Max Planck Institute for Physics

European Week of Astronomy and Space Science

THE GAMMA-RAY SKY

IN THE ERA OF FERMI AND CHERENKOV TELESCOPES

11 and 12 July 2013, Turku, Finland

TeV Blazar Mrk 421 during Flaring Activity in March 2010

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On behalf of the Fermi, MAGIC, VERITAS , Whipple collaborations and the participants/groups of the MW campaign on Mrk421 in 2010, which include GASP-WEBT, F-GAMMA and many others

11/07/2013

Markarian 421 (Mrk 421)

- a strong High-Synchrotron-Peaked (HSP) BL Lac object
- Very High Energy (VHE) gamma-ray flux ~0.5 Crab
- It can be detected at 5+ sigmas in order few minutes with MAGIC and VERITAS

- z = 0.03
- low Extragalactic Background Light absorption
- more intrinsic spectrum

Excellent laboratory for studying High Energy blazar emission

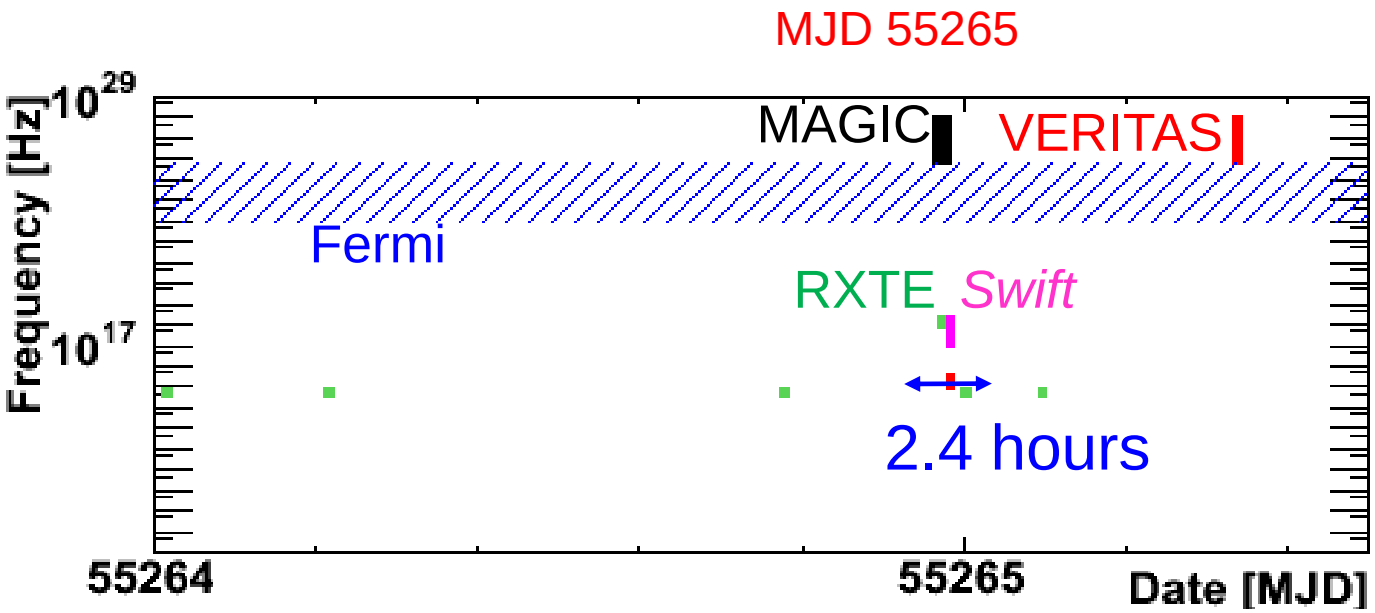
2010 Multi-wavelength(MW) Instruments/Bands

Wave band	instrument
VHE Gamma Rays	MAGIC
VHE Gamma Rays	VERITAS
VHE Gamma Rays	Whipple
HE Gamma Rays	Fermi
X-rays	RXTE/PCA
X-rays	SWIFT/BAT
X-rays	SWIFT/XRT
X-rays	RXTE/ASM
X-rays	MAXI
UV/UVW2	SWIFT/UVOT
UV/UVM2	SWIFT/UVOT
UV/UVW1	SWIFT/UVOT
Optical/b band	ROVOR
Optical/b band	Bradford Robotic Telescope

Wave band	instrument
Optical/v band	New Mexico Skies
Optical/v band	ROVOR
Optical/v band	Bradford Robotic Telescope
Optical/r band	New Mexico Skies
Optical/r band	ROVOR
Optical/r band	Bradford Robotic Telescope
Optical/r band	GLAST-AGILE Support Program
Optical/r band	Goddard Robotic Telescope
Optical/r band	Perkins
Optical/r band	Steward
Optical/r band	Crimean
Optical/r band	St.Petersburg
Optical/I band	ROVOR
Radio (37 GHz)	Metsahovi
Radio (14 GHz)	UMRAO
Radio (8 GHz)	UMRAO

Totally ~30 instruments/bands

Simultaneity of the MW Observations



Observations are truly simultaneous

→ Very important during flaring activity

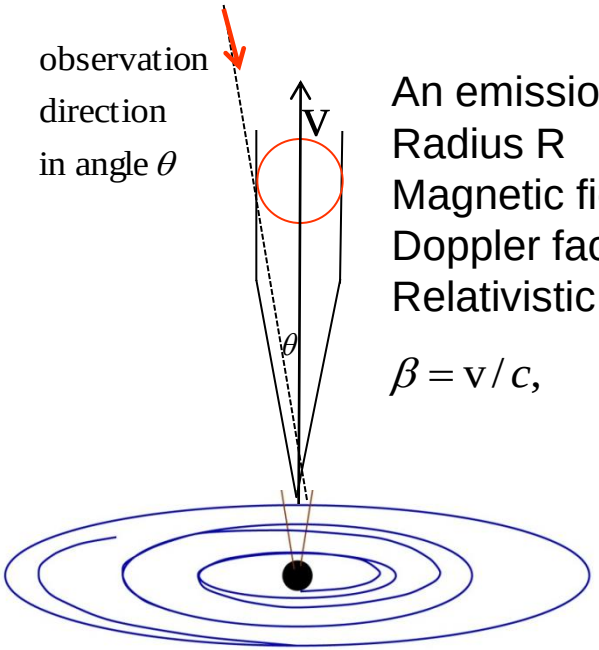
That means <u>high reliability</u> of the results derived with these data

Describe Spectra with One-Zone Synchrotron Self-Compton(SSC) Model

electron spectrum parameters

Environmental parameters

$\gamma_{\min}, \gamma_{\max}, \gamma_{break}, s_1, \ s_2, n_e[\mathrm{cm}^{-3}]$, B[mG], log(R[cm]), δ



An emission blob with:
Radius R
Magnetic field B
Doppler factor δ
Relativistic electrons

$$\beta = \mathrm{v}/c, \qquad \gamma = (1-\beta^2)^{-1/2}, \qquad \delta = \gamma^{-1}(1-\beta\cos\theta)^{-1}$$

Electron Energy Distribution (EED)

$(n_e, s_1, s_2, \gamma_{\min}, \gamma_{break}, \gamma_{\max})$

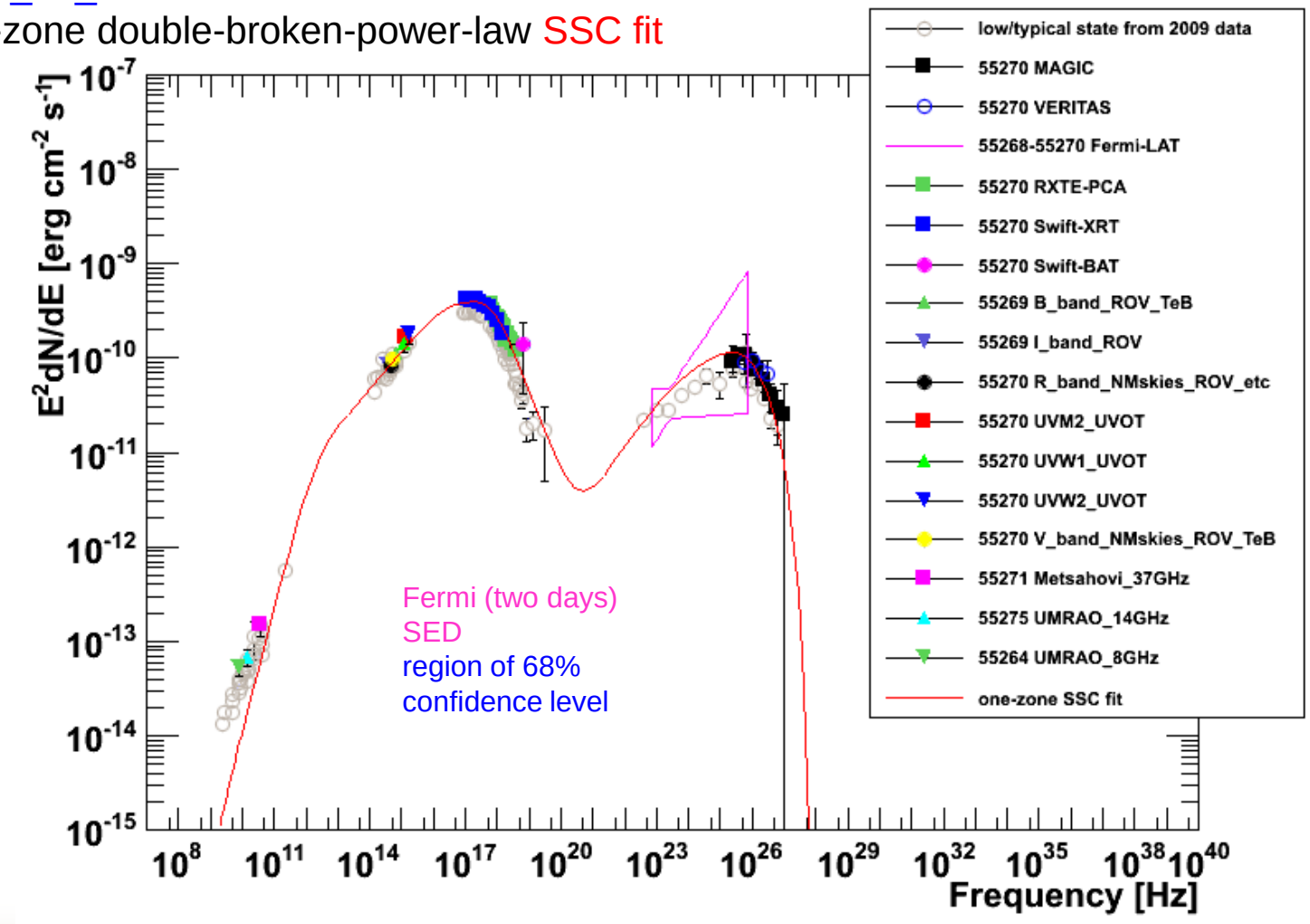
$$\frac{dN}{d\gamma} = \begin{cases} (\,for\ \gamma_{\min} < \gamma < \gamma_{break}) \ n_e \gamma^{-s_1} \\ (\,for\ \gamma_{break} < \gamma < \gamma_{\max}) \ n_e \gamma^{-s_2} \gamma_{break}^{s_2 - s_1} \end{cases}$$

Using Hajime Takami ‘s SSC code
Monthly Notices of the Royal Astronomical Society, Volume 413, Issue 3, pp. 1845-1851

Example for Spectral Energy Distribution(SED) and 1-zone SSC Modeling

Content of this plot:

1. reference: low/typical state SED from 2009 data (averaged)
2. 2010_03_15 SED
3. one-zone double-broken-power-law SSC fit



Example for SED and 2-zone SSC Modeling

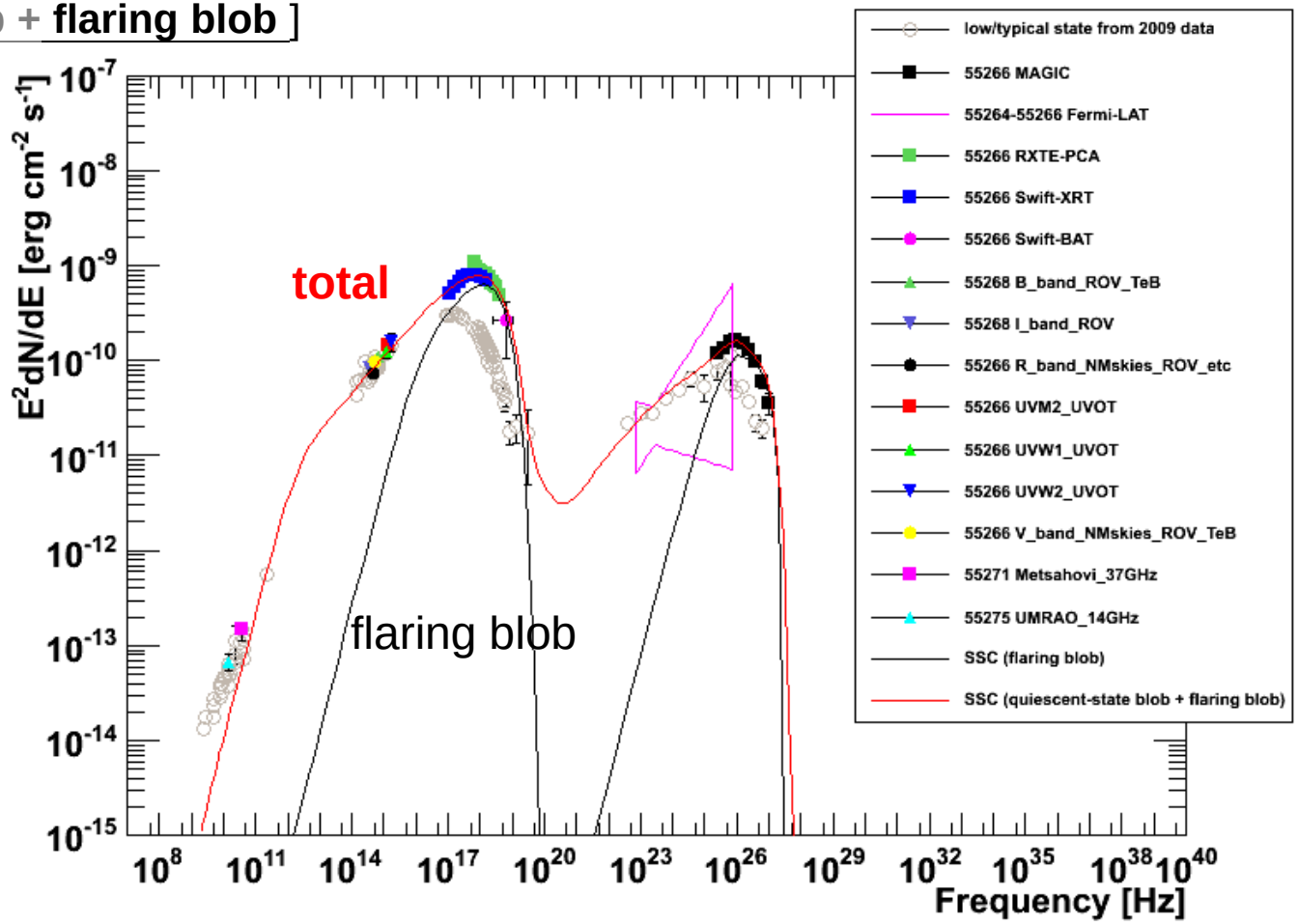
Content of this plot:

1. reference: low/typical state SED from 2009 data (averaged)
2. 2010_03_11(high state) SED
3. SSC fit [**quiescent blob + flaring blob**]
4. SSC fit [**flaring blob**]

quiescent blob
(parameter stay the same during the whole activity. Choose the lowest state, MJD 55274 (~2009 average)

flaring blob
(blob size smaller, EED and B change day by day)

total



Mrk421 MW light curves
flare 10th ~ 22nd March 2010

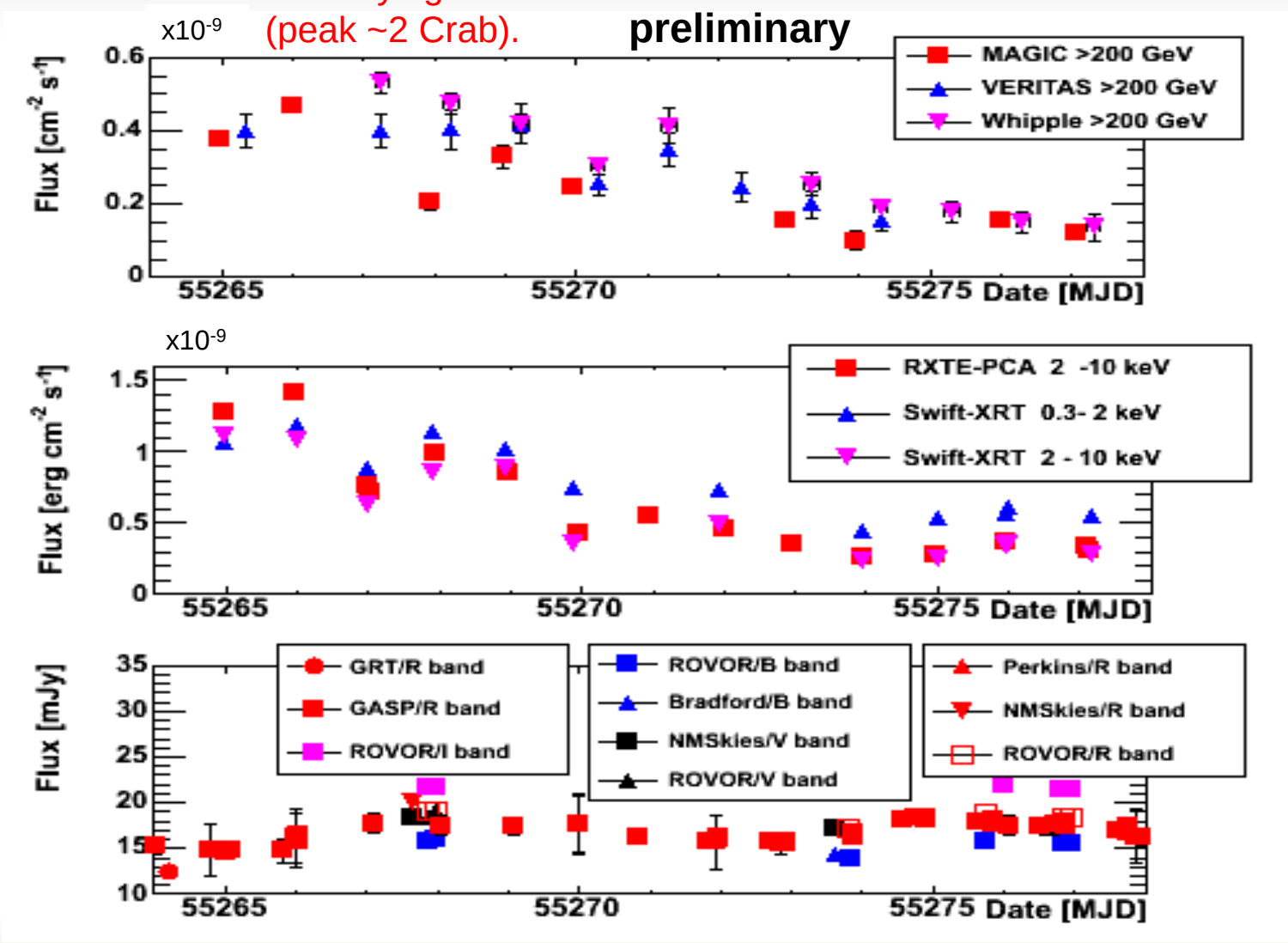
A decaying flare
(peak ~2 Crab).

preliminary

VHE

XRays

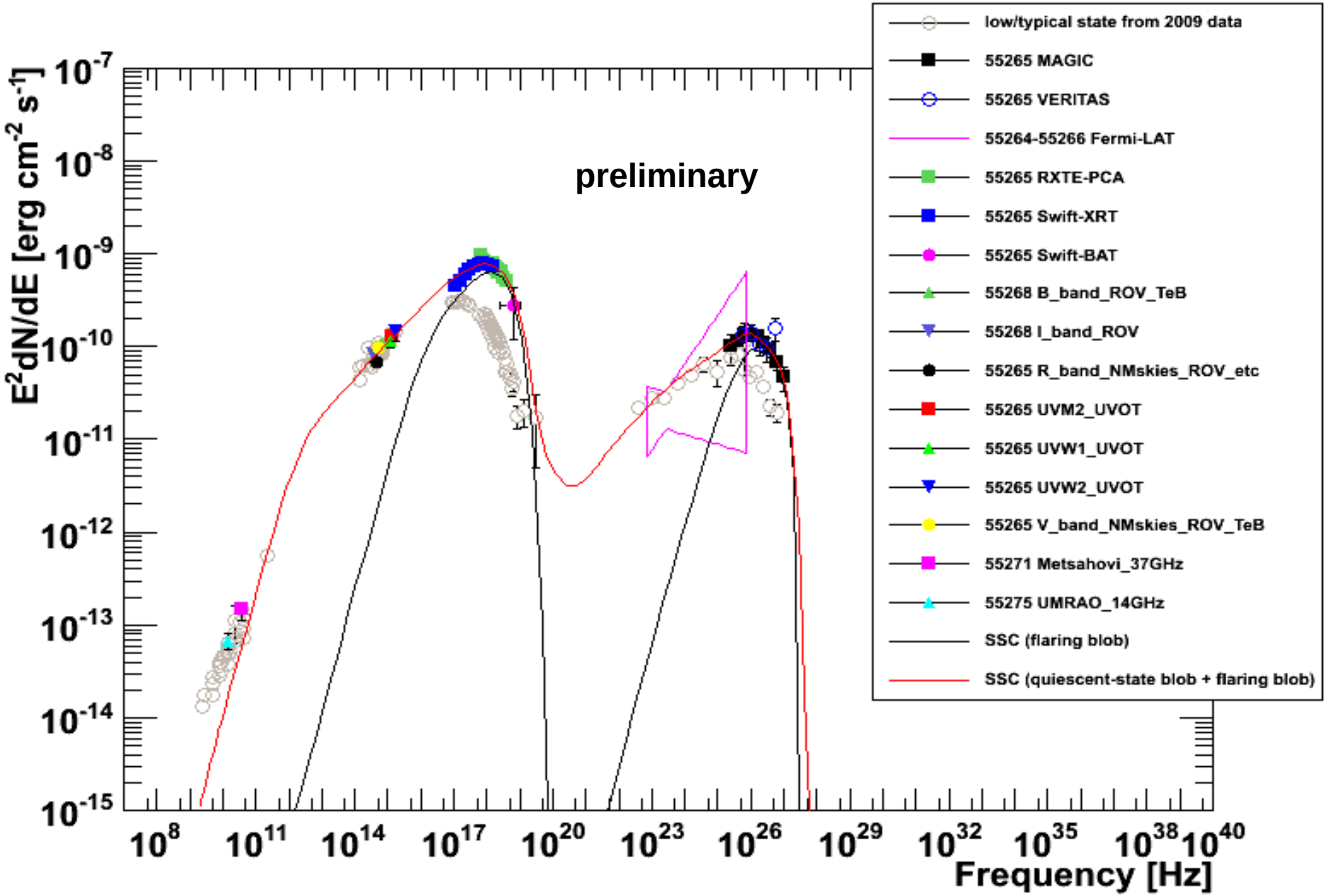
Optical



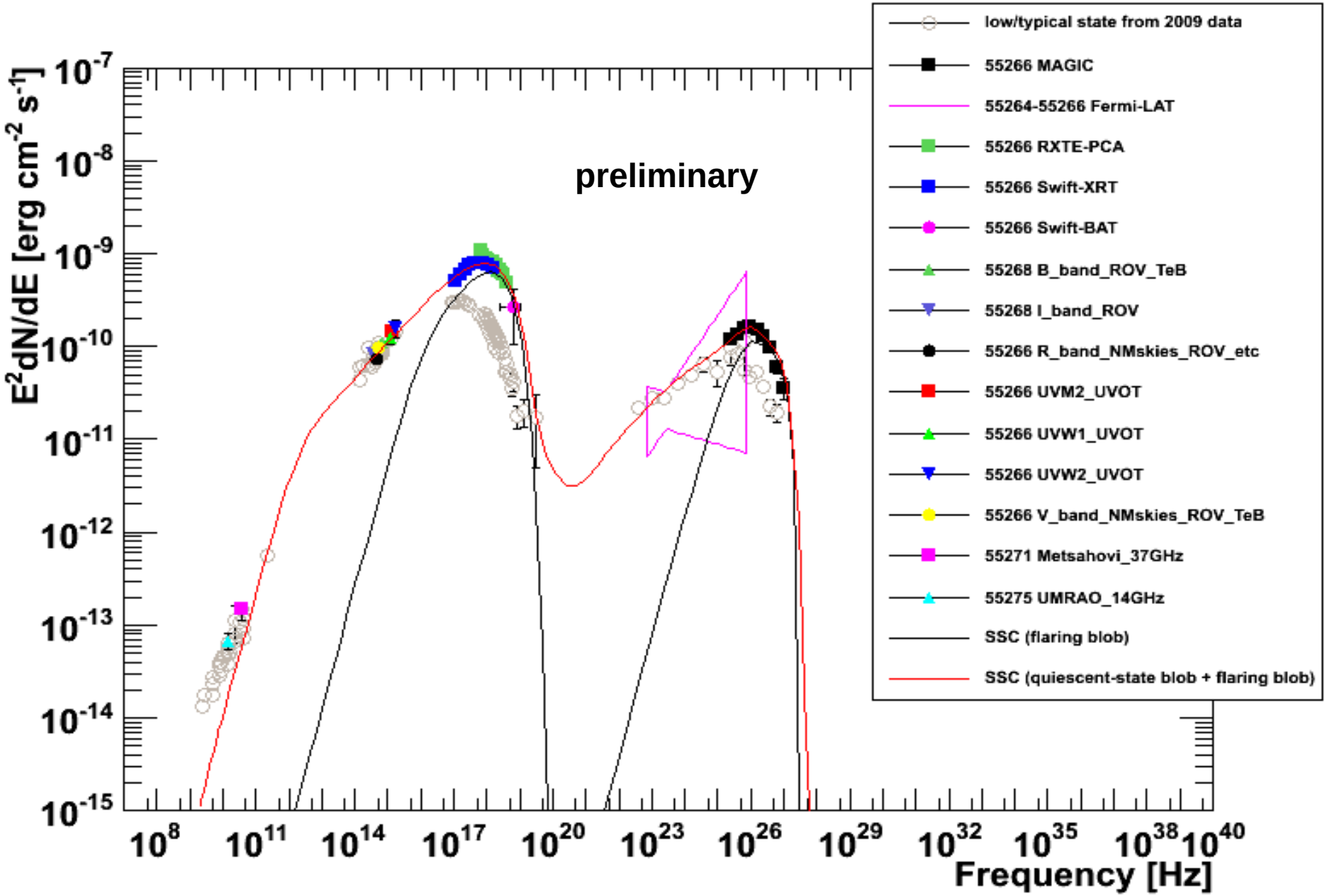
10th ~ 22nd March 2010

13 daily successive frames of broadband MW SEDs resolving the flare :

