Extensive multifrequency campaigns on the classical TeV blazars Mrk421 and Mrk501 in the Fermi era

D.Paneque, **J.Finke, M. Georganopoulos, A.Reimer, L.Stawarz, D.Tescaro**
On behalf of the Fermi, MAGIC, VERITAS collaborations and the participants/groups of the MW campaigns on Mrk421 and Mrk501 in 2009, which includes GASP-WEBT, F-GAMMA and many others

Outline of the talk

1 – Introduction

2 – Fermi view of Mrk421 and Mrk501

3 – Some results from the MW campaigns in 2009

4 - Conclusions

1 – Intro: Motivations for studying Mrk421 and Mrk501

Exquisite characterization of the high energy component, which can be detected with Fermi and Cherenkov Telescopes over 5 orders of magnitude (0.1 GeV – 10 TeV)

Excellent laboratory for studying High Energy blazar emission

Strong gamma ray source &
Nearby object; z = 0.03; "low" EBL absorption, we see "almost" intrinsic features

Knowledge acquired with Mrk421 and Mrk501 might be applied to other objects (fainter and/or larger z)*. Or maybe not… some sources might be special. CAVEAT (!!)*

Things we know about those classical TeV sources (and HBLs in general)

Dominant gamma-ray emission mechanism is believed to have a leptonic origin (SSC), at least in high (flaring) state

- **Fast variations (down to hours and sub-hours in VHE)**
- **X-rays/gamma-rays correlation (in general)**

2 - Fermi view of Mrk421 and Mrk501

2.1 – Intro: some info on Mrk421

RA =166.11 ; DEC=38.20
Z = 0.031
First extragalactic TeV emitter
(*Punch et al, 1992, Nature 358, 477*)

Known to be one of the fastest varying gamma-ray sources (*Gaidos, J.A. et al, 1996, Nature 383, 319; and many other publications*).

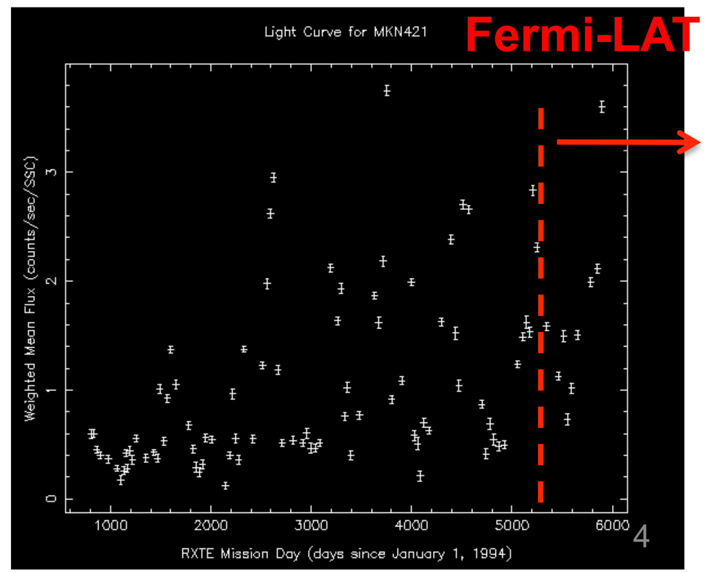
All detections of EGRET (9 years of operation)

Source VP[a]	(RA, Dec) MJD Range	Flux[b]	$\sqrt{(TS)}$[c]	Gamma[d]
Mrk 421	(166.10, 38.15)			
0.6	48383.7-386.8	19.7±11.3	2.2	...
4.0	48435.8-449.7	15.6±3.8	5.4	2.07±0.28
40.0	48882.7-903.6	21.6±6.9	4.0	2.01±0.34
V+218.0	49097.6-138.6	11.2±4.5	3.0	
V+227.0	49167.6-195.5	15.1±5.9	3.4	2.68±0.39
326.0	49482.7-489.6	24.4±6.7	5.3	1.47±0.29
V+322.0	49447.6-489.6	13.7±3.3	5.5	1.20±0.27

Detection significance (EGRET) <~ 5 sigma

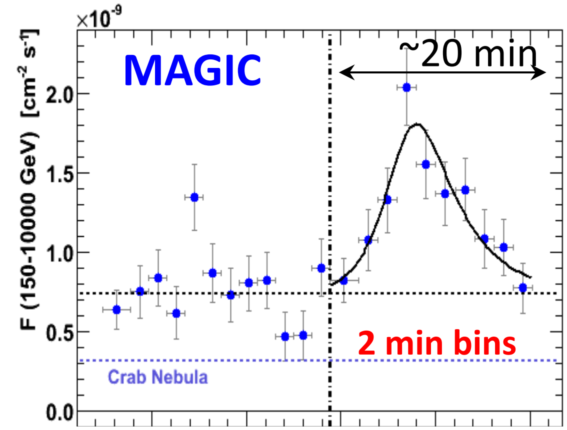
RXTE/ASM Light Curve (2-10 keV)

So far we lacked info on Gamma-ray emission Fermi-LAT provides key/missing information



2.2 – Intro: some info on Mrk 501

RA =253.47 ; DEC = 39.76 , z = 0.034
Discovery at VHE: Quinn et al., 1996
2nd Extragalactic source detected at TeV
- Huge flare in 1997 (many publications)
- Short flux variations detected in 2005
Albert et al., 2007, ApJ, 669, 862

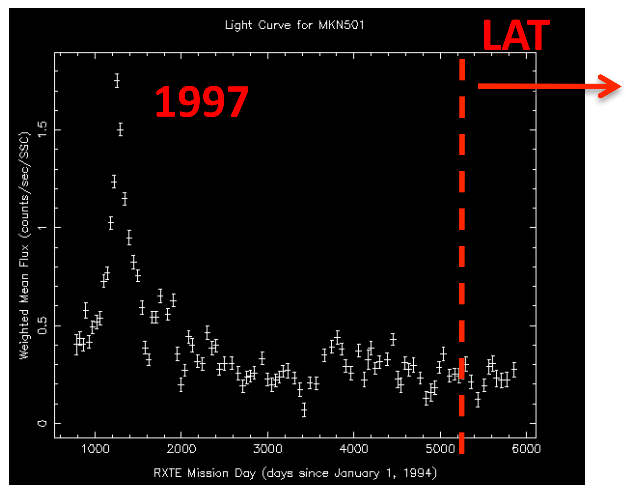


Not present in 3rd EGRET catalogue

The only detection (*~5 sigma at >500 MeV; 4 sigma at >100 MEV*) with EGRET was during a gamma-ray orphan flare in 1996 (Kataoka et al., 1999)

No EGRET detection during the big outburst in 97

RXTE/ASM Light Curve (2-10 keV)

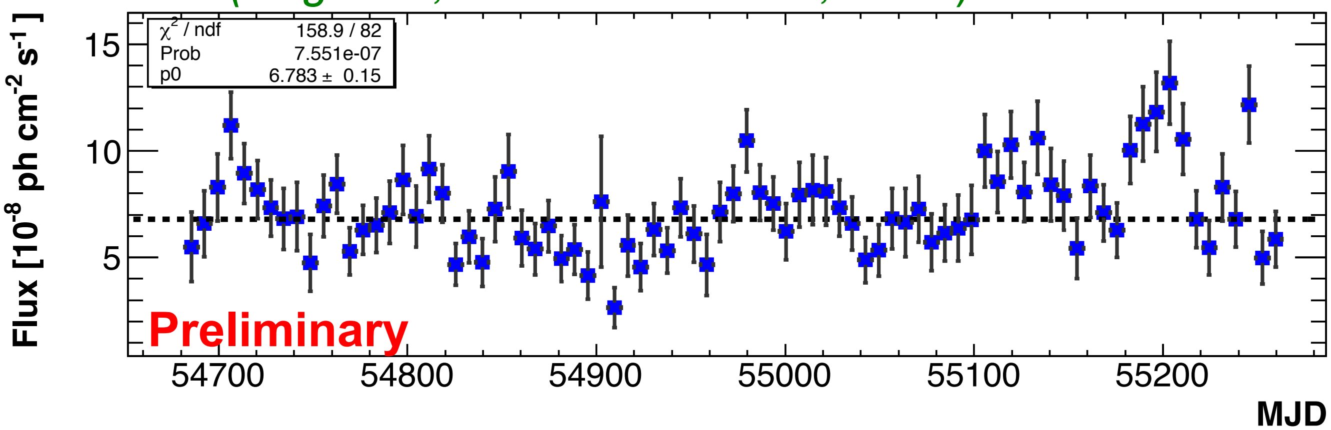


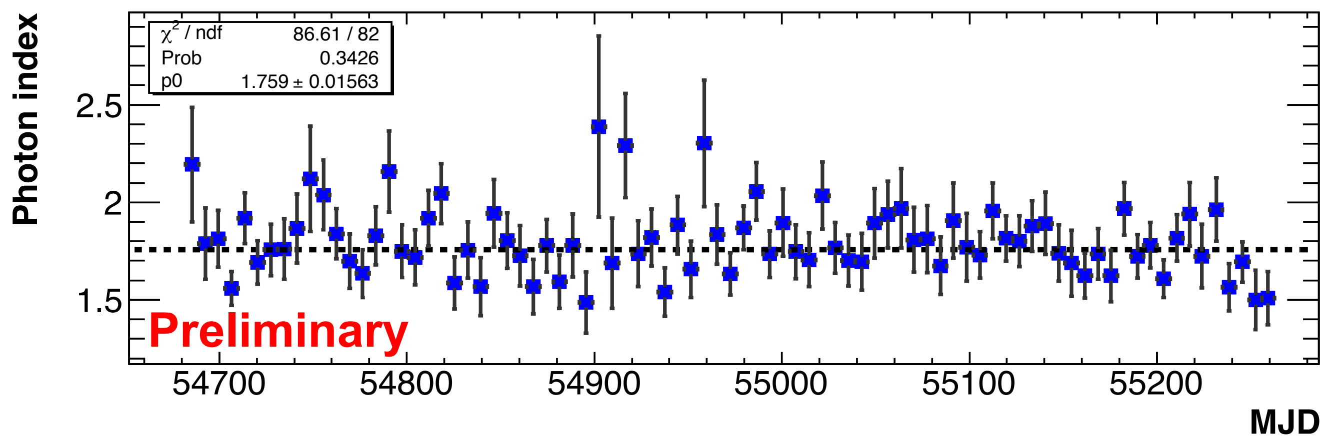
Source is relatively low at X-rays since Fermi operation

