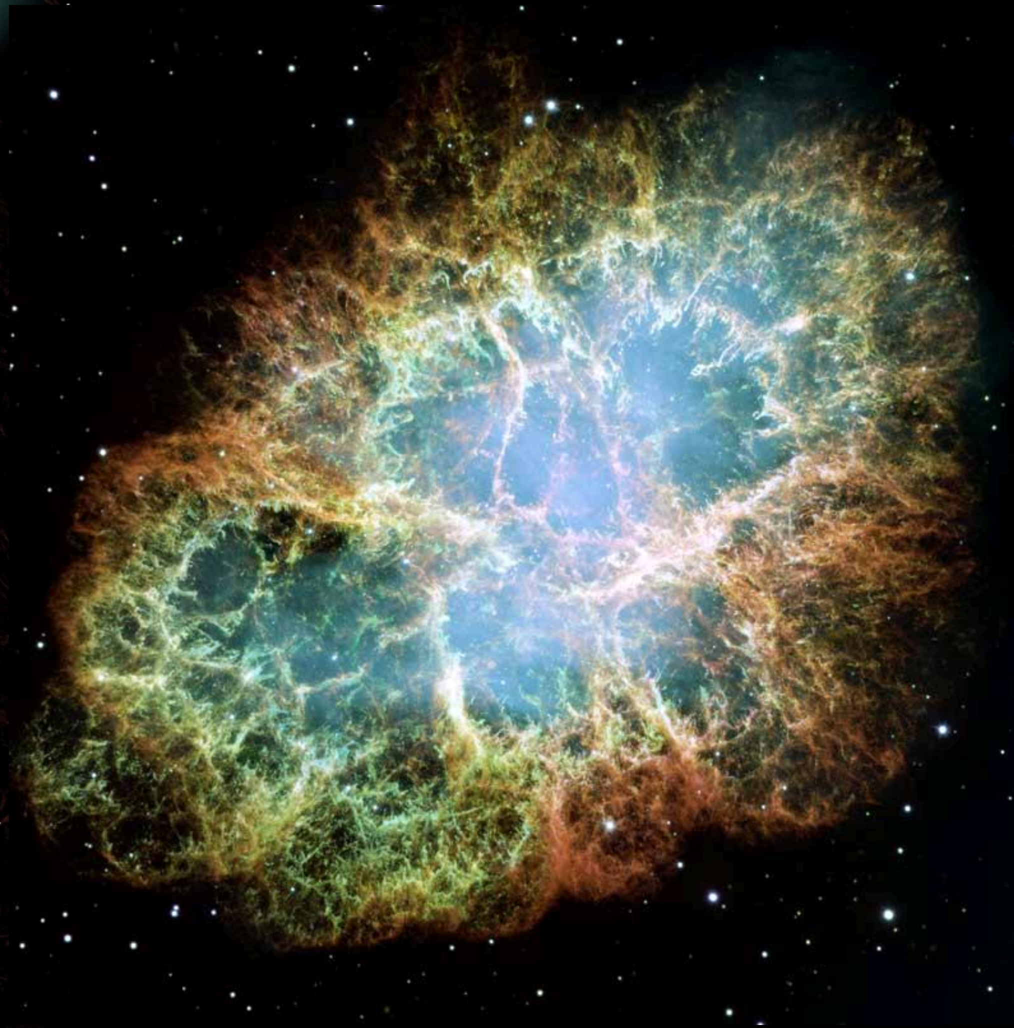
High-energy Astrophysics and particle acceleration: recent developments and challenges for plasma physics

M.Tavani

IGNITOR Plasma Workshop

Moscow, 13 maggio 2011

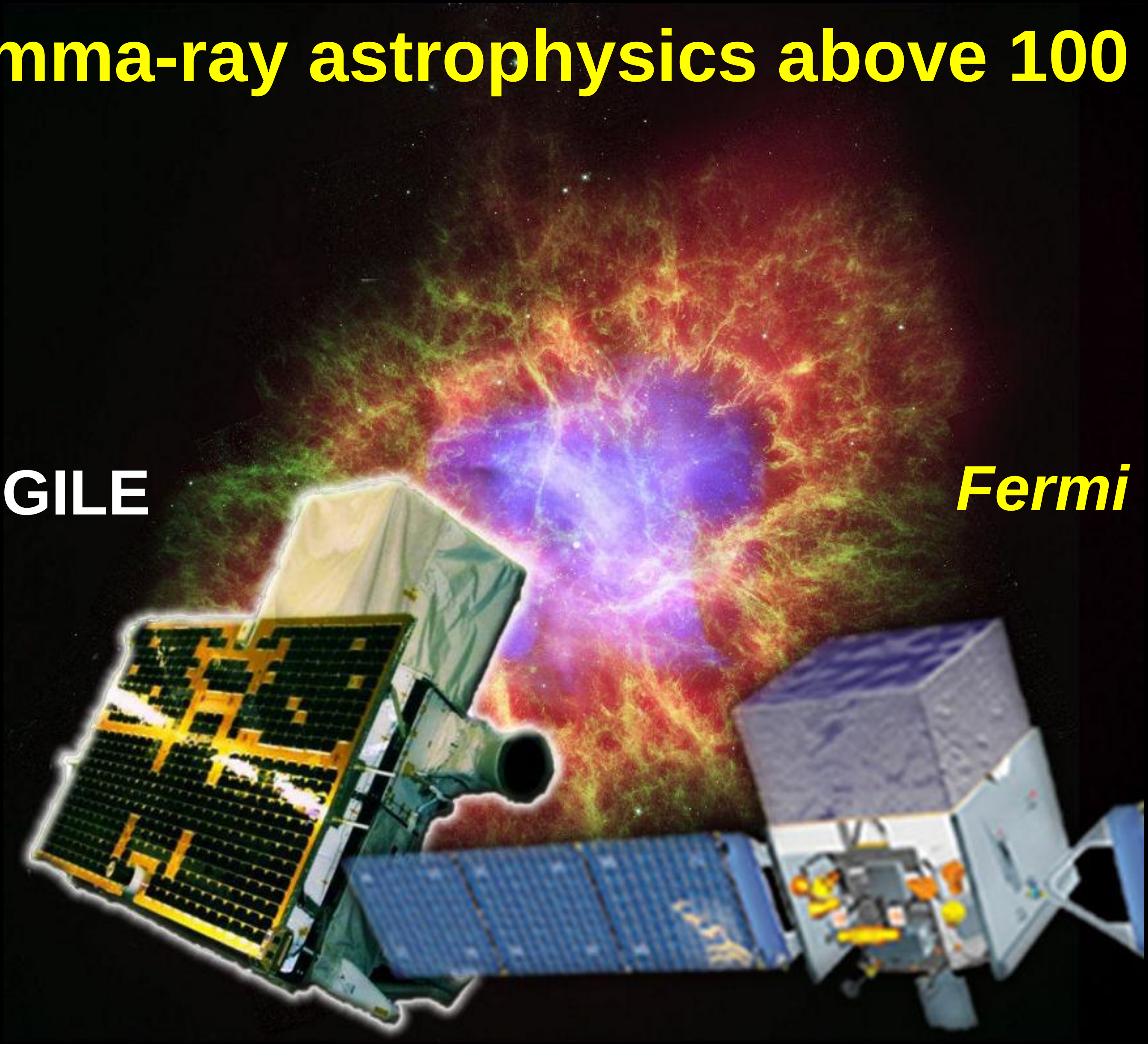
cosmic accelerators (hadronic vs. leptonic)



High-energy astrophysics challenges

- unique time for high-energy astrophysics
- more than a dozen observatories/facilities active in the range X-ray/gamma-rays/TeV
- particle acceleration in
  - Neutron stars and PWNe
  - Black holes
  - Supernova Remnants
  - AGNs (blazars)
  - GRBs

