Detection of very hard γ-ray spectrum from the TeV blazar Mrk 501

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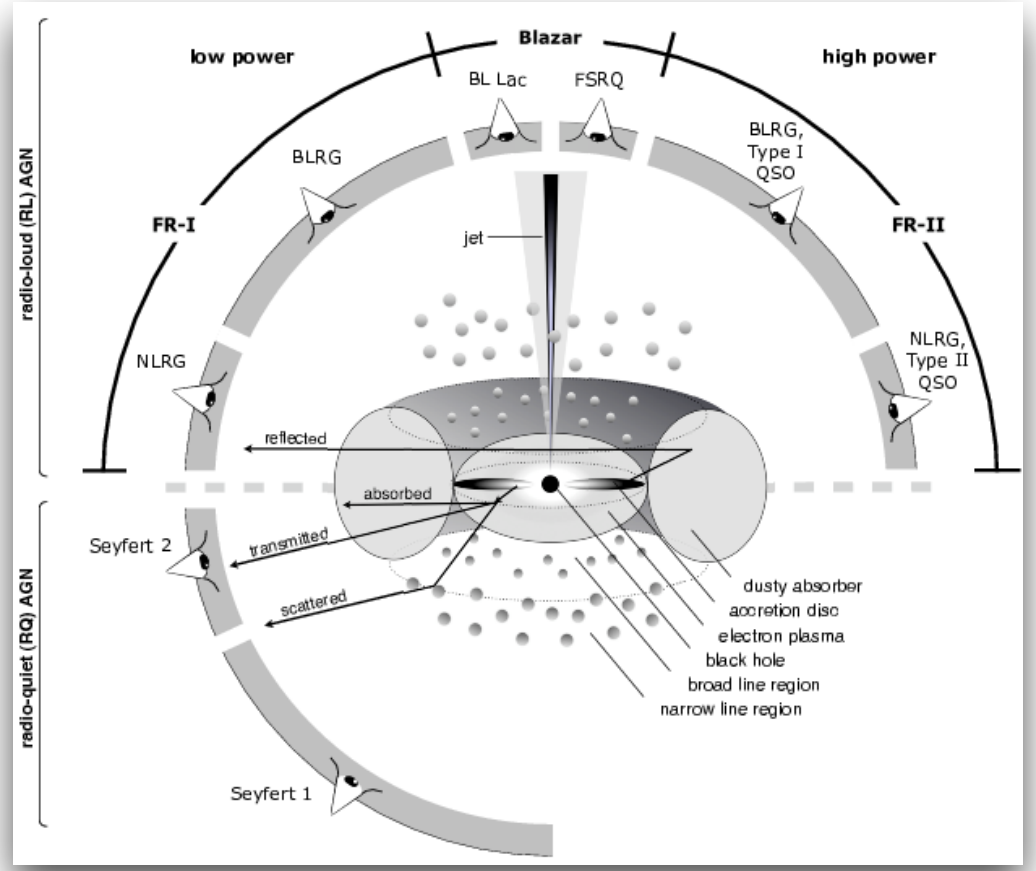
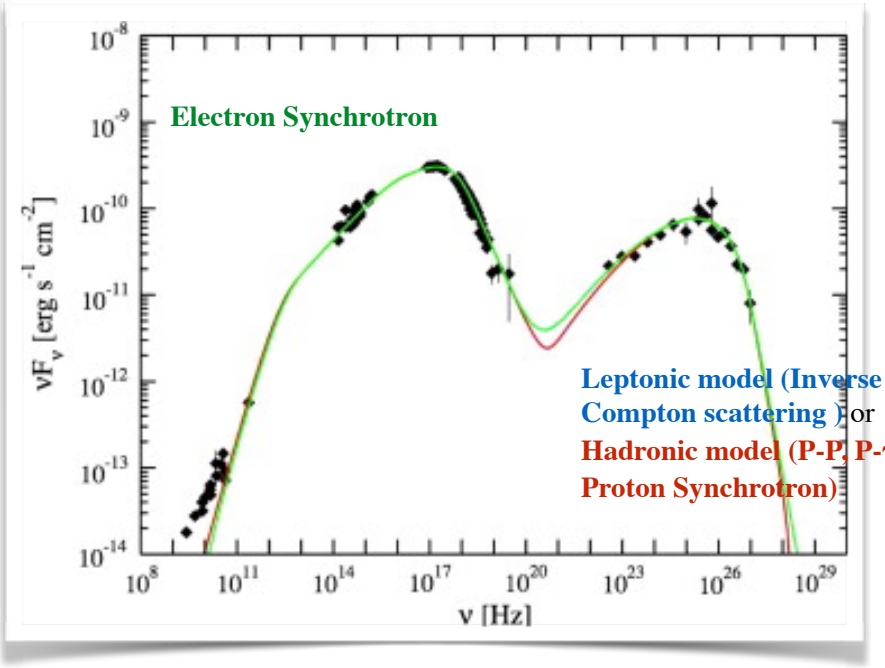
ASTROPHYSIK

Active Galactic Nuclei & Blazars



Unification scheme of AGN showing how the different classes of sources result from the relative orientation between observer and jet-accretion disk geometry. The image was adapted from Urry & Padovani (1995)

- Highly variable
- Blazar's broad band spectral energy distribution (SED) consists of typically two broad peaks.



