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

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on behalf of the *Fermi*-LAT, MAGIC, VERITAS collaborations
GASP-WEBT, F-GAMMA, and many participants

Outline

- Introduction: the challenge of studying blazars
- Extensive MW campaigns on Mrk421 and Mrk501
- Some highlighted results
- Conclusions

The challenge of studying Blazars

Why do we need to study blazars (→ AGNs and jets) ?

Although widely studied during many decades at different frequencies (from low-frequency radio up to very high γ-ray photon energies) they are still superficially understood objects.

Many key questions regarding extragalactic jets remain open:

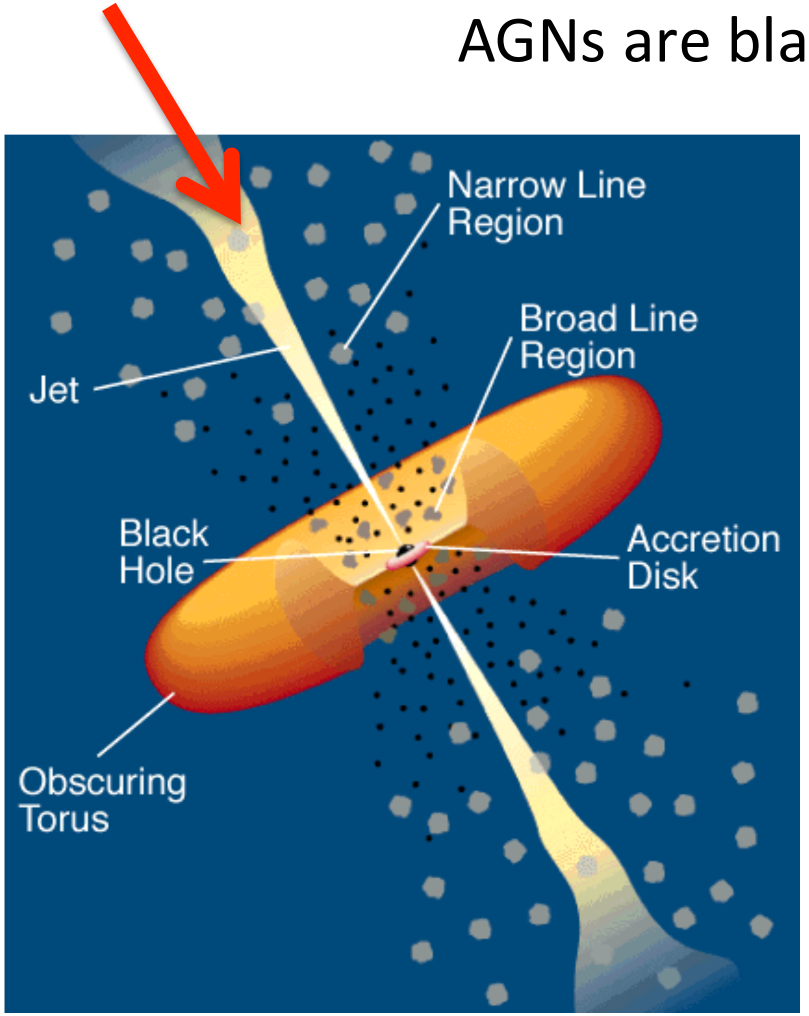
- Jet launching *(rotating SMBHs vs accretion disks)*
- Jet magnetic field *(how strong? what is its structure?)*
- Jet evolution and energetics *(kinetic power, lifetimes, "feedback")*
- Particle acceleration *(shocks? turbulence? reconnection?)*
- Location of high-energy emission
- What produces variability on various timescales
  (years down to minutes)

All these topics being discussed in this conference…

… and it seems that there is progress on all those …

Blazars are those radio loud AGNs with the jet pointing towards the Earth

Emission is doppler boosted.
Most known gamma-ray AGNs are blazars



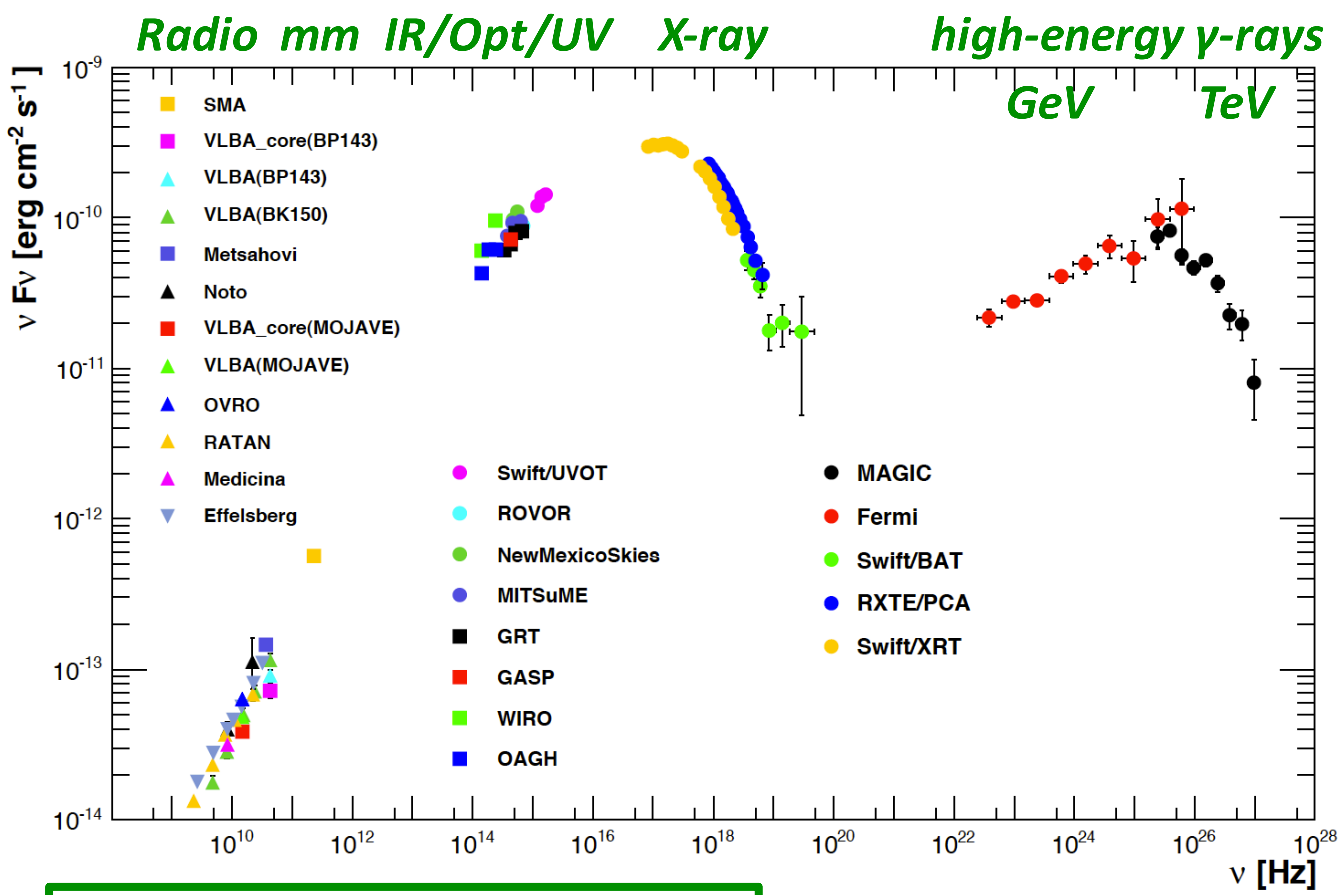
It is VERY CHALLENGING to study blazars

From <u>observational perspective</u>, there are two major practical challenges

a) Blazars emit over a very wide energy range (from radio to very high energy gamma-rays)

Emission in different energy bands could be produced by same population of particles

→ *Need many instruments (covering many bands) to fully study these objects*



Spectral energy distribution (SED) of the Blazar Markarian 421

This SED is one of the plots that has been shown most times in this conference…

Abdo et al 2011, ApJ 736, 131

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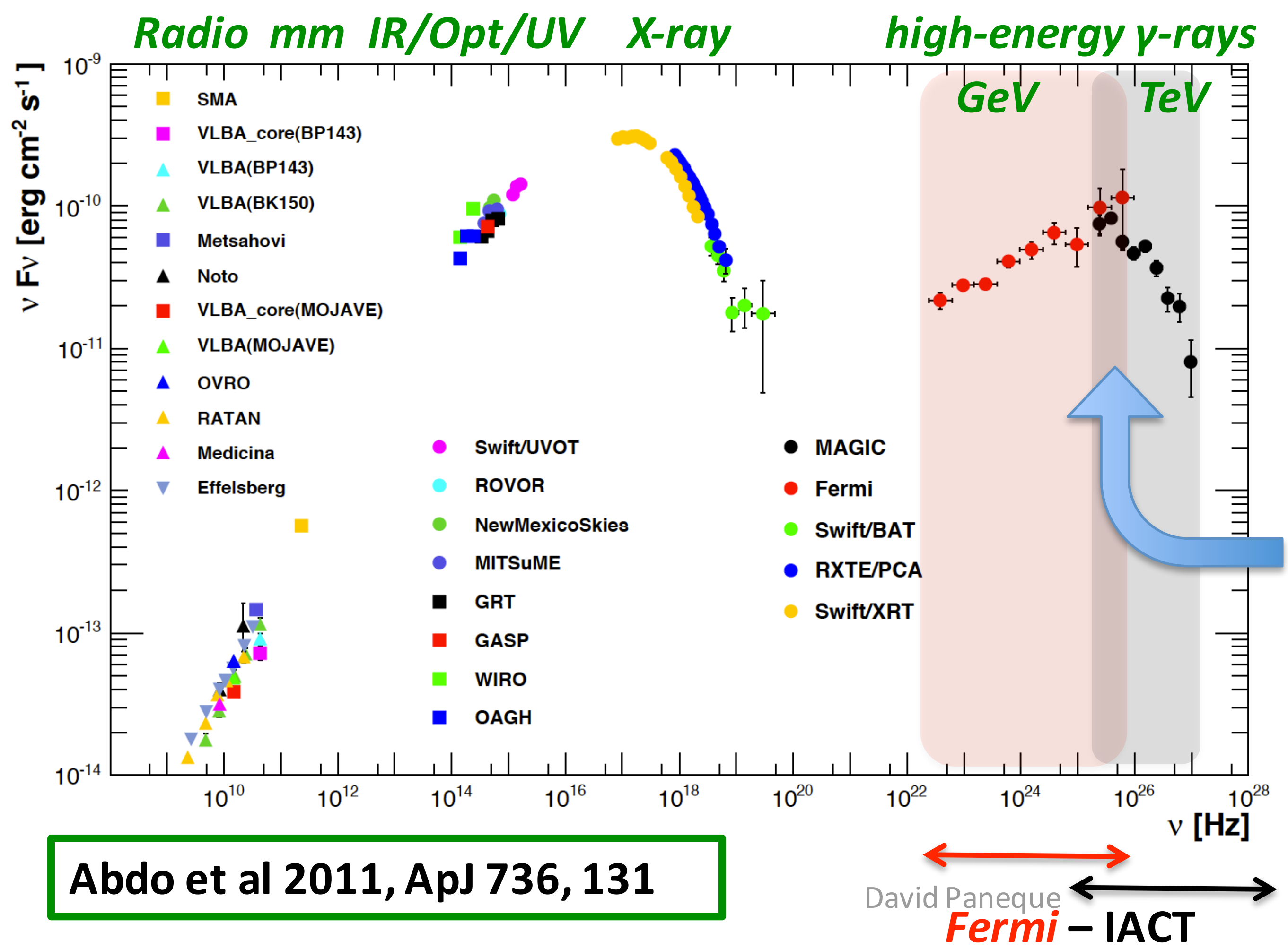

Abdo et al 2011, ApJ 736, 131

Spectral energy distribution (SED) of the Blazar Markarian 421

Gamma-ray bump could only be measured recently, with *Fermi*-LAT + modern IACTs like HESS/MAGIC/VERITAS

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

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

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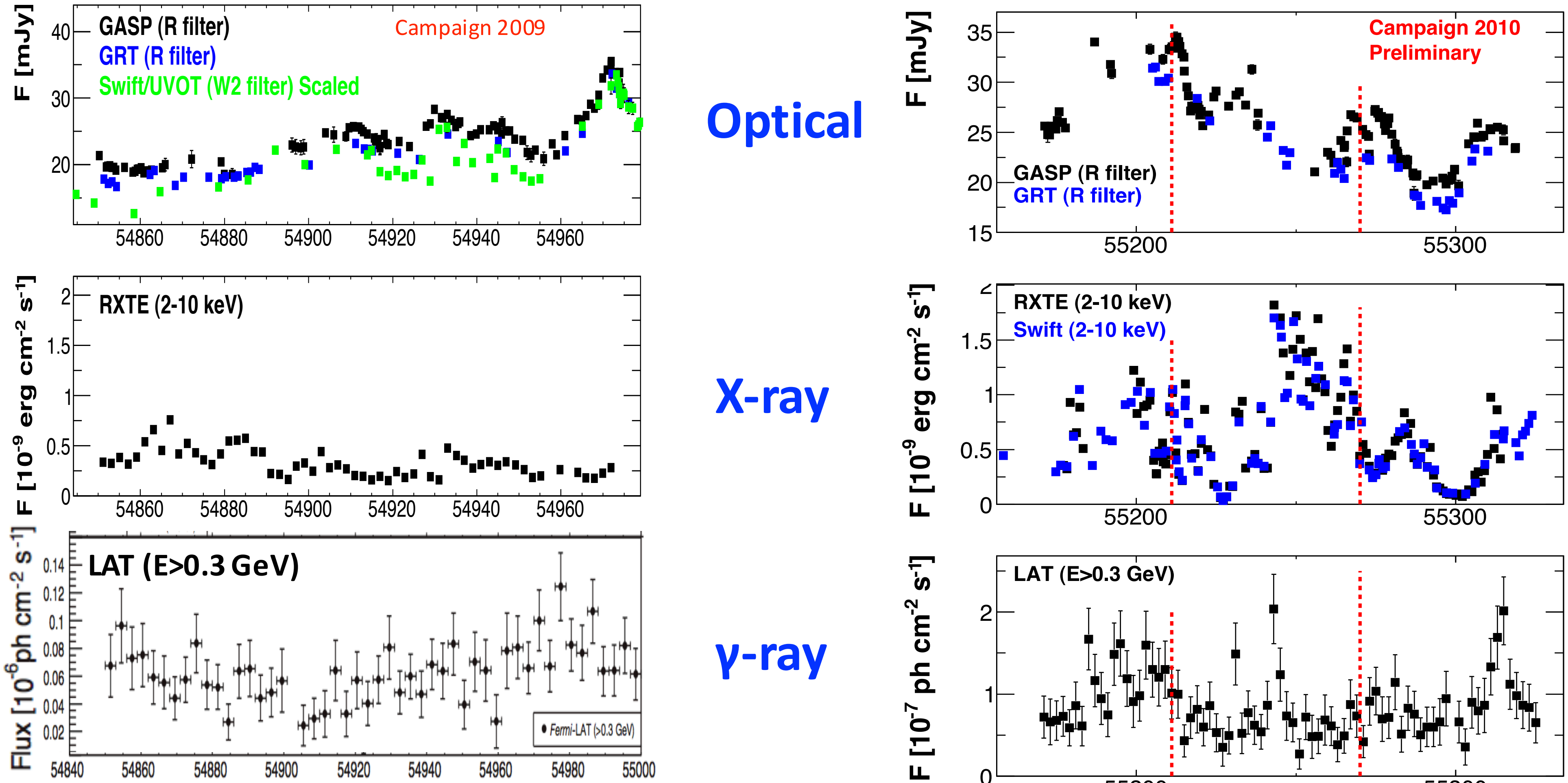
Mrk421 showed very distinct behavior in the 2009 and 2010 campaigns



It is VERY CHALLENGING to study blazars

From <u>observational perspective</u>, there are two major practical challenges

b) Blazar emission is variable on very different timescales (from years down to minutes)

Variability connected to acceleration/radiation processes

→ *The instruments need to observe simultaneously OFTEN and during LONG BASELINES*

See also talks this morning: Jorstad, Agudo, Larionov…

This observational challenge related to the short/long variability brings something positive:

→ Blazar variability can be used to break degeneracies between emission models

→ Important because models have many parameters (quite some freedom) to adjust to the data, and often a single SED is not sufficient to be able to distinguish between them

Non-thermal Emission Processes in AGN Jets: Leptons

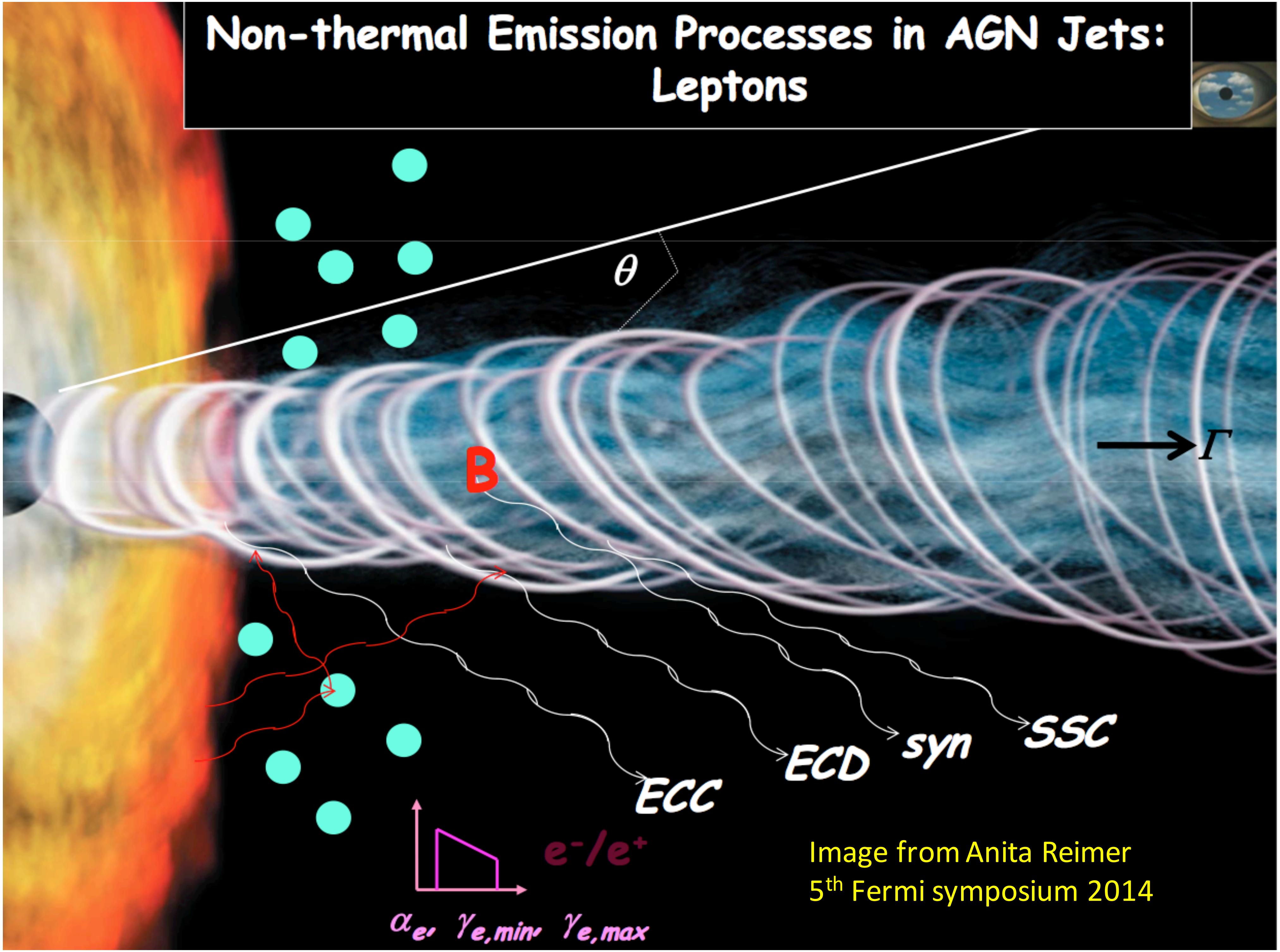
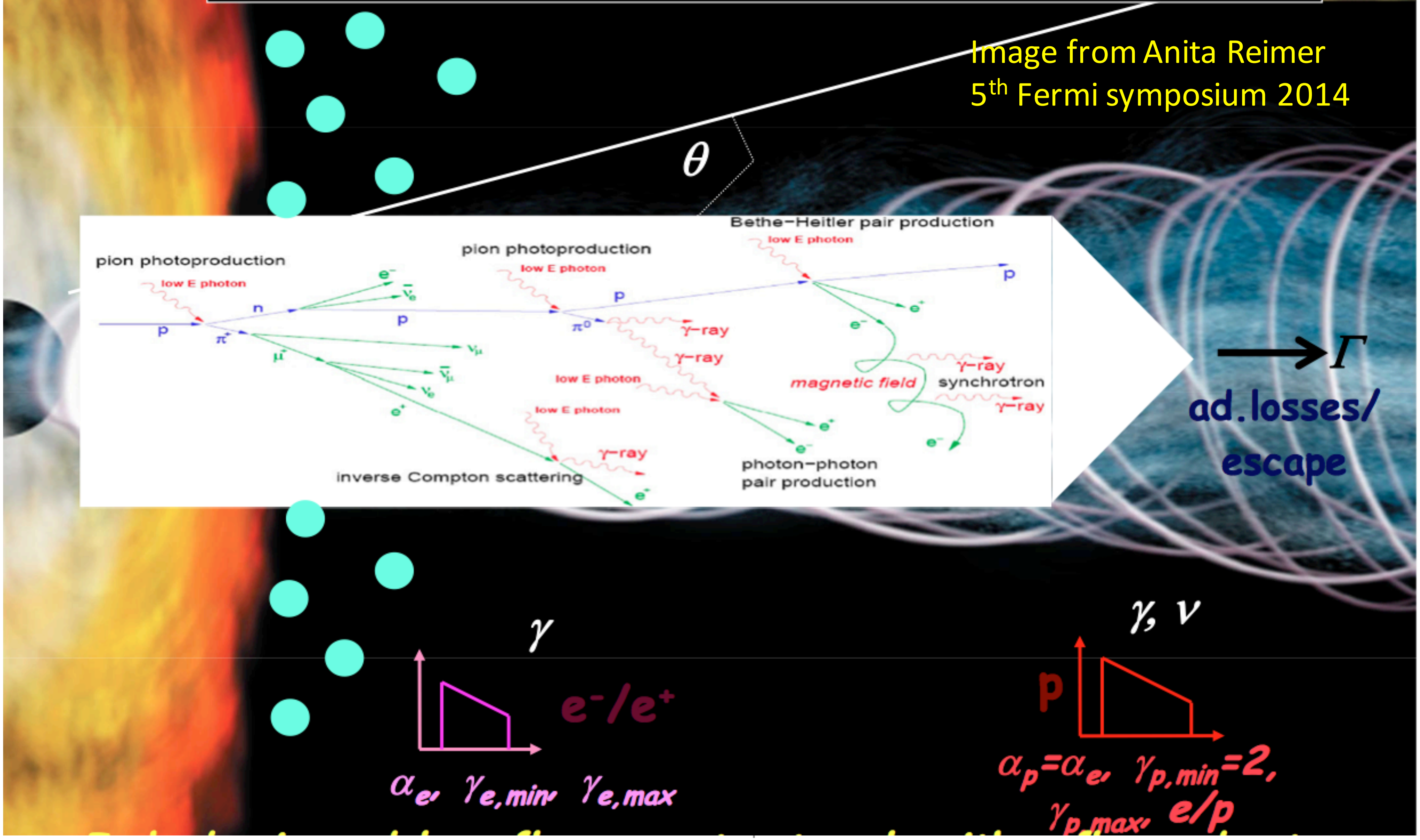


