Unravelling the complex behaviour of our closest very-high-energy gamma-ray blazars, Mrk421 and Mrk501

David Paneque (dpaneque@mppmu.mpg.de)

Max Planck Institute for Physics

On behalf of many collaborations/Instruments: *Fermi*, MAGIC, VERITAS, FACT, NuSTAR, RXTE, Swift, GASP-WEBT, F-GAMMA, SMA, VLBA, Metsahovi, OVRO, UMRAO …

And with the help of Many people:
M. Baloković, P. Becerra, M. Doert, G. Hughes, A. Shukla, F. Tavecchio, A. Tramacere, C. Wendel, K. Noda, K. Ishio, A. Babic, T. Hassan, D. Dorner, A . Furniss, M. Giroletti, S. Jorstad, V. Larionov, G. Madejski, M. Perri, H. Takami, M. Villata, P. Smith …

- The broadband and variable emission of blazars
- Extensive MW campaigns on Mrk421 and Mrk501
- Some highlighted results
  → *Peculiar behaviors (during low and high activity)*
- Conclusions

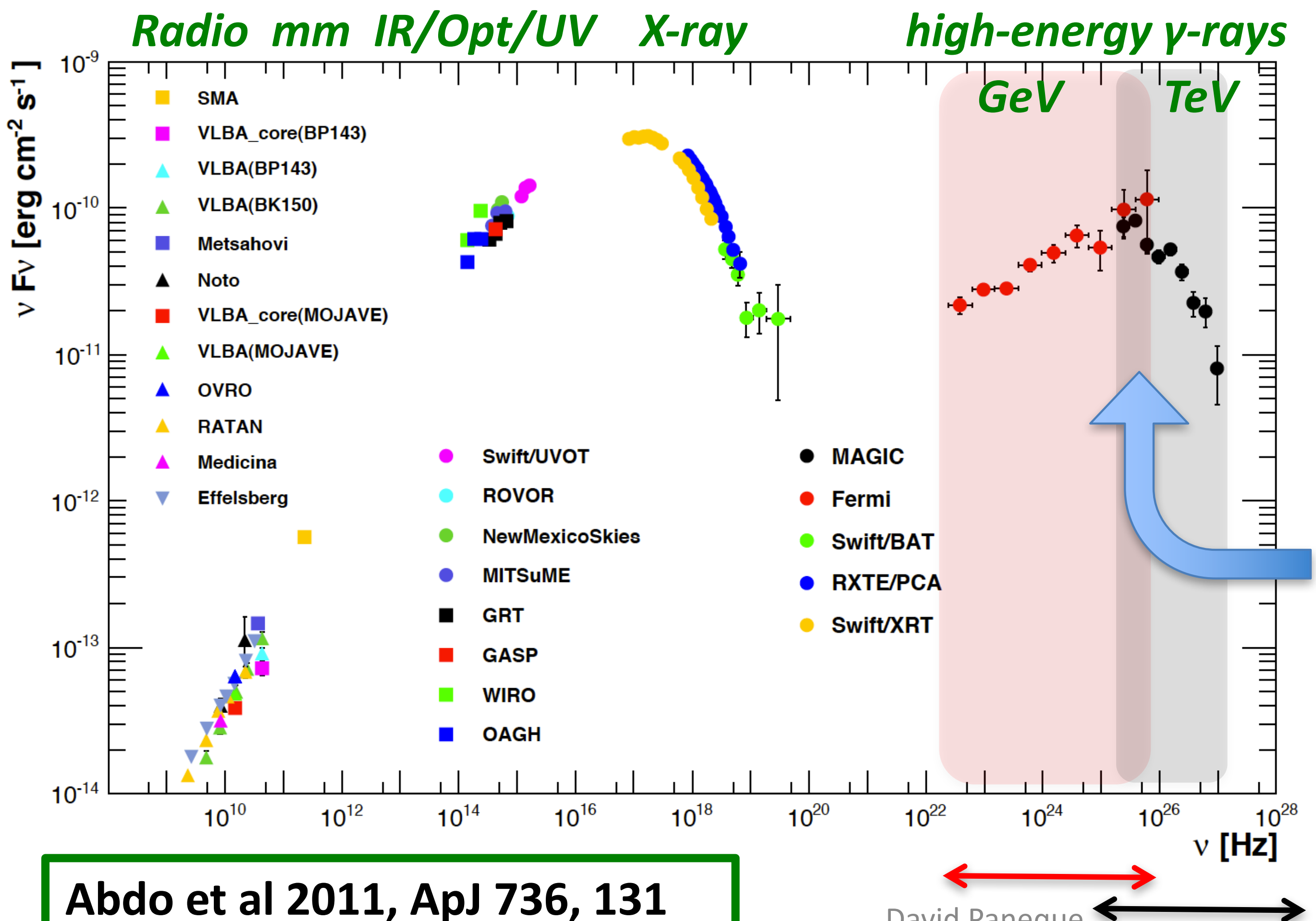
Blazars emit over a very wide energy range and show variability

Emission at different energies could be produced by same particles

→ *Need simultaneous observations from many instruments*

→ *The gamma-ray emission fully characterized "only" since 2009*

→ Connectivity among astronomers also grew in last decade



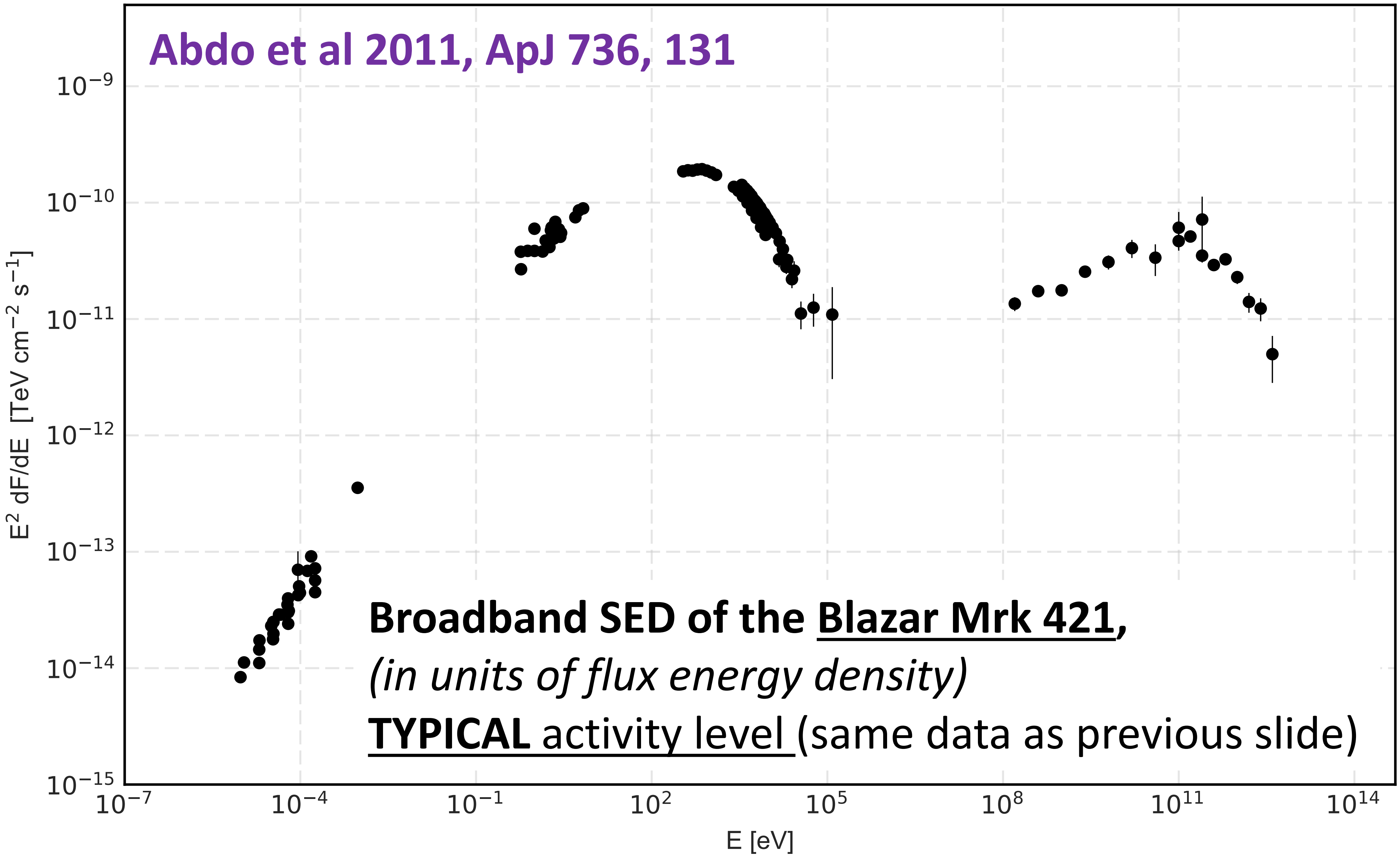
Abdo et al 2011, ApJ 736, 131

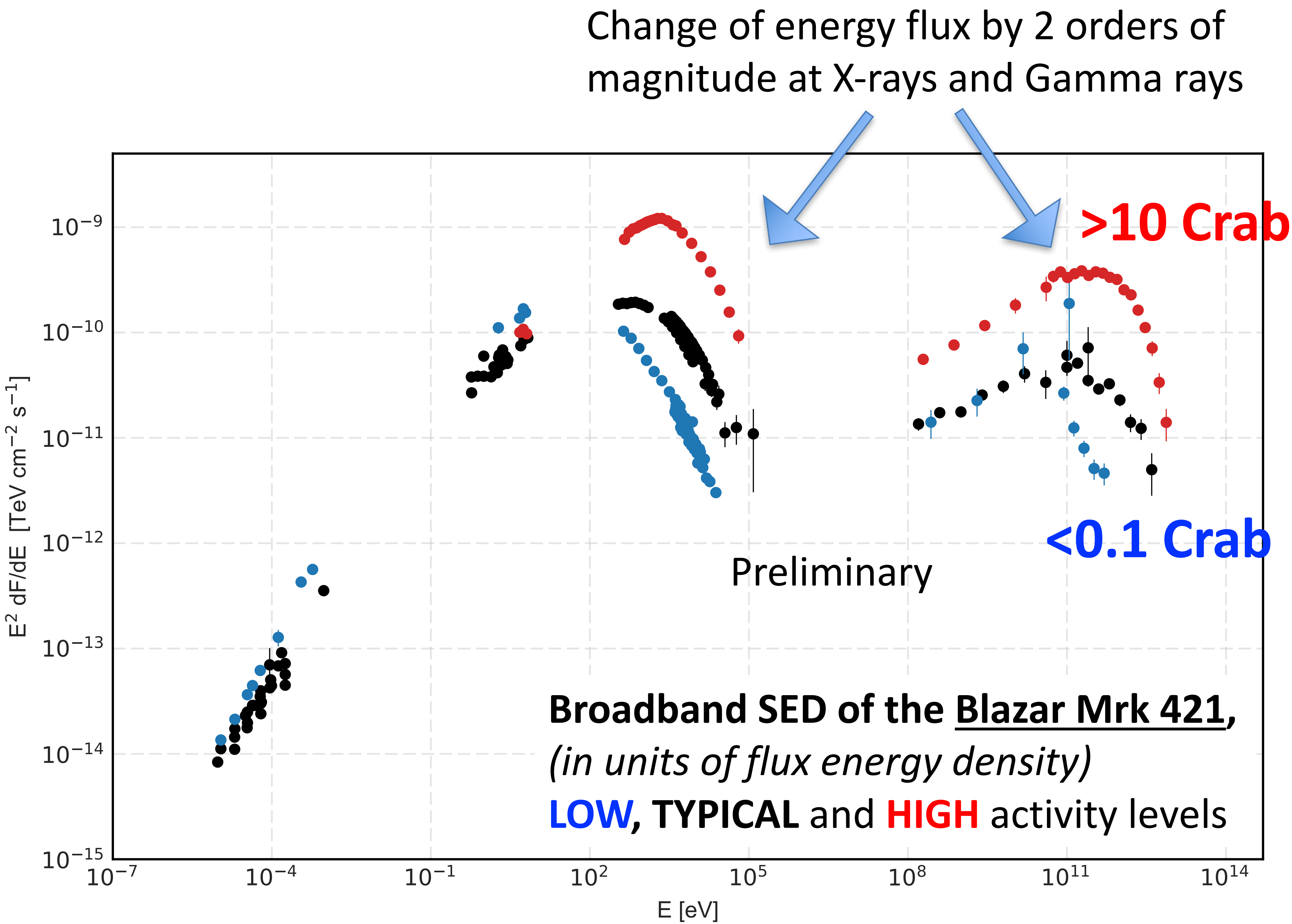
Fermi – IACT

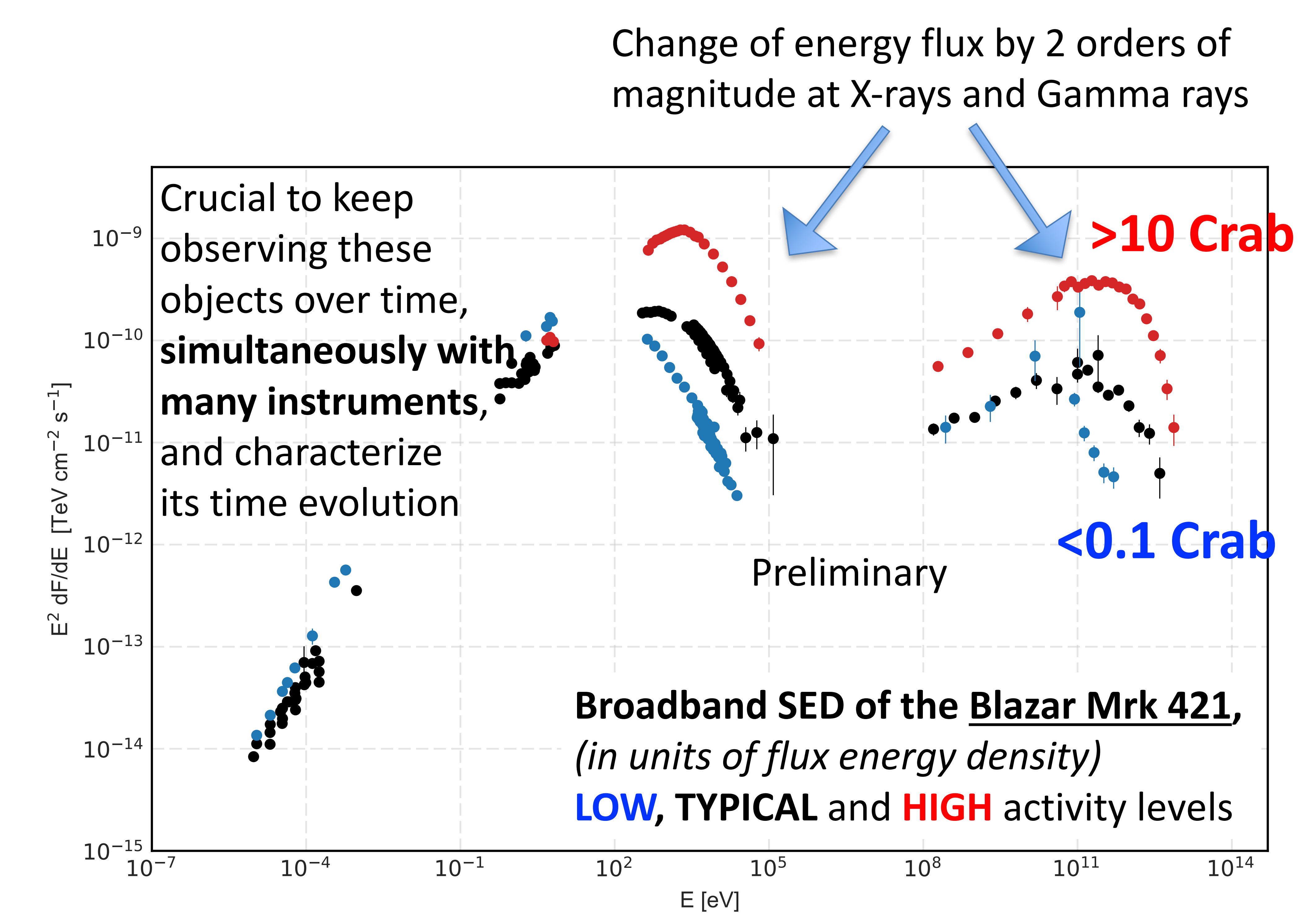
***Fermi* – IACT** spectra cover, <u>for the first time</u>, the complete high energy component over 5 orders of magnitude without gaps

→ *Crucial for the theoretical modeling of the broad emission*

Blazars are very variable objects: need multi-sampling



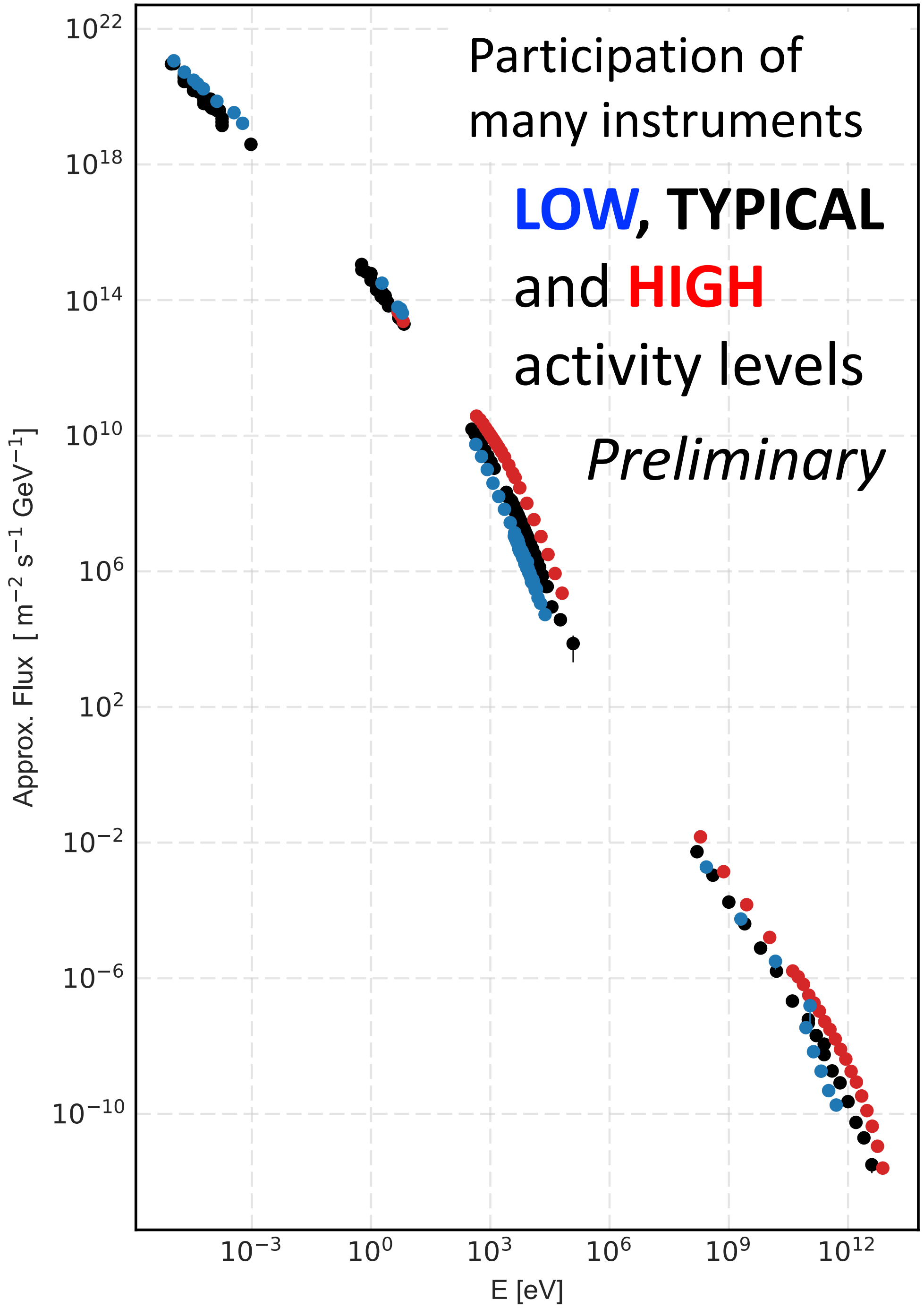

Change of energy flux by 2 orders of magnitude at X-rays and Gamma rays
>10 Crab
<0.1 Crab
Preliminary
Broadband SED of the Blazar Mrk 421,
(in units of flux energy density)
LOW, TYPICAL and HIGH activity levels
E² dF/dE [TeV cm⁻² s⁻¹]
E [eV]



Change of energy flux by 2 orders of magnitude at X-rays and Gamma rays
Crucial to keep observing these objects over time, **simultaneously with many instruments**, and characterize its time evolution
>10 Crab
<0.1 Crab
Preliminary
Broadband SED of the Blazar Mrk 421,
(in units of flux energy density)
LOW, TYPICAL and **HIGH** activity levels
E^2 dF/dE [TeV cm^{-2} s^{-1}]
E [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-7}
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
10^{14}

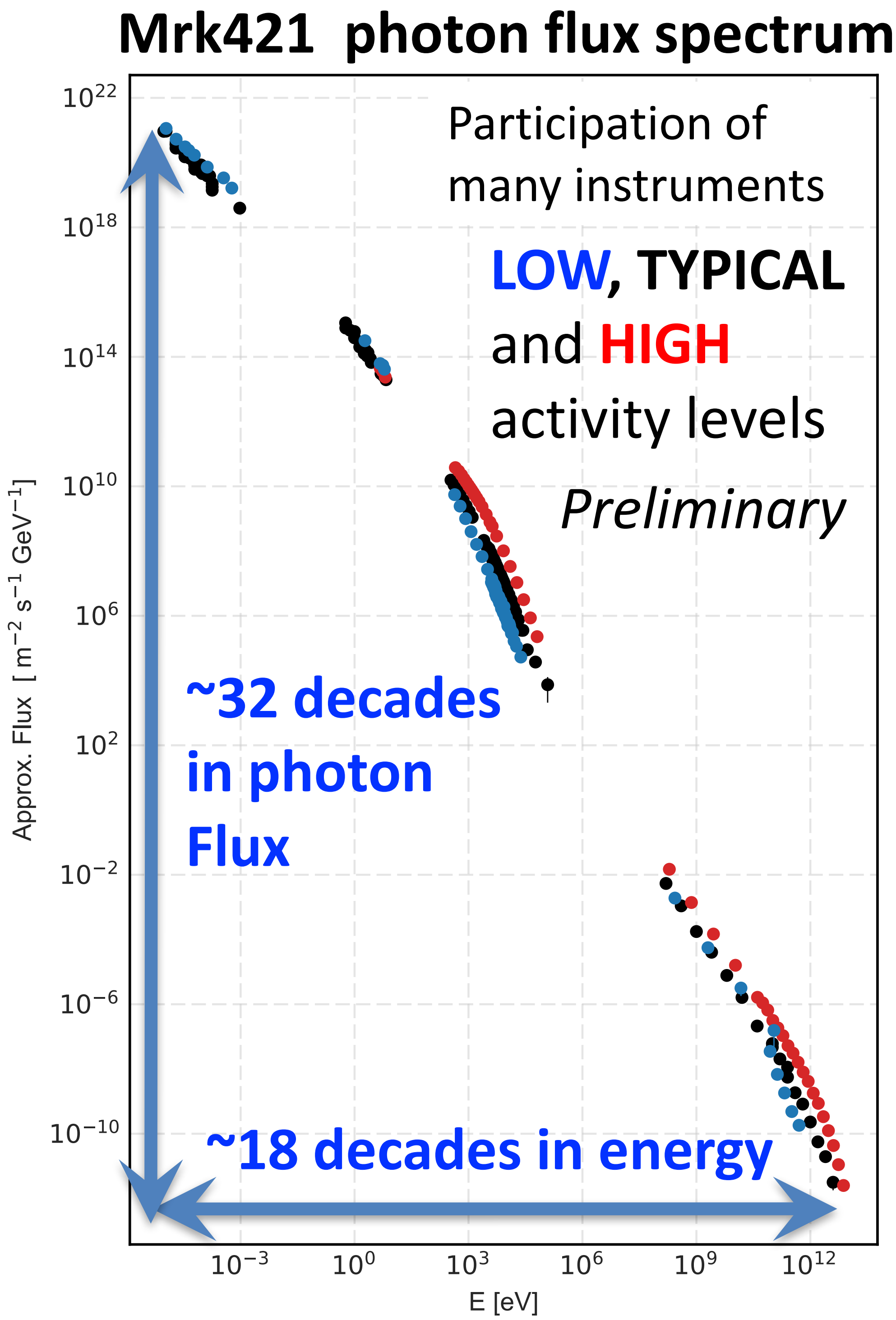
Broadband SED can be converted into a sort of photon flux spectrum *(representation often used to display the CR particle flux)*

Mrk421 photon flux spectrum



In this representation, the **Low**, **Typical** and **High** activities do not "look" that different ...

