The extreme character of our closest VHE blazars, Mrk421 and Mrk501

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

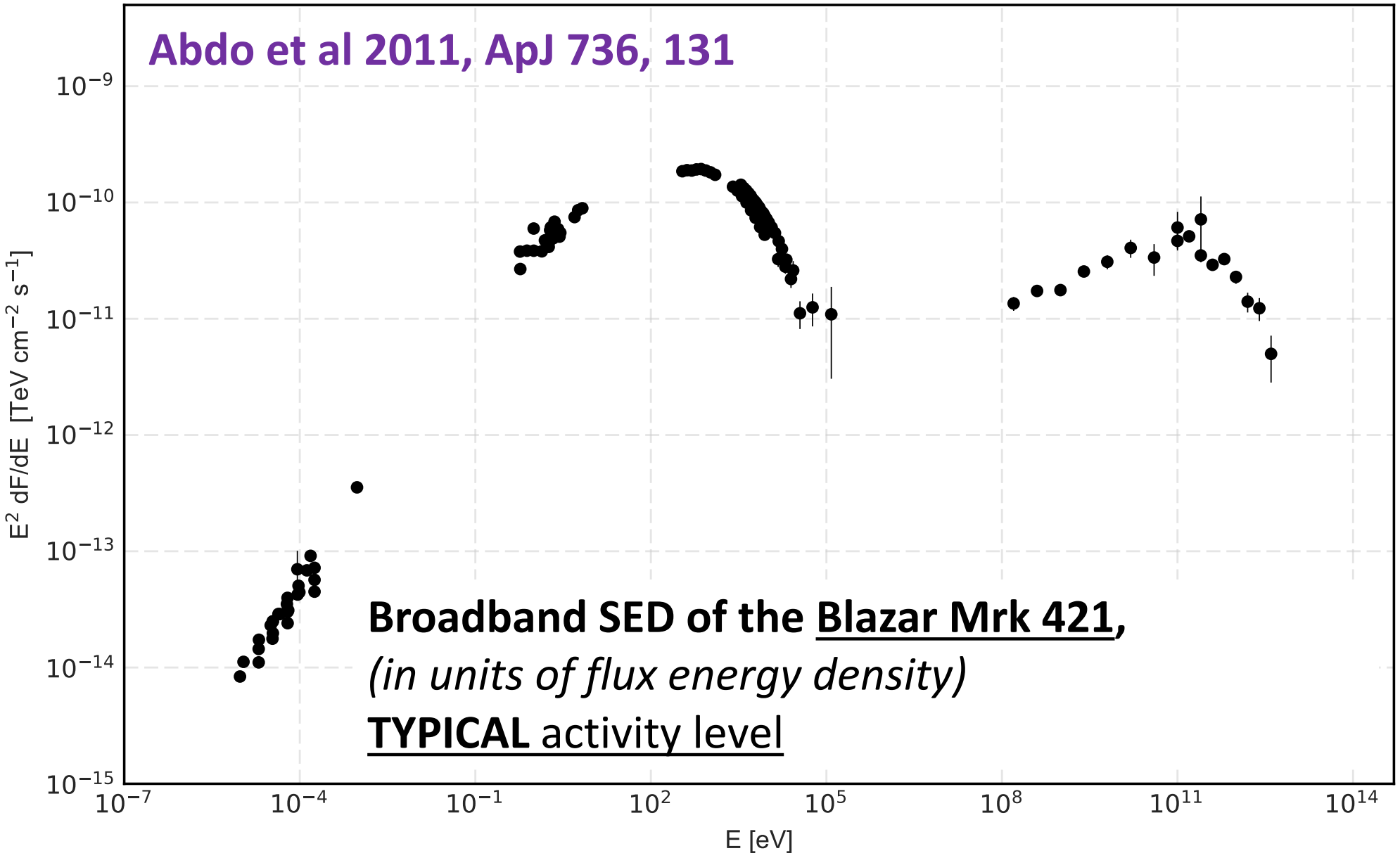
And with the help of many people:
A. Babic, M. Baloković, P. Becerra, M. Doert, T. Hassan, G. Hughes, A. Shukla, M. Perri, F. Tavecchio, A. Tramacere, C. Wendel, K. Noda, K. Ishio, D. Dorner, A . Furniss, M. Giroletti, S. Jorstad, V. Larionov, G. Madejski, H. Takami, M. Villata, P. Smith …

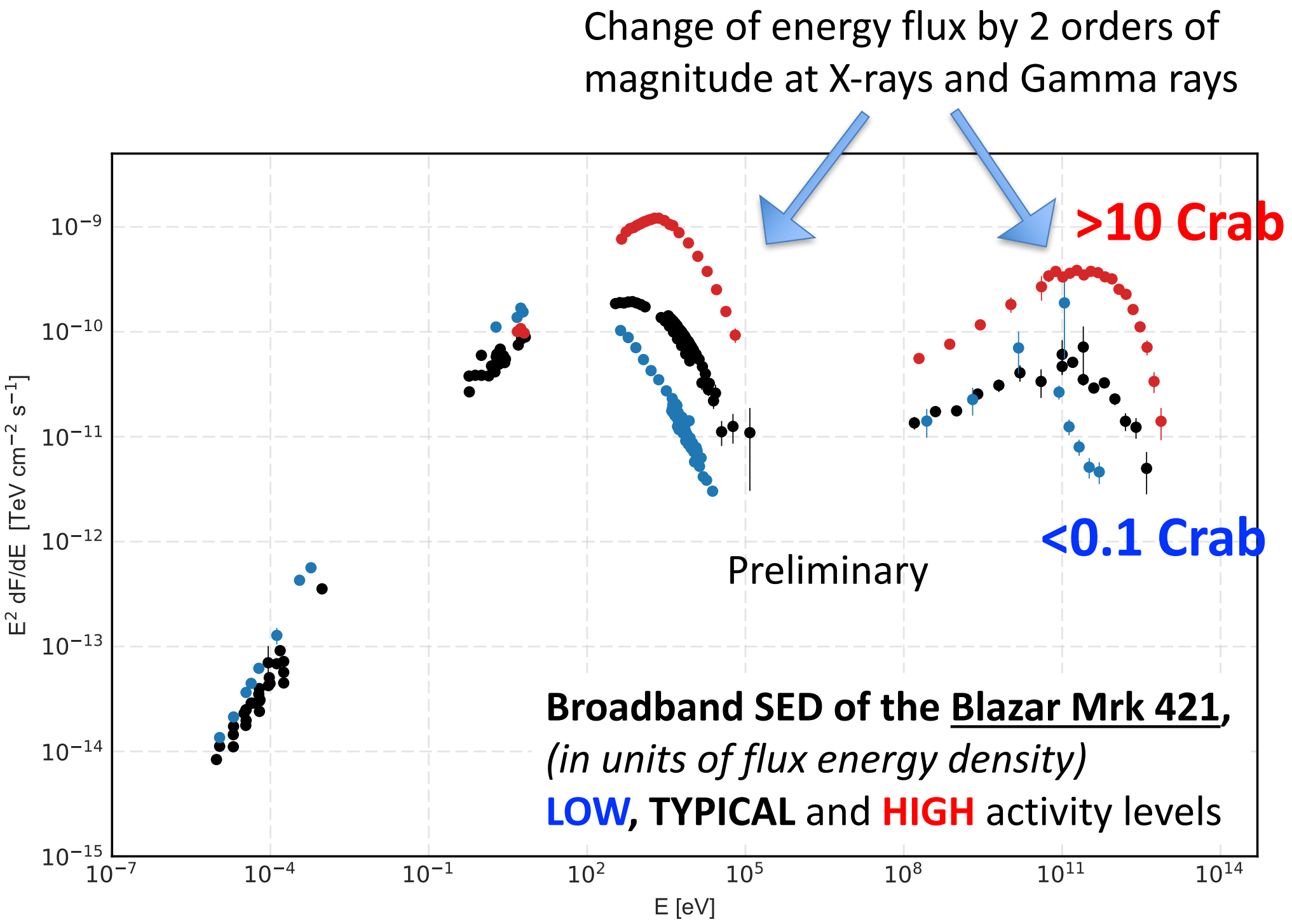
- The broadband and variable emission of blazars
- Extensive MW campaigns on Mrk421 and Mrk501
- Some highlight/recent results
  → *Peculiar behaviors (during low and high activity)*
- Conclusions

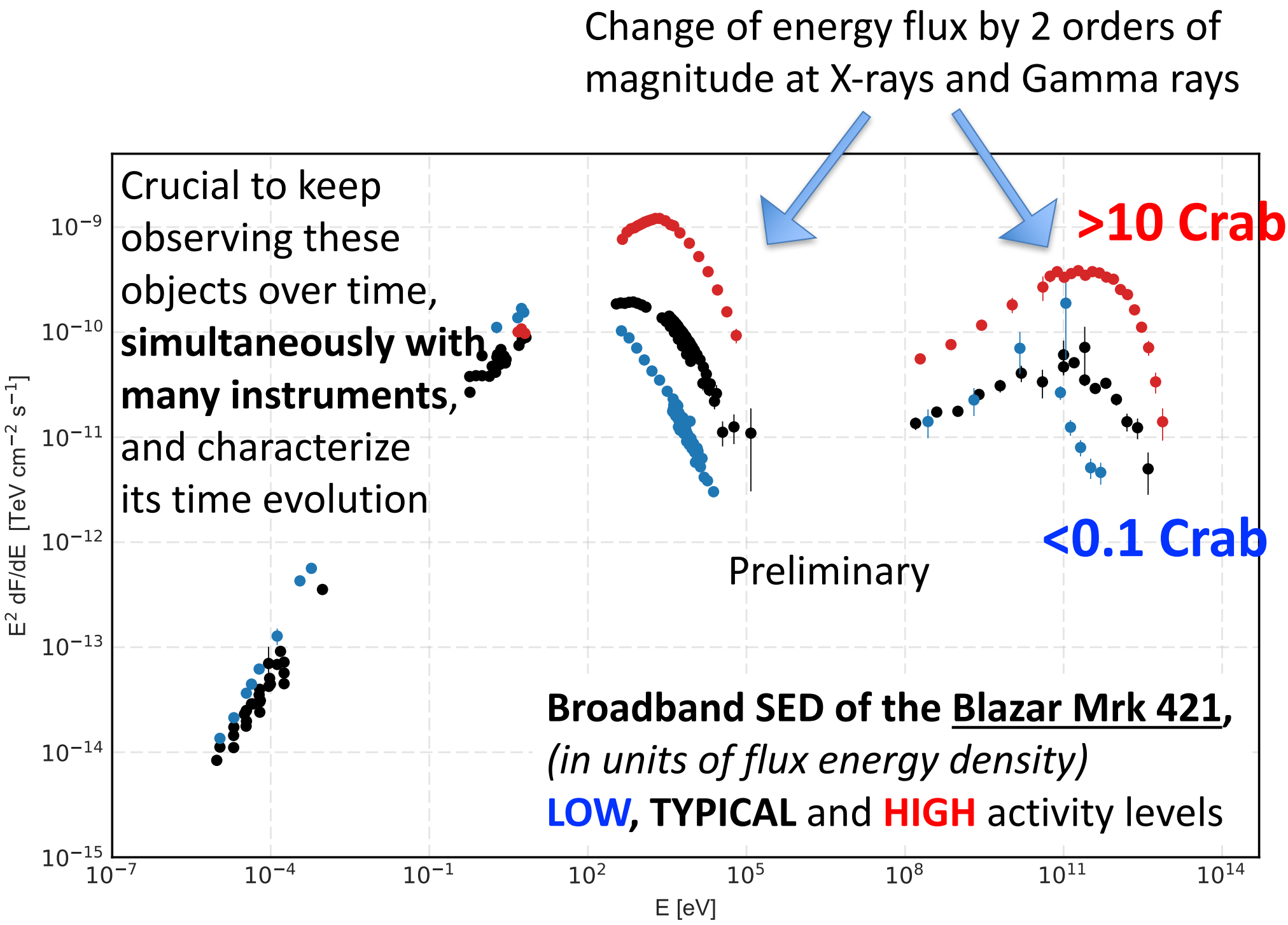
Blazars emit over a very wide energy range and show variability

Emission at different energies could be produced by same particles

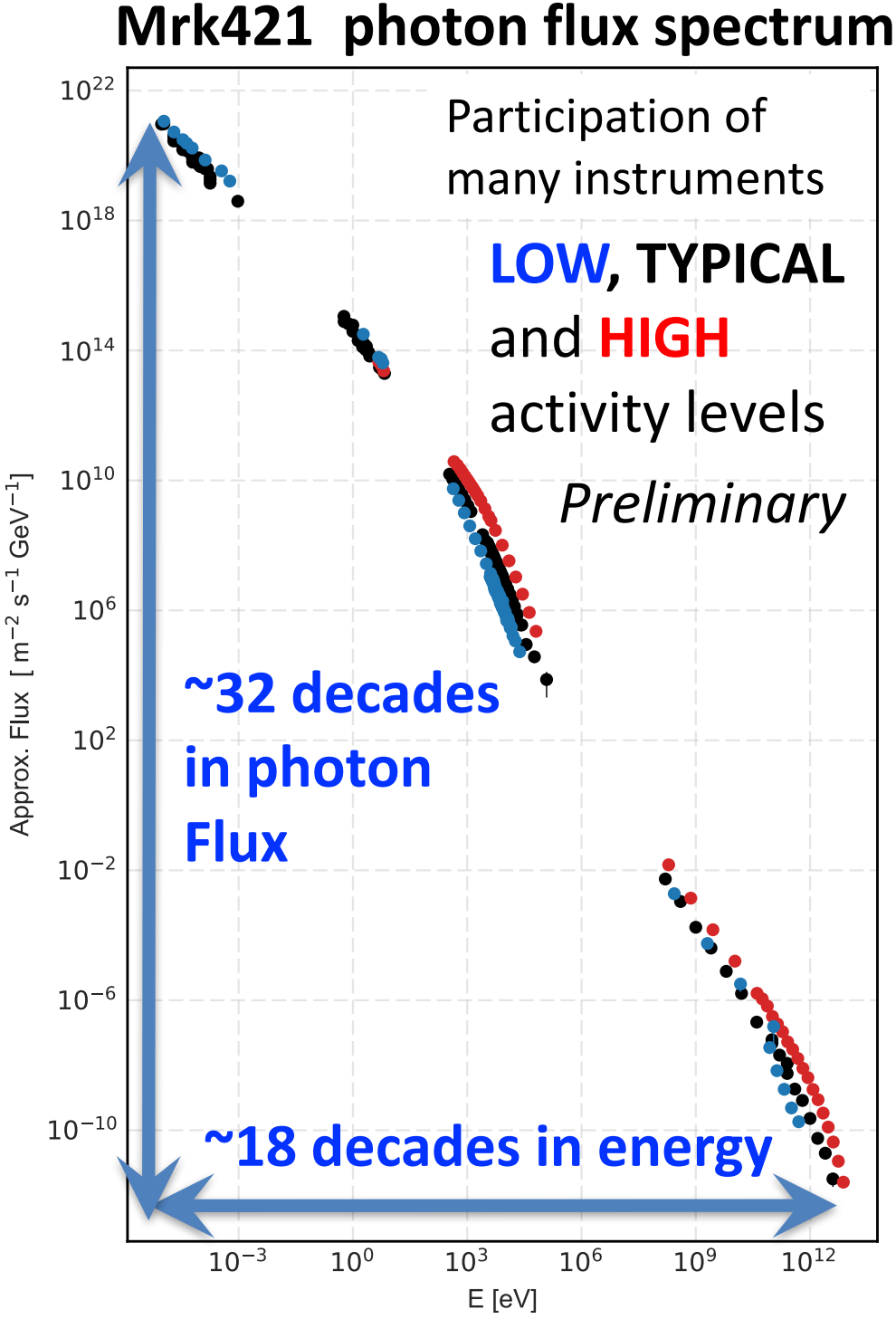
→ ***Need simultaneous observations from many instruments***




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]
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻⁷
10⁻⁴
10⁻¹
10²
10⁵
10⁸
10¹¹
10¹⁴

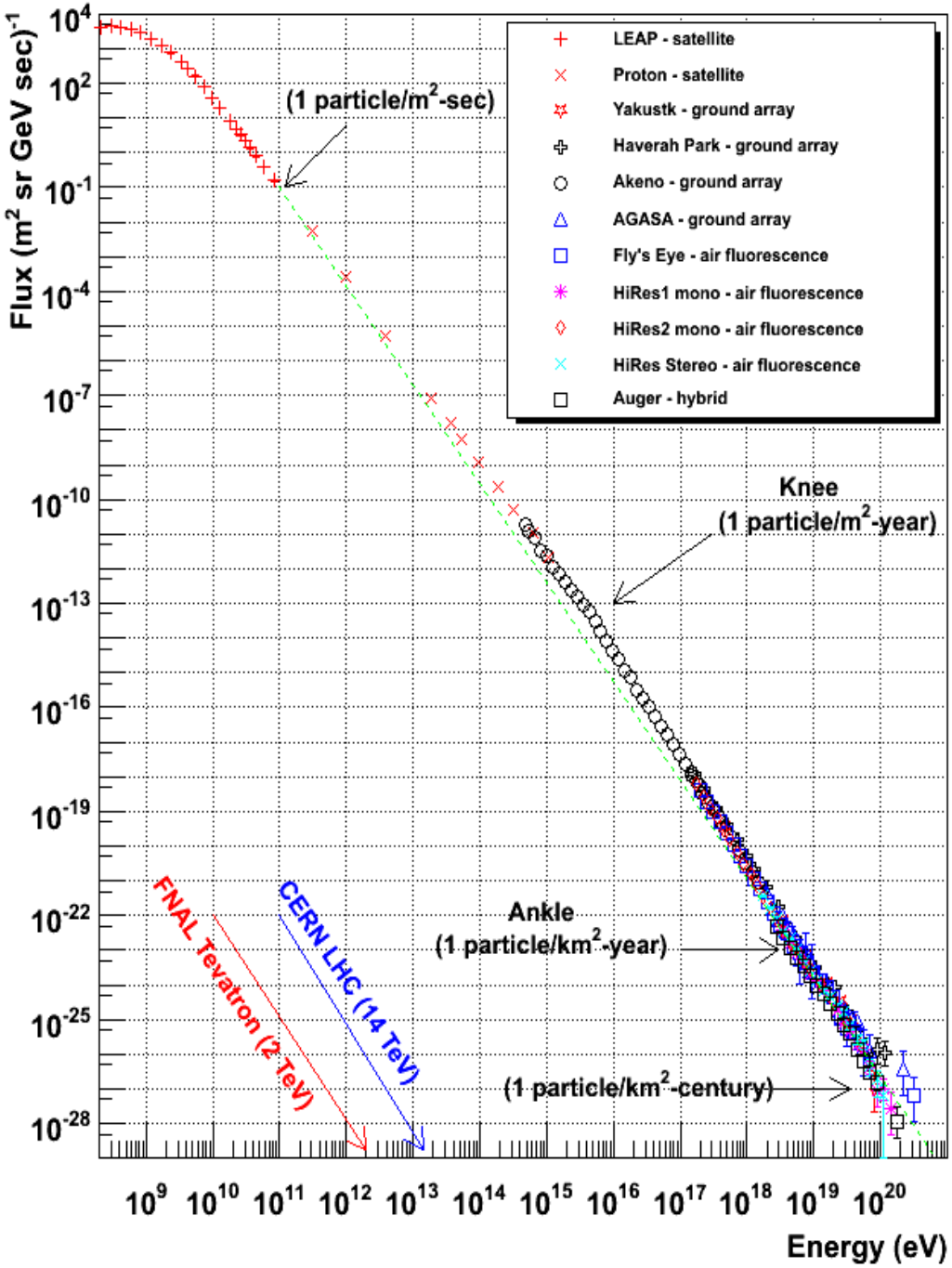

Change of energy flux by 2 orders of magnitude at X-rays and Gamma rays
Crucial to keep observing these objects over time, **simultaneously with many instruments**, and characterize its time evolution
>10 Crab
<0.1 Crab
Preliminary
Broadband SED of the Blazar Mrk 421,
(in units of flux energy density)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

