

Gamma-ray flares from the Crab Nebula

M.Tavani

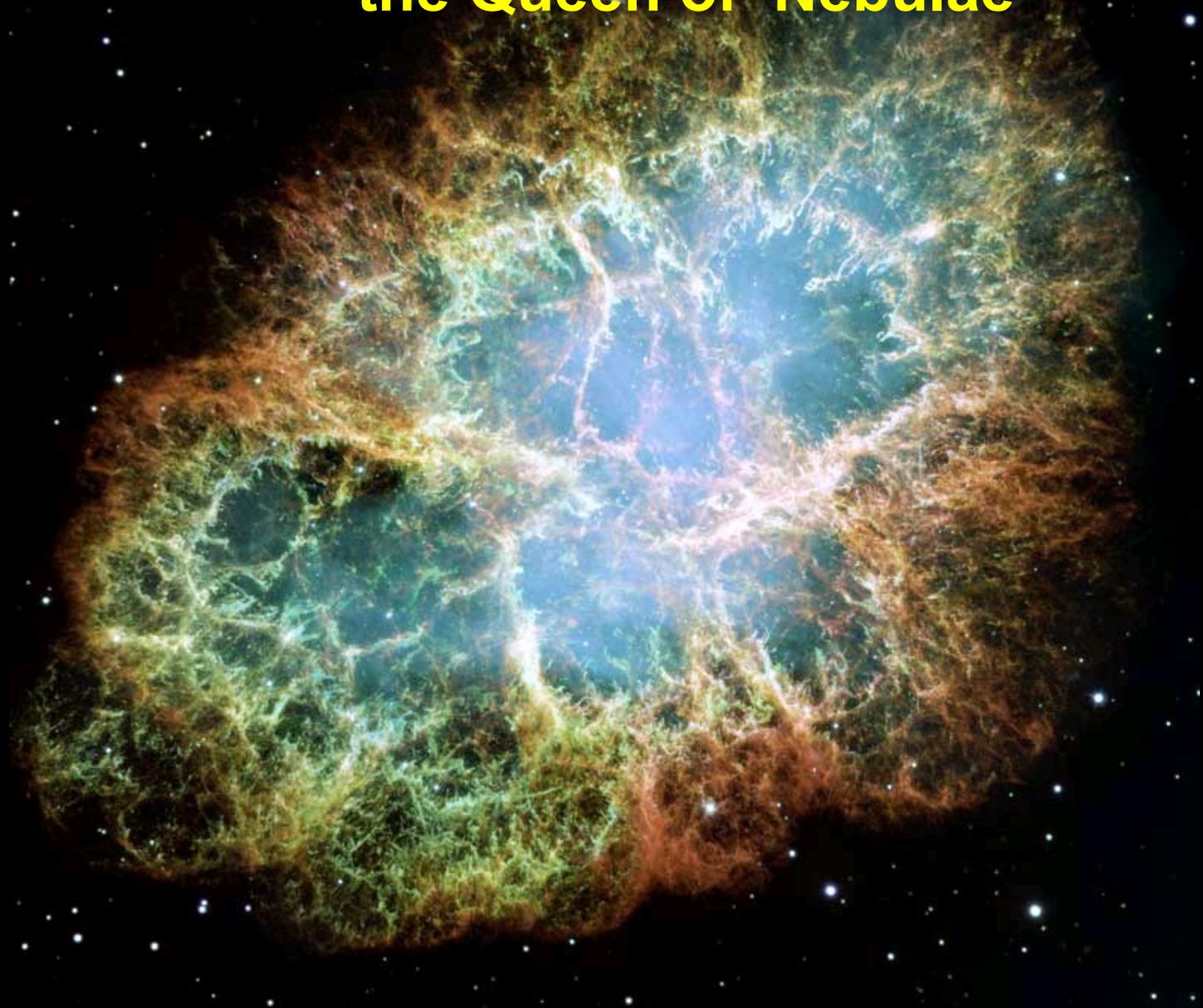
(INAF & Univ. Rome Tor Vergata)

凡十一日没三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

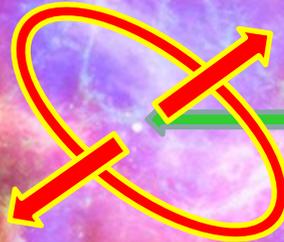
宋史卷九
三十三

CTA LINK Meeting,
Buenos Aires Nov. 20, 2012

The Crab Nebula (M1) : the Queen of Nebulae

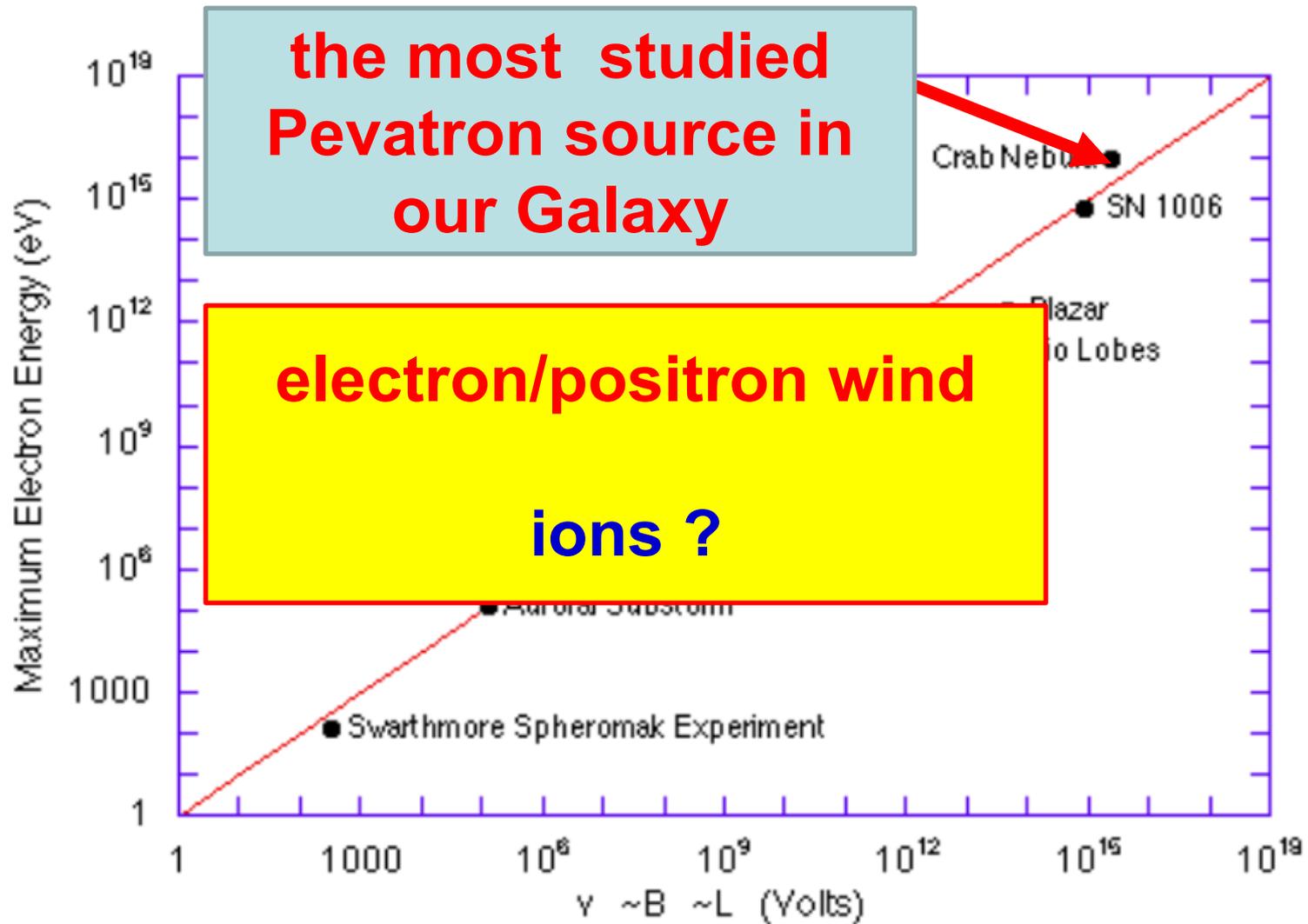


Crab Nebula: an ideal laboratory



**VERY ENERGETIC
PULSAR (rotating
30 times a second)**

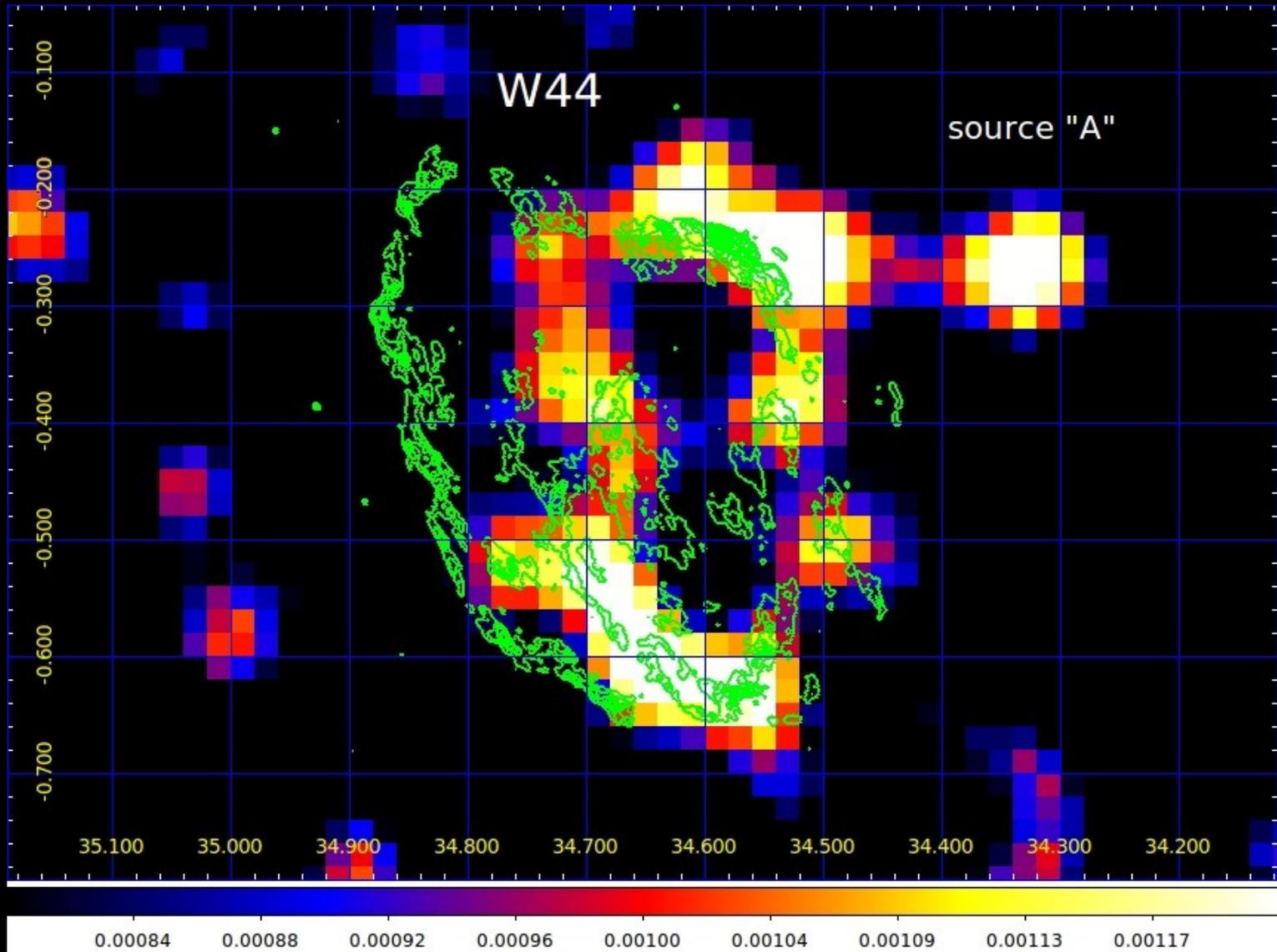
**RELATIVISTIC
PARTICLE WIND
FROM THE PULSAR:
STRONG SHOCKS IN
THE NEBULA**



from K. Makishima, "Energy non-equipartition processes in the Universe." 1999

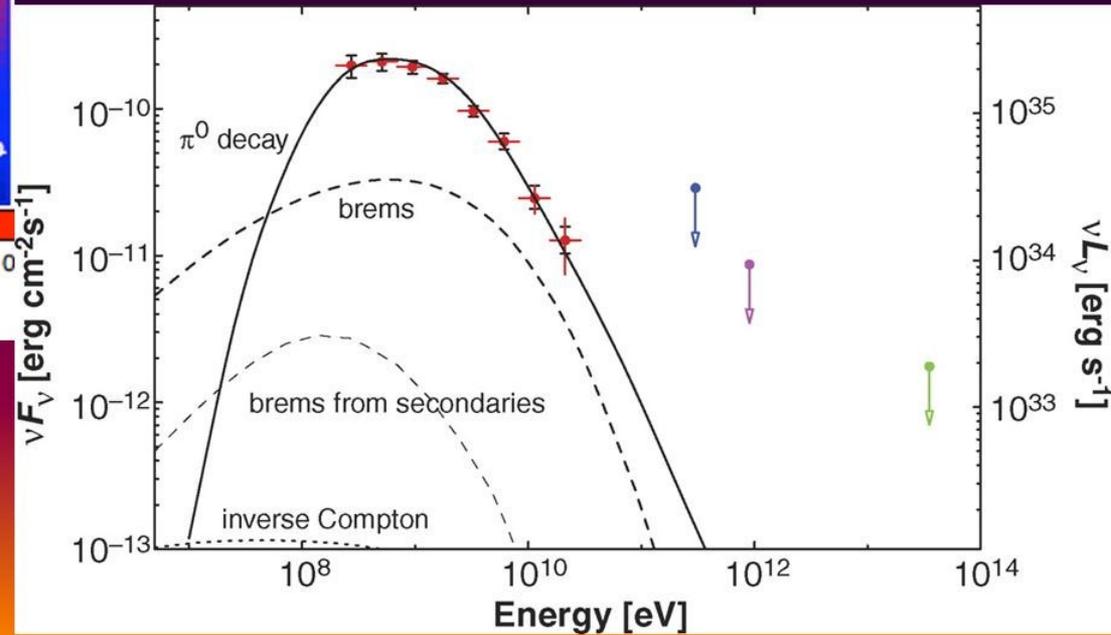
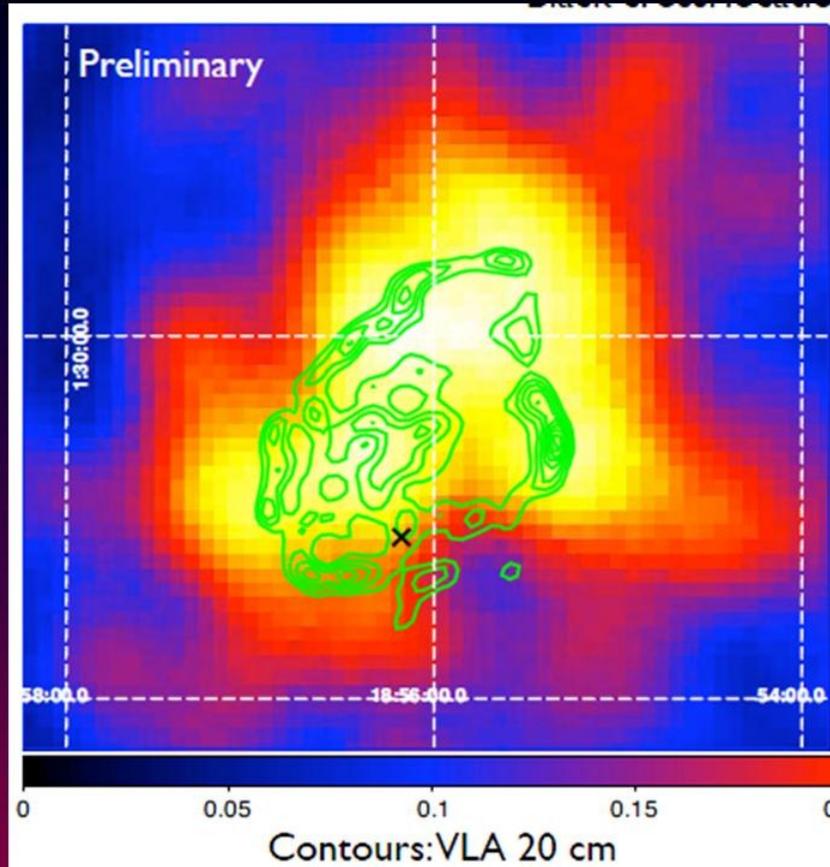
- **The complexity of SNRs producing CRs...**

W44: AGILE gamma-ray emission and radio (green)

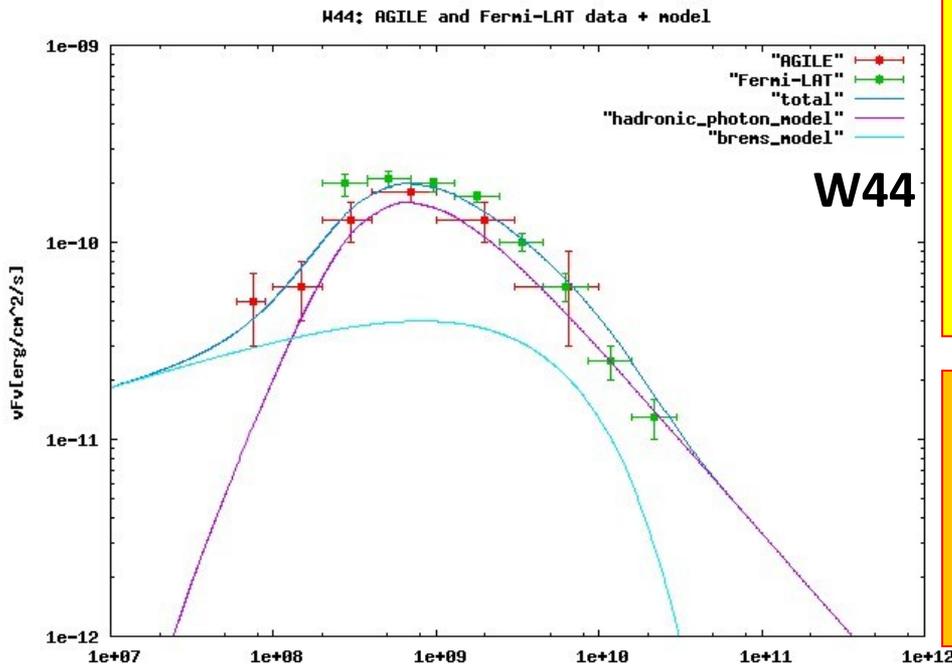


The SNRW44: Fermi-LAT

W44: Fermi-LAT
Abdo et al, 2010



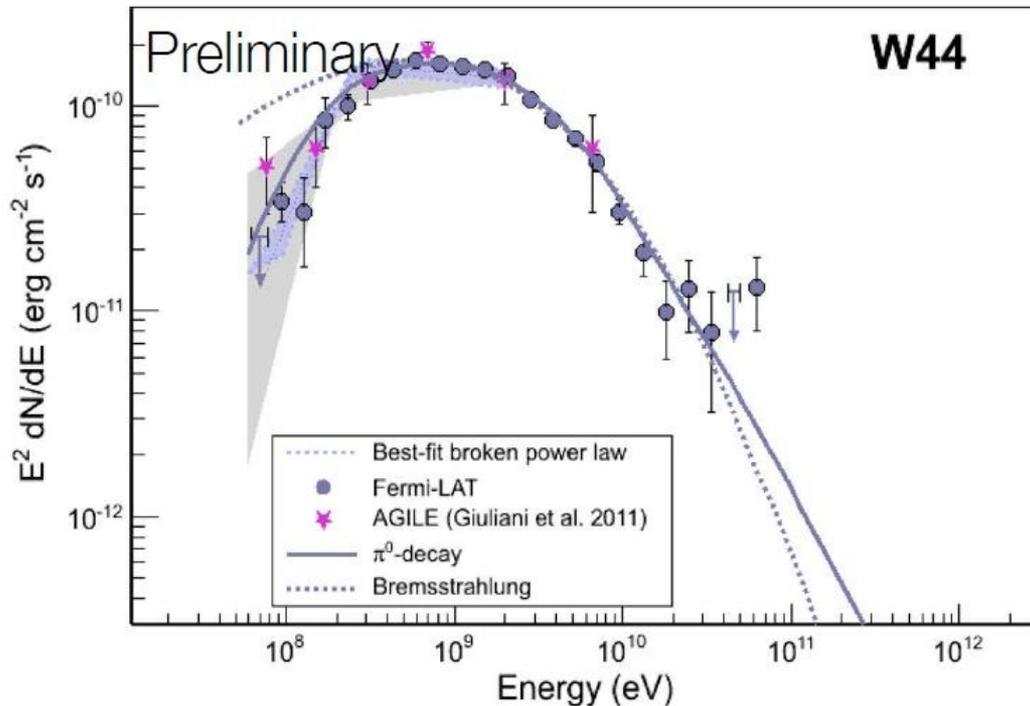
**AGILE-
GRID**



**PROOF OF HADRONIC
COSMIC-RAY
ACCELERATION IN THE
SUPERNOVA REMNANT
W44: THE π^0 SPECTRUM**

(Giuliani A., Cardillo M.,
Tavani, M., et al.,
ApJ Letters, 742, L30,
2011)

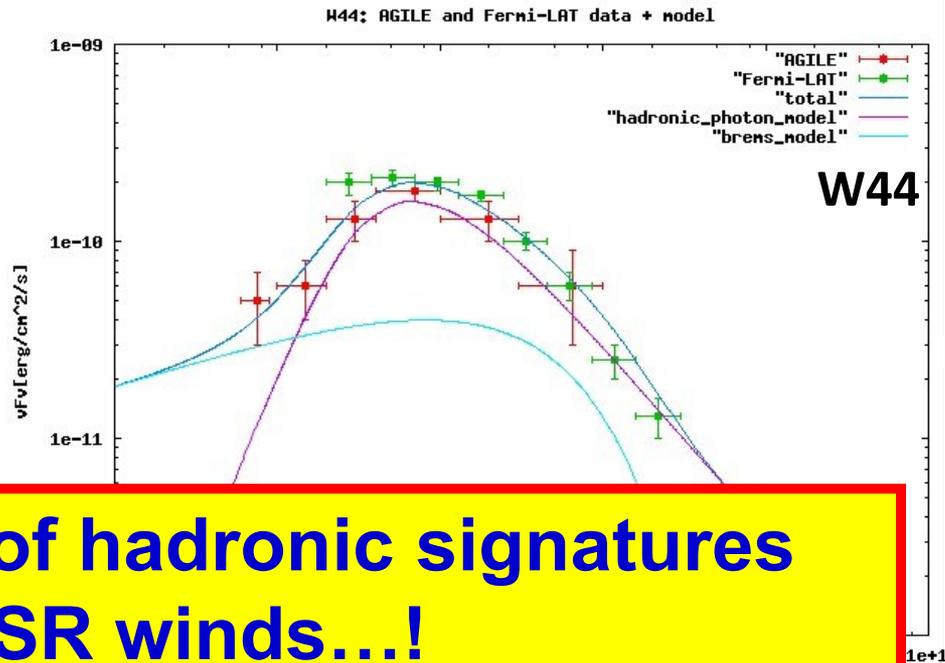
**Fermi-
LAT**



(Fermi Team,
Science,
submitted, 2012)

**PROOF OF HADRONIC
COSMIC-RAY
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W44: THE π^0 SPECTRUM**

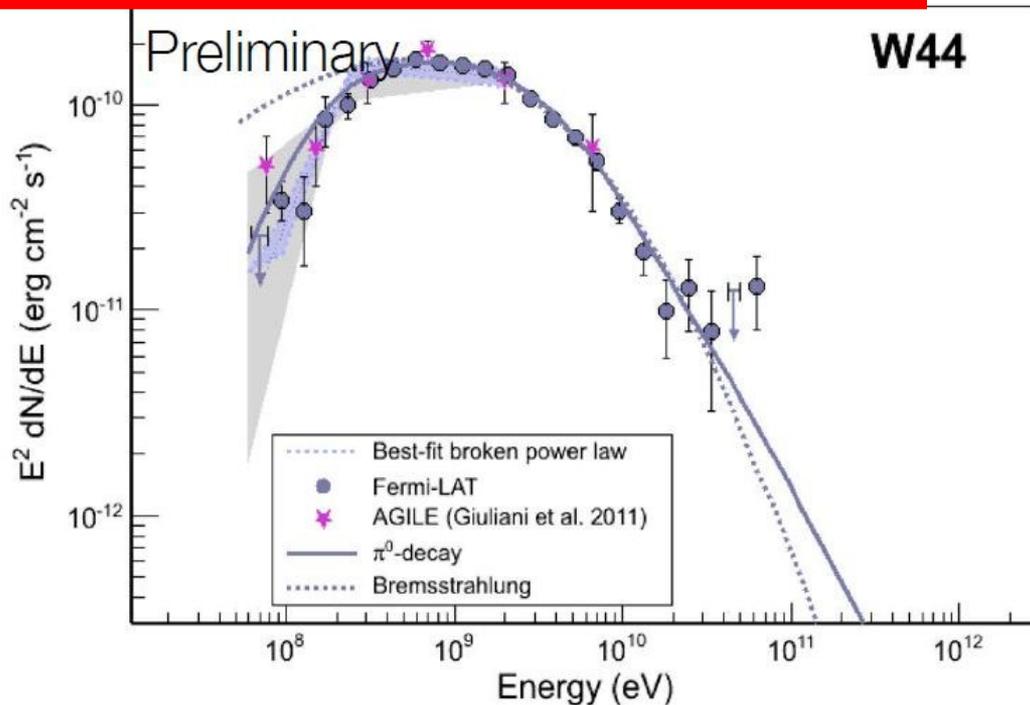
**AGILE-
GRID**



**lack of hadronic signatures
for PSR winds...!**

(Giuliani A., Cardillo M.,
Tavani, M., et al.,
ApJ Letters, 742, L30,
2011)

**Fermi-
LAT**



(Fermi Team,
Science,
submitted, 2012)

CRAB SNR and inner Nebula (from Hester, 2008)

The outer shock driven by ejecta into a low-density cavity is currently undetected

Shading represents density of ejecta freely expanding from explosion center

Shock velocity relative to freely expanding ejecta
 $v_s = v_{\text{observed}} - v_{\text{free, expansion}}$

Northwest:

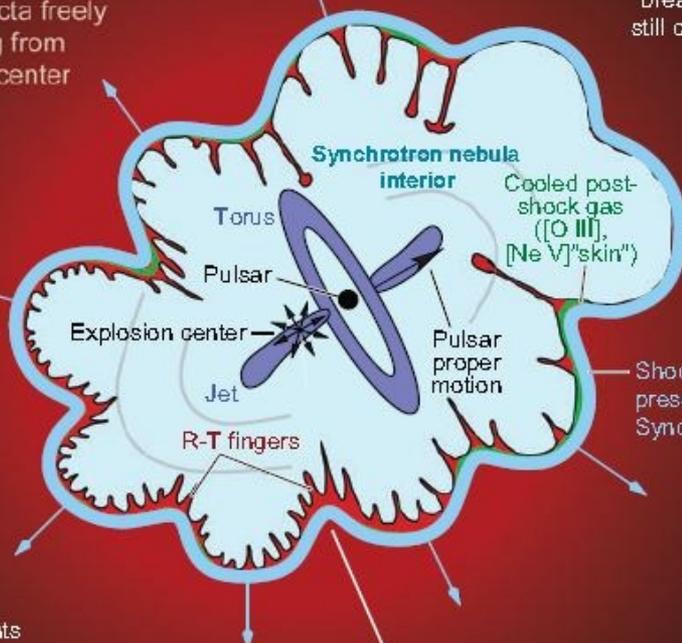
- Lower preshock density → high v_s
- Long cooling time
- Skin absent/no longer forms
- Fewer, older R-T filaments
- Synchrotron nebula appears to "break out" beyond filaments but is still confined by the shock.

Southeast:

- Higher preshock density → low v_s
- Short cooling time
- Skin present/still forming
- More [S II] in skin
- More, younger R-T filaments
- Synchrotron nebula confined within skin and thermal filaments

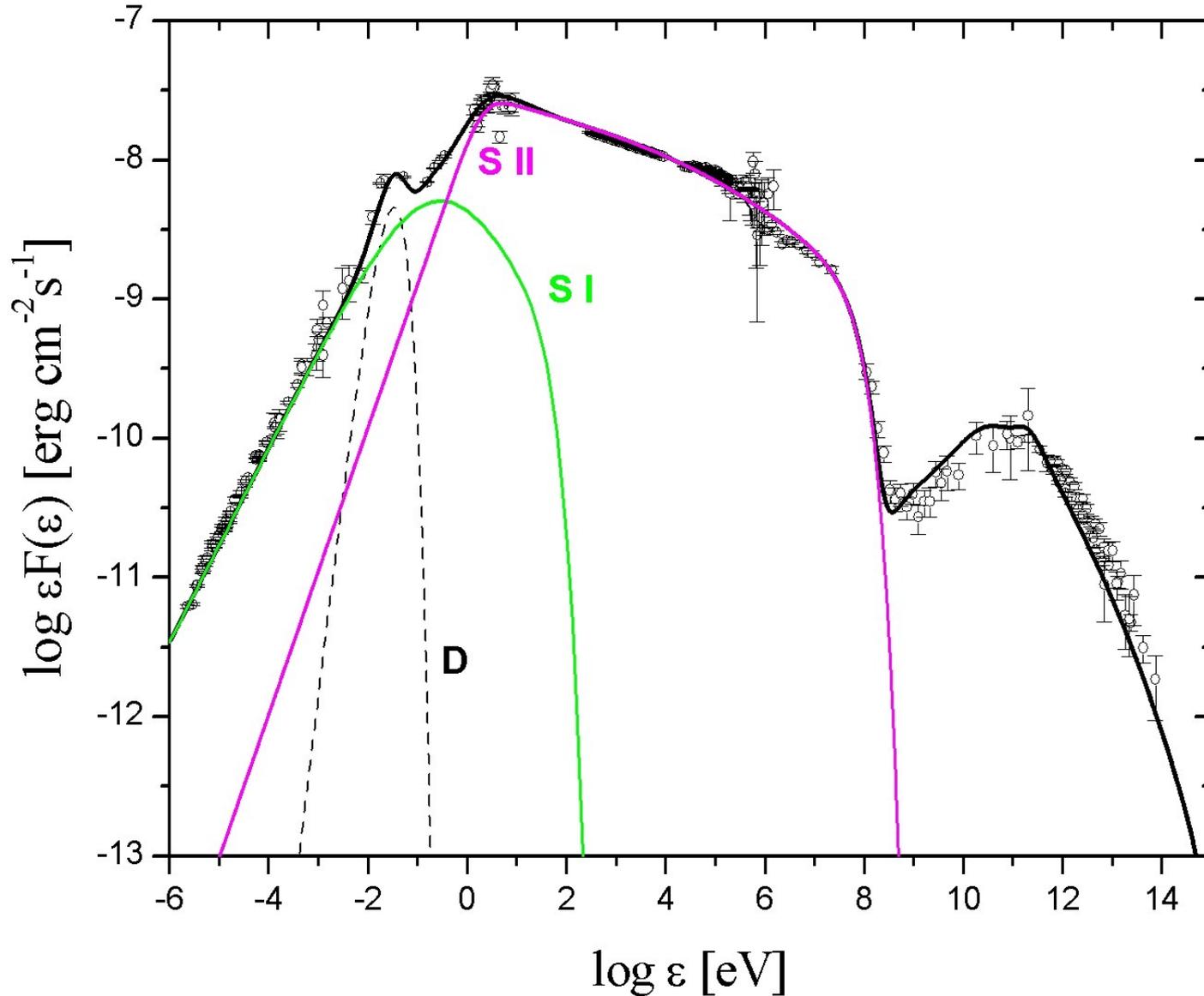
Prominent "classical filaments" in cusps of bubble-like shock structures, possibly formed by thin-sheet instabilities

Shock driven by pressure of combined Synchrotron nebula

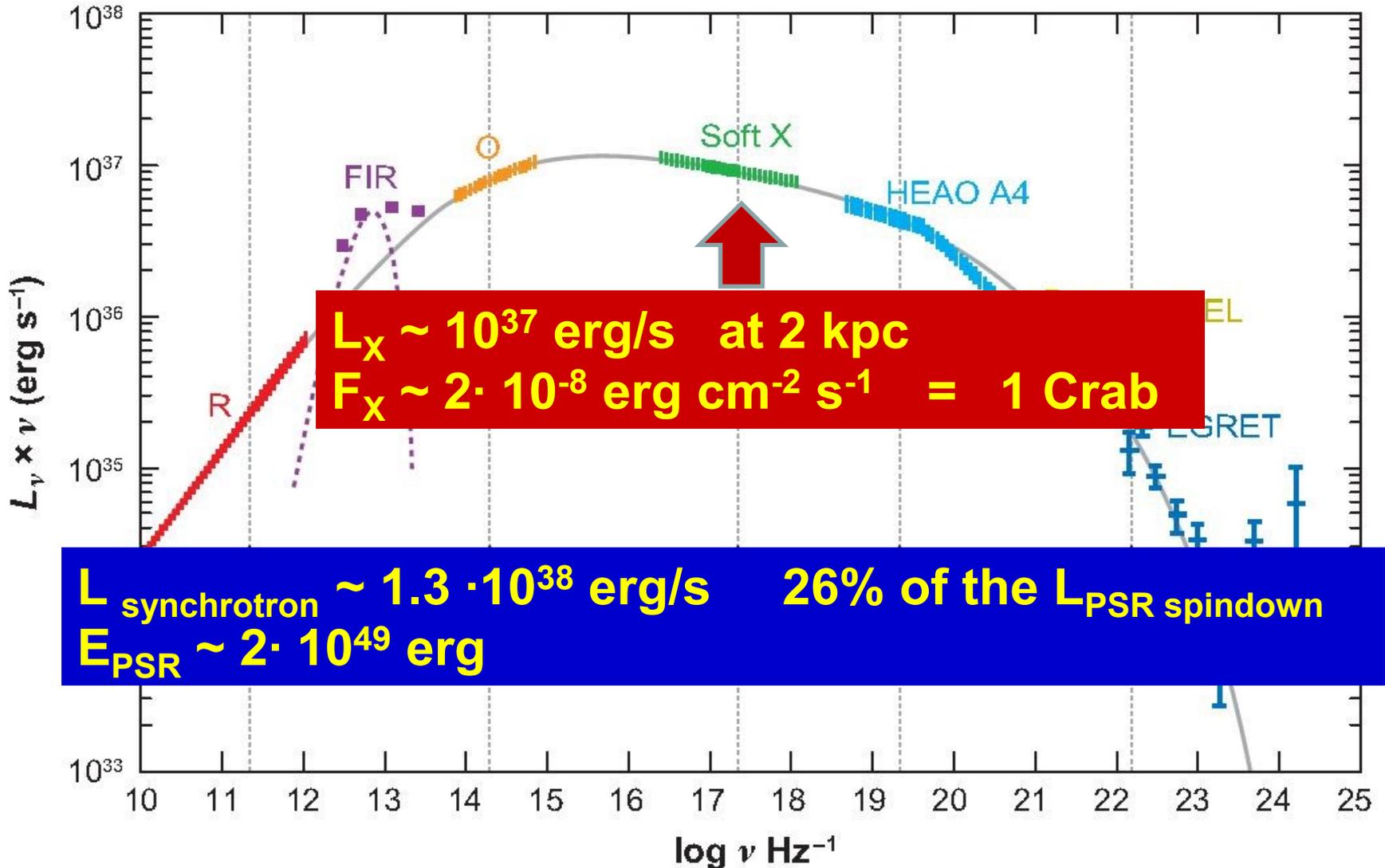


Crab Nebula spectrum from radio to TeV

(De Jager et al., 1996, Atoyan & Aronian 1996, Meyer et al. 2010, Tavani & Vittorini, 2012)



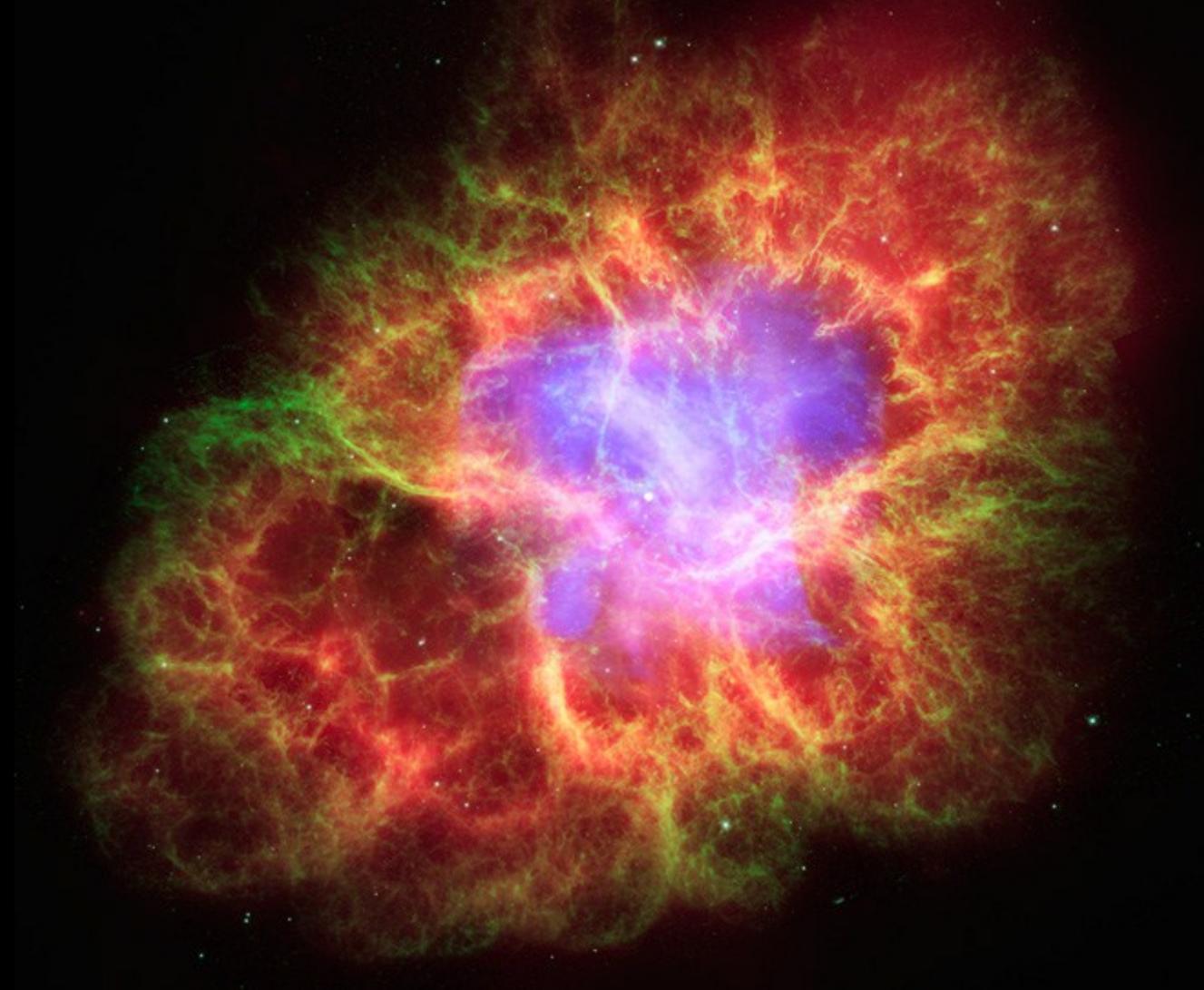
Crab Nebula spectrum (Hester 2008)



Synchrotron cooling timescales

- $\tau_s = (30 \text{ yrs}) B_{-4}^{-3/2} (E_{\text{ph}} / 1 \text{ keV})^{-1/2}$
- $\tau_s = (0.1 \text{ yrs}) B_{-4}^{-3/2} (E_{\text{ph}} / 100 \text{ MeV})^{-1/2}$

The Crab Nebula (M1) : the Queen of Nebulae



The Crab Nebula (M1) : a wonderful laboratory



The Crab Nebula (M1) : a wonderful laboratory

inner Nebula
opt/X-ray (wisp)
fluctuations
(weeks/months)

hints of large-scale
kinks in SE jet
variations
(5-10 years)



the PSR appears
to be “stable”

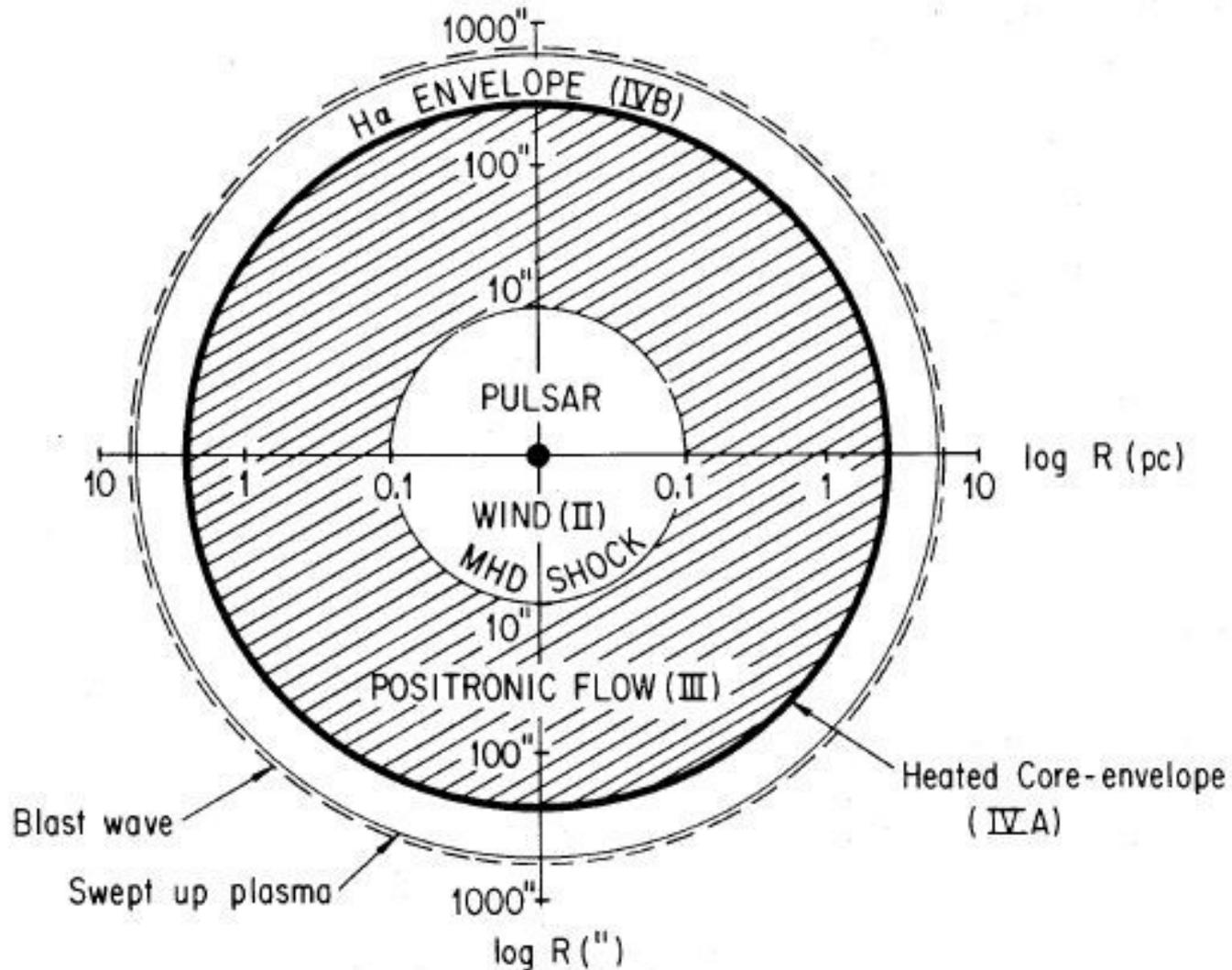
surprising
gamma-ray flares
(hrs/days/weeks)

secular X-ray
variations (years)