Gamma-ray astrophysics above 100 MeV

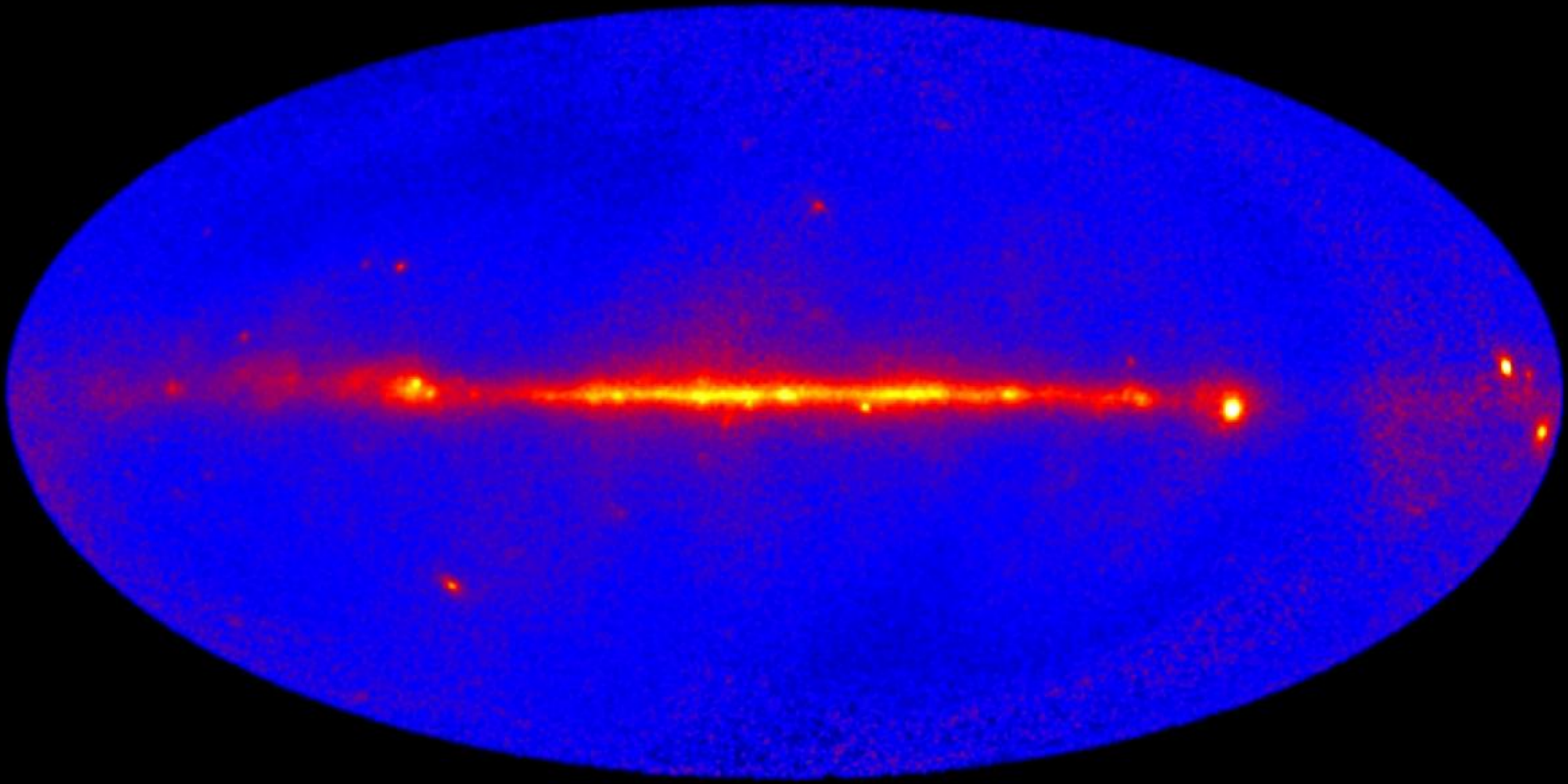


Picture of the day, Feb. 28, 2011, NASA-HEASARC

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



Challenges

- Compact stars
  - white dwarfs
  - neutron stars
  - black holes (BH)

- Particle acceleration
  - relativistic pulsar winds and nebulae
  - Supernova Remnants
  - relativistic jets
  - accretion disks
  - BH inner regions
  - Hypernovae
  - AGNs

- Active Galactic Nuclei (AGN)

Progress

- **Compact stars**
  - **white dwarfs: novae and gamma-ray emission**
  - **neutron stars: pulsars, millisecond pulsars, binary pulsars**
  - **black holes (BH): microquasars (Cygnus X-1, Cygnus X-3)**

- **Particle acceleration**
  - **relativistic pulsar winds and nebulae: Crab Nebula, Vela-X**
  - **Supernova Remnants: origin of cosmic-rays**
  - **relativistic jets: precursor activity and plasmoid ejection**
  - **accretion disks: Cyg X-3 instabilities, BH emission states**
  - **BH inner regions: Galactic Center, GRBs**
  - **Hypernovae: GRBs**
  - **AGNs: blazars**

- **Active Galactic Nuclei (AGN): blazars**

Progress

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- **Particle acceleration**
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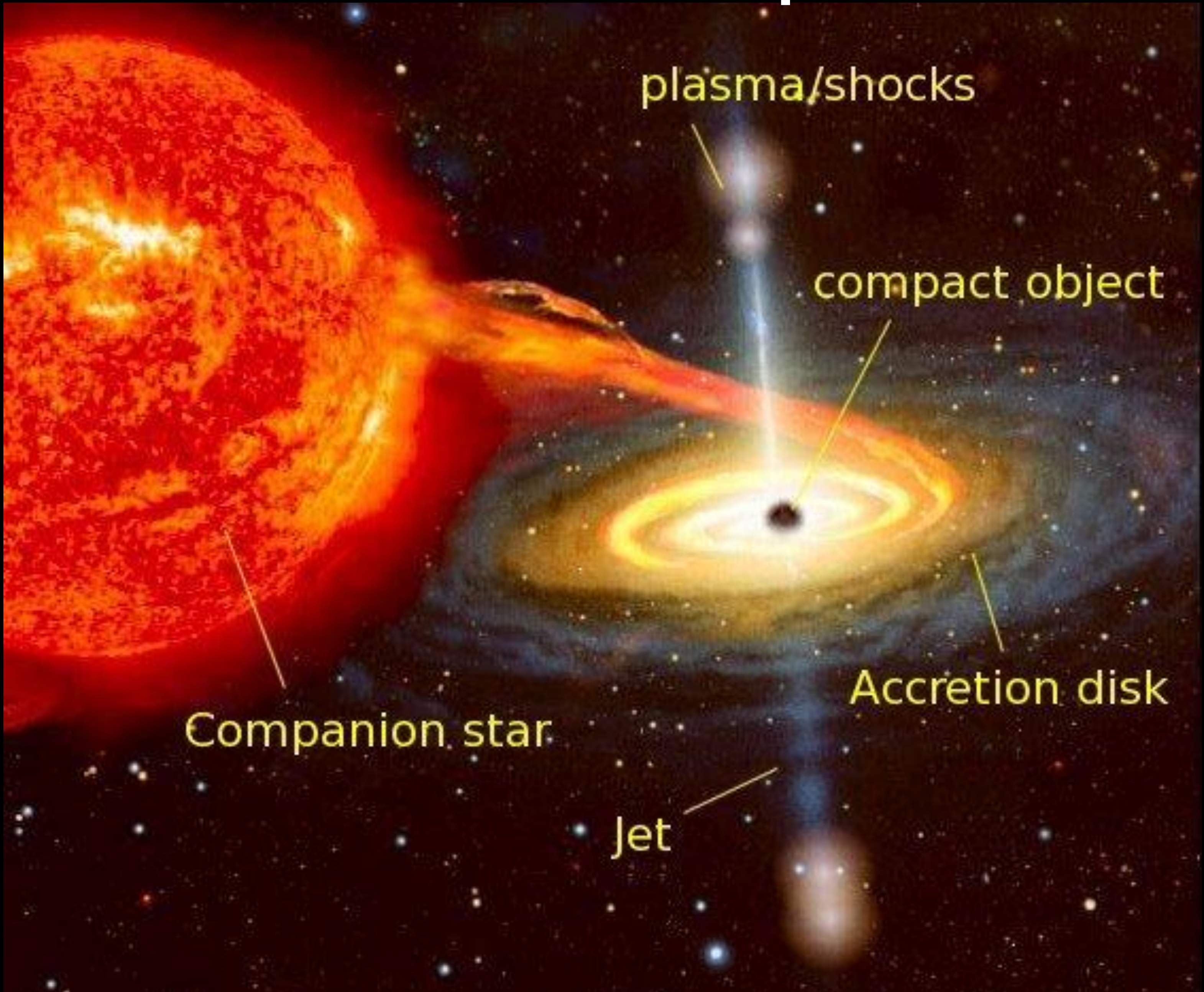
  - **Hypernovae: GRBs**
  - **AGNs: blazars**

