Crazy Crab

M.Tavani

IACHEC meeting,

11 Apr. 2011

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

Crab Nebula modelling

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

commonly adopted mechanisms

- **diffusive shock acceleration (DSA), first-order Fermi acc.**

- **shock-drift acceleration (SDA)**

results depends on particle content (ions, e+/e-), B-configuration, sigma-parameter, etc.

- Synchrotron cooling timescale

- τ_s = (30 yrs) $B_{-4}^{-3/2}$ $(E_{ph}$ /1 keV$)^{-1/2}$

- τ_s = (0.1 yrs) $B_{-4}^{-3/2}$ $(E_{ph}$ /100 MeV$)^{-1/2}$

"standard" paradigm for nebular emission (de Jager, Harding et al. 1996)

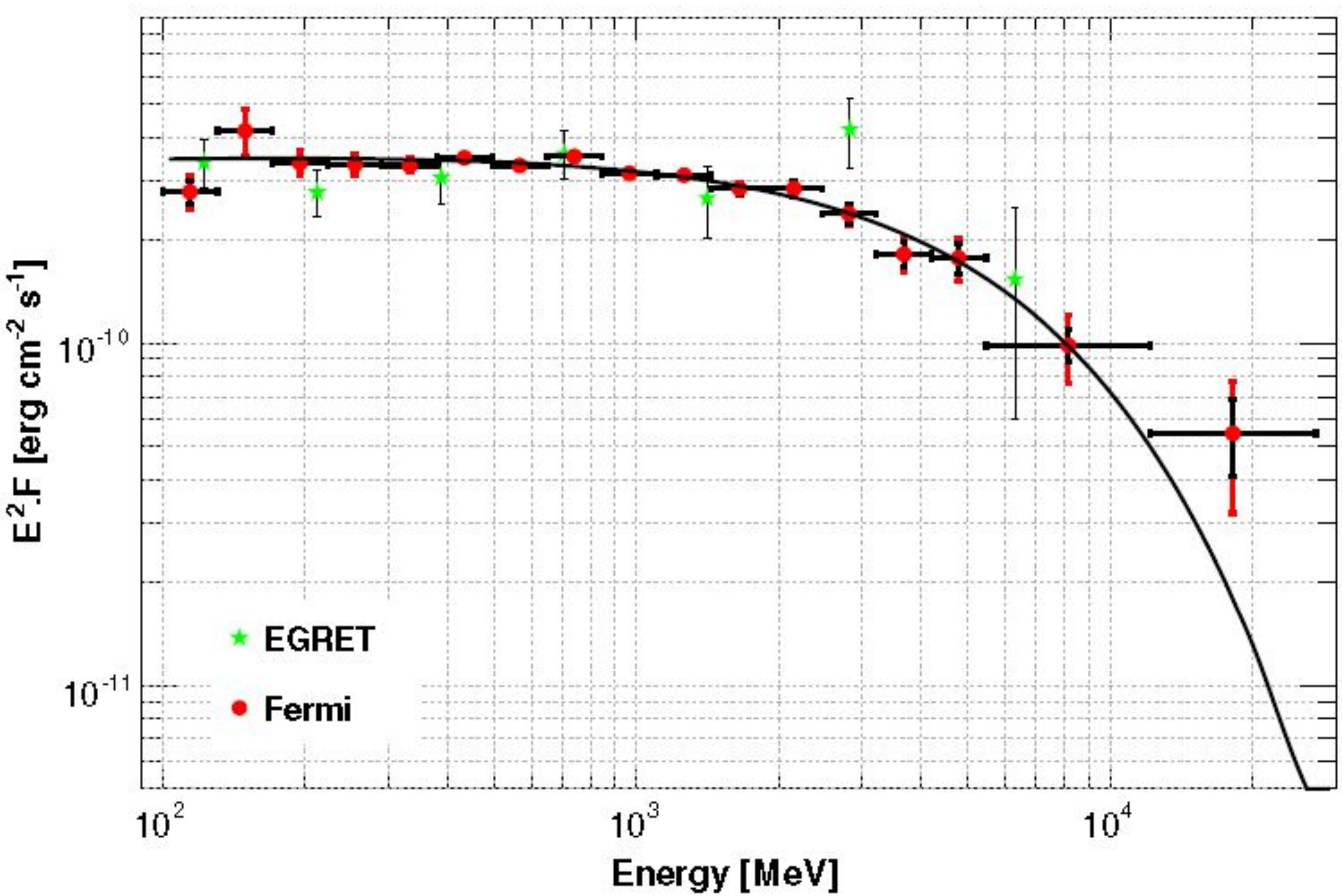
- max. emitted photon synchrotron energy is independent of the magnetic field B (for a Doppler factor δ): **synchrotron burn-off**

- $\mathbf{E_{max} = \hbar\, \omega_B\, \gamma_m^{\,2} \sim (50\ \mathrm{MeV})\ (\delta\, \alpha' / \sin\theta)}$

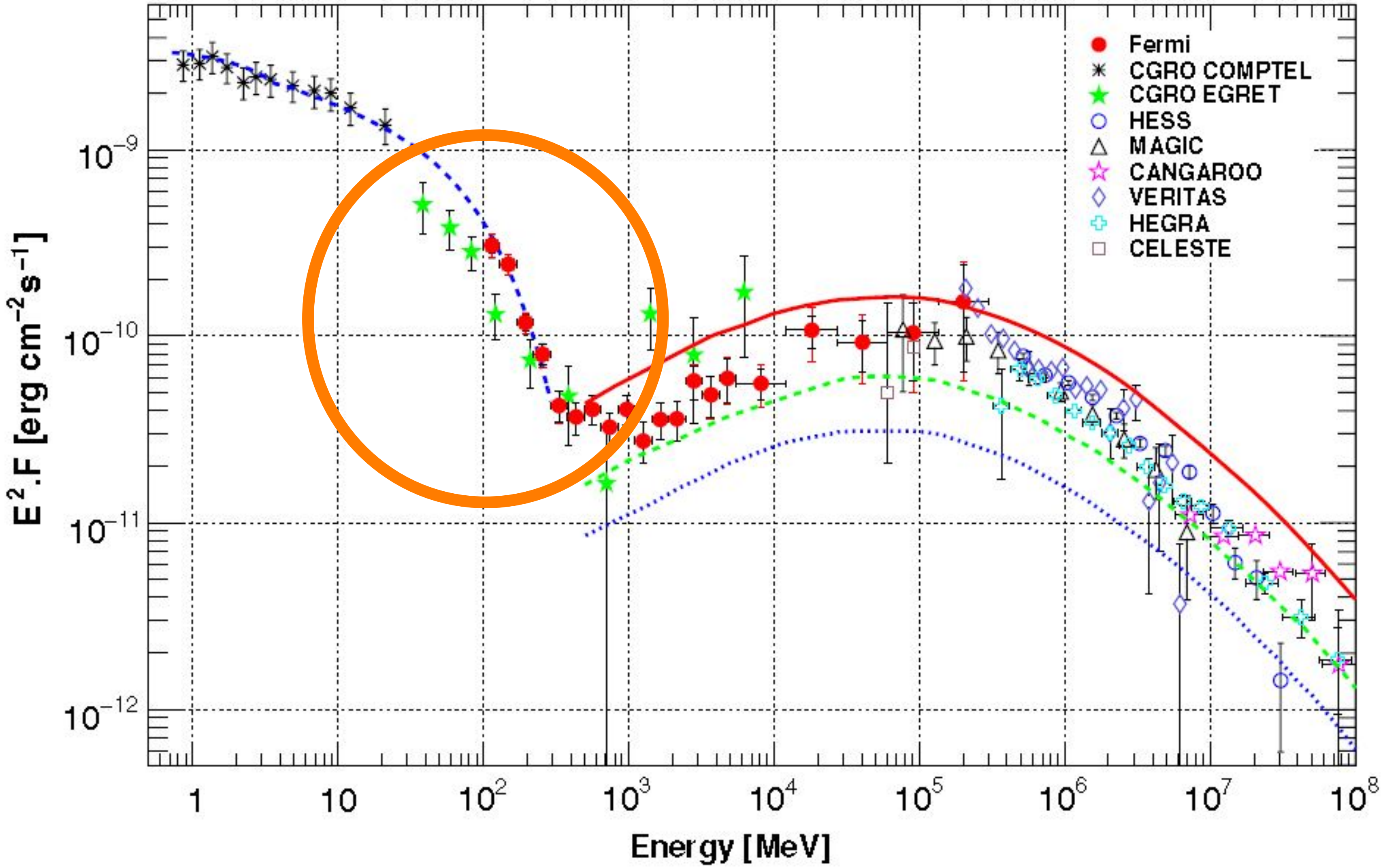
$$\varepsilon_{\gamma,max} \simeq \frac{9}{4} \left(\frac{E}{B}\right) \frac{m_e c^2}{\alpha} \left(\frac{\delta\,\alpha'}{\langle \sin(\theta') \rangle}\right)$$

$$\simeq (150\,\mathrm{MeV}) \left(\frac{E}{B}\right) \left(\frac{\delta\,\alpha'}{\langle \sin(\theta') \rangle}\right)$$

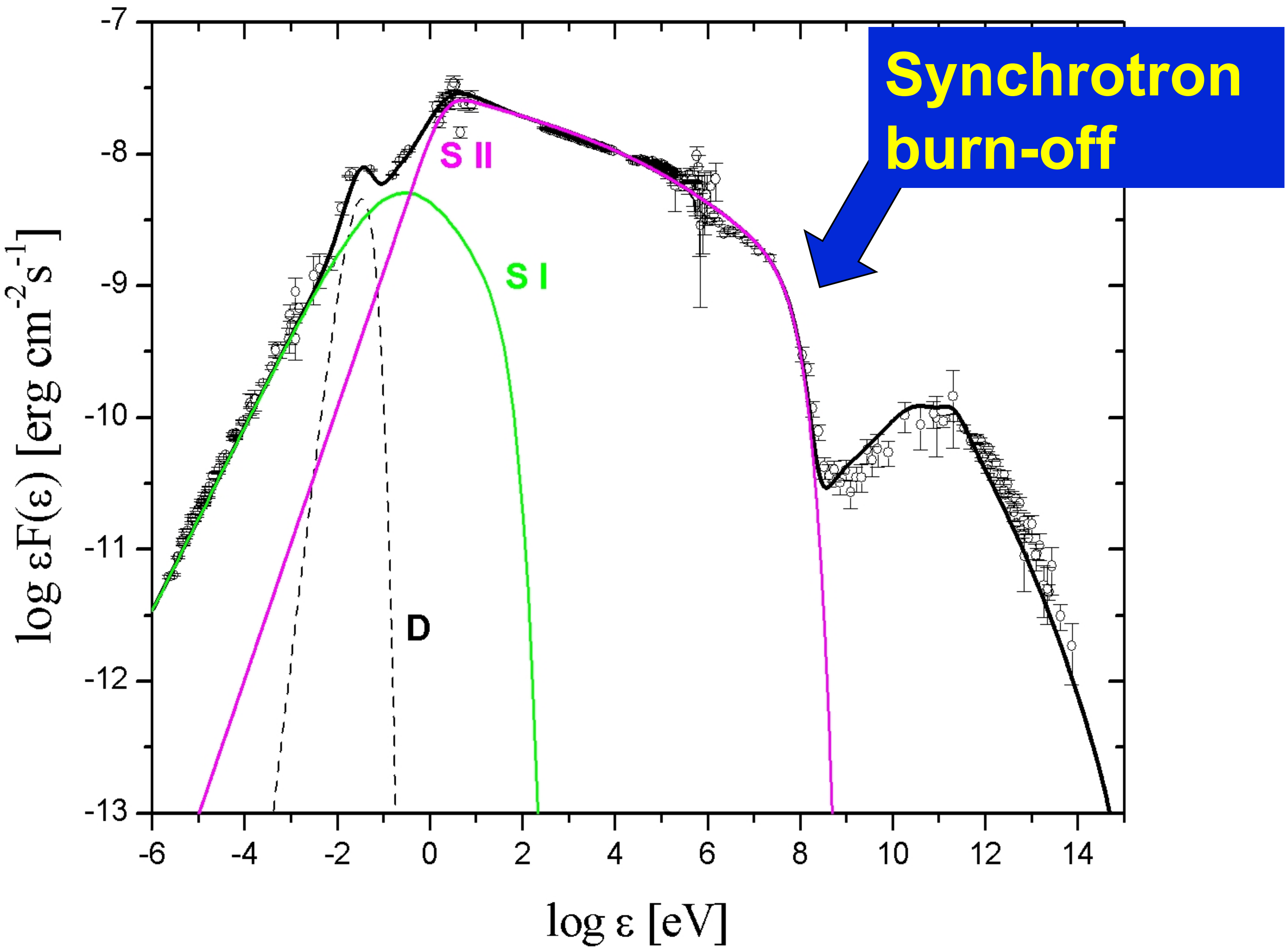
pulsed gamma-ray spectrum (Abdo et al 2010)



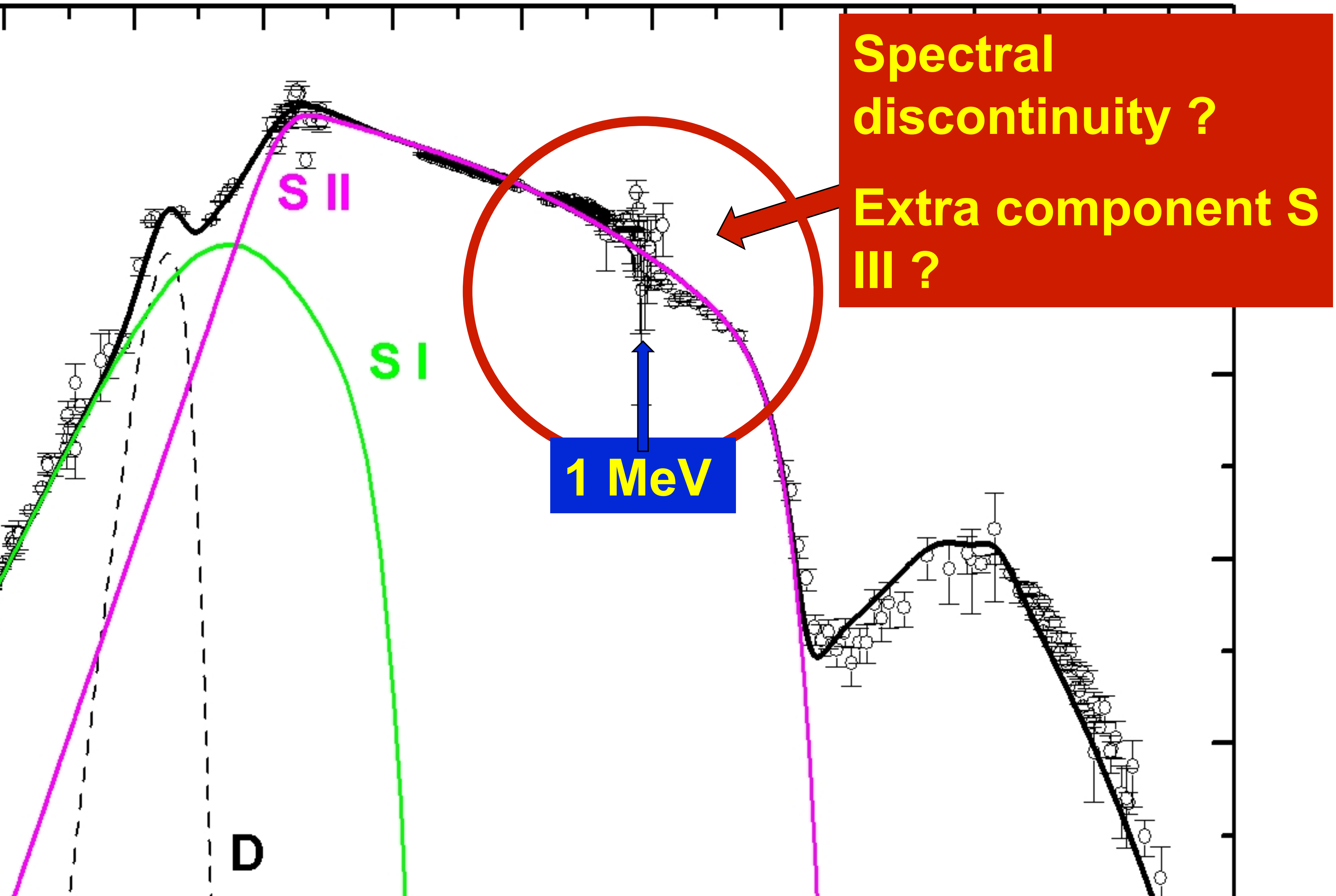
unpulsed (nebular) gamma-ray spectrum



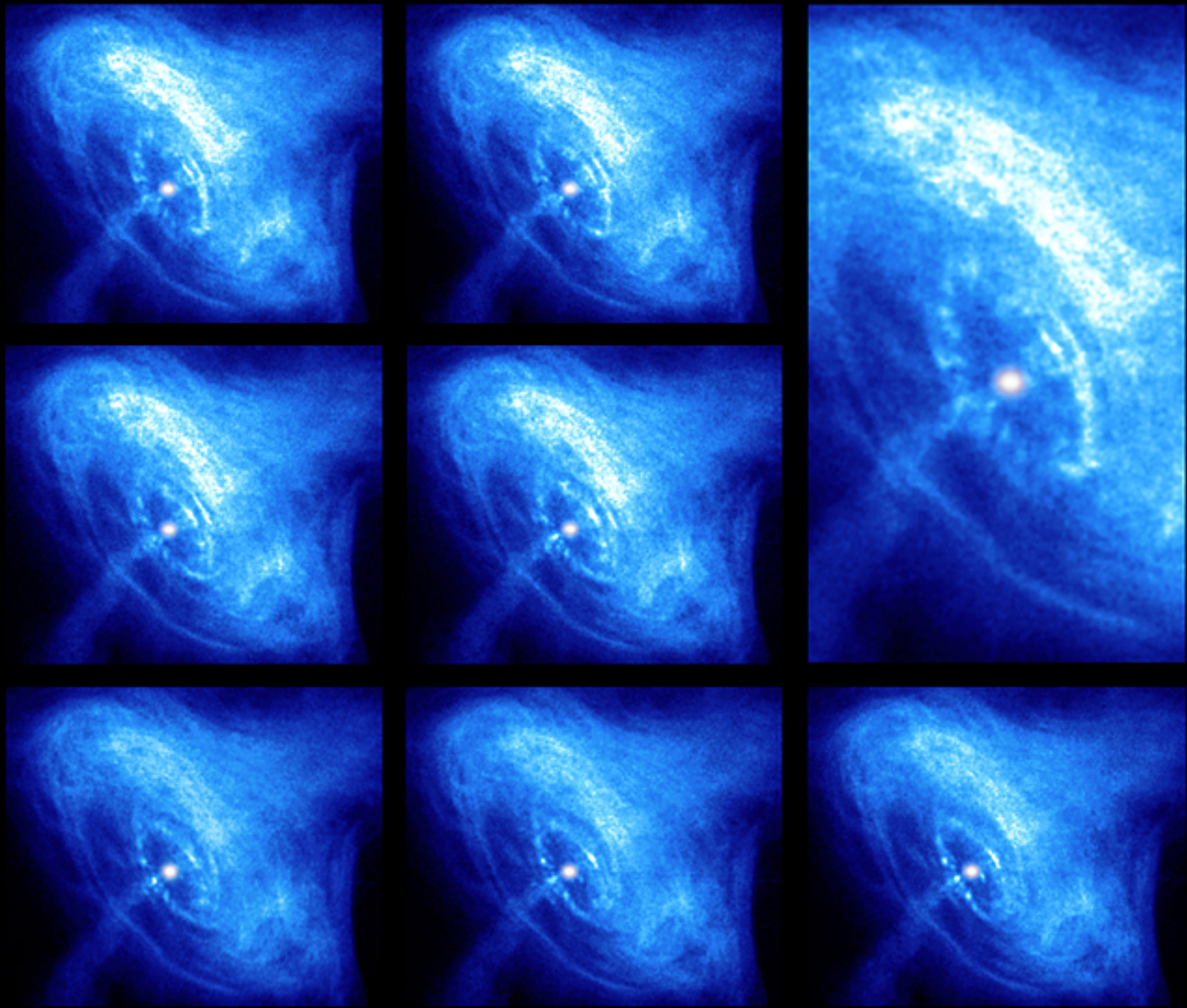
Crab Nebula spectrum



Crab Nebula spectrum



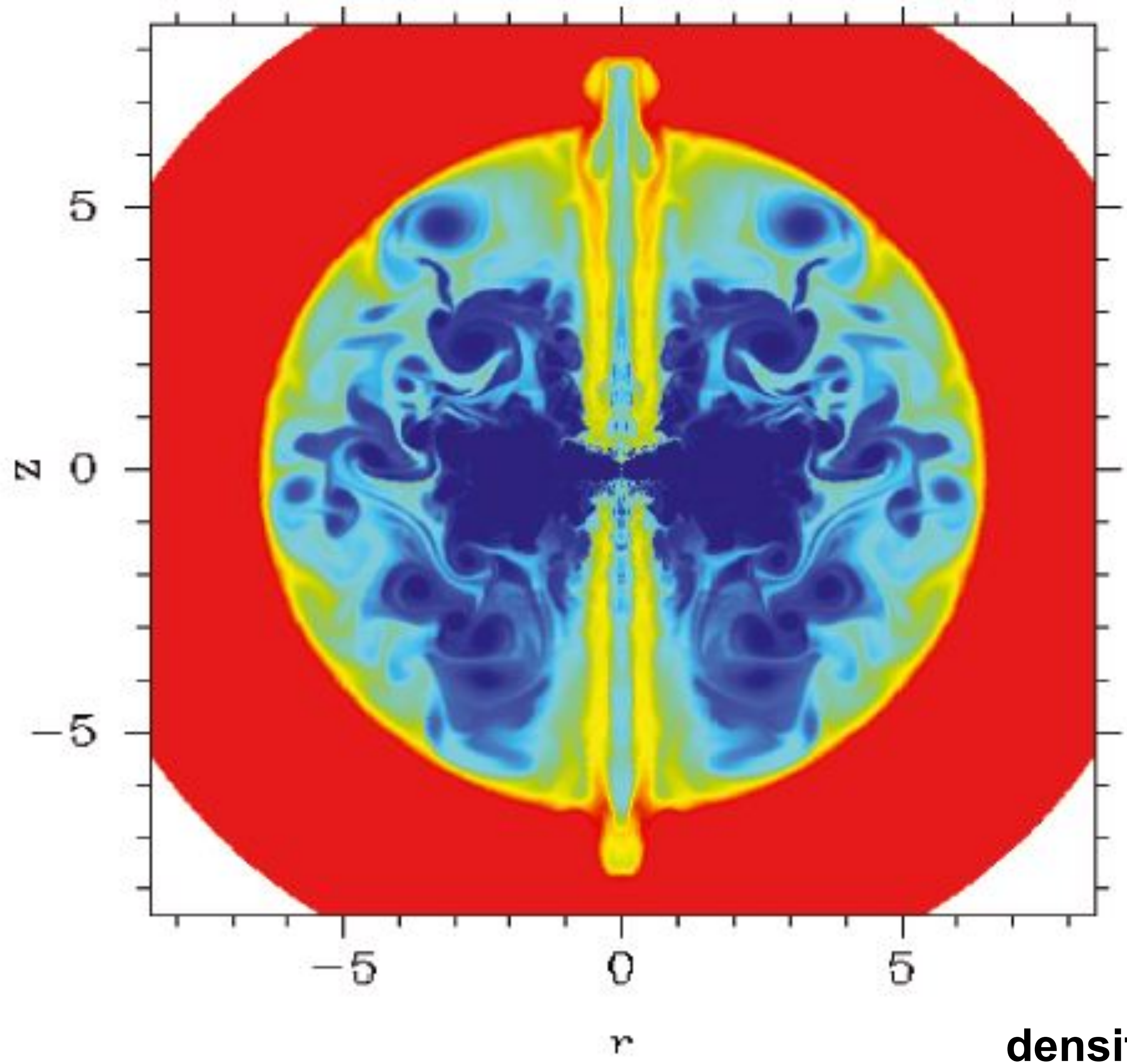

10 arcsec
HST/ACS F550M
2010-10-02
E



MHD models

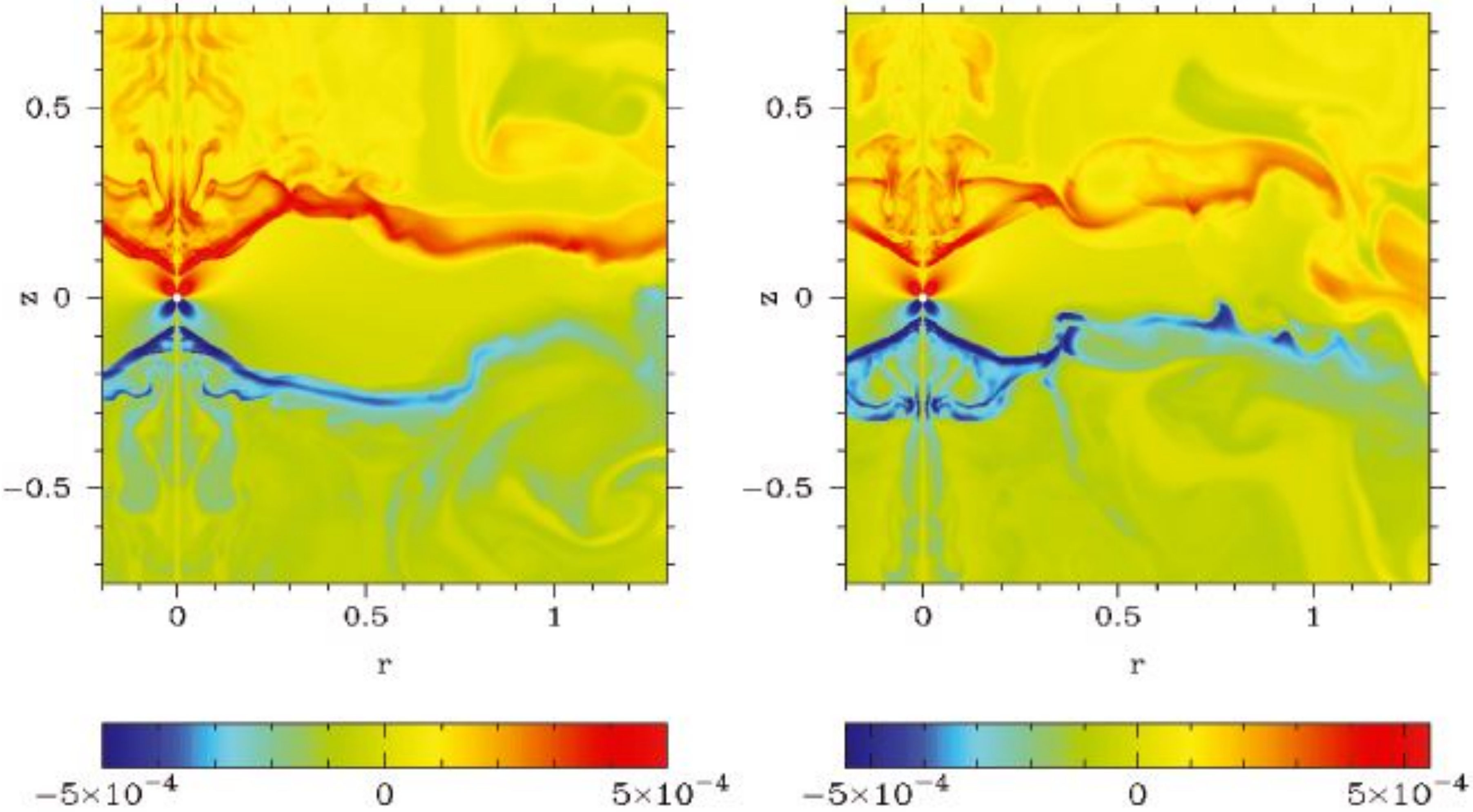
- Arons et al., 1992- 2010
- Komissarov, Lyubarsky, 2003, 2004
- Spitkowsky & Arons, 2004, ApJ, 603, 669
- Del Zanna, Volpi, Amato, Bucciantini, 2006, 2008
- Camus et al., 2009, MNRAS; 400, 1241

