Max Planck Institute for Physics

The MAGIC Telescope

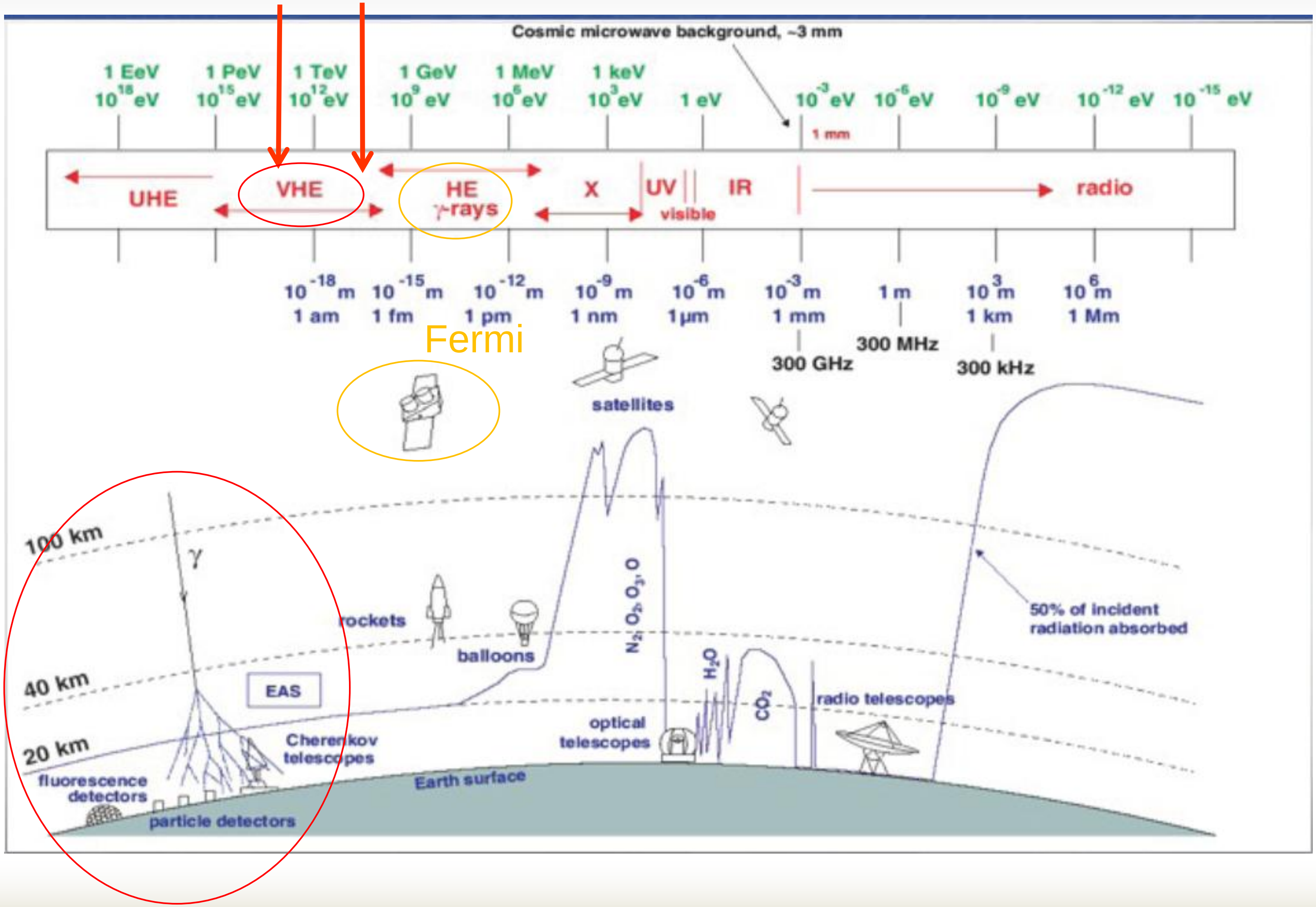
Multi-frequency Study on Markarian 421 during the First Year of Operation of the MAGIC Stereo Telescopes

ShangYu Sun

16_03_2012

Very High Energy Astronomy

MAGIC 50GeV-50TeV



VHE Observatories

Imaging Air Cherenkov Telescopes

Credits from R. Wagner

IACT Installations: the Key Players

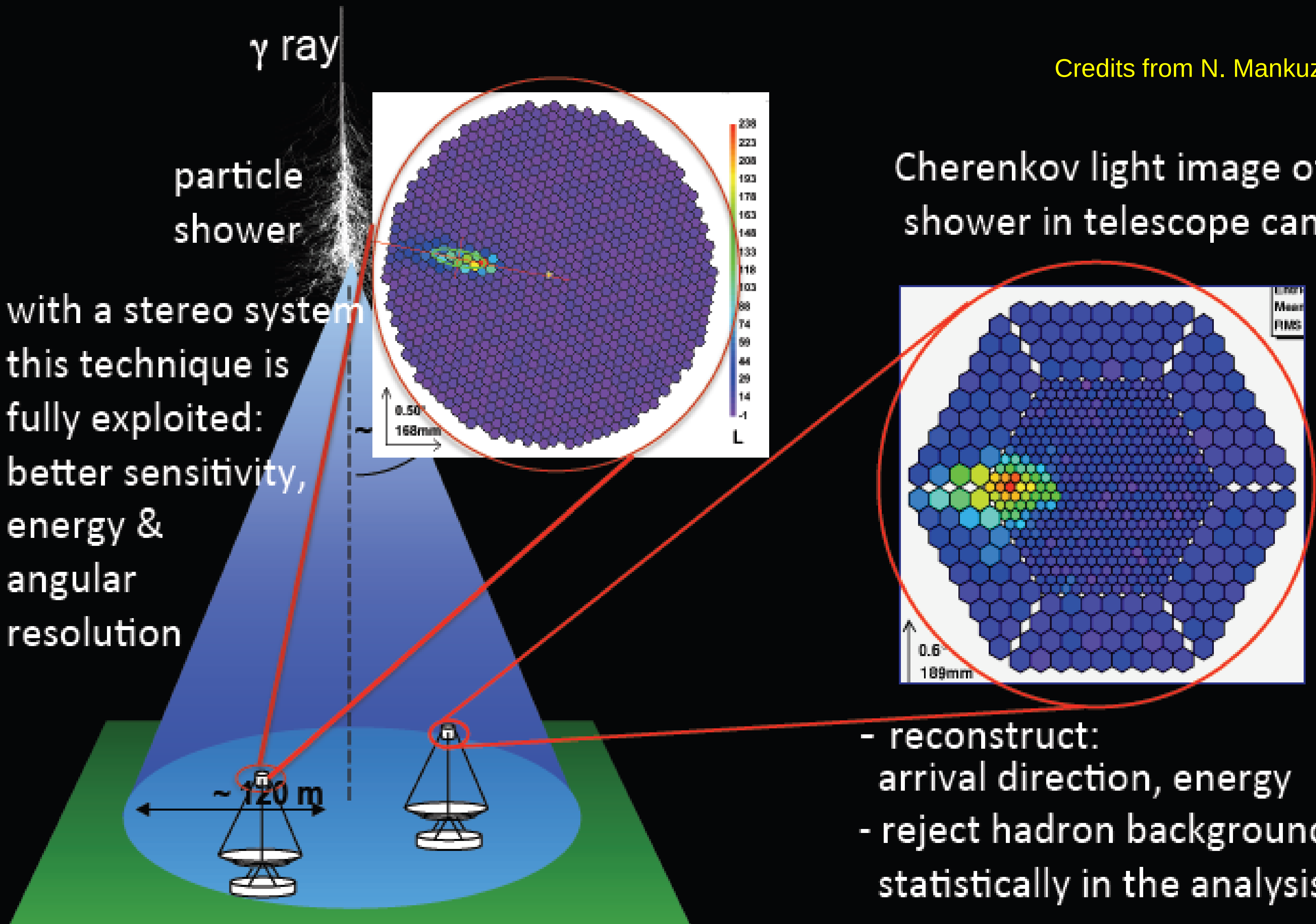
Credits from R. Wagner

	H.E.S.S.	MAGIC
Number of telescopes	4	2
Field of view	5°	3.5°
Reflector diameter	12 m	17 m (the largest IACT)
Working Energy Range	>160 GeV	>50 GeV

- Located @ Roque de Los Muchachos (La Palma, Canary Islands, Spain) 2200 m a.s.l.
- MAGIC-I since 2004
- MAGIC-II since 2009
- Sensitivity 0.8% Crab (for E>260GeV, 50hr)
- Energy resolution 20% at 100 GeV, 15% at 1TeV
- Angular resolution ~ 0.07° at 1 TeV
- Light weight carbon fiber structure -> Fast repositioning (GRB)
- sum trigger mode can lower energy threshold to 25 GeV (pulsar)
- Enhanced duty cycle due to moonlight & twilight observations

Imaging Air Cherenkov Technique

Credits from N. Mankuzhiyil



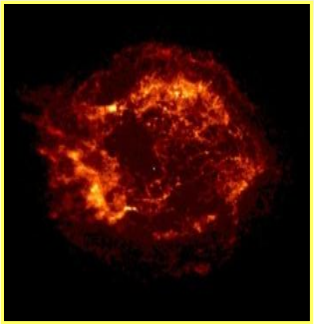
with a stereo system this technique is fully exploited: better sensitivity, energy & angular resolution

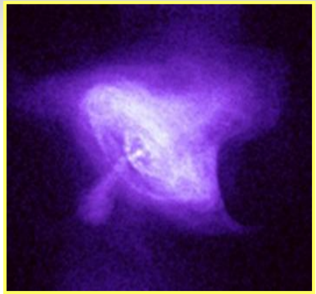
- reconstruct: arrival direction, energy
- reject hadron background statistically in the analysis

TeV Sources

extragalactic sources

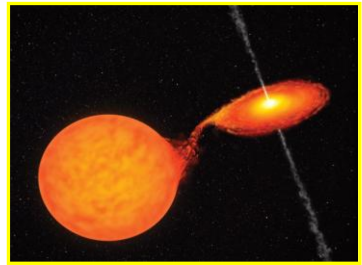
Supernova Remnant

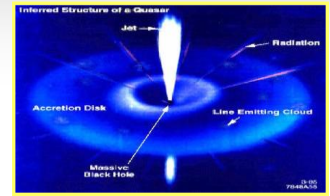




Pulsar
Pulsar Wind Nebula

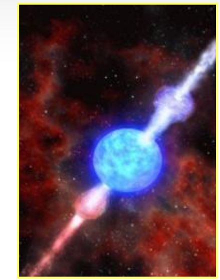
Micro quasar
X-ray binary

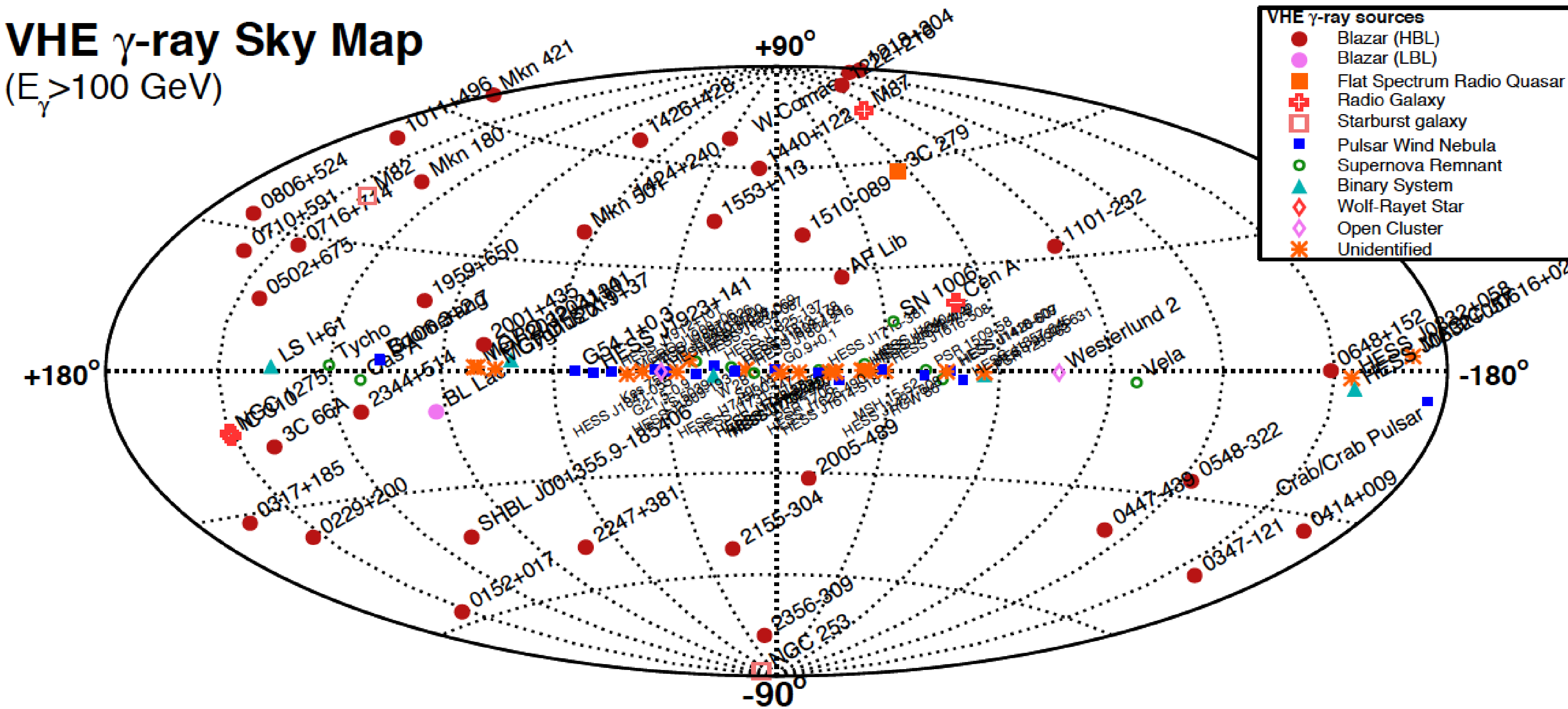




Active Galactic Nuclei

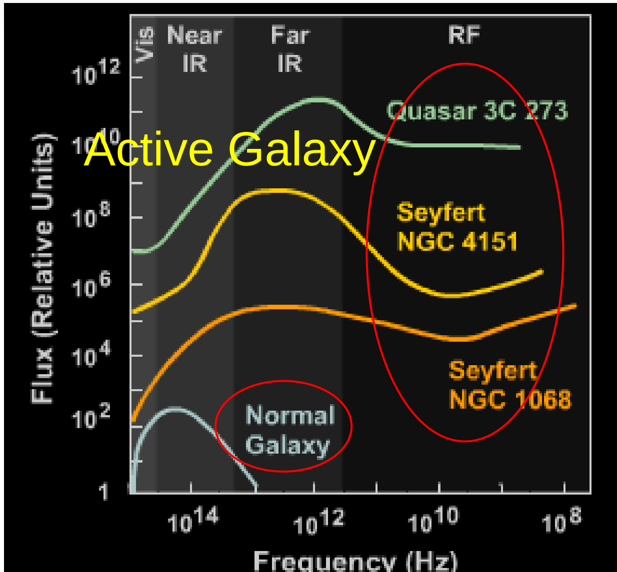
Gamma Ray Burst



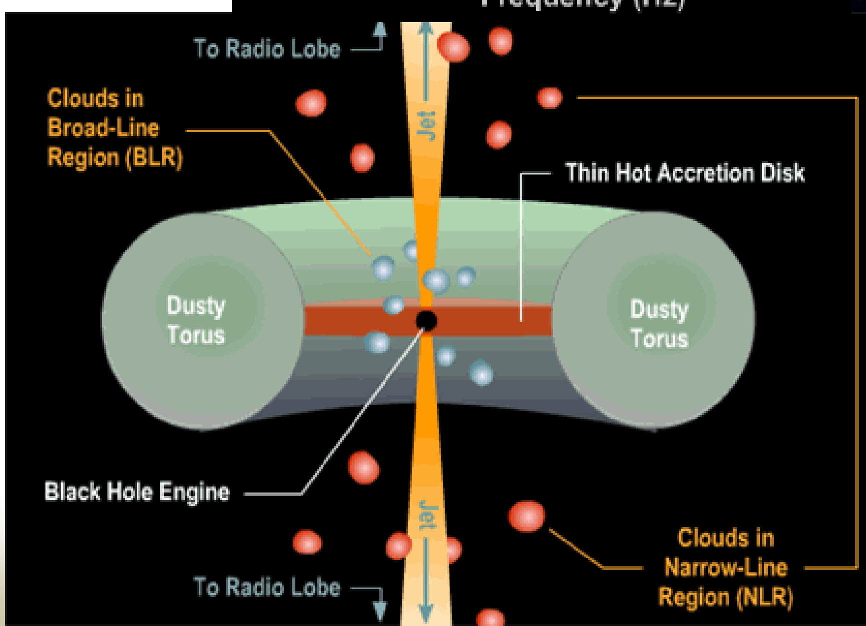


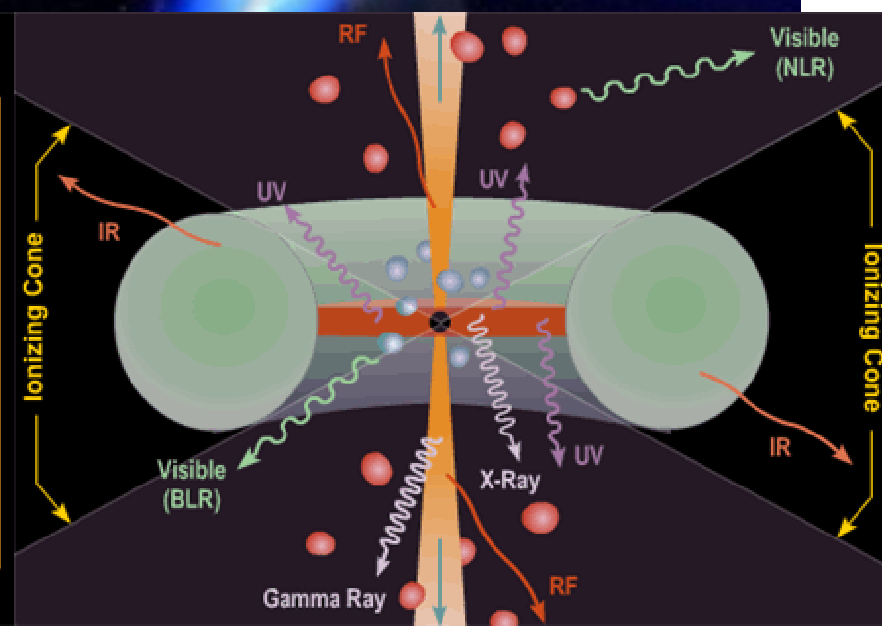
2010-11-11 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

Active Galactic Nuclei(AGN) of Active Galaxies



Credits from Brooks/Cole Thomson Learning





TeV Extragalactic Sources

Credits from R. Wagner

Name	redshift	reference
NGC 253	3.3 Mpc	Aharonian, et al., Science Express (09/2009)
Centaurus A	3.8 Mpc	Raue et al., arXiv0904.2654 (2009)
M 82	4.0 Mpc	Benbow et al., proc of ICRC (2009)
M 87	16.7 Mpc	Aharonian et al., A&A, 403, L1 (2003)
3C66B(?)	0.022	Aliu et al., ApJ, 692, L29 (2009)
Markarian 421	0.030	Punch et al., Nature, 358, 477 (1992)
Markarian 501	0.034	Quinn et al., ApJ, 456, L83 (1996)
1ES 2344+514	0.044	Catanese et al., ApJ, 501, 616 (1998)
Markarian 180	0.045	Albert et al., astro-ph/0606630 (2006)
1ES 1959+650	0.047	Nishiyama et al., 29th ICRC, 3, 370 (1999)
PKS 548-322	0.067	Superina et al., Proc. Of ICRC (2007)
BL Lacertae	0.069	Albert et al., astro-ph/0703084 (2007)
PKS 2005-489	0.071	Aharonian et al., A&A, 436, L17 (2005)
W Comae	0.102	Swordy et al., ATel #1422 (2008)
PKS 2155-304	0.116	Chadwick et al., ApJ, 513, 161 (1999)
RGB J0710+591	0.125	Ong et al., Atel#1941 (2009)
H 1426+428	0.129	Horan et al., ApJ, 571, 753 (2002)
1ES 0806+524	0.138	Swordy et al., ATel #1415 (2008)
1ES 0229+200	0.139	Proc. Of ICRC 2007
PKS 1424+240	0.16(?)	Ong et al., Atel#2084 (2009)
H 2356-309	0.165	Aharonian et al., Nature, 440, 1018 (2006)
1ES 1218+304	0.182	Albert et al., ApJ, 642, L119 (2006)
1ES 1101-232	0.186	Aharonian et al., Nature, 440, 1018 (2006)
1ES 0347-121	0.188	Proc. Of ICRC 2007
RBS 0413	0.190	Ong et al., Atel#2272 (2009)
PKS 0447-439	0.200	Raue et al., Atel #2350 (2009)
1ES 1011+496	0.212	Albert et al., ApJ, 667, L21 (2007)
1ES 0414+009	0.287	Hofmann, Fegan, et al., Atel #2293 (2009)
1ES 0502+675	0.341	Ong et al., Atel#2301 (2009)
VER J0521+211	???	Ong et al., Atel#2260 (2009)
PG 1553+113	>0.09?	Aharonian et al., A&A, 448, L19 (2006)
S50716+714	???	Teshima et al., Atel #1500 (2008)
3C 66A	>0.096	Swordy et al., ATel #1753 (2008)
3C 279	0.54	Errando et al., ArXiv preprint (2008)

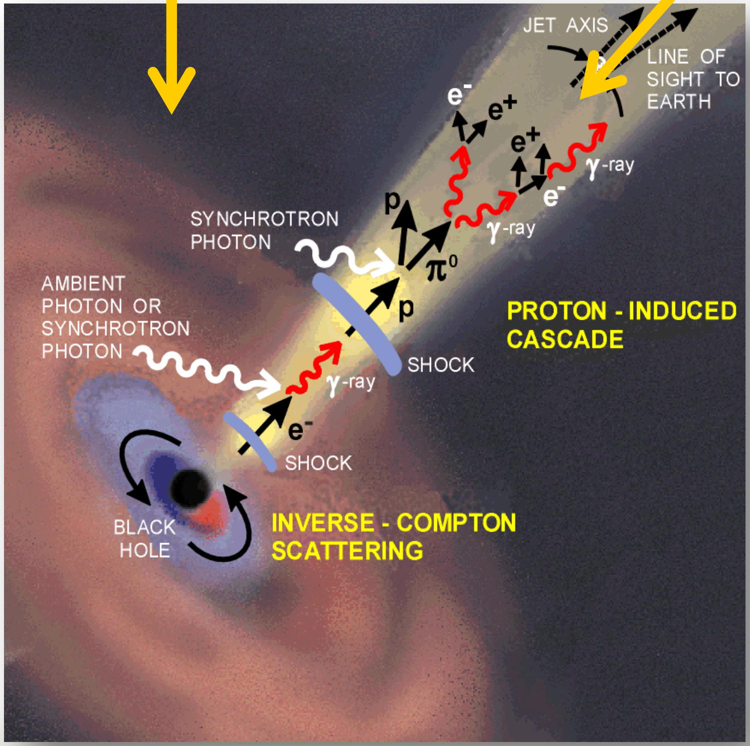
Star burst galaxies
Radio galaxies
Unclear
Blazars

46 TeV extragalacic sources

3 x FR-I,
2 x Starburst galaxies,
4 x FSRQs,
37 x BL Lacs

FRI, FRII (Radio Galaxies)

BL Lac, FSRQ (Blazars)



MAGIC

Why to study Markarian 421

Excellent laboratory for studying High Energy blazar emission

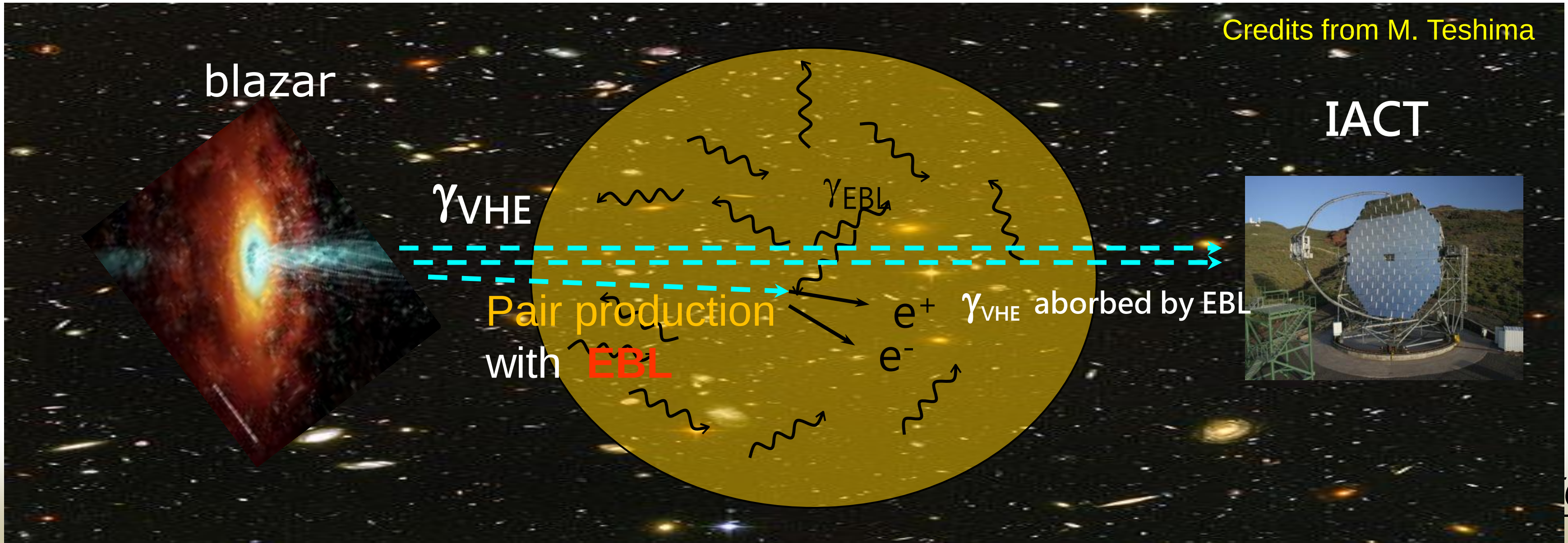
- **VHE flux ~0.5 Crab**
- **~3 minutes can reach 5 sigma of detection by MAGIC**