Broadband SED can be converted into a sort of photon flux spectrum *(representation often used to display the CR particle flux)*



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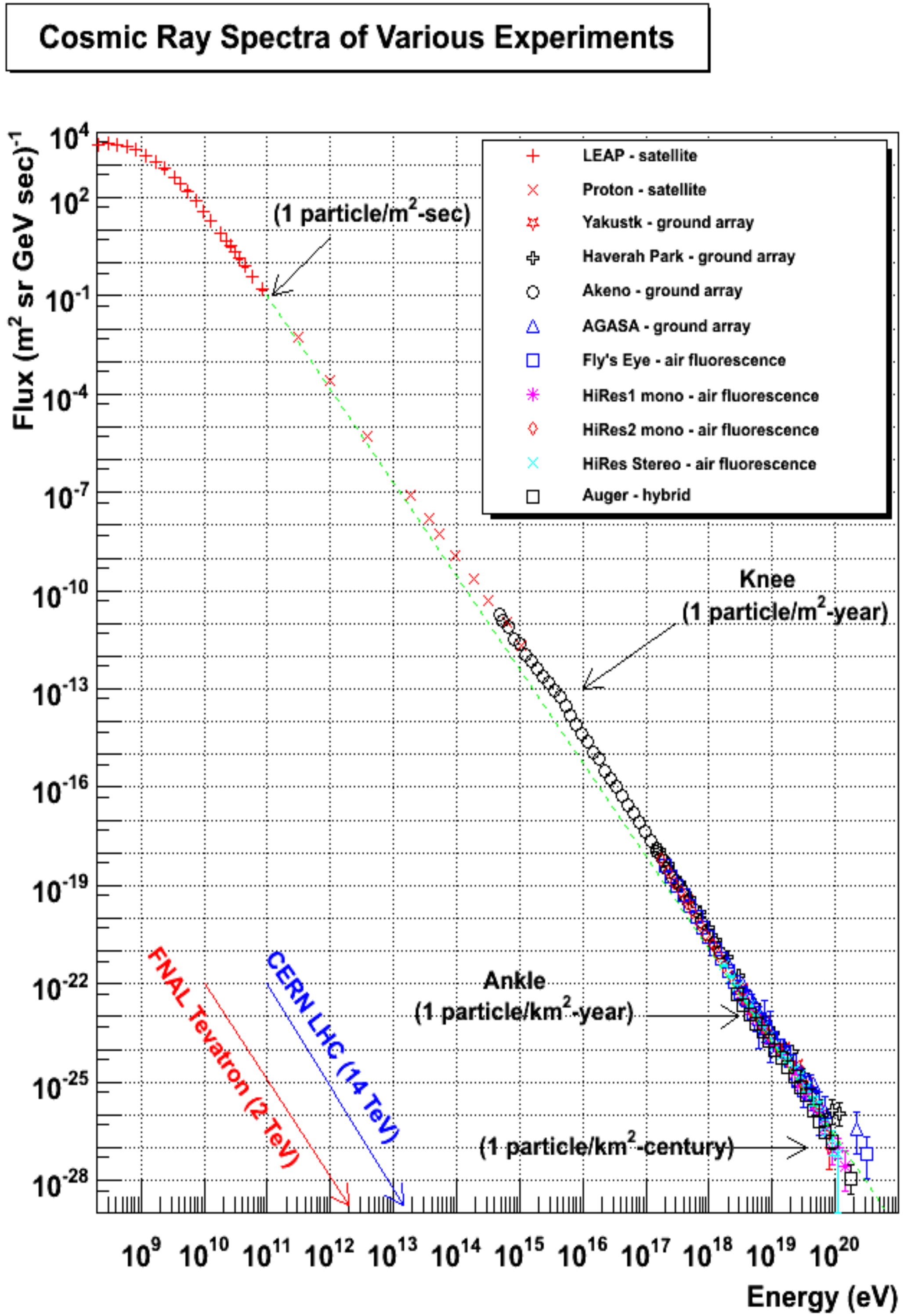
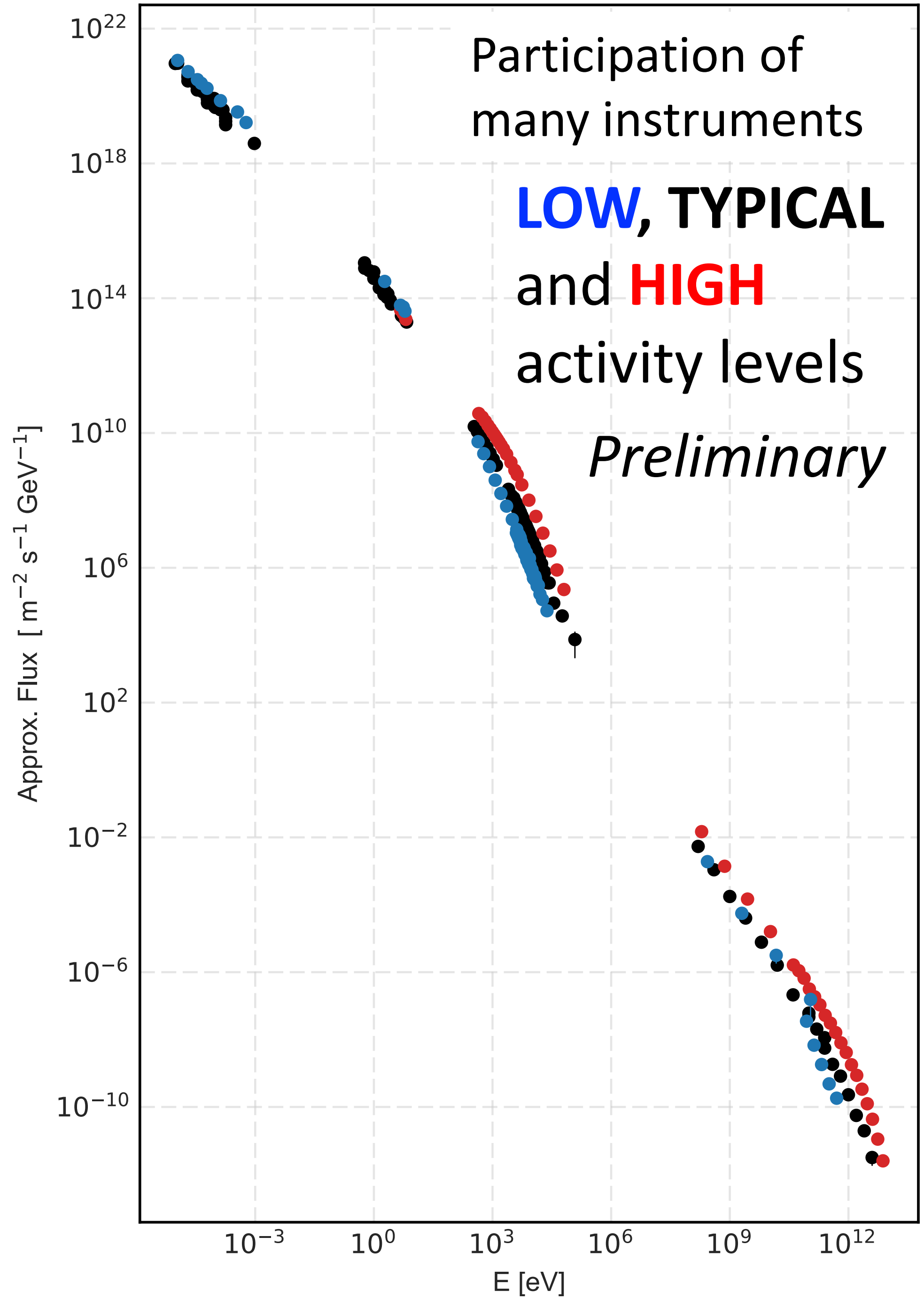


Mrk421 photon flux spectrum



Broadband SED can be converted into a sort of photon flux spectrum *(representation often used to display the CR particle flux)*

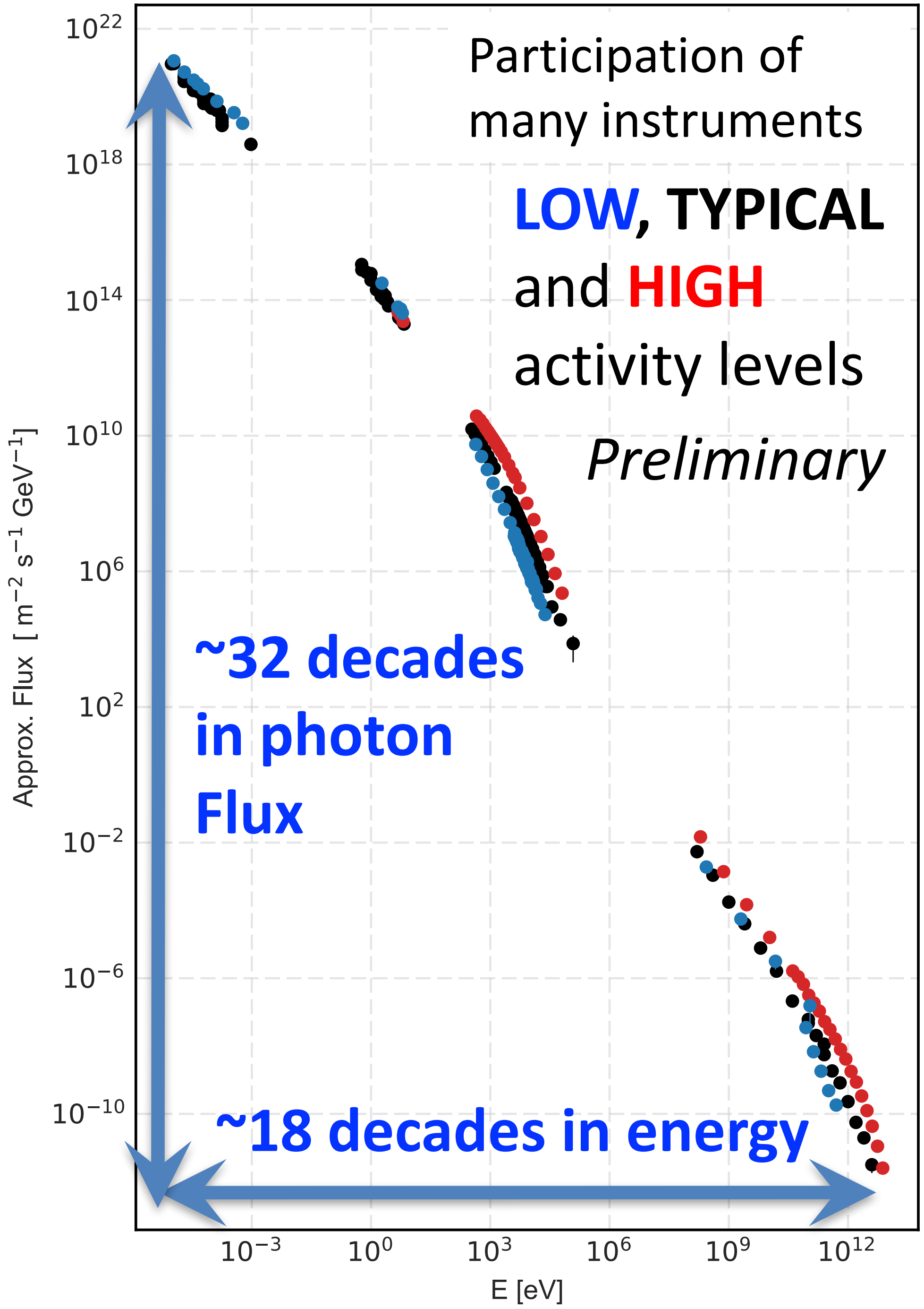
Similar energy and photon (→ particle) flux span than that of the CR spectrum

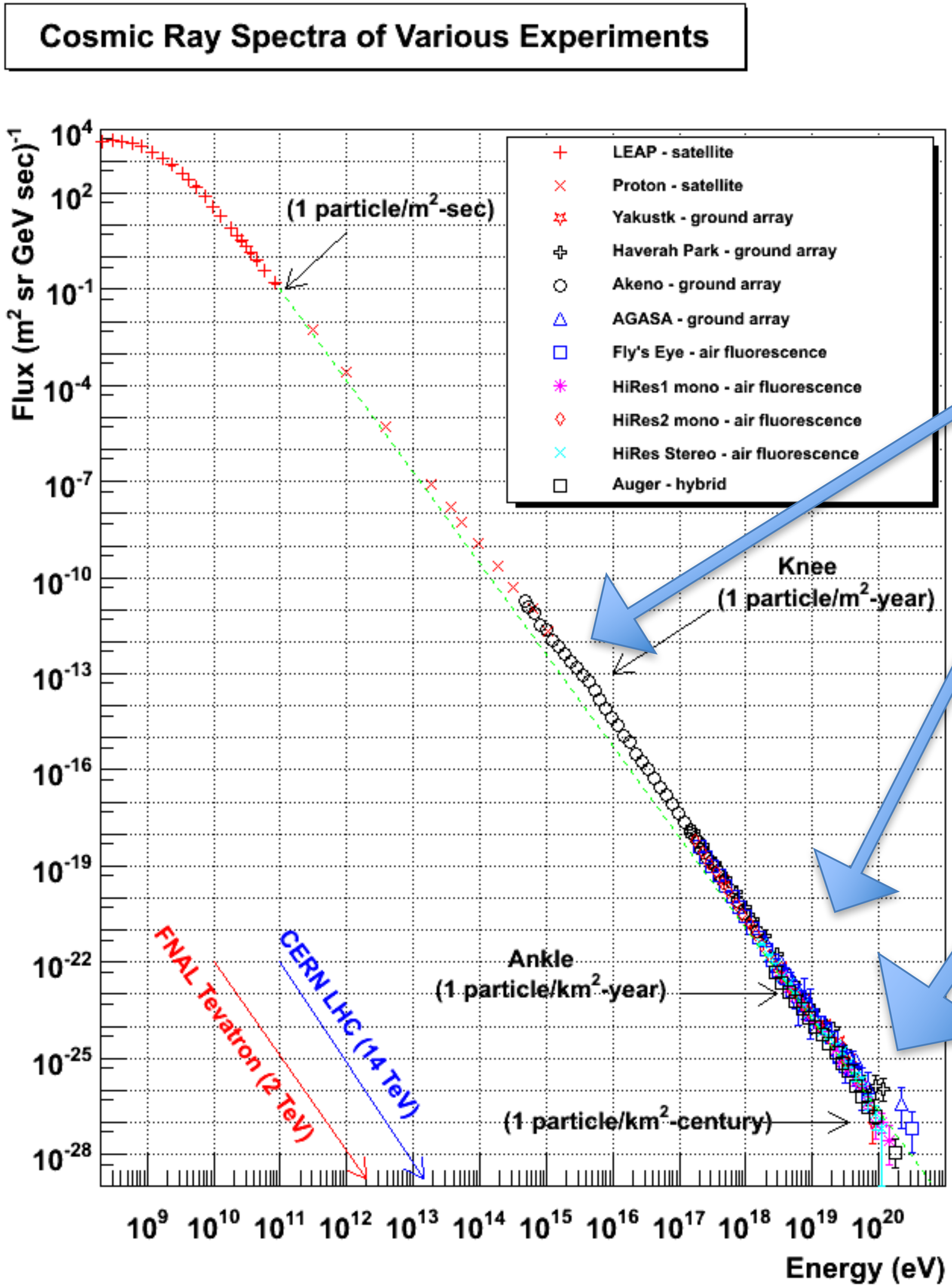
***Flux** : 32 vs 32 decades*

***Energy**: 12 vs 18 decades*

In this representation, the **Low**, **Typical** and **High** activities do not "look" that different ...

Mrk421 photon flux spectrum





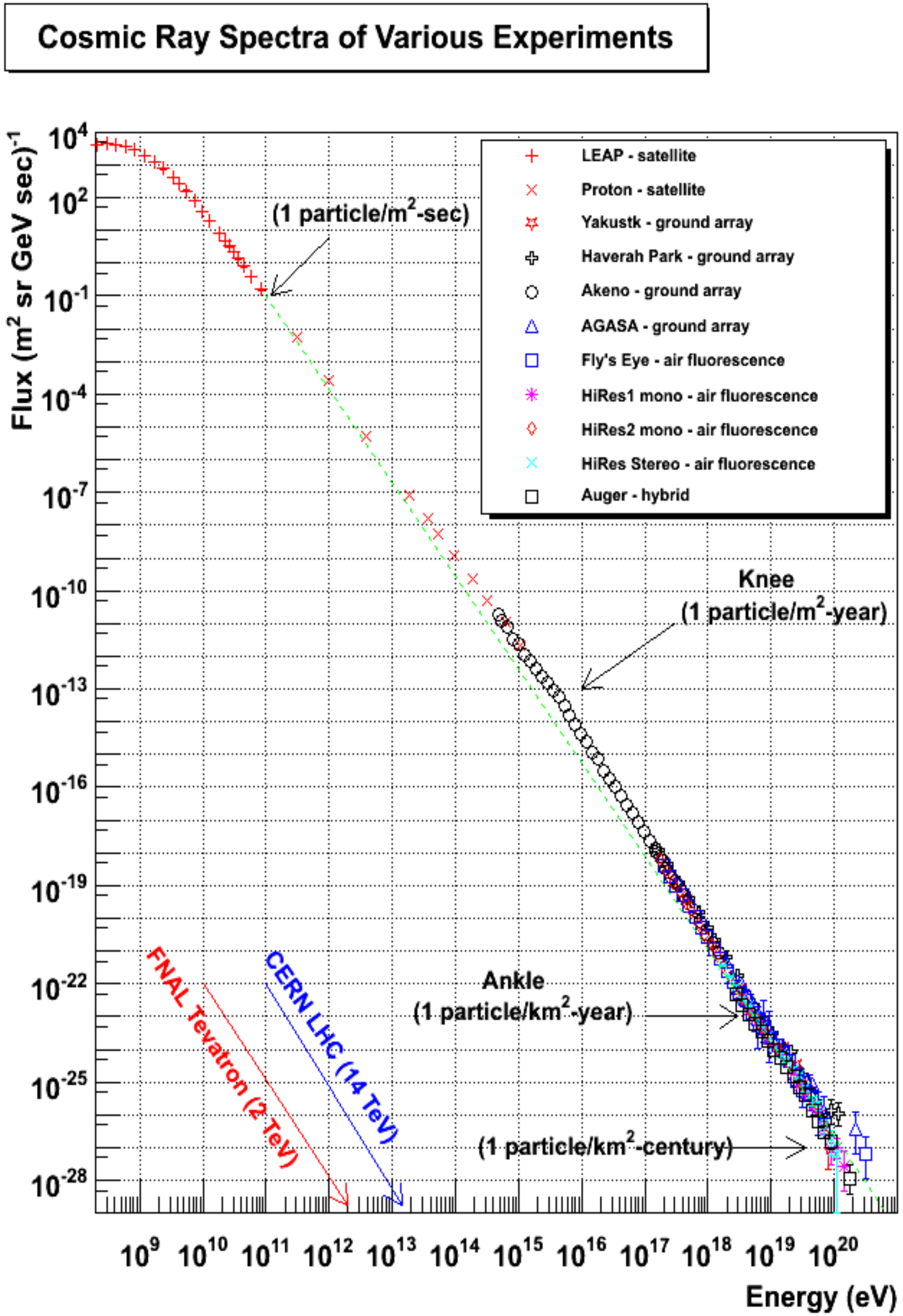
The "knee" may indicate the end of some CR population (*purely Galactic*)

The "ankle" may indicate the the dominance of some other CR population *(purely extragalactic)*

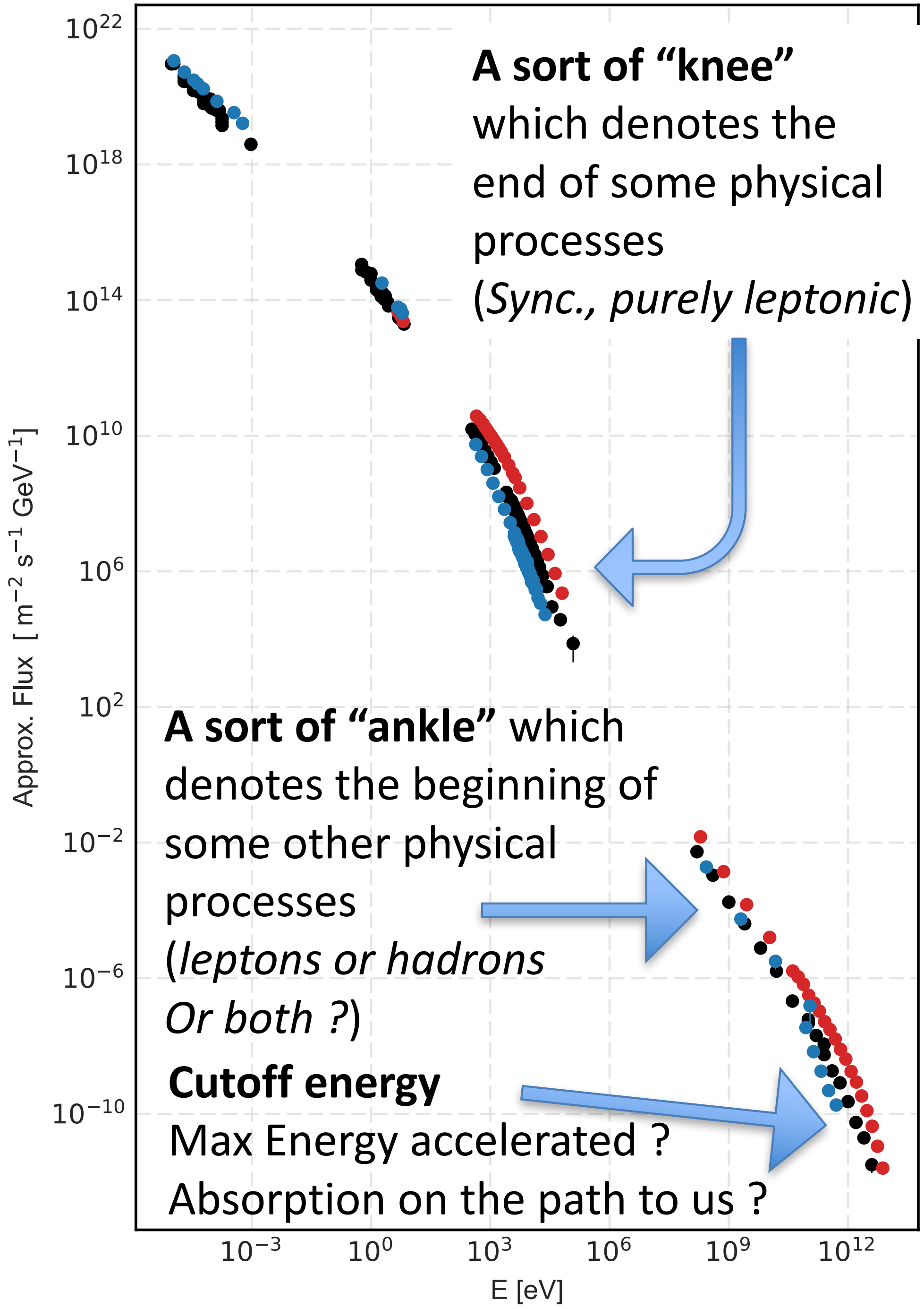
Cutoff energy

Propagation in the CMB (GZK effect $p\gamma \longrightarrow p\,\pi^0$ or $n\,\pi^+$)

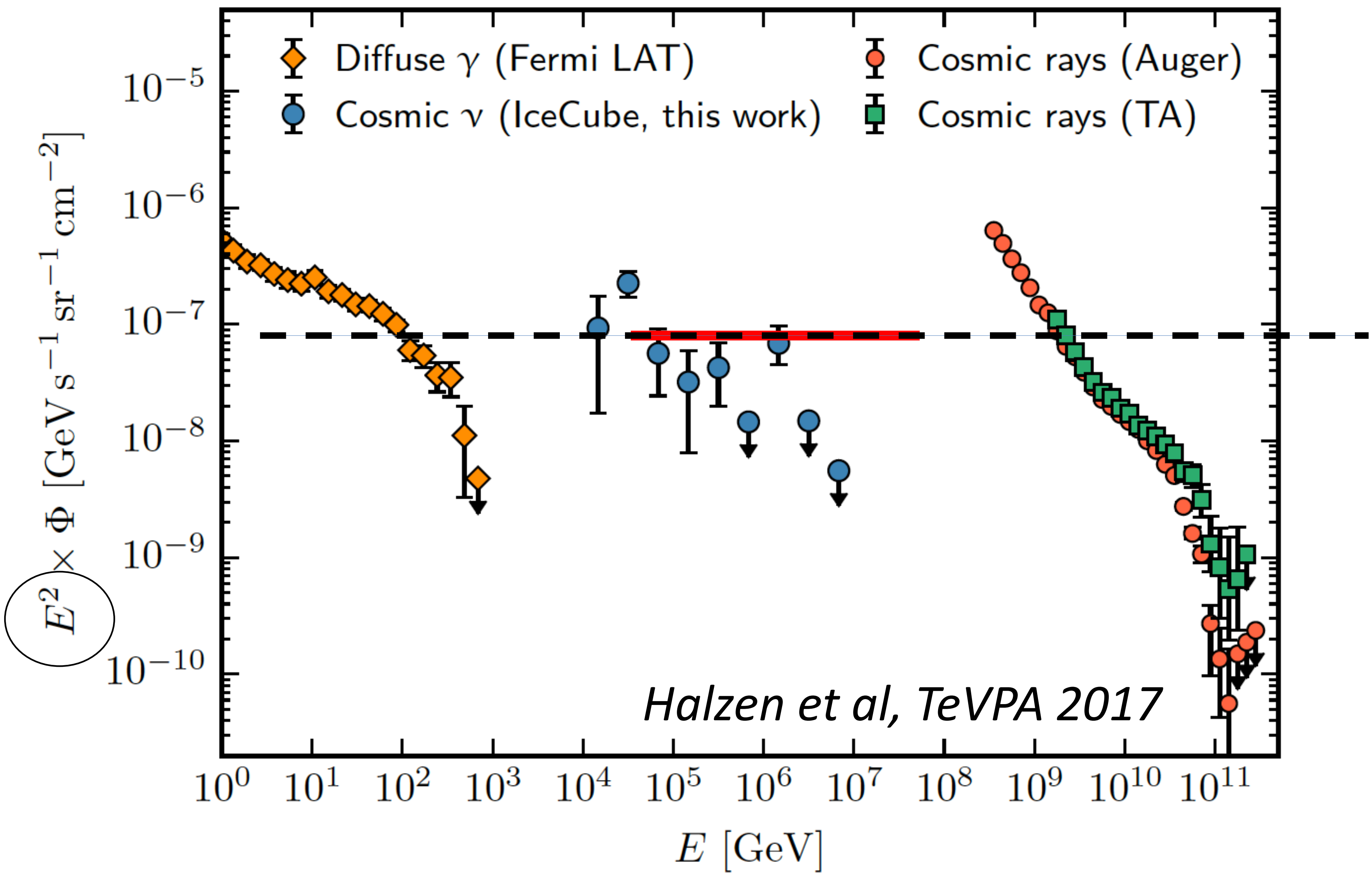
Additionally, can it be that the sources run out of power ?