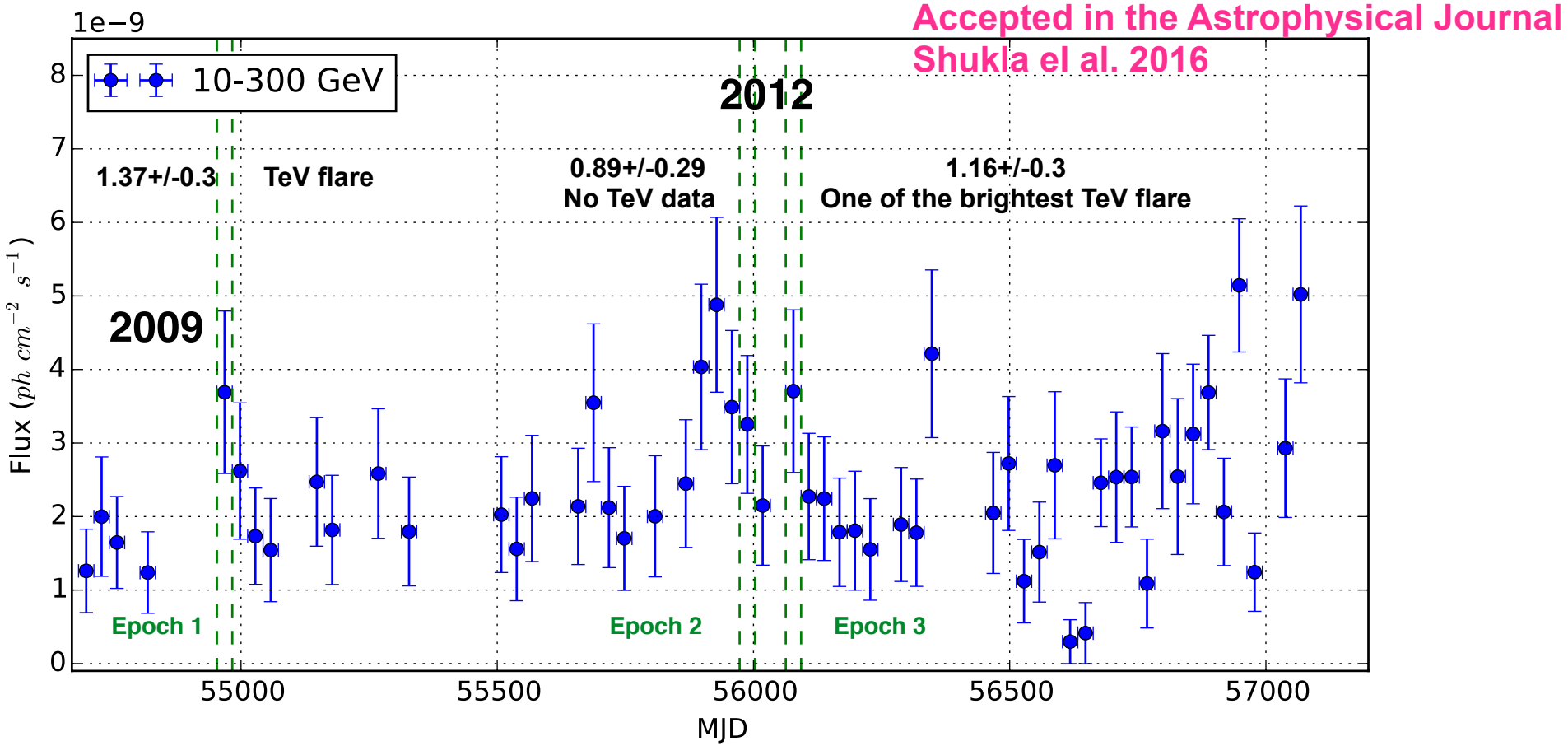
Mrk 421 (Abdo et.al 2011)

Detection of very hard spectra

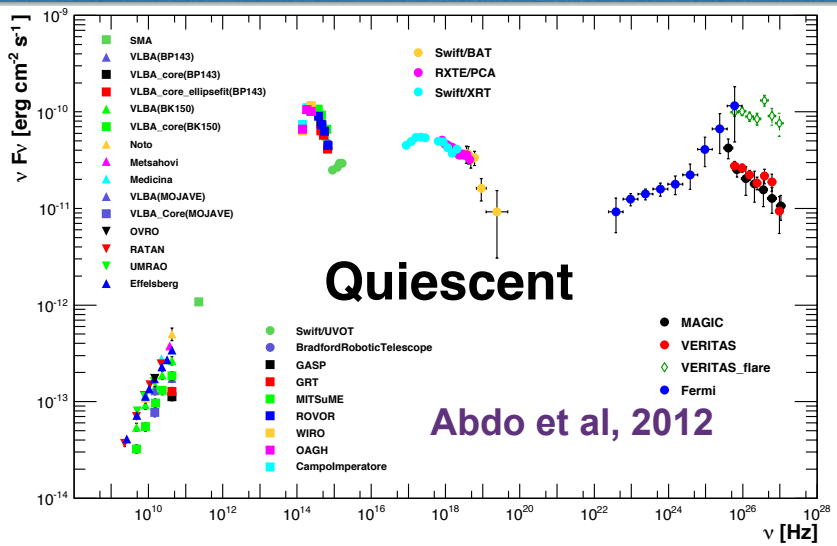
- Detection of very hard spectra above 10 GeV from Mrk 501 during an orphan flare in 2009 (photon index < 1.5)
  - Standard shock in jet scenario predicts the hardest photon index of 1.5 (Malkov & O'C Drury 2001).
- Due to the proximity of the source, observed γ-ray flux may not have suffered major degradation due to EBL in Fermi-LAT energy band
  - Intrinsic source spectra

