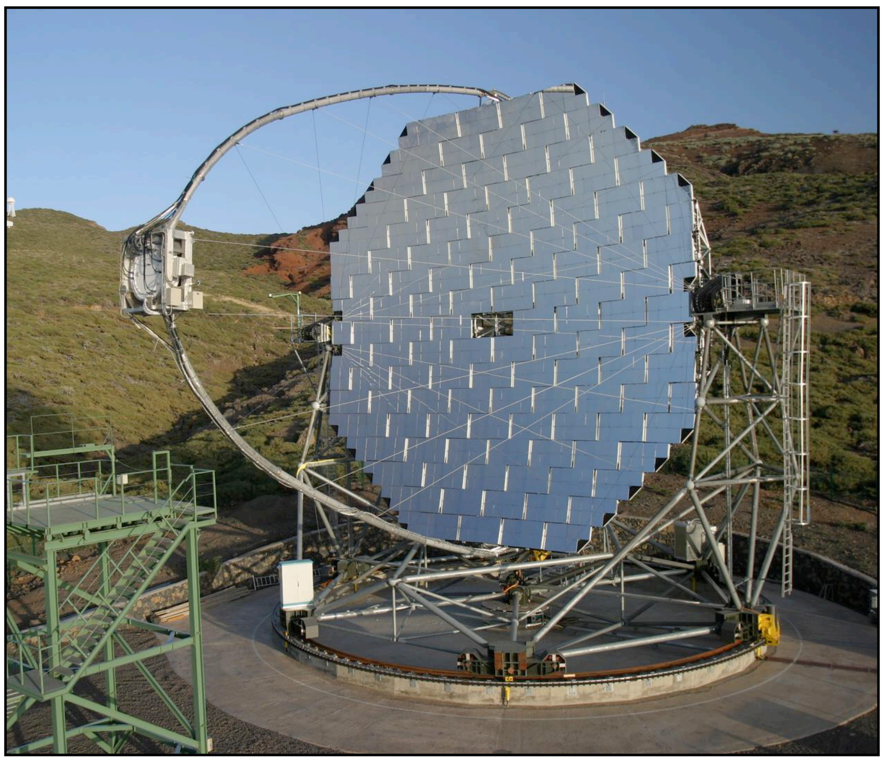
Study of Flux and Spectral Variations in the VHE Emission from the Blazar Markarian 501

David Paneque
on behalf of the MAGIC collaboration

Astro-ph/0702008 ; in press ApJ 669 (2007)



OUTLINE

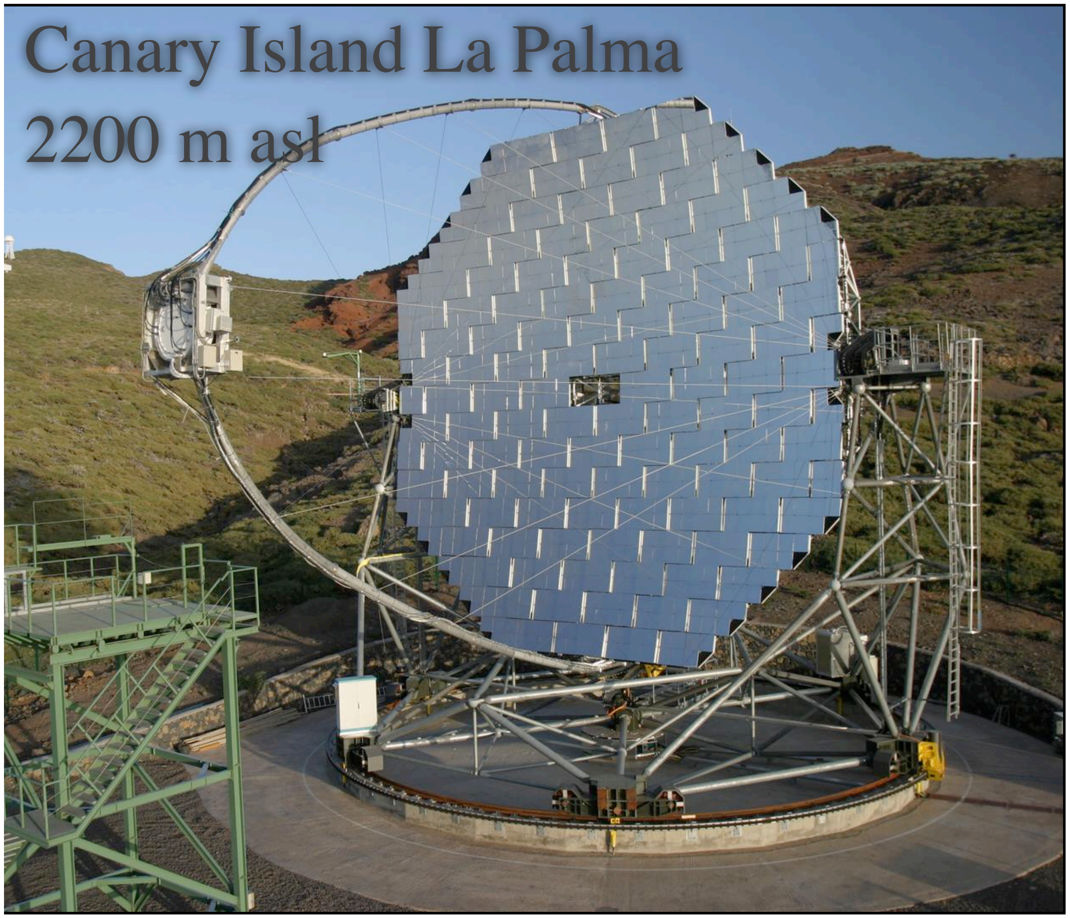
1- Motivation to observe Mrk 501 *(given previous talk)*

2- Highlights from the Mrk 501 observations performed with MAGIC in June-July 2005 (*details in the paper*)

3- Conclusions and outlook

2-The MAGIC Telescope (see Turini et al)

Largest Imaging Air Cherenkov Telescope (IACT)
for performing γ-ray astronomy. In operation since Sept. 2004



17 m ∅ mirror dish (**239 m^2**)
3.5^0 Field of View camera with **576 high-QE PMTs**
Fast repositioning **t_R< 40 s**

Trigger threshold energy: ~**50 GeV**
Minimum energy for spectral analysis : **100 GeV**
Angular resolution per incoming photon: **0.1^0-0.15^0**
Energy resolution : **20%-30%**
Point source sensitivity:
2.5% Crab / 50 hours

2- Analysis of the MAGIC data (24 nights, 32 h)

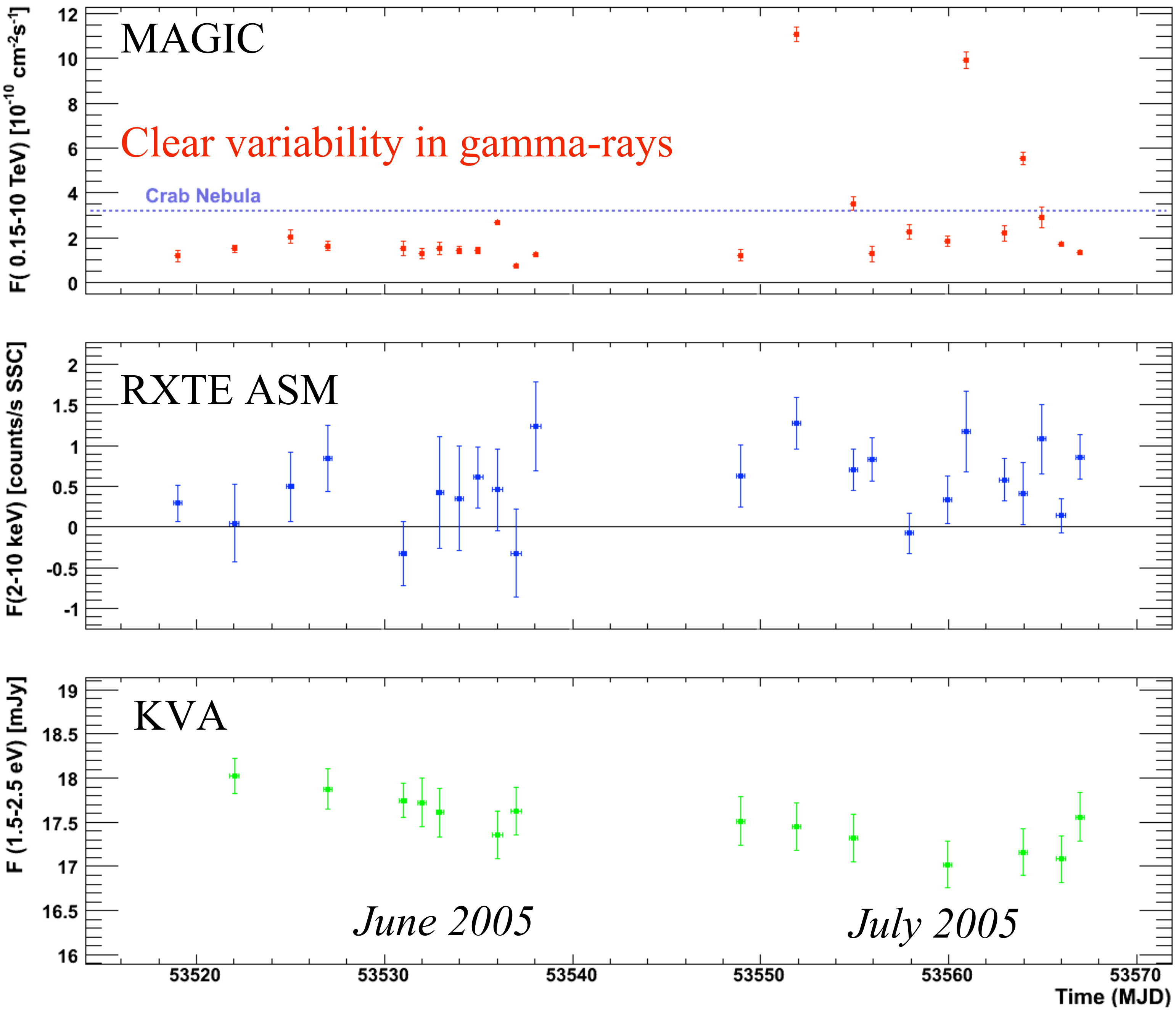
June-July 2005

Flux and spectra determined on a night-by-night basis

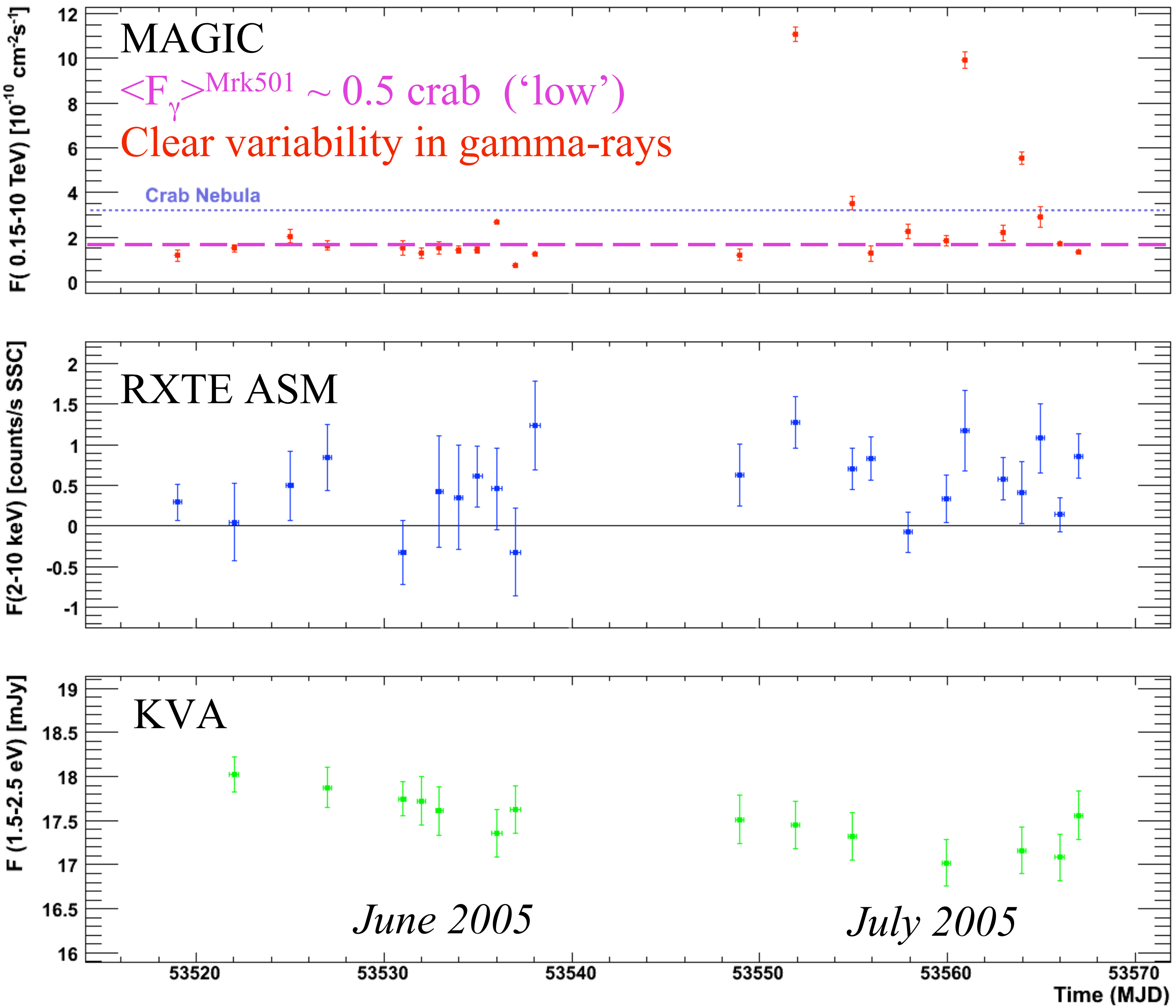
Obs. Nights | Gamma-Flux | Power Law fit to spectra

MJD Start	T_{obs} [a] (h)	ZA[b] (deg)	S_{comb} [c] sigma	$F_{>150\ GeV}$ [d] $(\frac{10^{-10}\ ph}{cm^2 \cdot s})$	$F_{>150\ GeV}$ $(Crab\ Units)$	K_0 [e] $(\frac{10^{-10}\ ph}{cm^2 \cdot s \cdot 0.3TeV})$	a [f]	χ^2/NDF [g]	P [h] (%)
53518.980	0.75	19.10-28.95	6.44	1.19 ± 0.25	0.37 ± 0.08	2.63 ± 0.48	2.17 ± 0.25	2.7/8	95.2
53521.966	1.85	9.97-30.10	8.90	1.51 ± 0.17	0.47 ± 0.05	2.94 ± 0.33	2.61 ± 0.16	10.8/7	15.0
53524.969	0.58	19.18-27.73	6.98	2.04 ± 0.29	0.64 ± 0.09	3.71 ± 0.53	2.47 ± 0.23	1.6/6	95.0
53526.975	0.98	9.96-28.94	8.69	1.63 ± 0.22	0.51 ± 0.07	3.26 ± 0.38	2.49 ± 0.17	3.8/9	92.4
53530.973	0.47	15.22-22.32	6.52	1.53 ± 0.32	0.48 ± 0.10	2.28 ± 0.65	1.97 ± 0.49	1.1/3	78.9
53531.959	0.90	15.21-25.15	6.98	1.29 ± 0.24	0.41 ± 0.07	2.69 ± 0.38	2.57 ± 0.30	9.1/6	16.6
53532.936	0.53	23.80-30.11	5.44	1.50 ± 0.28	0.47 ± 0.09	2.41 ± 0.53	2.34 ± 0.36	1.2/7	99.2
53533.933	1.63	12.85-30.09	7.83	1.44 ± 0.17	0.45 ± 0.05	2.46 ± 0.32	2.55 ± 0.19	10.3/8	24.2
53534.940	2.07	9.95-30.09	9.56	1.43 ± 0.15	0.45 ± 0.05	2.71 ± 0.27	2.68 ± 0.16	8.9/9	44.8
53535.934	3.43	9.95-30.07	18.58	2.69 ± 0.13	0.85 ± 0.04	4.45 ± 0.24	2.42 ± 0.06	11.9/12	45.3
53536.947	2.68	9.95-29.93	7.01	0.75 ± 0.13	0.24 ± 0.04	1.36 ± 0.21	2.73 ± 0.29	5.7/7	57.1
53537.971	3.08	9.95-30.10	11.52	1.25 ± 0.10	0.39 ± 0.03	2.08 ± 0.19	2.46 ± 0.14	8.2/8	41.4
53548.931	0.87	9.98-20.68	6.12	1.21 ± 0.25	0.38 ± 0.08	2.39 ± 0.38	2.28 ± 0.27	0.6/6	99.6
53551.905	1.09	12.86-25.15	32.02	11.08 ± 0.32	3.48 ± 0.10	17.37 ± 0.51	2.09 ± 0.03	26.2/11	0.6
53554.906	0.68	15.21-22.32	12.52	3.52 ± 0.30	1.11 ± 0.09	5.91 ± 0.47	2.26 ± 0.11	3.9/9	92.1
53555.914	0.44	12.85-22.32	6.08	1.27 ± 0.34	0.40 ± 0.11	2.96 ± 0.62	1.97 ± 0.29	1.9/6	92.5
53557.916	0.54	12.84-19.06	8.40	2.25 ± 0.32	0.71 ± 0.10	3.91 ± 0.48	2.30 ± 0.21	6.5/7	48.5
53559.920	0.98	9.94-17.22	10.05	1.85 ± 0.23	0.58 ± 0.07	3.10 ± 0.33	2.25 ± 0.13	8.4/8	39.9
53560.906	0.76	9.96-19.07	24.39	9.93 ± 0.38	3.12 ± 0.12	14.35 ± 0.56	2.20 ± 0.04	22.5/11	2.1
53562.911	1.63	9.94-16.79	11.08	2.19 ± 0.37	0.69 ± 0.12	2.83 ± 0.30	2.34 ± 0.13	14.1/8	8.2
53563.921	0.85	9.94-15.16	18.69	5.53 ± 0.28	1.74 ± 0.09	7.89 ± 0.39	2.25 ± 0.06	11.5/9	24.3
53564.917	0.34	9.94-15.18	8.91	2.89 ± 0.46	0.91 ± 0.15	4.88 ± 0.56	2.27 ± 0.20	5.4/6	49.7
53565.920	2.57	9.95-28.93	11.62	1.71 ± 0.13	0.54 ± 0.04	2.73 ± 0.22	2.49 ± 0.12	10.7/8	21.6
53566.953	1.91	9.99-30.10	11.63	1.33 ± 0.11	0.42 ± 0.04	2.16 ± 0.20	2.28 ± 0.13	7.4/10	69.0