Mrk421 photon flux spectrum

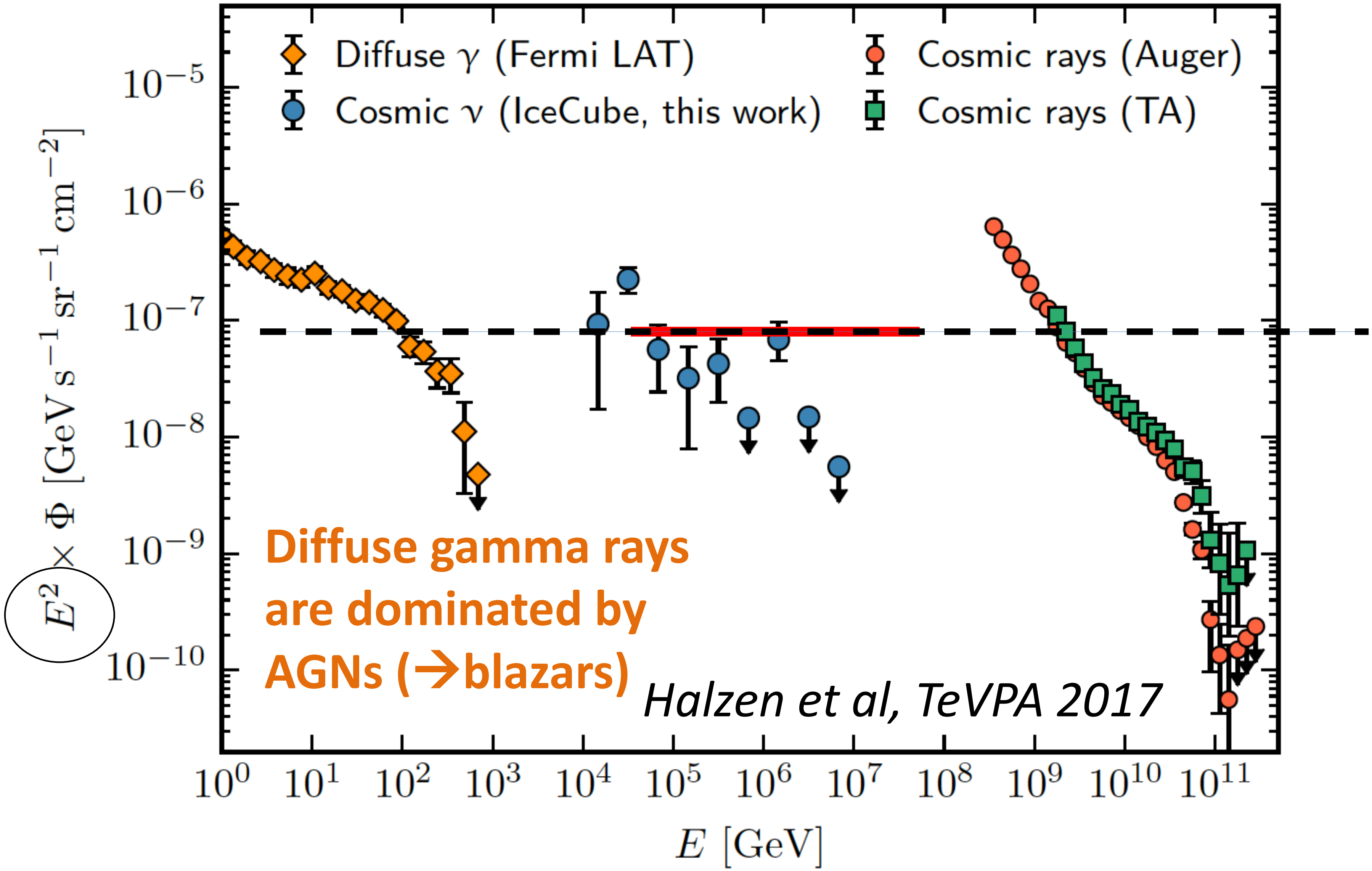


Energy in the Universe in gamma rays, neutrinos, and Cosmic Rays



Energy in the Universe in

gamma rays, neutrinos, and Cosmic Rays



Non-thermal Emission Processes in AGN Jets: Leptons

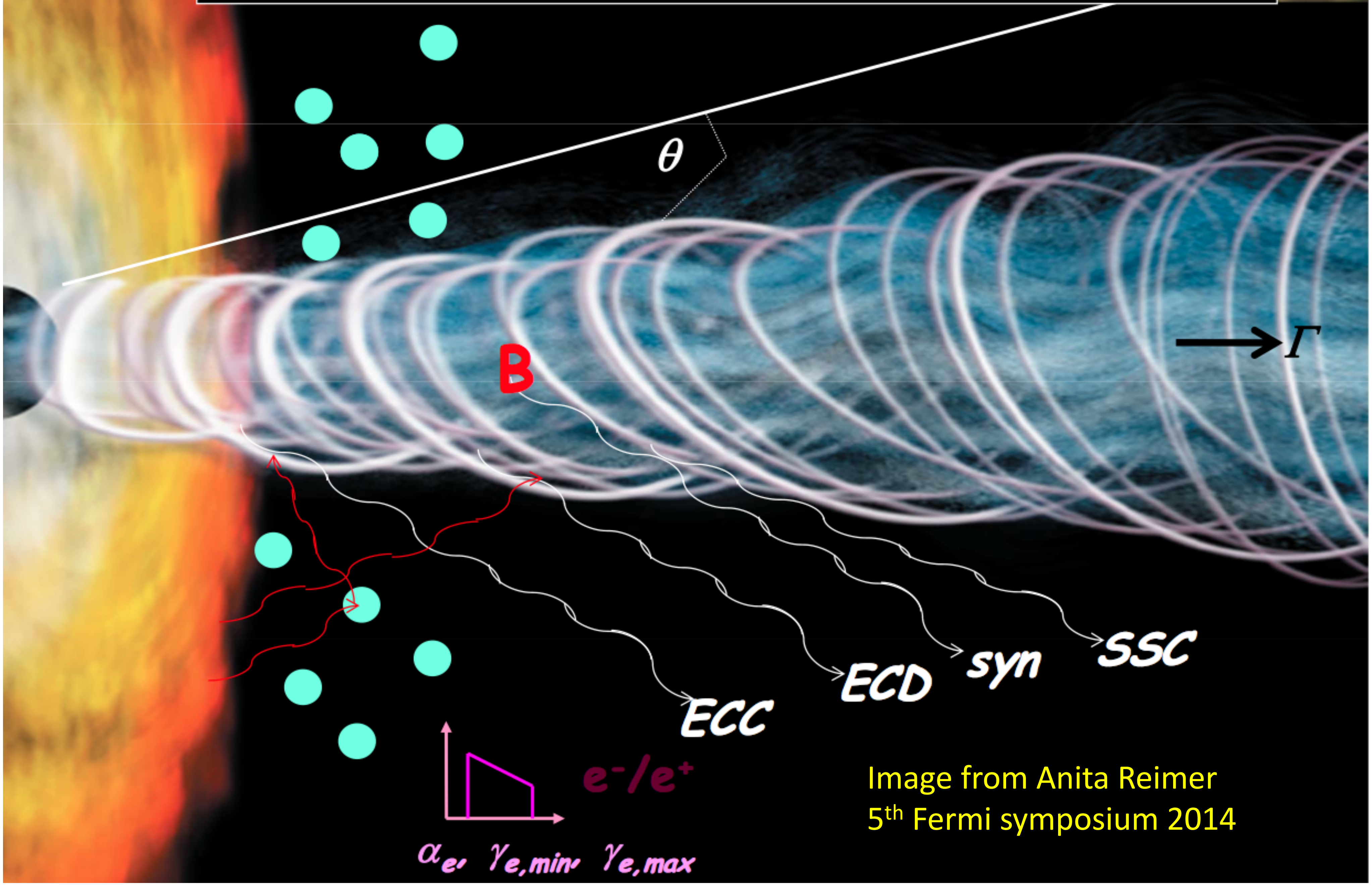
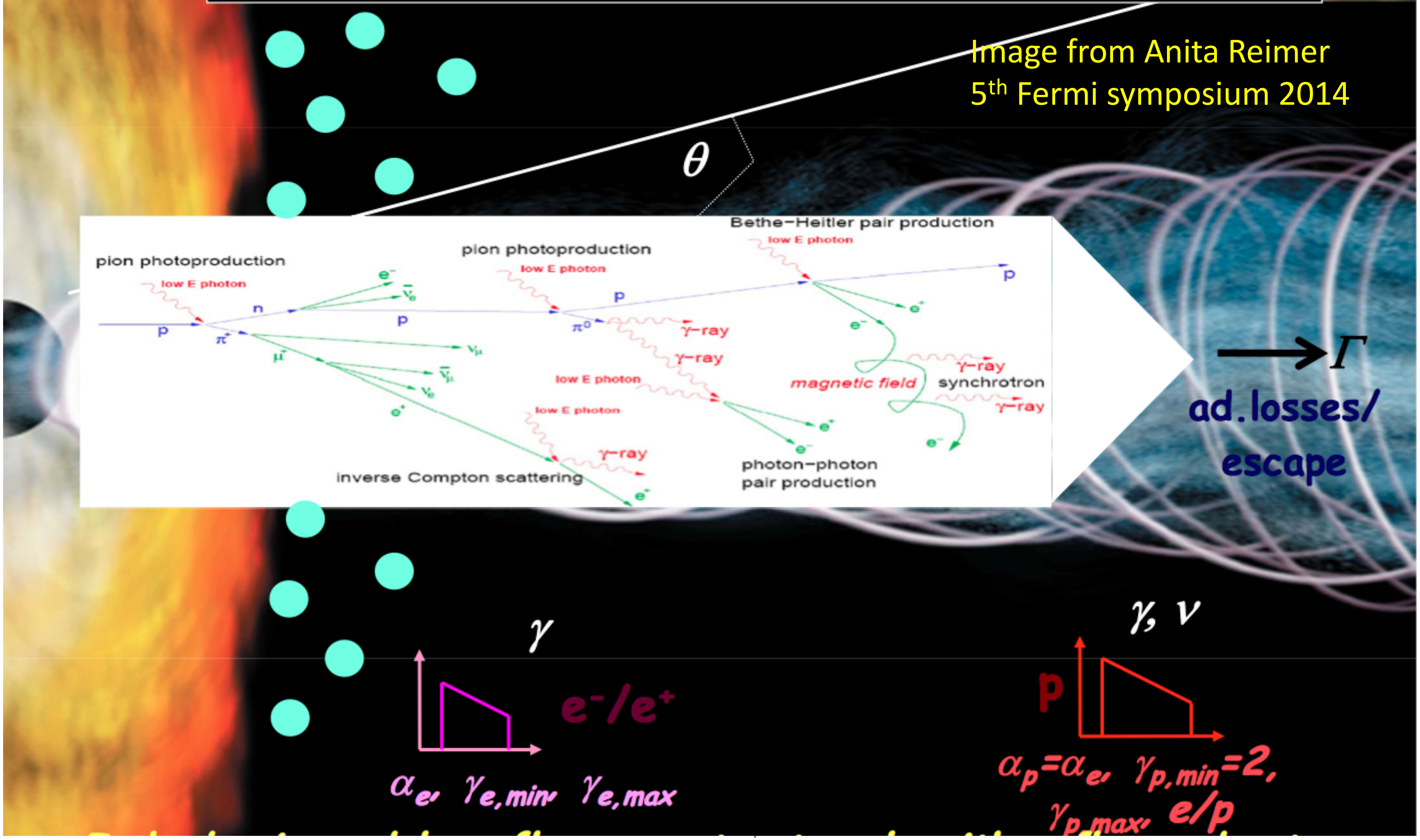
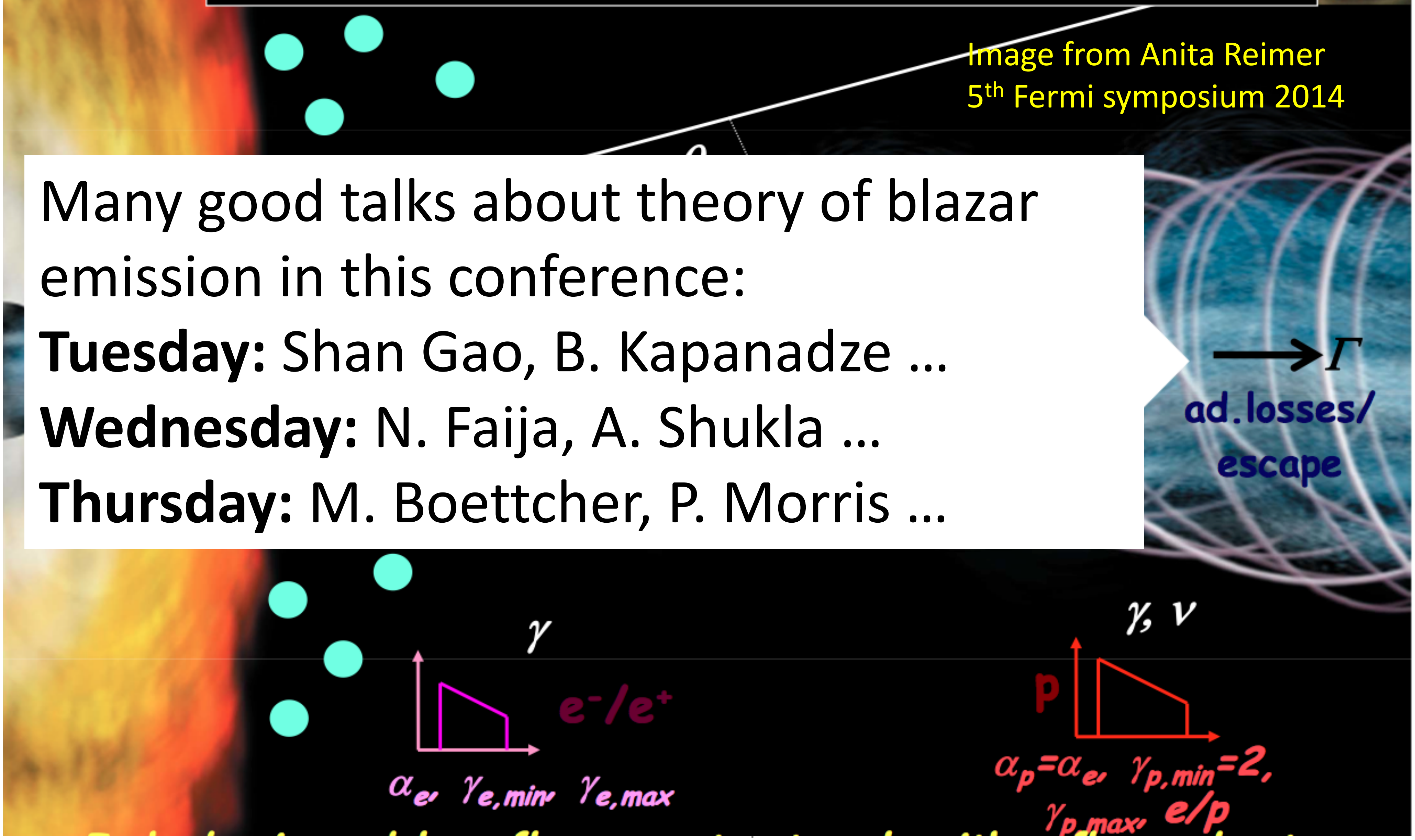


Image from Anita Reimer
5th Fermi symposium 2014

Non-thermal Emission Processes in AGN Jets: Leptons & Hadrons



Non-thermal Emission Processes in AGN Jets: Leptons & Hadrons



Many good talks about theory of blazar emission in this conference:

Tuesday: Shan Gao, B. Kapanadze …

Wednesday: N. Faija, A. Shukla …

Thursday: M. Boettcher, P. Morris …

Large inter-model degeneracy for broadband SEDs

Mrk421 SED described with a **Leptonic scenario**

→ need electrons with E>10^{13} eV

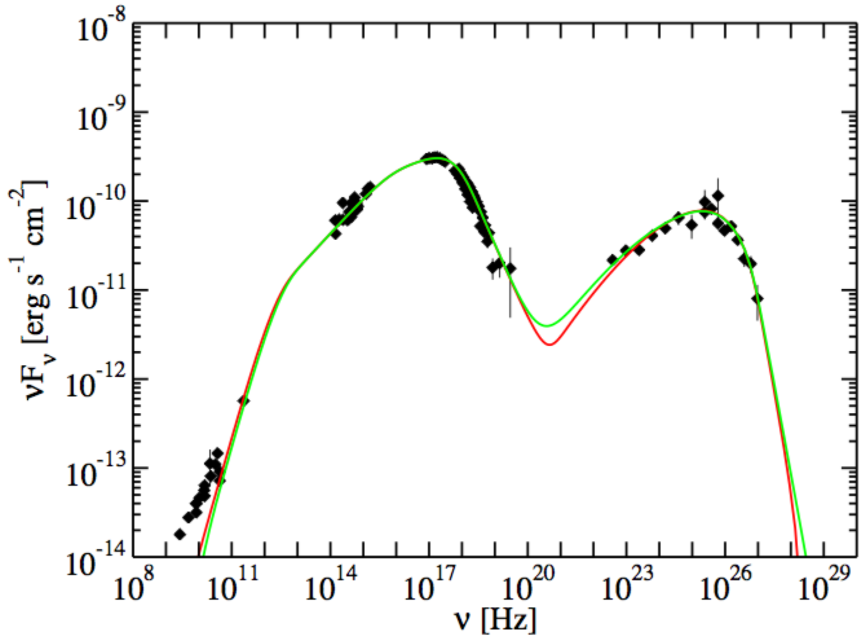


Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{var} = 1$ day (red curve) and $t_{var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

Mrk421 SED described with a **Hadronic scenario**

→ need protons with E>10^{18} eV

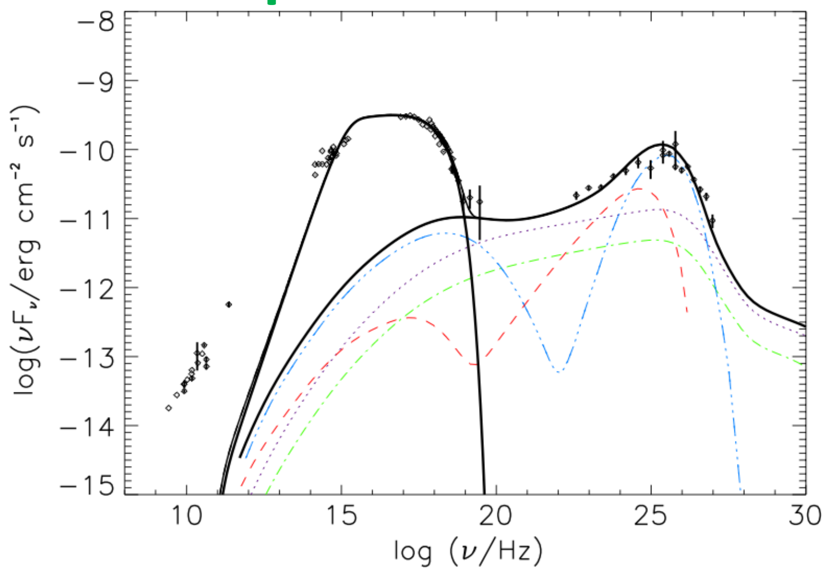


Figure 9. Hadronic model fit components: π^0-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), μ-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which also includes the synchrotron emission of the primary electrons at optical/X-ray frequencies). The resulting model parameters are reported in Table 3.

Abdo et al., ApJ 736 (2011) 131

Multi-band variability is key to distinguish between models

- **Extensive MW campaigns on Mrk421 and Mrk501**

Mrk421 and Mrk501 are excellent "blazar probes"

→ why studying these two blazars ?

- **Bright blazars**
  - → Easy to detect with IACTs, *Fermi*, and X-rays, Optical, radio instruments in short times
    - → "Relatively Easy" to characterize the entire SED in every "shot"
    - → See things that cannot be seen for other blazars (less bright)
      - → Can study the evolution of the entire SED

- **Nearby blazars (z~0.03; ~140 Mpc)**
  - → Imaging with VLBA possible down to scales of <0.01-0.1 pc (<100-1000 r_g)
  - → Minimal effect from EBL (among VHE blazars), which is not well known
    - → systematics for VHE blazar science

- **No strong BLR effects (another unknown… composition, shape…)**
  - → Fewer additional uncertainties than in FSRQs

In summary:

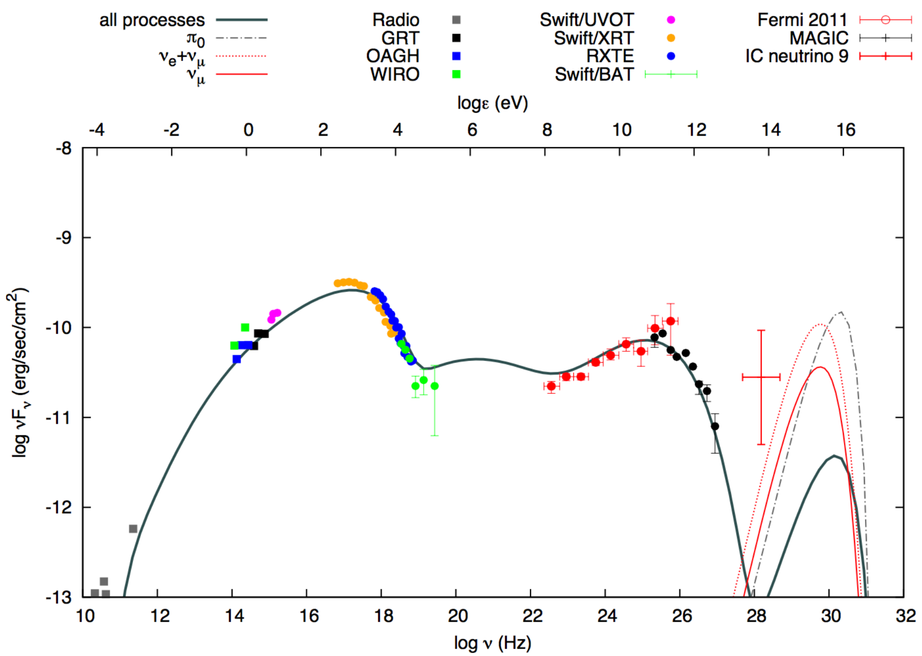
→ **Mrk421 and Mrk501 are among the "easiest" blazars to study**

It is more difficult to study other blazars that are farther away, dimmer, or have more complicated structures

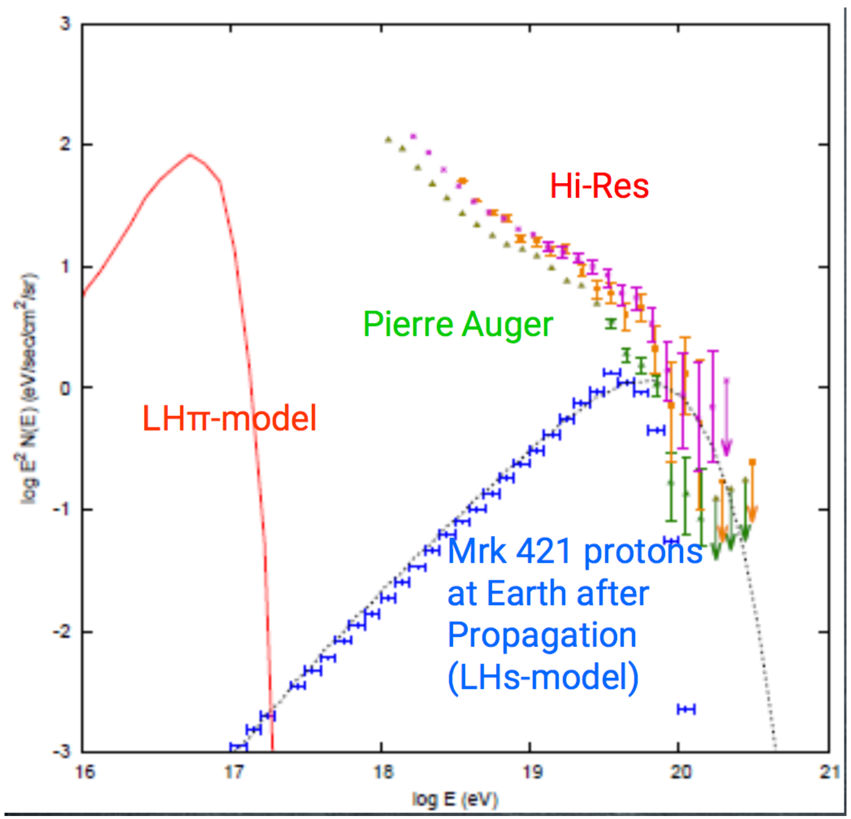
They can be used as high-energy physics laboratories to study blazars

Mrk421 and Mrk501 are excellent “blazar probes”

Possible sources of PeV neutrinos and 30 EeV CR



Petropoulou et al, 2015
MNRAS 448, 2412



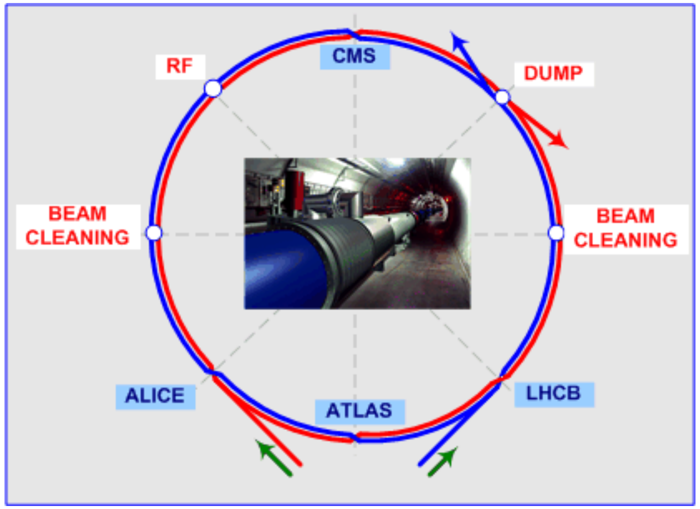
See also Dermer & Razzaque 2010, ApJ 724, 1366

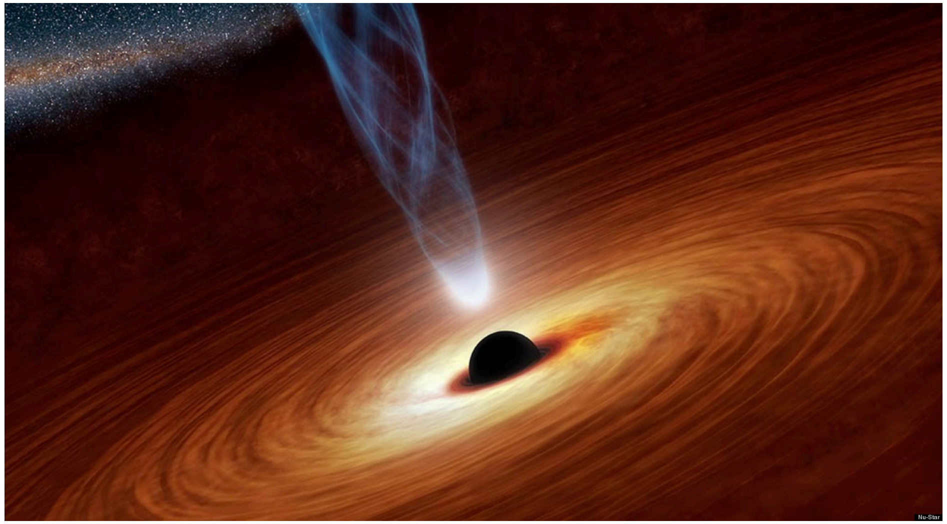
Bright blazars as our Extreme Cosmic Accelerators

LHC **vs** **bright blazar**

ATLAS/CMS
LHCb + Alice

MAGIC/VERITAS/HESS/Fermi
NuSTAR/Swift + Optical + radio





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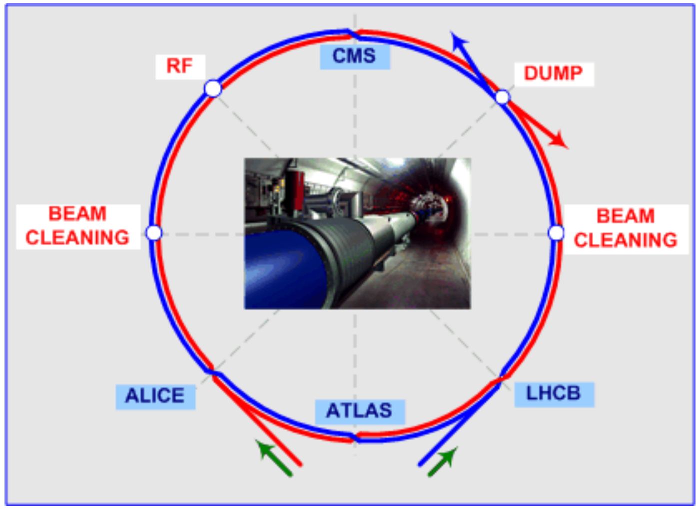
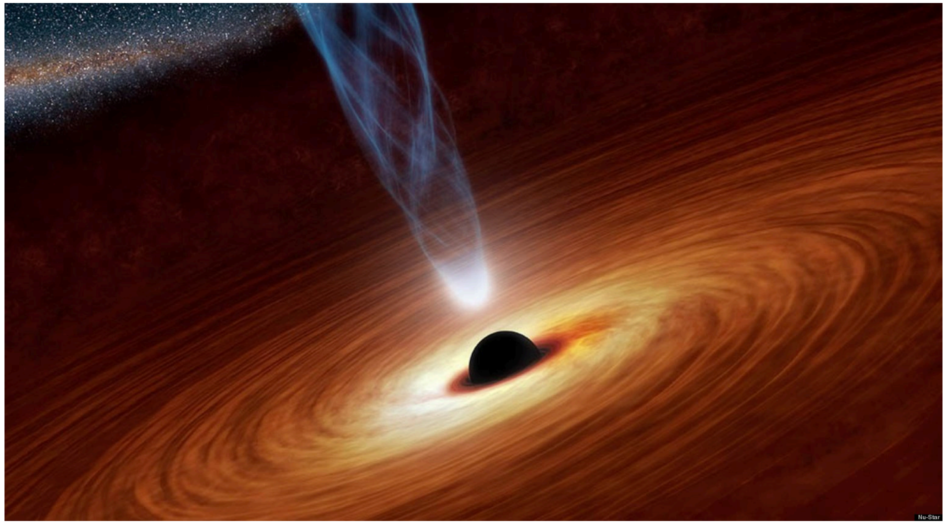




Physics studies with cosmic particle accelerators

Disadvantage: Cannot play with knobs in controlled environment

Advantage: Study extreme processes and environments

Much cheaper (*no need to build the accelerator…)*

The project requires "observing" over many years in order to integrate over sufficient data/effects → **long-term multi-instrument observations.**

Extensive MW Campaigns on Mrk421 and Mrk501

A multi-instrument and multi-year project

Since 2009, we have substantially **improved TEMPORAL and ENERGY coverage** of the sources in order to obtain SEDs as simultaneous as possible, as well as to be able to perform multi-frequency variability/correlation studies over a long baseline and correlate with high resolution radio images and polarizations (to learn about the jet structure)

•More than 25 instruments participate, covering frequencies from radio to VHE

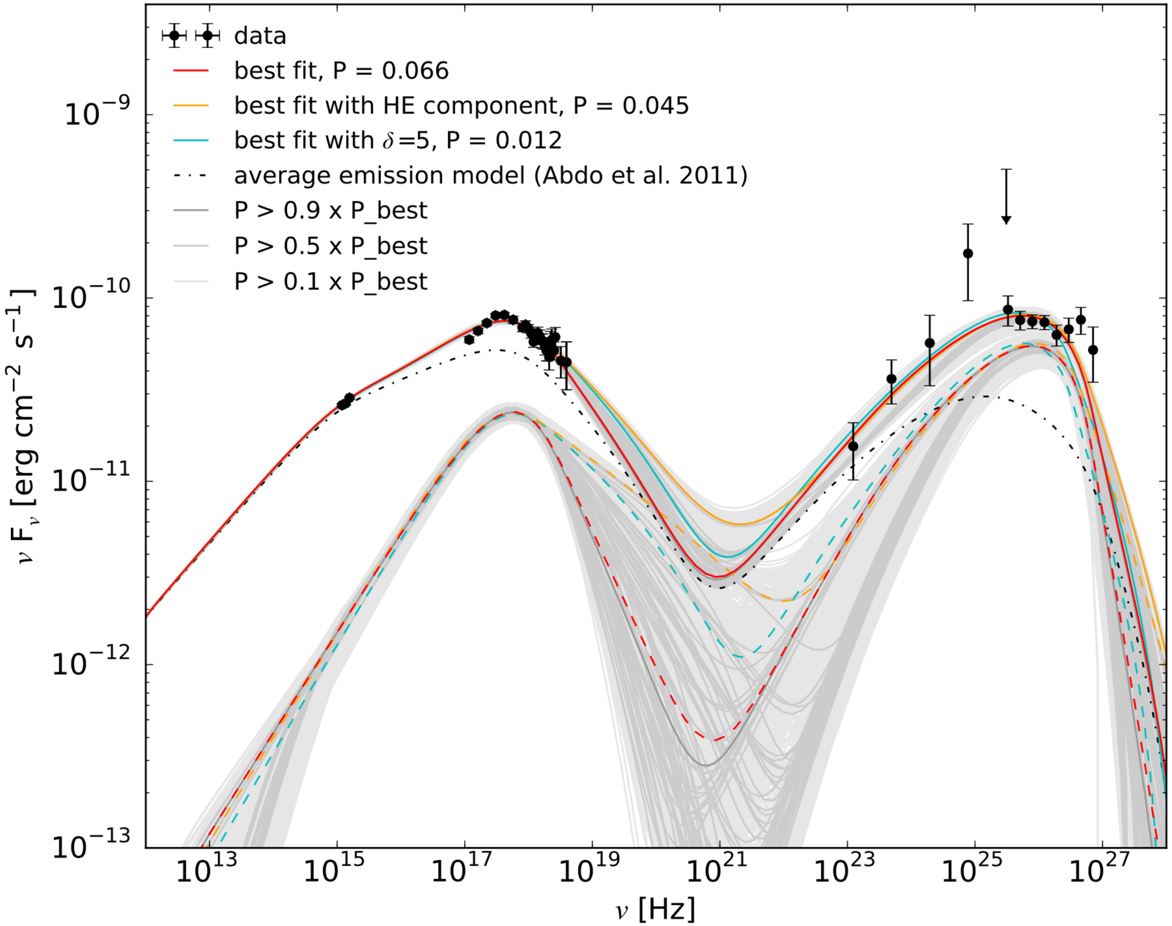
Radio: VLBA, OVRO, Effelsberg, Metsahovi…
mm: SMA, IRAM-PV
Infrared: WIRO, OAGH
Optical: GASP-WEBT, KVA, Liverpool, Kanata…
UV: Swift-UVOT
X-ray: (RXTE), Swift-XRT, NuSTAR
Gamma-ray: *Fermi*-LAT
VHE: MAGIC, VERITAS, FACT

Monitored regardless of activity (*increase coverage during flares*)
→ observed every few days for about half year (*every year* !)