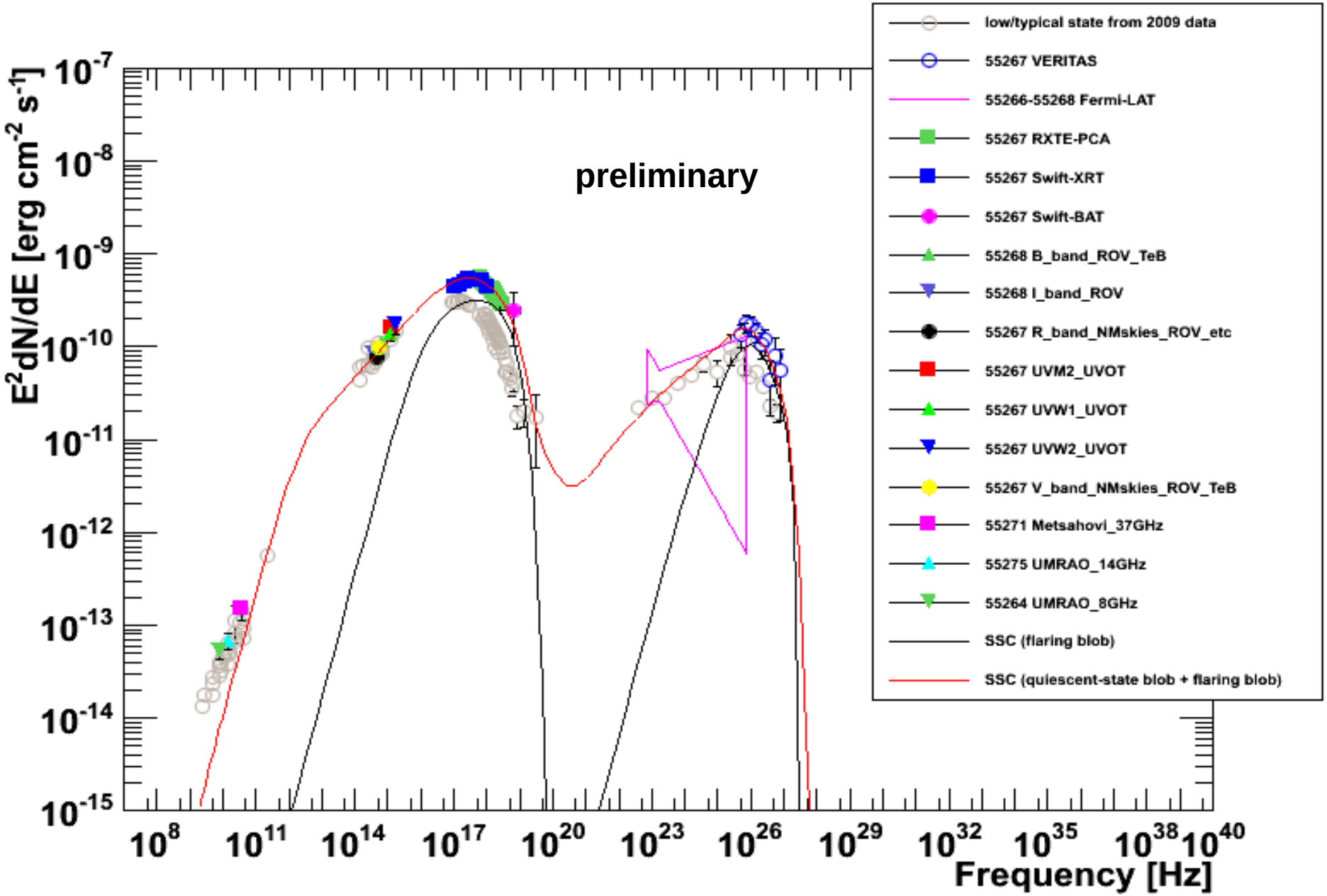
Mrk421 2010_03_10 (55265) [Day 1]



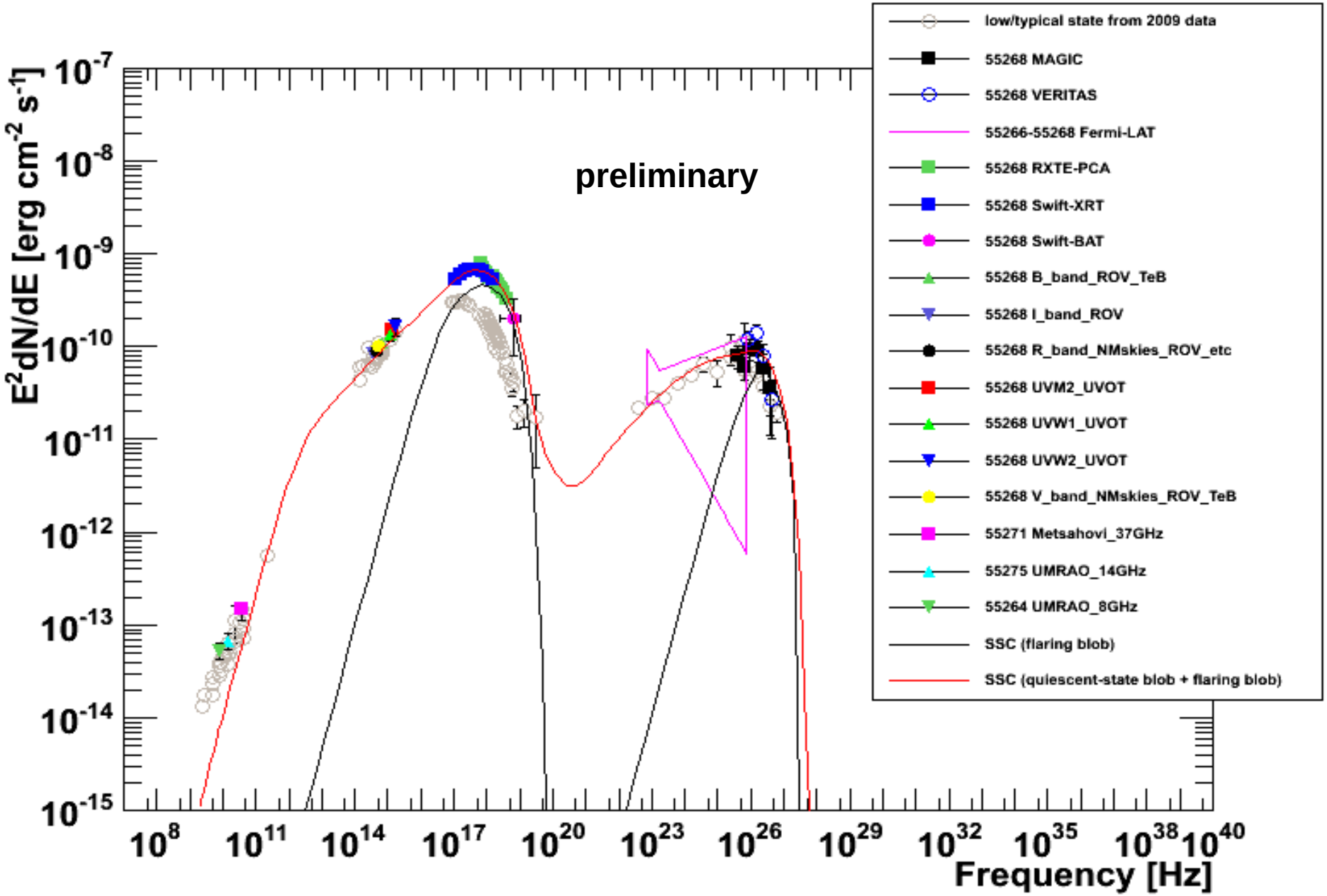
Mrk421 2010_03_11 (55266) [Day 2]



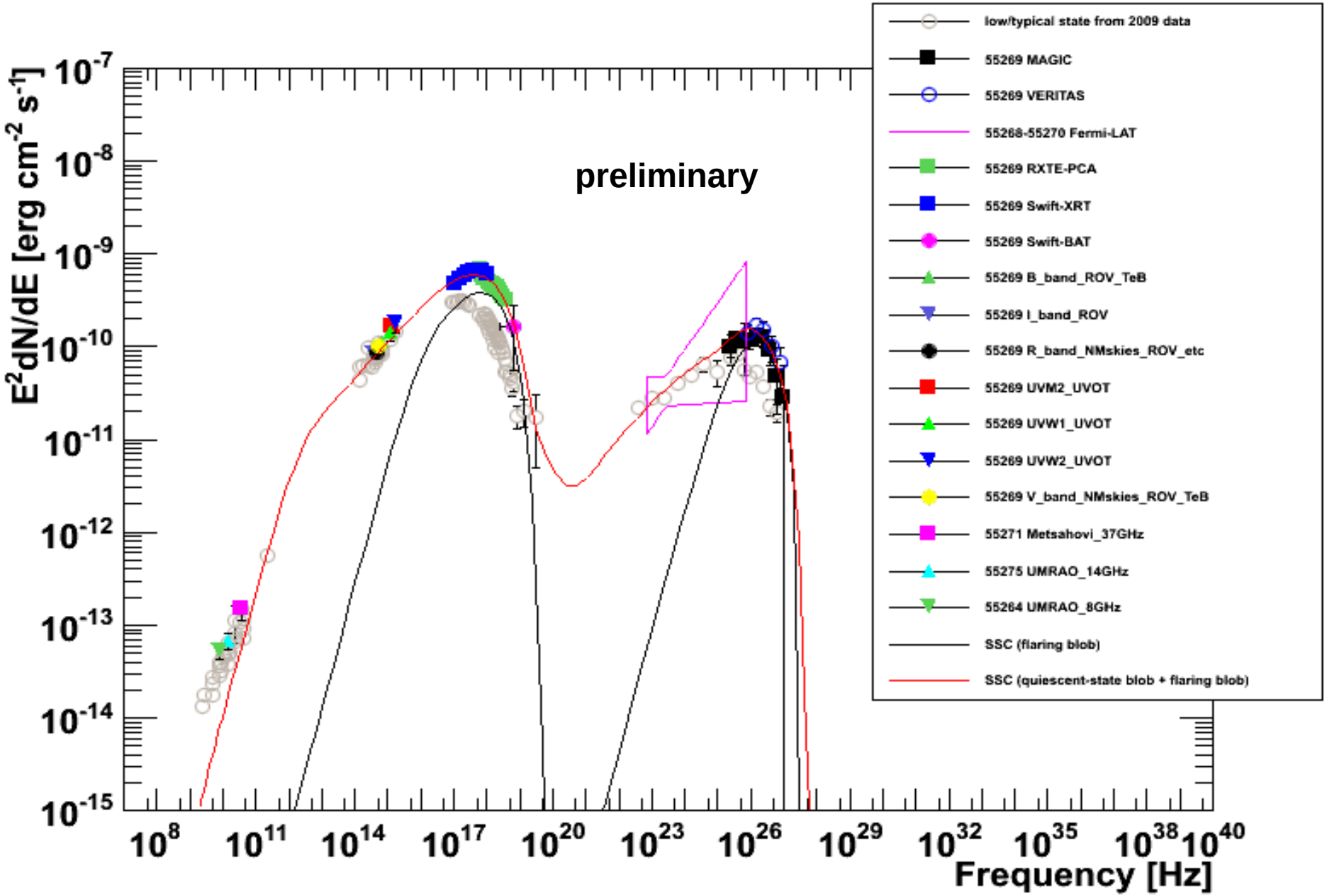
Mrk421 2010_03_12 (55267) [Day 3]



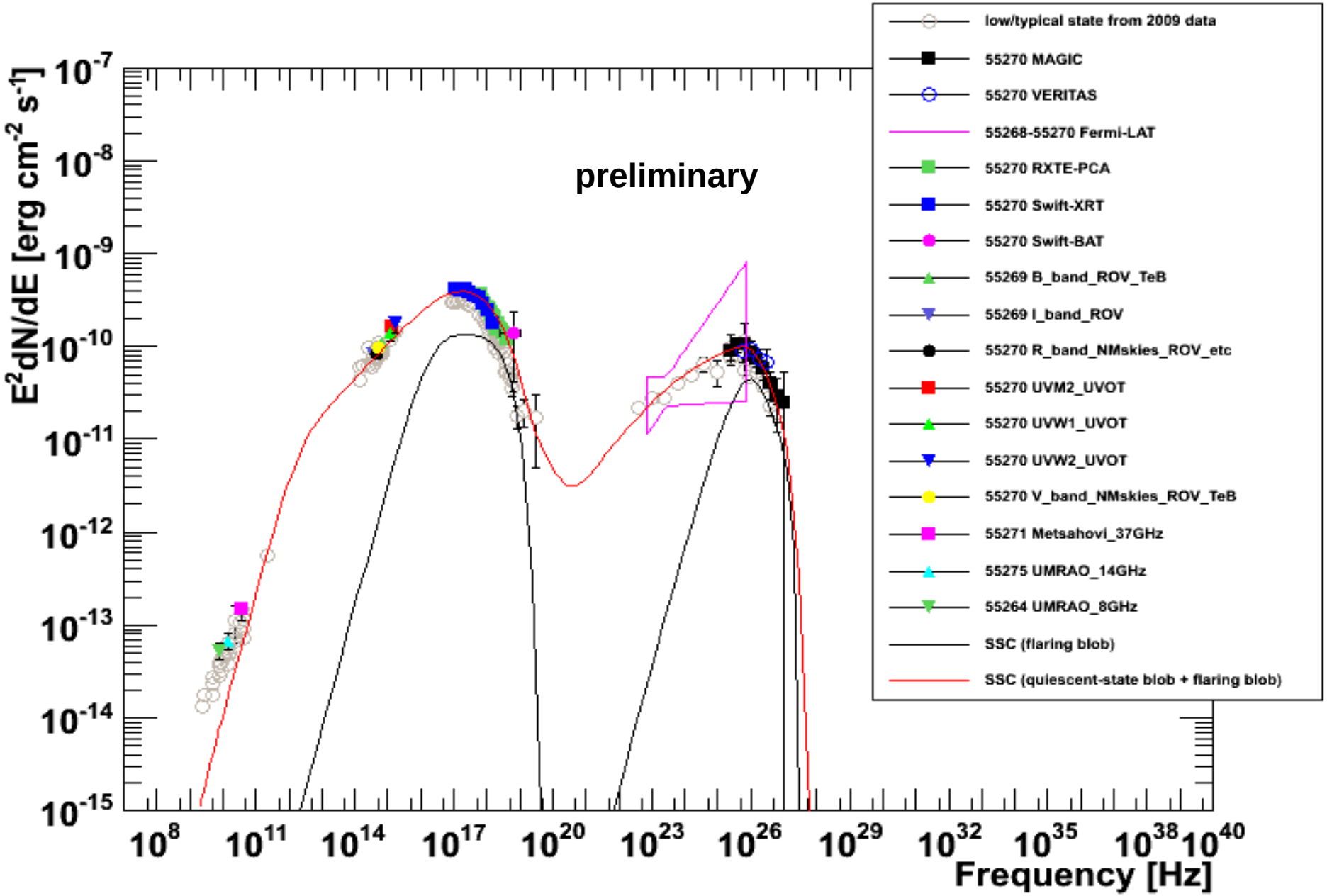
Mrk421 2010_03_13 (55268) [Day 4]



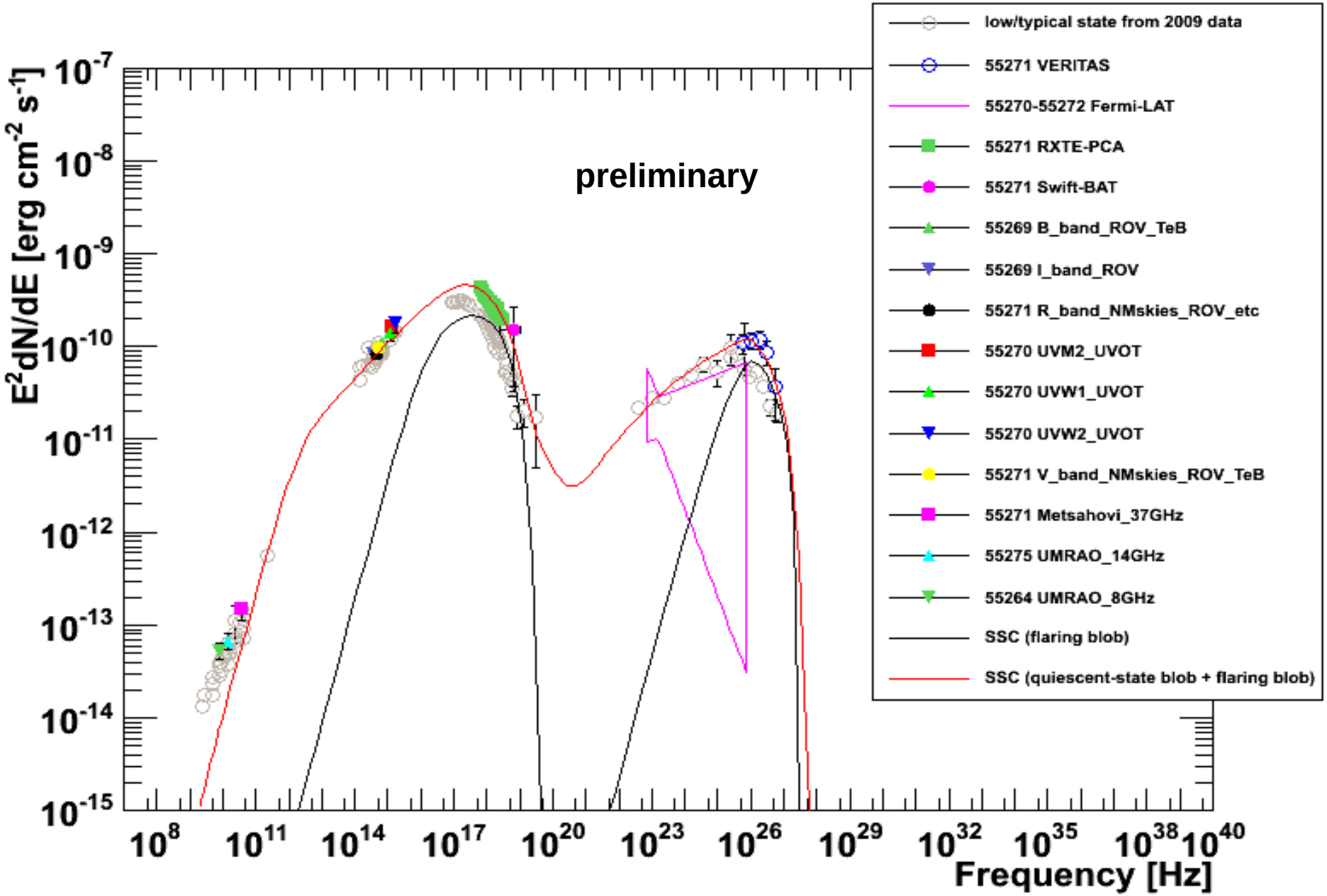
Mrk421 2010_03_14 (55269) [Day 5]



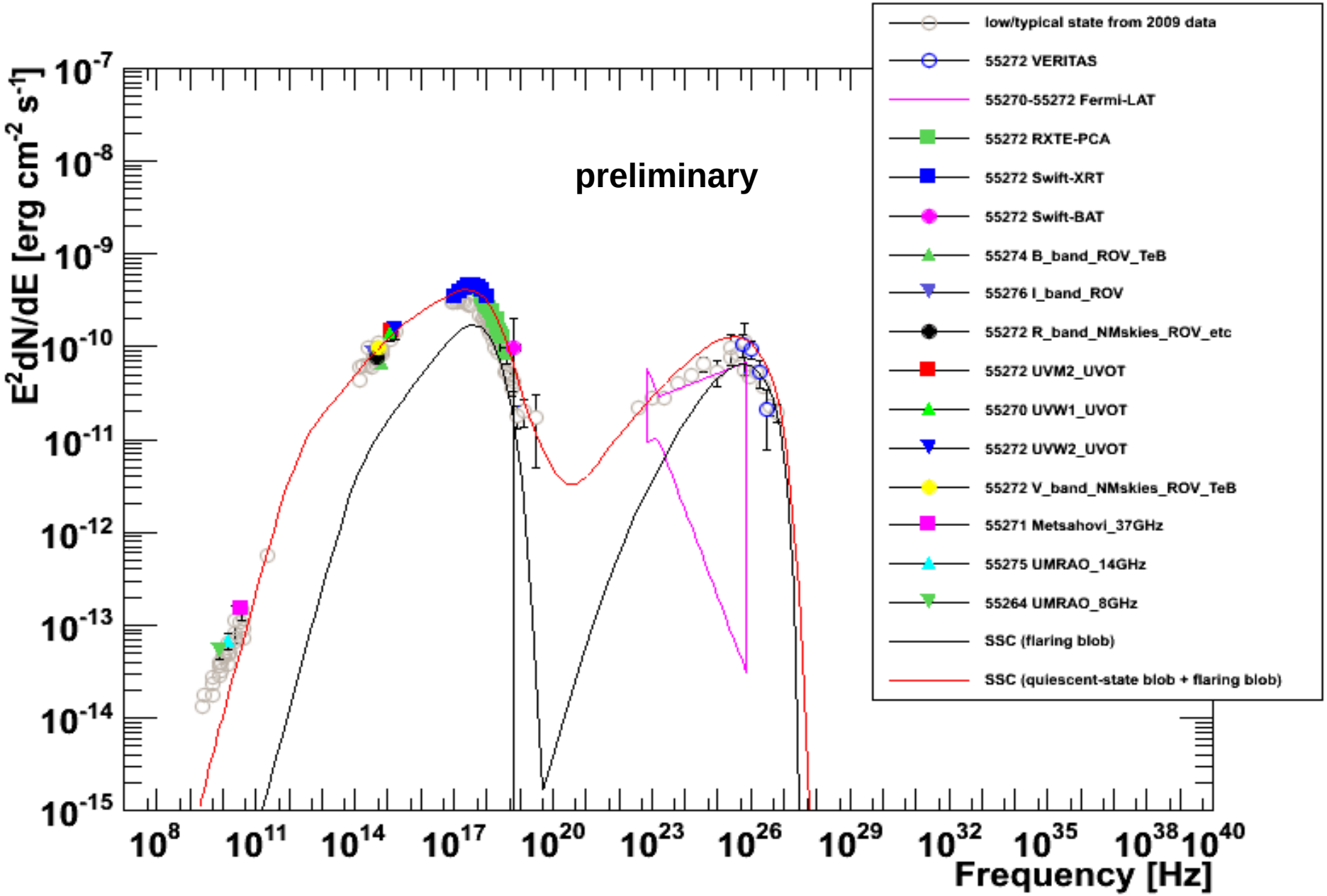
Mrk421 2010_03_15 (55270) [Day 6]