- **z = 0.03**
- **low EBL absorption**
- **more intrinsic spectrum**

Extragalactic Background Light (EBL)

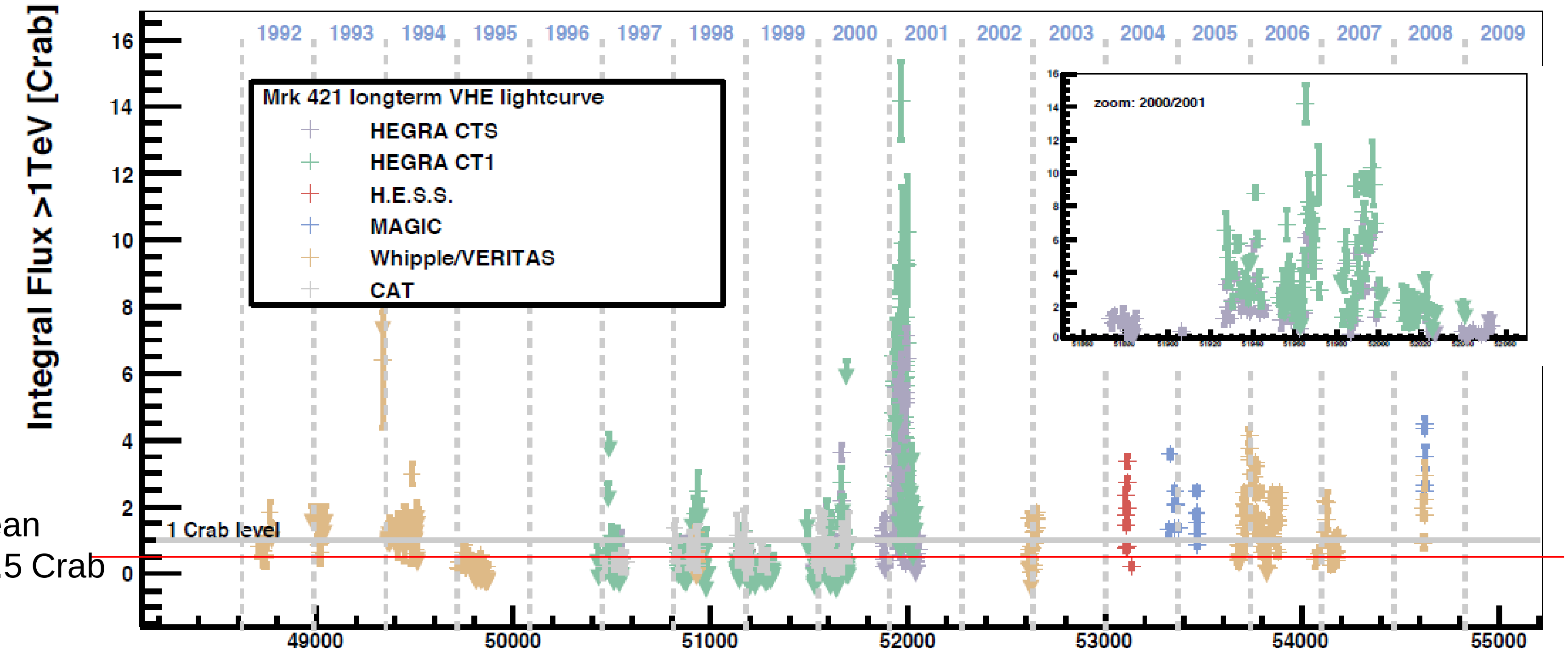
all the accumulated radiation in the Universe due to **star formation** processes, plus a contribution from **AGN**s.

- Primarily ultraviolet, optical, and infrared



Long Term TeV Monitoring on Mrk421

4 arXiv:1010.5659v1 M. Tluczykont et al.: Long-term γ-ray lightcurves



Mean
~0.5 Crab

At 12:00 on 1st Jan in 4713 B.C.

JD=0

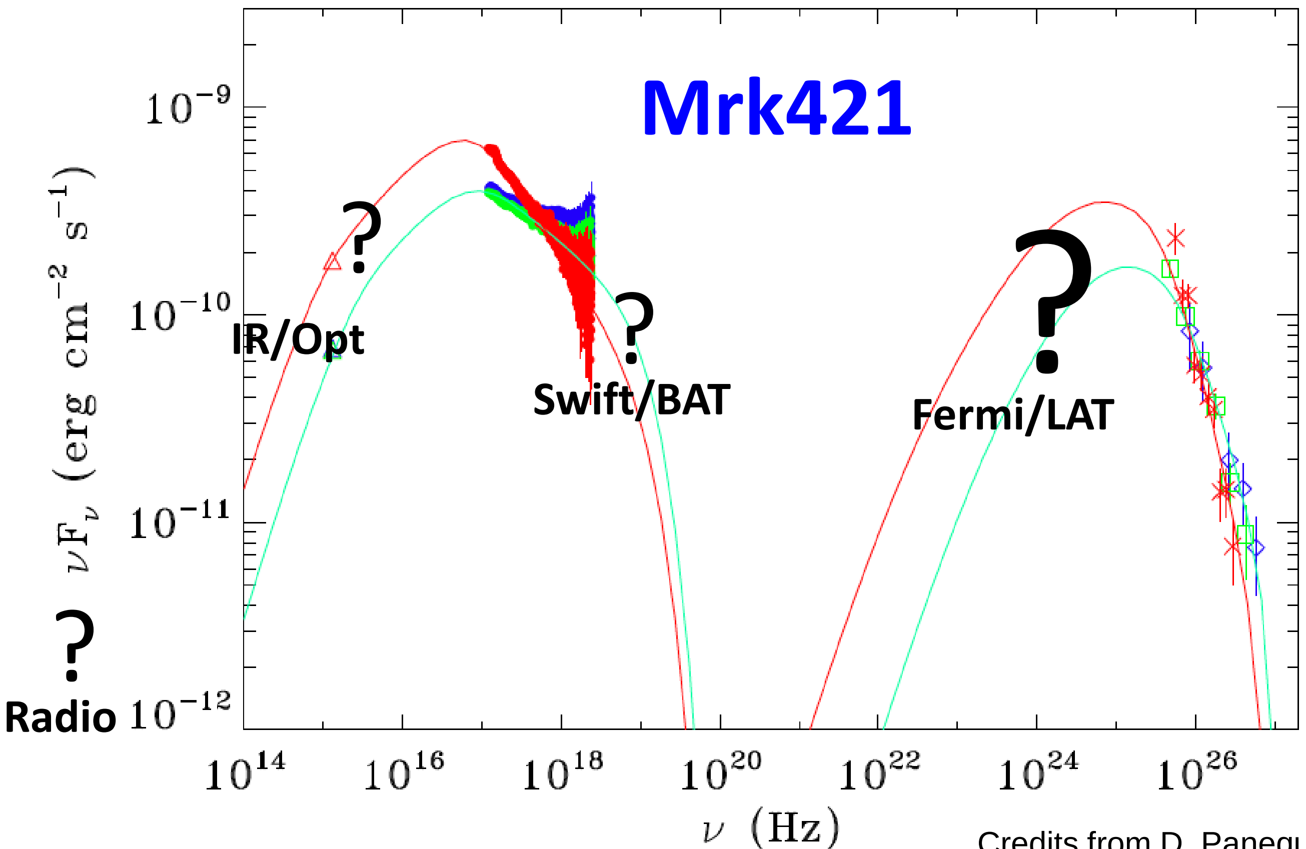
MJD = JD - 2400000.5

Fig. 1. Long-term lightcurve of Mrk 421 (day-wise integral flux). Data from the major γ-ray telescopes were combined and normalized to the same energy threshold (1 TeV) and converted to Crab units (see text). A zoom into the period of strong activity (2000/2001) is also shown.

Why do we need "extensive" multi-wavelength study on Markarian 421 ?

The Astrophysical Journal, 703:169–178, 2009 September 20

Flaring activity from 2 days in 2006 and 2008 : XMM, MAGIC, VERITAS (+Whipple)



Credits from D. Paneque

Too little data cannot well constrain parameters in the model

We need more data on different frequency bands to constrains emission models !!

MAGIC

Mrk421 multi-wavelength campaigns

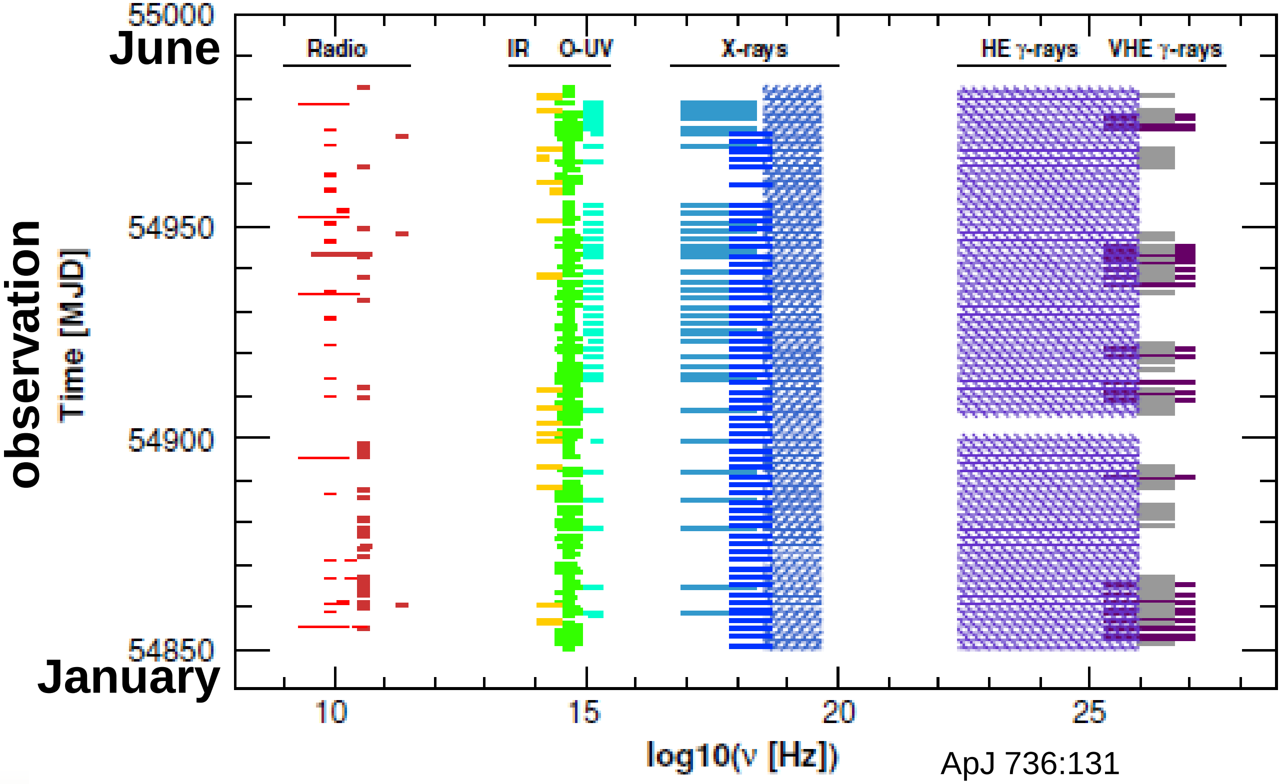
Past MW campaigns

Mrk421 (Jan19, 2009-Jun1 ,2009: 4.5 months)

Mrk421 (Dec8, 2009-Jun20 ,2010: 6 months)

Mrk421 (Dec1, 2010-Jun15 ,2011: 6 months)

Mrk421 2009 MW



ApJ 736:131

covered frequencies :from radio to TeV

More than 25 instruments
Radio: VLBA, OVRO, Effelsberg, Metsahovi…
mm: SMA, IRAM-PV
Infrared: WIRO, OAGH
Optical: GASP, GRT, MITSuMe, Kanata…
UV: Swift-UVOT
X-ray: Swift-XRT, RXTE-PCA, Swift_BAT
Gamma-ray: Fermi-LAT
VHE: MAGIC, VERITAS, Whipple

Mrk421 2009 MW Spectral Energy Distribution

The most complete Mrk421 spectrum that we ever collected !!

THE ASTROPHYSICAL JOURNAL, 736:131 (22pp), 2011 August 1 ABDO ET AL.

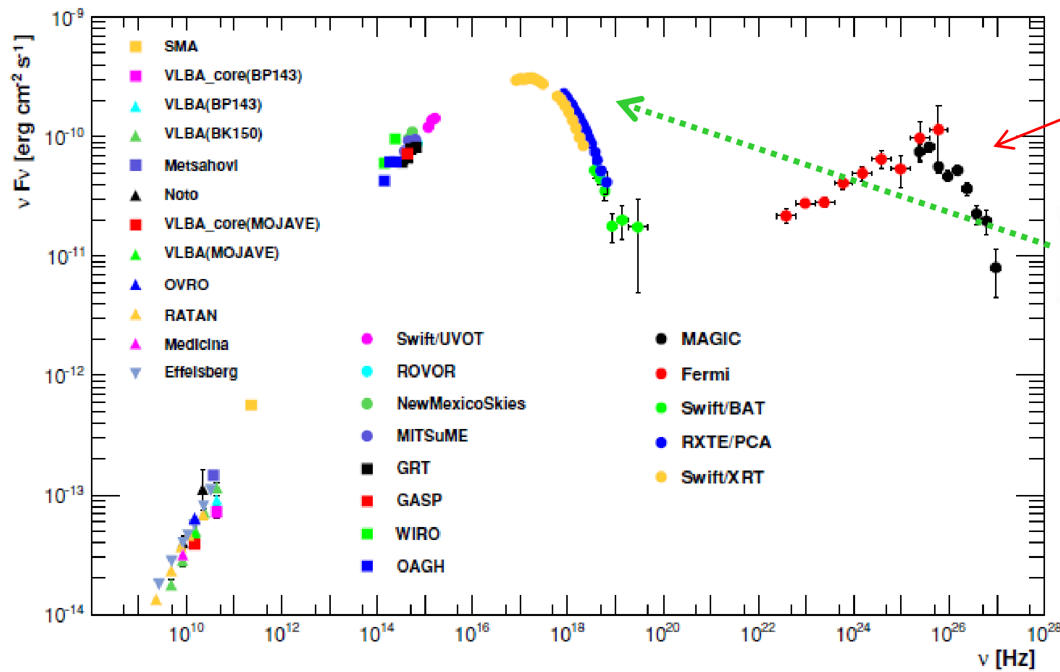
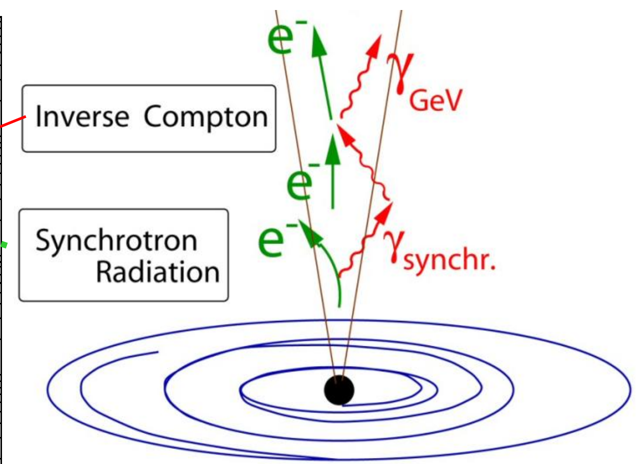
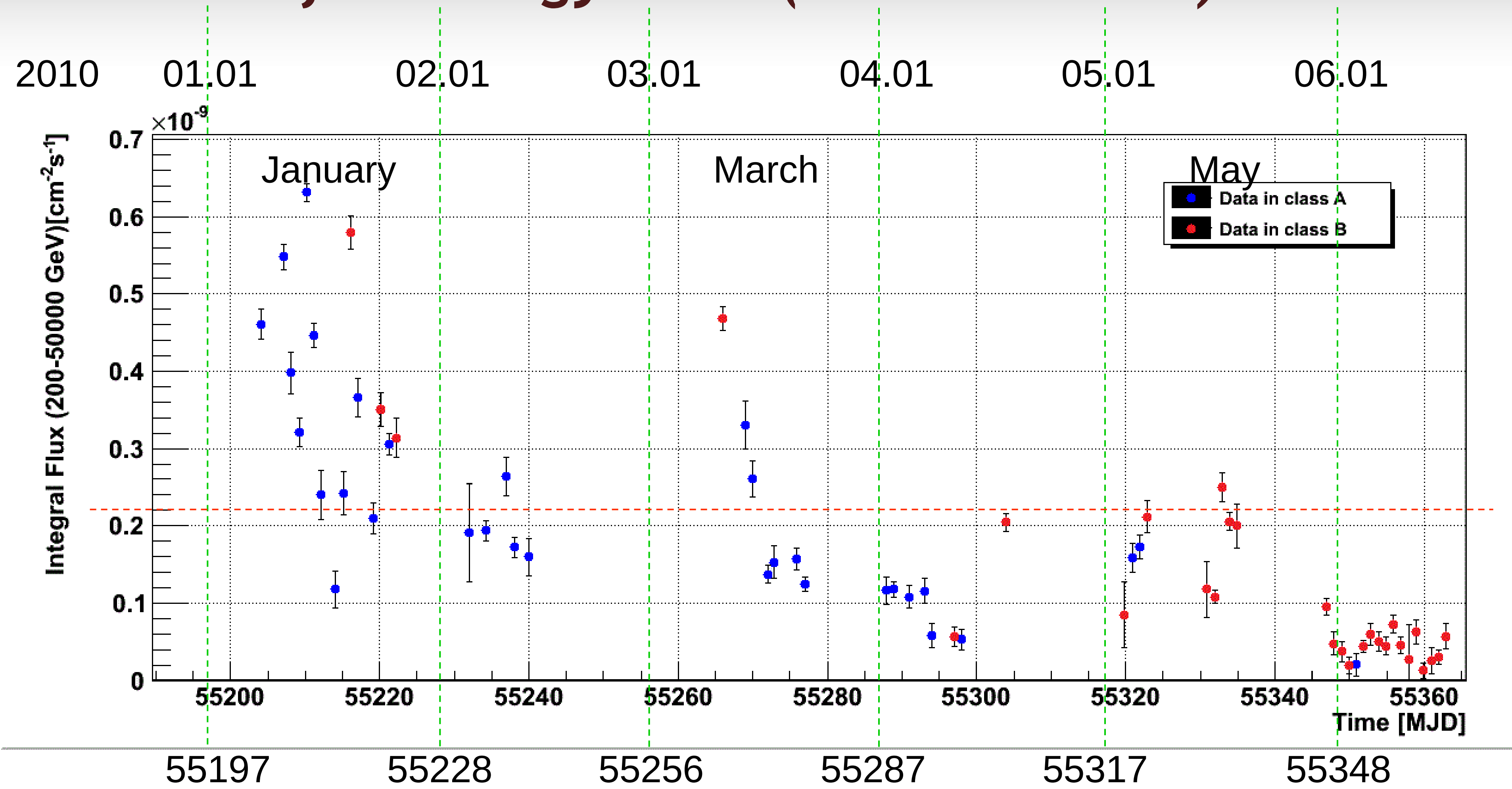


Figure 8. Spectral energy distribution of Mrk 421 averaged over all the observations taken during the multifrequency campaign from 2009 January 19 (MJD 54850) to 2009 June 1 (MJD 54983). The legend reports the correspondence between the instruments and the measured fluxes. The host galaxy has been subtracted, and the optical/X-ray data were corrected for the Galactic extinction. The TeV data from MAGIC were corrected for the absorption in the EBL using the prescription given in Franceschini et al. (2008).



Synchrotron Self-Compton Model

Mrk421 2010.01-06 light curve full energy band (200-5000 GeV)



MAGIC

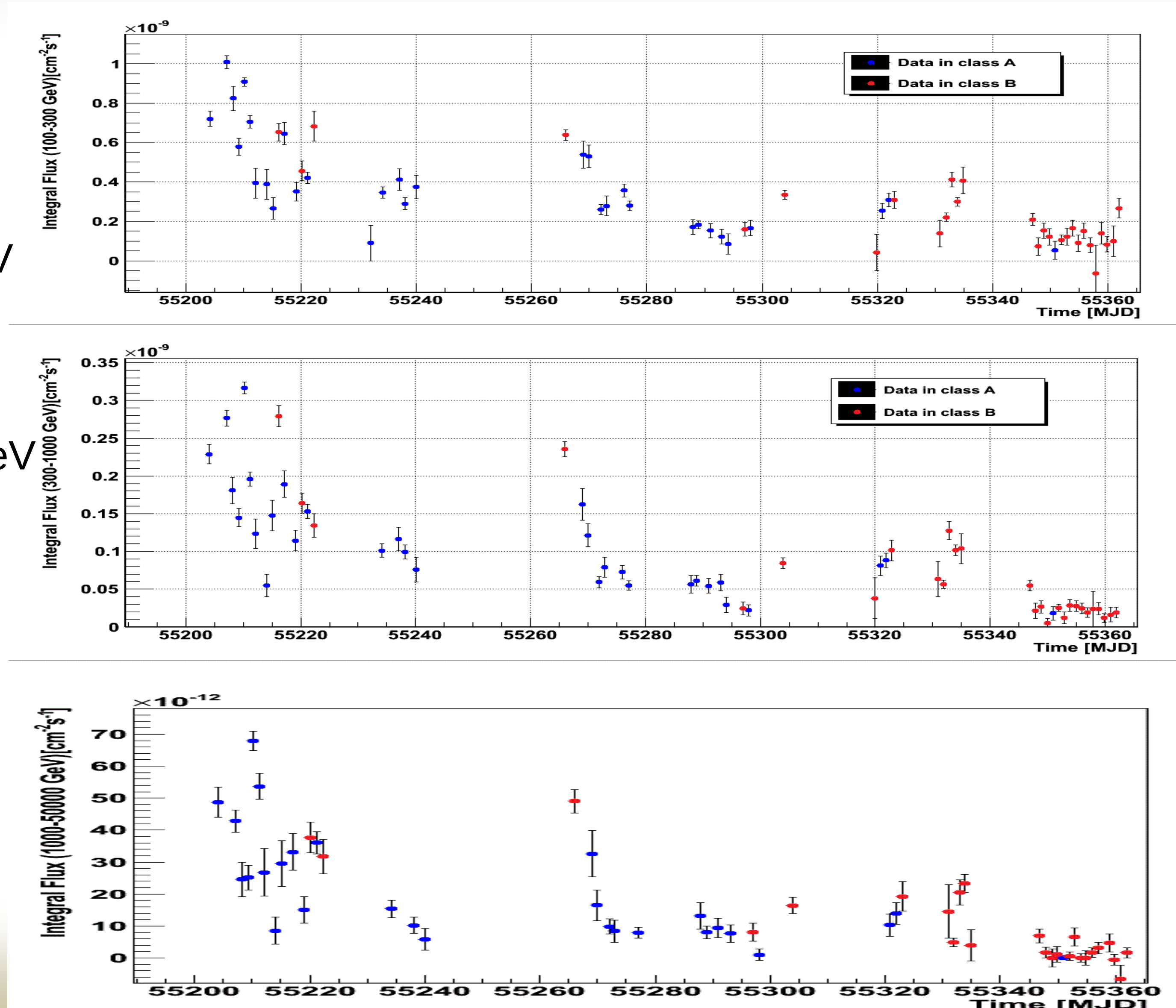
Light curve in 3 energy bands:

