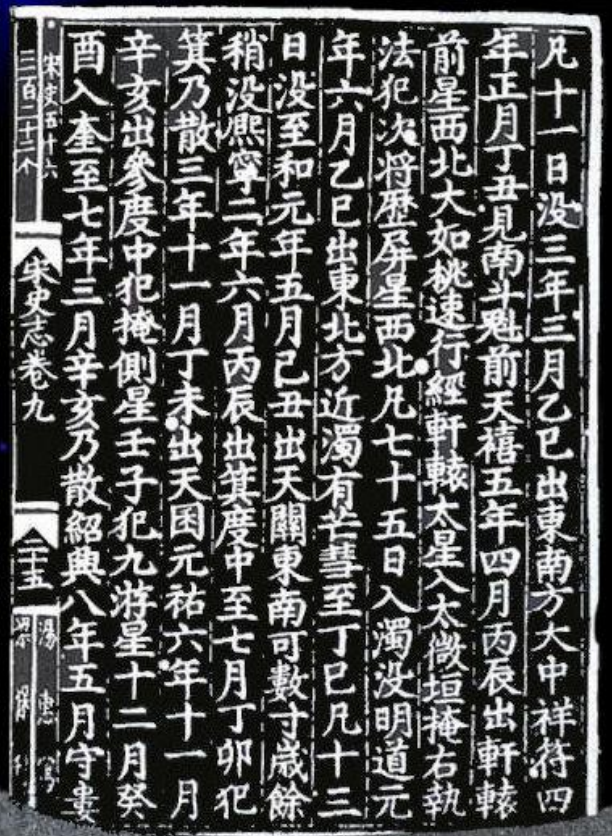
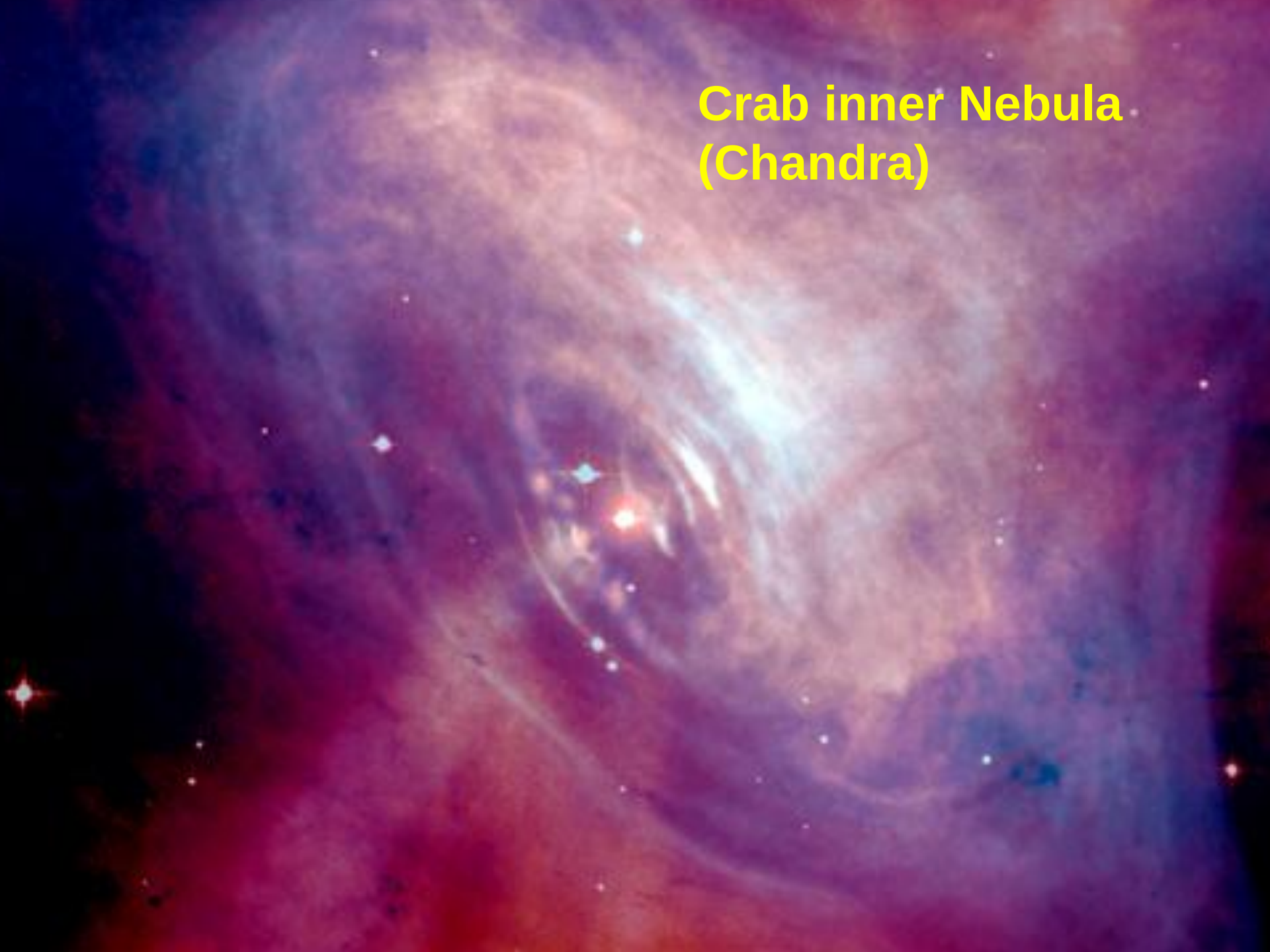
Crazy Crab

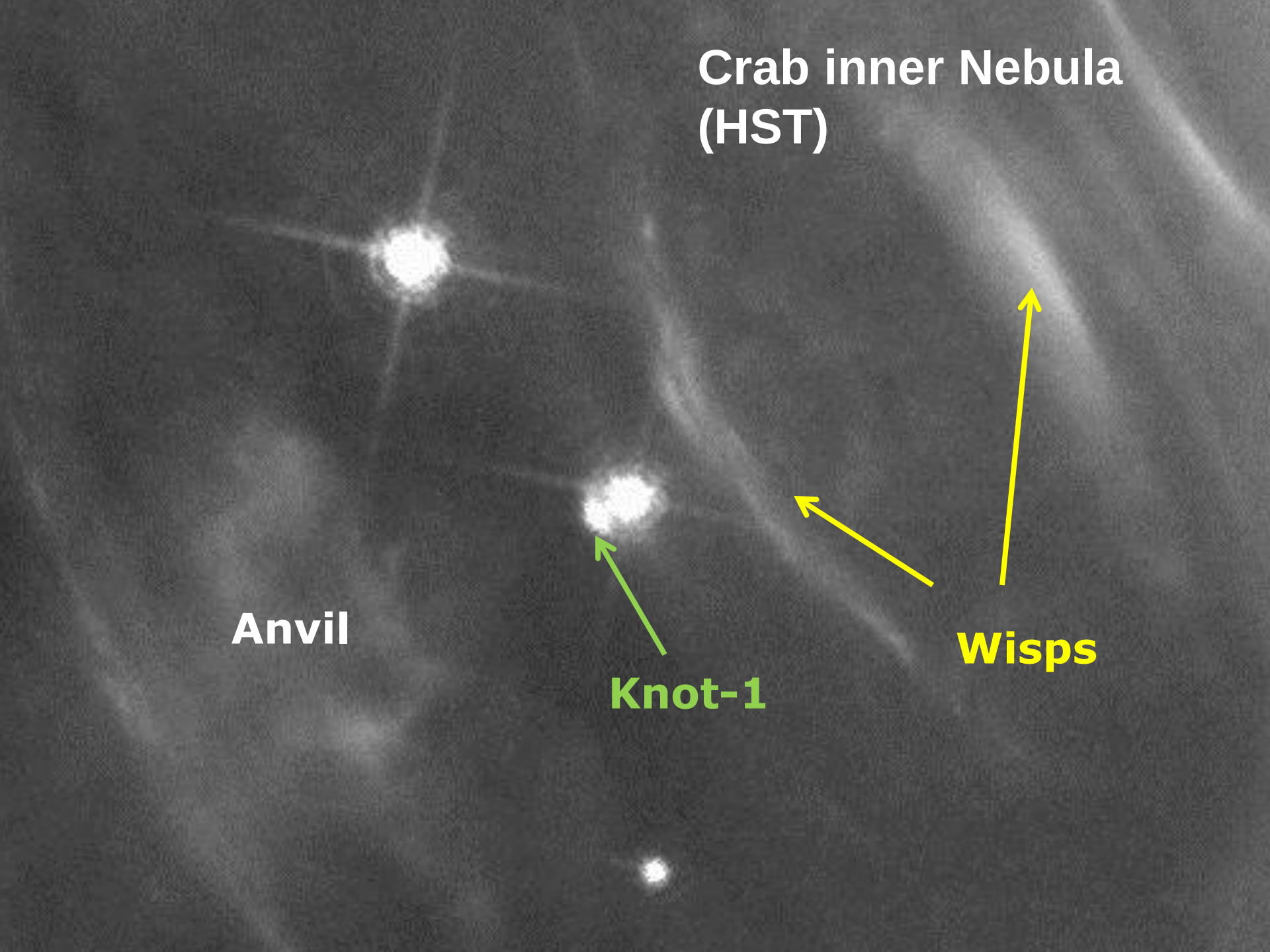
M.Tavani


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妻

宋史志卷九 三百二十六

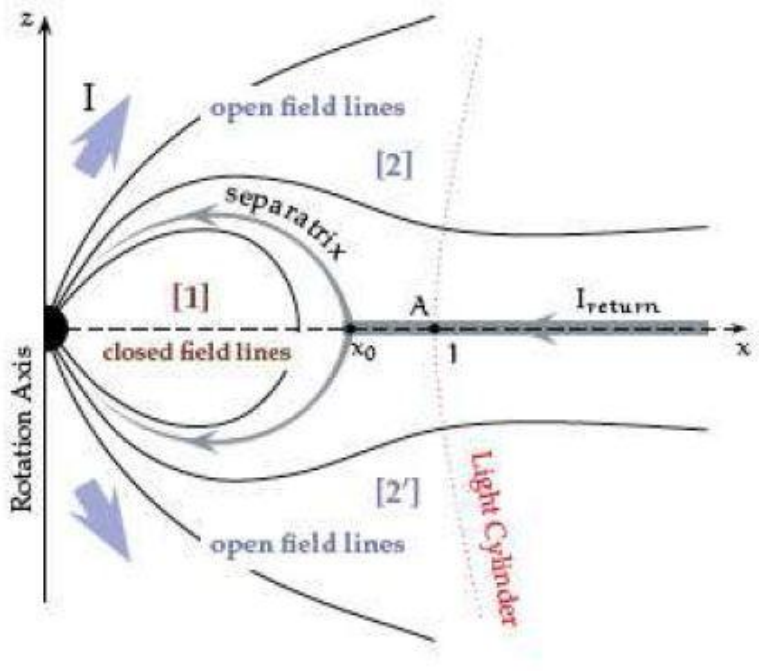
adapted from *Gravitation* by C.Misner, K.Thorne. J.A.Wheeler

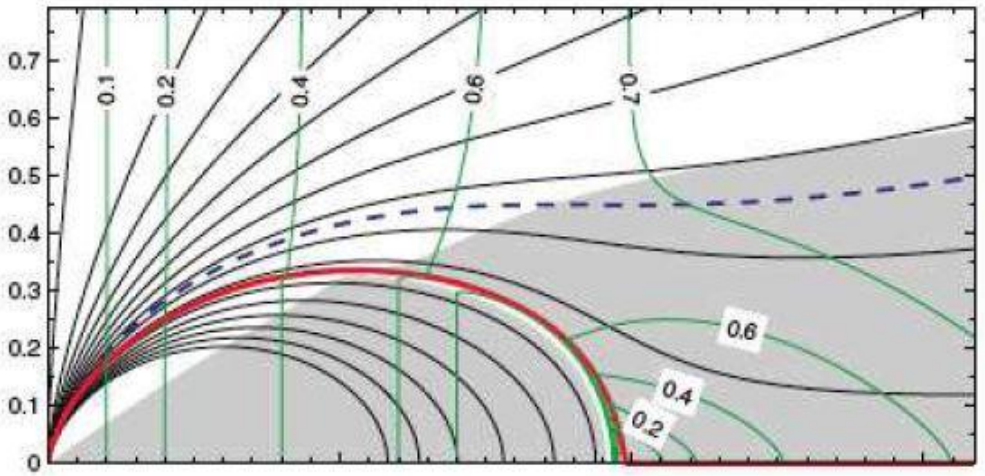

Crab inner Nebula
(Chandra)


Crab inner Nebula
(HST)
Anvil
Knot-1
Wisps

non-symmetric **PULSAR wind**

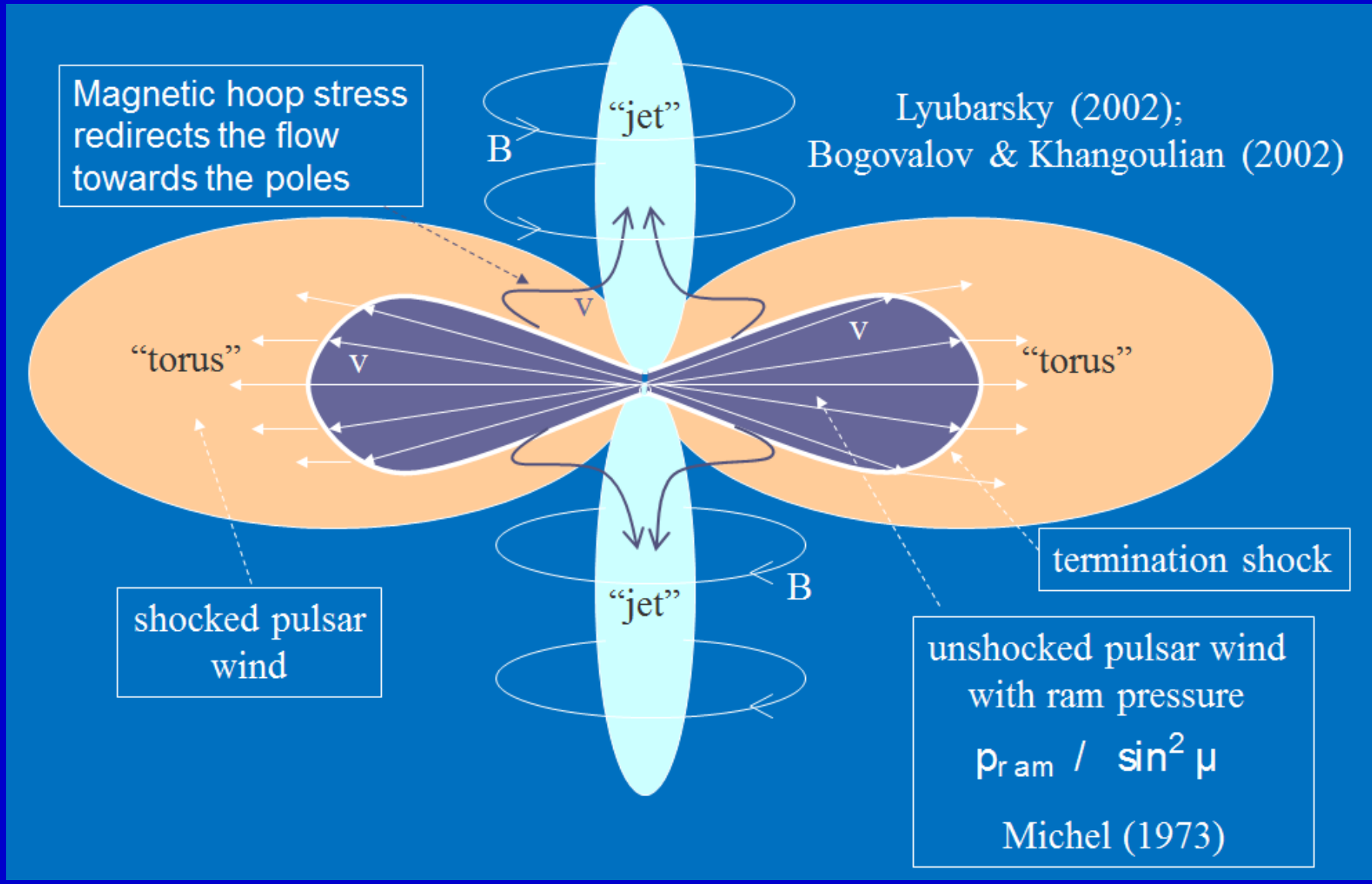
(relativistic e+/e-, ions (?), $\gamma_o \sim 10^2$-10^4)





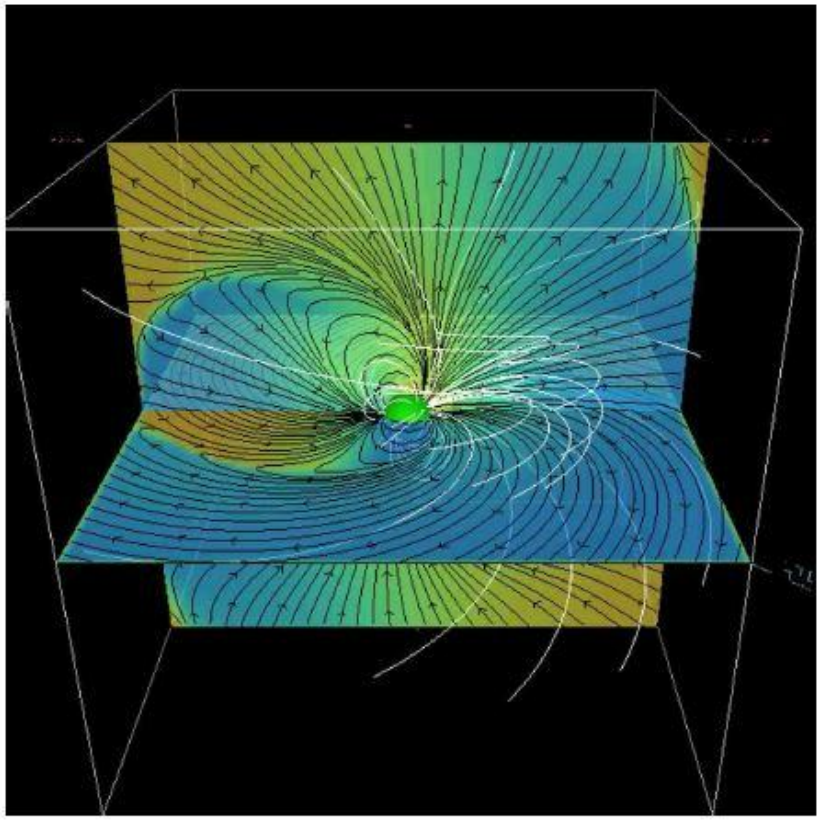
- $dN/dt = L_{sd} / (n \gamma m c^2) \sim 10^{40.5}\ s^{-1}$.
- much larger than GJ ! pair multipl. factor $\kappa \sim 10^4$

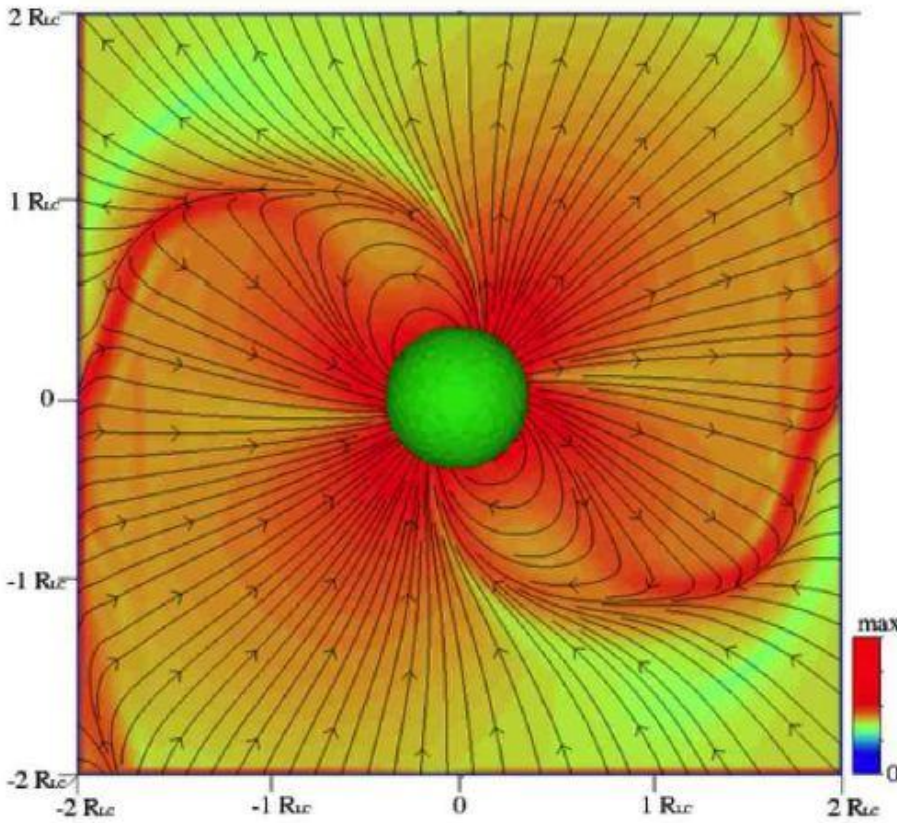
MHD modelling, torus + jets (e.g., Komissarov et al 2011)



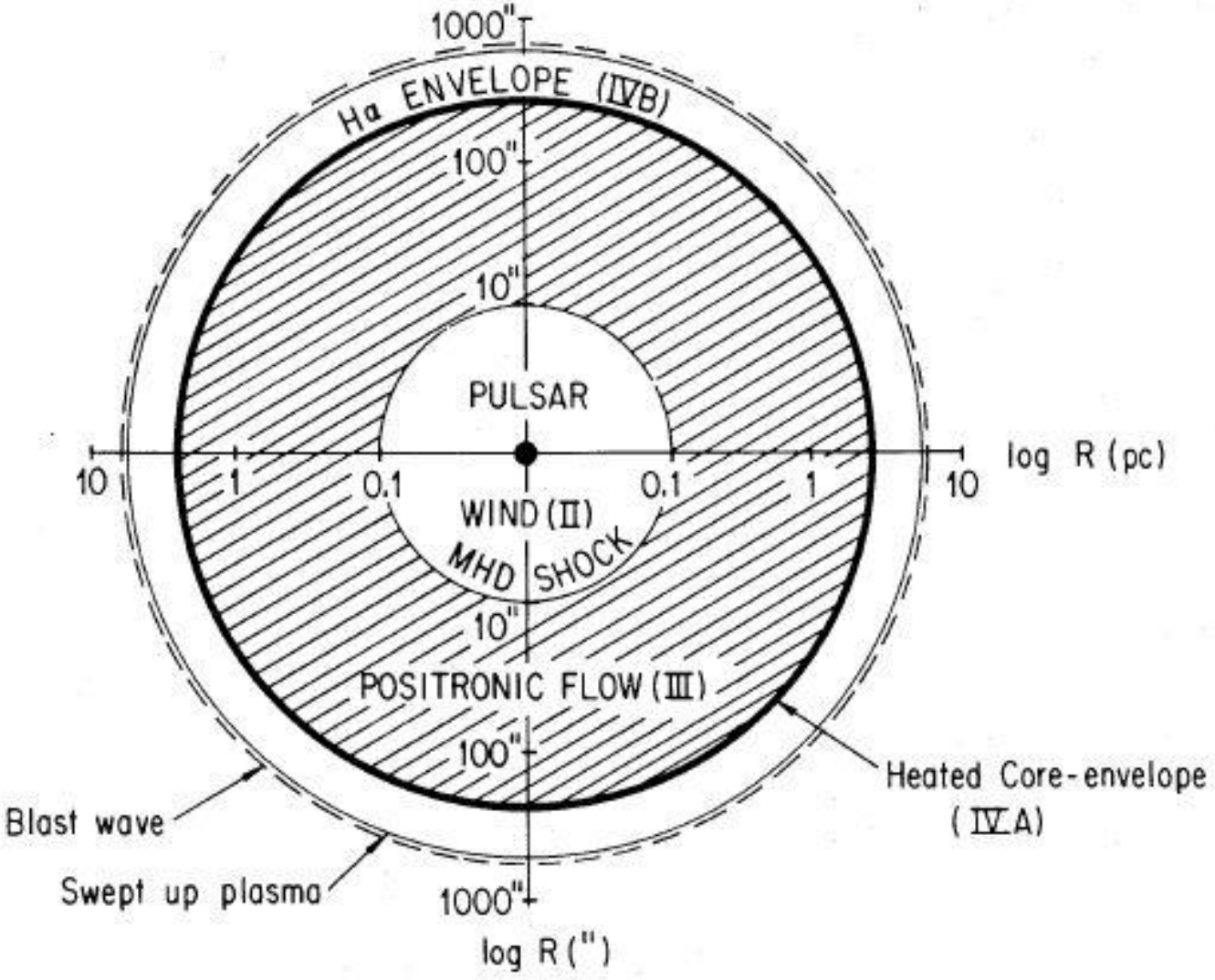
Credit: Serguei Komissarov

PSR magnetospheric modelling (Spitkovsky 2006)

