Unravelling the complex behaviour of our closest very-high-energy gamma-ray blazars, Mrk421 and Mrk501, through decades-long multi-instrument observations

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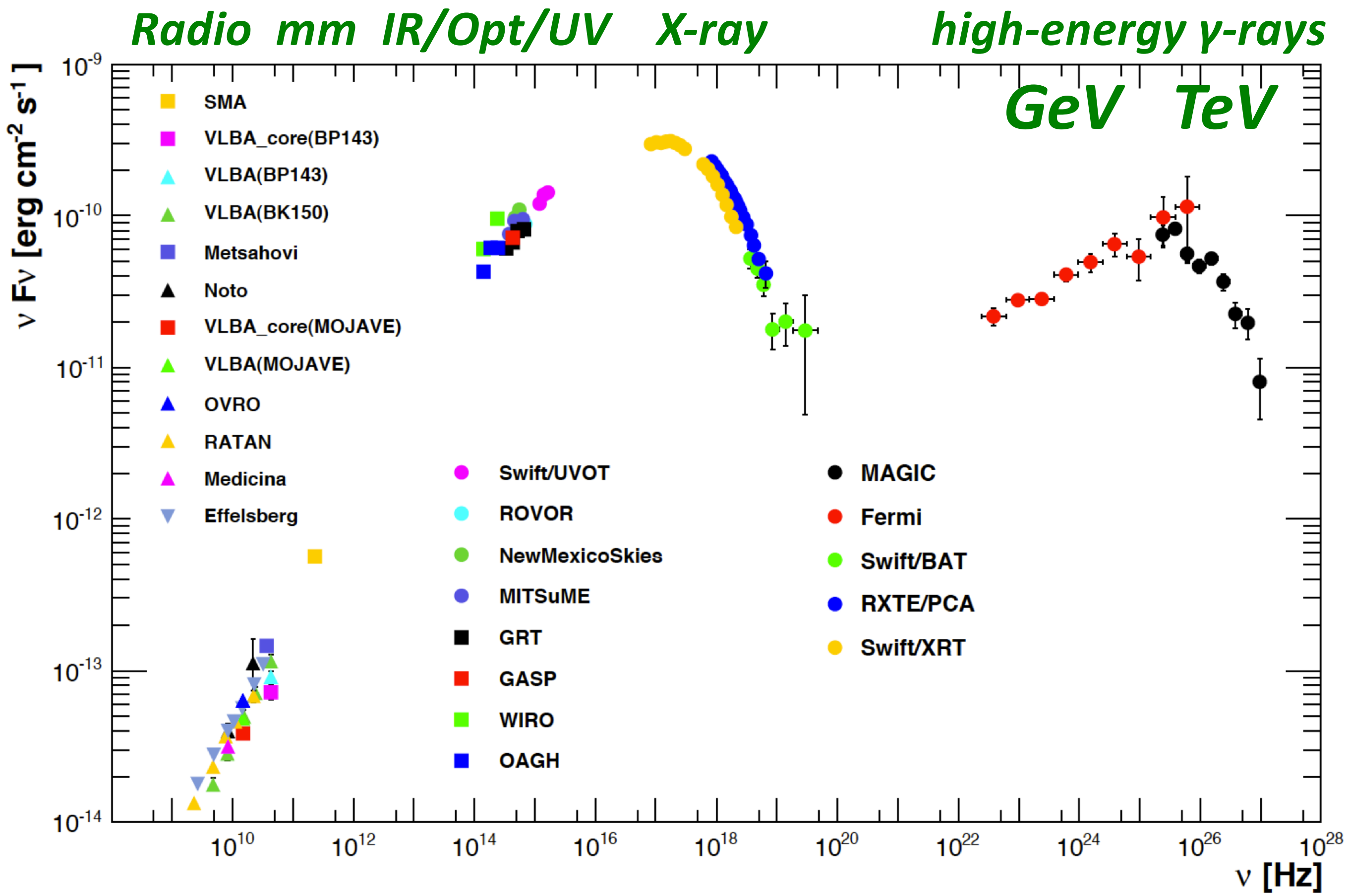
Roma International Conference on Astroparticle Physics (Sep-2022)

Challenges when studying AGNs (→blazars)

AGNs (→ blazars) emit radiation over a large energy range

Emission at different energies could be due to same particle population

→ *Need many instruments to fully characterize emission in these objects*



Spectral energy distribution (SED) of the Blazar Mrk 421

Abdo et al 2011, ApJ 736, 131

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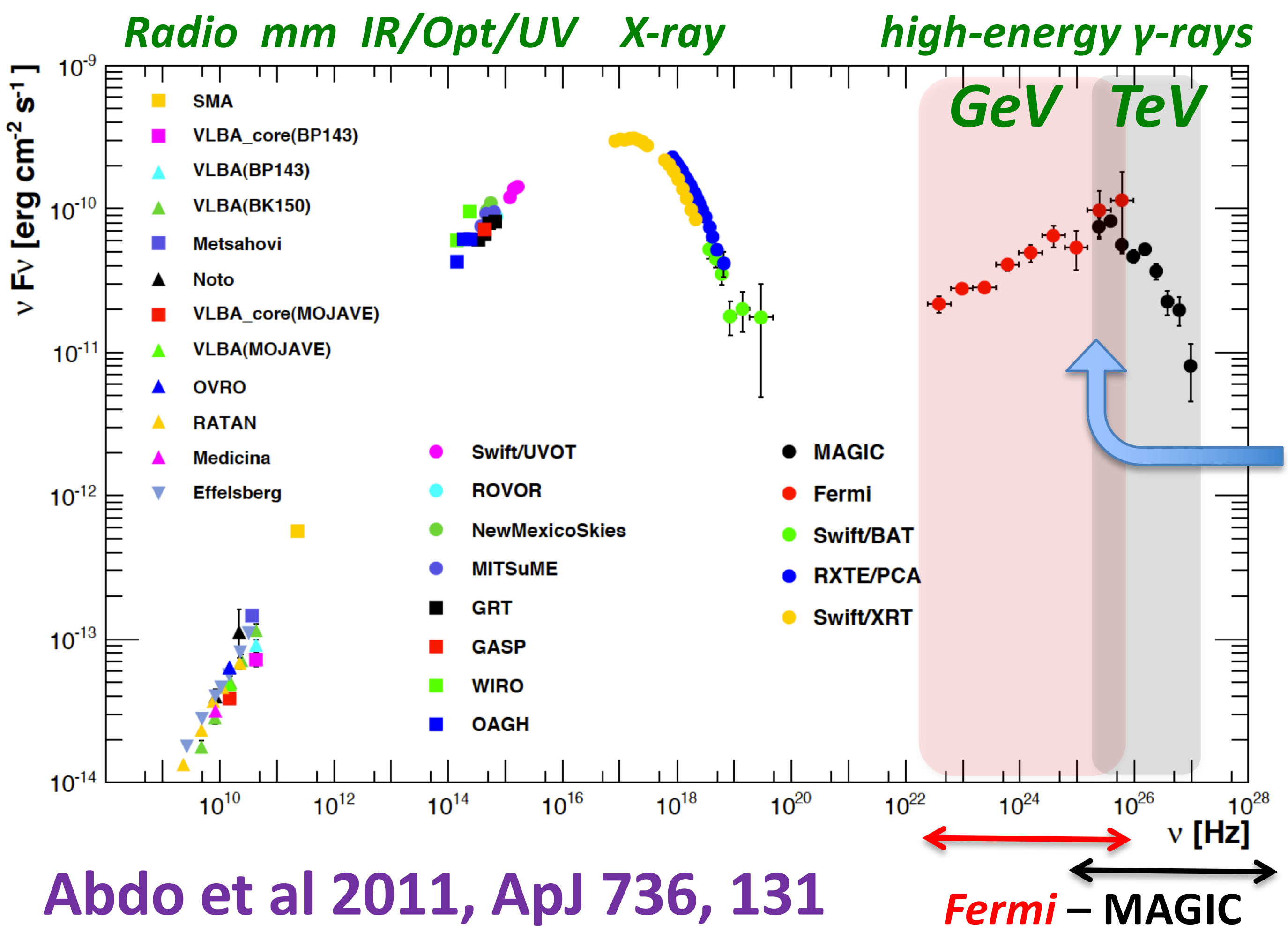


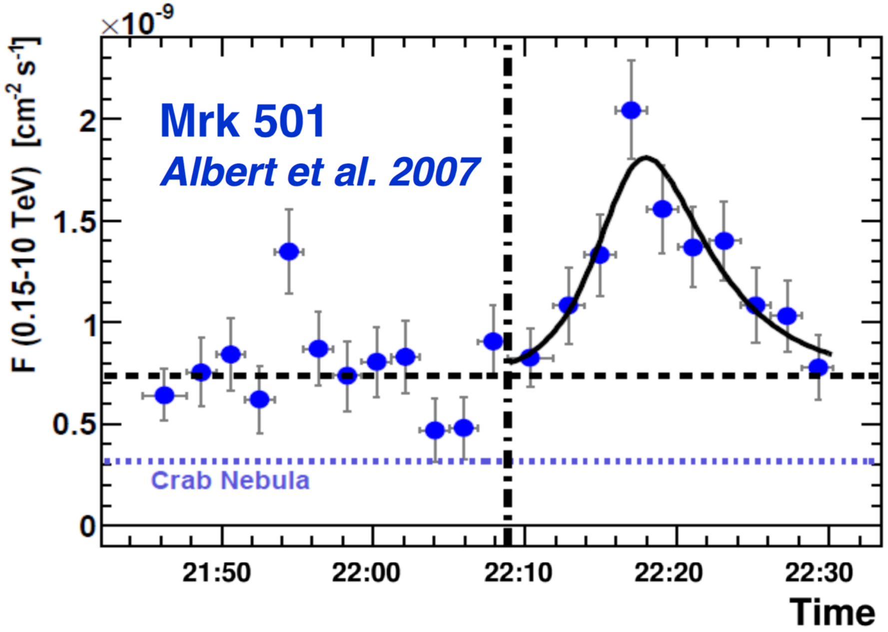
Spectral energy distribution (SED) of the Blazar Mrk 421

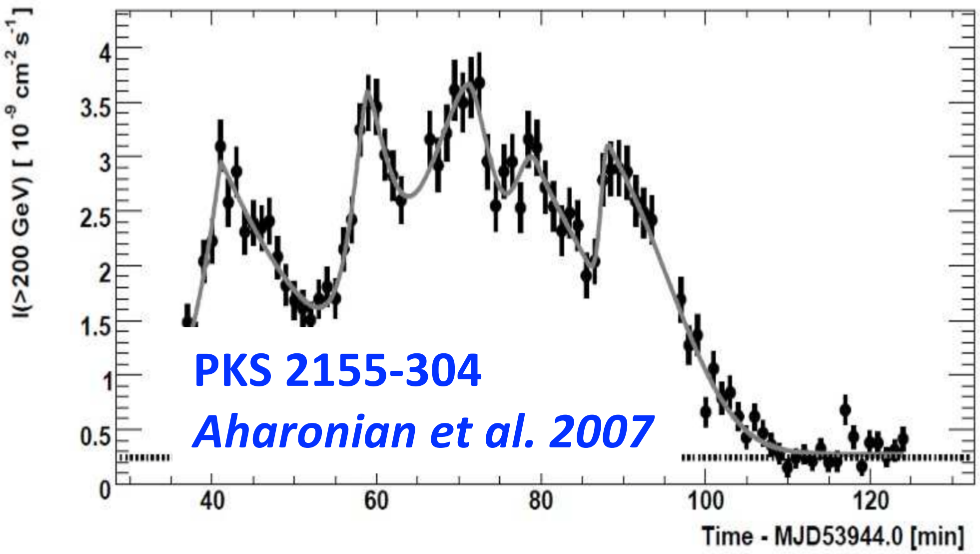
Gamma-ray bump of many sources could only be accurately measured with the advent of *Fermi*-LAT + modern IACTs like HESS/MAGIC/VERITAS

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

Abdo et al 2011, ApJ 736, 131

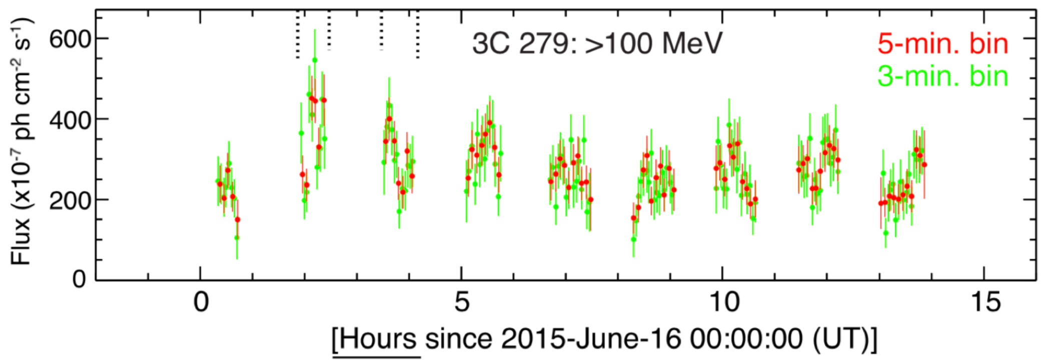
Blazars show SHORT variability timescales

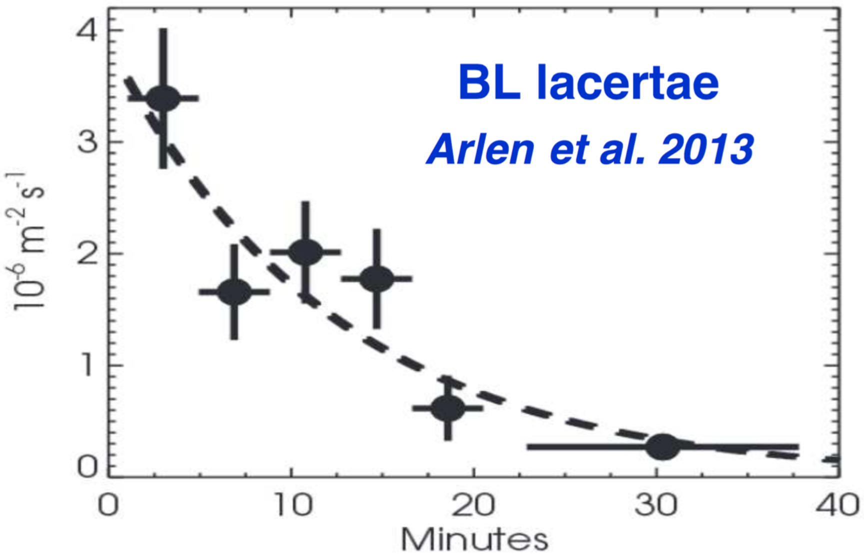




3C279

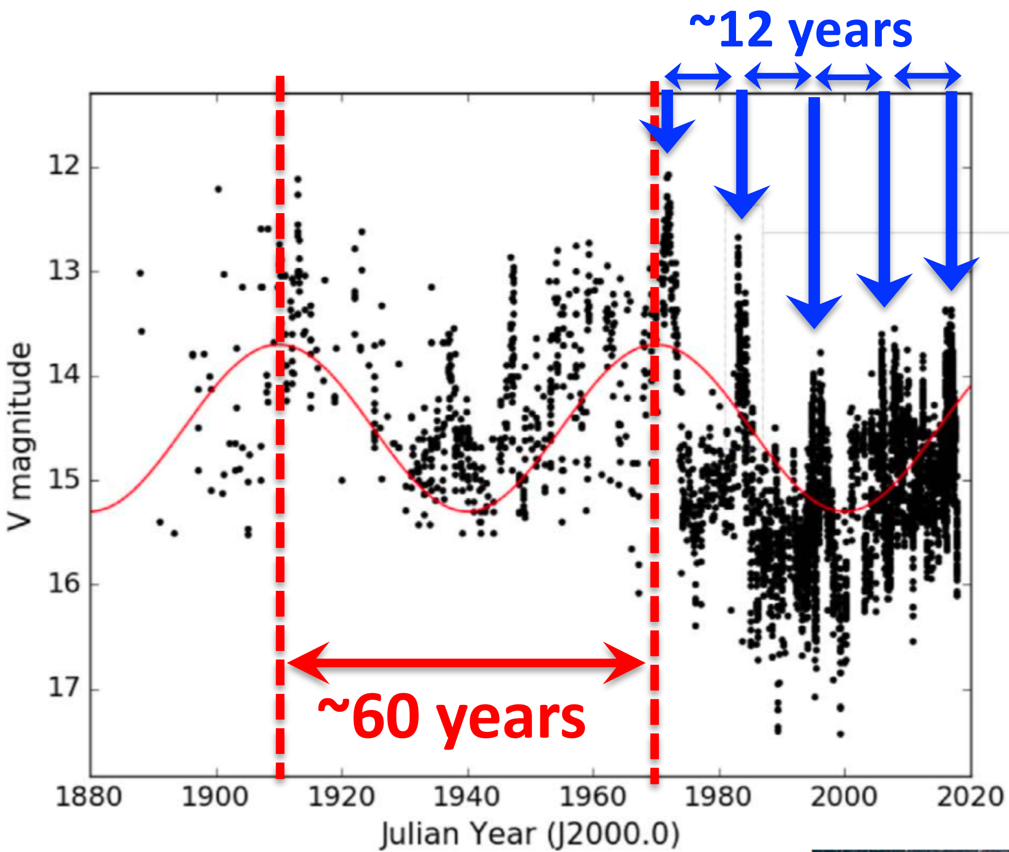
Ackermann et al 2016

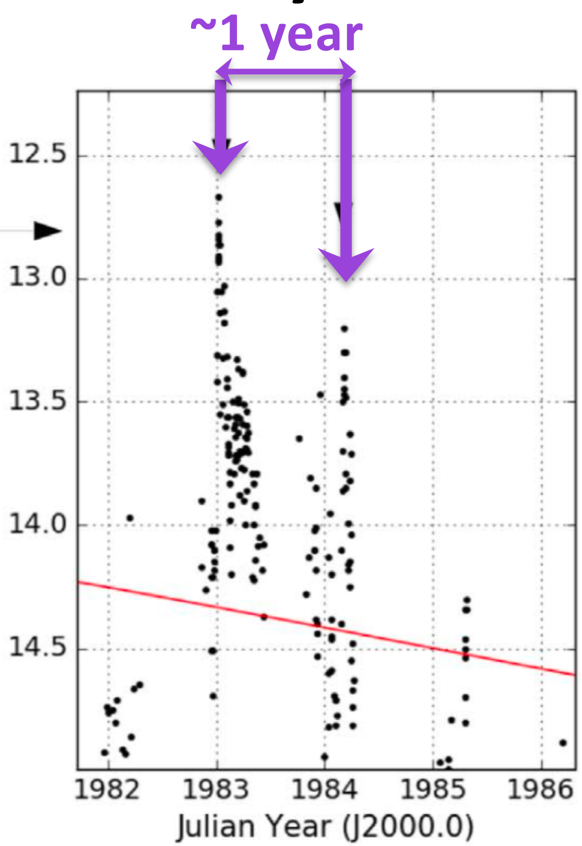




Sub-hour flux variations bring crucial information to study the accelerating & cooling, the size of region and their environments *(e.g. high doppler factors needed for short variability + TeV transparency)*

Blazars show LONG variability timescales

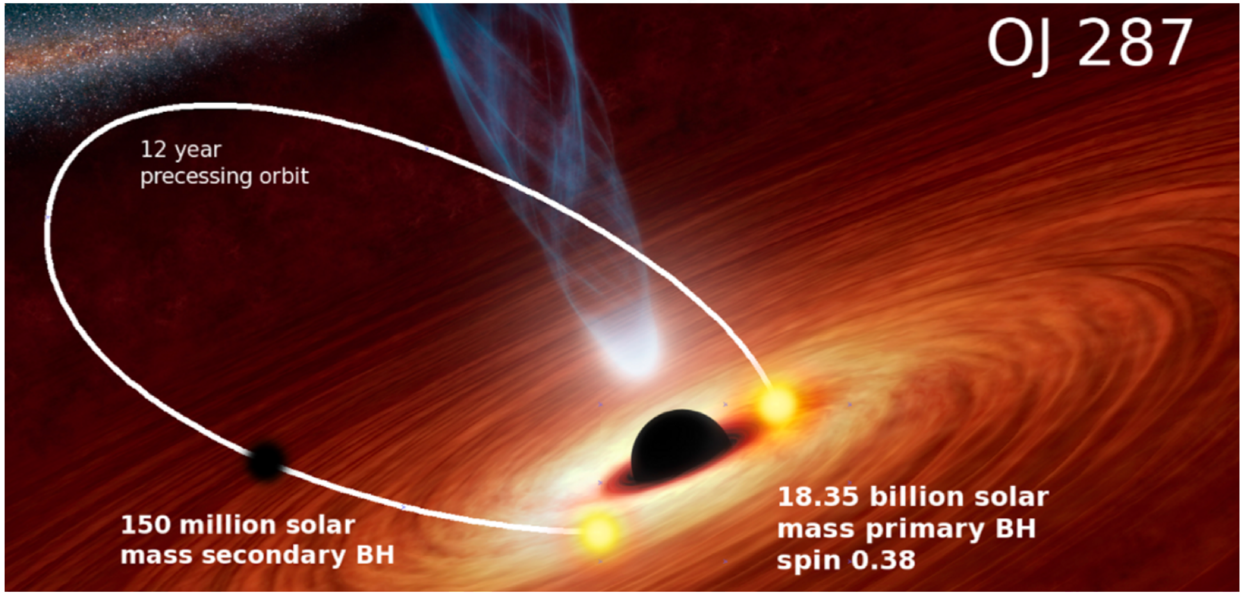




Century-long optical light curve of blazar OJ 287

Dei et al., ApJ 866 (2018) 11

Multi-year flux variations bring crucial information to understand the sources and their environment



Large observational challenges when studying blazars

1) Blazar emission extends over a very wide energy range
(from *micro-eV* to *tens of Tera-eV* → *dynamic range> 10^{16}*)

2) Blazar emission is variable on different timescales
(from *tens of years* down to *a few minutes* → *dynamic range> 10^{6}*)

And variability is energy dependent, as well as our instrumental ability to characterize it

The complete (deep) characterization of the blazar broadband emission is a very complicated observational challenge, that requires enormous efforts from the community

→ *Not surprising that AGNs are not well characterized after 50+ years of observations*

Mrk421 and Mrk501 are excellent "blazar probes"

→ **3 reasons to study these 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

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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

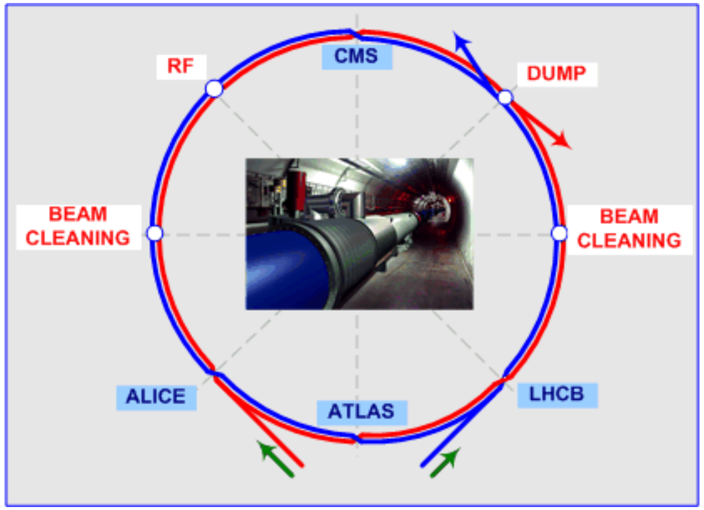
They can be used as high-energy physics laboratories to study blazars

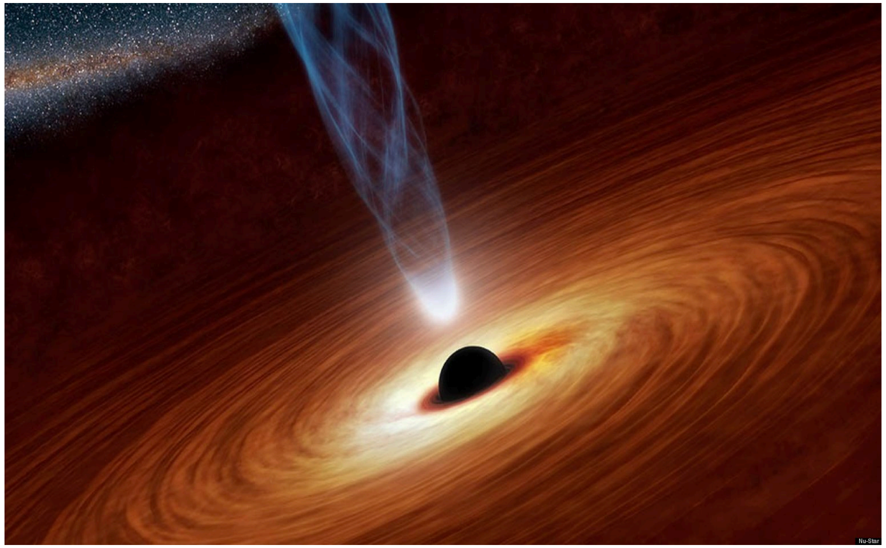
AGNs as our Extreme Particle Accelerators

LHC **vs** **bright AGN**

ATLAS/CMS
LHCb + Alice

MAGIC/VERITAS/HESS/Fermi,++
X-ray , Optical/radio, IceCube…





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

<u>**Since 2009,**</u> 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* !)