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

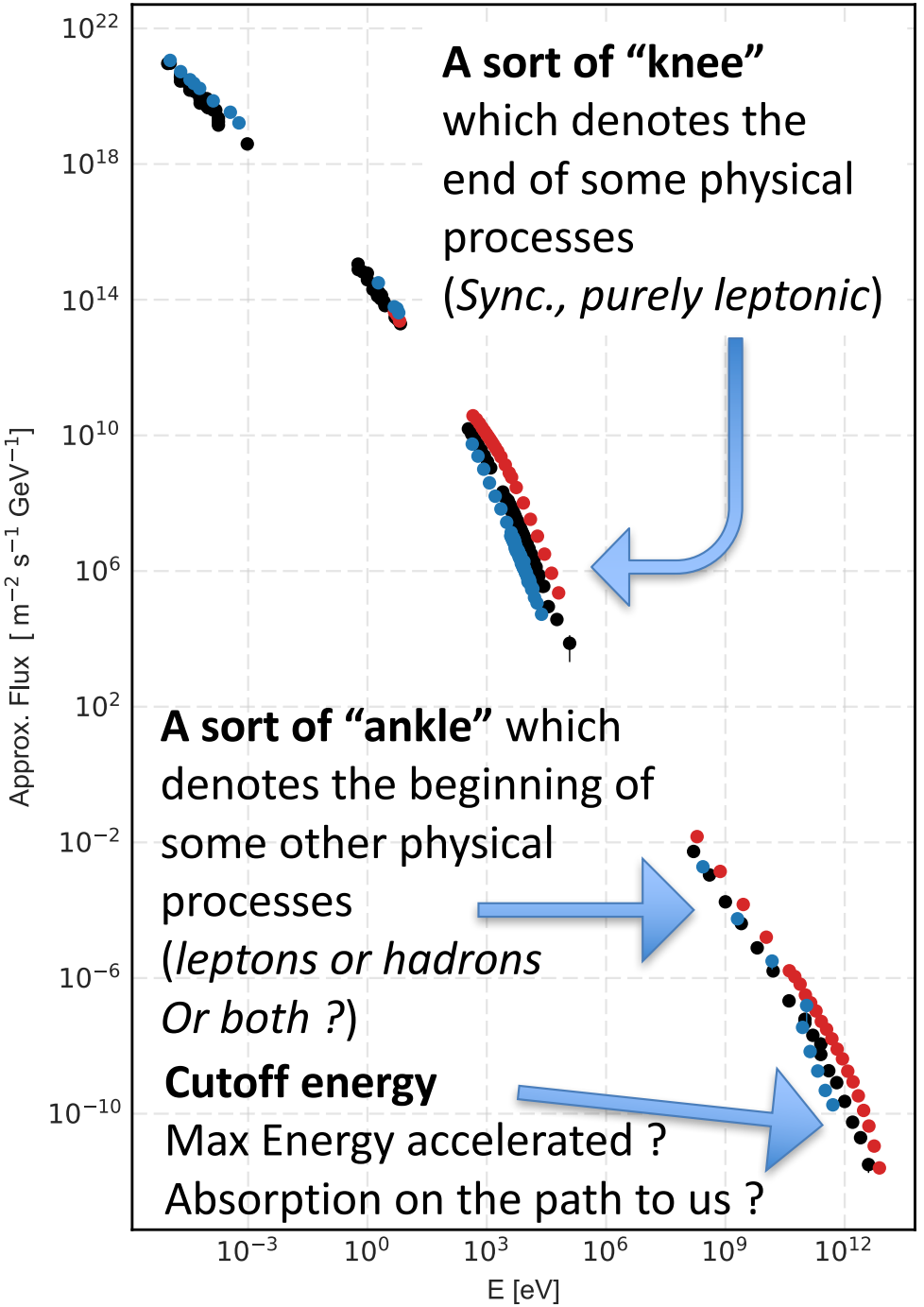


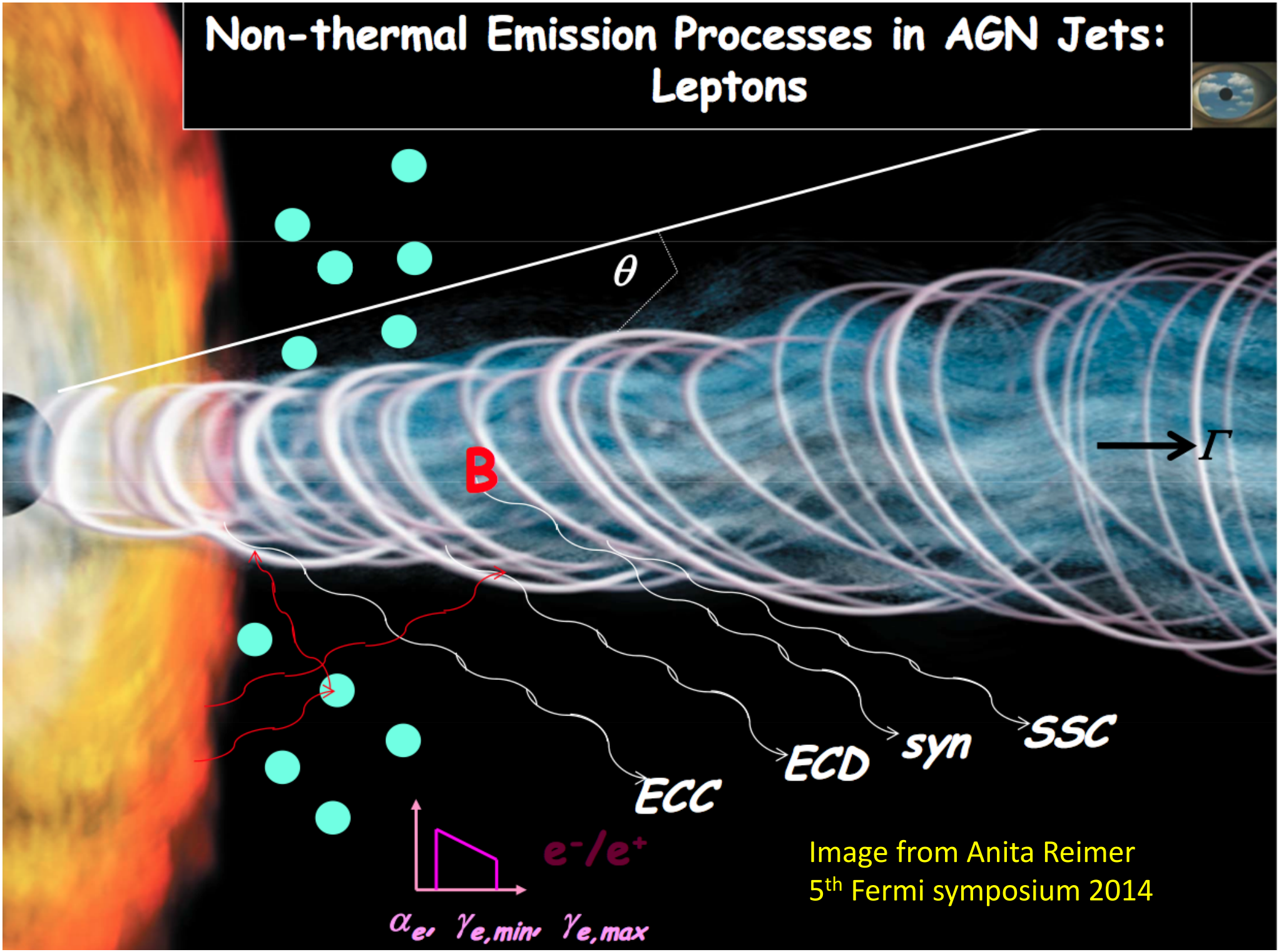
In this representation, the **Low**, **Typical** and **High** activities do not “look” that different ...

Cosmic Ray Spectra of Various Experiments



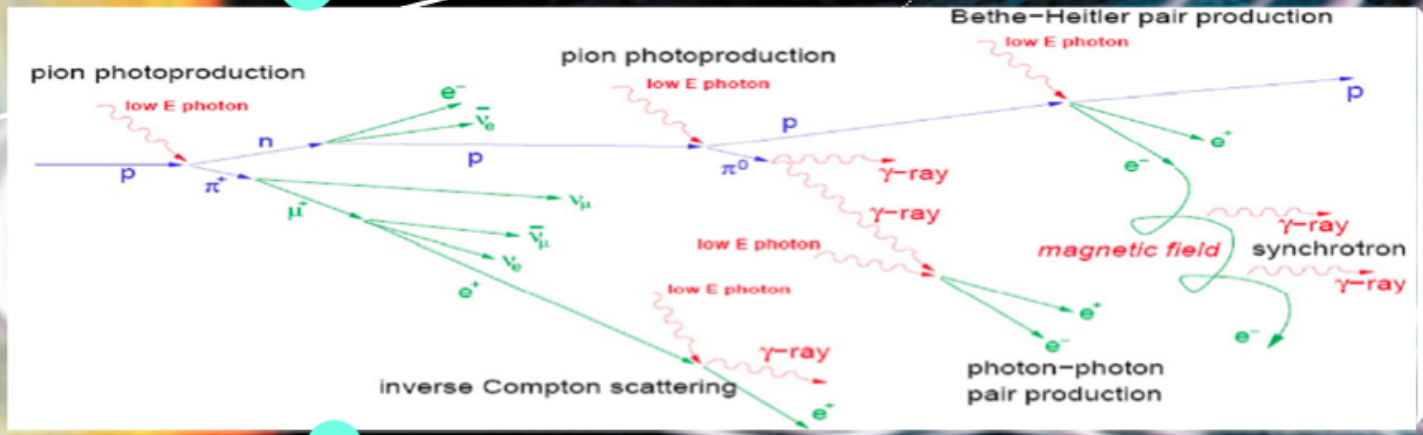
Mrk421 photon flux spectrum

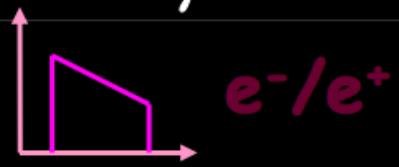


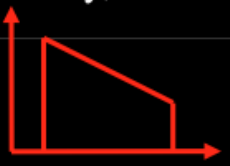

Non-thermal Emission Processes in AGN Jets:
Leptons
θ
B
Γ
ECC
ECD
syn
SSC
e⁻/e⁺
α_e, γ_e,min, γ_e,max
Image from Anita Reimer
5th Fermi symposium 2014

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

Image from Anita Reimer
5th Fermi symposium 2014

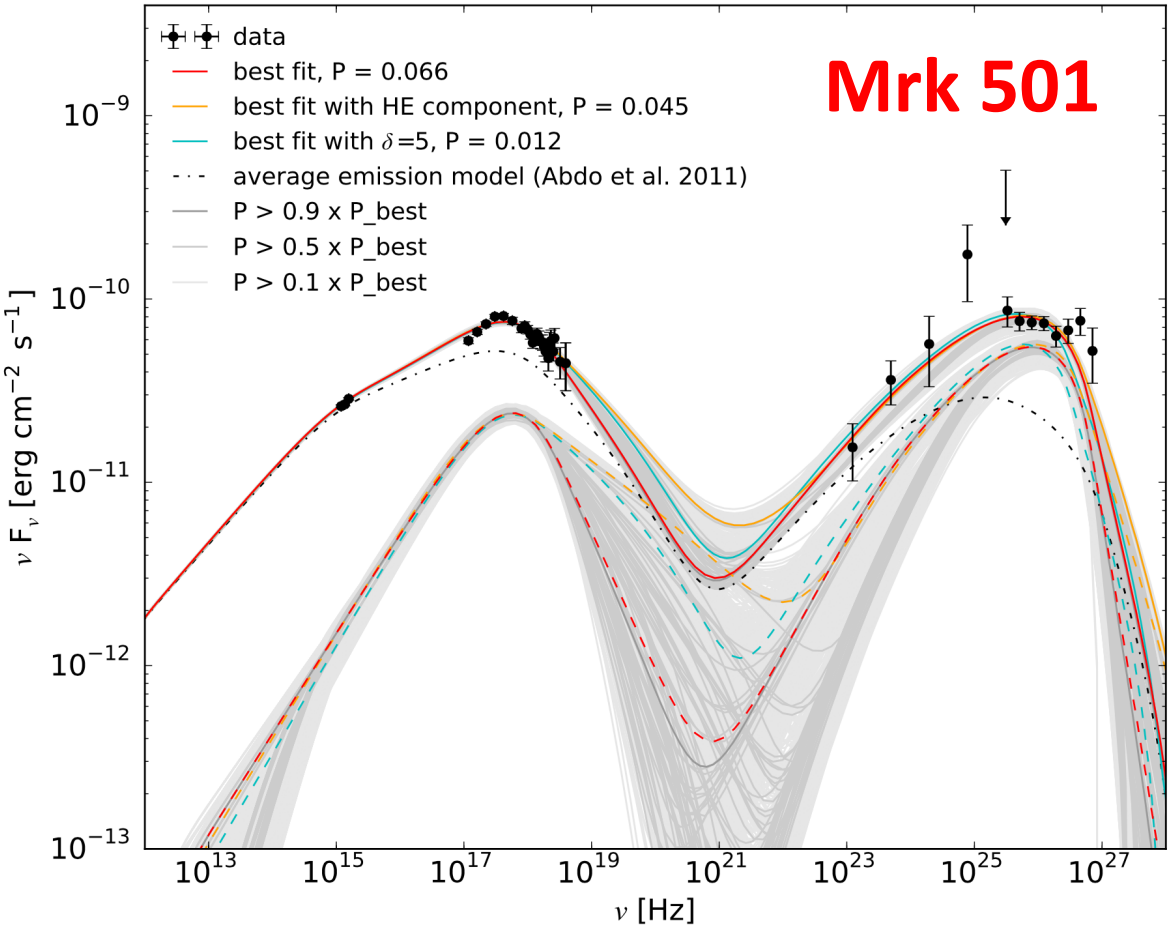






Large intra-model degeneracy for broadband SEDs

Broadband emission (*solid lines*) described with a "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.

Large inter-model degeneracy for broadband SEDs

Leptonic scenario

→ need electrons with $E>10^{13}$ eV

Hadronic scenario

→ need protons with $E>10^{18}$ eV

Abdo et al., ApJ 736 (2011) 131

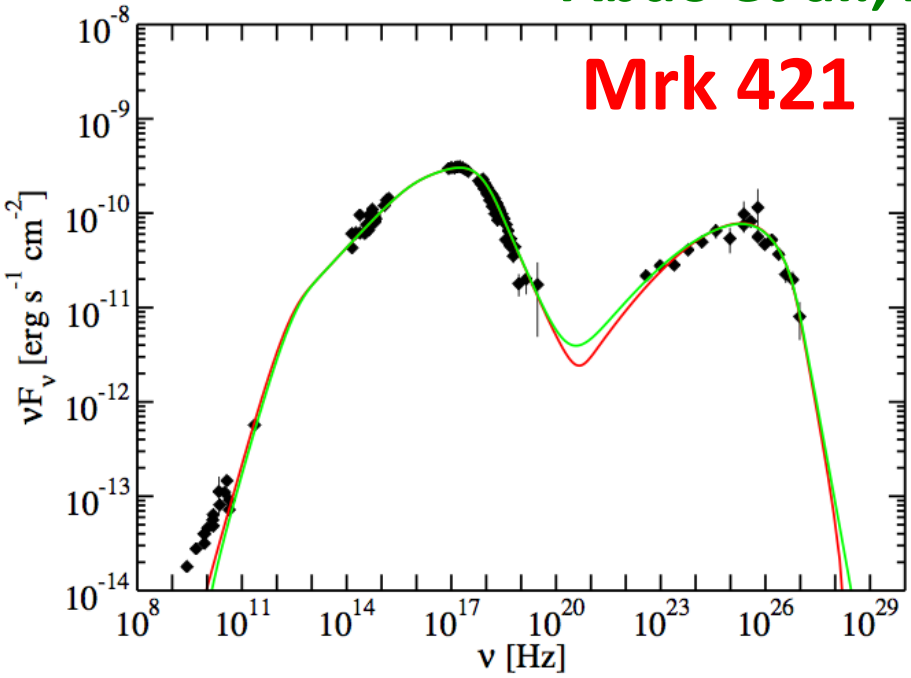


Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{var} = 1$ day (red curve) and $t_{var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

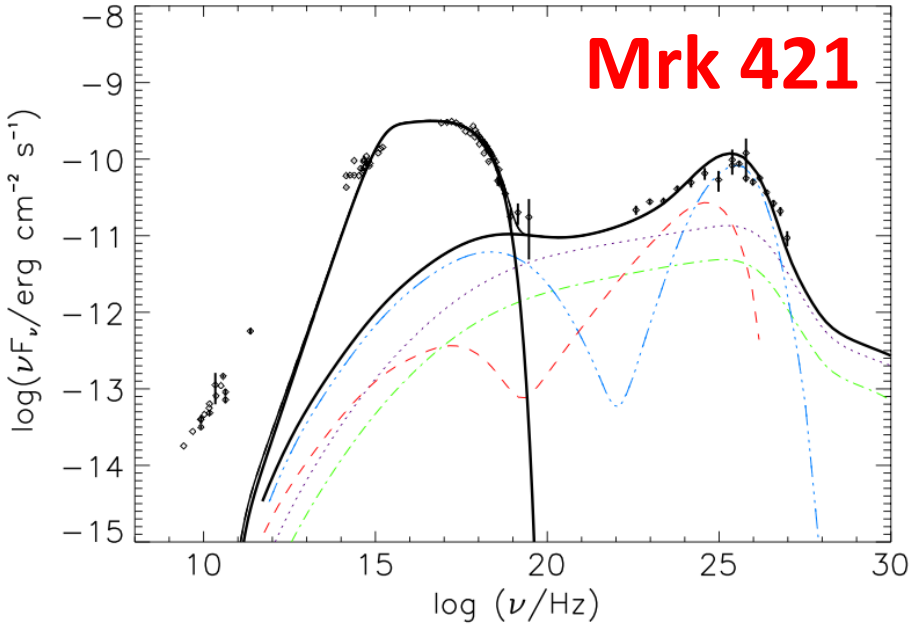


Figure 9. Hadronic model fit components: π^0-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), μ-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which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