Crab Nebula MHD models

- Kennel-Coroniti, 1984
- Komissarov, Lyubarsky, 2003, 2004
- Spitkovsky & Arons, 2004, ApJ, 603, 669
- Del Zanna, Volpi, Amato, Bucciantini, 2006, 2008
- Camus et al., 2009, MNRAS; 400, 1241

MHD Kennel-Coroniti picture of the Crab Nebula (1984)



KC MHD modelling: RH eqs.

the Rankine-Hugoniot relations for a strong, perpendicular shock reduce to

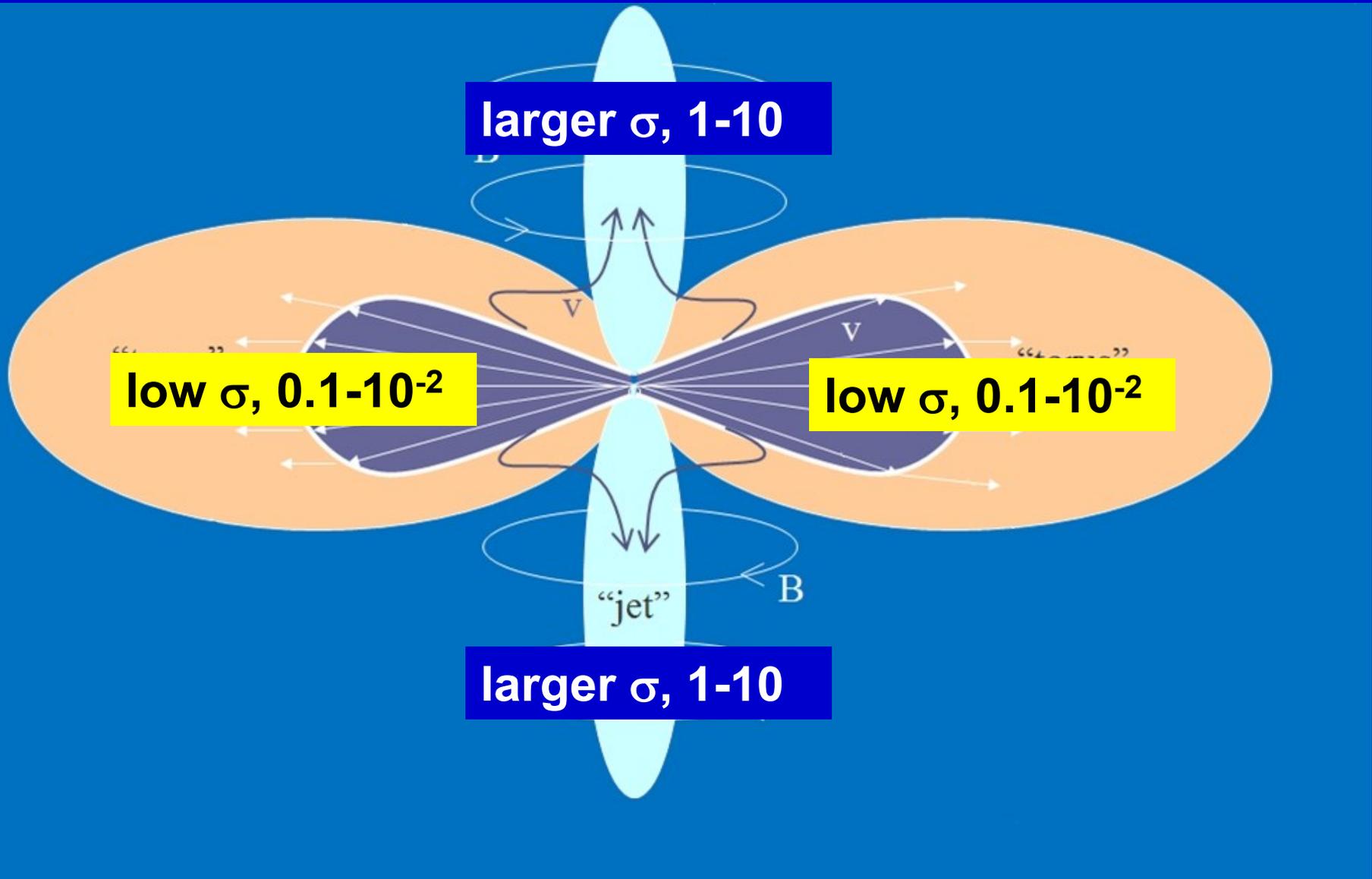
$$u_2^2 = \frac{8\sigma^2 + 10\sigma + 1}{16(\sigma + 1)} + \frac{1}{16(\sigma + 1)} [64\sigma^2(\sigma + 1)^2 + 20\sigma(\sigma + 1) + 1]^{1/2}$$

$$\frac{B_2}{B_1} = \frac{N_2}{N_1} = \frac{\gamma_2}{u_2},$$

$$\frac{P_2}{n_2 mc^2 u_1^2} = \frac{1}{4u_2 \gamma_2} \left[1 + \sigma \left(1 - \frac{\gamma_2}{u_2} \right) \right],$$

PSR wind magnetization $\sigma = \frac{B^2}{4\pi n u \gamma m c^2}$

PSR wind MHD modelling, torus + jets

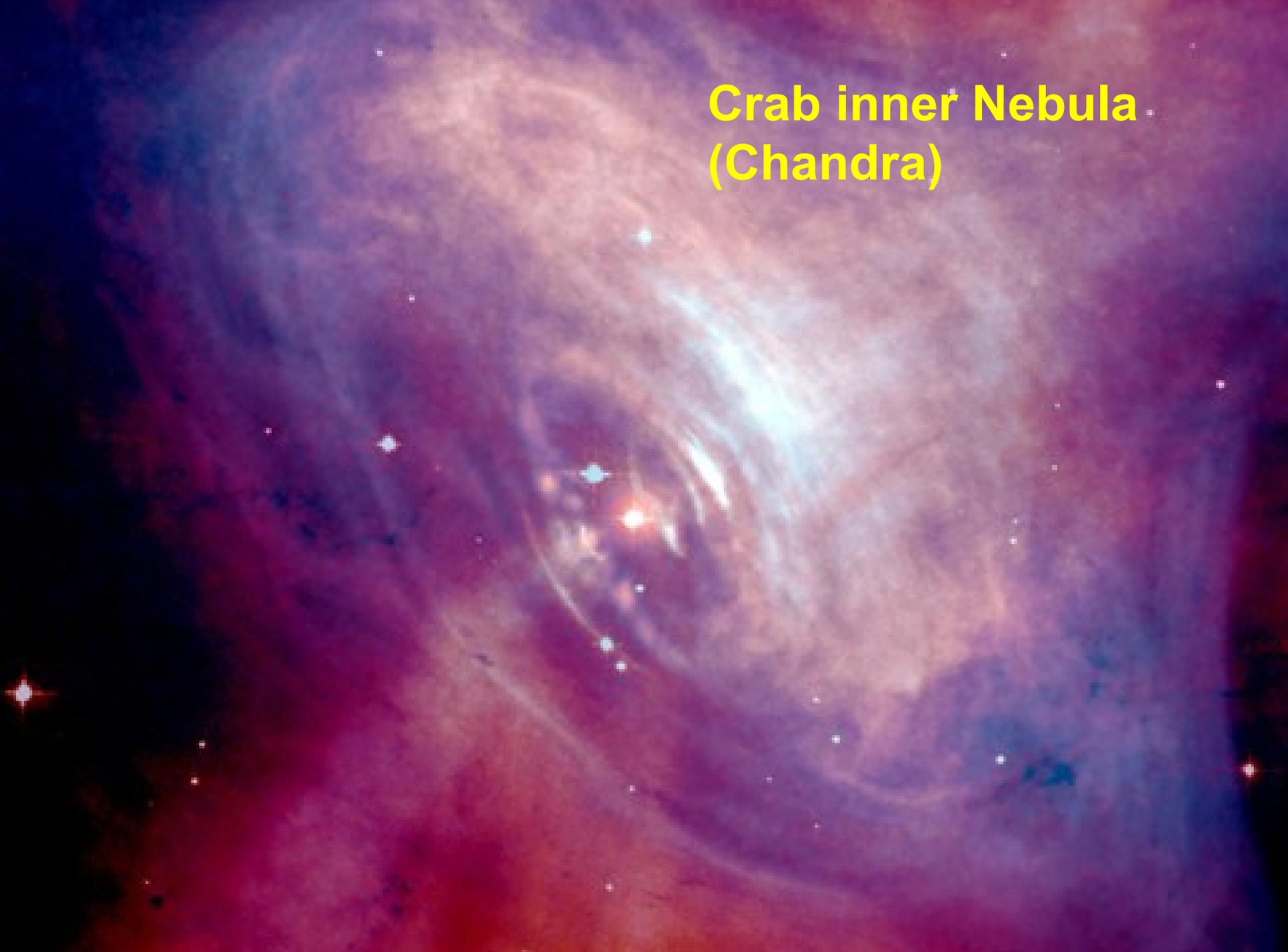


(adapted from Komissarov et al 2011)

Crab Nebula modelling

- average nebular magnetic field $\mathbf{B} = 200 \mu \mathbf{G}$
- PSR-injected particles (e⁺/e⁻ pairs)
 $\mathbf{dN/dt} \sim 10^{40.5} \mathbf{s}^{-1}$
- total radiating particles, $\mathbf{N} \sim 2 \cdot 10^{51}$
- many shock accelerating sites in the Nebula
- inner Nebula variability (weeks-months)
 - **Toroidal structures (wisps)**
 - **Jet-like structures (knots)**

**Crab inner Nebula
(Chandra)**



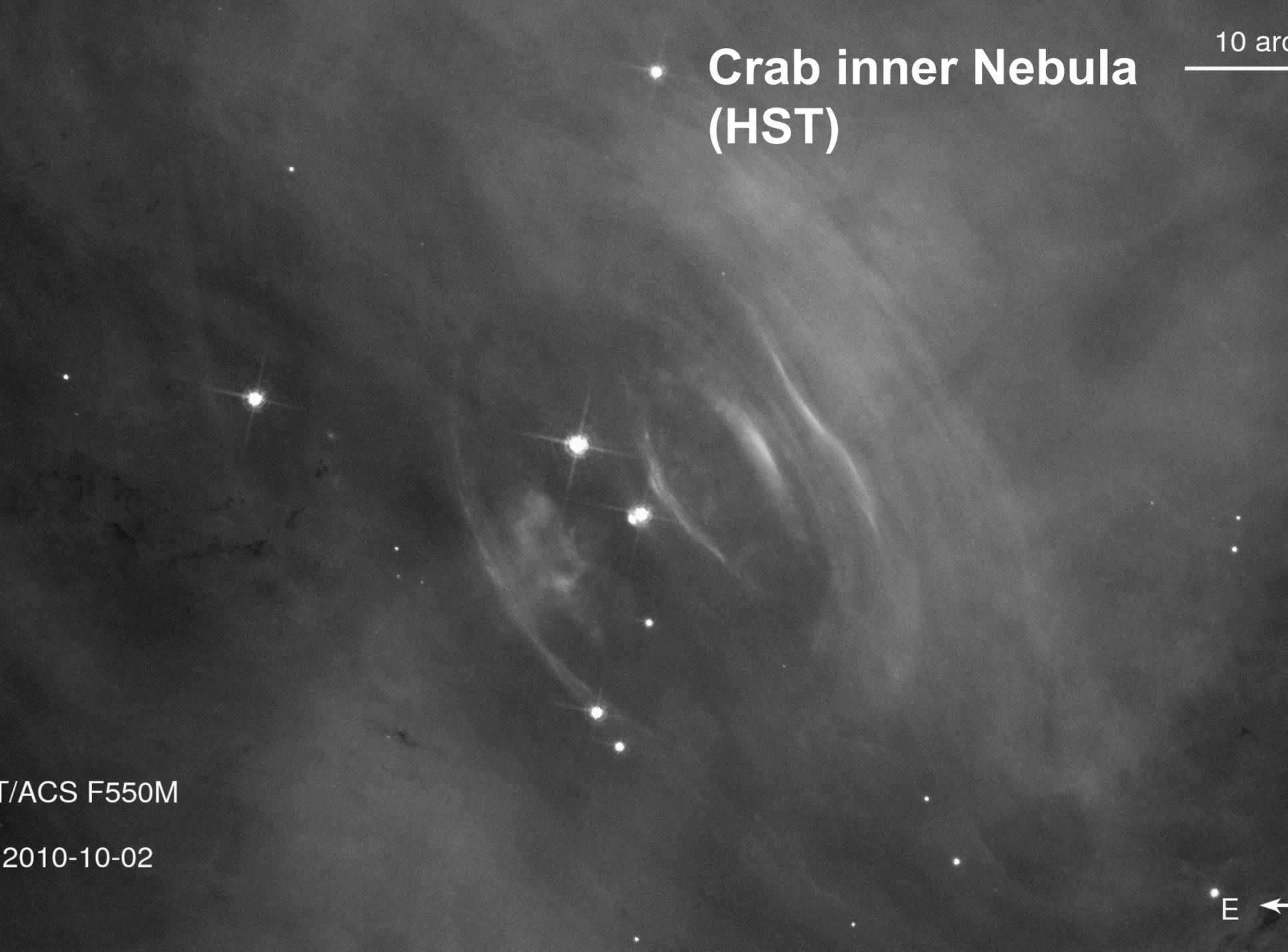
Crab inner Nebula (HST)

10 arc

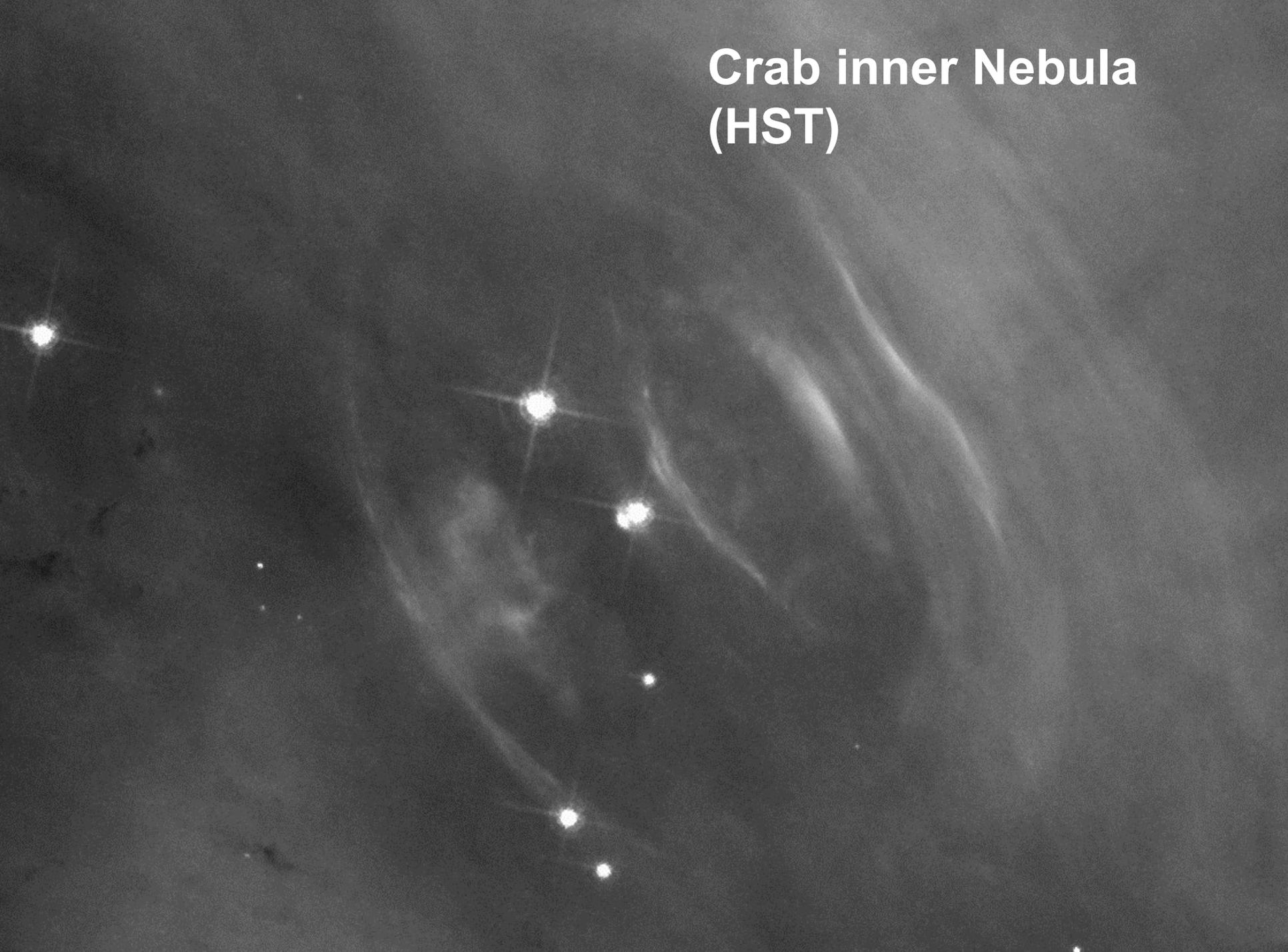
T/ACS F550M

2010-10-02

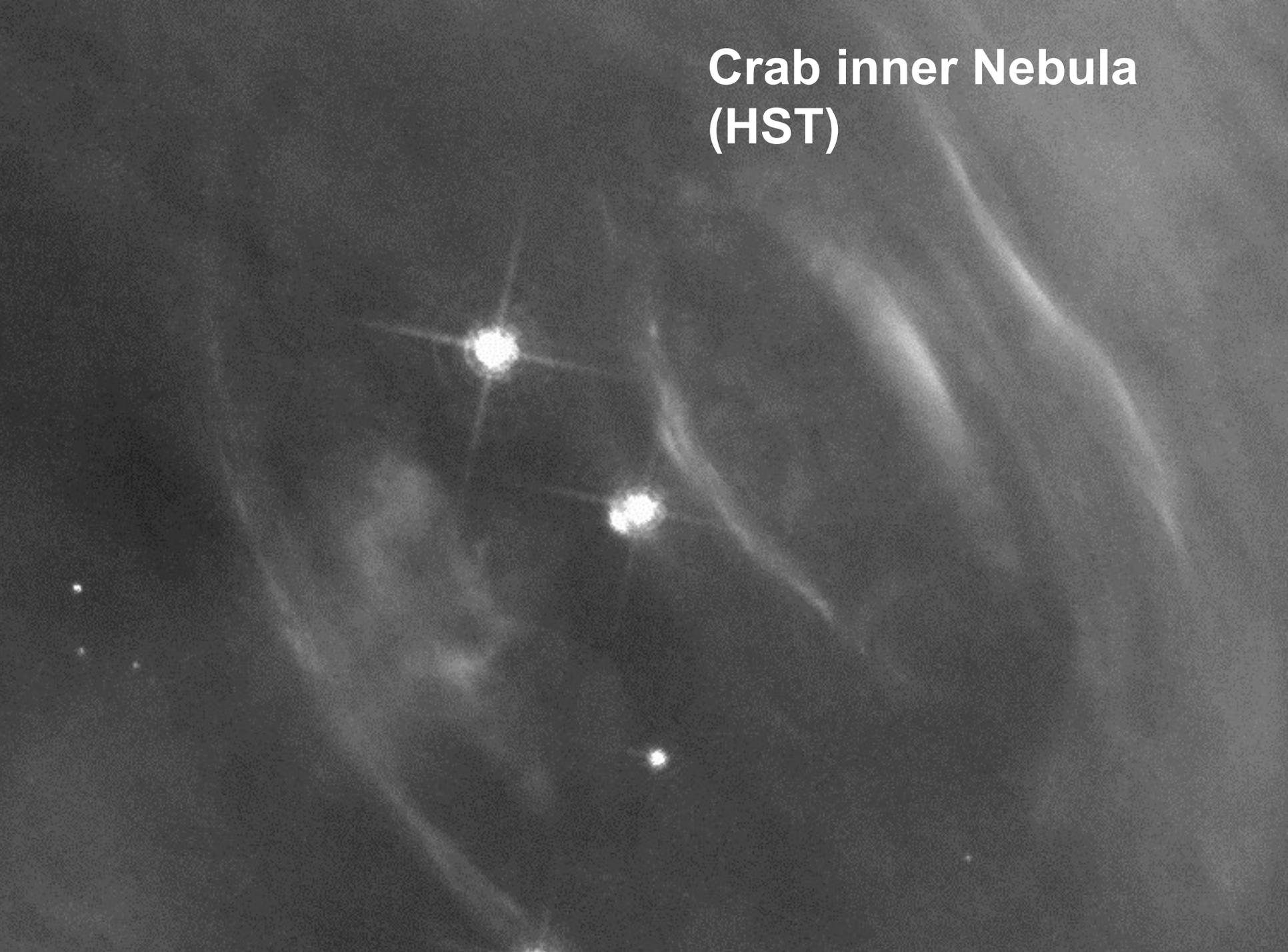
E ←



**Crab inner Nebula
(HST)**



**Crab inner Nebula
(HST)**



Crab inner Nebula (HST)

Pulsar

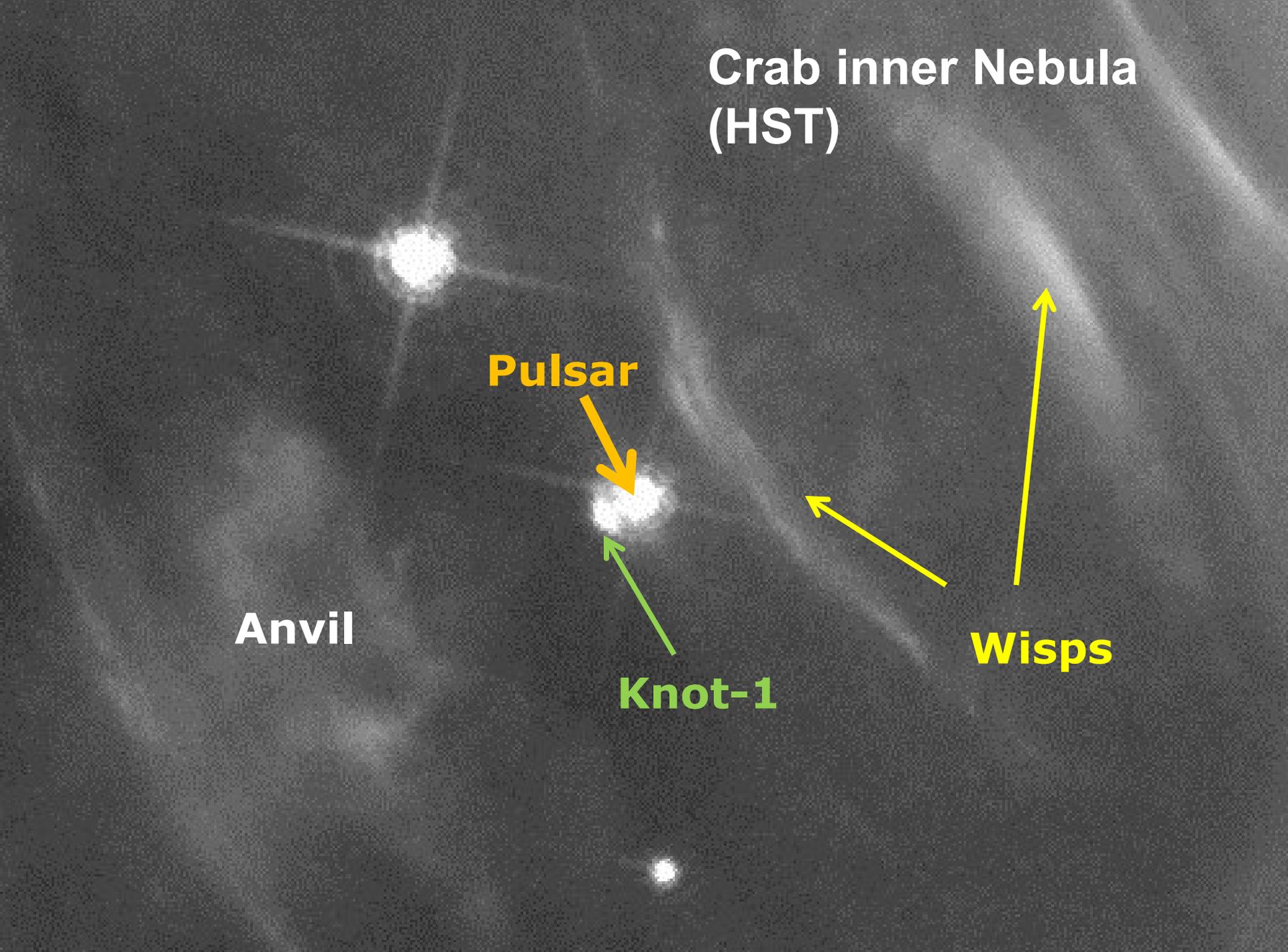
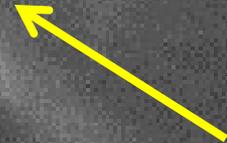


Knot-1



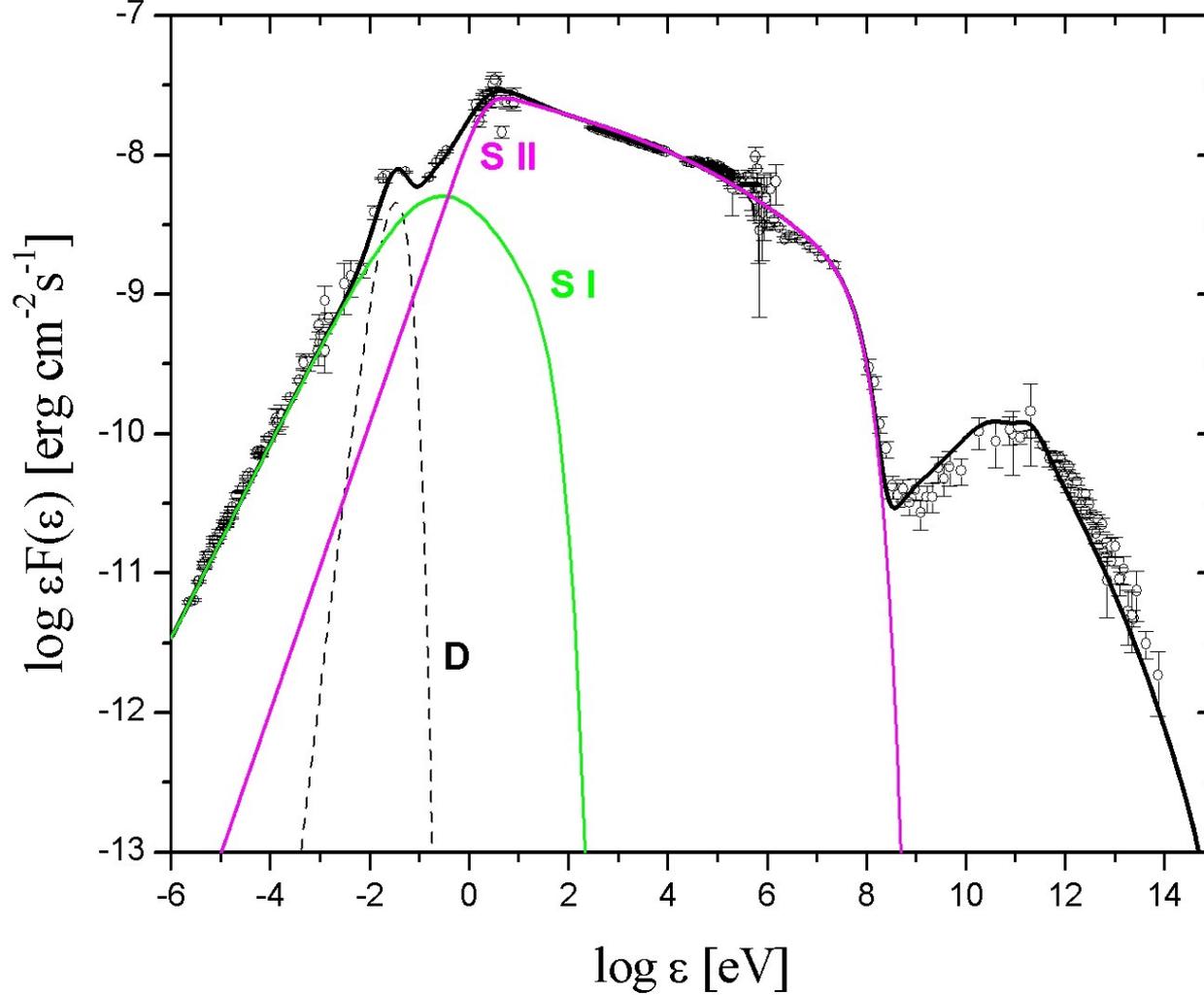
Anvil

Wisps



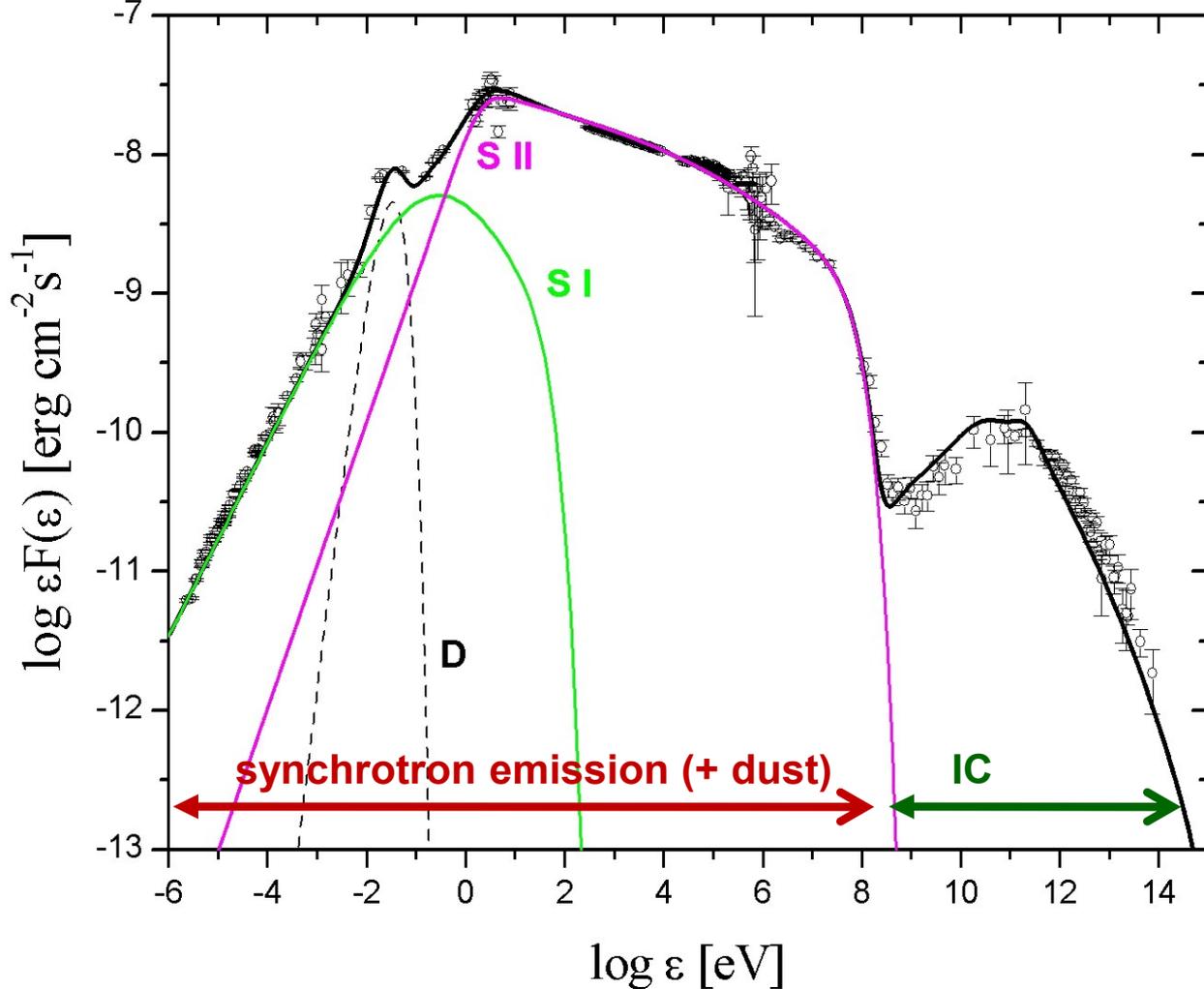
Crab Nebula spectrum from radio to TeV

(De Jager et al., 1996, Atoyan & Aronian 1996, Meyer et al. 2010, Tavani & Vittorini, 2012)



Crab Nebula spectrum from radio to TeV

(De Jager et al., 1996, Atoyan & Aronian 1996, Meyer et al. 2010, Tavani & Vittorini, 2012)



Pop. I
 $60 < \gamma < 2.5 \cdot 10^4$ $\alpha = 1.6$
 $2.5 \cdot 10^4 < \gamma < 2.5 \cdot 10^6$ $\alpha = 4.0$
 $R = 2.3 \cdot 10^{18}$ cm
 $N_{el} = 2.5 \cdot 10^{51}$
 $T_{syn} \sim 10^5$ years

Pop. II
 $5 \cdot 10^5 < \gamma < 3.8 \cdot 10^8$ $\alpha = 3.20$
 $3.8 \cdot 10^8 < \gamma < 3.5 \cdot 10^9$ $\alpha = 3.75$
 $R = 2 \cdot 10^{18}$ cm
 $N_{el} = 3 \cdot 10^{48}$
 $T_{syn} \sim 10$ years

Dust
 $L = 3 \cdot 10^{36}$ erg/s
 $T = 100$ °K

Average magnetic field
 $B = 200$ μ Gauss

the “standard” emiss. model (de Jager et al. 1996)

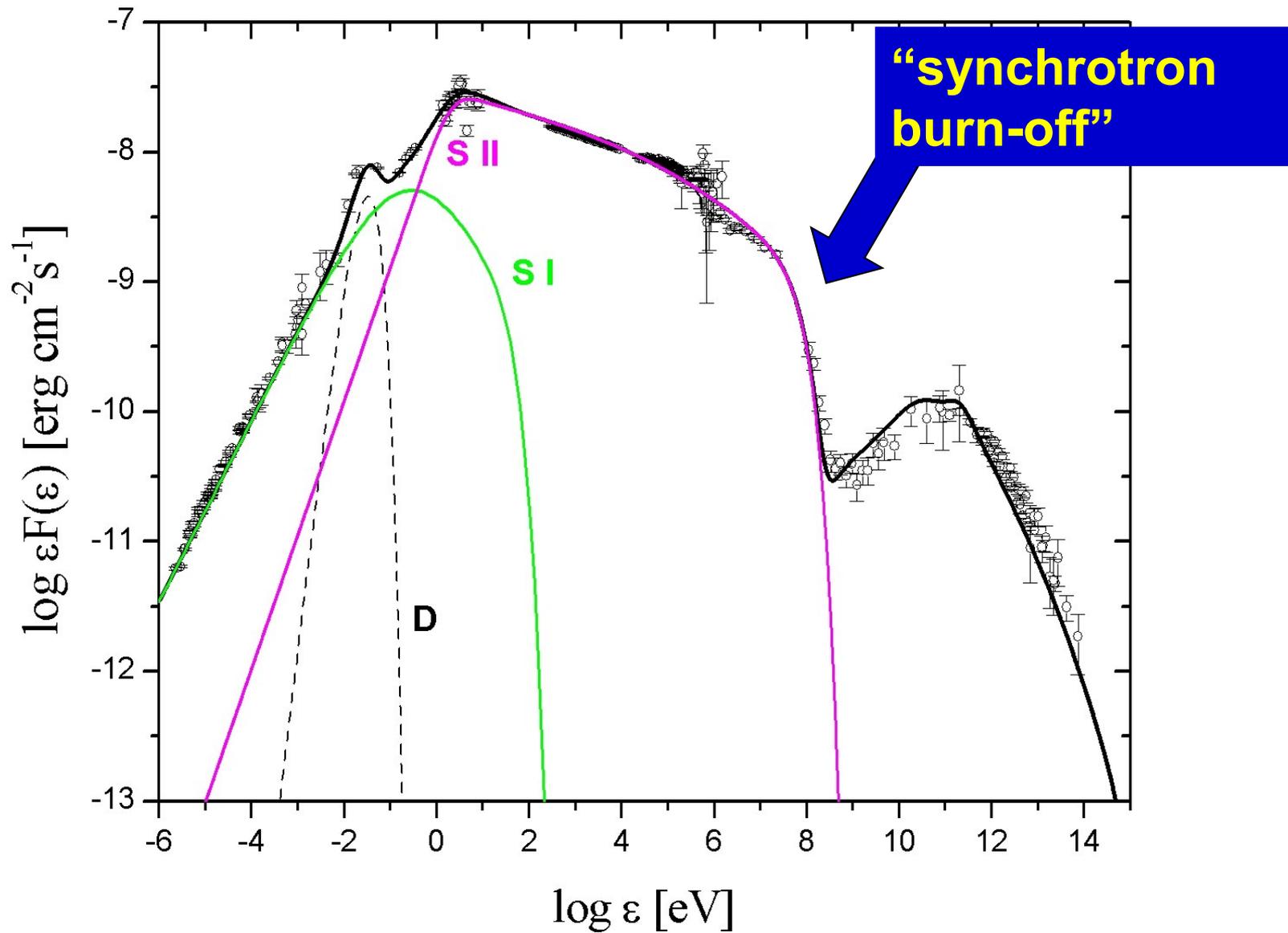
- particle acceleration by shocks or MHD/plasma instabilities, assumes $E/B = 1$
- $t_{\text{acc}}^{-1} \sim \alpha' \omega_B / \gamma$ ($\omega_B = eB/mc$; $\alpha' < 1$)
- $\gamma^{-1} d\gamma/dt = (eB/\gamma mc)(E/B)\alpha' - (2/3)\sigma_T(B^2/8\pi) \gamma/mc$
- $d\gamma/dt=0$ implies
$$\gamma_{\text{max}} \sim 3 \cdot 10^9 (E/B)^{1/2} (\alpha' / \sin^2 \theta B_{-3})^{1/2}$$

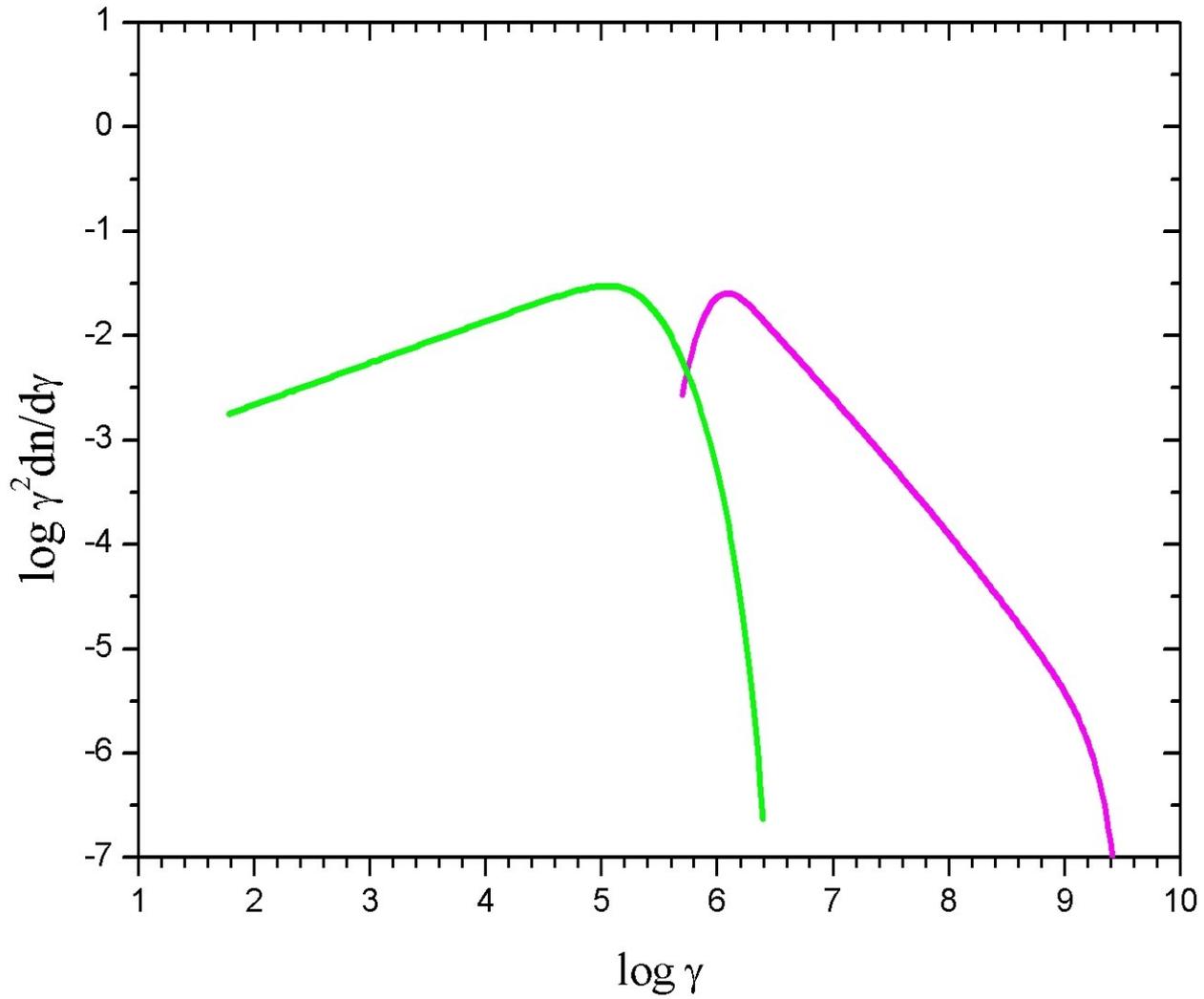
the old paradigm for nebular emission
(e.g., de Jager, Harding et al. 1996)

- max. emitted photon synchrotron energy is independent of the magnetic field B :
“**synchrotron burn-off**”
- $E_{\max} = (3/2) \hbar \omega_B \gamma_m^2 \simeq (230 \text{ MeV}) (\delta \alpha' / \sin\theta)$