Detection of Fermi-LAT Hard Spectra

- **A systematic search to detect hard spectra from Mrk 501 above 10 GeV in Fermi-LAT data**
- **First ~ 7 years of Fermi-LAT data between MJD 54683 – 57113 are divided into 83 time intervals of 30 days and a spectrum has been extracted for each epoch.**

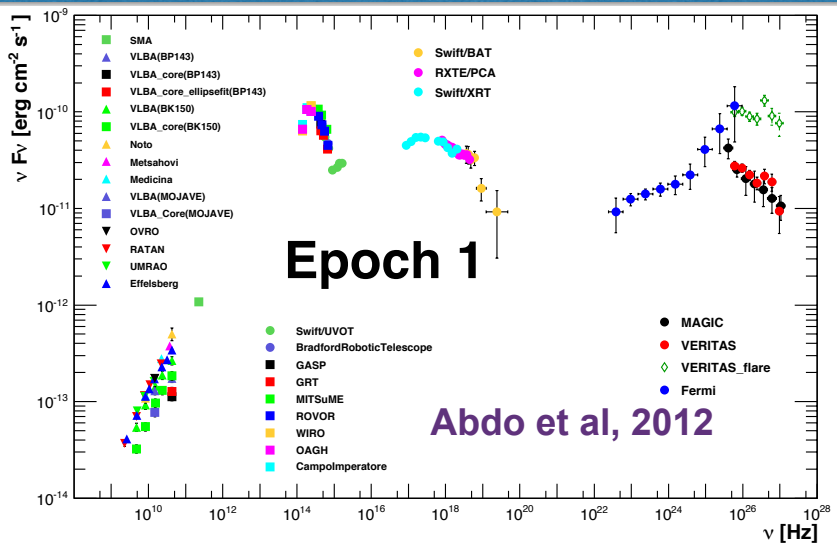


Spectra and Rapid variability

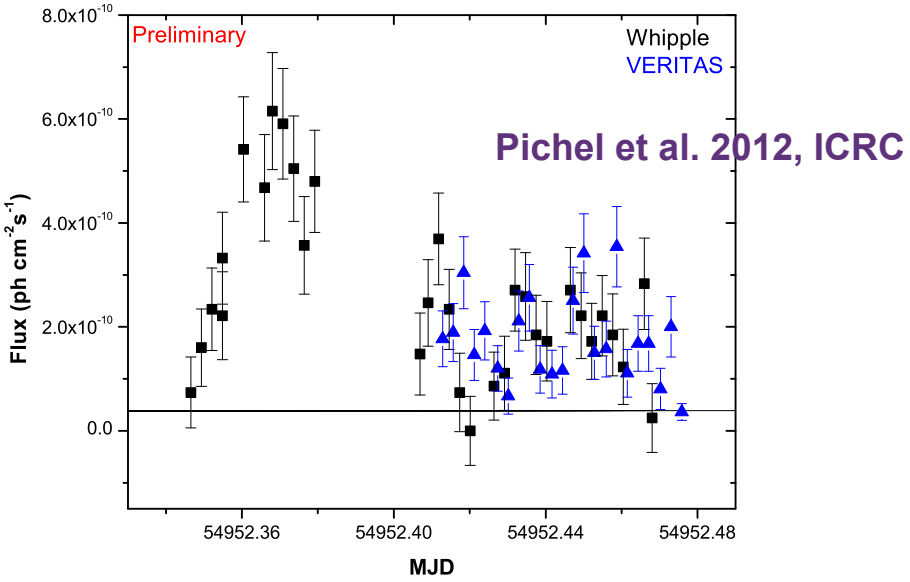


State	Flux Crab units	Swift-XRT Index	Fermi-LAT Index (0.1-400 GeV) (>10 GeV)	TeV Index	Correlated variability	Variability Time scale
Quiescent	0.3	1.96+/-0.04	1.74+/-0.05 , 1.44+/-0.14	~ 2.5	Yes	1-2 days
Epoch 1						
Epoch 2						
Epoch 3						
Rapid flare		-	-			

Hard Spectra and Rapid variability



May 2009



MJD 54953-54956 : ~ 5 CU flare

No prominent X-ray flux enhancement during any of the flares

But spectra were found to be hard

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Quiescent	0.3	1.96+/-0.04	1.74+/-0.05 , 1.44+/-0.14	~ 2.5	Yes	1-2 days
Epoch 1	~5	1.66+/-0.08	1.37+/-0.3	~ 2.26	No	~20 min
Epoch 2						
Epoch 3						
Rapid flare		-	-			

