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

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on behalf of the MAGIC collaboration

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OUTLINE

1- Motivation to observe Mrk 501

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

3- Conclusions and outlook

1- Motivation to observe Mrk 501 (again…)

The physics related to Mrk 501 (and AGNs in general) is not yet understood, despite these guys have been studied for >= 10 years ***(see talks from Monday; Padovani, Celotti…)***

Culprits

1 - Time evolving broad band spectra

Coordination of instruments covering different energies needed

2 - Poor sensitivity to study high energy part (E>1 GeV)

Large observation times (with EGRET and "old" IACTs) were required to have a decent signal to make physics.
Most of our HBL's knowledge relates to the high state

Current experimental data allows for a big inter-model and intra-model degeneracy

More and "higher quality" data required to constrain models

1- Motivation to observe Mrk 501 (again…)

Present and near future:

New Generation of IACTs came online (low Eth, high sensitivity)

GLAST in operation next year (~25 more sensitive than EGRET)

Excellent laboratory for studying High Energy blazar emission

Strong gamma ray source (0.2-0.5 crabs in low state)
z = 0.034; low EBL absorption, we see "almost" intrinsic features

Things we know about Mrk 501 (and HBLs in general)

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

- Fast variations (few hours in VHE)
- X rays- Gamma-rays correlation (in general)

2- Analysis of the MAGIC data (24 nights, 32.2 h)

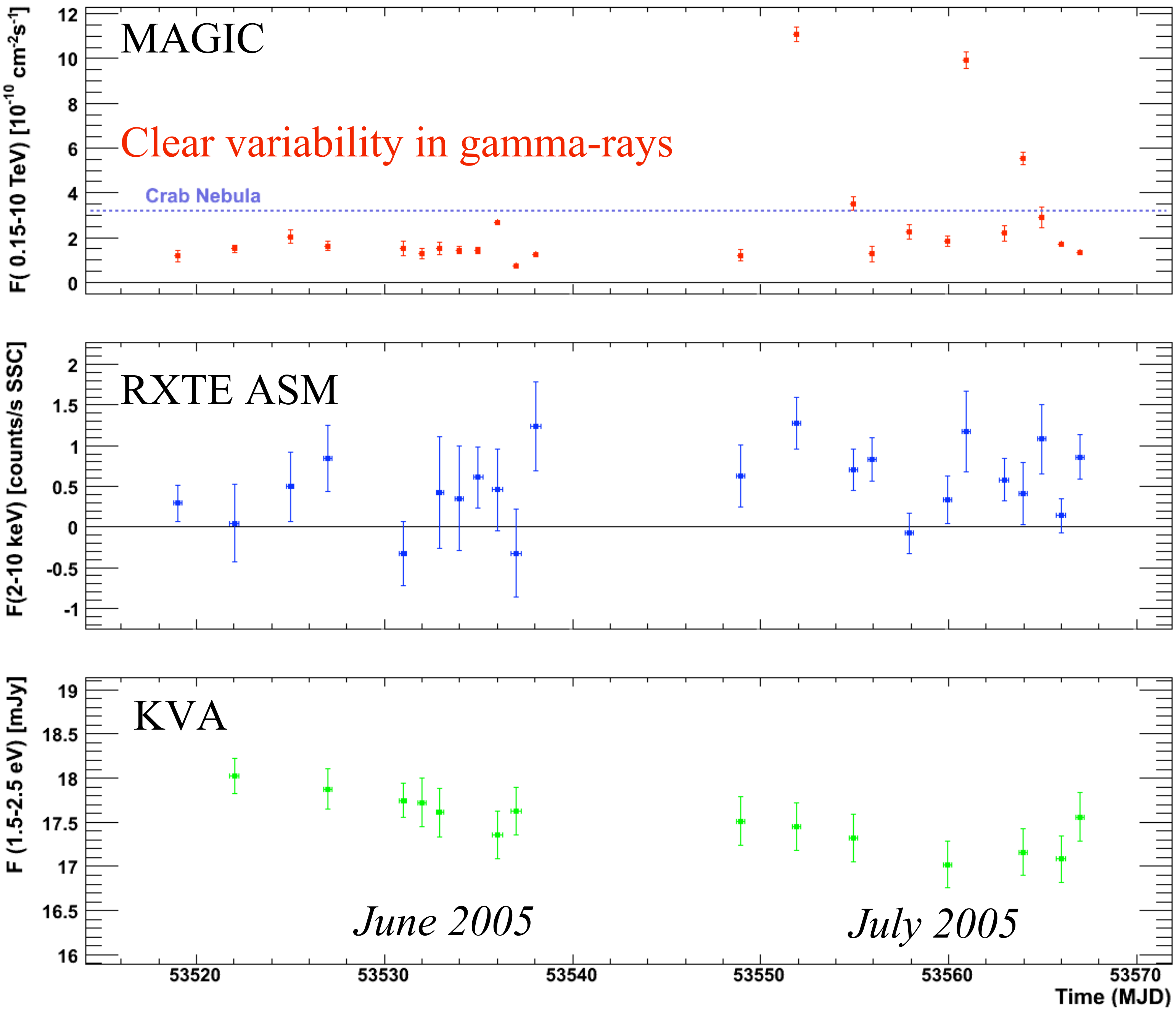
June-July 2005

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	0.91	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



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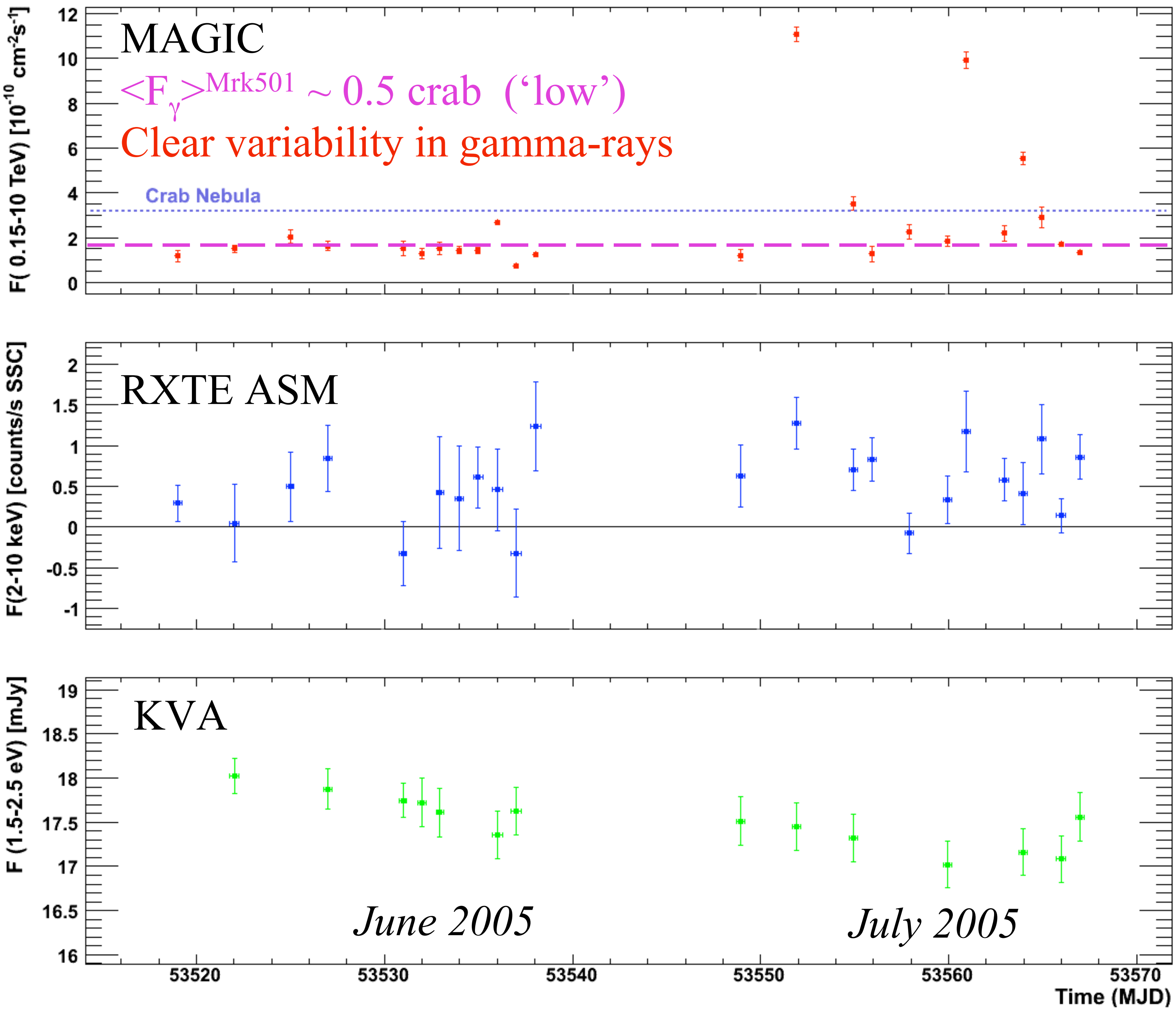