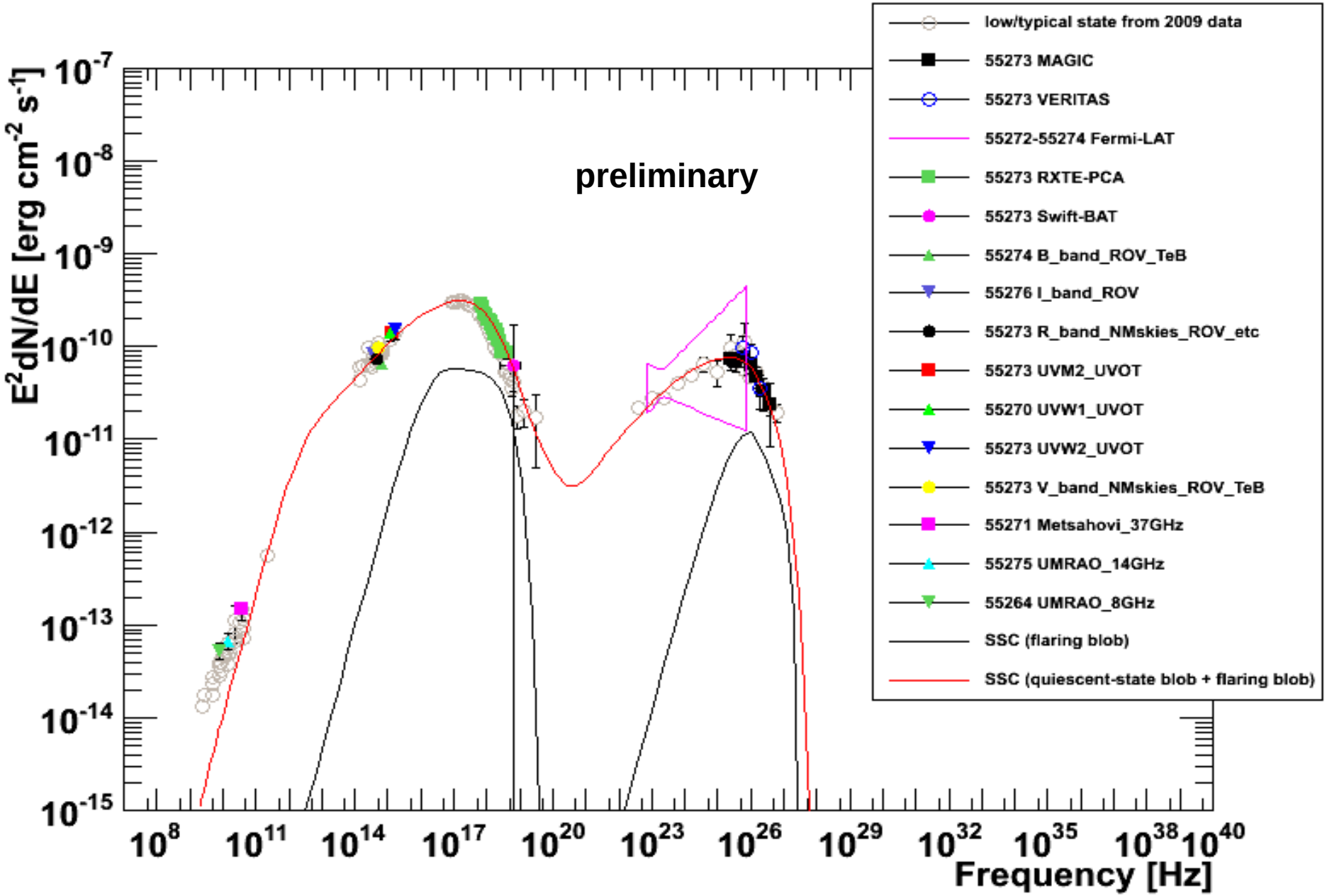
Mrk421 2010_03_16 (55271) [Day 7]



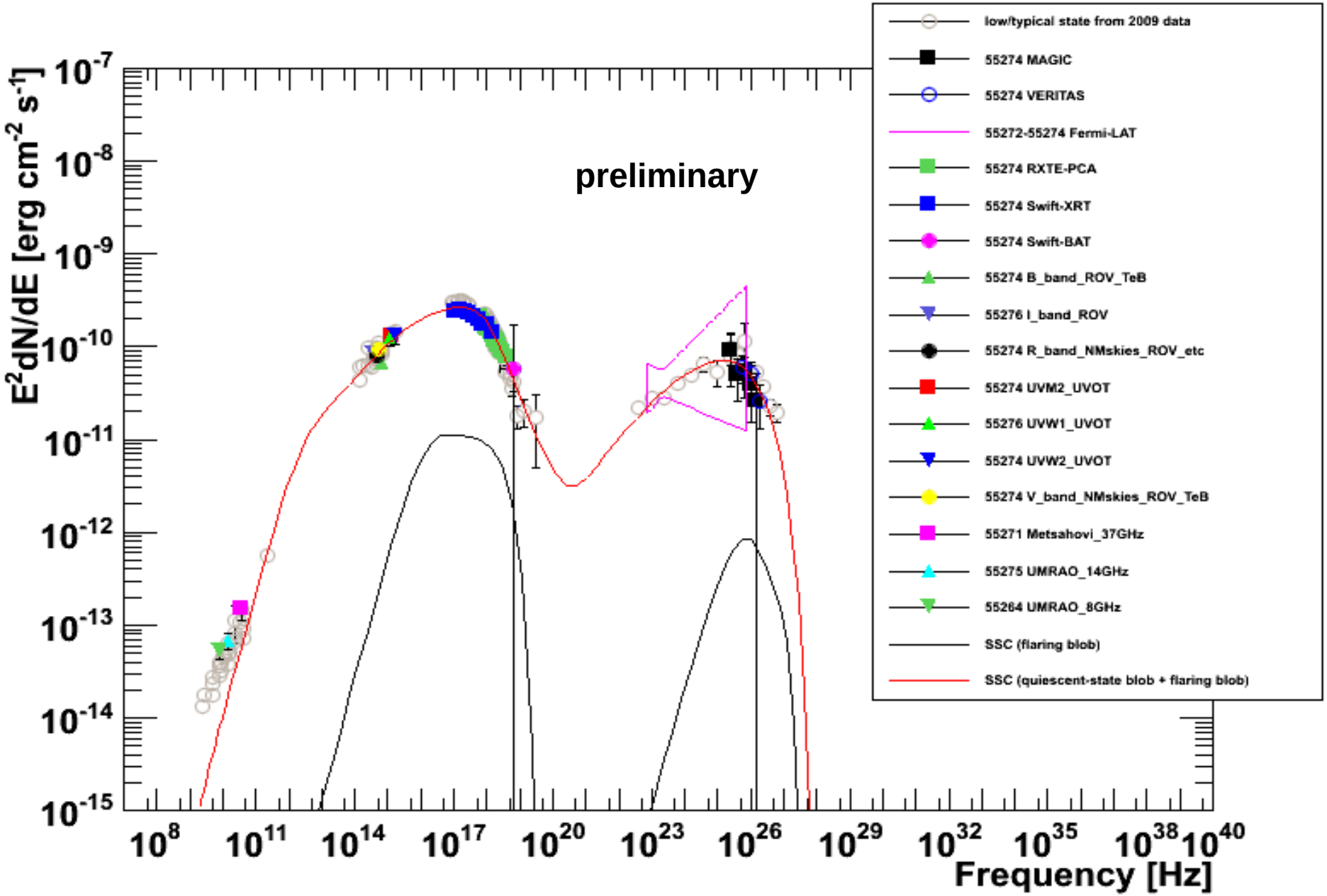
Mrk421 2010_03_17 (55272) [Day 8]



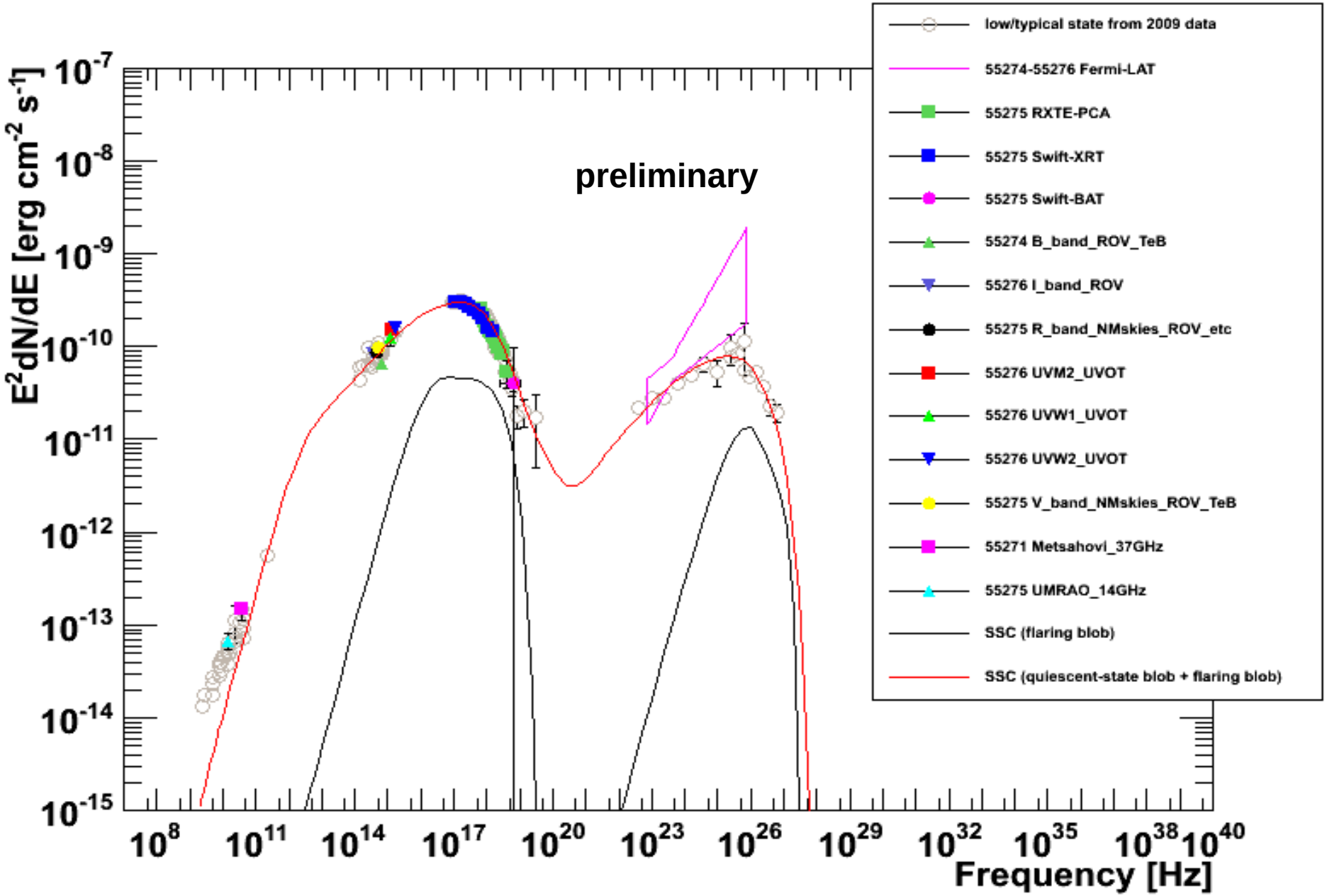
Mrk421 2010_03_18 (55273) [Day 9]



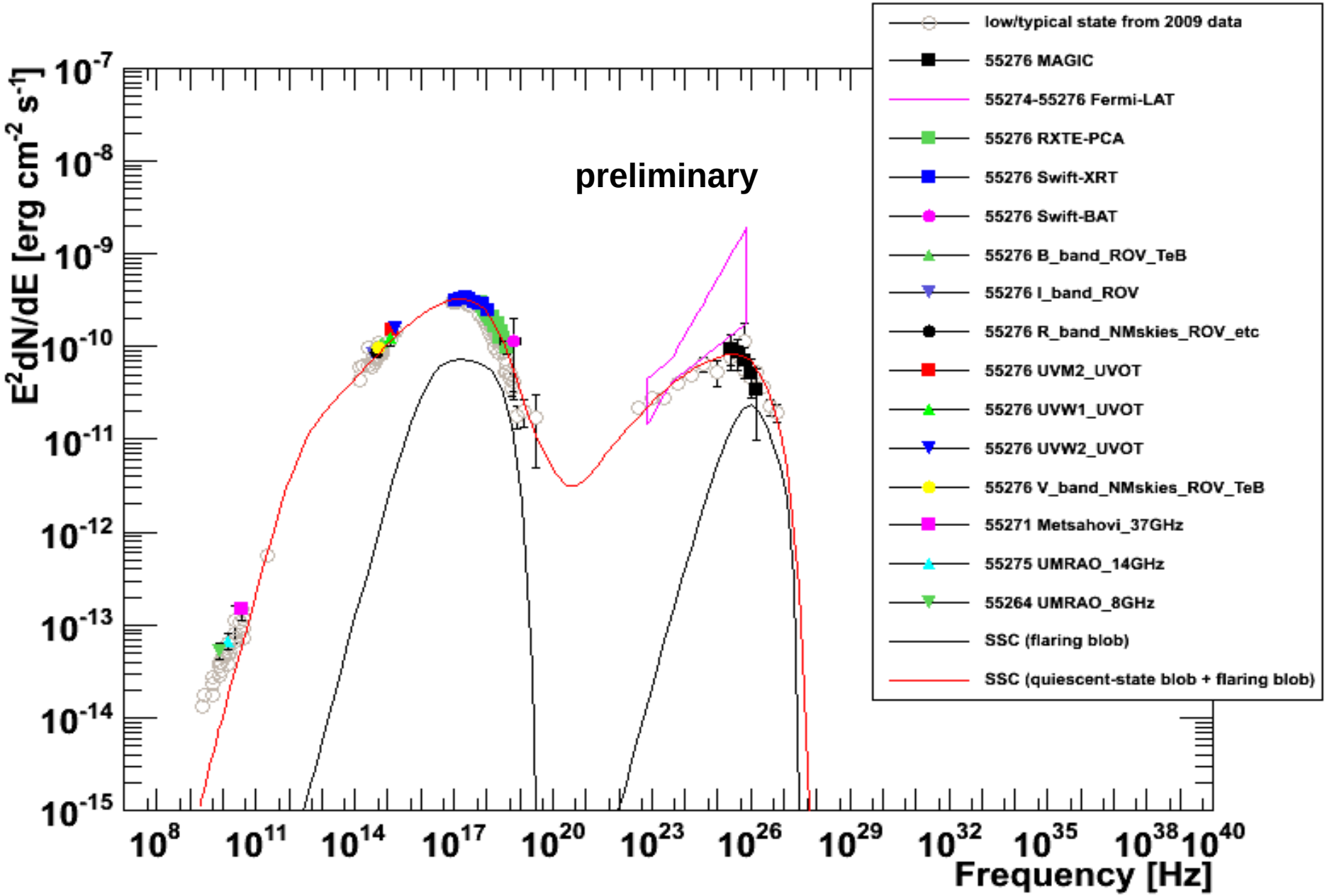
Mrk421 2010_03_19 (55274) [Day 10]



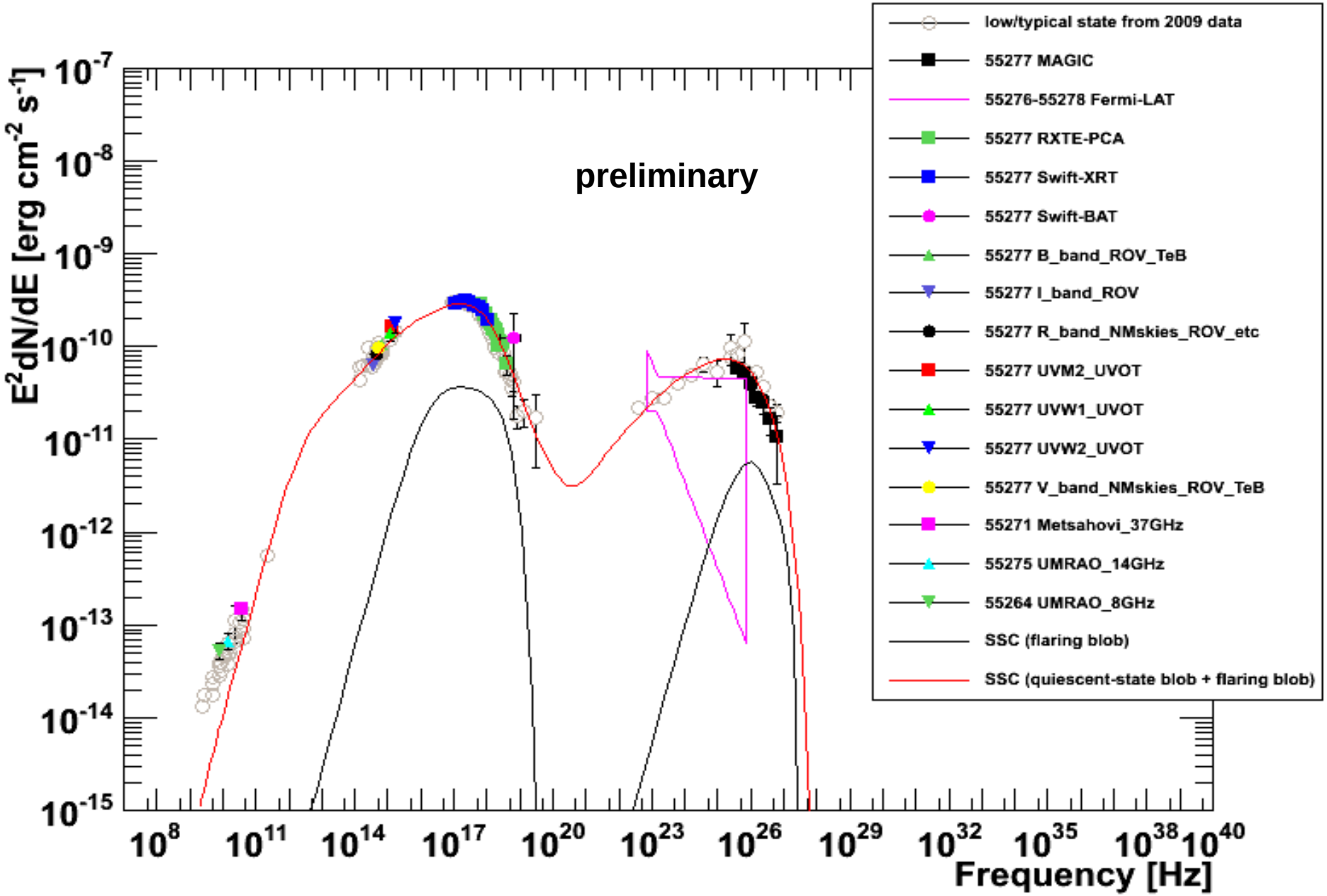
Mrk421 2010_03_20 (55275) [Day 11]



Mrk421 2010_03_21 (55276) [Day 12]



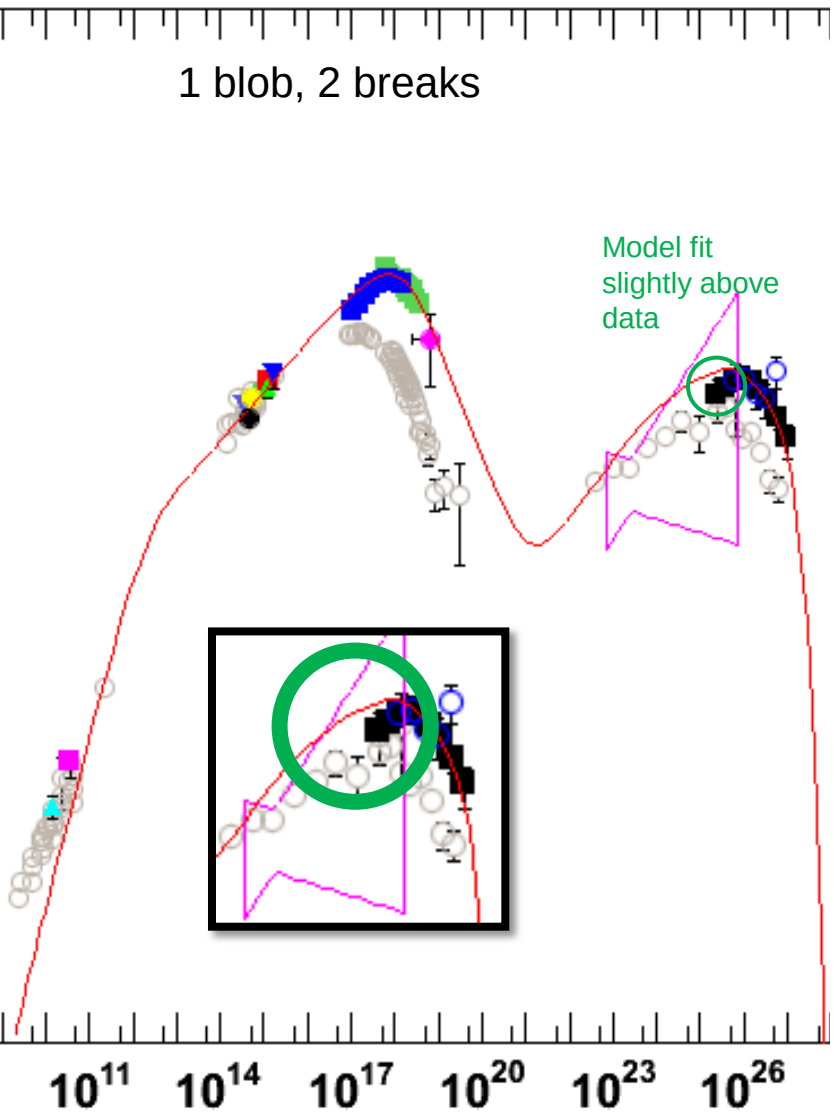
Mrk421 2010_03_22 (55277) [Day 13]



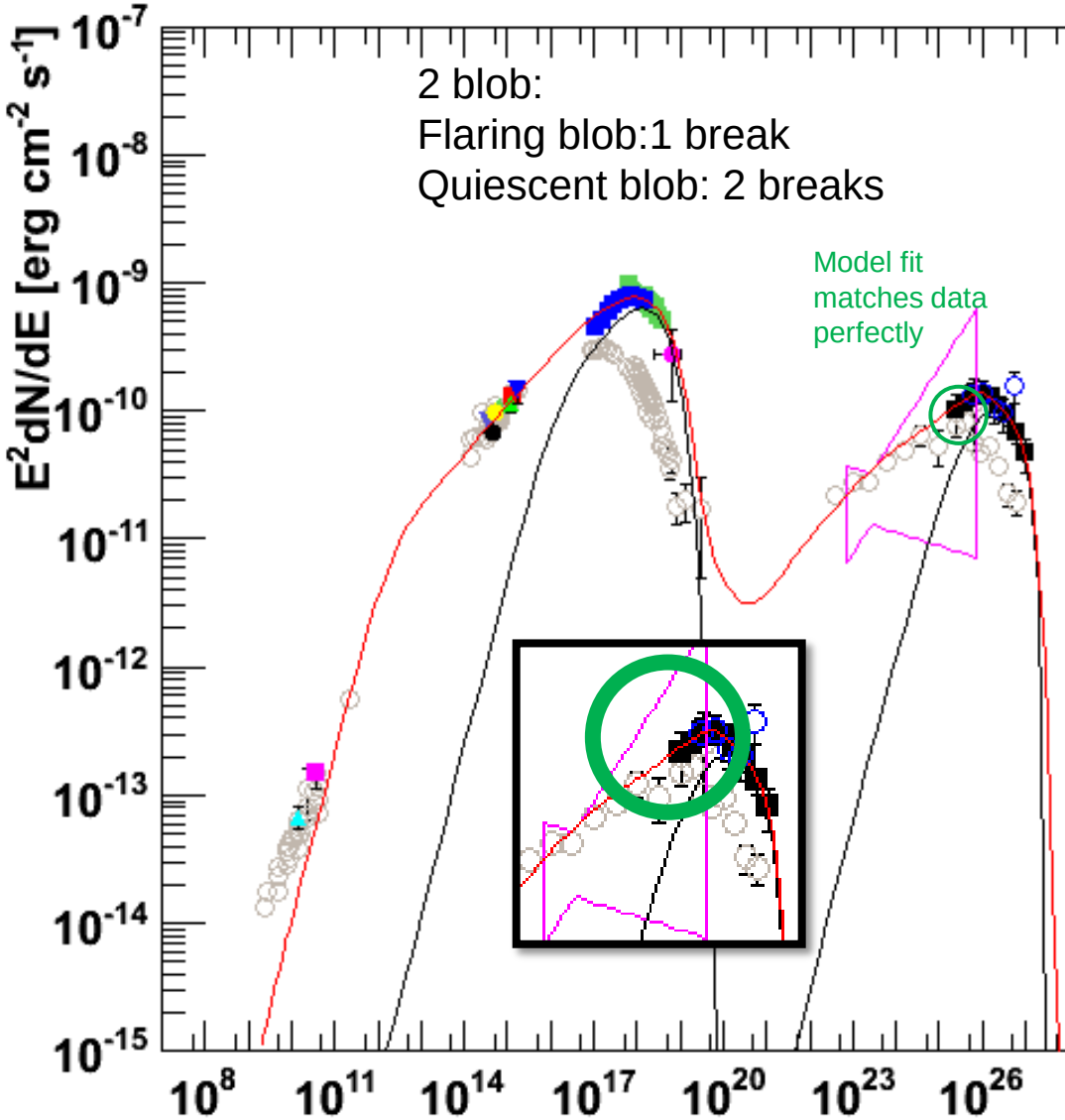
Mrk421 MW 2010_03_10 (55265) [Day 1]