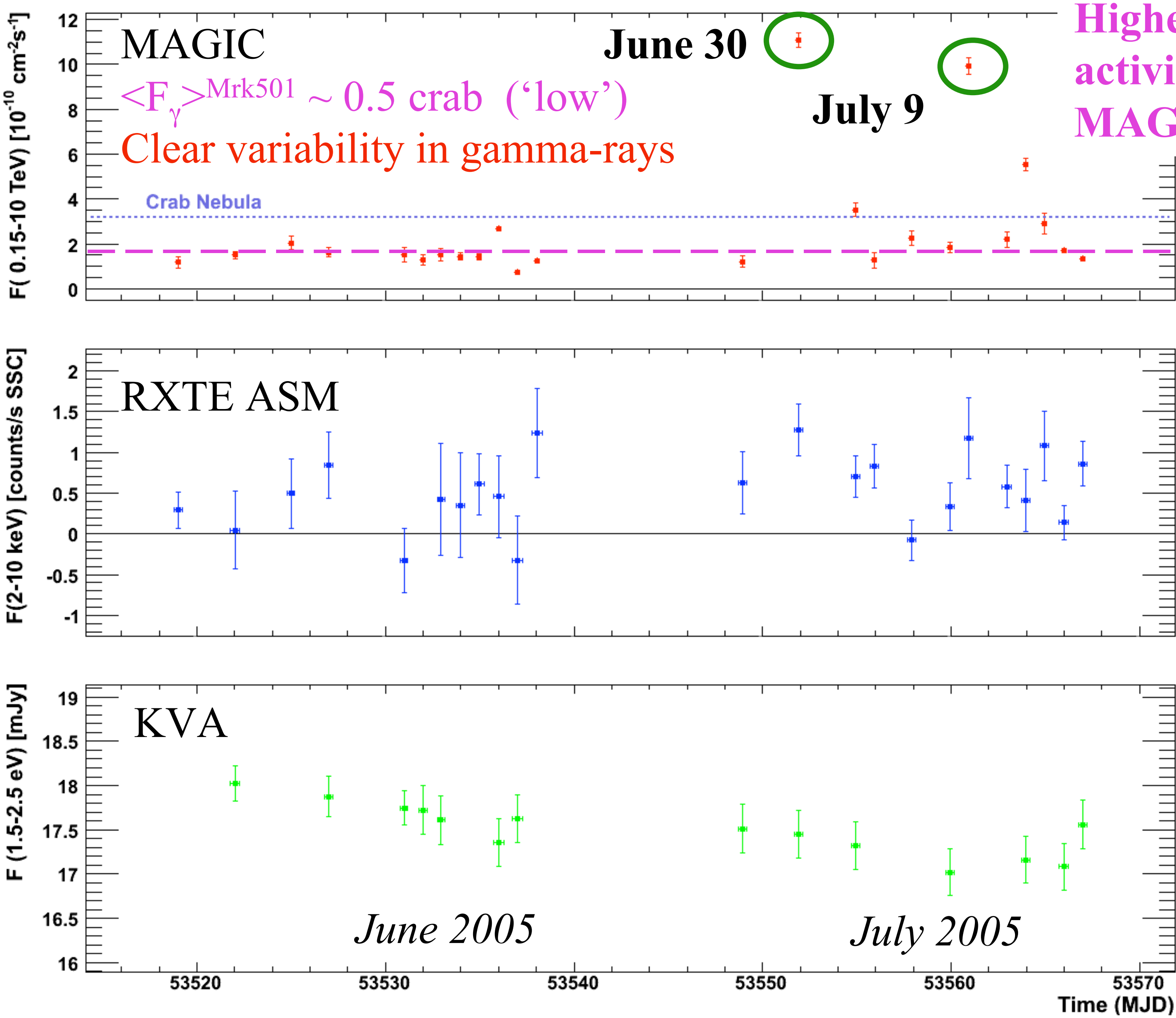
2.1- Light curves (LCs): Gamma, X-rays, Optical



2.1- Light curves (LCs): Gamma, X-rays, Optical



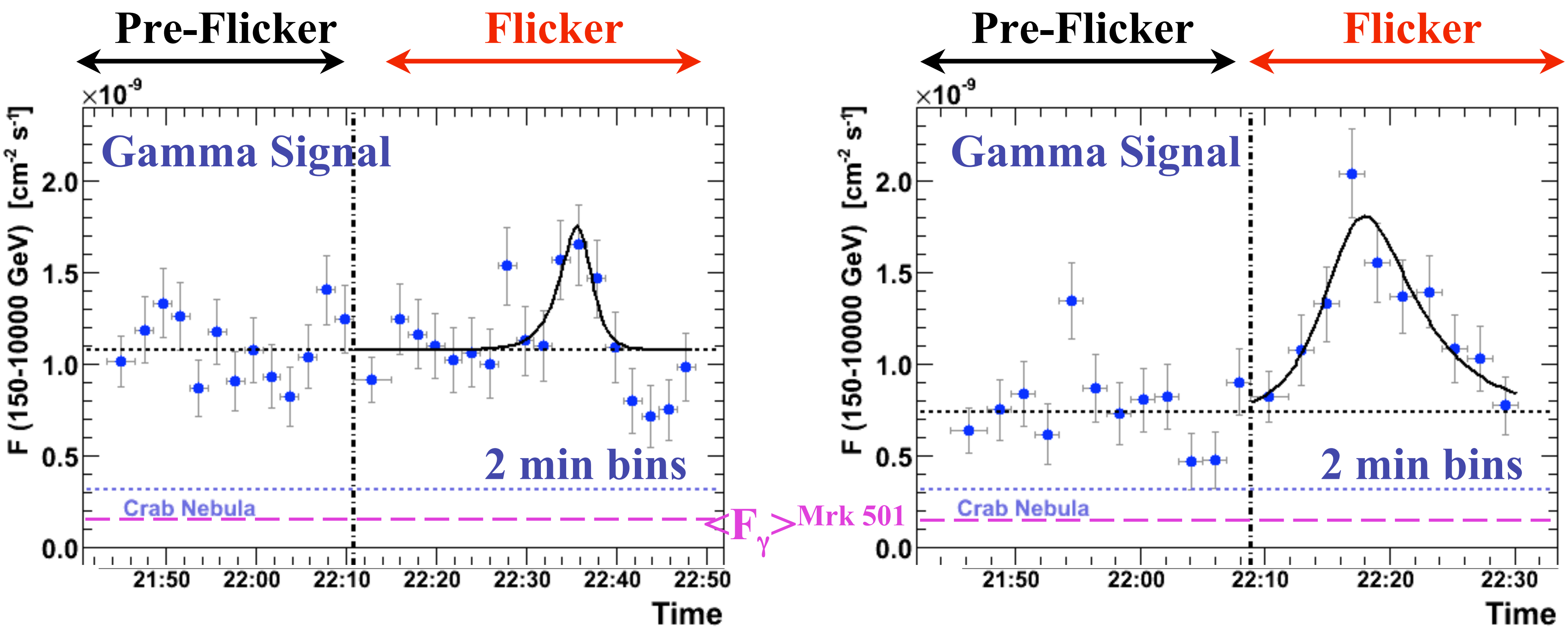
2.1- Light curves (LCs): Gamma, X-rays, Optical



Highest VHE activity during MAGIC obs.

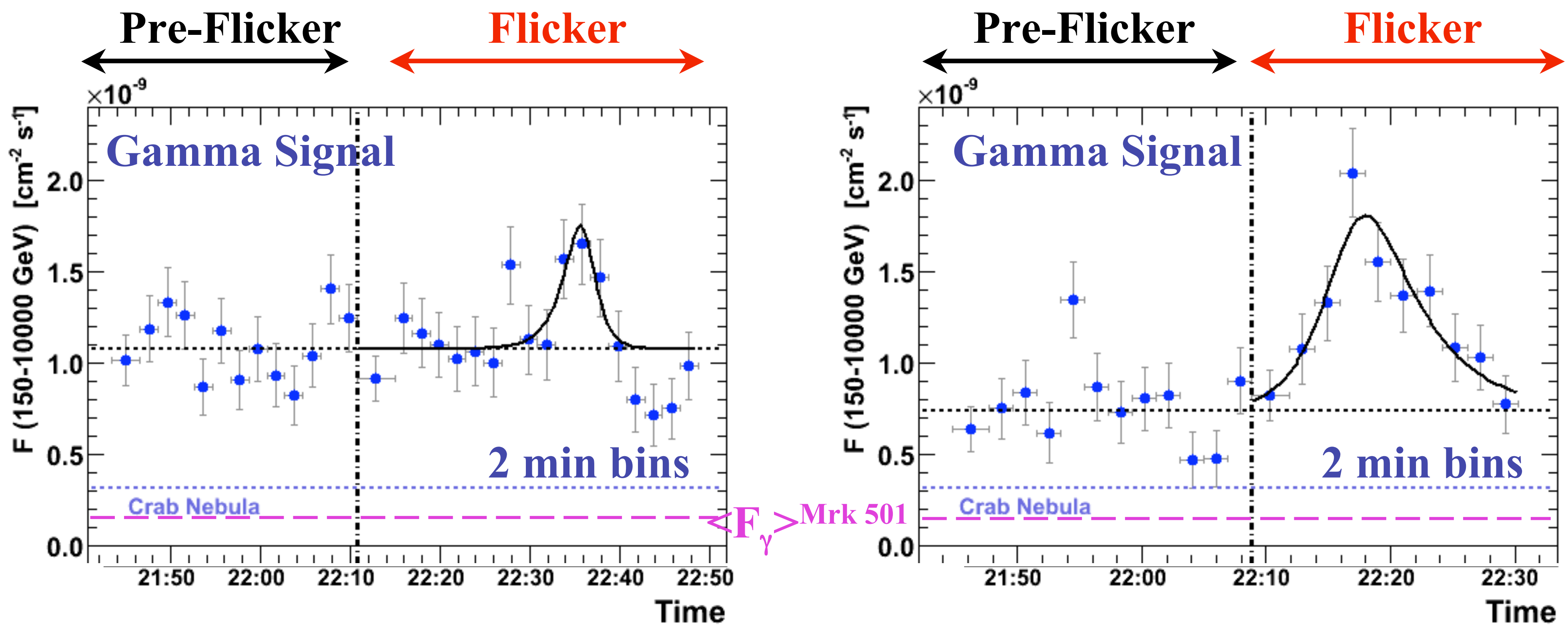
2.2- Intra-night flux variations (E > 150 GeV)

June 30th ⟵ Highest VHE activity ⟶ July 9th



2.2- Intra-night flux variations (E > 150 GeV)

June 30th ⟵ Highest VHE activity ⟶ July 9th



Assumption: **Flux variation (flare) on the top of a stable emission**

$$F(t) = a + \frac{b}{2^{-\frac{t-t_0}{c}} + 2^{\frac{t-t_0}{d}}}$$

a: pedestal (not fit)

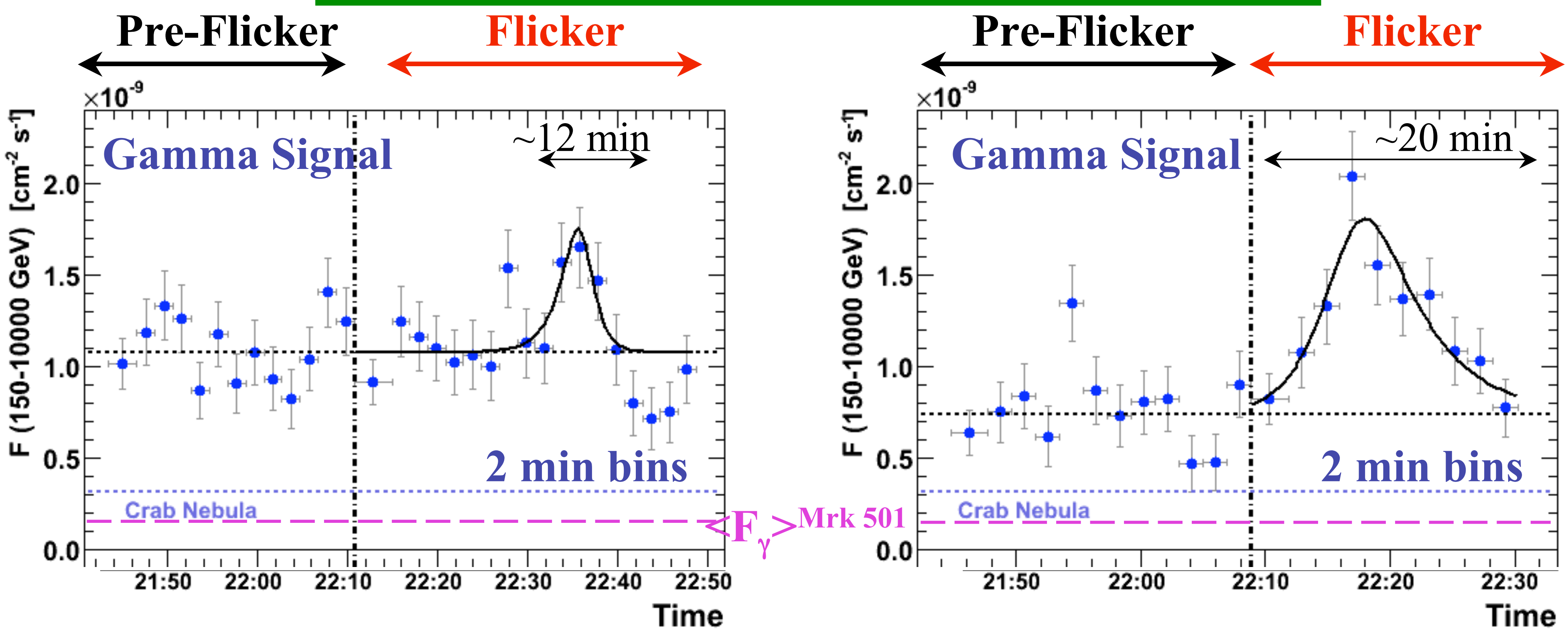
b: amplitude of flux variation

t_0: ~ peak position (not fit)

c, d: flux-doubling times

2.2- Intra-night flux variations (E > 150 GeV)

Fastest variability observed in Mrk 501



Assumption: **Flux variation (flare) on the top of a stable emission**

b $\left(\frac{10^{-10}\ ph}{cm^2 \cdot s}\right)$	c (s)	d (s)	χ^2/NDF [d]	P [e] $(\%)$
13.2±4.7	81±41	50±23	20.0/15	17.3[f]
20.3±3.3	95±24	185±40	4.2/7	75.8

a: pedestal (not fit)

b: amplitude of flux variation

t_0: ~ peak position (not fit)

c, d: flux-doubling times

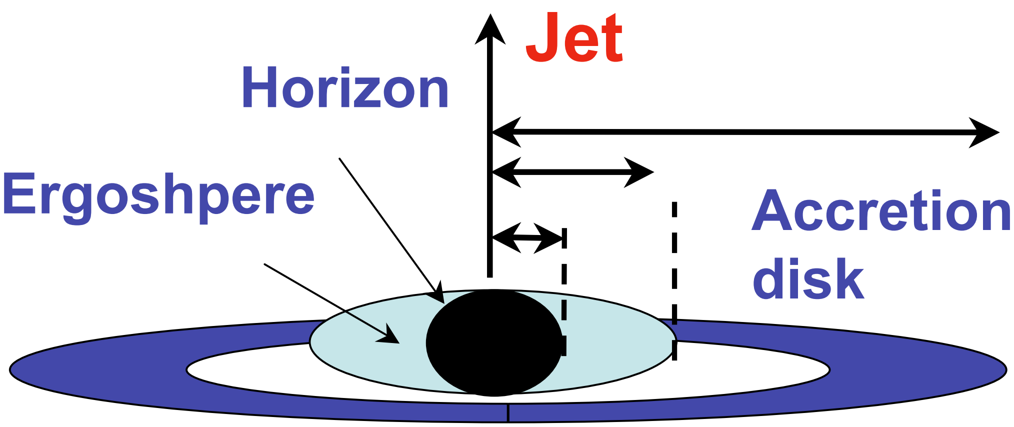
Constraints on the size of the emitting region

$$\boxed{R < c\frac{\delta}{1+z}\bullet t_{\mathrm{var}}}$$

$$\boxed{R < 0.8\delta \cdot 10^{8}\,km \sim 0.6\delta A.U.}$$

t_{var} ~ 5 min ; z = 0.034 c= 3×10^5 km/s

Which intrinsic engine scale can be used to compare?



Horizon scale is the smallest and the “simplest”

$$\boxed{\mathbf{R_s = 2GM/c^2 \sim 3\ km\ M/M_{sun}}}$$

$\mathbf{M^{Mrk501} \sim 10^9\ M_{sun}}$

Falomo et al, 2002, ApJ, 569, L35

Barth et al, 2003, ApJ, 583, 134

Uncertainties can be large (~5)   Rieger & Mannheim, A&A 397, 121 (2003)

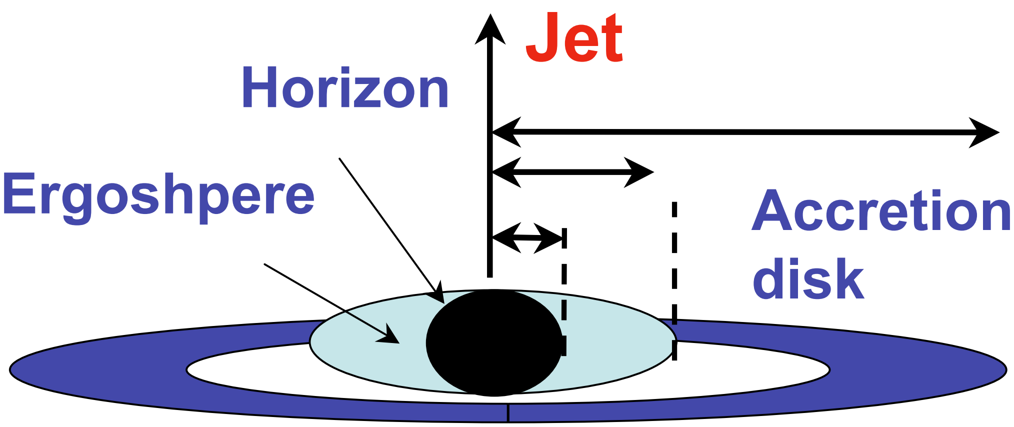
Constraints on the size of the emitting region

$$\boxed{R < c\,\frac{\delta}{1+z} \bullet t_{\mathrm{var}}}$$

$$\boxed{R < 0.8\delta \cdot 10^{8}\,km \sim 0.6\delta A.U.}$$

t_{var} ~ 5 min ; z = 0.034 c= $3\mathrm{x}10^5$ km/s

Which intrinsic engine scale can be used to compare?