2.1 – Flux and spectral variability from Mrk421

Light Curve (flux/index) at E>0.3 GeV for 7-day time intervals

(August 5, 2008 – March 12, 2010)





Before Fermi, Mrk421 was not significantly detected at GeV

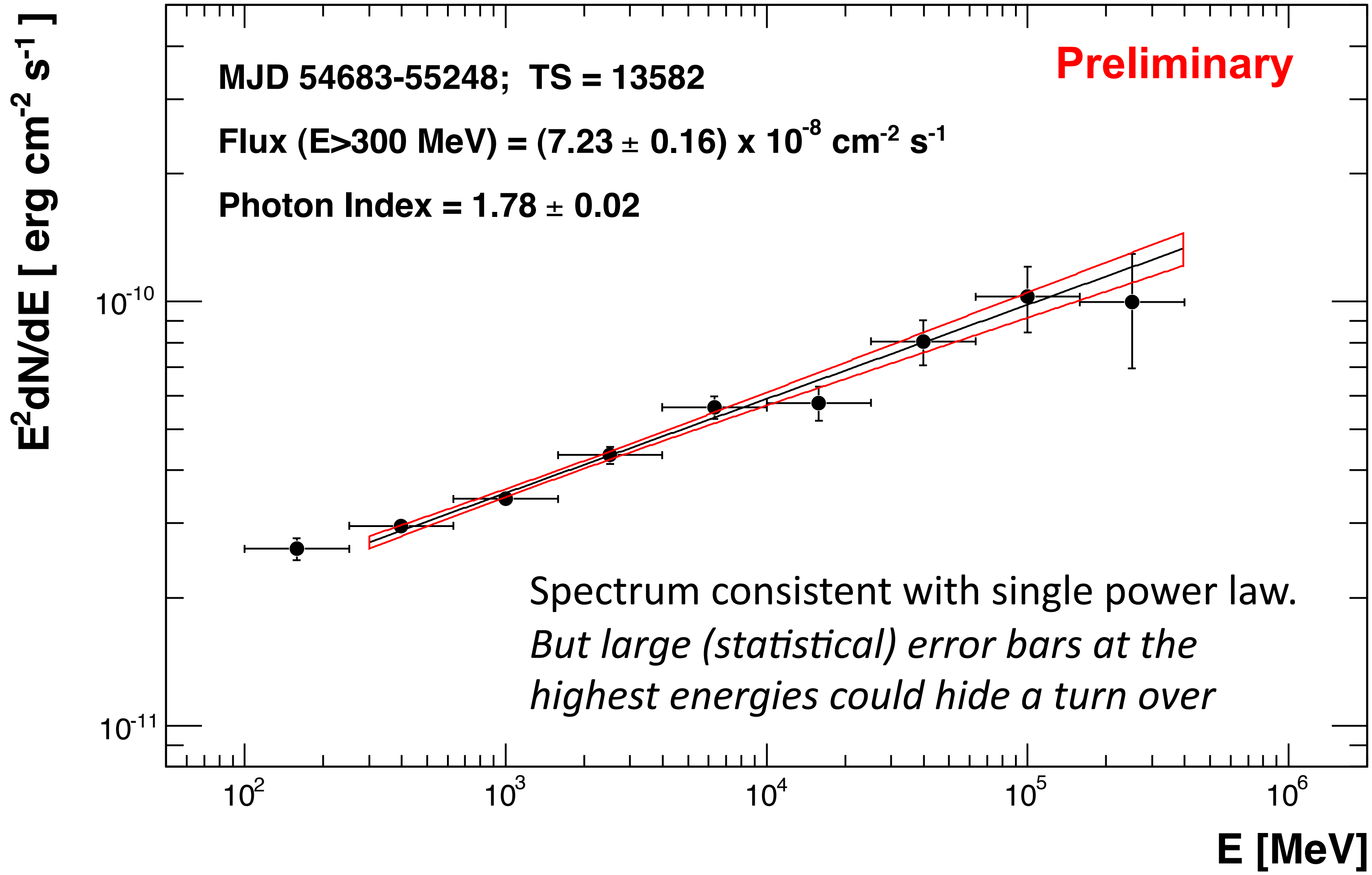
Now we can monitor the gamma-activity with good accuracy

Typically TS>100 (i.e., ~10 sigma) for all the 7-day time intervals

Mrk421 detected systematically with LAT regardless of activity

2.1 – Spectrum of Mrk421 up to 400 GeV

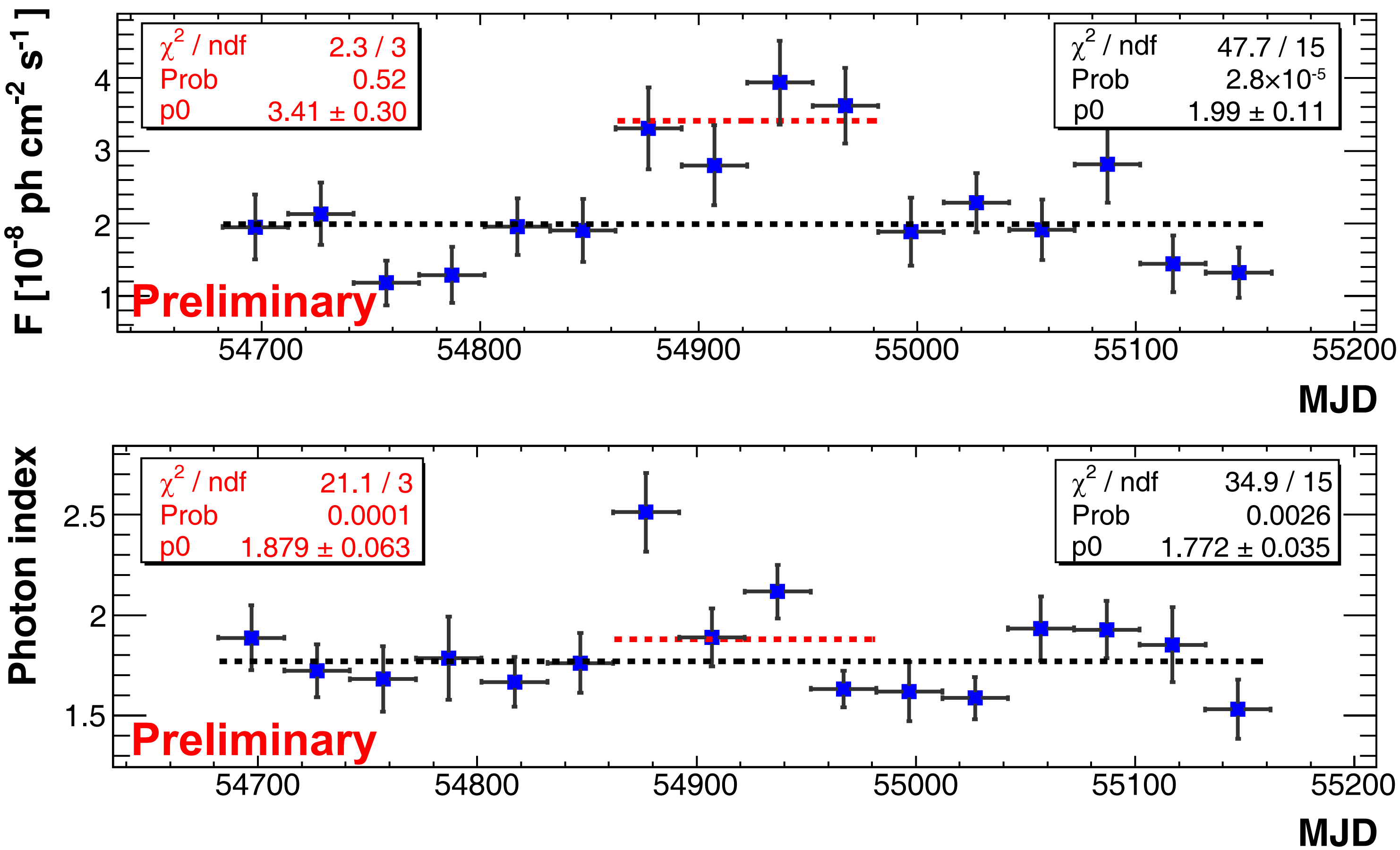
Spectrum computed using 1.5 years of Fermi data (Aug4,2008- Feb21,2010)



2.2 – Flux and spectral variability from Mrk501

Light Curve (flux/index) at E>0.3 GeV for 30-day time intervals

(August 5, 2008 – November 27, 2009)



