The flaring Crab Nebula: Surprises & Challenges

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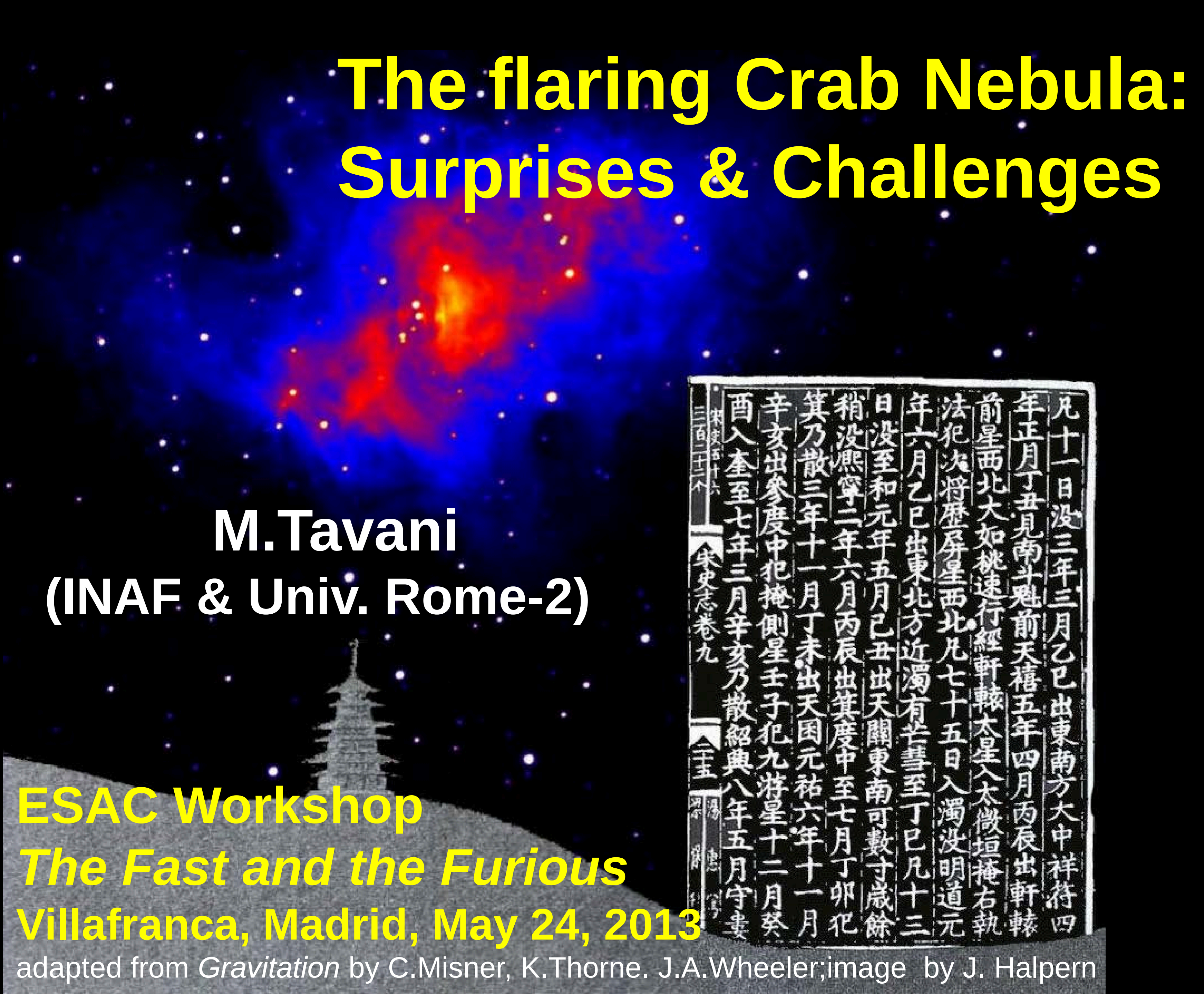
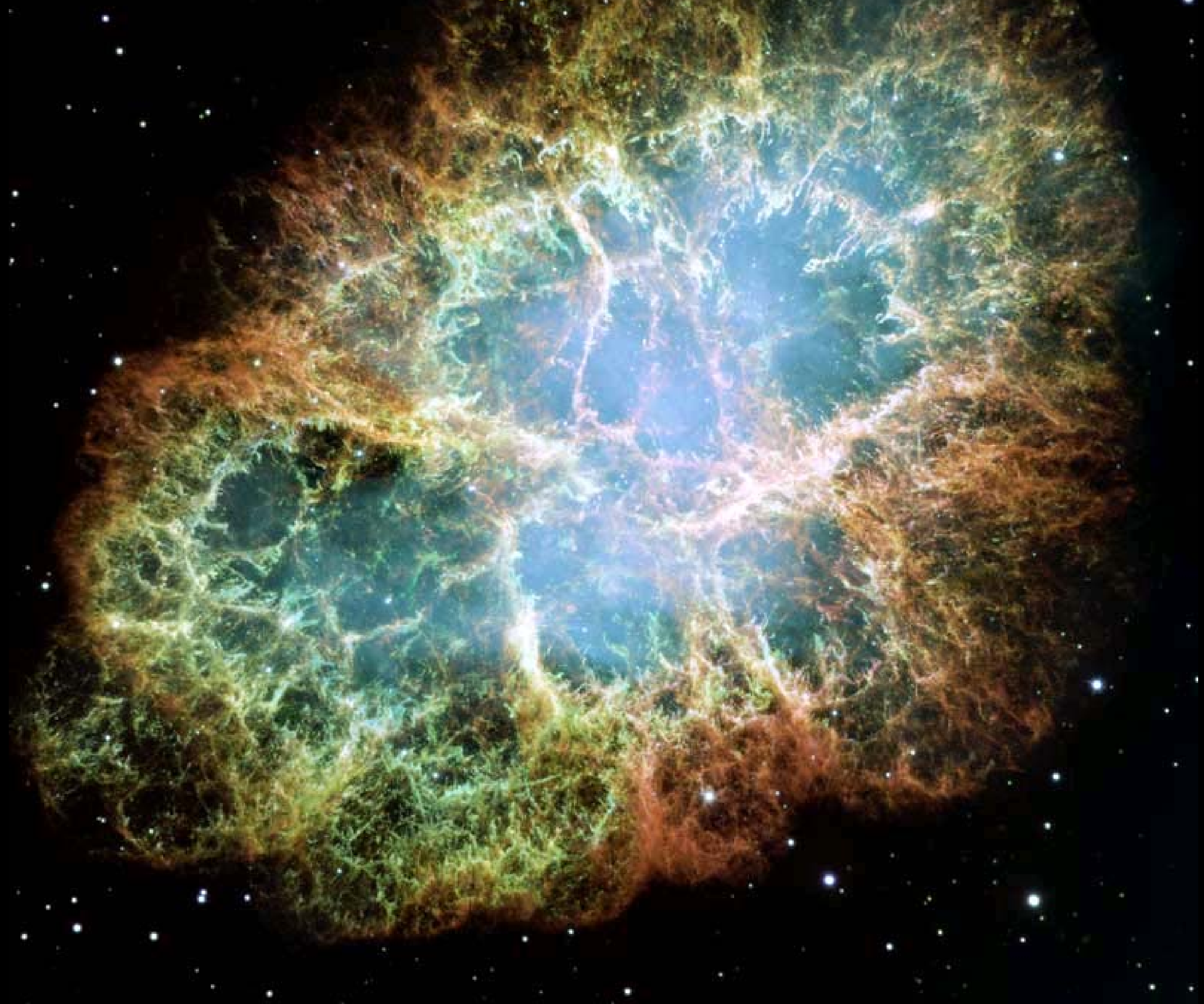
(INAF & Univ. Rome-2)



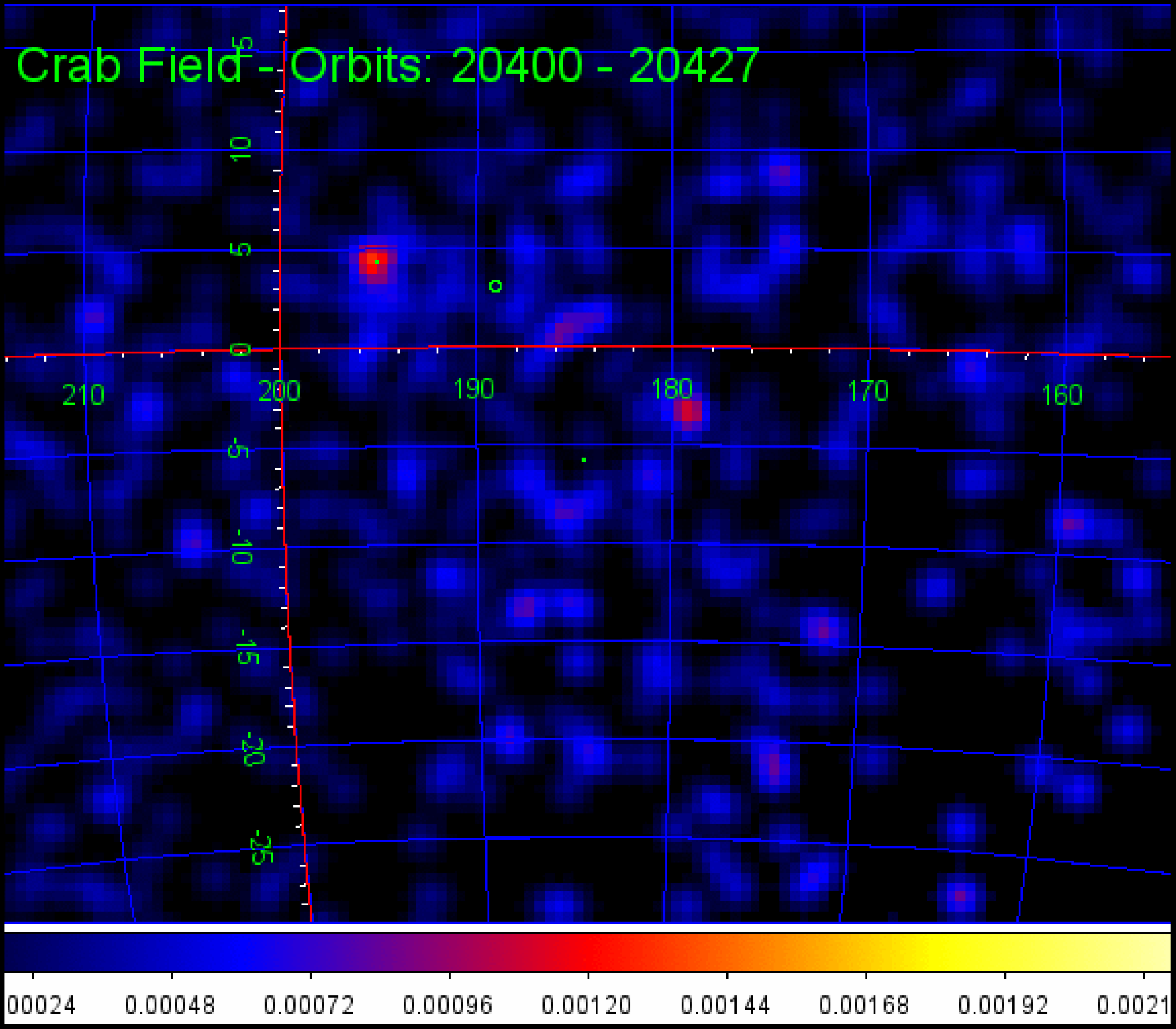
ESAC Workshop
The Fast and the Furious
Villafranca, Madrid, May 24, 2013

adapted from *Gravitation* by C.Misner, K.Thorne. J.A.Wheeler;image by J. Halpern

The Crab Nebula (M1) : the Queen of Nebulae



AGILE monitoring of the Crab (April 2011)



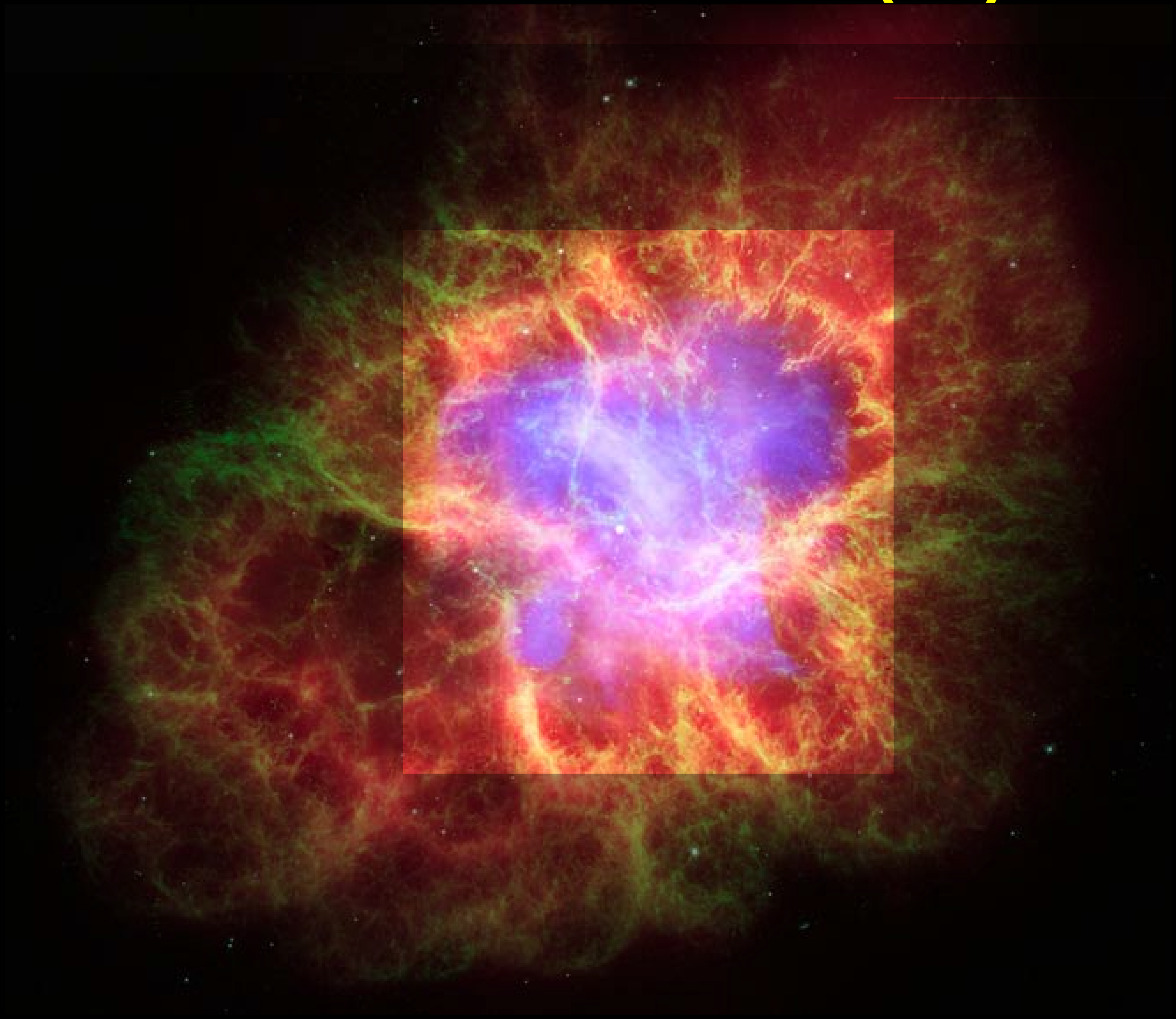
- **we are witnessing a very interesting and new phenomenon in the Crab.**
- **acceleration to extreme energies, with the particles' maximum energy limited by radiation reaction .**
- **super-acceleration (defying MHD approx.), mono-energetic distributions.**
- **large impact on a variety of objects, relativistic jets, feedback with laboratory plasmas.**

credits and acknowledgments

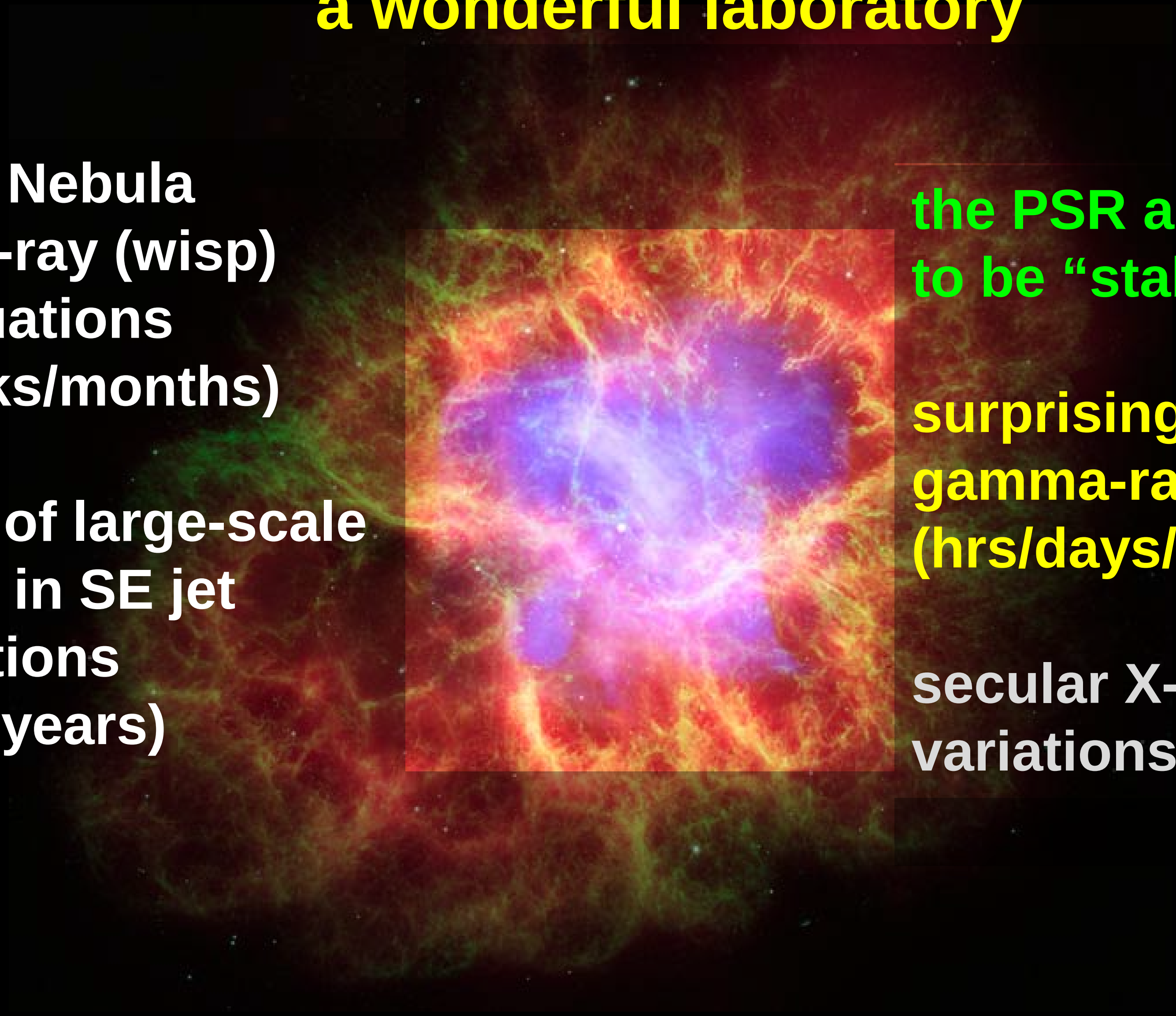
- AGILE Team
- Fermi Team (R. Buehler, …)
- M. Weisskopf, A. Tennant
- A. Ferrari, A. Mignone

- many discussions with J. Arons,
  R. Blandford, B. Coppi and many others…

The Crab Nebula (M1)



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)

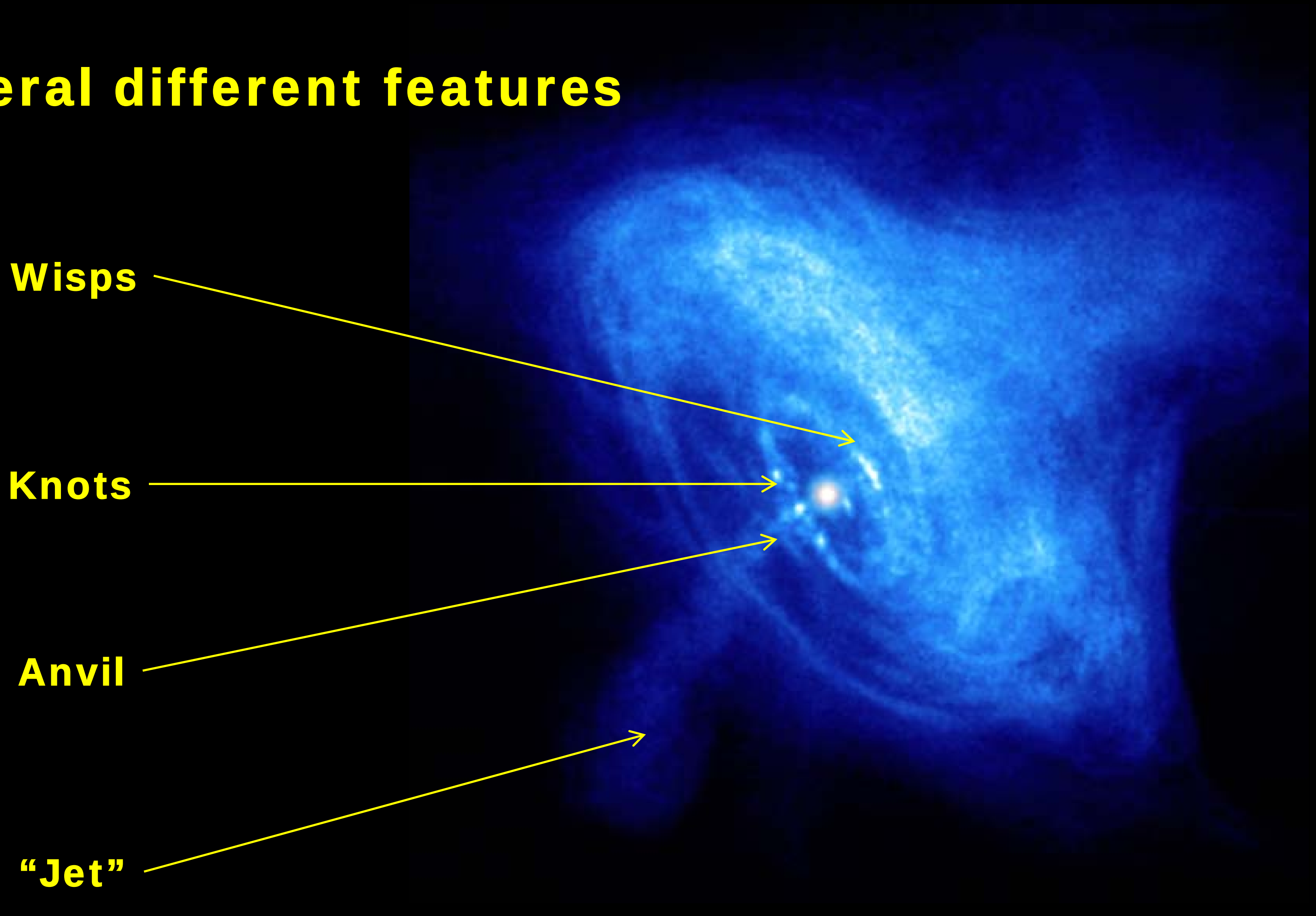
the PSR appears
to be “stable”

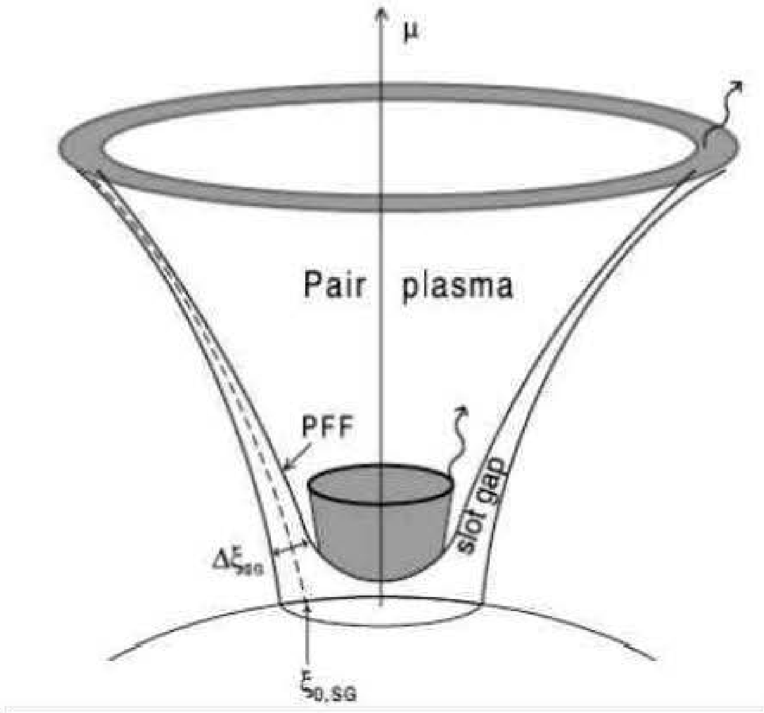
surprising
gamma-ray flares
(hrs/days/weeks)

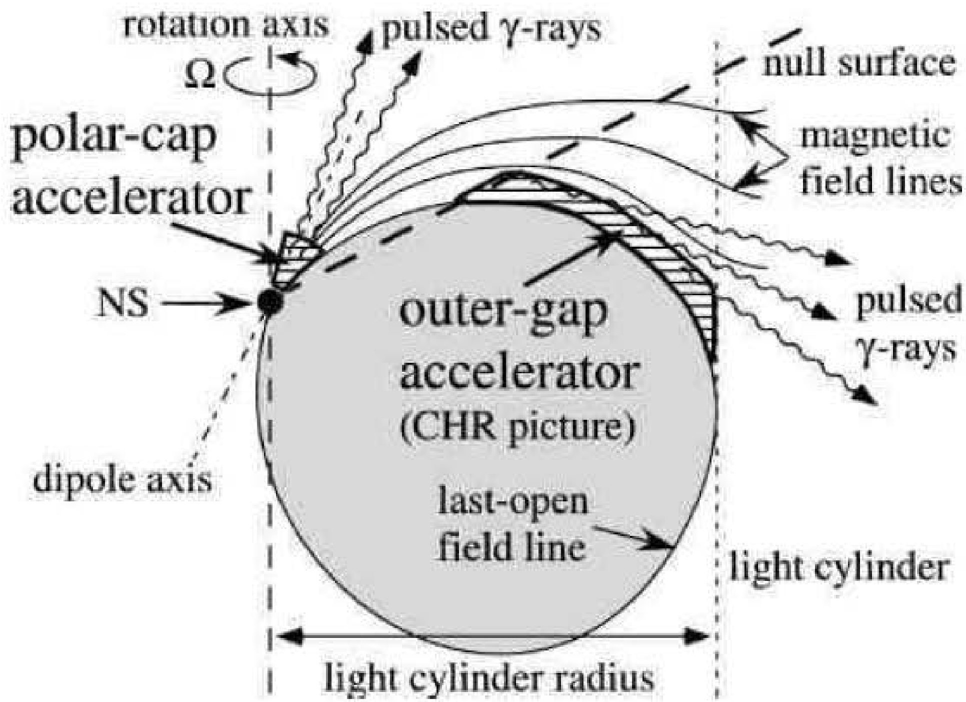
secular X-ray
variations (years)

Crab Nebula: X-ray imaging (Chandra: 1-10 keV)

Several different features

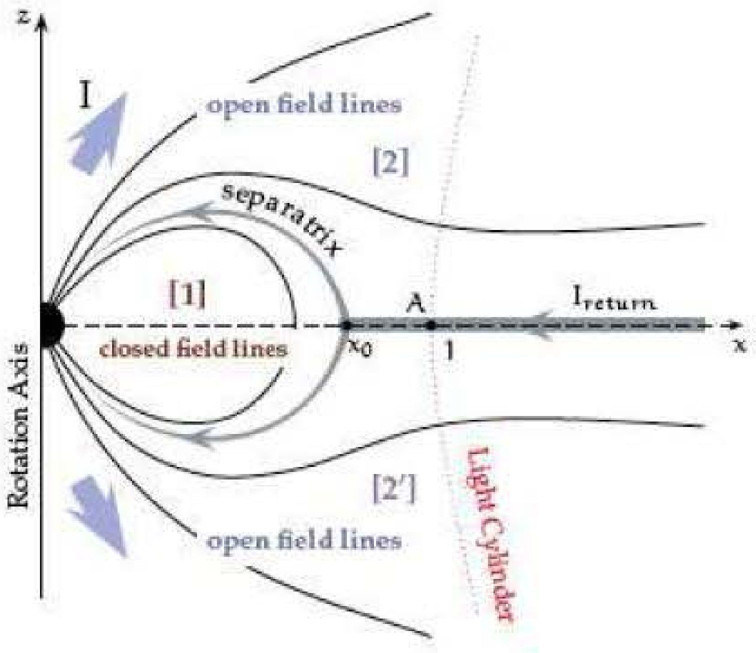


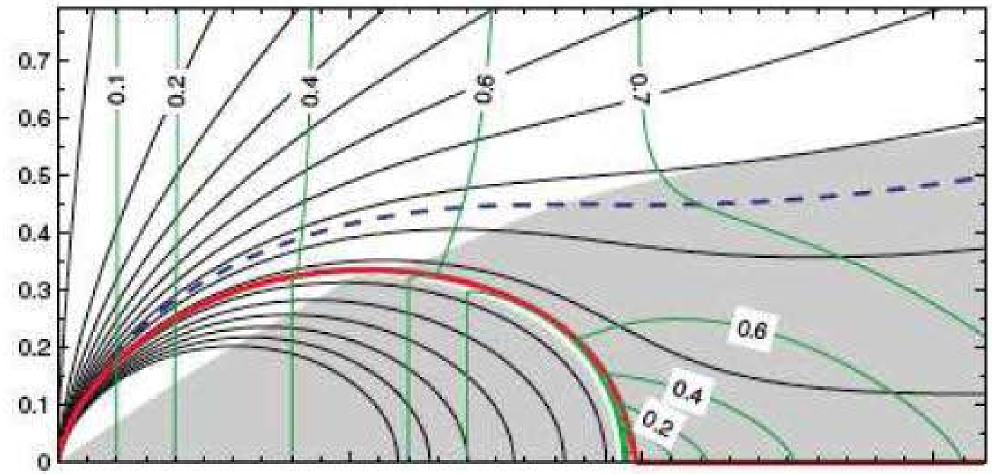




- Goldreich-Julian $n = -\, \mathbf{\Omega} \cdot \mathbf{B} / 2\pi e$

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

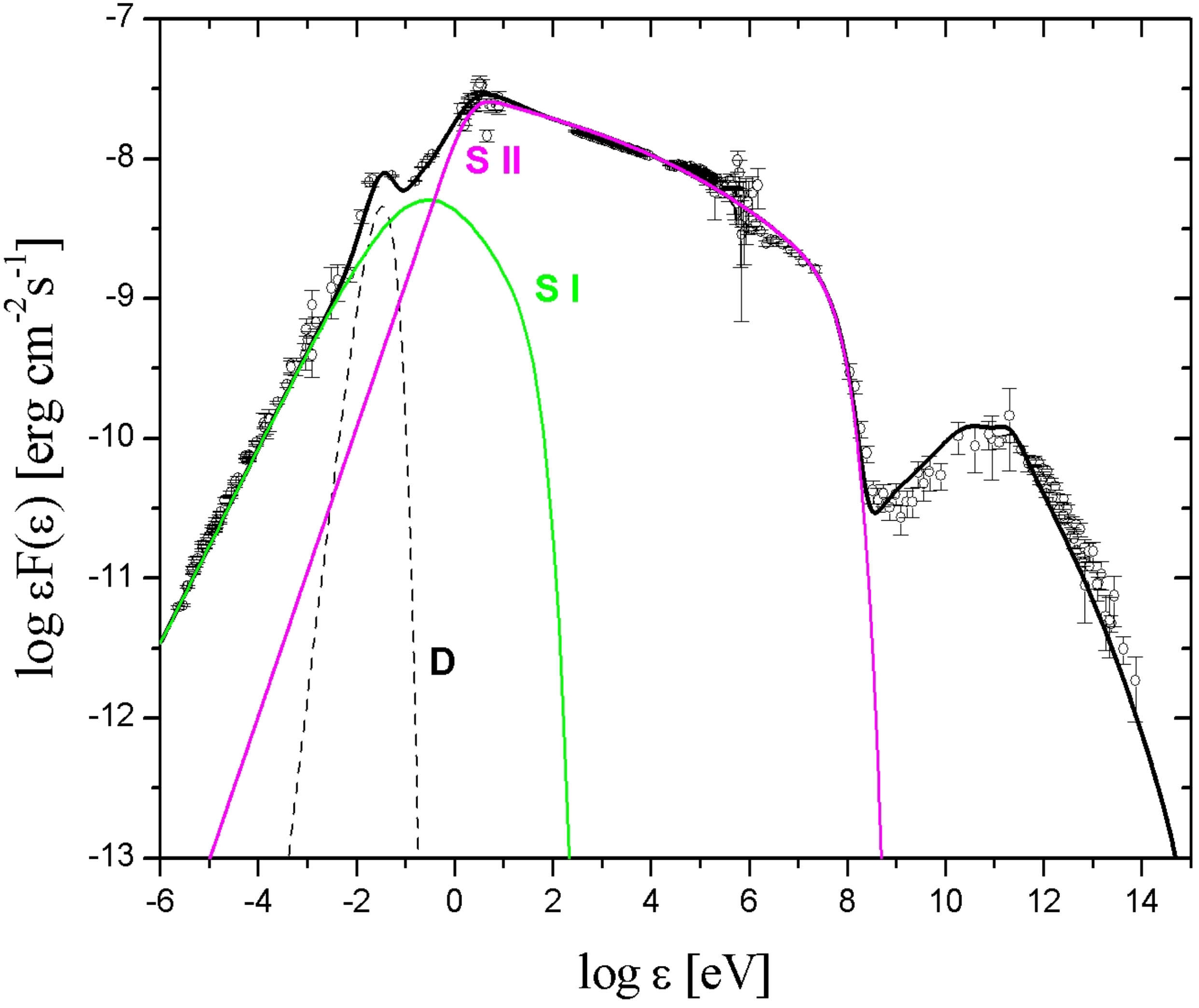




- **$dN/dt = L_{sd} / (n\, \gamma\, m\, c^2) \sim 10^{40.5}\ s^{-1}$.**
- **much larger than GJ ! pair multipl. factor $\kappa \sim 10^4$**

Crab Nebula spectrum from radio to TeV

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



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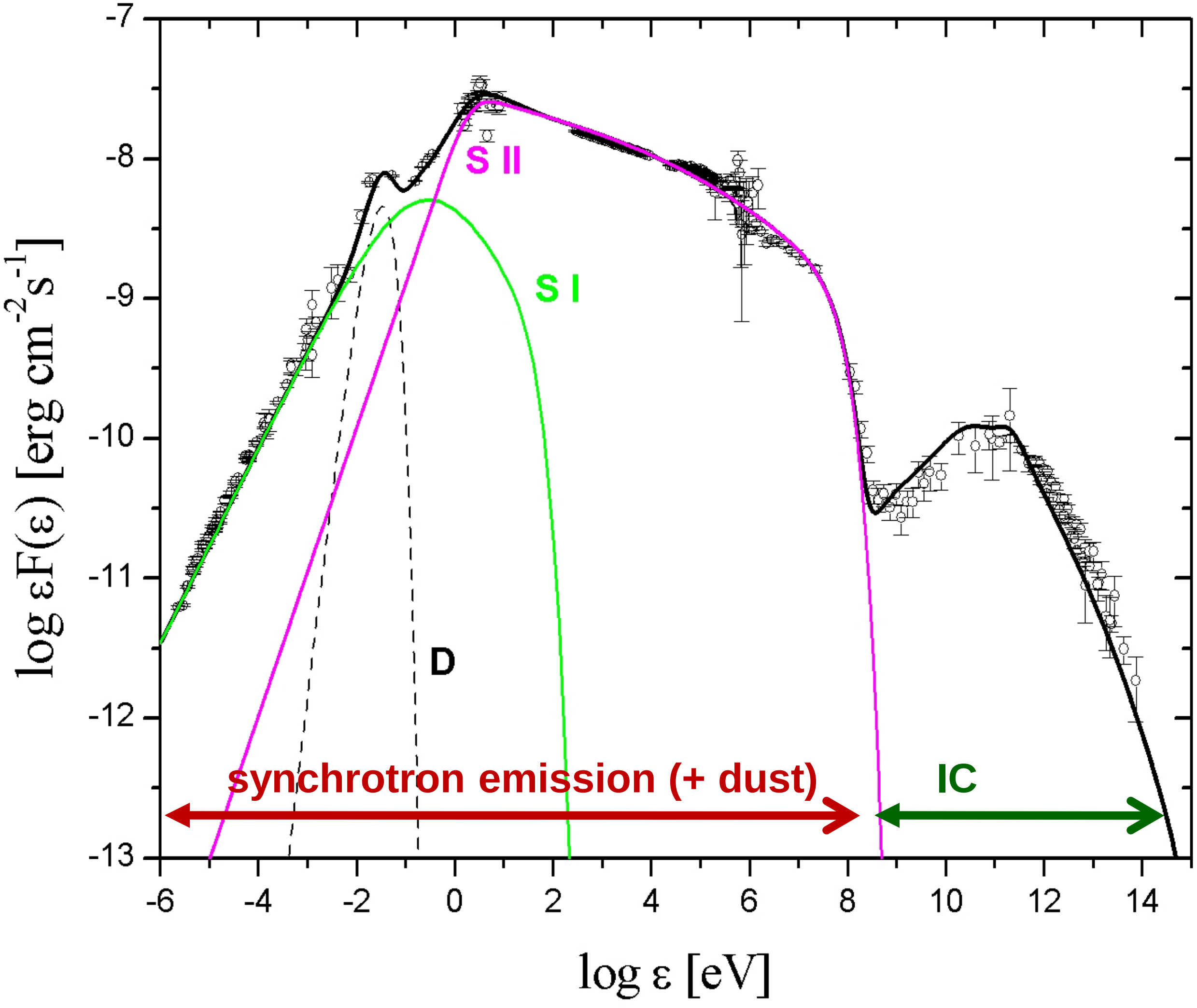


