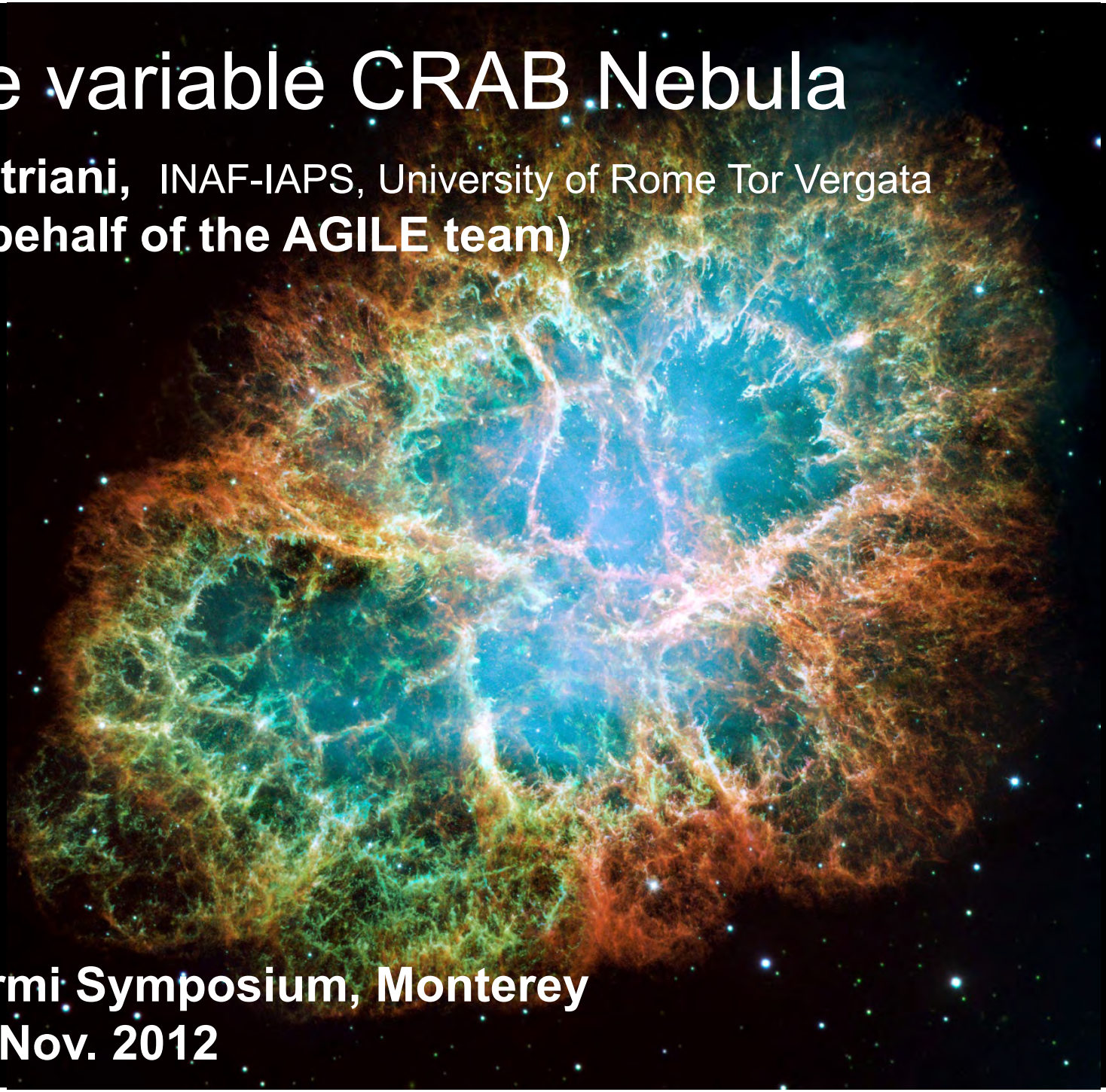
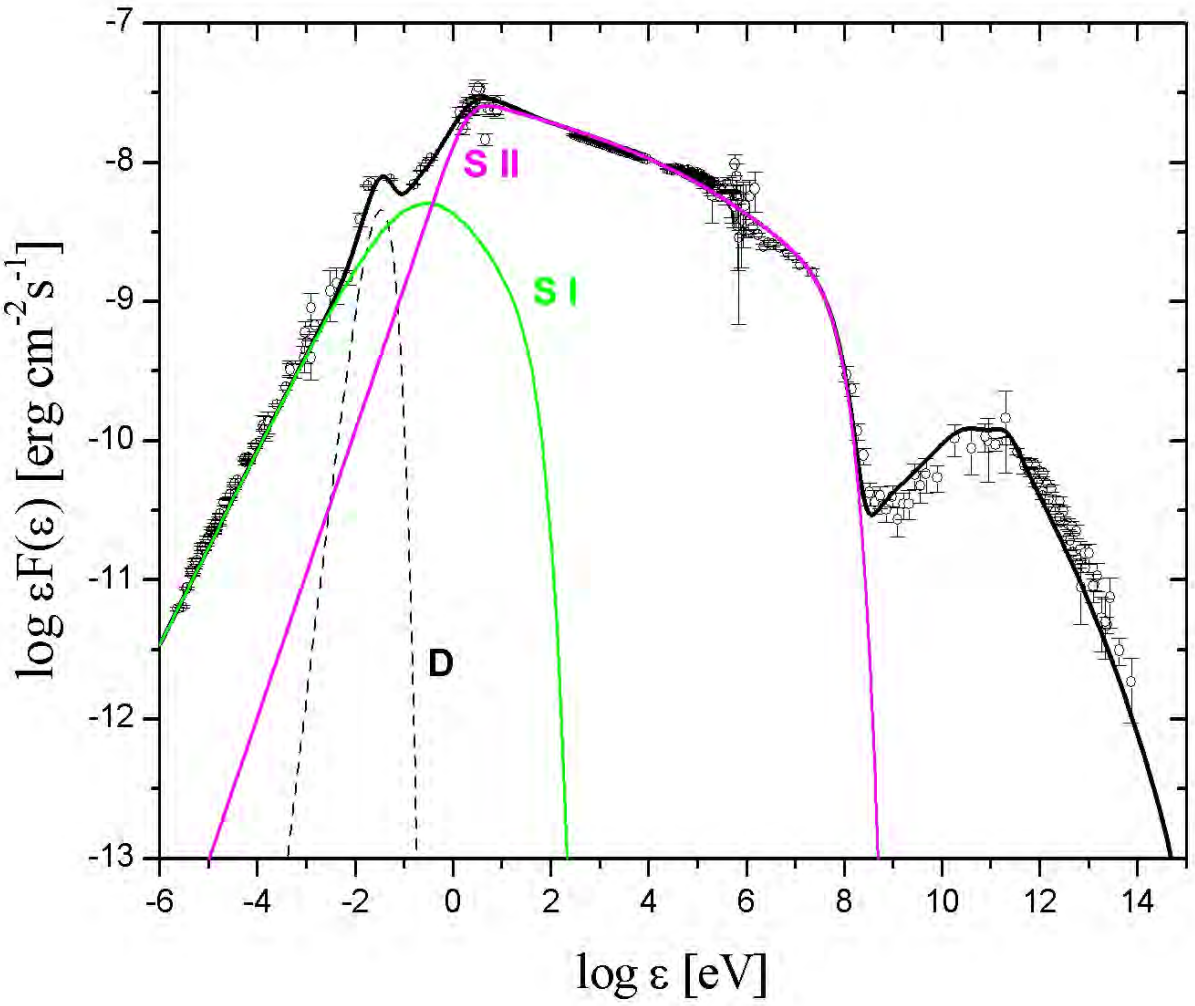
The variable CRAB Nebula

E . Striani, INAF-IAPS, University of Rome Tor Vergata
(on behalf of the AGILE team)



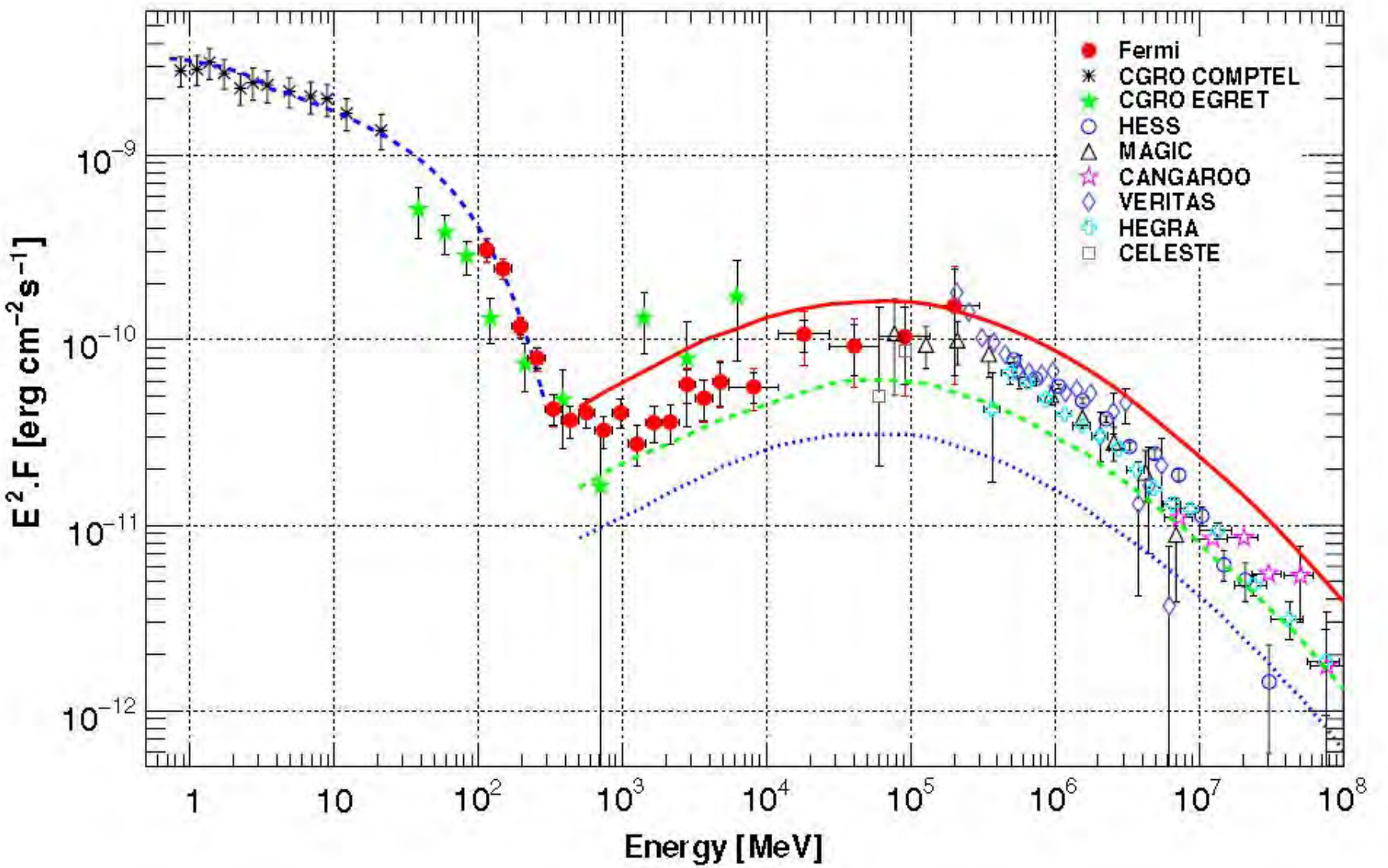
Fermi Symposium, Monterey
30 Nov. 2012

Crab Nebula spectrum



Unpulsed (nebular) gamma-ray spectrum

(Abdo et al 2010)

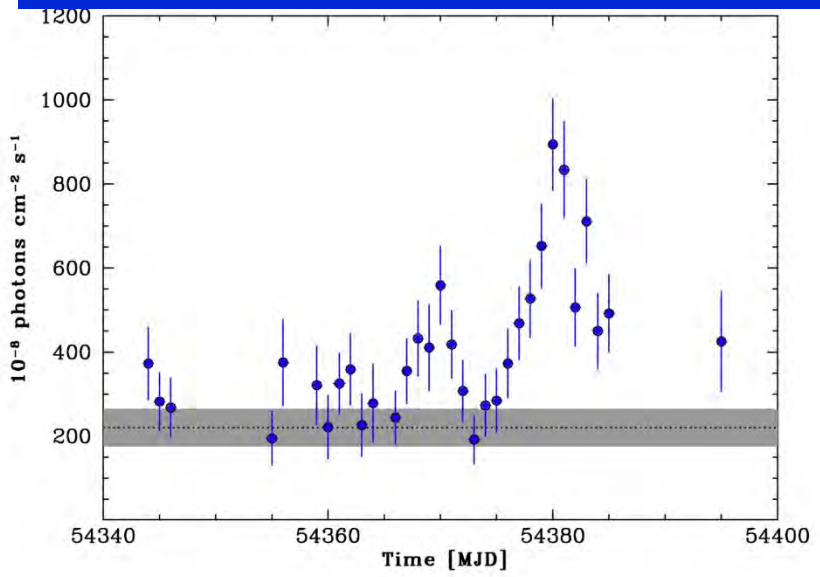


The Crab Nebula

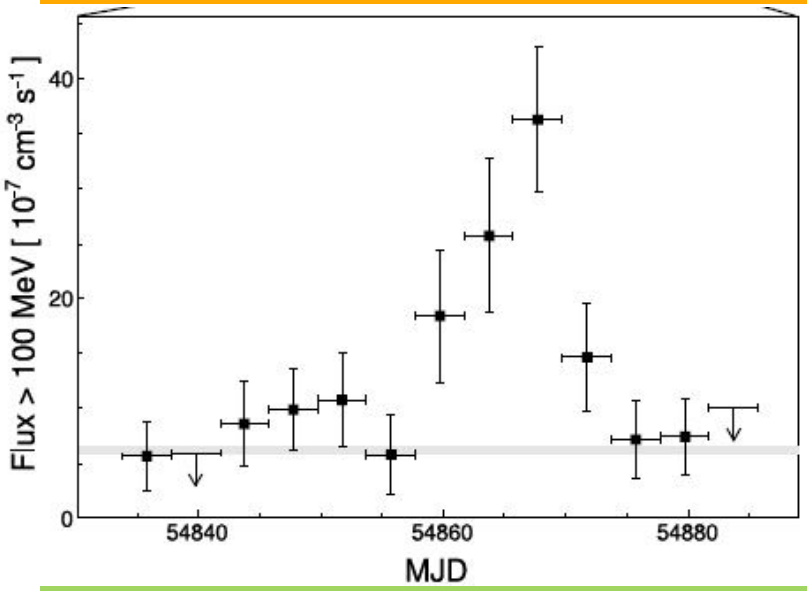
1. Stable (Standard candle)

