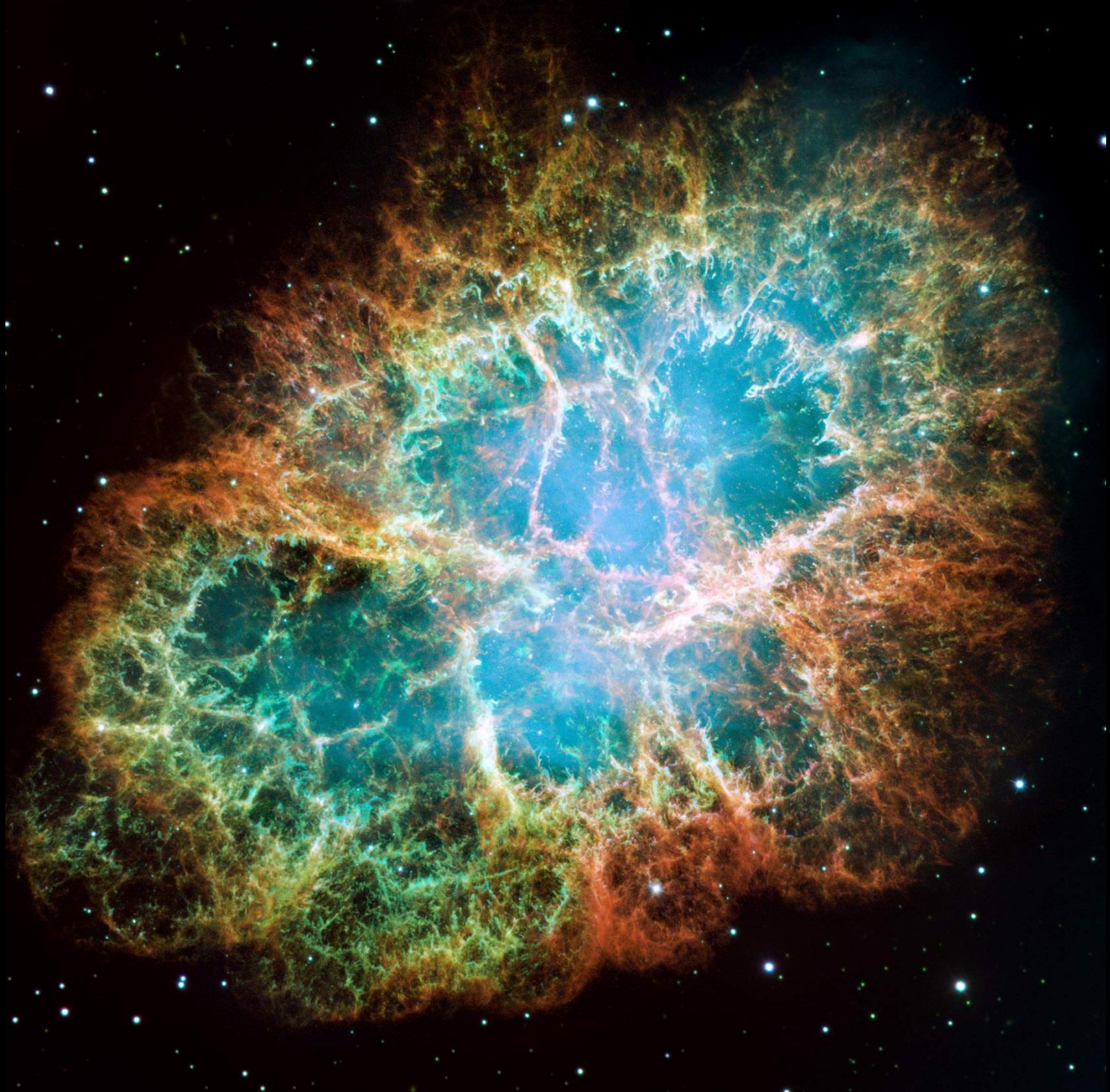
Updating on the CRAB Nebula

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

11th AGILE Science Workshop
16 May 2013



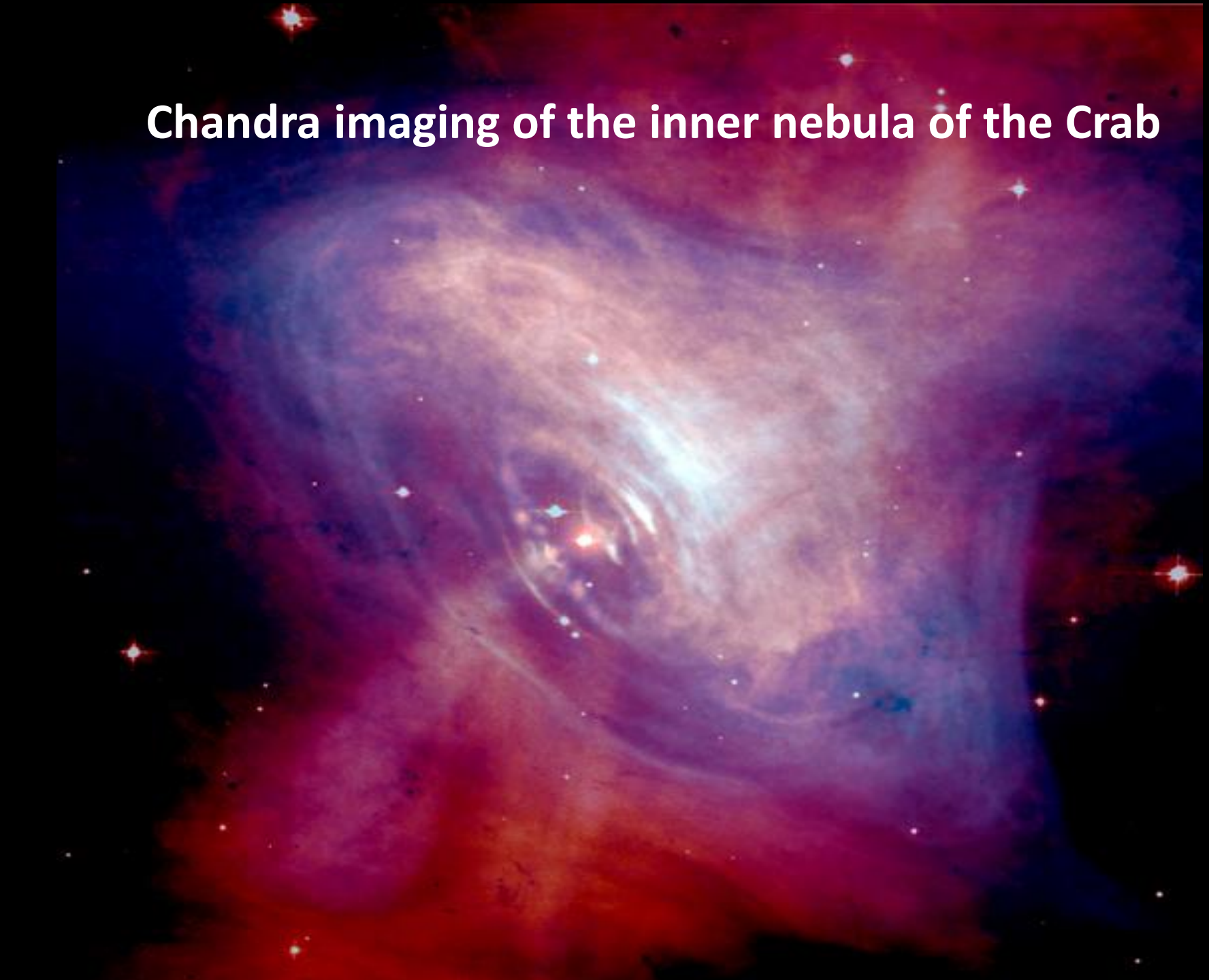
The CRAB

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

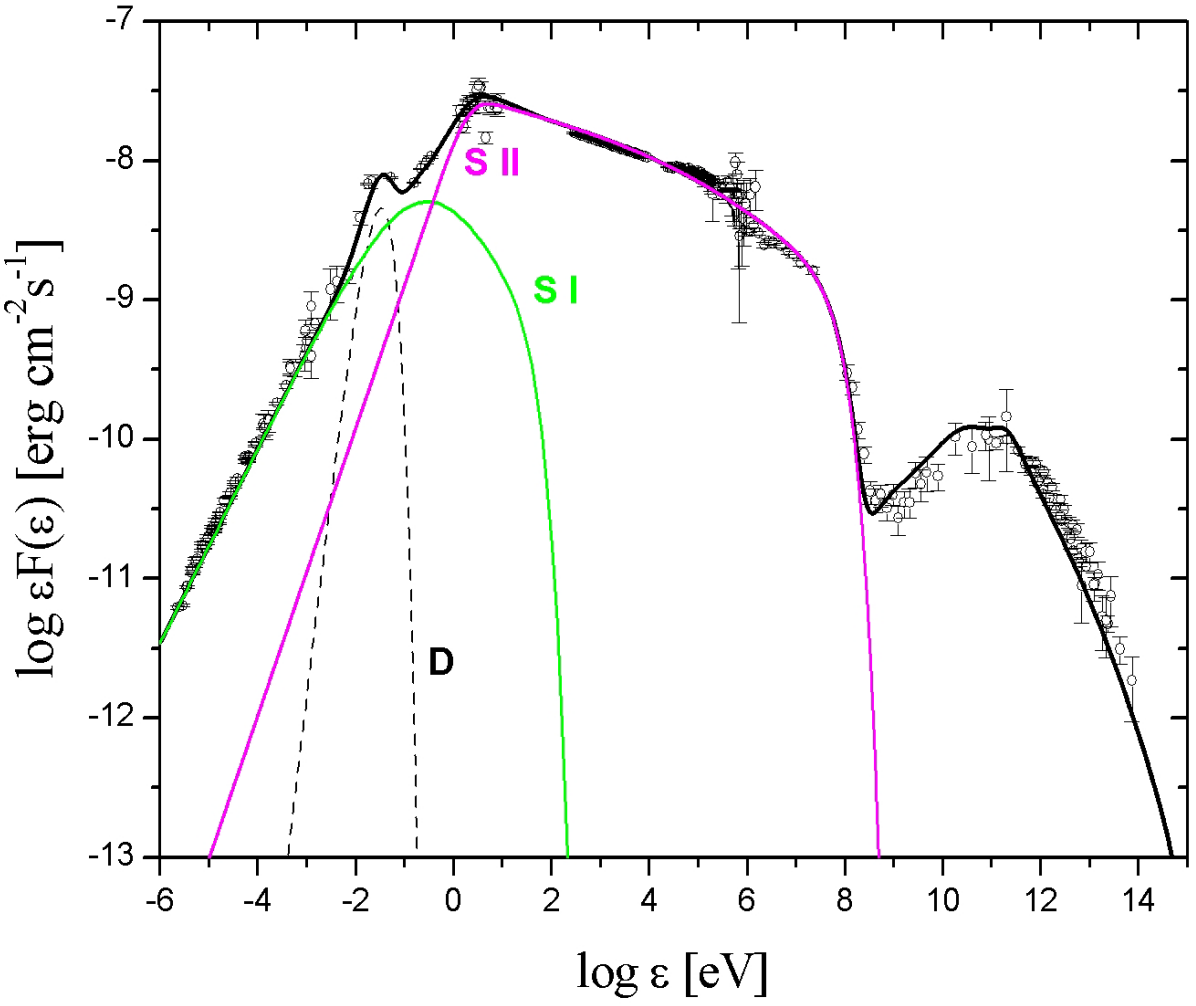
- Wave/particle output energizing the whole system