- **Some highlight results from the campaigns**

Broadband SED of Mrk 501 shows large degeneracy in model parameter values

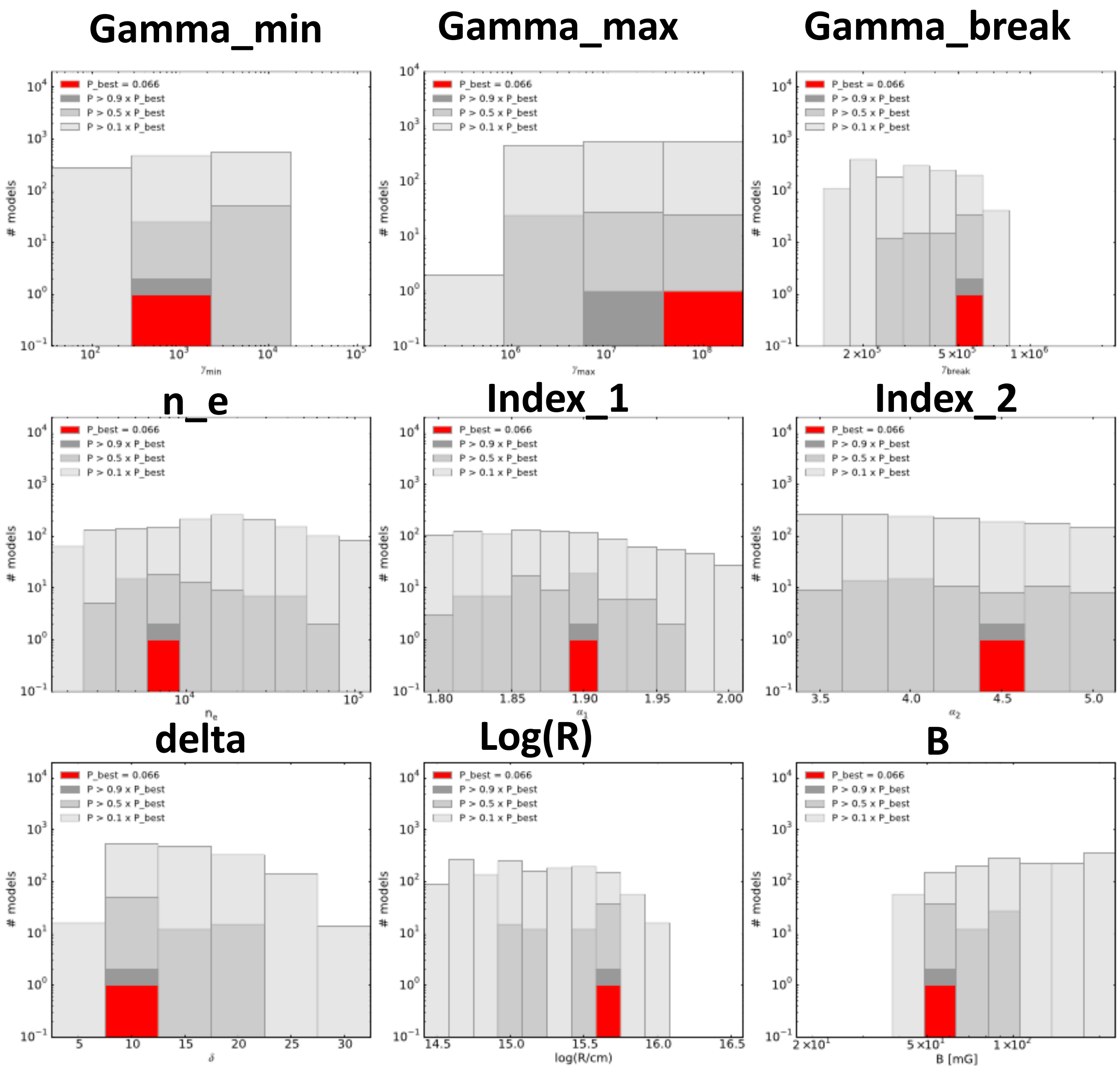
Broadband emission (*solid lines*) from a first quiescent region (*black dot-dashed line*) responsible for the average state reported in Abdo et al. 2011 (*ApJ 727, 129*), plus a **second emission region (*dashed lines*) modelled with grid-scan strategy using 10^8 realizations.**



Ahnen et al 2017
***A&A* 603 , A31**

The SED plot shows in different shades of grey all model curves (1684) with a data-model agreement better than 10% of that of the best model.

Broadband SED of Mrk 501 shows large degeneracy in model parameter values



Ahnen et al 2017
A&A 603 , A31

→ **Modeling results can only be indicative.**

→ Need larger energy coverage (~*MeV*) and better accuracy to constrain models better

Broadband SEDs for weak sources (i.e. large error bars) or obtained with limited energy coverage would lead to a much **larger degeneracy in the model parameters**

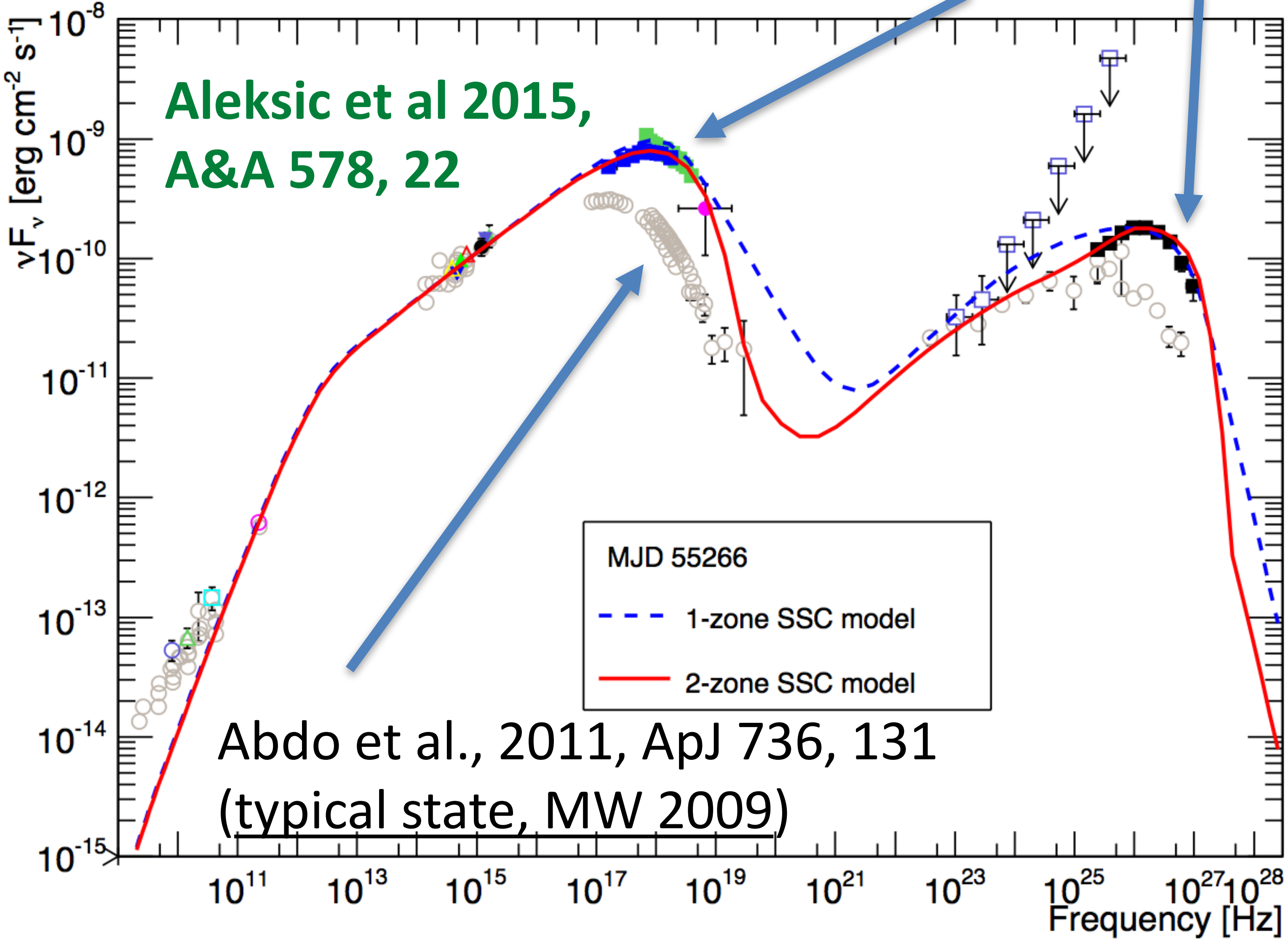
Mrk421 has shown X-ray and VHE spectral variability during flares

X-ray and VHE spectra becomes harder when flaring

→ peaks shift to high energies

→ highest variability at X-ray and VHE

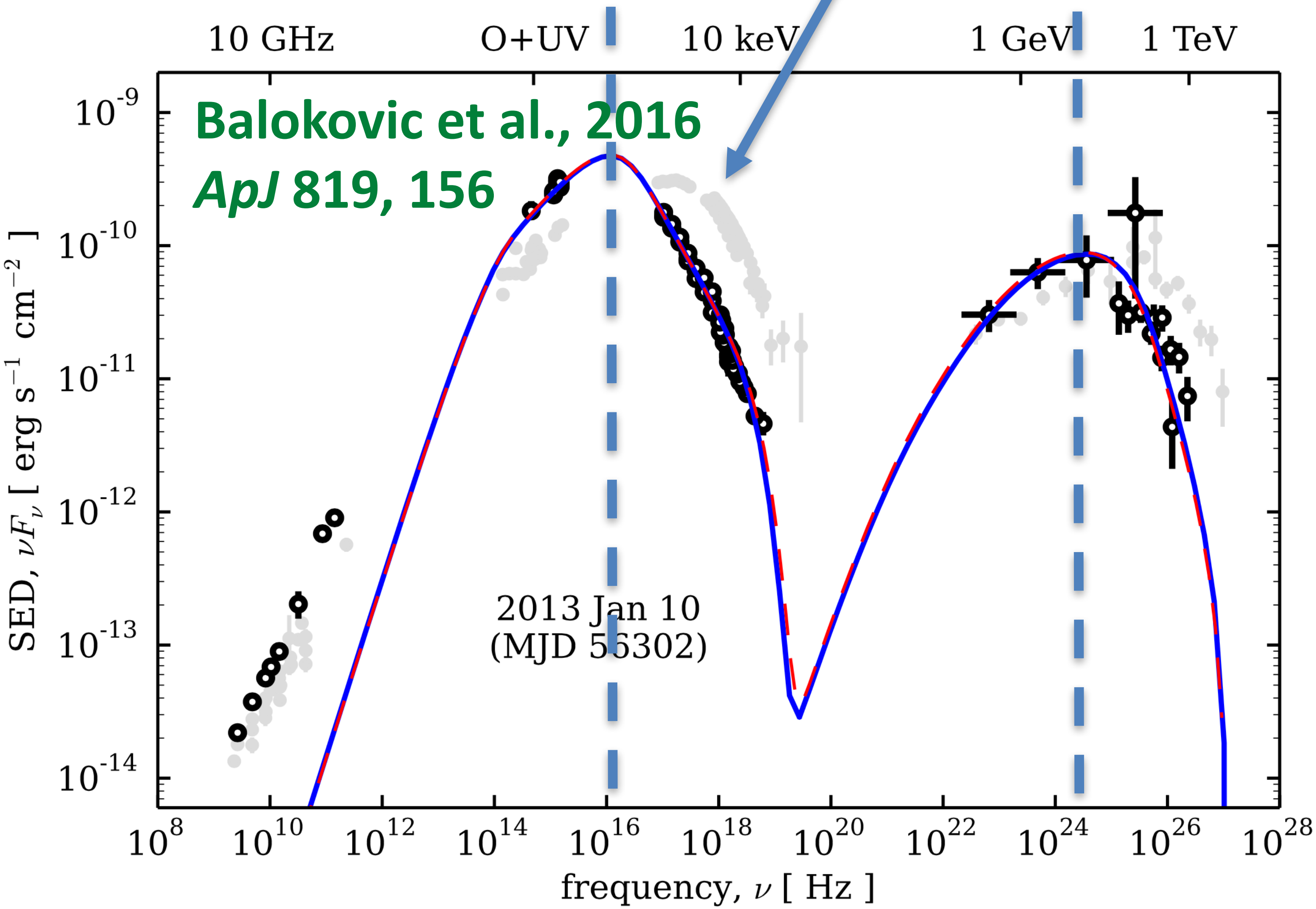
Flare from MW 2010



Mrk421 suffers a personality crisis (in 2013)

Peak position at ~10^{16} Hz (~40 eV)
Factor 10 lower than typical
→ *"HBL moving towards IBL"*

-Abdo et al., 2011, ApJ 736, 131
(typical state)



Low activity softened the X-ray and VHE spectra, but did not bring spectral cutoffs.
→ Electrons accelerated to highest energies

Mrk421 suffers a personality crisis (in 2013)

Peak position at ~10^{16} Hz (~40 eV)
Factor 10 lower than typical
→ *"HBL moving towards IBL"*

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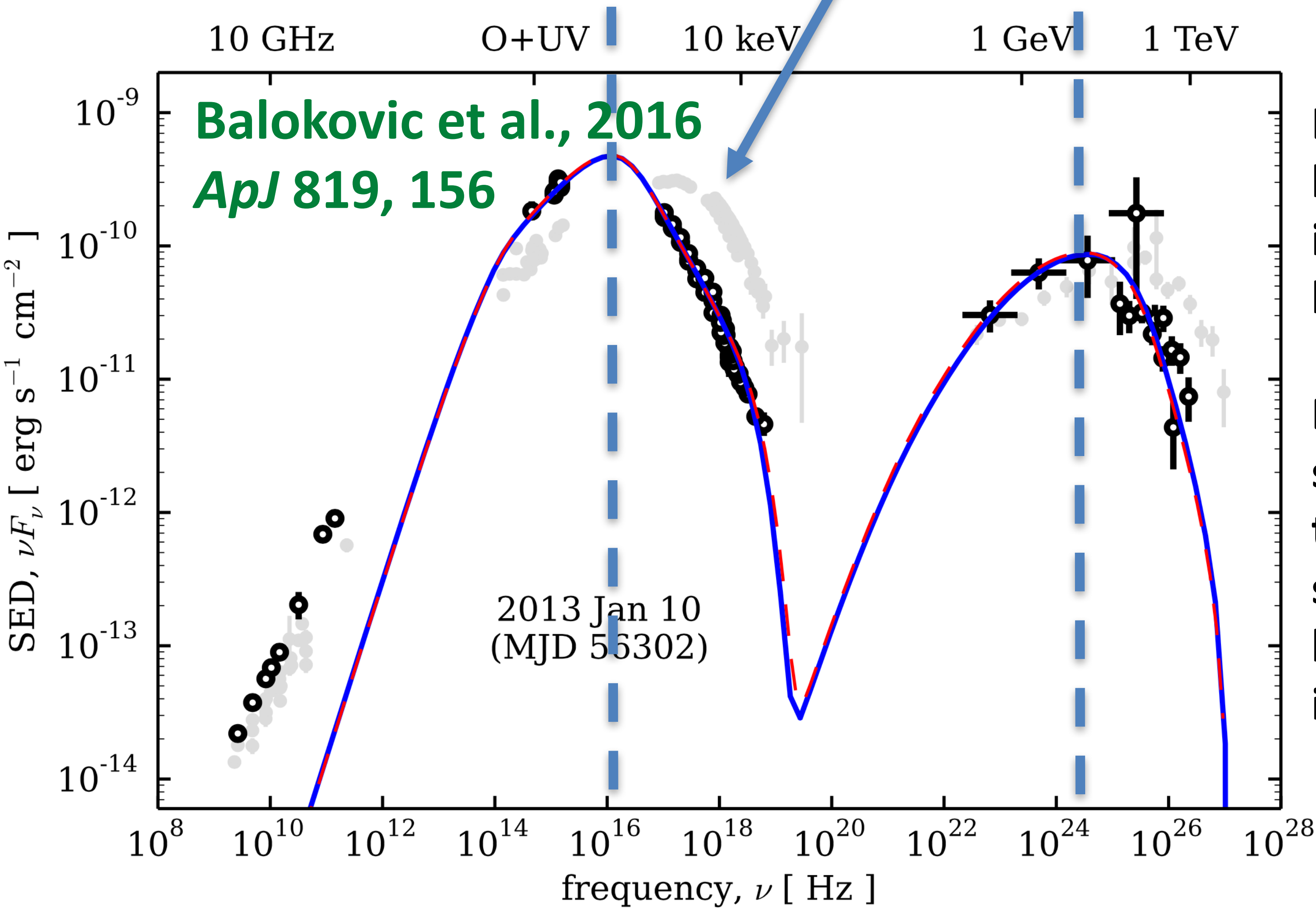


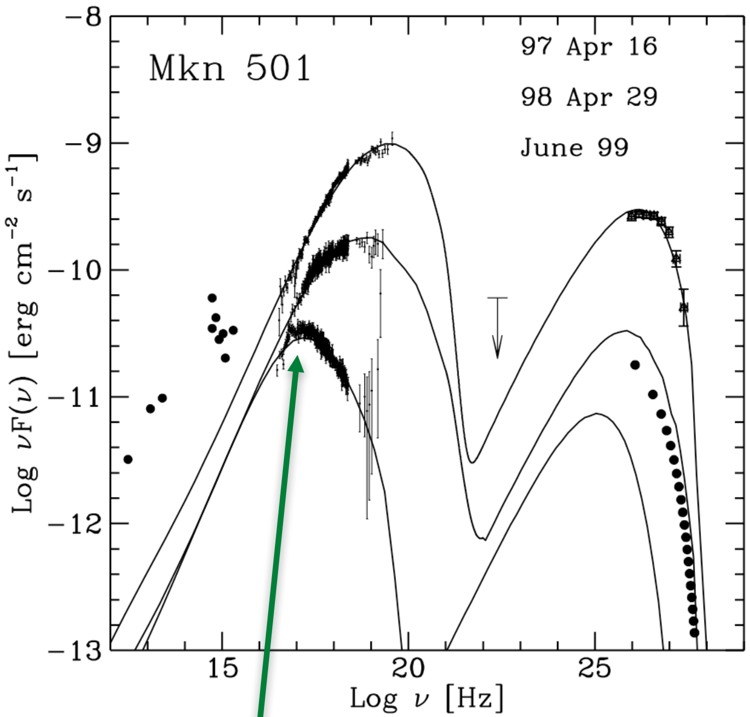
Low activity in blazars is as interesting as the high activity (flares)

But can only be studied in detail on the brightest sources and with highly sensitive instruments

Mrk501 has shown X-ray and VHE spectral variability during flares

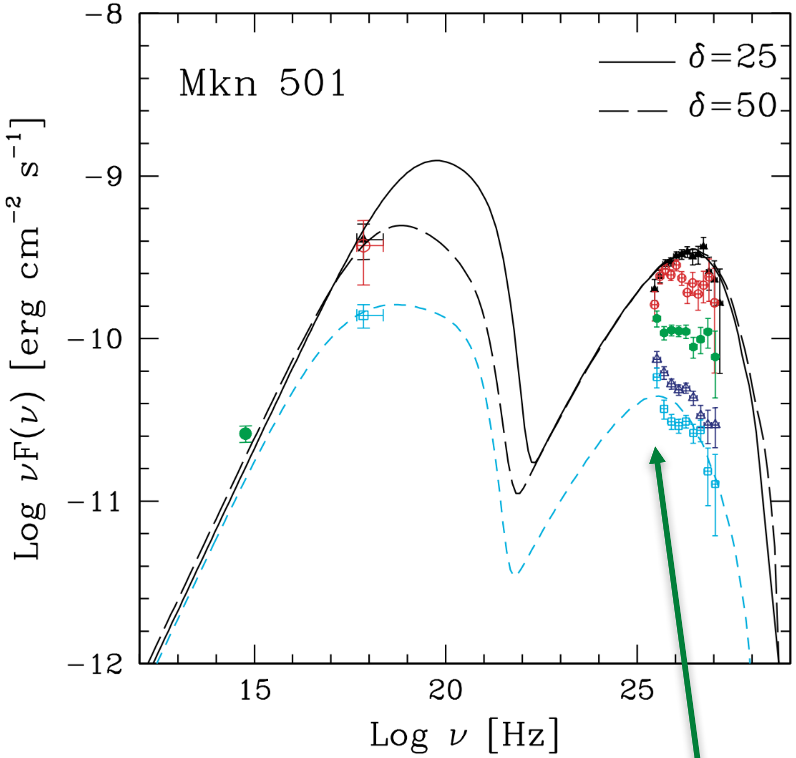
(Historical) flare in 1997

Tavecchio et al., 2001, ApJ 554,725



(fast variability) flare in 2005

Albert et al., 2007, ApJ 669,862



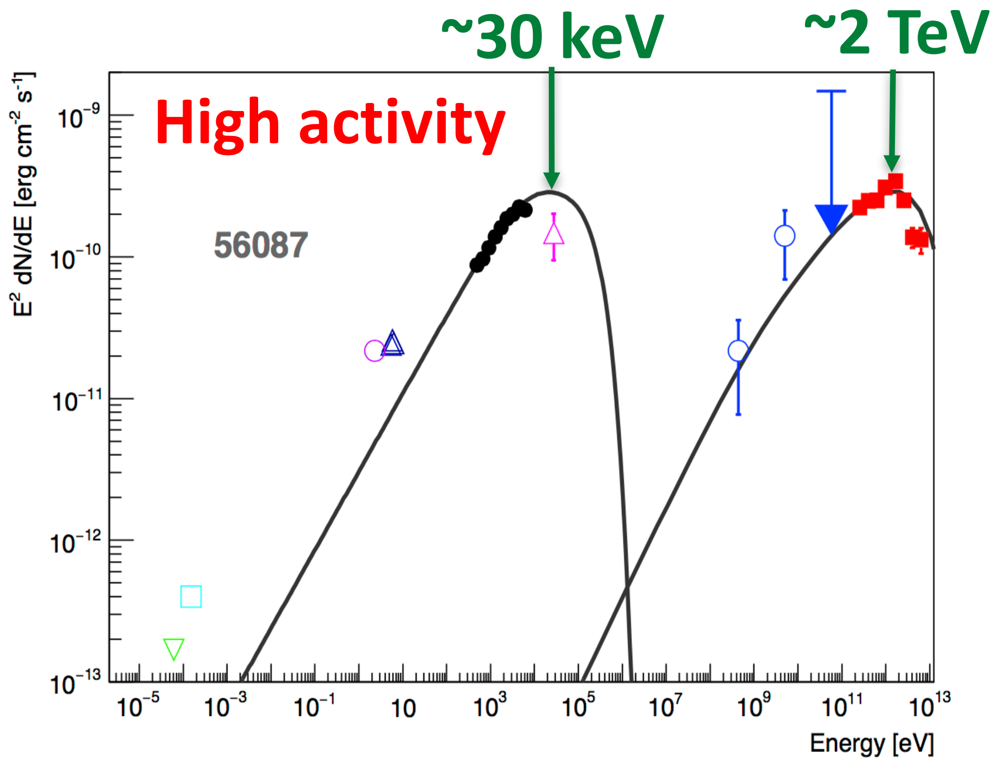
Hard spectra in Mrk501 <u>not observed</u> during low states,

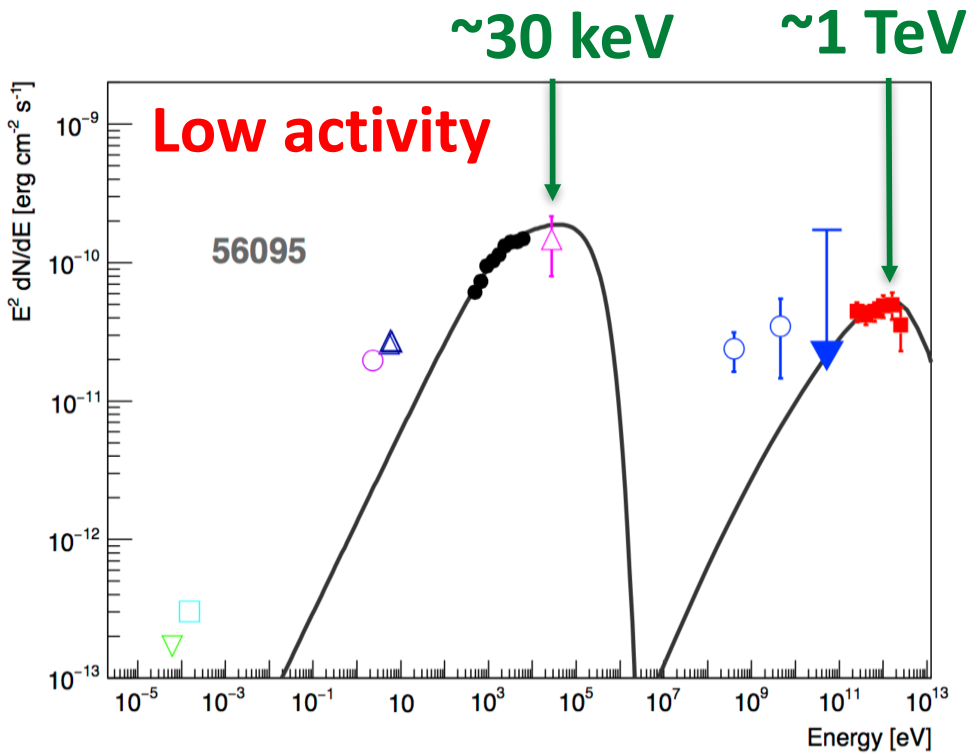
< 1 keV

< 0.1 TeV

Mrk501 suffers a personality crisis (in 2012)

VERY hard spectral index in X-rays and VHE gamma rays, regardless of activity (during MW 2012)





Radio:
OVRO
Metsahovi

X-ray:
Swift/XRT
Swift/BAT

Gamma ray:
Fermi-LAT
MAGIC

Optical/UV:
R-band (WEBT+)
Swift/UVOT

Ahnen et al., Accepted in A&A (*arXiv:1808.04300*)

