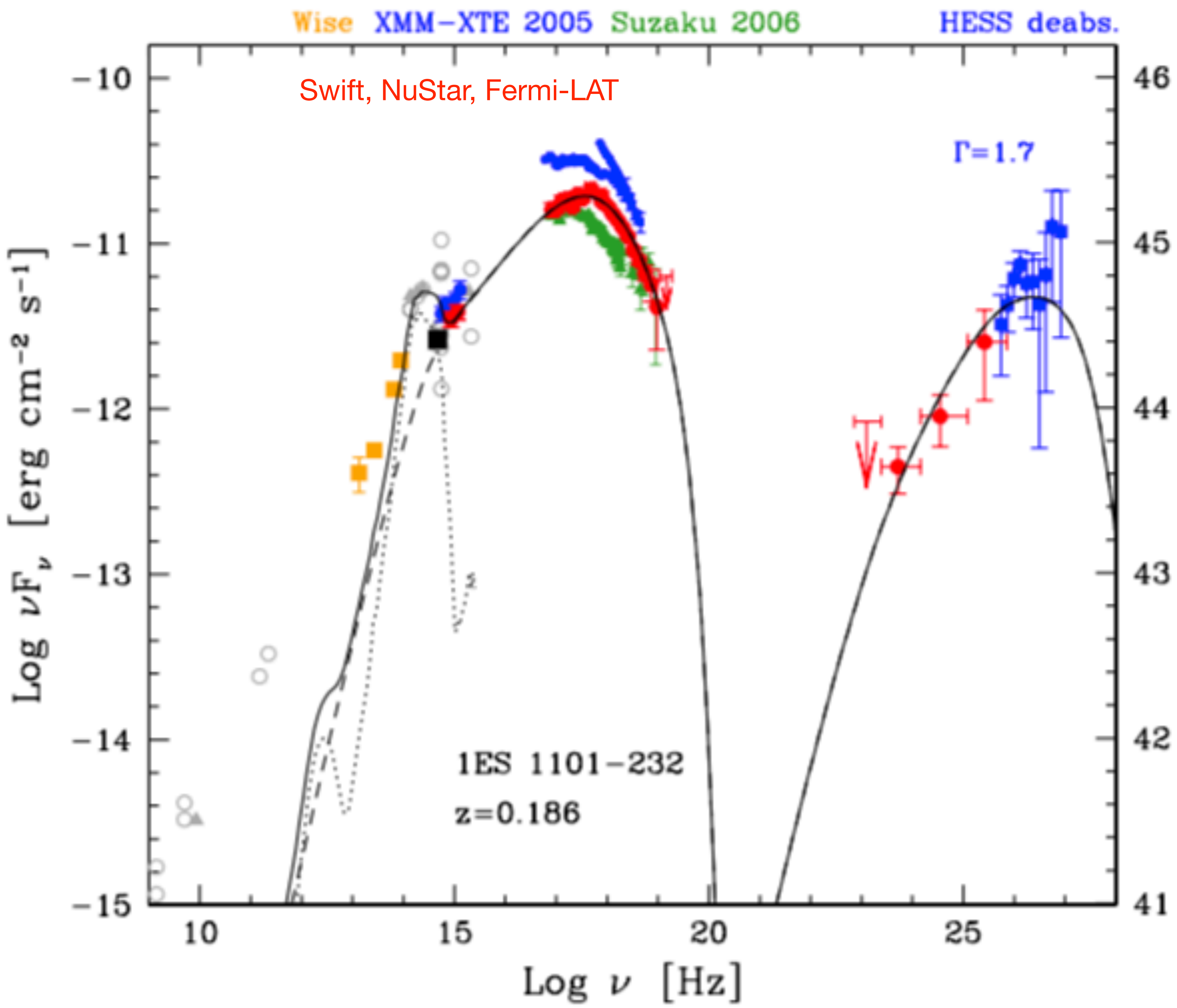
leptonic scenarios for extreme blazars

models with high γ_{min}

For the standard broken power-law electron spectrum, increasing the minimum electron Lorentz factor γ_{min} leads to a narrower distribution.

Very low B-field required to be able to neglect synchrotron cooling !

Source [1]	γ_0 [2]	n_0 [3]	γ_1 [4]	γ_b [5]	γ_2 [6]	n_1 [7]
1ES 0229+200 a	-	-	100	1.1×10^6	2×10^7	1.4
1ES 0229+200 b	-	-	2×10^4	1.5×10^6	2×10^7	2.0
1ES 0347-121 a	-	-	100	7.5×10^5	1.8×10^7	1.7
1ES 0347-121 b	-	-	3×10^3	7.5×10^5	1.8×10^7	2.0
1ES 0414+009 a	10	1.7	1×10^4	10^5	10^6	3.0
1ES 0414+009 b	-	-	3×10^4	5×10^5	3×10^6	2.0
RGB J0710+591	-	-	100	6×10^5	10^7	1.7
1ES 1101-232 a	-	-	3.5×10^4	1.1×10^6	6×10^6	2.2
1ES 1101-232 b	-	-	1.5×10^4	9.5×10^5	4×10^6	2.2
1ES 1218+304	100	1.3	3×10^4	10^6	4×10^6	2.85



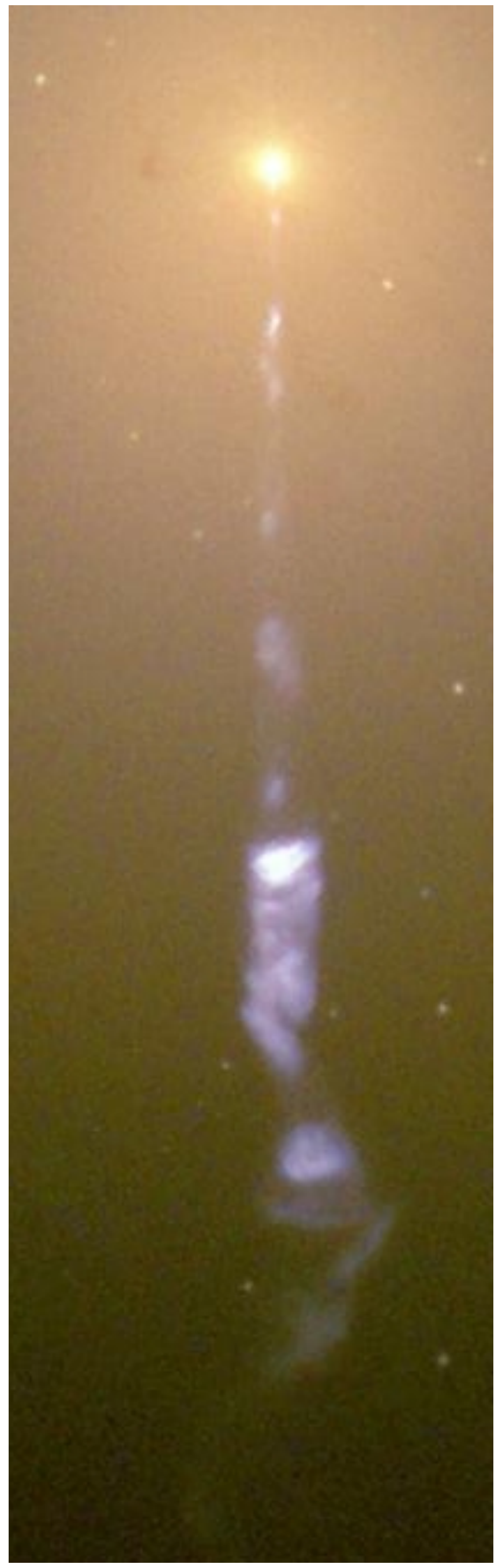
Costamante et al. 2018

e.g. *Costamante et al. 2018* :

- MWL analysis of six extreme TeV blazars
- SSC modelling requires high electron energies, very low (mG) magnetic fields and high γ_{min} or steep spectra

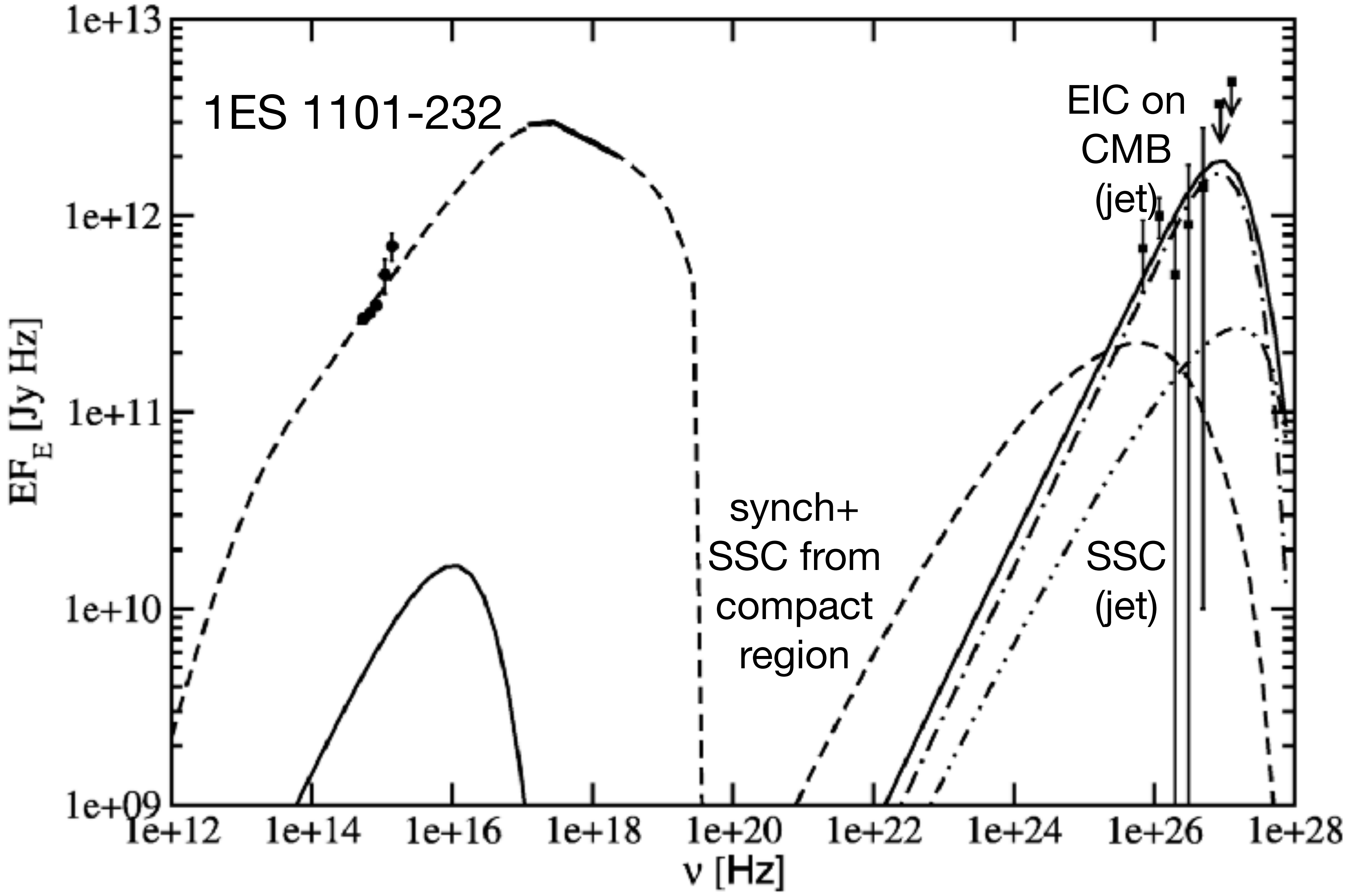
the problem : how to physically justify very low magnetization and very high γ_{min} ?

external Compton models



Compton up-scattering of **CMB photons** in the extended kpc jet can lead to an additional hard TeV component. (*Boettcher et al. 2008*)

problem: Disfavoured by variability ?
(yearly timescale for 1ES 0229+200 *Aliu et al. 2004* ;
daily for 1ES 1218+304 *Acciari et al. 2010*)



Boettcher et al. 2008

Other leptonic scenarios evoke very narrow particle distributions, e.g. from stochastic acceleration.

lepto-hadronic scenarios for extreme blazars

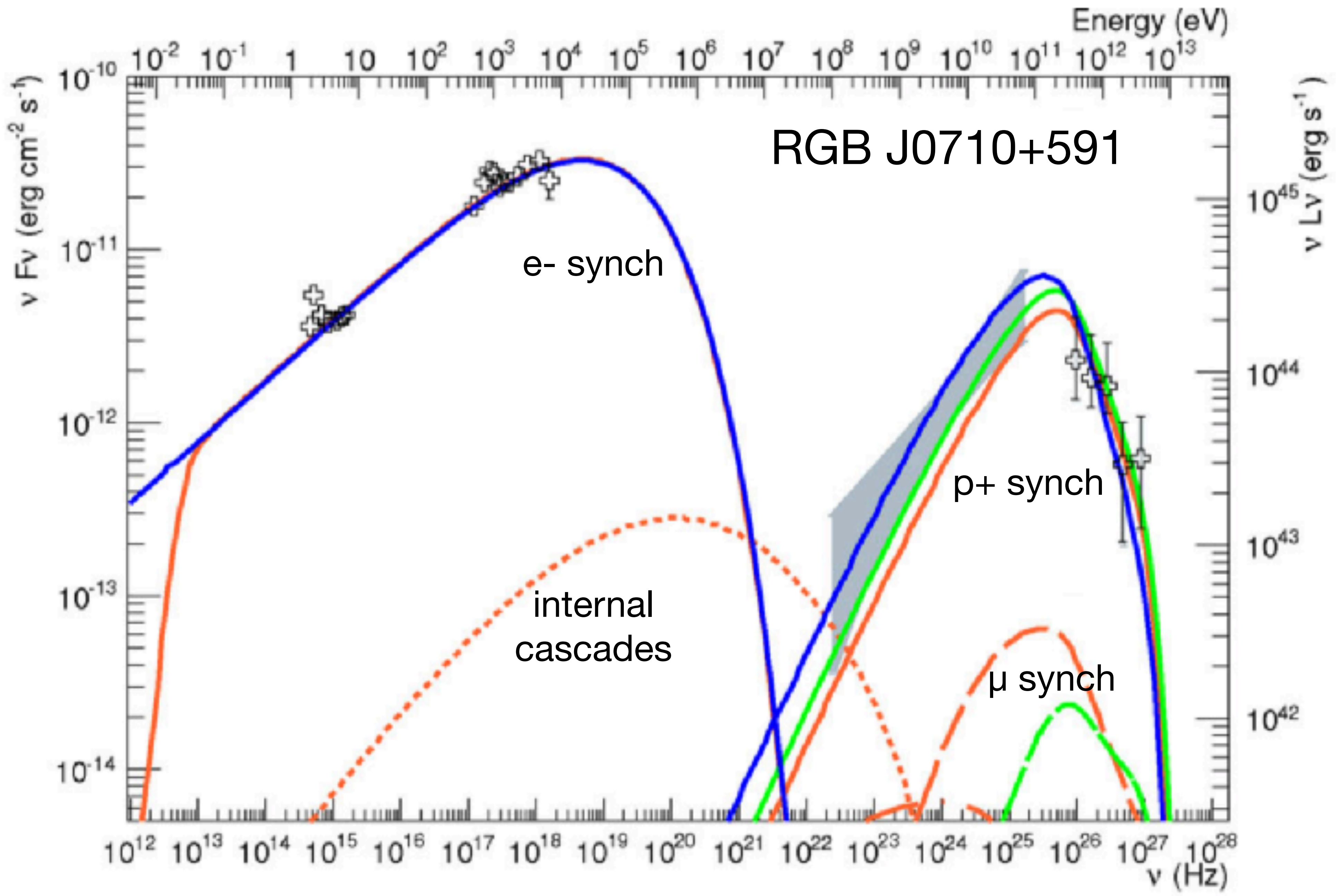
proton-synchrotron emission model

- synchrotron-proton blazar model
  (based on *Aharonian 2000, Mücke et al. 2001,2003*) :
  - protons and electrons co-accelerated
    in high magnetic field
  - proton-photon interactions & cascades

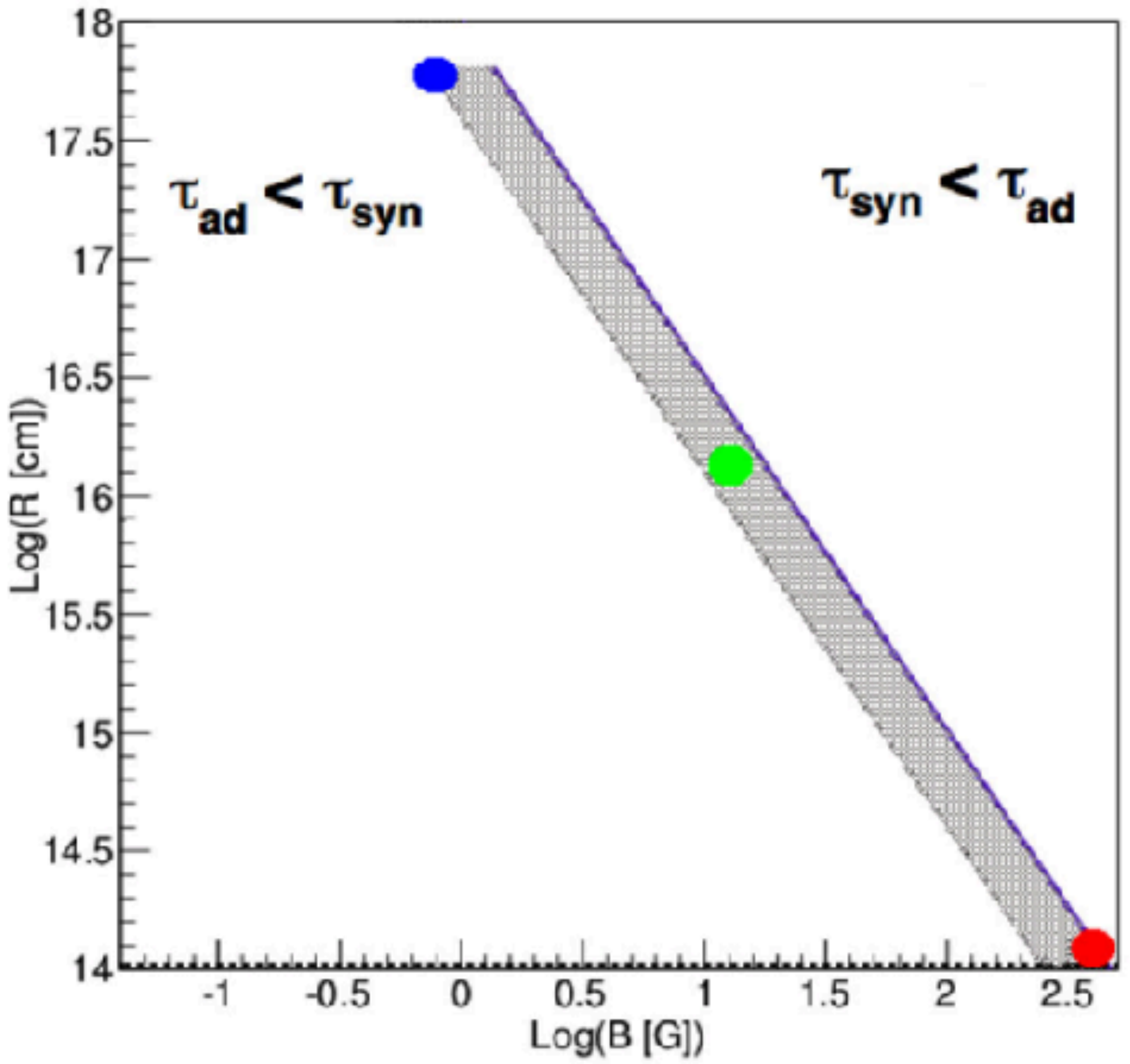
- parameter scan for 5 extreme blazars
  (*Cerruti, AZ et al. 2015*)
  -> solutions exist with acceptable jet power
  ($\lesssim L_{edd}$) and relatively small γ_{min}

- **problem** : proton spectra need to be very hard
  (n_p = 1.3 to 1.7) ;

- similar hadronic models for BL Lacs by *Reimer, Boettcher, Petropoulou,…*



Cerruti, AZ et al. 2015



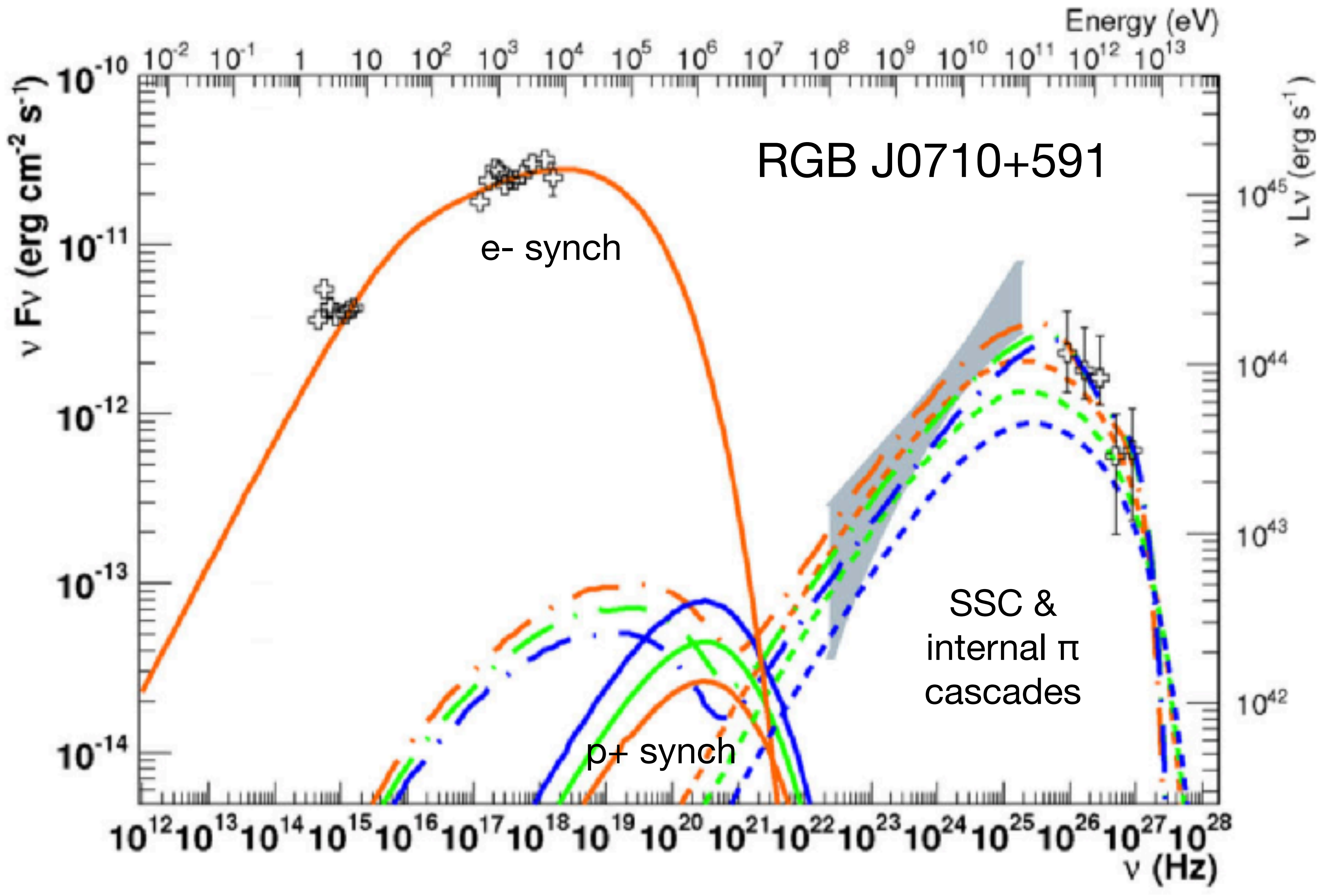
mixed lepto-hadronic emission model

- alternative scenario using the same setup (based on *Mannheim & Biermann 1992*) : high-energy bump is a combination of SSC and UHE proton-induced cascade emission

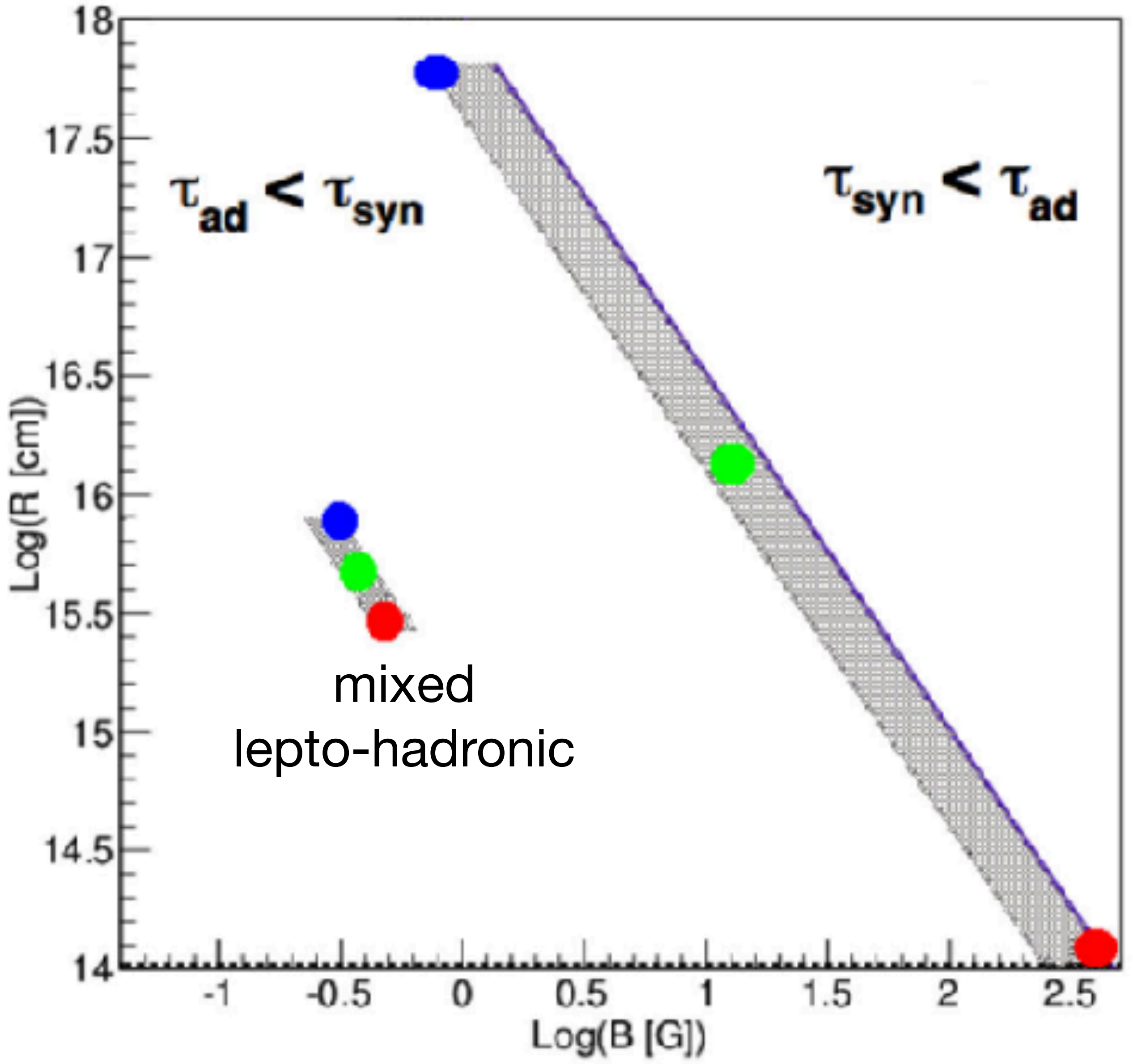
- parameter scan for 5 extreme blazars (*Cerruti, AZ et al. 2015*) -> solutions exist with acceptable jet power (≲ L_{edd}) and small γ_{min} for most sources

- **problem** : proton spectra need to be very hard (n_p = 1.3 to 1.7) ;