- 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

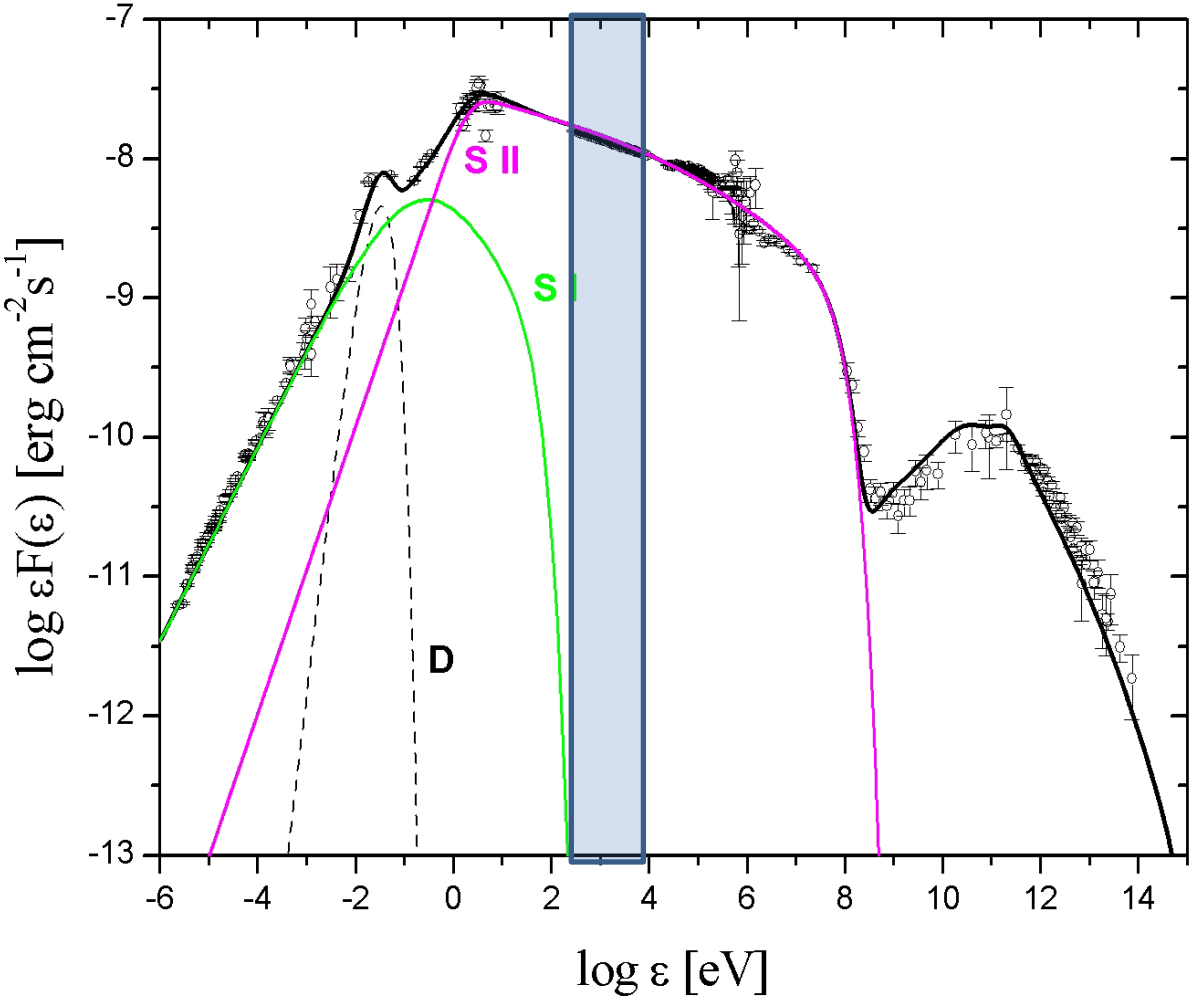
- Model from optical to gamma-rays: Synch with $B = 200\ \mu G$ (Nebula)


Chandra imaging of the inner nebula of the Crab

Crab Nebula spectrum

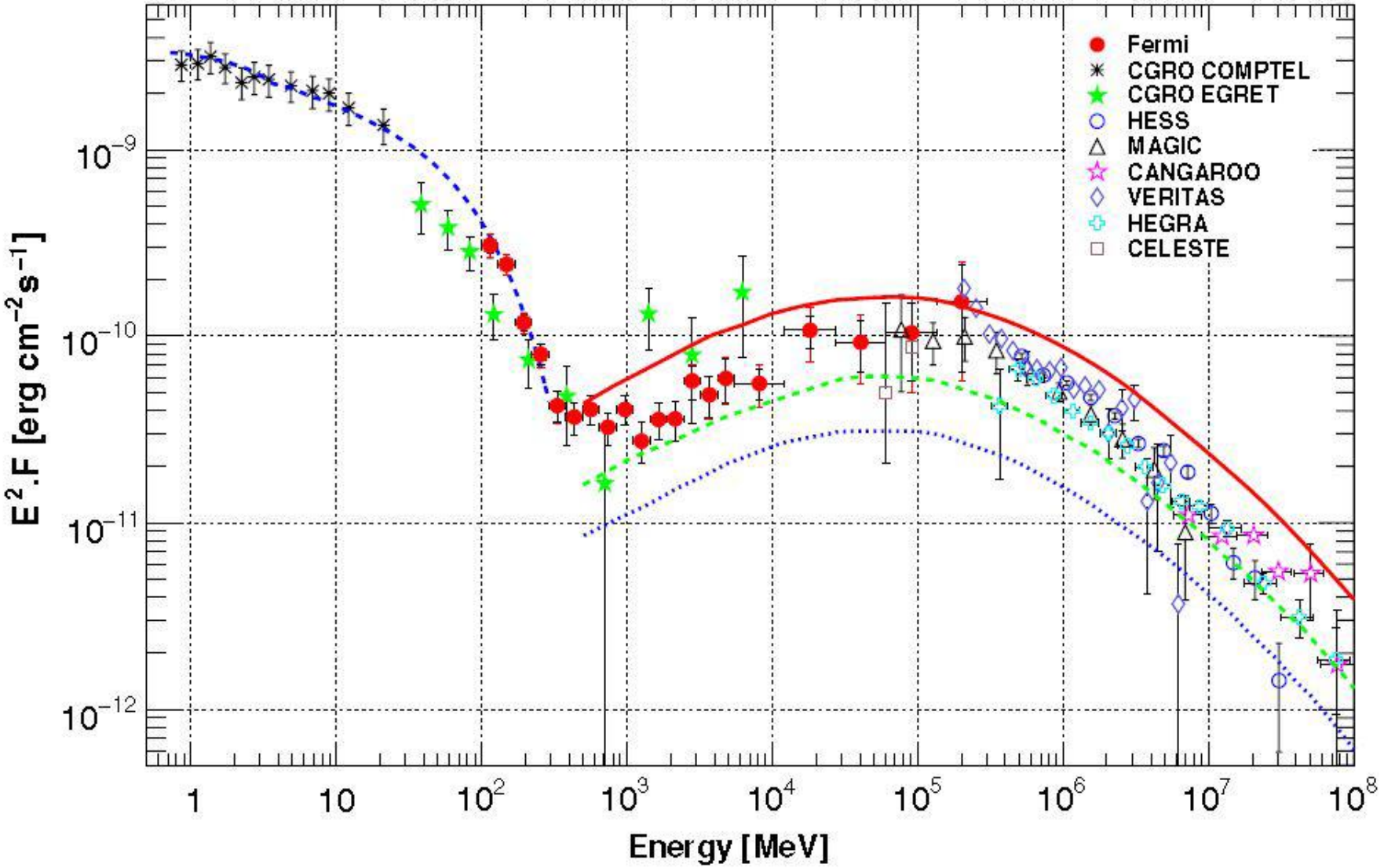


Crab Nebula spectrum



Unpulsed (nebular) gamma-ray spectrum

(Abdo et al 2010)



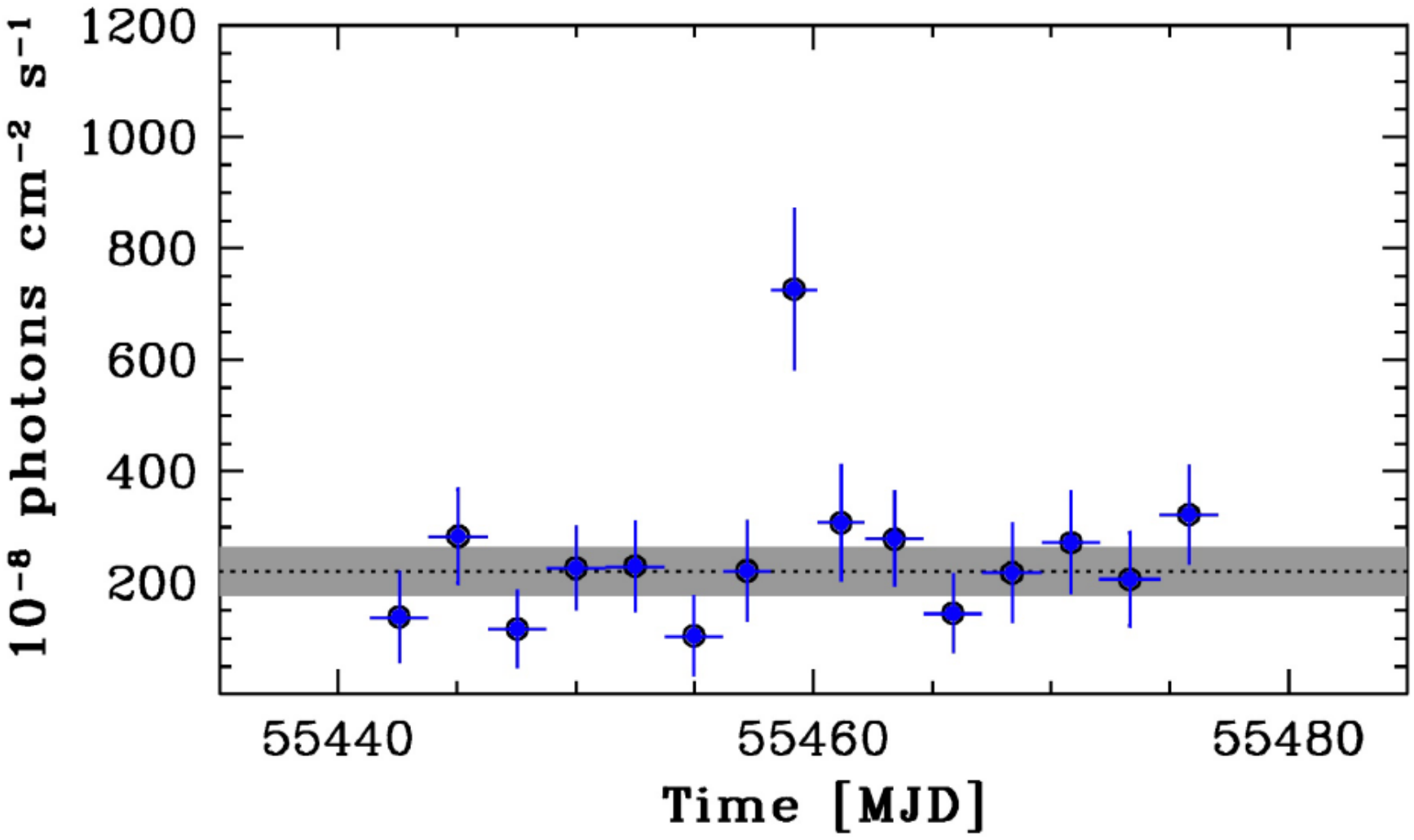
The Crab Nebula

1. Stable (**Standard candle**)

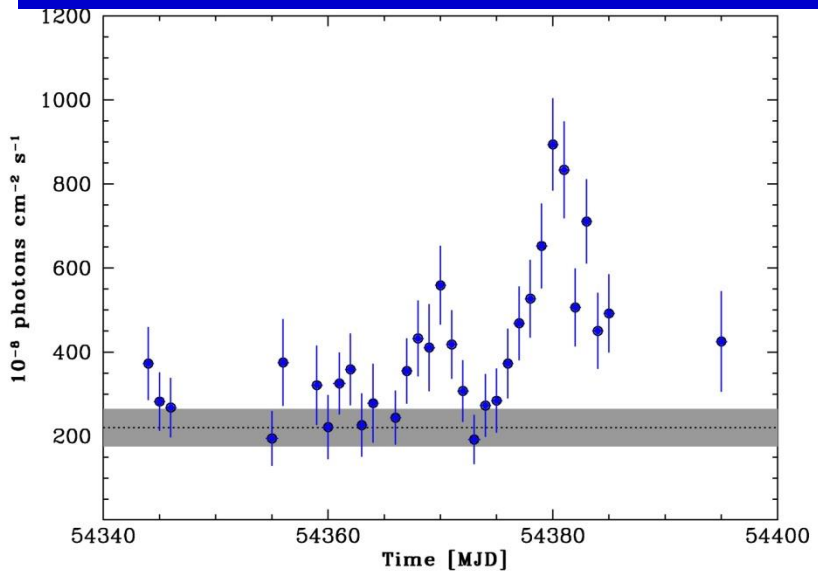
2. Cut-off in the spectrum around 150 MeV

