Mrk421 and Mrk501 as high-energy physics laboratories to study the nature of blazars

David Paneque

Max Planck Institute for Physics

(dpaneque@mppmu.mpg.de)

Many people: M. Aller, H. Aller, M. Baloković, P. Becerra, F. Borracci, J. Chiang, M. Doert, A . Furniss, M. Giroletti, T. Hovatta, G. Hughes, S. Jorstad, A. Lahteenmaki, V. Larionov, R. Lico, A. Marscher, G. Madejski, K. Noda, N. Nowak, M. Perri, A. Schukla, P. Smith, S. Sun, H. Takami, M. Villata, A. Wehrle …

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

- Introduction: the challenge of studying blazars
  - → Extensive MW campaigns on Mrk421 and Mrk501
- Some highlighted results
  - → Characteristics that get repeated over time
  - → *Peculiar behaviors (during low activity)*
- Conclusions

- **Introduction: the challenge of studying blazars**

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

The CHALLENGE of studying blazars

Many basic open questions… that persist since the 80s

→ e.g. see Talk by Esko Valtaoja

From observational perspective, there are two major practical challenges

a) Blazars emit over a very wide energy range

(from radio to very high energy gamma-rays)

b) Blazar emission is variable on very different timescales

(from years down to minutes)

→Need radio-to-gamma MW campaigns lasting many years

→ Fermi-LAT provides "constant temporal coverage" for all objects, but this does not occur at the other energy bands

→ Not possible to do for many objects

→Which objects should we study ?

Why studying Mrk421 and Mrk501 ?

- **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"
  → 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**

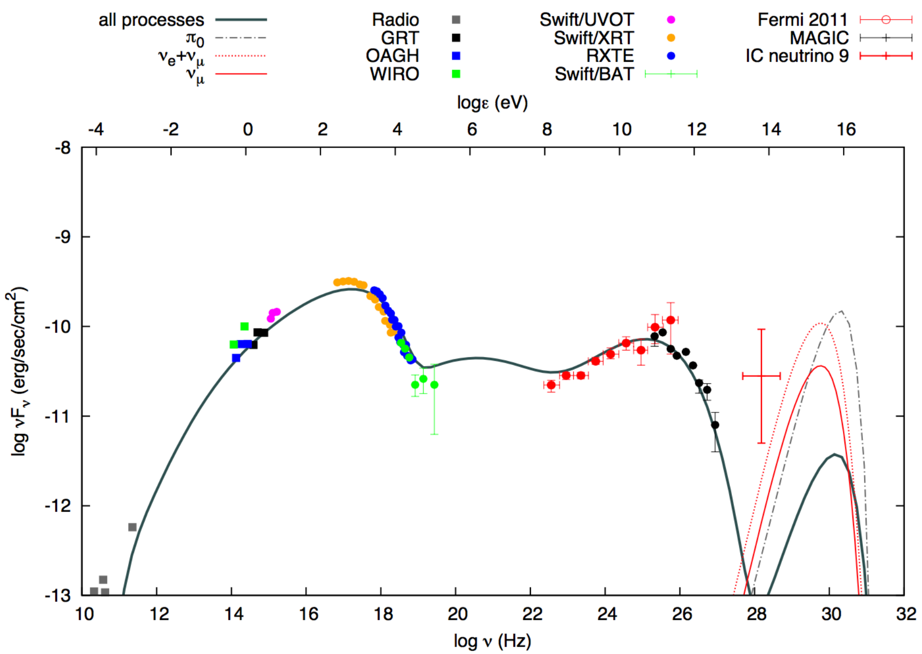
It is more difficult to study other blazars that are farther away, dimmer, or have more complicated structures

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

Why studying Mrk421 and Mrk501 ?

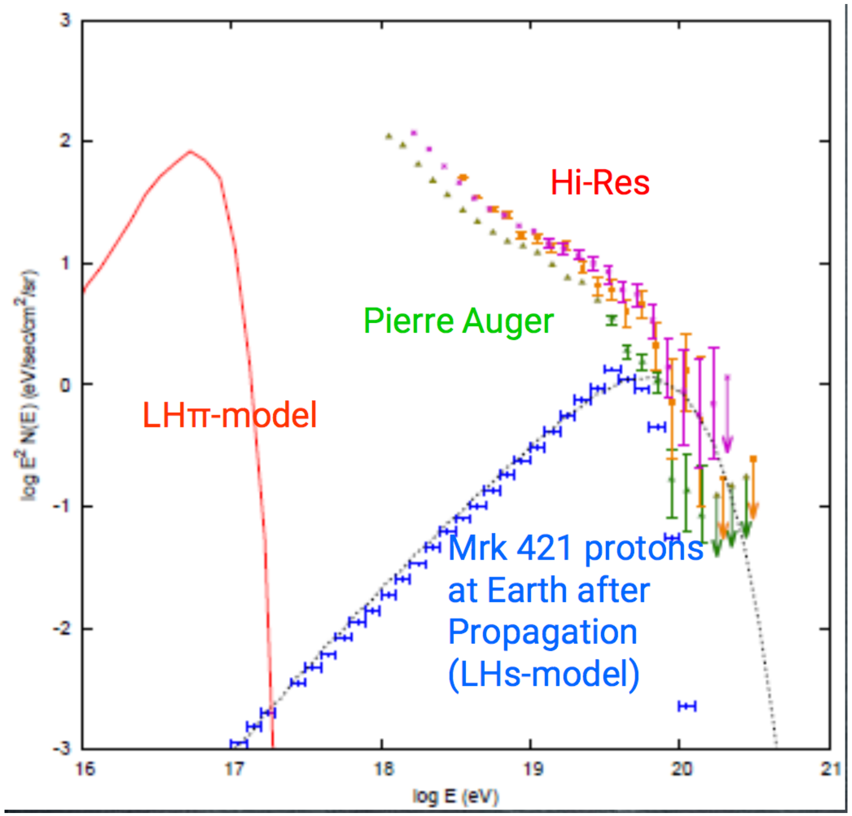
Mrk421 as possible source of PeV neutrinos and 30 EeV CR

See talk from P. Padovani (this conference)



Petropoulou et al 2015, MNRAS 448, 2412

See talk from A. Mastichiadis (this conference)



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, GRT, Liverpool, Kanata…
UV: Swift-UVOT
X-ray: (RXTE), Swift-XRT, NuSTAR
Gamma-ray: *Fermi*-LAT
VHE: MAGIC, VERITAS, FACT

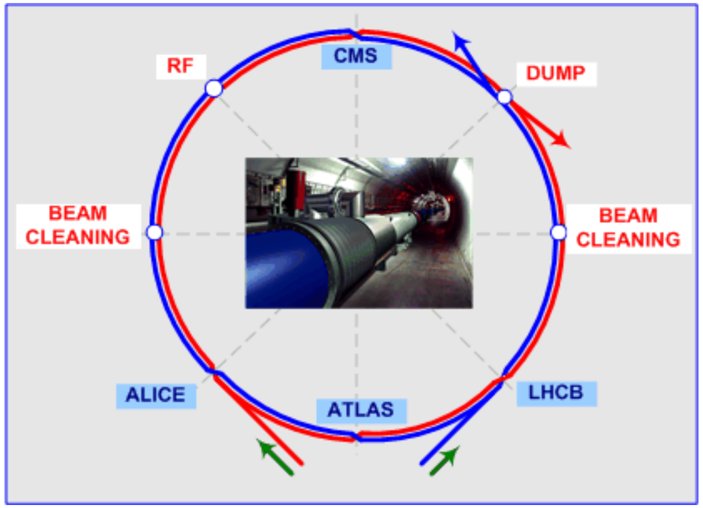
Monitored regardless of activity (*increase coverage during flares*)
→ observed every few days for about half year (*every year* !)

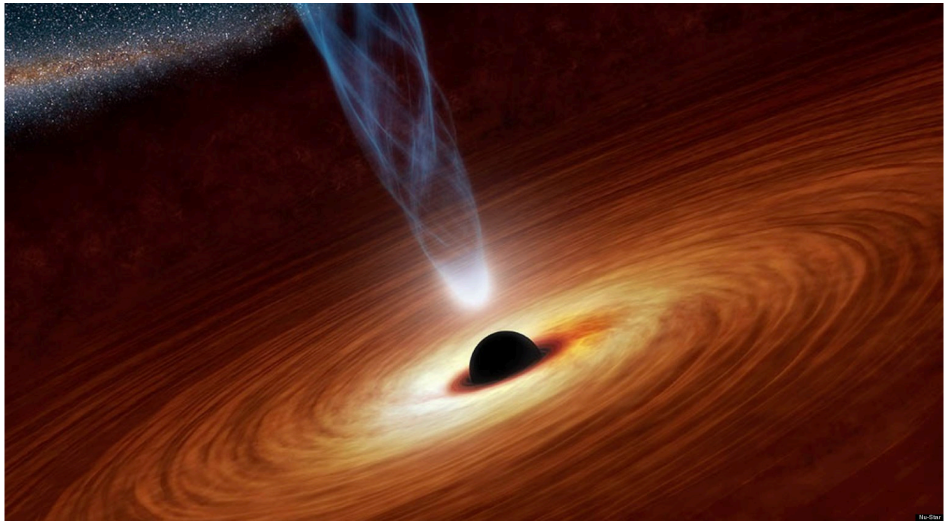
Extensive MW Campaigns on Mrk421 and Mrk501

LHC vs Mrk421/Mrk501

ATLAS/CMS
LHCb + Alice

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





LHC comes with "adjustable knobs" (controlled environment) and measure the interactions directly; while for Mrk421/Mrk501 we only can observe it in an indirect way (through secondary products) and aim at identifying when the "knobs changed"

In both cases we learn many things by using these "extreme particular accelerators"; and surely that requires "observing" over many years in order to integrate over sufficient data/effects.

Extensive MW Campaigns organized on Mrk421/Mrk501

Mrk421 (Jan19th, 2009-Jun1st ,2009: 4.5 months)- Planned observations: every 2 days

Mrk501 (Mar15th, 2009-Aug1st,2009: 4.5 months) -Planned observations: every 5 days

Mrk421 (Dec8, 2009-Jun20 ,2010: 6 months)- Planned observations: every 1-2 days

Mrk421 (Dec1, 2010-Jun15 ,2011: 6 months)- Planned observations: every 2 days

Mrk501 (March1, 2011-Sep1,2011: 6 months) -Planned observations: every 3 days

Mrk421 (Dec23, 2011-May31 ,2012: 5.5 months)- Planned observations: every 2 days

Mrk501 (Feb15, 2012-June31,2012: 4.5 months) -Planned observations: every 4 days

Mrk421 (Dec, 2012-May ,2013: 6 months)- Planned observations: every 2 days

Mrk501 (April, 2013-Sep,2013: 5 months) -Planned observations: every 4 days

Mrk421 (Dec, 2013-May ,2014: 6 months)- Planned observations: every 2 days

Mrk501 (March, 2014-Aug,2014: 5 months) -Planned observations: every 3 days

Mrk421 (January, 2015-June ,2015: 6 months)- Planned observations: every 2 days

Mrk501 (March, 2015-June ,2015: 4 months)- Planned observations: every 5-10 days

Mrk421 (Dec, 2015-June ,2016: 6 months)- Planned observations: every 2 days

Mrk501 (March, 2016-Sep ,2016: 6 months)- Planned observations: every 4 days **Current**

As we collect MW data on Mrk421/Mrk501 we learn new things about them, which led to several publications with data from single campaigns (and often with only a small fraction of the campaign data)

So far we have 12 publications:

Lico R, et al, 2012, A&A, 545, 117
Blasi, M.G., et al, 2013, A&A, 559,75
Lico, R. et al., 2014, A&A, 571, 54
Koyama, S., et al., 2015, PASJ, 164

4 with small dataset (focused on radio)

Abdo, A. A. et al. 2011, ApJ, 727, 129
Acciari, V. A. et al. 2011, ApJ, 729, 2
Abdo, A. A. et al. 2011, ApJ, 736, 131
Aleksic et al, 2015, *A&A* 573, 50
Aleksic et al., 2015, A&A 575, 128
Aleksic et al., 2015, A&A 578, 22
Furniss et al. 2015, ApJ 812, 65
Balokovic et al. *2016,* ApJ, 819, 156

8 with extensive MW dataset (includes TeV)

+ Additional papers coming soon…

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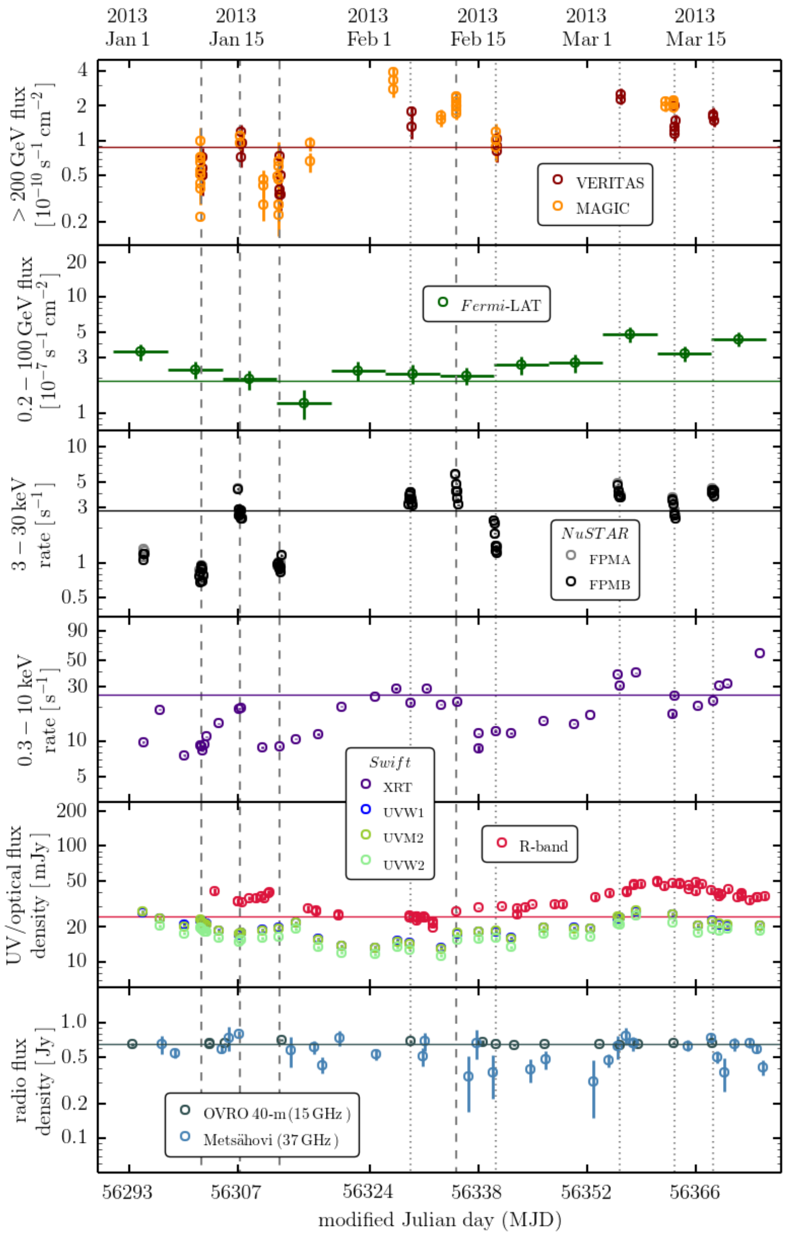
8 with extensive MW dataset (includes TeV)