Horizon scale is the smallest and the "simplest"

$$\boxed{R_s = 2GM/c^2 \sim 3\ \mathrm{km}\ M/M_{sun}}$$

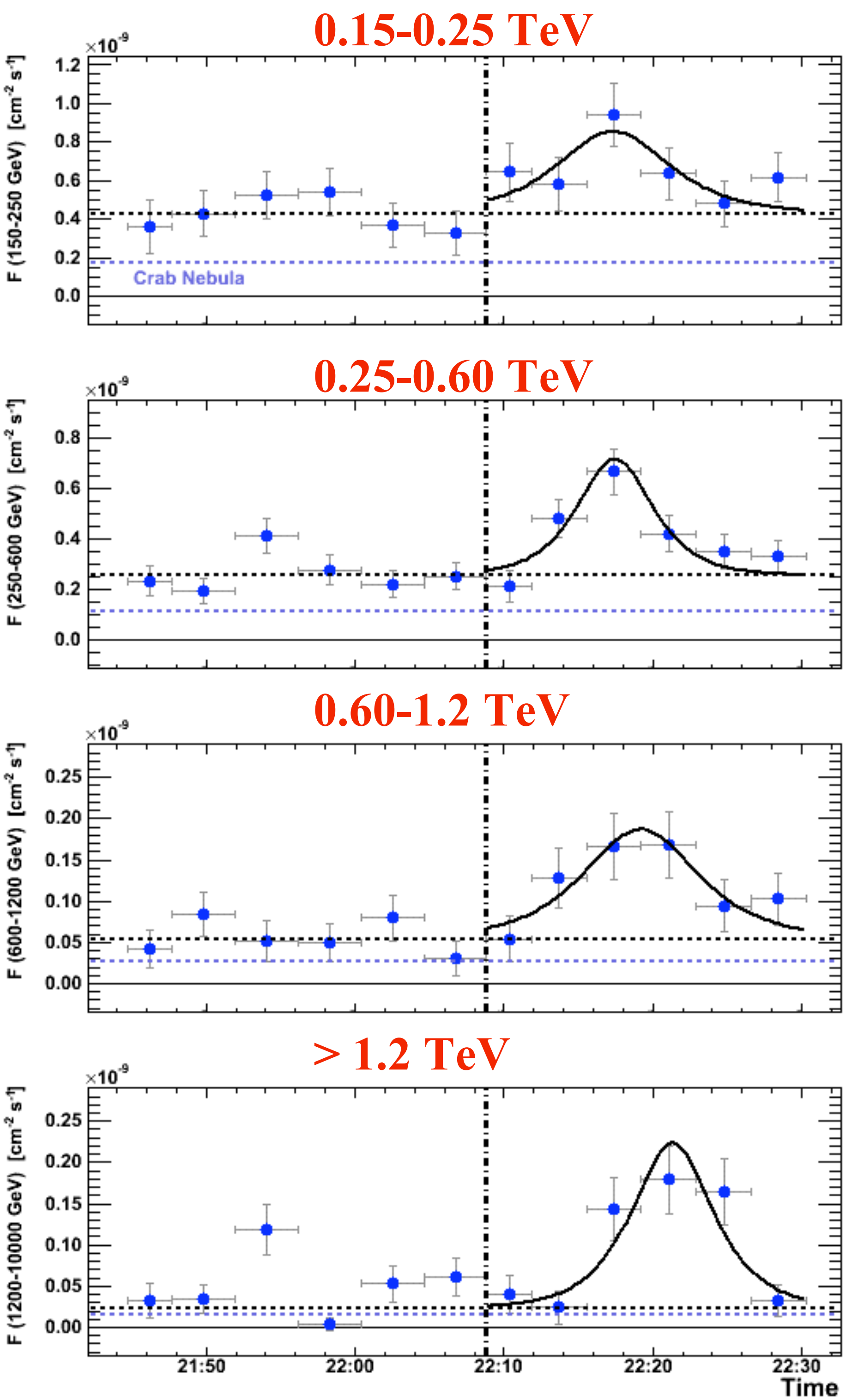
$M^{Mrk501} \sim 10^9\ M_{sun}$

Falomo et al, 2002, ApJ, 569, L35

Barth et al, 2003, ApJ, 583, 134

$$\boxed{R^{Mrk501}_{var} < \delta \times 1/33\ R_s^{Mrk501}}$$

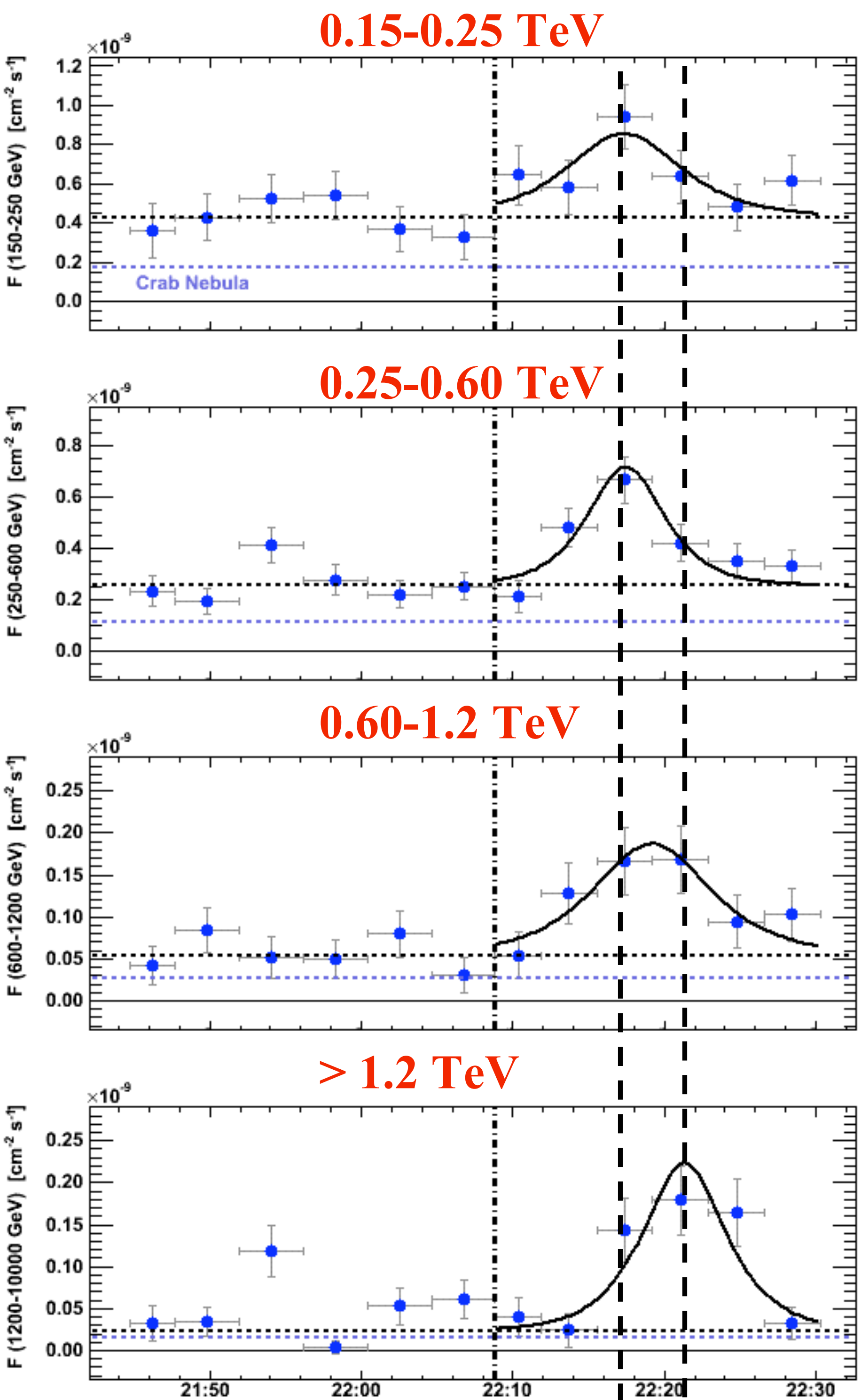
$\delta \sim 50$ to have an emitting region comparable to R_S



LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges



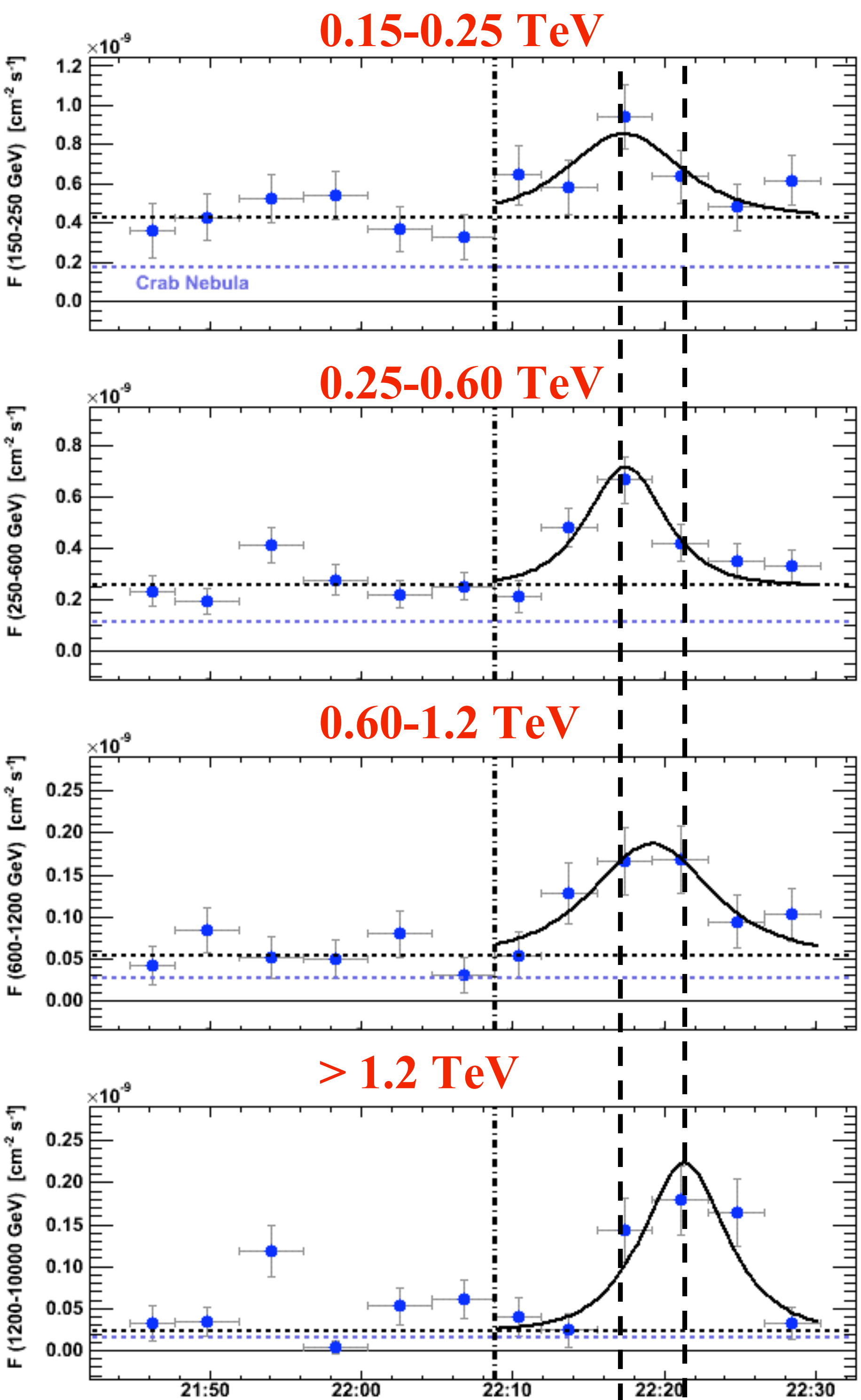
LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges

Time delay of 4 ± 1 minute between highest and lowest energy ranges

First time in VHE !!



LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges

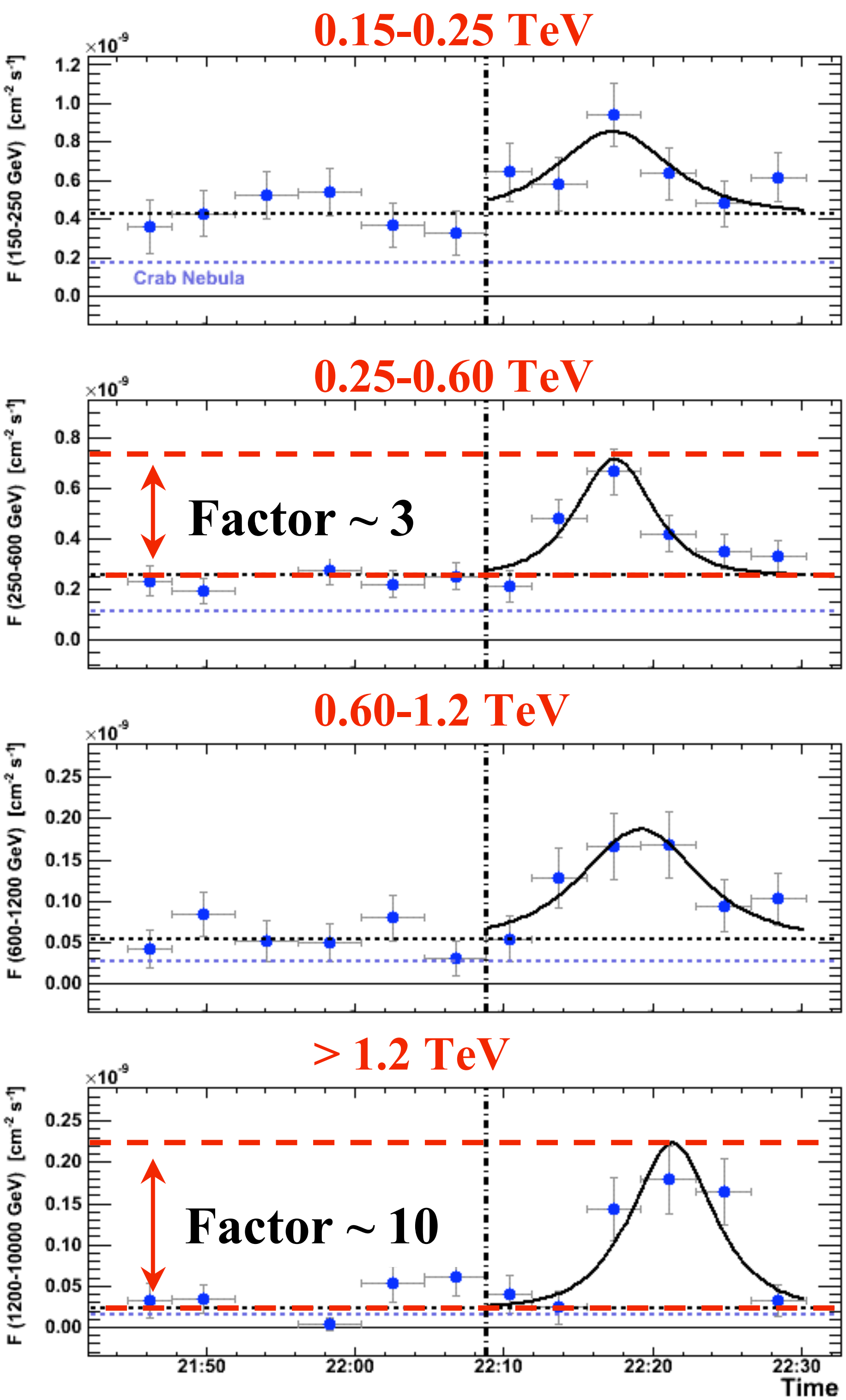
Time delay of 4 ± 1 minute between highest and lowest energy ranges

First time in VHE !!

IF

Photons at different energies were emitted simultaneously

This would have implications on non-conventional physics (see presentation by Sakharov et al)



LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges

Time delay of 4 ± 1 minute between highest and lowest energy ranges

First time in VHE !!

Flux variations are larger at the largest energies

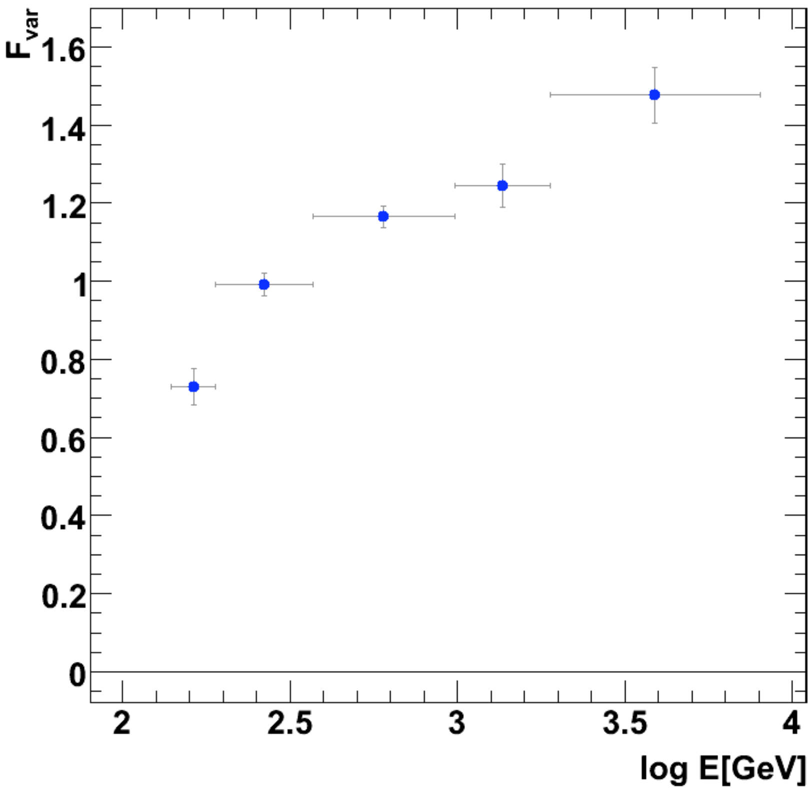
First time in VHE !!

