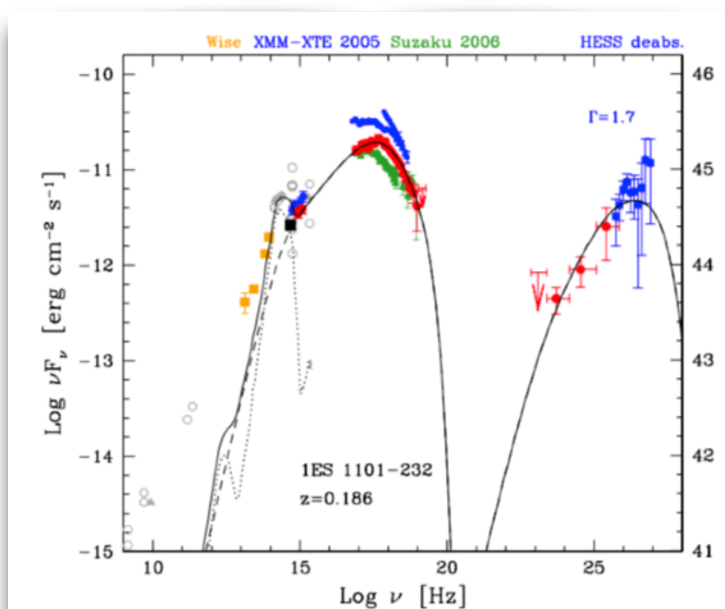
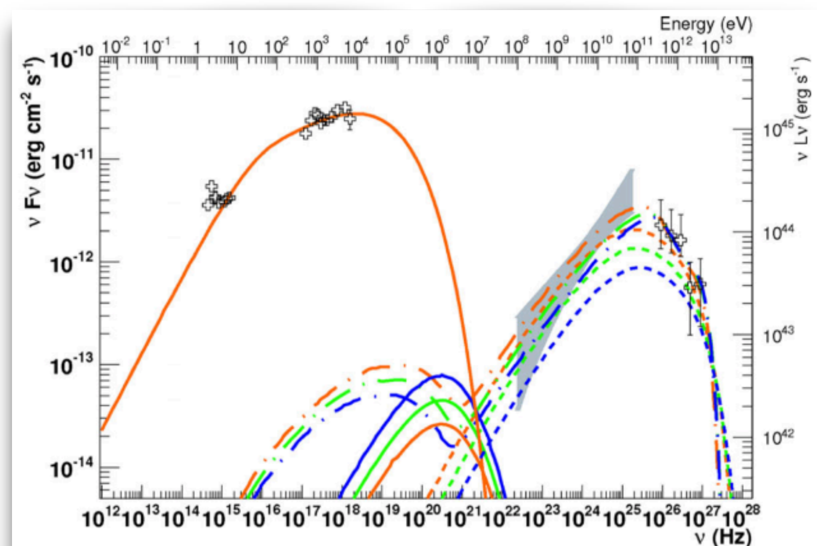
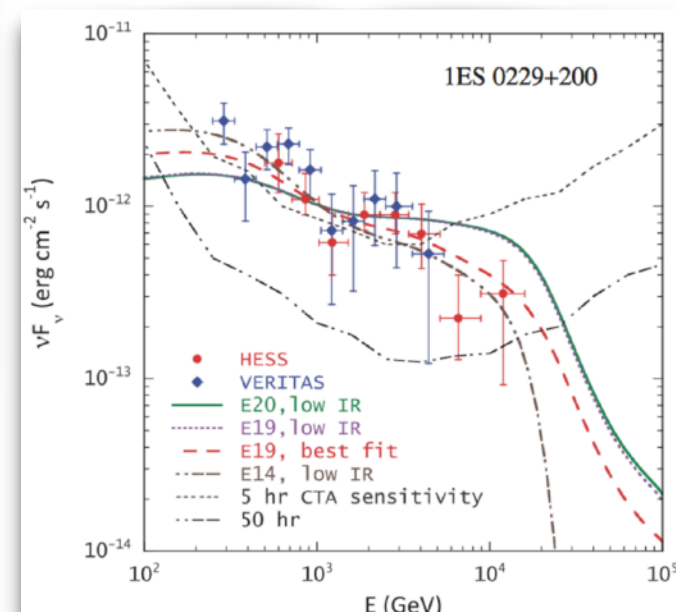
Modeling extreme blazars -
an attempt of a review







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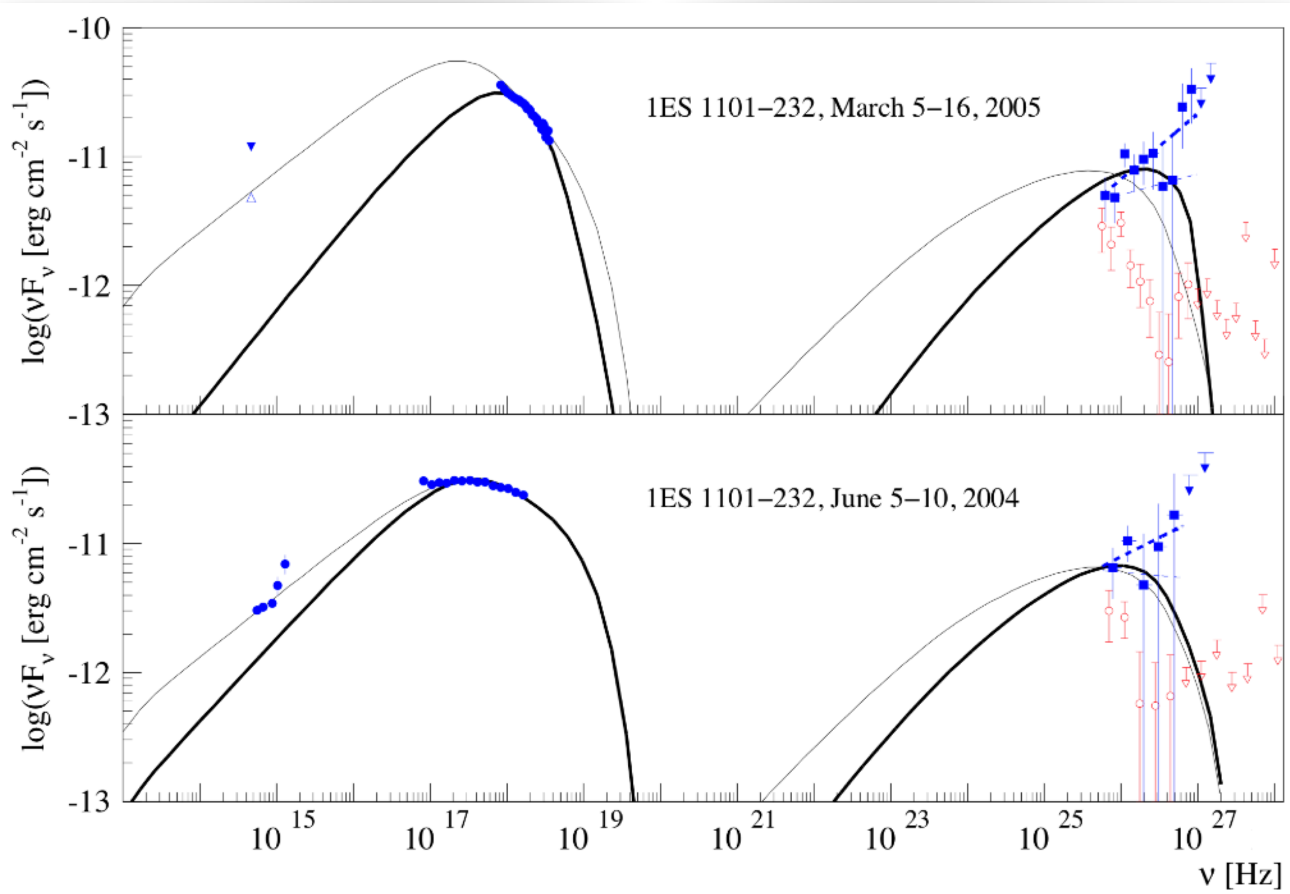
eXtreme19 workshop in Padua

Outline

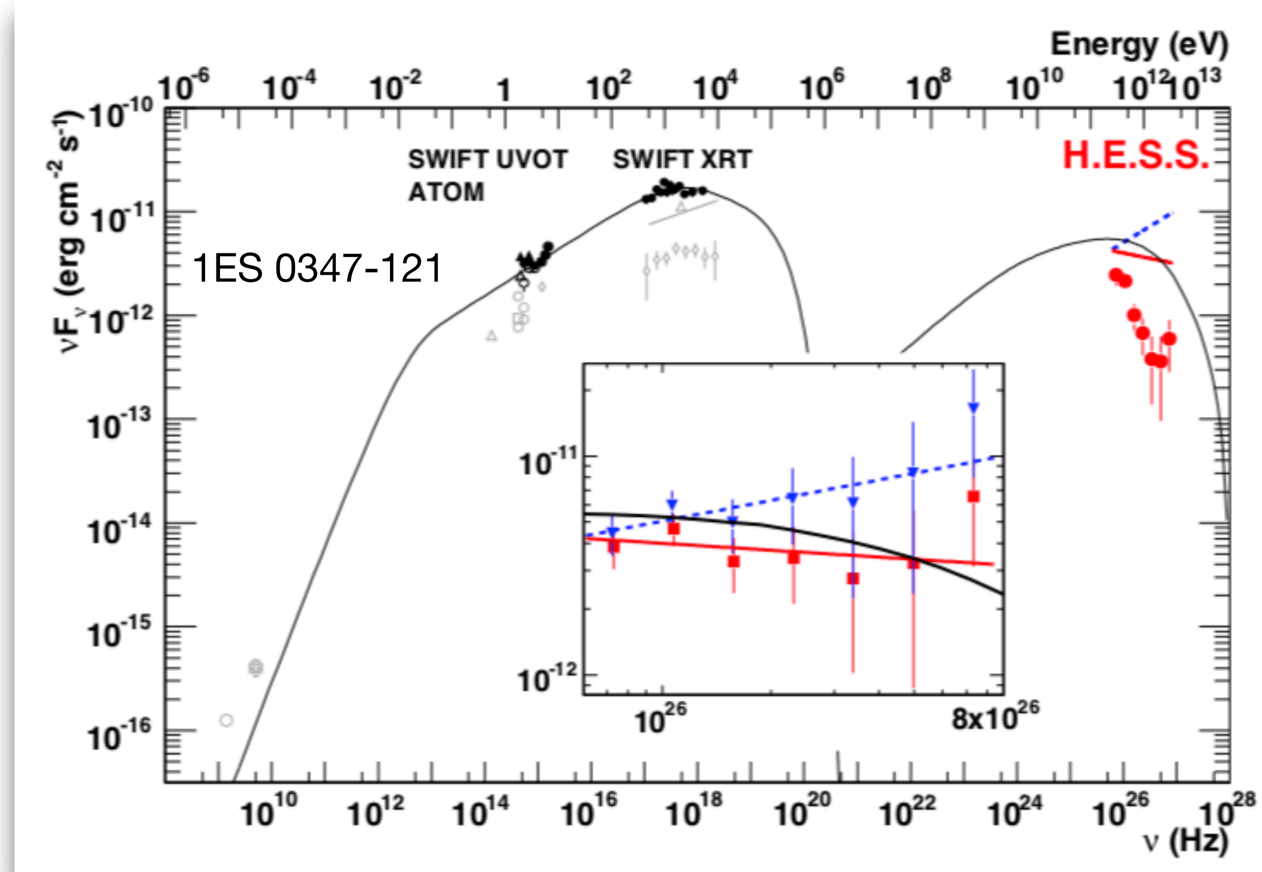
- the problem with the basic SSC scenario
- leptonic solutions for extreme blazars
- hadronic solutions for extreme blazars
- signatures of new physics ?
- outlook

the problem with the basic SSC scenario

lessons from the first extreme blazar SEDs



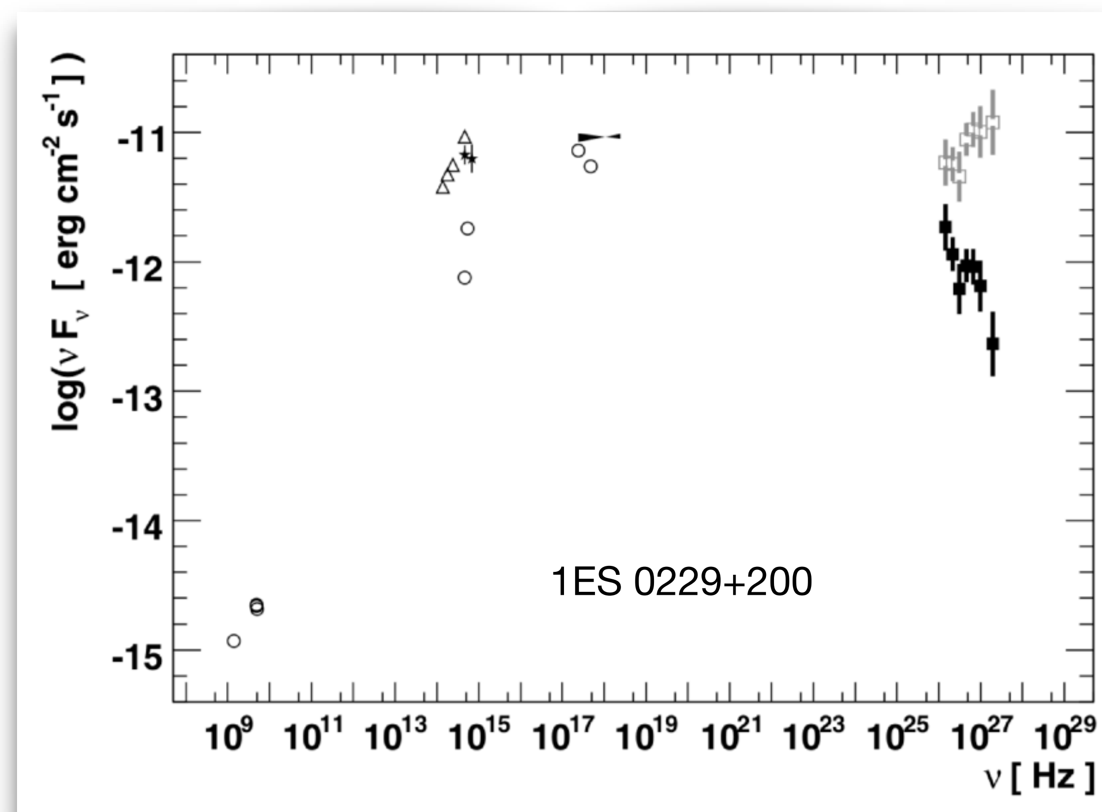
Aharonian et al. 2007a



Aharonian et al. 2007b

In 2007, three HESS publications on extreme blazars : 1ES 0229+200, 1ES 1101-232, 1ES 0347-121

-> very hard TeV spectra, difficult to reconcile with one-zone SSC models, even with hard particle spectra.
(dN/dE ~ $E^{-1.5}$ was considered a limit for shock acceleration, cf. *Aharonian et al. 2006*)



Aharonian et al. 2007c

the problem with very hard TeV spectra

- standard shock acceleration predicts particle spectra $dN/dE \sim E^{-2}$
- radiative (synchrotron) cooling softens initially hard particle spectra