Image from Anita Reimer
5th Fermi symposium 2014

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



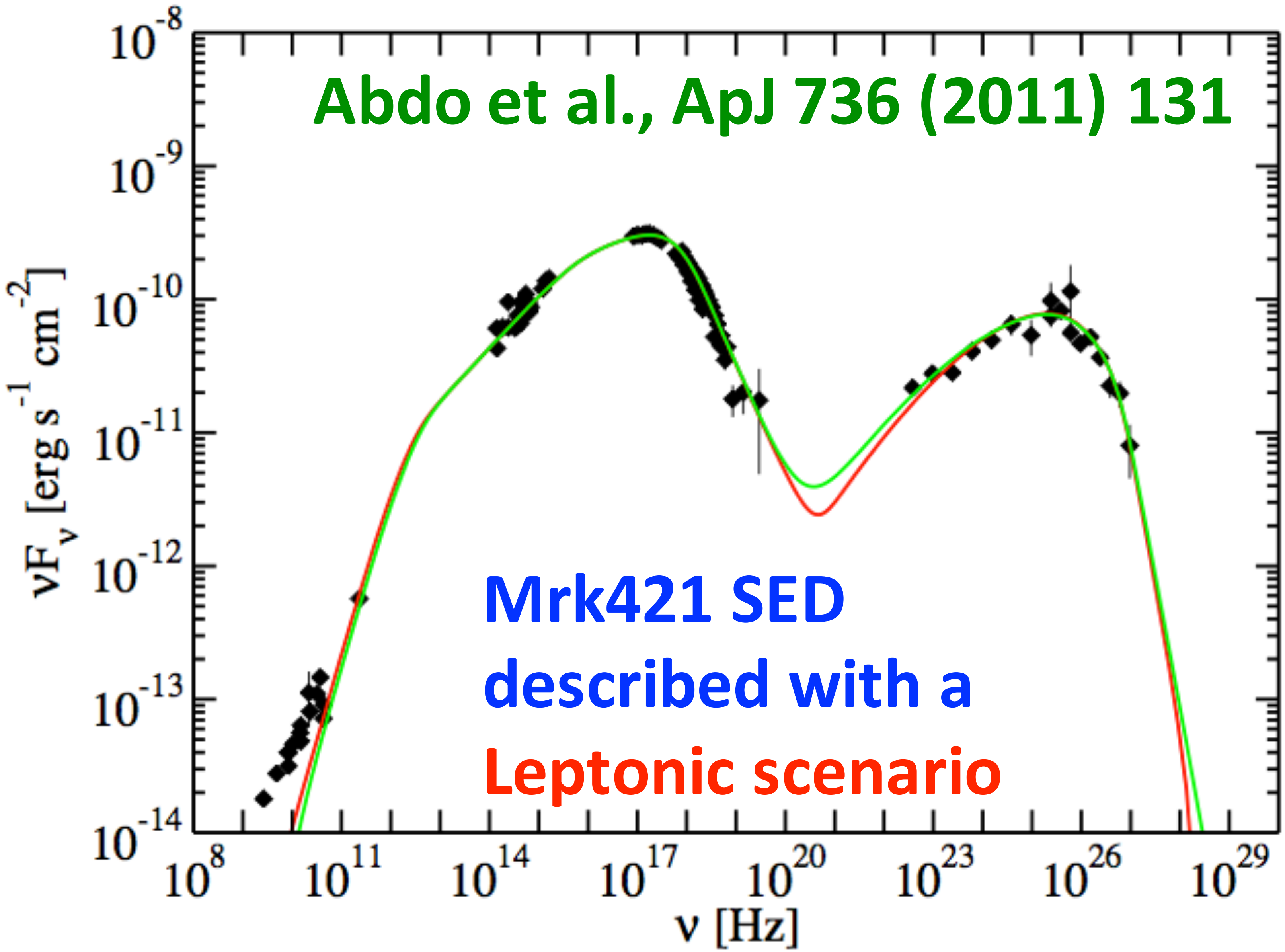


Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{var} = 1$ day (red curve) and $t_{var} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

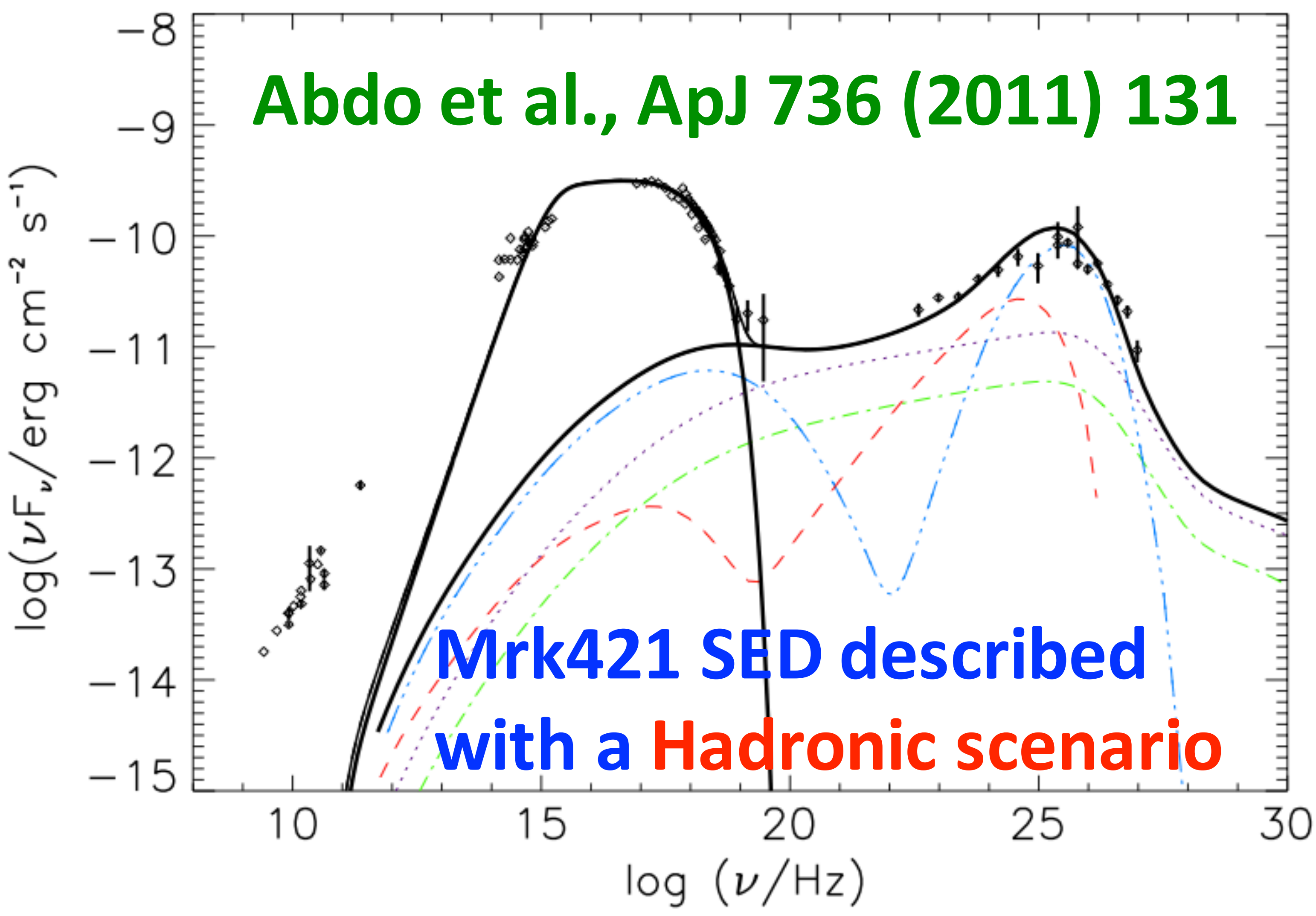


Figure 9. Hadronic model fit components: π^0-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), μ-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which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

It is VERY CHALLENGING to study blazars

From <u>observational perspective</u>, 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)

Studying blazars accurately requires excellent broadband (radio to gamma-rays) AND temporal (minutes to years) coverage

a+b

→Requirement for MW campaigns lasting many years

→ Not possible to do for many objects

→Which objects should we study ?

→ Many interesting objects (of different kind)

Extensive MW Campaigns on Mrk421 and Mrk501

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 <0.1 pc (<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

Mrk421 and Mrk501 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, 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 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

First MW campaigns with NuSTAR *See talk by A. Furniss*

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-July ,2015: 4 months)- Planned observations: every 4 days

Long term goals

The <u>practical goal</u> is to build a very complete pool of MW data that allows us to make detailed studies on the observables we have:

- Quantify the overall (entire SED) flux variability and correlations during long baseline

- Correlate with VLBA images and polarization measurements
  → VLBA can spatially resolve ~1.e16 cm for Mrk421/Mrk501
    → because these blazars are nearby !!
- Put strong experimental constrains on the currently used emission models
  → *Time dependent SED modeling !!*

The <u>ultimate goal</u> is to address fundamental questions on how Mrk421 and Mrk501 (and perhaps HBLs in general) work:

- Nature of the radiating particles (specially for the high-energy emission)
- Location of the blazar emission
- Acceleration and radiation processes
- How flux variations are being produced; what changes in the source
- NEED to connect with people working on simulations of *jet formation and collimation*
  → *See e.g. talks by J.C. McKinney, A. Tchekhovskoy, R. Narayan …*

→ *GRRMHD operational since 2014*

These multifrequency (multi-instrument) efforts allowed us to learn several things, which crystalized into several publications

So far, 11(+1) publications (and many more in the pipeline):
4 with small dataset & 7(+1) with extensive MW dataset (includes TeV)

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

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, Accepted in A&A (**arXiv:1412.3576**)
Furniss et al., Submitted to ApJ
Balokovic et al., to be submitted to ApJ within 1 month

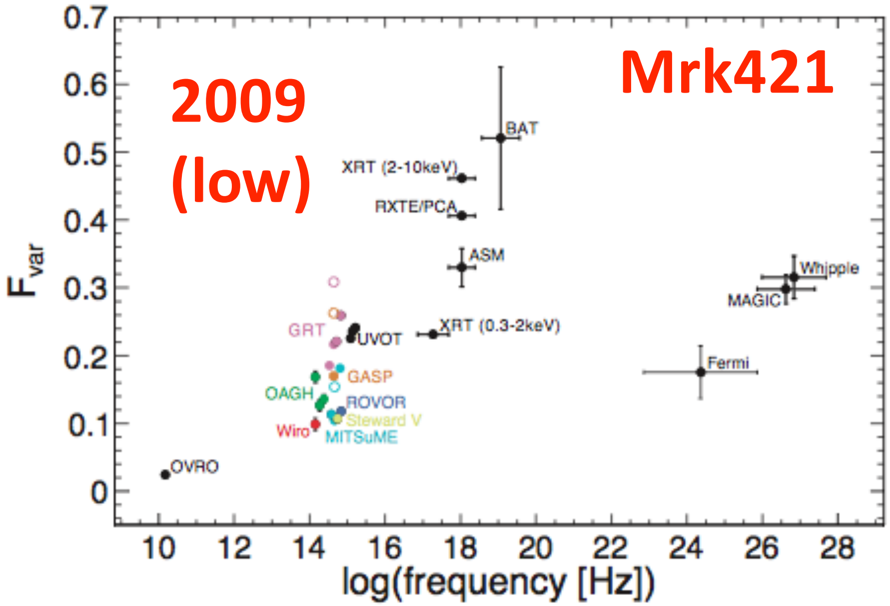
Some highlighted results from these campaigns

Results on several topics

3.1 – Multi-band flux Variability
3.2 – Multi-band flux Correlations
3.3 – SED modeling
3.4 – Correlations of gamma-ray flares with EVPA rotations and VLBA images

3.1 – Variability

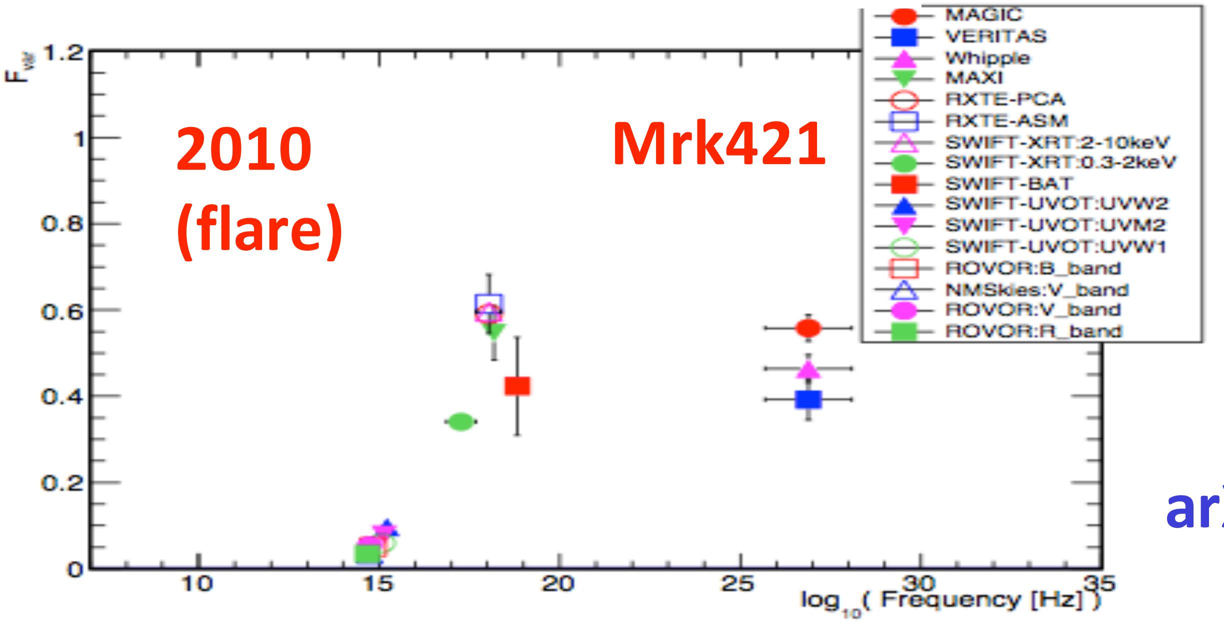
Variability quantified following prescription from Vaughan et al. 2003



Highest variability occurs at X-ray and VHE

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

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



arXiv:1412.3576

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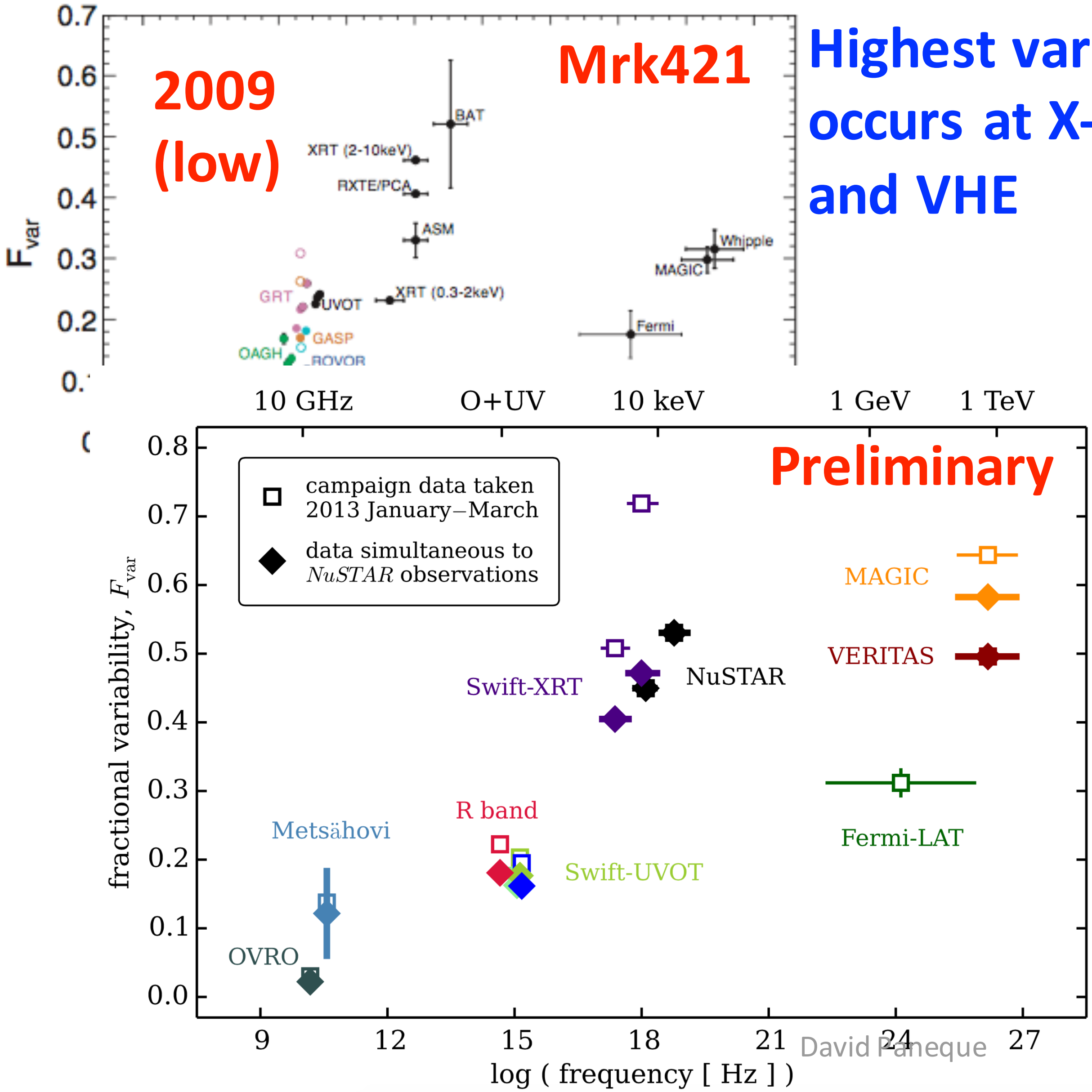