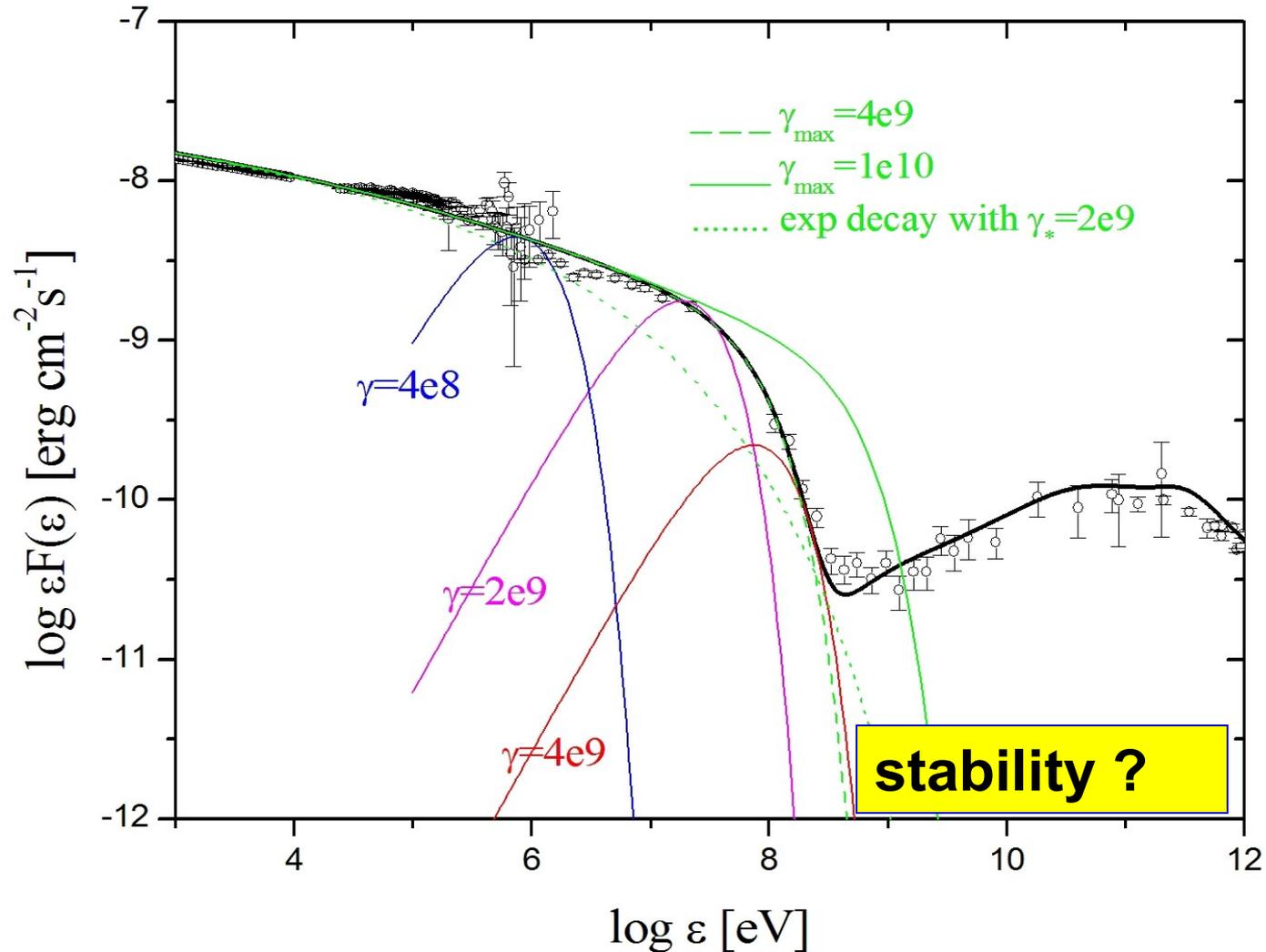
for a Doppler factor δ , $\delta \alpha' / \sin\theta \leq 1$

Crab Nebula average spectrum

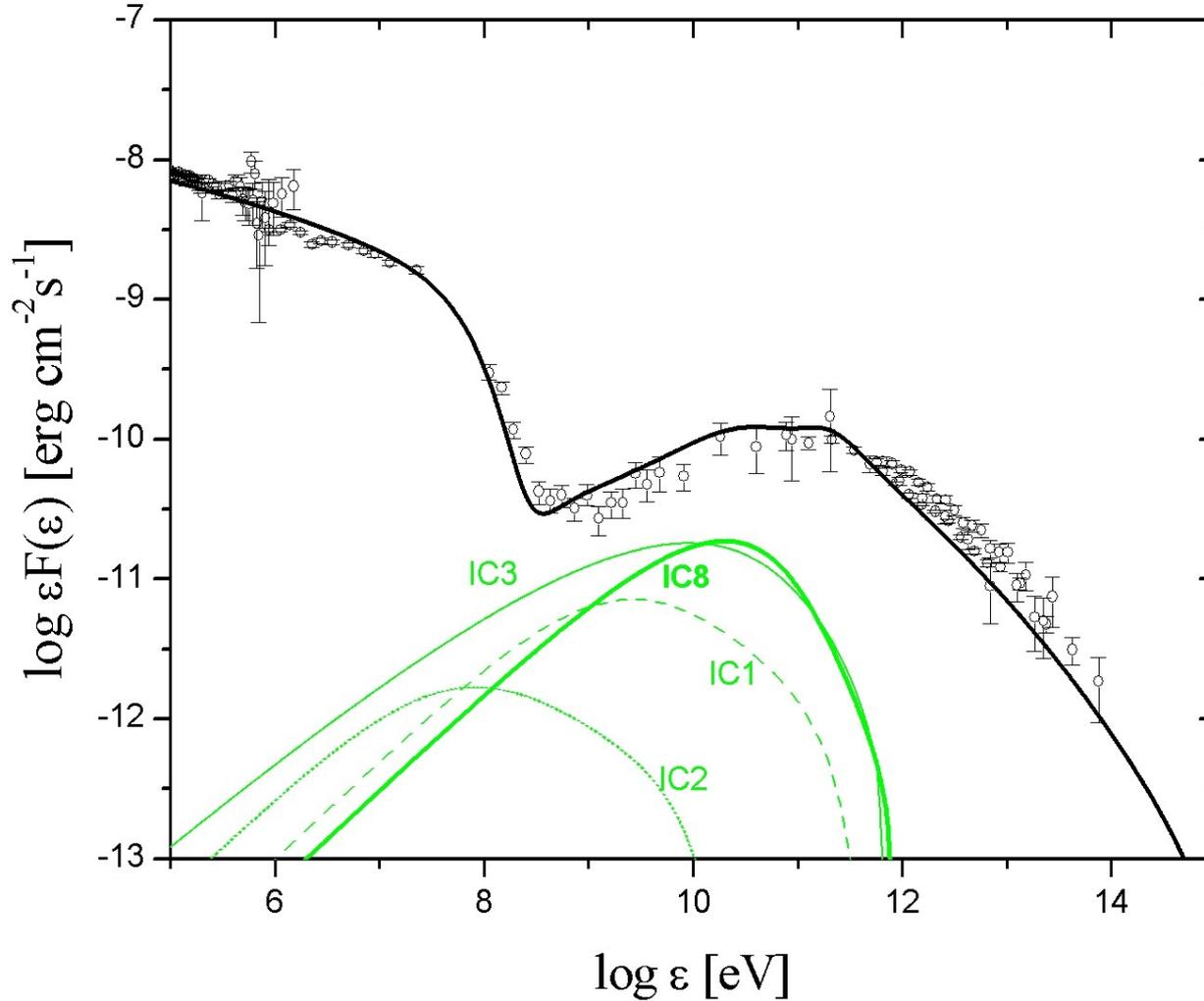




Crab Nebula spectrum at the synchr. cutoff (modelling for $B = 200 \mu\text{G}$; M.T. and Vittorini, 2012)



TeV nebular emission: inverse Compton



Inverse Compton contribution from **pop I** electrons scattering:

IC1 dust ph

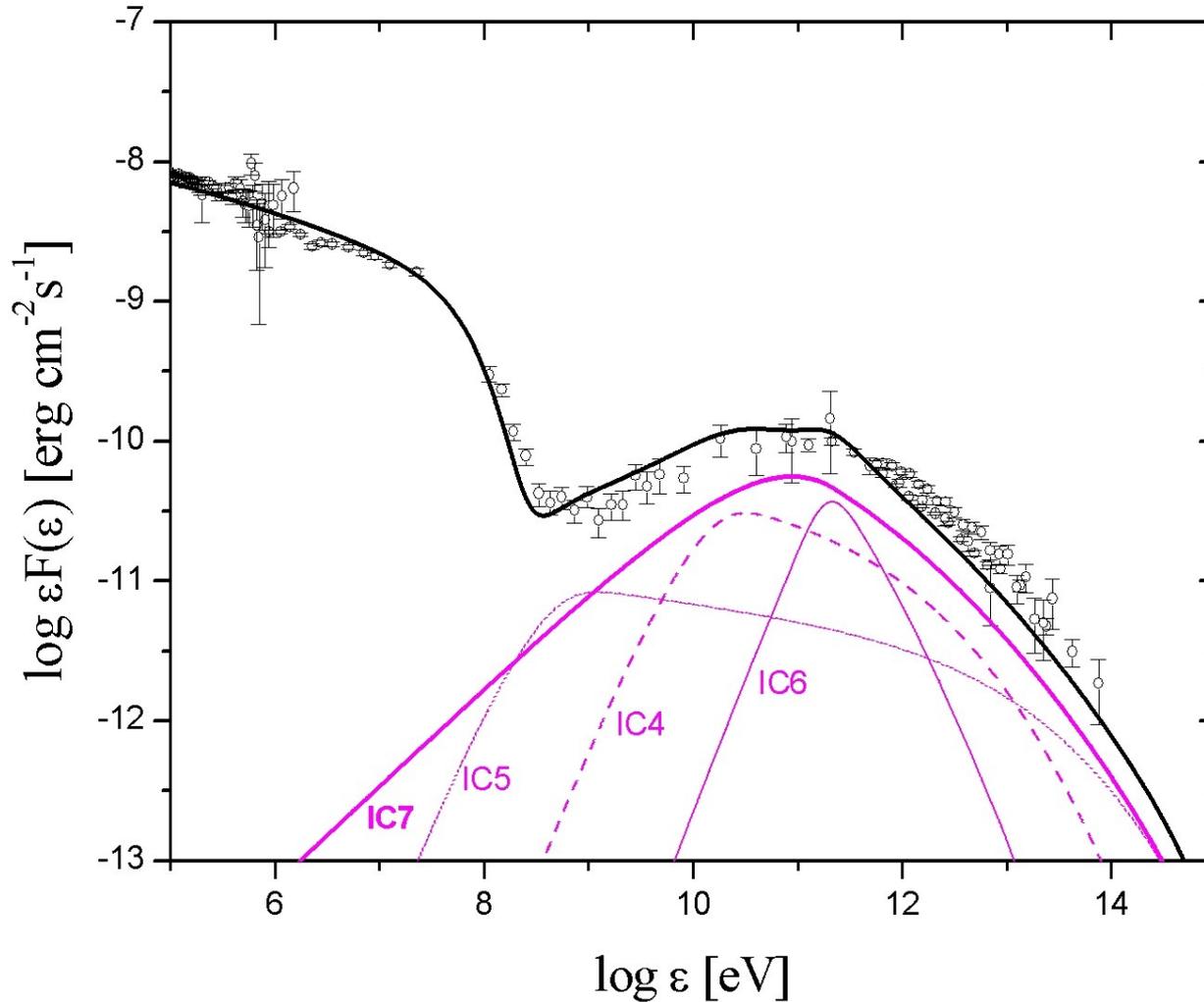
IC2 CMB ph

IC3 syn ph from **pop I**

IC8 syn ph from **pop II**

Vitorini & M.T. 2011

TeV nebular emission: inverse Compton



Inverse Compton contribution from **pop II** electrons scattering:

IC4 dust ph

IC5 CMB ph

IC6 syn ph from **pop II**

IC7 syn ph from **pop I**

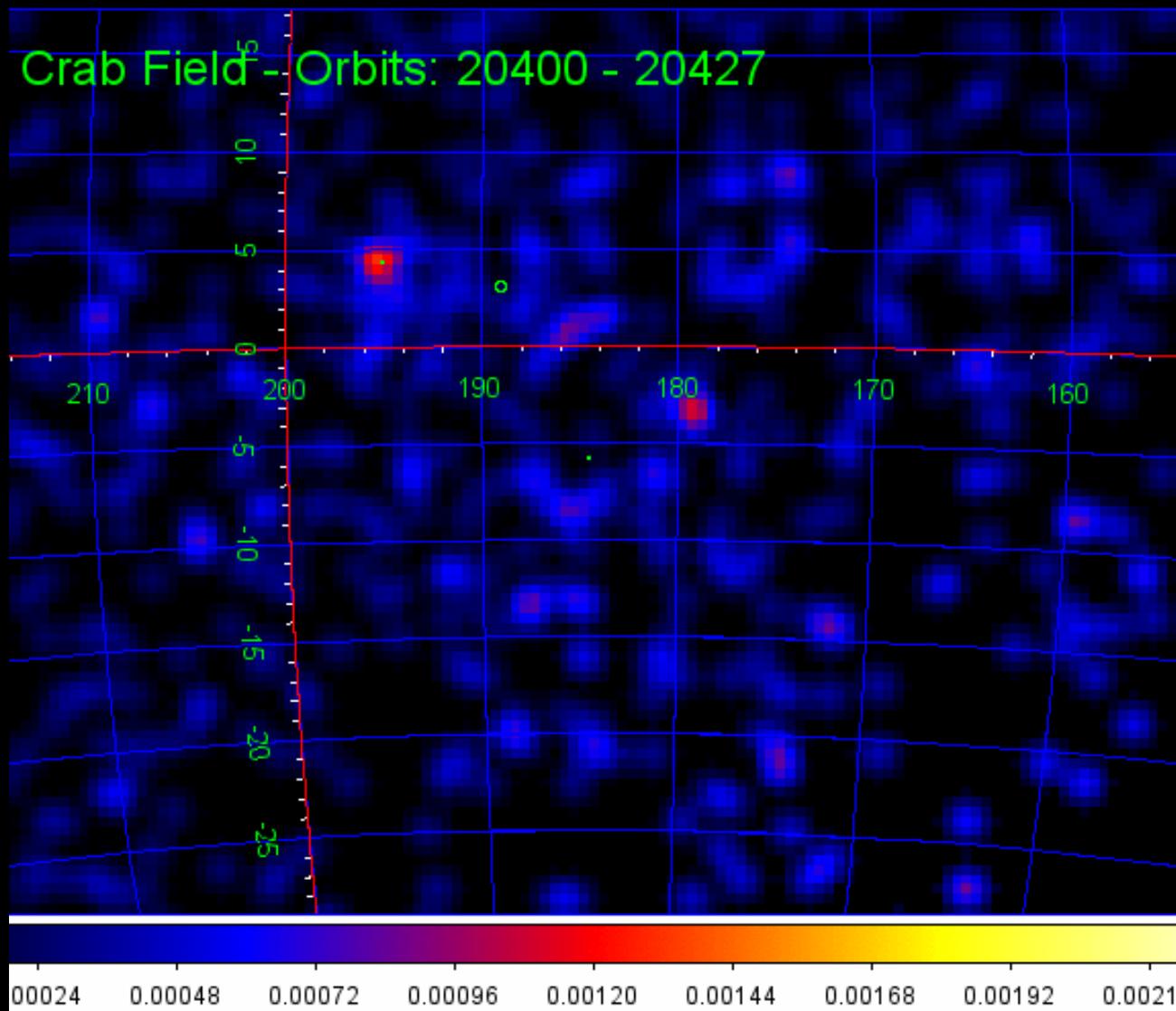
very stable !

Vittorini & M.T. 2011

but... the Crab is variable !

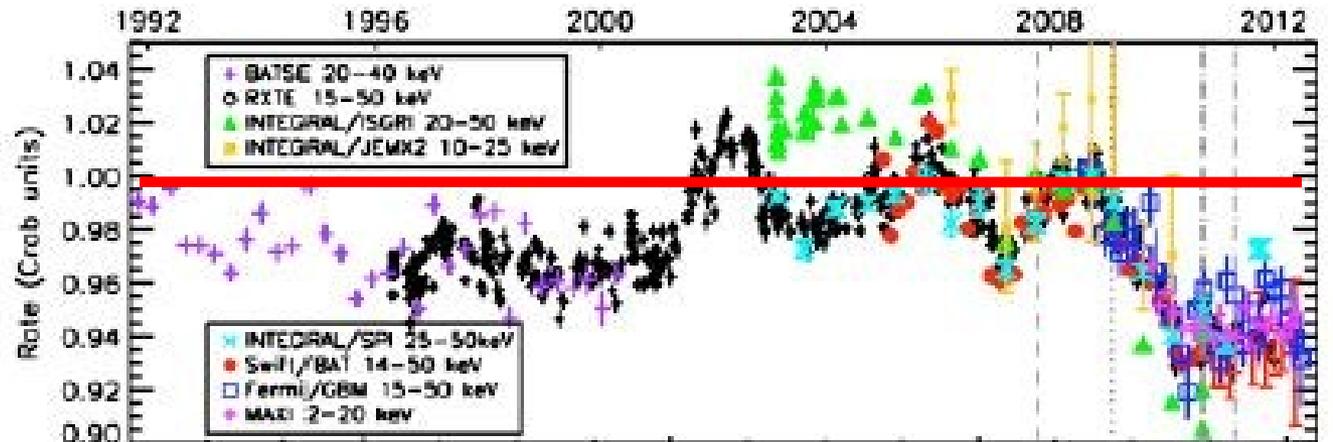
- **rapid (hours/days) very intense gamma-ray flares above 100 MeV (AGILE & Fermi-LAT)**
- **slow variation (years), 5-10 % of the X-ray flux (Fermi-GBM, Swift-BAT, XTE, Integral)**

AGILE gamma-ray monitoring of the Crab (April 2011)

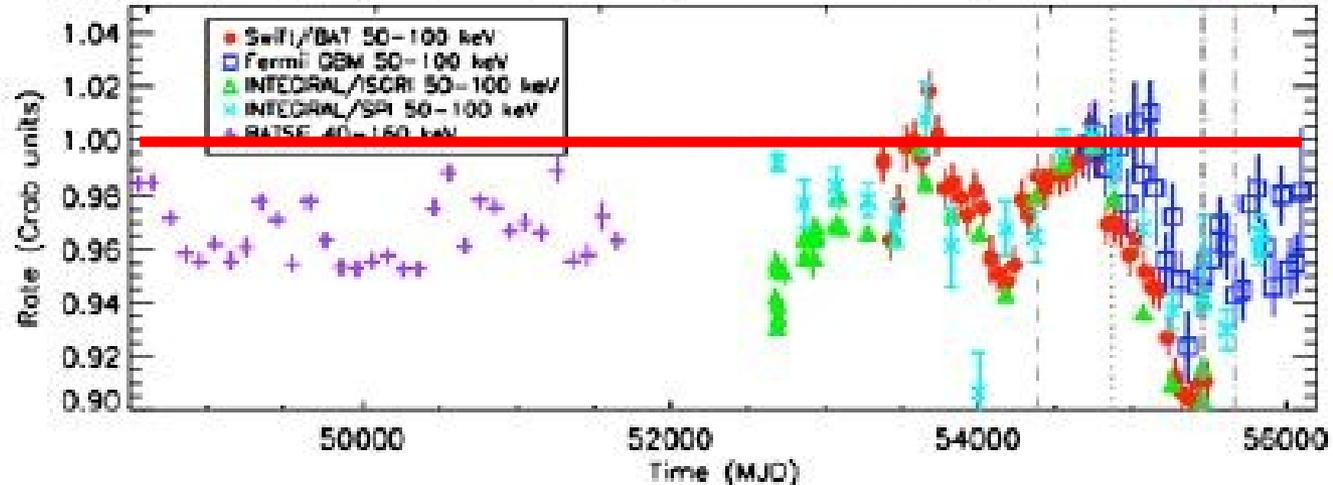


20-year Crab Nebula Light Curve

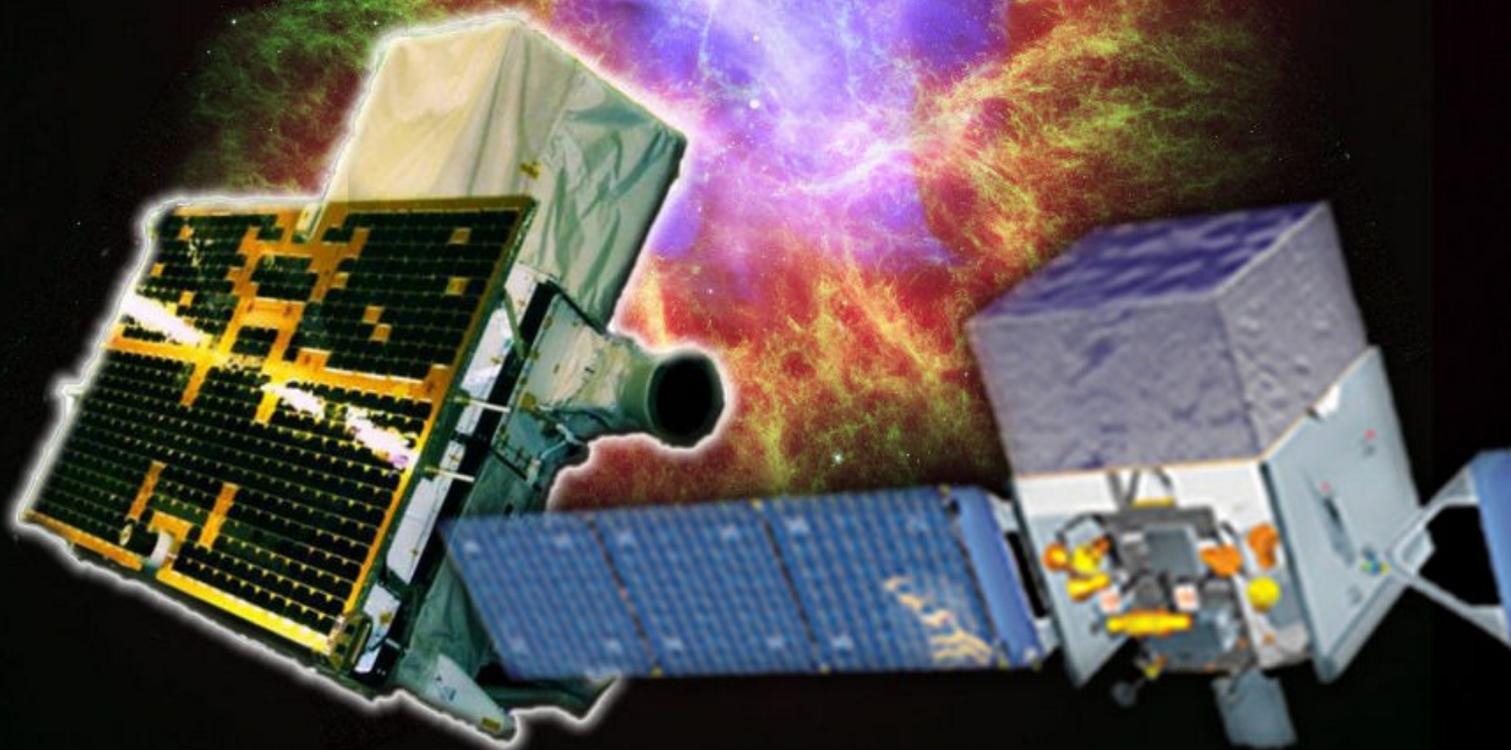
15-50 keV



50-100 keV



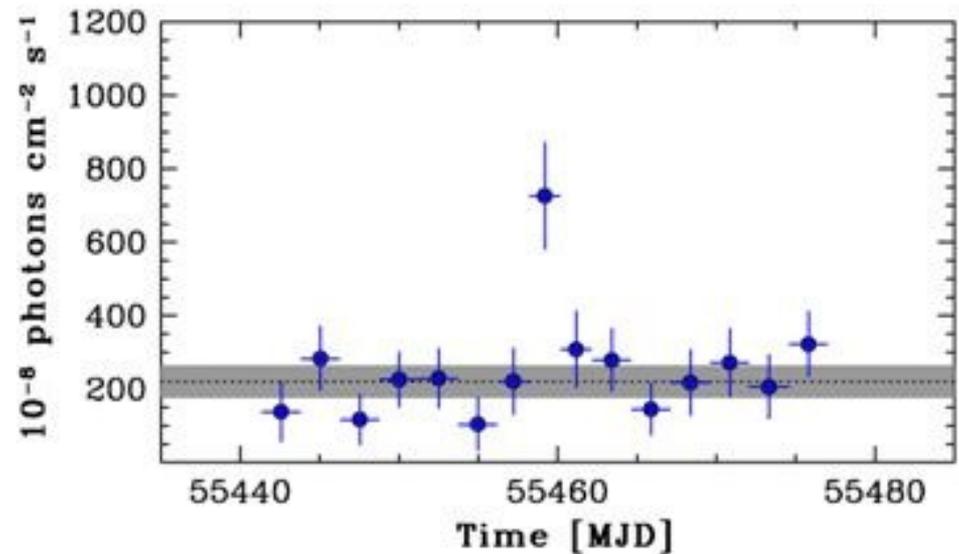
C. Wilson-Hodge (2012)



NASA-HEASARC Picture of the Day, Feb. 2011

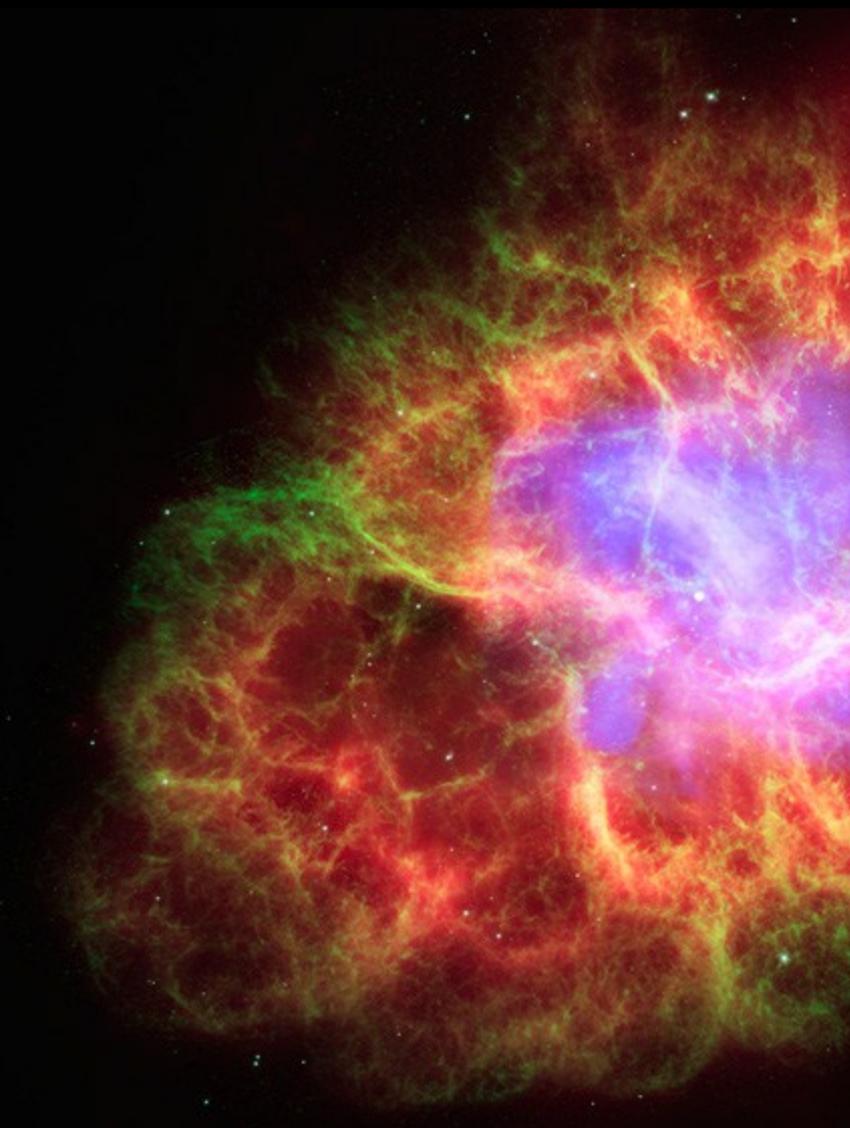
The Crab Nebula: flaring !?!

FIRST PUBLIC ANNOUNCEMENT Sept. 22, 2010: AGILE issues the Astronomer's Telegram n. 2855

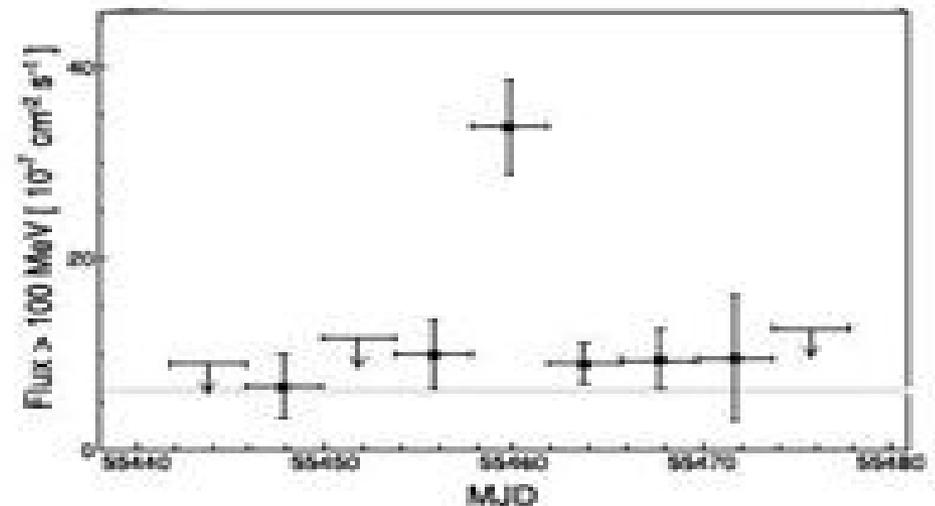


Science Express (6 January 2011)

The Crab Nebula: flaring !?!

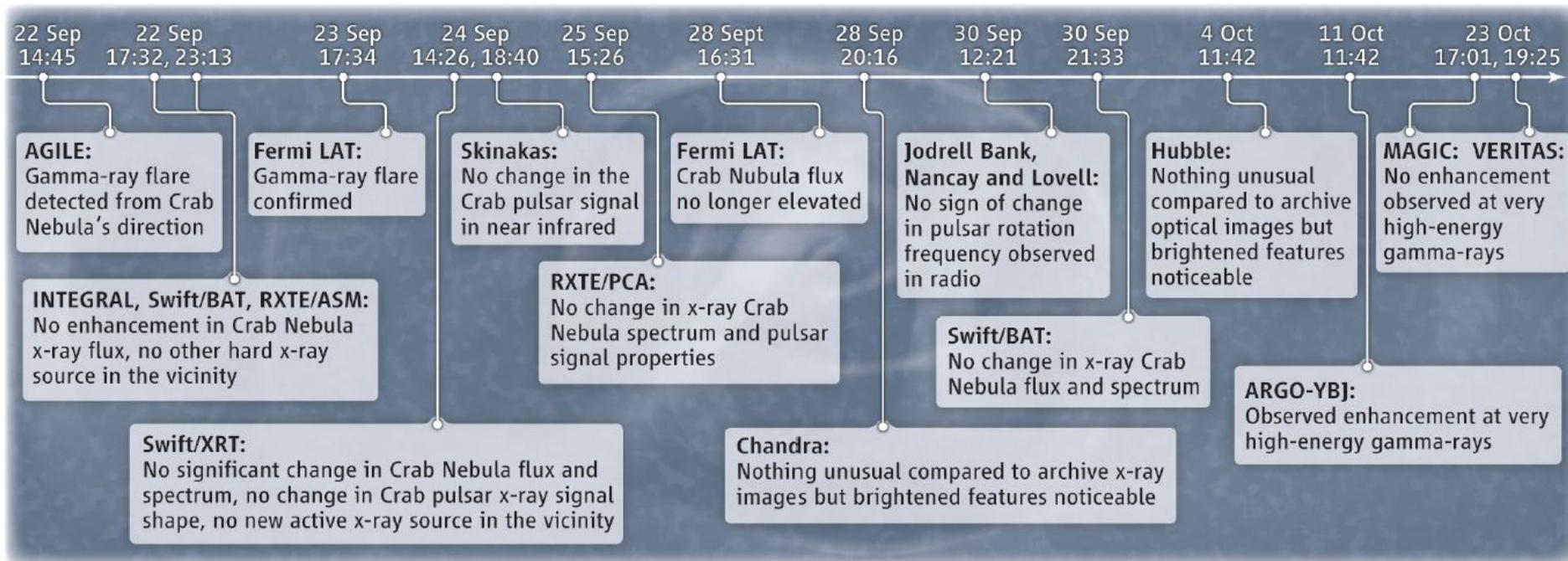


Fermi-LAT flare



Science Express (6 January 2011)

Crab's post-flare excitement



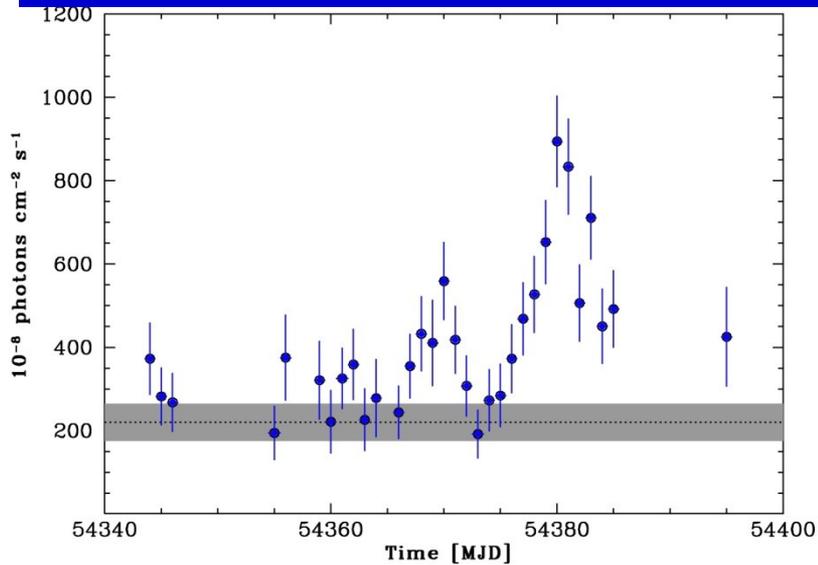
Bernardini E., 2011

- **Four major gamma-ray flaring episodes**

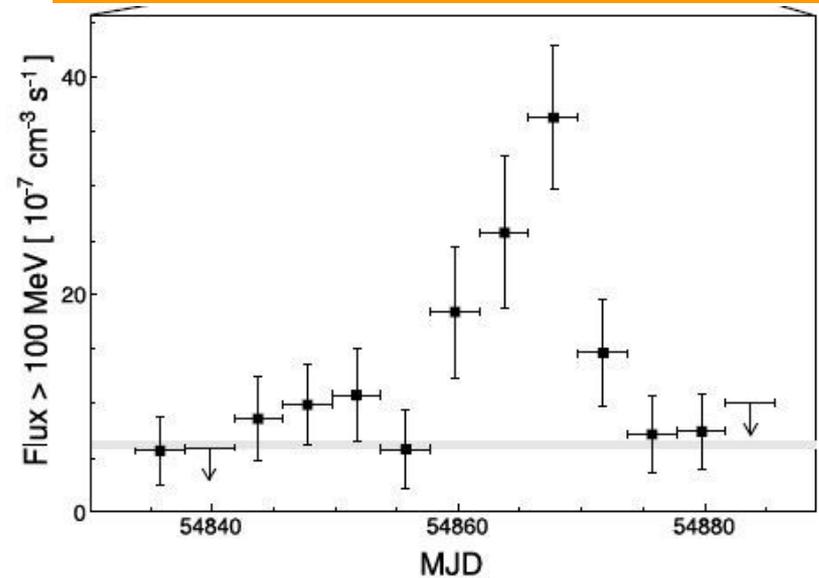
Flare date	Duration	Peak γ -ray flux	Instruments
October 2007	~ 15 days	~ $14 \cdot 10^{-6}$ ph cm ⁻² s ⁻¹	AGILE
February 2009	~ 15 days	~ $7 \cdot 10^{-6}$ ph cm ⁻² s ⁻¹	<i>Fermi</i>
September 2010	~ 4 days	~ $7 \cdot 10^{-6}$ ph cm ⁻² s ⁻¹	AGILE, <i>Fermi</i>
April 2011	~ 10 days	~ $24 \cdot 10^{-6}$ ph cm ⁻² s ⁻¹	AGILE, <i>Fermi</i>

major flare rate: 1-2/year

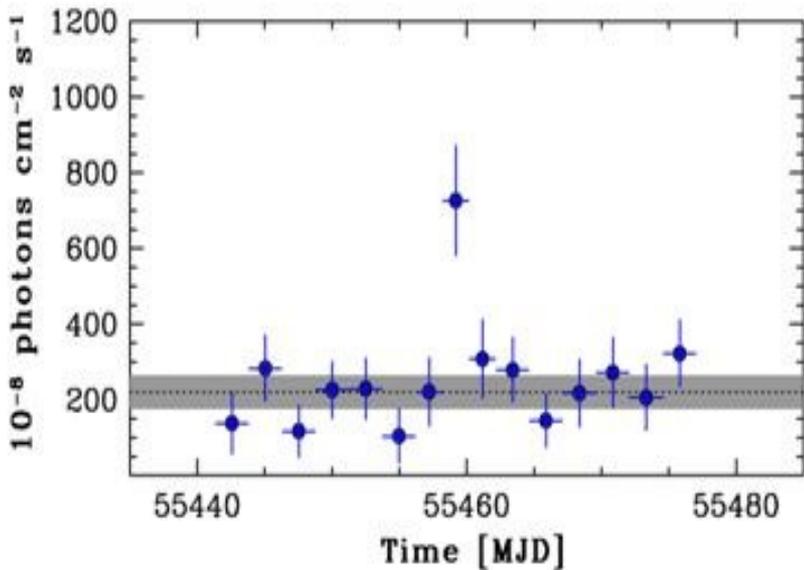
AGILE, 26 Nov. – 13 Oct. 2007



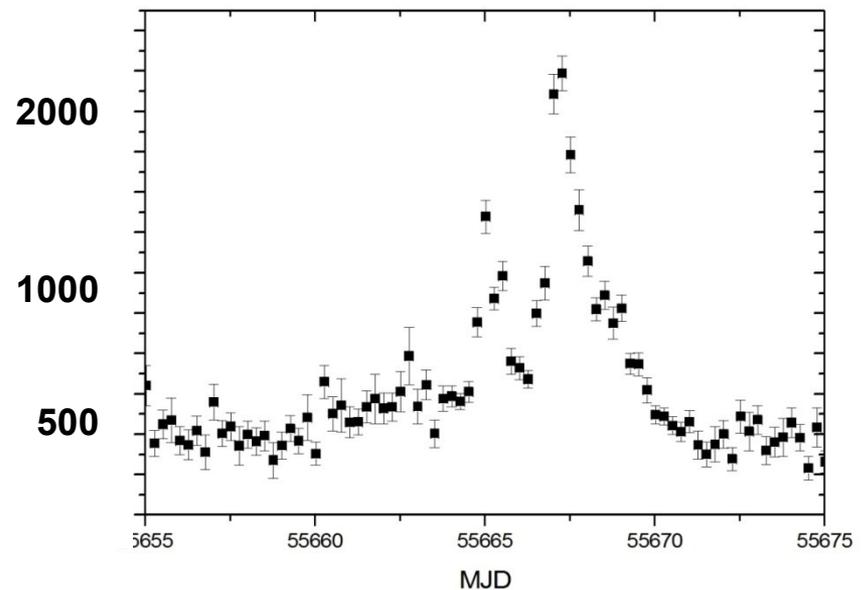
Fermi-LAT, 26 Jan. – 11 Feb. 2009



AGILE, 20-22 Sept. 2010

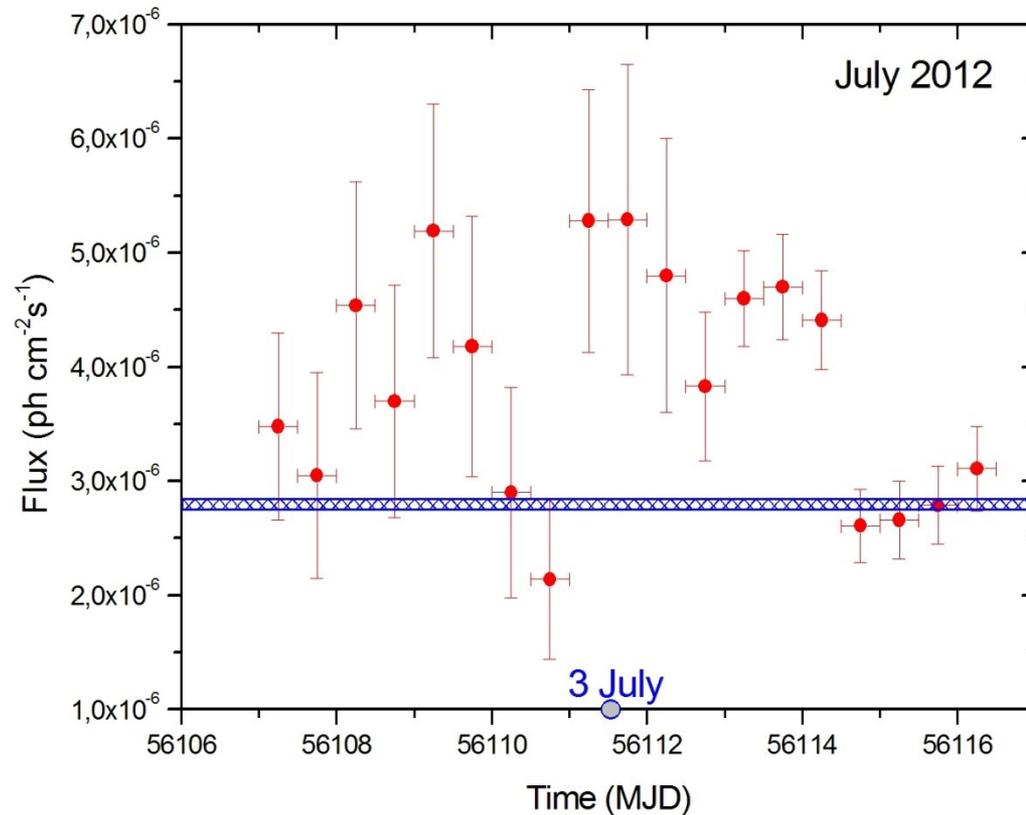


Fermi-AGILE, 12 – 20 Apr. 2011



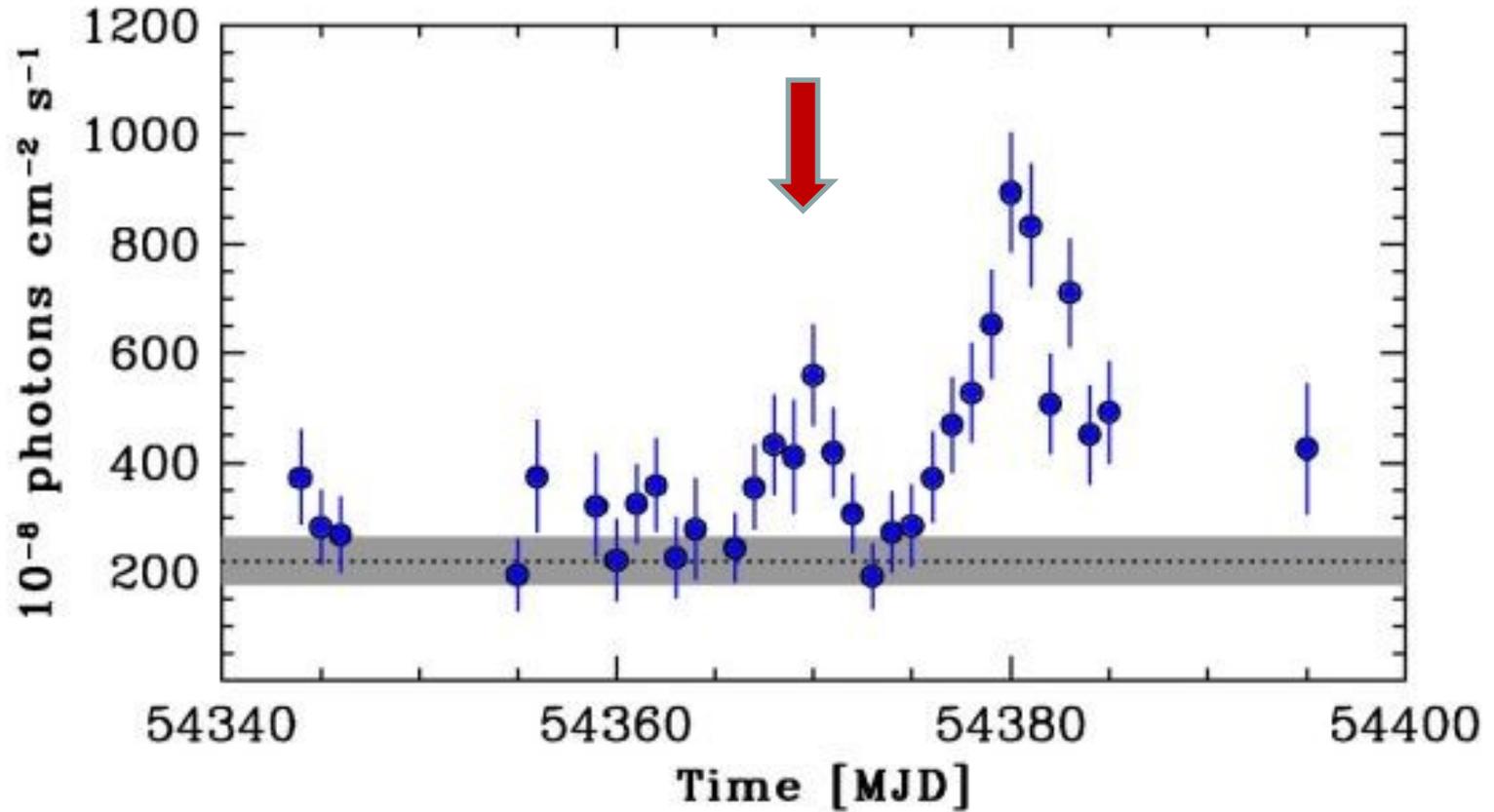
Most recent enhanced gamma-ray emission from the Crab, ATel n. 4239 (Ojha R., et al., July 5, 2012).