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



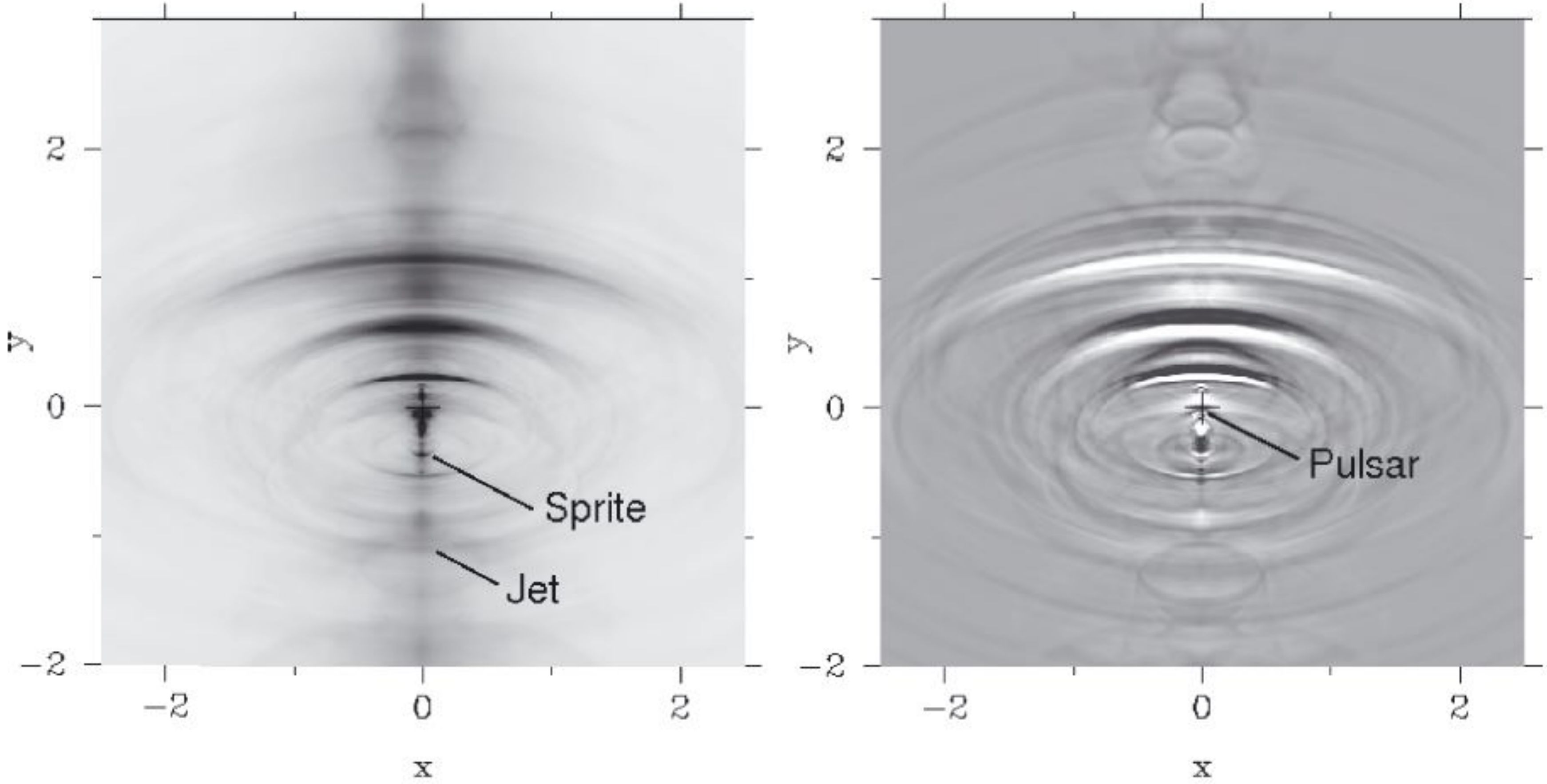
density profile

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



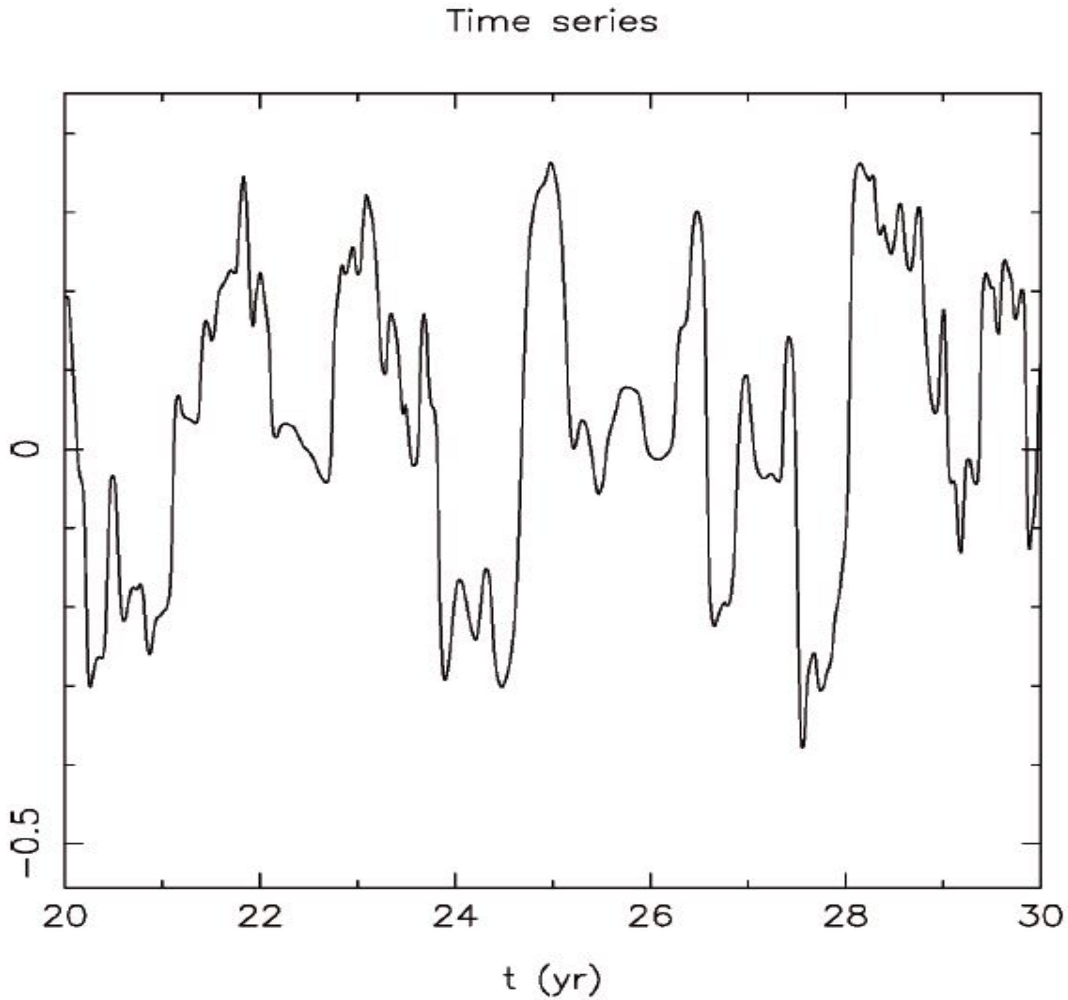
Magnetic field profile at different times

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



simulated synchrotron emissivity

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

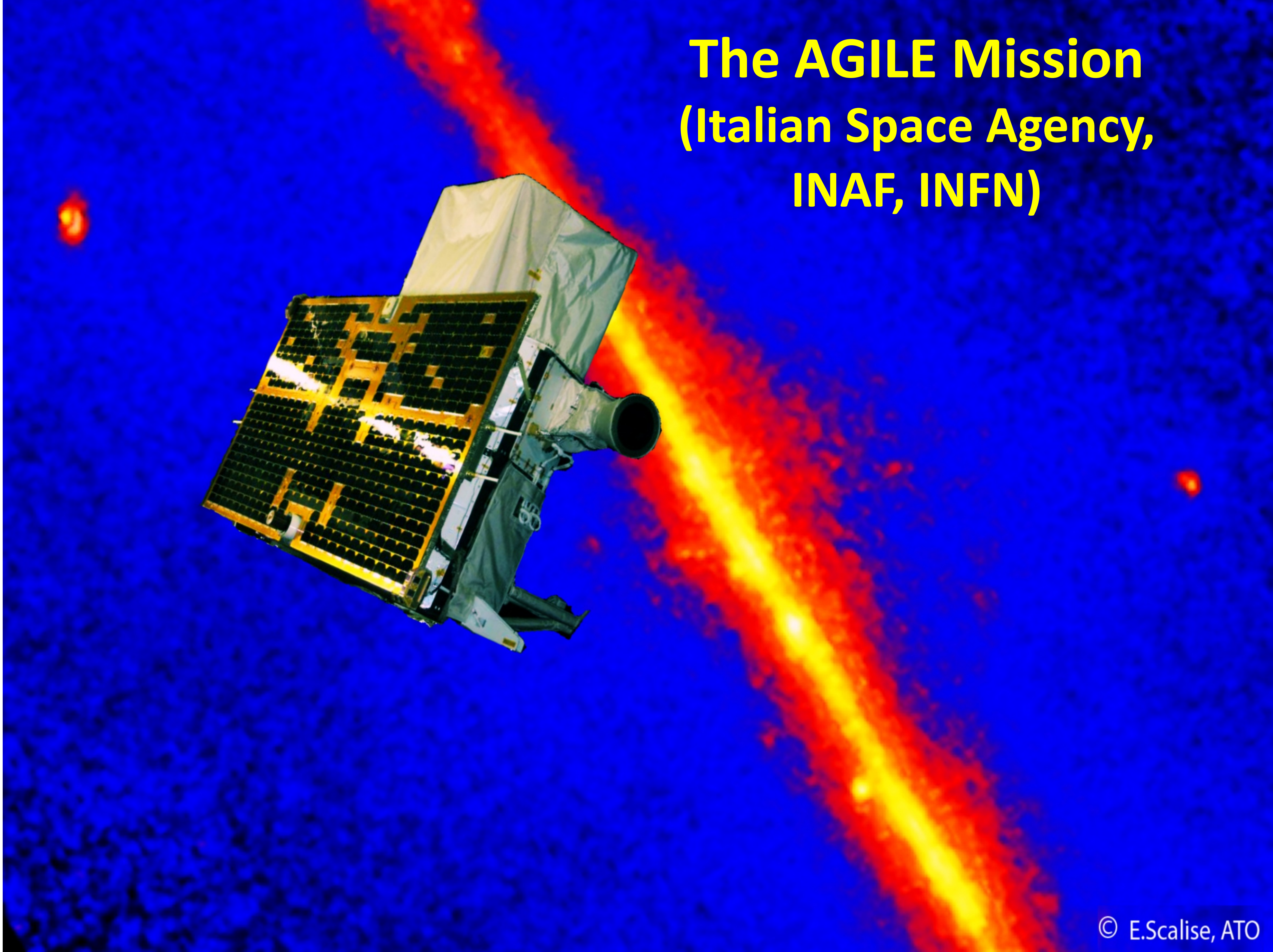


local magnetic field energy density

AGILE DISCOVERY OF THE CRAB NEBULA VARIABILITY IN GAMMA-RAYS

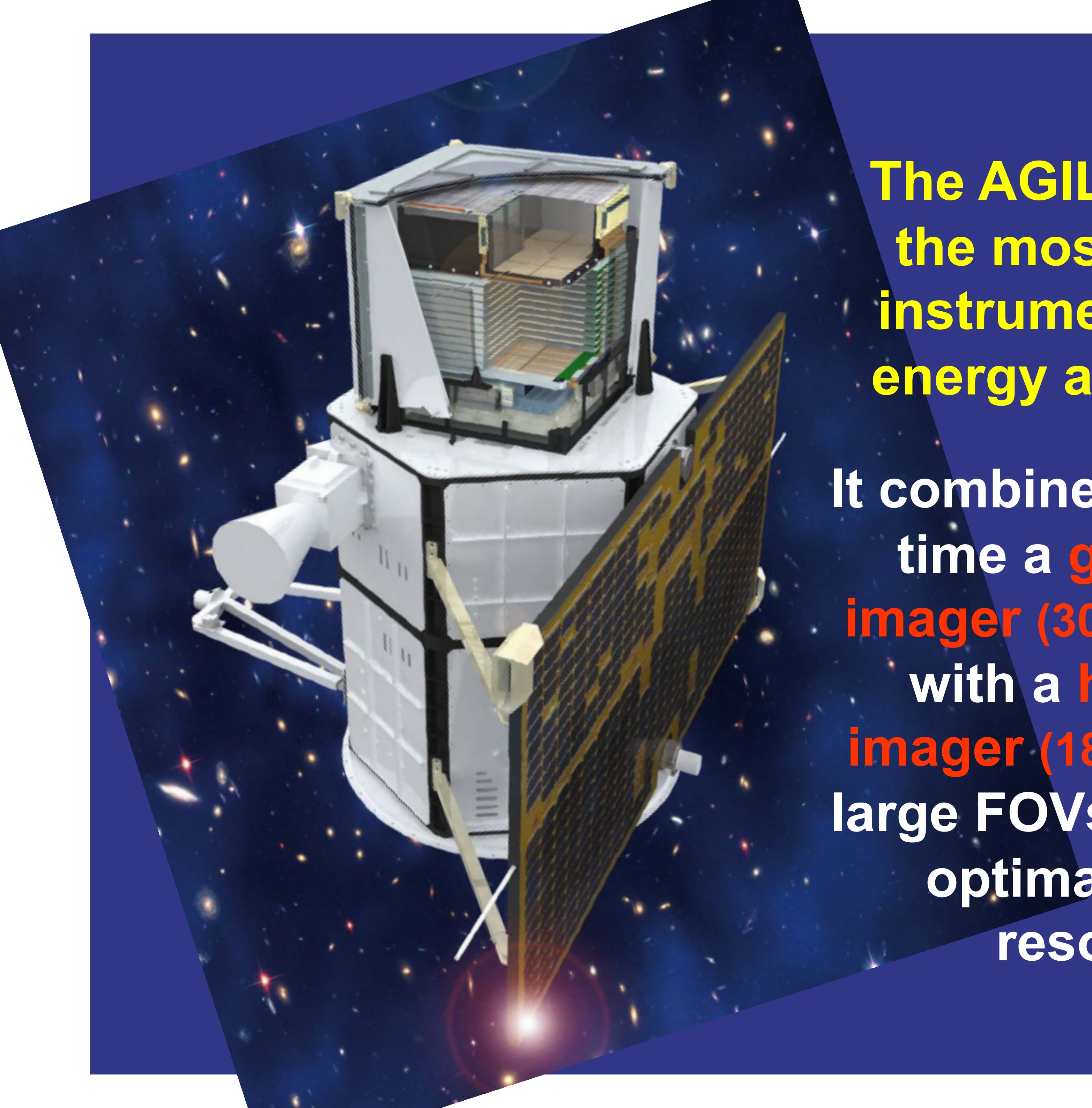
Tavani et al., Science, 331, 736 (2011)

Abdo et al., Science, 331, 739 (2011)


The AGILE Mission
(Italian Space Agency,
INAF, INFN)
© E.Scalise, ATO

Gamma-ray astrophysics missions (above 30 MeV)

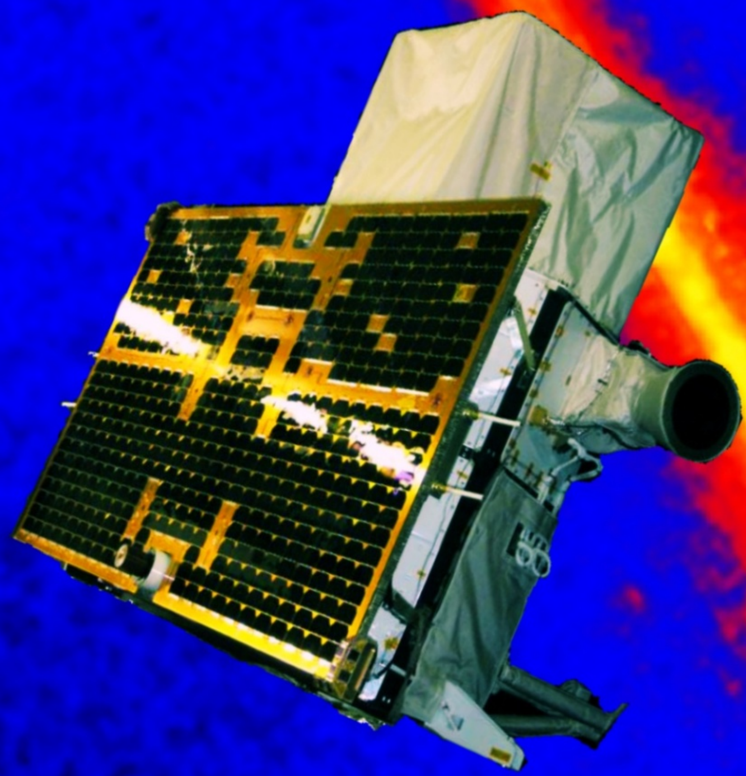
SAS-2	NASA	Nov. 1972 – July 1973
COS–B	ESA	Aug. 1975 – Apr. 1982
CGRO	NASA	Apr. 1991 – Jun. 2000
AGILE	ASI	April 23, 2007
Fermi	NASA	June 11, 2008



The AGILE Payload: the most compact instrument for high-energy astrophysics

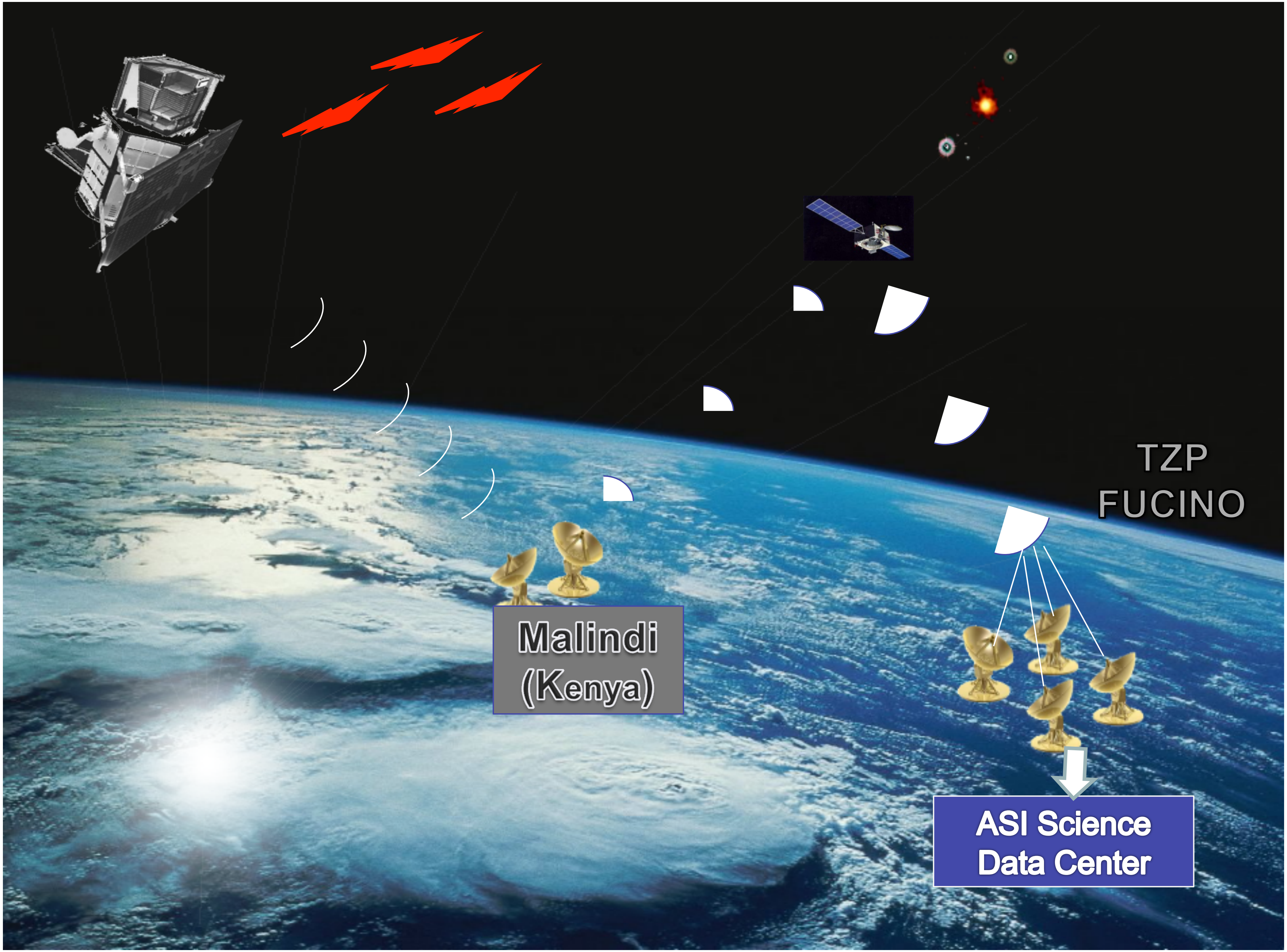
It combines for the first time a gamma-ray imager (30 MeV- 30 GeV) with a hard X-ray imager (18-60 keV) with large FOVs (1-2.5 sr) and optimal angular resolution

The AGILE Mission

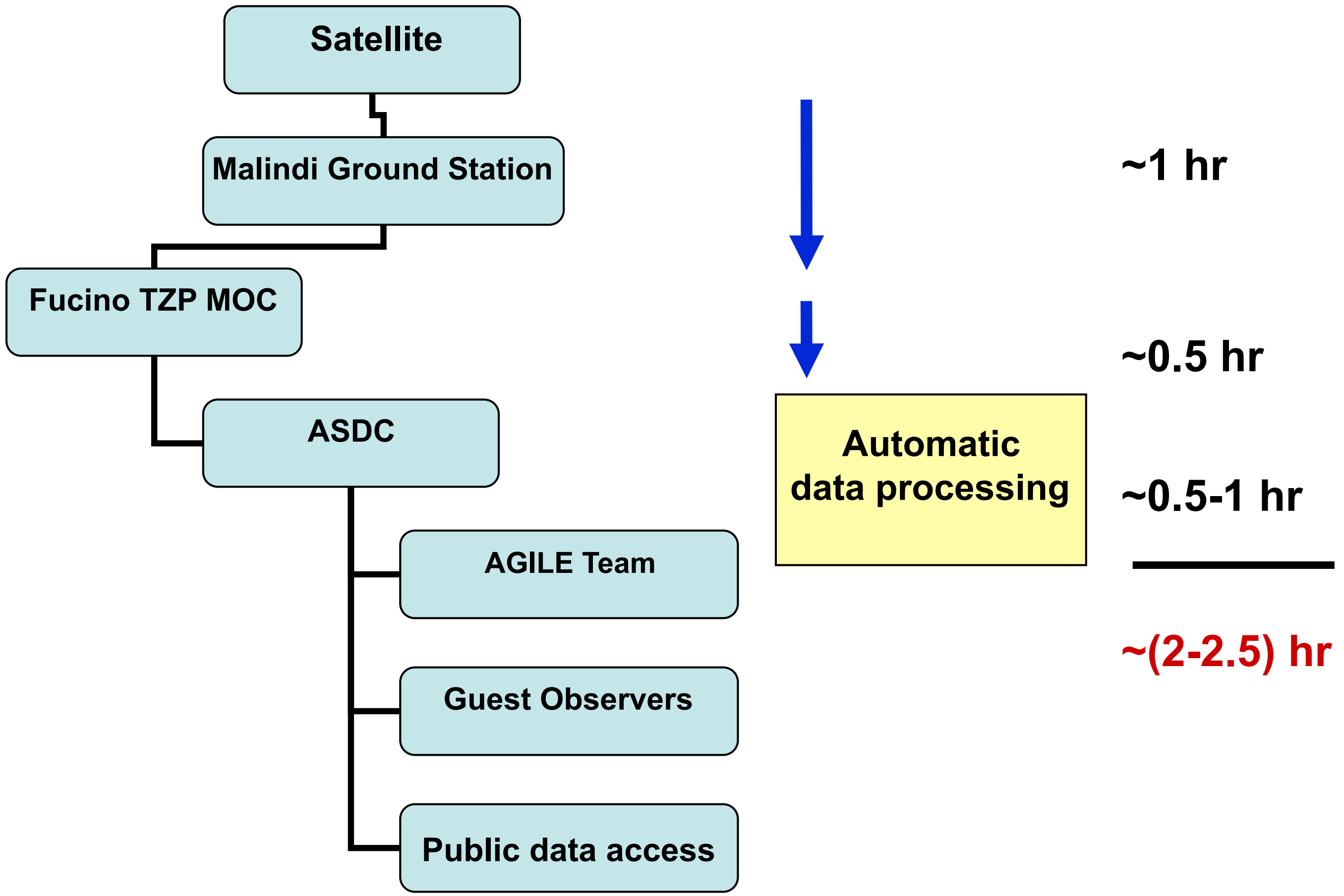


- Gamma-rays from microquasars (Cygnus X-3, Cygnus X-1)
- *Bright blazar states*
- SNRs and cosmic-ray acceleration
- *Terrestrial Gamma-Ray Flashes up to 100 MeV*
- the Crab Nebula is variable !!!