2. Cut-off in the spectrum around 150 MeV

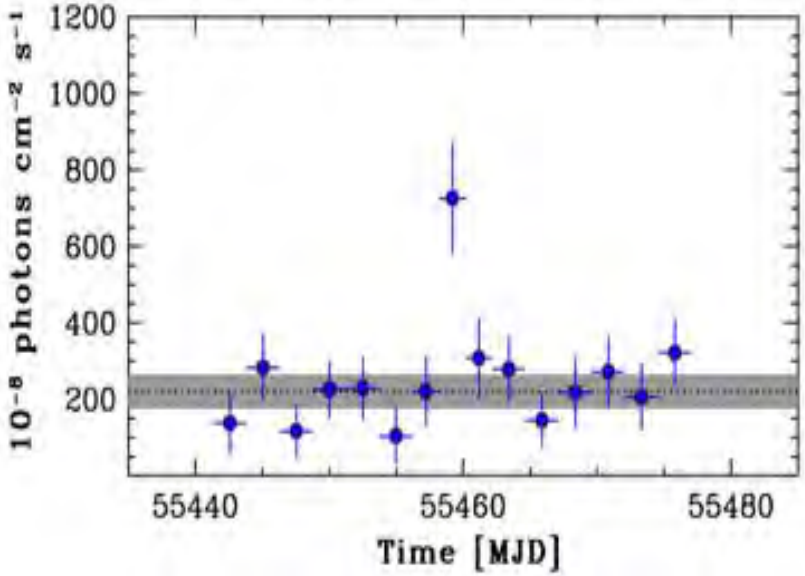
AGILE, 26 Nov. – 13 Oct. 2007



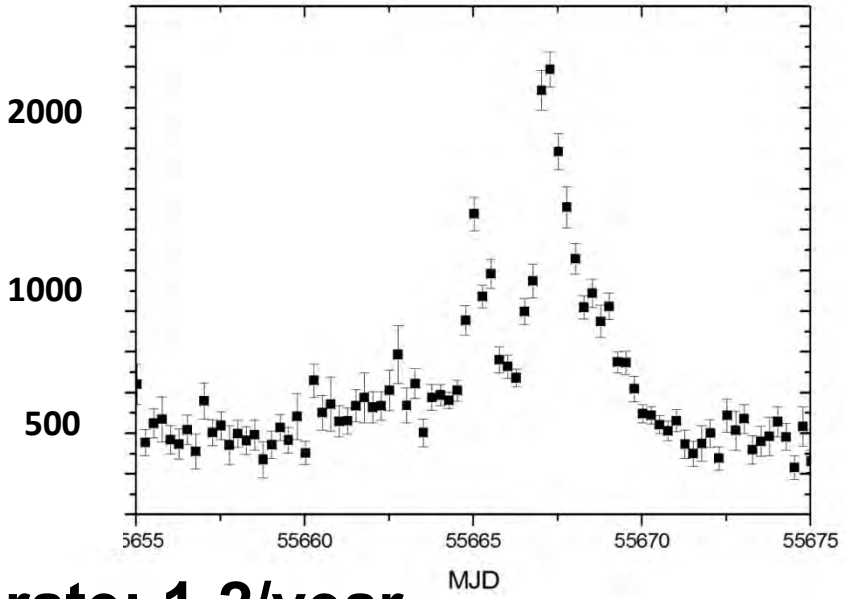
Fermi-LAT, 26 Jan. – 11 Feb. 2009



AGILE, 20-22 Sept. 2010



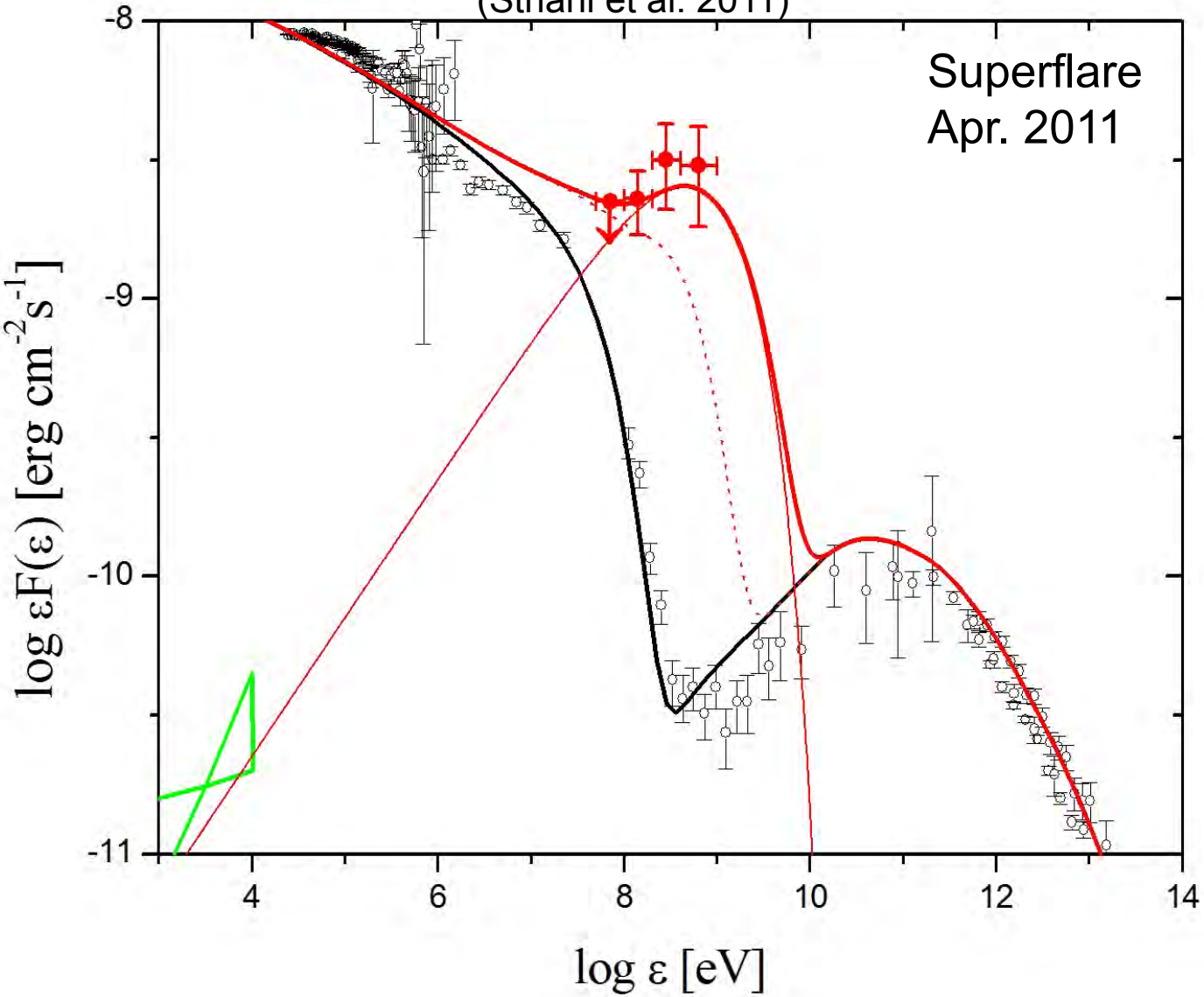
Fermi-AGILE, 12 – 20 Apr. 2011



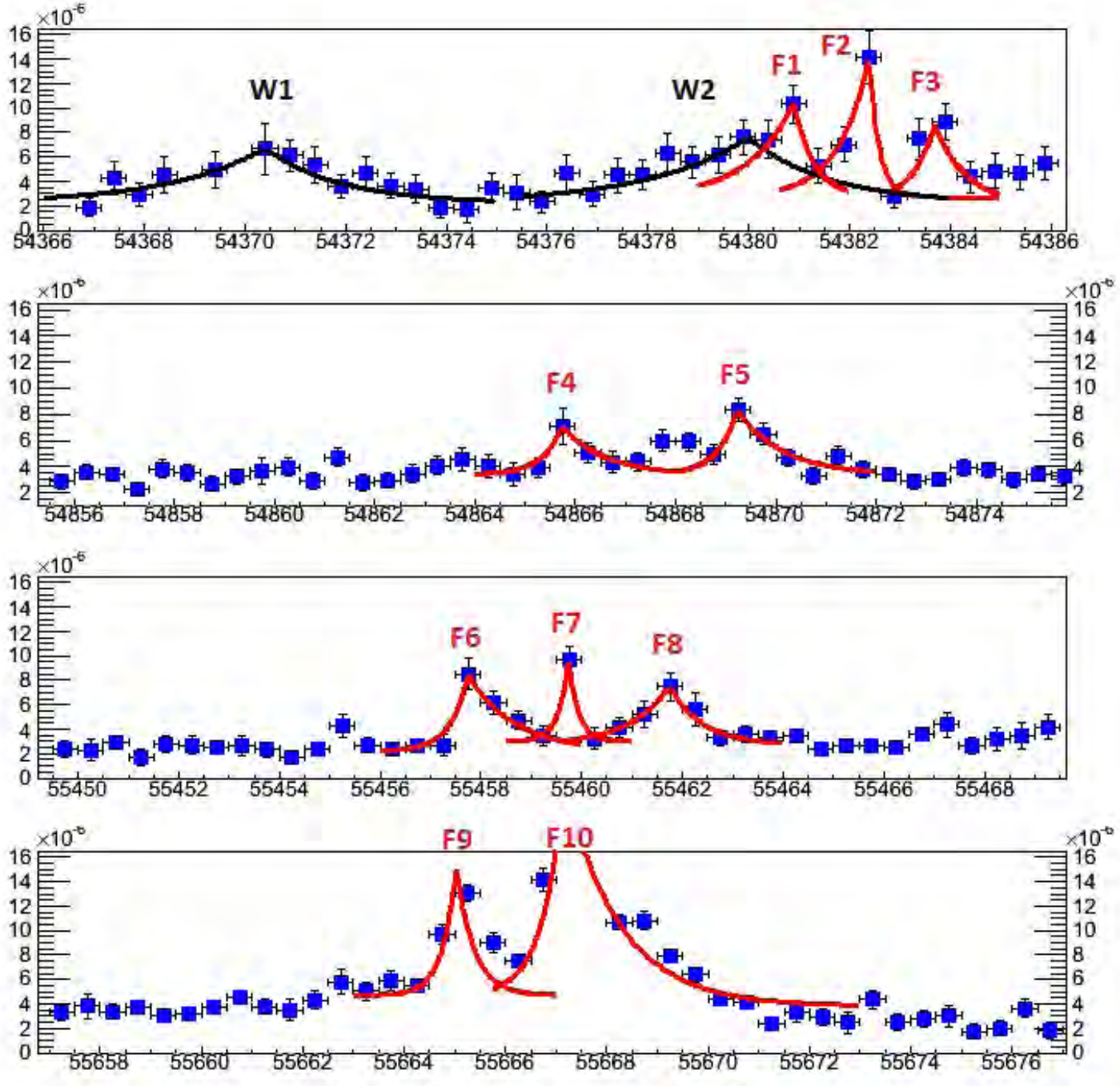
major flare rate: 1-2/year

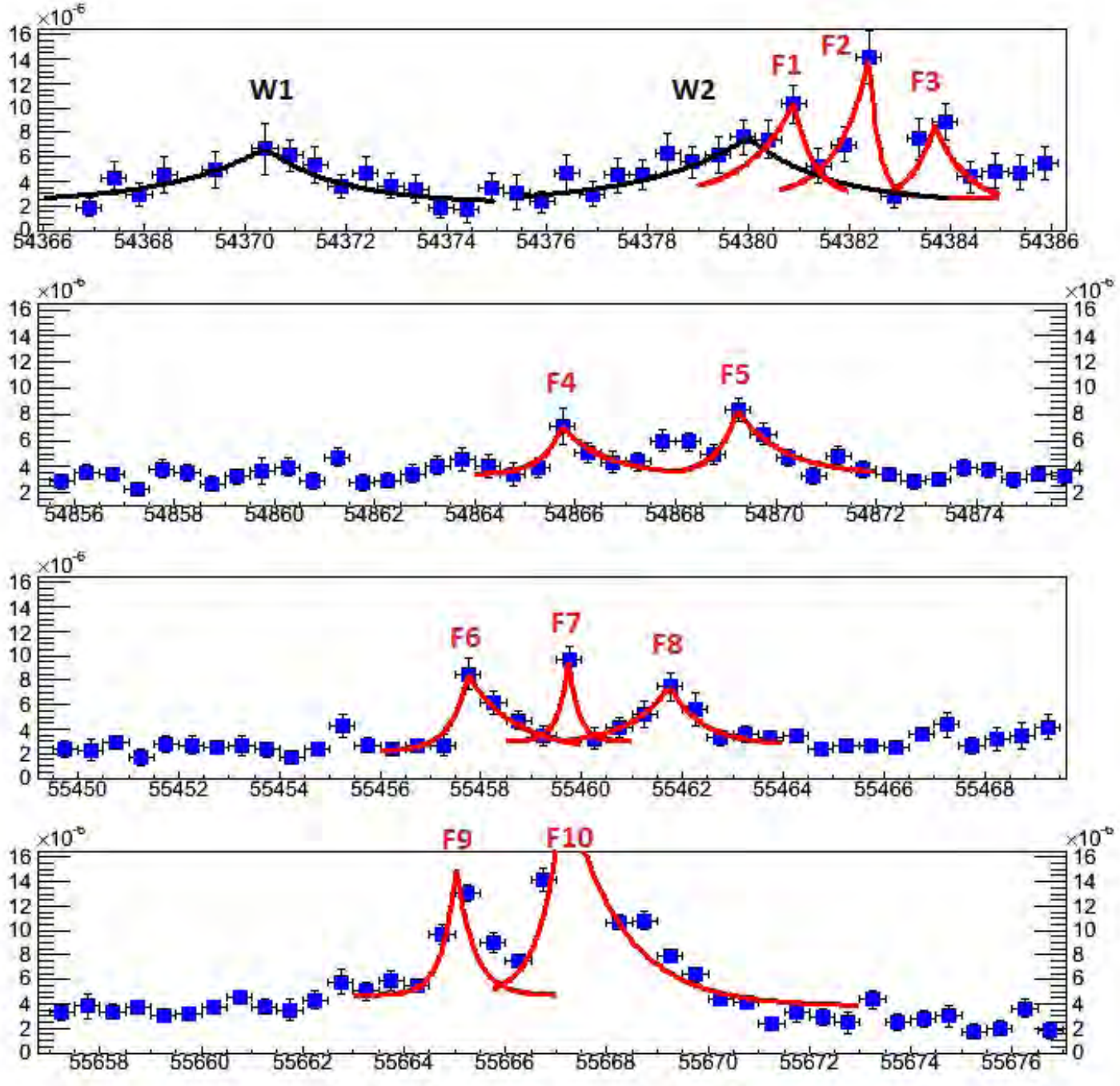
Agile Spectrum at the peak (12 hr)

(Striani et al. 2011)



Overview of the main gamma-ray flares


W1
W2
F1
F2
F3
F4
F5
F6
F7
F8
F9
F10

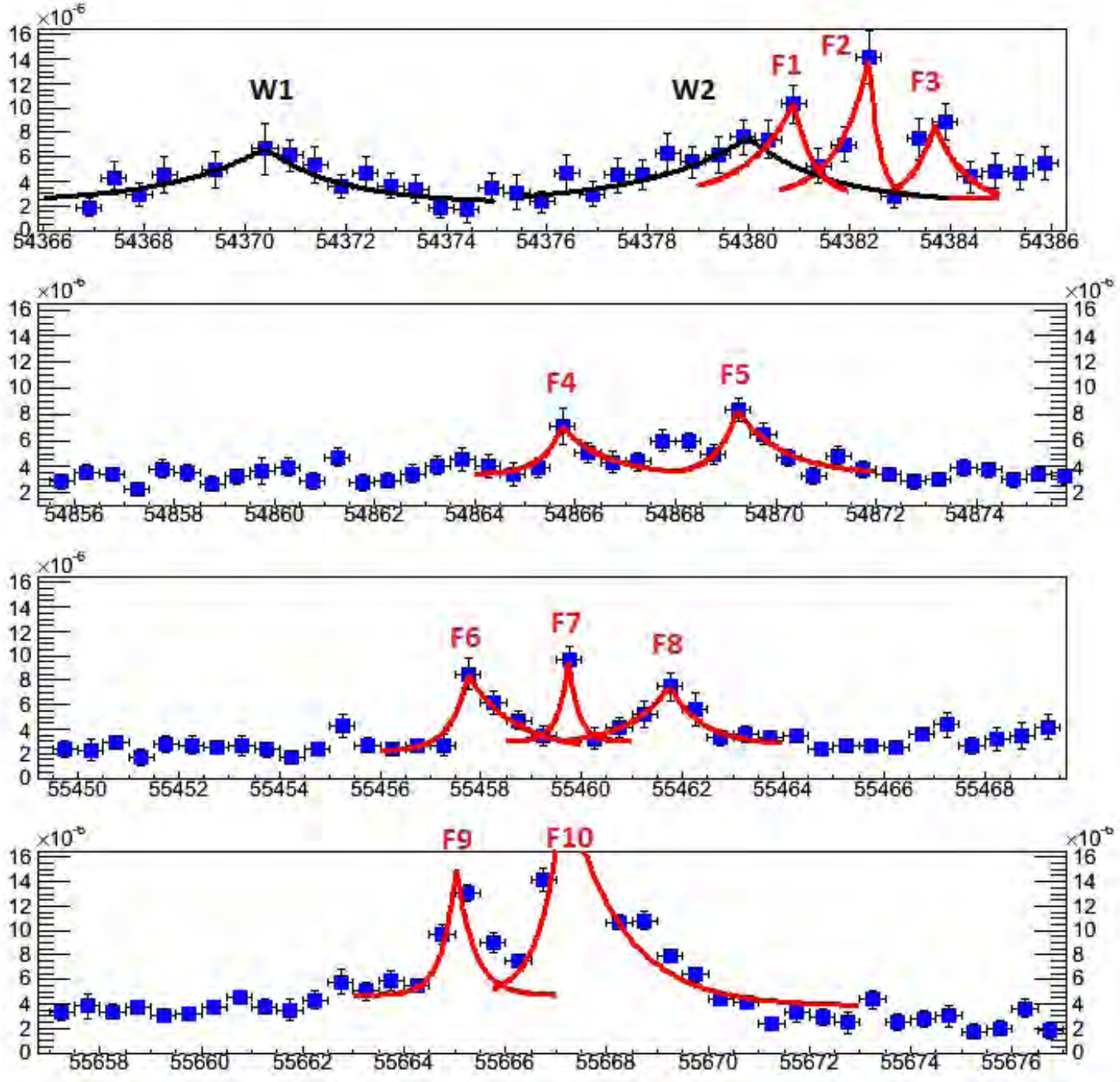


$$E_{peak} \propto \delta\, \gamma^2 B$$

$$\nu F_\nu \propto \delta^4 N_e R^3 \gamma^2$$

$$\tau_{rise} = \frac{R}{c\delta}$$

$$\tau_{cool} \propto \frac{1}{B^2 \gamma \delta}$$



$$E_{peak} \propto \delta\, \gamma^2 B$$

$$\nu F_\nu \propto \delta^4 N_e R^3 \gamma^2$$

$$\tau_{rise} = \frac{R}{c\delta}$$

$$\tau_{cool} \propto \frac{1}{B^2 \gamma \delta}$$

Five free parameters: $\gamma, \delta, B, N_e, R$

We fix $\delta = 1$, and determine the values of the other parameters with a multi parameter fit

Table of the ares (flux $> 7 \cdot 10^{-6}$ ph cm^{-2}s^{-1}) of the Crab Nebula found in the AGILE and Fermi data

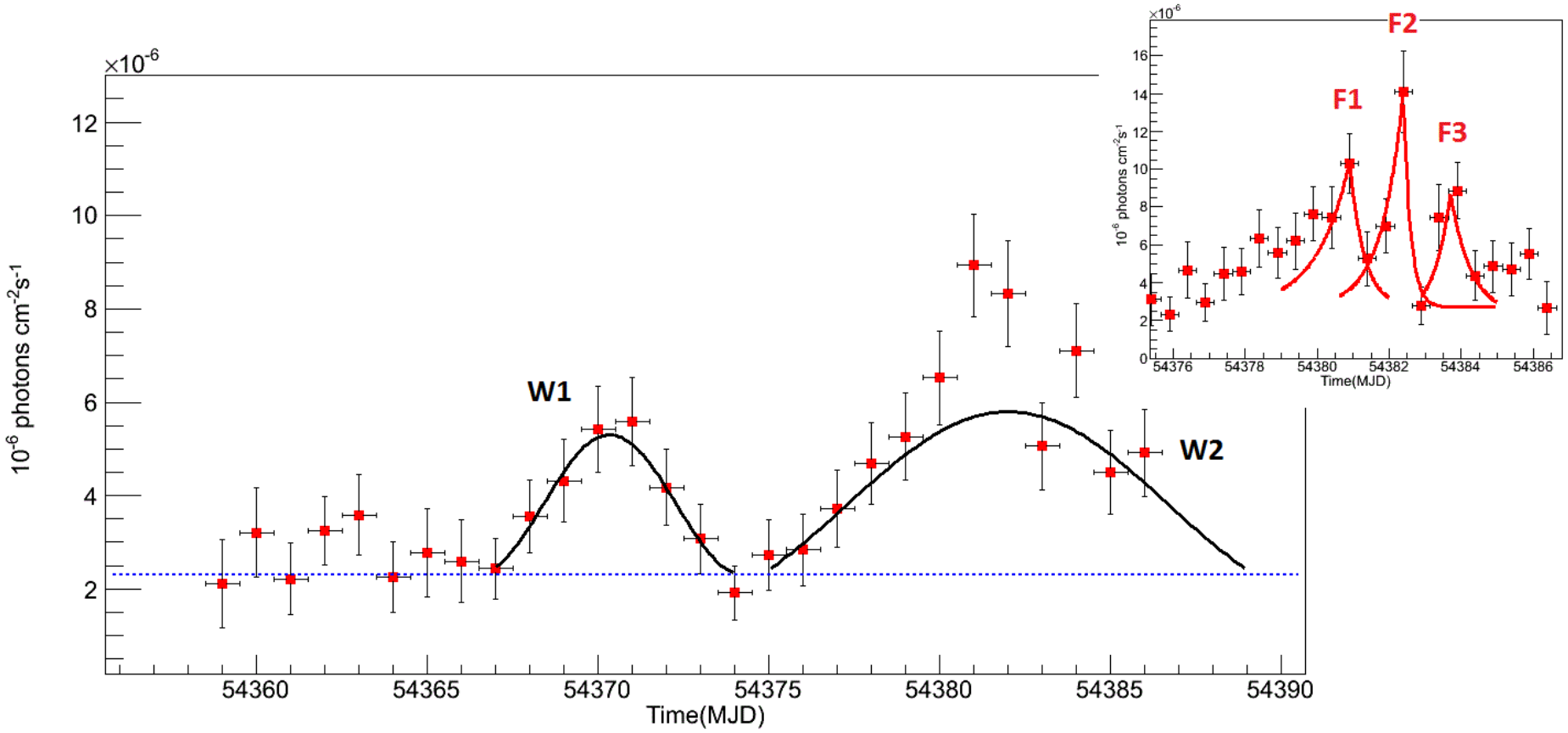
Striani et al., submitted to ApJ

	Name	MJD	τ_1 (hr)	τ_2 (hr)	Peak Flux (10^{-8} ph cm^{-2} s^{-1})	$B(mG)$	γ^* (10^9)	K/α (10^{-9}cm^{-3})
2007	F_1	54381.5	22 ± 11	10 ± 5	1000 ± 150	1.6	3.7	8
(AGILE)	F_2	54382.5	14 ± 7	6 ± 3	1400 ± 200	1.9	3.3	8
	F_3	54383.7	11 ± 5	14 ± 7	900 ± 150	1.6	3.7	7
2009	F_4	54865.8	10 ± 5	20 ± 10	700 ± 140	1.0	3.7	4
(FERMI)	F_5	54869.2	10 ± 5	22 ± 11	830 ± 90	1.1	3.7	4
	f_*	54981.0	24 ± 12	70 ± 45	472 ± 35			
2010	F_6	55457.8	8 ± 4	22 ± 11	850 ± 130	1.0	3.6	5
	F_7	55459.8	6 ± 3	6 ± 3	1000 ± 100	2.0	3.7	5
	F_8	55461.9	19 ± 10	8 ± 4	750 ± 110	1.1	3.6	5
2011	F_9	55665.0	9 ± 5	9 ± 5	1480 ± 80	1.7	3.9	8
	F_{10}	55667.3	10 ± 5	24 ± 12	2200 ± 85	1.8	3.8	10