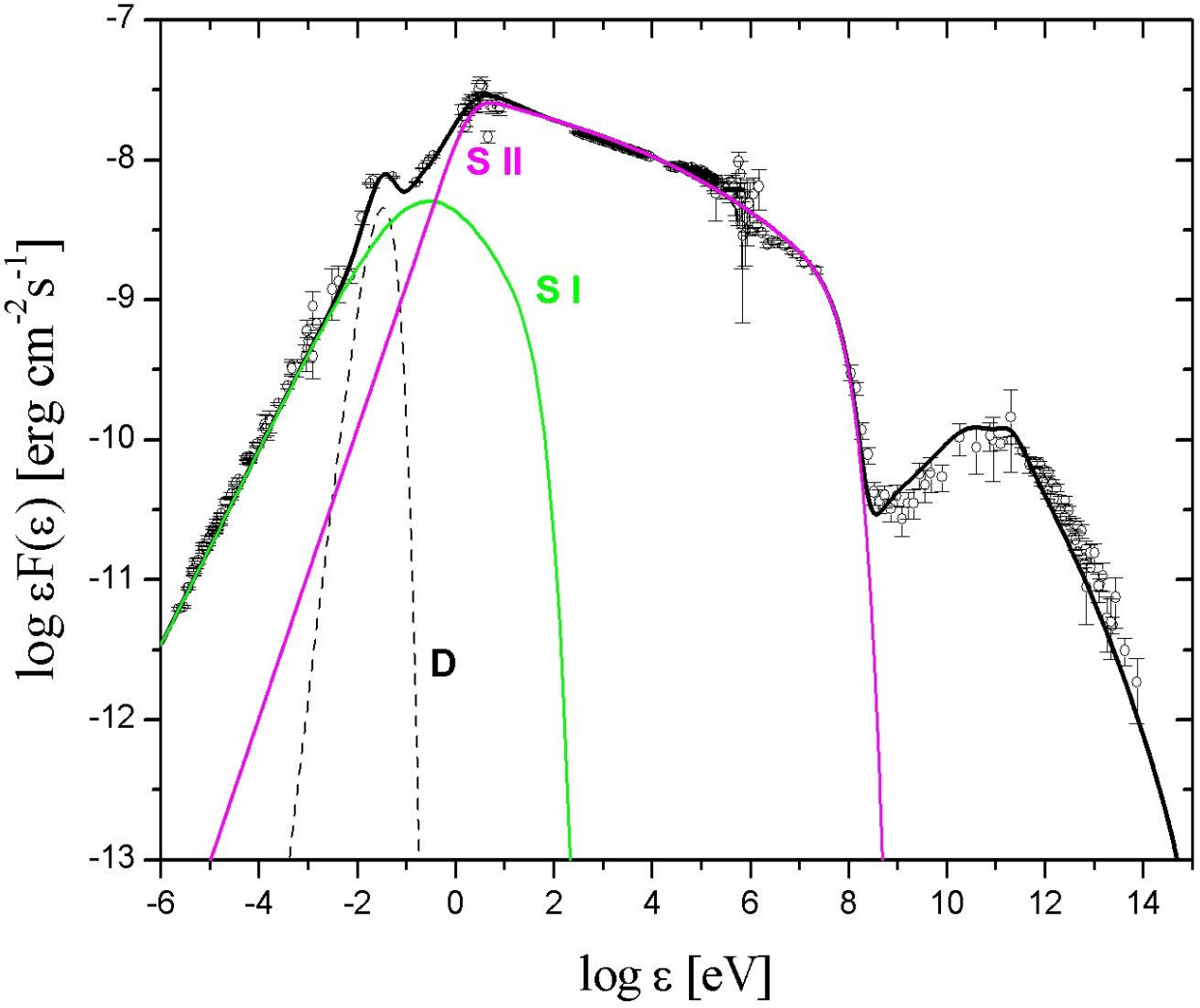




MHD Kennel-Coroniti picture of the Crab Nebula (1984)



De Jager et al., 1996, Atoyan & Aronian 1996, Meyer et al. 2010,
Vittorini & M.T. 2011



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

the “standard” nebular model (deJager etal. 1996)

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

- $\gamma^{-1} d\gamma/dt = (eB/\gamma mc)(\mathbf{E/B})\alpha' - (4/3)\sigma_T (B^2/8\pi)\, \gamma/mc$

- $d\gamma/dt = 0$ implies

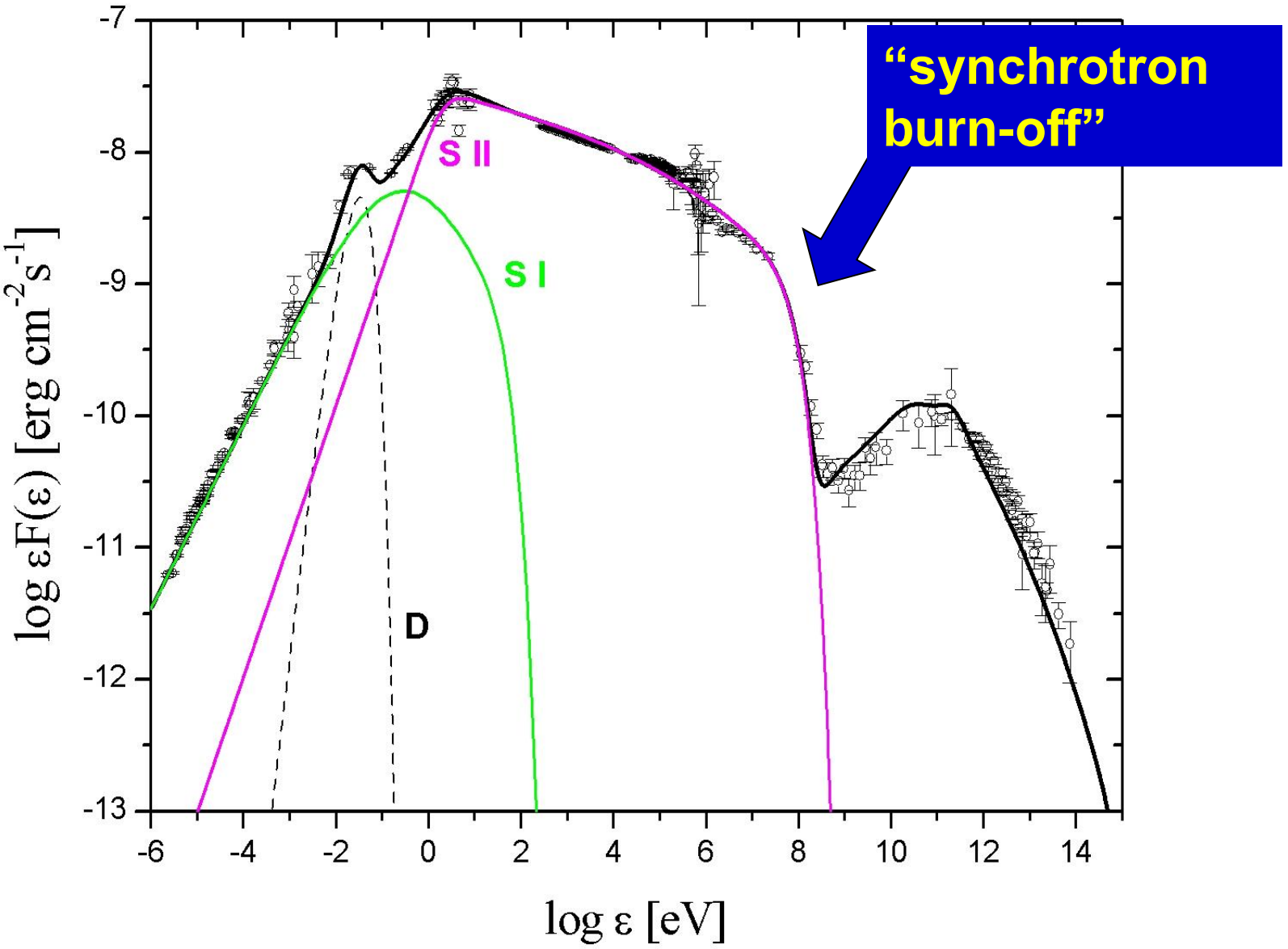
$$\mathbf{\gamma_{max} \sim 10^9 (E/B)^{1/2} (\alpha'/\sin^2\theta\, B_{-3})^{1/2}}$$

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

- max. emitted photon synchrotron energy is independent of the magnetic field B (for a Doppler factor δ): "**synchrotron burn-off"**

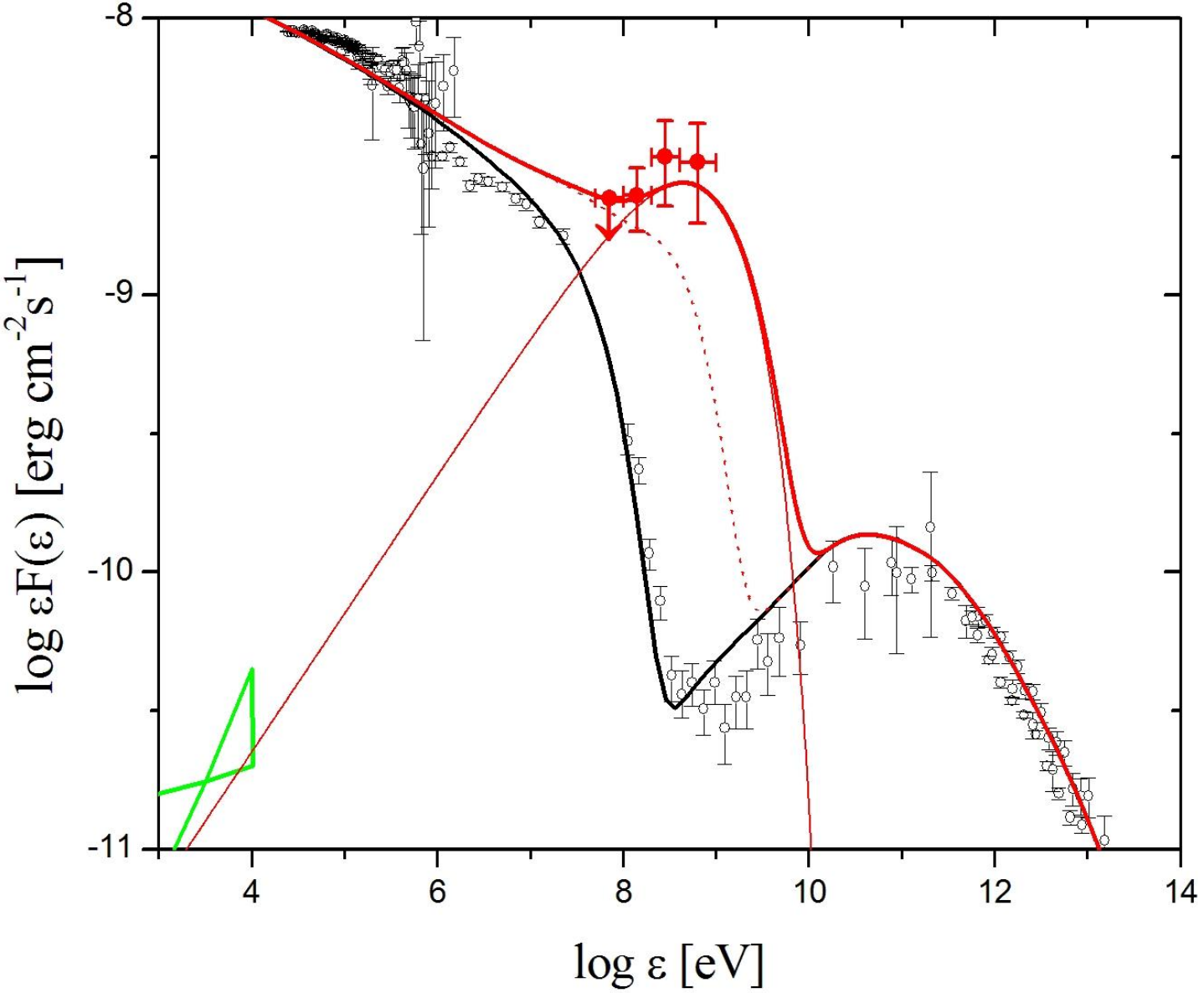
- $\mathbf{E_{max} = (3/2)\ \hbar\ \omega_B\ \gamma_m^2 \sim (200\ MeV)\ (\delta\ \alpha'/\sin\theta)}$

Crab Nebula average spectrum



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

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

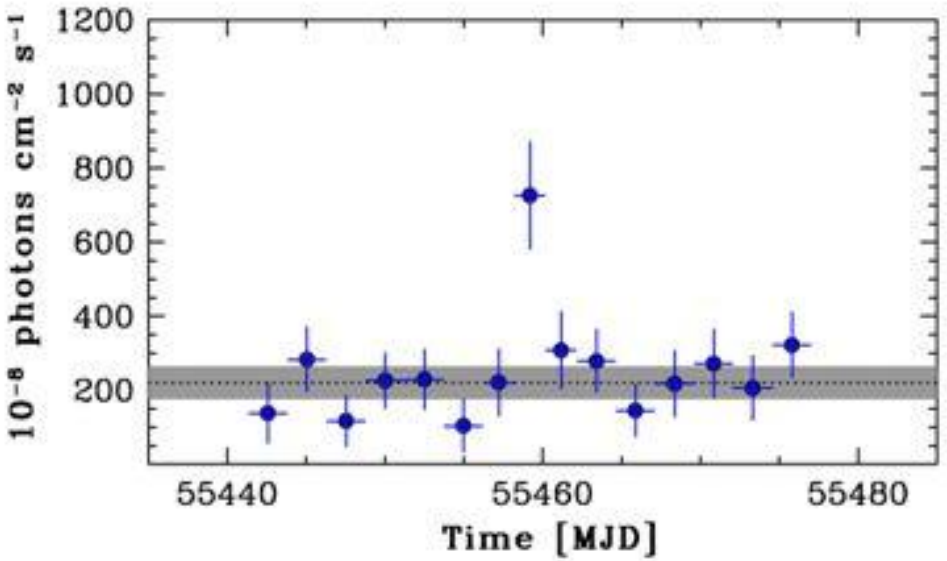


Crab Nebula MHD models

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

The Crab Nebula: a standard candle…?

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



Science Express **(6 January 2011)**

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, -6.0) +/- 0.4 (stat.) +/- 0.1 (syst.) deg. and

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*

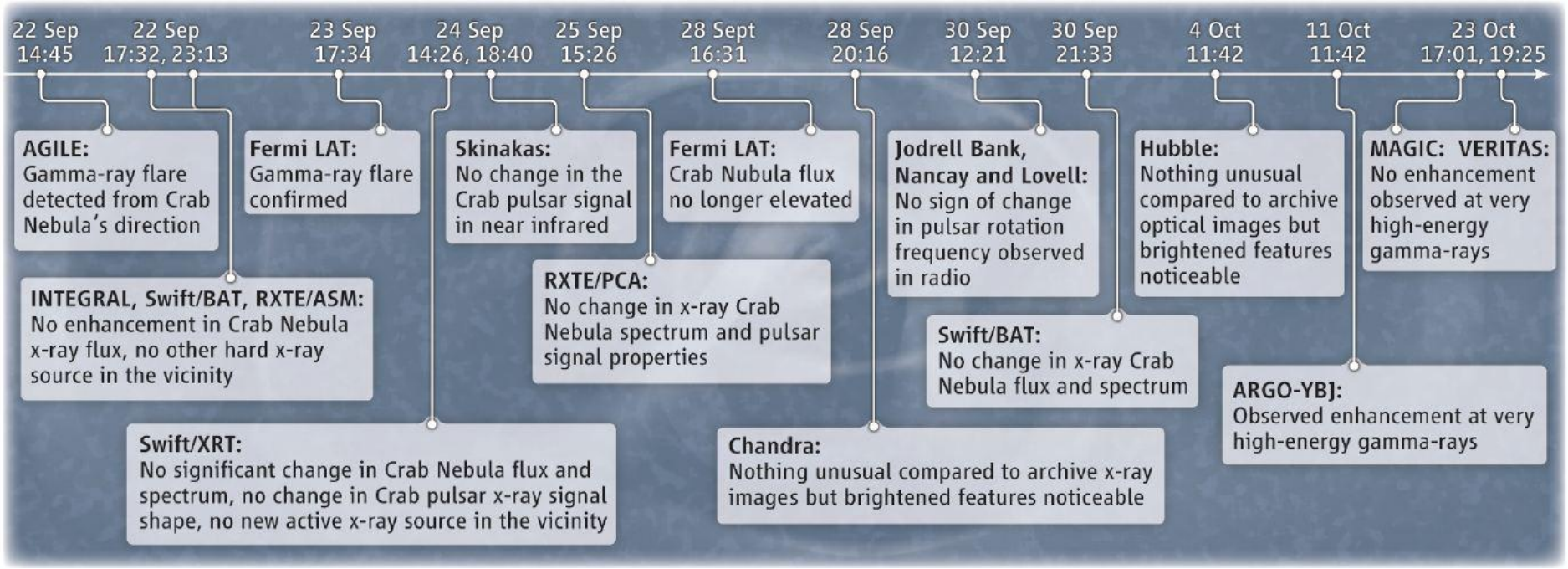
on 23 Sep 2010; 17:34 UT
Distributed as an Instant Email Notice (Transients)
Password Certification: Rolf Buehler (buehler@slac.stanford.edu)

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.

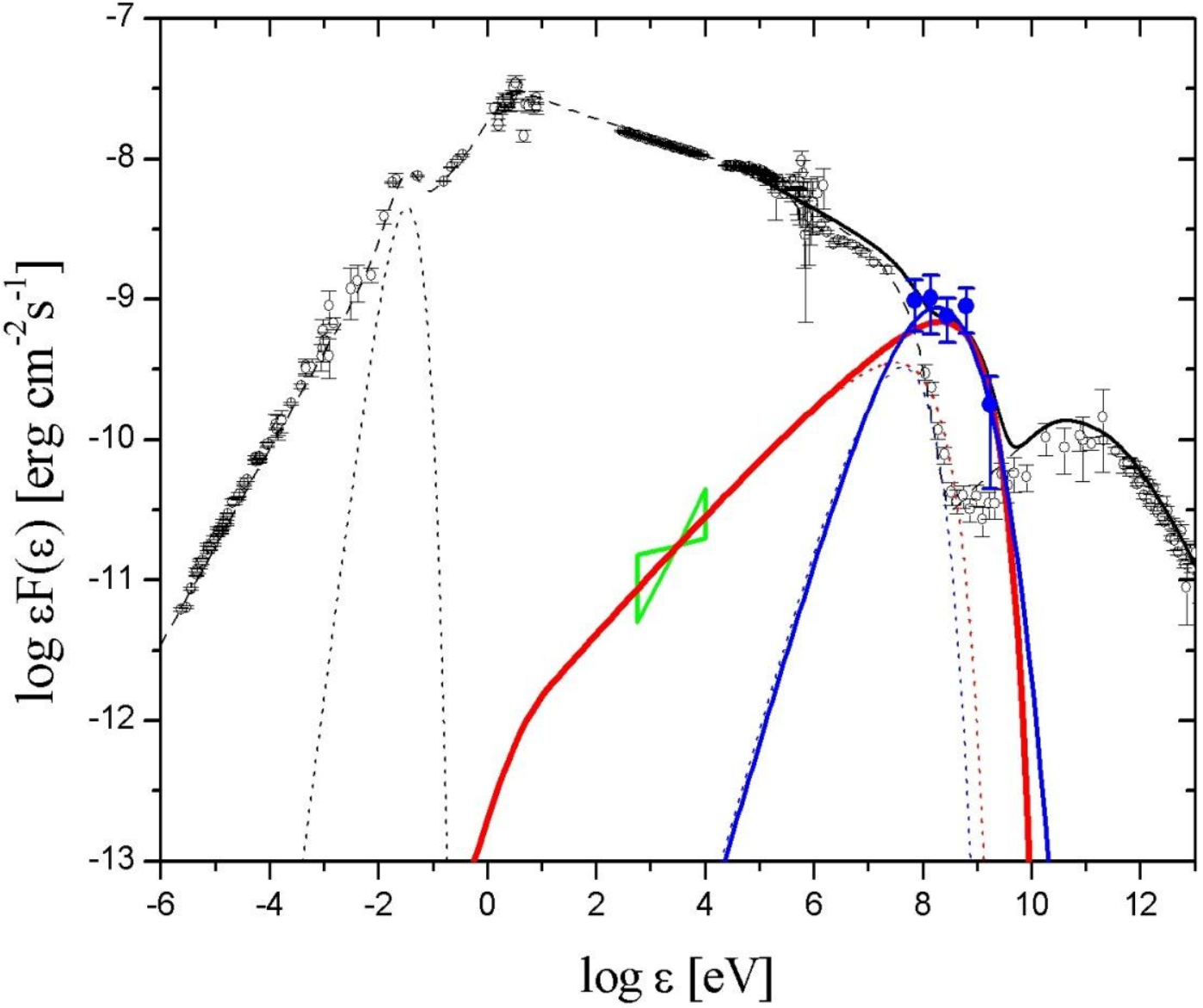
Preliminary LAT analysis indicates that the gamma-ray emission (E >100 MeV) observed during this time period at the location of the Crab Nebula is (606 +/- 43) x10^ -8 ph/cm2/sec, corresponding to an excess with significance >9 sigma with respect to the average flux from the Crab nebula of (286 +/- 2) x10^ -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.

post-flare excitement



Bernardini E., 2011

AGILE spectrum at the peak (2 days) (Science 2011)

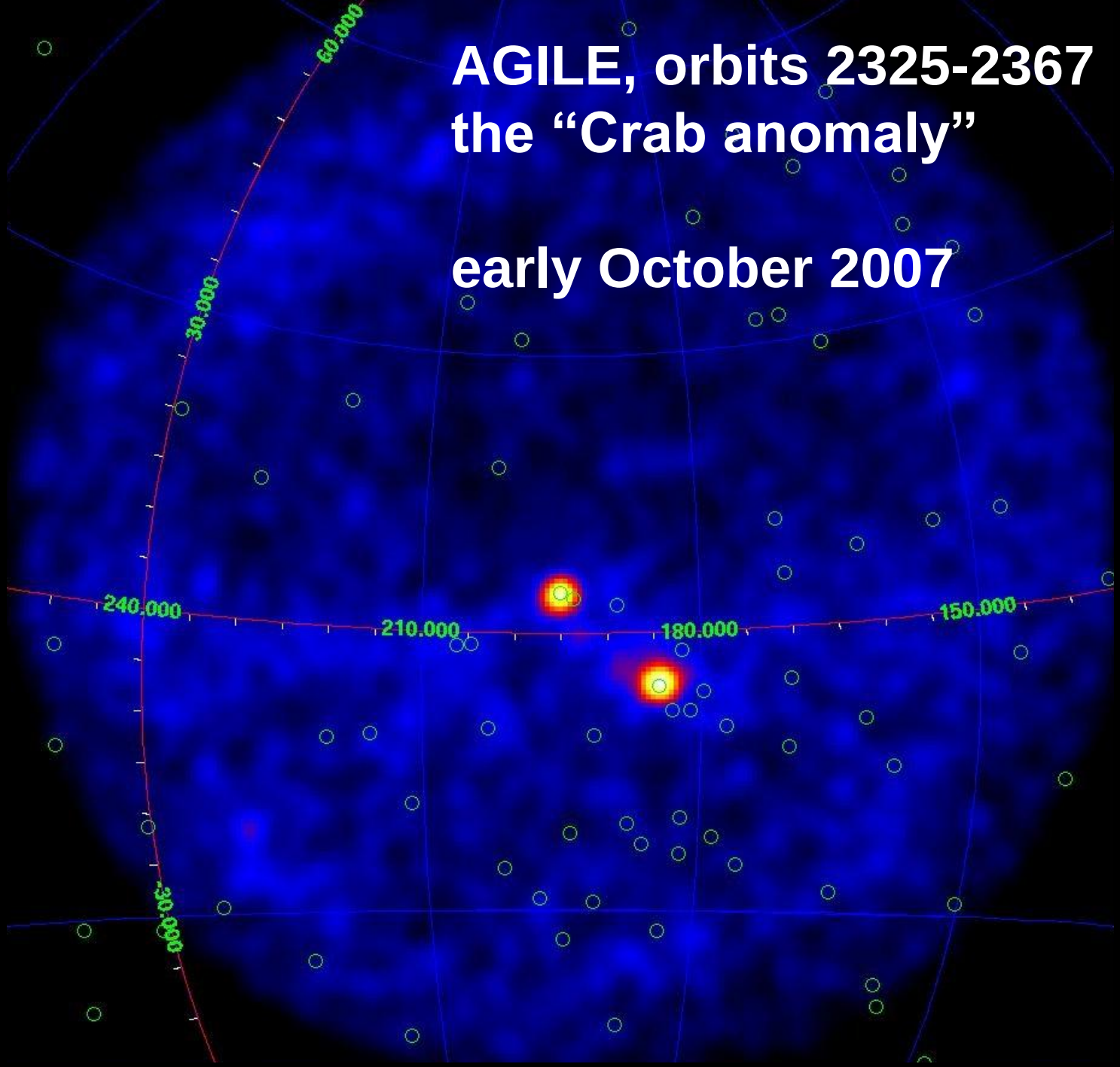


the AGILE Crab "anomaly"

- **internally, since October 2007 the AGILE team discussed the anomaly tens of times because of calibration issues**

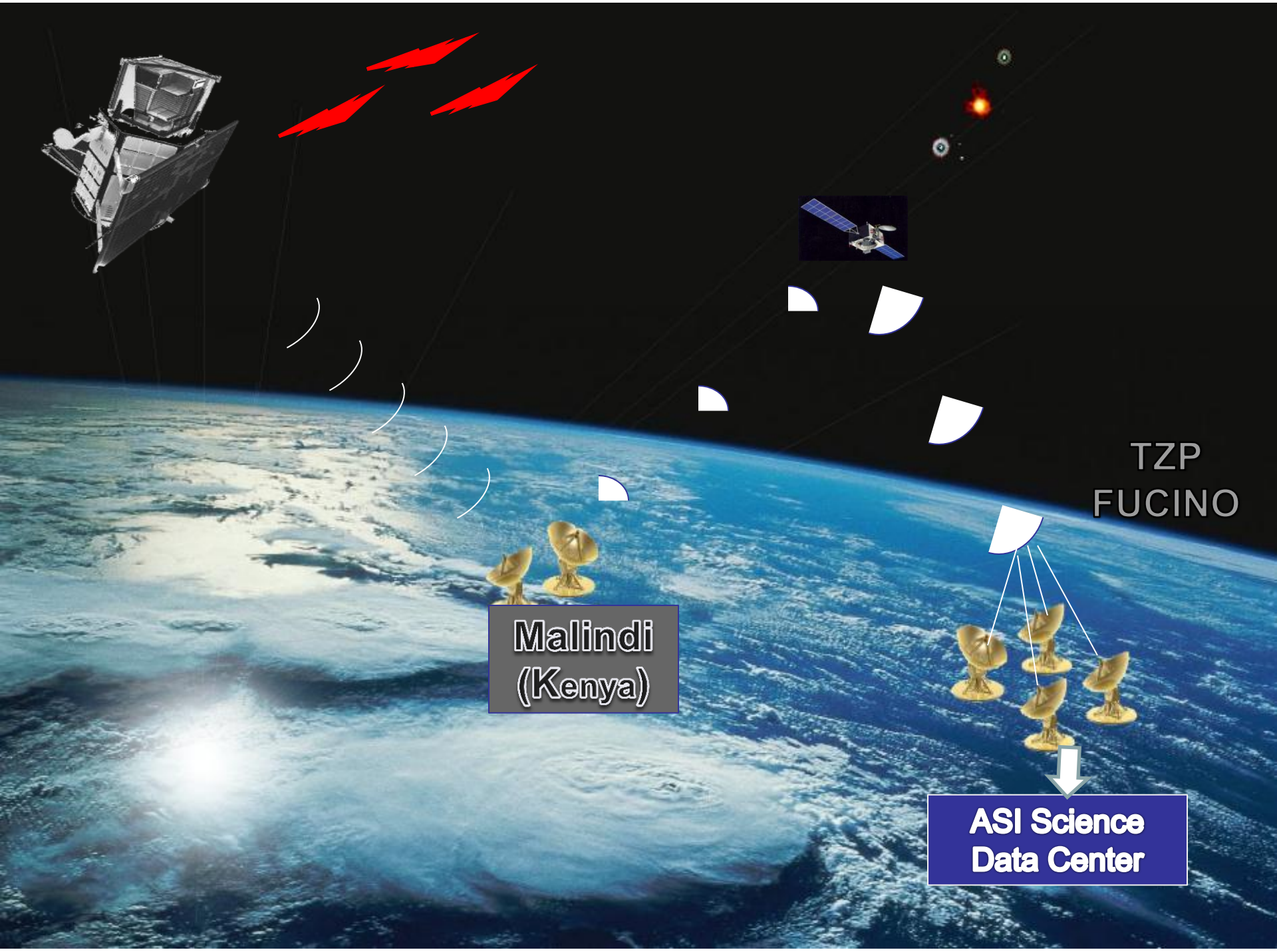
- **very serious problems in calibration if the anomalous 15 days were inserted !**