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

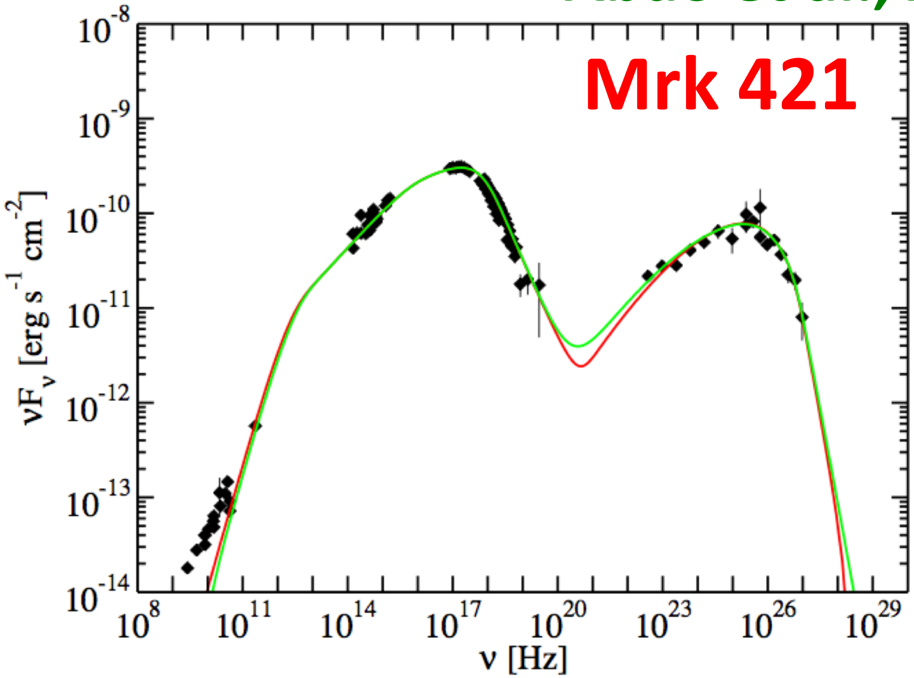


Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{\rm var} = 1$ day (red curve) and $t_{\rm var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

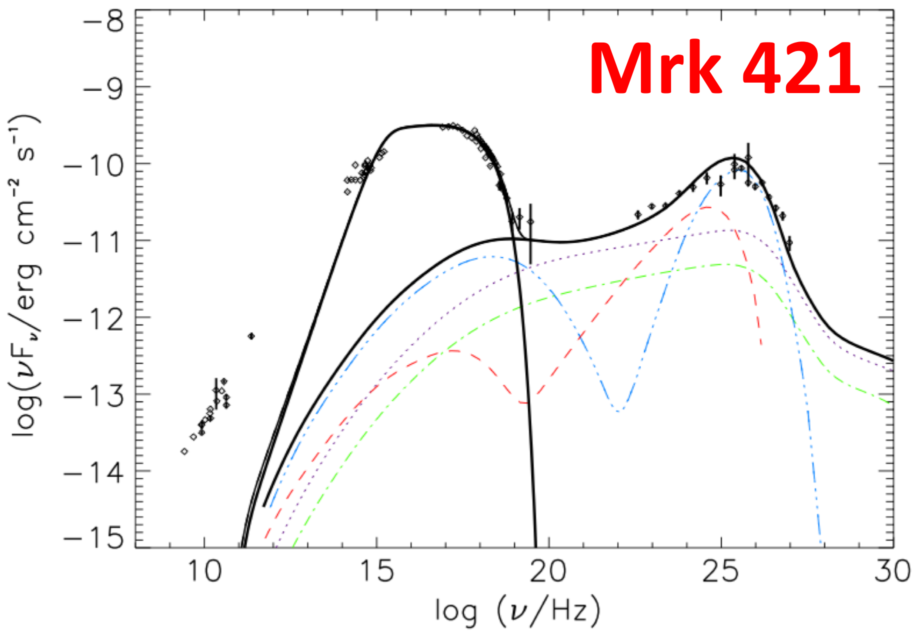


Figure 9. Hadronic model fit components: π^0-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), μ-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which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

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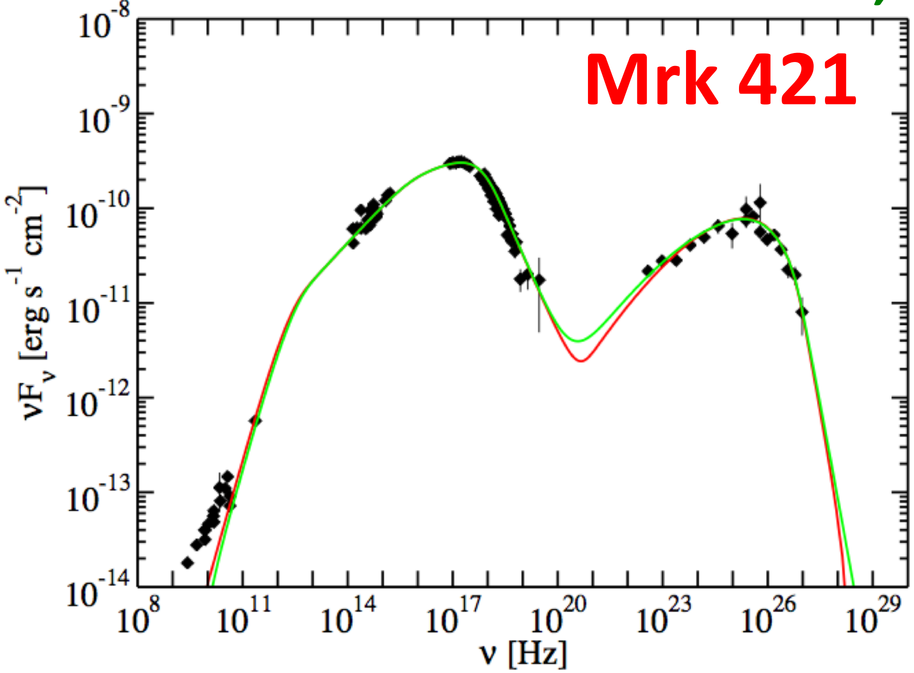
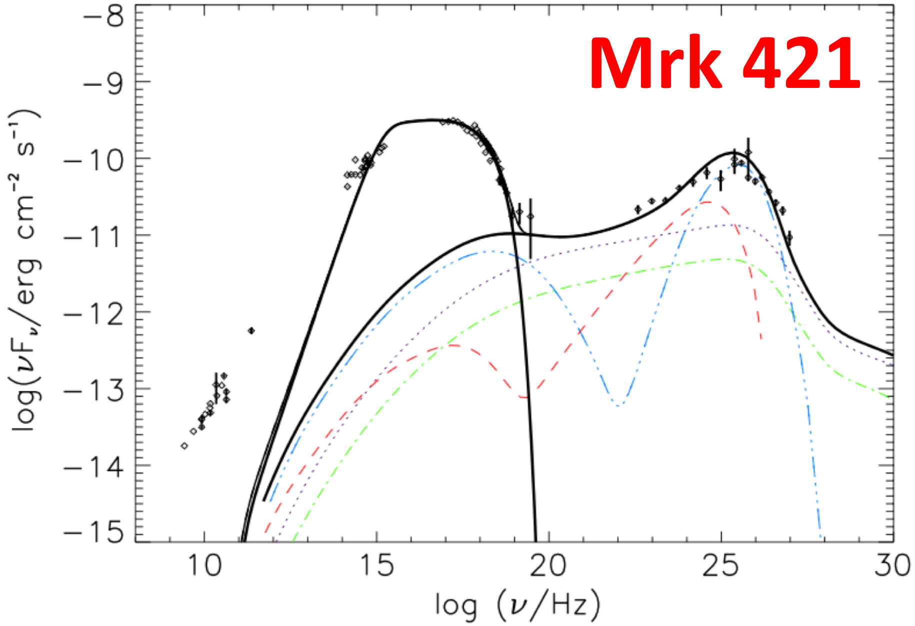




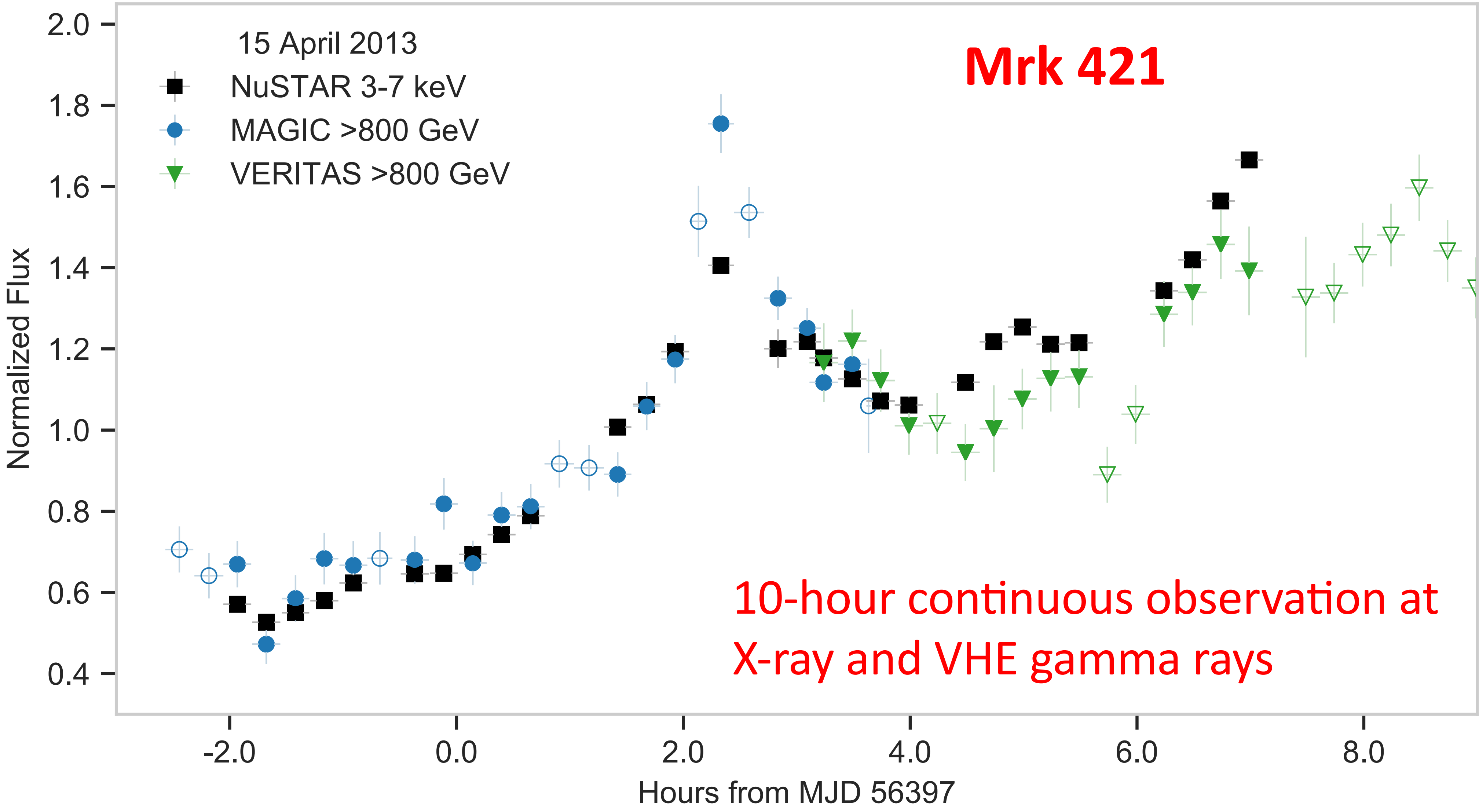
Multi-band variability is key to distinguish between models

→ **models predict different temporal evolutions for the two bumps**

But quantifying variability and correlations among enerby bands (*e.g. VHE vs X-rays*) is not a simple task either… even for extensive observations of bright sources like Mrk421.

Normalized light curves for single night (2013 April 15)

Acciari et al. ApJS 2020, 248, 29



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

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

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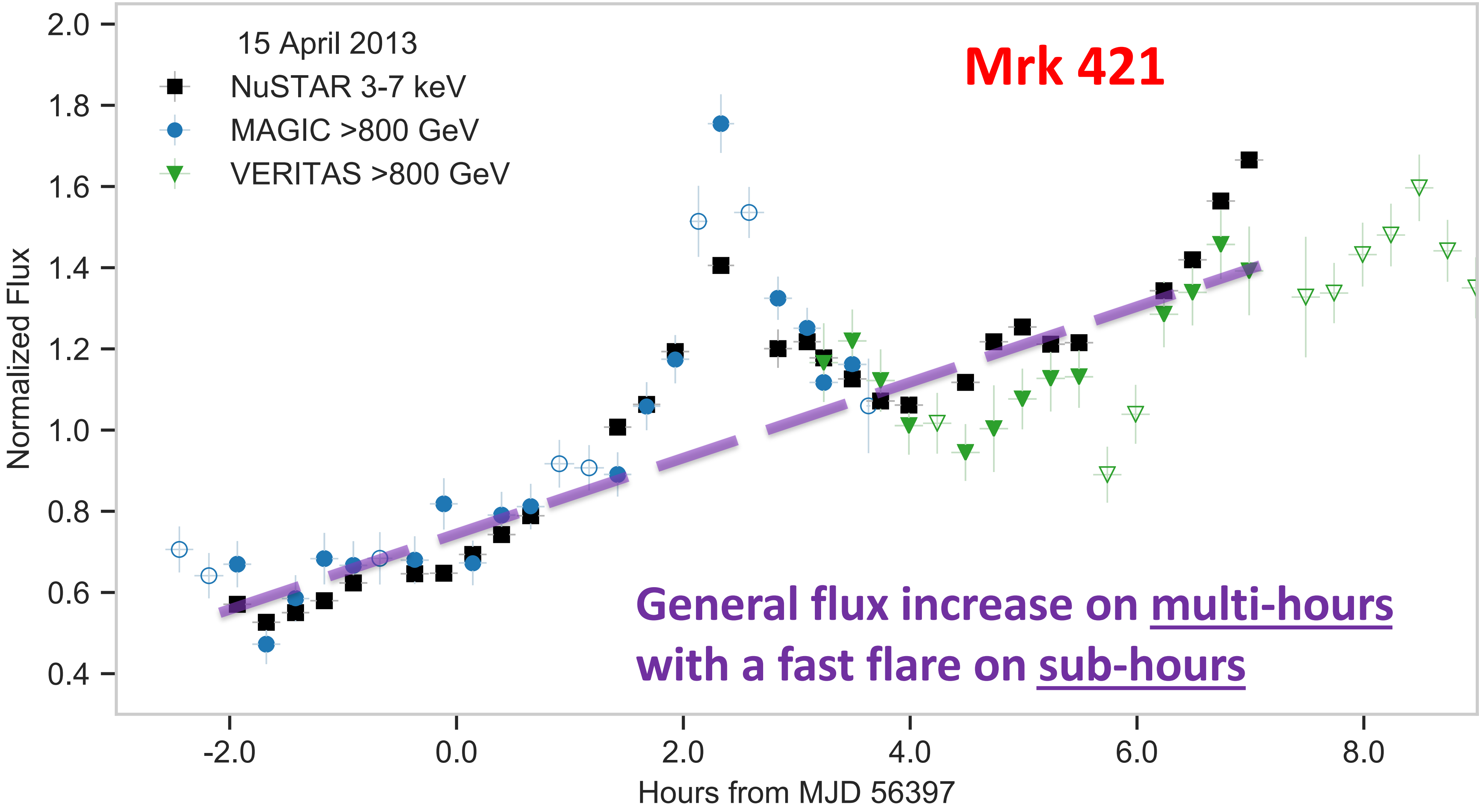
Acciari et al. ApJS 2020, 248, 29



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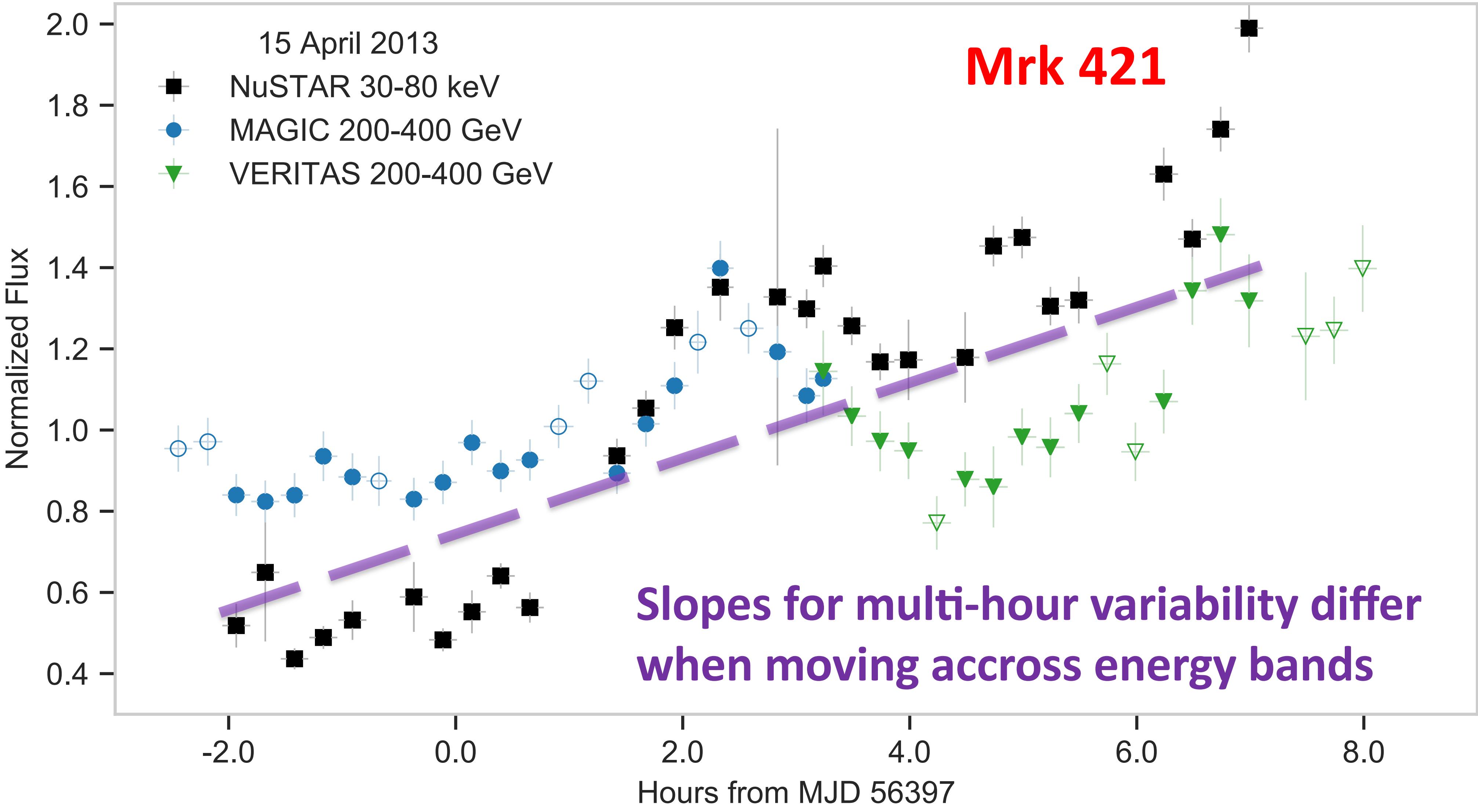

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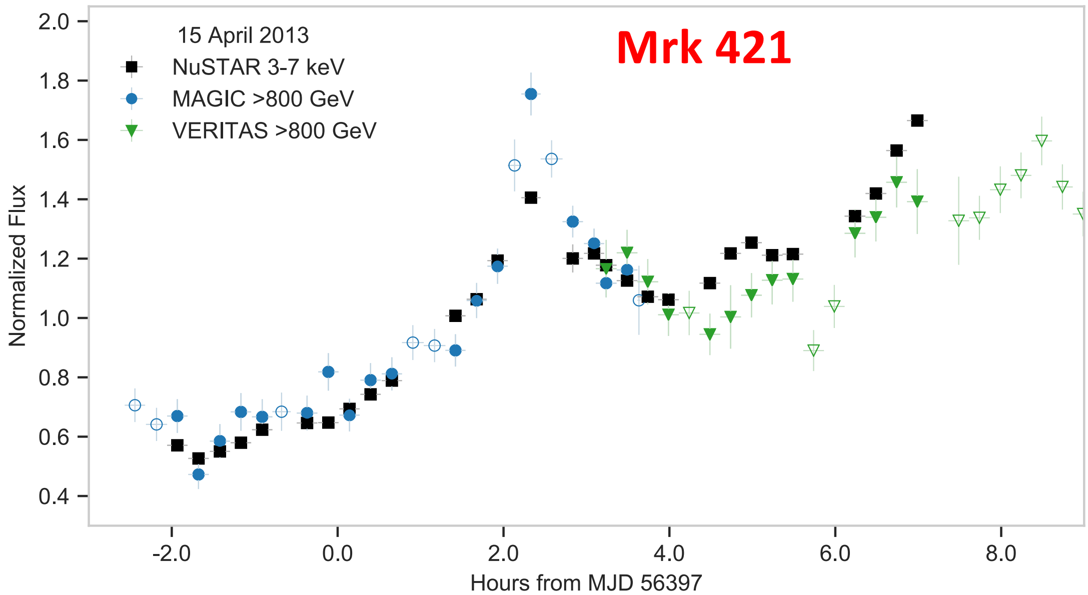
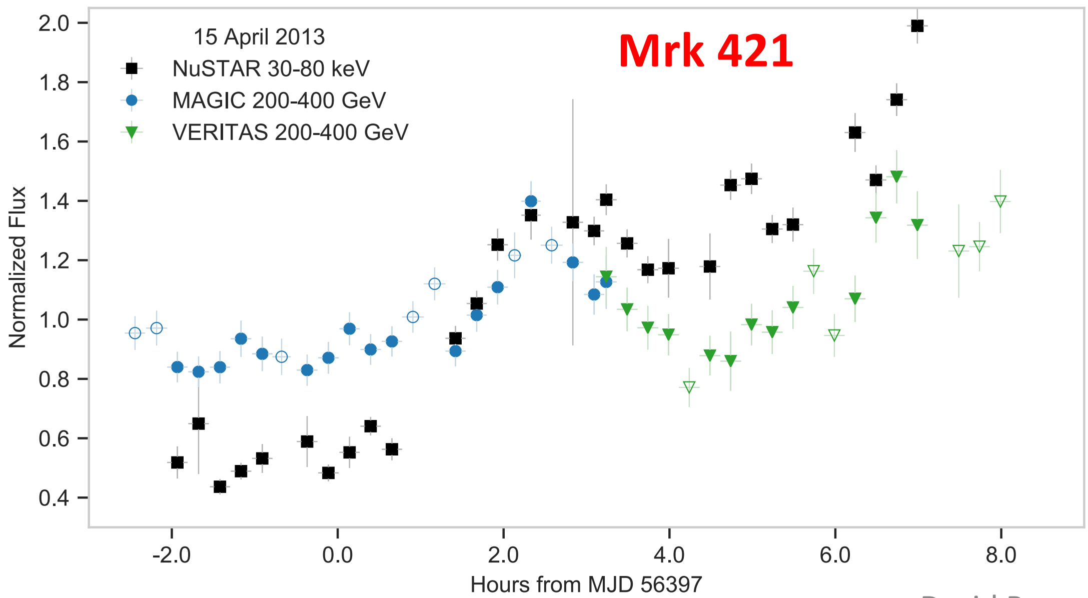