Hard Spectra and Rapid variability

Epoch 2 : No TeV data available

State	Flux Crab units	Swift-XRT Index	Fermi-LAT Index (0.1-400 GeV) (>10 GeV)	TeV Index	Correlated variability	Variability Time scale
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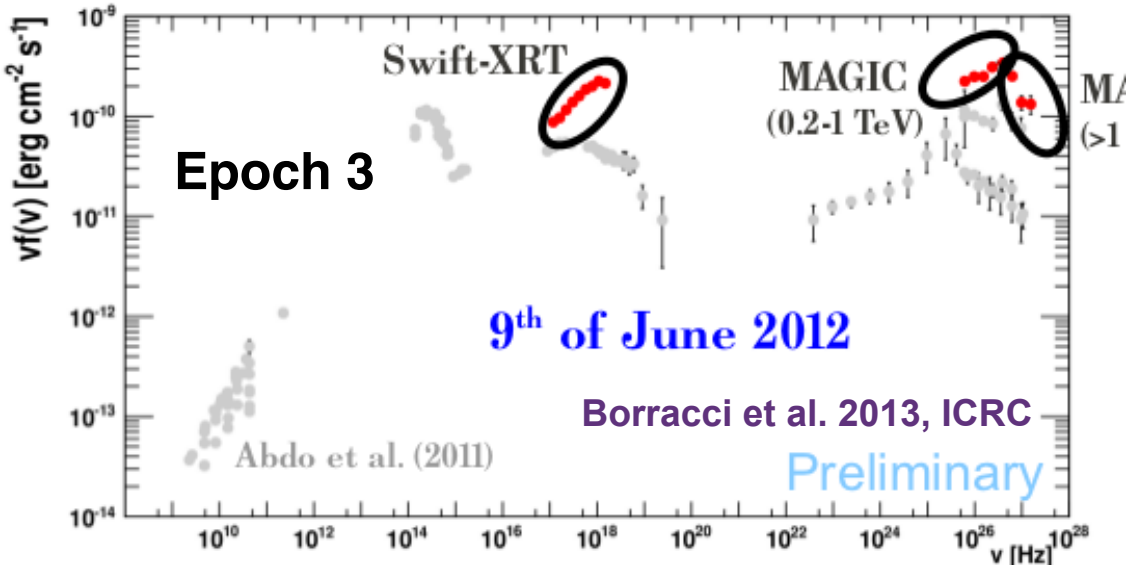
Epoch 1	~5	1.66+/-0.08	1.37+/-0.3	~ 2.26	No	~20 min
Epoch 2			0.89+/-0.29			
Epoch 3						
Rapid flare						

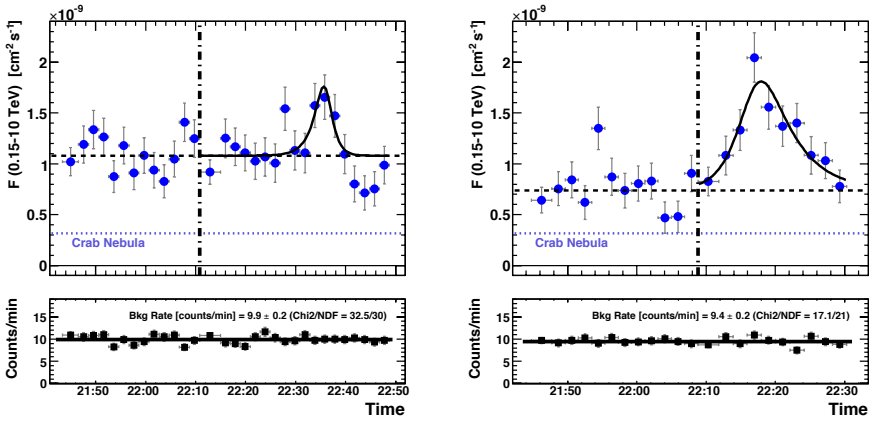
Hard Spectra and Rapid variability



- 9th June 2012 (MJD 56087) : ~ **5 CU (>1 TeV) flare**
- **No prominent X-ray flux enhancement during any of the flares**
- **But spectra were found to be hard**

State	Flux Crab units	Swift-XRT Index	Fermi-LAT Index (0.1-400 GeV) (>10 GeV)	TeV Index	Correlated variability	Variability Time scale
Quiescent	0.3	1.96+/-0.04	1.74+/-0.05 , 1.44+/-0.14	~ 2.5	Yes	1-2 days
Epoch 1	~5	1.66+/-0.08	1.37+/-0.3	~ 2.26	No	~20 min
Epoch 2			0.89+/-0.29			
Epoch 3	>5	?	1.16+/-0.3	~ 2	?	Few hrs ?
Rapid flare		-	-			

Hard Spectra and Rapid variability



Rapid flare : Albert et al. 2007

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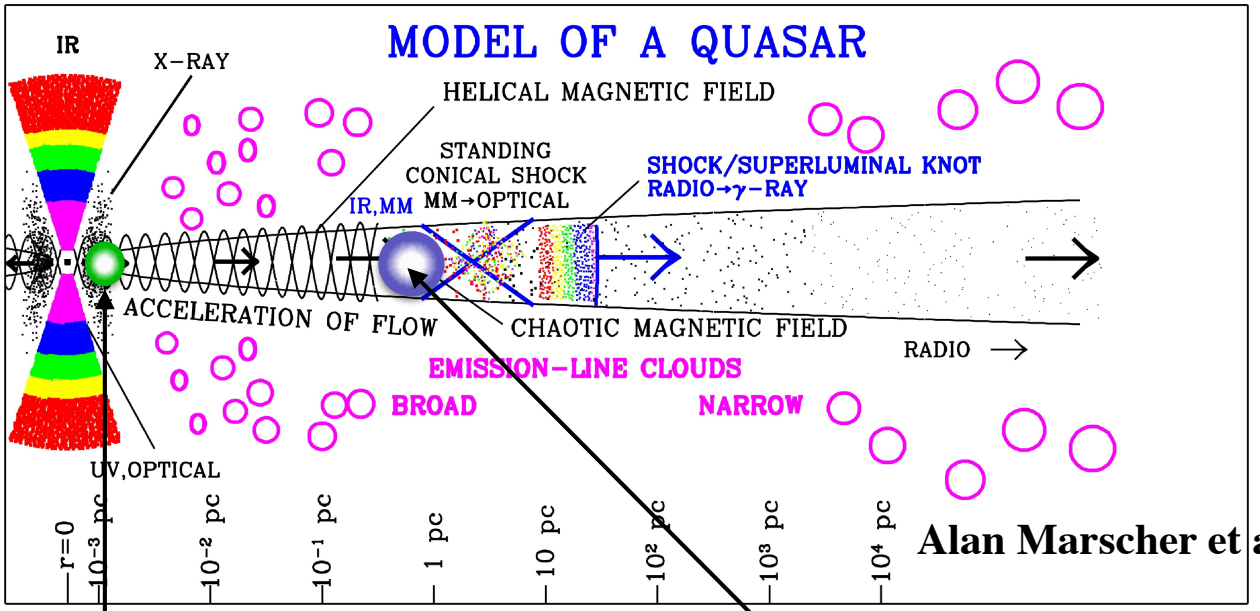
Epoch 1	~5	1.66+/-0.08	1.37+/-0.3	~ 2.26	No	~20 min
Epoch 2			0.89+/-0.29			
Epoch 3	>5	?	1.16+/-0.3	~ 2	?	Few hrs ?
Rapid flare	~5	-	Pre-Fermi era	2.1	No	~ 3 min