- **many internal AGILE documents showing the analyses and cure.**

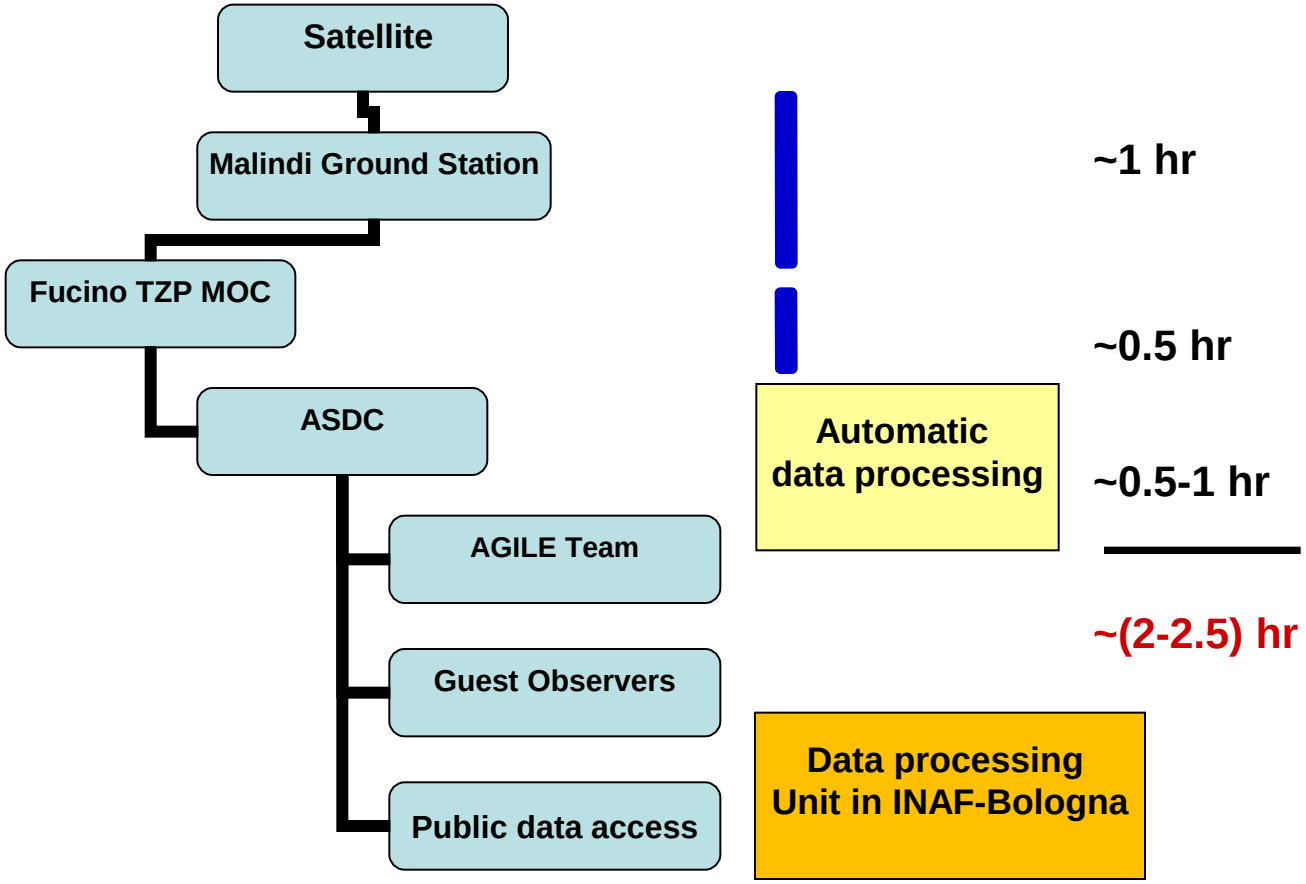

AGILE, orbits 2325-2367
the “Crab anomaly”
early October 2007
60.000
30.000
240.000
210.000
180.000
150.000
-30.000

AGILE Discovery of Crab Nebula Variability: a Chronology

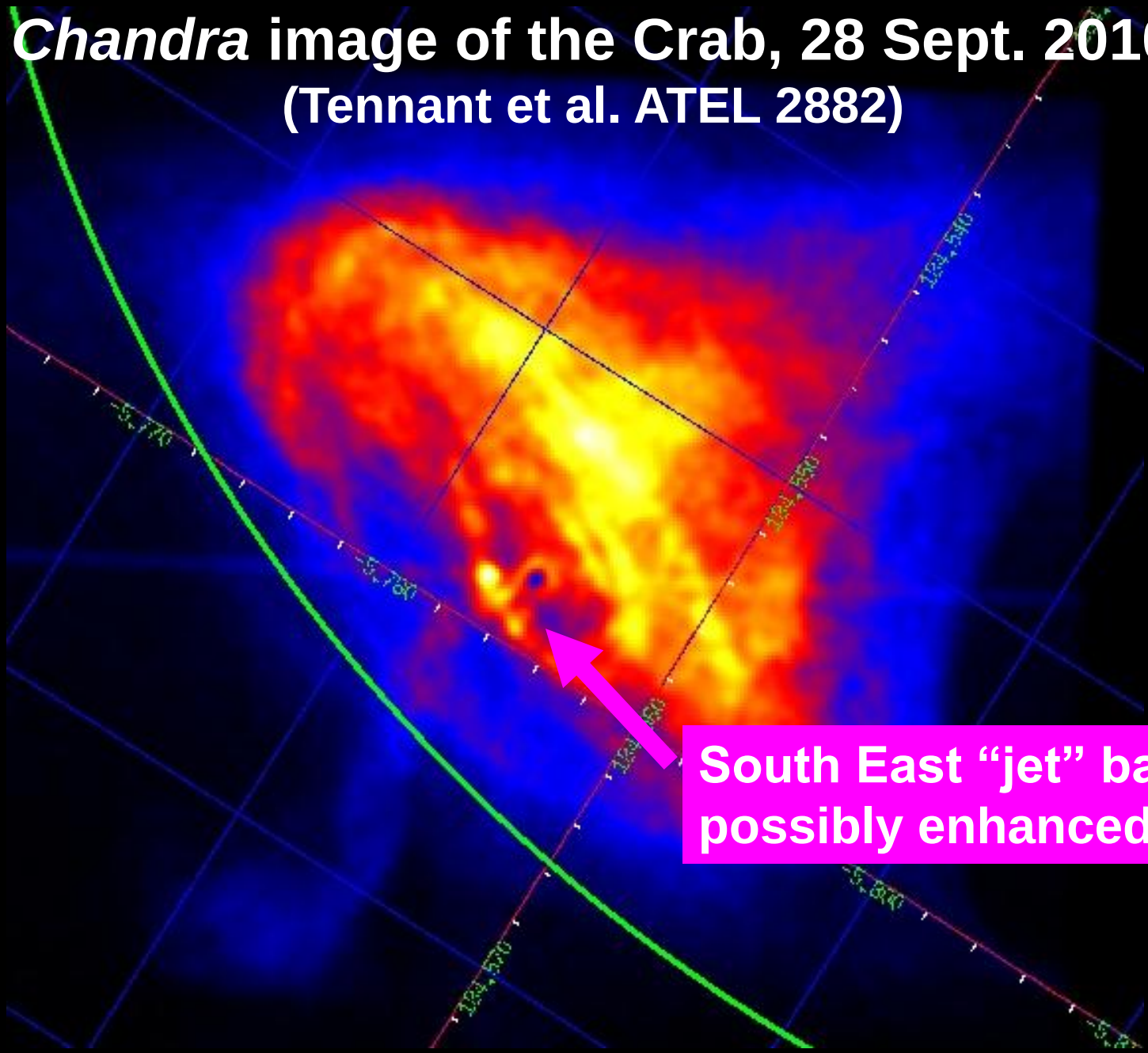
- April 2007: AGILE launch.
- October 2007: AGILE detects the first “anomalous” gamma-ray flare from the Crab.
- Oct. 23, 2007: AGILE team meeting and first discussion of the Crab event (STAG n. 39 Minutes of Meeting).
- Sept. 2009: Pittori et al. *Astron. & Astrophys*., 509, 1563, 2009:“the anomalous 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** pointings

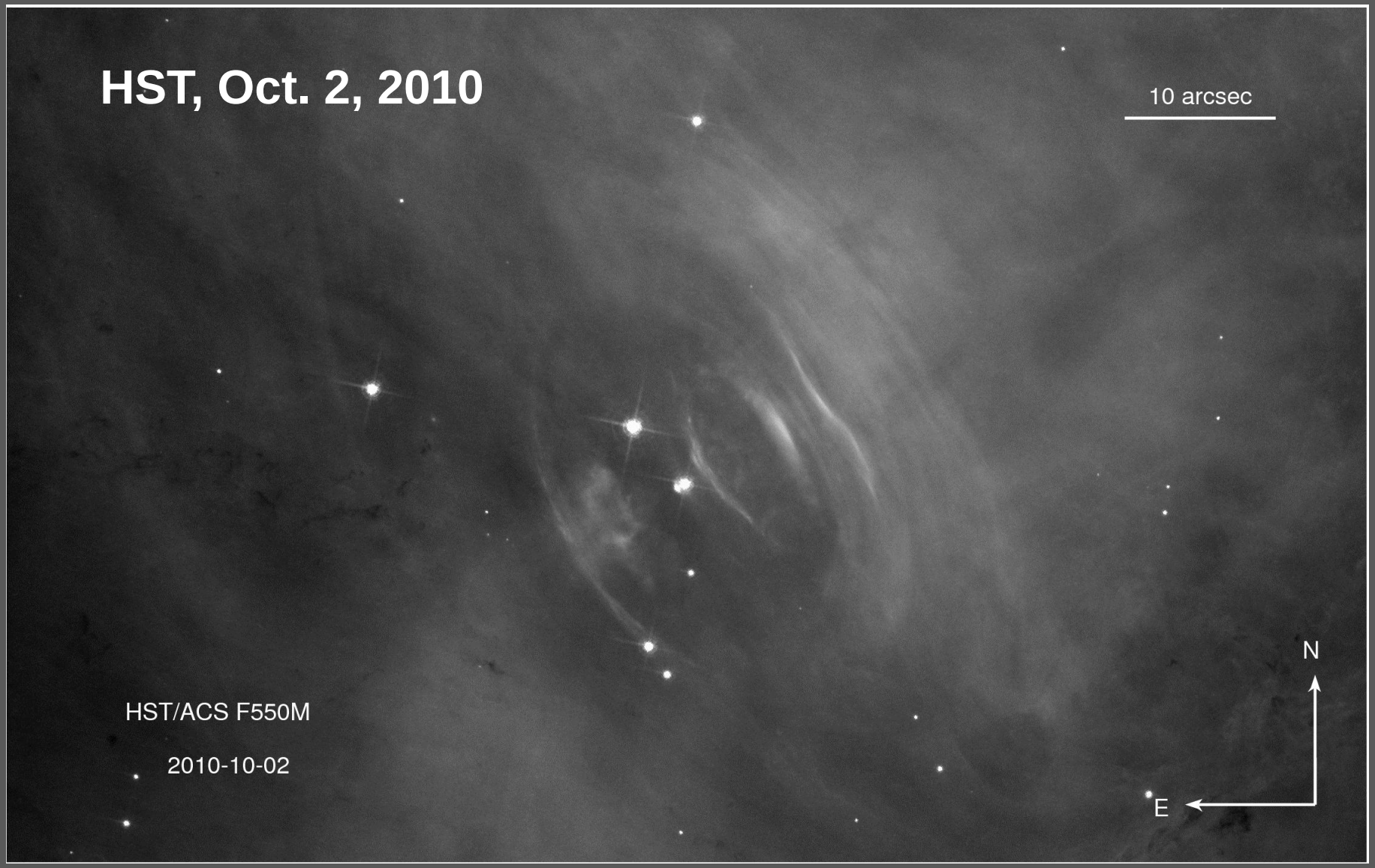

TZP
FUCINO
Malindi
(Kenya)
ASI Science
Data Center

AGILE: l'analisi a terra la più rapida



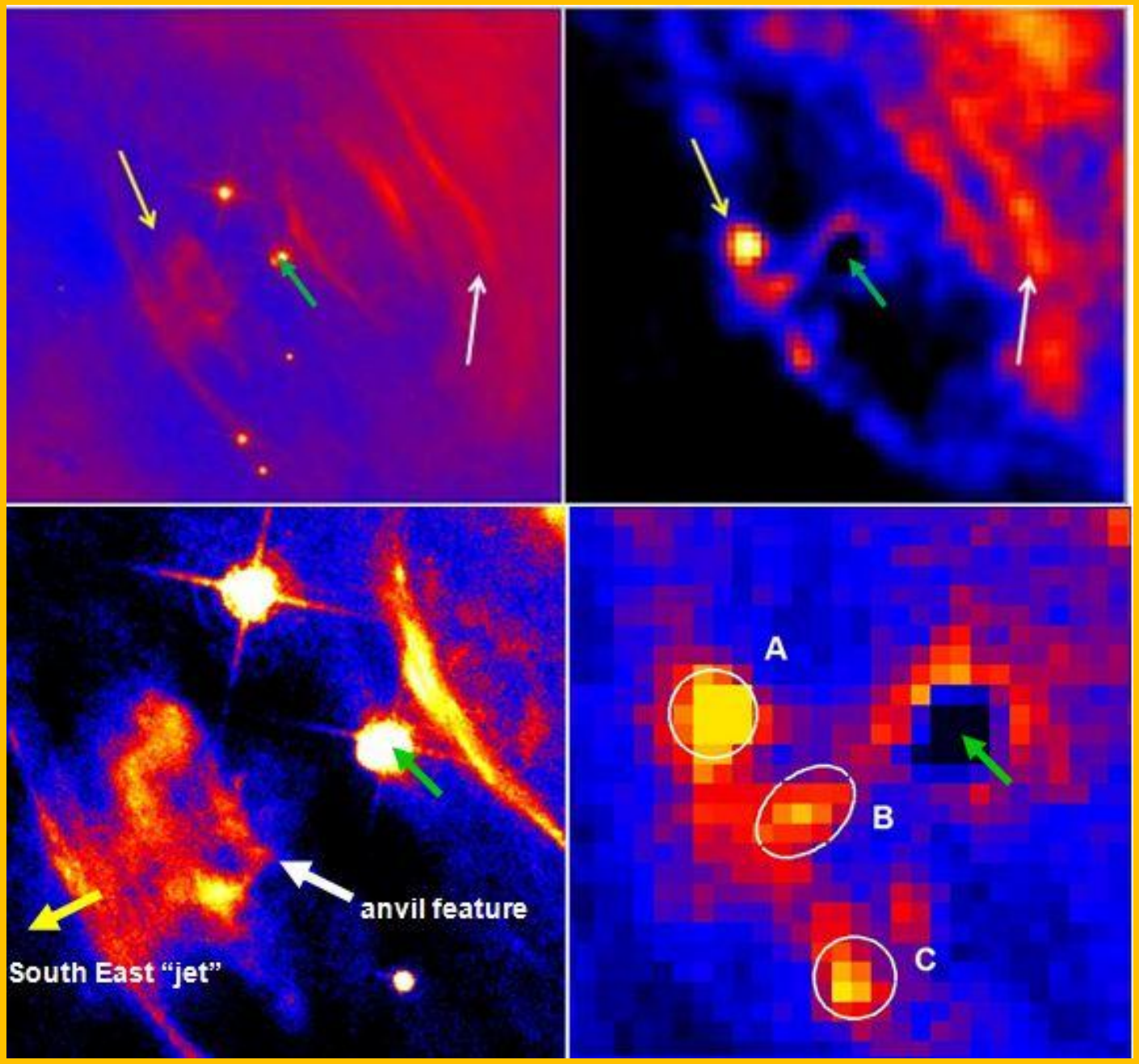
Chandra image of the Crab, 28 Sept. 2010
(Tennant et al. ATEL 2882)




HST, Oct. 2, 2010
10 arcsec
HST/ACS F550M
2010-10-02
N
E

HST

Chandra



HST

Chandra

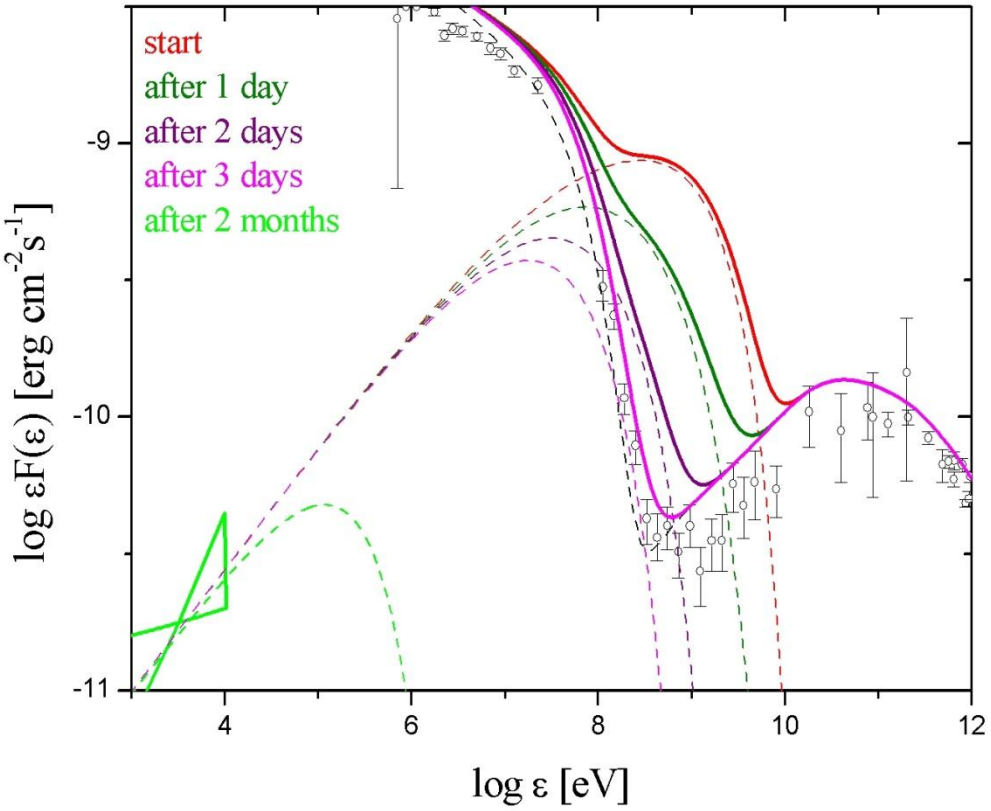
Flare origin

- no noticeable PSR-signal variation with the current sampling, no post-flare variation
- **flare attributed to the Nebula**
- chance coincidence with another source ?
  - $F > 2 \cdot 10^{-6}$ ph cm^{-2} s^{-1}, few sources, $P < 6 \cdot 10^{-5}$
  - no known blazar in error box (0.06), X-ray observation 2 days after the Sept. Flare (ATEL 2868), $P < 10^{-4}$
  - “soft” average gamma-ray spectrum, very unusual, chance-coincidence P very small.

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

- $dN(\gamma)/d\gamma = \gamma^{-p1}$ for $\gamma_{min} < \gamma < \gamma_{break}$ with $p_1 = 2.1$, $\gamma_{min} = 5 \cdot 10^5$, $\gamma_{break} = 2 \cdot 10^9$
- $dN(\gamma)/d\gamma = \gamma^{-p2}$ for $\gamma_{break} < \gamma < \gamma_{max}$, 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**
- $\gamma_{max} \approx \gamma_{break} \leq 10^{9.5} (E/B)(\delta\, \alpha'/\sin\theta)^{1/2} (B/10^{-3}\ G)^{-1/2}$
- **Doppler factor $\delta = 1$**

a synchr. cooling model of the Sept. 2010 flare
(Vittorini V., M.T. et al., ApJ, 2011)



a synchr. cooling model of the Sept. 2010 flare
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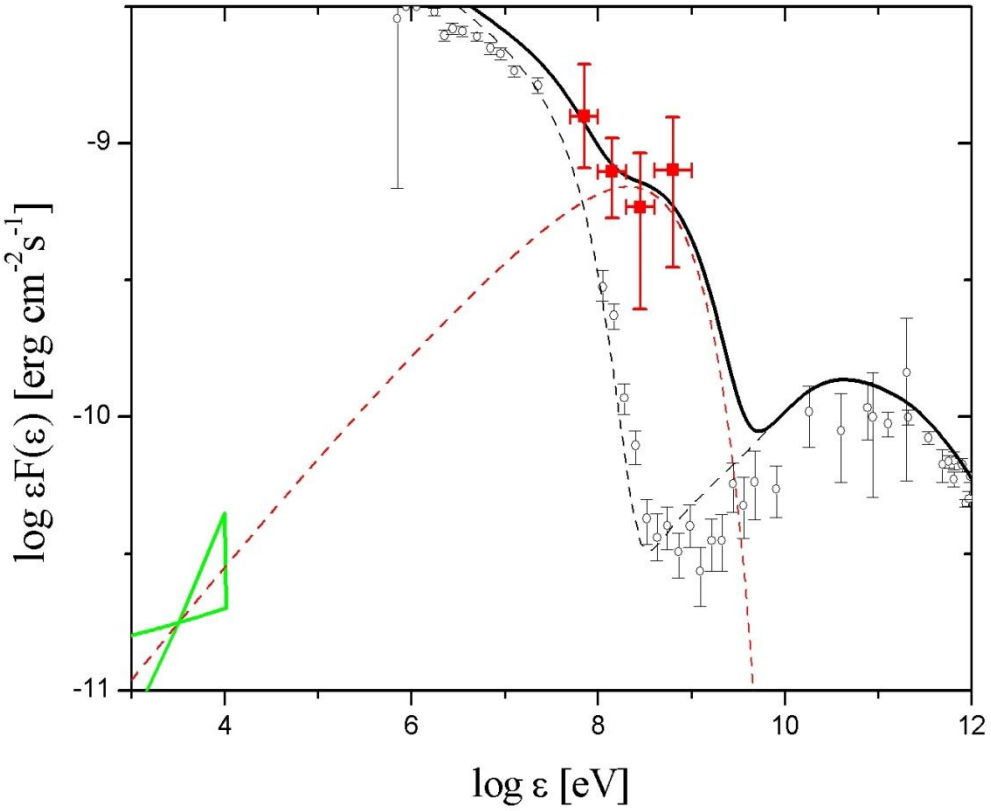

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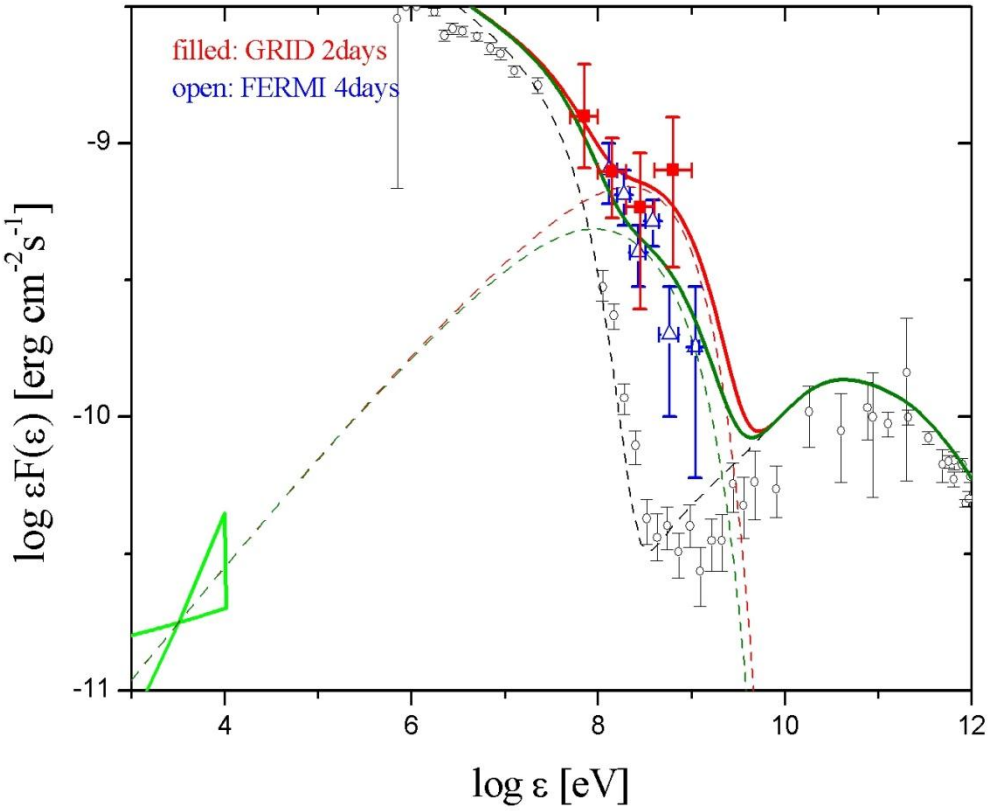