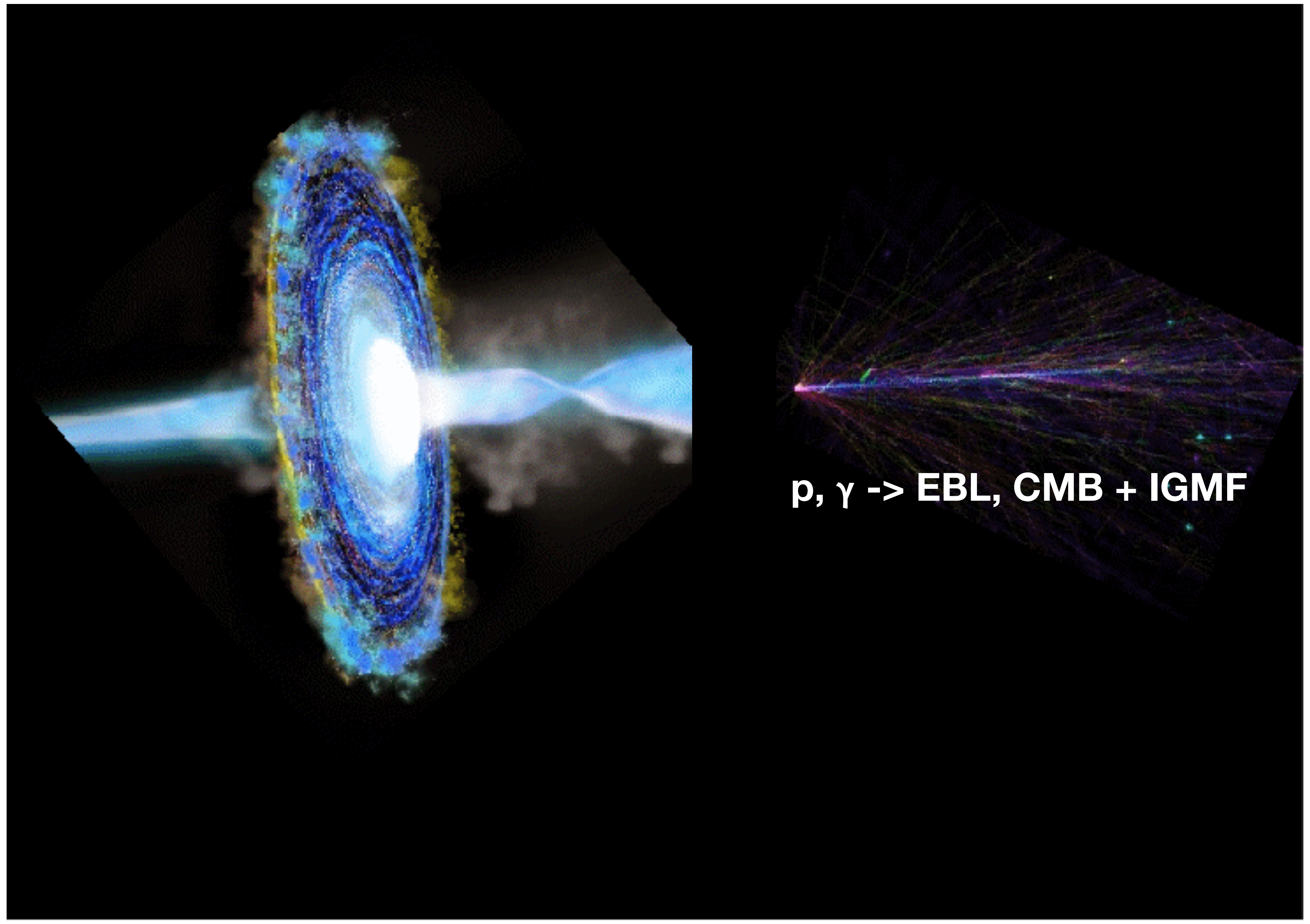
- similar hadronic models for BL Lacs by *Reimer, Boettcher, Petropoulou,…*

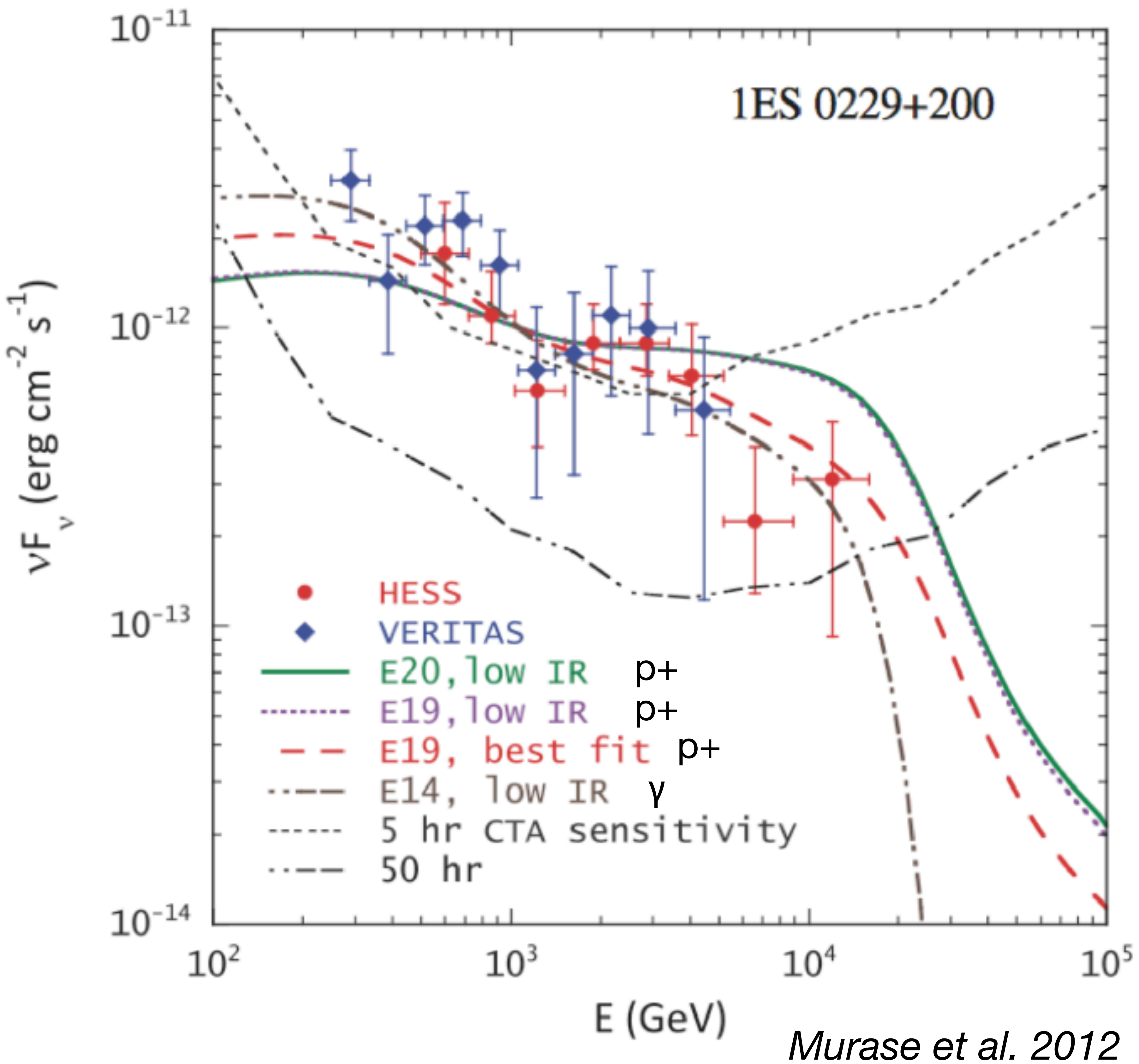


Cerruti, AZ et al. 2015



external cascade models





Murase et al. 2012

Intergalactic **IC-pair cascades** from interactions of **VHE / UHE γ-rays or UHE cosmic rays** (protons or nuclei) with the EBL / CMB can lead to a hard spectral component at TeV energies.

problems : - Models depend strongly on assumptions on Intergalactic Magnetic Field
- Not consistent with observed variability.

co-acceleration on shocks and re-acceleration ?

hadron-lepton co-acceleration on shocks

We assume a pure proton-electron plasma :

$n_p = n_e$

Co-acceleration of protons and electrons on relativistic shocks leads to **approximate equipartition** of their energies, as seen in PIC simulations (e.g. *Vanthiegem et al. 2020*) and models of GRB afterglows :

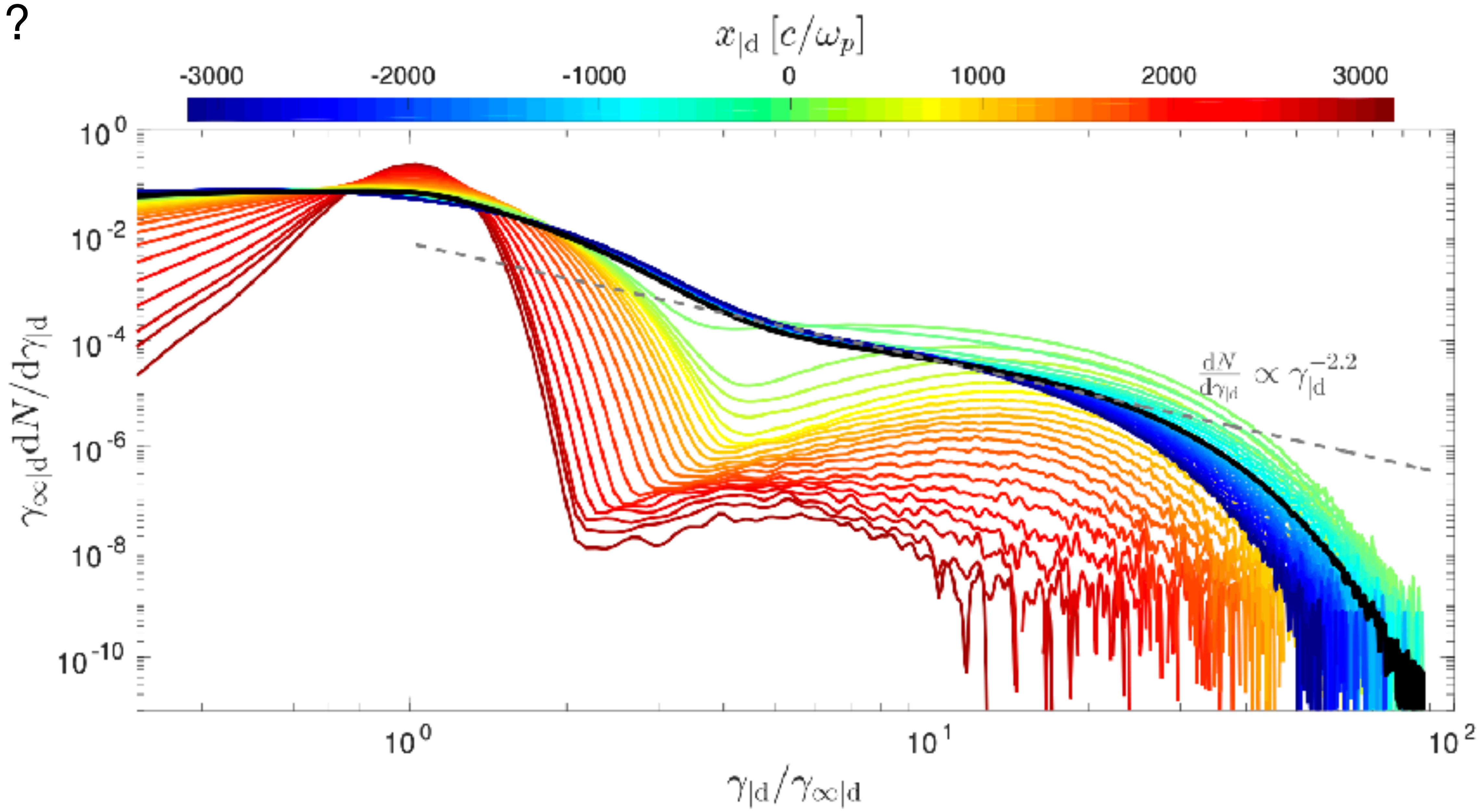
$$< E_e > / < E_p > \approx 1$$

Mechanism : different drift velocities lead to charge separation and to the emergence of a coherent electric field that transfers energy to electrons via **collisionless Joule heating** ? (*Lemoine 2019*)

PIC simulations for relativistic, weakly magnetised electron-ion shocks (*Sironi & Spitkovsky 2011, Sironi et al. 2013*) :

$$\gamma_{e,min} \simeq 0.3\,\gamma_{sh}\,\frac{m_p}{m_e} \simeq 600\,\gamma_{sh} \qquad \gamma_{p,min} \simeq \gamma_{sh}$$

Mildly relativistic shocks are seen to induce power-law distributions with index $p \sim 2.2$.



PIC simulation of a pair plasma on a relat. shock.
Vanthieghem et al. 2020

the role of magnetization

Efficient shock acceleration is only possible for **weak magnetization** :
in the fully relativistic regime ($\gamma_{sh} \gtrsim 3-5$) , efficient acceleration for $\sigma \lesssim 10^{-3}$.

Scattering constraint $t_{acc} \approx t_{scatt} \lesssim t_{gyro}$ ensures that particles scatter effectively in the microturbulence at shocks (*Vanthieghem et al. 2020)* :

$$\gamma_{max} \lesssim \frac{\gamma_{min}}{\sqrt{\sigma}}$$

Due to instabilities induced by the accelerated particles, the **effective magnetization** in the downstream (radiation) region of the shock σ_{rad} can be orders of magnitude larger than the initial magnetization :

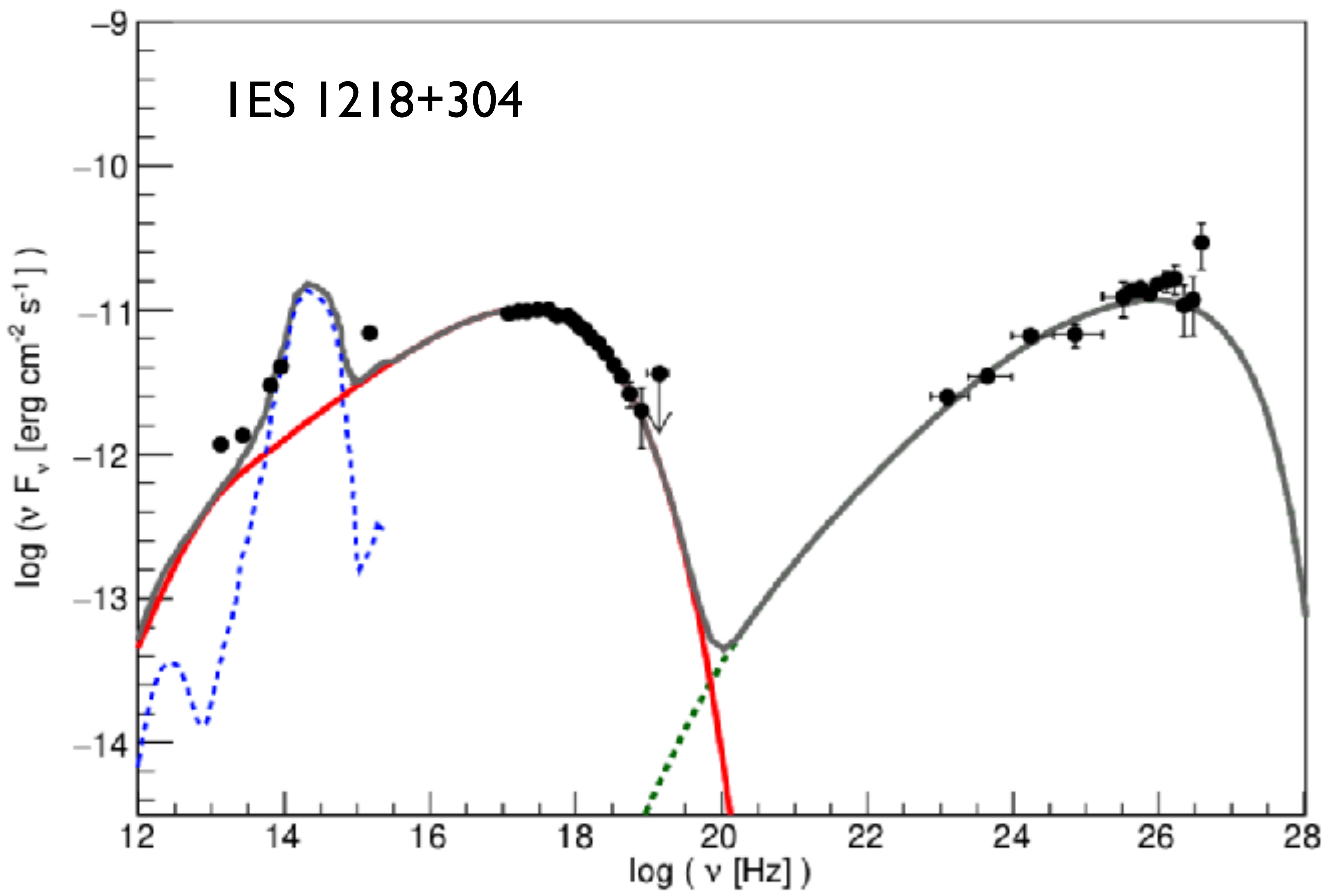
$$\sigma \ll \sigma_{rad} \lesssim 10^{-2}$$

Since σ_{rad} is still low, the particle distribution follows a simple power law (without break),
with only an exponential cutoff :

$$dN/d\gamma = \Phi_0\ \gamma^{-2.2}\ e^{-\gamma/\gamma_{max}}$$

e- p+ co-acceleration on a single shock

application of the model to sources from the *Costamante et al. 2018* NuStar sample :



$\delta = 60$

$\gamma_{sh} \sim 3$ -> $\gamma_{e,min} \sim 10^3$
$\gamma_{e,max} \sim 5 \times 10^5$
-> $\sigma \sim 1.3 \times 10^{-5}$

$n_e \sim 1\ \mathrm{cm}^{-3}$
B ~ 8 mG
-> $\sigma_{rad} \sim 1.4 \times 10^{-4}$

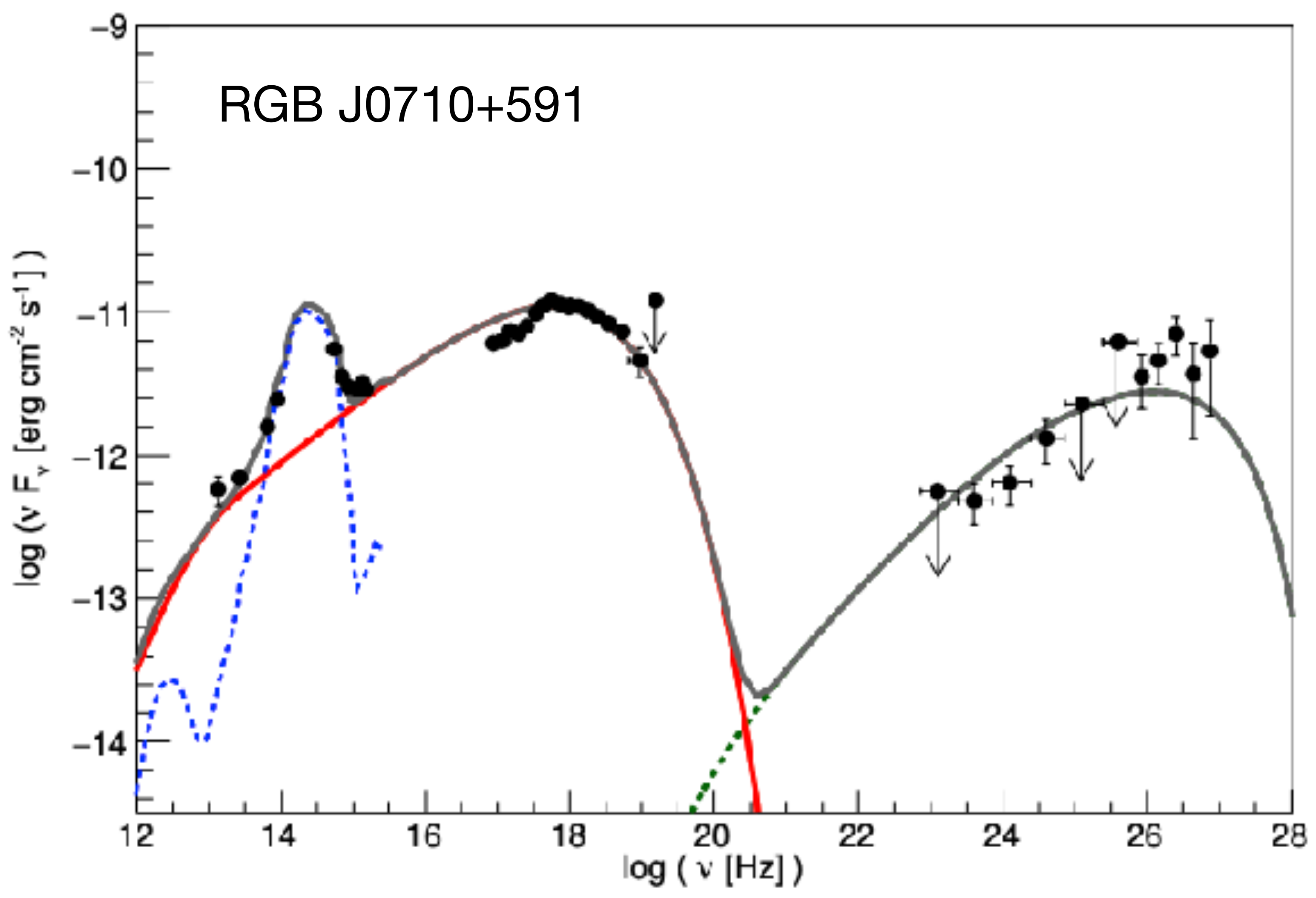
$R \sim 10^{16}$ cm
-> $L_{jet} \sim 9 \times 10^{44}$ erg/s ~ 0.06 L_{edd}

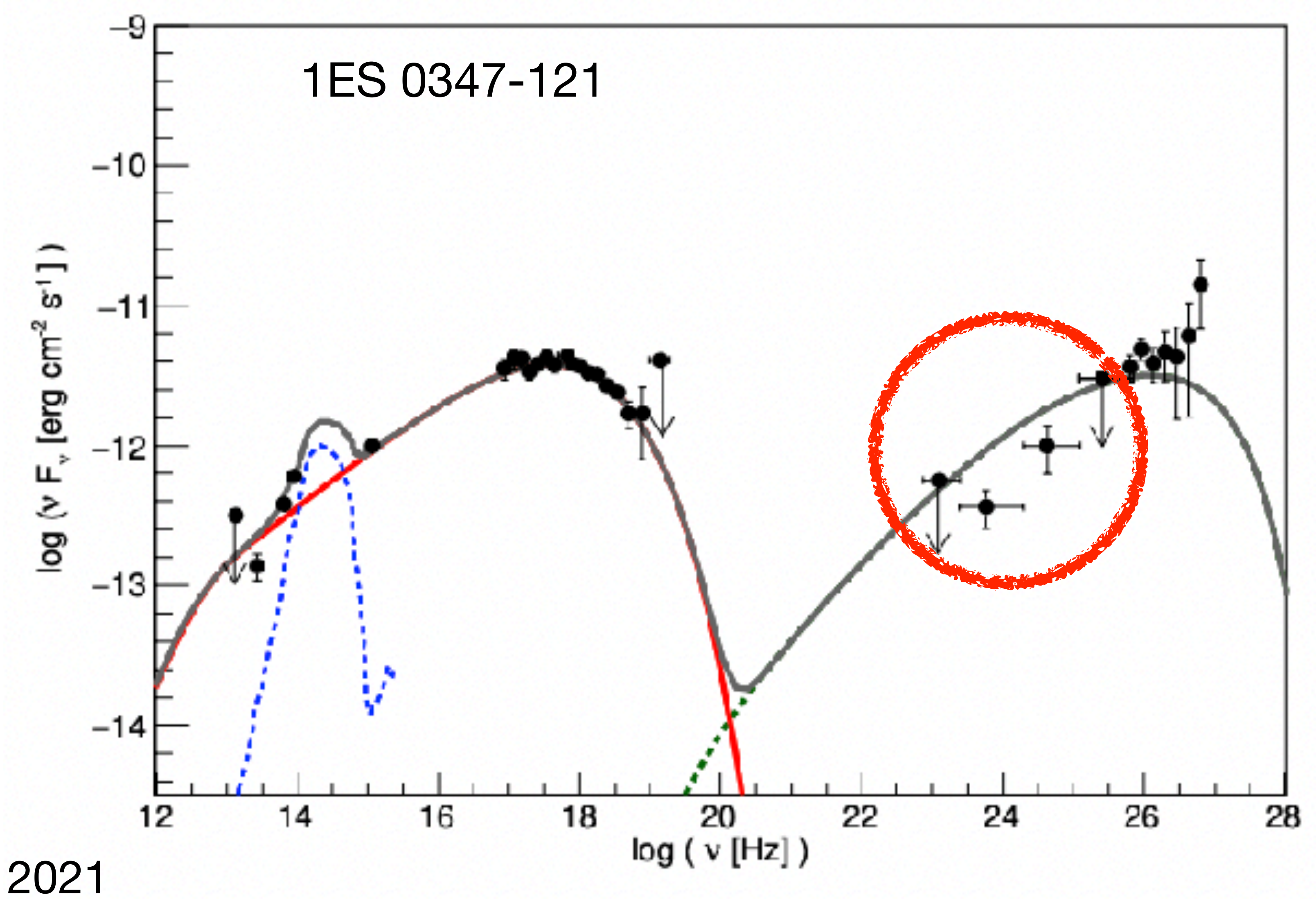
AZ, M. Lemoine 2021

very good representation with a minimum of free parameters

low B-field, low proton energies, $n_e = n_p$ -> radiative emission from protons negligible

e- p+ co-acceleration on a single shock





AZ, M. Lemoine 2021

Similarly good results for RGB J0710+591.

Poor result for 1ES 0347-121 (Fermi-LAT).

Difficult to find acceptable solutions for the **two hardest sources :**

1ES 1101-232 : requires $\gamma_{e,min} \sim 6 \times 10^3$, i.e. $\gamma_{sh} \sim 10$ and $\Gamma_j \sim 500$ for recollimation shock

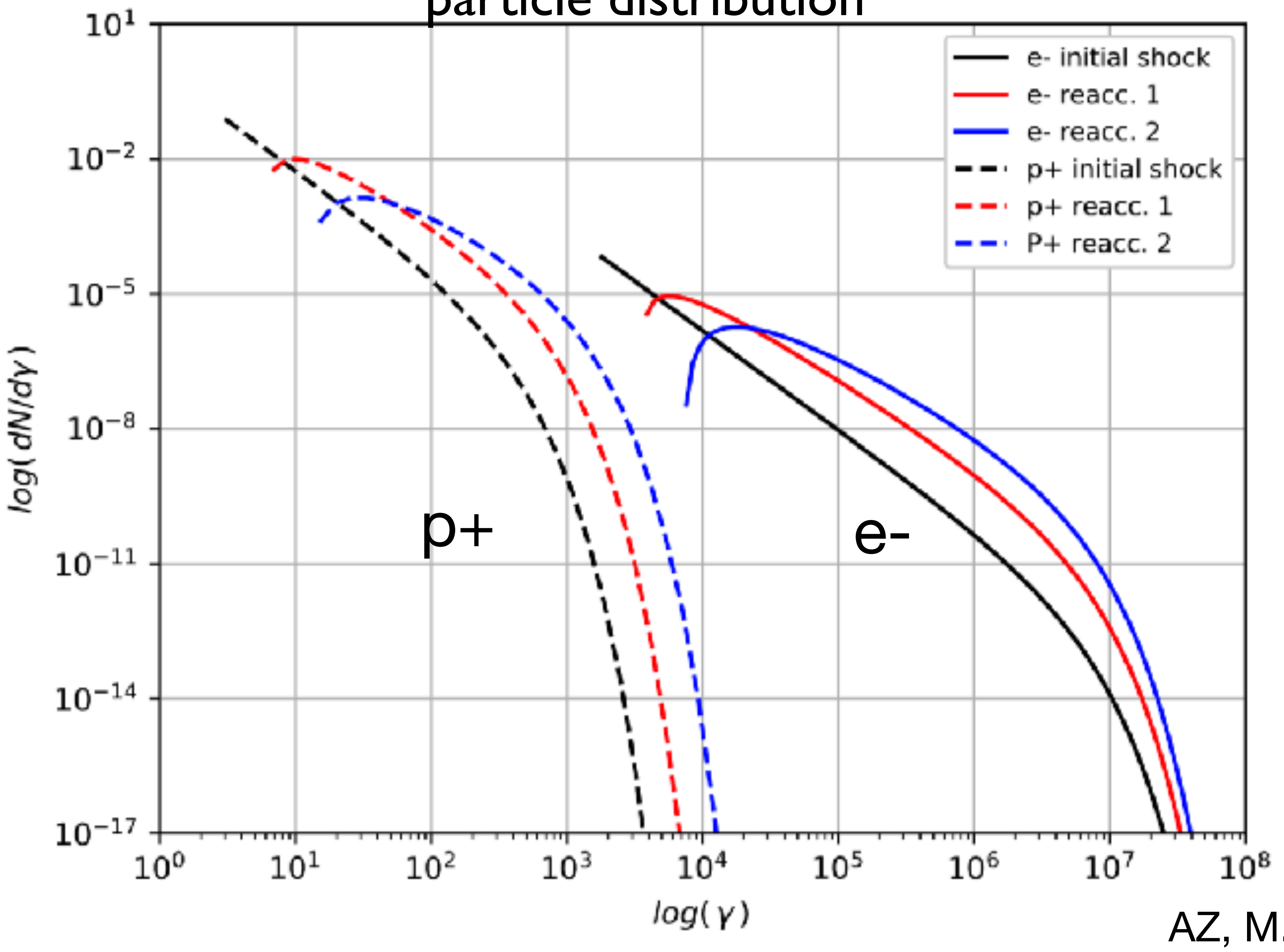
1ES 0229+200 : requires $\gamma_{e,min} \sim 10^4$, i.e. $\gamma_{sh} \sim 20$ and $\Gamma_j \sim 10^3$ for recollimation shock

Such high $\gamma_{e,min}$ might still be possible for shocks from blob-jet interactions.