Fermi-LAT public data



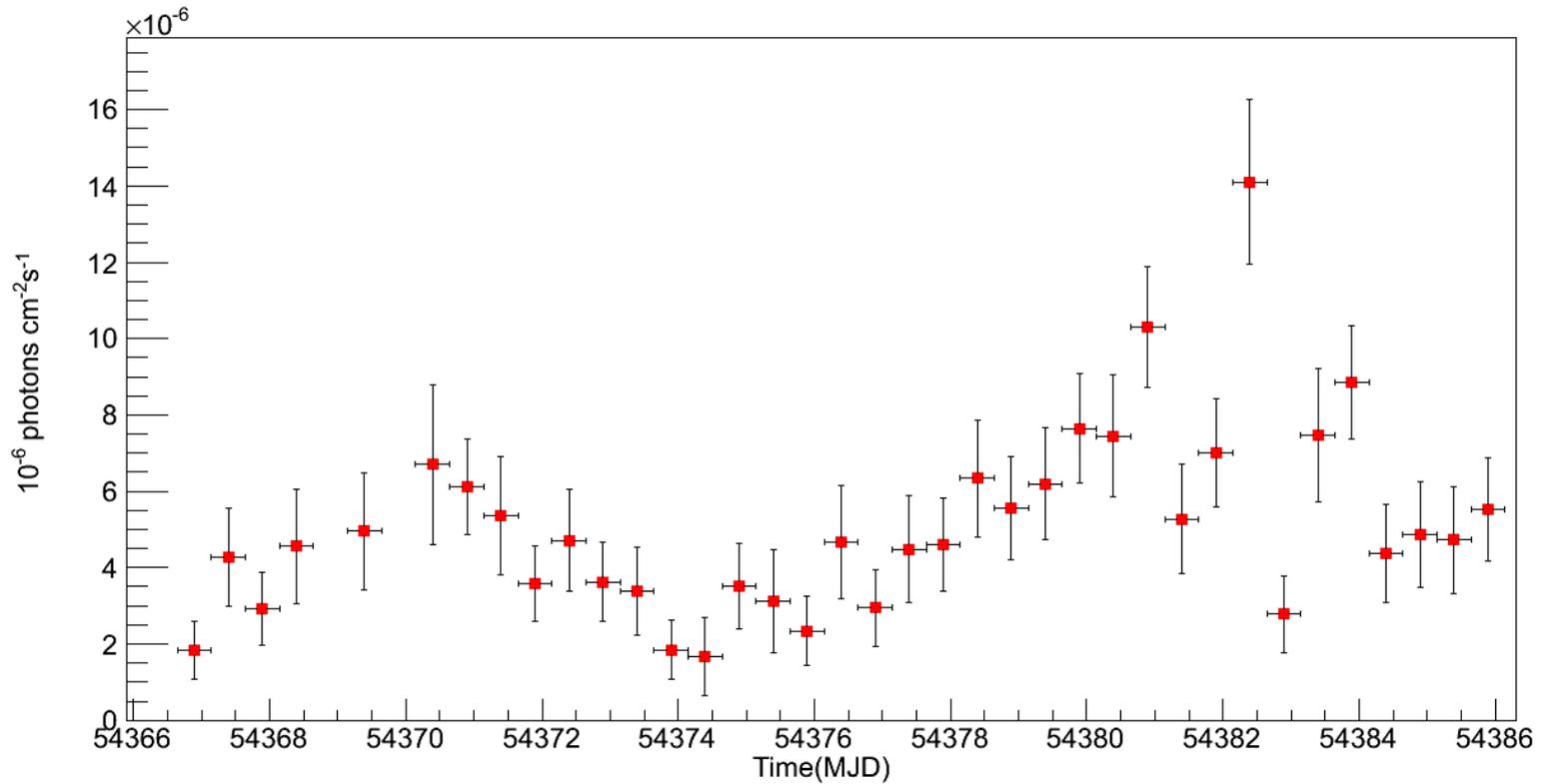
2007 flare, 1-day bin (Agile)

28 Sept. 2007

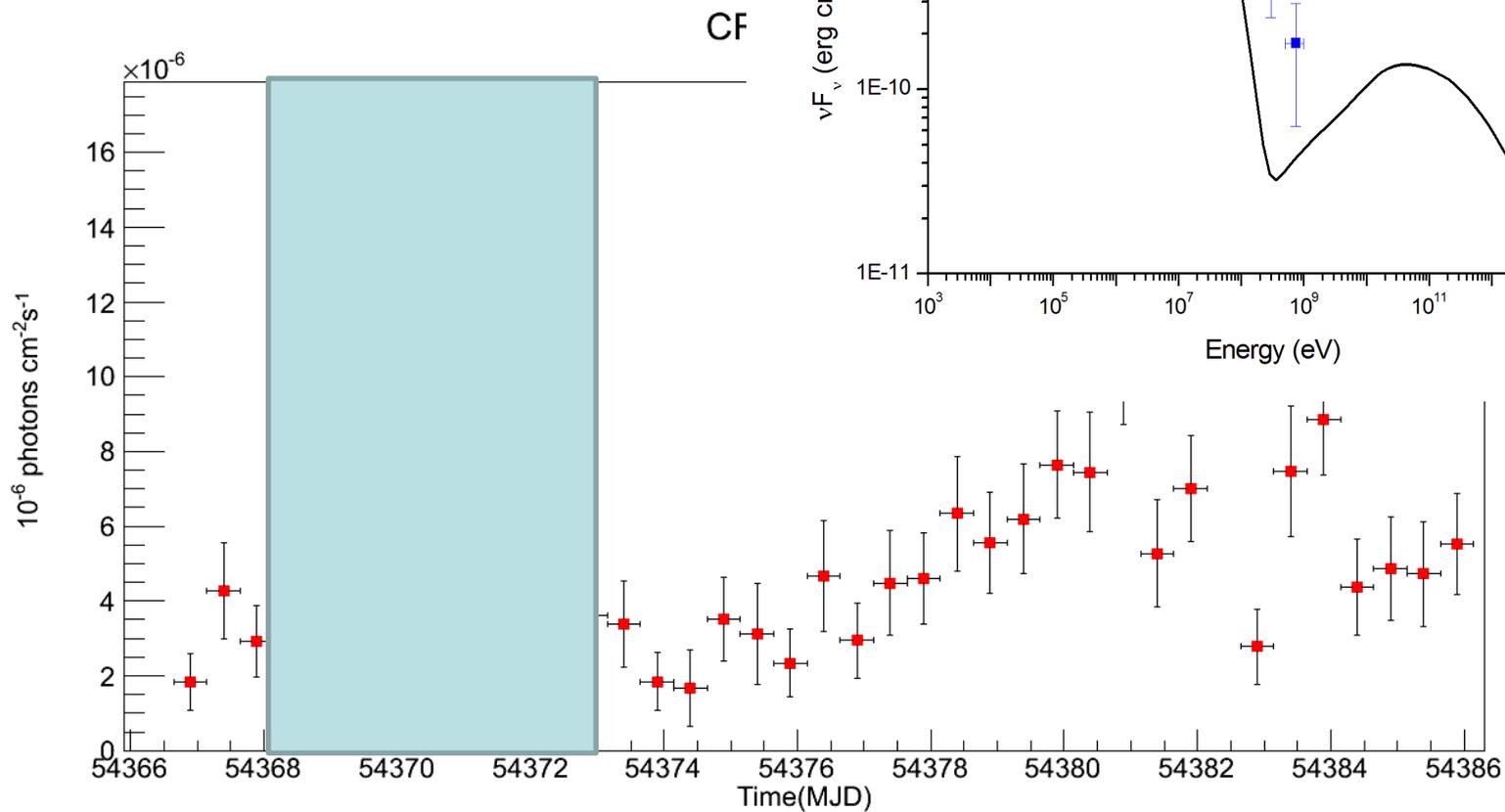


2007 flare, 12-hr bin (Agile)

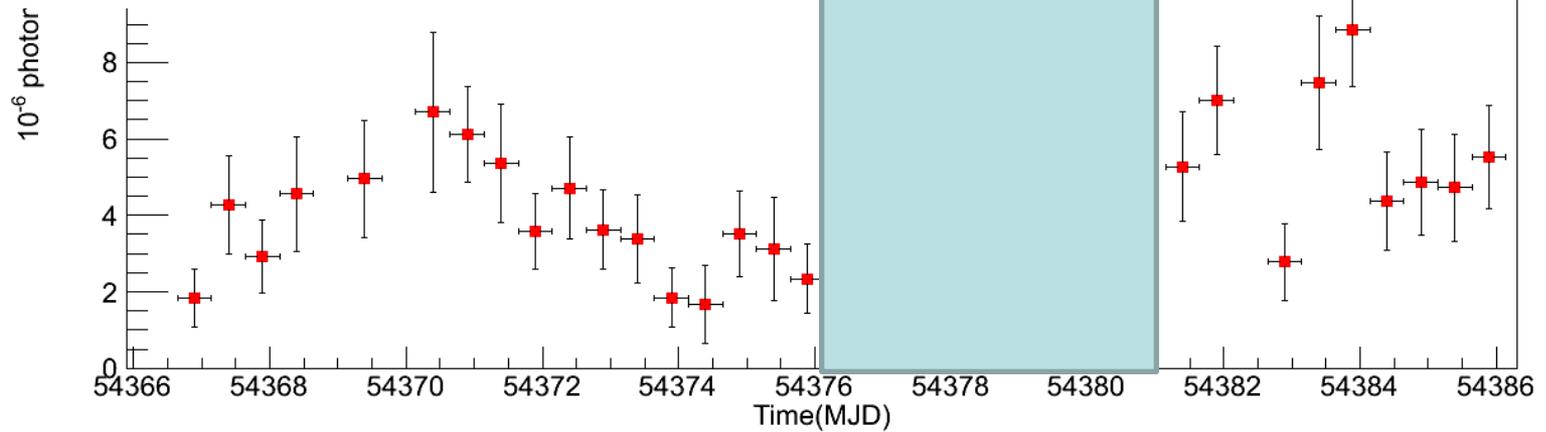
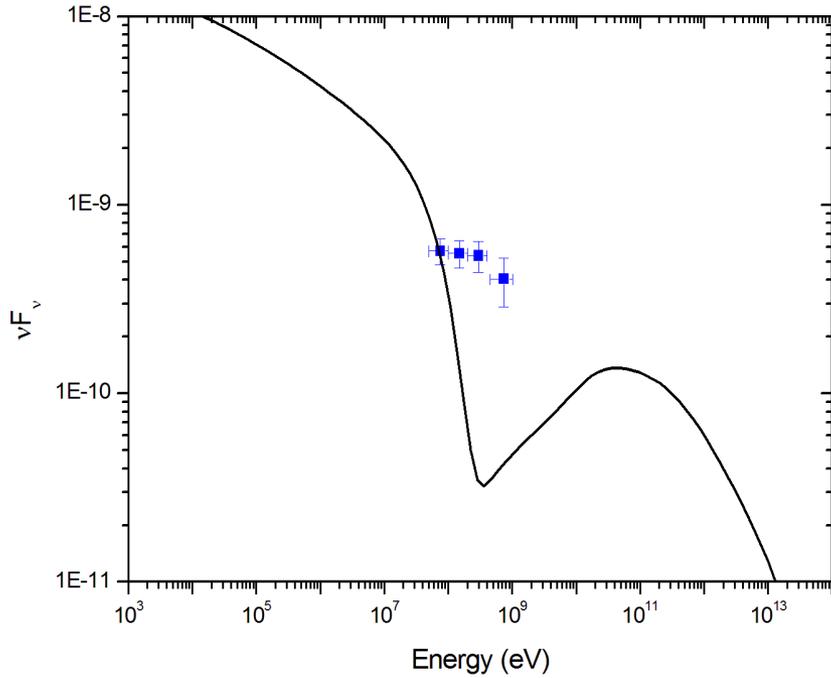
CRAB 2007



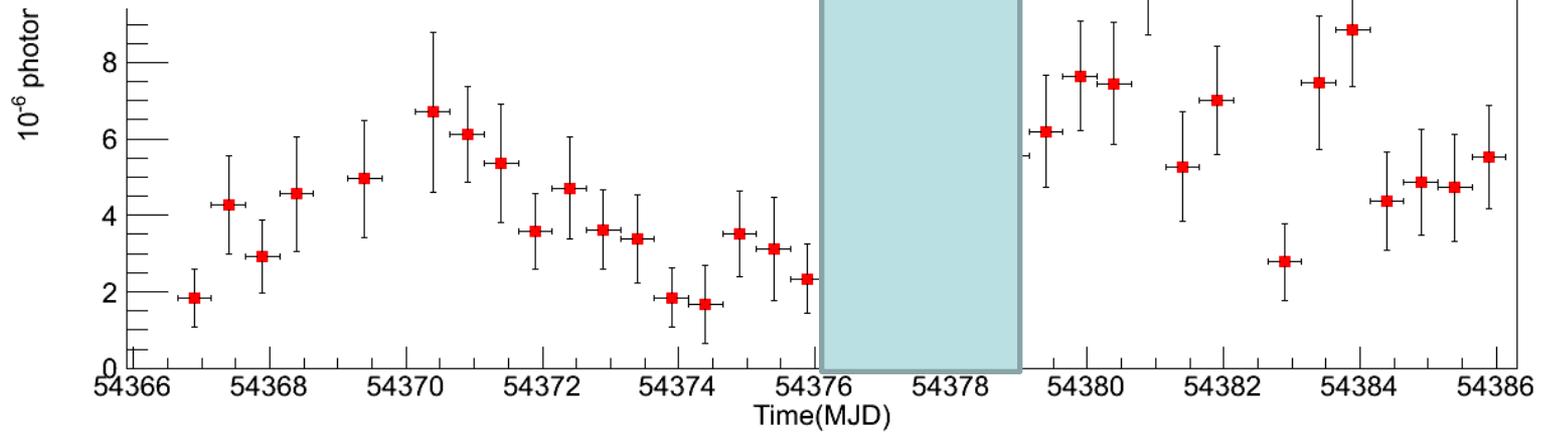
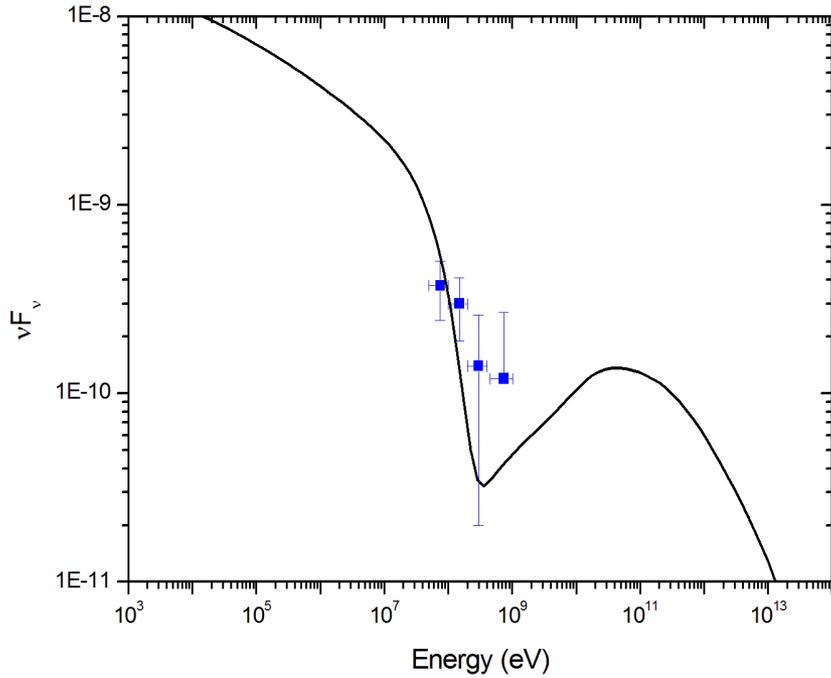
2007 flare, 12-hr bin (Agile)



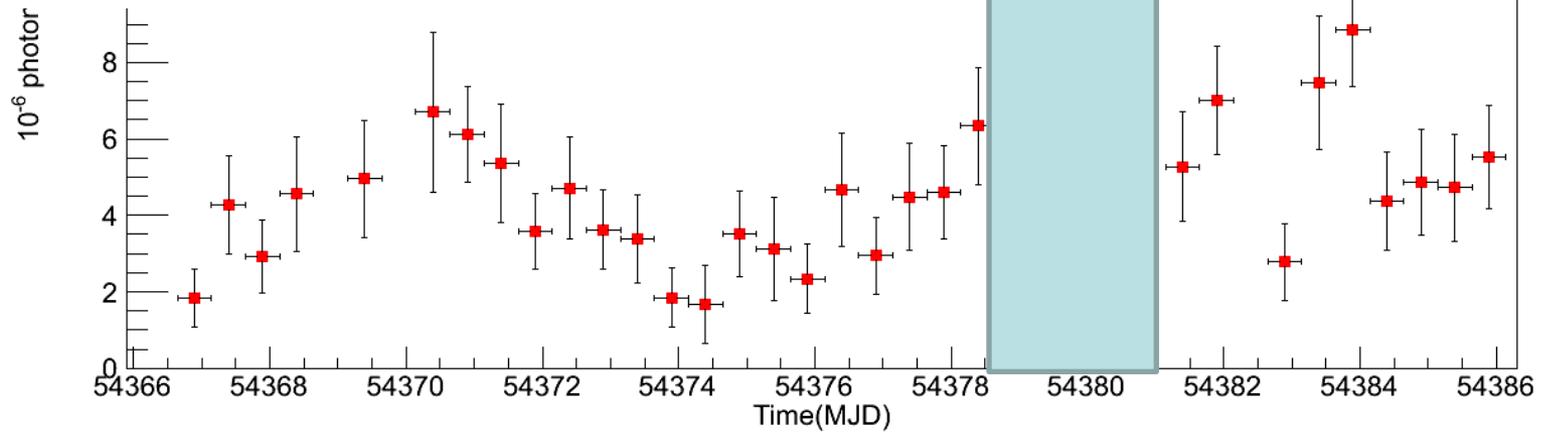
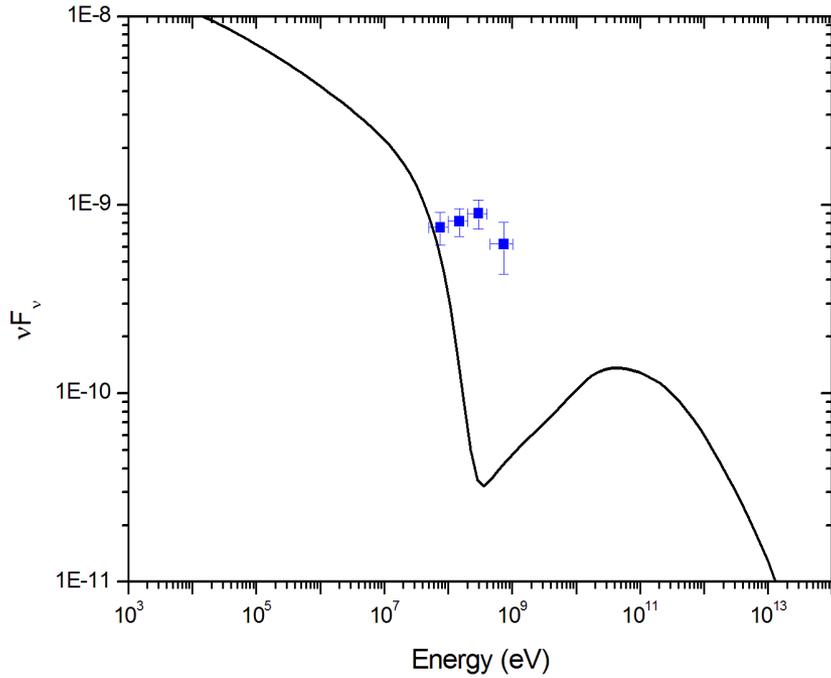
2007 flare, 12-hr bin (Agile)

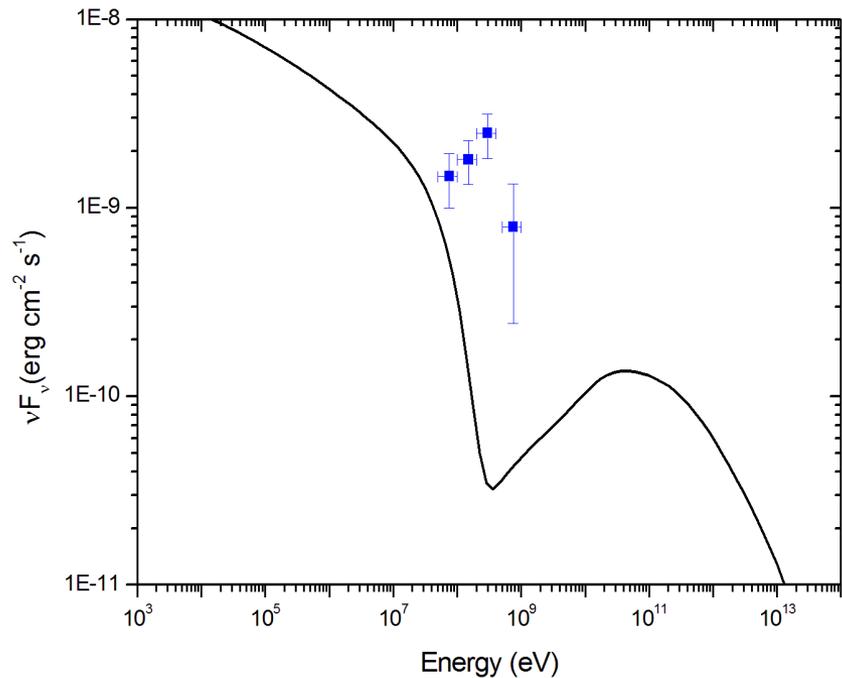


2007 flare, 12-hr bin (Agile)

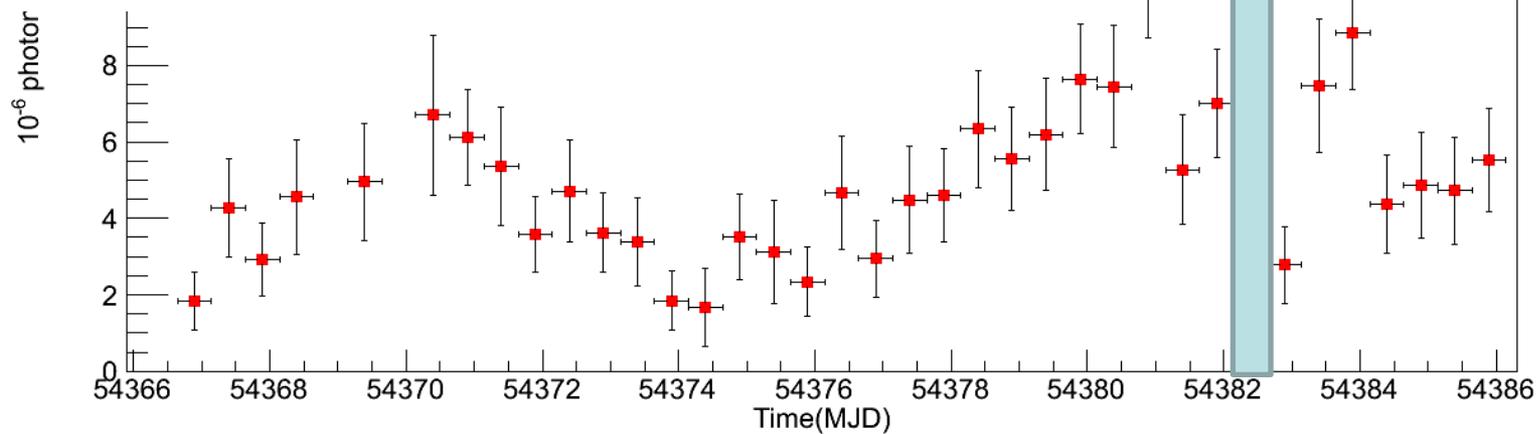


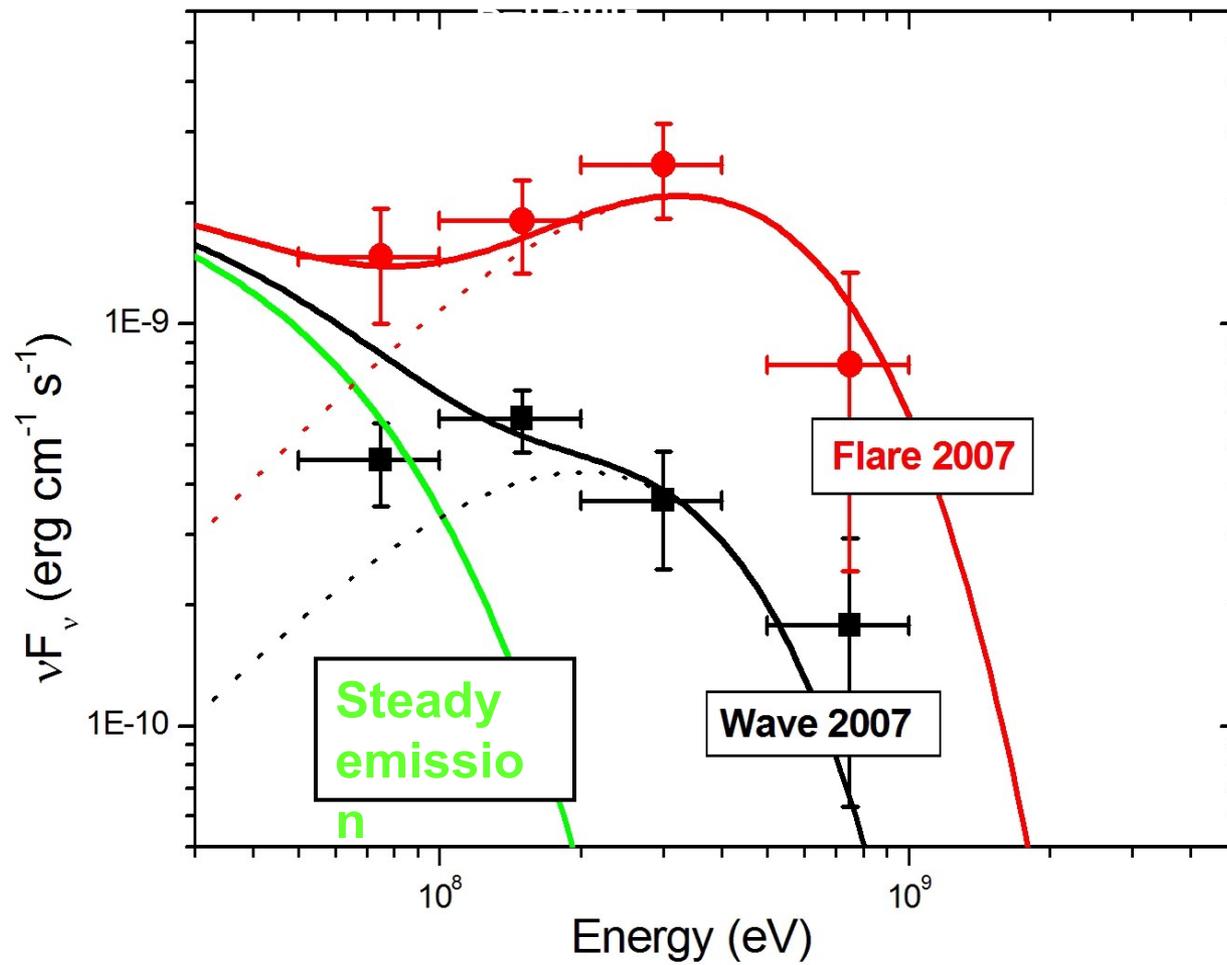
2007 flare, 12-hr bin (Agile)



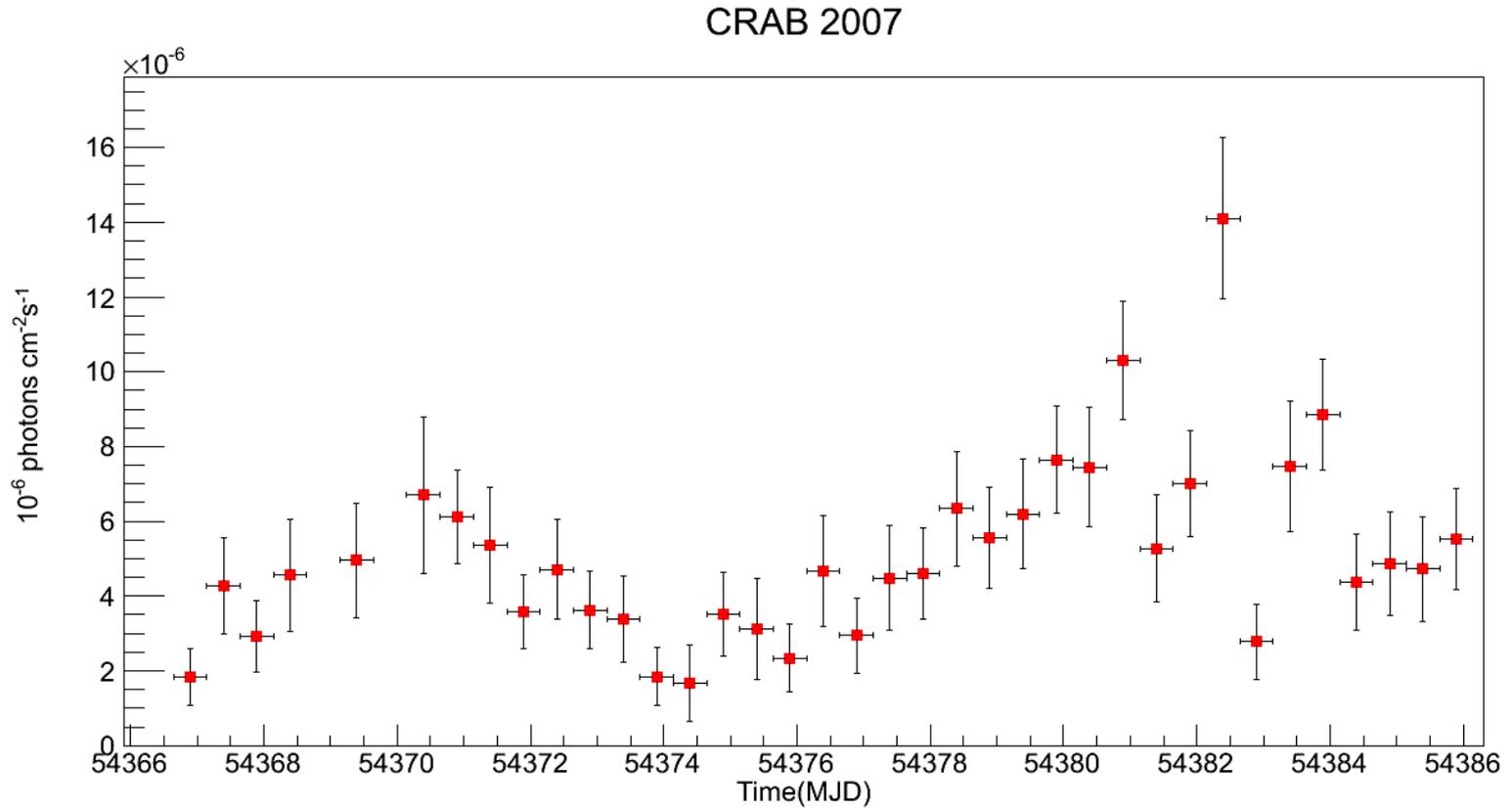


2007 flare, 12-hr bin (Agile)