The Discovery

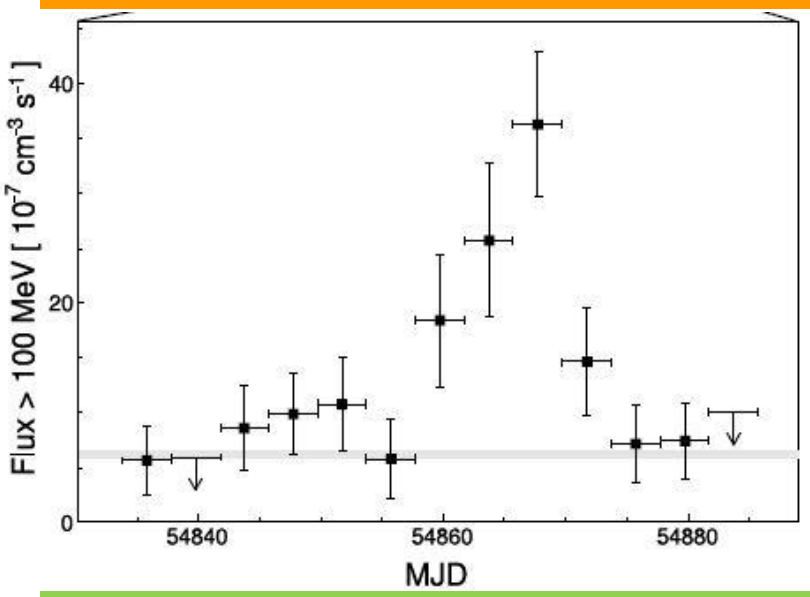
CRAB Nebula Flare (Tavani et al. 2010, Science)