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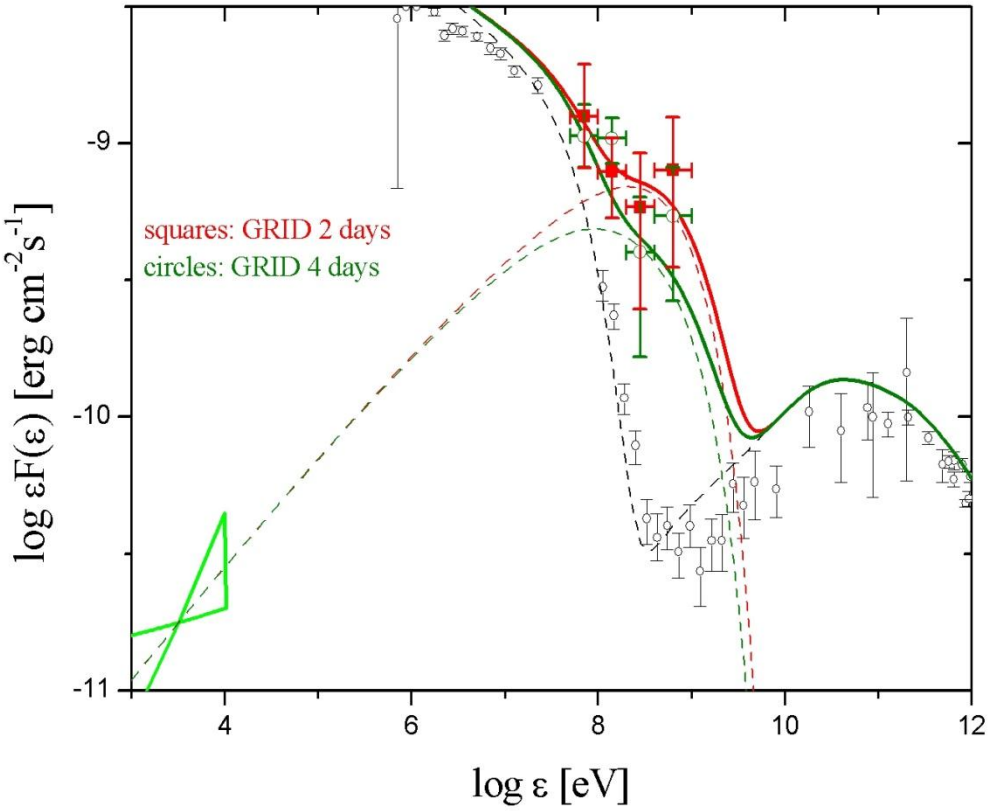

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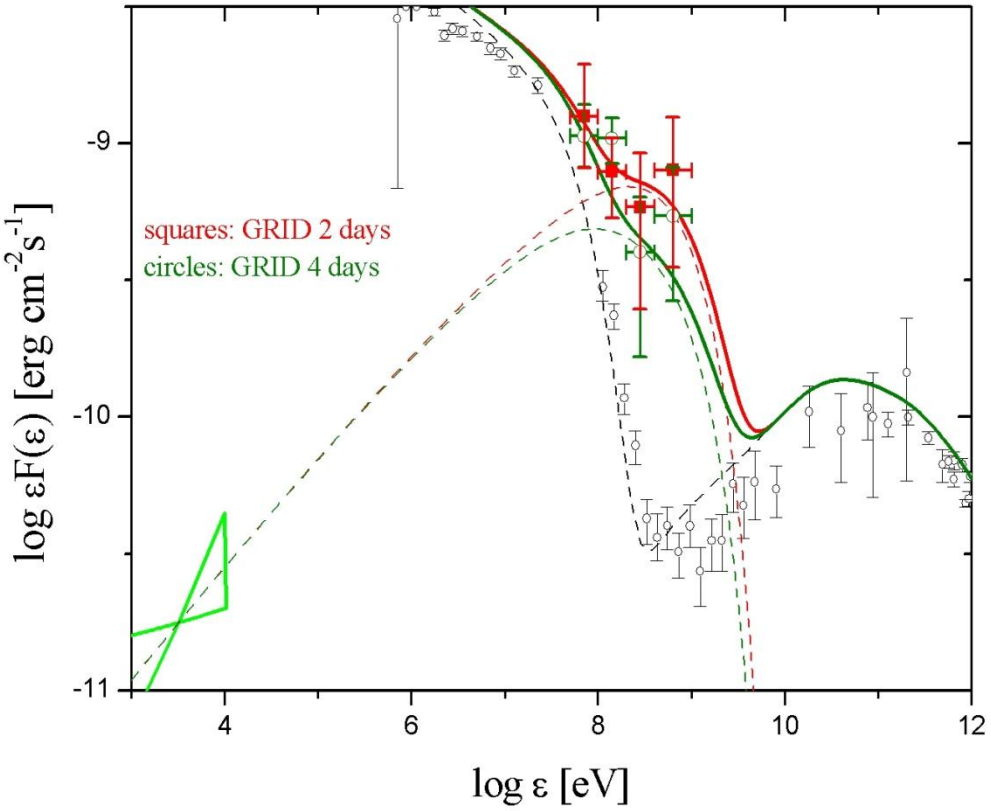

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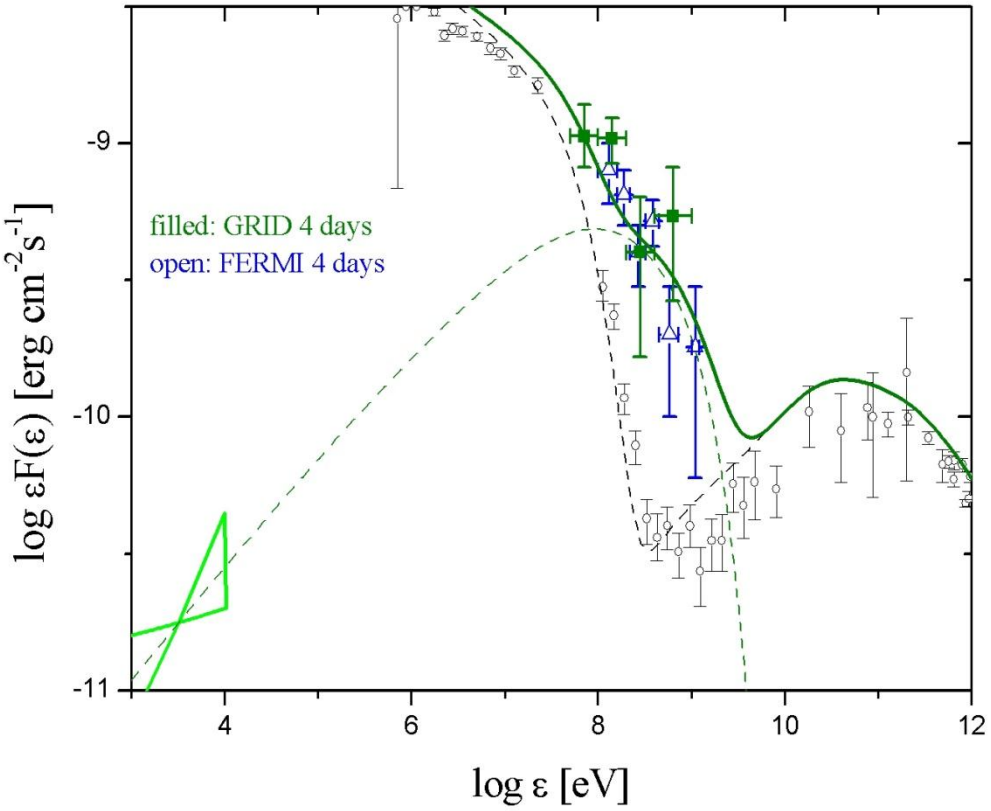

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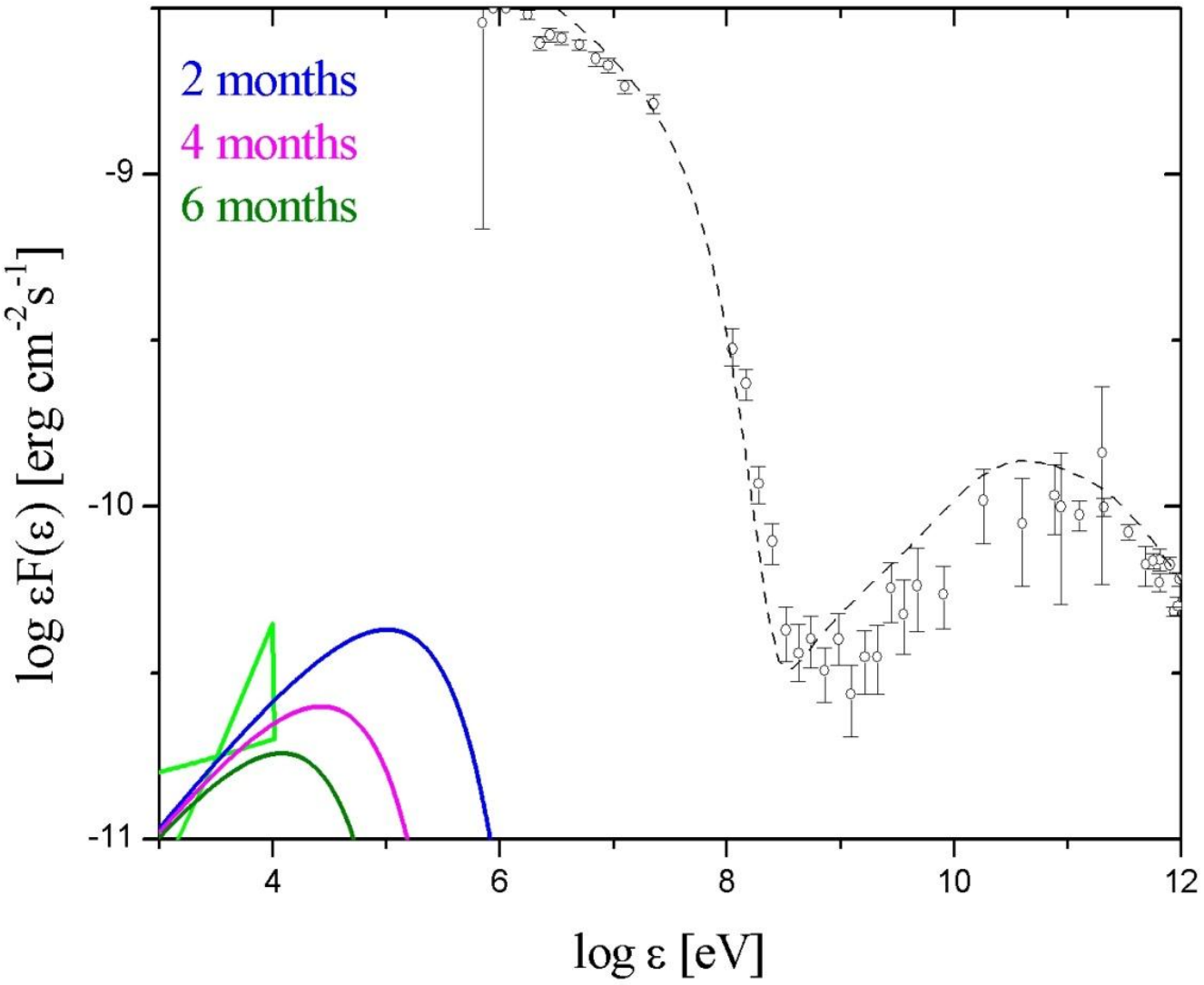
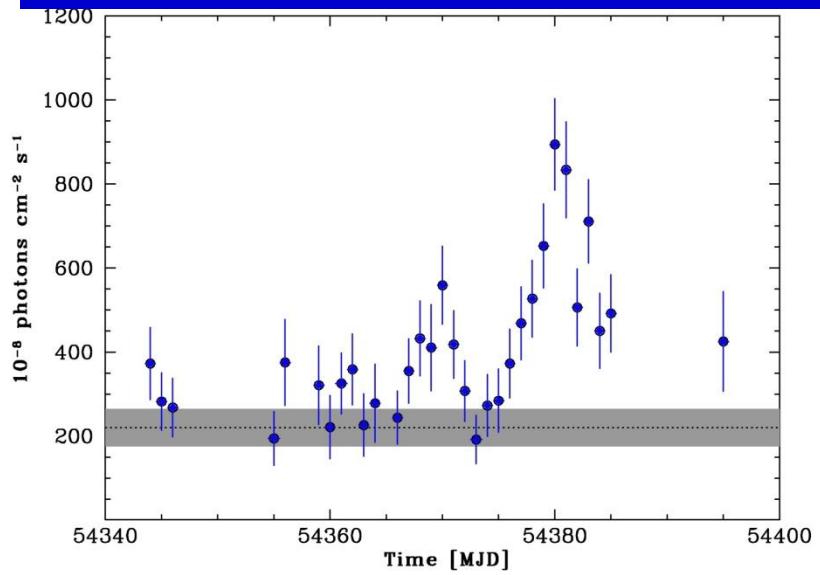


- **Four major gamma-ray flaring episodes**

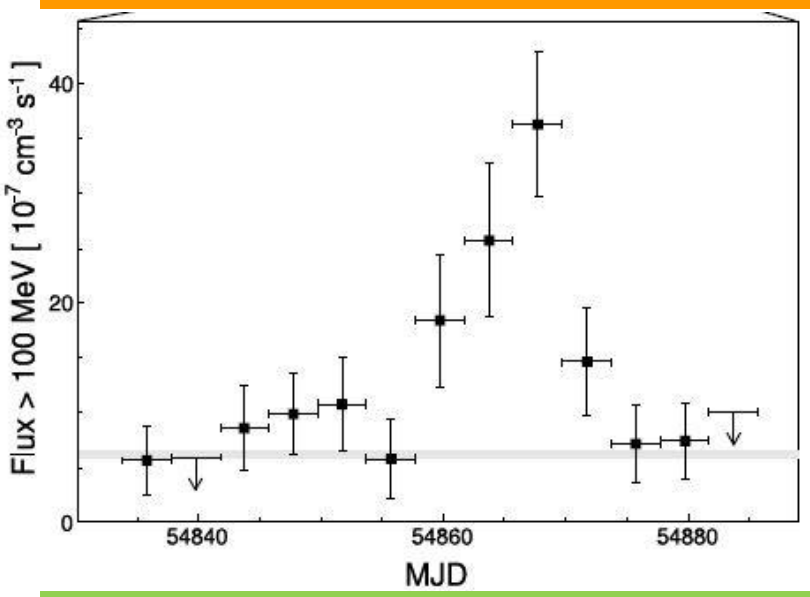
Flare date	Duration	Peak γ-ray flux	Instruments
October 2007	~ 15 days	~ 9 ·10^{-6} ph cm^{-2} s^{-1}	AGILE
February 2009	~ 15 days	~ 7 ·10^{-6} ph cm^{-2} s^{-1}	*Fermi*
September 2010	~ 4 days	~ 7 ·10^{-6} ph cm^{-2} s^{-1}	AGILE, *Fermi*
April 2011	~ 10 days	~ 30 ·10^{-6} ph cm^{-2} s^{-1}	AGILE, *Fermi*

major flare rate: 1-2/year

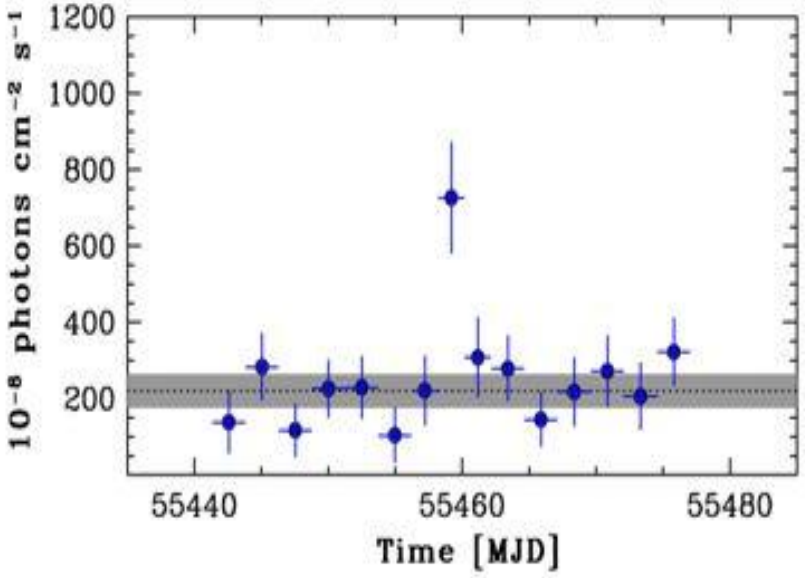
AGILE, 26 Nov. – 13 Oct. 2007



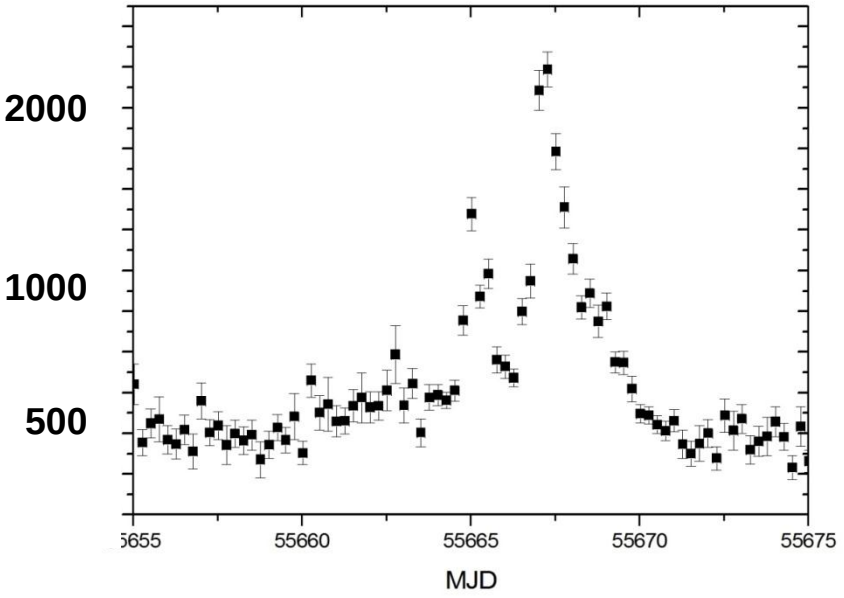
Fermi-LAT, 26 Jan. – 11 Feb. 2009



AGILE, 20-22 Sept. 2010

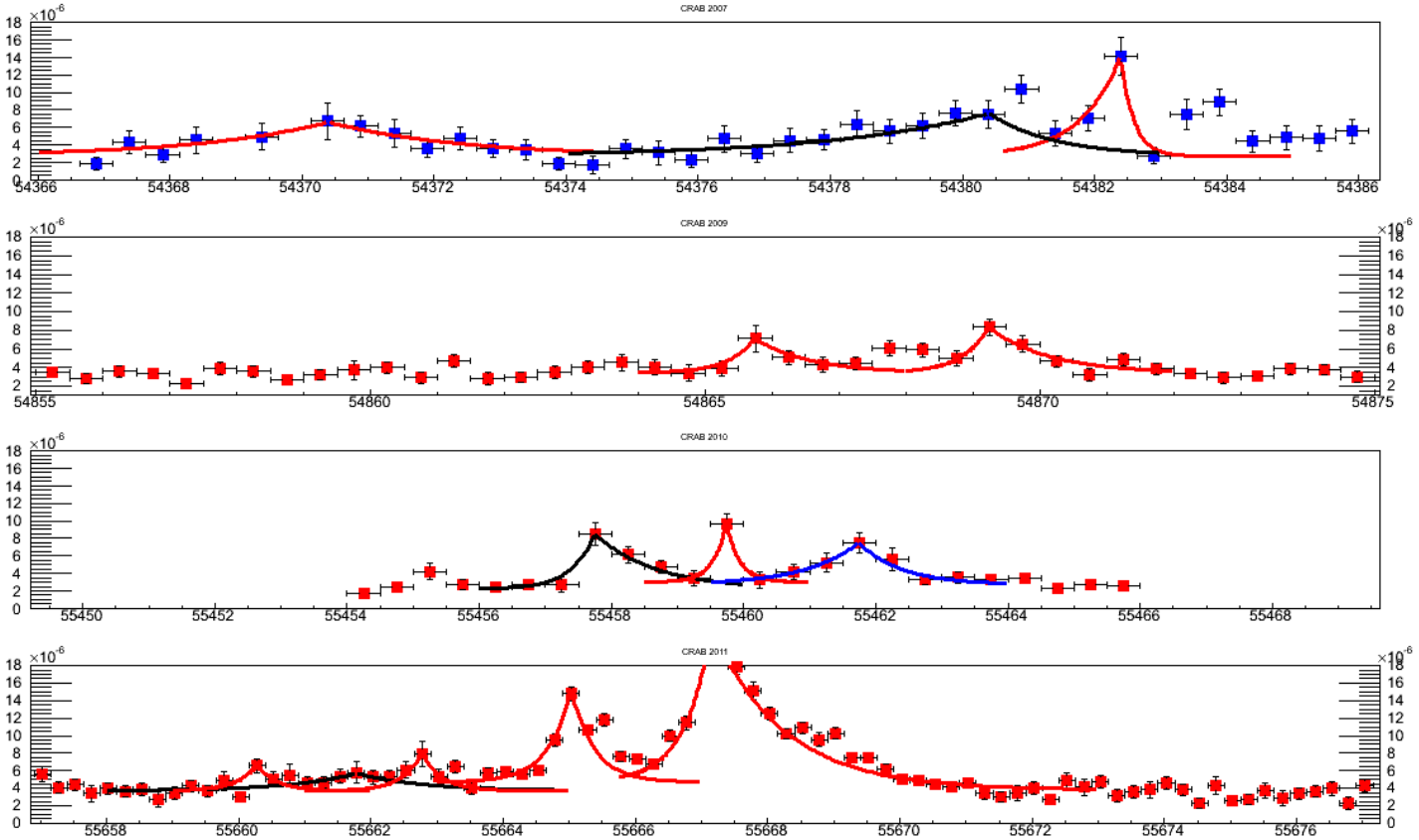


Fermi-AGILE, 12 – 20 Apr. 2011



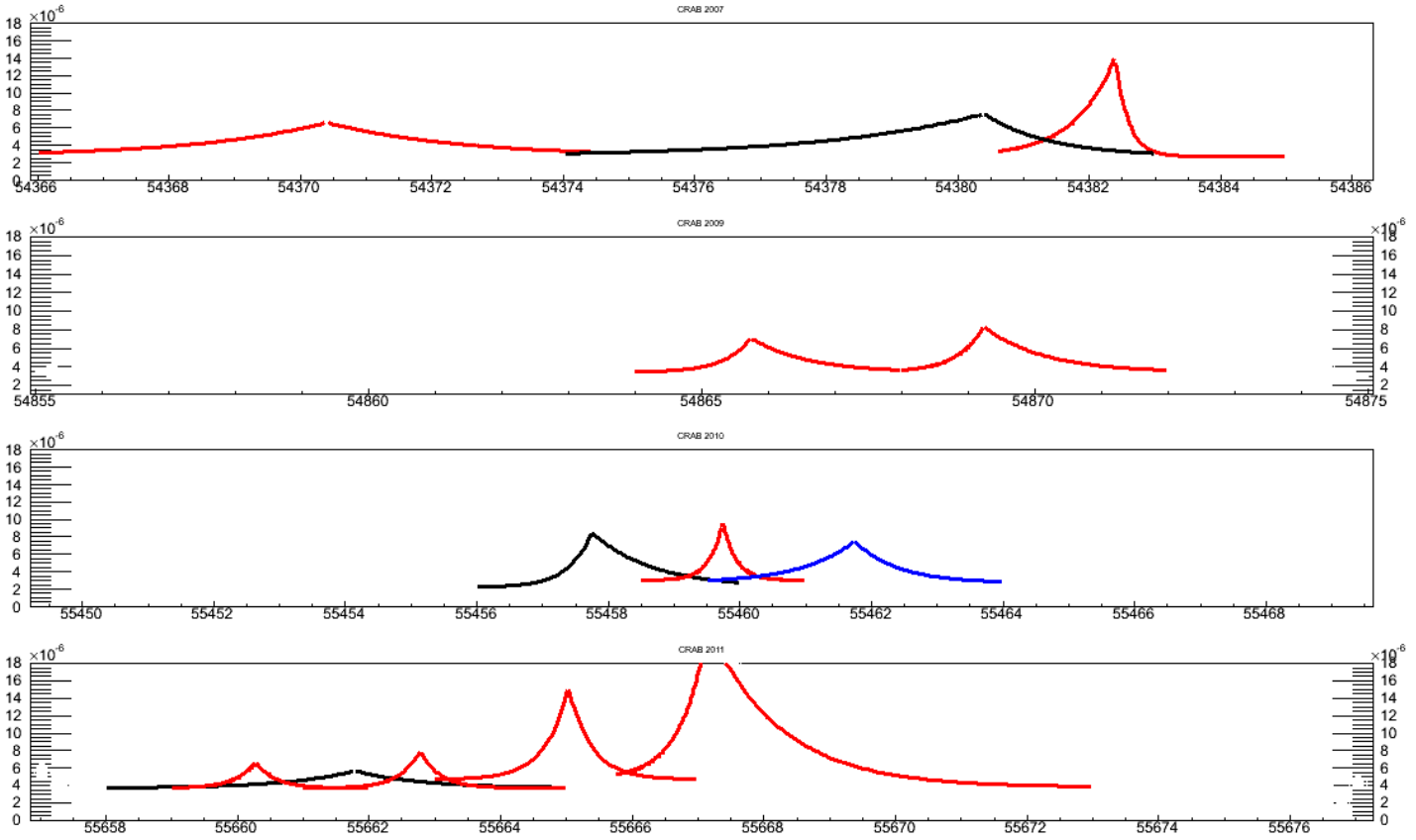
The Crab major gamma-ray flaring episodes

(E. Striani et al., 2012)



The Crab major gamma-ray flaring episodes

(E. Striani et al., 2012)



Breaking a tabu: the Crab is not a standard candle in gamma-rays

- **inadequacy of the MHD modelling used so far**
- **necessity of a very fast and efficient acceleration, diffusive processes are not fast enough**
- **most likely fast acceleration in localized regions subject to plasma instabilities and magnetic field reconnection**