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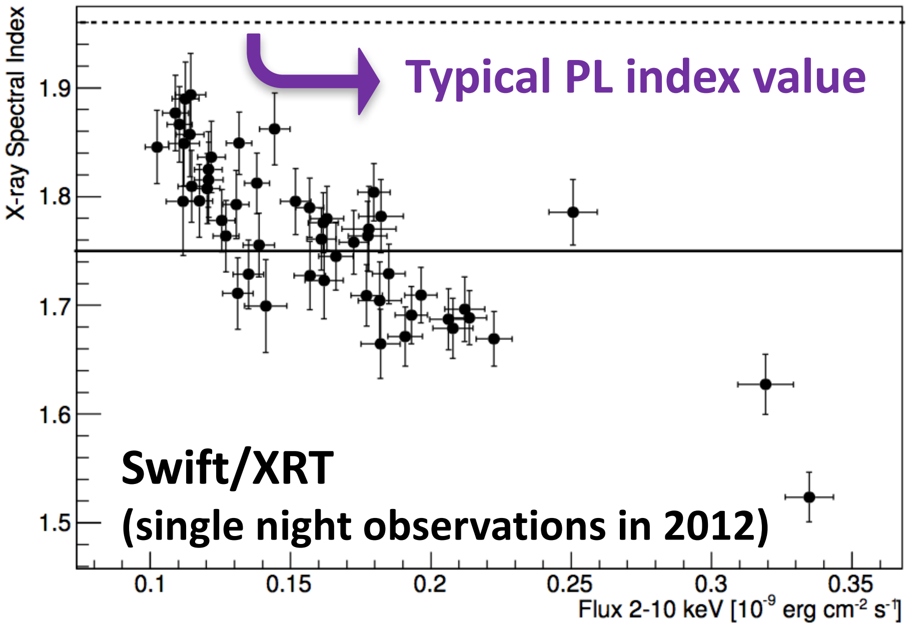
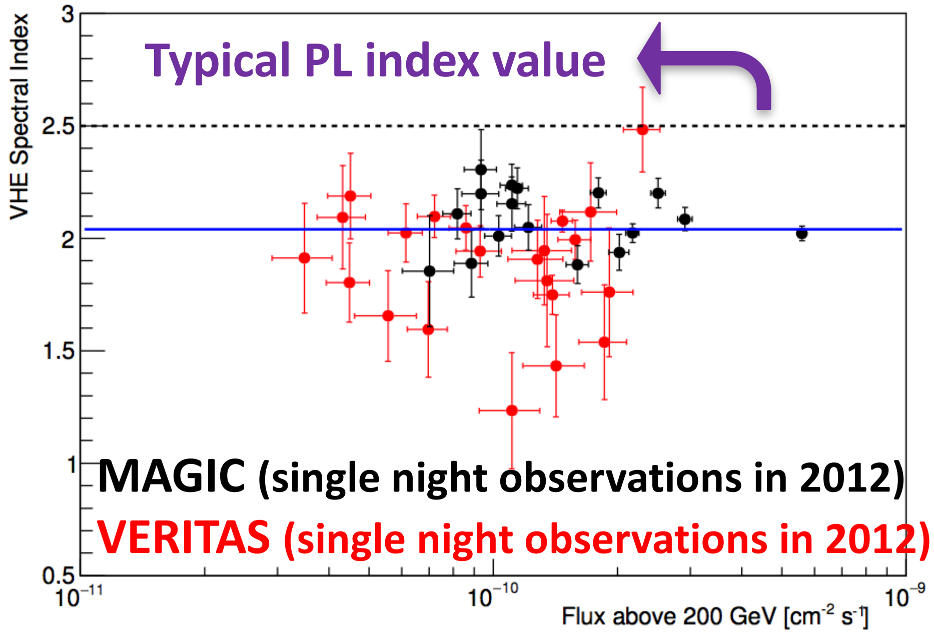




→ **Mrk 501 behaved as Extreme HBL!**

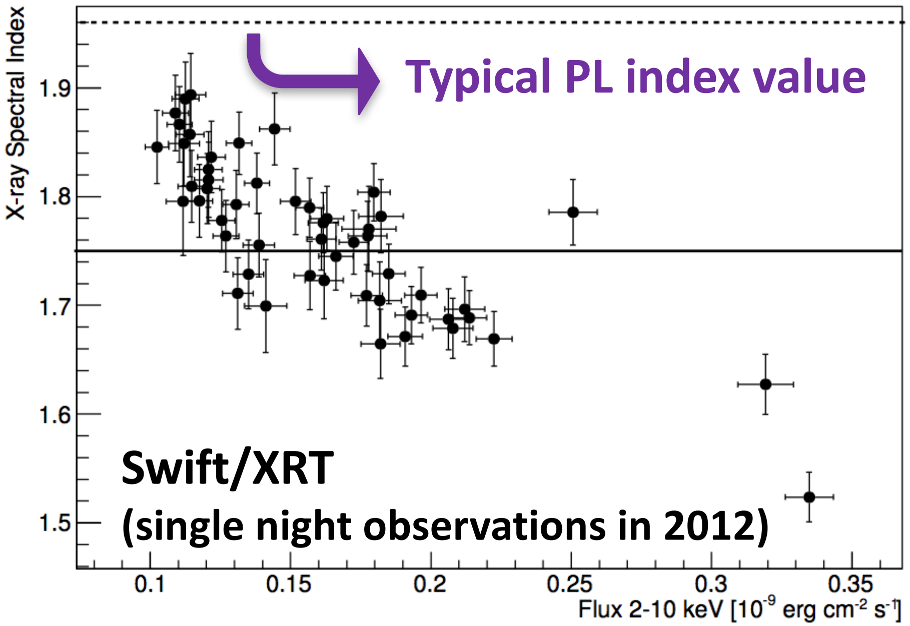
Similar X-ray/VHE spectra as 1ES 0229+200, 1ES 0347-121 (Peaks at ~10 keV and ~1TeV)

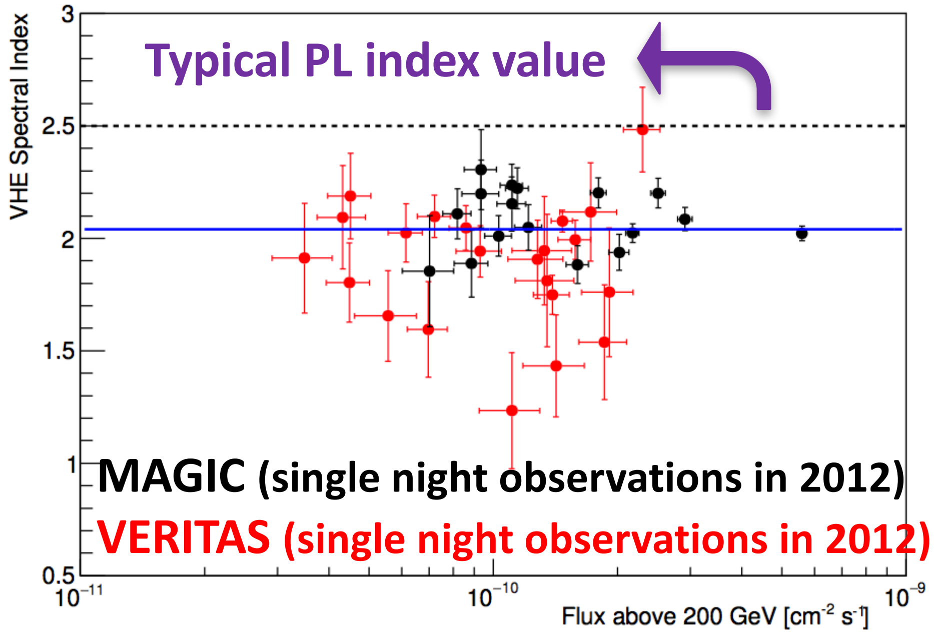
Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic

Mrk501 suffers a personality crisis (in 2012)

VERY hard spectral index in X-rays and VHE gamma rays, regardless of activity (during MW 2012)

Ahnen et al., Accepted in A&A (*arXiv:1808.04300*)





Mrk501_F^{TeV} > ~10 x 1ES0229_F^{TeV}

Similar quality spectra need observations 100 time longer than those needed for Mrk501

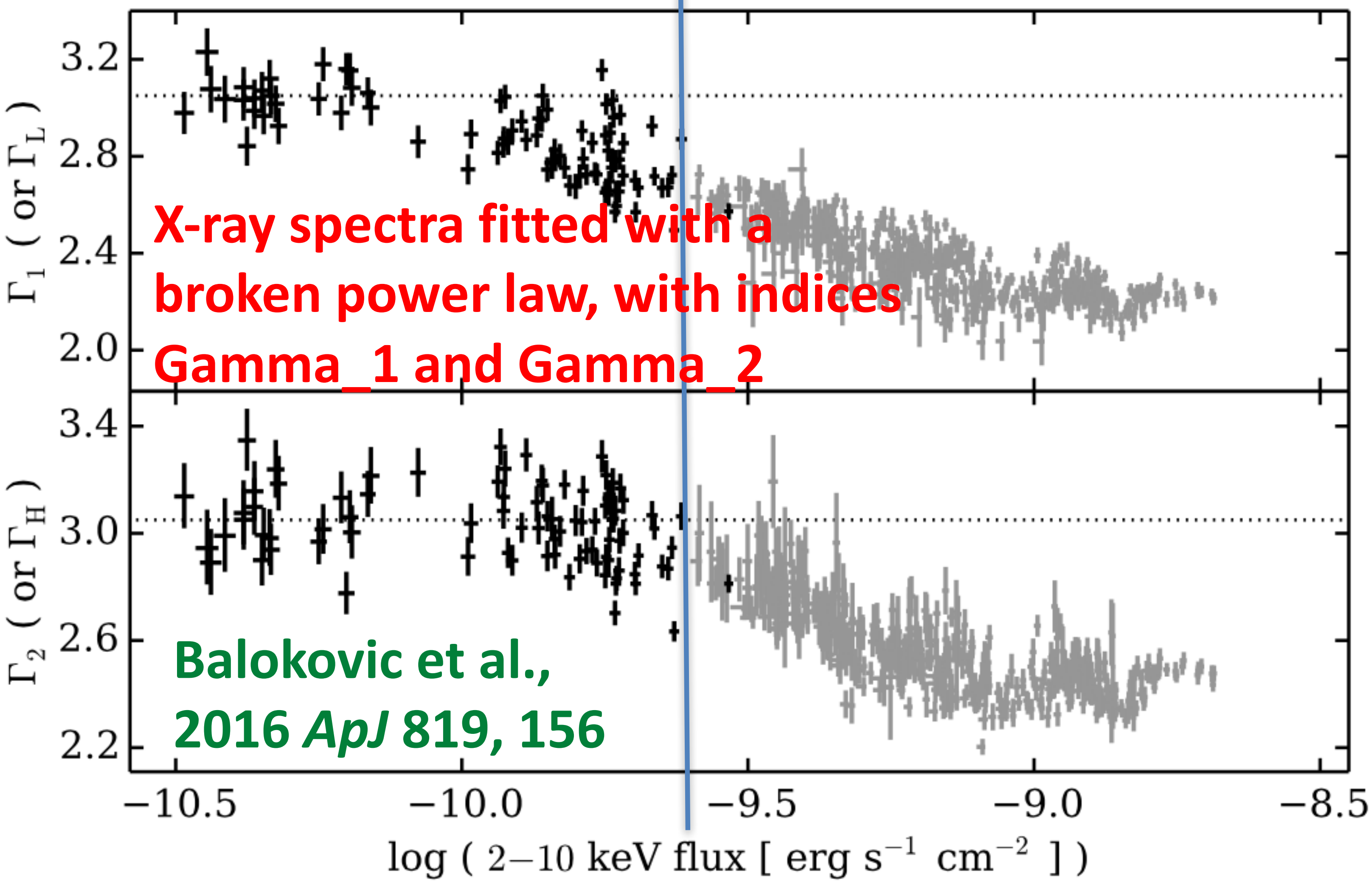
Precision on 1ES 0229 needs CTA !!

Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic

X-ray spectral shape vs. X-ray flux for Mrk421

NuSTAR spectra (2013 campaign)

RXTE-PCA spectra from Giebels et al., 2007, A&A, 462, 29



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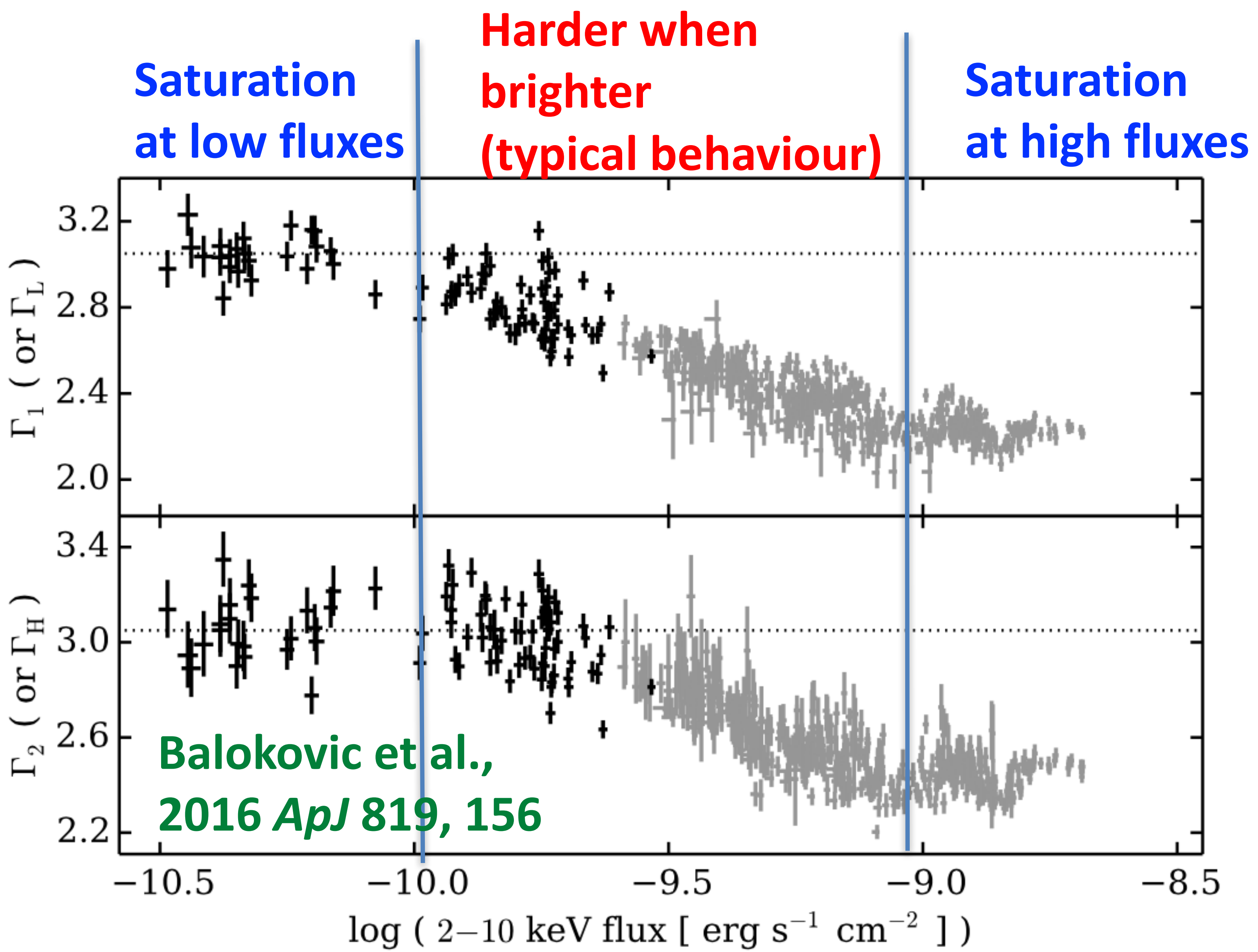
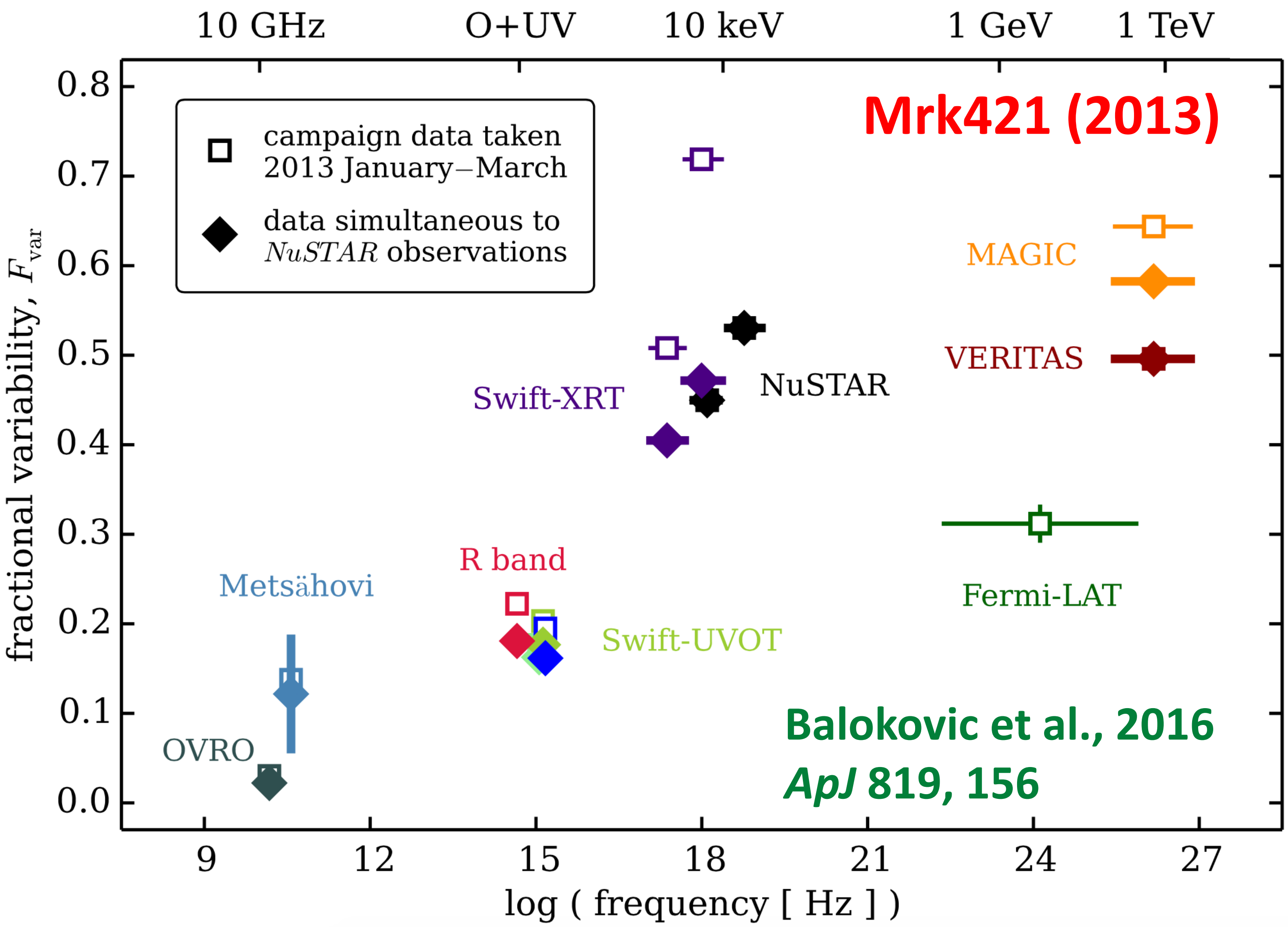


Variability vs. Energy for Mrk421

Variability quantified following prescription from Vaughan et al. 2003

Highest variability occurs at X-ray and VHE

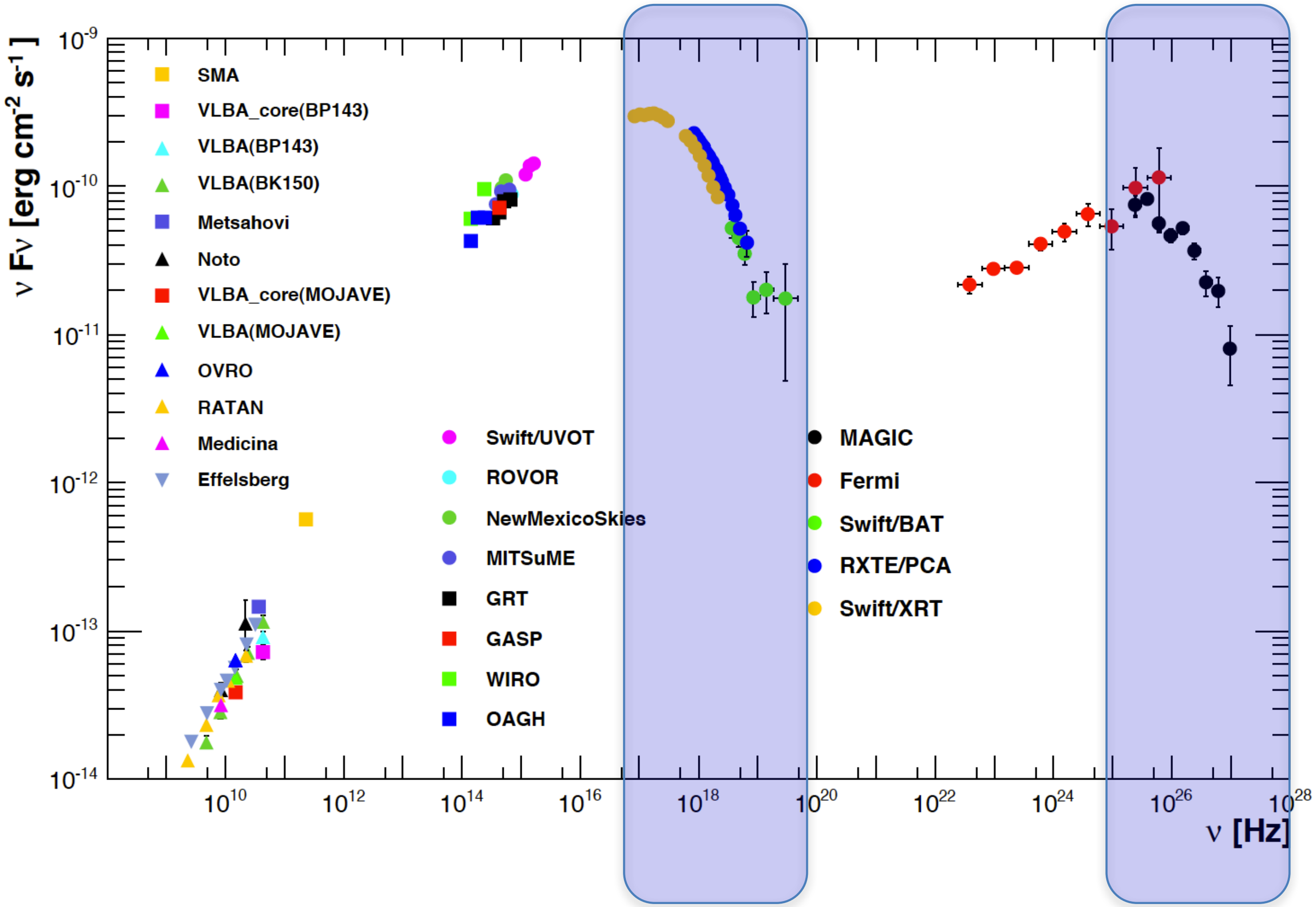
$$F_{var} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$



Double-bump structure (same as SED)

For each bump, variability increases with energy

Variability vs. Energy for Mrk421



Abdo et al., 2011 (ApJ 736, 131)

"Falling segments" of the low- and high-energy bumps in Mrk421 are more variable than the "rising segments" (ALWAYS!!)

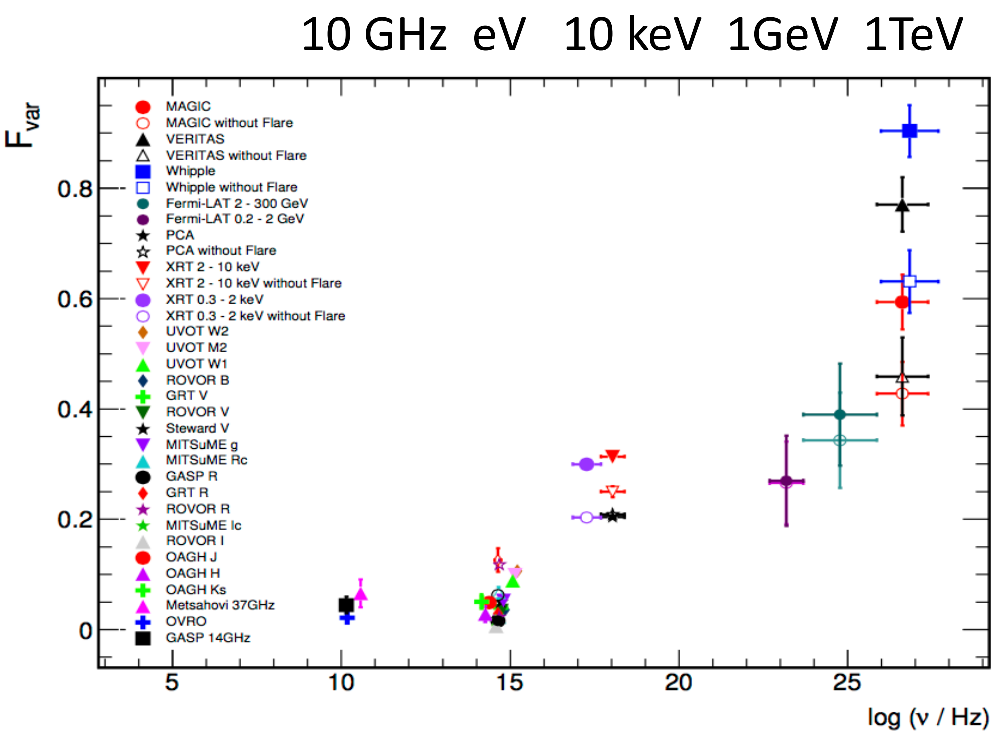
→ *Within the Synchrotron self-Compton scenario, the X-ray and VHE emission is produced by the highest-energy electrons*

Variability vs. Energy for Mrk501

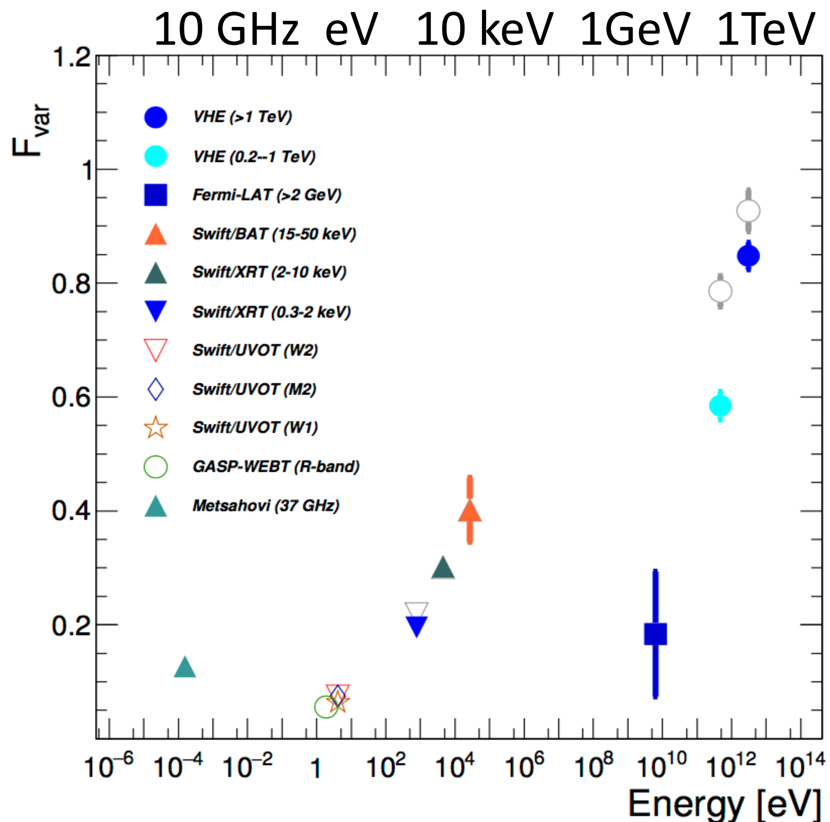
Variability quantified following prescription from Vaughan et al. 2003