high state

Model 1



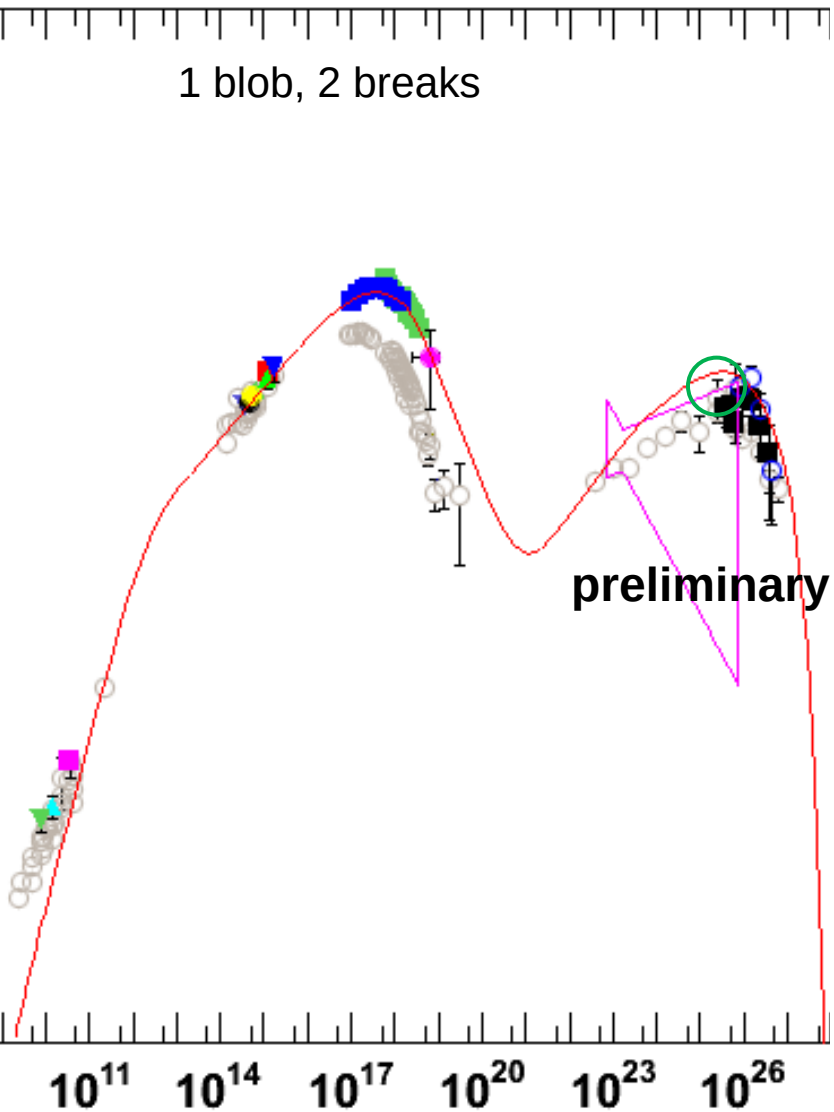
Model 2



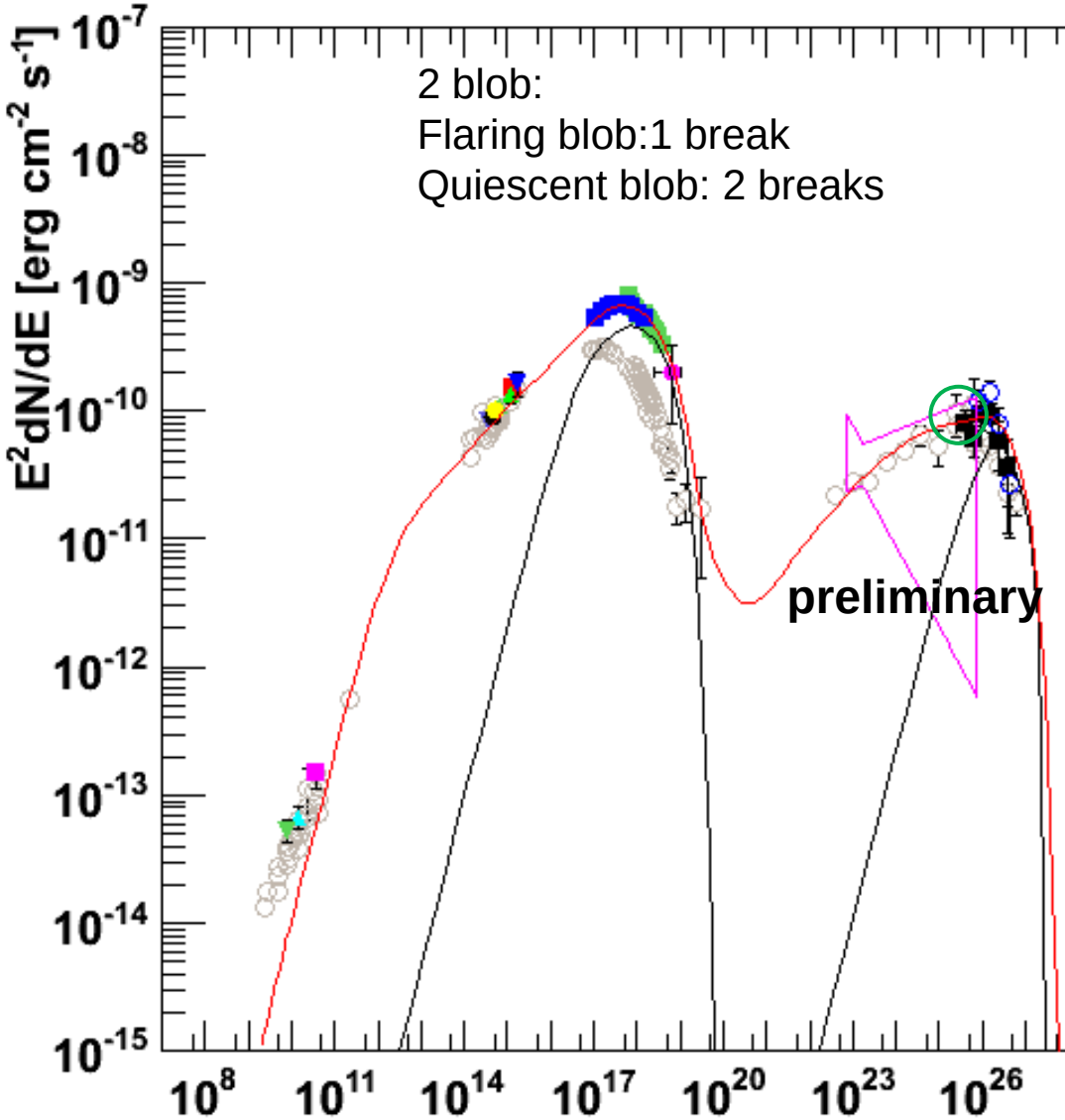
Mrk421 MW 2010_03_13 (55268) [Day 4]

high state

Model 1



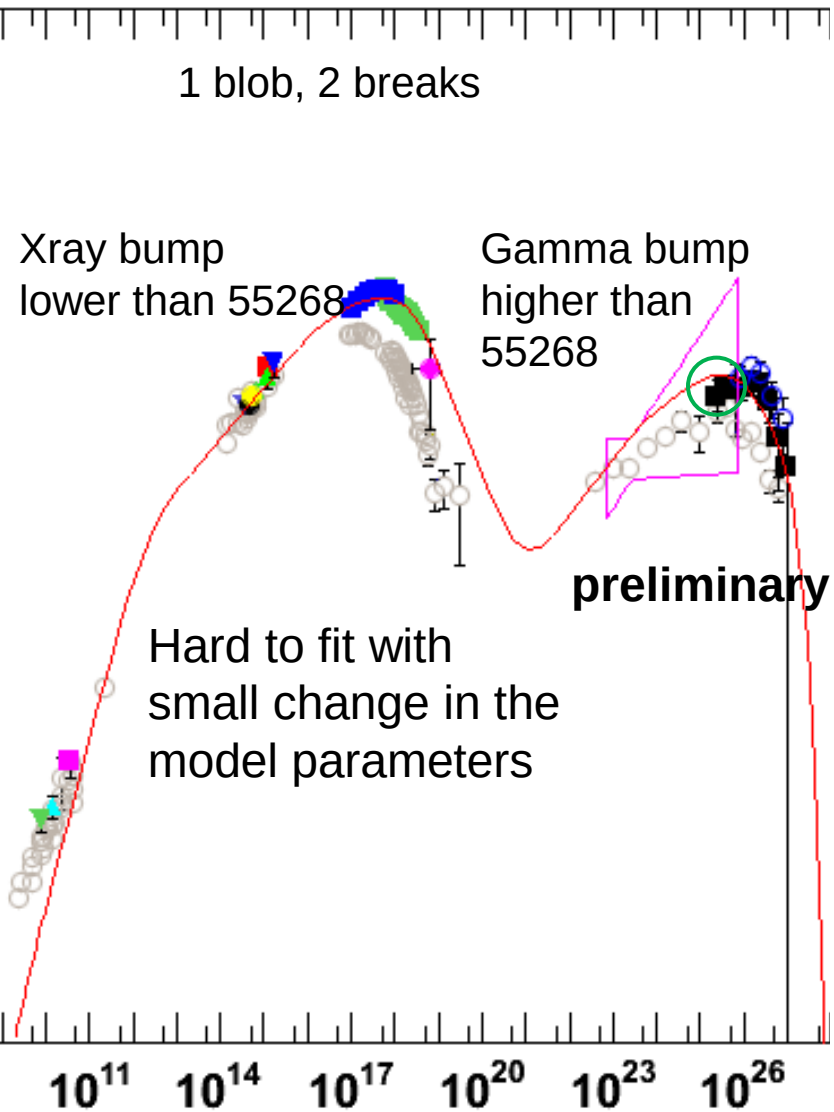
Model 2



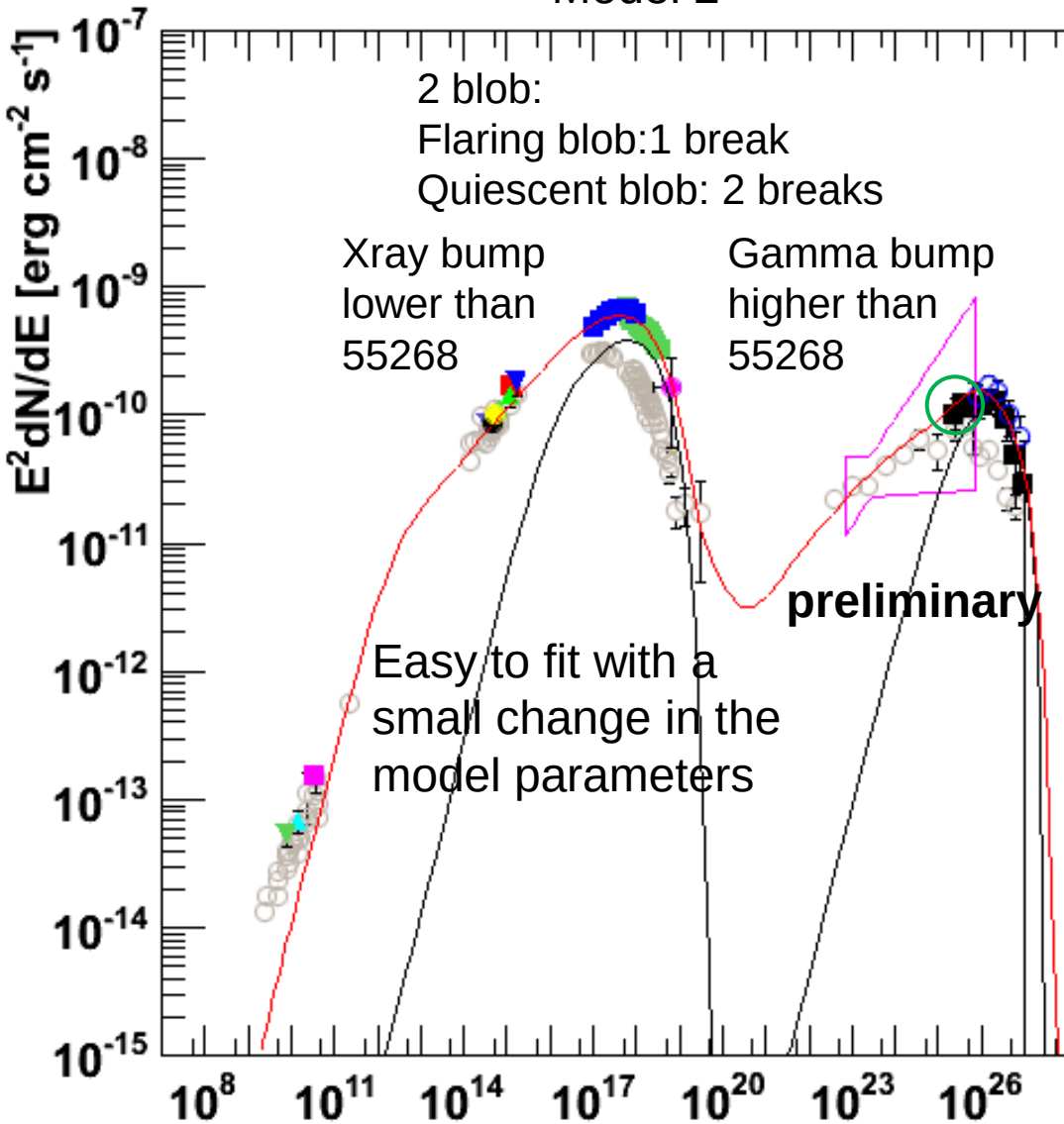
Mrk421 MW 2010_03_14 (55269) [Day 5]

high state

Model 1



Model 2

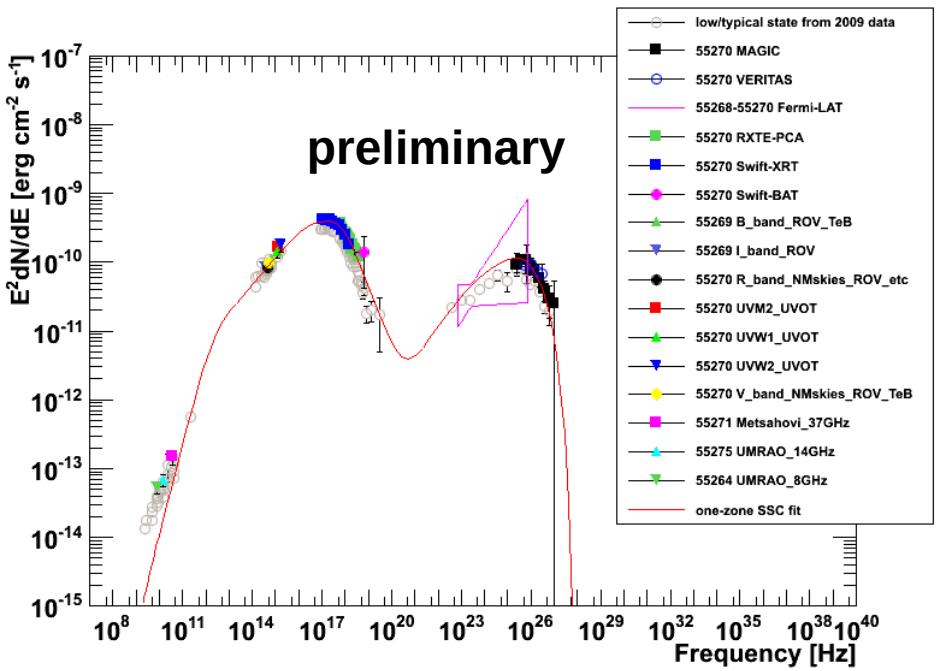


Mrk421 MW 2010_03_15 (55270) [Day 6]

Going into low states

Model 1

1 blob, 2 breaks

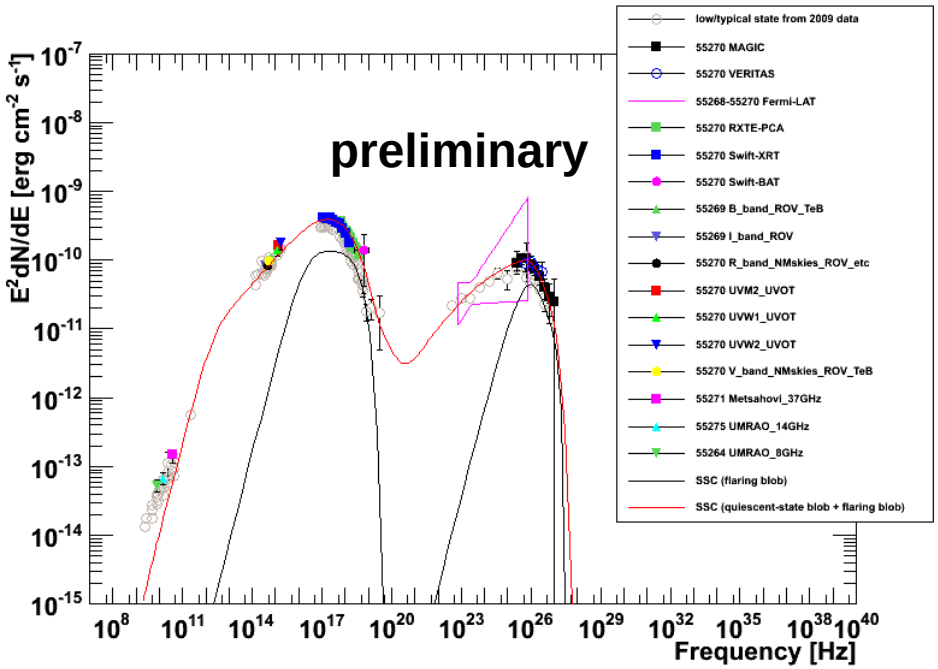


Model 2

2 blob:

Flaring blob:1 break

Quiescent blob: 2 breaks

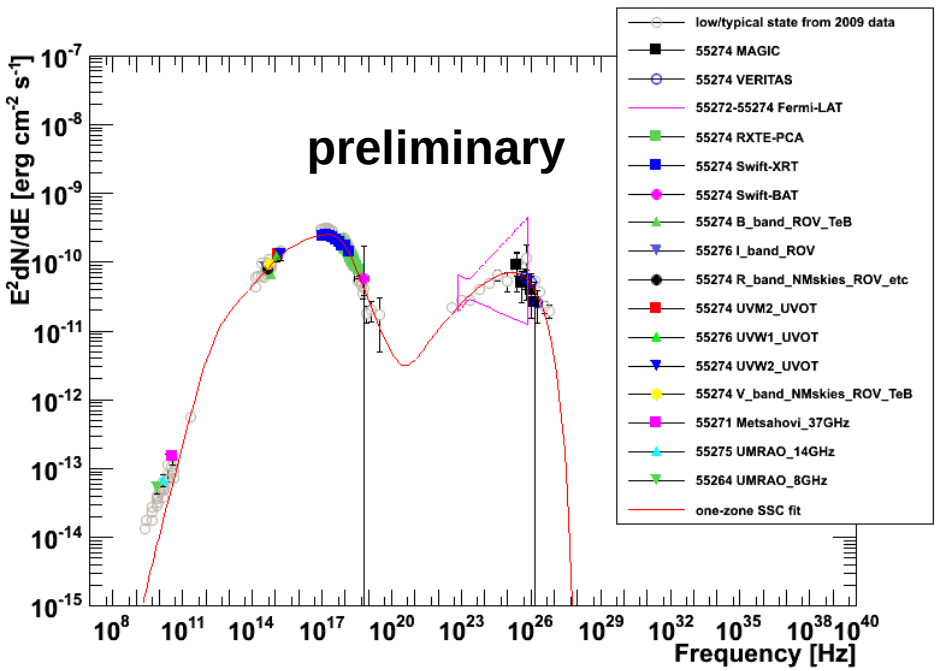


Mrk421 MW 2010_03_19 (55274) [Day 10]

lowest state: quiescent blob emission=this SED

Model 1

1 blob, 2 breaks

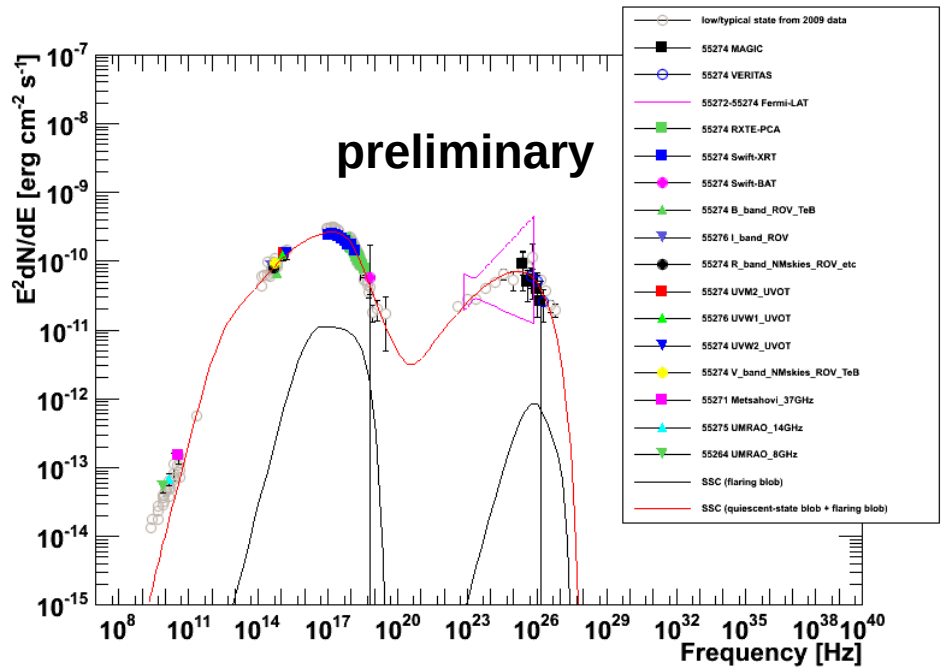


Model 2

2 blob:

Flaring blob:1 break

Quiescent blob: 2 breaks

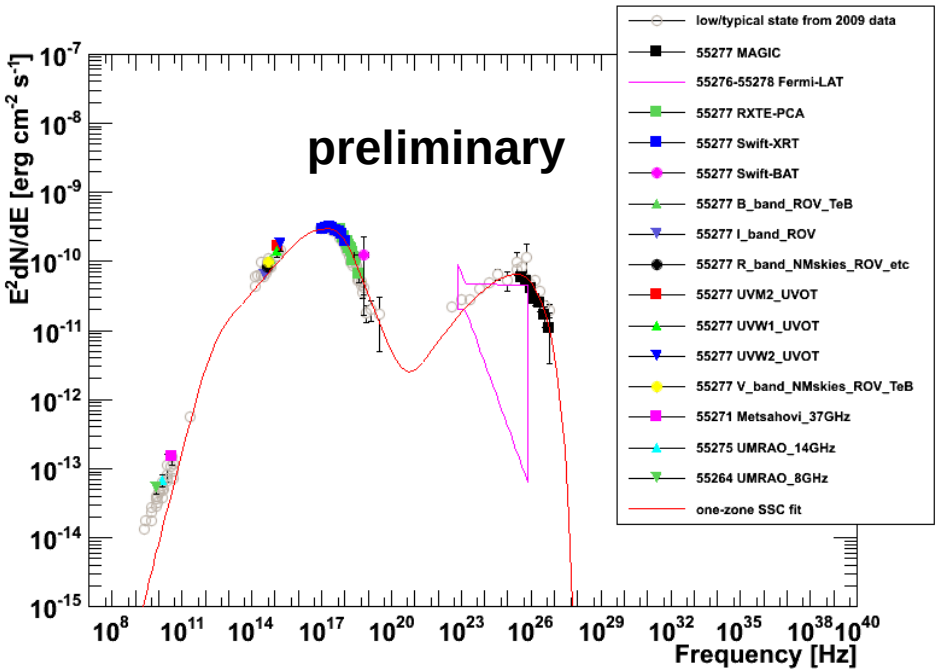


Mrk421 MW 2010_03_22 (55277) [Day 13]

The last day (also low state)

Model 1

1 blob, 2 breaks

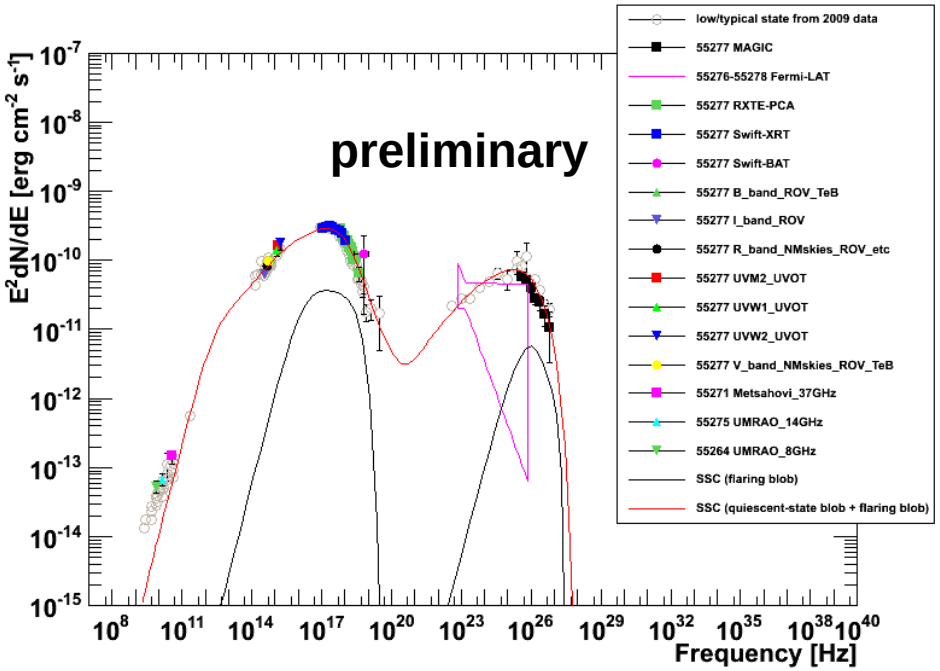


Model 2

2 blob:

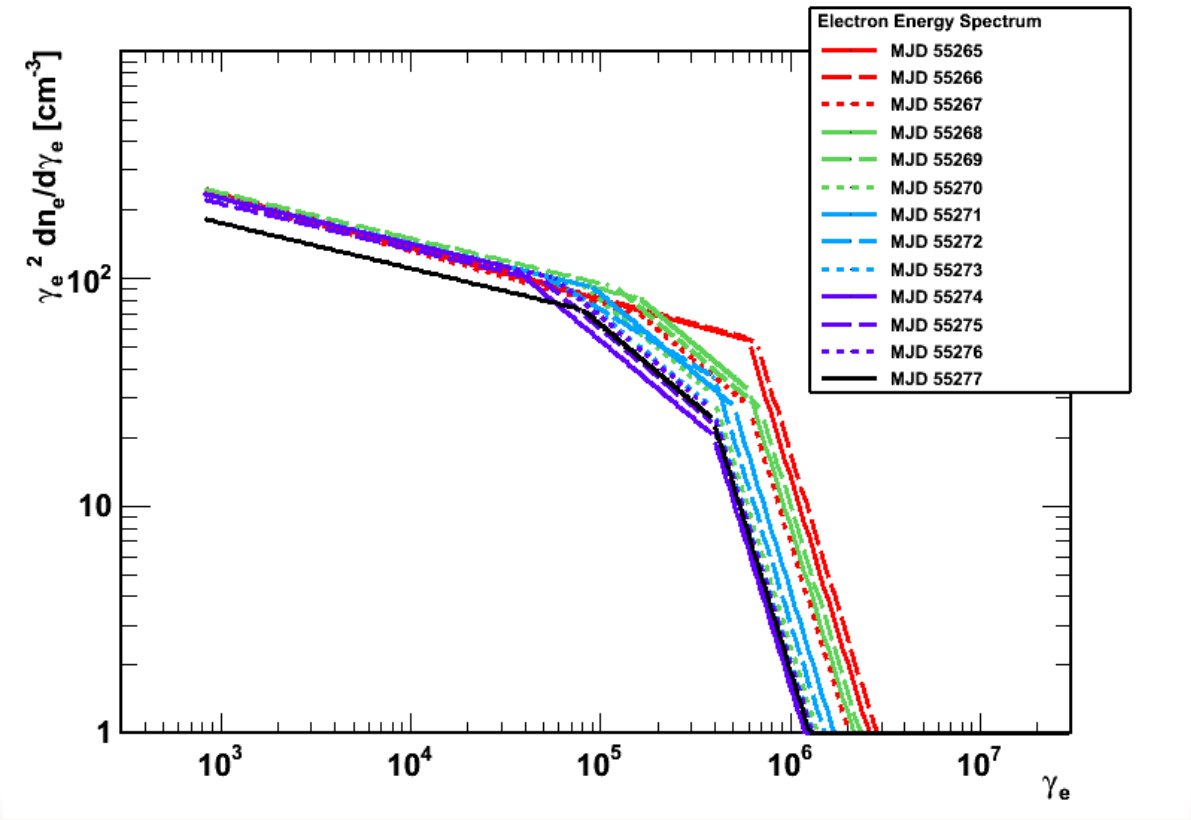
Flaring blob:1 break

Quiescent blob: 2 breaks



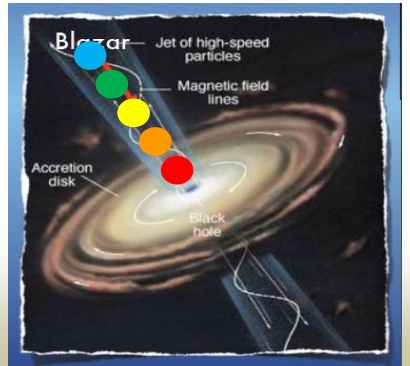
Describe Variation of SED with Electron Energy Distribution(EED): 1-zone SSC model

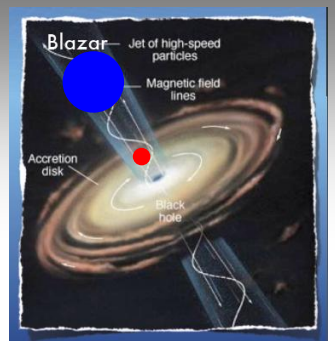
The evolution of the SED during the flare can be explained, within the one-zone Synchrotron Self-Compton scenario, with variations in the high-energy part of the electron energy distribution, rather than the environment parameters (B,R, Doppler factor).