Full energy band

Low Energy Band 100-300 GeV

Medium Energy Band 300-1000 GeV

High Energy Band >1TeV

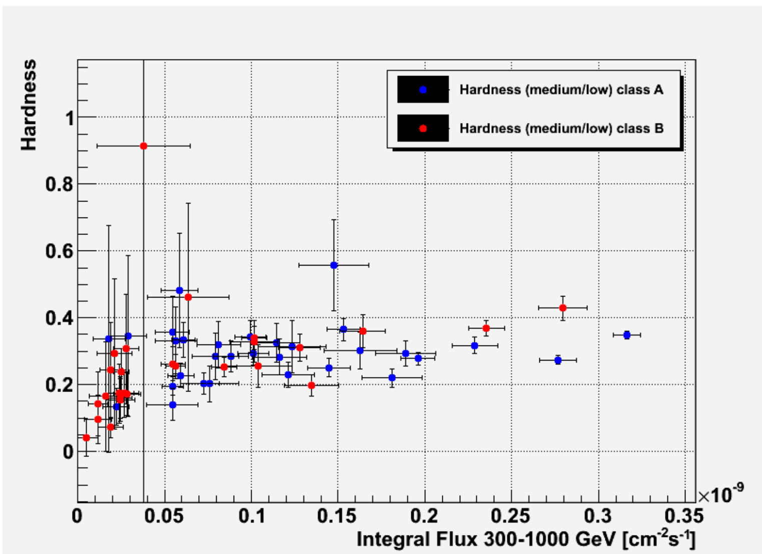


ShangYu SUN

Hardness Ratio vs Flux

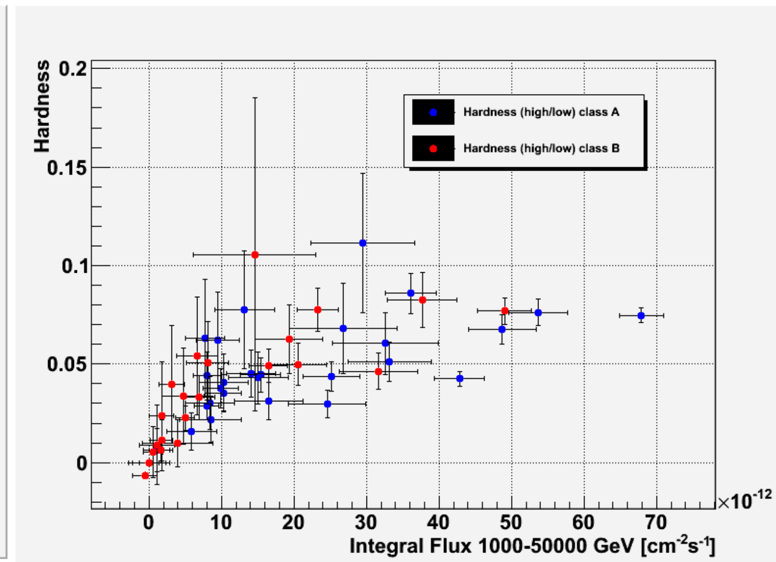
Hardness Ratio1

= $Flux_{medium\_energy}$ / $Flux_{low\_energy}$

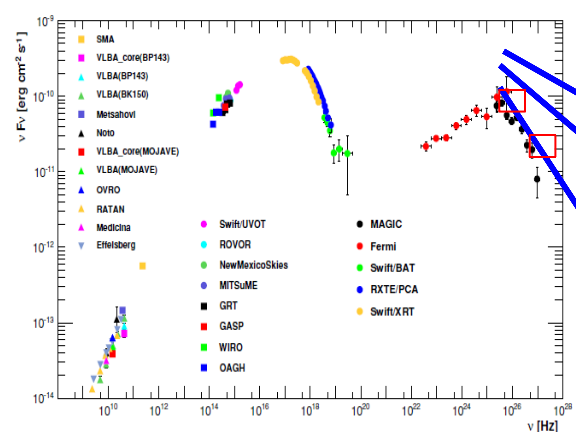


Hardness Ratio2

= $Flux_{high\_energy}$ / $Flux_{low\_energy}$



low (100-300 GeV)
medium (300-1000 GeV)
high (>1TeV)