The 2007 AGILE event

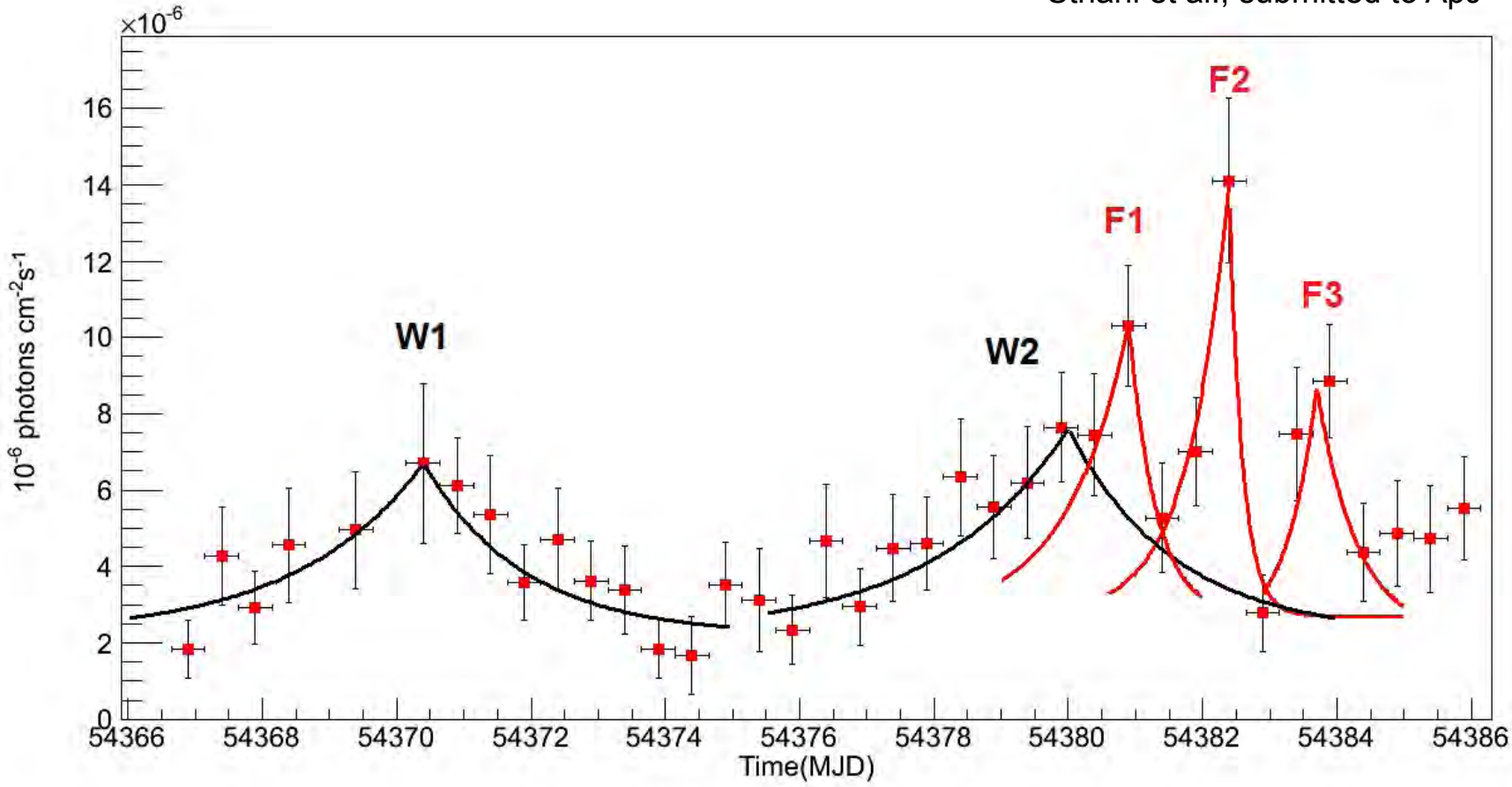
AGILE 1-day bin lightcurve of the 2007 event

Striani et al., submitted to ApJ

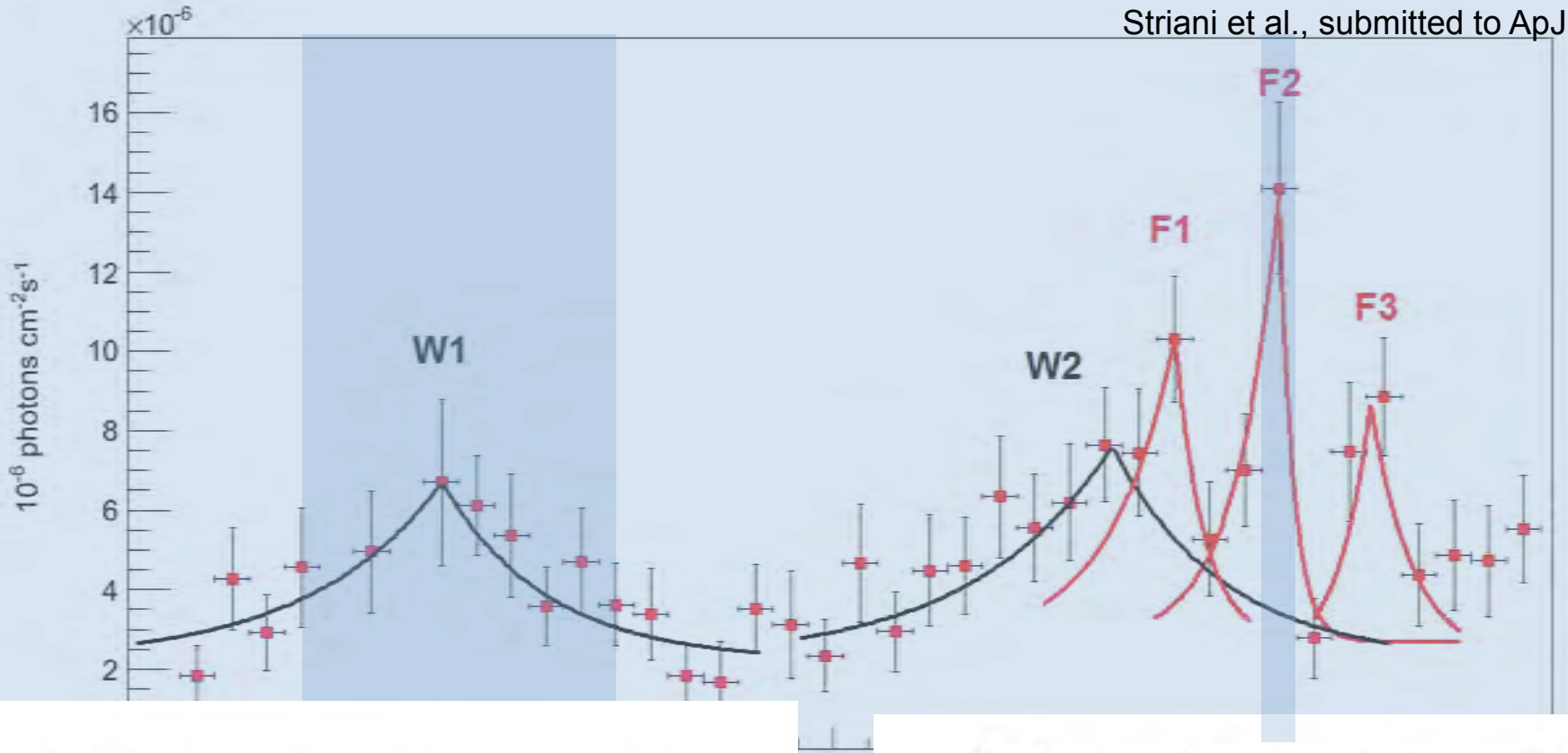


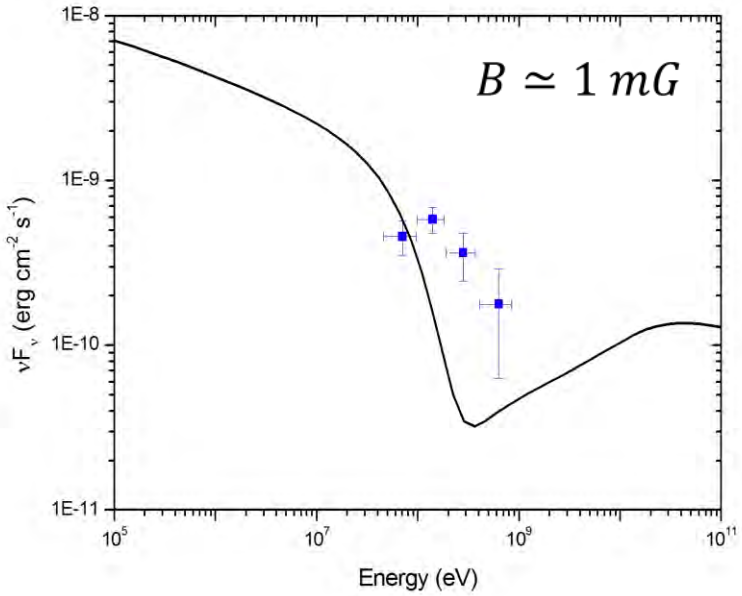
AGILE 12-hr bin lightcurve of the 2007 event

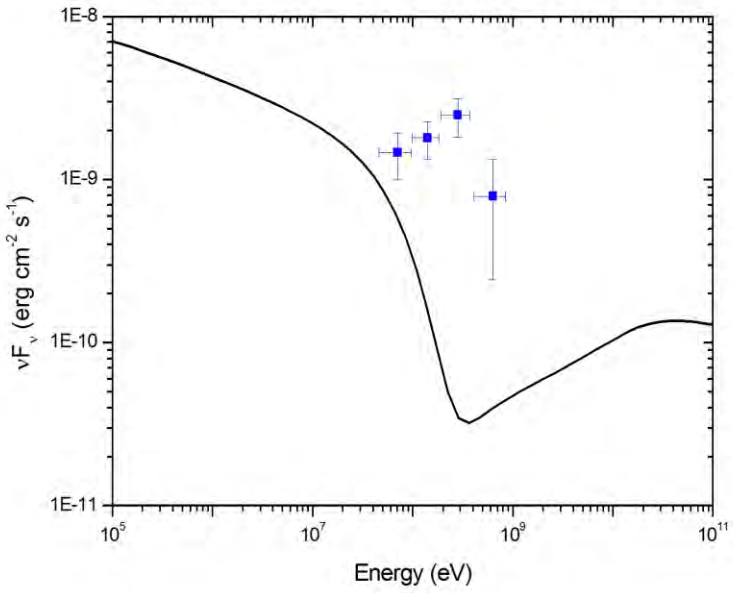
Striani et al., submitted to ApJ



Striani et al., submitted to ApJ

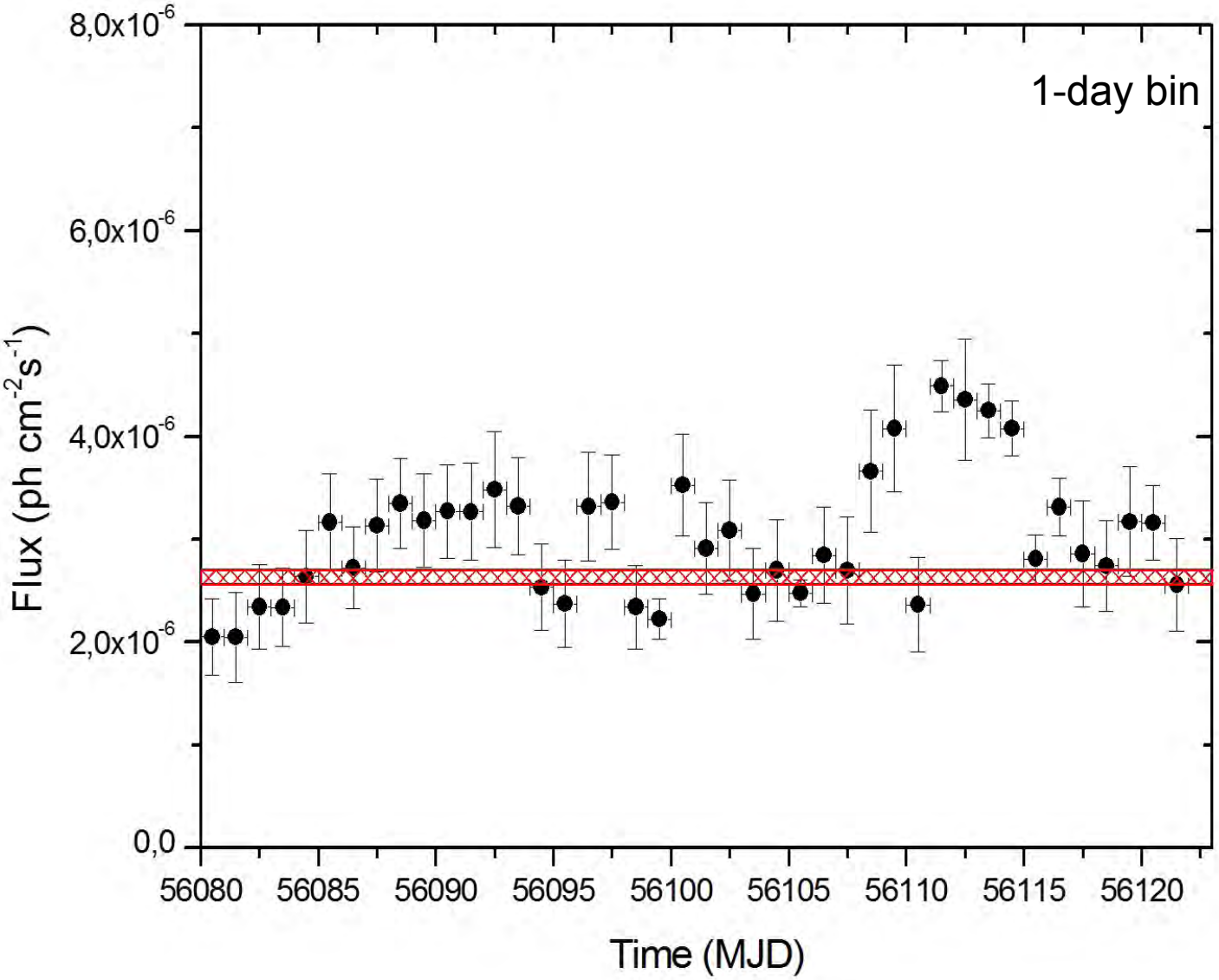




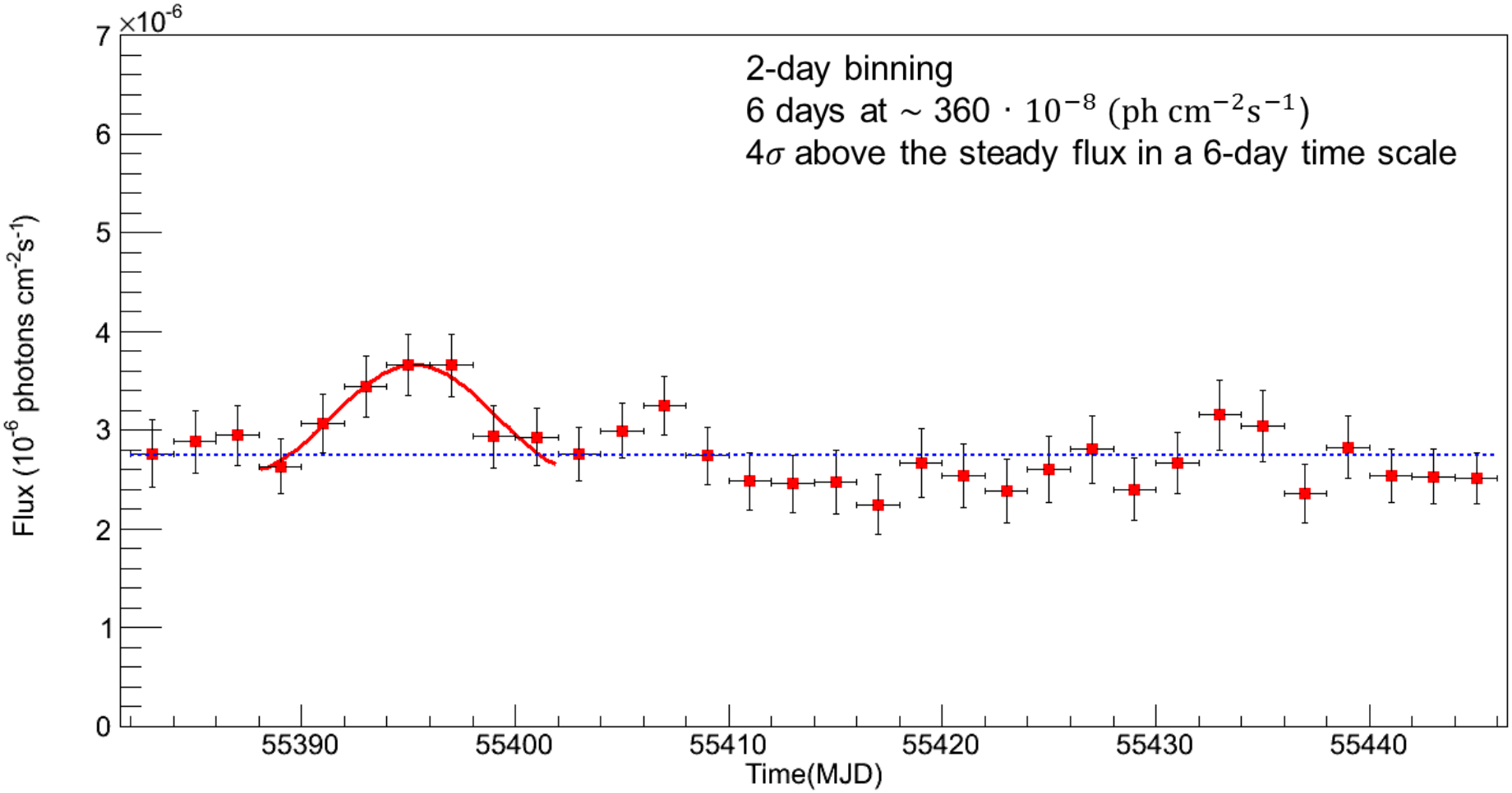


Fermi Data

Fermi Atel # 4239 (July 2012, during the Flaring Crab meeting in Frascati)
(data from the Fermi-LAT monitored source list page)