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

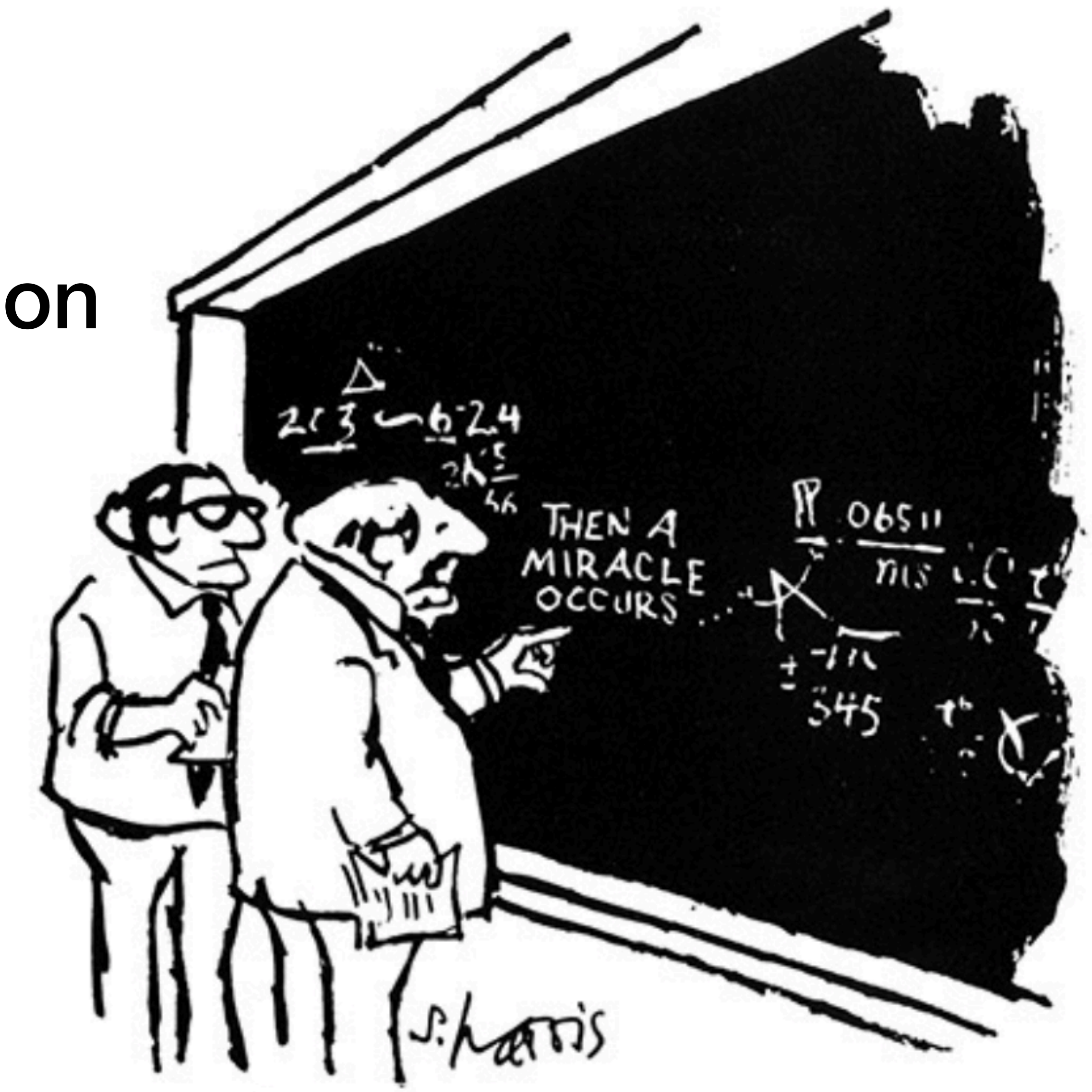
- in addition, at TeV energies, flux reduction due to :

  - high electron energies -> scattering partly in the **Klein-Nishina** regime

  - redshifts non-negligible -> TeV γ-rays are absorbed on the **EBL**
    (*e.g. 1ES0229+200:* z = 0.1396, *1ES1101-232:* z = 0.186, *1ES0347-121:* z = 0.188)

leptonic solutions for extreme blazars :

- high minimum Lorentz factor
- Maxwellian-like electron distribution
- external Compton models



"I think you should be more explicit here in step two."

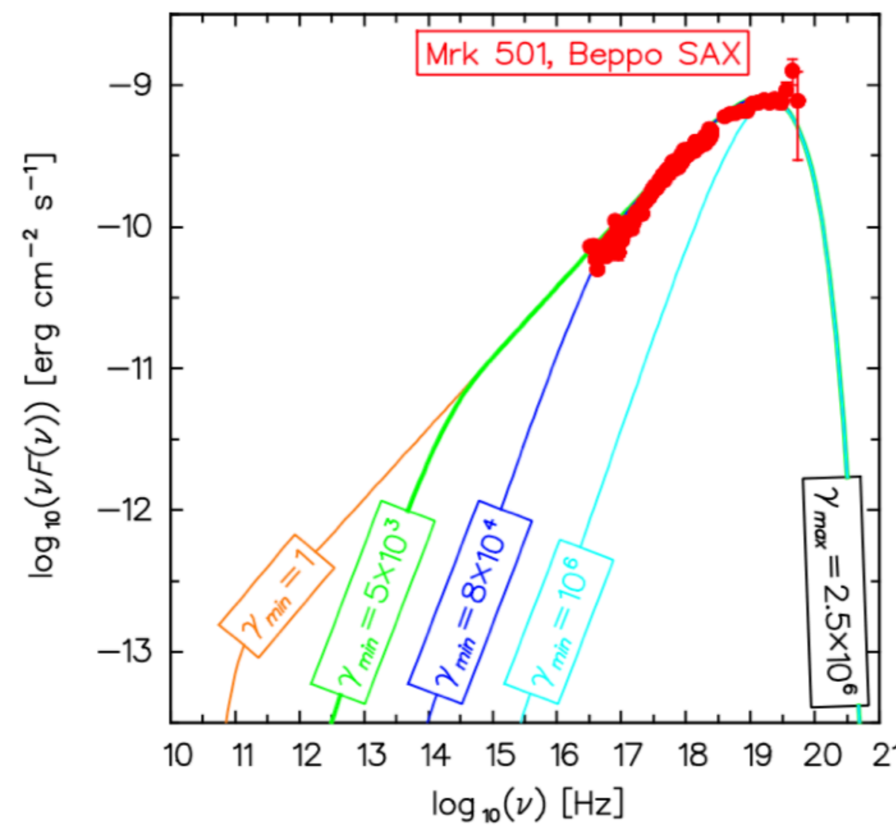
models with high $\gamma_{\min}$

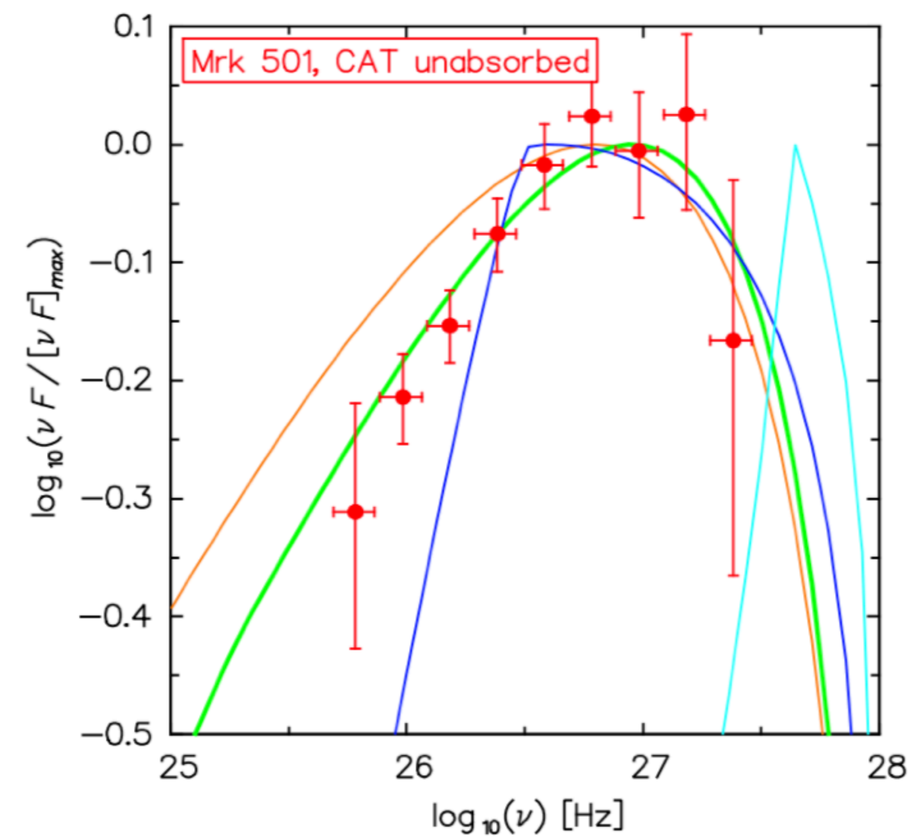
For the standard broken power-law electron spectrum, increasing the minimum electron Lorentz factor $\gamma_{\min}$ leads to a narrower distribution.

-> 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, $\boxed{\gamma_{\min} = 5 \times 10^5}$ (Tavecchio et al. 2009); $\delta = 40$, $B = 0.032$ G, $R = 10^{18}$ cm, $\boxed{\gamma_{\min} = 4 \times 10^5}$ (Kaufmann et al. 2011); $\delta > 53$, $B = 0.8$–3.3 mG, $R = (5$–$30) \times 10^{15}$ cm, $\gamma_{\min} = (2.5$–$4.5) \times \boxed{10^4}$ (Aliu et al. 2014);
1ES 0347−121	0.188	$\delta = 25$, $B = 0.035$ G, $R = 3.2 \times 10^{16}$ cm, $\boxed{\gamma_{\min} = 10^3}$ (Aharonian et al. 2007b) $\delta = 61$, $B = 1.3$ mG, $R = 1.6 \times 10^{17}$ cm, $\boxed{\gamma_{\min} = 2 \times 10^4}$ (Tanaka et al. 2014);
RGB J0710+591	0.125	$\Gamma = 30$, $B = 0.036$ G, $R = 2 \times 10^{16}$ cm, $\boxed{\gamma_{\min} = 6 \times 10^4}$ (Acciari et al. 2010b);
1ES 1101−232	0.186	$\delta = 25$, $B = 0.1$ G, $R \approx 10^{16}$ cm $\boxed{\gamma_{\min} = 10^3}$ (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

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*)

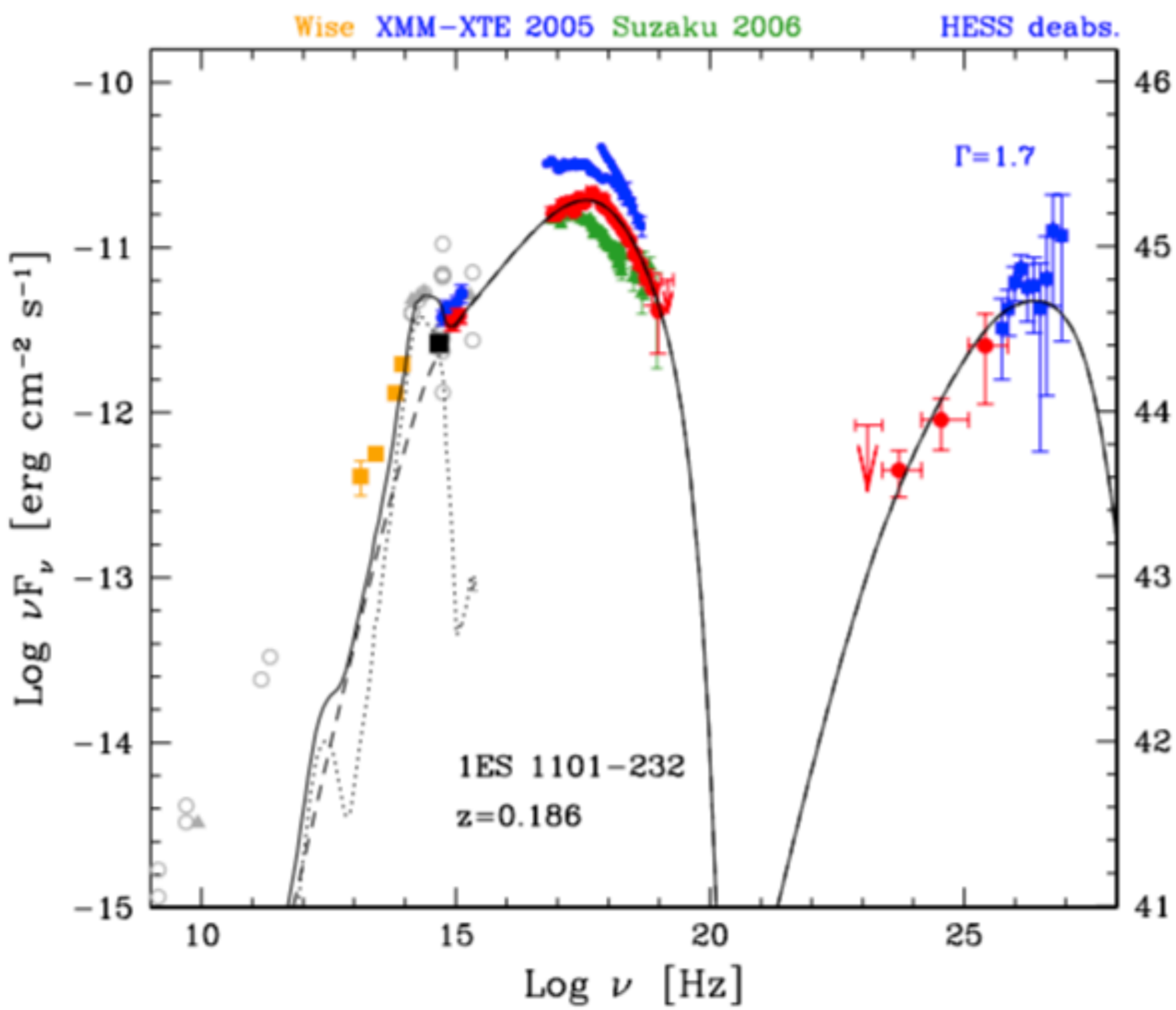
What about the very small magnetic field ?

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*).

models with high γ_{min}

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



- MWL analysis of six hard-TeV BL Lacs with contemporaneous SWIFT and NuSTAR data.
- SSC modelling requires high electron energies, very low (mG) magnetic fields, far out of equipartition, and - in general - high γ_{min}

-> UV emission in 1ES0229+200 and RGBJ0710+591 from separate region ?

-> low magnetic energy density seems to rule out magnetic reconnection scenarios !