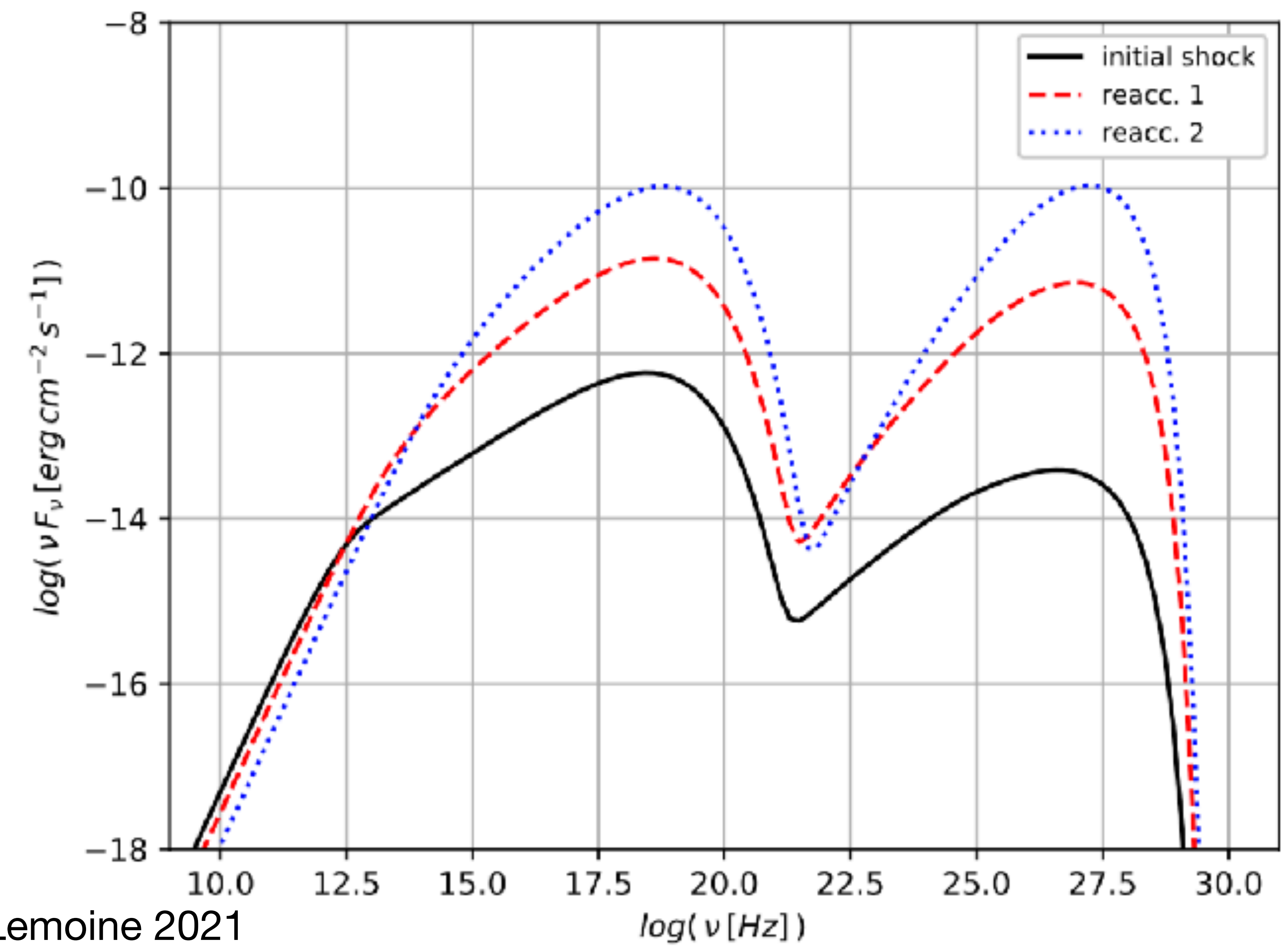
re-acceleration on consecutive shocks ?

Harder electron spectra are achievable with re-acceleration on consecutive shocks.

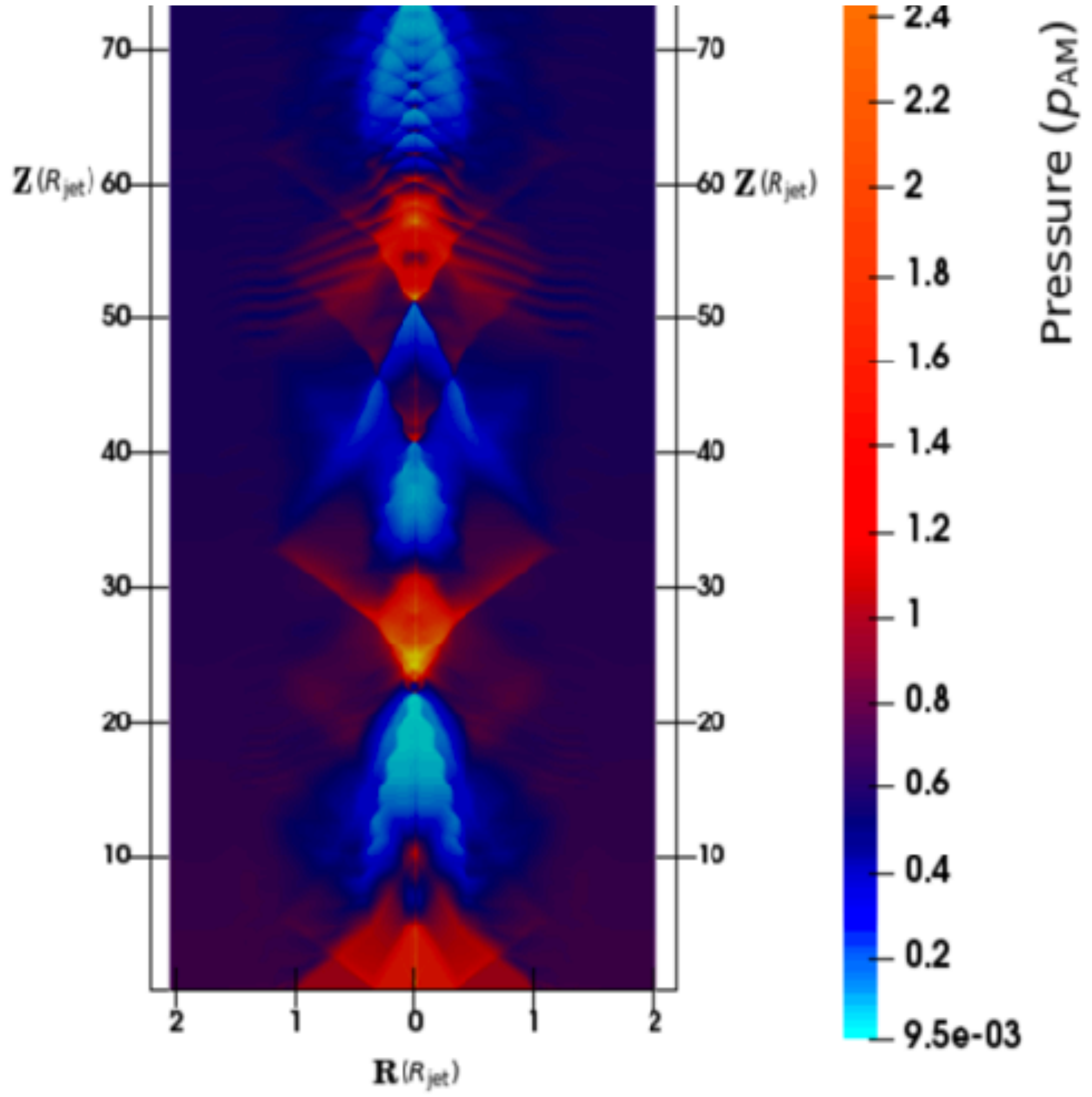
particle distribution



spectral energy distribution



AZ, M. Lemoine 2021

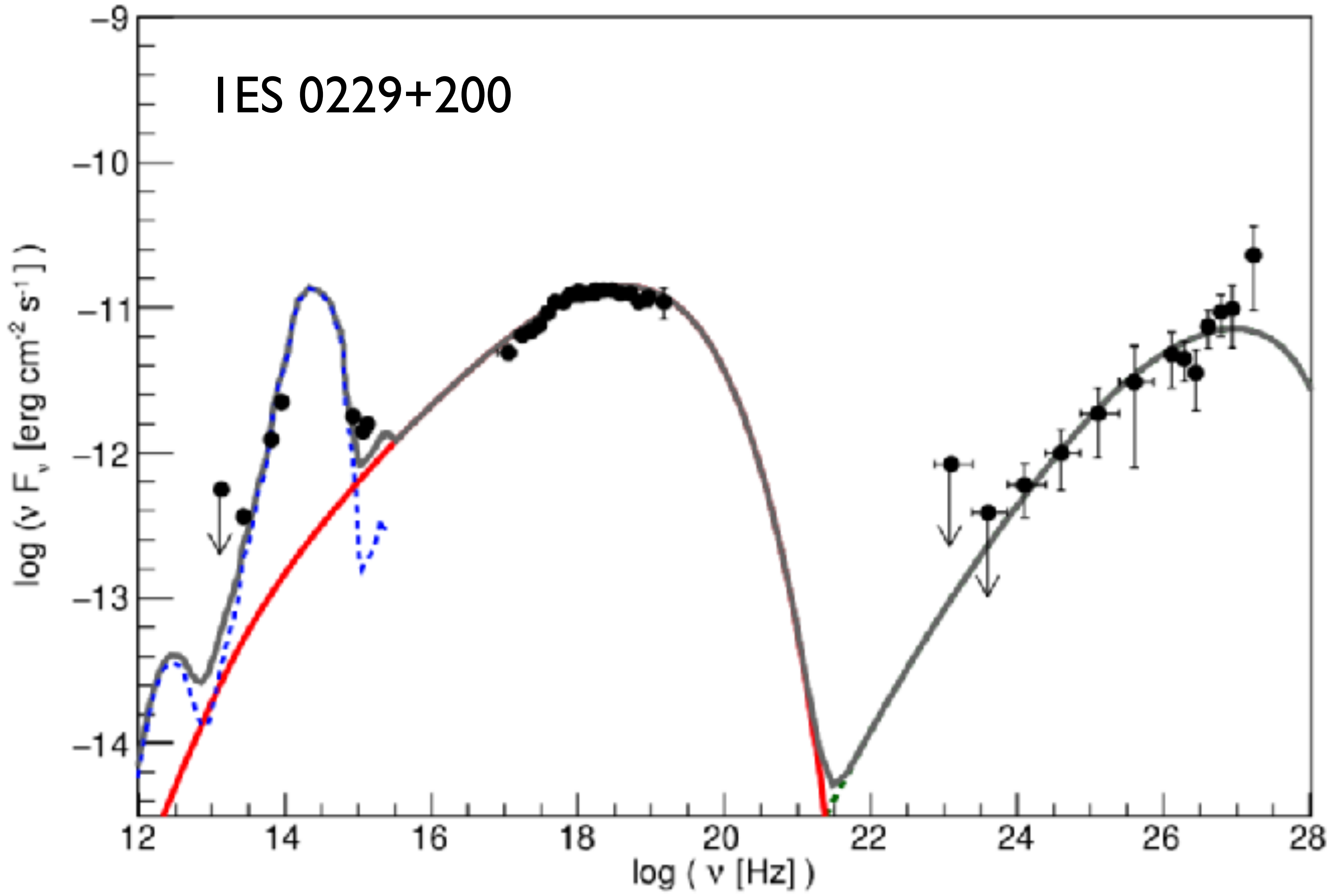


recollimation shocks in an 2D MHD jet simulation
(G. Fichet de Clairfontaine et al. 2021)

$$\frac{dN_>^{(n)}}{dp_>} = \frac{(s-1)^{n+1}}{n!\, g^n\, p_{\rm min}} \left(\frac{p_>}{g^n\, p_{\rm min}}\right)^{-s} \ln\left(\frac{p_>}{g^n\, p_{\rm min}}\right)^{n}$$

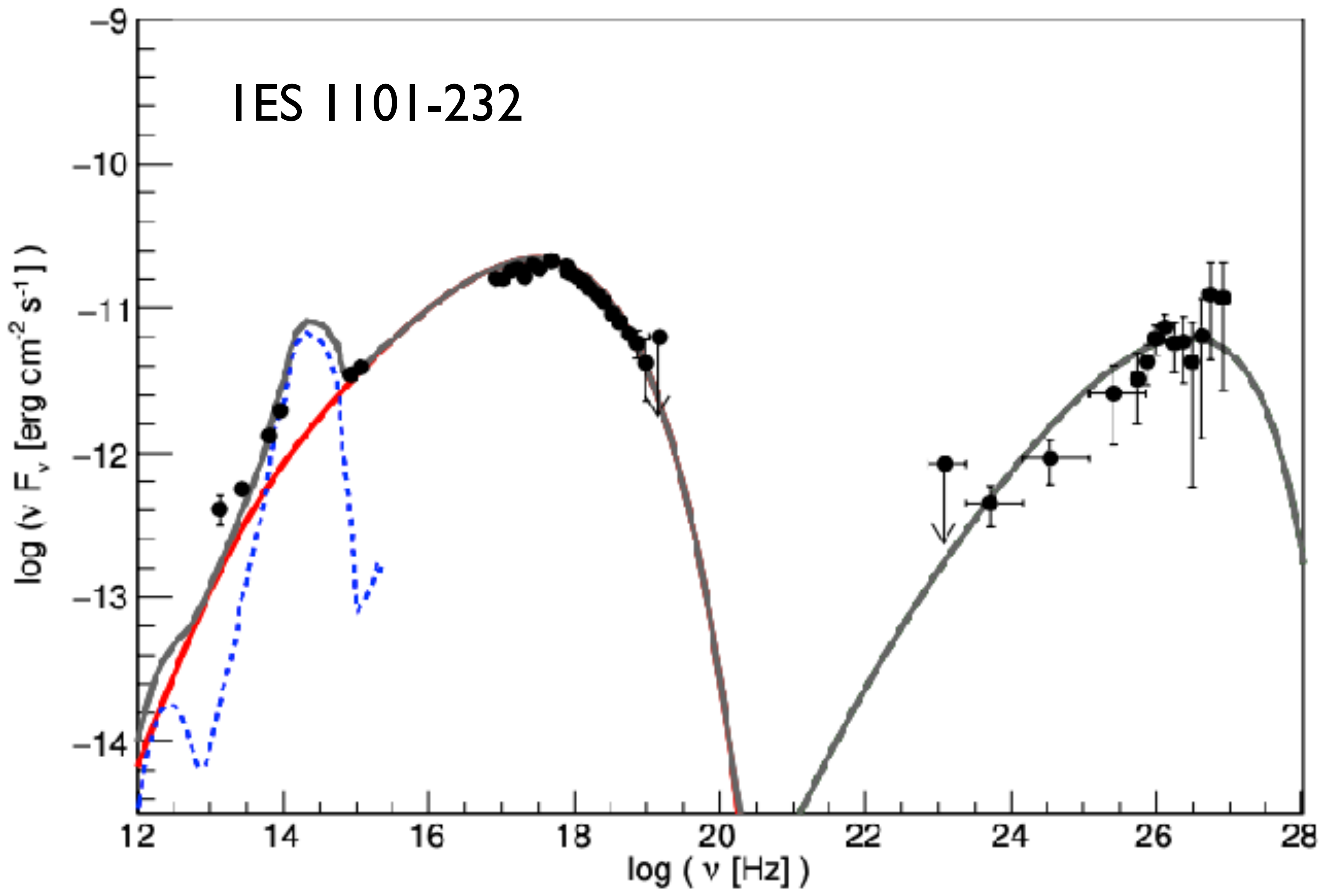
with s ~ 2.2 for relativistic shock
g ~ 2 energy gain through shock crossing
(*Pope & Melrose 1993*)

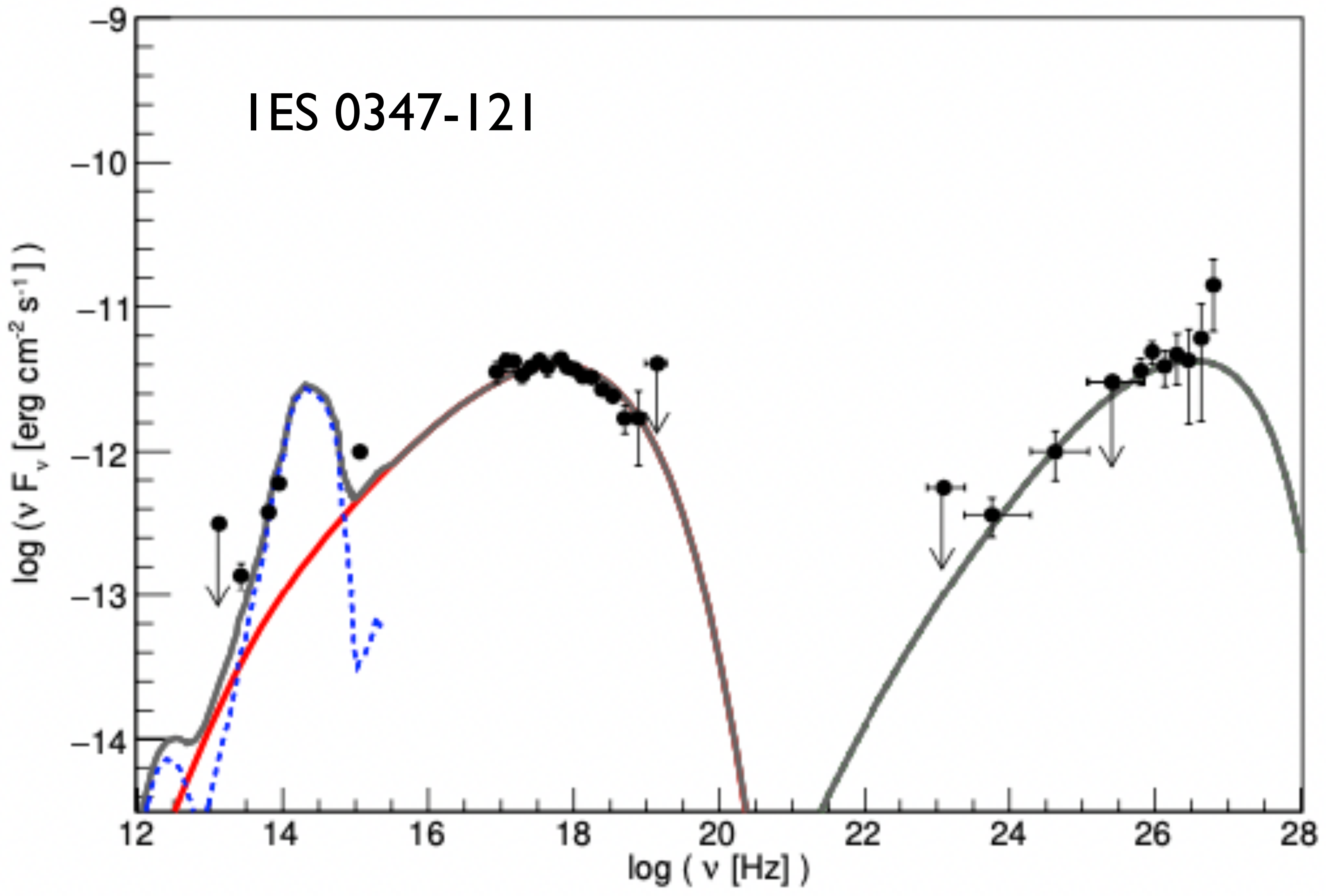
re-acceleration on a second shock



$n_e \sim 0.1\ cm^{-3}$
$\gamma_{sh} \sim 3 \Rightarrow \gamma_{e,min} \sim 10^3$
$\gamma_{e,max} \sim 3 \times 10^6$
$\delta = 50$
$R \sim 10^{16}$ cm
$B \sim 4$ mG
$\sigma \sim 4 \times 10^{-7}$
$\sigma_{rad} \sim 10^{-4}$
$L_{jet} \sim 4 \times 10^{44}$ erg/s $\sim 0.002\ L_{edd}$

-> Very good representations even for the hardest sources.





AZ, M. Lemoine 2021

stochastic re-acceleration ?

Tavecchio et al. 2022 : 3D HD simulations show that recollimation shocks trigger centrifugal instabilities that inject turbulences and disrupt the jet.

Instabilities are damped by magnetic fields for a critical magnetization that is estimated to be around $\sigma_{cr} \gtrsim 10^{-3}$.

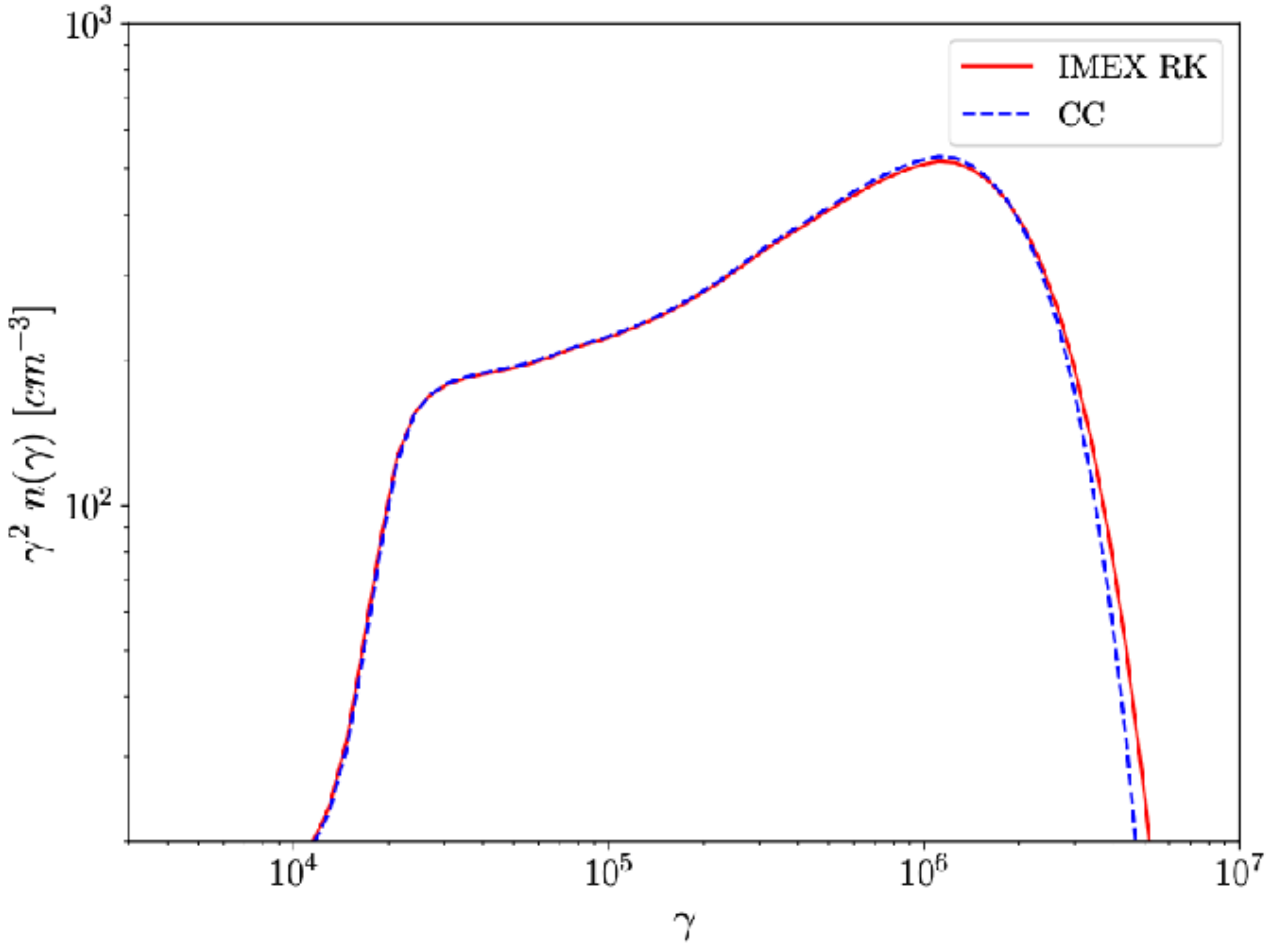
Alternative scenario to re-acceleration on multiple shocks:
stochastic re-acceleration on turbulences.

Caveat :

Prediction of a low degree of polarization might be in contradiction with IXPE results from blazar observations.

