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

**David Paneque** (dpaneque@mppmu.mpg.de)
**Max Planck Institute for Physics**

**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, T. Hassan, G. Hughes, A. Shukla, M. Perri, K. Noda, F. Tavecchio, A. Tramacere, C. Wendel, K. Ishio, D. Dorner, A . Furniss, S. Jorstad, V. Larionov, G. Madejski, M. Villata, P. Smith, J. Finke, M. Petropoulou …

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

- **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**

# 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* !)**

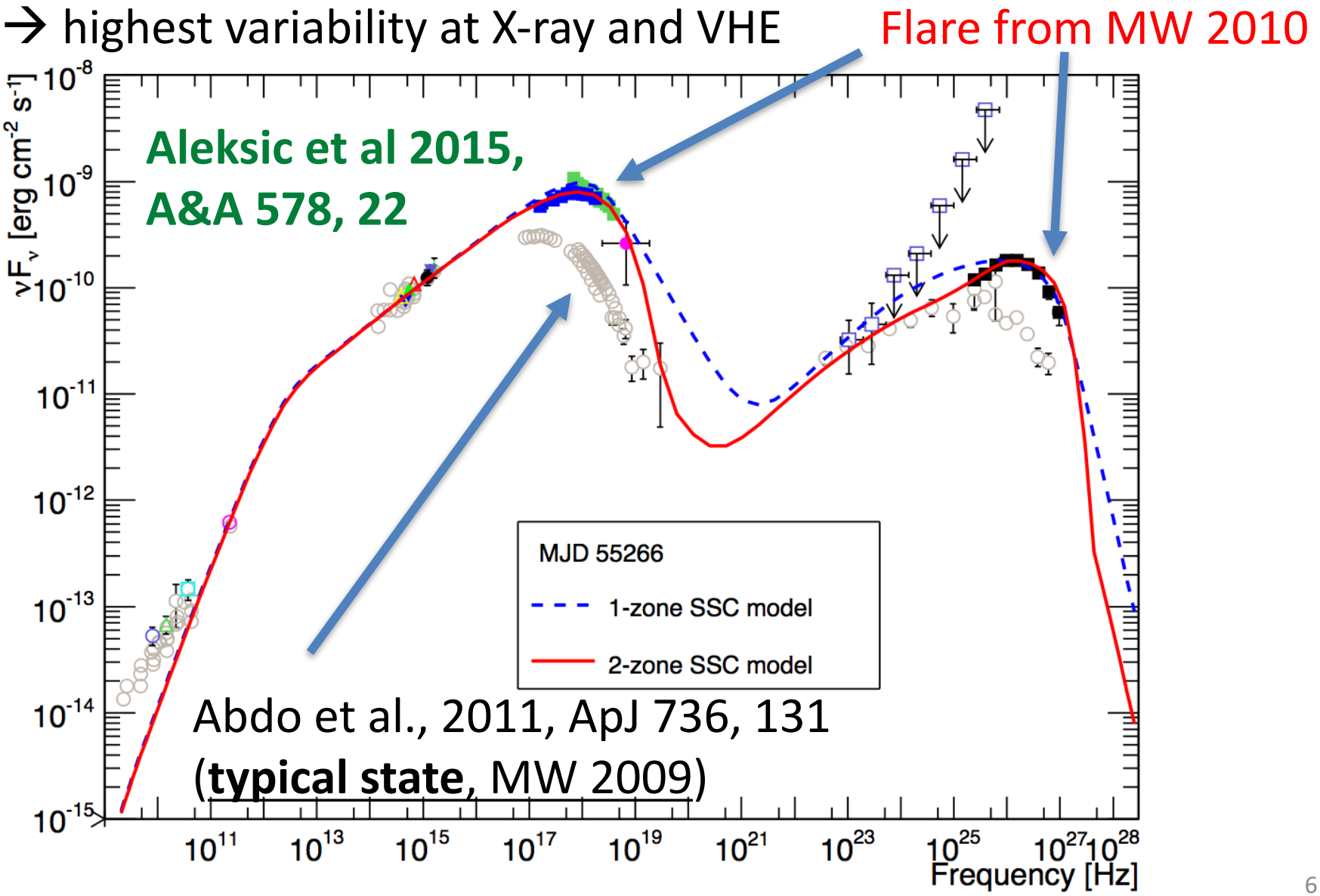
- **Some recent results from the campaigns**