Highest variability occurs at X-ray and VHE

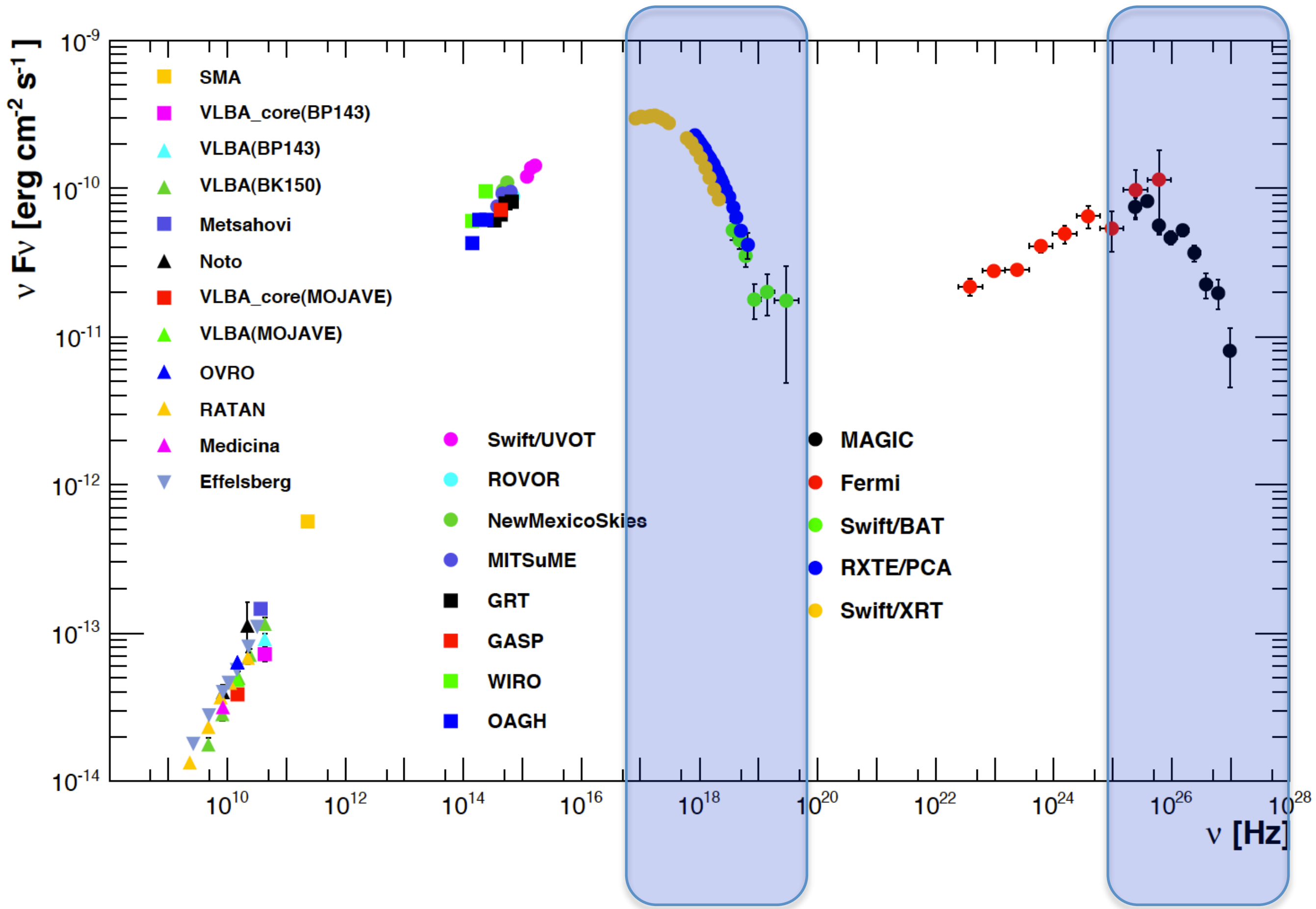
$$F_{var} = \sqrt{\frac{S - \langle \sigma_{err} \rangle^2}{\langle Flux \rangle^2}}$$

Mrk421 2013 (low)

arXiv:1309.4494 & Balokovic et al, To be Submitted to ApJ

3.1 – Variability

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



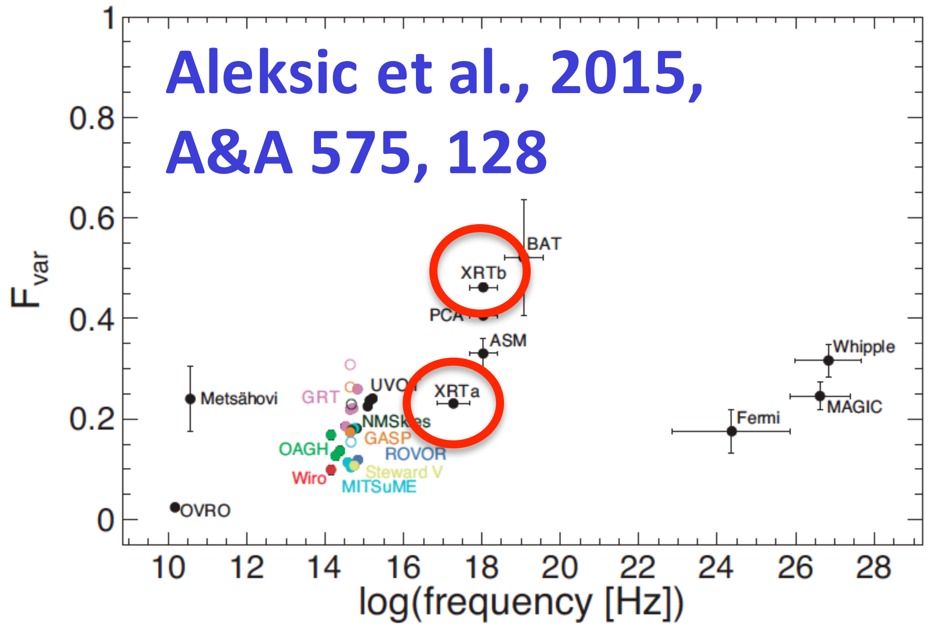
"Falling segments" of the low- and high-energy bumps are more variable than the "rising segments"

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

Fractional variability larger in the 2-10 keV than in the 0.3-2 keV

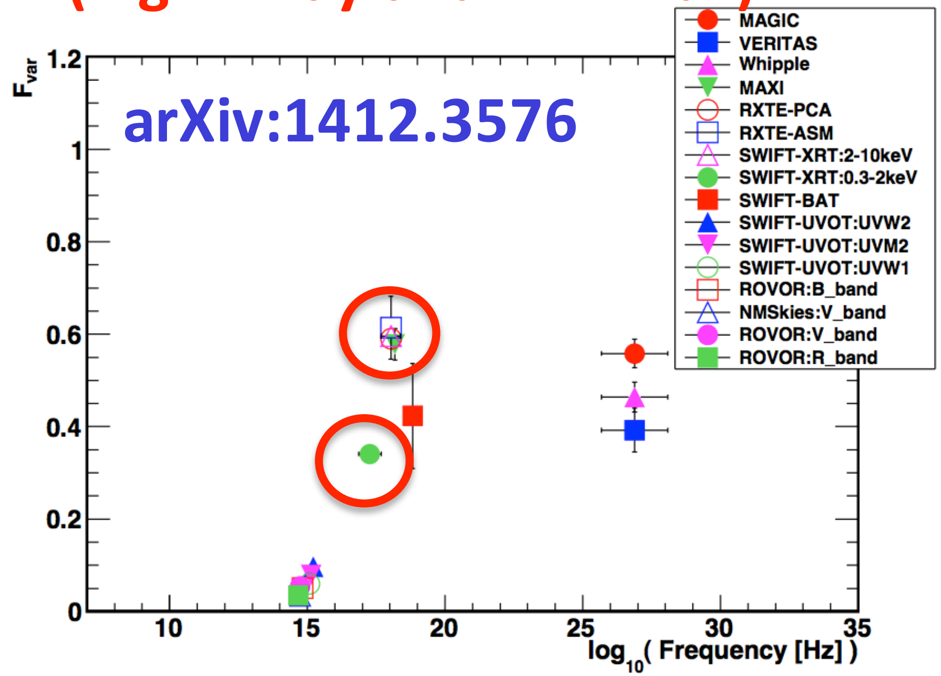
Mrk421 MW 2009

(low X-ray and VHE flux)



Mrk421 MW 2010 (March)

(high X-ray and VHE flux)

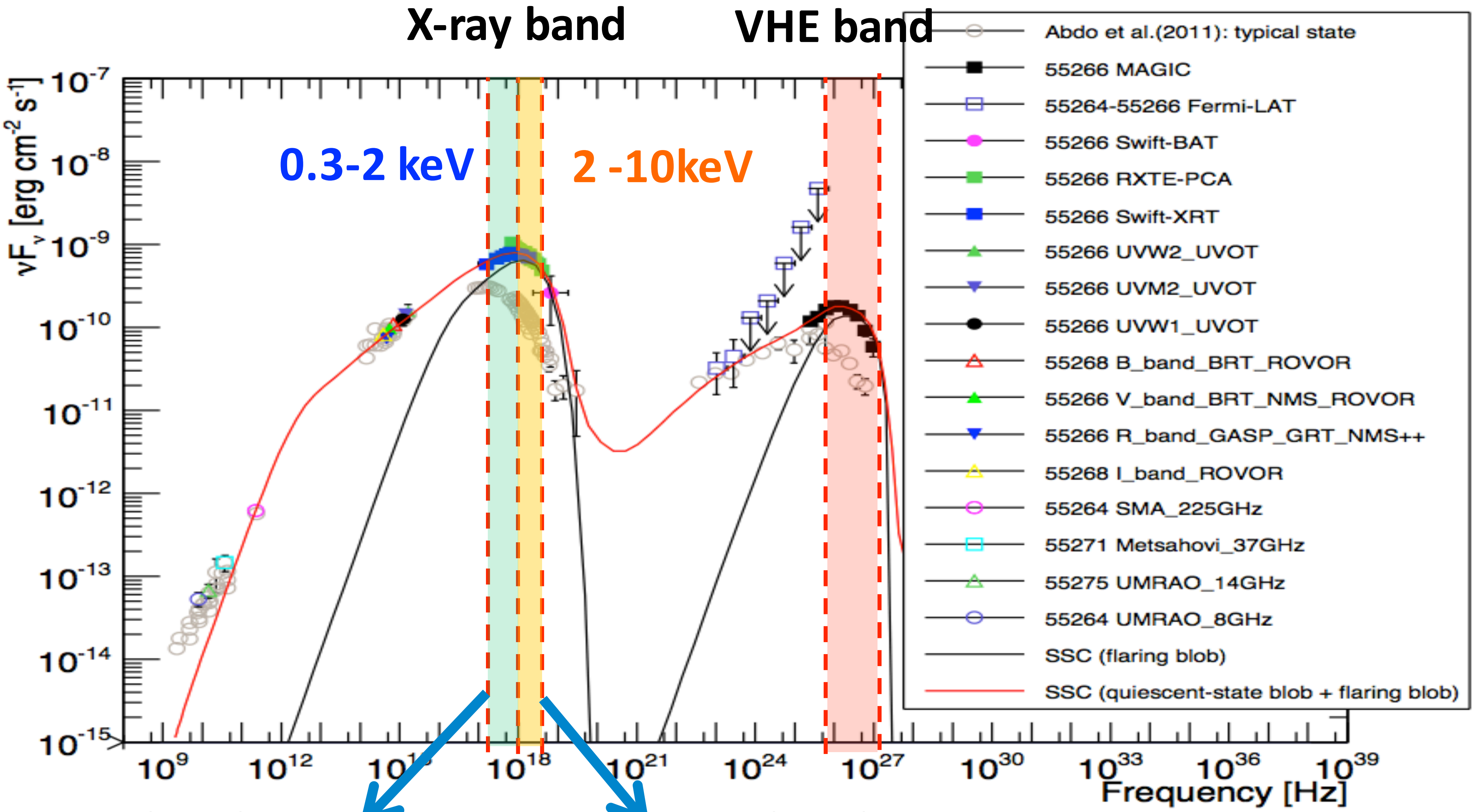


Similar behaviour observed during the non-flaring and the flaring activity of Mrk421 in the campaigns from 2009 and 2010

→ Some features get repeated over time, in high and low state (intrinsic characteristic of the source)

3.1 – Variability

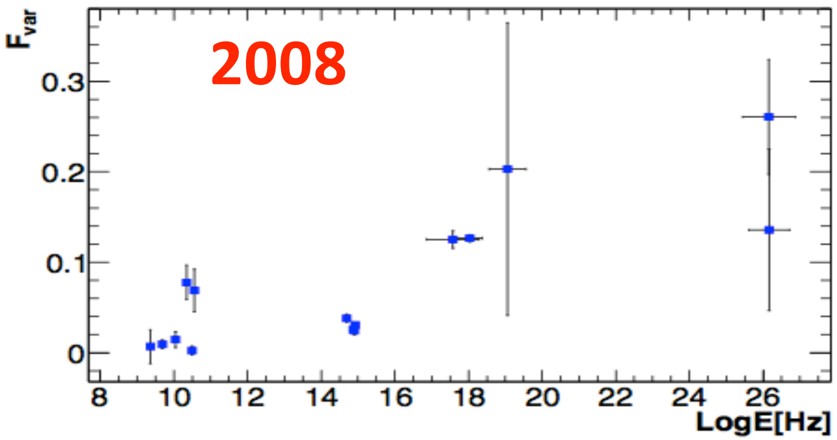
arXiv:1412.3576

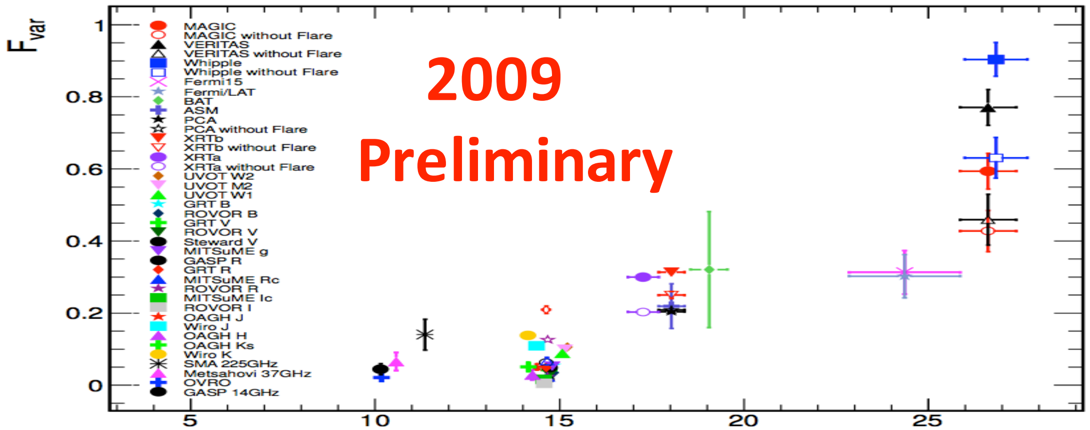


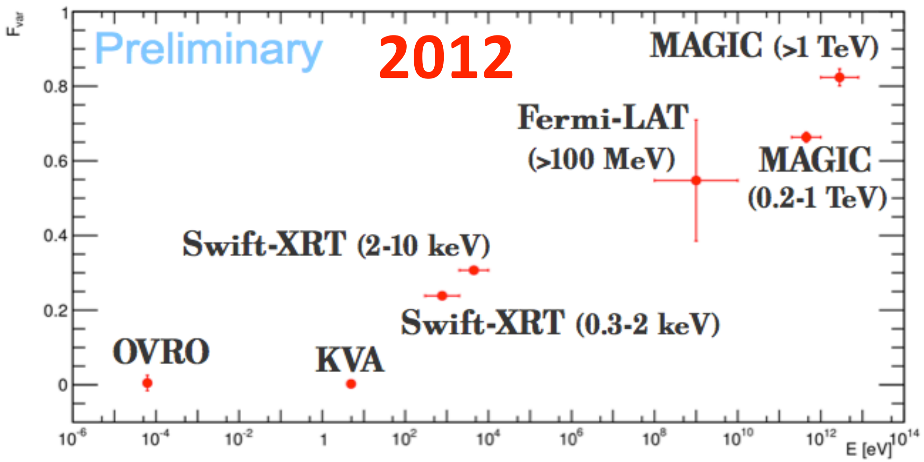
0.3-2 keV band
samples the emission
At or BEFORE the Sync. peak

2-10 keV band
samples the emission
At or AFTER the Sync. peak

Variability Mrk501







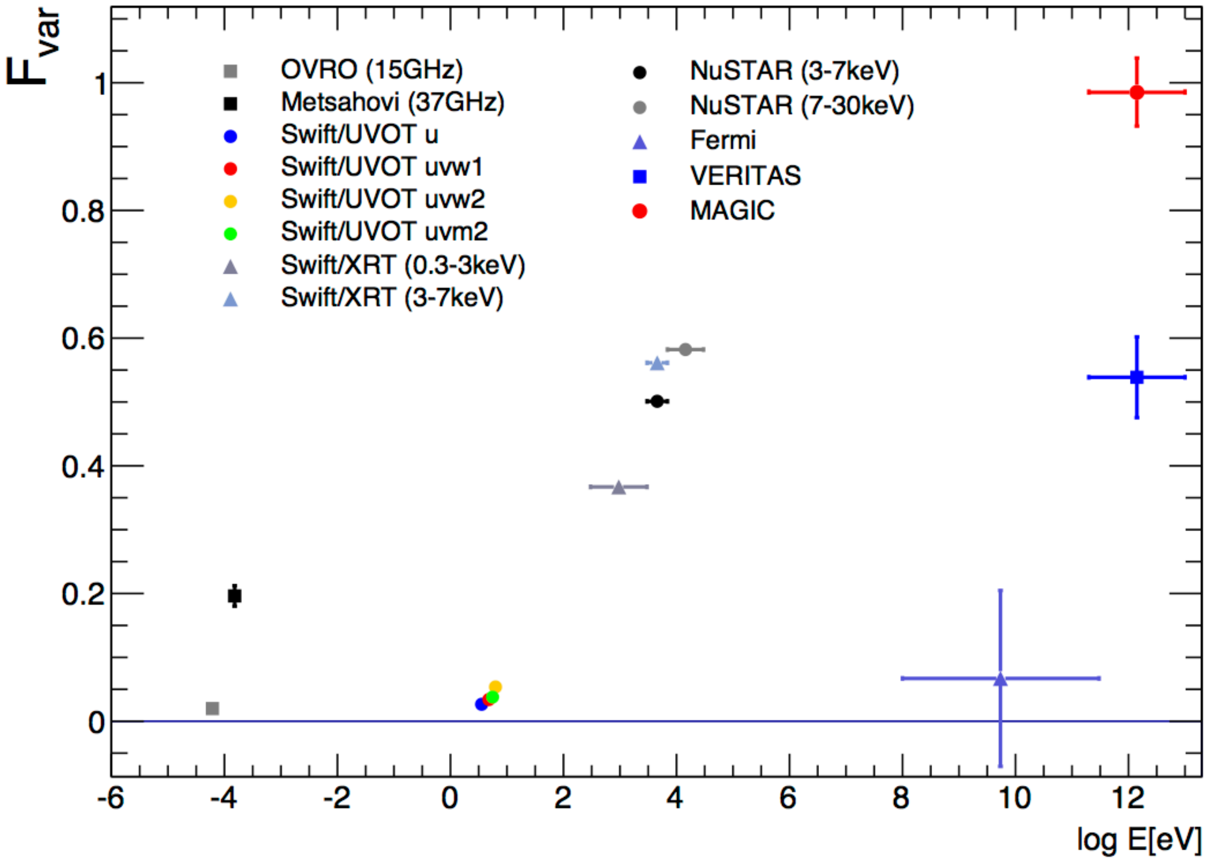
For Mrk501, the variability at VHE is relatively higher than that measured for X-rays. Different with respect to what is typically observed for Mrk421

Aleksic et al, 2015, *A&A* 573, 50

Doert and Paneque, ICRC 2013 (arXiv:1307.8344)