MAGIC + VERITAS >0.8 TeV
NuSTAR 3-7 keV

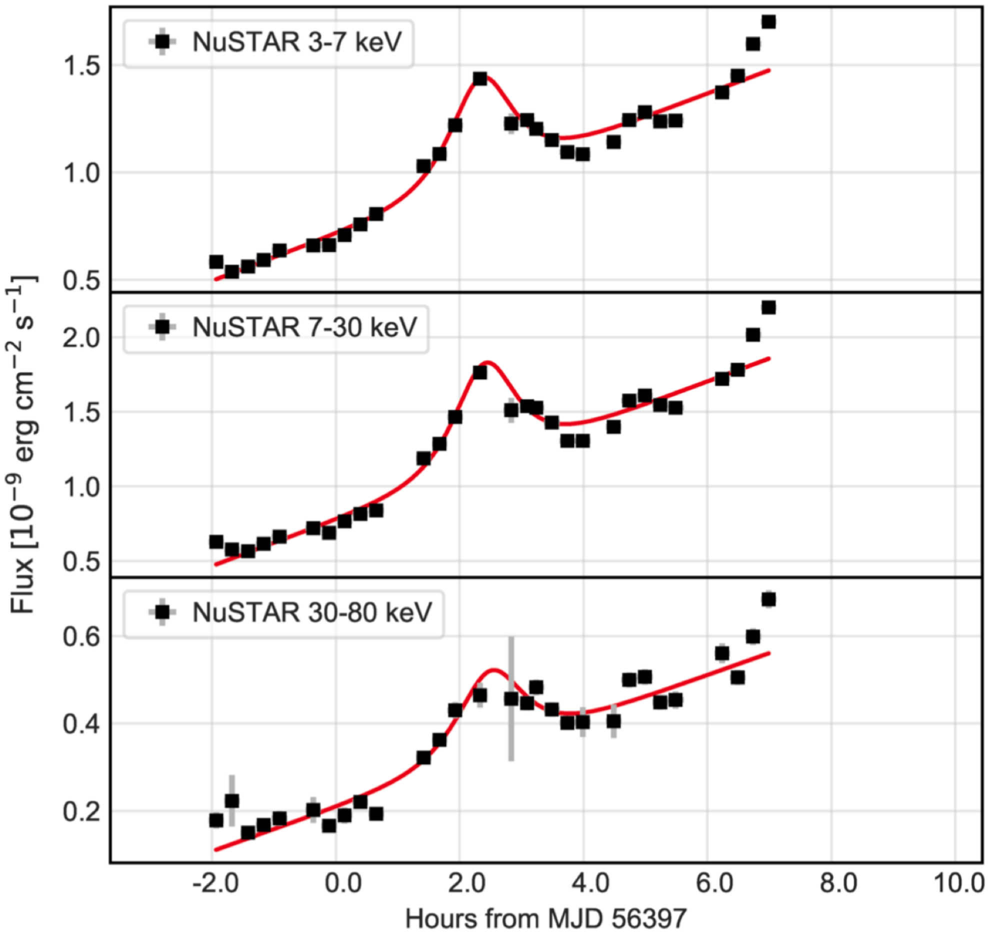
Large change in the overall shape and structure of LCs
when moving across X-ray and VHE bands

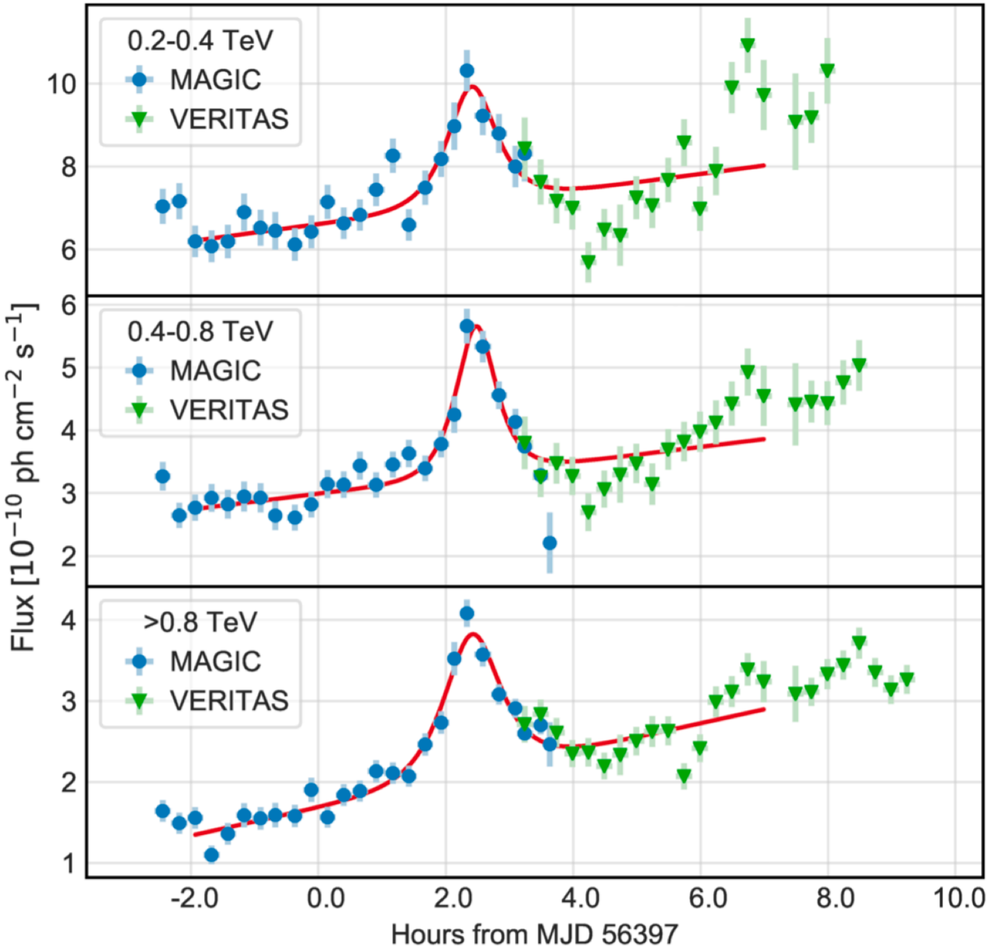


MAGIC + VERITAS 0.2-0.4 TeV
NuSTAR 30-80 keV

X-ray and VHE Light curves for single night (April 15th)

Acciari et al. ApJS 2020, 248, 29





The red curve shows a fit with a two-component function, applied to the time interval with simultaneous X-ray and VHE observations

→ <u>Close relation between X-ray and gamma-rays</u> → Leptons !!

→ But *complex X-ray vs VHE variability and correlation pattern*

Acciari et al. ApJS 2020, 248, 29

Table 3. Parameters resulting from the fit with Eq. 3 to the X-ray and VHE multi-band light curves from 2013 April 15.

Band	$Offset^{a}$	$Slope$ $[h^{-1}]$	Flare Amplitude A	Flare flux-doubling time[b] [h]	Flare t_0 [h]	χ^2/d.o.f
15 April 2013						
3-7 keV	0.71 ± 0.01	0.153 ± 0.006	0.49 ± 0.07	0.30 ± 0.04	2.35 ± 0.06	836/24
7-30 keV	0.78 ± 0.02	0.199 ± 0.009	0.59 ± 0.11	0.30 ± 0.04	2.41 ± 0.06	889/24
30-80 keV	0.21 ± 0.01	0.241 ± 0.018	0.56 ± 0.18	0.32 ± 0.09	2.50 ± 0.10	111/24
0.2-0.4 TeV	6.60 ± 0.17	0.031 ± 0.008	0.40 ± 0.09	0.23 ± 0.07	2.41 ± 0.09	96.9/38
0.4-0.8 TeV	2.99 ± 0.07	0.042 ± 0.008	0.72 ± 0.09	0.19 ± 0.03	2.47 ± 0.04	68.1/42
>0.8 TeV	1.68 ± 0.05	0.103 ± 0.010	0.82 ± 0.08	0.27 ± 0.03	2.41 ± 0.04	90.0/45

[a] For VHE bands in 10^{-10} ph cm^{-2} s^{-1}, for X-ray bands in 10^{-9} erg cm^{-2} s^{-1}.

[b] Parameters $t_{\rm rise}$ and $t_{\rm fall}$ in Eq. 3 are set to be equal, and correspond to the Flare flux-doubling time in the Table.

Large energy-dependence difference between the slow and the fast components

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

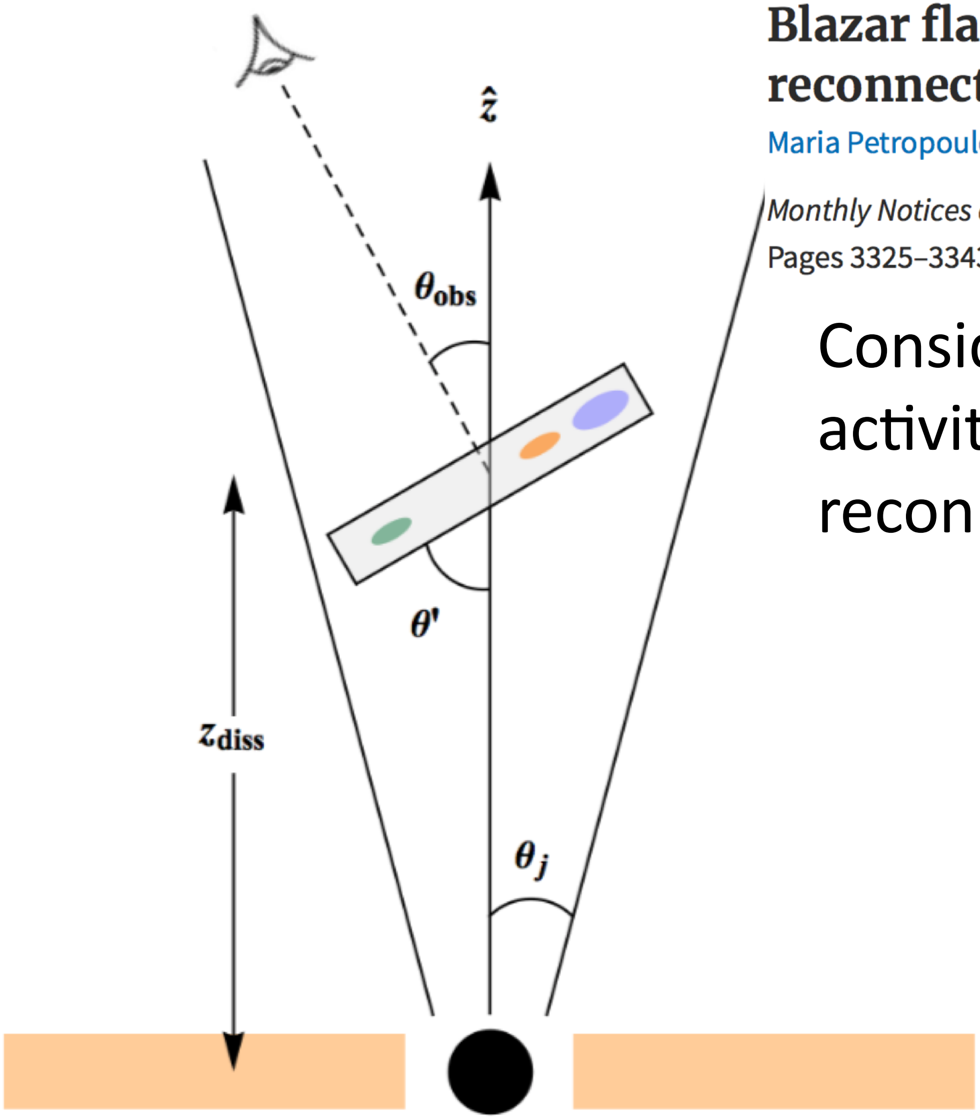


Figure 9. Sketch of a reconnection layer (of half-length L') forming in the jet at a distance $z_{\rm diss}$ (not in scale). The layer forms an angle θ' (as measured in the jet's rest frame) with respect to the jet axis. Plasmoids of different sizes and velocities move towards the sides of the layer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

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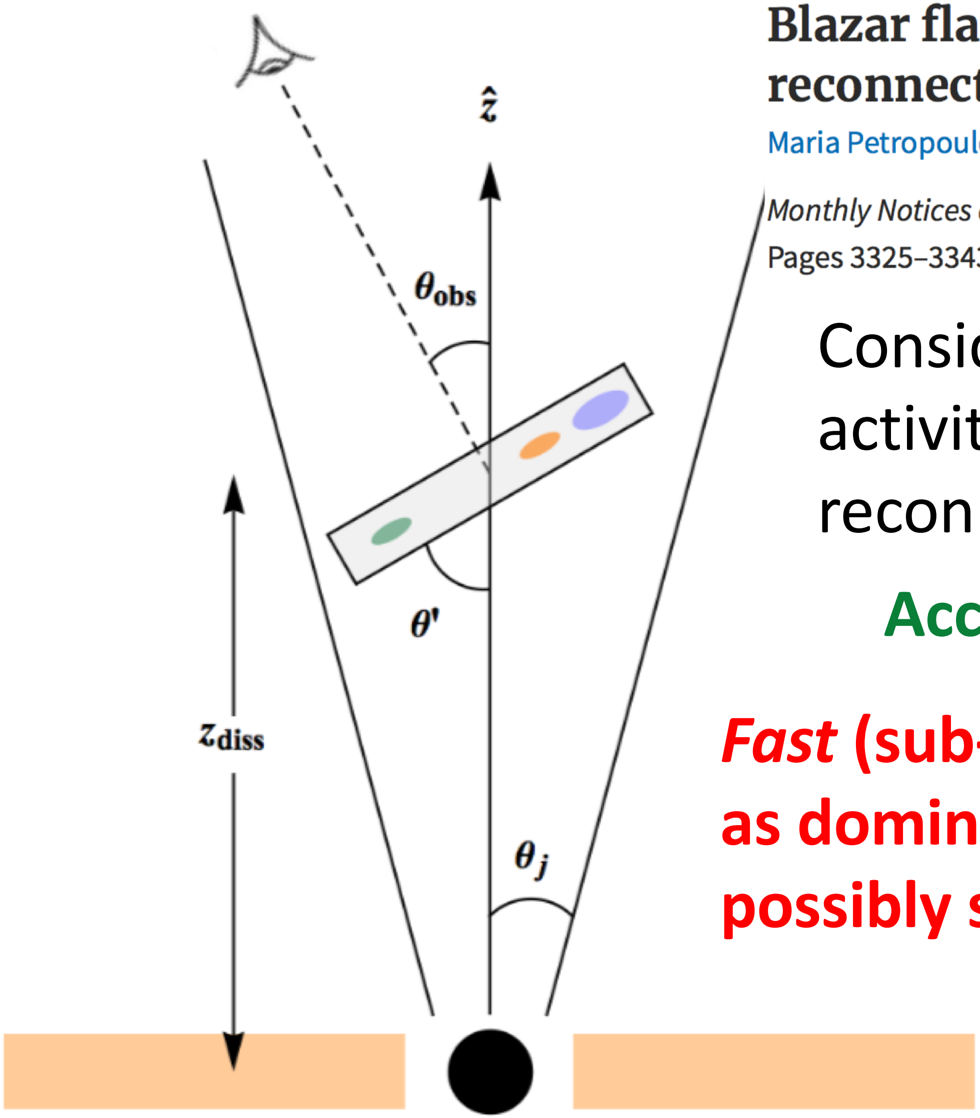

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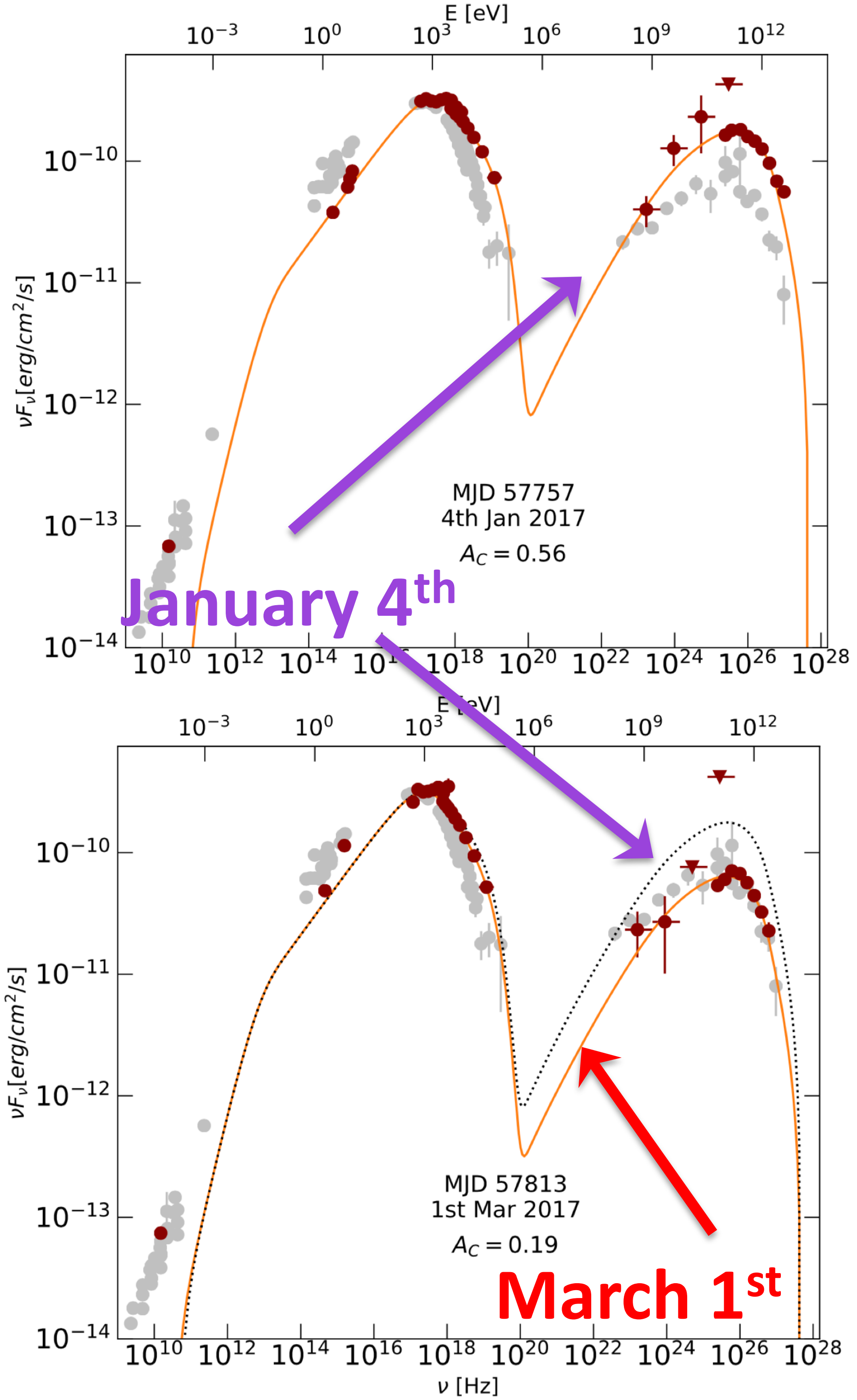
Acciari et al. ApJS 2020, 248, 29

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**



Multi-Instrument study of Mrk421 during 2017 showed a <u>decreased in the gamma-ray</u> emission by factor ~3, <u>without substantial change in the X-ray emission</u>

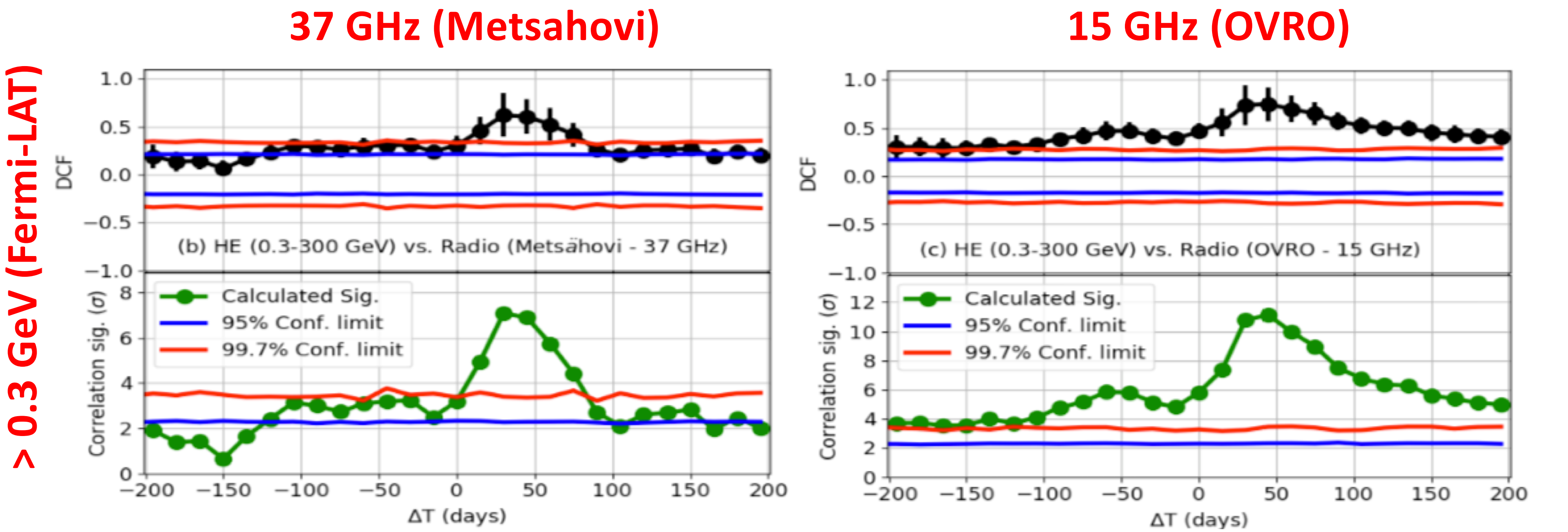
Could be described within a one-zone leptonic scenario with an adiabatic expansion of the emitting region:

R~1x10^{16} cm → R~2x10^{16} cm

Acciari et al 2021, A&A 655, 89

GeV-radio correlation in Mrk421 (2007-2016)

Acciari et al 2021, MNRAS 504, 1427



Correlation in the flux variations is particularly important with radio because the radio instruments have the best angular resolution, and hence they can help locating the regions responsible for the electromagnetic emission that we measure.