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

X-ray and VHE spectra becomes harder when flaring

→ SED bumps shift to high energies

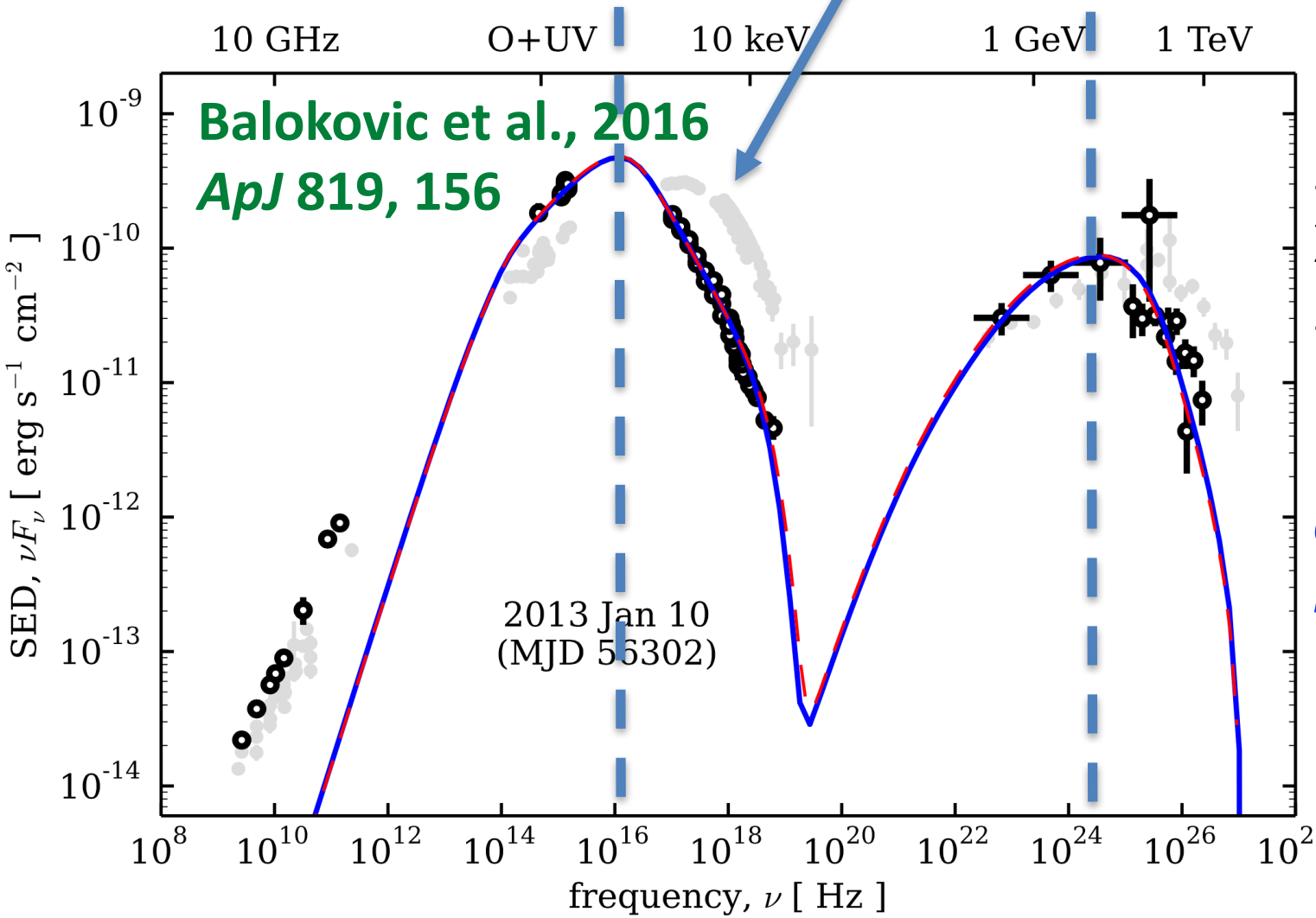
→ highest variability at X-ray and VHE



# 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**)



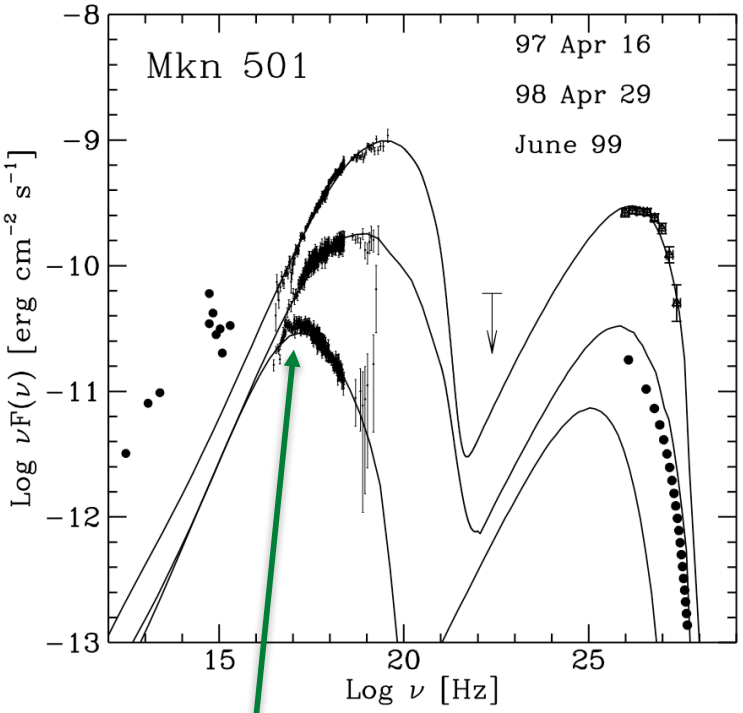

Low activity softened the X-ray and VHE spectra, but did not bring cutoffs

***→ Electrons accelerated to highest energies***

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

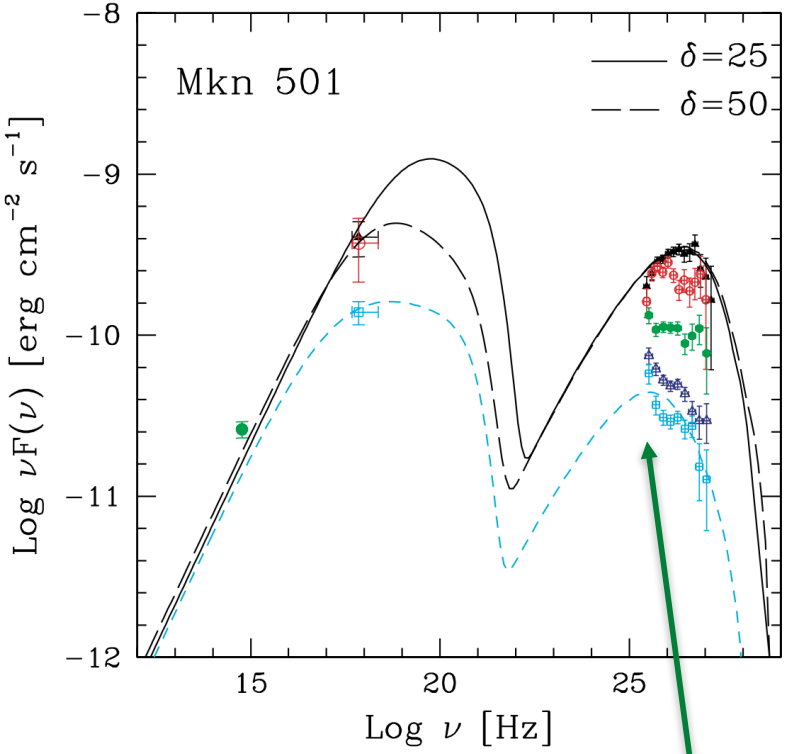
(Historical) flare in 1997

**Tavecchio et al., 2001, ApJ 554,725**




(fast variability) flare in 2005

**Albert et al., 2007, ApJ 669,862**



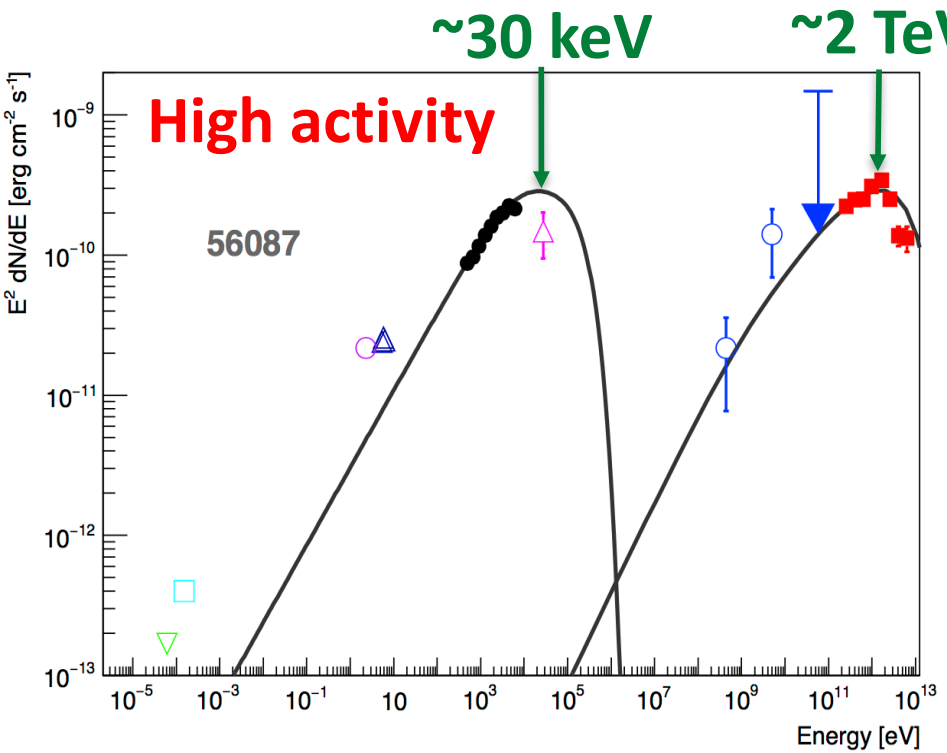

Hard spectra in Mrk501 not observed during low states,

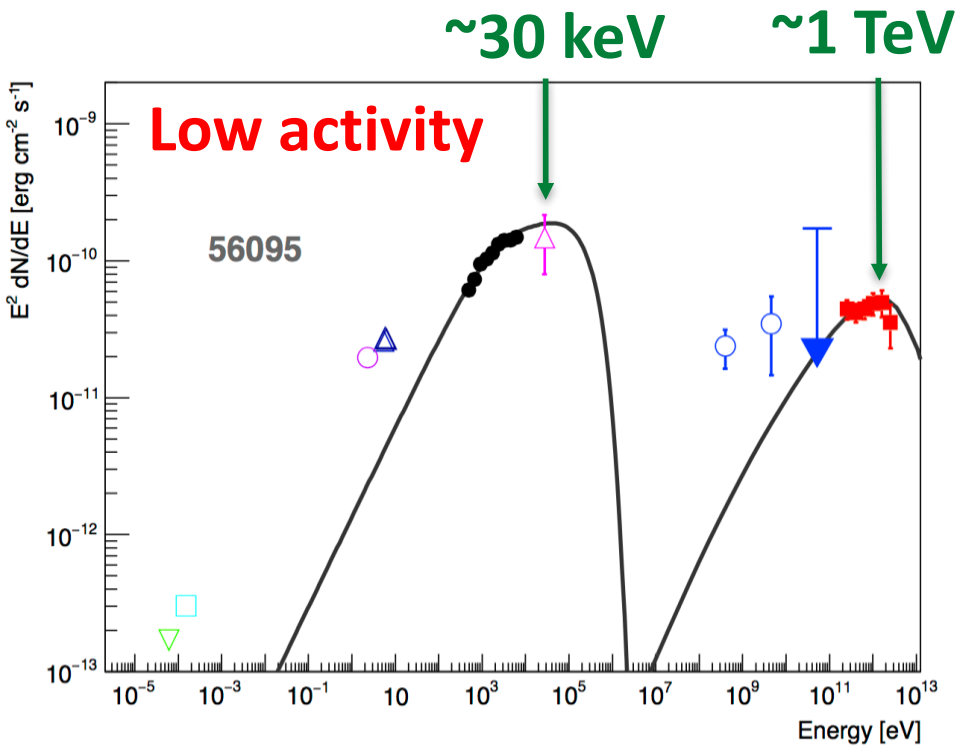
**< 1 keV**

**< 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

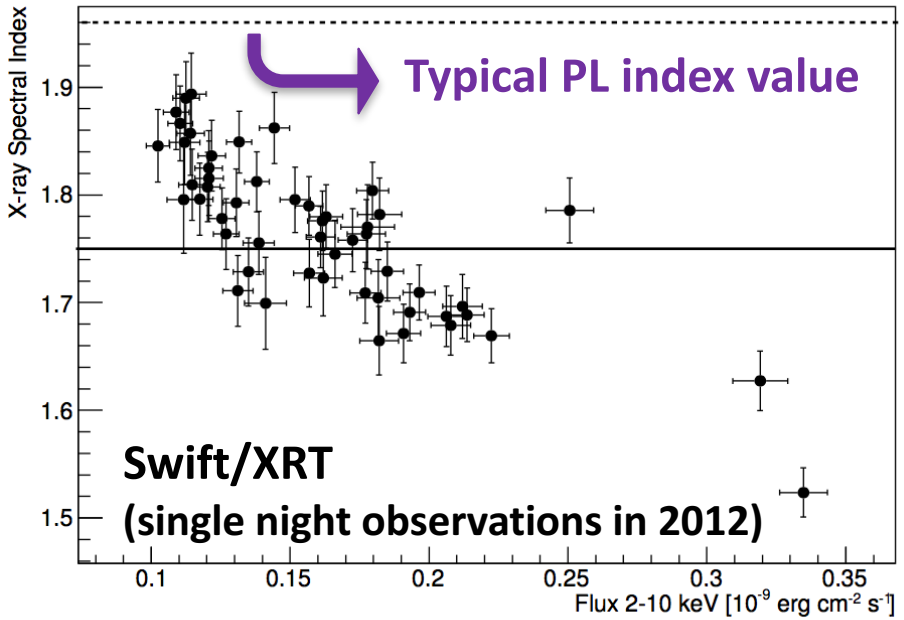
**Optical/UV:**
R-band (WEBT+)
Swift/UVOT

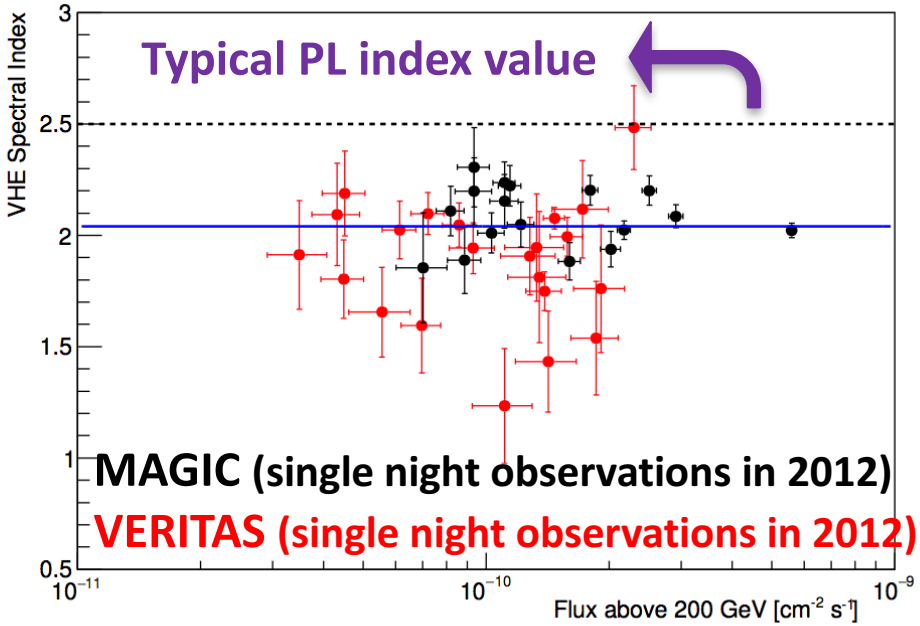
**Ahnen et al., 2018**
**A&A 620 , 181**

# 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**




→ **Mrk 501 behaved as Extreme HBL!**

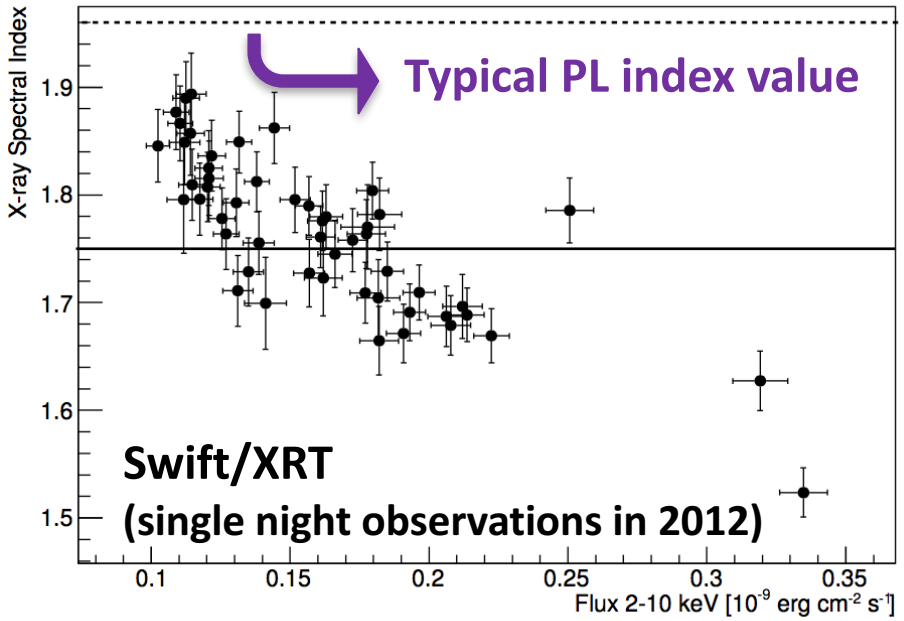
*Similar X-ray/VHE spectra as 1ES 0229+200, 1ES 0347-121 (Peaks at ~10 keV and ~1TeV)*

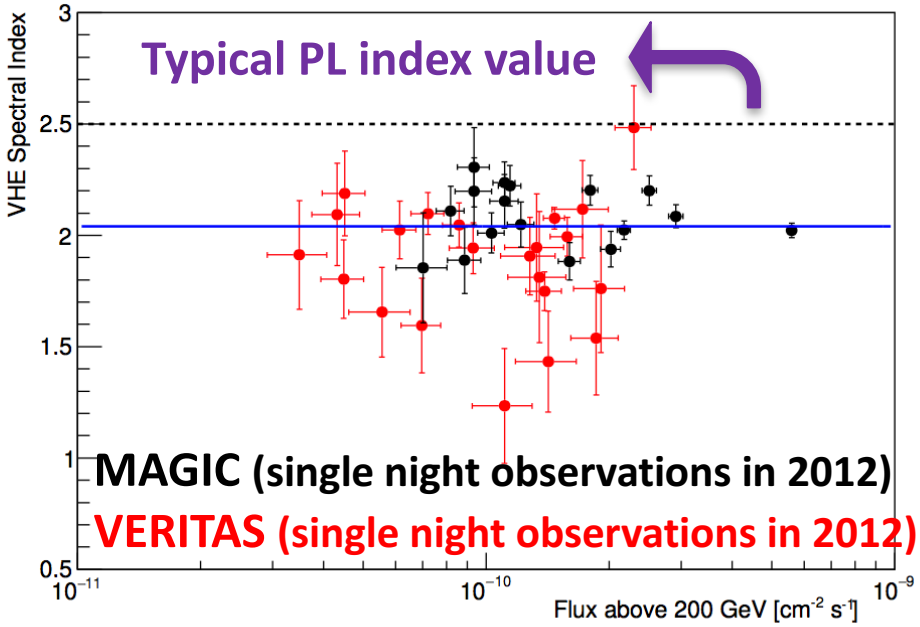
**Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic**