Highest variability occurs at VHE

$$F_{var} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$



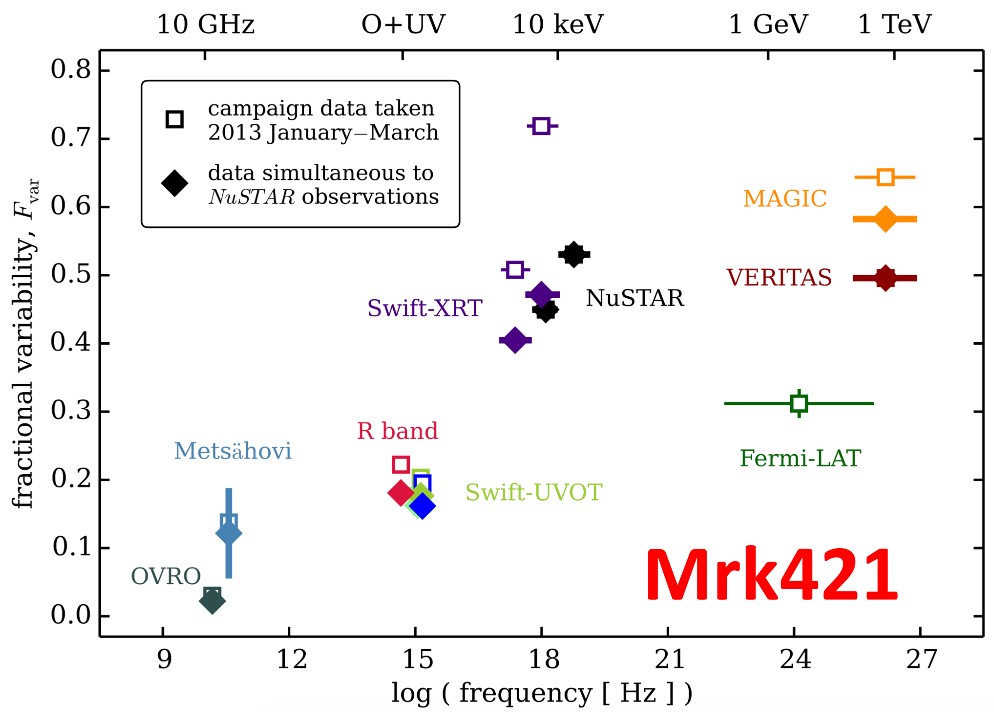
Ahnen et al 2017
***A&A* 603 , A31**



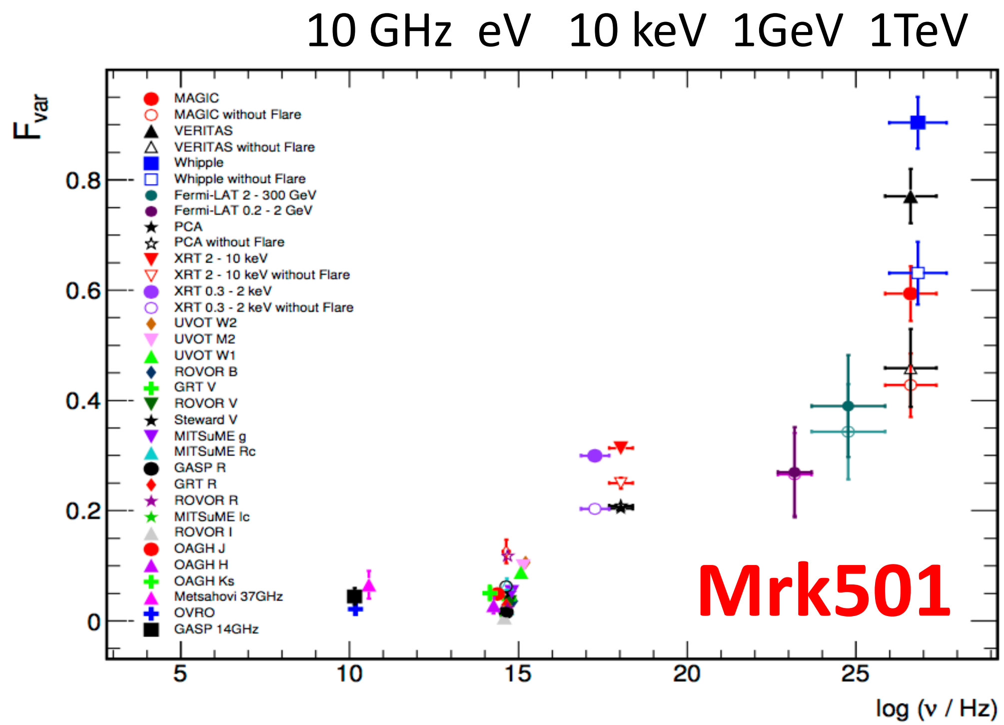
Ahnen et al., Accepted in A&A
(*arXiv:1808.04300*)

Comparison of variability between the two archetypical TeV blazars: Mrk421 vs. Mrk501

Balokovic et al., 2016 *ApJ* 819, 156



Ahnen et al 2017 *A&A* 603 , A31



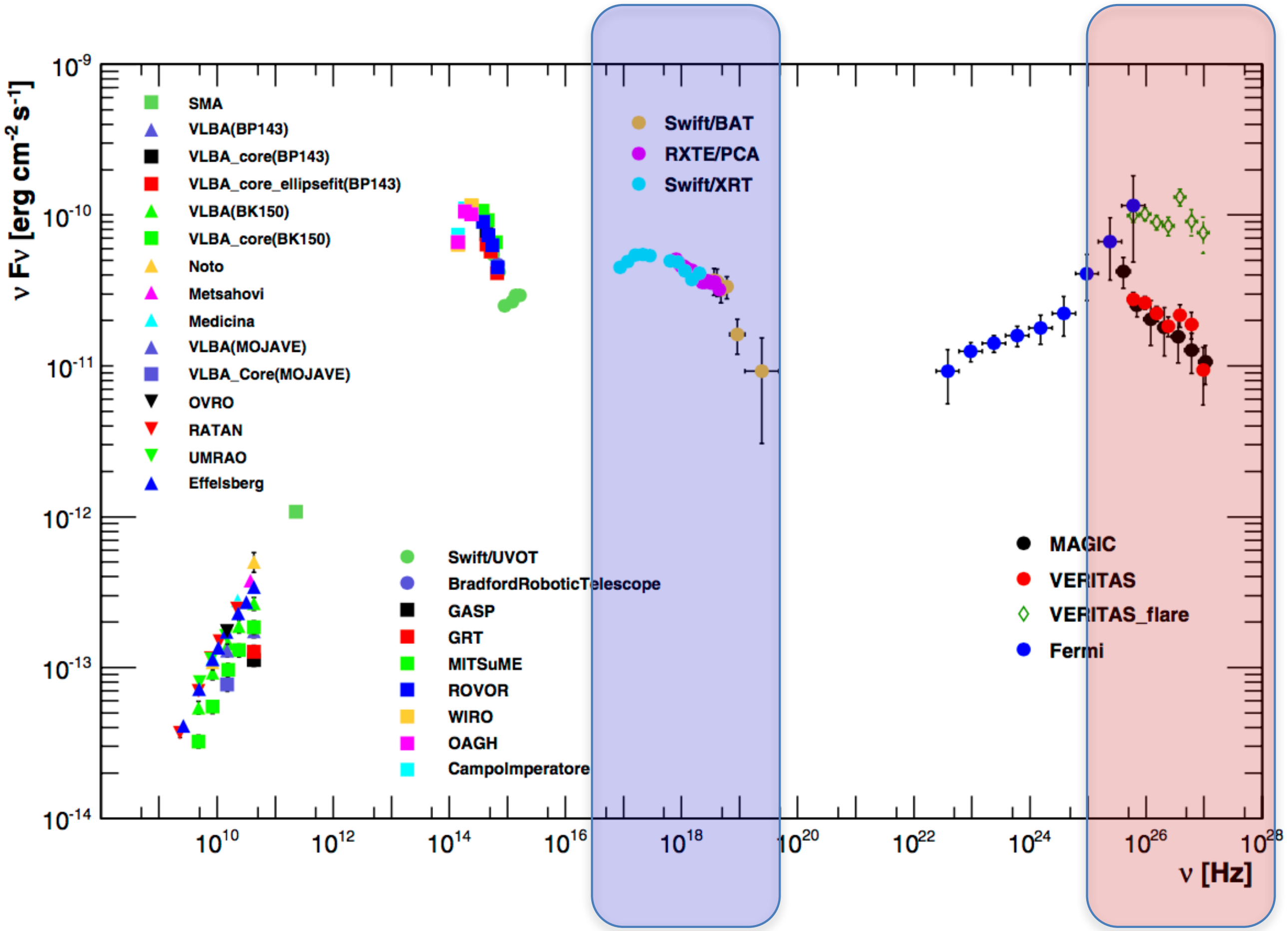
Typically:

Fvar (**Mkr421**): clear double-peaked structure, **Fvar (X-rays) ~ Fvar(VHE)**

Fvar (**Mrk501**): general increase with energy, **Fvar(X-rays) < Fvar(VHE)**

Fundamental difference in variability of these two "sister sources"

Variability vs. Energy for Mrk501



Abdo et al., 2011 (ApJ 727, 129)

"Falling segment" of the high-energy bumps in Mrk501 is more variable than the "falling segment" of low-energy bump (ALWAYS!!)

→ *the X-ray and VHE emission produced by same electrons ?*

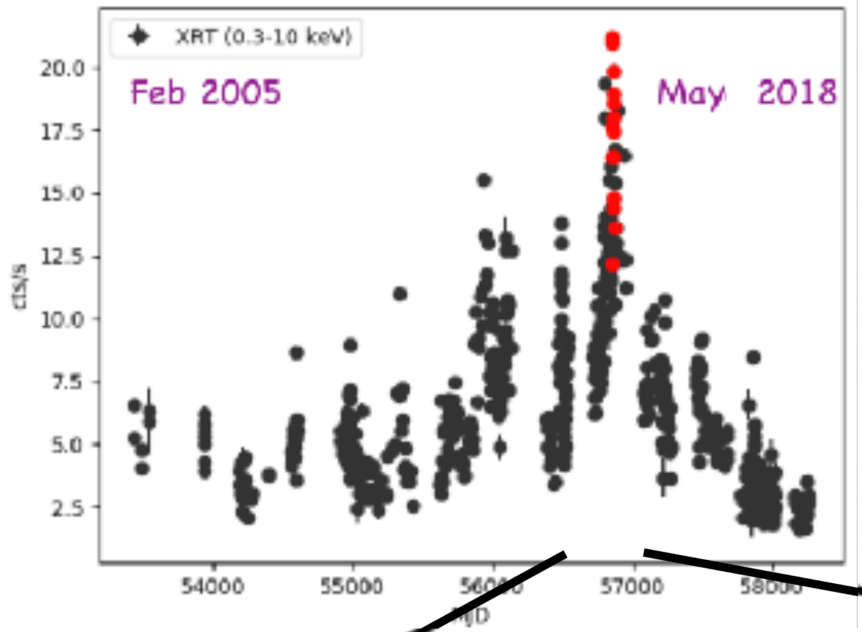
→ *Need external compton ? Or multi-component ?*

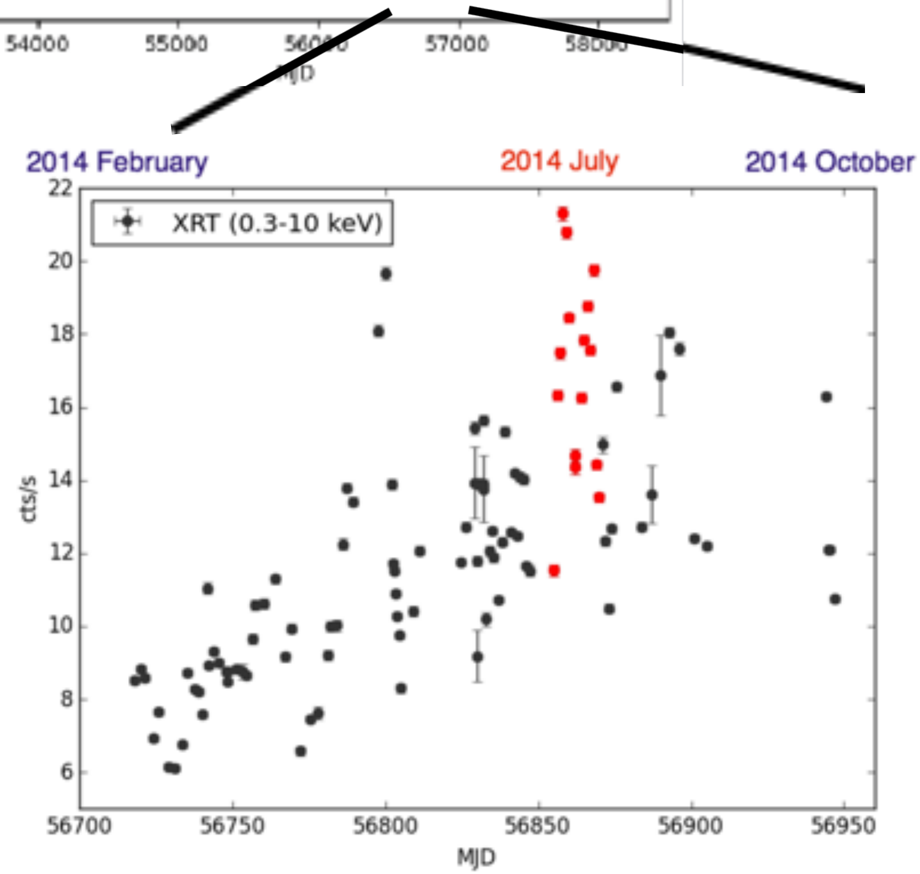
Large flaring activity of Mrk501 in July 2014

Swift-XRT

Historical light curve

in almost **14 years**





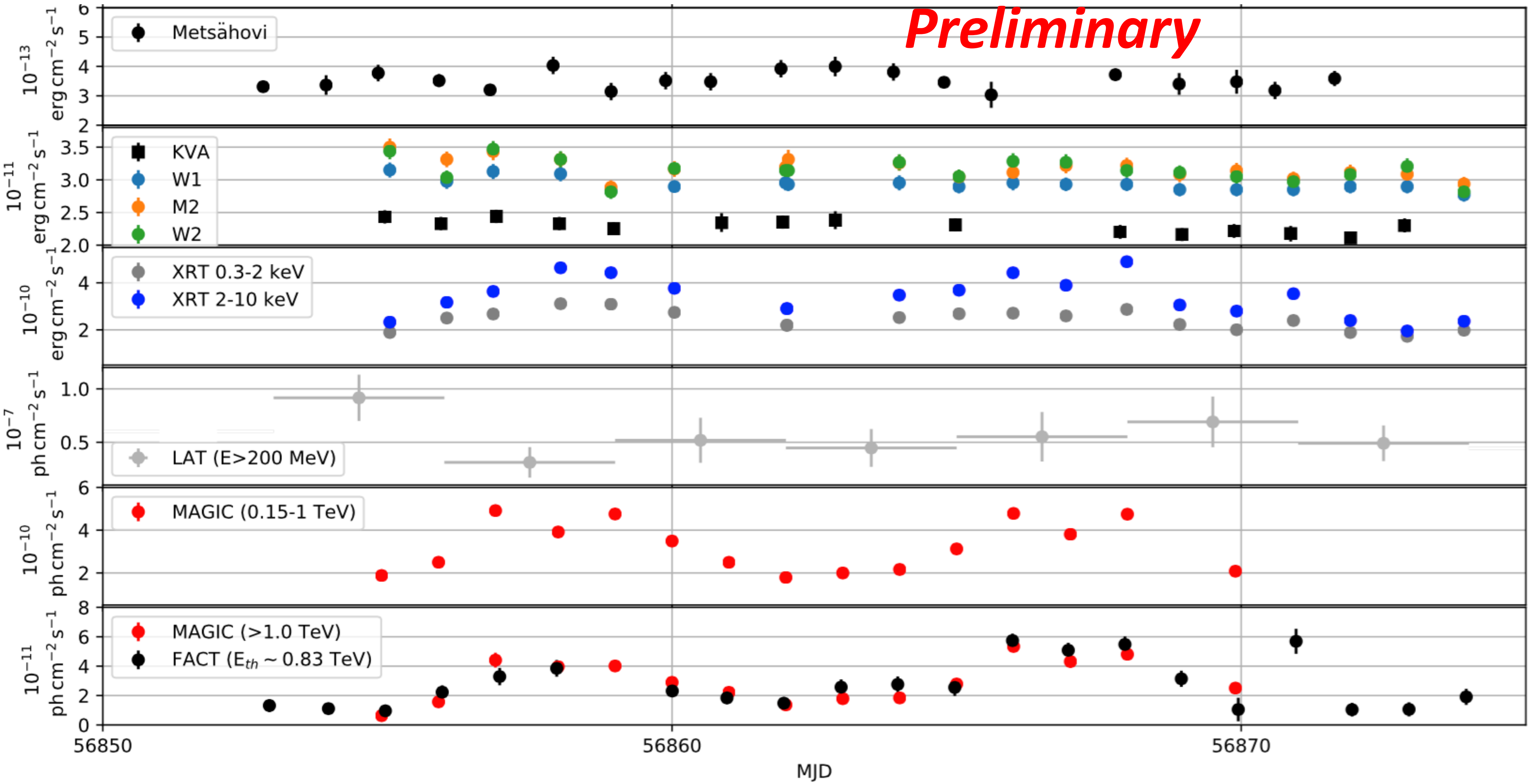
Largest X-ray activity occurred in July 2014

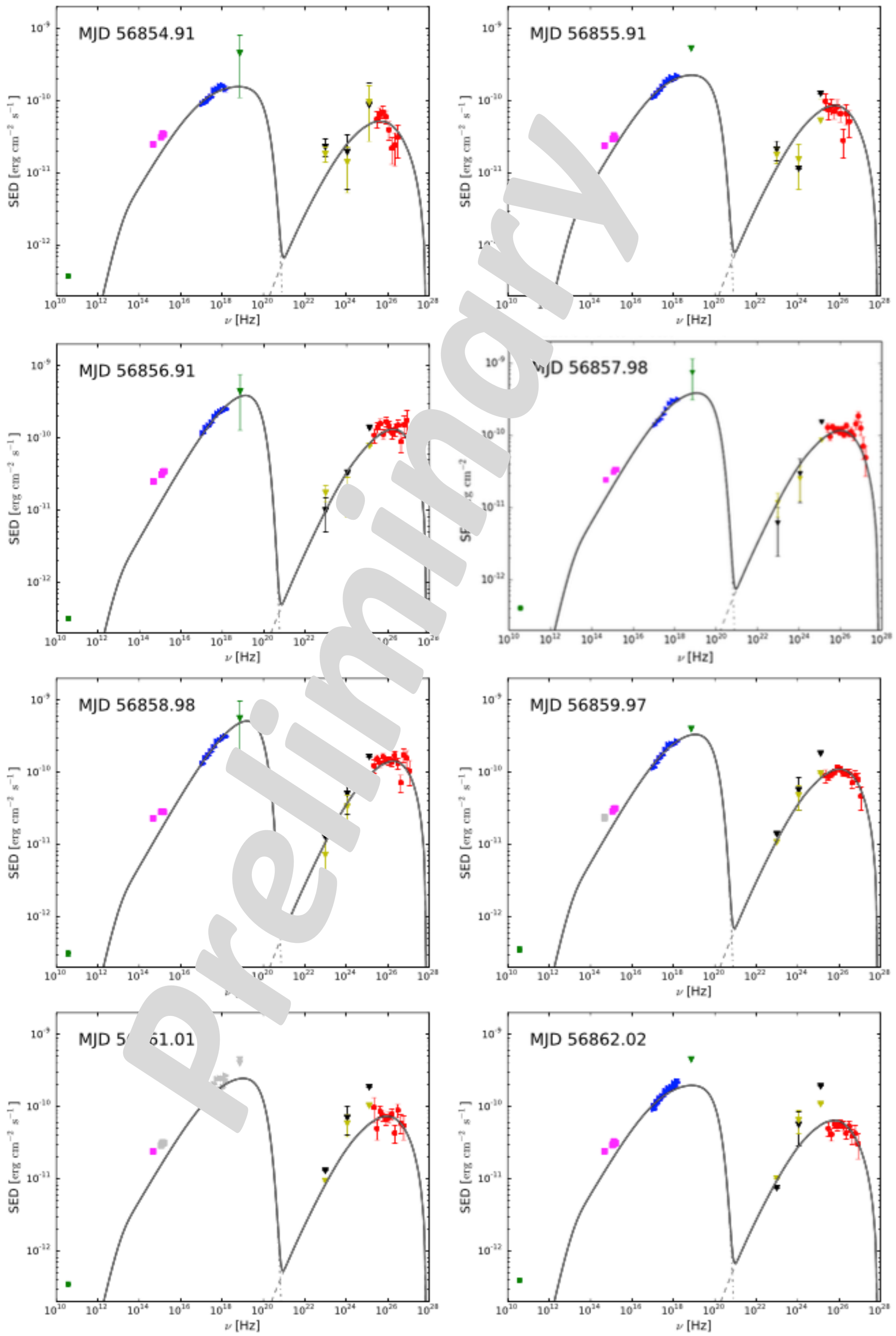
Multi-band Light Curve during the July 2014 flaring activity

Largest variability occurs in X-rays and VHE

→ Simultaneous Mrk501 X-ray/VHE observations for every night

July 12, 2014 **July 22, 2014** **Aug 1, 2014**

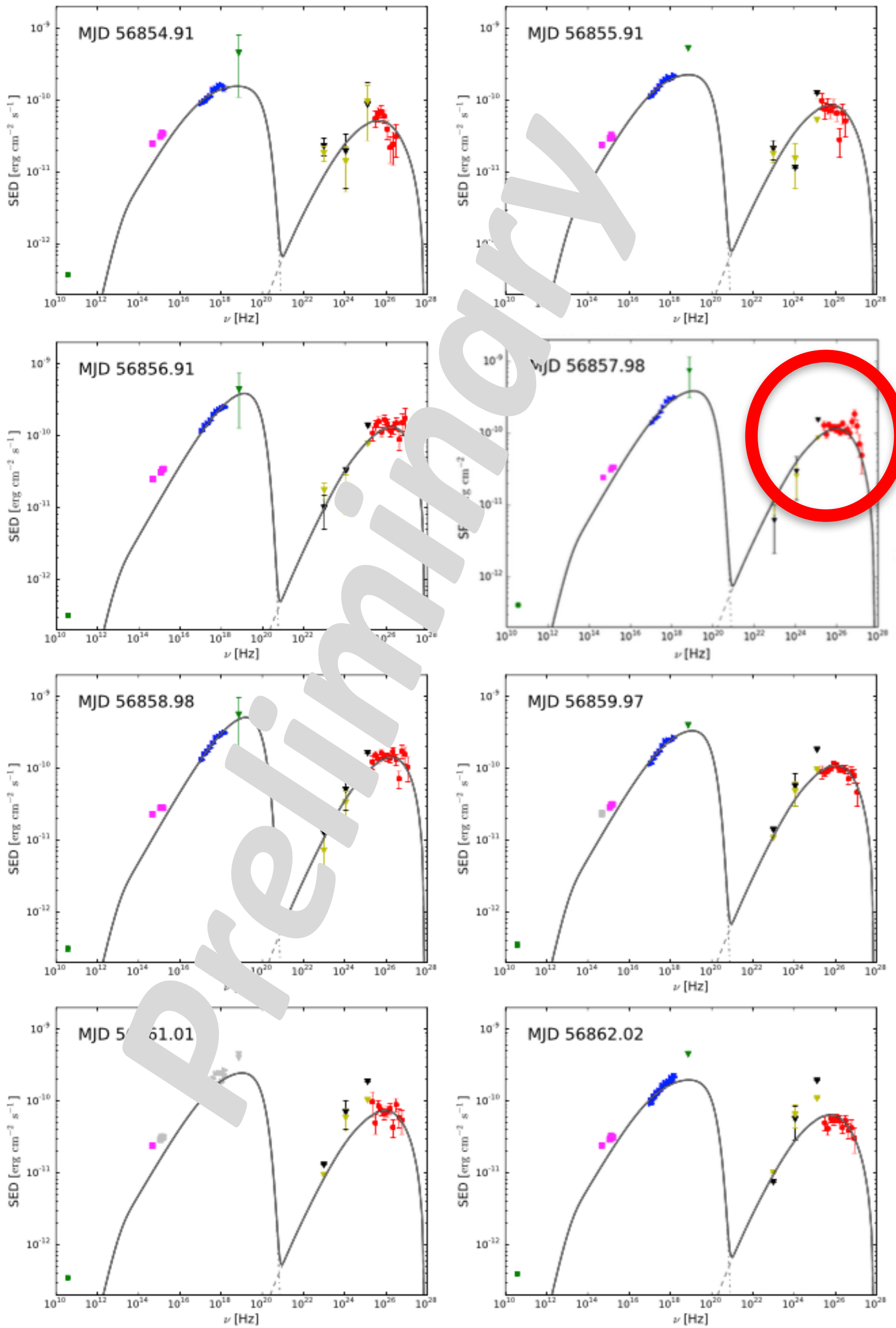




Large flaring activity of Mrk501 in July 2014

Broadband SEDs can be constructed for single (observations) nights

→ One-zone SSC can describe the most prominent and variable components



que

Large flaring activity of Mrk501 in July 2014

Narrow feature at ~3 TeV found in the VHE spectrum of MJD 56857.98 (July 19th, 2014), when X-ray flux was highest

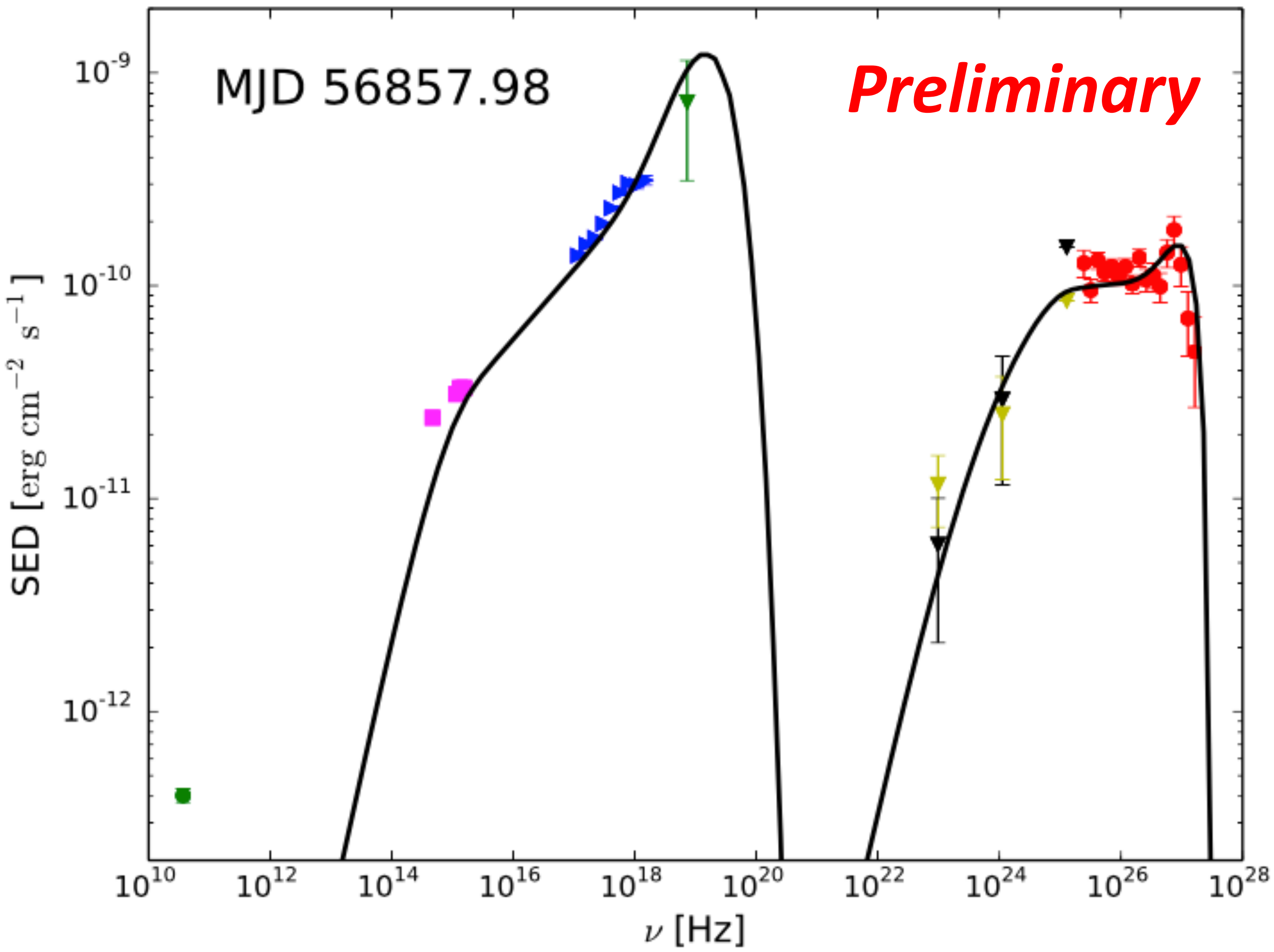
This feature is inconsistent at more than 3**σ** with the classical functions for VHE spectra (*power law, log-parabola, and log-parabola with exp. cutoff*)

statistical fluctuation (>3σ) or new component ?