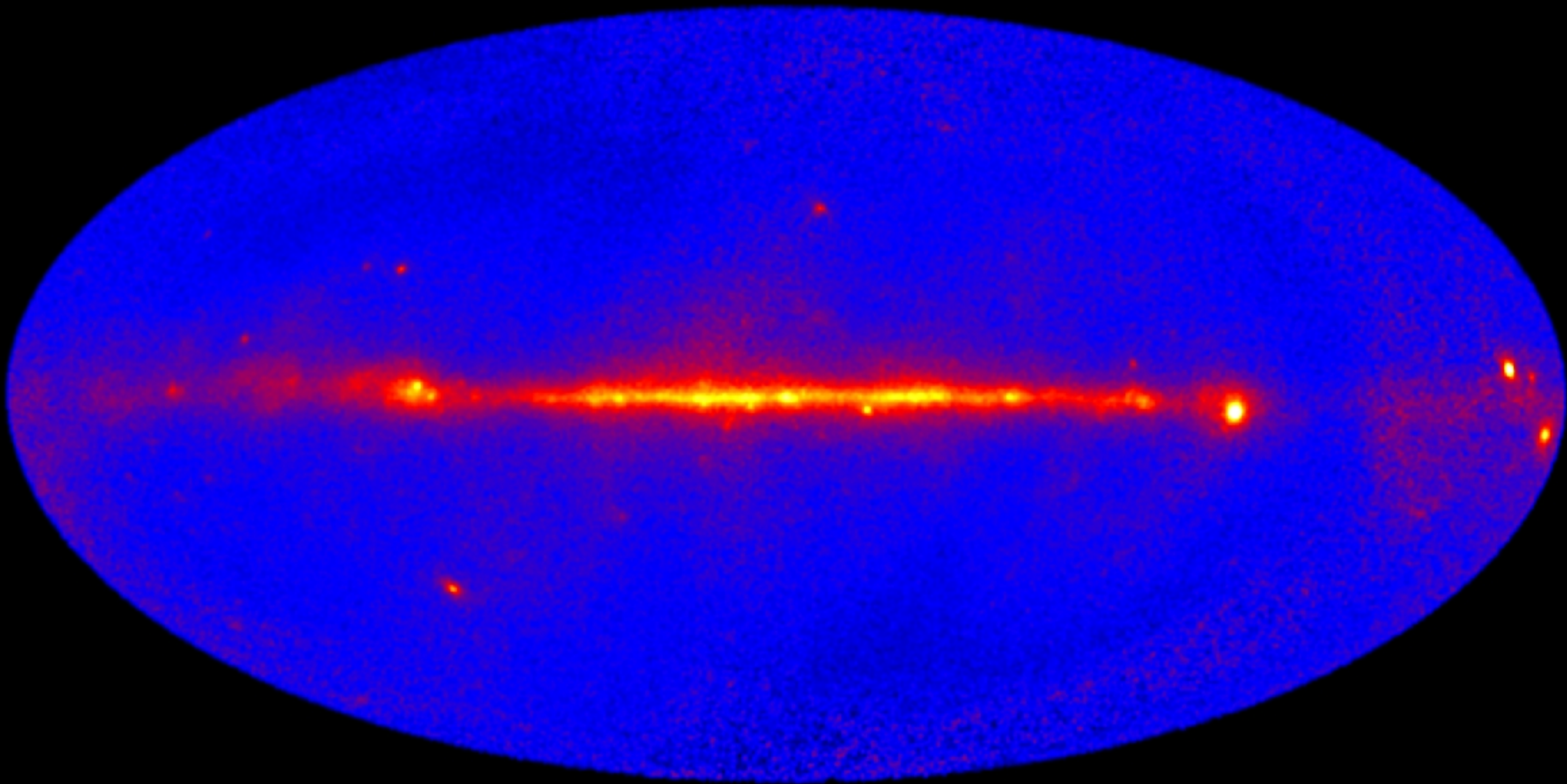
- **optimal sensitivity at "low" energies (E < 200 MeV)**
- **VERY EFFICIENT ALERT SYSTEM FOR TRANSIENTS**

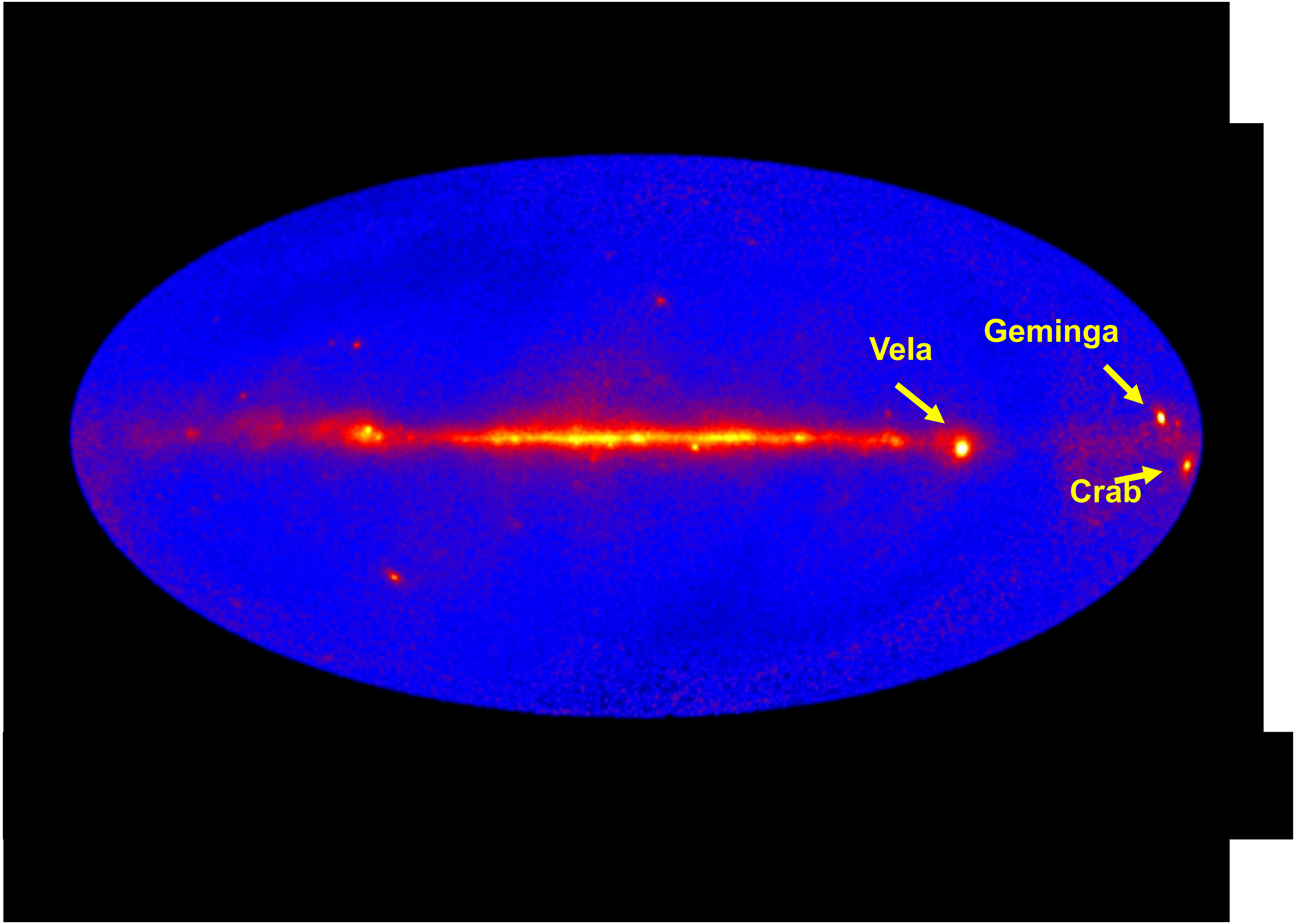

TZP
FUCINO
Malindi
(Kenya)
ASI Science
Data Center

AGILE: the "fastest" Ground Segment



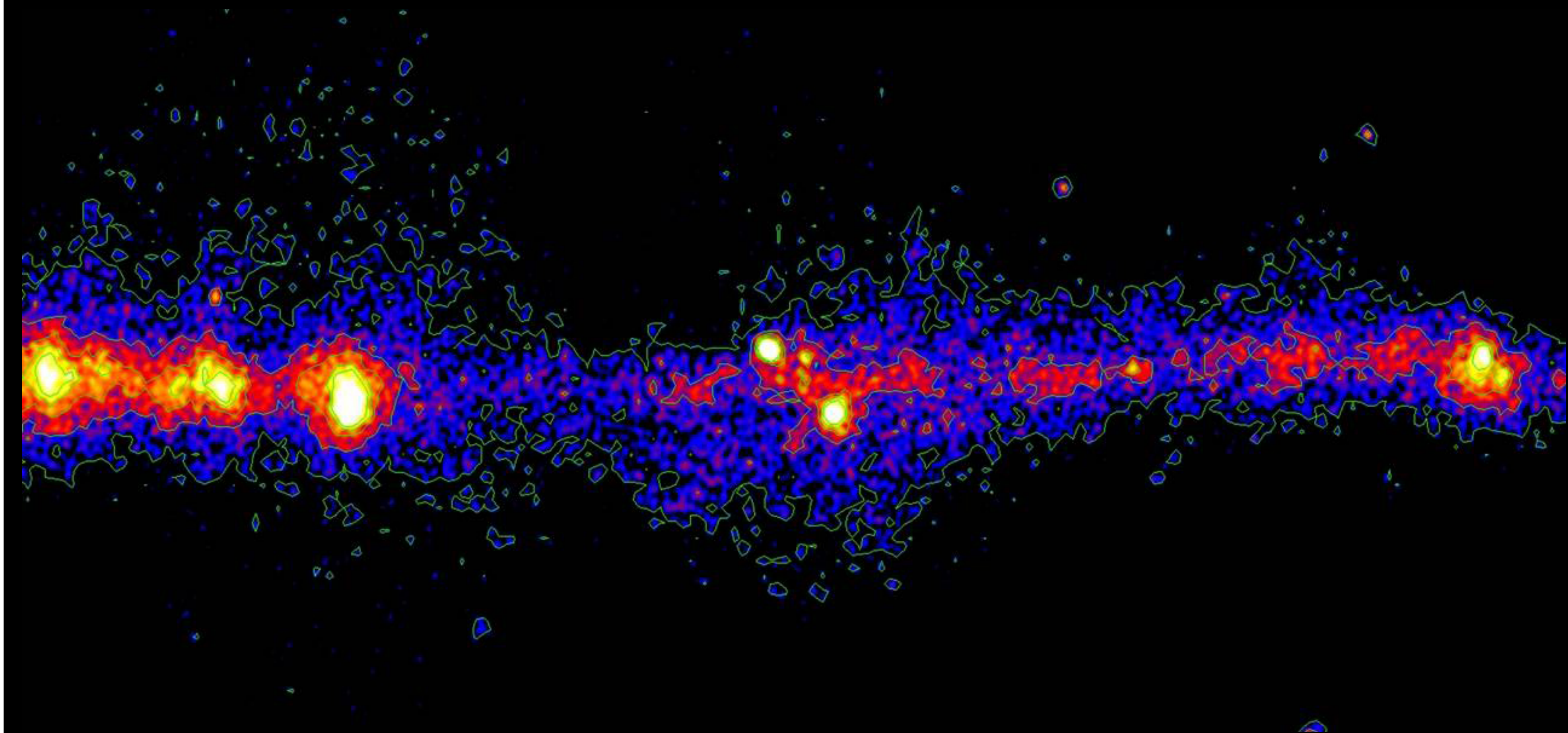
The AGILE gamma-ray sky (E > 100 MeV)
2 year exposure: July 2007 – June 2009



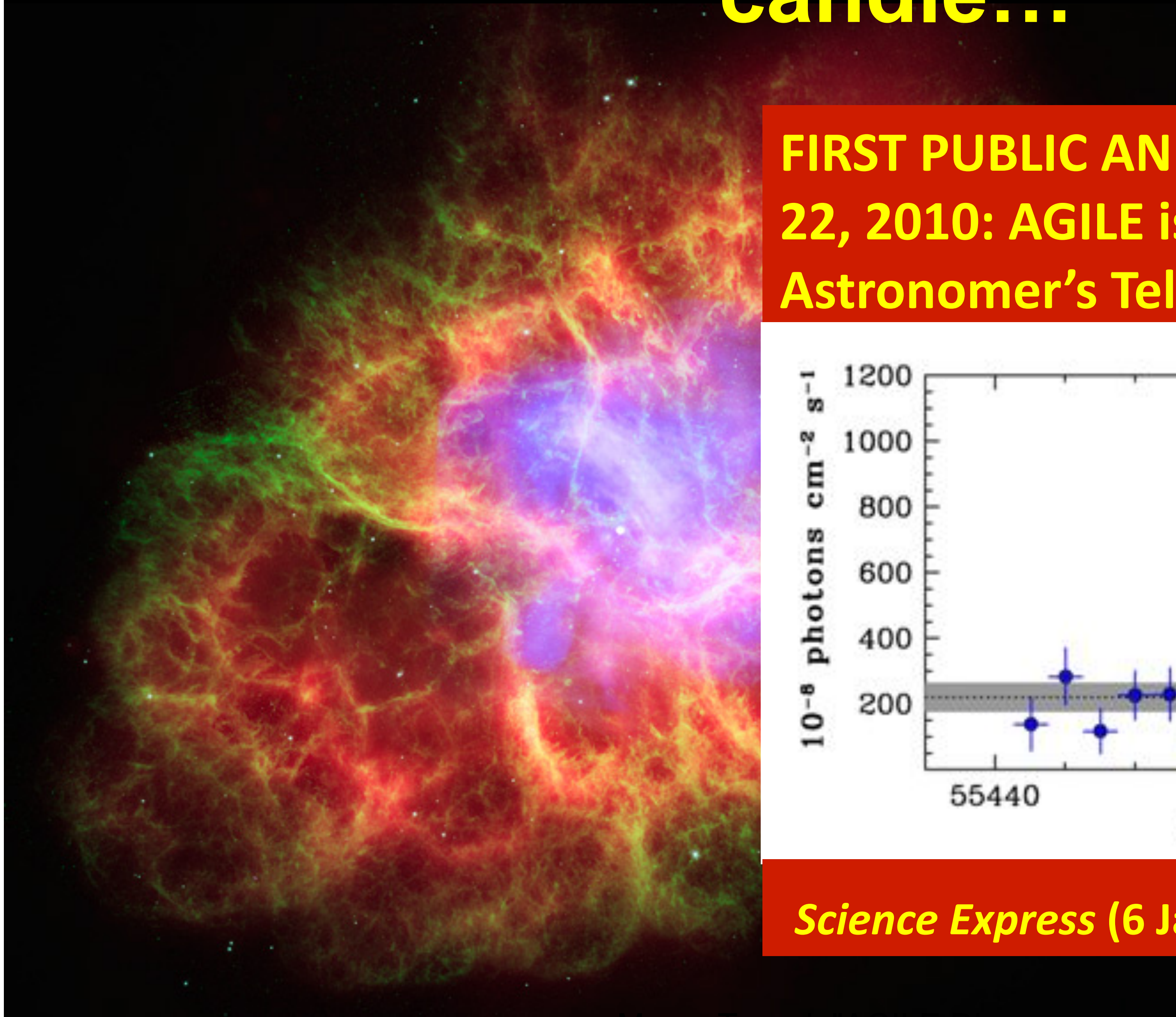

Vela
Geminga
Crab

AGILE map: Galactic anticenter:

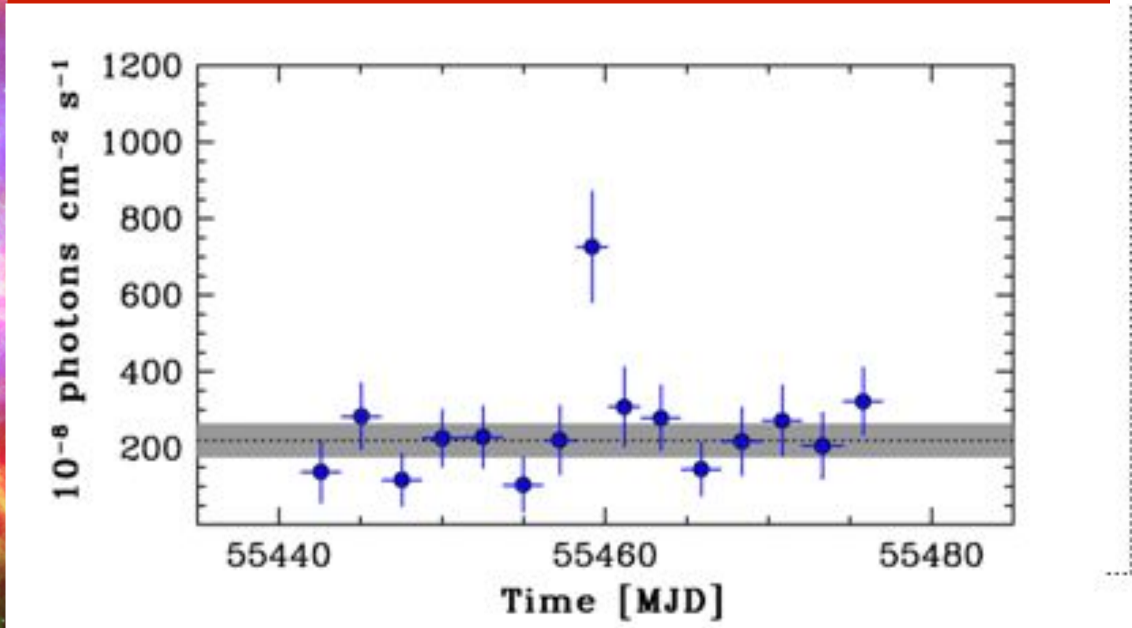
(E > 100 MeV; Jul. 2007 - Nov. 2009)



The Crab Nebula: a standard candle…



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

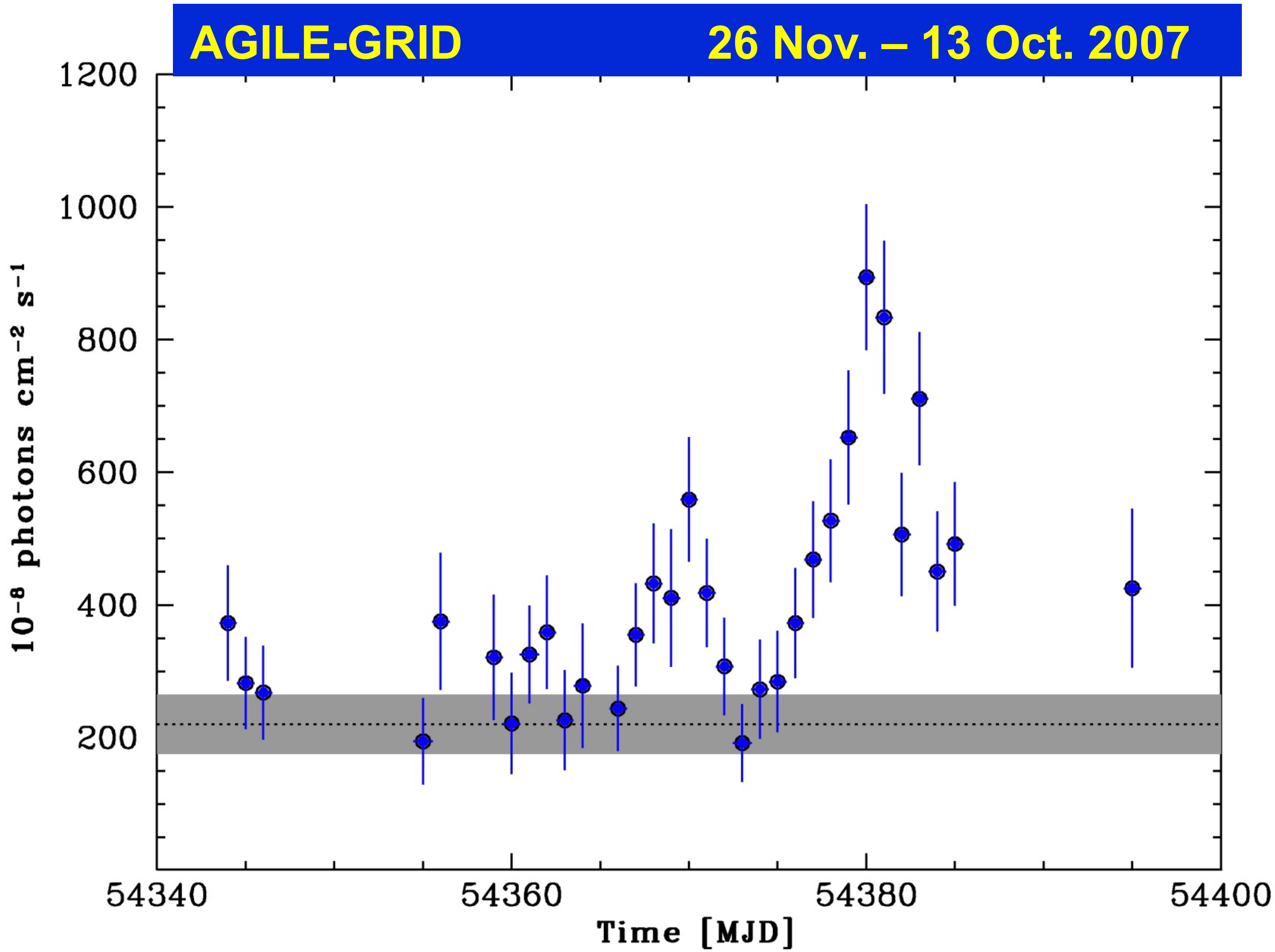


Science Express **(6 January 2011)**

Crab Nebula

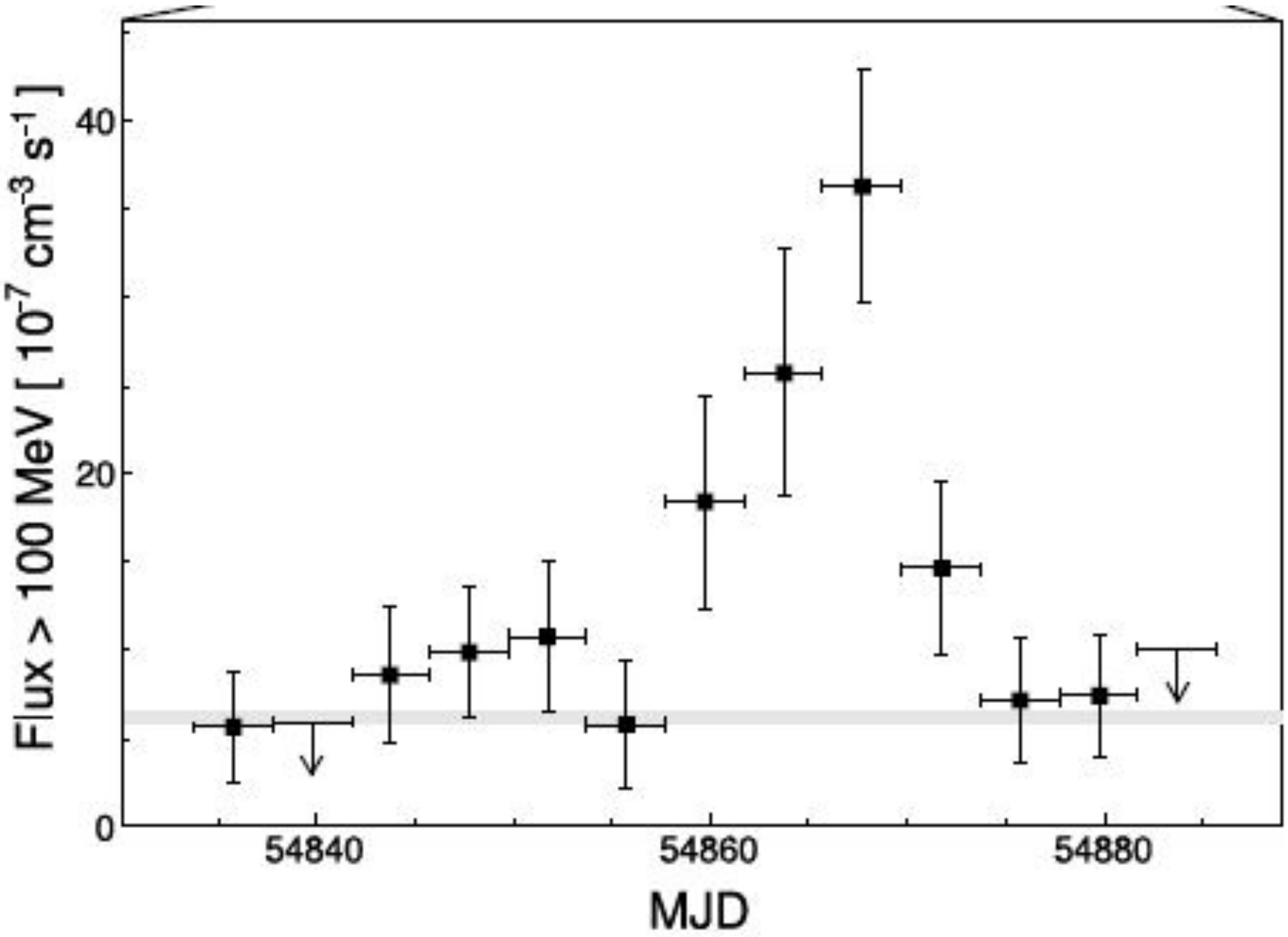
- **Three major gamma-ray flaring episodes**