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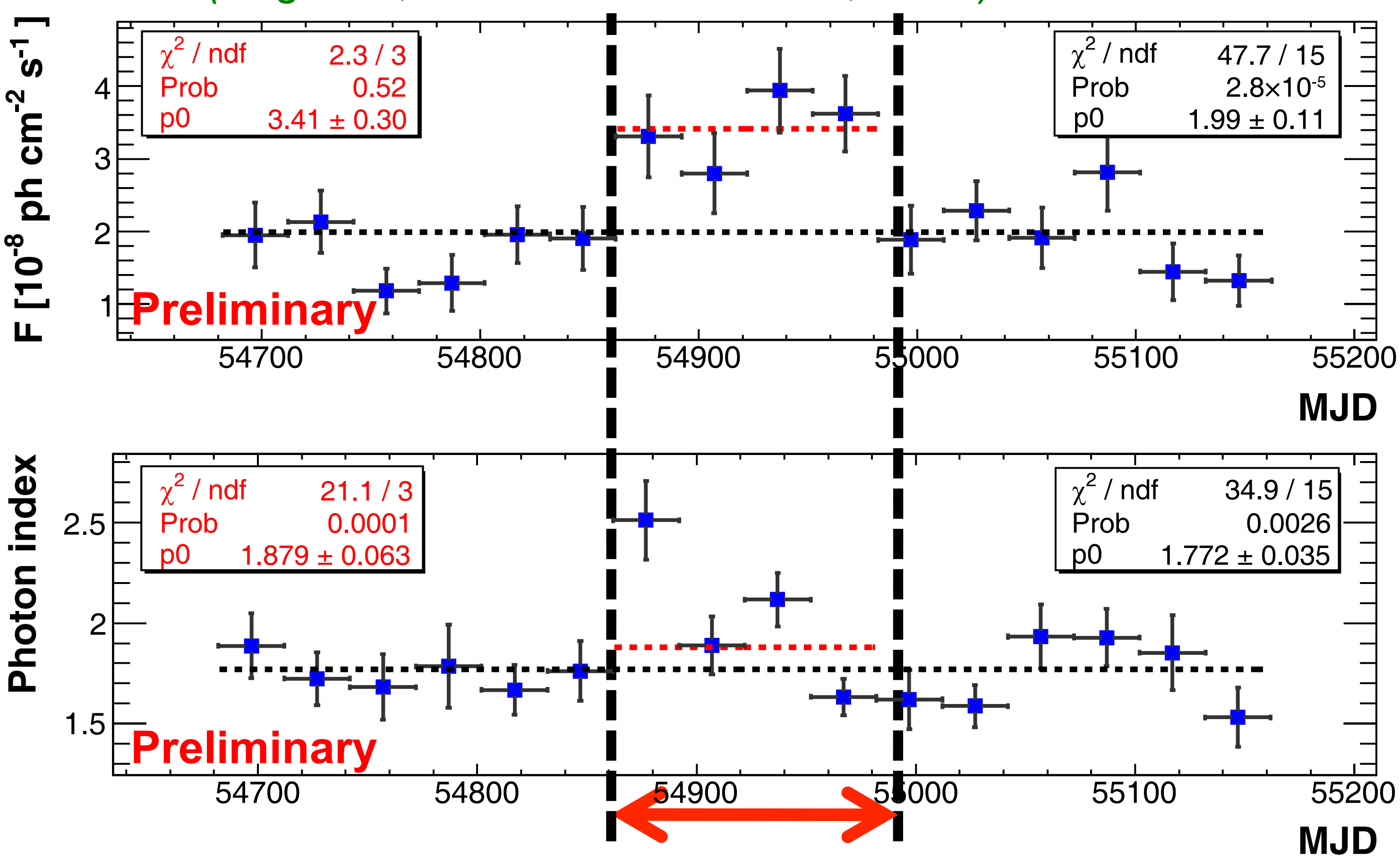


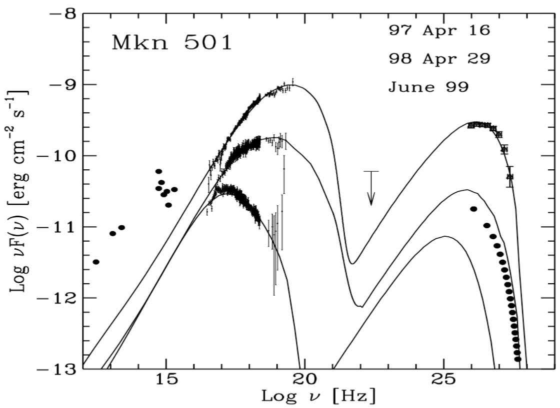
120-day interval with enhanced photon flux and LARGE spectral changes:

Hardest index =1.64+/- 0.09; Softest index =2.51+/-0.20

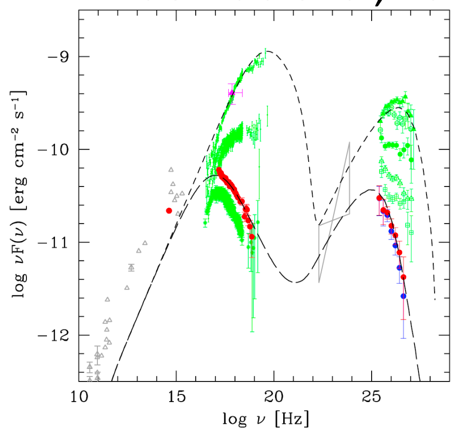
2.2 – Flux and spectral variability

Light Curve (flux/index) at E>0.3 GeV for 30-day time intervals

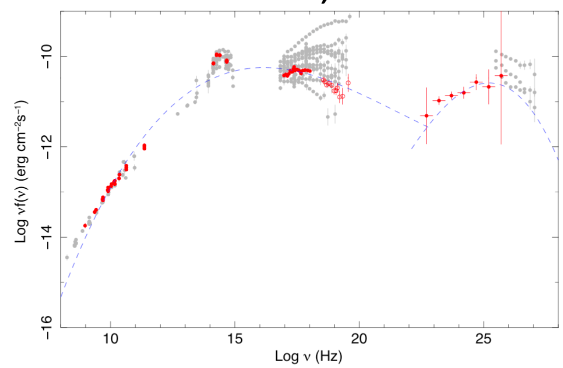
Tavecchio et al, 2001



Anderhub et al, 2009



Abdo et al, 2009



None of the previous publications (models) considered the possibility of photon index 2.5 for Mrk501 in the GeV range

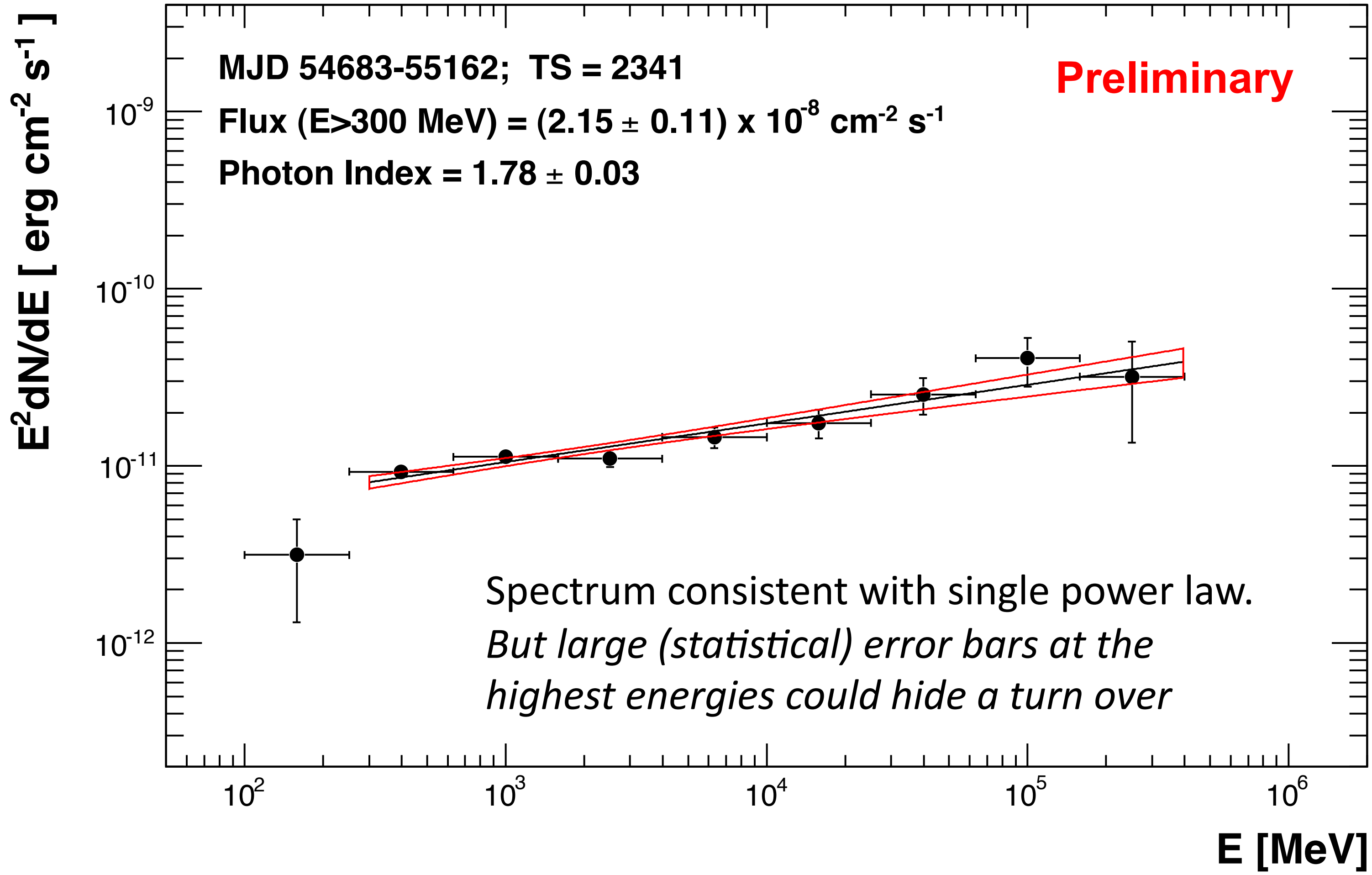
← **Unexpected !!!!**

120-day interval with enhanced photon flux and LARGE spectral changes:

Hardest index =1.64+/- 0.09; Softest index =2.51+/-0.20

2.2 – Spectrum of Mrk501 up to 400 GeV

Spectrum computed using 16 months of Fermi data (Aug4,2008- Nov27,2009)



3 – Some Results from the multi-instrument 2009 campaigns for Mrk421 and Mrk501

3.1 – Broad Band SED of Mrk421 and Mrk501

Blazars emit over a **broad energy range + emission is variable.**

→ Contemporaneous multi-instrument observations are required

Extensive campaigns on Mrk421 and Mrk501

Mrk421 (Jan19th, 2009-Jun1st ,2009: 4.5 months)- Planned observations: every 2 days
https://confluence.slac.stanford.edu/display/GLAMCOG/Campaign+on+Mrk421+(Jan+2009+to+May+2009

Mrk501 (Mar15th, 2009-Aug1st,2009: 4.5 months) -Planned observations: every 5 days
https://confluence.slac.stanford.edu/display/GLAMCOG/Campaign+on+Mrk501+(March+2009+to+July+2009