→ **Large fraction of results reported in this talk relate to this paper.**

- **Some highlight results from the campaigns**

Mrk421 data from Jan/Feb/March 2013

First MW campaign on Mrk421 that includes NuSTAR (3-80 keV)



~TeV

~GeV

~10 keV

~ 1keV

~1 eV

~10 microeV

Balokovic et al., 2016
ApJ 819, 156

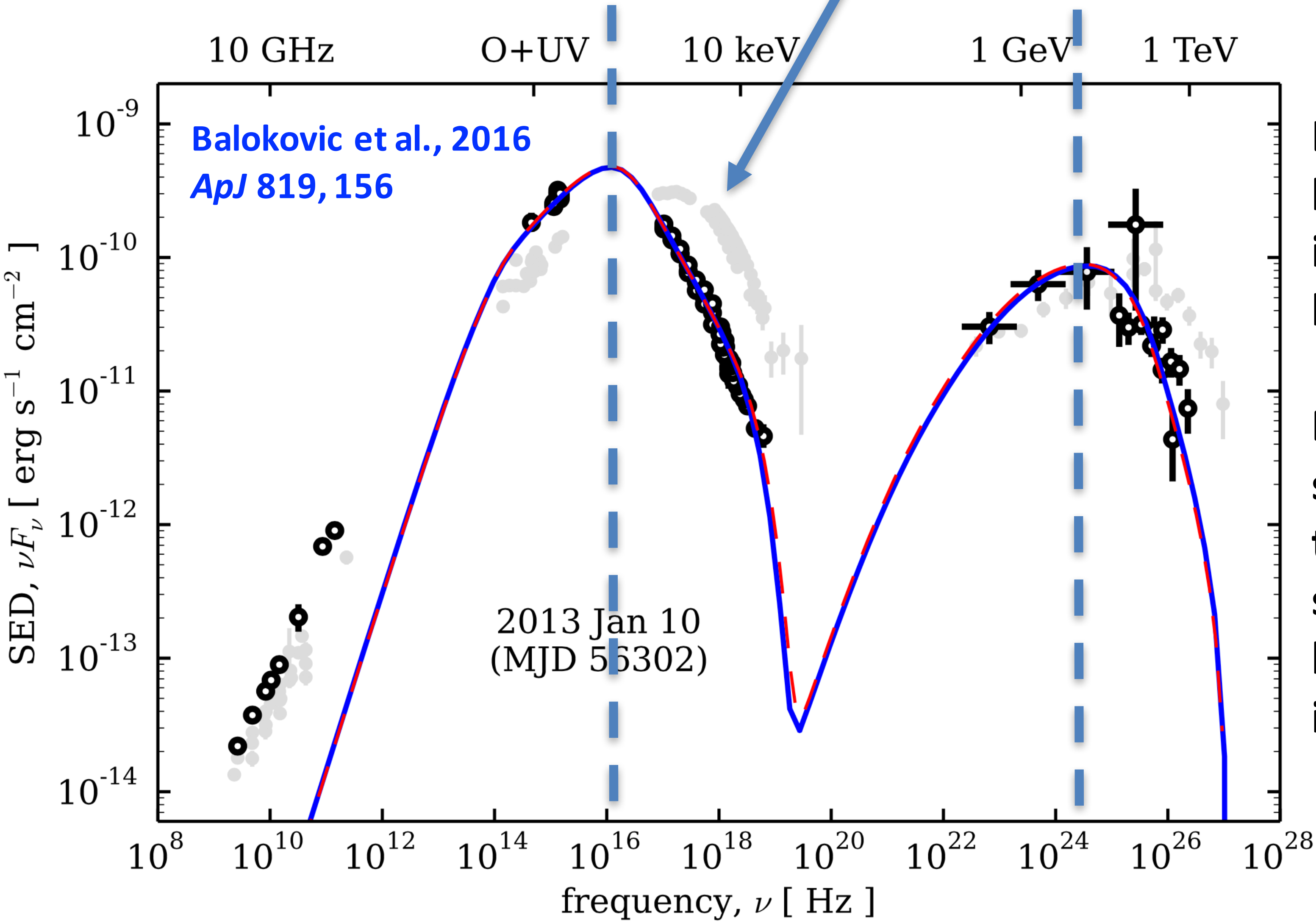
At VHE it was typically below 0.5 Crabs, with fluxes as low as 15% Crab

Among lowest fluxes ever reported at X-ray and VHE

SED peak positions shifted to lower energies by factor ~10

Peak position at ~10^{16} Hz (~40 eV)
First time we see such big shift
→ *"HBL moving towards IBL"*

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



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

SED peak positions shifted to lower energies by factor ~10

Peak position at ~10^{16} Hz (~40 eV)
First time we see such big shift
→ *"HBL moving towards IBL"*

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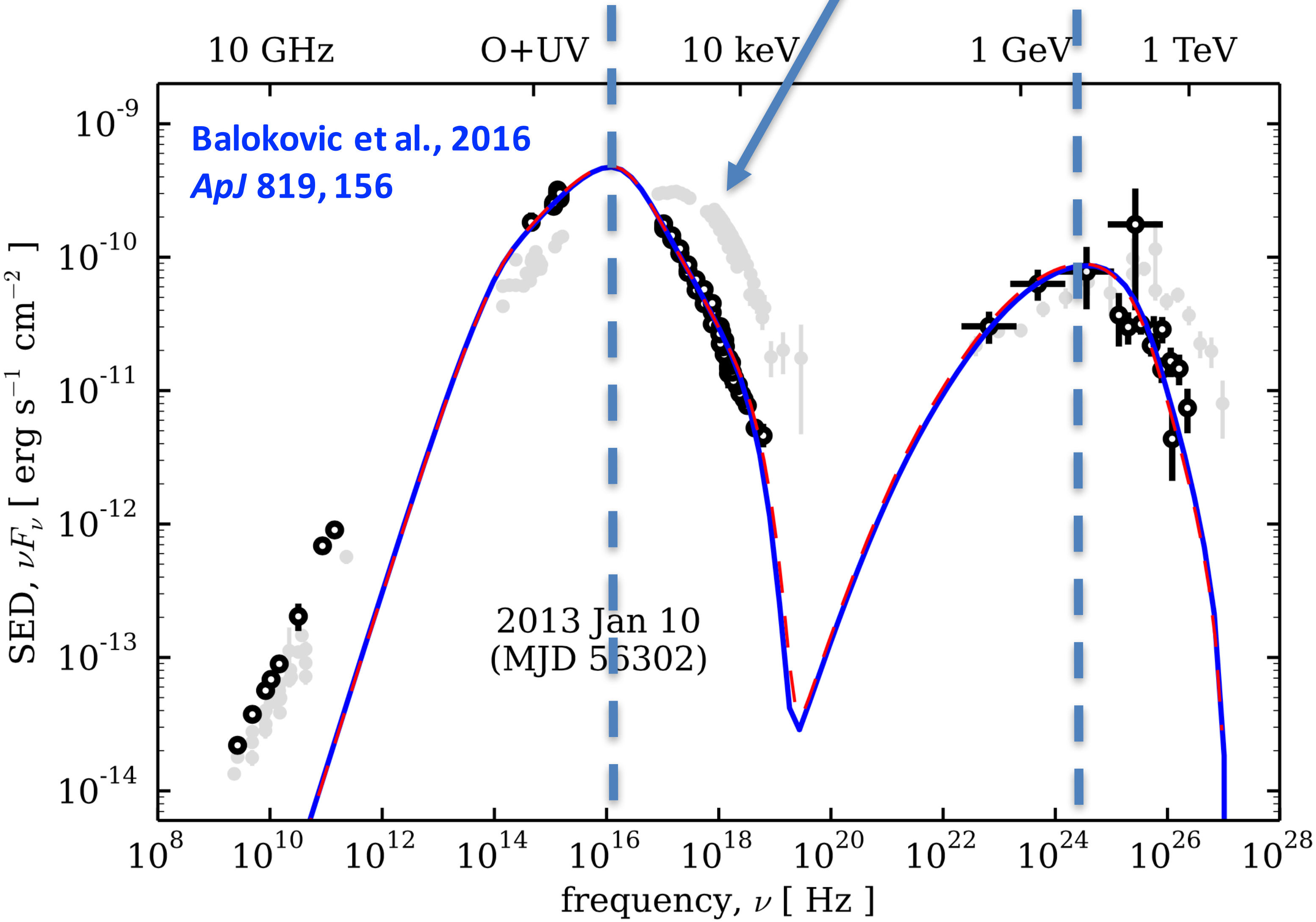


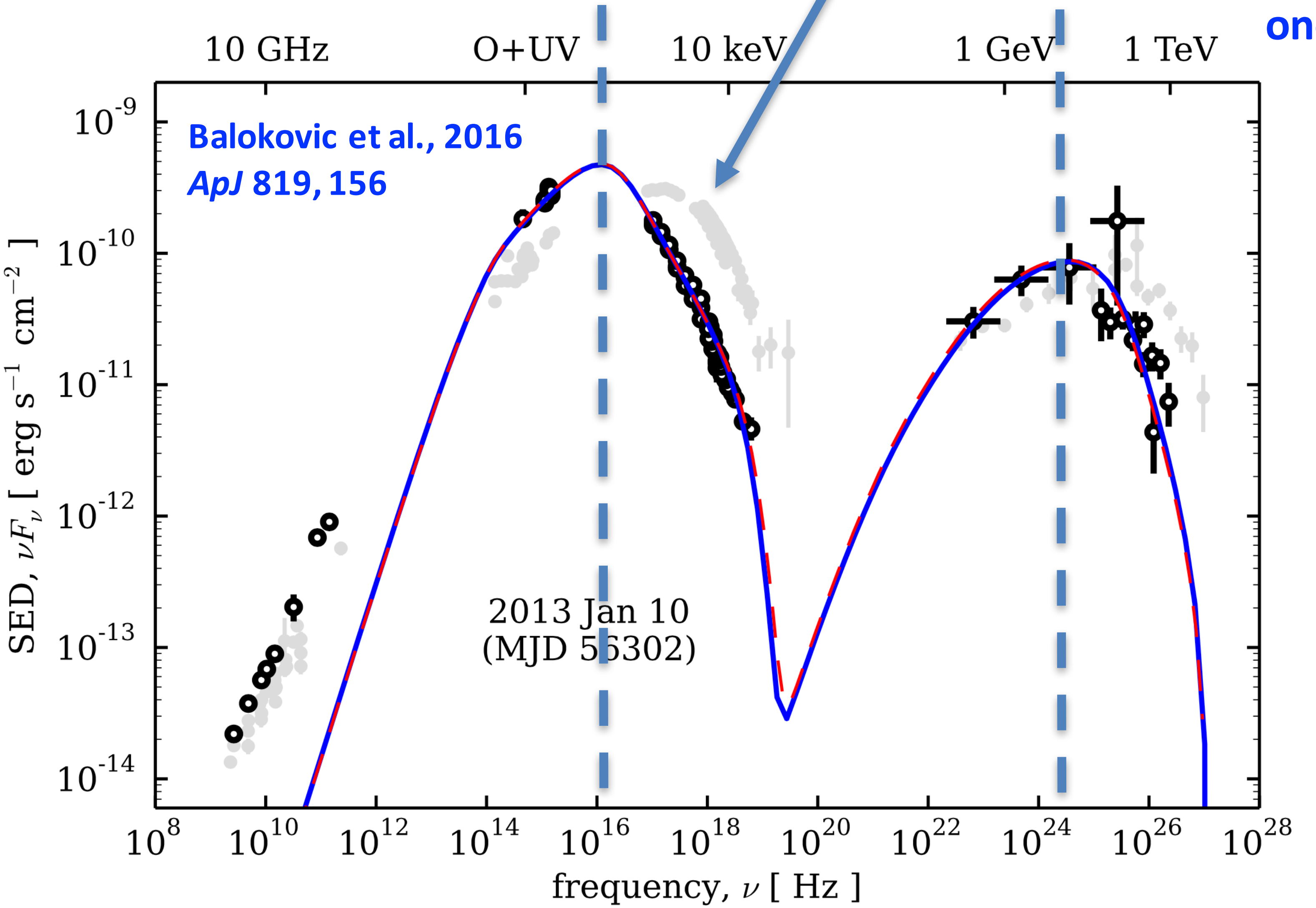
Low activity softened the X-ray and VHE spectra, but did not bring spectral cutoffs.
→ Electrons accelerated to highest energies

SED peak positions shifted to lower energies by factor ~10

Peak position at ~10^{16} Hz (~40 eV)
First time we see such big shift
→ *"HBL moving towards IBL"*

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

Spectrum can be described with a one-zone SSC model



→ *Main Differences with respect to typical SED can be explained (mostly) with (much) lower electron energies, smaller size R, and higher B field*

However, in the paper we argue that the observed variability patterns suggest that a multi-zone scenario is preferred

Remember: Large intra-model and inter-model degeneracy for fitting single broadband SEDs