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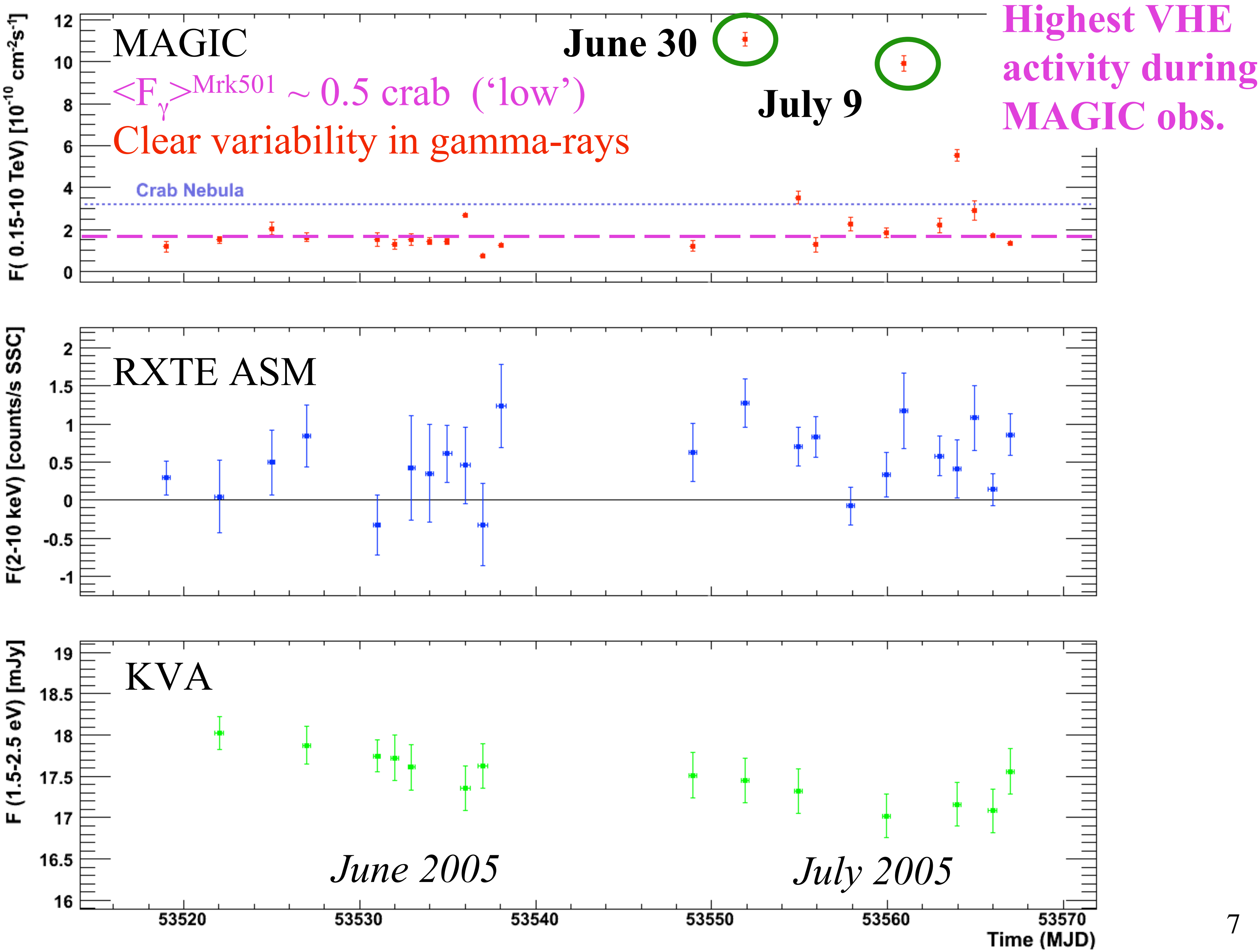
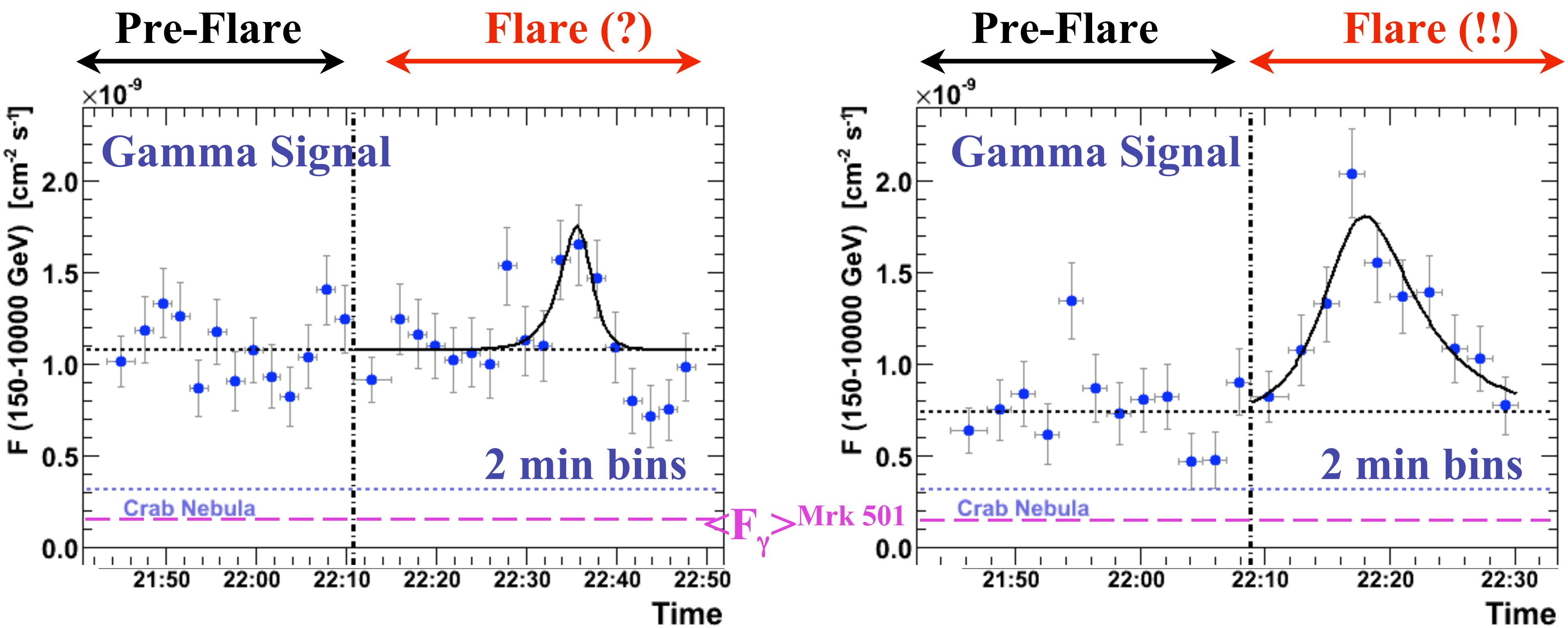