- **Active Galactic Nuclei (AGN): blazars**

surprises for plasma astrophysics: unexpected discoveries about:

- **Cygnus X-3**
- **Crab Nebula**
- **SNRs and origin of cosmic rays**

Galactic micro-quasars

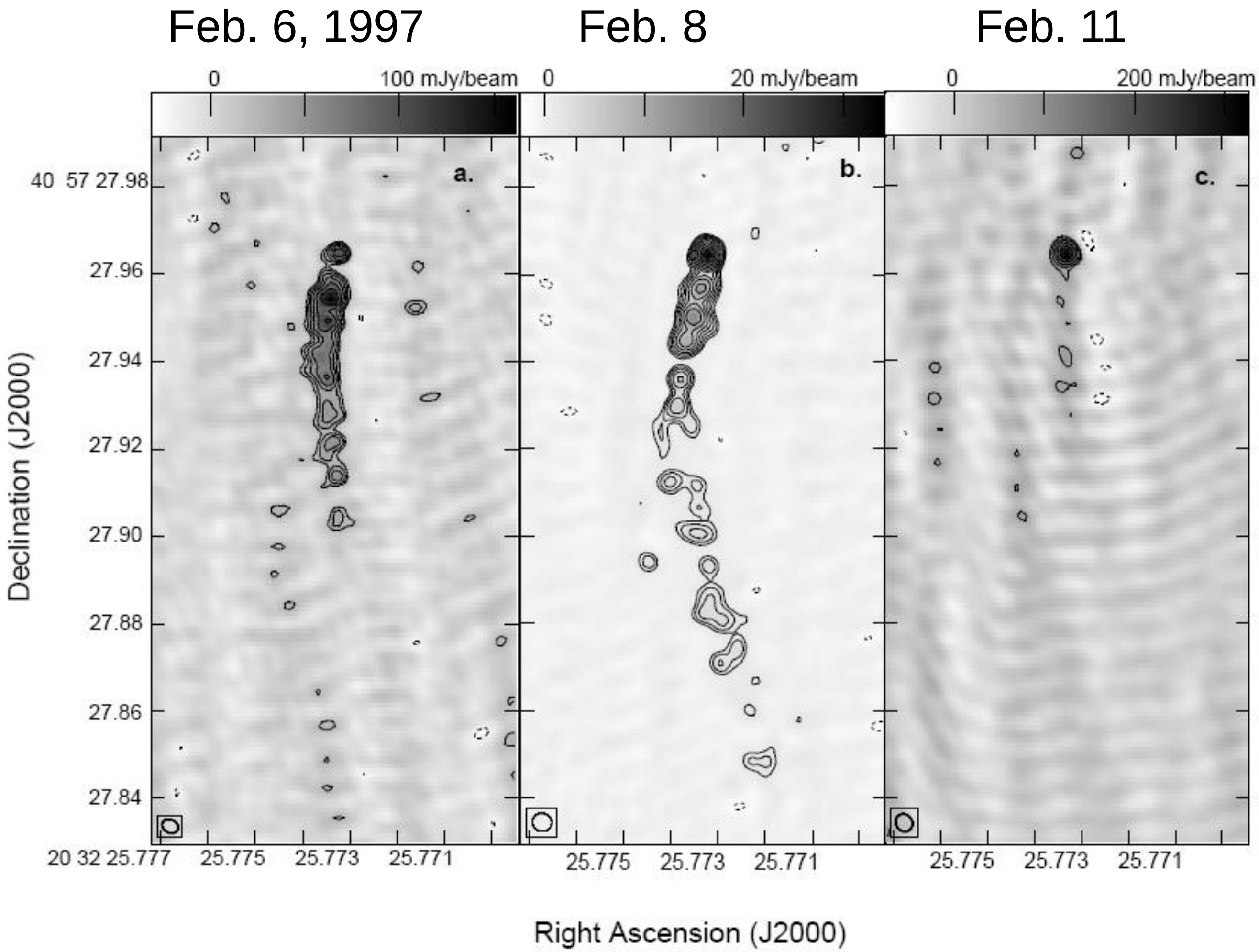


Galactic "Micro-quasars"

	Θ (degrees)	β	Γ	L_X/L_E	γ/TeV
Cyg X-1	?	?	?	0.1-1	YES
Cyg X-3	< 14	> 0.8	> 1.6	0.1-1	YES
SS 433	80	0.26	1.03	0.01	no
GRS 1915+104	70	0.92	2.5	0.1-1	no
GRO J1655-40	> 70	0.9	2.5	1	no
GRS 1758-258	?			0.1-1	no
XTE J1550-564	60-70	> 0.8	1.5	0.1-1	no
Sco X-1	> 70	> 0.8	> 1.6	0.1-1	no
LS I 61 303	?	?	?	10^{-4}	yes
LS 5039	< 80	> 0.2	?	10^{-4}	yes

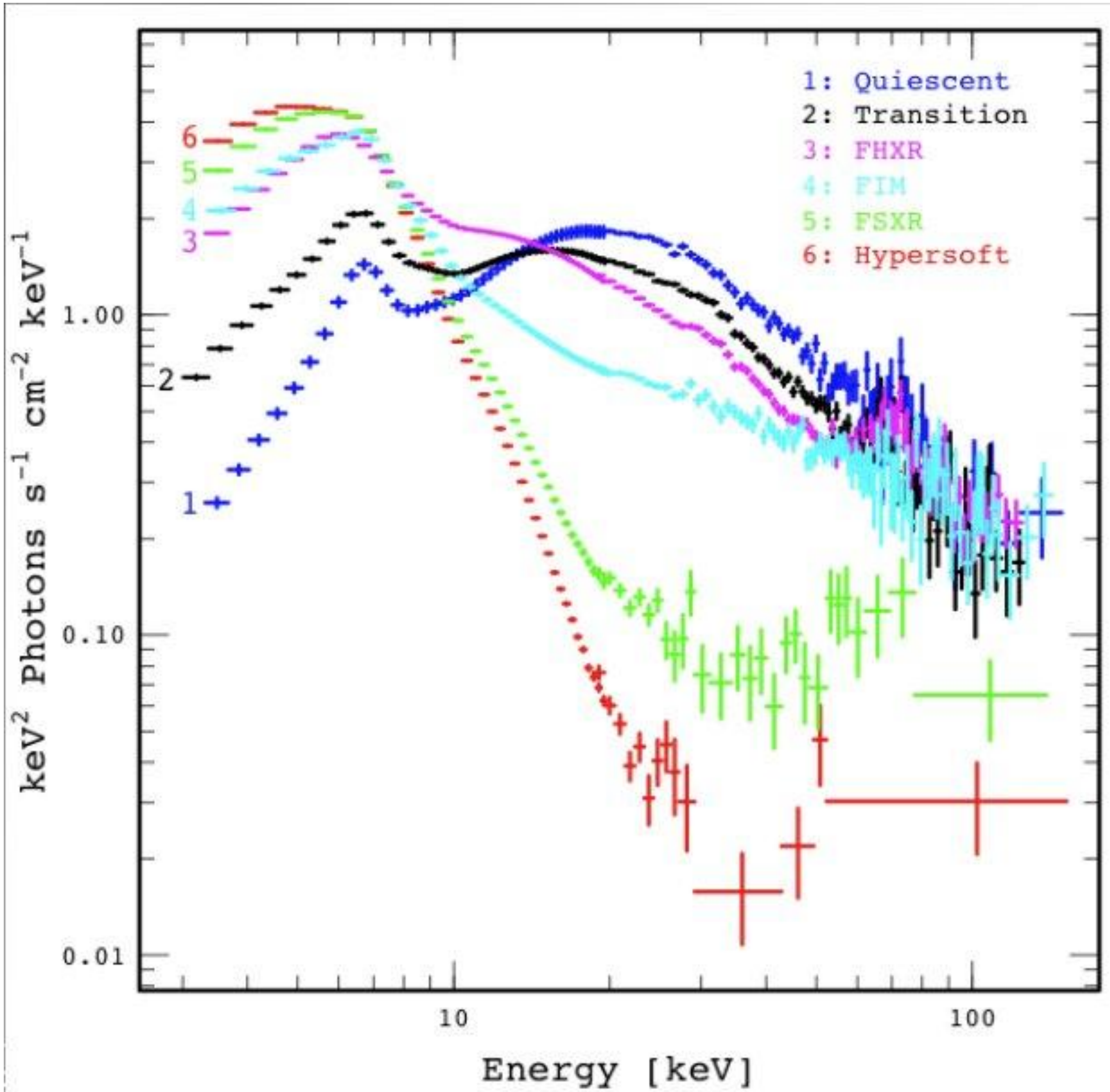
Relativistic jets from Cyg X-3

(Mioduszewski, Rupen, Hjellming, Pooley, Waltman, 2001)