Gamma-ray 2-day binned lightcurve (Fermi data)



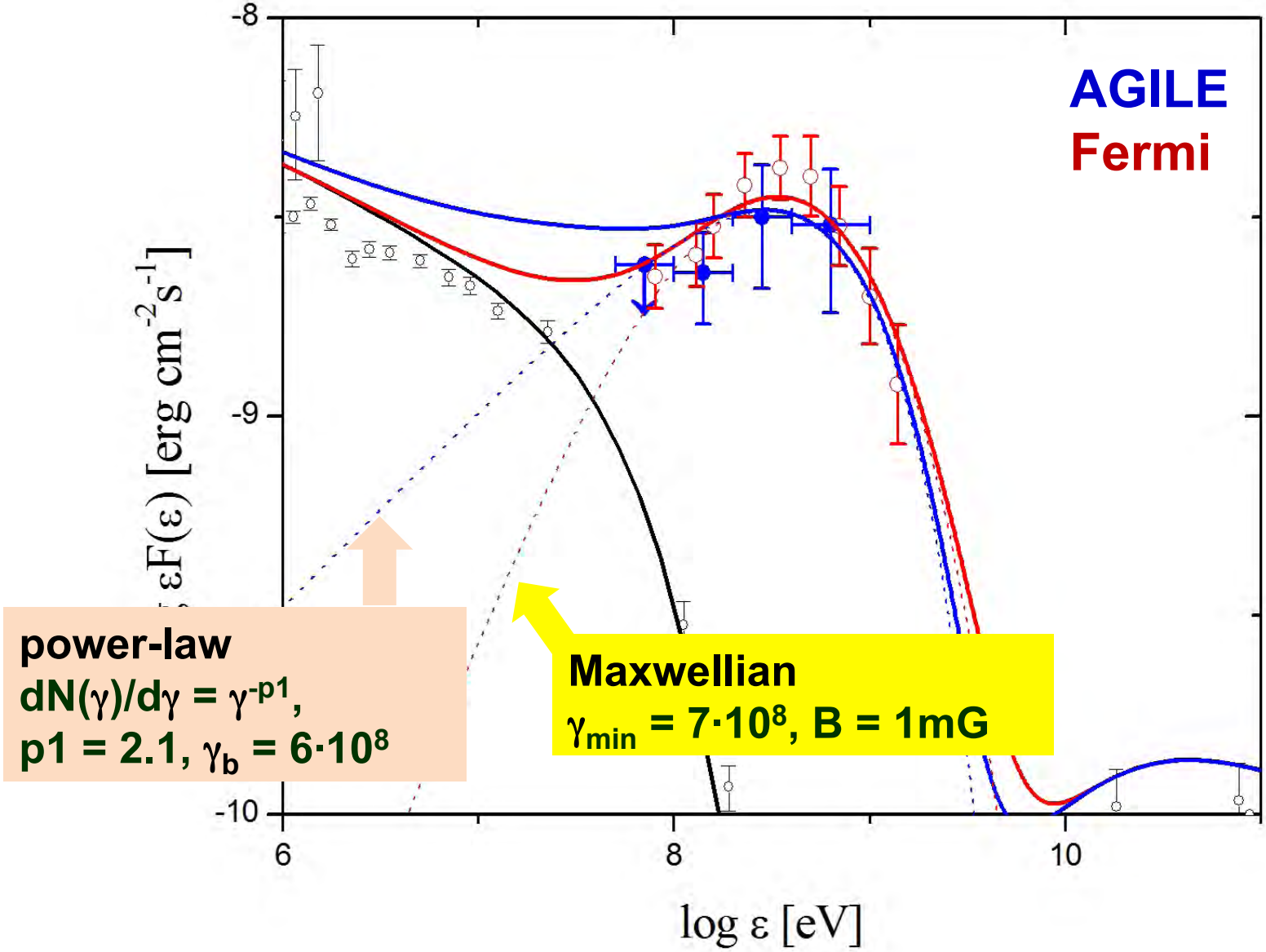
The Crab

- A standard candle
- Strong and impulsive flares (12-24 hr), ~1/ year
- Slower, less intense variability, and rather more frequent (waves)

From our model, waves imply (with respect to flares)

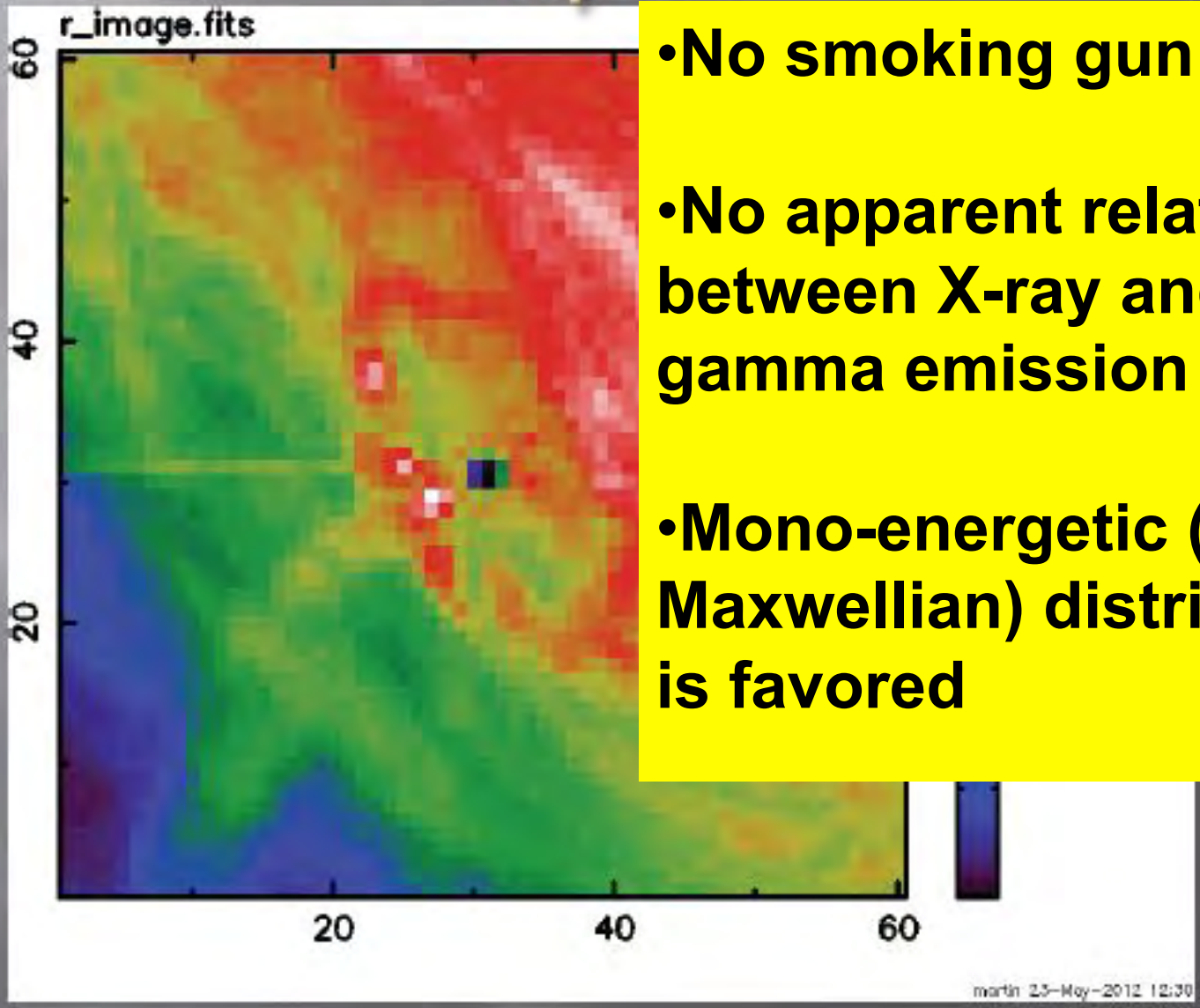
- a less intense magnetic field (B~ (0.6 – 1) mG)
- a larger emitting region
- smaller density of the emitting particles.

Modelling of the April 2011 super-flare



The average Chandra image 2011 April

(M. Weisskopf, 2012)



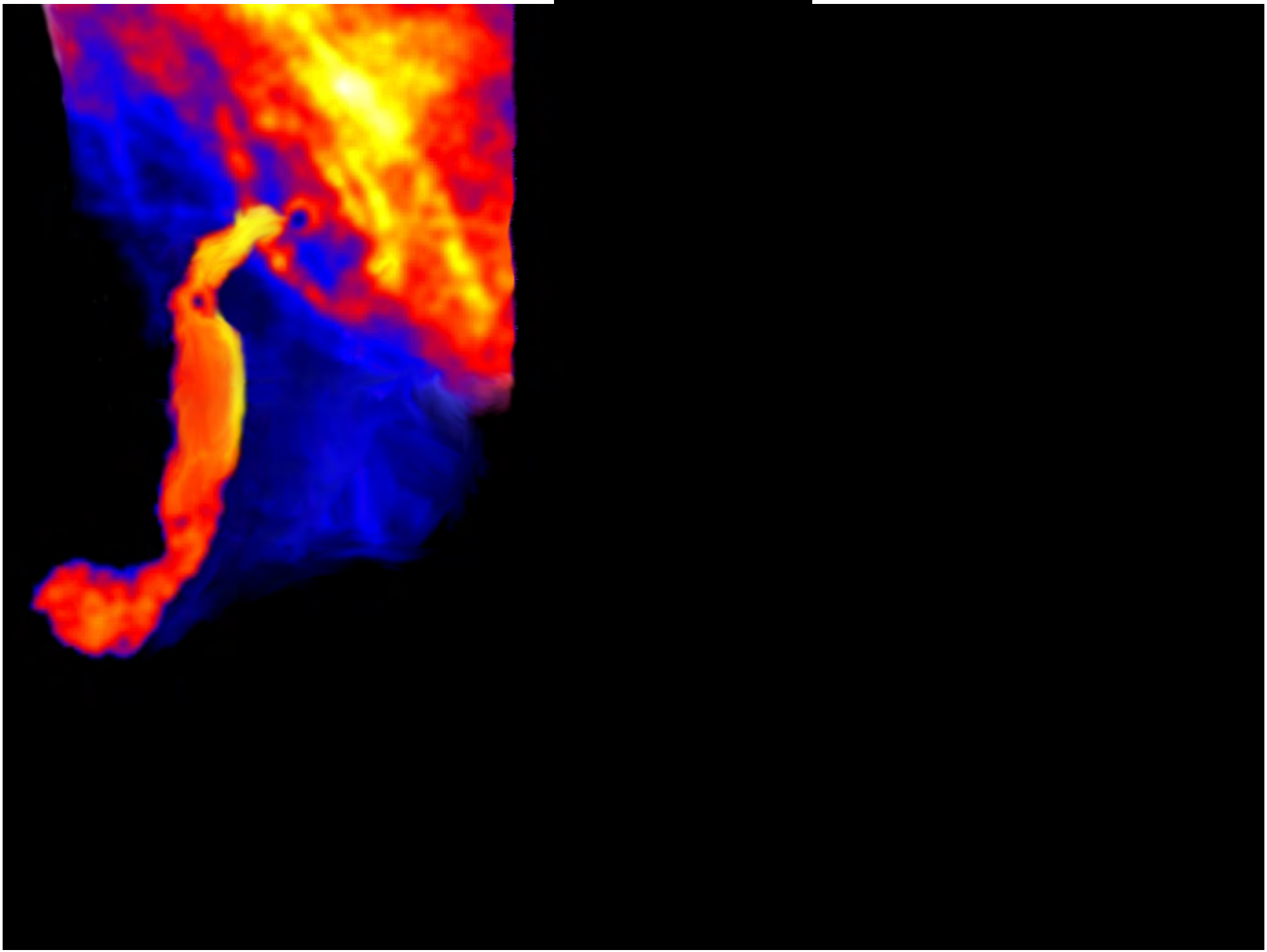
- **No smoking gun**
- **No apparent relation between X-ray and gamma emission**
- **Mono-energetic (relativ. Maxwellian) distribution is favored**

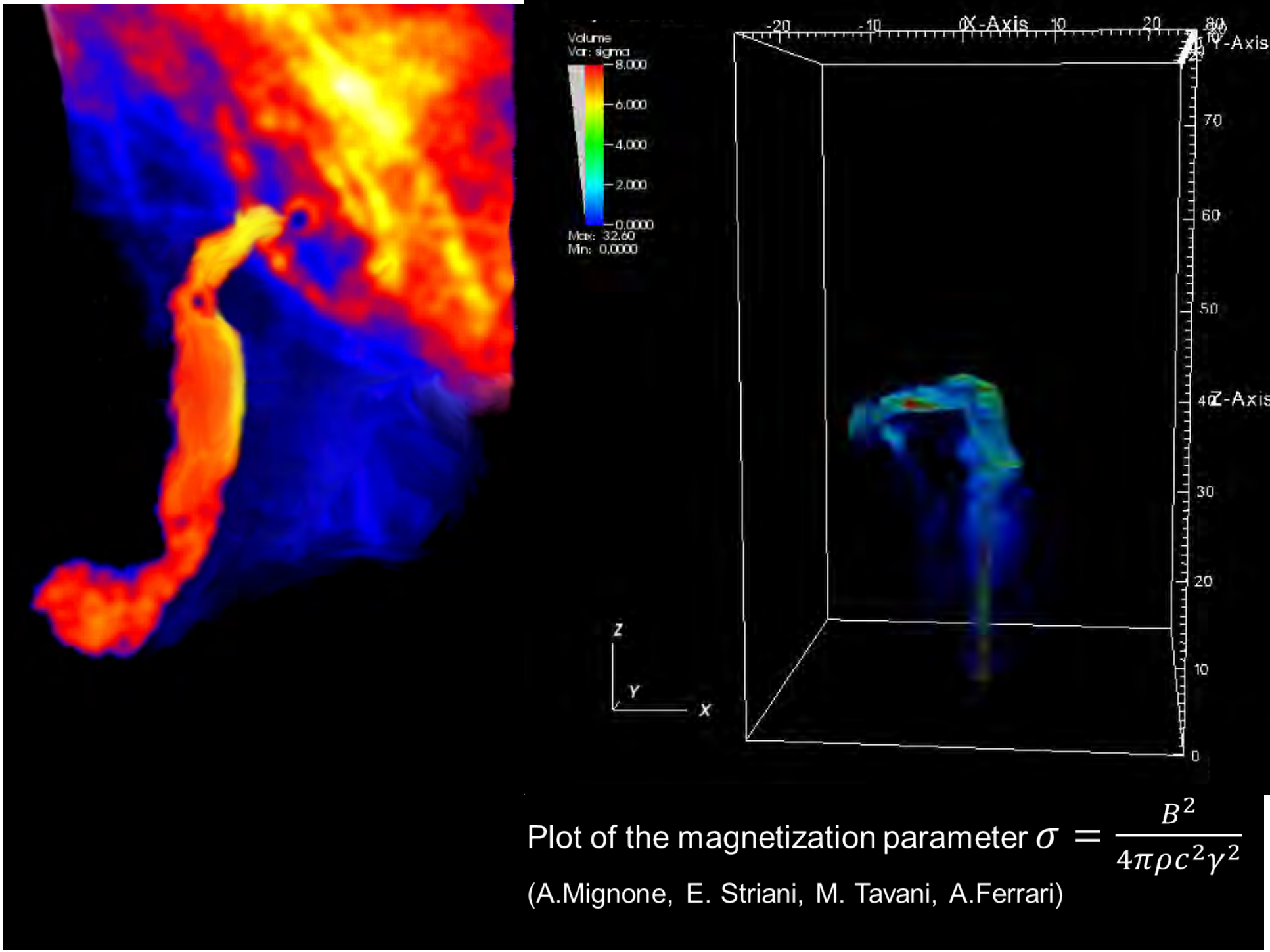
already several models, many ideas…

- Tavani et al. (2011, 2012)
- Abdo et al. (2011, 2012)
- Bednarek & Idec (2011)
- Komissarov & Lyutikov (2011)
- Vittorini et al., Striani et al. (2011)
- Lyutikov, Balsara, Matthews (2011)
- Bykov, Pavlov, Artemyev, Uvanov (2011)
- Cerutti, Uzdensky, Begelman (2012)
- Arons (2012)
- Lyubarsky (2012)
- Sturrock & Aschwanden (2012)
- Kommissarov (2012)
- Blandford & Li (2012)
- Mignone et al. (2012, in prep.)
- Striani el al. (2012, in prep.)