Pop. I

$60<\gamma<2.5\ 10^4$ $\alpha=1.6$

$2.5e4<\gamma<2.5e6$ $\alpha=4.0$

R=2.3e18 cm

N_{el}=2.5e51

T_{syn} ~ 10^5 years

Pop. II

$5e5<\gamma<3.8e8$ $\alpha=3.20$

$3.8e8<\gamma<3.5e9$ $\alpha=3.75$

R=2e18 cm

N_{el}=3e48

T_{syn} ~ 10 years

Dust

L=3e36 erg/s

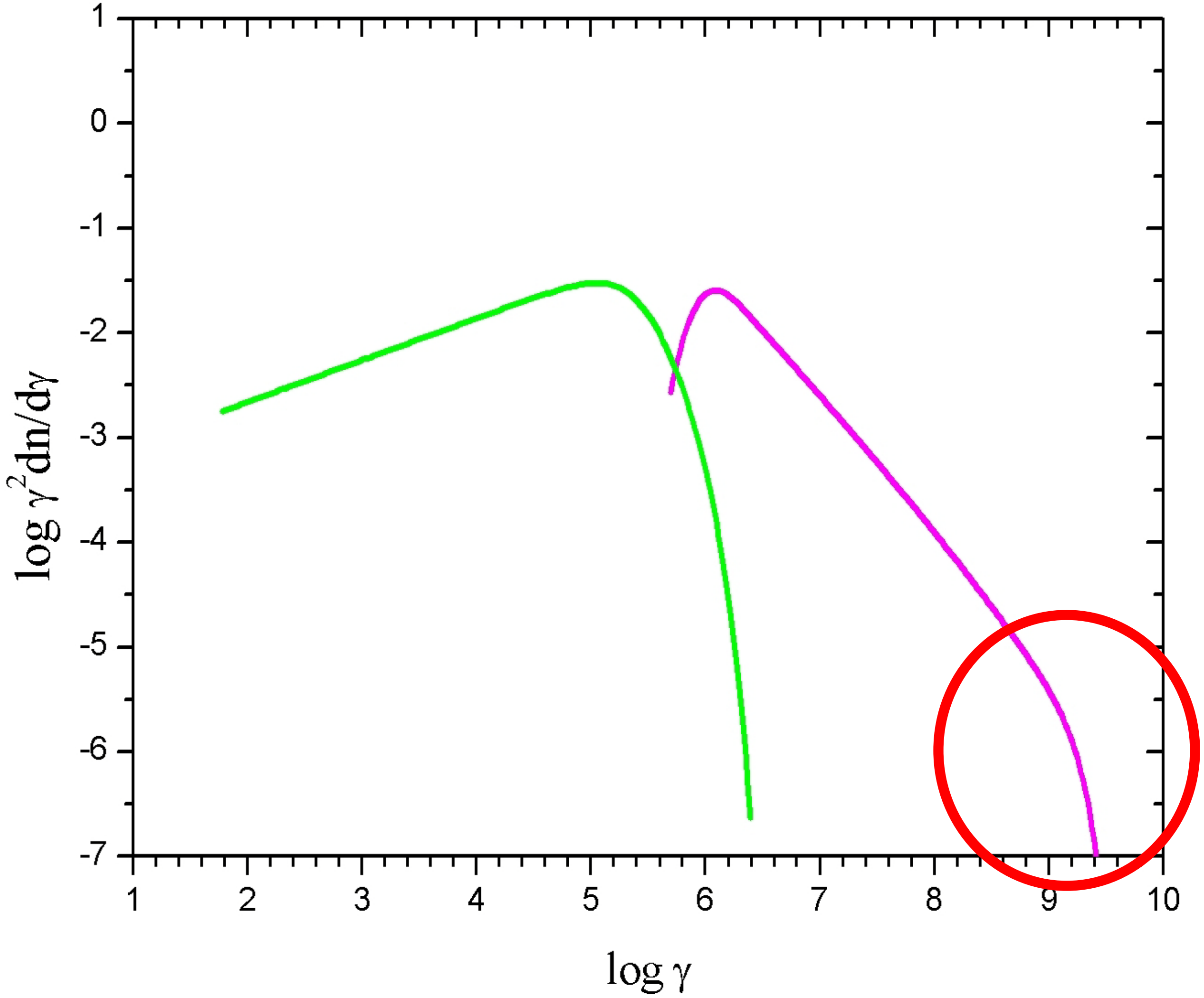
T=100 °K

Average magnetic field

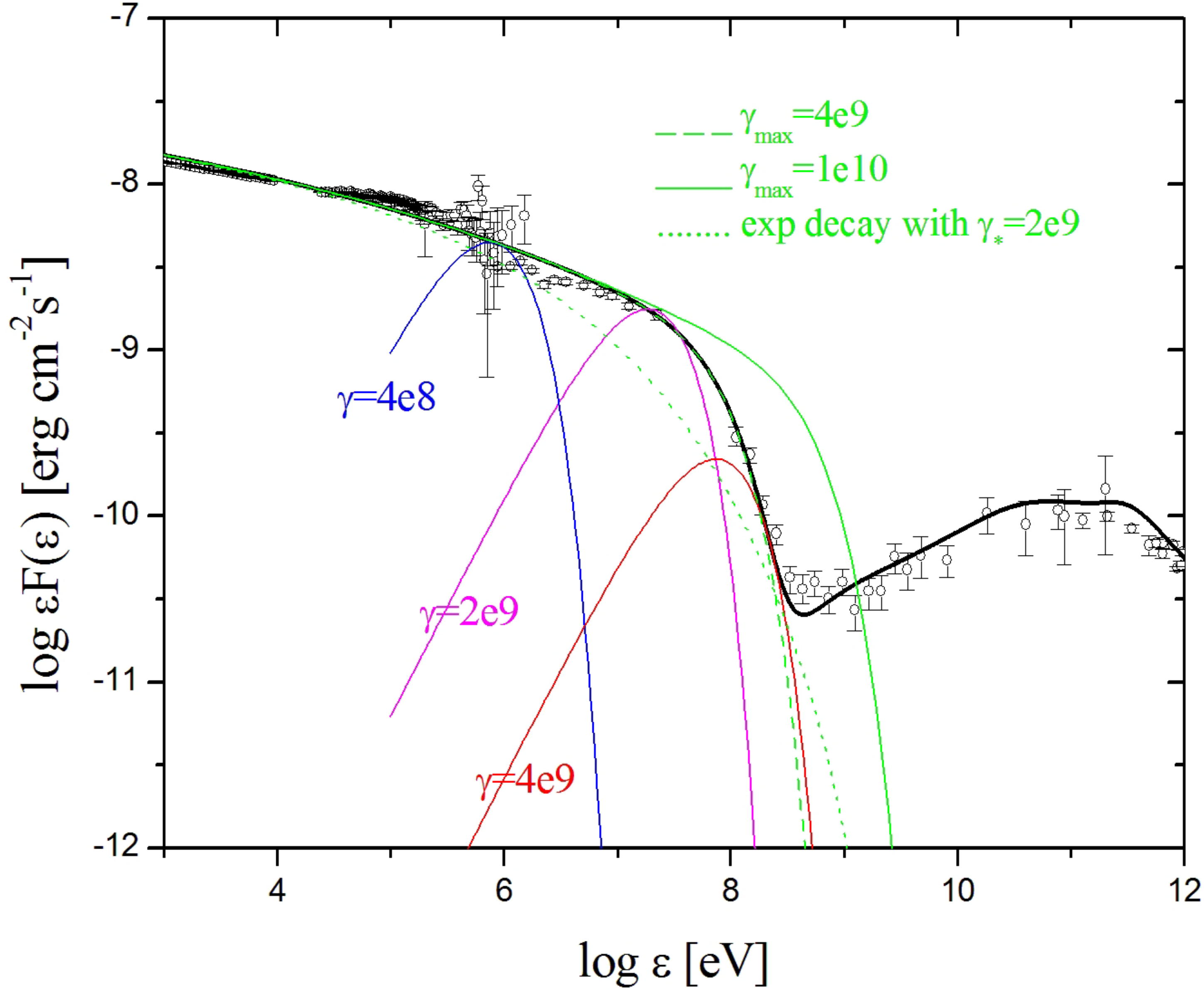
B=200 μGauss

(from Hester 2008)

particle distribution functions (Vittorini & M.T. 2011)



<B> = 200 micro G



γ_{max}=4e9
γ_{max}=1e10
exp decay with γ_*=2e9
γ=4e8
γ=2e9
γ=4e9
-7
-8
-9
-10
-11
-12
4
6
8
10
12
log εF(ε) [erg cm^{-2}s^{-1}]
log ε [eV]

Crab Nebula modelling

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

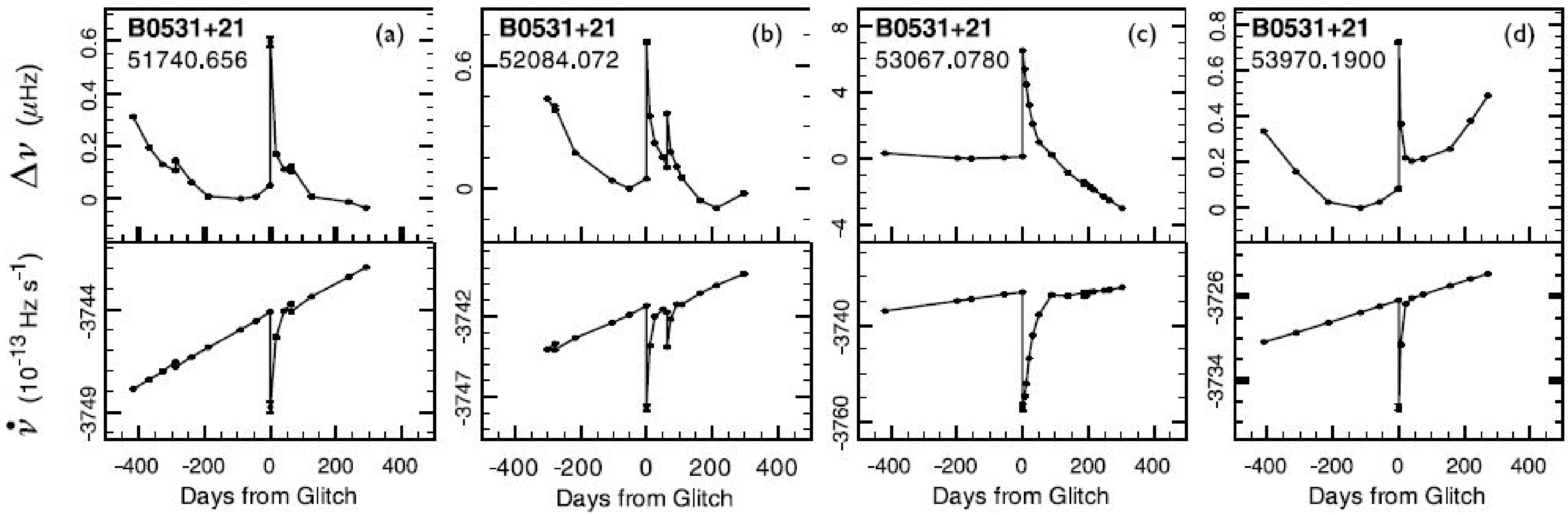
a variable Crab ?

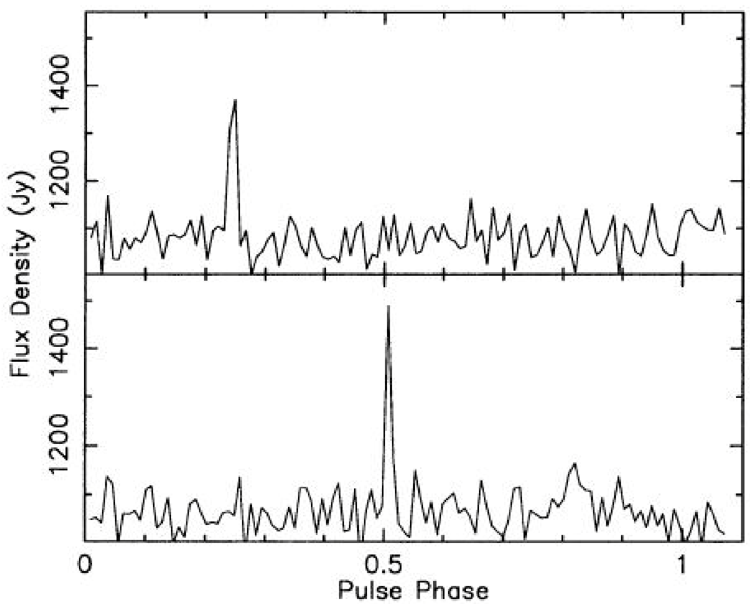
- yes, wisp and knot flickering, continuous outflow from the PSR

- PSR radio glitches, giant radio flares (no correlation with high-energy emission)

- some unconfirmed claims
  - e.g., Oct. 6, 1971 vs. July 23, 1973 difference in pulsed and unpulsed emission K.Greisen et al. ApJ, 197, 471 (1975)

Crab PSR glitches (Espinoza etal. 2011)



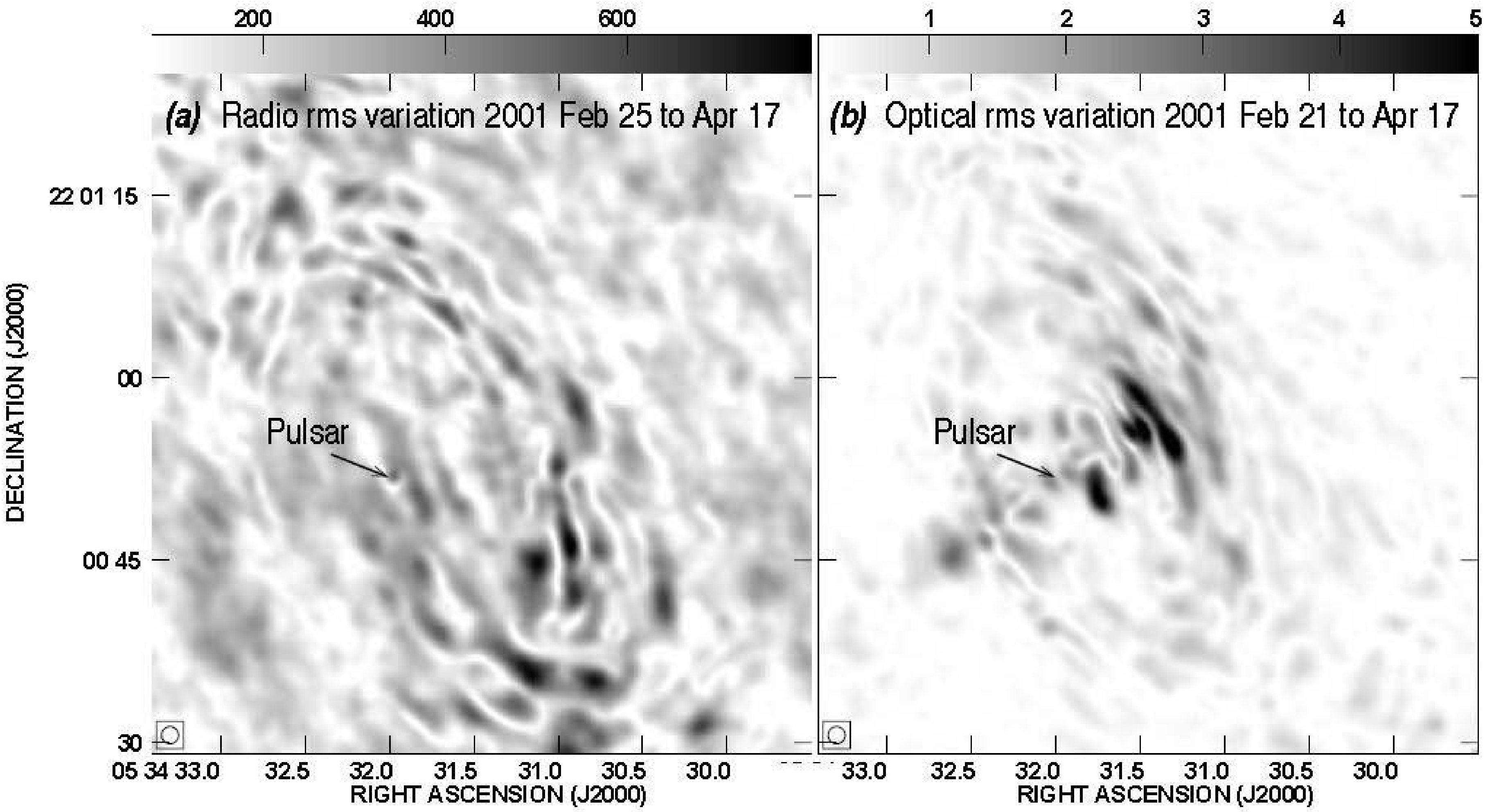


Crab PSR giant pulse (Cordes etal. 1995)

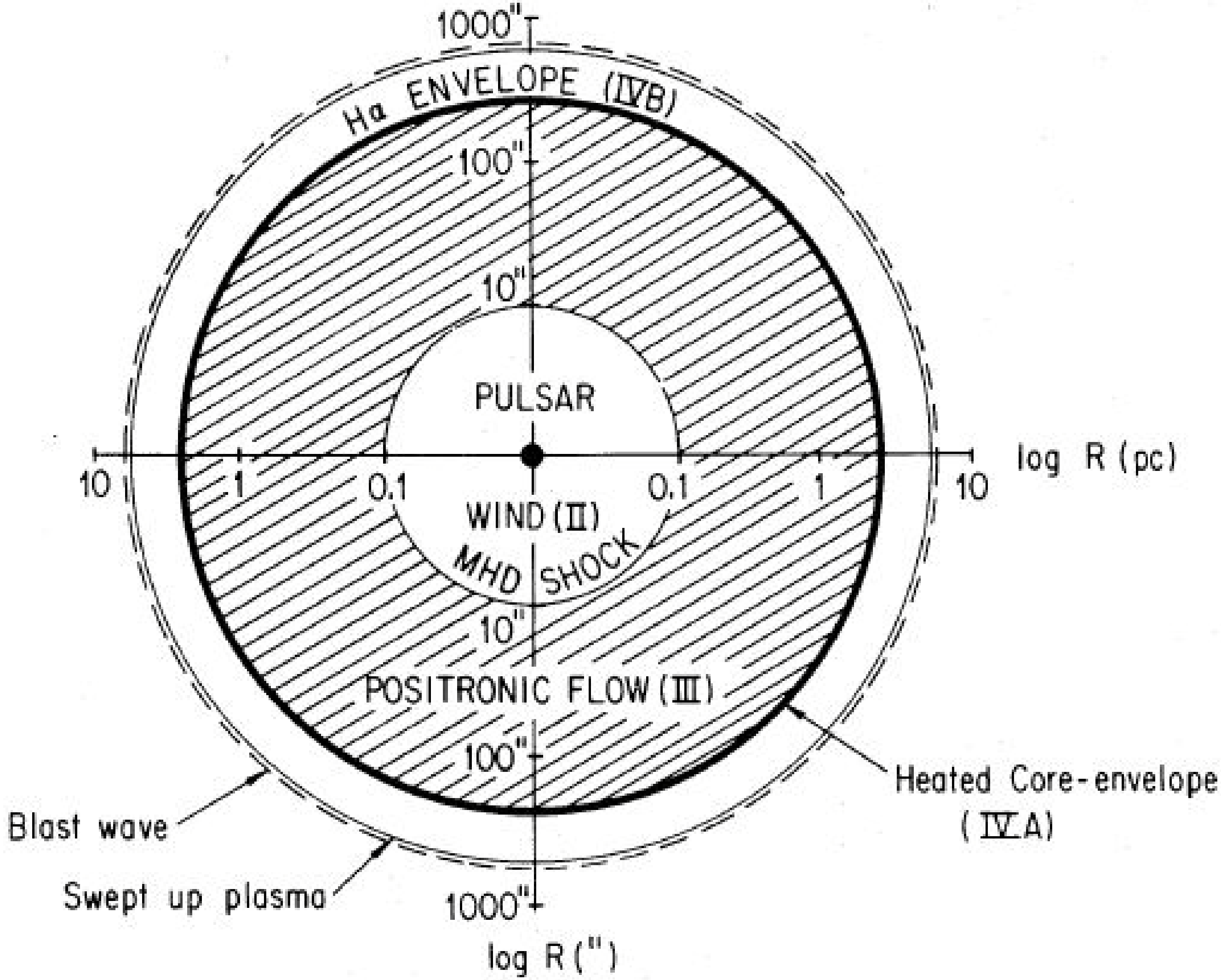
No evidence of connection with nebular variability

Crab Nebula variations

(Bietenholz M.F., Hester J.J., Frail D.A., Bartel N., 2004)



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



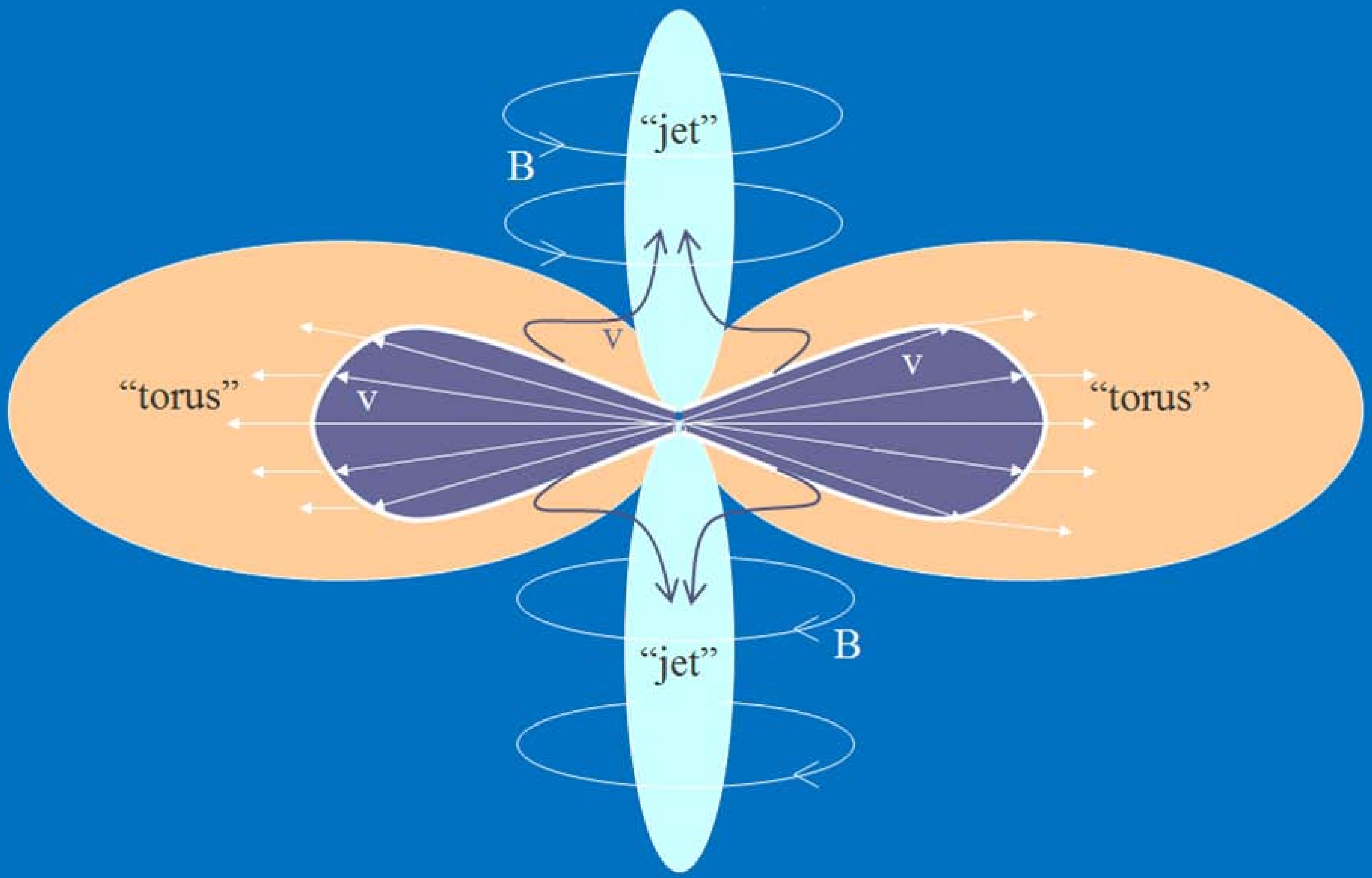
KC MHD modelling:

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

KC solution in the toroidal shock: $\sigma \le 0.01$

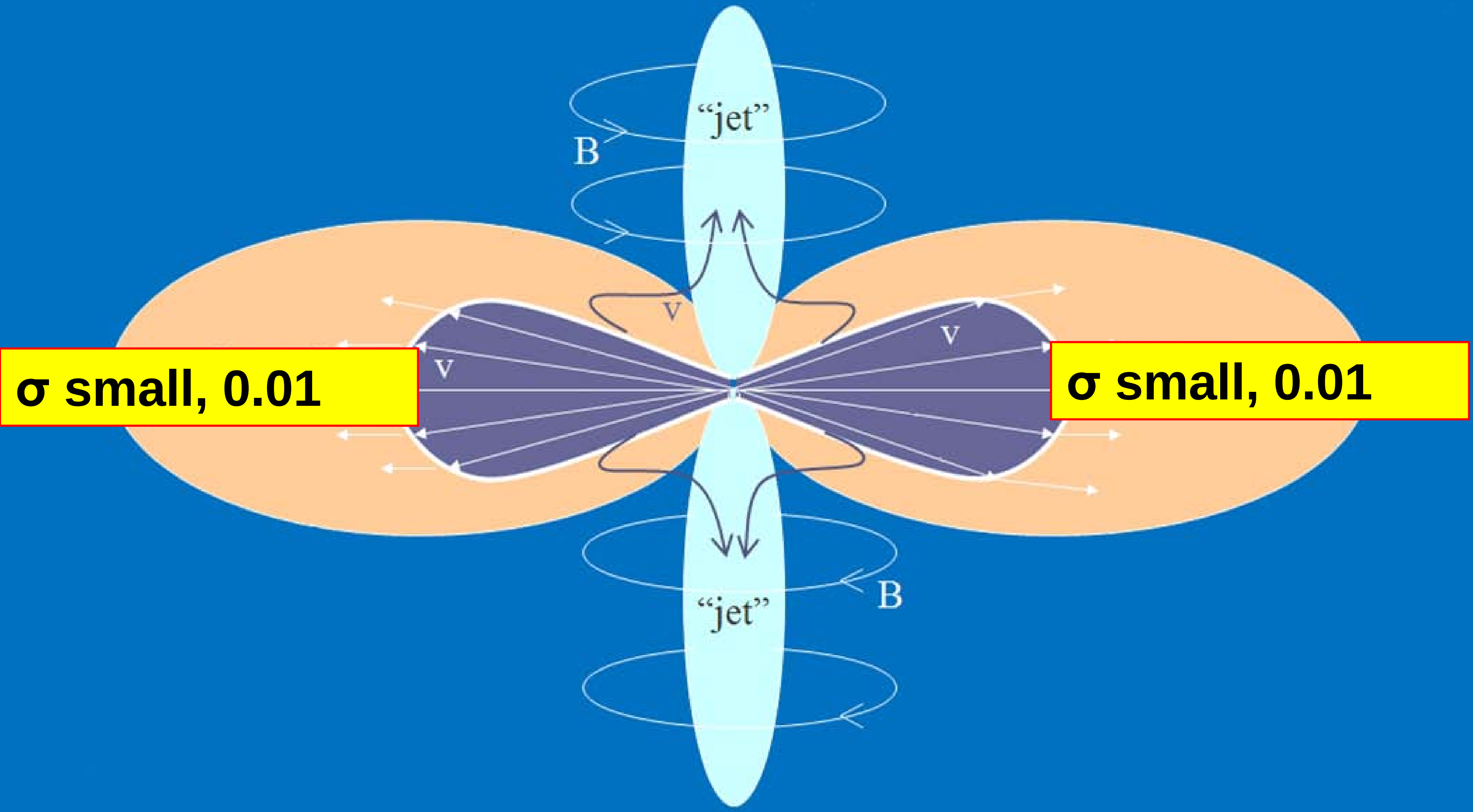
sigma-problem

modelling the Crab PSR wind, torus + jets



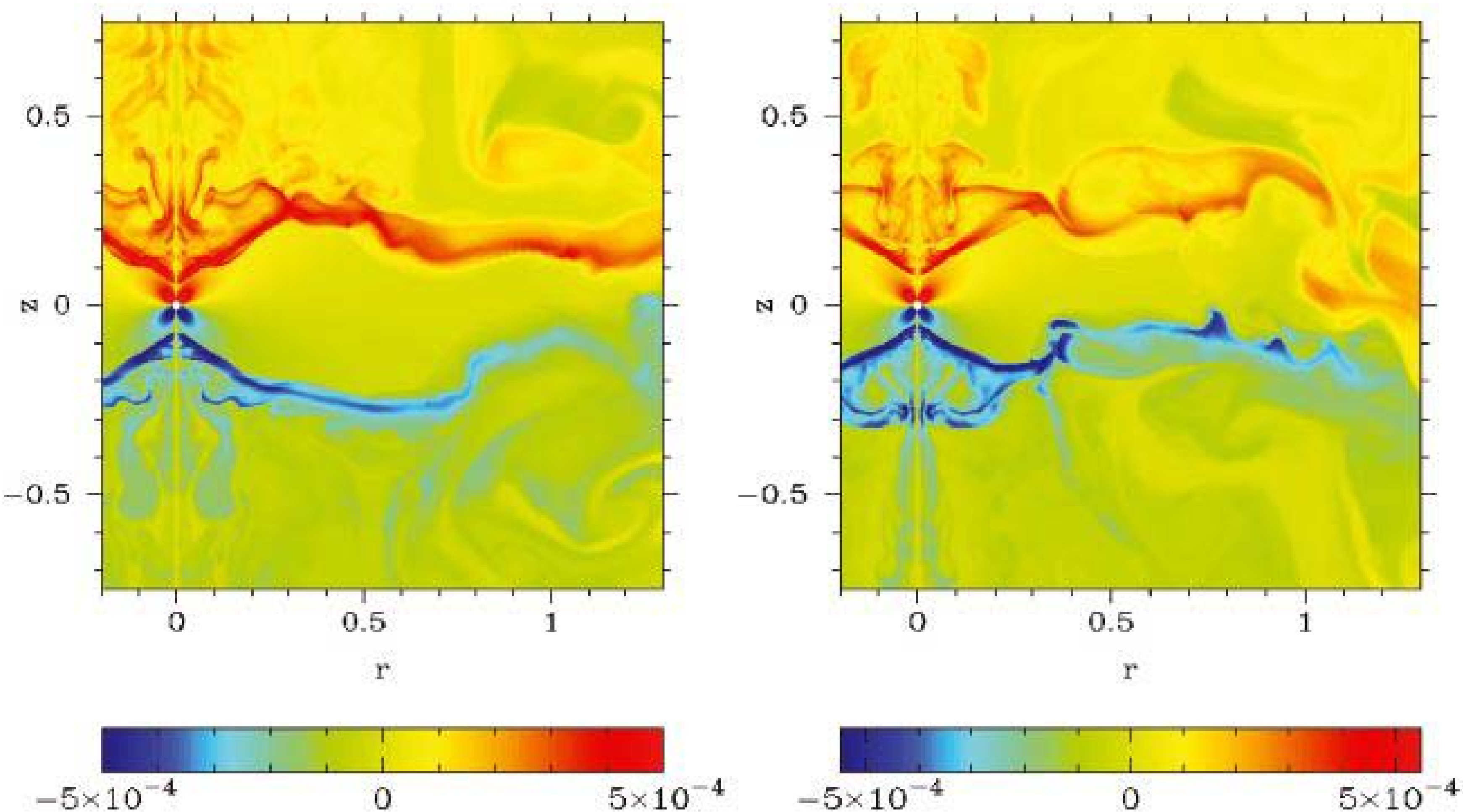
adapted from S. Komissarov (2011)

modelling the Crab PSR wind, torus + jets



adapted from S. Komissarov (2011)

Camus, Komissarov, Bucciantini, Hughes, MNRAS, 400, 1241 (2009)

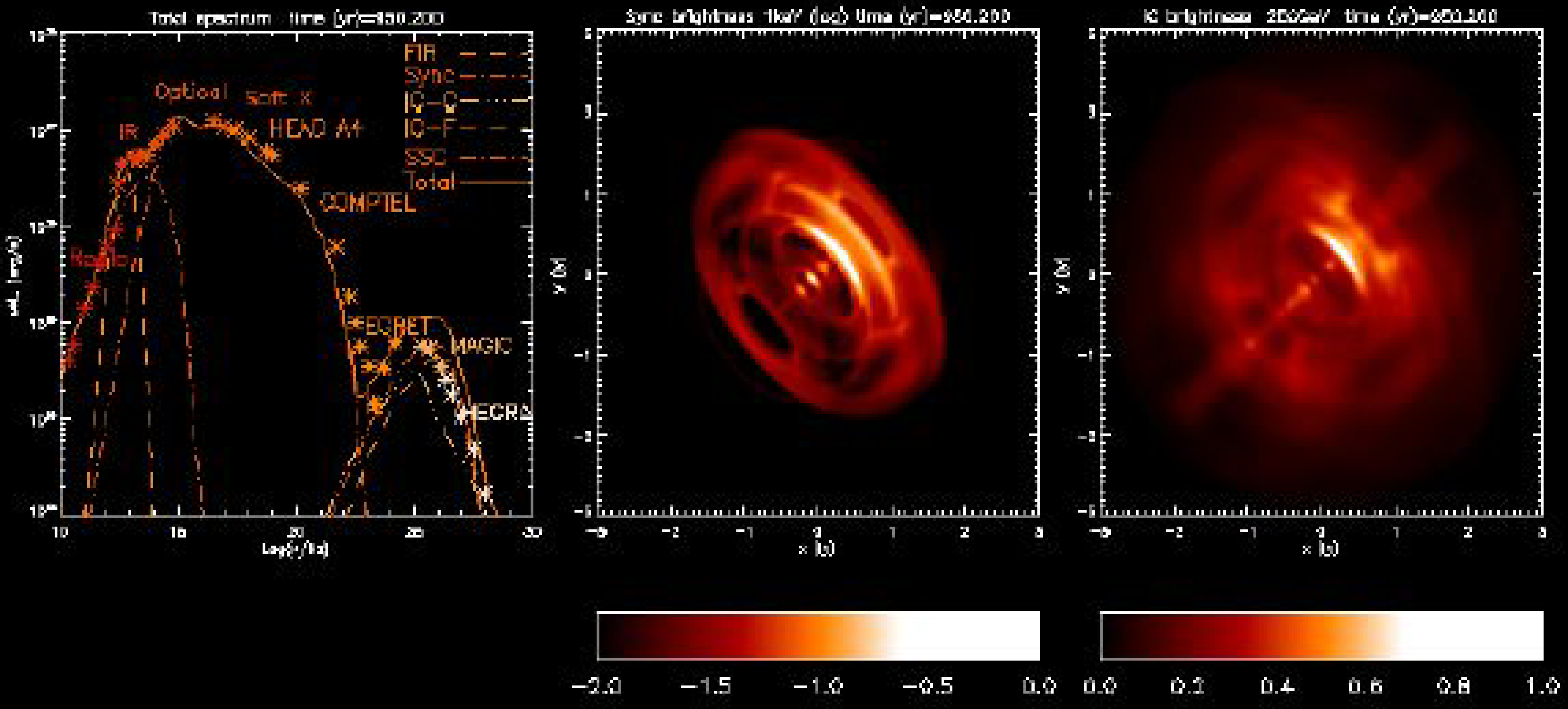


Magnetic field profile at different times

Variability in MHD models

From the Arcetri group

Courtesy E. Amato



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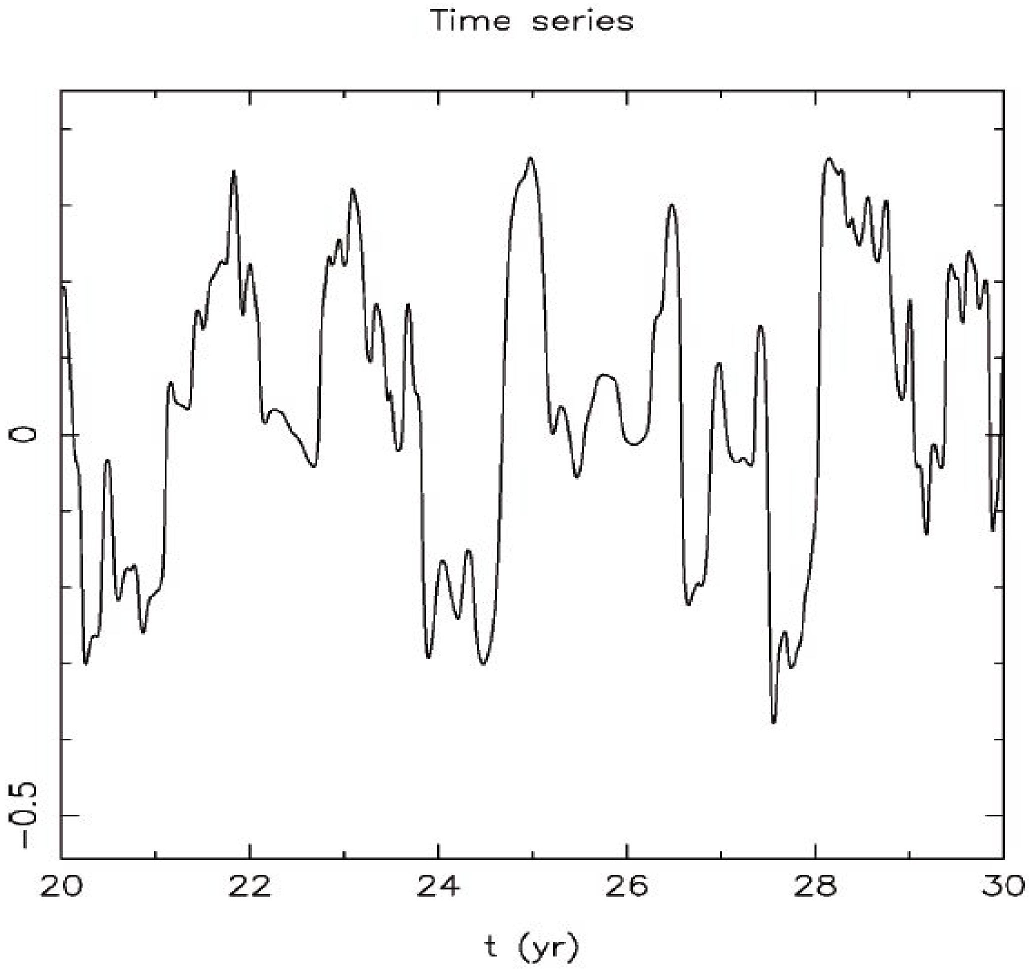
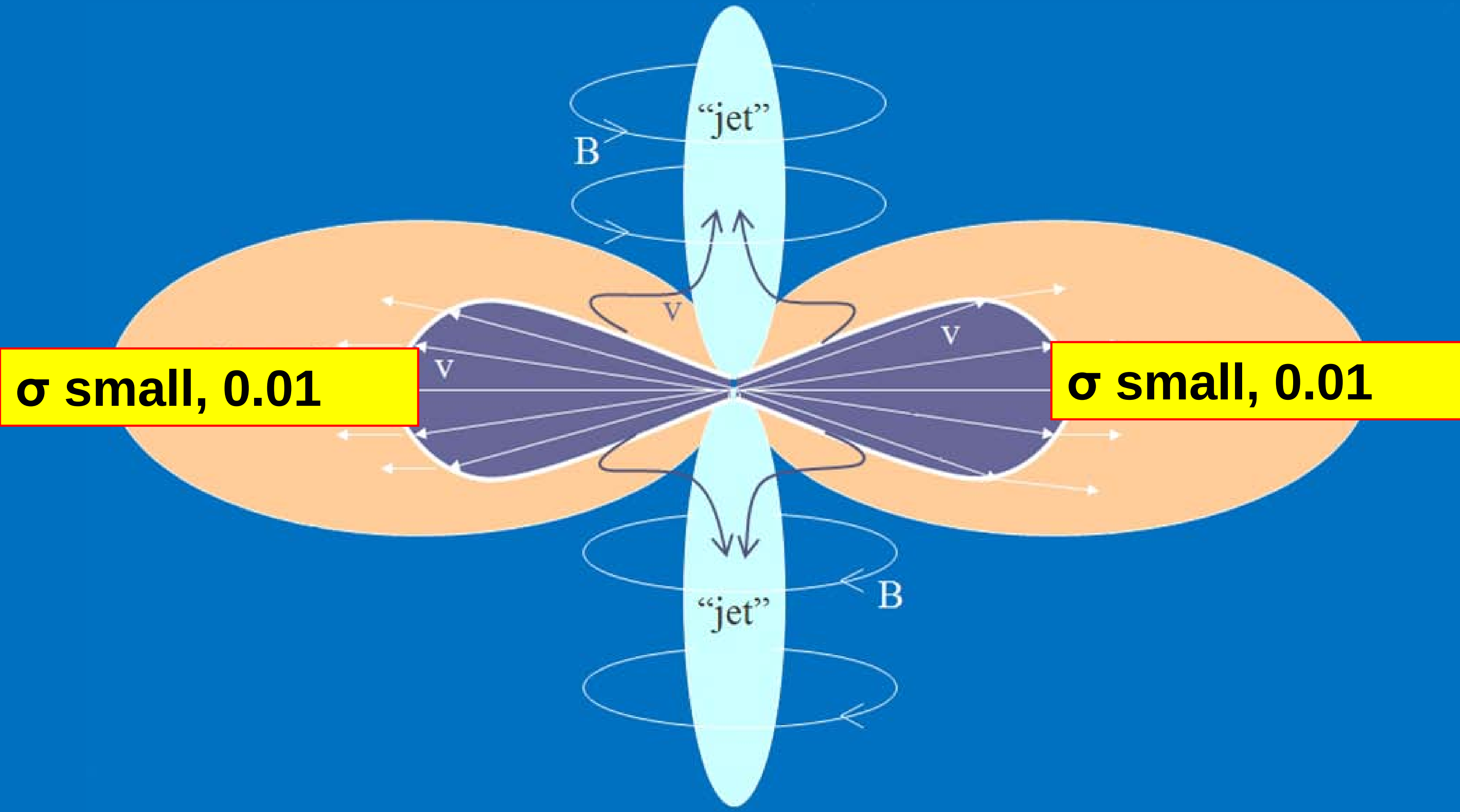