Fixed Parameters

γ_{min}	800
γ_{max}	10^8
B[mG]	38
log(R[cm])	16.72
δ	21





Describe Variation of SED in 2-zone SSC Model

It provides slightly better fits than 1-zone model (Gamma min helps a lot)

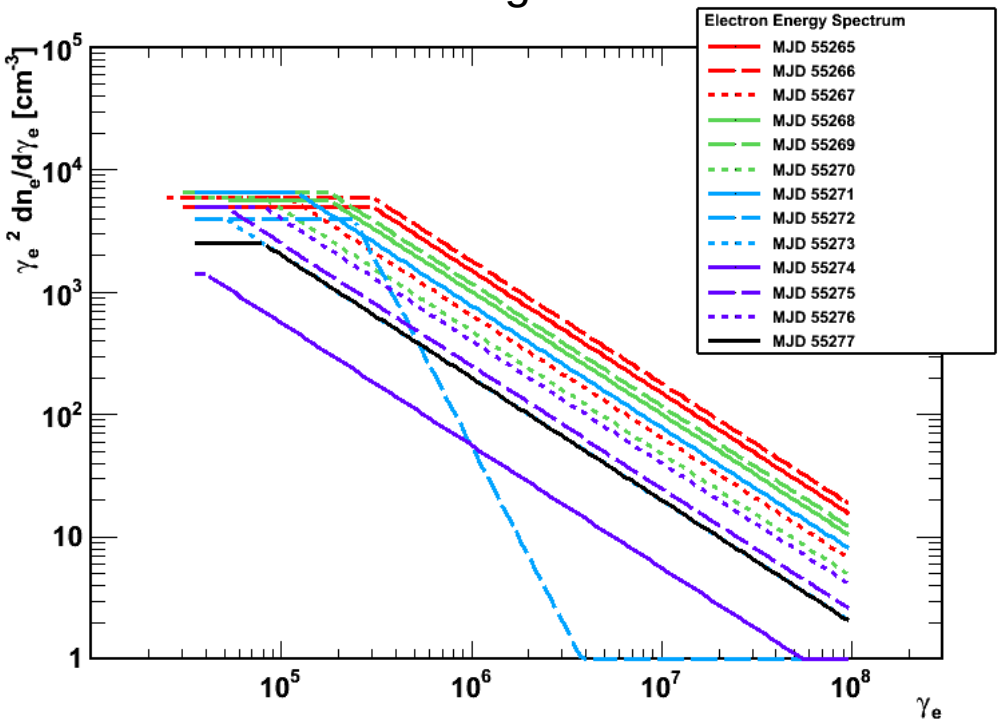
the flaring blob

Date[MJD]	Flux[$cm^{-2}s^{-1}$]	$B[mG]$	$log(R[cm])$	δ
55265	3.8×10^{-10}	105.	15.51	35.
55266	4.7×10^{-10}	100.	15.51	35.
55267	4.0×10^{-10} (v)	100.	15.51	35.
55268	2.1×10^{-10}	100.	15.51	35.
55269	3.3×10^{-10}	85.	15.51	35.
55270	2.3×10^{-10}	75.	15.51	35.
55271	3.5×10^{-10} (v)	75.	15.51	35.
55272	1.4×10^{-10}	75.	15.51	35.
55273	1.5×10^{-10}	75.	15.51	35.
55274	9.9×10^{-11}	60.	15.51	35.
55275	1.8×10^{-10} (w)	60.	15.51	35.
55276	1.6×10^{-10}	60.	15.51	35.
55277	1.2×10^{-10}	60.	15.51	35.

the quiescent blob

38. 16.72 21.

The flaring blob



Conclusion

Evolution of the broadband SED could be described with a one-zone or a two-zone SSC model

Lower states: broader bumps in SEDs,
double-broken power law needed to describe EEDs
both one-zone and two-zone models are fine

Higher states: sharper bumps in SEDs,
broken power law needed to describe EEDs
two-zone model is better in describing the SED evolution

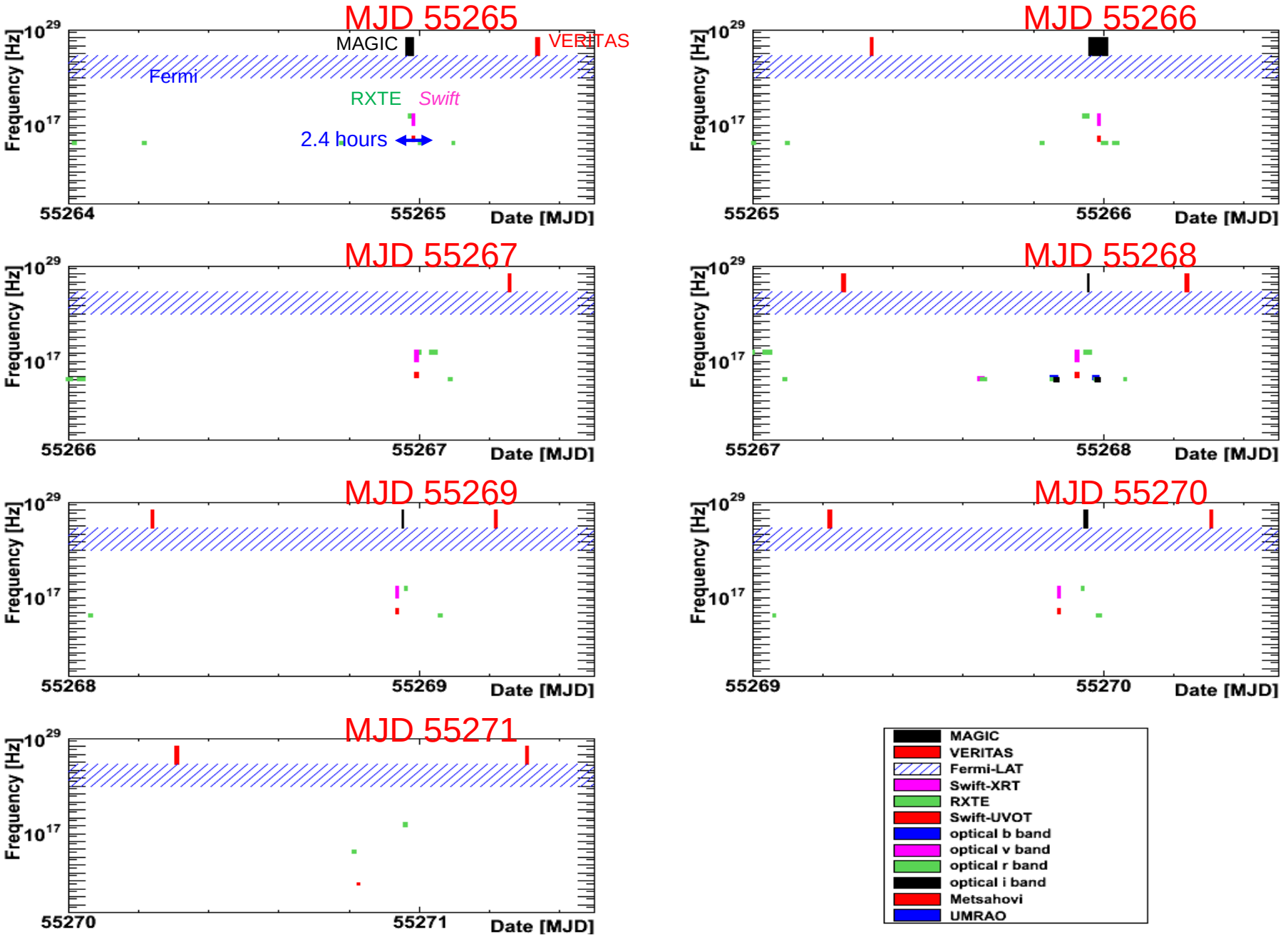
Overall: The observed evolution of the SEDs favors the presence of two blobs, rather than the one single blob used typically to describe flares in TeV blazars

Backup Slides

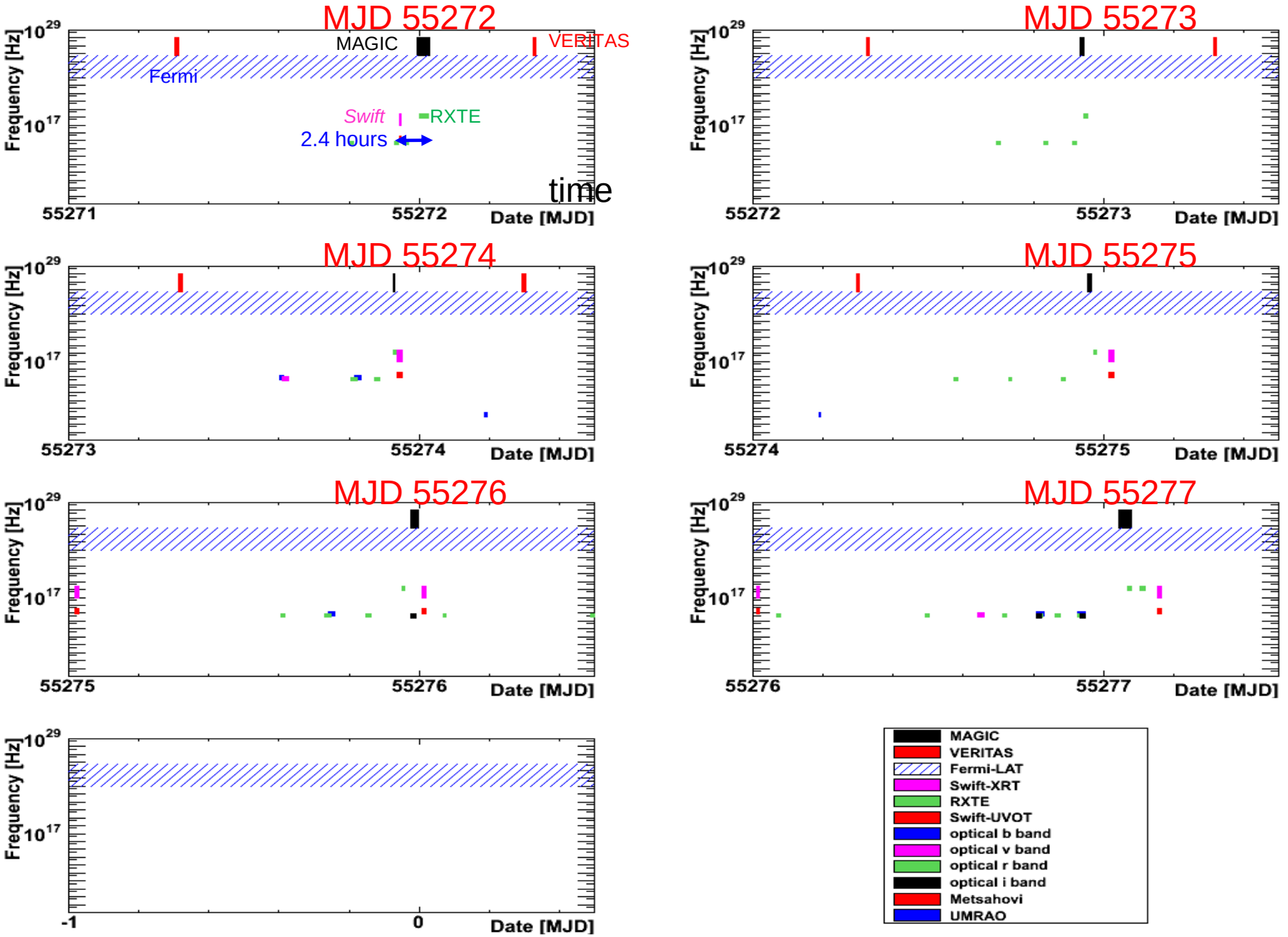
Outline
Flaring-Activity Study

- Data quality guarantee:
  - ✓ multi-wavelength coverage [energy]
  - ✓ simultaneity of observations [time]
- General situation: light curves
- Further study: spectra
  - ✓ Sample, model introduction, spectrum modeling samples
  - ✓ Day-by-day spectra
  - ✓ Summary of the evolution of spectra
- Conclusion

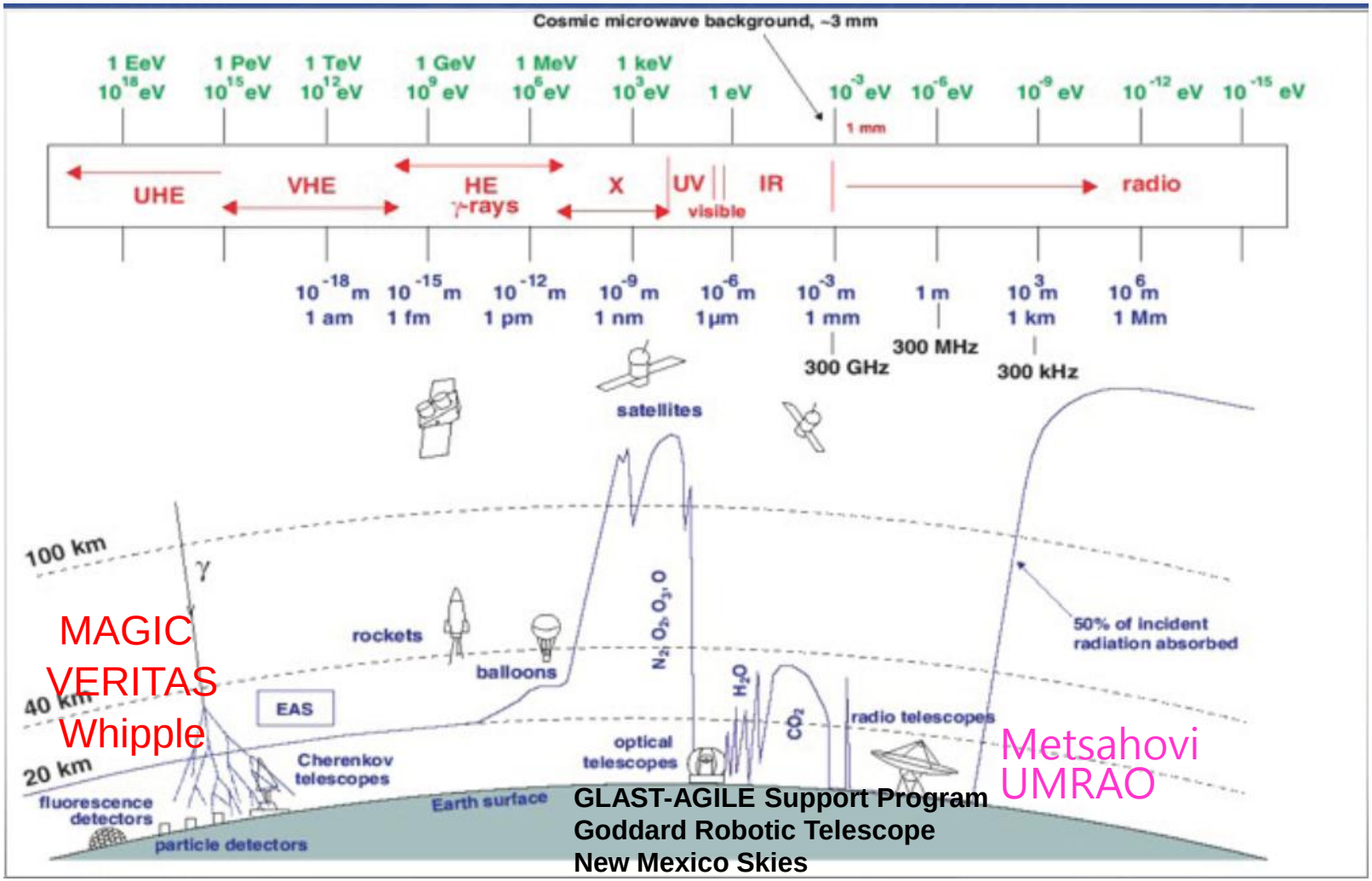
MW Simultaneity (I)



MW Simultaneity (II)



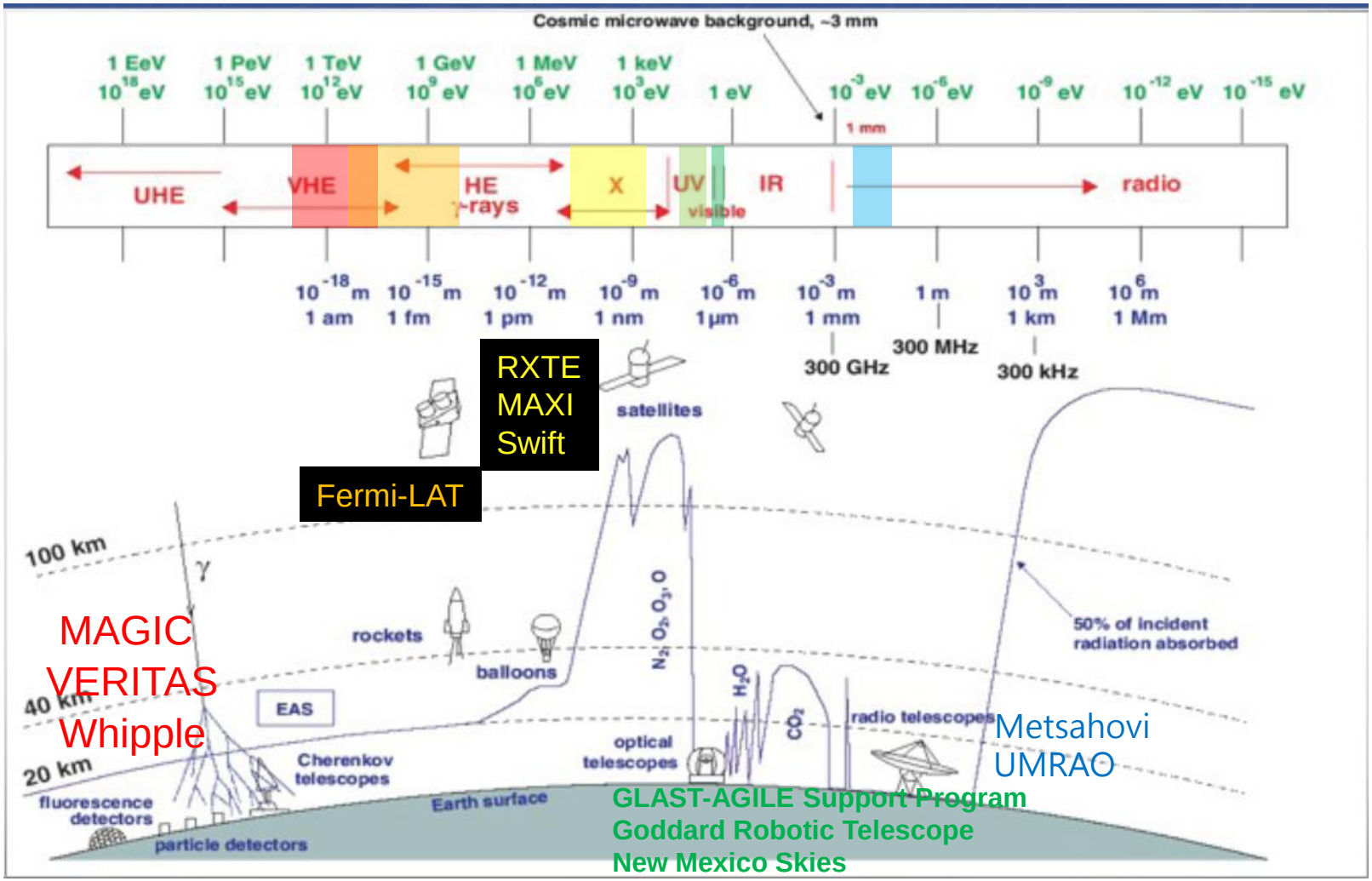
2010 Multi-wavelength Campaign for Mrk 421



GLAST-AGILE Support Program
Goddard Robotic Telescope
New Mexico Skies
ROVOR
St.Petersburg ……

2010 Multi-wavelength Campaign for Mrk 421

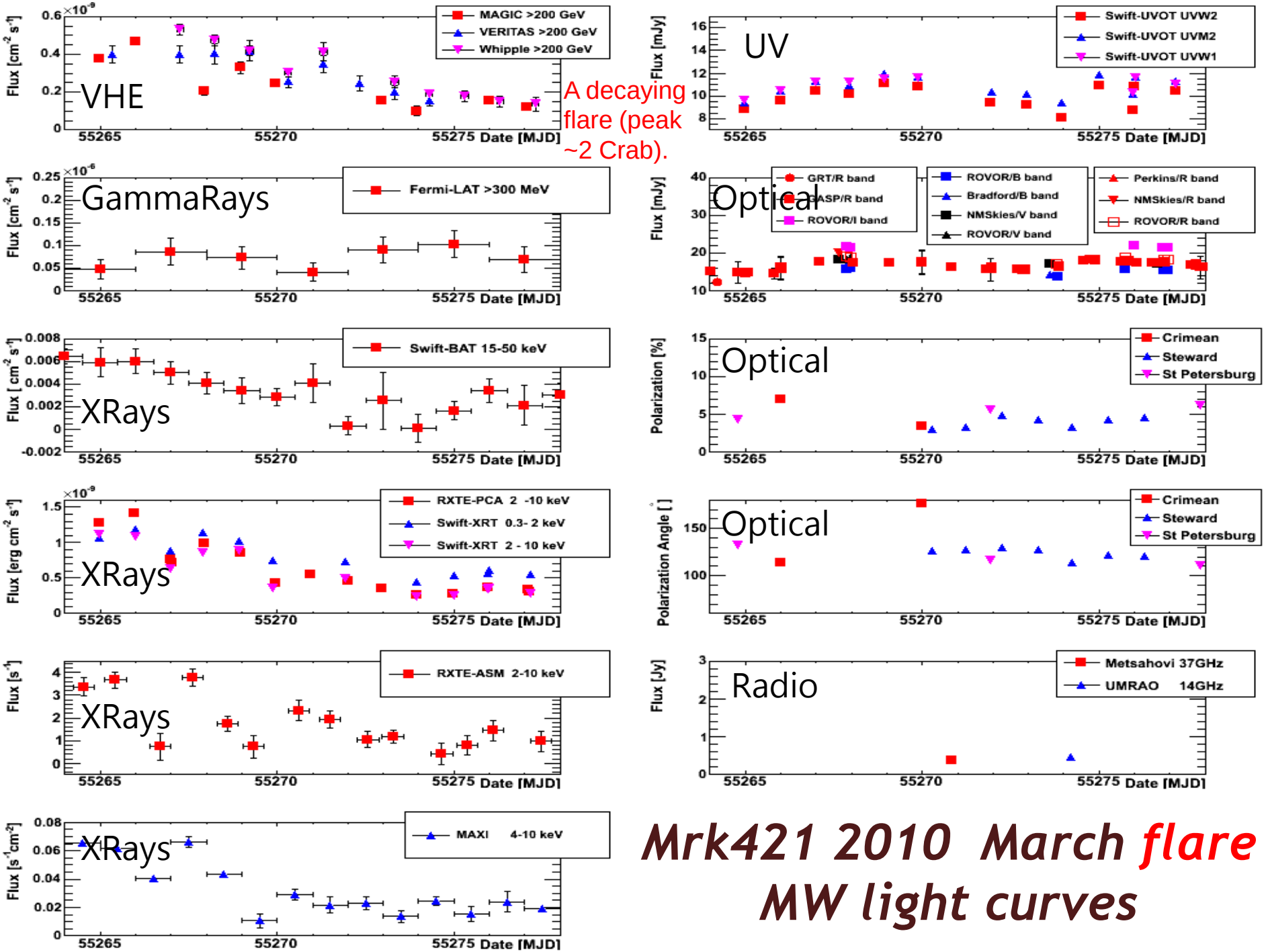
50TeV-50GeV | 300GeV-300MeV | 50keV-300 eV



GLAST-AGILE Support Program
Goddard Robotic Telescope
New Mexico Skies
ROVOR
St.Petersburg …….