Among the interpretations there is the possible role of impulsive particle acceleration in magnetic field reconnection by transient electric fields violating the condition $E/B < 1$

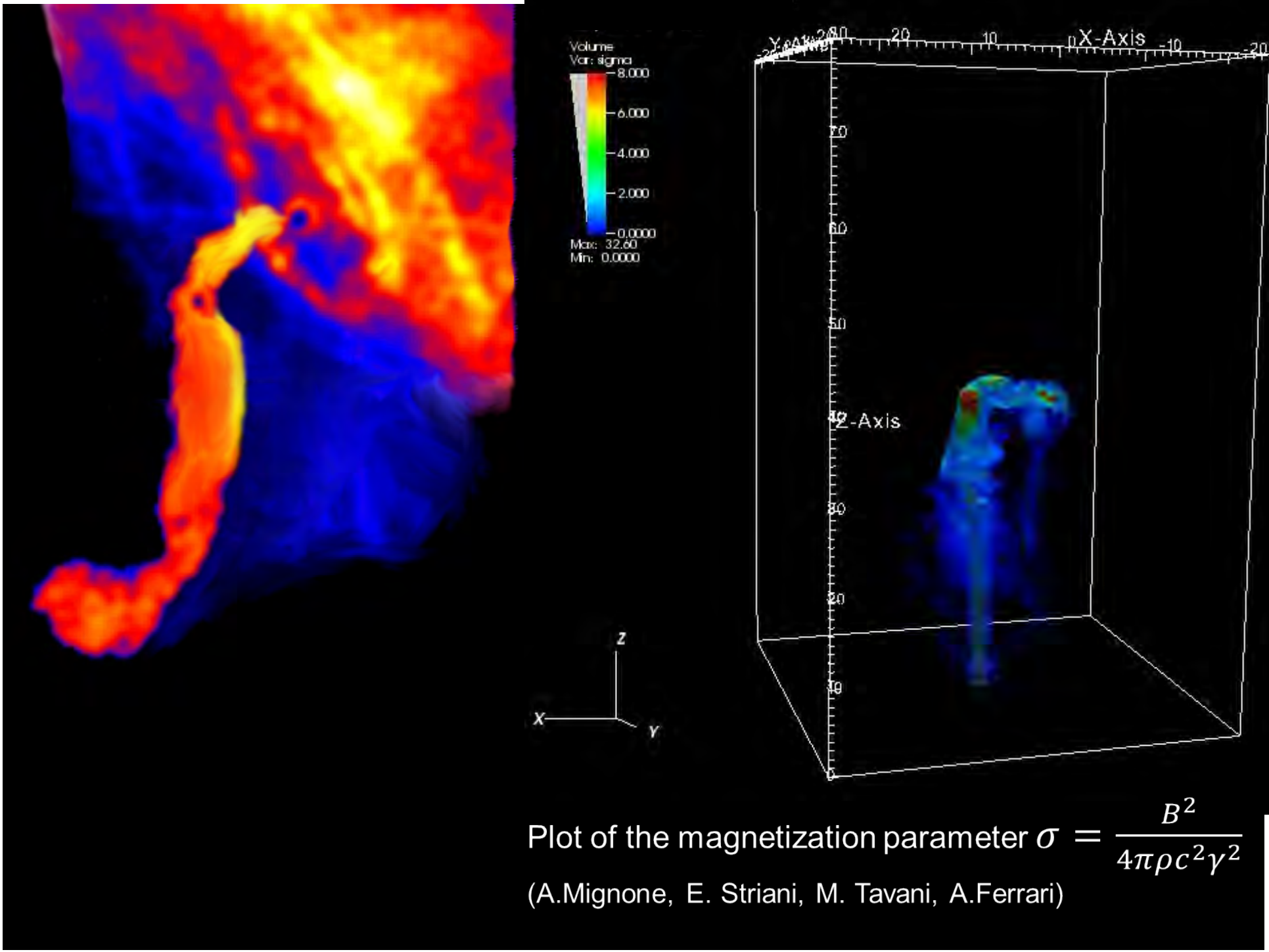
Several regions can be considered for the flaring particle acceleration site including the South-East jet





Plot of the magnetization parameter $\sigma = \frac{B^2}{4\pi\rho c^2 \gamma^2}$

(A.Mignone, E. Striani, M. Tavani, A.Ferrari)



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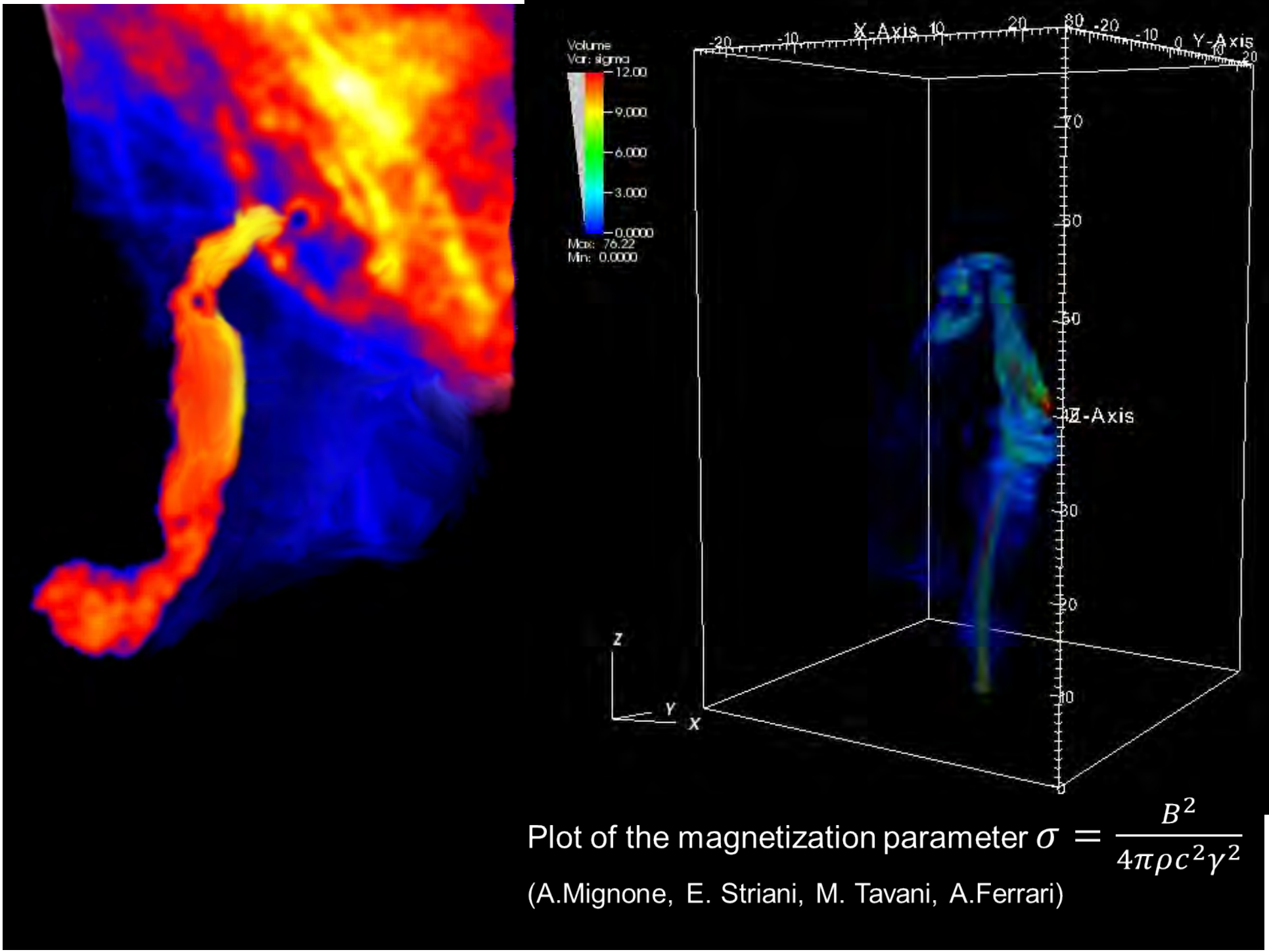

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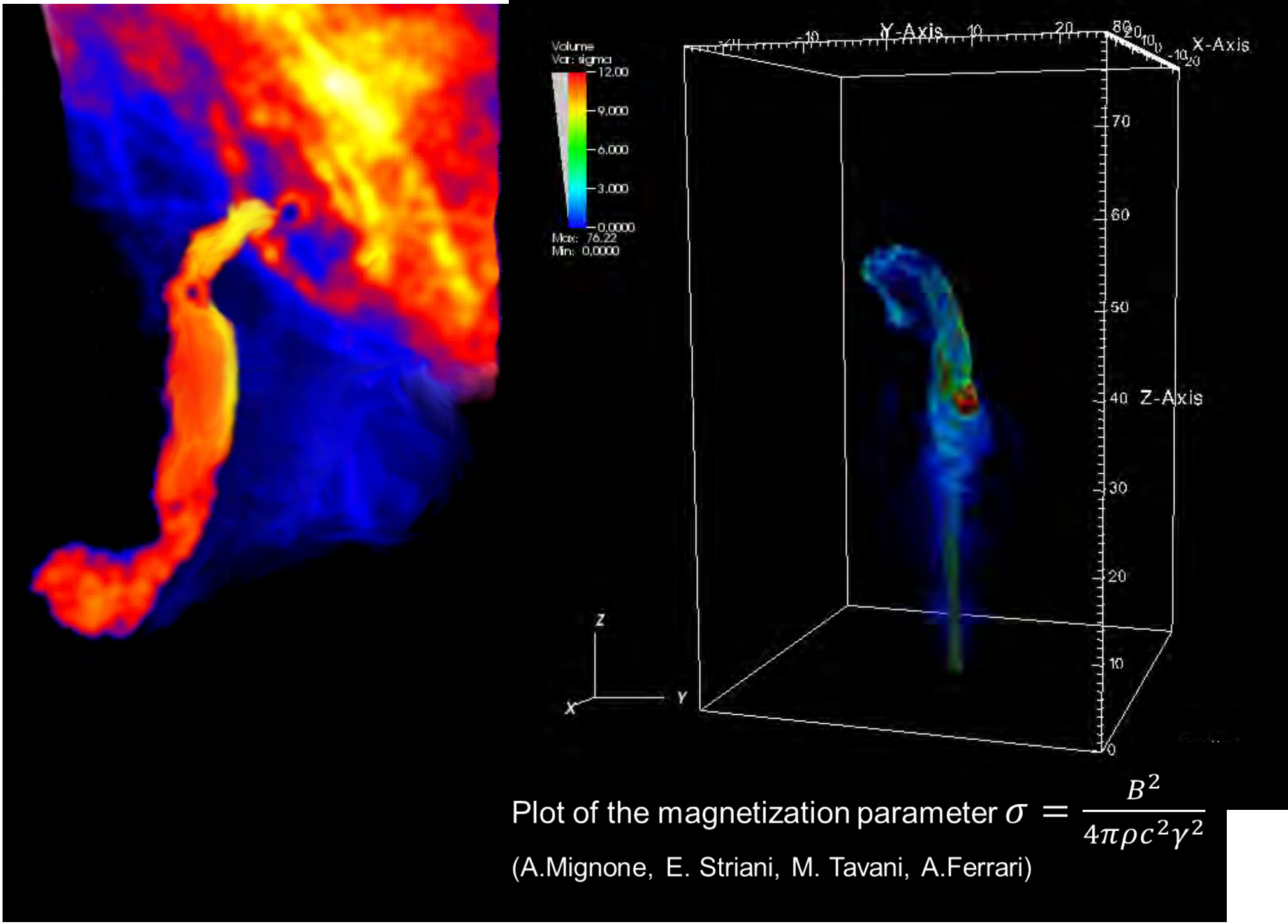


Plot of the magnetization parameter $\sigma = \frac{B^2}{4\pi\rho c^2 \gamma^2}$

(A.Mignone, E. Striani, M. Tavani, A.Ferrari)

Conclusions

- Four major flares from the Crab Nebula, that challenged previous theoretical models of particle acceleration in PWN
- evidence for 2 types of enhanced emission, **fast** (flares) and **slow** (“waves”)
- Gamma-ray continuous monitoring of the Crab is really crucial: flares discovered because of this capability by AGILE and Fermi

Thank You

backup

- "Diffusive Shock Acceleration"

- *DSA time* **vs** *Synch cooling time*
- **Synchrotron burnoff:**

$$\left(t_{cyc} = \frac{2\pi\gamma mc}{eB}, \quad t_{synch} = \frac{6\pi mc^2}{c\sigma_T B^2 \gamma}\right)$$

$$E_{max} \sim 50\ MeV$$

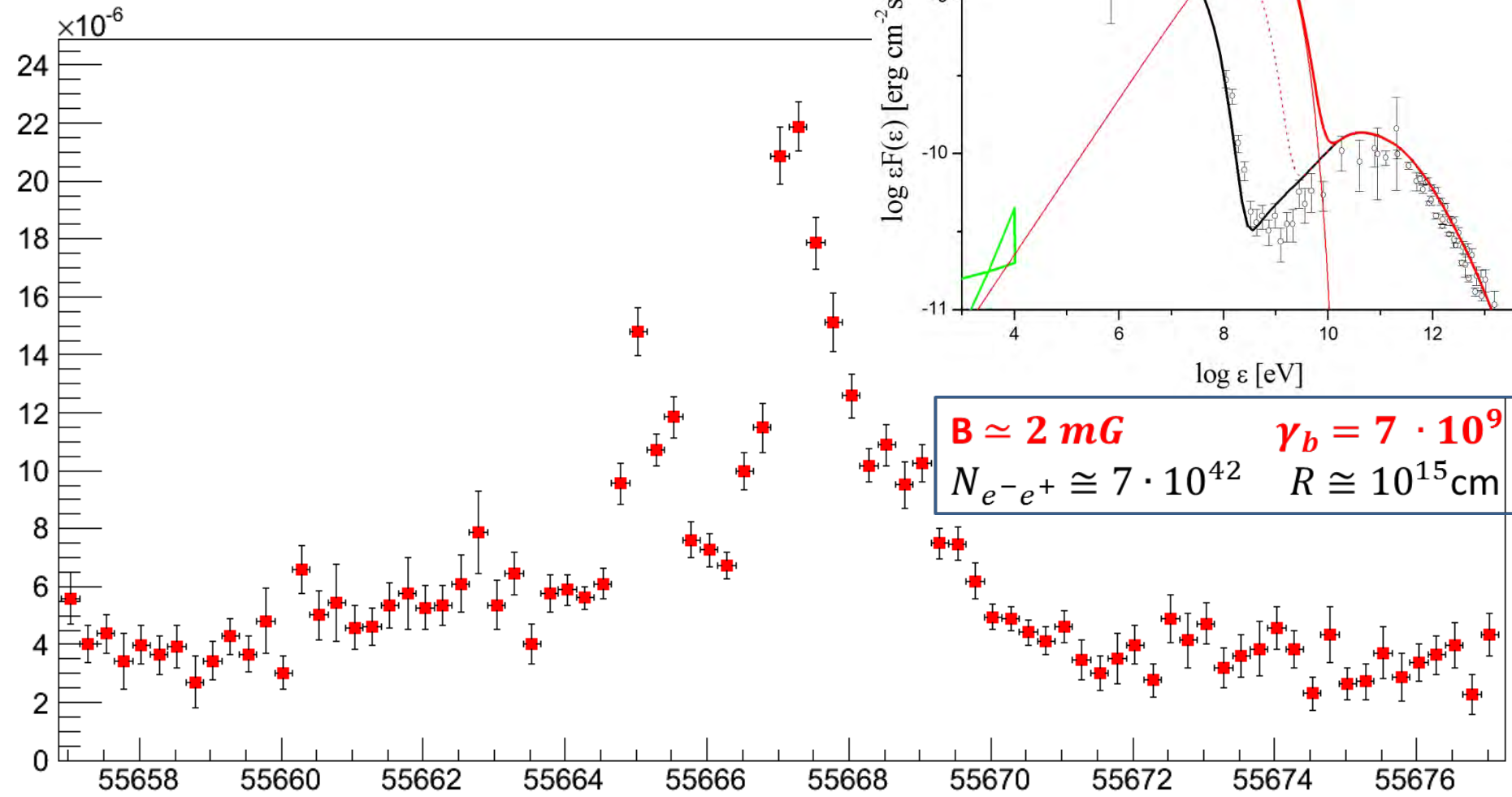
$$E_{\max,\gamma} \sim 150\ MeV \left(\frac{E}{B}\right)\left(\frac{\delta\alpha}{\sin\theta}\right)$$ **MHD expectation**

DSA requires $E < B$: $E = -v \times B/c$

<u>Due to Synchrotron Losses, DSA cannot create PeV electrons</u>

Flare 2011

(Fermi data)



Agile Spectrum at the peak (12 hr)

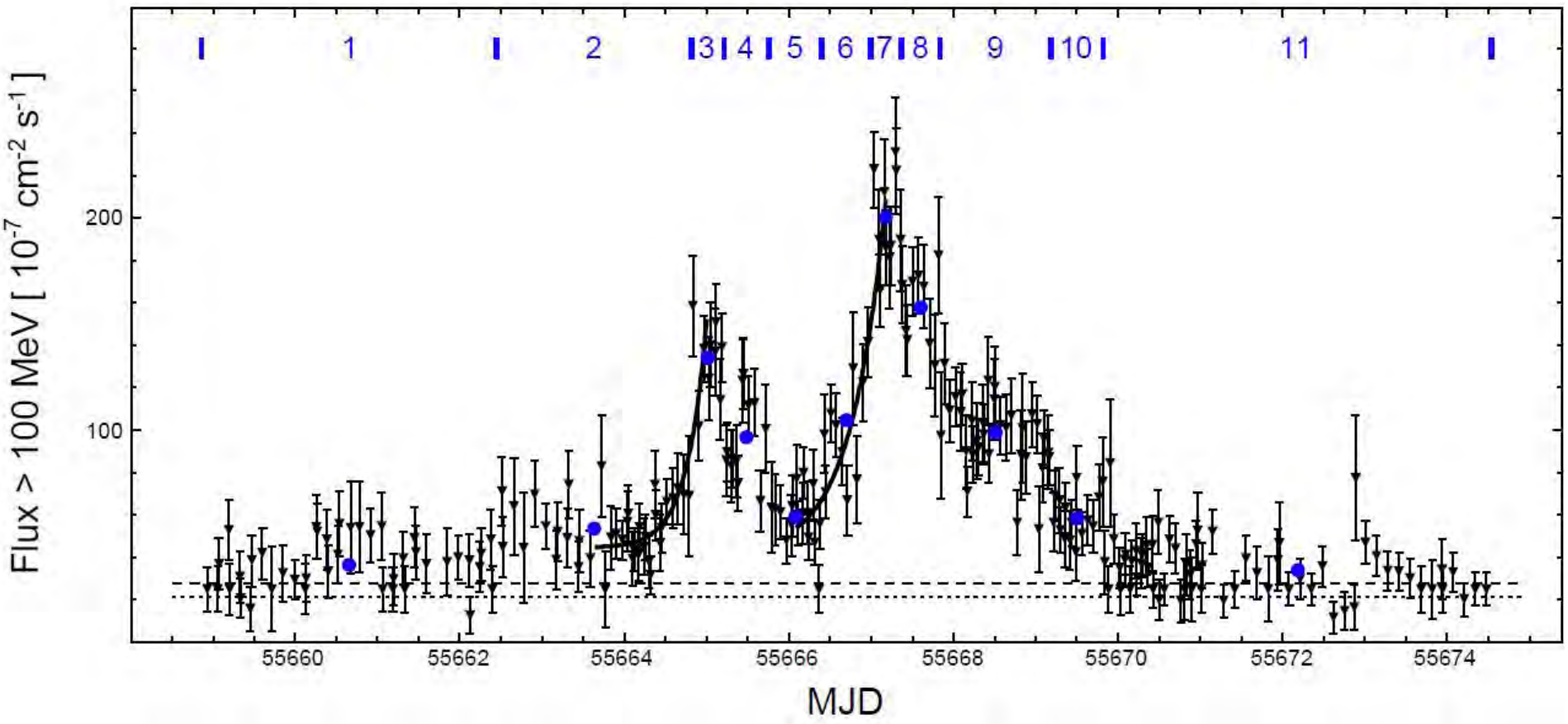
(Striani et al. 2011)