Mrk421 SED described with a
Leptonic scenario

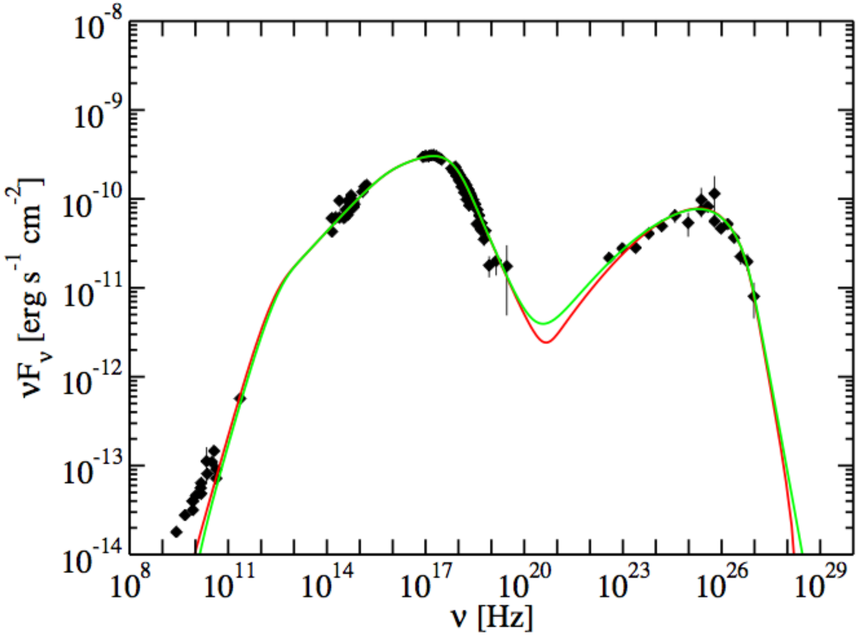


Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{var} = 1$ day (red curve) and $t_{var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

Mrk421 SED described with a
Hadronic scenario

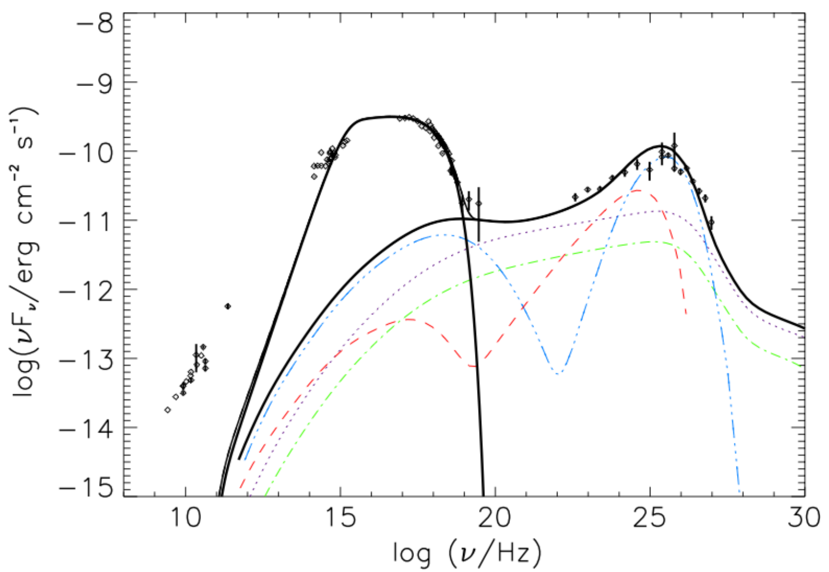
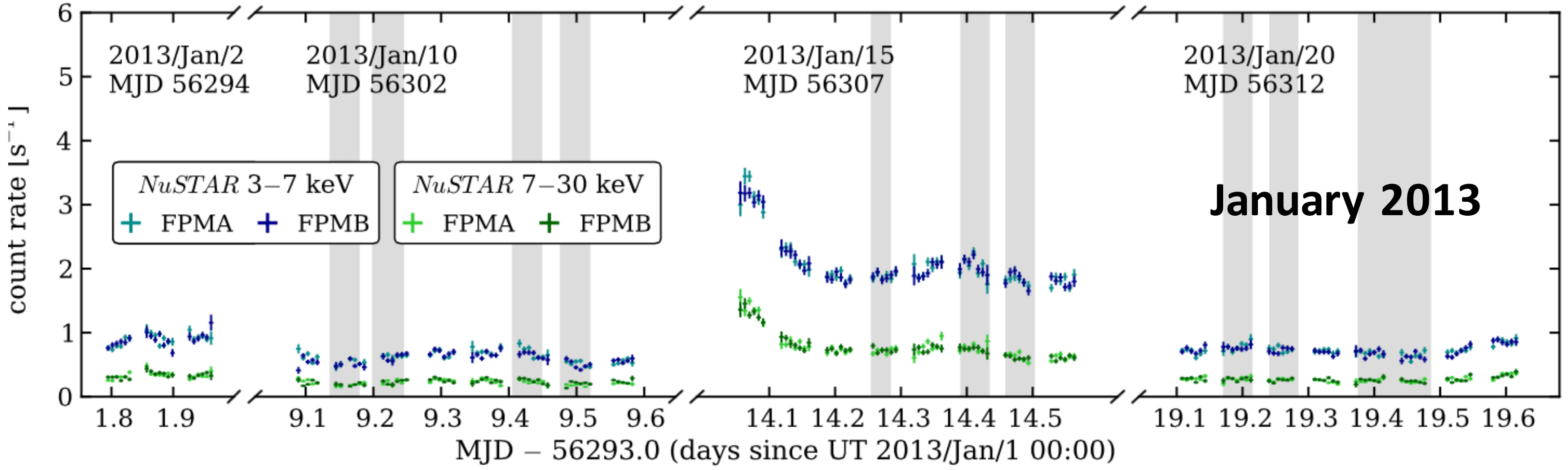


Figure 9. Hadronic model fit components: π^0-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), μ-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which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

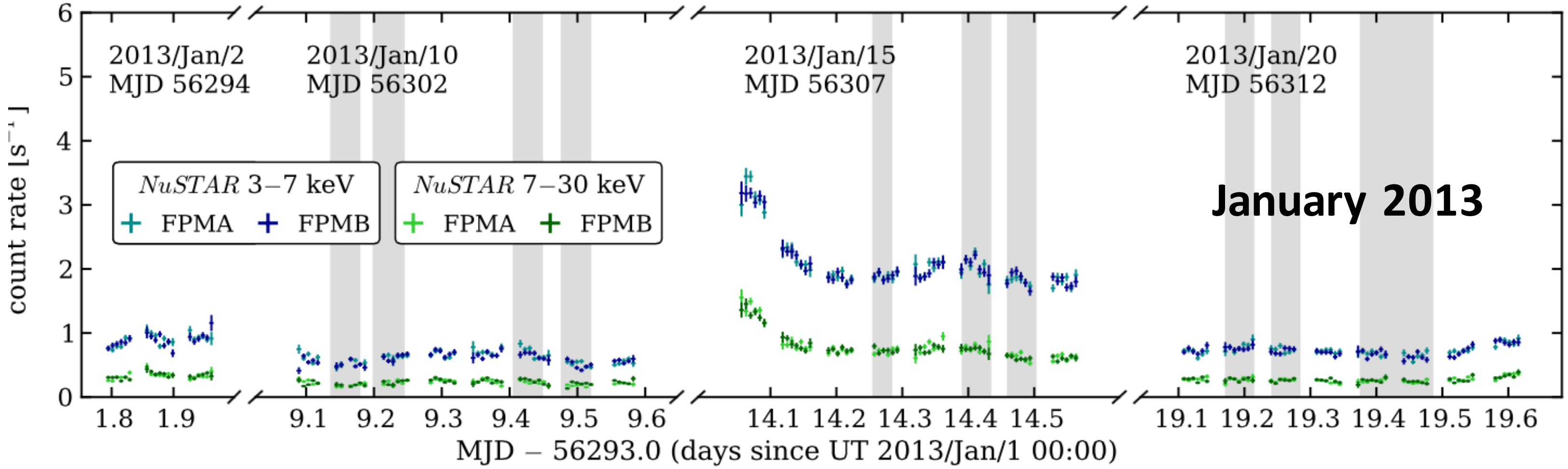
Abdo et al., ApJ 736 (2011) 131

Multi-band variability is key to distinguish between models



NuSTAR LC
10 min bins
intranight variability, in most nights

Shaded areas depict time intervals with MAGIC/VERITAS observations



NuSTAR LC
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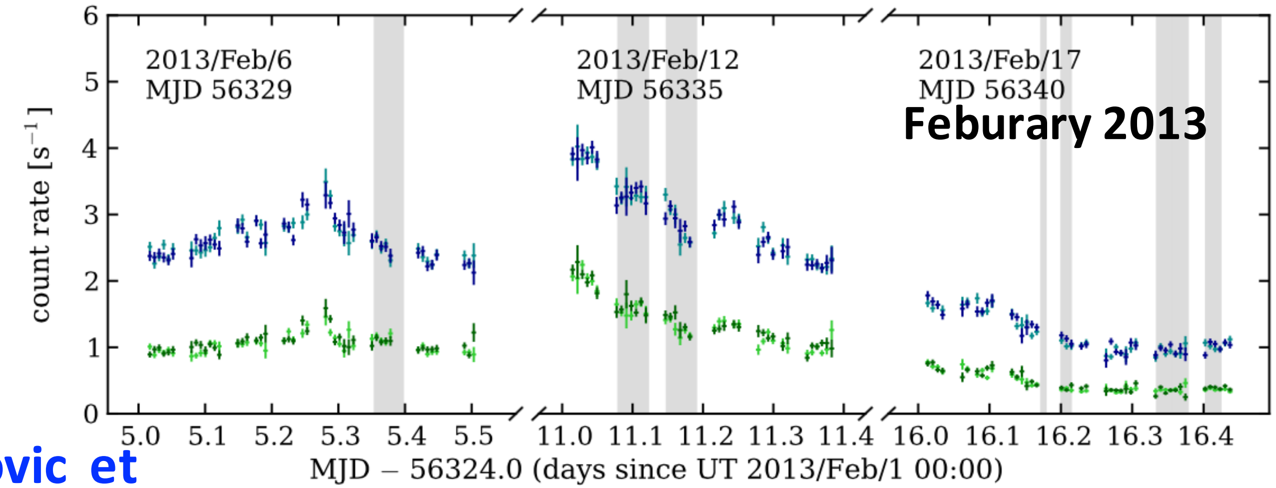
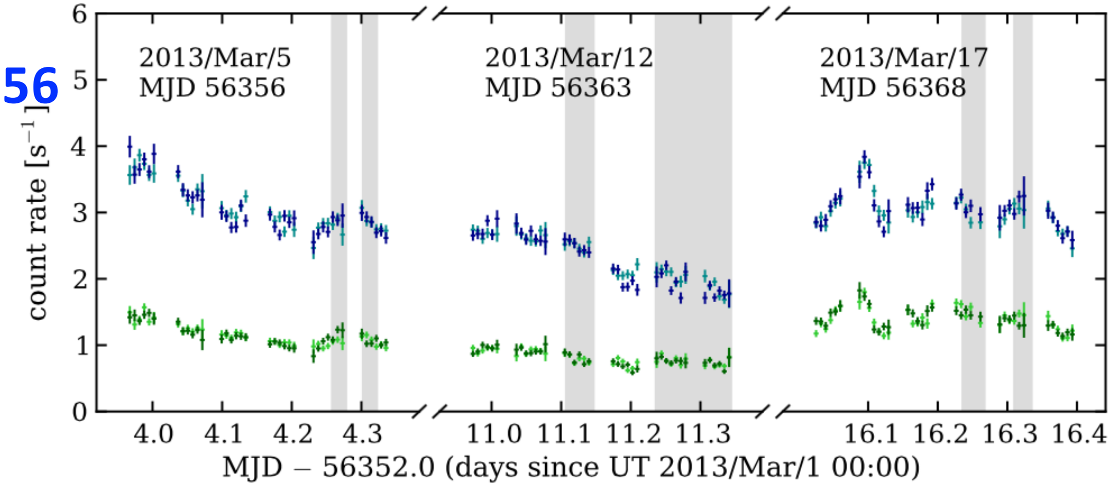


Large/smooth variations in the count rate can be described with a timescale of 6-12 hours

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

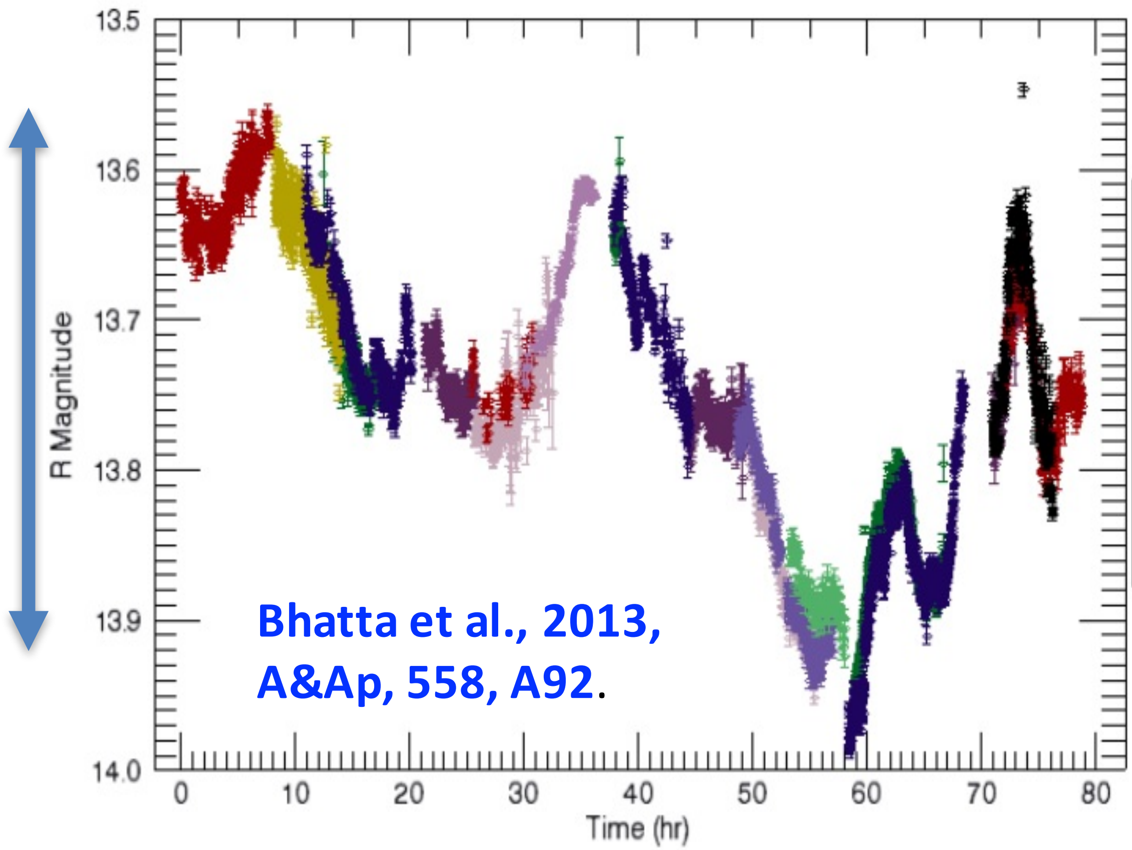


March 2013

Shaded areas depict time intervals with MAGIC/VERITAS observations

NuSTAR X-ray LC (during tens of hours) on Mrk421 with ~30-50% peak to peak variations is similar to multi-instrument optical LC on 0716+714 during 78 hours