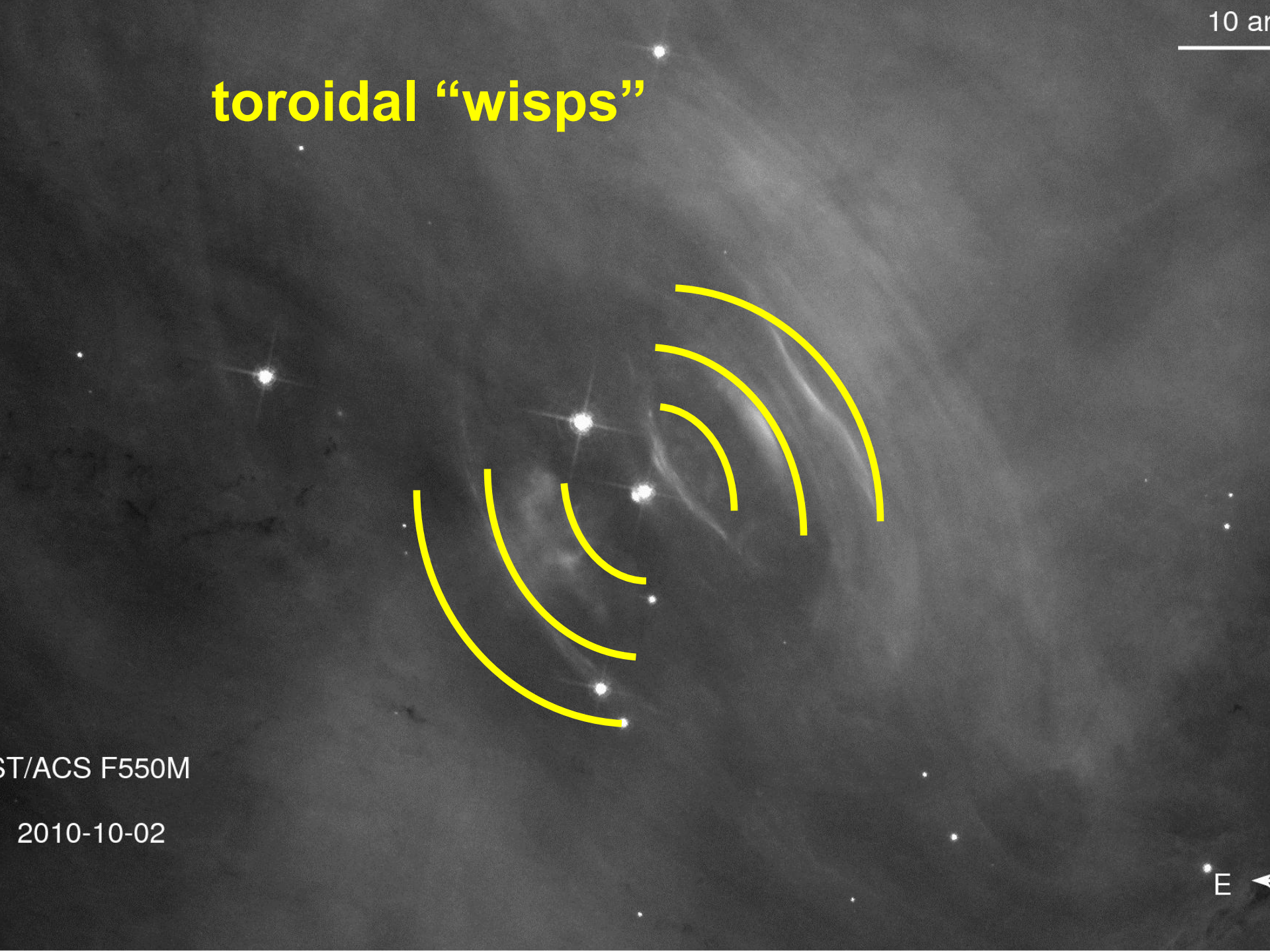
- **if it's nebular emission, what is the ultimate cause of it?**
  - **PSR wind enhancement (density, local B, change of sigma)**
  - **Plasma physics, shock changes, sudden change of B-configuration, reconnection (?)**
  - **near PSR effects (?)**
  - **Knot-1 (?)**
  - **"Anvil" region (?)**
  - **Wisp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

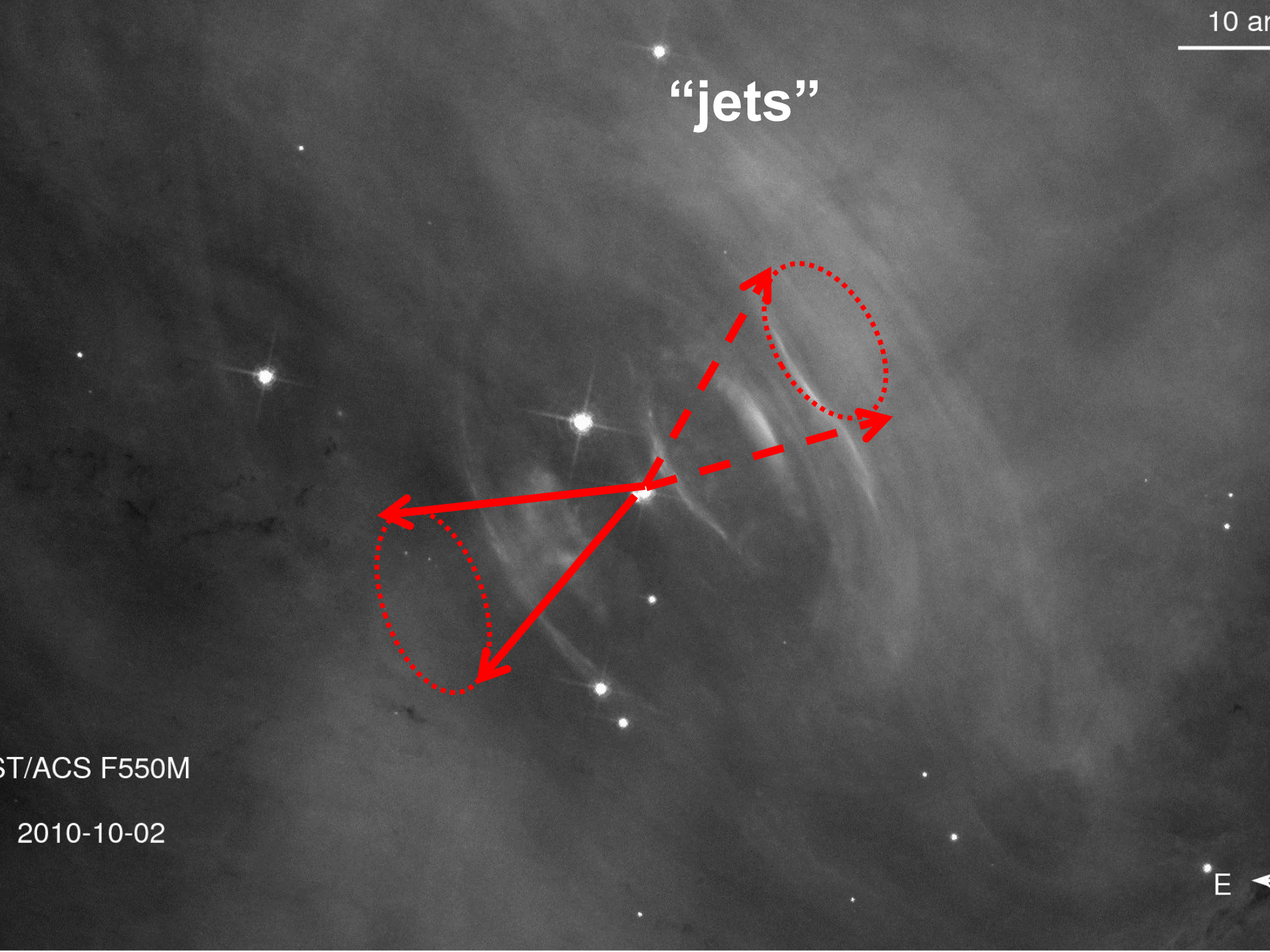
issues

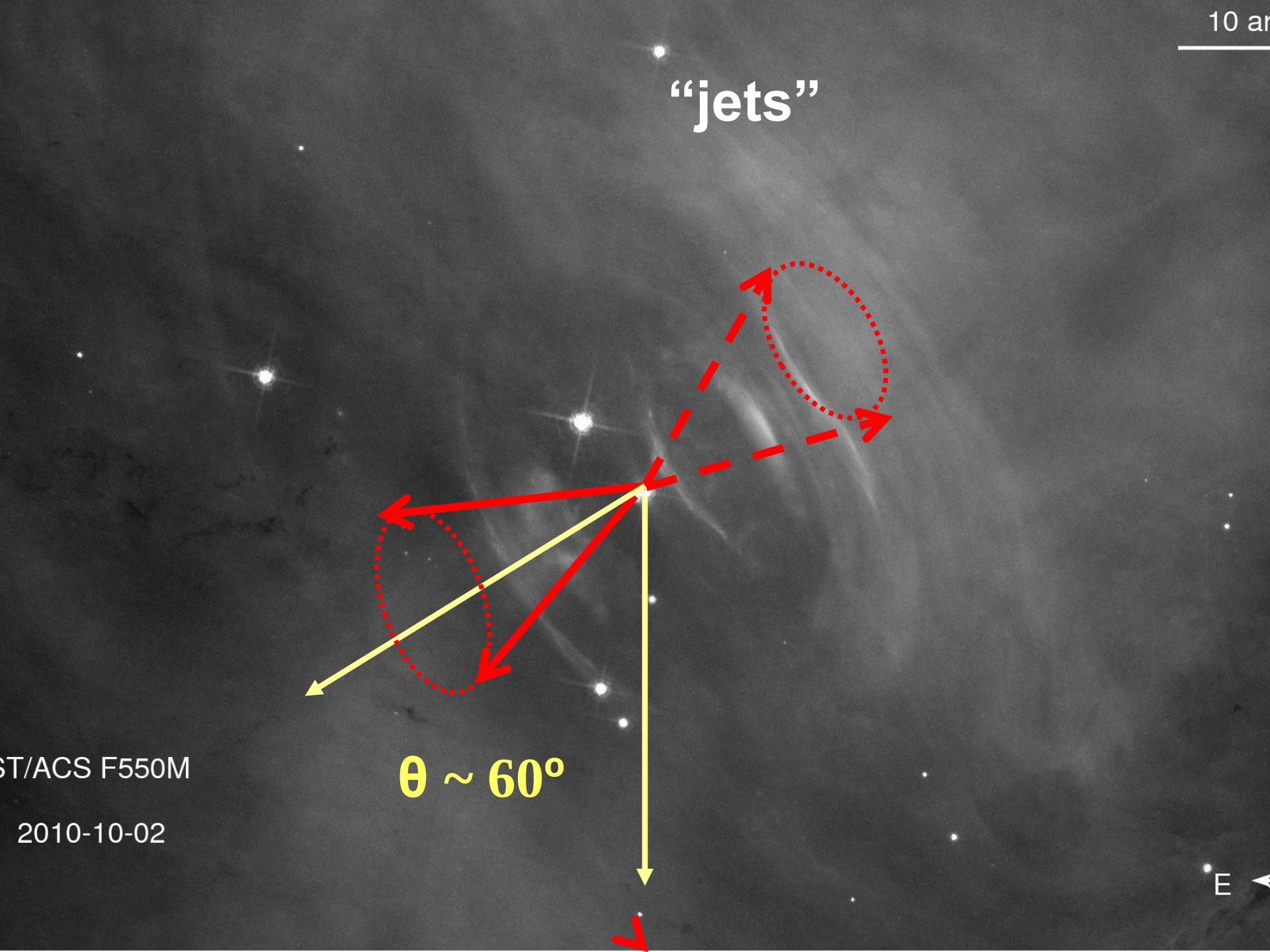
- **standard MHD simulations give too long timescales**
- **detailed acceleration mechanism to be identified**
- **not clear how a strong “E-parallel” is produced**

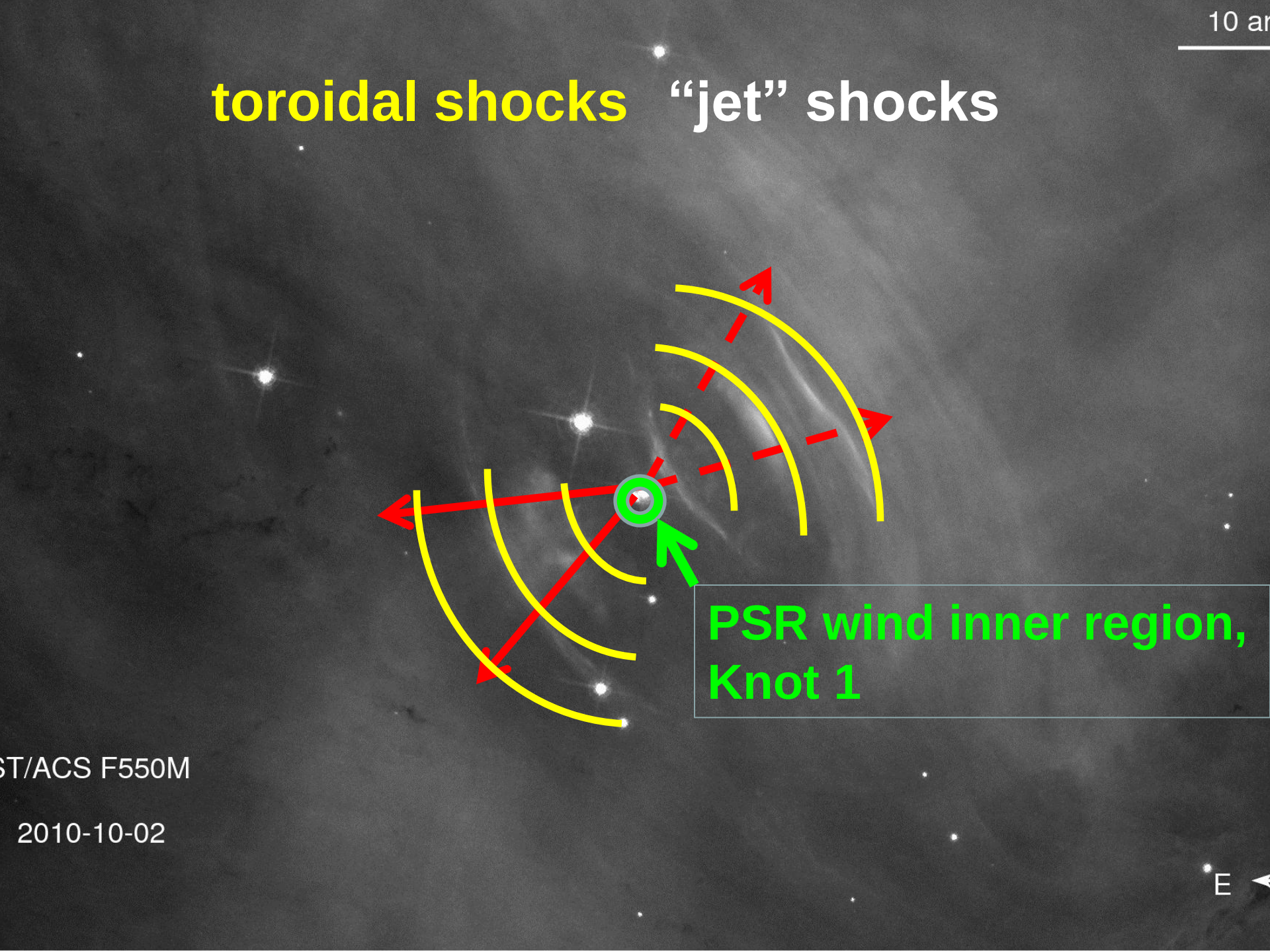
ideas

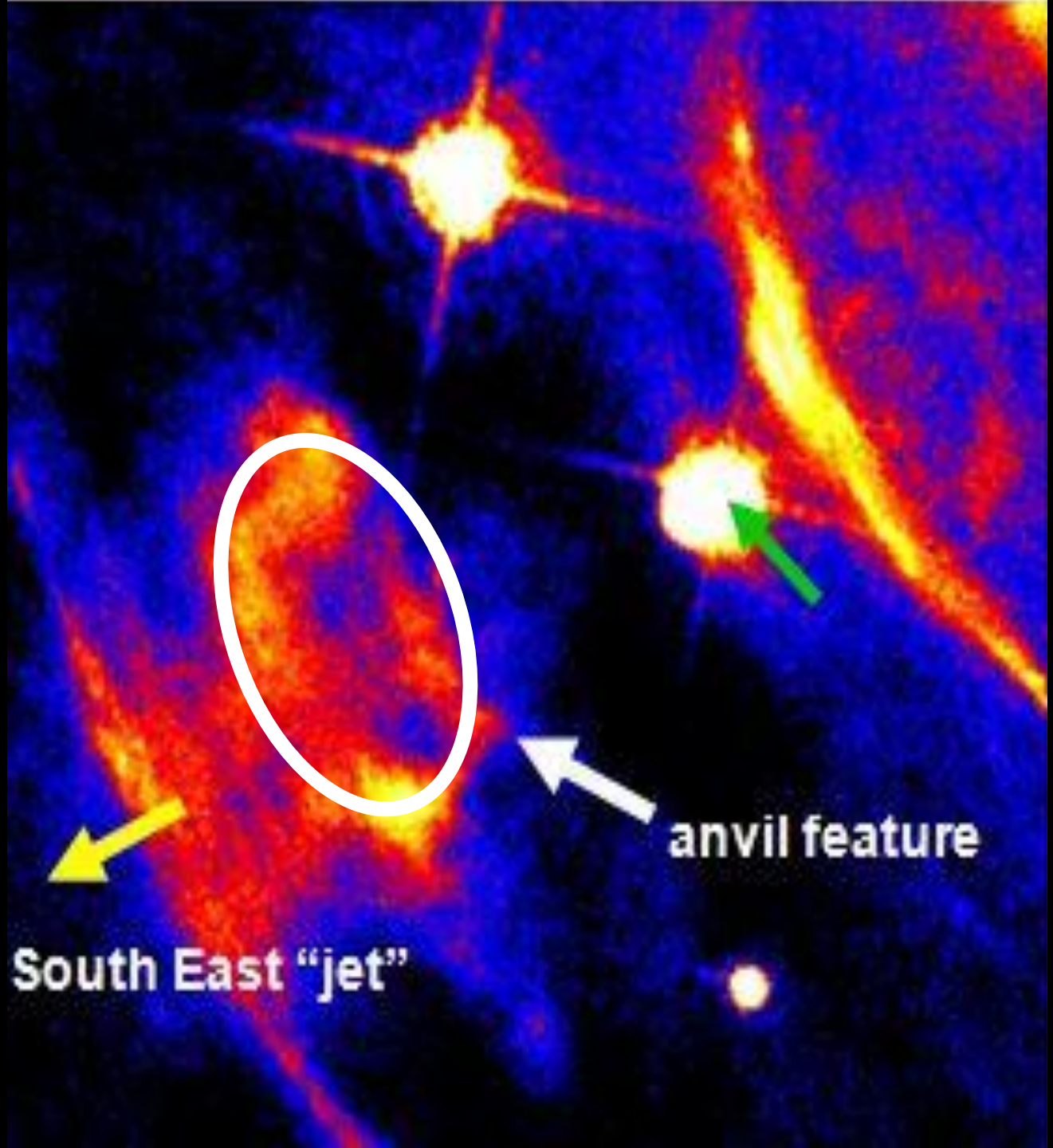
- **Doppler boosting**
- **instabilities: magnetic field reconnection, magnetic “islands”**
  - in the polar (South East) “jet” region
- **current sheet instabilities in wisp rings**
- **relativistic shocks developing E-parallel**


toroidal “wisps”
10 ar
ST/ACS F550M
2010-10-02
E


10 ar
“jets”
ST/ACS F550M
2010-10-02
E


10 ar
"jets"
θ ~ 60°
ST/ACS F550M
2010-10-02
E

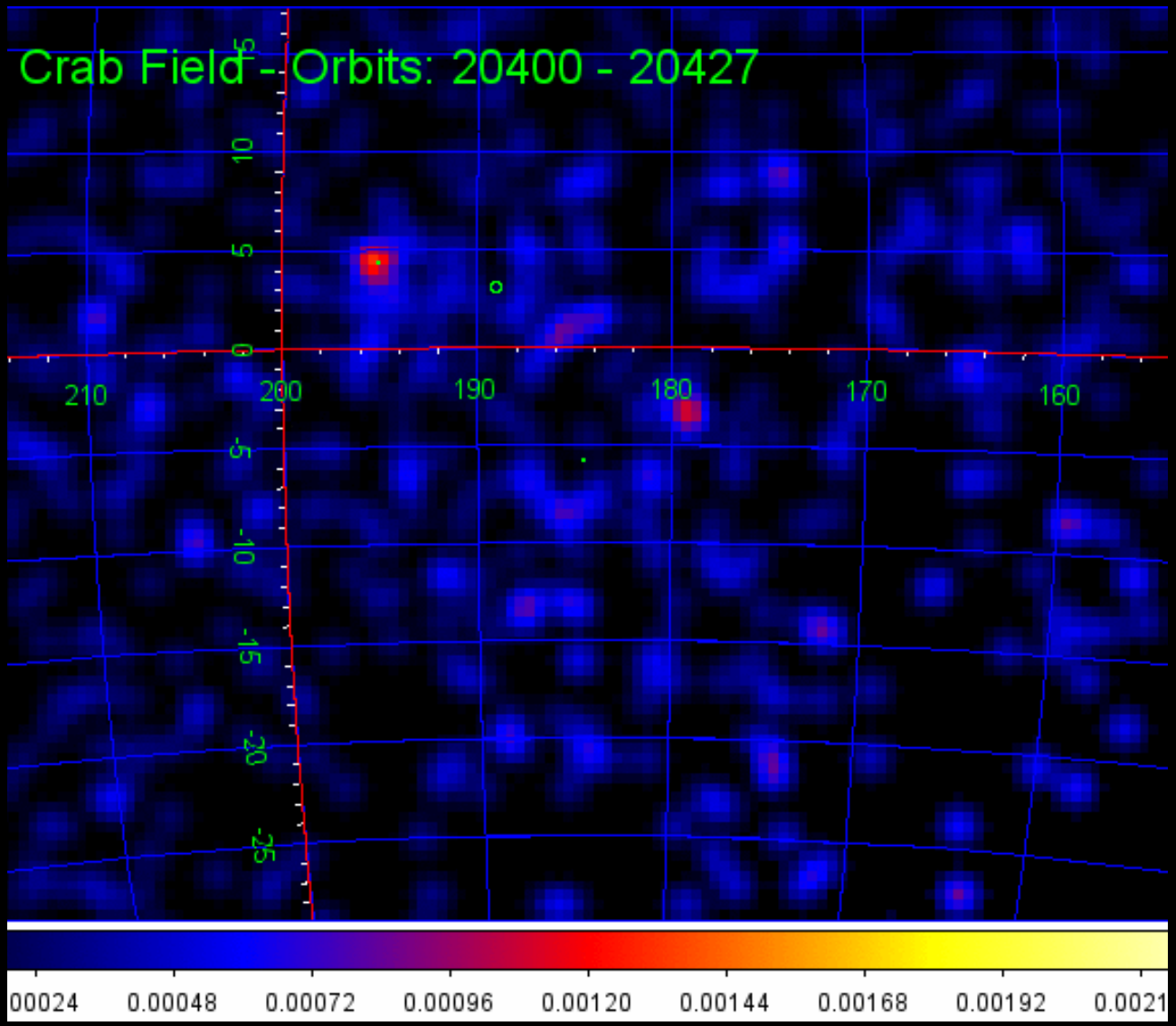

10 ar
toroidal shocks
“jet” shocks
PSR wind inner region,
Knot 1
ST/ACS F550M
2010-10-02
E



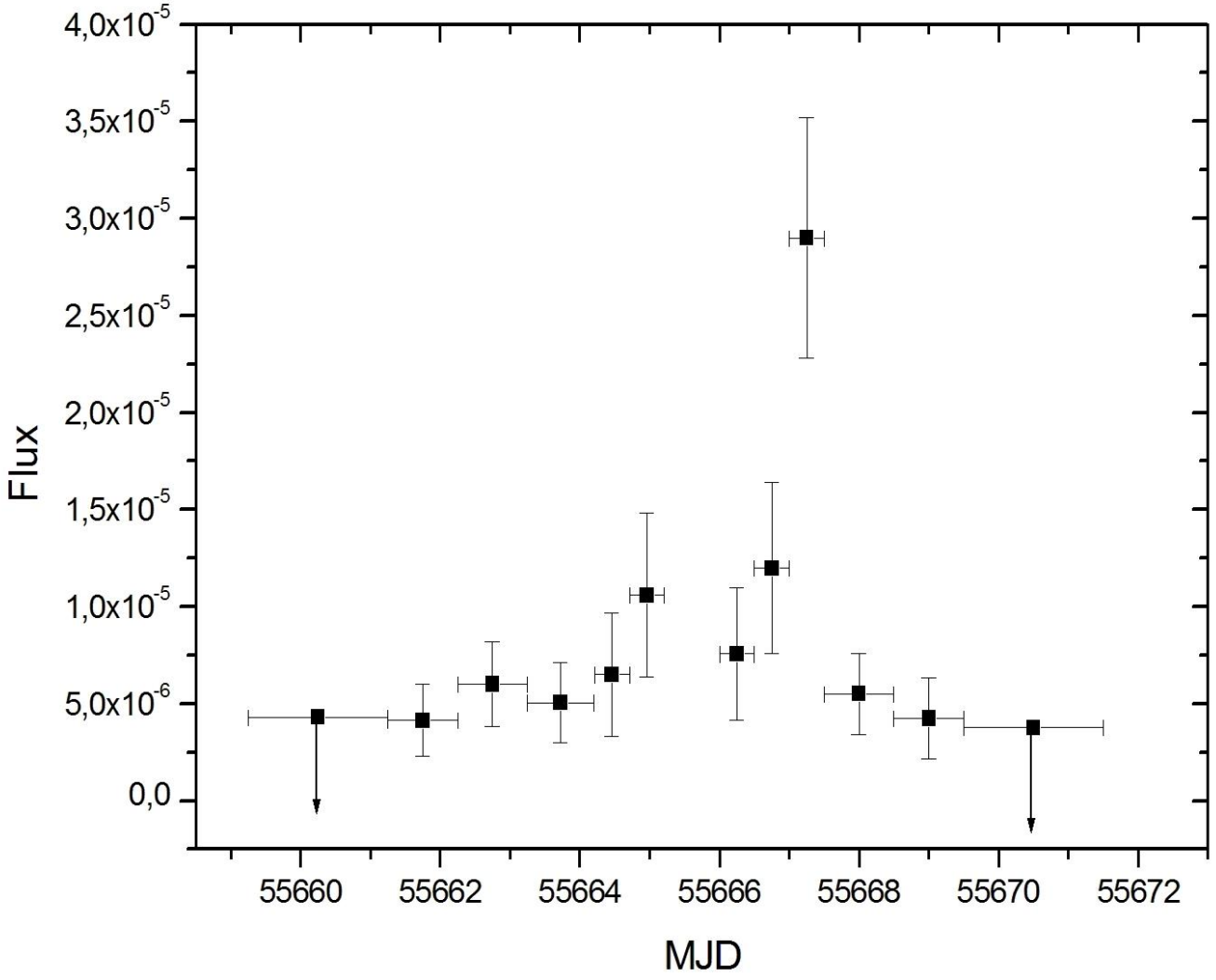
HST,
Oct. 2, 1010

The Crab super-flare (12-18 April 2011)