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**

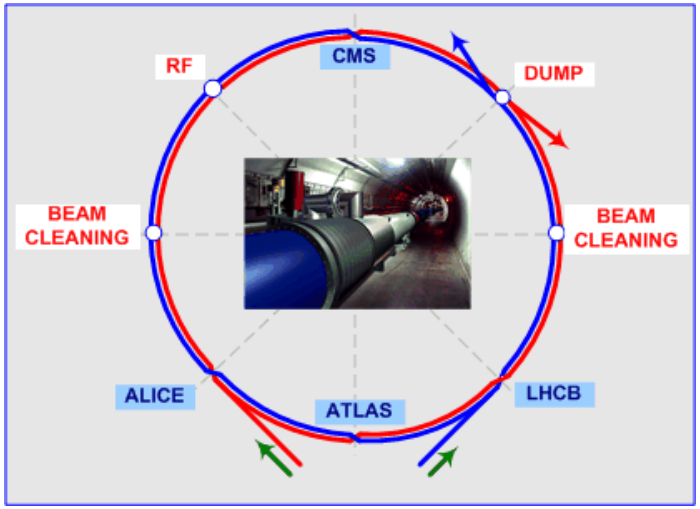
It is more difficult to study other blazars that are farther away, dimmer, or have more complicated structures

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

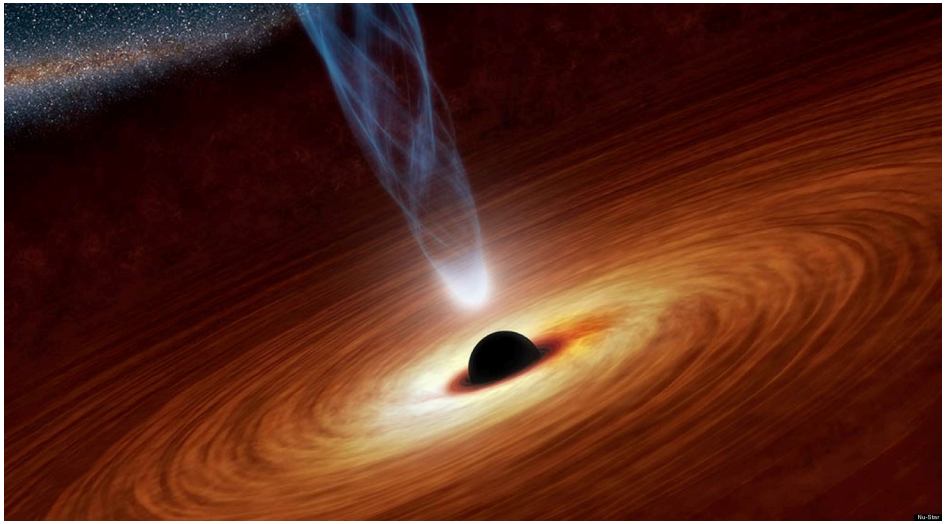
Bright blazars as our Extreme Cosmic Accelerators

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

ATLAS/CMS
LHCb + Alice



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



Bright blazars as our Extreme Cosmic Accelerators

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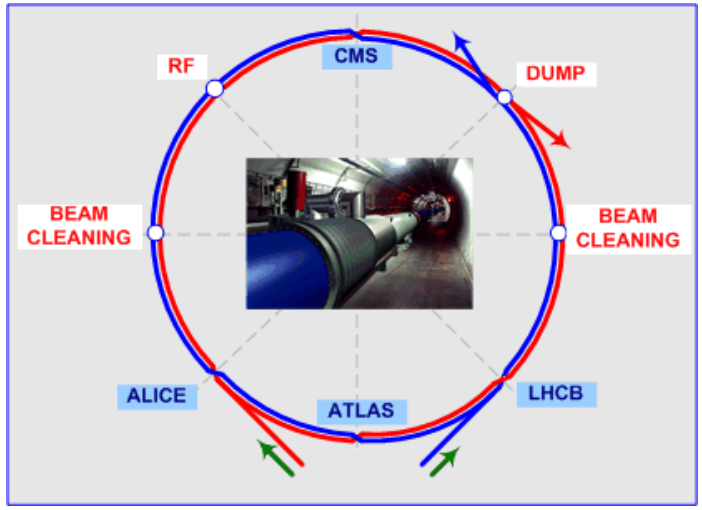
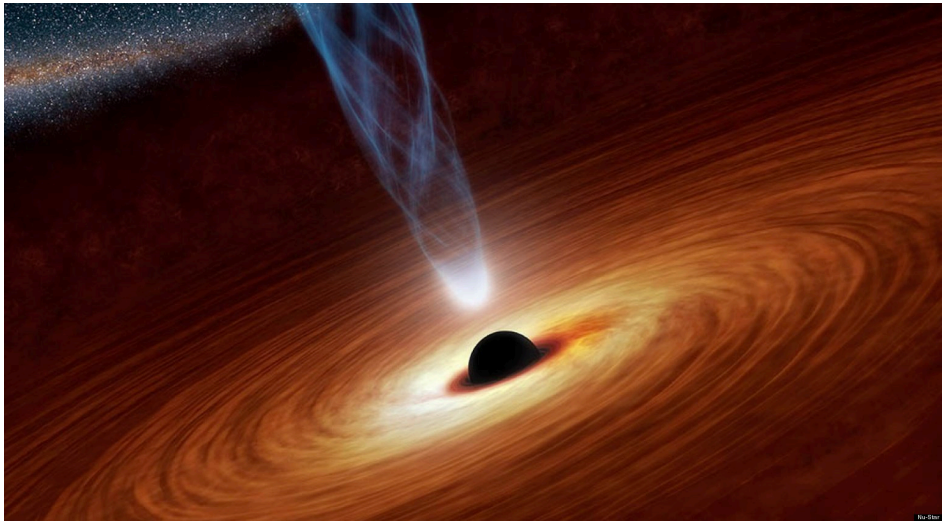




Physics studies with cosmic particle accelerators

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* !)

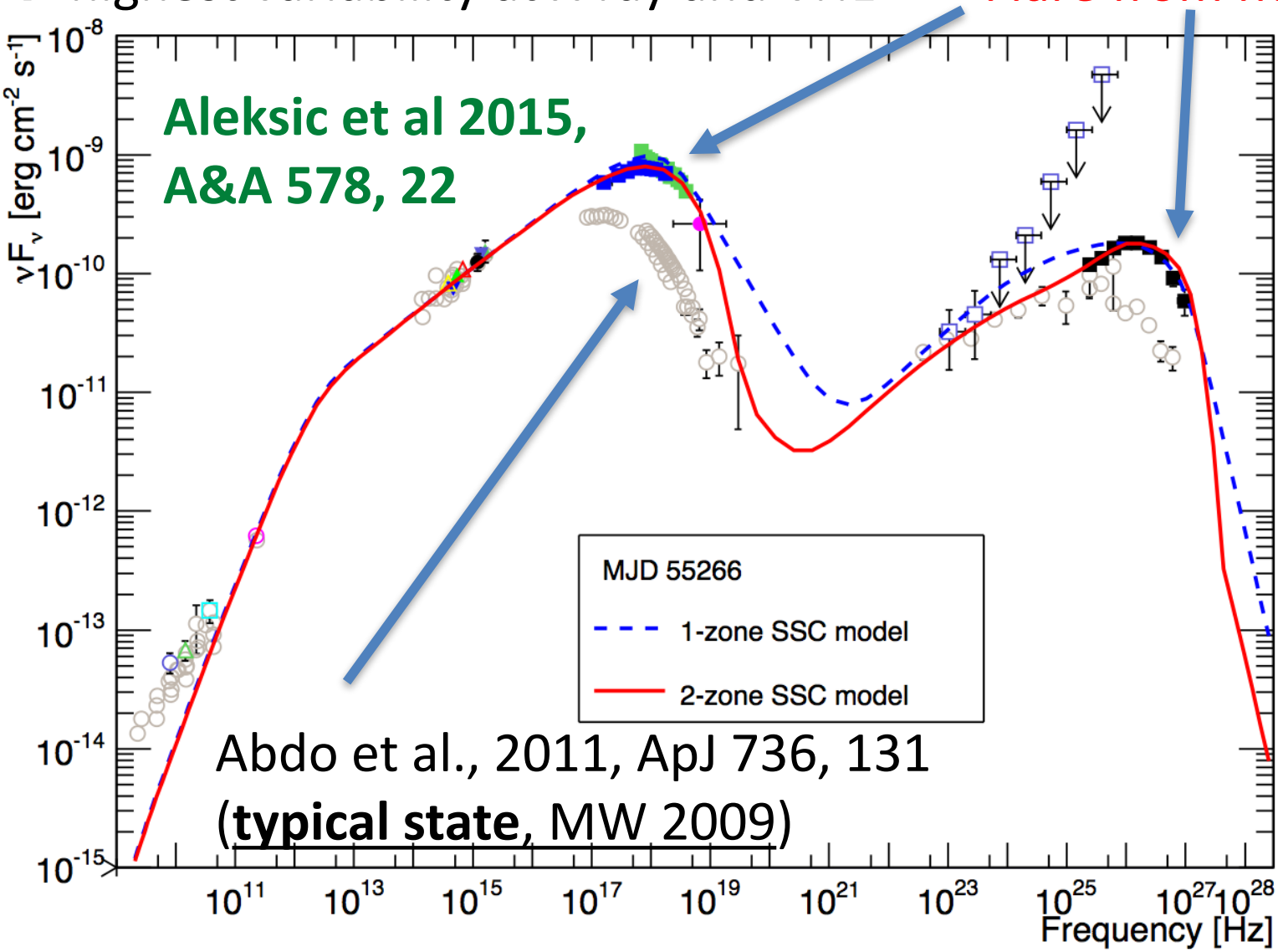
- **Some recent results from the campaigns**

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

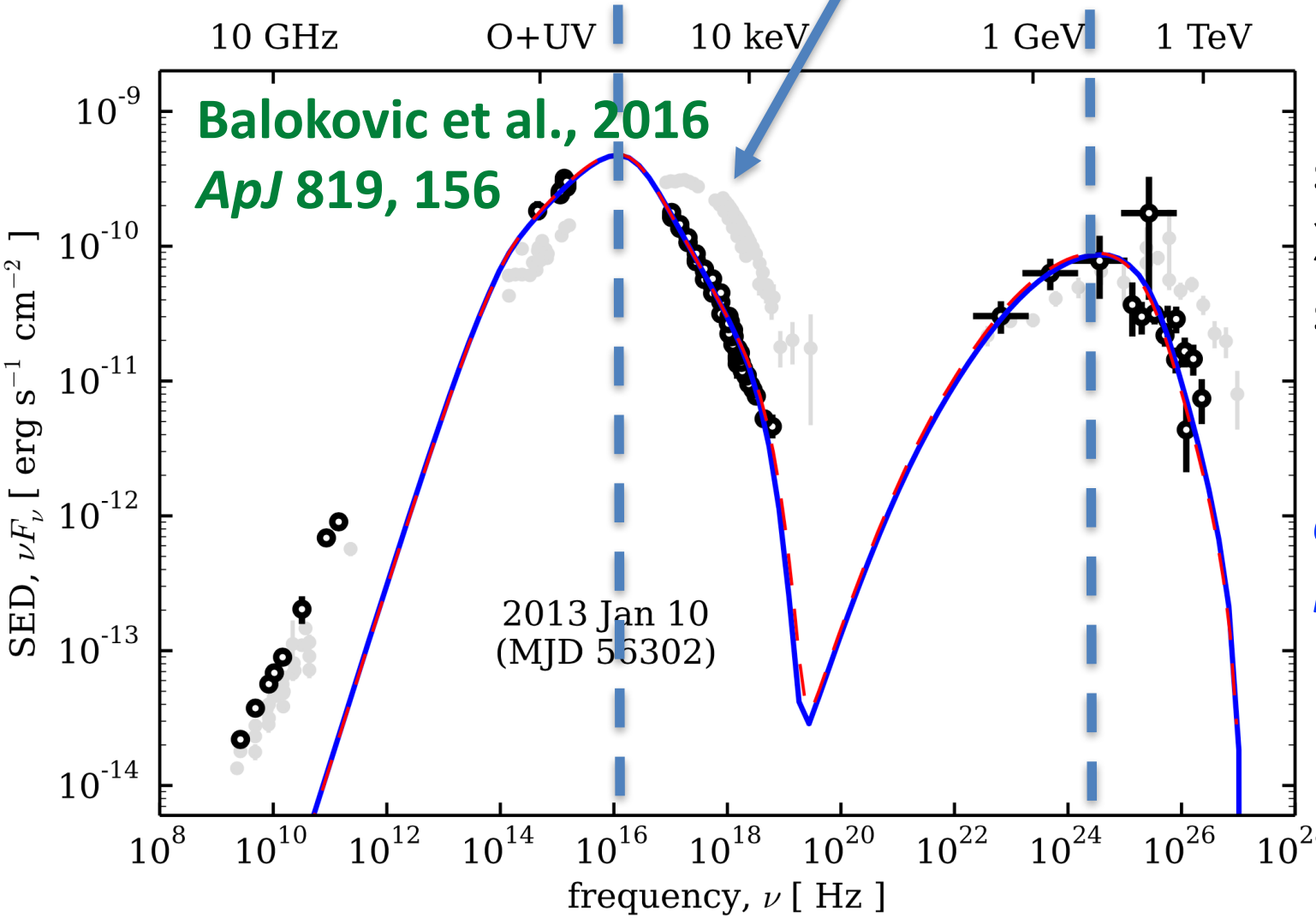
→ highest variability at X-ray and VHE



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**)



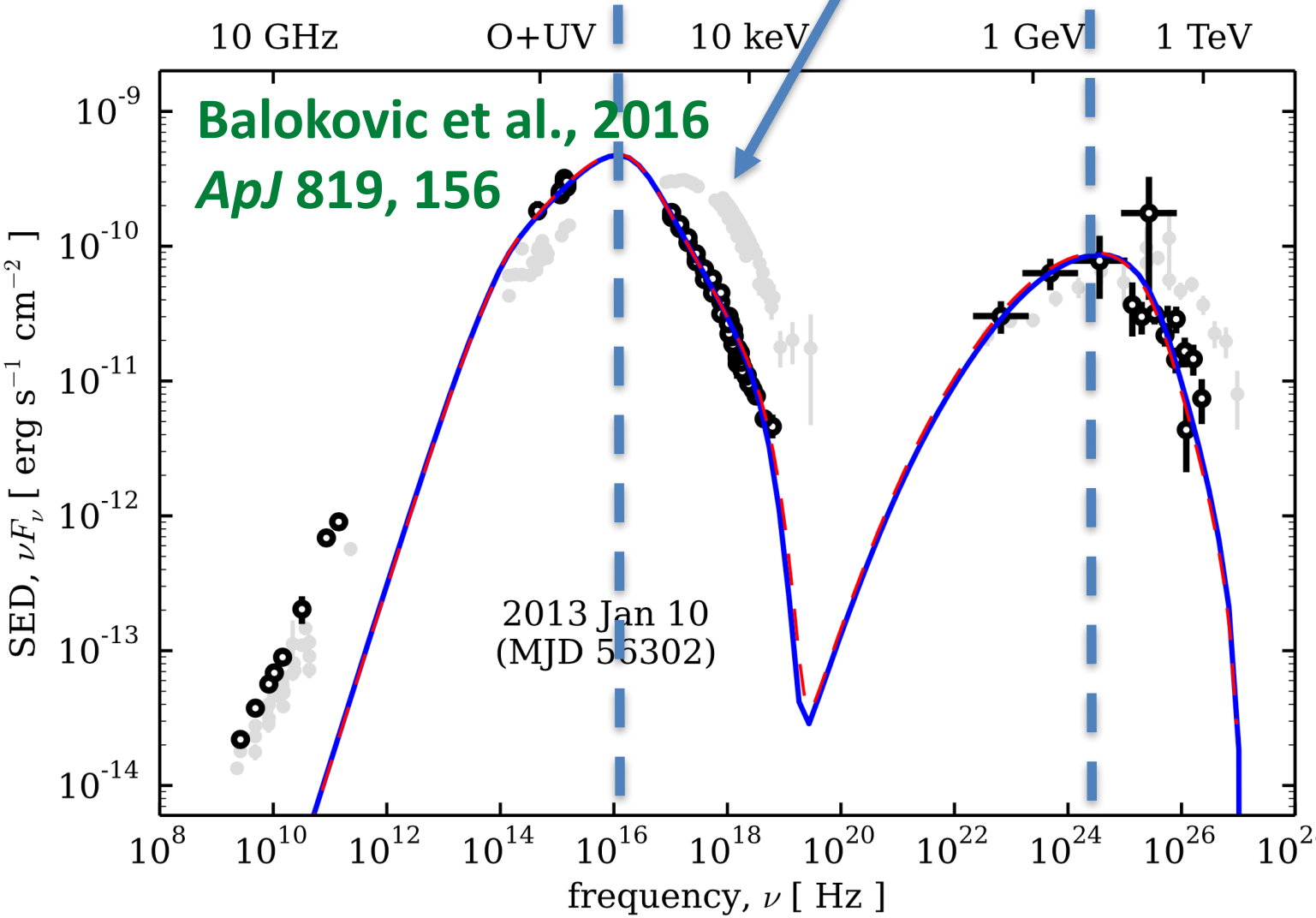
Low activity softened the X-ray and VHE spectra, but did not bring cutoffs

→ 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"*

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

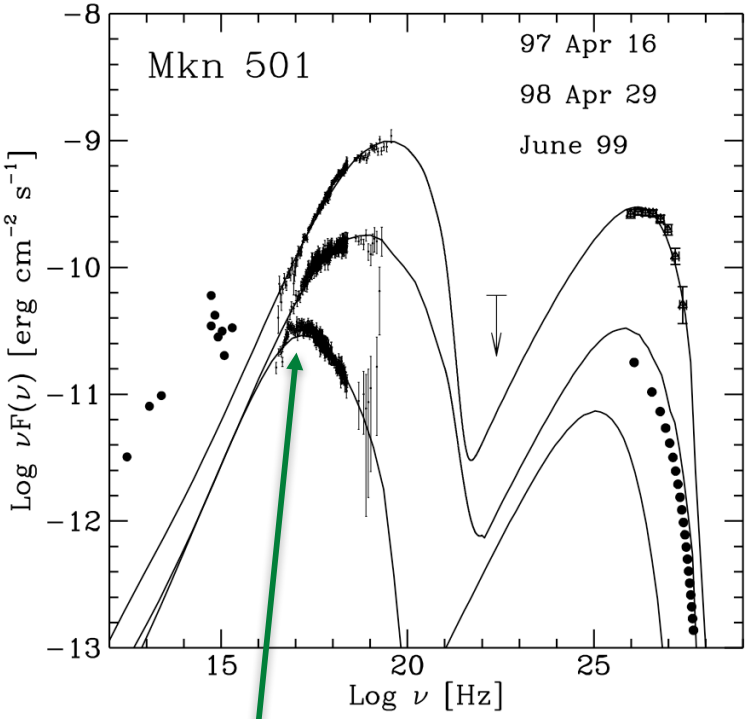


Low activity is as interesting as high activity (flares), *but can only be studied in detail on the brightest sources and with highly sensitive instruments*