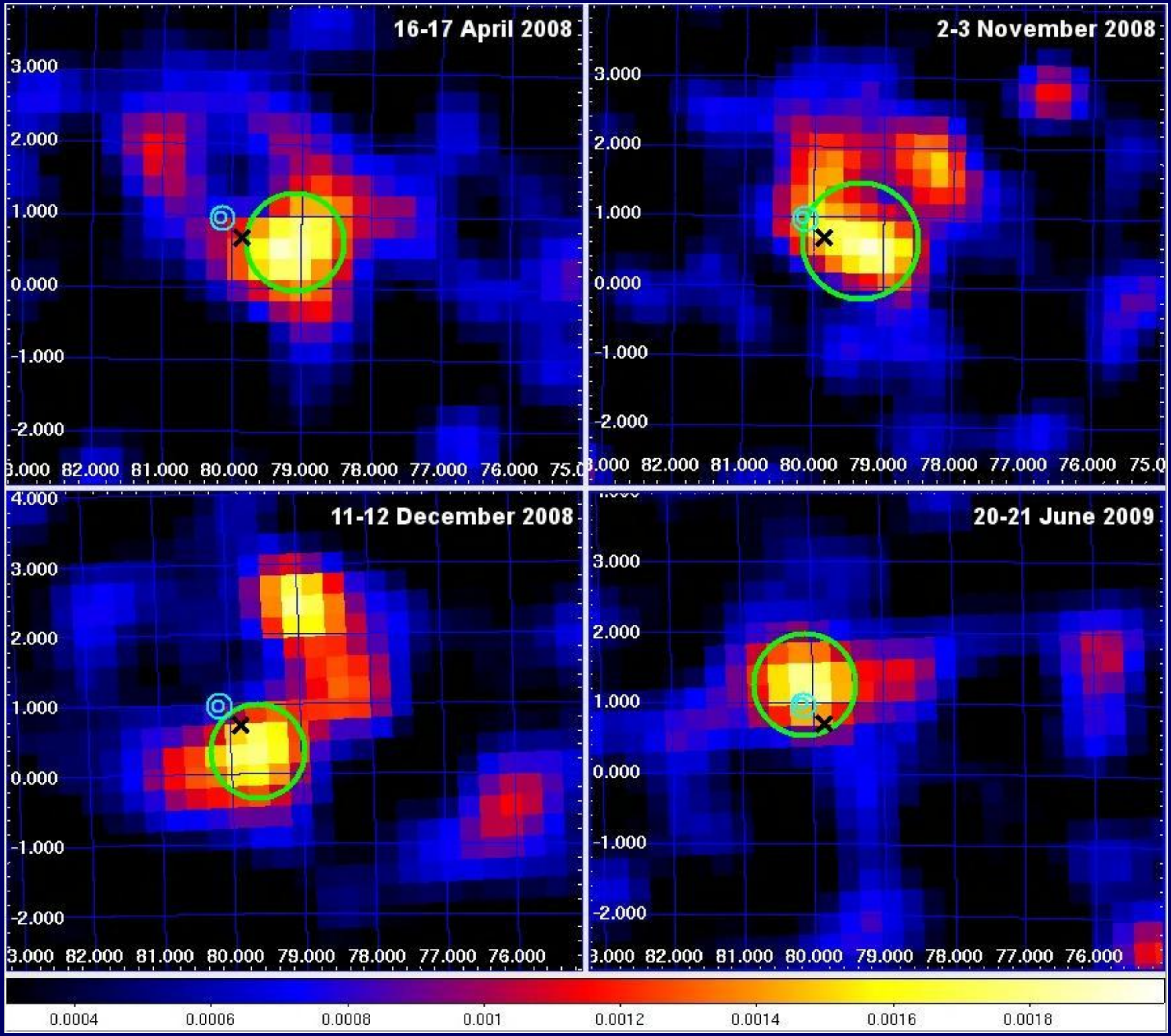


CYGNUS X-3 spectral states

(Koljionen et al., 2010 Szostek, Zdziarski, Mc Collough et al., 2008)

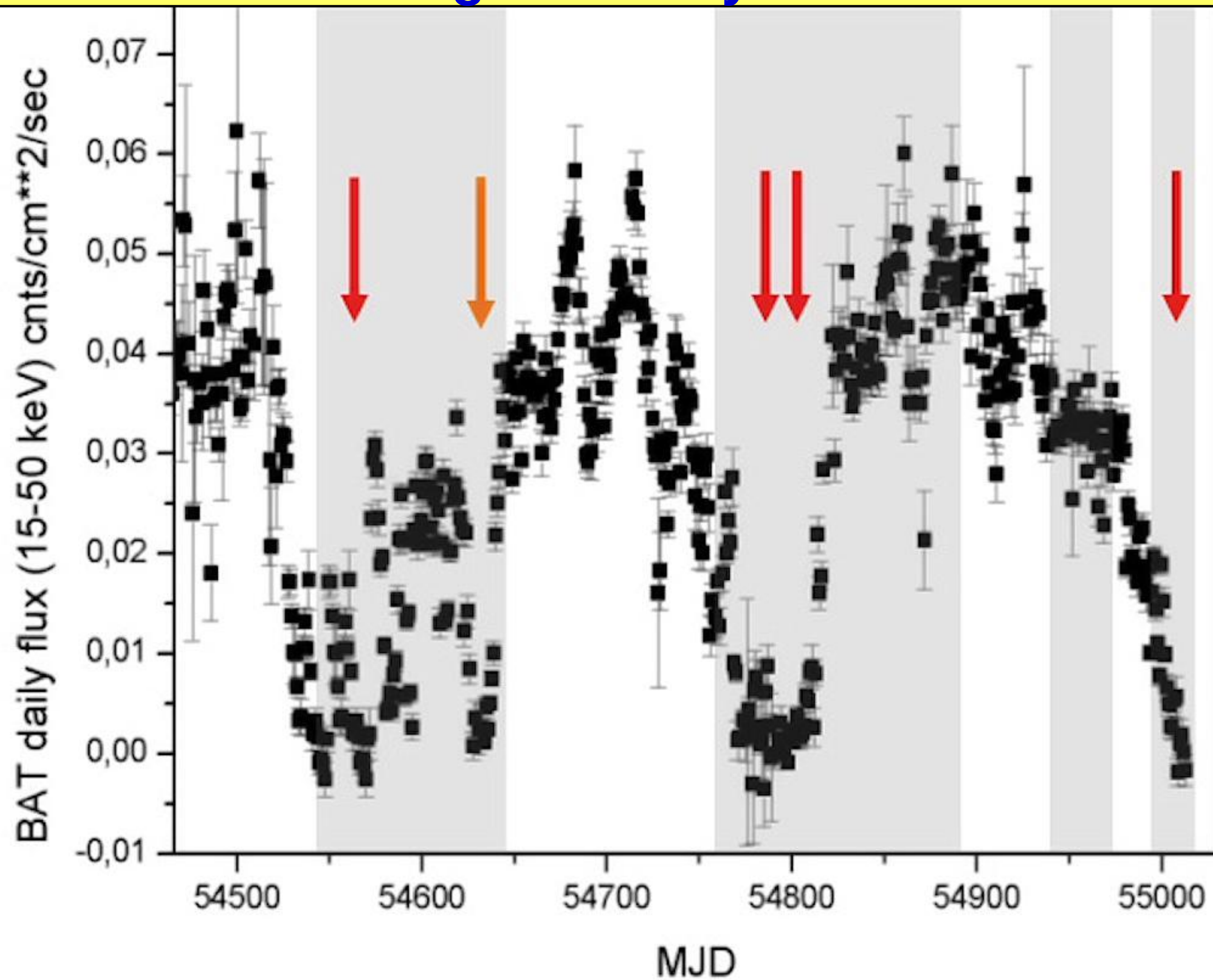


AGILE discovery of transient gamma-ray emission from Cygnus X-3 (*Nature*, 462, 620, 2009)