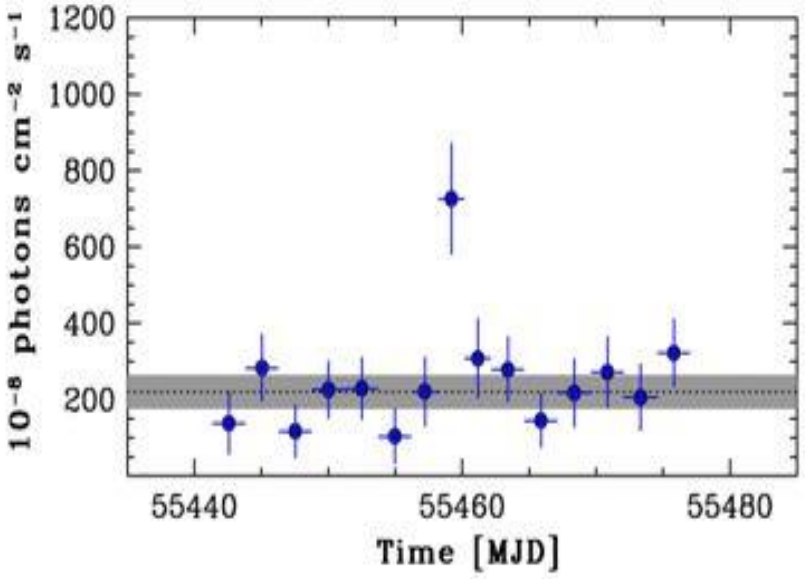
AGILE, 26 Nov. – 13 Oct. 2007



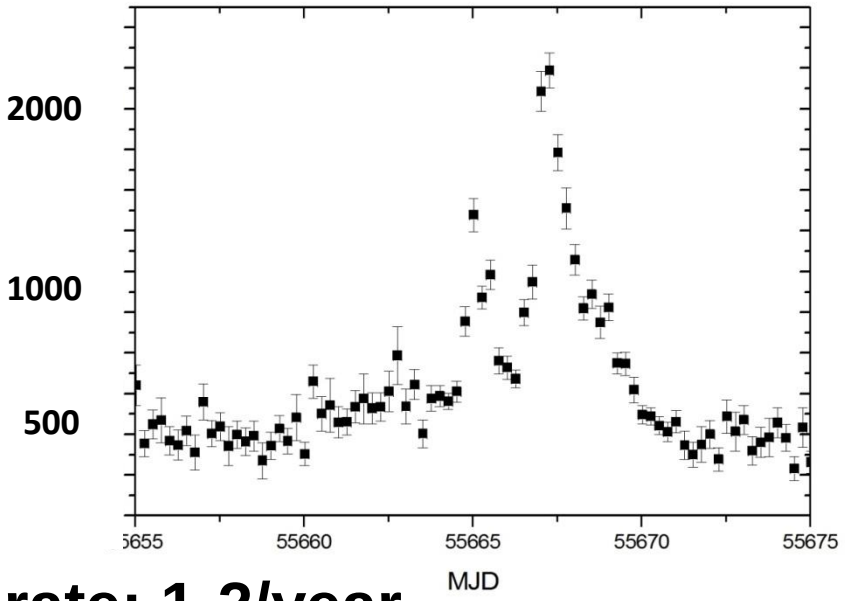
Fermi-LAT, 26 Jan. – 11 Feb. 2009



AGILE, 20-22 Sept. 2010



Fermi-AGILE, 12 – 20 Apr. 2011

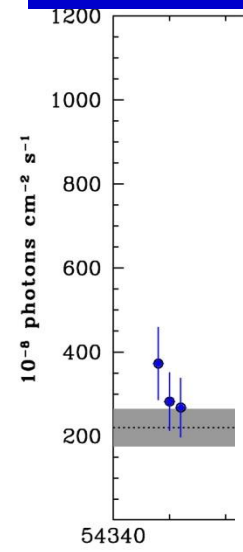


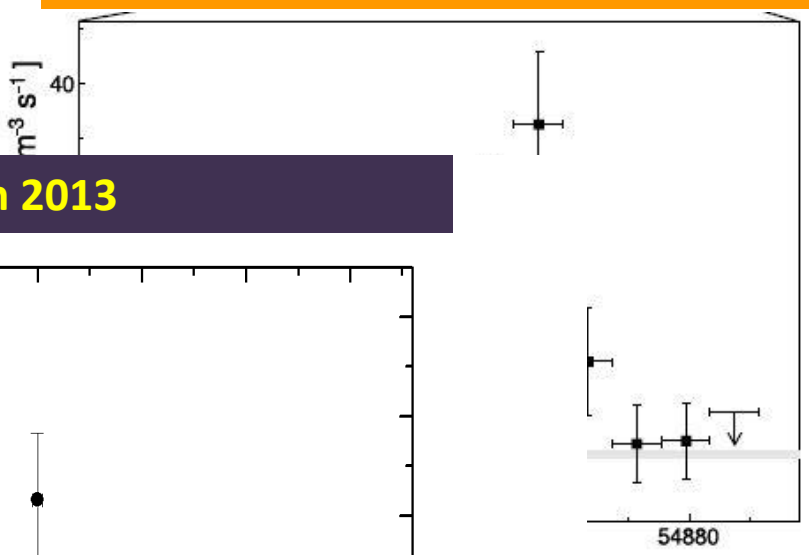
major flare rate: 1-2/year

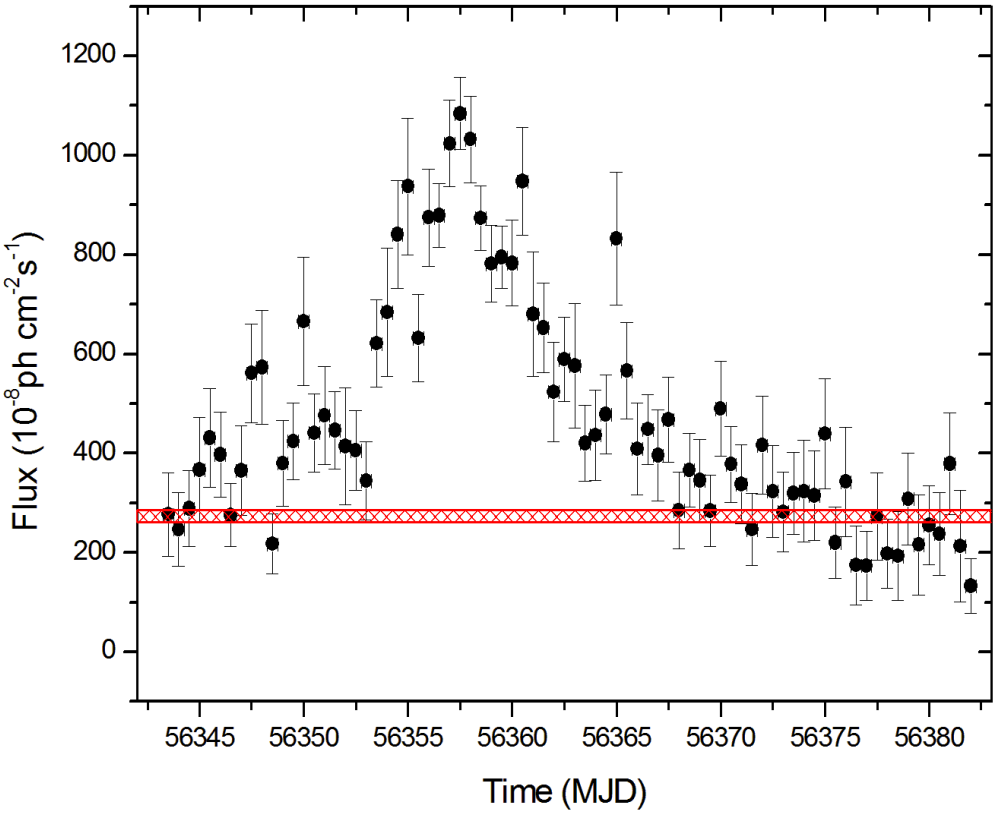
AGILE, 26 Nov. – 13 Oct. 2007

Fermi-LAT, 26 Jan. – 11 Feb. 2009

March 2013

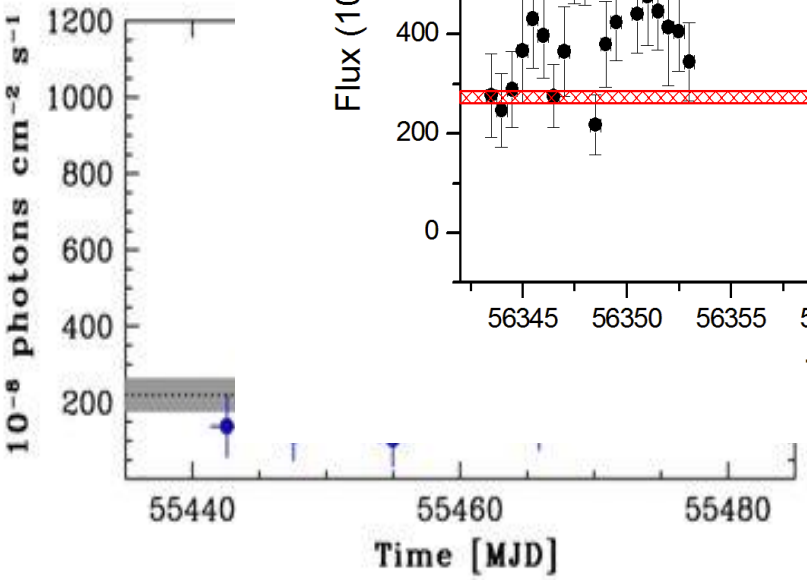


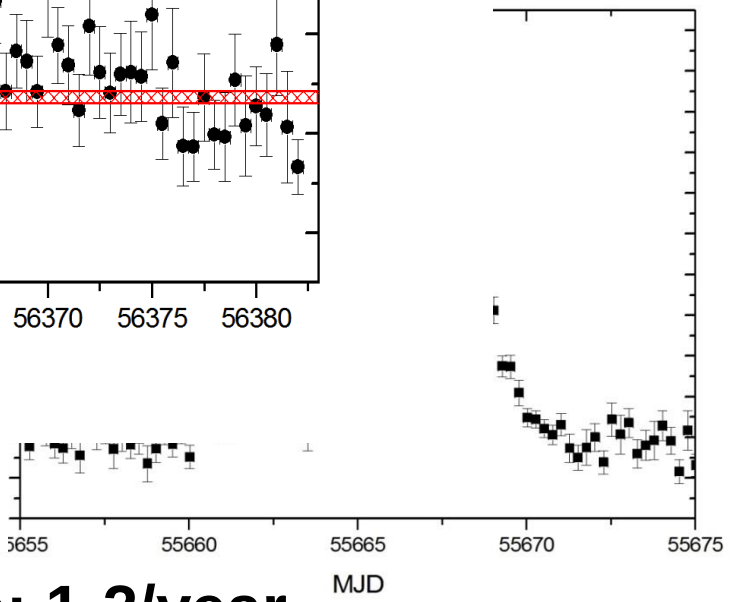




AGILE, 20-

2011

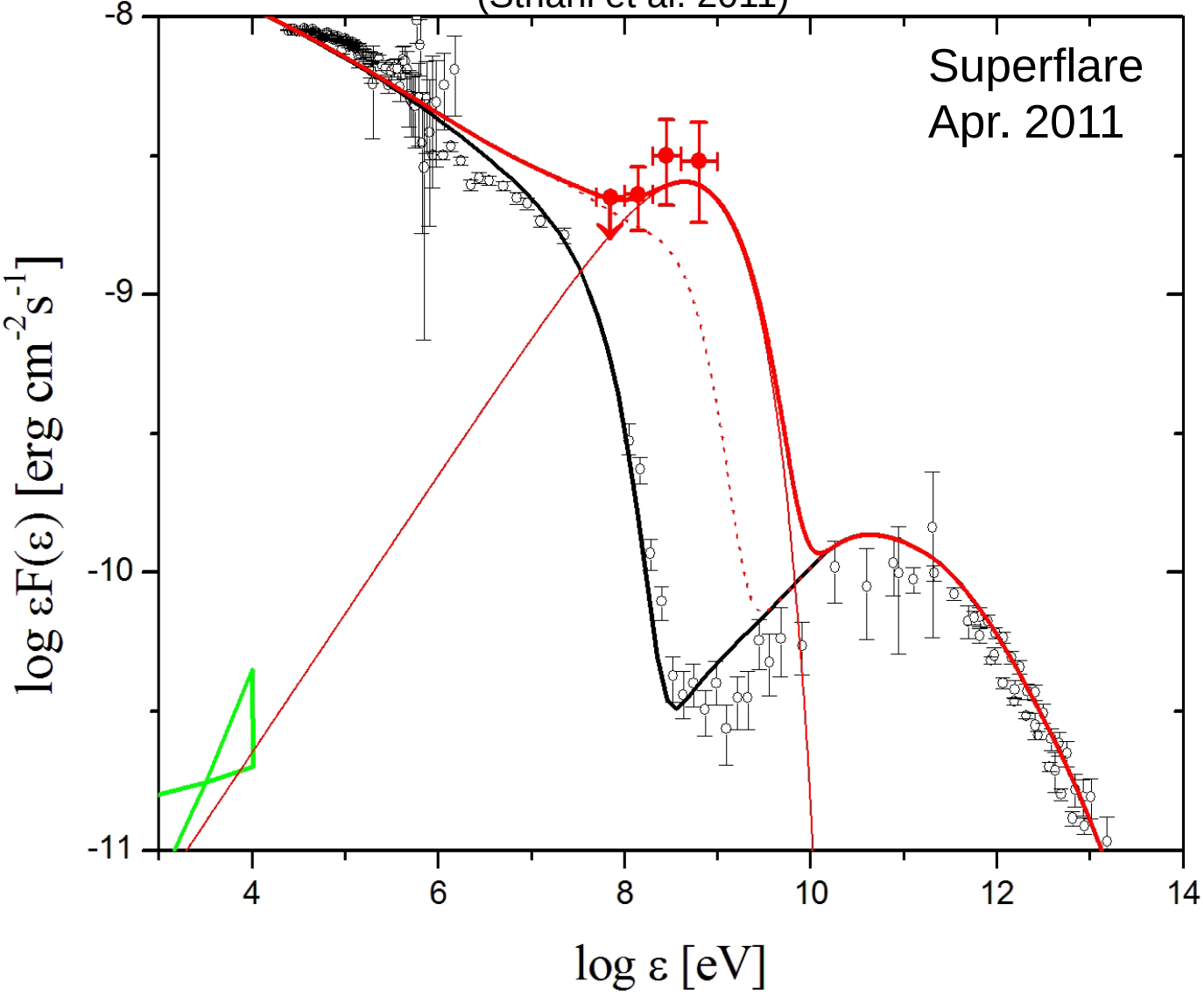




major flare rate: 1-2/year

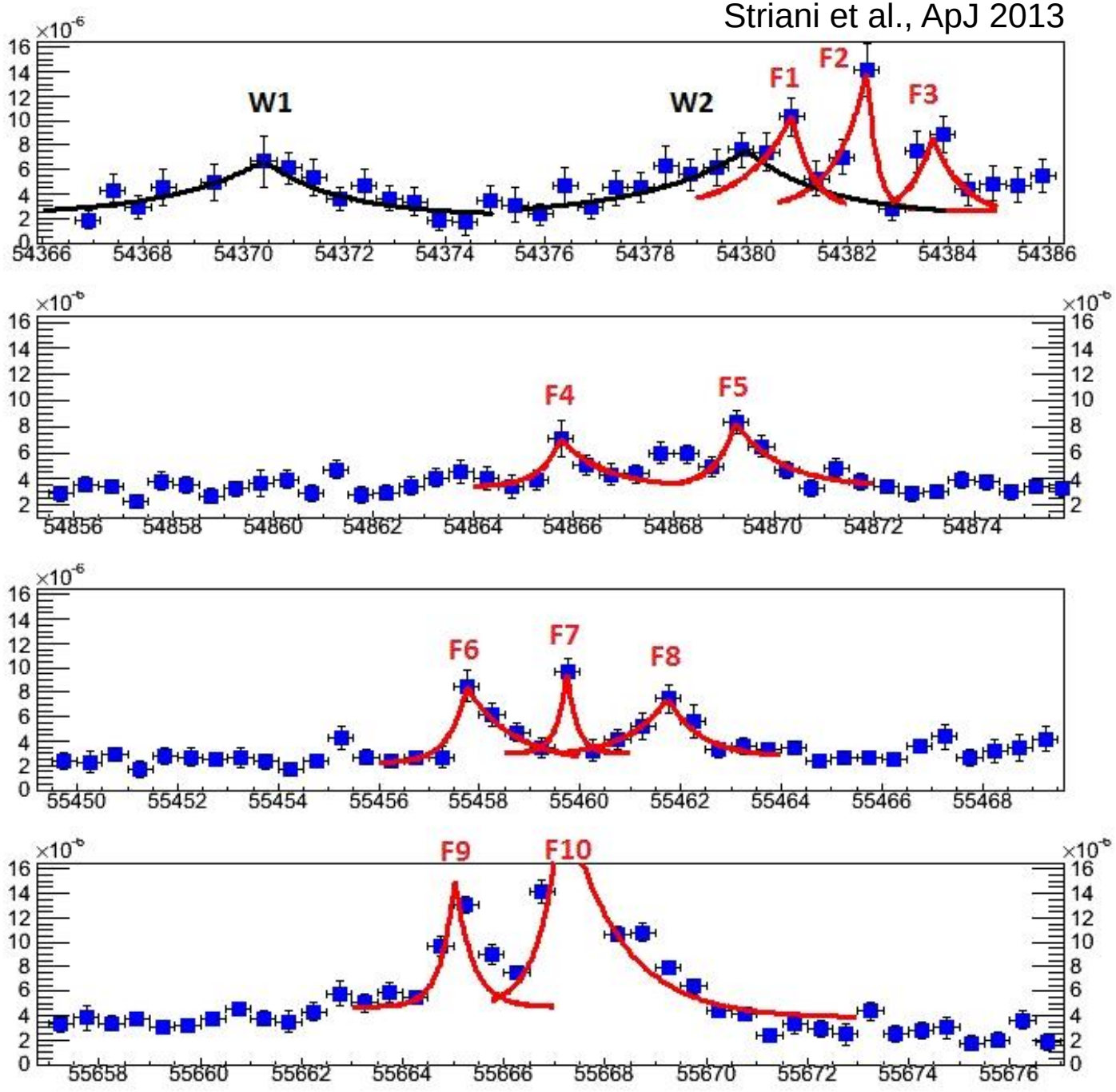
Agile Spectrum at the peak (12 hr)

(Striani et al. 2011)

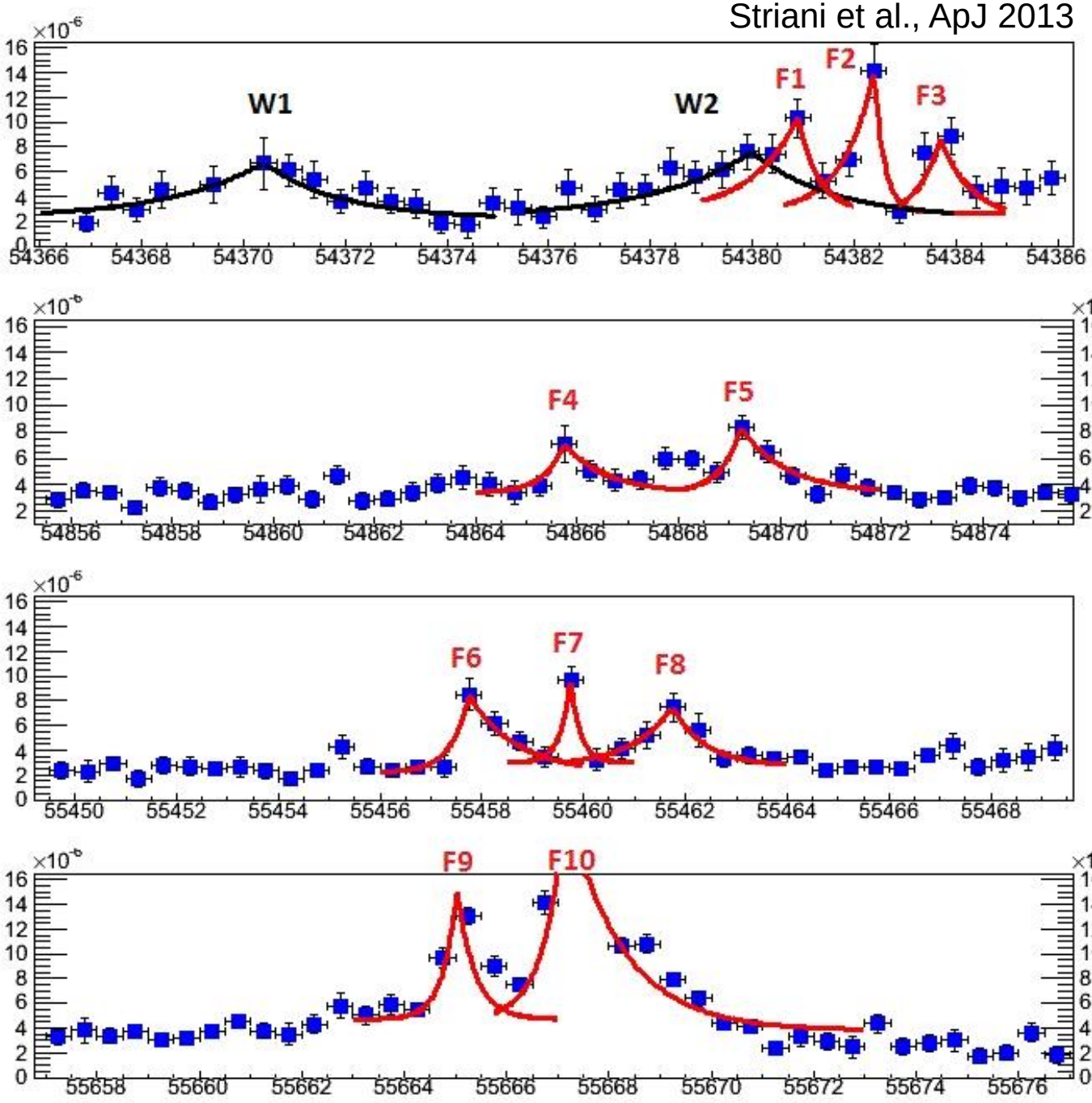


Overview of the main gamma-ray flares

Striani et al., ApJ 2013



Striani et al., ApJ 2013



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

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

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

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

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

Striani et al., ApJ 2013

The *Flares* ($F \geqslant 700 \times 10^{-8}$ ph cm^{-2} s^{-1}) of the Crab Nebula Found in the *AGILE* and *Fermi* Data from 2007 September