Flare date	Duration	Peak γ-ray flux	Instruments
October 2007	~ 15 days	~ $6 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	AGILE
February 2009	~ 15 days	~ $4 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	*Fermi*
September 2010	~ 4 days	~ $5 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	AGILE, *Fermi*



AGILE-GRID
26 Nov. – 13 Oct. 2007
1200
1000
800
600
400
200
10^{-8} photons cm^{-2} s^{-1}
54340
54360
54380
54400
Time [MJD]

Fermi-LAT, 26 Jan. – 11 Feb. 2009



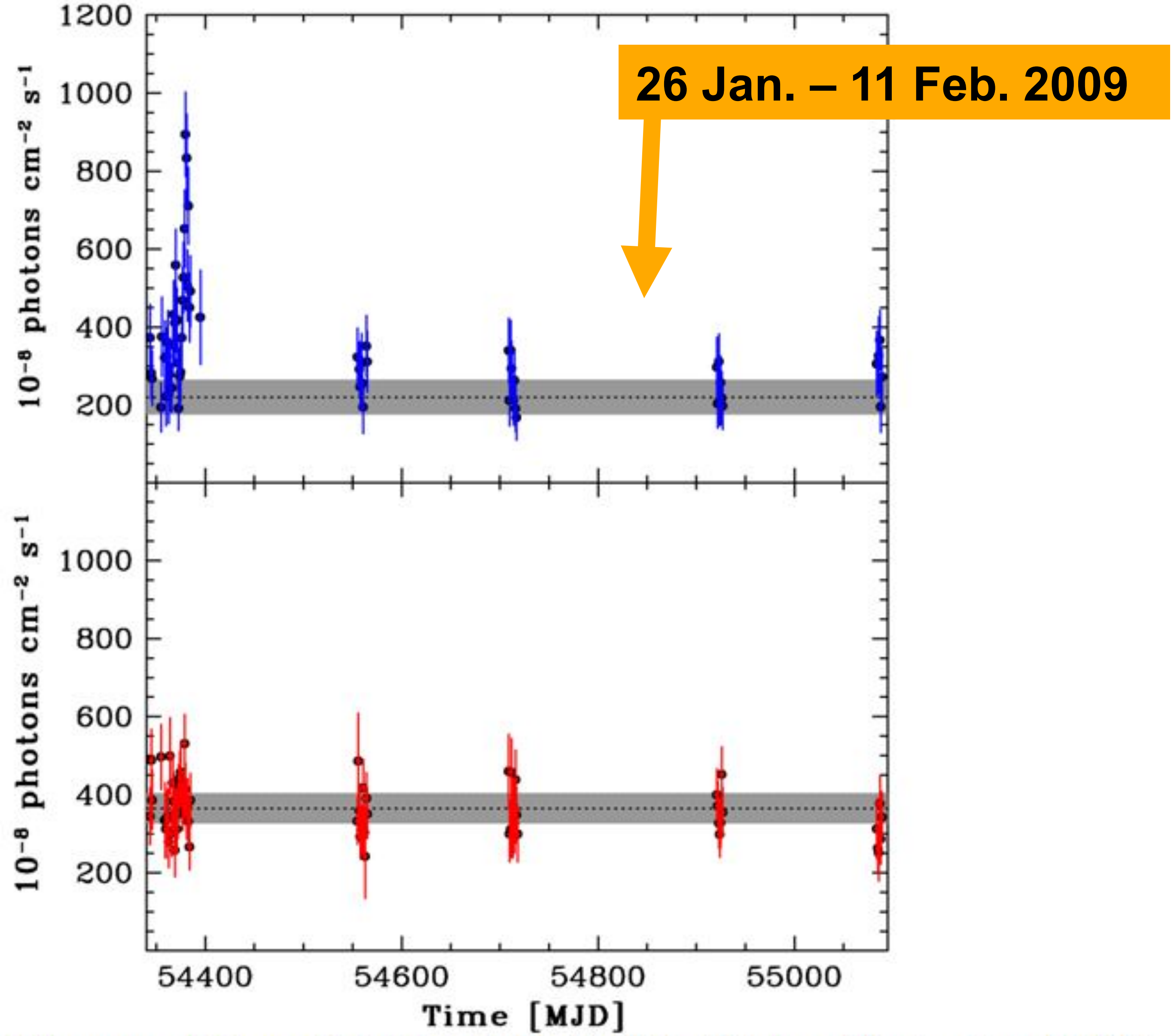


Fig. S1 – The AGILE gamma-ray light curve (1-day binning) of the Crab Pulsar/Nebula and Geminga above 100 MeV during the period **2007-09-01 – 2009-09-15** with the satellite pointing **within 35 degrees** from the source. Gaps in the light curve are due to the satellite pointing at fields different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

- Two classes of gamma-ray flaring episodes

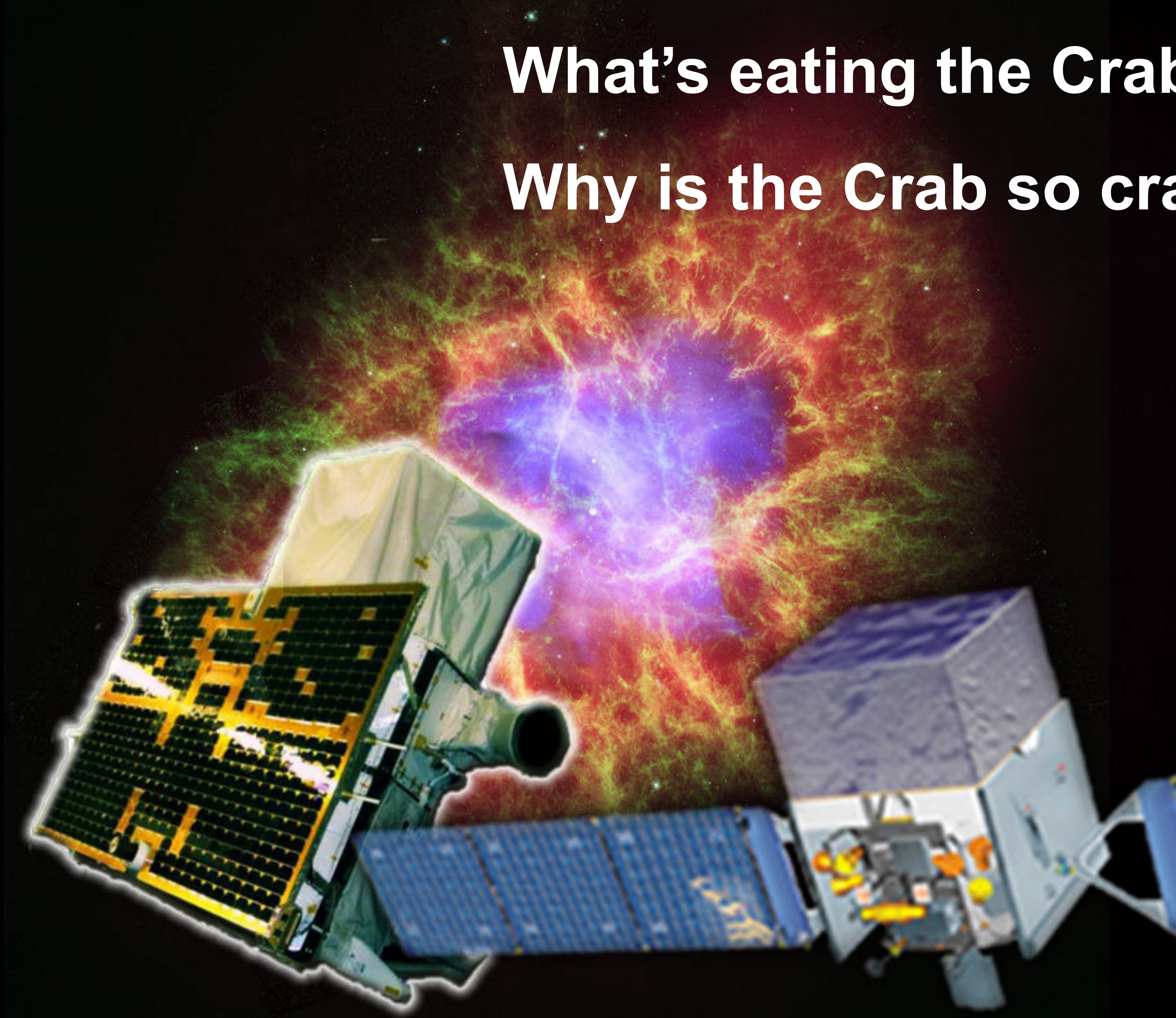
Flare date	Duration	Peak γ-ray flux	γ-ray E_{total}	γ-ray eff.	Instrument
Oct. 2007	~ 15 days	~ $6 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	~ 10^{42} erg	~ $8 \cdot 10^{-4}$	AGILE
Feb. 2009	~ 15 days	~ $4 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	~ 10^{42} erg	~ $6 \cdot 10^{-4}$	*Fermi*
Sept. 2010	~ 4 days	~ $5 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	~ 10^{41} erg	~ $5 \cdot 10^{-4}$	AGILE, *Fermi*

Major gamma-ray flaring rate: 1-2/year

HEASARC Picture of the Week, 28 Feb. 2011

What’s eating the Crab ?

Why is the Crab so crabby ?



Last but not least…
the X-ray surprise..!

- **long timescale X-ray variability reaching almost 10% in 3 years !**

Wilson-Hodge et al. 2010)

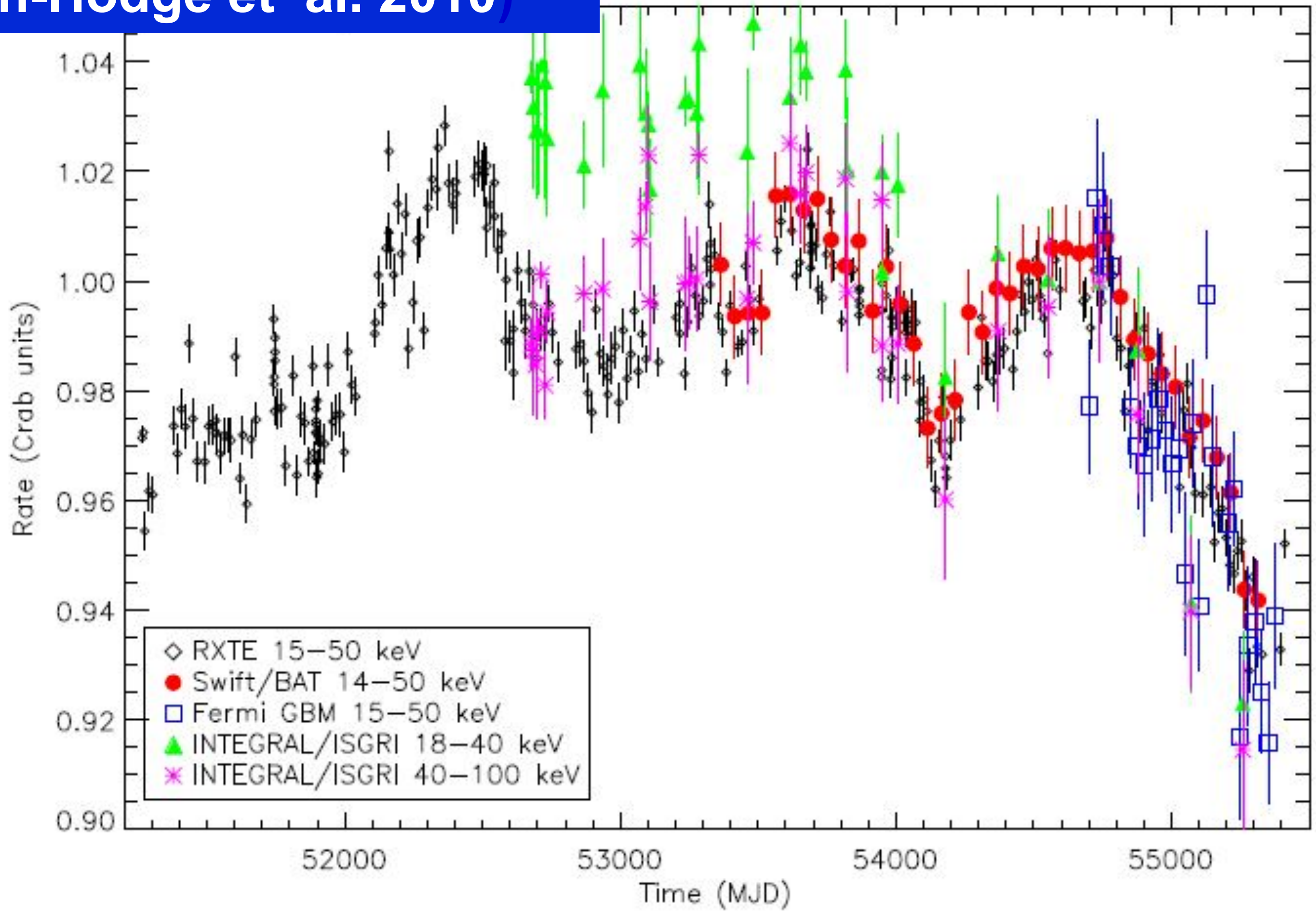
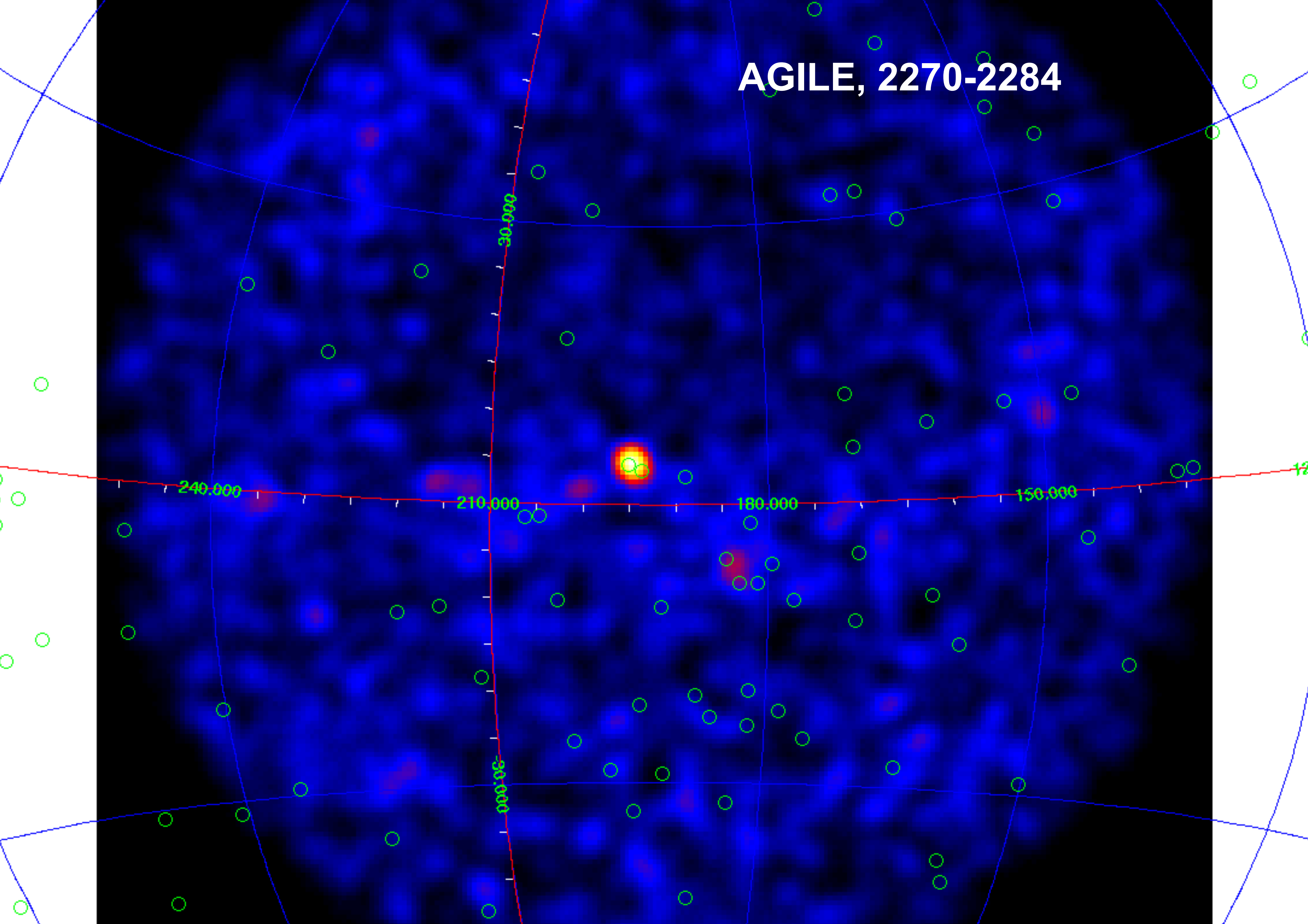
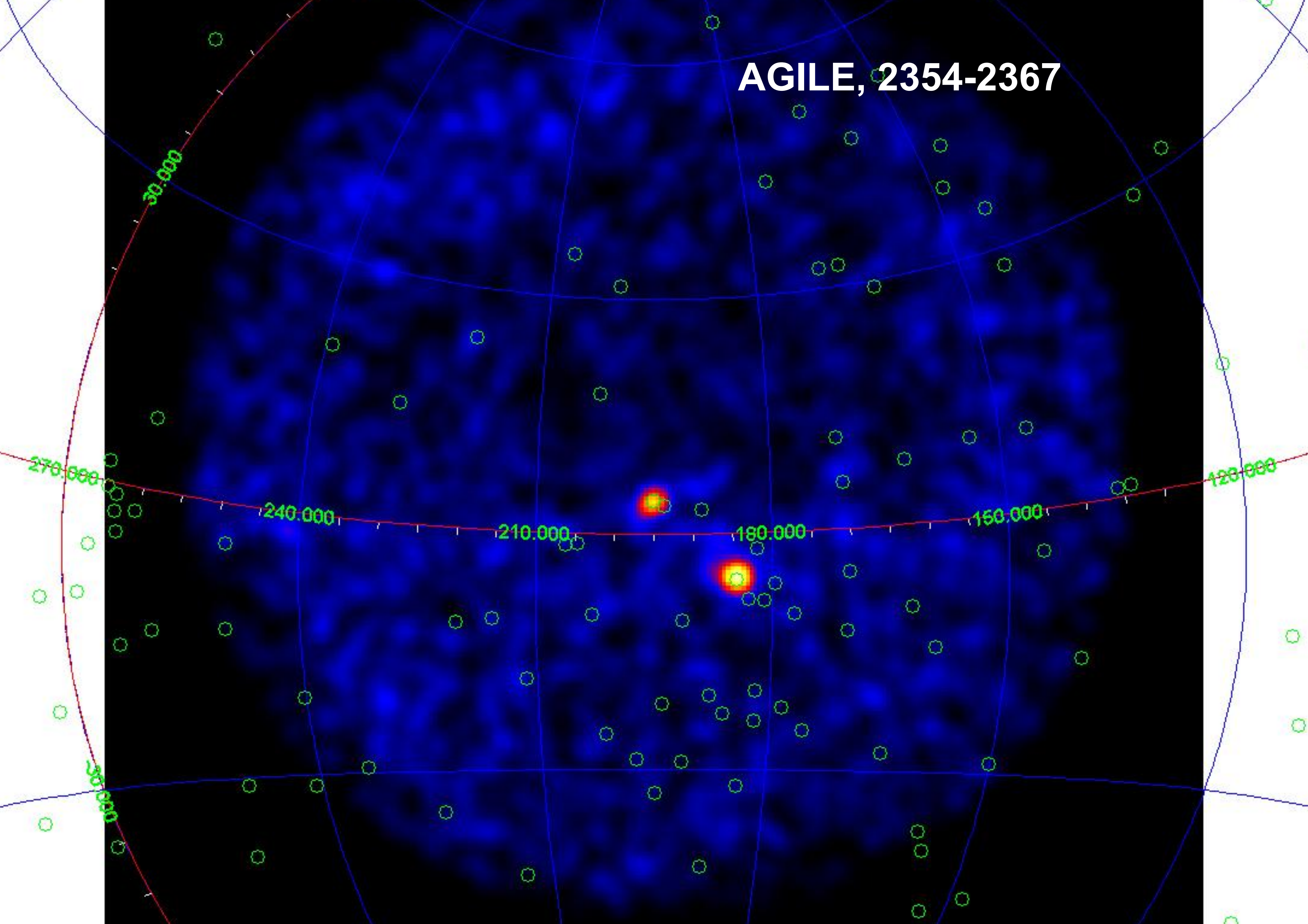
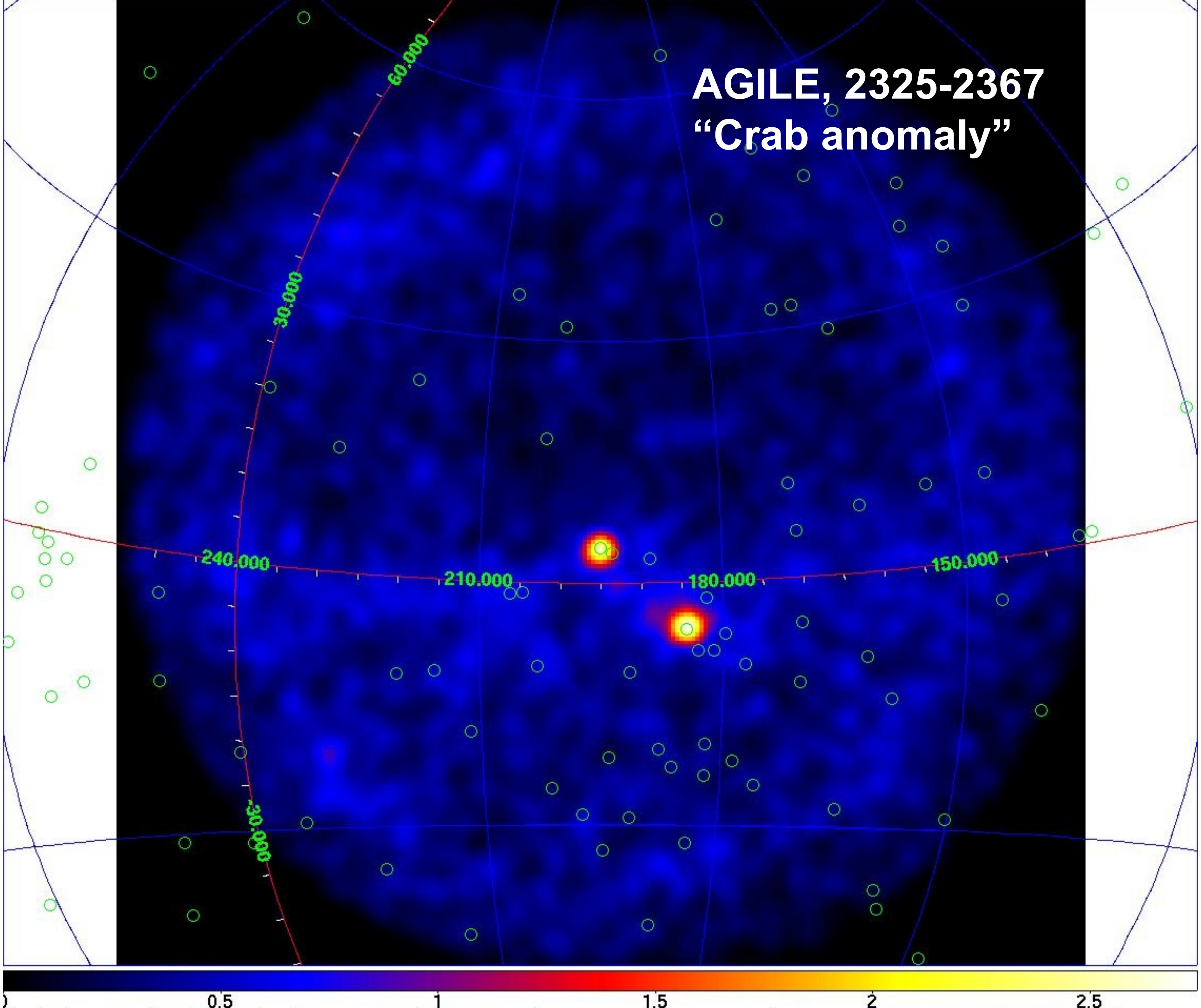