$B \simeq 2\ mG$ $\gamma_b = 7 \cdot 10^9$

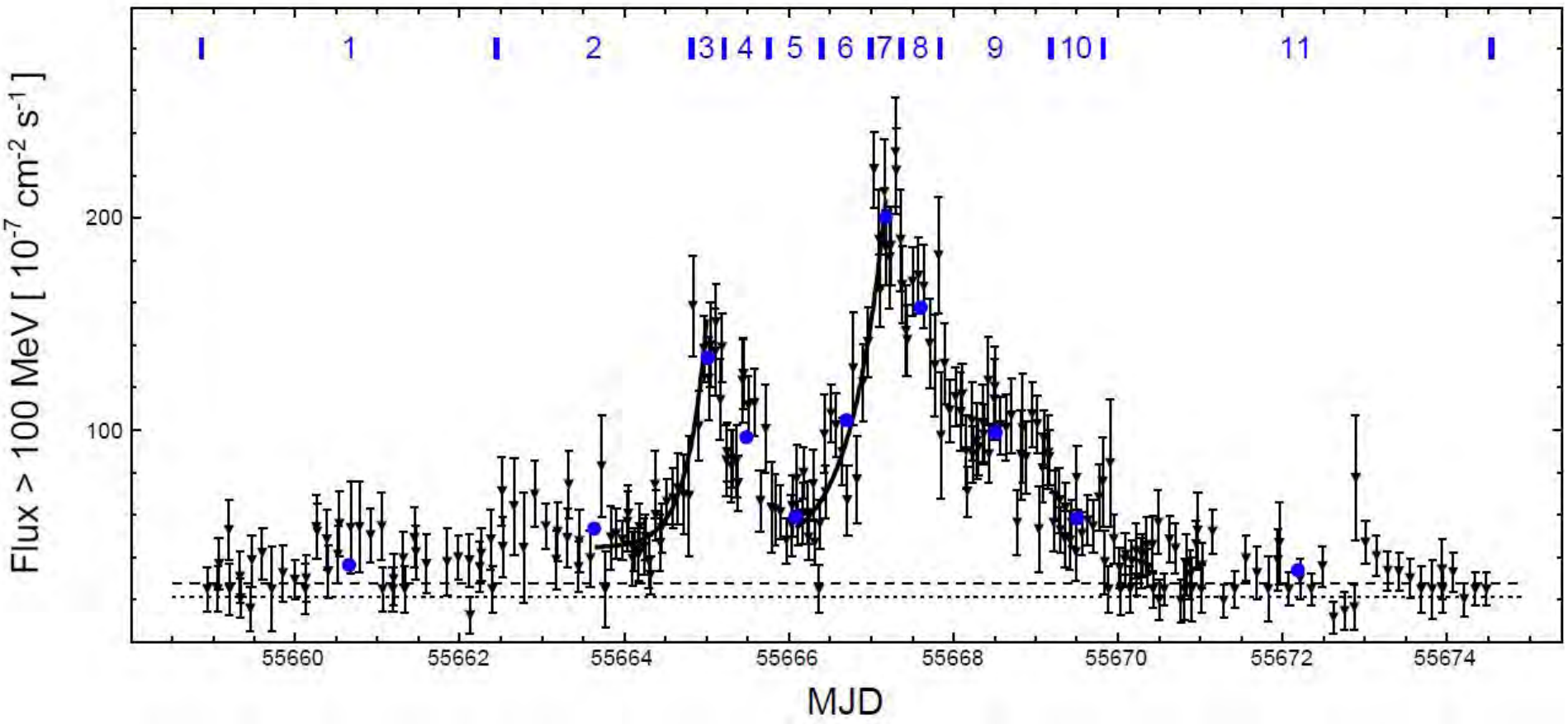
$N_{e^-e^+} \cong 7 \cdot 10^{42}$ $R \cong 10^{15}$cm

Super Flare 2011
Fermi data

CRAB Nebula Superflare (R. Buehler et al. 2011)

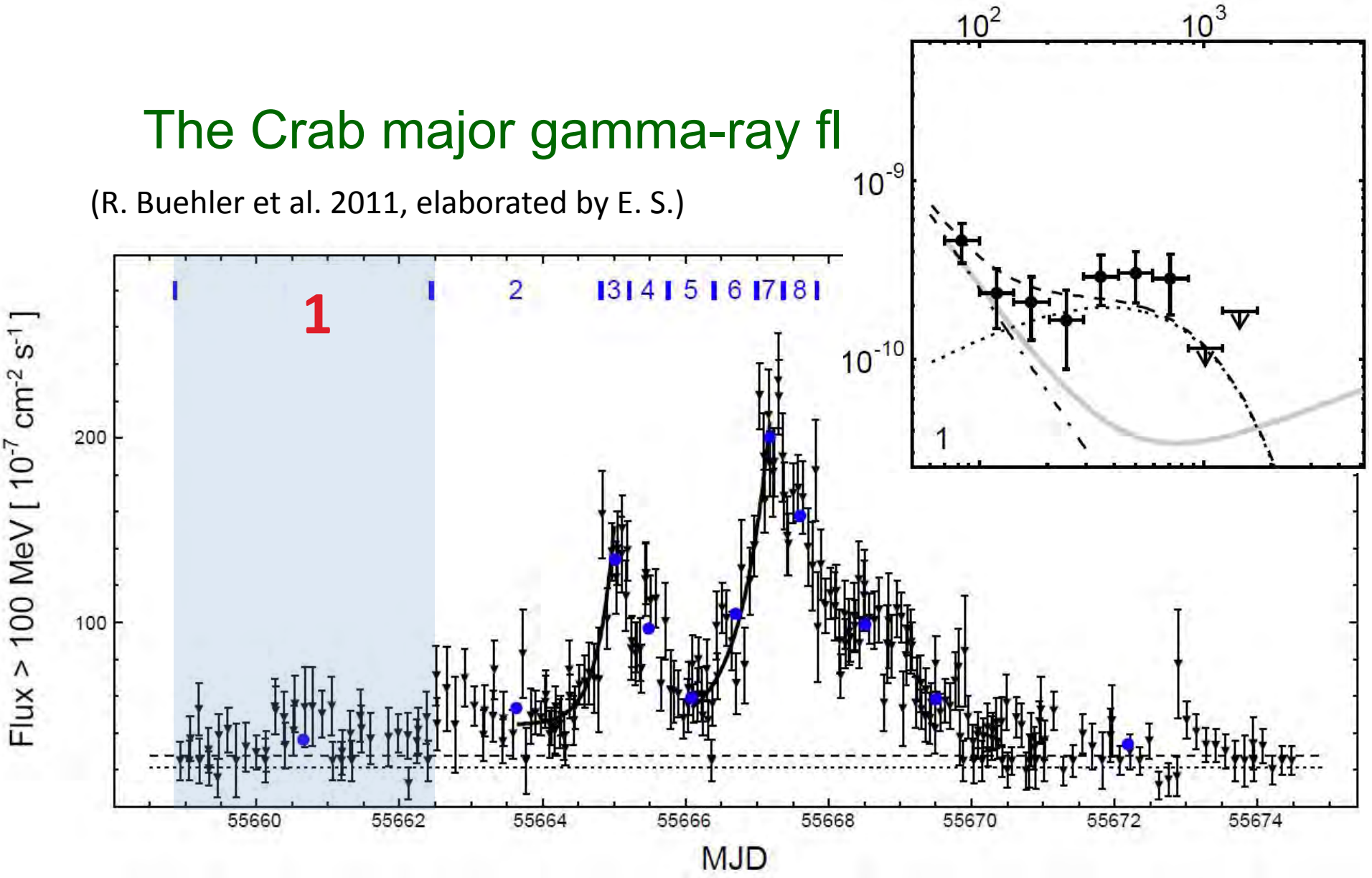


The Crab major gamma-ray flare in April 2011



The Crab major gamma-ray fl

(R. Buehler et al. 2011, elaborated by E. S.)



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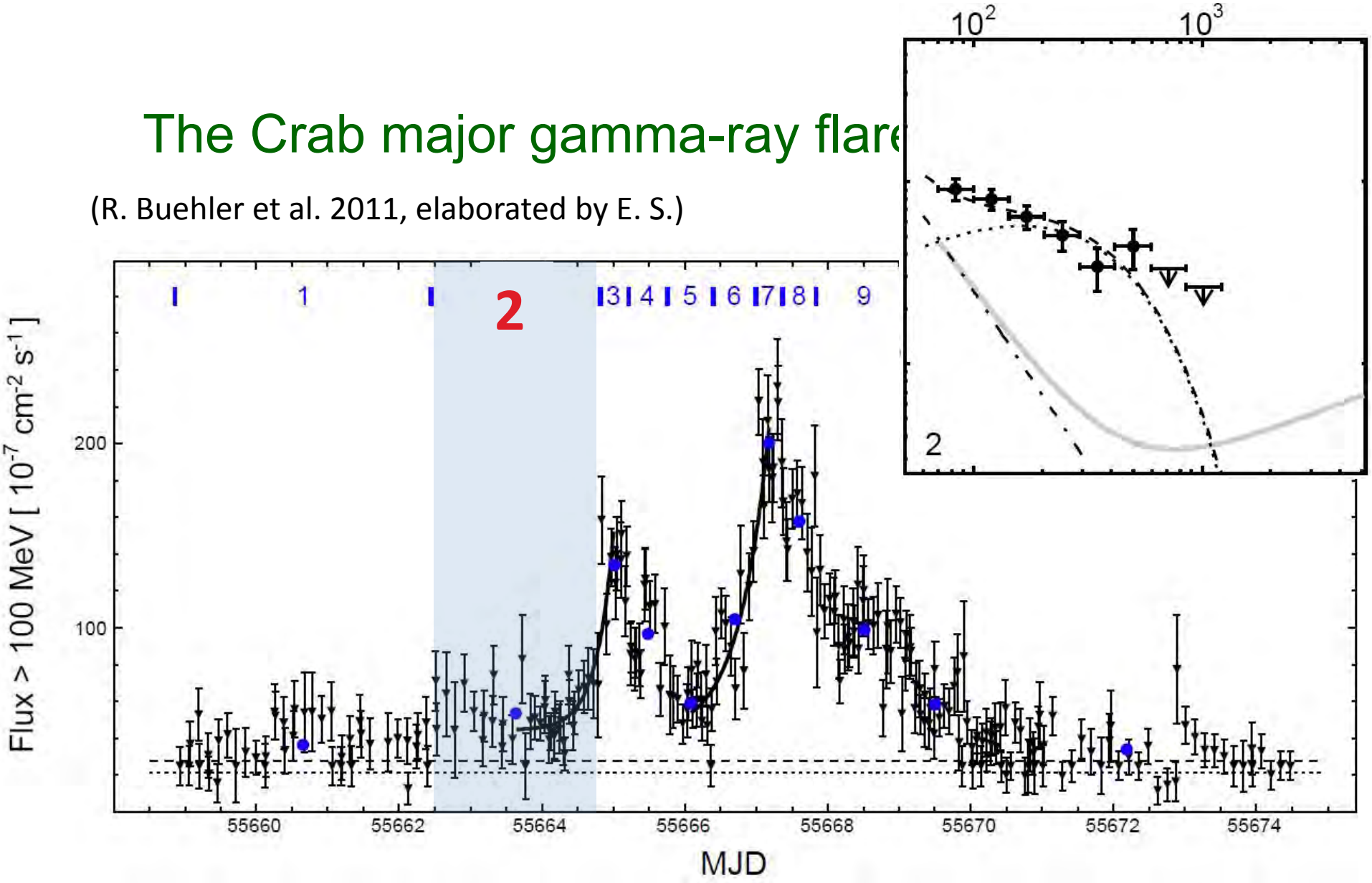

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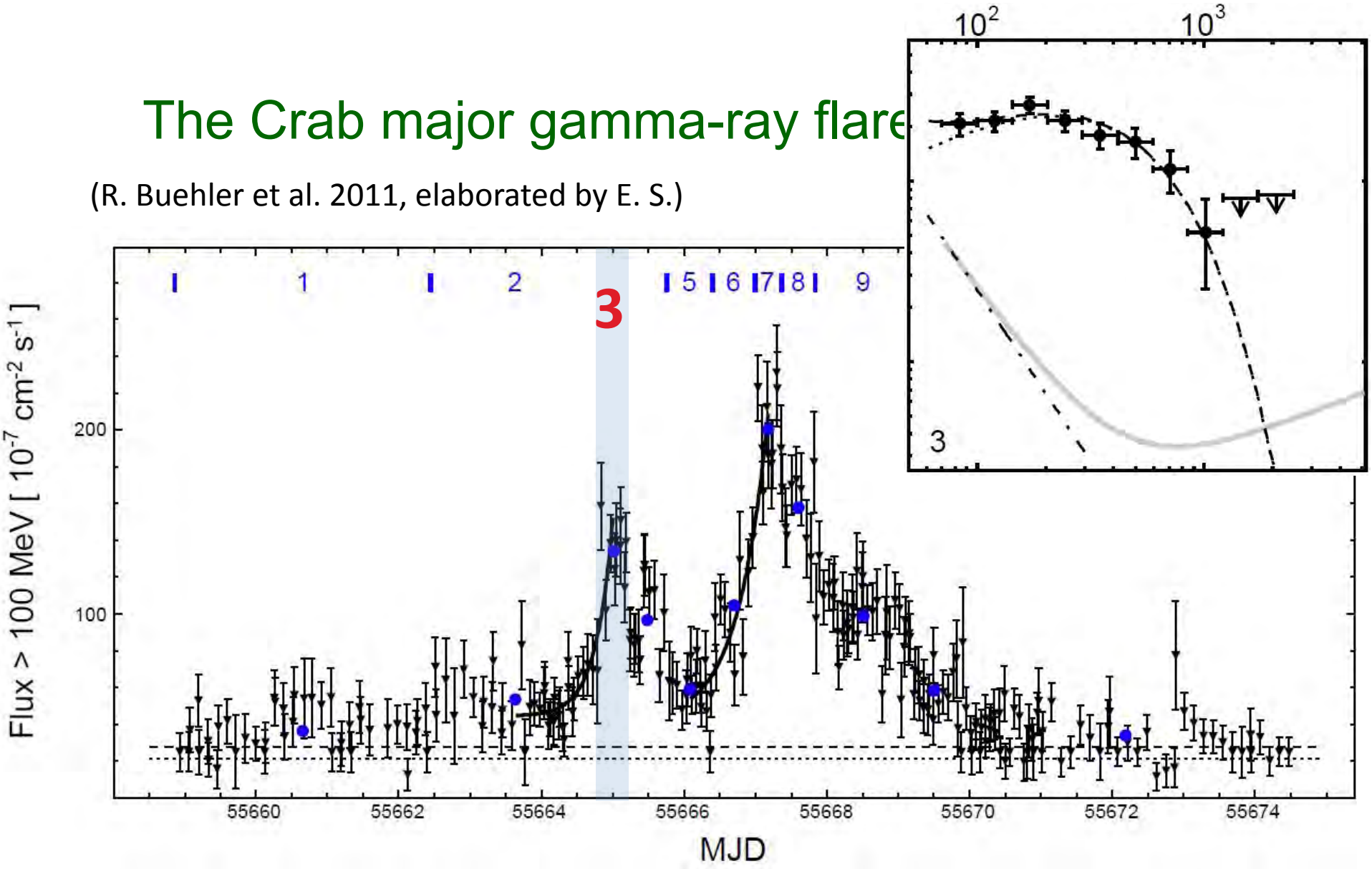

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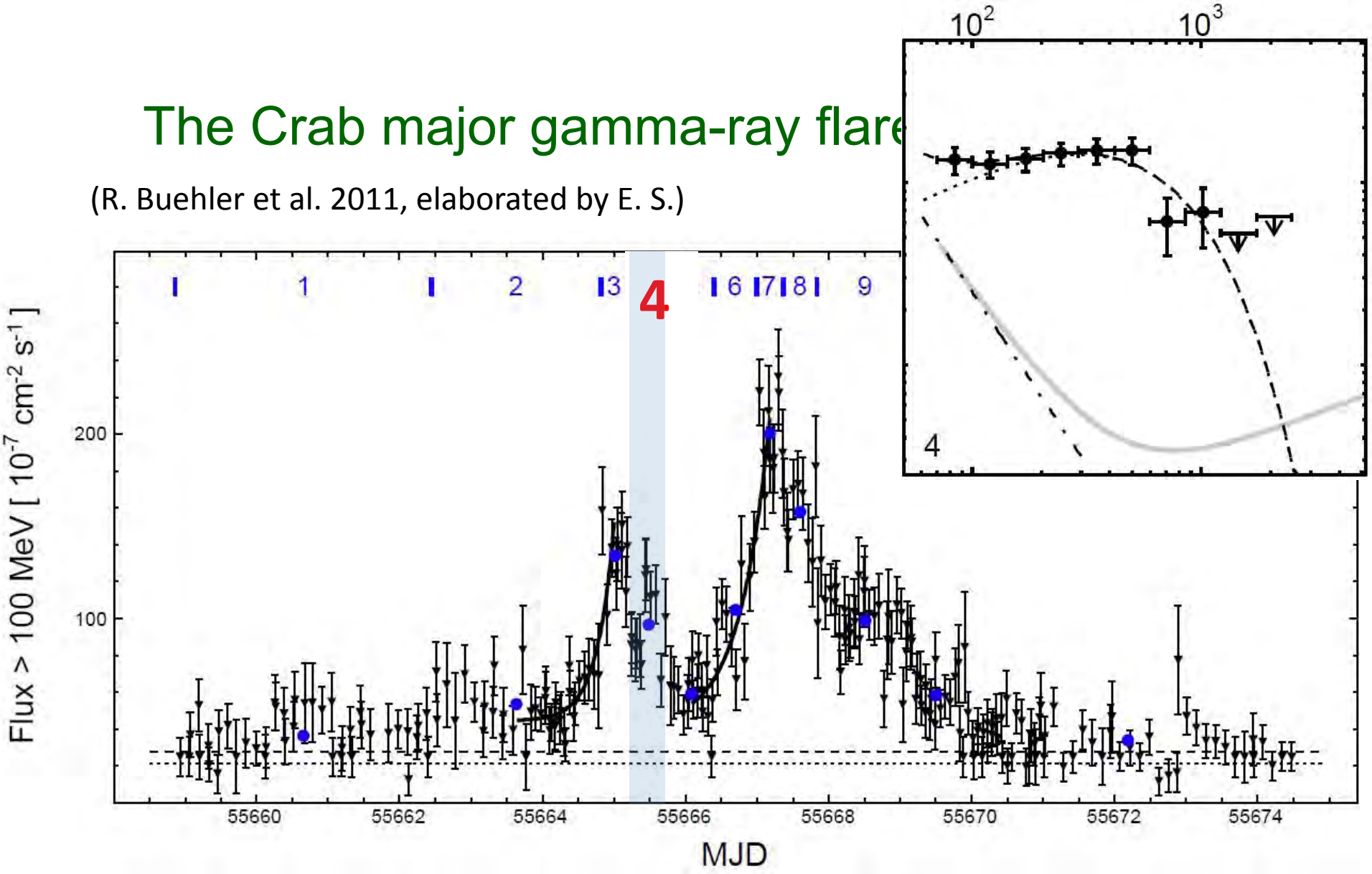