→ If correlation exists, the two emission bands must be connected

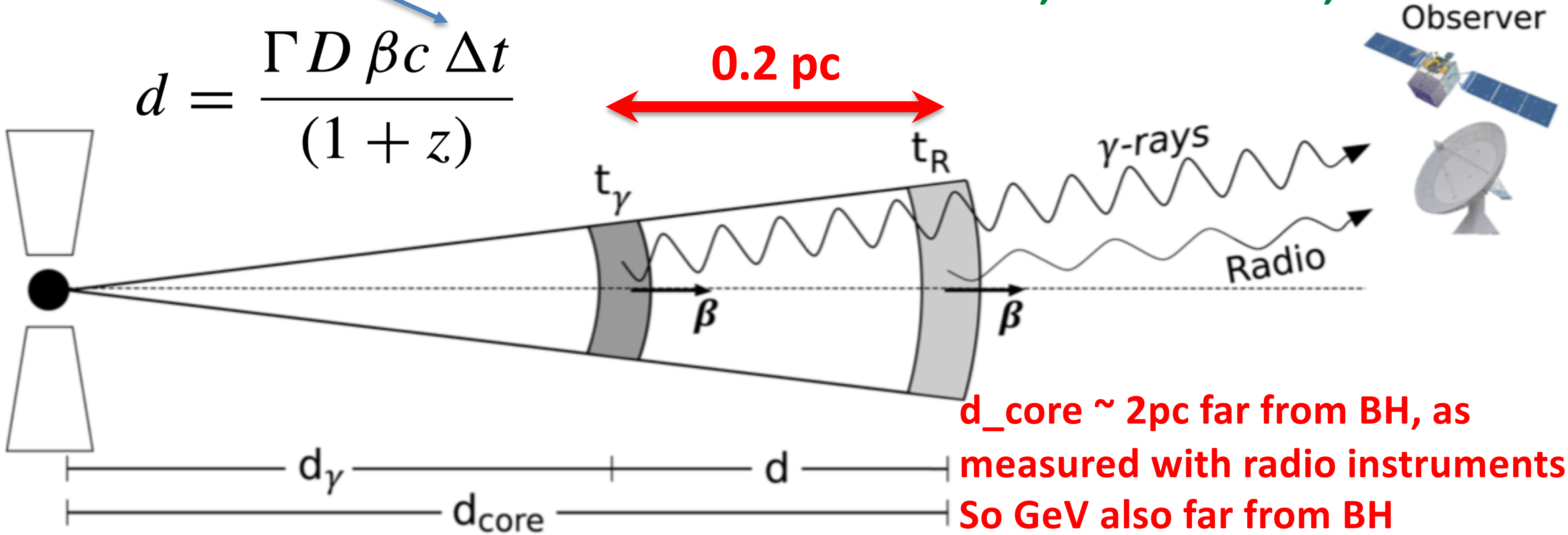
Radio-GeV correlation in Mrk421 (2007-2016)

The correlation GeV-radio and Optical-radio, with a time lag of ~45 days is an intrinsic characteristic in the multi-year emission of Mrk421, and not a particularity of a rare flaring activity.

Acciari et al 2021, MNRAS 504, 1427

$$d = \frac{\Gamma D \beta c \Delta t}{(1+z)}$$

0.2 pc



d_core ~ 2pc far from BH, as measured with radio instruments So GeV also far from BH

Emission may be produced by plasma (or jet disturbance) moving along the jet of Mrk421, first crossing the surface of unit gamma-ray opacity and then, **about 0.2 pc down the jet**, crossing the surface of unit radio opacity

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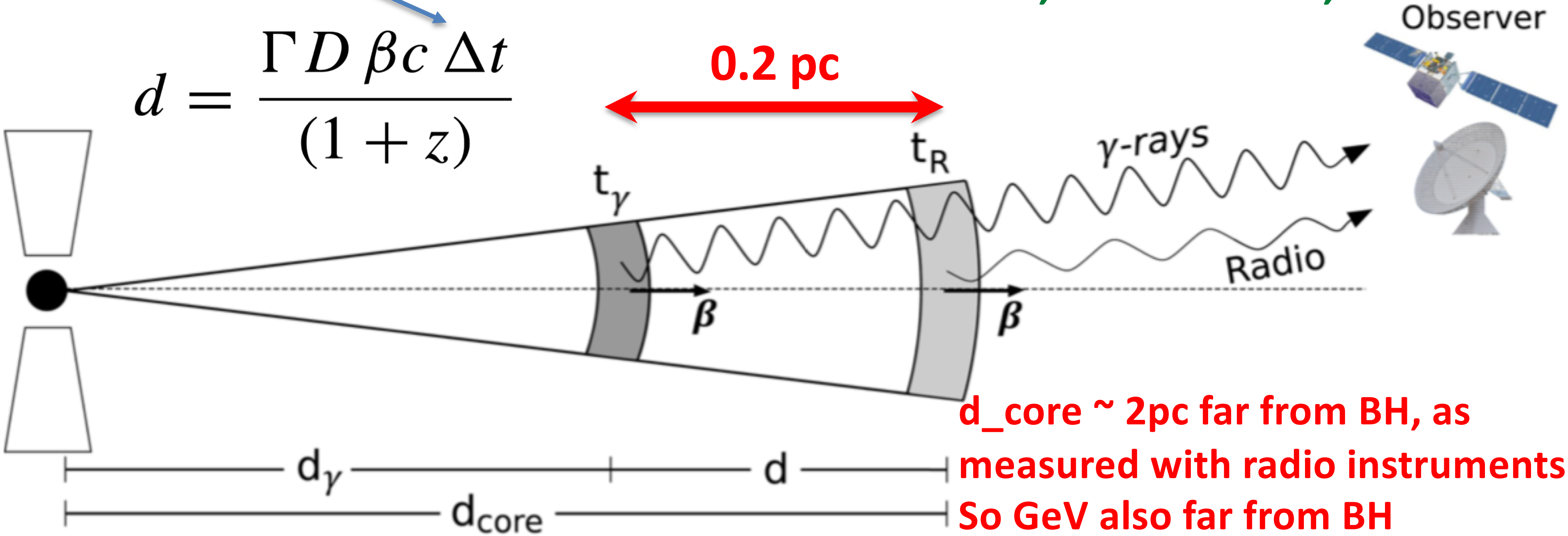


d_core ~ 2pc far from BH, as measured with radio instruments
So GeV also far from BH

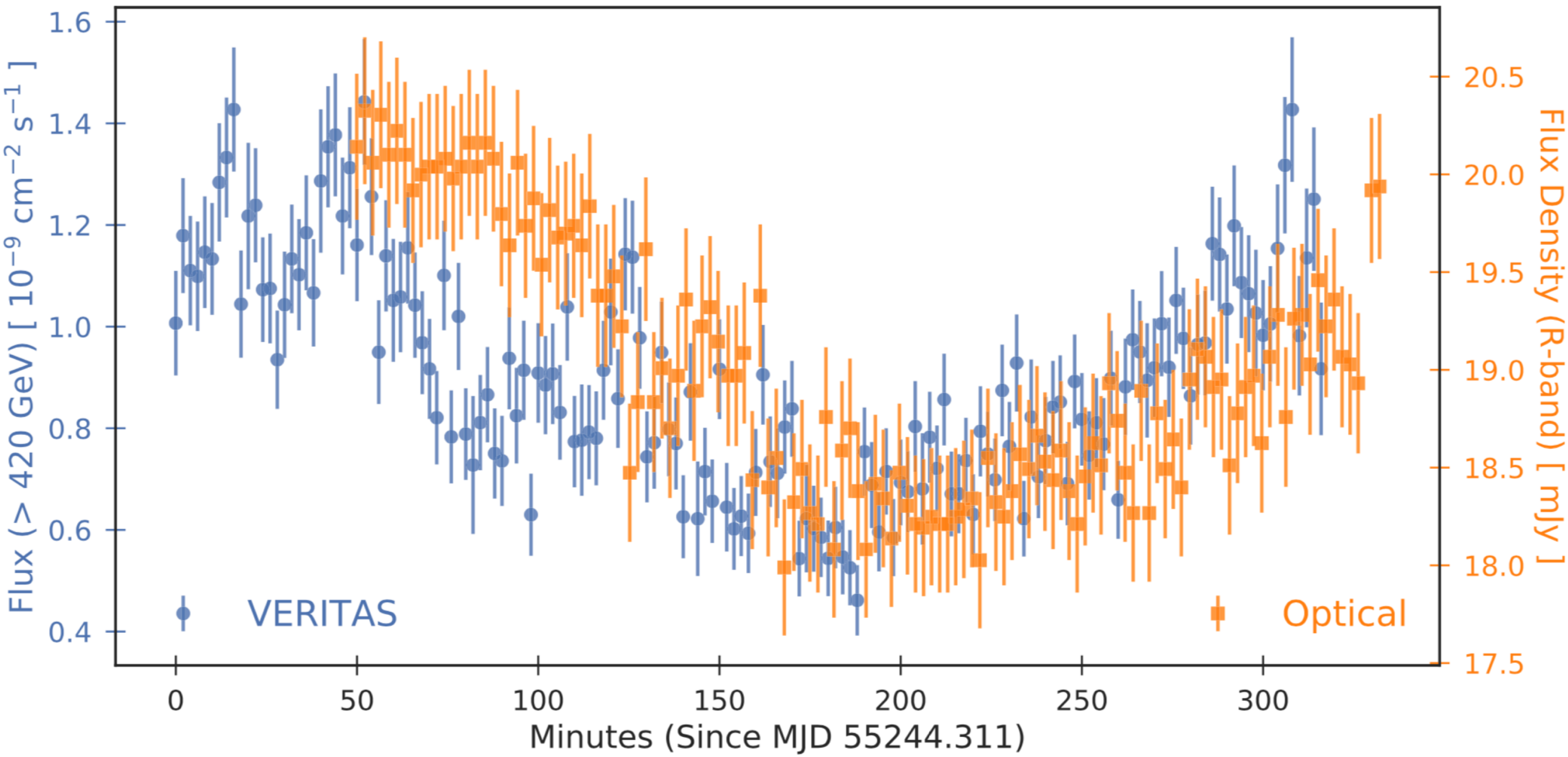
VHE/X-ray may be produced in a small region with very high energy particles close to the central engine, very far away from the radio/optical/GeV emission. This would explain naturally the (typical) lack of correlation between VHE/X-ray and optical/GeV

Besides all the observational and theoretical (modeling) challenges mentioned before, we have the additional difficulty that, occasionally, AGNs show peculiar (rare) behaviours

Intra-night Optical-TeV correlation in Mrk421 during unprecedented flaring activity (February 17th, 2010)

Abeysekara et al. ApJ 2020, 890, 97

Largest TeV flare of Mrk421 to date (27 x Crab Nebula above 1 TeV)



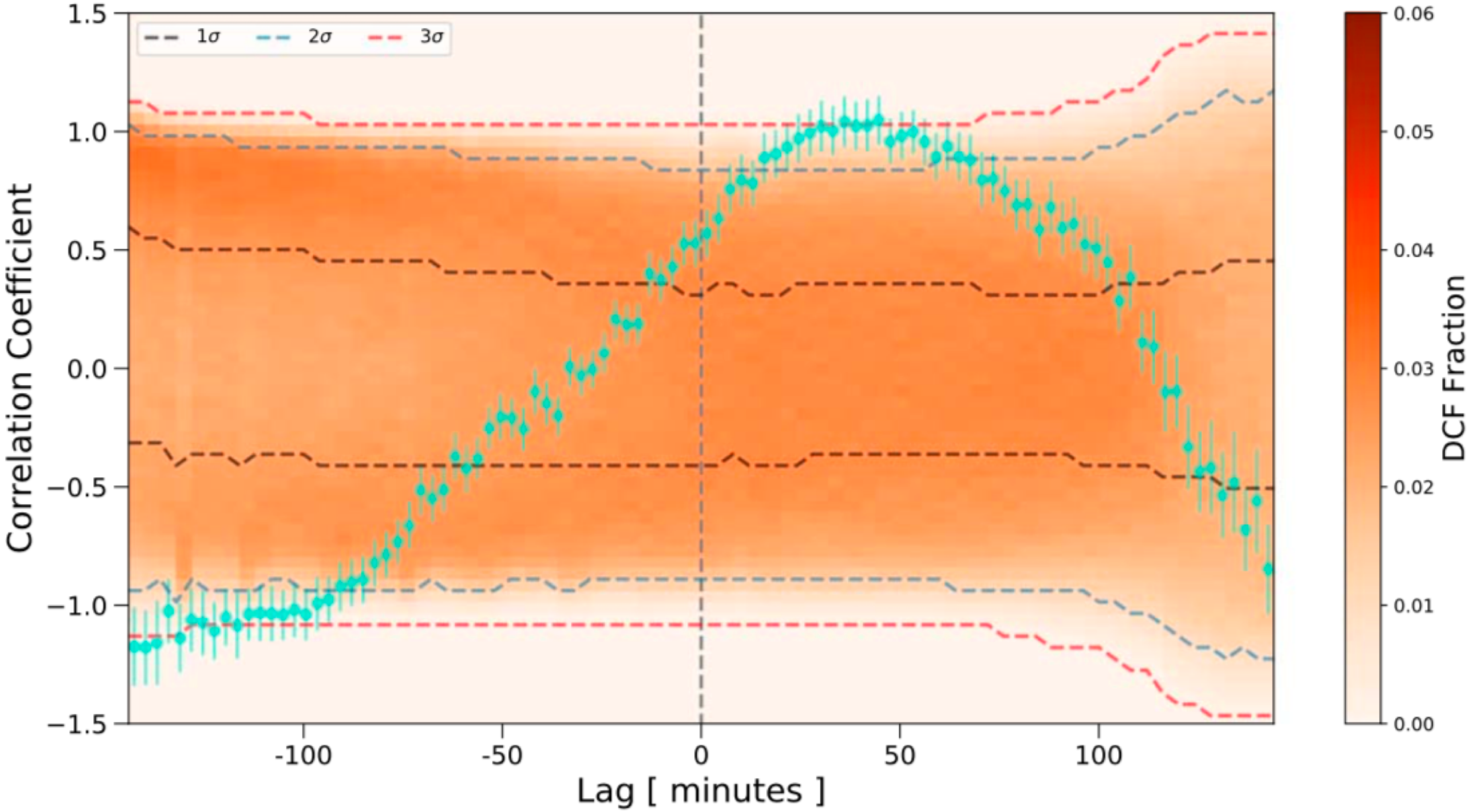
Intra-night Optical-TeV correlation in Mrk421 during unprecedented flaring activity (February 17th, 2010)

Abeysekara et al. ApJ 2020, 890, 97

Correlation at 3 sigma, with a time lag of about 40 minutes

→ *TeV and eV emission co-spatial (at least partially) during this flare*

→ *Very atypical event, suggesting distinct processes during this flare*



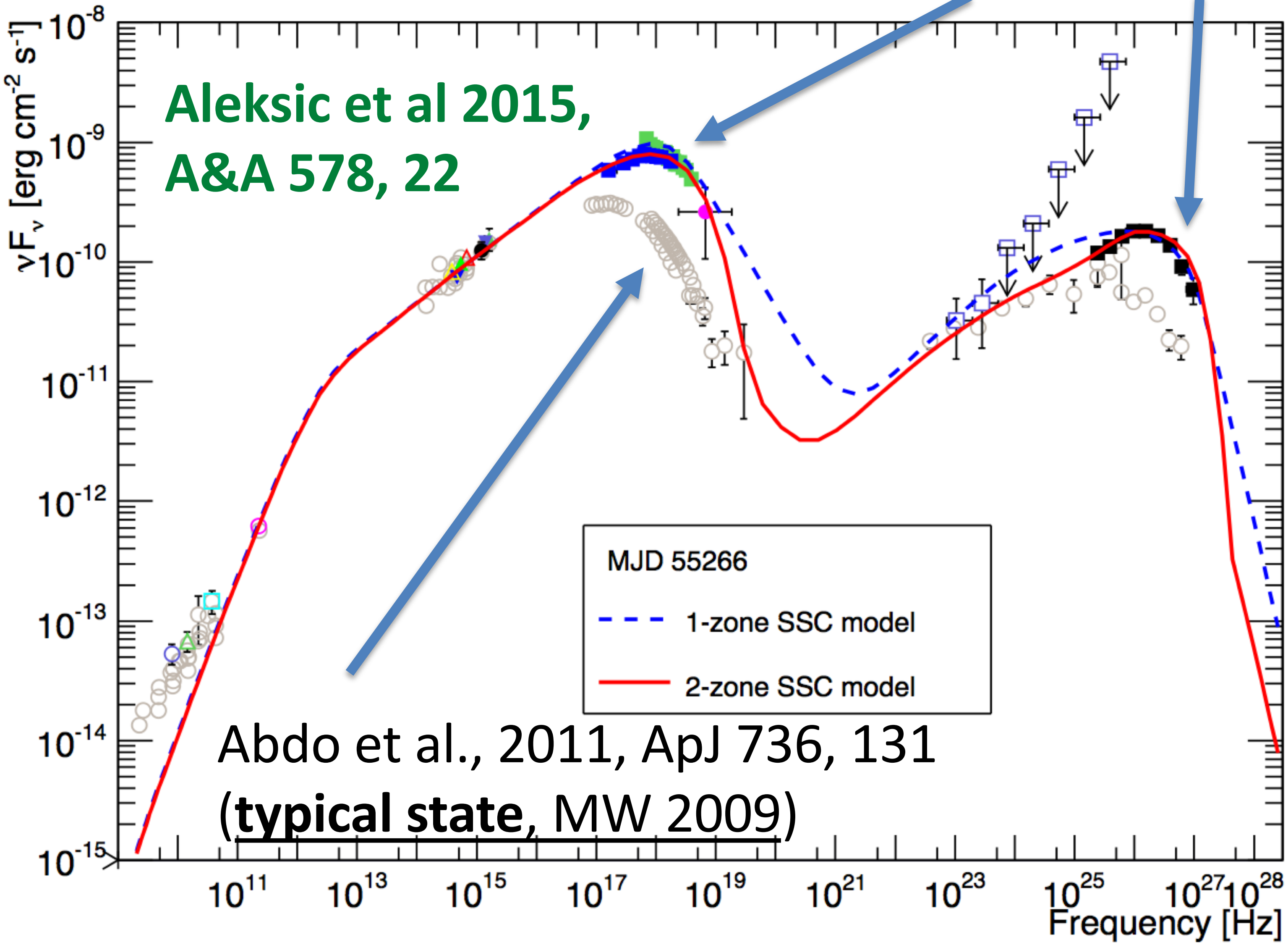
Mrk421 has shown X-ray and VHE spectral variability during flares

X-ray and VHE spectra becomes harder when flaring

→ SED bumps shift to high energies

→ highest variability at X-ray and VHE

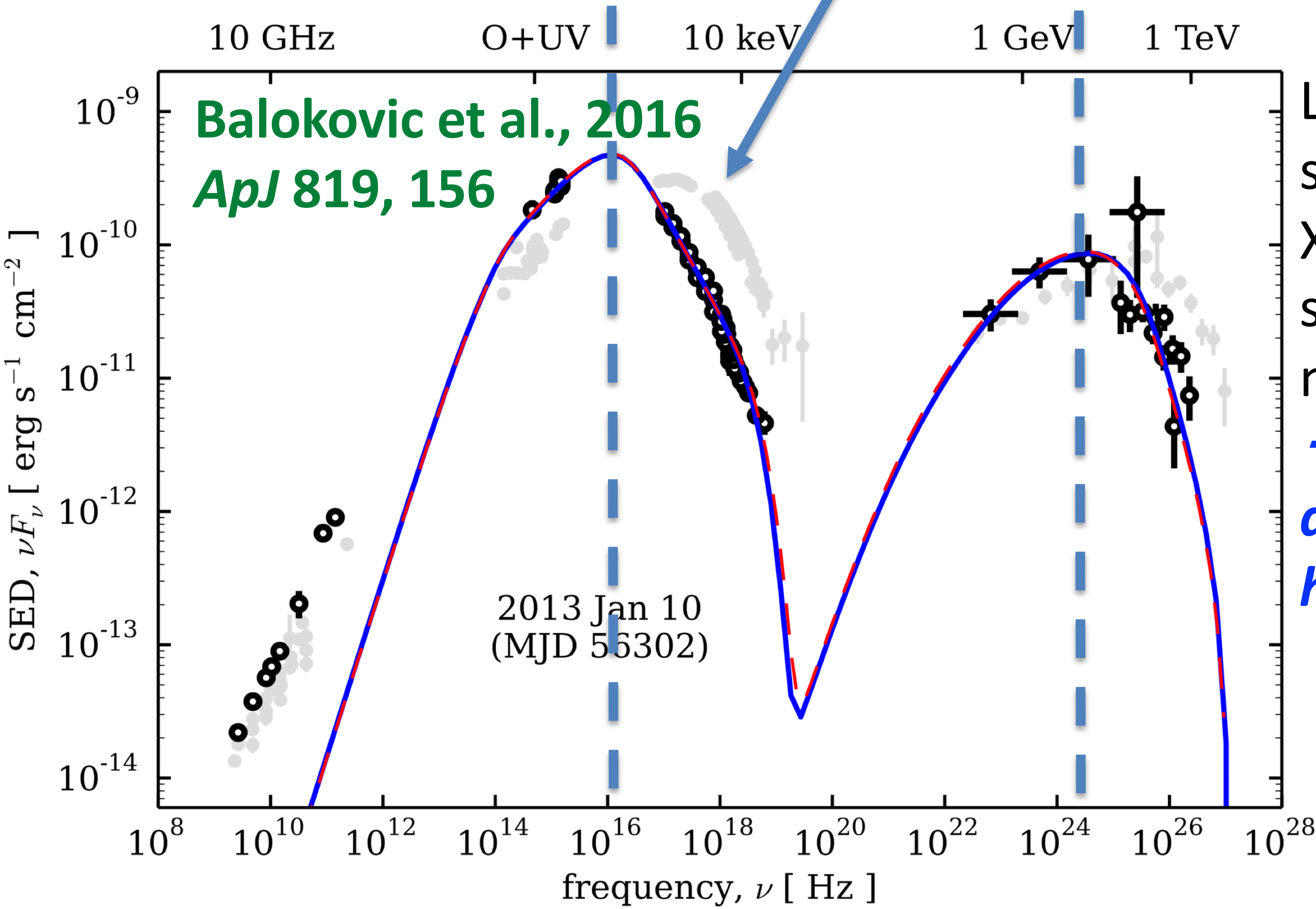
Flare from MW 2010



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**)



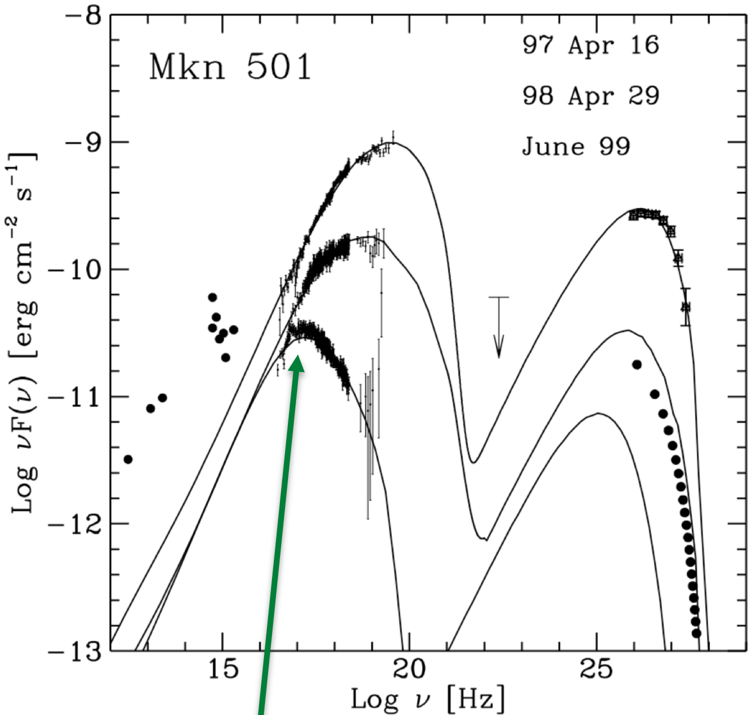
Low activity softened the X-ray and VHE spectra, but did not bring cutoffs