Source monitored regardless of activity

•20ish instruments participated covering frequencies from radio to TeV

Radio: VLBA, OVRO, Effelsberg, Metsahovi…
mm: SMA
Infrared: WIRO, OAGH
Optical: GASP, GRT, MITSuMe ..
UV: Swift-UVOT
X-ray: Swift-XRT, RXTE-PCA, Swift/BAT
Gamma-ray: Fermi-LAT
VHE: MAGIC, VERITAS

3.1 – Broad Band SED of Mrk421

Extensive Campaign: Instruments that participated and energy covered by them

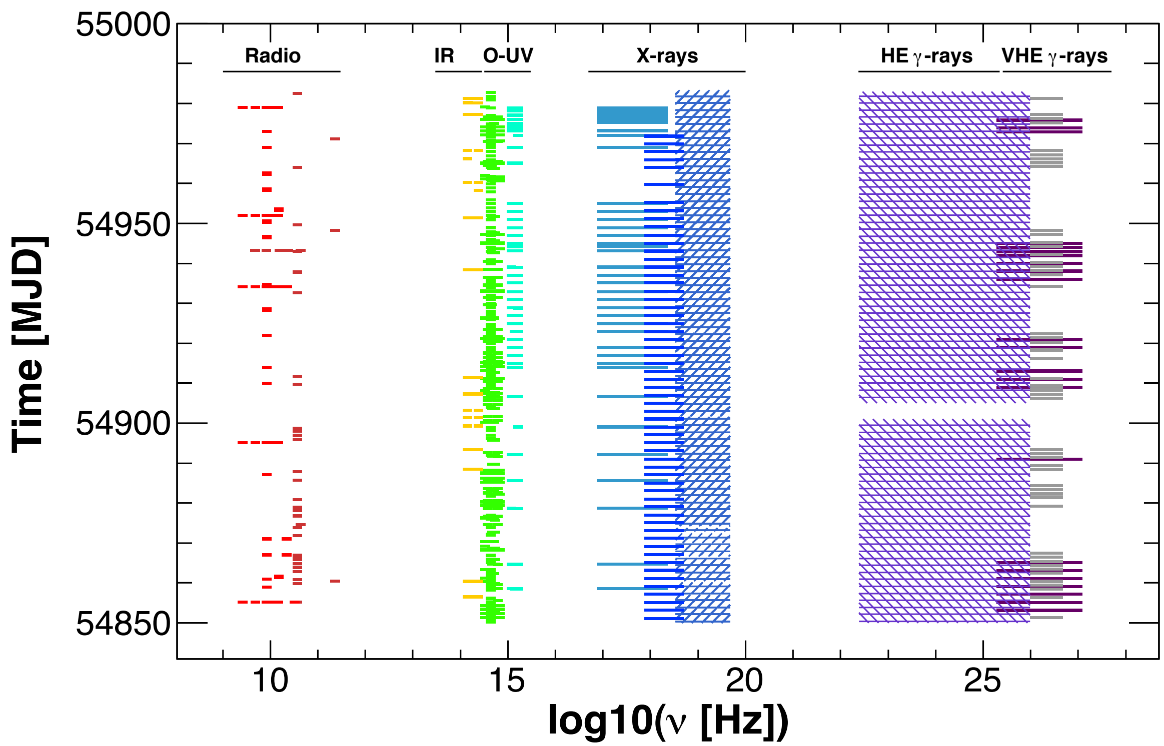
Instrument/Observatory	Energy range covered	Web page
MAGIC	0.08-5.0 TeV	http://wwwmagic.mppmu.mpg.de/
Whipple[a]	0.4-2.0 TeV	http://veritas.sao.arizona.edu/content/blogsection/6/40/
Fermi-LAT	0.1-400 GeV	http://www-glast.stanford.edu/index.html
Swift-BAT	14-195 keV	http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html/
RXTE-PCA	3-32 keV	http://heasarc.gsfc.nasa.gov/docs/xte/rxte.html
Swift-XRT	0.3-9.6 keV	http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html
Swift-UVOT	UVW1, UVM2, UVW2	http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html
Abastumani (through GASP-WEBT program)	R band	Webpagetobeplacehere
Lulin (through GASP-WEBT program)	R band	Webpagetobeplacehere
Roque de los Muchachos (KVA) (through GASP-WEBT program)	R band	Webpagetobeplacedhere
St. Petersburg (through GASP-WEBT program)	R band	Webpagetobeplacedhere
Talmassons (through GASP-WEBT program)	R band	Webpagetobeplacedhere
Valle d'Aosta (through GASP-WEBT program)	R band	Webpagetobeplacedhere
GRT	V, R, B, I bands	http://asd.gsfc.nasa.gov/Takanori.Sakamoto/GRT/index.html
ROVOR	B, R, V bands	http://rovor.byu.edu/
New Mexico Skies	R, V bands	http://www.nmskies.com/equipment.html/
MitSume	g, Rc, Ic bands	http://www.hp.phys.titech.ac.jp/mitsume/index.html
OAGH	H, J, K bands	http://astro.inaoep.mx/en/observatories/oagh/
WIRO	J, K bands	http://physics.uwyo.edu/~chip/wiro/wiro.html
SMA	225 GHz	http://sma1.sma.hawaii.edu/
VLBA	4.8, 8.3, 15.4, 23.8, 43.2 GHz	http://www.vlba.nrao.edu/
Noto	8.4, 22.3 GHz	http://www.noto.ira.inaf.it/
Metsähovi	37 GHz	http://www.metsahovi.fi/
VLBA (through MOJAVE program)	15 GHz	http://www.physics.purdue.edu/MOJAVE/
OVRO	15 GHz	http://www.ovro.caltech.edu/
Medicina	8.4 GHz	http://www.med.ira.inaf.it/index_EN.htm
UMRAO (through GASP-WEBT program)	4.8, 8.0, 14.5 GHz	http://www.to.astro.it/blazars/webt/
RATAN-600	2.3, 4.8, 7.7, 11.1, 22.2 GHz	http://w0.sao.ru/ratan/
Effelsberg (through FGAMMA program)	2.6, 4.6, 7.8, 10.3, 13.6, 21.7, 31 GHz	http://www.mpifr-bonn.mpg.de/div/effelsberg/index_e.html/

Note. — The energy range shown in column 2 is the actual energy range covered during the Mrk 421 observations, and not the instrument nominal energy range, which might only be achievable for bright sources and excellent observing conditions.

Note. — (*a*) The Whipple spectra were not included in Figure 8. See text for further comments.

3.2 – Broad Band (radio-TeV) SED of Mrk421

Time and Energy coverage during the campaign



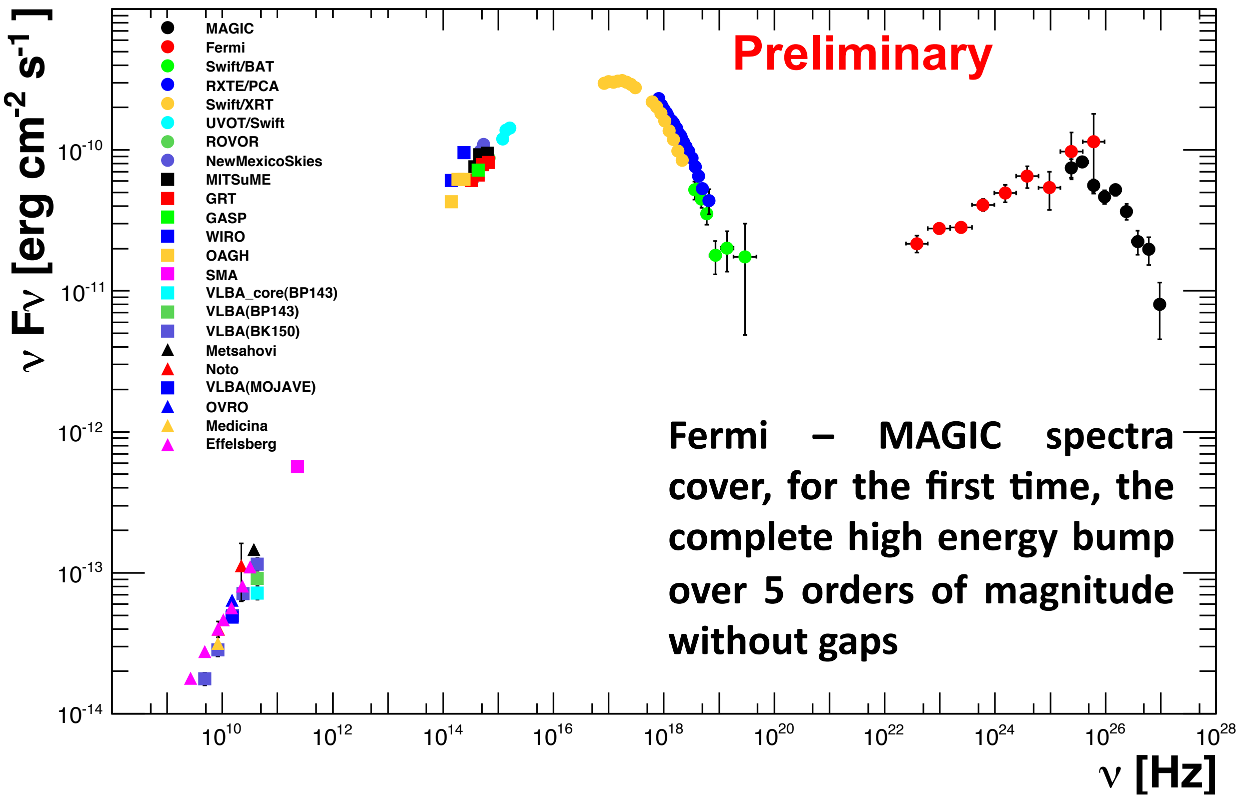
Most complete Time & Energy coverage of Mrk421 up to date

Collected data can be used to produce a good representation of the TRUE SED

Reliable interpretation of the SED (!!)

3.2 – Broad Band (radio-TeV) SED of Mrk421

Average SED from the campaign observations



Fermi – MAGIC spectra cover, for the first time, the complete high energy bump over 5 orders of magnitude without gaps

Agreement in overlapping energies among instruments (with different time coverage) indicates that we managed to get the true average SED of Mrk421 during the 4.5 months campaign.