# 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_$F^{TeV}$**

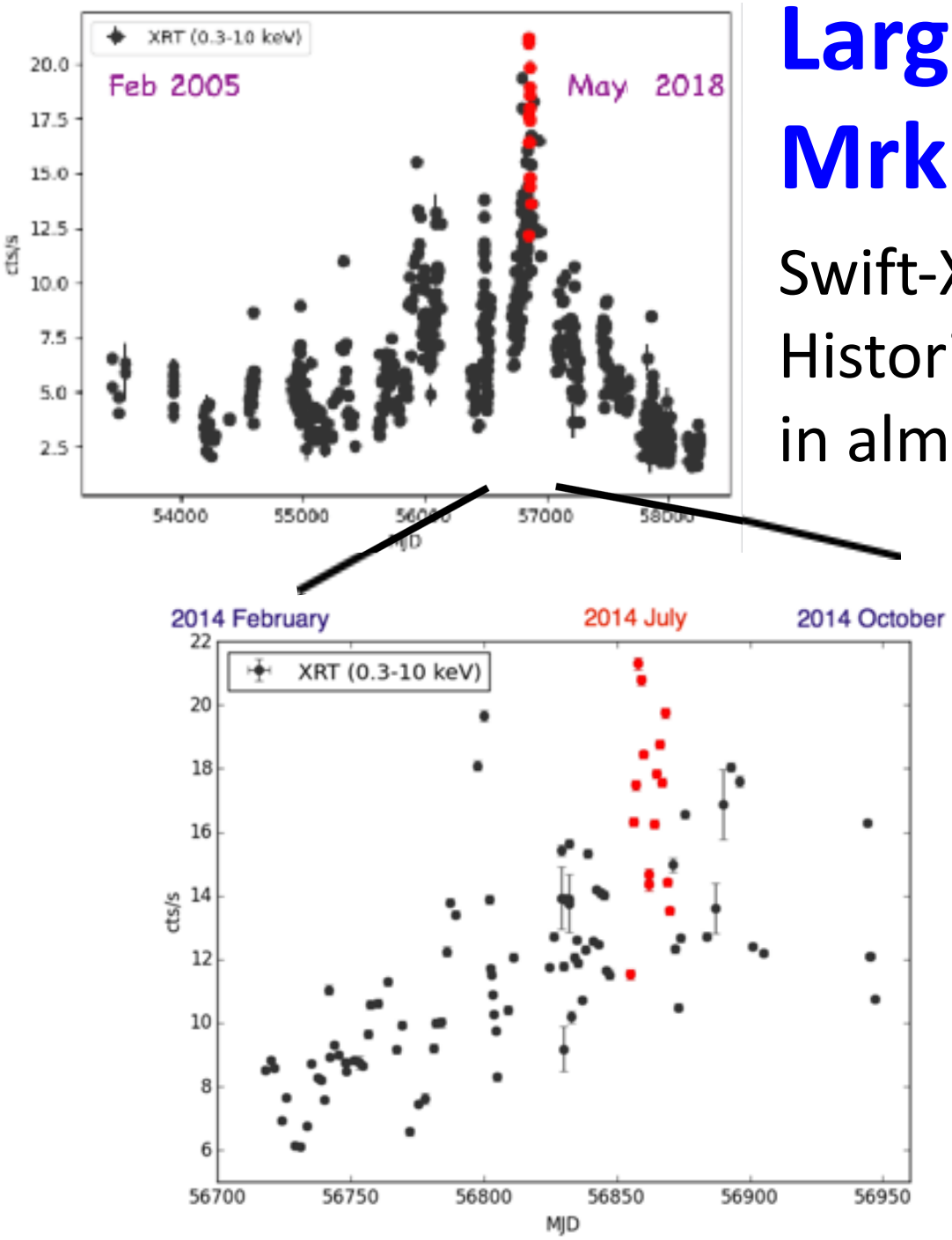
**Similar quality spectra need observations 100 time longer than those needed for Mrk501**

**Precision on 1ES 0229 needs CTA !!**

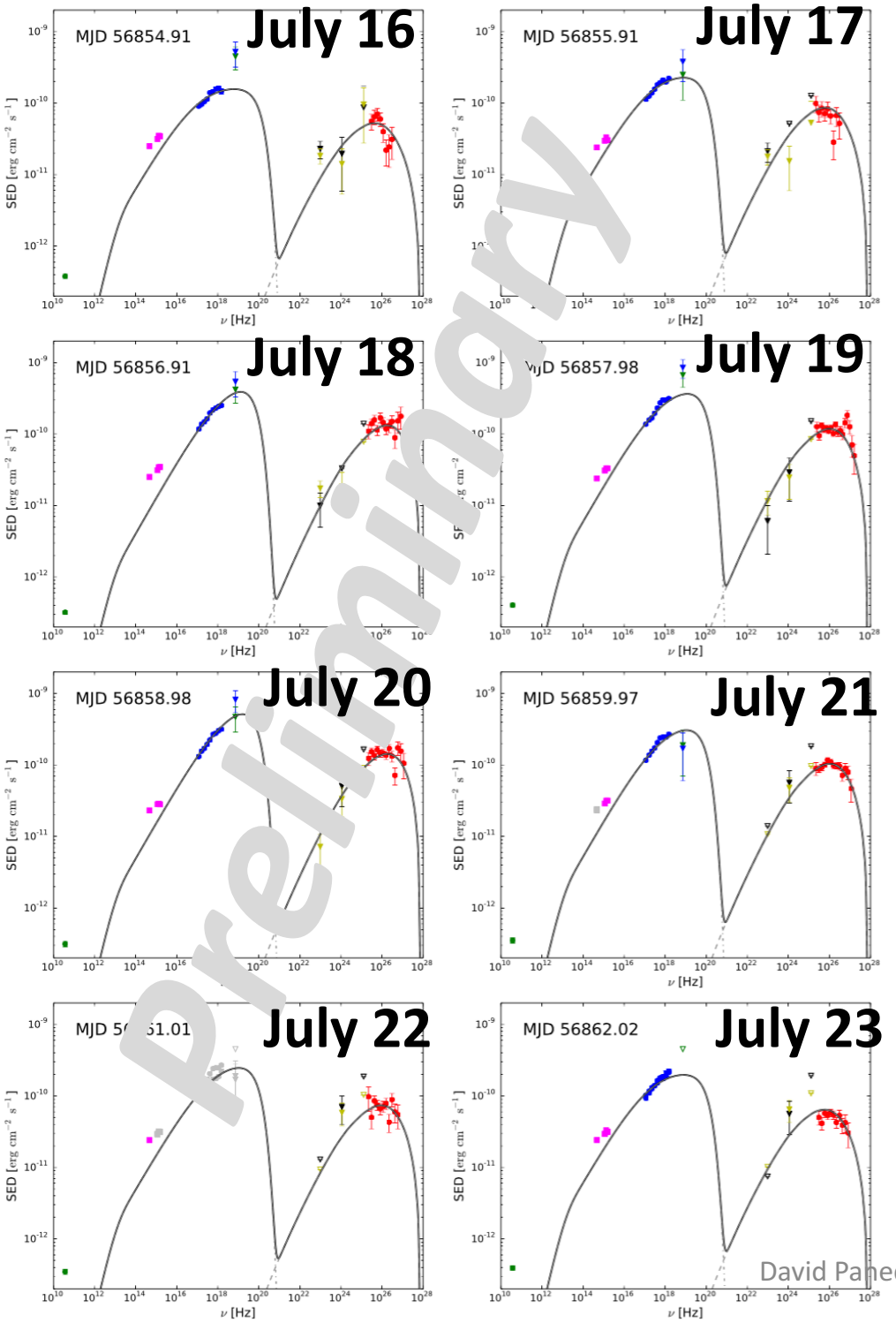
**Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic**

# 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**

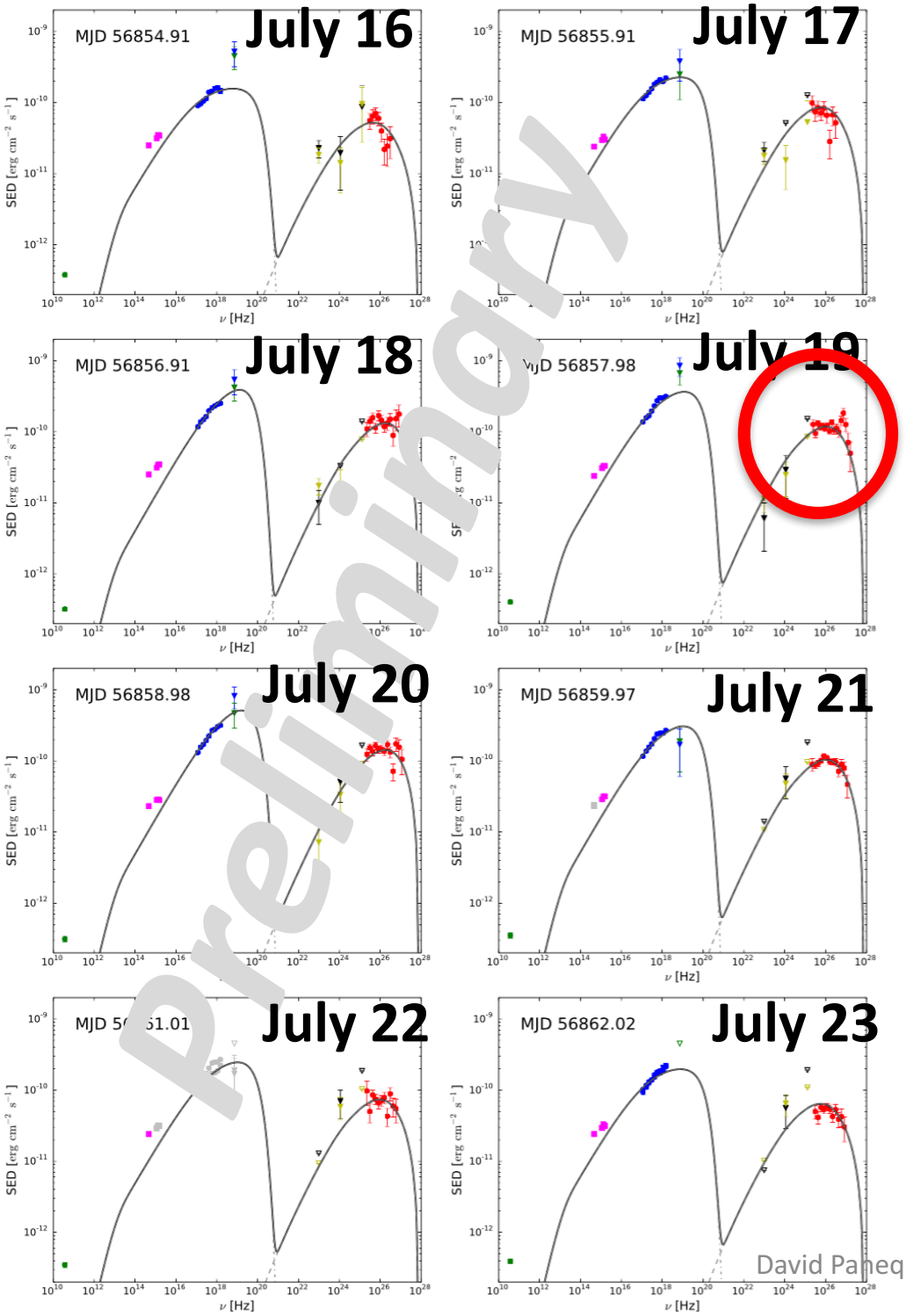



# Large flaring activity of Mrk501 in July 2014

**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*)

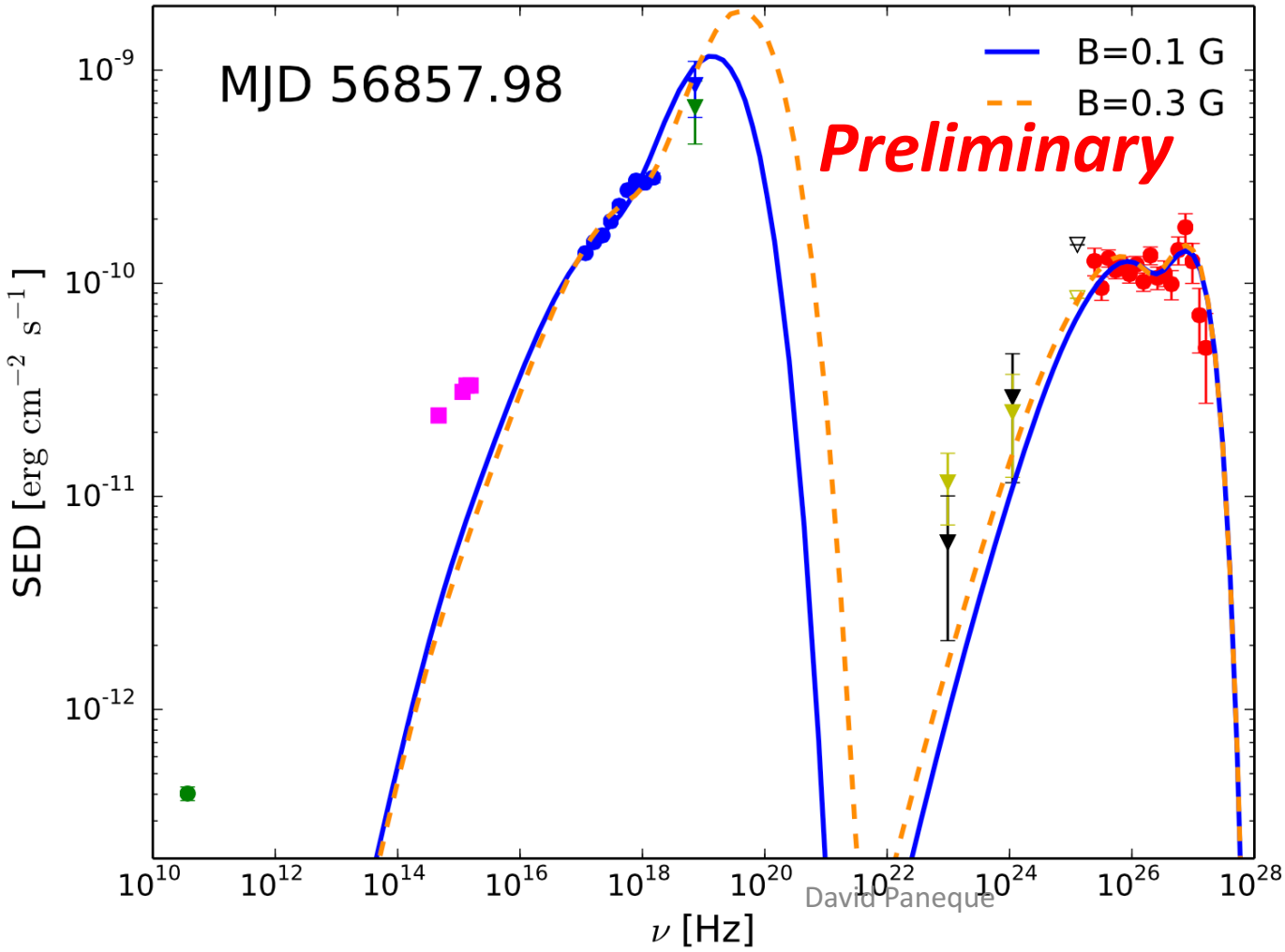
**statistical fluctuation (>3σ) or new component ?**