→ Electrons accelerated to highest energies

Typically: Mrk501 shows X-ray & VHE spectral hardening during flares

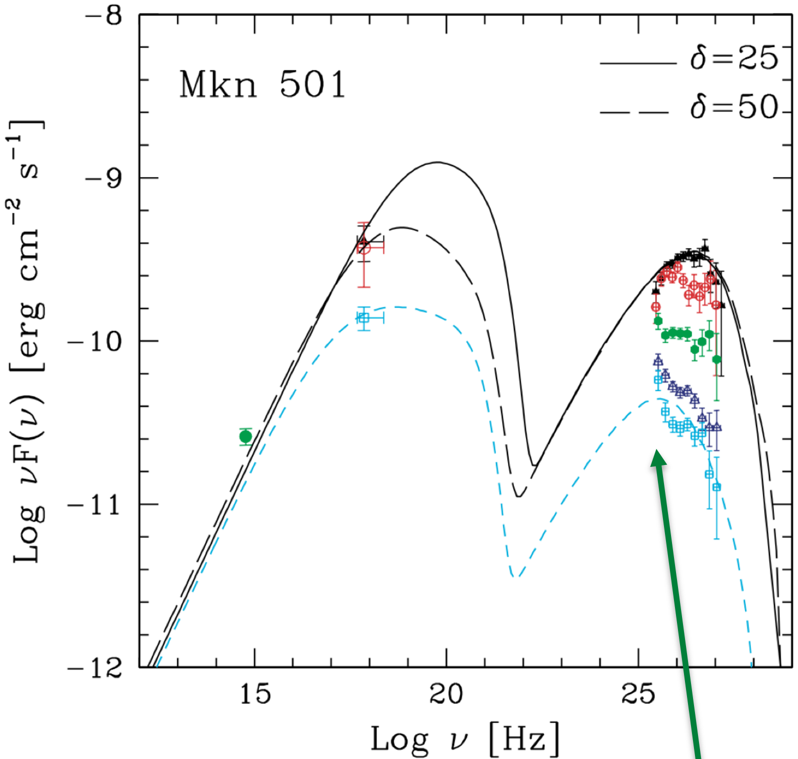
(Historical) flare in 1997

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,

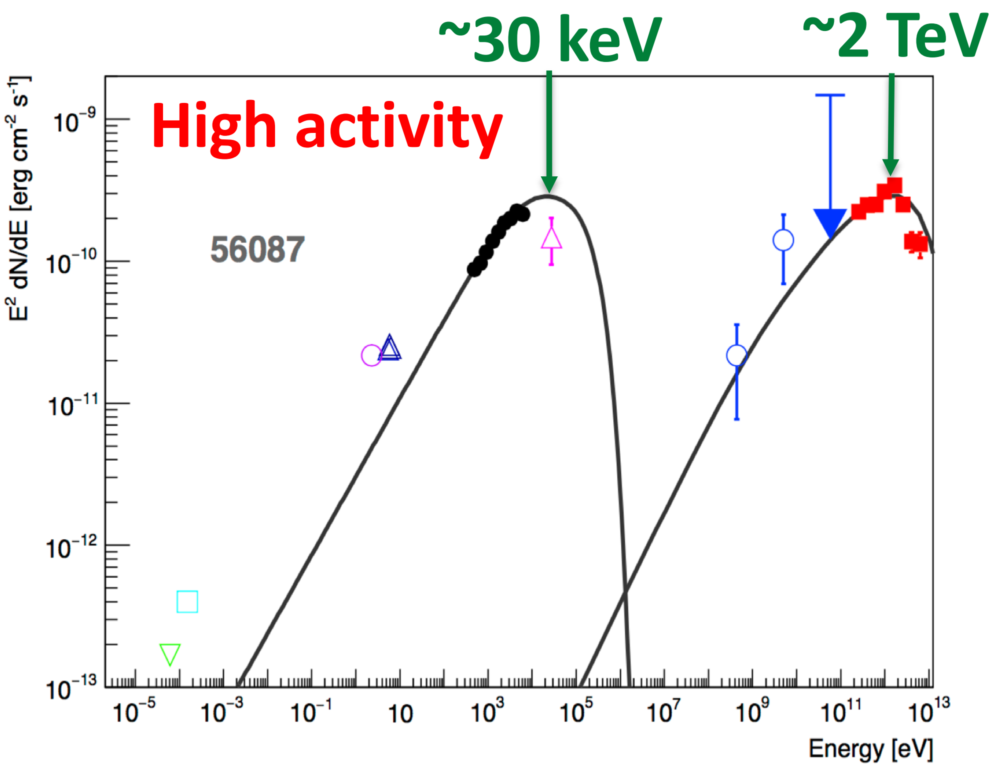
< 1 keV

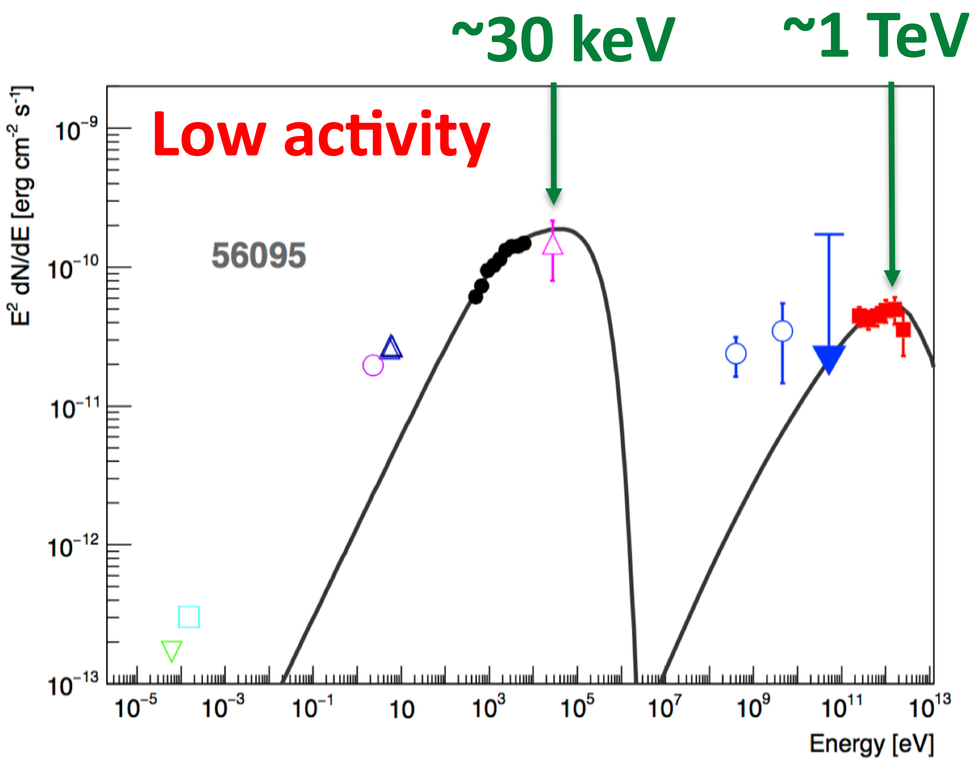
This is the typical behaviour of Mrk501, what we have seen in 20+ years of observations

< 0.1 TeV

But… in year 2012, Mrk501 suffered a personality crisis

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





Radio:
OVRO
Metsahovi

X-ray:
Swift/XRT
Swift/BAT

Gamma ray:
Fermi-LAT
MAGIC

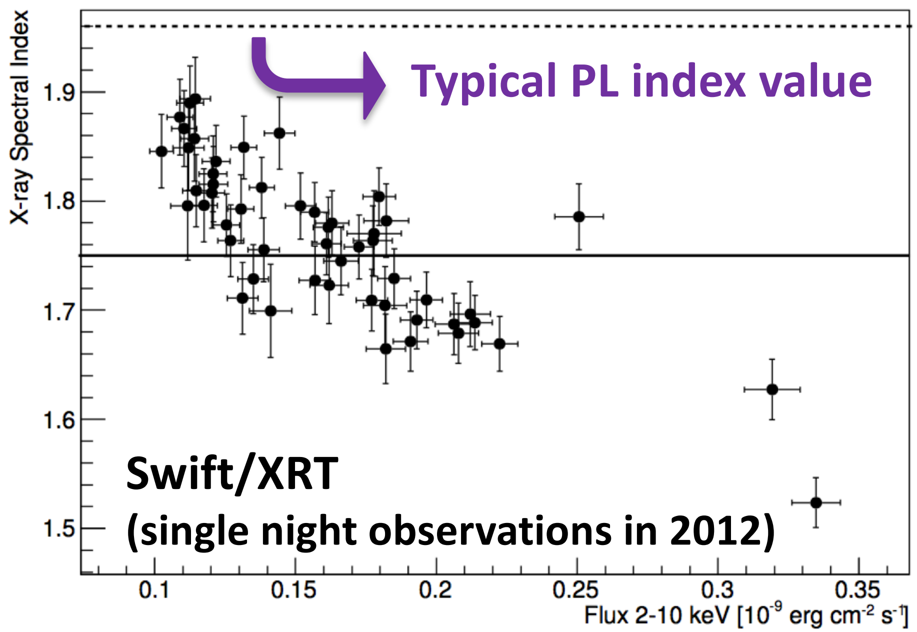
Optical/UV:
R-band (WEBT+)
Swift/UVOT

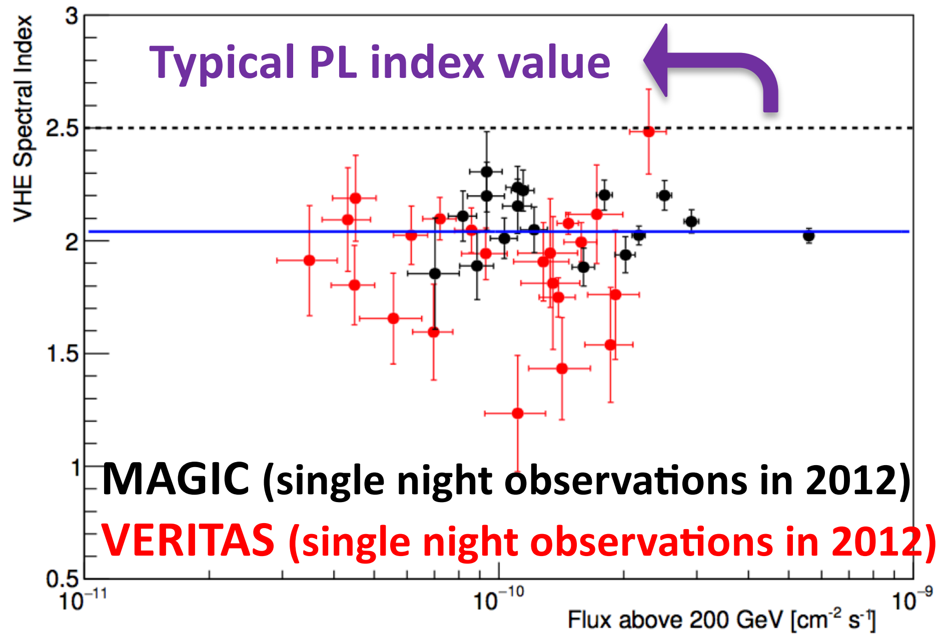
Ahnen et al., 2018
A&A 620 , 181

But... in year 2012, Mrk501 suffered a personality crisis

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

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





→ **Mrk 501 behaved as Extreme HBL!**

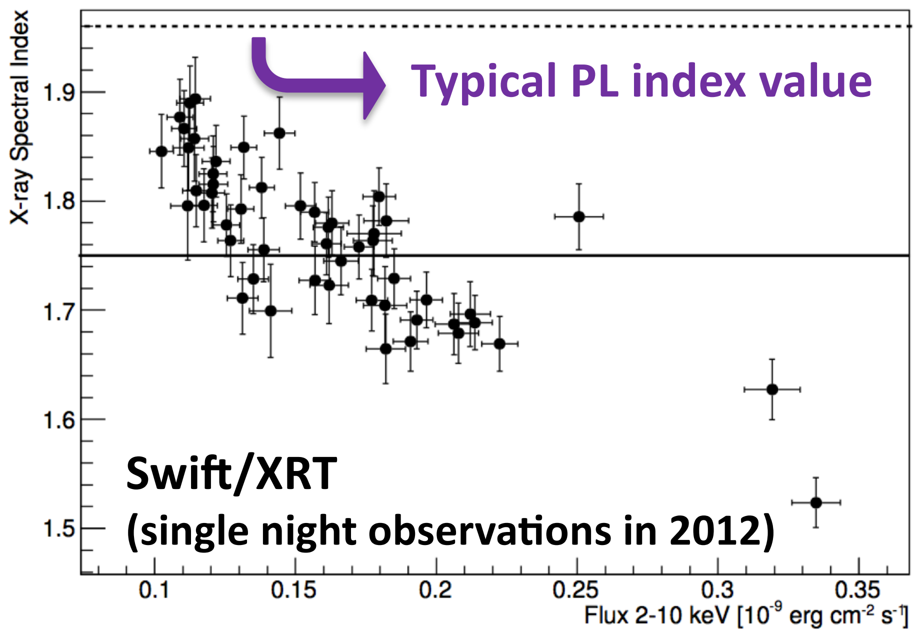
Similar X-ray/VHE spectra as 1ES 0229+200, 1ES 0347-121 (Peaks at ~10 keV and ~1TeV)

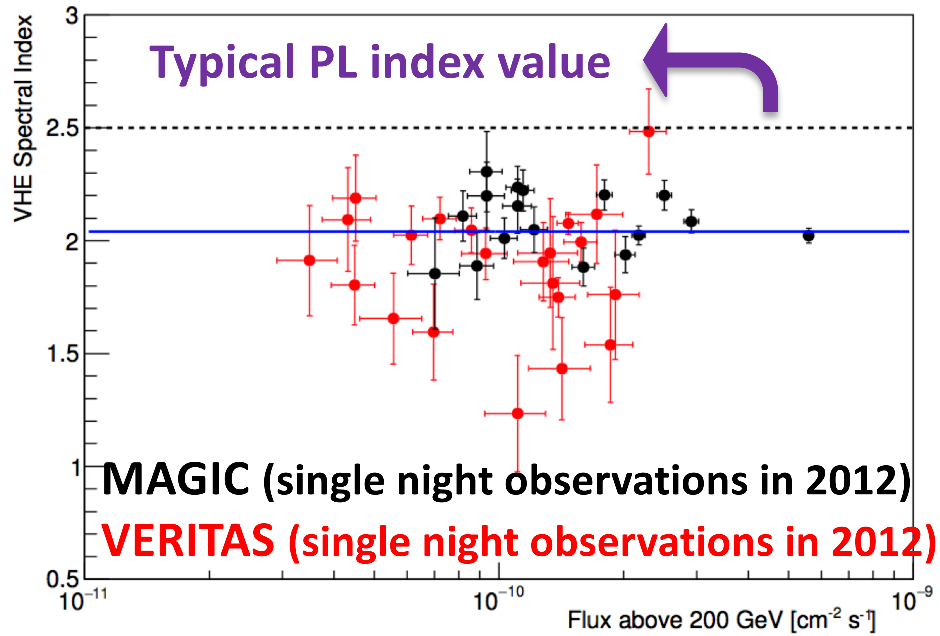
Being "extreme HBL" may be a temporal state, rather than intrinsic blazar characteristic

But… in year 2012, Mrk501 suffered a personality crisis

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

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





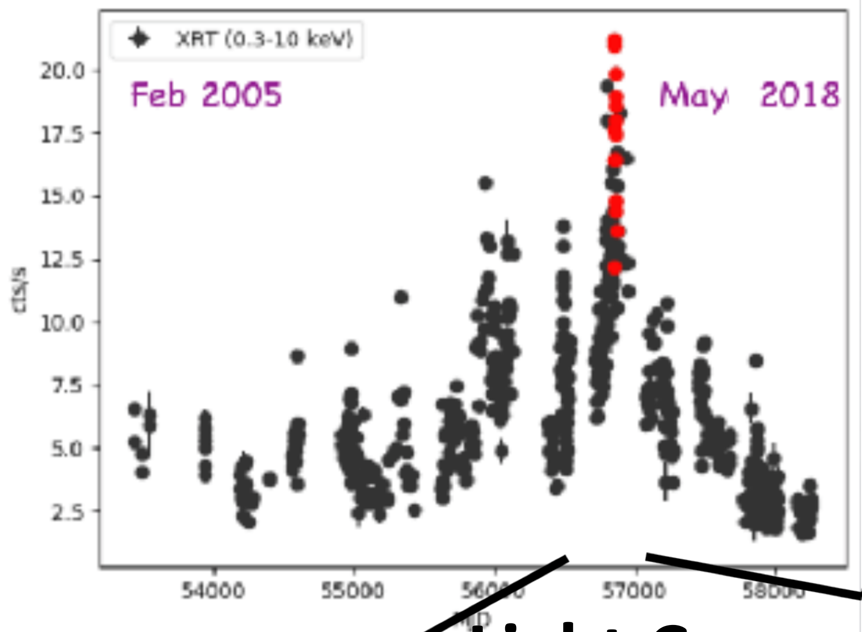
Mrk501_F^{TeV} > ~10 x 1ES0229_F^{TeV}

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

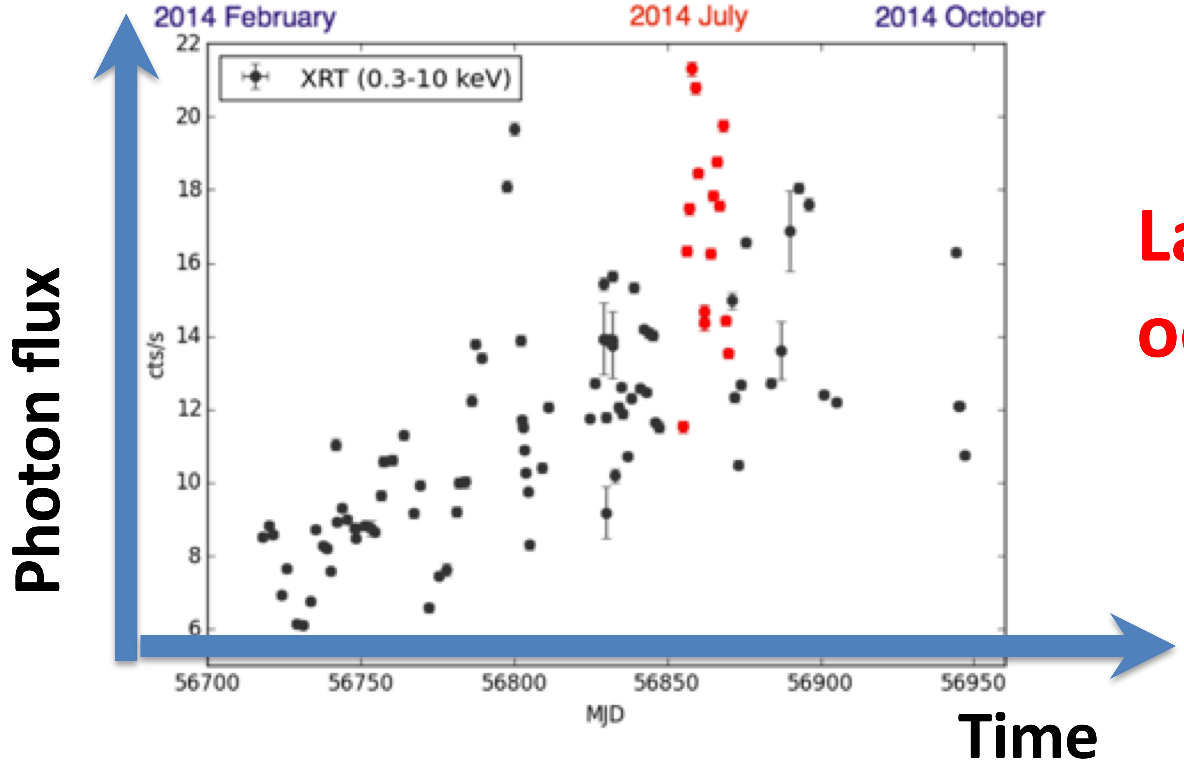
Hints of narrow spectral feature in gamma-ray spectrum during large flaring activity in Mrk501 (July 2014)



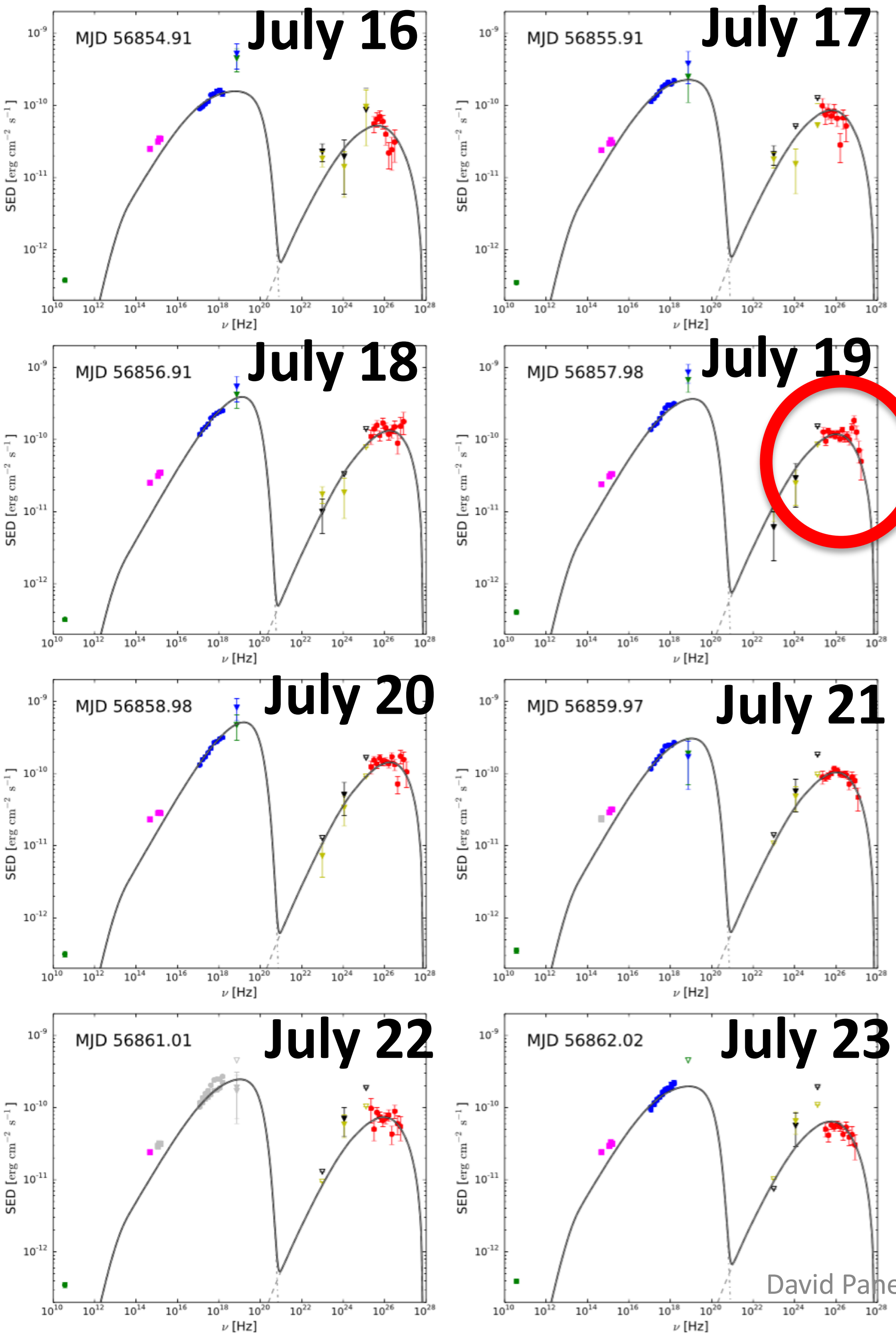
Swift-XRT

Historical light curve in ~**16 years**

Light Curve (LC)



Largest X-ray activity occurred in July 2014



Acciari et al
A&A 2020, 637, 86

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 ?