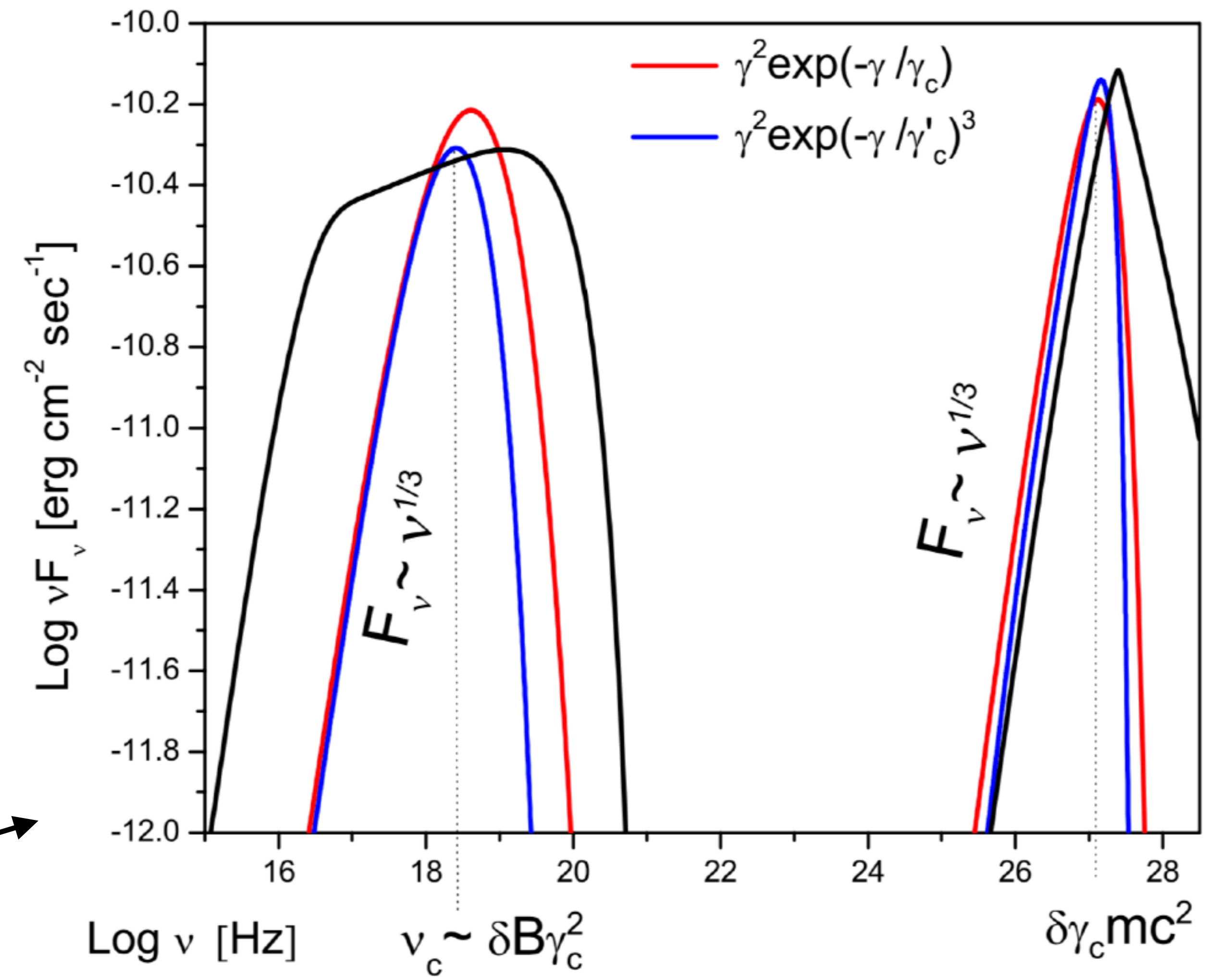
-> L. Costamante (talk on Tuesday)

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

-> 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 ?

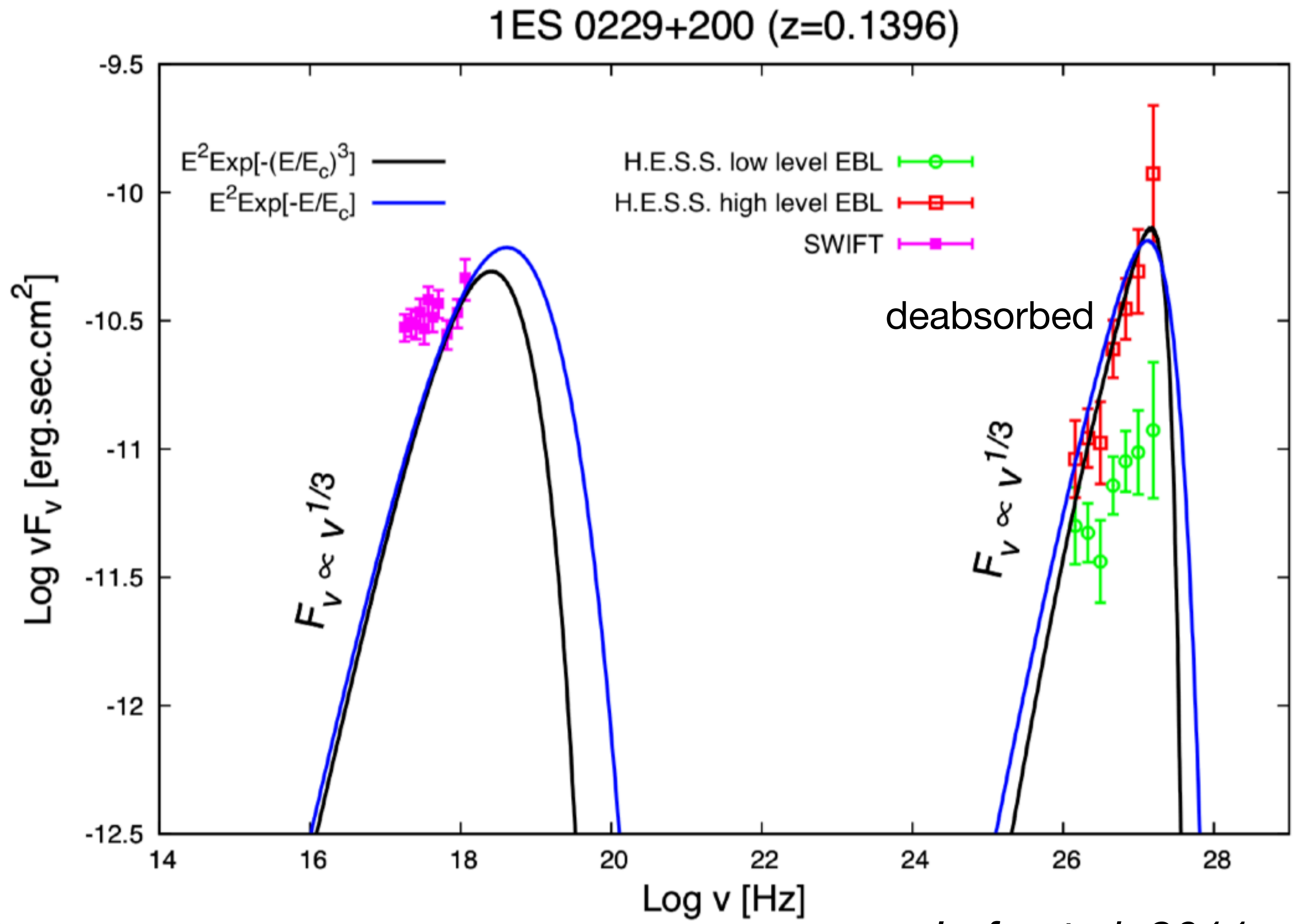


Lefa et al. 2011

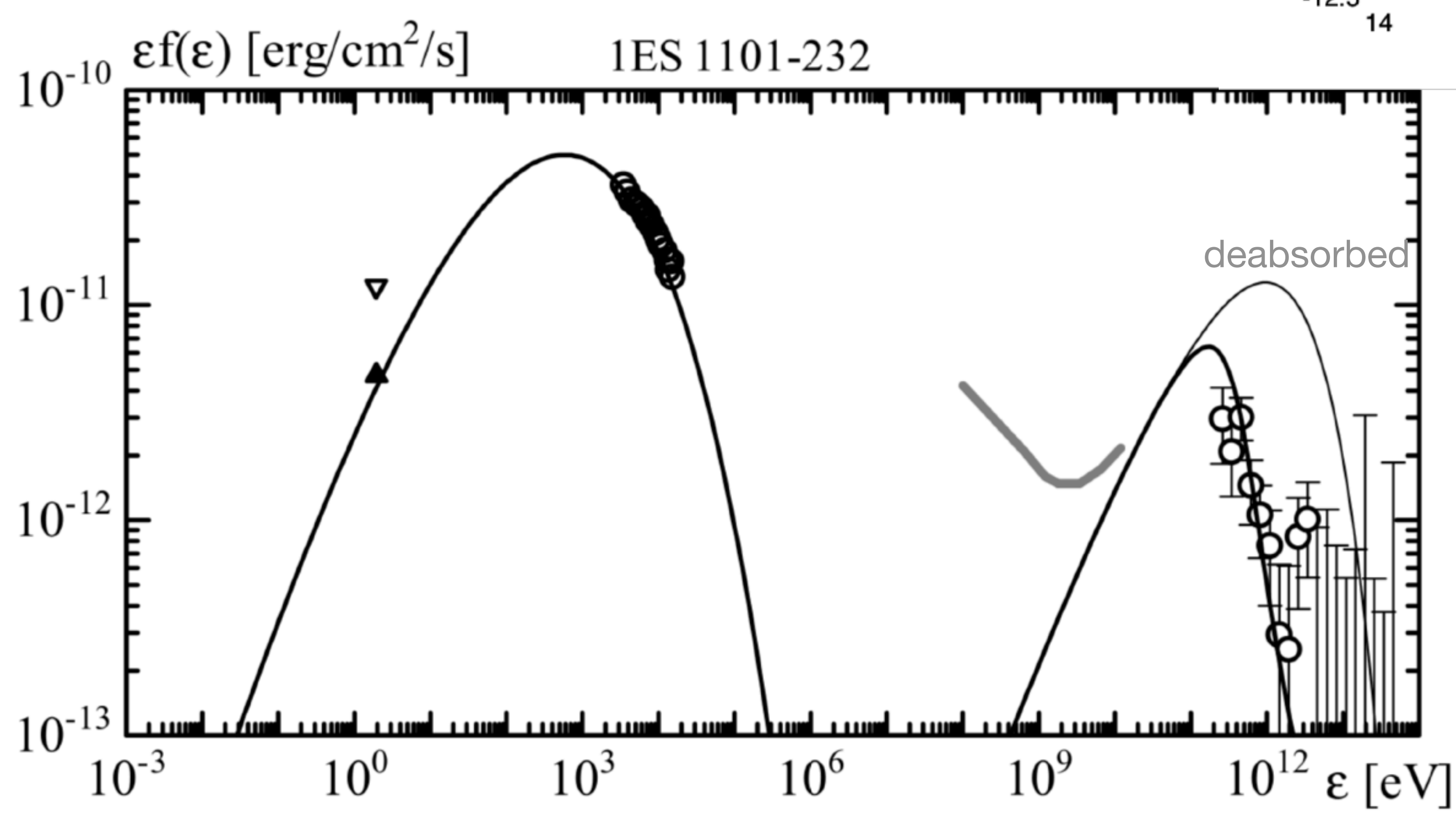
cf. also *Saugé & Henri 2006, Giebels et al. 2007,…*

Maxwellian-like electron distributions

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



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*)

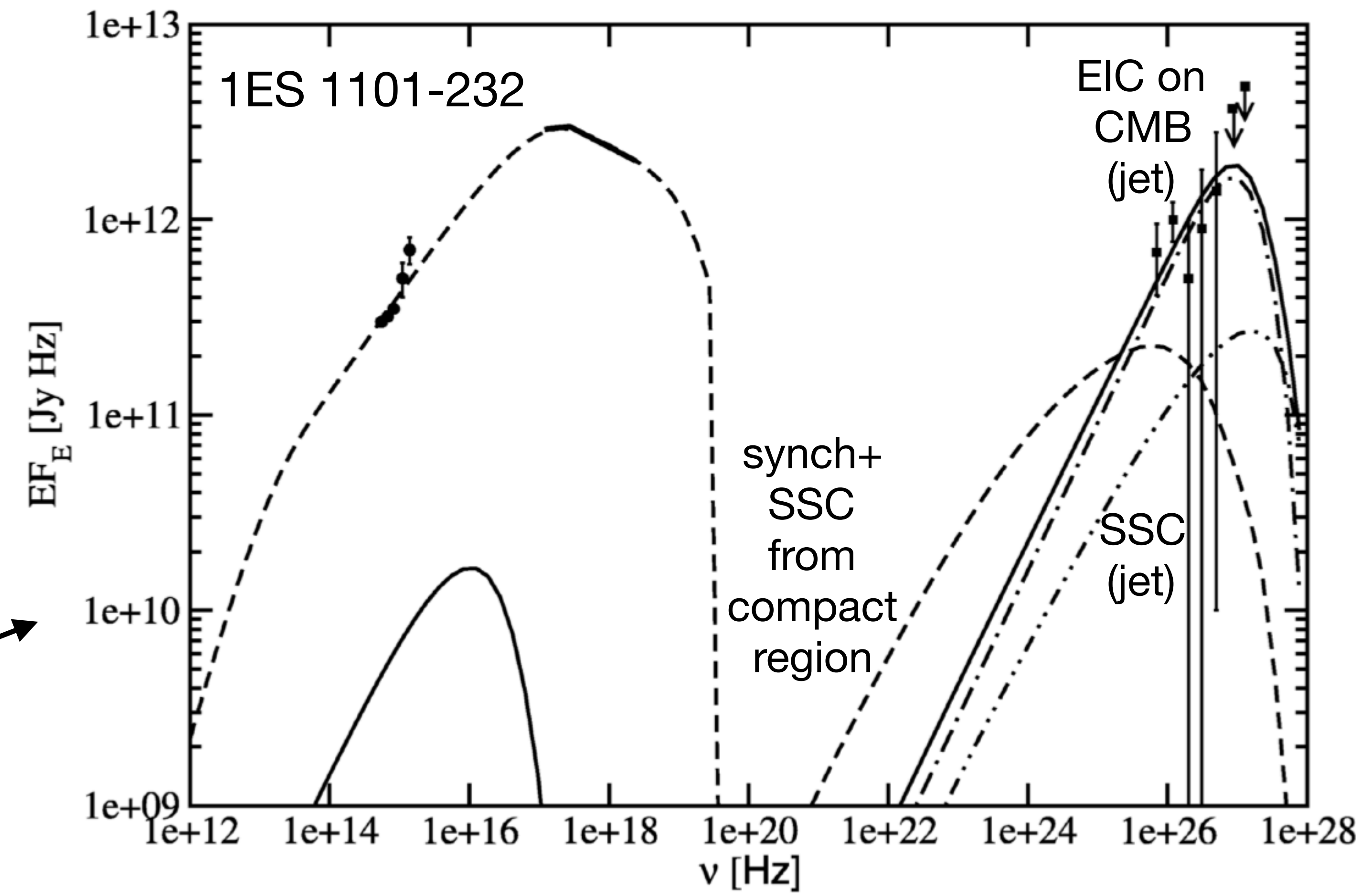
-> stochastic acceleration: A. Tramacere (talk on Thursday)

external Compton models

- up-scattering of **BLR photons** by a Maxwellian electron distribution can lead to harder VHE spectrum ($F_\nu \sim \nu$). (*Lefa et al. 2011*)

  -> requires sufficiently luminous BLR !

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



Boettcher et al. 2008

problem: Disfavoured by variability ?
(yearly timescale for 1ES 0229+200 Aliu et al. 2004 ; daily for 1ES1218+304 Acciari et al. 2010)

-> emission at sub-parsec scales could be responsible for variable synchrotron and SSC emission ?