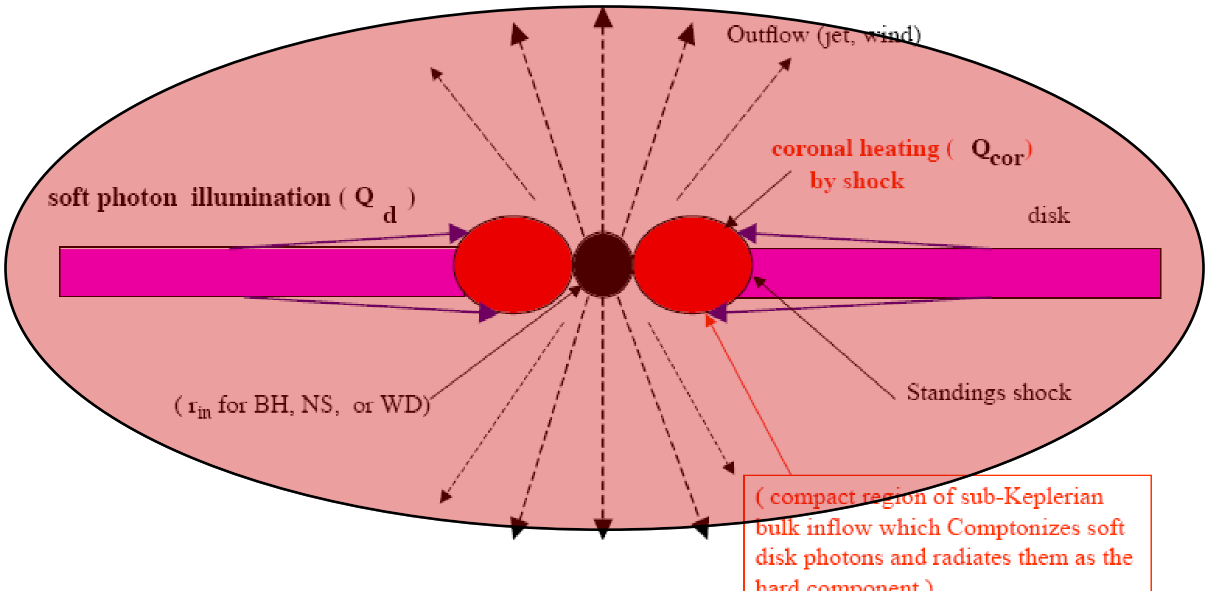
Cyg X-3 gamma-ray flares anticorrelated with hard X-rays

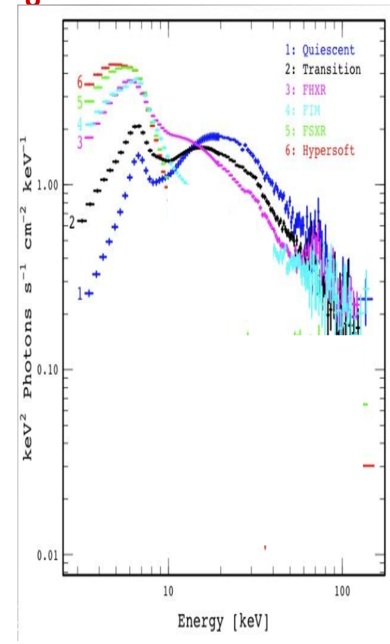
Plasma diagnostics with hard X-rays: acceleration with gamma-rays

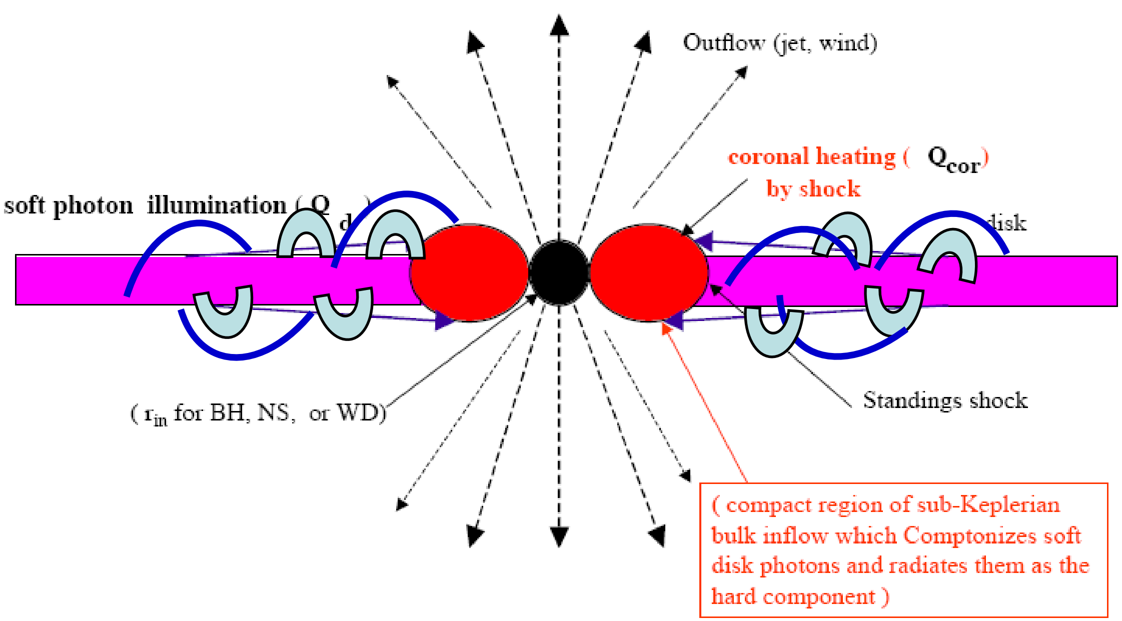


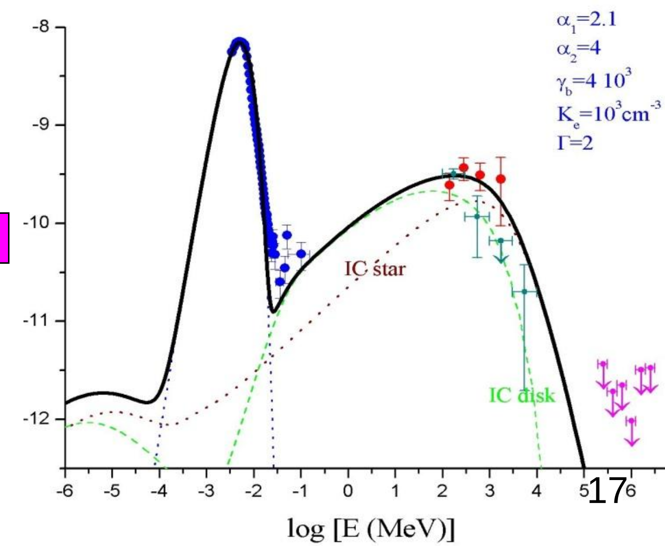
Plasma diagnostics (and acceleration) around a BH

Compton-thick cloud, $\tau = \sigma_T\, n\, R \sim 1\text{-}10$ $n \sim (10^{15}\ \mathrm{cm^{-3}})\ R_8^{-1}$