~30% peak to peak variations,



See J. Webb and G. Bhatta talks (this conference)

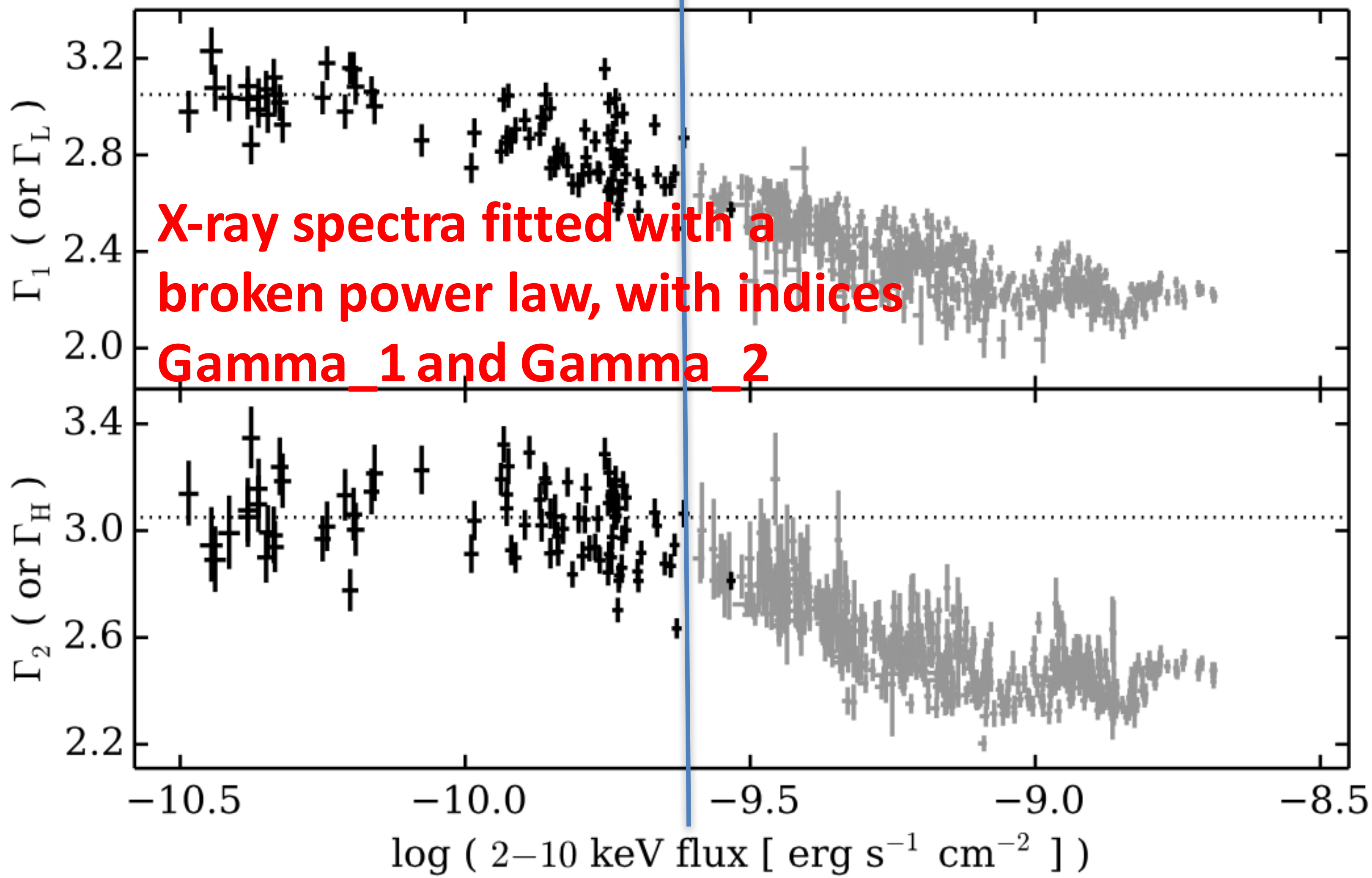
In both cases, these LCs suggest a superposition of emission from various regions

→ During strong flares, a single region may dominate

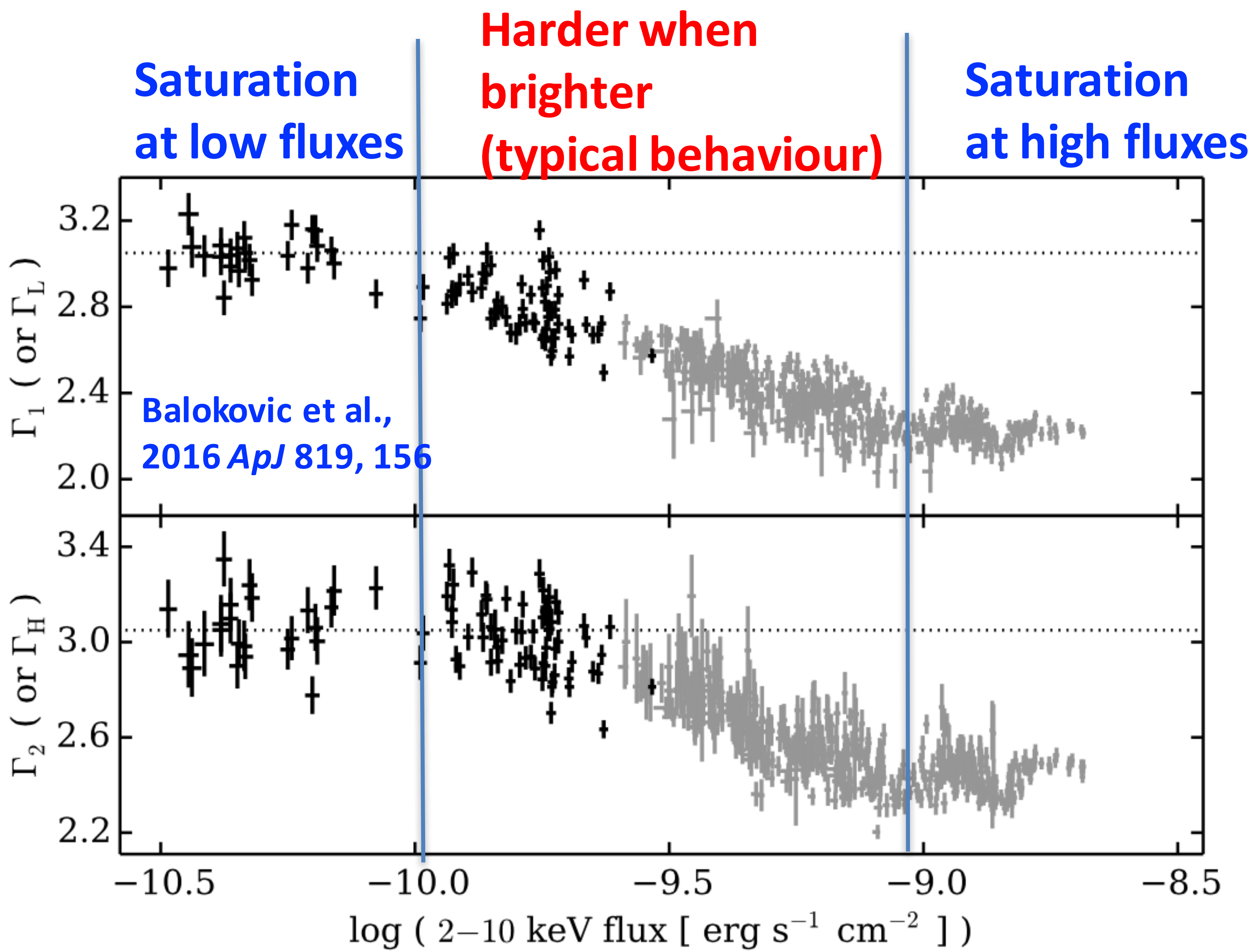
X-ray spectral shape vs. flux

NuSTAR spectra (2013 campaign)

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



X-ray spectral shape vs. flux

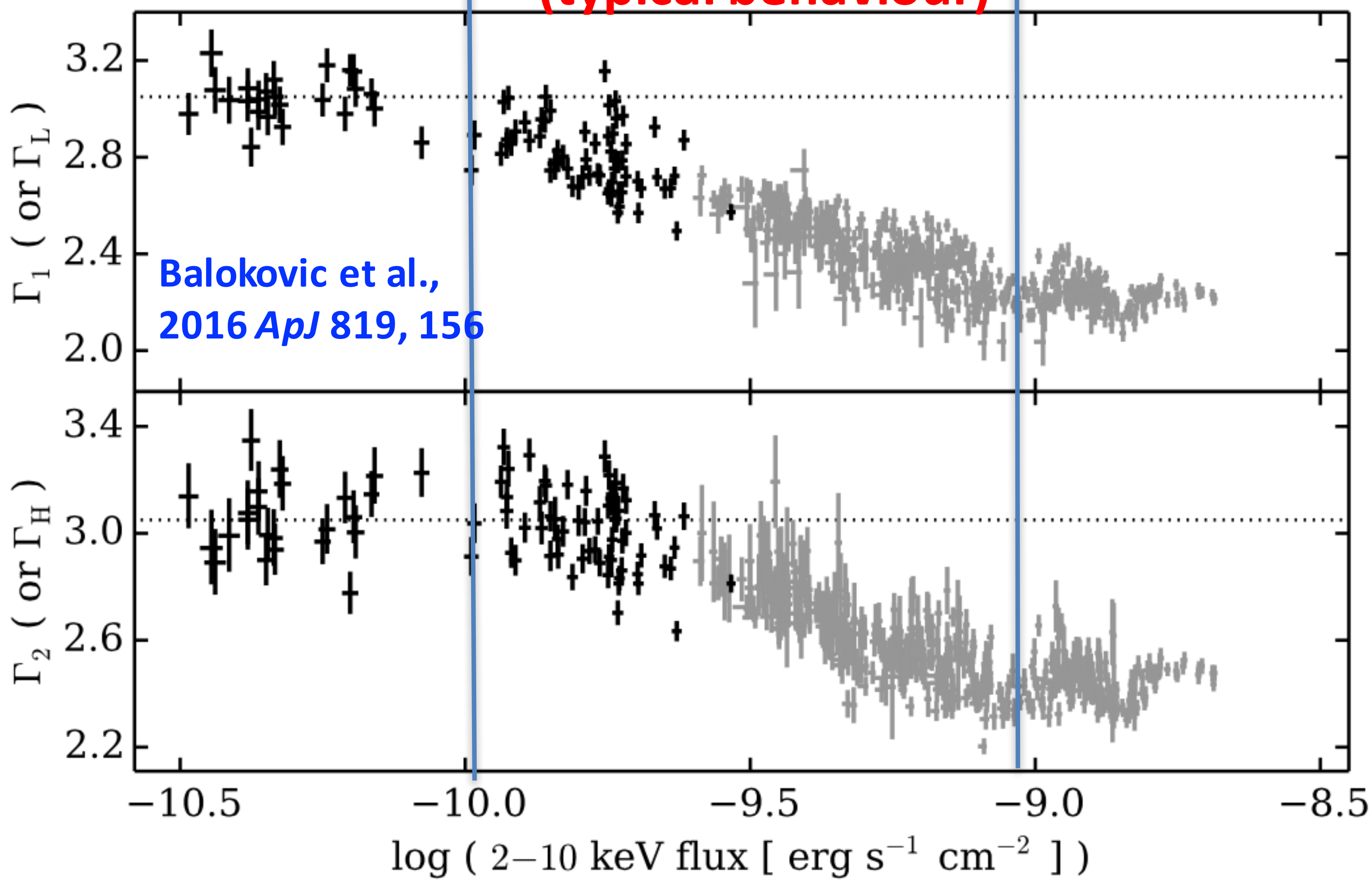


X-ray spectral shape vs. flux

Saturation at low fluxes

Harder when brighter (typical behaviour)

Harder when brighter also observed in optical (See poster by Y. Troitskaya, this conf.)