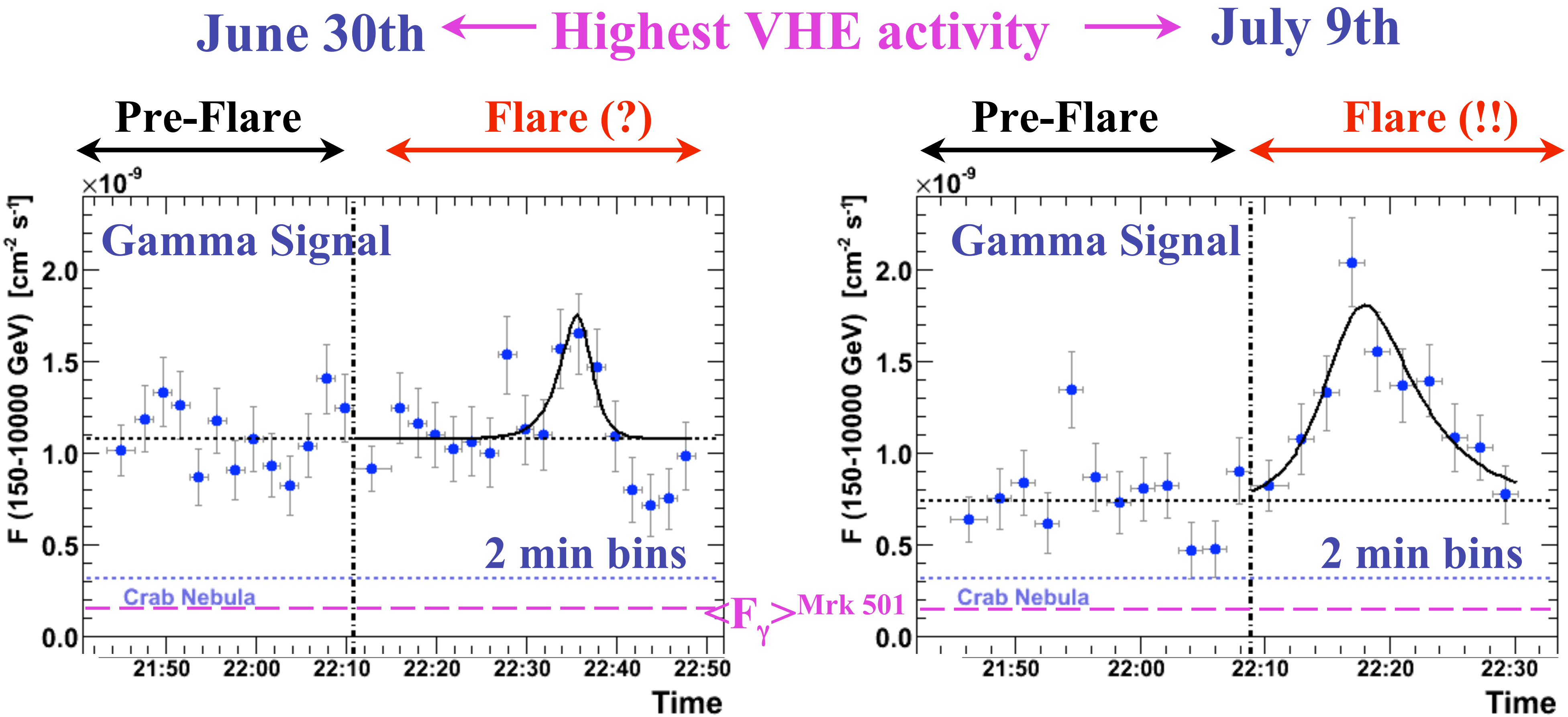
2.2- Intra-night flux variations (E > 150 GeV)

June 30th ⟵ Highest VHE activity ⟶ July 9th



Flaring and *Flickering* (see talk S.Wagner on Monday)

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



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)