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

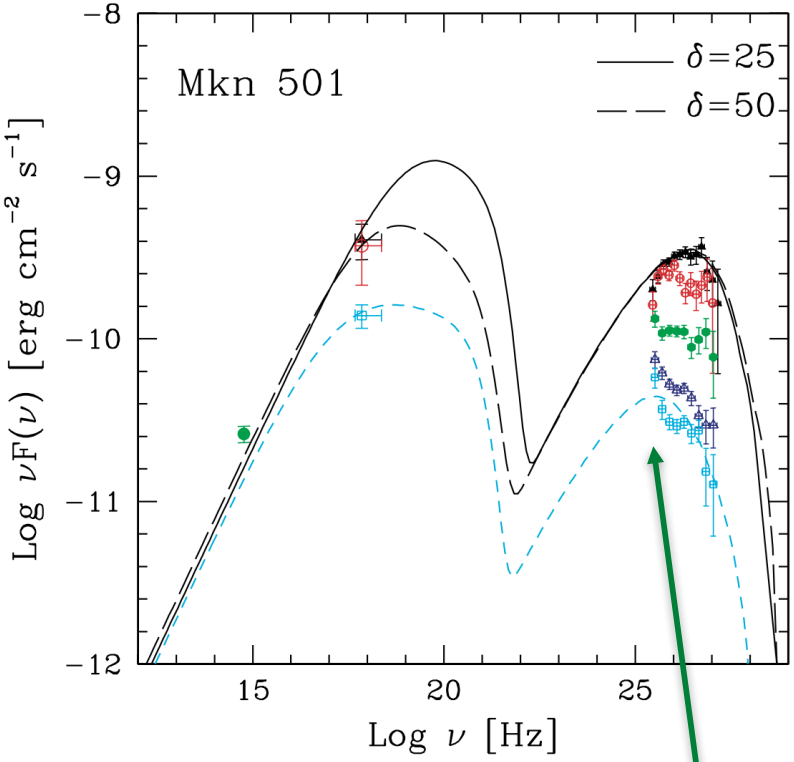
(Historical) flare in 1997

Tavecchio et al., 2001, ApJ 554,725



(fast variability) flare in 2005

Albert et al., 2007, ApJ 669,862



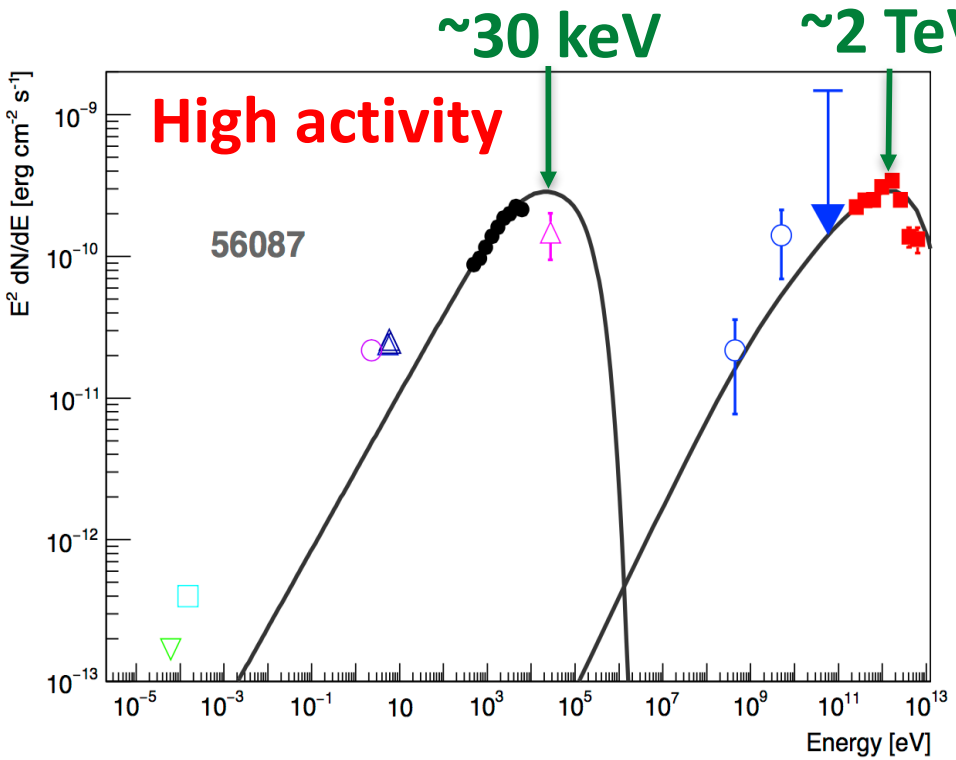
Hard spectra in Mrk501 not observed during low states,

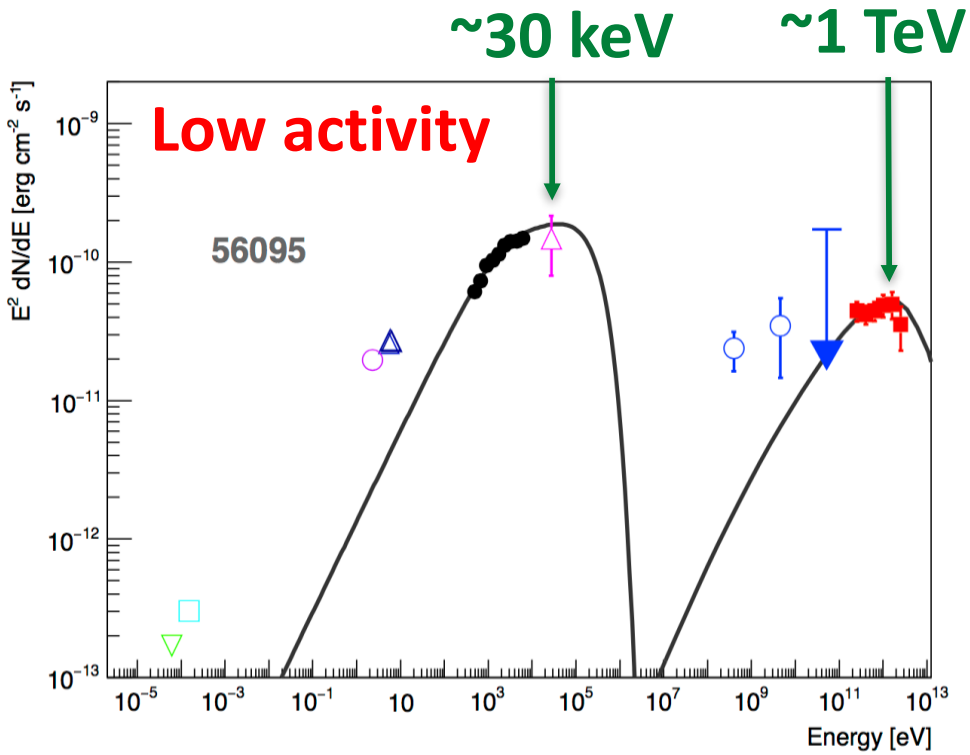
< 1 keV

< 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., 2018
A&A 620 , 181

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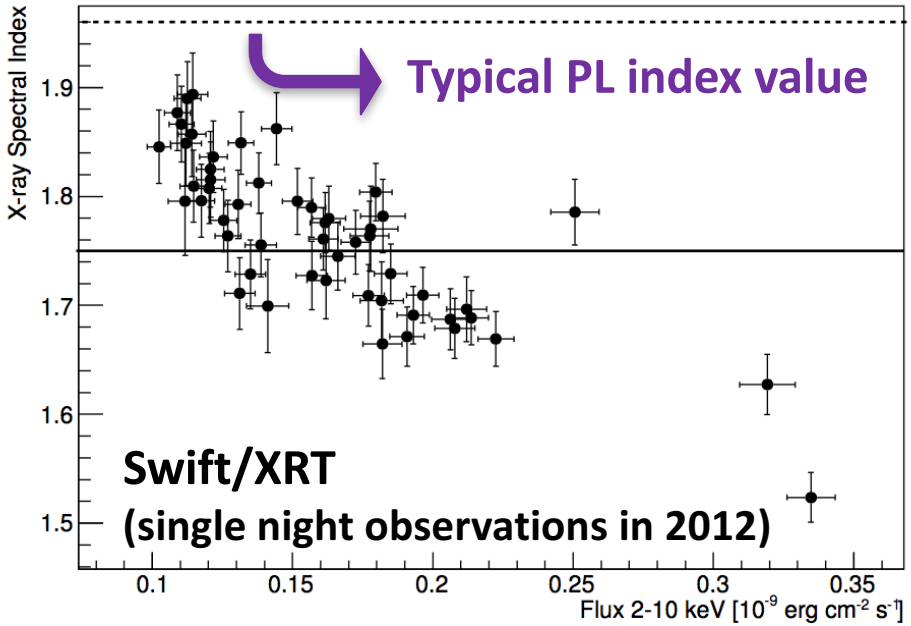
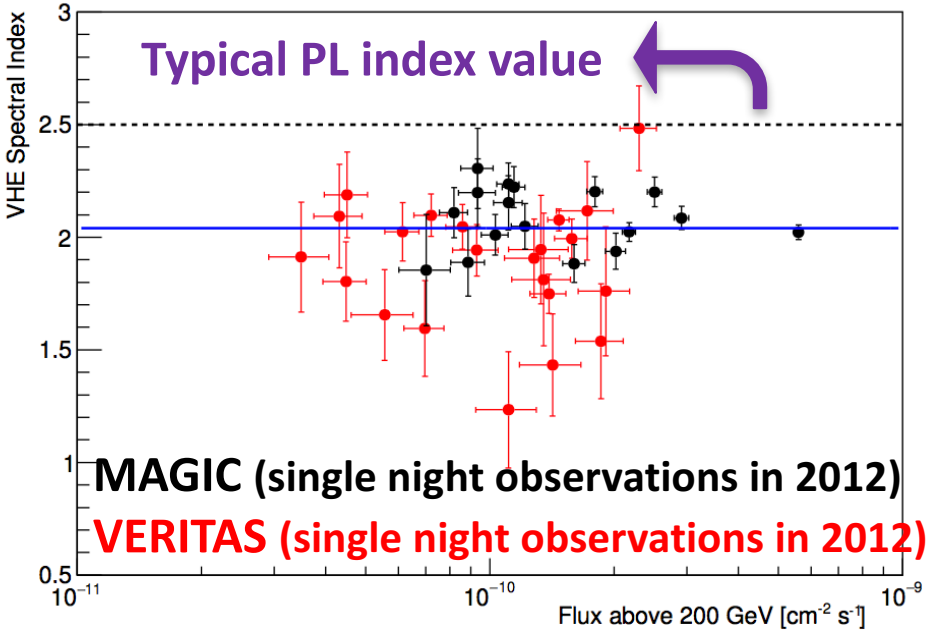
Ahnen et al., 2018 A&A 620 , 181





→ **Mrk 501 behaved as Extreme HBL!**

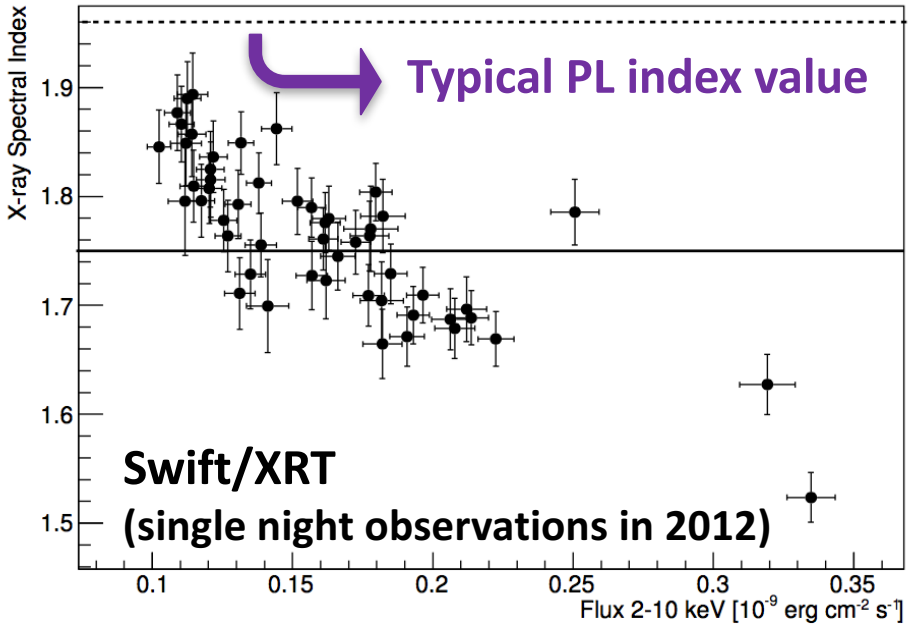
Similar X-ray/VHE spectra as 1ES 0229+200, 1ES 0347-121 (Peaks at ~10 keV and ~1TeV)

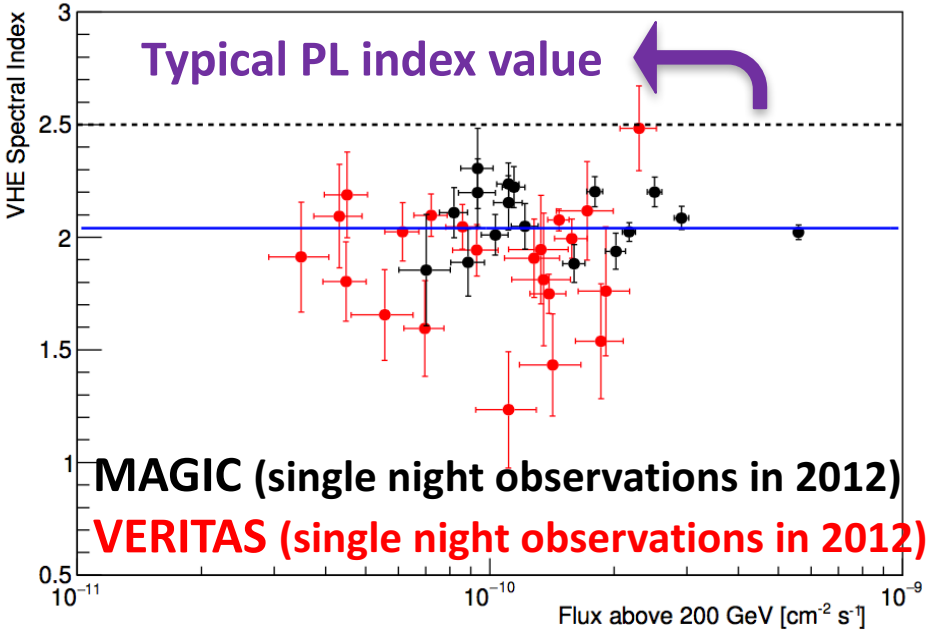
Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic

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., 2018 A&A 620 , 181





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

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

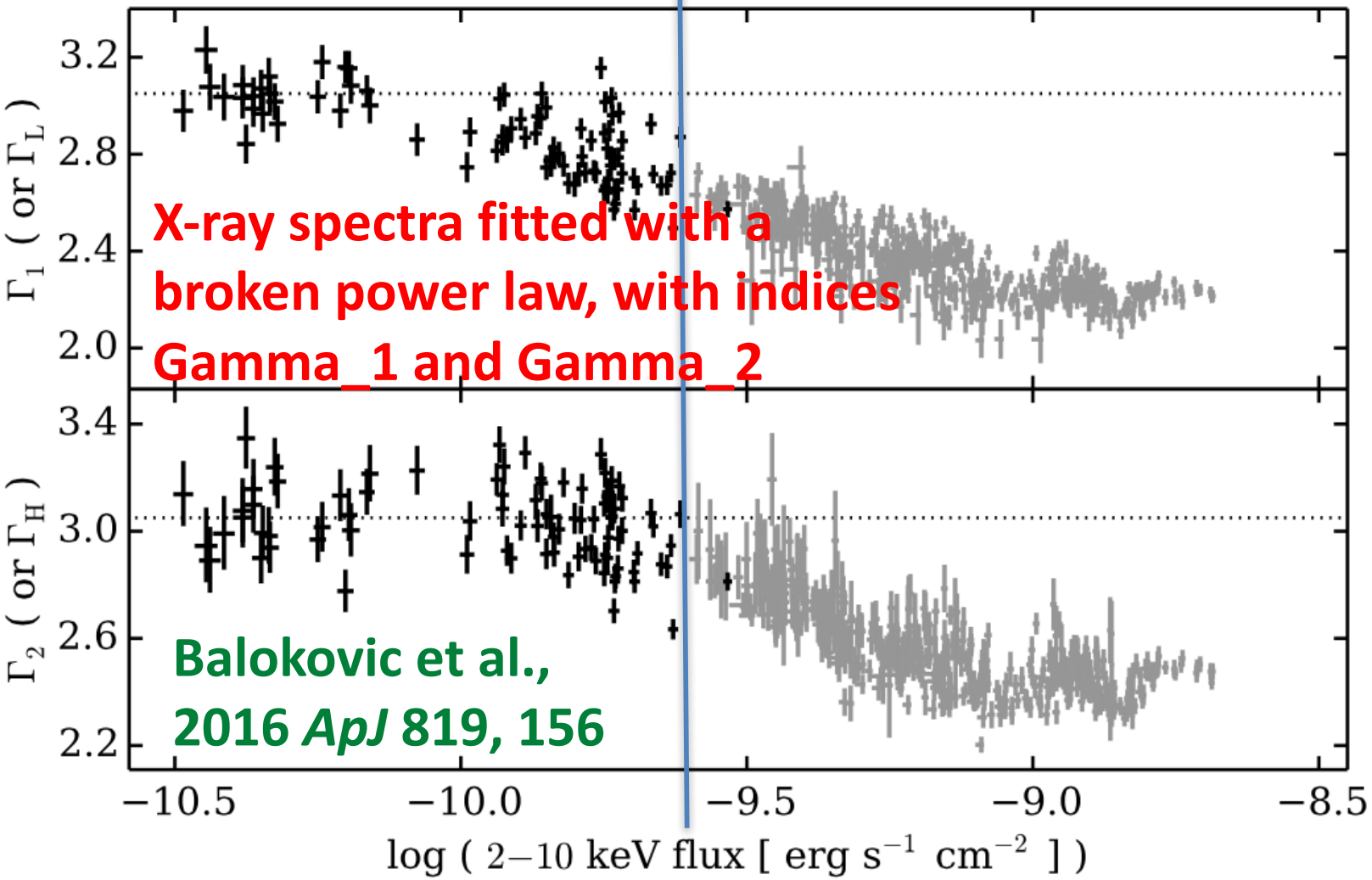
Precision on 1ES 0229 needs CTA !!