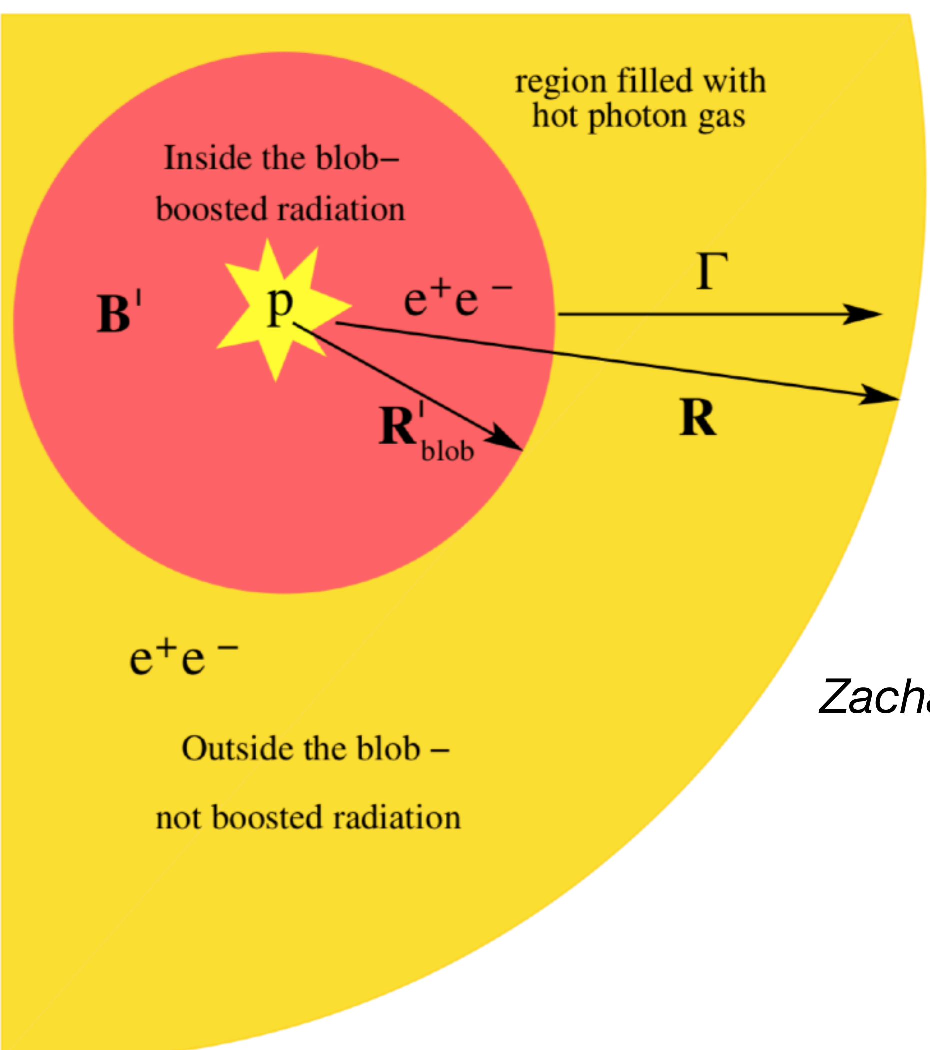
-> requires very energetic particle distribution over large scales

hadronic solutions for extreme blazars :

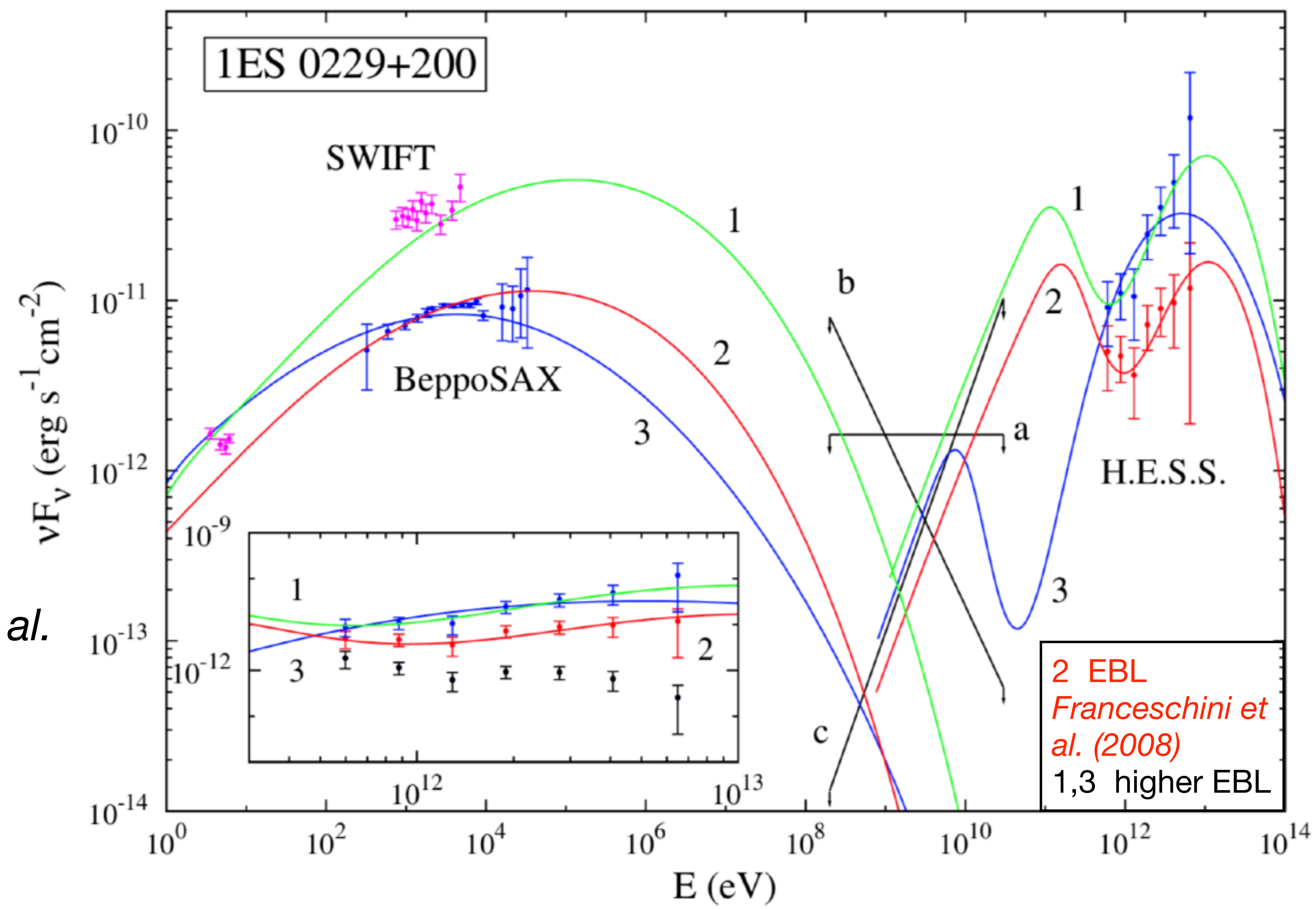
- internal absorption
- proton-synchrotron emission model
- lepto-hadronic emission model
- external cascade models

"It's black, and it looks like a hole.
I'd say it's a black hole."

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, …*

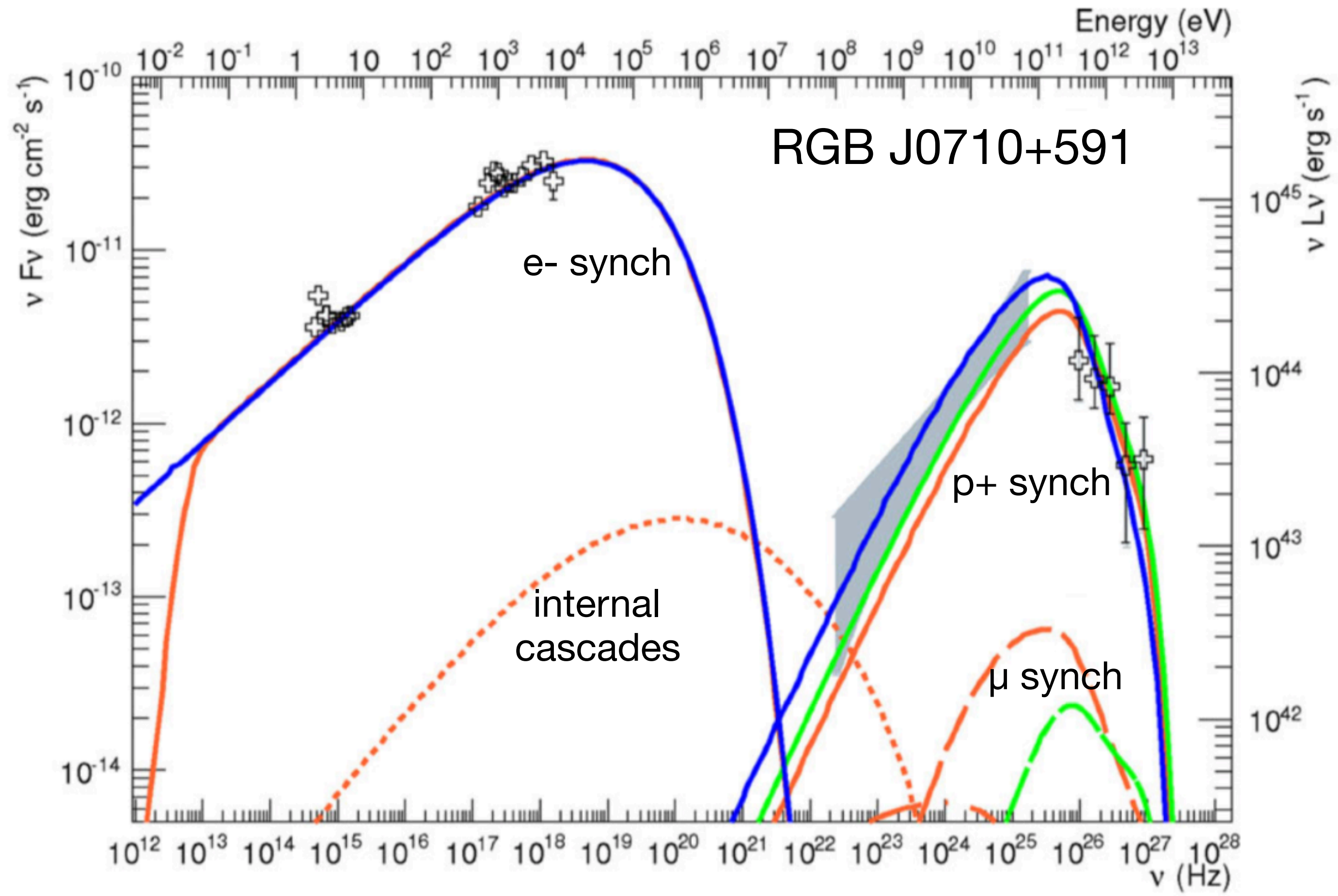
proton-synchrotron emission model

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

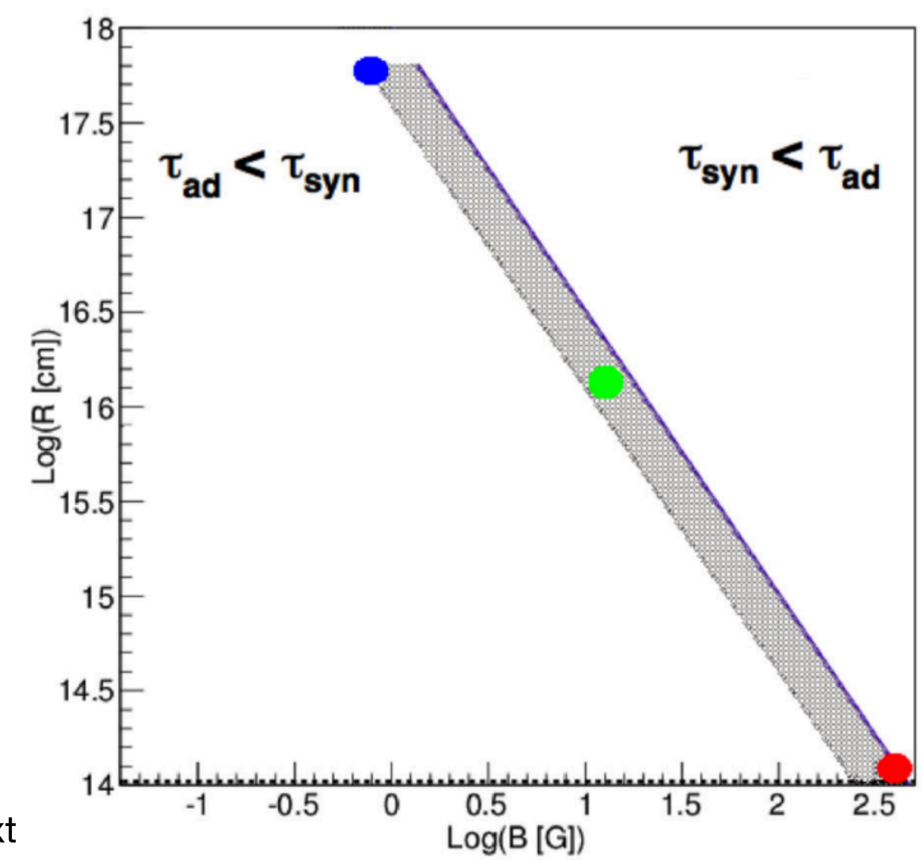
- parameter scan for 5 extreme blazars
  (*Cerruti, AZ et al. 2015*)
  -> solutions exist with acceptable jet power
  (< L_{edd}) and small γ_{min}

- **problem** : proton spectra need to be very hard
  (n_p = 1.3 to 1.7) ;
  out of equipartition by at least 10^2 dominated
  by B-field

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



Cerruti, AZ et al. 2015



lepto-hadronic emission model

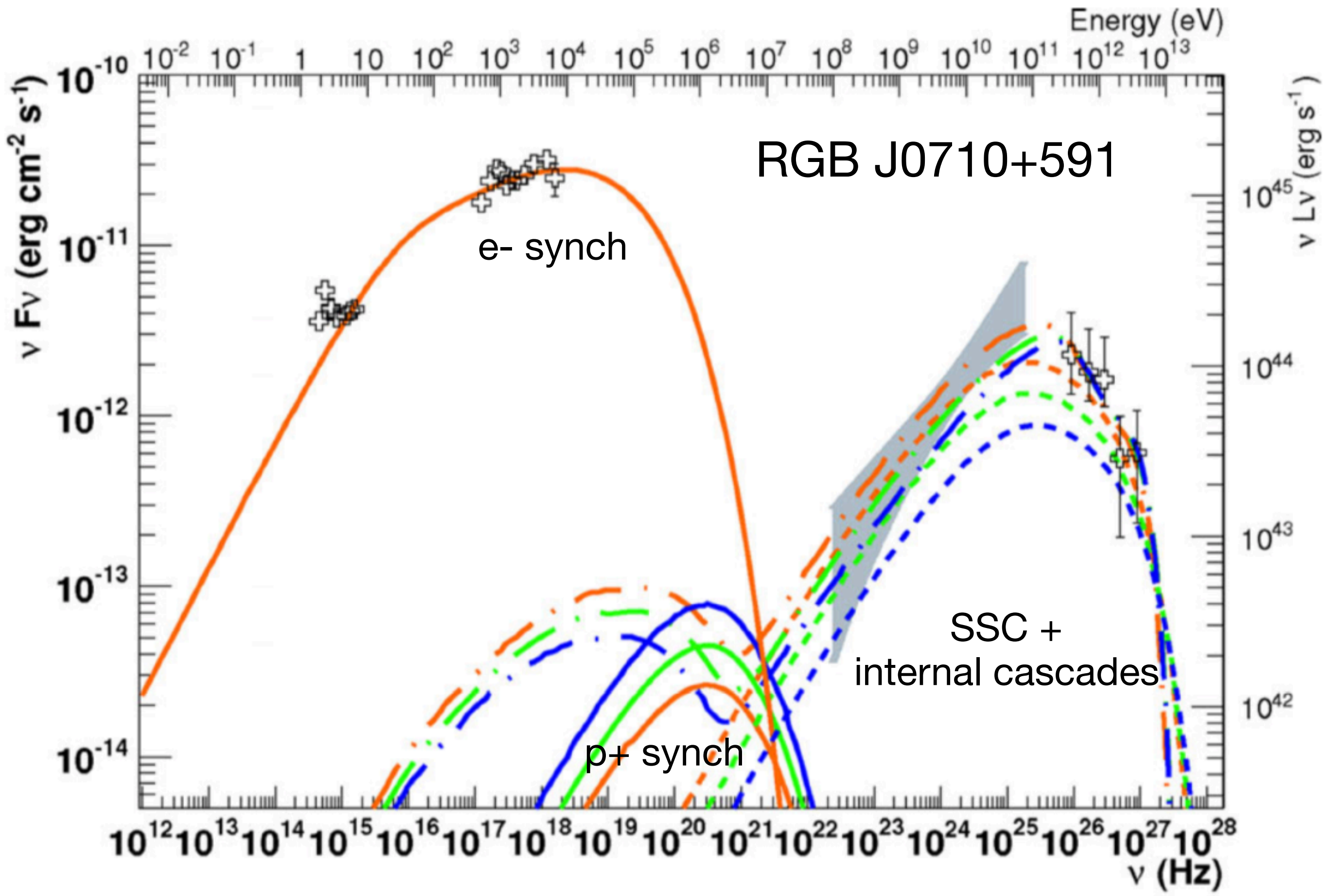
- alternative scenario using the same setup : high-energy bump is a combination of SSC and UHE proton-induced cascade emission