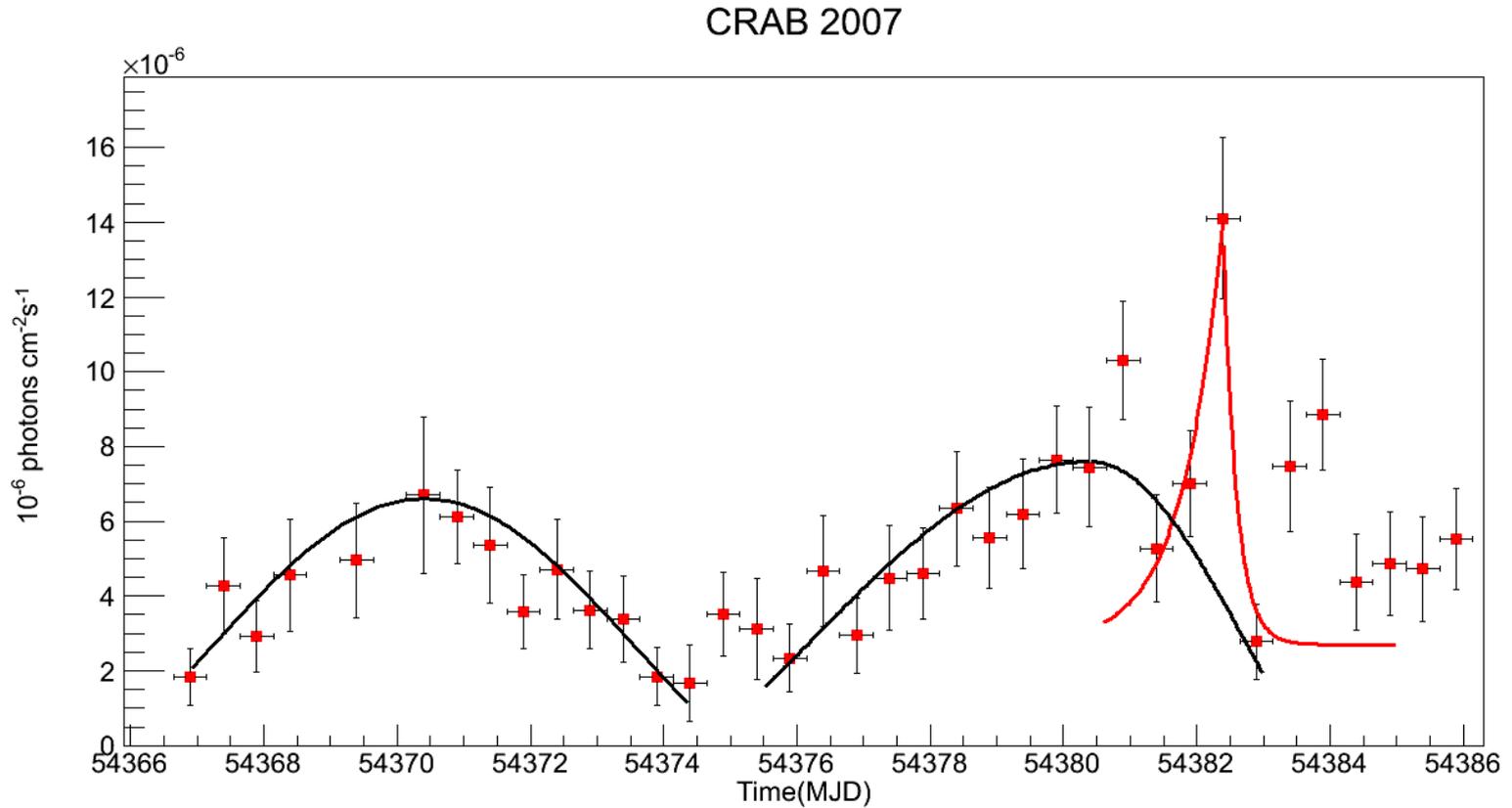




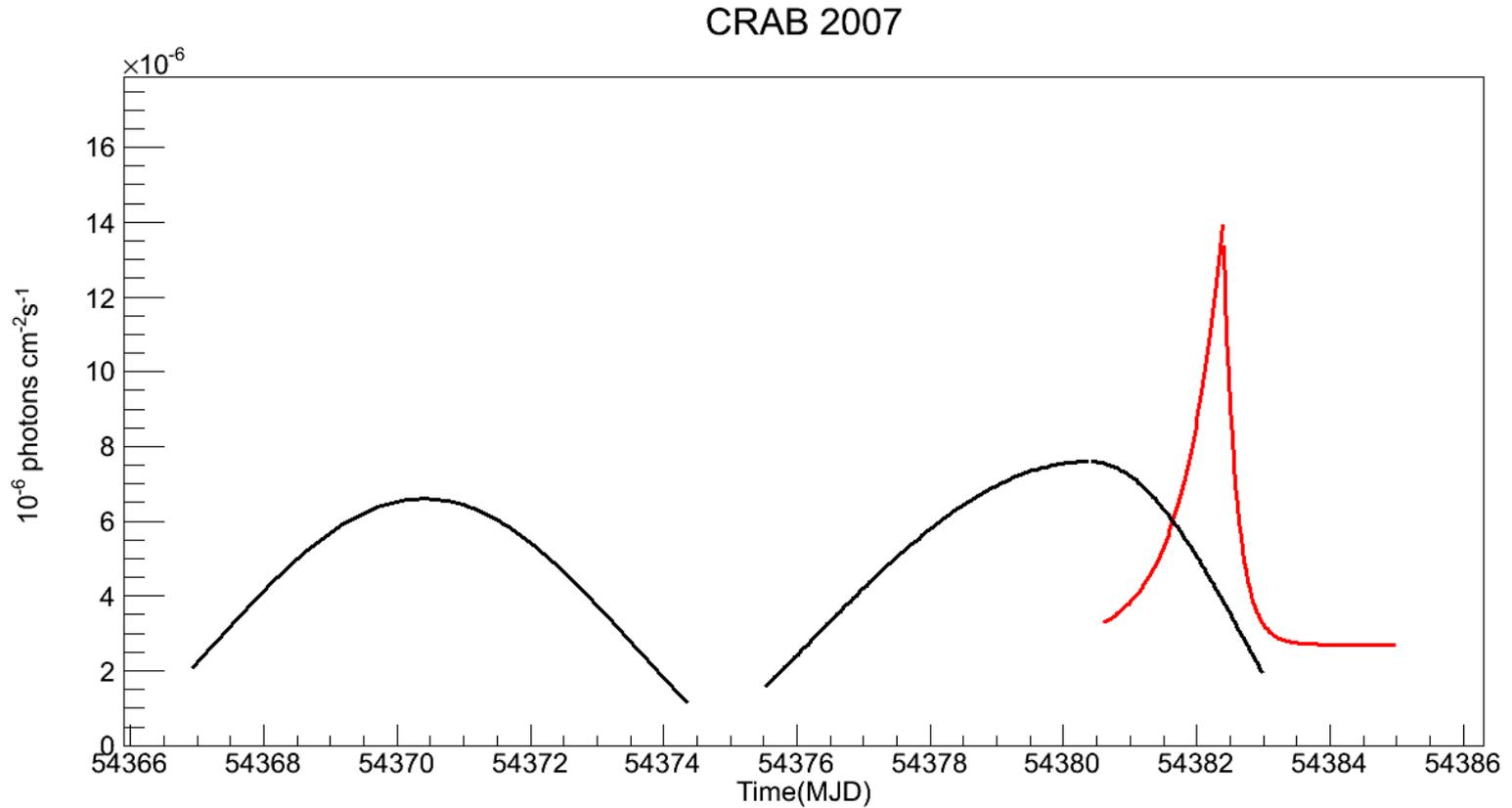
Flare 2007 – AGILE data



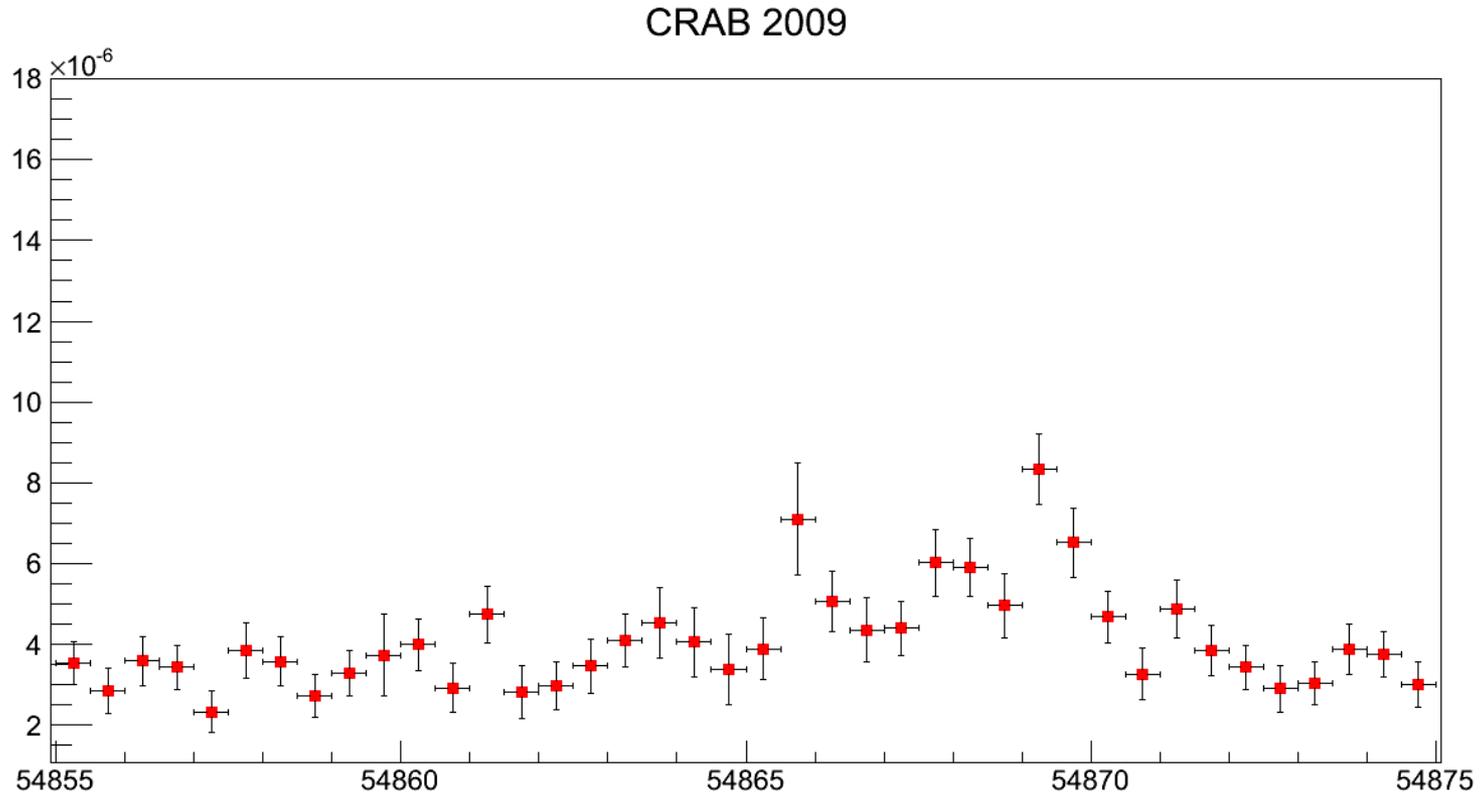
Flare 2007 – AGILE data



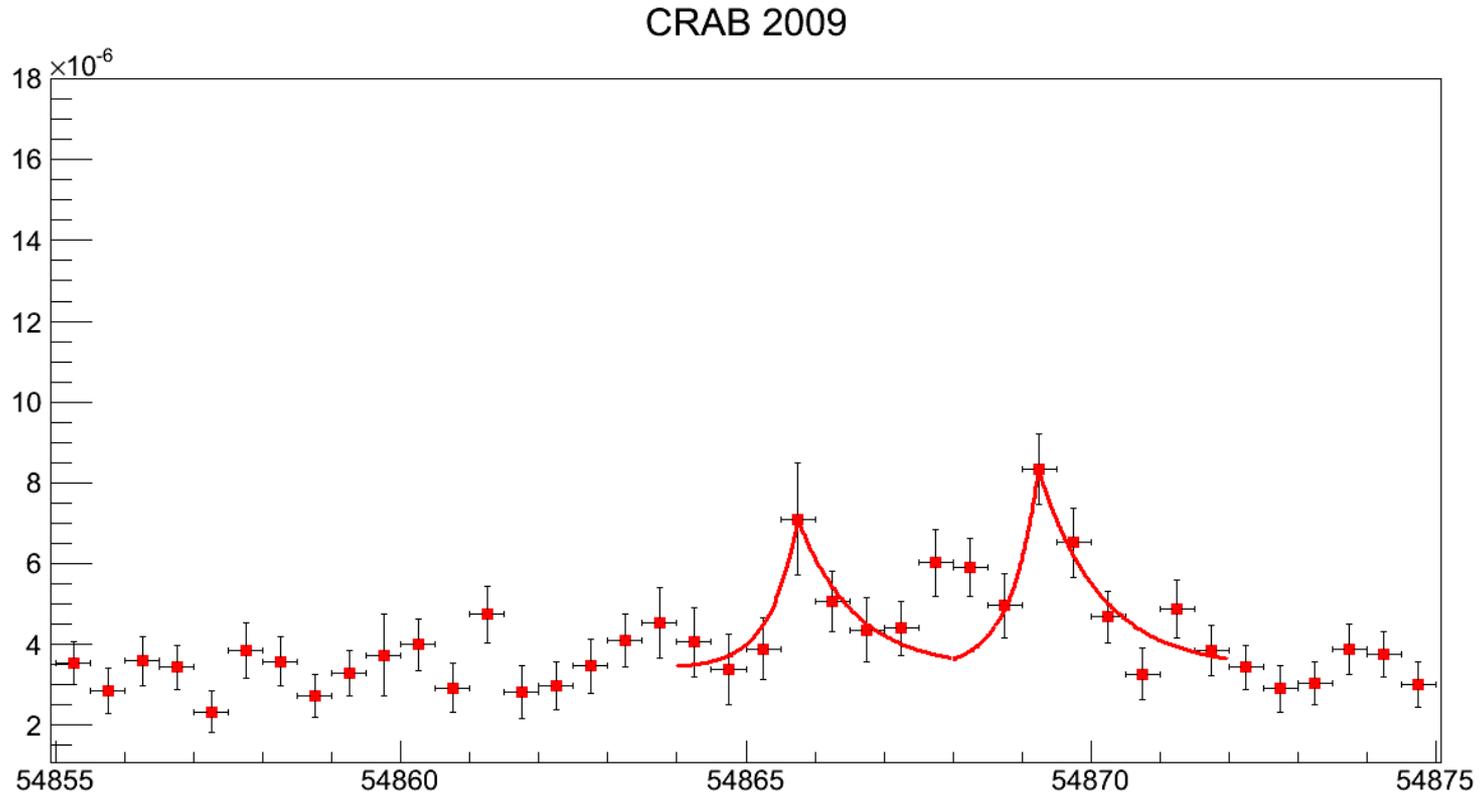
Flare 2007 – AGILE data



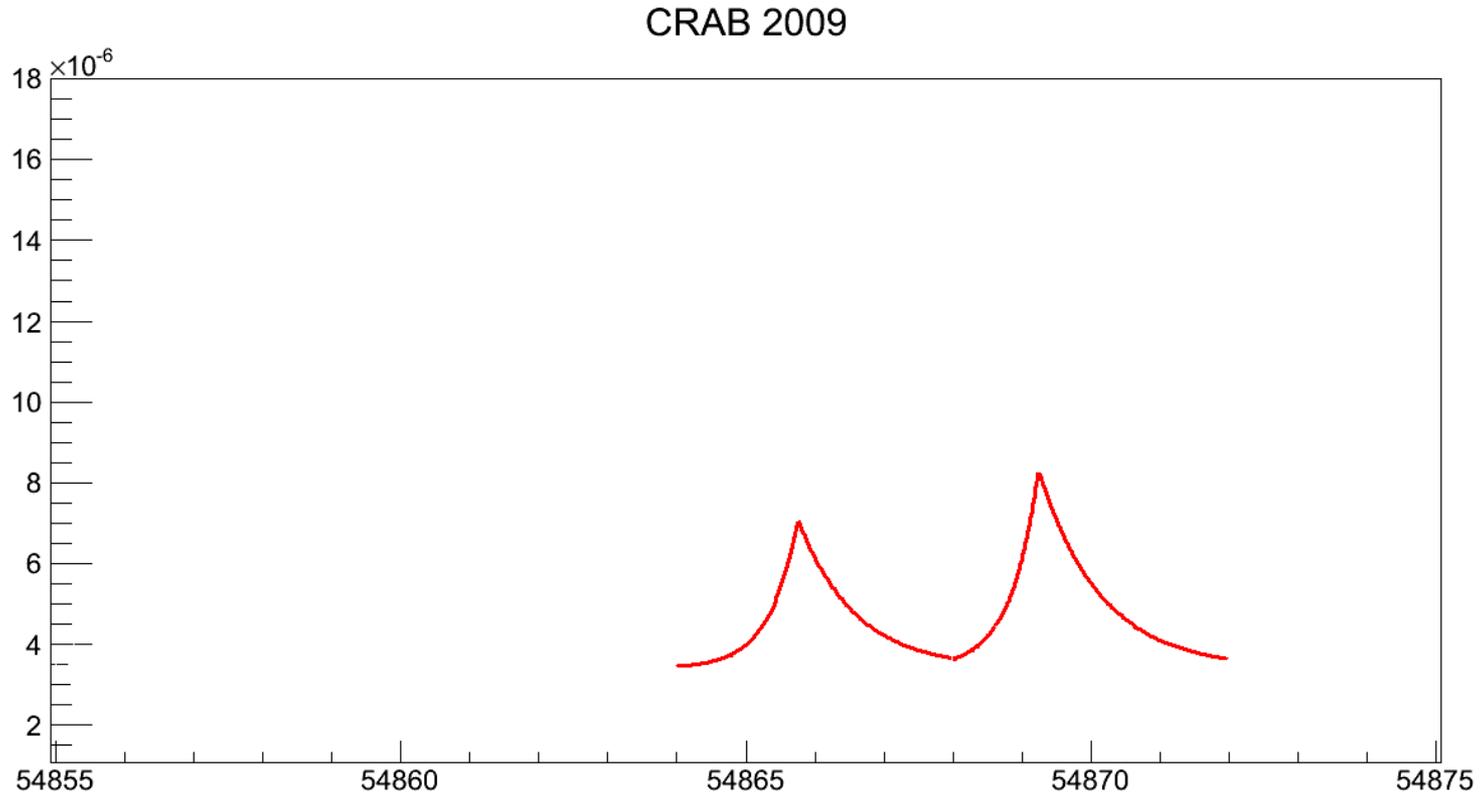
Flare 2009 – FERMI data



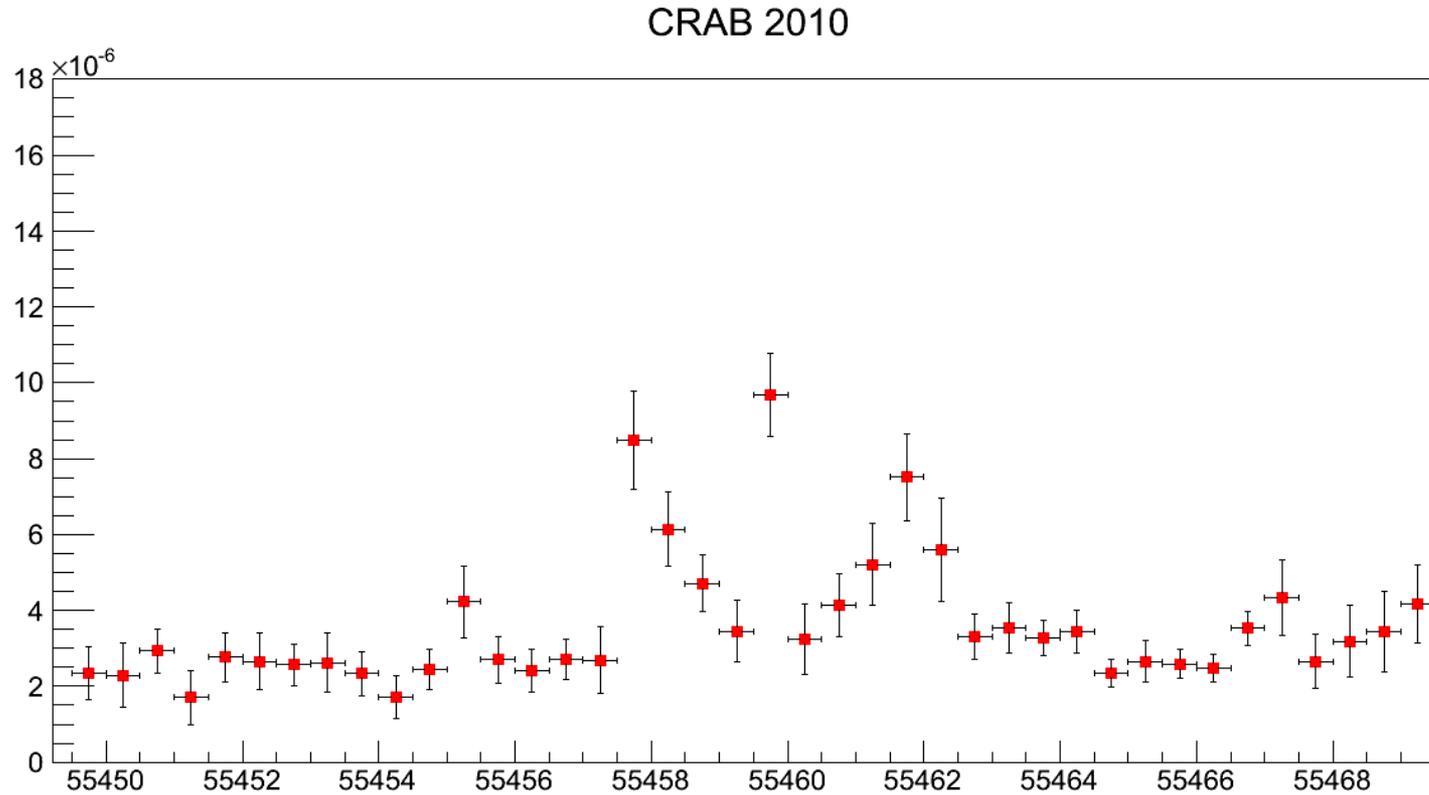
Flare 2009 – FERMI data



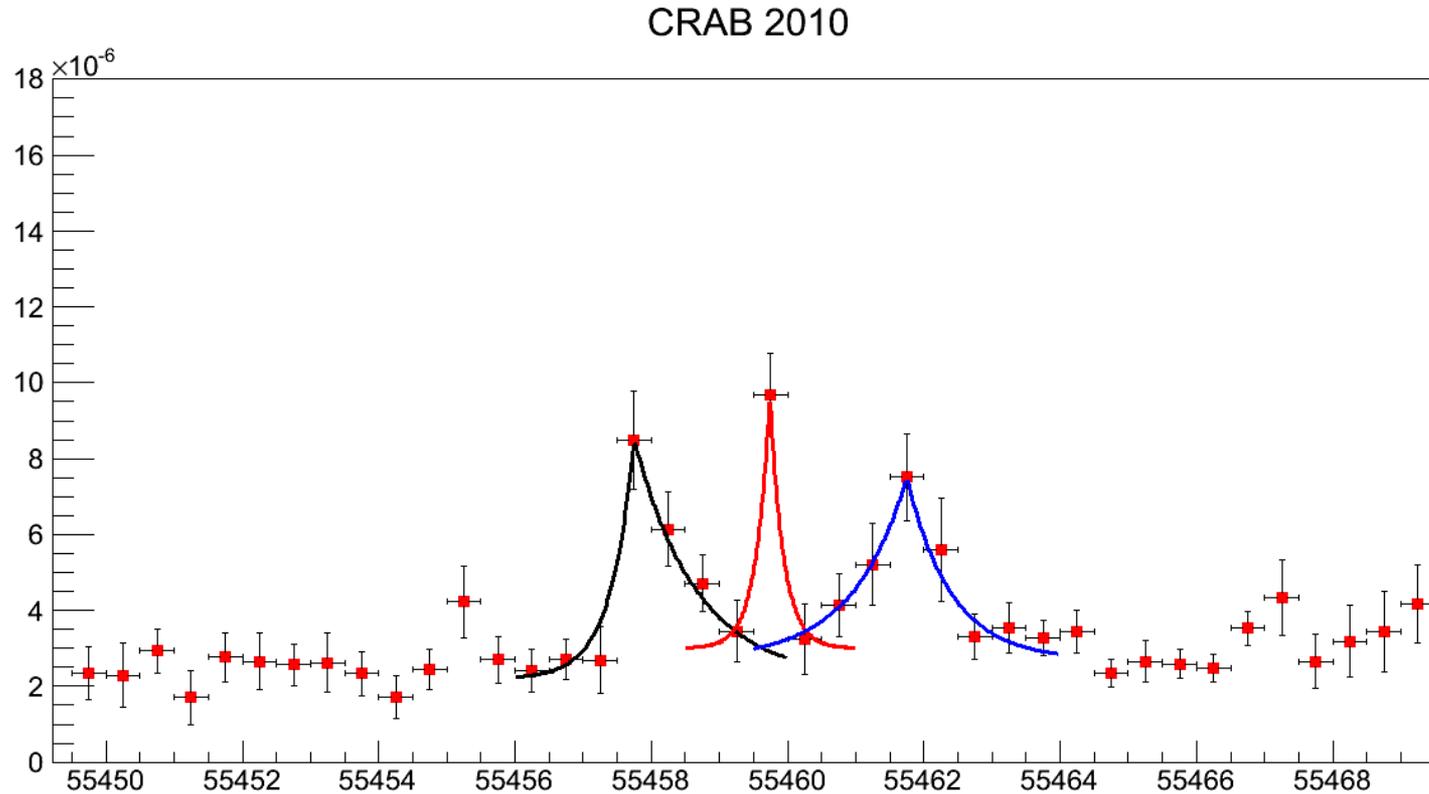
Flare 2009 – FERMI data



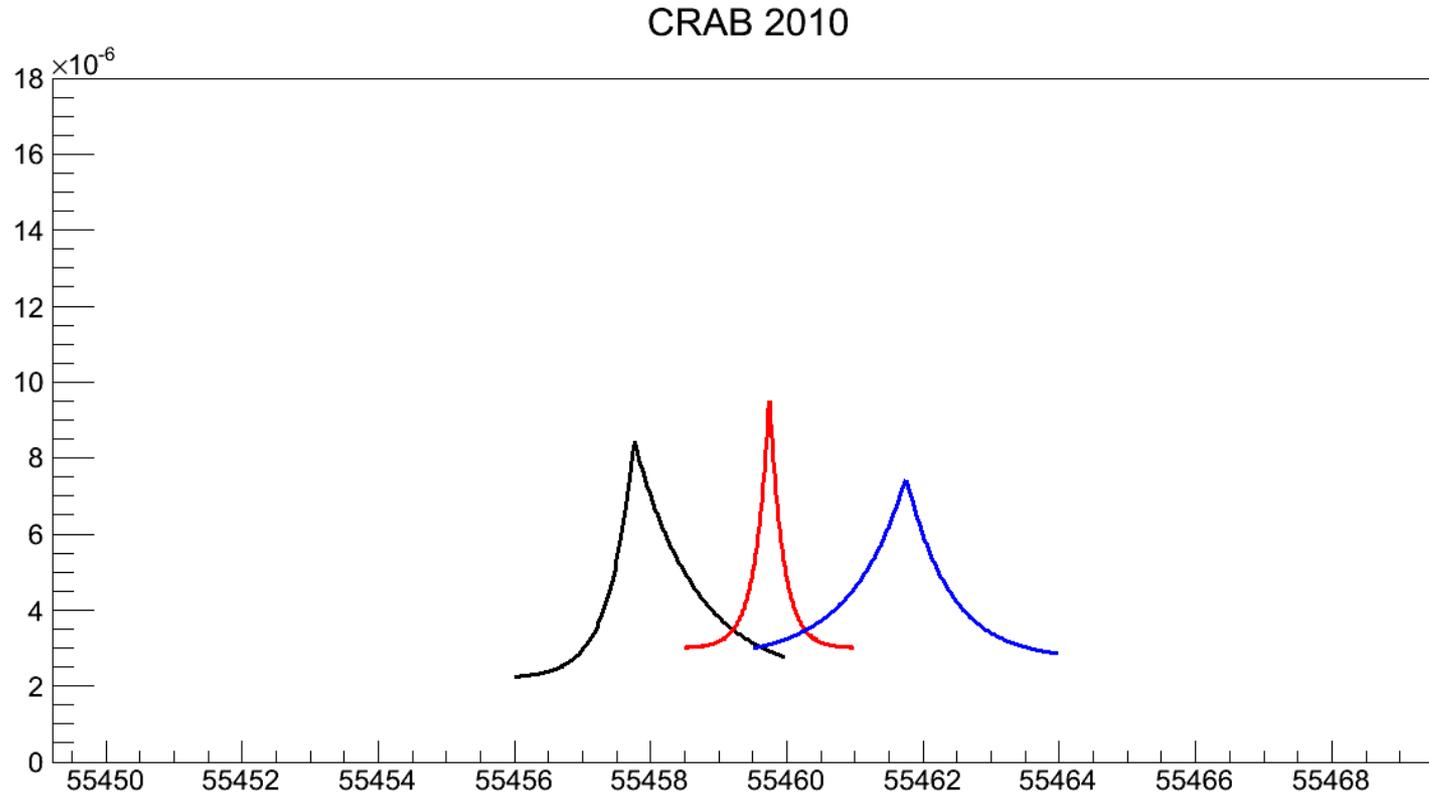
Flare 2010 – FERMI data



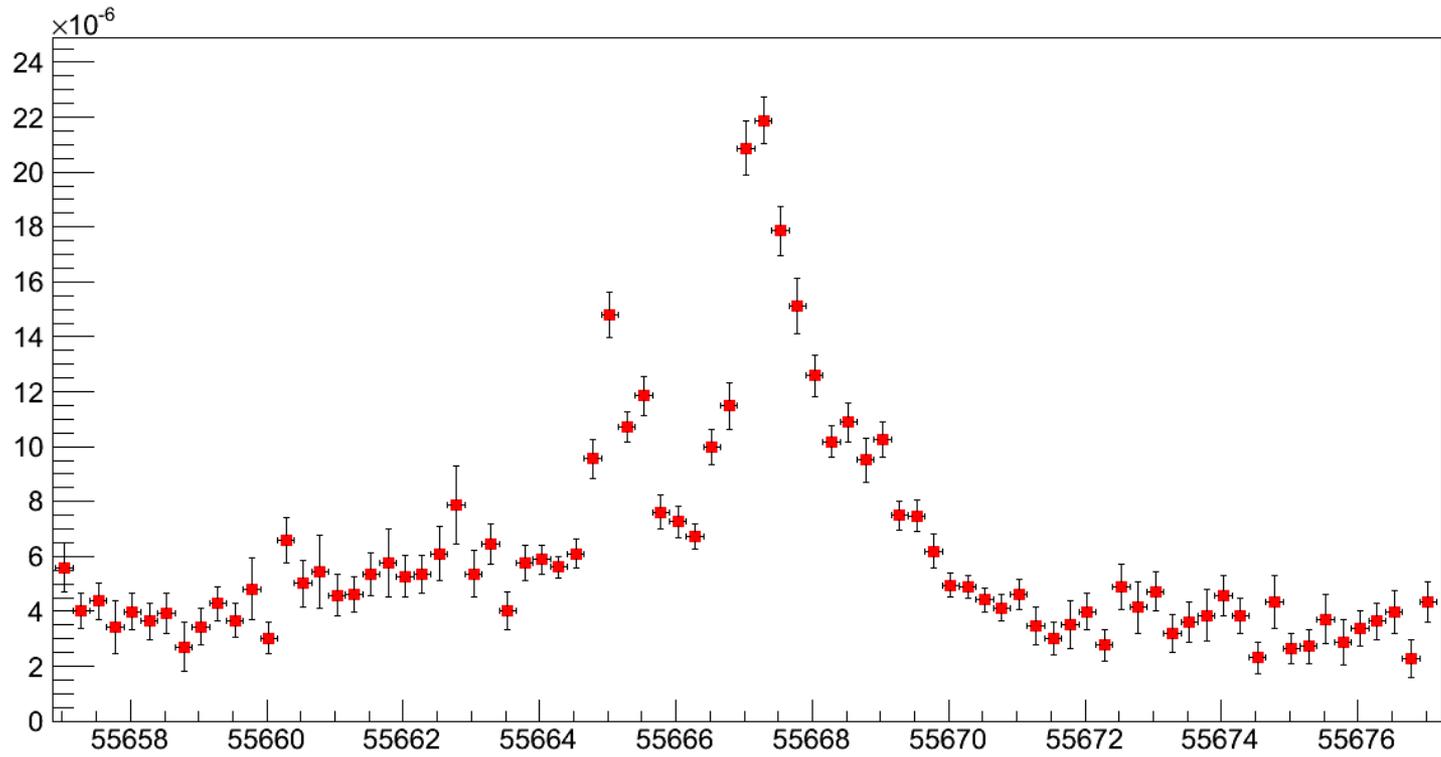
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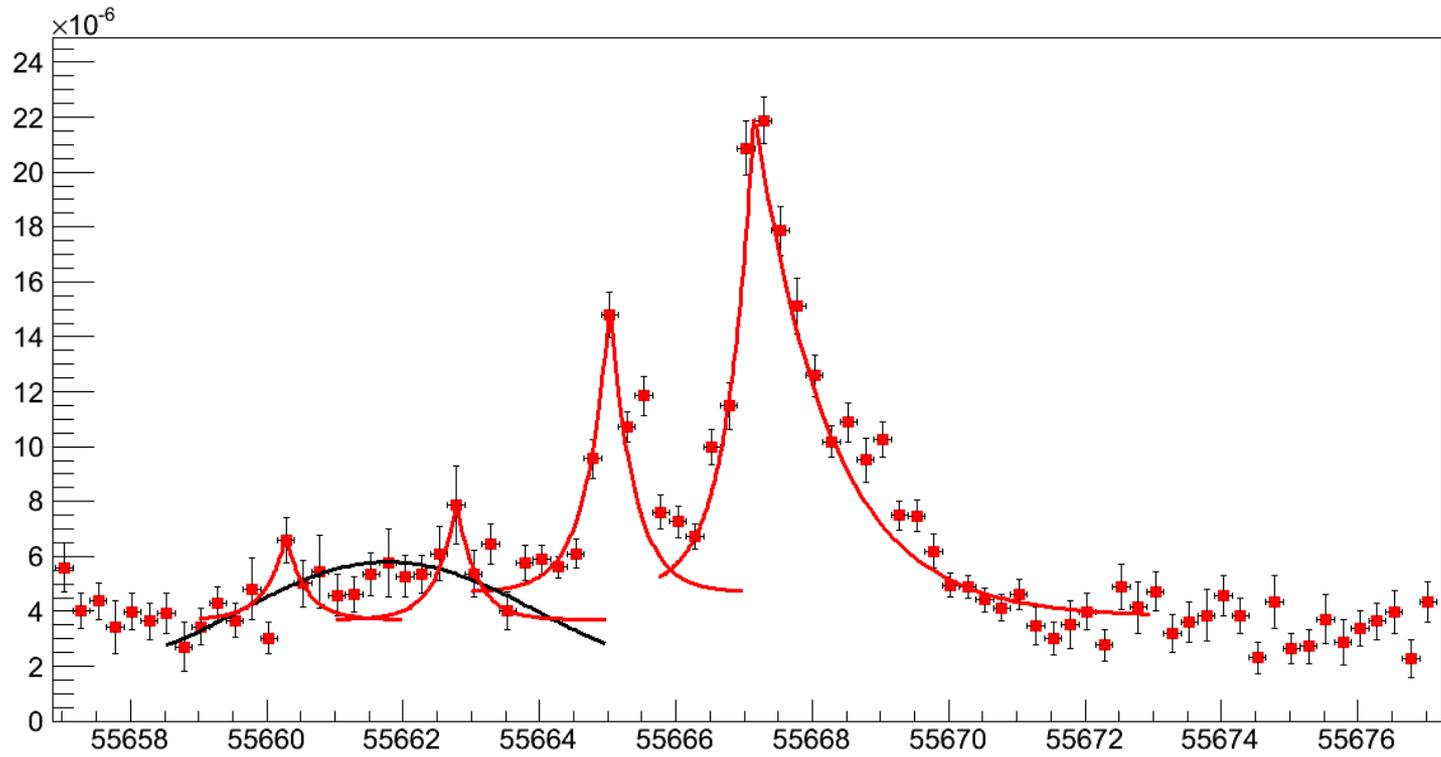
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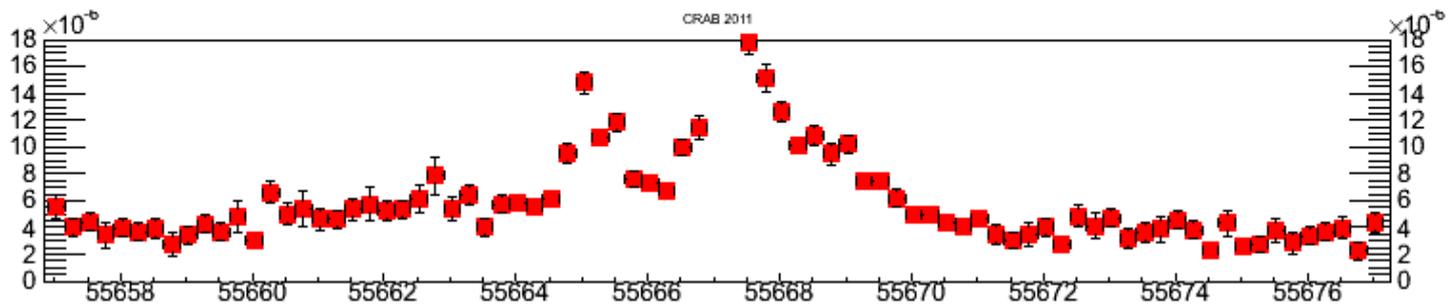
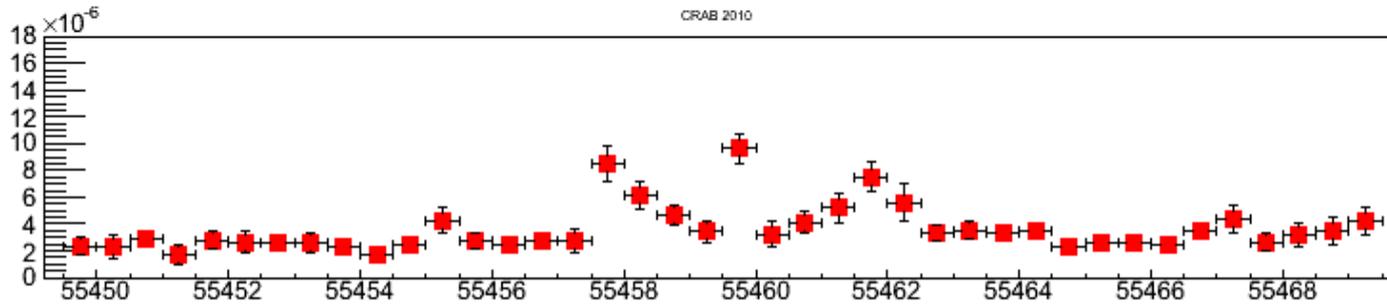
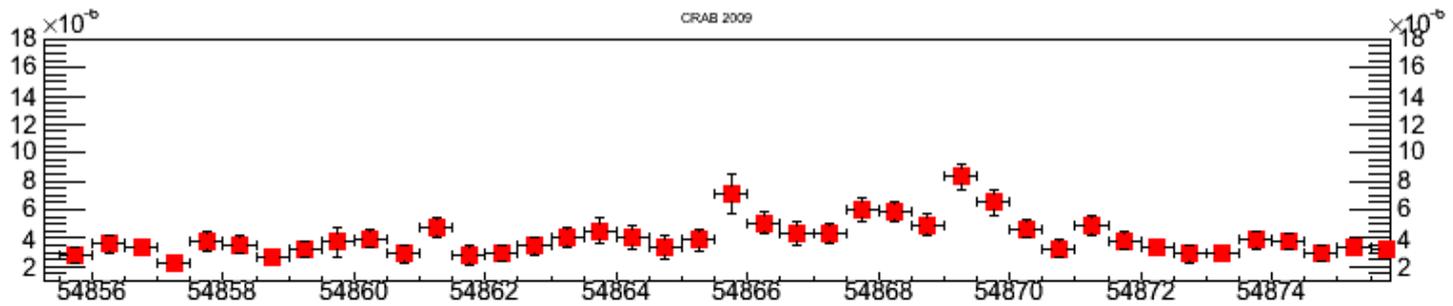
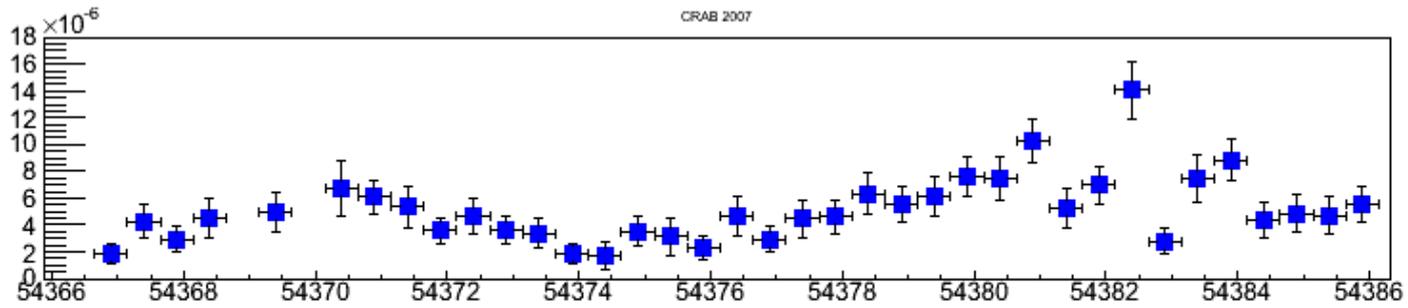


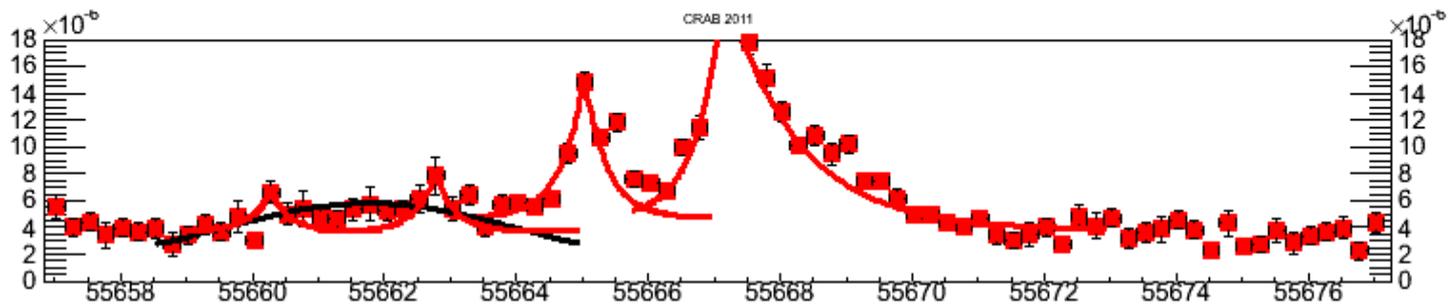
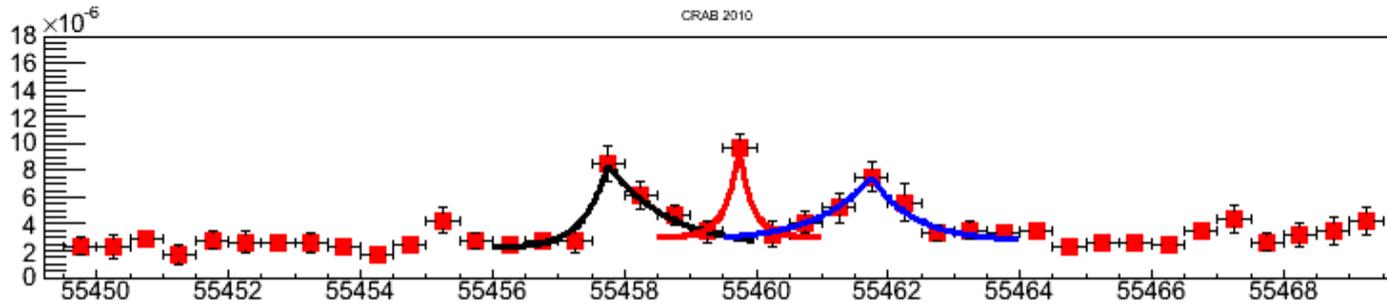
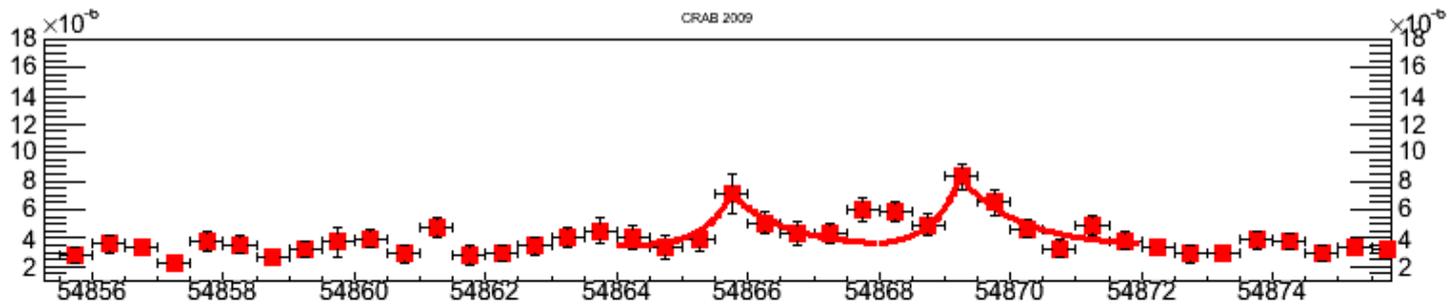
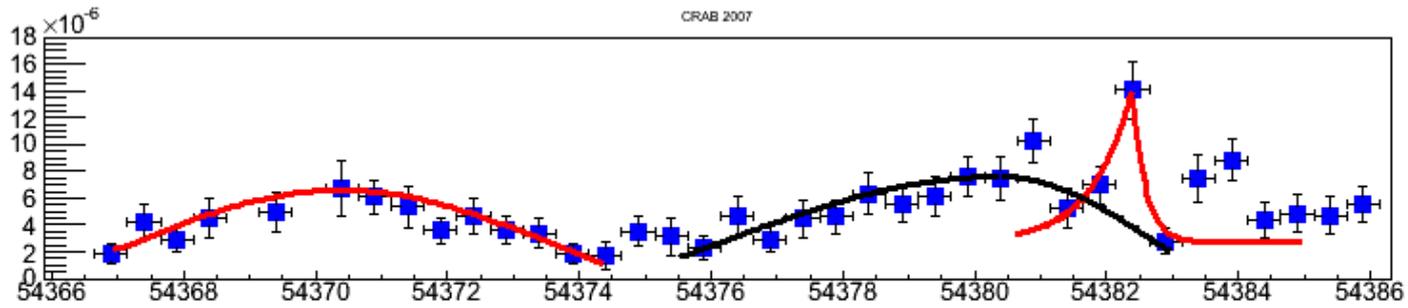
CRAB 2011

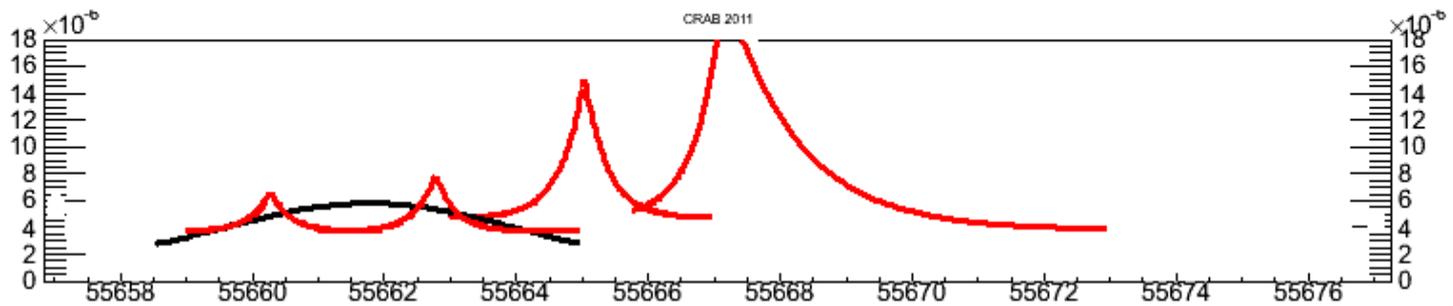
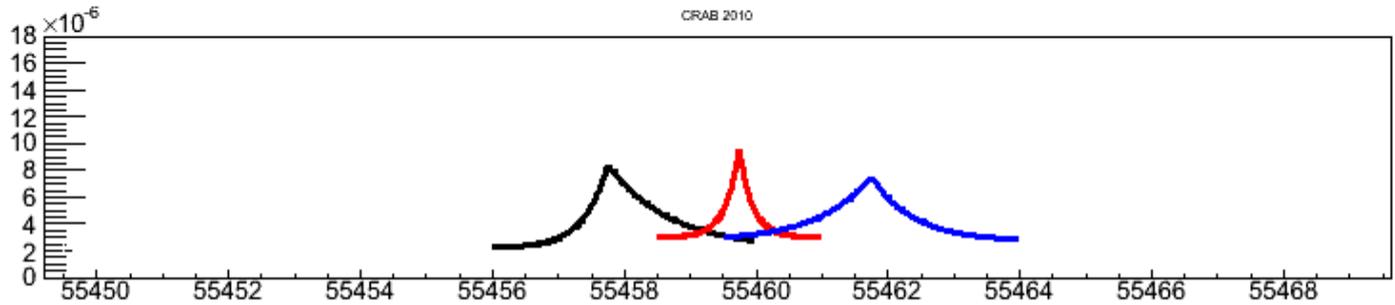
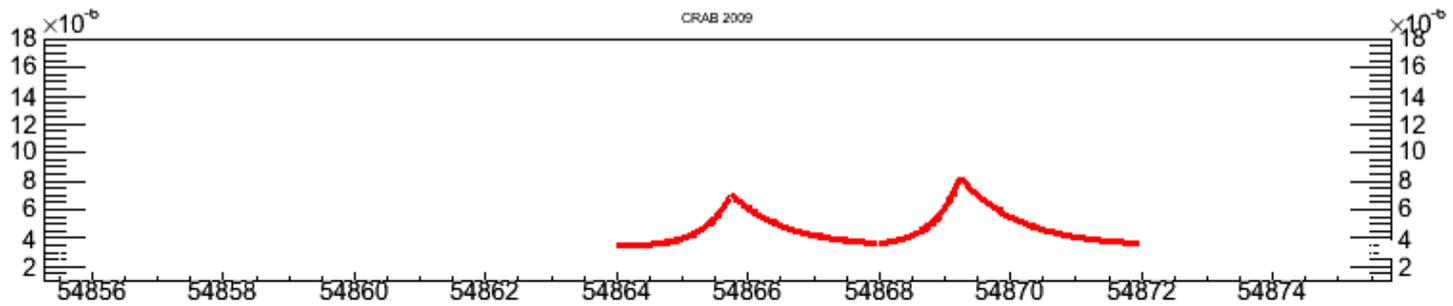
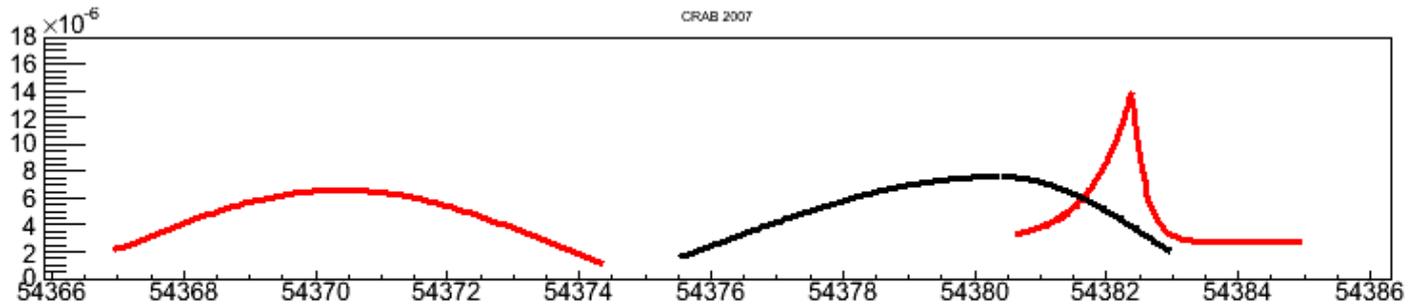