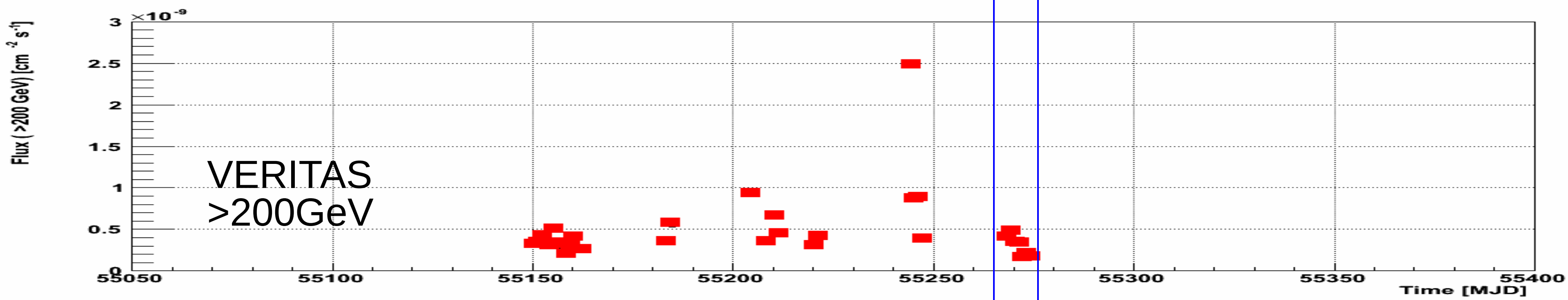


Hard spectrum, high flux

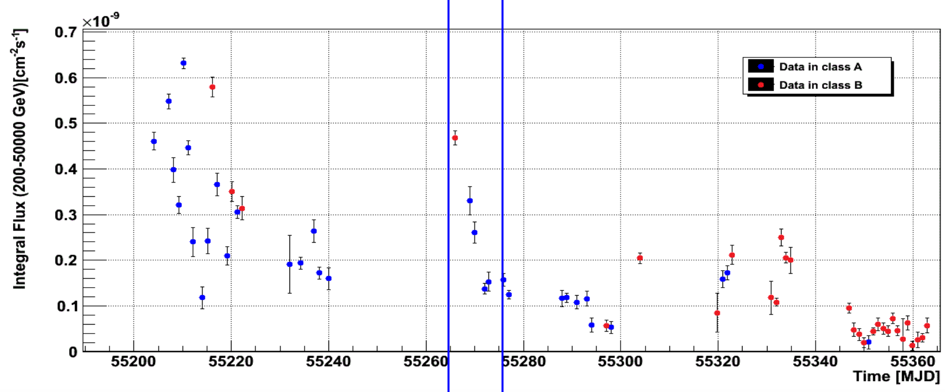
Soft spectrum, low flux

Mrk421 2010 MW light curves: VHE and Gamma rays

2010 March

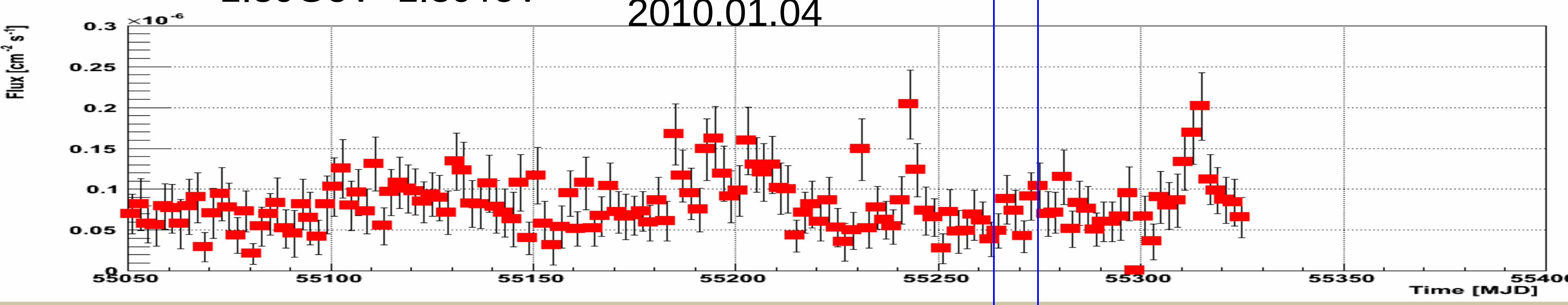


MAGIC
200GeV~50TeV

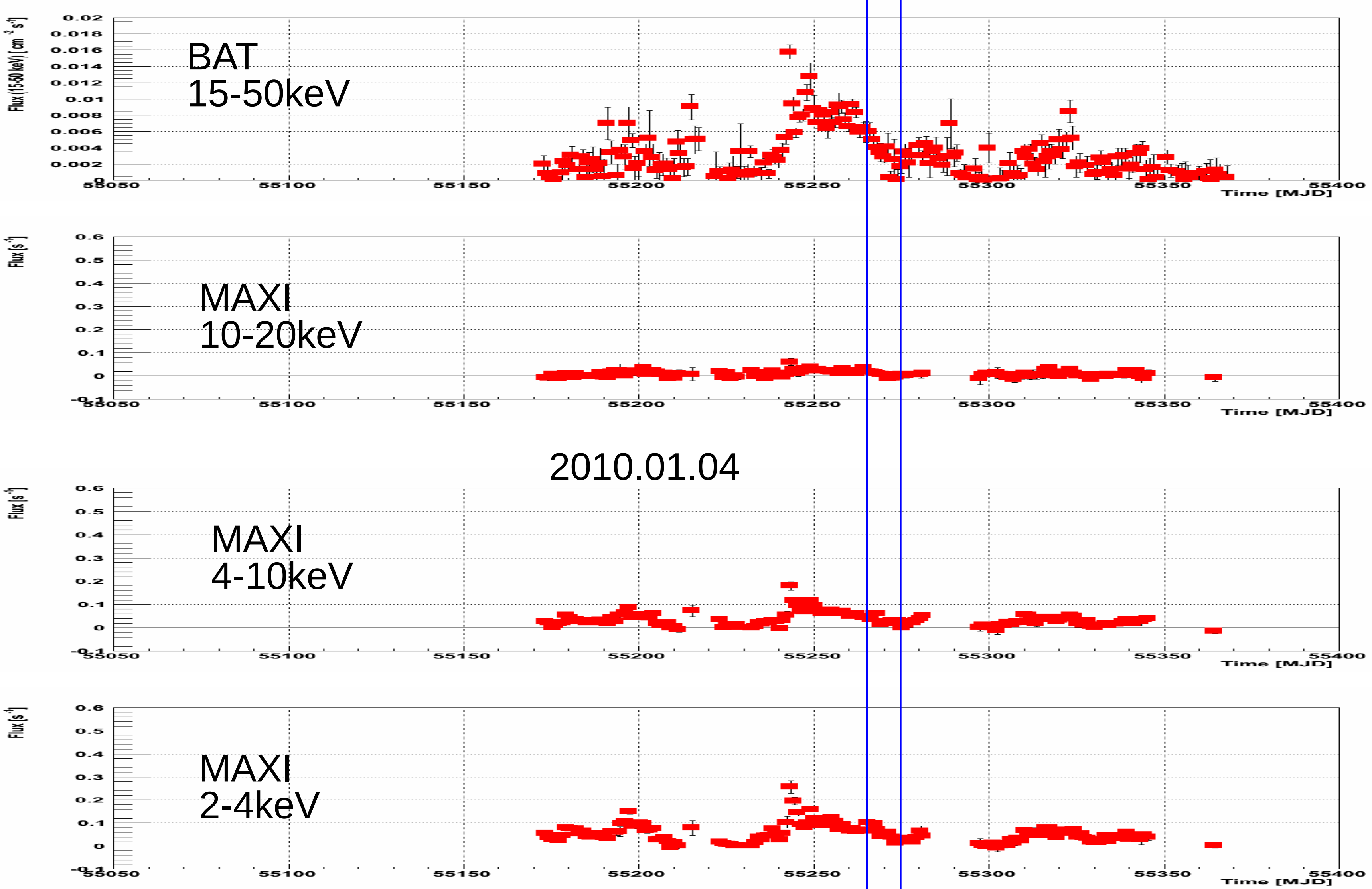


Fermi
1.89GeV~1.89TeV

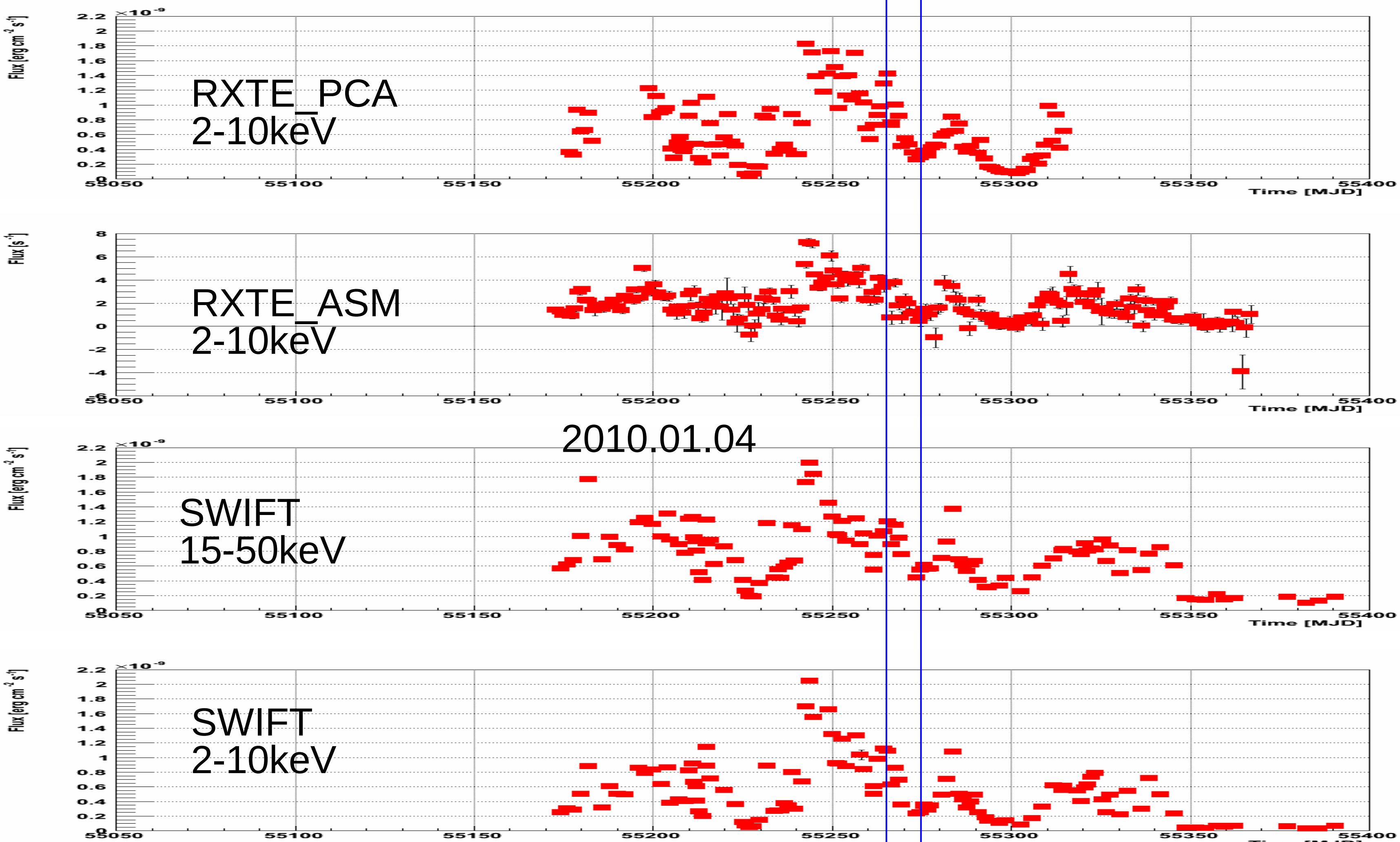
2010.01.04



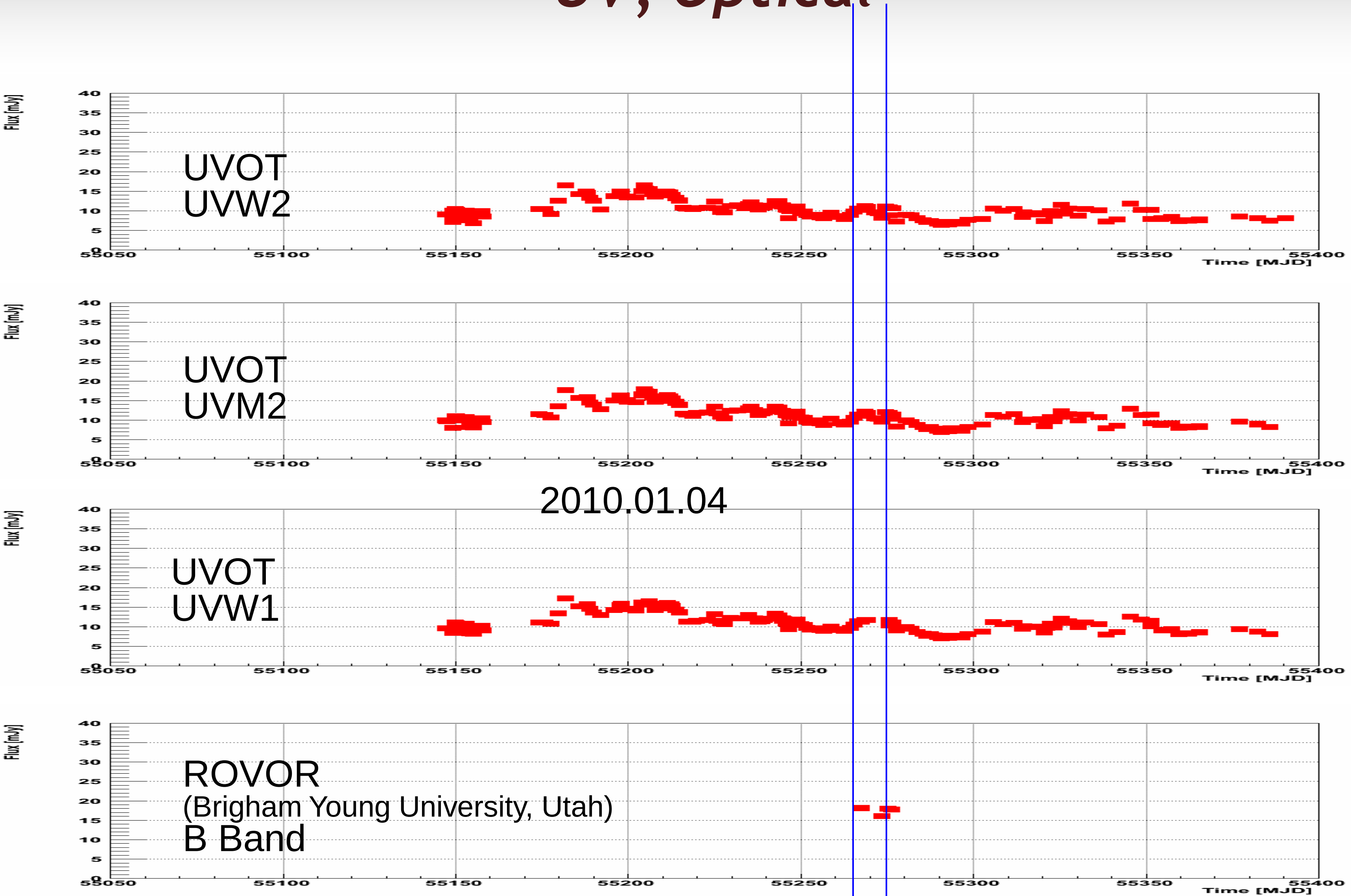
Mrk421 MW light curves: Xrays



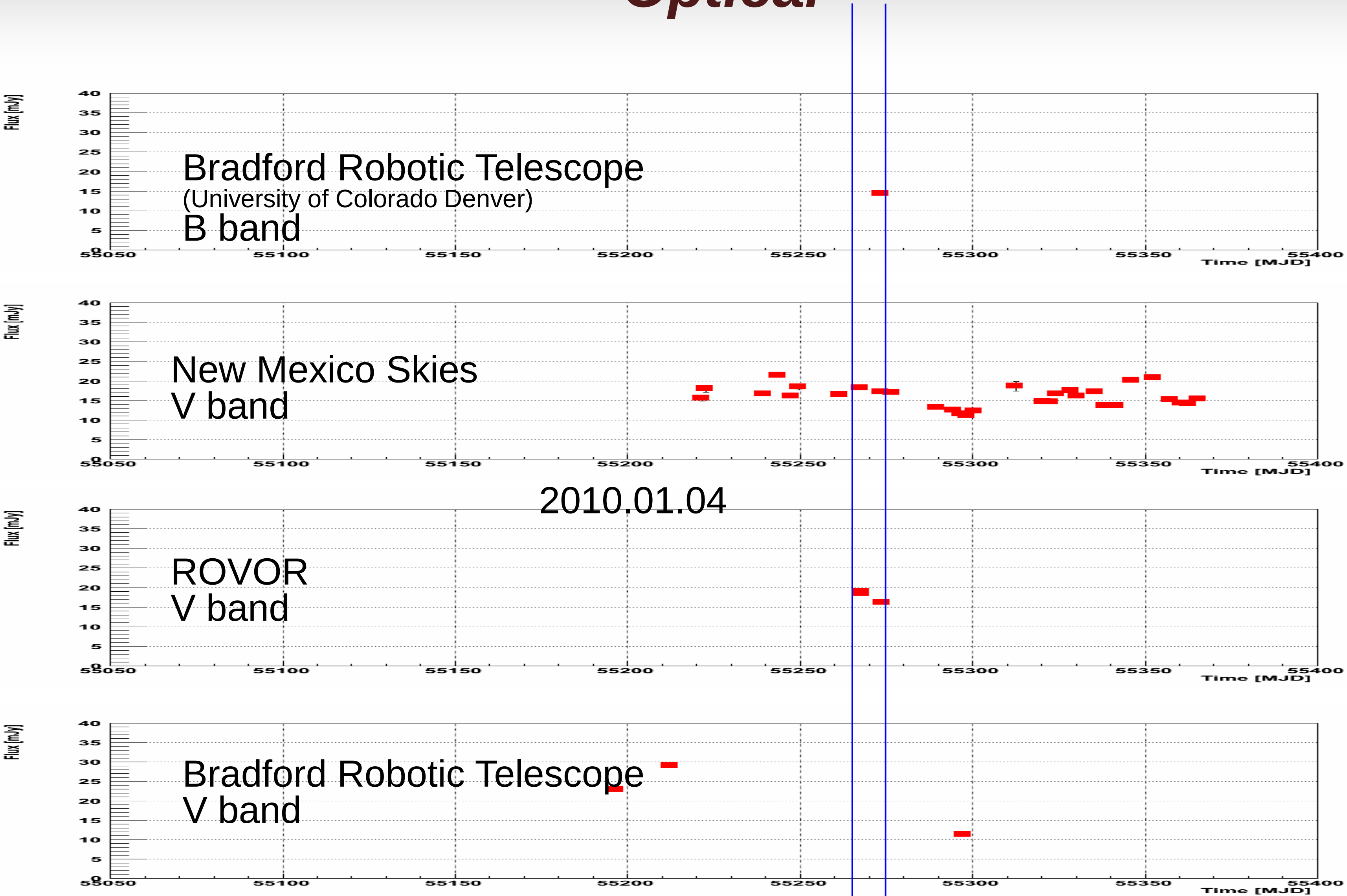
Mrk421 MW light curves: Xrays



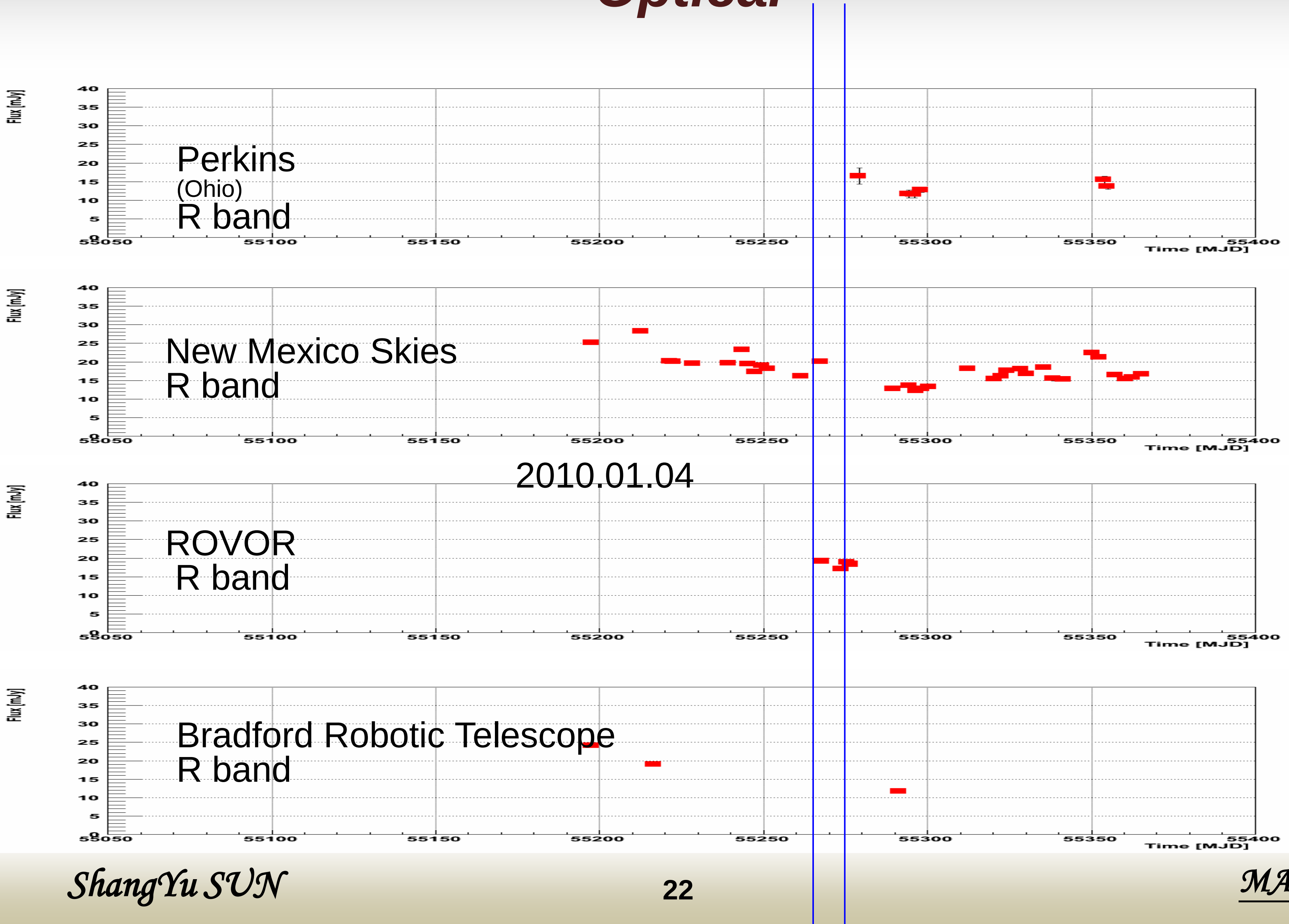
Mrk421 MW light curves: UV, Optical



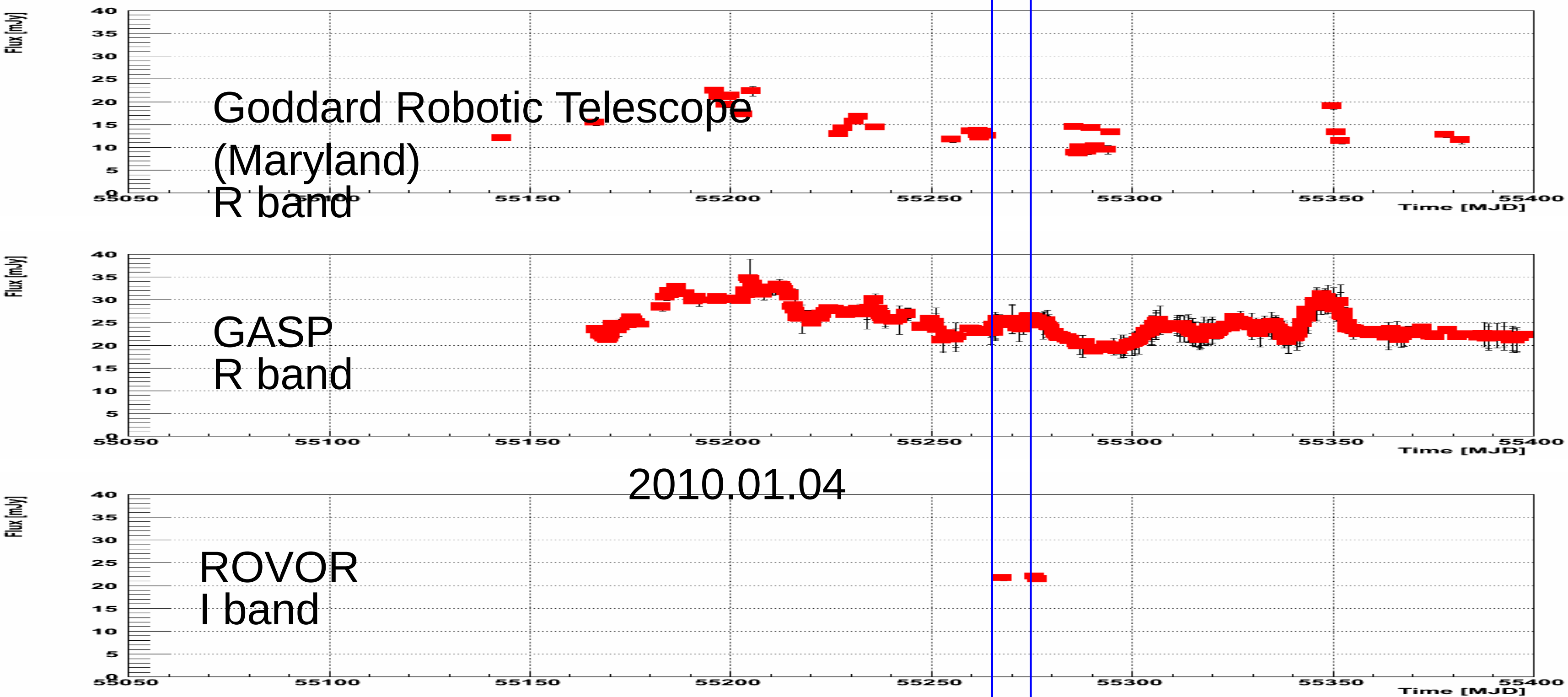
Mrk421 MW light curves: Optical



Mrk421 MW light curves: Optical

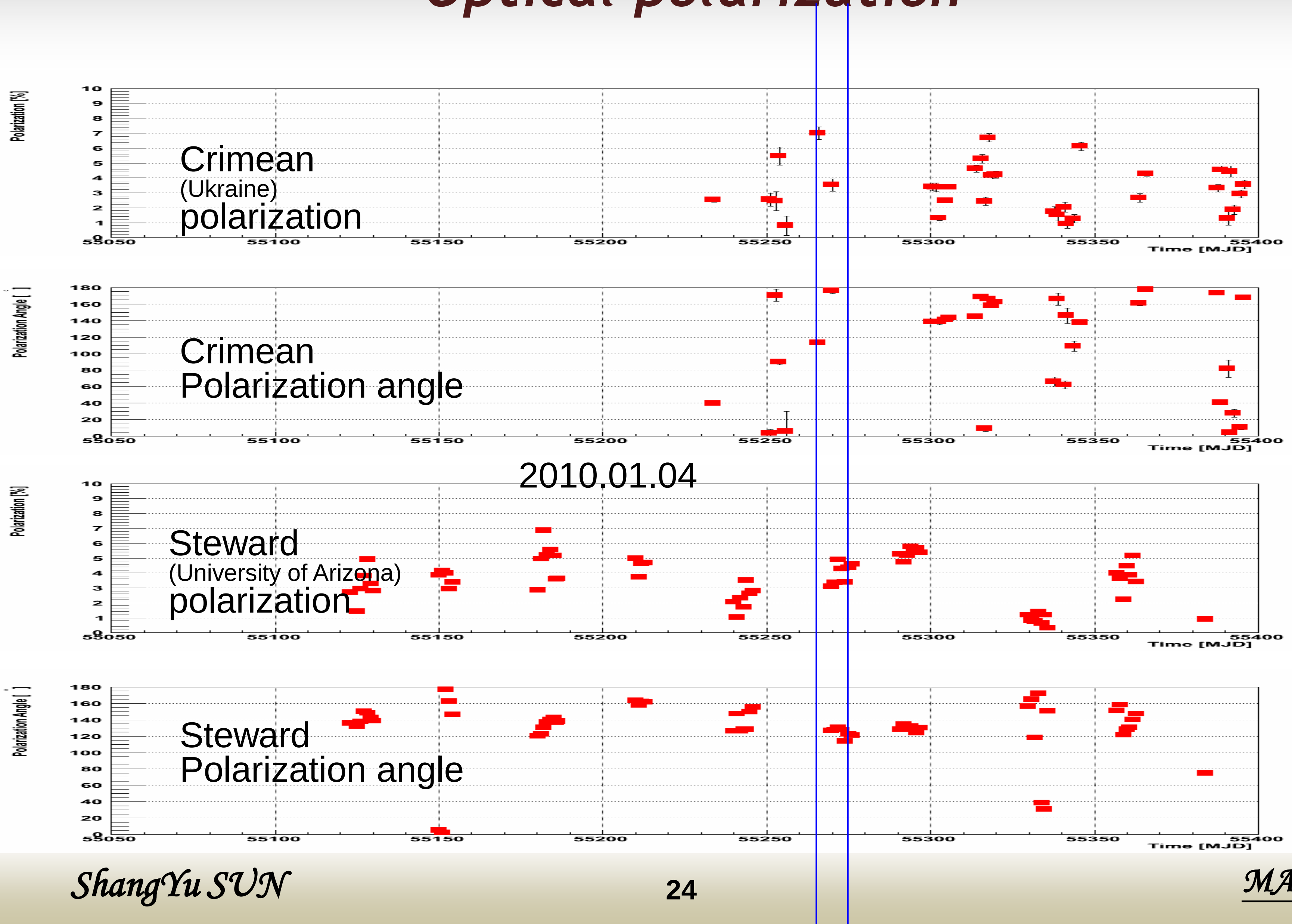


Mrk421 MW light curves: Optical

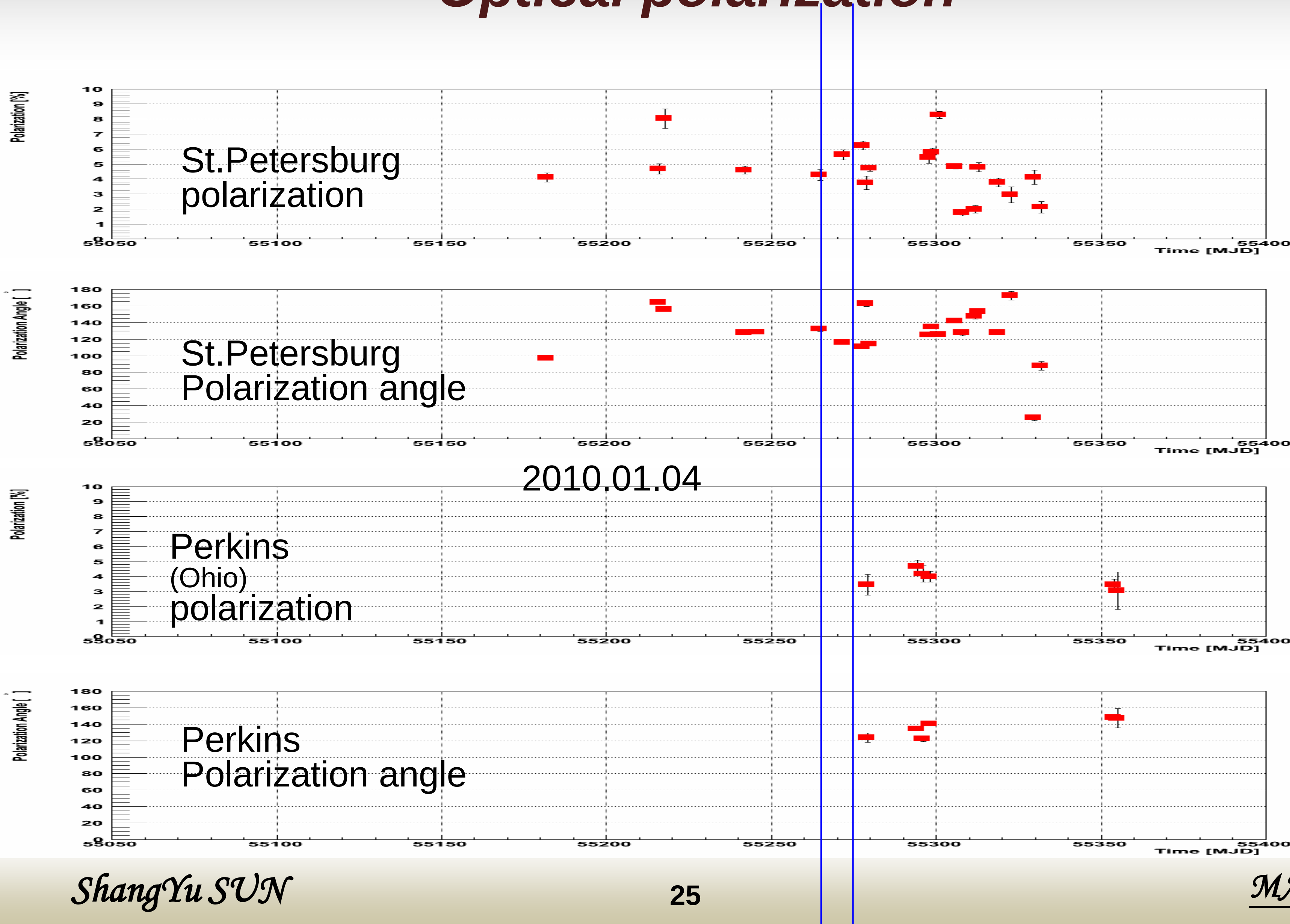


The GLAST-AGILE Support Program (GASP)

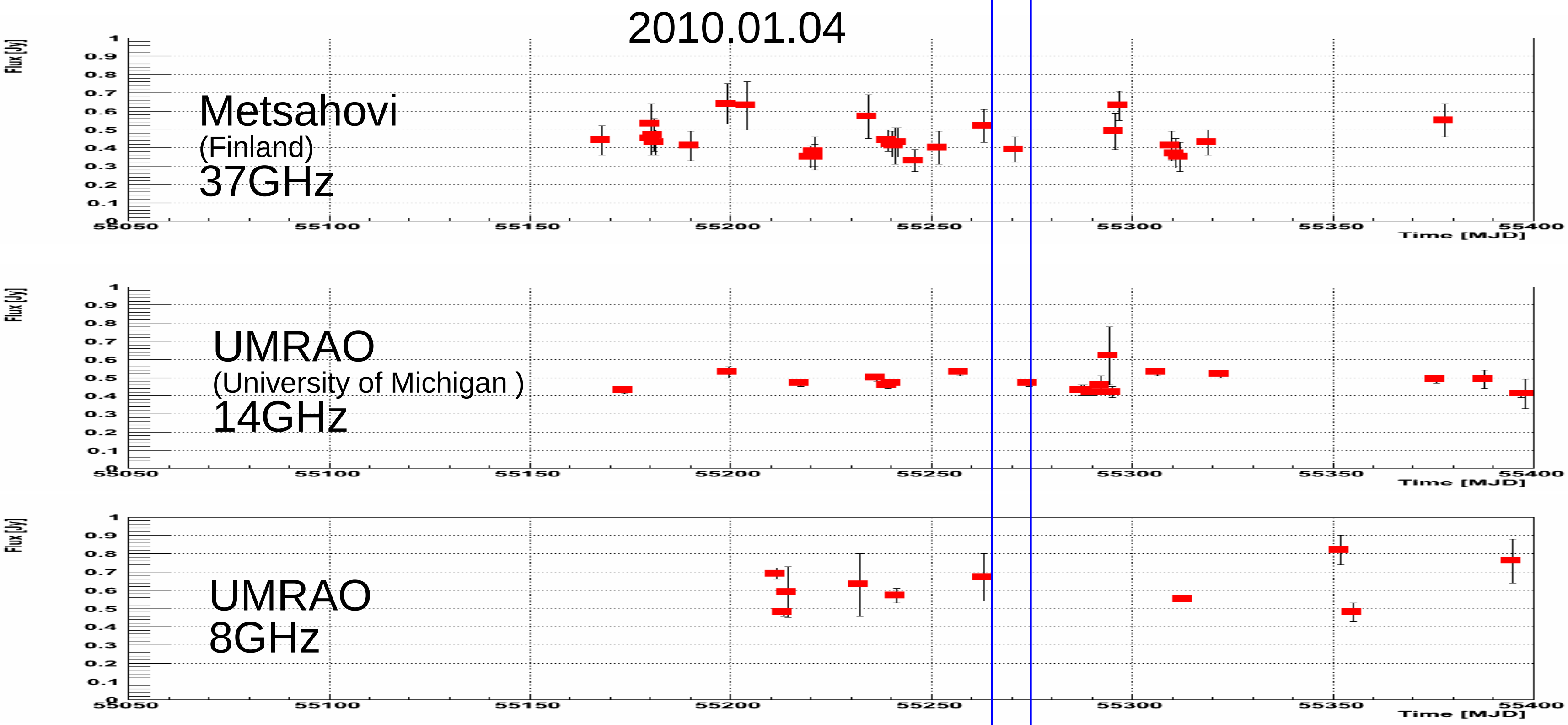
Mrk421 MW light curves: Optical polarization



Mrk421 MW light curves: Optical polarization



Mrk421 MW light curves: Radio



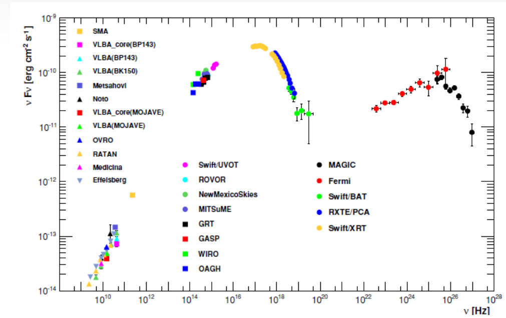
Mrk421 2010 MW Light Curve Variability

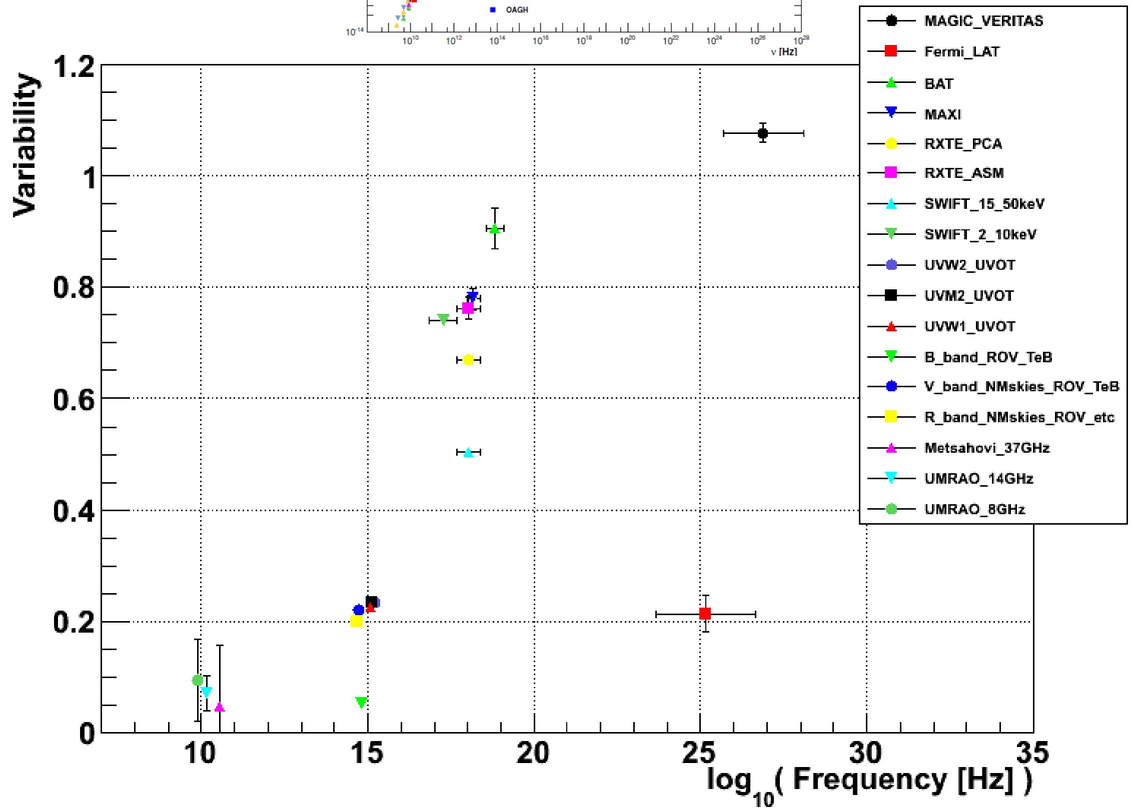
Variability: the quantity showing how much each light curve fluctuates

Variability

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

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





Time Correlations between Light Curves

Why to study time correlation

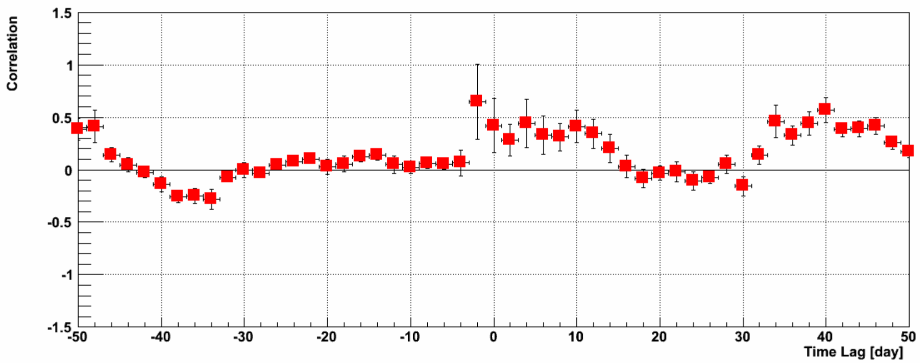
- Goal: to know which AGN structure or emission mechanism the observed photons of different energy correspond to

- Spatial resolution is bad=>different emission mechanisms are mixed

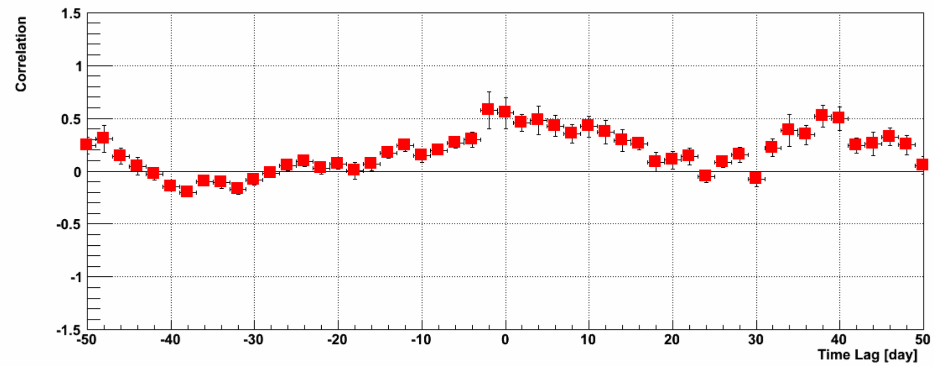
- We try to use time resolution to find how correlated each pair of energy bands =>high correlated energy bands imply the same emission mechanism