- 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

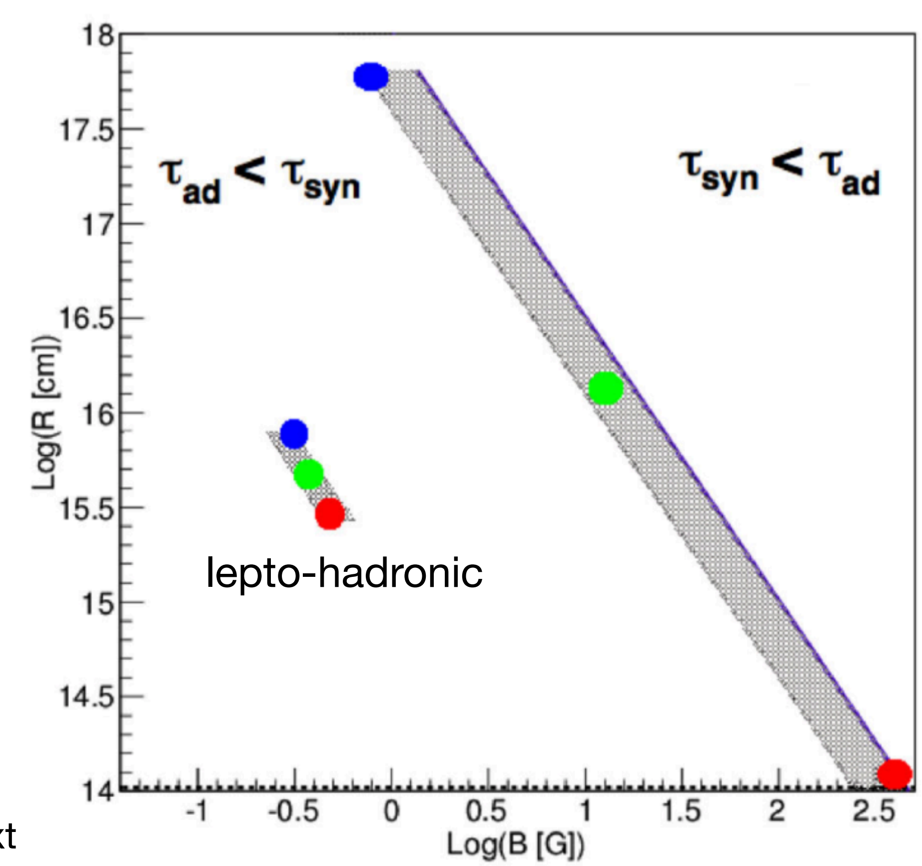
- **problem** : proton spectra need to be very hard (n_p = 1.3 to 1.7) ;
  out of equipartition by at least 10^2 dominated by kinetic proton energy density

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

- similar scenario by *Cao & Wang 2014*, but with lower energy protons -> requires very high jet power >> L_{edd}



Cerruti, AZ et al. 2015



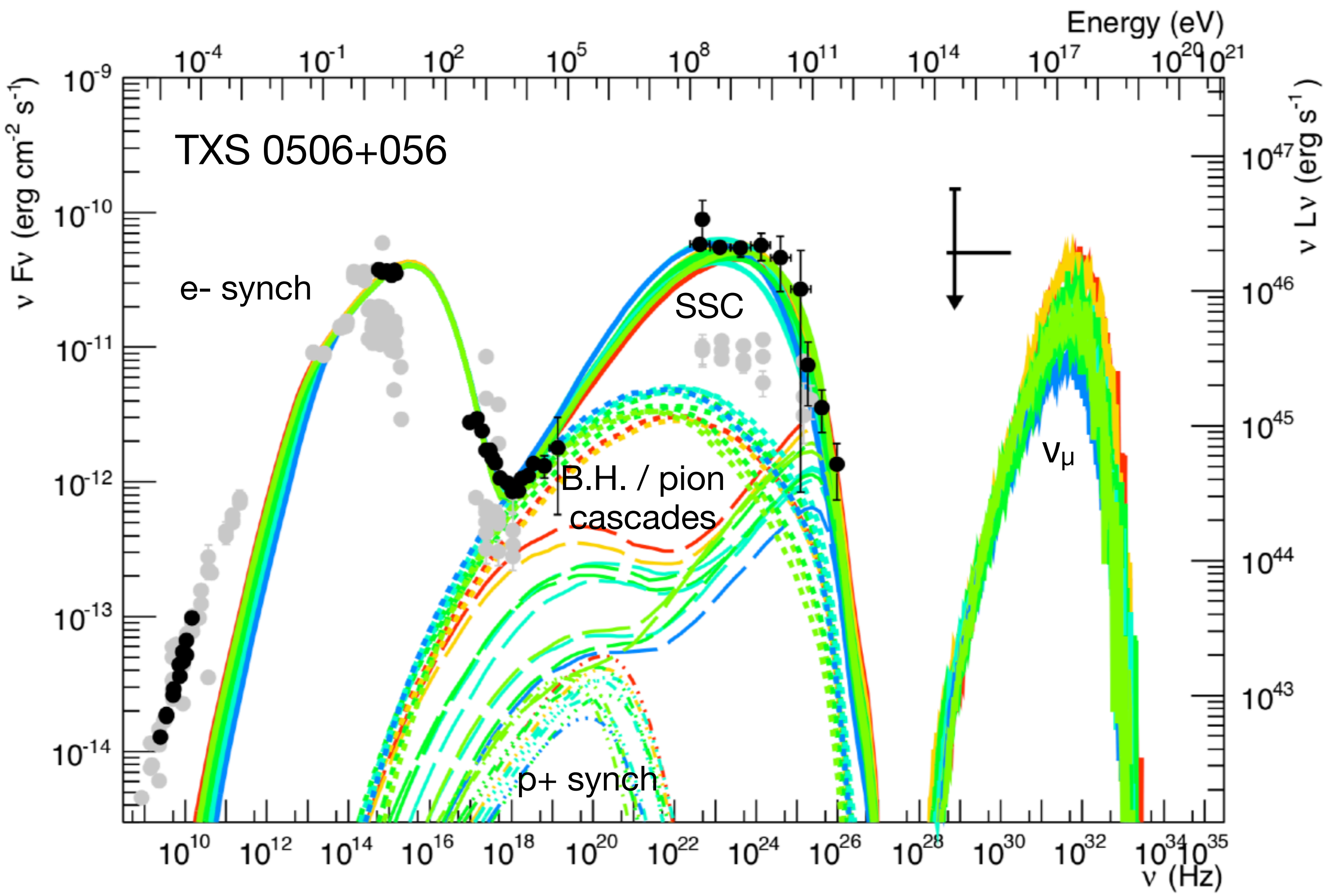
a side note : extreme blazars and neutrinos ?

- *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 lepto-hadronic scenario for TXS 0506+056 can account for MWL and (just so…) for neutrino emission (*Cerruti, AZ et al. 2018*).

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

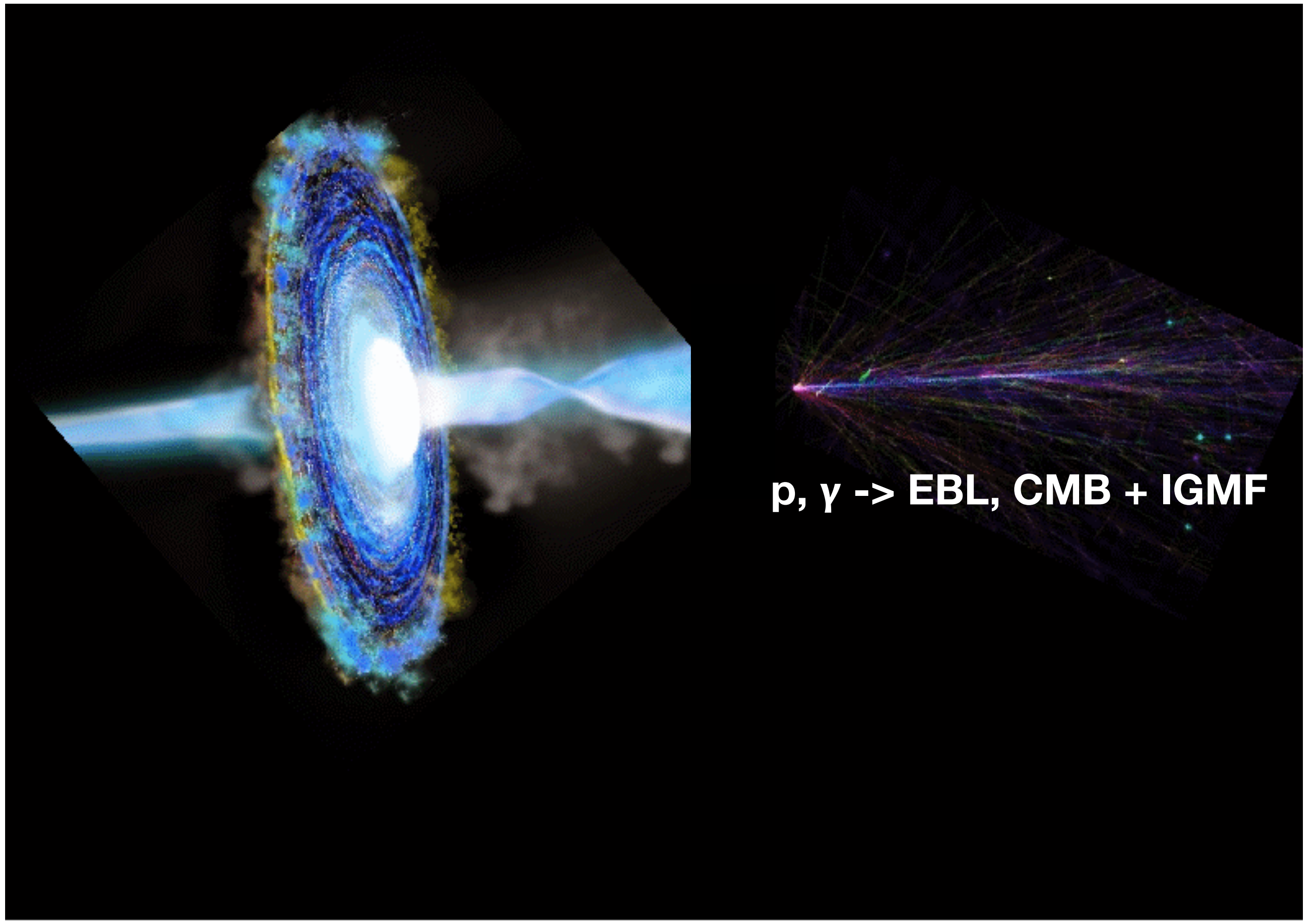
  A neutrino flux is also expected from extreme blazars in this type of scenario.

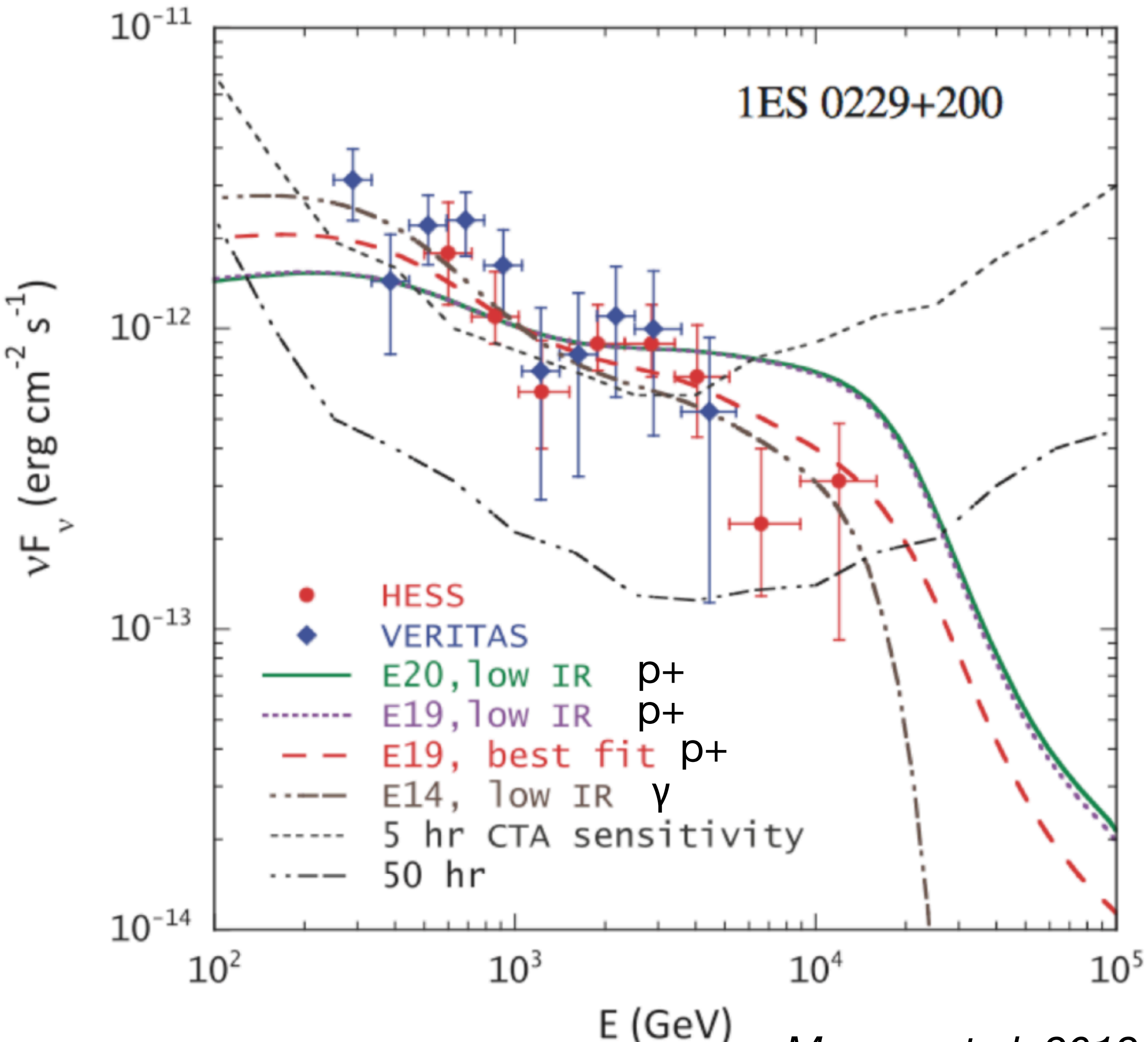


Cerruti, AZ et al. 2018

-> neutrino talks on Thursday afternoon

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.