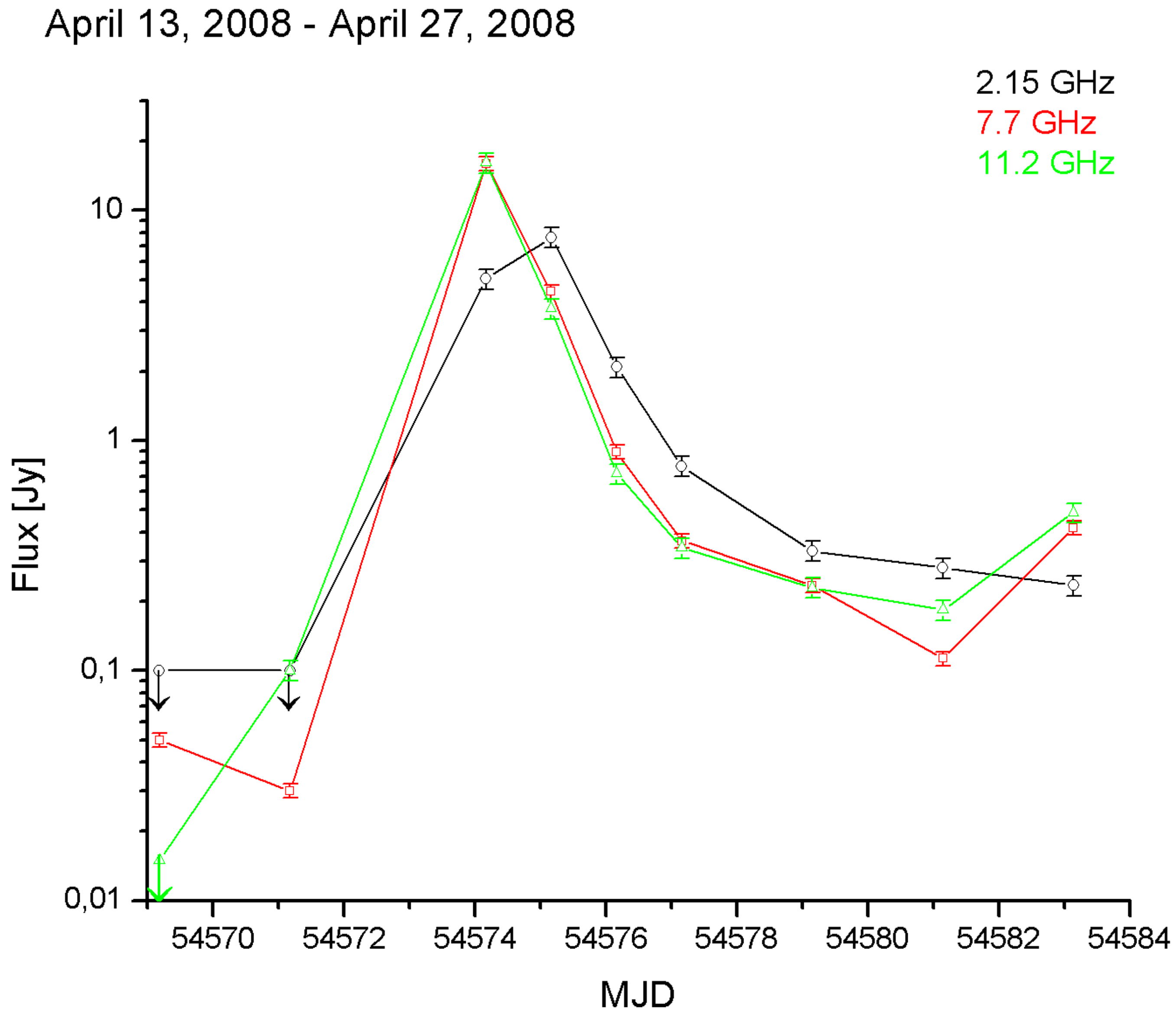








RATAN Obs. (S. Truskhin et al.) Apr. 13 – Apr. 27, 2008

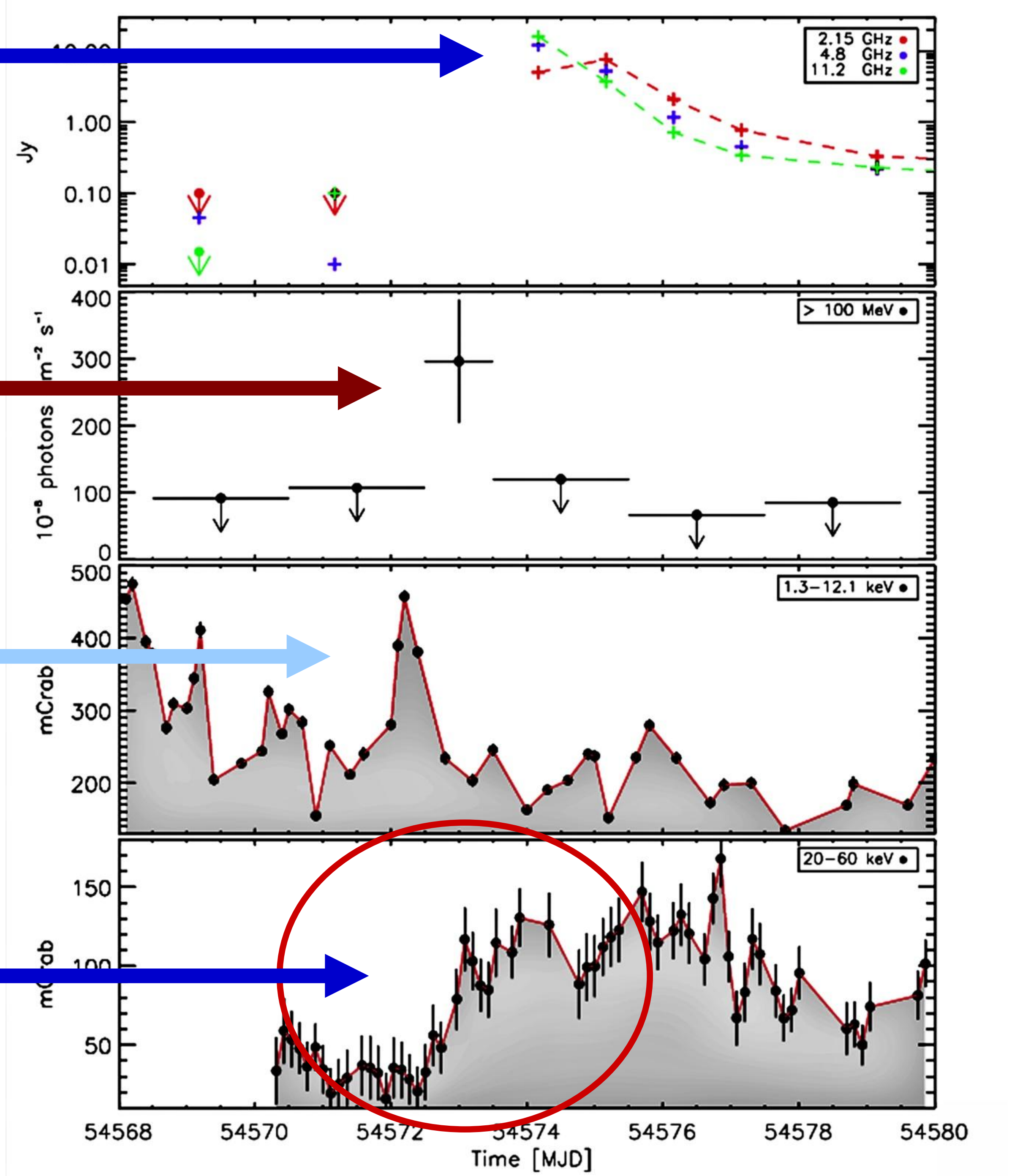


very strong radio flare, presumably with jet ejection

strong gamma-ray flare

X-ray (1-10 keV) flare

Hard X-ray flux state change (Super-A monitoring)



Major gamma-ray flares in special transitional states in preparation of radio flares ! (Tavani etal. Nature 2009)