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

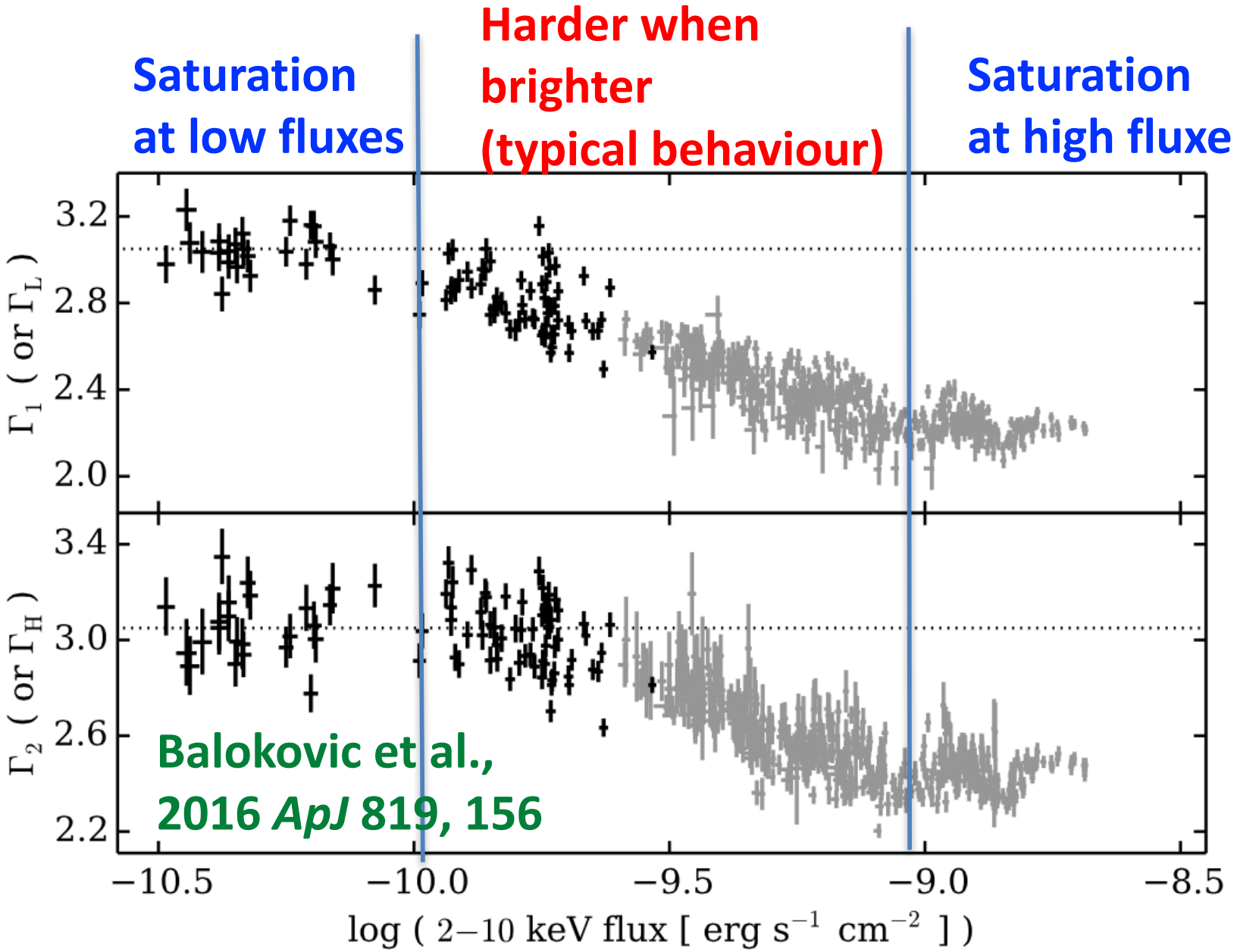
X-ray spectral shape vs. X-ray flux for Mrk421

NuSTAR spectra (2013 campaign)

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

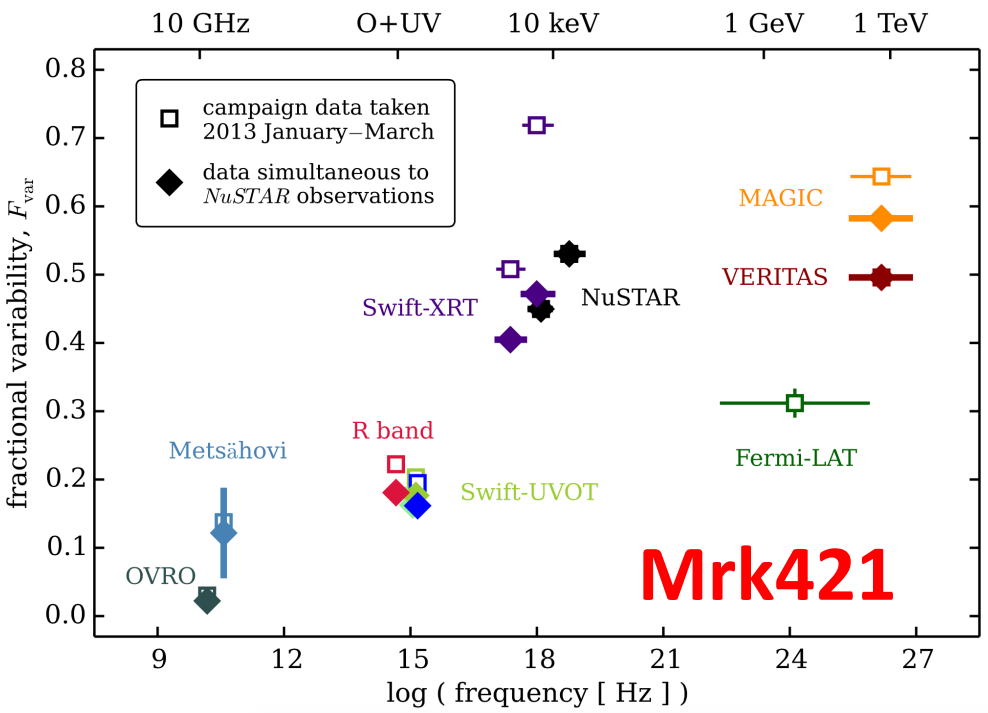


X-ray spectral shape vs. X-ray flux for Mrk421

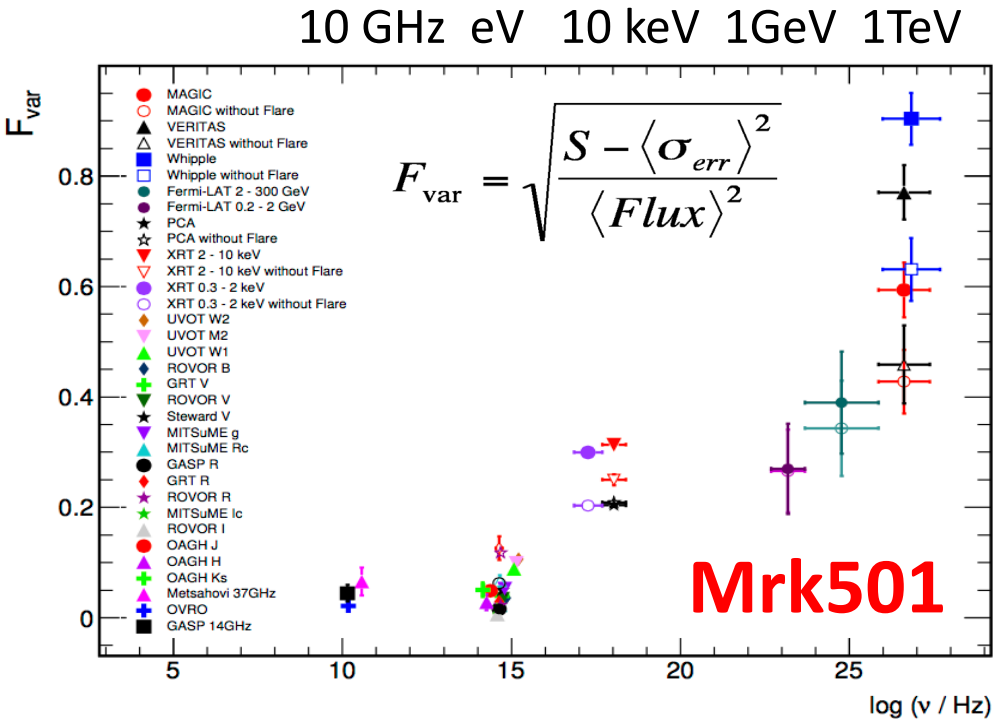


Comparison of variability between the two archetypical TeV blazars: Mrk421 vs. Mrk501

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



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



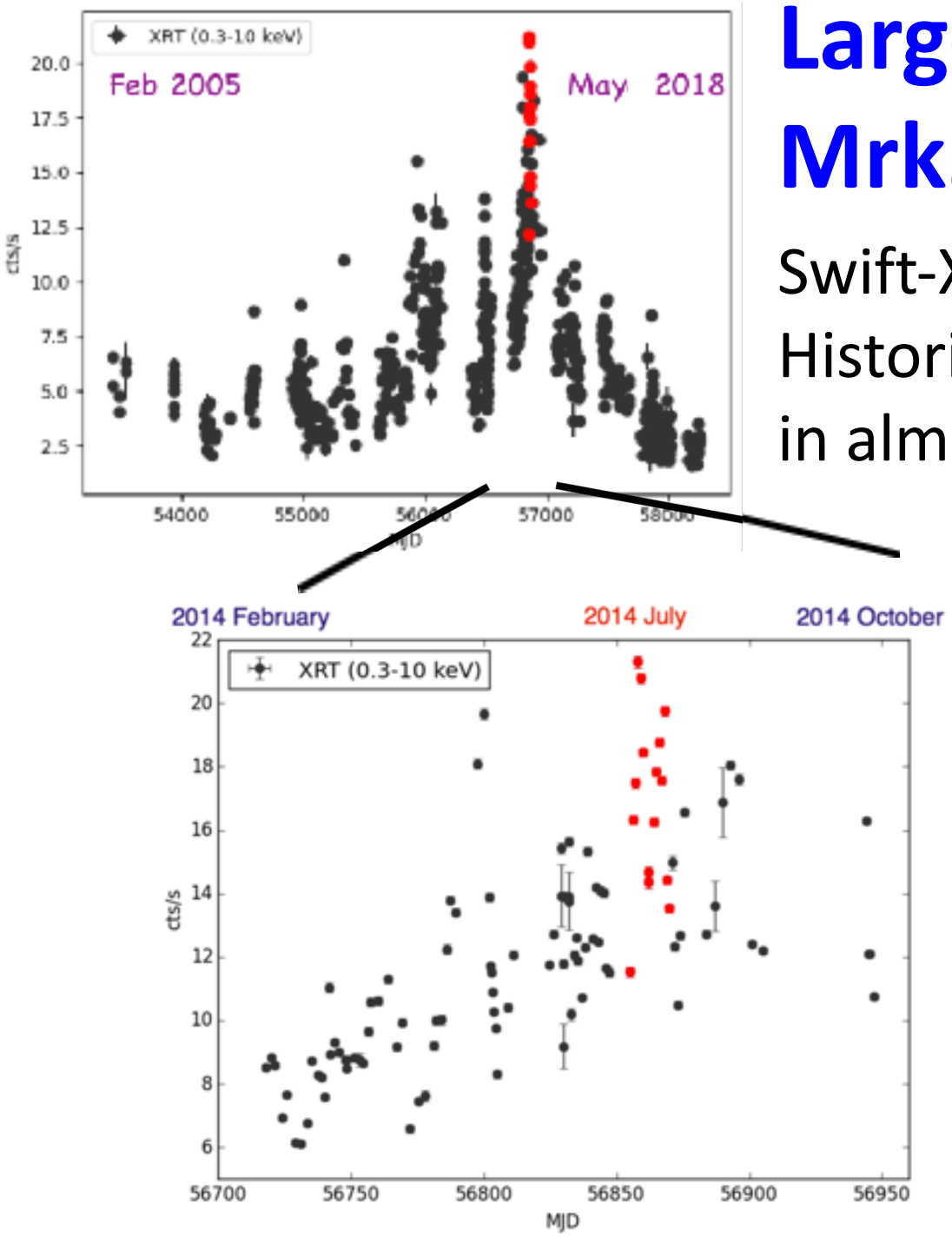
Typically:

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”

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

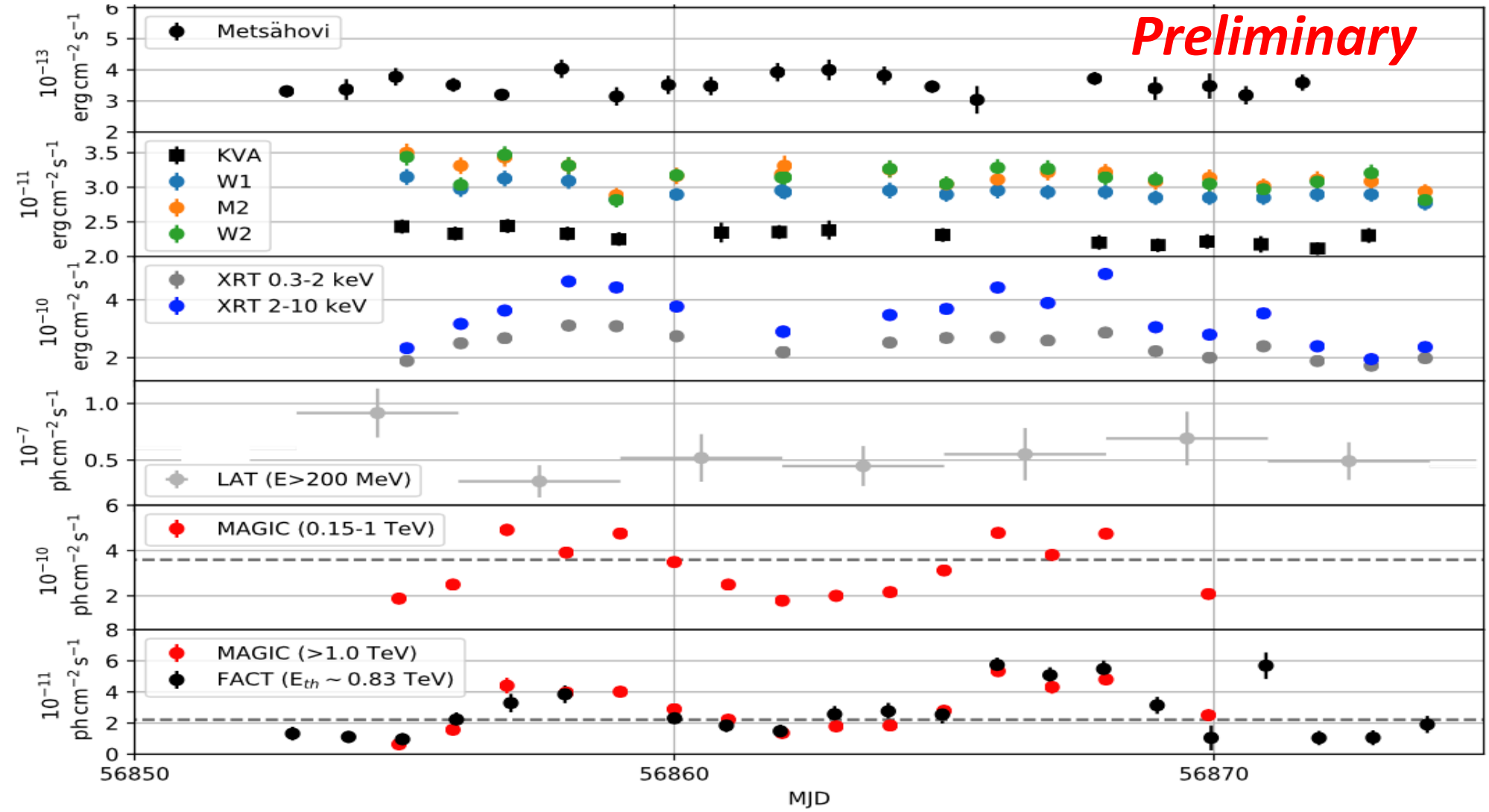
Multi-band Light Curve during the July 2014 flaring activity

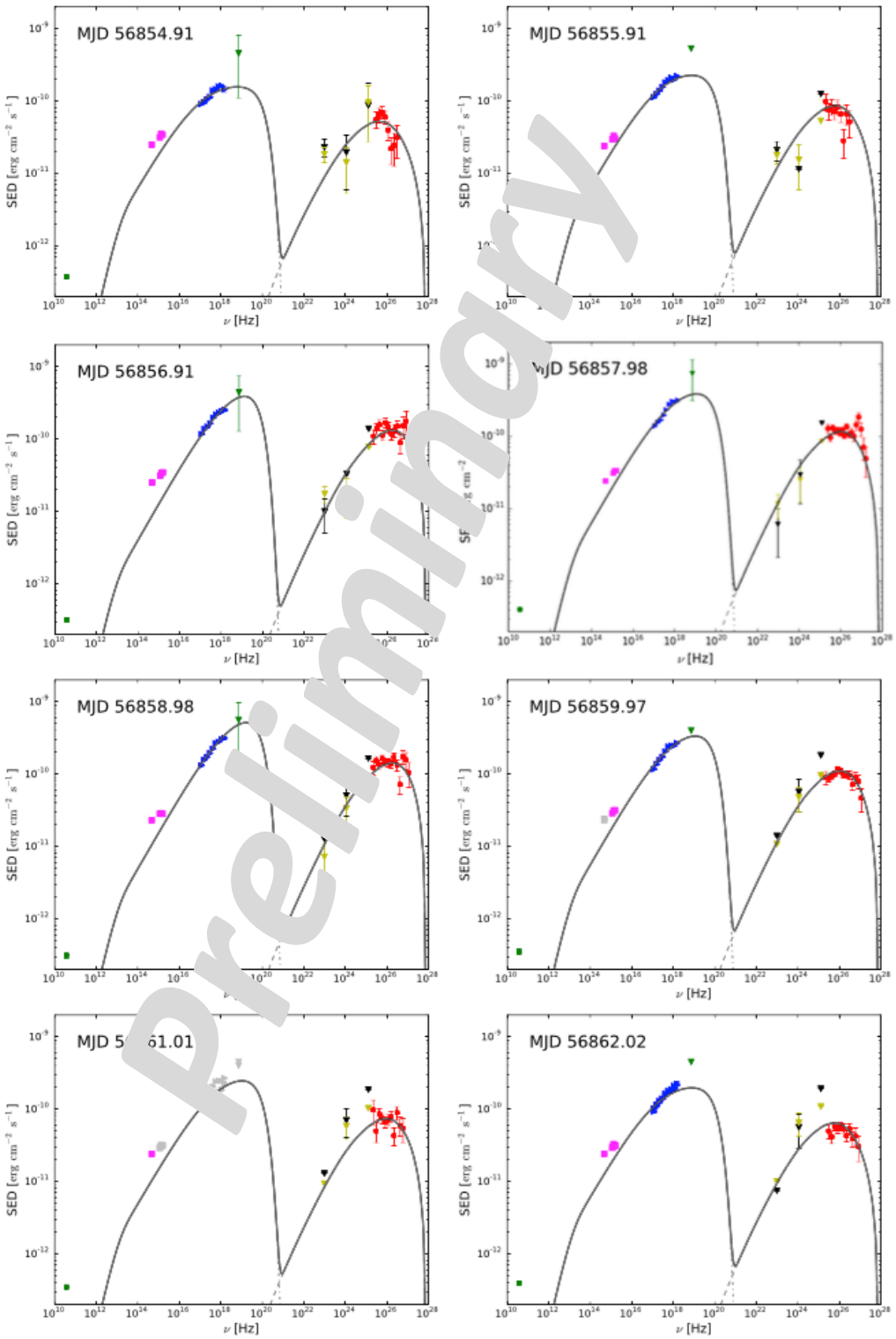
Largest variability occurs in X-rays and VHE