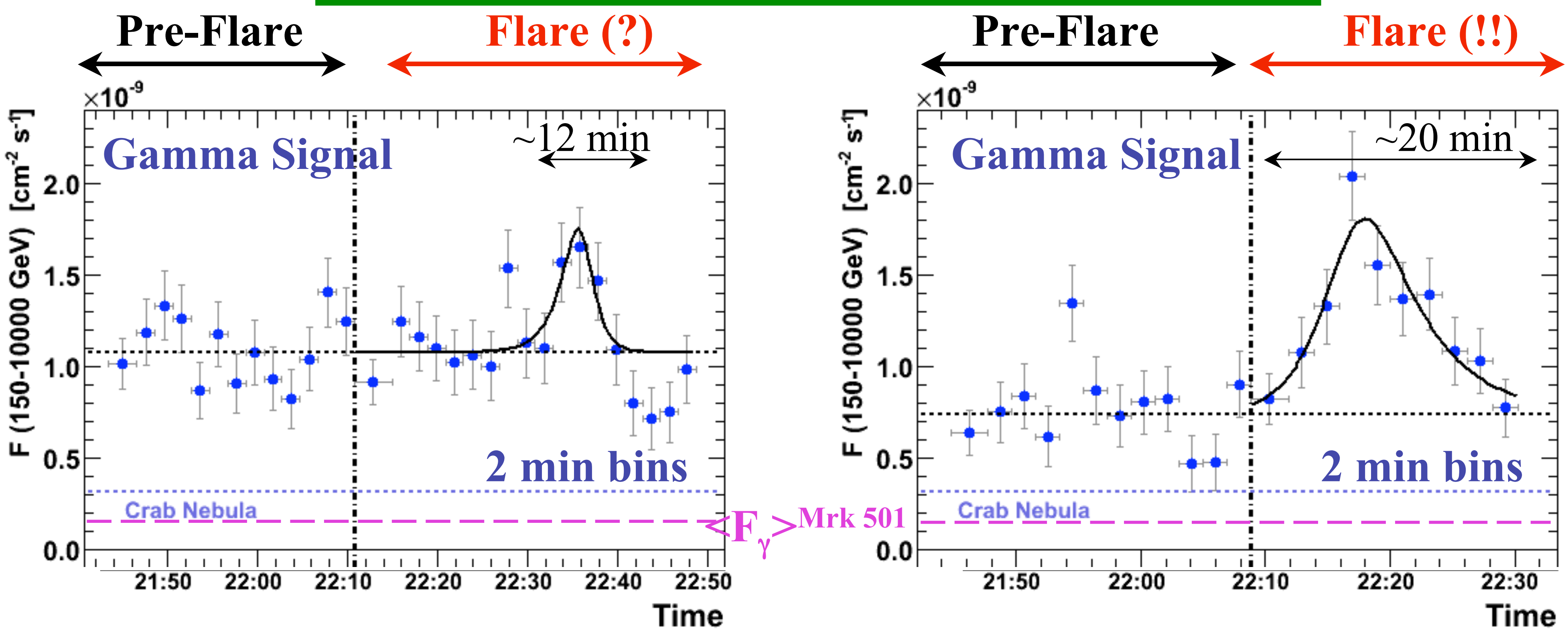
b: amplitude of flux variation

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**

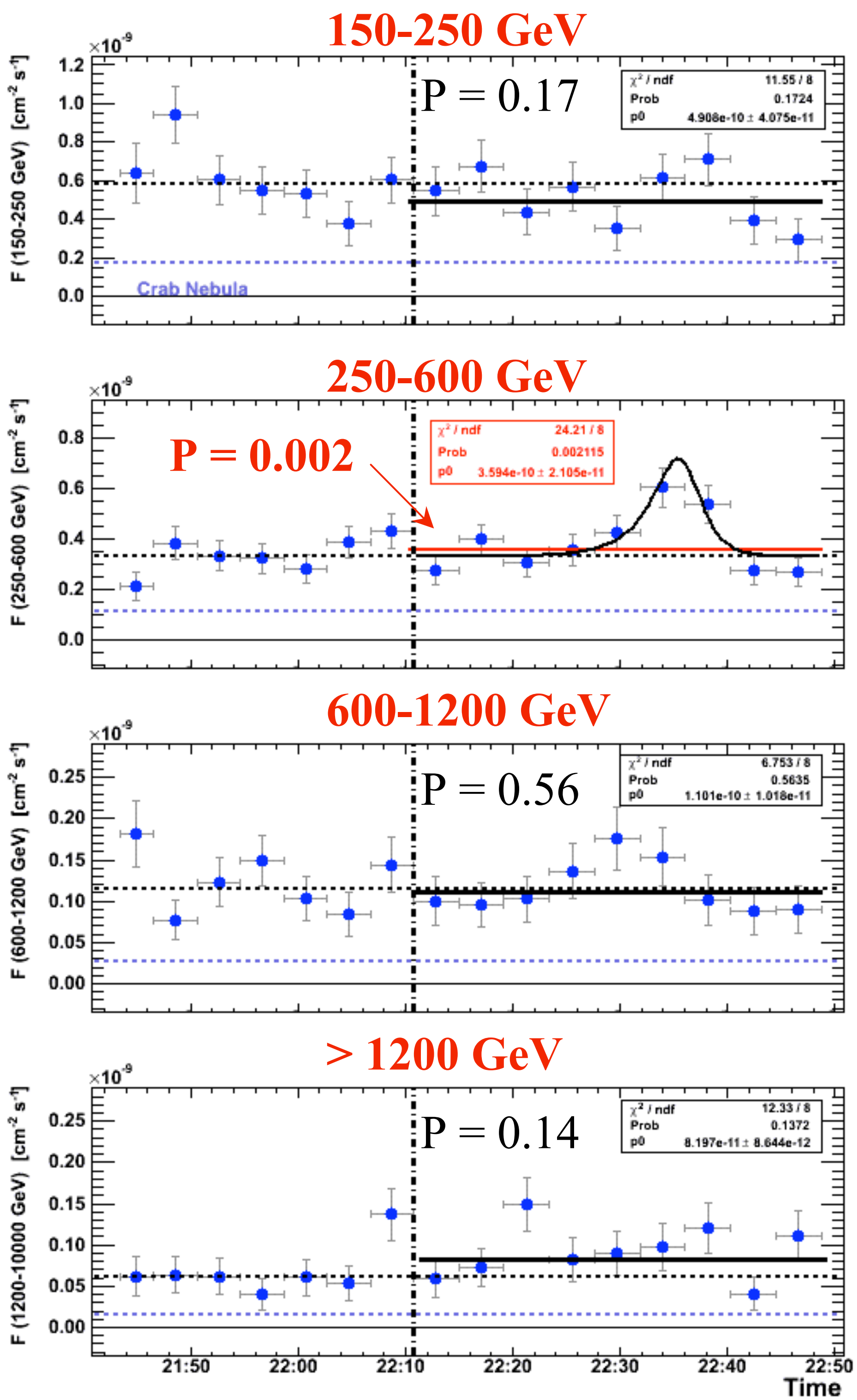
b $\left(\frac{10^{-10}\ ph}{cm^2 \cdot s}\right)$	c (s)	d (s)	χ^2/NDF[d]	P[e] (%)
13.2±4.7	81±41	50±23	20.0/15	17.3[f]
20.3±3.3	95±24	185±40	4.2/7	75.8

a: pedestal (not fit)

b: amplitude of flux variation

t_0: ~ peak position (not fit)

c, d: flux-doubling times

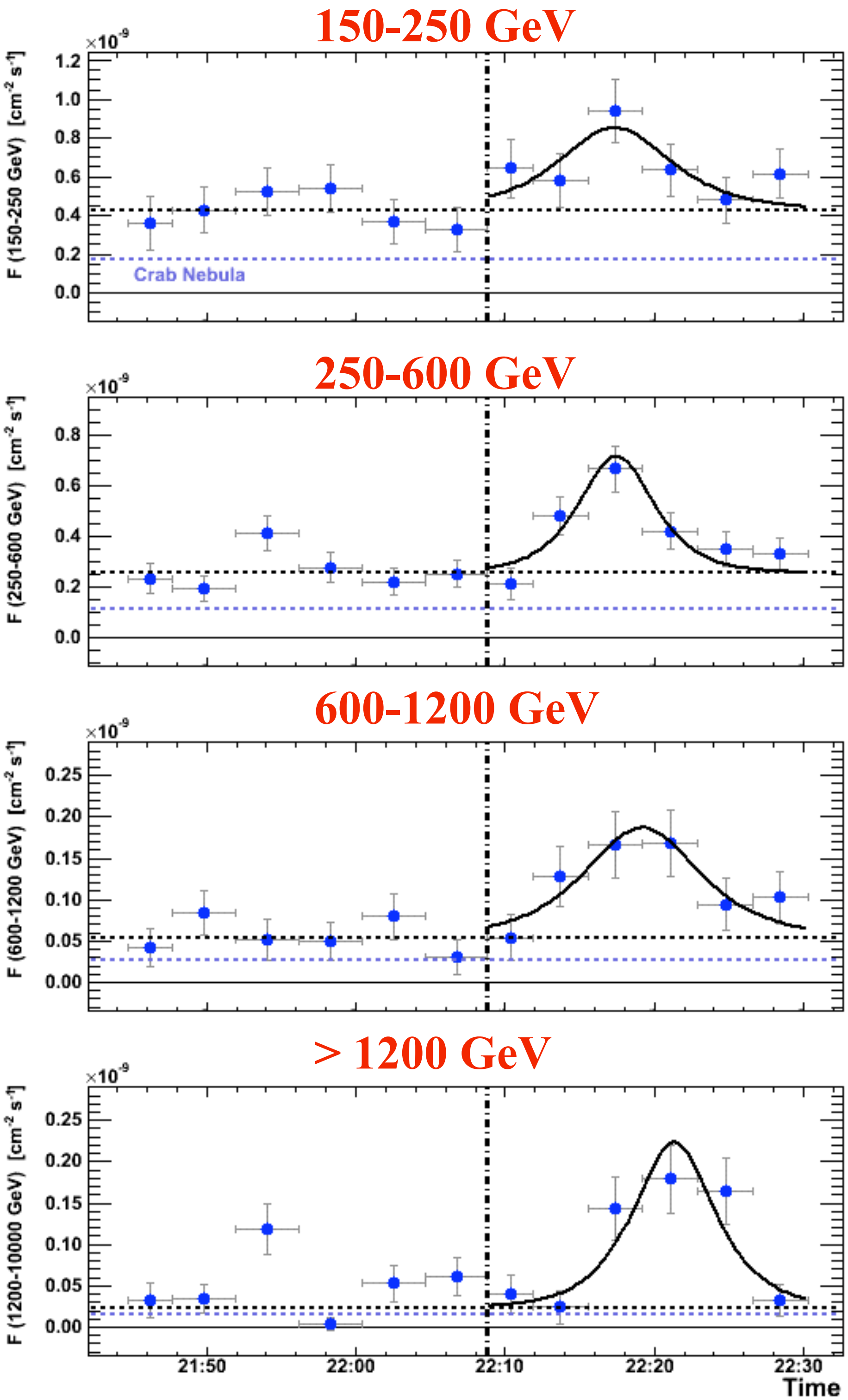


LCs for different energy ranges (4 min bins)