To be explored :

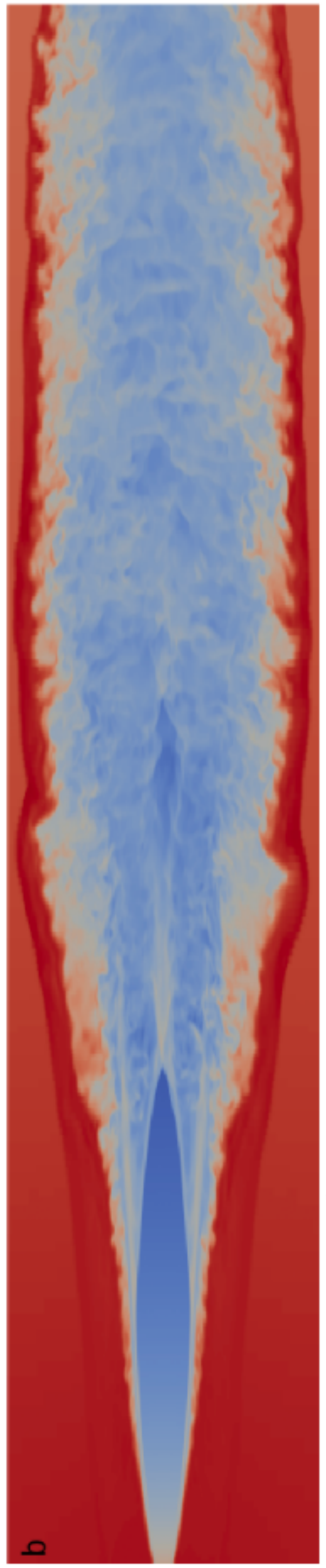
Impact of jet structure (e.g. spine-in-sheeth) on the development of the instability ?



electron distribution
Sciaccaluga & Tavecchio 2024

turbulent jet

recollimation shock



Gourgouliatos & Komissarov 2018

variability of RGB J0710+591 with AstroSAT

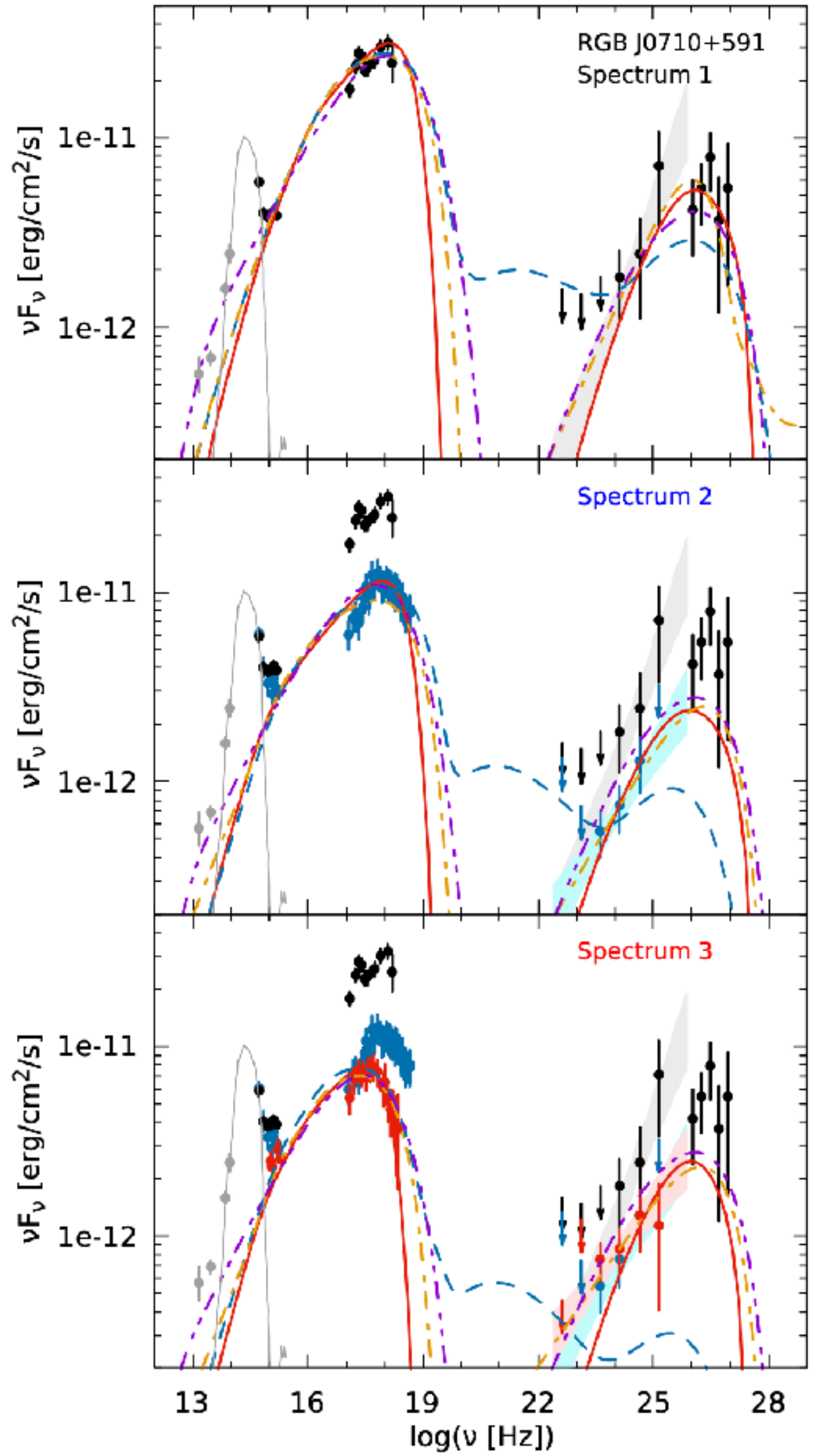
New study of three spectral states of this extreme blazar :

2008/09 - 2009/08 highest flux state (Swift, Fermi, Veritas)
2013/01 - 2016/12 intermediate flux state (Swift, NuSTAR, Fermi)
2017/01 - 2021/01 lowest flux state (AstroSAT, Fermi)

Different models were tested: SSC, co-acceleration, lepto-hadronic cascades, proton-synchrotron.

co-acc. model : softening of HE spectrum and lowering of synch. peak frequency from state 1 -> 2 -> 3 requires increase of radius and decrease of B-field.

-> very slow expansion of a moving emission region ?



P. Goswami et al. (inc. AZ) 2024

Conclusions

Extreme TeV blazars have particularly hard spectra that cannot be easily interpreted with the usual SSC models.

interpretation with models:

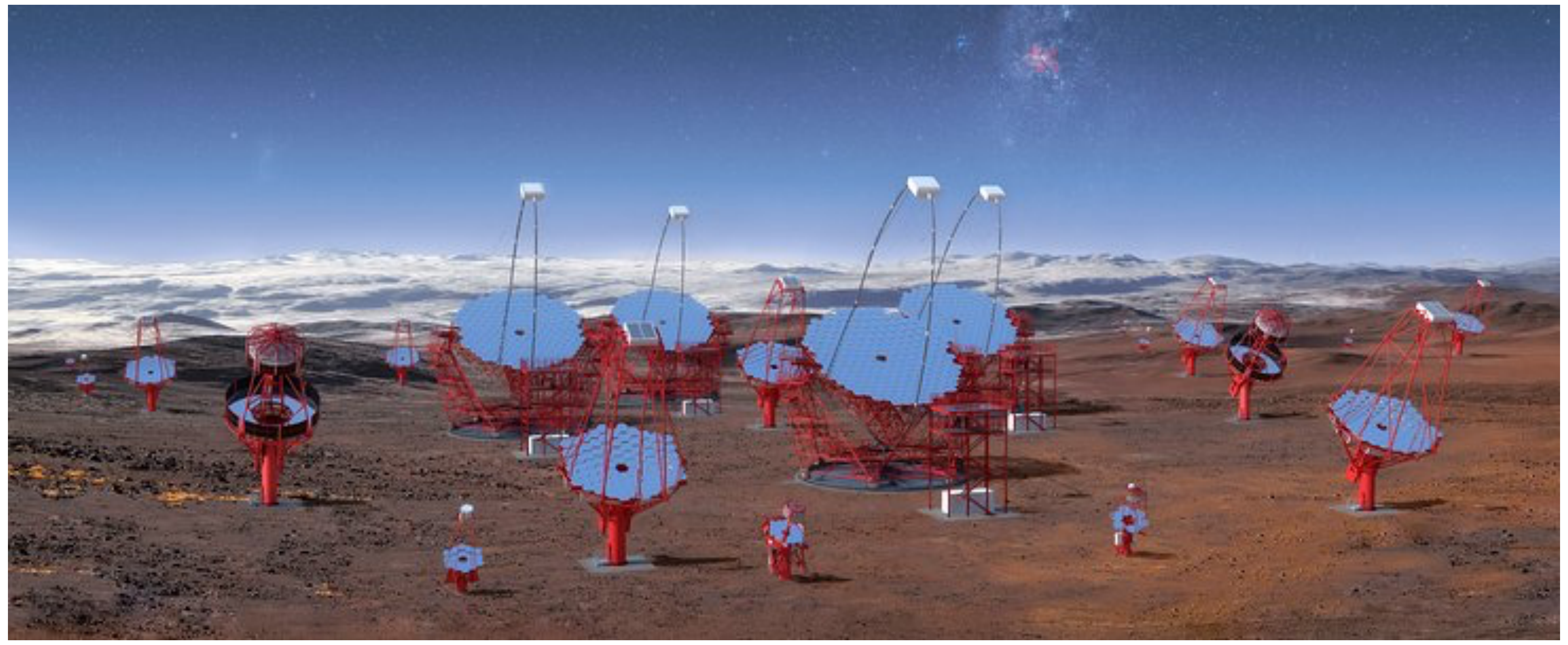
SED modelling in the SSC framework requires either very high values of γ_{min} or very hard spectral indices p << 2, and low magnetization.

Electron-proton co-acceleration on shocks and re-acceleration on shocks and/or turbulences may provide a coherent and natural explication of all the observed characteristics.

Observational support for shock acceleration from recent IXPE results on hard blazars (Mrk421, Mrk501, PKS 2155-304...).

future observations :

CTA (especially its Small-Size Telescopes) should provide strong constraints on the multi-TeV spectra and on their variability.



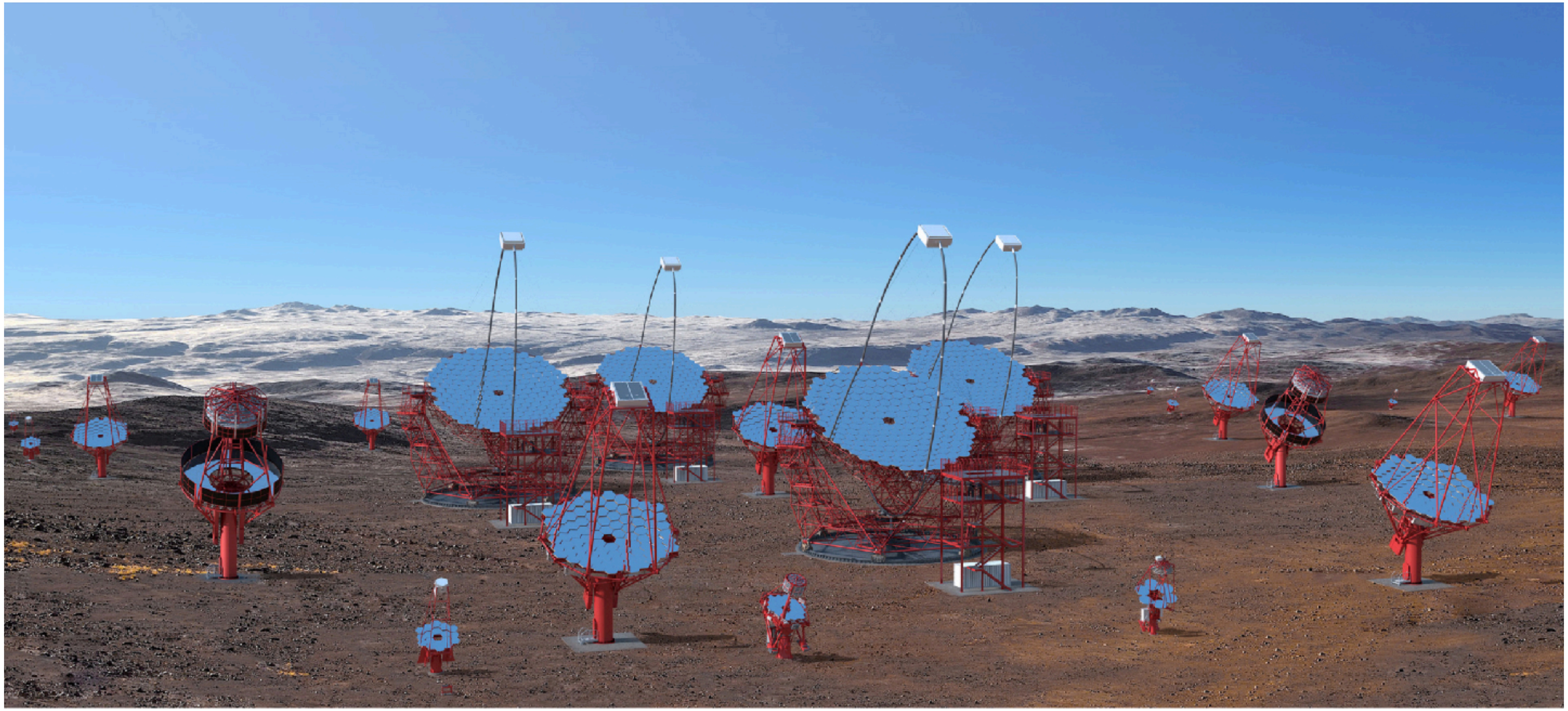
A. Zech, HEASA 2024

Backup Slides

Outline

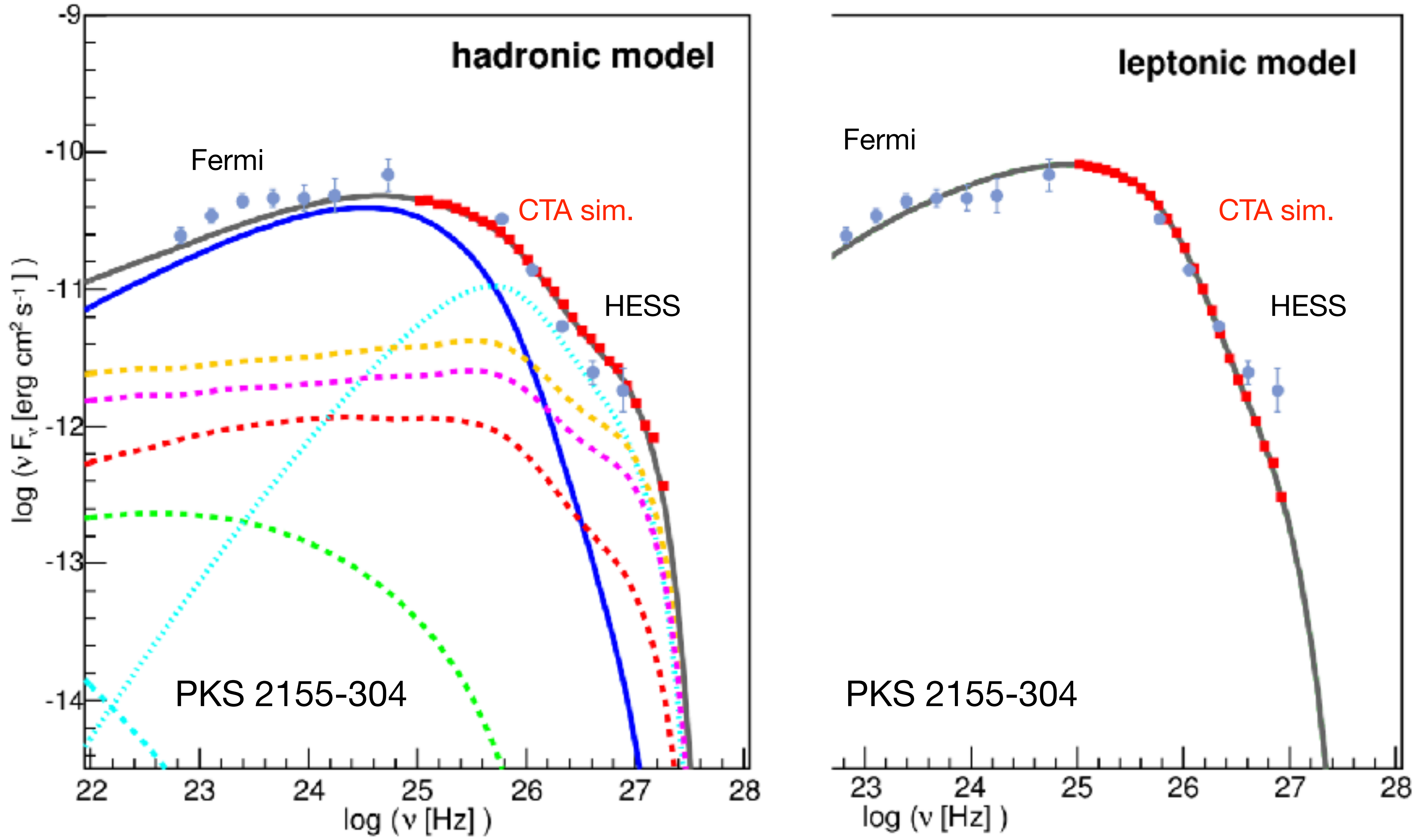
- a short introduction to blazars
- extreme blazars
- leptonic scenarios for extreme blazars
- lepto-hadronic scenarios for extreme blazars
- co-acceleration on shocks and re-acceleration ?
- conclusions

outlook & conclusions

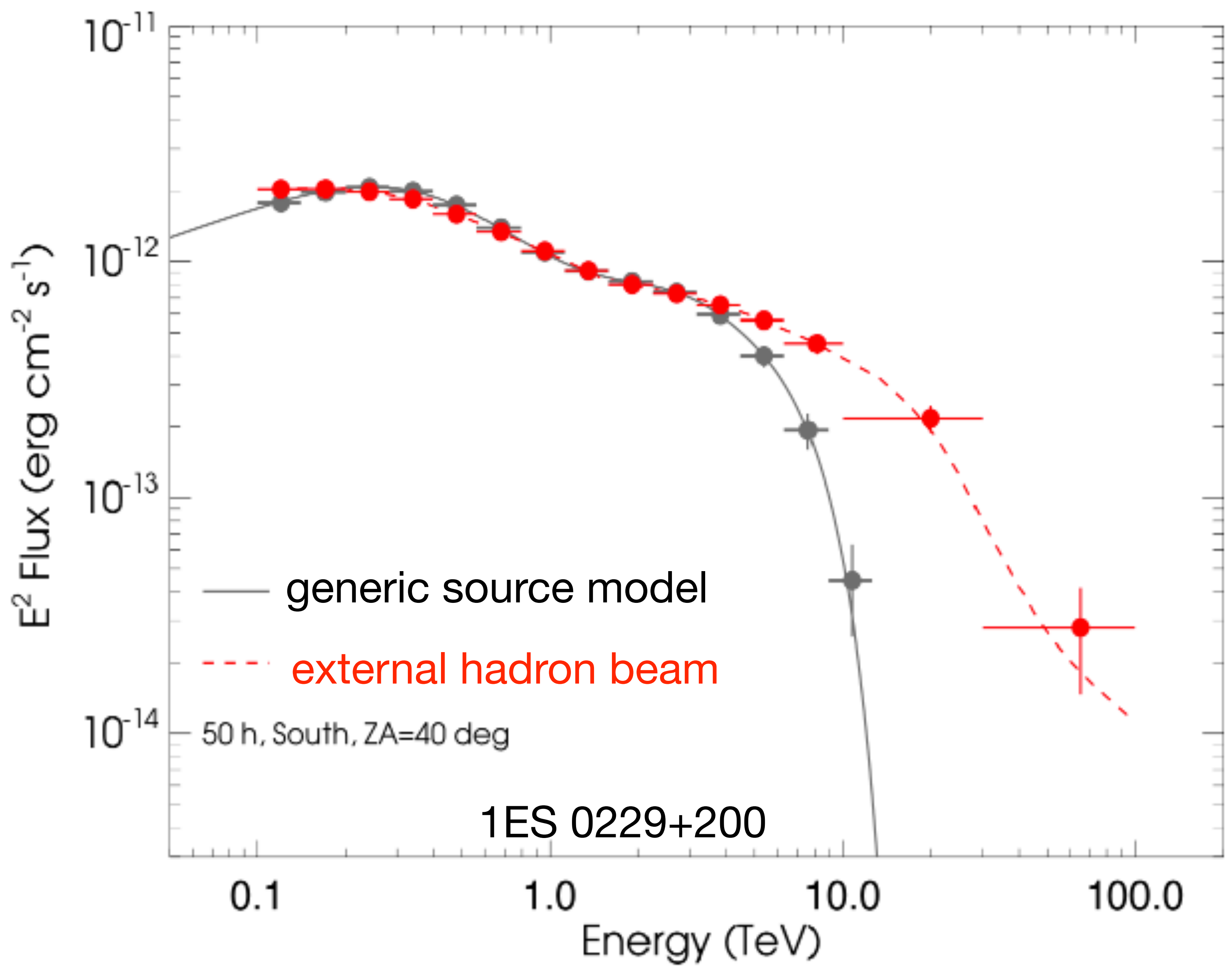


Credit: Gabriel Pérez Diaz, IAC / Marc-André Besel, CTAO

lepto-hadronic models : cascade signatures with CTA ?



AZ, Cerruti et al. 2017
Acharya et al. 2017



Tavecchio et al. 2018

In the proton-synchrotron scenario, spectral hardening at VHE can be expected from internal cascades for BL Lac objects (not for extreme-TeV BL Lacs though).

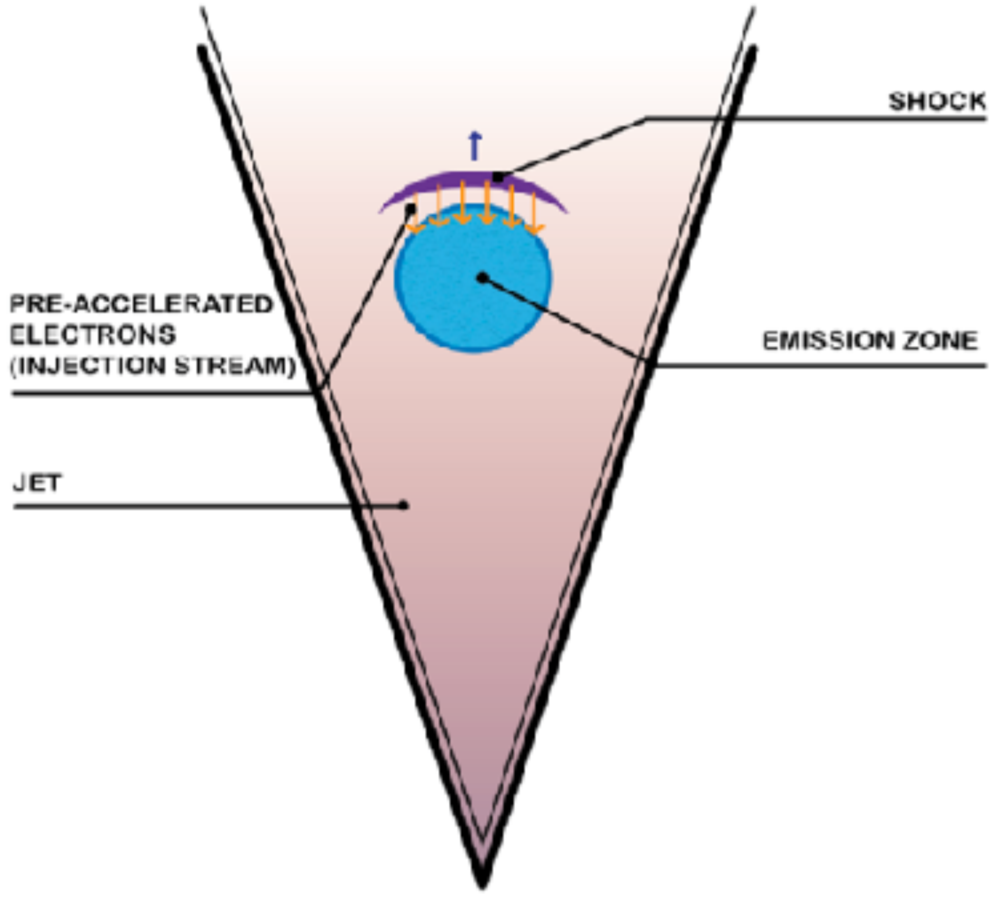
UHECR induced external cascades should lead to detectable signatures with future instruments.

The CTAO should be able to detect internal pair-synchrotron cascades and external pair-IC cascades for a few particularly bright sources.

moving vs. standing shocks

moving shocks (e.g. "blob-in-jet" with bow shock)

- shock Lorentz factor is set by relative Lorentz factor between jet and blob : $\gamma_{sh} \sim \Gamma_b/(2\Gamma_j)$ for $\Gamma_b \gg \Gamma_j \gg 1$
- mildly relativistic shocks for Γ_b a few $2\Gamma_j$
- *e.g. for $\Gamma_b \sim \delta/2$ (i.e. viewing angle ~ 0), for $\Gamma_j \sim \delta/12$ one gets a shock with $\gamma_{sh} \sim 3$*

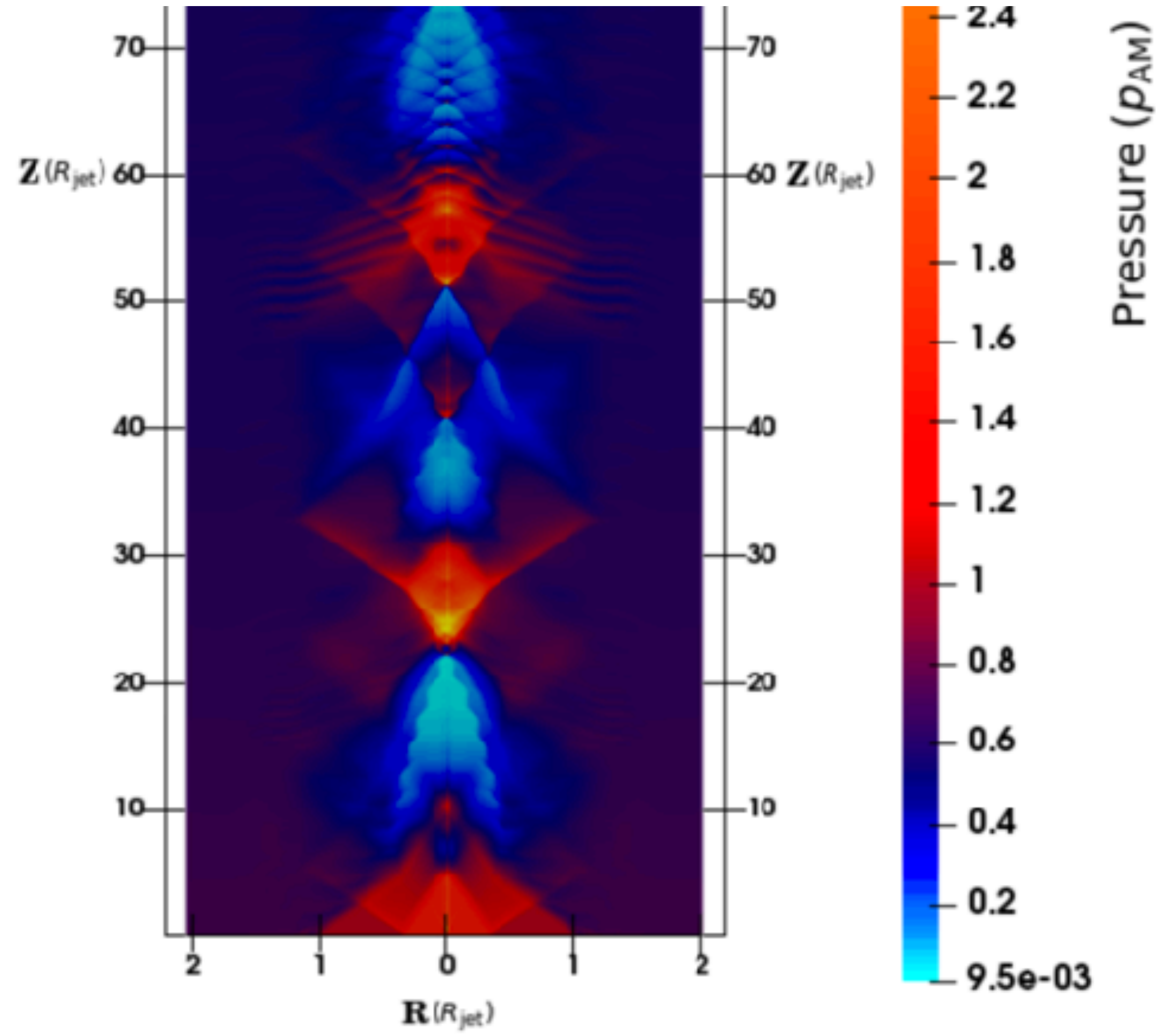


blob-in-jet scenario with leading shock (A. Dmytriiev et al. 2021)

standing shocks (e.g. recollimation shocks)