David Paneque

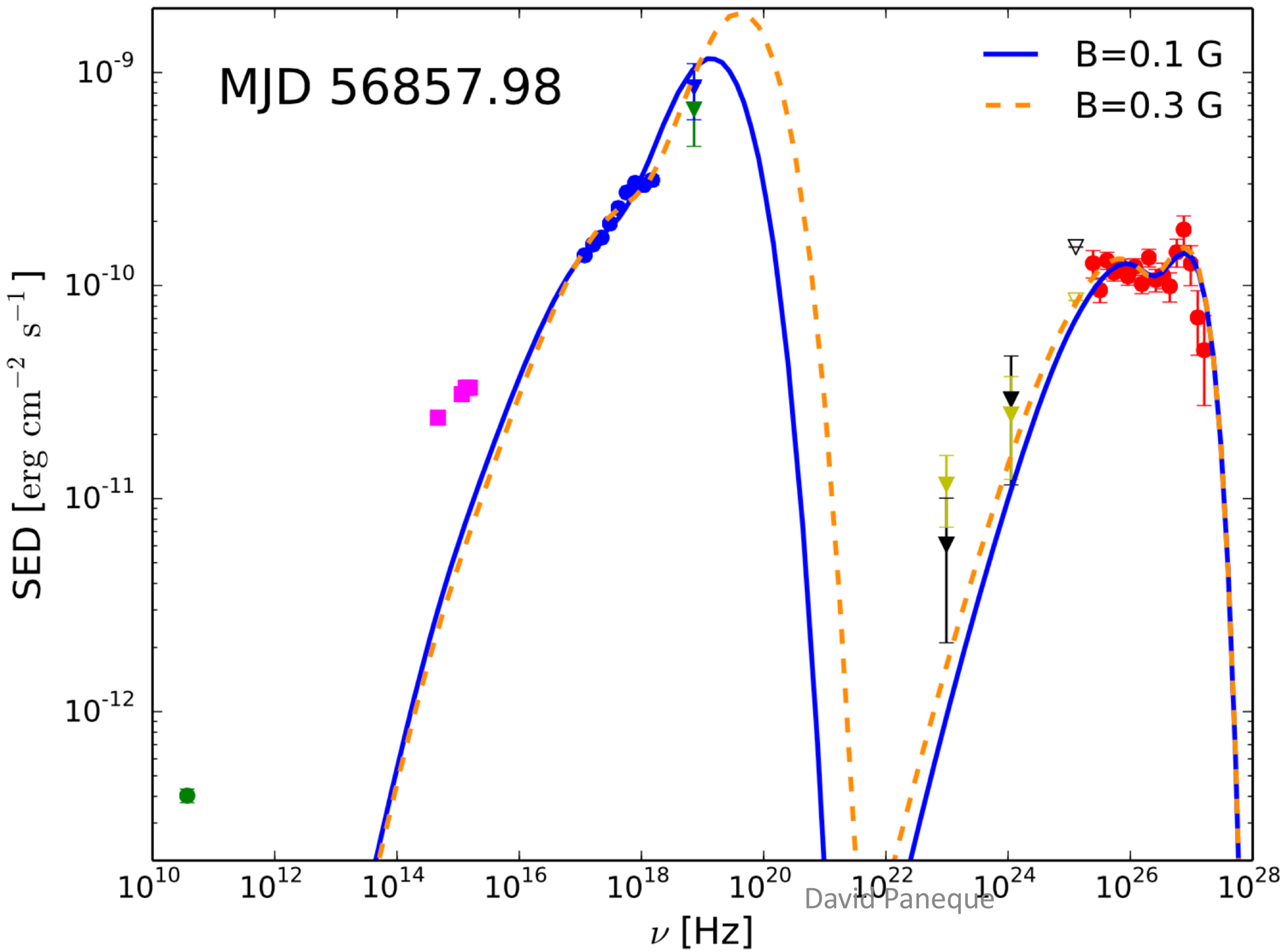
Pile-up in the electron energy distribution due to stochastic acceleration

Acciari et al A&A 2020, 637, 86

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

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

Mrk501



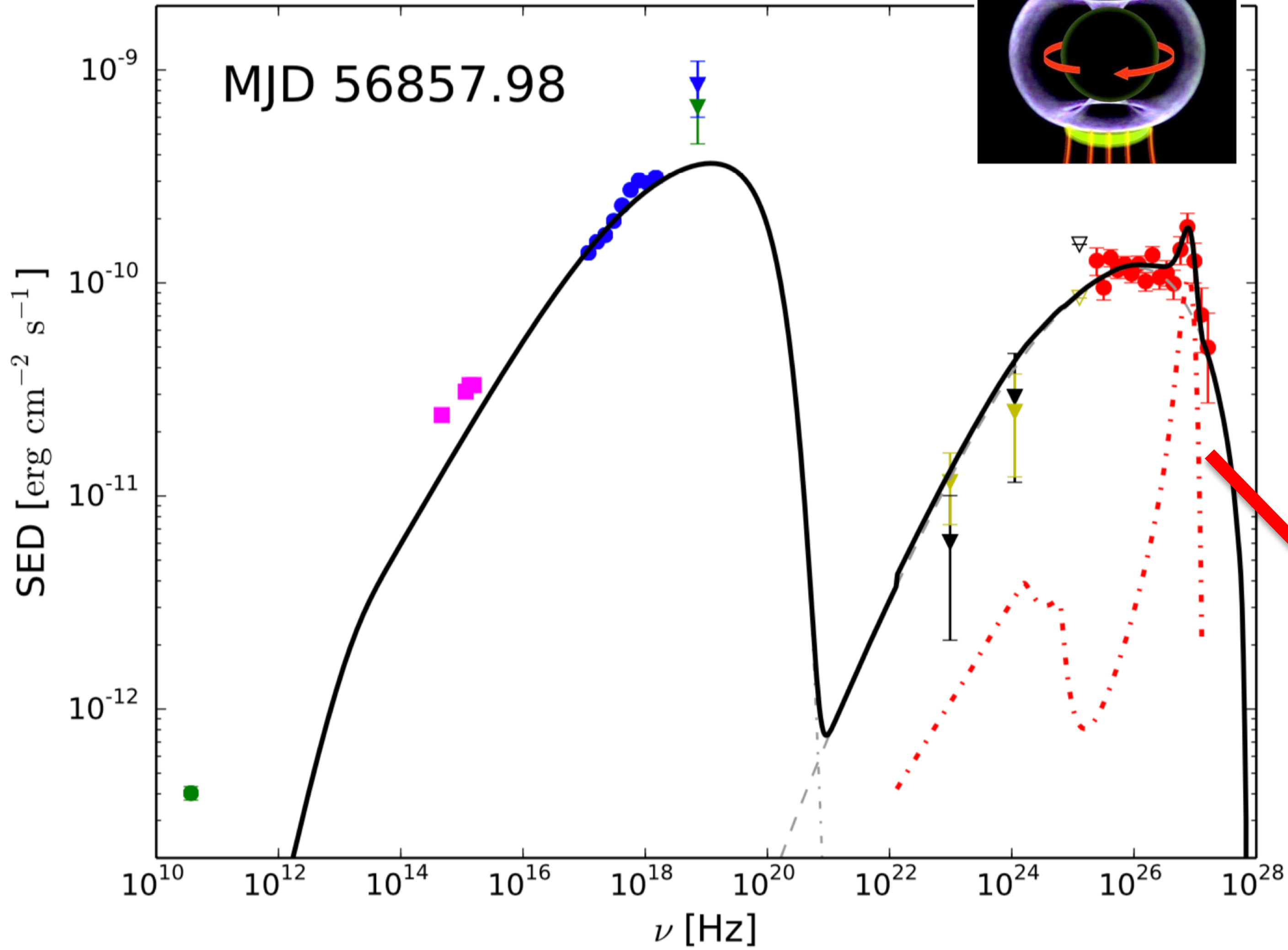
Model performed by Andrea Tramacere

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

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 A&A 2020, 637, 86

Mrk501



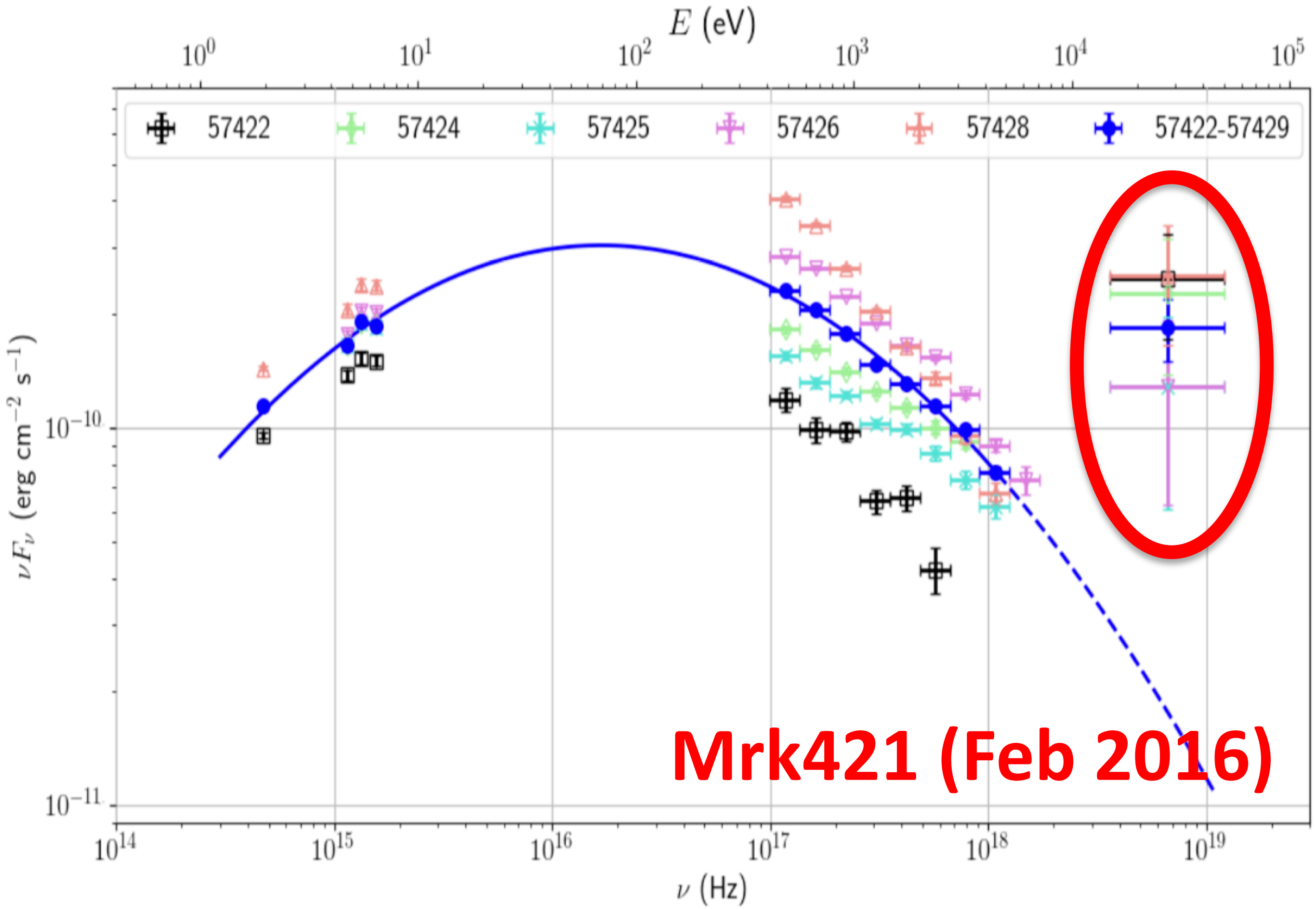
Model by Christoph Wendel

(for details, see Wendel et al A&A 2021, 646, 115)

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

Emission from narrow EED accelerated in Magnetospheric vacuum gap

Swift BAT excess in X-ray spectrum of Mrk421 in low state

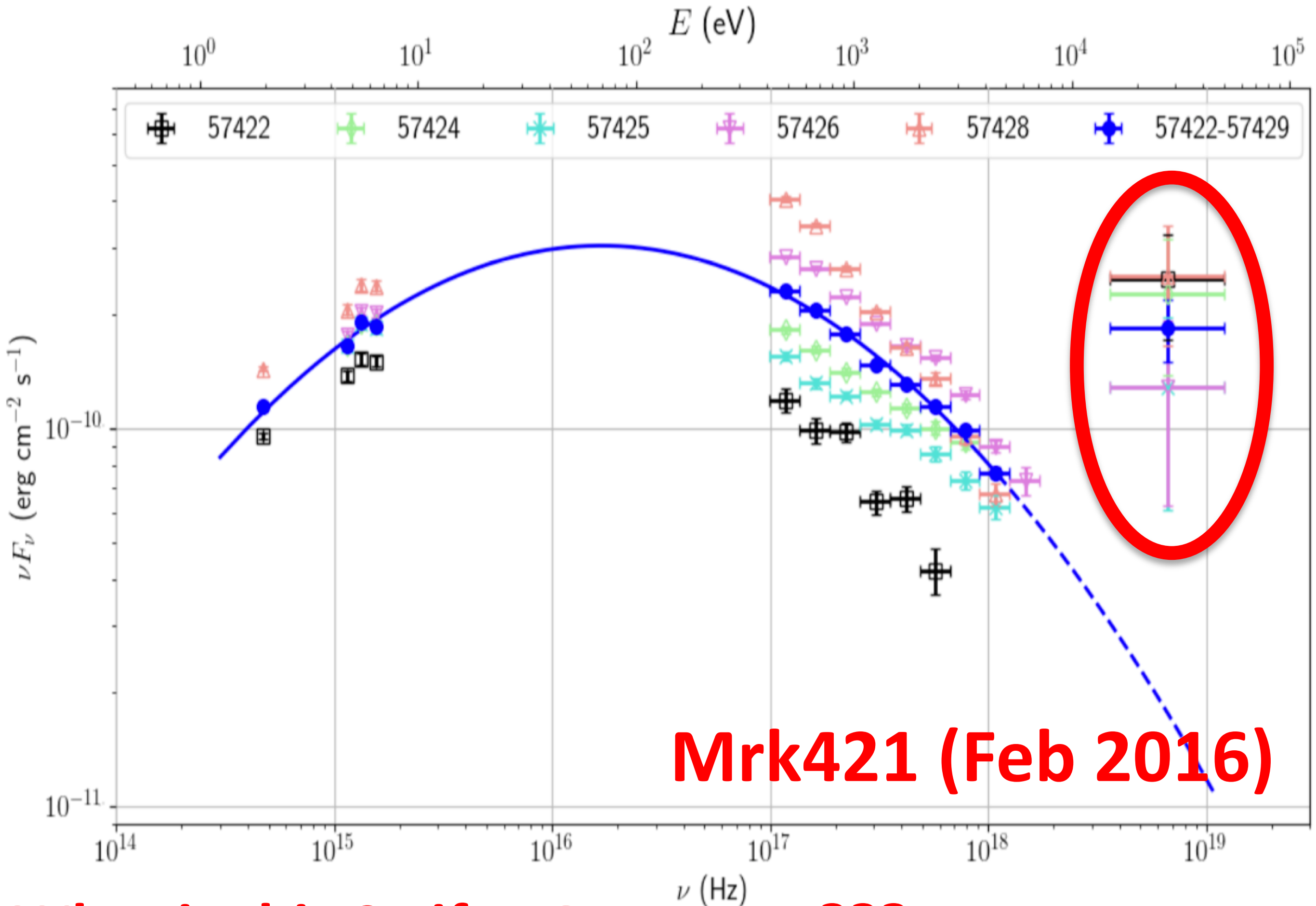


Acciari et al 2021, MNRAS 504, 1427

Single spectra (colors) during a 7-day time interval in 2016 Feb. 4—11

And also 7-day average spectra (blue)

Swift BAT excess in X-ray spectrum of Mrk421 in low state



Acciari et al 2021, MNRAS 504, 1427

Single spectra (colors) during a 7-day time interval in 2016 Feb. 4—11

And also 7-day average spectra (blue)

What is this Swift-BAT excess ???

<u>Onset of IC component</u> (*as suggested Kataoka&Stawrz 2016 using NuSTAR hint*) ?

OR

<u>Inverse-Compton produced by high-energy electrons from the spine</u> region up-scattering the synchrotron photons from the layer (*as proposed by Chen 2017*) ?

OR

<u>new narrow component</u>, as in Mrk501 in 2014 (*Acciari et al 2020, Wendel etal 2021)* ?

Conclusions

Accurate AGN studies require wide broadband (radio to gamma-rays) AND temporal (years down to minutes) coverage

→ *Variability in the multi-band emission can break degeneracies*

AGNs are complicated "cosmic animals"

This complexity can be hidden when the observations suffer from limited sensitivity, and limited **energy & time** coverage

→ Extensive MWL campaigns on Mrk421 & Mrk501 benefit from bright sources and high sensitive instruments, and wide energy coverage and dense time coverage

Conclusions

Multi-instrument data from Mrk421&Mrk501 show 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 (in 2012)

→ during non-flaring activity

Mrk501: hints of a narrow spectral feature at 3 TeV

Mrk421: hints of extra (narrow) component at 20 keV

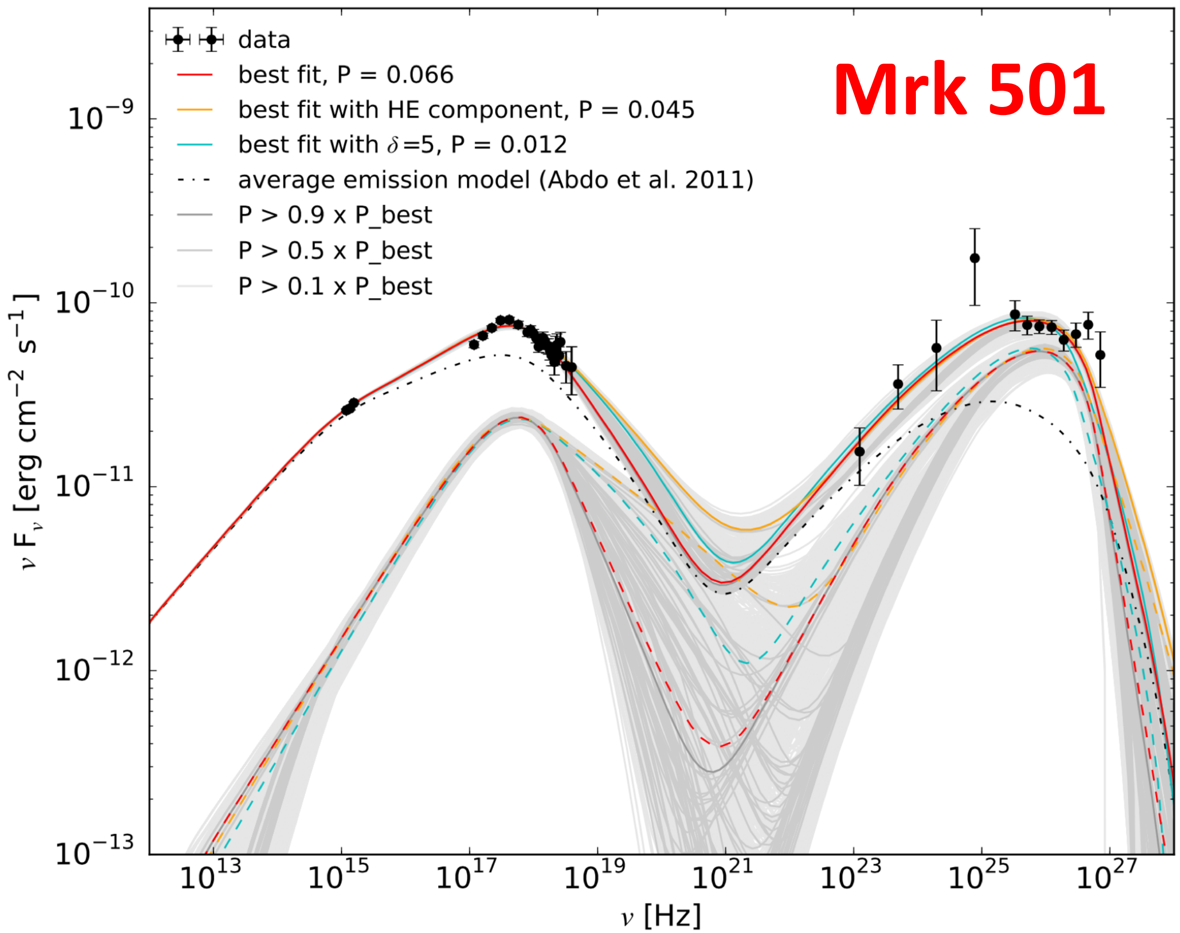
→ ***Are these recurrent episodes ? Occur on other blazars ?***

- Next generation of gamma-ray instruments, e.g., CTA, will allow to perform these studies on many other AGNs (*x10 dimmer at VHE*)

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.