Mrk421 2010 Correlation

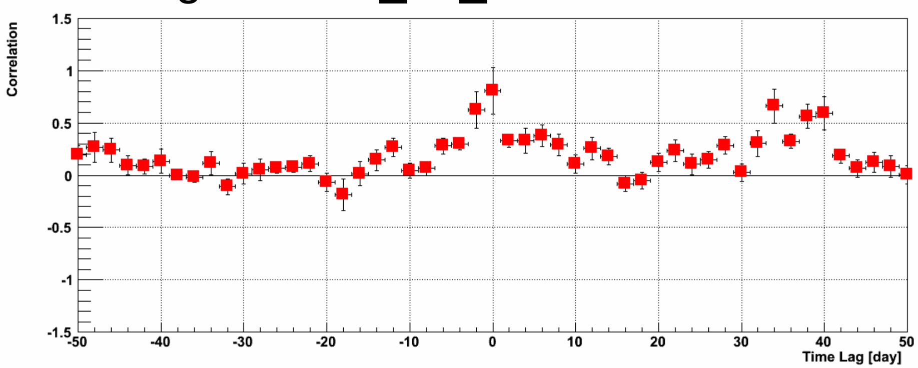
Lag=MAXI-MAGIC



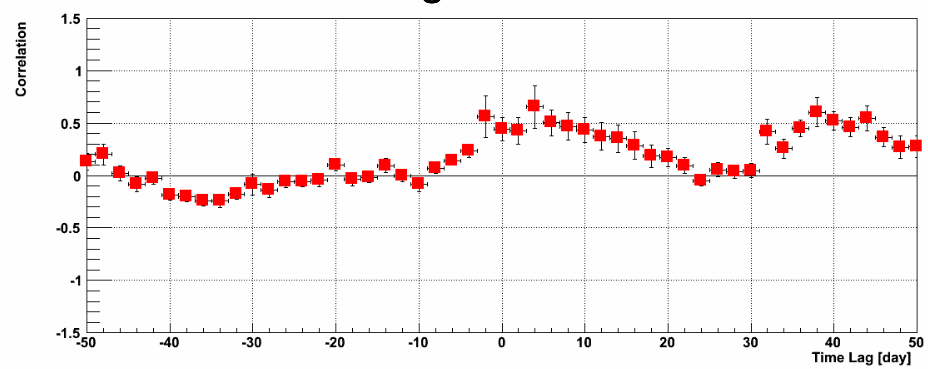
Lag=ASM-MAGIC



Lag=SWIFT_15_50keV-MAGIC

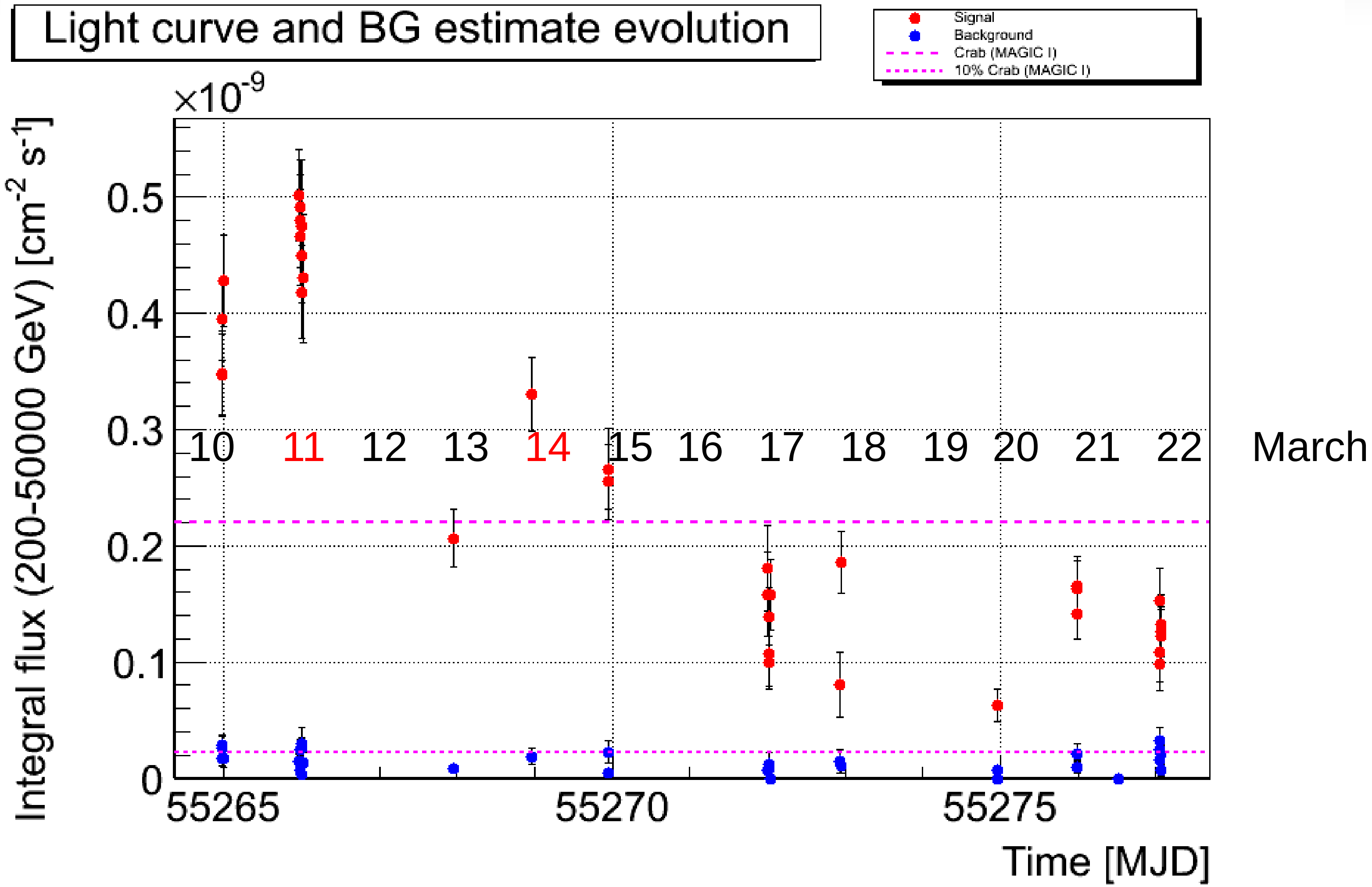


Lag=BAT-MAGIC

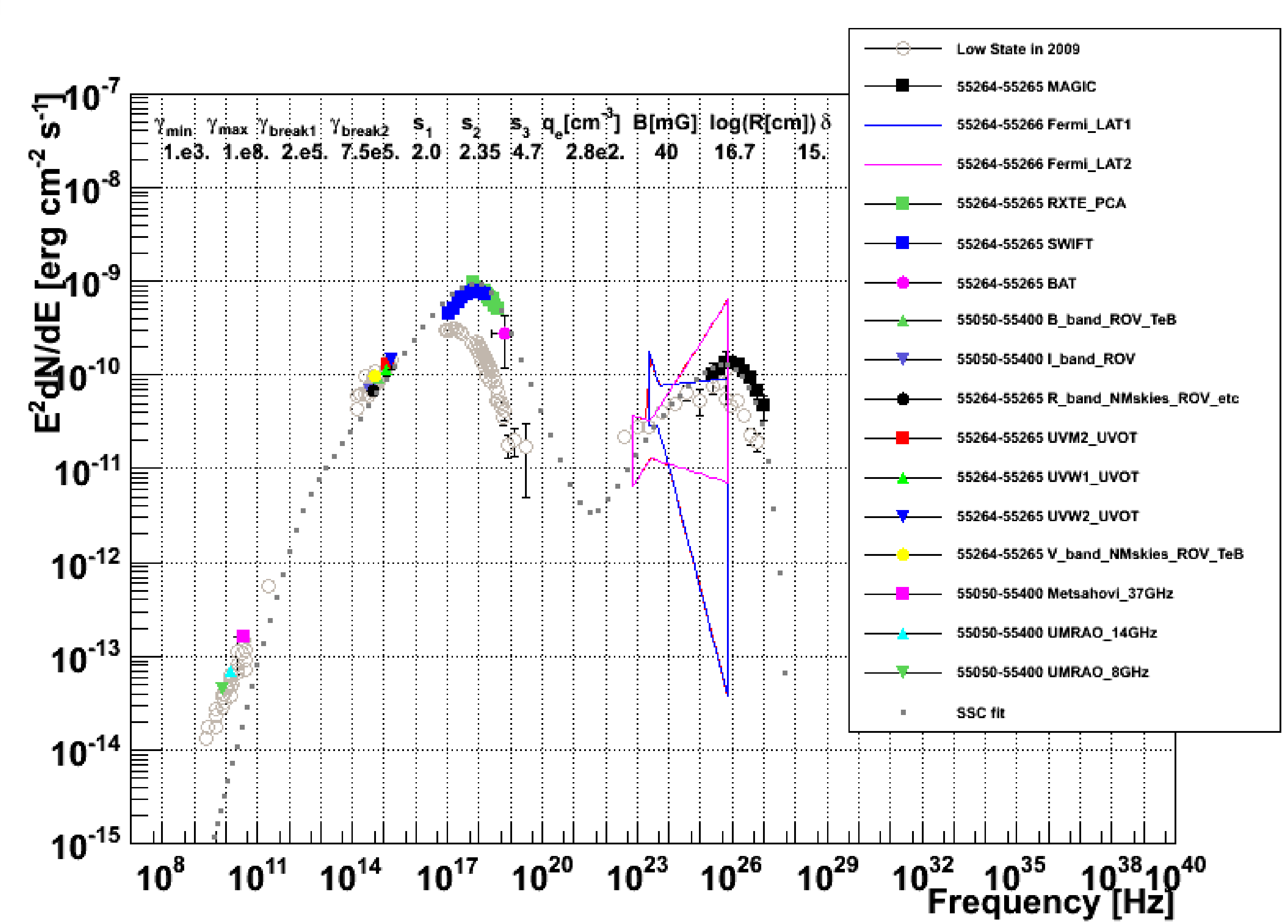


TeV emission are most correlated with Xray emission!

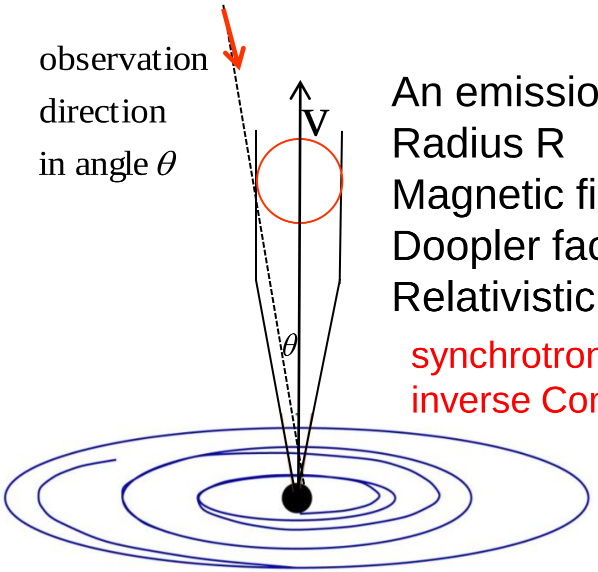
Mrk421 2010 March Light Curve



Mrk421 MW 2010_03_10



Describe Spectra with Synchrotron Self-Compton Model



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

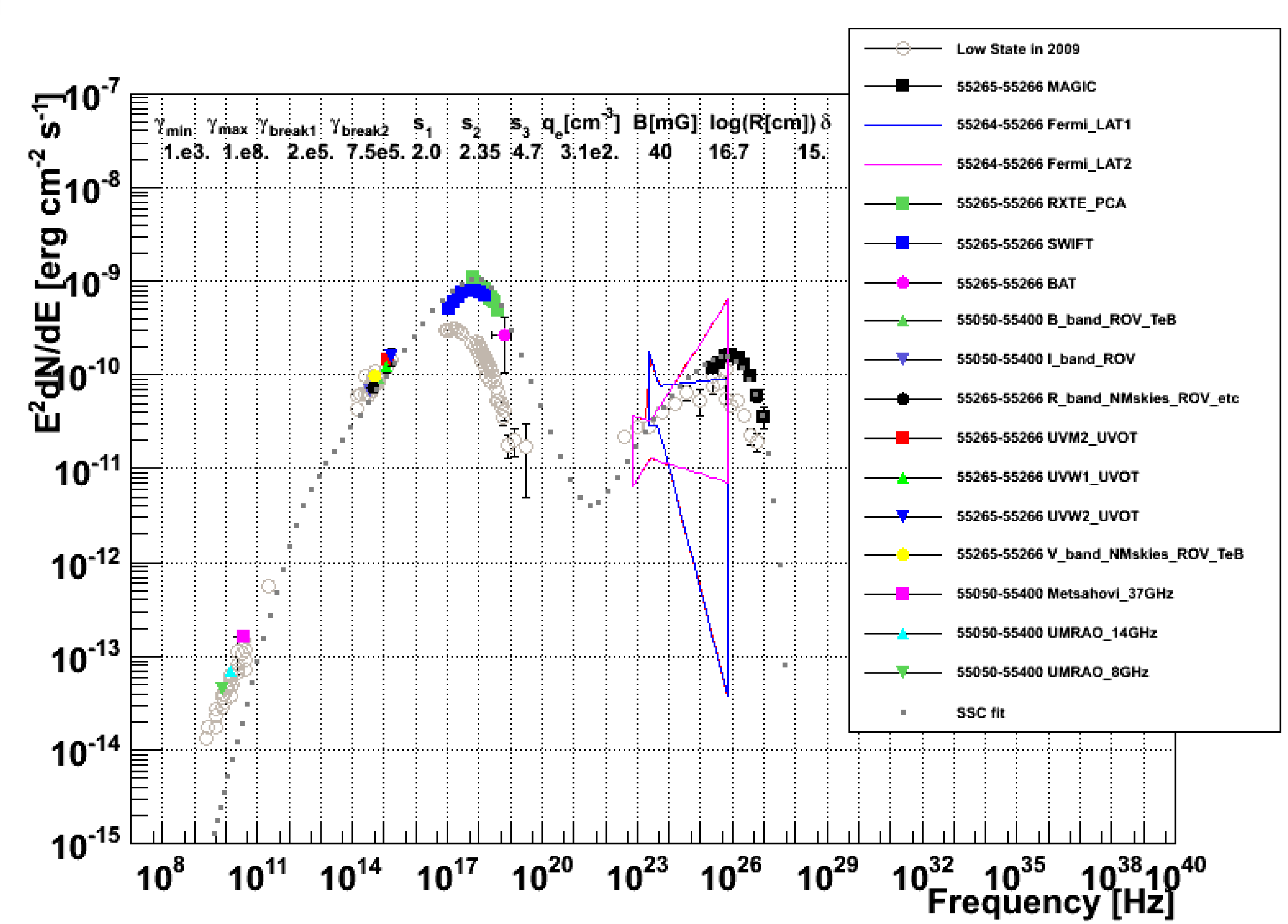
synchrotron radiation=>Xray,
inverse Compton process=>GammaRay

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

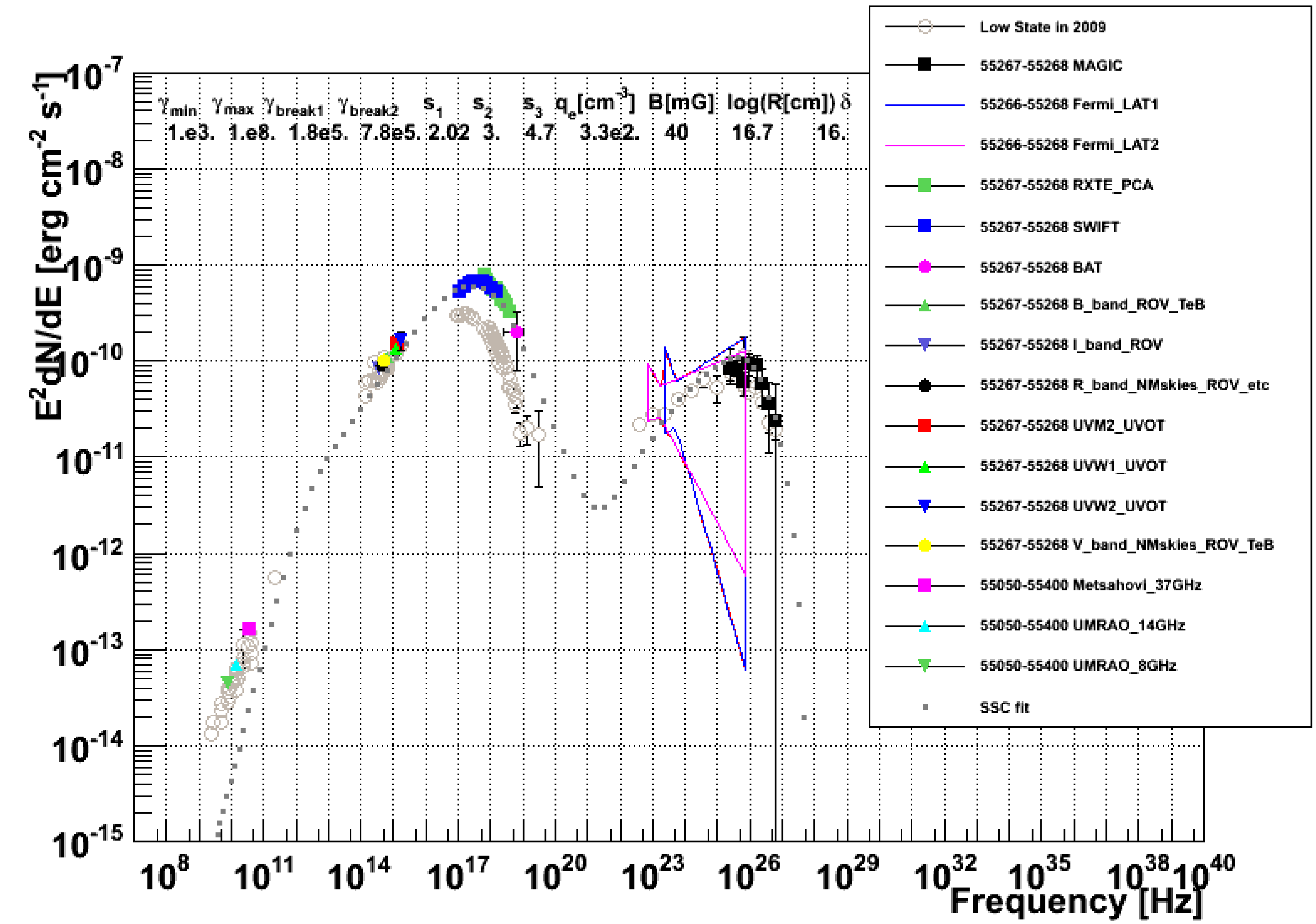
electron injection spectrum $(n_e, s_1, s_2, s_3, \gamma_{\min}, \gamma_{break1}, \gamma_{break2}, \gamma_{\max})$

$$\frac{dN}{d\gamma} = \begin{cases} (\,for\ \gamma_{\min} < \gamma < \gamma_{break1})\ n_e \gamma^{-s_1} \\ (\,for\ \gamma_{break1} < \gamma < \gamma_{break2})\ n_e \gamma^{-s_2} \gamma_{break1}^{s_2-s_1} \\ (\,for\ \gamma_{break2} < \gamma < \gamma_{\max})\ n_e \gamma^{-s_3} \gamma_{break2}^{s_3-s_2} e^{-\gamma/\gamma_{\max}} e^{-\gamma_{break2}/\gamma_{\max}} \end{cases}$$