Fig. 5.— Composite Crab light curve for *RXTE*/PCA (15-50 keV - black diamonds), *Swift*/BAT (14-50 keV - red filled circles), *Fermi*/GBM (15-50 keV - open blue squares), *INTEGRAL*/ISGRI (18-40 and 40-100 keV - green triangles and purple asterisks, respectively.) Each data set has been normalized to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


AGILE, 2270-2284
30.000
240.000
210.000
180.000
150.000
-30.000



AGILE, 2354-2367
30.000
270.000
240.000
210.000
180.000
150.000
120.000



AGILE, 2325-2367
"Crab anomaly"
60.000
30.000
-30.000
240.000
210.000
180.000
150.000
0
0.5
1
1.5
2
2.5

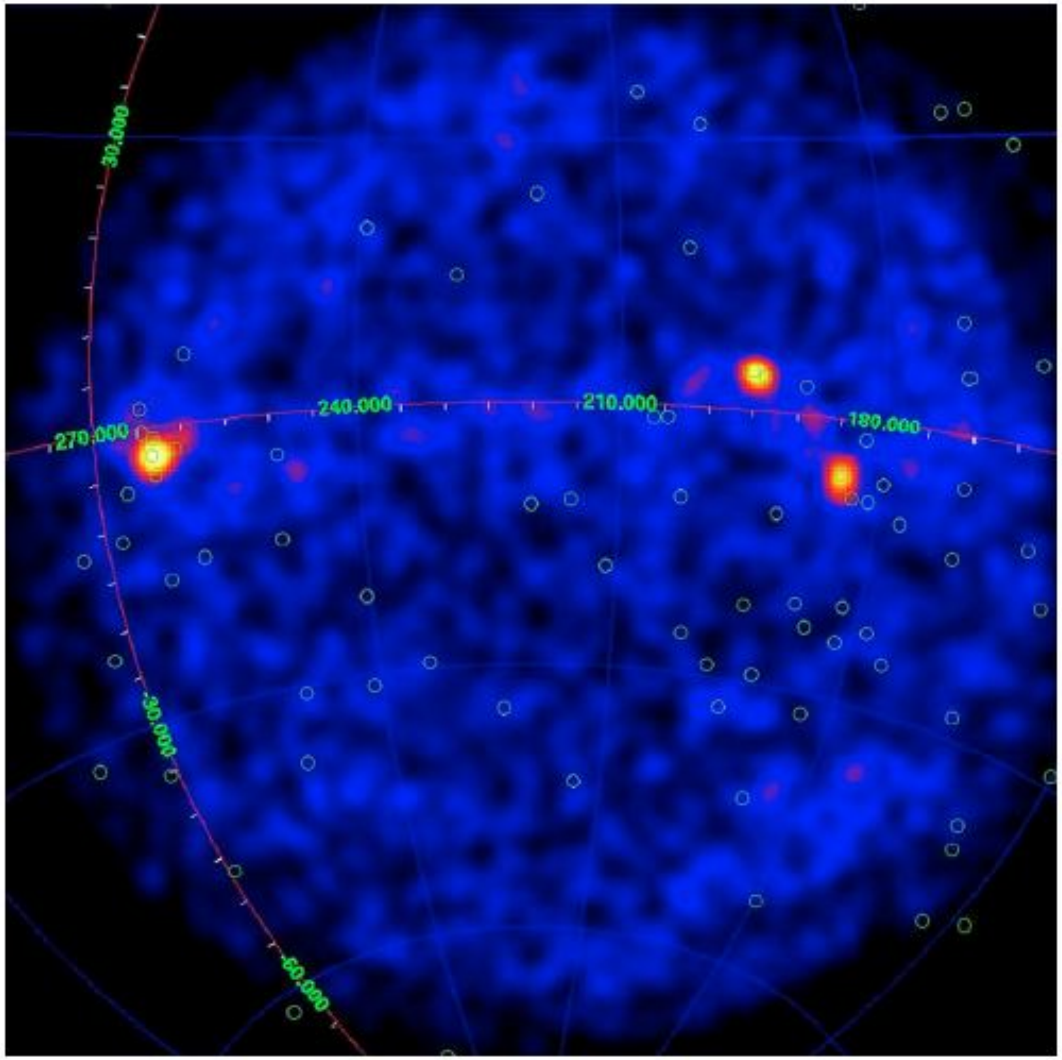
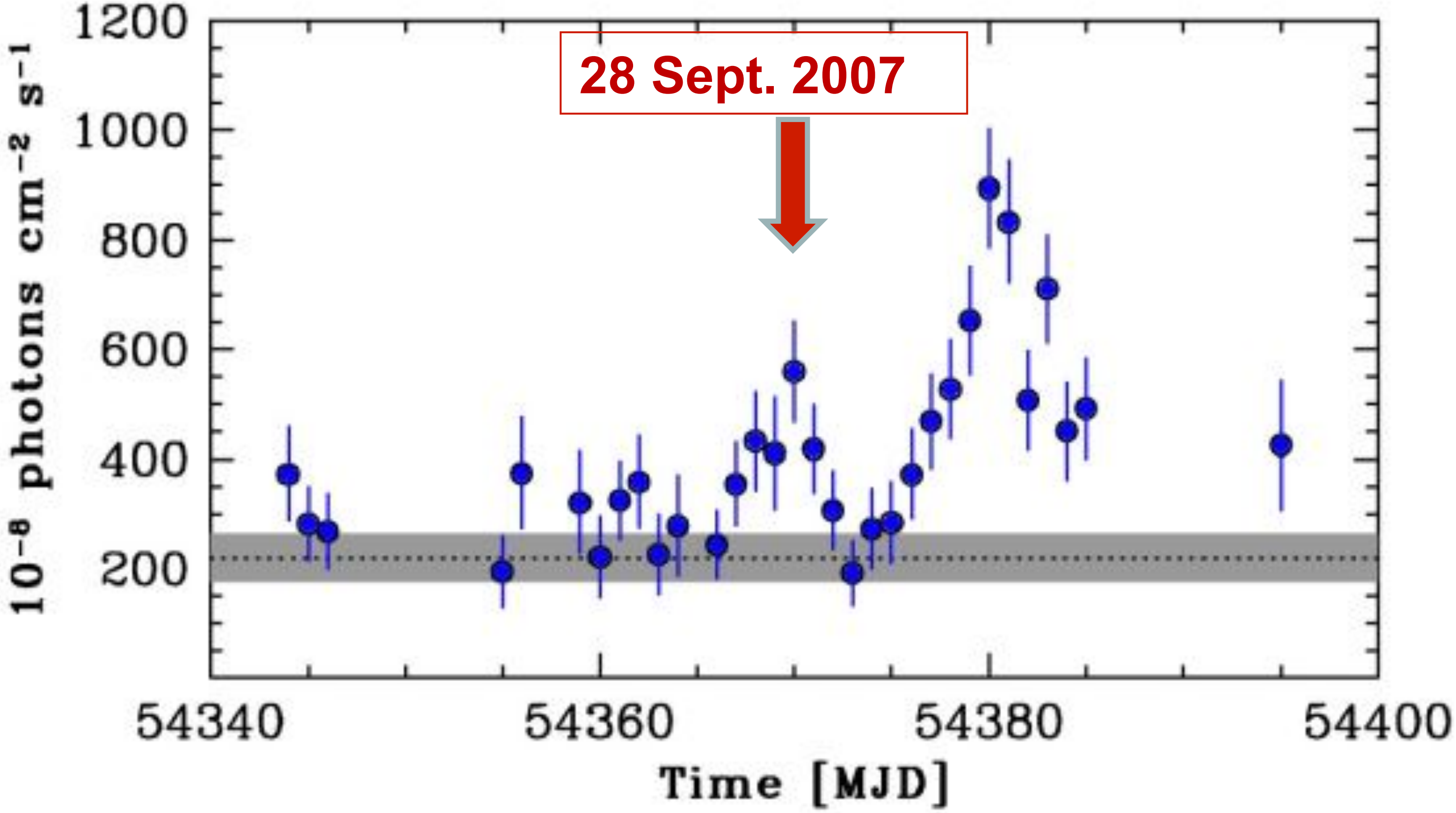


Fig. 25. The AGILE-GRID 1-day gamma-ray counts map for photons above 100 MeV obtained on 2007 September 28. The unprecedently large FOV includes for the first time in a single map all three of the most important gamma-ray pulsars: Vela, Crab, and Geminga.


28 Sept. 2007
1200
1000
800
600
400
200
10⁻⁸ photons cm⁻² s⁻¹
54340
54360
54380
54400
Time [MJD]

A&A 506, 1563–1574 (2009)
DOI: 10.1051/0004-6361/200911783

Astronomy & Astrophysics

First AGILE catalog of high-confidence gamma-ray sources

C. Pittori[1], F. Verrecchia[1], A. W. Chen[2,3], A. Bulgarelli[4], A. Pellizzoni[5], A. Giuliani[2,3], S. Vercellone[6], F. Longo[7,8], M. Tavani[9,10,11,3], P. Giommi[1,12], G. Barbiellini[7,8,3], M. Trifoglio[4], F. Gianotti[4], A. Argan[9], A. Antonelli[13], F. Boffelli[14], P. Caraveo[2], P. W. Cattaneo[14], V. Cocco[10], S. Colafrancesco[1,12], T. Contessi[2], E. Costa[9], S. Cutini[1], F. D'Ammando[9,10], E. Del Monte[9], G. De Paris[9], G. Di Cocco[4], G. Di Persio[9], I. Donnarumma[9], Y. Evangelista[9], G. Fanari[1], M. Feroci[9], A. Ferrari[3,15], M. Fiorini[2], F. Fornari[2], F. Fuschino[4], T. Froysland[3,11], M. Frutti[9], M. Galli[16], D. Gasparrini[1], C. Labanti[4], I. Lapshov[9,17], F. Lazzarotto[9], F. Liello[9], P. Lipari[18,19], E. Mattaini[2], M. Marisaldi[4], M. Mastropietro[9,21], A. Mauri[4], F. Mauri[14], S. Mereghetti[2], E. Morelli[4], E. Moretti[7,8], A. Morselli[11], L. Pacciani[9], F. Perotti[2], G. Piano[9,10,11], P. Picozza[10,11], M. Pilia[22,2,5], C. Pontoni[3,8], G. Porrovecchio[9], B. Preger[1], M. Prest[8,22], R. Primavera[1], G. Pucella[9], M. Rapisarda[20], A. Rappoldi[14], E. Rossi[4], A. Rubini[9], S. Sabatini[10], P. Santolamazza[1], E. Scalise[9], P. Soffitta[9], S. Stellato[1], E. Striani[10], F. Tamburelli[1], A. Traci[4], A. Trois[9], E. Vallazza[8], V. Vittorini[9,3], A. Zambra[2,3], D. Zanello[18,19], and L. Salotti[12]

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-

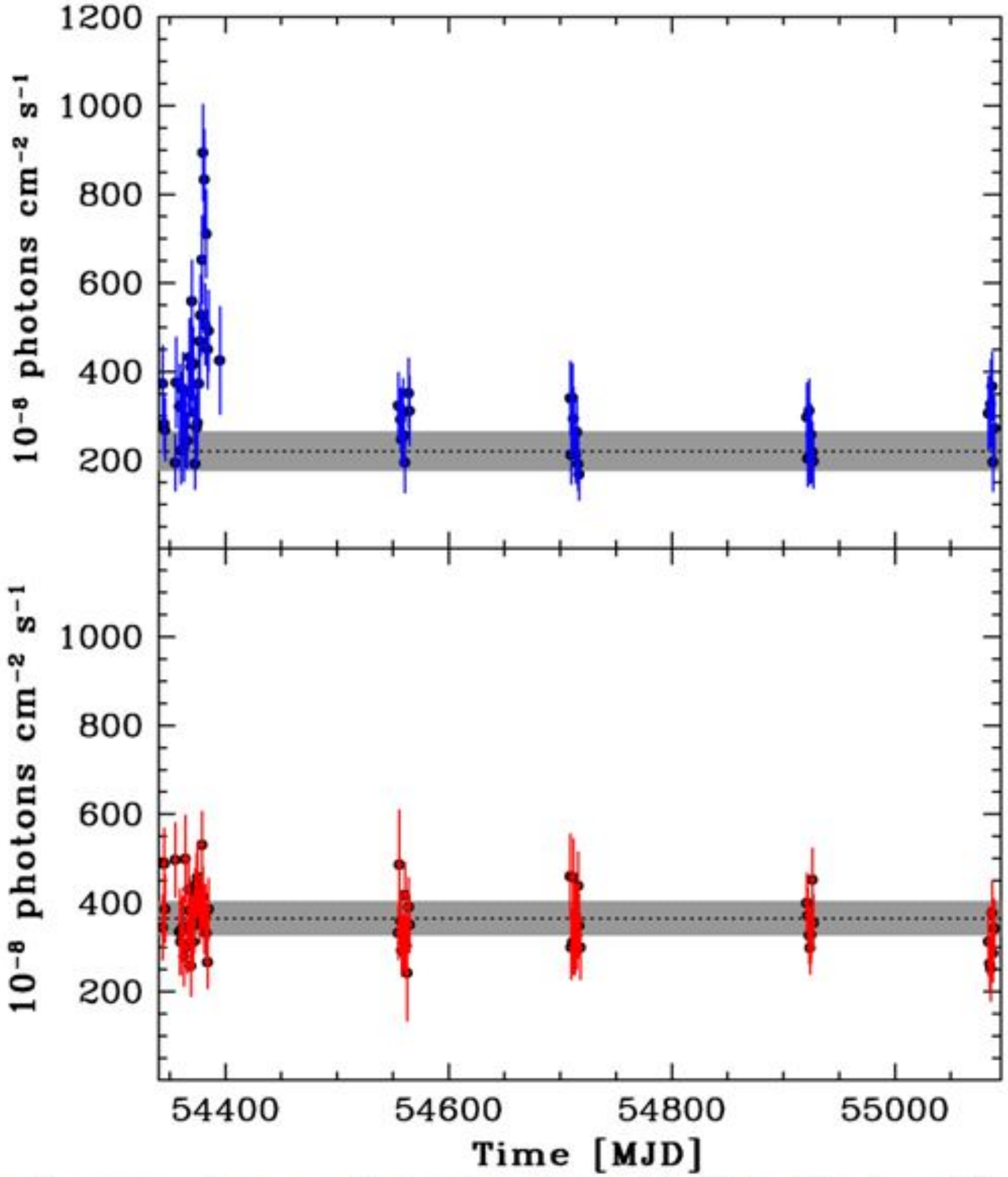


Fig. S1 – The AGILE gamma-ray light curve (1-day binning) of the Crab Pulsar/Nebula and Geminga above 100 MeV during the period **2007-09-01 – 2009-09-15** with the satellite pointing **within 35 degrees** from the source. Gaps in the light curve are due to the satellite pointing at fields different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

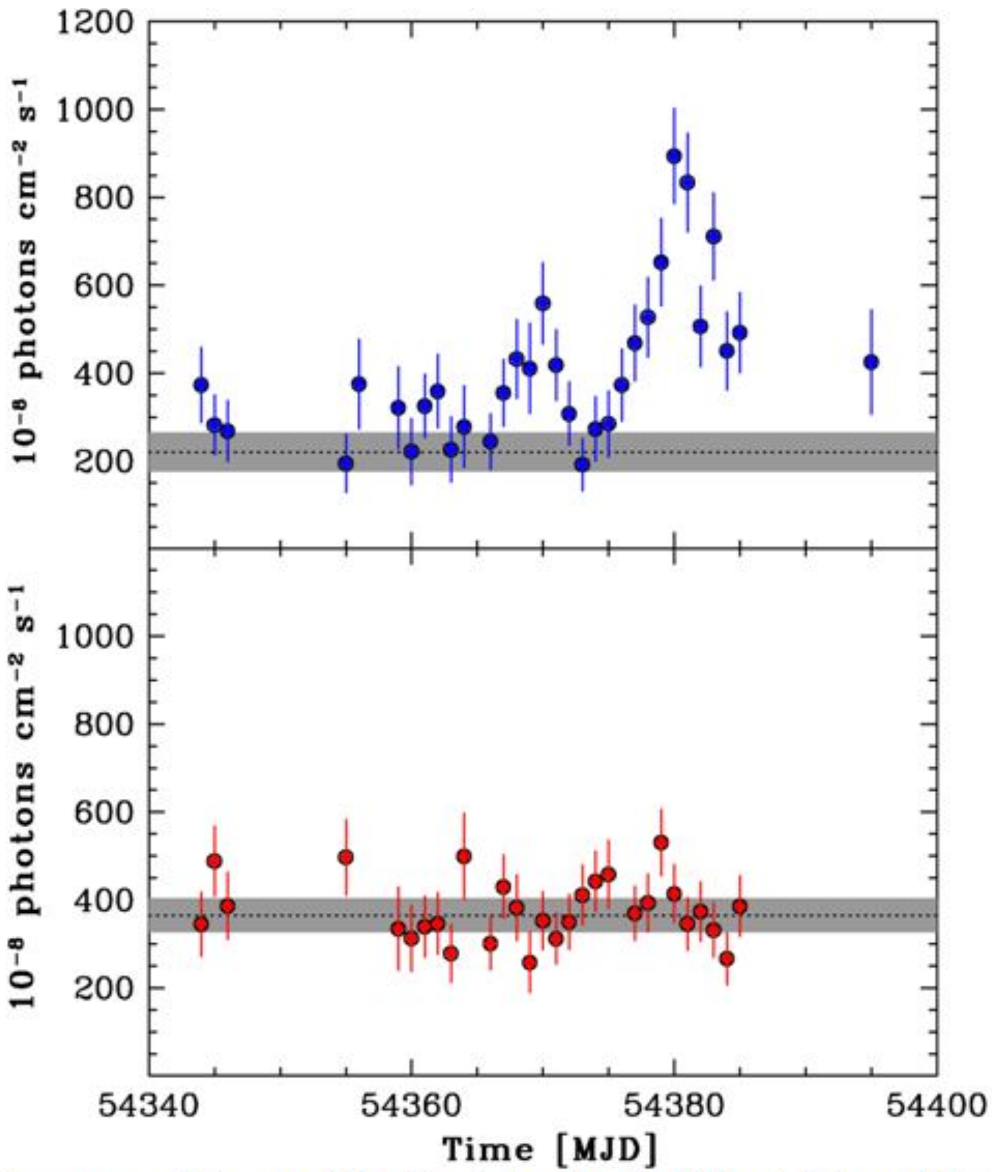


Fig. S2 – The AGILE gamma-ray lightcurve (1-day binning) of the Crab Pulsar/nebula and Geminga above 100 MeV during the period **2007-08-28 – 2007-10-27** with the satellite in pointing mode.

the 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 !**

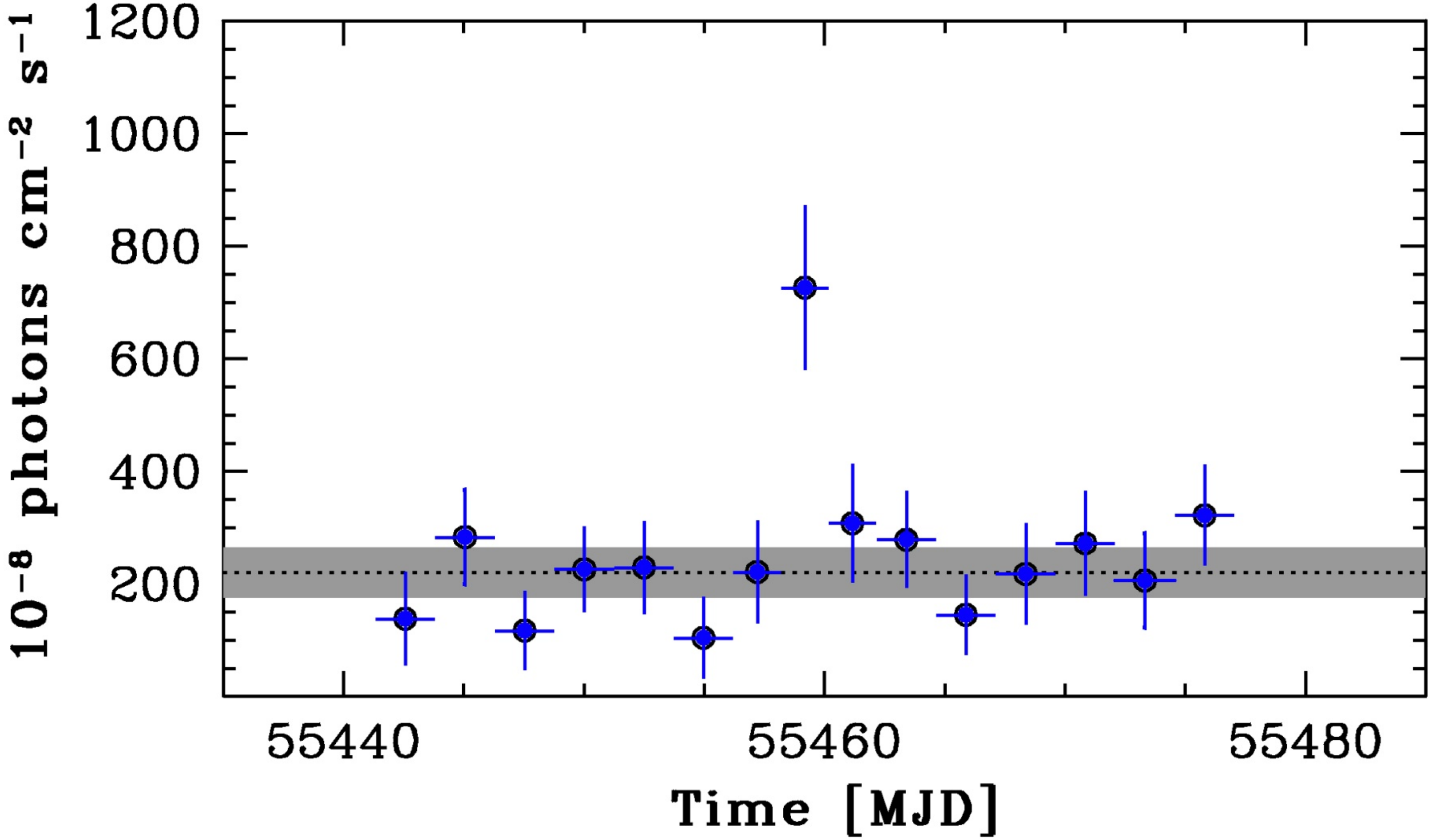
- **many internal AGILE documents showing the analyses and cure.**

AGILE 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

AGILE lightcurve (2-day binning)