CRAB 2011









Crab Apr. 2011 flare

- gamma-ray flare peak luminosity

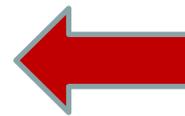
$$L \approx 2 \cdot 10^{36} \text{ erg s}^{-1}$$

- kin. power fraction of PSR spindown L_{sd} ,

$$\varepsilon \approx 0.003 (\eta_{-1}/0.1) \approx 0.03$$

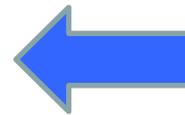
- timescales:

– risetime \leq a few hrs



**very efficient
acceleration !**

– decay: \sim 1-2-3 days



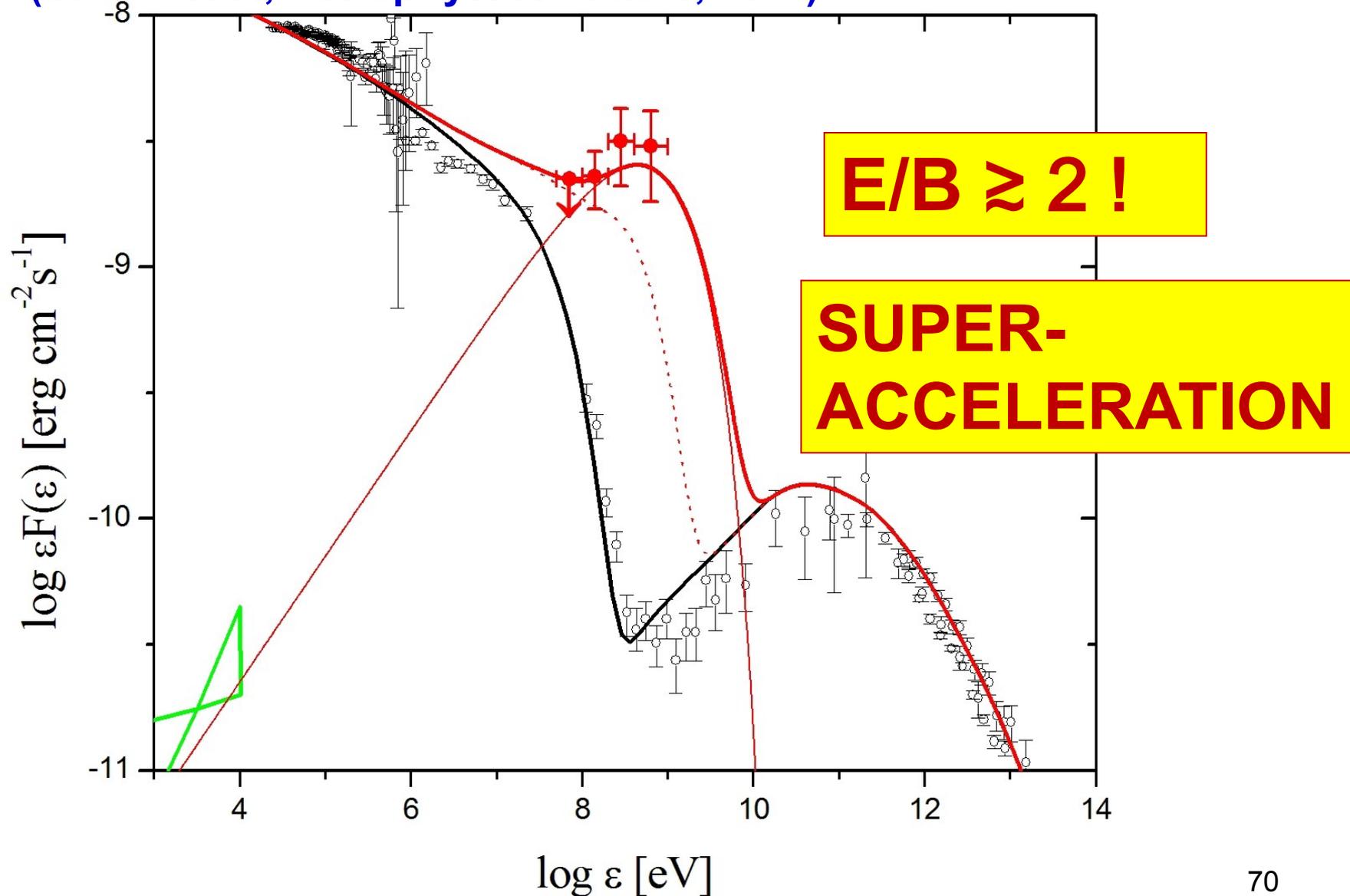
**fast cooling,
B, Lorentz γ**

a PL model (Striani, M.T., Vittorini et al., ApJ, 2011)

- $dN(\gamma)/d\gamma = \gamma^{-p_1}$ for $\gamma_{\min} < \gamma < \gamma_{\text{break}}$
with $p_1 = 2.1$, $\gamma_{\min} = 5 \cdot 10^5$, $\gamma_{\text{break}} = 5 \cdot 10^9$
- $dN(\gamma)/d\gamma = \gamma^{-p_2}$ for $\gamma_{\text{break}} < \gamma < \gamma_{\max}$,
with $p_2 = 2.7$,
- total particle number $N_{e-/e+} = 10^{42}$.
- size, Larmor radius $R \leq 10^{16}$ cm
- local $B \approx 10^{-3}$ G (~ 10 times larger than average)
- $\gamma_{\max} \approx \gamma_b \leq 7 \cdot 10^9 (E/3B)(\delta \alpha'/\sin\theta)^{1/2} (B/10^{-3} \text{ G})^{-1/2}$
- $\delta = 2-3$

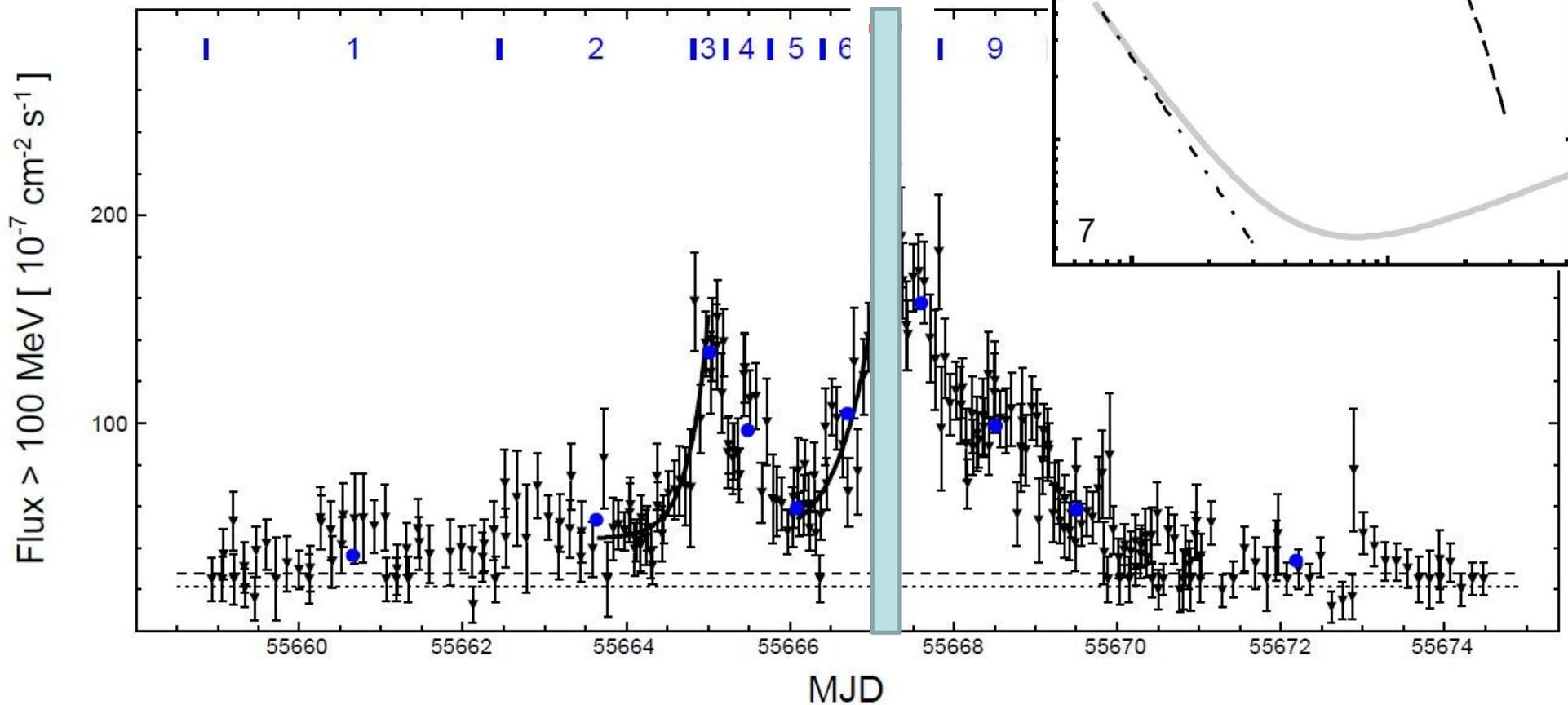
Crab Nebula super-flare spectrum (Apr. 16, 2011)

(Striani et al, Astrophys. J. Letters, 2011)

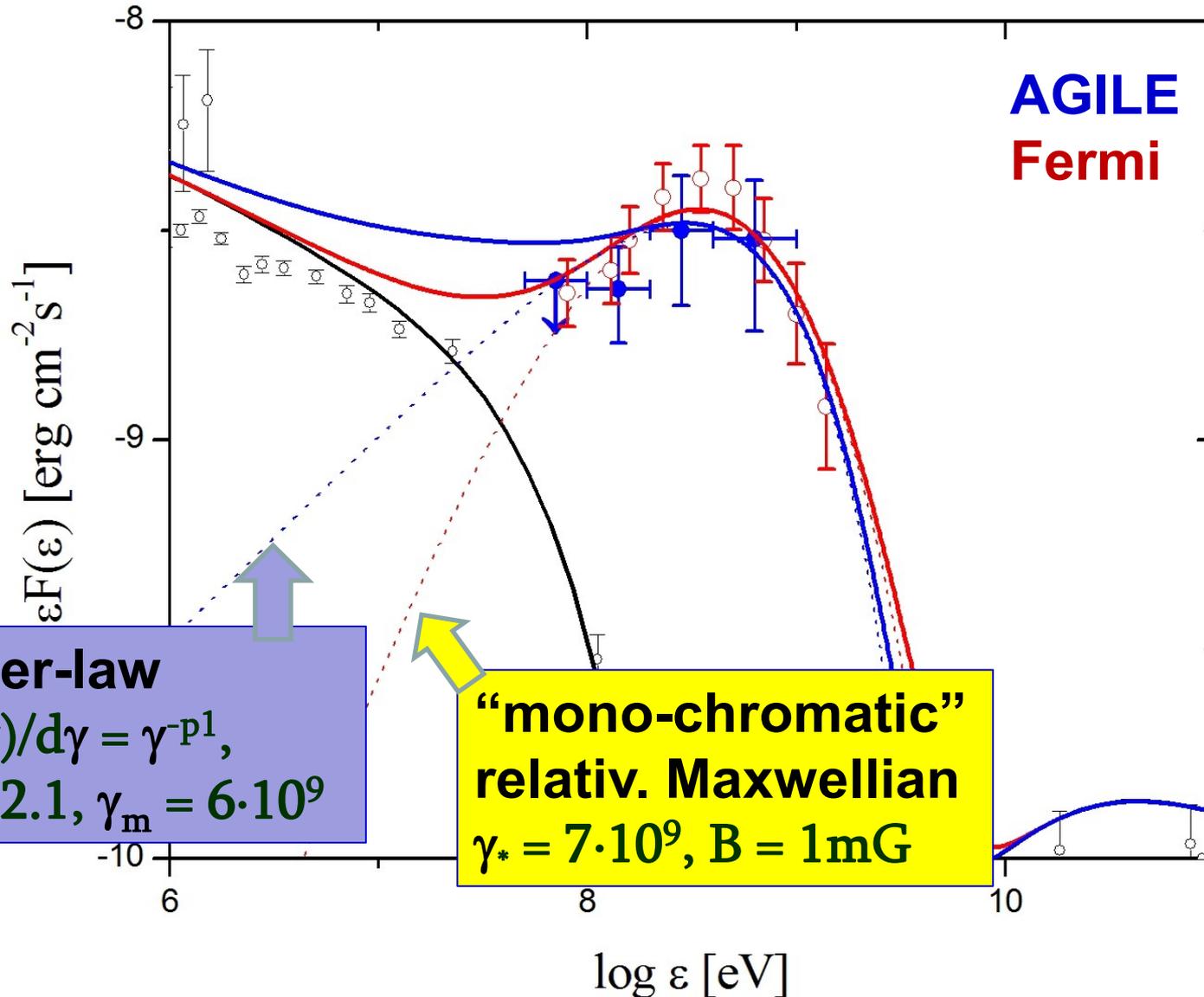


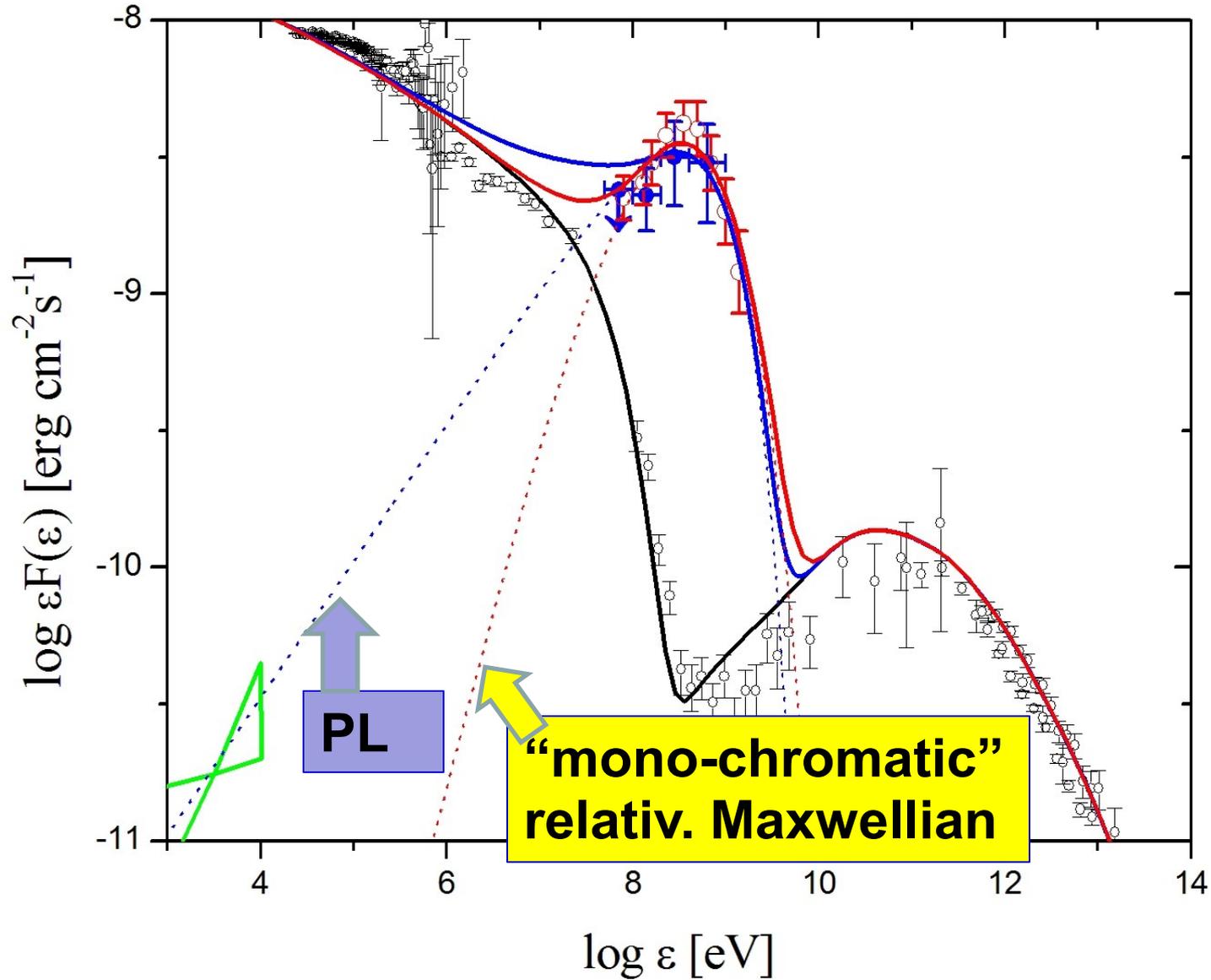
Fermi-LAT

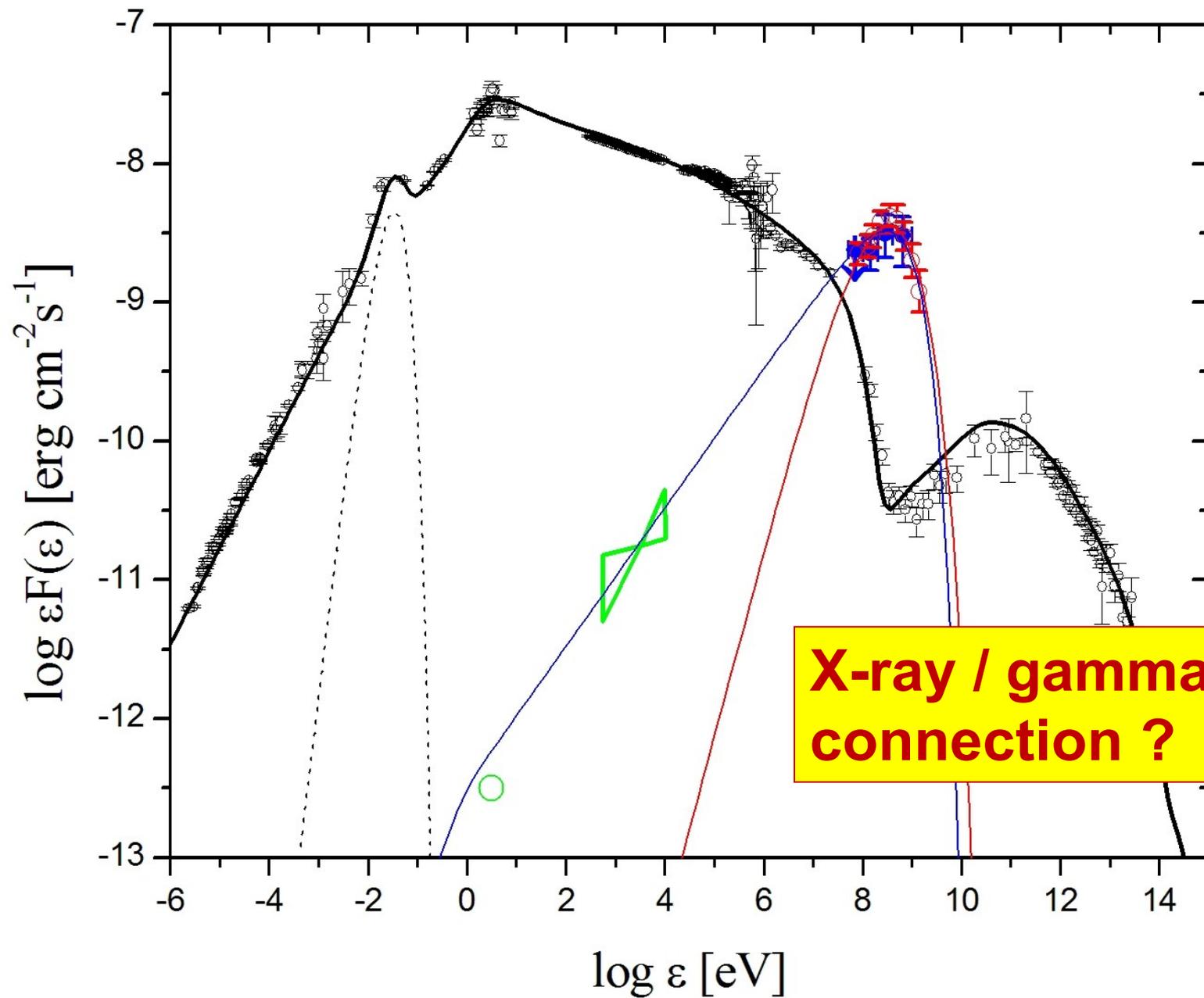
(Buehler et al. 2012)



modelling of the April 2012 super-flare





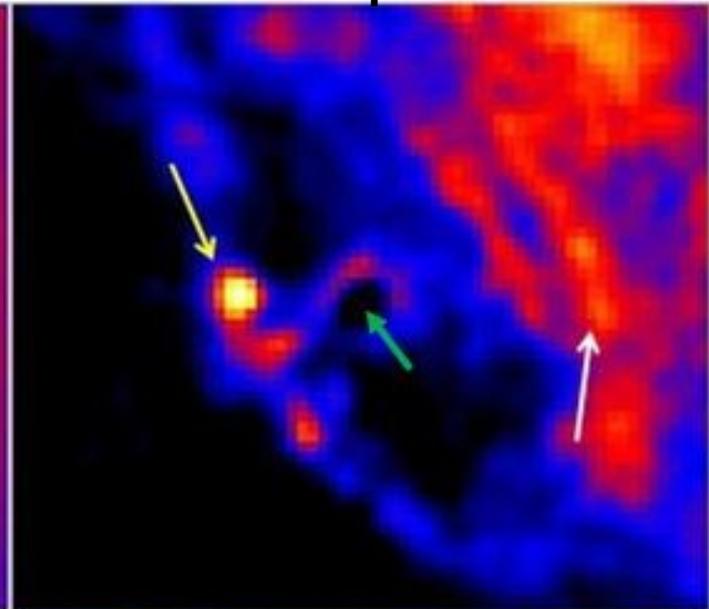
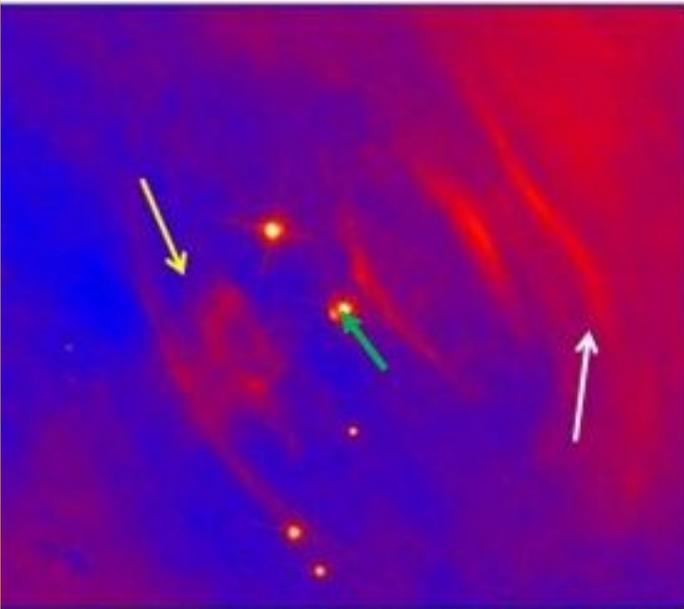


**X-ray / gamma-ray
connection ?**

2 Oct. 2010

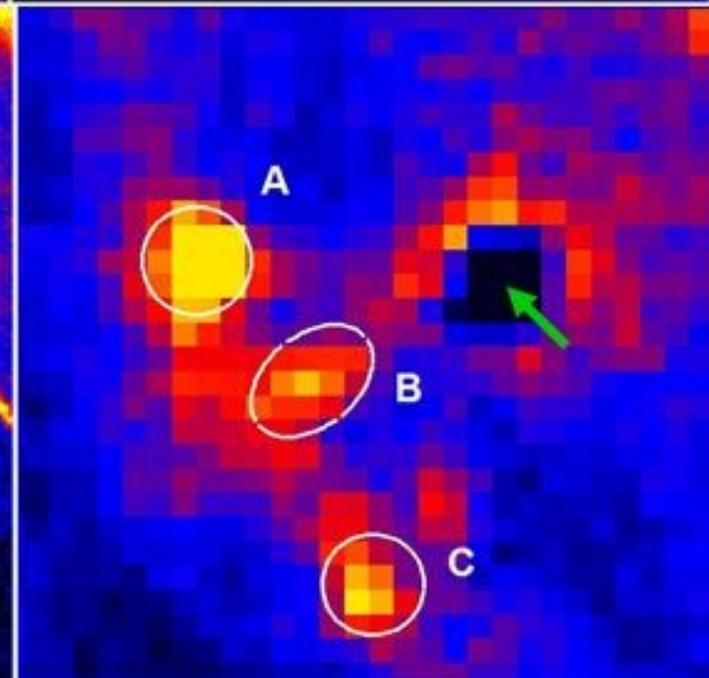
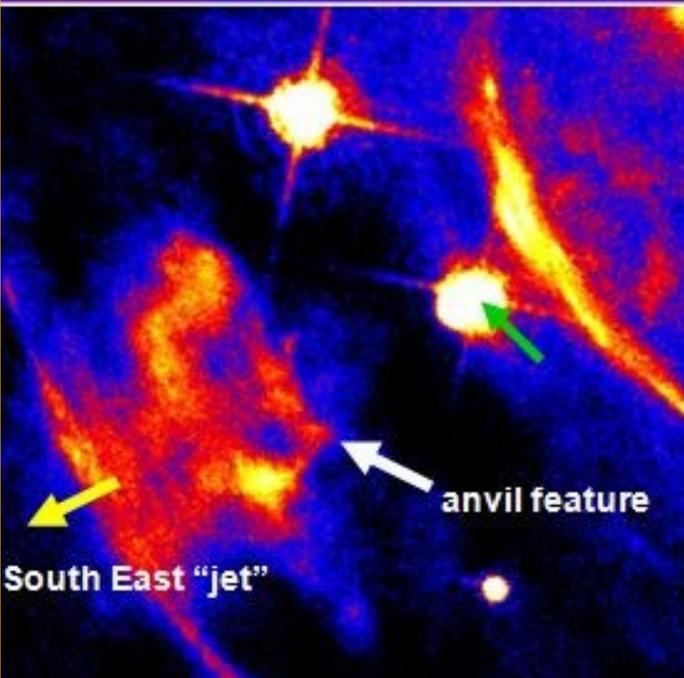
30 Sept. 2010

HST



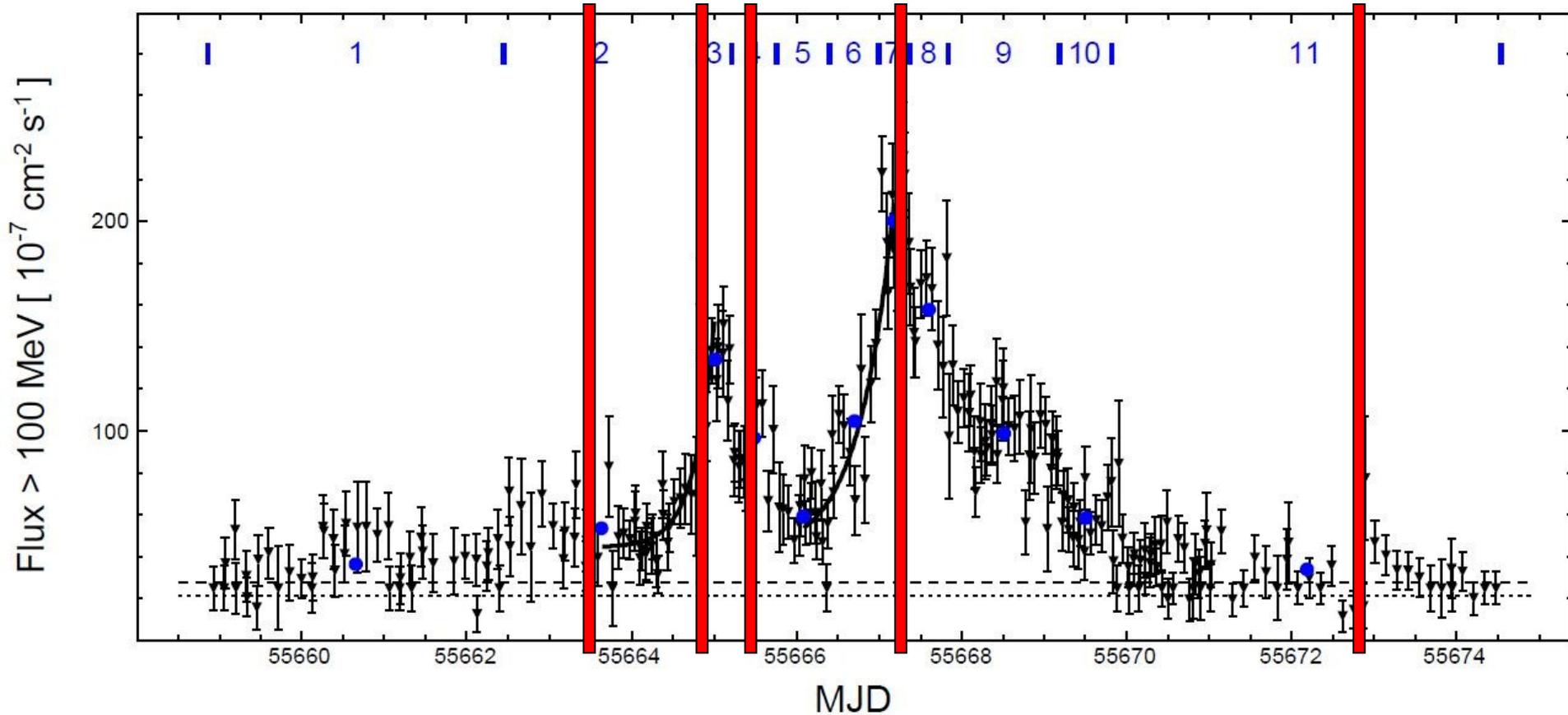
Chandra

HST



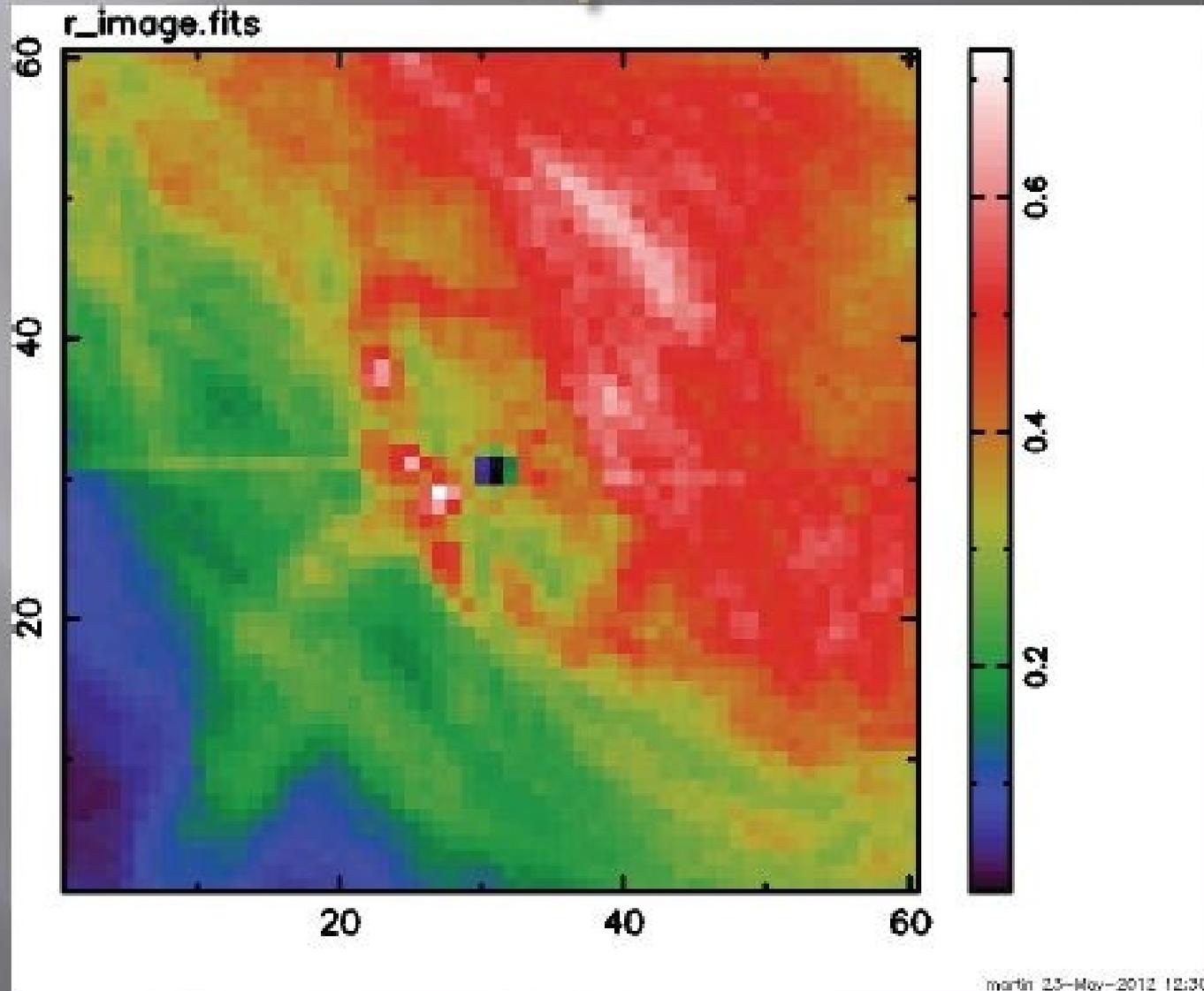
Chandra

Chandra observations during the major gamma-ray flare in April 2011 !



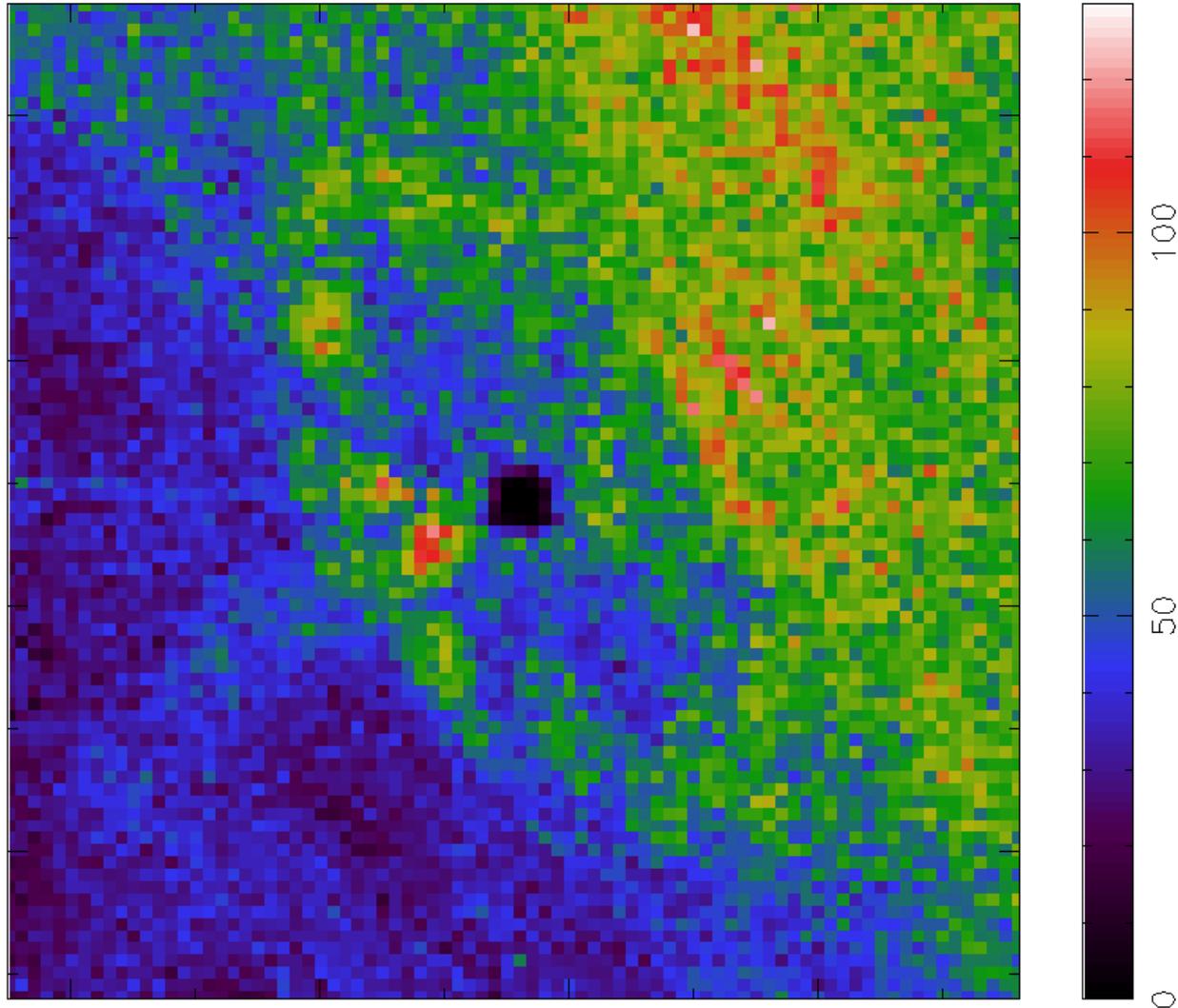
The average Chandra image 2011

(M. Weisskopf, 2012) April



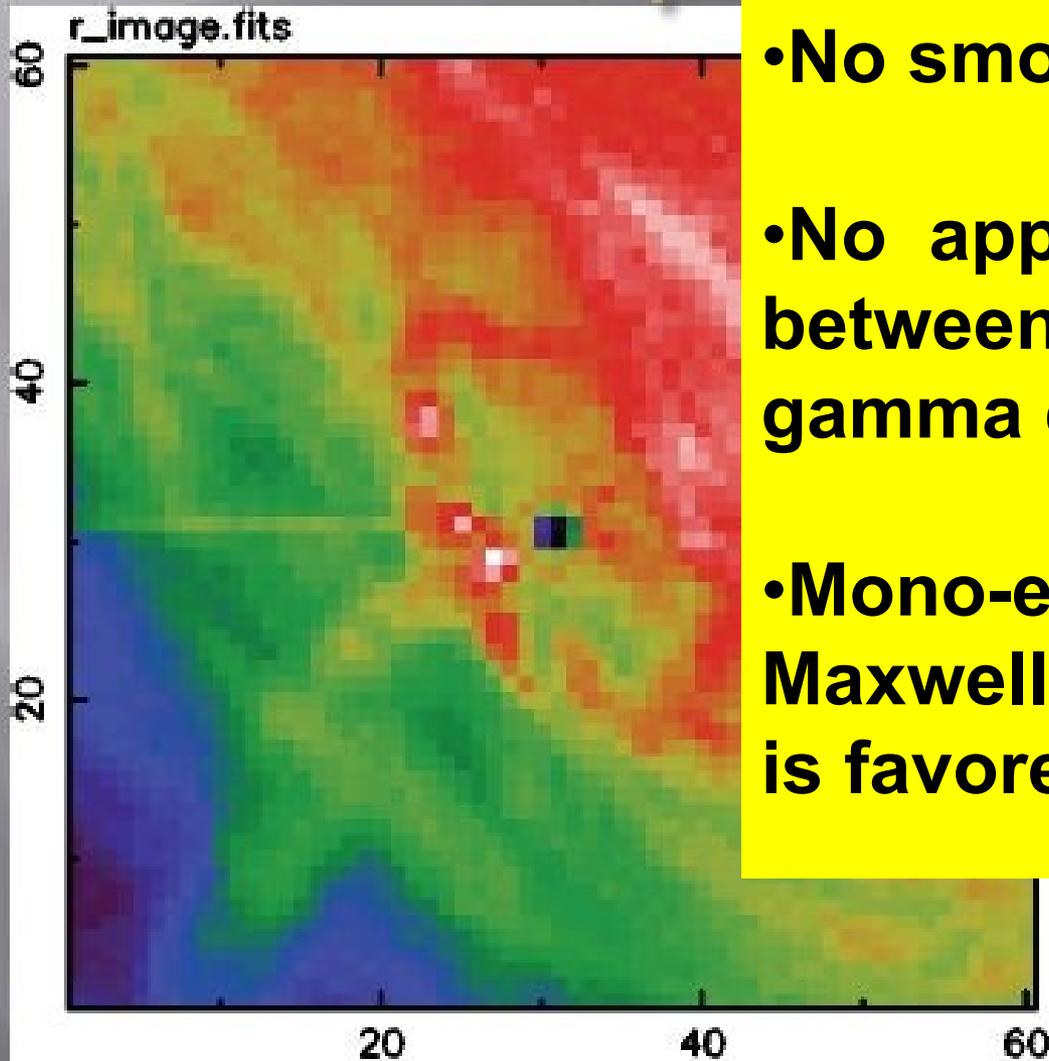
Crab super-flare: Chandra monitoring (12, 13, 14, 21 Apr. 2011: A. Tennant, M. Weisskopf)

13207 (2011-04-12)



The average Chandra image 2011

(M. Weisskopf, 2012) April



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

- **if it's nebular emission, what is the ultimate cause of it?**
 - PSR wind enhancement (density, local B, change of sigma)
 - Plasma physics, shock changes, sudden change of B-configuration, reconnection (?)
 - near PSR effects (?)
 - Knot-1 (?)
 - “Anvil” region (?)
 - Wisp regions (?)

issues

- **standard MHD simulations give too long timescales**
- **detailed acceleration mechanism to be identified**
- **a strong “E-parallel” is produced: magnetic field reconnection (!)**

already several models, many ideas...