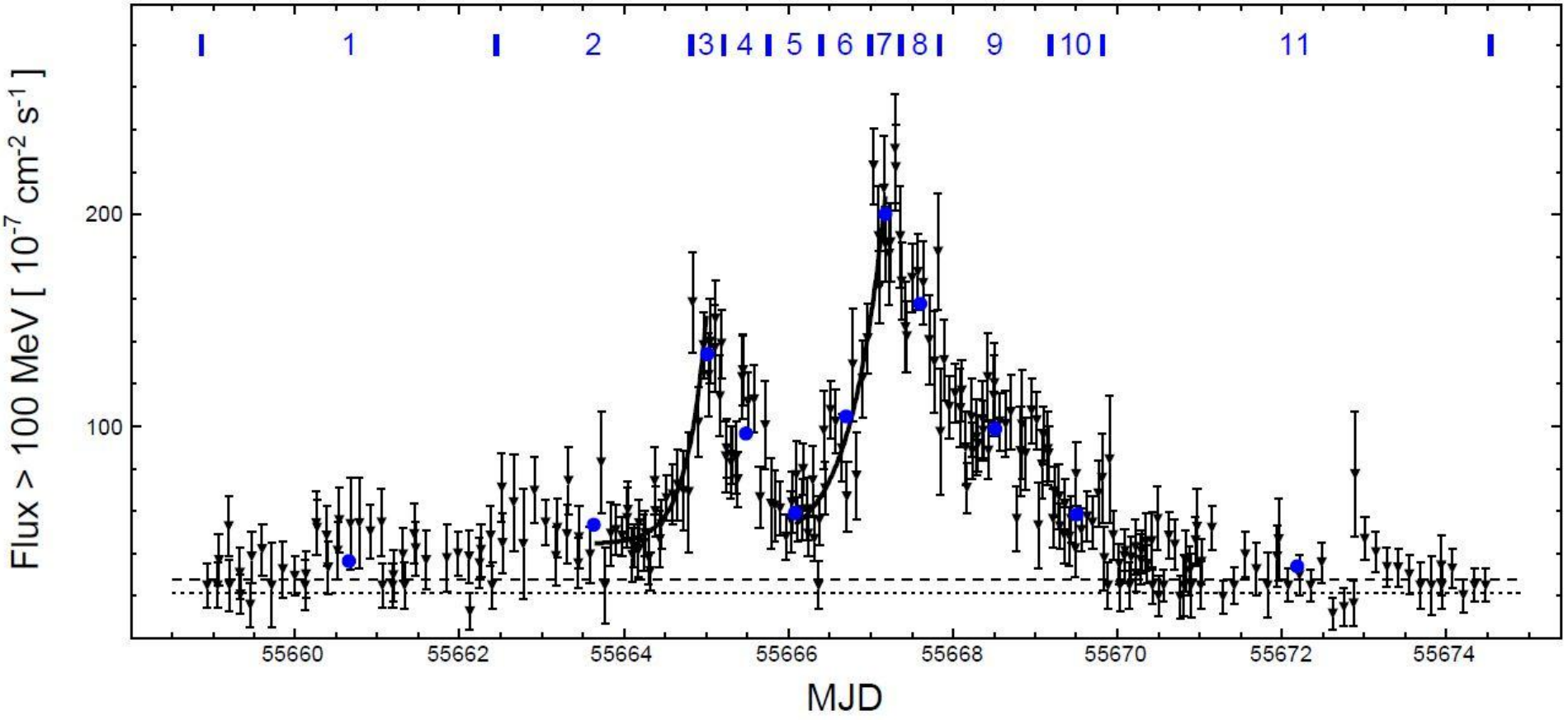
AGILE monitoring of the Crab (April 2011)



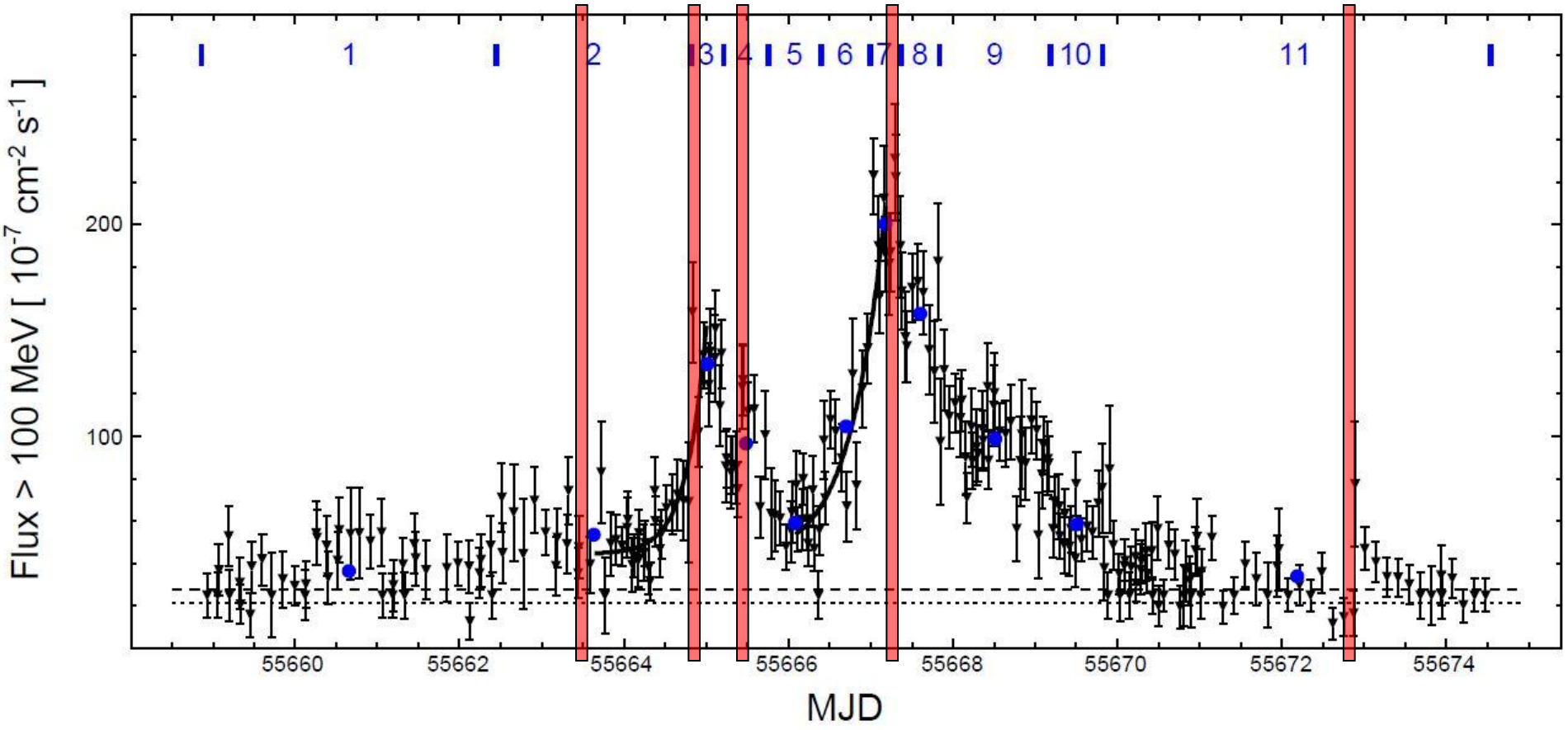
AGILE monitoring (April 2011) (Striani et al. 2012)



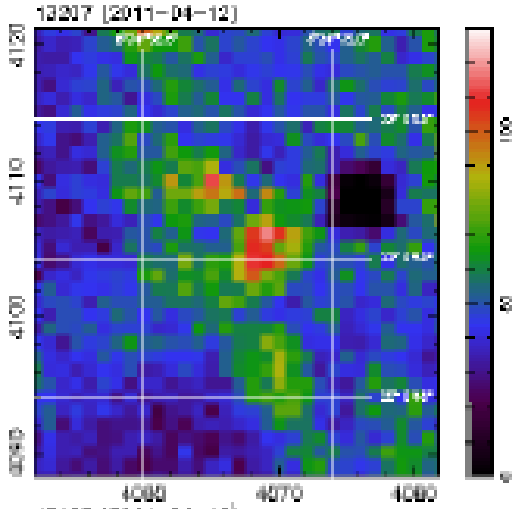
Fermi-LAT monitoring (April 2011) (Boehler et al. 2012)

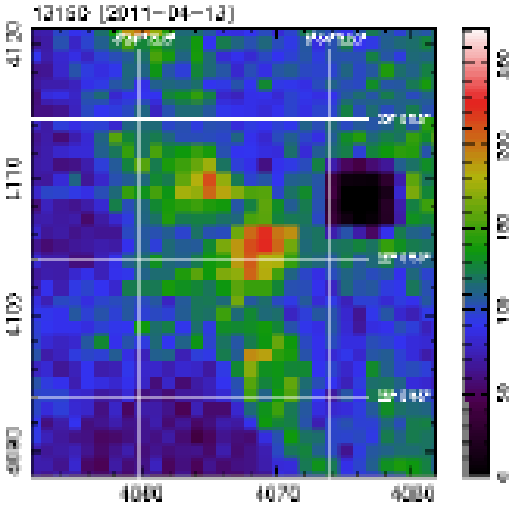


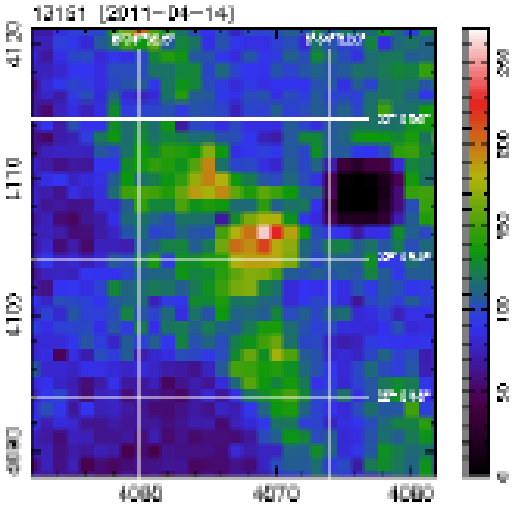
Chandra pointings

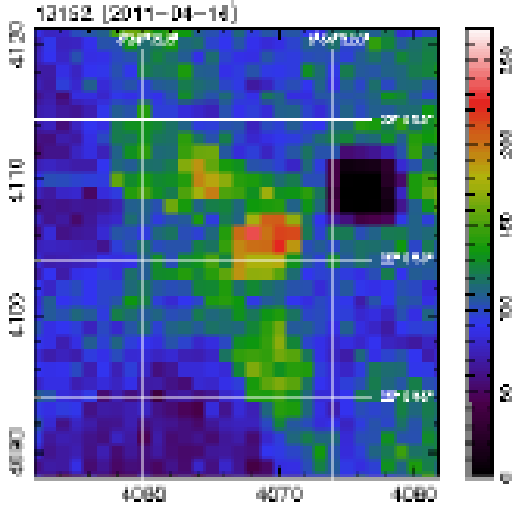


Chandra X-ray observations of the April 2011 Crab flare

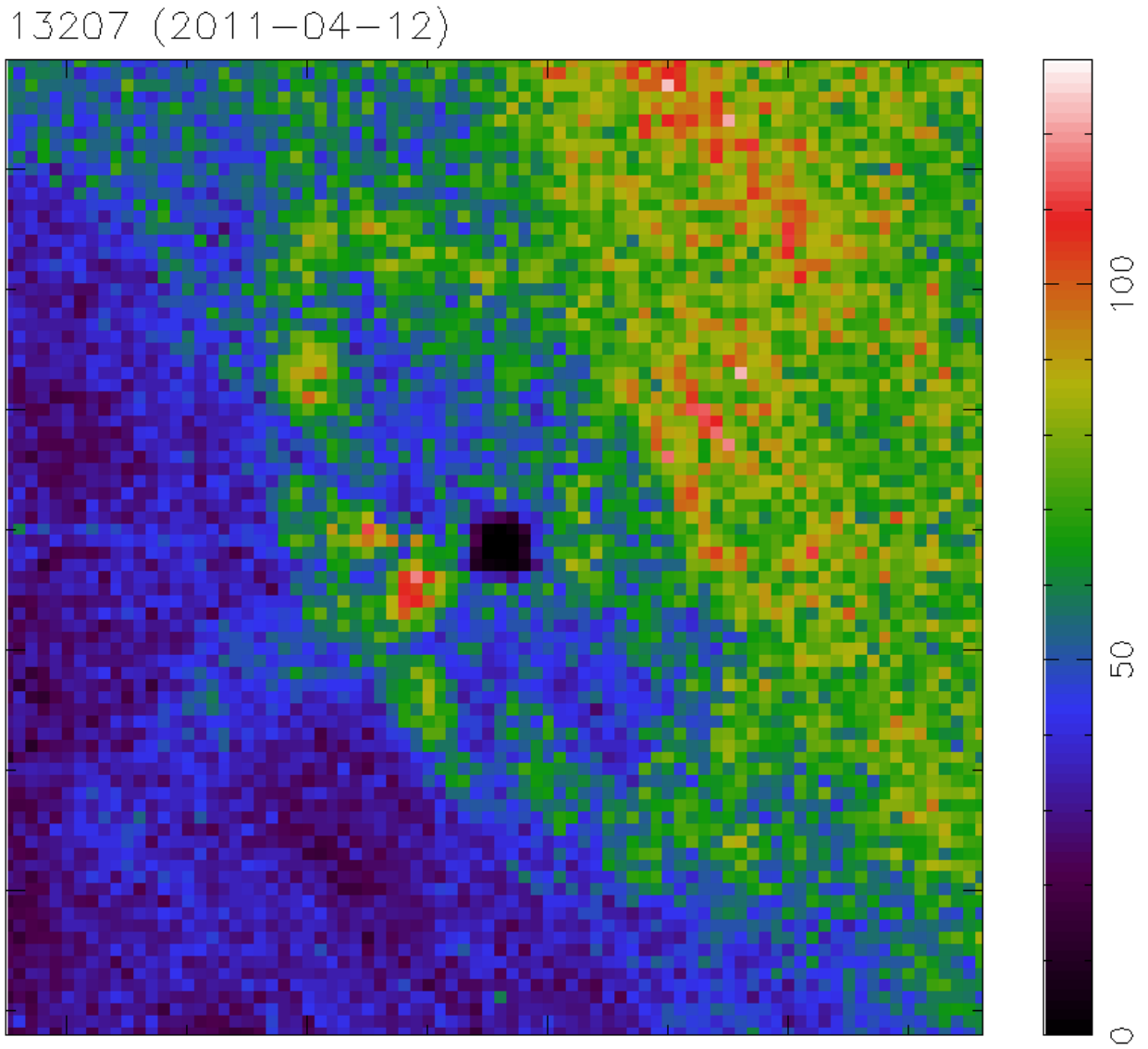






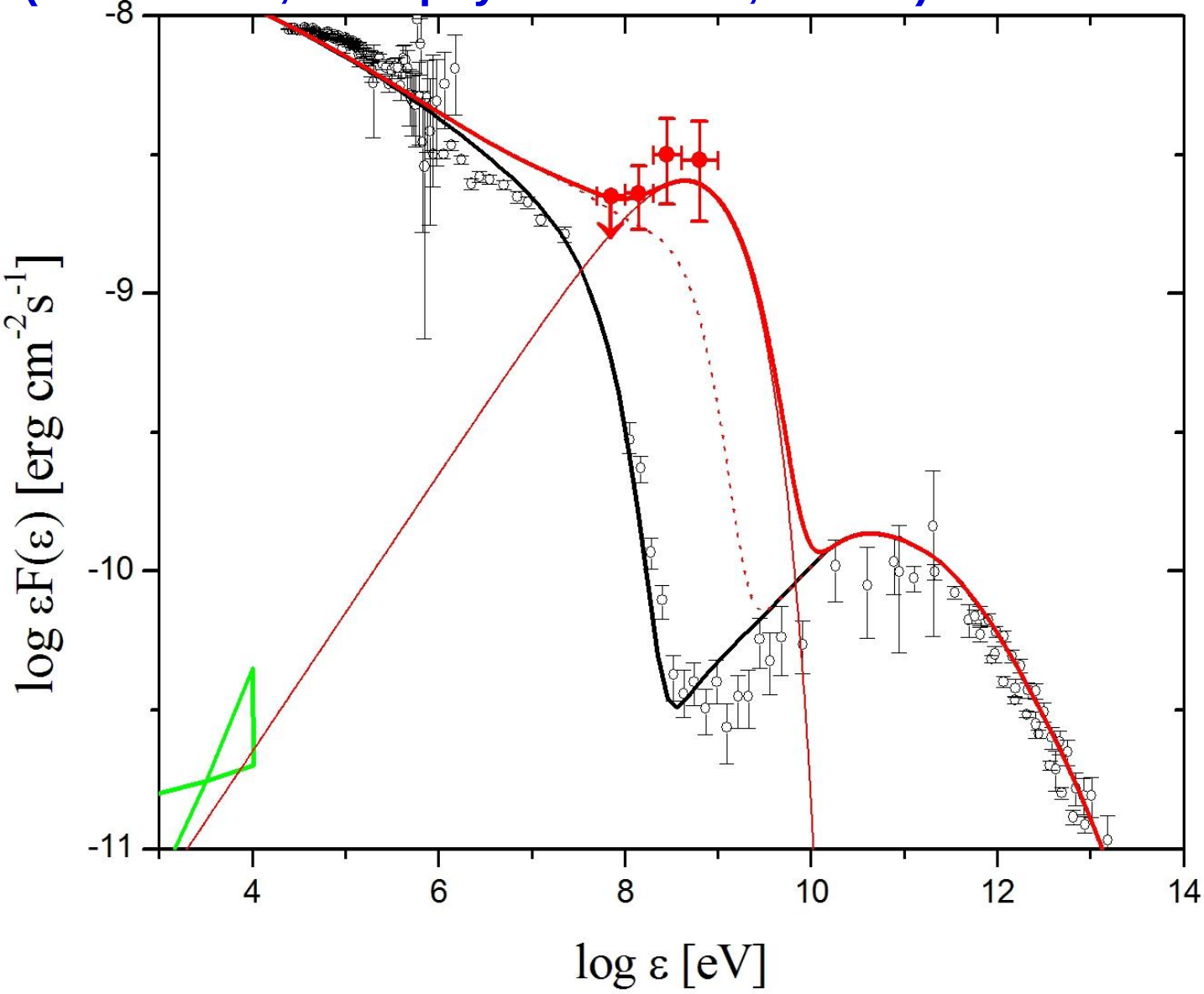


Crab super-flare: Chandra monitoring
(12, 13, 14, 21 Apr. 2011: A. Tennant, M. Weisskopf)



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

(Striani et al, Astrophys. J. Letters, on line)



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},**

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

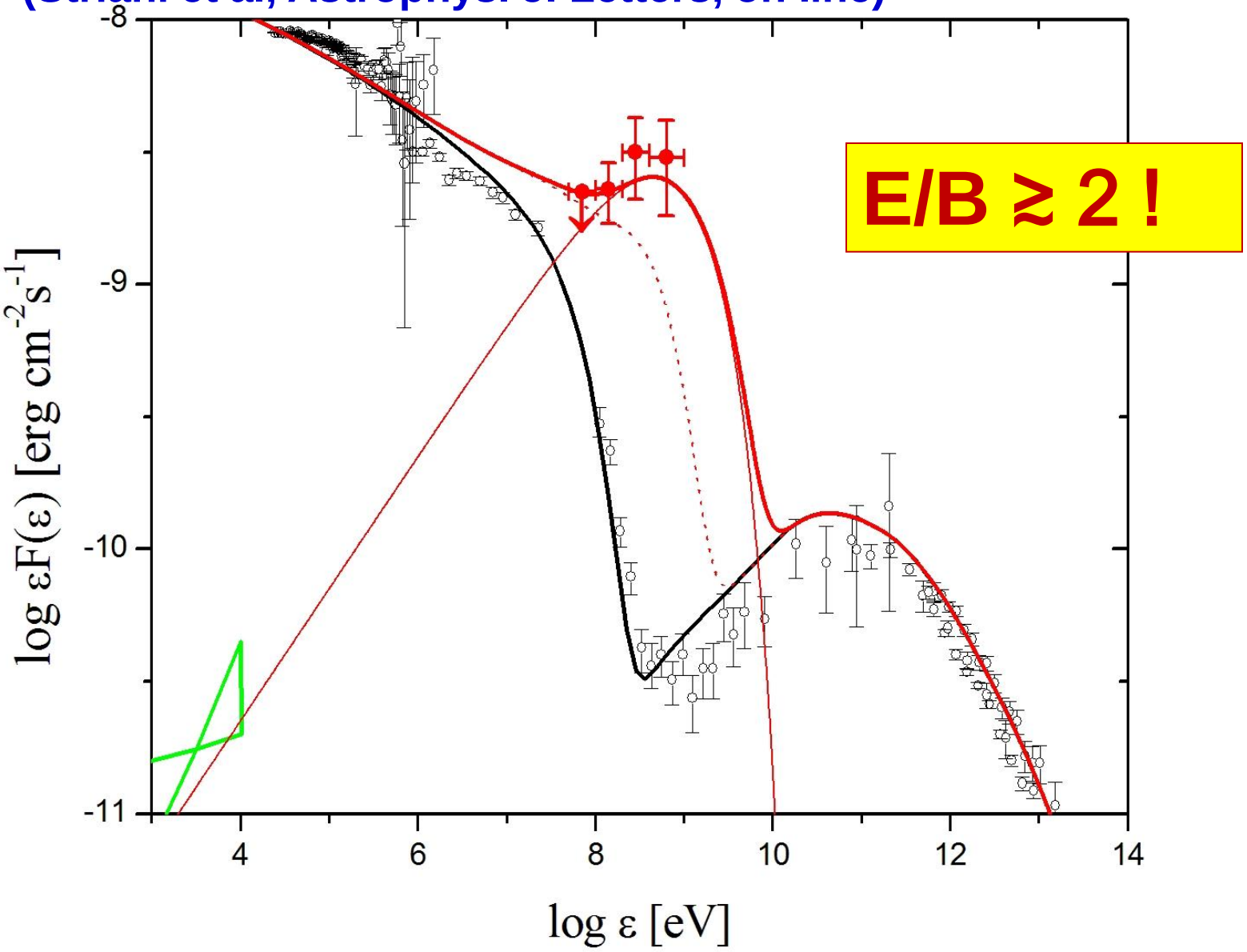
- **timescales:**
  - **risetime** $\leq$ a few hrs ⟵ **very efficient acceleration !**
  - **decay:** ~ 1-2-3 days ⟵ **fast cooling, B, Lorentz γ**

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

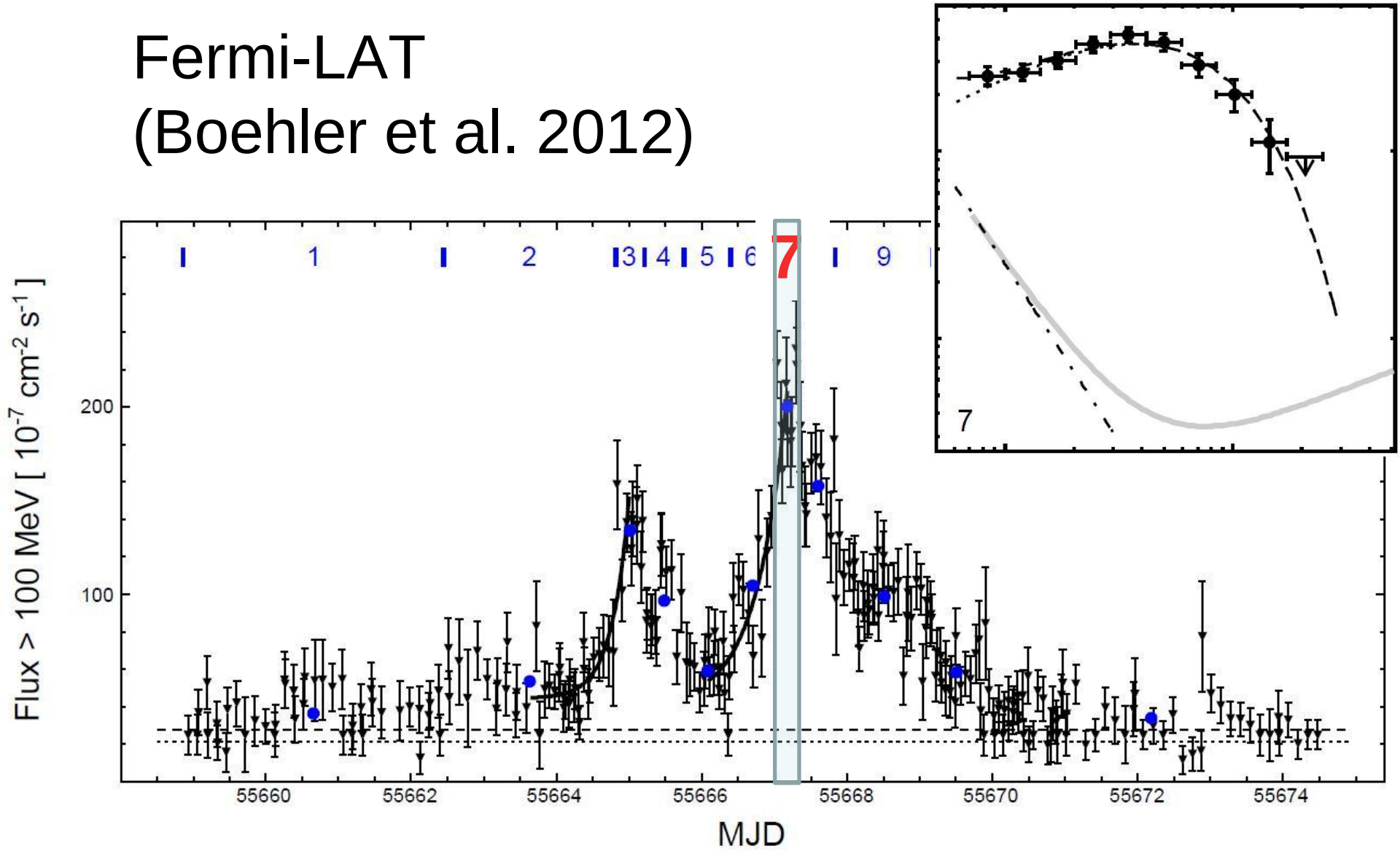
- $dN(\gamma)/d\gamma = \gamma^{-p1}$ for $\gamma_{min} < \gamma < \gamma_{break}$ with $p_1 = 2.1$, $\gamma_{min} = 5 \cdot 10^5$, $\gamma_{break} = 5 \cdot 10^9$
- $dN(\gamma)/d\gamma = \gamma^{-p2}$ for $\gamma_{break} < \gamma < \gamma_{max}$, with $p_2 = 2.7$,
- total particle number $N_{e-/e+} = 10^{42}$.
- size, Larmor radius $R \leq 10^{16}$ cm
- **local $B \approx 10^{-3}$ G (10 times larger than average)**
- $\gamma_{max} \approx \gamma_b \leq 7 \cdot 10^9 (E/3B)(\delta\, \alpha'/\sin\theta)^{1/2} (B/10^{-3}\ G)^{-1/2}$
- **δ = 2-3**