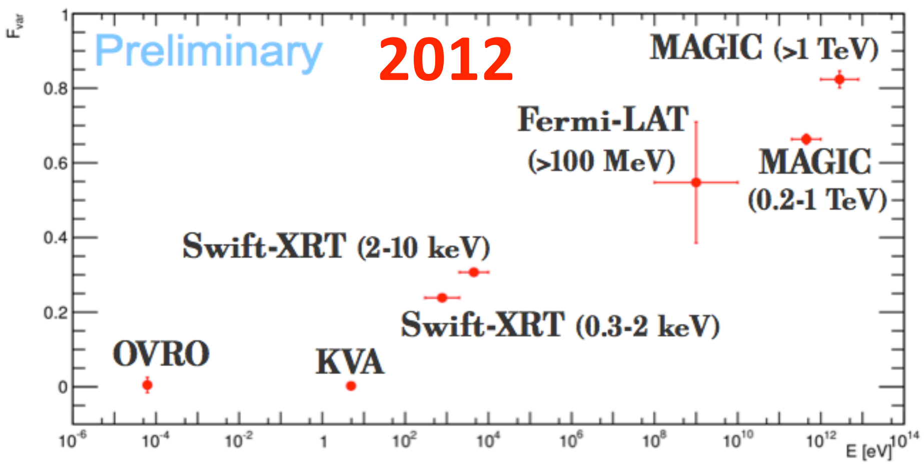
Borracci et al, ICRC 2013

Variability Mrk501



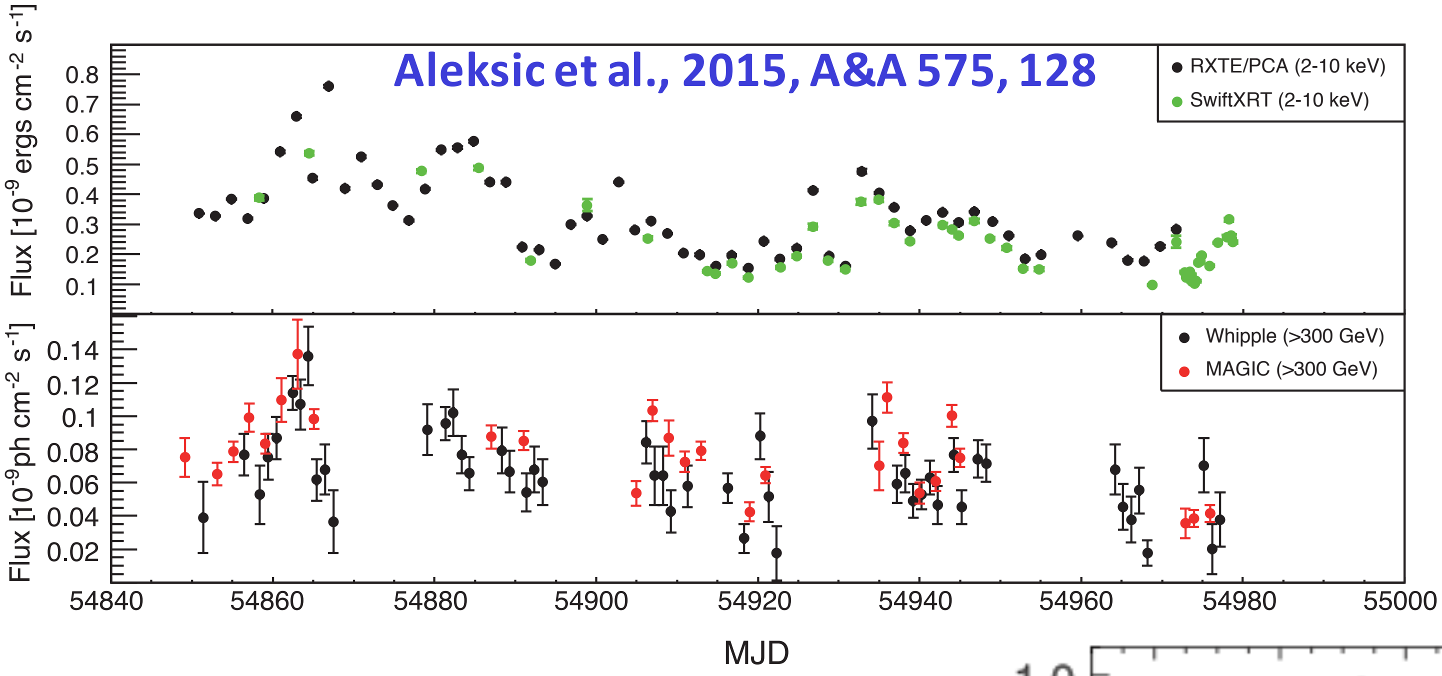
2013

Furniss et al, Submitted to ApJ



Borracci et al, ICRC 2013

3.2 – Correlations

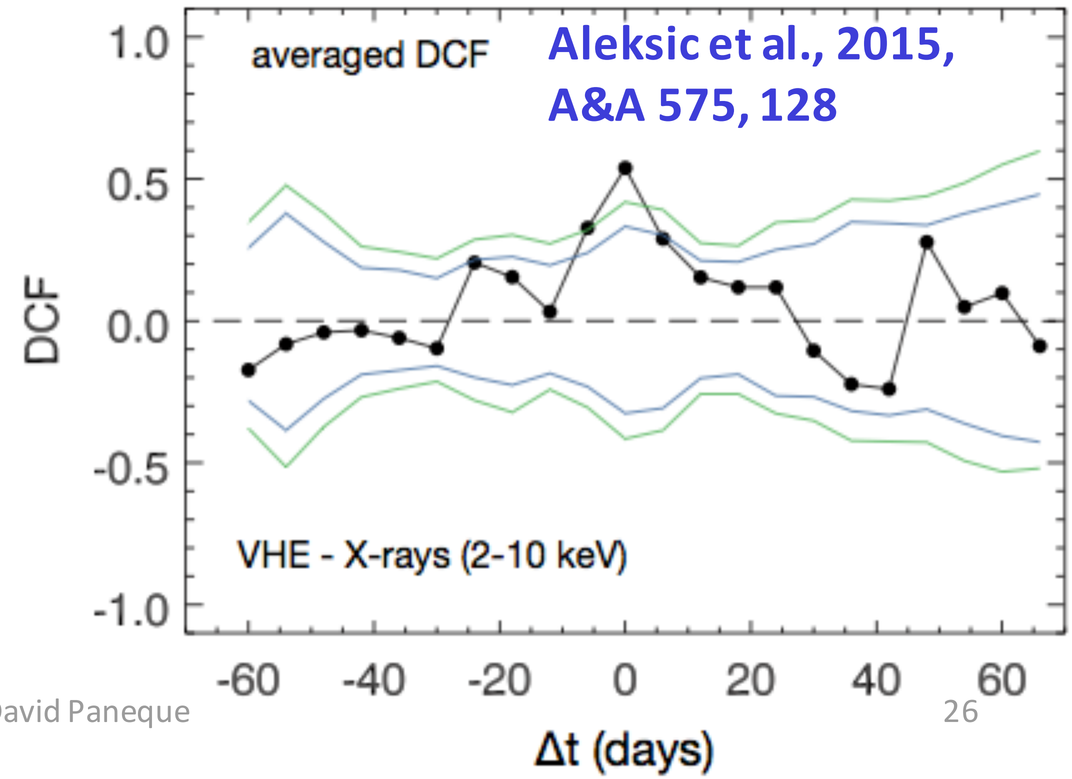


Mrk421
MW 2009

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**



3.2 – Correlations

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

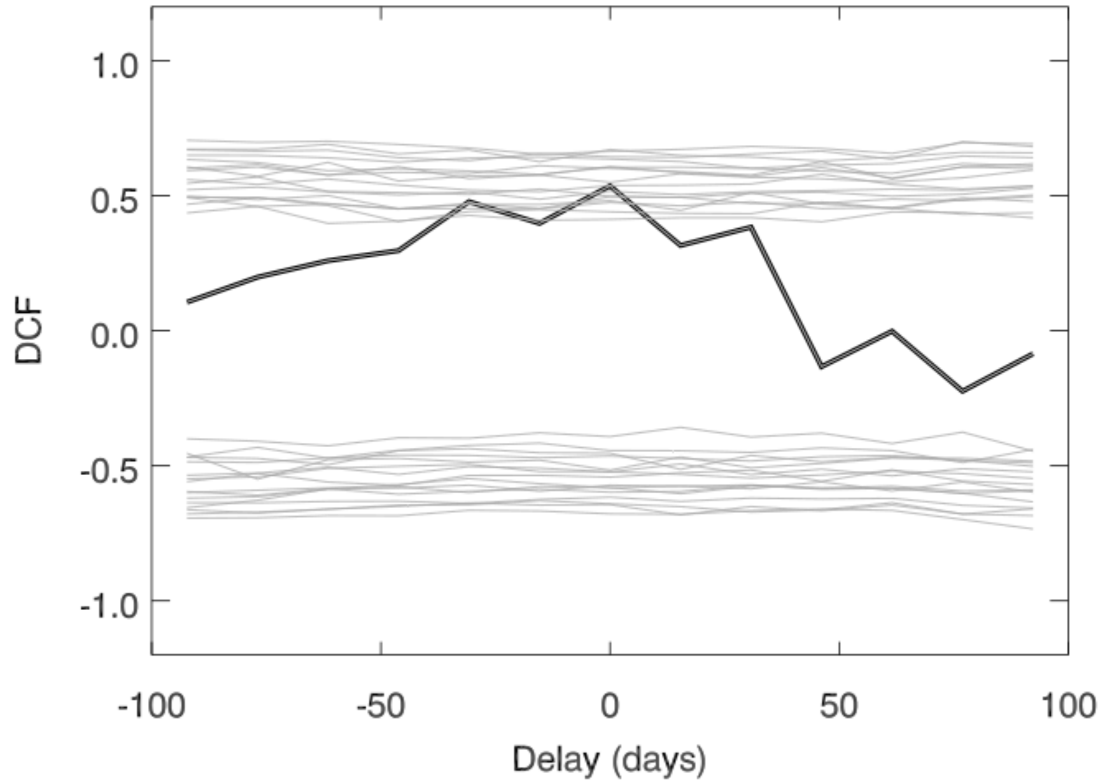


Fig. 7. Discrete cross-correlation function between the γ-ray and the 43 GHz radio light curves (black curve). The gray curves represent the 99.7% confidence limits relative to stochastic variability, obtained from the combination of different power spectral density slopes. See section 3.5 for more details.

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

3.2 – Correlations

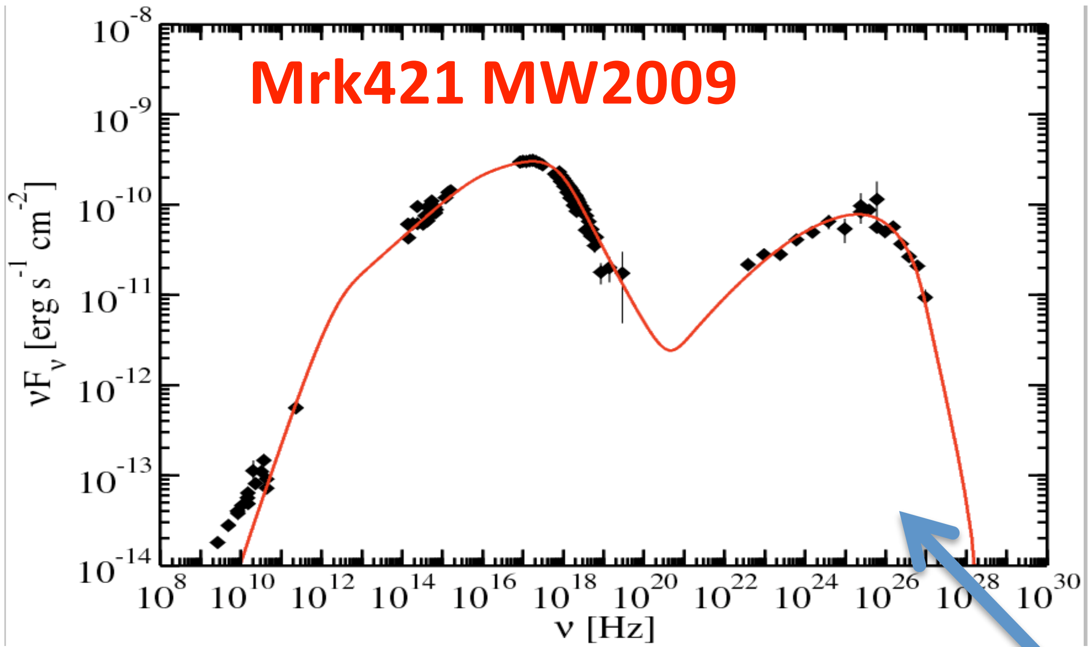
Correlations **Radio/GeV** and **X-ray/TeV**
on months timescales during non-flaring activity

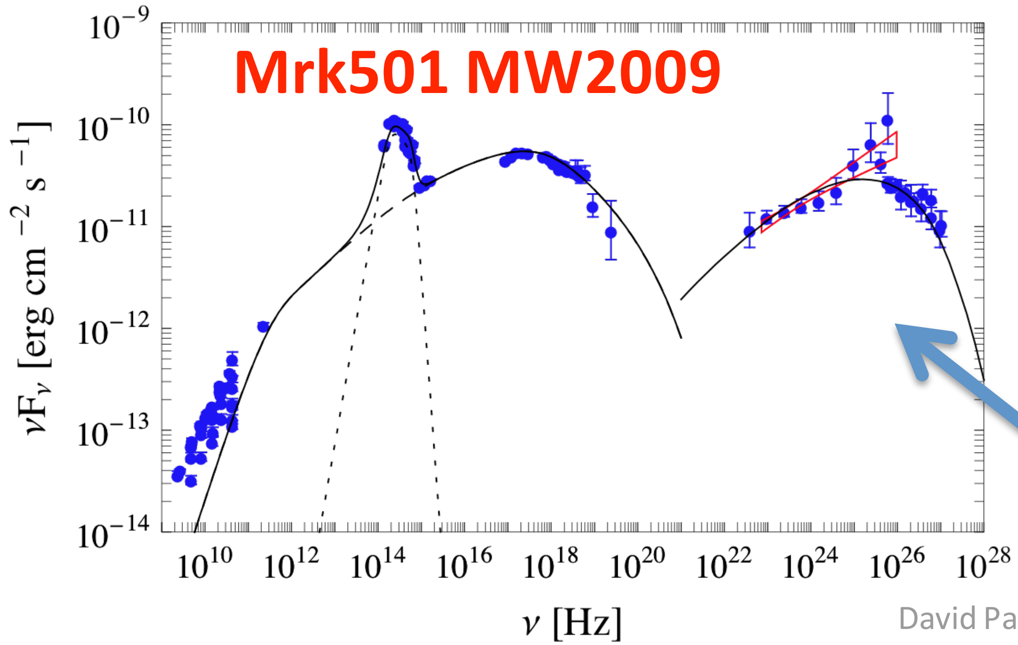
→ **Favor leptonic scenarios**

Hadronic scenarios cannot explain this persistent correlation (radio/GeV and X-ray/TeV) during non-flaring activity and long timescales

An hadronic component is not excluded, but it cannot dominate the overall broadband variability

3.3 – SED modeling





One-zone SSC describes well the broadband (radio to VHE) data collected for Mrk421 and Mrk501 during non-flaring activity

→Done many times in the past, but with less temporal and energy coverage.
First time with Fermi-LAT !!

Abdo et al., ApJ 736 (2011) 131

Abdo et al., ApJ 727 (2011) 129

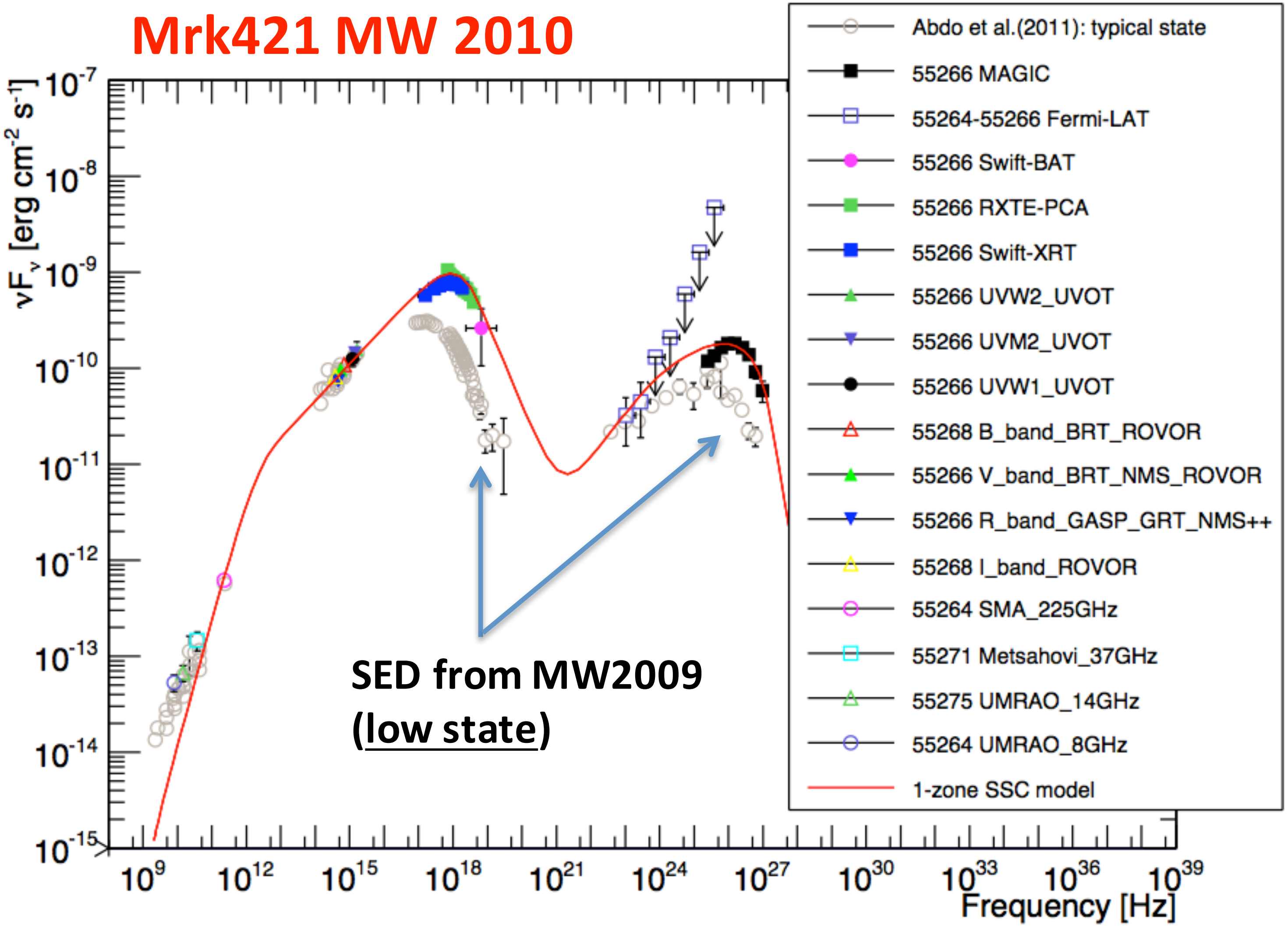
3.3 – SED modeling

One-zone SSC also describes well the broadband (radio to VHE) data collected for Mrk421 when it flares

→ Done many times in the past, but with less temporal and energy coverage

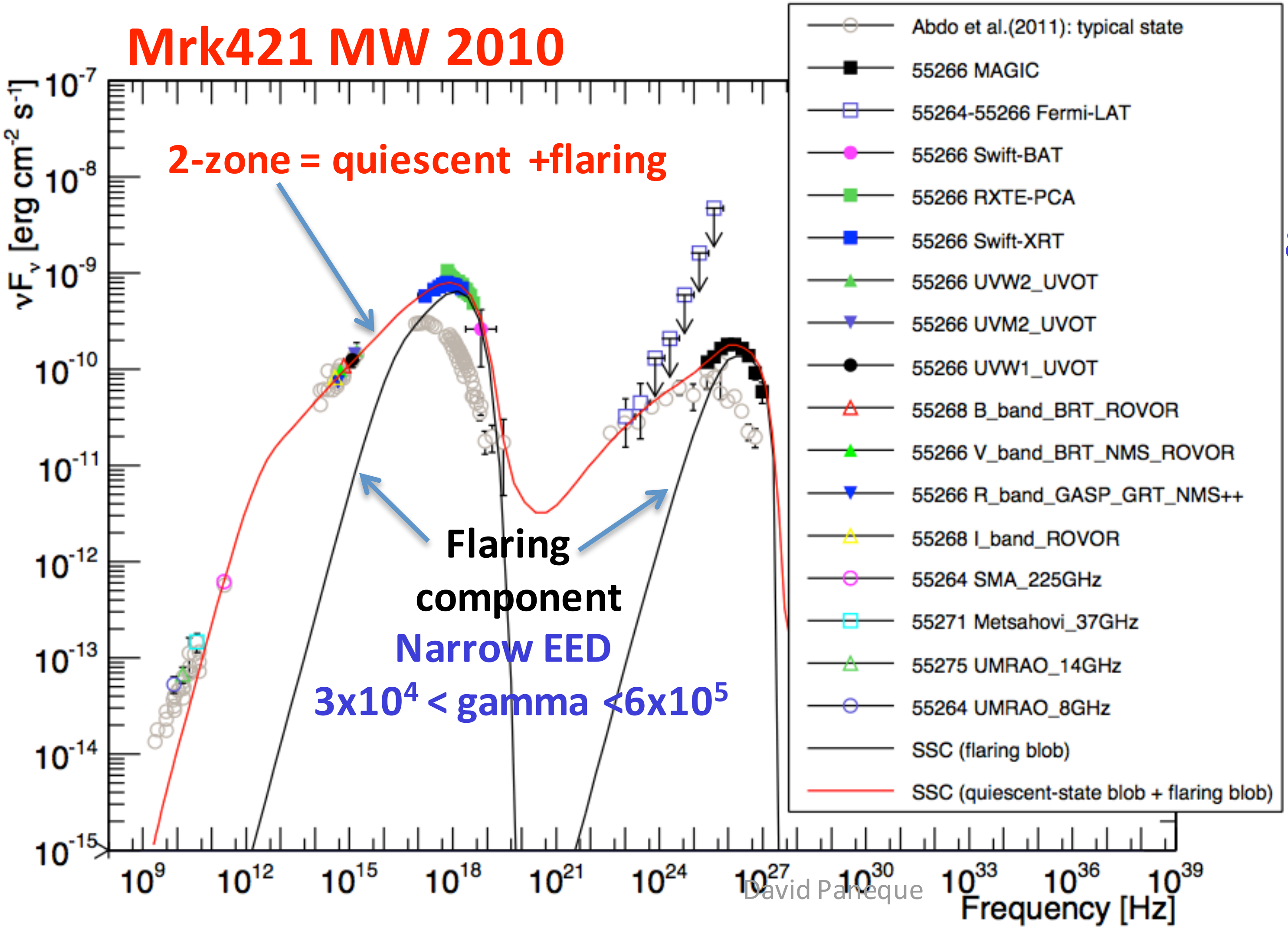
Mrk421 MW 2010

arXiv:1412.3576



3.3 – SED modeling

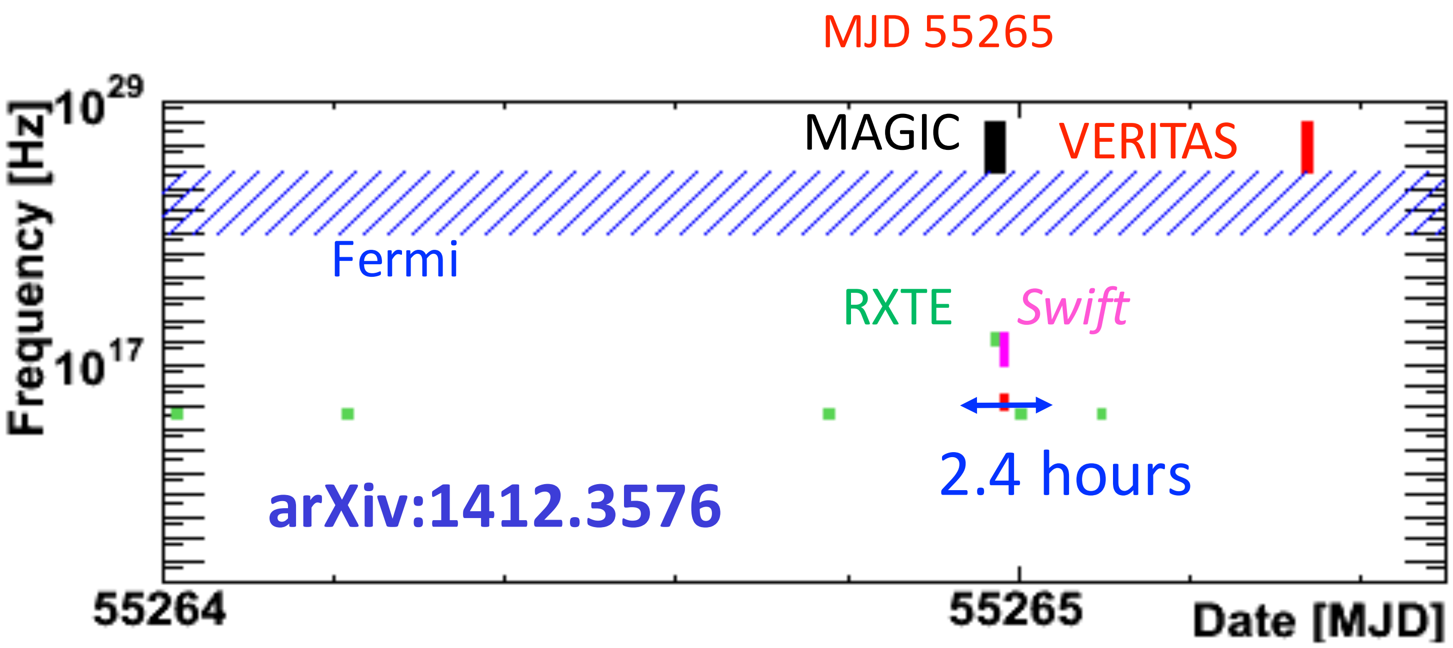
We also successfully modeled the SED with a two-zone SSC
→ quiescent + flaring (essentially only in X-ray and VHE)



arXiv:1412.3576

SED modeling (Mrk421, 2010 March flare)