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

Acciari et al, submitted

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



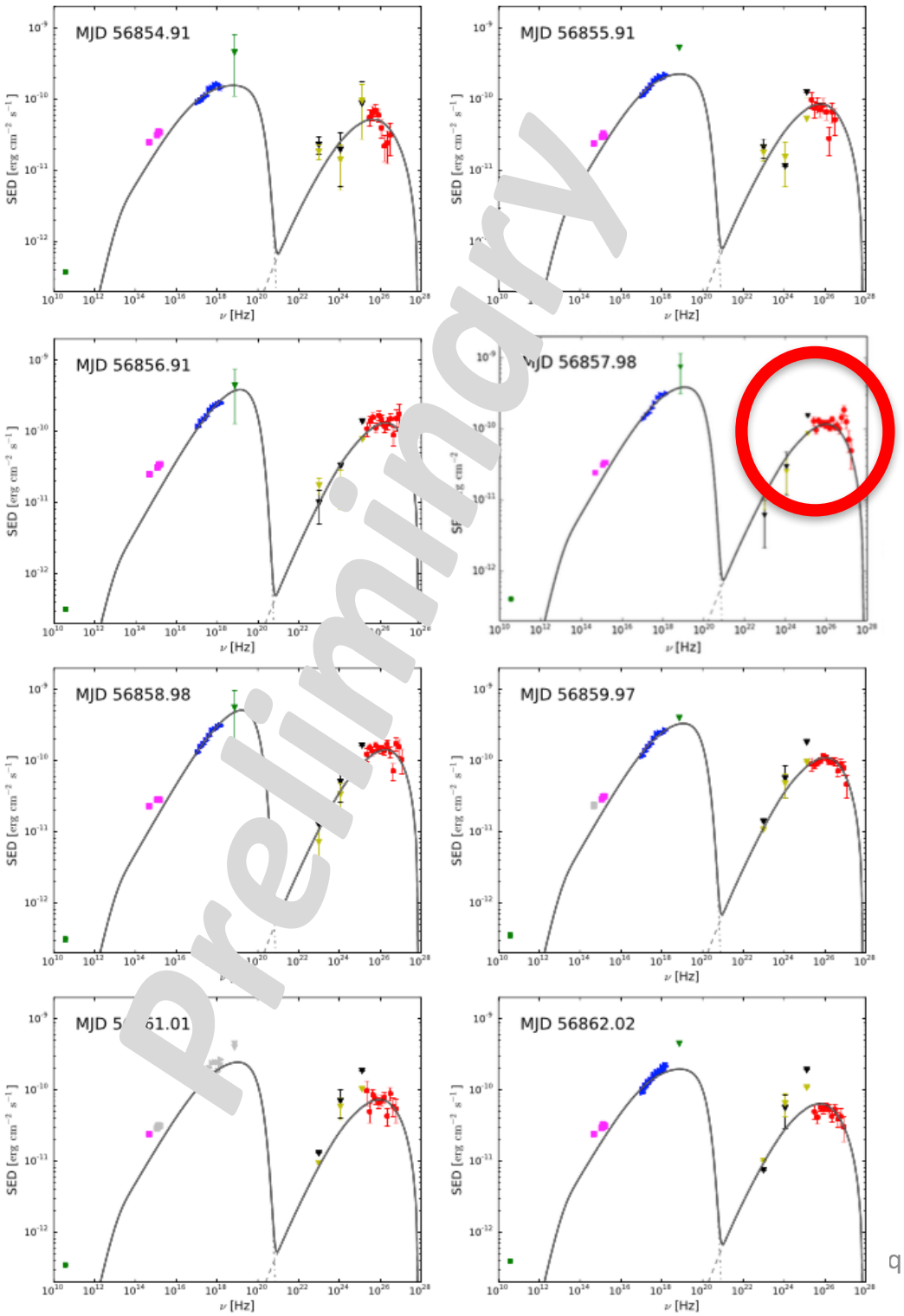


Large flaring activity of Mrk501 in July 2014

Acciari et al, submitted

Broadband SEDs can be constructed for single (observations) nights

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



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 ?

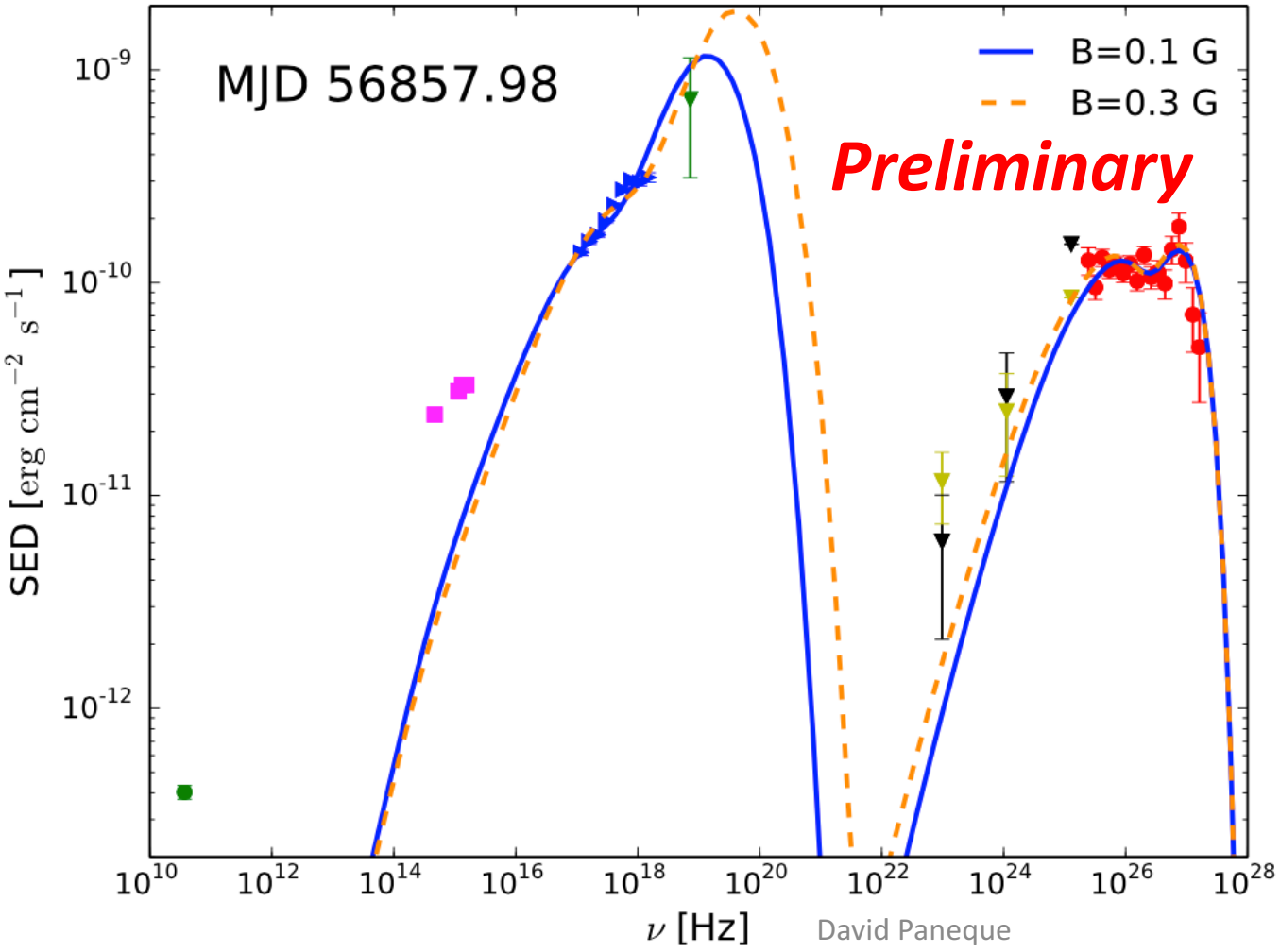
que

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

Acciari et al, submitted

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

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



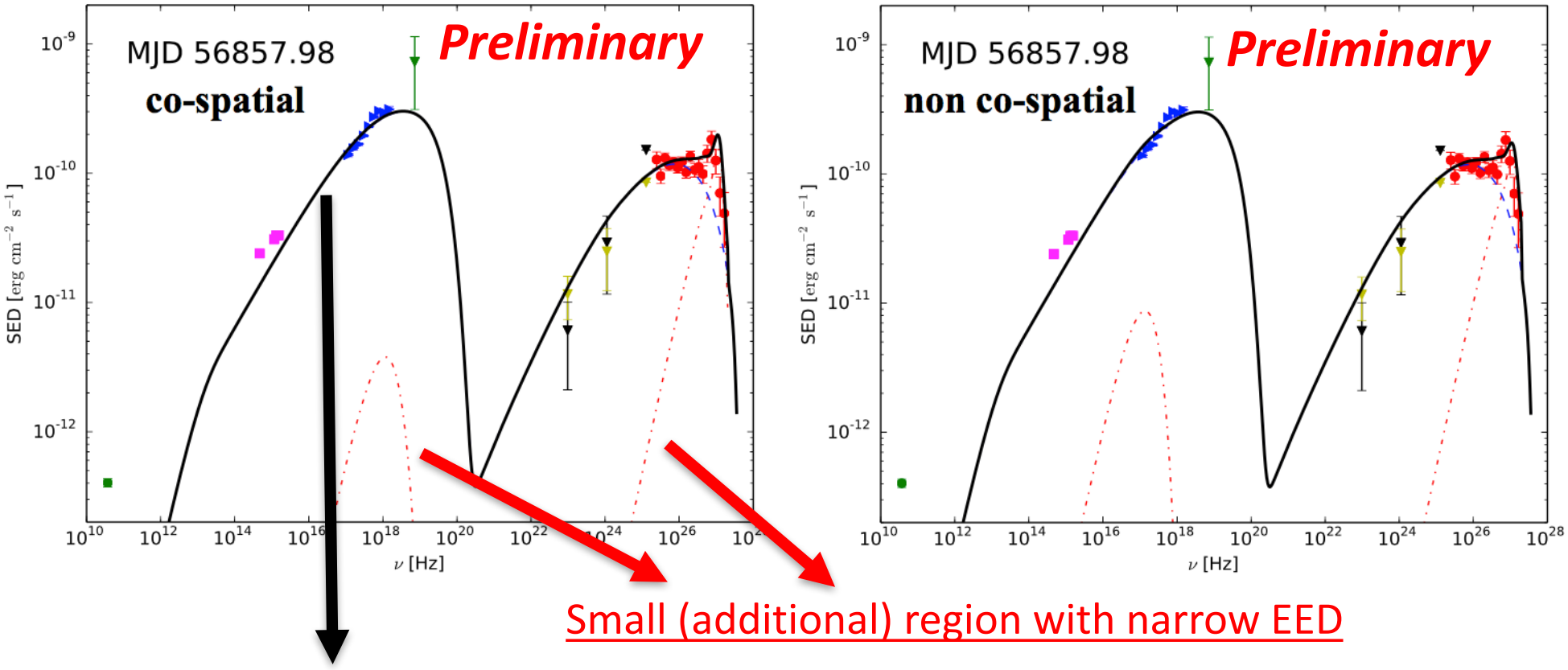
Model proposed by Andrea Tramacere

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

See Tramacere's talk Thursday morning

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

Acciari et al, submitted



Small (additional) region with narrow EED

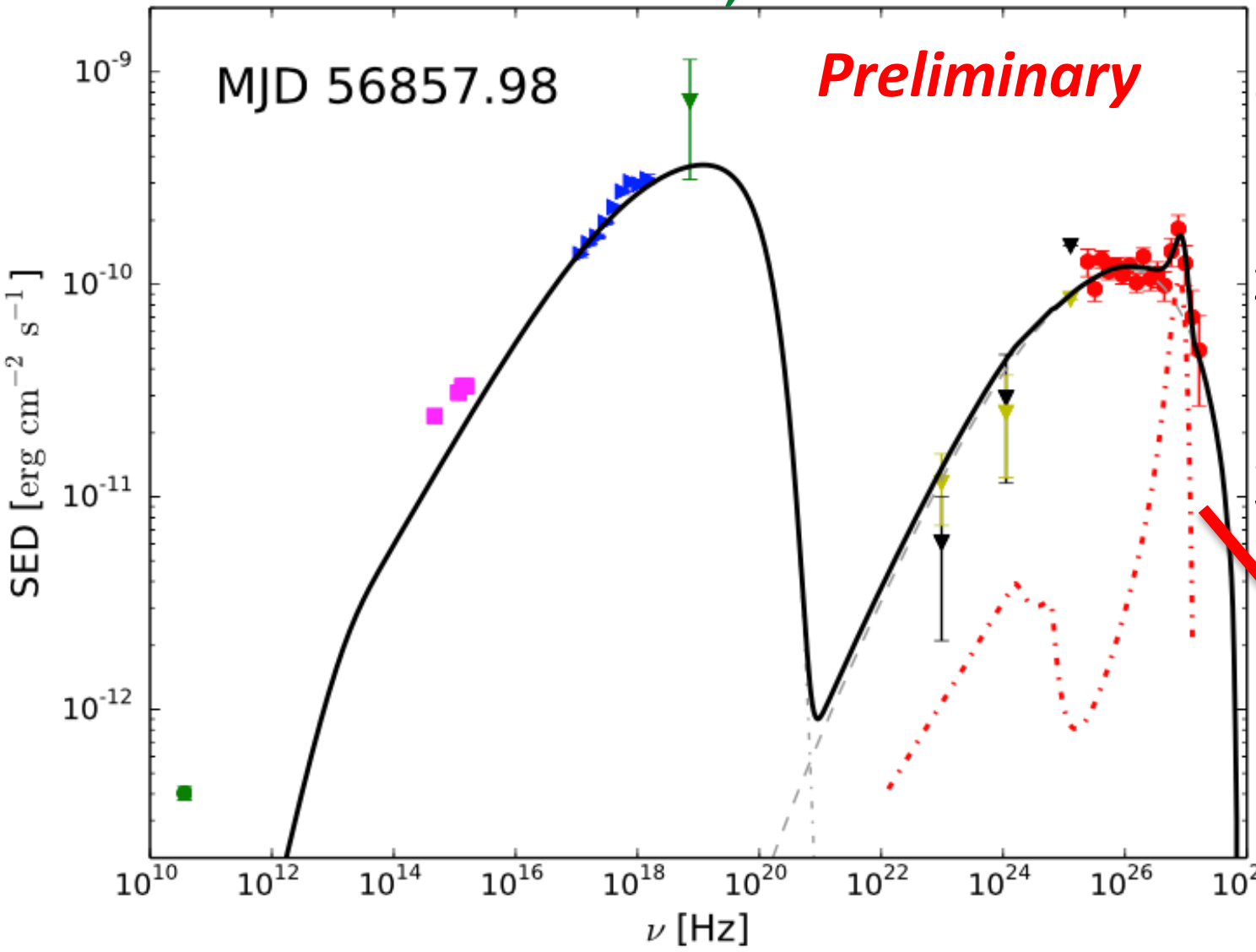
Sum of the two SSC components

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

Acciari et al, submitted



Model proposed by Christoph Wendel

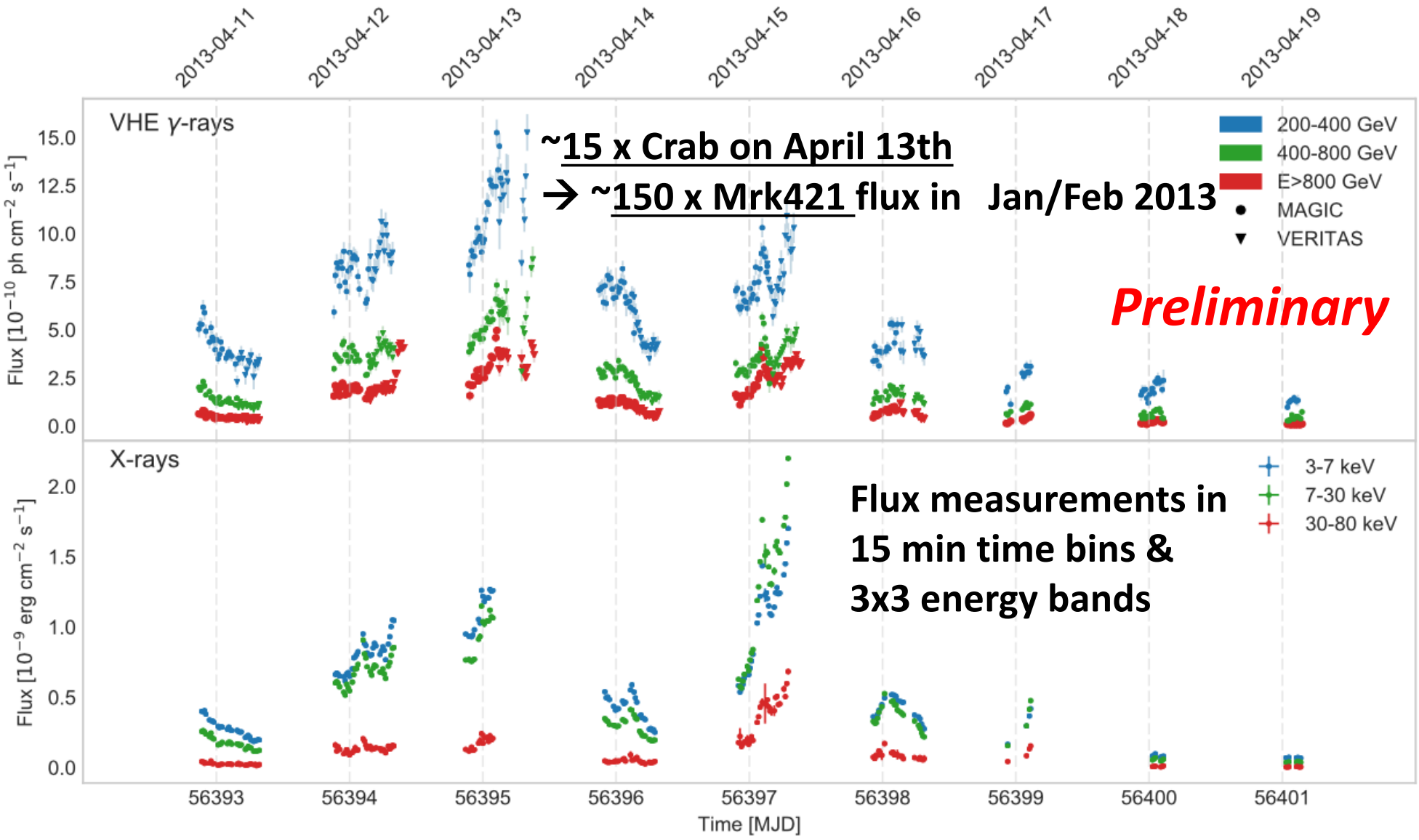
Based on
Zdziarski 1988,
Levinson&Rieger 2011,
Ptitsyna&Neronov 2016
and
Wendel et al 2017