Active night: June 30

Flare is NOT seen in all energies

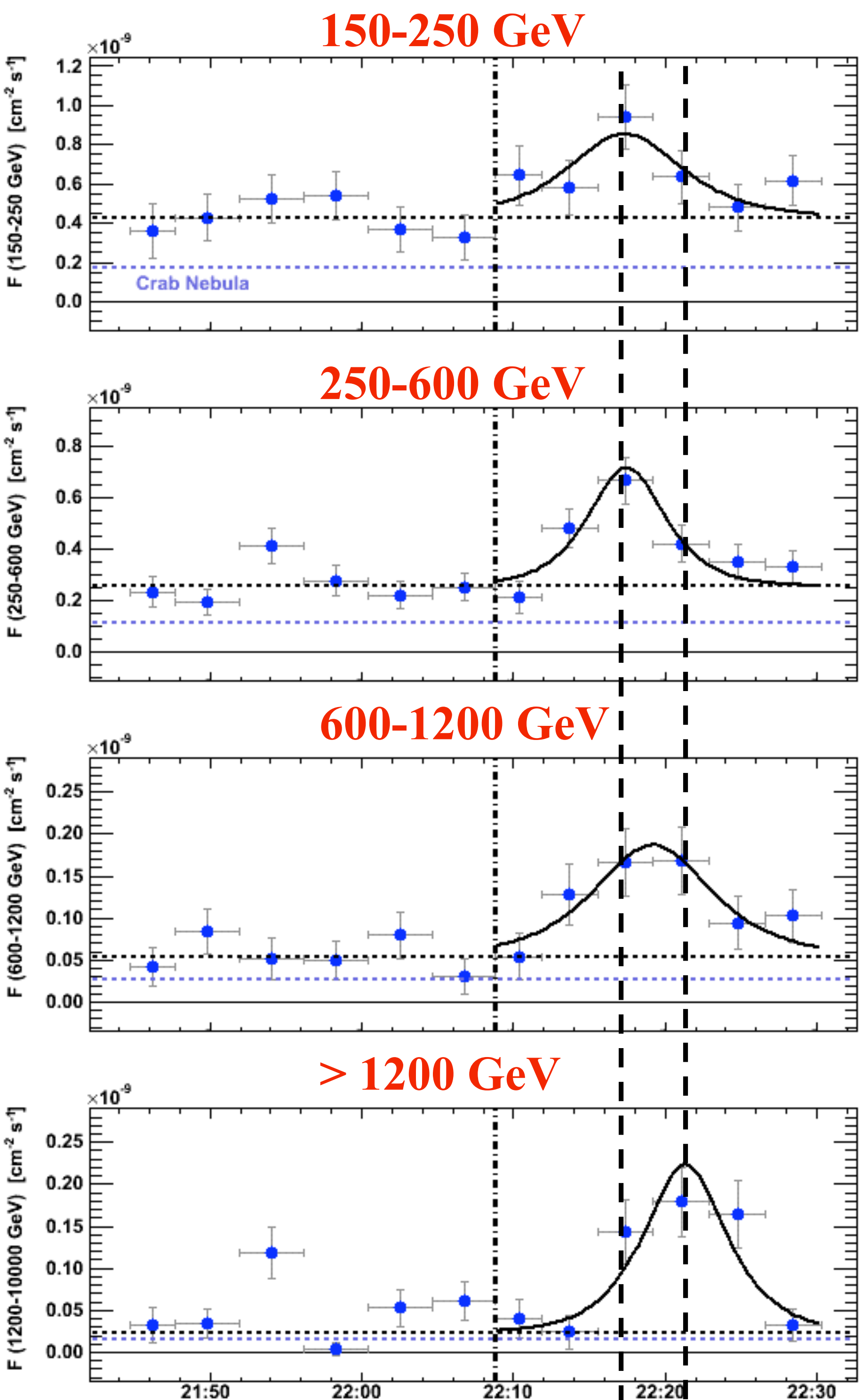
All energies are compatible with a constant flux emission, except for the range 250-600 GeV, where a constant emission is highly improbable



LCs for different energy ranges (4 min bins)

Active night: July 9

Flare is seen in all energy ranges



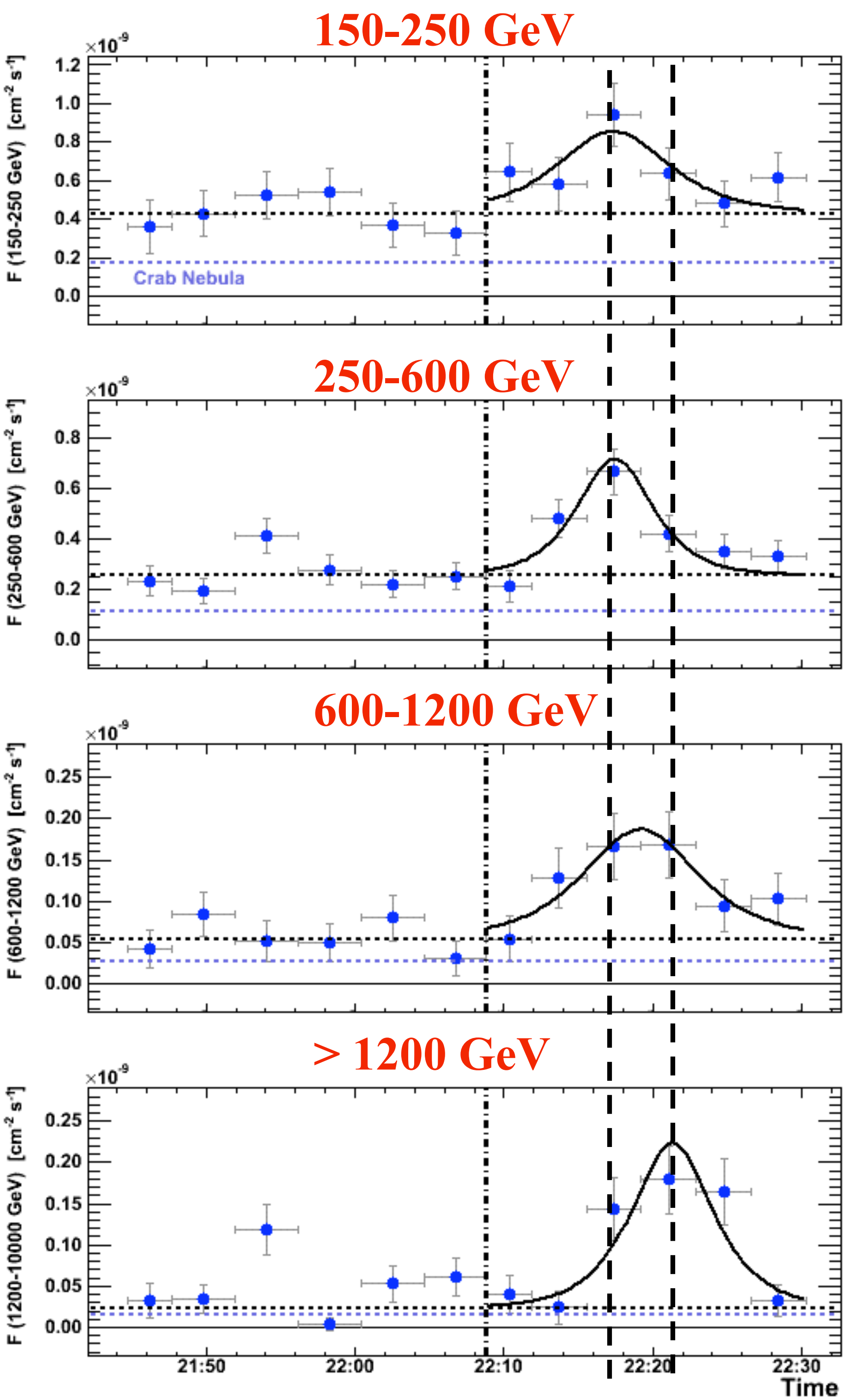
LCs for different energy ranges (4 min bins)