Very good simultaneity in MW observations

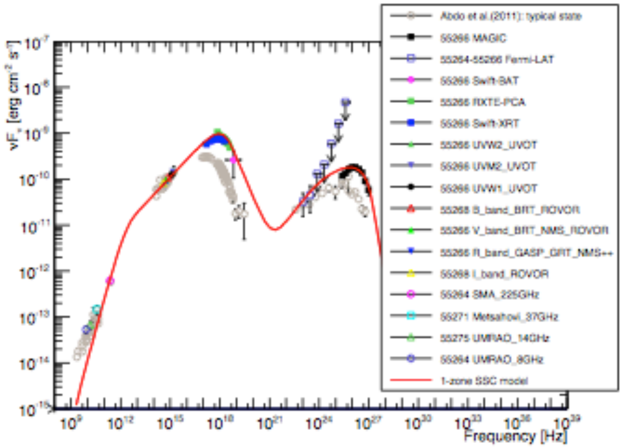


Observations are truly simultaneous

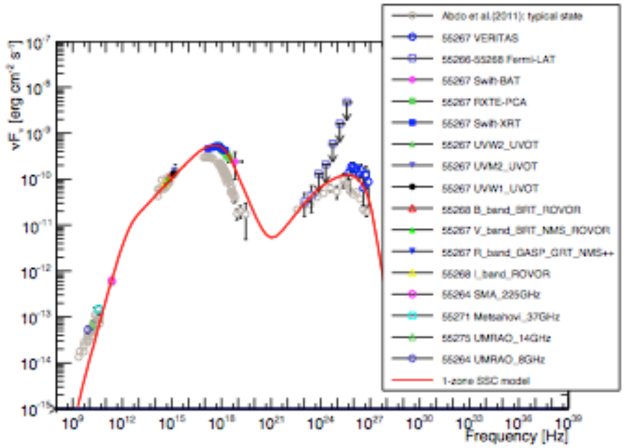
→ Very important during flaring activity

→ reliability in the results derived with these data

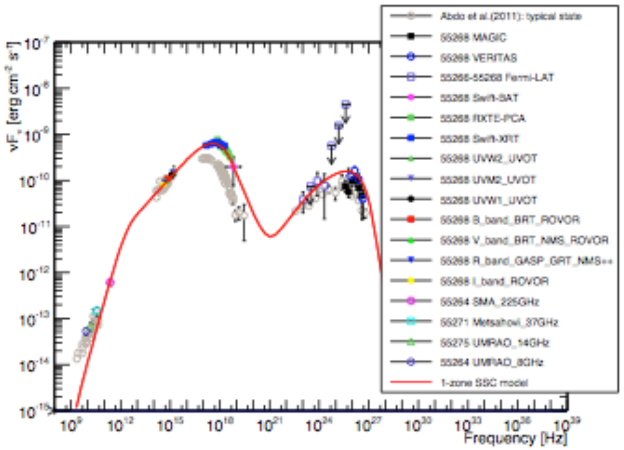
We can study the evolution of the SED during 13 consecutive days



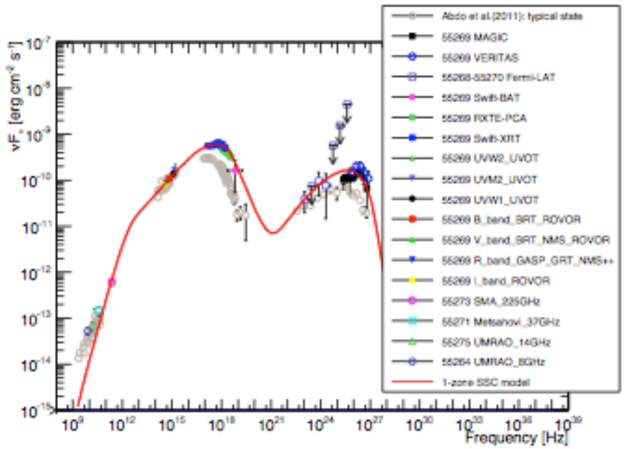
(a) MJD 55266.



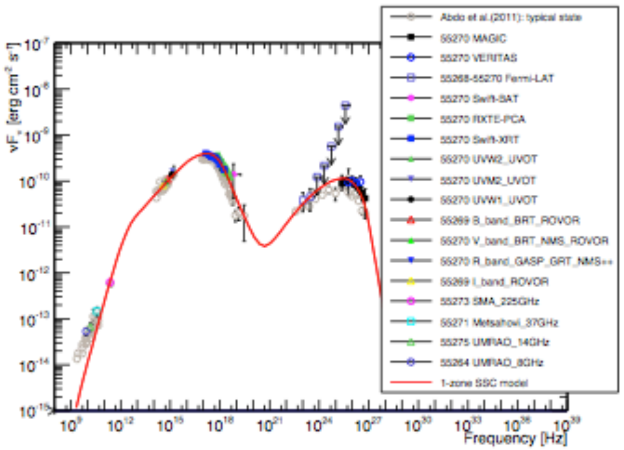
(b) MJD 55267.



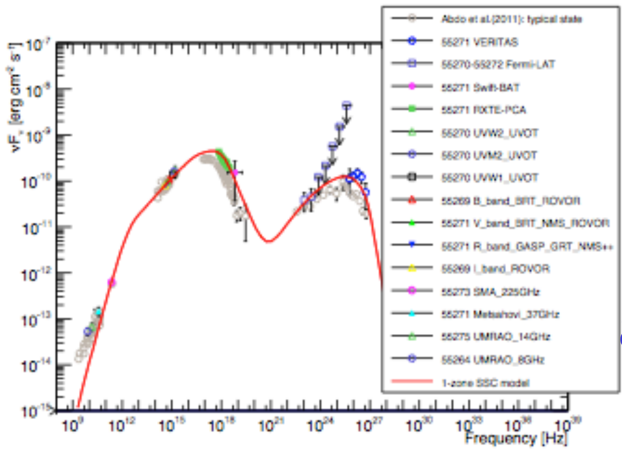
(c) MJD 55268.



(d) MJD 55269.



(e) MJD 55270.

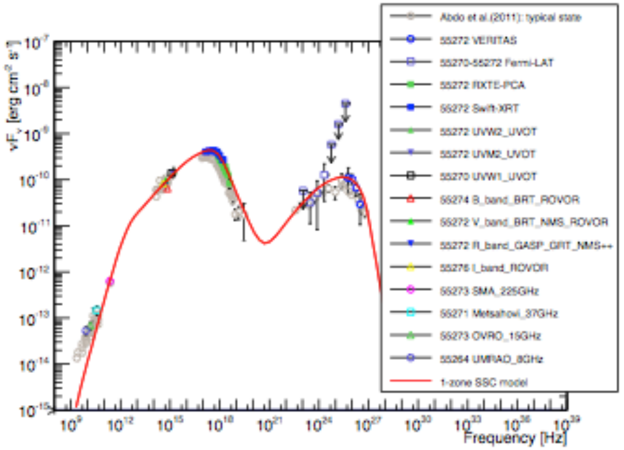


(f) MJD 55271.

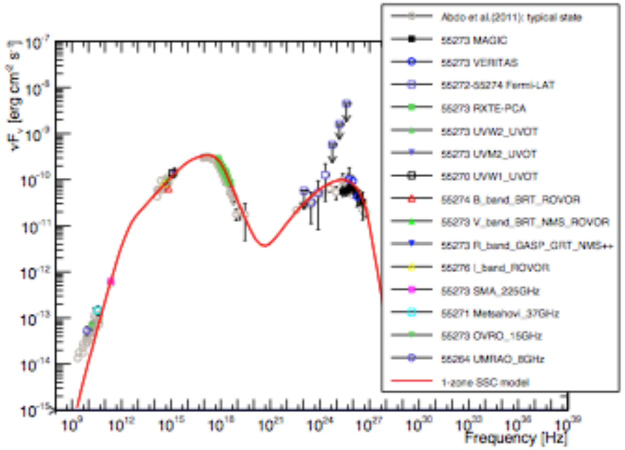
Mrk421 13-day long flaring activity during March 2010

Broadband SEDs measured on single days can be described with 1-zone SSC model (Part 1)

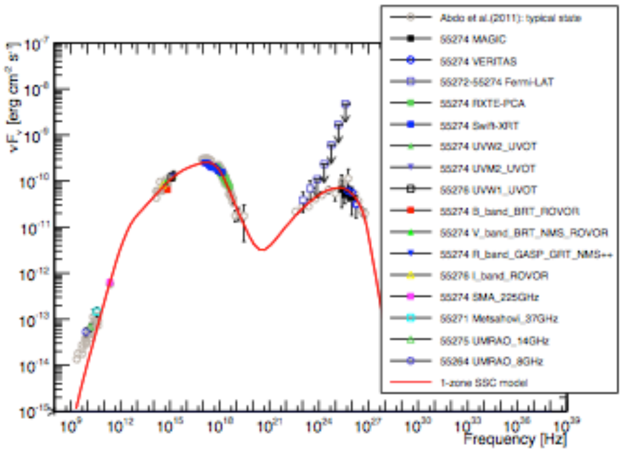
arXiv:1412.3576



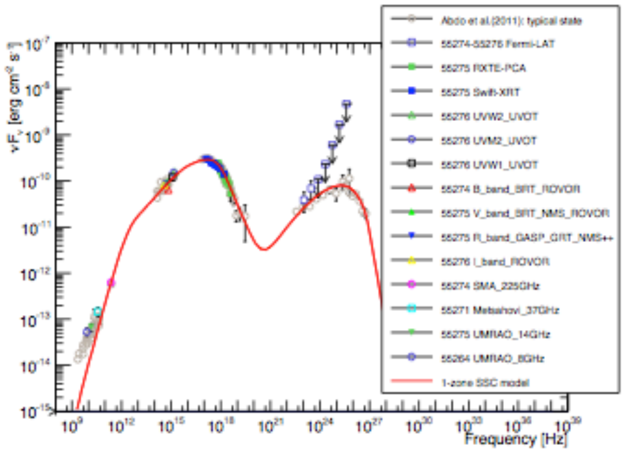
(a) MJD 55272.



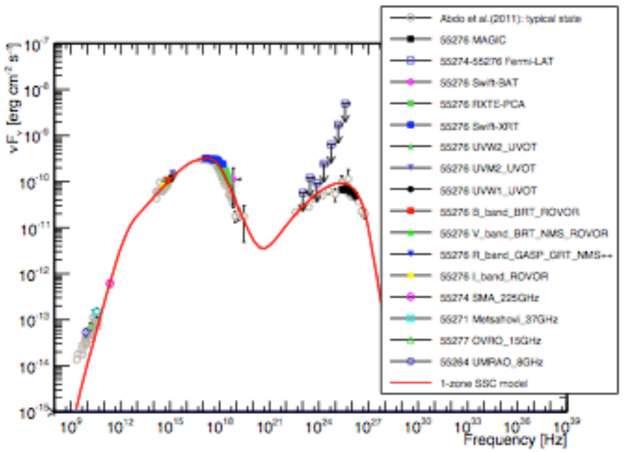
(b) MJD 55273.



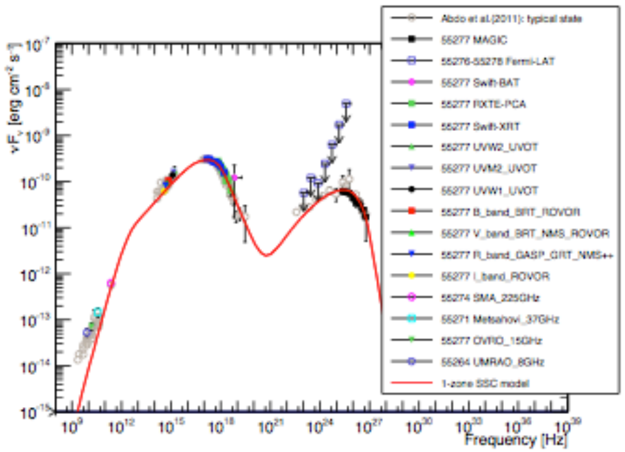
(c) MJD 55274.



(d) MJD 55275.



(e) MJD 55276.

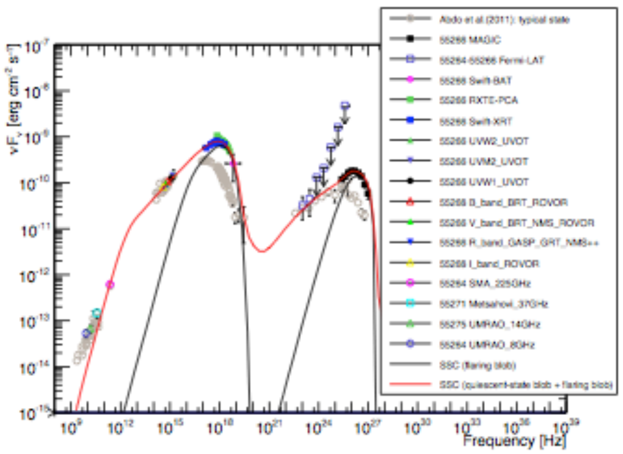


(f) MJD 55277.

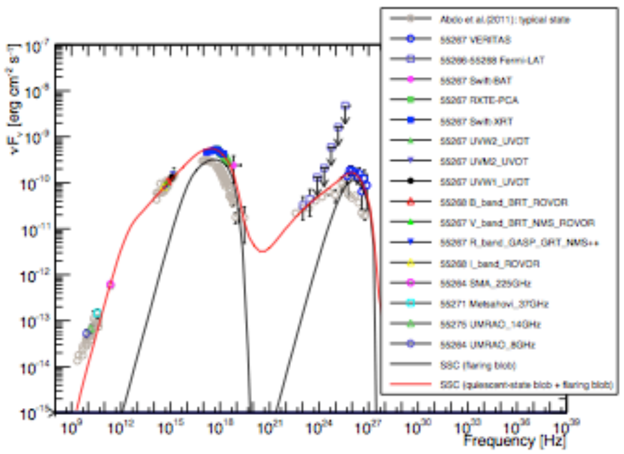
Mrk421 13-day long flaring activity during March 2010

Broadband SEDs measured on single days can be described with 1-zone SSC model (Part 2)

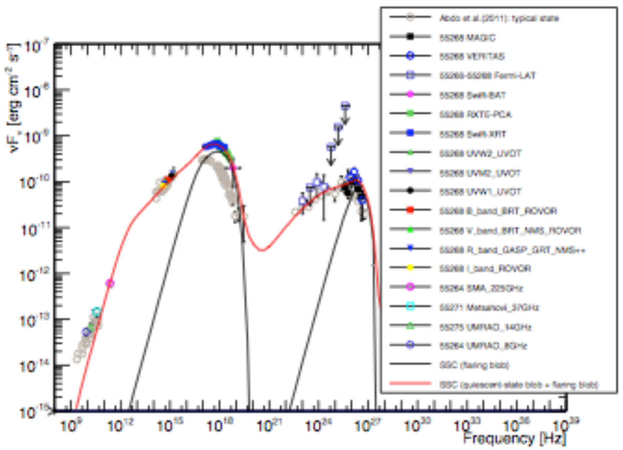
arXiv:1412.3576



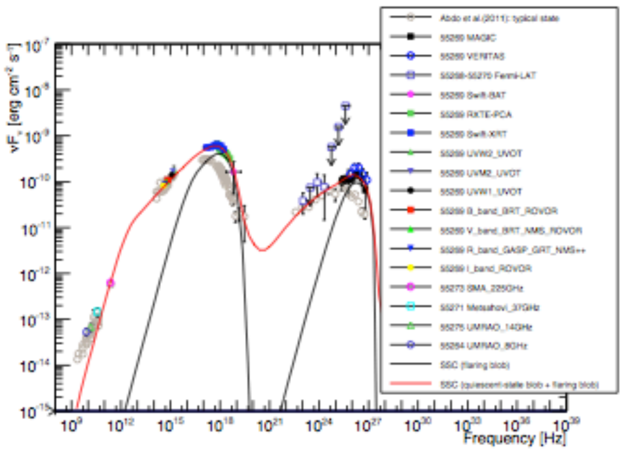
(a) MJD 55266.



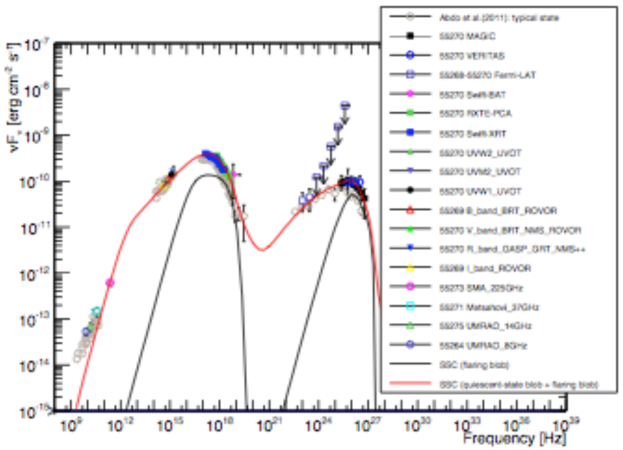
(b) MJD 55267.



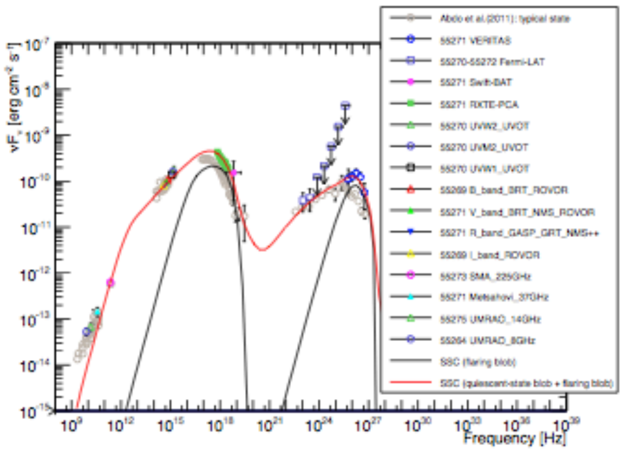
(c) MJD 55268



(d) MJD 55269.



(e) MJD 55270.

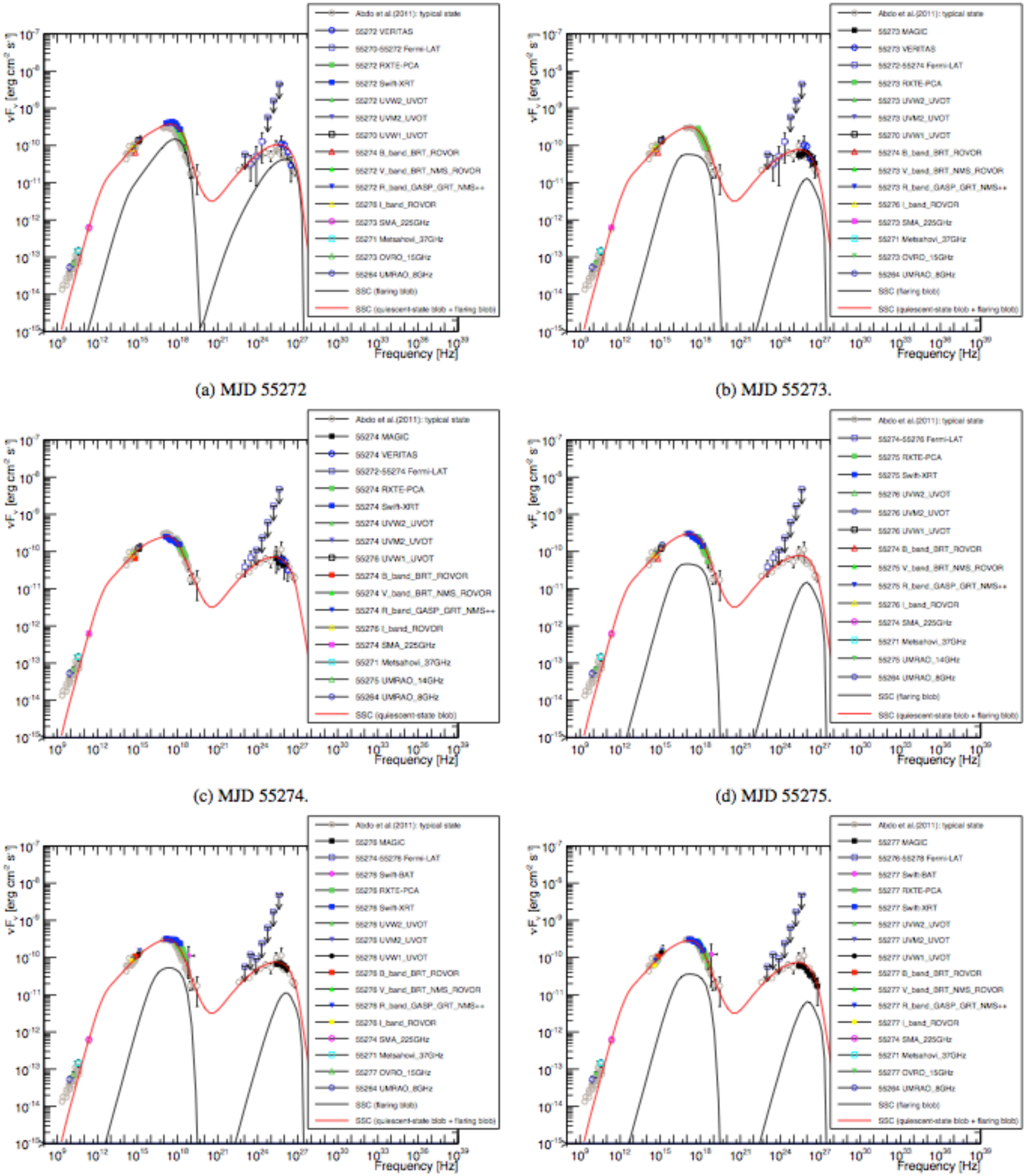


(f) MJD 55271.