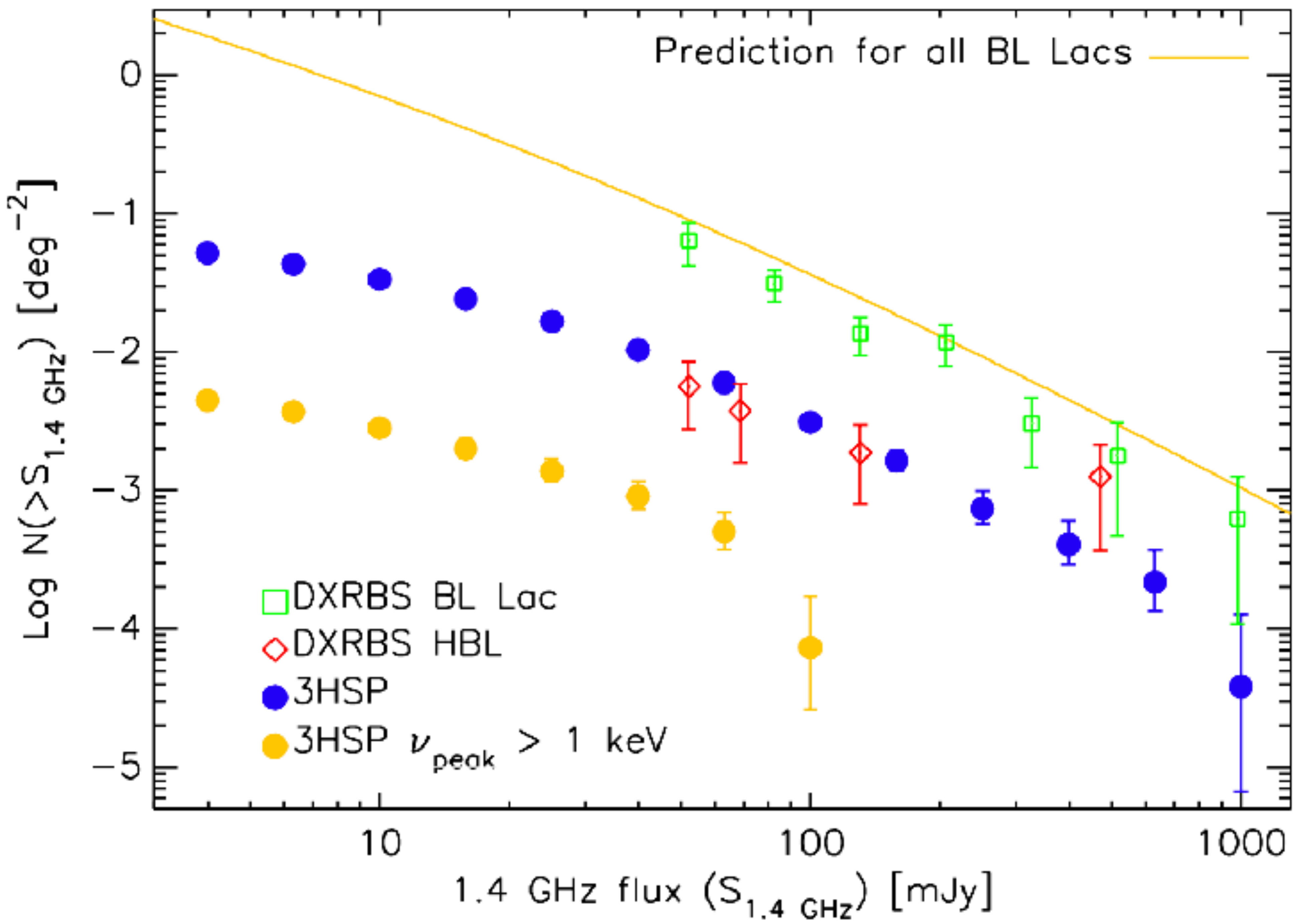
- oblique shocks : γ_{sh} depends on jet Lorentz factor and shock geometry
- One gets $\Gamma_{j,ds}\, \gamma_{sh|shock} \approx \Gamma_{j,us}$
  where $\Gamma_{j,ds}$ (jet downstream of the shock) in the source frame controls the Doppler boosting of the emission and $\gamma_{sh|shock}$ in the shock normal frame controls the electron heating
- *e.g. for $\Gamma_{j,ds} \sim \delta/2$, for $\Gamma_{j,us} \sim 3\,\delta/2$, one gets $\gamma_{sh|shock} \sim 3$*

- natural explanation for persistent emission !



recollimation shocks in an MHD jet simulation (G. Fichet de Clairfontaine et al. 2021)

characterization of extreme blazars



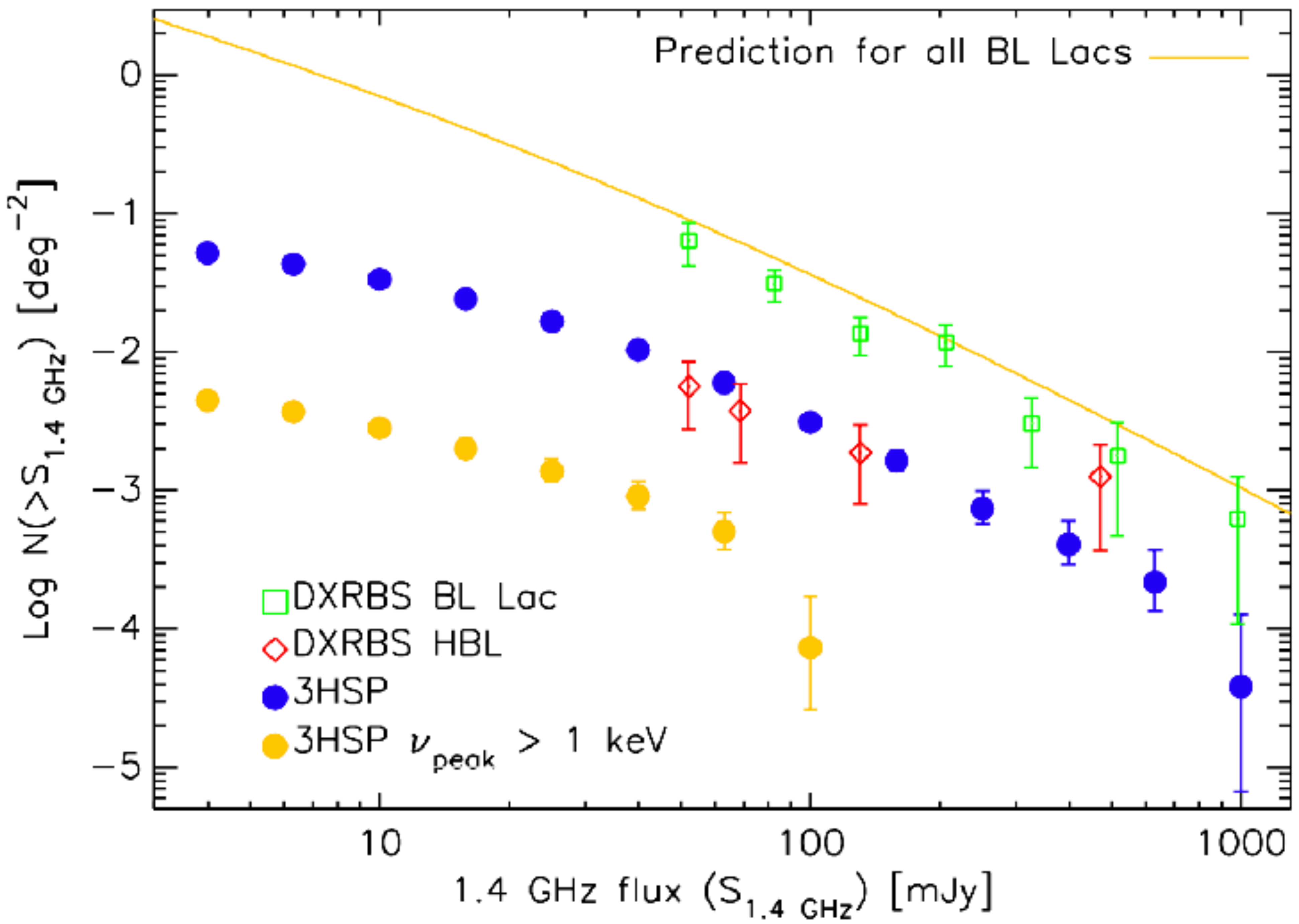
radio number counts of different BL Lac classes ;
extreme-synchrotron blazars in yellow
(Biteau et al. 2020)

Source Name	redshift z	X-ray spectrum	γ-ray spectrum	Flux at 1 keV [$erg\,cm^{-2}\,s^{-1}$]	Flux at 100 GeV [$erg\,cm^{-2}\,s^{-1}$]
Mkn 421	0.031	SH	S	$10^{-12} - 10^{-9}$	10^{-10}
Mkn 501	0.034	SH	SH	$10^{-11} - 10^{-10}$	$10^{-10.5}$
1ES 2344+514	0.044	SH	S	$10^{-11.5} - 10^{-10.5}$	10^{-11}
1ES 1959+650	0.048	SH	S	$10^{-11} - 10^{-10}$	10^{-11}
TXS 0210+515	0.049	H	H	10^{-11}	10^{-12}
1ES 2037+521	0.053	H	H?	$10^{-11.5}$	10^{-12}
1ES 1727+502	0.055	HS	SH	10^{-11}	$10^{-11.5}$
PGC 2402248	0.065	H	S?	$10^{-11.5}$	10^{-12}
PKS 0548-322	0.069	H	H	10^{-11}	10^{-12}
RGB J0152+017	0.08	H	S	$10^{-11.5}$	10^{-12}
1ES 1741+196	0.084	H	H	$10^{-11.5}$	$10^{-11.5}$
SHBL J001355.9-185406	0.095	H	S	10^{-11}	10^{-12}
1ES 1312-423	0.105	H	S	10^{-11}	10^{-12}
RGB J0710+591	0.125	H	H	10^{-11}	10^{-12}
1ES 1426+428	0.129	H	SH	10^{-11}	$10^{-11.5}$
RX J1136.5+6737	0.1342	H	S	$10^{-11.5}$	10^{-12}
1ES 0229+200	0.1396	H	H	$10^{-11.5}$	10^{-12}
1ES 1440+122	0.163	H	S	10^{-11}	10^{-12}
H 2356-309	0.165	H	H	10^{-11}	10^{-12}
1ES 1218+304	0.182	HS	H	10^{-11}	10^{-11}
1ES 1101-232	0.186	HS	H	10^{-11}	$10^{-11.5}$
1ES 0347-121	0.188	H	H	10^{-11}	10^{-12}
RBS 0723	0.198	H	S	$10^{-11.5}$	10^{-12}
1ES 0414+009	0.287	S	H	10^{-11}	$10^{-11.5}$

Extreme-synchrotron blazars make up ~10% of High-frequency peaked BL Lacs (HBLs), which account themselves for ~10% of all BL Lacs.

About 200 extreme-synchrotron blazars expected to be detectable over the whole sky.

characterization of extreme blazars



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Extreme-synchrotron blazars make up ~10% of High-frequency peaked BL Lacs (HBLs), which account themselves for ~10% of all BL Lacs.

About 200 extreme-synchrotron blazars expected to be detectable over the whole sky.

-> I will focus on extreme TeV blazars in the following.

models with high γ_{min}

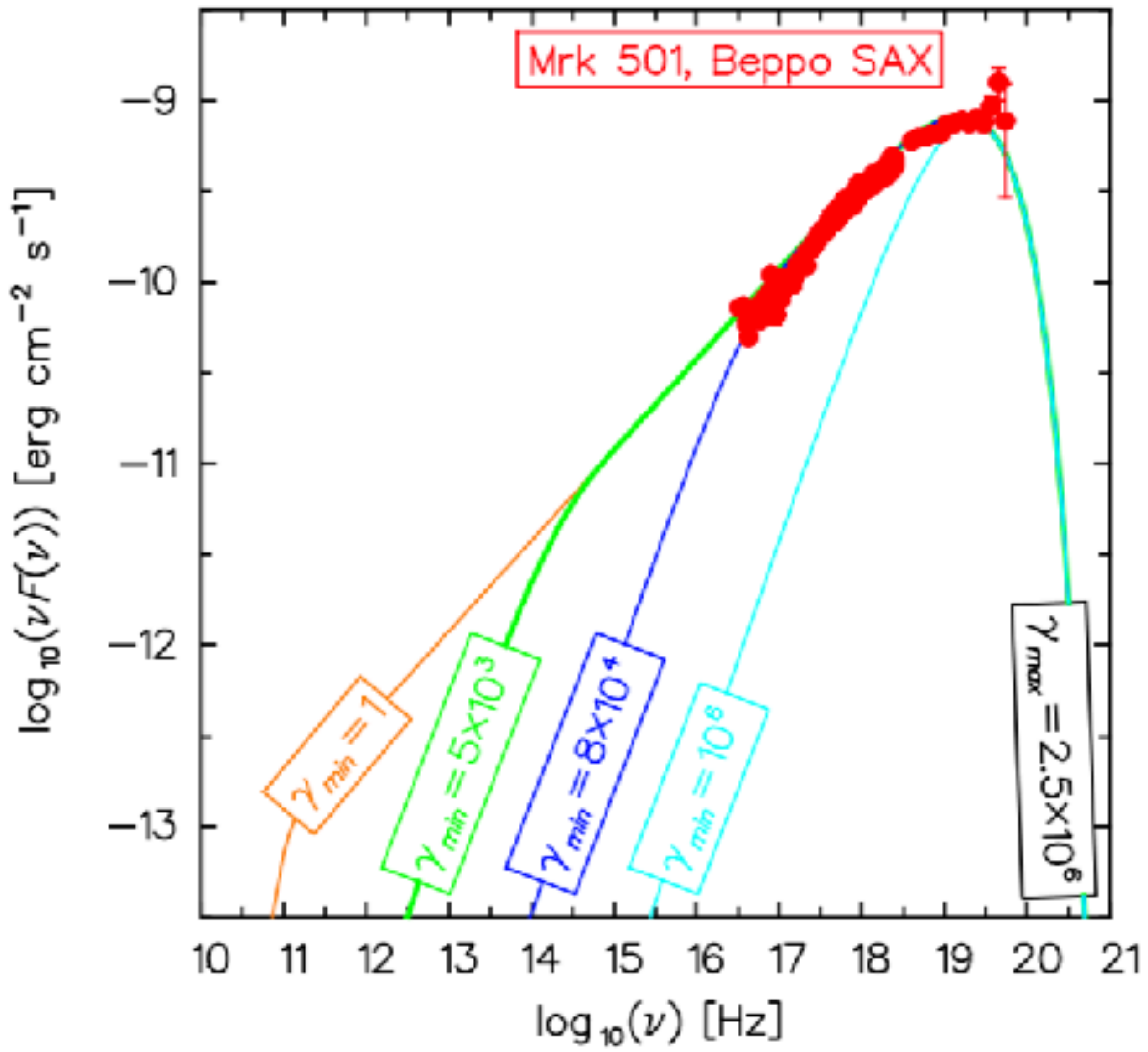
For the standard broken power-law electron spectrum, increasing the minimum electron Lorentz factor γ_{min} leads to a narrower distribution.

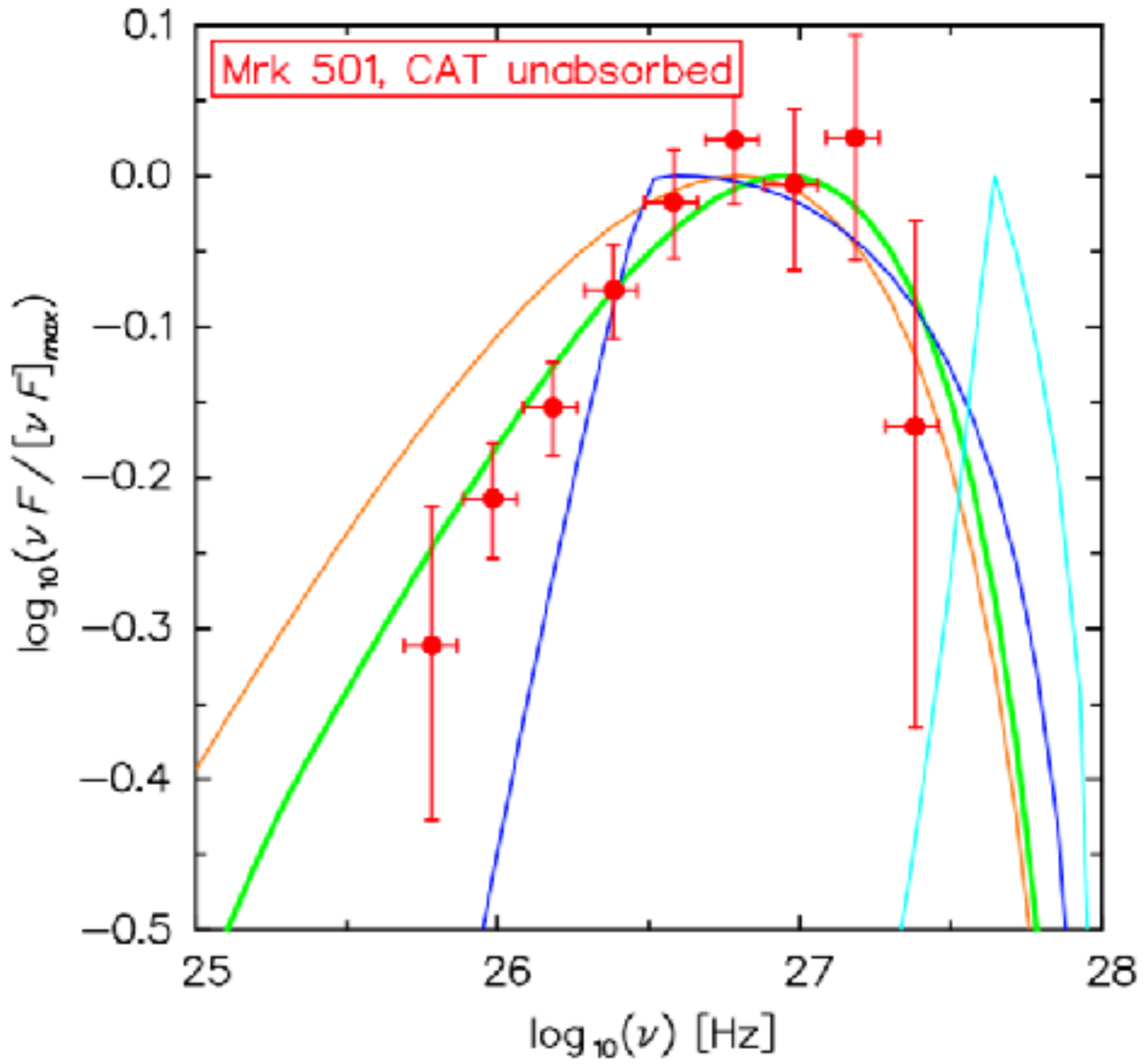
Very low B-field required to be able to neglect synchrotron cooling !

-> hard TeV spectrum up to a limit of $F_\nu \sim \nu^{1/3}$
(= limit of mono-energetic distribution)

Object	z	SSC parameters
1ES 0229+200	0.140	$\delta = 50$, B =0.4mG $R = 54 \times 10^{15}$ cm, $\gamma_{min} = 5 \times 10^5$ (Tavecchio et al. 2009); $\delta = 40$, $B = 0.032$ G, $R = 10^{18}$ cm, $\gamma_{min} = 4 \times 10^5$ (Kaufmann et al. 2011); $\delta > 53$, $B = 0.8$–3.3 mG, $R = (5$–$30) \times 10^{15}$ cm, $\gamma_{min} = (2.5$–$4.5) \times 10^4$ (Aliu et al. 2014);
1ES 0347−121	0.188	$\delta = 25$, $B = 0.035$ G, $R = 3.2 \times 10^{16}$ cm, $\gamma_{min} = 10^3$ (Aharonian et al. 2007b) $\delta = 61$, $B = 1.3$ mG, $R = 1.6 \times 10^{17}$ cm, $\gamma_{min} = 2 \times 10^4$ (Tanaka et al. 2014);
RGB J0710+591	0.125	$\Gamma = 30$, $B = 0.036$ G, $R = 2 \times 10^{16}$ cm, $\gamma_{min} = 6 \times 10^4$ (Acciari et al. 2010b);
1ES 1101−232	0.186	$\delta = 25$, $B = 0.1$ G, $R \approx 10^{16}$ cm $\gamma_{min} = 10^3$ (Aharonian et al. 2007a);
1ES 1218+304	0.184	$\delta = 80$, $B = 0.04$ G, $R = 3 \times 10^{15}$ cm (Rüger, Spanier & Mannheim 2010); $\delta = 44$, $B = 0.12$ G, $R = 3 \times 10^{15}$ cm (Weidinger & Spanier 2010);

Cerruti et al. 2015





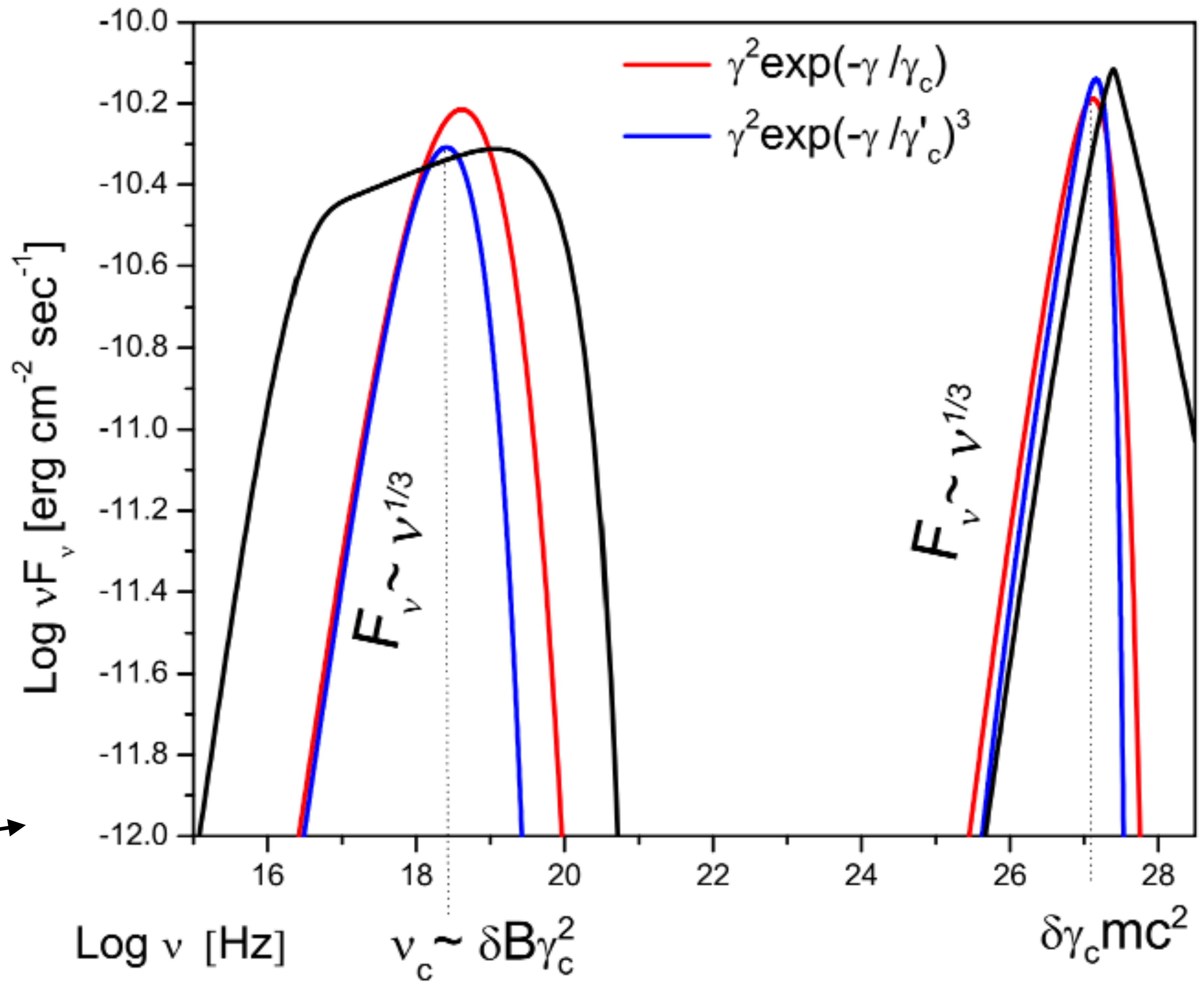
Katarzynski et al. 2006

Maxwellian-like electron distributions

Instead of the “standard” broken-power-law distribution, assume a relativistic Maxwellian electron distribution.

natural outcome of **stochastic acceleration** on turbulence + cooling; turbulence might be due to instabilities in the jet triggered by recollimation

shape varies for different turbulence regimes and cut-off energy



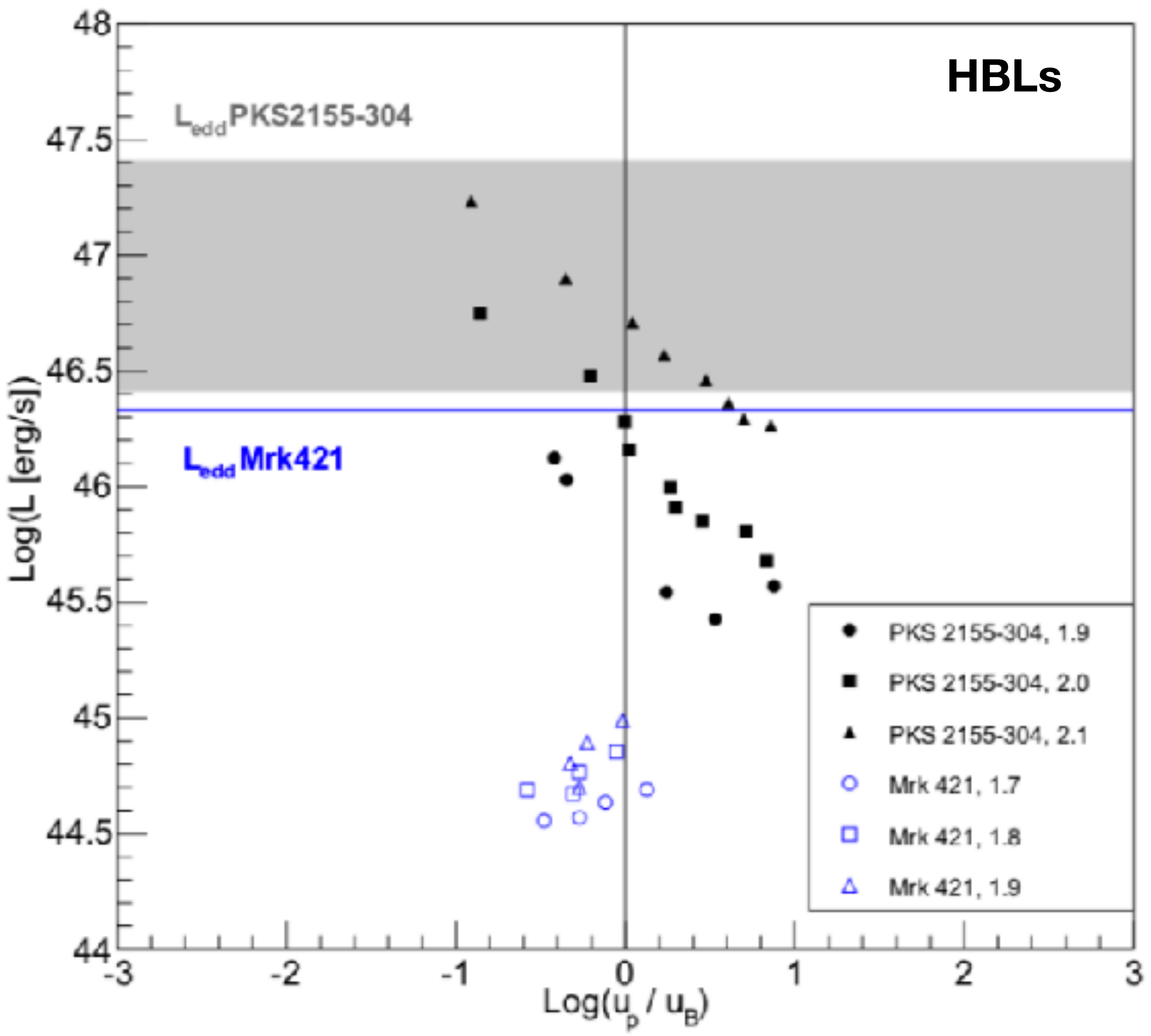
Lefa et al. 2011

-> narrow electron distribution with no need for very low B-field values

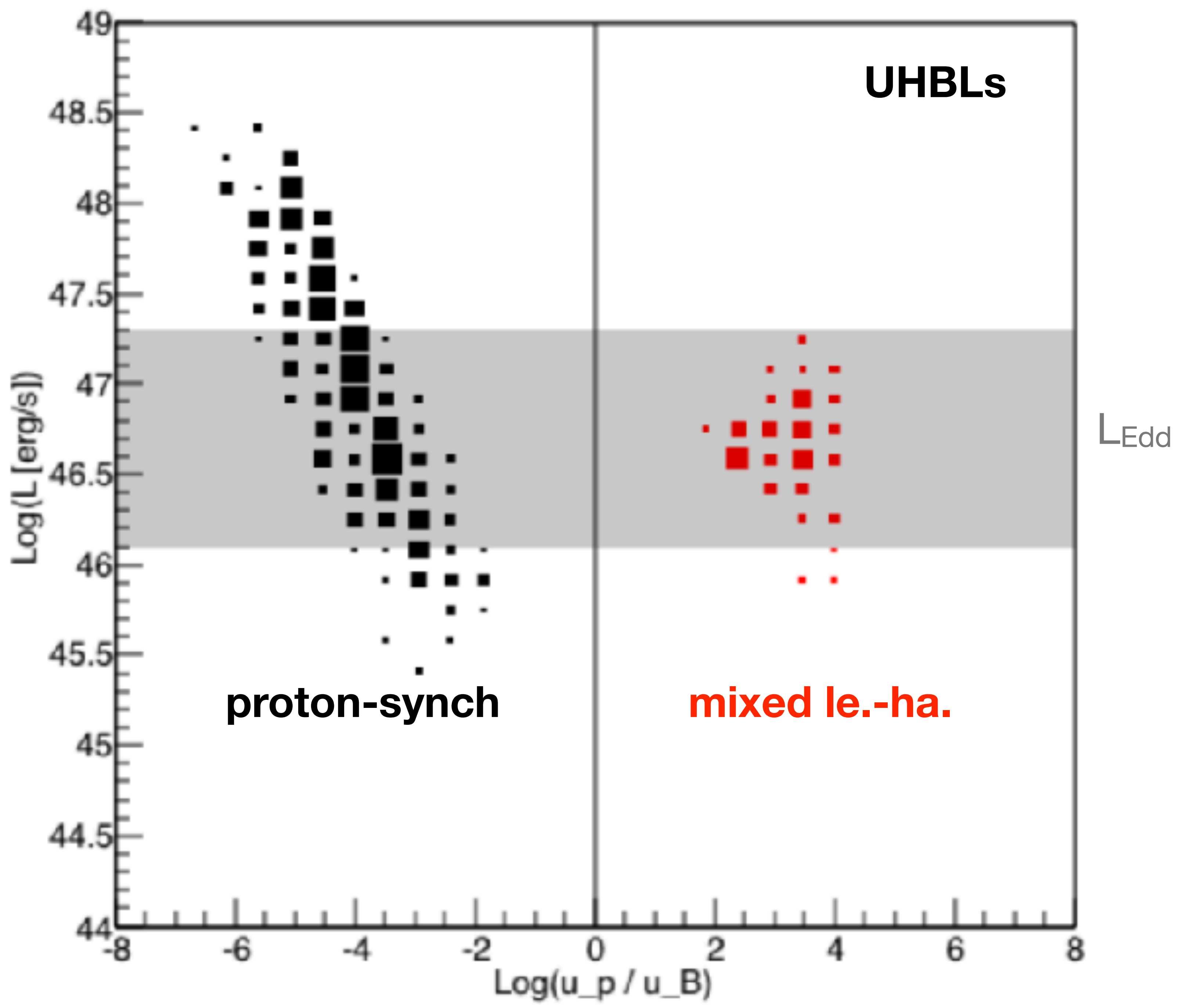
problem : possible to fit at the same time X-ray and VHE range ?