2010 MW Light-Curve Frequency-Bands

Wave band	instrument	flux unit	mean freq. Hz	low freq. Hz	high freq. Hz	low energy	high energy
VHE	MAGIC	count/cm^2/s		4.84E+025	1.21E+028	200GeV	
VHE	VERITAS	count/cm^2/s		4.84E+025	1.21E+028	200GeV	
VHE	Whipple	count/cm^2/s		9.68E+025	1.21E+028	400GeV	
GammaRays	Fermi	ph/cm2/s		6.06E+022	6.06E+025	300MeV	300GeV
XRays	RXTE/PCA	erg/cm2/s		4.84E+017	7.26E+018	2.00keV	30.0keV
Xrays	SWIFT/BAT	count/cm2/s		3.63E+018	1.21E+019	15keV	50keV
Xrays	SWIFT/XRT	erg/cm2/s		4.84E+017	2.41E+018	2keV	10keV
Xrays	SWIFT/XRT	erg/cm2/s		7.25E+016	4.84E+017	0.3keV	2keV
Xrays	RXTE/ASM	ph/s		4.84E+017	2.41E+018	2keV	10keV
XRays	MAXI	ph/s		9.67E+017	2.41E+018	4keV	10keV
UVW2	SWIFT/UVOT	mJy	1.60E+015	1.37E+015	1.93E+015		
UVM2	SWIFT/UVOT	mJy	1.38E+015	1.24E+015	1.55E+015		
UVW1	SWIFT/UVOT	mJy	1.19E+015	1.05E+015	1.37E+015		
b	ROVOR	mJy	6.81E+014	6.14E+014	7.66E+014		
b	Bradford Robotic Telescope	mJy	6.81E+014	6.14E+014	7.66E+014		
v	New Mexico Skies	mJy	5.45e14	5.04e14	5.92e14		
v	ROVOR	mJy	5.45e14	5.04e14	5.92e14		
v	Bradford Robotic Telescope	mJy	5.45e14	5.04e14	5.92e14		
r	New Mexico Skies	mJy	4.68E+014	4.20E+014	5.29E+014		
r	ROVOR	mJy	4.68e14	4.20e14	5.29e14		
r	Bradford Robotic Telescope	mJy	4.68e14	4.20e14	5.29e14		
r	GLAST-AGILE Support Program	mJy	4.68e14	4.20e14	5.29e14		
r	Goddard Robotic Telescope	mJy	4.68e14	4.20e14	5.29e14		
r	Perkins	mJy	4.68e14	4.20e14	5.29e14		
r	Steward	mJy	4.68e14	4.20e14	5.29e14		
r	Crimean	mJy	4.68e14	4.20e14	5.29e14		
r	St.Petersburg	mJy	4.68e14	4.20e14	5.29e14		
I	ROVOR	mJy	3.79e14	3.47e14	4.19e14		
Radio	Metsahovi	Jy	37GHz	3.63E+010	3.87E+010	1.5e-4eV	1.6e-4eV
Radio	UMRAO	Jy	14GHz	1.26E+010	1.64E+010	5.2e-5eV	6.8e-5eV
Radio	UMRAO	Jy	8GHz	7.25E+009	8.70E+009	3.0e-5eV	3.6-5eV



Mrk421 2010 March flare MW light curves

Light Curve Variability

Variability: the quantity showing how much each light curve fluctuates

Variability

(S. Vaughan et al. Mon.Not.Roy.Astron.Soc.345:1271,2003)

$$F_{\mathrm{var}} = \sqrt{\frac{S_f^{\,2} - \overline{\sigma_i^{\,2}}}{\bar{f}^{\,2}}}$$

$$S_f^{\,2} = \frac{\sum_i^{N_f} (f_i - \bar{f})^2}{N_f - 1}$$

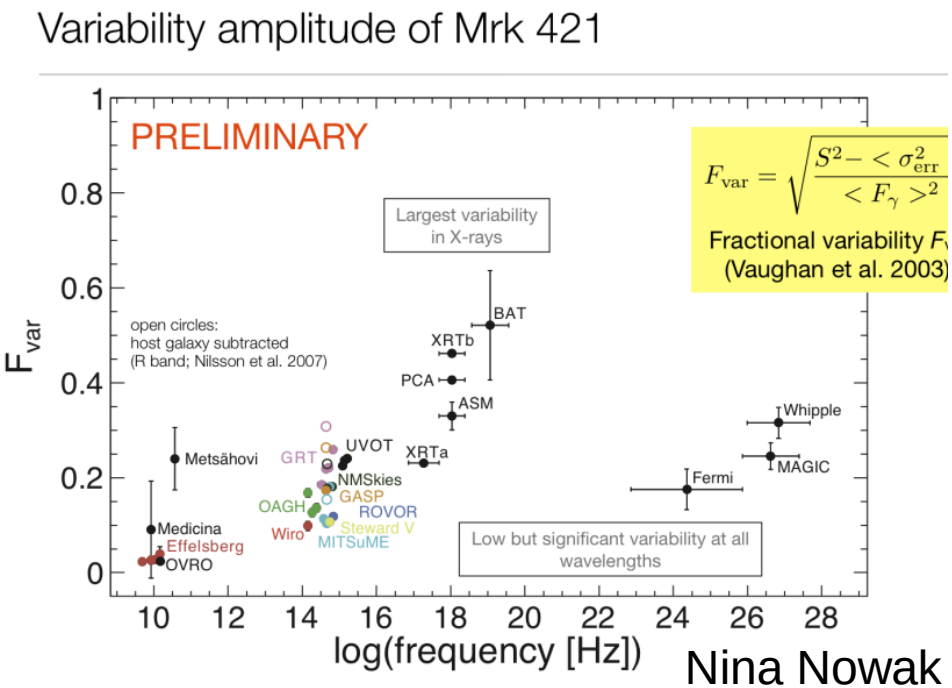
$S_f^{\,2}$ Variance of Flux

$\overline{\sigma_i^{\,2}}$ Mean of error sq.

$\bar{f}$ Mean of Flux

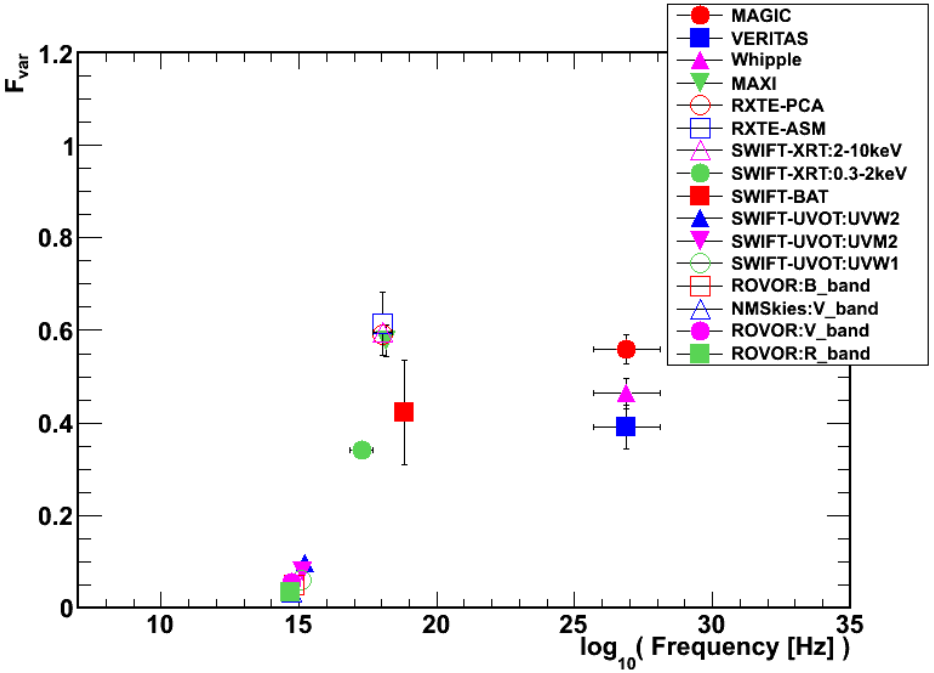
Light Curve Variability

2009

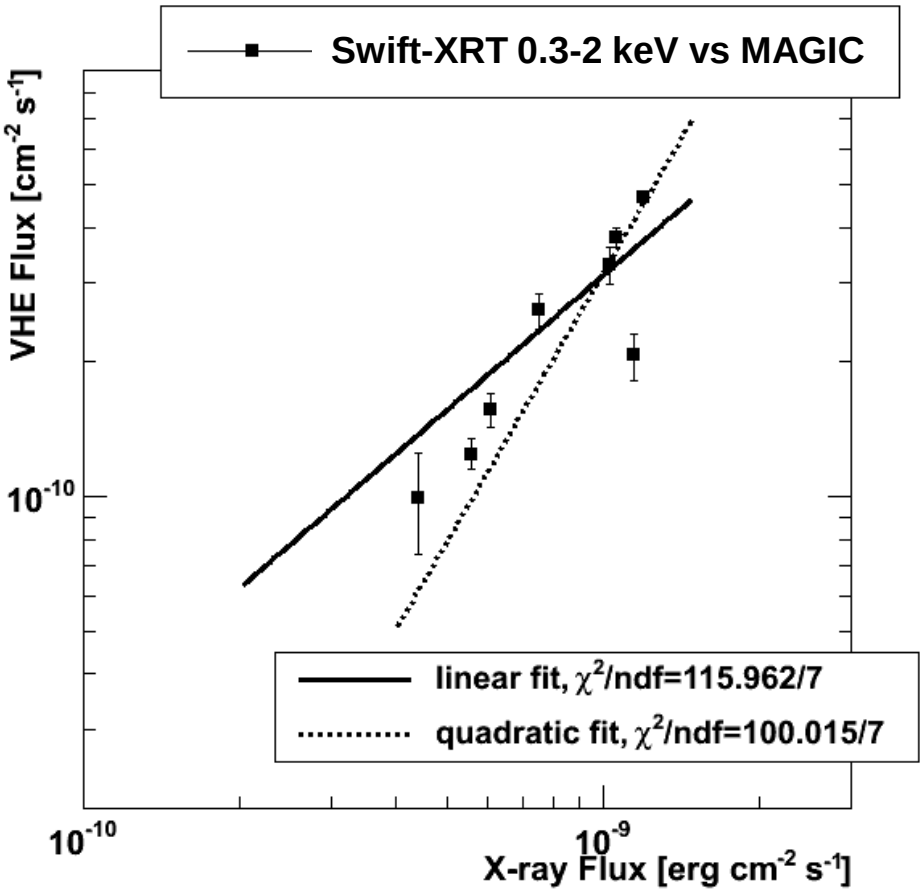


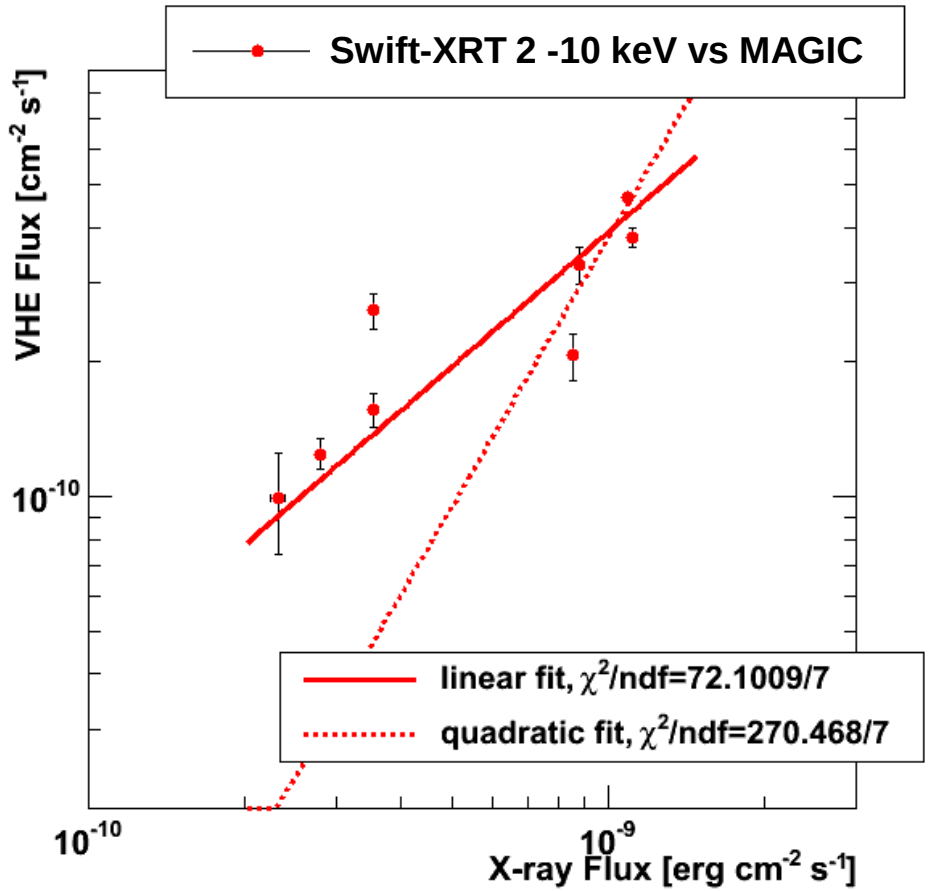
Nina Nowak

2010 March



Relation of VHE band - HIGH/LOW Energy X-ray band: Inverse-Compton(IC) regime

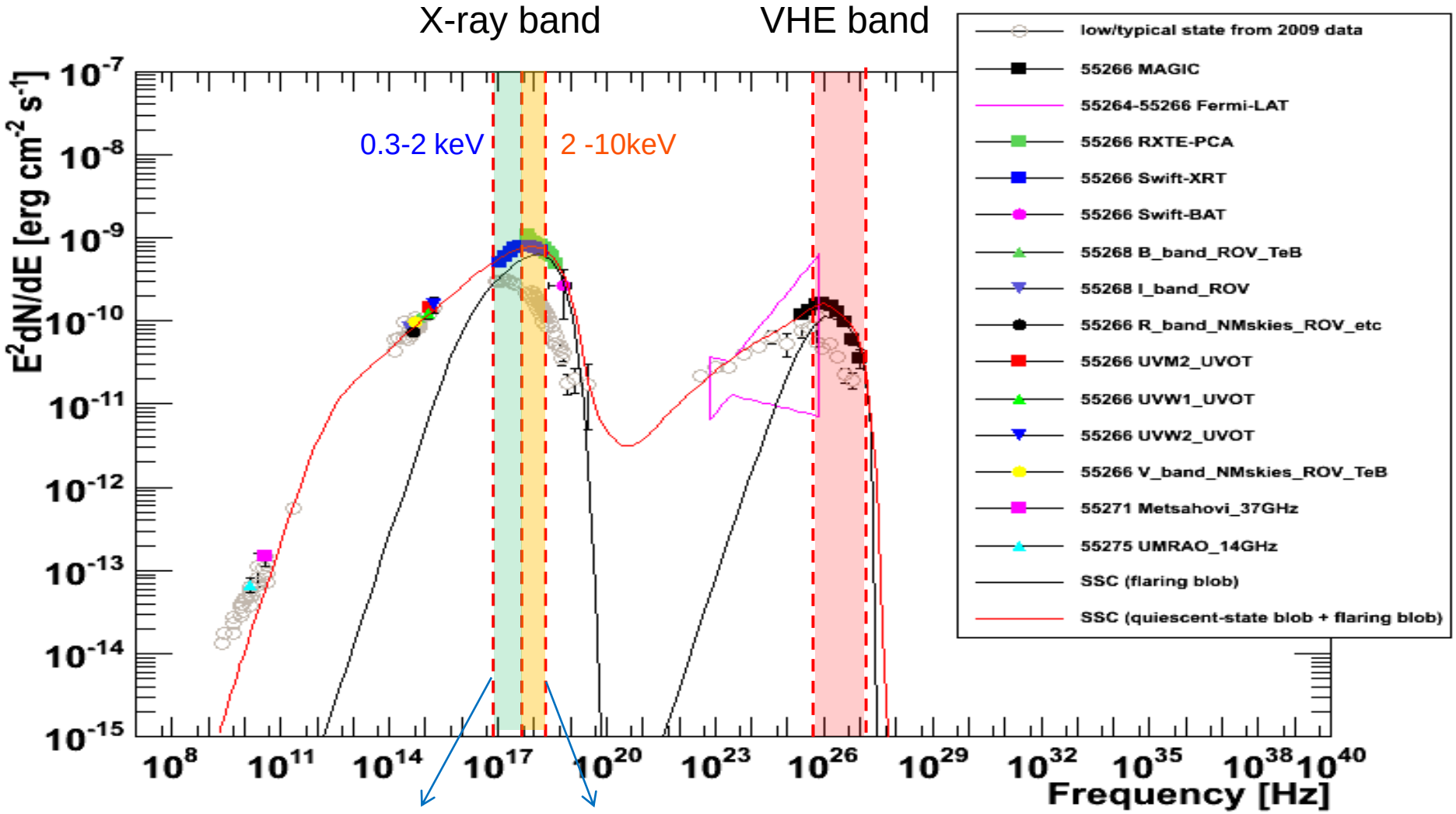




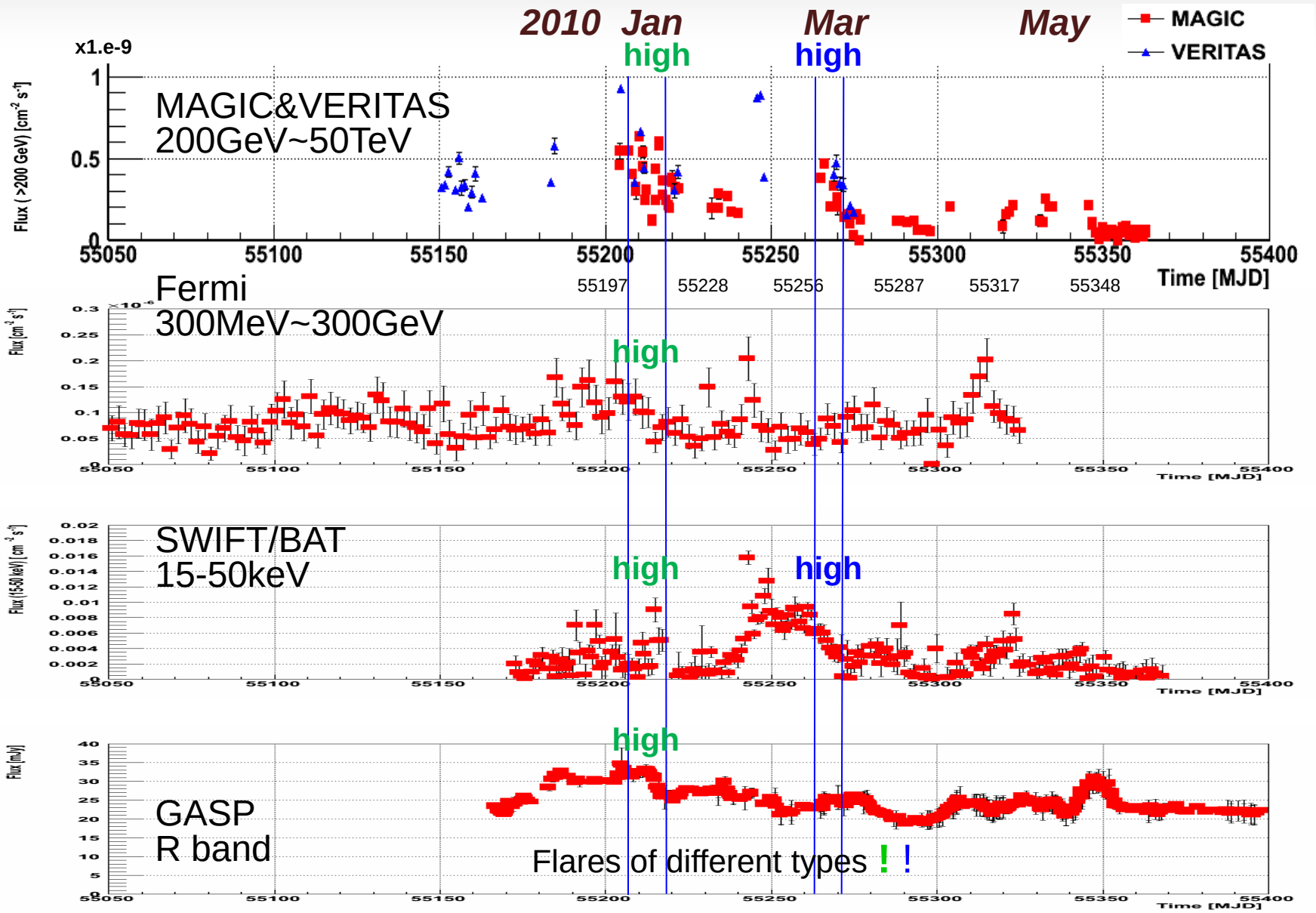
approximately QUADRTIC
(IC in Thomson regime)

approximately LINEAR
(IC in Klein-Nishina regime)

VHE band and HIGH/LOW Energy X-ray band



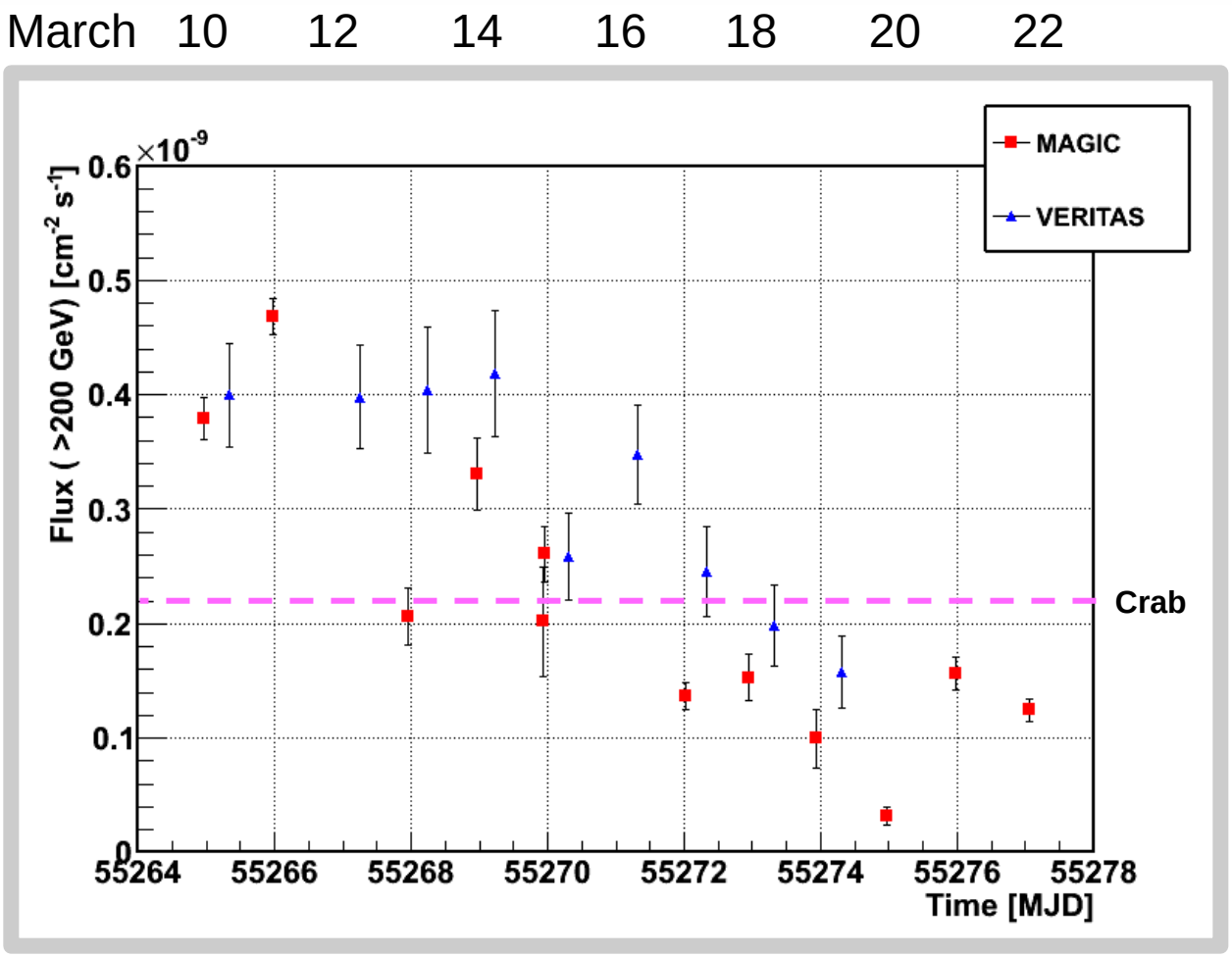
Mrk421 2010 Flares
VHE, HE, Xray, Optical light curves



Mrk421 2010 March
Very High Energy Light Curve

- A decaying flare in was observed by MAGIC and VERITAS in March (peak ~2 Crab). (Low state around 50% Crab)
- 10/03/2010 (55255) - 22/03/2010 (55267) ; MAGIC 11 nights (10~ 80 min obs.) VERITAS 9 nights (~10 min obs.)