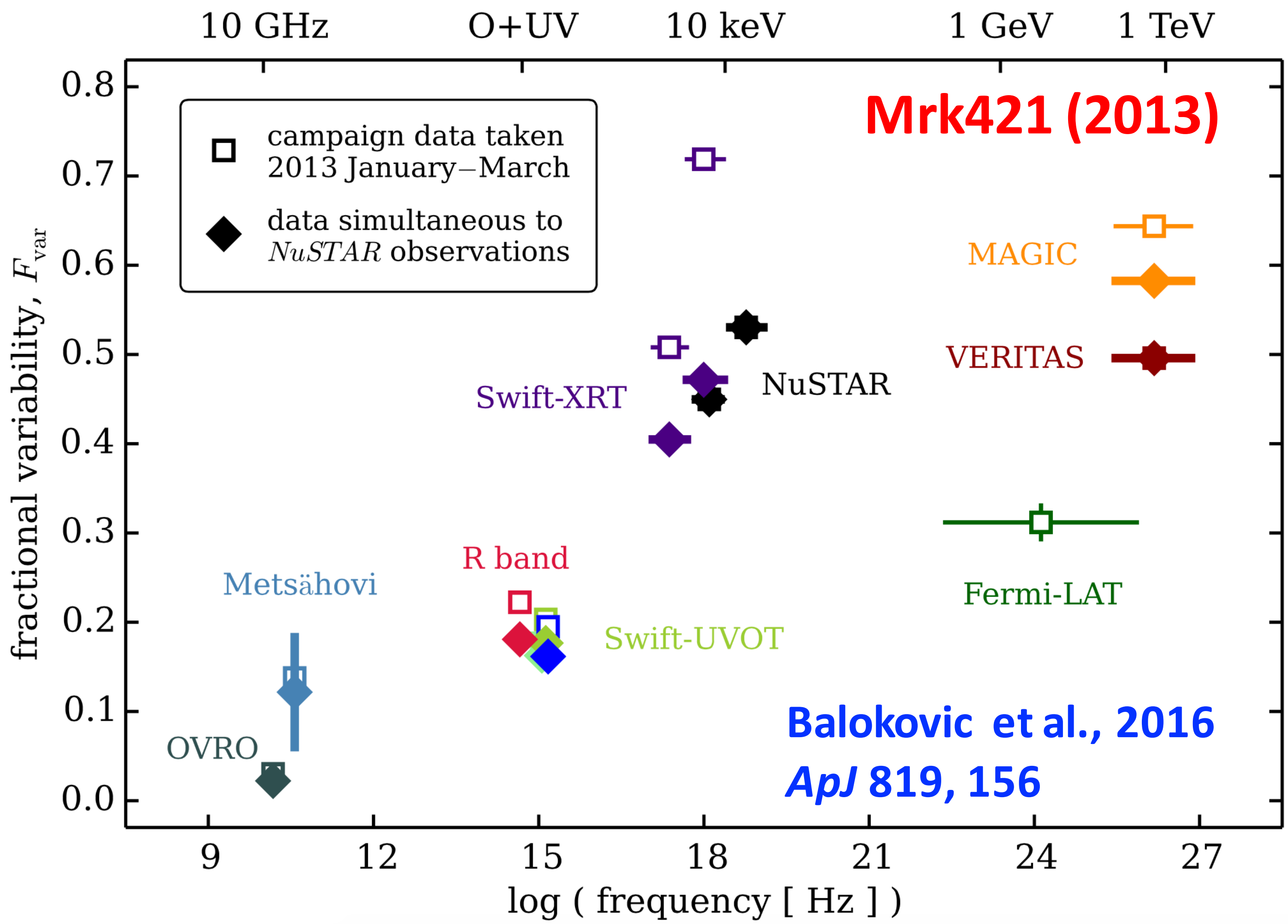


Variability vs. Energy

Variability quantified following prescription from Vaughan et al. 2003

Highest variability occurs at X-ray and VHE

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

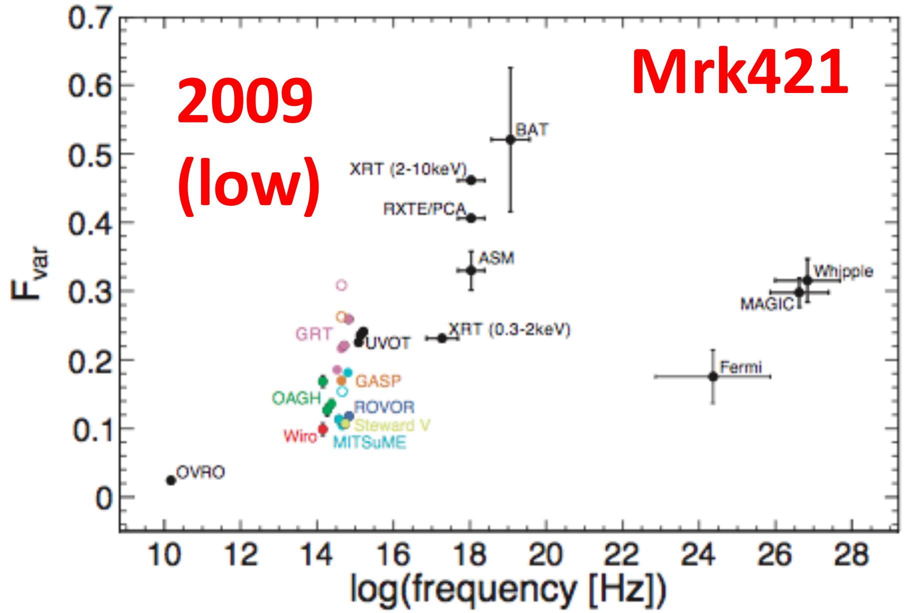


Double-bump structure (same as SED)

For each bump, variability increases with energy

Variability vs. Energy

Variability quantified following prescription from Vaughan et al. 2003



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

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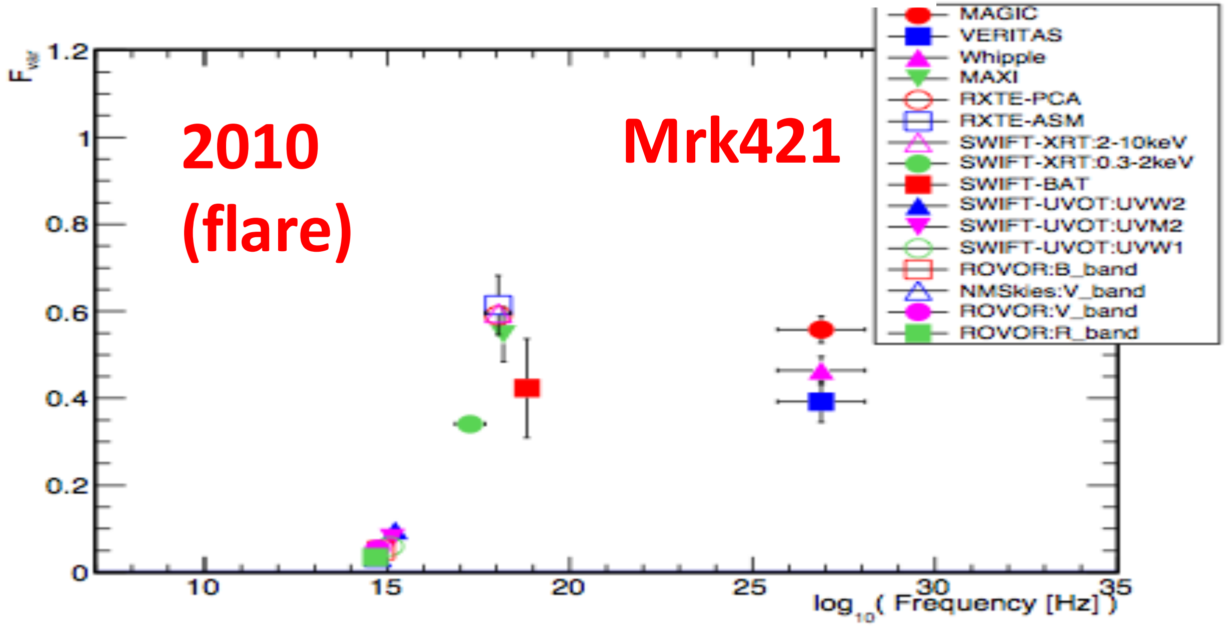
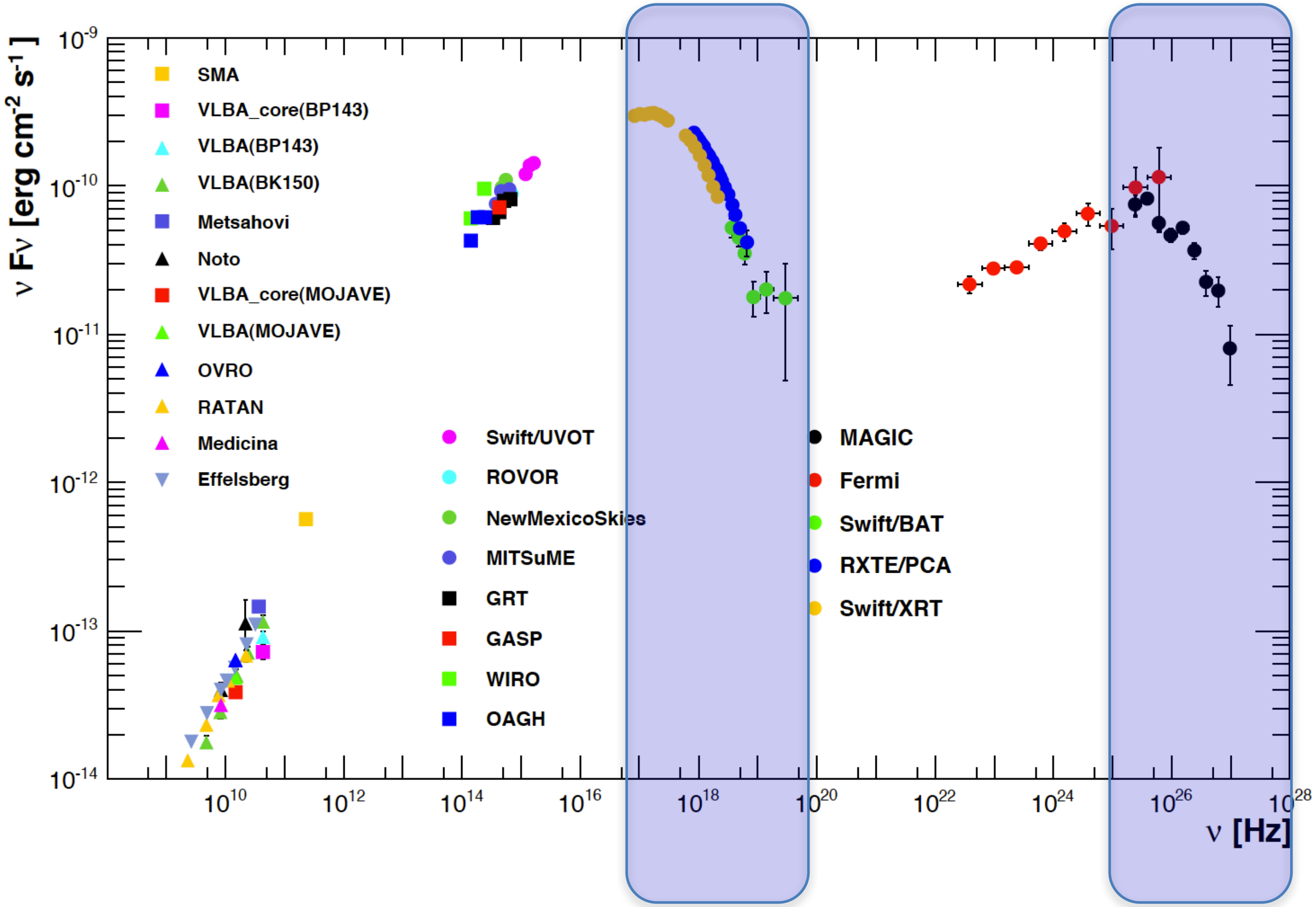


Aleksic et al., 2015
A&A 578, 22

Typical characteristic of Mrk421, in both high and low state

Variability vs. Energy

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



"Falling segments" of the low- and high-energy bumps 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*

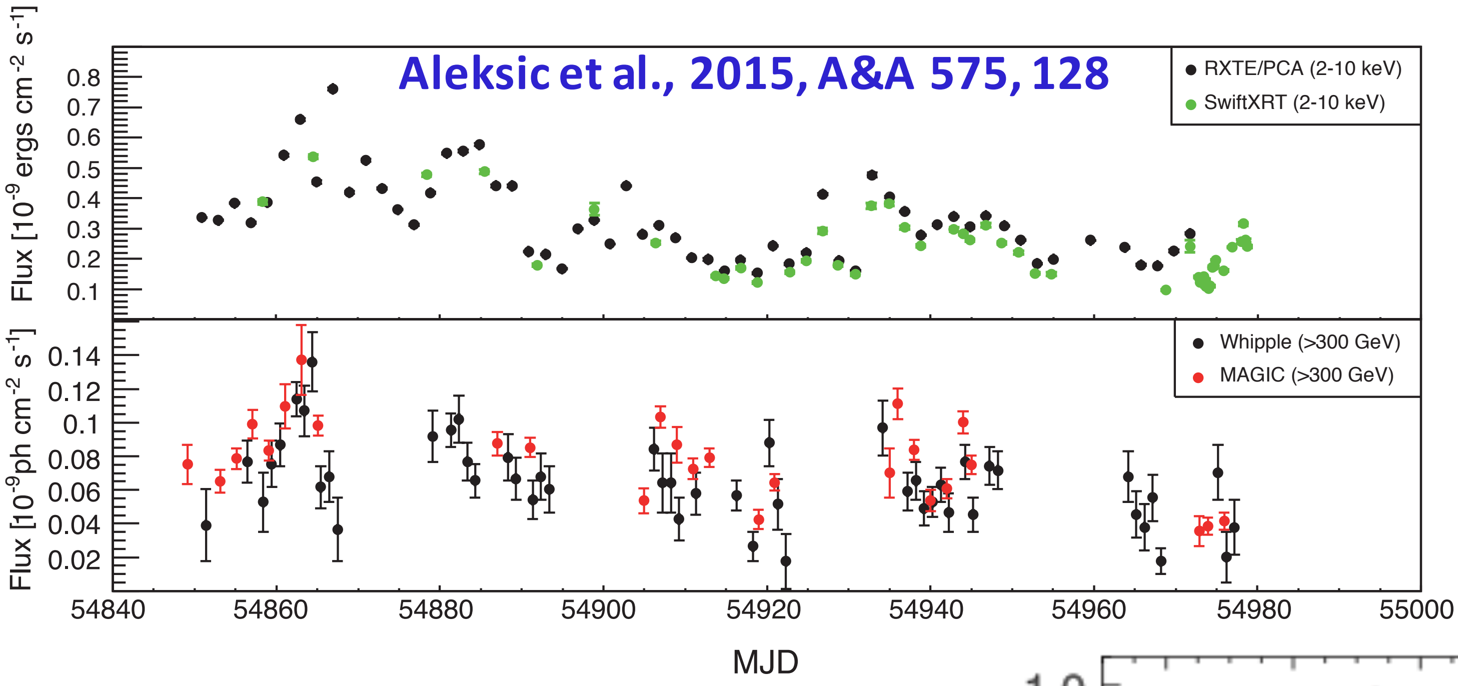
F_{var} with energy and the hardening of the X-ray spectra with increasing flux suggest that the variability in the emission of Mrk 421 is produced by chromatic changes in the electron energy distribution, with the highest-energy electrons varying the most.