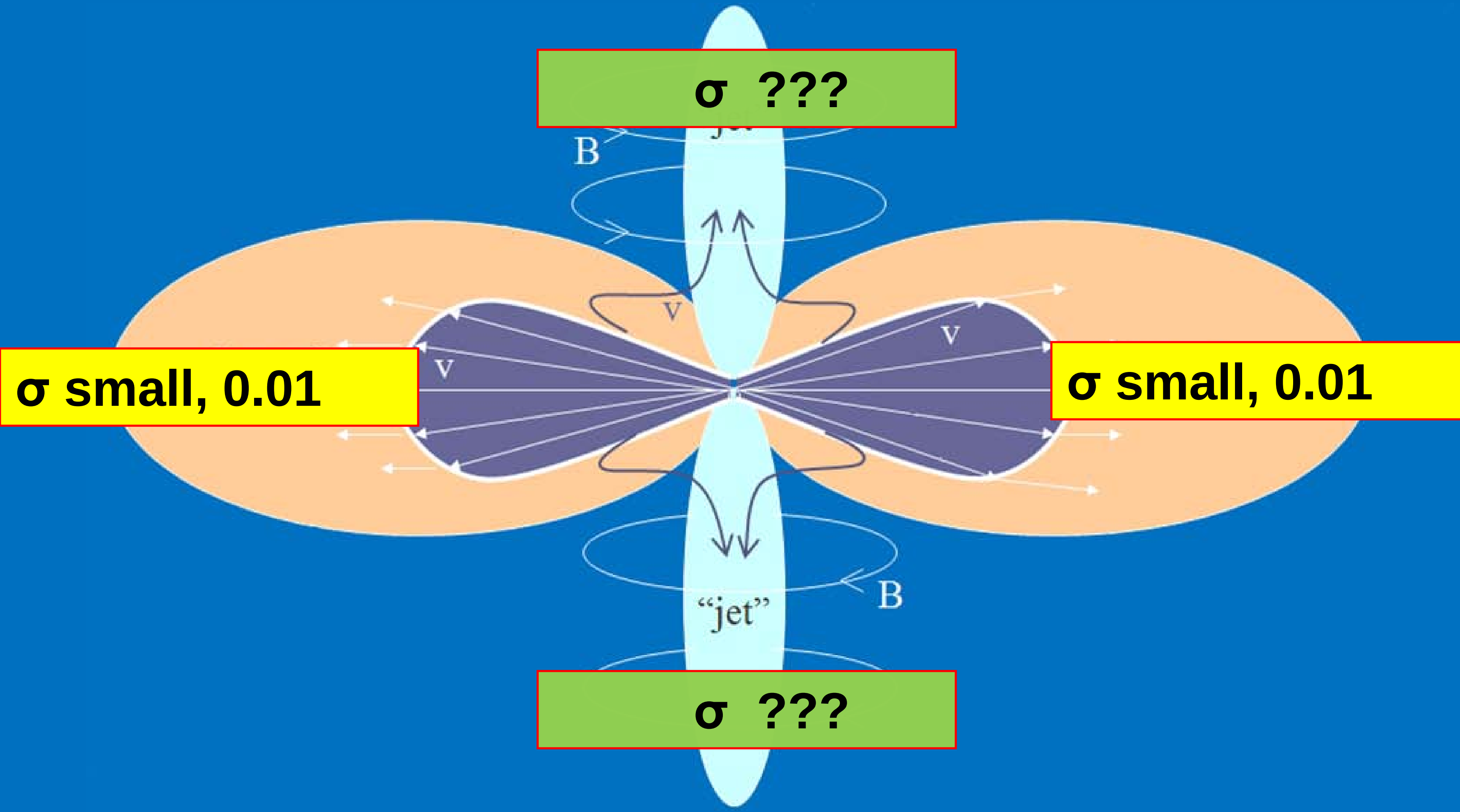
local magnetic field energy density

modelling the Crab PSR wind, torus + jets



adapted from S. Komissarov (2011)

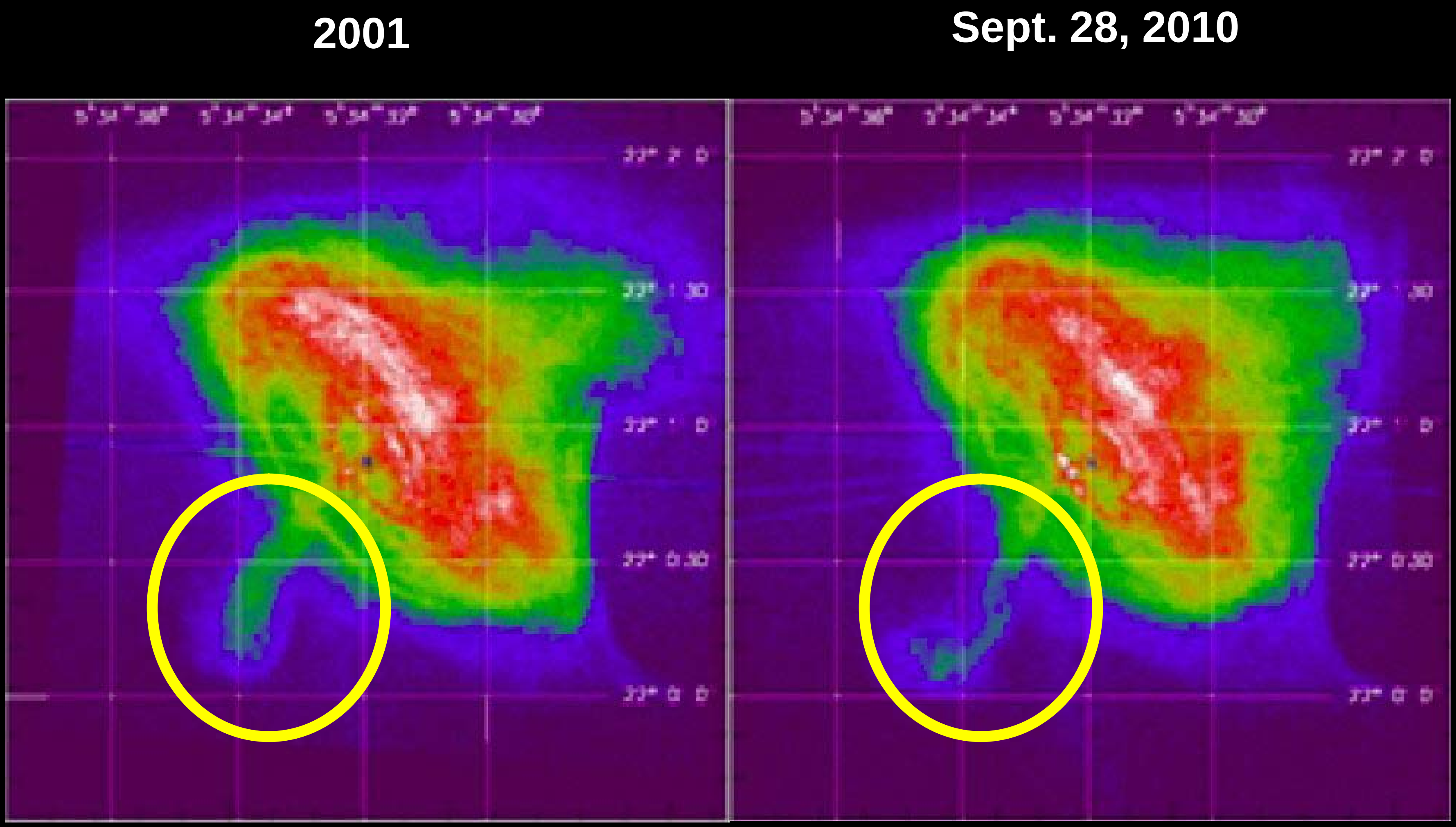
modelling the Crab PSR wind, torus + jets

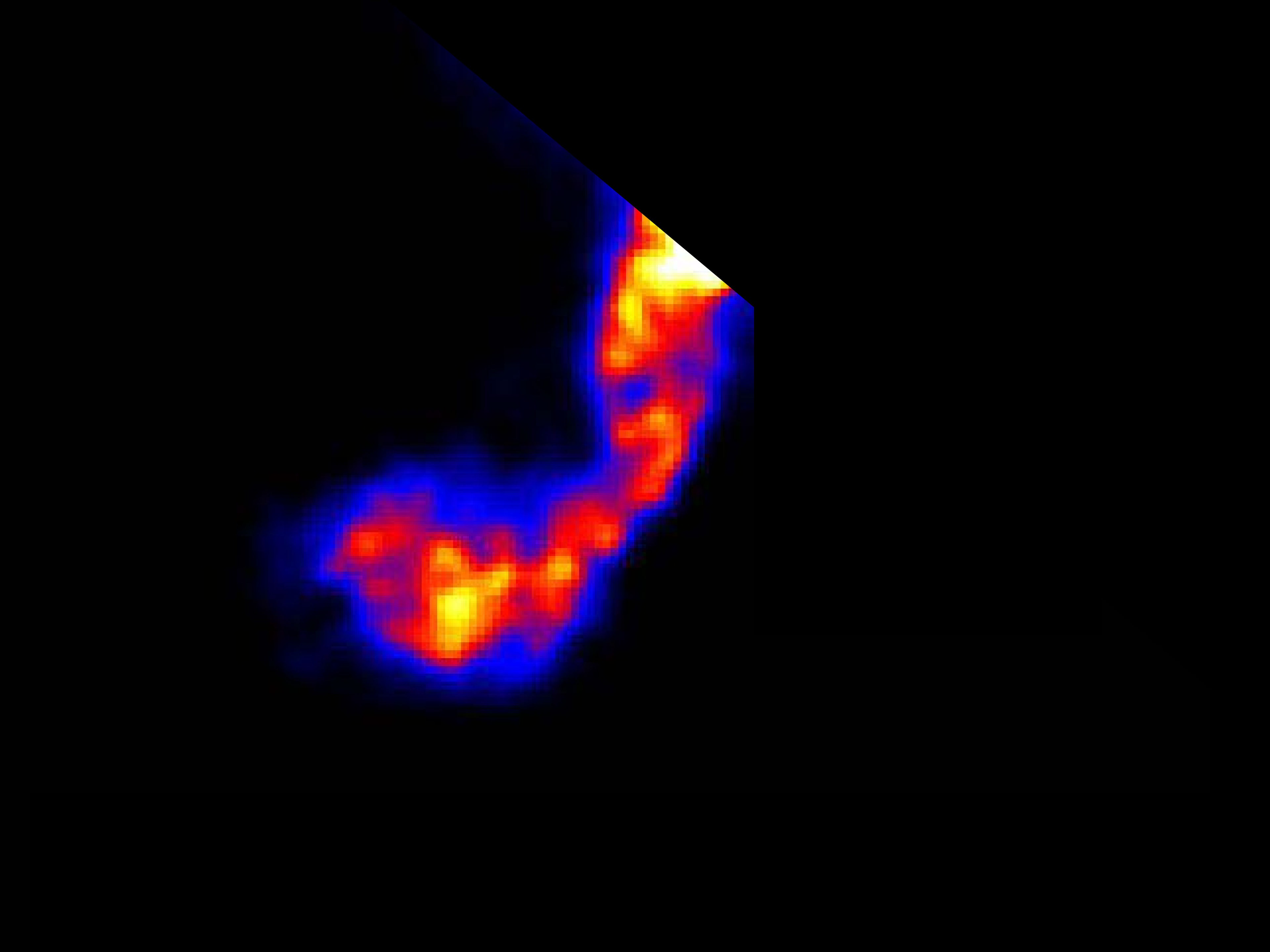


adapted from S. Komissarov (2011)

Large scale variations of the SE jet

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





an MHD accel. framework

(de Jager, Harding etal. 1996)

- particle acceleration by shocks or MHD/plasma instabilities, assumes E/B = 1
- $t_{acc}^{-1} \sim \alpha' \omega_B / \gamma \quad (\omega_B = eB/mc; \quad \alpha' < 1)$

- $\gamma^{-1} d\gamma/dt = (eB/\gamma mc)\, \alpha'$ **-** $(2/3)\sigma_T (B^2/8\pi)\, \gamma/mc$

- $d\gamma/dt = 0$ implies

$$\boldsymbol{\gamma_{max} \sim 3 \cdot 10^9 \, (\alpha' / \sin^2\theta \, B_{-3})^{1/2}}$$

but, notice…

- particle acceleration by shocks or MHD/plasma instabilities, assuming **E/B ≠ 1**
- $t_{acc}^{-1} \sim \quad \alpha' \, \omega_B / \gamma \qquad (\omega_B = eB/mc; \quad \alpha' < 1)$

- $\gamma^{-1} d\gamma/dt = (eB/\gamma mc)(\mathbf{E/B})\alpha' - (2/3)\sigma_T (B^2/8\pi)\, \gamma/mc$

- $d\gamma/dt = 0$ implies

$$\gamma_{max} \sim 3 \cdot 10^9 (\mathbf{E/B})^{1/2} (\alpha'/\sin^2\theta \, B_{-3})^{1/2}$$

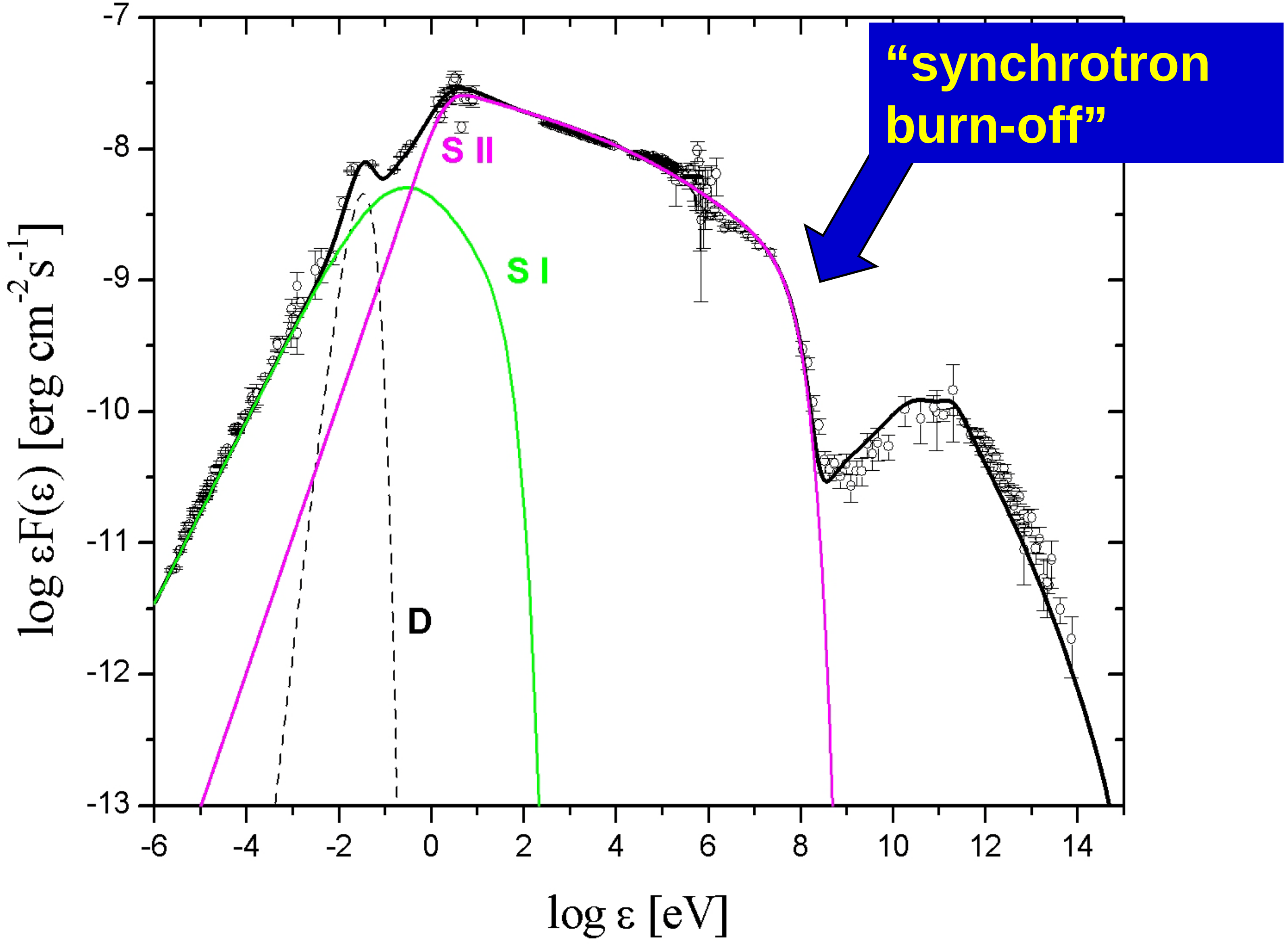
a paradigm for nebular emission
(e.g., de Jager, Harding et al. 1996)

- max. emitted photon synchrotron energy is independent of the magnetic field B: "**synchrotron burn-off**"

- $\mathbf{E_{max} = (3/2)\hbar\omega_B\, \gamma_m^{\,2} \backsimeq (230\ MeV)(\delta\, \alpha'/sin\theta)\ E/B}$

Doppler factor δ, $\delta\, \alpha'/\sin\theta \le 1$

Crab Nebula average spectrum

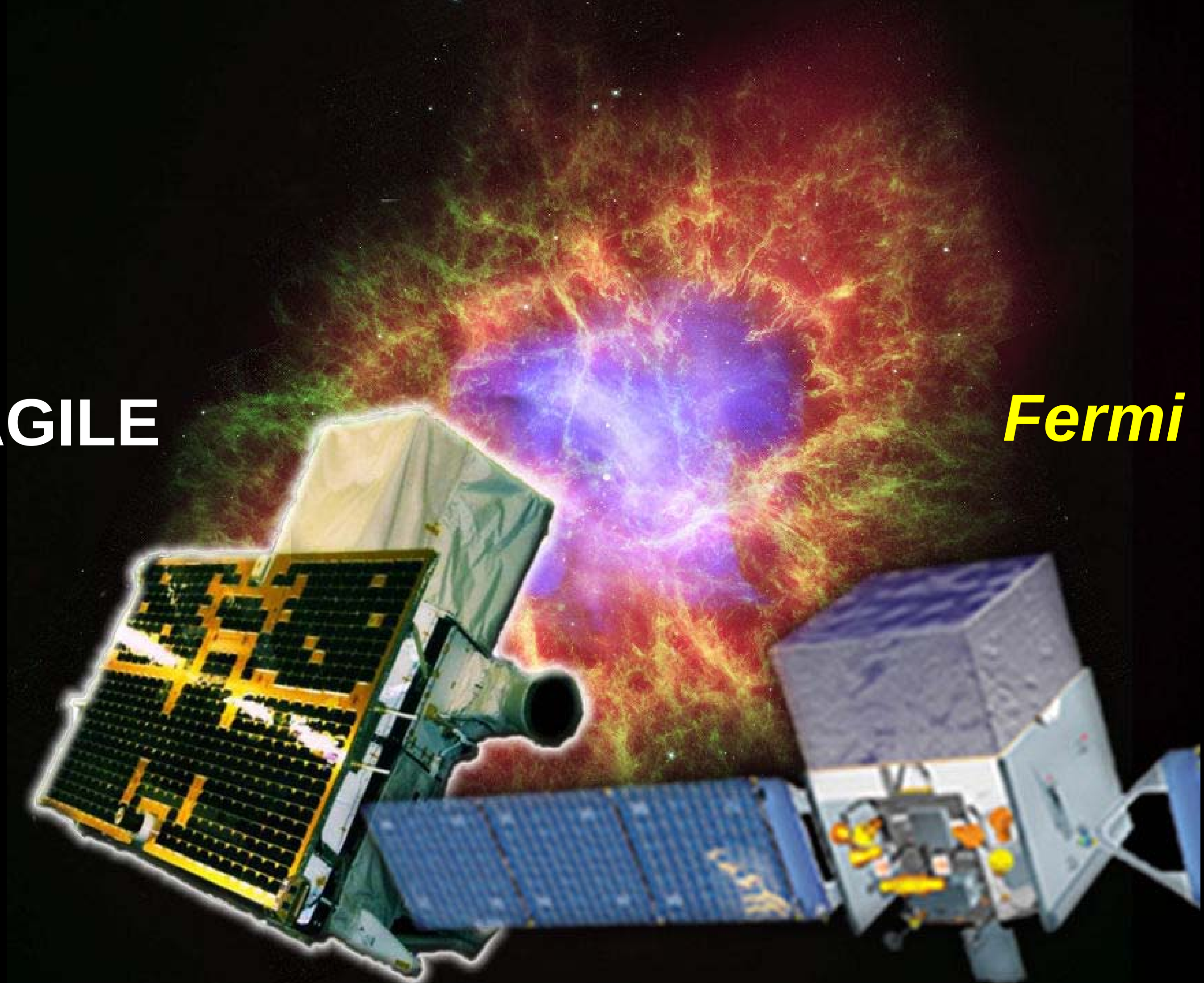


but… the Crab is variable !

- **rapid (hours/days) very intense gamma-ray flares above 100 MeV (AGILE & Fermi-LAT)**

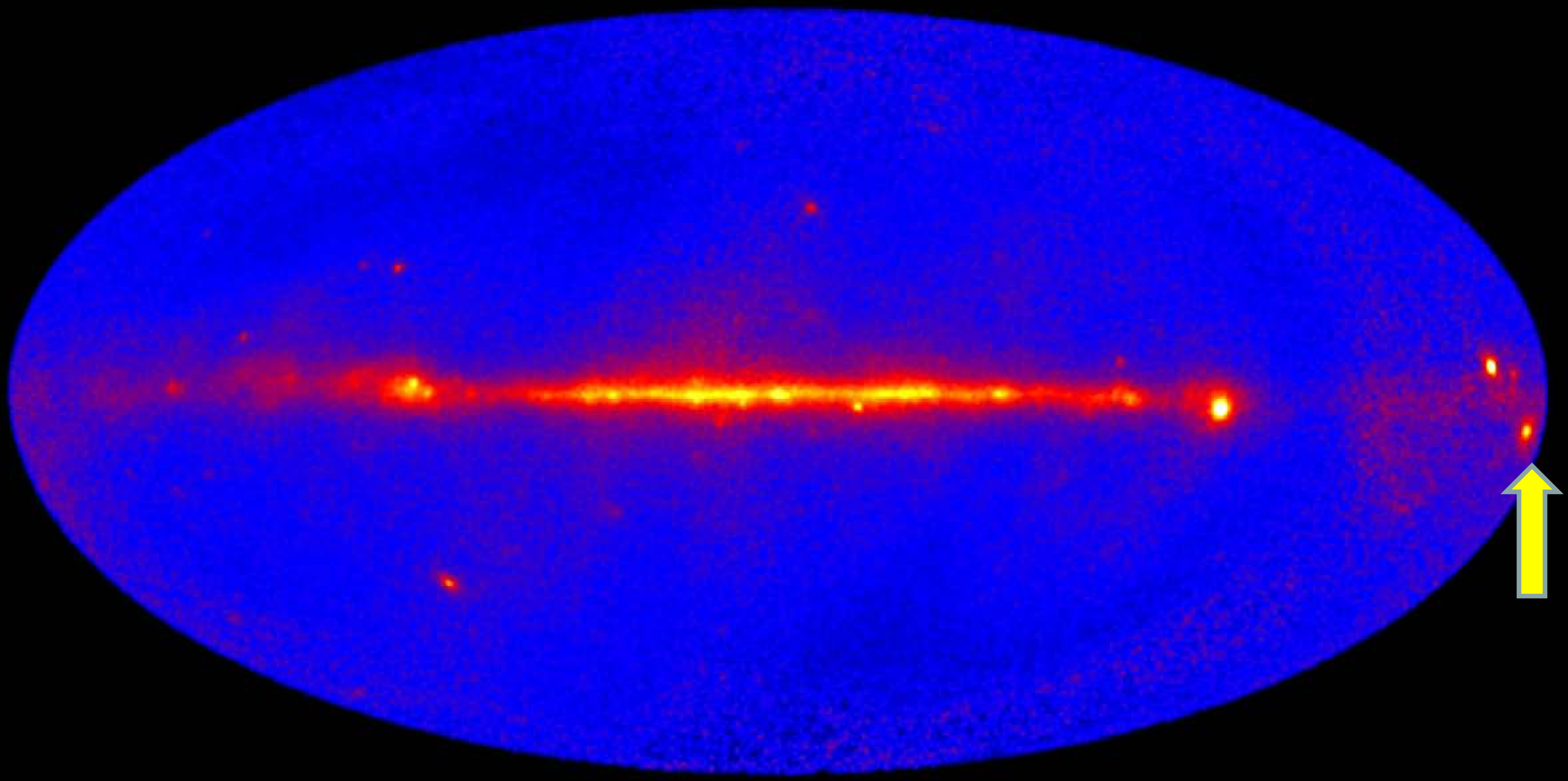
- **slow variation (years), 5-10 % of the X-ray flux (Fermi-GBM, Swift-BAT, XTE, Integral)**

The Crab above 100 MeV



Picture of the day, Feb. 28, 2011, NASA-HEASARC

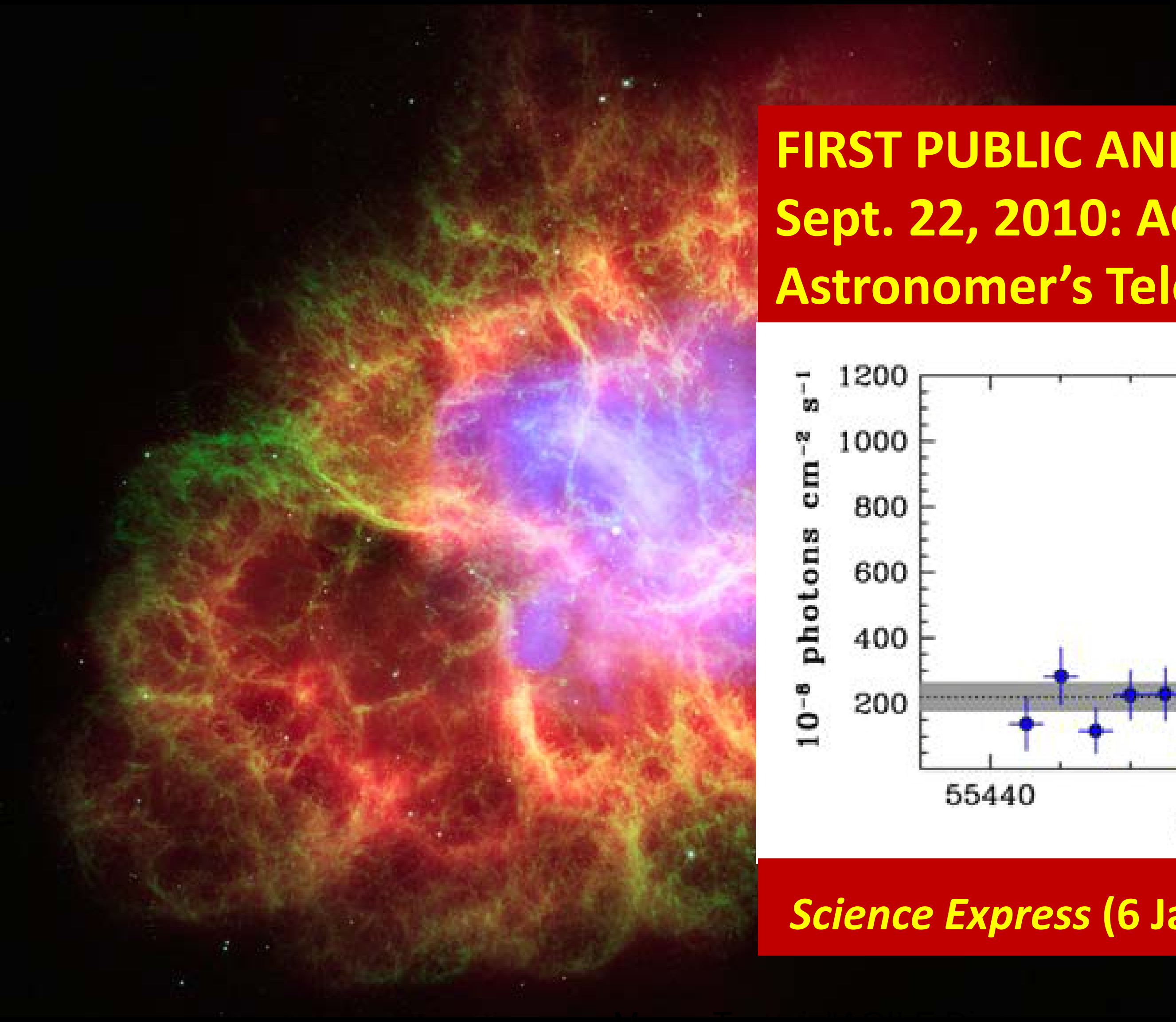
The AGILE gamma-ray sky (E > 100 MeV)
2 year exposure: July 2007 – June 2009



The Crab Nebula: flaring in gamma-rays !?!

FIRST PUBLIC ANNOUNCEMENT
Sept. 22, 2010: AGILE issues the Astronomer's Telegram n. 2855 announcing a gamma-ray flare from the Crab Nebula region

The Crab Nebula: flaring !?!



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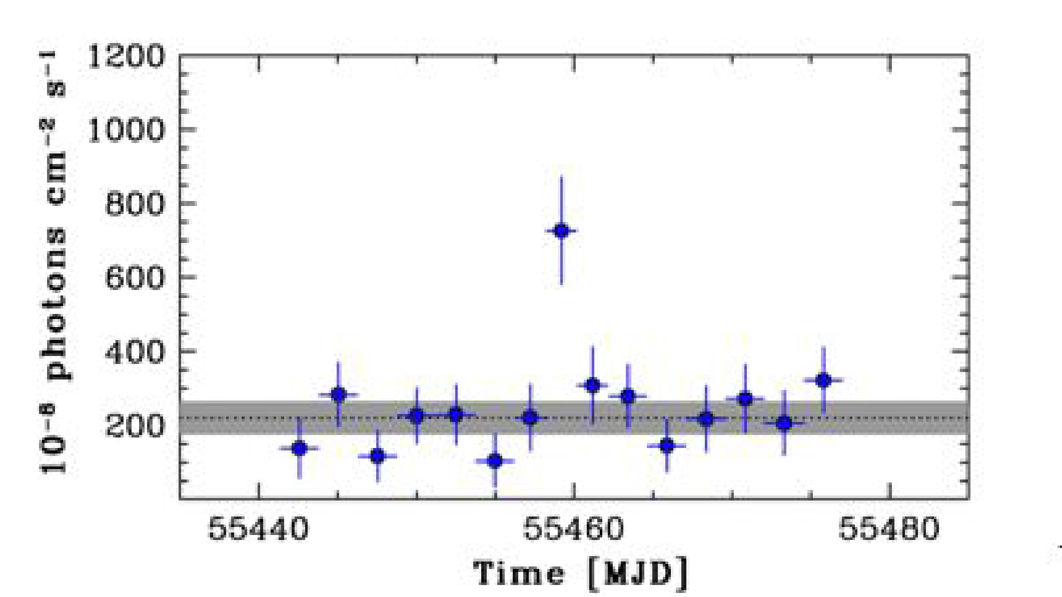
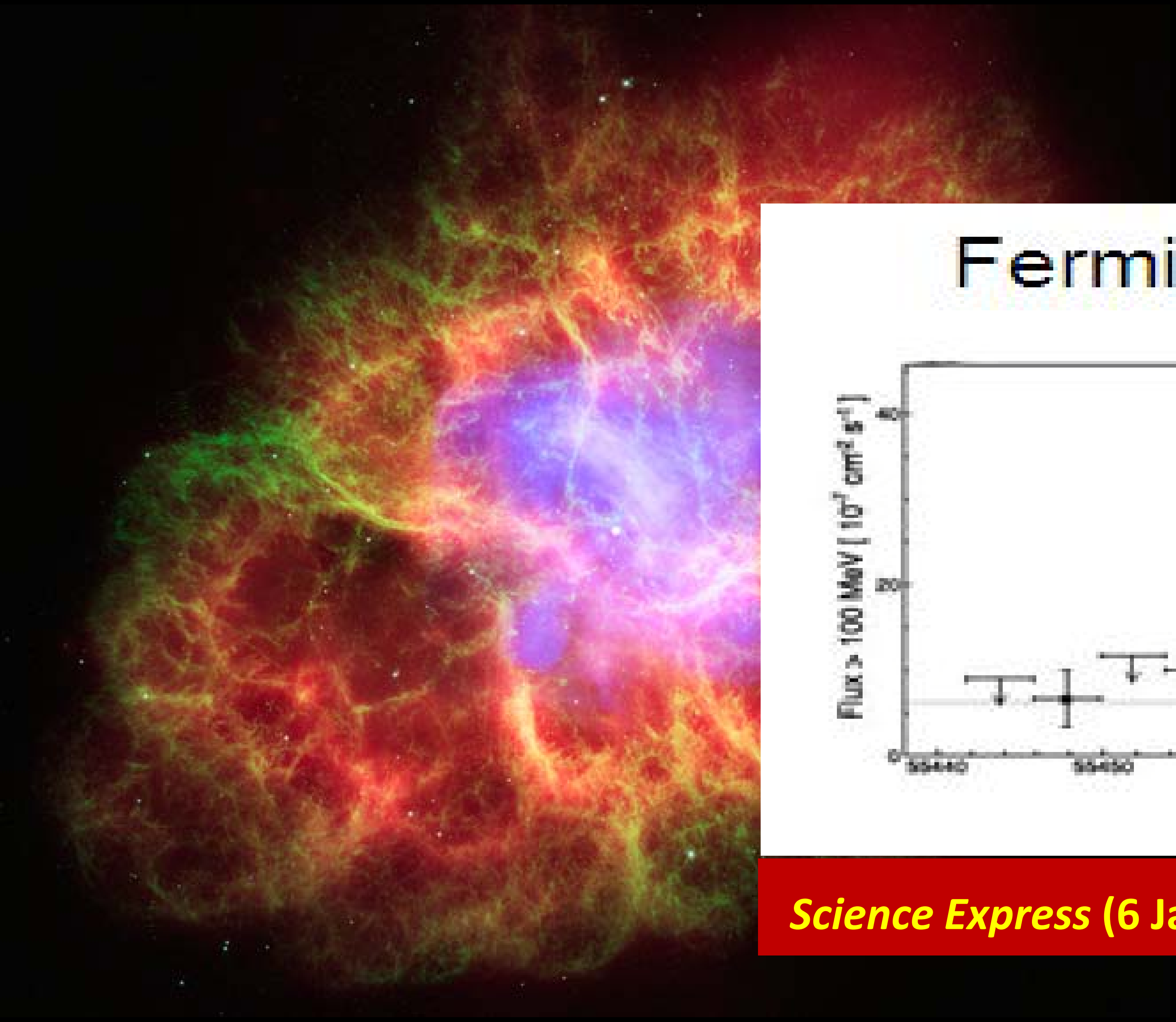
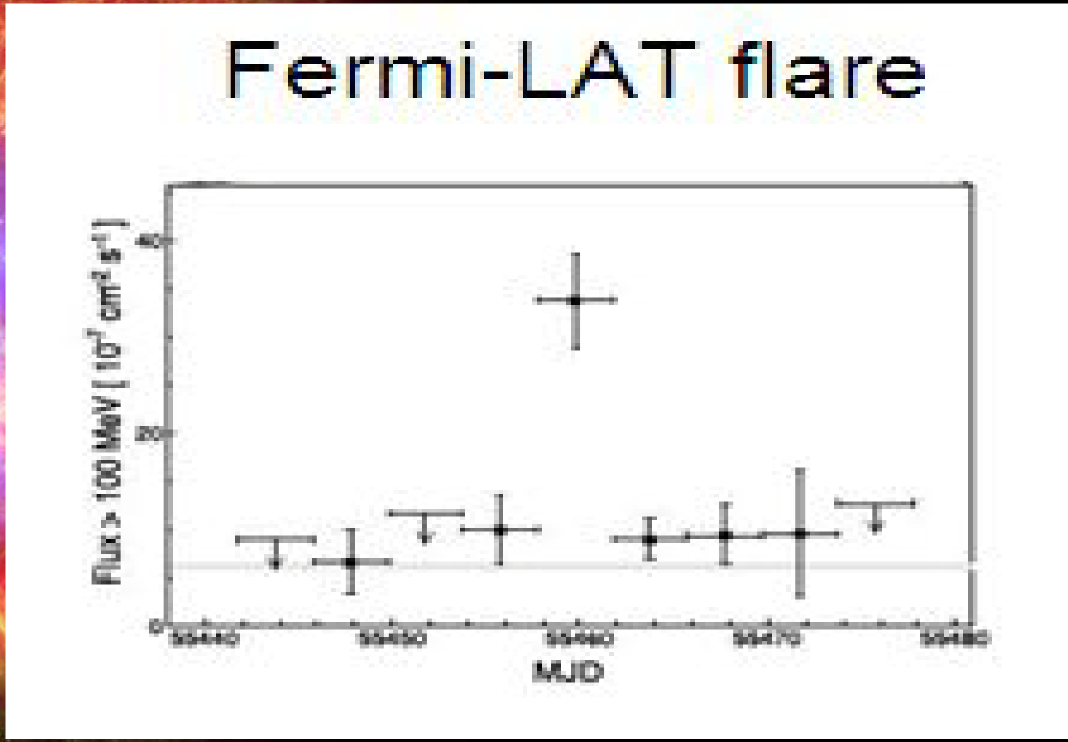


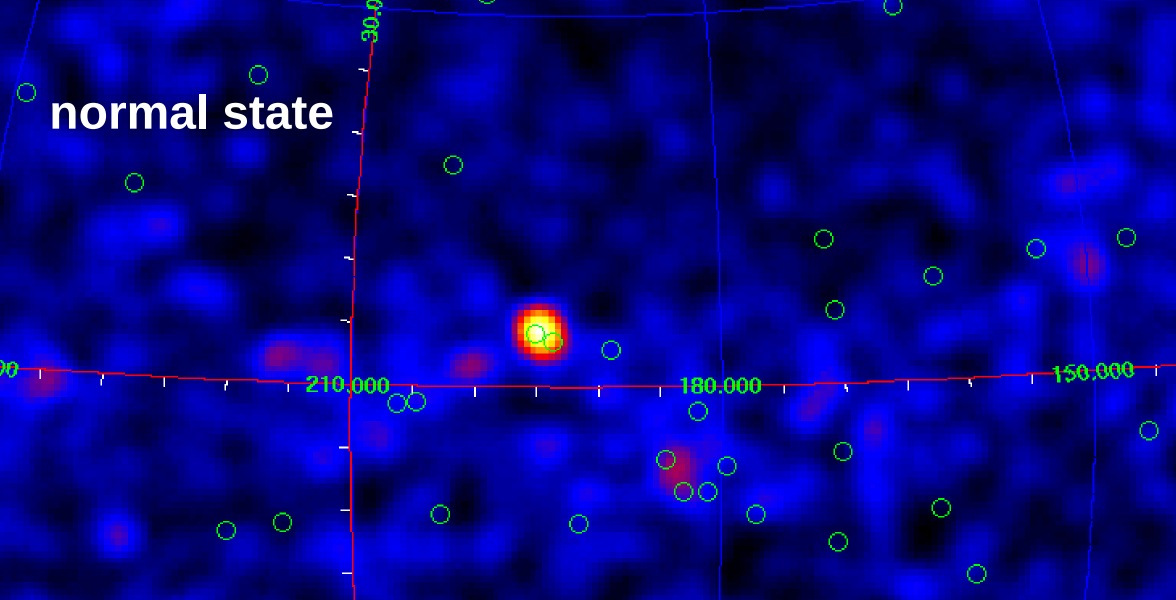
Science Express **(6 January 2011)**

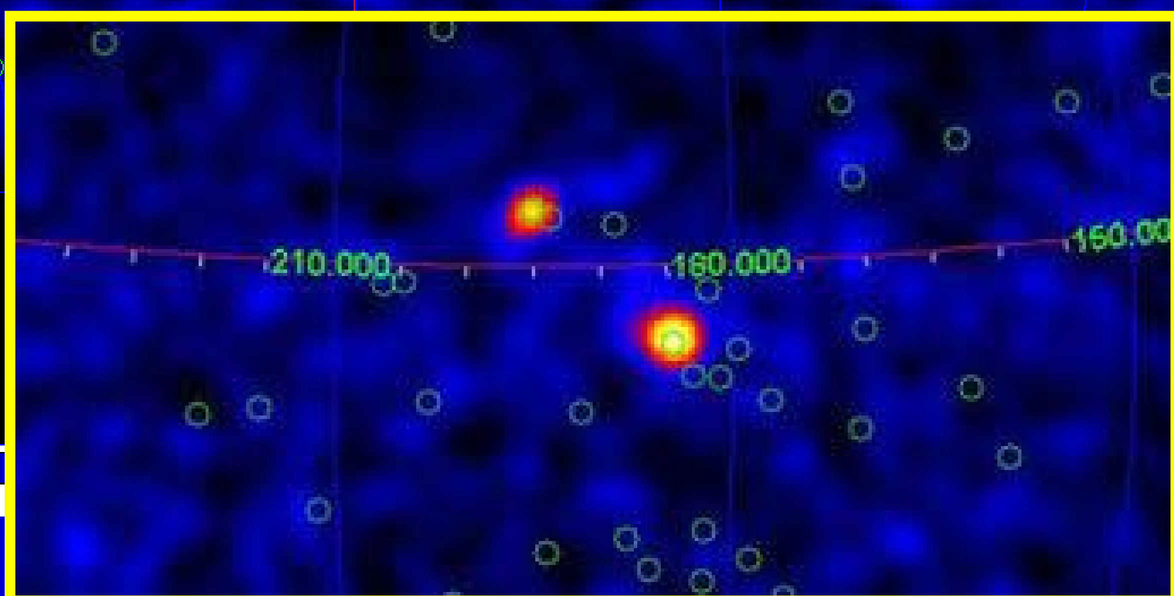
The Crab Nebula: flaring !?!