2.3 - Flux variability vs Energy

Quantification following prescription given in *Vaughan et al. 2003*

$$F_{var} = \sqrt{\frac{S^2 - <\sigma^2_{err}>}{<F_\gamma>^2}}$$

All the observing nights (low and high state) included



F_{var}^{Mrk501}(VHE) increases with energy

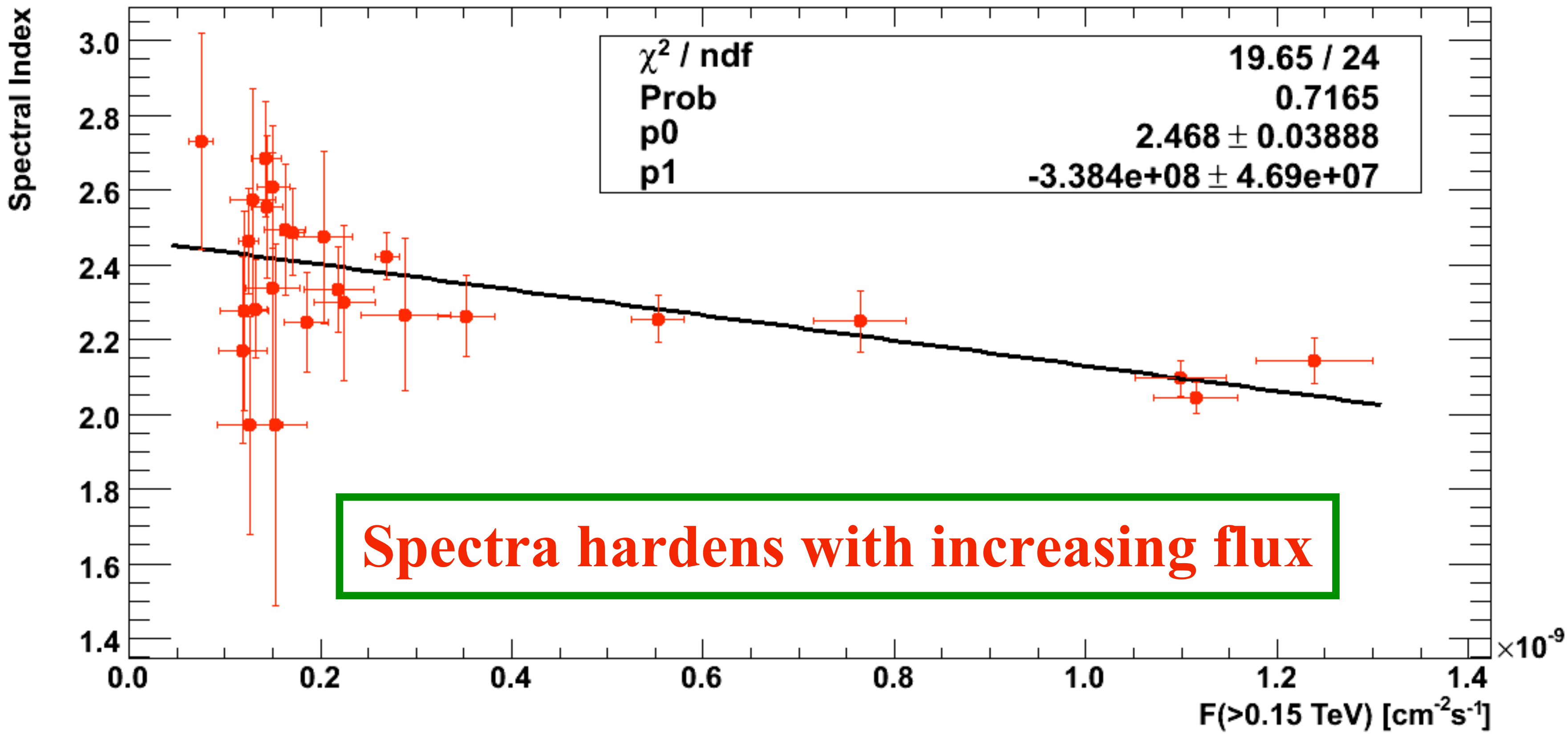
F_{var}^{Mrk501} increases with energy aslo at X-rays (see Gliozzi et al. 2006)

F_{var}^{Mrk501}(VHE) > F_{var}^{Mrk501}(X-rays)

The highest ***F_{var}^{Mrk501}(X-rays)*** is ~0.6 (in 1998). In 1997, year with very high activity, the highest ***F_{var}^{Mrk501}(X-rays)*** was ~0.4. ***Perhaps flux variability is highest when source is in low state***

2.4 - Correlation spectral index - gamma flux (E>0.15 TeV)

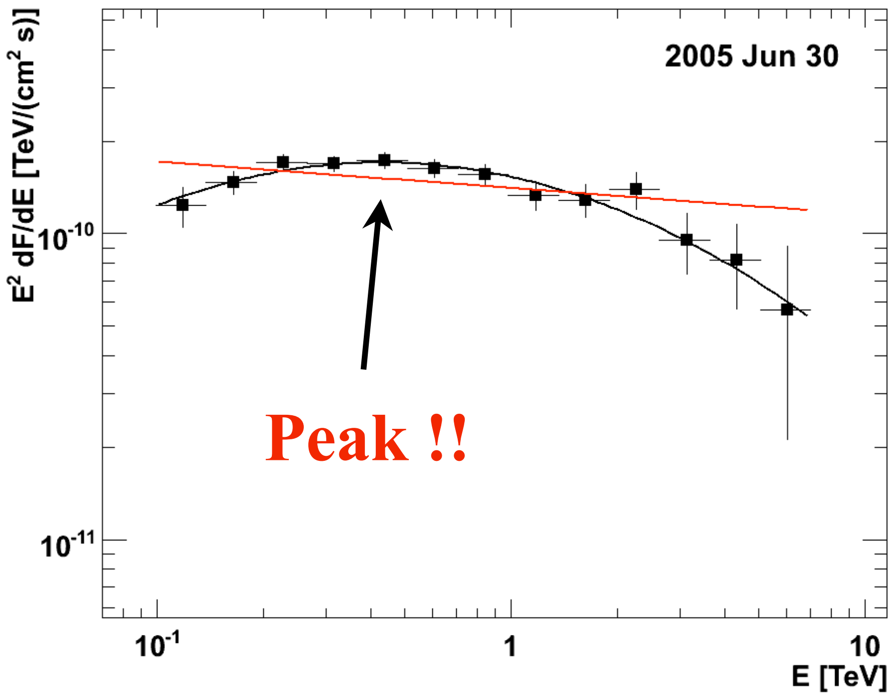
All 24 nights included
Flare nights split into 2 (“pre-flicker” and “flicker”)

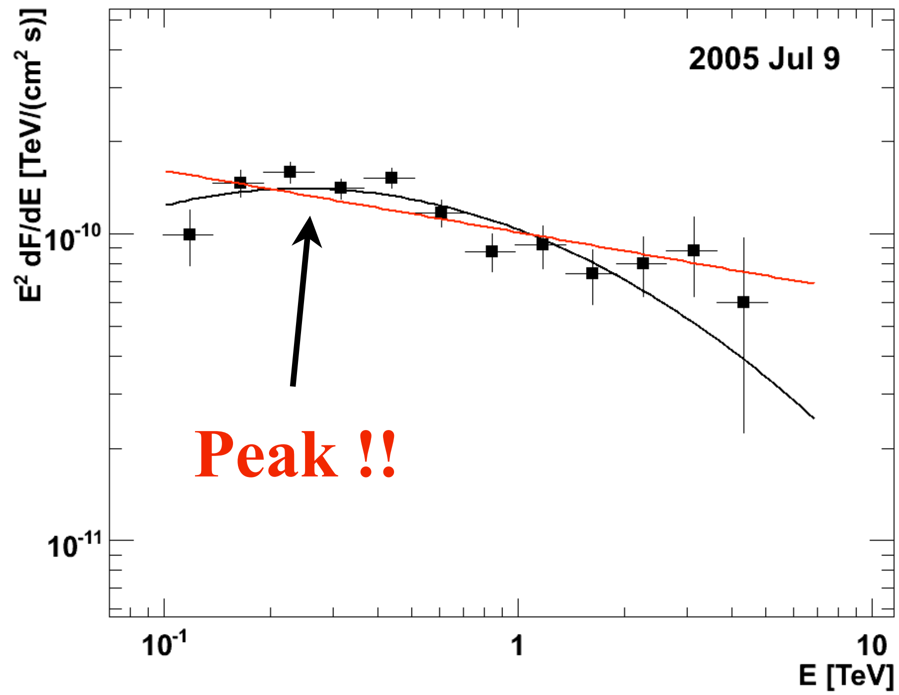


Constant fit gives Chi2/NDF = 76.6/25 (Prob 4 e-7)

2.5 - Spectra for the 2 nights with the highest VHE activity

Curved spectra is favoured over simple power law



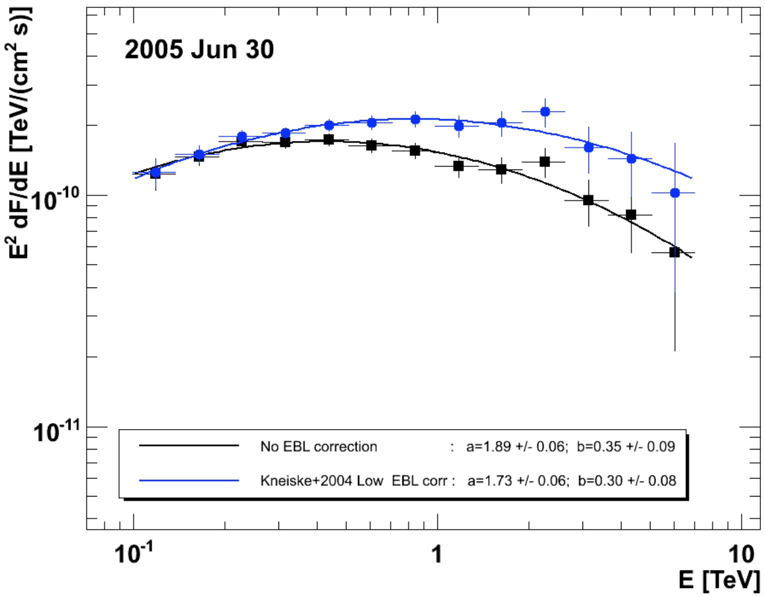


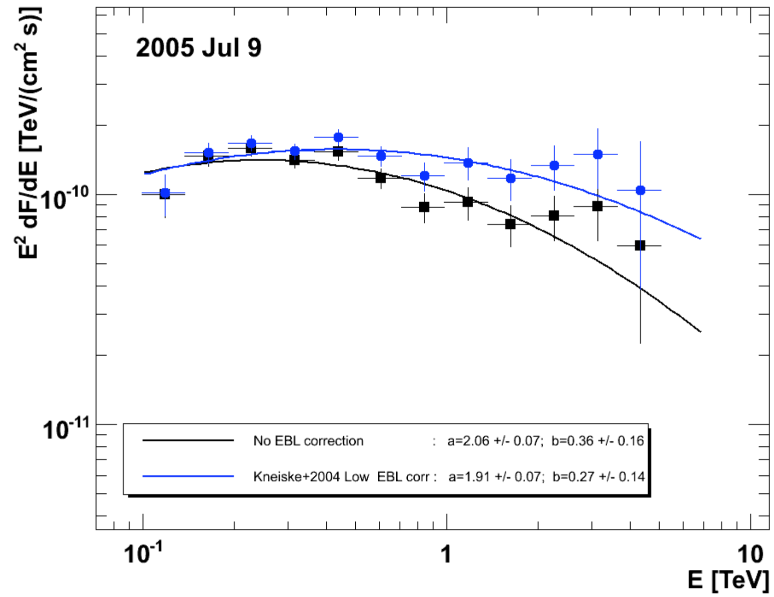
Power law **Log-Parabolic func.**

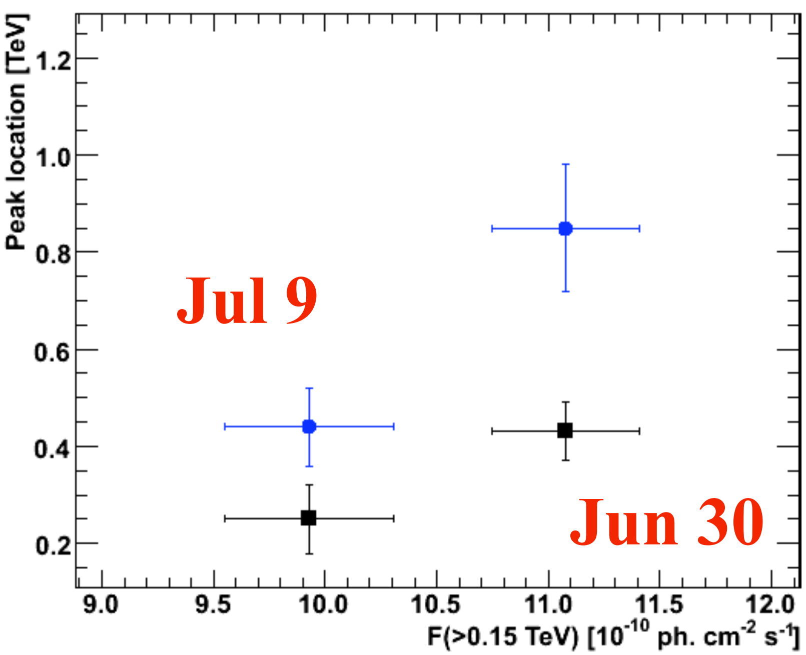
	Fit performed with formula 5				Fit performed with formula 6				
Date	K_0 $\left(\frac{10^{-10}\ ph}{cm^2 \cdot s \cdot 0.3TeV}\right)$	a	χ^2/NDF	P[h] (%)	K_0 $\left(\frac{10^{-10}\ ph}{cm^2 \cdot s \cdot 0.3TeV}\right)$	a	b	χ^2/NDF	P[h] (%)
June 30	17.4±0.05	2.09±0.03	26.1/11	0.6	18.6±0.06	1.89±0.06	0.35±0.09	6.1/10	80.1
July 9	14.3±0.06	2.20±0.04	22.5/11	2.1	15.5±0.07	2.06±0.07	0.36±0.16	15.2/10	12.5

2.6 - Position of spectral peak before and after EBL correction

Model used: ‘low’ EBL from Kneiske et al 2004





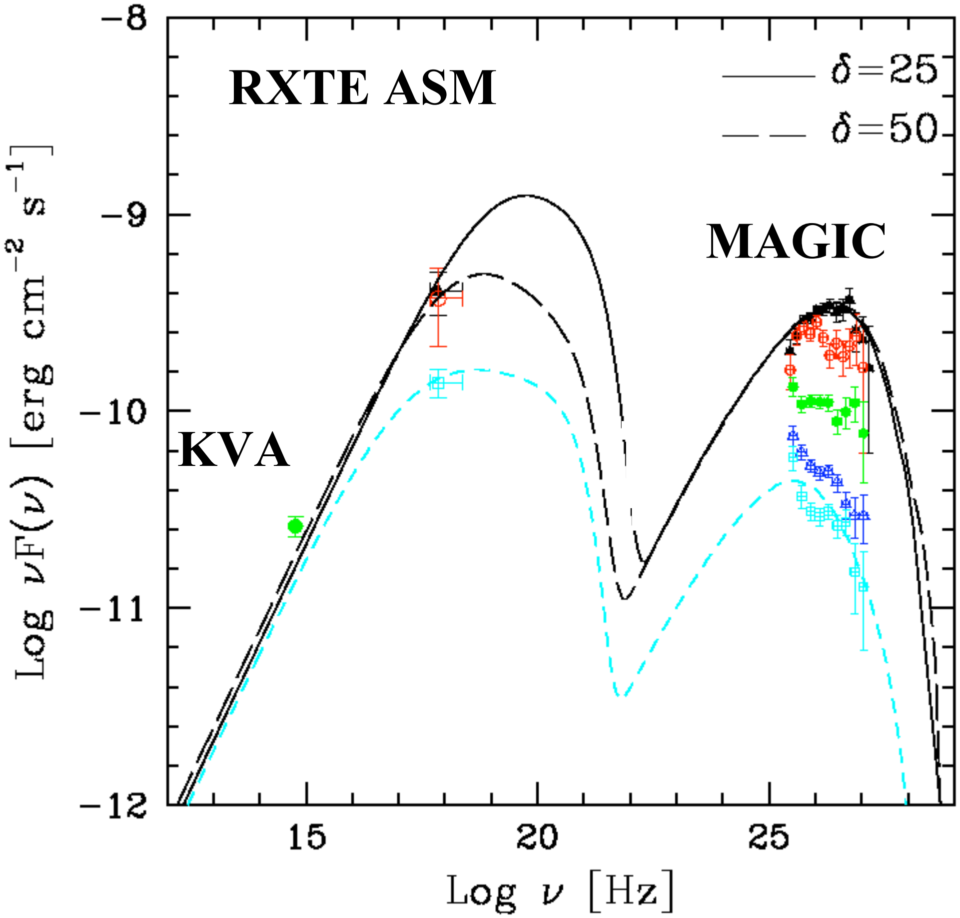


EBL correction moves the spectral peak to higher energies

During the nights of low activity, the flare is not seen at E > 100 GeV

Peak location seems to depend on the source luminosity

2.7 - Overall SED during these observations



Very dynamic spectra in VHE:
3 flux levels + 2 active nights =
= 5 different spectra

Unluckily, we do not have simultaneous broad band X-rays: big intra-model degeneracy

It is important to organize multiwavelength campaigns

SED fit with one zone SSC model (Tavecchio et al. 2001)

spectrum	γ_{min}	γ_{br}	γ_{max}	n1	n2	B Gauss	K particle/cm^3	R cm	Doppler factor
June 30	1	10^6	10^7	2	3.5	0.52	$2.5 \cdot 10^4$	10^{15}	25
June 30 (bis)	1	$5 \cdot 10^5$	10^7	2	3.5	0.115	$2.5 \cdot 10^4$	10^{15}	50
Low flux	1	10^5	$5 \cdot 10^6$	2	3.2	0.55	$1.6 \cdot 10^4$	10^{15}	25

CONCLUSIONS

Observations of Mrk 501 with MAGIC allowed us to study flux and spectra variations down to 100 GeV on a night by night basis

1 - Changes in flux and spectra on several timescales:
months, days, and few minutes

2 - Intra-day variations with flux-doubling times ~2 minutes
Much shorter than previous Mrk 501 and Mrk 421 observations
Tight constraints on the size of the emitting region

3 - Flux variability increases with energy

4 - Time delay of ~4 minutes between flare location at E <0.25 TeV and E > 1.2 TeV

5 - Spectra hardens with flux

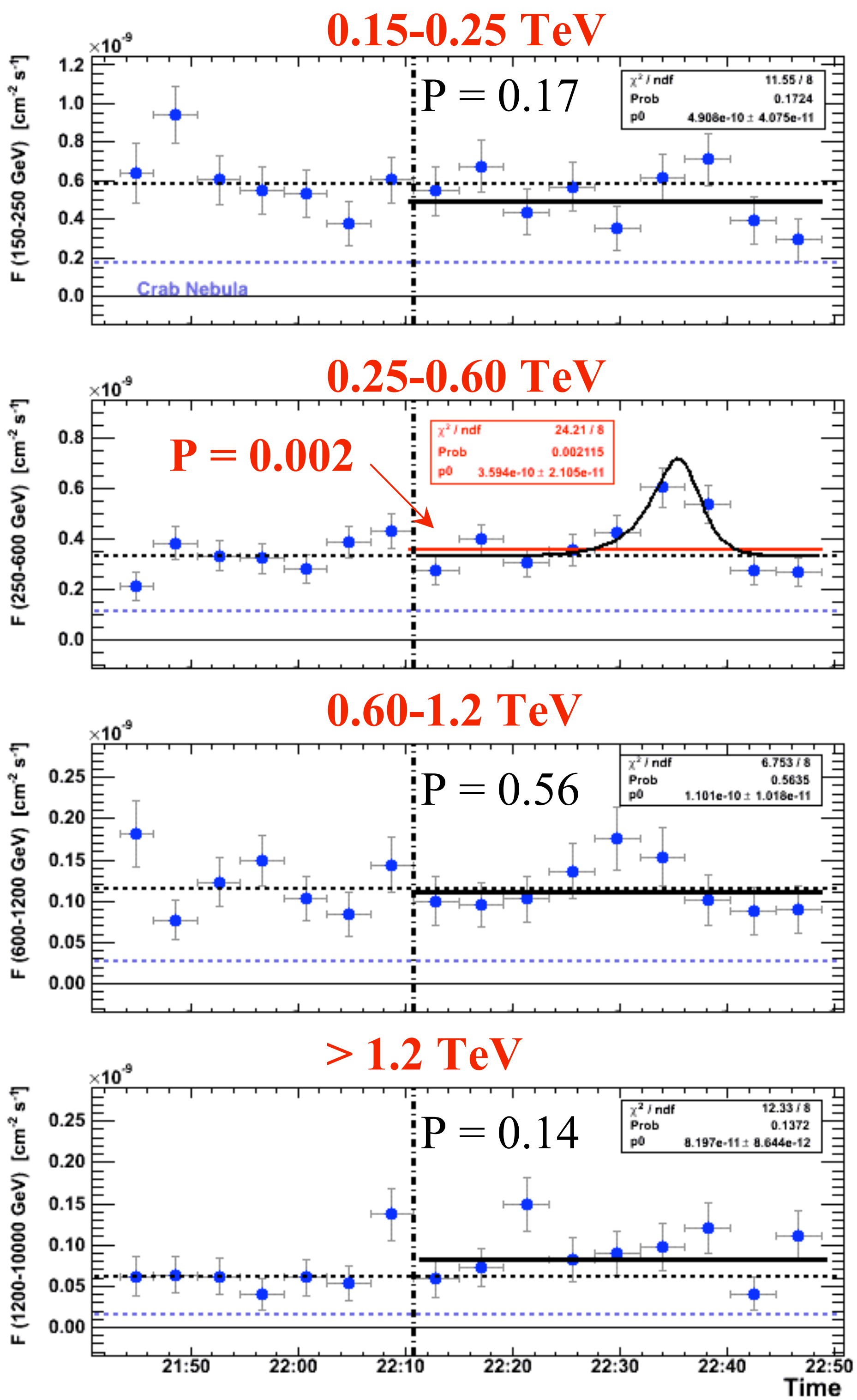
6 - Detection of the IC peak in the SED for the most active nights