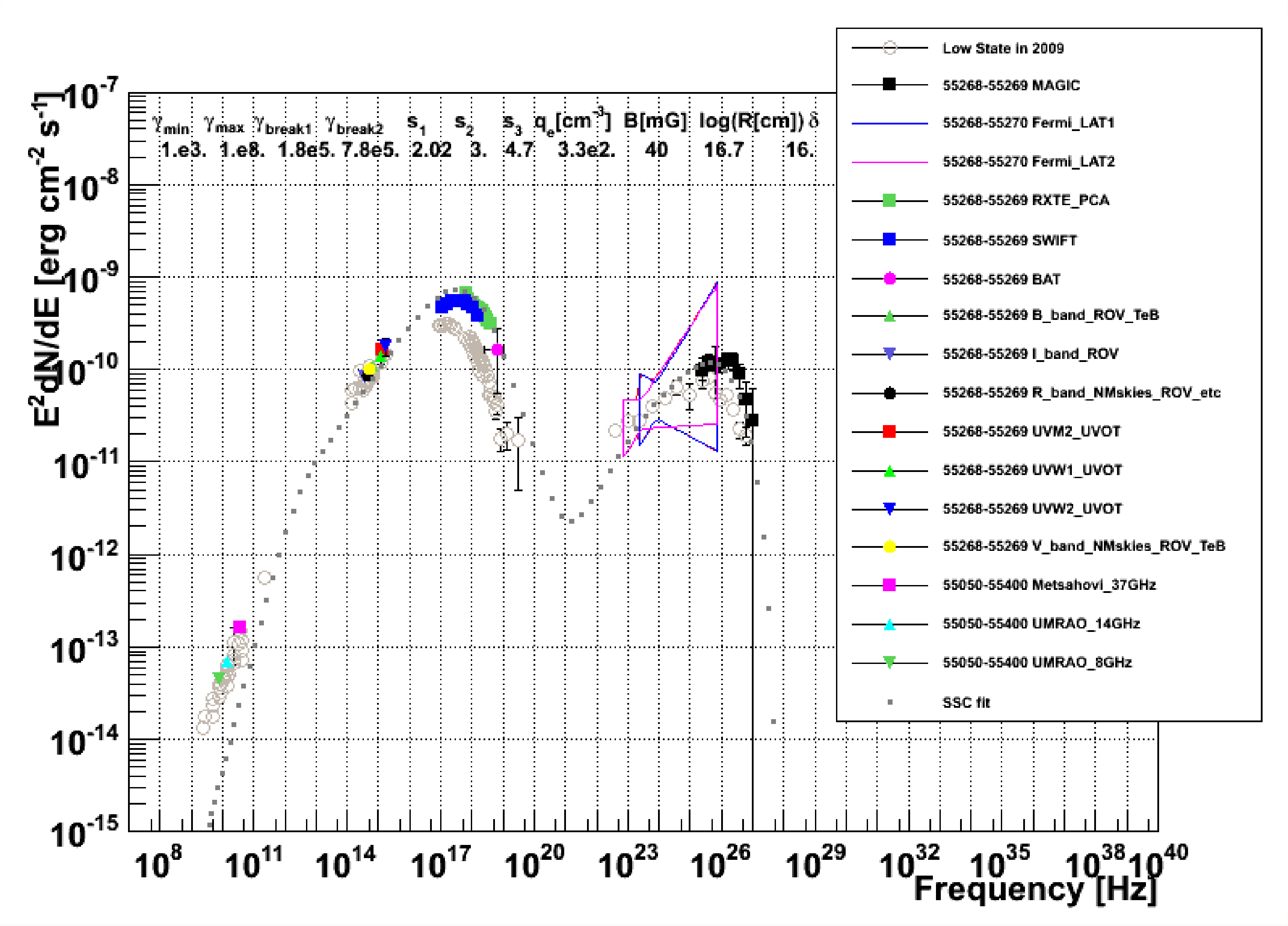
Mrk421 MW 2010_03_11



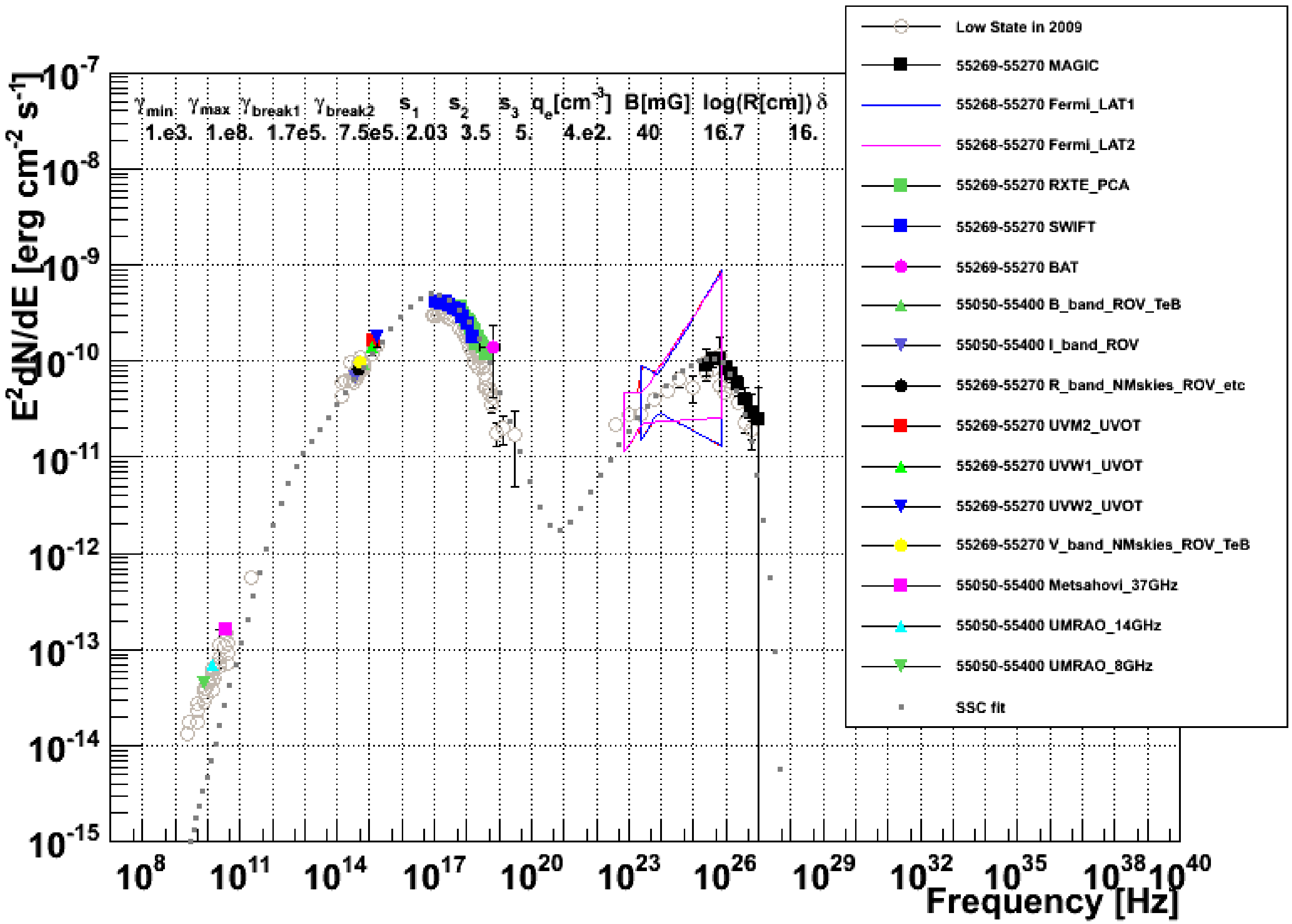
Mrk421 MW 2010_03_13



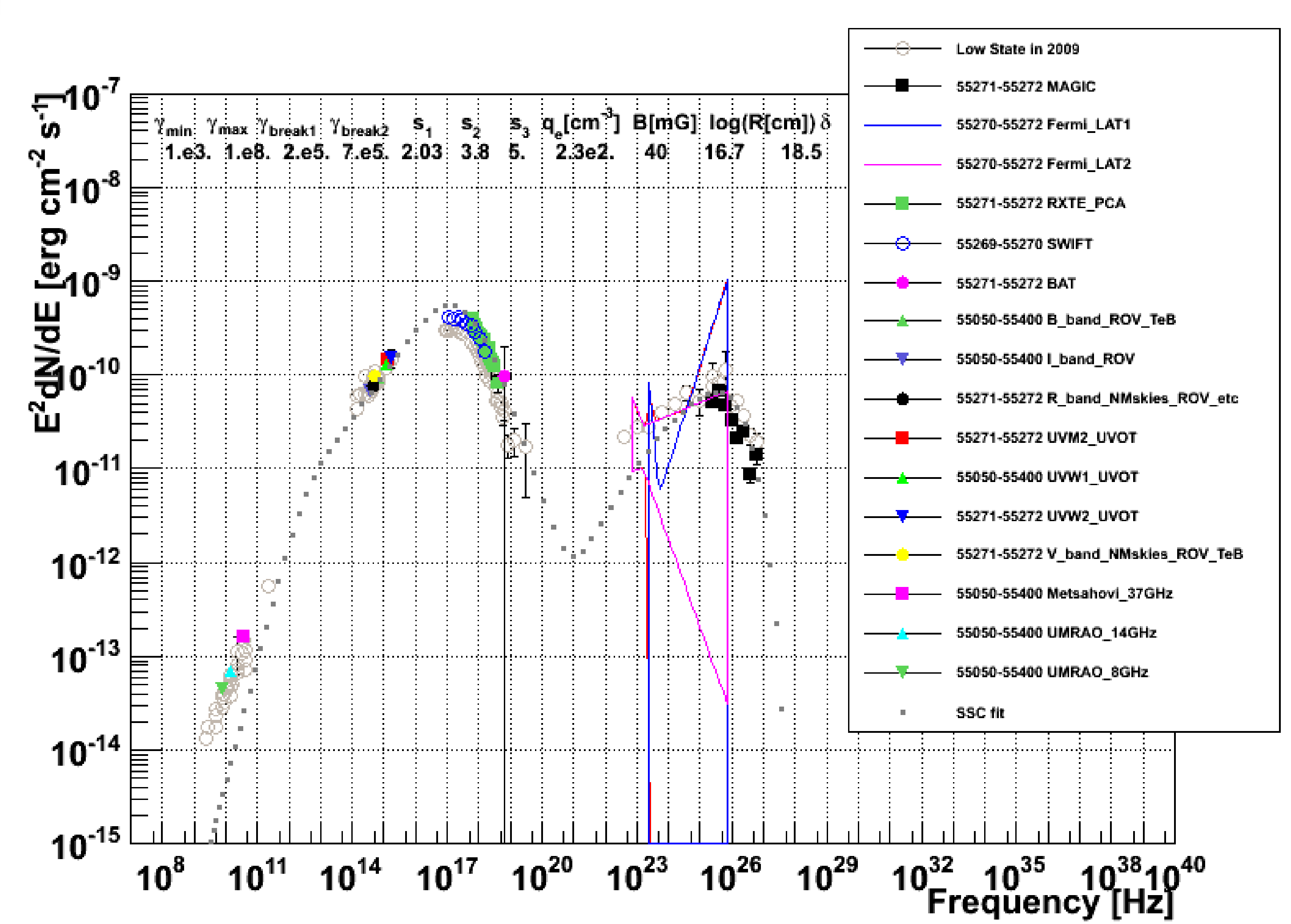
Mrk421 MW 2010_03_14



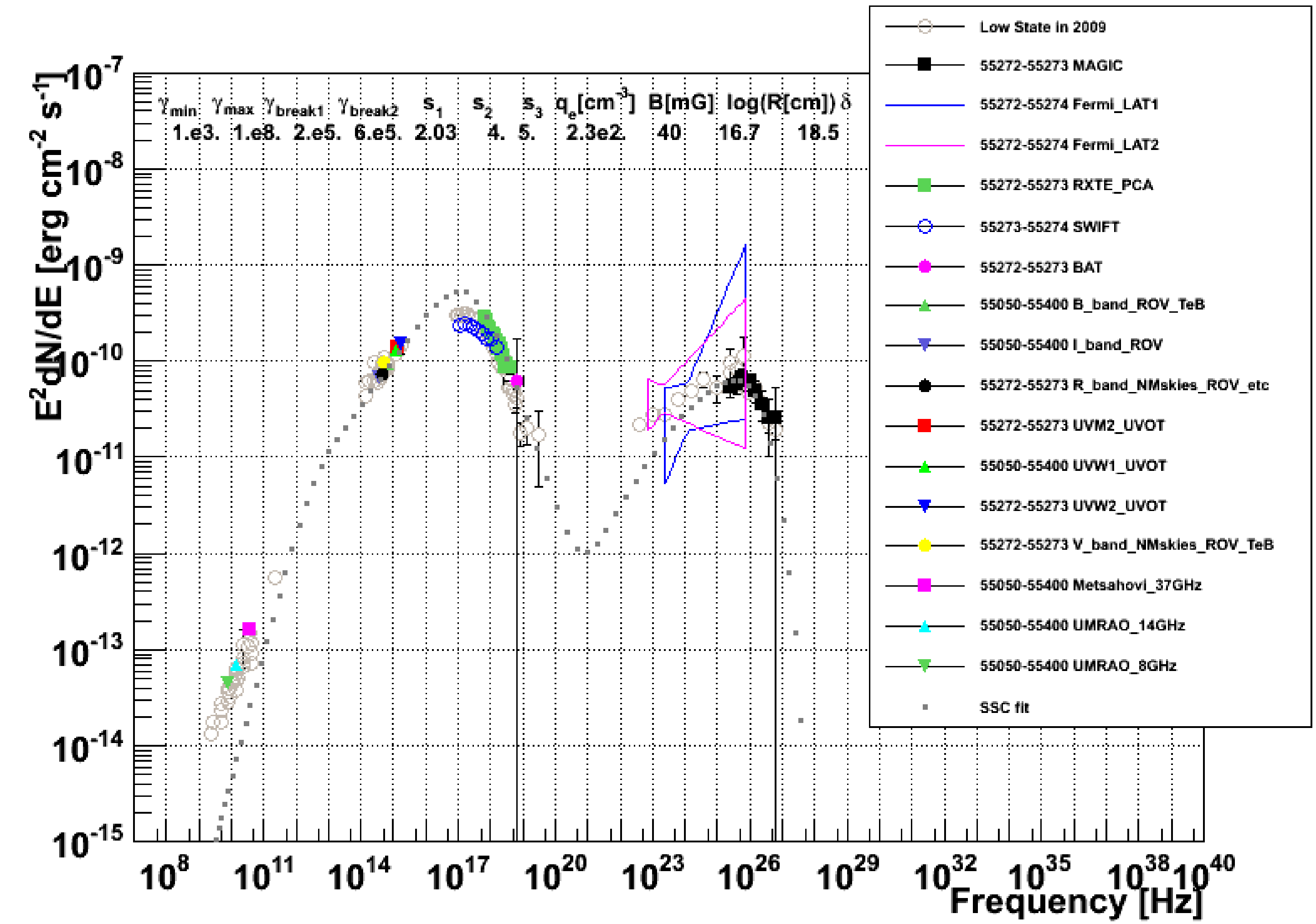
Mrk421 MW 2010_03_15



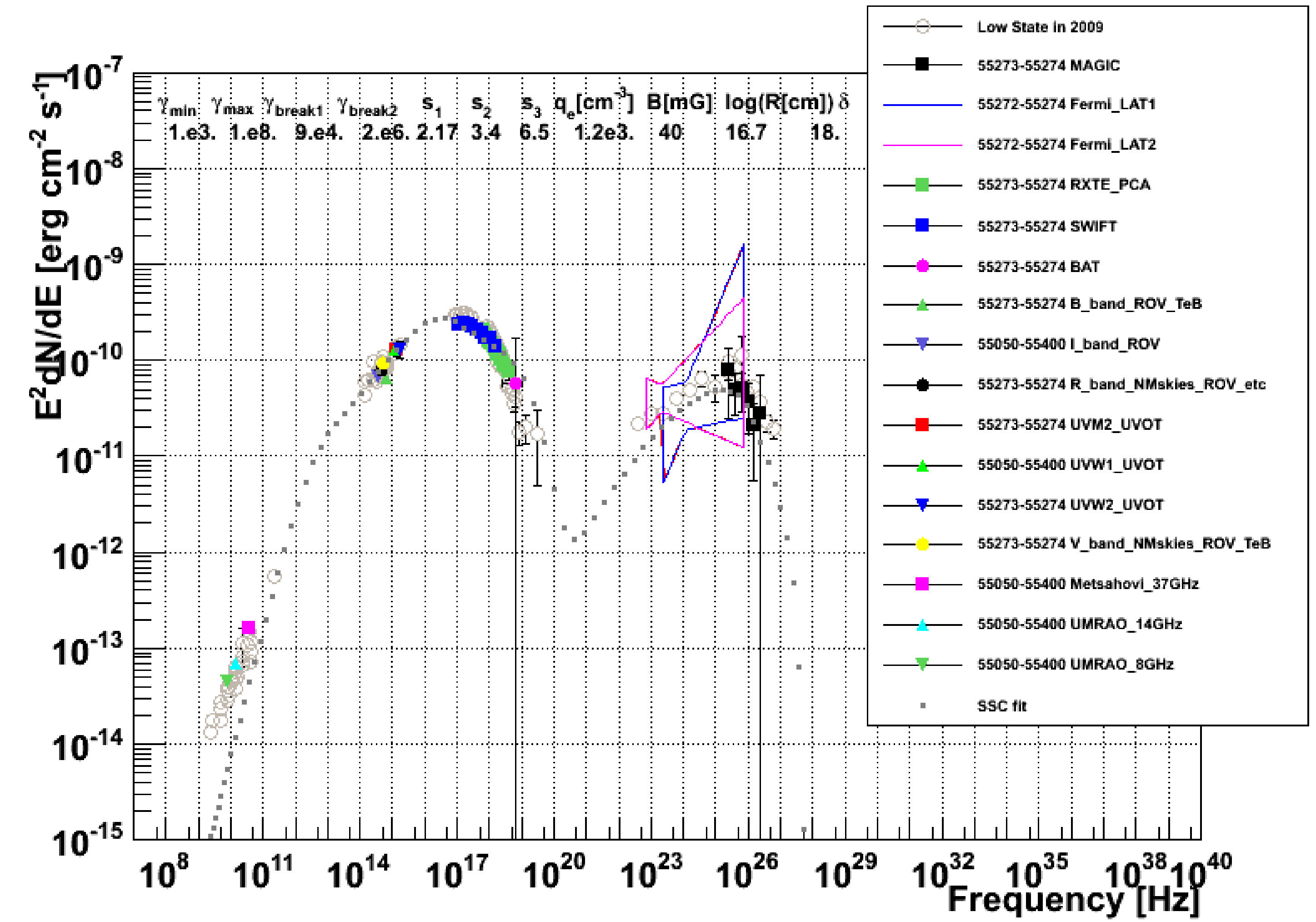
Mrk421 MW 2010_03_17



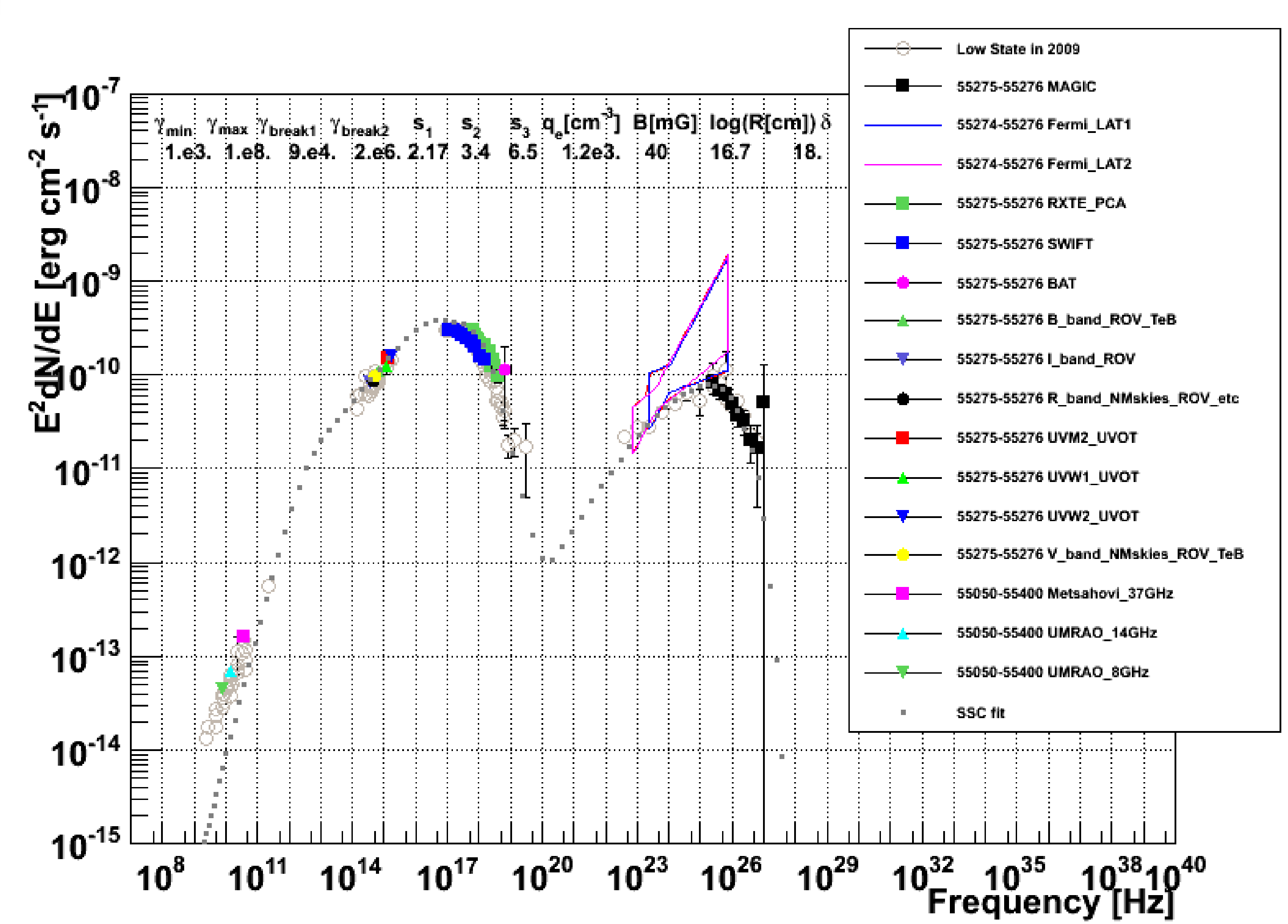
Mrk421 MW 2010_03_18



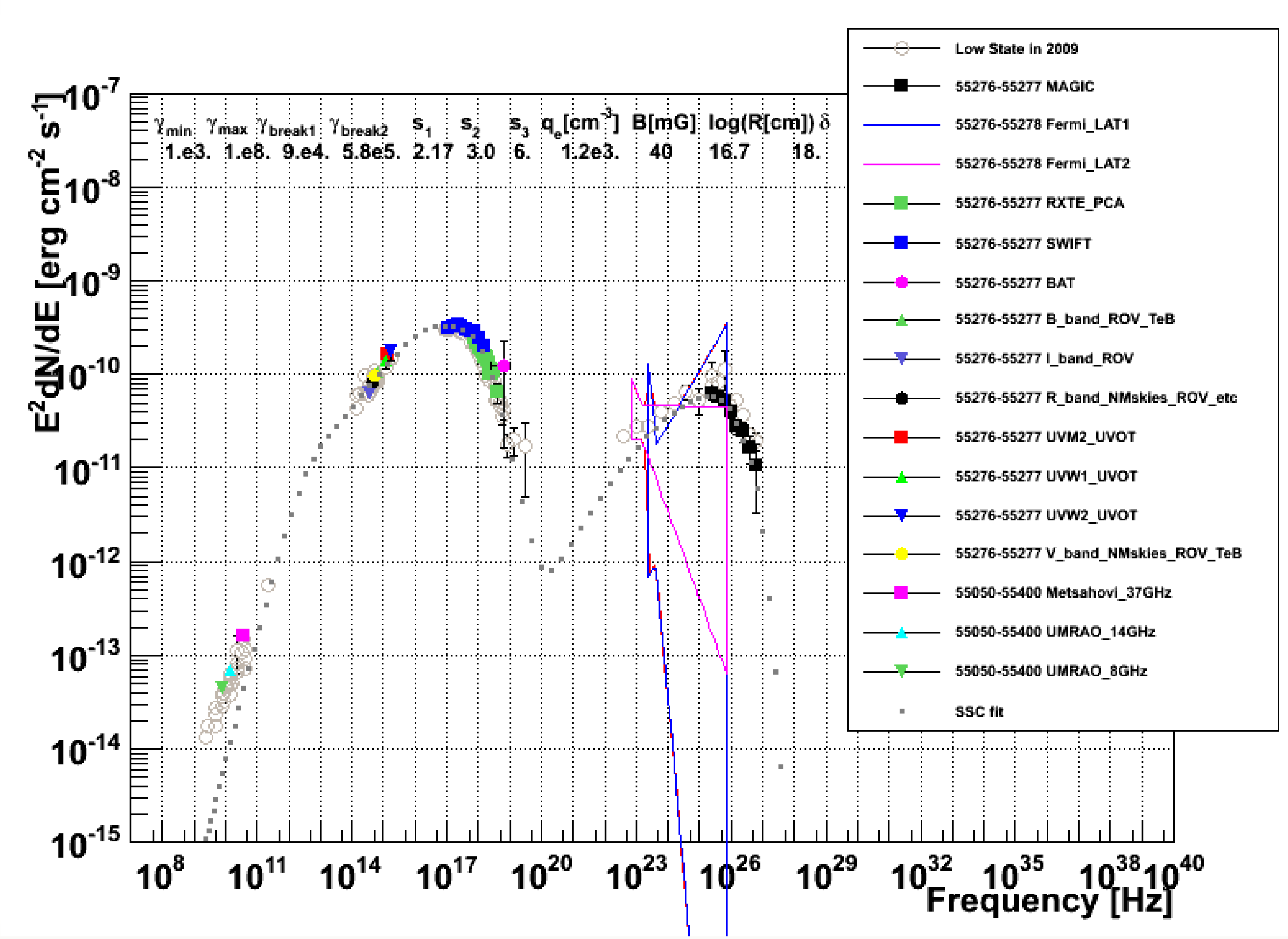
Mrk421 MW 2010_03_19



Mrk421 MW 2010_03_21



Mrk421 MW 2010_03_22



Describe Spectra with Synchrotron Self-Compton Model

	$\gamma_{\min}$,	$\gamma_{\max}$,	γ_{break1},	γ_{break2},	S_1,	S_2,	S_3,	n_e[cm^{-3}],	B[mG],	log(R[cm]),	δ
03_10	1.e3.	1.e8.	2. e5.	7.5e5.	2.0	2.35	4.7	2.8e2.	40	16.7	15.
03_11	1.e3.	1.e8.	2. e5.	7.5e5.	2.0	2.35	4.7	3.1e2.	40	16.7	15.
03_13	1.e3.	1.e8.	1.8e5.	7.8e5.	2.02	3.	4.7	3.3e2.	40	16.7	16.
03_14	1.e3.	1.e8.	2.2e5.	8. e5.	2.02	3.	5.	3.3e2.	40	16.7	16.
03_15	1.e3.	1.e8.	1.7e5.	7.5e5.	2.03	3.5	5.	4. e2.	40	16.7	16.
03_17	1.e3.	1.e8.	2. e5.	7. e5.	2.03	3.8	5.	2.3e2.	40	16.7	18.5
03_18	1.e3.	1.e8.	2. e5.	6. e5.	2.03	4.	5.	2.3e2.	40	16.7	18.5
03_19	1.e3.	1.e8.	9. e4.	2. e6.	2.17	3.4	6.5	1.2e3.	40	16.7	18.
03_20	1.e3.	1.e8.	9. e4.	5.8e5.	2.17	3.1	6.	1.2e3.	40	16.7	18.
03_21	1.e3.	1.e8.	9. e4.	5.8e5.	2.17	3.0	6.	1.4e3.	40	16.7	18.
03_22	1.e3.	1.e8.	9. e4.	5.8e5.	2.17	3.0	6.	1.2e3.	40	16.7	18.

It suggests:

The physical properties which changes during flare might be the intrinsic characteristics of electrons, rather than the environment parameters(B,R).

Summary

1. Mrk 421 is cosmologically local blazar, with average TeV flux ~0.5 Crab, can be detected with 5 sigma by MAGIC stereo(sensitivity ~0.8 Crab), in ~3 minutes, and its TeV spectra can be resolved in ~15 minutes.

2. MAGIC in its first year(2010) of stereo observation on Mrk 421 caught three TeV flares: January (~3 Crab), March (~2 Crab), May (~1 Crab)

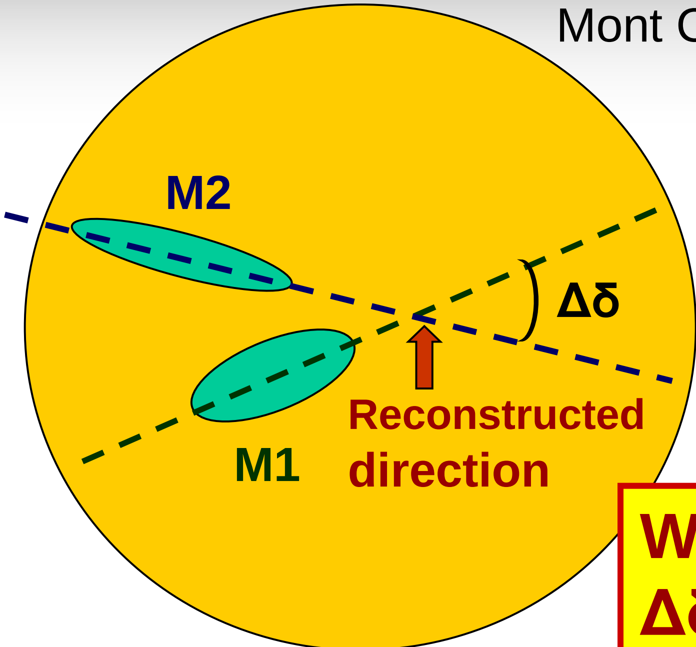
3. Mrk 421 2010 MW light curves: Xray and TeV Gamma ray have the highest variability, ~3 times higher than that of optical and MeV gamma bands. Correlations of {TeV,MeV} and {TeV,Xray} are both >0.5

4. MAGIC stereo had 11 observation on Mrk421 in March 2010, catching its flare state to post-flare state, with fluxes of 4 observations > 1 Crab, with simultaneous spectra from Optical, SWIFT/XRT*BAT, RXTE/ASM, Fermi, MAGIC in 9 observations.

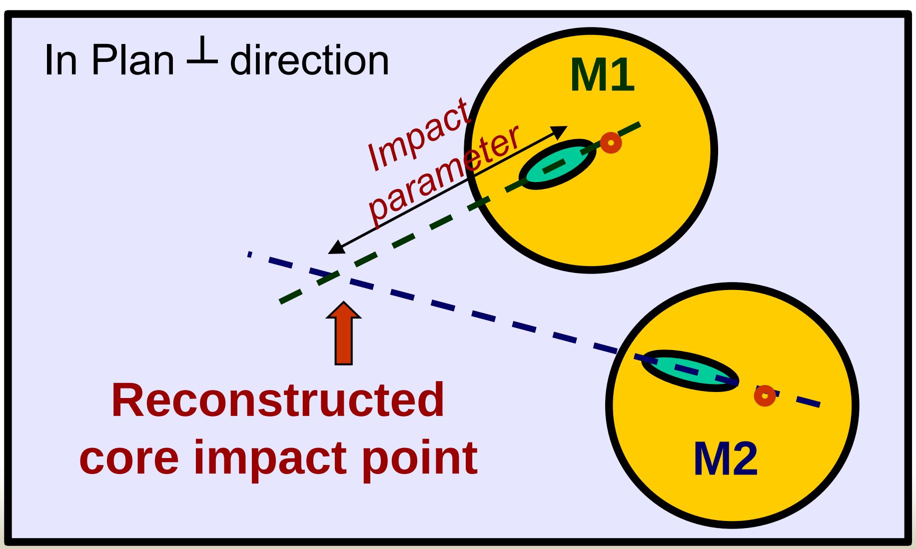
5. Synchrotron Self-Compton Emission Model can describe well Mrk 421 spectrum evolution. The physical properties which changes during flare might be the intrinsic characteristics of electrons, rather than the environment parameters(B,R).