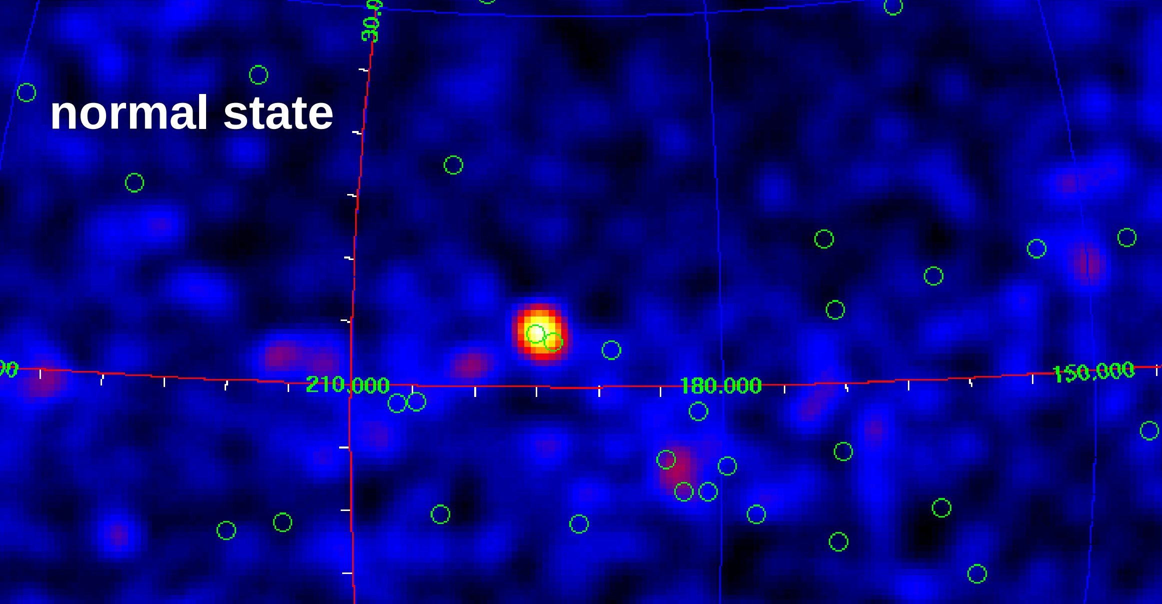


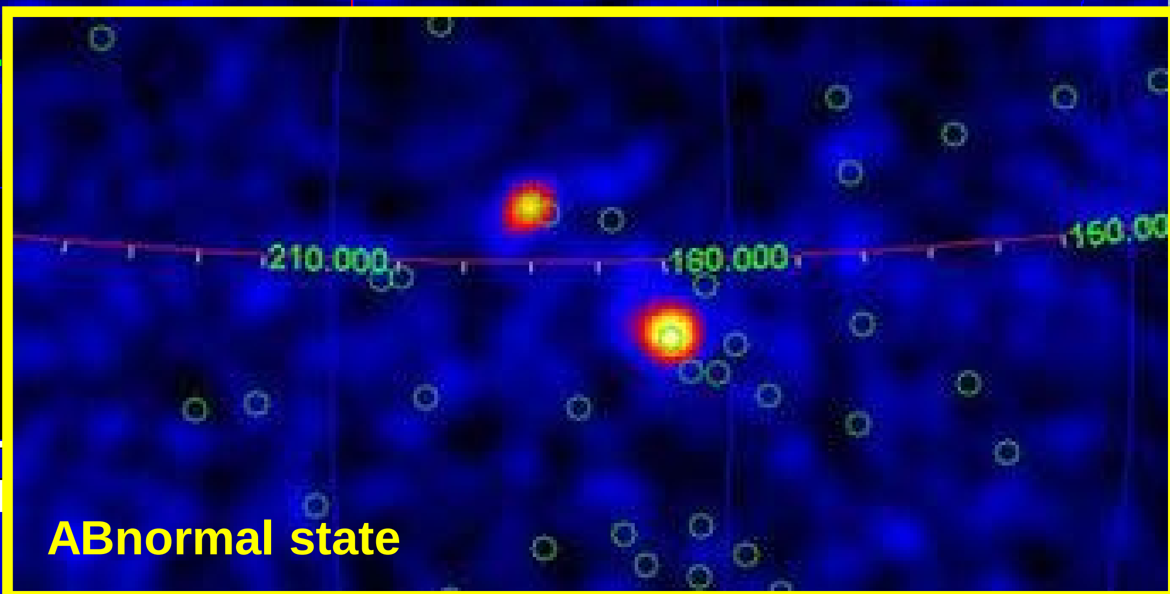
Science Express (6 January 2011)





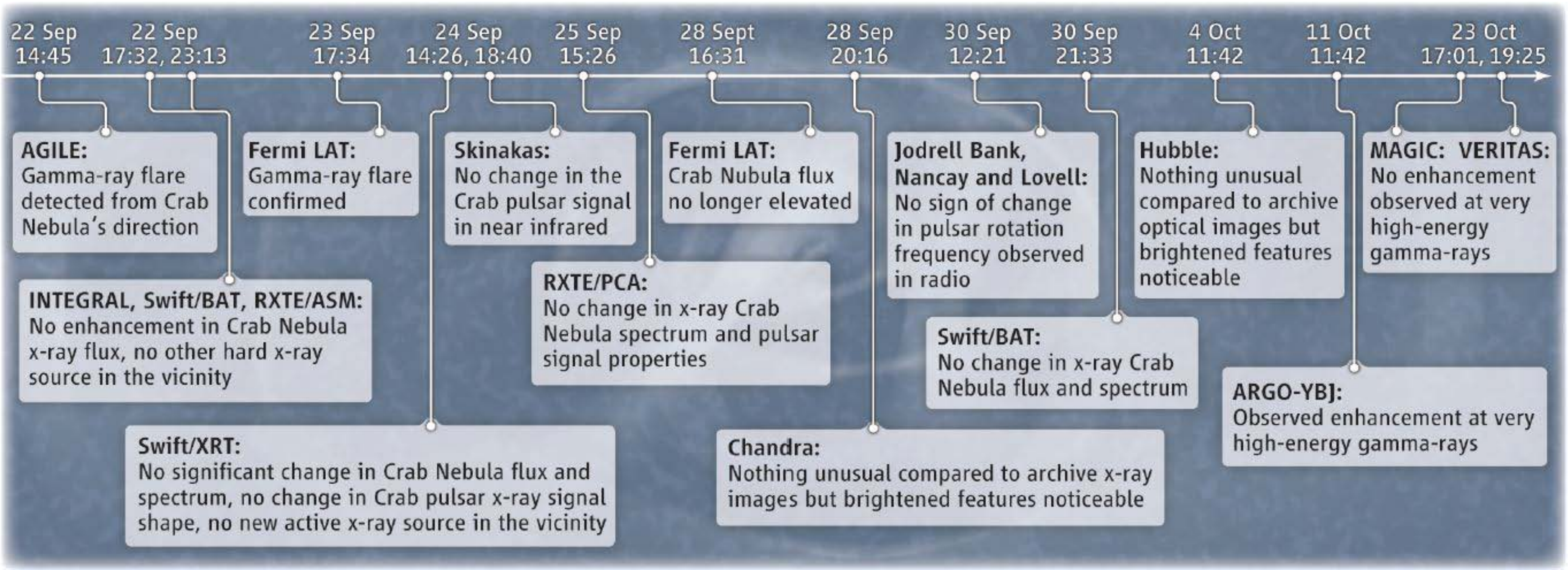
Gamma-ray flaring state: 20-21 Sept. 2010





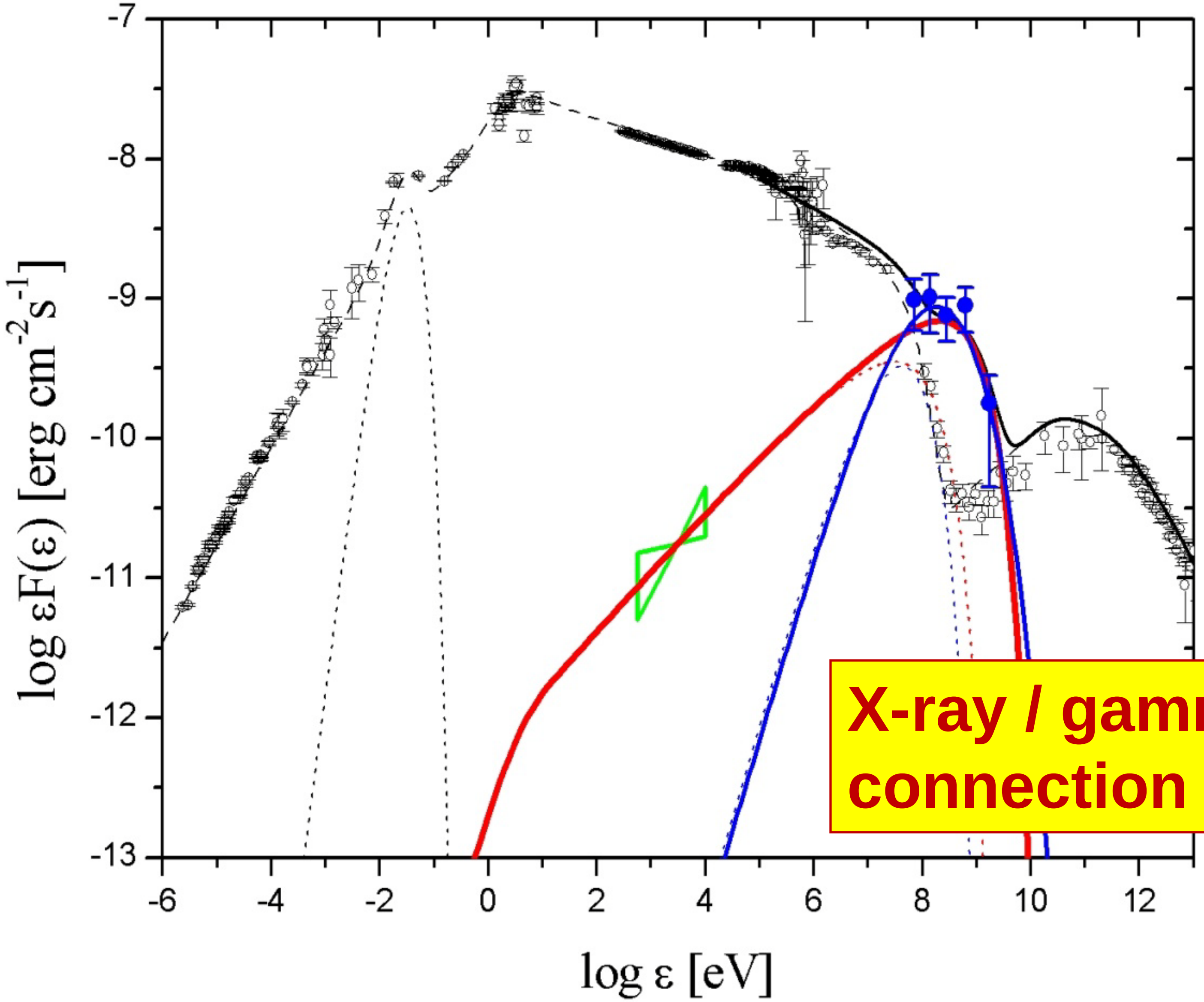
Gamma-ray flaring state: 20-21 Sept. 2010

Crab's post-flare excitement

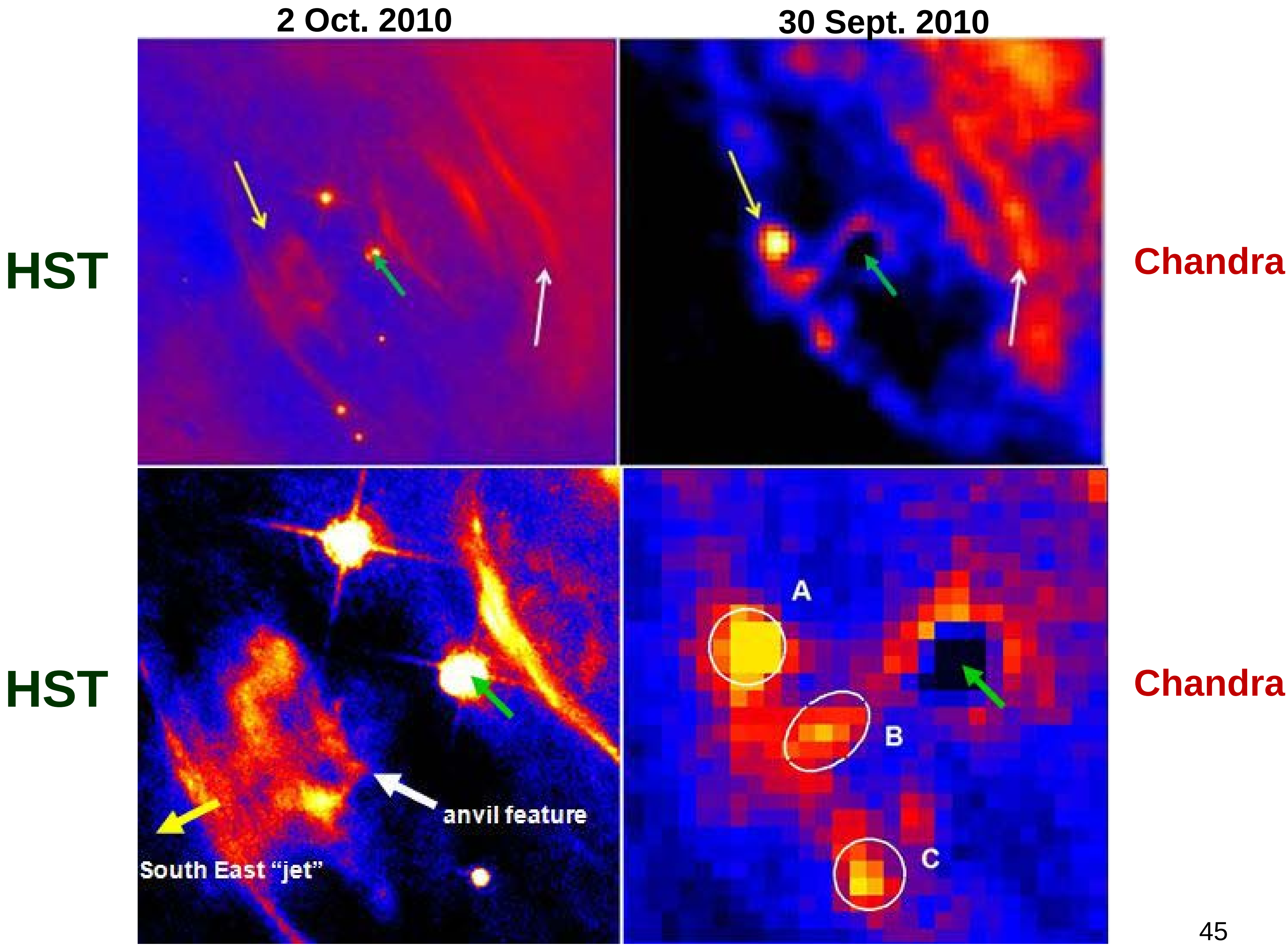


Bernardini E., 2011

Sept. 2010: AGILE spectrum at the peak (Tavani et al. 2011)



X-ray / gamma-ray connection ?



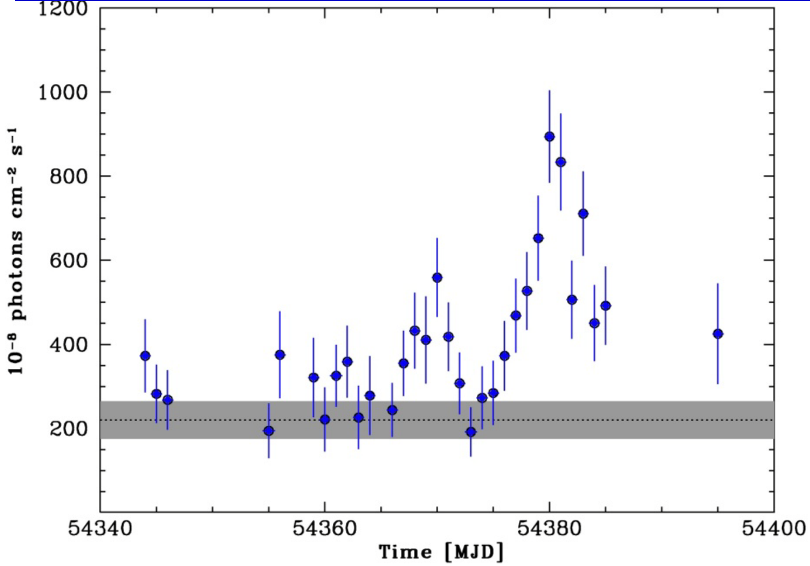
(Tavani et al. , 2011)

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

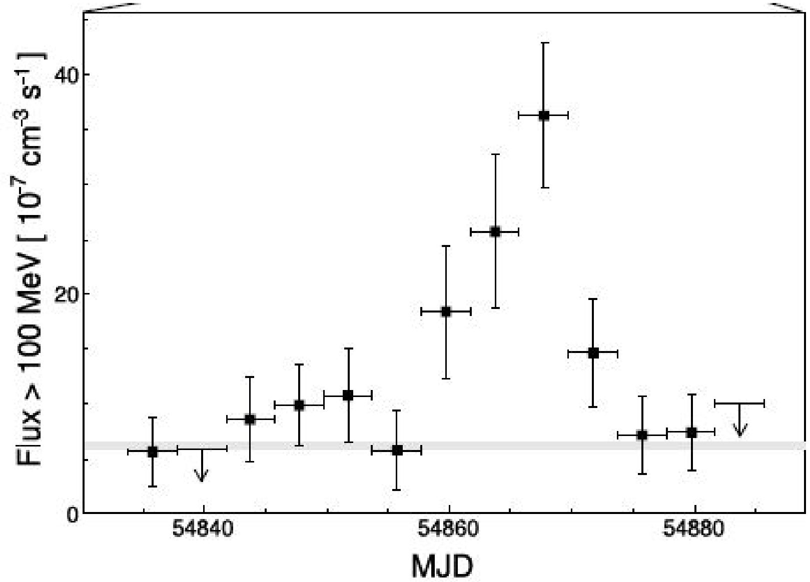
Flare date	Duration	Peak γ-ray flux	Instruments
October 2007	**~ 15 days**	**~ 14 $\cdot 10^{-6}$ ph cm^{-2} s^{-1}**	**AGILE**
February 2009	**~ 15 days**	**~ 7 $\cdot 10^{-6}$ ph cm^{-2} s^{-1}**	***Fermi***
September 2010	**~ 4 days**	**~ 7 $\cdot 10^{-6}$ ph cm^{-2} s^{-1}**	**AGILE, *Fermi***
April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

major flare rate: ~ 1/year

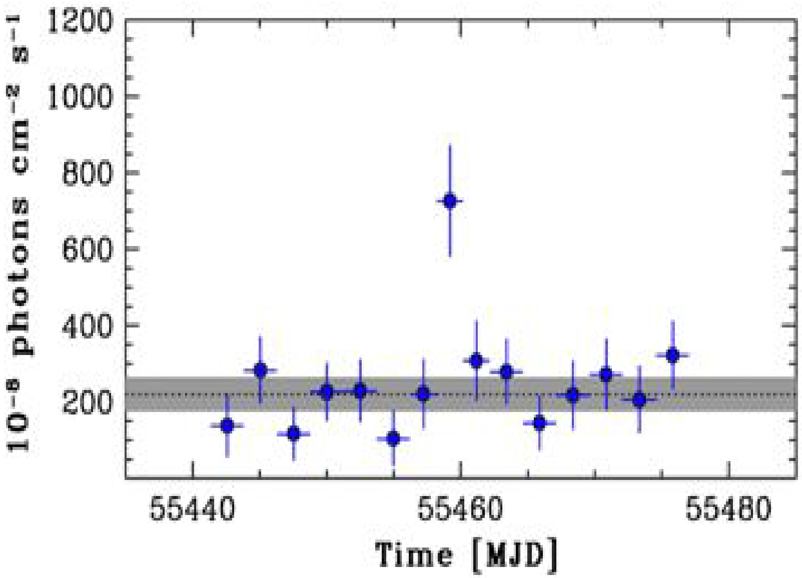
AGILE, 26 Nov. – 13 Oct. 2007



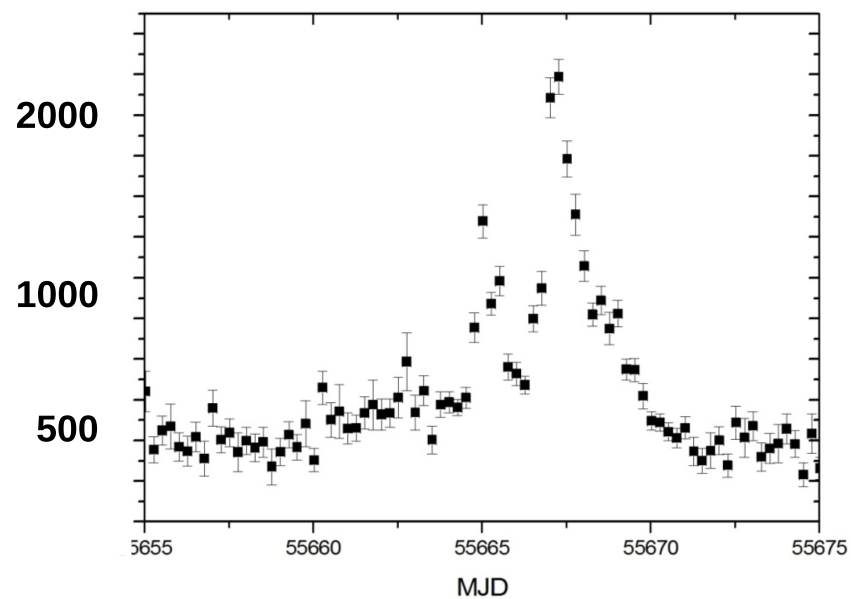
Fermi-LAT, 26 Jan. – 11 Feb. 2009



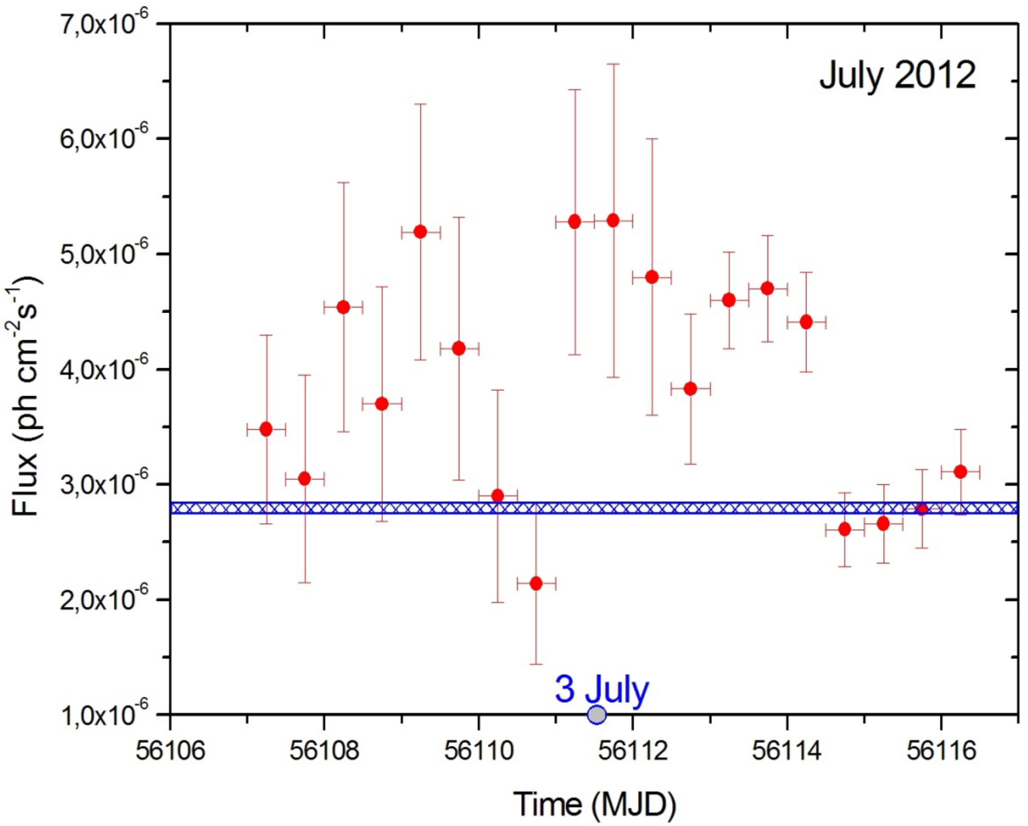
AGILE, 20-22 Sept. 2010

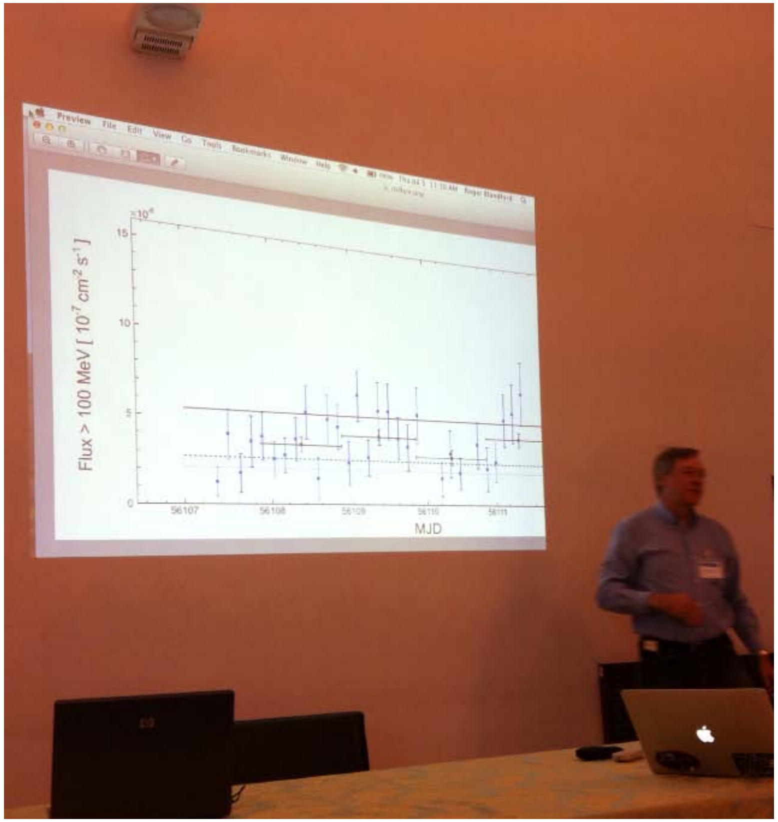


Fermi-AGILE, 12 – 20 Apr. 2011



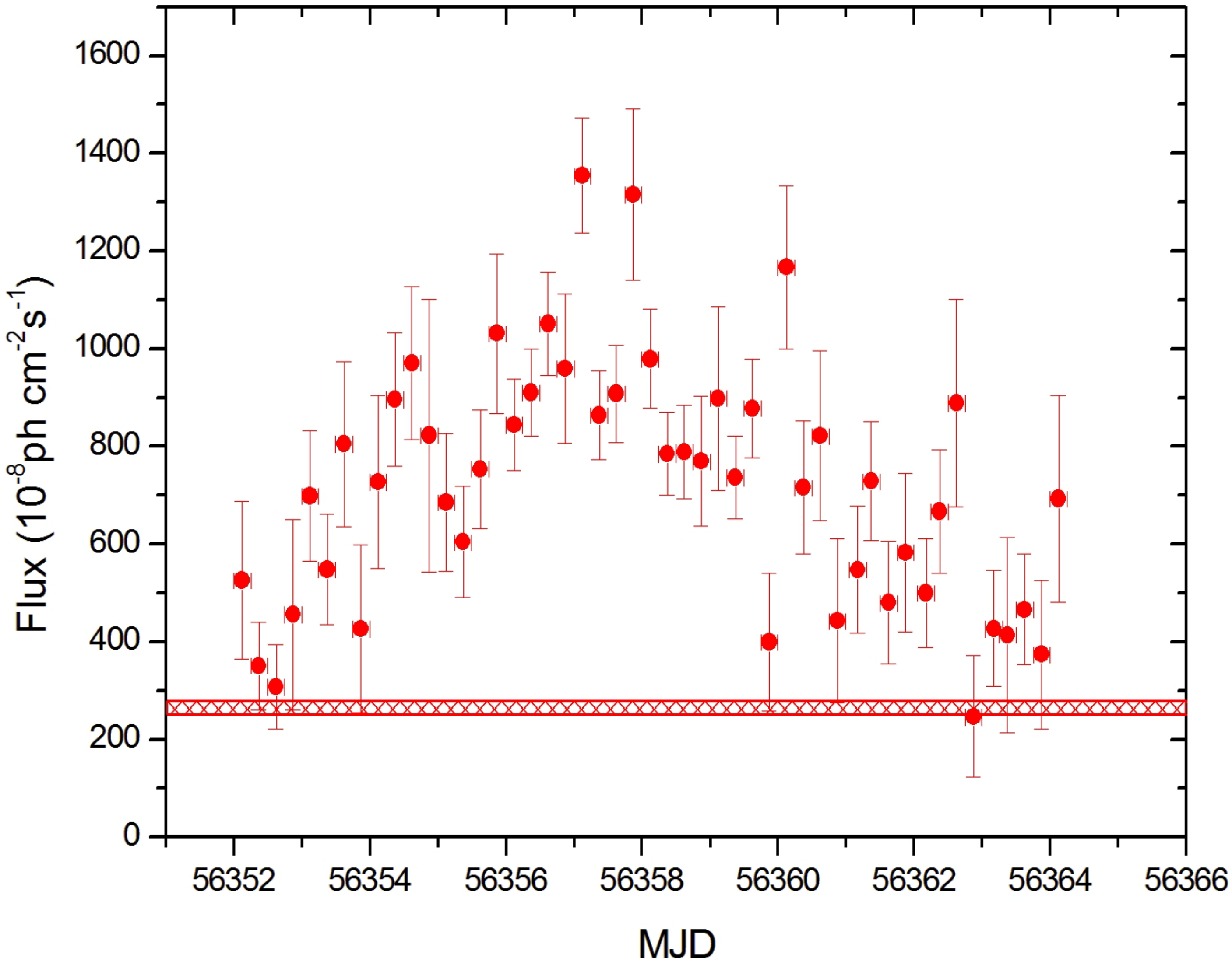
Enhanced gamma-ray emission from the Crab, ATel n. 4239 (Ojha R., et al., July 5, 2012).



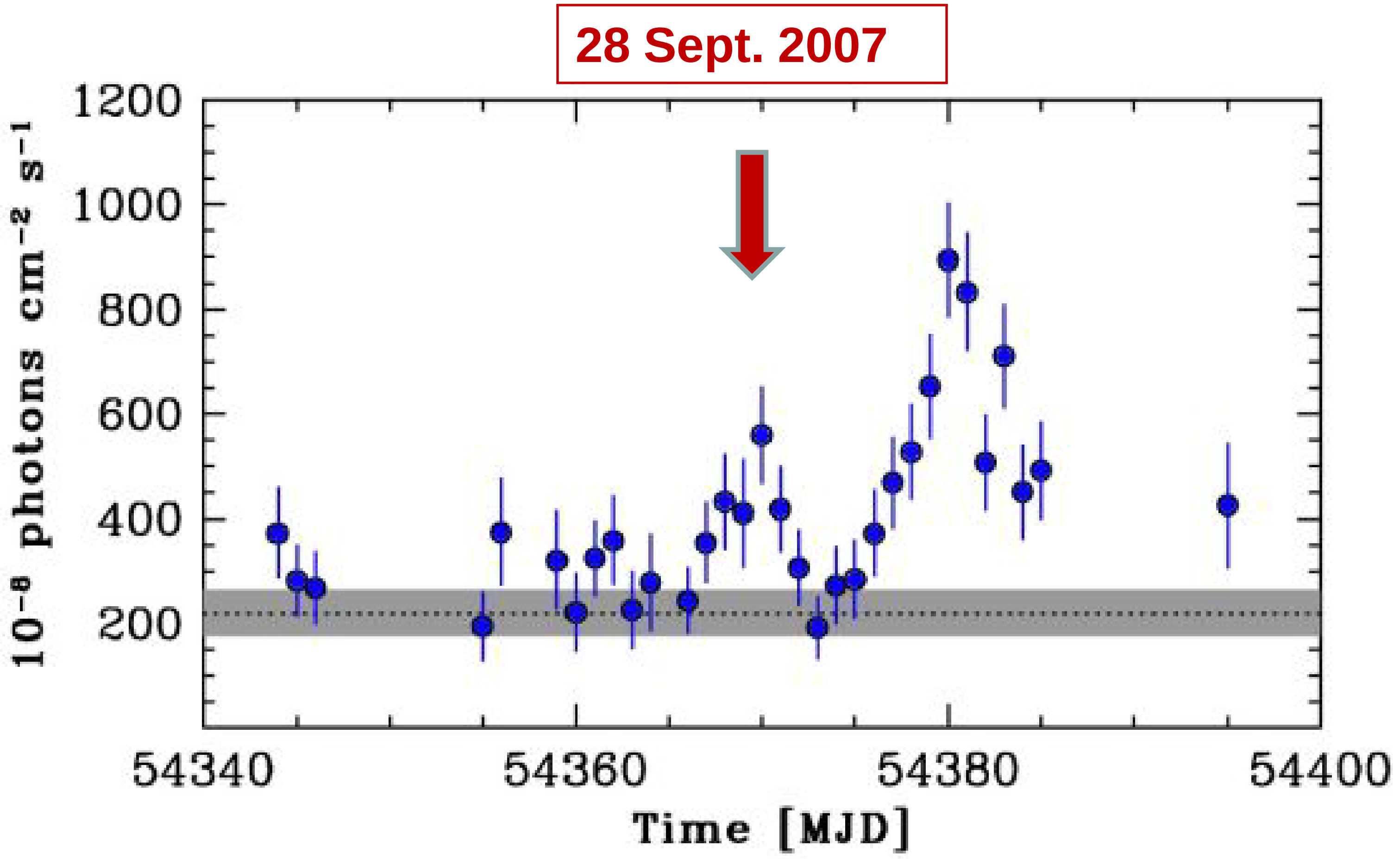


Announced in Frascati on the 4th of July 2012, during the meeting "The Flaring Crab Nebula: Surprise and Impact"
http://www.iasf-roma.inaf.it/Flaring_Crab

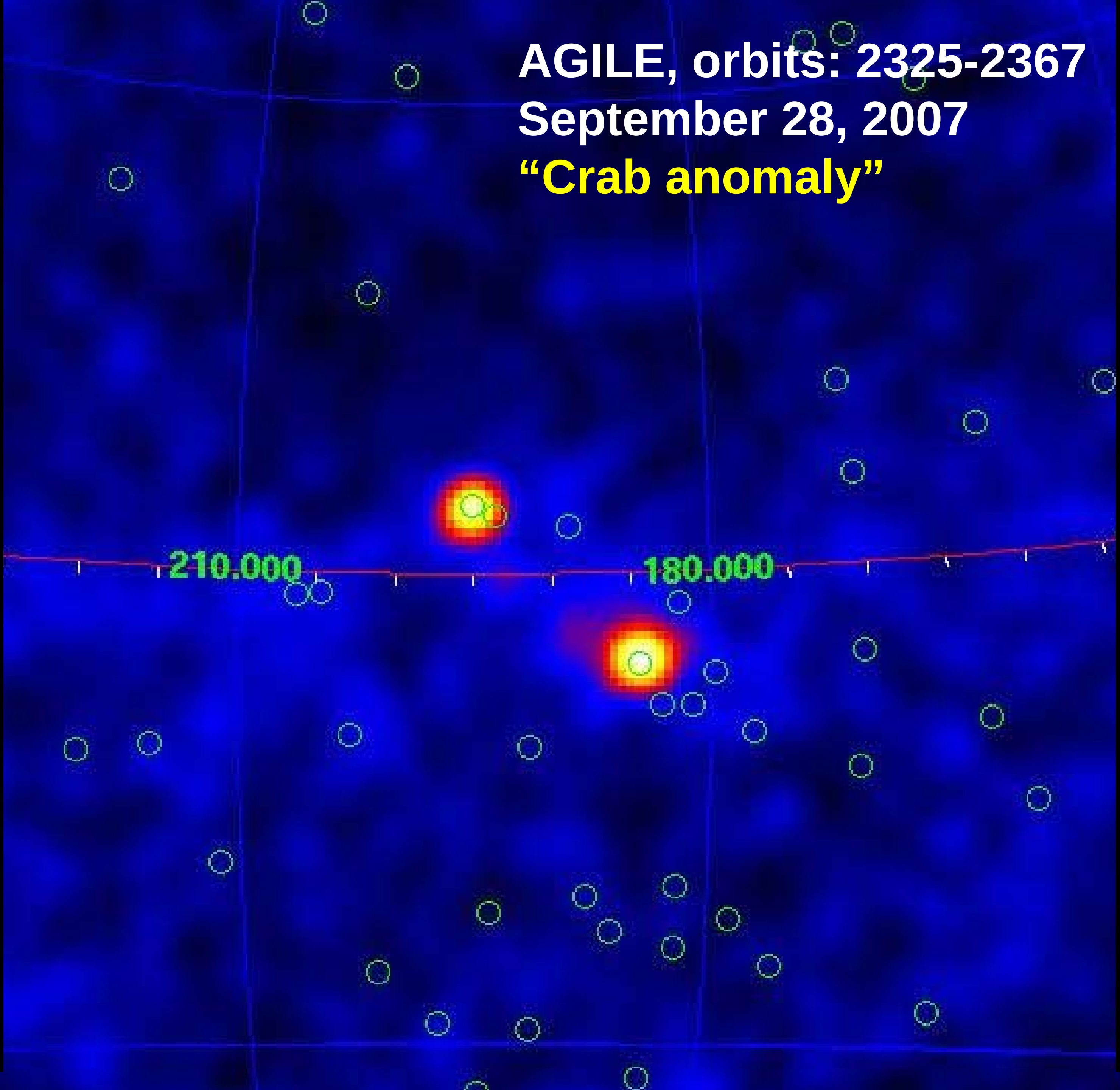
Most recent strong gamma-ray flaring from the Crab (started on March 2, 2013). (Fermi-LAT data, also AGILE)



2007 flare, 1-day bin
(Agile)