Possible origin (Theories) of hard spectrum

- Inverse Compton scattering from narrow electron energy distribution such as narrow Powerlaw or Relativistic Maxwellian.
- Emission from vacuum gaps in the magnetosphere of a rotating black hole.
- Hadronic models (Proton Synchrotron)
- Emission from γ-ray induced cascades in the intergalactic medium or oscillation of photon into axion like particles

Model setup & Particle acceleration



Alan Marscher et al., 2005

Fermi - second order + Fermi-first order

$$N(\gamma)d\gamma = \begin{cases} K\gamma^{-p_1}d\gamma, & \gamma_{min} < \gamma < \gamma_b \\ K\gamma_b^{(p_2-p_1)}\gamma^{-p_2}d\gamma, & \gamma_b < \gamma < \gamma_{max} \end{cases}$$

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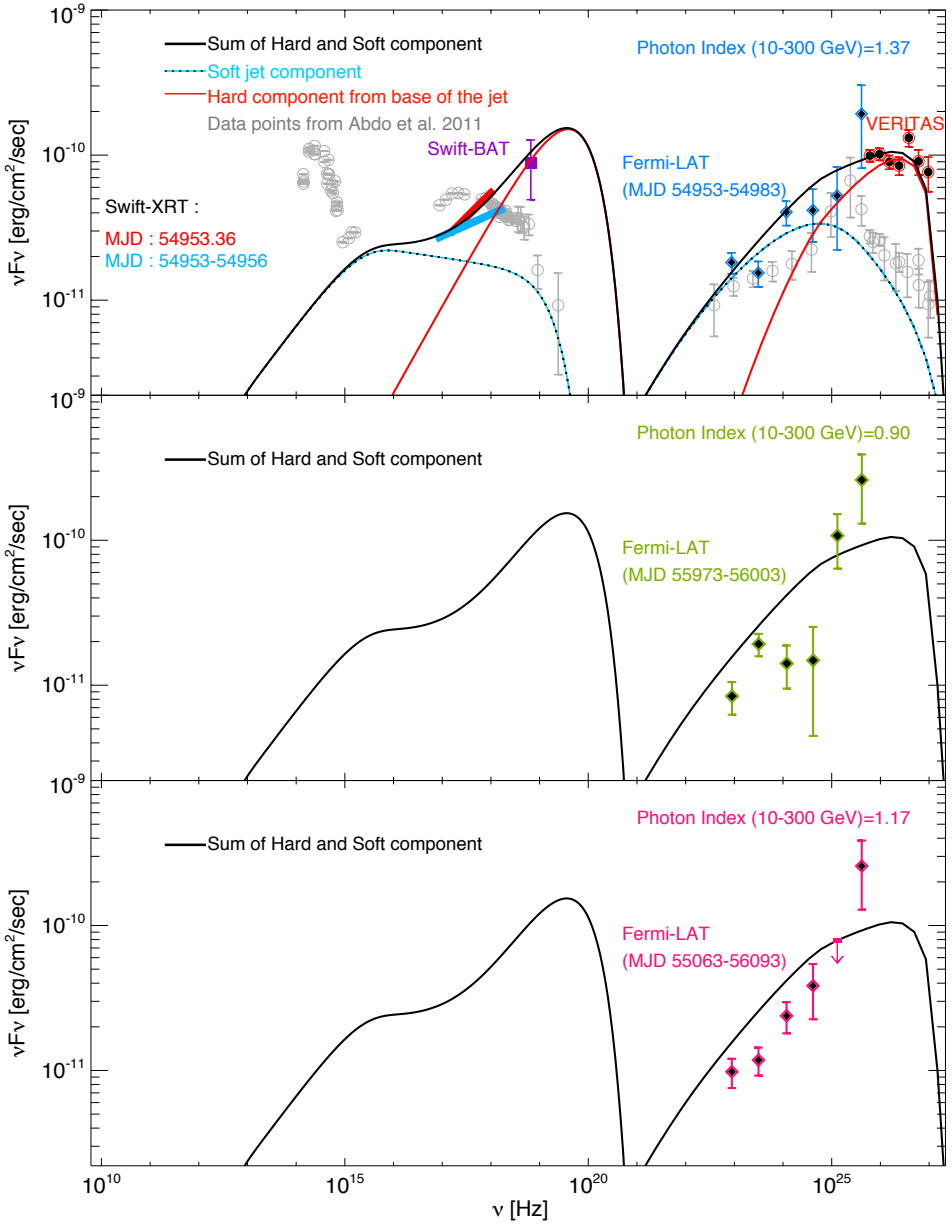
or