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

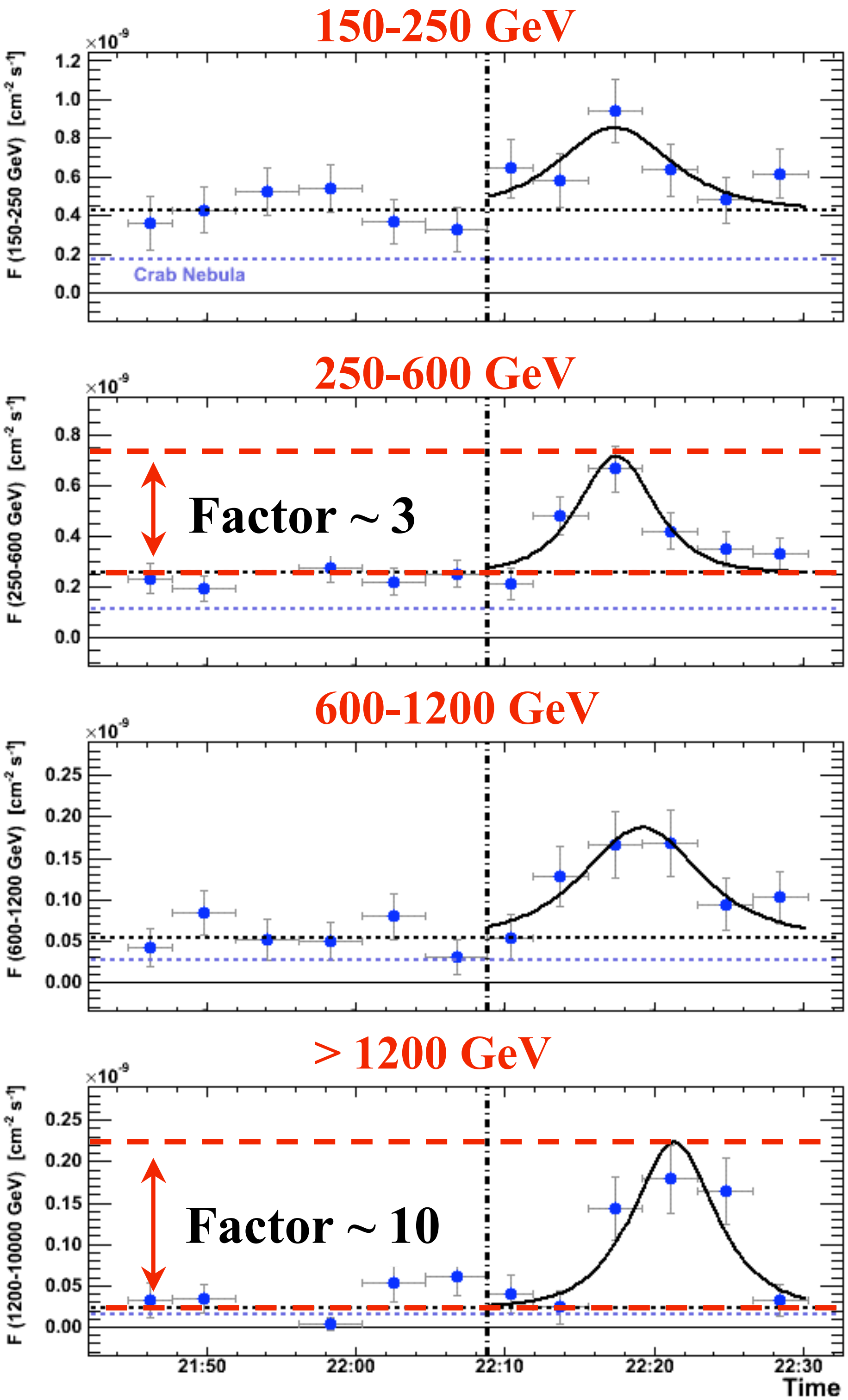
First time in VHE !!

IF

Photons at different energies were emitted simultaneously

$\Delta T = 4 \pm 1\ min;\ \Delta E \sim 1\ TeV$

$$E_{QG} = \frac{L}{c} \cdot \frac{\Delta E}{\Delta t} = (0.6 \pm 0.2) \cdot 10^{17}\, GeV$$



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

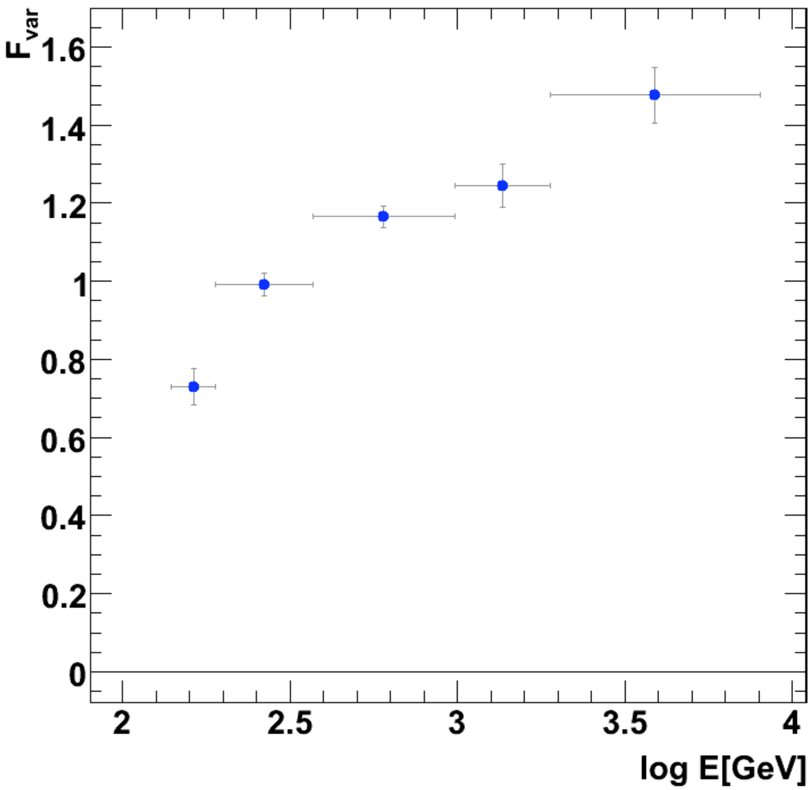
First time in VHE !!