cf. also *Saugé & Henri 2006, Giebels et al. 2007,…*

jet powers in lepto-hadronic models



AZ, Cerruti et al. 2017



The lepto-hadronic models for HBLs and extreme TeV blazars (UHBLs) seem to occupy different regions in parameter space, with UHBLs being **farther from equipartition**.

co-acceleration scenario : physical implications

nature and location of the emission region

- *moving blob* ? : would expect flux variations on timescales < 1 yr, but depends on jet geometry

- *recollimation shocks* ? : given size of emission region, it could lie up to several 10 pc from jet base

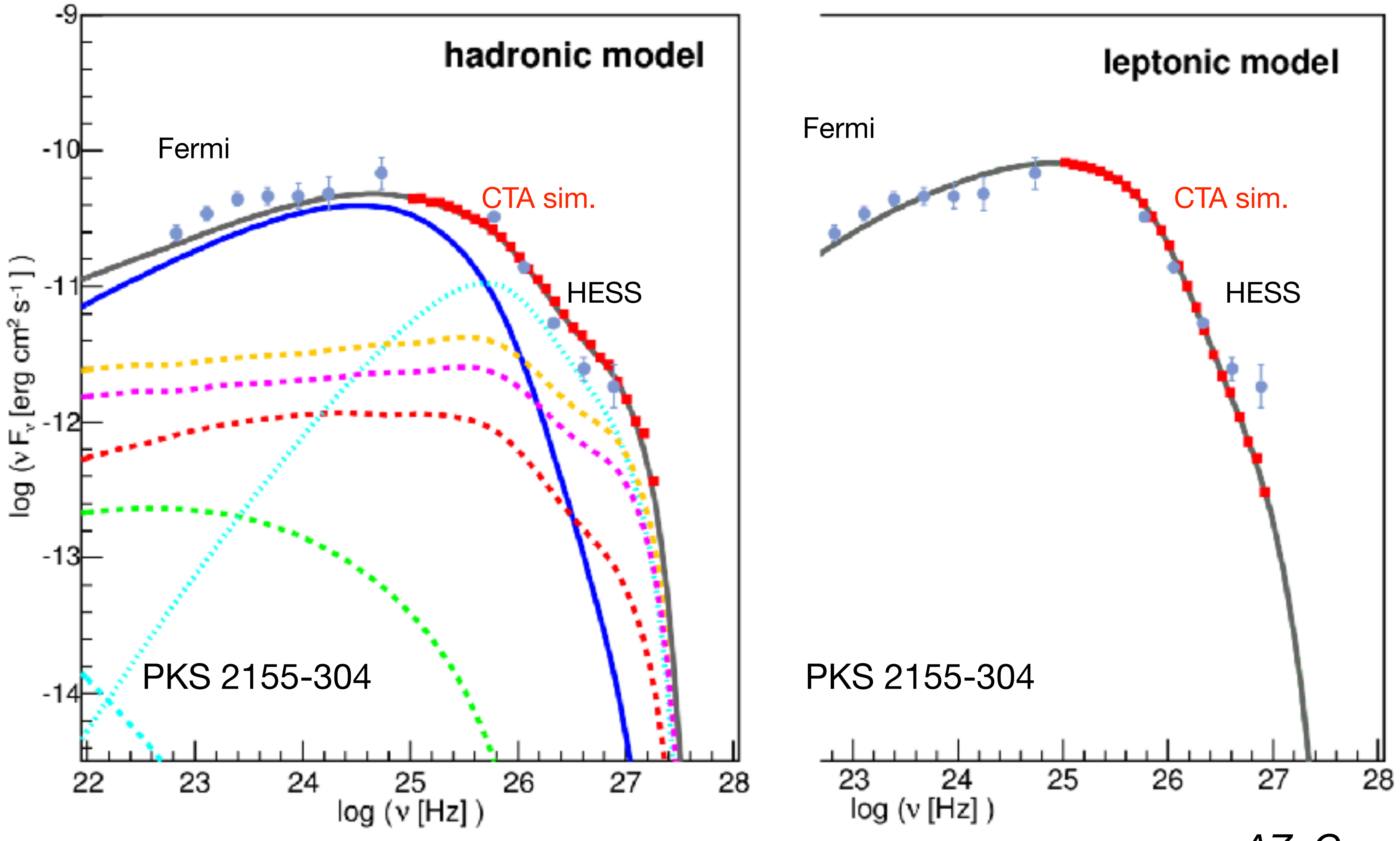
Re-acceleration without strong radiative losses -> distances of not more than a few pc between shocks.

Jet power, magnetization

Jet power << L_{Edd} for all solutions.

How to achieve low magnetisation $\sigma \ll 10^{-2}$?
Differential collimation becomes inefficient for $\sigma \sim 1$, so in the Blandford-Znajek framework, non-standard mechanisms are required. (Note that this is a general problem for SSC models for BL Lacs !)

lepto-hadronic models : Internal cascade signatures with CTA ?



AZ, Cerruti et al. 2017
Acharya et al. 2017

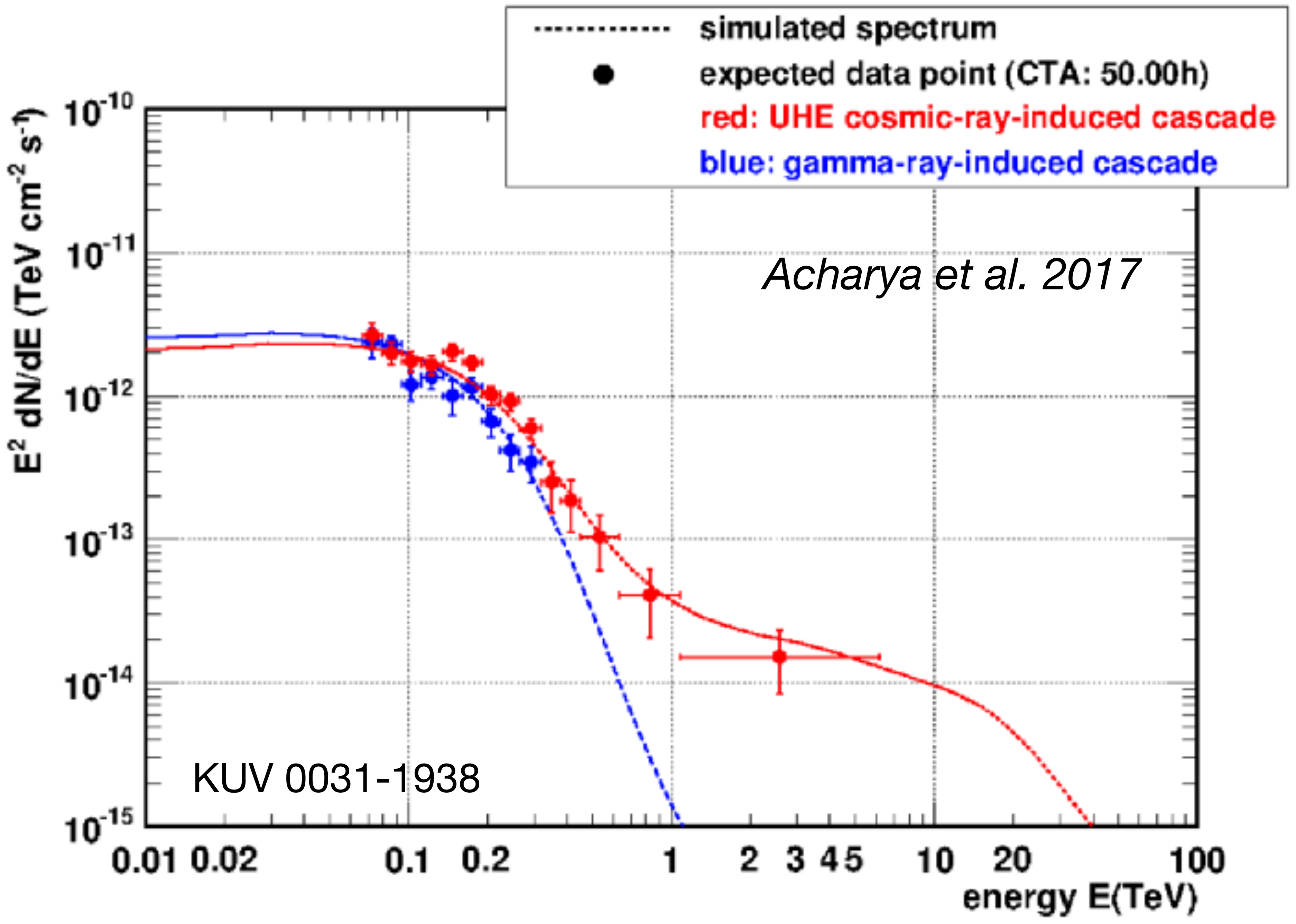
In the proton-synchrotron scenario, spectral hardening at VHE can be expected from internal cascades for BL Lacs.

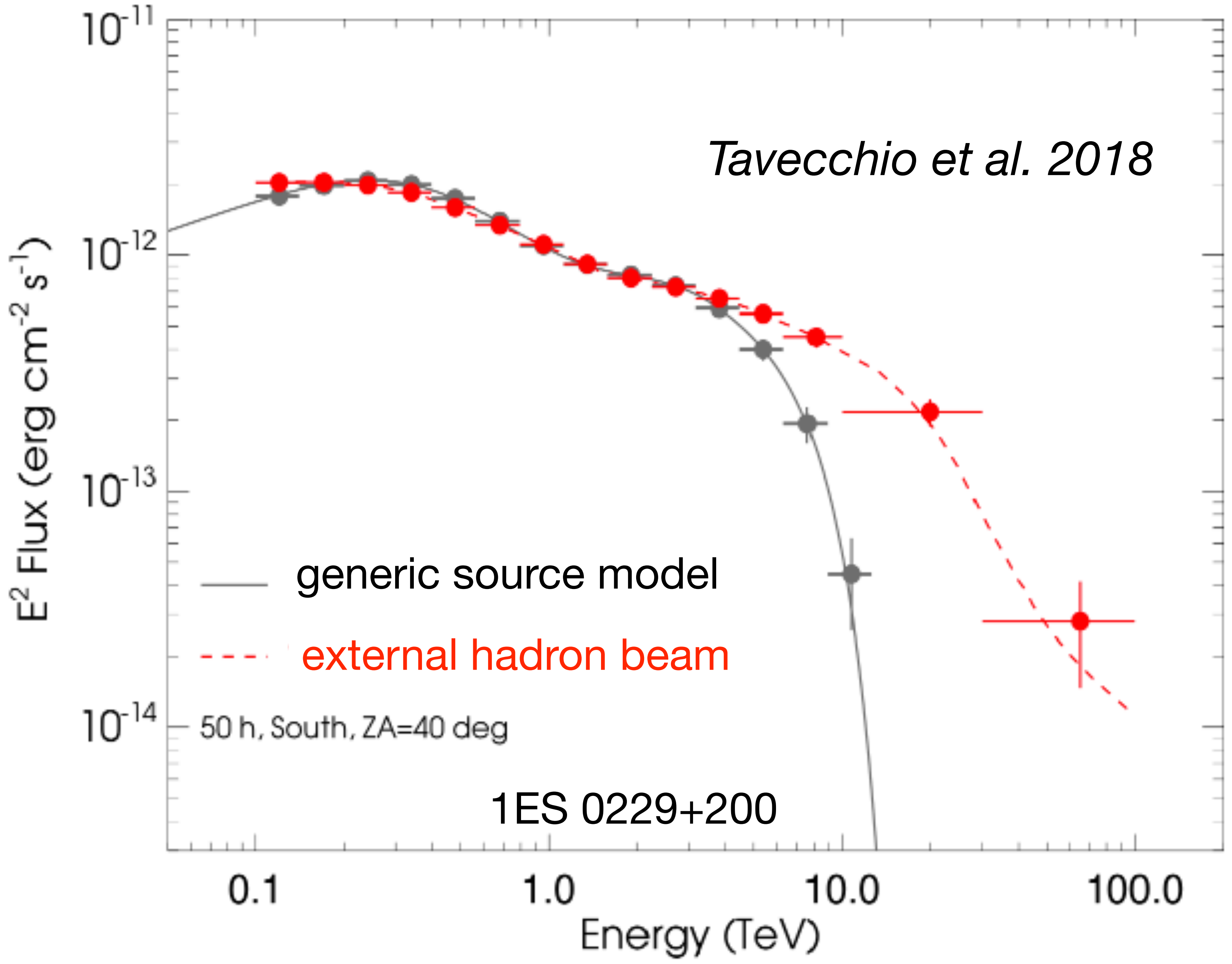
Such hardening is not predicted for lepto-hadronic solutions for extreme blazars.
- larger source extension, less dense, harder proton spectra -> cascades at low flux level
- intrinsic features are also suppressed by the EBL for large redshifts

lepto-hadronic models : External cascade signatures with CTA ?

UHECR induced external cascades should lead to detectable signatures with future instruments.

CTA should be able to detect external pair-IC cascades and distinguish between UHE photon and proton primaries with < 50h of observations.





hadronic emission processes

proton-synchrotron emission

$p^+ + \vec{B} \rightarrow p^+ + \vec{B} + \gamma$ (for high energy peak, requires ultra-relativistic protons and B ~ 10 – 100 G)

proton-photon interactions

$p^+ + \gamma \rightarrow p^+ + e^+ + e^-$ (Bethe-Heitler pair production)

$p^+ + \gamma \rightarrow p^+ + \pi^0 \rightarrow p^+ + \gamma + \gamma$ (photo-pion production)

$p^+ + \gamma \rightarrow n^0 + \pi^+ \rightarrow n^0 + \mu^+ + \nu_\mu \rightarrow n^0 + e^+ + \nu_\mu + \nu_e$

synchrotron-pair cascades

leptons and gamma-rays produced in proton-photon interactions are at ultra-high energy and interact with photon field or B-field
→ trigger cascades of synchrotron emission and pair production (or Inverse Compton emission and pair production)

proton-proton interactions

$p^+ + p^+ \rightarrow p^+ + p^+ + \pi^0 + \pi^+ + \pi^- + \ldots$ (only in very dense jets → generally not applicable to blazar jets)

models with high γ_{min}

How to explain such high γ_{min} values ?

Injection of an already truncated power-law spectrum from a shock region & inefficient cooling (*Katarzynski et al. 2006*) - but what is the origin ? Magnetic reconnection ? (*Tavecchio et al. 2008*)

Cooling of accelerated particles is partially compensated by stochastic turbulent **re-acceleration** -> γ_{min} = equilibrium energy where cooling and re-acceleration balance ? (*Katarzynski et al. 2006*)

What about the very small magnetic field ?

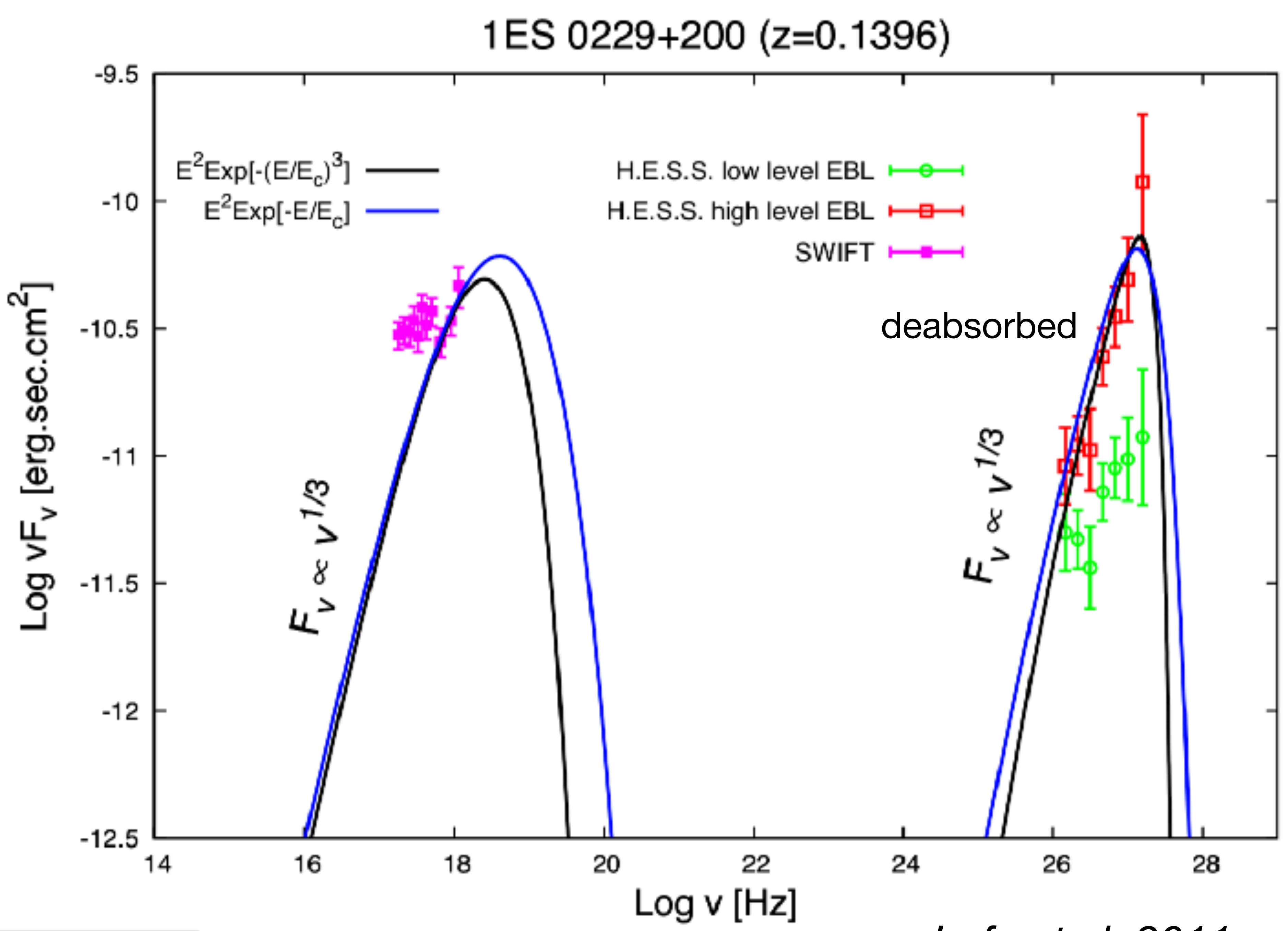
Constraints on magnetic field can be relaxed, when accounting for **adiabatic looses** -> inefficient radiative cooling.

Hard VHE spectrum remains, if adiabatic losses dominate over synchrotron losses below γ_{min} (*Lefa et al. 2011*).

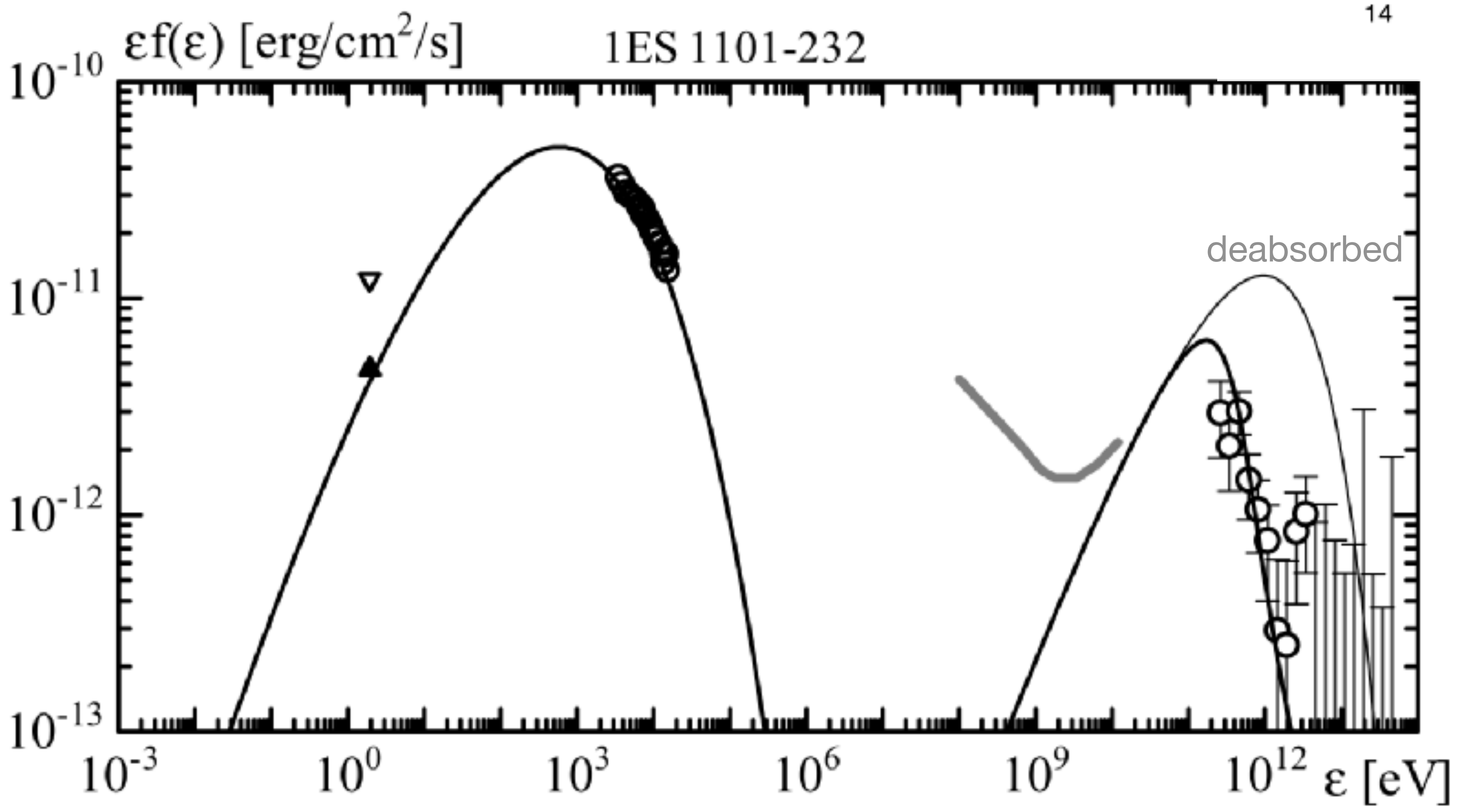
Maxwellian-like electron distributions

Modelling of 1ES 0229+200 with Maxwellian electron distributions
(EBL model *Franceschini et al. 2008*)

Problem: a magnetic field well below equipartition implies a **slow acceleration process** in this case.