Most complete SED ever collected for Mrk421

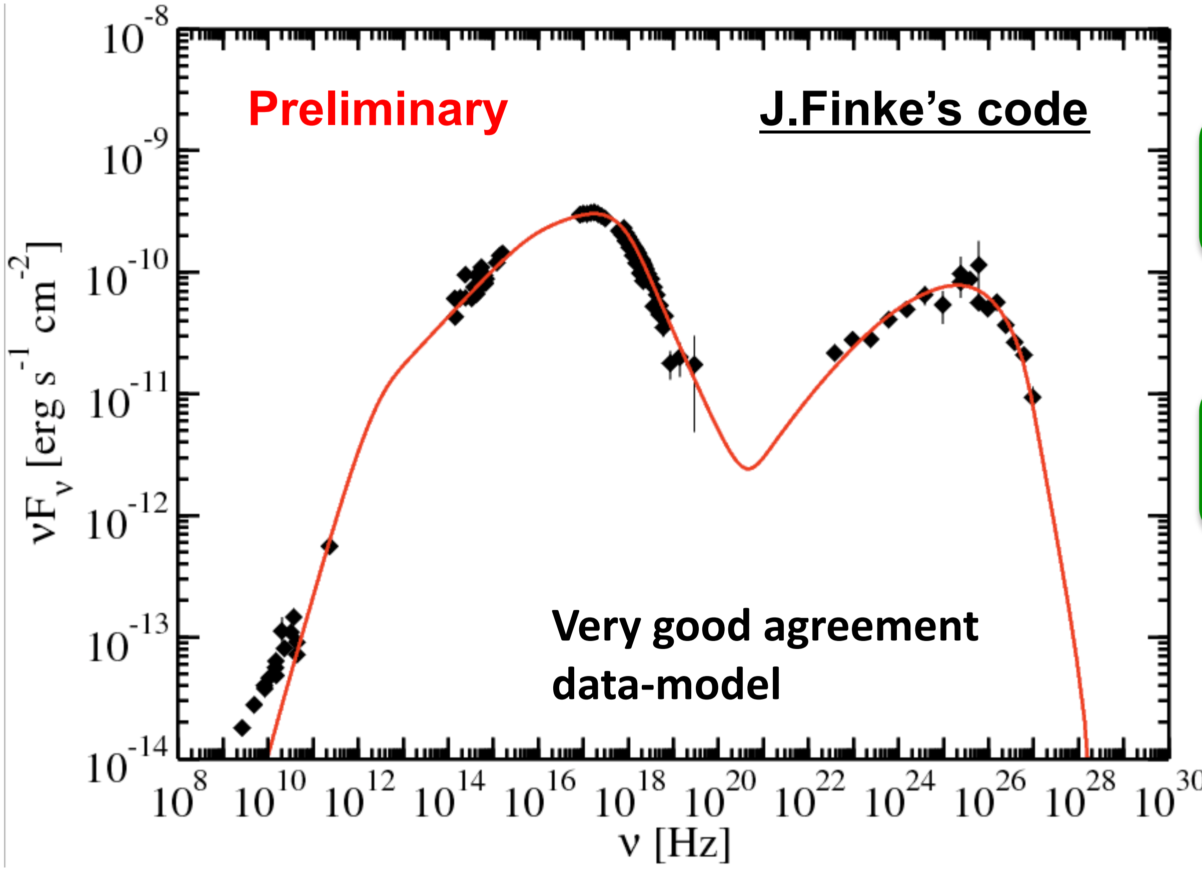
3.2 – Modeling the Mrk421 SED

"Standard approach" in modelling TeV-emitting BL Lacs:
one-zone homogeneous synchrotron self-Compton (SSC) scenario.

Two breaks in the electron energy distribution are required to fit the data

$$n'_e(\gamma) \propto \begin{cases} \gamma^{-s_1} & \text{for} \quad \gamma_{min} \leq \gamma < \gamma_{br,1} \\ \gamma^{-s_2} & \text{for} \quad \gamma_{br,1} \leq \gamma < \gamma_{br,2} \\ \gamma^{-s_3} \exp\left[-\gamma/\gamma_{max}\right] & \text{for} \quad \gamma_{br,2} \leq \gamma \end{cases}$$

3.2 – Modeling the Mrk421 SED



R [cm]	5.2e16
B [G]	3.8e-2
delta	21.0
η_e	10
γ_{min}	800
s1	2.2
γ_{brk_1}	5.e4
s2	2.7
γ_{brk_2}	3.9e5
s3	4.7
γ_{max}	1.0e8

Modeling results differ with respect to previous Mrk421 modeling in several parameters (R,B, γ_{min} and s1)

Main reasons for the difference is that in the past:

- Mrk421 was modeled mostly during flaring activity
- The models typically considered only X-ray and TeV

In this work we used the entire broad-band SED during a low state

3.1 – Broad Band SED of Mrk501

<u>Extensive Campaign</u>: Instruments that participated and energy covered by them

Instrument/observatory	Energy range covered	Web page
MAGIC	0.12-5.8 TeV	http://wwwmagic.mppmu.mpg.de/
VERITAS	0.20-5.0 TeV	http://veritas.sao.arizona.edu/
Whipple[a]	0.4-1.5 TeV	http://veritas.sao.arizona.edu/content/blogsection/6/40/
Fermi-LAT	0.1-400 GeV	http://www-glast.stanford.edu/index.html
Swift-BAT	14-195 keV	http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html/
RXTE-PCA	3-28 keV	http://heasarc.gsfc.nasa.gov/docs/xte/rxte.html
Swift-XRT	0.3-9.6 keV	http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html
Swift-UVOT	V, B, U, UVW1, UVM2, UVW2	http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html
Abastumani (through GASP-WEBT program)	R band	Webpagetobeplacehere
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St. Petersburg (through GASP-WEBT program)	R band	Webpagetobeplacedhere
Talmassons (through GASP-WEBT program)	R band	Webpagetobeplacedhere
Valle d'Aosta (through GASP-WEBT program)	R band	Webpagetobeplacedhere
GRT	V, R, B bands	http://asd.gsfc.nasa.gov/Takanori.Sakamoto/GRT/index.html
MitSume	g, Rc, Ic bands	http://www.hp.phys.titech.ac.jp/mitsume/index.html
ROVOR	B, R, V, I bands	http://rovor.byu.edu/
Campo Imperatore (through GASP-WEBT program)	H, J, K bands	http://www.to.astro.it/blazars/webt/
OAGH	H, J, K bands	http://astro.inaoep.mx/en/observatories/oagh/
WIRO	J, K bands	http://physics.uwyo.edu/~chip/wiro/wiro.html
SMA	225 GHz	http://sma1.sma.hawaii.edu/
VLBA	4.8, 8.3, 15.4, 23.8, 43.2 GHz	http://www.vlba.nrao.edu/
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Note. — The energy range shown in column two is the actual energy range covered during the Mrk 501 observations, and not the instrument's nominal energy range, which might only be achievable for bright sources and excellent observing conditions.

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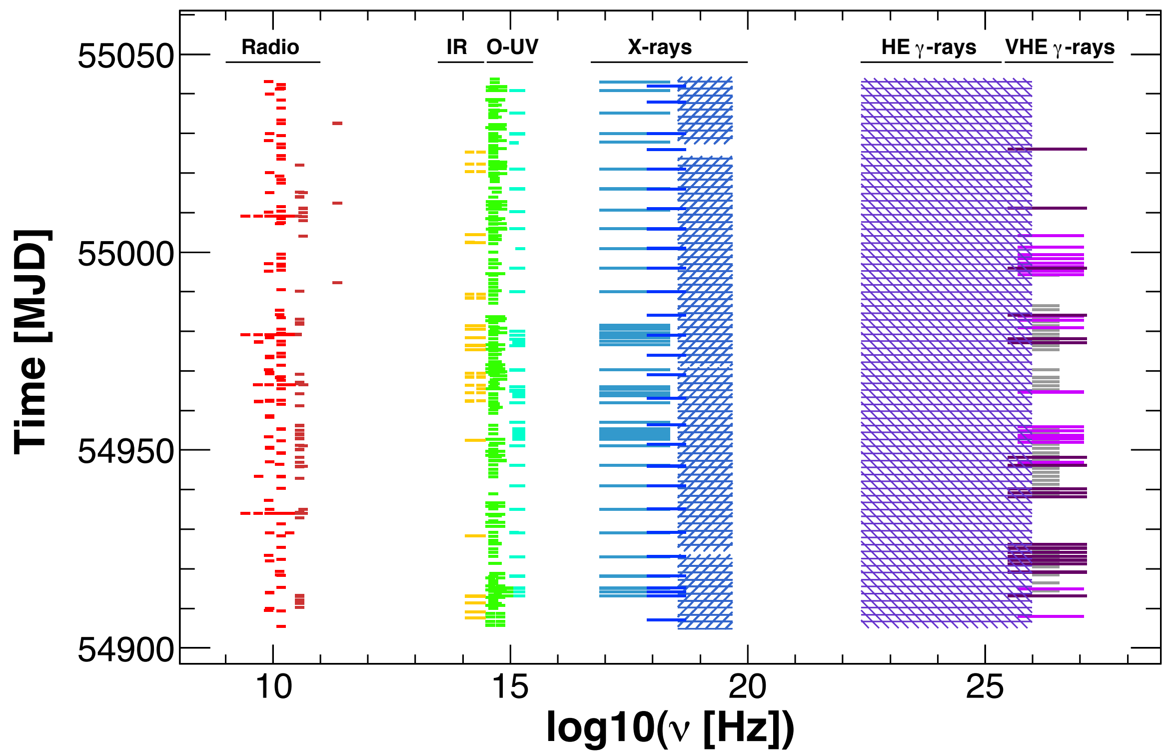
3.3 – Broad Band (radio-TeV) SED of Mrk501