New IACTs increased our capability to study blazars (low/high)

GLAST will increase it further next year

Good times for gamma-ray astronomy !!

backup



LCs for different energy ranges (4 min bins)

Active night: June 30

Flare is NOT seen in all energies

All energies are compatible with a constant flux emission, except for the range 0.25-0.60 TeV, where a constant emission is highly improbable

Results from fit with the idealistic flare function

$$F(t) = a + \frac{b}{2^{-\frac{t-t_0}{c}} + 2^{\frac{t-t_0}{d}}}$$

a: pedestal (not fit)

b: amplitude of flux variation

t_0: ~ peak position

c, d: flux-doubling times

E > 150 GeV

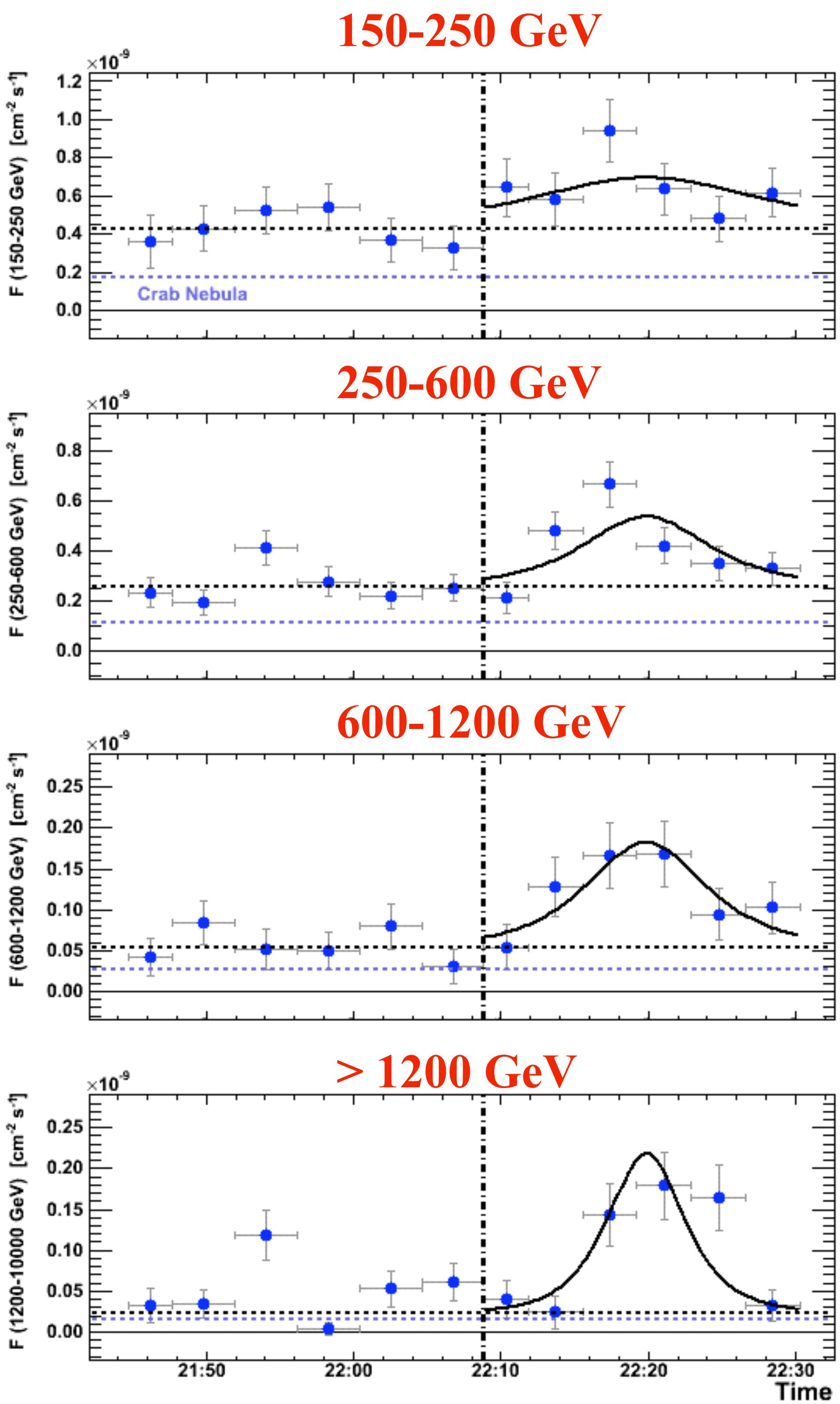
	b ($\frac{10^{-10}\ ph}{cm^2 \cdot s}$)	c (s)	d (s)	χ^2/NDF[d]	P[e] (%)
Jun30	13.2±4.7	81±41	50±23	20.0/15	17.3[f]
Jul09	20.3±3.3	95±24	185±40	4.2/7	75.8

Fit gives rather compatible numbers for these 2 energy ranges

July 9th: Combined fit to all LCs with symmetric flare (c=d); Chi2/NDF =14/12

P = 0.3

Energy Range (TeV)	a[a] ($\frac{10^{-10}\ ph}{cm^2 \cdot s}$)	a (Crab Units)	b ($\frac{10^{-10}\ ph}{cm^2 \cdot s}$)	c (s)	$t_0 - t_0^{LC\ E\ 0.15-0.25TeV}$[b] ($s$)
0.15-0.25	4.23±0.49	2.48±0.28	8.6±3.7	143±92	0 ± 68
0.25-0.6	2.55±0.24	2.32±0.09	9.3±2.5	95±28	7 ± 36
0.6-1.2	0.53±0.10	1.96±0.37	2.7±0.9	146±56	111 ± 91
1.2-10	0.23±0.06	1.51 ±0.39	4.0±0.9	103±19	239 ± 40



LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges

Combined fit with flare location common for all energy ranges is less probable

Chi2/NDF =25.6/15 (P =0.04)

If flare position is the same, then the shape of the flare should change with energy

Results from fit with the idealistic flare function

$$F(t) = a + \frac{b}{2^{-\frac{t-t_0}{c}} + 2^{\frac{t-t_0}{d}}}$$

a: pedestal (not fit)

b: amplitude of flux variation

t_0: ~ peak position

c, d: flux-doubling times

E > 150 GeV

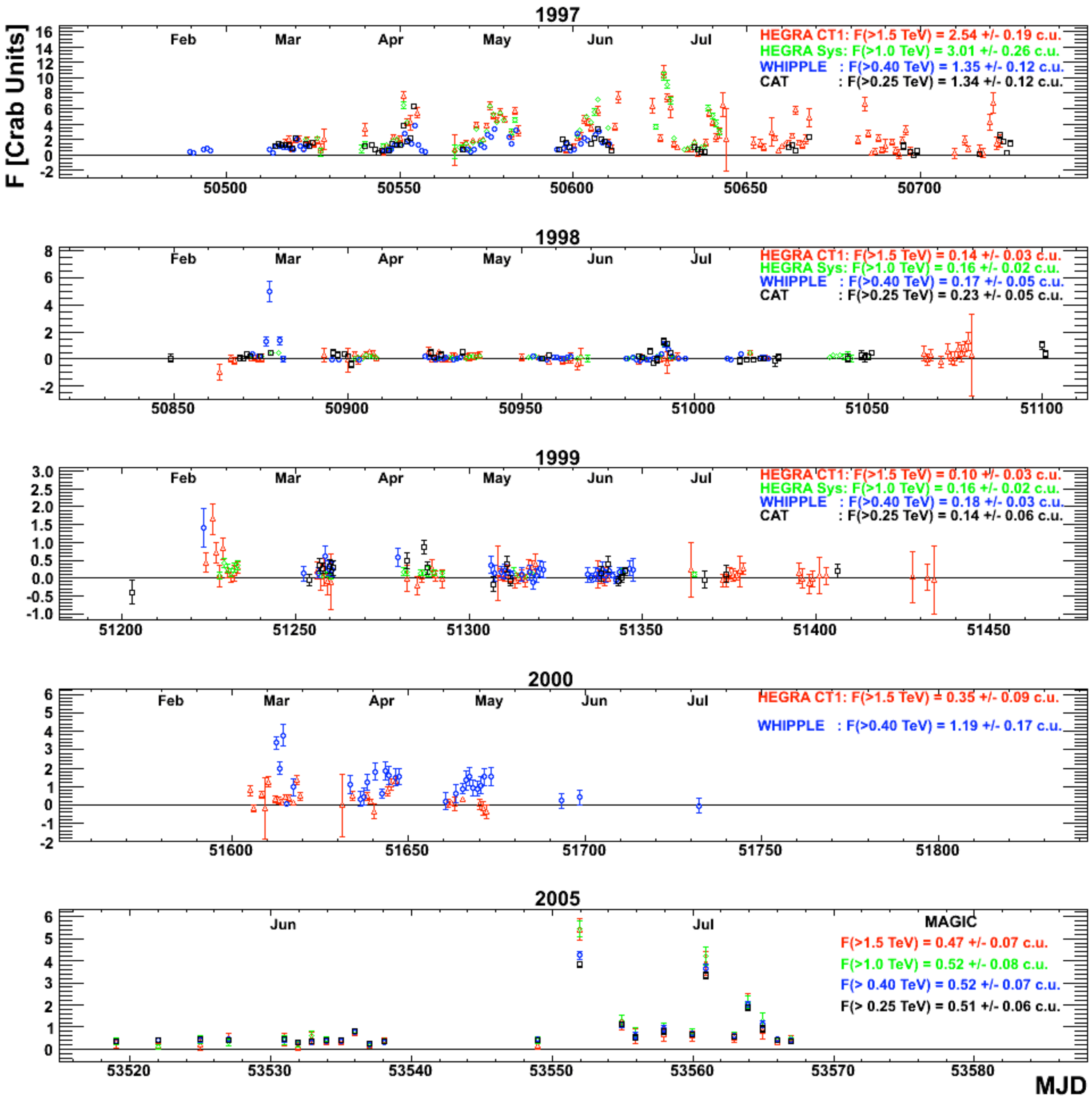
	b $(\frac{10^{-10}\ ph}{cm^2 \cdot s})$	c (s)	d (s)	χ^2/NDF [d]	P [e] (%)
Jun30	13.2±4.7	81±41	50±23	20.0/15	17.3[f]
Jul09	20.3±3.3	95±24	185±40	4.2/7	75.8

July 9th: Combined fit to all LCs with symmetric flare (c=d); Chi2/NDF =25.6/15
Common flare location for all energy ranges

P = 0.04

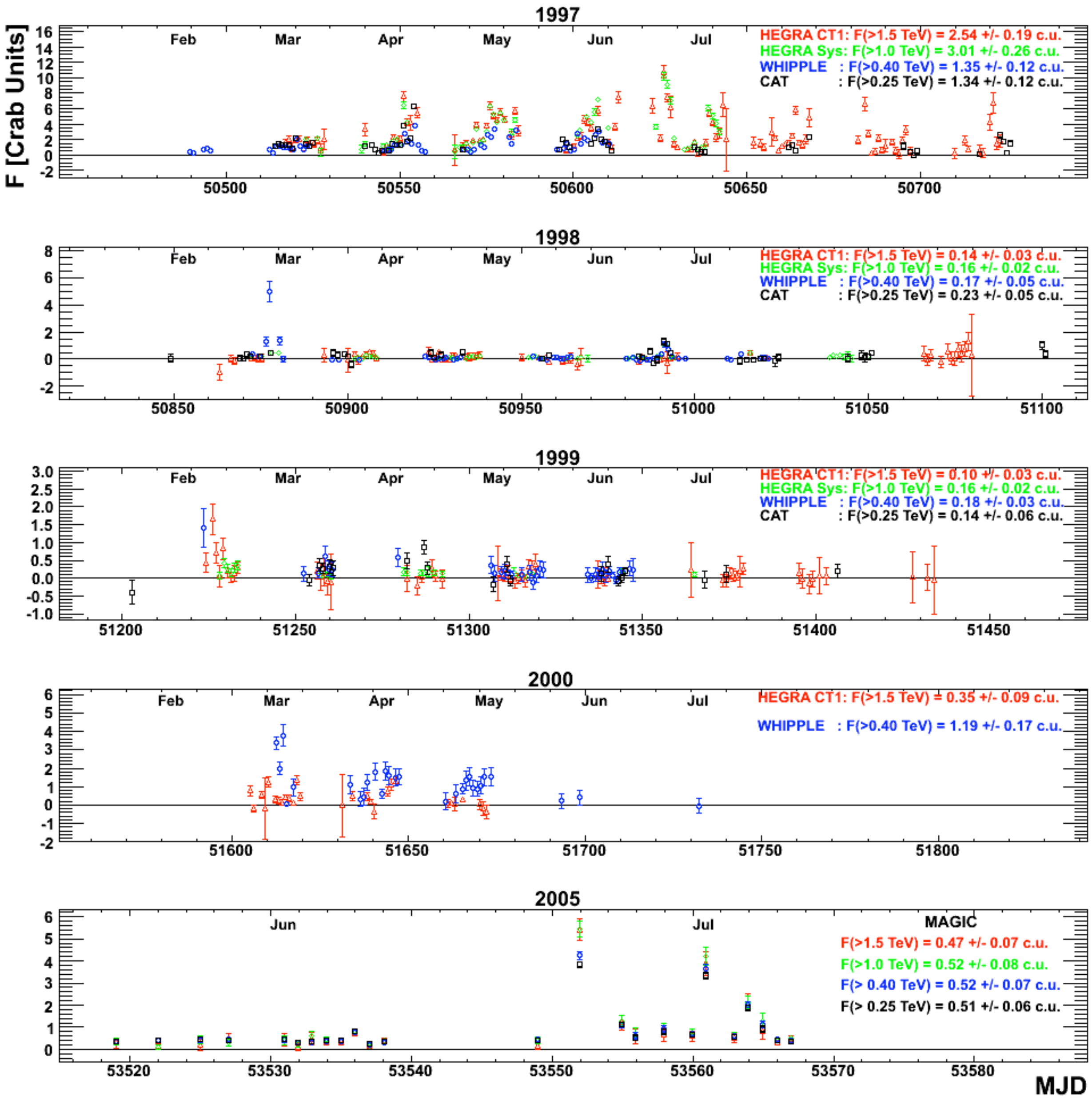
Energy Range (TeV)	a [a] $(\frac{10^{-10}\ ph}{cm^2 \cdot s})$	a *(Crab Units)*	b $(\frac{10^{-10}\ ph}{cm^2 \cdot s})$	c (s)	$t_0 - t_0^{LC\ E\ 0.15-0.25TeV}$ [b] (s)
0.15-0.25	4.23±0.49	2.48±0.28	5.4±2.2	301±210	0 ± 42
0.25-0.6	2.55±0.24	2.32±0.09	5.7±1.5	162±63	0 ± 42
0.6-1.2	0.53±0.10	1.96±0.37	2.6±0.8	153±56	0 ± 42
1.2-10	0.23±0.06	1.51 ±0.39	3.9±1.0	97±22	0 ± 42

2.3 historical light curves (@ VHE) from Mrk501



In 2005 campaign, lower flux than in 1997, but larger than in 1998-1999

2.3 historical light curves (@ VHE) from Mrk501



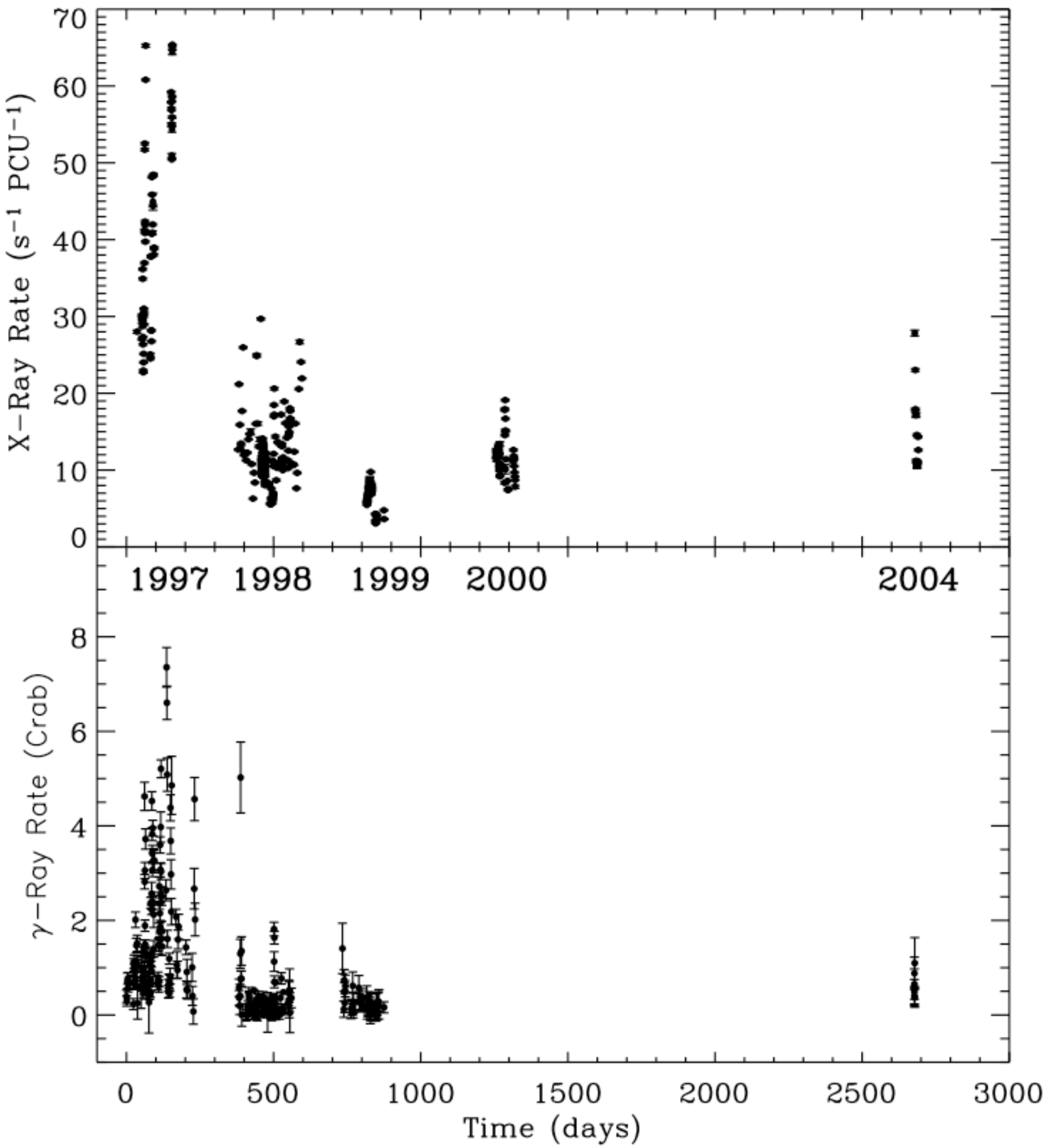
23 days periodicity observed by HEGRA CT 1 data in 1997