2.3 - Flux variability vs Energy

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

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

All the observing nights (low and high state) included



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

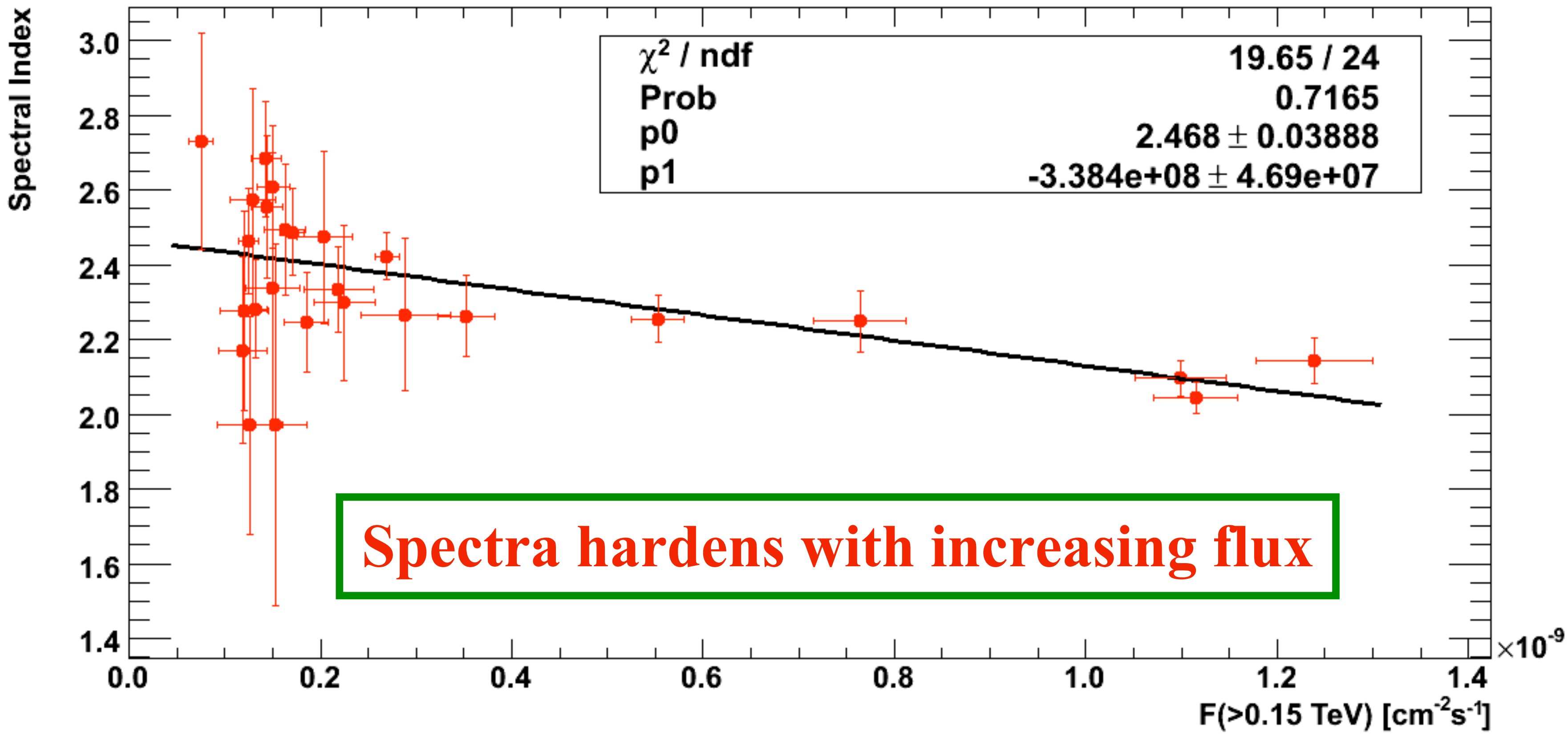
F_{var}^{Mrk501} increases with energy aslo at X-rays (see Gliozzi et al. 2006)

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>150 GeV)

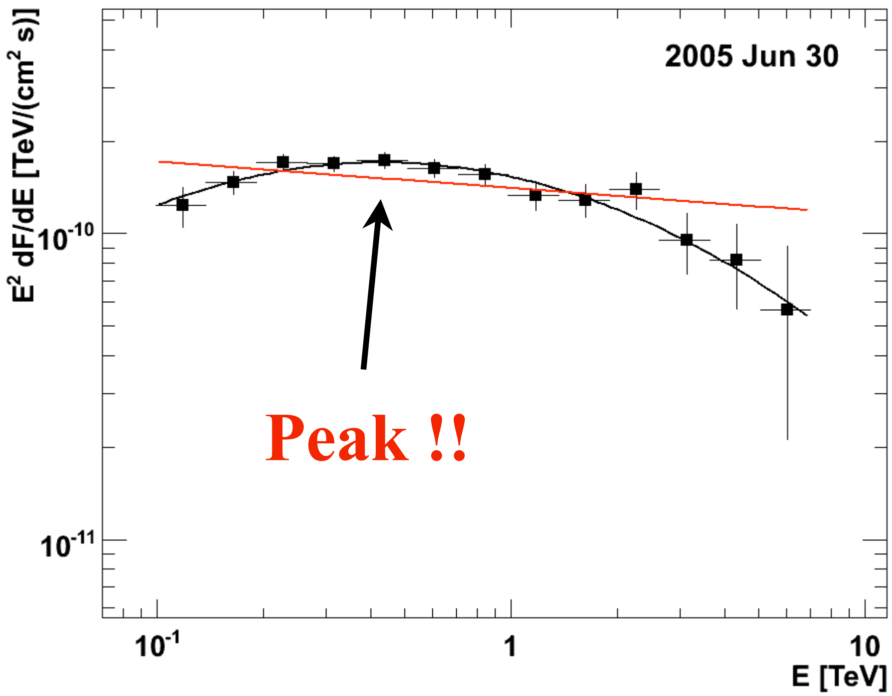
All 24 nights included
Flare nights split into 2 (“pre-flare” and “flare”)

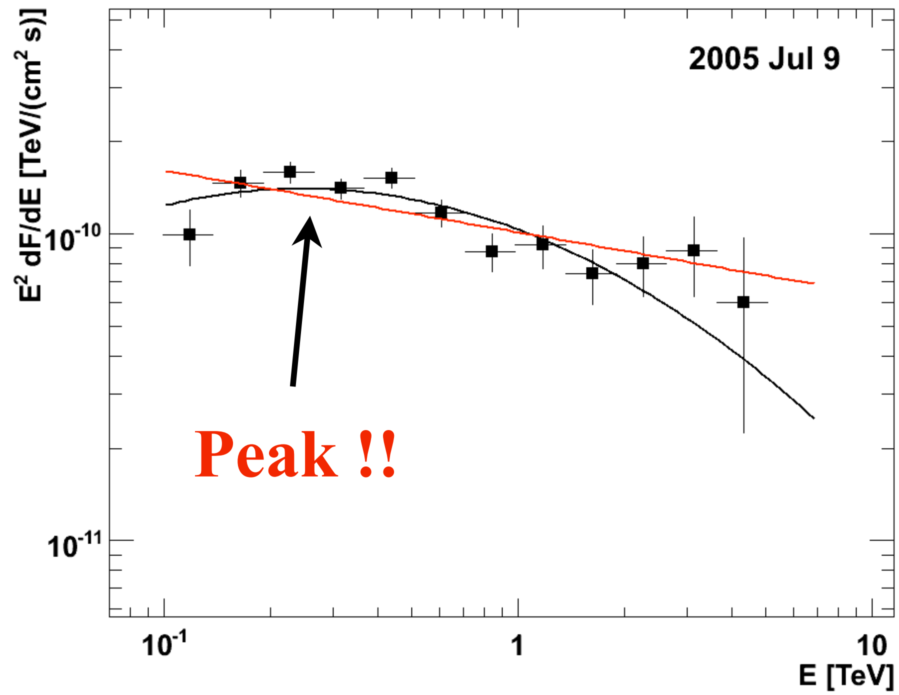


Constant fit gives Chi2/NDF = 76.6/25 (Prob 4 e-7)