Emission from narrow EED accelerated in Magnetospheric vacuum gap

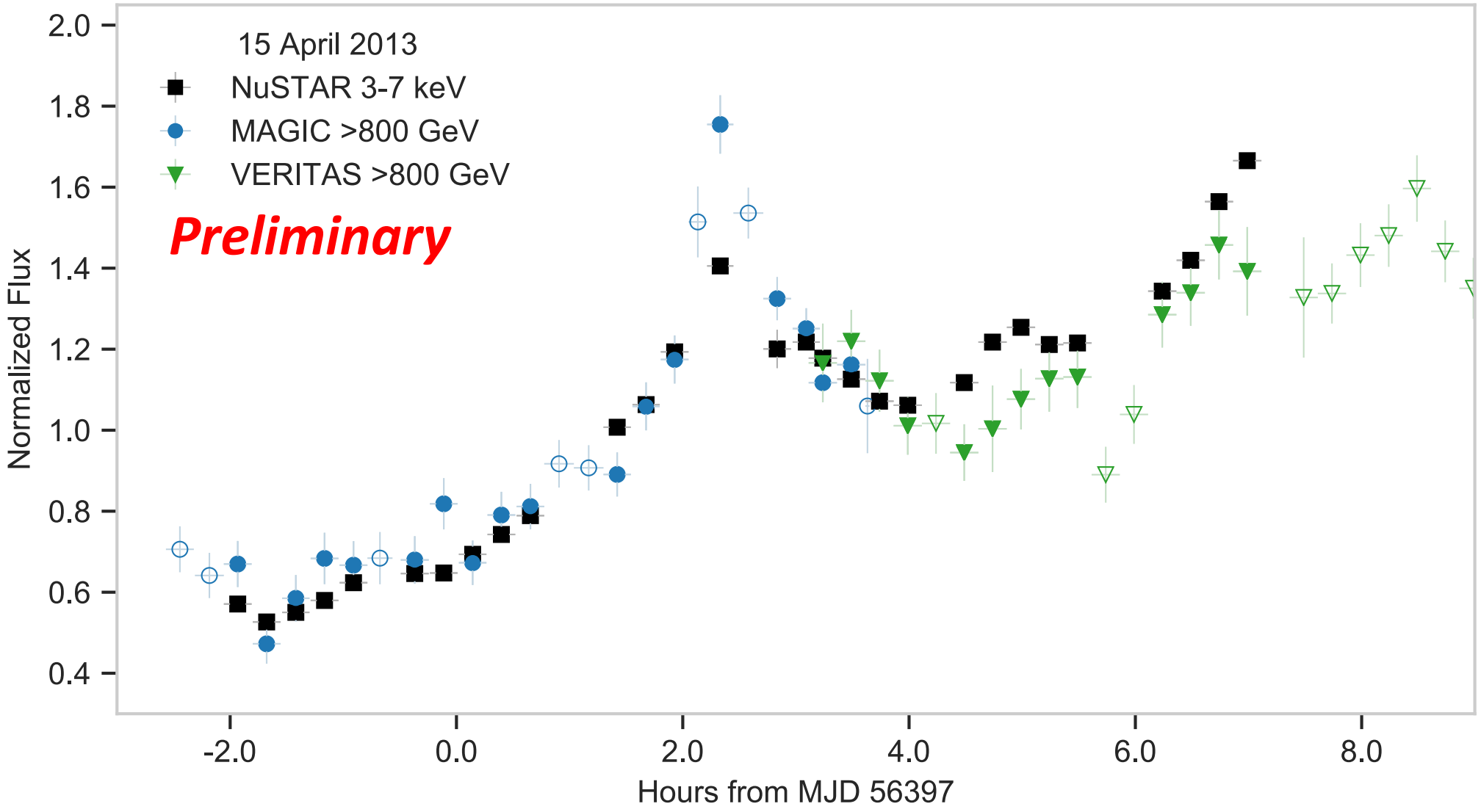
Mrk421 April 2013: Multi-band X-ray and VHE LCs

MAGIC+VERITAS cover flare for 70 hours and NuSTAR for 80 hours

About 45 hours of strictly simultaneous VHE and NuSTAR data



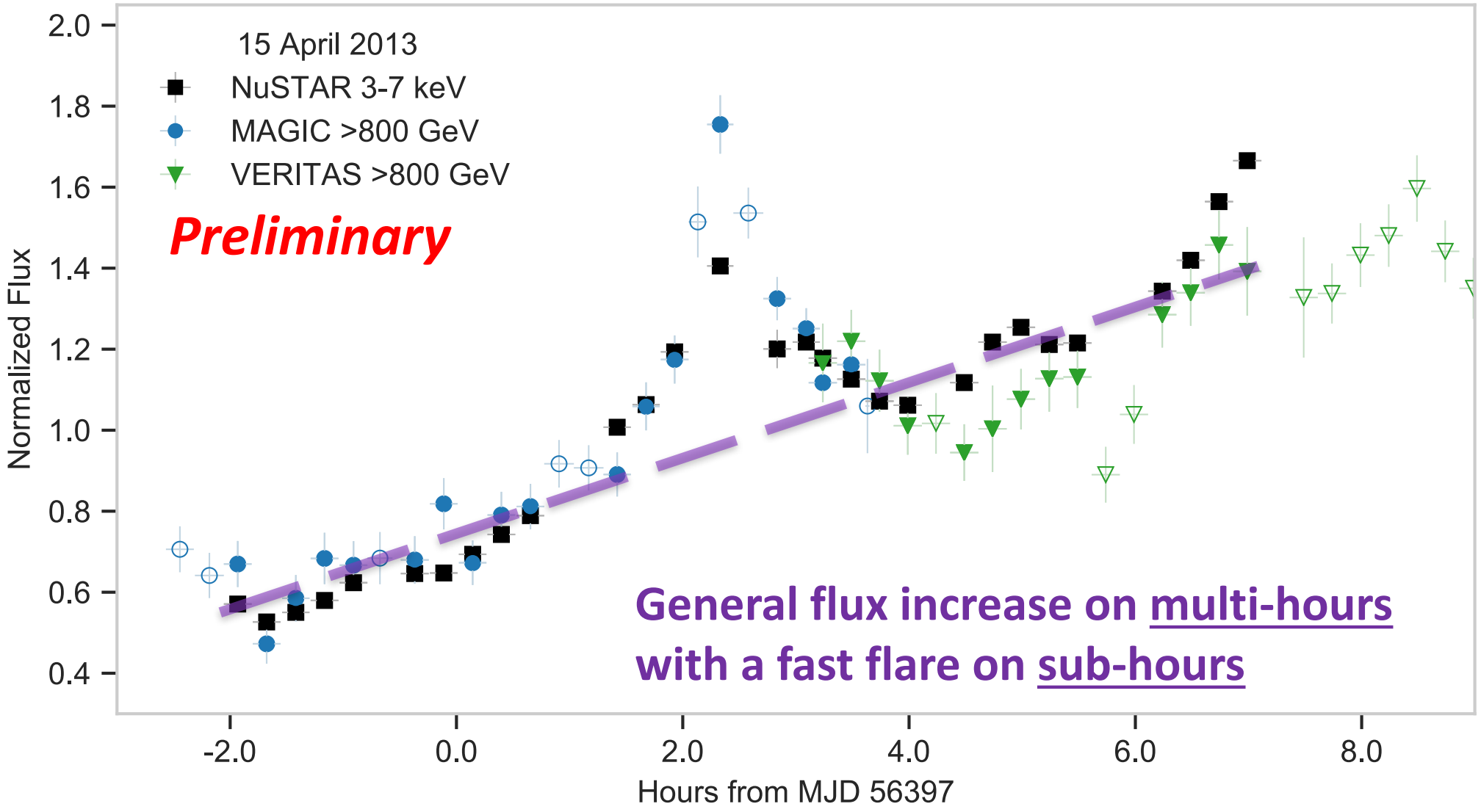
Normalized light curves for single nights (April 15th)



Full markers indicate time bins with strictly simultaneous VHE/X-ray data

Normalized flux: flux normalized to night mean flux from simultaneous data

Normalized light curves for single nights (April 15th)



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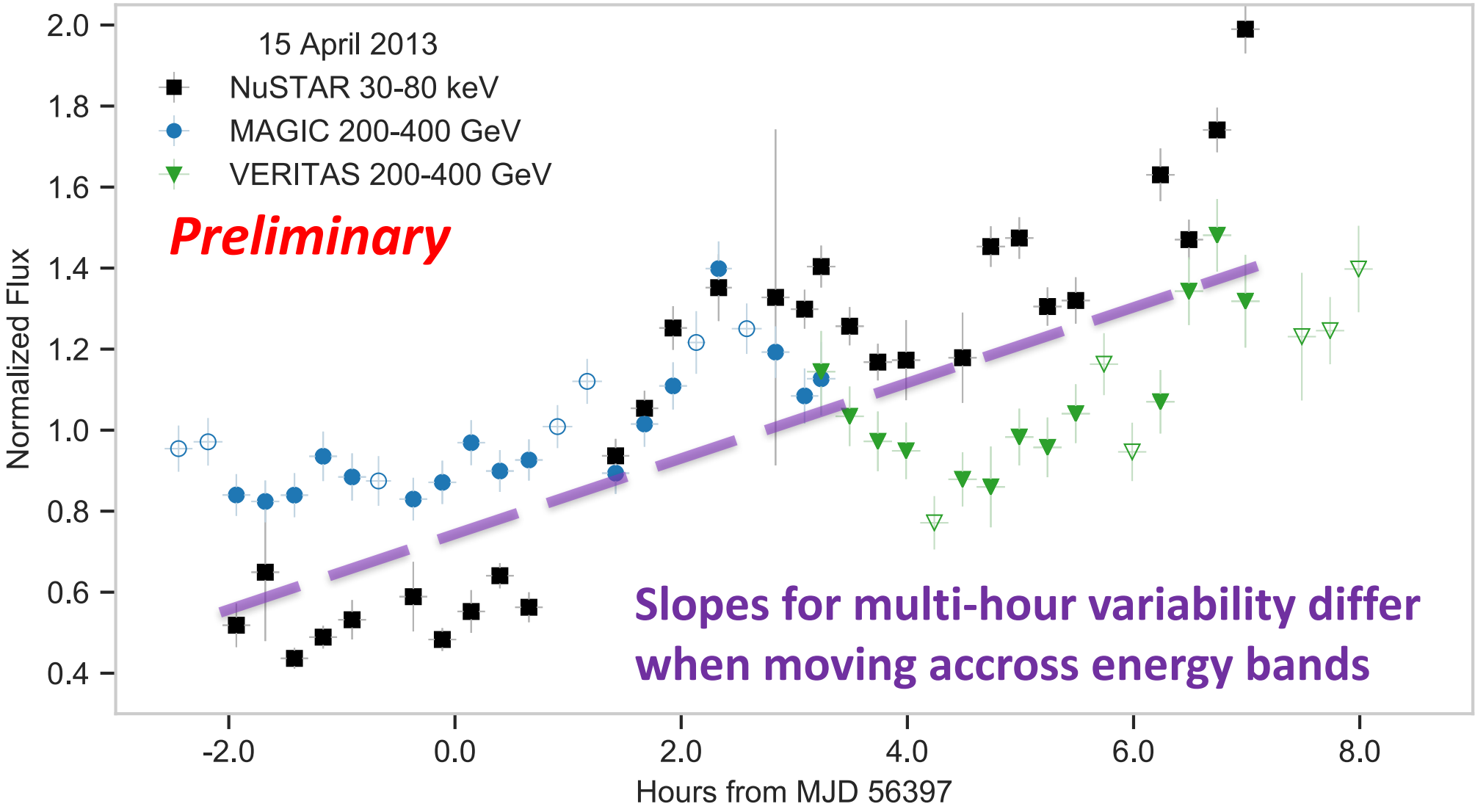

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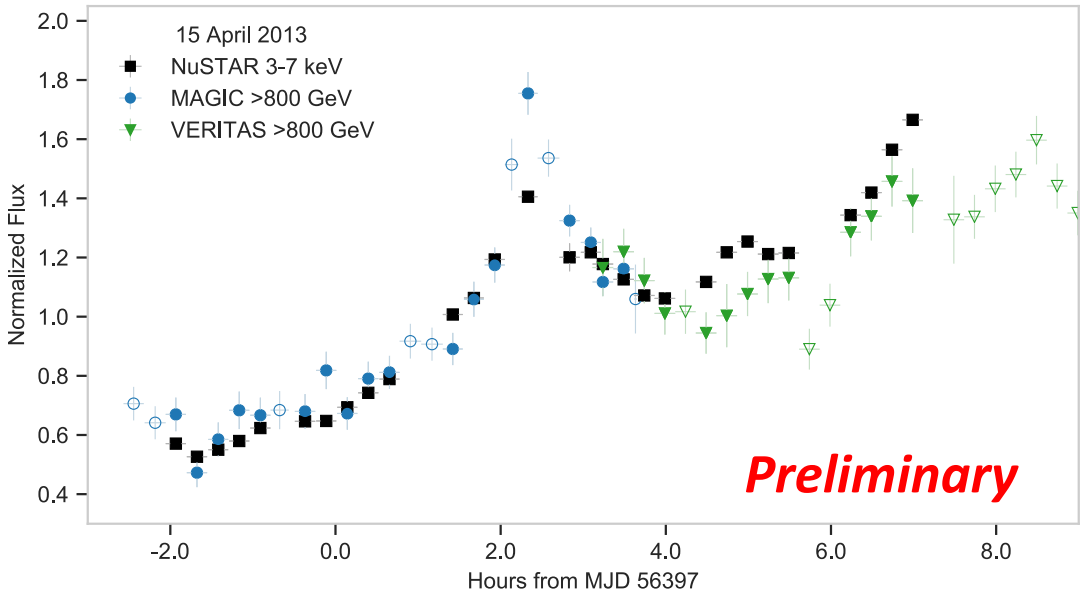
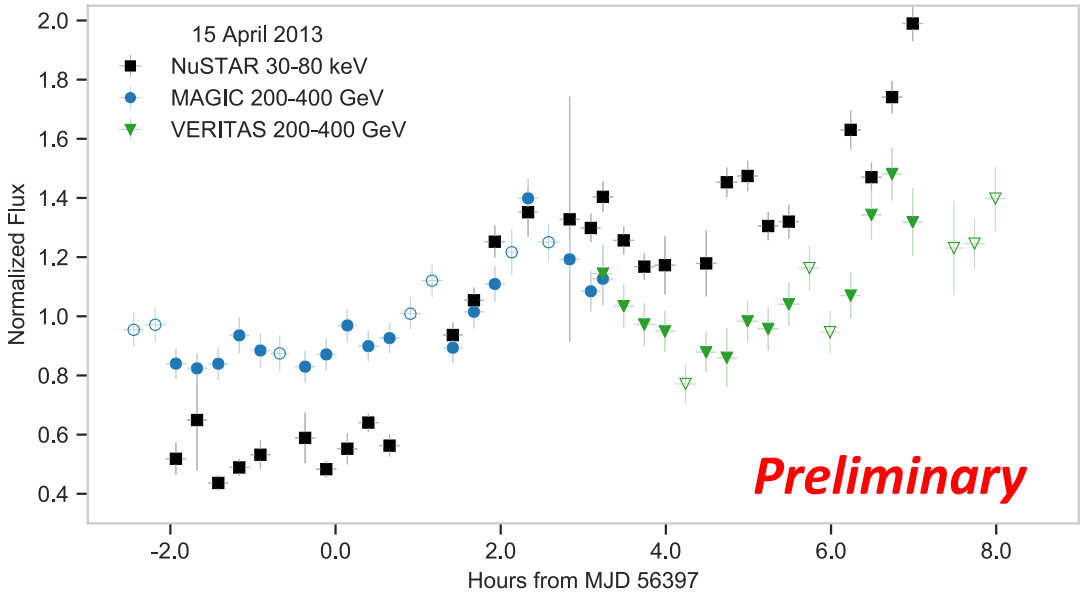


MAGIC + VERITAS >0.8 TeV

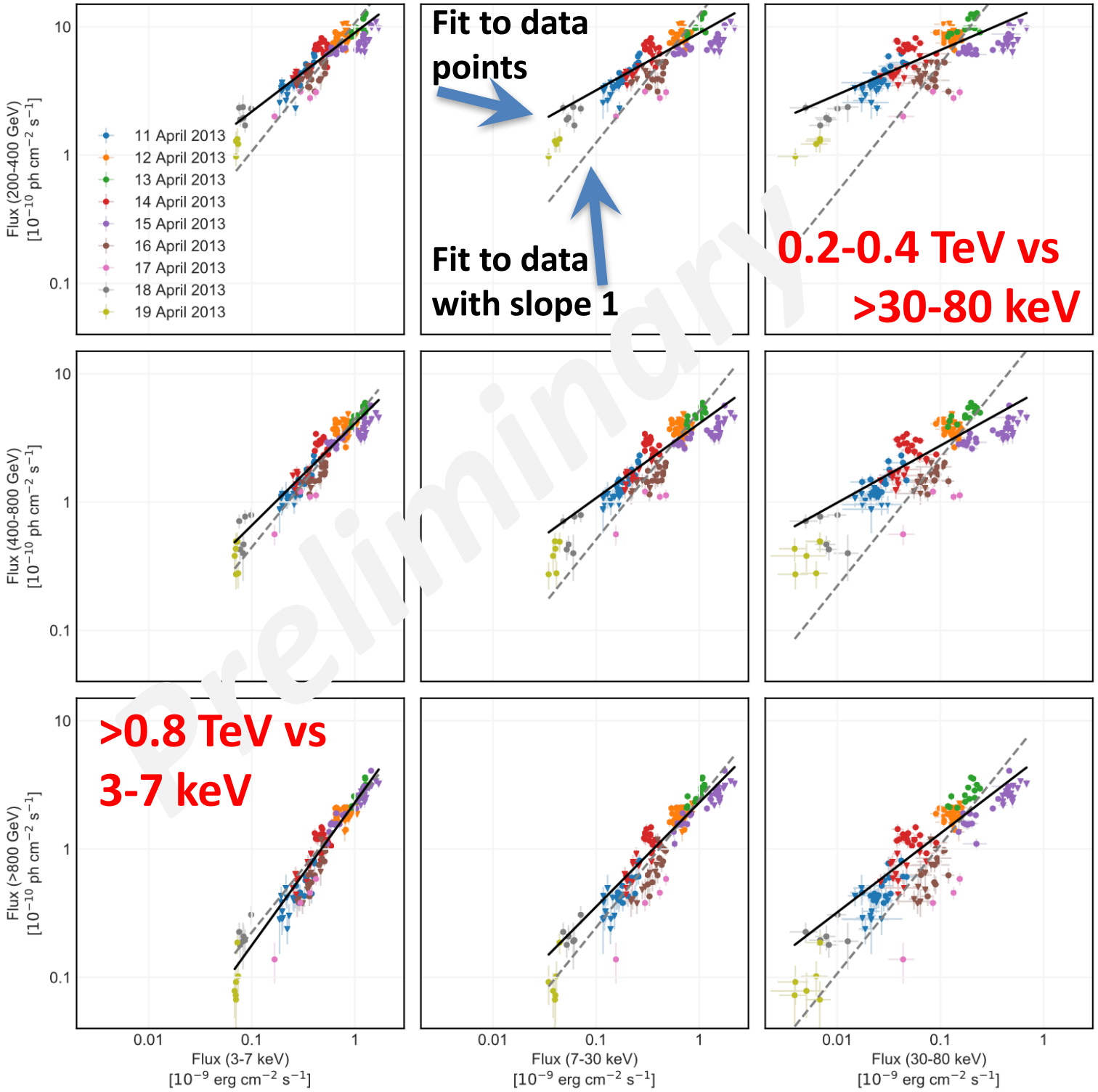
NuSTAR 3-7 keV



Large change in the overall shape and structure of LCs when moving across X-ray and VHE bands