Mrk421 13-day long flaring activity during March 2010

Broadband SEDs measured on single days can be described with 2-zone SSC model (Part 1)

arXiv:1412.3576



(a) MJD 55272

(b) MJD 55273.

(c) MJD 55274.

(d) MJD 55275.

(e) MJD 55276.

(f) MJD 55277.

Mrk421 13-day long flaring activity during March 2010

Broadband SEDs measured on single days can be described with 2-zone SSC model (Part 2)

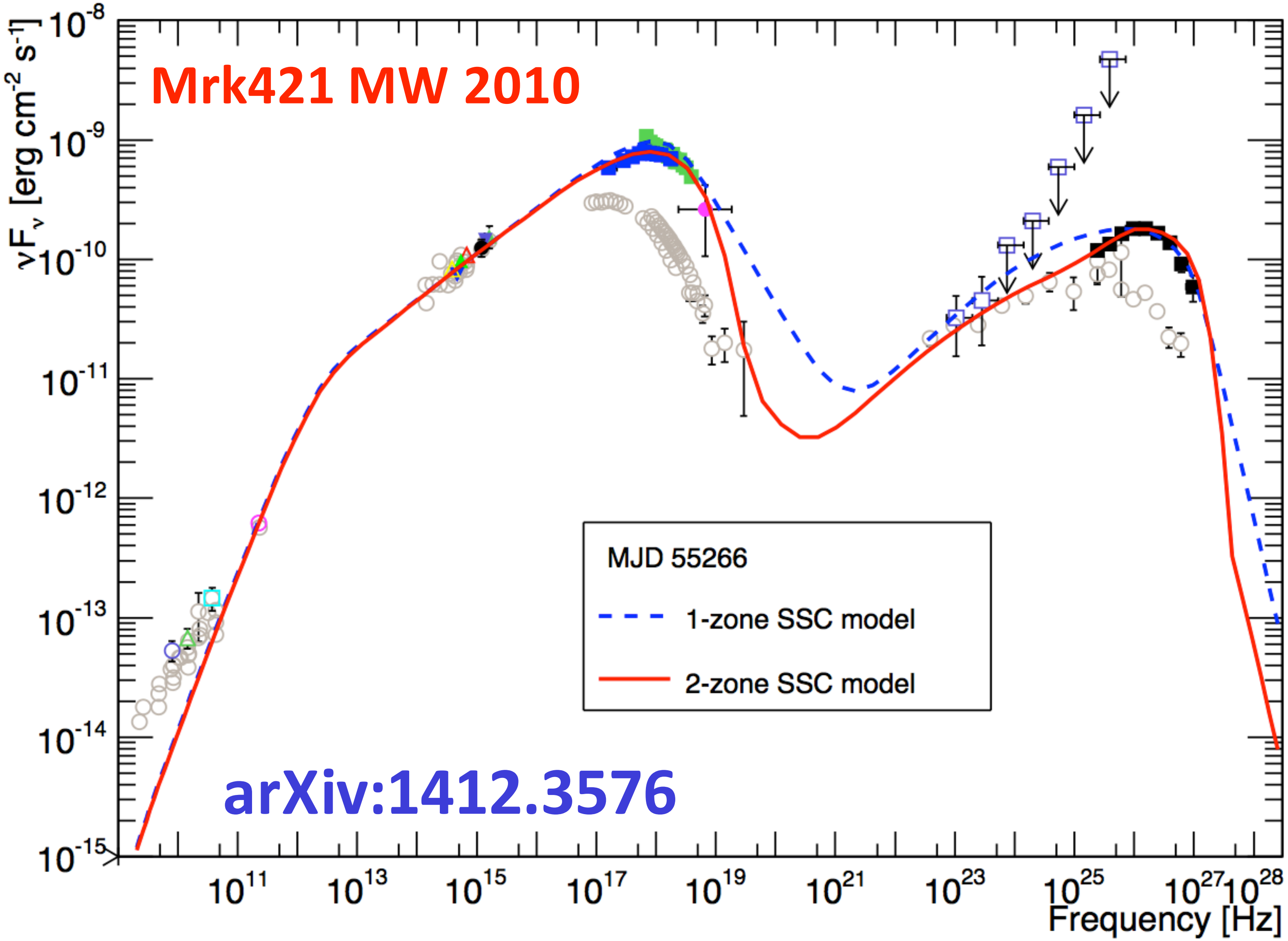
arXiv:1412.3576

3.3 – SED modeling

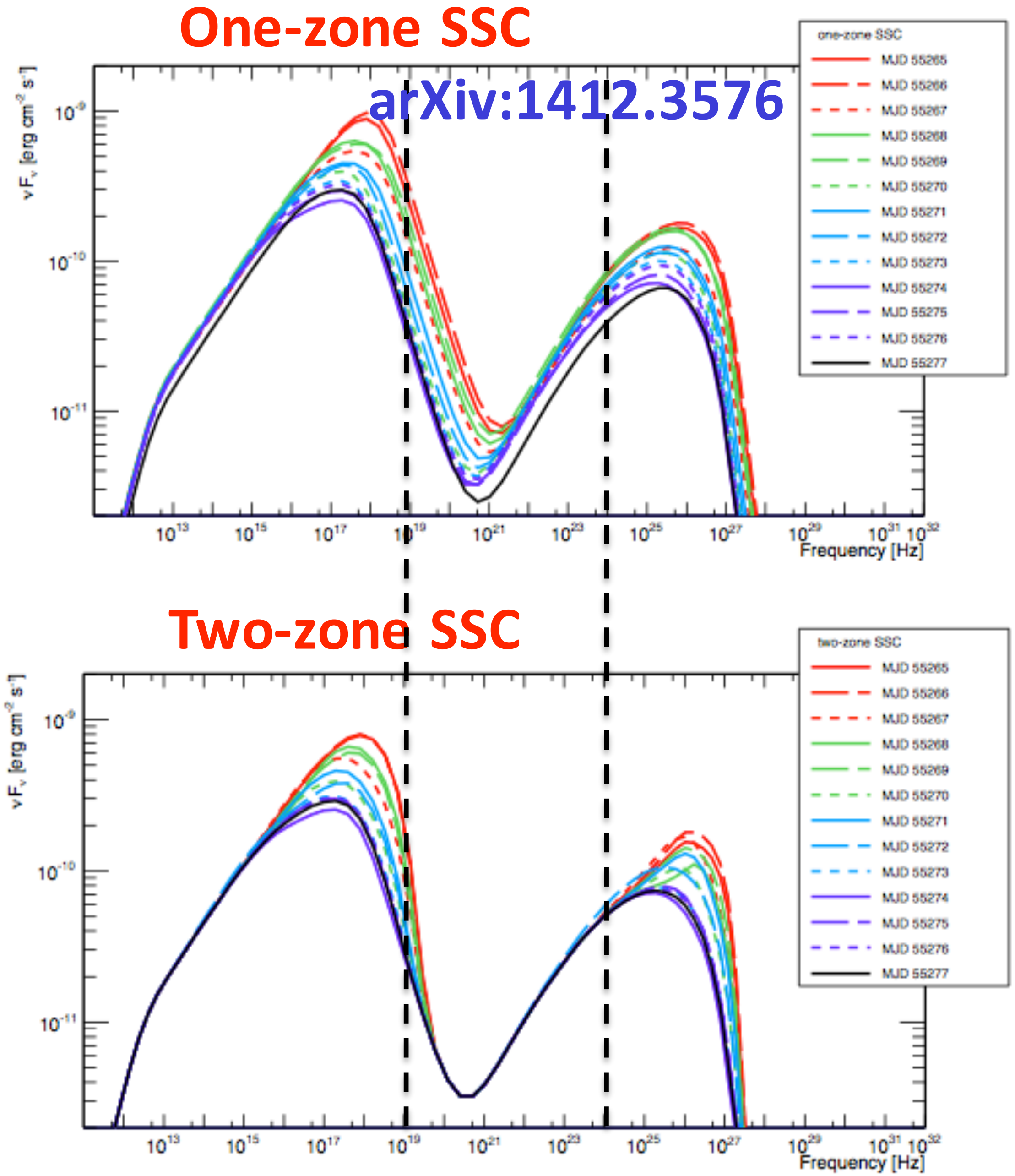
One-zone vs two-zone SSC model

→ Both of them provide reasonably good agreement

→ Two-zone SSC describes slightly better the narrow peaks



3.3 – SED modeling: SEDs



Mrk421 MW 2010

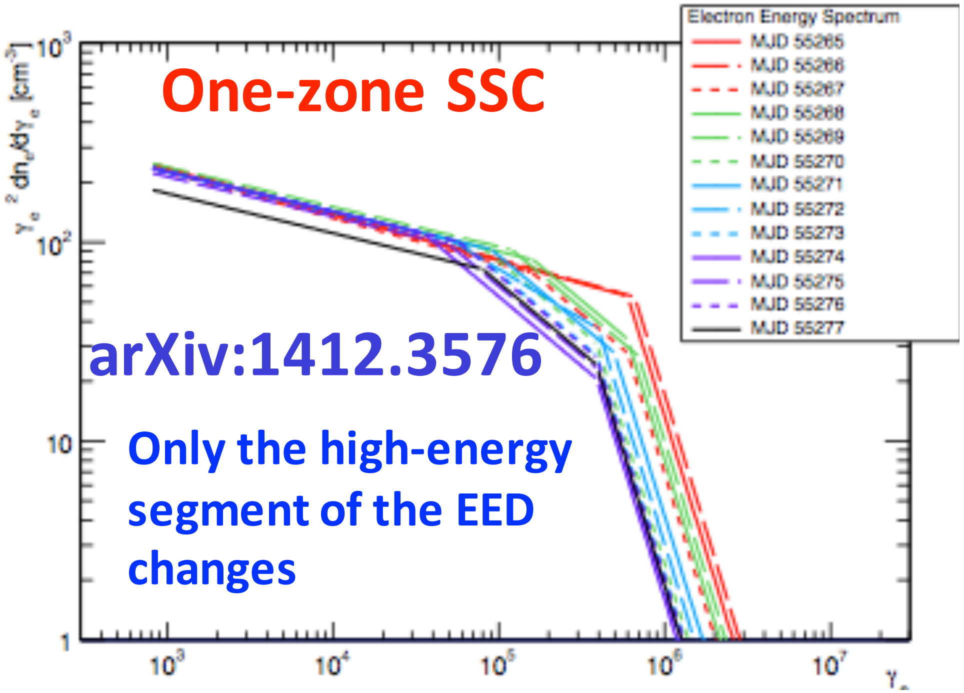
13 SEDs from models

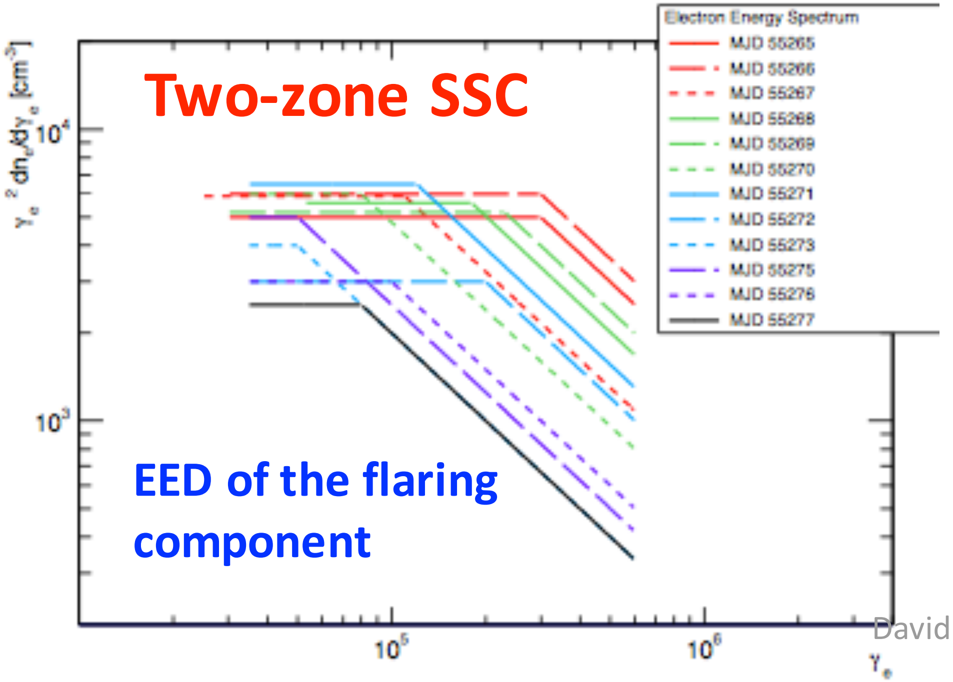
Variability patterns for the one-zone and two-zone SSC broadband emission is somewhat different, specially in the range between 50 keV and 50 GeV

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

3.3 – SED modeling: EEDs

Mrk421 MW 2010





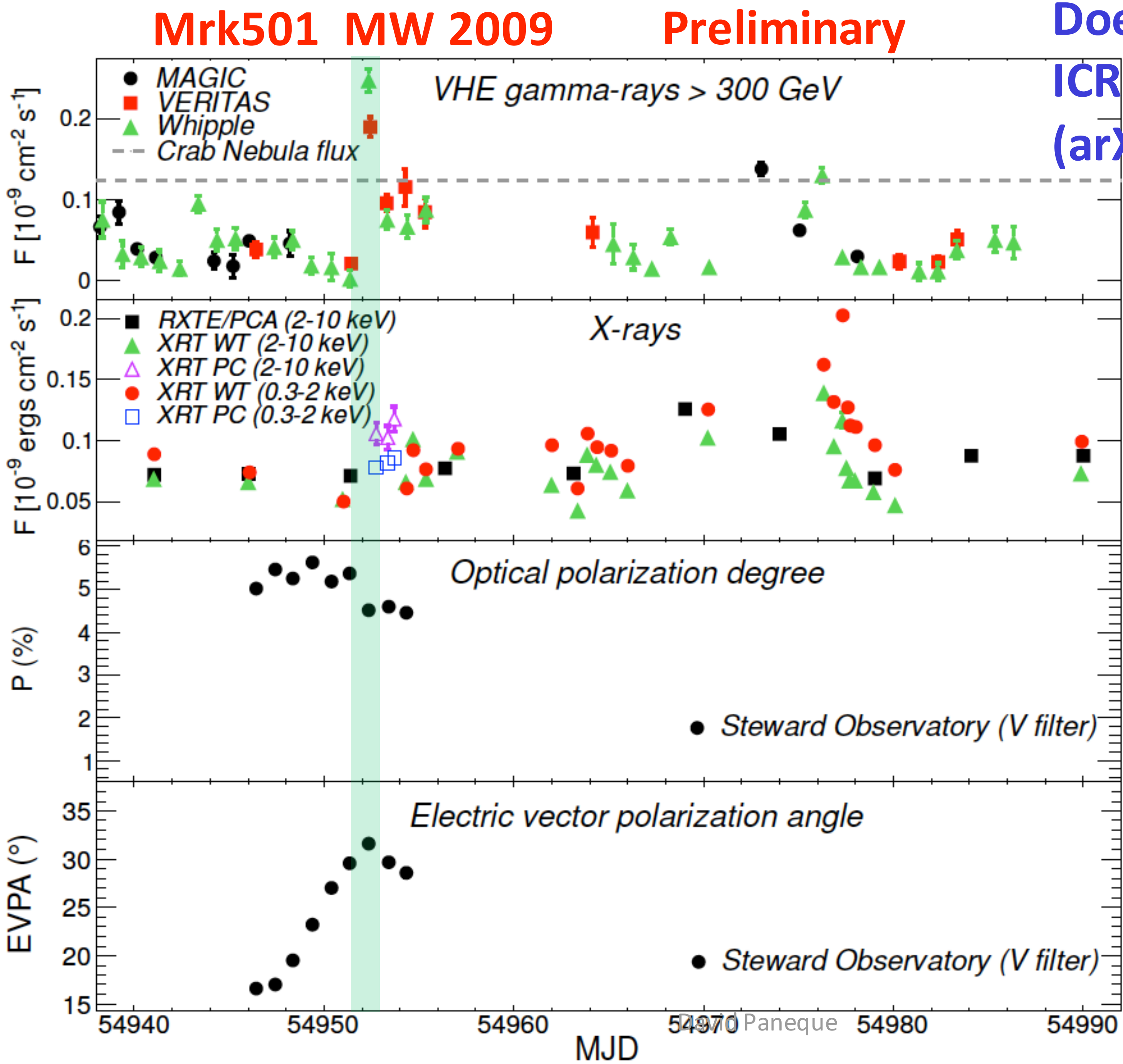
One-zone vs two-zone SSC model

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

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

3.4 - Flaring activity with EVPA rotation

Doert and Paneque, ICRC 2013 (arXiv:1307.8344)



Rotation of EVPA that stops right at the day of the big TeV flare

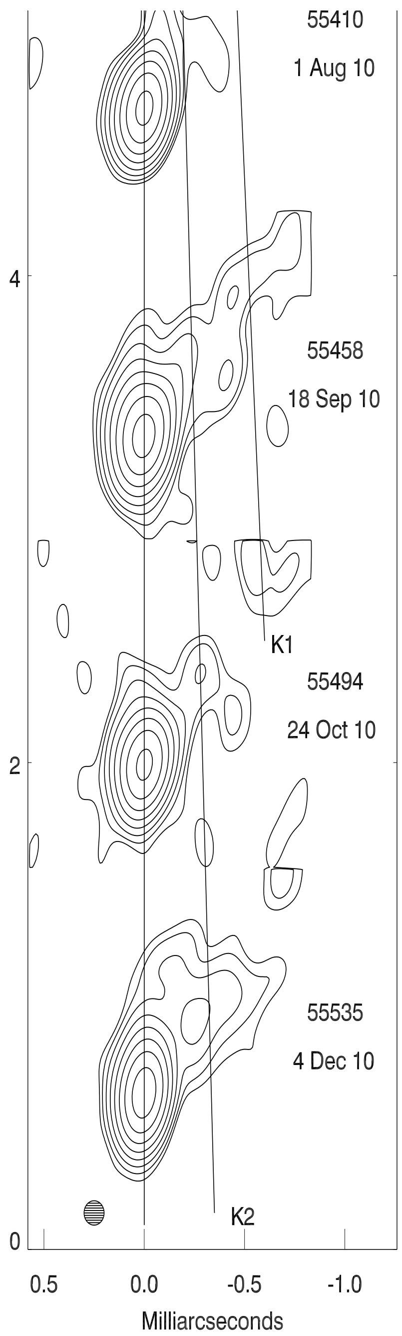
NEVER observed before for Mrk501

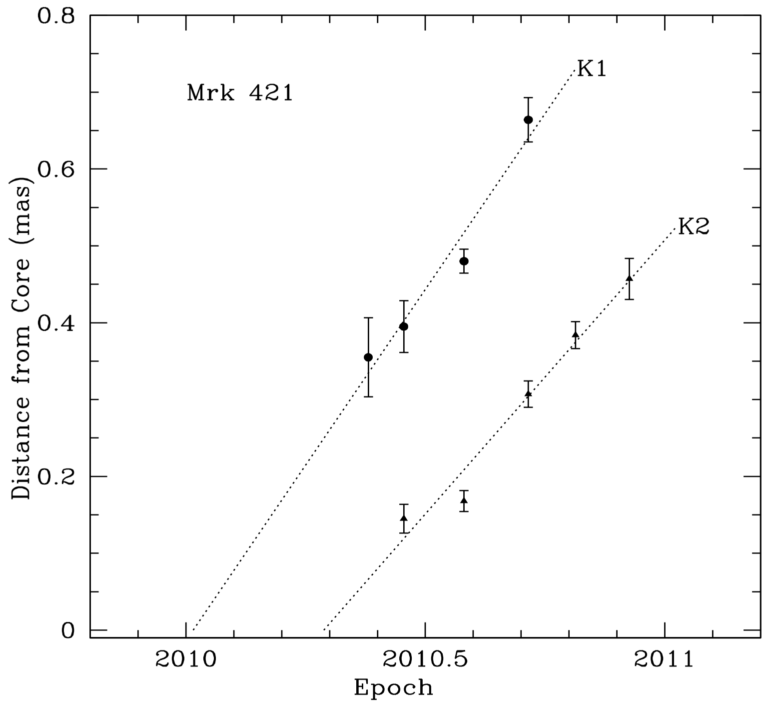
3.4 - Flaring activity with ejection of VLBA blobs

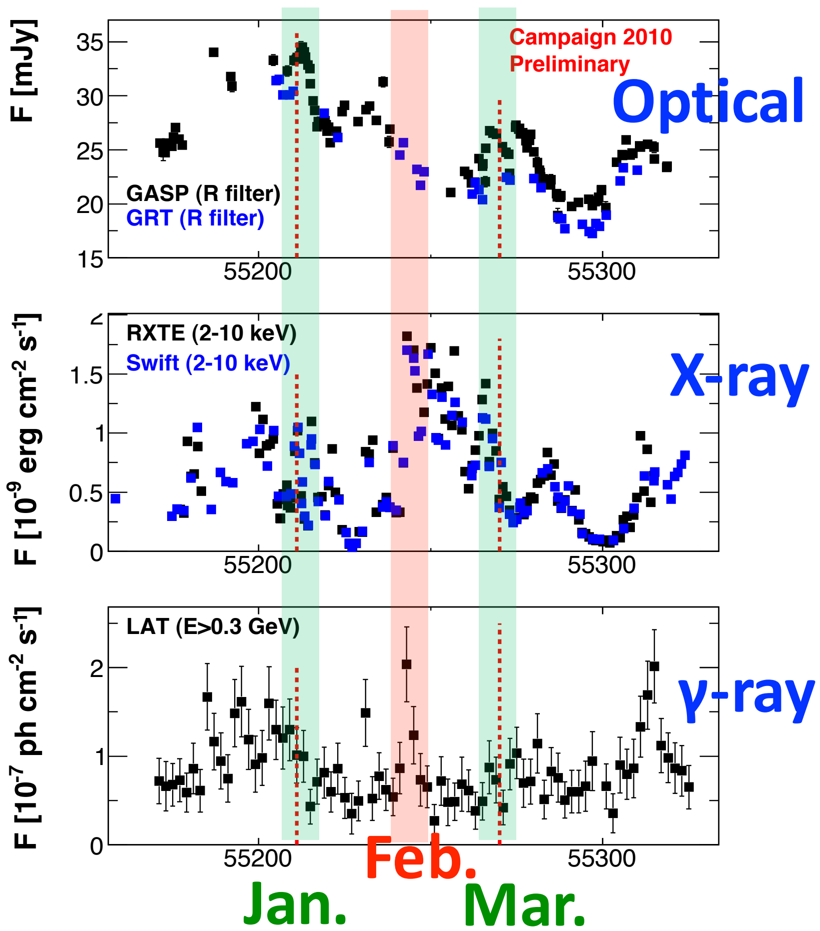
Mrk421 is also monitored with VLBA by the Boston Univ. Blazar group

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

Flaring activity with EVPA rotation
+
Flaring activity with ejection of VLBA blobs

Similar (but not identical !!) behaviour observed for various other sources (LBLs and FSRQs) in the last years:

BL Lacertae : Marscher et al, Nature 452 (966), 2008
PKS 1510-089 : Marscher et al, ApJL, 710 (126), 2010, Aleksic et al, A&A, 569 (46), 2014
3C 279 : Abdo et al, Nature 463 (919), 2010
3C 454.3 : Jorstad et al, ApJ 715 (362), 2010
OJ 287 : Agudo et al, ApJ 726 (13), 2011
AO 0235+164 : Agudo et al, ApJ 735 (10), 2011

See also Sevetlana Jorstad talk this morning for many more examples of these

NEVER observed before for Mrk421, Mrk501 or any other HBL

→ similar physical processes occur in jets of different blazar subclasses (which have different apparent jet speeds and overall power outputs).