Kranich 2000 (PhD thesis)

Osone 2006 (Astropart. Phys. 26), also in RXTE data

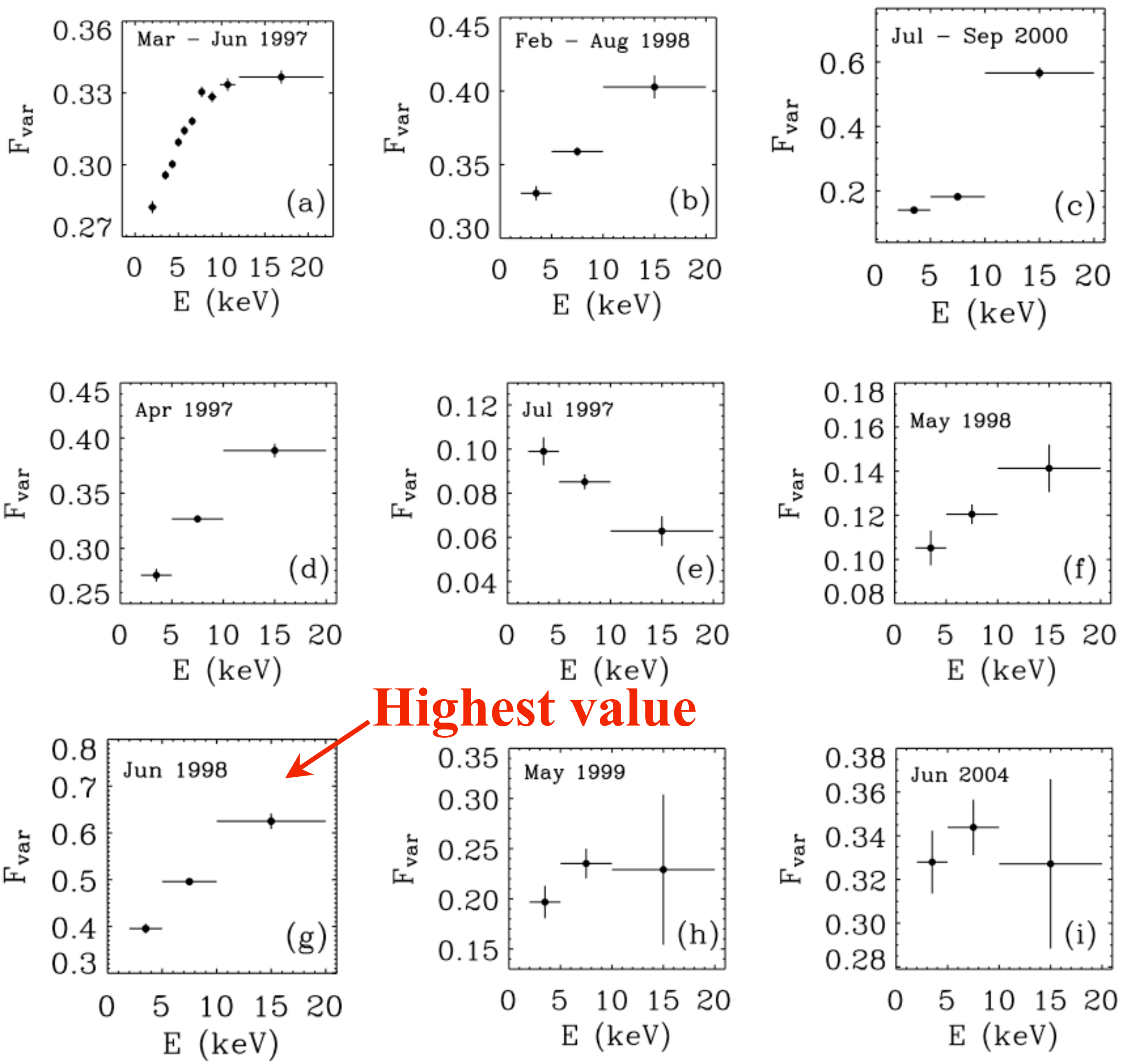
In 2005 campaign, lower flux than in 1997, but larger than in 1998-1999

Comparison with Fvar at X-rays (Gliozzi et al. 2006, ApJ, 646)



Collection of X-ray and gamma-ray data over years 1997-2000 and 2004

Comparison with Fvar at X-rays (Gliozzi et al. 2006, ApJ, 646)

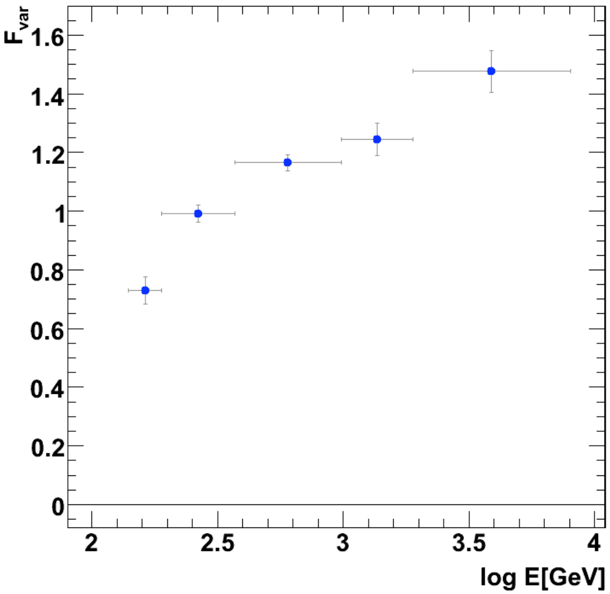


In general, F_{var} increases with energy

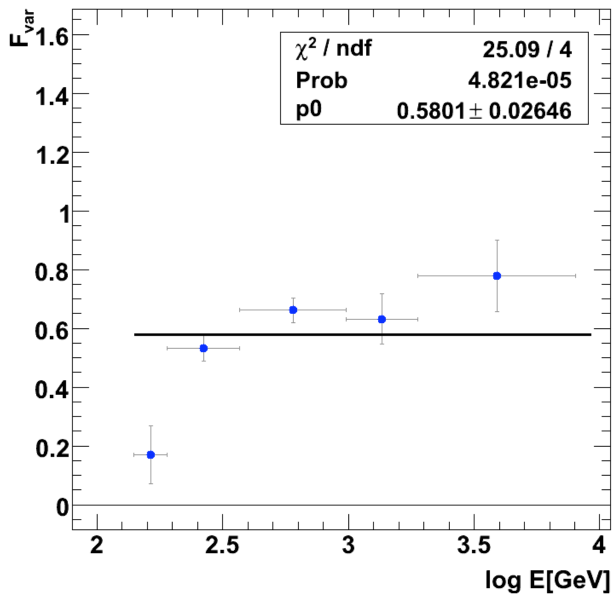
Highest F_{var} value was not obtained in 2007, when X-ray (and gamma) flux was highest

Fractional variability vs energy

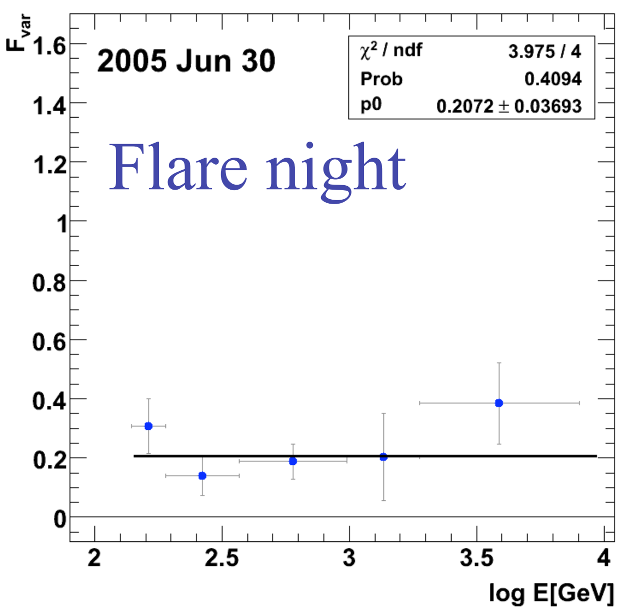
All nights included

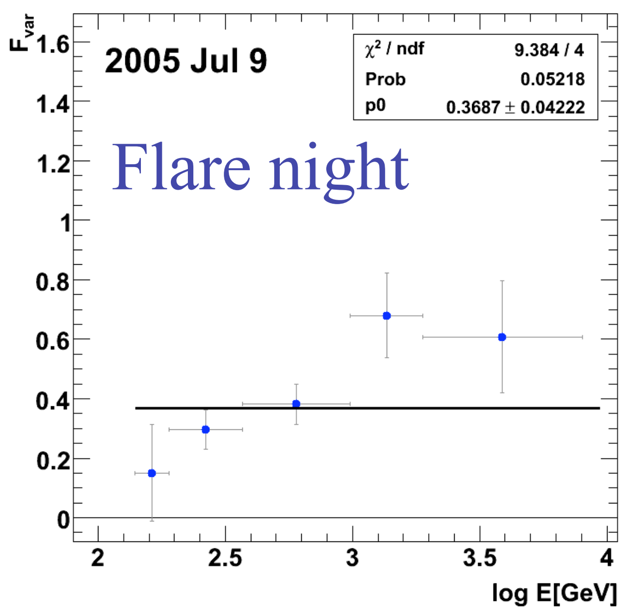


Flare nights excluded



F_{var} increases with energy





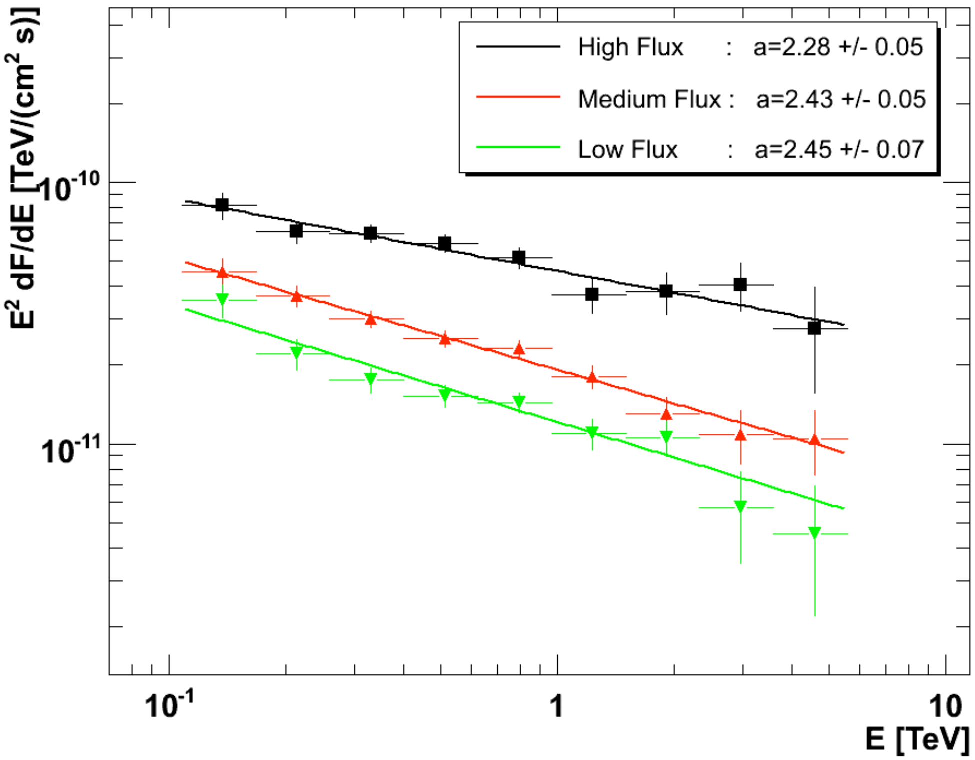
F_{var} seems to increase with energy for Jul 9 flare

2.4 - Overall flux levels

Low : Flux (E>150 GeV) < 0.5 Crab 12 days

Medium : Flux > 0.5 Crab && Flux < 1.0 Crab 8 days

High : Flux > 1.0 Crab (Flare nights excluded) 2 days



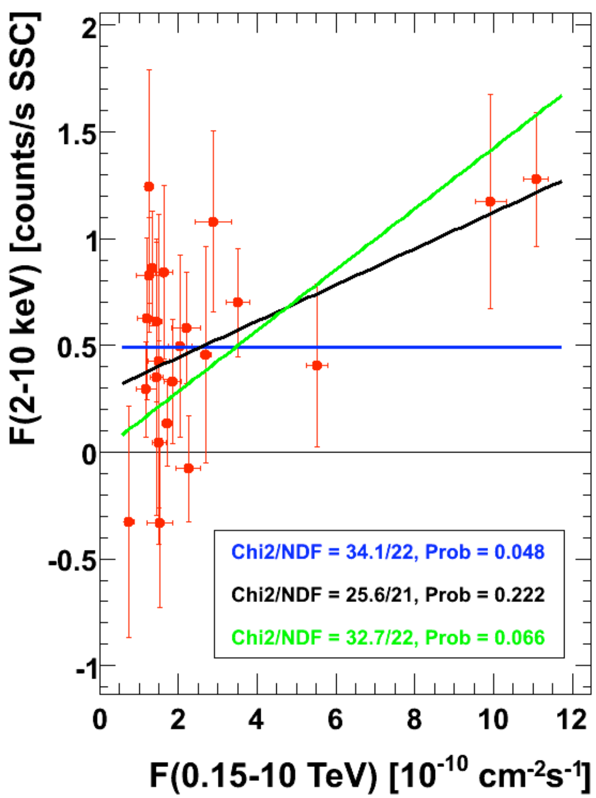
Evidence of hardening of spectra with flux level

Agreement with previous evidences (Pian et al 1998, Tavecchio et al. 2001…) which used the VERY BIG flare of 1997

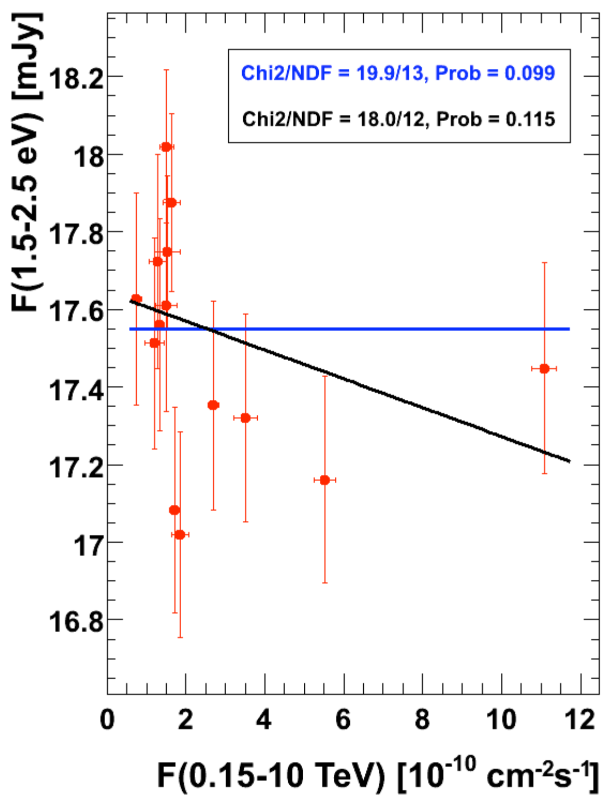
Flux Level[m]	T_{obs} [a] (h)	ZA[b] (deg)	S_{comb}[c] sigma	$F_{>150\ GeV}$[d] ($\frac{10^{-10}\ ph}{cm^2 \cdot s}$)	$F_{>150\ GeV}$ (Crab Units)	K_0[e] ($\frac{10^{-10}\ ph}{cm^2 \cdot s \cdot 0.3TeV}$)	a[f]	χ^2/NDF[g]	P[h] (%)
Low	17.2	9.96-30.1	16.7	1.24± 0.08	0.39 ± 0.02	2.31±0.13	2.45 ± 0.07	7.8/7	34.6
Medium	11.0	9.95-30.0	22.8	2.11± 0.09	0.66 ± 0.03	3.57±0.15	2.43 ± 0.05	2.9/7	89.4
High	1.52	9.95-22.3	21.7	4.62± 0.21	1.45 ± 0.07	7.13±0.32	2.28 ± 0.05	4.8/7	68.7

2.2- Frequency Correlations: data distributions from LCs

X-rays/γ-rays



Optical/ γ-rays



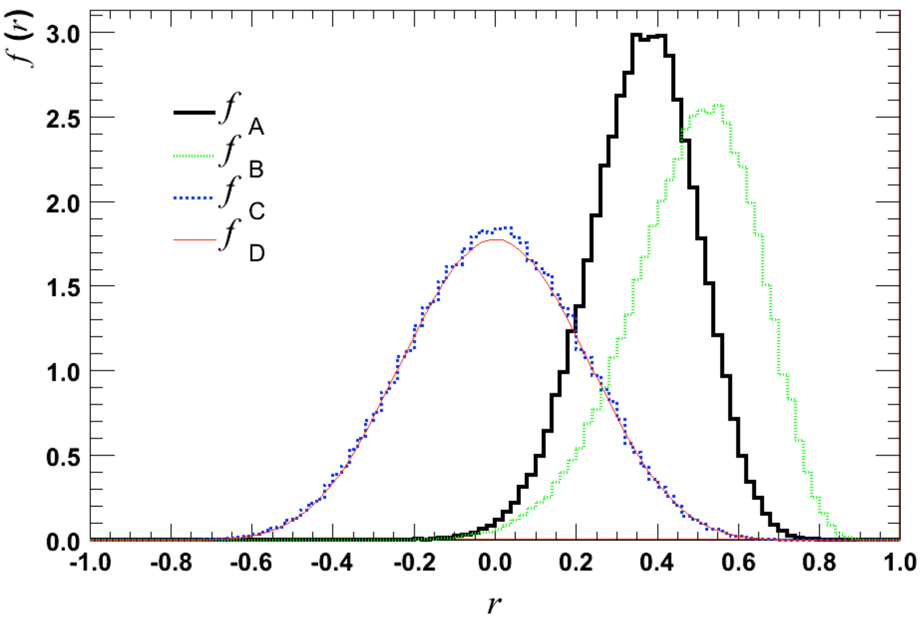
X-rays and optical flux measurment errors are relatively large

From these plots: existence of correlation is not evident.