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

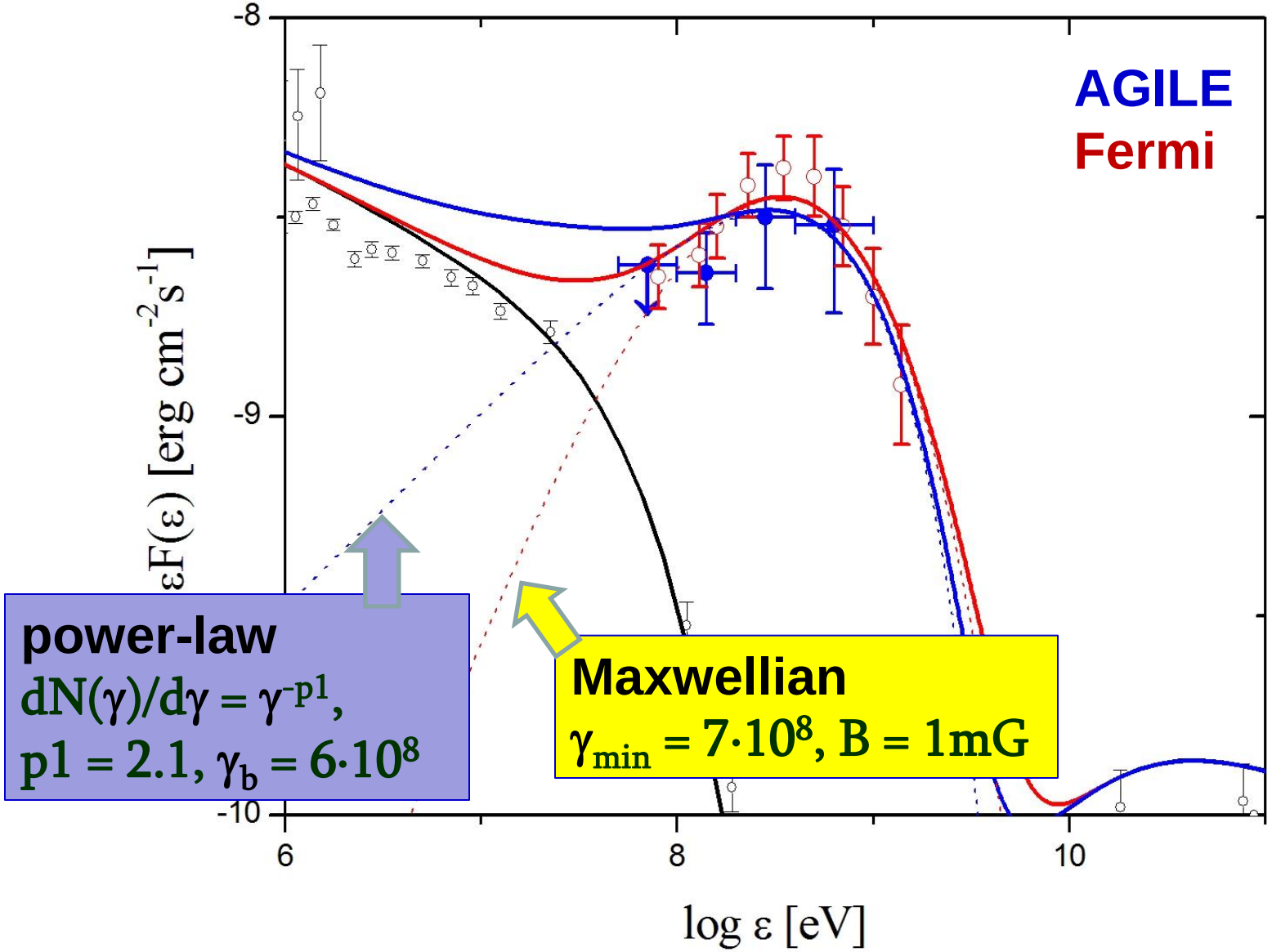
(Striani et al, Astrophys. J. Letters, on line)

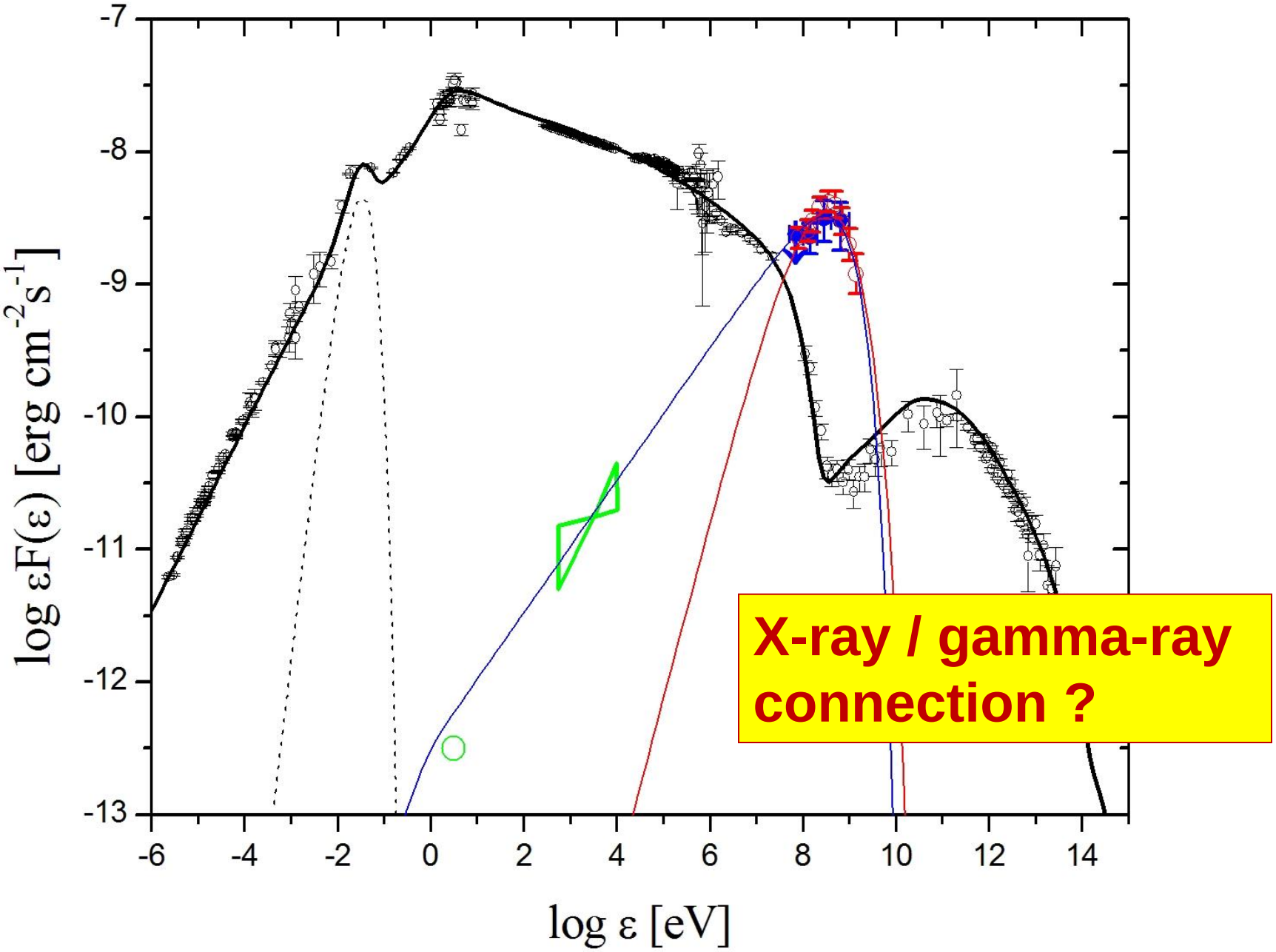


Fermi-LAT
(Boehler et al. 2012)



modelling of the April 2012 super-flare
(M.T., E. Striani, V. Vittorini, in preparation).



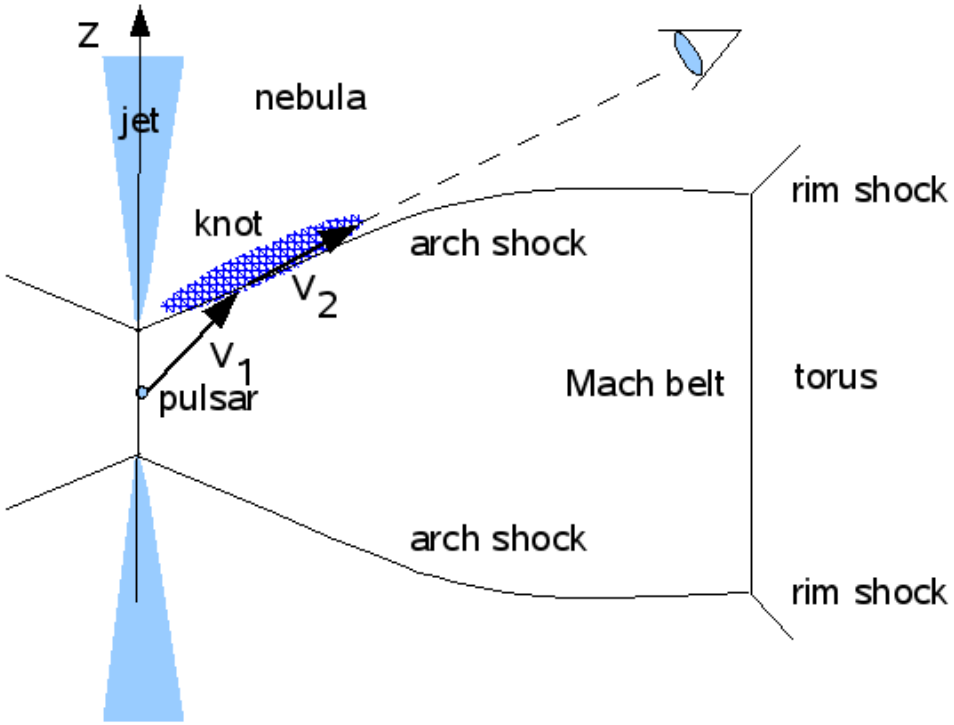

log εF(ε) [erg cm^{-2}s^{-1}]
log ε [eV]
-7
-8
-9
-10
-11
-12
-13
-6
-4
-2
0
2
4
6
8
10
12
14
X-ray / gamma-ray connection ?

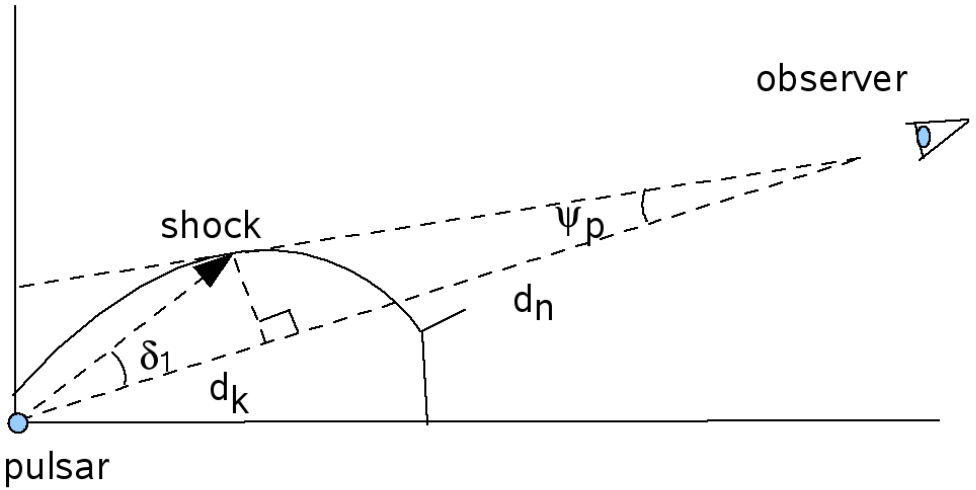
already several models, many ideas…

- Tavani et al., Abdo et al. (2011)
- Bednarek & Idec (2011)
- Komissarov & Lyutikov, MNRAS, 414, 2011 (2011)
- Vittorini et al., Striani et al. (2011)
- Lyutikov, Balsara, Matthews (2011)
- Blandford, Buehler, Funk (2011)
- Bykov, Pavlov, Artemyev, Uvanov (2011)
- Cerutti, Uzdensky, Begelman (2012)
- Arons (2012)
- …..

Komissarov, Lyutikov 2011

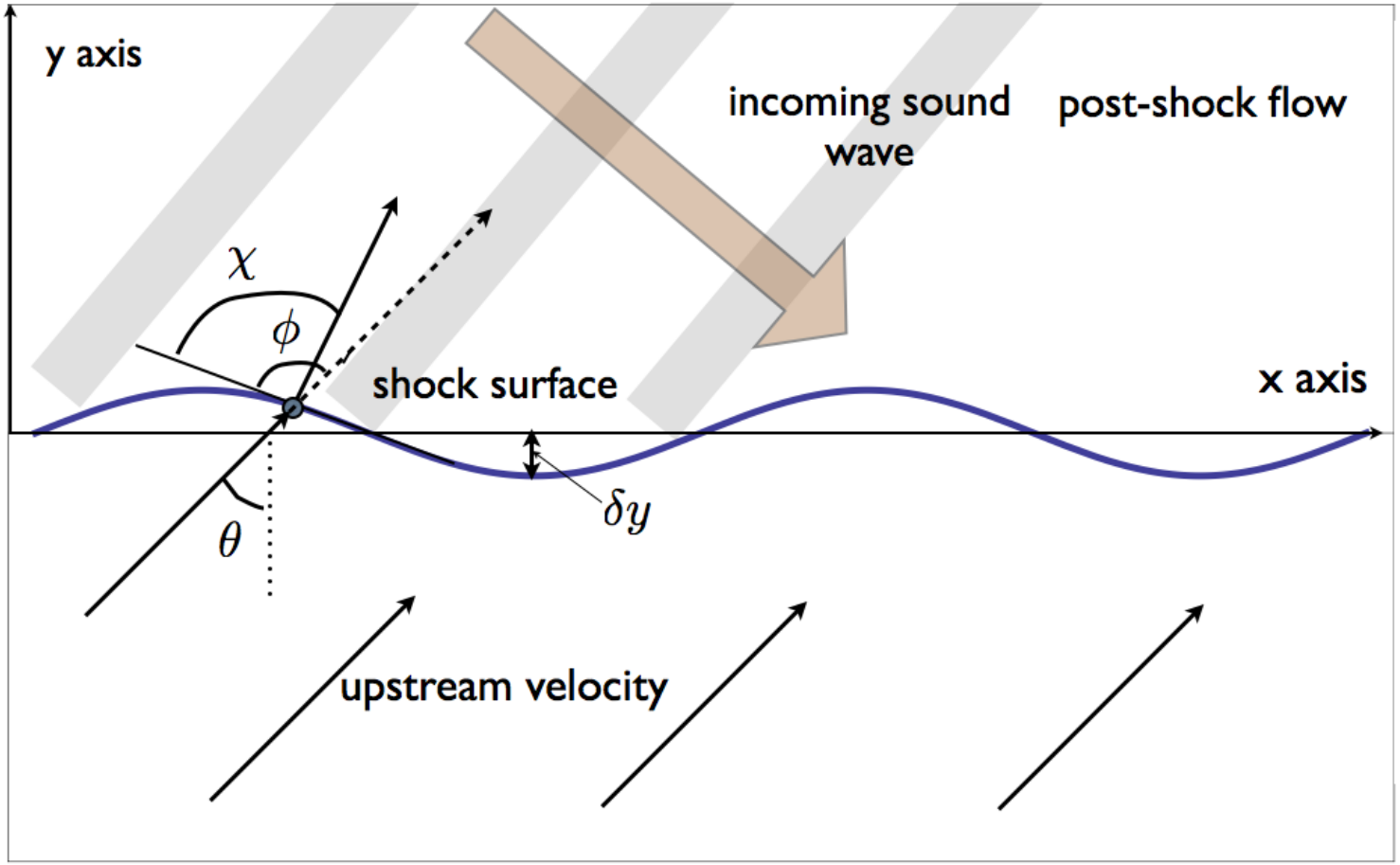
Knot-1 region



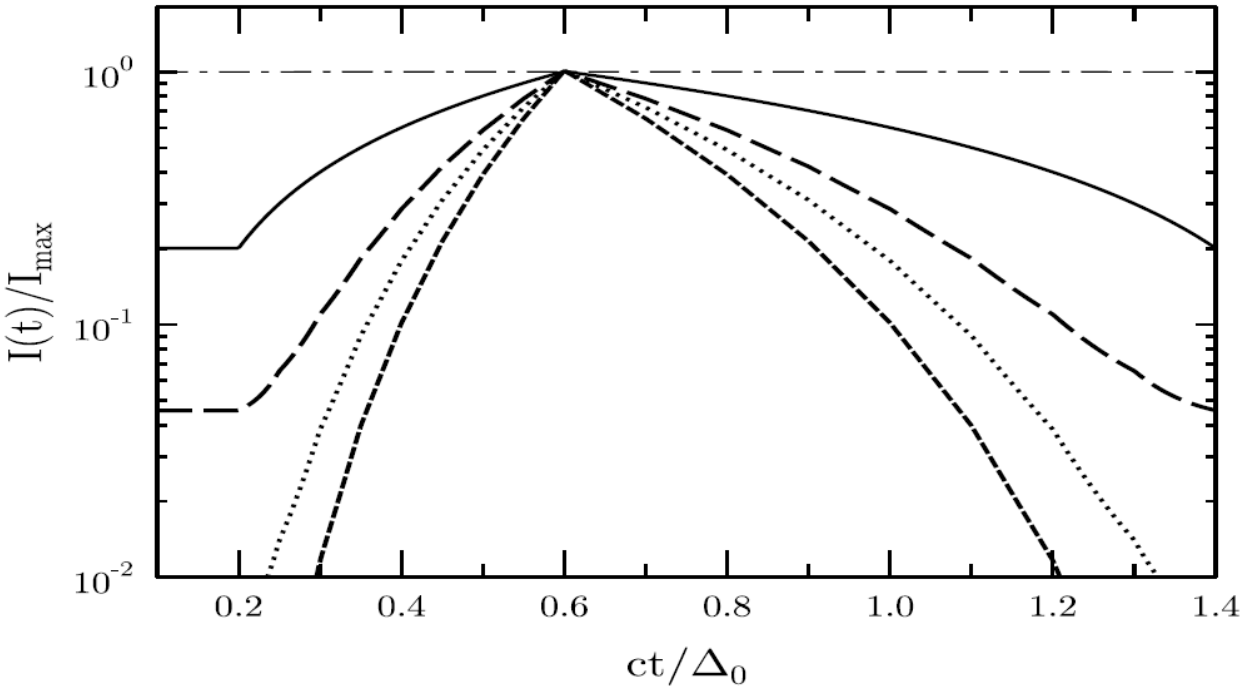


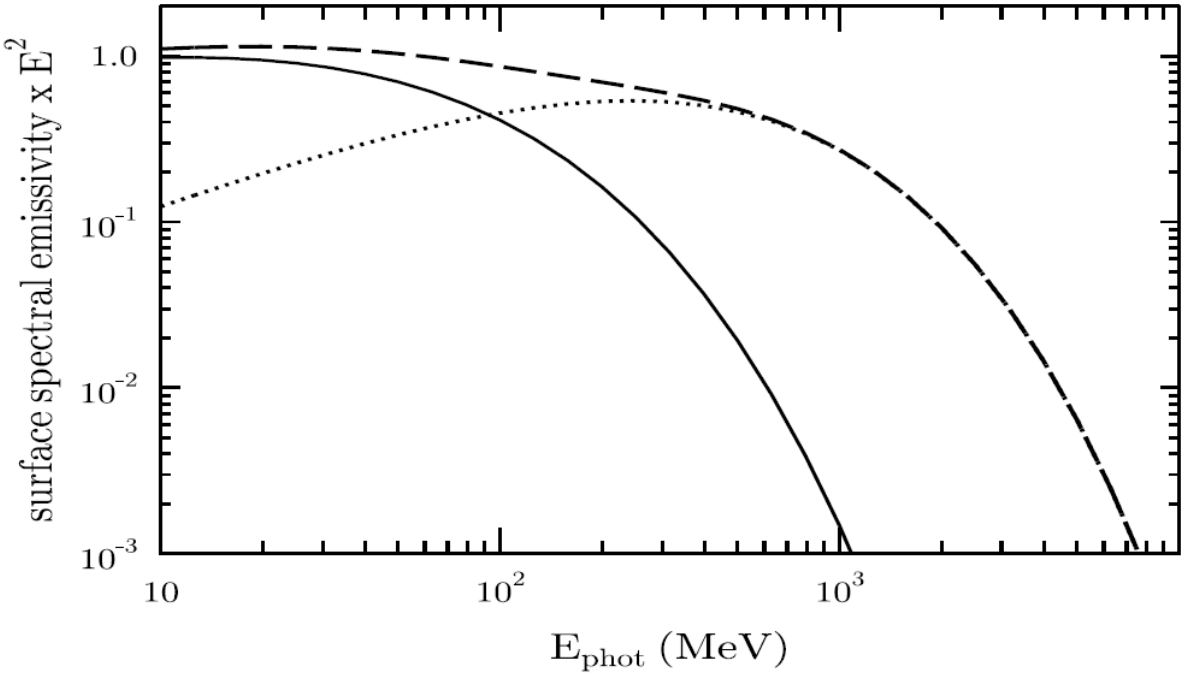
Corrugated shock

Lyutikov 2011



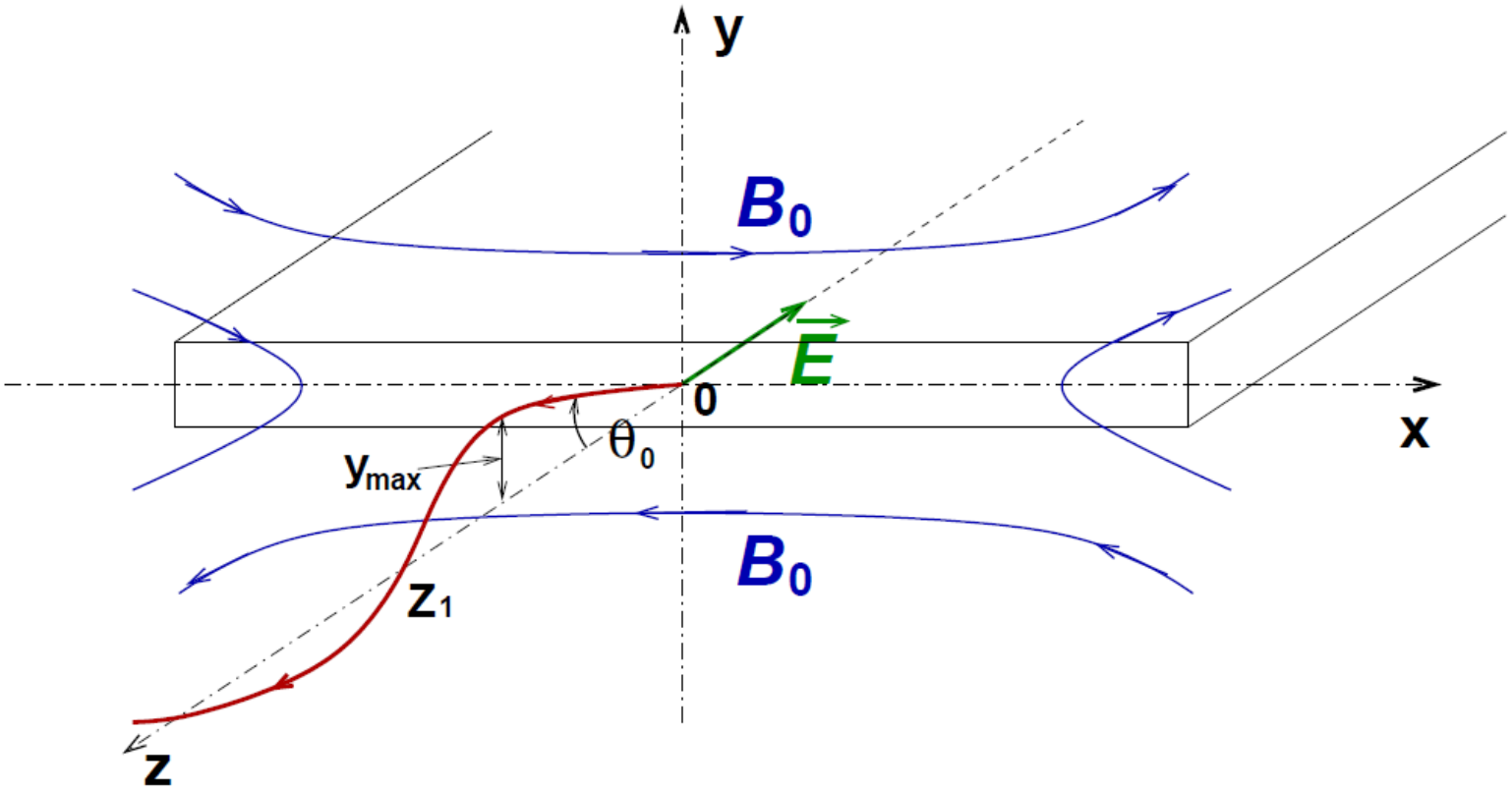
Bykov 2012


10^0
10^{-1}
10^{-2}
$I(t)/I_{max}$
0.2
0.4
0.6
0.8
1.0
1.2
1.4
ct/Δ_0


1.0
10^{-1}
10^{-2}
10^{-3}
surface spectral emissivity x E^2
10
10^2
10^3
E_{phot} (MeV)