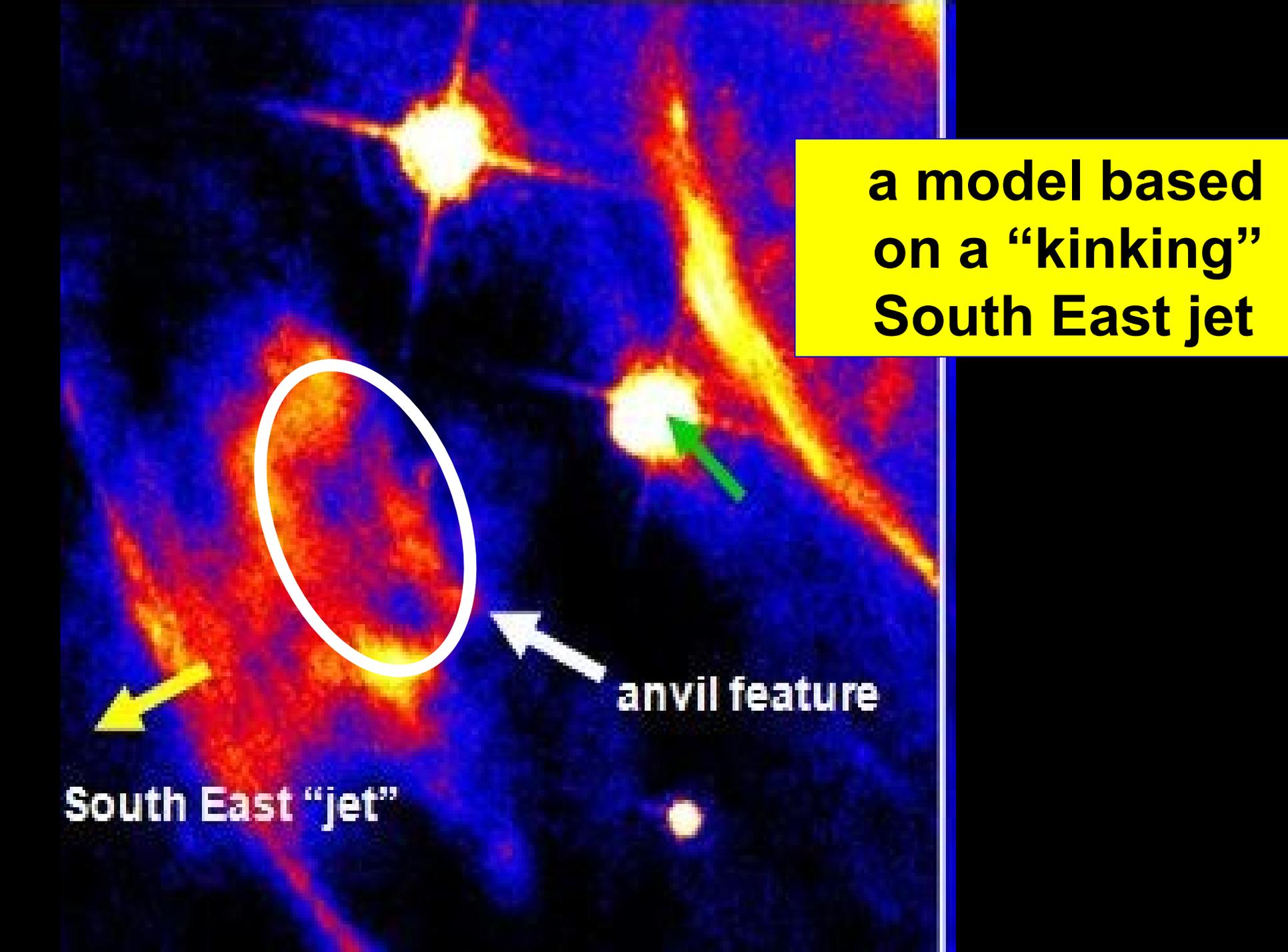
- **Tavani et al. (2011, 2012)**
- **Abdo et al. (2011, 2012)**
- **Bednarek & Idec (2011)**
- **Komissarov & Lyutikov (2011)**
- **Vittorini et al., Striani et al. (2011)**
- **Lyutikov, Balsara, Matthews (2011)**
- **Bykov, Pavlov, Artemyev, Uvanov (2011)**
- **Cerutti, Uzdensky, Begelman (2012)**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

ingredients...

- **Doppler boosting**
- **instabilities: magnetic field reconnection, magn. “islands”, kinks**
 - in the polar (South East) “jet” region
- **current sheet instabilities in inner ring**
 - Tearing mode instabilities
- **relativistic shocks developing E-parallel**

but...

- Is magnetic reconnection really occurring ?
(only indirect theoretical arguments).
What triggers it ?
- **Can it explain super-acceleration ?**
- **What is the fraction of accelerated particles vs. bulk motion ?**
Can we get some help by laboratory experiments (runaway particles, disruptive instabilities, “explosive” reconnection...) ?
- **What is the resulting spectrum ?**
Is it shaped by radiation reaction ?



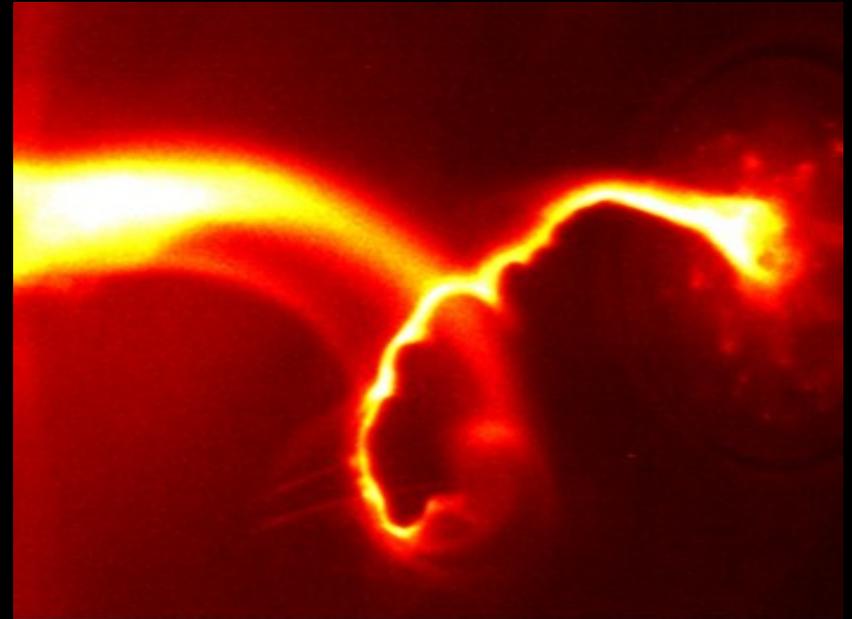
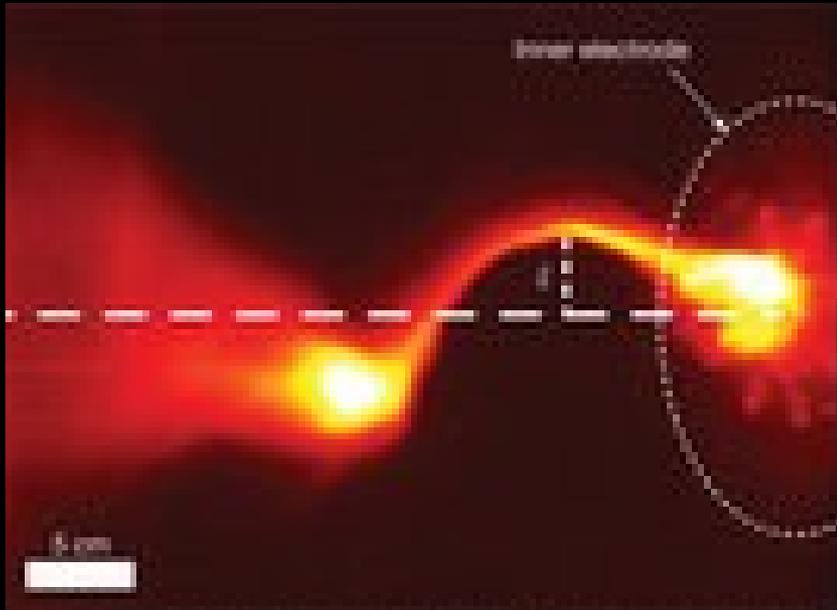
a model based
on a “kinking”
South East jet

anvil feature

South East “jet”

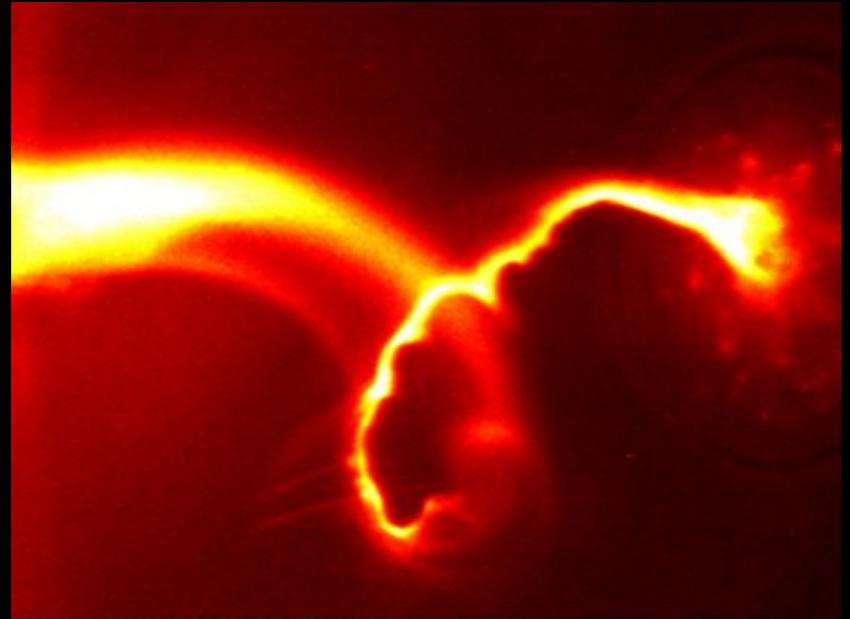
Plasma kink instability

A.L. Moser, P. Bellan, *Nature* , 482, 379 (2012)



Plasma kink instability

1. magnetic field reconnection in “islands” related to kink instabilities
2. reconnection detected in tomakaks as “sawtooth oscillations” and/or runaway acceleration
3. **particle acceleration in kink-driven reconnection events**
4. a framework for the Crab gamma-ray flares originating in the “anvil” region.

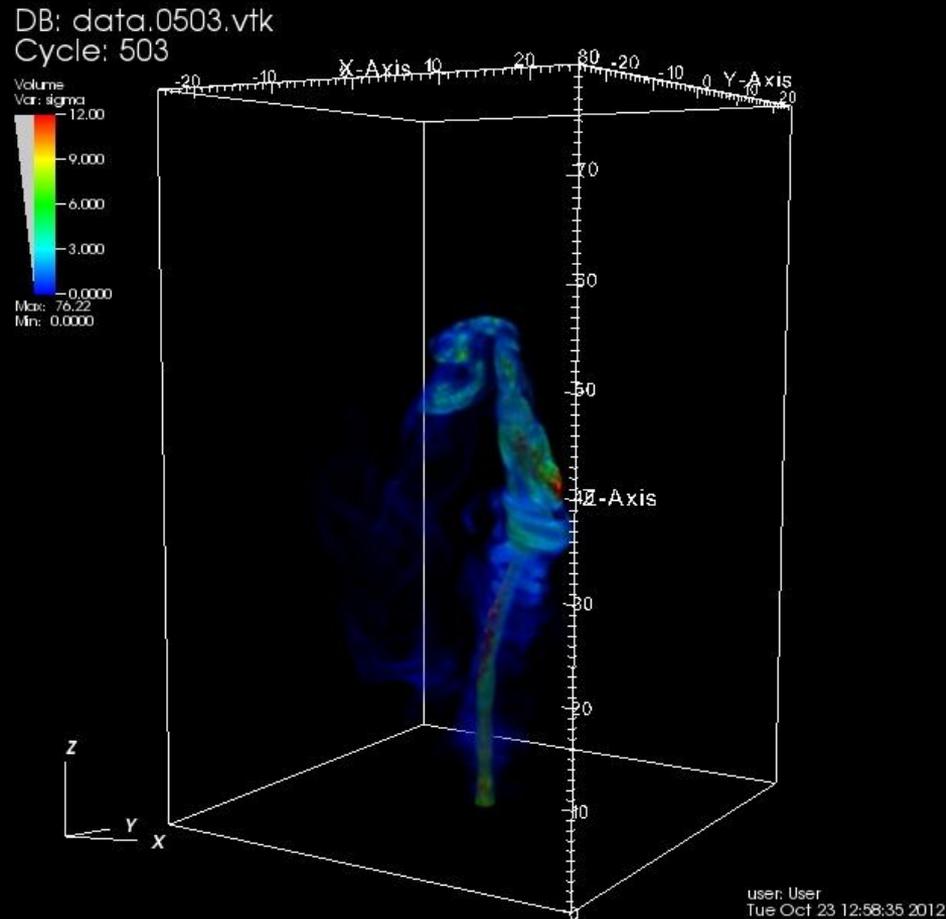


3D MHD simulations

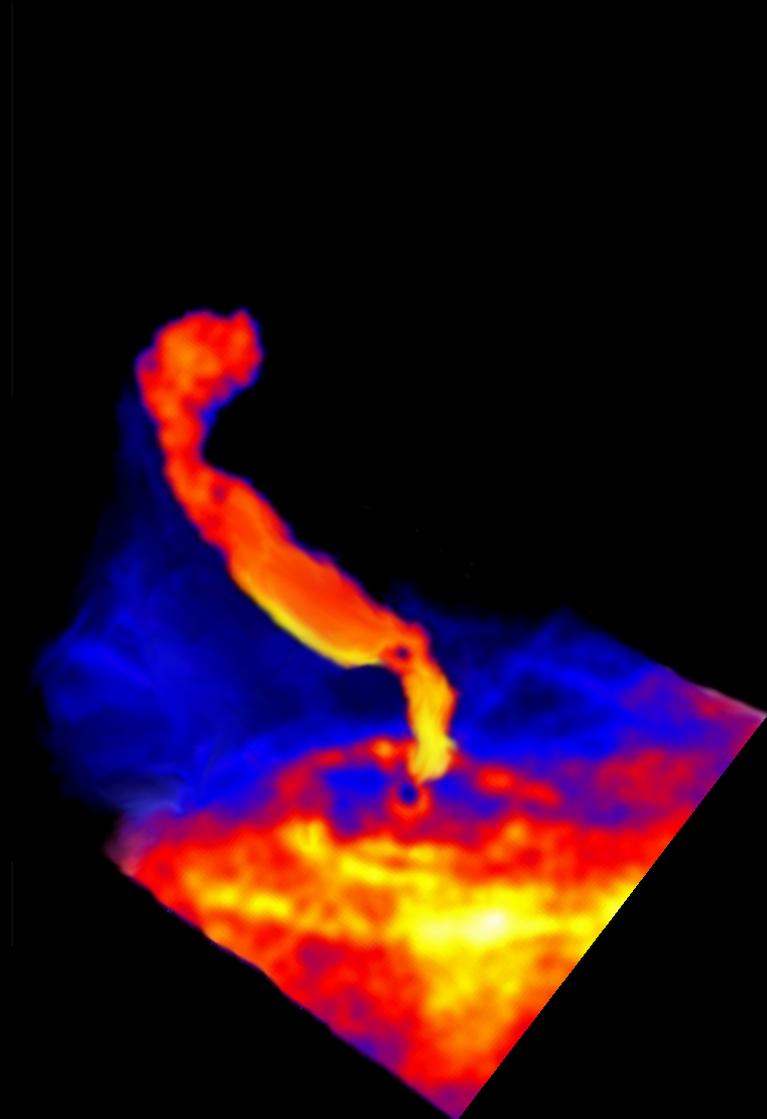
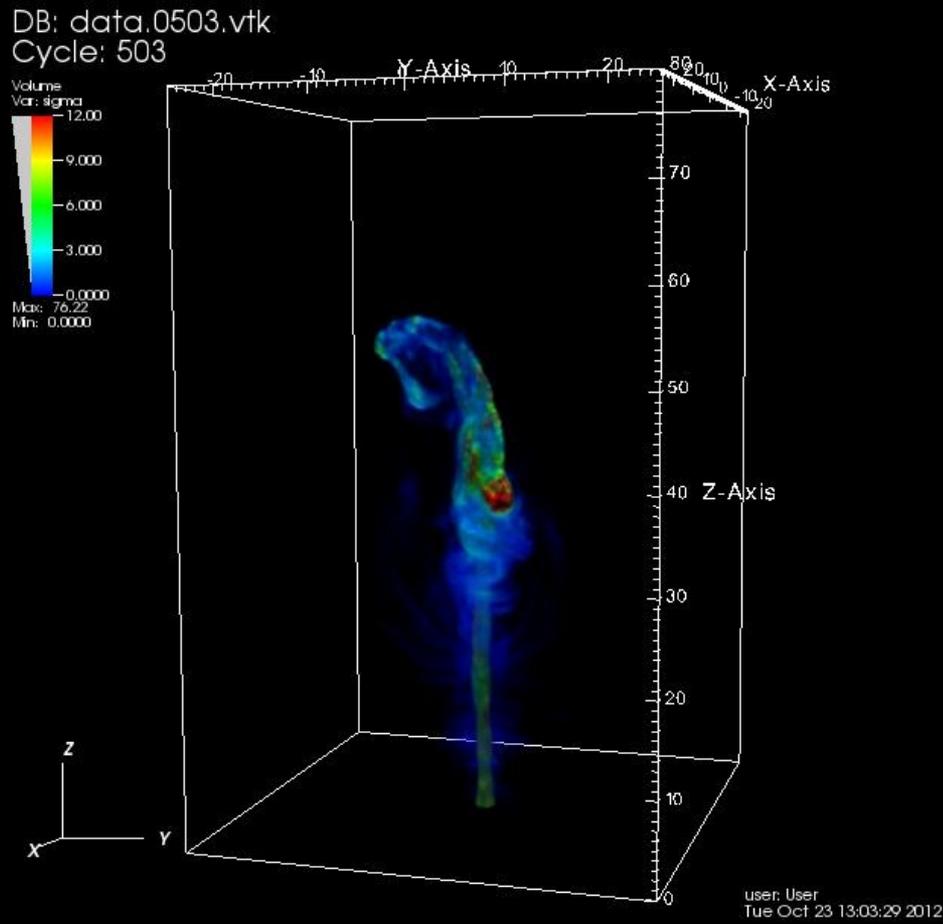
(PLUTO code, A. Mignone et al. 2012)

case	bulk Lorentz Γ	Wind magnetization (sigma)
A1	2	0.1
A2	2	1
A3	2	10
B1	4	0.1
B2	4	1
B3	4	10

case B3 (step 503) $\Gamma = 4, \sigma = 10$
(Mignone, Ferrari, Striani, Tavani, in prepar.)



case B3 (step 503) $\Gamma = 4, \sigma = 10$
(Mignone, Ferrari, Striani, Tavani, in prepar.)



- **“jet kinking” (by internal plasma instabilities) can be the solution**
- **the kinked inner South East jet can provide conditions for magnetic field reconnection**
- **large E_{parallel} ,**
- **tubular (kinked filament) size $\sim 10^{15}$ cm**
- **local $B \sim 1$ mG**
- **magnetization-sigma $\sim 1-10$**

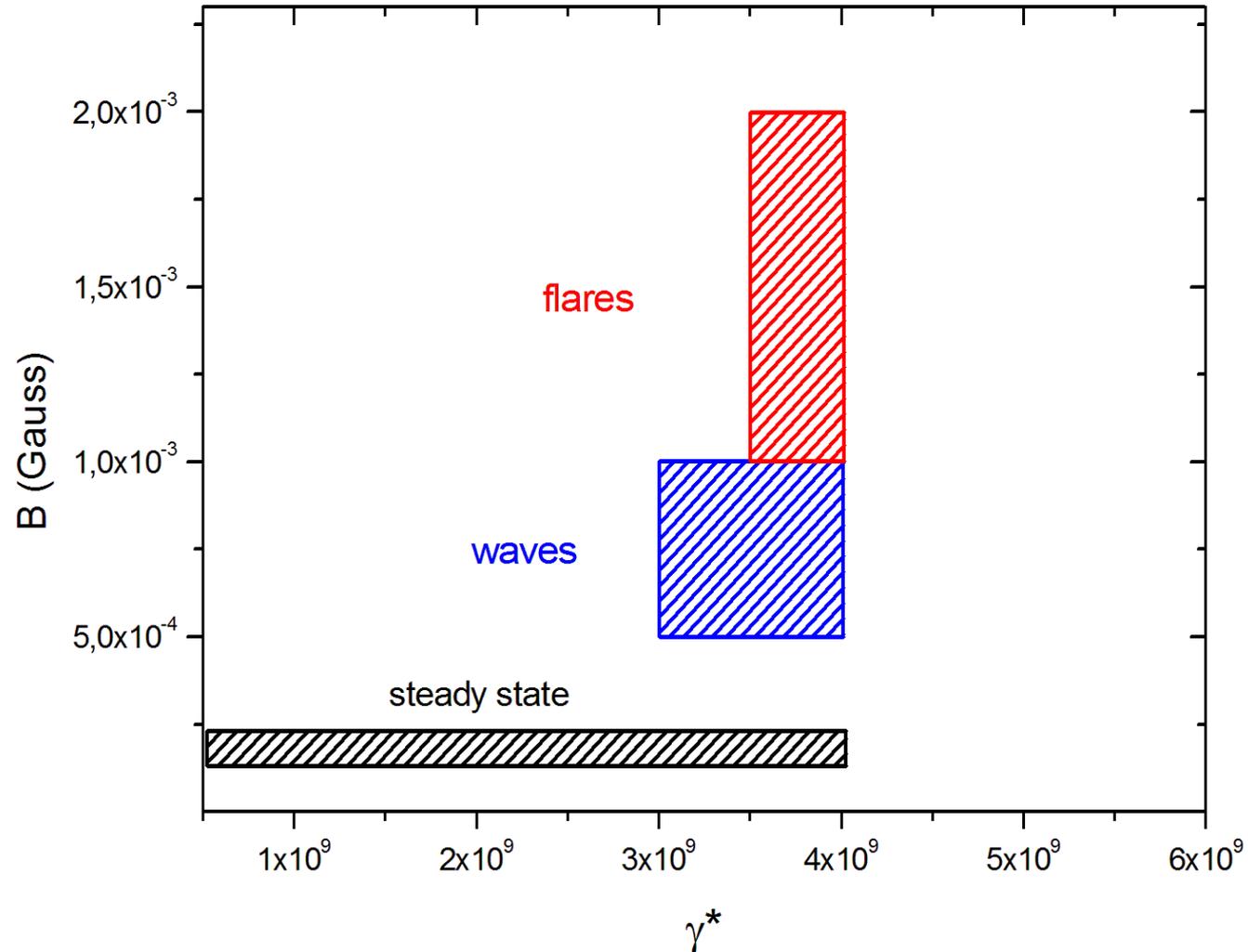
- **max. energy set by radiation reaction,**

$$\gamma = 10^8 B^{-1/2}$$

not only in the perpendicular component of the momentum (synchr. rad.), but also in the parallel direction.

- **“mono-chromatic” spectrum**
- **“super-acceleration” with $E/B \gtrsim 2 =$ magnetic field reconnection along a kinked jet (?)**

Crab Nebula accel. states (M.T. et al. 2012)



Impacts

- **Super-acceleration: a rare event or the normal mechanism in the Crab Nebula ?**
- **Instabilities along jets: transport of energy and dissipation at a large distance from central source.**
- **It may help resolving a variety of problems relativistic jets (micro-qso's, blazars).**

- **the flaring Crab phenomenon unveils a novel mechanism of particle acceleration with very wide applications**
- **“mono-chromatic” spectra !**
- **efficient magnetic field reconnection in collisionless plasmas, current-sheet formation and instabilities, kink-driven acceleration (?)**
- **jet sources, dissipation far from compact source**
- **crucial “feedback” with laboratory plasmas**

- **Crab, the Queen of Nebulae !**
- **an everlasting wonderful laboratory**
- **Monitoring programs (HST, Chandra, ...)**
- **more surprises to come...**

Back-up slides

AGILE detection of enhanced gamma-ray emission from the Crab Nebula region

ATel #2855; M. Tavani (INAF/IASF Roma), E. Striani (Univ. Tor Vergata), A. Bulgarelli (INAF/IASF Bologna), F. Gianotti, M. Trifoglio (INAF/IASF Bologna), C. Pittori, F. Verrecchia (ASDC), A. Argan, A. Trois, G. De Paris, V. Vittorini, F. D'Ammando, S. Sabatini, G. Piano, E. Costa, I. Donnarumma, M. Feroci, L. Pacciani, E. Del Monte, F. Lazzarotto, P. Soffitta, Y. Evangelista, I. Lapshov (INAF-IASF-Rm), A. Chen, A. Giuliani (INAF-IASF-Milano), M. Marisaldi, G. Di Cocco, C. Labanti, F. Fuschino, M. Galli (INAF/IASF Bologna), P. Caraveo, S. Mereghetti, F. Perotti (INAF/IASF Milano), G. Pucella, M. Rapisarda (ENEA-Roma), S. Vercellone (IASF-Pa), A. Pellizzoni, M. Pilia (INAF/OA-Cagliari), G. Barbiellini, F. Longo (INFN Trieste), P. Picozza, A. Morselli (INFN and Univ. Tor Vergata), M. Prest (Universita` dell'Insubria), P. Lipari, D. Zanello (INFN Roma-1), P.W. Cattaneo, A. Rappoldi (INFN Pavia), P. Giommi, P. Santolamazza, F. Lucarelli, S. Colafrancesco (ASDC), L. Salotti (ASI)

on 22 Sep 2010; 14:45 UT

Distributed as an Instant Email Notice (Transients)

Password Certification: Marco Tavani (tavani@iasf-roma.inaf.it)

Subjects: Pulsars

Referred to by ATel #: 2856, 2858, 2861, 2866, 2867, 2868, 2872, 2879, 2882, 2889, 2893, 2903, 2921, 2967, 2968, 2994, 3058

AGILE is detecting an increased gamma-ray flux from a source positionally consistent with the Crab Nebula.

Integrating during the period 2010-09-19 00:10 UT to 2010-09-21 00:10 UT the AGILE-GRID detected enhanced gamma-ray emission above 100 MeV from a source at Galactic coordinates (l,b) = (184.6, -5.0) +/- 0.4 (stat.) +/- 0.1 (svst.) deg. and

Marco Tavani, "AGILE Discovery of Gamma-Ray flares from the Crab Nebula"

Fermi LAT confirmation of enhanced gamma-ray emission from the Crab Nebula region

ATel #2861; *R. Buehler (SLAC/KIPAC), F. D'Ammando (INAF-IASF Palermo), E. Hays (NASA/GSFC) on behalf of the Fermi Large Area Telescope Collaboration*

on 23 Sep 2010; 17:34 UT

Distributed as an Instant Email Notice (Transients)

Password Certification: Rolf Buehler (buehler@slac.stanford.edu)

Subjects: >GeV, Pulsars

Referred to by ATel #: [2866](#), [2867](#), [2868](#), [2872](#), [2879](#), [2882](#), [2889](#), [2893](#), [2903](#), [2921](#), [2967](#), [2968](#), [2994](#), [3058](#)

Following the detection by AGILE of increasing gamma-ray activity from a source positionally consistent with the Crab Nebula occurred from September 19 to 21 (ATel #[2855](#)), we report on the analysis of the >100 MeV emission from this region with the Large Area Telescope (LAT), one of the two instruments on the Fermi Gamma-ray Space Telescope.

Preliminary LAT analysis indicates that the gamma-ray emission ($E > 100$ MeV) observed during this time period at the location of the Crab Nebula is $(606 \pm 43) \times 10^{-8}$ ph/cm²/sec, corresponding to an excess with significance >9 sigma with respect to the average flux from the Crab nebula of $(286 \pm 2) \times 10^{-8}$ ph/cm²/sec, estimated over all the Fermi operation period (only statistical errors are given). Ongoing Fermi observations indicate that the flare is continuing.

A prelude (pre-discovery)

- The Crab is a calibration source: in gamma-rays above 100 MeV it is the brightest source for a spectrum E^{-2}

AGILE pointings at the Crab (2007-2009)

+

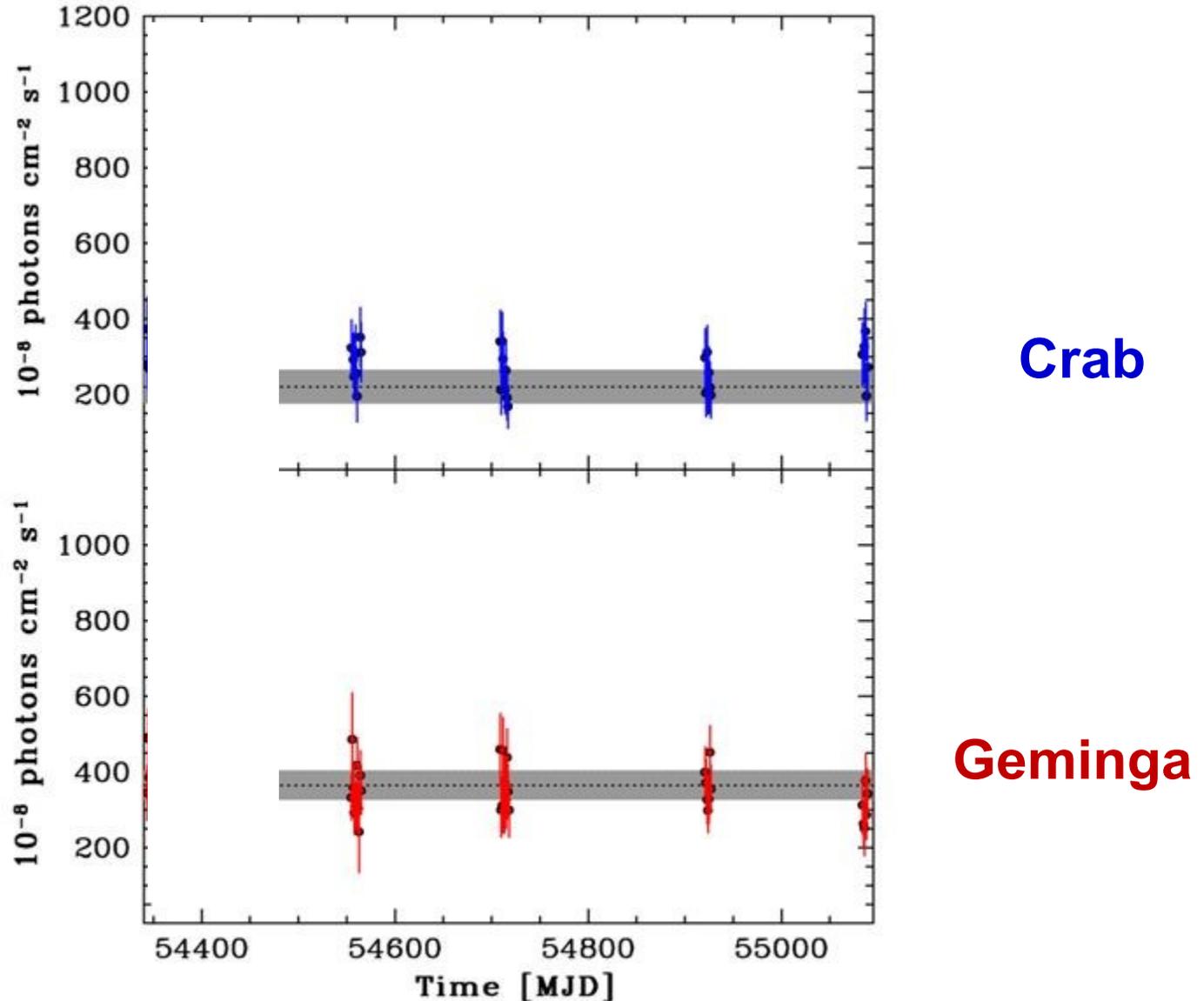


Fig. S1 – The AGILE gamma-ray light curve (1-day binning) of the Crab Pulsar/Nebula and Geminga above 100 MeV during the period 2007-09-01 – 2009-09-15 with the satellite pointing within 35 degrees from the source. Gaps in the light curve are due to the satellite pointing at fields different from the Crab region.

AGILE pointings at the Crab (2007-2009)

+

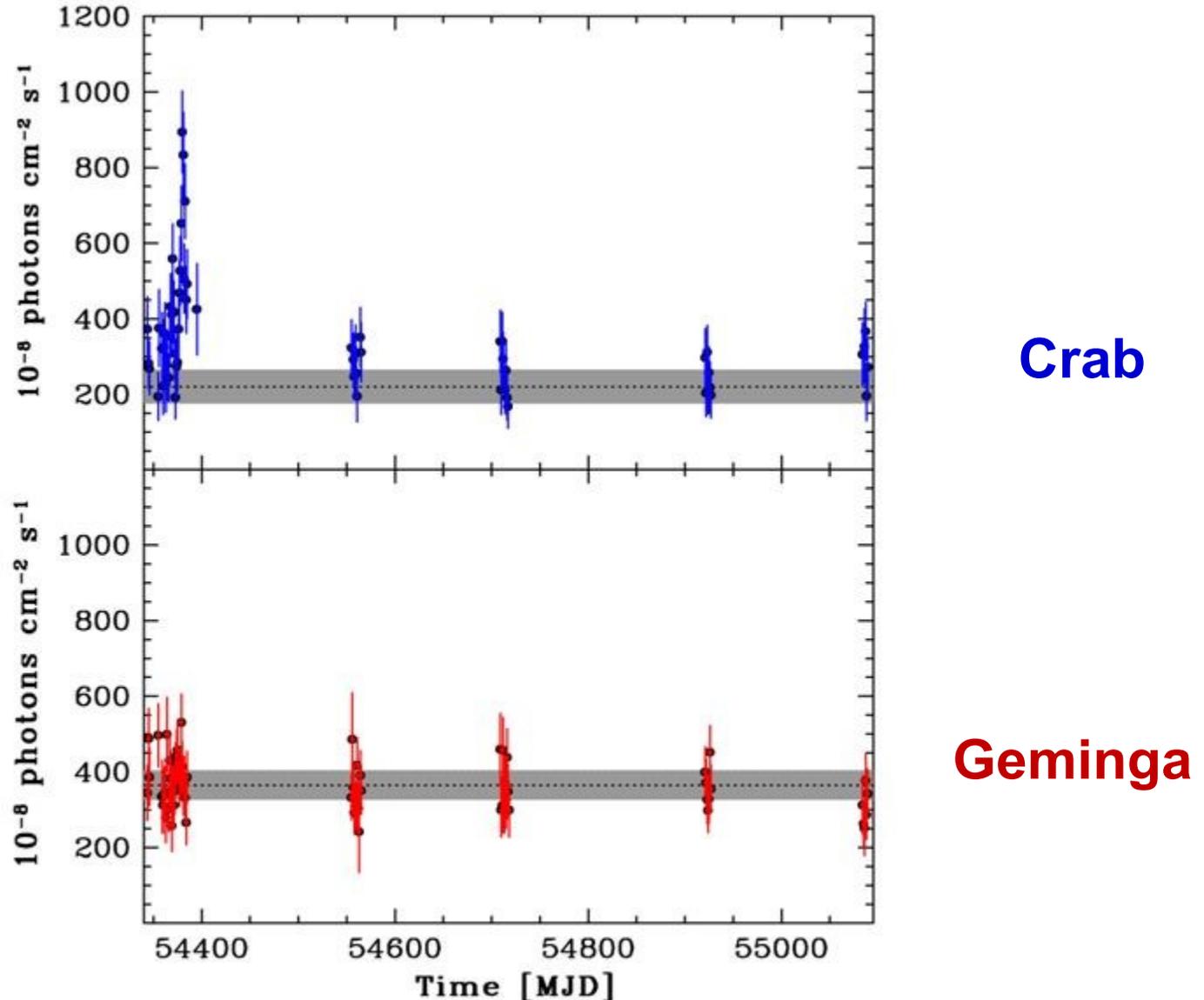
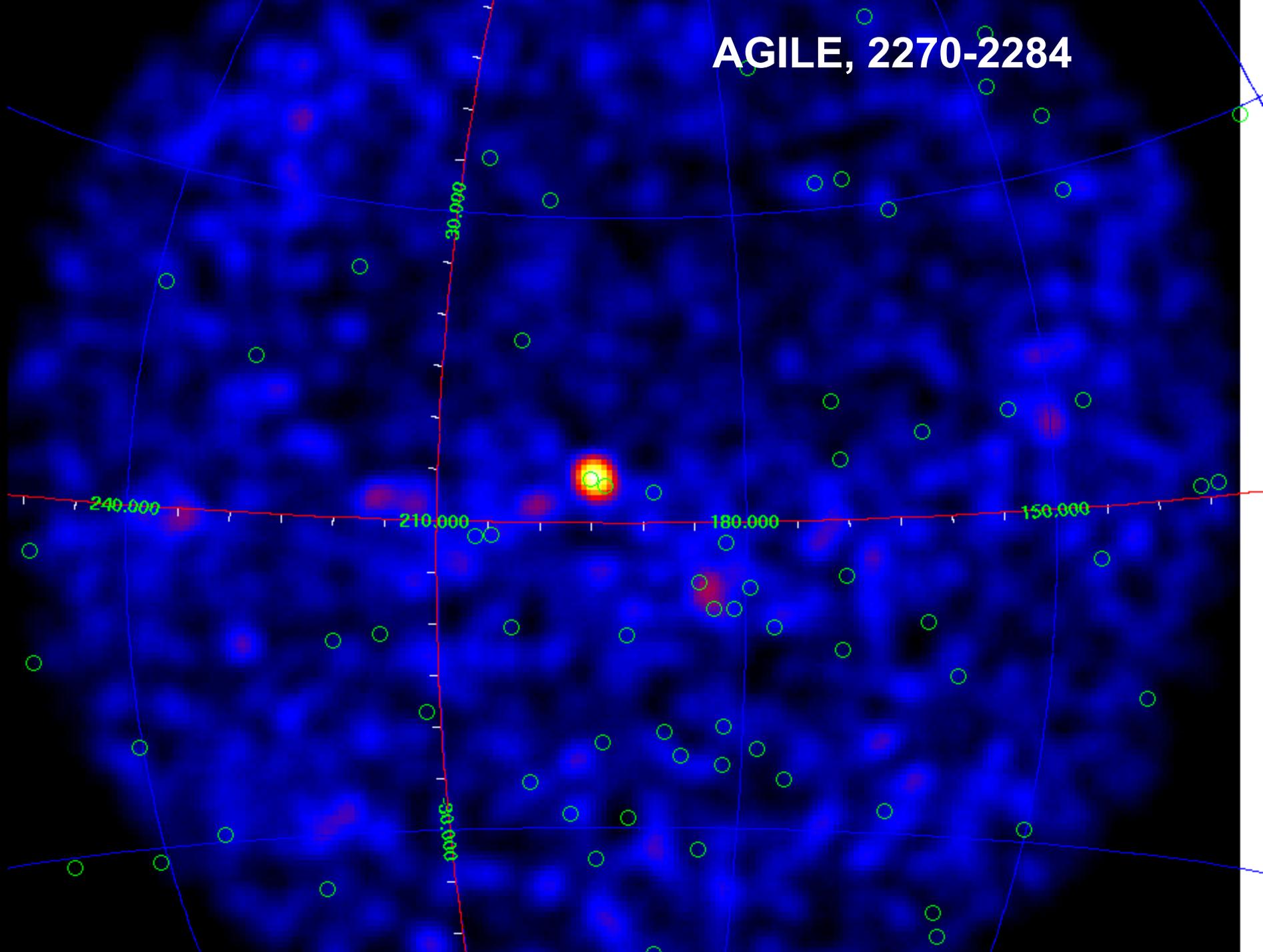
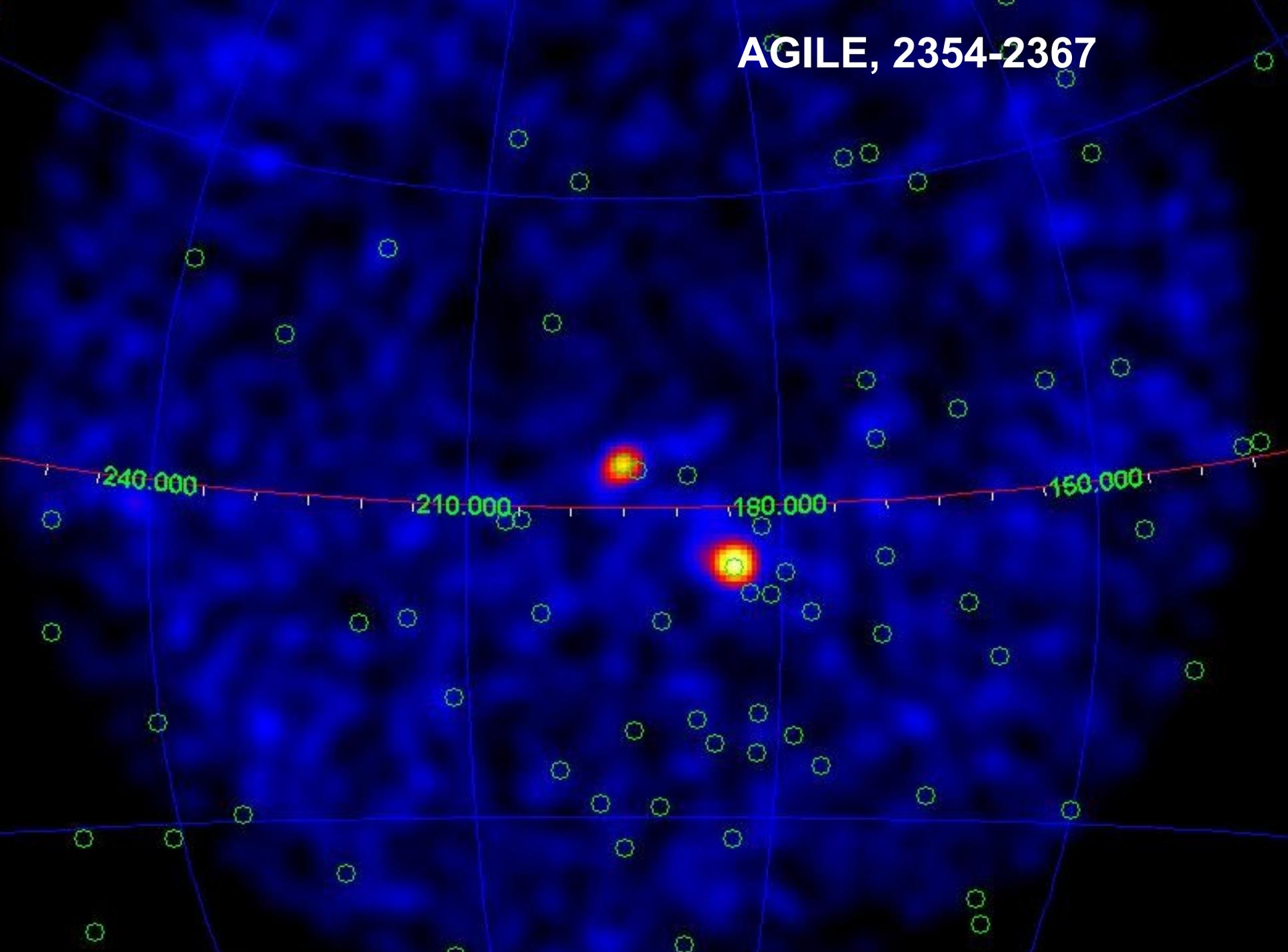


Fig. S1 – The AGILE gamma-ray light curve (1-day binning) of the Crab Pulsar/Nebula and Geminga above 100 MeV during the period 2007-09-01 – 2009-09-15 with the satellite pointing within 35 degrees from the source. Gaps in the light curve are due to the satellite pointing at fields different from the Crab region.