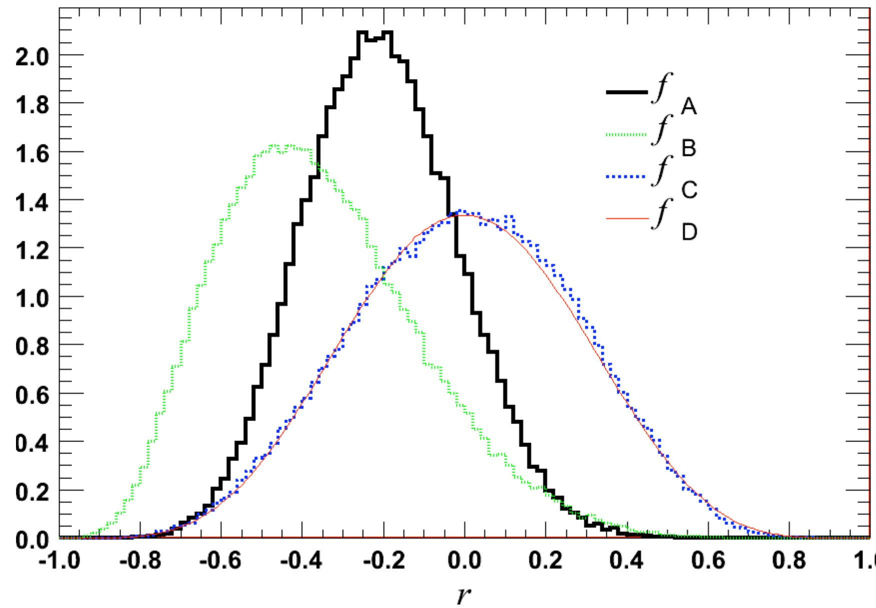
A correlation analysis is done in the paper: *X/γ* are linearly correlated (very probable) while both anti-correlation and no-correlation are possible for optical/*γ-rays*

Correlation analysis

Gamma/X-rays

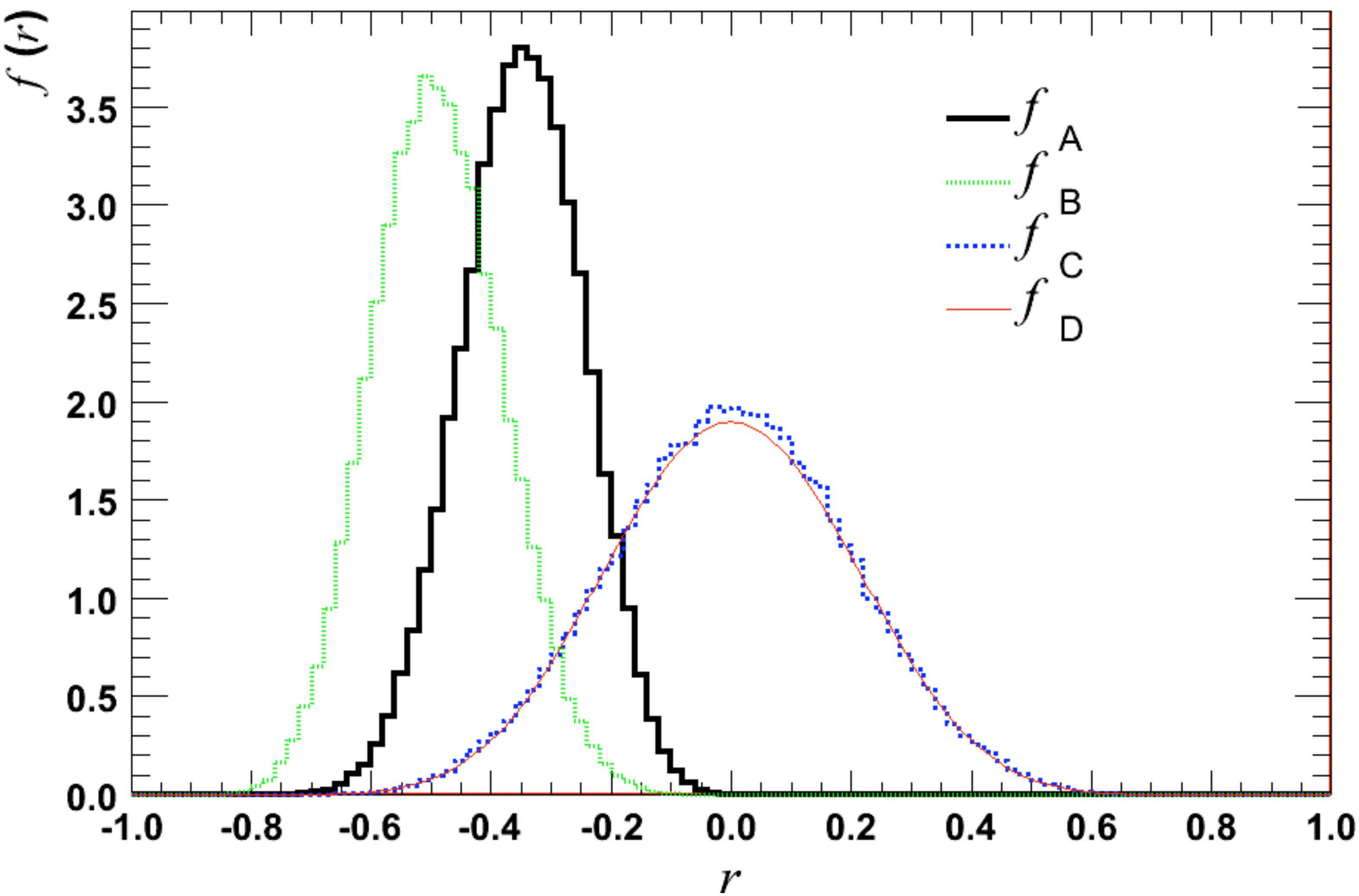


Gamma/optical

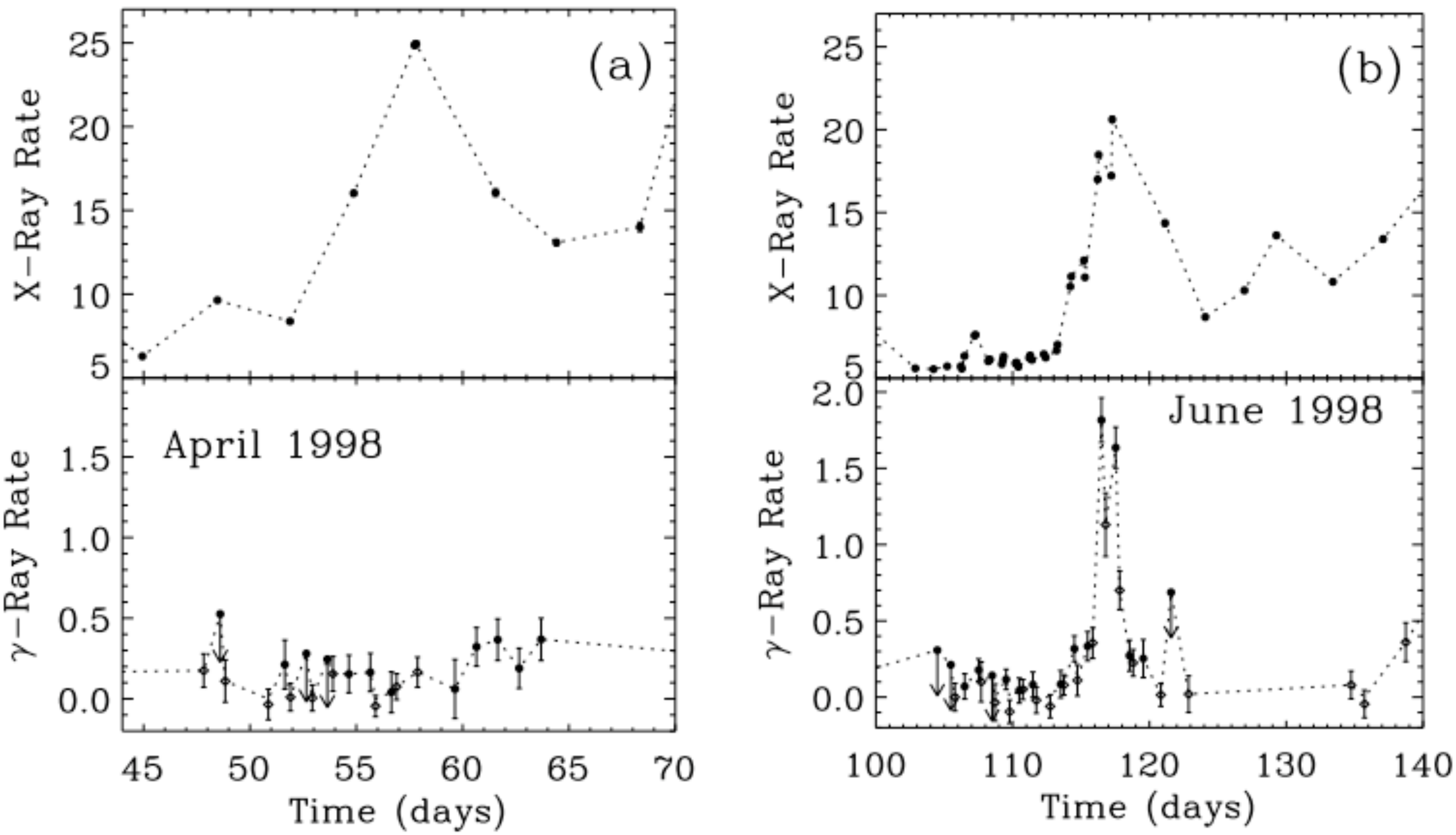


Correlation analysis

Spectral index - flux



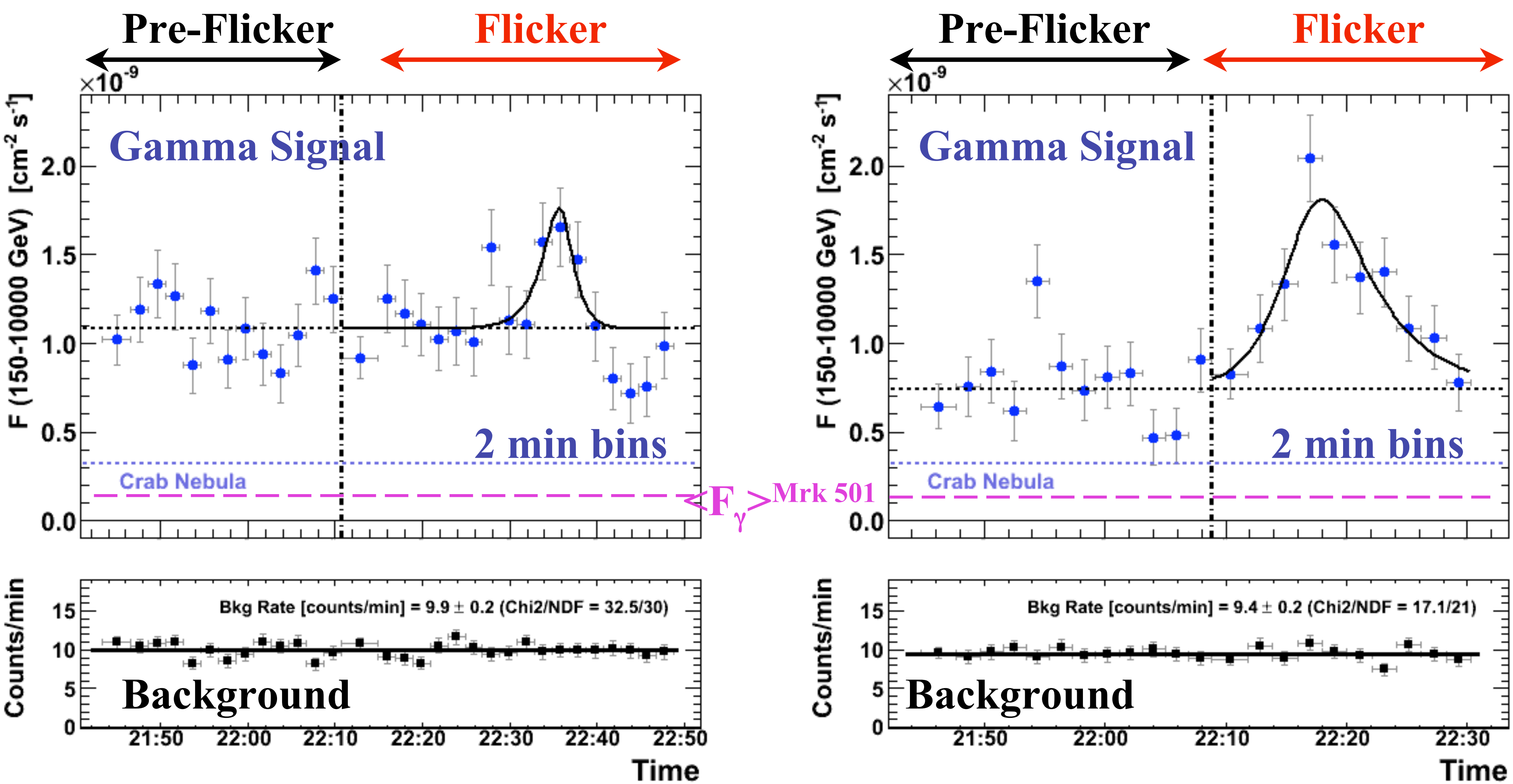
Correltation X-rays / Gamma-rays in flares



2.7 Spectra for the flaring nights (pre-flicker and flicker)

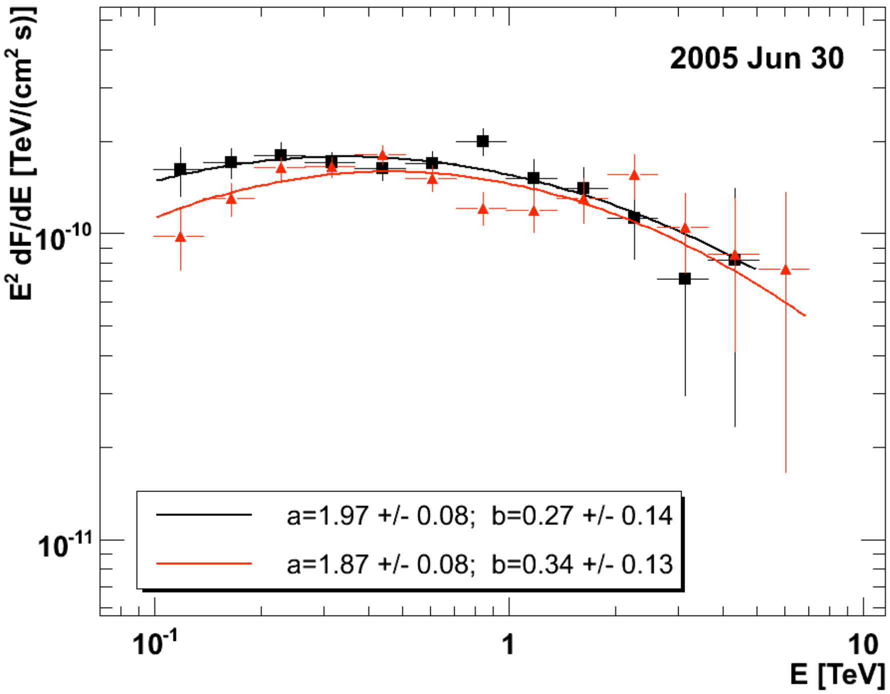
Definition of **pre-flicker** and **flicker** in the LC

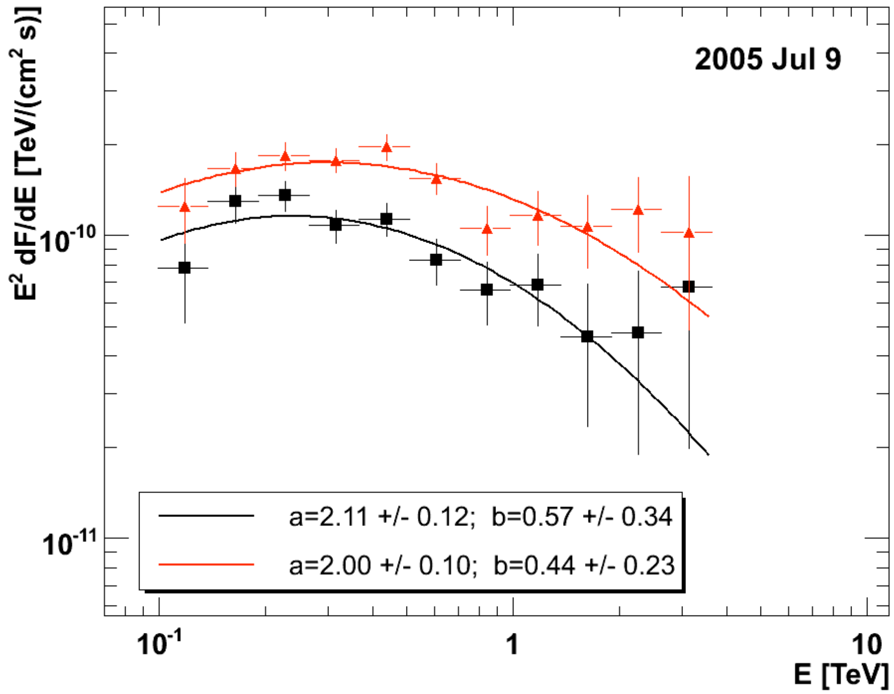
June 30th ⟵ Highest VHE activity ⟶ July 9th



2.7 Spectra for the flaring nights (pre-flicker and flicker)

During **flickering**, the spectra seems a bit harder; yet not significant

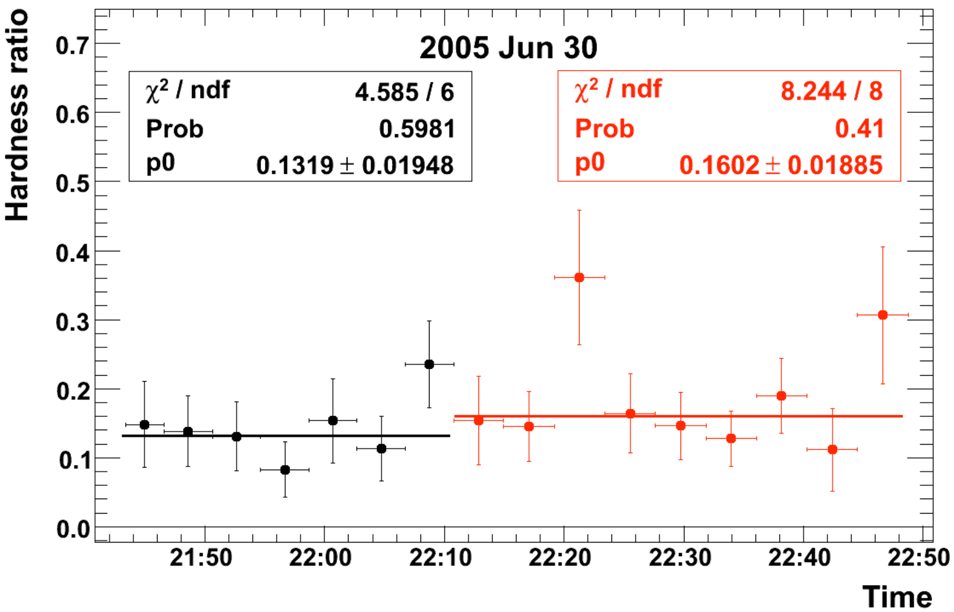


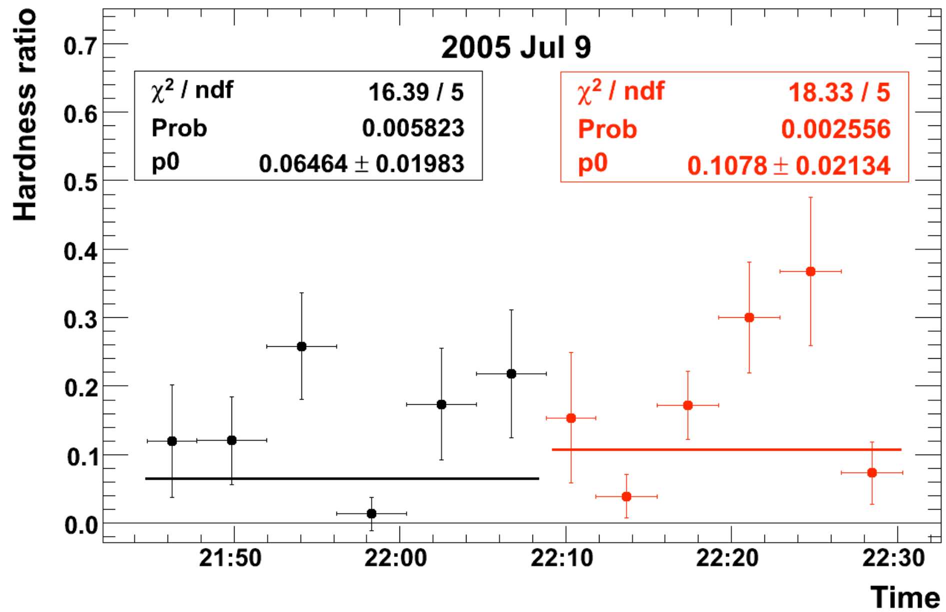


Results of the fit with a log-parabola on the active nights

	MJD Start	T_{obs} [a] (h)	S_{comb} [c] sigma	$F_{>150\ GeV}$ [d] $(\frac{10^{-10}\ ph}{cm^2 \cdot s})$	$F_{>150\ GeV}$ $(Crab\ Units)$	K_0 $(\frac{10^{-10}\ ph}{cm^2 \cdot s \cdot 0.3TeV})$	a	b	χ^2/NDF	P [h] (%)
Jun30	53551.905	0.46	22.3	10.99±0.48	3.46±0.15	19.8±1.0	1.97±0.08	0.27±0.14	8.2/9	51.2
	53551.924	0.63	24.7	11.15±0.43	3.50±0.14	17.2±0.8	1.87±0.08	0.34±0.13	13.8/10	18.1
Jul09	53560.906	0.40	15.2	7.64 ± 0.48	2.40 ± 0.15	12.7±1.1	2.11±0.12	0.57±0.34	6.4/8	59.8
	53560.923	0.36	19.6	12.39 ± 0.60	3.89 ± 0.19	19.3±1.3	2.00±0.10	0.44±0.23	8.9/8	35.2