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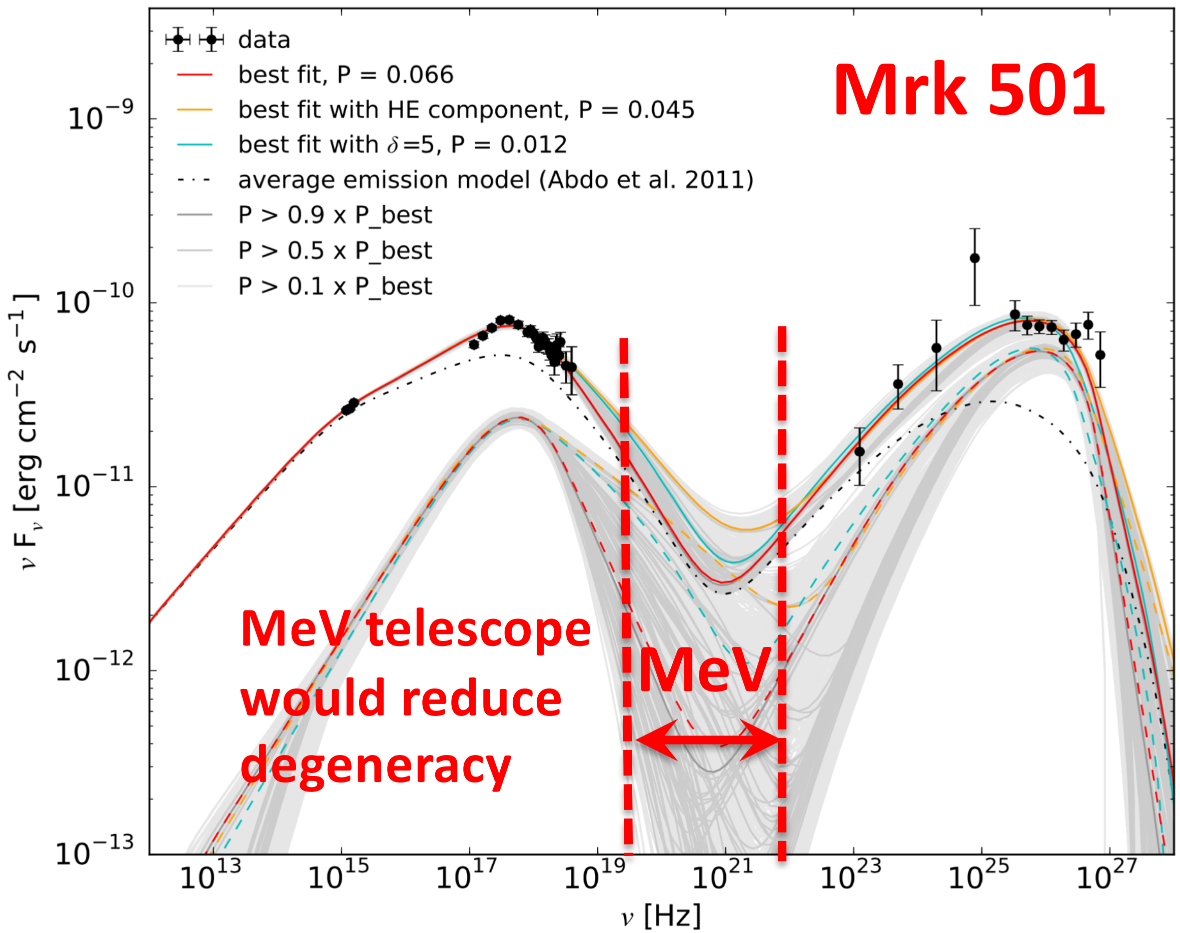


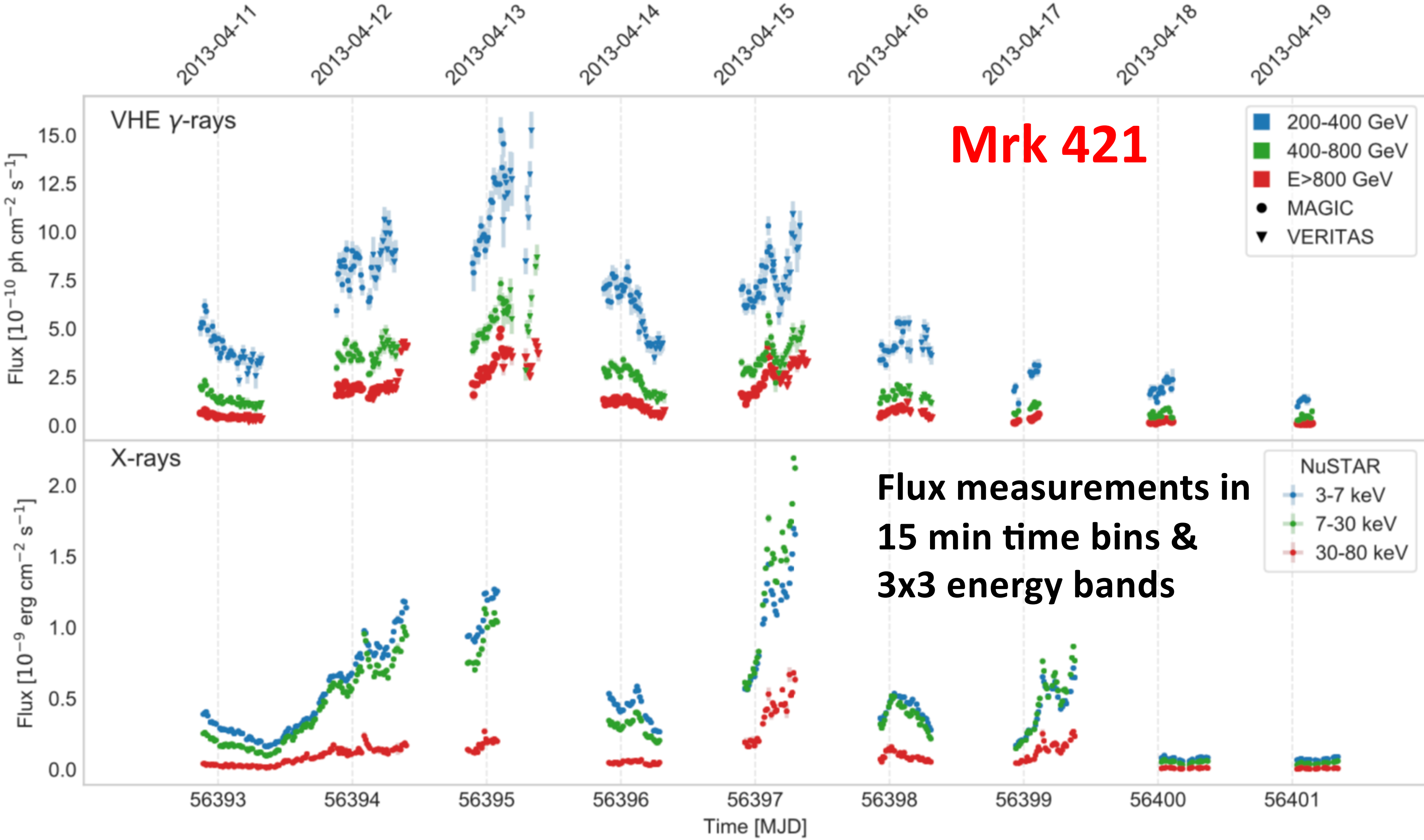
Ahnen et al 2017
***A&A* 603 , A31**

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.

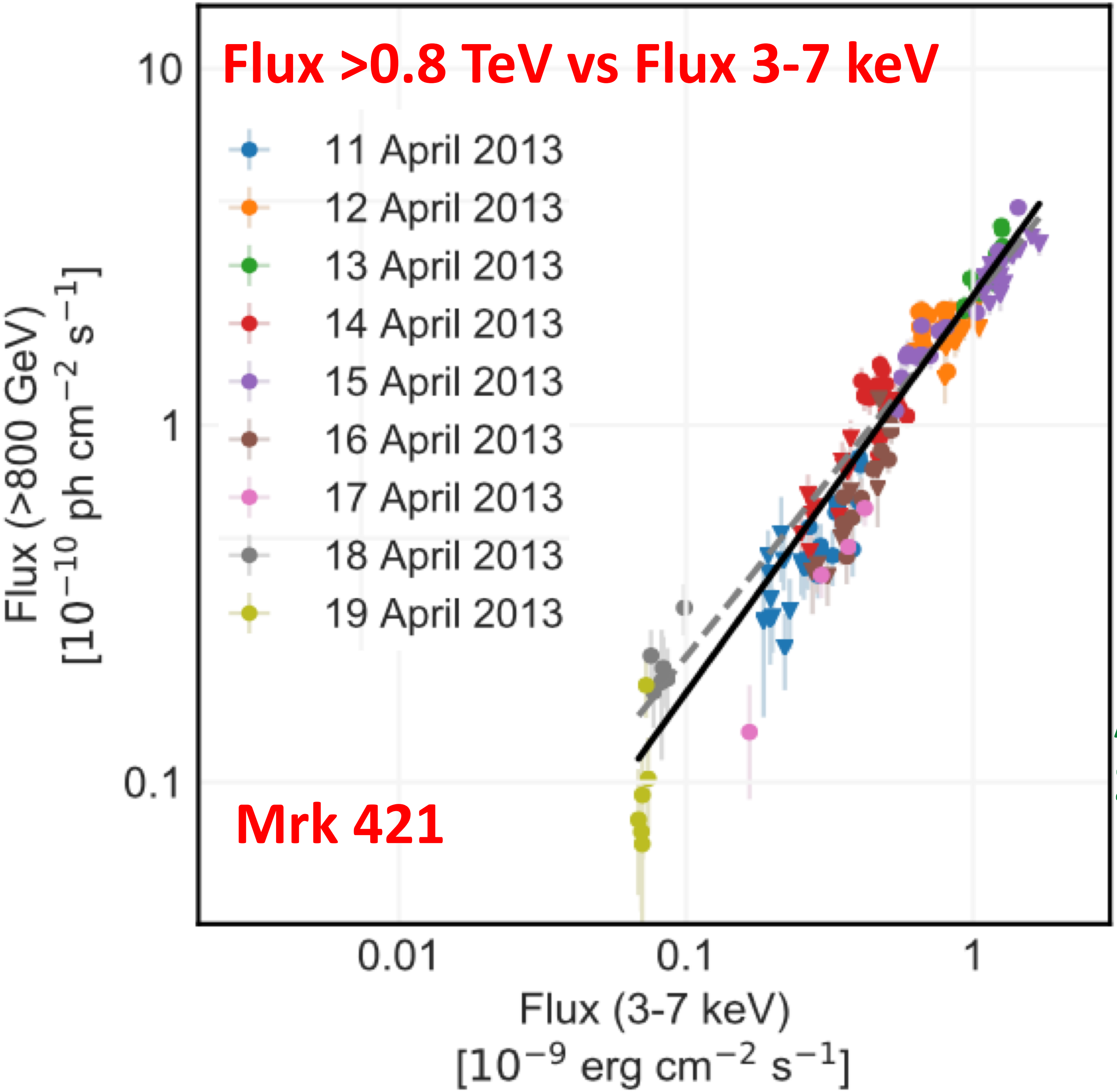
Full VHE and X-ray LCs for Mrk421 activity 2013 April

About 45 hours of strictly simultaneous VHE and hard X-ray data

Acciari et al. ApJS 2020, 248, 29



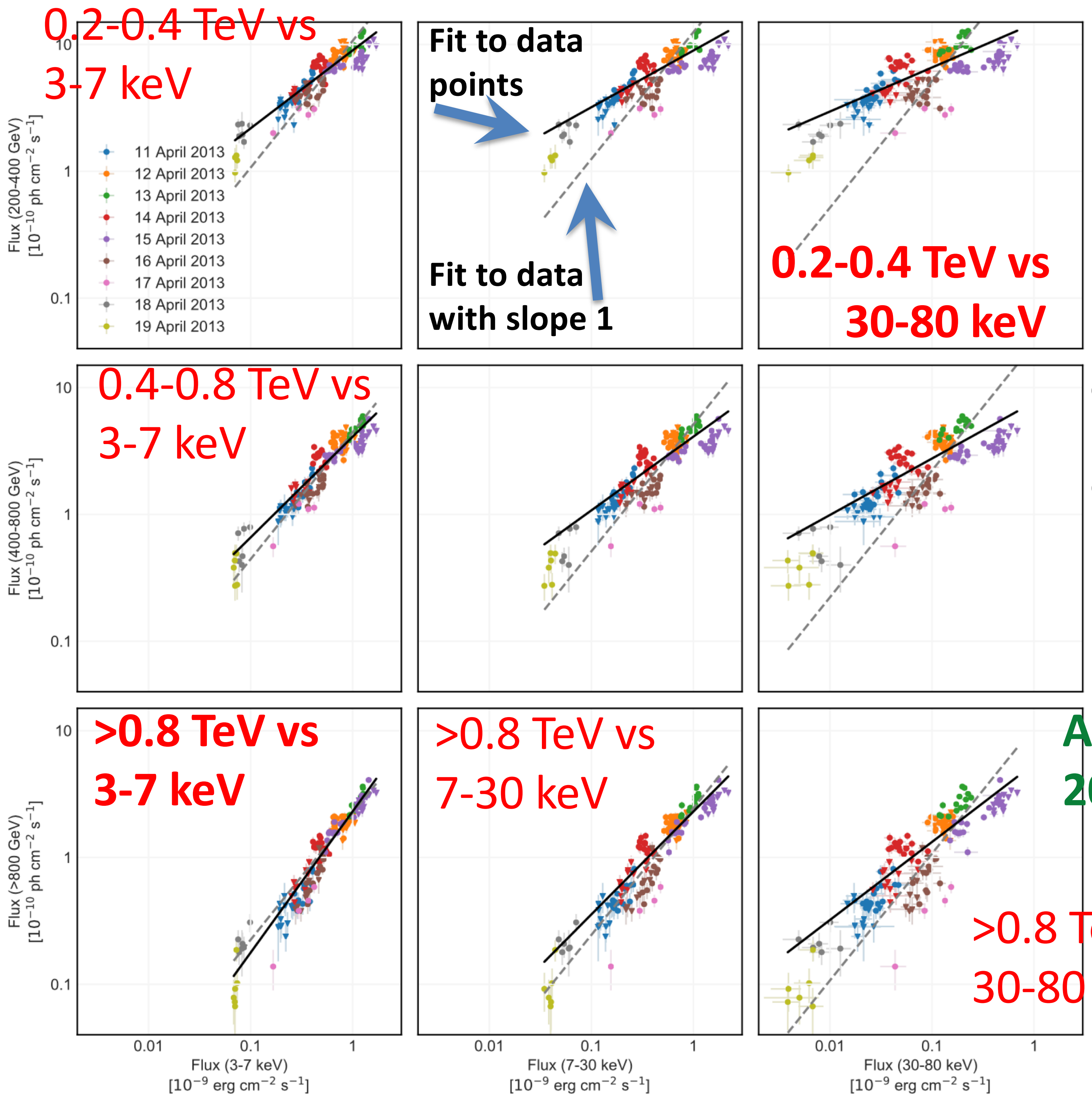
Flux measurements in 15 min time bins & 3x3 energy bands



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

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

Acciari et al. ApJS 2020, 248, 29

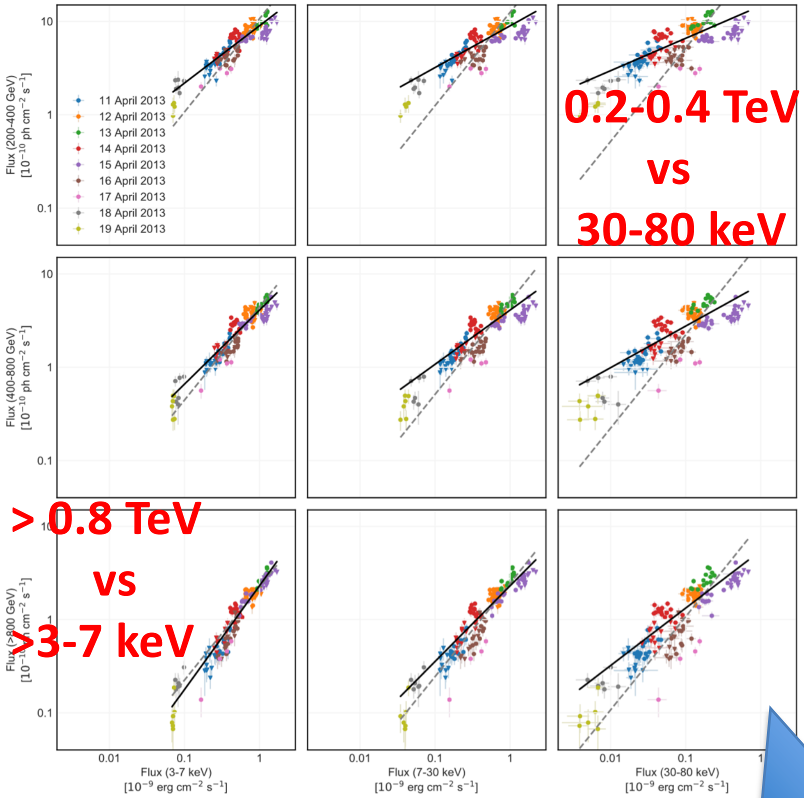


Gamma-ray vs X-ray flux (9-day “full” flare)

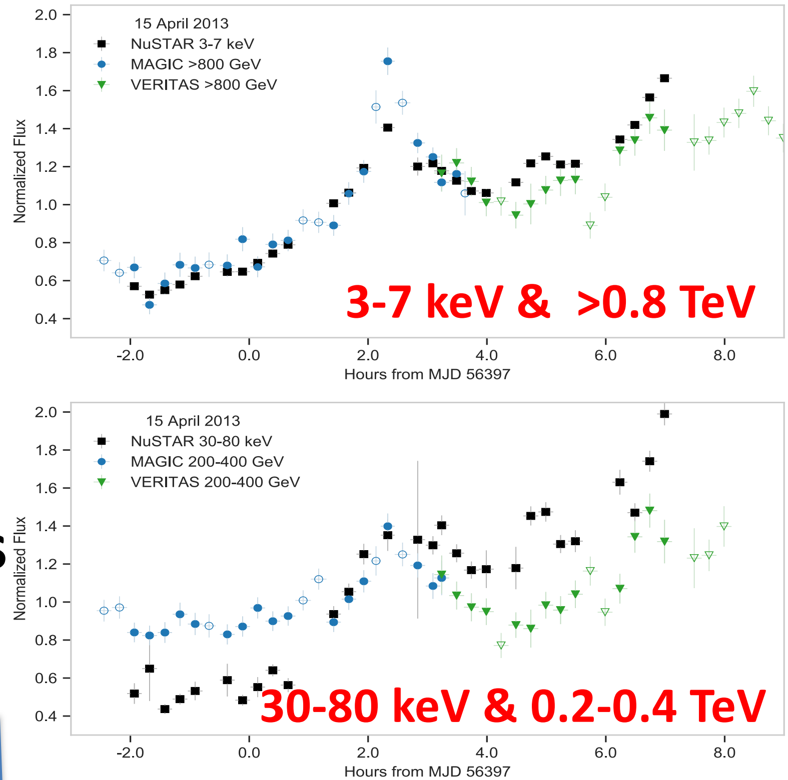
characterization in 3 (X-ray) x 3 (gamma) energy bands

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

Acciari et al. ApJS 2020, 248, 29



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



There is not such thing as a generic X-ray vs VHE correlation in a given AGN, it can have a strong energy dependence

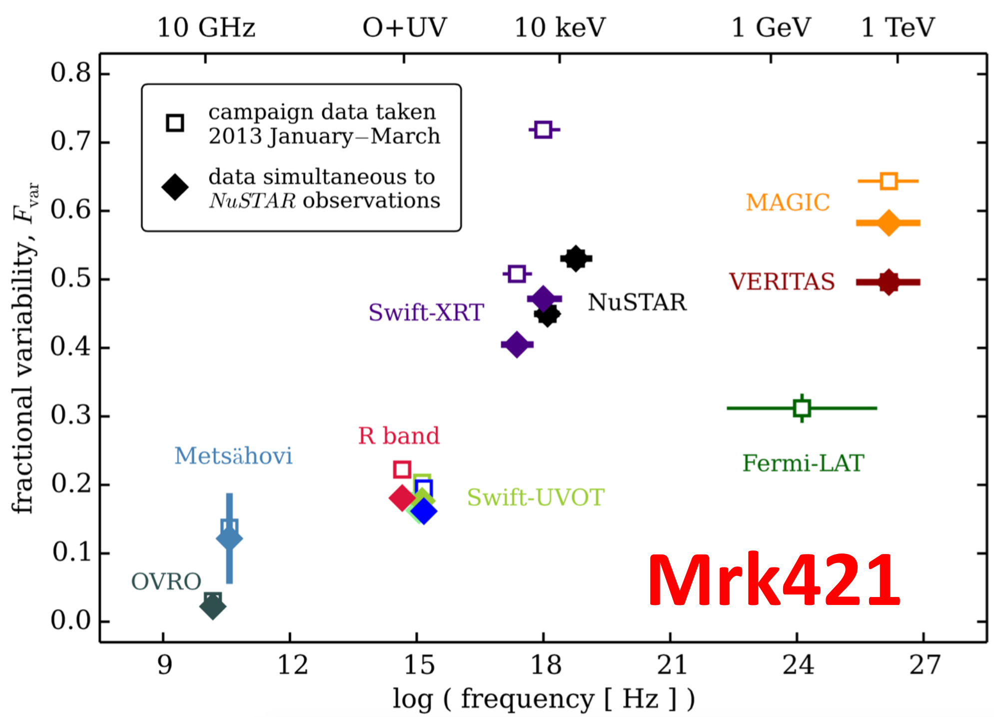
The variability in a given energy band, and its relation with the other bands, can strongly depend on the probed timescale (sub-hours, hours, days, months)

Dynamics in AGN broadband emission is very complex

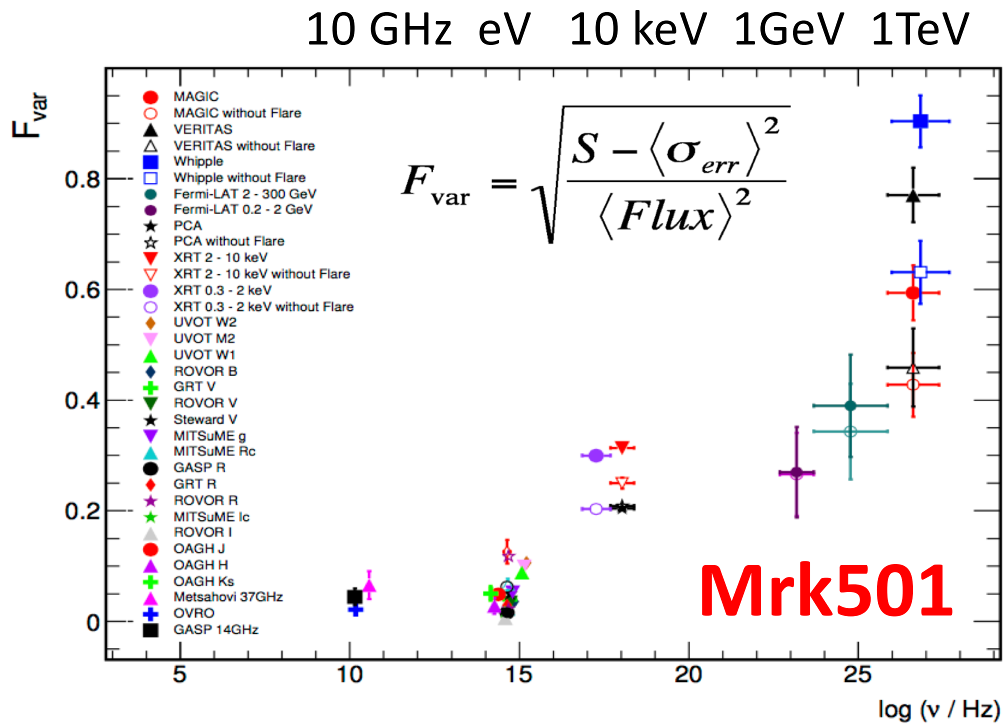
→ Important to cover many energy bands and timescales

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)**

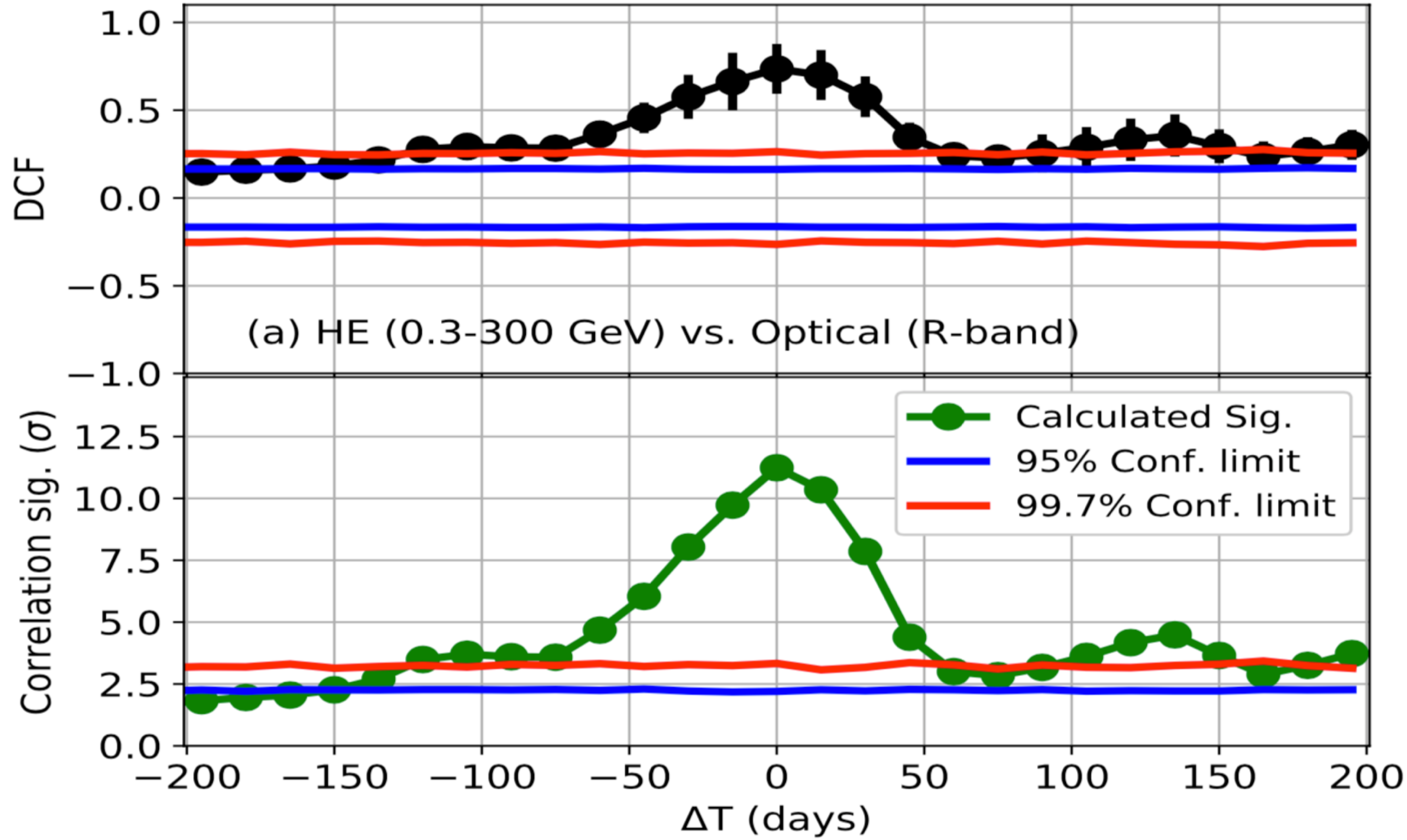
Fvar (**Mrk501**): general increase with energy, **Fvar(X-rays) < Fvar(VHE)**