	Name	MJD	τ_1 (hr)	τ_2 (hr)	Peak Flux	B (mG)	γ^* (10^9)	l (10^{15} cm)
2007	F_1	54381.5	22 ± 11	10 ± 5	1000 ± 150	1.0–2.0	2.6–4.8	1.2–3.6
(*AGILE*)	F_2	54382.5	14 ± 7	6 ± 3	1400 ± 200	1.1–2.1	2.3–4.3	0.8–2.2
	F_3	54383.7	11 ± 5	14 ± 7	900 ± 150	1.0–2.0	2.6–4.8	0.8–1.7
2009	F_4	54865.8	10 ± 5	20 ± 10	700 ± 140	0.7–1.3	2.6–4.8	0.6–1.6
(*Fermi*)	F_5	54869.2	10 ± 5	22 ± 11	830 ± 90	0.8–1.4	2.6–4.8	0.6–1.6
2010	F_6	55457.8	8 ± 4	22 ± 11	850 ± 130	0.7–1.3	2.5–4.7	0.5–1.3
(*AGILE* and	F_7	55459.8	6 ± 3	6 ± 3	1000 ± 100	1.4–2.6	2.6–4.8	0.3–0.9
Fermi)	F_8	55461.9	19 ± 10	8 ± 4	750 ± 110	0.8–1.4	2.5–4.8	0.9–3.1
2011	F_9	55665.0	9 ± 5	9 ± 5	1480 ± 80	1.2–2.2	2.8–5.0	0.5–1.5
(*Fermi* and	F_{10}	55667.3	10 ± 5	24 ± 12	2200 ± 85	1.3–2.3	2.7–4.9	0.6–1.6
AGILE)								

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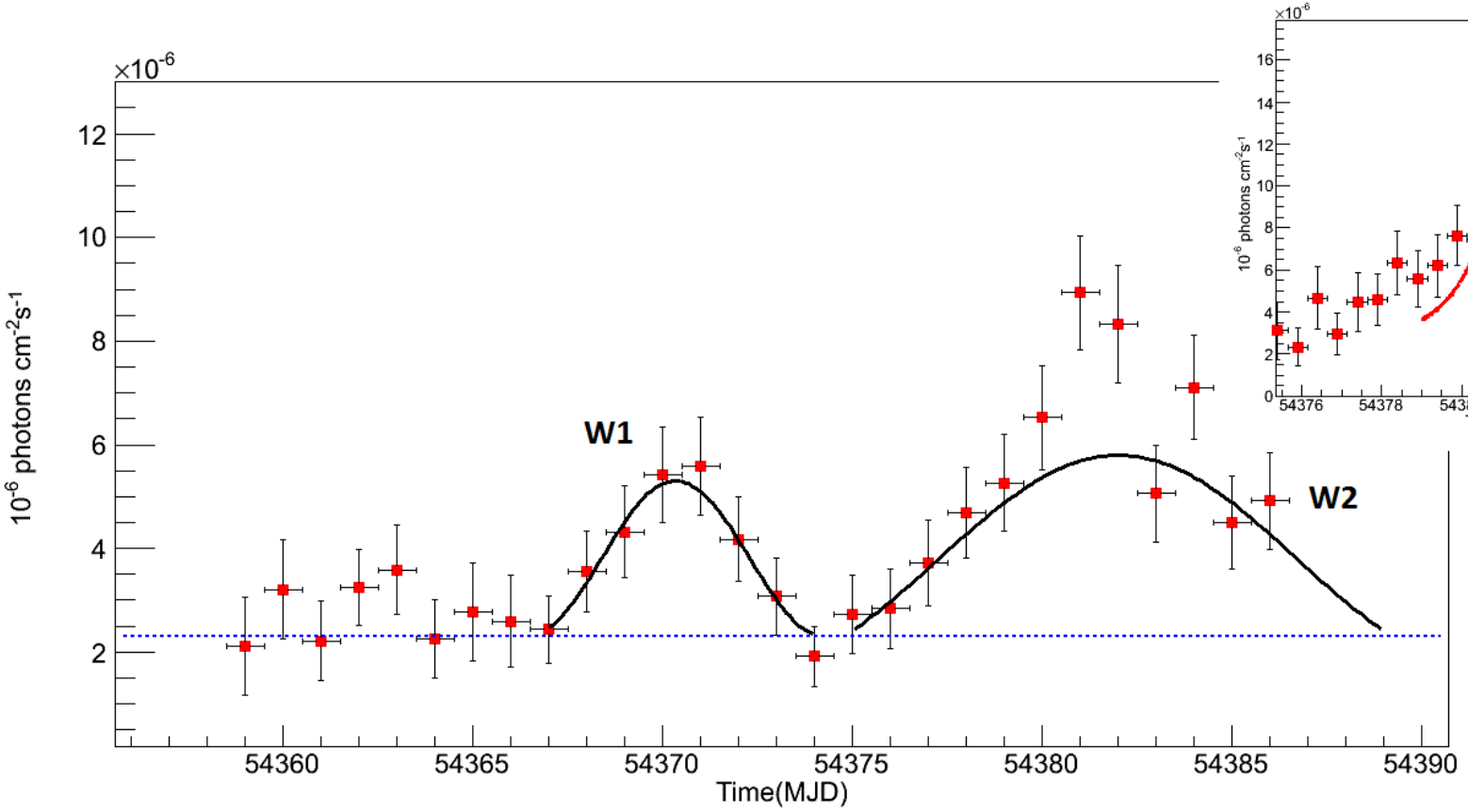
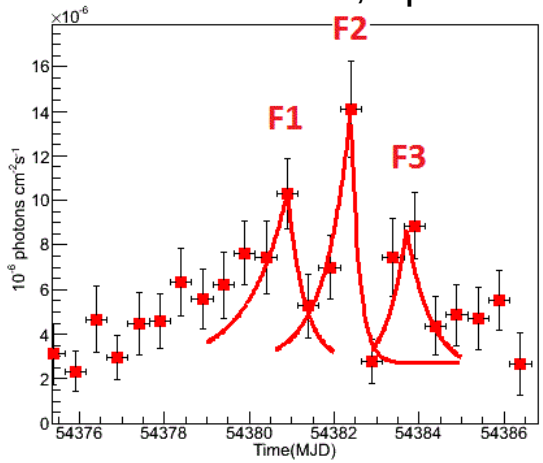
AGILE)								

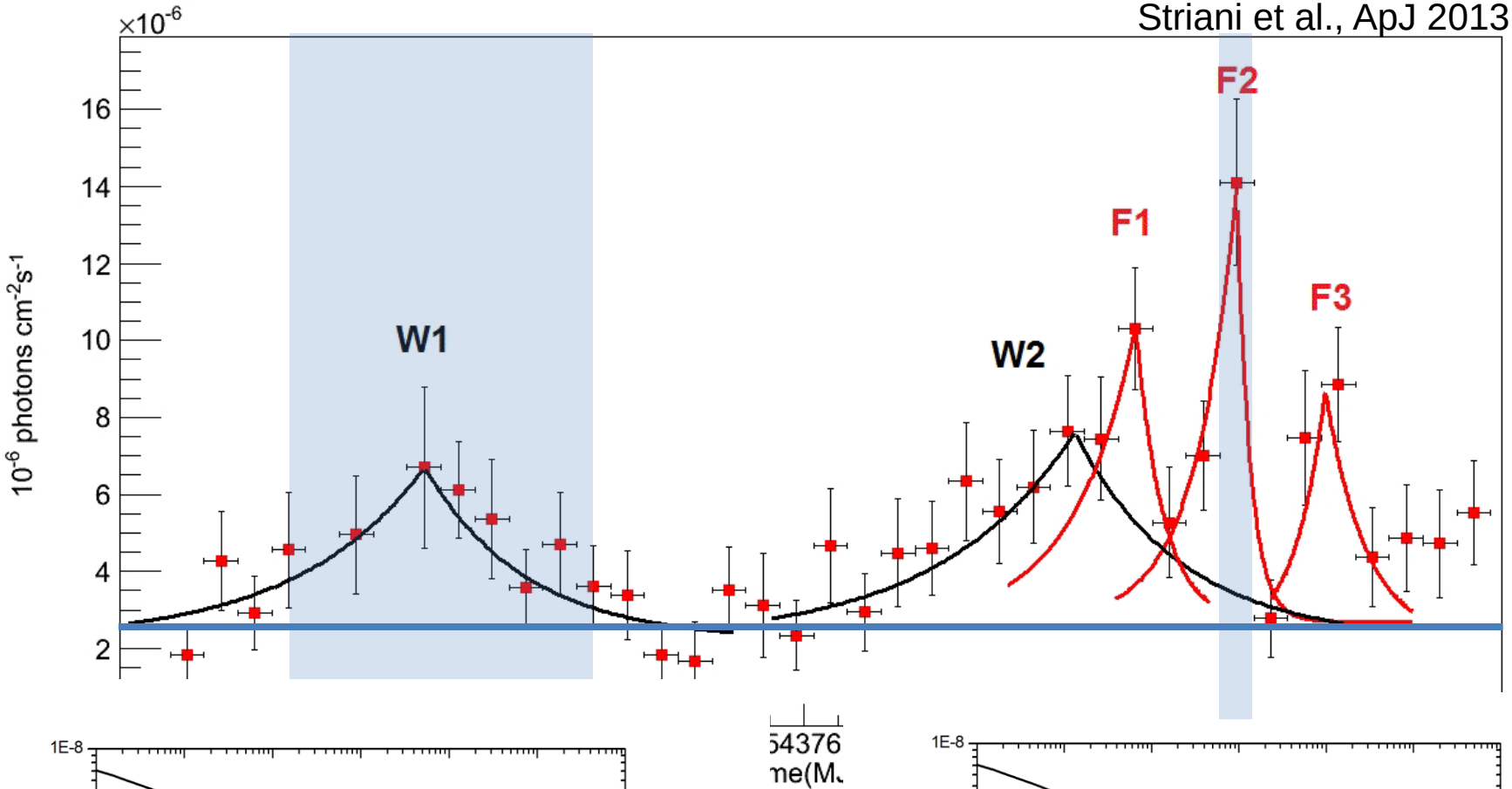
AGILE 1-day bin lightcurve of the 2007 event