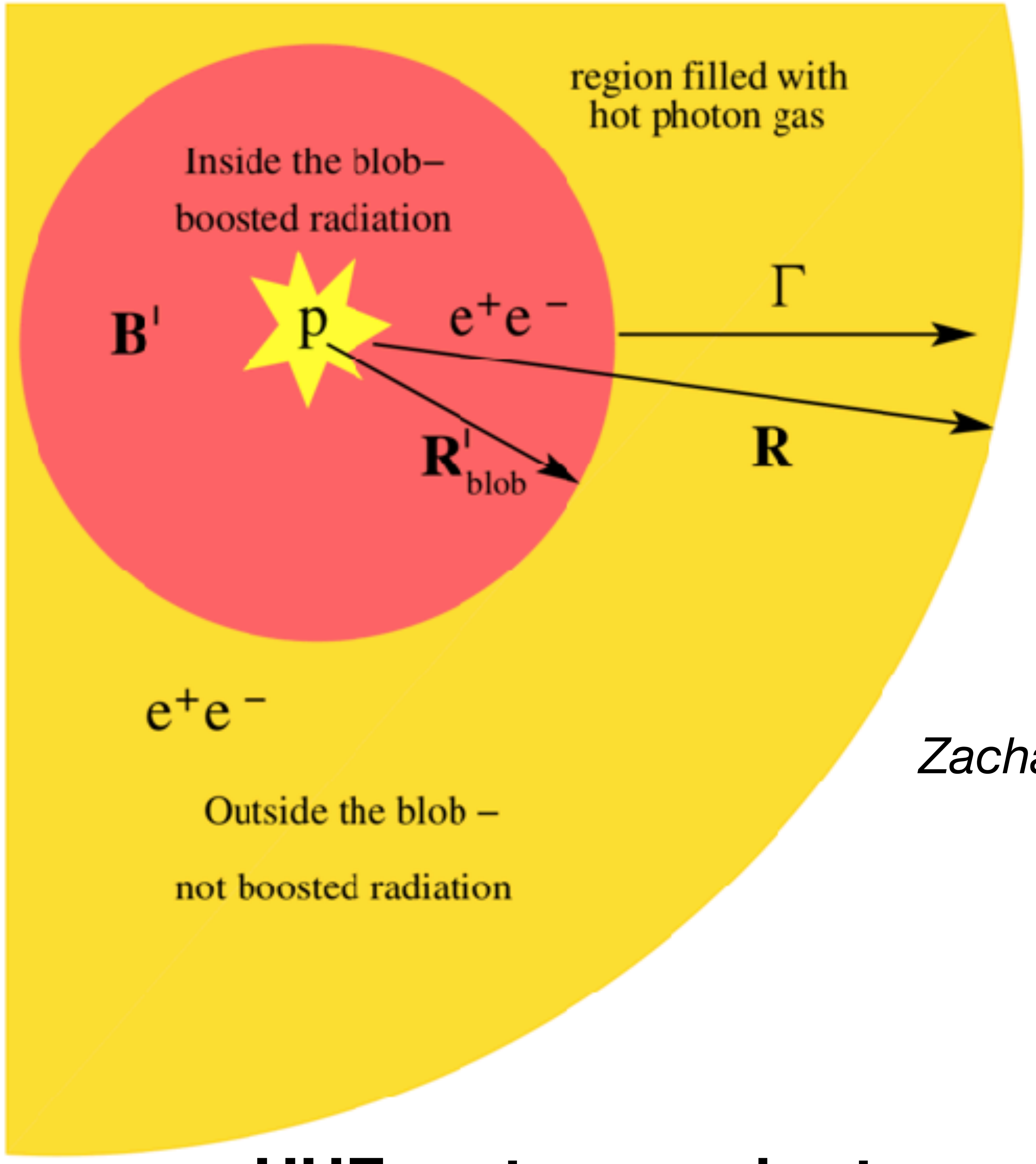
Lefa et al. 2011



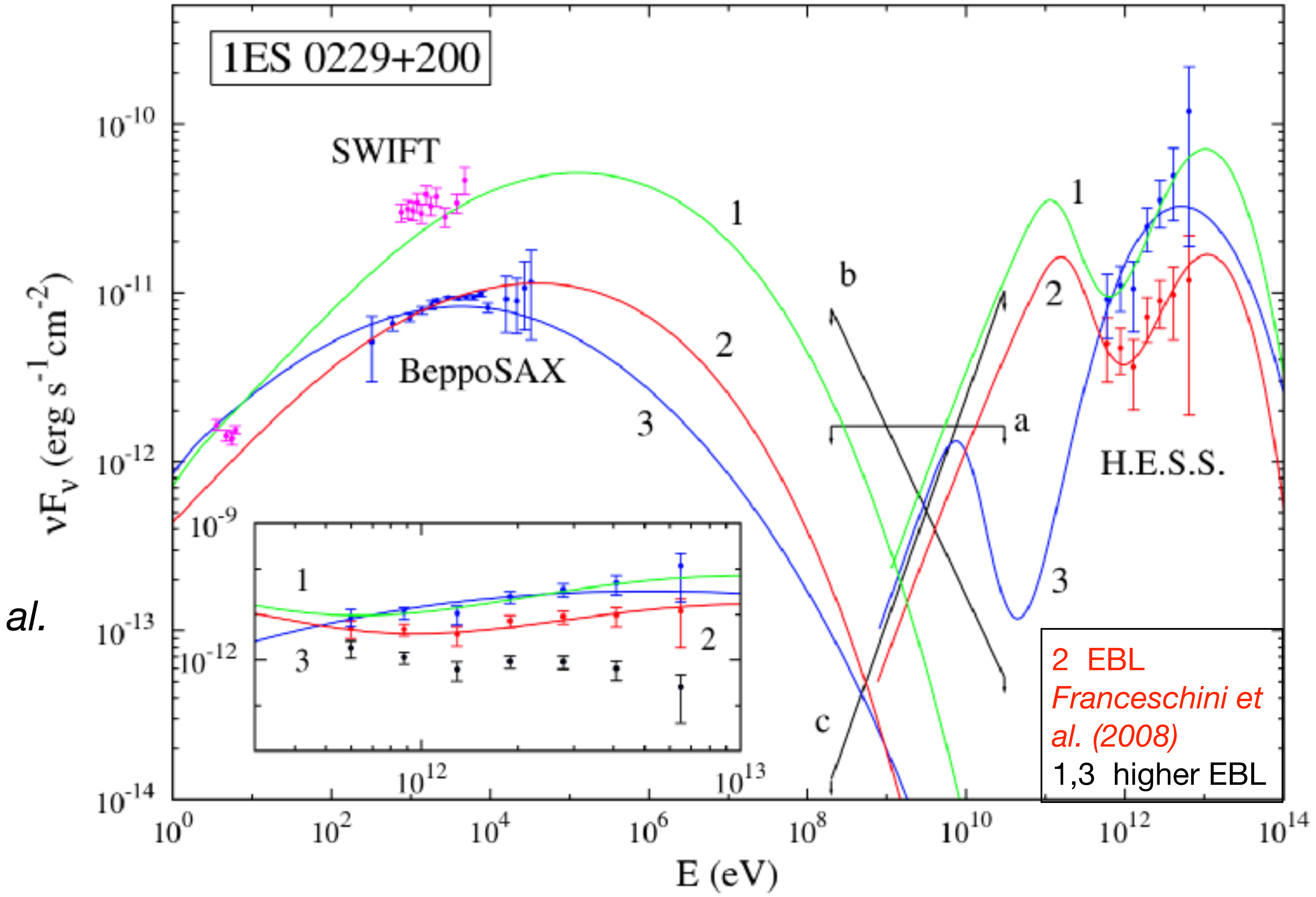
Asano et al. 2014

comprehensive time-dependent (steady-state) Fermi II modelling for 1ES 1101-232 assuming Kolmogorov turbulence
(EBL model *Kneiske et al. 2004*)

spectral hardening through internal absorption



Zacharopoulou et al. 2011



- **UHE proton synchrotron** radiation, absorbed on **dense internal photon fields with narrow energy distribution** (BLR ?), can lead to hard TeV spectrum (Zacharopoulou et al. 2011).

- Secondary pairs inside the “blob” are responsible for the lower-energy component.

- **problems**: A very hard proton distribution is assumed, $dN/dE \sim E^{+0.5}$, citing the “converter mechanism” (*Derishev et al. 2003*). These particular predictions not compatible with newer Fermi data.

cf. also *Aharonian 2008, Poutanen & Stern 2010, …*

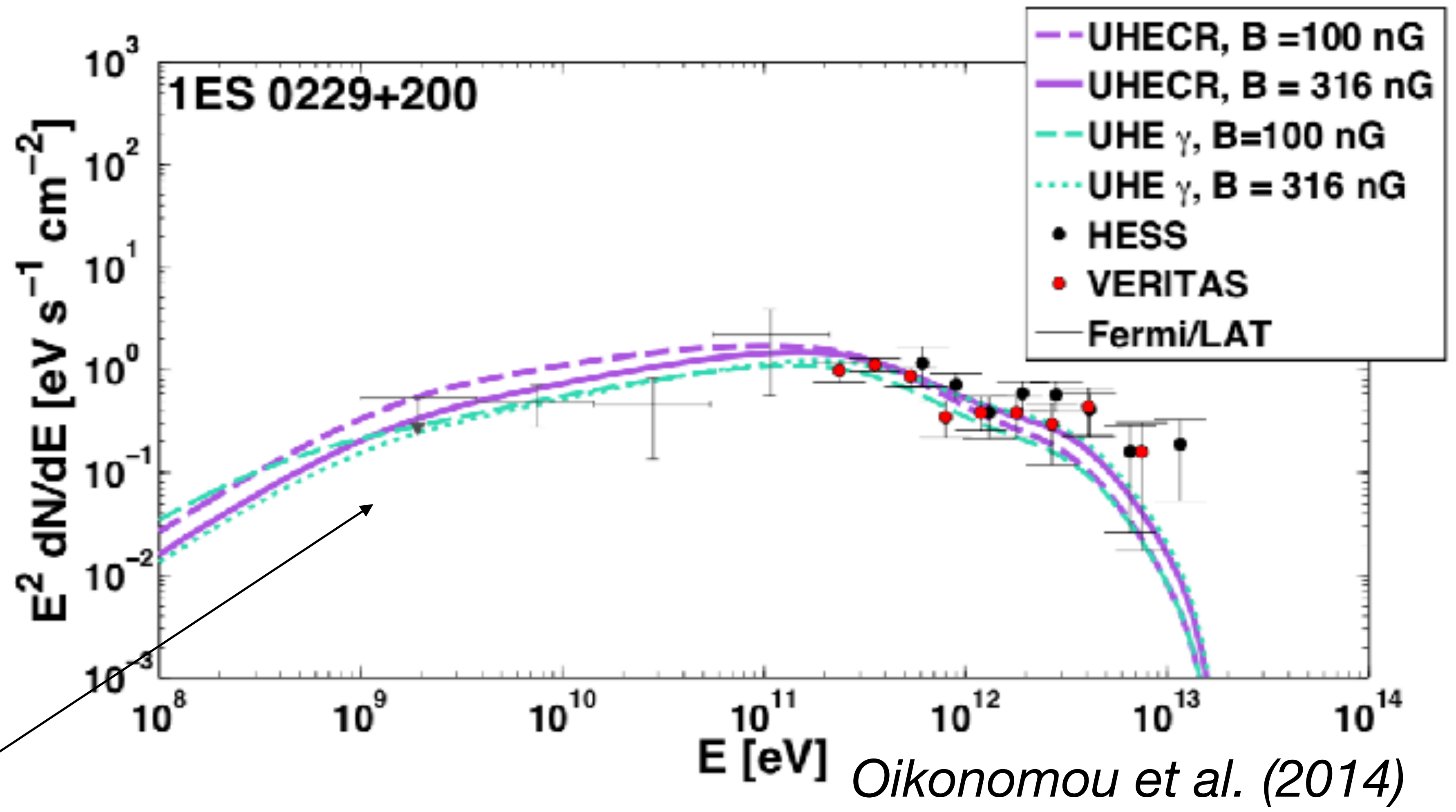
external cascade models

problem: external cascades disfavoured by the observation of some variability ?

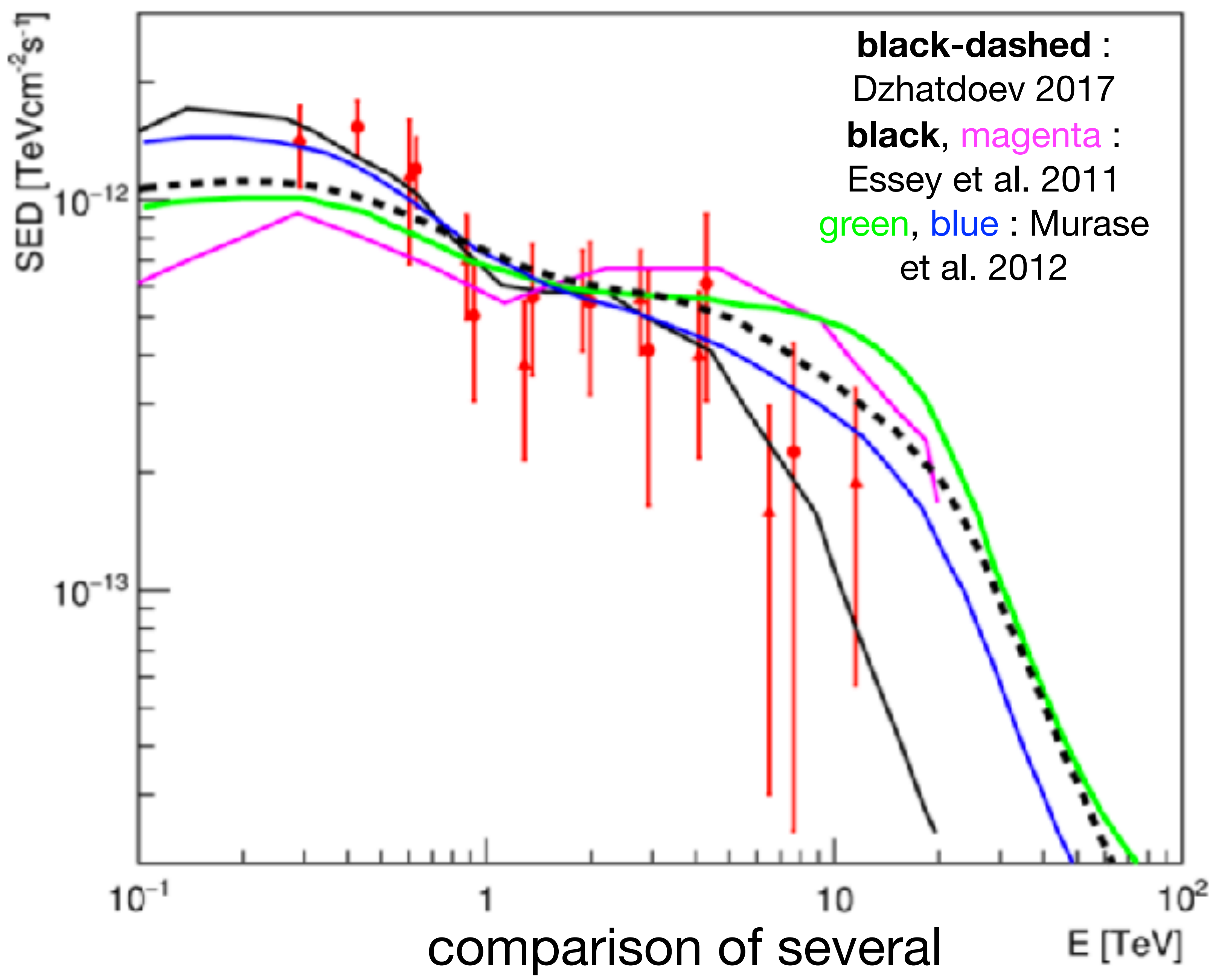
F. Oikonomou et al. (2014) : extreme blazars embedded in structured regions with magnetic fields of ~10^{-7} G.

-> secondary synchrotron emission from primary UHE protons or photons can produce hard TeV spectra

-> UHE photon primaries can possibly accommodate variability < 1 yr



Oikonomou et al. (2014)



comparison of several hadronic cascade models; *Dzhatdoev et al. 2017*

Many other flavours exist:
cf. also *Essey, Kusenko 2010, Essey et al. 2010,2011, Neronov et al. 2011, Taylor et al. 2011, Razzaque 2012, Dermer 2012, Vovk et al. 2012, Murase 2012, Takami 2013, Zheng et al. 2013, Tavecchio 2014, …*

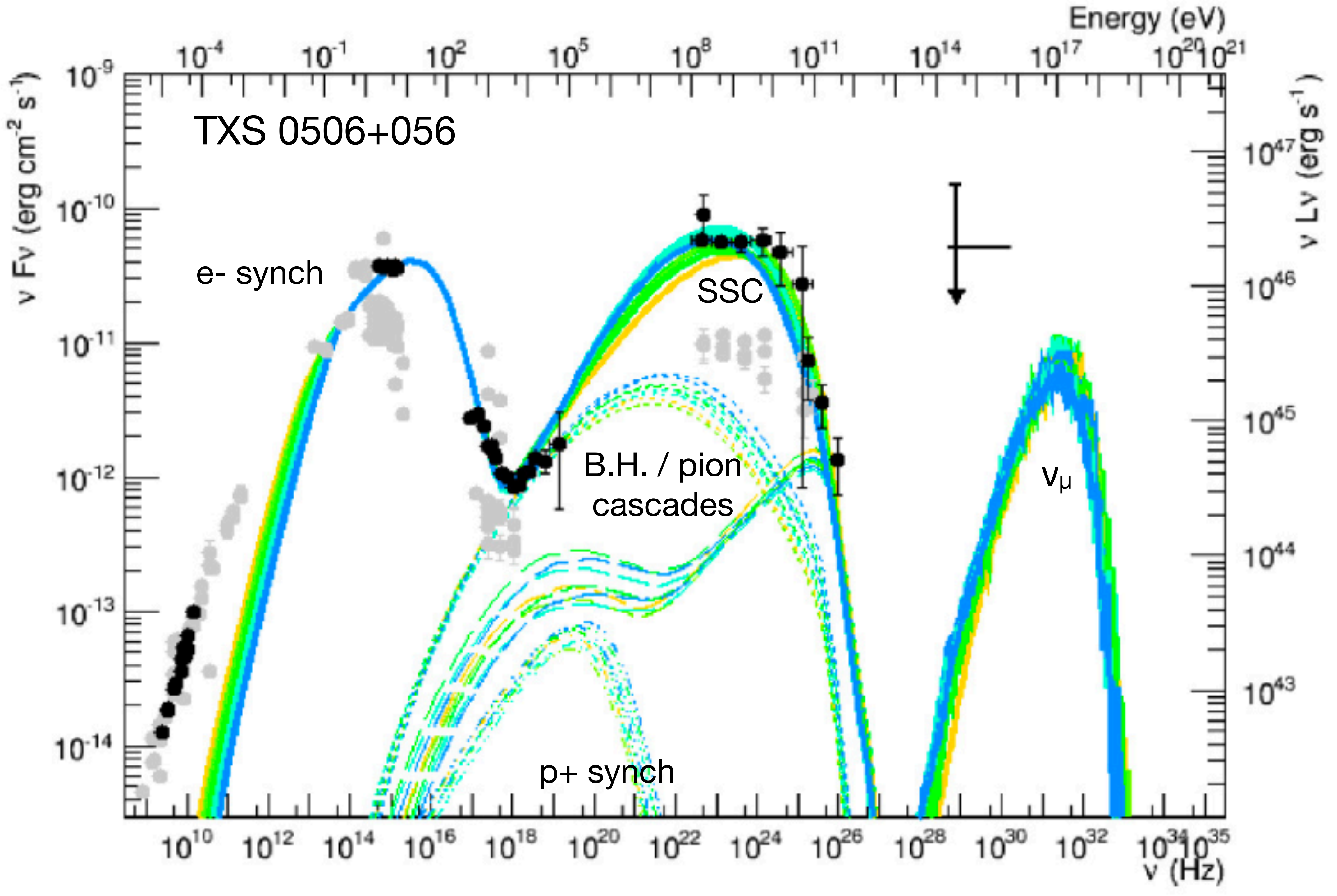
a side note : extreme blazars and neutrinos ?

Padovani et al. 2016 :
cross-correlations between γ-ray catalogs and IceCube data indicate a correlation with extreme blazars ($\nu_s > 10^{15}$ Hz)

The one-zone proton-synchrotron and mixed lepto-hadronic scenario for TXS 0506+056 do not well account for MWL and neutrino emission (*Cerruti, AZ et al. 2018*).

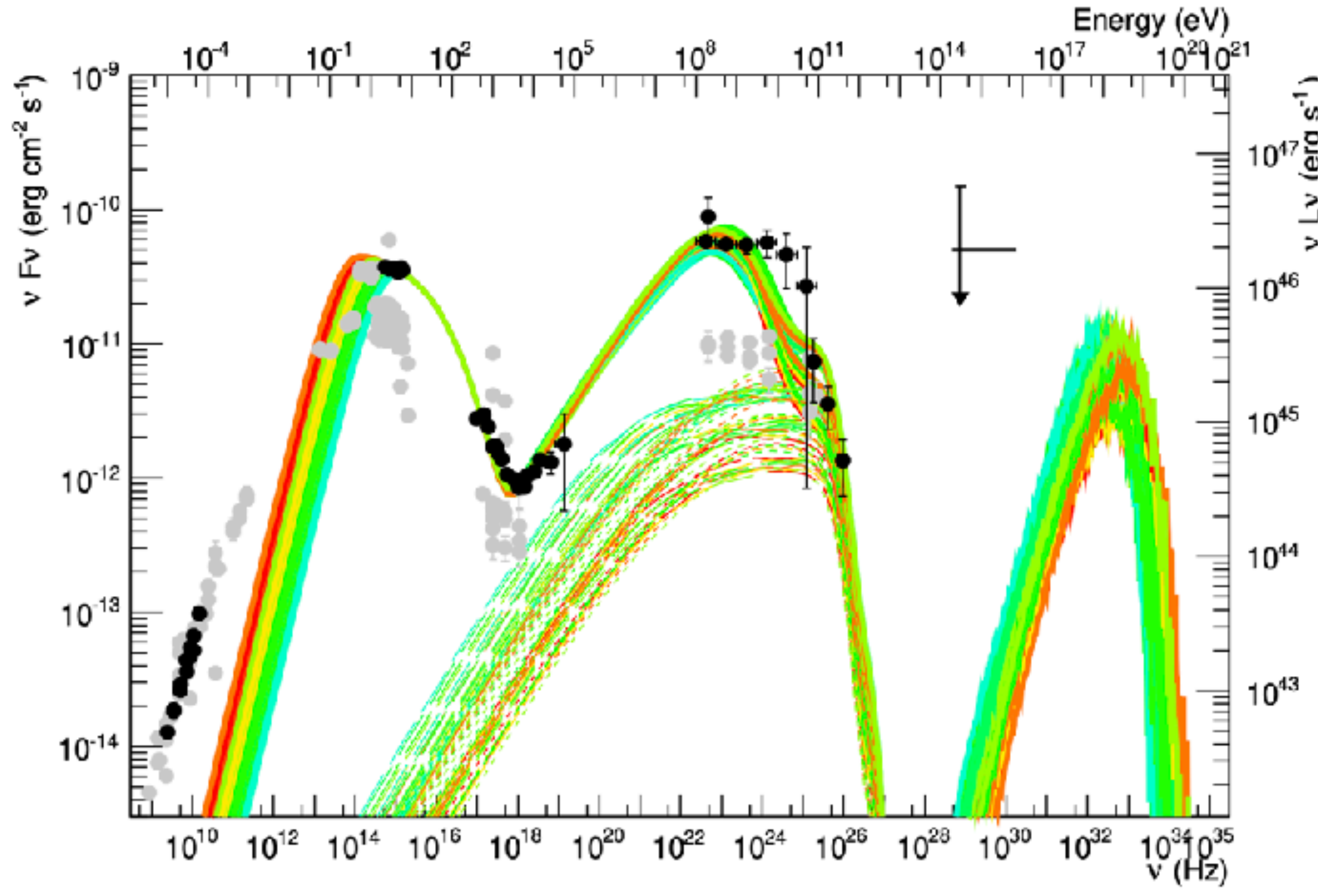
Internal photon fields (cf. *Padovani et al. 2019*) might help to produce more and lower-energy neutrinos (cf. also *Ansoldi et al. 2018*, etc.…)

A neutrino flux may also be expected from extreme blazars if there are additional photon fields...

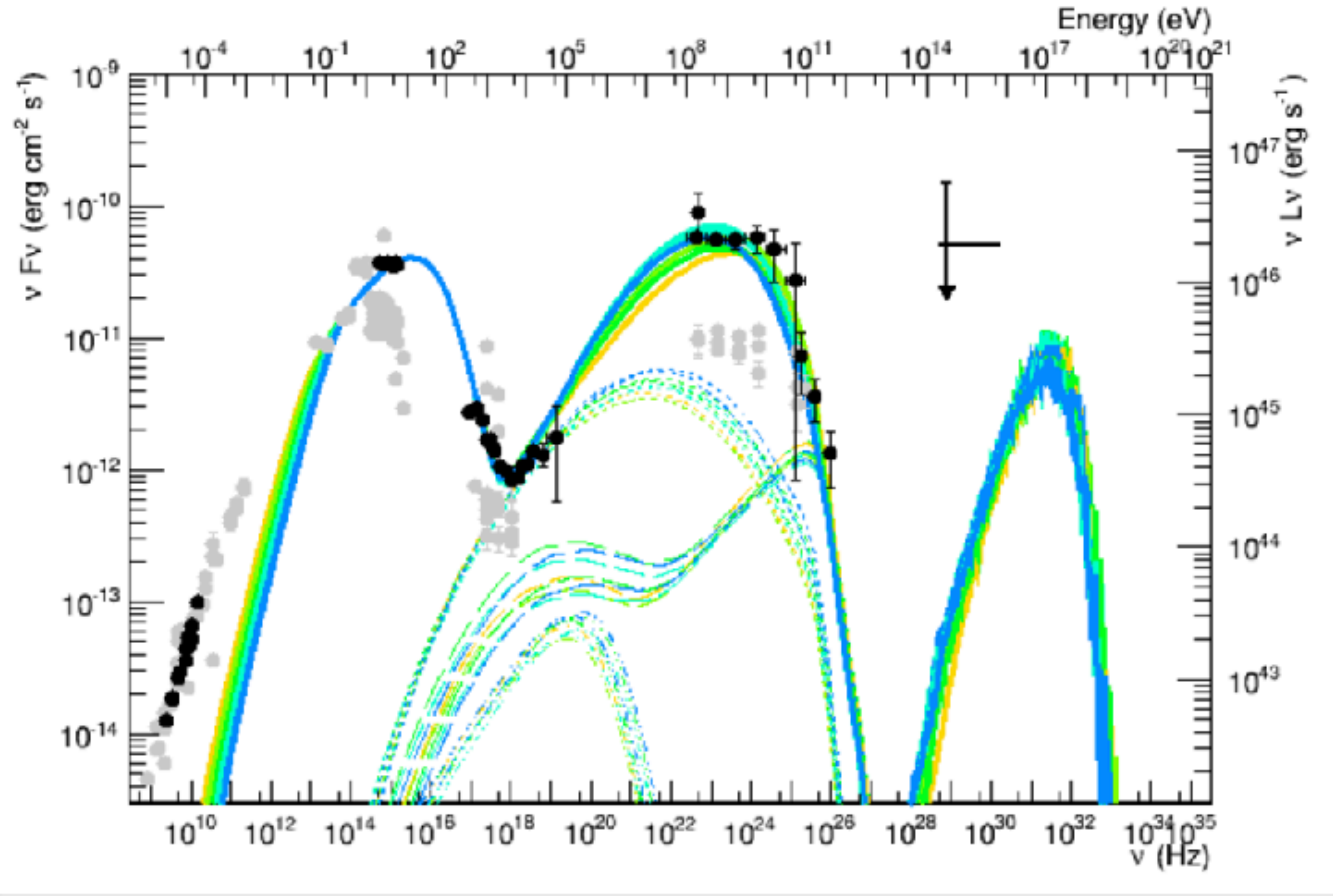


Cerruti, AZ et al. 2018

TXS 0506 with one-zone models



(a) Proton synchrotron modeling of TXS 0506+056



(b) Lepto-hadronic modeling of TXS 0506+056

Prob. of detecting one muon neutrino during high state is $< 0.1\%$.

Prob. of detecting one muon neutrino during high state is 2.2%.

Cerruti, AZ et al. 2018

stochastic re-acceleration ?

Tavecchio et al. 2022 : 3D HD simulations show that recollimation shocks trigger centrifugal instabilities that inject turbulences and disrupt the jet.

Instabilities are damped by magnetic fields for a critical magnetization that is estimated to be around $\sigma_{cr} \gtrsim 10^{-3}$.

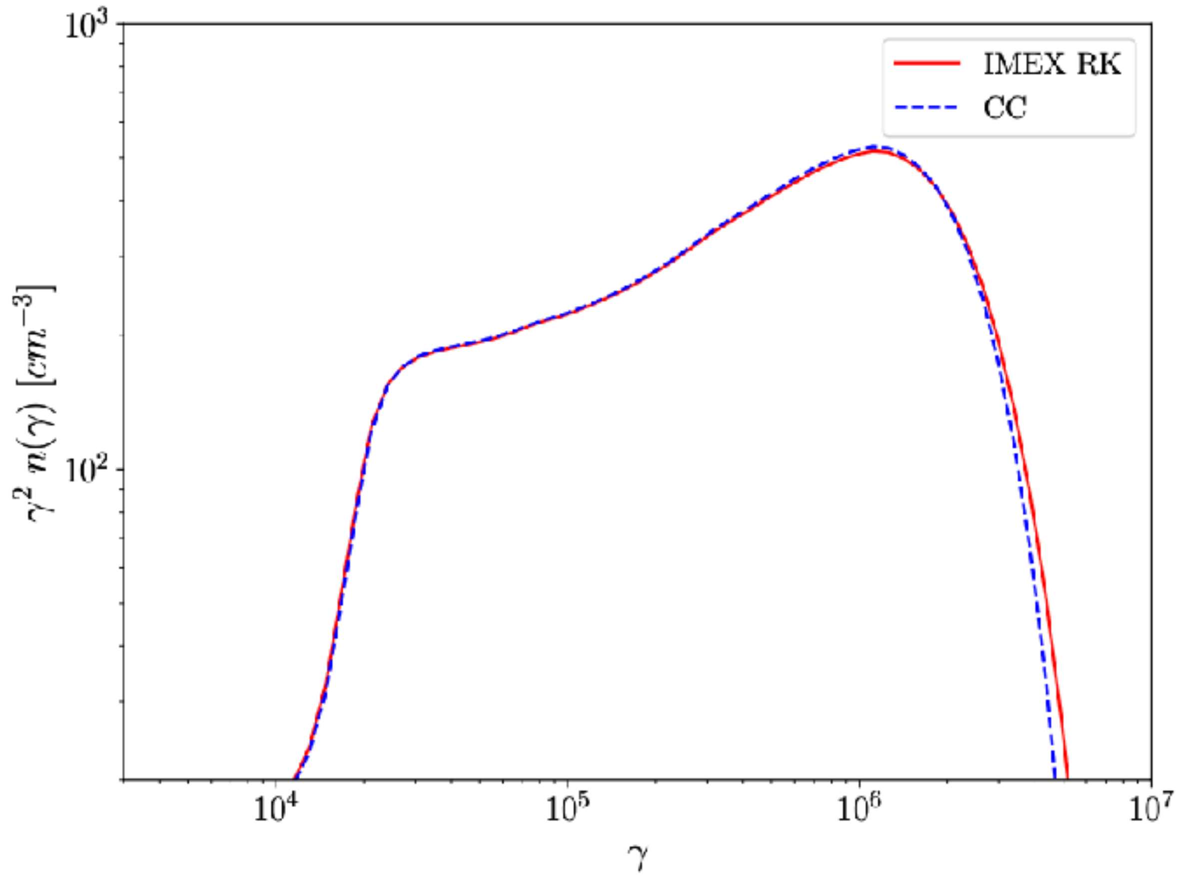
Alternative scenario to re-acceleration on multiple shocks: **stochastic re-acceleration on turbulences**.