Fundamental difference in variability of these two "sister sources"

GeV-optical correlation in Mrk421 (2007-2016)

Clear correlation between HE and optical over a wide range of time-lags of about 60 days, and centered at a time-lag of zero

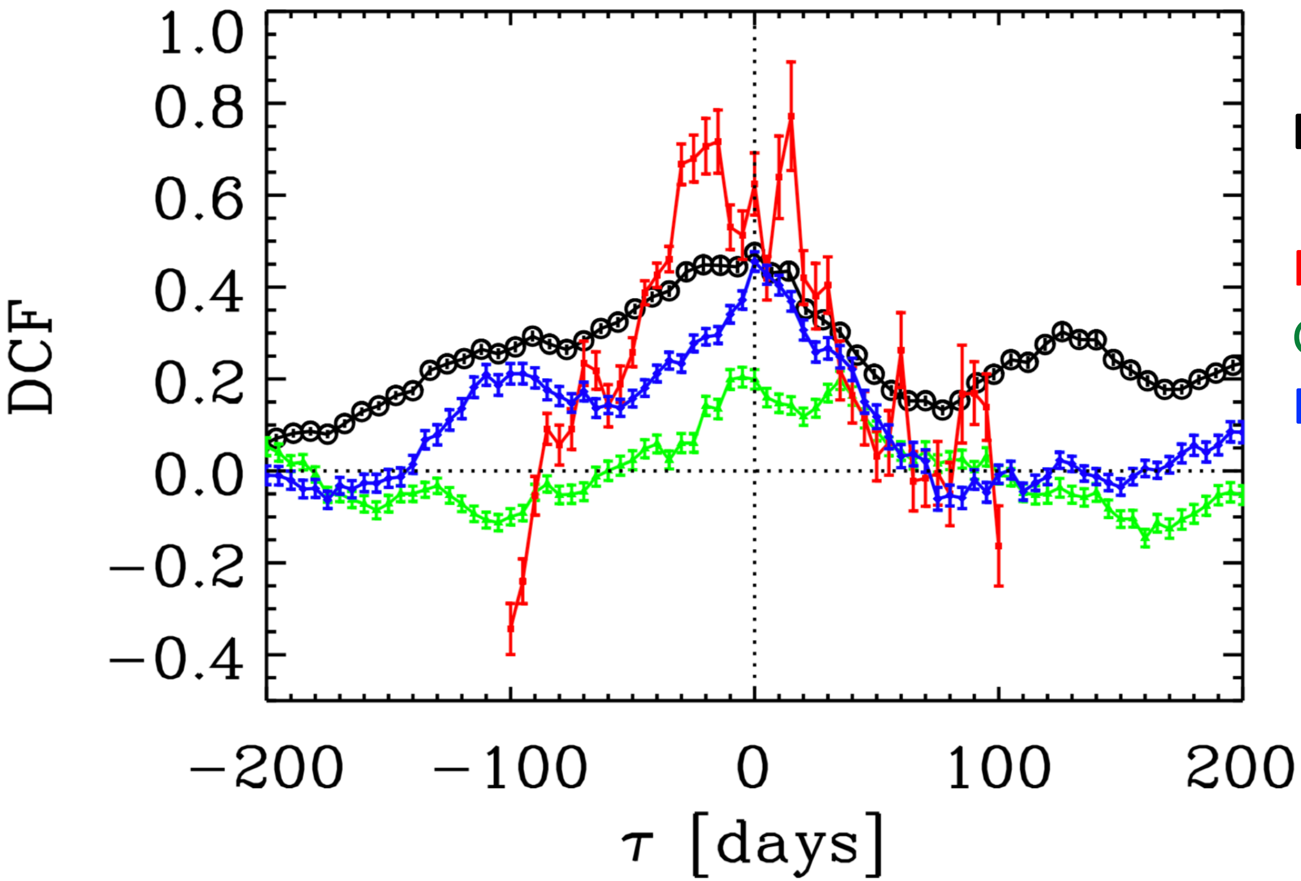
Acciari et al 2020, MNRAS in press (arXiv:2012.01348)



GeV-optical correlation in Mrk421 (2007-2016)

HE-optical correlation over a large range of time-lags was also reported in another long-term (**2007-2015**) Mrk421 study, that also used 15 days time bins

Carnerero et al. 2017, MNRAS, 472, 3789



Black- All data

Red – Around Flare 2012

Green – Before Flare 2012

Blue – After flare 2012

Radio-GeV correlation in Mrk421 (2007-2016)

Correlated behaviour with a time lag of ~45 days (Radio lags) reported by:

Max-Moerbeck et al 2014, MNRAS 445, 428

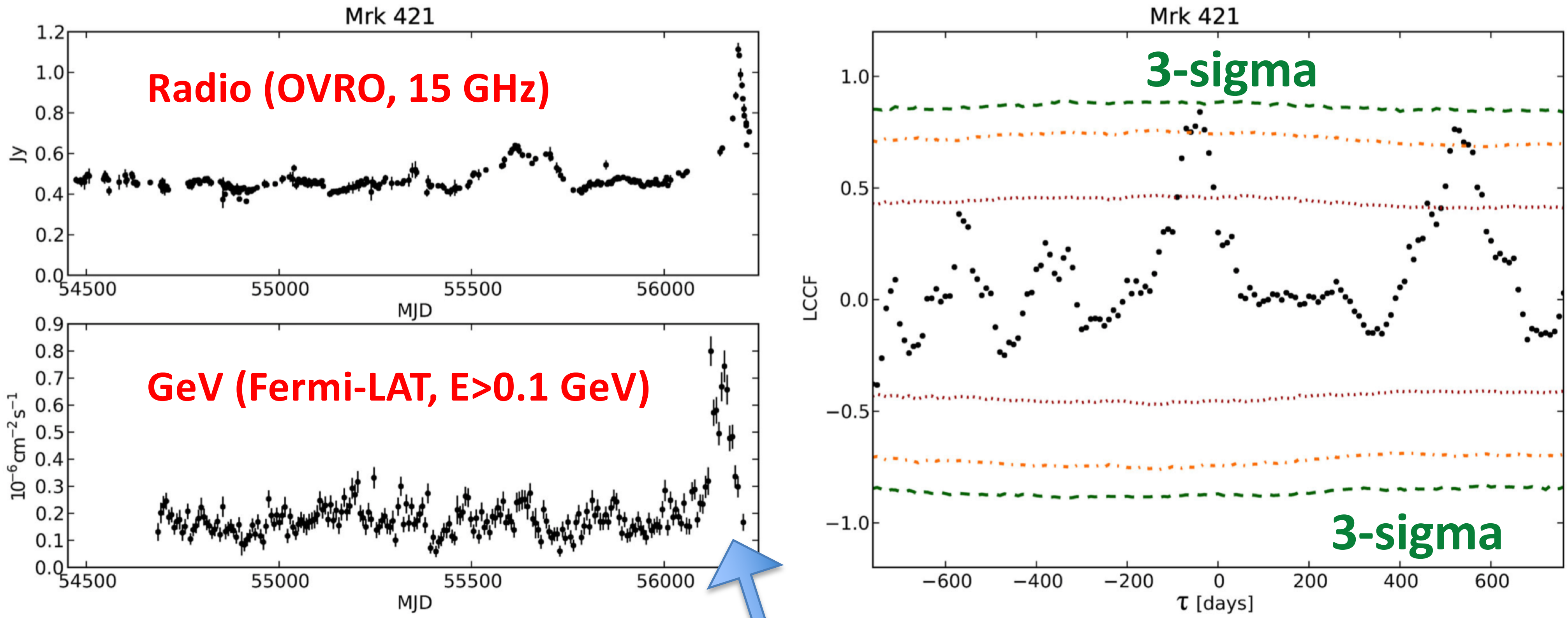


Figure 2. Light curves (left) and cross-correlation (right) for Mrk 421. The most significant peak is at −40 ± 9 d with 98.96 per cent significance. Colours and line styles as in Fig. 1.

40 +/- 9 days

Back then, the correlated behaviour was marginally signifincant (~3 sigma) and strongly dominated by the large flare in 2012

Function used to parameterize the main trends in the multi-hour X-ray& VHE Light curves

$$\mathrm{Flux}(t) = \mathrm{Slow}(t) + \mathrm{Fast}(t)$$

$$\mathrm{Slow}(t) = \mathrm{Offset}(1 + \mathrm{Slope} * t)$$

$$\mathrm{Fast}(t) = \frac{2}{2^{-\frac{t-t_0}{rise}} + 2^{\frac{t-t_0}{fall}}} \times (\mathrm{Flare\ Amplitude}) \times (\mathrm{Slow}(t_0))$$

Parameters:

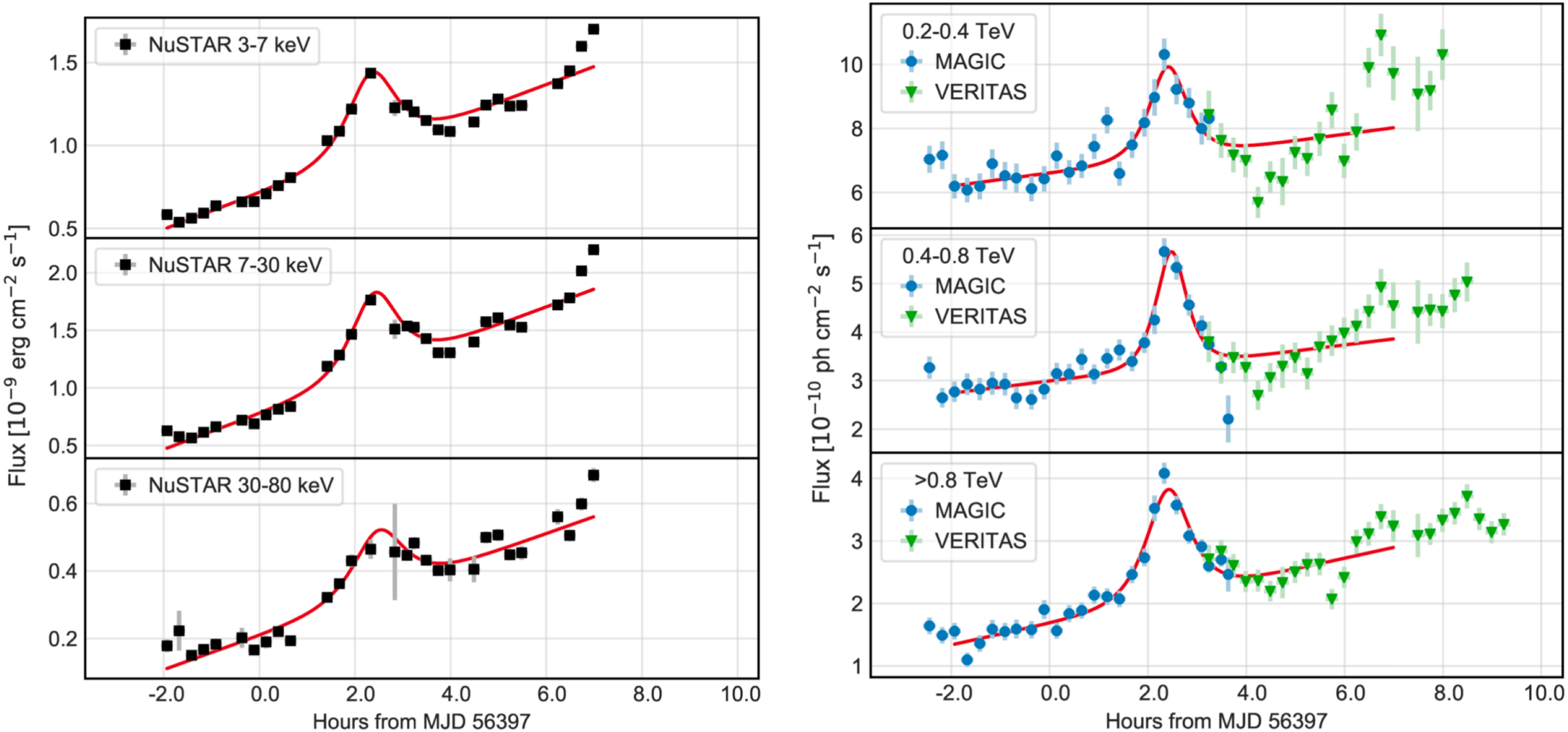
Simplification: rise=fall → timescale

- offset = starting flux
- amplitude = max. strength of the flare relative to slow(t0) flux
- timescale = flux doubling time scale
- slope = (slow component) flux would increase by this factor in 1 day

This parameterization provides normalized slopes and amplitudes, which allows for a direct comparison of the values among different various X-ray and VHE bands

X-ray and VHE Light curves for single night (April 15th)

Acciari et al. ApJS 2020, 248, 29



The red curve shows a fit with a two-component function, applied to the time interval with simultaneous X-ray and VHE observations

→ Close relation between X-ray and gamma-rays → Leptons !!

→ But *complex X-ray vs VHE variability and correlation pattern*

Acciari et al. ApJS 2020, 248, 29

Table 3. Parameters resulting from the fit with Eq. 3 to the X-ray and VHE multi-band light curves from 2013 April 15.

Band	$Offset^{a}$	$Slope$ $[h^{-1}]$	Flare Amplitude A	Flare flux-doubling time[b] [h]	Flare t_0 [h]	χ^2/d.o.f
15 April 2013						
3-7 keV	0.71 ± 0.01	0.153 ± 0.006	0.49 ± 0.07	0.30 ± 0.04	2.35 ± 0.06	836/24
7-30 keV	0.78 ± 0.02	0.199 ± 0.009	0.59 ± 0.11	0.30 ± 0.04	2.41 ± 0.06	889/24
30-80 keV	0.21 ± 0.01	0.241 ± 0.018	0.56 ± 0.18	0.32 ± 0.09	2.50 ± 0.10	111/24
0.2-0.4 TeV	6.60 ± 0.17	0.031 ± 0.008	0.40 ± 0.09	0.23 ± 0.07	2.41 ± 0.09	96.9/38
0.4-0.8 TeV	2.99 ± 0.07	0.042 ± 0.008	0.72 ± 0.09	0.19 ± 0.03	2.47 ± 0.04	68.1/42
>0.8 TeV	1.68 ± 0.05	0.103 ± 0.010	0.82 ± 0.08	0.27 ± 0.03	2.41 ± 0.04	90.0/45

[a] For VHE bands in 10^{-10} ph cm^{-2} s^{-1}, for X-ray bands in 10^{-9} erg cm^{-2} s^{-1}.

[b] Parameters $t_{\rm rise}$ and $t_{\rm fall}$ in Eq. 3 are set to be equal, and correspond to the Flare flux-doubling time in the Table.

Large energy-dependence difference between the slow and the fast components

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.

Acciari et al. ApJS 2020, 248, 29

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

Gamma-ray vs X-ray flux-flux plot (April 15th)

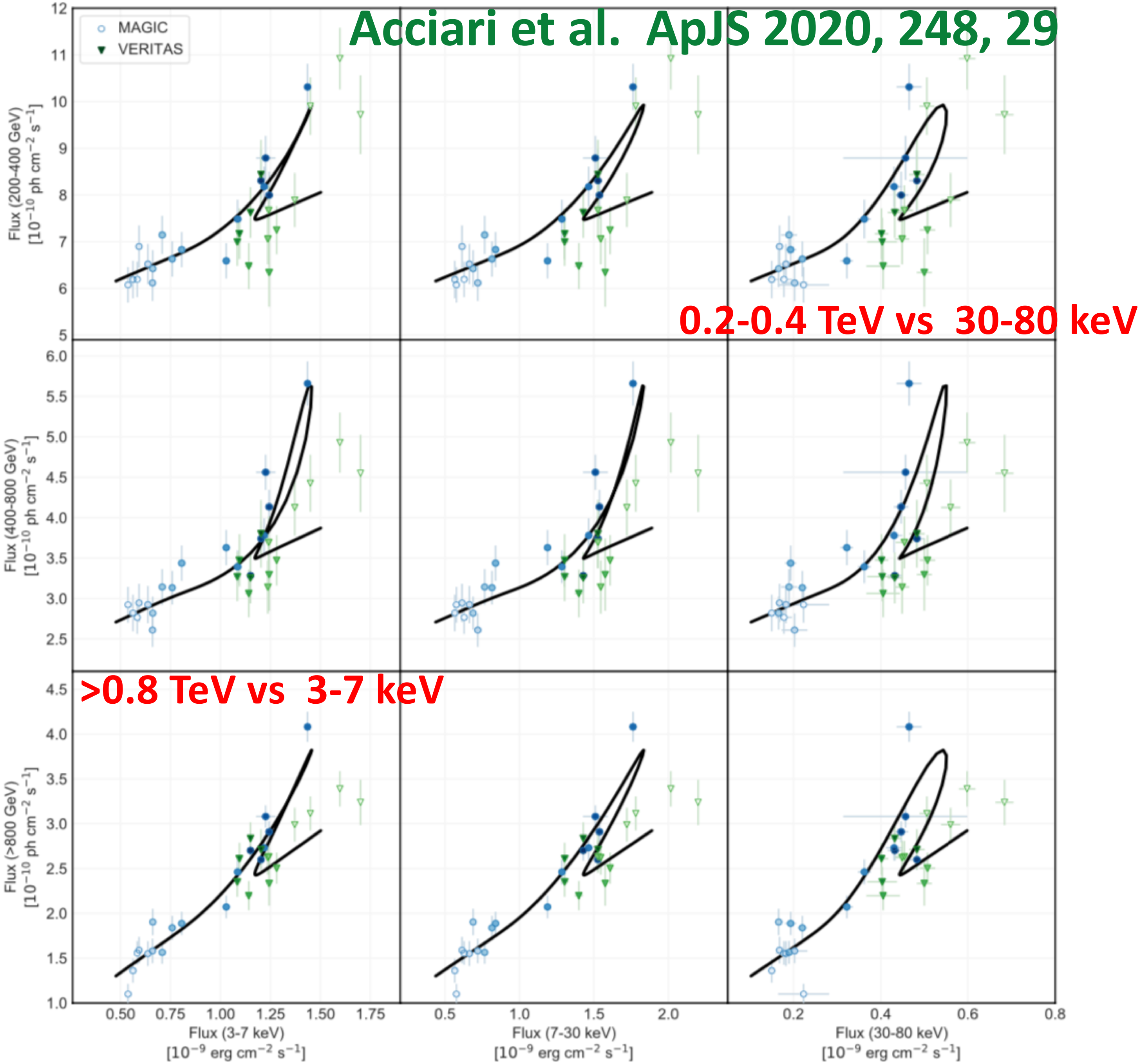

Figure 7. VHE flux vs. X-ray flux in three X-ray and three VHE energy bands for April 15. The black line is the track predicted by Slow+Fast component fit from Eq. 2. The lightness of symbols follows time: for MAGIC data lightness decreases with time, and for VERITAS data it increases in time, so that the central part of the night, where MAGIC and VERITAS observations overlap, is plot using darker symbols.

Curves depict the expectation from the envelopes from the fit function (slow+fast) to the light curve at the 3x3 energy bands

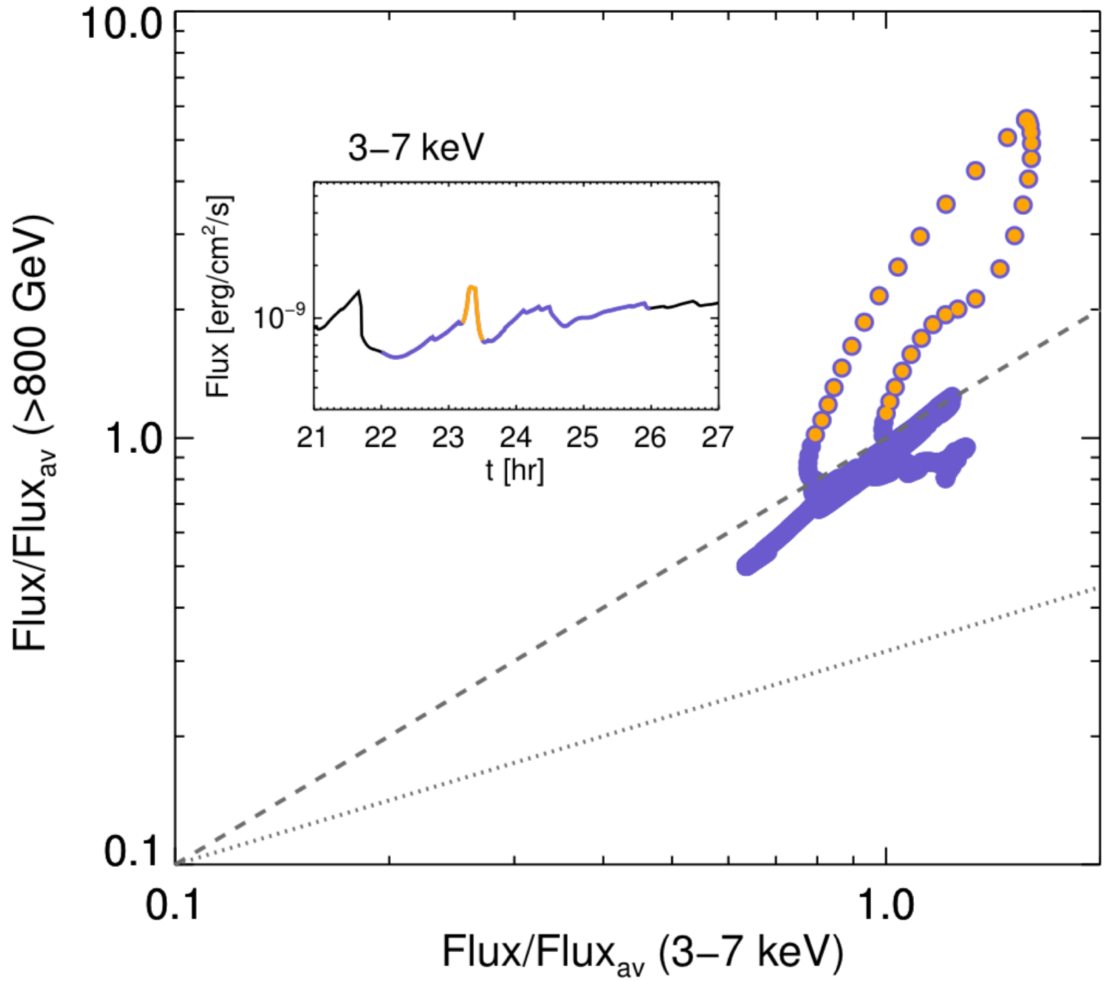

Figure 9. VHE flux (> 800 GeV) versus X-ray flux (3–7 keV) of a plasmoid-powered light curve, computed for a "vanilla" model of a BL Lac source (see model BL10 in Christie et al. 2019). The fluxes are extracted from a 4-hr time window of the total light curve (see purple line in the inset plot) and are normalized to their time-averaged values. The loop-like structure in the flux-flux plot is produced during a fast flare of duration ∼ 0.3 hr (see orange points). Lines with slopes 1 (dashed) and 0.5 (dotted) are overplotted to guide the eye.

Flux-flux plot for a portion of a LC produced by plasmoids (**simulation**)

The loop is produced by a fast flare, dominated by a single plasmoid
Similar shape to that found in the data