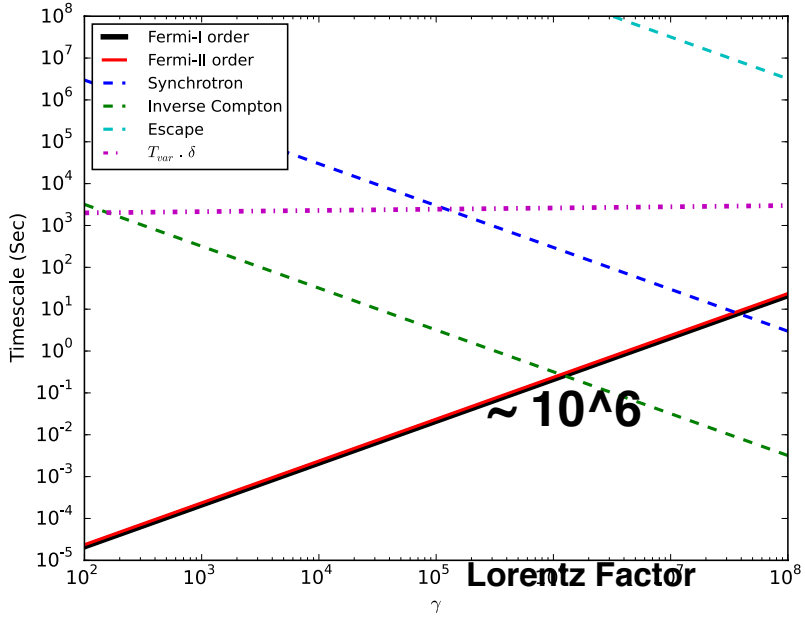
$$f(\gamma) = A\gamma^2 e^{-(\frac{\gamma}{\gamma_c})^{1+\alpha_p}}$$