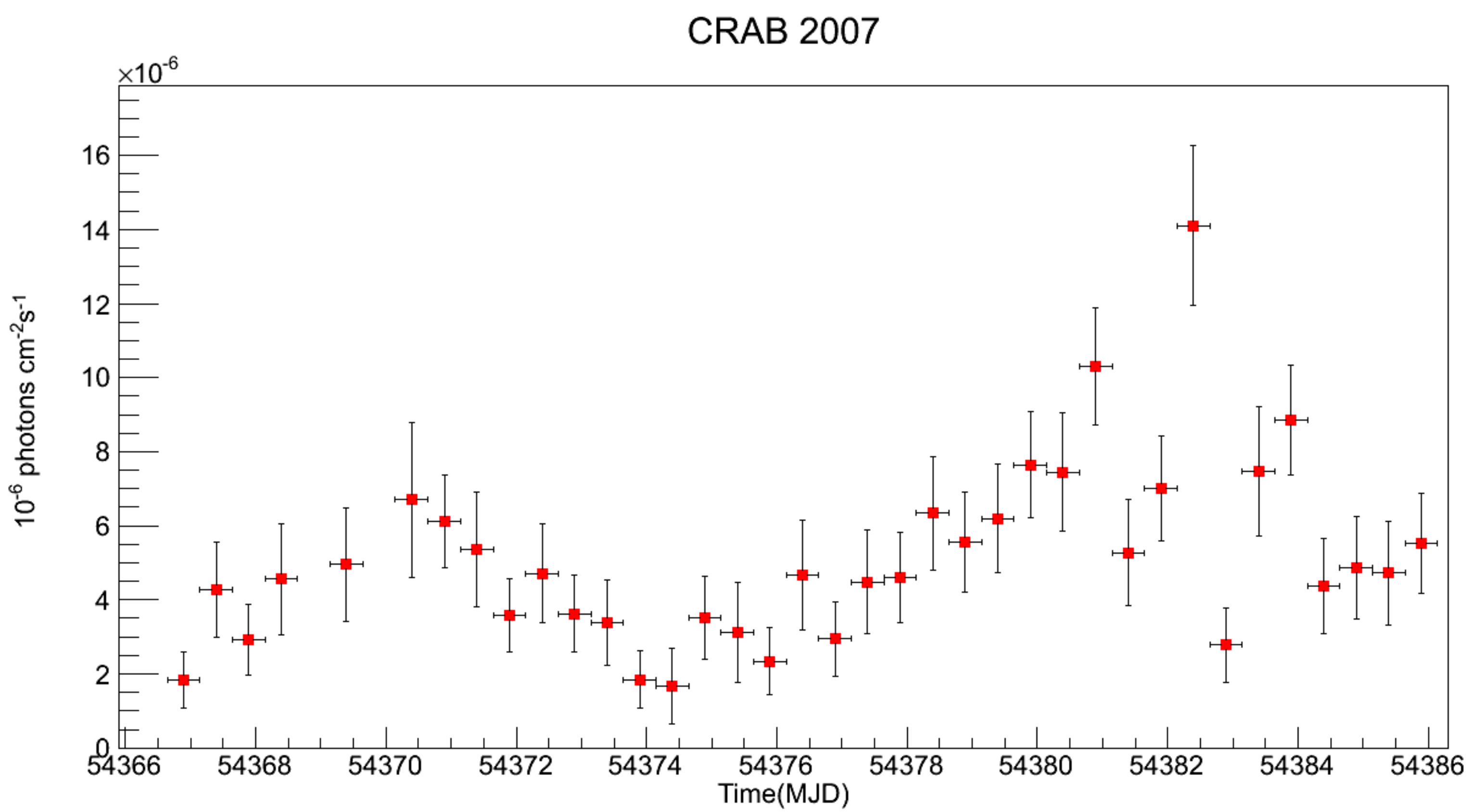


AGILE, orbits: 2325-2367
September 28, 2007
"Crab anomaly"



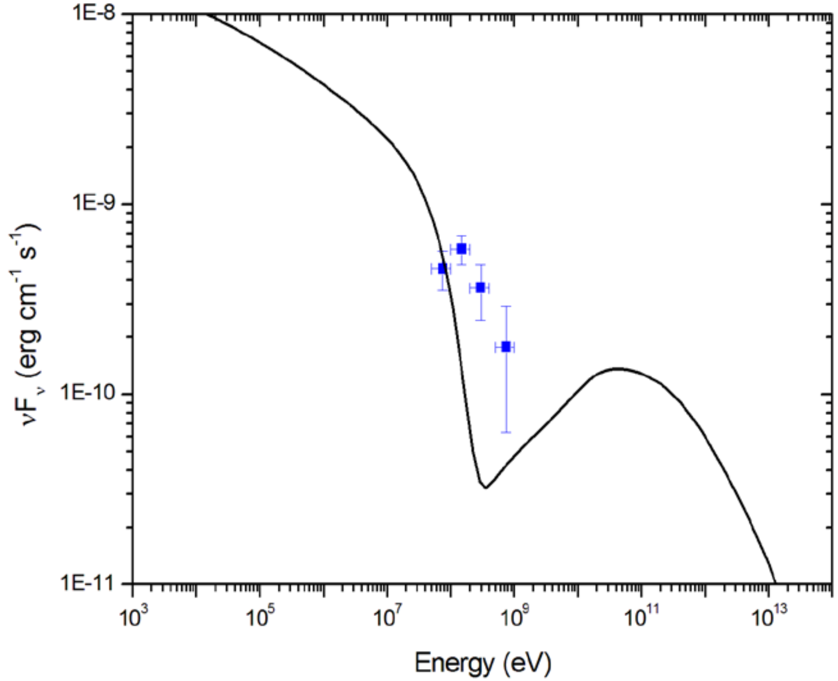
2007 flare, 12-hr bin

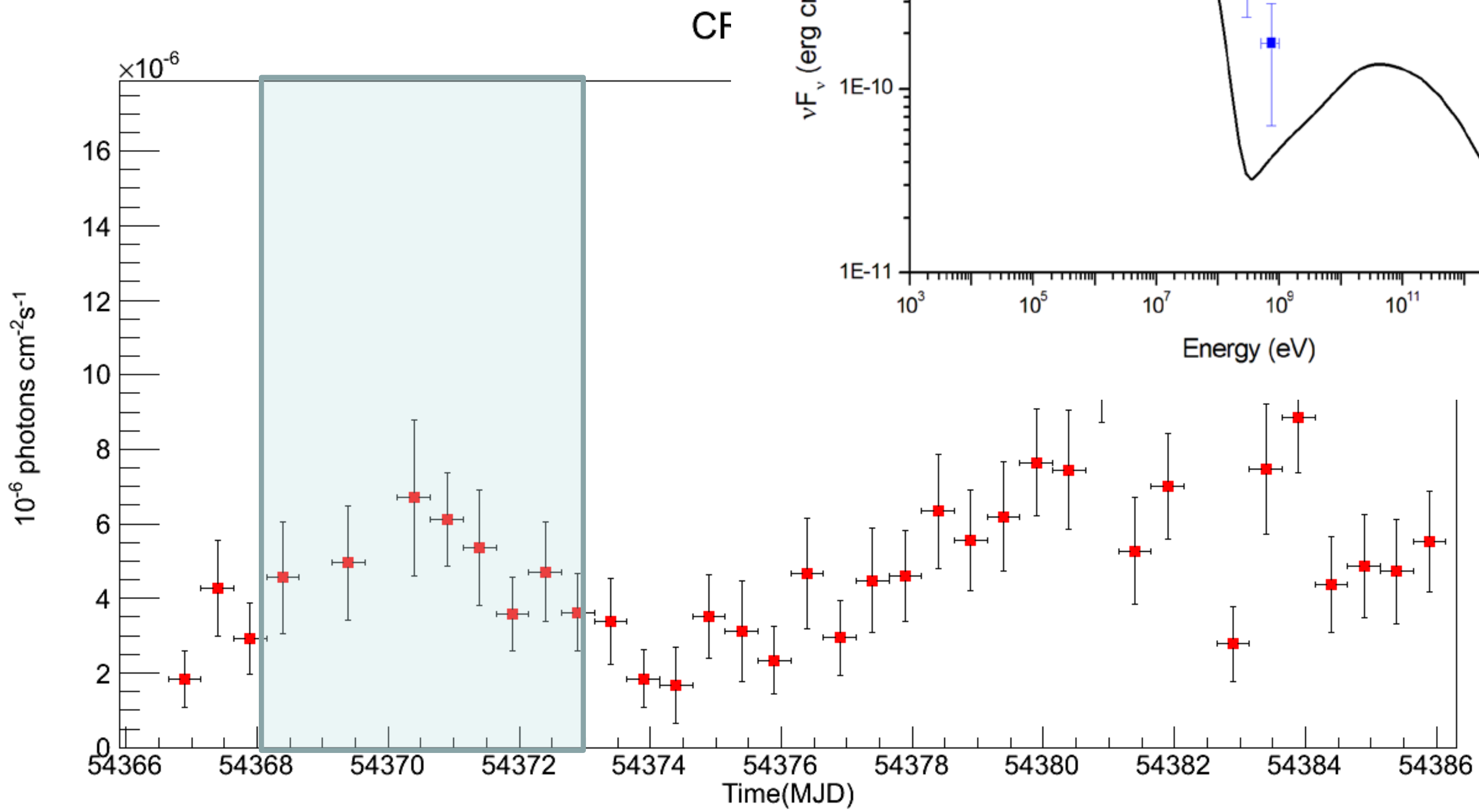
(Agile, Striani et al. 2012)



2007 flare, 12-hr bin

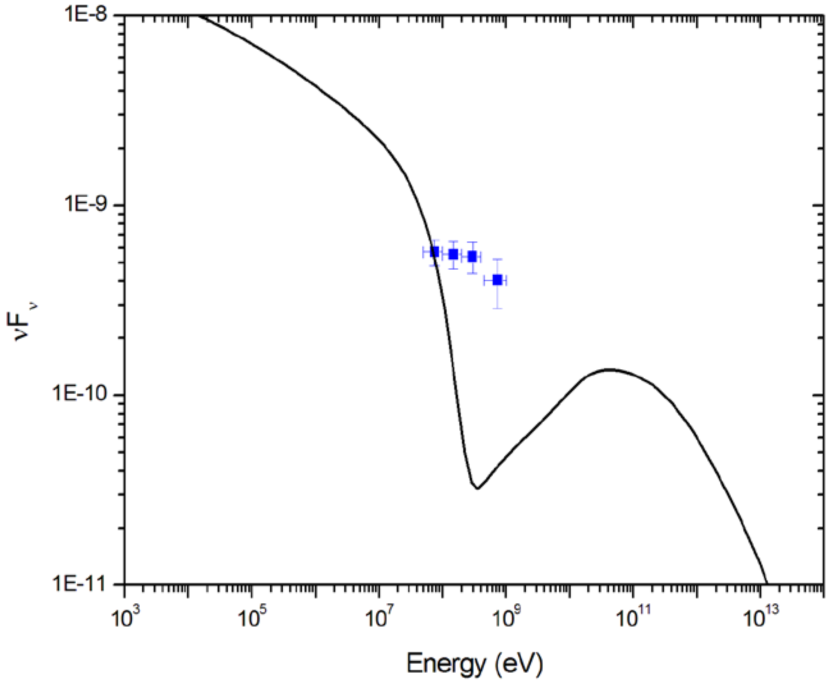
(Agile, Striani et al. 2012)

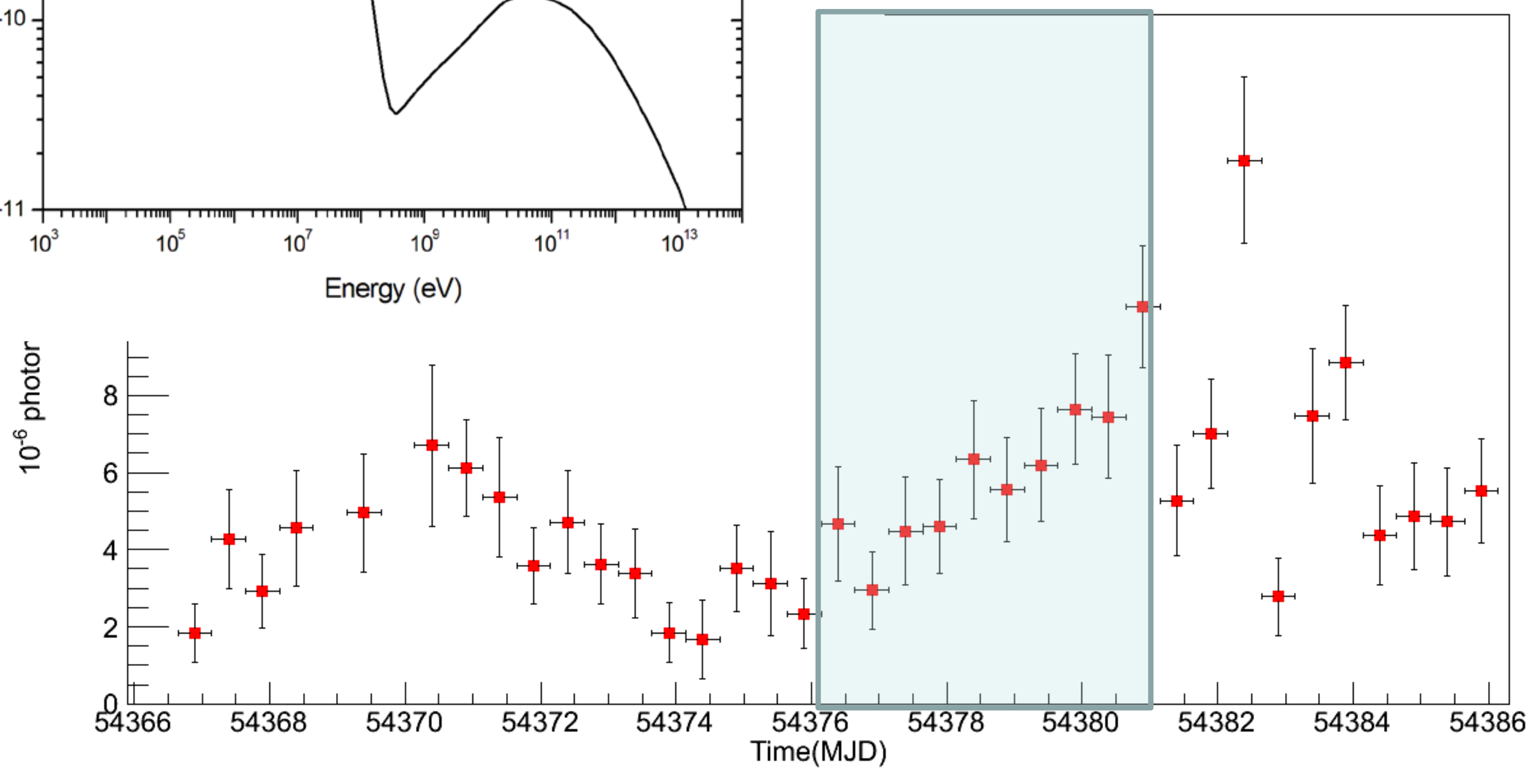




2007 flare, 12-hr bin

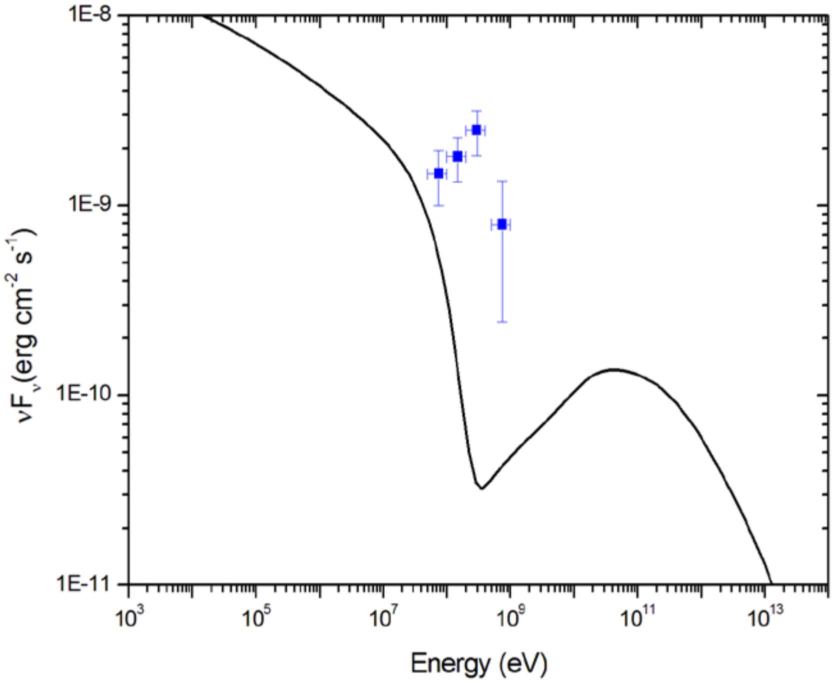
(Agile, Striani et al. 2012)

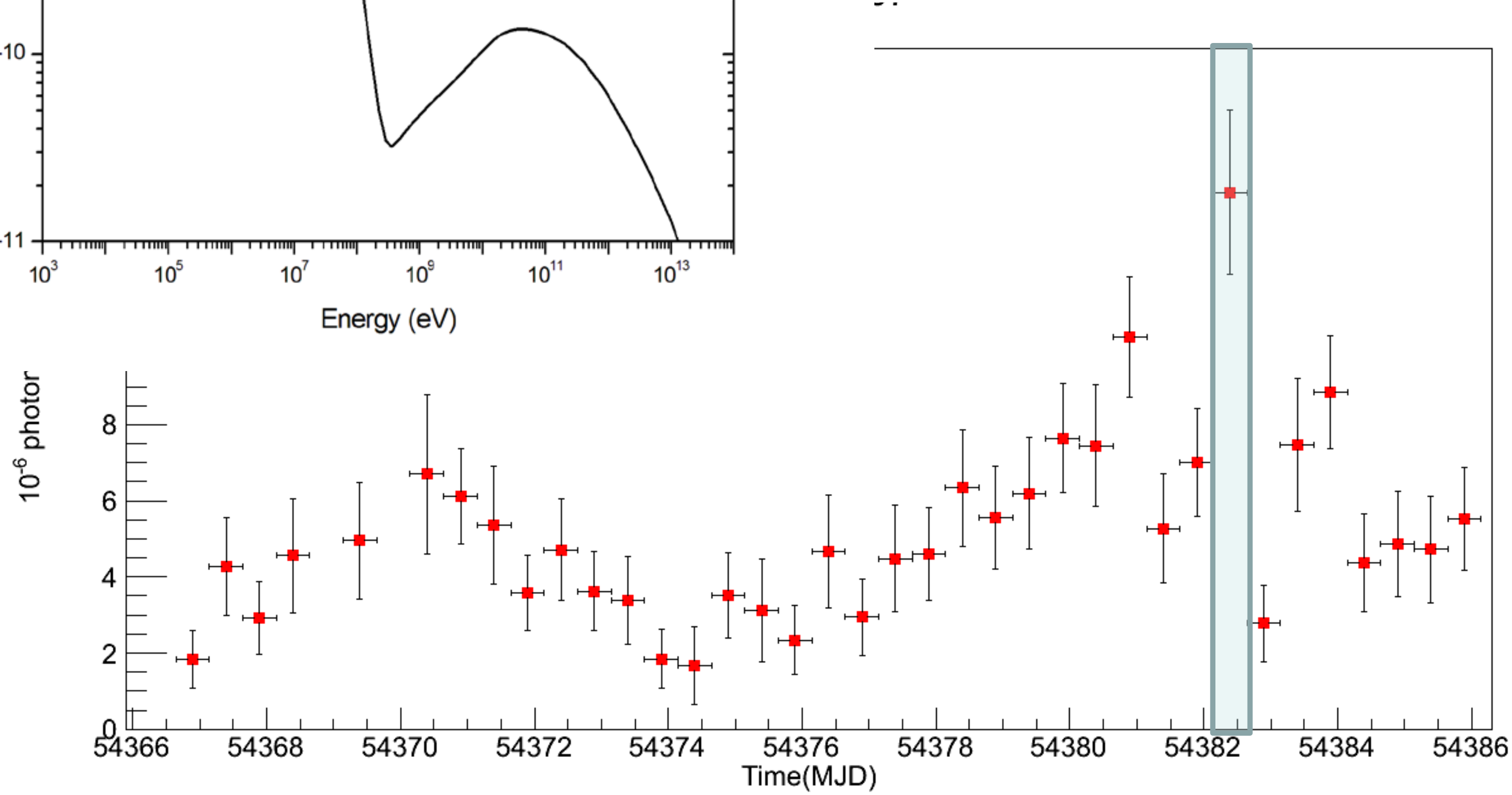




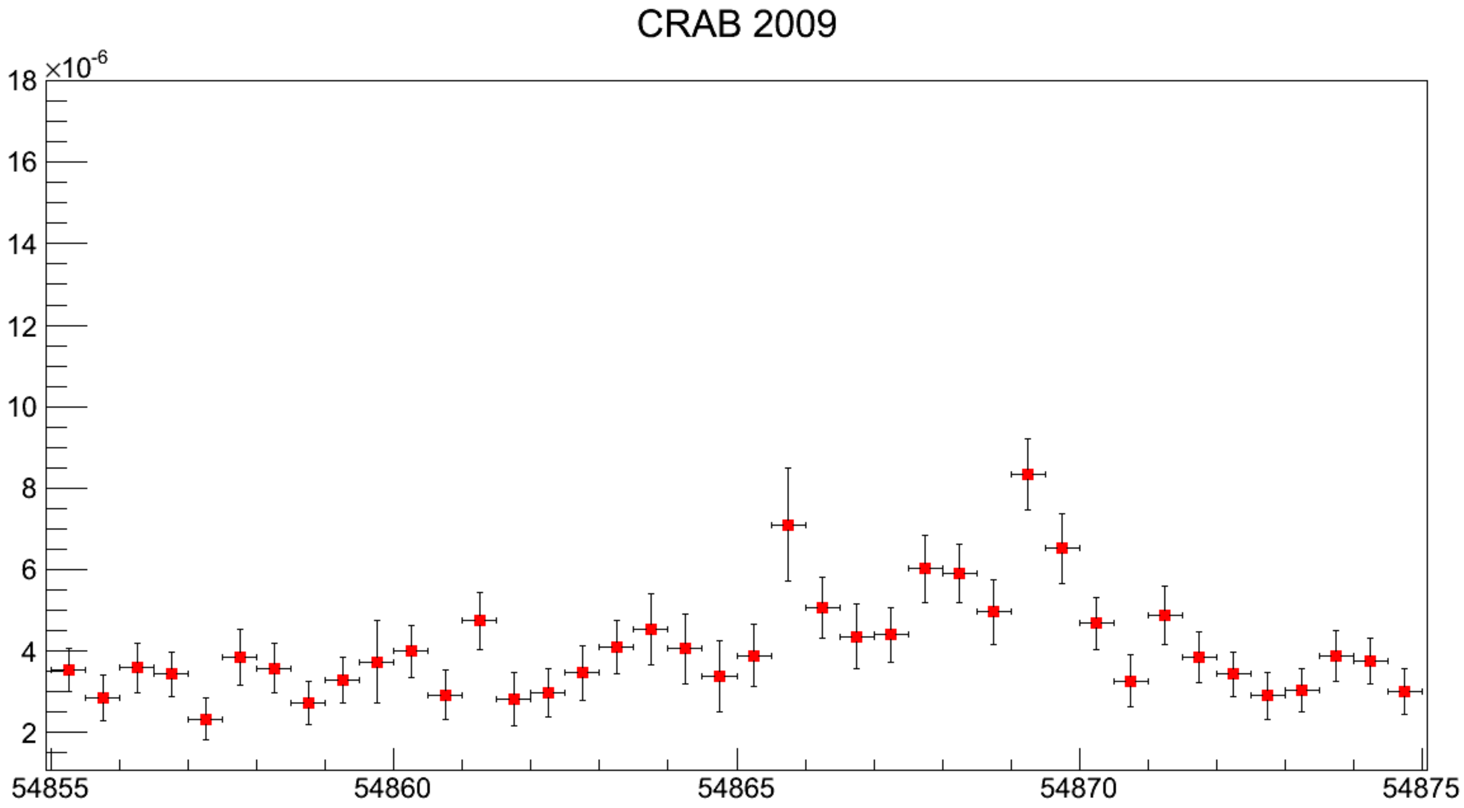
2007 flare, 12-hr bin

(Agile, Striani et al. 2012)

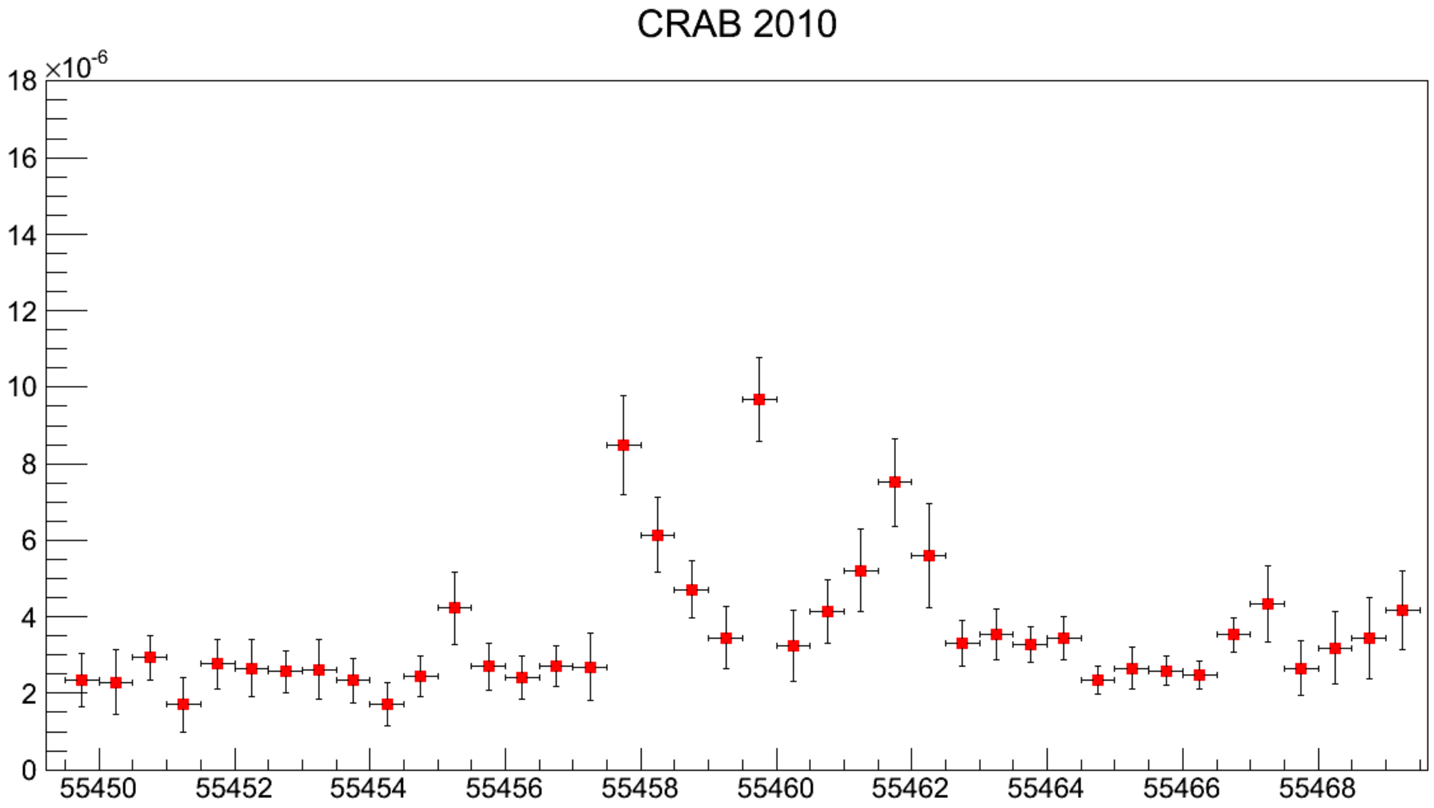




2009 flare – FERMI data

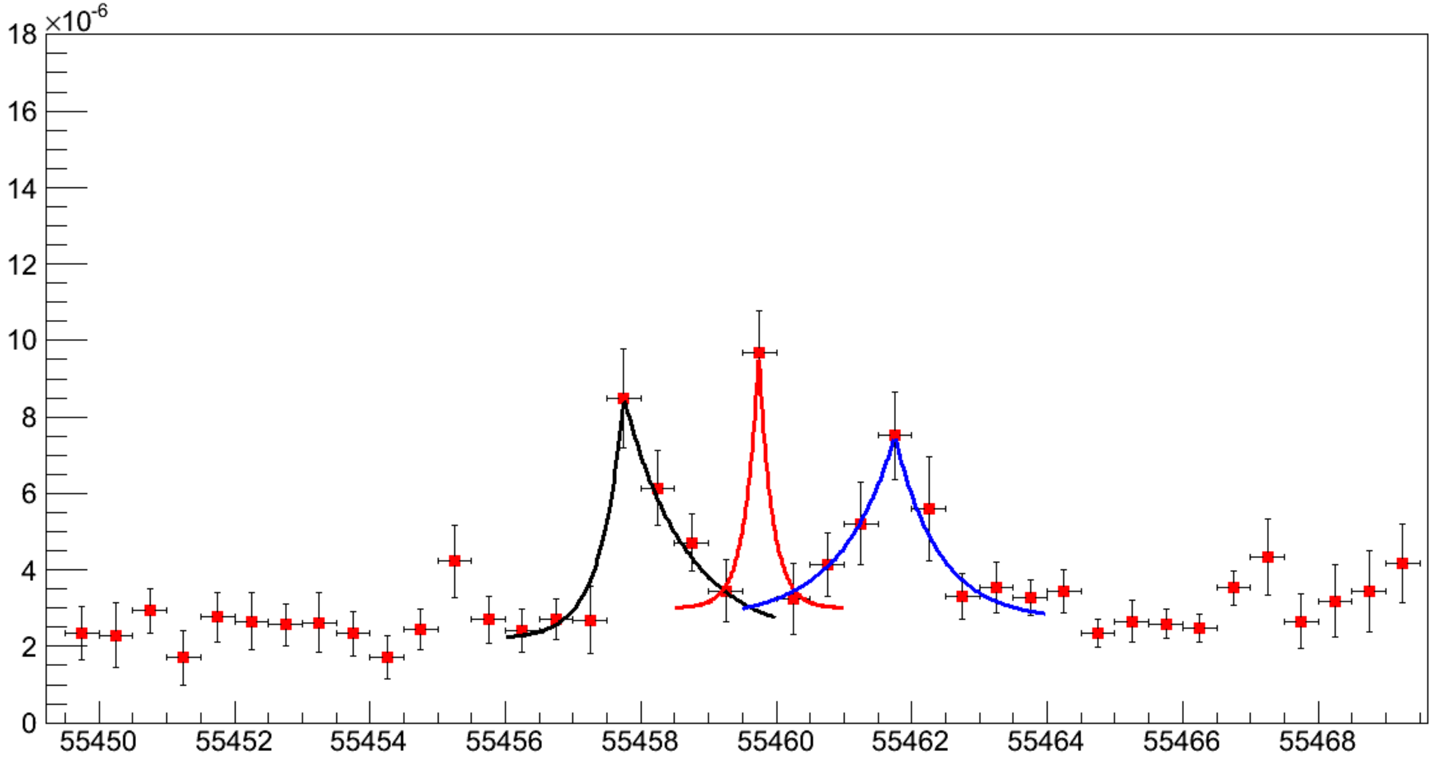


revisiting the Sept. 2010 flare FERMI data

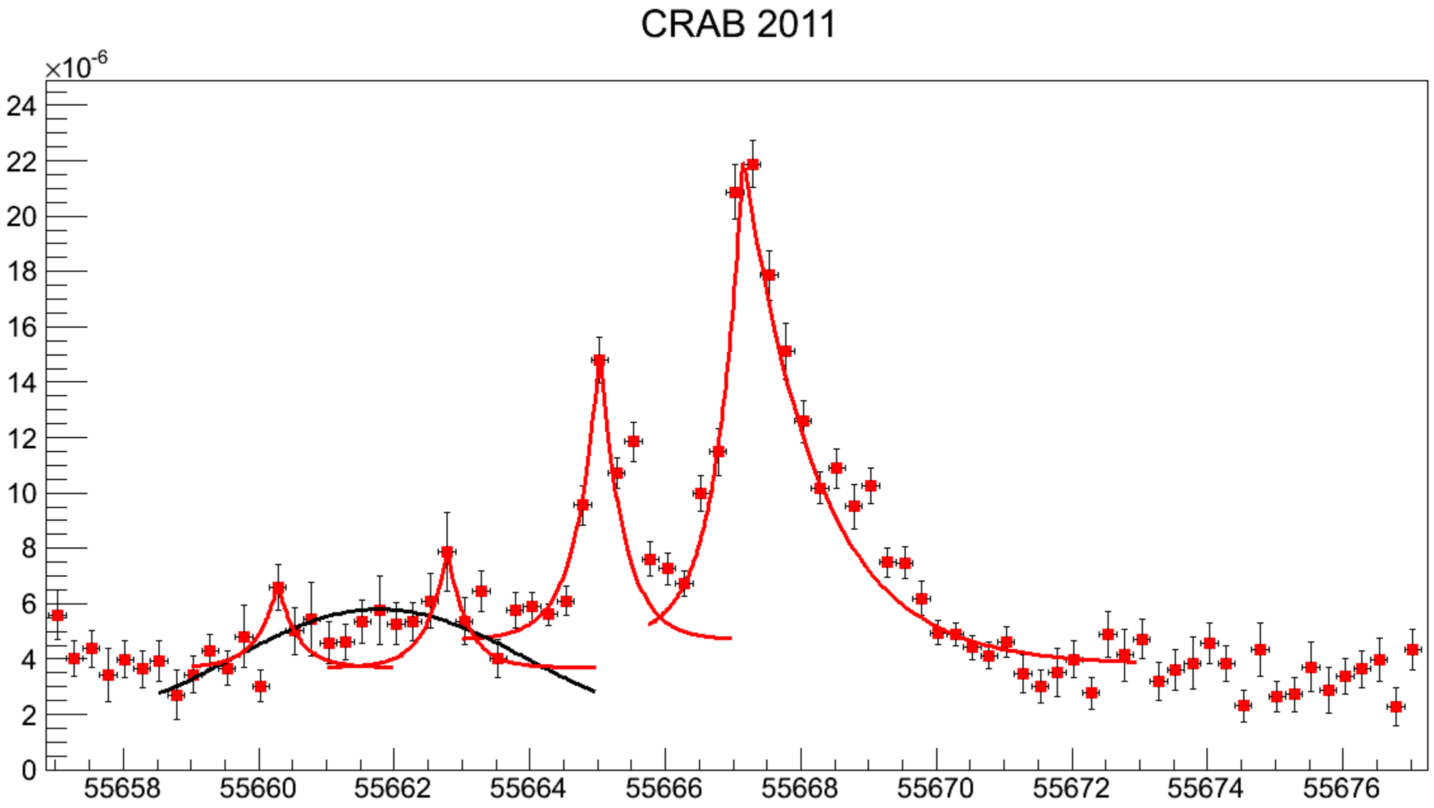


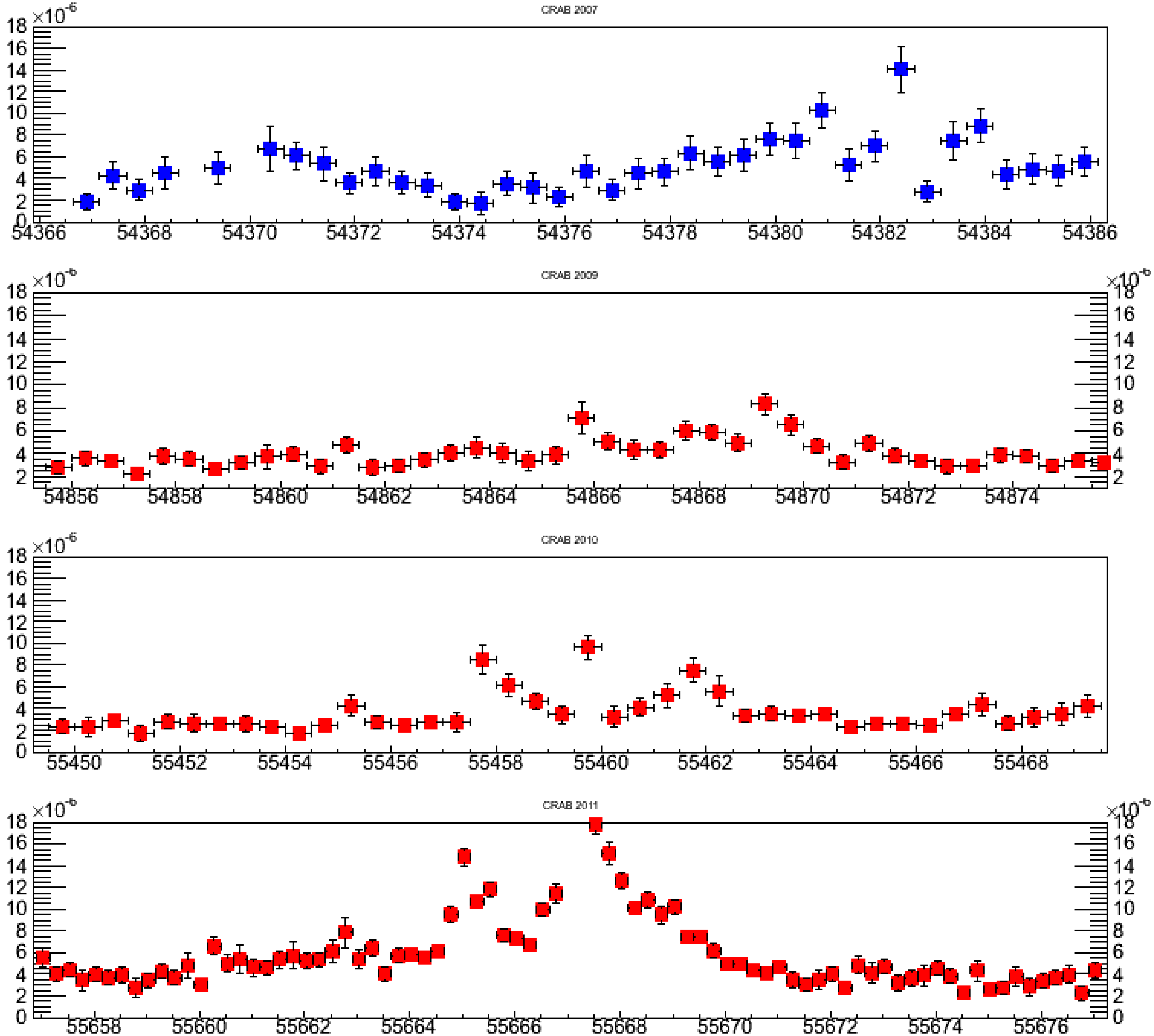
revisiting the Sept. 2010 flare FERMI data

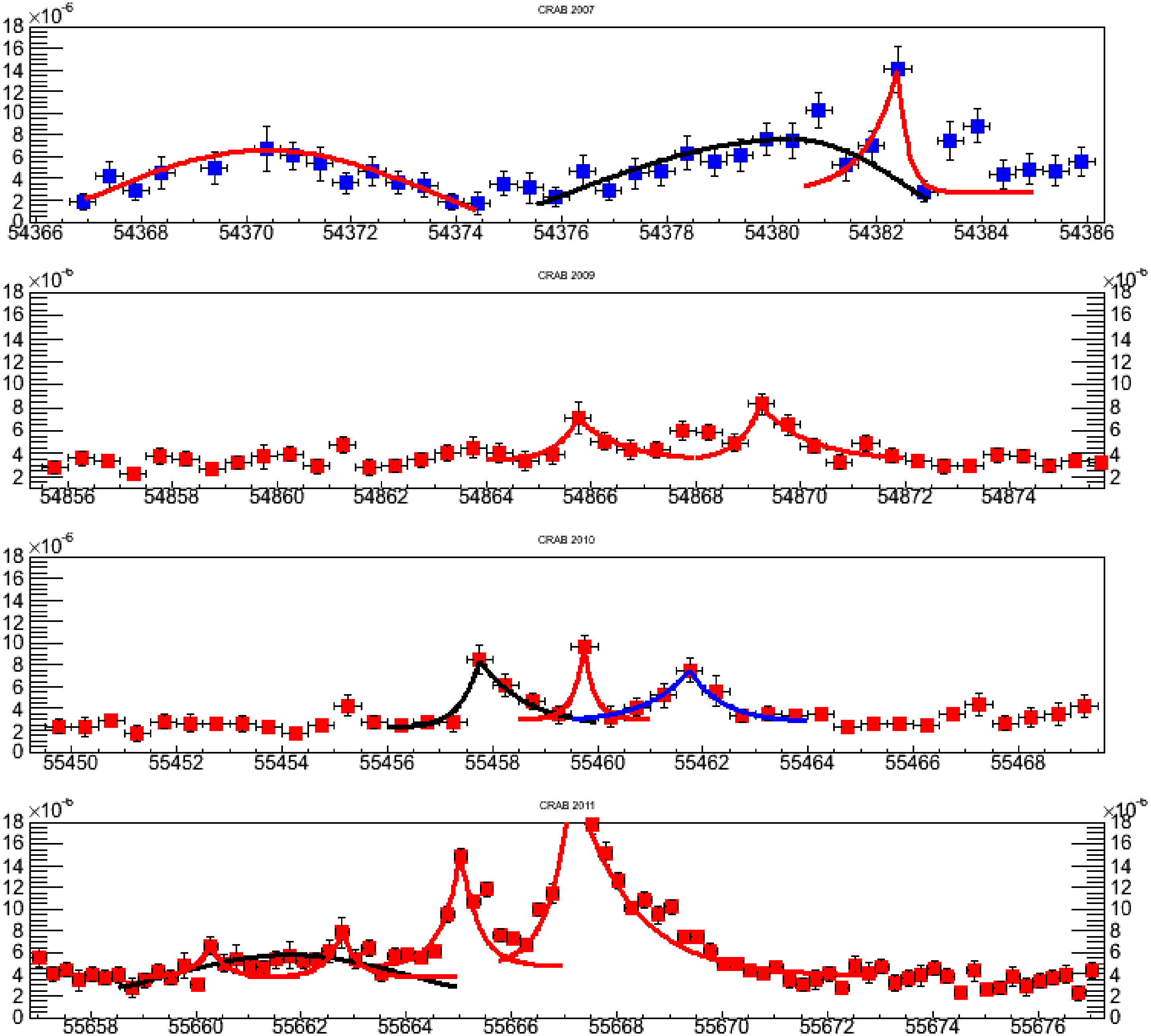
(Balbo et al., A&A, 527, L4, 2011)