Some flares may occur in the "acceleration and collimation region" (highly ordered B field)

Other flares may occur in the "quasi-stationary VLBA core" (turbulent B field, 1-100 pc downstream the supermassive black hole)

4 - Conclusions

New Instrumentation for gamma-ray astronomy (Fermi and modern IACTs like HESS/MAGIC/VERITAS) **provides a perspective that did not exist few years ago**

New instruments + good usage of the ones at low frequencies is already helping us to study blazars (and AGNs in general).
We also have new X-ray facilities: NuSTAR in operation since summer 2012 and, Astrosat in 2015 and Astro-H in 2016.

Need long-term studies on selected sources lasting many years

→Not possible to organize multi-year and multi-instrument campaigns for all objects

→ Need to select few objects (how many ?)

→**Brightest objects are a natural choice**

4 - 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, and many more to come*

We can use Mrk421 and Mrk501 as our blazar physics laboratory

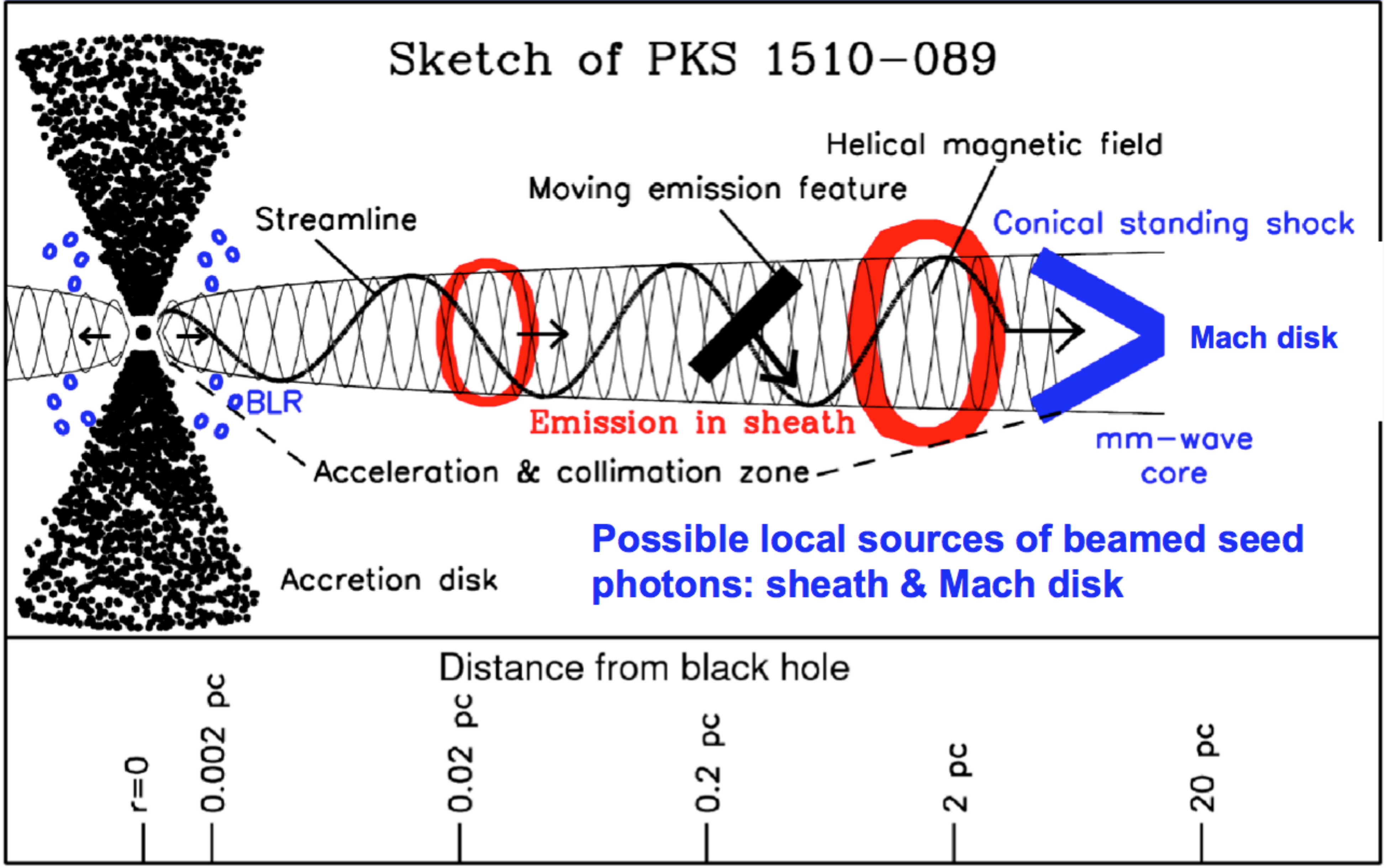
Lessons learnt might be applied to other blazars (farther away or weaker)

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

→Lots of things to learn….

backup

Sites of γ-ray Flares in PKS 1510-089 (Marscher et al. 2010 ApJL)

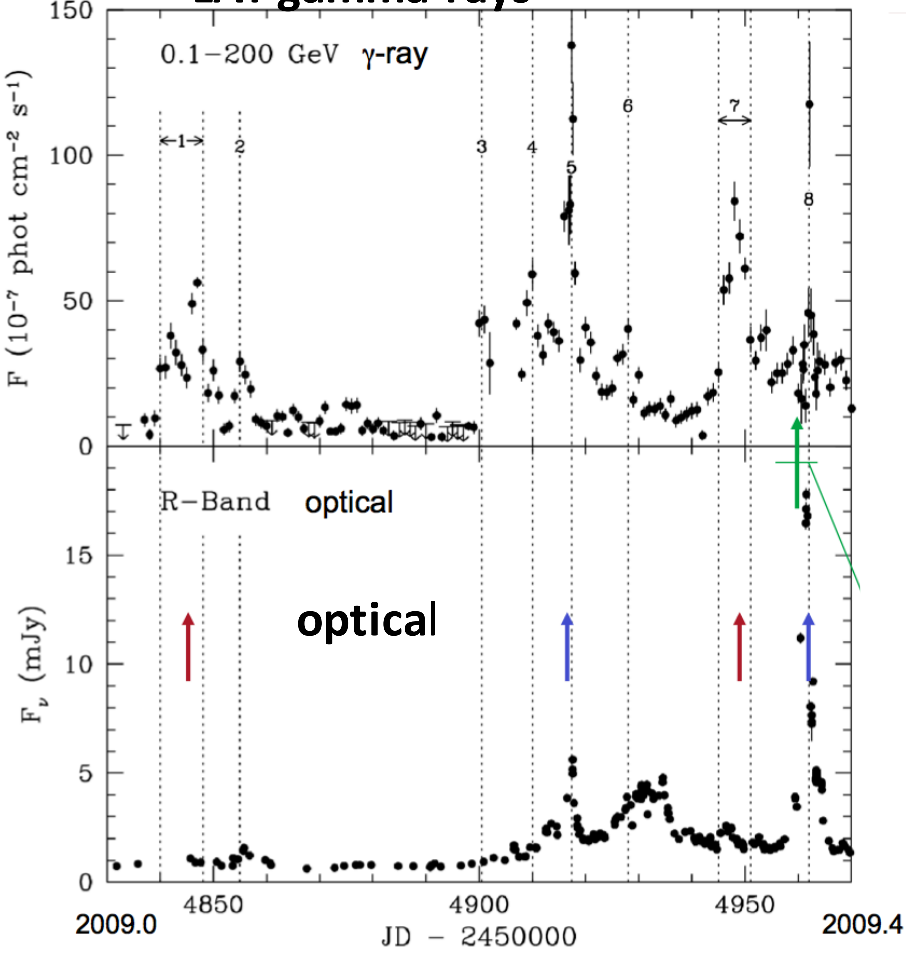


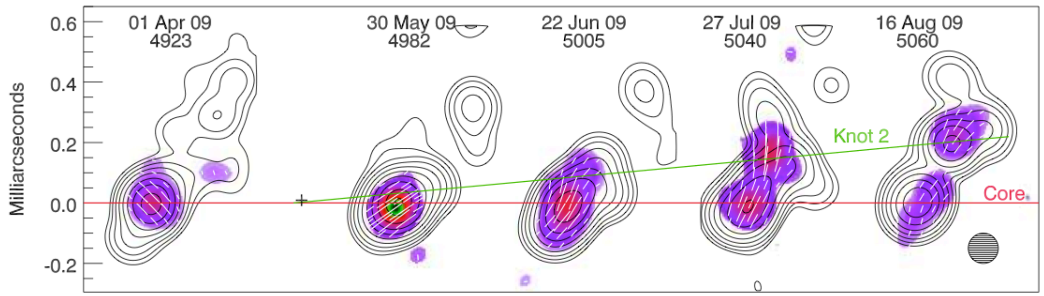
Possible local sources of beamed seed photons: sheath & Mach disk

Correlations with VLBA images and polarization

FSRQ PKS1510-089 (Marscher et al, 2010, ApJL, 710)

LAT gamma-rays

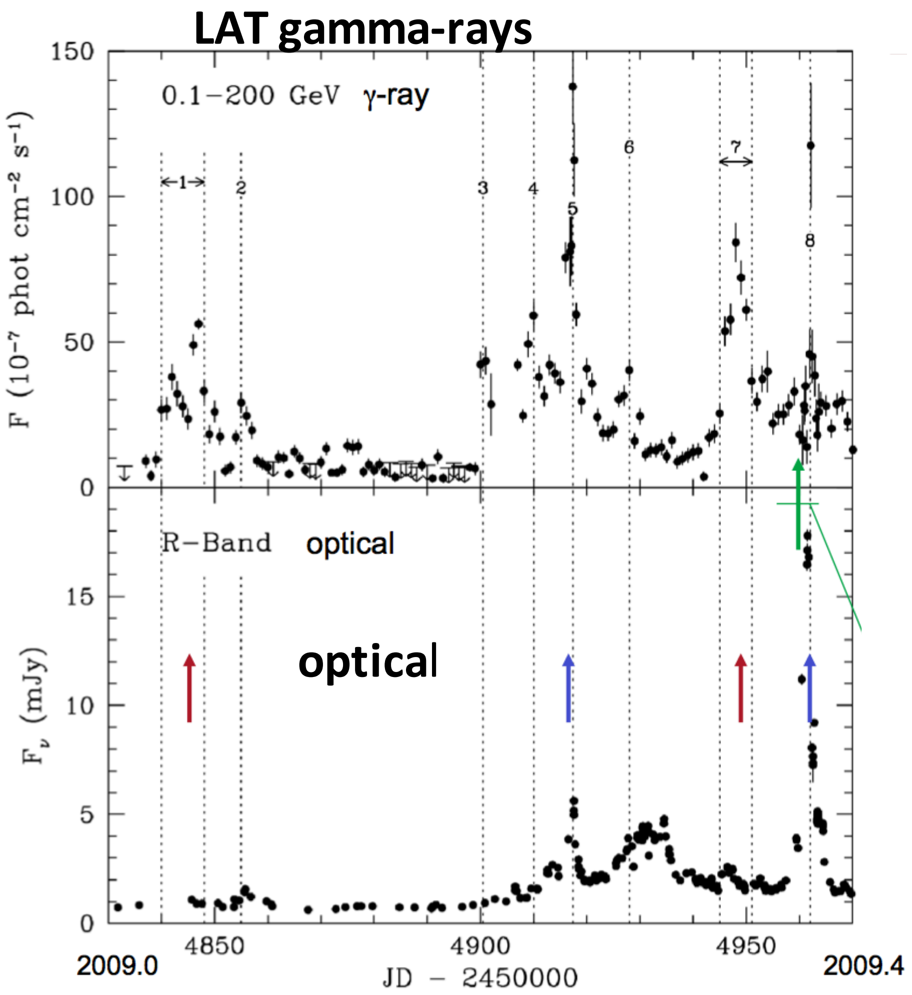


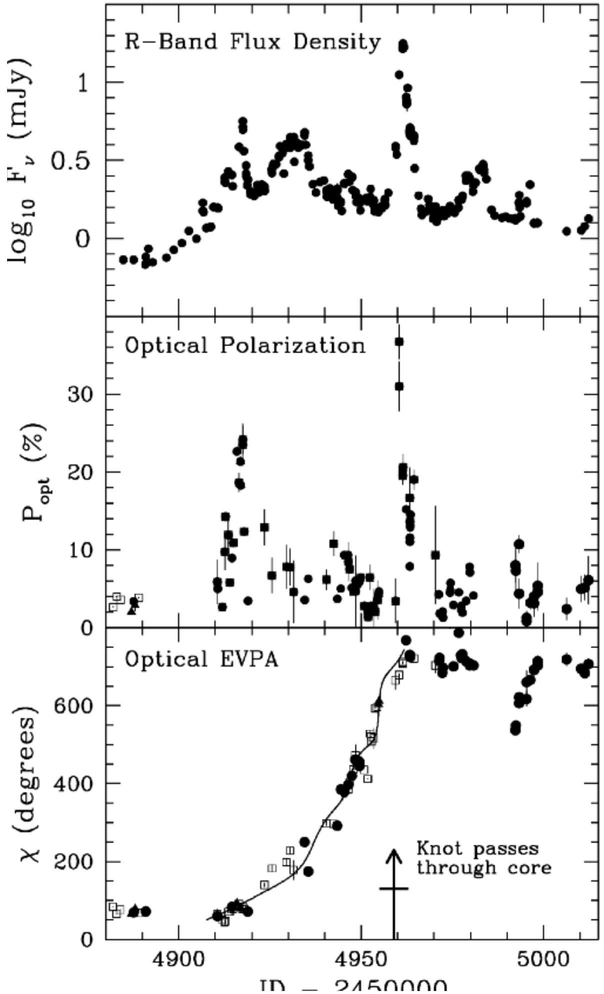


VLBA
43 GHz

Correlations with VLBA images and polarization

FSRQ PKS1510-089 (Marscher et al, 2010, ApJL, 710)

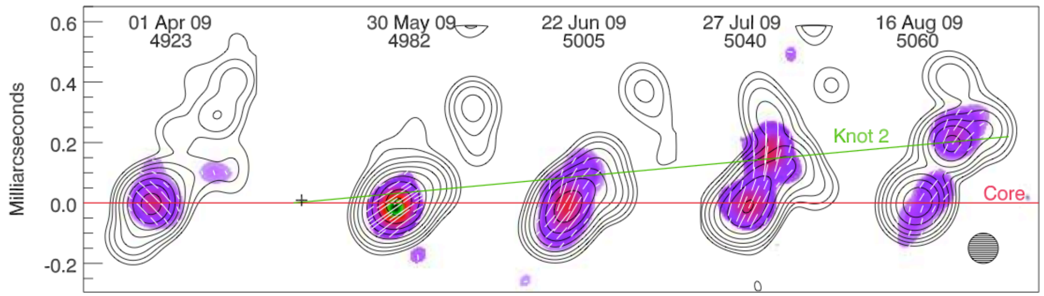




Optical flux (R band)

Optical polarization

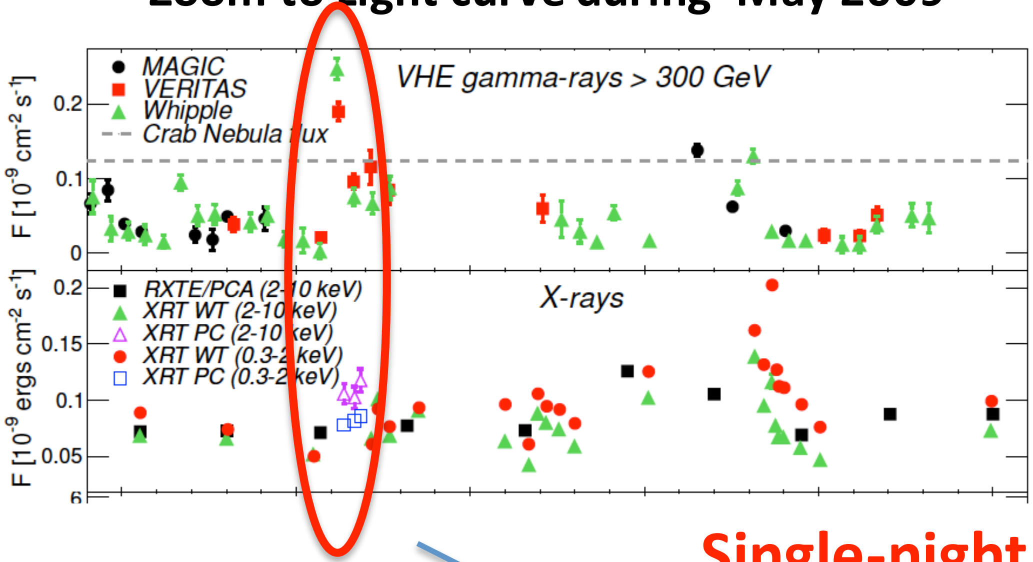
polarization angle



VLBA 43 GHz

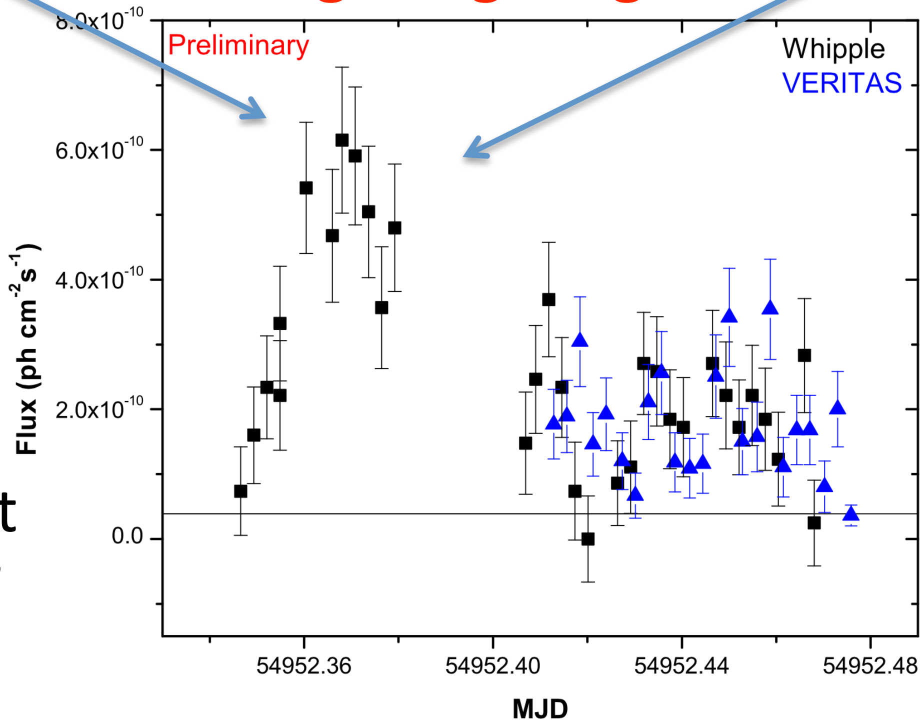
Mrk501 MW 2009

Zoom to Light curve during May 2009



Doert and Paneque, ICRC 2013 (arXiv:1307.8344)

Single-night light curve



Peak shows ~4 Crabs, which were reached in ~25 min

From the light curve, it seems that there is no much activity in X-rays

It looks like a sort of "orphan flare"