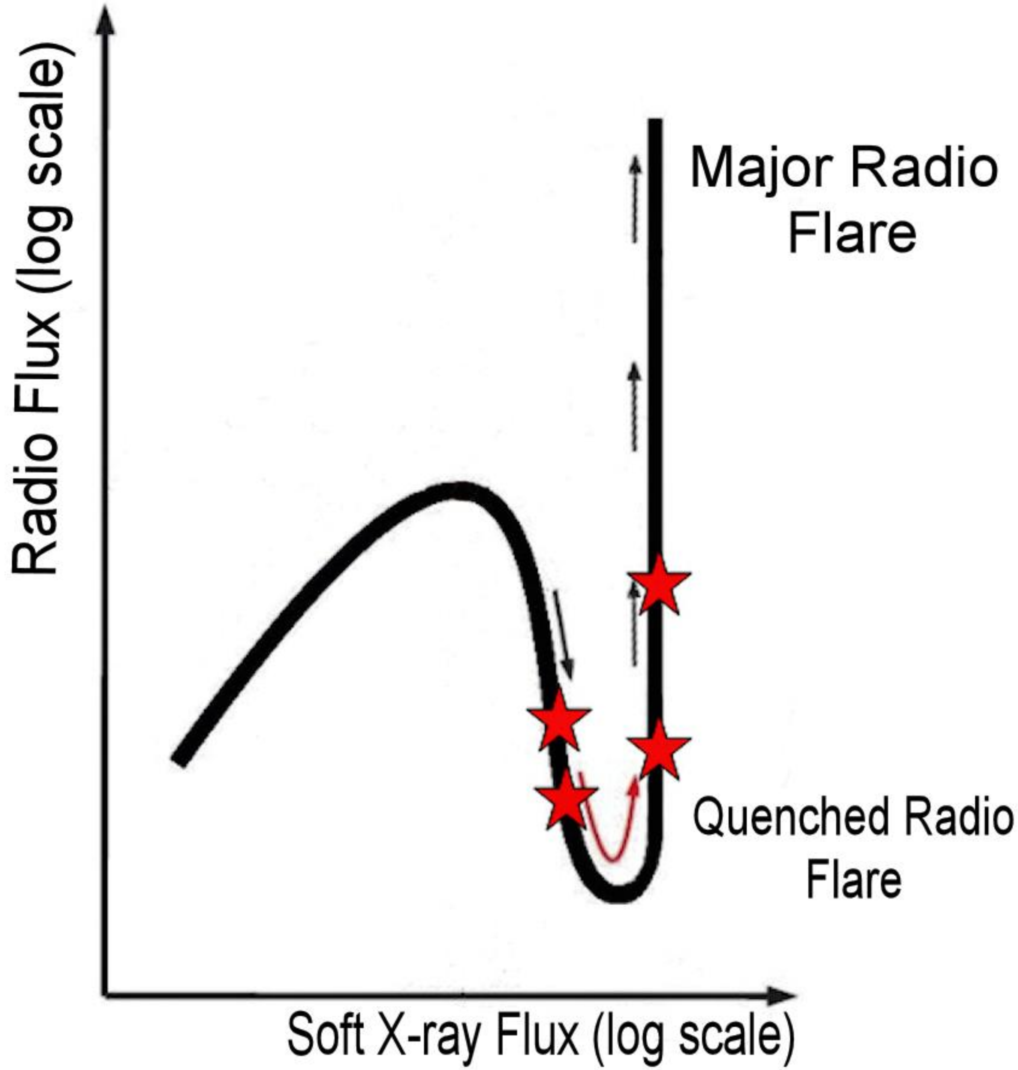
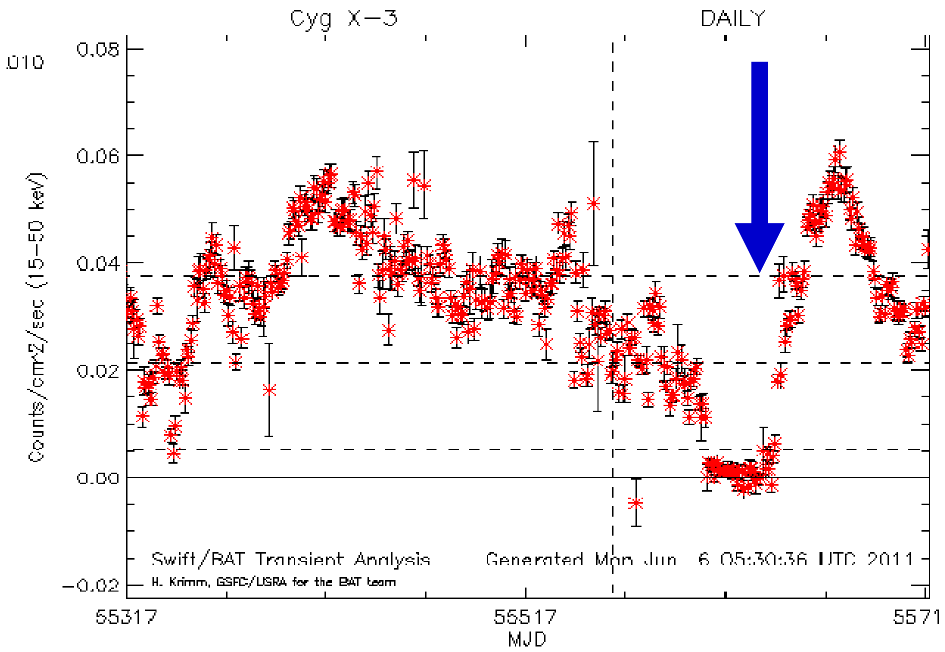
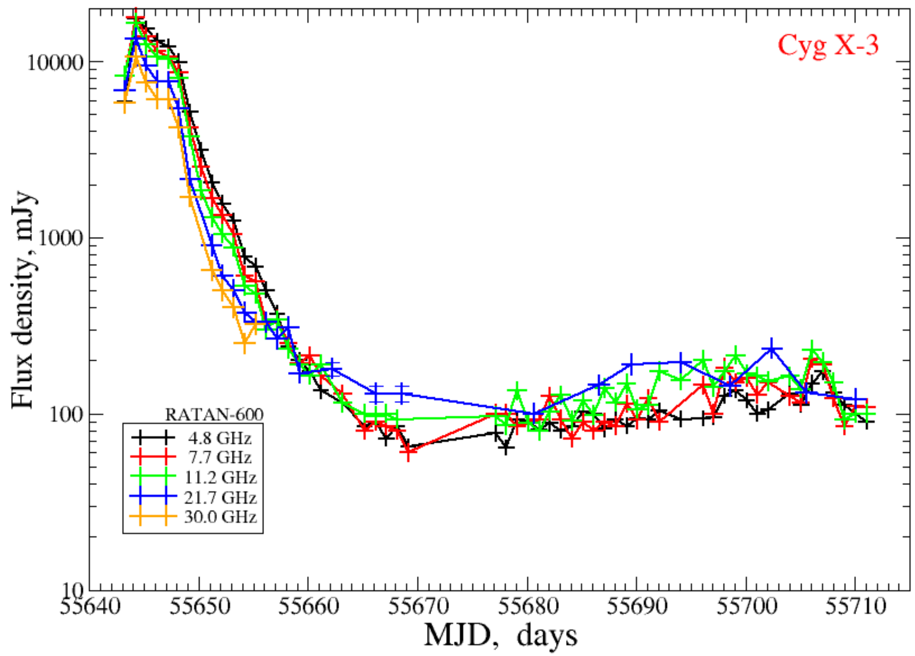


figure adapted from Szostek Zdziarski & McCollough (2008)

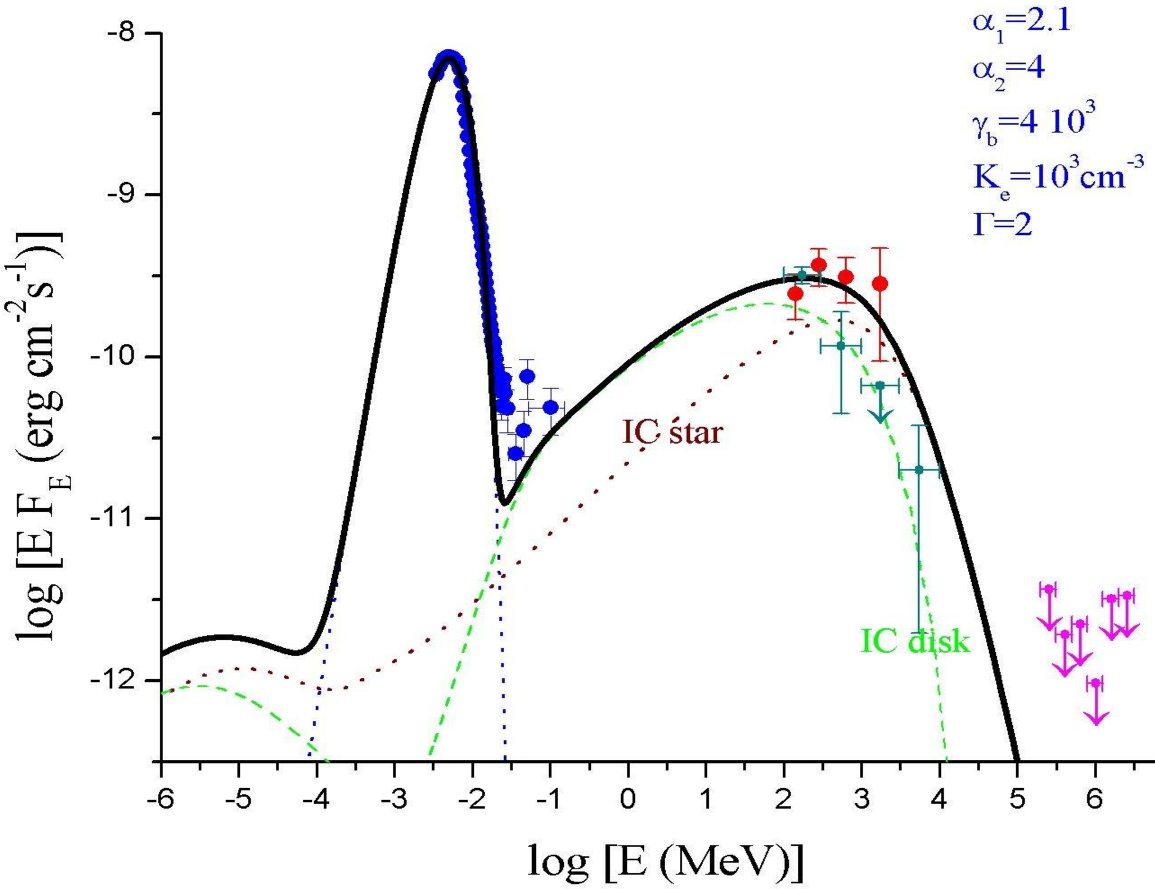
last pre-flare and major radio flare episode of Cyg X-3