Multi-Zone SED Model of Mrk 501

Narrow Powerlaw

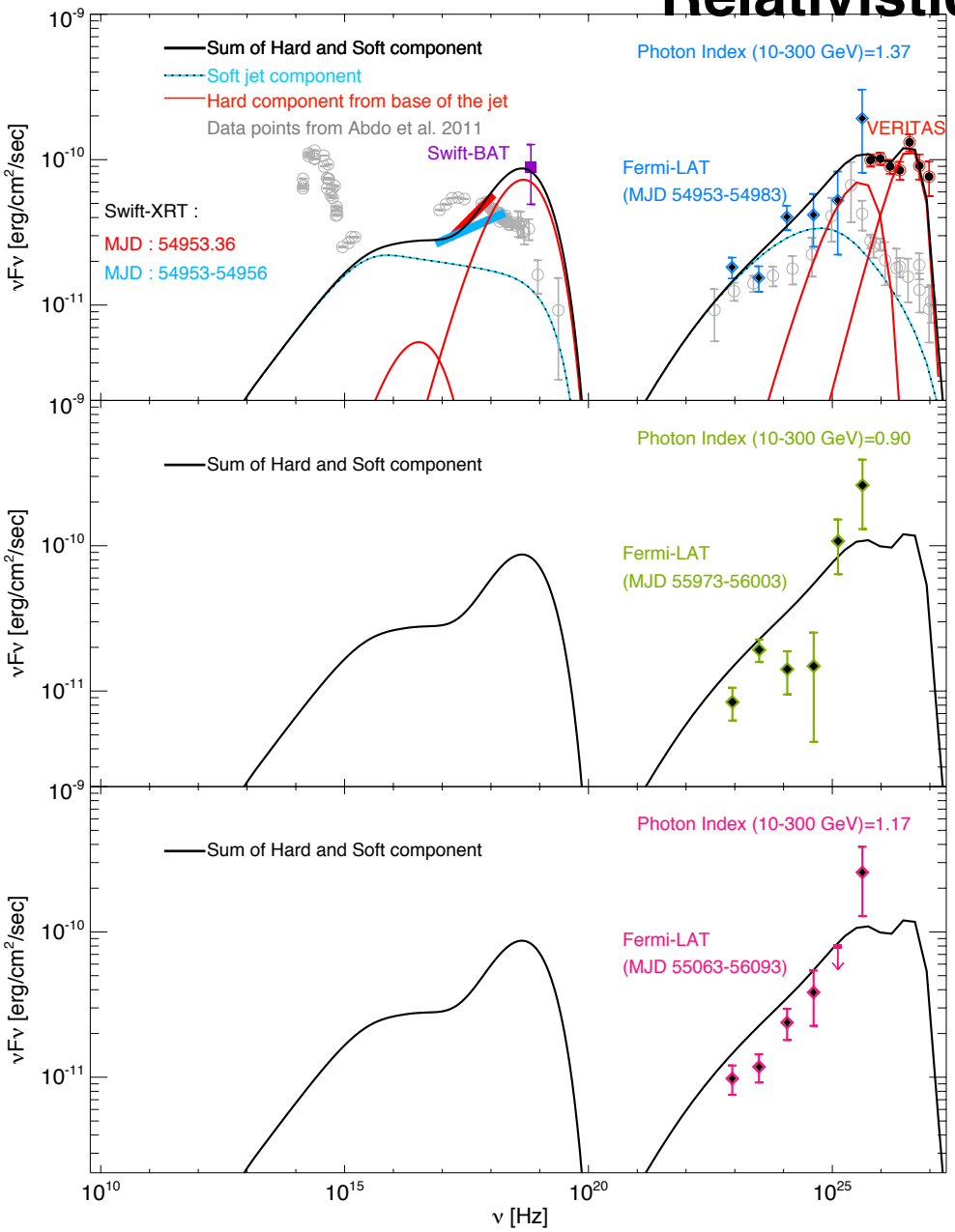


Parameters	Jet	NPL
T_var (Hours)	24	0.091
Magnetic field (G)	0.047	1.6
Doppler factor	10	10
γ_{Min}	1.26×10^3	5.0×10^3
γ_{Max}	3.17×10^6	1.26×10^6
γ_{Break}	3.9×10^4	9.79×10^6
P1	2.1	1.8
P2	3.1	2.7
$U_e(erg/cm^3)$	$7\times10^{-}3$	36
γ_c	-	-
η	77.8	353.4

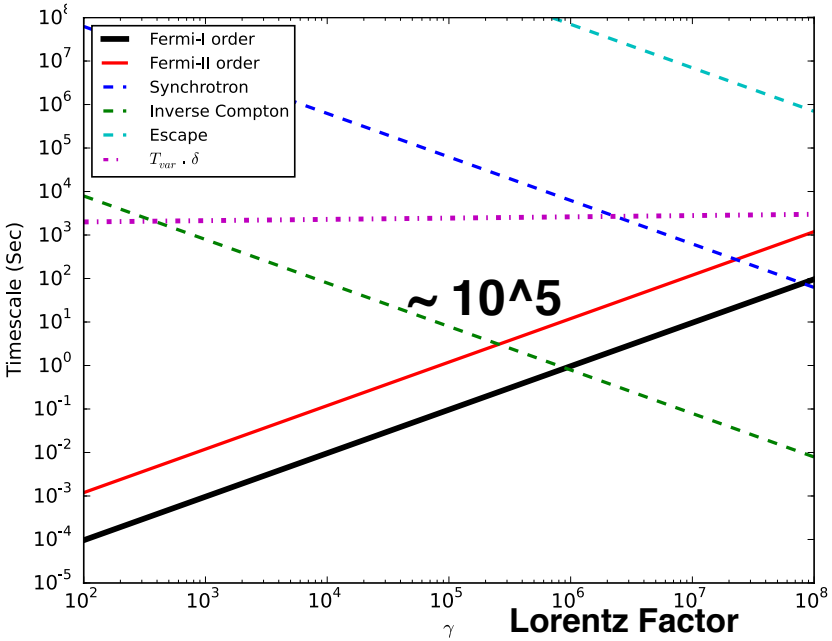


Multi Zone SED Model of Mrk 501

Relativistic Maxwellian



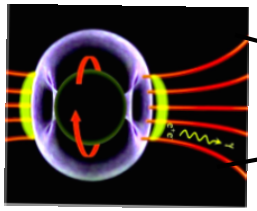
Parameters	Jet	RM1	RM2
T_var (Hours)	24	1	0.091
Magnetic field (G)	0.047	0.08	0.35
Doppler factor	10	10	10
γ_{Min}	1.26×10^{3}	-	-
γ_{Max}	3.17×10^{6}	-	-
γ_{Break}	3.9×10^{4}	-	-
P1	2.1	-	-
P2	3.1	-	-
$U_e(erg/cm^3)$	7×10^{-3}	1.2	1.9×10^{2}
γ_c	-	6.6×10^{4}	3.8×10^{5}
η	77.8	4712	38981.4