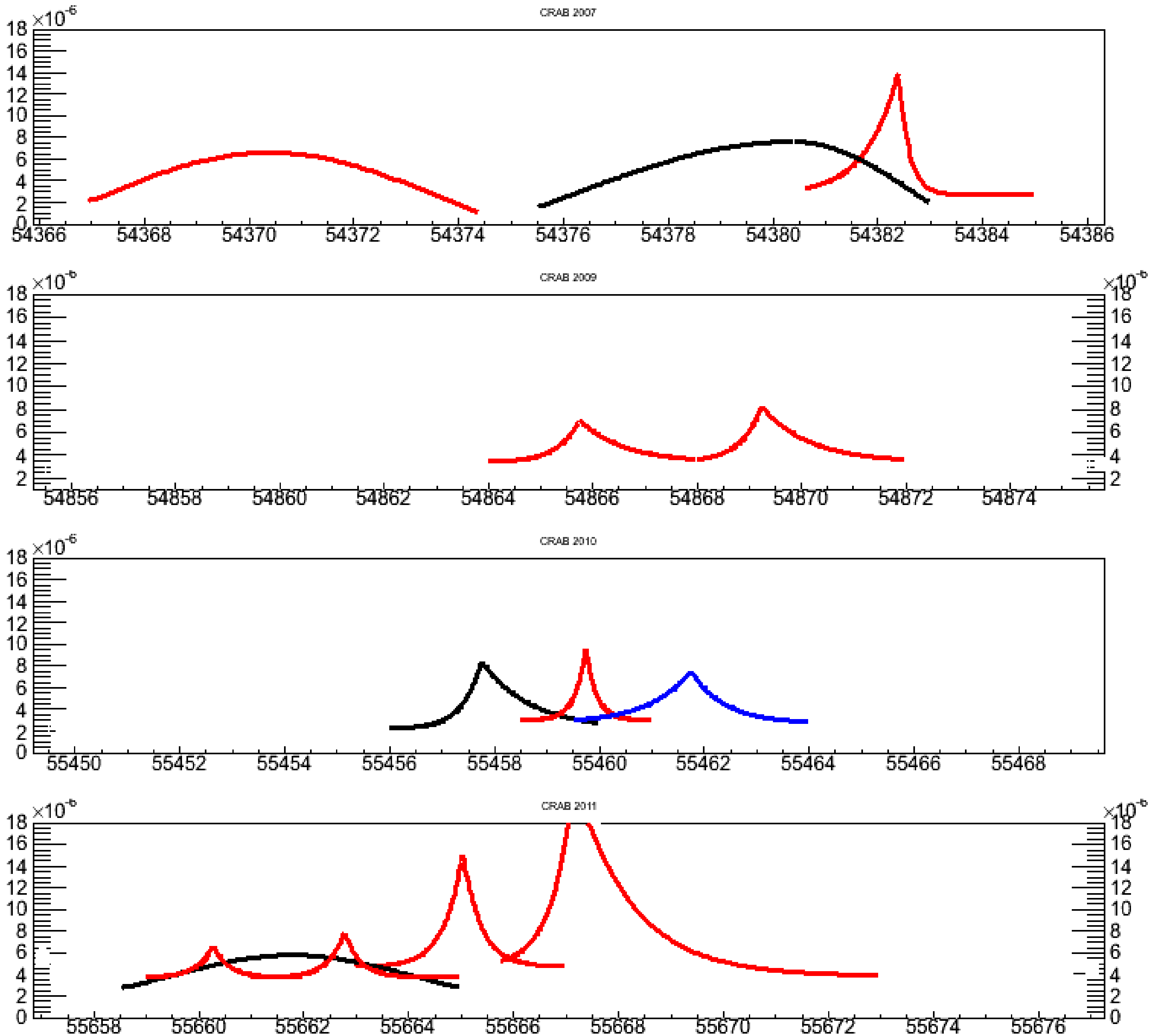
Crab super-flare (April 2011)
Fermi data




CRAB 2007
×10⁻⁶
0 2 4 6 8 10 12 14 16 18
54366 54368 54370 54372 54374 54376 54378 54380 54382 54384 54386
CRAB 2009
×10⁻⁶
2 4 6 8 10 12 14 16 18
54856 54858 54860 54862 54864 54866 54868 54870 54872 54874
CRAB 2010
×10⁻⁶
0 2 4 6 8 10 12 14 16 18
55450 55452 55454 55456 55458 55460 55462 55464 55466 55468
CRAB 2011
×10⁻⁶
0 2 4 6 8 10 12 14 16 18
55658 55660 55662 55664 55666 55668 55670 55672 55674 55676



CRAB 2007
×10-6
18 16 14 12 10 8 6 4 2 0
54366 54368 54370 54372 54374 54376 54378 54380 54382 54384 54386
CRAB 2009
×10-6
18 16 14 12 10 8 6 4 2
54856 54858 54860 54862 54864 54866 54868 54870 54872 54874
CRAB 2010
×10-6
18 16 14 12 10 8 6 4 2 0
55450 55452 55454 55456 55458 55460 55462 55464 55466 55468
CRAB 2011
×10-6
18 16 14 12 10 8 6 4 2 0
55658 55660 55662 55664 55666 55668 55670 55672 55674 55676



CRAB 2007
×10⁻⁶
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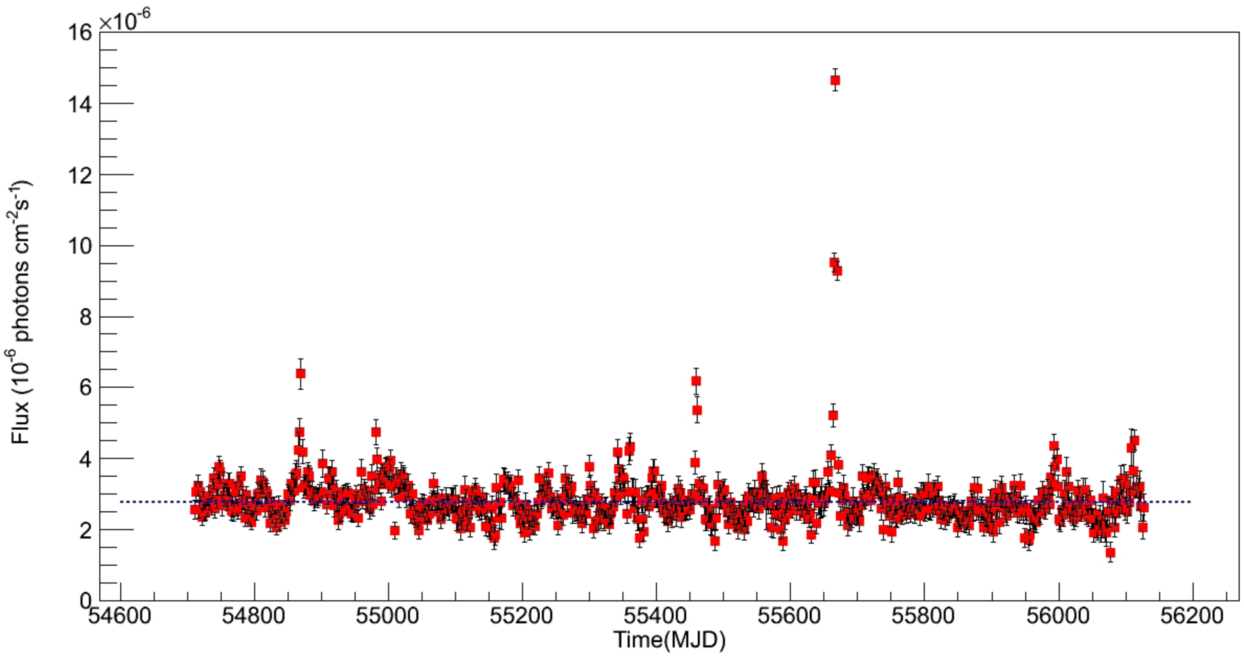
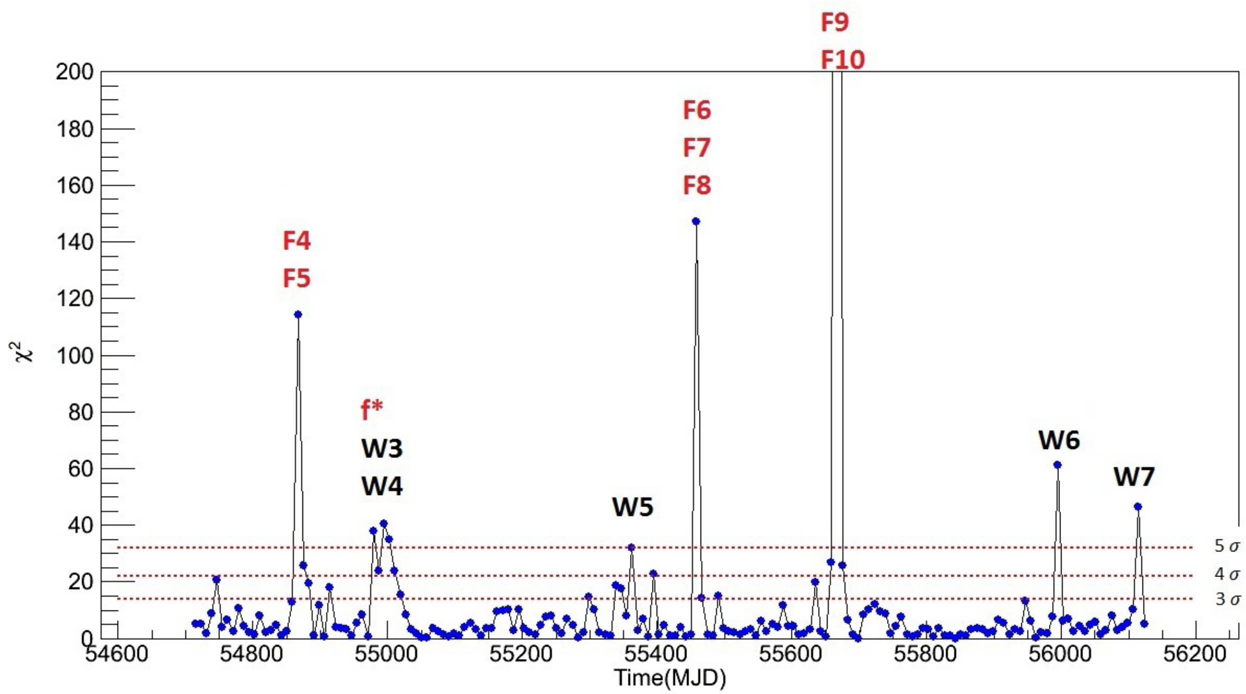
54366 54368 54370 54372 54374 54376 54378 54380 54382 54384 54386
CRAB 2009
×10⁻⁶
2 4 6 8 10 12 14 16 18
54856 54858 54860 54862 54864 54866 54868 54870 54872 54874
CRAB 2010
×10⁻⁶
0 2 4 6 8 10 12 14 16 18
55450 55452 55454 55456 55458 55460 55462 55464 55466 55468
CRAB 2011
×10⁻⁶
0 2 4 6 8 10 12 14 16 18
55658 55660 55662 55664 55666 55668 55670 55672 55674 55676

Crab gamma-ray “flares” and “waves” (Striani et al. 2013)

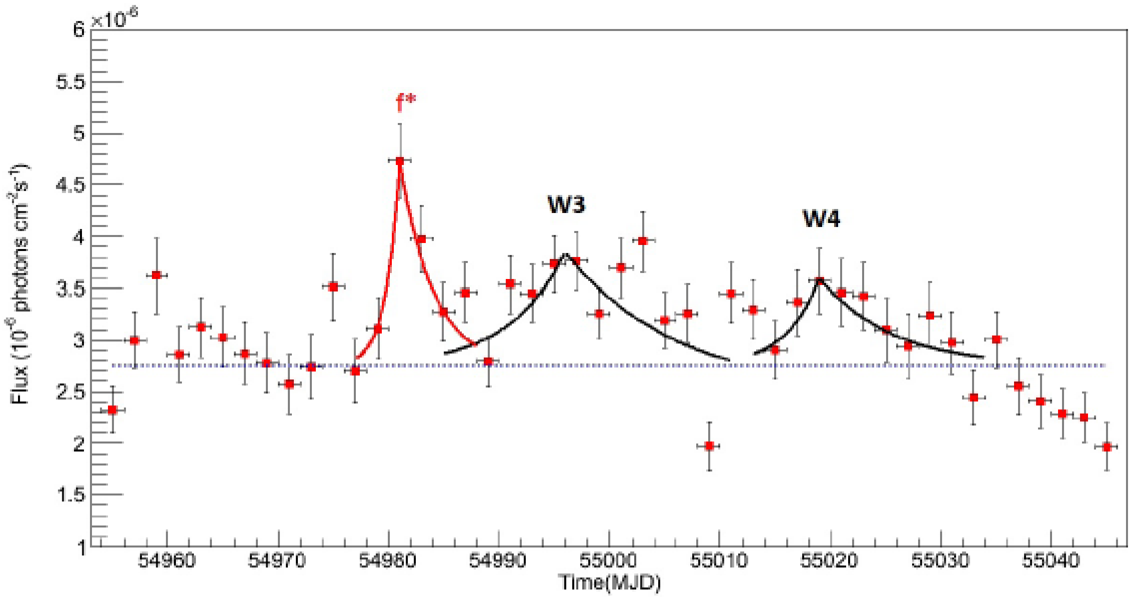
Fermi data shown here: identification of low-flux long-timescale events similar to the Sept. 2007 event.



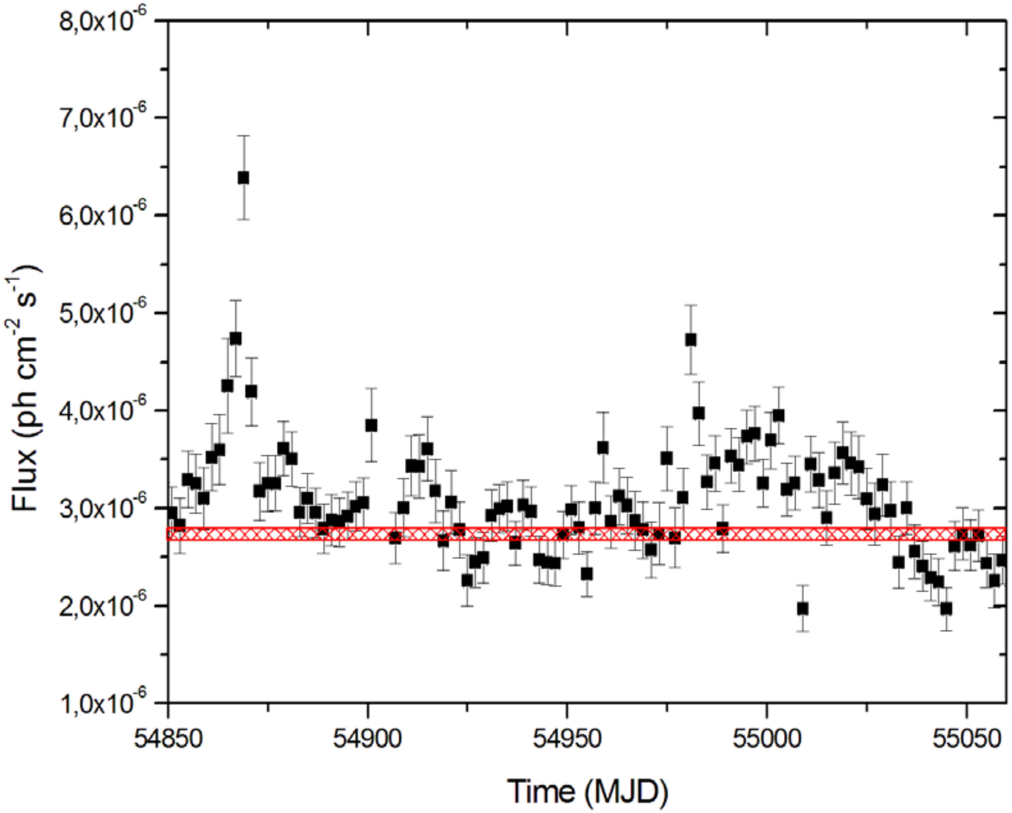


“Wave” Crab events (Striani et al 2013)

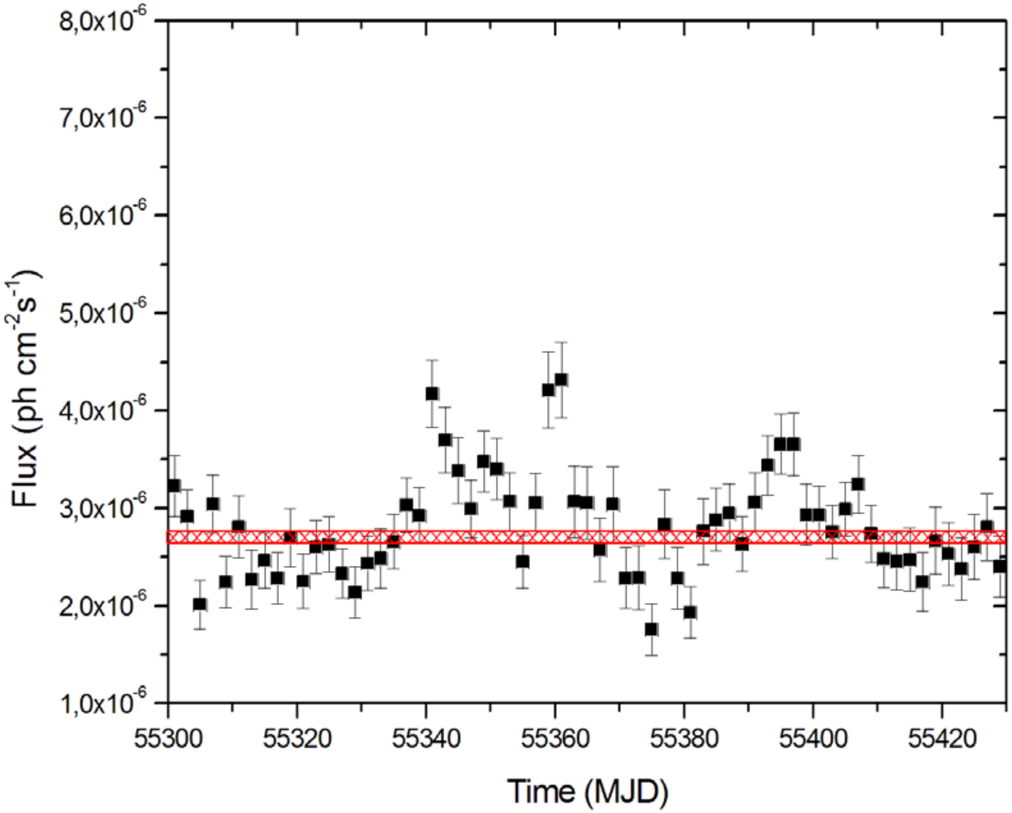
Name	MJD	Duration (days)	τ_1 (days)	τ_2 (days)	Average Flux ($10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$)	Peak Flux ($10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$)	Pre-trial p-value	Post-trial significance
W_1	54368-54373	5	2 ± 1	2 ± 1	440 ± 40	670 ± 200	4.5×10^{-8}	5.0
W_2	54376.5-54382.5	6	2.5 ± 1	2 ± 1	480 ± 40	760 ± 140	3.0×10^{-9}	5.5
W_3	54990-55008	18	5 ± 2.5	10 ± 5	352 ± 9	380 ± 30	1.0×10^{-8}	4.6
W_6	55988-56000	12	5 ± 2.5	3.5 ± 1.5	367 ± 12	435 ± 35	1.8×10^{-12}	6.2
W_7	56108-56114	6	3 ± 1.5	3 ± 1.5	431 ± 22	450 ± 30	1.9×10^{-9}	5.9



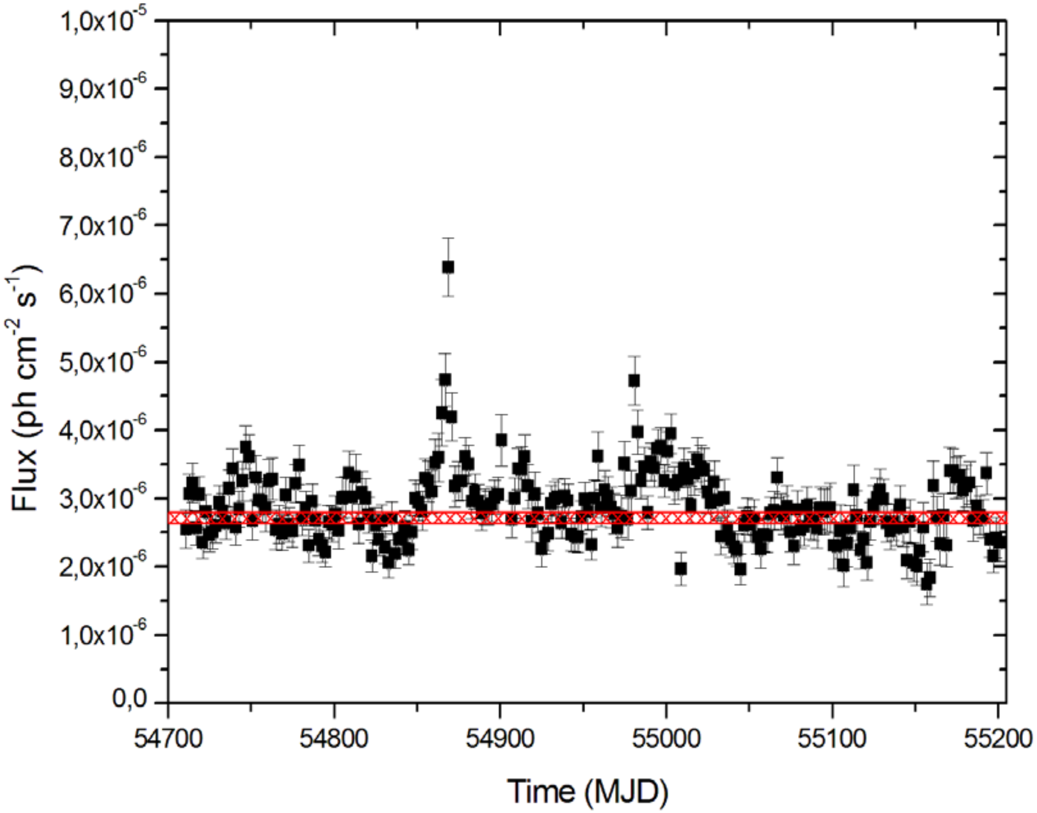
Fermi data, 2-day bin



Fermi data, 2-day bin



Fermi data, 2-day bin



typically for "flares" (and also "waves")

- **gamma-ray flare radiated energy**

  $$E \approx 10^{41}\ \text{erg}$$

- **kin. energy fraction of PSR spindown E_{sd},**

  $$\varepsilon \approx 0.001\ (\eta_{-1}/0.1) \approx 0.01$$

- **timescales:**
  - **flares:** ~ 1-3 days
  - **"waves":** ~ 1 week

Crab Apr. 2011 flare

- **gamma-ray flare peak luminosity**

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

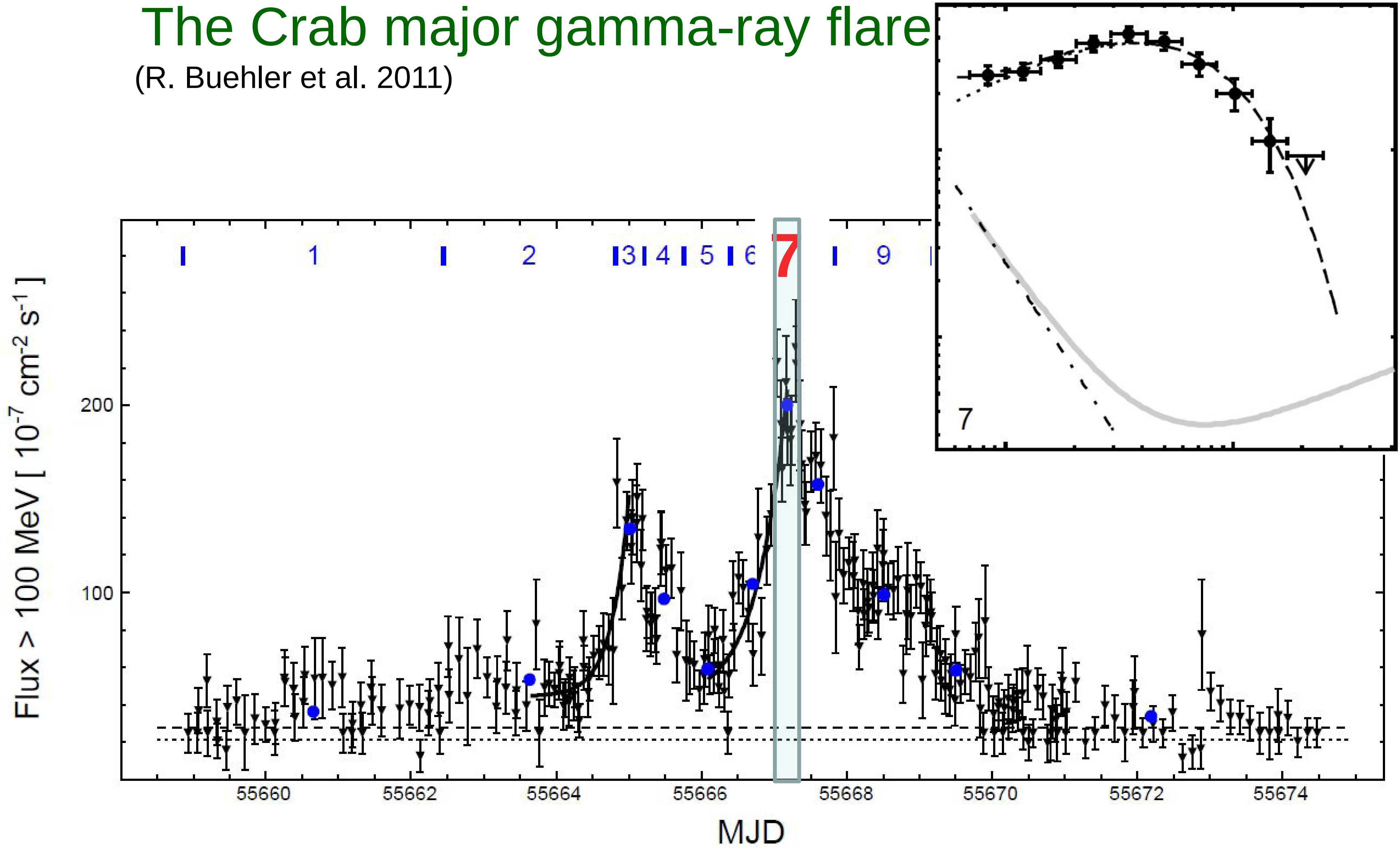
- **kin. power fraction of PSR spindown L_{sd},**

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

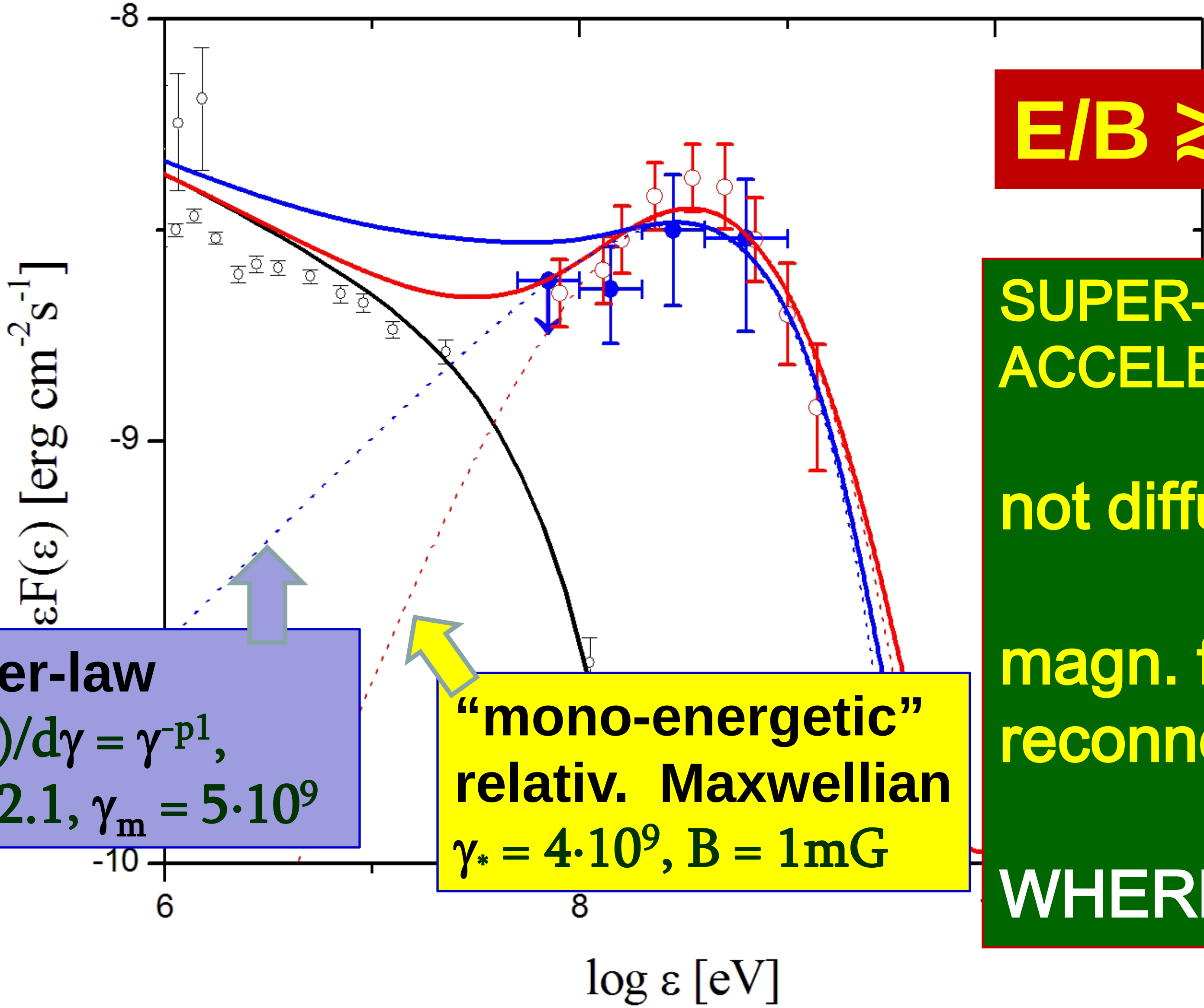
- **timescales:**
  - **risetime** $\leq$ a few hrs ← **very efficient acceleration !**
  - **decay:** ~ 1-2-3 days ← **fast cooling, B, Lorentz γ**

The Crab major gamma-ray flare

(R. Buehler et al. 2011)



modelling of the April 2012 super-flare



E/B ≳ 2 !

power-law
$dN(\gamma)/d\gamma = \gamma^{-p1}$,
$p1 = 2.1$, $\gamma_m = 5 \cdot 10^9$

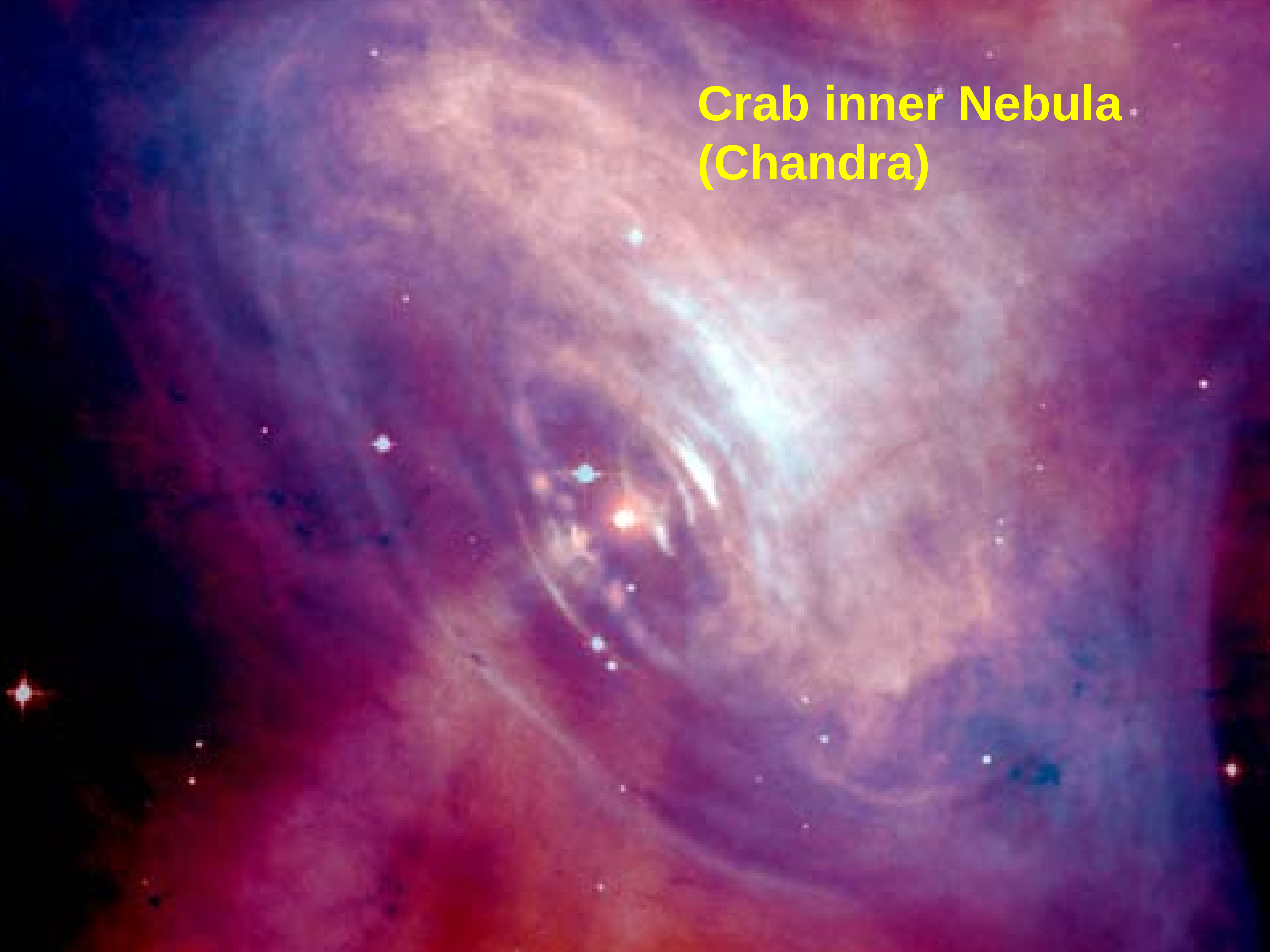
"mono-energetic"
relativ. Maxwellian
$\gamma_* = 4 \cdot 10^9$, $B = 1$mG

SUPER-
ACCELERATION

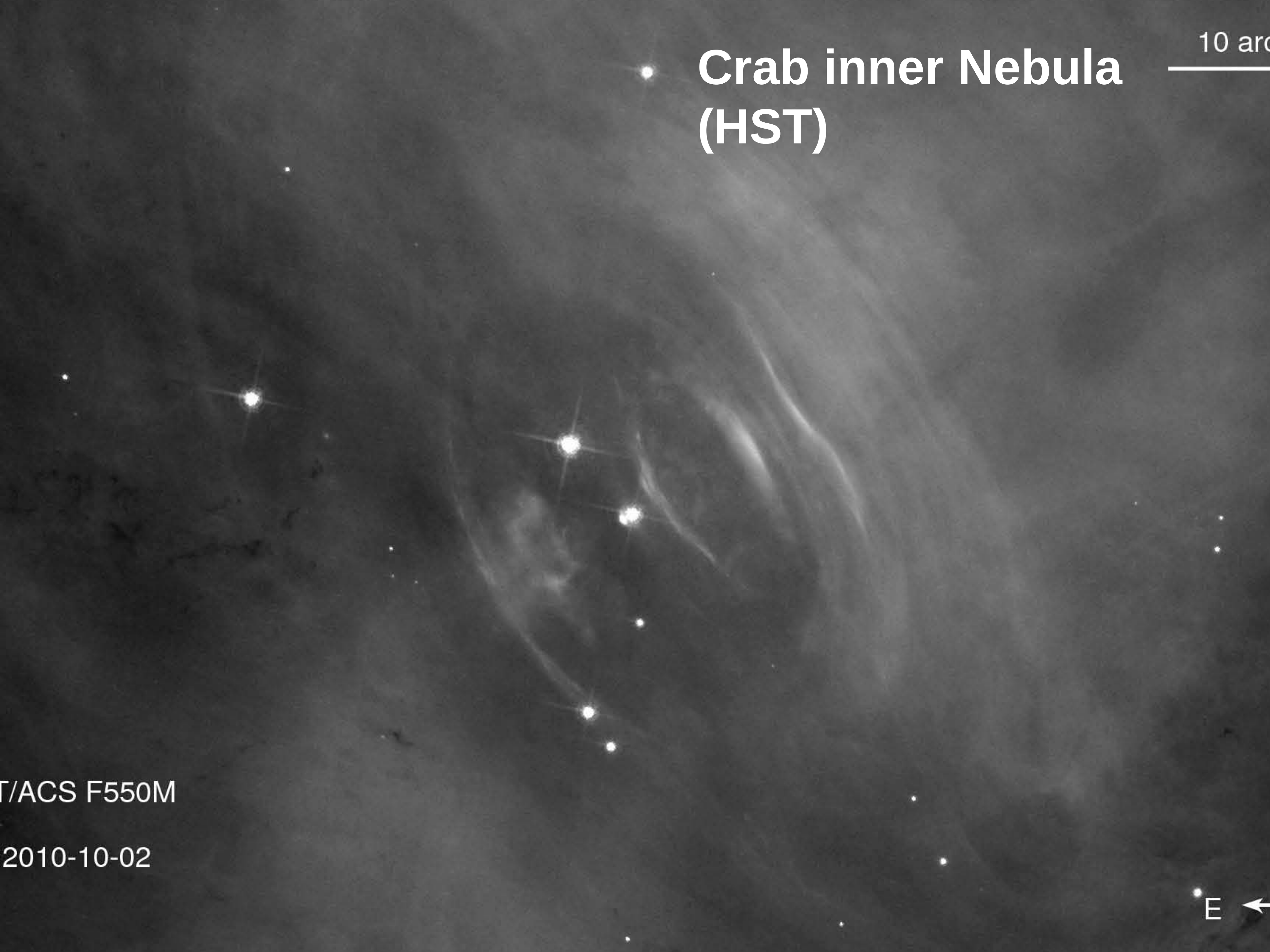
not diffusive !

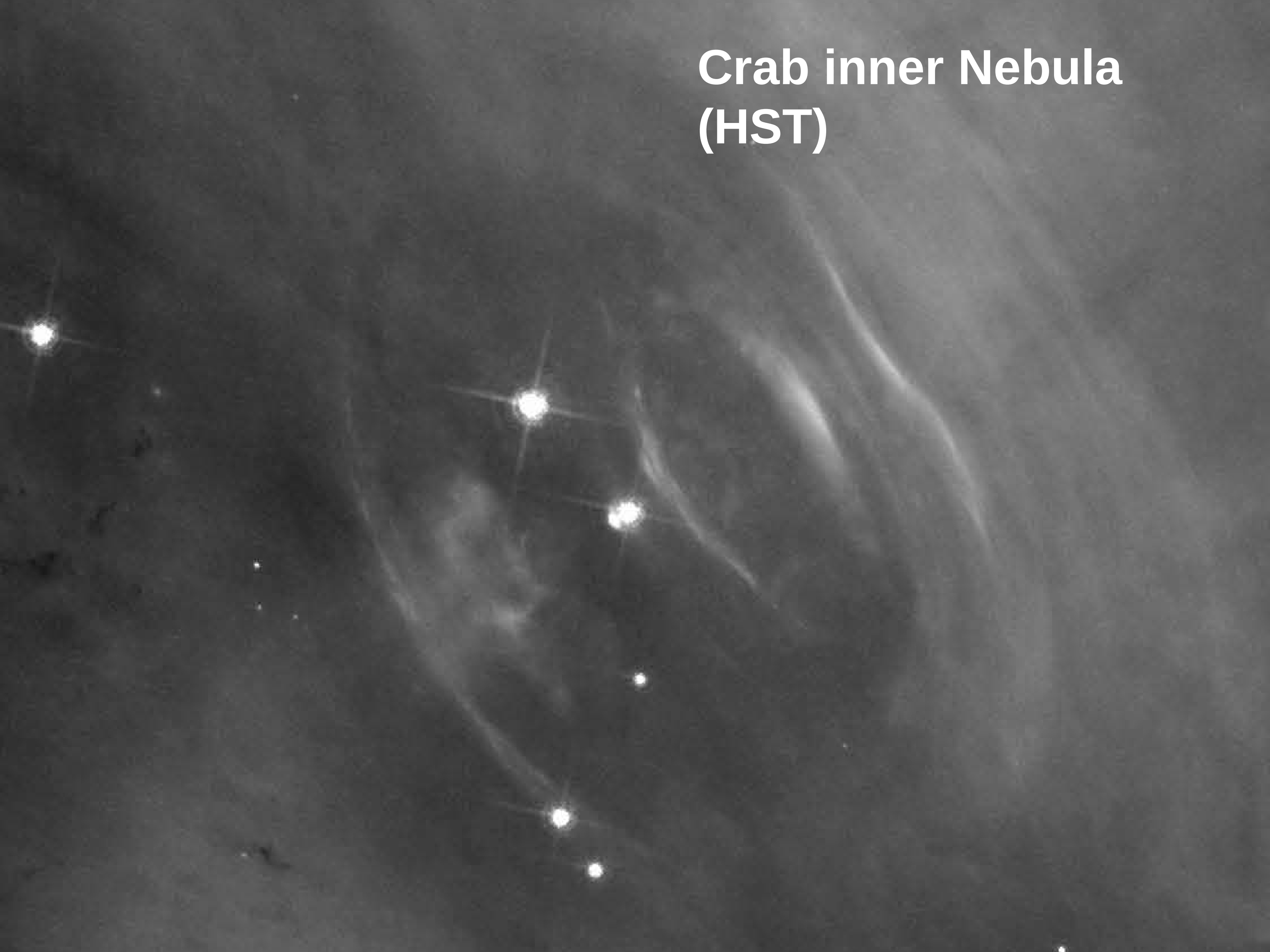
magn. field
reconnection ?