Time and Energy coverage during the campaign



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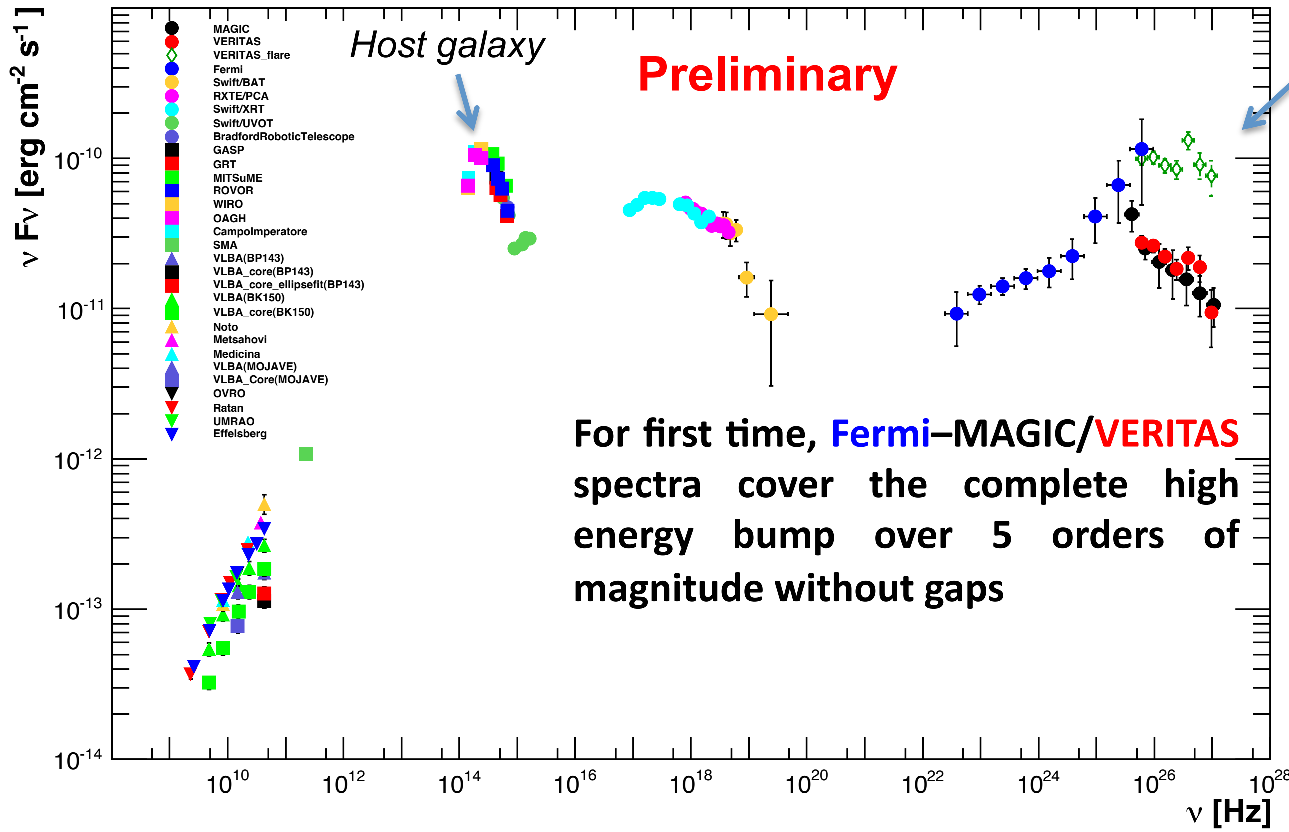
Collected data can be used to produce a good representation of the TRUE SED

Reliable interpretation of the SED (!!)

3.3 – Broad Band (radio-TeV) SED of Mrk501

Average SED from the 2009 MW campaign on Mrk501

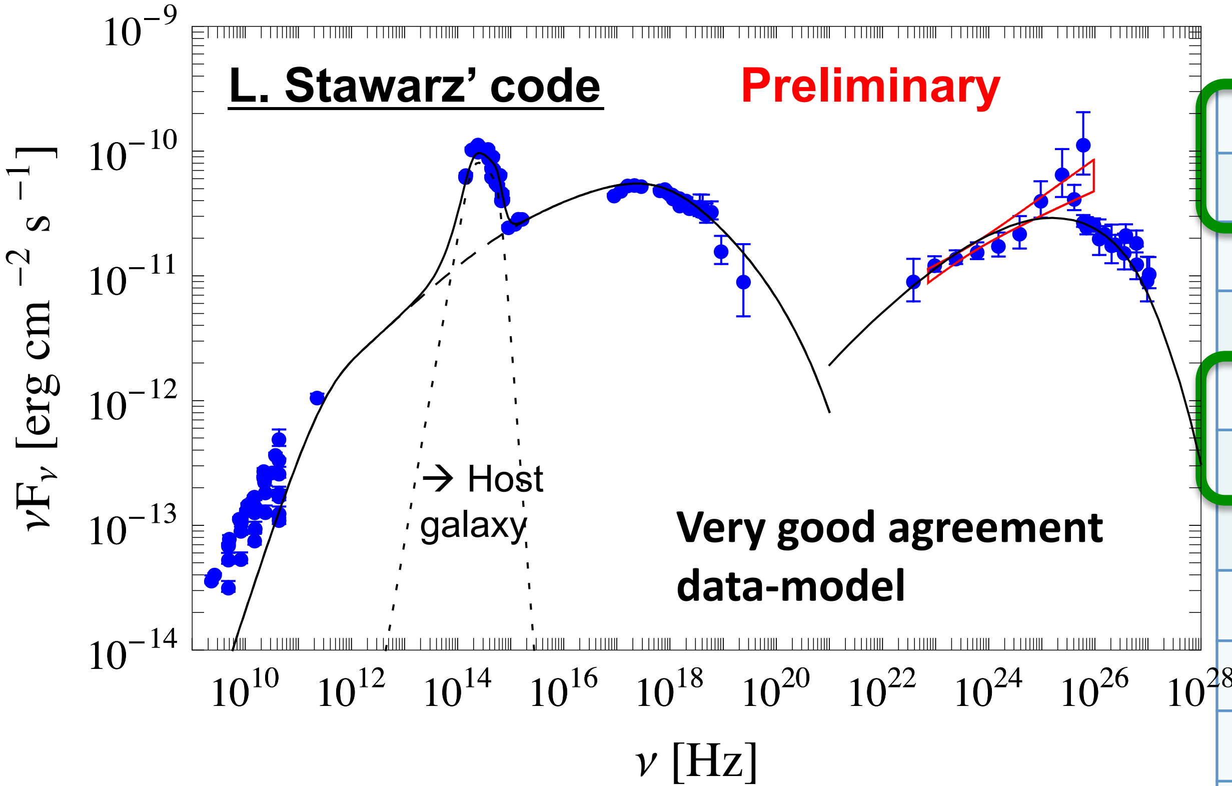


3-day spectrum from TeV flaring activity

Agreement in overlapping energies among instruments (with different time coverage) indicates that we managed to get the true average SED of Mrk501 during the 4.5 months campaign.

Most complete SED ever collected for Mrk501

3.3 – Modeling the Mrk501 SED



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η_e	56
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In this work we used the entire broad-band SED during a relatively low state

3.4 – Modeling the Mrk501 and Mrk421 SED

Preliminary

Mrk501: Stawarz' code

R [cm]	1.3e17
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Mrk421: Finke's code

R [cm]	5.2e16
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s3	4.7
γ_{max}	1.0e8

Similar model parameters for Mrk421 and Mrk501 (both during relatively low activity)

Is it by chance ?? Or are we dealing with some common properties for those 2 objects ??
Can we extrapolate this to other HSP - BL Lacs ??

3.4 – Modeling the Mrk501 and Mrk421 SED

Preliminary

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s2	2.7
γ_{brk_2}	3.9e5
s3	4.7
γ_{max}	1.0e8

High γ_{min} and s1=2.2 is consistent with the models of diffuse (1st order Fermi) particle acceleration in relativistic, proton-mediated shocks

Efficient acceleration for electrons above γ_{min} = 600-800

3.5 – Discussion: First spectral break

The first spectral break located at ~25 GeV for Mrk421 and ~ 20 GeV for Mrk501
In both cases the break produces a change in index from 2.2 to 2.7

Is it by chance ???

This break must be internal to the acceleration mechanism.

Internal breaks observed in many blazars detected by Fermi

The Astrophysical Journal, 710:1271–1285, 2010 February 20
doi:10.1088/0004-637X/710/2/1271

SPECTRAL PROPERTIES OF BRIGHT *FERMI*-DETECTED BLAZARS IN THE GAMMA-RAY BAND

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ABSTRACT

The gamma-ray energy spectra of bright blazars of the LAT Bright AGN Sample (LBAS) are investigated using *Fermi*-LAT data. Spectral properties (hardness, curvature, and variability) established using a data set accumulated over 6 months of operation are presented and discussed for different blazar classes and subclasses: flat spectrum radio quasars (FSRQs), low-synchrotron peaked BLLacs (LSP-BLLacs), intermediate-synchrotron peaked BLLacs (ISP-BLLacs), and high-synchrotron peaked BLLacs (HSP-BLLacs). The distribution of photon index (Γ, obtained from a power-law fit above 100 MeV) is found to correlate strongly with blazar subclass. The change in spectral index from that averaged over the 6 months observing period is < 0.2–0.3 when the flux varies by about an order of magnitude, with a tendency toward harder spectra when the flux is brighter for FSRQs and LSP-BLLacs. A strong departure from a single power-law spectrum appears to be a common feature for FSRQs. This feature is also present for some high-luminosity LSP-BLLacs, and a small number of ISP-BLLacs. It is absent in all LBAS HSP-BLLacs. For 3C 454.3 and AO 0235+164, the two brightest FSRQ source and LSP-BLLac source, respectively, a broken power law (BPL) gives the most acceptable of power law, BPL, and curved forms. The consequences of these findings are discussed.