# 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 $\gamma_{eq}$**

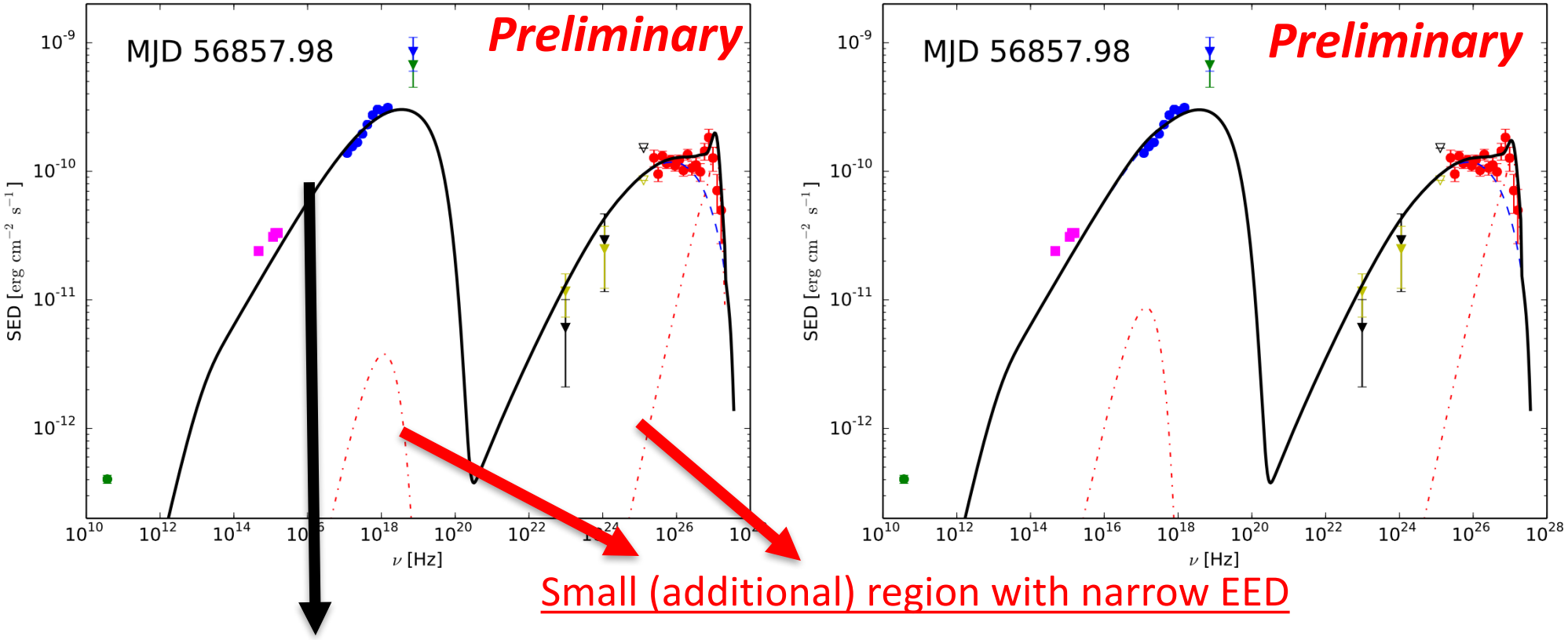



**Model performed by Andrea Tramacere**

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

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

## Acciari et al, submitted




Small (additional) region with narrow EED

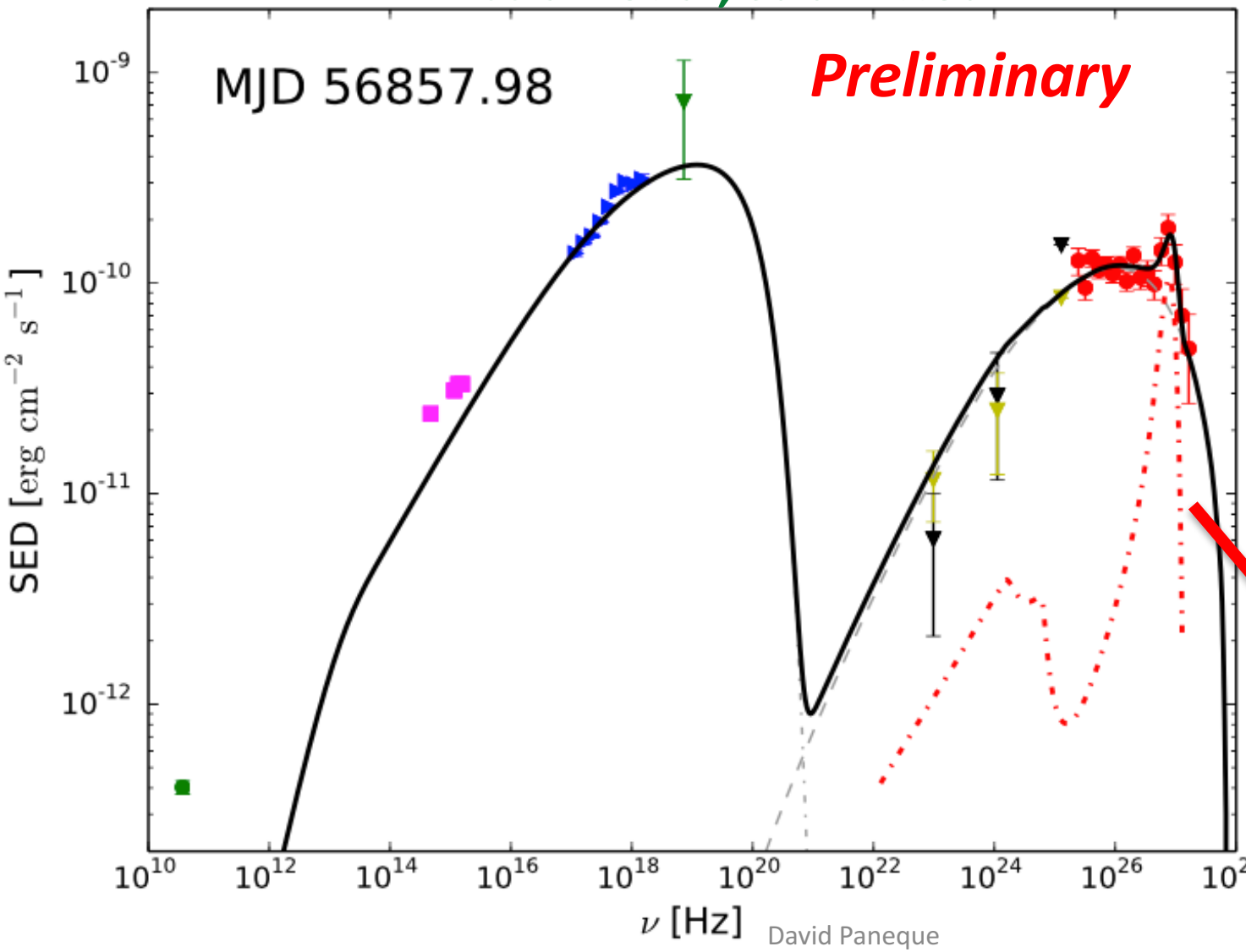
Sum of the two SSC components

**Model performed 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 by Christoph Wendel**

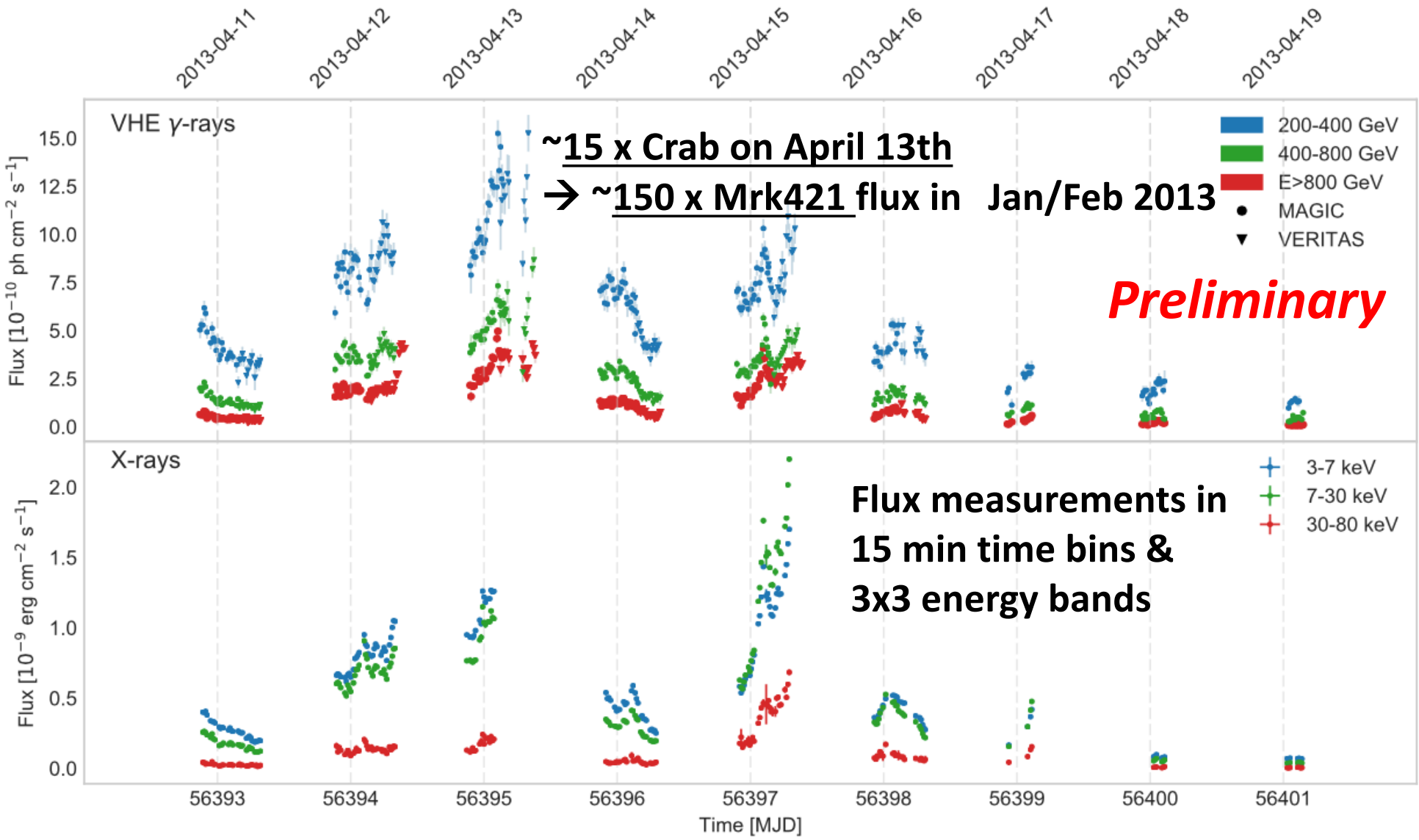
Based on Zdziarski 1988, Levinson&Rieger 2011, Ptitsyna&Neronov 2016 and Wendel et al 2017