WHERE ?

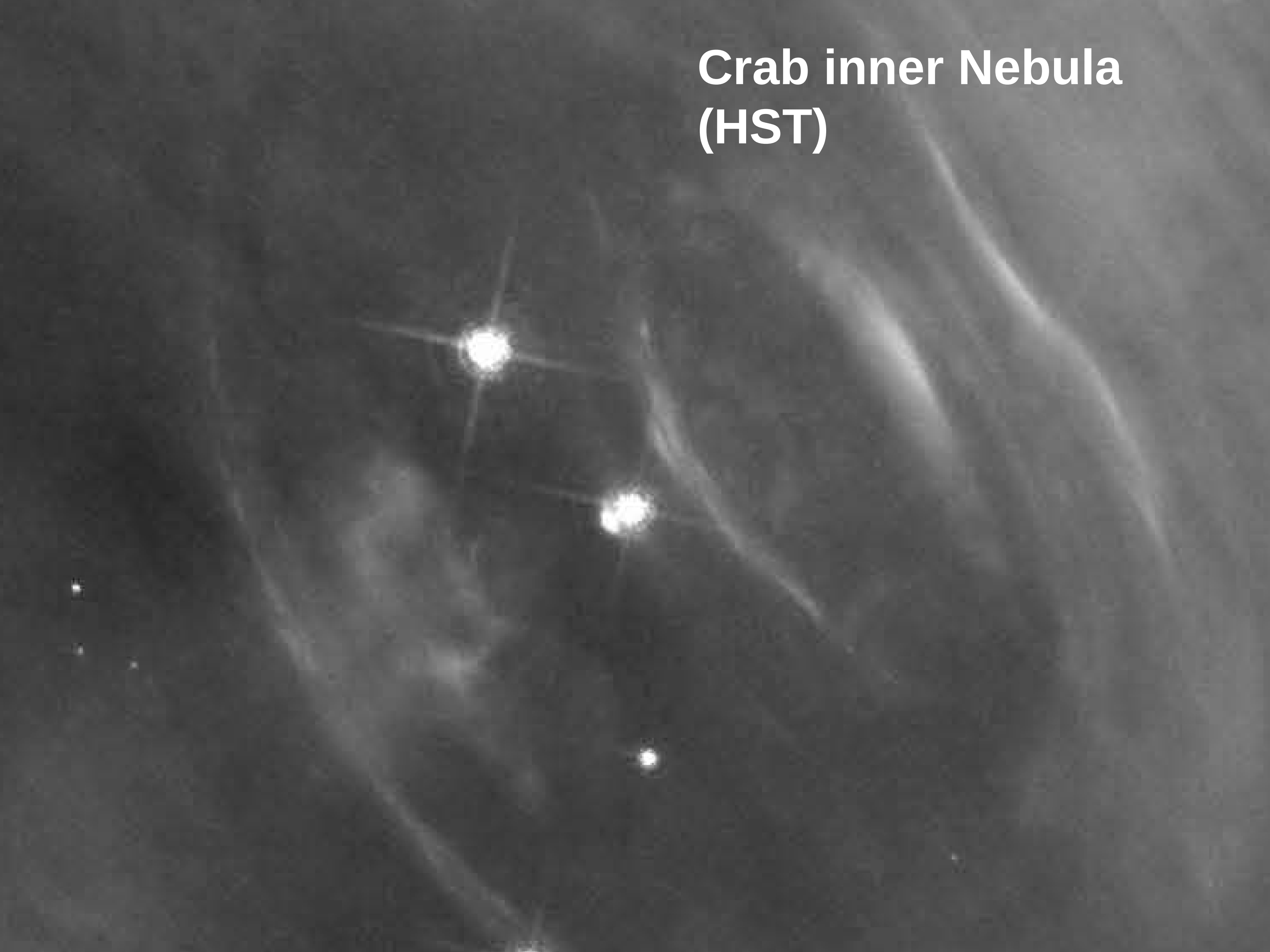

Crab inner Nebula
(Chandra)

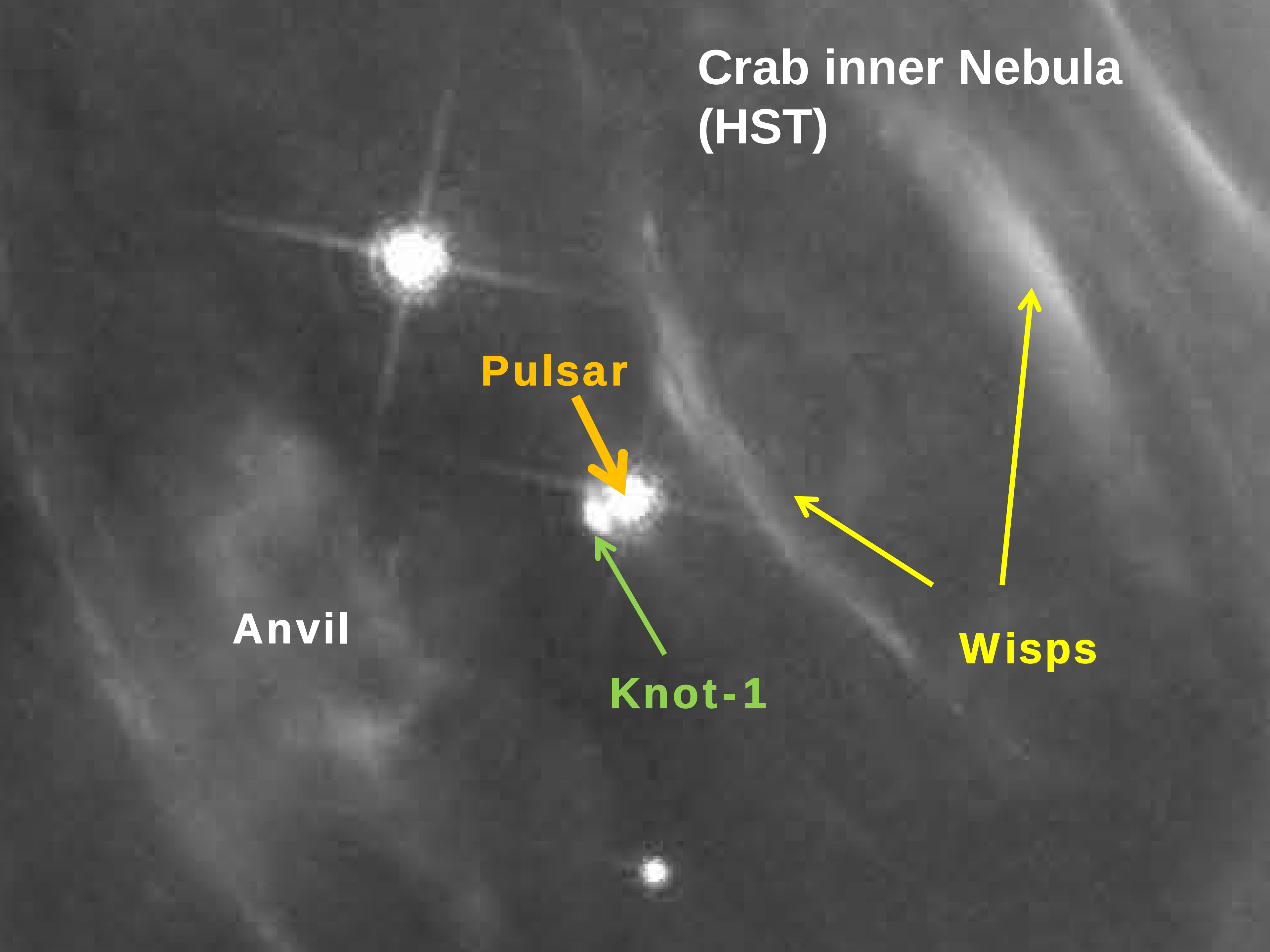
Crab inner Nebula (HST)




Crab inner Nebula
(HST)

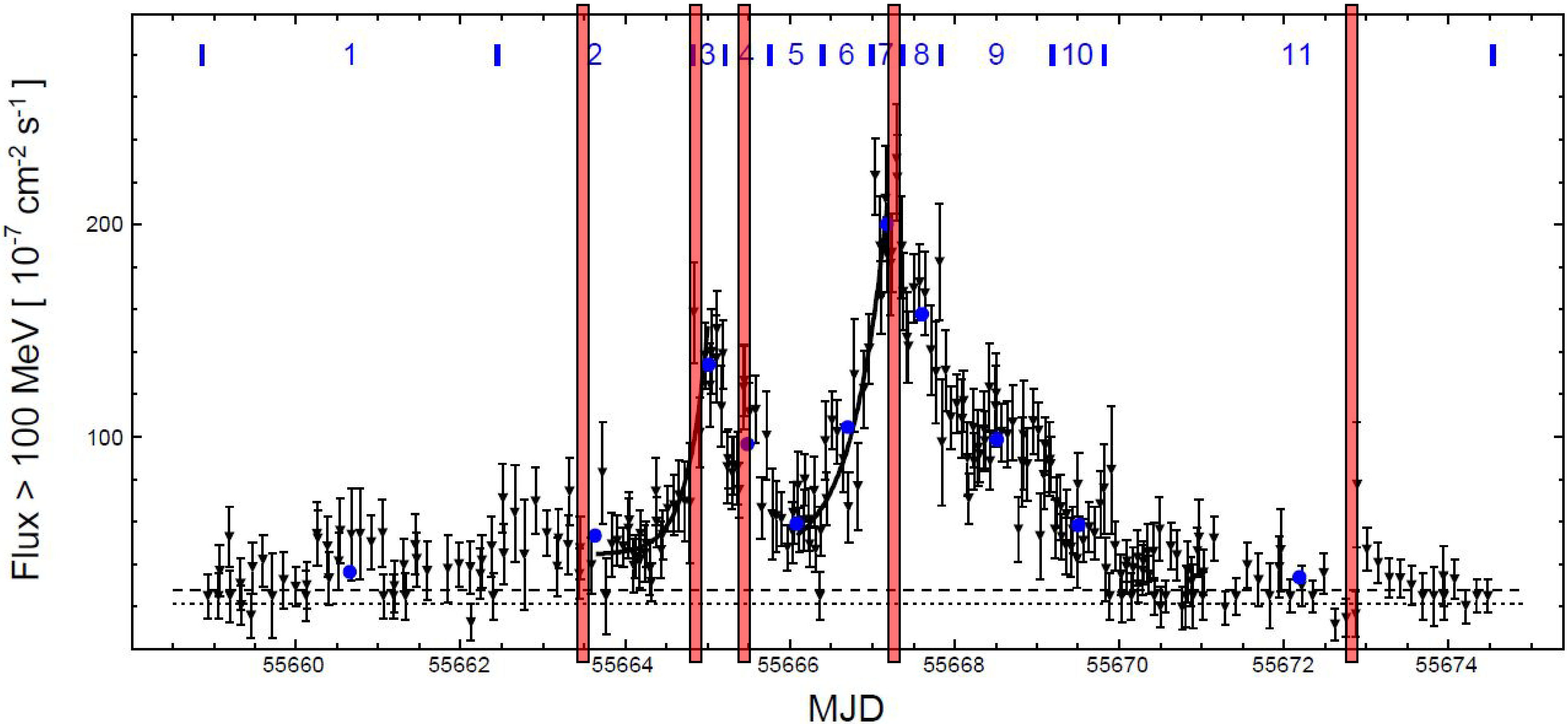
Crab inner Nebula (HST)





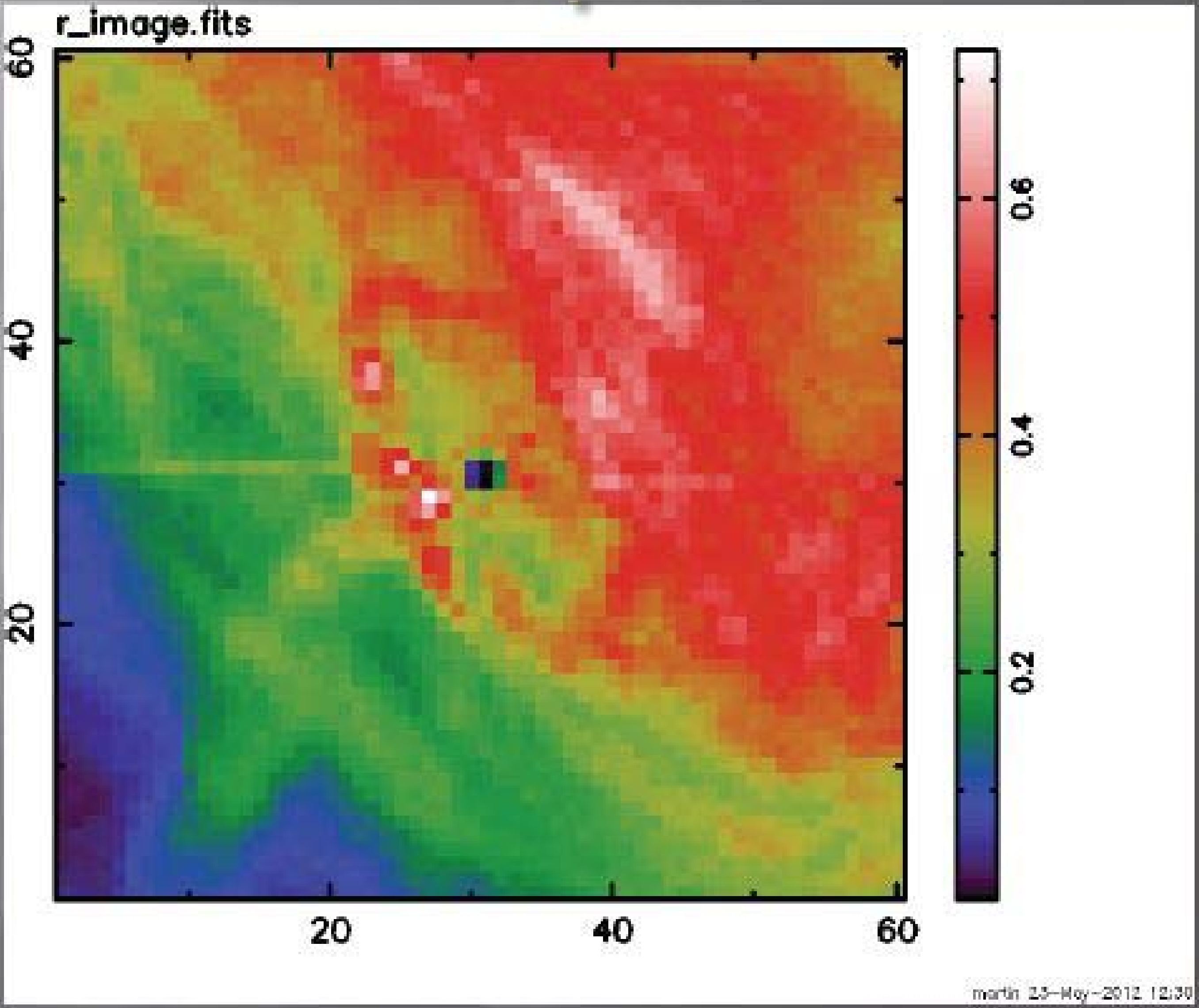
Crab inner Nebula
(HST)
Pulsar
Anvil
Knot-1
Wisps

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

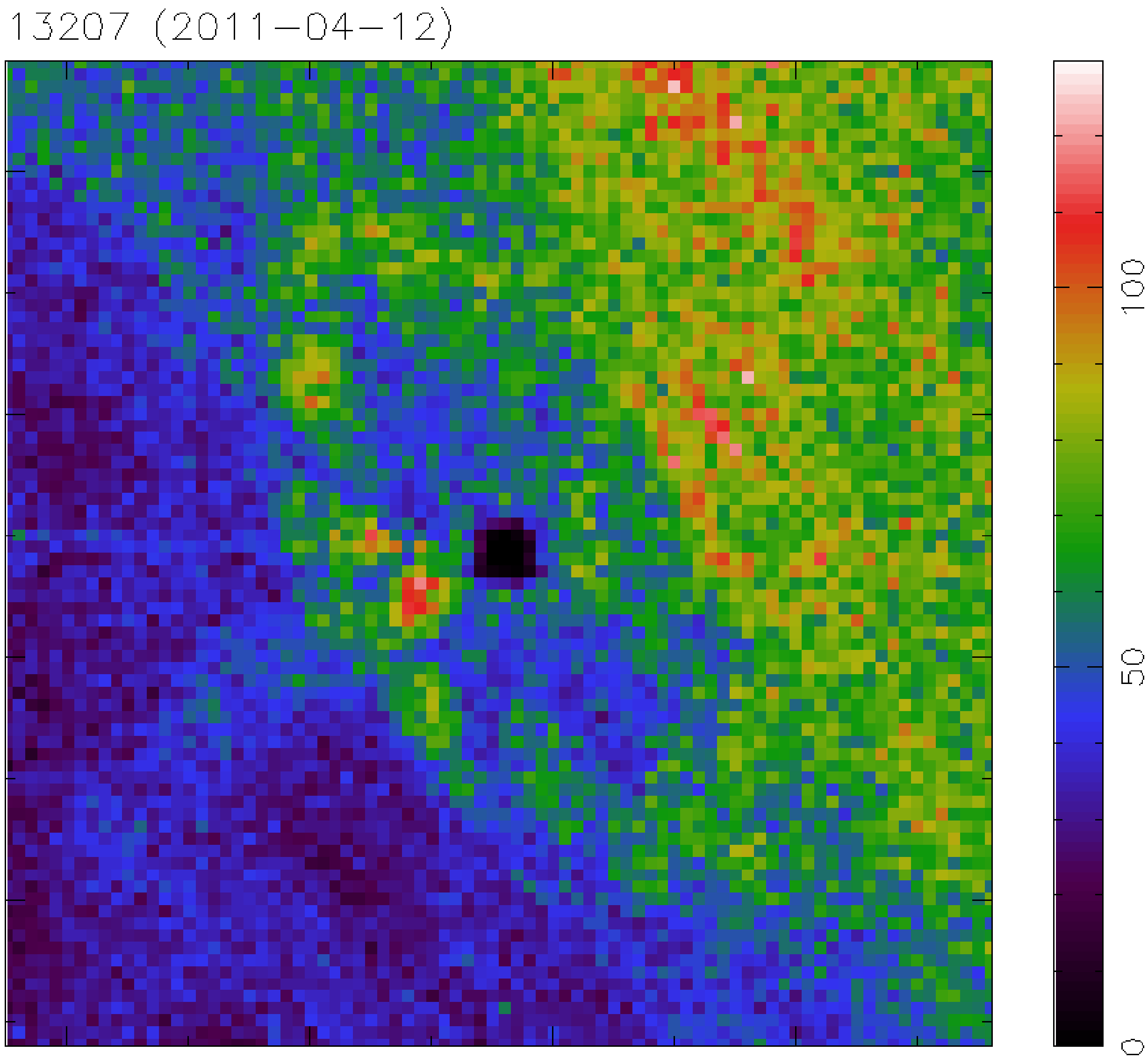


The average Chandra image 2011

(M. Weisskopf et al., 2012)

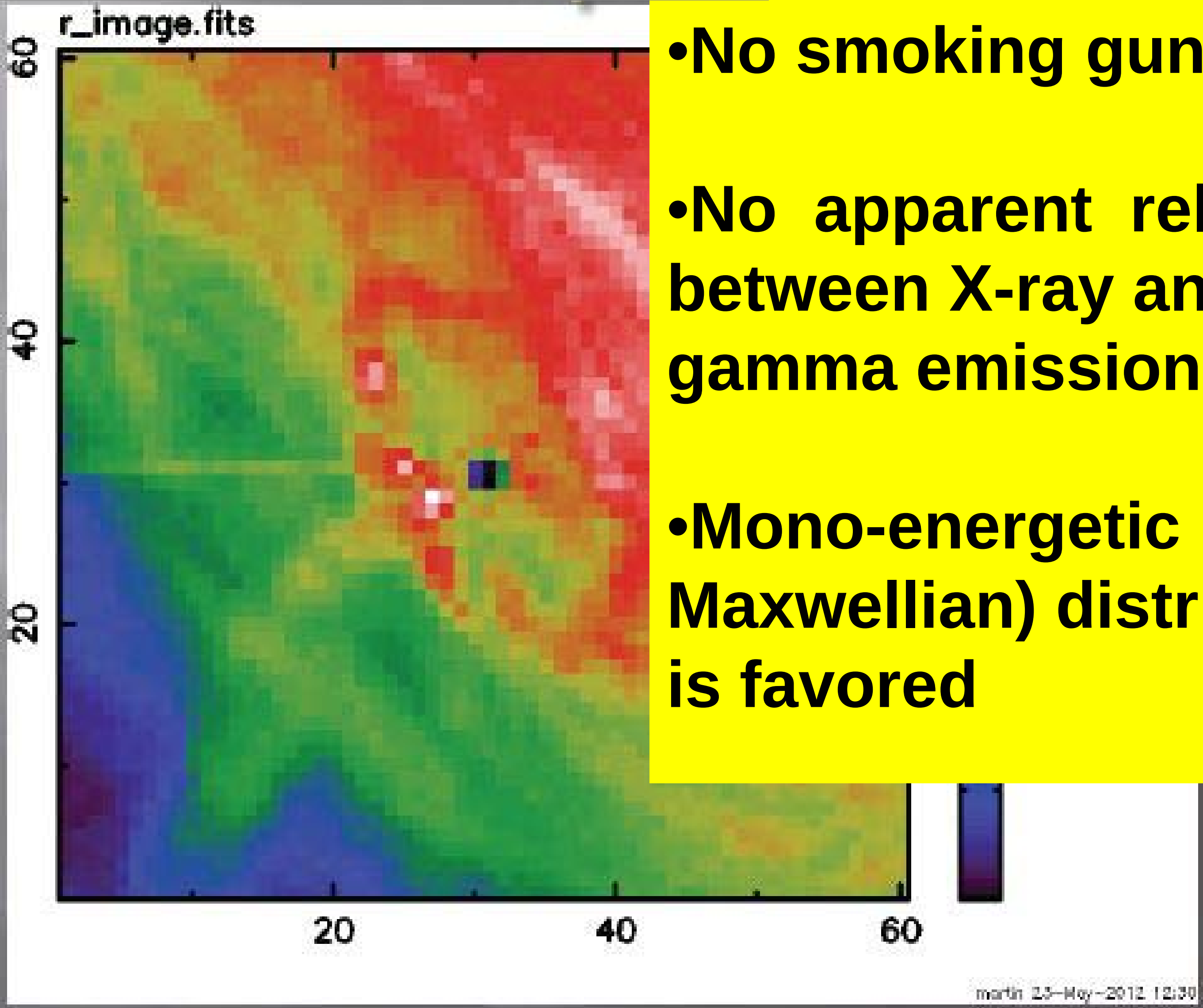


Crab super-flare: Chandra monitoring
(12, 13, 14, 21 Apr. 2011: A. Tennant, M. Weisskopf)



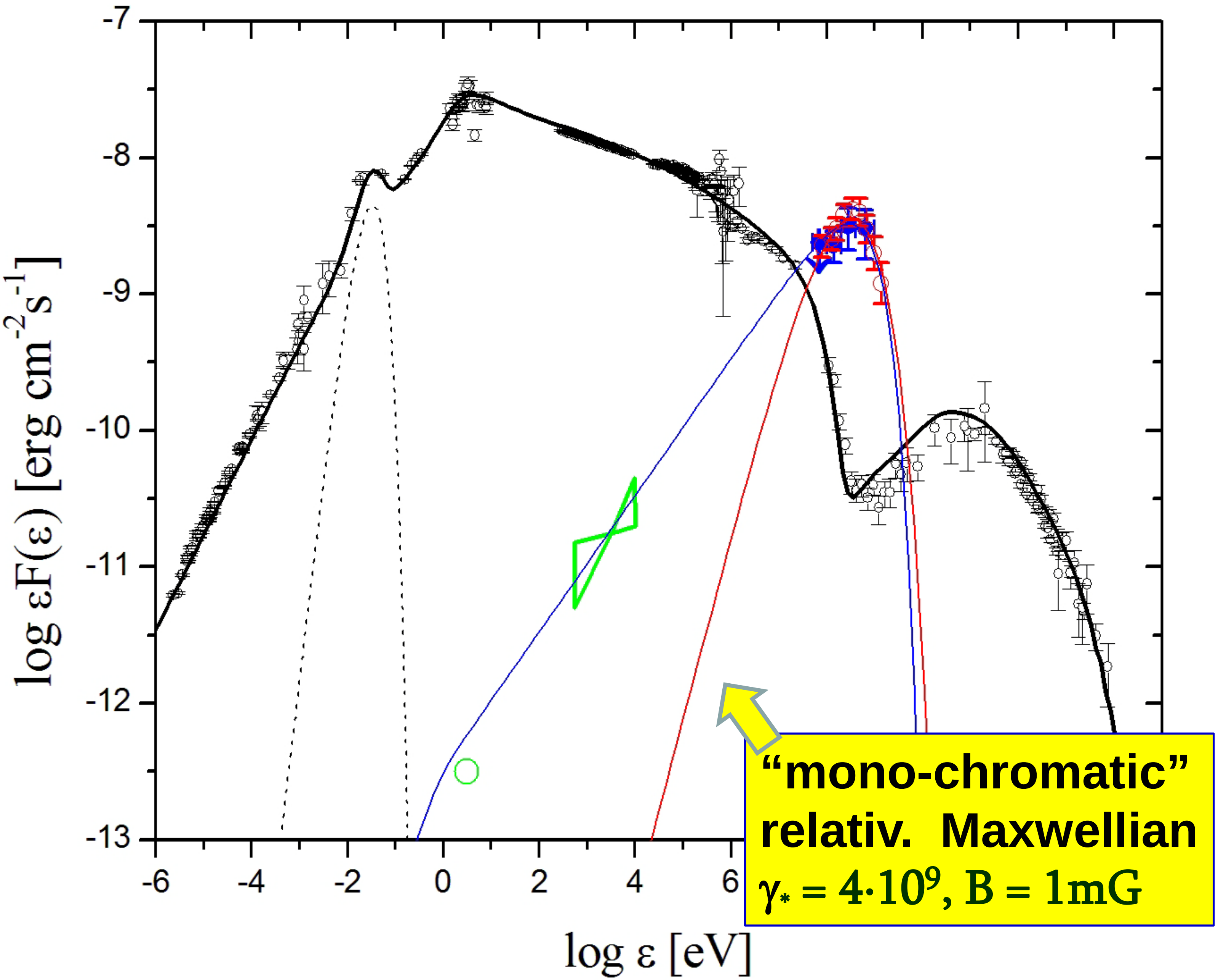
The average Chandra image 2011

(M. Weisskopf et al., 2012)



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

April 2011 event: Crab gamma-ray flare spectrum at its peak



issues

- **standard MHD is inadequate to explain spectrum and timescales**

- **detailed acceleration mechanism is to be identified**

- **a strong “E-parallel” may be required: magnetic field reconnection (?)**

- **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 (?)**

already many ideas…(incomplete list)

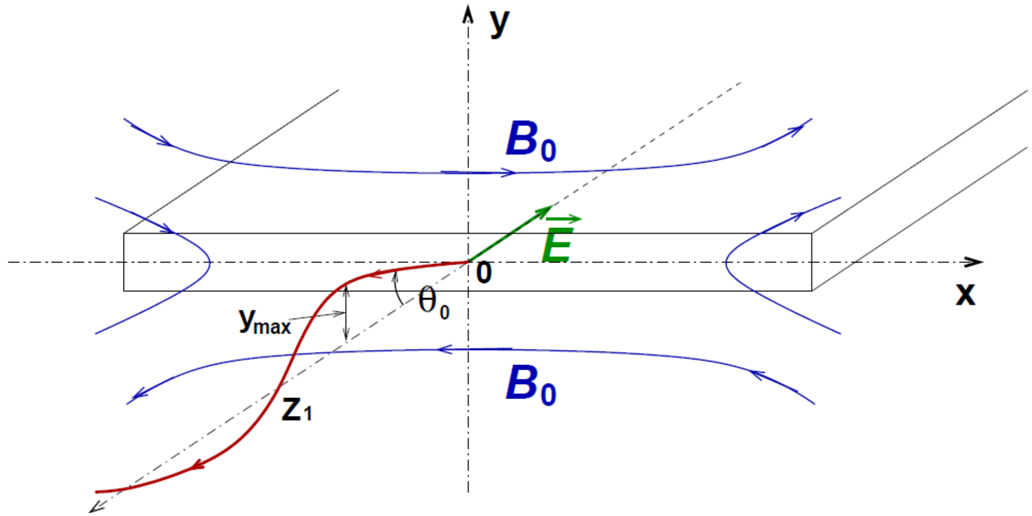
- **Tavani et al. (2011, 2012)**
- **Abdo et al. (2011, 2012)**
- **Bednarek & Idec (2011)**
- **Komissarov & Lyutikov (2011)**
- **Vittorini et al., Striani et al. (2011)**
- **Lyutikov, Balsara, Matthews (2011)**
- **Bykov, Pavlov, Artemyev, Uvanov (2011)**
- **Cerutti, Uzdensky, Begelman (2012, 2013)**
- **Arons (2012)**
- **Mignone et al. (2012)**
- **Salvati (2012)**
- **Lyubarsky (2012)**
- **Blandford & Li (2012)**
- **Striani et al. (2012)**

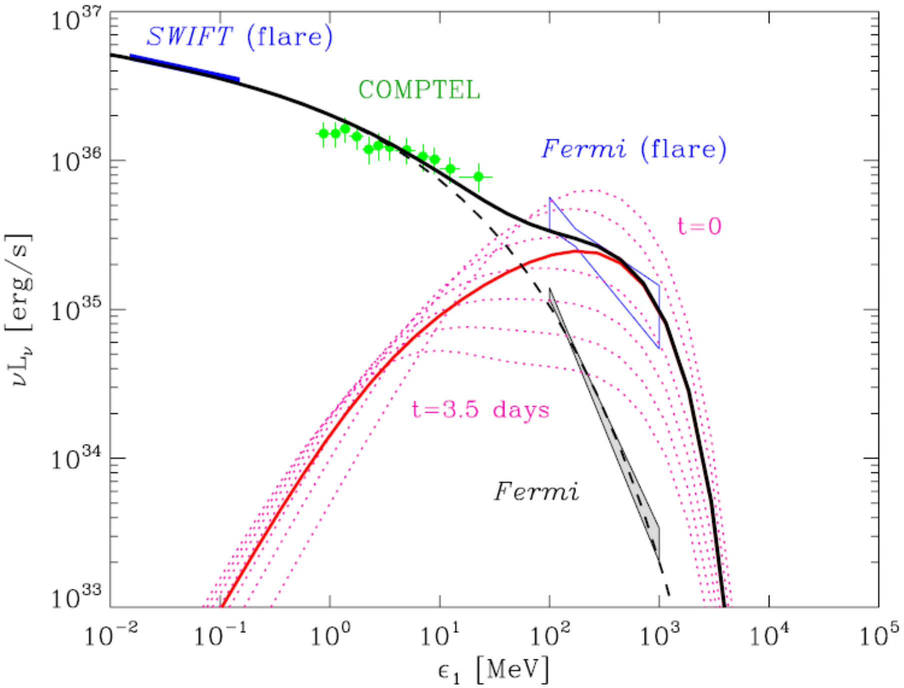
ingredients…

- **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**

Magnetic field reconnection in current sheets (test particle calculation)

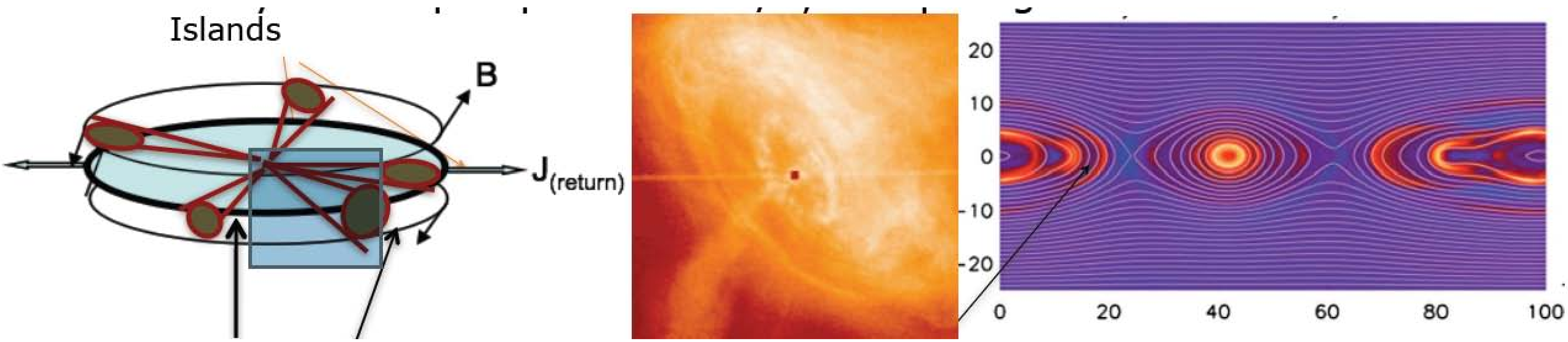
Cerutti, Uzdensky, Begelman, ApJ 2012

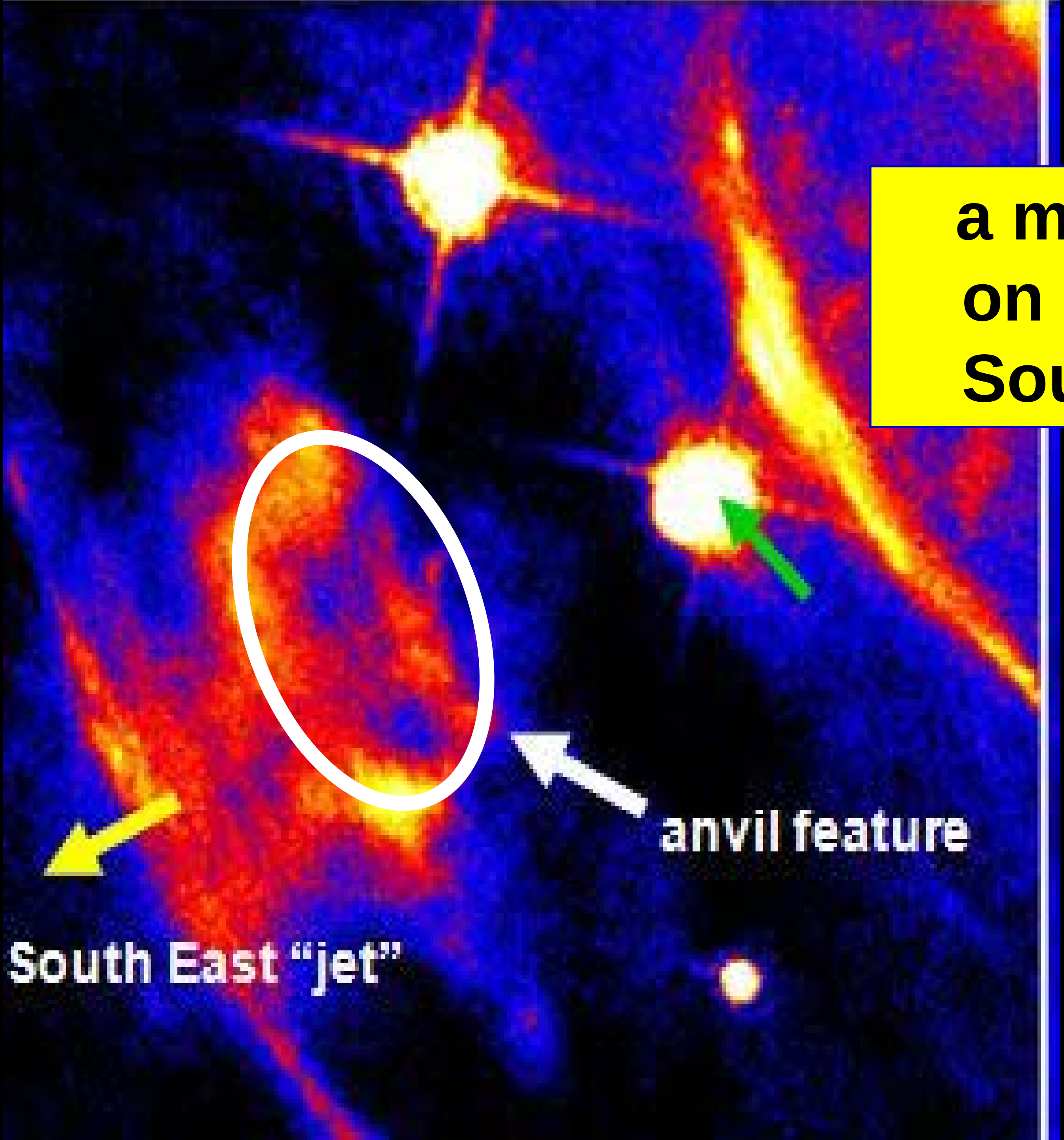




Magnetic field reconnection in current sheets in toroidal regions

J. Arons (2012)

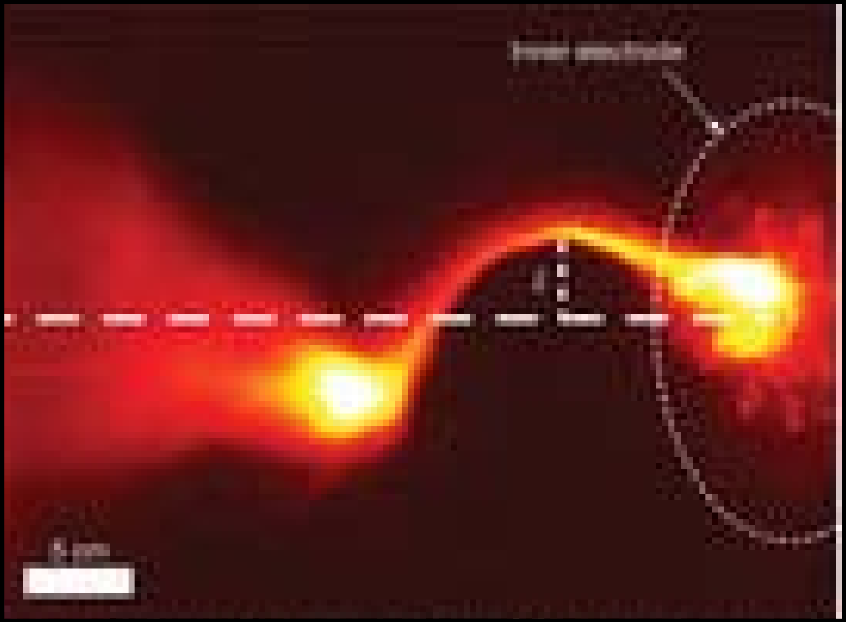


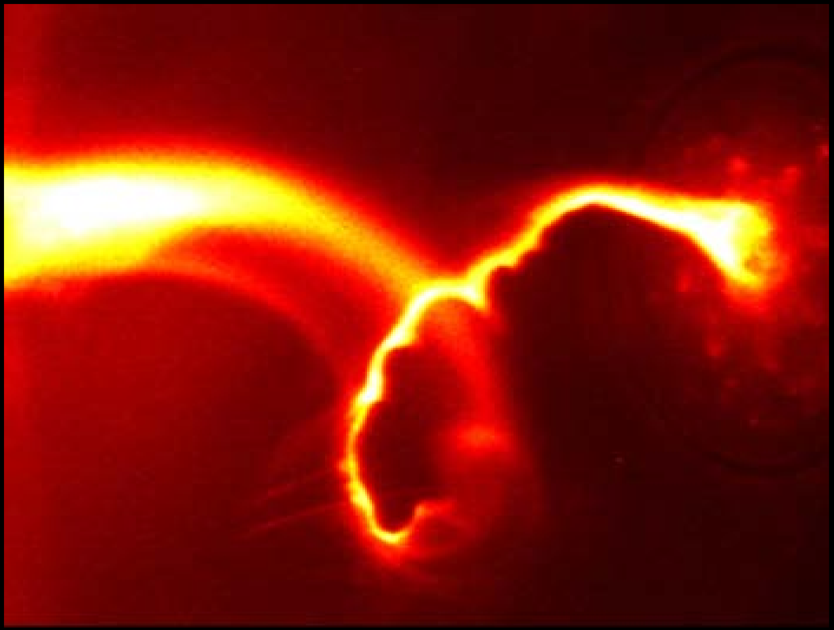


a model based on a "kinking" South East jet

Plasma kink instability

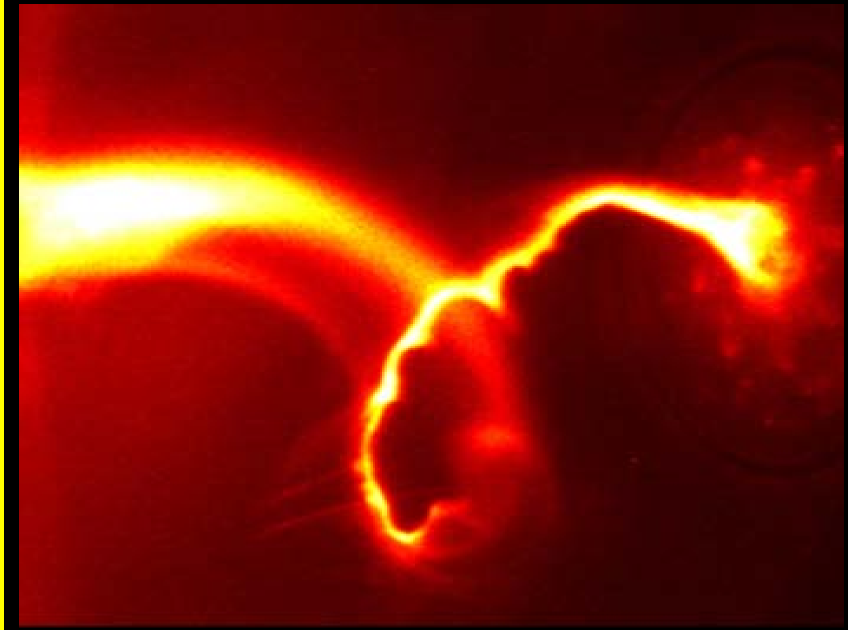
A.L. Moser, P. Bellan, Nature , 482, 379 (2012)