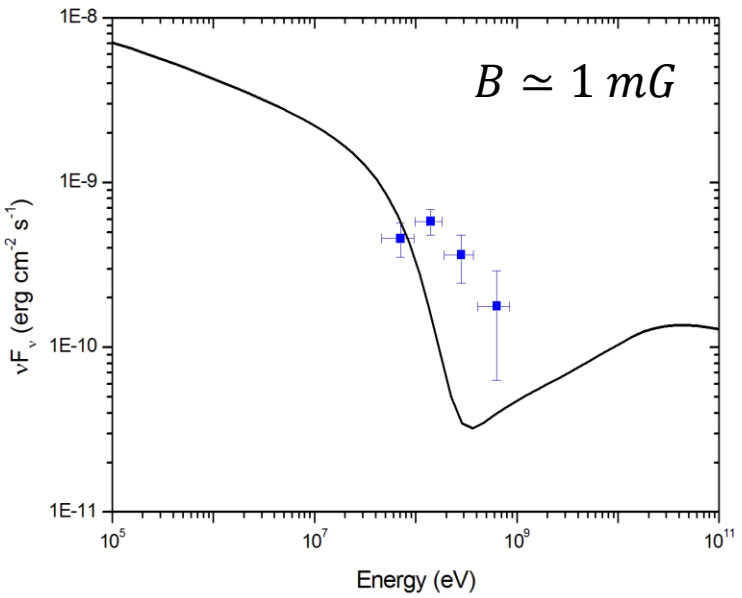
Striani et al., ApJ 2013

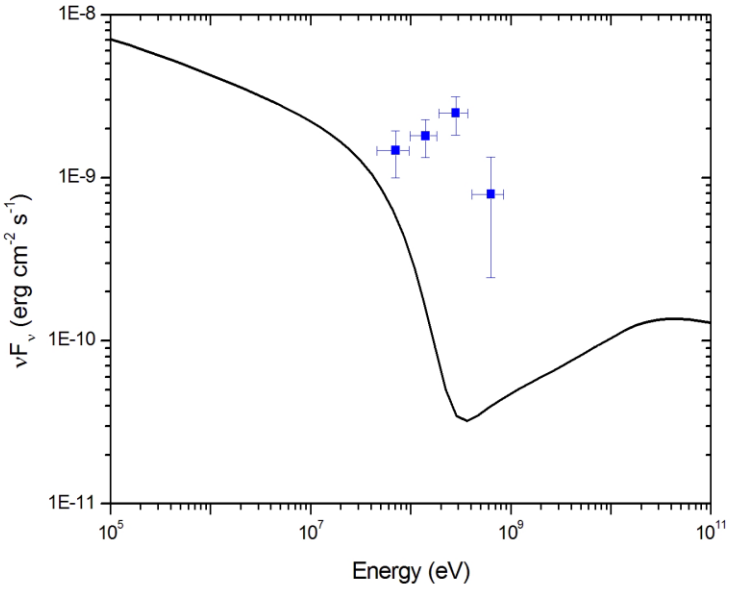




Striani et al., ApJ 2013

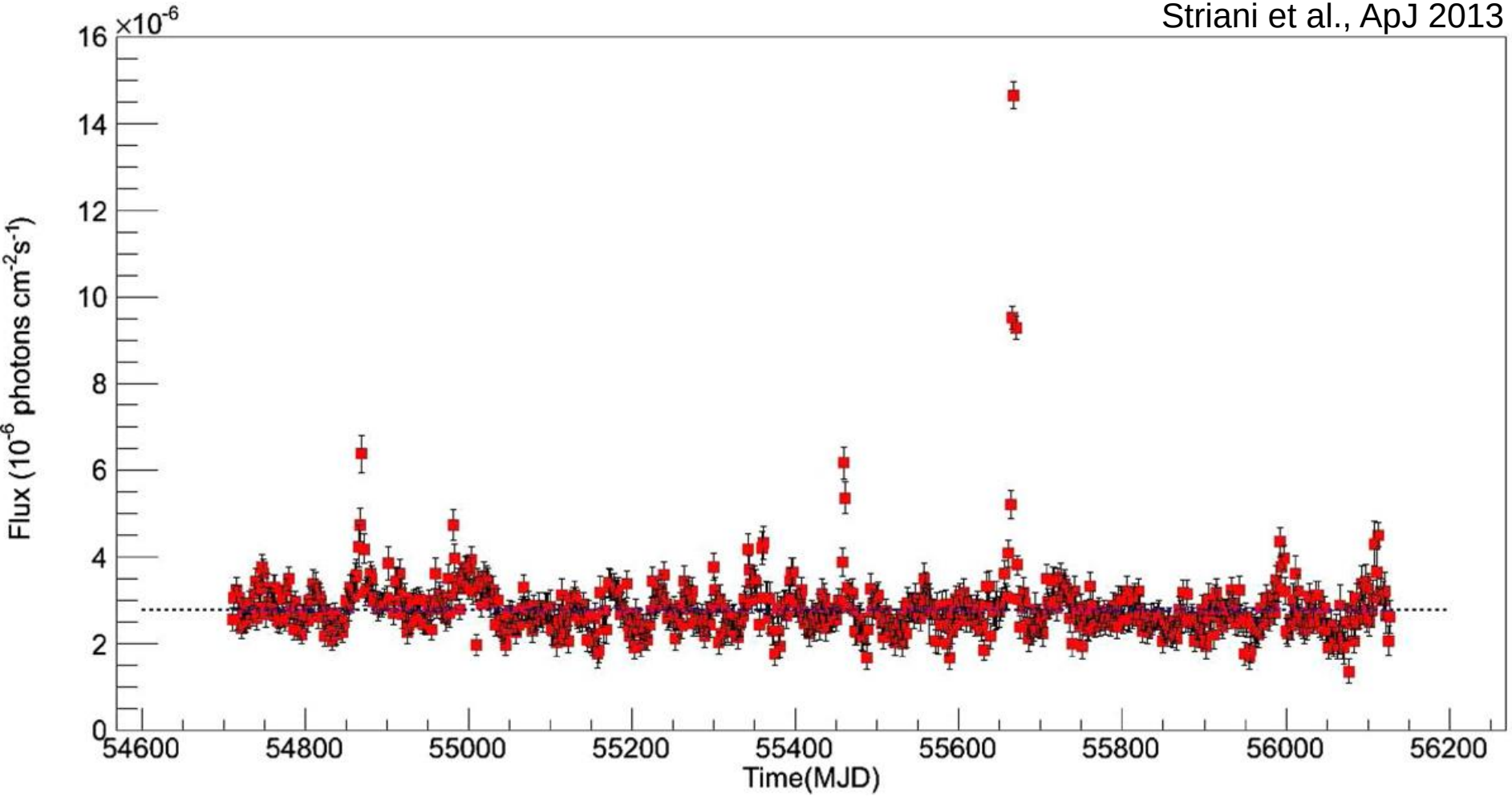




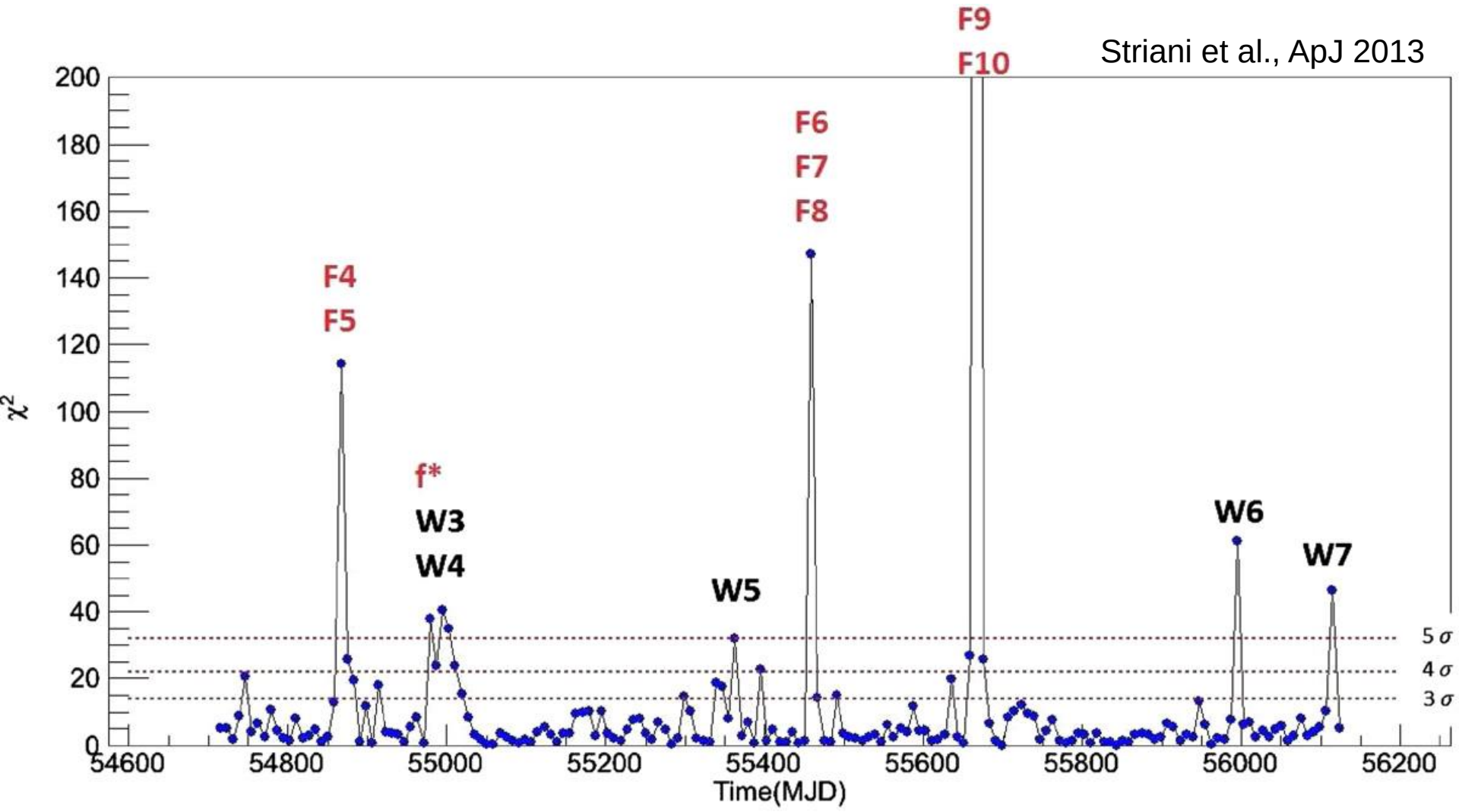


Fermi-LAT 2 day bin lightcurve above 100 MeV of the Crab (4 years)

Striani et al., ApJ 2013

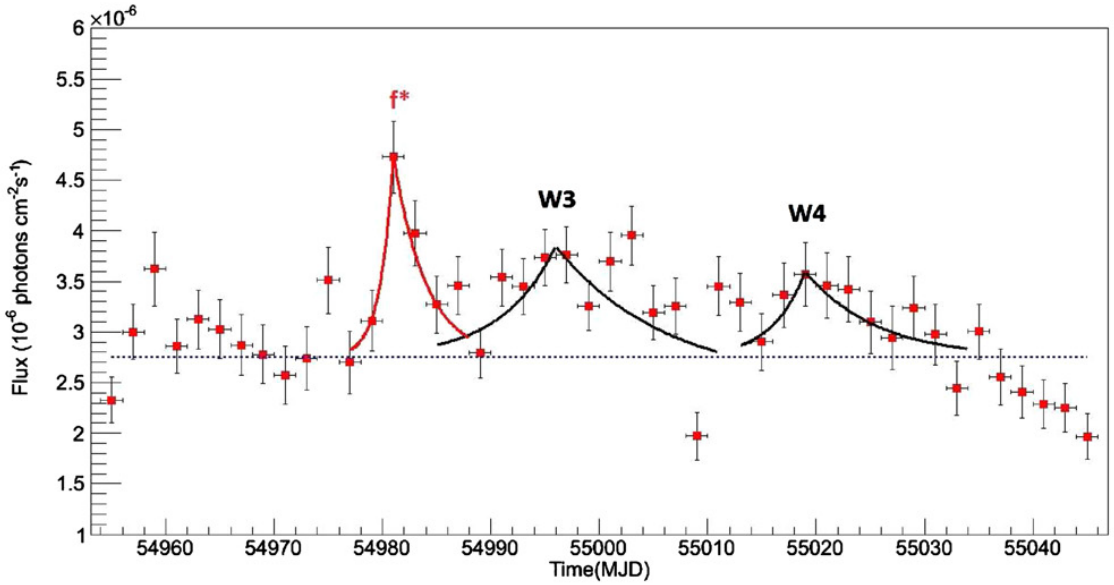


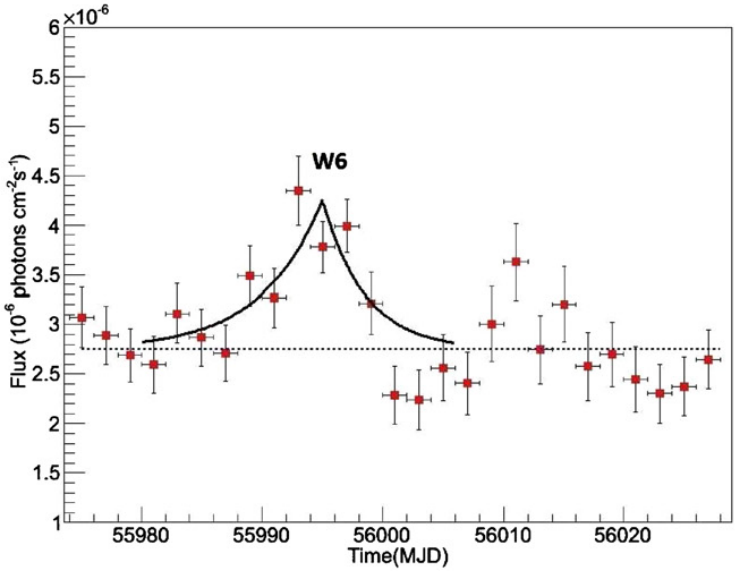
Plot of the $\chi 2$ values as a function of time