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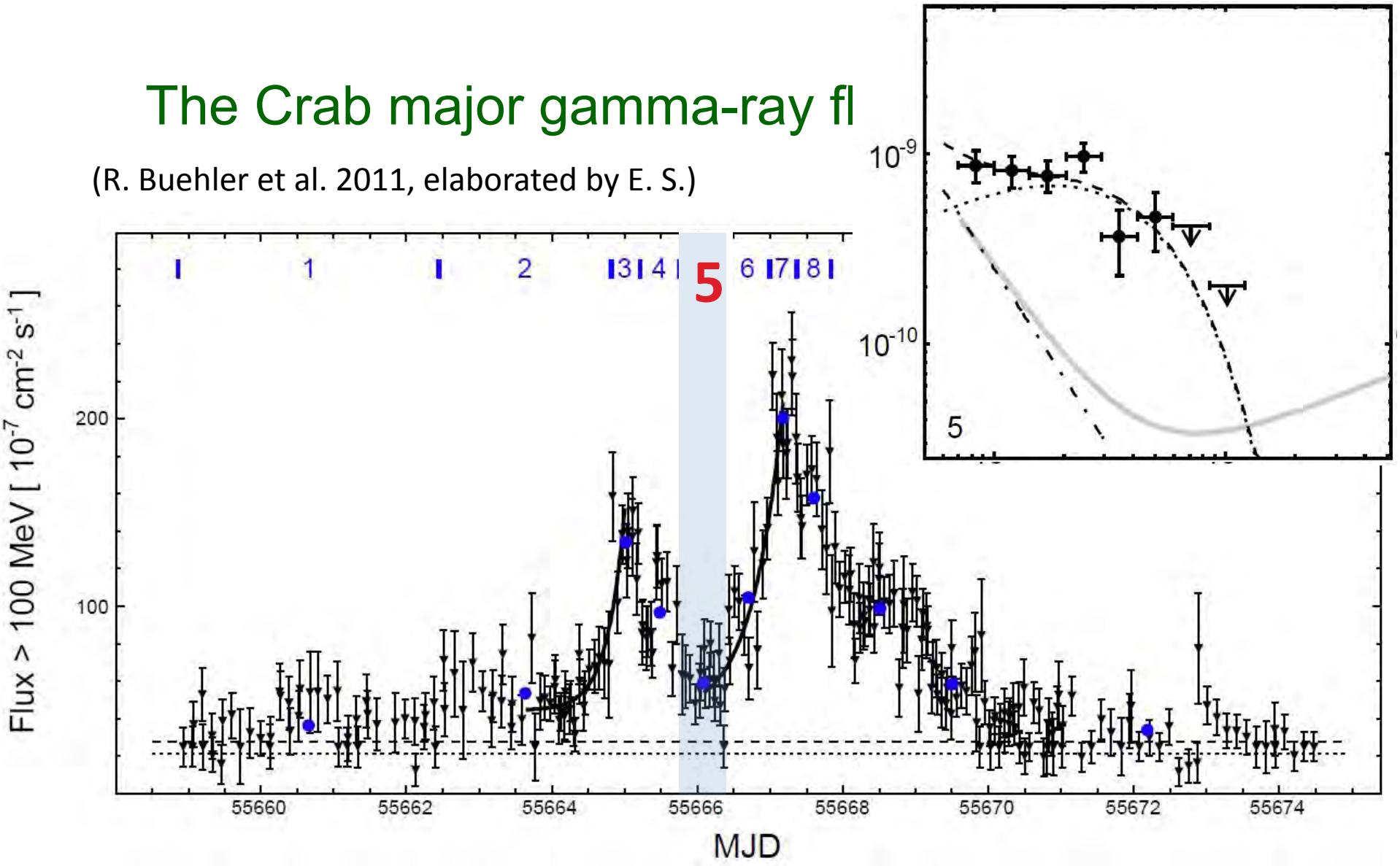
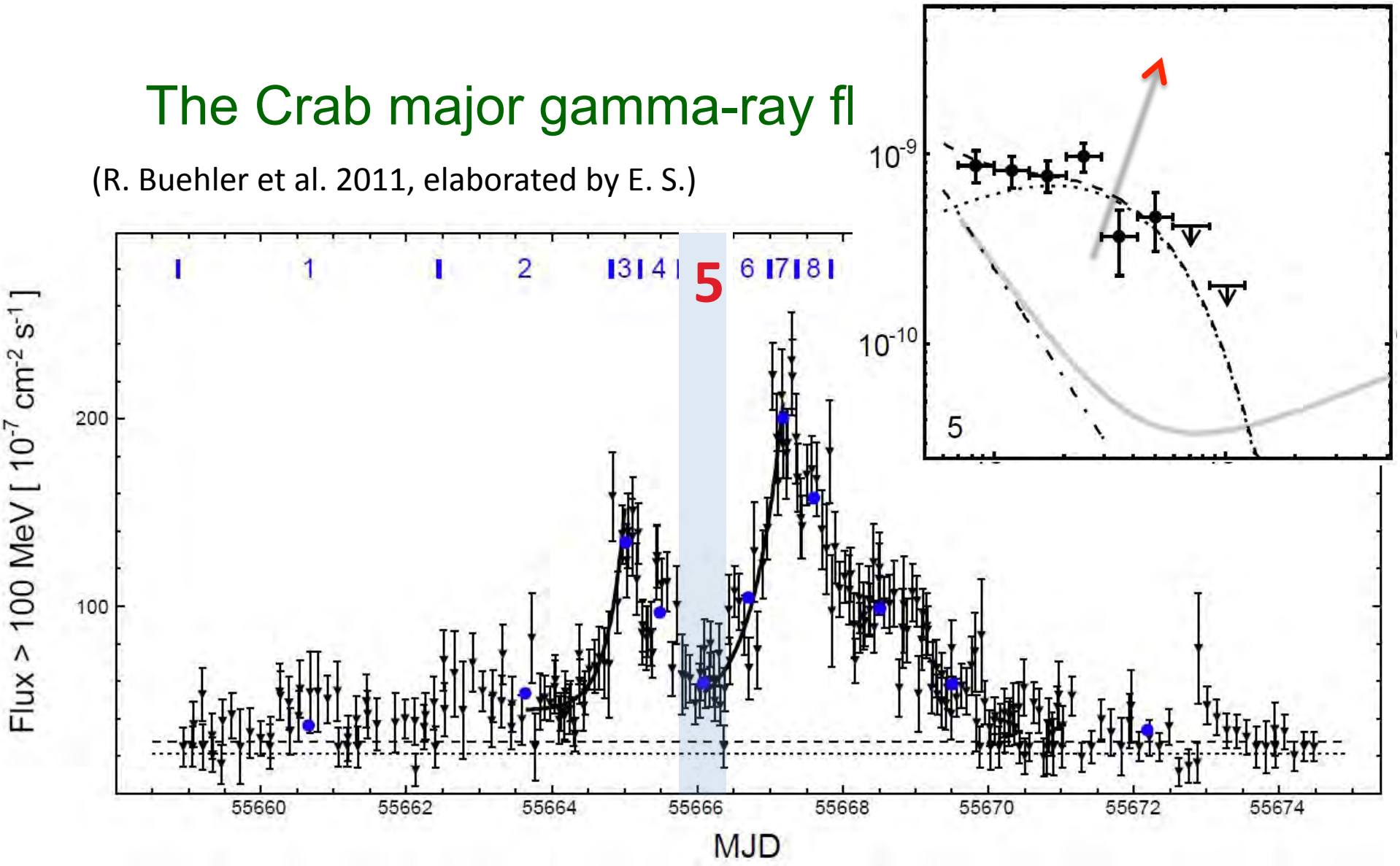


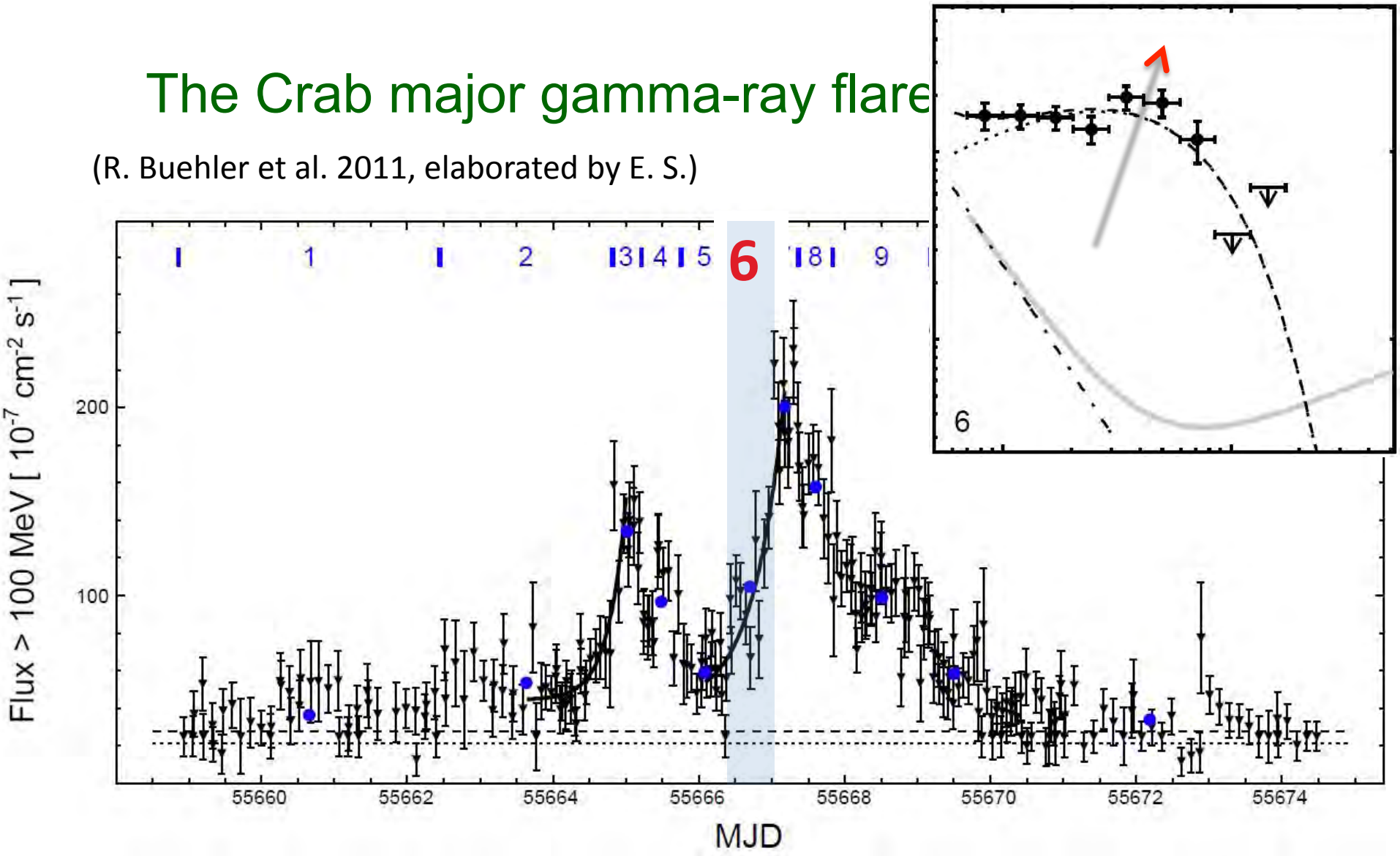
The Crab major gamma-ray fl

(R. Buehler et al. 2011, elaborated by E. S.)



The Crab major gamma-ray flare

(R. Buehler et al. 2011, elaborated by E. S.)



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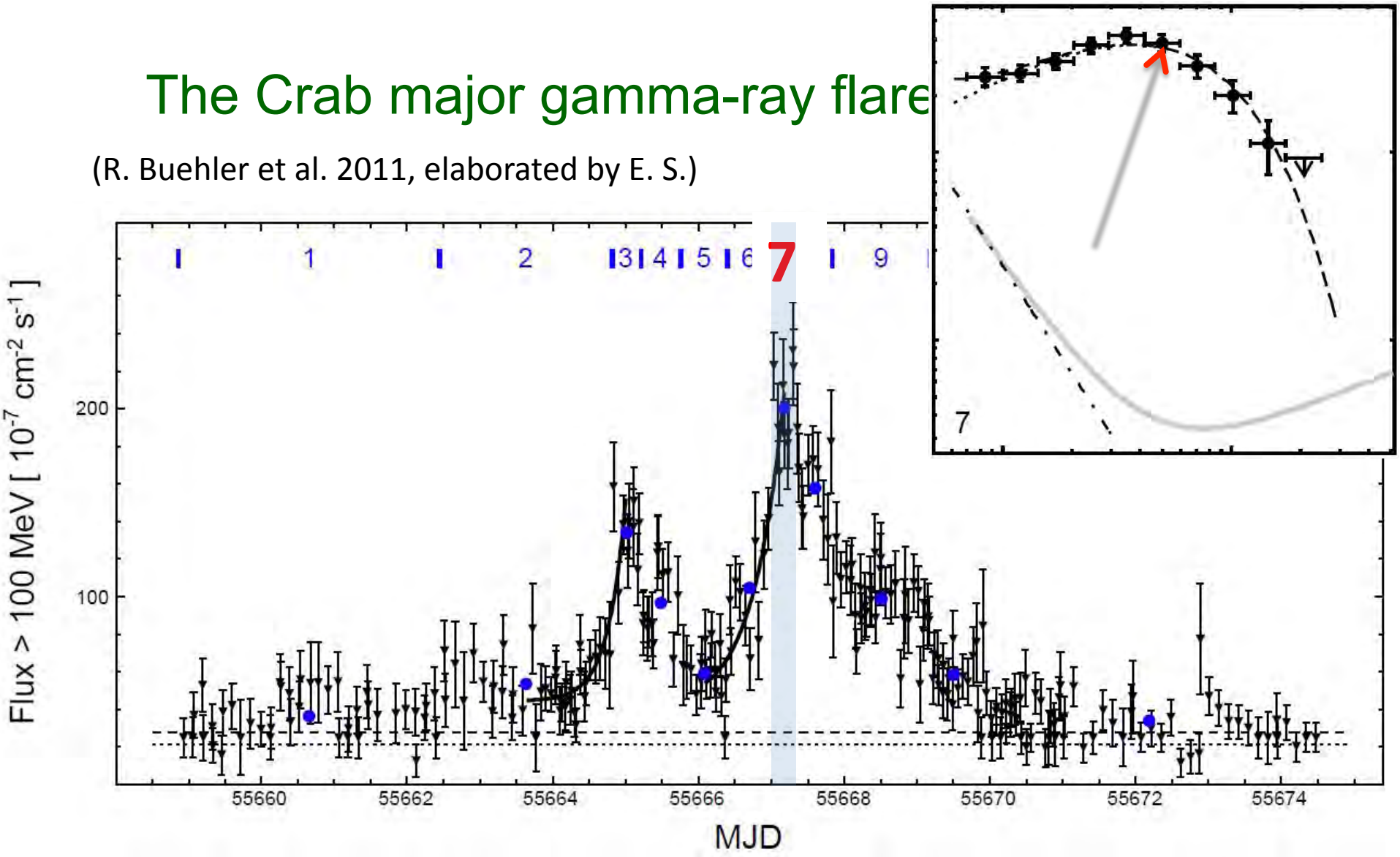

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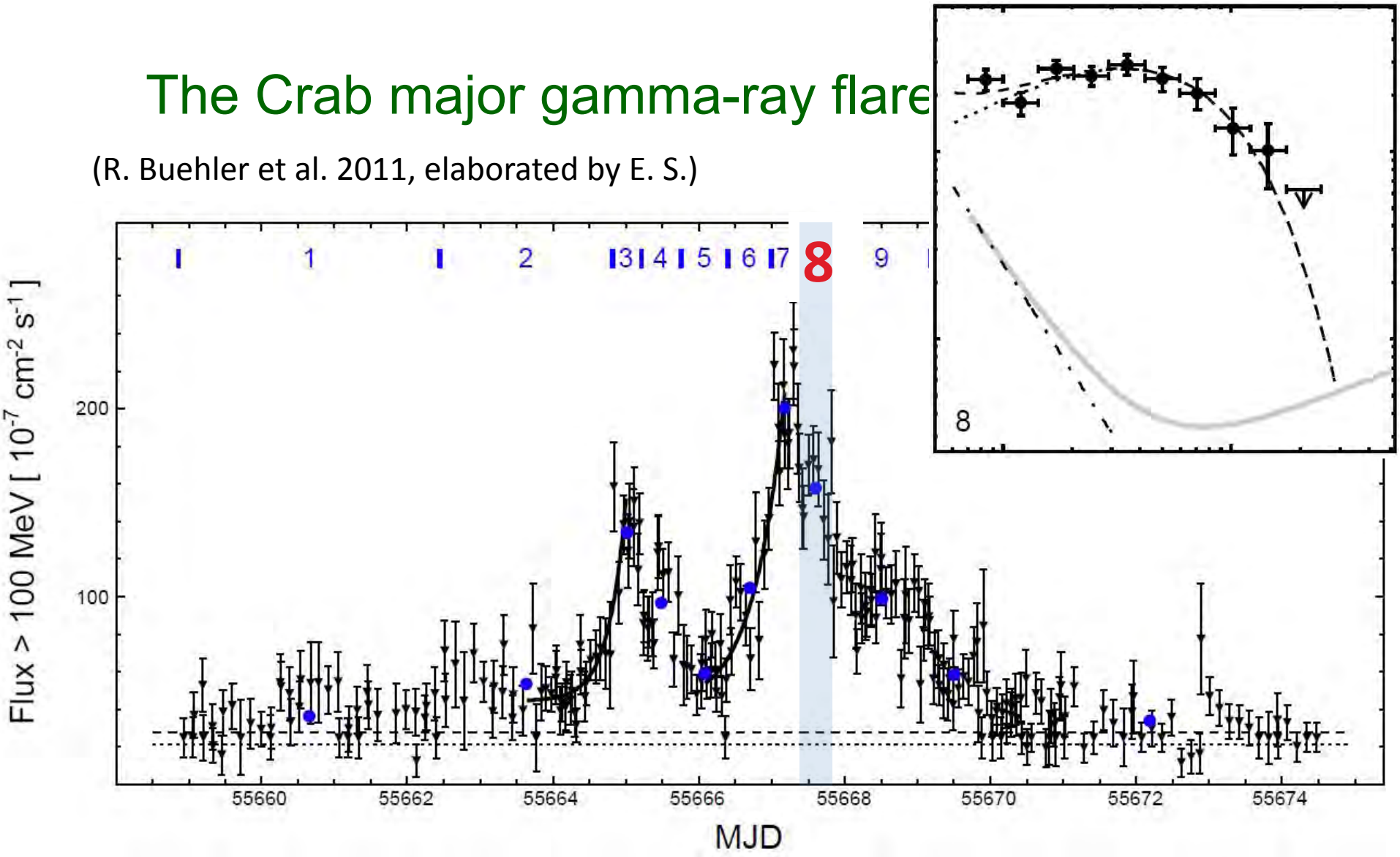
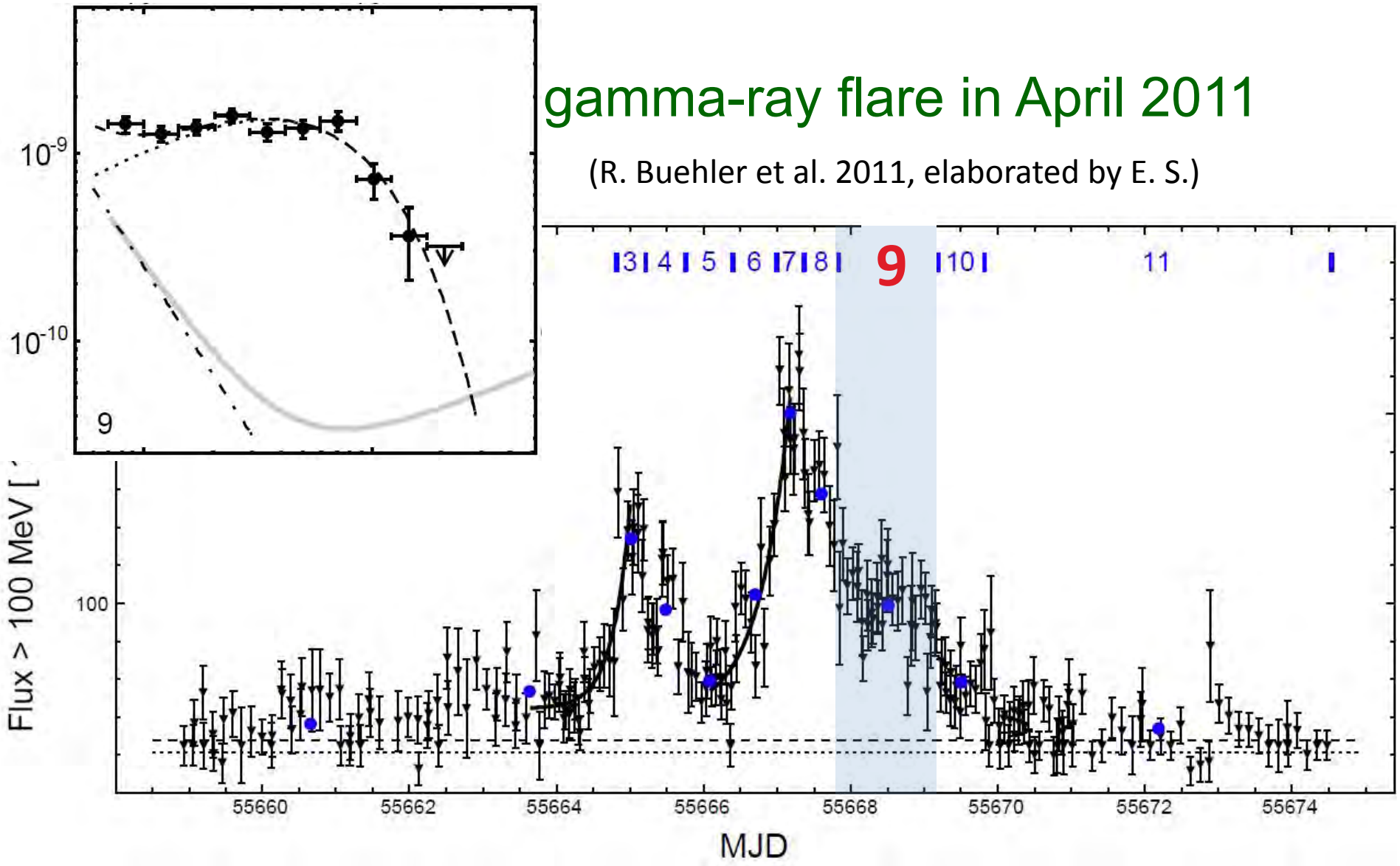
(R. Buehler et al. 2011, elaborated by E. S.)