- Primary hadrons produce harder spectra due to the long energy loss length for Bethe-Heitler pair production. -> Possibility of distinguishing γ-ray vs. hadronic cascades with future data. (*cf. Takami et al. 2013*)

- **problem** : models depend strongly on assumptions on IGMF - not too strong so as not to suppress cascades.

external cascade models

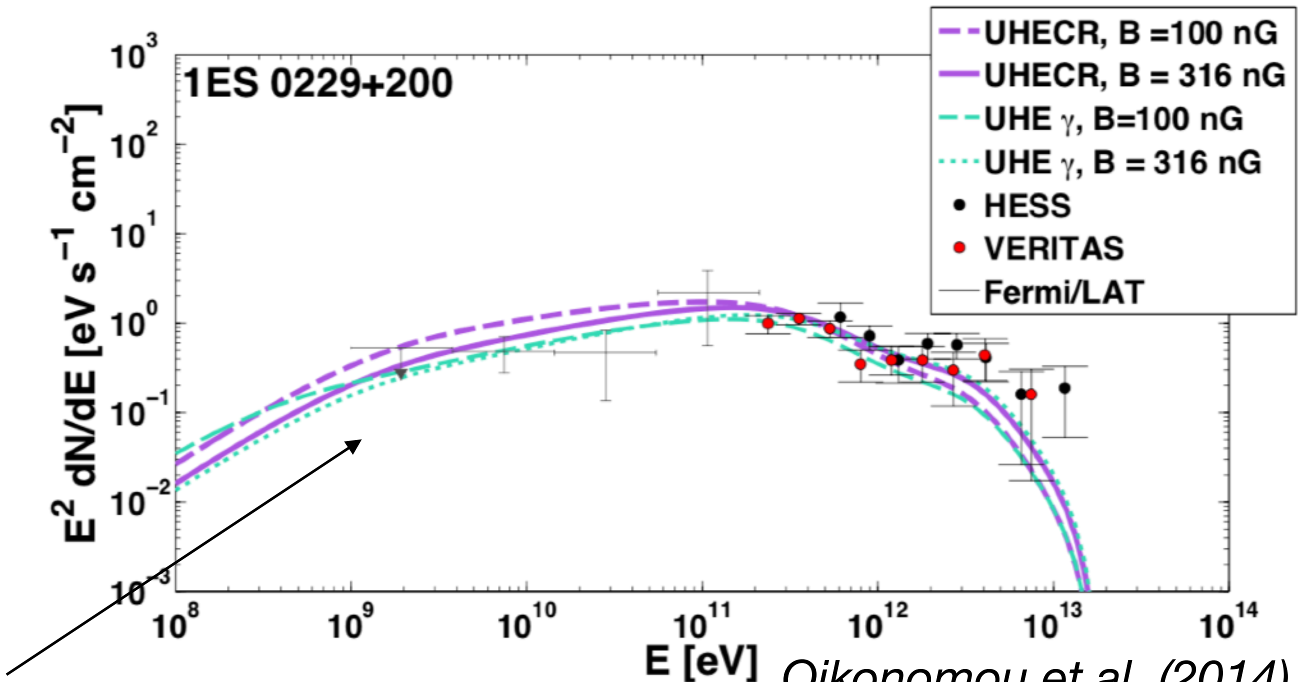
- **problem**: external cascades disfavoured by the observation of some variability ?

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

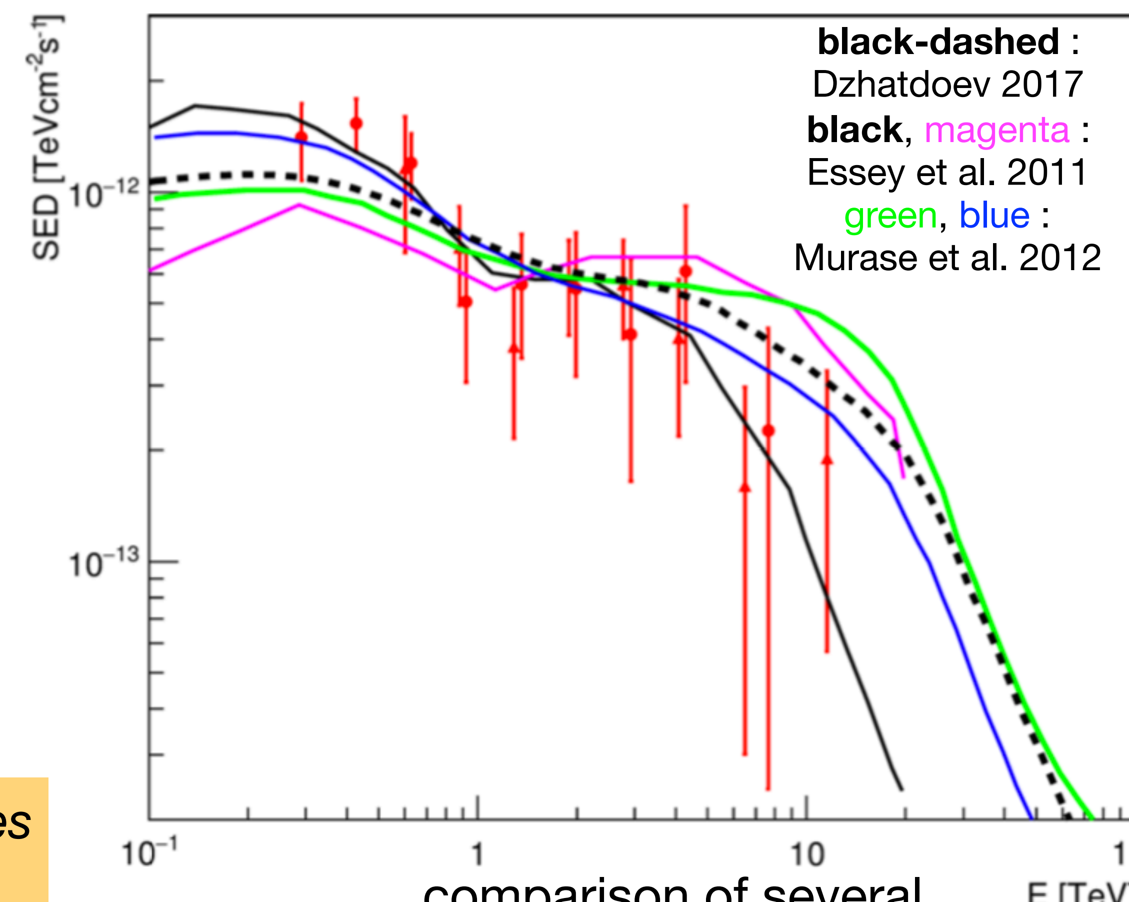
  -> secondary synchrotron emission from primary UHE protons or photons can produce hard TeV spectra; might be difficult to distinguish !

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

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, …*



Oikonomou et al. (2014)

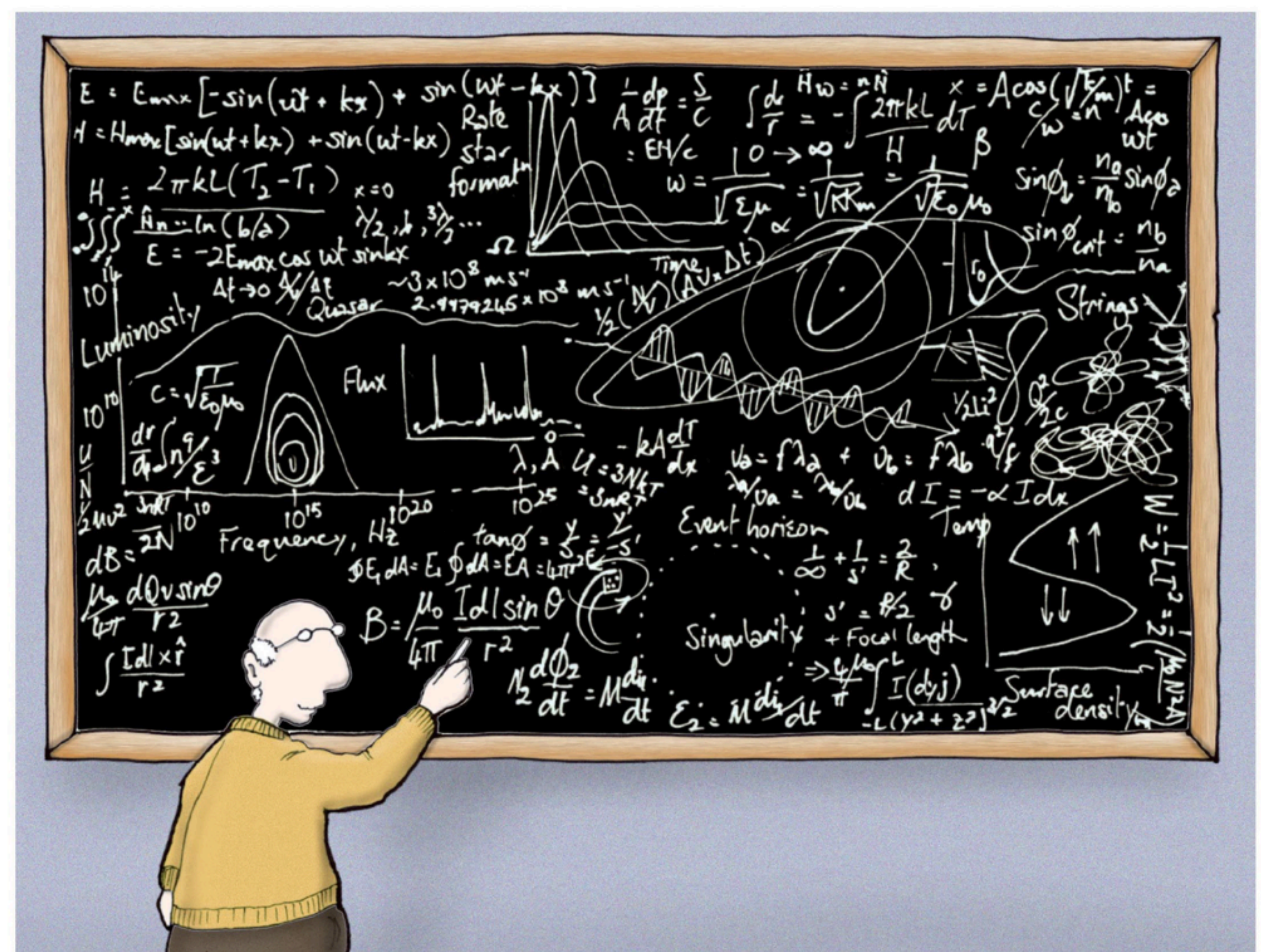


comparison of several hadronic cascade models; *Dzhatdoev et al. 2017*

-> T. Dzhatdoev: talk on cascades and "cosmology" session on Thursday

signatures of new physics ?

- Lorentz-Invariance violation
- Axion-like particles



Astrophysics made simple

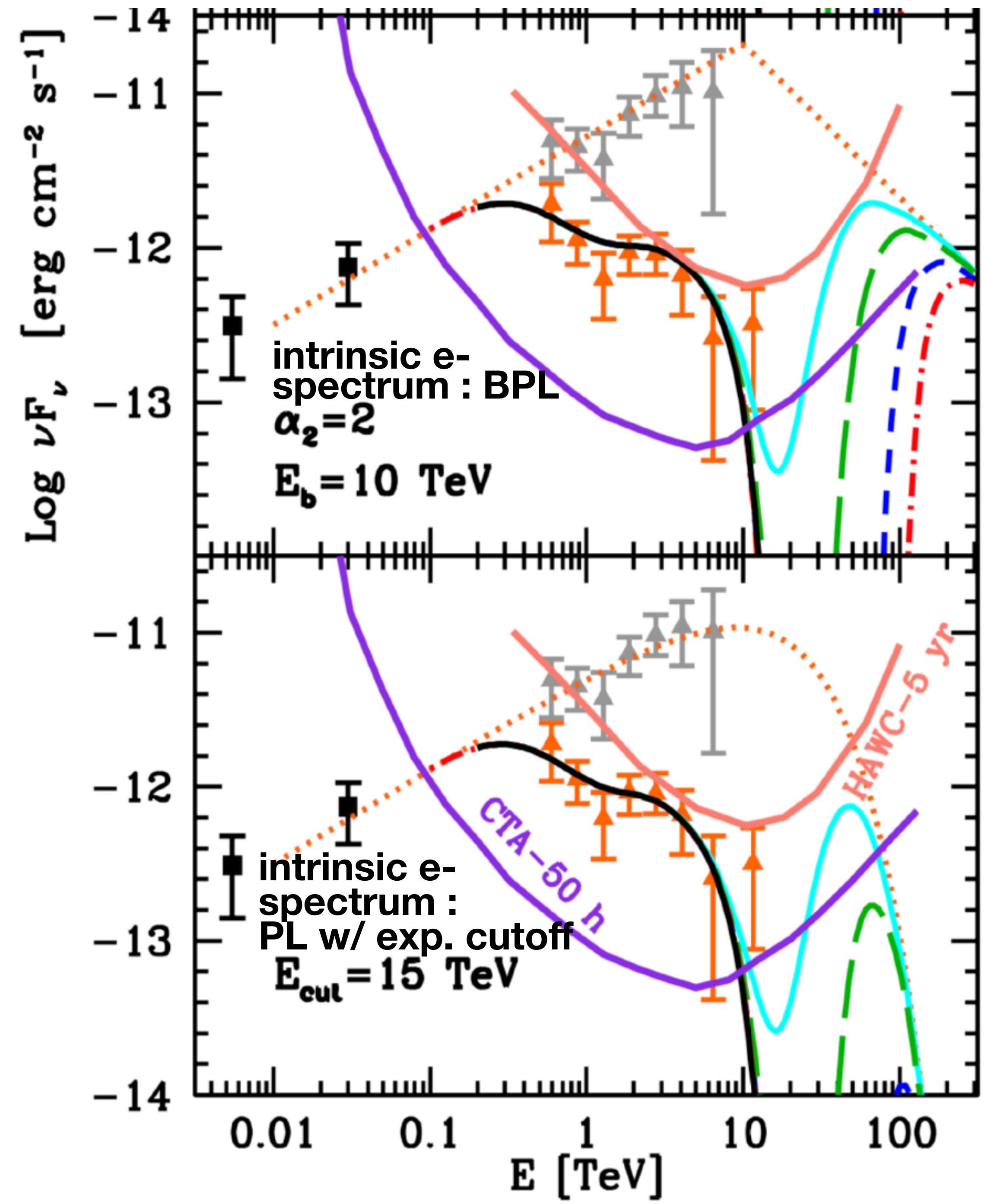
Lorentz-Invariance violation

- 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)