The saturation of the X-ray spectral shape at the extremely high and low X-ray fluxes indicates that, for these periods of outstanding activity, the flux variability is instead dominated by other processes that lead to achromatic variations in the X-ray emission

→ **Mrk421 has "many personalities"…**

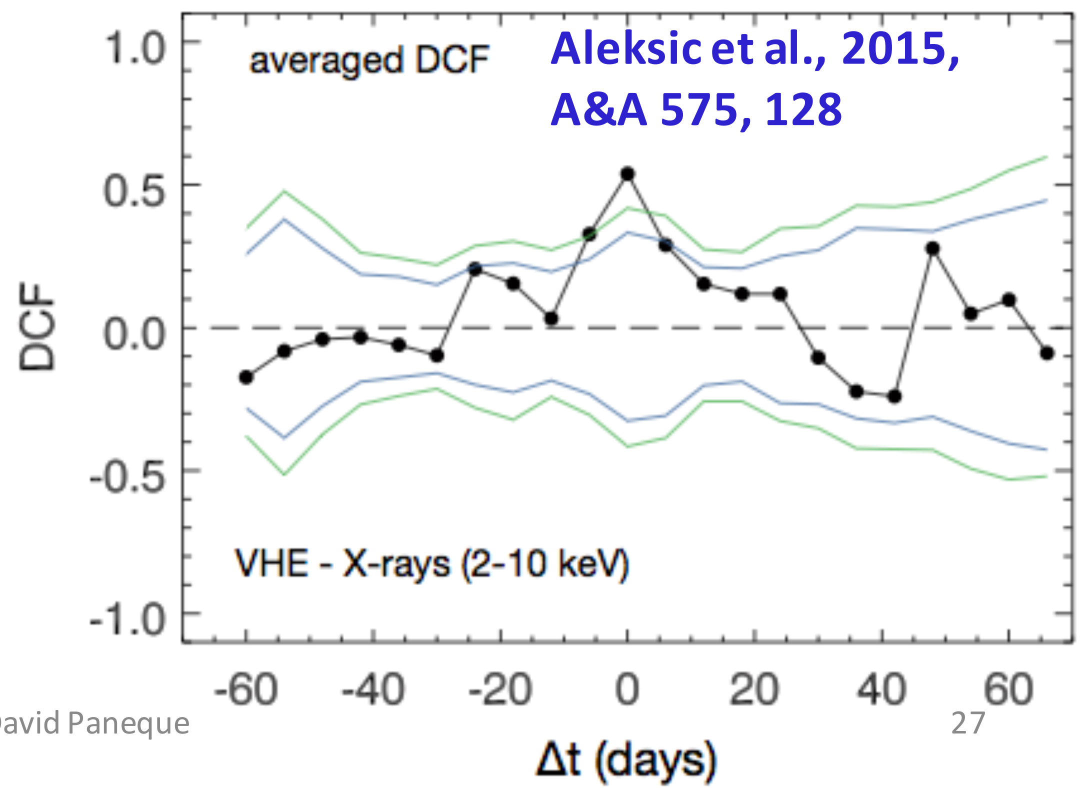
Correlations

Mrk421
MW 2009



Low state and little variability in X-ray/VHE (no flares !!)

X-ray and VHE are correlated ALSO on long-term timescales and during the low activity (no flaring activity)



→ Similar processes during flaring and non-flaring activity

Correlations

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

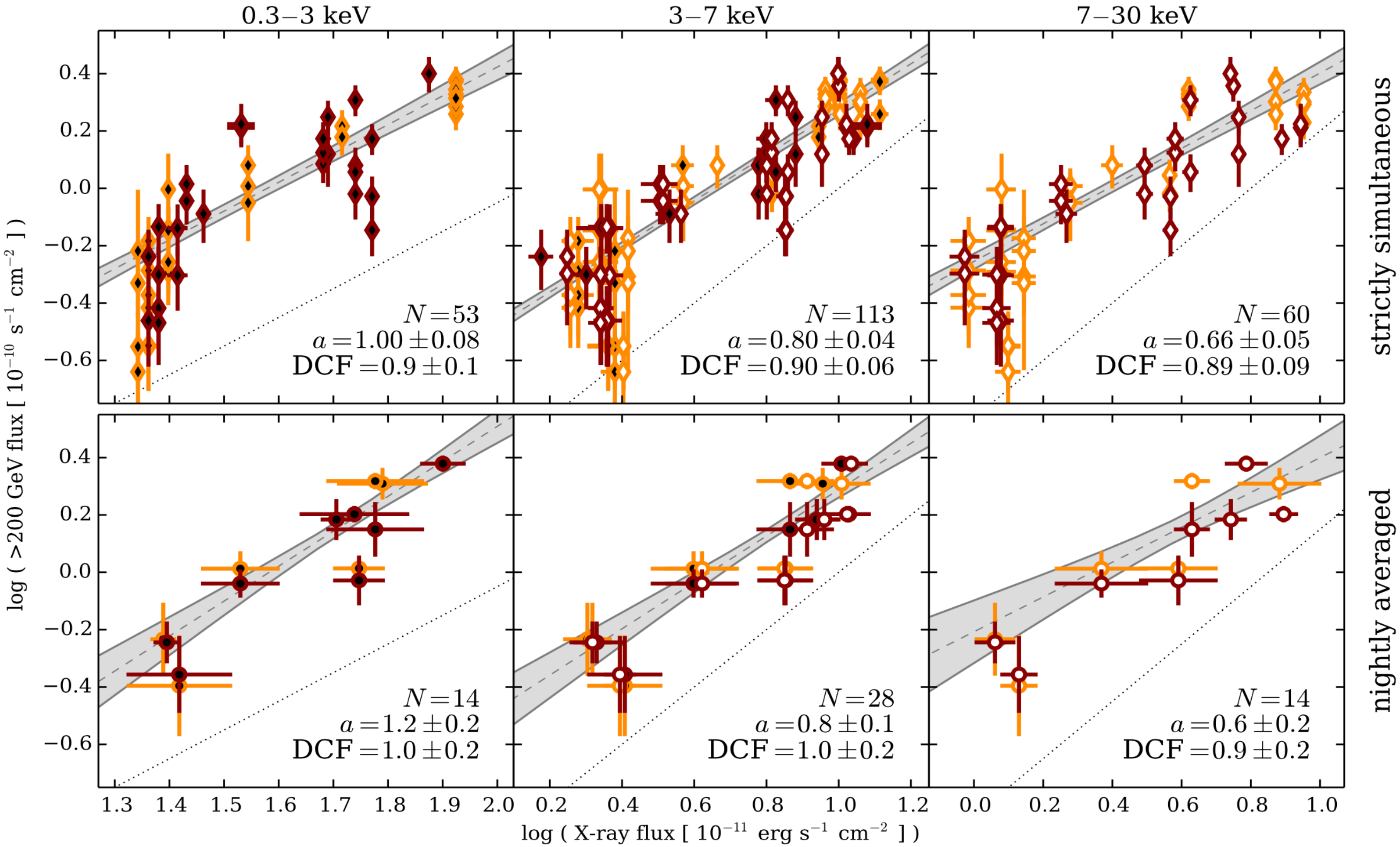
→ Correlation on strictly simultaneous observations and nightly averages

→ **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

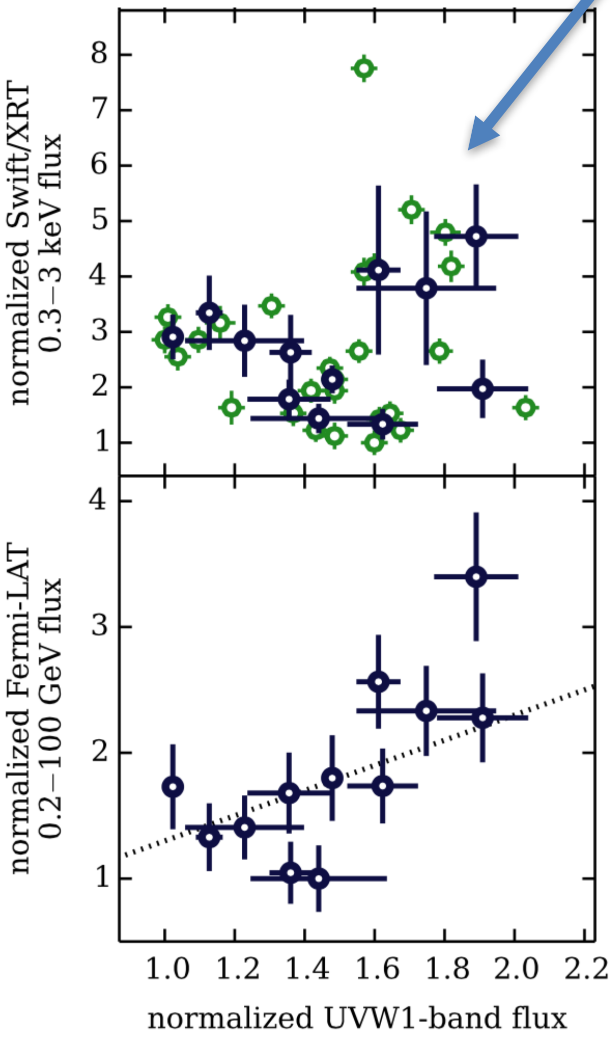


Mrk421 MW 2013

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

Correlations

Balokovic et al., 2016
ApJ 819, 156



X-ray and UV fluxes do NOT correlate

<u>Lack of overall correlation optical/X-ray is common</u>
in 2009 (Aleksic et al., 2015, A&A 575, 128),
In 2010 (Aleksic et al., 2015, *A&A* 578, 22)
In 2007-2009 (Ahnen et al 2016, arXiv:1605.09017)
In 2007-2015 (*See Poster from M.I. Carnerero*)

→ Two different components

OR

→ Variability mostly on high-E electrons

→ Low-E electrons vary independently

Marginal correlation (2.5-3 sigma) of Fermi GeV and UV fluxes

→ Expected from SSC models, where both optical/UV and MeV/GeV fluxes are related to low energy electrons

Correlations

Correlation between radio (VLBA 43 GHz) and gamma (>0.1 GeV) also detected for Mrk421 during non-flaring (but variable !!) activity

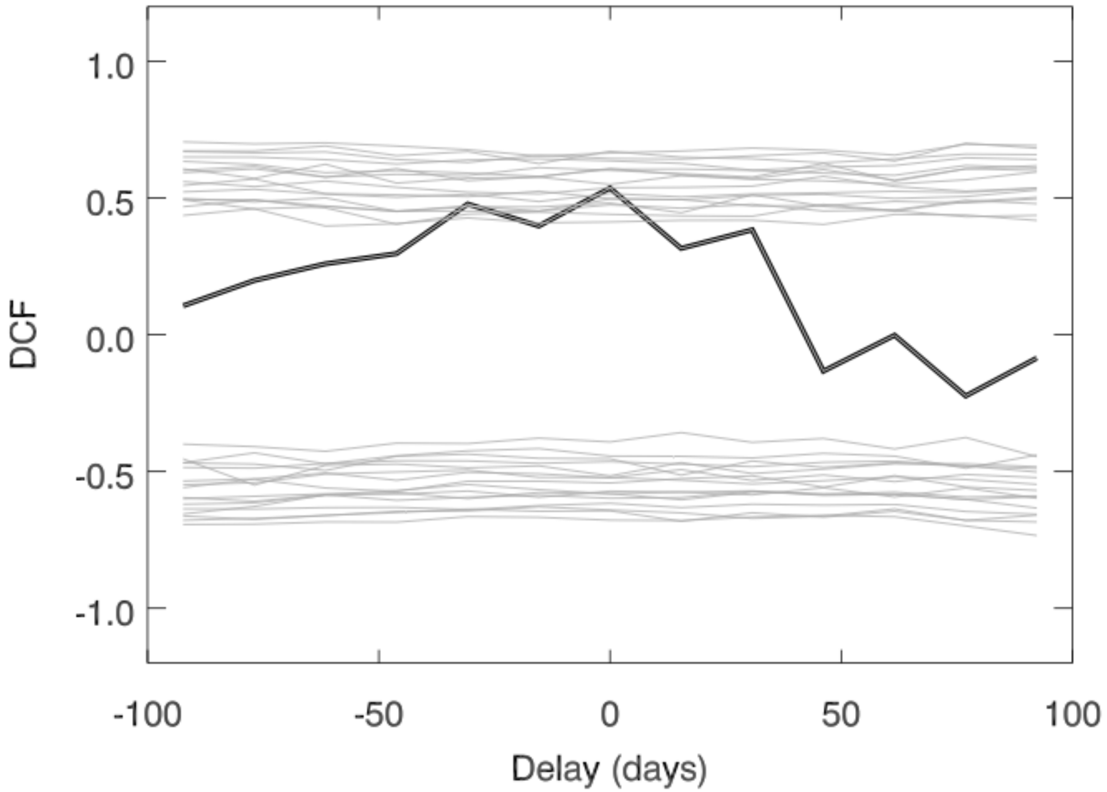


Fig. 7. Discrete cross-correlation function between the γ-ray and the 43 GHz radio light curves (black curve). The gray curves represent the 99.7% confidence limits relative to stochastic variability, obtained from the combination of different power spectral density slopes. See section 3.5 for more details.