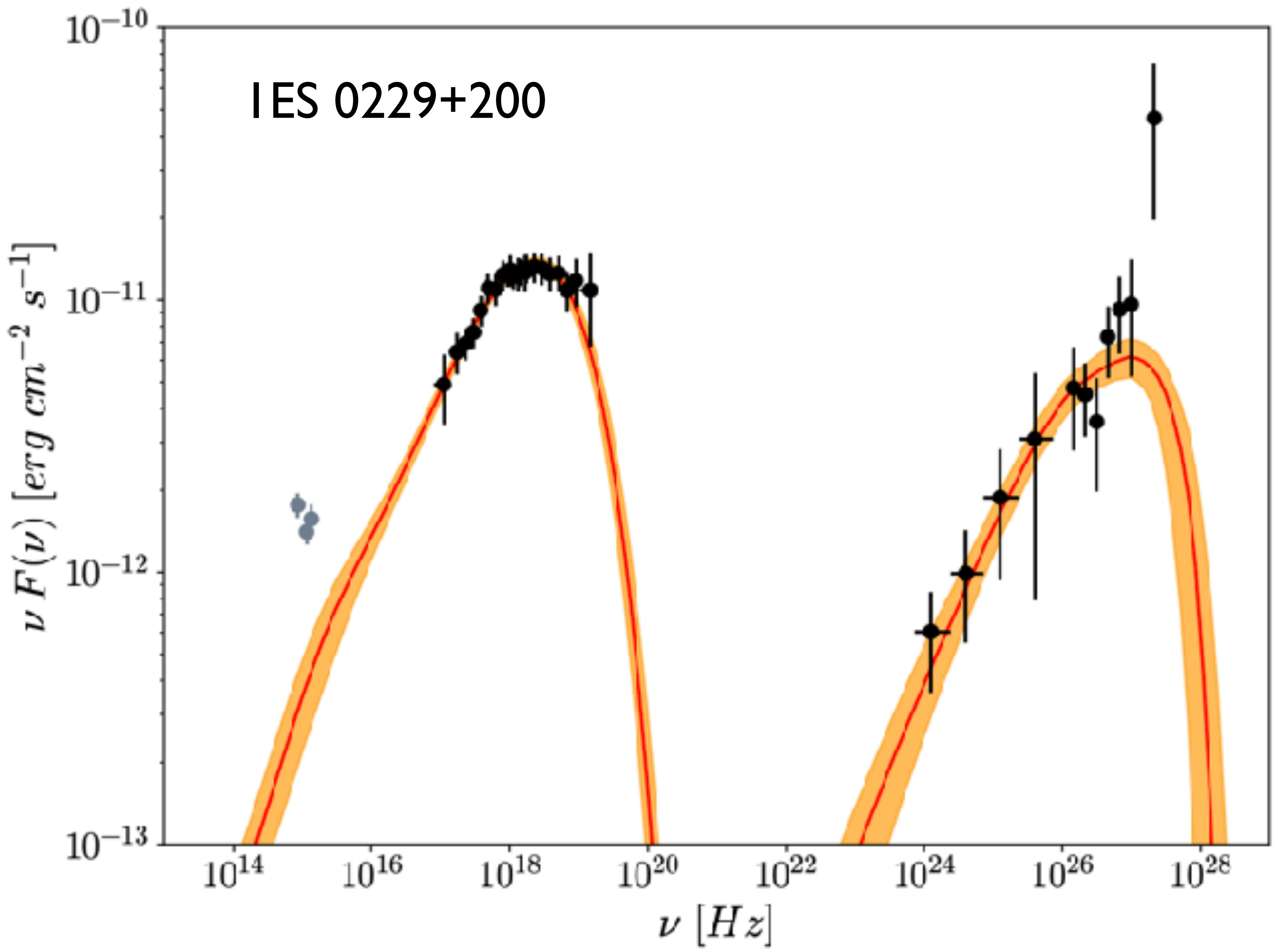
Caveat :

Prediction of a low degree of polarization might be in contradiction with IXPE results from blazar observations.

To be explored :

Impact of jet structure (e.g. spine-in-sheeth) on the development of the instability ?

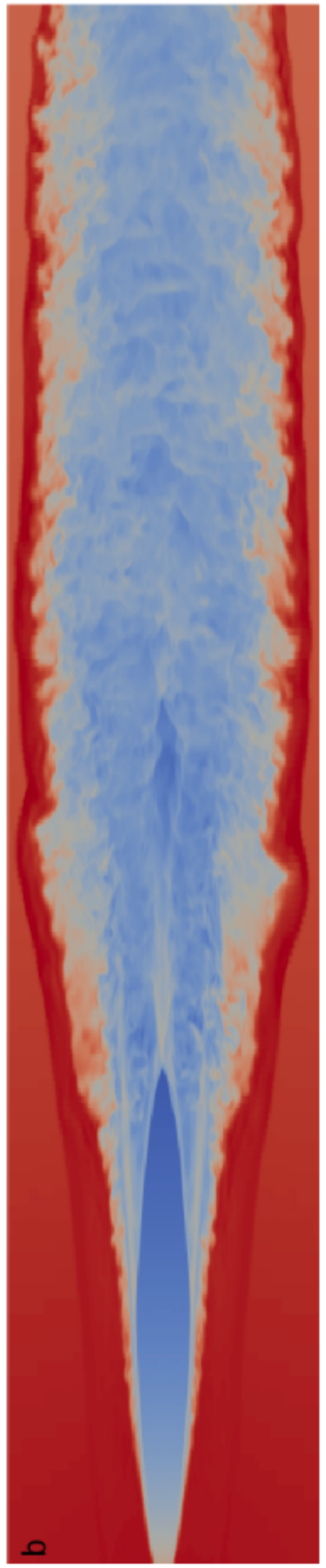




Sciaccaluga & Tavecchio 2024

turbulent jet

recollimation shock



Gourgouliatos & Komissarov 2018

TXS 0506 with one-zone models

	Proton-synchrotron	Lepto-hadronic
δ	$35-50$	$35-45$
R [10^{16} cm]	$0.4-7.8$	$0.2-1.0$
$^\star\tau_{\rm obs}$ [days]	$0.06-1.0$	$0.02-0.15$
B	$0.8-12$	$0.2-0.9$
$^\star u_B$ [erg cm^{-3}]	$0.03-6.2$	$1.7\times10^{-3}-0.03$
$\gamma_{e,\rm min}$	500	500
$\gamma_{e,\rm break}$	$=\gamma_{e,\rm min}$	$=\gamma_{e,\rm max}$
$\gamma_{e,\rm max}$ [10^4]	$0.3-0.9$	$0.8-1.8$
$\alpha_{e,1}=\alpha_{p,1}$	2.0	2.0
$\alpha_{e,2}=\alpha_{p,2}$	3.0	3.0
K_e [cm^{-3}]	$6.3-9.2\times10^2$	$1.4\times10^4-2.6\times10^5$
$^\star u_e$ [10^{-5} erg cm^{-3}]	$0.4-46$	$3.4\times10^3-47\times10^3$
$\gamma_{p,\rm min}$	1	1
$\gamma_{p,\rm break}$ [10^9]	$=\gamma_{p,\rm max}$	$=\gamma_{p,\rm max}$
$\gamma_{p,\rm max}$ [10^9]	$0.4-1.6$	$0.04-0.07$
η	$10-50$	10
K_p [cm^{-3}]	$36-8.4\times10^3$	$2.0\times10^4-3.5\times10^5$
$^\star u_p$ [erg cm^{-3}]	$1.1-240$	$550-9200$
$^\star u_p/u_B$	$6.3-150$	$2.2\times10^5-4.6\times10^5$
$^\star L$ [10^{46} erg s^{-1}]	$23-110$	$160-350$
$^\star\nu_{\rm EHE}$ [yr^{-1}]	$7.3\times10^{-3}-0.11$	$0.07-0.30$
$^\star\nu_{\rm EHE,(0.183-4.3)\,PeV}$ [yr^{-1}]	$1.9\times10^{-4}-4.0\times10^{-3}$	$0.006-0.044$
$^\star\nu_{\rm PS}$ [yr^{-1}]	$0.016-0.25$	$0.19-0.93$

Cerruti, AZ et al. 2018

parameters p-synch model

Table 3. Parameters used for the hadronic modelling of our sources (proton-synchrotron scenario).

	1ES 0229+200	1ES 0347−121	RGB J0710+591	1ES 1101−232	1ES 1218+304
z	0.140	0.188	0.125	0.186	0.184
δ	30	30	30	30	30
$R_{\rm src}$ [10^{16} cm]	0.1–68	0.03–65	0.01–67	0.1–66	0.03–6.6
B [G]	1.0–160	1.0–296	1.0–446	1.0–133	3.4–454
$^\star u_B$ [erg cm^{-3}]	0.04–1017	0.04–3480	0.04–7900	0.04–704	0.5–8210
$\gamma_{\rm e;\,min}$ [10^2]	1.6–20	2.2–38	0.01	4.3–50	2.3–27
$\gamma_{\rm e;\,break}$ [10^3]	$\leq\gamma_{\rm e,\,min}$	$\leq\gamma_{\rm e,\,min}$	0.001–0.03	$\leq\gamma_{\rm e,\,min}$	$\leq\gamma_{\rm e,\,min}$
$\gamma_{\rm e;\,max}$ [10^5]	0.3–4.1	0.1–2.1	0.2–3.7	0.07–0.8	0.04–0.5
$\alpha_{\rm e;\,1} = \alpha_{\rm p;\,1}$	1.3	1.7	1.35	1.7	1.7
$\alpha_{\rm e;\,2} = \alpha_{\rm p;\,2}$	2.3	2.7	2.35	2.7	2.7
$K_{\rm e}$ [cm^{-3}]	7.0×10^{-8}–0.36	0.05–1.2×10^5	7.3×10^{-5}–1040	0.3–7.2×10^4	3.2×10^{-3}–8.0×10^4
$^\star u_{\rm e}$ [erg cm^{-3}]	2.2×10^{-11}–3.2×10^{-5}	5.7×10^{-7}–0.7	1.6×10^{-9}–2.8×10^{-2}	2.6×10^{-6}–0.4	2.6×10^{-8}–0.4
$\gamma_{\rm p;\,min}$	1	1	1	1	1
$\gamma_{\rm p;\,break}$[10^9]	2.6–57	2.4–56	2.8–47	3.7–56	1.0–26
$\gamma_{\rm p;\,max}$[10^9]	4.8–57	3.2–56	2.8–47	4.8–56	3.1–26
η	(9.7–19) $\times10^{-6}$	(0.7–18) $\times10^{-6}$	(1.0–3.3) $\times10^{-7}$	(0.2–2.6) $\times10^{-6}$	2.1×10^{-6}–0.02
$^\star u_{\rm p}$ [erg cm^{-3}]	6.1×10^{-8}–0.08	4.9×10^{-7}–4.8	3.0×10^{-7}–6.4	5.4×10^{-7}–0.5	5.9×10^{-5}–3.5
$^\star(u_{\rm p}+u_{\rm e})/u_B$[$10^{-5}$]	0.04–36	0.8–540	0.3–200	2.5–430	0.9–2.2×10^3
$^\star L$ [10^{45} erg s^{-1}]	4.6–1670	2.1–1120	1.7–460	4.6–1120	2.6–610
$^\star\min(\tau_{\rm ad};\,\tau_{\rm syn}(\gamma_{\rm p;\,max}))$ [h]	12–1.2×10^4	4.3–1.2×10^4	1.9–1.2×10^4	19–1.2×10^4	1.9–1.2×10^3

parameters mixed le.-ha. model

Table 4. Parameters used for the hadronic modelling of our sources (lepto-hadronic scenario).

	1ES 0229+200	1ES 0347−121	RGB J0710+591	1ES 1101−232	1ES 1218+304
z	0.140	0.188	0.125	0.186	0.184
δ	30	30	30	30	30
R_{src} [10^{16} cm]	0.1–3.2	0.6–3.2	0.3–0.8	5.0–10	0.2–0.9
B [G]	0.1–1.4	0.1–0.7	0.3–0.6	0.1–0.2	0.2–1.8
$^{\star}u_B$ [erg cm^{-3}]	3.0×10^{-4}–0.08	6.2×10^{-4}–0.02	3.6×10^{-3}–0.01	$(0.5–2.4) \times 10^{-3}$	3.4×10^{-3}–0.1
$\gamma_{e,\,min}$ [10^2]	0.01	47–108	0.01	100–150	37–92
$\gamma_{e,\,break}$ [10^3]	3.9–31	4.7–15	12–18	10–15	3.7–9.2
$\gamma_{e,\,max}$ [10^5]	3.4–14	2.6–5.9	4.6–6.5	1.5–2.3	0.6–1.5
$\alpha_{e,\,1} = \alpha_{p,\,1}$	1.3	1.7	1.5	1.7	1.7
$\alpha_{e,\,2} = \alpha_{p,\,2}$	2.3	2.7	2.5	2.7	2.7
K_e [cm^{-3}]	5.6×10^{-3}–1.5	2.9–135	2.7–29	0.5–3.5	26–2190
$^{\star}u_e$ [erg cm^{-3}]	1.4×10^{-5}– 2.2×10^{-2}	4.2×10^{-5}– 2.4×10^{-3}	1.0×10^{-3}– 9.2×10^{-3}	7.3×10^{-6}– 4.9×10^{-5}	3.0×10^{-4}– 0.03
$\gamma_{p,\,min}$	1	1	1	1	1
$\gamma_{p,\,break}$[10^9]	$=\gamma_{p,\,max}$	$=\gamma_{p,\,max}$	$=\gamma_{p,\,max}$	$=\gamma_{p,\,max}$	$=\gamma_{p,\,max}$
$\gamma_{p,\,max}$[10^9]	0.06–0.3	0.15–0.45	0.1–0.15	0.6–1.0	0.1–0.4
$\eta = K_p/K_e$	0.1–0.8	0.1–0.3	0.04–0.1	0.05–0.1	0.1–0.4
$^{\star}u_p$ [erg cm^{-3}]	2.3–238	1.7–21	9.3–28	0.1–0.3	15–270
$^{\star}(u_p + u_e)/u_B$[10^3]	2.6–8.7	0.9–4.0	1.8–2.9	0.1–0.2	1.1–8.5
$^{\star}L$ [10^{45} erg s^{-1}]	4–57	15–44	3.9–12	17–27	12–42
$^{\star}\min(\tau_{ad}; \tau_{syn}(\gamma_{p;\,max}))$ [h]	19–590	120–590	56–150	930–1.9×10^3	33–180

Note. For a description, see Table 3.

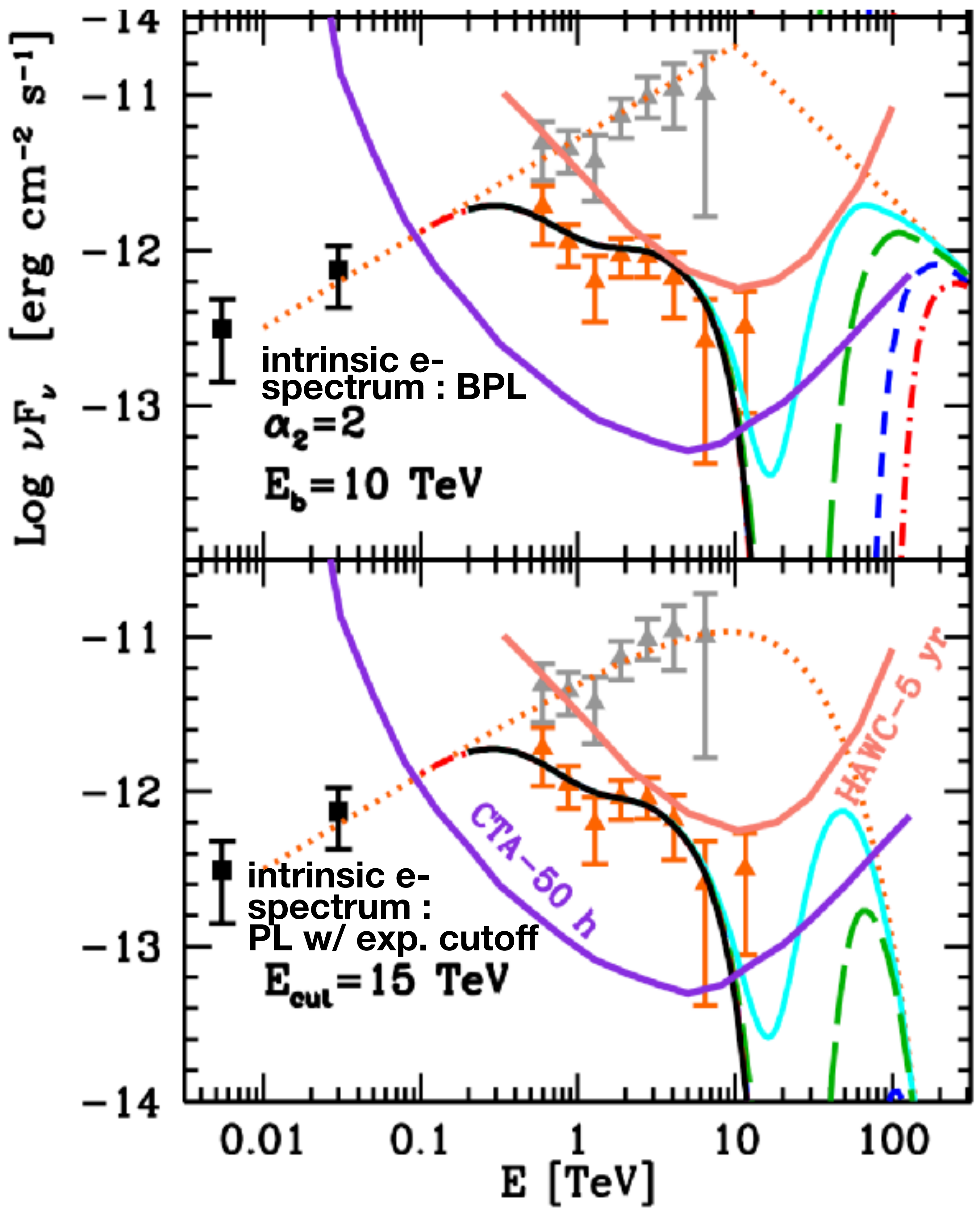
Lorentz-Invariance violation

- EBL absorption can be partially avoided when allowing for a modified pair-production threshold in case of (hypothetical) Lorentz-invariance violation.

- **problem** : existence of a variety of LIV scenarios

cf. also *Fairbairn 2014*, *Acharya et al. 2017*,…

-> F. Tavecchio (talk on Friday)



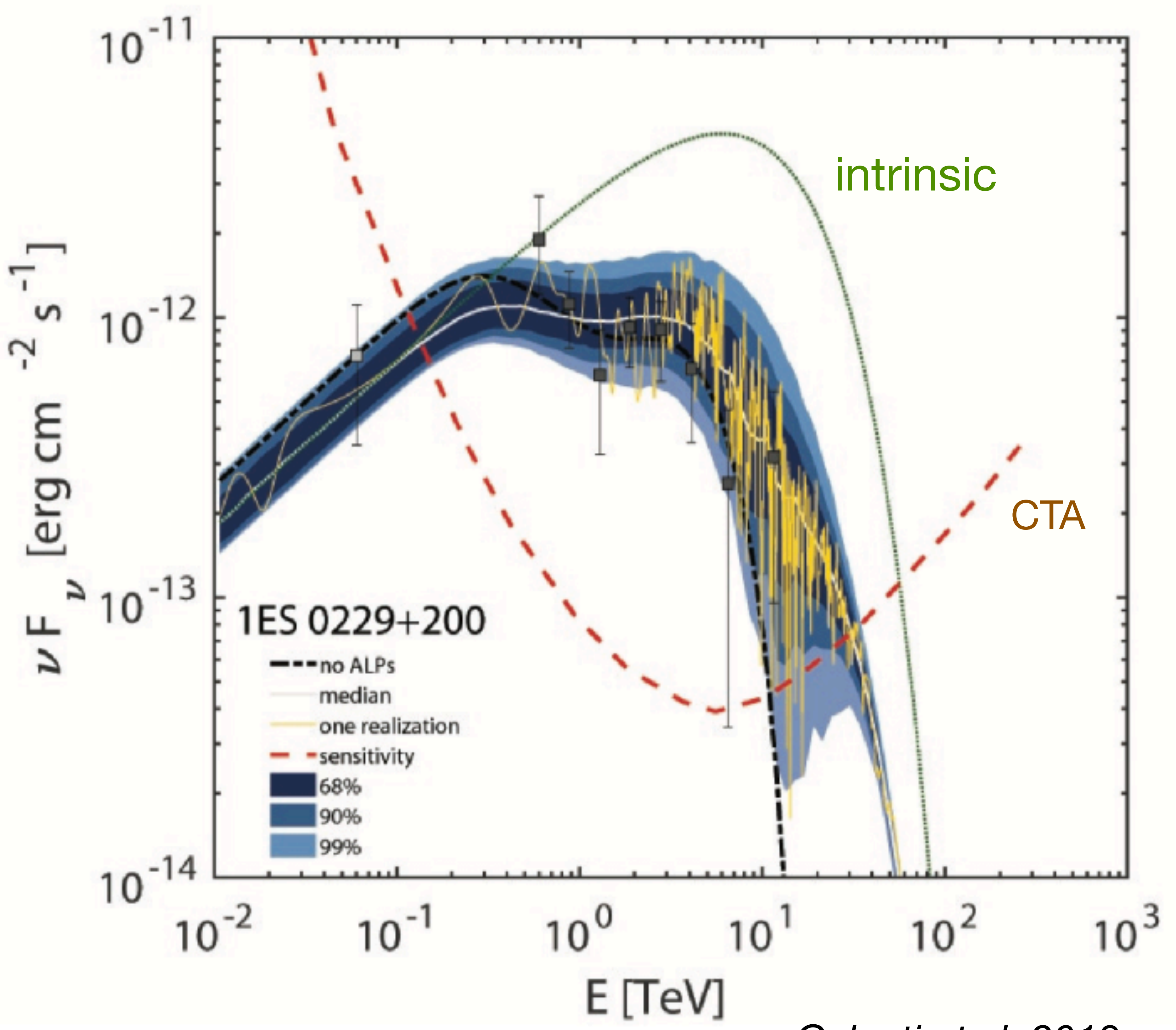
Prediction of observed VHE spectra for 1ES 0229+200 for different intrinsic spectra and characteristic LIV energy scales (1e19 / 3e19 /1e20 / 2e20 GeV)
Tavecchio & Bonnoli 2016

Axion-like particles

- Another way to avoid EBL absorption is through (hypothetical) photon-ALP oscillations in magnetic fields (jet, host galaxy, extragalactic, Galactic).

- **problem**: uncertainty on the choice of ALP parameters (mass, coupling); magnetic fields not well constrained

cf. also *Sanchez-Condé et al. 2009, De Angelis 2009, Acharya et al. 2017*,…



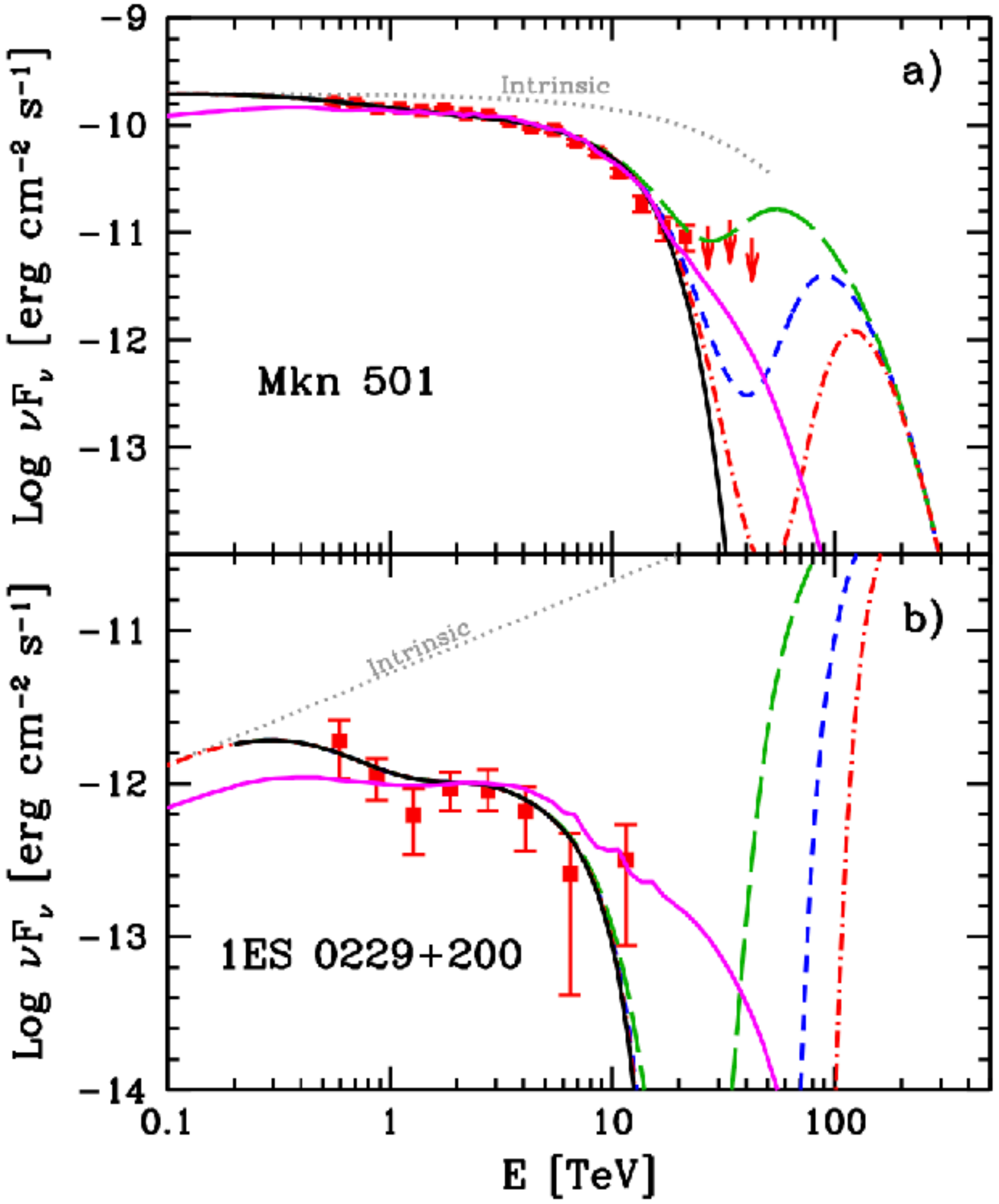
Galanti et al. 2018

-> *G. Galanti (talk on Friday)*

Exotic physics ?

Expected modifications of EBL absorption in case of **Lorentz Invariance Violation** (green - E_{LIV} = 3 x 10^{19} GeV, blue - E_{LIV} = 10^{20} GeV , red - E_{LIV} = 2 x 10^{20} GeV).

Expected modification of EBL absorption in case of mixing of γ-rays with axion-like particles (ALPs) : magenta line.



Biteau et al. 2020