Emission from narrow EED accelerated in Magnetospheric vacuum gap

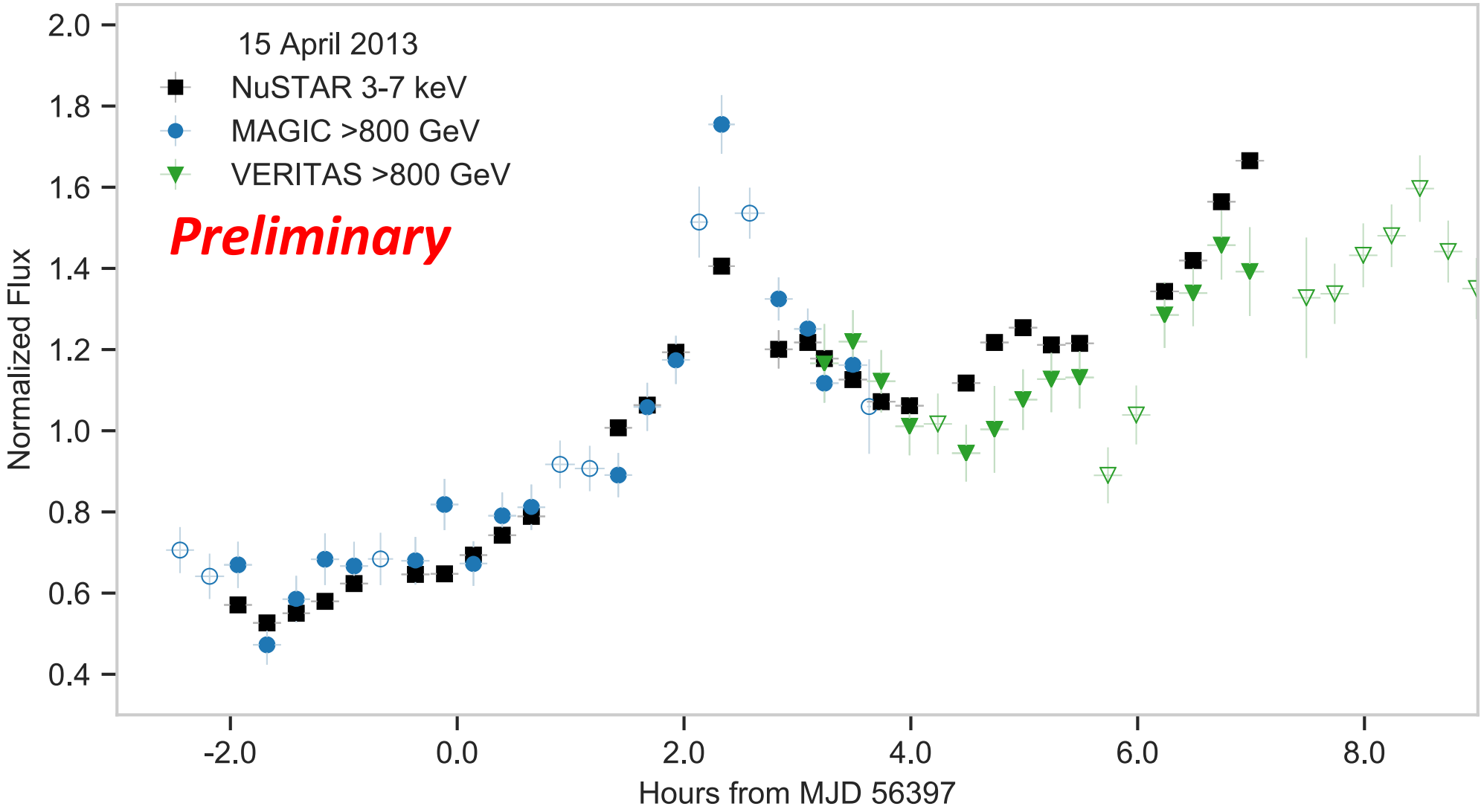
# Mrk421 April 2013: Multi-band X-ray and VHE LCs

**MAGIC+VERITAS observed for 70 hours and NuSTAR for 80 hours**

**About 45 hours of strictly simultaneous VHE and NuSTAR data**



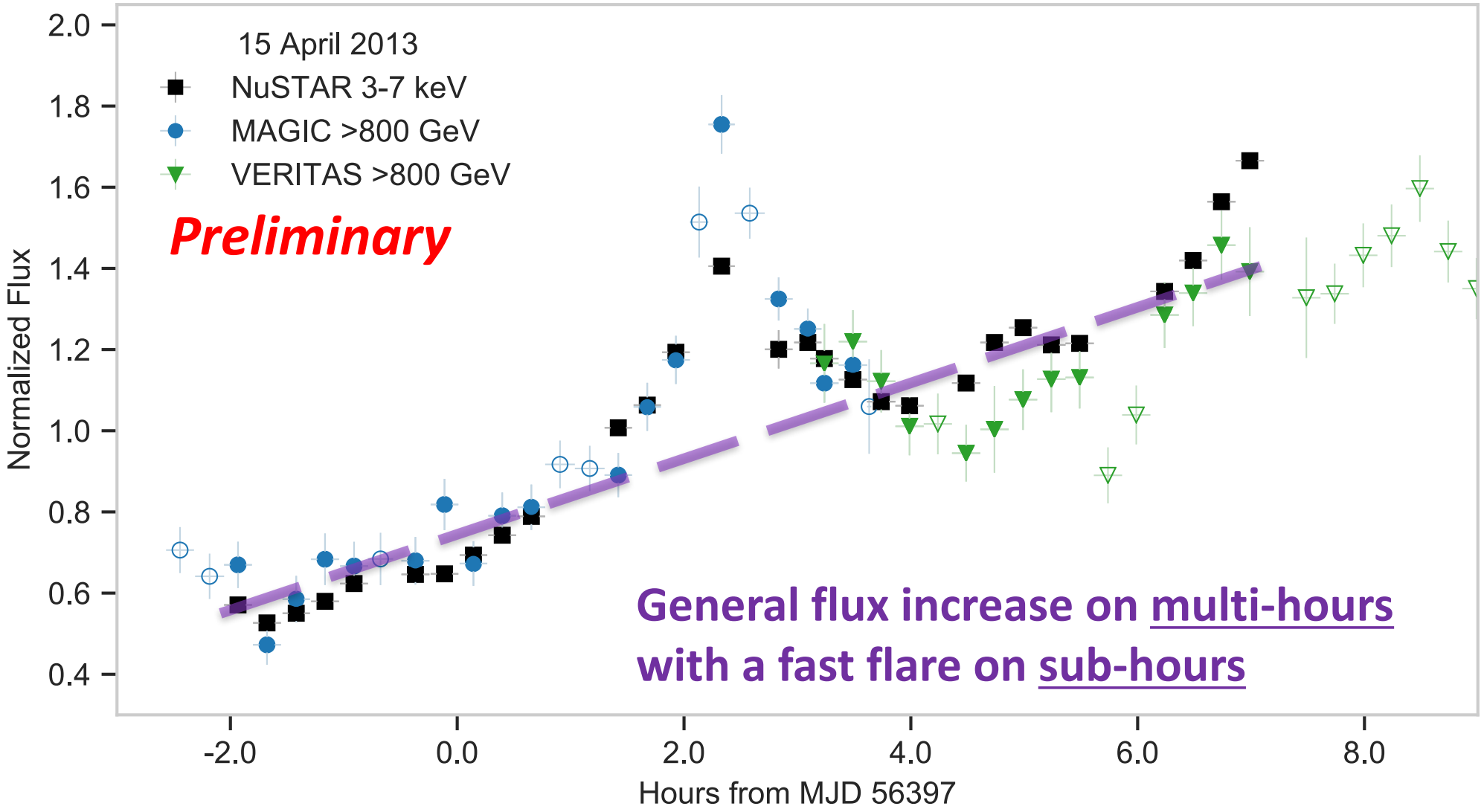
# Normalized light curves for single nights (April 15th)




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

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

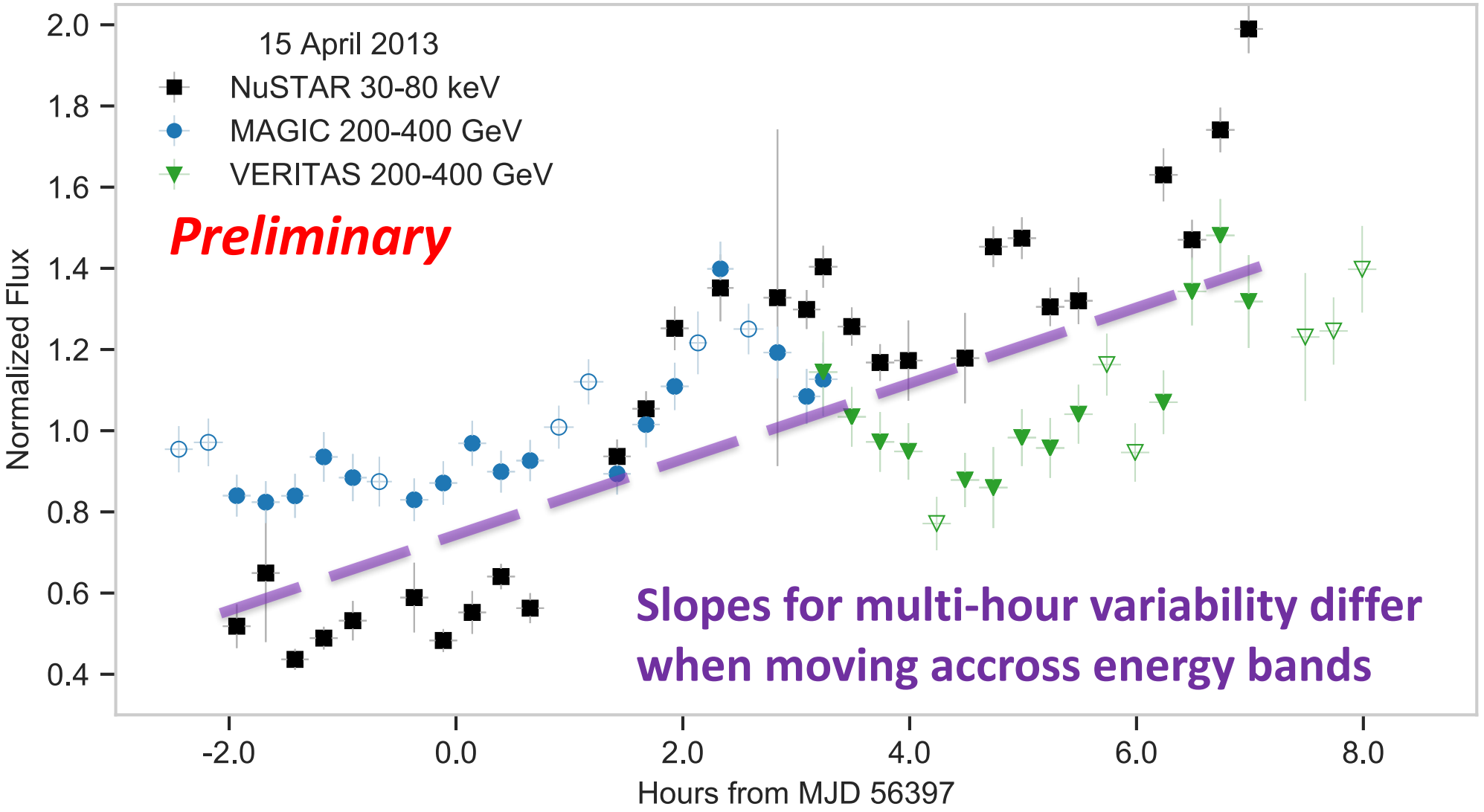
# Normalized light curves for single nights (April 15th)




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

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

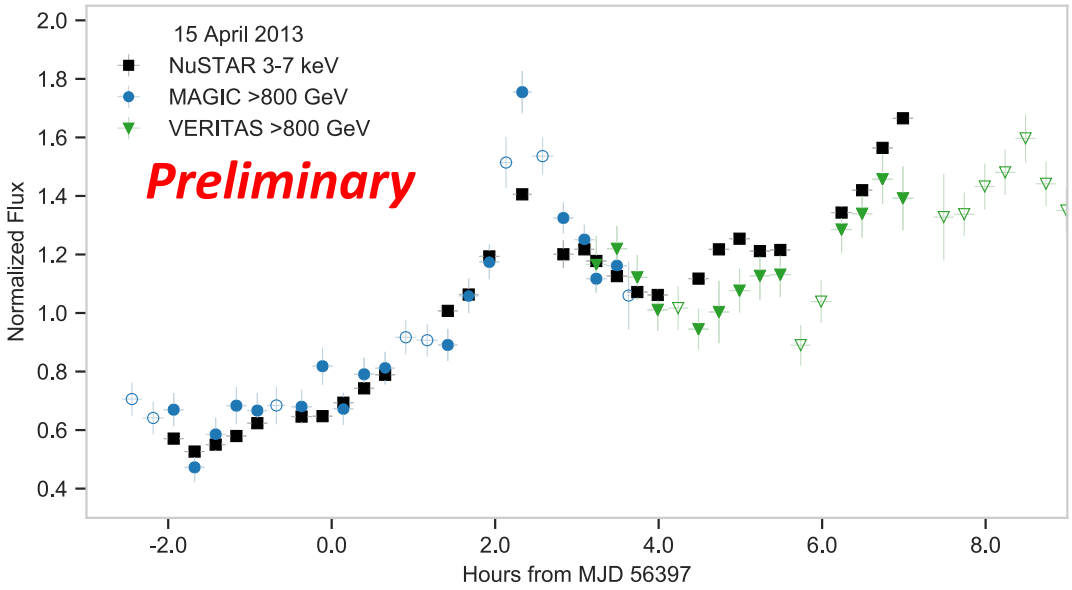
# Normalized light curves for single nights (April 15th)