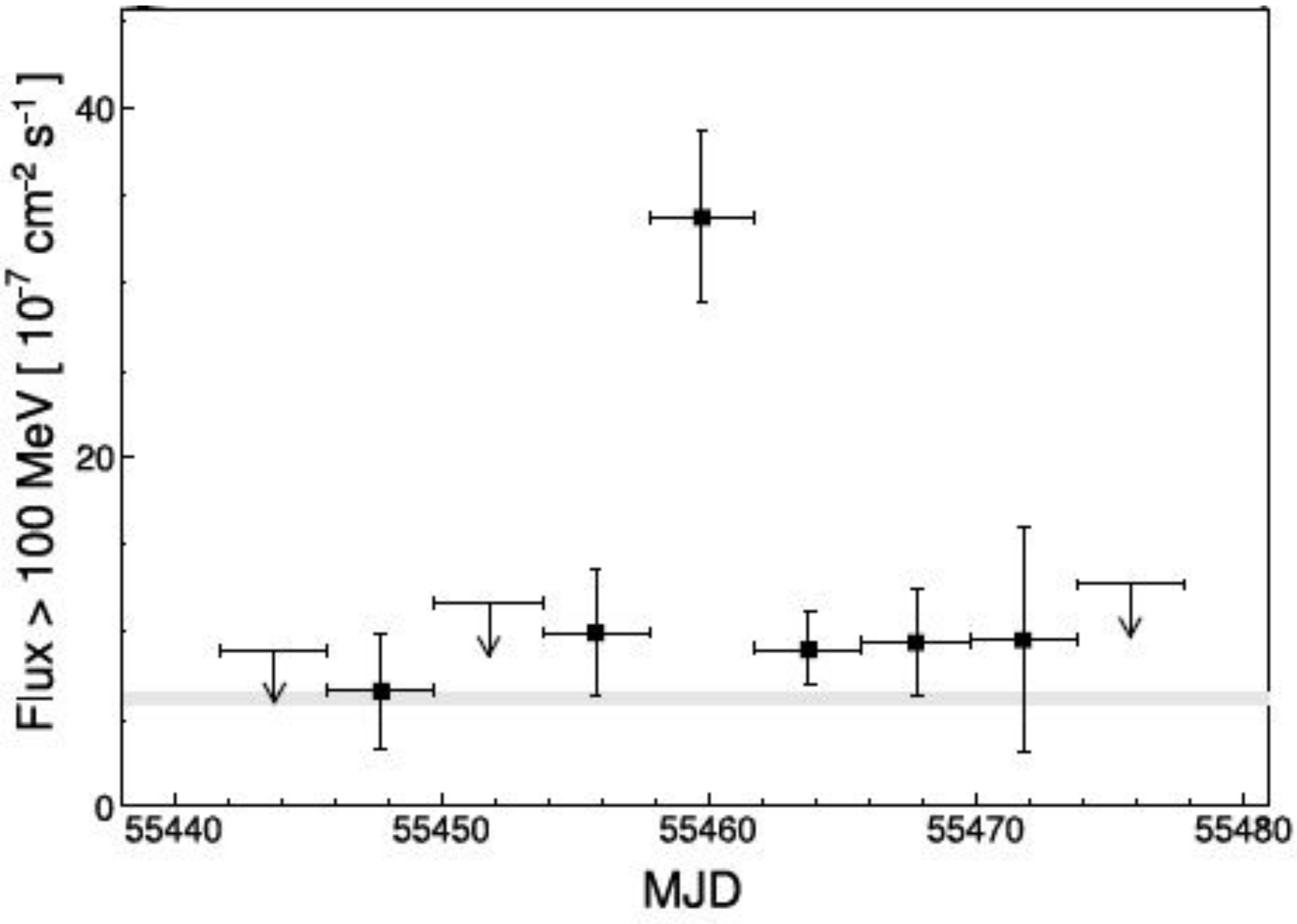
(PSR + Nebula)



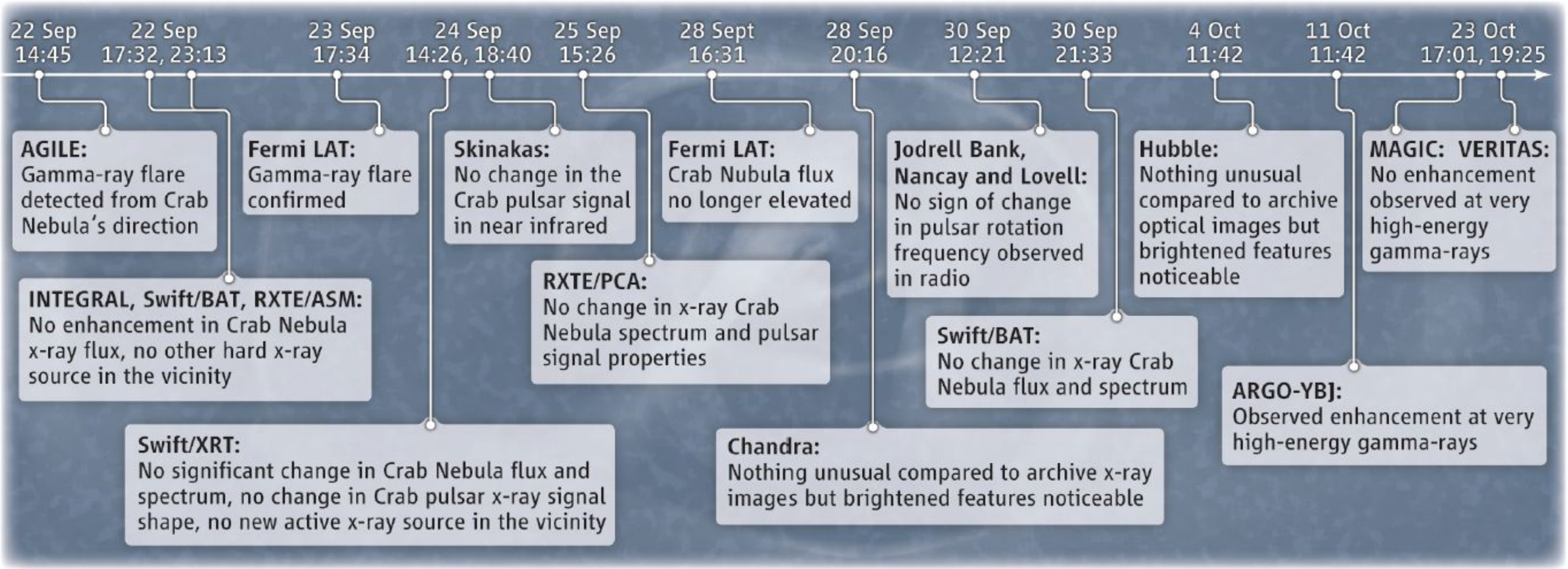
0

Fermi-LAT lightcurve (4-day binning)

(Nebula only)

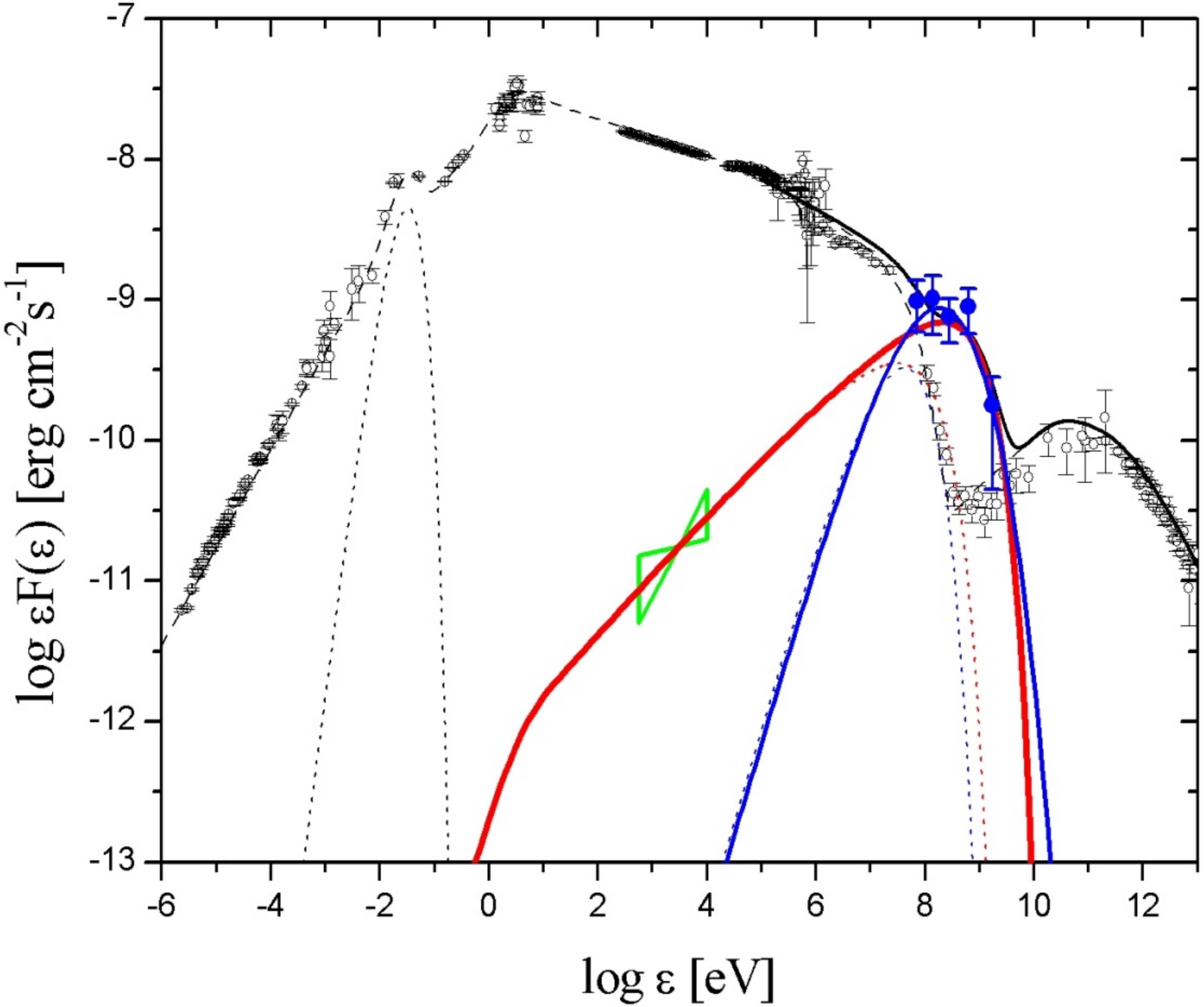


post-flare excitement



Bernardini E., 2011

AGILE-GRID spectrum at the peak (2 days)



Fermi-LAT spectrum (4-day integration for Sept. 2010)

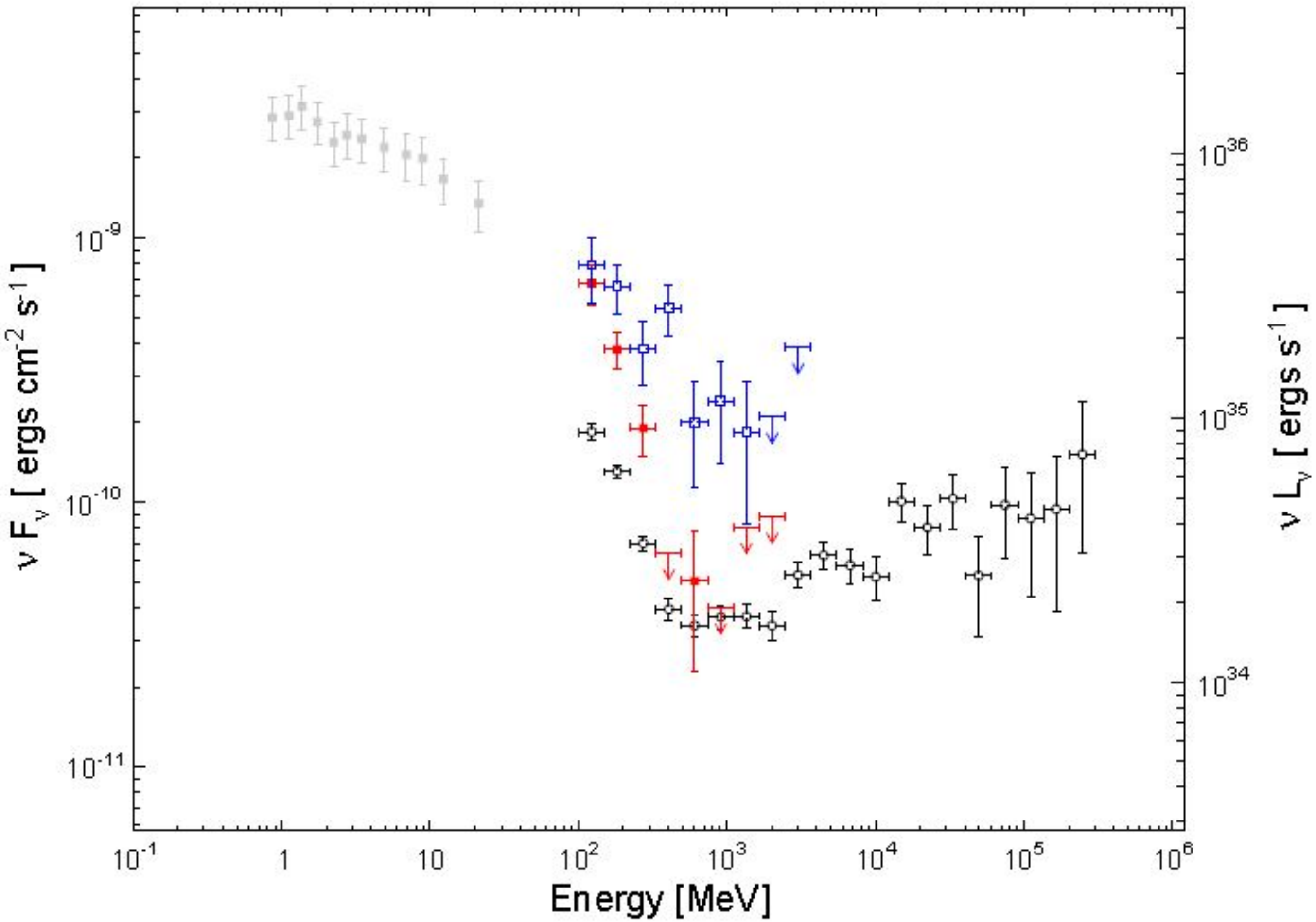


Figure 1: Spectral energy distribution of the Crab Nebula. Black open circles show the average spectrum measured by the LAT in the first 25 months of observations. Red boxes show the energy spectrum during the flare of February 2009 (MJD 54857.73-54873.73) and blue open boxes the spectrum in September 2010 (MJD 55457.73-55461.73). Gray boxes show historical data from the COMPTEL telescope (*39*). Arrows indicate 95% confidence flux limits.

Crab Sept. 2010 flare

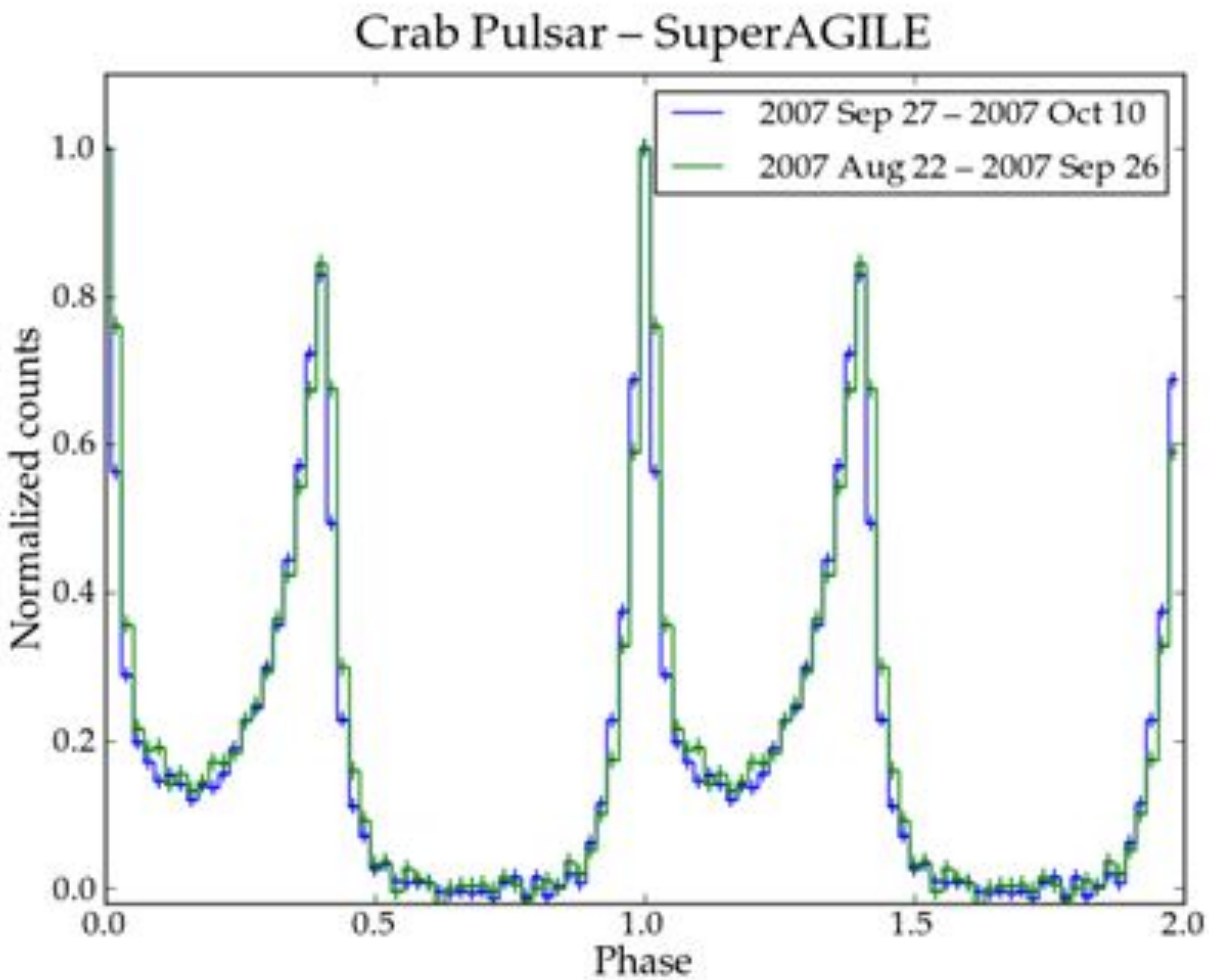
- **gamma-ray flare peak luminosity**

$$L_{peak} \approx 5 \cdot 10^{35} \text{ erg cm}^{-2} \text{ s}^{-1}$$

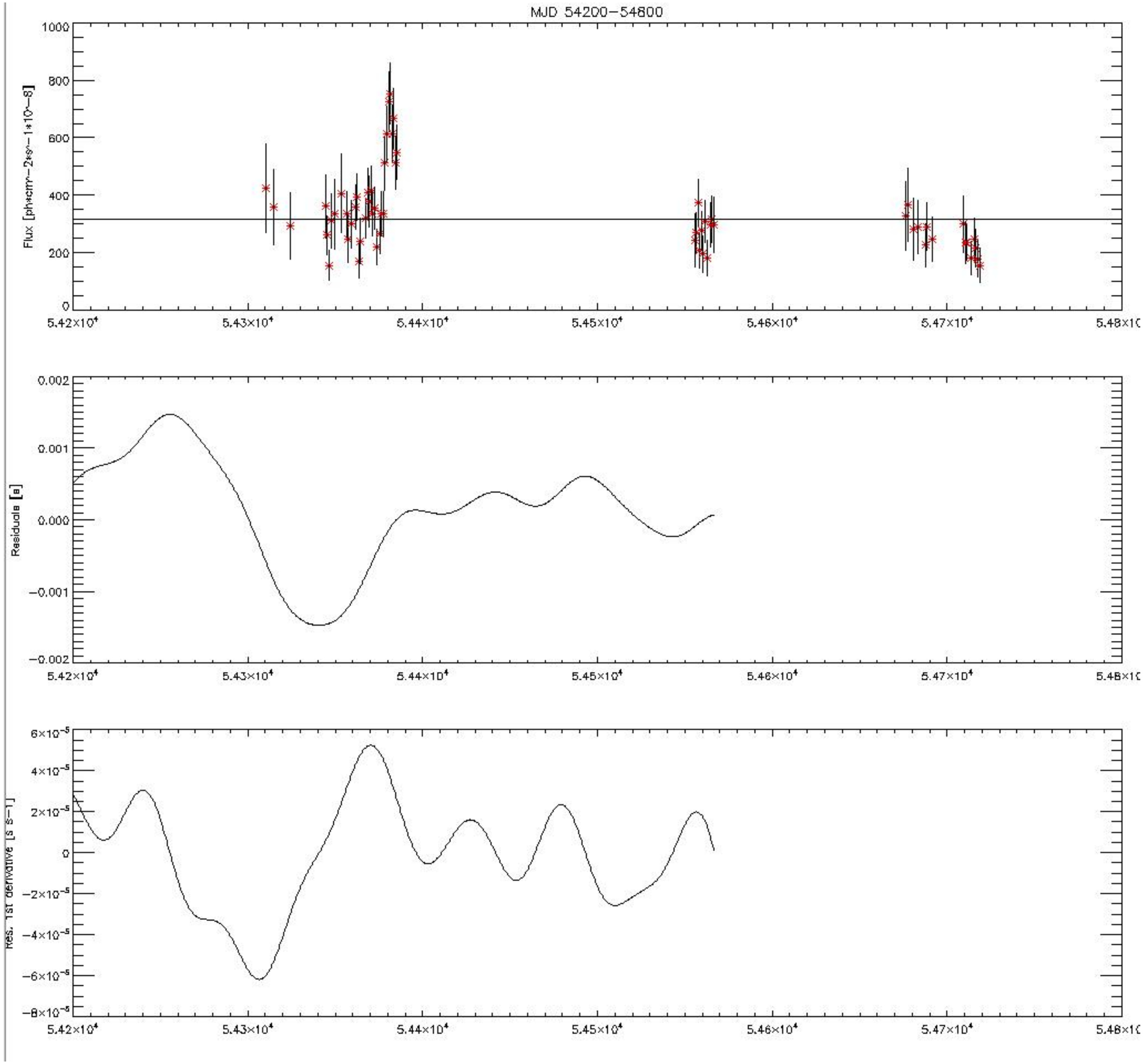
$$\varepsilon_{peak} \approx 0.001 \cdot L_{sd}$$

- **what could it be ?**
  - **PSR or NS emission**
    - **33 ms pulsed gamma-ray signal (but no evidence of pulsed profile changes during the AGILE flare, no pulsar glitch)**
    - **exotic neutron star gamma-ray flare (never observed before)**
  - **NEBULA emission**
    - **Formation of giant “wisps” or shocks in the “jet”-like region, relativistic PSR wind interaction in the gaseous nebula, and transient gamma-ray emission**

no X-ray pulsar variation: the Oct. 2007 case



no obvious connection with pulsar time residuals:
the Oct. 2007 case



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 ?
  - no known blazar in error box (0.06), X-ray observation 2 days after the Sept. Flare (ATEL 2868), $P < 10^{-4}$
  - $F > 2{\cdot}10^{-6}$ ph cm^{-2} s^{-1}, few sources, $P < 6{\cdot}10^{-5}$
  - “soft” average gamma-ray spectrum, very unusual, chance-coincidence P very small.