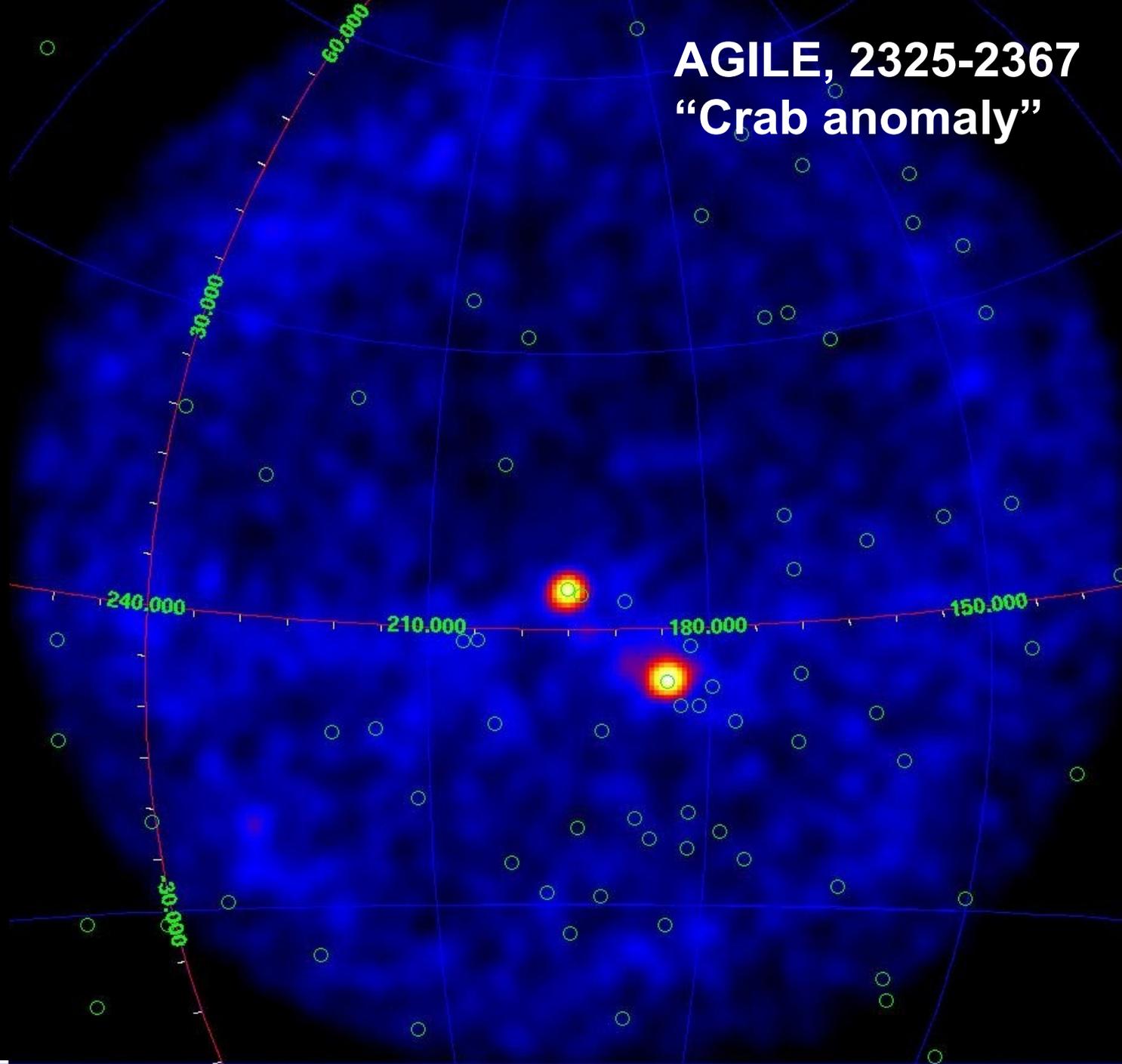
AGILE, 2270-2284



AGILE, 2354-2367



AGILE, 2325-2367 “Crab anomaly”



the Crab “anomaly”

- **internally, since October 2007 the AGILE Team discussed the anomaly because of calibration issues**
- **very serious problems in calibration if the anomalous 15 days were inserted !**
- **several AGILE documents showing the analyses and the “cure”.**

AGILE Discovery of Crab Nebula Variability: a Chronology

- April 2007: AGILE launch.
- October 2007: AGILE detects the first “anomalous” gamma-ray flare from the Crab.
- Oct. 23, 2007: AGILE team meeting and first discussion of the Crab event (STAG n. 39 Minutes of Meeting).
- Sept. 2009: Pittori et al. *Astron. & Astrophys.*, 509, 1563, 2009: “the anomalous flux from the Crab in Oct. 2007 is under investigation.”
- Sept. 19-21, 2010: detection of the second Crab γ -ray flare by the AGILE Alert System: **evidence for a repetitive phenomenon.**
- **Sept. 22, 2010: AGILE issues Astronomer’s Telegram 2855 announcing the discovery of a γ -ray flare from the Crab.**
- **Sept. 23, 2010: *Fermi* issues ATel 2861 confirming the flare.**
- Sept. 28, 2010: first post-flare ***Chandra*** pointing.
- Oct. 2, 2010: ***Hubble*** points at the Crab; several **Swift** pointings¹⁰⁸

The AGILE Mission

M. Tavani^{1,2,3}, G. Barbiellini^{3,4,5}, A. Argan¹, F. Boffelli¹³, A. Bulgarelli⁸, P. Caraveo⁶, P. W. Cattaneo¹³, A. W. Chen^{3,6}, V. Cocco², E. Costa¹, F. D’Ammando^{1,2}, E. Del Monte¹, G. De Paris¹, G. Di Cocco⁸, G. Di Persio¹, I. Donnarumma¹, Y. Evangelista¹, M. Feroci¹, A. Ferrari^{3,16}, M. Fiorini⁶, F. Fornari⁶, F. Fuschino⁸, T. Froyland^{3,7}, M. Frutti¹, M. Galli⁹, F. Gianotti⁸, A. Giuliani^{3,6}, C. Labanti⁸, I. Lapshov^{1,15}, F. Lazzarotto¹, F. Liello⁵, P. Lipari^{10,11}, F. Longo^{4,5}, E. Mattaini⁶, M. Marisaldi⁸, M. Mastropietro²⁴, A. Mauri⁸, F. Mauri¹³, S. Mereghetti⁶, E. Morelli⁸, A. Morselli⁷, L. Pacciani¹, A. Pellizzoni⁶, F. Perotti⁶, G. Piano¹, P. Picozza^{2,7}, C. Pontoni^{3,5}, G. Porrovecchio¹, M. Prest⁵, G. Pucella¹, M. Rapisarda¹², A. Rappoldi¹³, E. Rossi⁸, A. Rubini¹, P. Soffitta¹, A. Traci⁸, M. Trifoglio⁸, A. Trois¹, E. Vallazza⁵, S. Vercellone⁶, V. Vittorini^{1,3}, A. Zambra^{3,6}, D. Zanello^{10,11}, C. Pittori¹⁴, B. Preger¹⁴, P. Santolamazza¹⁴, F. Verrecchia¹⁴, P. Giommi¹⁴, S. Colafrancesco¹⁴, A. Antonelli¹⁷, S. Cutini¹⁴, D. Gasparrini¹⁴, S. Stellato¹⁴, G. Fanari¹⁴, R. Primavera¹⁴, F. Tamburelli¹⁴, F. Viola¹⁸, G. Guarnera¹⁸, L. Salotti¹⁸, F. D’Amico¹⁸, E. Marchetti¹⁸, M. Crisconio¹⁸, P. Sabatini¹⁹, G. Annoni¹⁹, S. Alia¹⁹, A. Longoni¹⁹, R. Sanquerin¹⁹, M. Battilana¹⁹, P. Concari¹⁹, E. Dessimone¹⁹, R. Grossi¹⁹, A. Parise¹⁹, F. Monzani²⁰, E. Artina²⁰, R. Pavesi²⁰, G. Marseguerra²⁰, L. Nicolini²⁰, L. Scandelli²⁰, L. Soli²⁰, V. Vettorello²⁰, E. Zardetto²⁰, A. Bonati²⁰, L. Maltecca²⁰, E. D’Alba²⁰, M. Patané²⁰, G. Babini²¹, F. Onorati²¹, L. Acquaroli²¹, M. Angelucci²¹, B. Morelli²¹, C. Agostara²¹, M. Cerone²², A. Michetti²², P. Tempesta²², S. D’Eramo²², F. Rocca²², F. Giannini²², G. Borghi²³, B. Garavelli²⁵, M. Conte²⁰, M. Balasini²⁰, I. Ferrario²⁵, M. Vanotti²⁵, E. Collavo²⁵, and M. Giacomazzo²⁵

The AGILE Mission

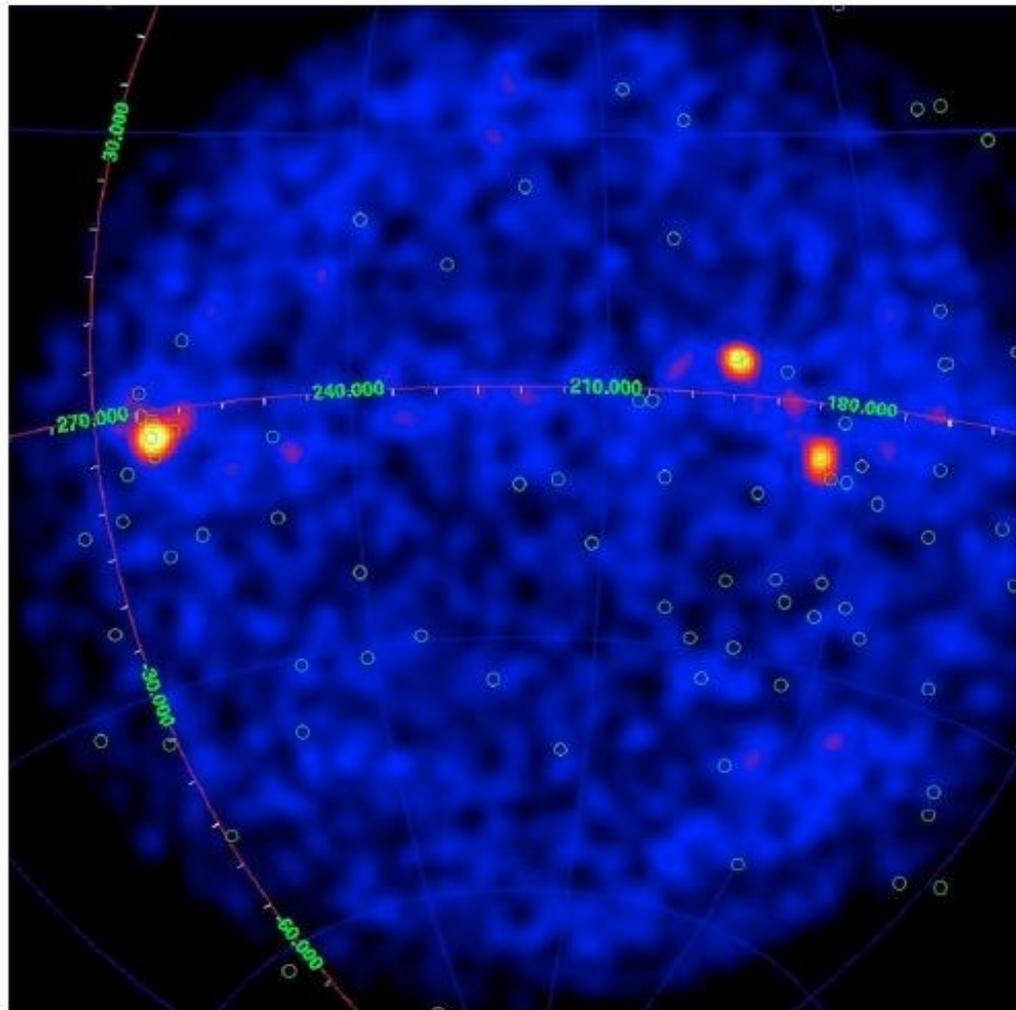


Fig. 25. The AGILE-GRID 1-day gamma-ray counts map for photons above 100 MeV obtained on 2007 September 28. The unprecedentedly large FOV includes for the first time in a single map all three of the most important gamma-ray pulsars: Vela, Crab, and Geminga.

First AGILE catalog of high-confidence gamma-ray sources

C. Pittori¹, F. Verrecchia¹, A. W. Chen^{2,3}, A. Bulgarelli⁴, A. Pellizzoni⁵, A. Giuliani^{2,3}, S. Vercellone⁶, F. Longo^{7,8}, M. Tavani^{9,10,11,3}, P. Giommi^{1,12}, G. Barbiellini^{7,8,3}, M. Trifoglio⁴, F. Gianotti⁴, A. Argan⁹, A. Antonelli¹³, F. Boffelli¹⁴, P. Caraveo², P. W. Cattaneo¹⁴, V. Cocco¹⁰, S. Colafrancesco^{1,12}, T. Contessi², E. Costa⁹, S. Cutini¹, F. D’Ammando^{9,10}, E. Del Monte⁹, G. De Paris⁹, G. Di Cocco⁴, G. Di Persio⁹, I. Donnarumma⁹, Y. Evangelista⁹, G. Fanari¹, M. Feroci⁹, A. Ferrari^{3,15}, M. Fiorini², F. Fornari², F. Fuschino⁴, T. Froyland^{3,11}, M. Frutti⁹, M. Galli¹⁶, D. Gasparri¹, C. Labanti⁴, I. Lapshov^{9,17}, F. Lazzarotto⁹, F. Liello⁹, P. Lipari^{18,19}, E. Mattaini², M. Marisaldi⁴, M. Mastropietro^{9,21}, A. Mauri⁴, F. Mauri¹⁴, S. Mereghetti², E. Morelli⁴, E. Moretti^{7,8}, A. Morselli¹¹, L. Pacciani⁹, F. Perotti², G. Piano^{9,10,11}, P. Picozza^{10,11}, M. Pilia^{22,2,5}, C. Pontoni^{3,8}, G. Porrovecchio⁹, B. Preger¹, M. Prest^{8,22}, R. Primavera¹, G. Pucella⁹, M. Rapisarda²⁰, A. Rappoldi¹⁴, E. Rossi⁴, A. Rubini⁹, S. Sabatini¹⁰, P. Santolamazza¹, E. Scalise⁹, P. Soffitta⁹, S. Stellato¹, E. Striani¹⁰, F. Tamburelli¹, A. Traci⁴, A. Trois⁹, E. Vallazza⁸, V. Vittorini^{9,3}, A. Zambra^{2,3}, D. Zanello^{18,19}, and L. Salotti¹²

1AGL J0535+2205 and 1AGL J0634+1748 (Crab and Geminga). These two well known strong γ -ray pulsars, together with the Vela pulsar, were used for in-flight AGILE calibrations. We report the flux values obtained during calibration subperiods. These values agree with pulsed flux values reported in (Pellizzoni et al. 2009). We note, however, that we observed higher flux values, over 1σ from the reported mean flux, for both sources when merging all the data, including shorter (1 day) integration periods during 2007. This point is under investigation.

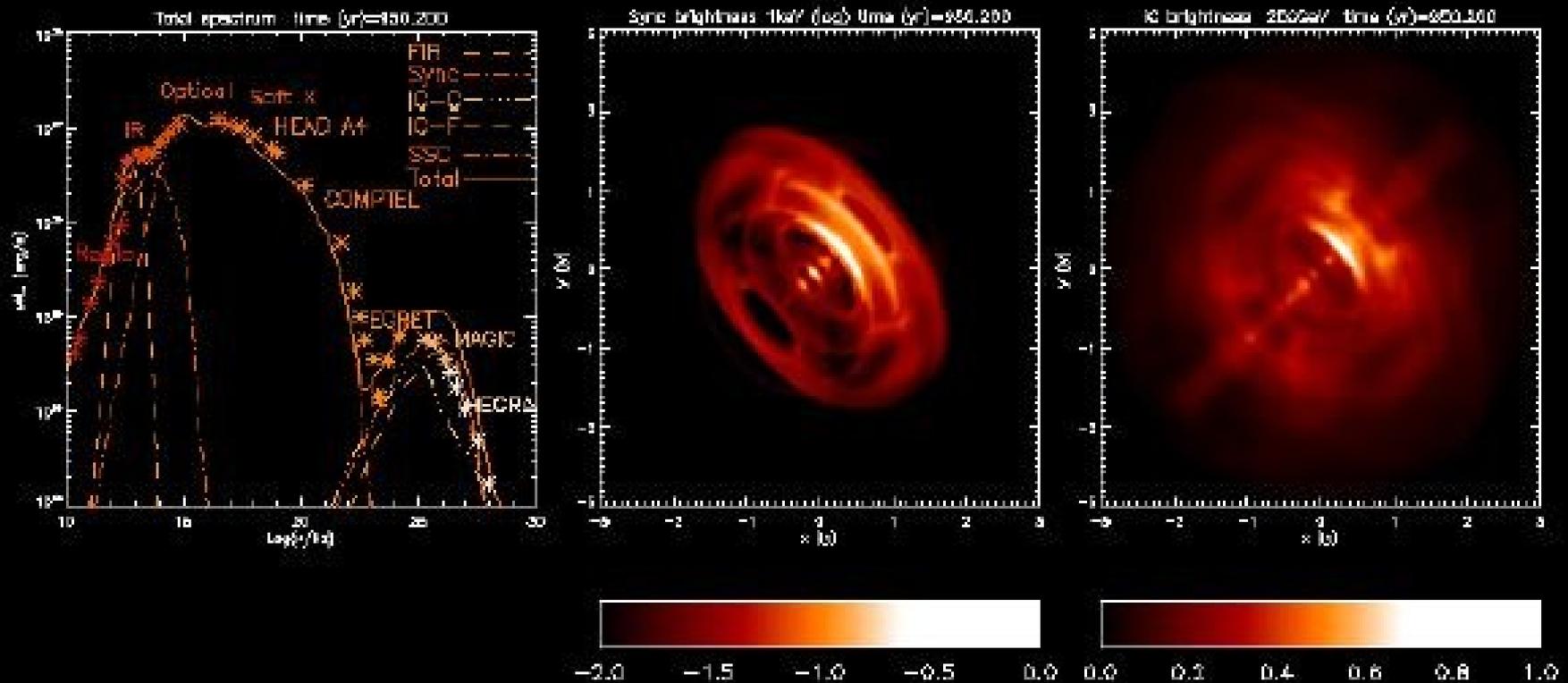
1AGL J0617+2236. This AGILE detection provides an improved positioning compared to the 3EG J0617+2238 error box. This source is positionally coincident with the SNR IC443 (Tavani et al. 2009c). The AGILE error box also contains the PSR J0614+2229.

1AGL J0657+4554 and 1AGL J0714+3340. These two high-latitude ($b \approx \pm 10$ deg) AGILE sources, associated with blazars

Variability in MHD models

From the Arcetri group

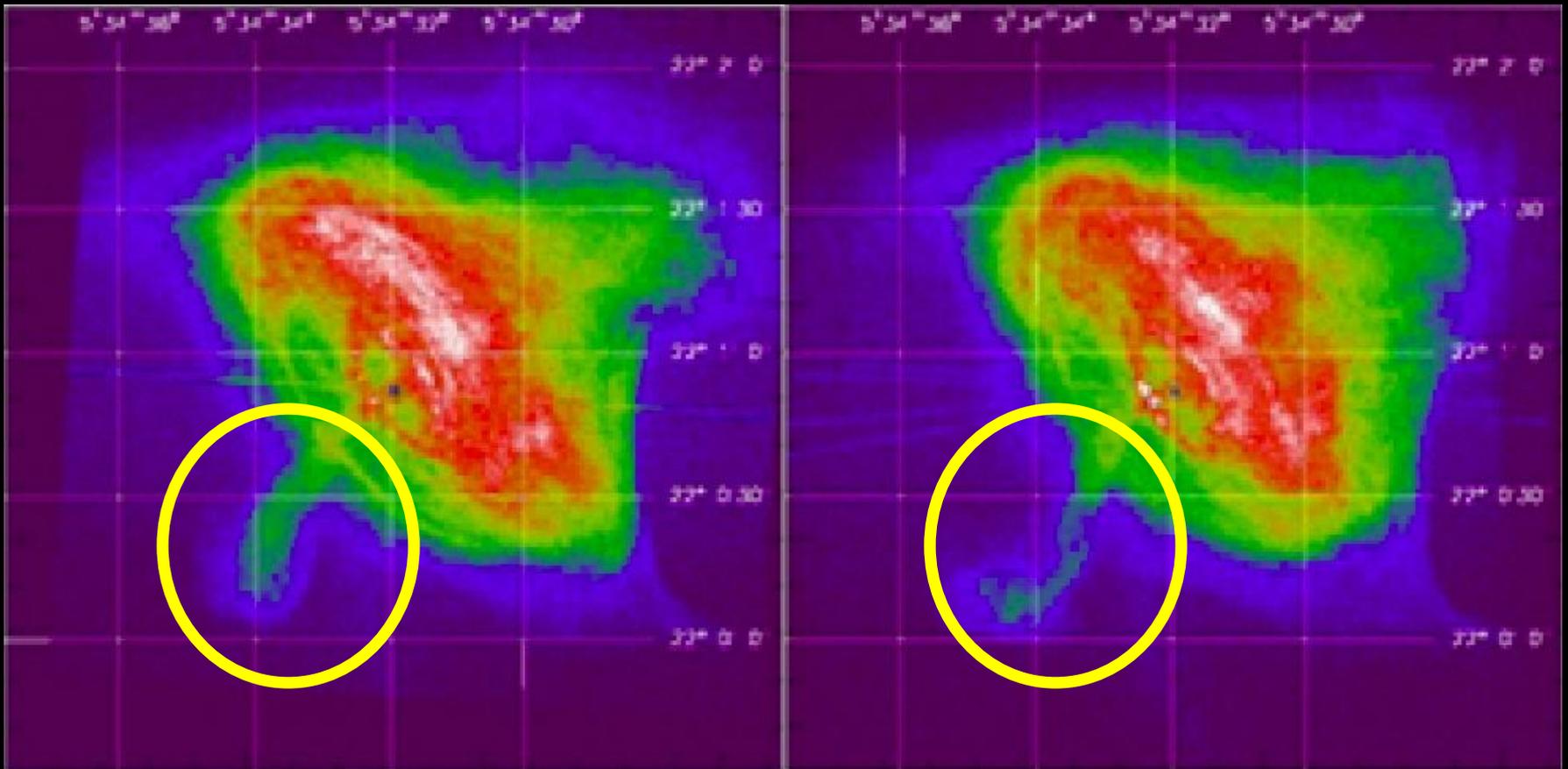
Courtesy E. Amato

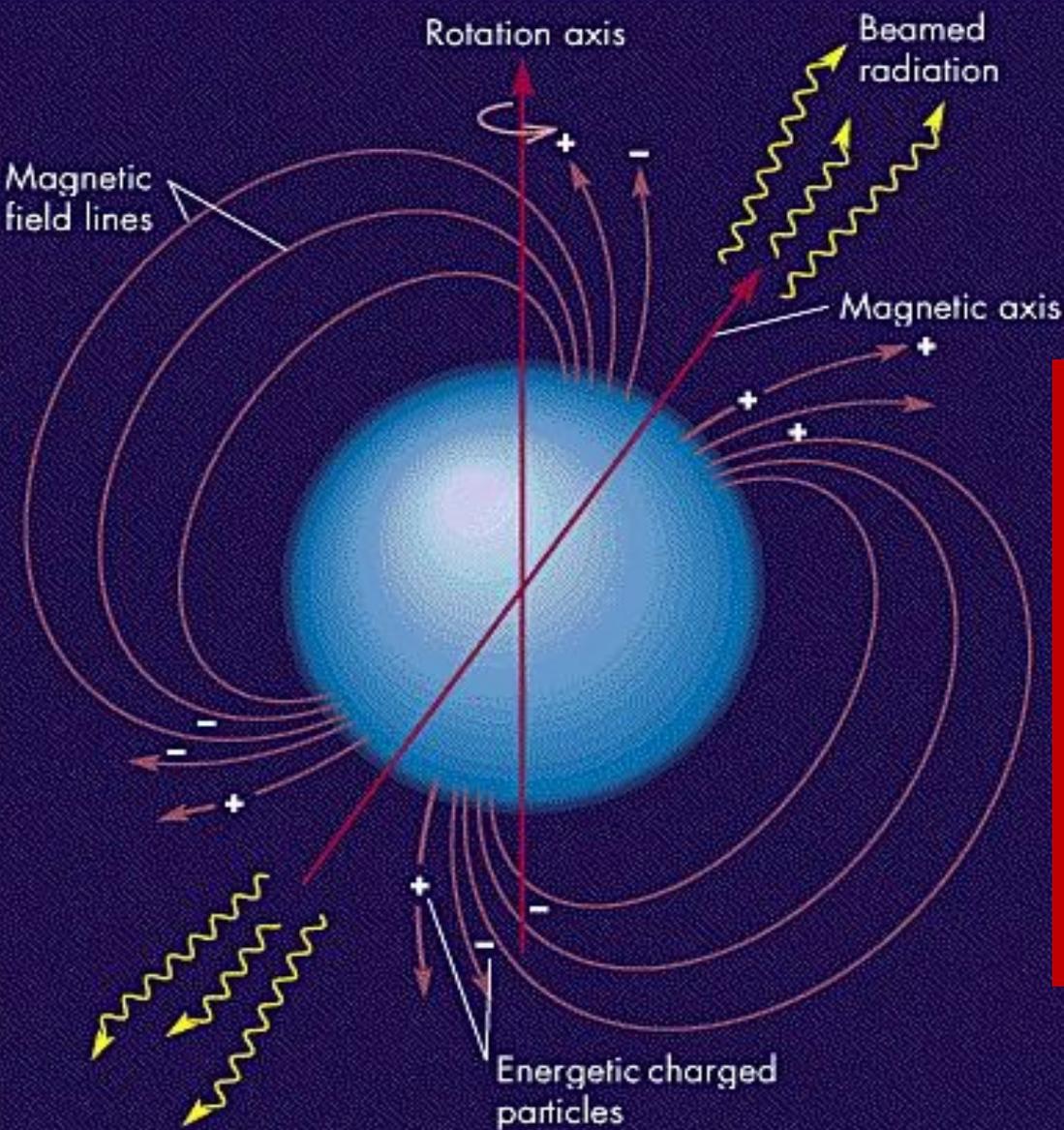


Chandra observations of the Crab Nebula (1-10 keV)

2001

Sept. 28, 2010



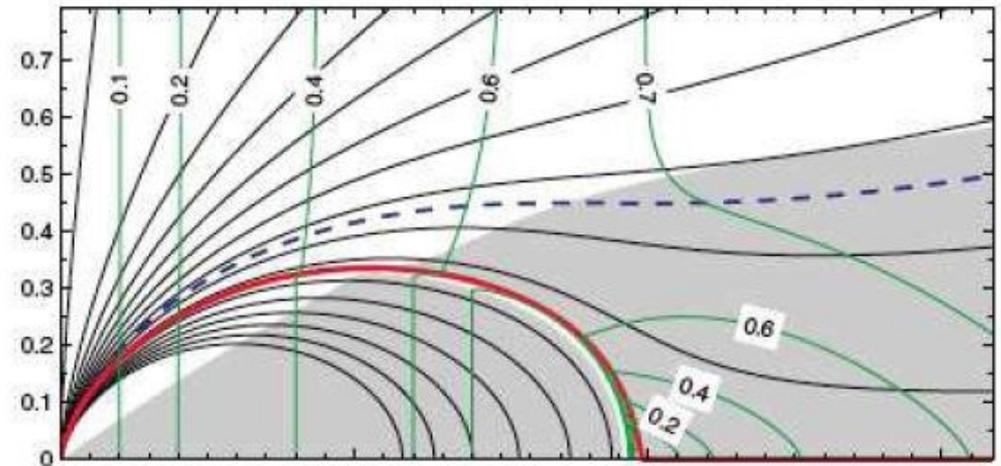
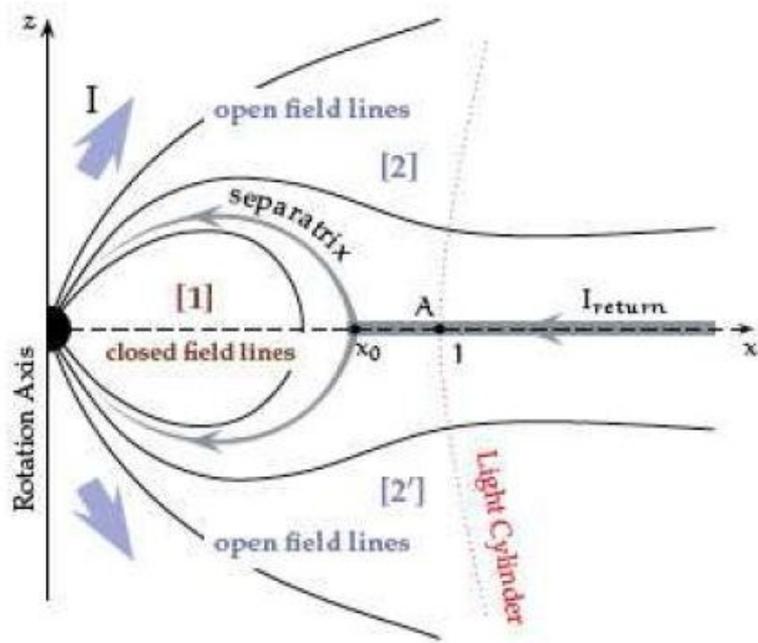


**A NEUTRON STAR WITH A
STRONG MAGNETIC FIELD:**

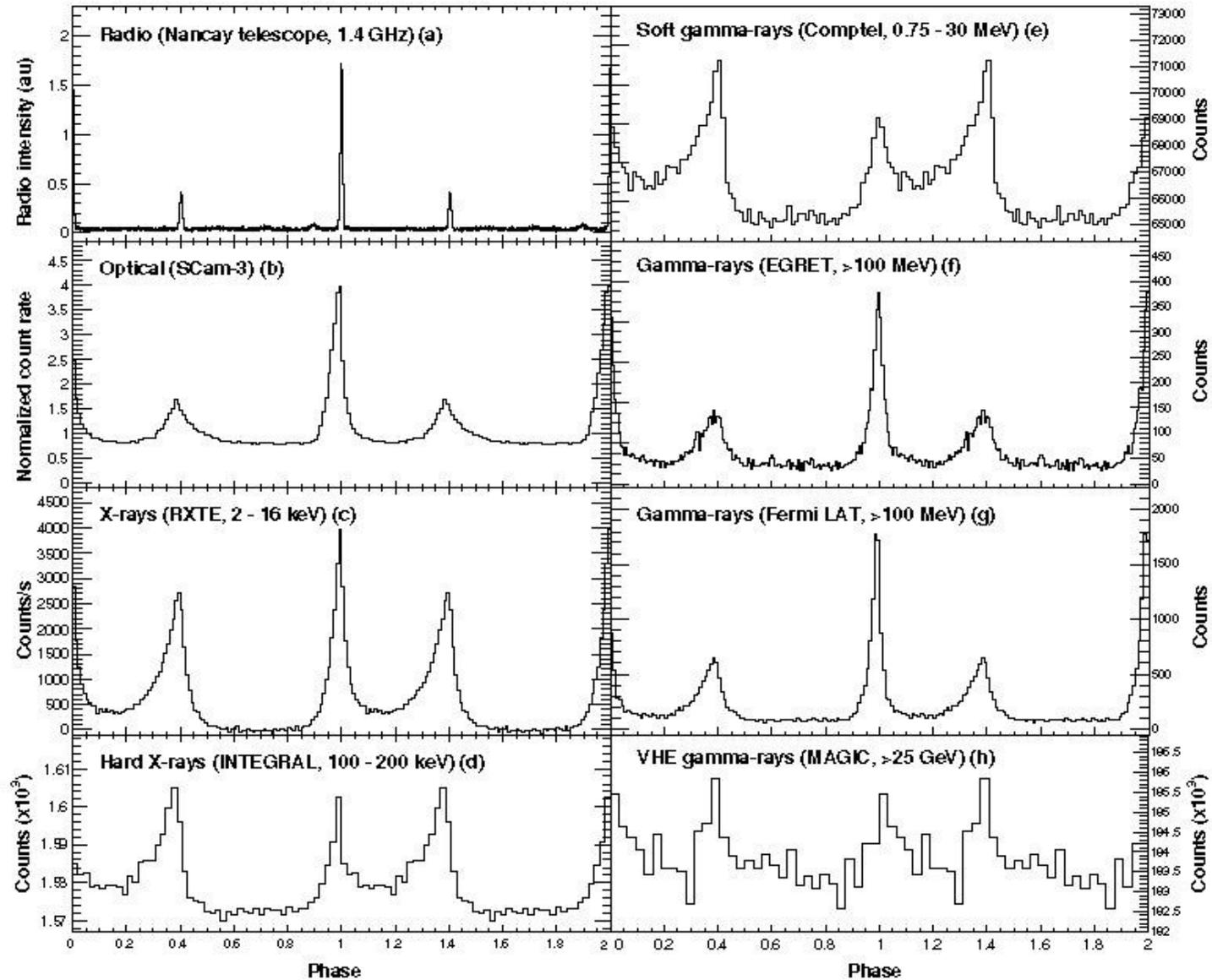
**FAST ROTATING PULSAR
(P = 33 msec)**

$L(\text{spindown}) = 5 \cdot 10^{38} \text{ erg/s}$

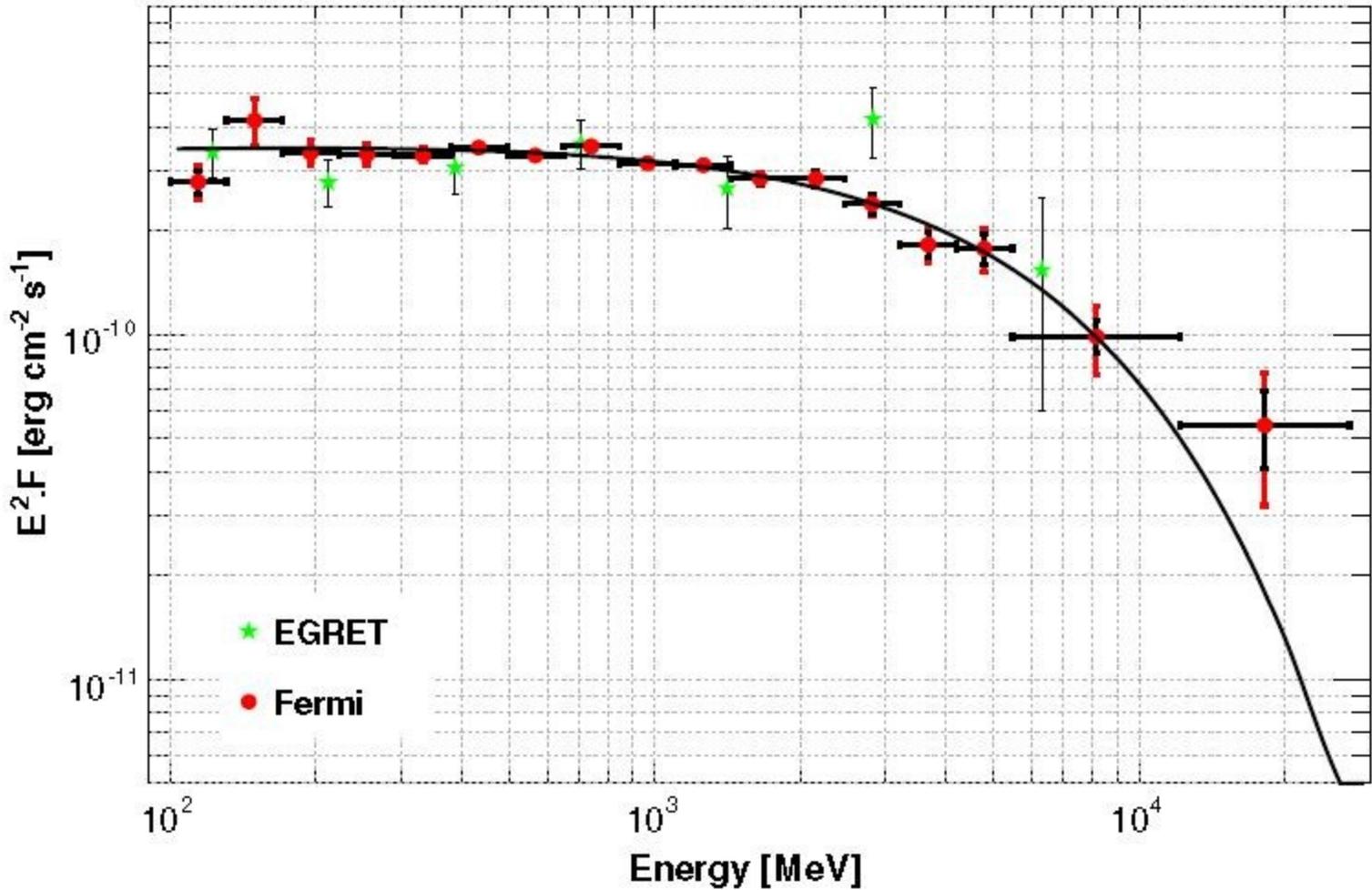
NON-SYMMETRIC relativistic pulsar wind (e⁺/e⁻, ions (?), $\gamma_0 \sim 10^2$ - 10^4)



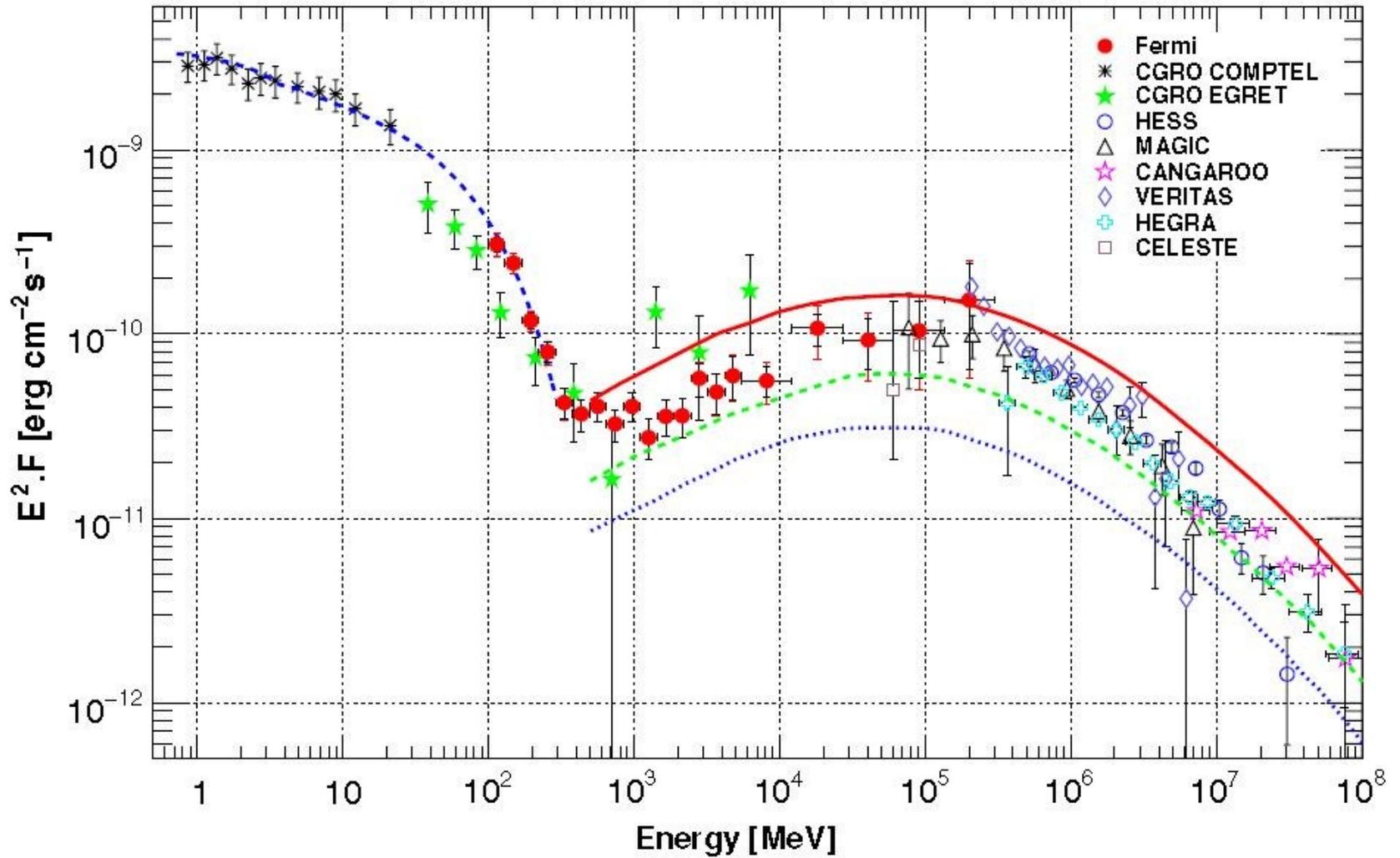
- $dN/dt = L_{sd} / (n \gamma m c^2) \sim 10^{40.5} \text{ s}^{-1}$.
- much larger than GJ ! pair multipl. factor $\kappa \sim 10^4$



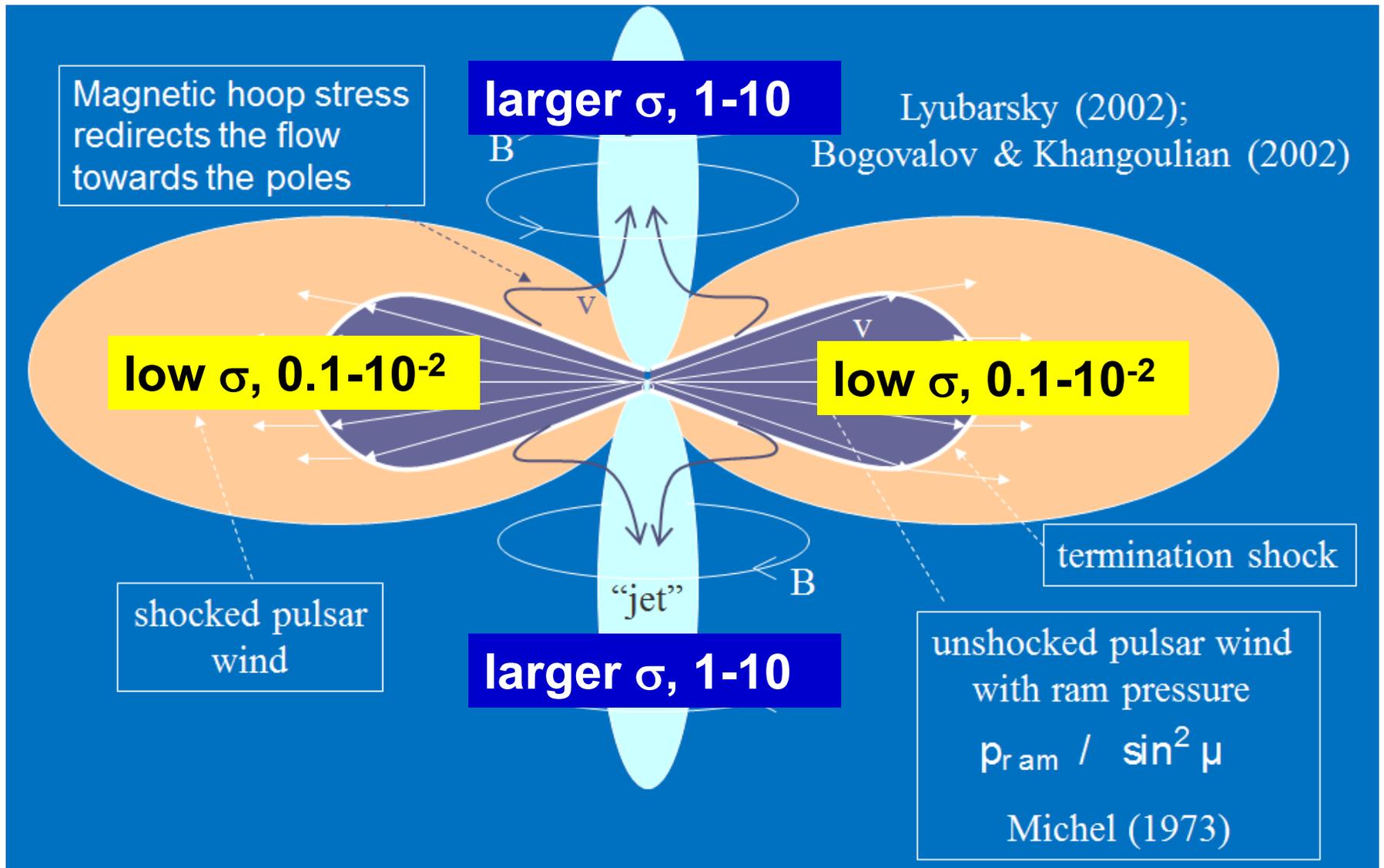
pulsed gamma-ray spectrum (Abdo et al 2010)



unpulsed (nebular) gamma-ray spectrum



MHD modelling, torus + jets (e.g., Komissarov et al 2011)



Credit: Serguei Komissarov