Date[MJD]	Obs. Time[min.]
55265	40.75
55266	83.53
55268	10.94
55269	11.38
55270	19.38
55272	55.40
55273	19.40
55274	6.15
55275	20.88
55276	34.40
55277	58.45



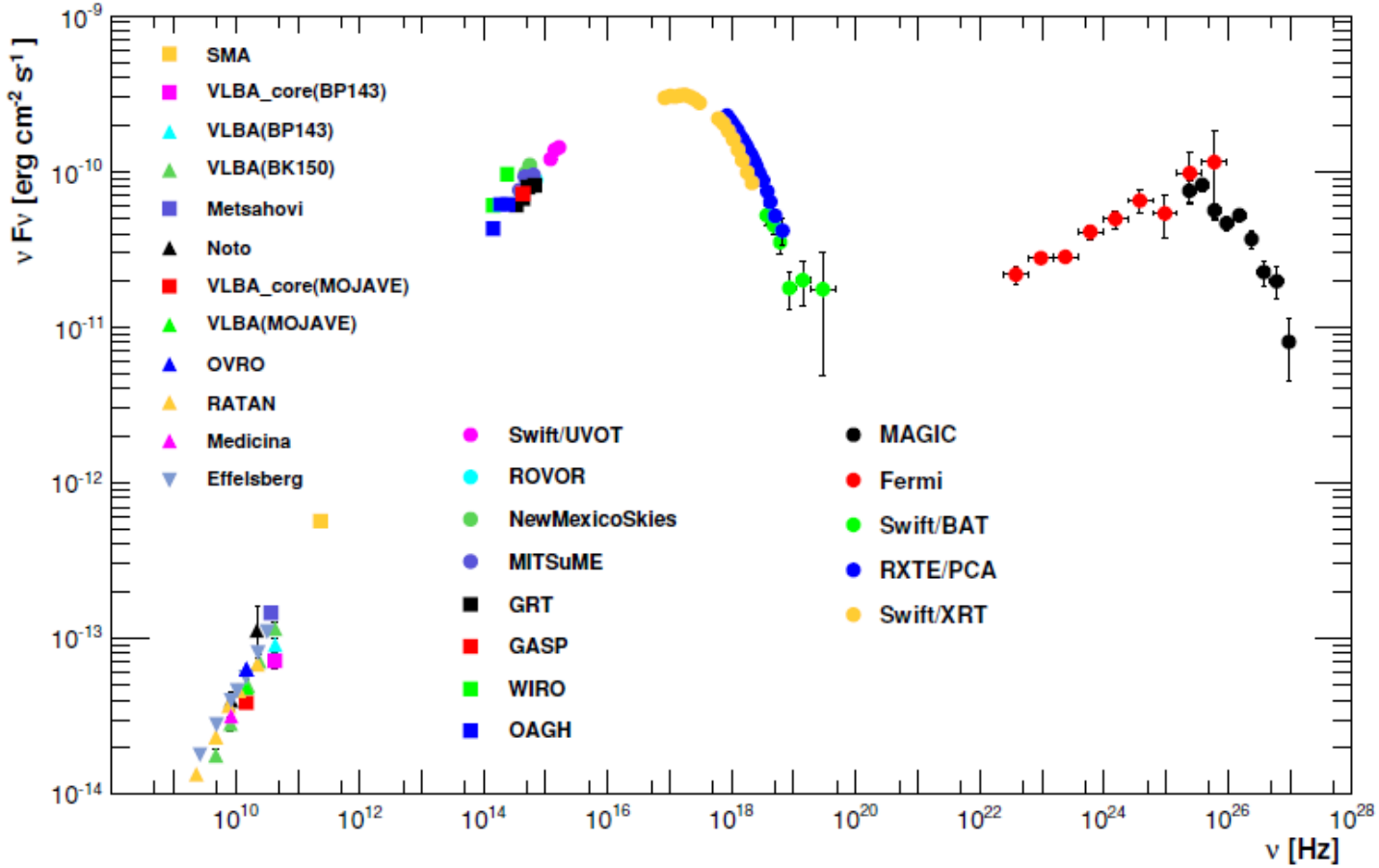
Next: unprecedented data for blazar study:
day-by-day broadband Mrk421 SEDs in flaring activity

Broadband Spectral Energy Distribution (SED)

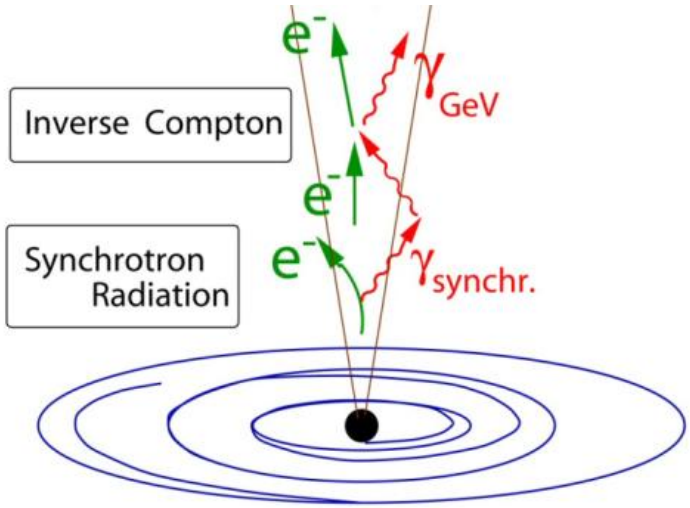
Mrk421 2009 averaged SED

The Astrophysical Journal, 736:131 (22pp), 2011 August 1

Abdo et al.

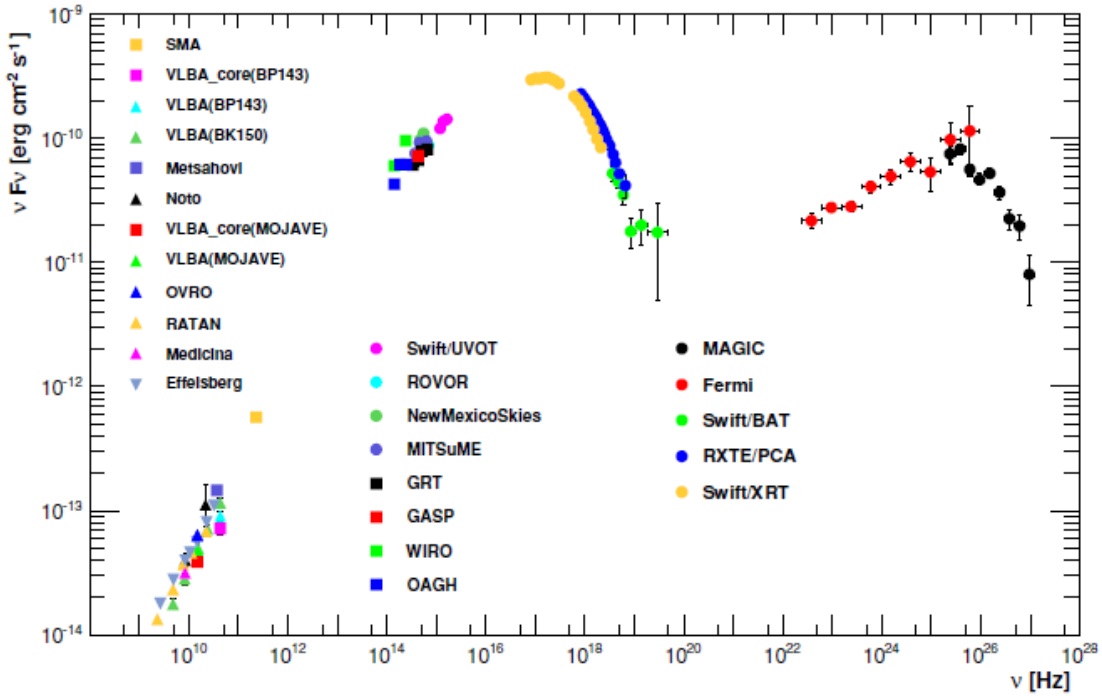


Describe Spectra with One-Zone Synchrotron Self-Compton Model



synchrotron radiation
=>Xray

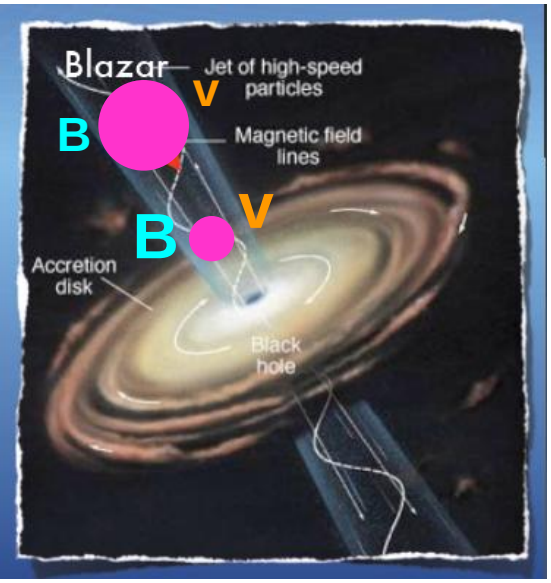
inverse Compton
=>GammaRay

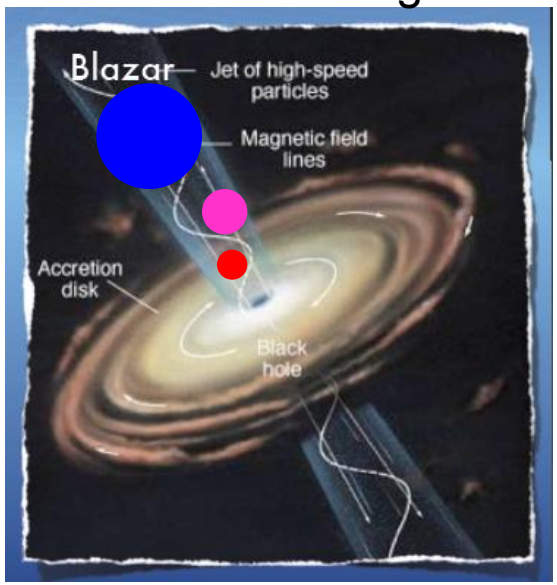


What changes during flaring activity?

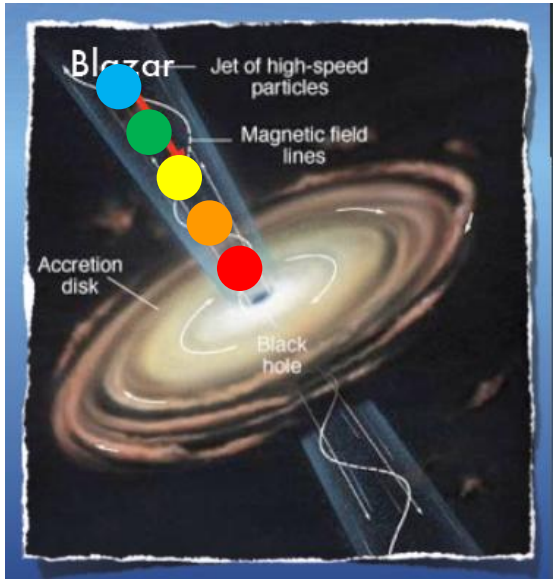
Multiple blobs?
long-lasting quiescent blob
+ short-burst flaring blob + …

Magnetic field ?
Blob speed ?
Blob size?



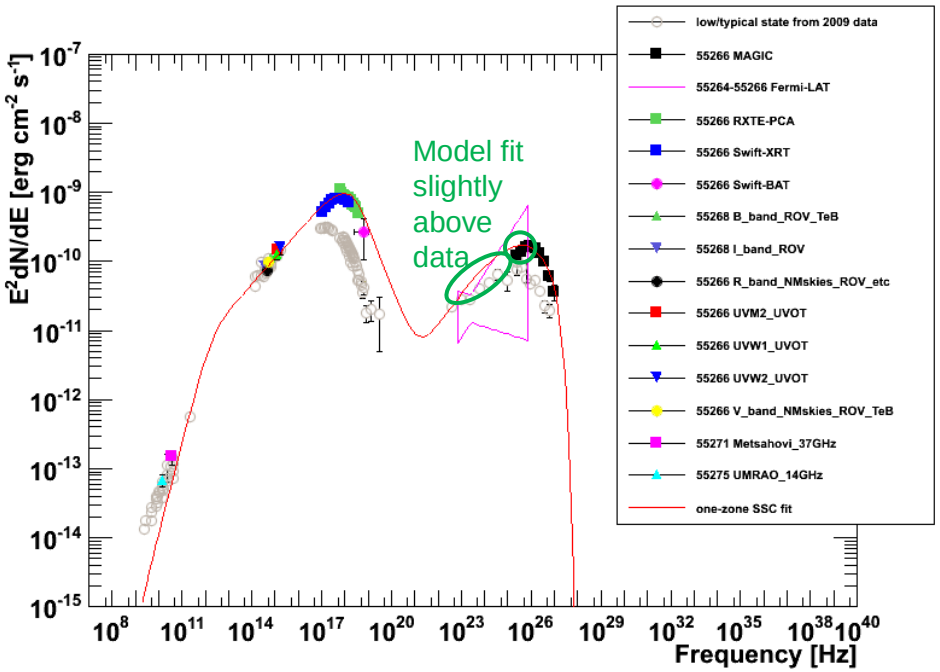


Electron energy ?

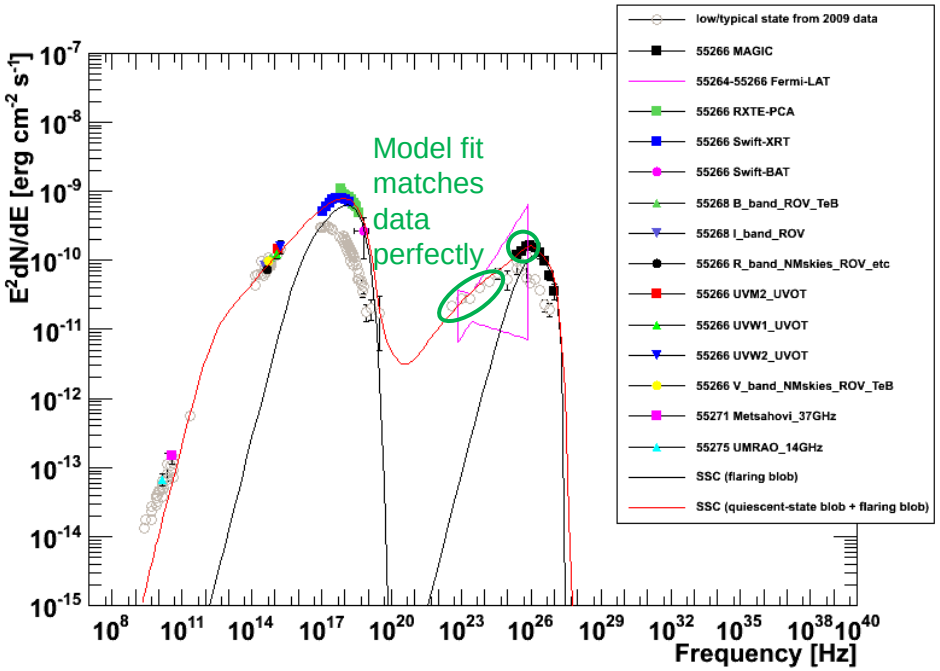


Mrk421 MW 2010_03_11 (55266)

1 blob, 2 breaks

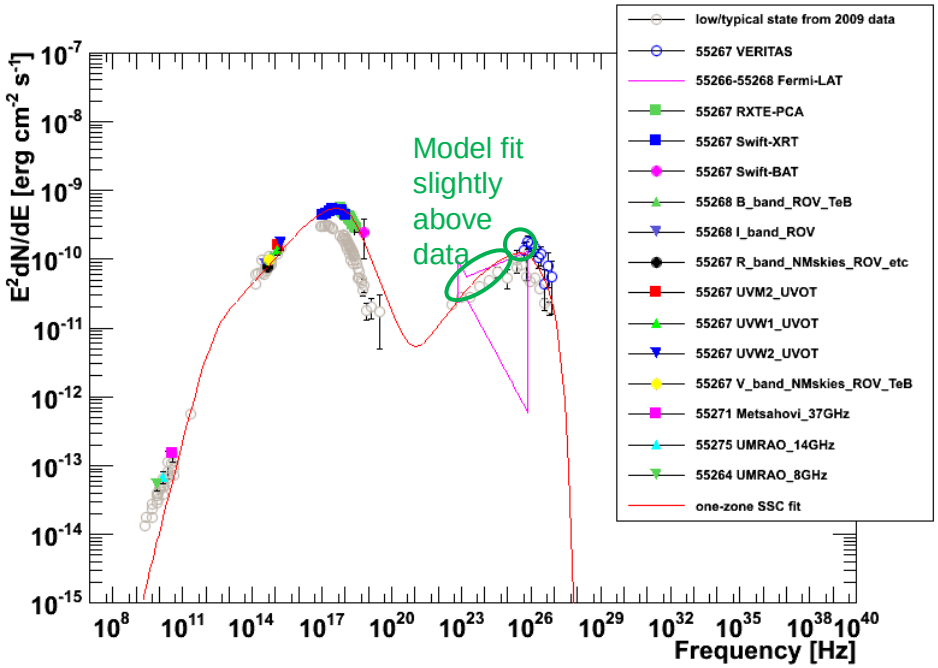


2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks

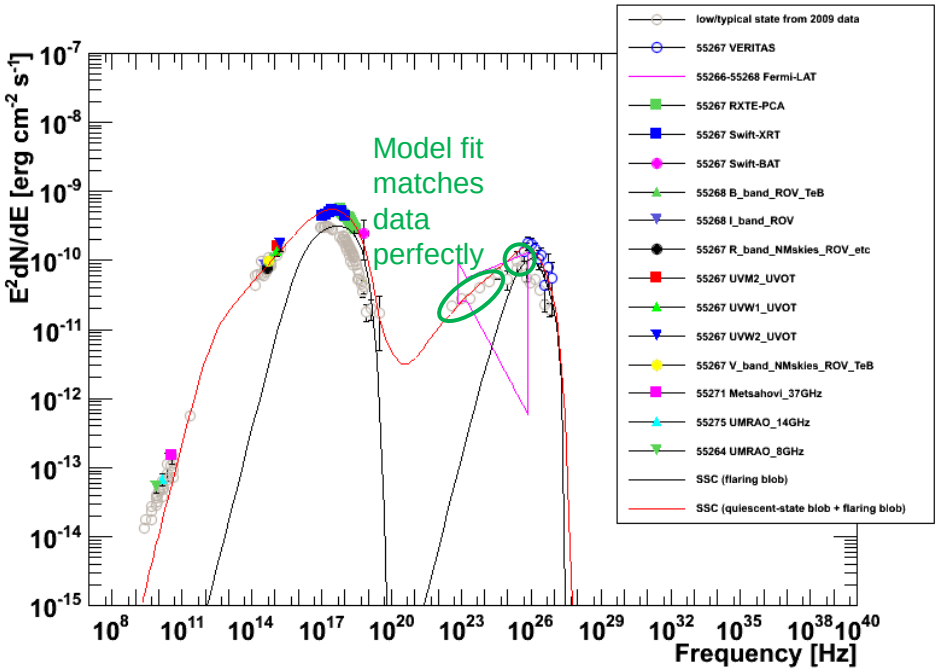


Mrk421 MW 2010_03_12 (55267)

1 blob, 2 breaks

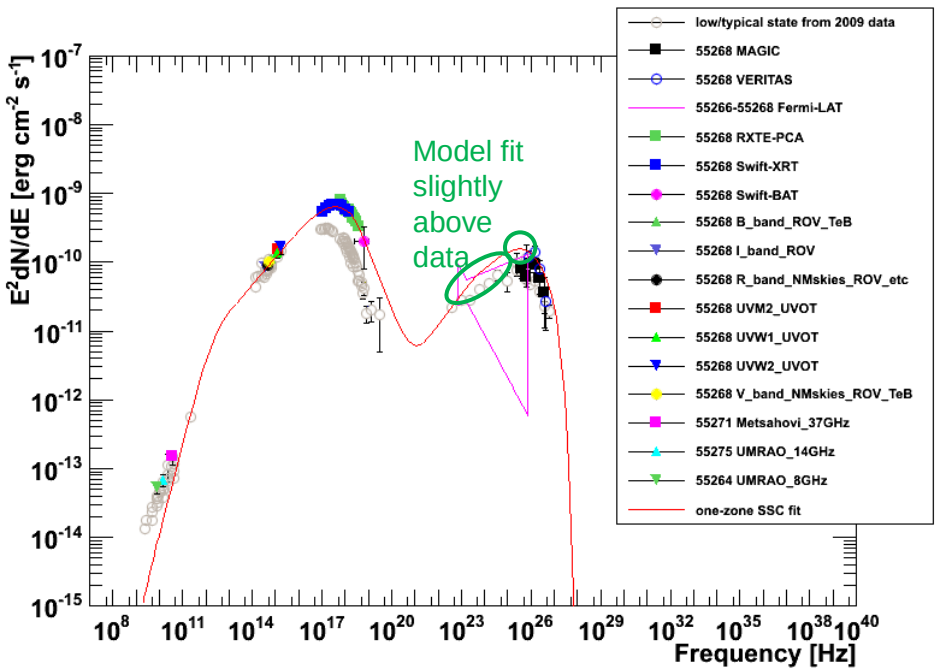


2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks

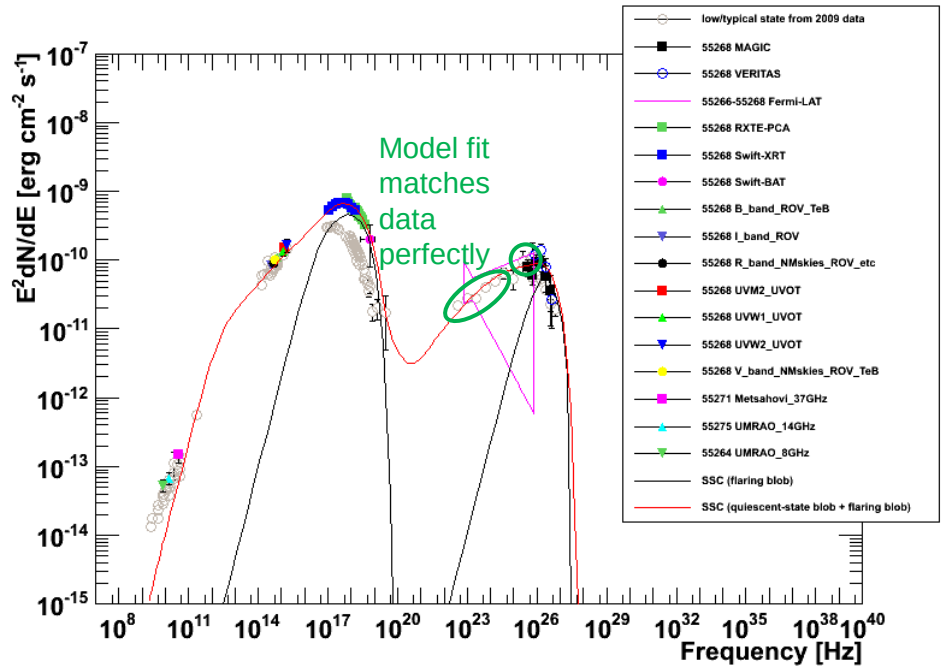


Mrk421 MW 2010_03_13 (55268)