MAGIC + VERITAS 0.2-0.4 TeV

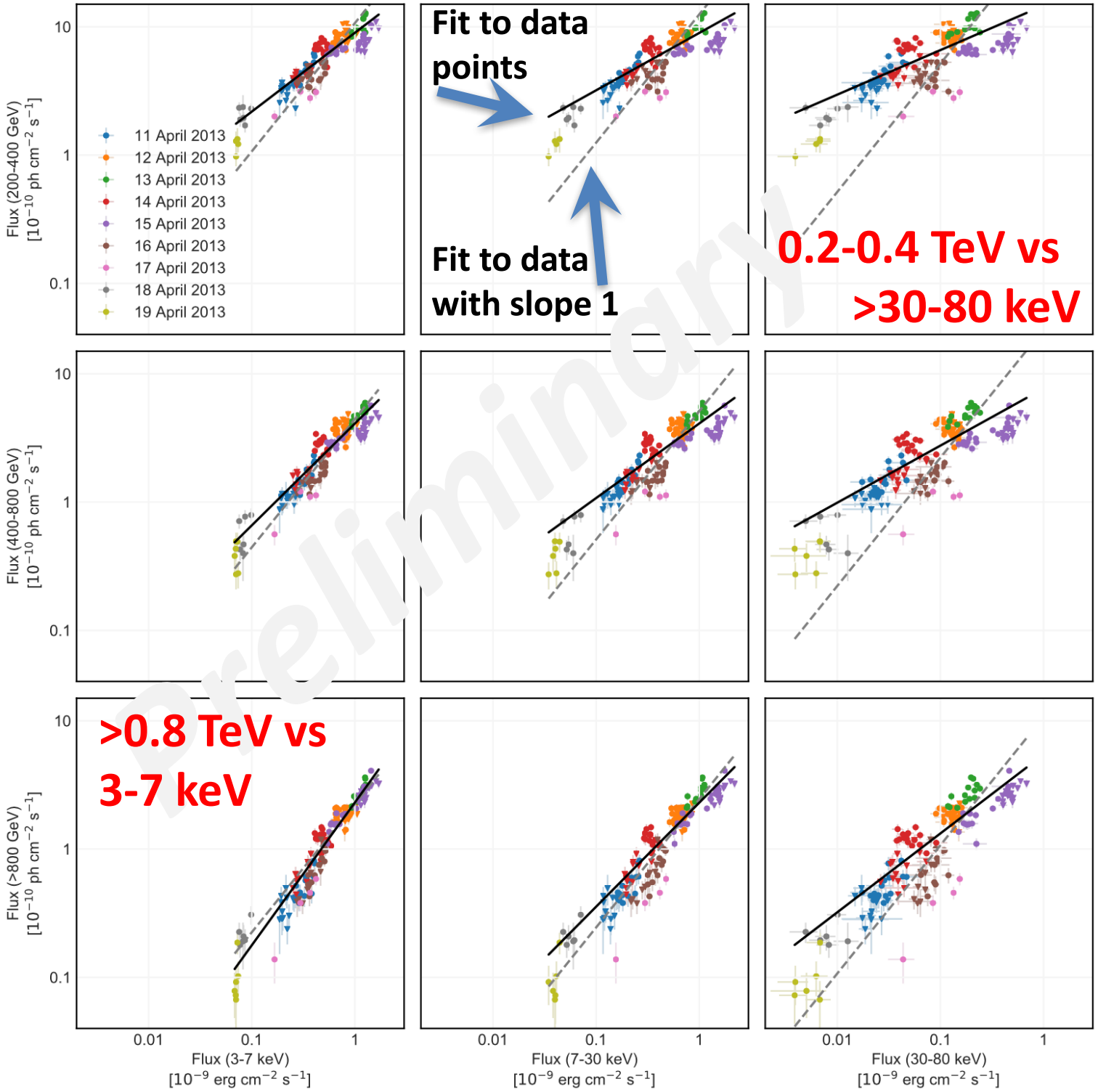
NuSTAR 30-80 keV



Gamma-ray vs X-ray flux (9-day "full" flare)

characterization in 3 (X-ray) x 3 (gamma) energy bands

Flux measurements in gamma rays and X-rays @ 15min



Gamma-ray vs X-ray flux (9-day "full" flare)

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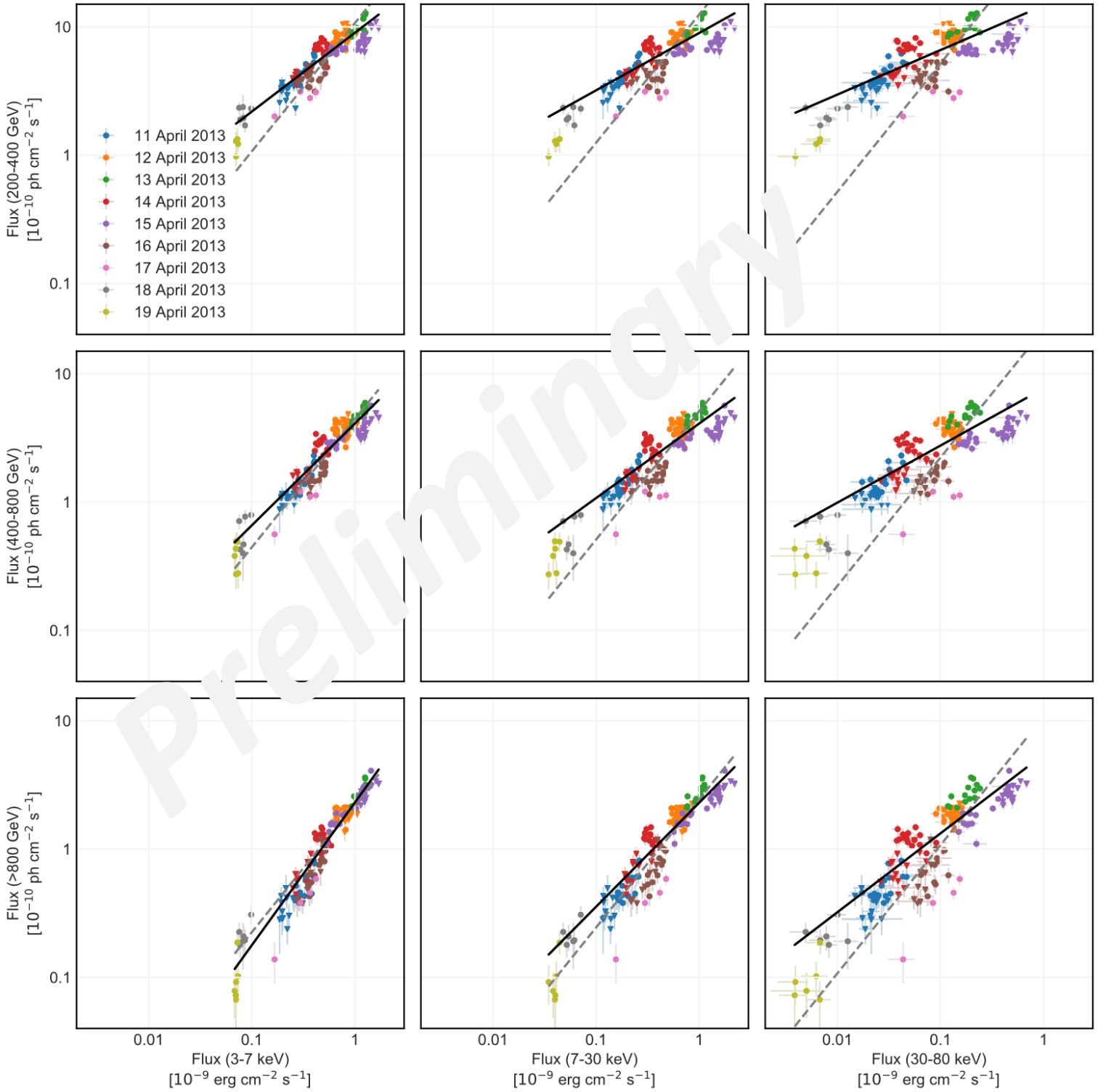
Flux measurements in gamma rays and X-rays @ 15min

Several flavours of X-ray vs VHE correlation when moving across bands

Gamma-ray vs X-ray flux (9-day "full" flare)



Different days (color coded) occupy different regions in plot, and sometimes show different behaviour

Quantification of the VHE vs X-ray correlations

Positive correlation exists (and very significant) for all the energy bands

Table 5. Correlation coefficients and slopes of the linear fit to the VHE vs X-ray flux (in log scale) derived with the 9-day flaring episode of Mrk421 in April 2013.

VHE band	Xray band	Pearson coeff.	Nsigma in Pearson	DCF	Slope from linear fit	Chi2/d.o.f
200-400 GeV	3-7 keV	0.920 + 0.011 - 0.013	20.2	0.928 ± 0.117	0.61 ± 0.02	1183 / 162
	7-30 keV	0.871 + 0.018 - 0.020	17.0	0.879 ± 0.111	0.45 ± 0.03	1891 / 162
	30-80 keV	0.790 + 0.028 - 0.032	13.6	0.805 ± 0.108	0.35 ± 0.02	2277 / 162
400-800 GeV	3-7 keV	0.946 + 0.007 - 0.009	23.4	0.955 ± 0.114	0.79 ± 0.03	1038 / 170
	7-30 keV	0.909 + 0.012 - 0.014	19.8	0.918 ± 0.108	0.58 ± 0.03	1725 / 170
	30-80 keV	0.838 + 0.021 - 0.024	15.8	0.855 ± 0.105	0.45 ± 0.03	2160 / 170
>800 GeV	3-7 keV	0.964 + 0.005 - 0.006	26.0	0.971 ± 0.108	1.11 ± 0.03	704 / 170
	7-30 keV	0.947 + 0.007 - 0.008	23.5	0.955 ± 0.105	0.81 ± 0.03	1245 / 170
	30-80 keV	0.892 + 0.015 - 0.017	18.6	0.908 ± 0.103	0.61 ± 0.03	1736 / 170

Many different trends in the VHE vs X-ray correlation when moving across “nearby” energy bands

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Many different trends in the VHE vs X-ray correlation when moving across "nearby" energy bands

The combination > 0.8TeV and 3-7 keV shows the highest degree of correlation, highest slope, and less scattering

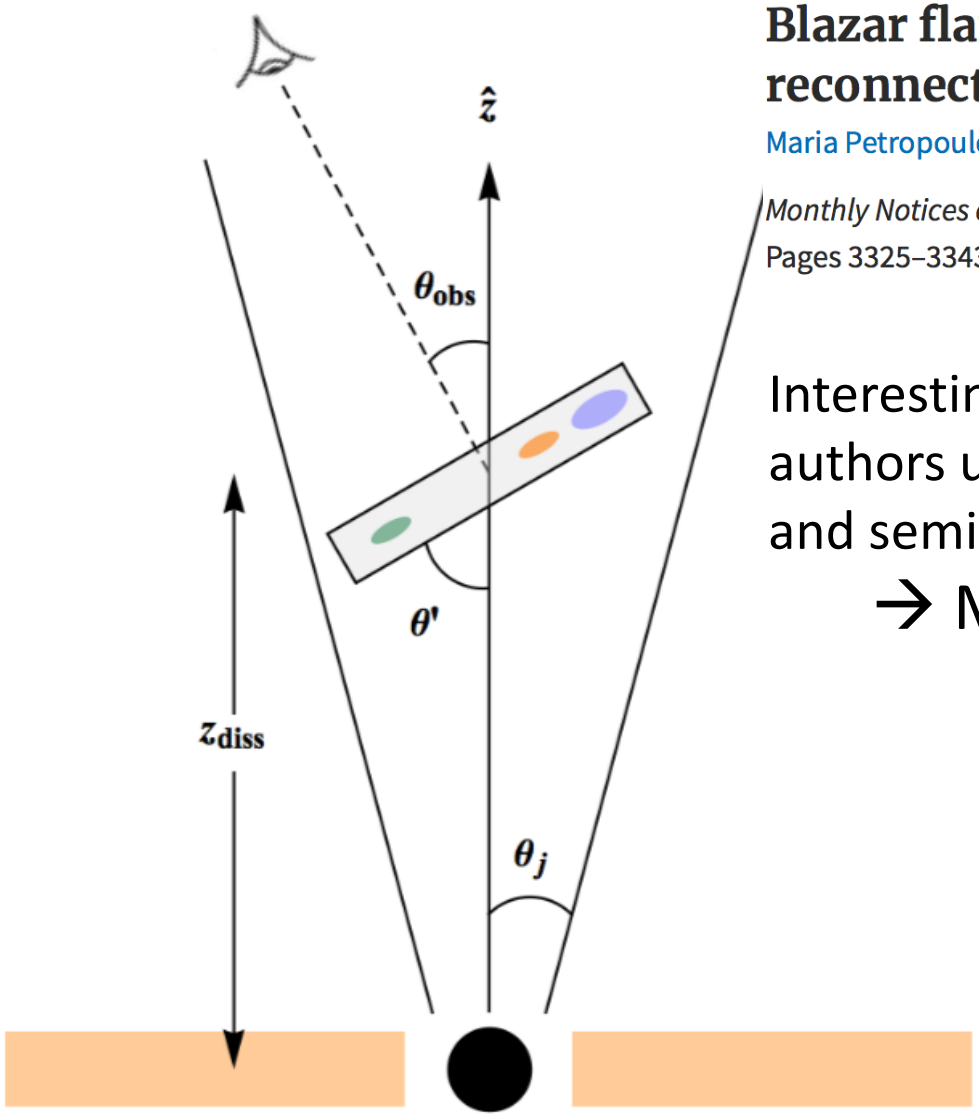


Figure 9. Sketch of a reconnection layer (of half-length L') forming in the jet at a distance z_{diss} (not in scale). The layer forms an angle θ' (as measured in the jet's rest frame) with respect to the jet axis. Plasmoids of different sizes and velocities move towards the sides of the layer while radiating. The jet has an opening angle θ_j and a bulk Lorentz factor Γ_j.

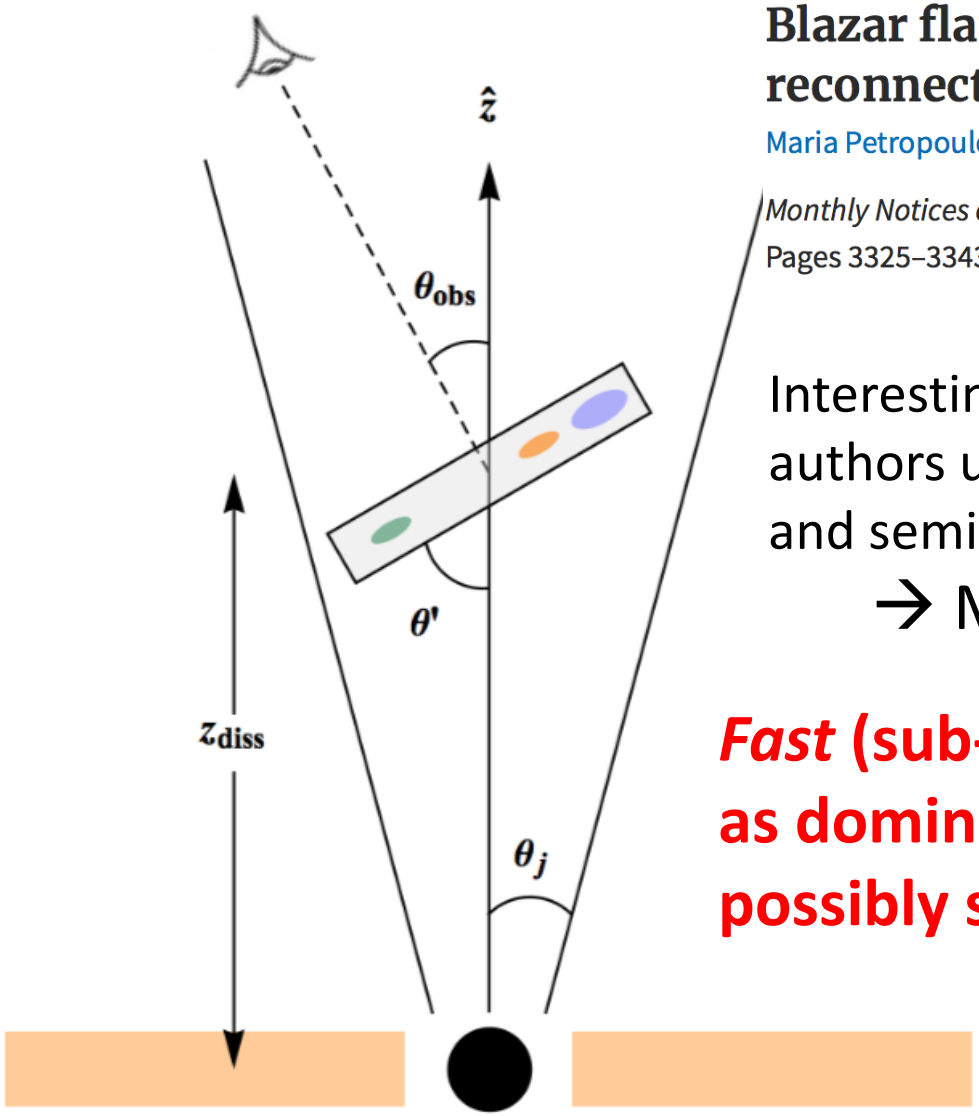
Blazar flares powered by plasmoids in relativistic reconnection

Maria Petropoulou ✉, Dimitrios Giannios, Lorenzo Sironi

Monthly Notices of the Royal Astronomical Society, Volume 462, Issue 3, 1 November 2016, Pages 3325–3343, https://doi.org/10.1093/mnras/stw1832

Interesting to relate with studies done by several authors using Particle in Cell (PIC) simulations and semi-analytic approaches

→ M. Petropoulou and J. Finke



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Fast **(sub-hour) flares may be understood as dominated by a single plasmoid, possibly small and highly relativistic**

Slow **(multi-hour) but more luminous component of the light curve, may be understood as dominated by superposition of many plasmoids of different sizes and speeds**

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 extensive campaigns on Mrk421 & Mrk501 we have both, bright sources and high sensitive instruments with wide energy and dense 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*