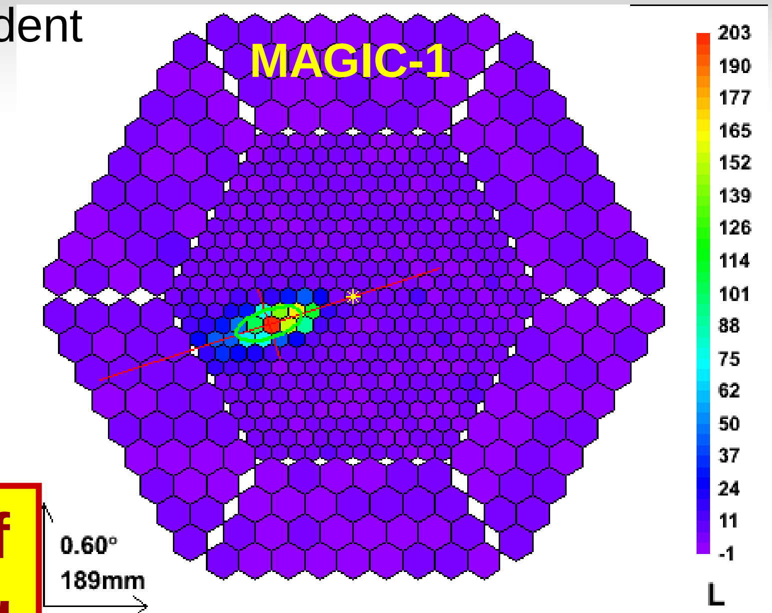
Geometrical reconstruction

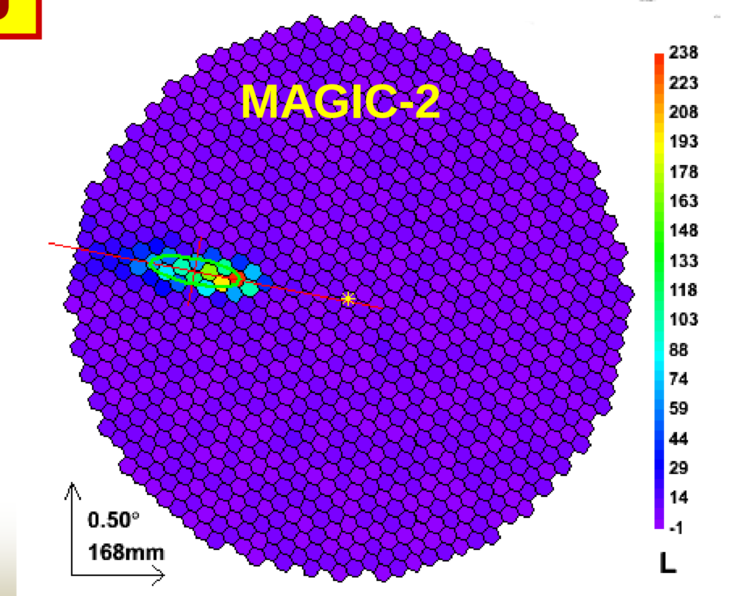
Mont Carlo independent



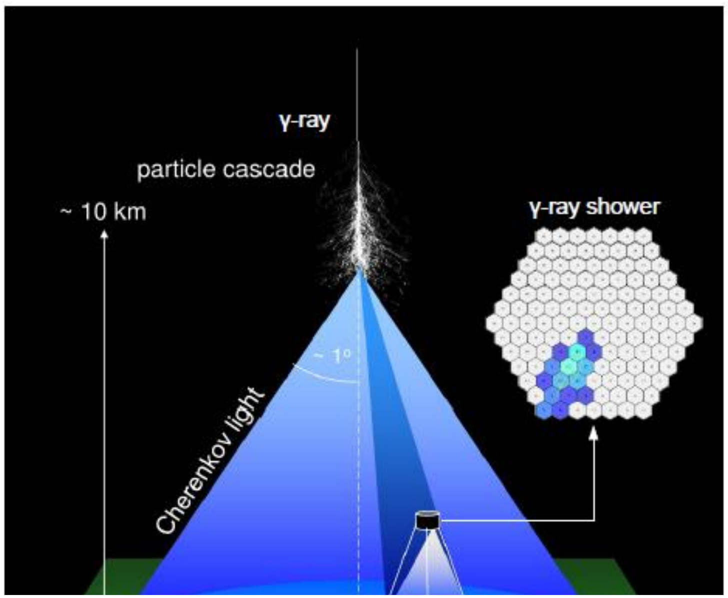
Work well if
$\Delta\delta \geq 30$ deg

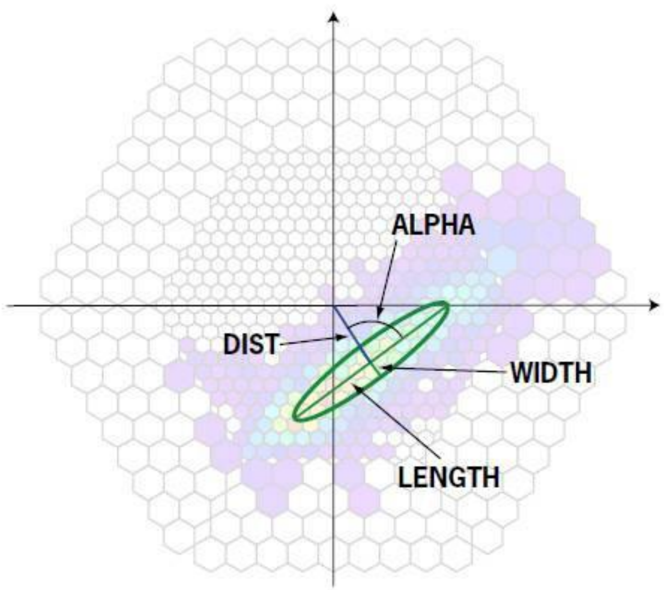


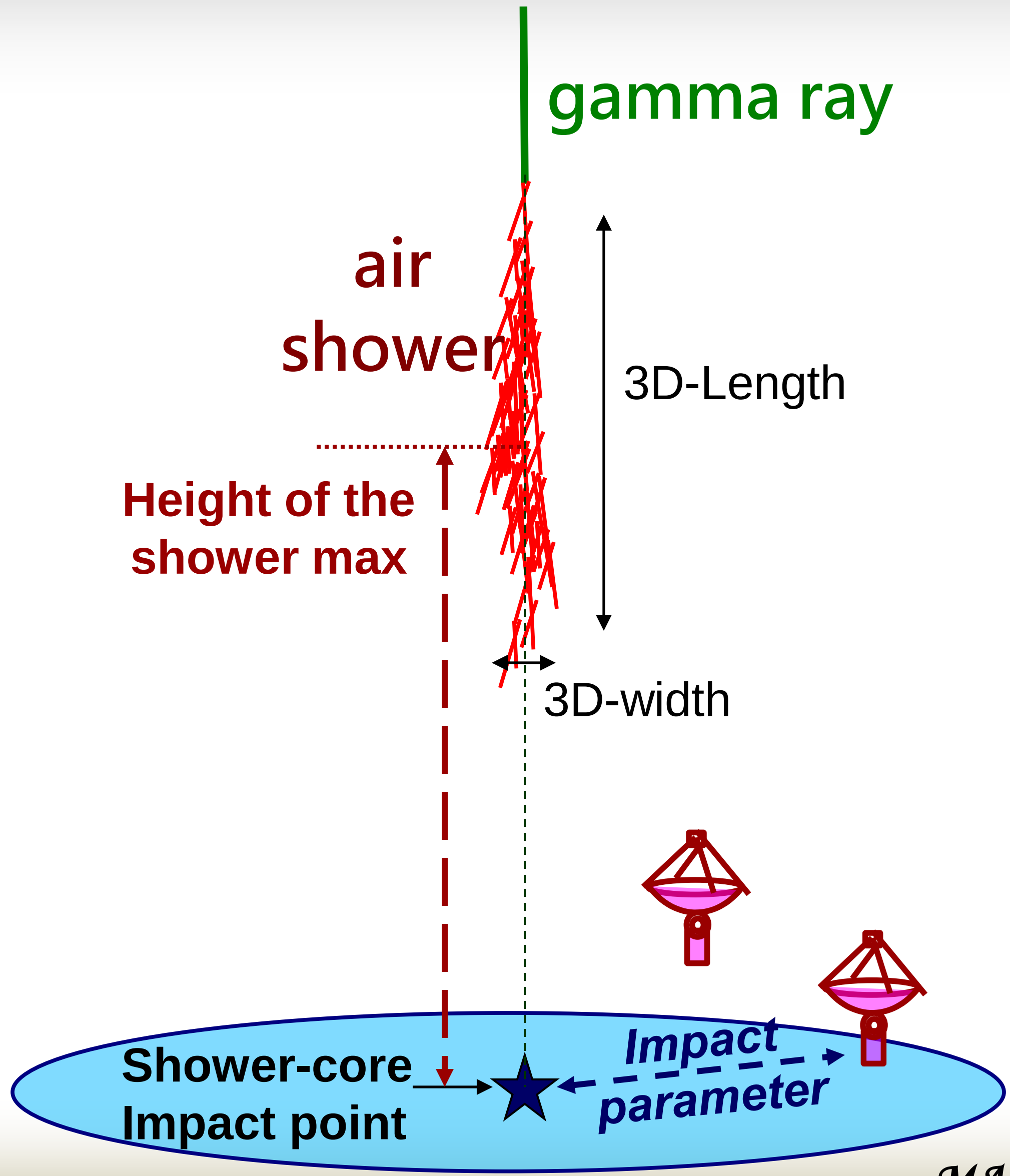




4th step: 3D Parameters

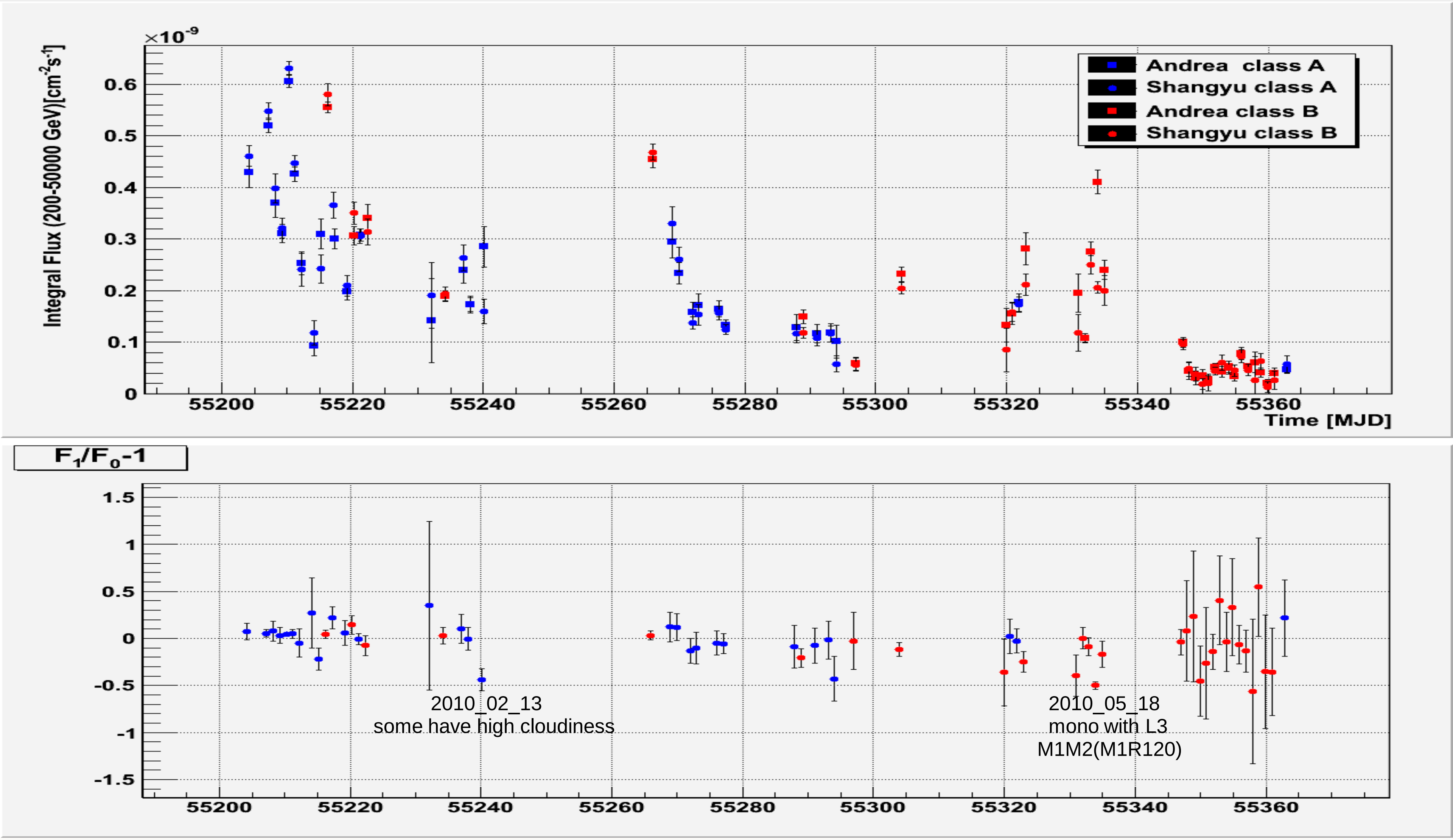






MAGIC

Cross check of light curve



Outlook on Mrk421 2010 MW data analysis

Past MW campaigns

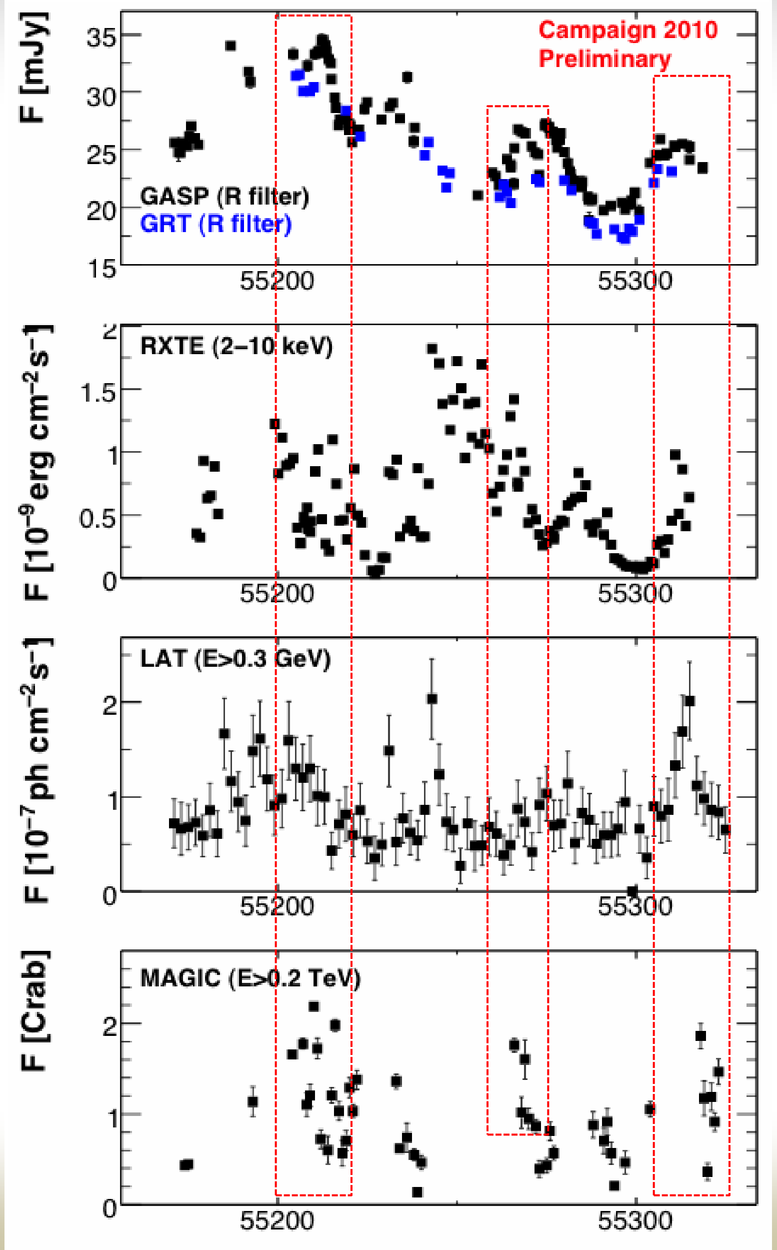
Mrk421 (Jan19th, 2009-Jun1st ,2009: 4.5 months)

Mrk421 (Dec8, 2009-Jun20 ,2010: 6 months)

Mrk421 (Dec1, 2010-Jun15 ,2011: 6 months)

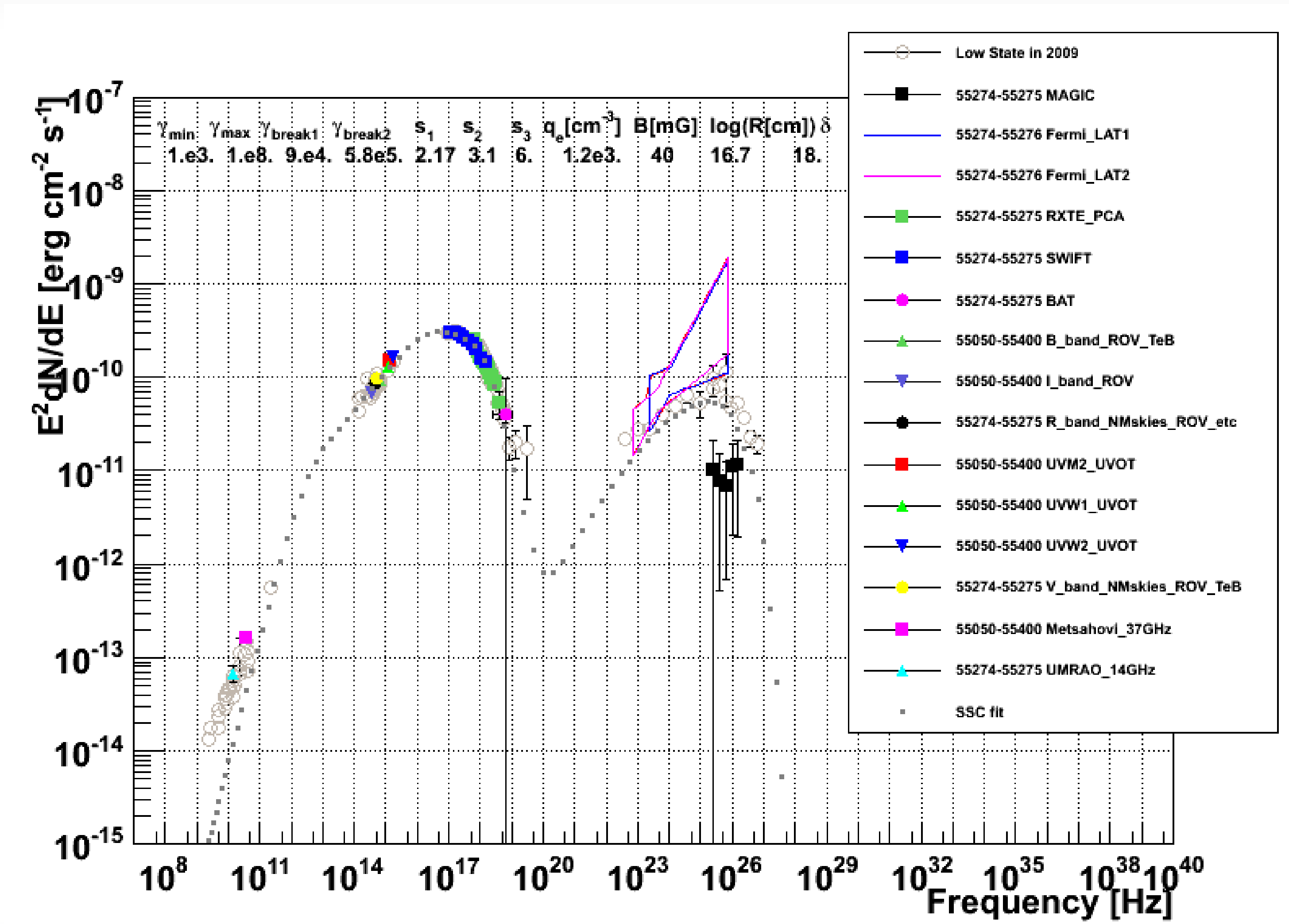
More than 25 instruments participate covering frequencies from radio to TeV

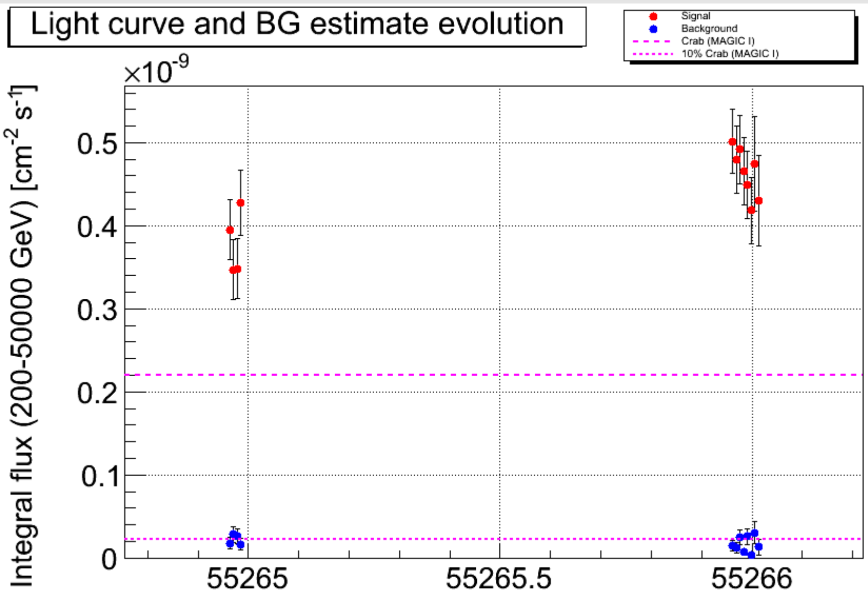
Radio: VLBA, OVRO, Effelsberg, Metsahovi…
mm: SMA, IRAM-PV
Infrared: WIRO, OAGH
Optical: GASP, GRT, MITSuMe, Kanata…
UV: Swift-UVOT
X-ray: Swift-XRT, RXTE-PCA, Swift_BAT
Gamma-ray: Fermi-LAT
VHE: MAGIC, VERITAS, Whipple

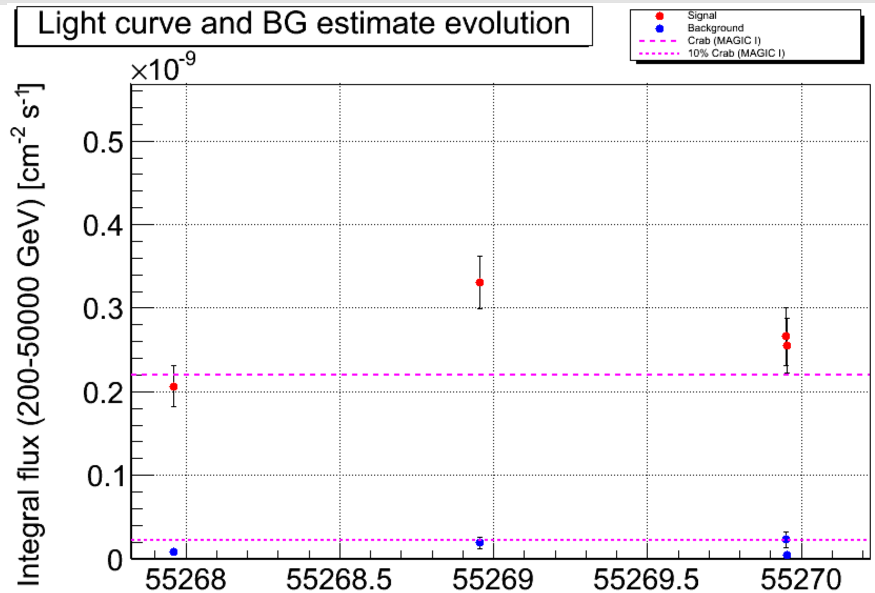


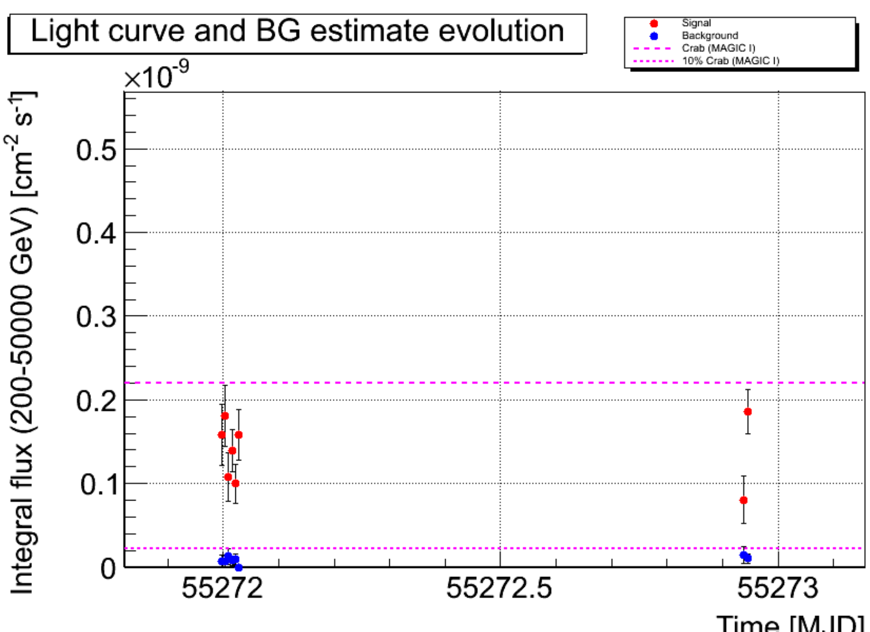
Different flavors of flaring activity will be studied!