gamma-ray flare in April 2011

(R. Buehler et al. 2011, elaborated by E. S.)



gamma-ray flare in April 2011

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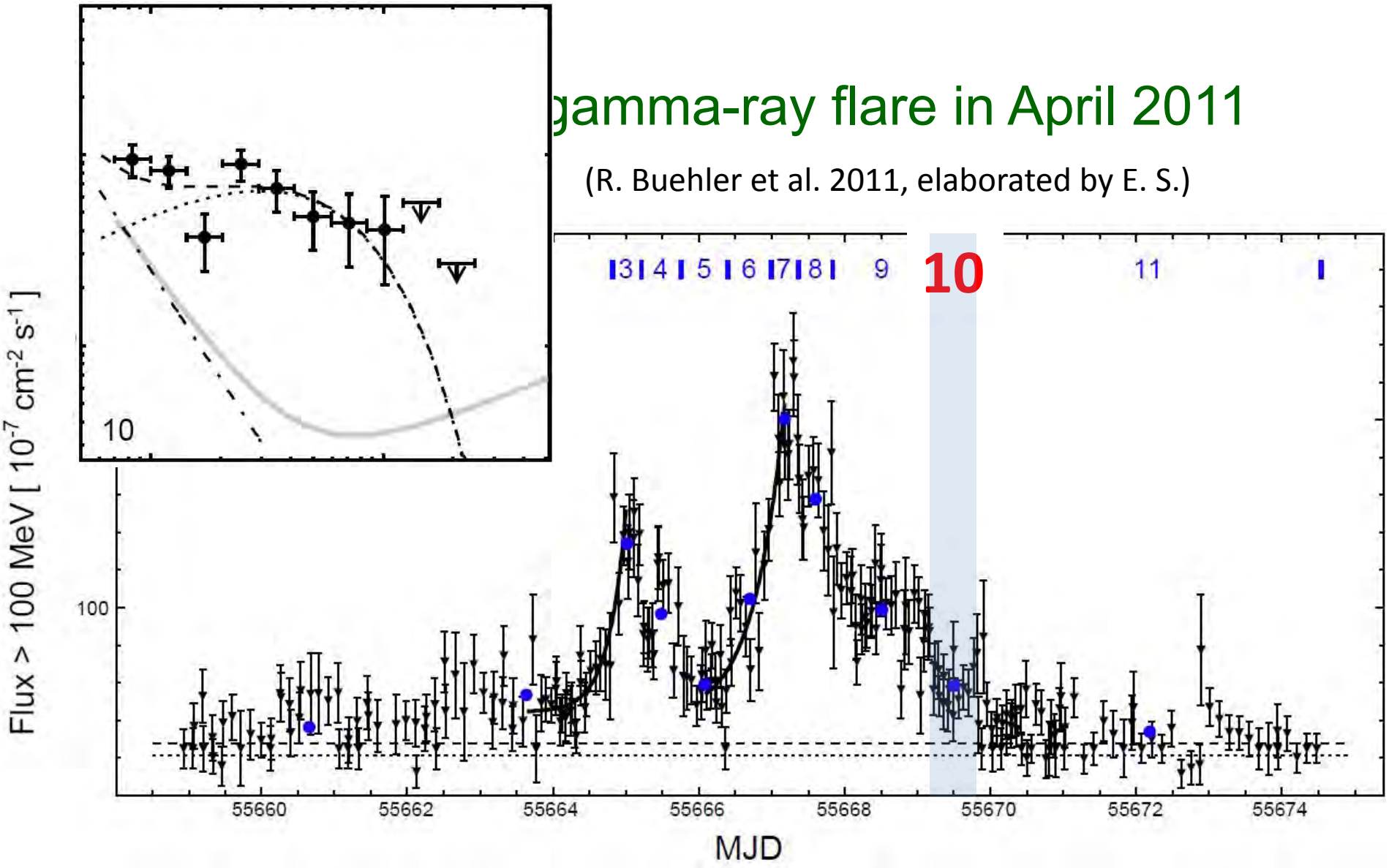

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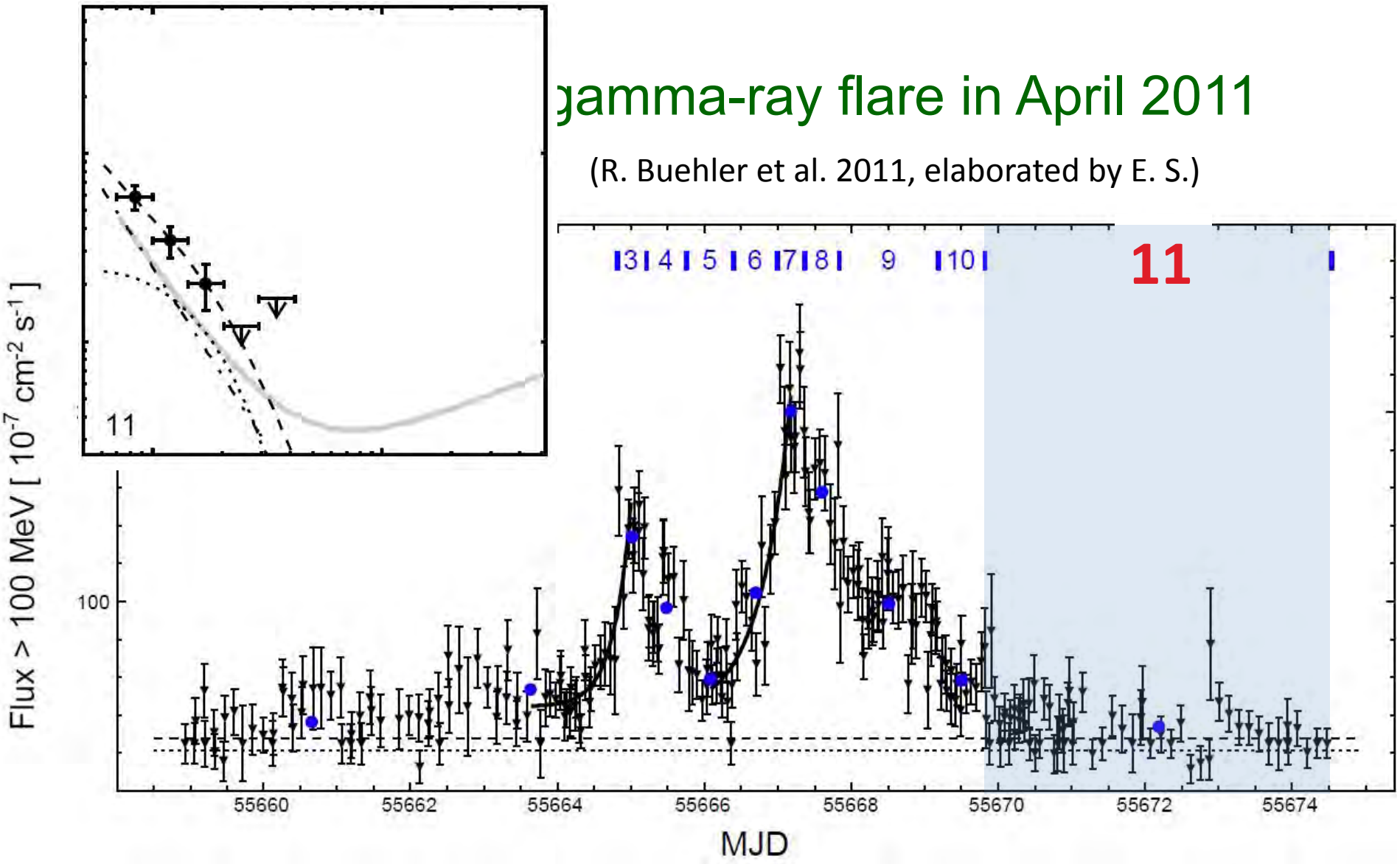
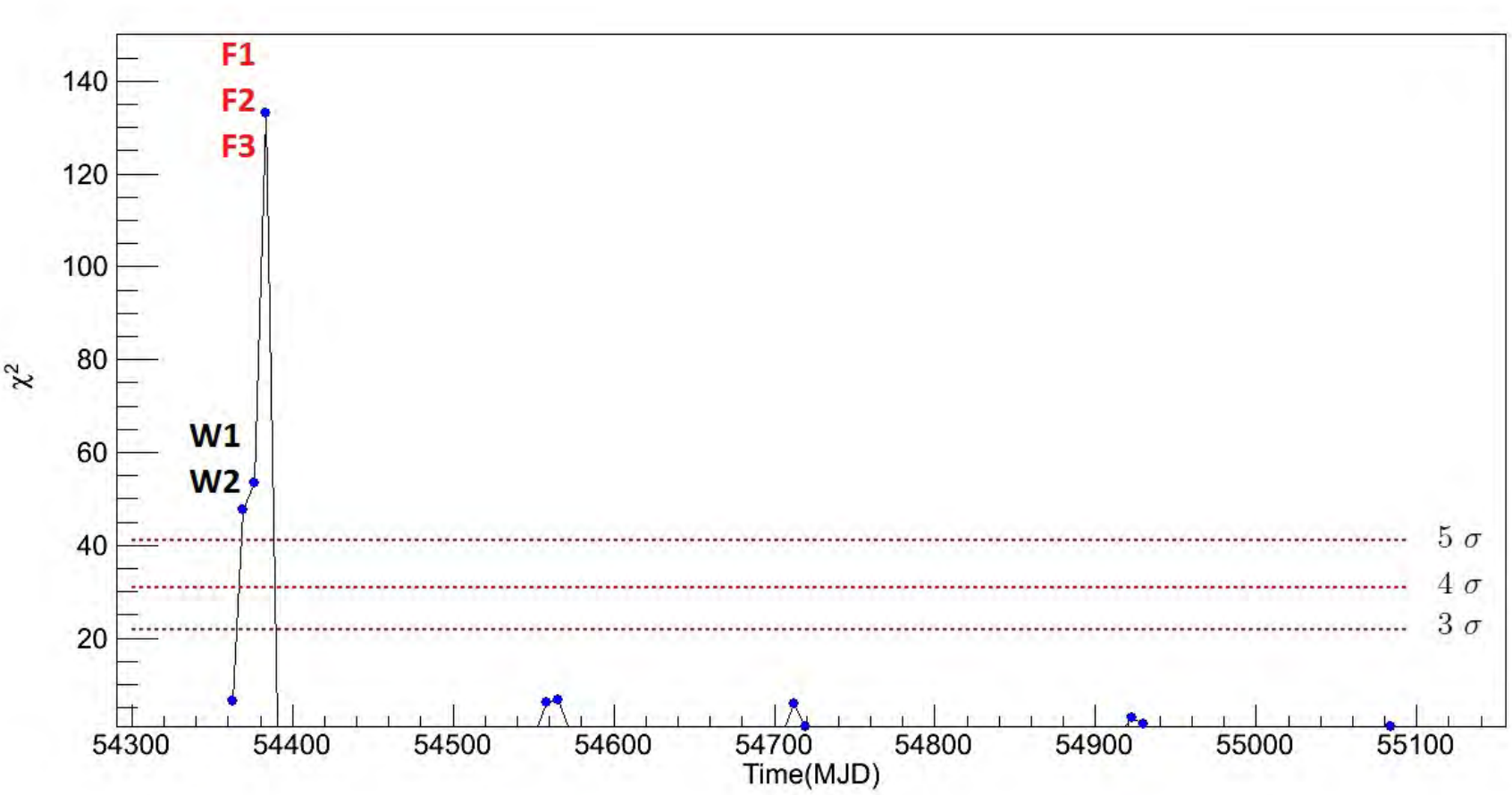
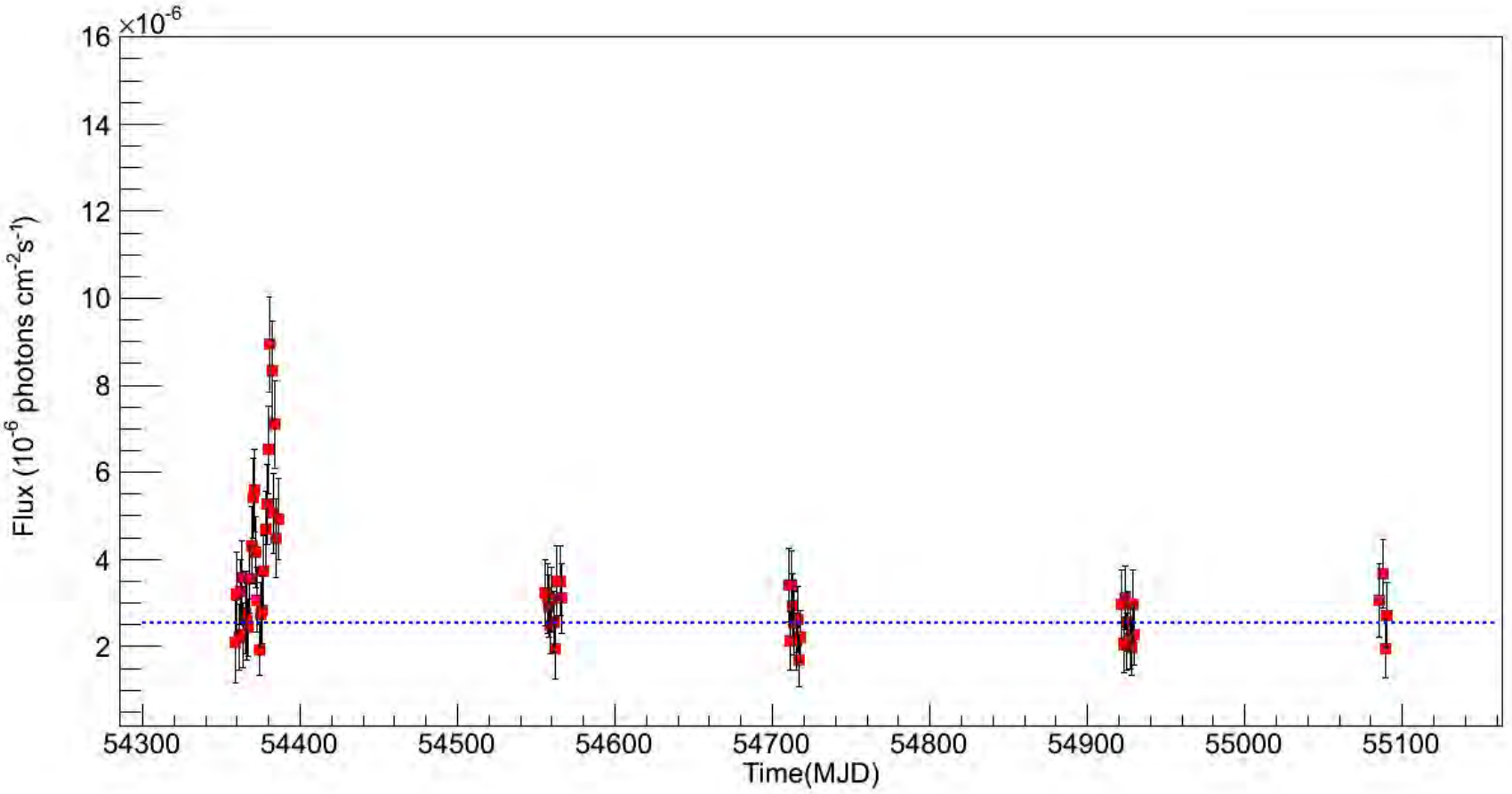


Striani et al., submitted to ApJ



AGILE observations of the Crab Nebula in pointing mode (Sept. 2007 - Oct. 2009)

Striani et al., submitted to ApJ



The CRAB

- $P = 33$ ms
- $L_{PSR} = 5 \cdot 10^{38}$erg/s
- $\dot{n} = 10^{40}\ e^{+}e^{-}/s$

- Wave/particle output energizing the whole system

- The MHD pulsar wind interacts with environment through a sequence of **"shocks"** ($\sim 10^{17}$cm $\cong$ 0.1 pc)
  - "Diffusive Shock Acceleration"
  - 2 main populations of accelerated electrons/ positrons

- Model from radio to gamma rays: Synch with $B = 200\ \mu G$ (Nebula)