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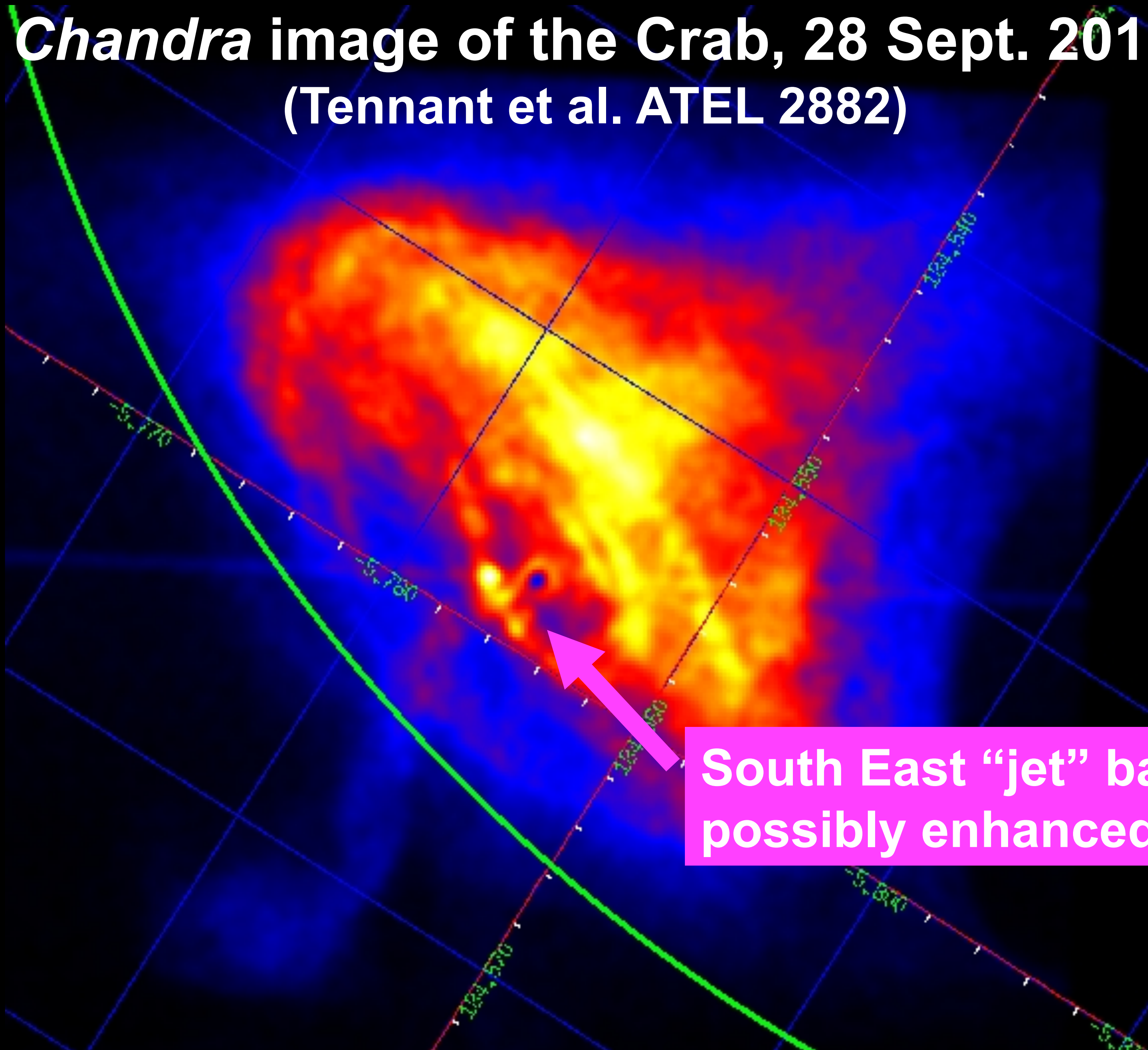
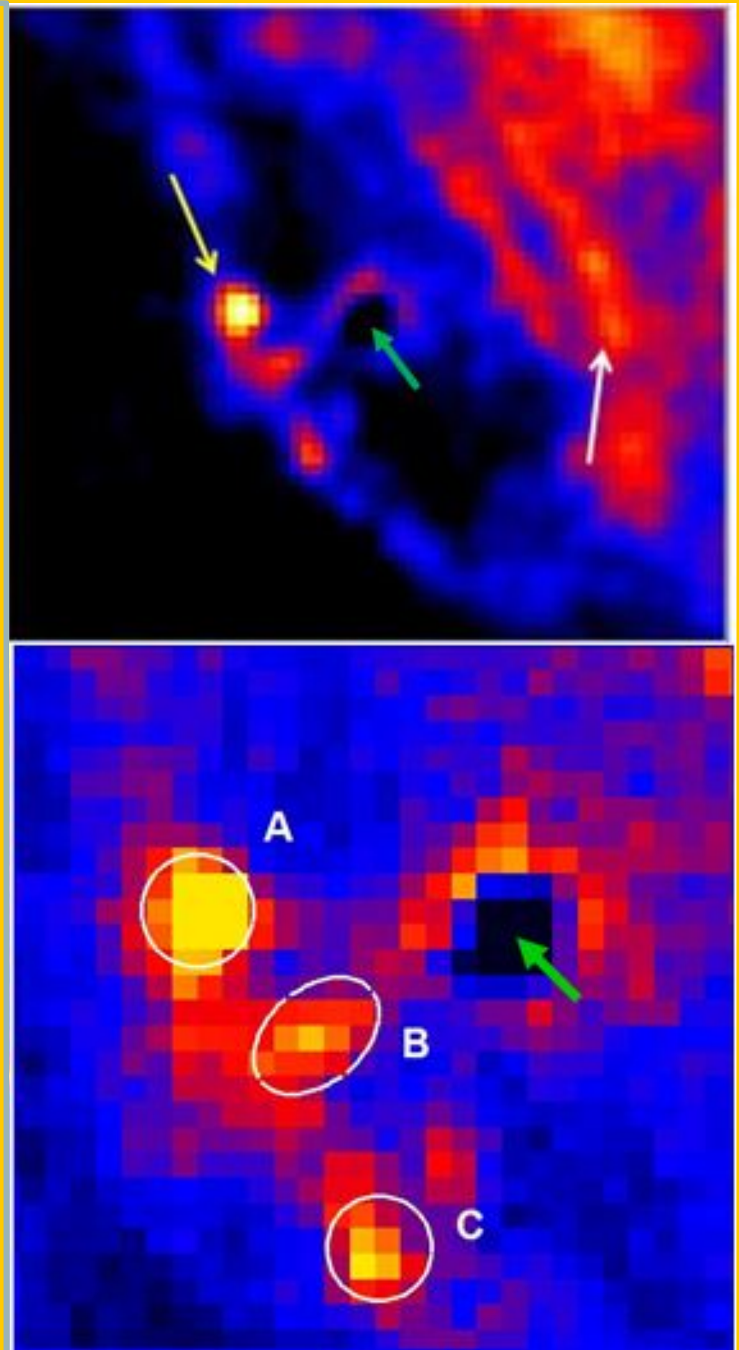
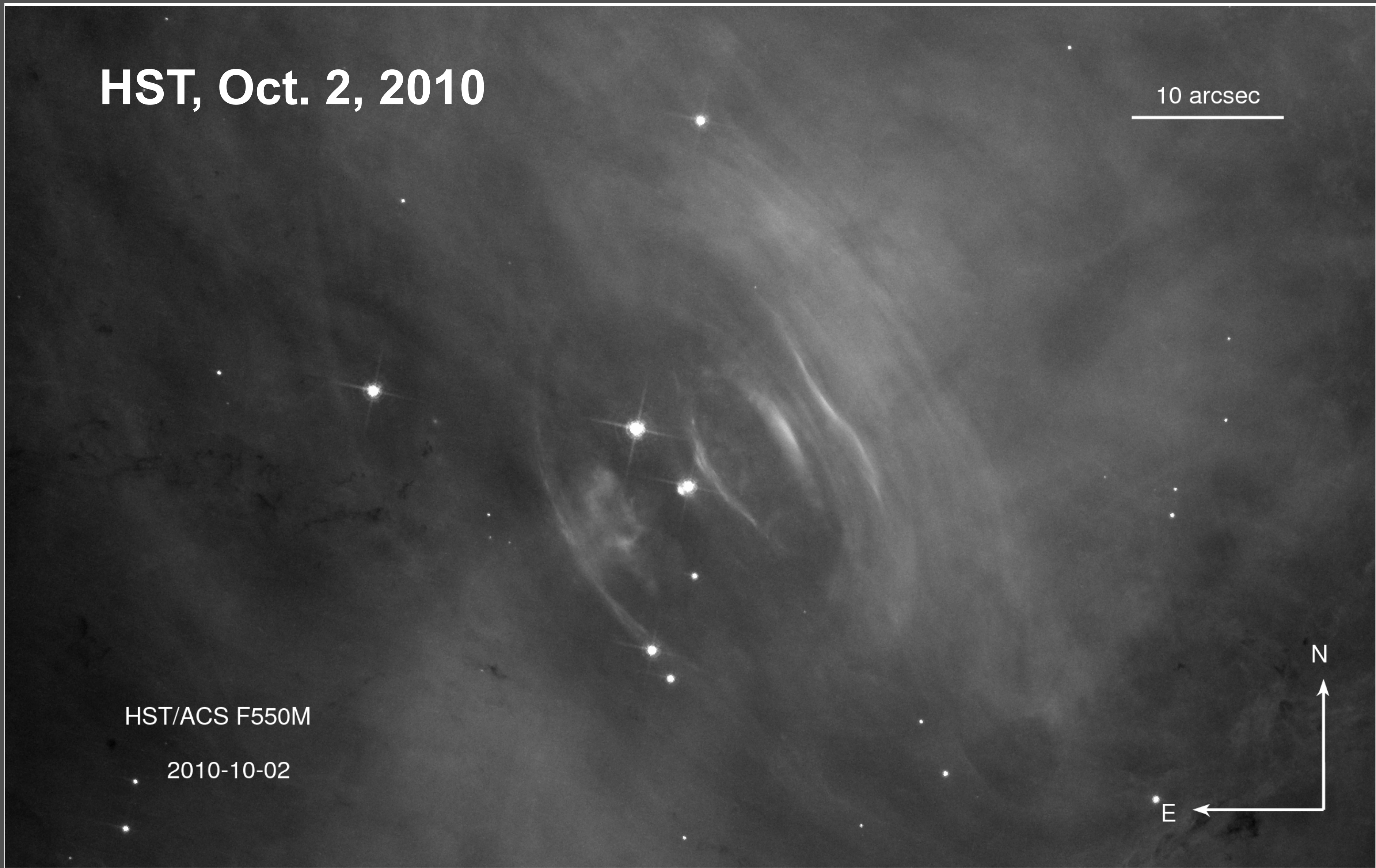
- if it’s nebular emission, what is the ultimate cause of it?
  - PSR wind enhancement (density, local B, change of sigma)
  - Plasma physics, shock changes, sudden change of B-configuration, reconnection (?)
  - near PSR effects (?)
  - Knot-1 (?)
  - “Anvil” region (?)

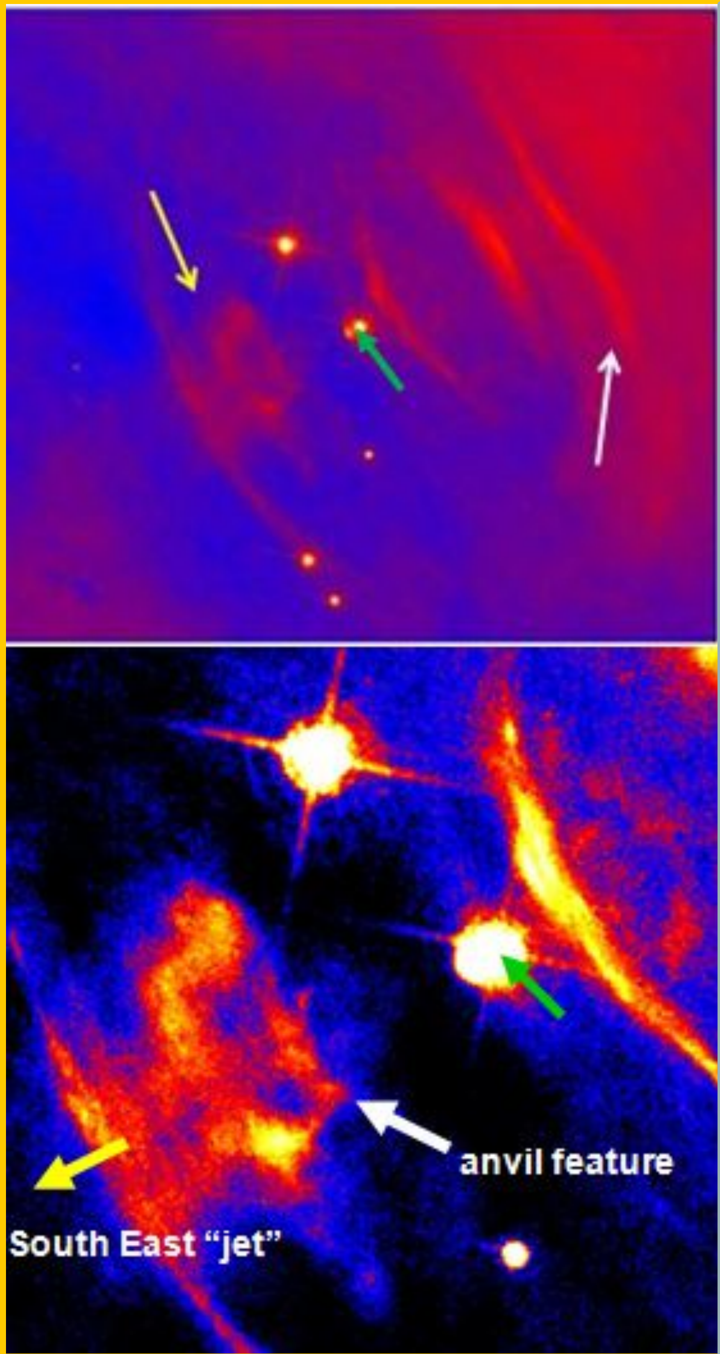
Chandra image of the Crab, 28 Sept. 2010
(Tennant et al. ATEL 2882)

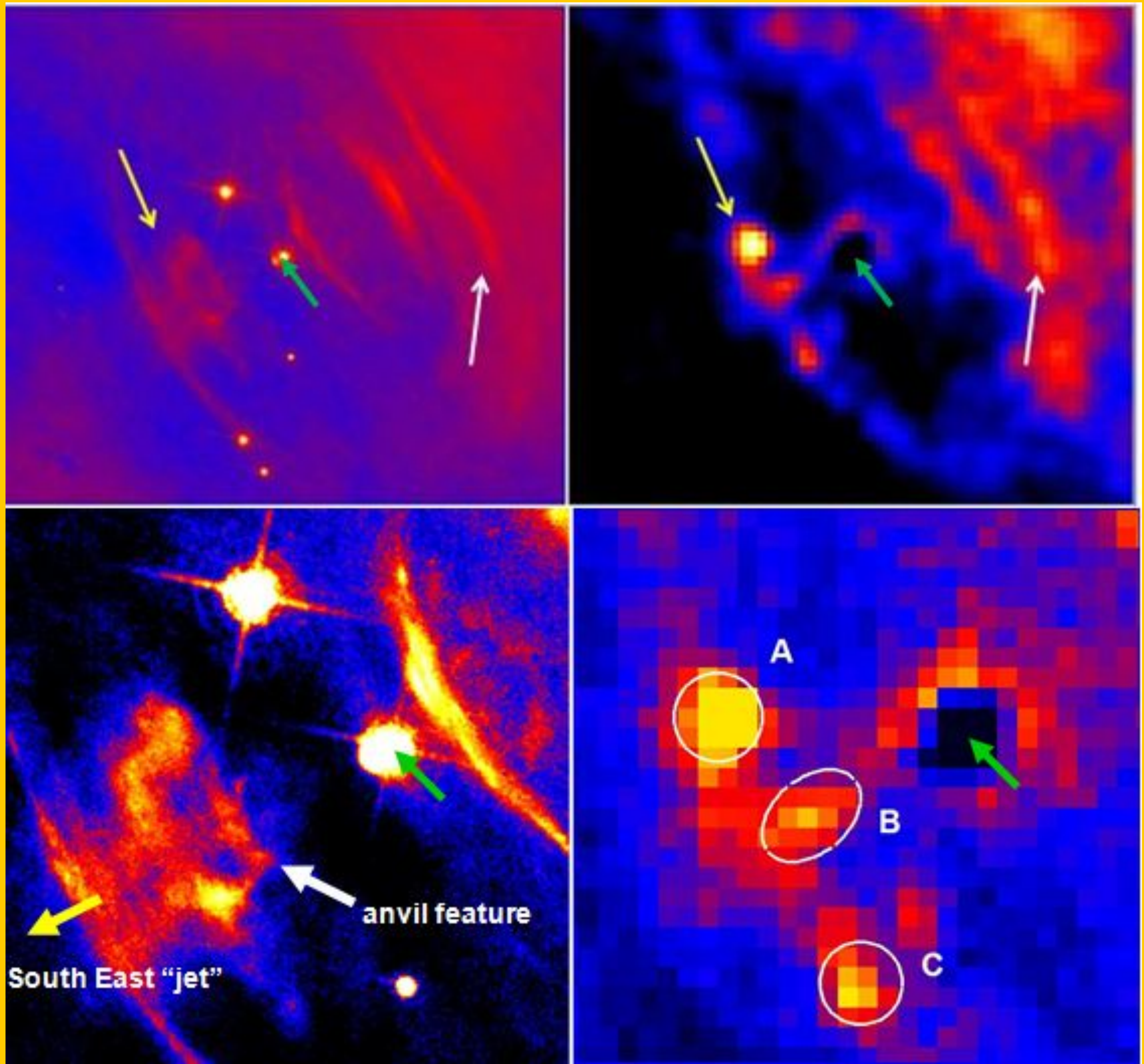


South East “jet” base, possibly enhanced (!?)


A
B
C

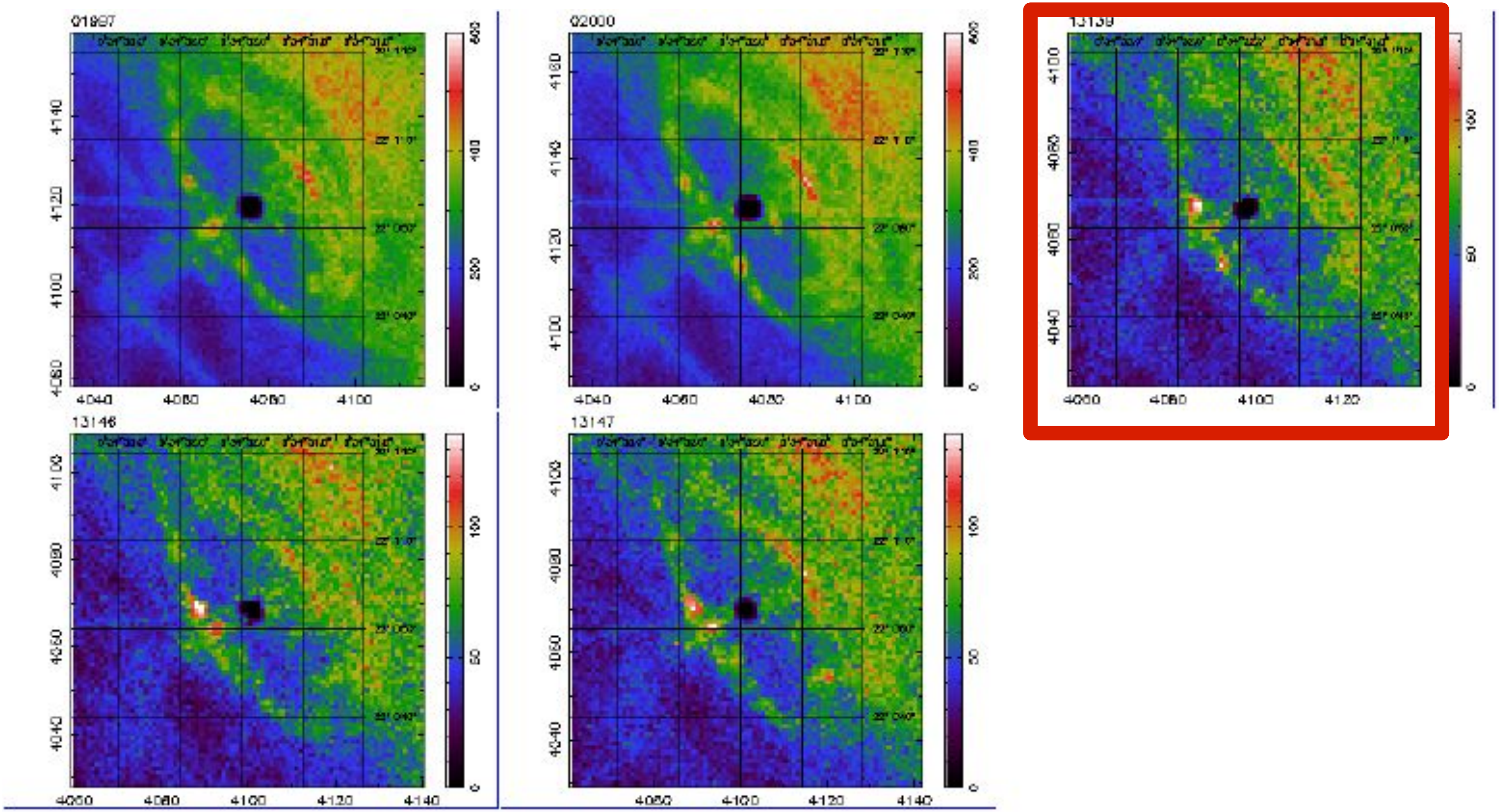

HST, Oct. 2, 2010
10 arcsec
HST/ACS F550M
2010-10-02
N
E

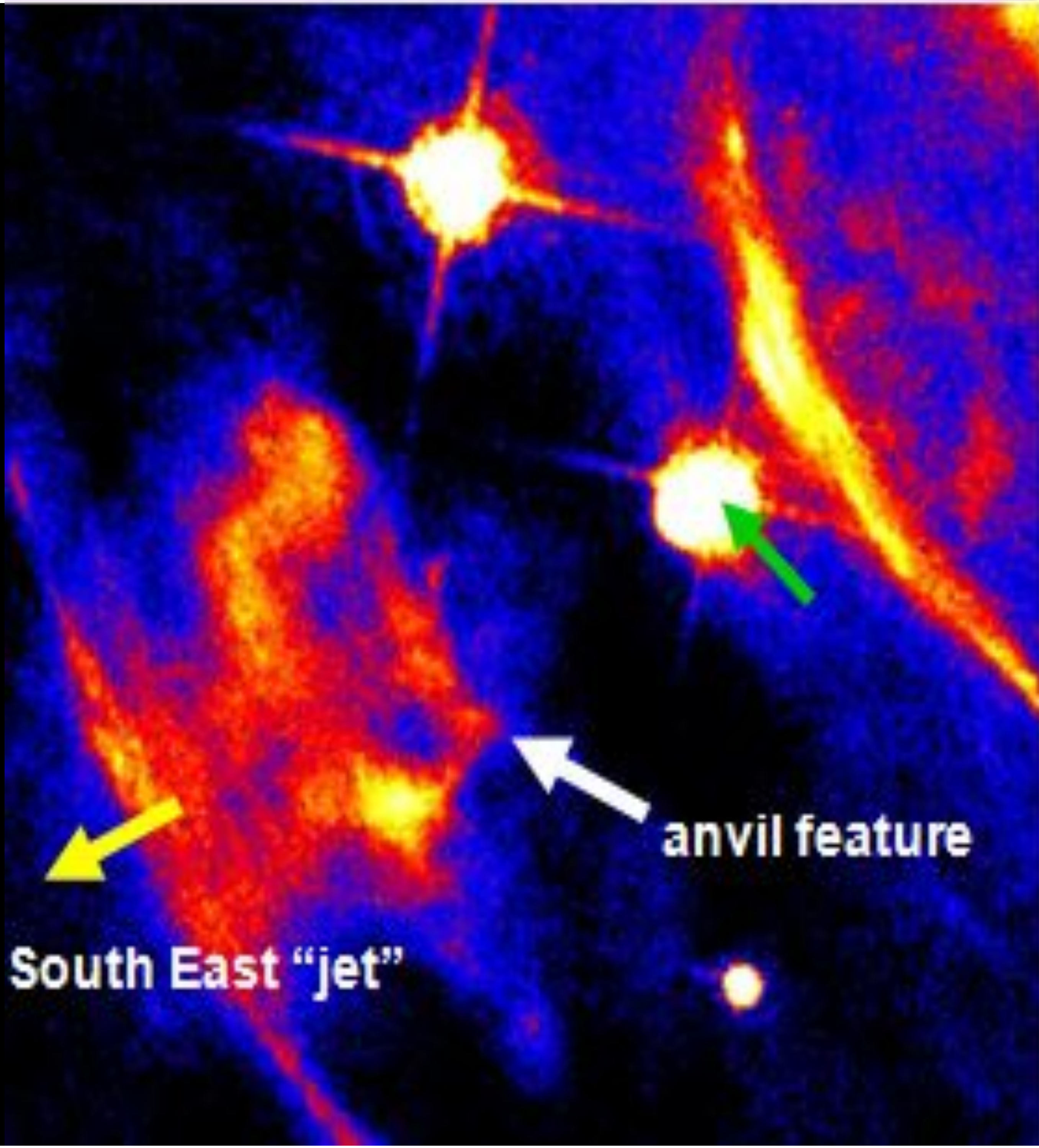

anvil feature
South East "jet"


A
B
C
anvil feature
South East "jet"

sequence of *Chandra* images of the Crab

(A. Tennant, V. Weisskopf)





HST,
Oct. 2, 1010

Crab Sept. 2010 flare

- gamma-ray flare peak luminosity

  $L \approx 5 \cdot 10^{35}$ erg cm^{-2} s^{-1}

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

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

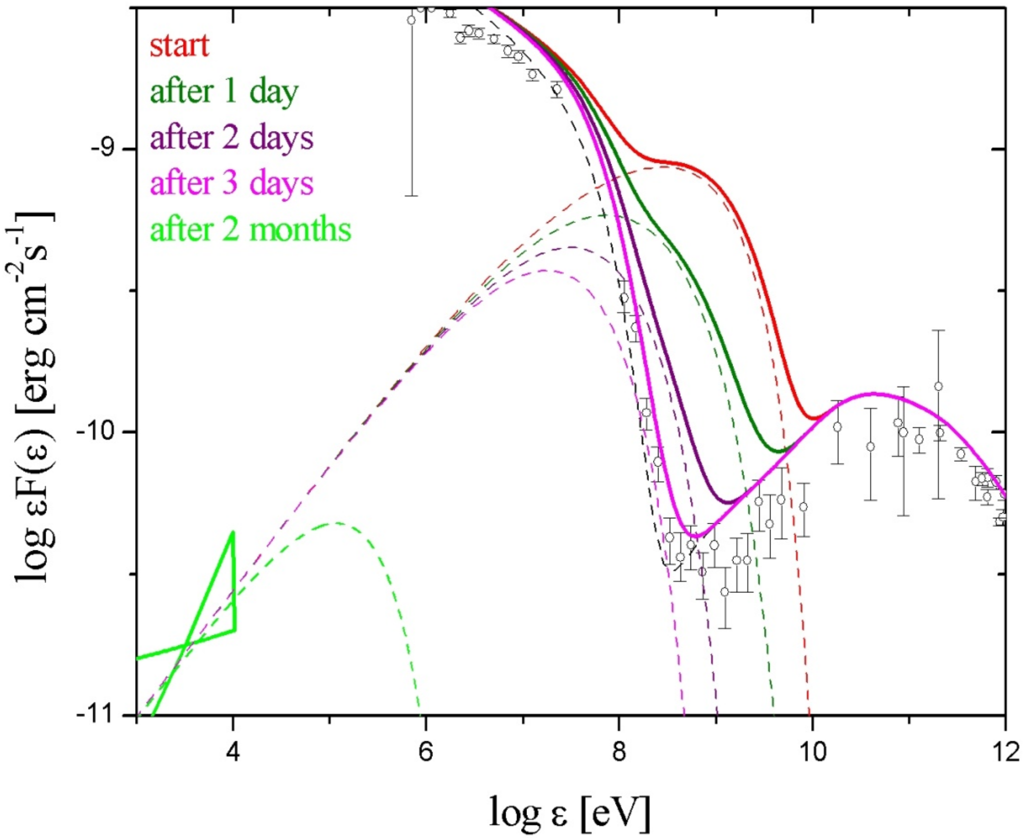
- timescales:
  - risetime: $\leq$ 1 day ← very efficient acceleration !
  - decay: ~ 2-3 days ← fast cooling, B, Lorentz γ