2.8 - Hardness ratio F(1.2 −10TeV)/F(0.25−1.2TeV) vs time

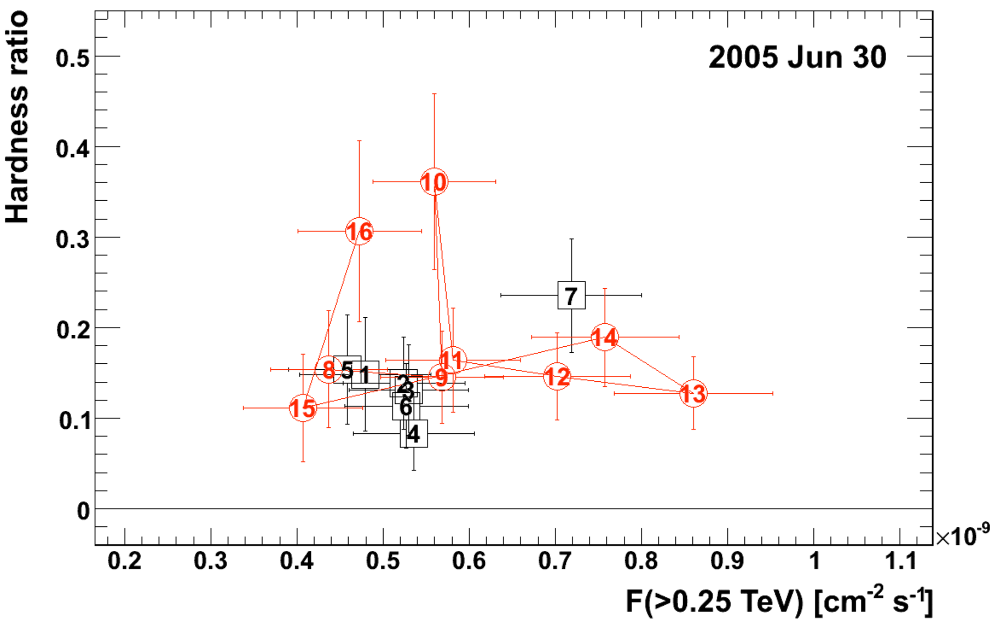


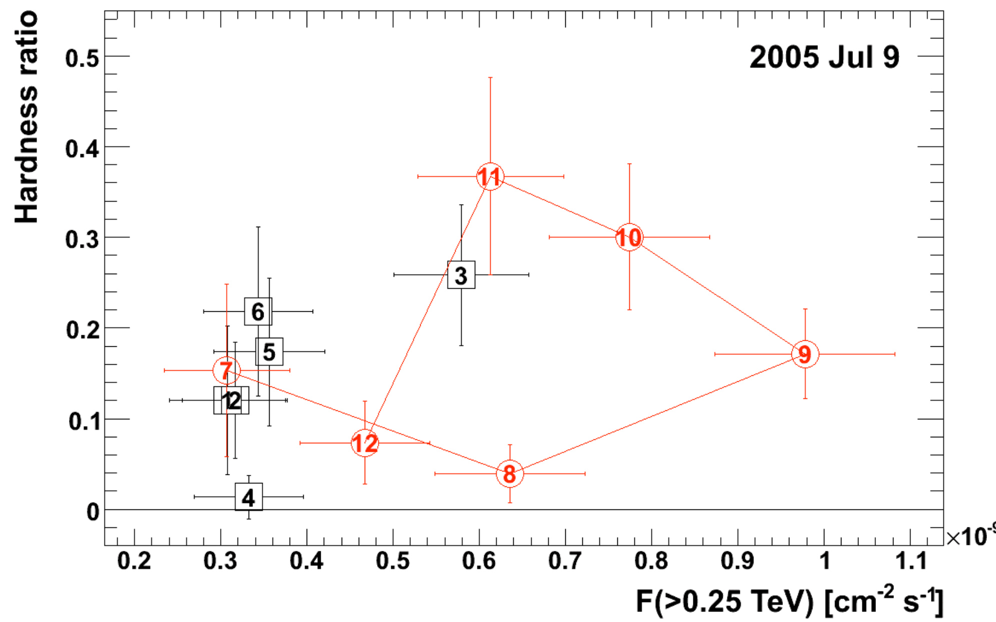


Hardness ratio is a bit higher during the **flickering** for both nights, but not very significant (1-2 sigmas)

Hardness ratio is probably NOT constant during flare July 9th

2.9 - Hardness ratio F(1.2 −10TeV)/F(0.25−1.2TeV) vs Flux

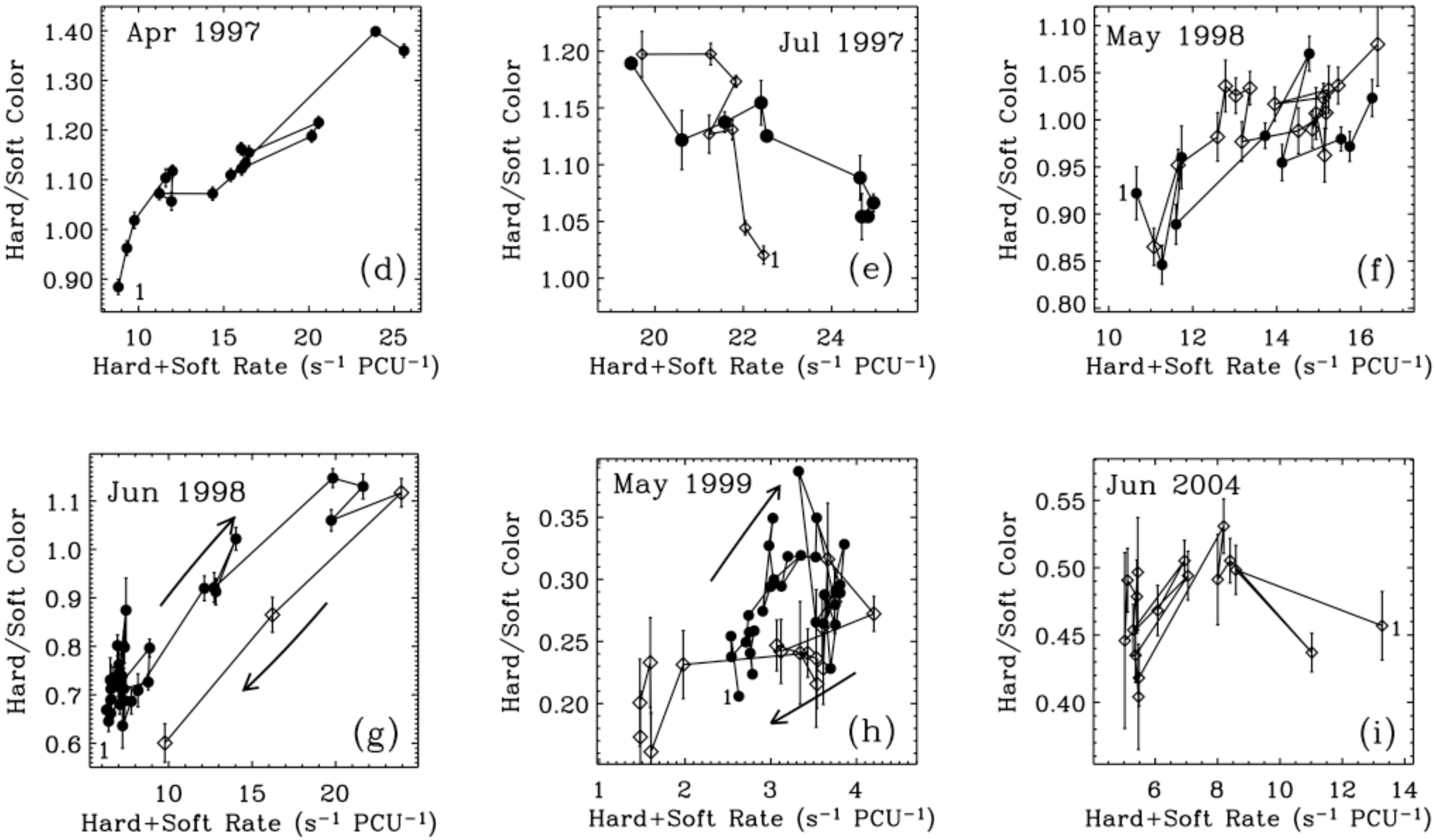




Larger spread in points from flickering (with respect to pre-flickering)

Evolution of points for flare July 9th shows a clear loop pattern rotating counterclockwise; this might indicate similar variability, cooling, acceleration timescales, as pointed out by Kirk&Mastichiadis (1999)

Comparison with Hardness ratio at X-rays (Gliozzi et al. 2006)



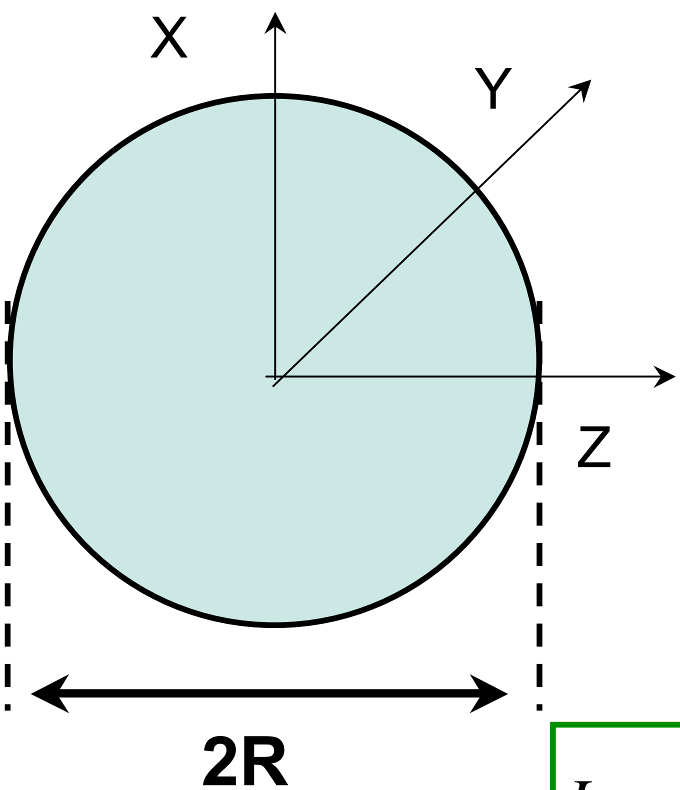
When pattern is clear, it is actually rotating clockwise; i.e.
opposite pattern to the gamma-ray flare observed in July 9th

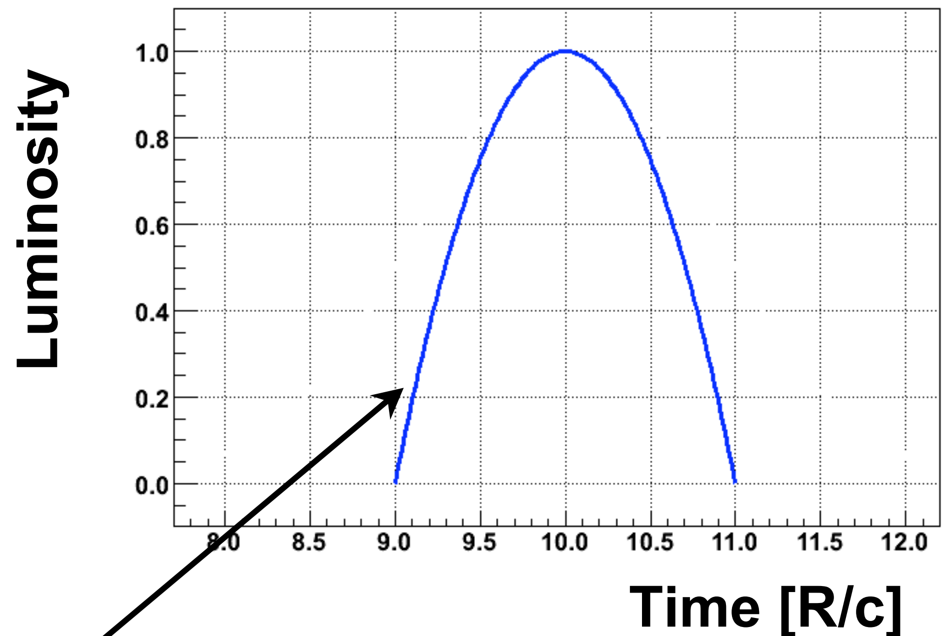
2 - Variability and size of the emitting region

In the reference frame:

Let’s assume a spherical region of radius R emitting photons isotropically at a time t0 for a infinitessimal time window (DeltaT -> 0)

Light pulse (light curve) seen by observer located **10xR** from the center of the sphere





$$L = \frac{K}{R^2} \bullet \left(R^2 - \left[t \cdot c - 10 \cdot R \right]^2 \right)$$

t=9.0R/c; L=0.0

t=9.3R/c; L=0.5

t=9.5R/c; L=0.75

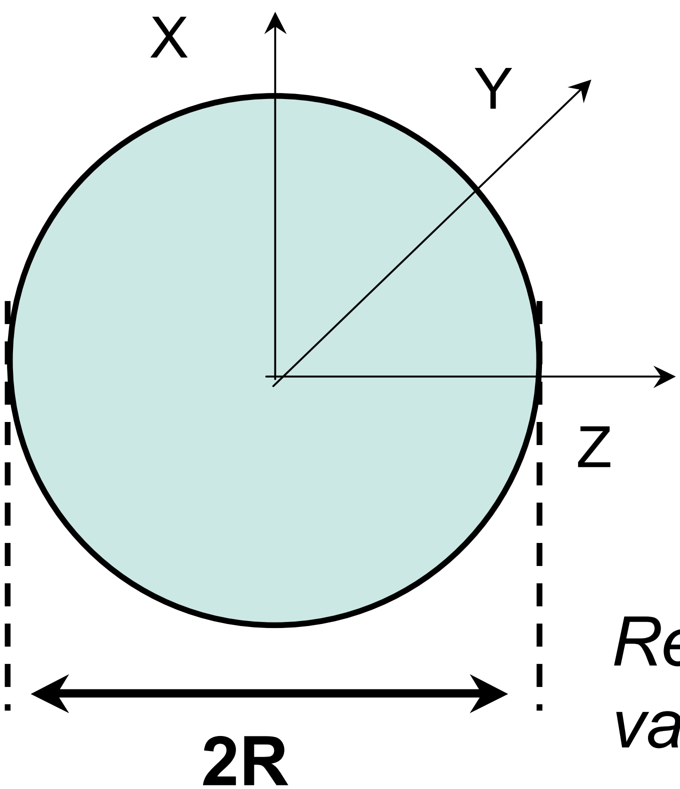
t=10R/c; L=1.0

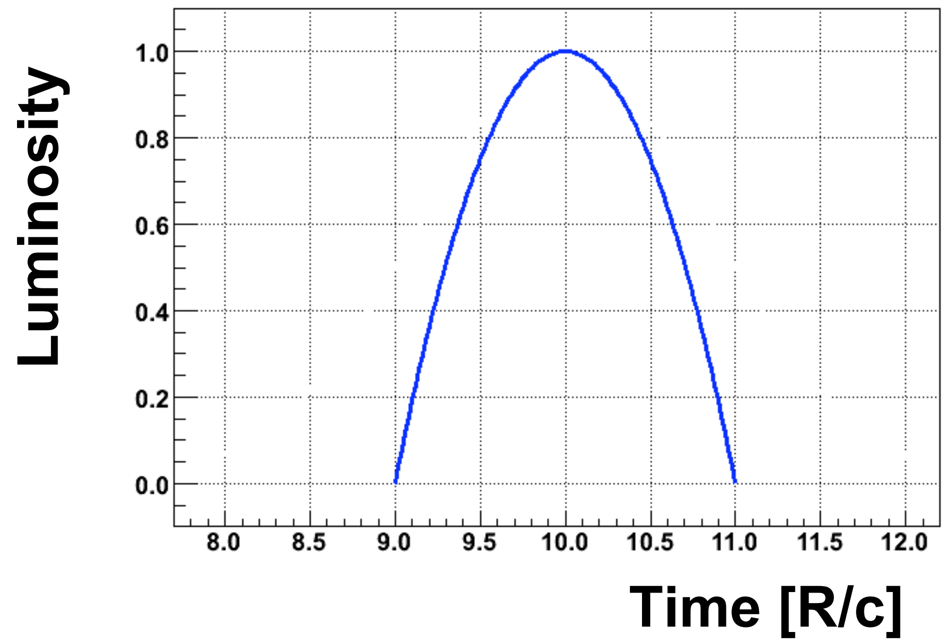
2 - Variability and size of the emitting region

In the reference frame:

Let's assume a spherical region of radius R emitting photons isotropically at a time t0 for a infinitessimal time window (DeltaT -> 0)

Light pulse (light curve) seen by observer located 10xR from the center of the sphere





Relation between flux variability and size of emitting region

$$\boxed{R = c\, t_{var} / 2}$$