Pichel and Paneque, ICRC 2011 (arXiv:1110.2549)

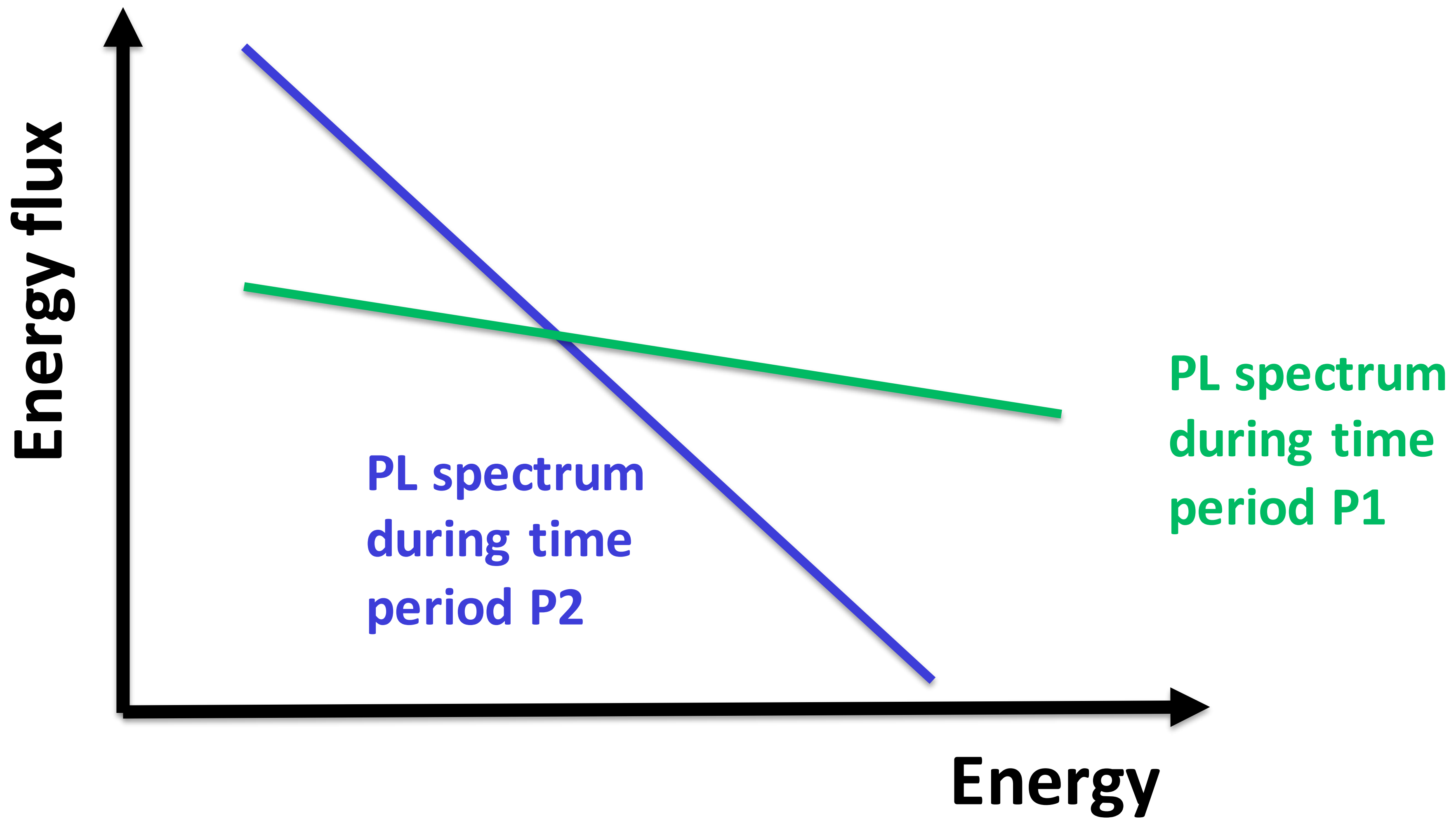
Some interesting targets (given the recent publications/measurements)

Bright HBL objects: **Mrk421, Mrk501, PKS2155-304, 1es1959+650**
High-redshift HBLs : **1es0229+200, PG1553, PKS1224+240**
LBLs : **W66A, Wcomae, BL Lacertae**
FSRQs : **3c279, PKS1510, PKS1222, 3C454.3**
Radio galaxies: **NGC1275, M87, IC310**
NLSy1: **J0948+0022, 1H 0323+342, SBS 0846+513, PKS 1502+036**
...

CAVEAT: Because of sensitivity of current gamma instruments, when sources are not flaring one needs to integrate over long periods of time. Because of variable nature of these sources, we might be integrating over different activity levels (different spectral shapes !!!) and hence robust interpretation of the experimental results is complicated

→ The brighter the object, the easier is to study it (less biased)

Example of potential problems when using accumulated data over a time period containing spectral variability



Integrated spectrum during time period P1+P2 will show an upturn with respect to a “simple PL fit”

Table 2: Integral flux above 200 GeV and parameters of the one-zone SSC model. Bold-faced text is used to depict the model parameters that were varied to describe the SED during the 13-day period.

Date [MJD]	MAGIC flux [10^{-10}cm^{-2}s^{-1}]	VERITAS flux [10^{-10}cm^{-2}s^{-1}]	Whipple flux [10^{-10}cm^{-2}s^{-1}]	γ_{min} [10^2]	γ_{max} [10^8]	γ_{br1} [10^4]	γ_{br2} [10^5]	s_1	s_2	s_3	n_e [10^3cm^{-3}]	B [mG]	log(R) [cm]	δ
55265	3.8 ± 0.2	4.0 ± 0.5		8	1	**60.**	**6.0**	**2.23**	**2.23**	4.70	**1.14**	38	16.72	21
55266	4.7 ± 0.2			8	1	**66.**	**6.6**	**2.23**	**2.23**	4.70	**1.16**	38	16.72	21
55267		4.0 ± 0.5	5.3 ± 0.3	8	1	**16.**	**6.0**	**2.23**	**2.70**	4.70	**1.10**	38	16.72	21
55268	2.1 ± 0.3	4.0 ± 0.6	4.8 ± 0.3	8	1	**16.**	**6.0**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55269	3.3 ± 0.3	4.2 ± 0.6	4.2 ± 0.3	8	1	**12.**	**7.0**	**2.20**	**2.70**	4.70	**0.95**	38	16.72	21
55270	2.3 ± 0.2	2.6 ± 0.4	3.0 ± 0.2	8	1	**8.0**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55271		3.5 ± 0.4	4.1 ± 0.5	8	1	**9.0**	**5.0**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55272		2.5 ± 0.4		8	1	**5.0**	**4.0**	**2.20**	**2.50**	4.70	**0.90**	38	16.72	21
55273	1.5 ± 0.2	2.0 ± 0.4	2.5 ± 0.3	8	1	**6.0**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55274	1.0 ± 0.3	1.6 ± 0.3	1.9 ± 0.2	8	1	**3.5**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55275			1.8 ± 0.3	8	1	**5.0**	**3.9**	**2.20**	**2.70**	4.70	**0.85**	38	16.72	21
55276	1.6 ± 0.2		1.5 ± 0.3	8	1	**5.7**	**3.9**	**2.20**	**2.70**	4.70	**0.90**	38	16.72	21
55277	1.2 ± 0.1		1.4 ± 0.4	8	1	**8.0**	**3.9**	**2.20**	**2.70**	4.70	**0.70**	38	16.72	21

Notes. VERITAS and Whipple fluxes were measured around seven hours after the MAGIC observations.

Table 3: Integral flux above 200 GeV and parameters of the two-zone SSC model. Bold-faced text is used to depict the model parameters that were varied to describe the SED during the 13-day period.

Date [MJD]	MAGIC flux [10^{-10}cm^{-2}s^{-1}]	VERITAS flux [10^{-10}cm^{-2}s^{-1}]	Whipple flux [10^{-10}cm^{-2}s^{-1}]	γ_{min} [10^4]	γ_{max} [10^5]	γ_{br1} [10^5]	γ_{br2} [10^5]	s_1	s_2	s_3	n_e [10^3cm^{-3}]	B [mG]	log(R) [cm]	δ
the quiescent blob														
Parameters fixed for all dates to those from MJD 55274 one-zone SSC				0.08	1000	0.35	3.9	2.2	2.7	4.7	0.9	38	16.72	21
the flaring blob														
55265	3.8 ± 0.2	4.0 ± 0.5		**3.0**	6	**3.0**	- -	2.0	3.0	- -	**5.0**	**105**	15.51	35
55266	4.7 ± 0.2			**3.0**	6	**3.0**	- -	2.0	3.0	- -	**6.0**	**100**	15.51	35
55267		4.0 ± 0.5	5.3 ± 0.3	**2.5**	6	**1.1**	- -	2.0	3.0	- -	**5.9**	**100**	15.51	35
55268	2.1 ± 0.3	4.0 ± 0.6	4.8 ± 0.3	**5.3**	6	**1.8**	- -	2.0	3.0	- -	**5.6**	**100**	15.51	35
55269	3.3 ± 0.3	4.2 ± 0.6	4.2 ± 0.3	**3.0**	6	**2.3**	- -	2.0	3.0	- -	**5.2**	**90**	15.51	35
55270	2.3 ± 0.2	2.6 ± 0.4	3.0 ± 0.2	**3.5**	6	**0.8**	- -	2.0	3.0	- -	**6.0**	**75**	15.51	35
55271		3.5 ± 0.4	4.1 ± 0.5	**3.5**	6	**1.2**	- -	2.0	3.0	- -	**6.5**	**75**	15.51	35
55272		2.5 ± 0.4		**3.5**	6	**2.0**	- -	2.0	3.0	- -	**3.0**	**75**	15.51	35
55273	1.5 ± 0.2	2.0 ± 0.4	2.5 ± 0.3	**3.5**	6	**0.5**	- -	2.0	3.0	- -	**4.0**	**75**	15.51	35
55274	1.0 ± 0.3	1.6 ± 0.3	1.9 ± 0.2	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
55275			1.8 ± 0.3	**3.5**	6	**0.5**	- -	2.0	3.0	- -	**5.0**	**60**	15.51	35
55276	1.6 ± 0.2		1.5 ± 0.3	**3.5**	6	**1.0**	- -	2.0	3.0	- -	**3.0**	**60**	15.51	35
55277	1.2 ± 0.1		1.4 ± 0.4	**3.5**	6	**0.8**	- -	2.0	3.0	- -	**2.5**	**60**	15.51	35

Notes. On MJD 55274, Mrk 421 had the lowest broadband activity among all the 13 dates. The quiescent blob emission was fixed to the SED of this date, and consequently the emission of the flaring blob on this date is null.

Table 4: Peak positions and widths of the synchrotron and inverse-Compton bumps derived from the two-zone SSC model parameters reported in Table 3.

Date	ν^{syn}_{peak}	$(\nu F_\nu)^{syn}_{peak}$	ν^{syn}_1	ν^{syn}_2	$\log(\nu^{syn}_2/\nu^{syn}_1)$	ν^{ic}_{peak}	$(\nu F_\nu)^{ic}_{peak}$	ν^{ic}_1	ν^{ic}_2	$\log(\nu^{ic}_2/\nu^{ic}_1)$
- -	$[10^{17}]$	$[10^{-10}]$	$[10^{15}]$	$[10^{18}]$	- -	$[10^{25}]$	$[10^{-11}]$	$[10^{23}]$	$[10^{26}]$	- -
[MJD]	[Hz]	[erg $cm^{-2}s^{-1}$]	[Hz]	[Hz]	- -	[Hz]	[erg $cm^{-2}s^{-1}$]	[Hz]	[Hz]	- -
55265	8.1	7.9	34.	6.1	2.3	10.	15.	60.	9.5	2.2
55266	8.1	8.0	34.	5.9	2.2	10.	18.	94.	9.9	2.0
55267	4.0	5.5	11.	3.3	2.5	10.	17.	56.	5.1	2.0
55268	4.0	6.6	30.	4.5	2.2	17.	11.	16.	7.3	2.7
55269	4.0	6.1	1.9	4.5	2.4	10.	14.	42.	7.8	2.3
55270	2.0	3.9	5.7	2.3	2.6	6.0	10.	11.	4.3	2.6
55271	2.0	4.6	9.0	2.6	2.5	1.0	13.	30.	5.4	2.3
55272	4.0	3.8	4.9	2.8	2.8	3.4	11.	7.4	4.5	2.8
55273	2.0	3.1	3.1	1.9	2.8	1.9	7.7	3.9	3.0	2.9
55274	2.0	2.5	1.8	1.6	2.9	1.9	7.1	3.0	2.4	2.9
55275	2.0	3.0	2.8	1.8	2.8	3.4	7.9	4.2	3.0	2.9
55276	2.0	3.1	3.1	1.8	2.8	1.9	7.5	3.6	3.2	2.9
55277	2.0	2.9	2.7	1.7	2.8	1.9	7.4	3.4	2.8	2.9

Notes. ν^{syn}_{peak}: the peak frequency of the synchrotron bump; $(\nu F_\nu)^{syn}_{peak}$: the peak energy flux of the synchrotron bump; ν^{ic}_{peak}: the peak frequency of the inverse-Compton bump; $(\nu F_\nu)^{ic}_{peak}$: the peak energy flux of the inverse-Compton bump. For each bump in the SED, the value of $(\nu F_\nu)_{peak}/2$ determines the two frequencies (ν_1 and ν_2) that are used to quantify the width of the bump in the logarithmic scale $\log(\nu_2/\nu_1)$.

Table 5: Jet powers and luminosities derived with the parameters from the one-zone SSC model reported in Table 2.

Date --- [MJD]	N_e $[10^{-1}]$ $[\mathrm{cm}^{-3}]$	$\langle\gamma_e\rangle$ $[10^3]$ ---	L_e $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_p $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_B $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	U'_e/U'_B $[10^1]$ ---	L_{jet} $[10^{44}]$ $[\mathrm{erg\ s^{-1}}]$	L_{syn} $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	L_{IC} $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	L_{ph} $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$
55265	2.5	3.4	7.8	4.2	6.5	1.2	1.3	6.6	14.	8.1
55266	2.5	3.4	8.0	4.3	6.5	1.2	1.3	7.2	16.	8.8
55267	2.4	3.3	7.3	4.0	6.5	1.1	1.2	4.6	11.	5.7
55268	2.5	3.5	7.9	4.2	6.5	1.2	1.3	5.4	14.	6.7
55269	2.6	3.4	8.2	4.4	6.5	1.3	1.3	5.5	14.	6.9
55270	2.5	3.3	7.5	4.1	6.5	1.2	1.2	3.5	9.8	4.5
55271	2.5	3.4	7.6	4.1	6.5	1.2	1.2	4.0	11.	5.1
55272	2.5	3.3	7.5	4.1	6.5	1.1	1.2	3.7	10.	4.7
55273	2.5	3.2	7.3	4.1	6.5	1.1	1.2	3.1	8.7	4.0
55274	2.5	3.1	7.0	4.1	6.5	1.1	1.2	2.5	6.5	3.1
55275	2.3	3.2	6.8	3.9	6.5	1.1	1.1	2.8	7.2	3.5
55276	2.5	3.2	7.3	4.1	6.5	1.1	1.2	3.0	8.2	3.8
55277	1.9	3.3	5.8	3.2	6.5	.90	.97	2.6	5.7	3.2

Notes. N_e: total electron number density; $\langle\gamma_e\rangle$: mean electron Lorentz factor; L_e: jet power carried by electrons; L_p:the jet power carried by protons; L_B: jet power carried by the magnetic field; U'_e/U'_B: the ratio of comoving electron and magnetic-field energy densities; L_{jet}: total jet power; L_{syn}: the synchrotron luminosity; L_{IC}: inverse-Compton luminosity; L_{ph}: total photon luminosity from the SSC model. See the calculation explanation in Section 5.

Table 6: Jet powers and luminosities derived with the parameters from the two-zone SSC model reported in Table 3.

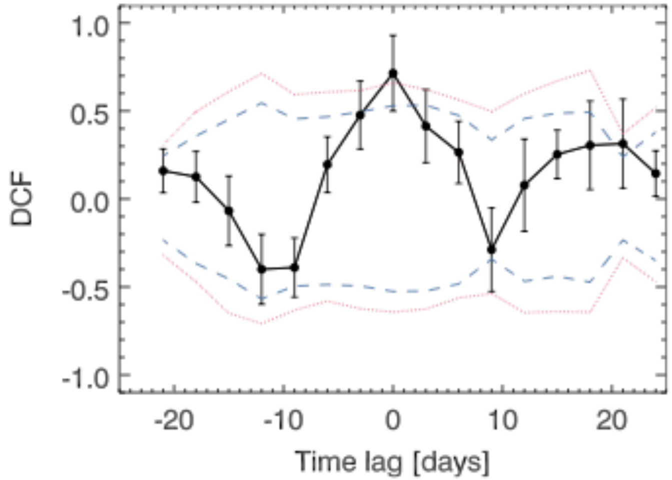
Date --- [MJD]	N_e $[10^{-1}]$ $[\mathrm{cm}^{-3}]$	$\langle\gamma_e\rangle$ $[10^4]$ ---	L_e $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_p $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	L_B $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	U'_e/U'_B $[10^1]$ ---	L_{jet} $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	L_{syn} $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	L_{IC} $[10^{40}]$ $[\mathrm{erg\ s^{-1}}]$	L_{ph} $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_e$ $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_p$ $[10^{43}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_B$ $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{jet}$ $[10^{44}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{syn}$ $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{IC}$ $[10^{41}]$ $[\mathrm{erg\ s^{-1}}]$	$^{sum}L_{ph}$ $[10^{42}]$ $[\mathrm{erg\ s^{-1}}]$
the quiescent blob																	
- -	2.5	.31	7.0	410	65.	1.1	12.	25.	65.	31.							
the flaring blob											the quiescent blob + the flaring blob						
55265	1.6	9.0	1.4	2.8	5.3	2.6	1.5	13.	18.	15.	8.4	4.1	7.0	1.3	3.8	8.3	4.6
55266	1.9	9.0	1.7	3.4	4.8	3.4	1.7	13.	23.	15.	8.7	4.1	7.0	1.4	3.8	8.8	4.6
55267	2.1	6.5	1.3	3.8	4.8	2.8	1.4	7.9	18.	9.7	8.3	4.1	7.0	1.3	3.3	8.3	4.1
55268	.89	12.	1.1	1.6	4.8	2.2	1.1	9.5	8.8	10.	8.1	4.1	7.0	1.3	3.4	7.4	4.1
55269	1.6	8.6	1.4	2.9	3.9	3.5	1.4	8.7	15.	10.	8.4	4.1	6.9	1.3	3.4	8.0	4.1
55270	1.3	7.6	1.0	2.4	2.7	3.7	1.1	3.4	7.3	4.2	8.0	4.1	6.8	1.3	2.8	7.2	3.5
55271	1.6	8.4	1.3	2.9	2.7	4.8	1.4	5.0	12.	6.2	8.3	4.1	6.8	1.3	3.0	7.7	3.7
55272	.77	9.3	.71	1.4	2.7	2.6	.76	3.5	9.9	4.5	7.7	4.1	6.8	1.3	2.8	7.5	3.5
55273	.74	6.9	.50	1.3	2.7	1.9	.54	1.5	1.9	1.7	7.5	4.1	6.8	1.3	2.7	6.7	3.3
55274	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	7.0	4.1	6.5	1.2	2.5	6.5	3.1
55275	.93	6.9	.63	1.7	1.7	3.6	.66	1.2	2.2	1.5	7.6	4.1	6.7	1.3	2.6	6.7	3.2
55276	.70	8.0	.56	1.3	1.7	3.2	.59	1.3	1.7	1.5	7.6	4.1	6.7	1.3	2.6	6.7	3.2
55277	.56	7.6	.42	1.0	1.7	2.4	.45	.92	.95	1.0	7.4	4.1	6.7	1.2	2.6	6.6	3.2

Notes. N_e: total electron number density; $\langle\gamma_e\rangle$: mean electron Lorentz factor; L_e: jet power carried by electrons; L_p: jet power carried by protons; L_B: jet power carried by the magnetic field; U'_e/U'_B: ratio of comoving electron and magnetic-field energy densities; L_{jet}: total jet power; L_{syn}: synchrotron luminosity; L_{IC}: inverse-Compton luminosity; L_{ph}: total photon luminosity from the SSC model. See the calculation explanation in Section 5. The quantities with the ^{sum} superscript report the sums of the quantities from the quiescent and the flaring blob.

Correlations

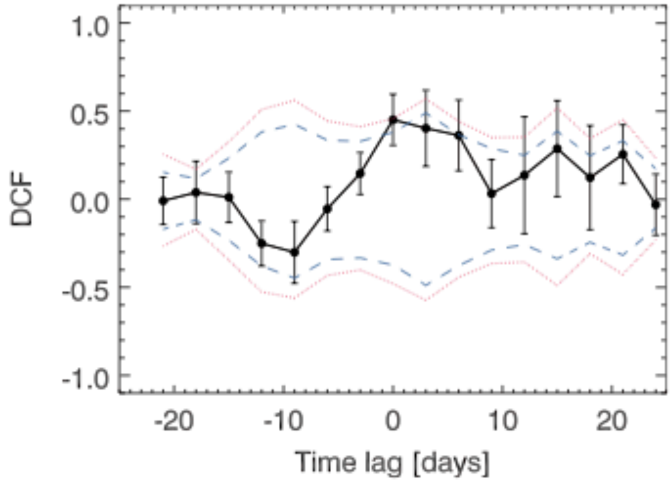
Mrk501

Aleksic et al, 2015, *A&A* 573, 50



(a) *RXTE*/PCA vs. *Swift*/XRT

Little variability in 2008 (see marginal correlation RXTE with SwiftXRT)



(b) *RXTE*/PCA vs. MAGIC & VERITAS

Marginal correlation for X-ray and VHE