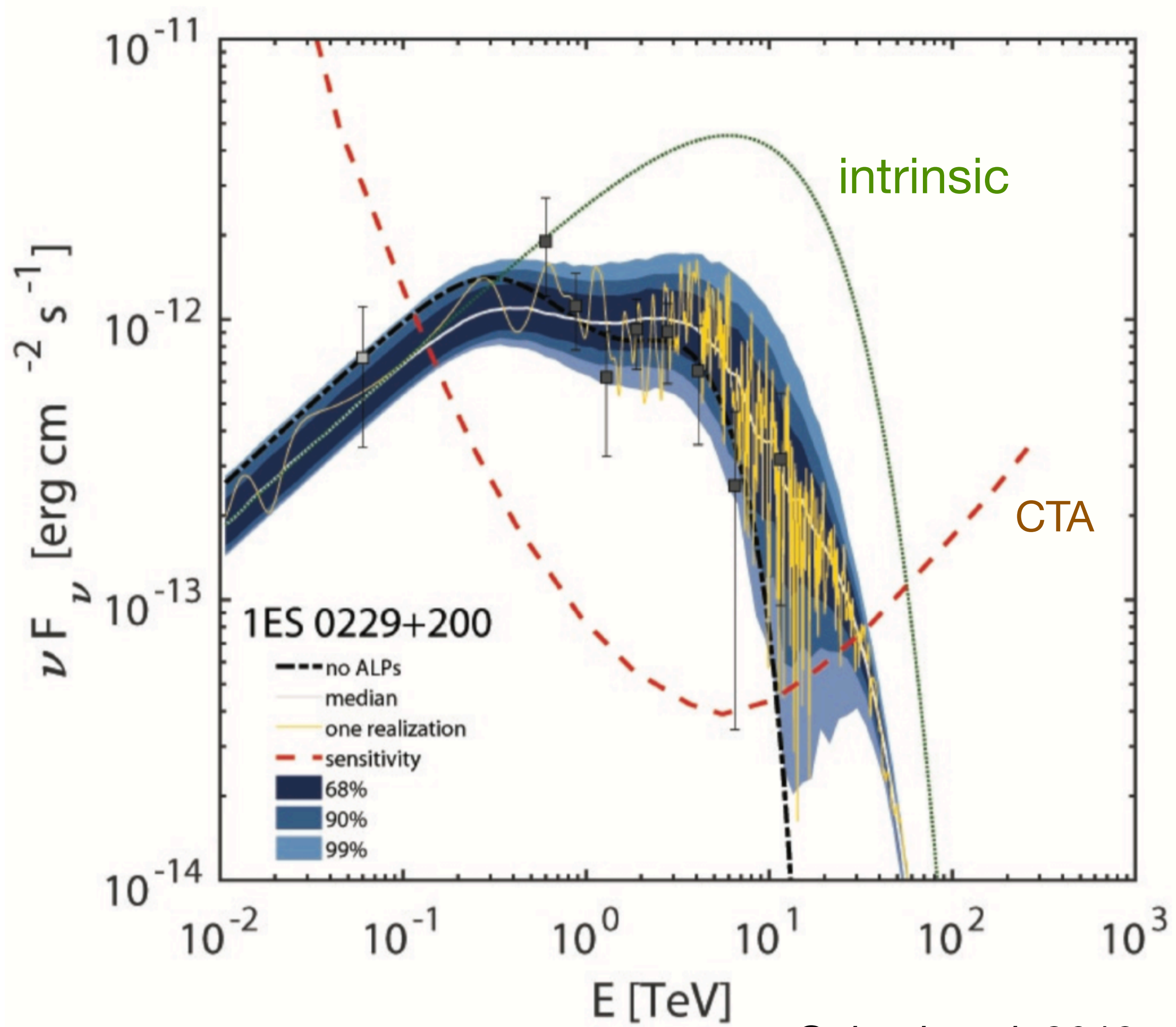
Prediction of observed VHE spectra for 1ES 0229+200 for different intrinsic spectra and characteristic LIV energy scales (1e19 / 3e19 /1e20 / 2e20 GeV)
Tavecchio & Bonnoli 2016

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

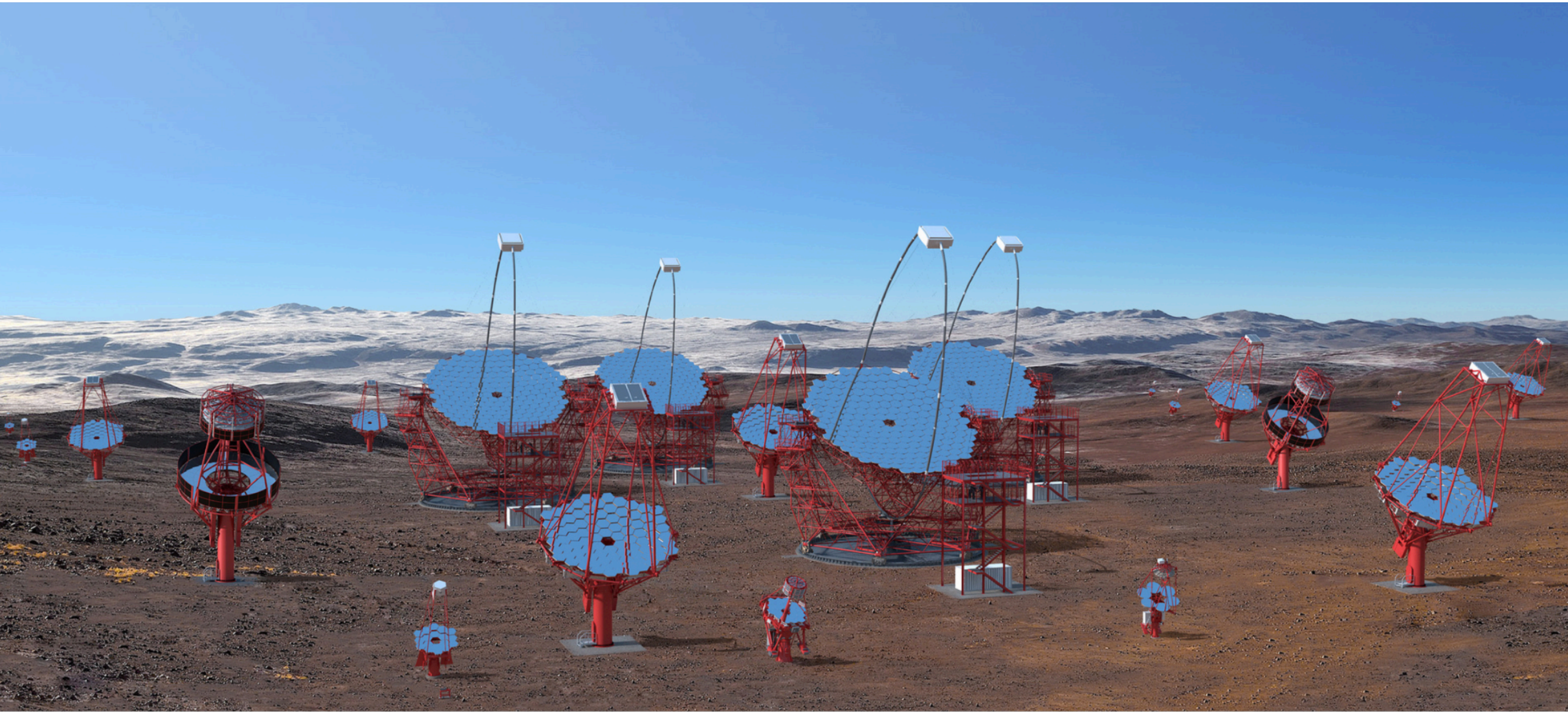
cf. also *Sanchez-Condé et al. 2009, De Angelis 2009, Acharya et al. 2017*,…



Galanti et al. 2018

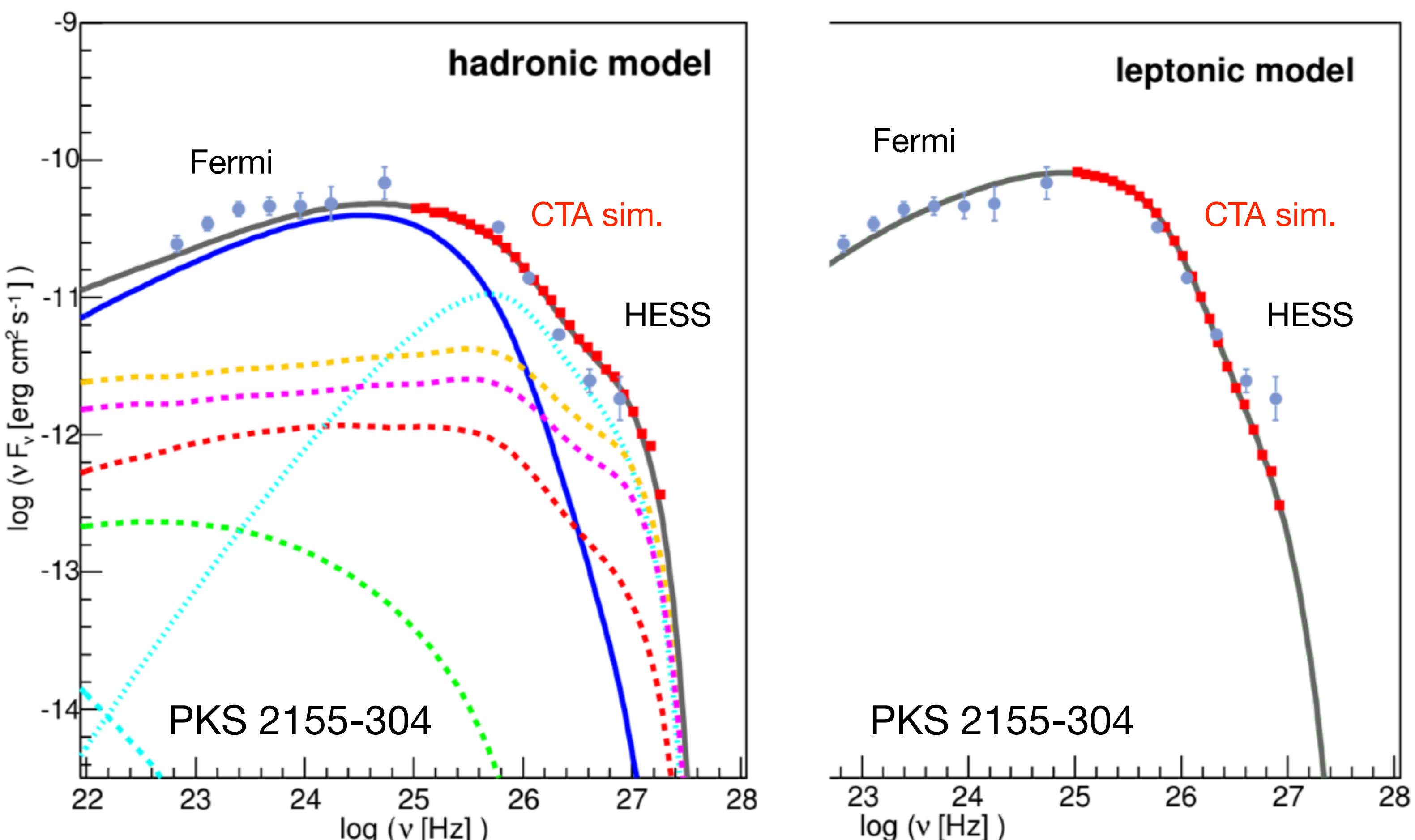
-> G. Galanti (talk on Friday)

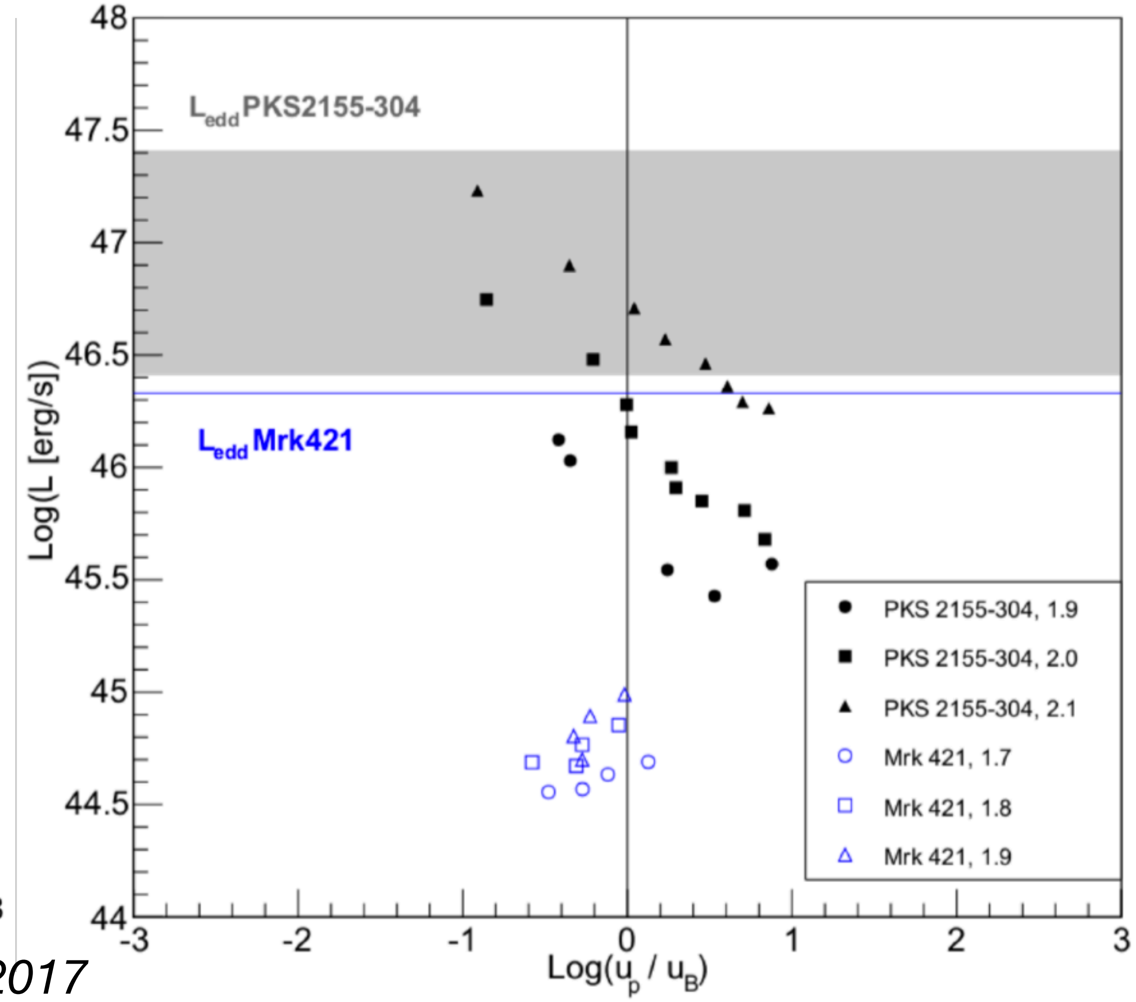
outlook



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

Internal cascade signatures ?