Pile-up in the electron energy distribution due to stochastic acceleration

$\text{Time}_{\text{Acceleration}}(\gamma_{eq}) \sim \text{Time}_{\text{Cooling}}(\gamma_{eq}) \ll \text{Time}_{\text{Escape}}$

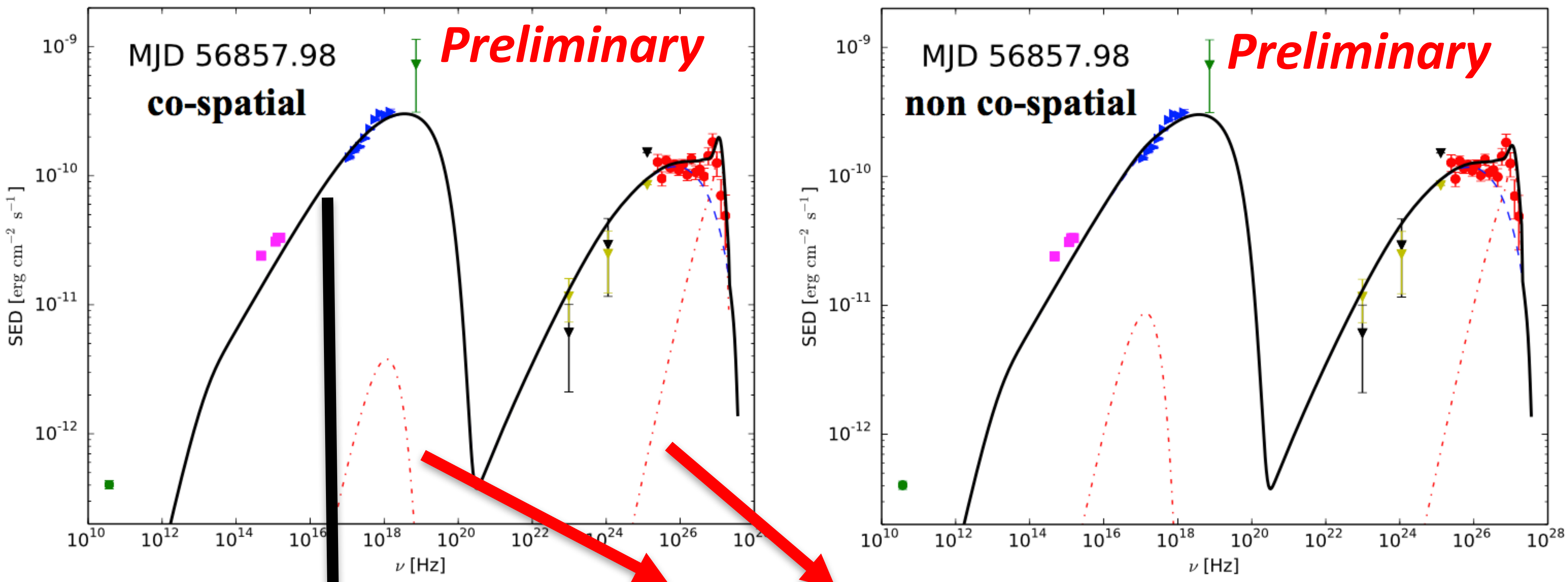
***Usual* log-parabolic EED at $\gamma \ll \gamma_{eq}$, Relativistic Maxwellian EED at γ_{eq}**



Model proposed by Andrea Tramacere

Based on
Stawarz&Petrosian 2008
Tramacere et al 2011
Lefa et al 2011

Additional SSC model component with a narrow electron energy distribution (EED)



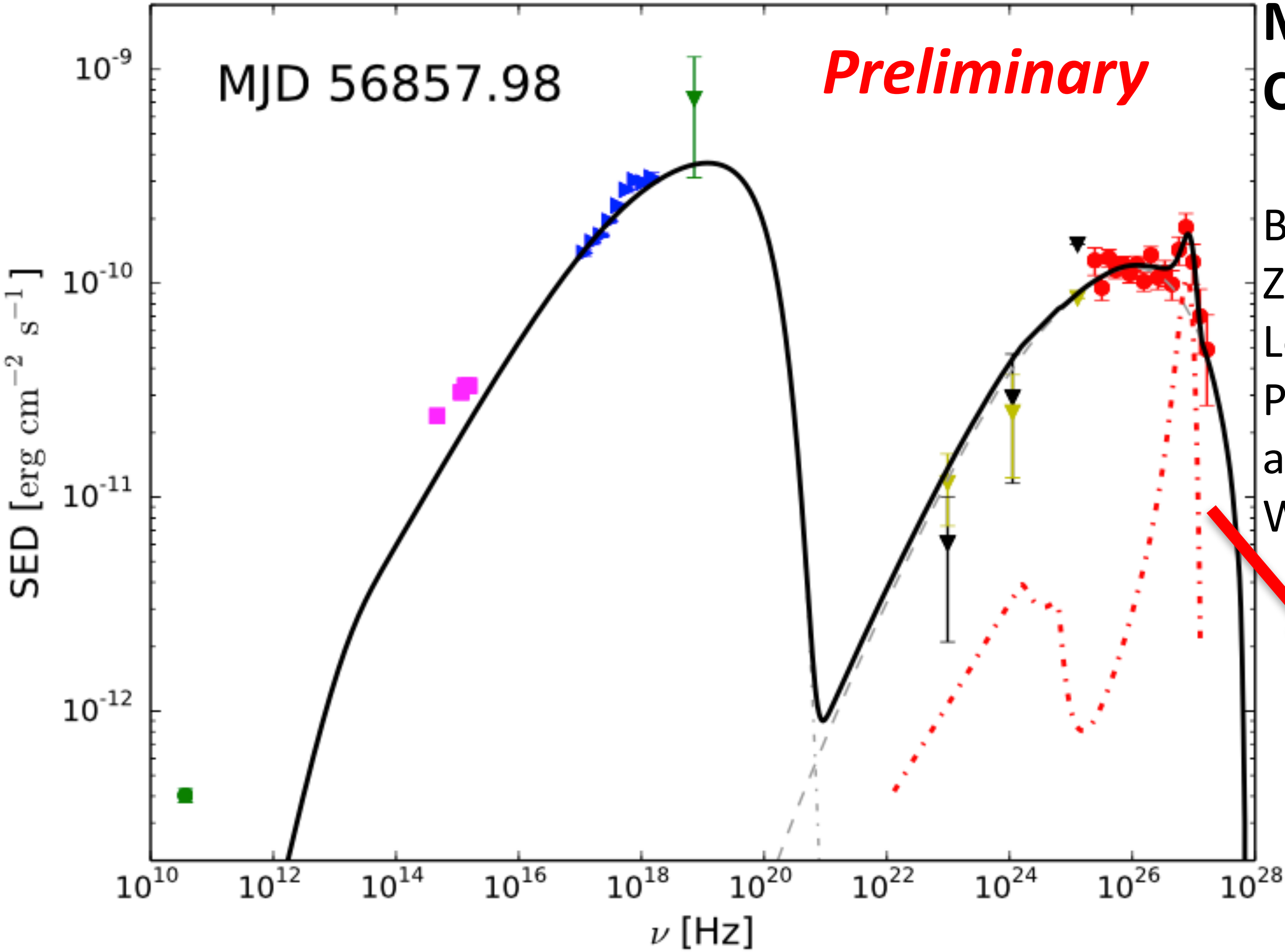
Small (additional) region with narrow EED

Sum of the two SSC components

Model proposed by Pepa Becerra and Fabrizio Tavecchio

Similar scenario used in Aleksic et al 2015 (A&A 578, 22) and Ahnen et al 2017 (*A&A* 603 , A31)

Additional component produced via an Inverse Compton pair cascade induced by electrons accelerated in a magnetospheric vacuum gap close to the Black Hole



Model proposed by Christoph Wendel

Based on
Zdziarski 1988,
Levinson&Rieger 2011,
Ptitsyna&Neronov 2016
and
Wendel et al 2017

Emission from narrow EED accelerated in Magnetospheric vacuum gap

Conclusions

- Large complexity in the temporal evolution of the broadband (radio to VHE γ-rays) SED.

→ **One-zone SSC model can be used to approximately model the most prominent & variable segments of the SED (X-ray and VHE).**

→ BUT accurate modeling of the broadband SED would require additional components

→ Complex (*and variable !!)* variability patterns

→ **These sources have complicated "cosmic personalities":**

Mrk421: HBL trying to become IBL (in 2013)

Mrk501: HBL became EHBL (in2012)

→ during non-flaring activity

Mrk501: hints of a ~1-day narrow feature at 3 TeV

→ ***Are these recurrent episodes ? Occur on other blazars ?***

- Mrk421 and Mrk501 as blazar physics laboratory

→ *Lessons learnt might be applied to other blazars (farther away or weaker)*

Conclusions

- **Deepest Temporal and Energy coverage of any TeV object**

The MW campaigns on Mrk421 and Mrk501 are a multi-year AND multi-instrument program that is running since 2009.

- **Blazars are “complicated cosmic animals“**

This complexity can be hidden when working with limited sensitivity, limited **energy&time** coverage

In the Extensive campaigns on Mrk421 and Mrk501 we have both, bright sources and high sensitive instruments with large energy&time coverage

- **Pathfinder to some of the extragalactic science that will be possible with CTA (in 2022+).**

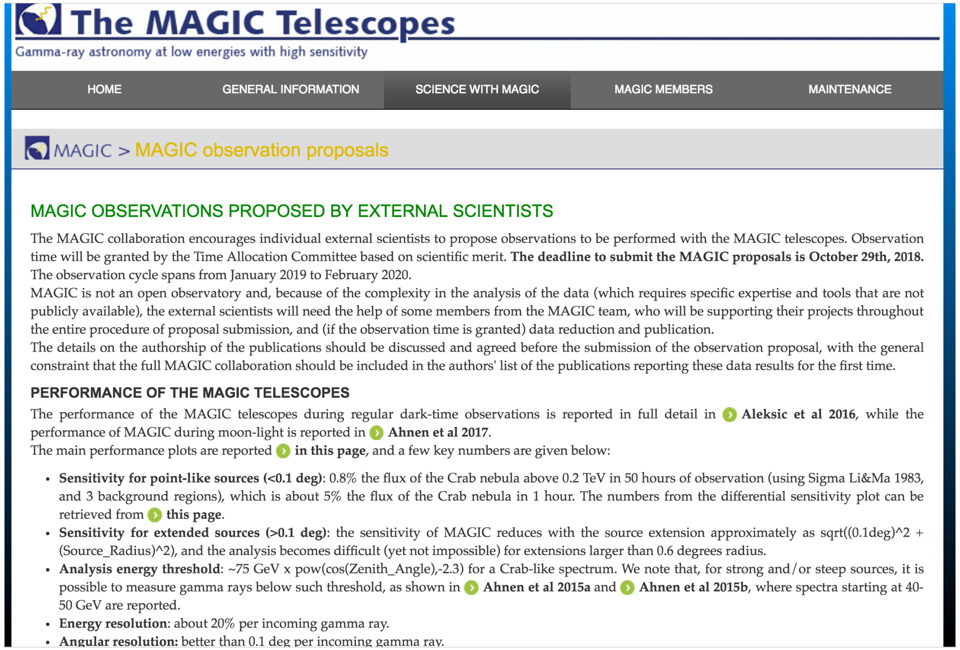
→ *We have VHE spectra from Mrk421/Mkr501 with a resolution comparable to full CTA for the typical VHE blazar (“<5% Crab blazars”)*

→ *Studies done TODAY on Mrk421/Mrk501 will be repeated in 4+ years on other blazars with CTA*

Open call for MAGIC observation proposals

If you are interested in studying your favourite AGN at VHE gamma-ray energies, there is a new MW opportunity for you:
external scientists can apply for observation time with MAGIC

https://magic.mpp.mpg.de/outsiders/magicop/


The MAGIC Telescopes
Gamma-ray astronomy at low energies with high sensitivity

HOME | GENERAL INFORMATION | SCIENCE WITH MAGIC | MAGIC MEMBERS | MAINTENANCE

MAGIC > MAGIC observation proposals

MAGIC OBSERVATIONS PROPOSED BY EXTERNAL SCIENTISTS

The MAGIC collaboration encourages individual external scientists to propose observations to be performed with the MAGIC telescopes. Observation time will be granted by the Time Allocation Committee based on scientific merit. **The deadline to submit the MAGIC proposals is October 29th, 2018.** The observation cycle spans from January 2019 to February 2020.
MAGIC is not an open observatory and, because of the complexity in the analysis of the data (which requires specific expertise and tools that are not publicly available), the external scientists will need the help of some members from the MAGIC team, who will be supporting their projects throughout the entire procedure of proposal submission, and (if the observation time is granted) data reduction and publication.
The details on the authorship of the publications should be discussed and agreed before the submission of the observation proposal, with the general constraint that the full MAGIC collaboration should be included in the authors' list of the publications reporting these data results for the first time.

PERFORMANCE OF THE MAGIC TELESCOPES

The performance of the MAGIC telescopes during regular dark-time observations is reported in full detail in **Aleksic et al 2016**, while the performance of MAGIC during moon-light is reported in **Ahnen et al 2017**.
The main performance plots are reported **in this page**, and a few key numbers are given below:

- **Sensitivity for point-like sources (<0.1 deg)**: 0.8% the flux of the Crab nebula above 0.2 TeV in 50 hours of observation (using Sigma Li&Ma 1983, and 3 background regions), which is about 5% the flux of the Crab nebula in 1 hour. The numbers from the differential sensitivity plot can be retrieved from **this page**.
- **Sensitivity for extended sources (>0.1 deg)**: the sensitivity of MAGIC reduces with the source extension approximately as sqrt((0.1deg)^2 + (Source_Radius)^2), and the analysis becomes difficult (yet not impossible) for extensions larger than 0.6 degrees radius.
- **Analysis energy threshold**: ~75 GeV x pow(cos(Zenith_Angle),-2.3) for a Crab-like spectrum. We note that, for strong and/or steep sources, it is possible to measure gamma rays below such threshold, as shown in **Ahnen et al 2015a** and **Ahnen et al 2015b**, where spectra starting at 40-50 GeV are reported.
- **Energy resolution**: about 20% per incoming gamma ray.
- **Angular resolution:** better than 0.1 deg per incoming gamma ray.

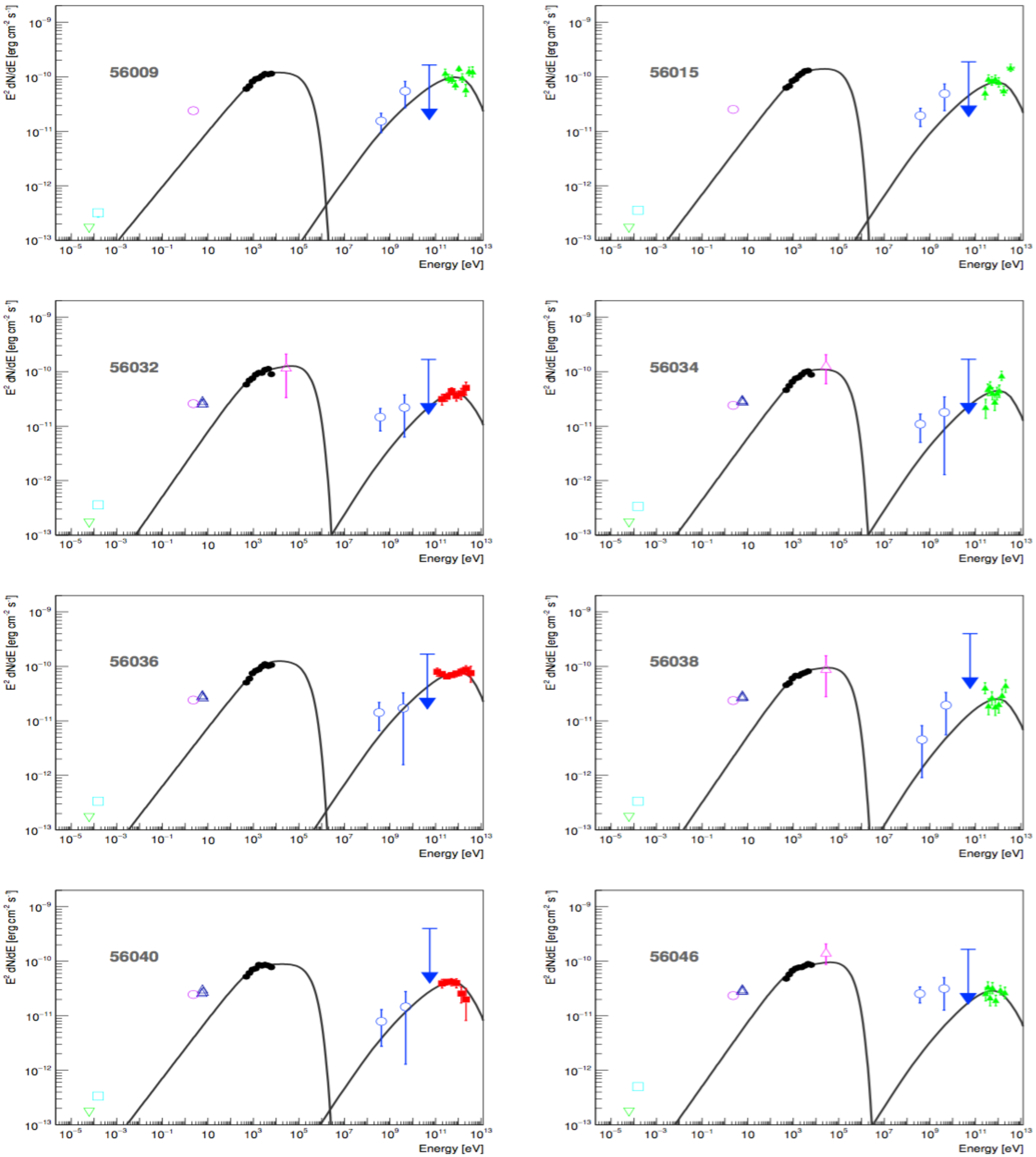
Observation cycle spans from Jan. 2019 to Feb. 2020

Possibility to obtain up to 150 ks of XMM observing time through the submission of MAGIC proposals

Submission deadline: October 29th, 2018

If you would like to apply, contact me (*dpaneque@mppmu.mpg.de*), preferably before October 2018, so that we have time to discuss and potentially tune the observation proposal

Backup

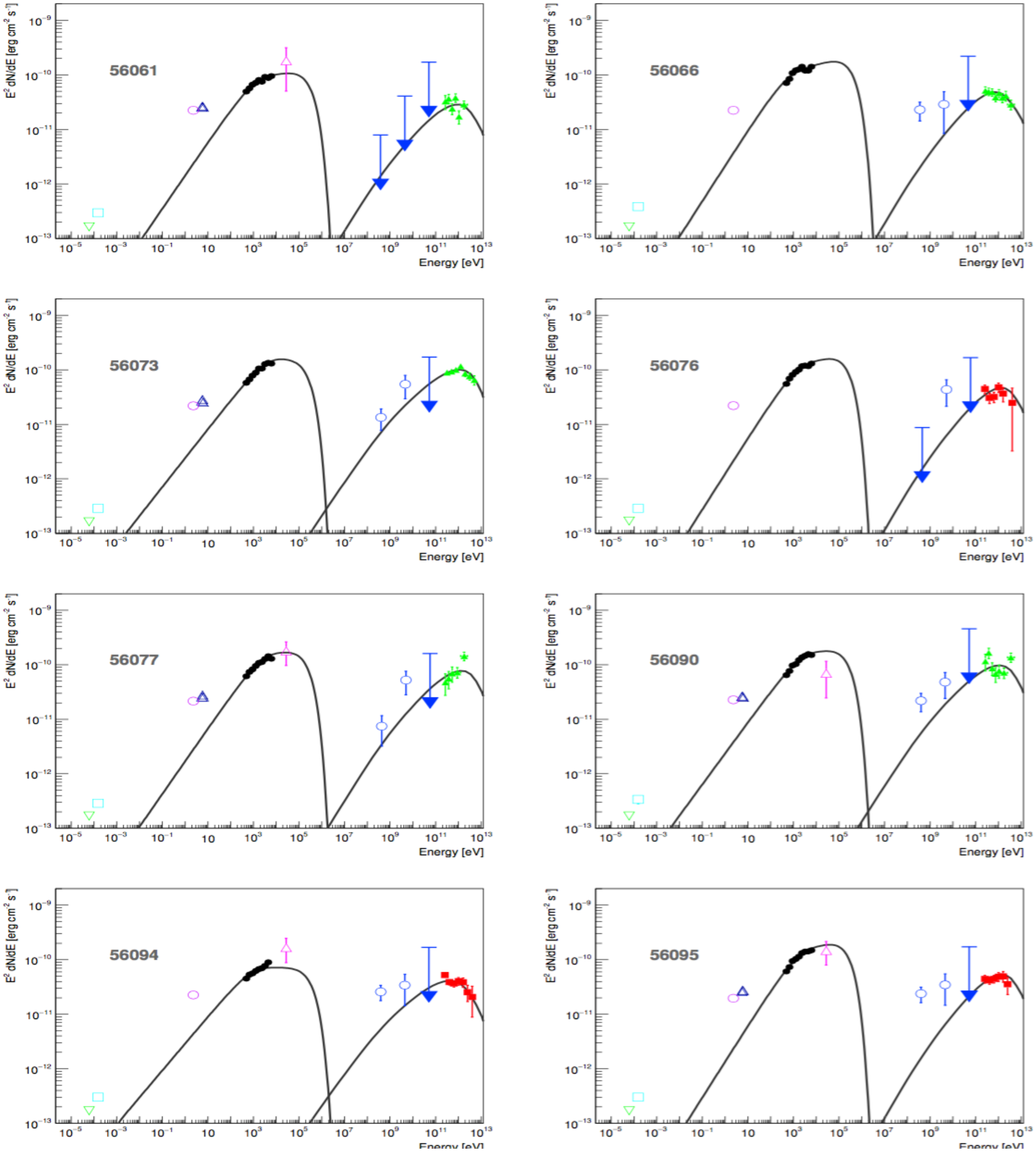


Broadband SED and SSC model fit for 17 days with simultaneous X-ray and VHE

Most X-ray and VHE data taken less than 1-2 hour apart from each other
(biggest difference is 4 hours)

Ahnen et al., Accepted in A&A (*arXiv:1808.04300*)

(Part 1)



Broadband SED and SSC model fit for 17 days with simultaneous X-ray and VHE

Most X-ray and VHE data taken less than 1-2 hour apart from each other
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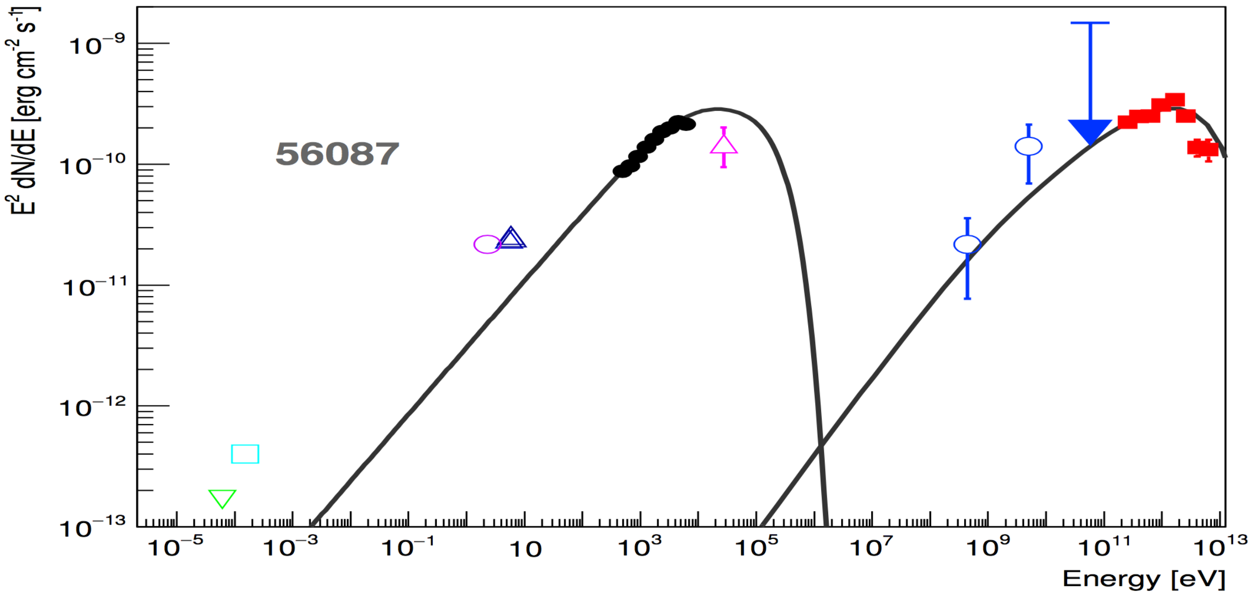
Ahnen et al., Accepted in A&A (*arXiv:1808.04300*)

(Part 2)

June 9th 2012 flare



Broadband SED and SSC model fit for 17 days with simultaneous X-ray and VHE

(Part 3)

Ahnen et al., Accepted in A&A (*arXiv:1808.04300*)

Zoom into the VHE band

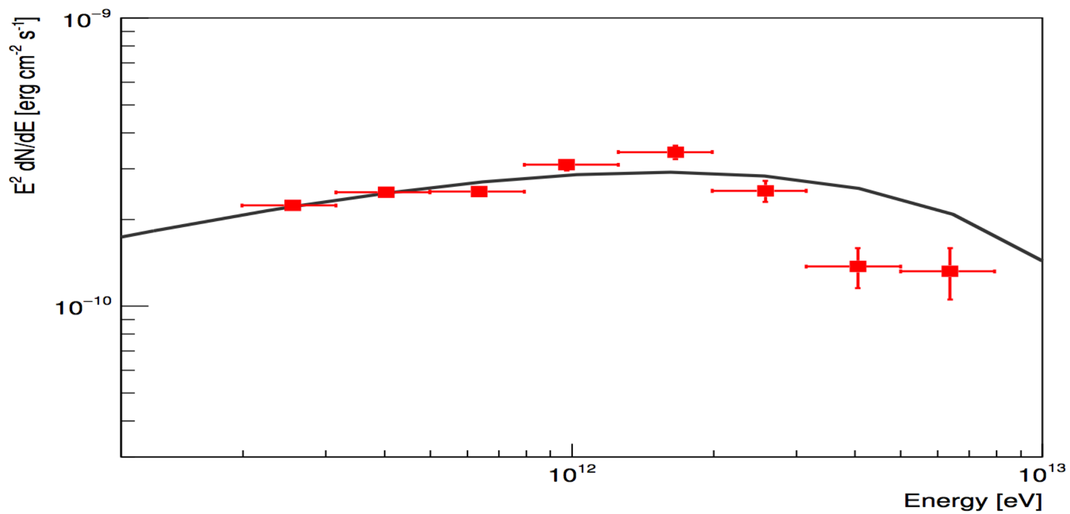


Table 2. One–zone SSC Model Results. The following parameters were fixed; Region size (R) 2.65×10^{16}cm, the Doppler factor (δ) 10, γ_{min} 3.17×10^{2} and γ_{max} 7.96×10^{6}. V refers to VERITAS and M to MAGIC observations.