- Lico et al., 2014 (A&A 571, 54)

Correlations

Correlations **Radio/optical/GeV** and **X-ray/TeV** on <u>months timescales during non-flaring activity</u>

→ Naturally explained with leptonic scenarios

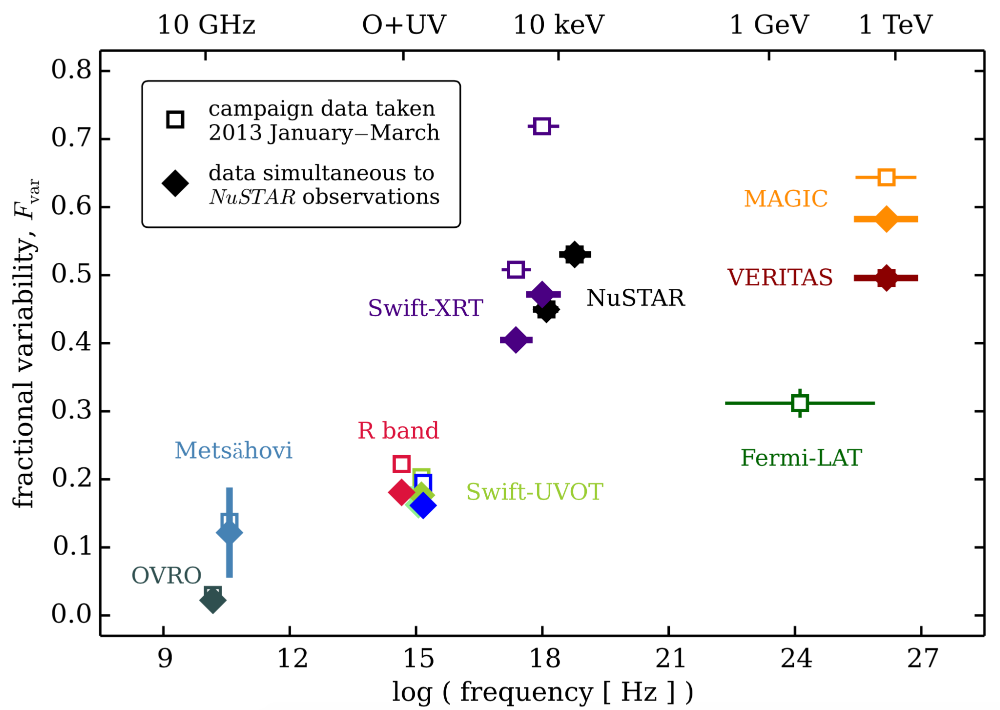
→Difficult with lepto-hadronic with Psync

→ Possible with lepto-hadronic with photo-pion

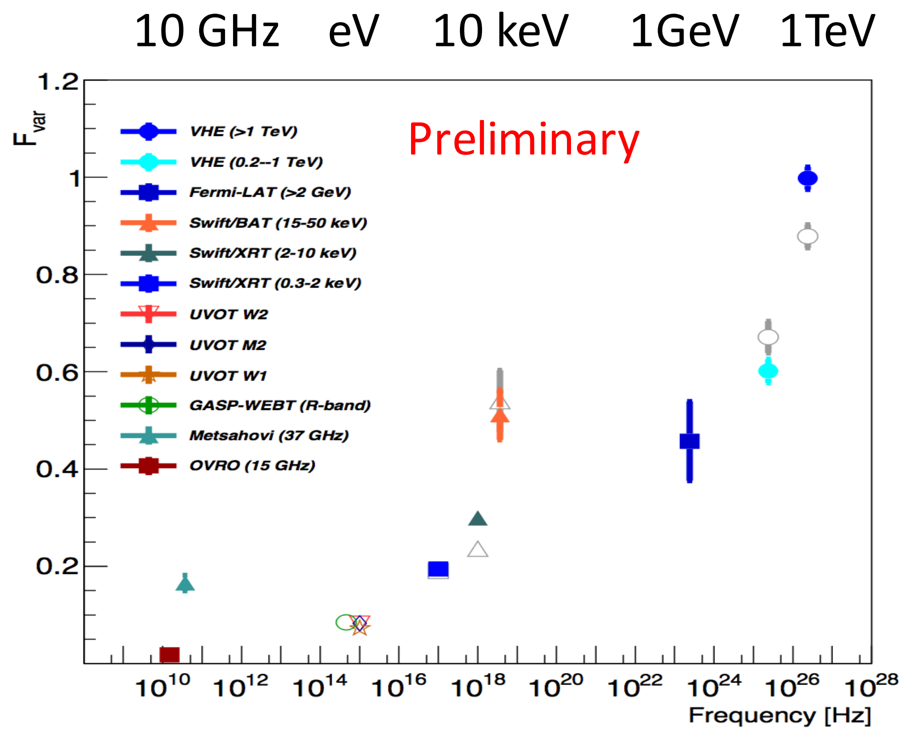
→But then we need to keep an eye on the energetics

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

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



Hughes et al., ICRC 2015



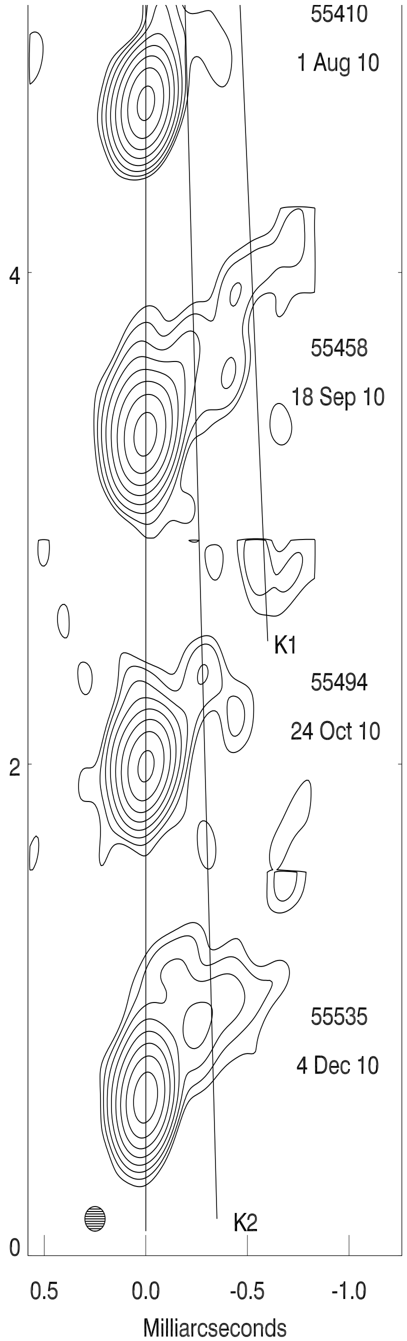
Typically:

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

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

→ **<u>See further details in the Poster of Pepa Becerra (this conference)</u>**

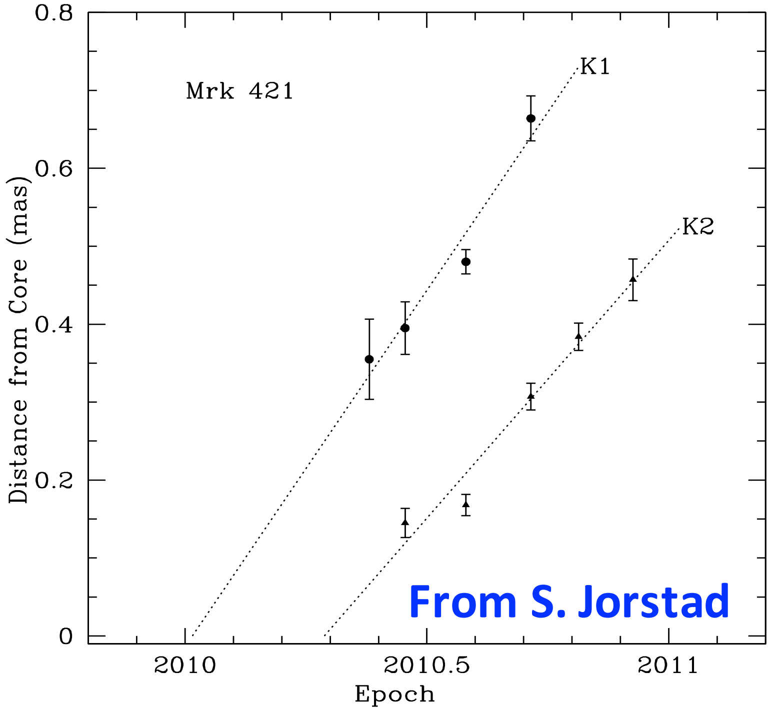
Flaring activity with ejection of VLBA blobs



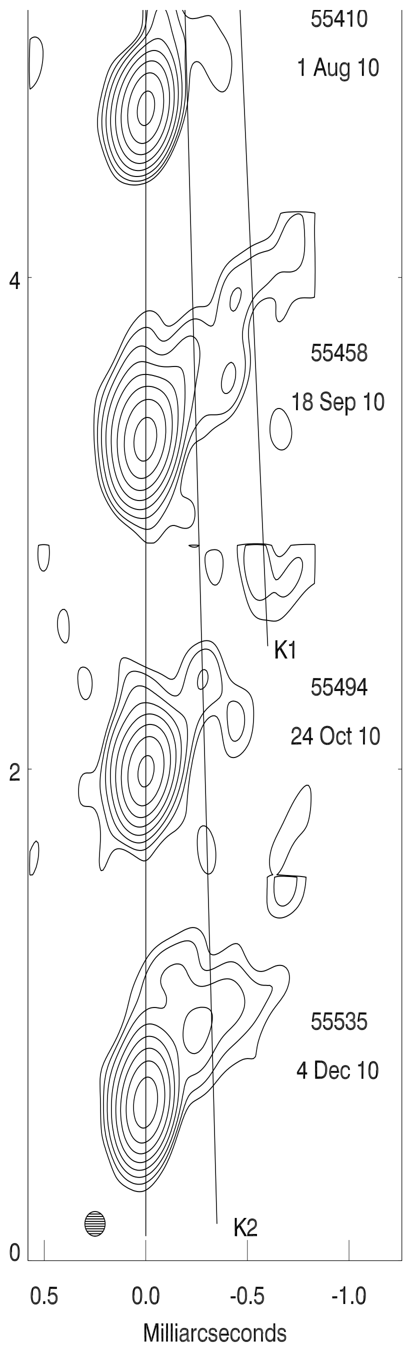
Mrk421 regularly monitored with VLBA (Boston + Bologna groups)

Talk by Lico reported VLBA measurements in 2011 (steady components)

But in 2010, VLBA components K1 and K2, traced back to the VLBA core in January and March 2010



Flaring activity with ejection of VLBA blobs

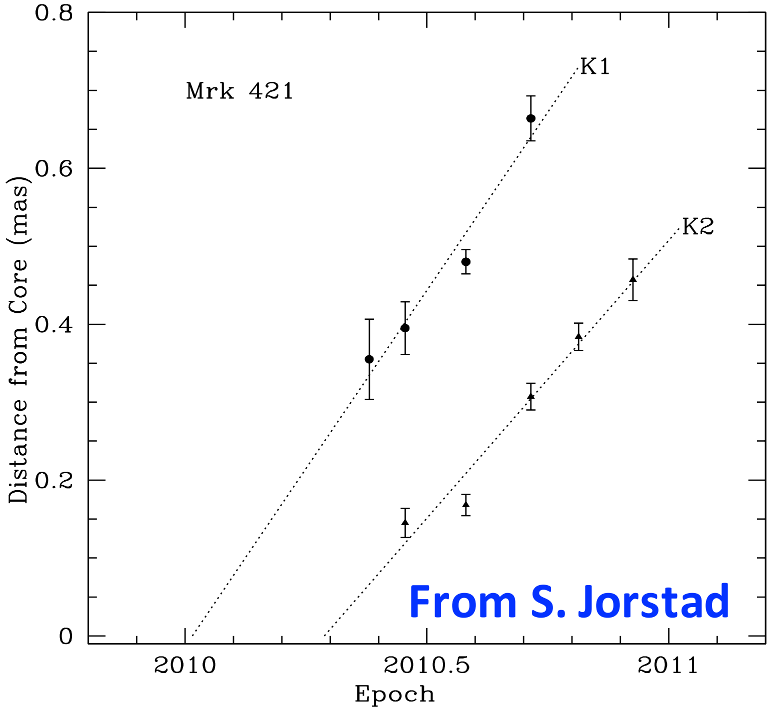


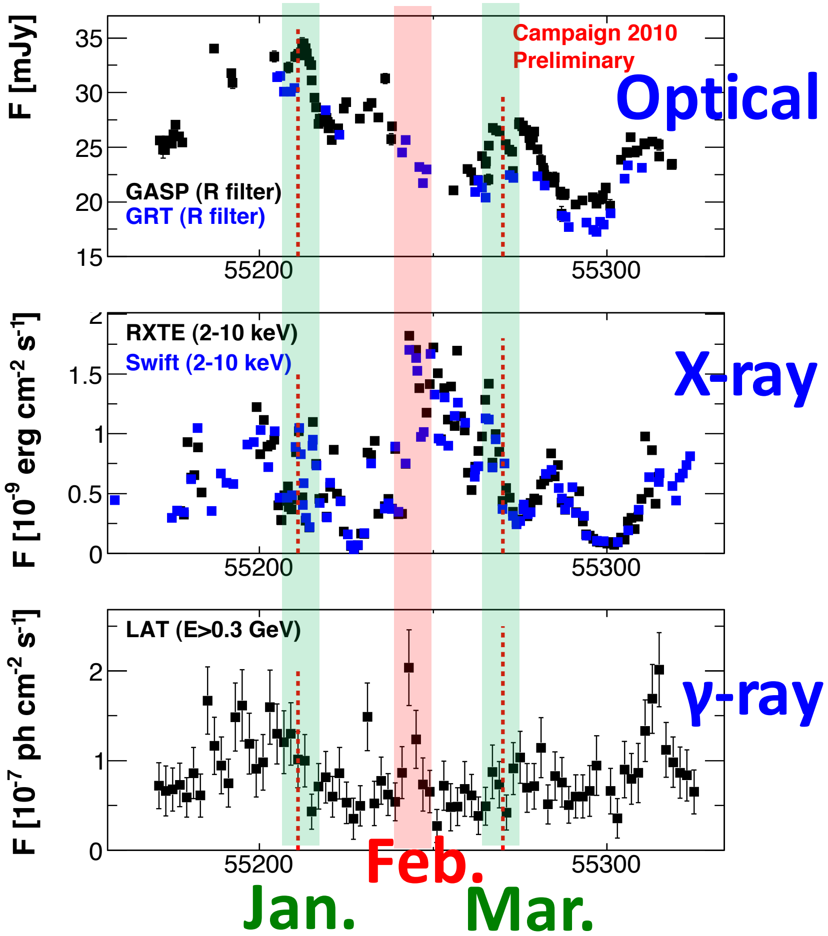
Mrk421 regularly monitored with VLBA (Boston + Bologna groups)

Talk by Lico reported VLBA measurements in 2011 (steady components)

But in 2010, VLBA components K1 and K2, traced back to the VLBA core in January and March 2010, coinciding with the flaring activities in 2010 January and March (but NOT with the BIG Flare in February)

Correlation between flaring activity and "ejection" of VLBA blobs (NEVER seen before for Mrk421)





David Paneque

Mrk501 suffers a personality crisis (in 2012)