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SPECTRAL PROPERTIES OF BRIGHT *FERMI*-DETECTED BLAZARS IN THE GAMMA-RAY BAND

A. A. Abdo[1,2], M. Ackermann[3], M. Ajello[3], W. B. Atwood[4], M. Axelsson[5,6], L. Baldini[7], J. Ballet[8], G. Barbiellini[9,10], D. Bastieri[11,12], K. Bechtol[3], R. Bellazzini[7], B. Berenji[3], R. D. Blandford[3], E. D. Bloom[3], E. Bonamente[13,14],

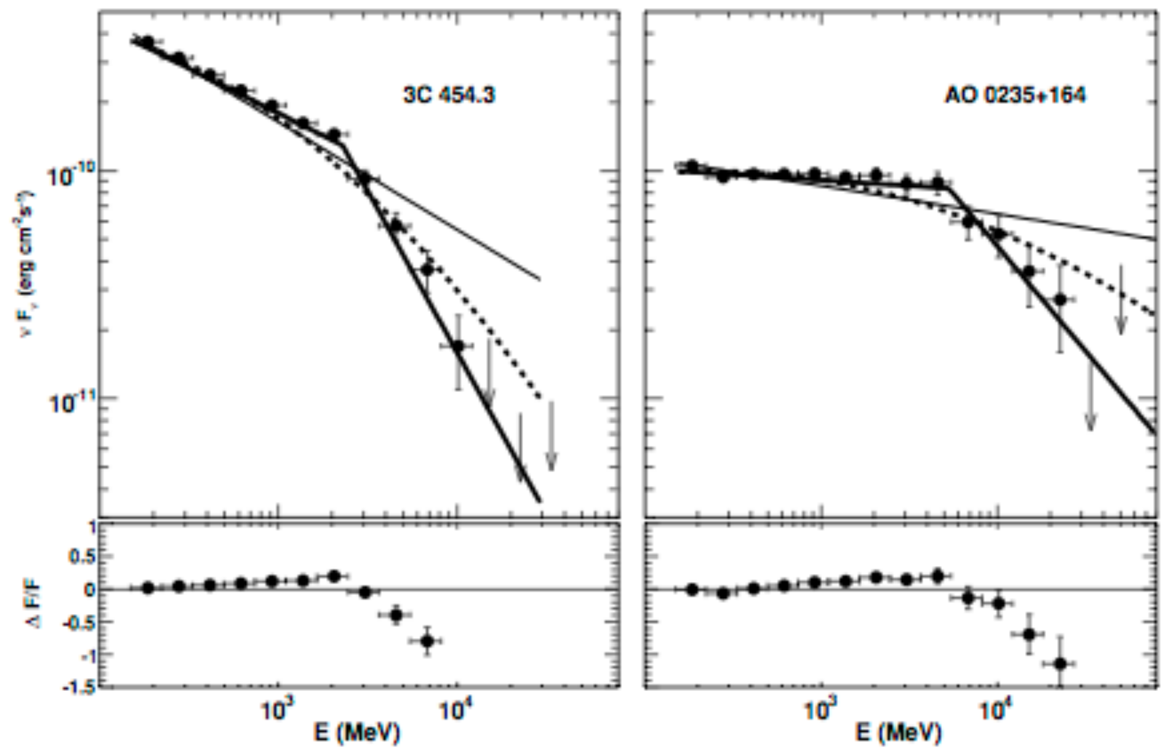

Figure 13. Upper panels: energy spectra of 3C 454.3 (left panel) and AO 0235+164 (right panel) compared with fit results obtained with different models: PL (thin solid), BPL (thick solid), and log-parabola (dashed).

Likely to be produced by breaks intrinsic to the electron energy distribution (see *Abdo, A. A., et al. 2009, ApJ, 699, 817*)

3.5 – Discussion: First spectral break

The first spectral break located at ~25 GeV for Mrk421 and ~ 20 GeV for Mrk501
In both cases the break produces a change in index from 2.2 to 2.7

Is it by chance ???

This break must be internal to the acceleration mechanism.

Internal breaks observed in many blazars detected by Fermi

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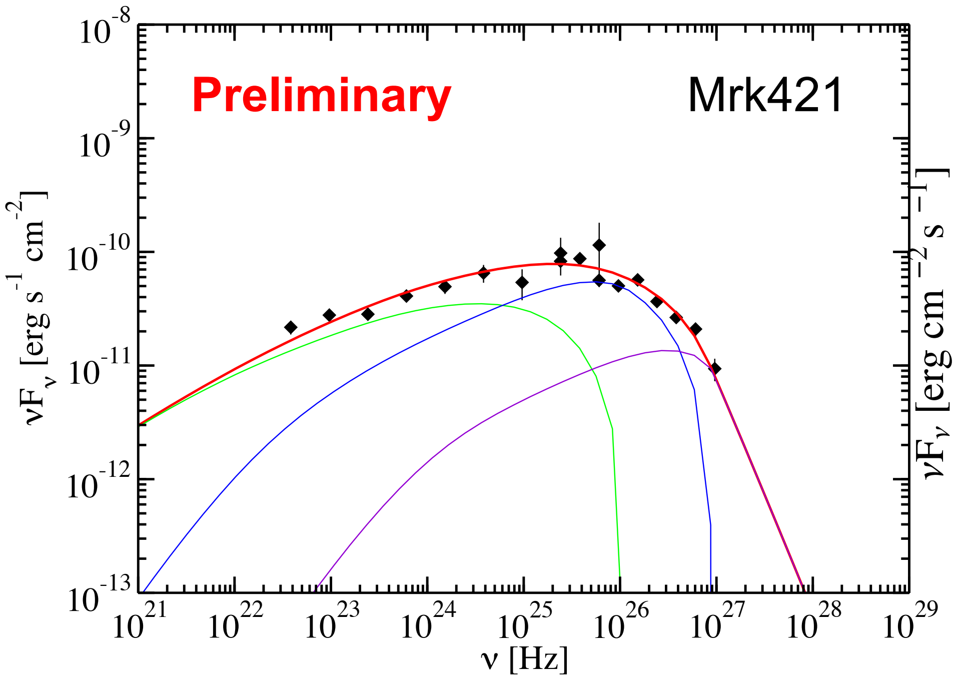
It seems that HSP BL Lacs ALSO show spectral breaks in the electron energy distribution, but those breaks are "not visible" in the (SSC) high energy bump, while they are visible in the (EC) high energy bump of FSRQs

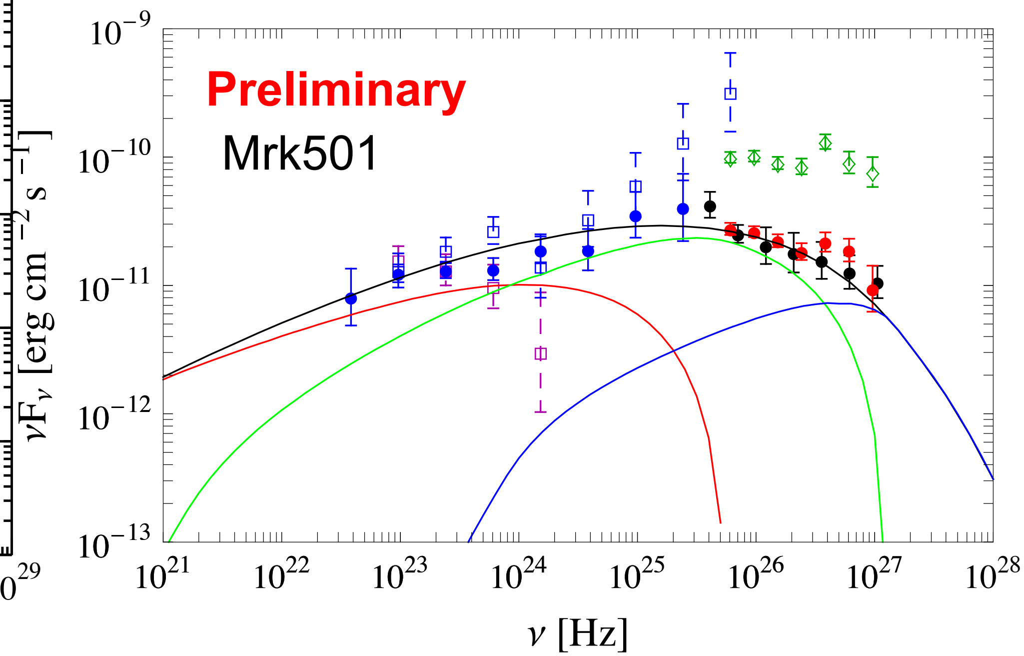
We may access those spectral breaks through the modeling of the SEDs

3.6 – Discussion: Variability

Close look to the high energy bump of Mrk421 and Mrk501

Contributions of the different segments of the electron energy distribution





green $\gamma_{min} < \gamma < \gamma_{br,1}$
blue $\gamma_{br,1} < \gamma < \gamma_{br,2}$
purple $\gamma_{br,2} < \gamma$ (emit at $\nu > 10^{17}$ Hz)

red $\gamma_{min} < \gamma < \gamma_{br,1}$
green $\gamma_{br,1} < \gamma < \gamma_{br,2}$
blue $\gamma_{br,2} < \gamma$ (emit at $\nu > 10^{17}$ Hz)