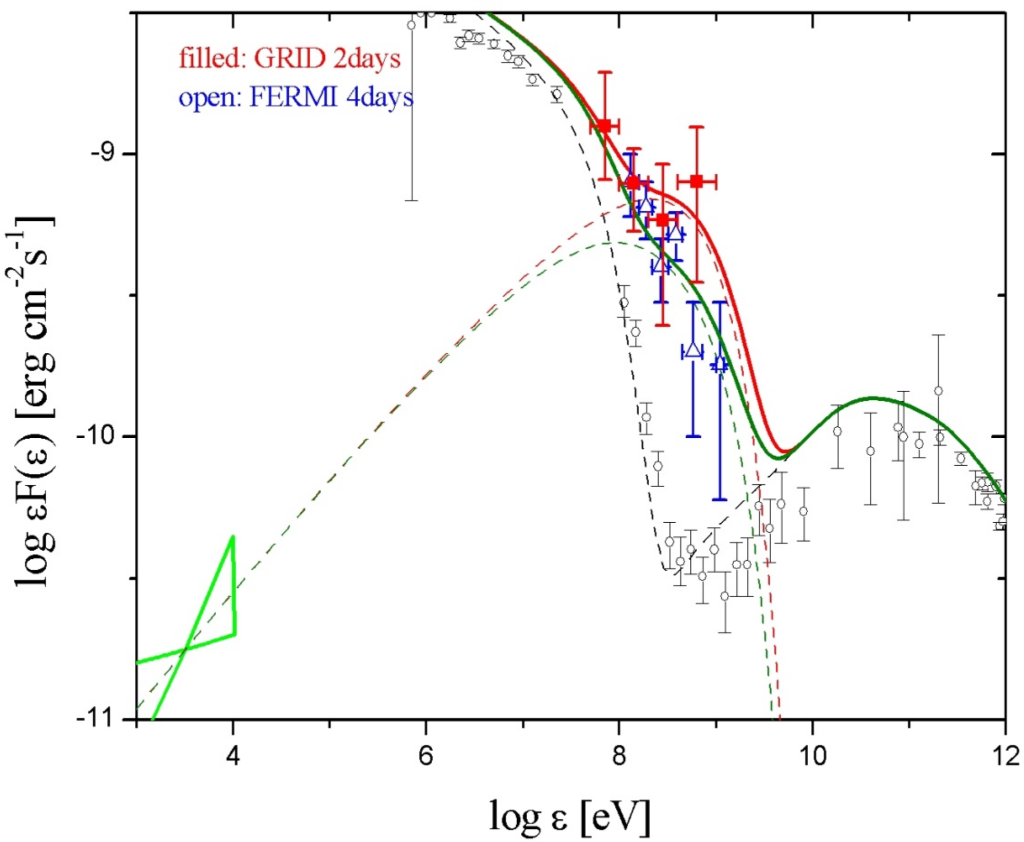
- **crucial constraints on particle acceleration theory !**
  - **e-/e+ shock acceleration by magnetic turbulence (diffusive vs. non-diffusive)**
  - **ion cyclotron absorption (e.g., J.Arons et al.)**

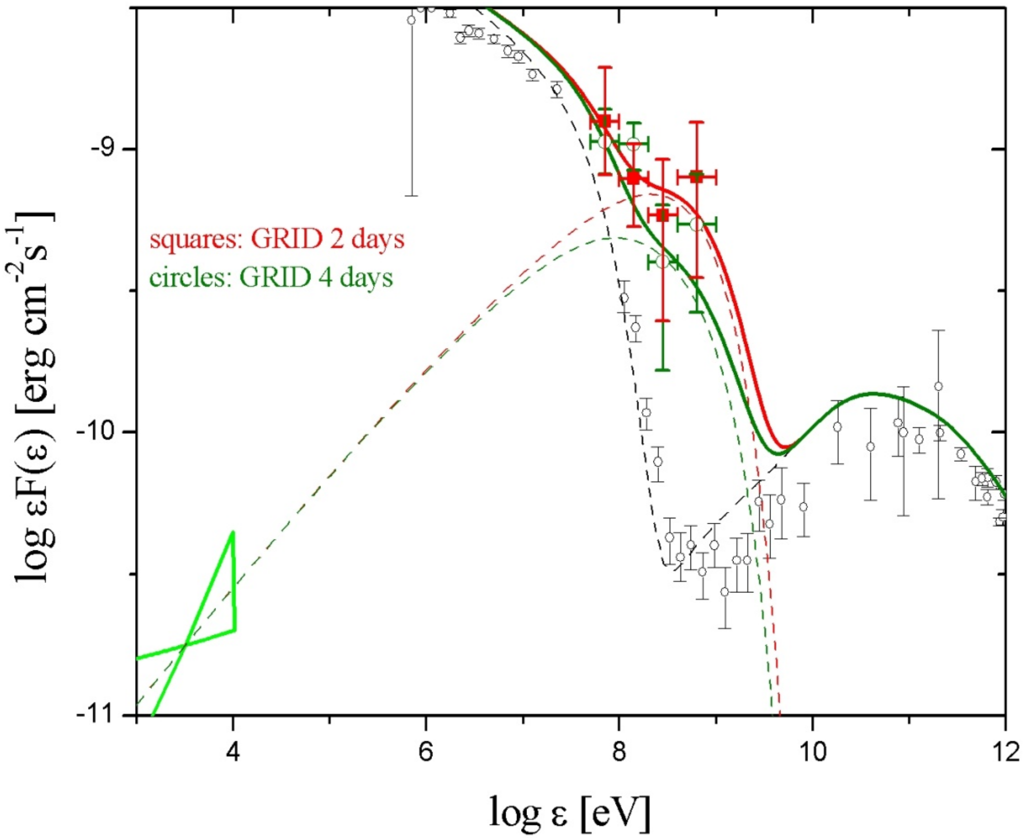
- **Crab Nebula shocks able to accelerate electrons/positrons at $\gamma \sim 10^9$ (PeV) !**
  - **already inferred from "static" Nebula models (e.g., deJager & Harding, Atoyan & Aharonian)**
  - **never observed within a 1 day timescale !**

a model (Vittorini V., M.T. et al., ApJ, accepted 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**
- $\gamma_{max} \approx \gamma_{break} \leq 10^9 \, (E/B)(\delta\, \alpha'/\sin\theta)^{1/2} \, (B/10^{-3}\text{ G})^{-1/2}$
- $\delta = 1$


start
after 1 day
after 2 days
after 3 days
after 2 months
-9
-10
-11
4
6
8
10
12
log εF(ε) [erg cm-2 s-1]
log ε [eV]


filled: GRID 2days
open: FERMI 4days
log εF(ε) [erg cm-2 s-1]
log ε [eV]
-9
-10
-11
4
6
8
10
12


log εF(ε) [erg cm-2s-1]
log ε [eV]
squares: GRID 2 days
circles: GRID 4 days
-9
-10
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4
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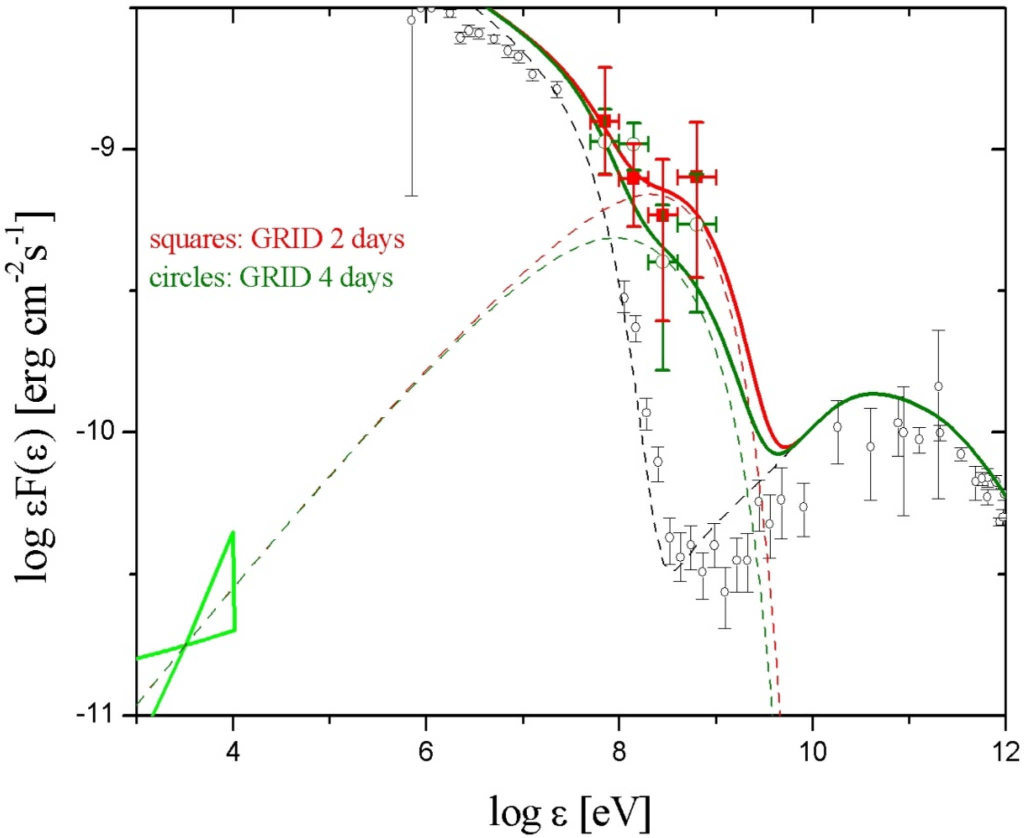
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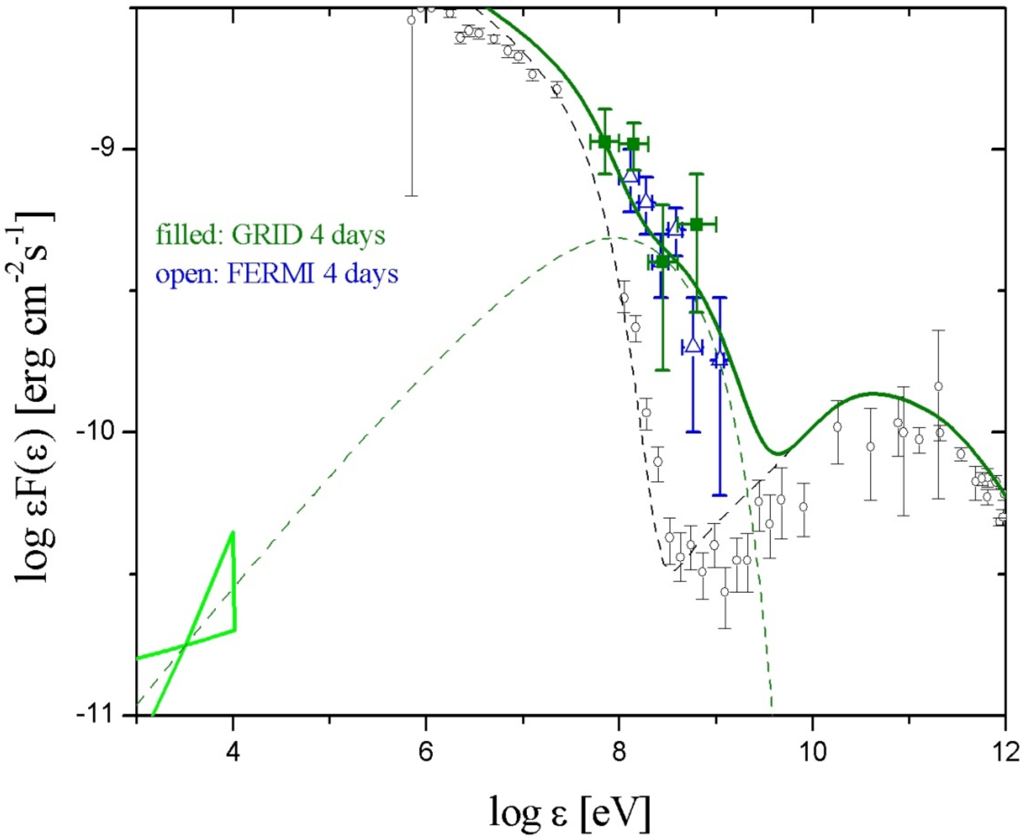
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filled: GRID 4 days
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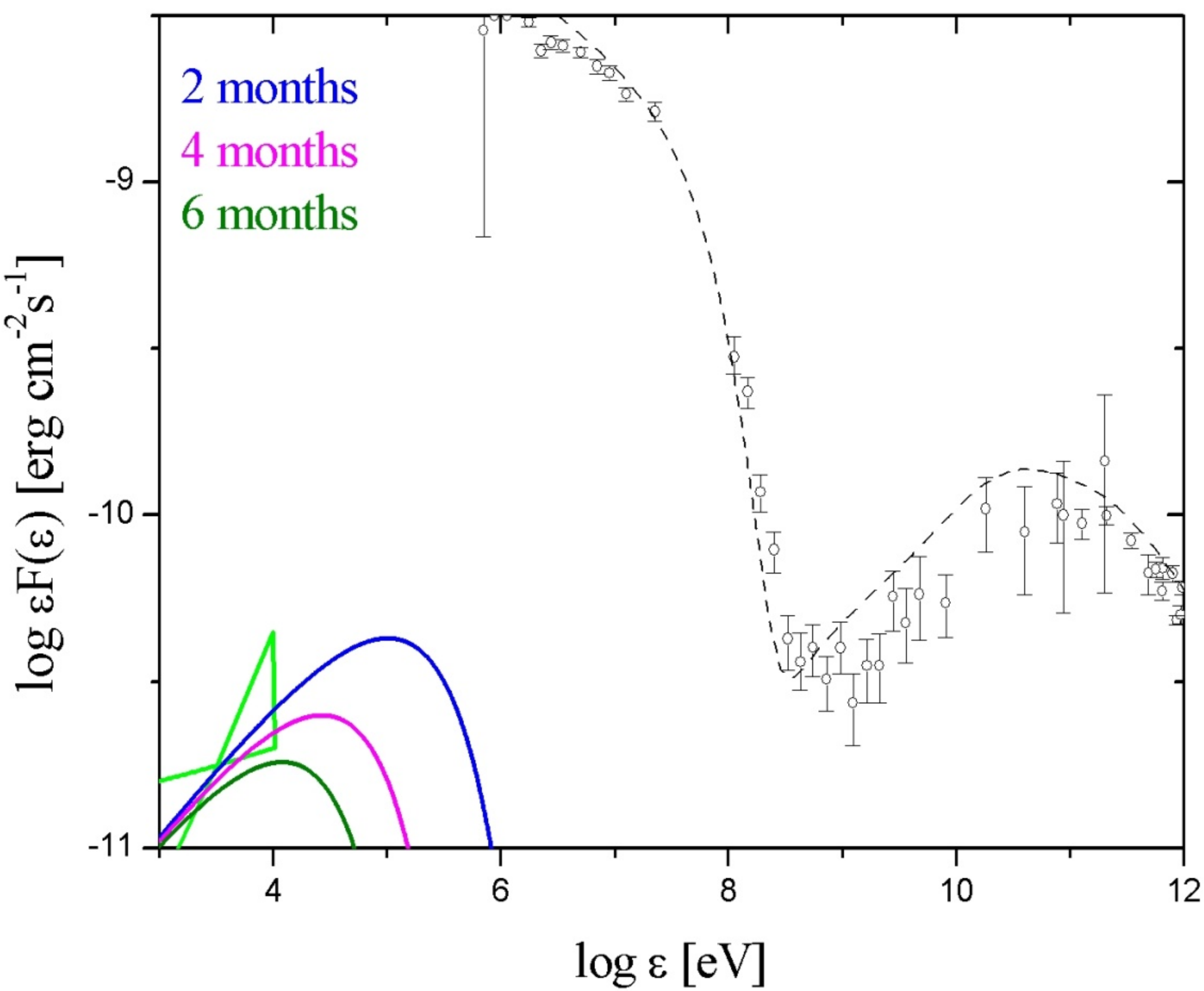

2 months
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12
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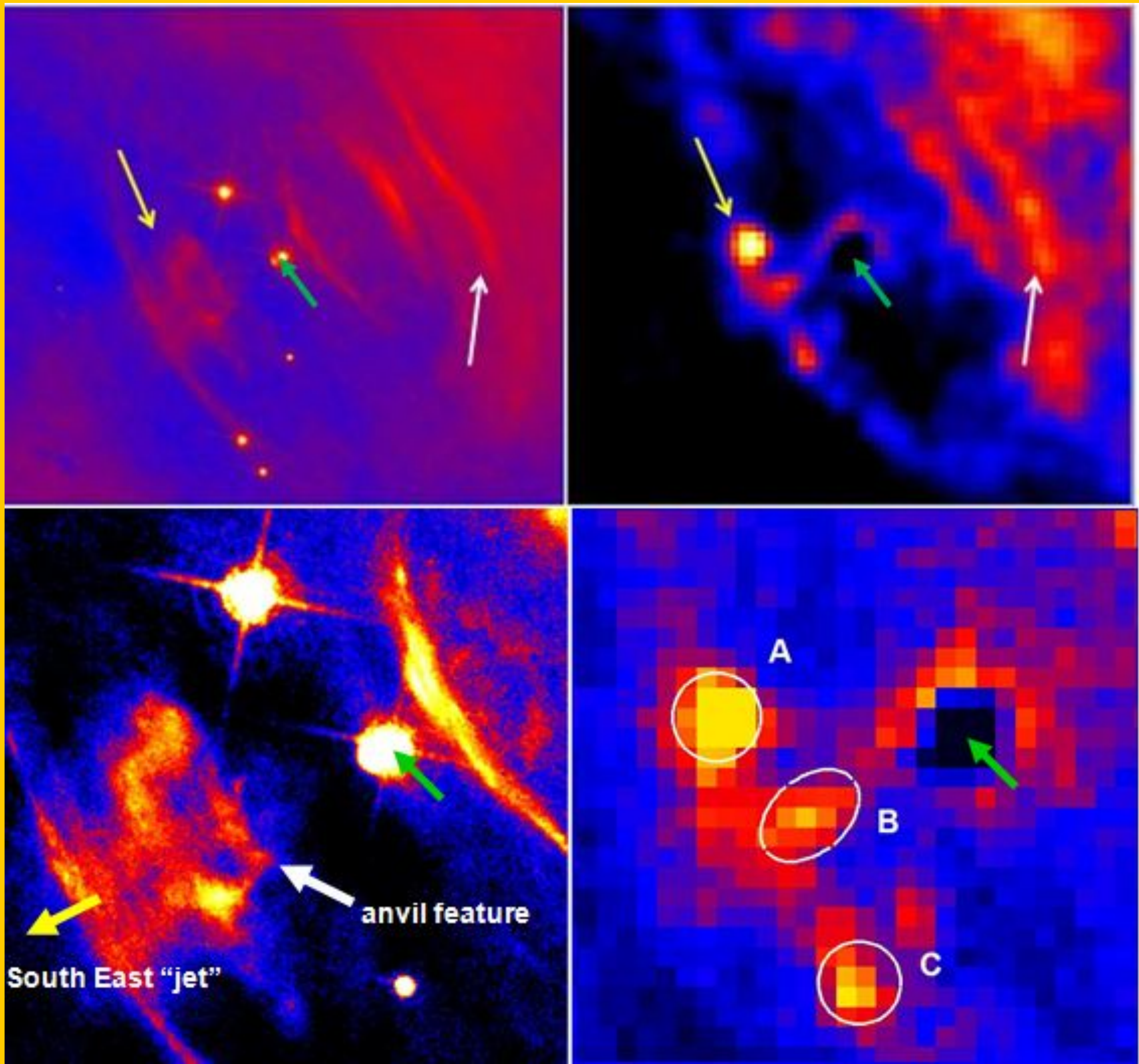
Hubble (optical) Oct. 2, 2010 *Chandra* (X-rays) Sept. 28, 2010



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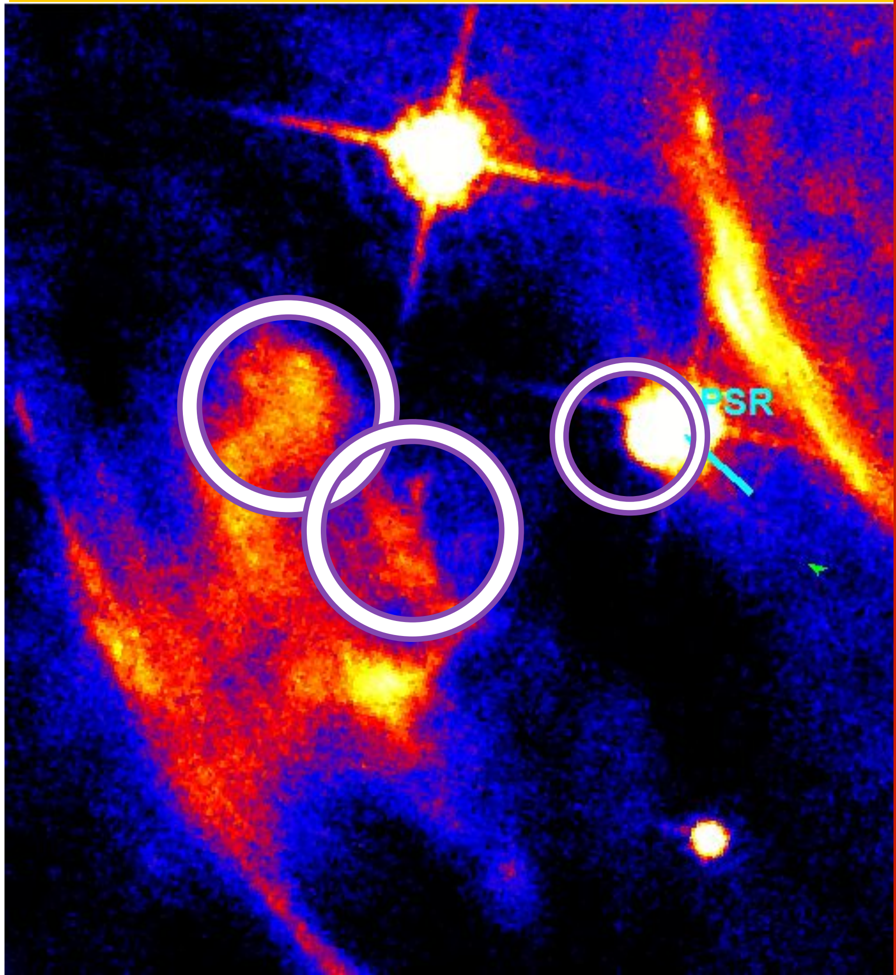

PUZZLING ACCELERATION:

- fast flares imply VERY EFFICIENT particle acceleration, and "small" emission sites

- *FAST ACCELERATION inconsistent with "slow" diffusion processes, a big challenge*

- acceleration up to 10^{15} eV, 1000 times larger than Tevatron or LHC

-

- shock structures might be the sites of transient gamma-rays,
HST and Chandra candidates

issues

- MHD simulations give too long timescales
- detailed acceleration mechanism to be identified
- not clear if the right E-parallel is produced

E-parallel

- Instability: magnetic field reconnection
  - Multi-island dynamics
- Current sheets
- Relativistic shocks

- **Work in progress**
  - **old MHD models appear inadequate**
  - **combination of MHD and magnetic field reconnection**
  - **complex calculations: more work to be done**

- **short timescale Crab variability (Sept. 2010):**

  - currently published data:
    - 2-day integration (AGILE)
    - 4-day integration (Fermi)

  - study 1-day and 12-hr integrations

  - are AGILE and Fermi data consistent with 12-hr variability ?

- **very exciting results, the Crab Nebula produces ~day-long gamma-ray flares ! Not a standard candle in gamma-rays.**

- **nebular origin, not clear yet the association with a wisp or feature, South East “jet” base ?**

- **dramatic confirmation of high-efficiency relativistic particle acceleration**

- **we need extended monitoring of the Crab Nebula**
  - **Chandra**
  - **HST**
  - **…**

- **we need fast reaction to the next gamma-ray flares**

Conclusions

- **we "lost" the stability of an ideal reference source, but gained tremendous information about the fundamental process of particle acceleration**

- **a big theoretical challenge**
  - **shock acceleration + magnetic field reconnection ?**
  - **current sheet and MHD instabilities**
  - **Doppler boosting ?**

- **the ultimate site of particle acceleration needs to be established: future surprises**