Plasma kink instability

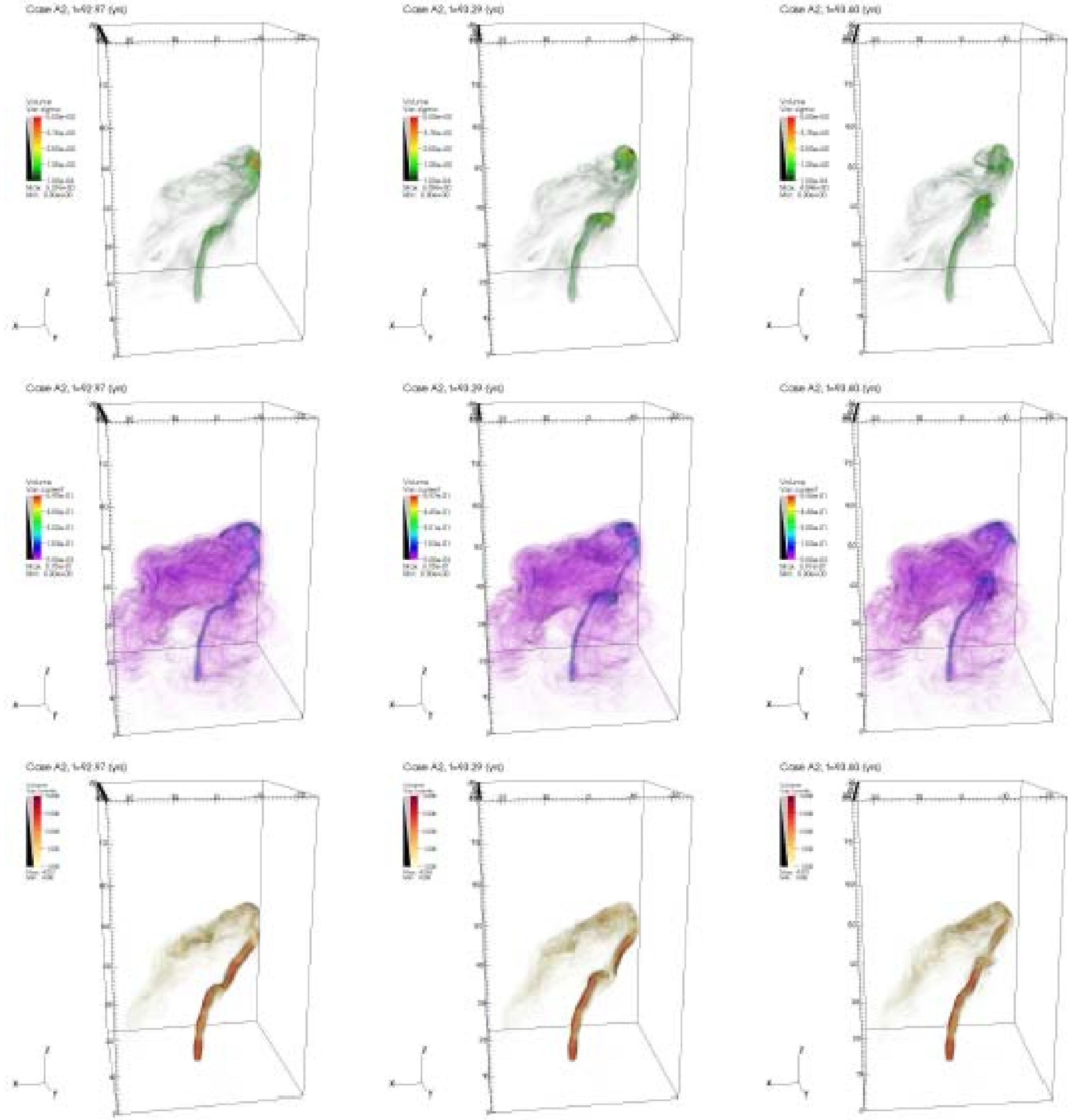
1. magnetic field reconnection in “islands” related to kink instabilities
2. reconnection detected in tomakaks as “sawthooth oscillations” and/or runaway acceleration
3. **particle acceleration in kink-driven reconnection events**
4. a framework for the Crab gamma-ray flares originating in the “anvil”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

the A2 case,
Γ = 2, σ = 1

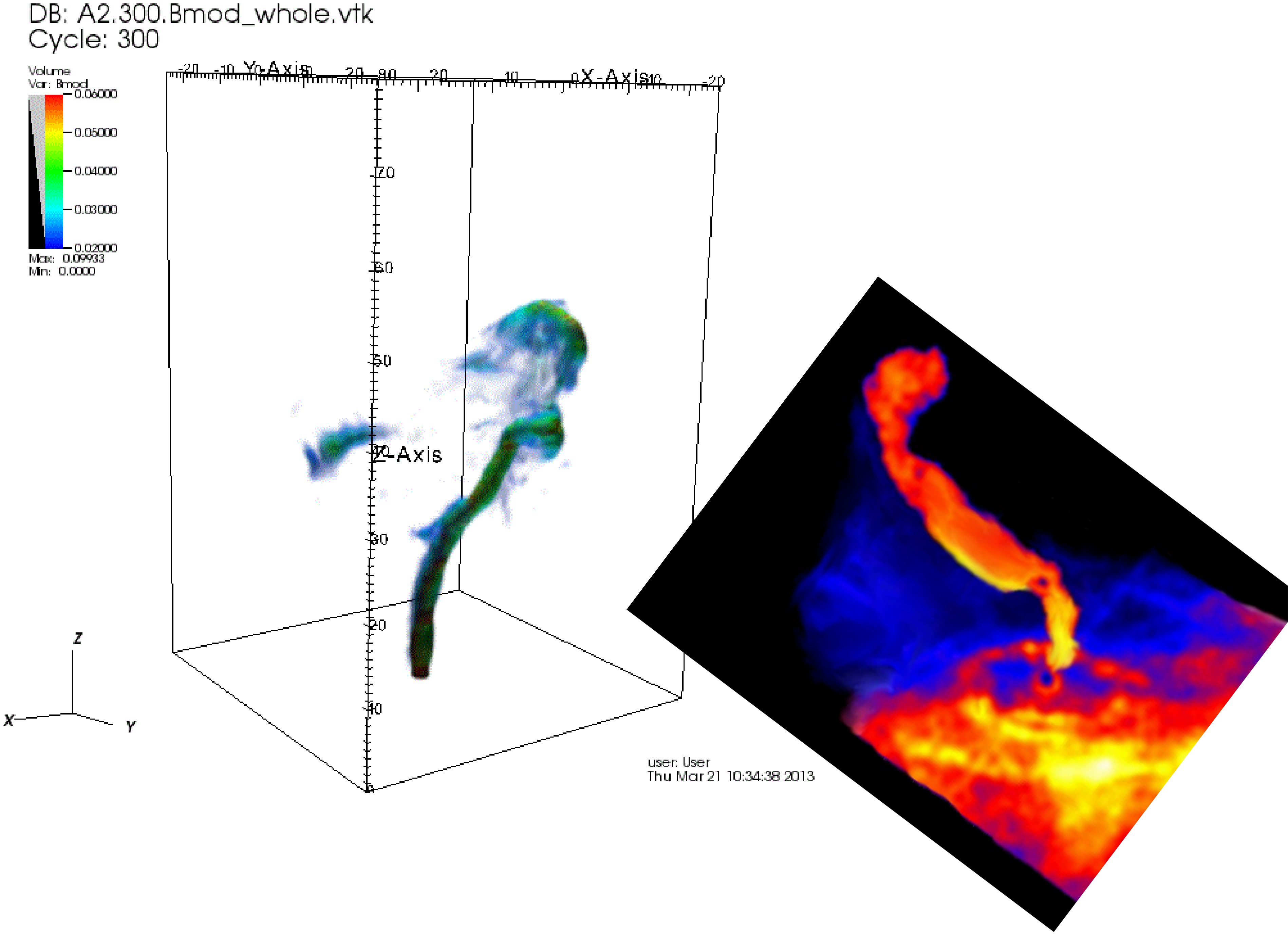


magnetization

current

bulk Lorentz Γ

Figure 6. Volume rendering of of the σ parameter (top panels), magnitude of the current density $J = \nabla \times B$ (middle panels) and bulk flow Lorentz factor (bottom panels) for the A2 case at $t \approx 93$ (left), $t \approx 93.3$ (central) and $t \approx 93.6$ (right) years.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Cycle: 300
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Var: Bmod
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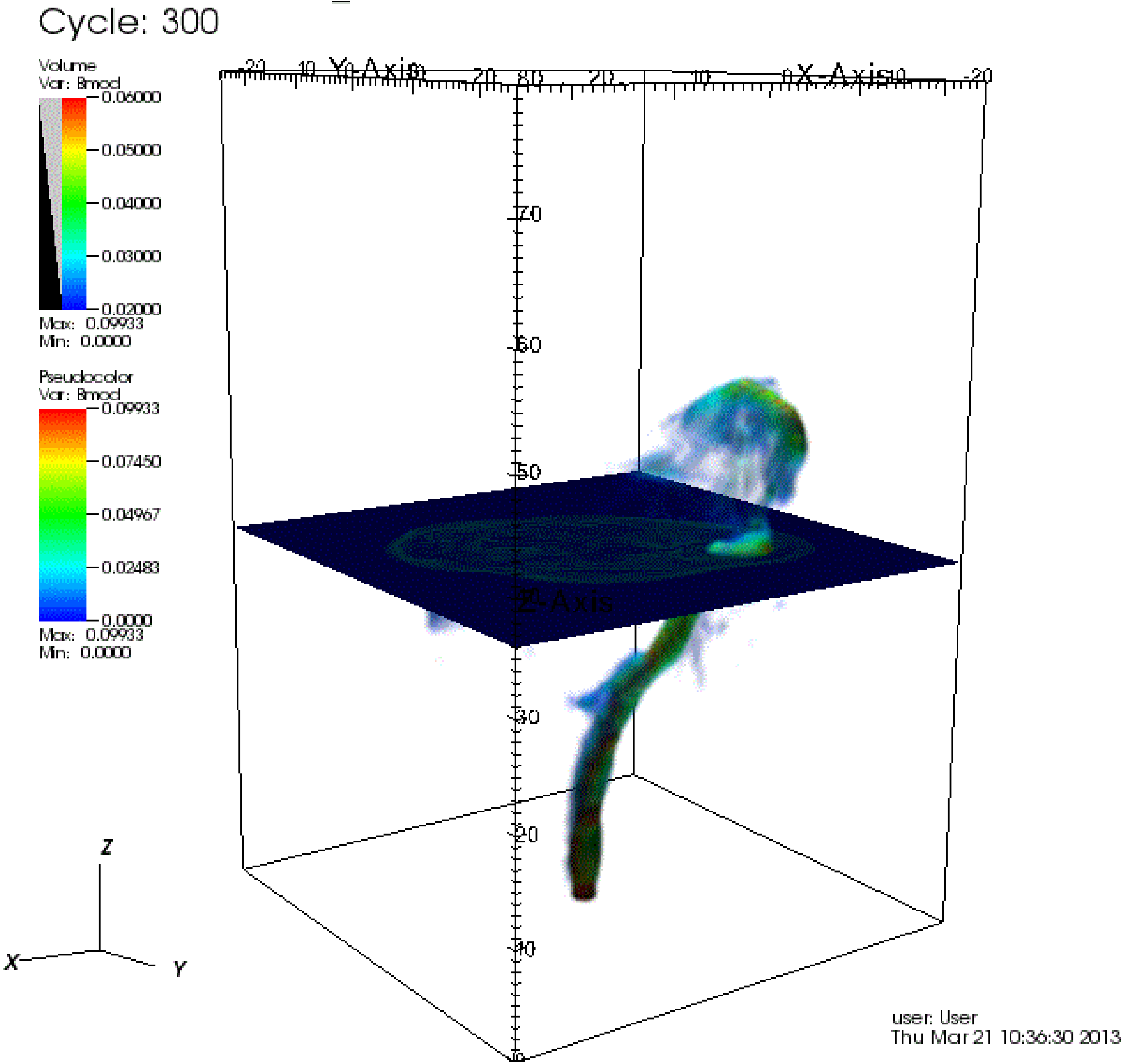
0.05000
0.04000
0.03000
0.02000
Max: 0.09933
Min: 0.0000
Y-Axis
X-Axis
Z-Axis
Z
X
Y
user: User
Thu Mar 21 10:34:38 2013



Cycle: 300
Volume
Var: Bmod
0.06000
0.05000
0.04000
0.03000
0.02000
Max: 0.09933
Min: 0.0000
Pseudocolor
Var: Bmod
0.09933
0.07450
0.04967
0.02483
0.0000
Max: 0.09933
Min: 0.0000
Y-Axis
X-Axis
Z-Axis
70
60
50
30
20
10
Z
X
Y
user: User
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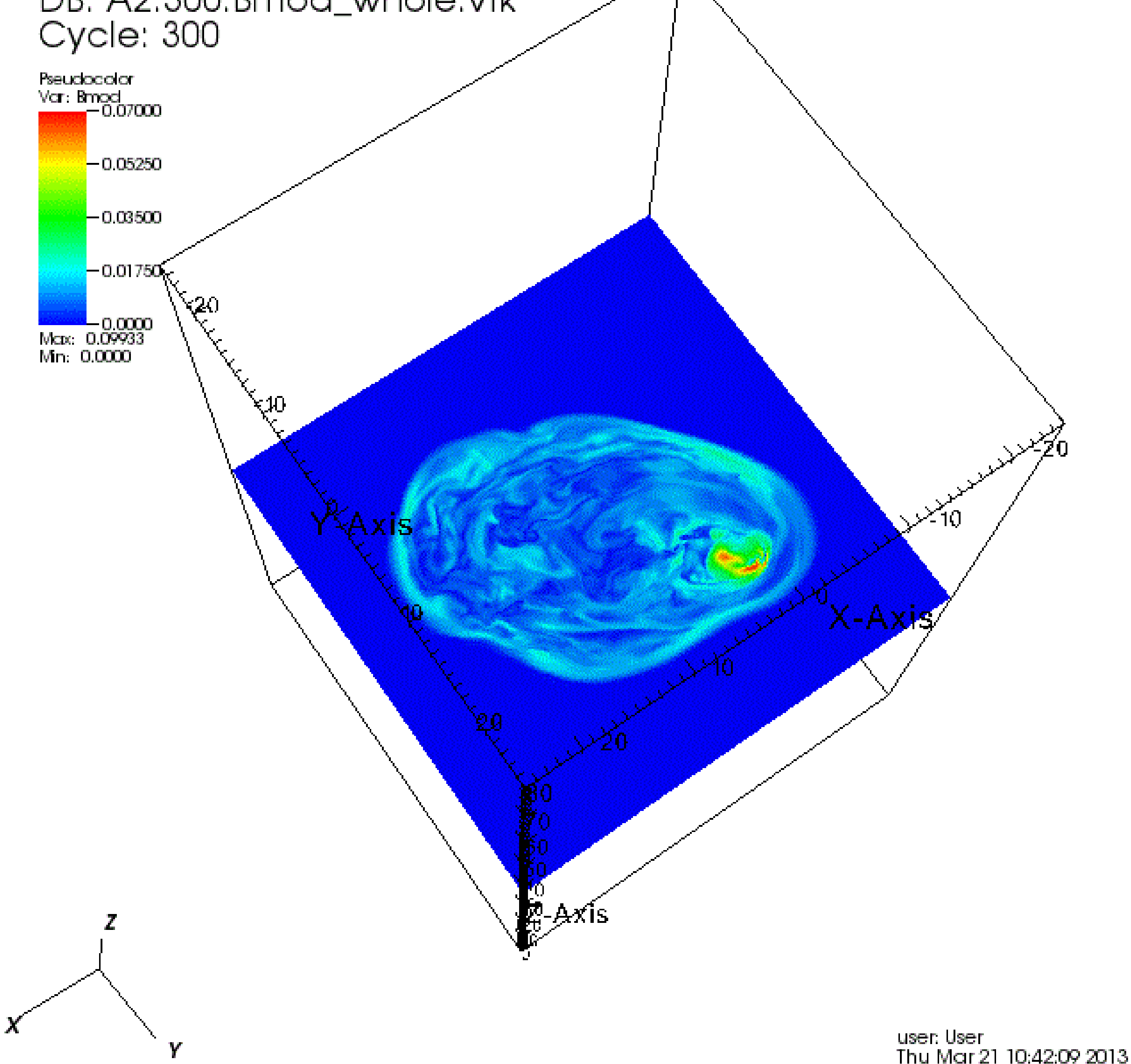

Cycle: 300
Pseudocolor
Var: Bmod
0.07000
0.05250
0.03500
0.01750
0.0000
Max: 0.09933
Min: 0.0000
Y-Axis
X-Axis
Z-Axis
user: User
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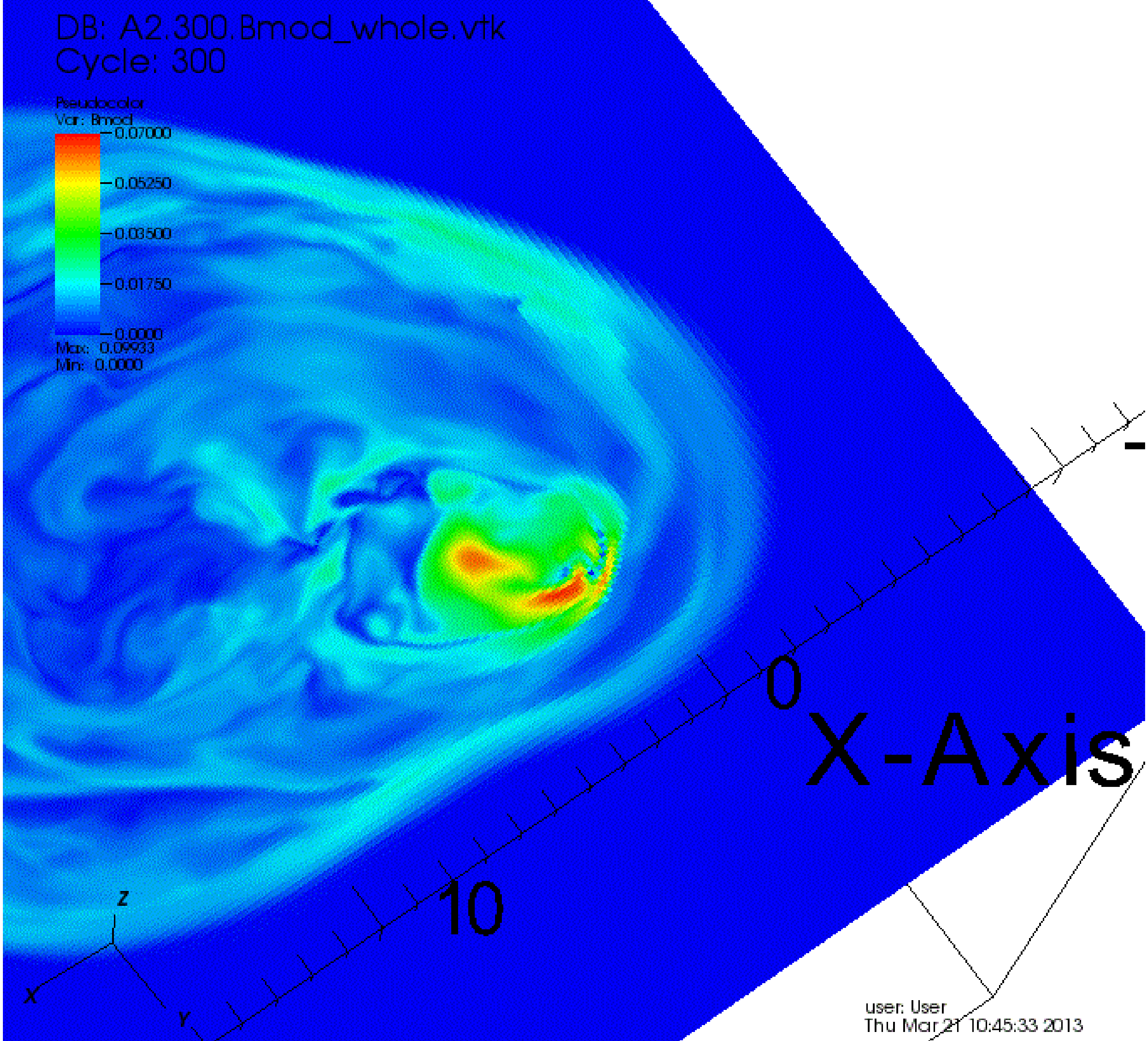
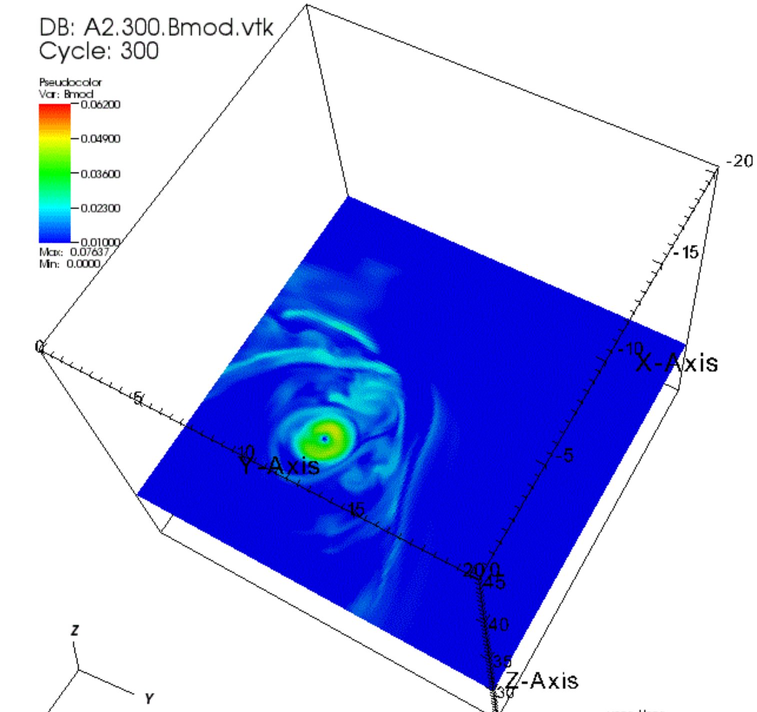


DB: A2.300.Bmod_whole.vtk
Cycle: 300
Pseudocolor
Var: Bmod
0.07000
0.05250
0.03500
0.01750
0.0000
Max: 0.09933
Min: 0.0000
0
10
X-Axis
Z
X
Y
user: User
Thu Mar 21 10:45:33 2013


DB: A2.300.Bmod.vtk
Cycle: 300
Pseudocolor
Var: Bmod
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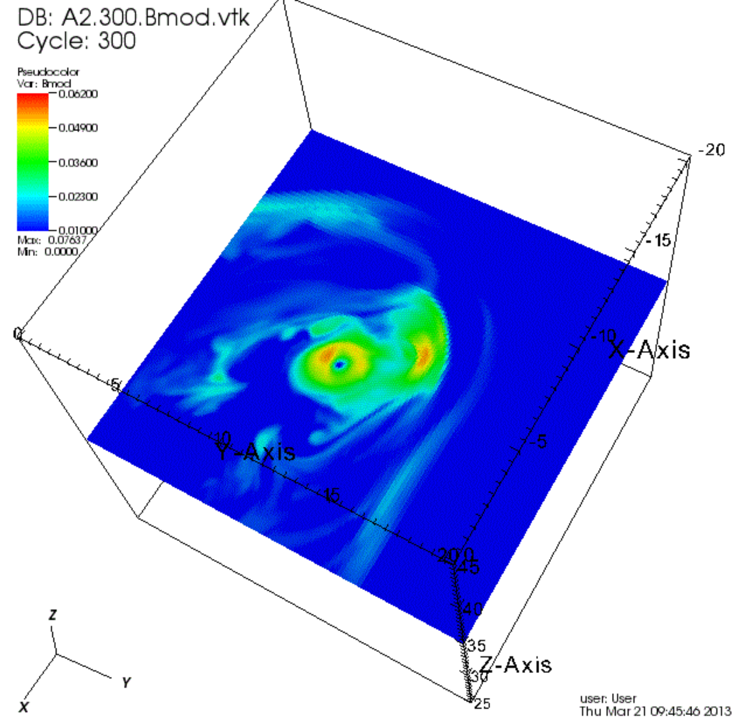
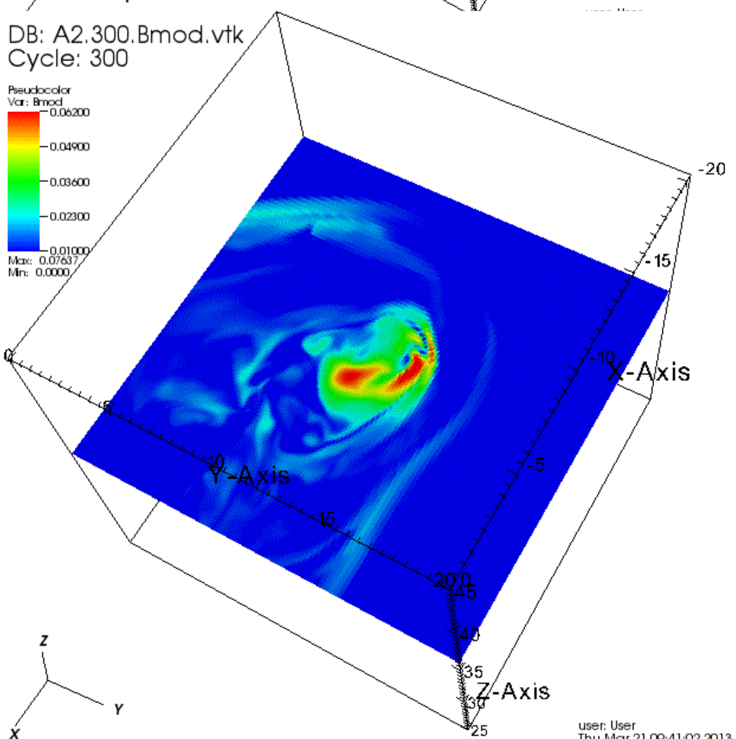
0.04900
0.03600
0.02300
0.01000
Max: 0.07637
Min: 0.0000
X-Axis
Y-Axis
Z-Axis


DB: A2.300.Bmod.vtk
Cycle: 300
Pseudocolor
Var: Bmod
0.06200
0.04900
0.03600
0.02300
0.01000
Max: 0.07637
Min: 0.0000
X-Axis
Y-Axis
Z-Axis
user: User
Thu Mar 21 09:45:46 2013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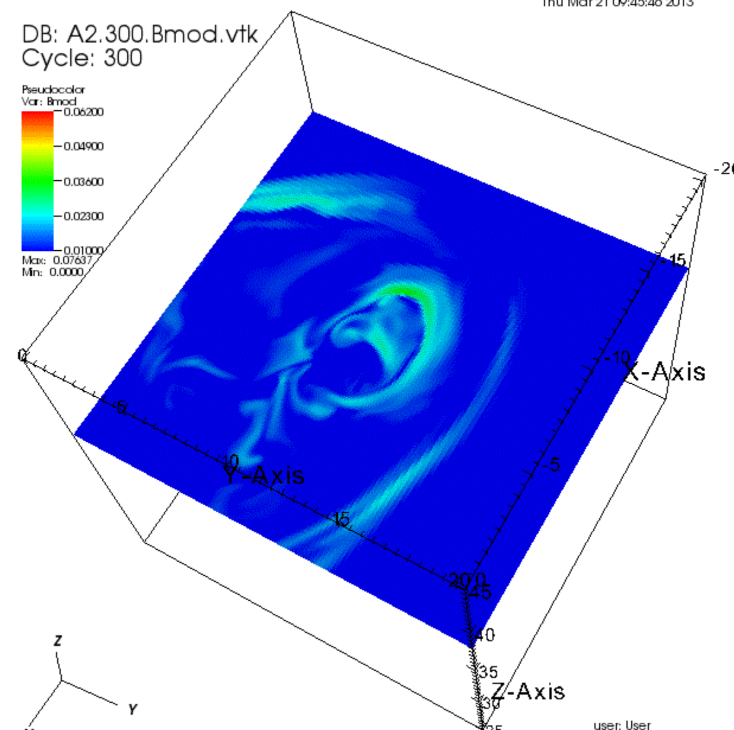
X-Axis
Y-Axis
Z-Axis
user: User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Pseudocolor
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0.04900
0.03600
0.02300
0.01000
Max: 0.07637
Min: 0.0000
X-Axis
Y-Axis
Z-Axis
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- **“jet kinking” (by 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 ~10^{15} cm**
- **local B ~ 1 mG**
- **magnetization-sigma ~ 1-10**

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

$$\gamma_{max} \backsimeq 10^8\, B^{-1/2} \qquad \text{(B in Gauss)}$$

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

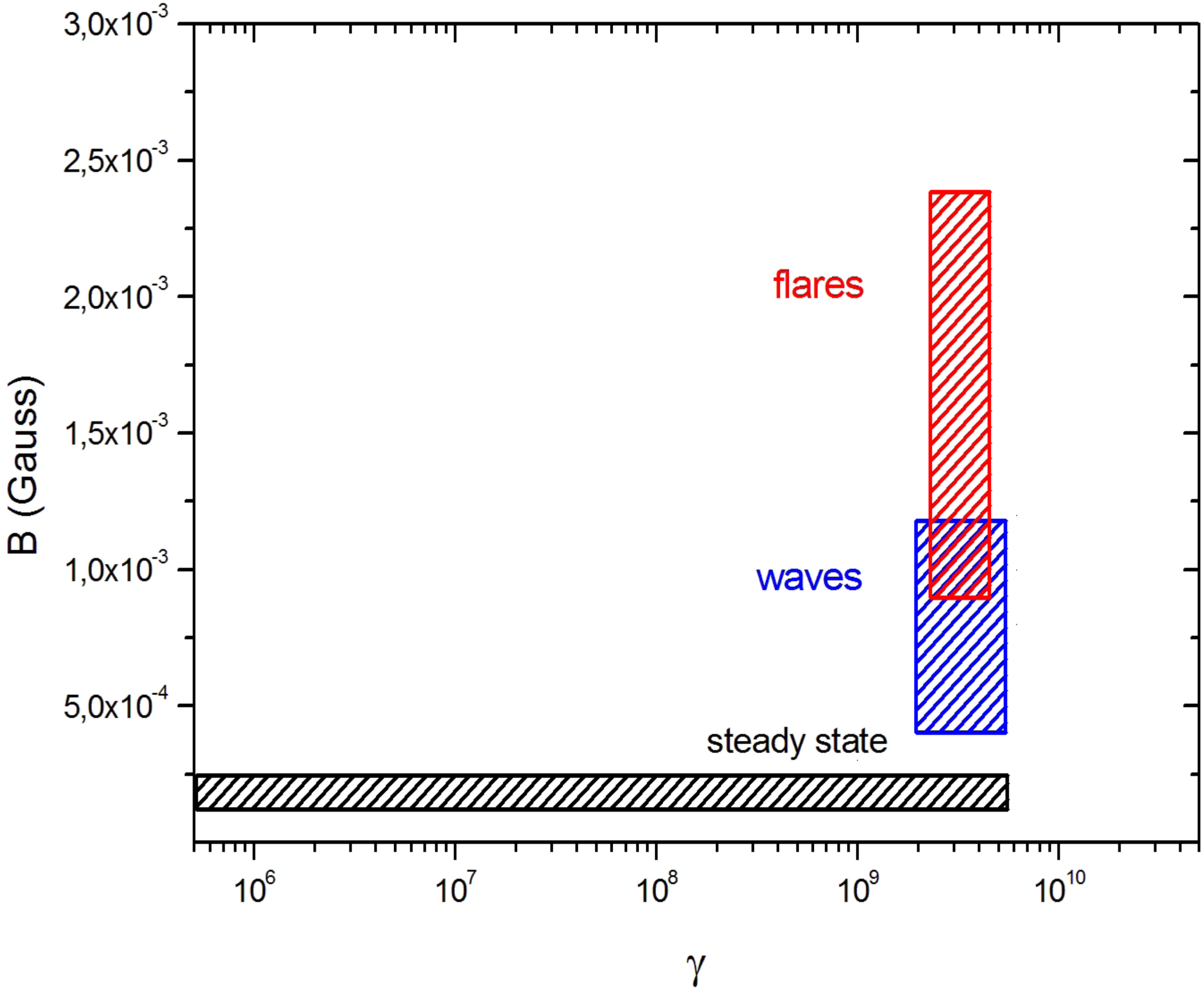
$$\dot{\gamma}_{\shortparallel} = \frac{e\,E_{\shortparallel}}{m\,c} - \frac{2}{3}\,\frac{r_e^2}{m\,c}\,\left[E_\perp^2 + B_\perp^2 - 2\,\vec{\mathbf{E}} \times \vec{\mathbf{B}} \cdot \hat{\mathbf{v}}\right]\,\gamma_{\shortparallel}^2$$

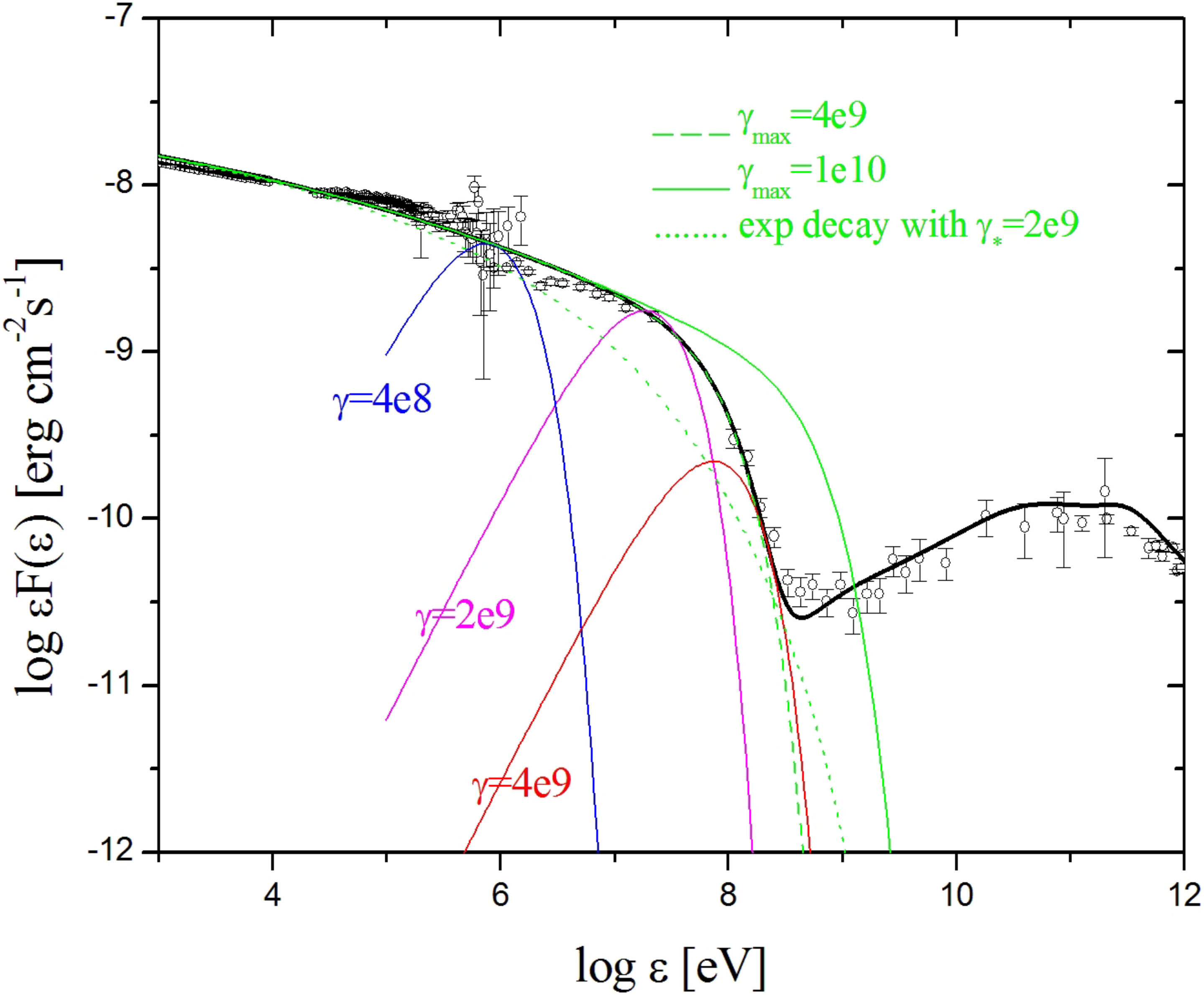
- **“mono-energetic” spectrum**

- **“super-acceleration” with E/B ≳ 2,**
  B-field reconnection along a kinked jet (?)

Crab Nebula super-acceleration states

(Striani et al. 2012, M.T. 2013)





log εF(ε) [erg cm-2s-1]
log ε [eV]
-7
-8
-9
-10
-11
-12
4
6
8
10
12
γmax=4e9
γmax=1e10
exp decay with γ*=2e9
γ=4e8
γ=2e9
γ=4e9

Impacts

- **Super-acceleration: a rare event or the normal mechanism in the Crab Nebula ? Other PWNe ?**

- **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).**

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 ? Mono-energetic ?**

Crab monitoring

- **AGILE and Fermi**
- **Chandra and HST**
  - **(about 8 times/year, great database !)**
- **Keck**
- **radio telescopes**
- **TeV telescopes also look …**

- **March 2013 flare observed by Chandra, HST, Keck (see A. De Luca's talk)**

- **Crab, the Queen of Nebulae**
- **an everlasting wonderful laboratory**
- **more surprises to come…**