Electrons above $\gamma_{br,2}$ emit X-rays

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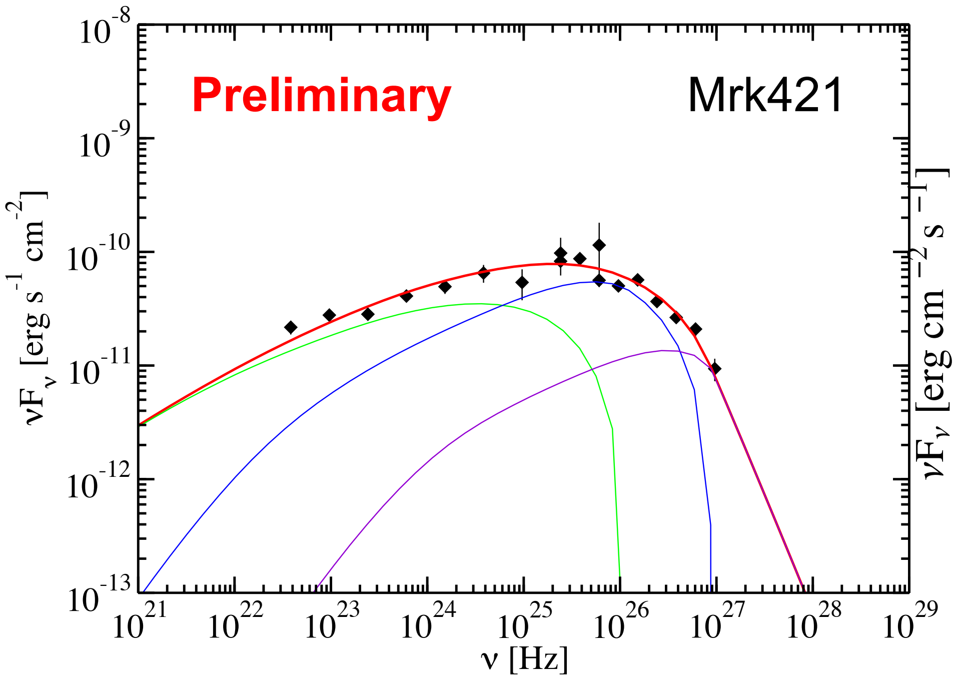
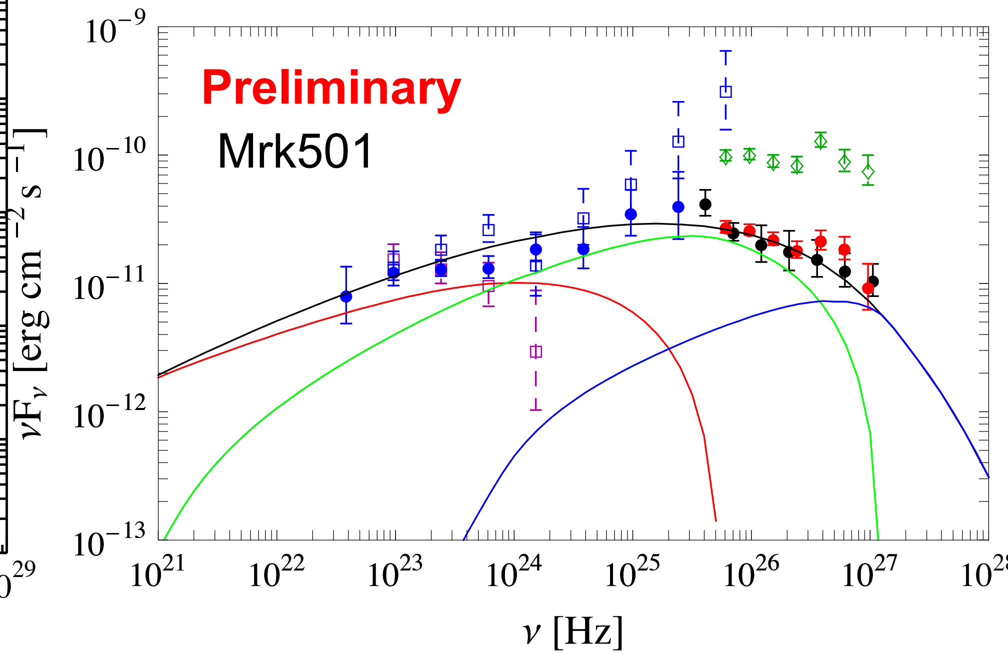




The electrons above 2nd break are responsible for the X-rays, and electrons above 1st and 2nd break responsible for the TeV

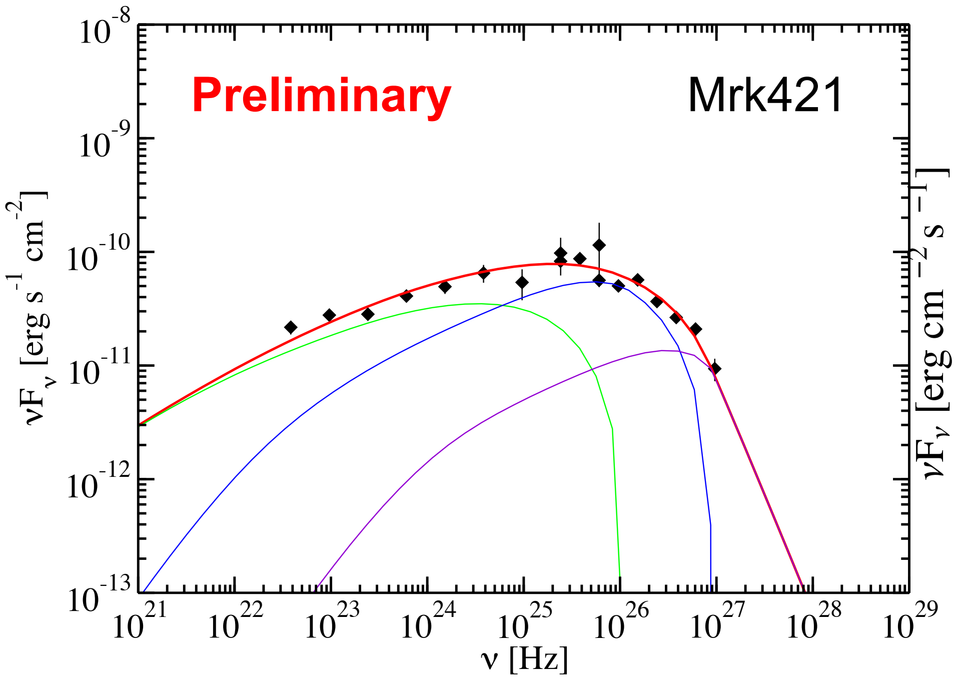
→ Correlation X-ray/TeV must exist but the relation is NOT trivial

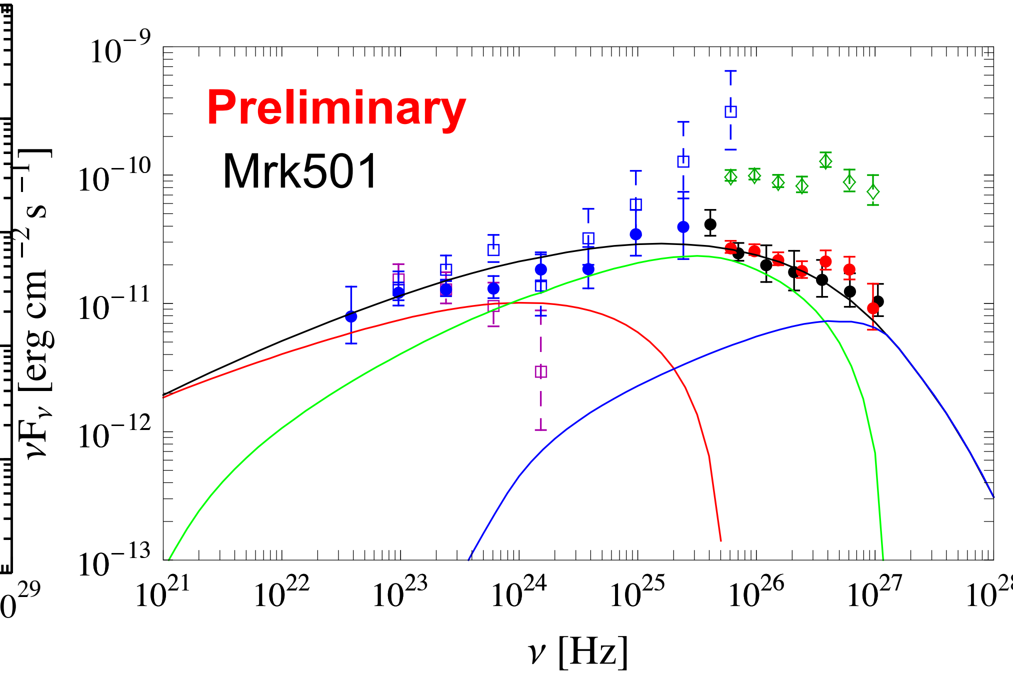
MeV/GeV Fermi photons produced mostly by electrons BELOW 1st break

3.6 – Discussion: Variability

Close look to the high energy bump of Mrk421 and Mrk501

Contributions of the different segments of the electron energy distribution





Larger flux variations above few GeV energies (as measured by Fermi/LAT during the first 1.5 years of scientific operation) could be produced by larger variations in the number of electrons above the first (internal) breaks $\gamma_{br,1}$ ~ 20-25 GeV

4 - Conclusions

The Fermi/LAT monitoring of Mrk501 and Mrk421 showed that variability above few GeV is larger than that below few GeV

The MW data collected during 4.5 month long campaigns allowed us to produce the most complete SED ever determined for both Mrk501 and Mrk421 (includes the full coverage of the γ-ray bump)*. Both sources were in relatively low/quiescent state.*

The SED can be described with one-zone SSC with an electron distribution with 2 breaks:

break Internal to particle acceleration (20 GeV and 25 GeV for Mrk501 and Mrk421)

break related to synchrotron cooling (500 GeV and 180 GeV for 501 and 421 (?))

X-ray produced mostly by electrons above 2nd break (fast cooling regime)
TeV dominated by electrons above 1st and 2nd break
MeV/GeV (Fermi) produced mostly by electrons below 1st break, but also above 1st break

Larger variability above multi-GeV photon energies suggests larger variability in the number of electrons above the first (internal to particle acceleration) break

Electron distribution consistent with being produced through 1st order Fermi acceleration

Similar properties for Mrk421 and Mrk501: is it by chance ?? Or is it a common property of these two objects ? Can we extend this to HSP-BL Lacs ??

4 - Conclusions

Fermi operates in survey mode since August 2008, boosting our current capabilities to study AGNs.

→ **Uniform exposure + Coverage of 20% sky at any time + Large effctive area + small PSF**

Study of the classical (bright) TeV sources has the advantage that, together with the IACTs, Fermi data constrain the high energy bump

- Fermi data opens a "new window" to study those objects

→ Spectra reaching E>0.1 TeV; overlap with IACTs

- Collection of MW data is ESSENTIAL for understanding those complex objects.

This presentation shows "first" results from the 2009 MW campaigns on Mrk421/Mrk501. There will be further results from those MW campaigns frpm 2009, as well as from the campaigns we had in 2010.