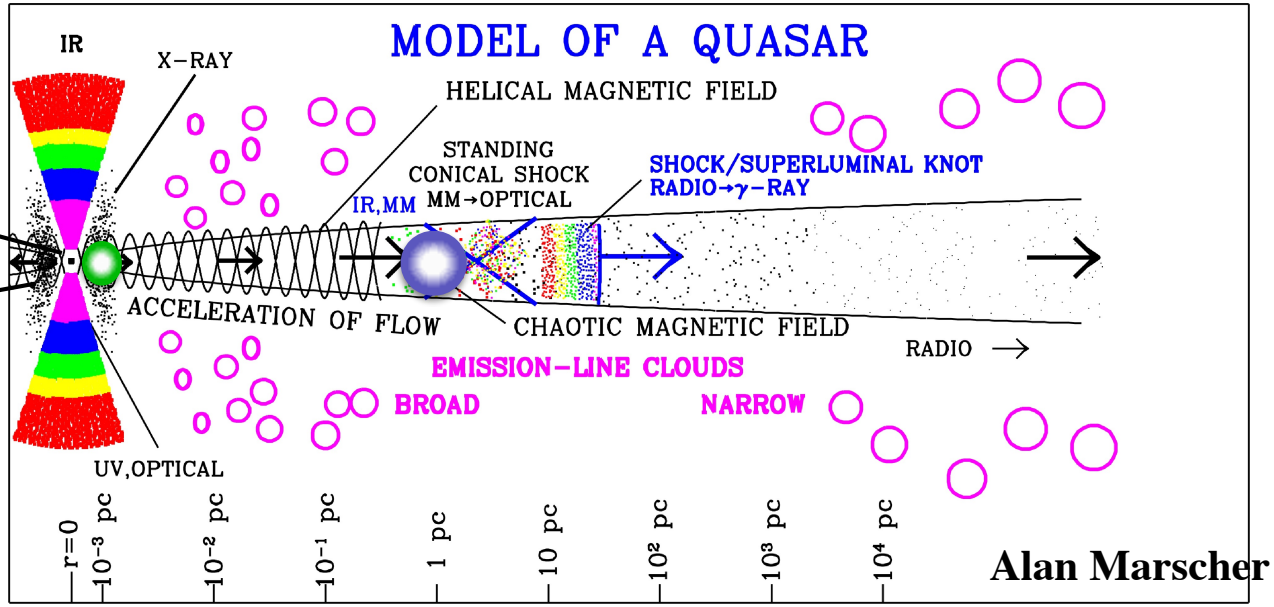


Results

- **Hardest photon index $\sim 0.89 \pm 0.29$.**
- **Multiple turbulent regions produced by magnetic reconnection at the base of the jet**
- **Signatures of intermittent injection of sharply peaked and localized particle distributions from the base of the jet.**
- **We propose a multi-zone scenario consisting of a slowly variable component with a soft spectrum from a shock in the jet and a rapidly variable hard components at the base of the jet.**
- **First order Fermi acceleration is assumed to be responsible for the shock-in-jet component, whereas second order Fermi acceleration is assumed to be responsible for the intermittent hard-spectrum component.**

Summary





Aleksic et al. 2015,

SCIENCE 346, 1080 (2014)

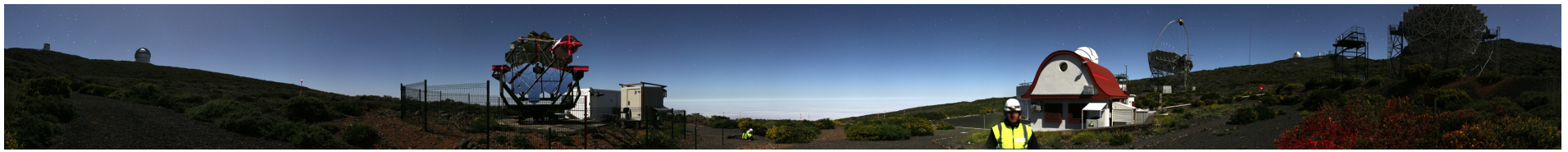
Alan Marscher et al., 2005

Fermi - second order + Fermi-first order

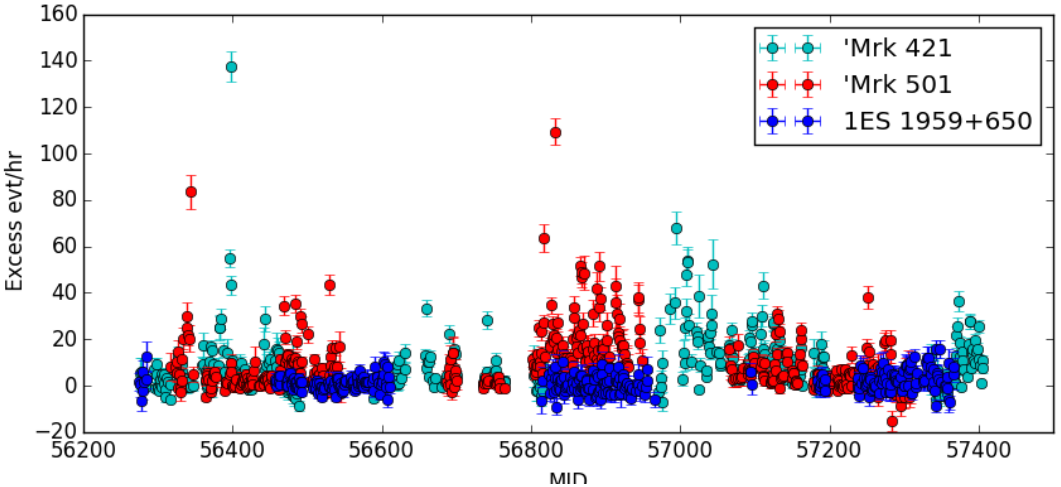
(Fast variability) **(Day scale variability)**

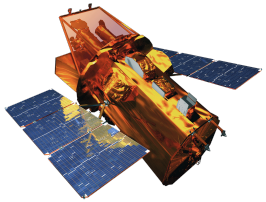
Distinguishing the site of origin of hard spectrum between the base of the jet or the BH magnetosphere will require unbiased simultaneous X-ray observations during TeV flares.

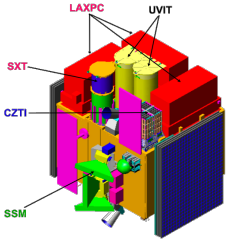
Strategy to pin down the emission mechanism



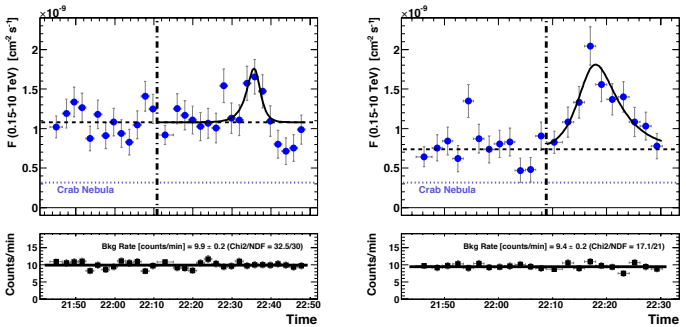
- **Mrk 421**
- **Mrk 501**
- **1ES1959+650**
- **IC 310**







http://fact-project.org/monitoring/



Search for Rapid variability by MAGIC, VERITAS and MACE