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

Curved spectra is favoured over simple power law



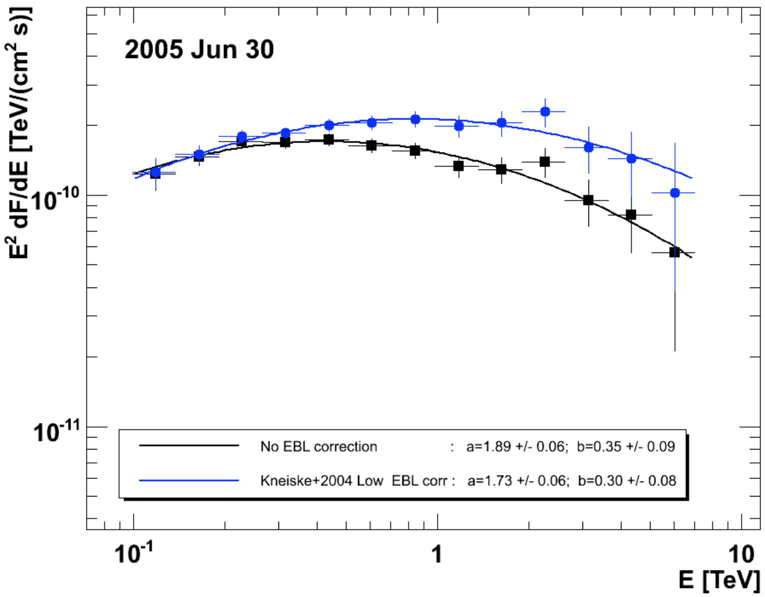


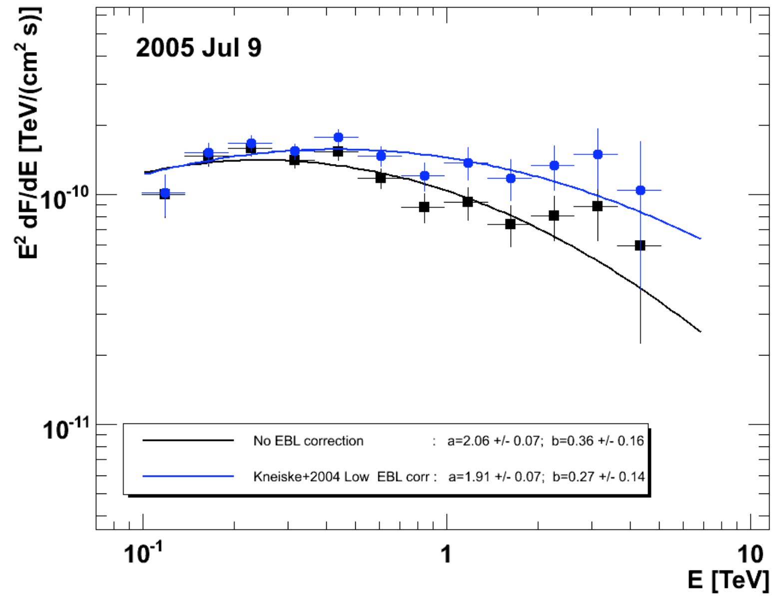
Power law **Log-Parabolic func.**

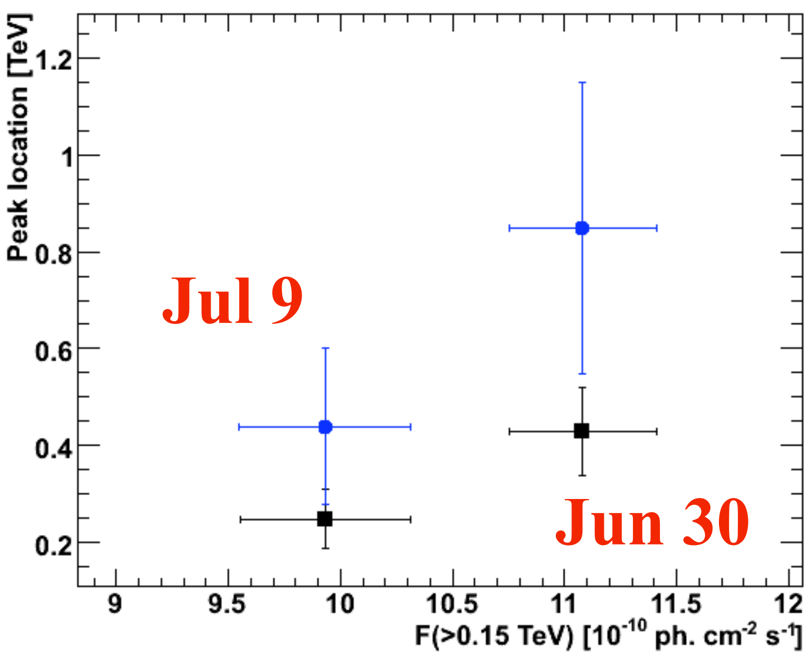
	Fit performed with formula 5				Fit performed with formula 6				
Date	K_0 $(\frac{10^{-10}\ ph}{cm^2 \cdot s \cdot 0.3TeV})$	a	χ^2/NDF	P (%)	K_0 $(\frac{10^{-10}\ ph}{cm^2 \cdot s \cdot 0.3TeV})$	a	b	χ^2/NDF	P (%)
June 30	17.4±0.05	2.09±0.03	26.1/11	0.6	18.6±0.06	1.89±0.06	0.35±0.09	6.1/10	80.1
July 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





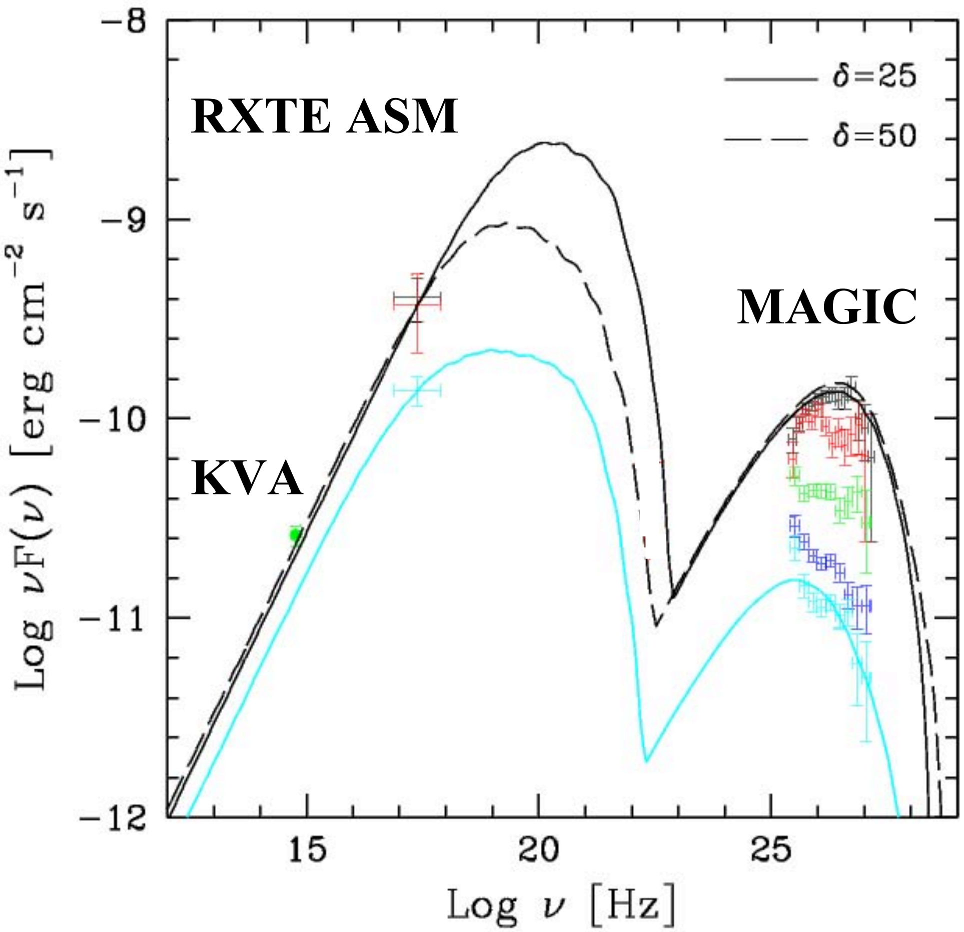


EBL correction moves the spectral peak to higher energies

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

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 !!