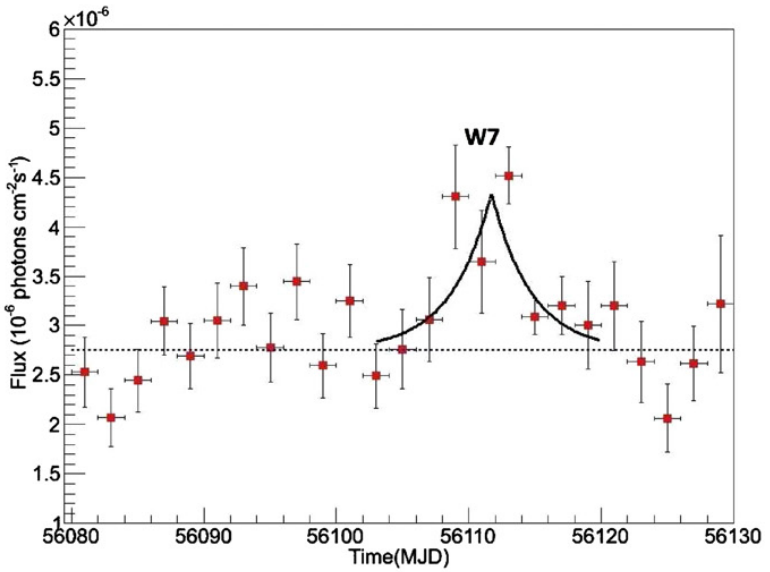


Most prominent *wave* episodes in the *Fermi*-LAT data

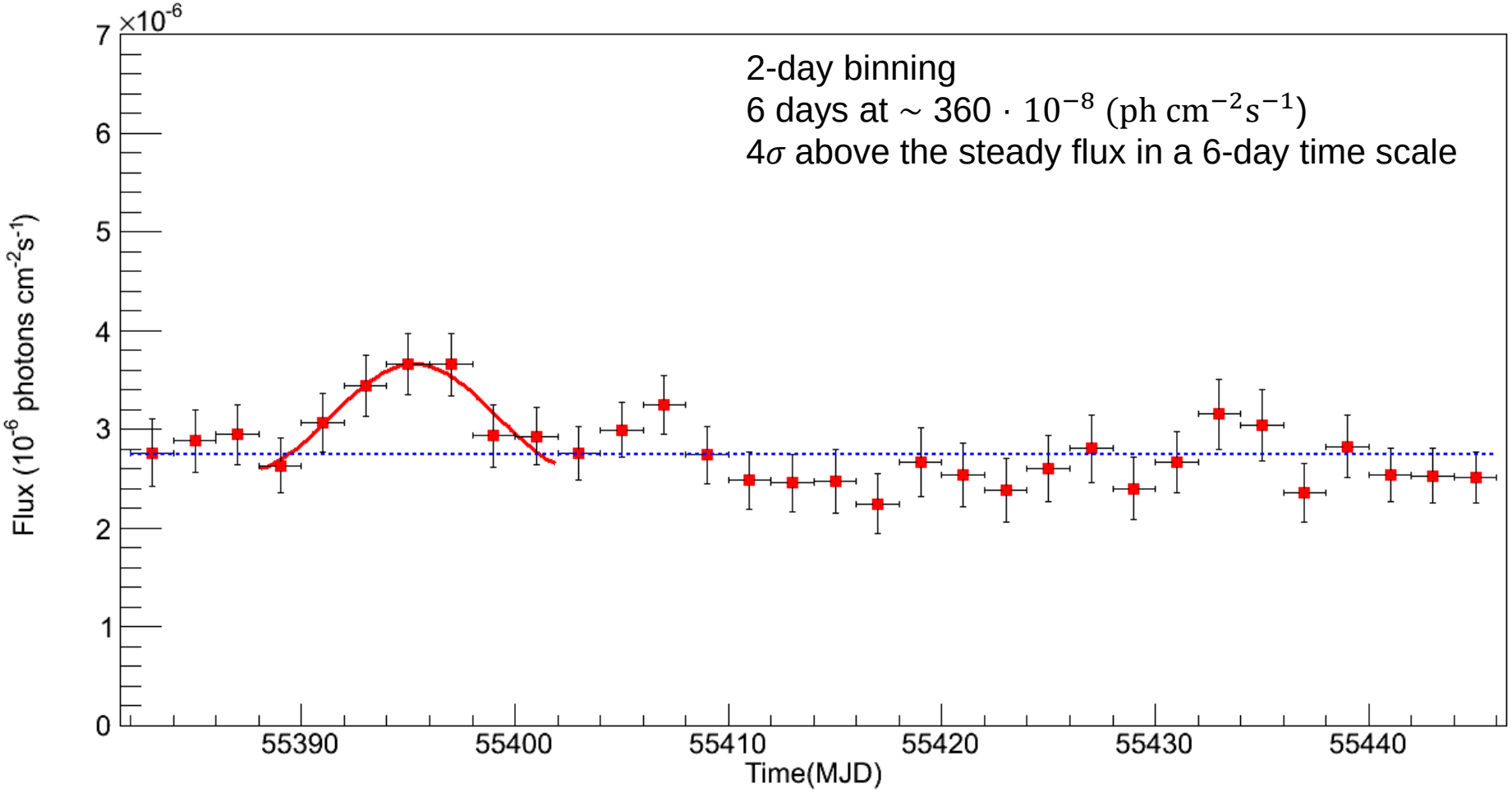
Striani et al., ApJ 2013







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



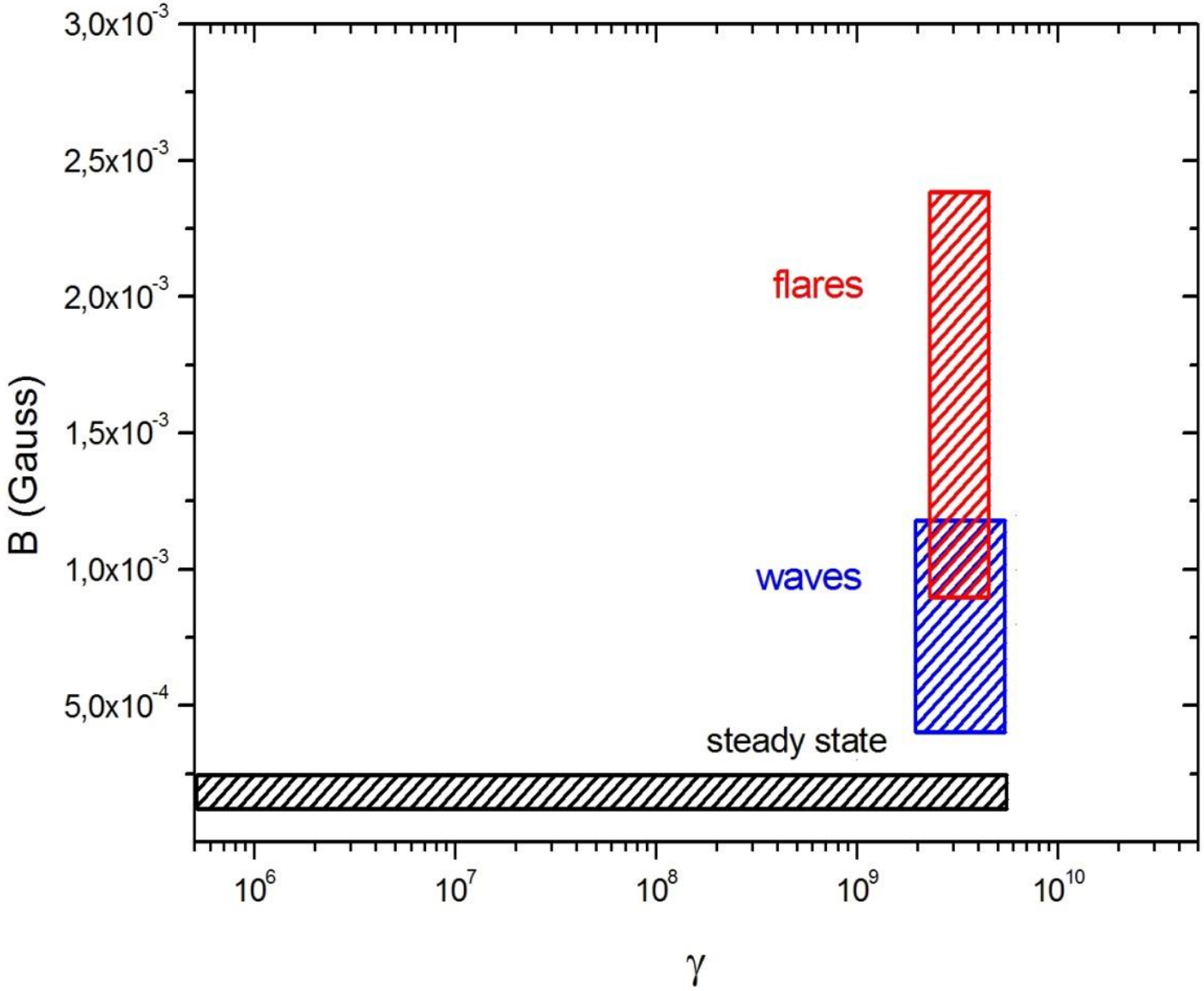
The *Waves* above 5σ (Pre-trial) from the Crab Average Emission Found in the *AGILE* and *Fermi* Data

The *Waves* above 5σ (Pre-trial) from the Crab Average Emission Found in the *AGILE* and *Fermi* Data

Name	MJD	Duration (days)	τ_1 (days)	τ_2 (days)	Average Flux (10^{-8} ph cm^{-2} s^{-1})	Peak Flux (10^{-8} ph cm^{-2} s^{-1})	Pre-trial p-value	Post-trial Significance
W_1	54368–54373	5	2 ± 1	2 ± 1	440 ± 40	670 ± 200	4.5×10^{-8}	5.0
W_2	54376.5–54382.5	6	2 ± 1	2 ± 1	480 ± 40	760 ± 140	3.0×10^{-9}	5.5
f^*	54980.0–54986	6	1 ± 0.5	2 ± 1	470 ± 35	380 ± 40	8.0×10^{-7}	4.2
W_3	54990–55008	18	5 ± 2	10 ± 5	352 ± 9	380 ± 30	1.0×10^{-8}	4.6
W_4	55010–55025	15	3 ± 1	6 ± 3	326 ± 10	360 ± 30	4.6×10^{-7}	3.8
W_5	55358–55362	4	2 ± 1	2 ± 1	426 ± 27	430 ± 30	5.6×10^{-7}	3.7
W_6	55988–56000	12	5 ± 2	3 ± 1	367 ± 12	435 ± 35	1.8×10^{-12}	6.2
W_7	56108–56114	6	3 ± 1	3 ± 1	431 ± 22	450 ± 30	1.9×10^{-9}	5.9

Waves: B ~ 0.5 – 1 mG

(Flares: B ~ 1 – 3 mG)