1 blob, 2 breaks

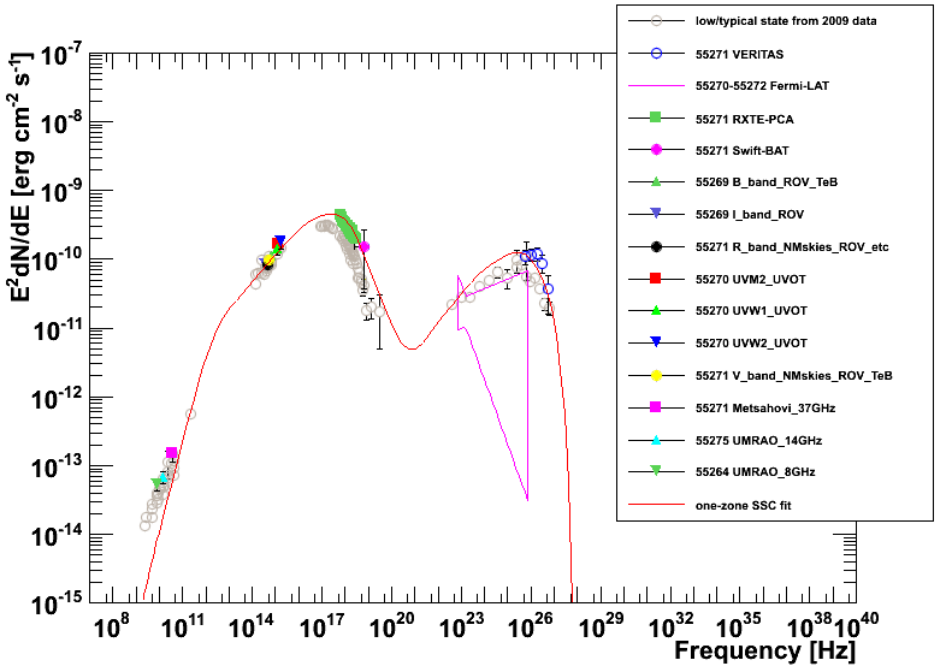


2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks

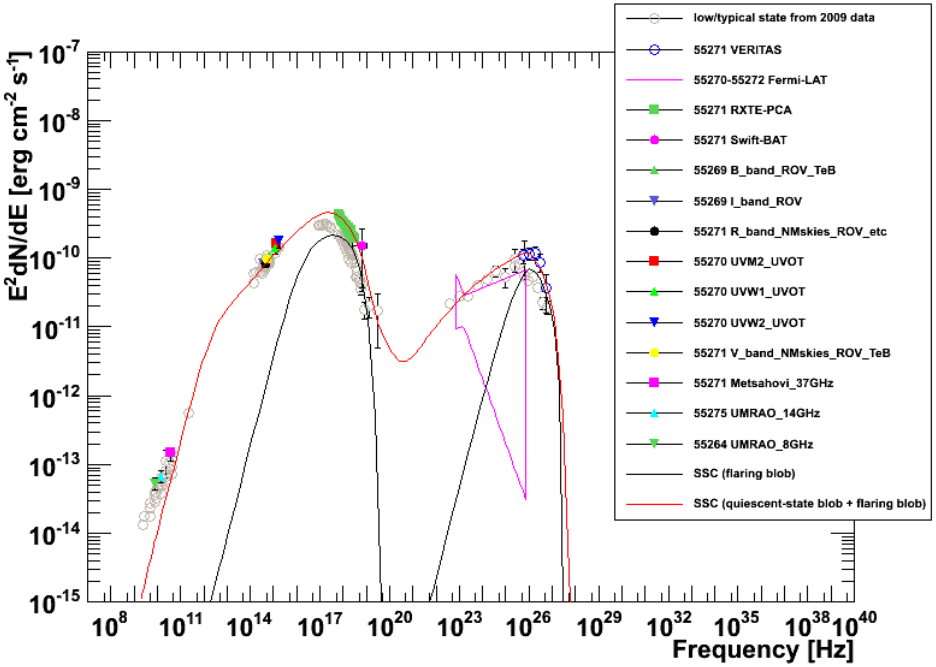


Mrk421 MW 2010_03_16 (55271)

1 blob, 2 breaks

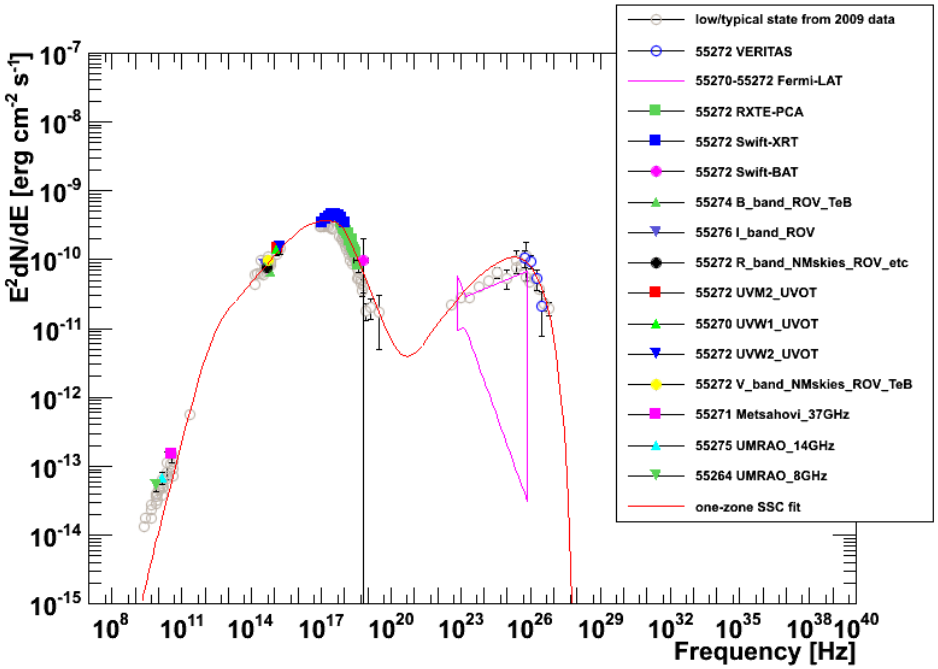


2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks

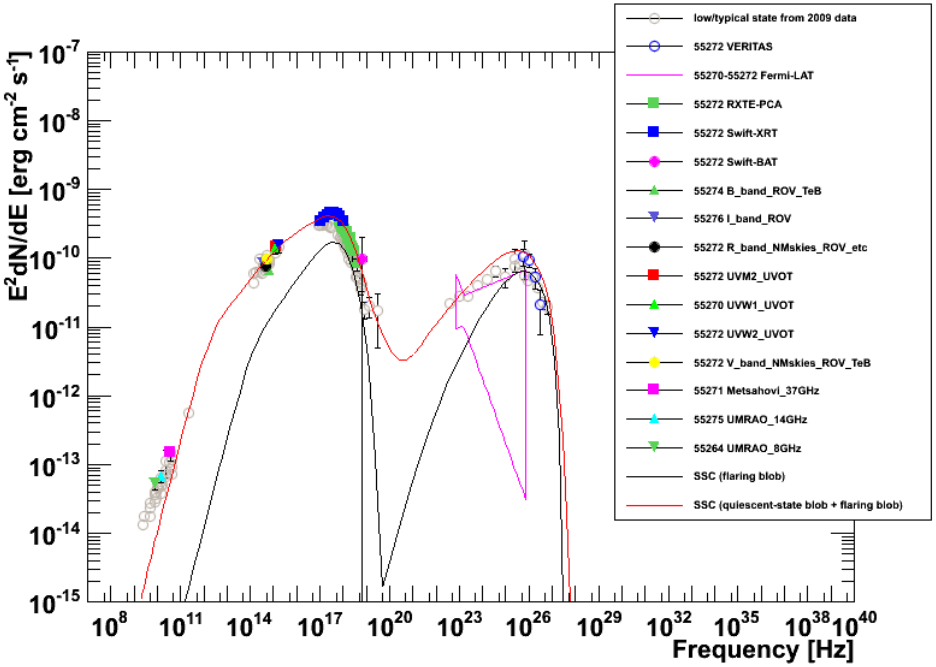


Mrk421 MW 2010_03_17 (55272)

1 blob, 2 breaks

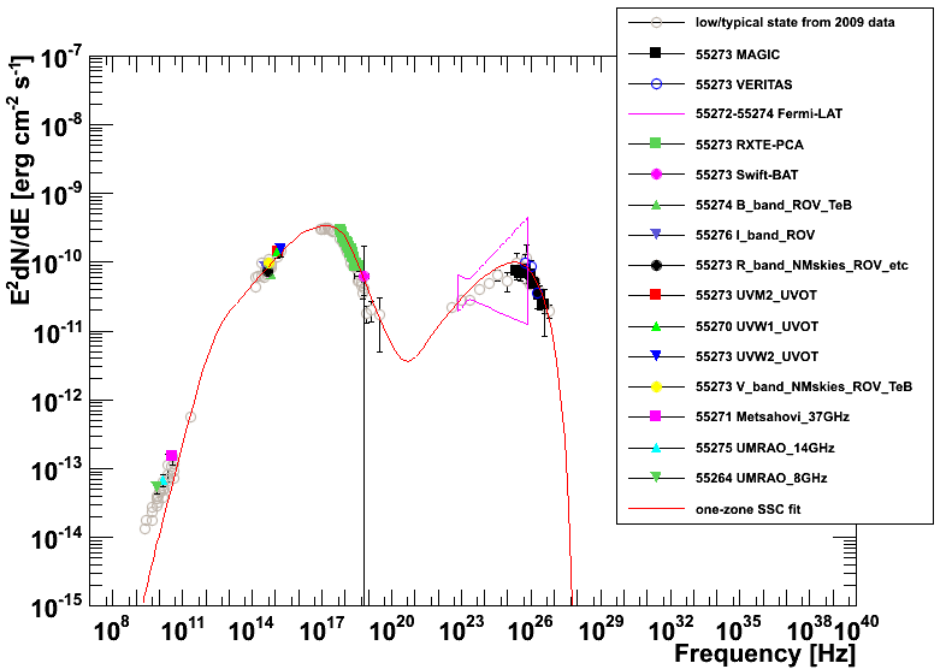


2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks

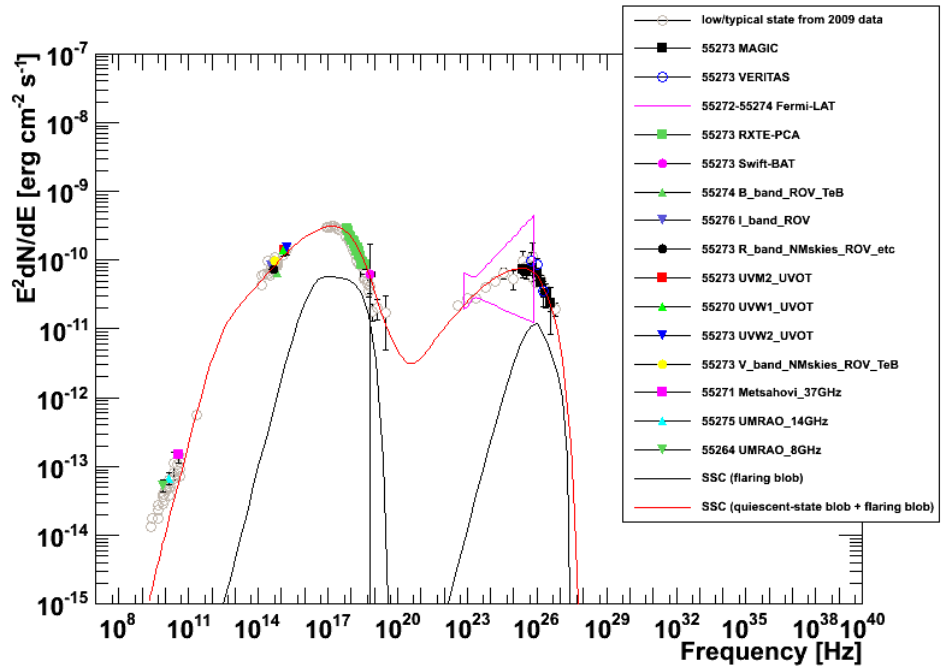


Mrk421 MW 2010_03_18 (55273)

1 blob, 2 breaks

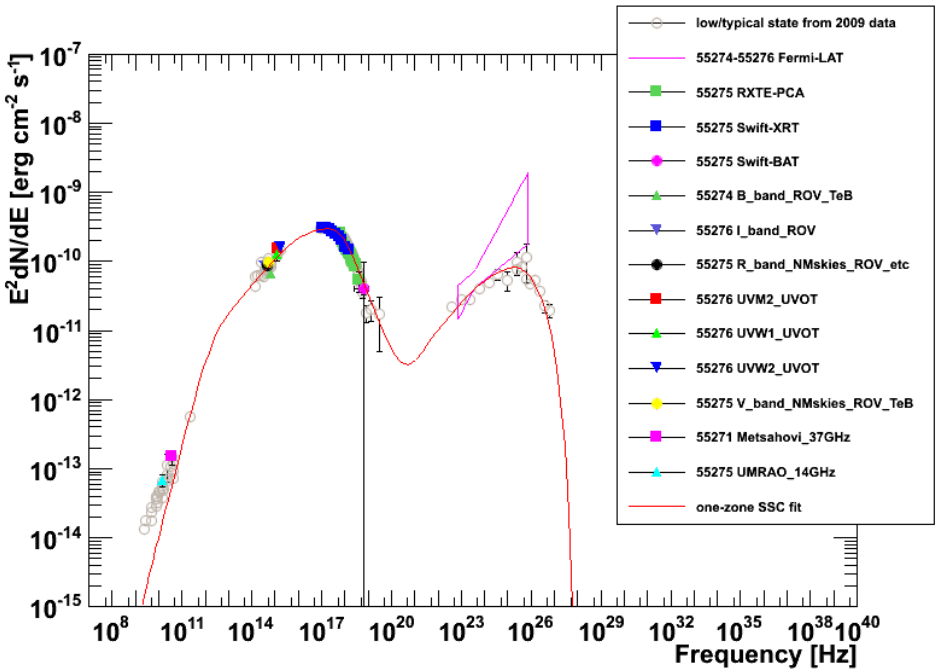


2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks

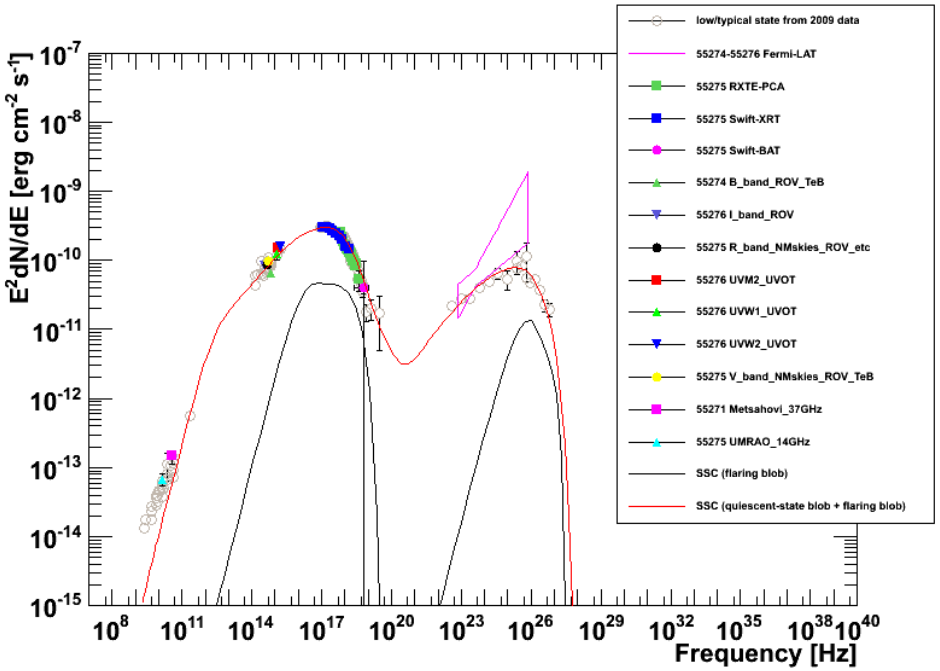


Mrk421 MW 2010_03_20 (55275)

1 blob, 2 breaks

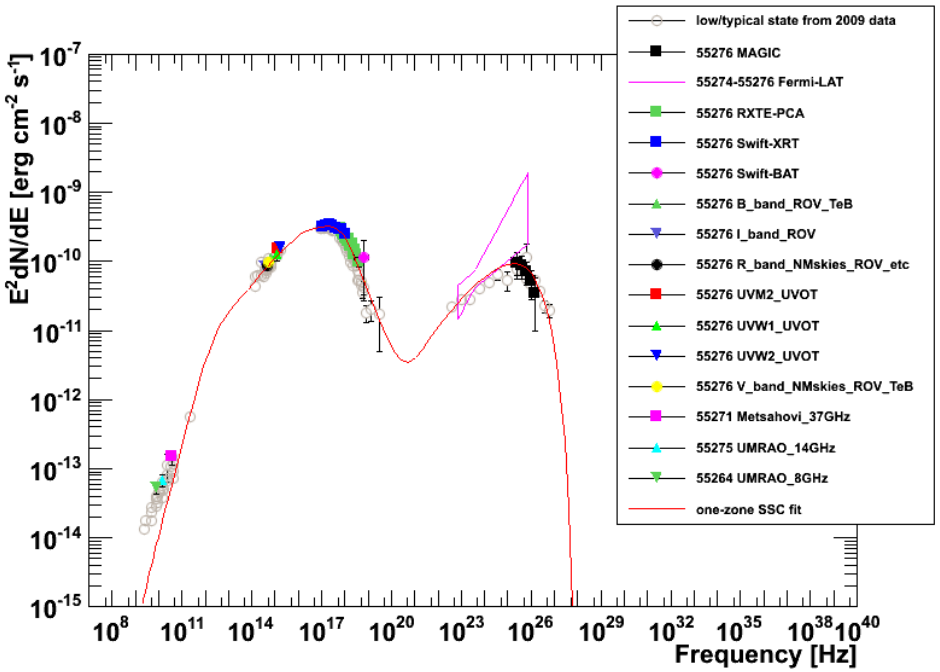


2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks

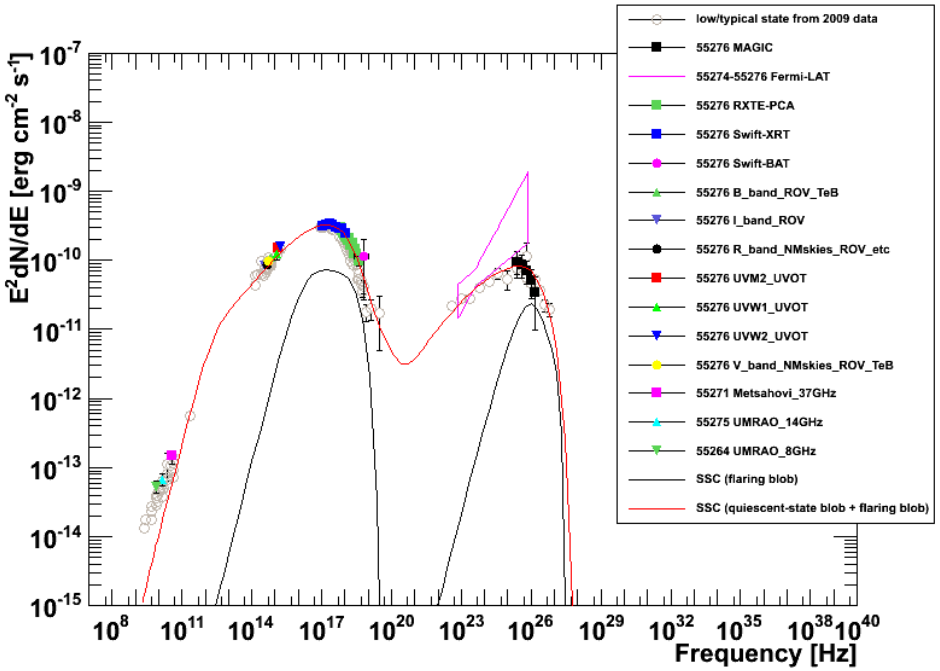


Mrk421 MW 2010_03_21 (55276)

1 blob, 2 breaks



2 blob:
Flaring blob:1 break
Quiescent blob: 2 breaks



1-blob Model

Table 2. Integral Flux and Fit Parameters of One-zone SSC Model

Date[MJD]	Flux($E > 200GeV$)[$cm^{-2}s^{-1}$]	γ_{min}	γ_{max}	γ_{break1}	γ_{break2}	s_1	s_2	s_3	$n_e[cm^{-3}]$	$B[mG]$	$log(R[cm])$	δ
55265	3.8×10^{-10}	8.e2.	1.e8.	6.0e5.	6.0e5.	2.23	2.23	4.70	1.14e3.	38.	16.72	21.
55266	4.7×10^{-10}	8.e2.	1.e8.	6.6e5.	6.6e5.	2.23	2.23	4.70	1.16e3.	38.	16.72	21.
55267	4.0×10^{-10} $^{(v)}$	8.e2.	1.e8.	1.6e5.	6.0e5.	2.23	2.70	4.70	1.10e3.	38.	16.72	21.
55268	2.1×10^{-10}	8.e2.	1.e8.	1.6e5.	6.0e5.	2.20	2.70	4.70	0.90e3.	38.	16.72	21.
55269	3.3×10^{-10}	8.e2.	1.e8.	1.2e5.	7.0e5.	2.20	2.70	4.70	0.95e3.	38.	16.72	21.
55270	2.3×10^{-10}	8.e2.	1.e8.	8.0e4.	3.9e5.	2.20	2.70	4.70	0.90e3.	38.	16.72	21.
55271	3.5×10^{-10} $^{(v)}$	8.e2.	1.e8.	9.0e4.	5.0e5.	2.20	2.70	4.70	0.90e3.	38.	16.72	21.
55272	1.4×10^{-10}	8.e2.	1.e8.	5.0e4.	4.0e5.	2.20	2.50	4.70	0.90e3.	38.	16.72	21.
55273	1.5×10^{-10}	8.e2.	1.e8.	6.0e4.	3.9e5.	2.20	2.70	4.70	0.90e3.	38.	16.72	21
55274	9.9×10^{-11}	8.e2.	1.e8.	3.5e4.	3.9e5.	2.20	2.70	4.70	0.90e3.	38.	16.72	21.
55275	1.8×10^{-10} $^{(w)}$	8.e2.	1.e8.	5.0e4.	3.9e5.	2.20	2.70	4.70	0.85e3.	38.	16.72	21.
55276	1.6×10^{-10}	8.e2.	1.e8.	5.7e4.	3.9e5.	2.20	2.70	4.70	0.90e3.	38.	16.72	21.
55277	1.2×10^{-10}	8.e2.	1.e8.	8.0e4.	3.9e5.	2.20	2.70	4.70	0.70e3.	38.	16.72	21.

Note. — The flux is from the MAGIC measurement except the case of no observation, in which VERITAS or Whipple measurement is instead used.

Note. — $^{(v)}$ VERITAS measurement. This flux value was measured around 7 hours after the simultaneous MW observation time.

Note. — $^{(w)}$ Whipple measurement. This flux value was measured around 7 hours after the simultaneous MW observation time.

2-zone Model

Table 3. Integral Flux and Fit Parameters of Two-zone SSC Model

Date[MJD]	Flux($E > 200GeV$)[$cm^{-2}s^{-1}$]	γ_{min}	γ_{max}	γ_{break1}	γ_{break2}	s_1	s_2	s_3	$n_e[cm^{-3}]$	$B[mG]$	$log(R[cm])$	δ
					the quiescent blob							
for all dates	- -	8.e2.	1.e8.	3.5e4.	3.9e5.	2.2	2.7	4.7	0.9e3.	38.	16.72	21.
					the flaring blob							
55265	3.8×10^{-10}	3.0e4.	6.e5.	3.0e5.	- -	2.0	3.0	- -	5.0e3.	105.	15.51	35.
55266	4.7×10^{-10}	3.0e4.	6.e5.	3.0e5.	- -	2.0	3.0	- -	6.0e3.	100.	15.51	35.
55267	4.0×10^{-10} (v)	2.5e4.	6.e5.	1.1e5.	- -	2.0	3.0	- -	5.9e3.	100.	15.51	35.
55268	2.1×10^{-10}	5.3e4.	6.e5.	1.8e5.	- -	2.0	3.0	- -	5.6e3.	100.	15.51	35.
55269	3.3×10^{-10}	3.0e4.	6.e5.	1.8e5.	- -	2.0	3.0	- -	6.5e3.	85.	15.51	35.
55270	2.3×10^{-10}	3.5e4.	6.e5.	0.8e5.	- -	2.0	3.0	- -	6.0e3.	75.	15.51	35.
55271	3.5×10^{-10} (v)	3.5e4.	6.e5.	1.2e5.	- -	2.0	3.0	- -	6.5e3.	75.	15.51	35.
55272	1.4×10^{-10}	3.5e4.	6.e5.	2.4e5.	- -	2.0	5.0	- -	4.0e3.	75.	15.51	35.
55273	1.5×10^{-10}	3.5e4.	6.e5.	0.5e5.	- -	2.0	3.0	- -	4.0e3.	75.	15.51	35.
55274	9.9×10^{-11}	3.5e4.	6.e5.	0.4e5.	- -	2.0	3.0	- -	1.4e3.	60.	15.51	35.
55275	1.8×10^{-10} (w)	3.5e4.	6.e5.	0.5e5.	- -	2.0	3.0	- -	5.0e3.	60.	15.51	35.
55276	1.6×10^{-10}	3.5e4.	6.e5.	0.8e5.	- -	2.0	3.0	- -	5.0e3.	60.	15.51	35.
55277	1.2×10^{-10}	3.5e4.	6.e5.	0.8e5.	- -	2.0	3.0	- -	2.5e3.	60.	15.51	35.

Conclusion

During this flaring episode, VHE and X-ray bands vary the most.

VHE vs X-ray show a linear trend for 0.3-2 keV band, while a quadratic trend for the 2-10 keV band

Evolution of the broadband SED could be described with a one-zone or a two-zone SSC model

Lower states: broader bumps in SEDs,
at least 3 power-law indices needed to describe EEDs
both one-zone and two-zone models are fine

Higher states: sharper bumps in SEDs,
at least 2 power-law indices needed to describe EEDs
two-zone model is better in describing the SED evolution

Overall: The observed evolution of the SEDs favors the presence of two blobs, rather than the one single blob used typically to describe flares in TeV blazars