5 parameters modified are not fully independent. Imposed that break is related to electron cooling, which yields two relations:

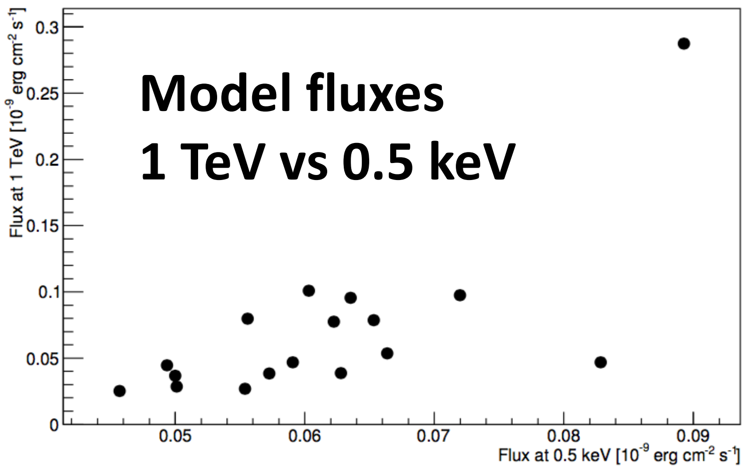
- p_1 and p_2
- B and g_{brk}

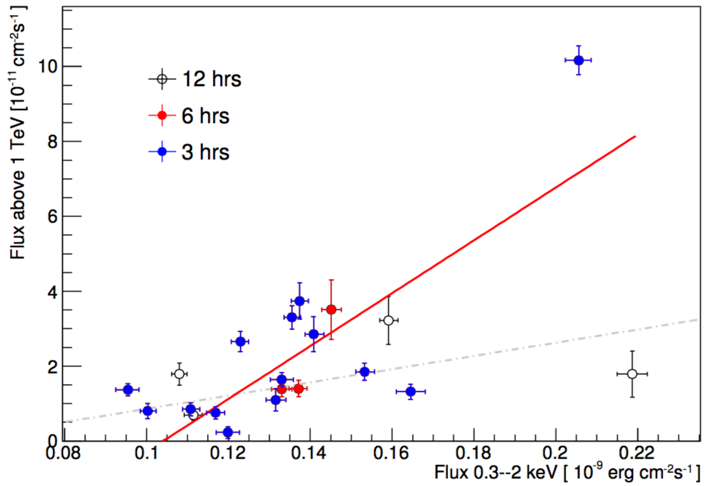
MJD (χ^2/DoF)	B [10^{-2} G]	γ_{brk} [10^{6}]	p_1	p_2	U_e [10^{-3} erg/cm^3]	η [U_e/U_B]
56009 V (34.0/13)	2.26	0.85	1.90	2.87	11.96	589
56015 V (29.9/11)	2.34	0.81	1.90	2.87	9.27	425
56032 M (19.9/10)	2.99	0.49	1.88	2.77	5.20	146
56034 V (24.3/12)	2.22	0.90	1.86	2.90	6.88	350
56036 M (21.0/11)	2.00	1.07	1.93	2.96	10.50	659
56038 V (19.8/10)	2.55	0.63	1.78	2.82	4.50	173
56040 M (18.8/11)	3.00	0.51	1.91	2.93	5.98	166
56046 V (23.5/12)	3.26	0.41	1.81	2.82	4.30	102
56061 V (24.0/10)	2.65	0.65	1.78	2.82	4.66	166
56066 V (36.0/12)	3.39	0.42	1.70	2.73	5.11	112
56073 V (13.3/11)	2.00	1.28	1.93	2.96	11.70	736
56076 M (19.7/10)	2.13	0.81	1.69	2.70	6.57	361
56077 V (17.7/9)	1.96	1.07	1.80	2.82	9.29	607
56087 M (62.5/12)	1.64	1.70	1.89	2.91	21.30	1398
56090 V (32.7/10)	2.21	0.91	1.86	2.83	10.10	520
56094 M (18.0/10)	2.98	0.50	2.00	2.97	7.04	199
56095 M (16.8/10)	2.25	0.84	1.68	2.73	6.78	336

Ahnen et al., Accepted in A&A (*arXiv: 1808.04300*)

Main results derived from the SSC modeling:

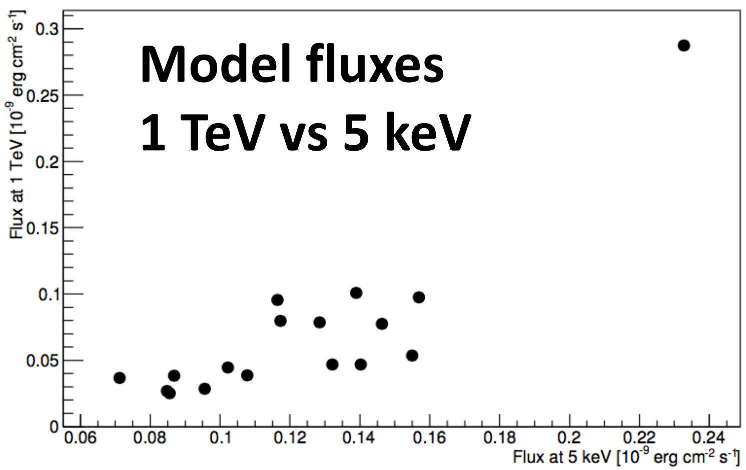
1) **p1 is always harder than 2 (driven by hard X-ray and VHE spectra)**
   → Need acceleration process producing hard EED
2) **Correlation at 7 sigma between VHE flux and U_e**
   → Variability could be explained by injection of electrons
3) **Data-Model agreement for the flare day (MJD 56087) is bad**
   → For this day, “something else” happened (*2-zone gives better agreement*)
4) **“loose” X-ray/VHE Model correlation, which increases with X-ray Energy**

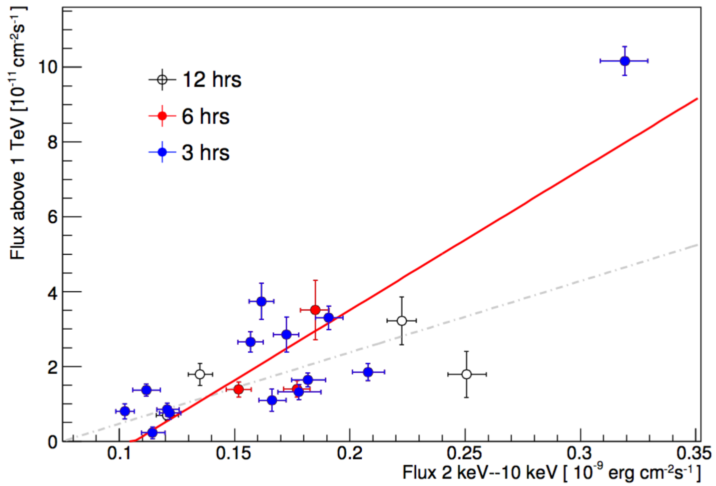




Data fluxes

>1 TeV vs 0.3-2 keV

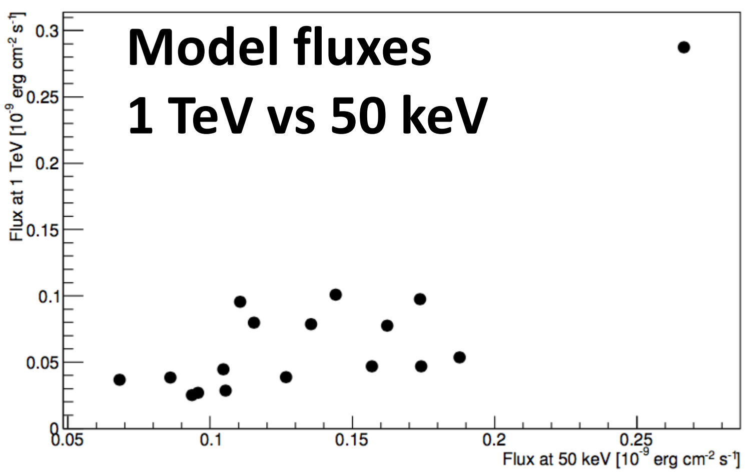




Data fluxes

>1 TeV vs 2-10 keV

Ahnen et al., Accepted in A&A (*arXiv: 1808.04300*)



One-zone SSC model produces similar flux-flux correlations as the data

→ electrons producing the keV X-rays are not exactly those producing TeV VHE

Quantification of the X-ray/VHE flux correlation (Data and Model)

	Pearson correlation coefficient (σ)
Data: 0.3–2 keV vs > 1 TeV	$0.78^{+0.10}_{-0.15}$ (3.9)
Excluding June 9 flare:	$0.39^{+0.23}_{-0.29}$ (1.6)
Data: 2–10 keV vs > 1 TeV	$0.88^{+0.06}_{-0.10}$ (4.9)
Excluding June 9 flare:	$0.59^{+0.16}_{-0.24}$ (2.5)

Data

When excluding the flare, we have a loose (marginal) correlation of VHE and X-ray fluxes.
This correlation increases when increasing the X-ray energy

Ahnen et al., Accepted in A&A
(*arXiv: 1808.04300*)

Quantification of the X-ray/VHE flux correlation (Data and Model)

	Pearson correlation coefficient (σ)
Data: 0.3–2 keV vs > 1 TeV	$0.78^{+0.10}_{-0.15}$ (3.9)
Excluding June 9 flare:	$0.39^{+0.23}_{-0.29}$ (1.6)
Data: 2–10 keV vs > 1 TeV	$0.88^{+0.06}_{-0.10}$ (4.9)
Excluding June 9 flare:	$0.59^{+0.16}_{-0.24}$ (2.5)
Model: 0.5 keV vs 1 TeV	$0.71^{+0.11}_{-0.16}$ (3.3)
Excluding June 9 flare:	$0.44^{+0.19}_{-0.25}$ (1.7)
Model: 5.0 keV vs 1 TeV	$0.87^{+0.06}_{-0.09}$ (4.8)
Excluding June 9 flare:	$0.63^{+0.14}_{-0.20}$ (2.7)
Model: 50.0 keV vs 1 TeV	$0.77^{+0.09}_{-0.13}$ (3.8)
Excluding June 9 flare:	$0.73^{+0.11}_{-0.16}$ (3.4)

Data

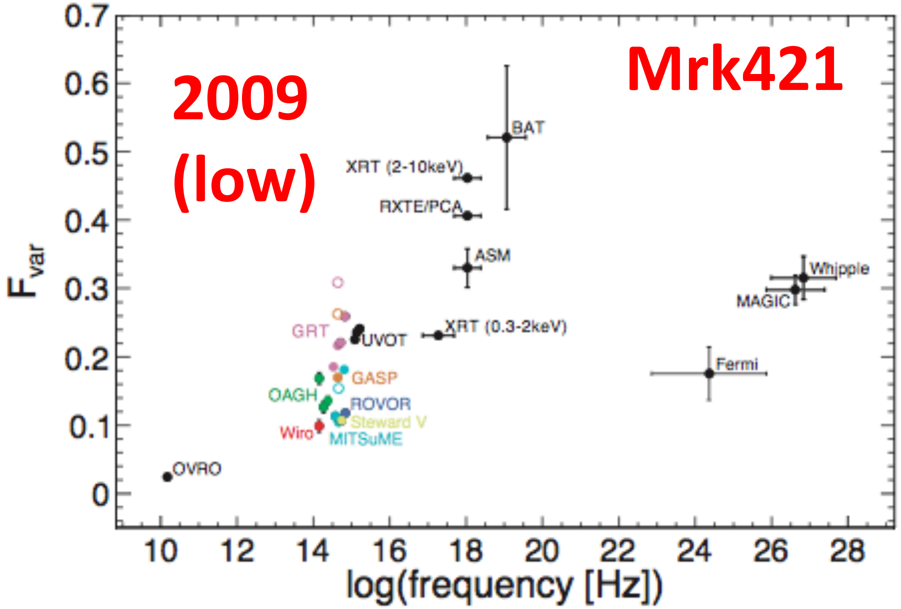
SSC Model

Significance of the correlation is comparable for Data and SSC model

Significance of the correlation increases with increasing X-ray energy

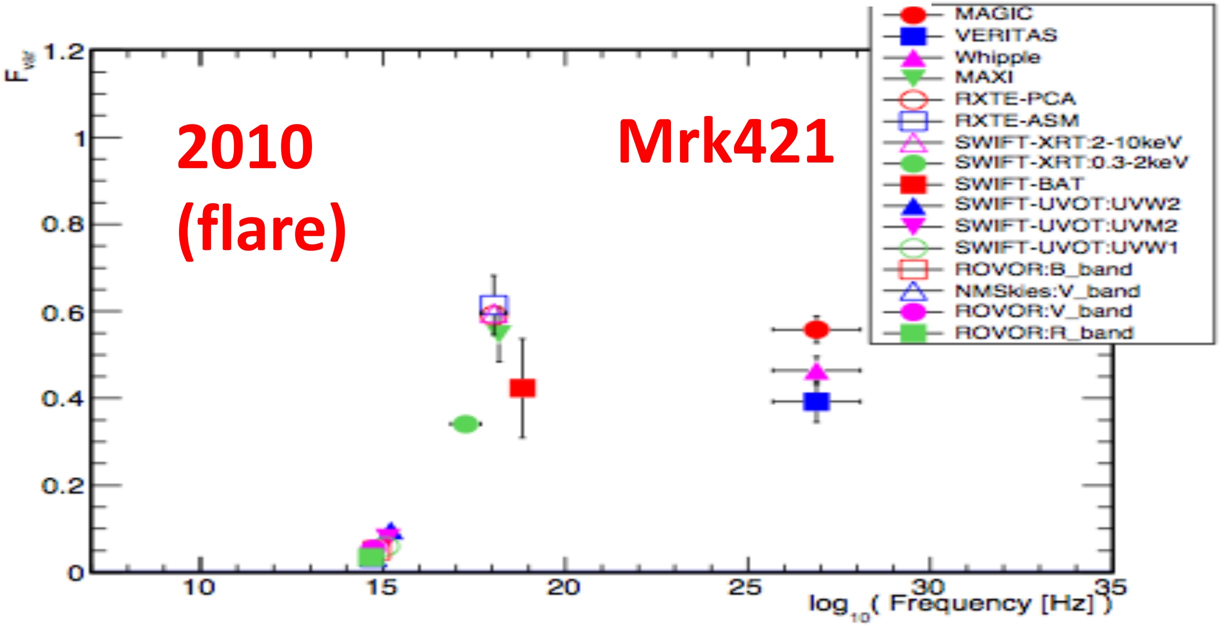
Variability vs. Energy for Mrk421

Variability quantified following prescription from Vaughan et al. 2003



Aleksic et al., 2015
A&A 575, 128

$$F_{var} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$



Aleksic et al., 2015
A&A 578, 22

Typical characteristic of Mrk421, in both high and low state

Correlations

Clear correlation between X-rays and VHE fluxes (on even lower flux)

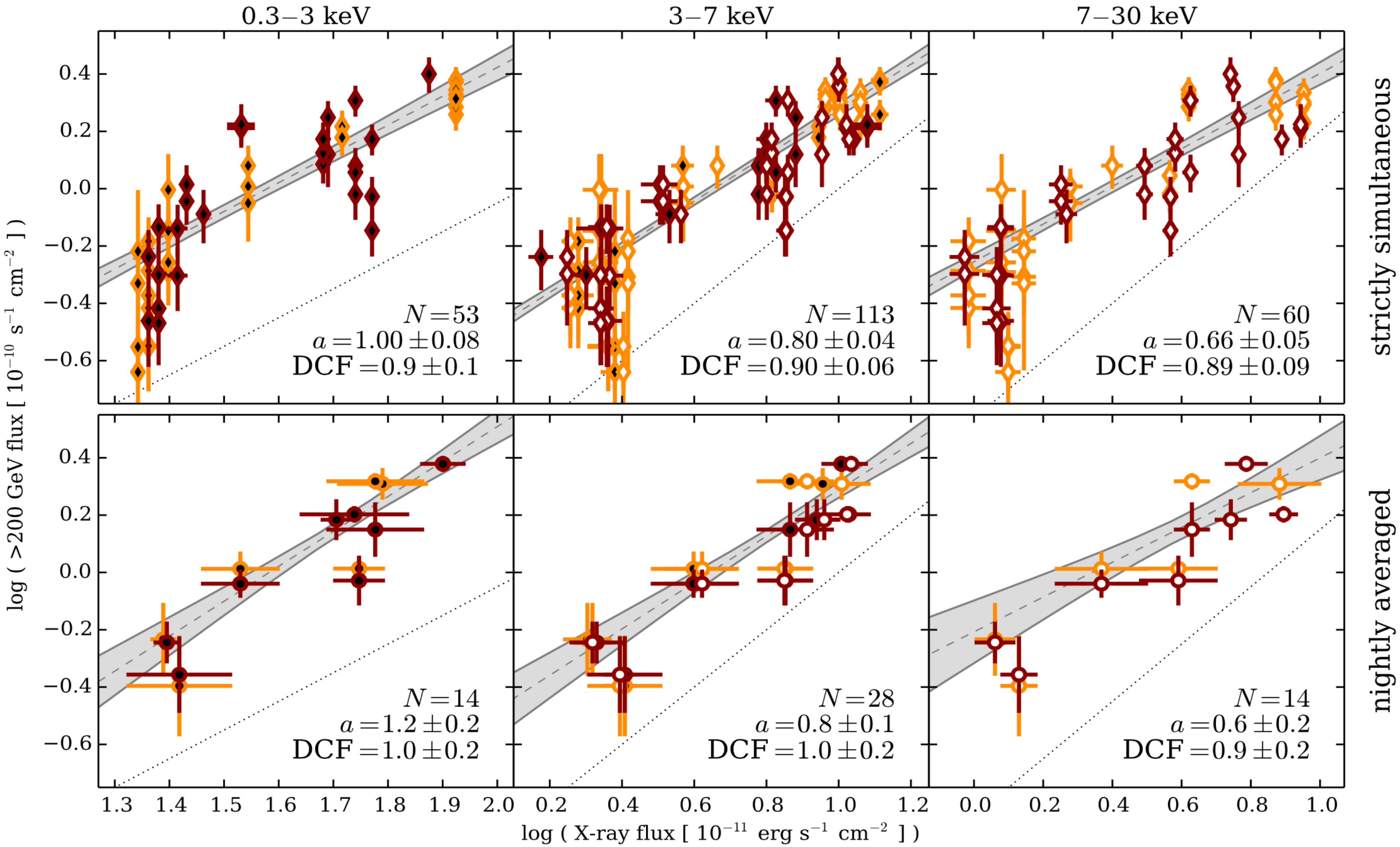
→ Correlation on strictly simultaneous observations and nightly averages

→ **There is a change in slope with the X-ray energy band considered**

→ Linear behaviour with soft X-rays (*inverse-Compton scattering in Klein-Nishina*)

→ Less than linear with the hard X-rays (7-30 keV)

→ The super-high energy electrons *contribute less* to >200 GeV flux

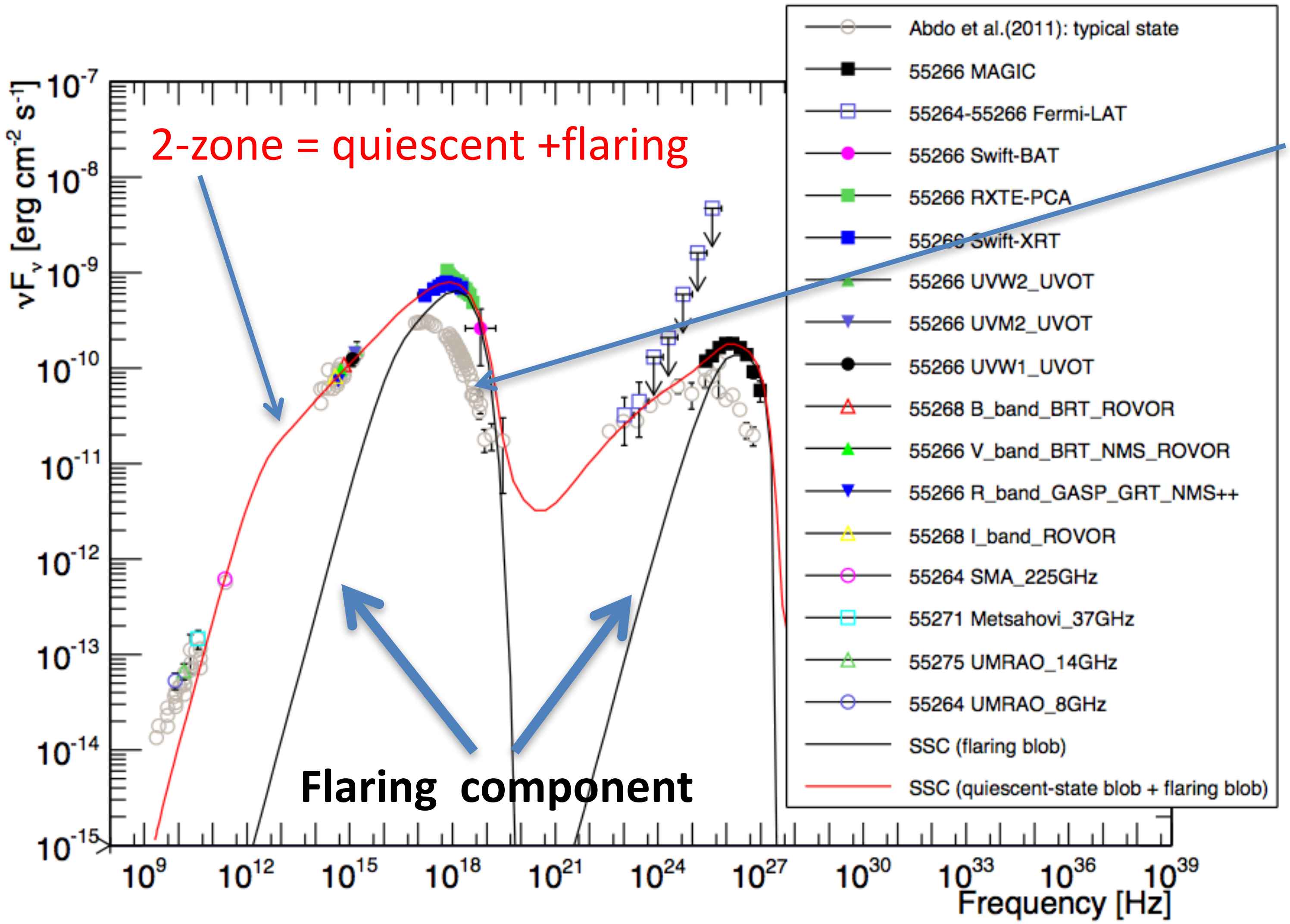


Mrk421 MW 2013

Balokovic et al., 2016 *ApJ* 819, 156

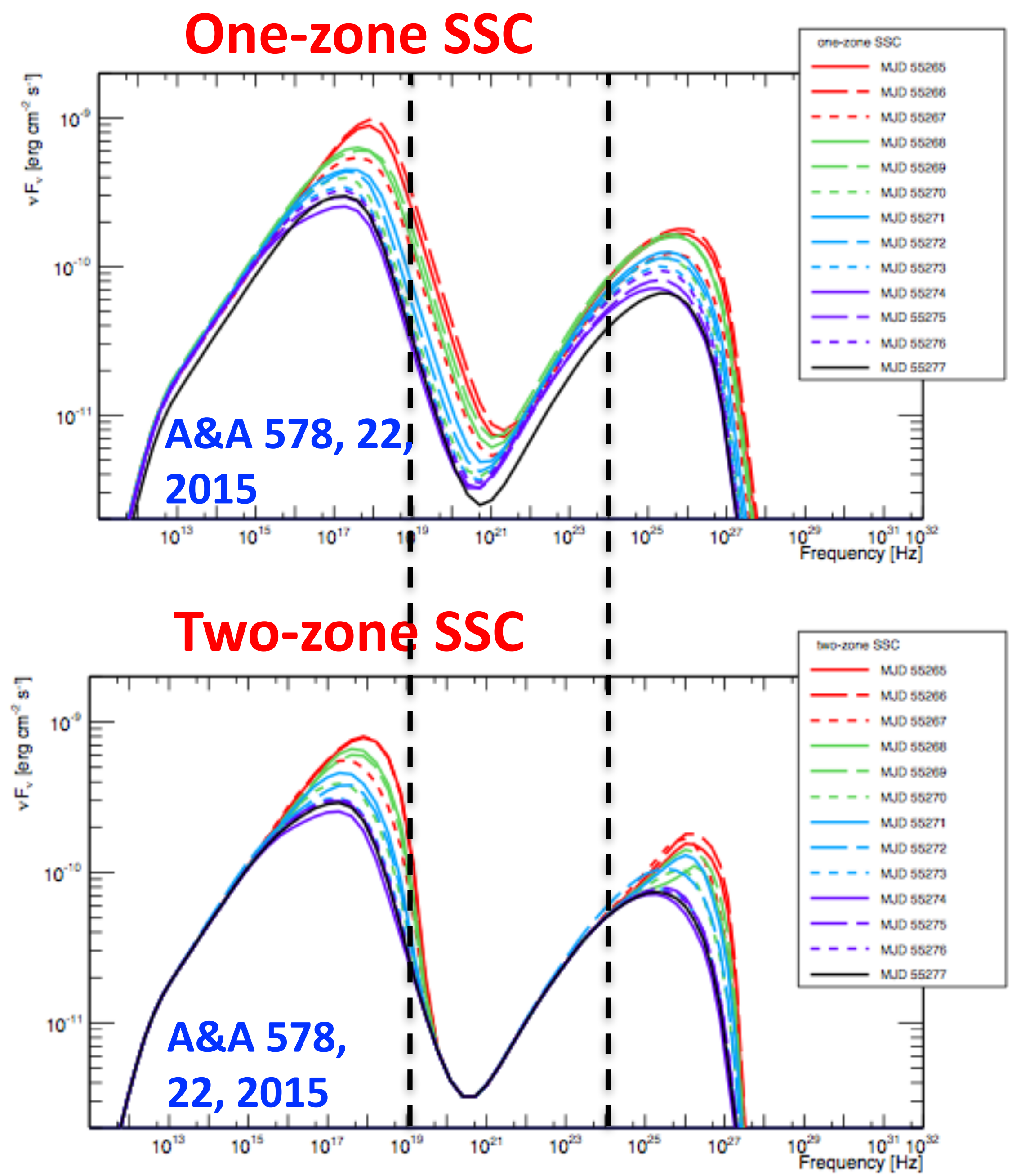
Aleksic et al., 2015, A&A 578, 22 (Mrk421 MW2010)

Temporal evolution of the flaring broadband SED modelled successfully during 13 consecutive days with a one-zone SSC (*standard*) and a two-zone SSC (*quiescent + flaring component at X-ray and VHE*)



Abdo et al., 2011, ApJ 736, 131 (grey open circles, typical state)

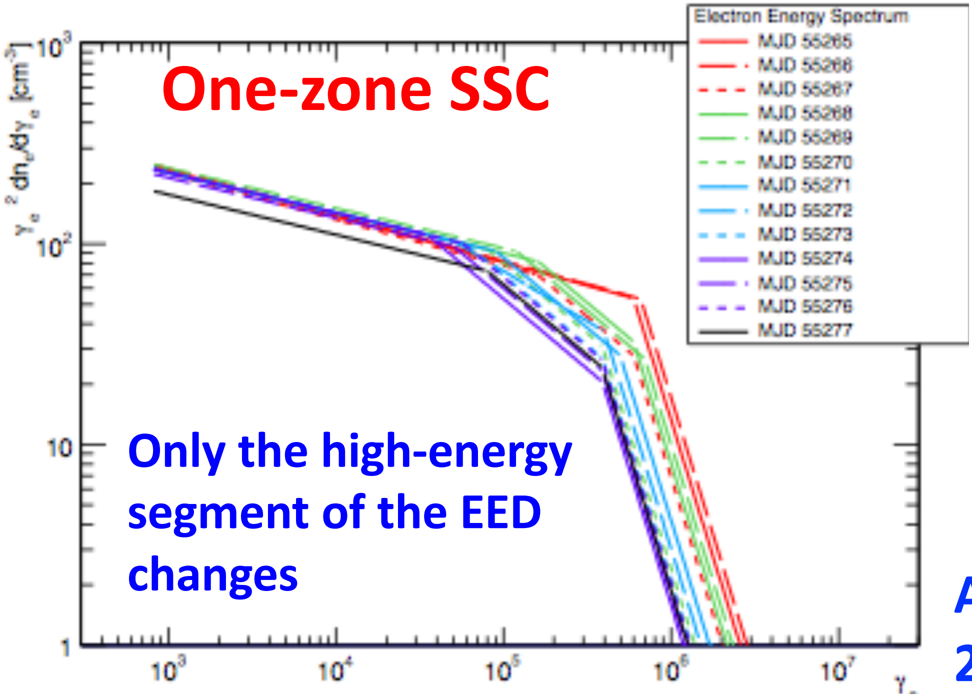
SED modeling for 13-day flaring activity in 2010

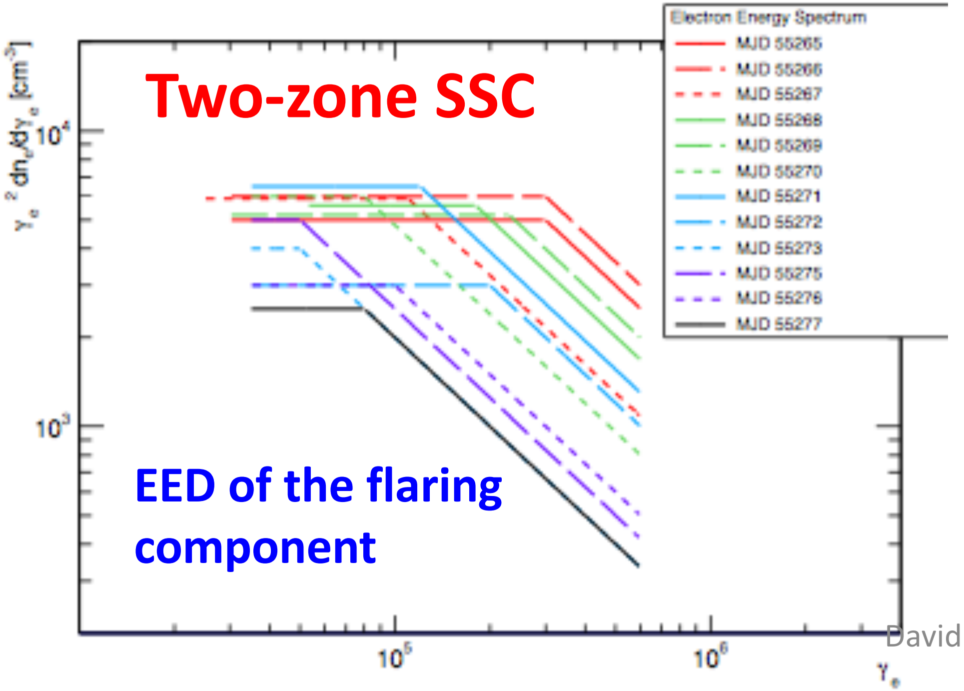


Variability patterns for the one-zone and two-zone SSC broadband emission is somewhat different, specially in the range between 50 keV and 50 GeV

The multi-band variability measured during the 13-day long flare in March 2010 could not distinguish between these two scenarios. *More prominent and longer flaring activities might make this distinction possible*

SED modeling: EEDs





Mrk421 MW 2010

One-zone vs two-zone SSC model

In both cases we could describe the 13-day long flaring activity with changes in the electron energy distribution (EED)

A&A 578, 22, 2015

Variations in the broadband SED during the flaring episodes in blazars may be dominated by particle acceleration-and-cooling