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

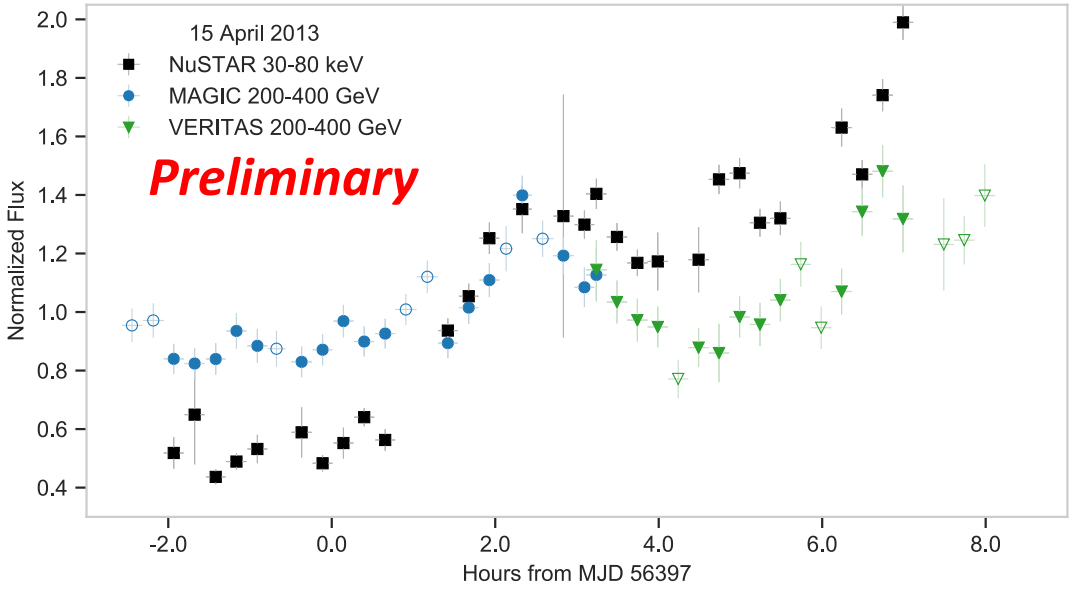
*Full markers indicate time bins with strictly simultaneous VHE/X-ray data*

# Normalized light curves for single nights (April 15th)




MAGIC + VERITAS >0.8 TeV

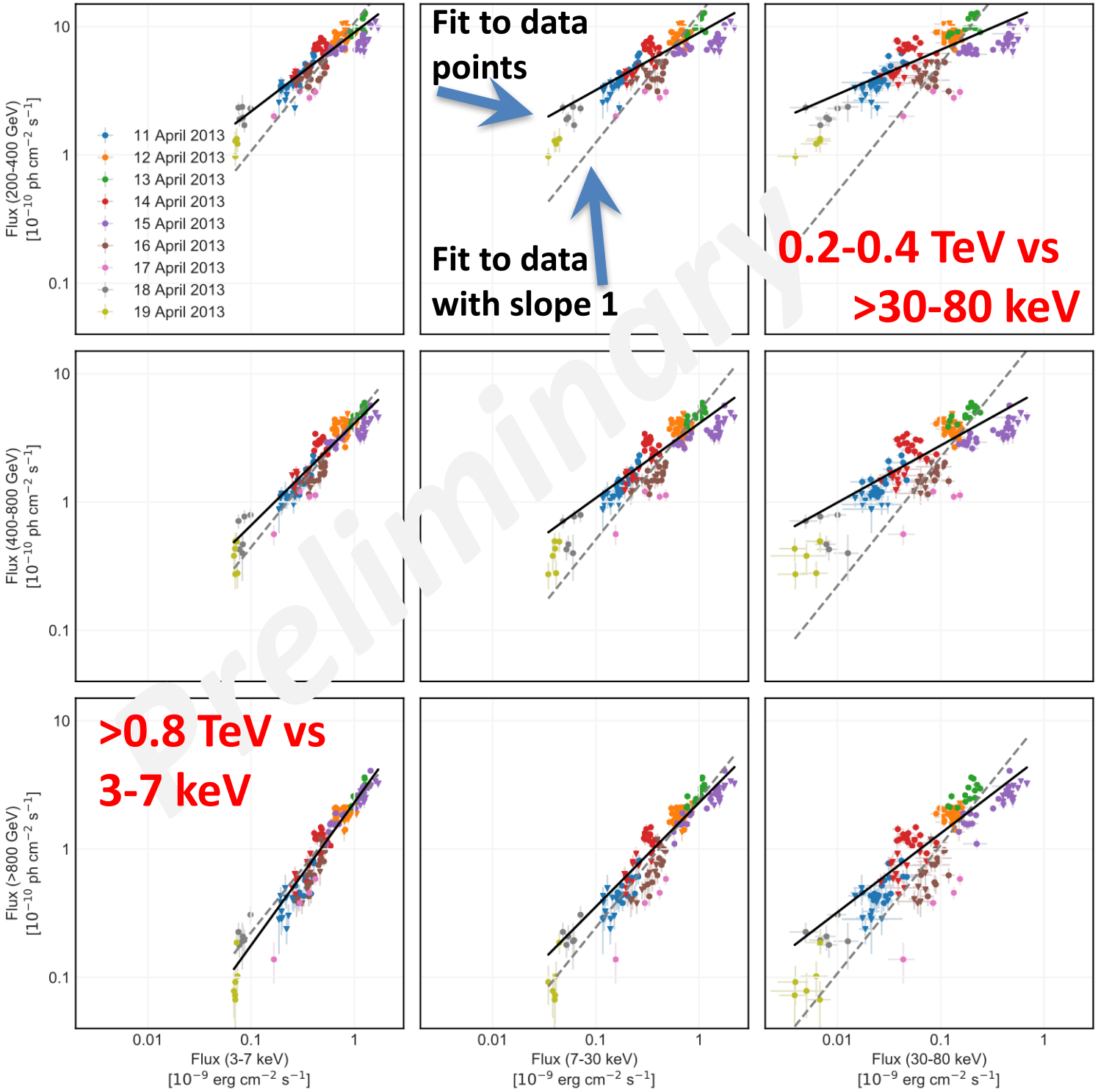
NuSTAR 3-7 keV




**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

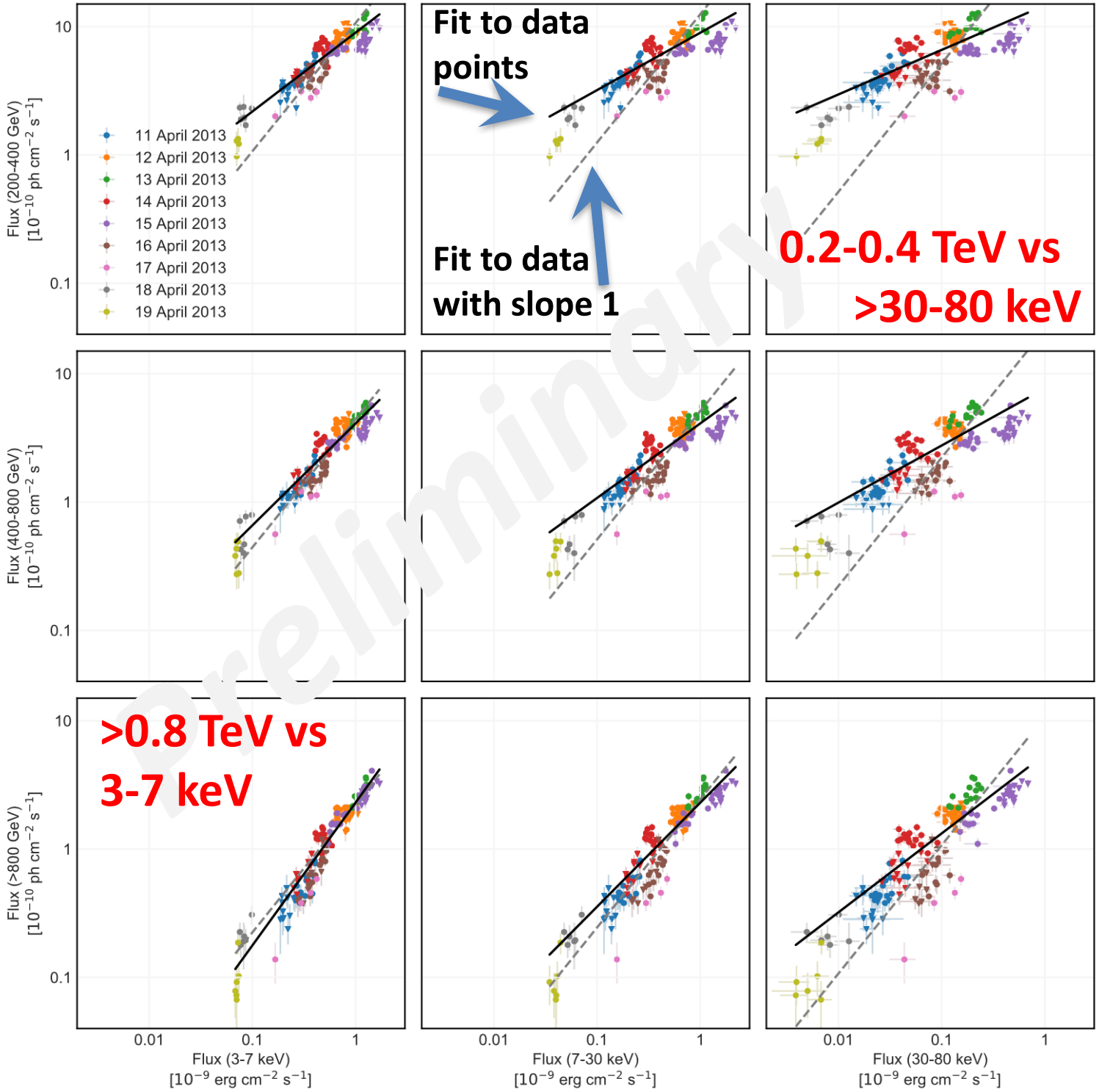
NuSTAR 30-80 keV




# 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)

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

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

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

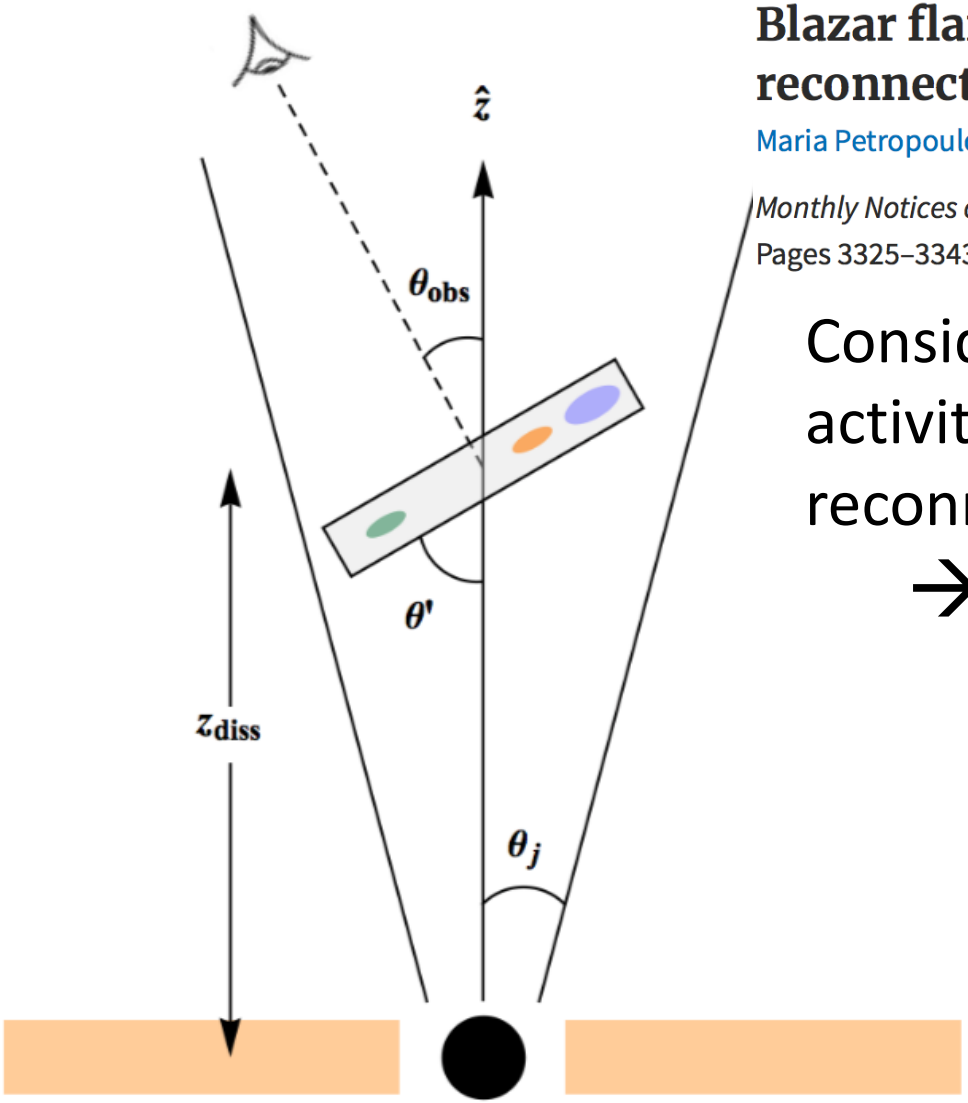



**Figure 9.** Sketch of a reconnection layer (of half-length $L'$) forming in the jet at a distance $z_{\rm diss}$ (not in scale). The layer forms an angle $\theta'$ (as measured in the jet's rest frame) with respect to the jet axis. Plasmoids of different sizes and velocities move towards the sides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