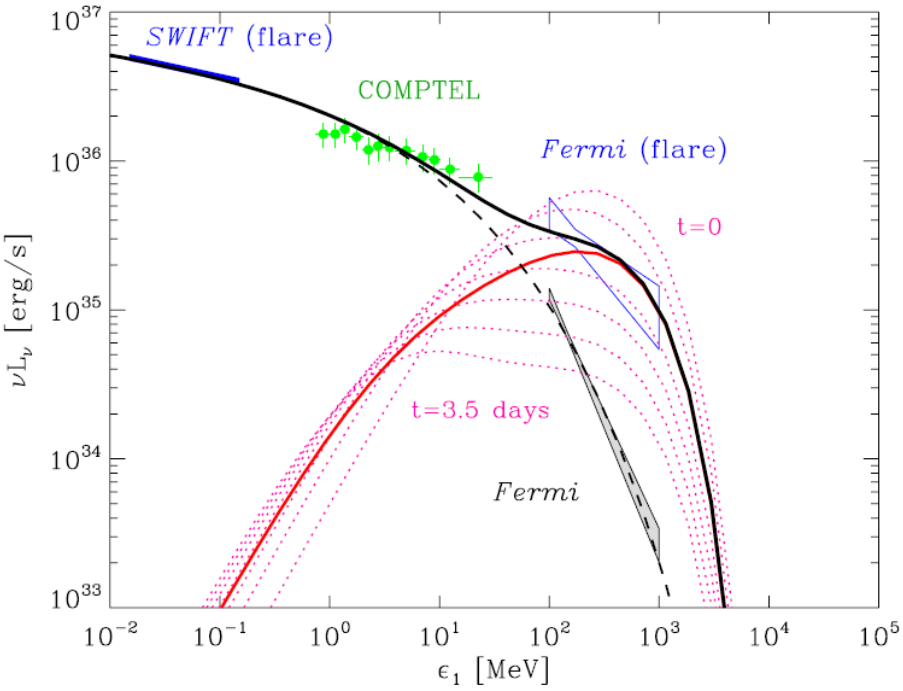
Magnetic field reconnection in current sheets…

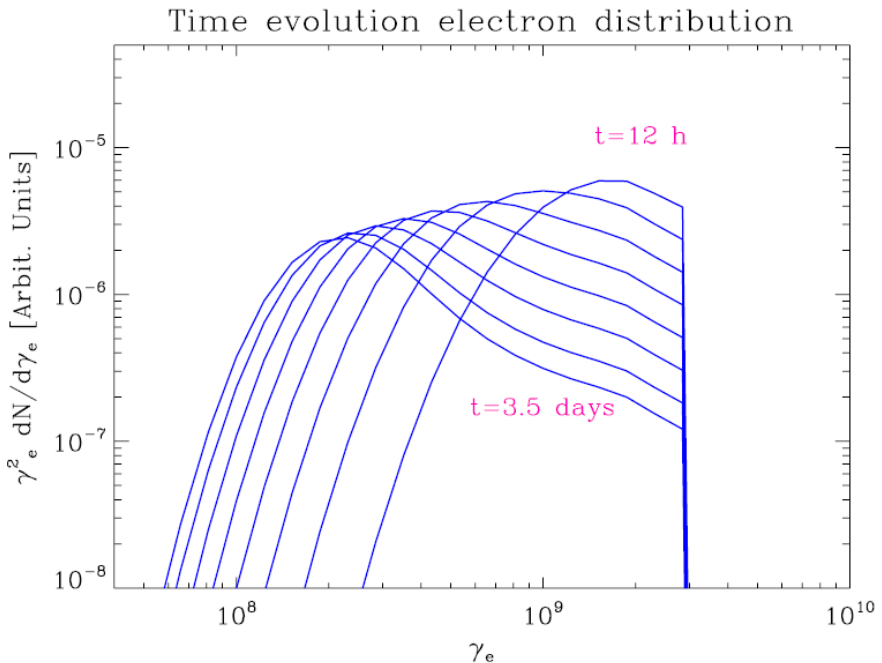
Cerutti, Uzdensky, Begelman, ApJ 2012



Cerutti, Uzdensky, Begelman, ApJ 2012

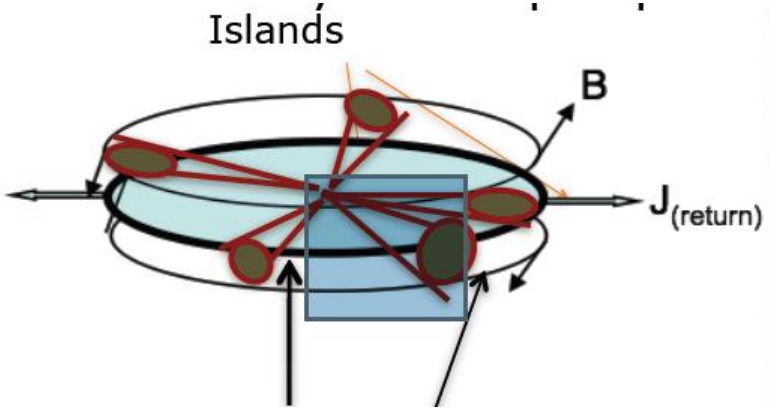
Top panel: spectral modeling of the Crab Nebula gamma-ray emission during the 2010 September flare.
The black dashed line represents the “quiescent” spectrum and the red solid line is the synchrotron spectrum of the particles accelerated in the reconnection layer averaged over the duration of the flare (four days).
The magenta dotted lines show the evolution of the flaring spectrum sampled every 12 hr (top line $t = 0$ and bottom line $t = 3.5$ days, see the text for more details about the modeling).
The distance of the Crab Nebula is fixed at 2 kpc. The flaring inverse Compton emission is negligible. Bottom panel: time evolution of the radiating electron distribution sampled every 12 hr injected in the Crab Nebula during the 2010 September gamma-ray flare.

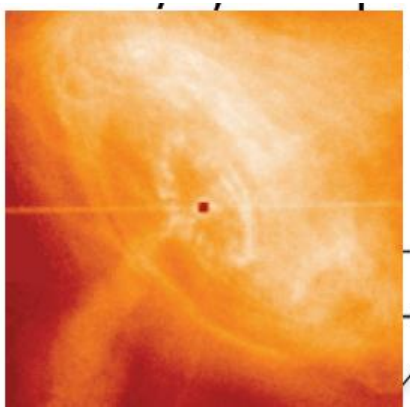


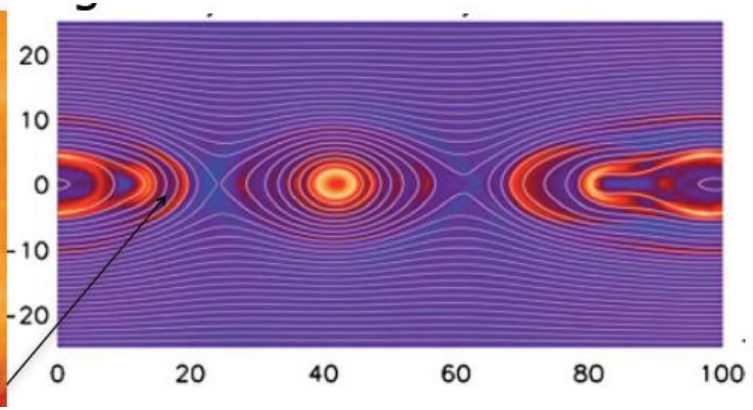


Magnetic field reconnection in current sheets…

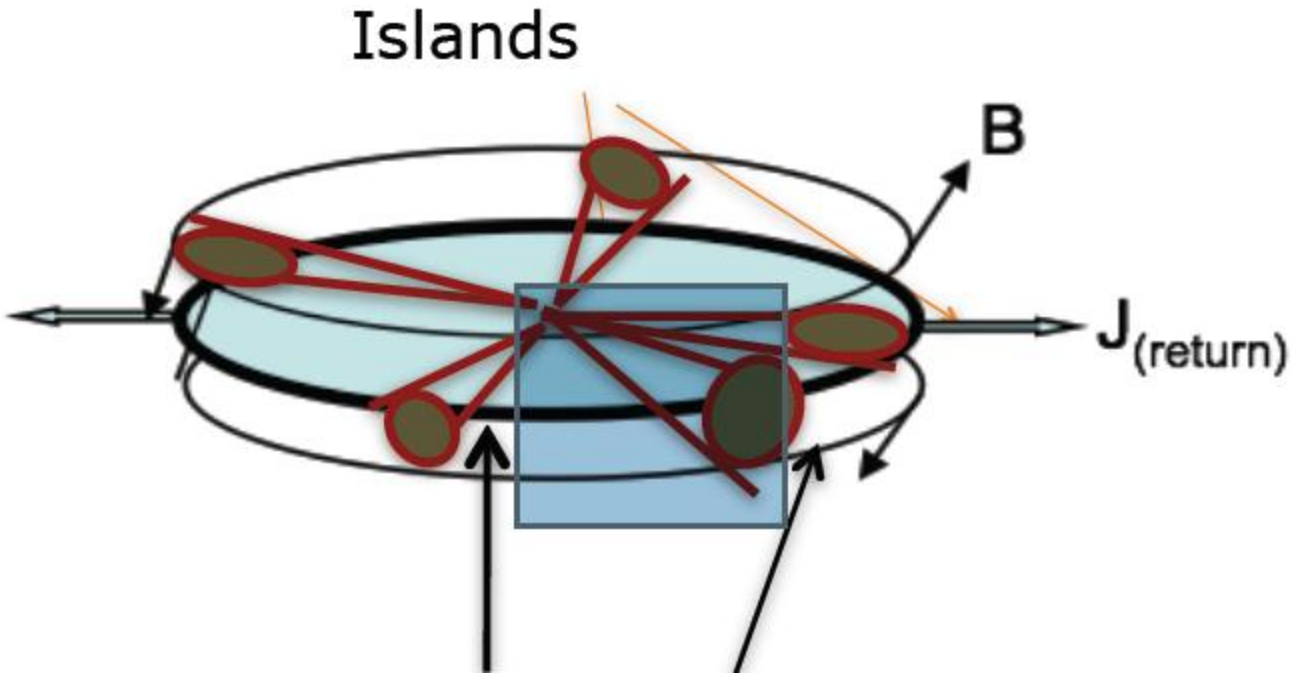
J. Arons (2012)





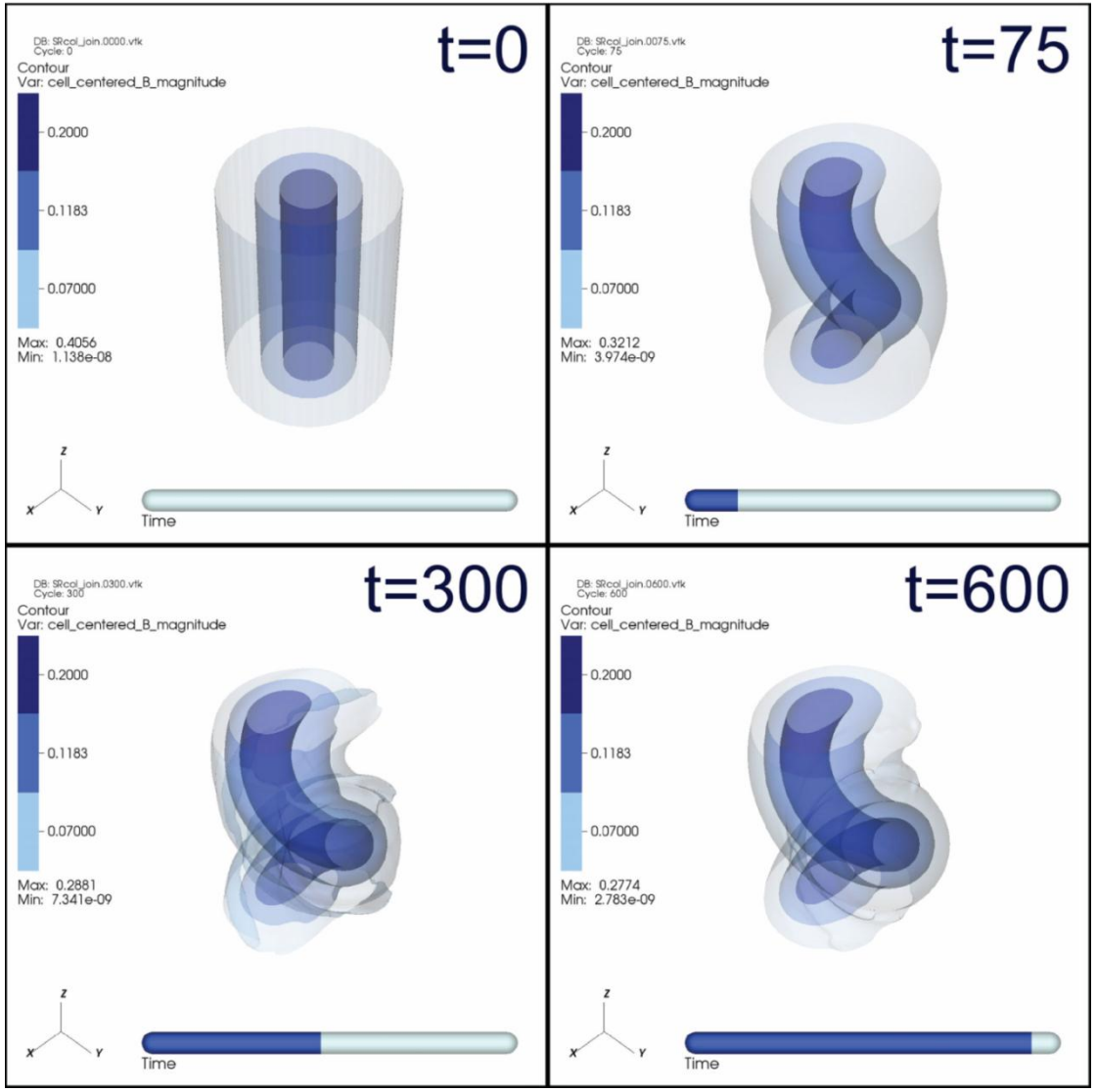


Arons



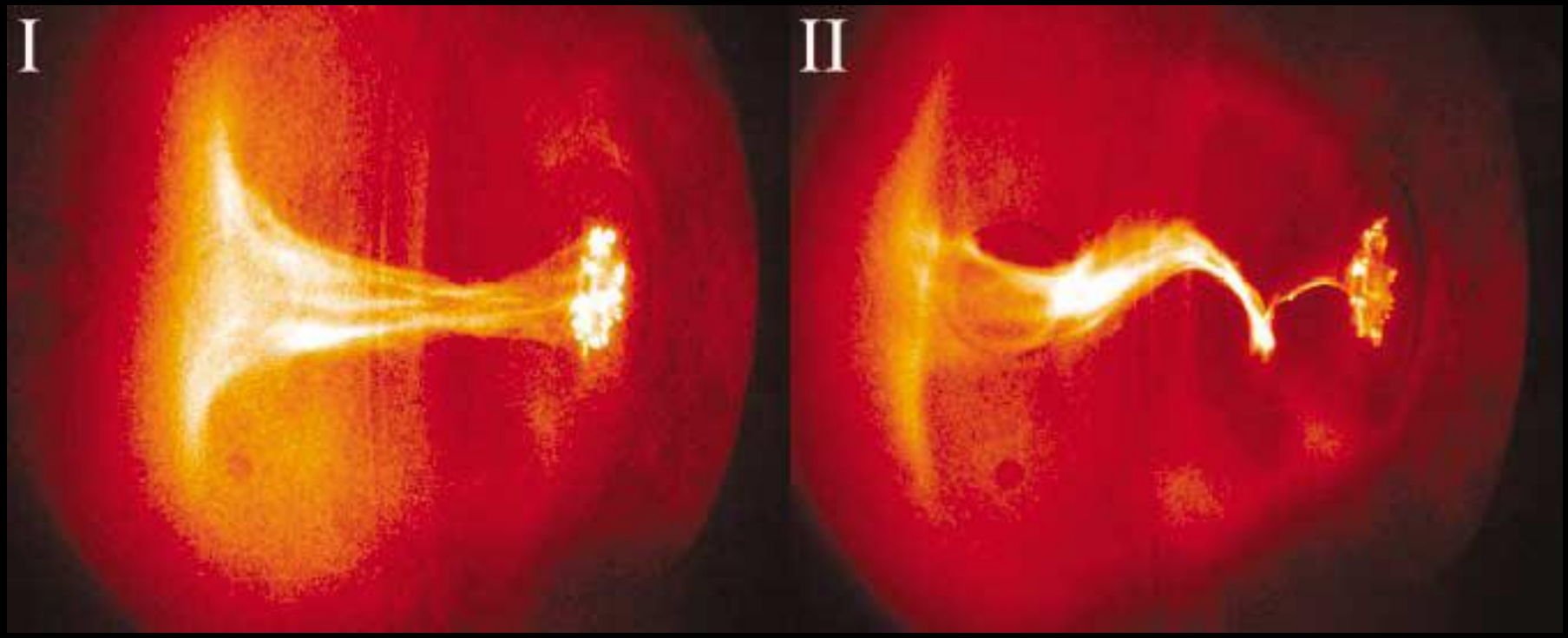
Kink (m=1) instability

O'Neill, Beckwith, Begelman 2012



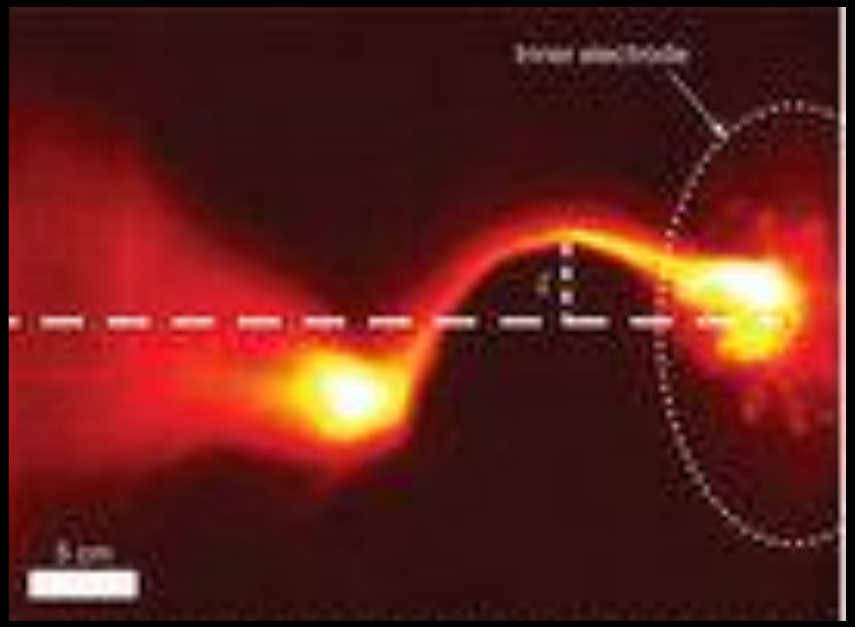
Plasma kink instability

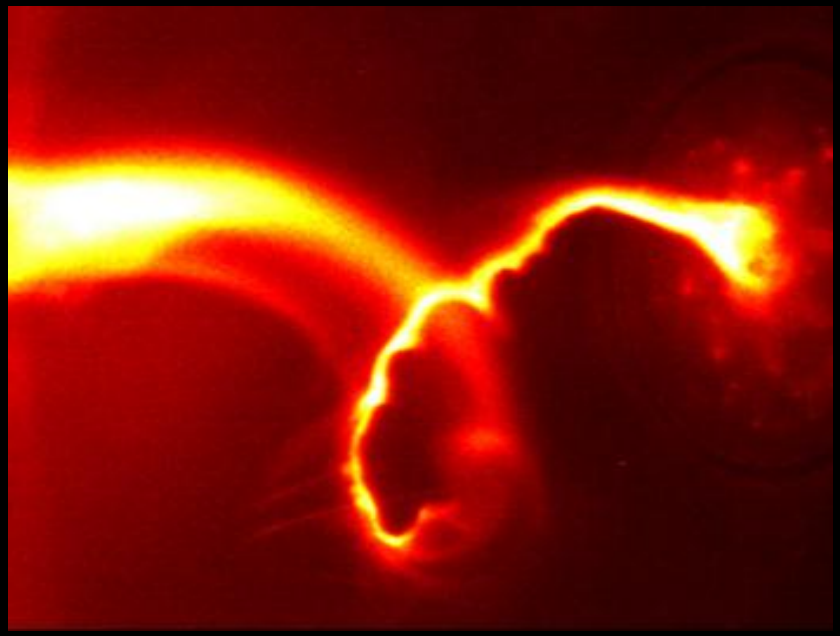
S.C.Hsu, P.M. Bellan, Phys. Rev. Letters, 90, 215001-2 (2003)



Plasma kink instability

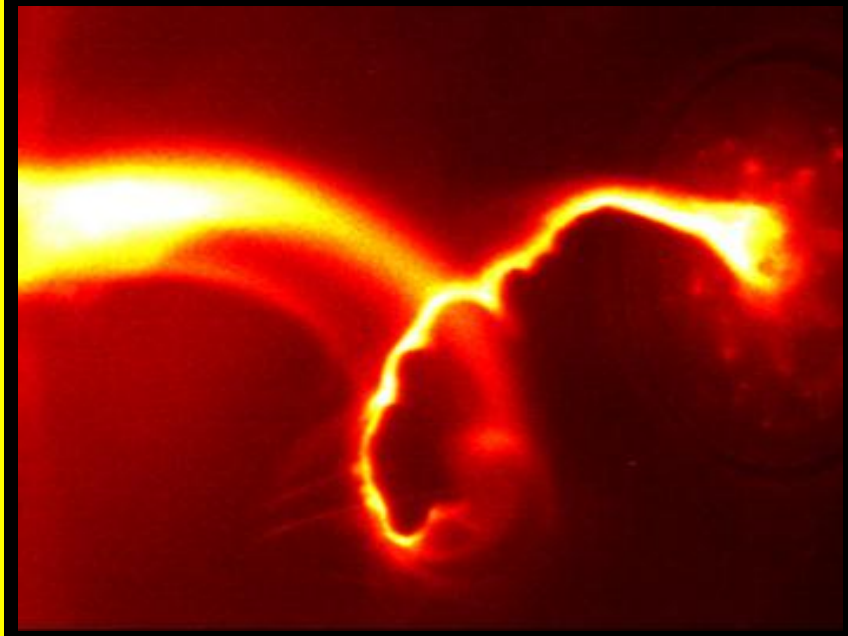
A.L. Moser, P. Bellan, Nature , 482, 379 (2012)





Plasma kink instability

1. magnetic field reconnection in “islands” related to kink instabilities
2. reconnection detected in tomakaks as “sawthooth oscillations” (e.g., P. Buratti & collaborators at the FTU in Frascati)
3. **particle acceleration in kink-driven reconnection events**
4. a framework for the Crab gamma-ray flares originating in the “anvil” region.



Wilson-Hodge et al. 2010

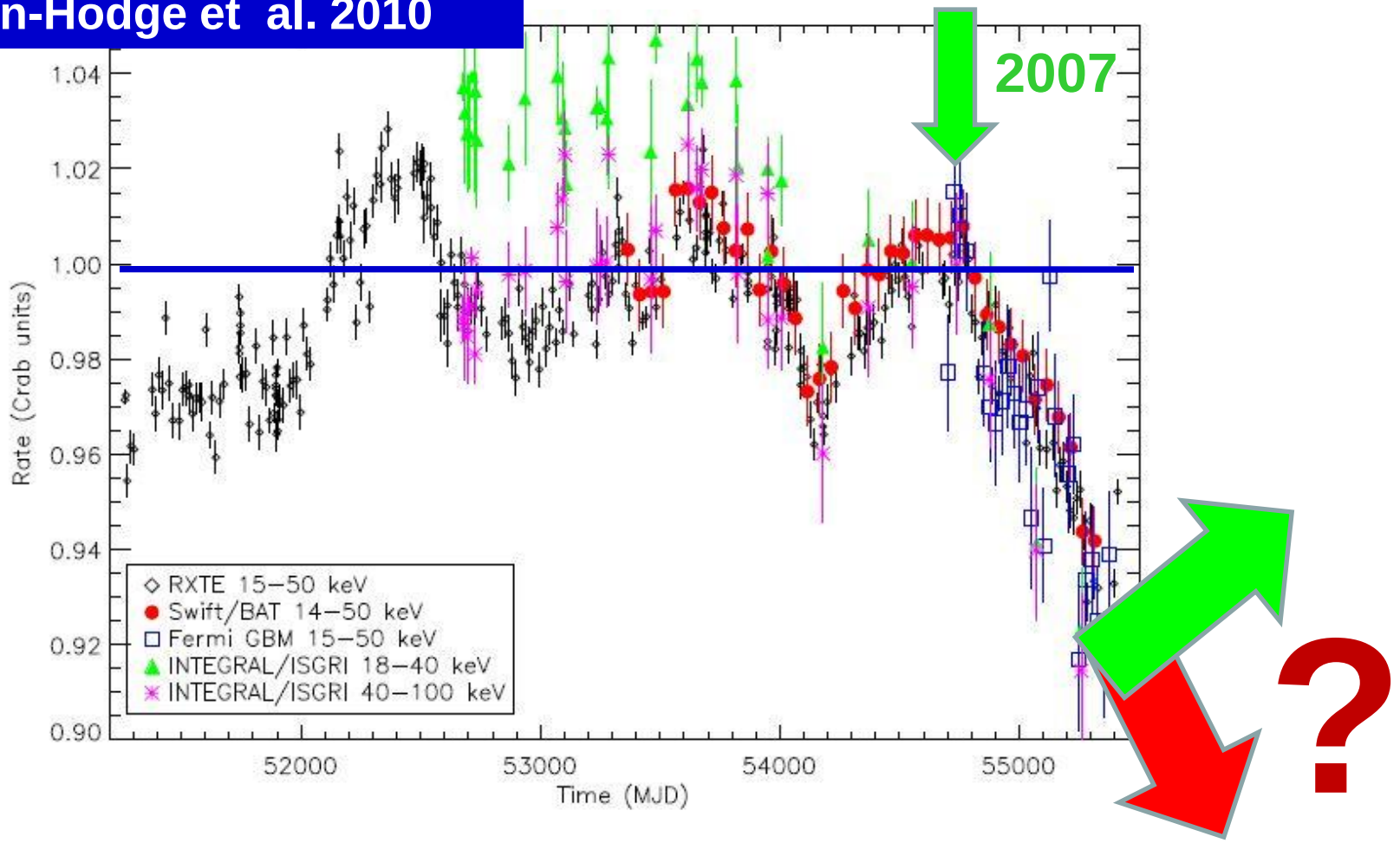


Fig. 5.— Composite Crab light curve for *RXTE*/PCA (15-50 keV - black diamonds), *Swift*/BAT (14-50 keV - red filled circles), *Fermi*/GBM (15-50 keV - open blue squares), *INTEGRAL*/ISGRI (18-40 and 40-100 keV - green triangles and purple asterisks, respectively.) Each data set has been normalized to its mean rate in the time interval MJD 54690-54790. All error bars include only statistical errors.

- **a (mostly theoretical) meeting entitled *The Flaring Crab: Surprises and Impacts*.**

- **Frascati (Villa Mondragone), July 4-5-6 2012**

- **Crazy Crab !**
- **An everlasting wonderful laboratory**
- **more surprises to come…**