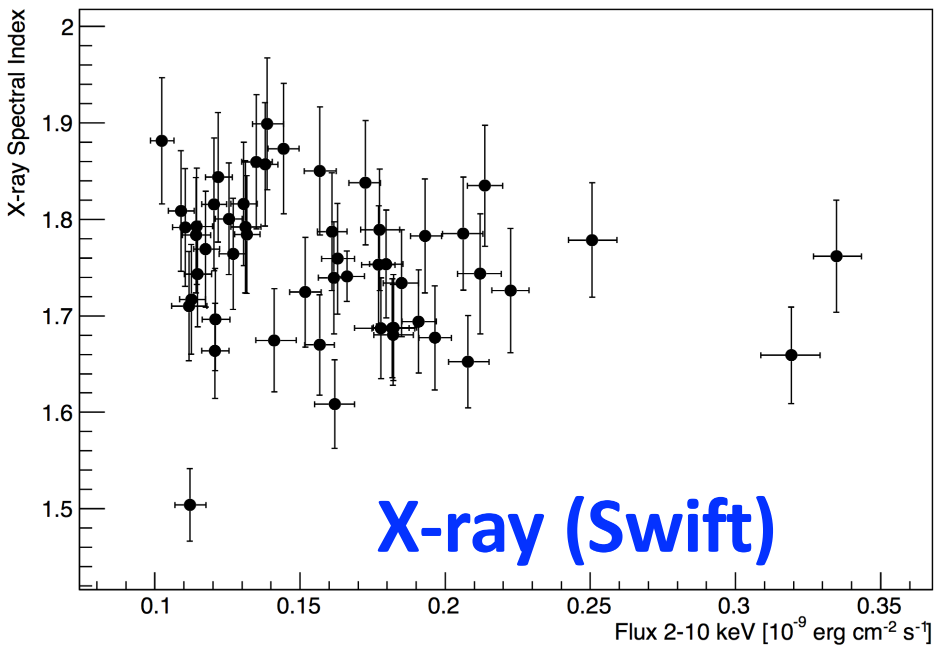
- **VERY hard spectral index, regardless of activity (during MW 2012)**

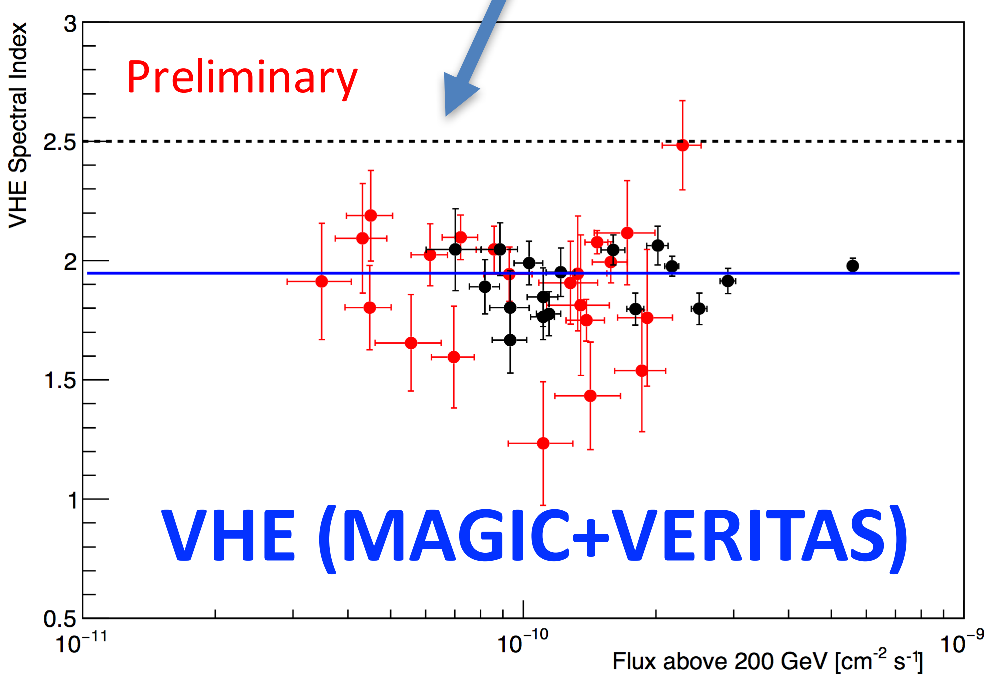
X-ray $\Gamma > -2$

gamma-ray $\Gamma \gtrsim -2$

Hughes et al., ICRC 2015

Typical Mrk501 VHE PL Index ~ 2.5

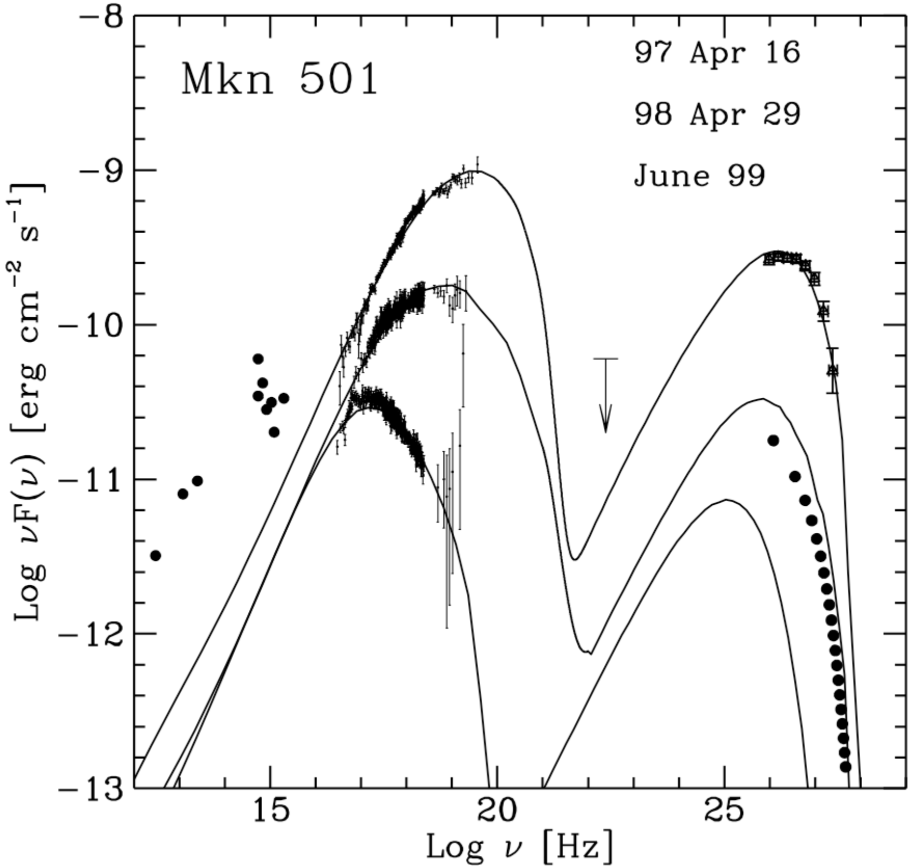




Mrk501 has shown X-ray and VHE spectral variability during flares

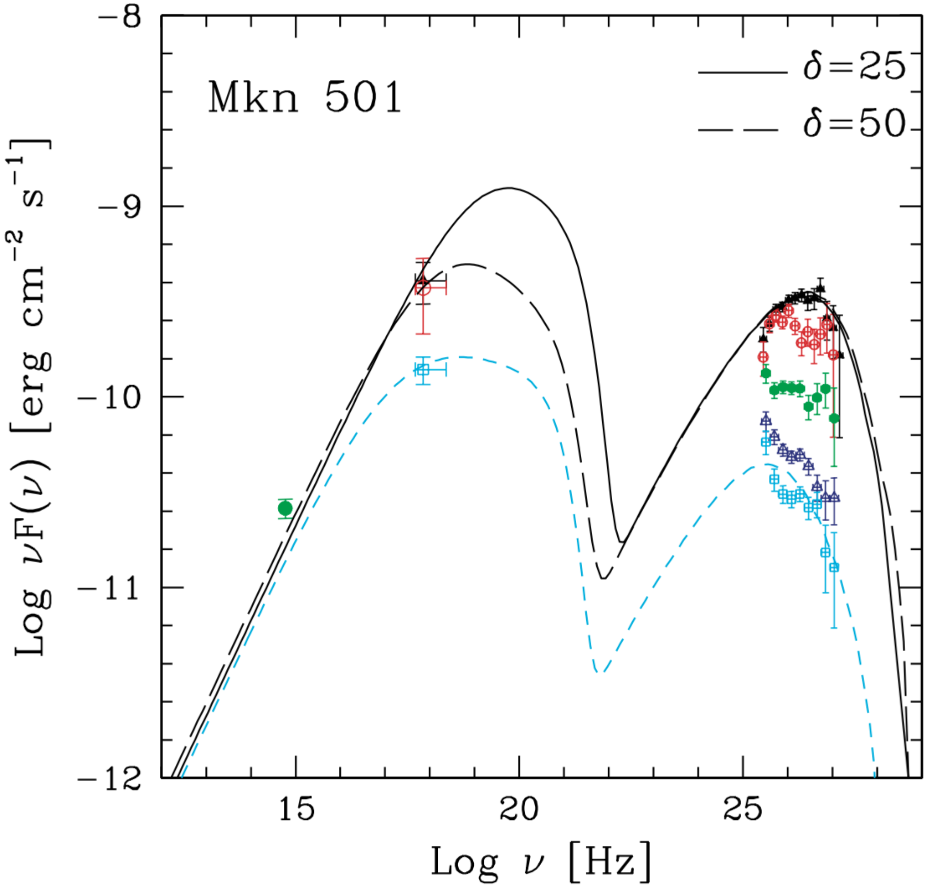
(Historical) flare in 1997

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, and
<u>VHE spectral index NEVER observed harder than 2 (until year 2012)</u>

Mrk501 suffers a personality crisis (in 2012)

- **VERY hard spectral index, regardless of activity (during MW 2012)**

X-ray $\Gamma > -2$

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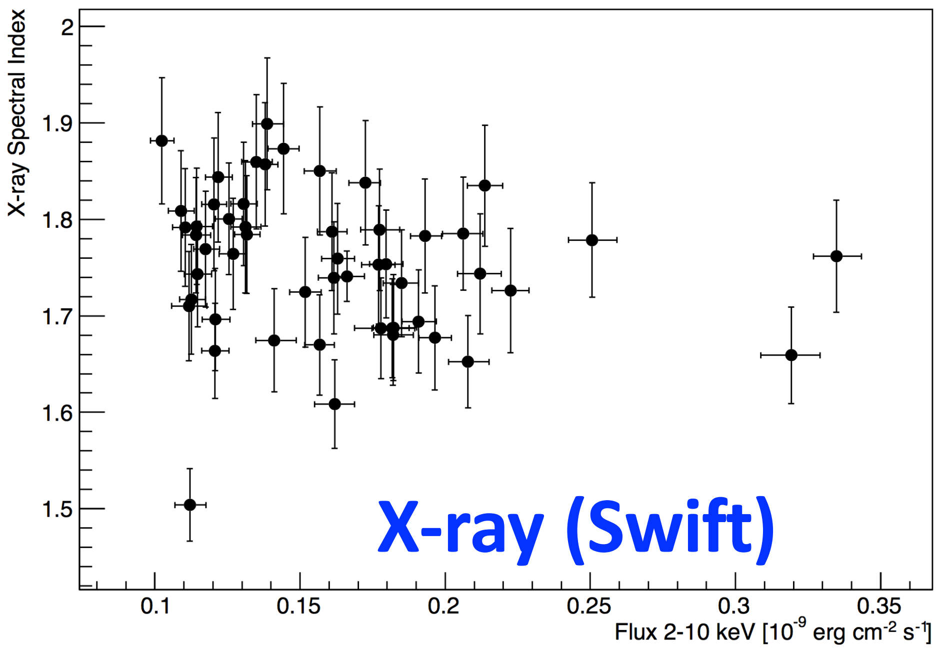

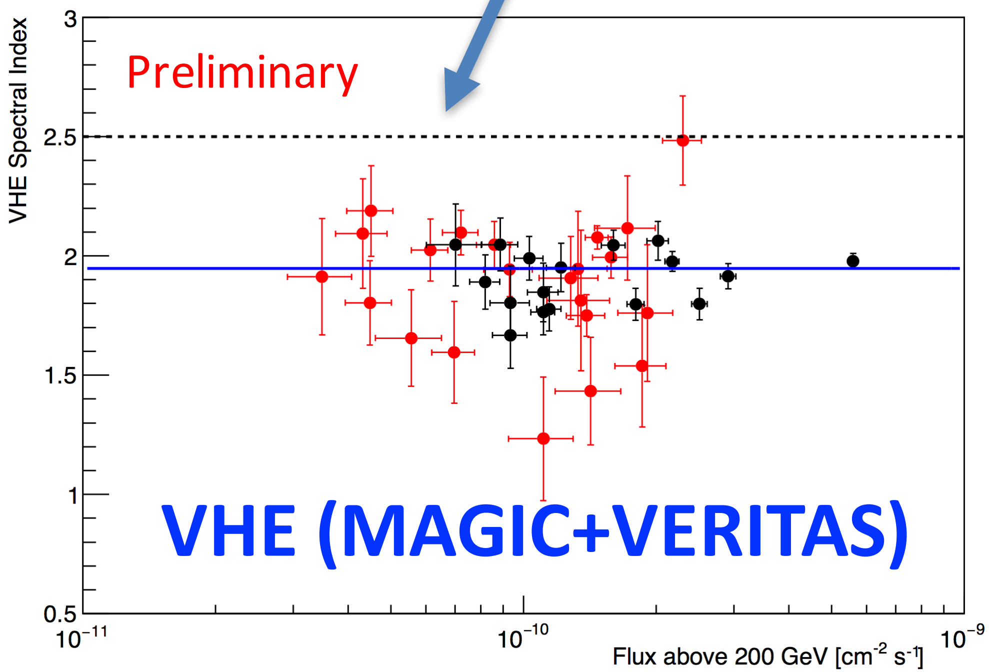

→ Mrk 501 **behaved like Extreme HBL!**

Similar X-ray/VHE spectra as 1ES 0229+200, 1ES 0347-121

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

3 – General Conclusions

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

Deepest Temporal and Energy coverage of any TeV object

→ *Many interesting (novel) results*

→ Large complexity in the temporal evolution of the broadband SED.

→ Complicated personalities. e.g.:

Mrk421: trying to become ISP

Mrk501: became EHBL (in2012)

During non-flaring activity

→ *Does it occur on other blazars?*

→ *Impact for Blazar Sequence ?*

We can use Mrk421 and Mrk501 as our blazar physics laboratory

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