## 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

Considered that the large X-ray/VHE activity is produced in a magnetic reconnection layer

→ M. Petropoulou

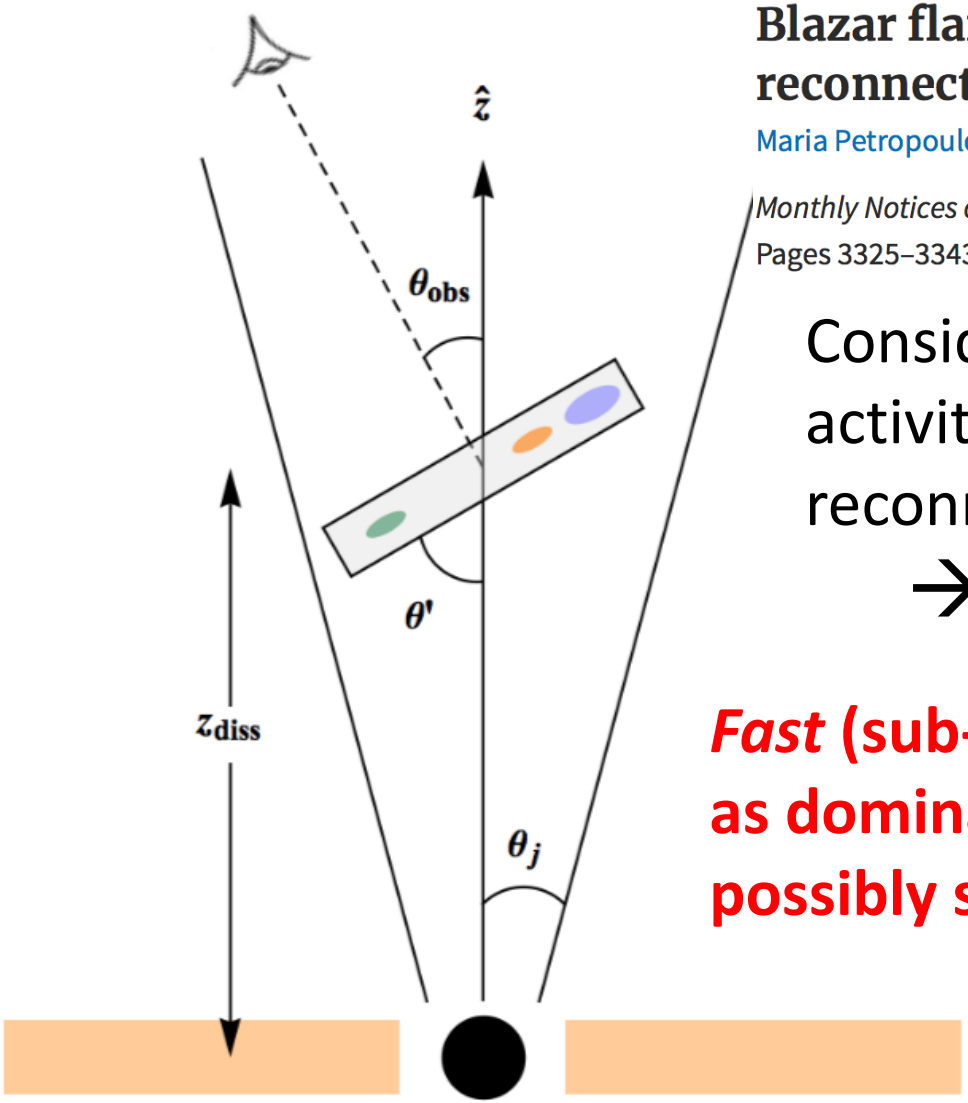



**Figure 9.** Sketch of a reconnection layer (of half-lengt forming in the jet at a distance $z_{diss}$ (not in scale). layer forms an angle $\theta'$ (as measured in the jet's rest fr with respect to the jet axis. Plasmoids of different size velocities move towards the sides of the layer while radia The jet has an opening angle $\theta_j$ and a bulk Lorentz f $\Gamma_j$.

## 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

Considered that the large X-ray/VHE activity is produced in a magnetic reconnection layer

→ M. Petropoulou

***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

**- 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

**- 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.

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

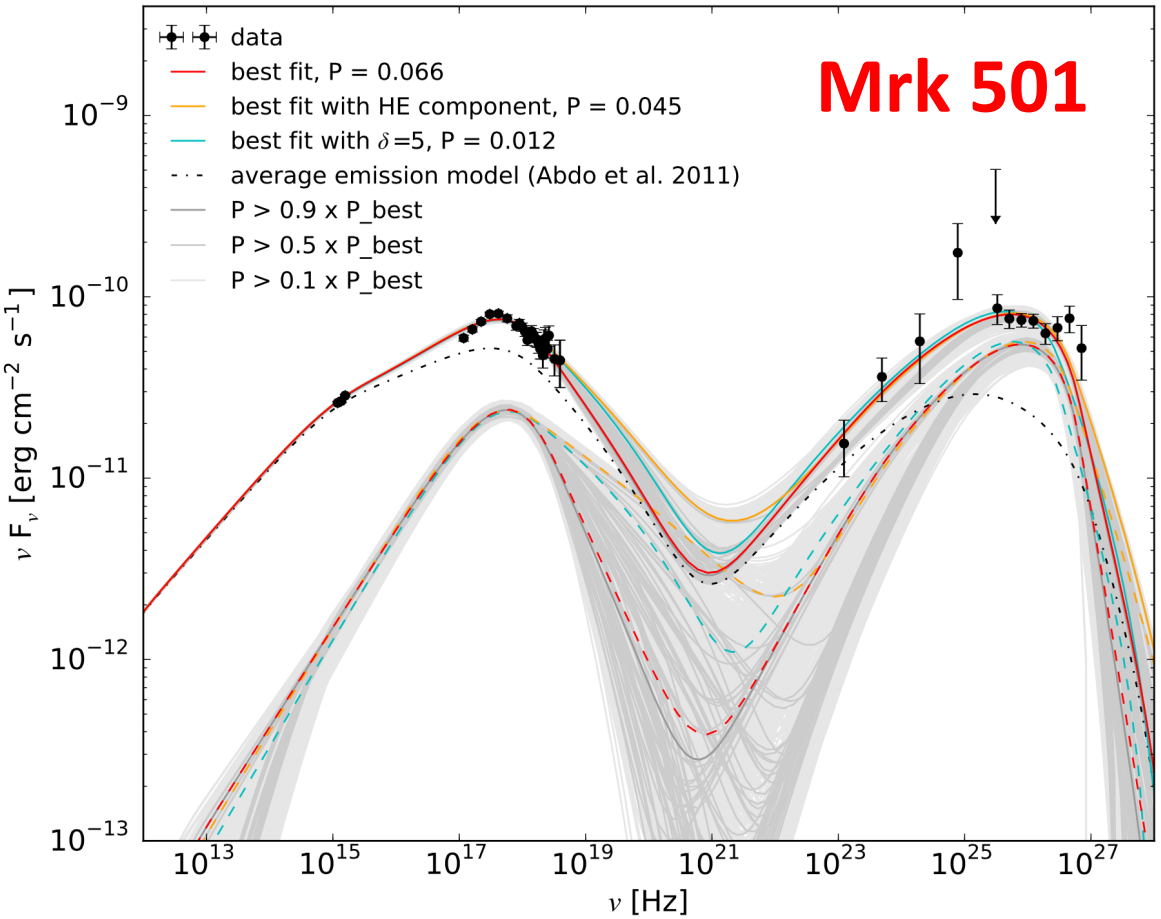
→ *We have VHE spectra from Mrk421/Mkr501 with a resolution comparable to full CTA for the typical VHE blazar ("<5% Crab blazars")*

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

Backup

# 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**

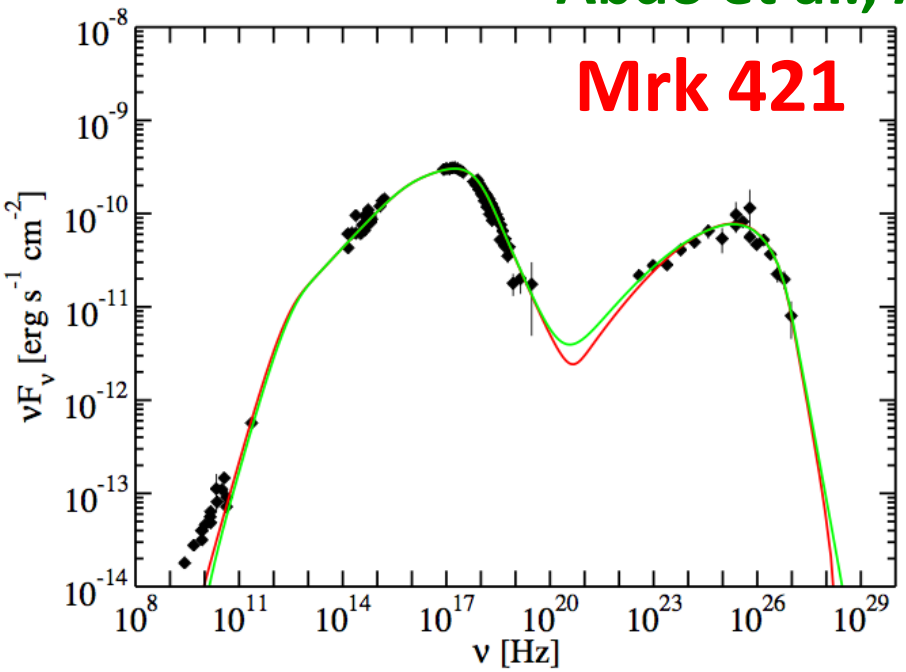



**Figure 11.** SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{var} = 1$ day (red curve) and $t_{var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