3,0x10-3
2,5x10-3
2,0x10-3
1,5x10-3
1,0x10-3
5,0x10-4
B (Gauss)
flares
waves
steady state
10^6
10^7
10^8
10^9
10^10
γ

The Crab

- A standard candle

The Crab

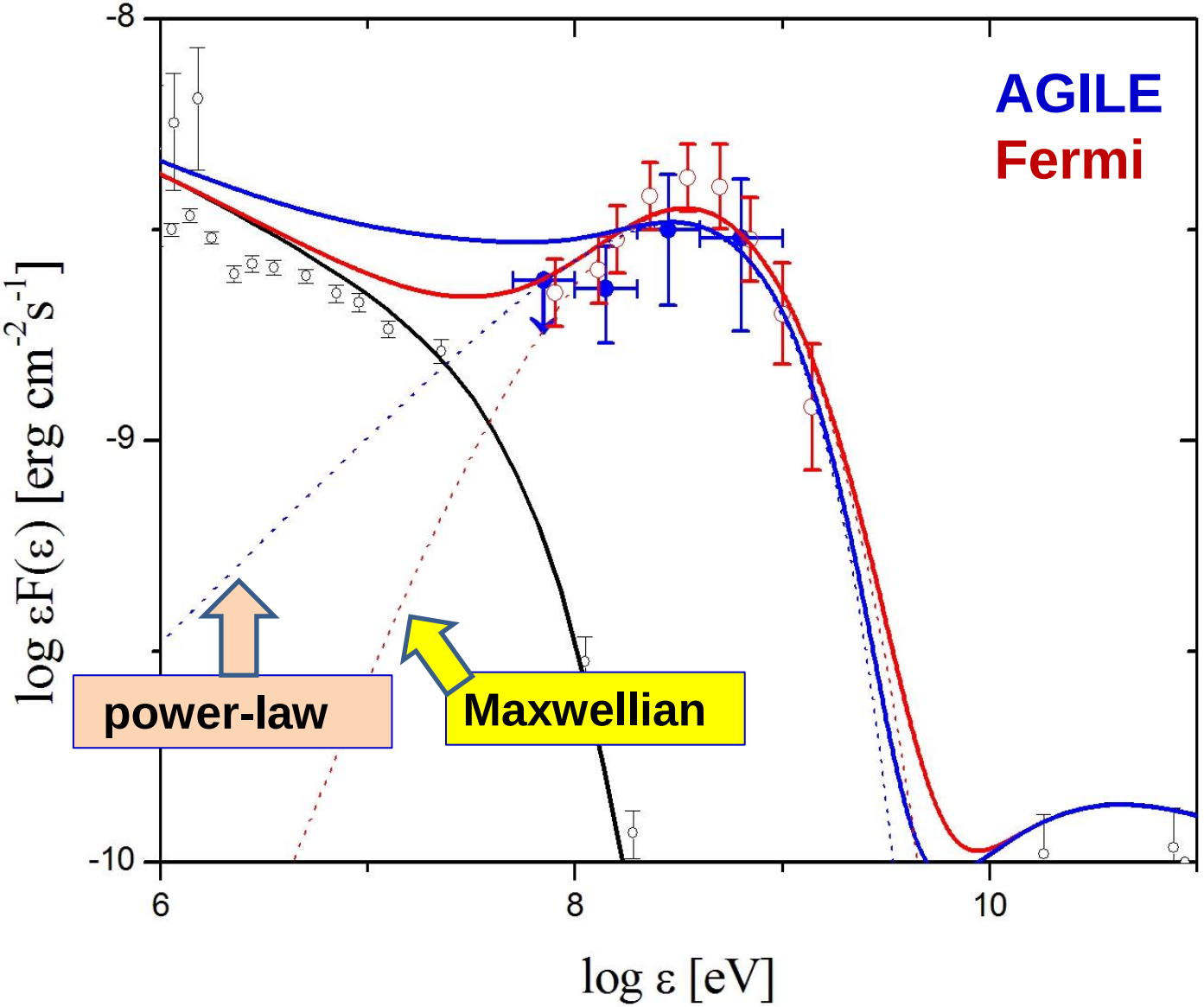
- A standard candle

- Strong and impulsive flares (12-24 hr), ∼1/year

The Crab

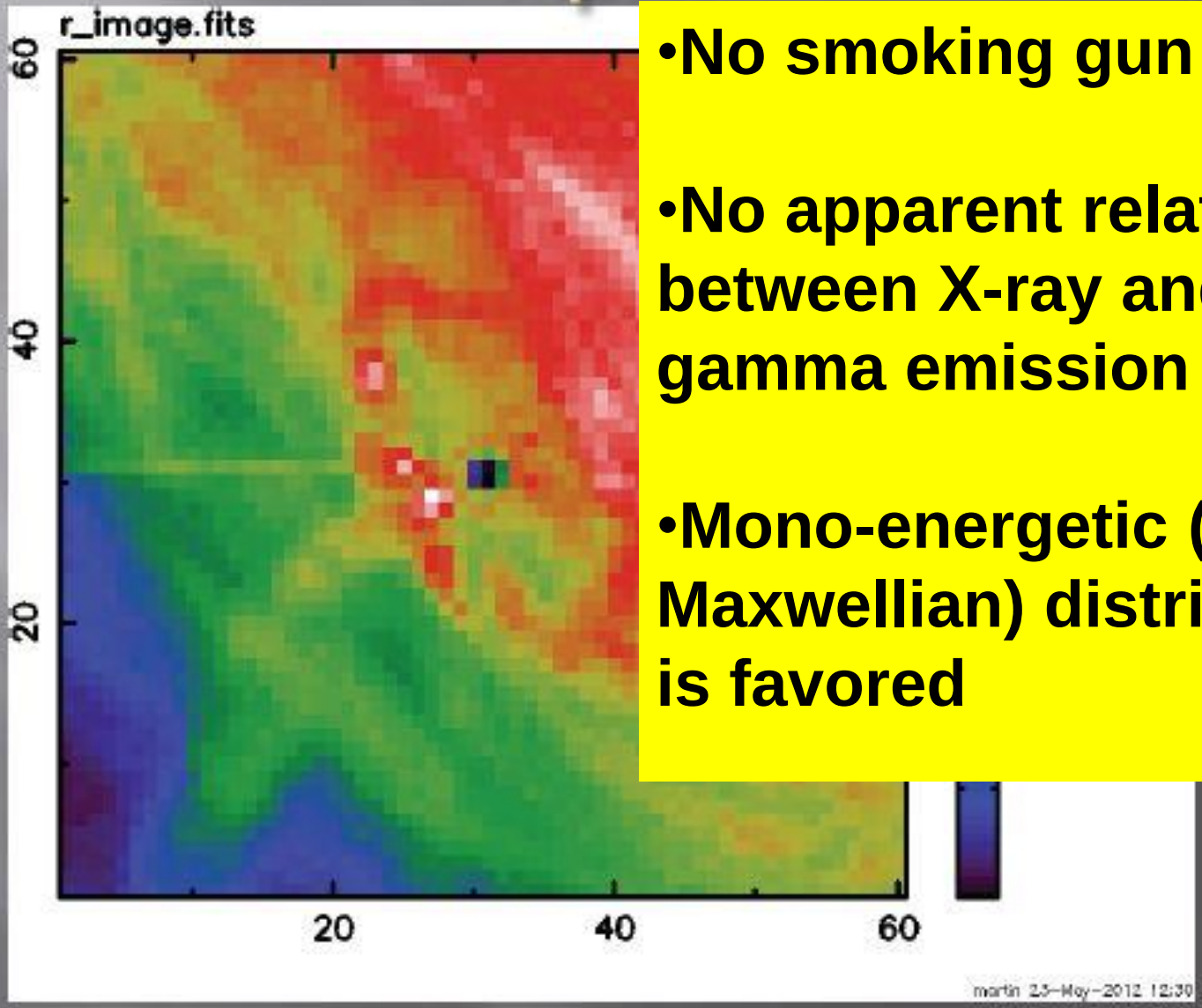
- A standard candle
- Strong and impulsive flares (12-24 hr), ∼1/year
- Slower, less intense variability, and rather more frequent (waves)

Modelling of the April 2011 super-flare



The average Chandra image 2011 April

(M. Weisskopf, 2012)



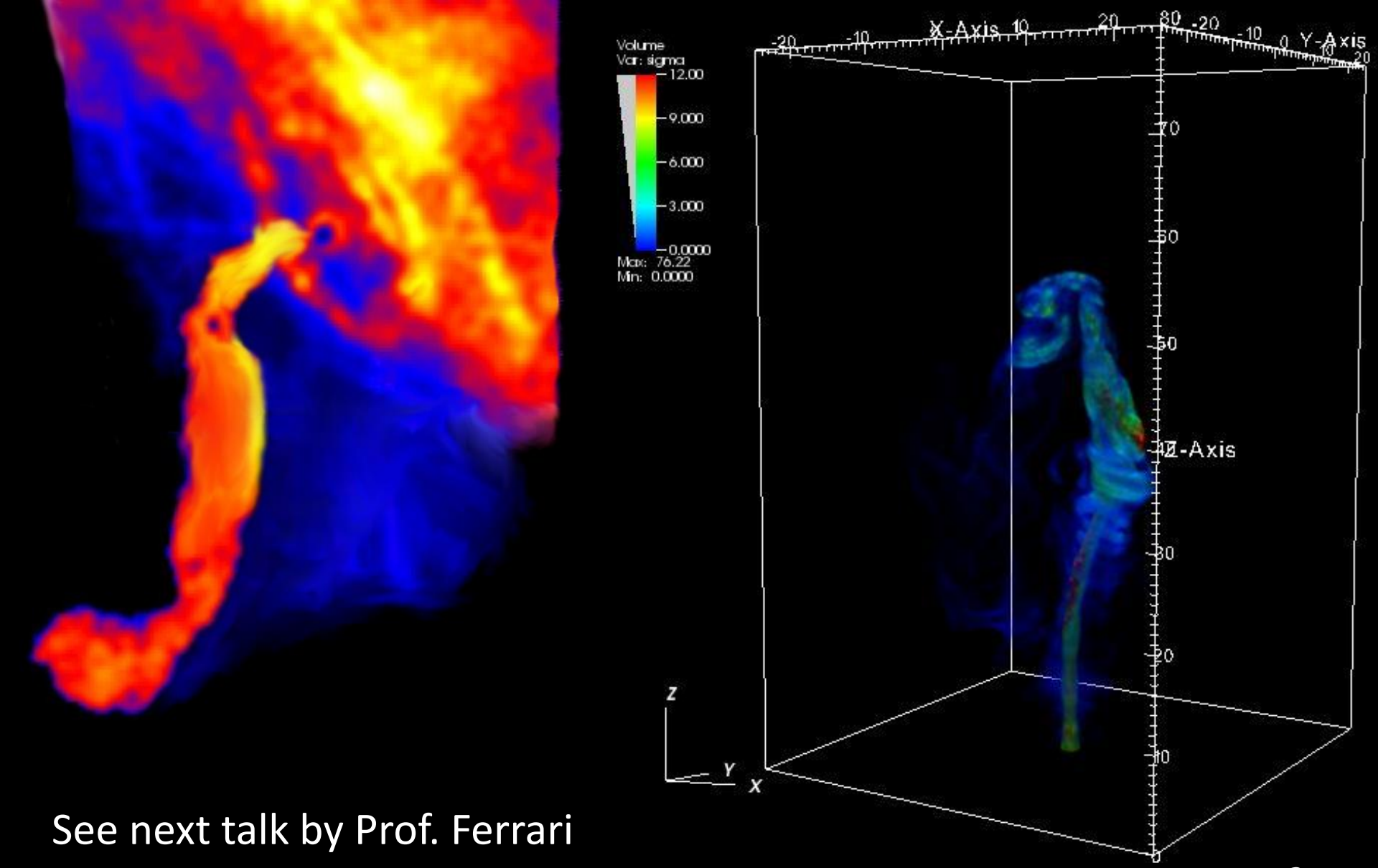
- **No smoking gun**
- **No apparent relation between X-ray and gamma emission**
- **Mono-energetic (relativ. Maxwellian) distribution is favored**

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



See next talk by Prof. Ferrari

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

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

Conclusions

- Five 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