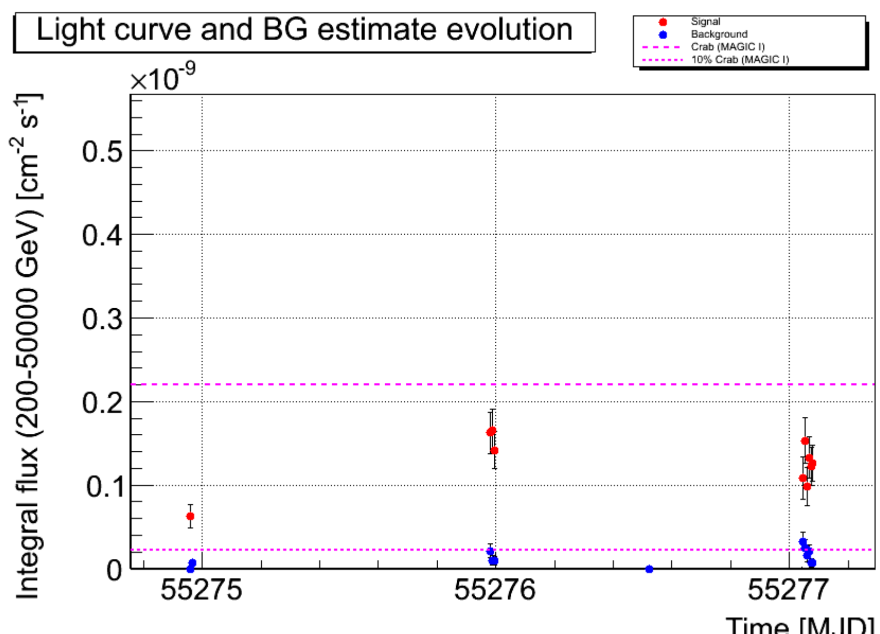
Mrk421 MW 2010_03_20



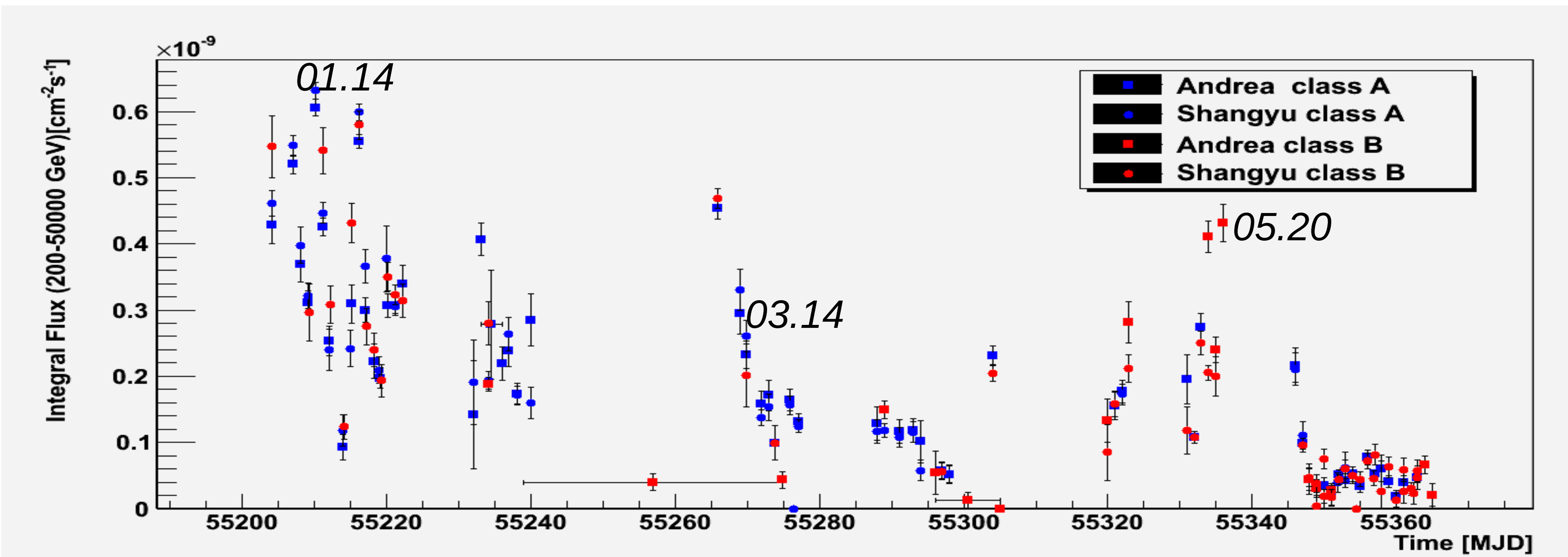

Light curve and BG estimate evolution
Signal
Background
Crab (MAGIC I)
10% Crab (MAGIC I)
Integral flux (200-50000 GeV) [cm^{-2} s^{-1}]
$\times 10^{-9}$
0
0.1
0.2
0.3
0.4
0.5
55265
55265.5
55266


Light curve and BG estimate evolution
Signal
Background
Crab (MAGIC I)
10% Crab (MAGIC I)
Integral flux (200-50000 GeV) [cm^{-2} s^{-1}]
$\times 10^{-9}$
0
0.1
0.2
0.3
0.4
0.5
55268
55268.5
55269
55269.5
55270


Light curve and BG estimate evolution
Signal
Background
Crab (MAGIC I)
10% Crab (MAGIC I)
Integral flux (200-50000 GeV) [cm^{-2} s^{-1}]
$\times 10^{-9}$
0
0.1
0.2
0.3
0.4
0.5
55272
55272.5
55273
Time [MJD]


Light curve and BG estimate evolution
Signal
Background
Crab (MAGIC I)
10% Crab (MAGIC I)
Integral flux (200-50000 GeV) [cm^{-2} s^{-1}]
$\times 10^{-9}$
0
0.1
0.2
0.3
0.4
0.5
55275
55276
55277
Time [MJD]

Mrk421 2010.01-06 light curve

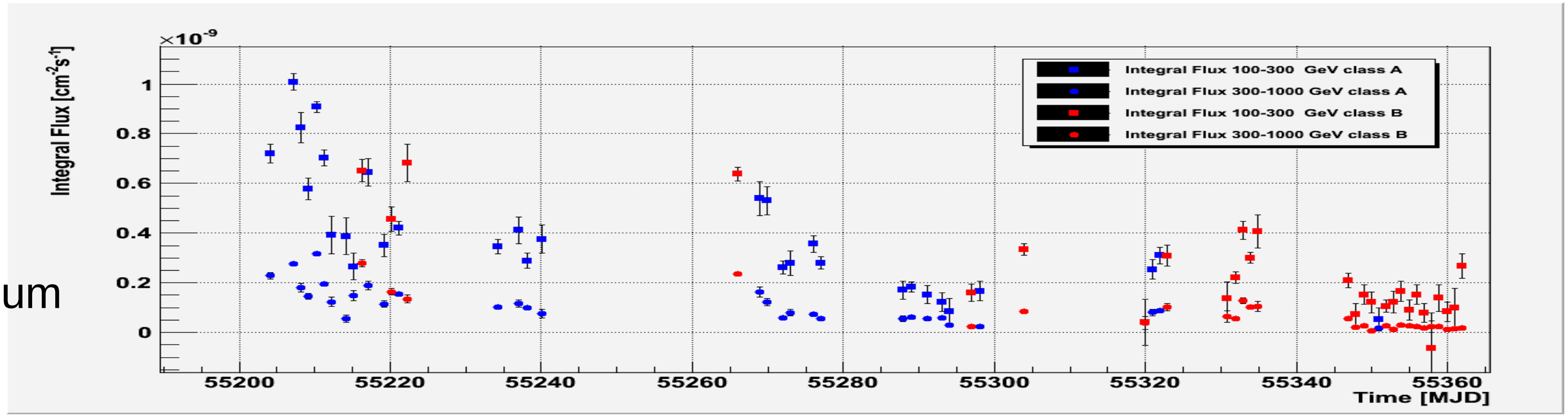


Light curve in 3 energy bands:

low energy 100-300 GeV
medium energy 300-1000 GeV
high energy >1TeV

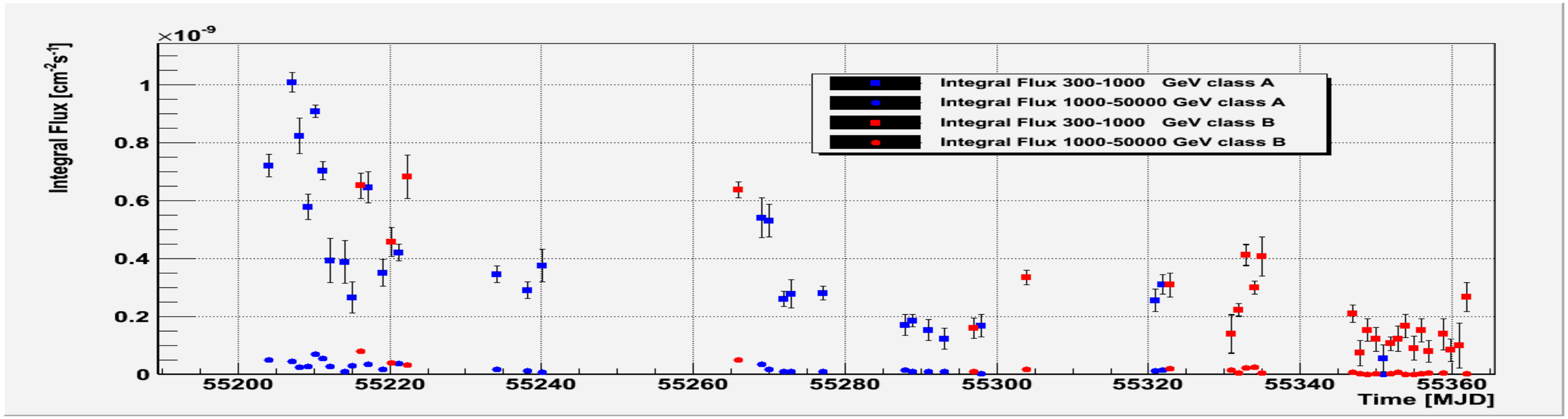
low

medium

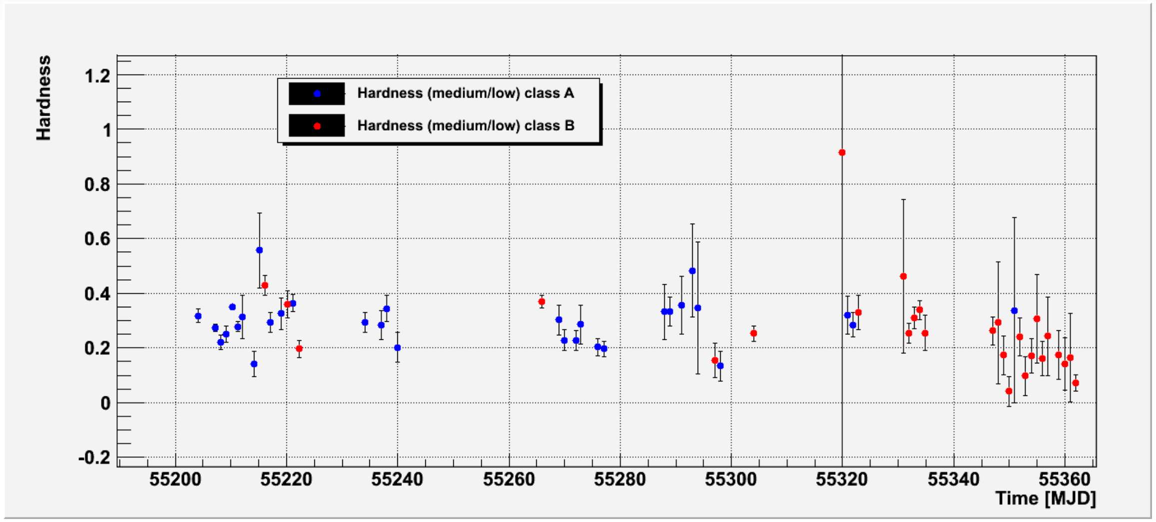


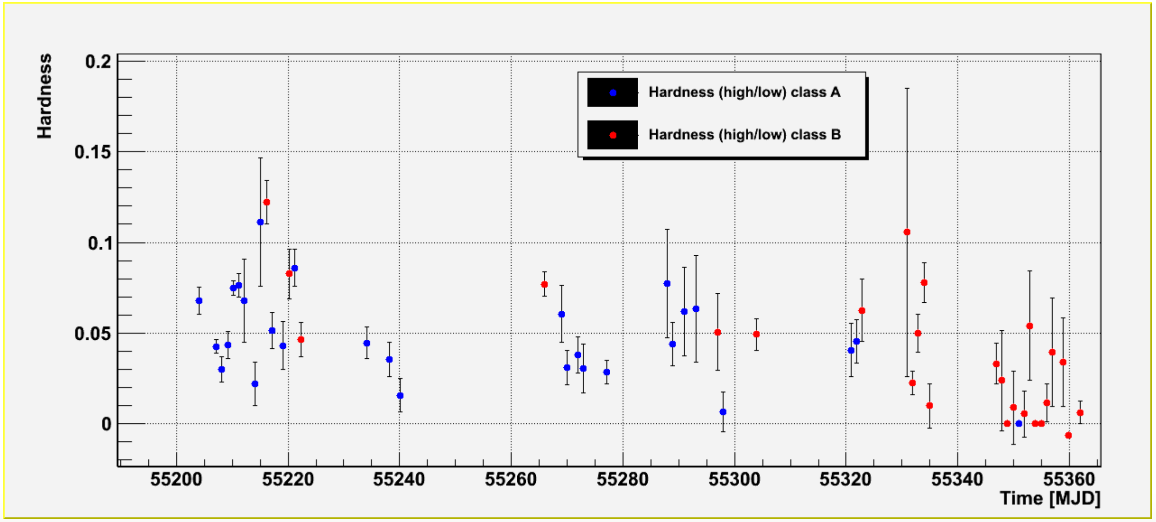
low

high



Hardness variation over time





- The GLAST-AGILE Support Program (GASP) was organized within the Whole Earth Blazar Telescope to provide optical-to-radio long-term continuous monitoring of a list of selected gamma-ray-loud blazars during the operation of the AGILE and GLAST satellites.

- **AGILE** (**Astro-rivelatore Gamma a Immagini LEggero**) is an X-ray and Gamma ray astronomical satellite of the Italian Space Agency (ASI).

Time Correlation between 2 Lightcurves

$$UDCF_{ij} = \frac{(a_i - \bar{a})(b_i - \bar{b})}{\sqrt{(\sigma_a{}^2 - \overline{err_a}^2)(\sigma_b{}^2 - \overline{err_b}^2)}}$$

Discrete Correlation Function

$$DCF(\tau) = \frac{1}{M} \sum UDCF_{ij}$$

$$\tau - \Delta\tau/2 < \Delta t_{ij} = t_j^a - t_i^b < \tau + \Delta\tau/2$$

Lag

$\tau = 2$ days

$\Delta\tau = 2$ days

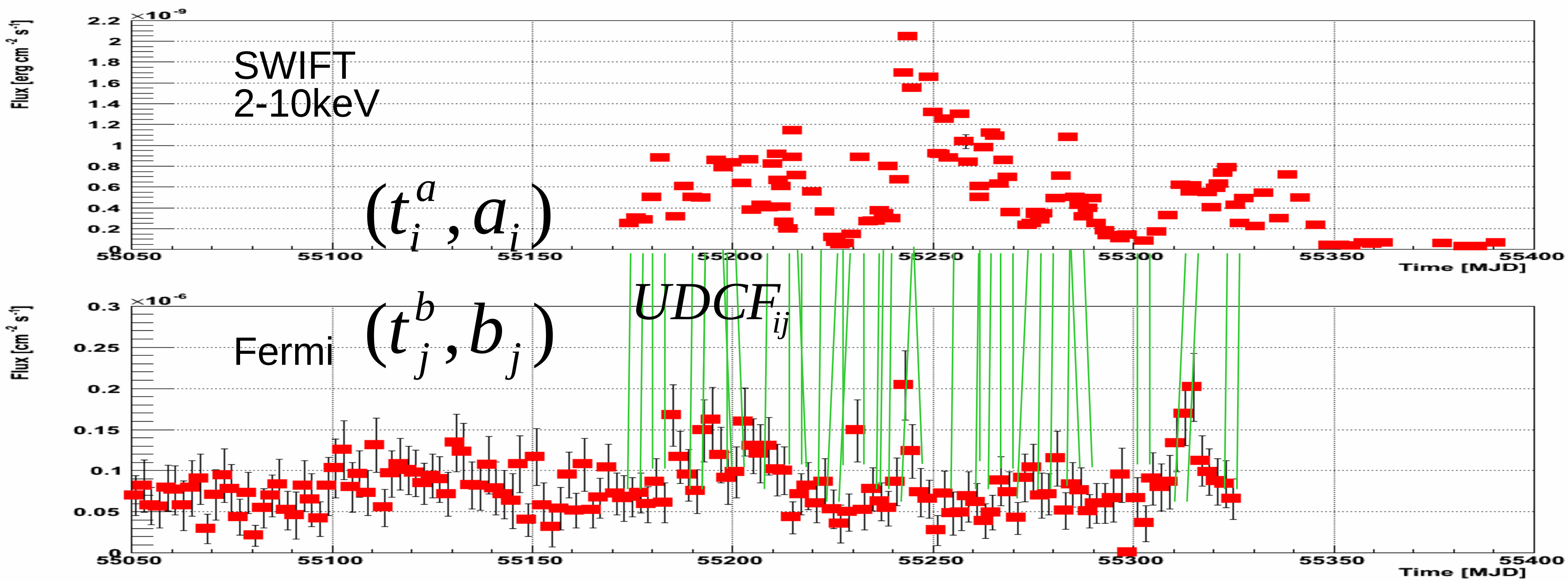
$-1\,\text{day} < \Delta t_{ij} = t_j^a - t_i^b < +1\,\text{day}$

$-5\,\text{days} < \Delta t_{ij} = t_j^a - t_i^b < -3\,\text{days}$

$-3\,\text{days} < \Delta t_{ij} = t_j^a - t_i^b < -1\,\text{days}$

$+1\,\text{day} < \Delta t_{ij} = t_j^a - t_i^b < +3\,\text{days}$

$+3\,\text{days} < \Delta t_{ij} = t_j^a - t_i^b < +5\,\text{days}$



IACT Installations: the Key Players

Credits from R. Wagner

	H.E.S.S.	MAGIC
Number of telescopes	4	2
Field of view	5°	3.5°
Reflector diameter	12 m	17 m (the largest IACT)
Working Energy Range	>160 GeV	>50 GeV

- Located @ Roque de Los Muchachos (La Palma, Canary Islands, Spain) 2200 m a.s.l.
- MAGIC-I since 2004
- MAGIC-II since 2009
- Sensitivity 0.8% Crab (for E>260GeV, 50hr)
- Energy resolution 20% at 100 GeV, 15% at 1TeV
- Angular resolution ~ 0.07° at 1 TeV
- Light weight carbon fiber structure -> Fast repositioning (GRB)
- sum trigger mode can lower energy threshold to 25 GeV (pulsar)
- Enhanced duty cycle due to moonlight & twilight observations

Time Correlation between 2 Light Curves

Why to study time correlation

- Goal: to know which AGN structure or emission mechanism the observed photons of different energy correspond to
- Spatial resolution is bad=>different emission mechanisms are mixed
- We try to use time resolution to correlate several bands of light curves together =>implies that these bands correspond to the same emission mechanism

Discrete Correlation Function

$$DCF(\tau) = \frac{1}{M}\sum UDCF_{ij}$$

(for ij pair meeting this criteia : $\tau - \Delta\tau/2 < \Delta t_{ij} = t_j^a - t_i^b < \tau + \Delta\tau/2$)

Time lag

$$UDCF_{ij} = \frac{(a_i - \bar{a})(b_i - \bar{b})}{\sqrt{(\sigma_a{}^2 - \overline{err_a}^2)(\sigma_b{}^2 - \overline{err_b}^2)}}$$

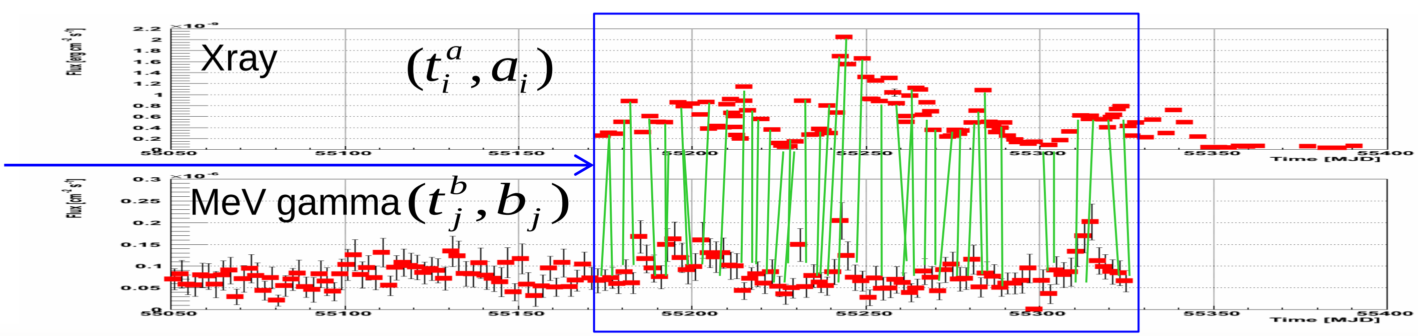
One example:

$\tau = 2$ days

$\Delta\tau = 2$ days

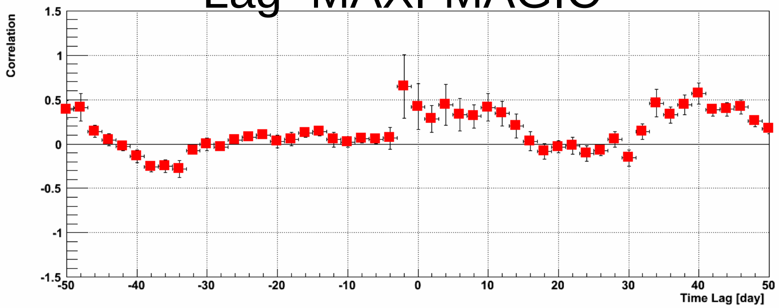
$-1\,\text{day} < \Delta t_{ij} = t_j^a - t_i^b < +1\,\text{day}$

Time lag

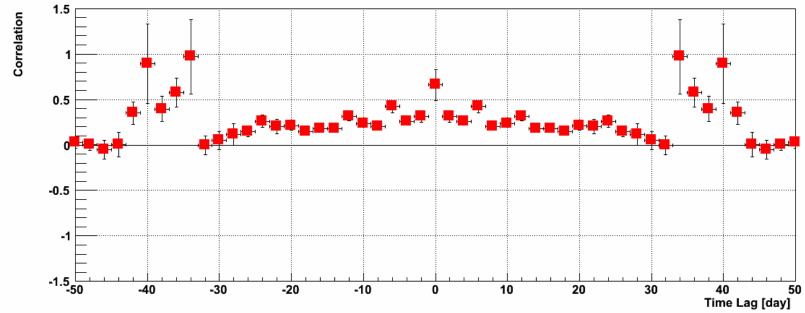


Mrk421 2010 Correlation

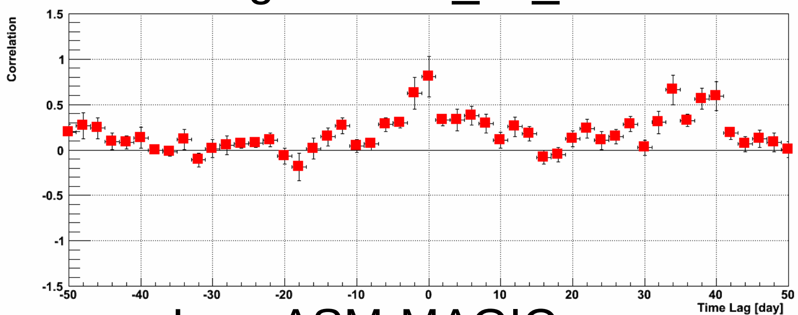
Lag=MAXI-MAGIC



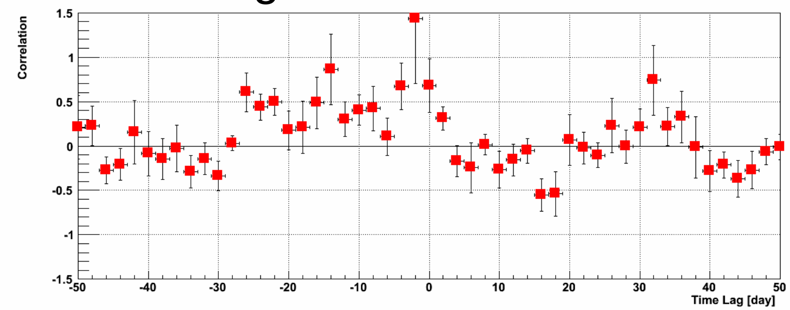
Lag=MAGIC-MAGIC



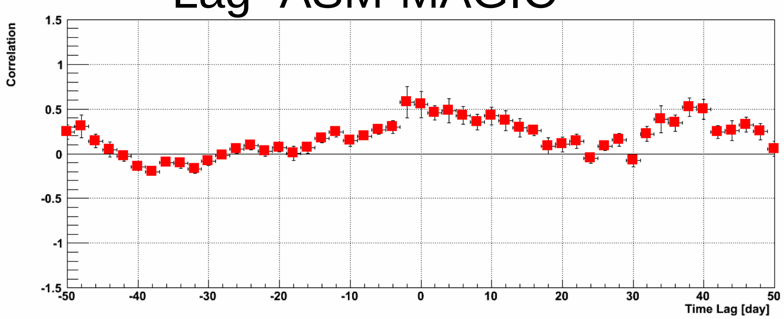
Lag=SWIFT_15_50keV-MAGIC



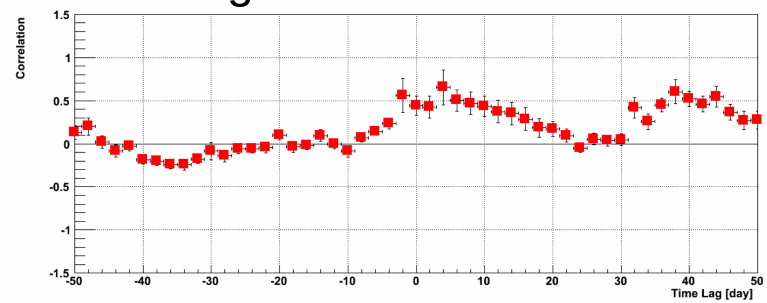
Lag=Fermi-MAGIC



Lag=ASM-MAGIC



Lag=BAT-MAGIC



Summary

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2. MAGIC in its first year(2010) of stereo observation on Mrk 421 caught three TeV flares: January (~3 Crab), March (~2 Crab), May (~1 Crab)
   high state: TeV,MeV,X,Opt TeV,X,Opt TeV,MeV,X,Opt

3. Mrk 421 2010 MW light curves: Xray and TeV Gamma ray have the highest variability, ~3 times higher than that of optical and MeV gamma bands. Correlations of {TeV,MeV} and {TeV,Xray} are both >0.5

4. MAGIC stereo had 11 observation on Mrk421 in March 2010, catching its flare state to post-flare state, with fluxes of 4 observations > 1 Crab, with simultaneous spectra from Optical, SWIFT/XRT*BAT, RXTE/ASM, Fermi, MAGIC in 9 observations.

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