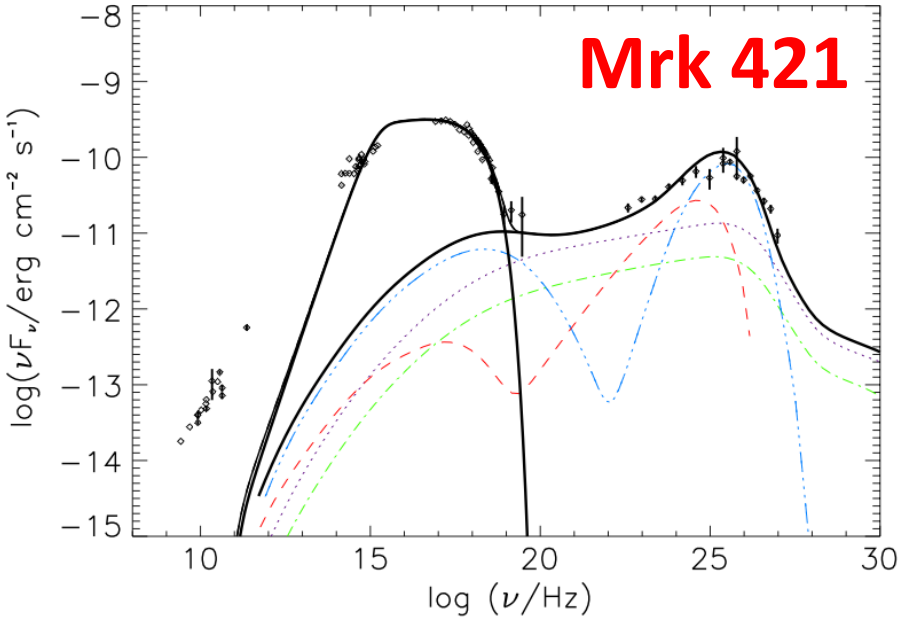


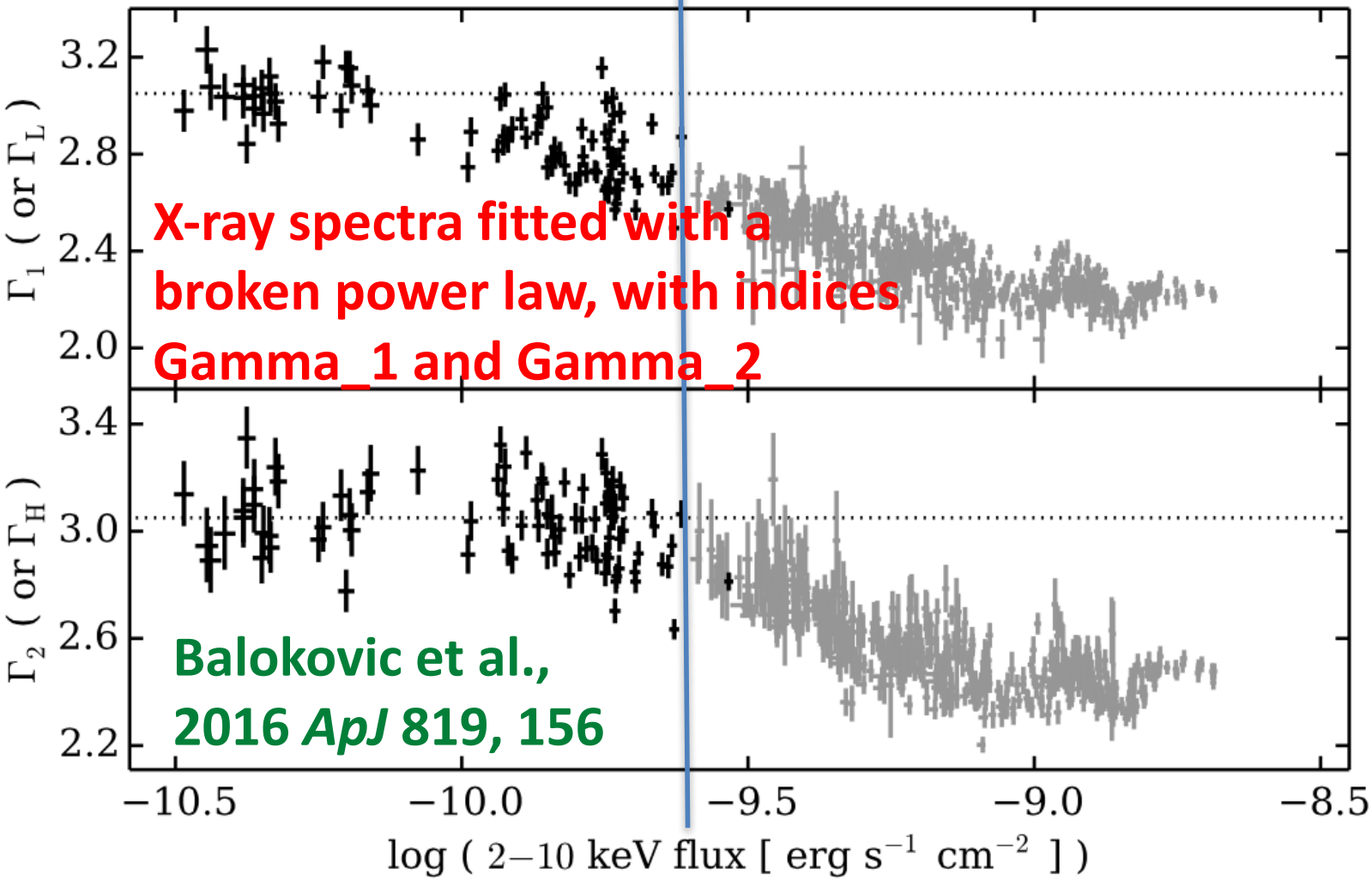

**Figure 9.** Hadronic model fit components: $\pi^0$-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), $\mu$-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (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**

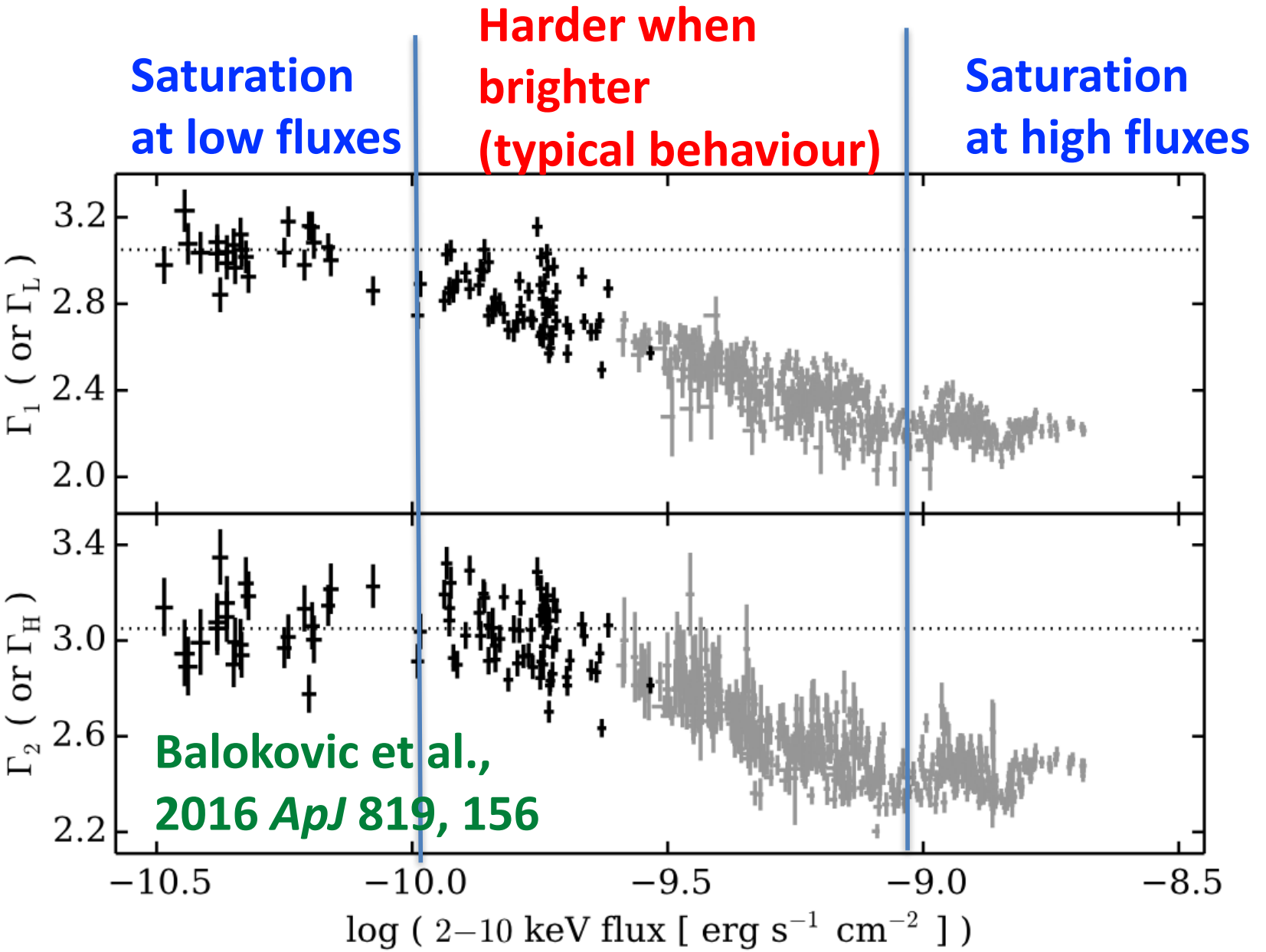
# X-ray spectral shape vs. X-ray flux for Mrk421

**NuSTAR spectra (2013 campaign)**

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

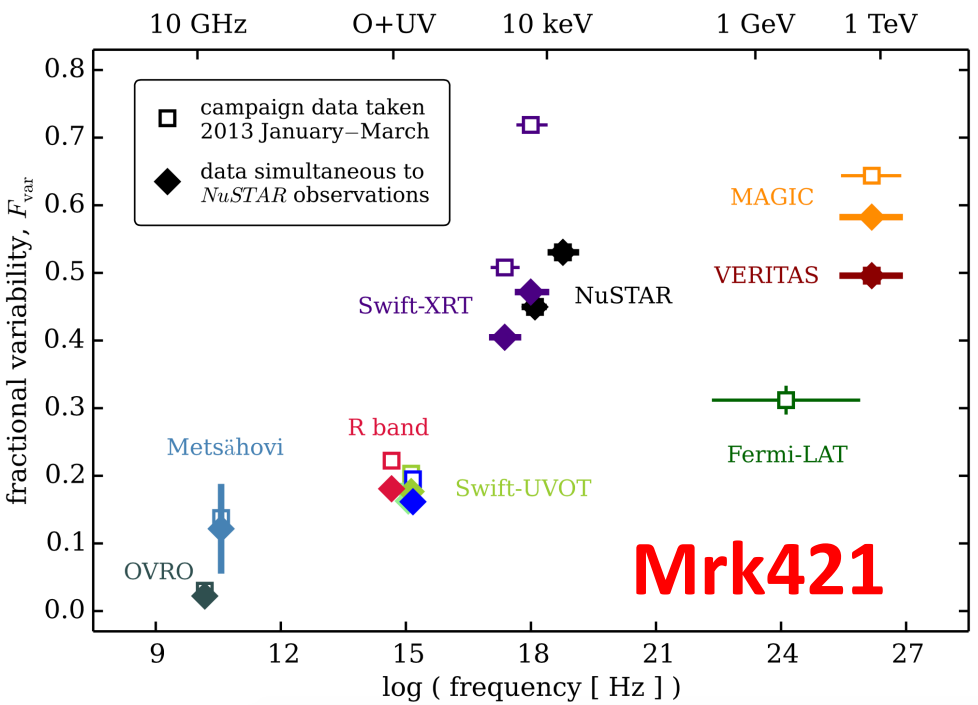


# X-ray spectral shape vs. X-ray flux for Mrk421

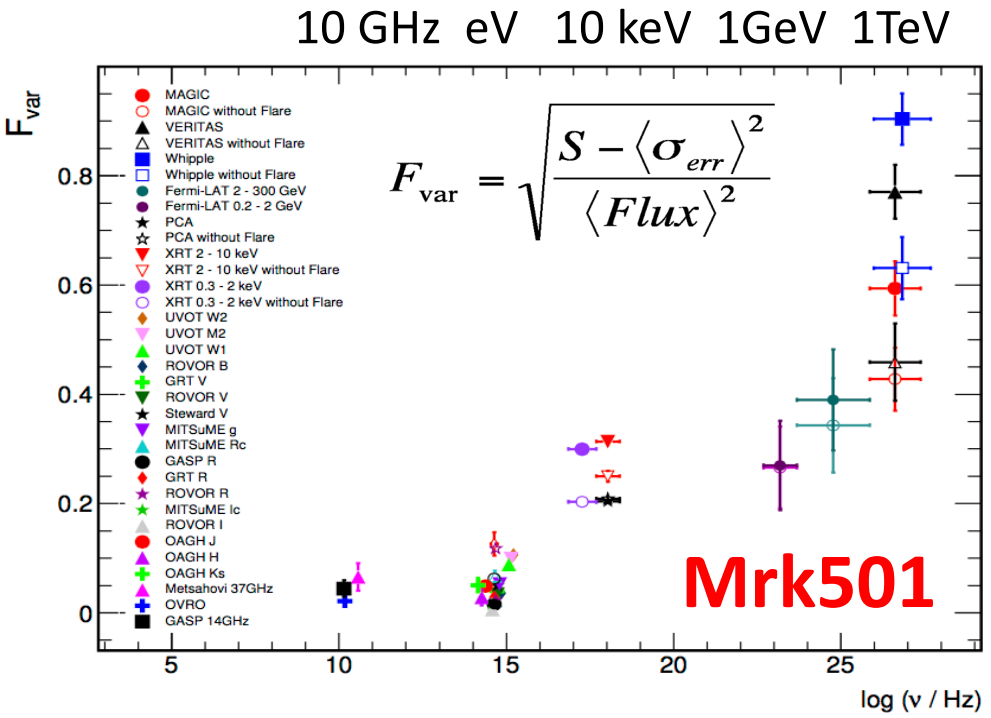


# Comparison of variability between the two archetypical TeV blazars: Mrk421 vs. Mrk501

**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”**