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

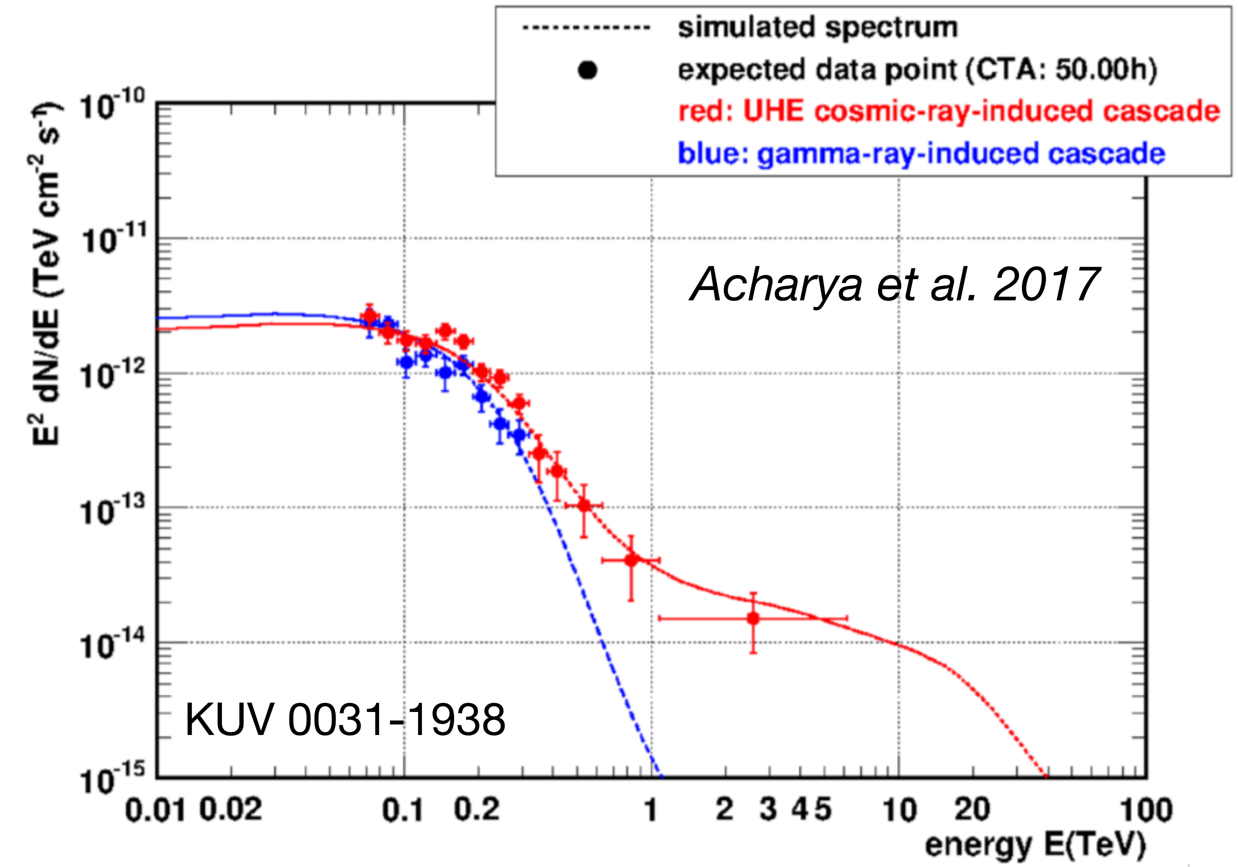
AZ, Cerruti et al. 2017

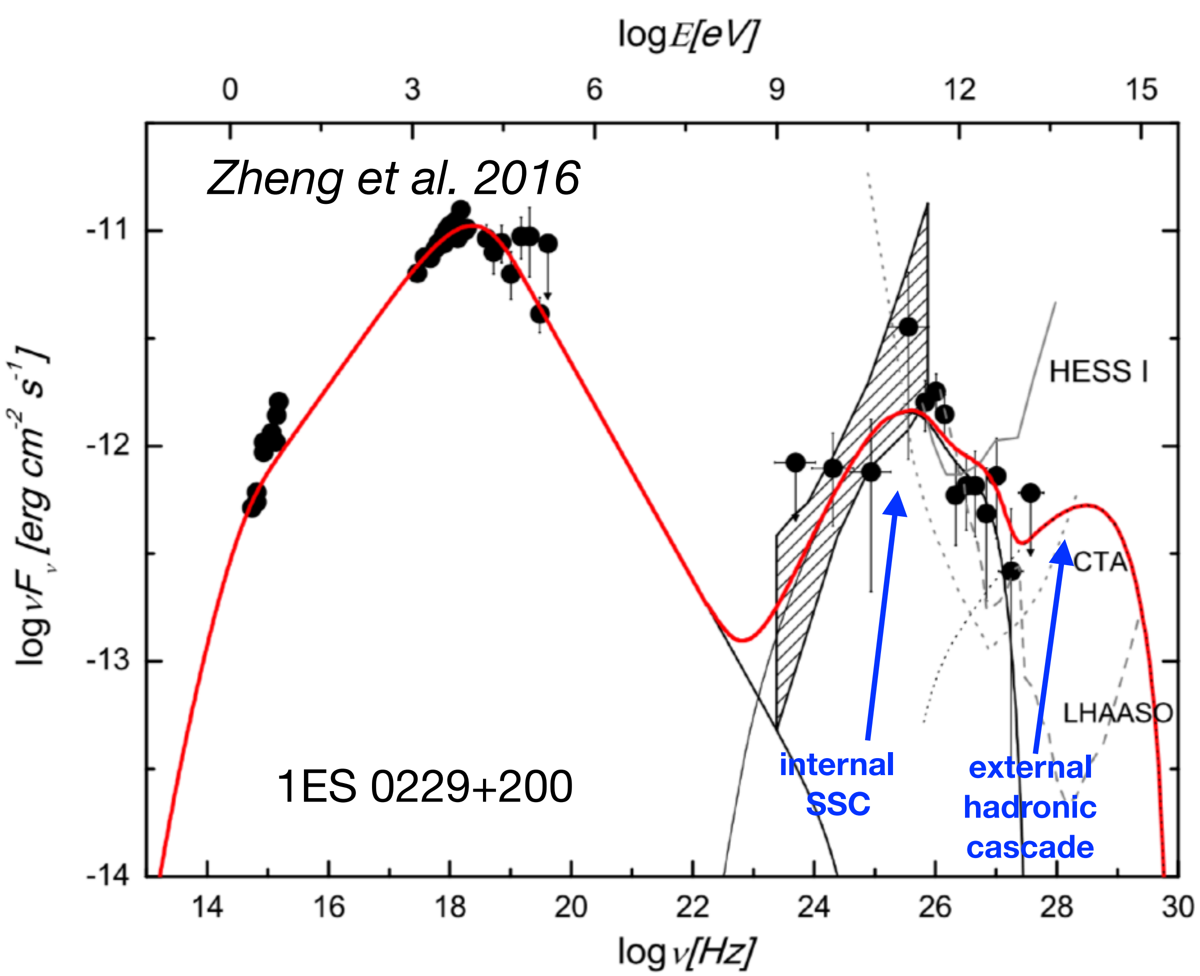
- In the proton-synchrotron scenario, spectral hardening at VHE can be expected from internal cascades for BL Lacs.

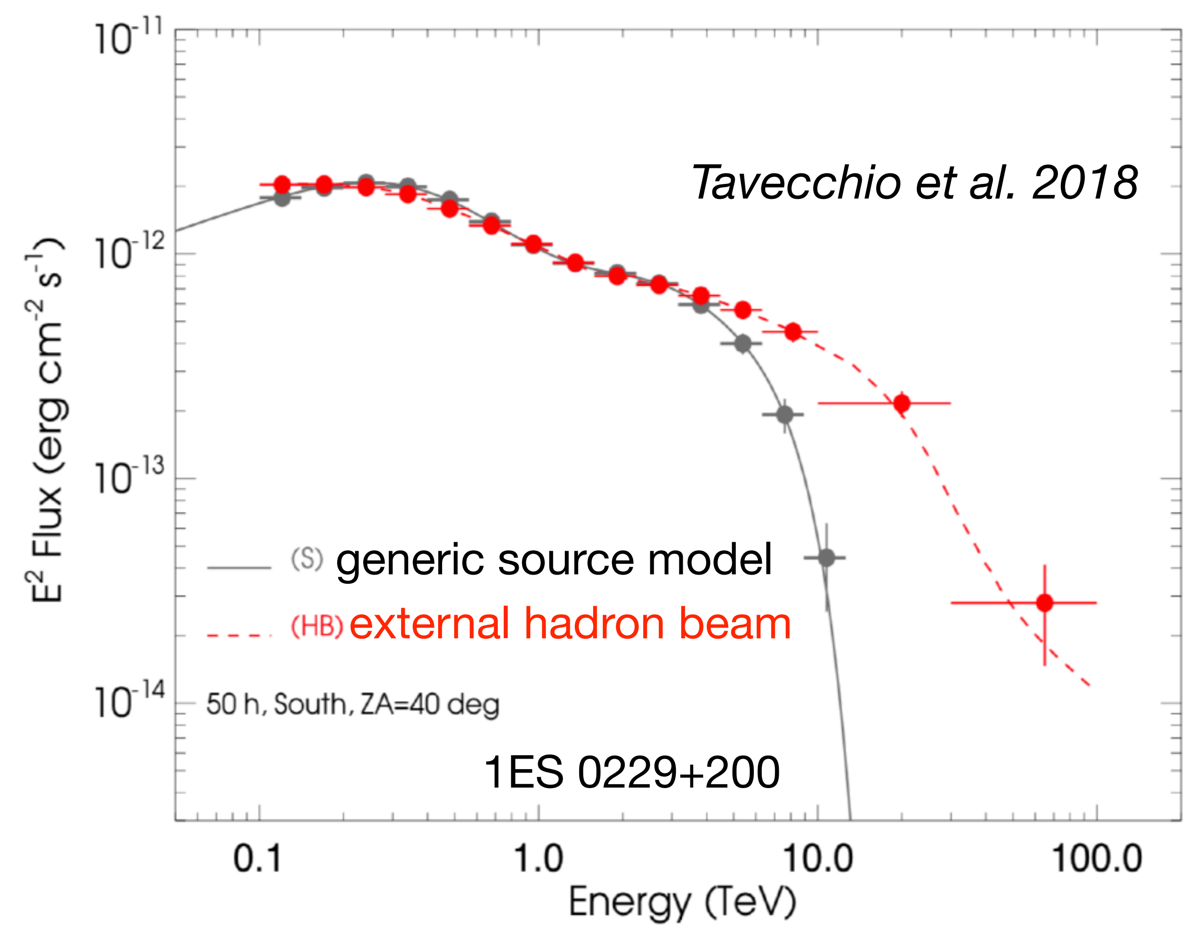
- But: such hardening is not predicted for solutions for extreme blazars.
  - larger source extension, less dense, harder proton spectra -> cascades at low flux level
  - intrinsic features are also suppressed by the EBL for large redshifts

External cascade signatures ?

- 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.







Conclusions

A variety of models (leptonic, hadronic, exotic) exist to explain very hard VHE spectra of extreme blazars !

How to decide ?

- **leptonic models**
  “high γ_{min} “, “Maxwellian” : depends strongly on our understanding of acceleration processes in the jet…

  EIC in jet : multi-band variability, input from radio galaxies (Cen A extension) ?

- **hadronic models**
  one-zone : neutrinos, multi-band variability

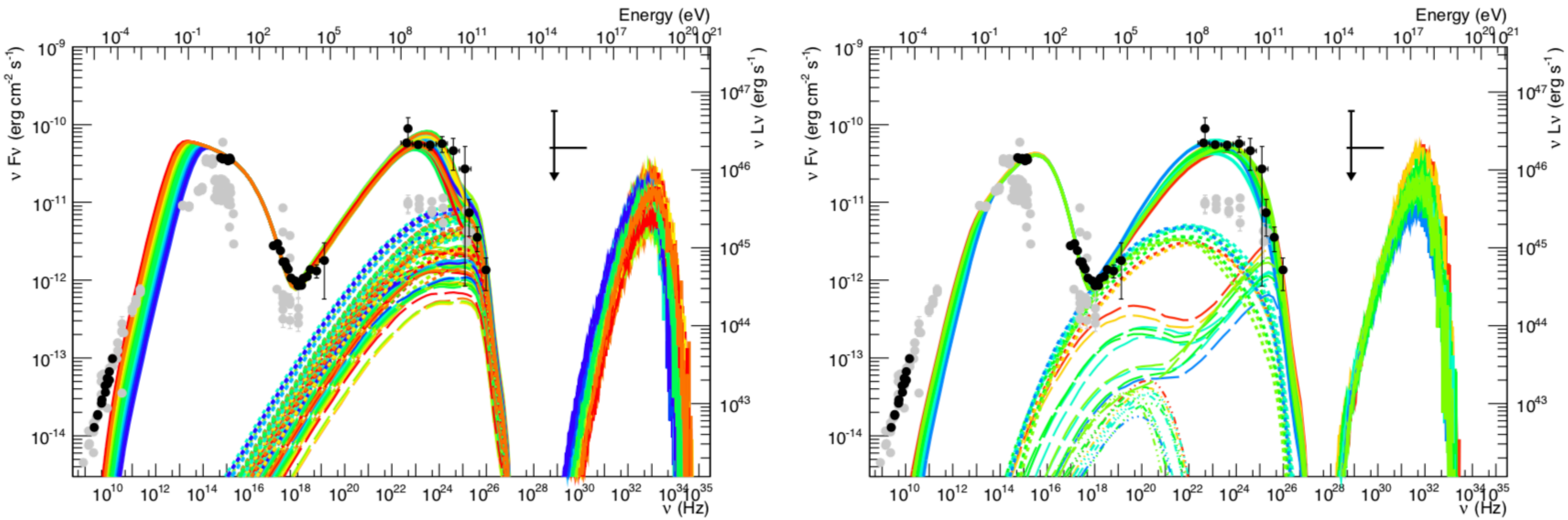
  external cascades : spectral signatures with CTA, neutrinos ?, variability

- **exotic models**
  LIV : particular spectral shape detectable with CTA,
  complementary information from time-delay observations

  A*LPs* : particular spectral shape detectable with CTA
  -> difficult to distinguish from external cascades ?
  chance of direct detection in accelerator experiments

Backup Slides

TXS 0506 with one-zone models



(a) Proton synchrotron modeling of TXS 0506+056

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

	Proton-synchrotron	Lepto-hadronic
z	0.337	0.337
δ	35 – 50	30 – 50
R [10^{16} cm]	0.1 – 9.7	0.2 – 1.5
$^\star\tau_{\rm obs}$ [days]	0.01 – 1.0	0.02 – 0.3
B	0.8 – 32	0.13 – 0.65
$^\star u_B$ [erg cm^{-3}]	0.02 – 0.16	6.5×10^{-4} – 0.017
$\gamma_{e,\rm min}$	500	500
$\gamma_{e,\rm break}$	$= \gamma_{e,\rm min}$	$= \gamma_{e,\rm max}$
$\gamma_{e,\rm max}$ [10^4]	0.6 – 1.0	0.8 – 1.7
$\alpha_{e,1} = \alpha_{p,1}$	2.0	2.0
$\alpha_{e,2} = \alpha_{p,2}$	3.0	3.0
K_e [cm^{-3}]	$6.3 - 9.1 \times 10^3$	$9.5 \times 10^3 - 2.6 \times 10^5$
$^\star u_e$ [10^{-5} erg cm^{-3}]	0.4 – 15.1	$2.2 \times 10^3 - 43 \times 10^3$
$\gamma_{p,\rm min}$	1	1
$\gamma_{p,\rm break}$[10^9]	$= \gamma_{p,\rm max}$	$= \gamma_{p,\rm max}$
$\gamma_{p,\rm max}$[10^9]	0.4 – 2.5	0.06 – 0.2
η	20 – 50	10
K_p [cm^{-3}]	$10.4 - 2.0 \times 10^4$	$3.5 \times 10^3 - 6.6 \times 10^4$
$^\star u_p$ [erg cm^{-3}]	0.7 – 45	100 – 1400
$^\star u_p / u_B$	1.0 – 89	$3.9 \times 10^4 - 79 \times 10^4$
$^\star L$ [10^{46} erg s^{-1}]	0.8 – 170	35 – 350
$^\star\nu$ [year^{-1}]	5.7×10^{-3} – 0.2	0.11 – 3.0
$^\star\nu_{183-4300\,\rm TeV}$ [year^{-1}]	$2.4 \times 10^{-5} - 1.7 \times 10^{-3}$	0.008 – 0.11

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jet power for HBL and UHBL