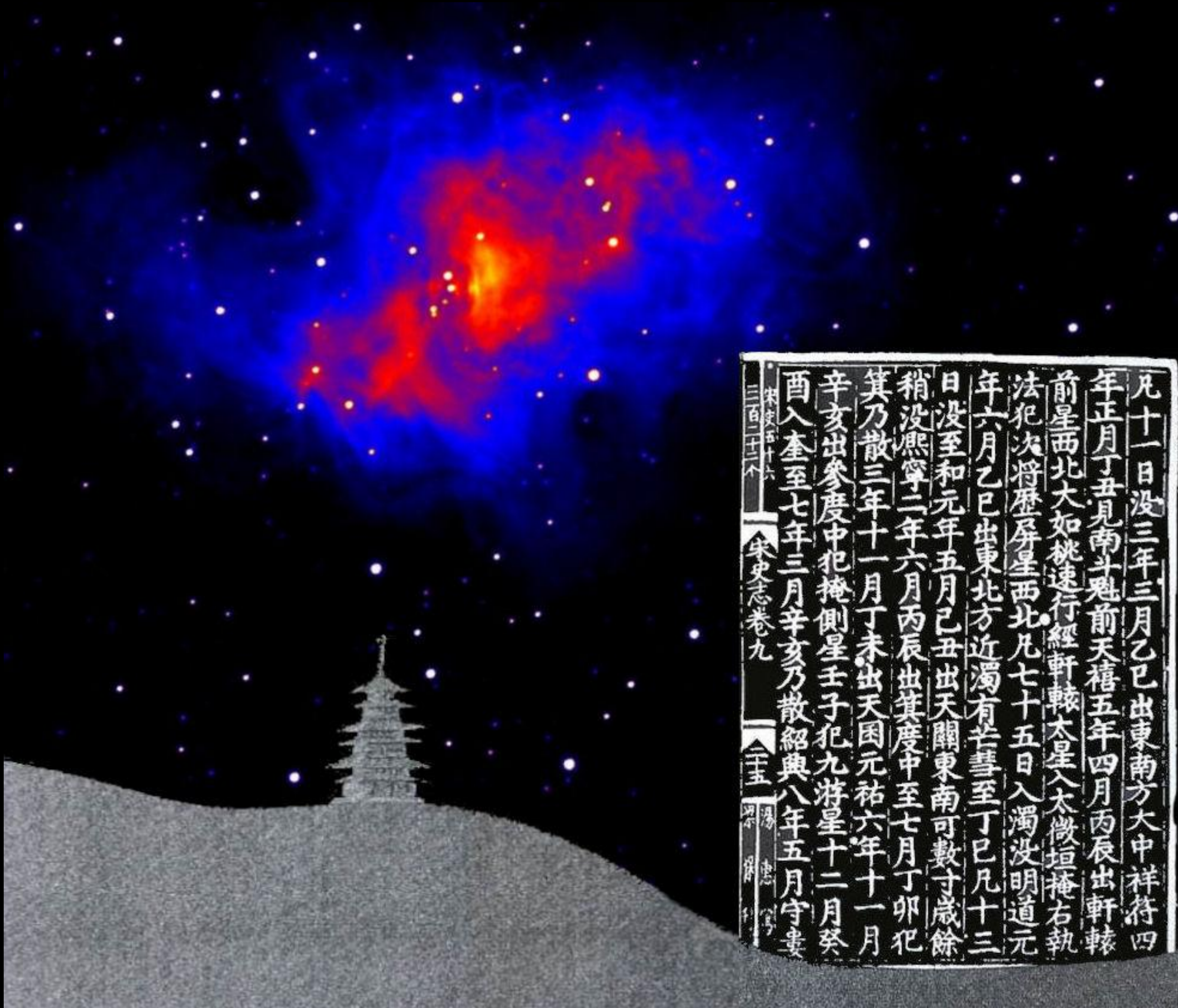


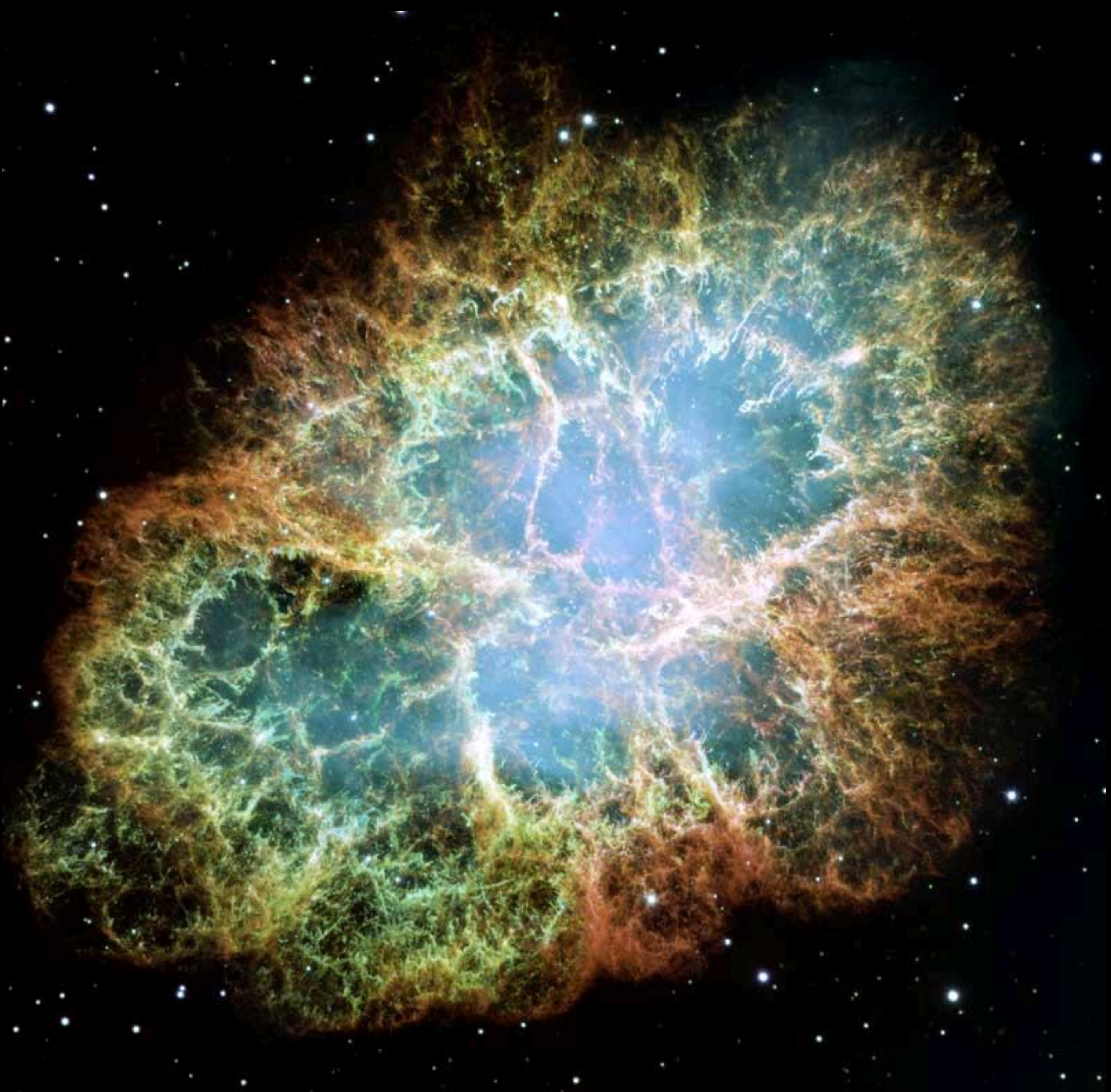
clear indication from Cyg X-3

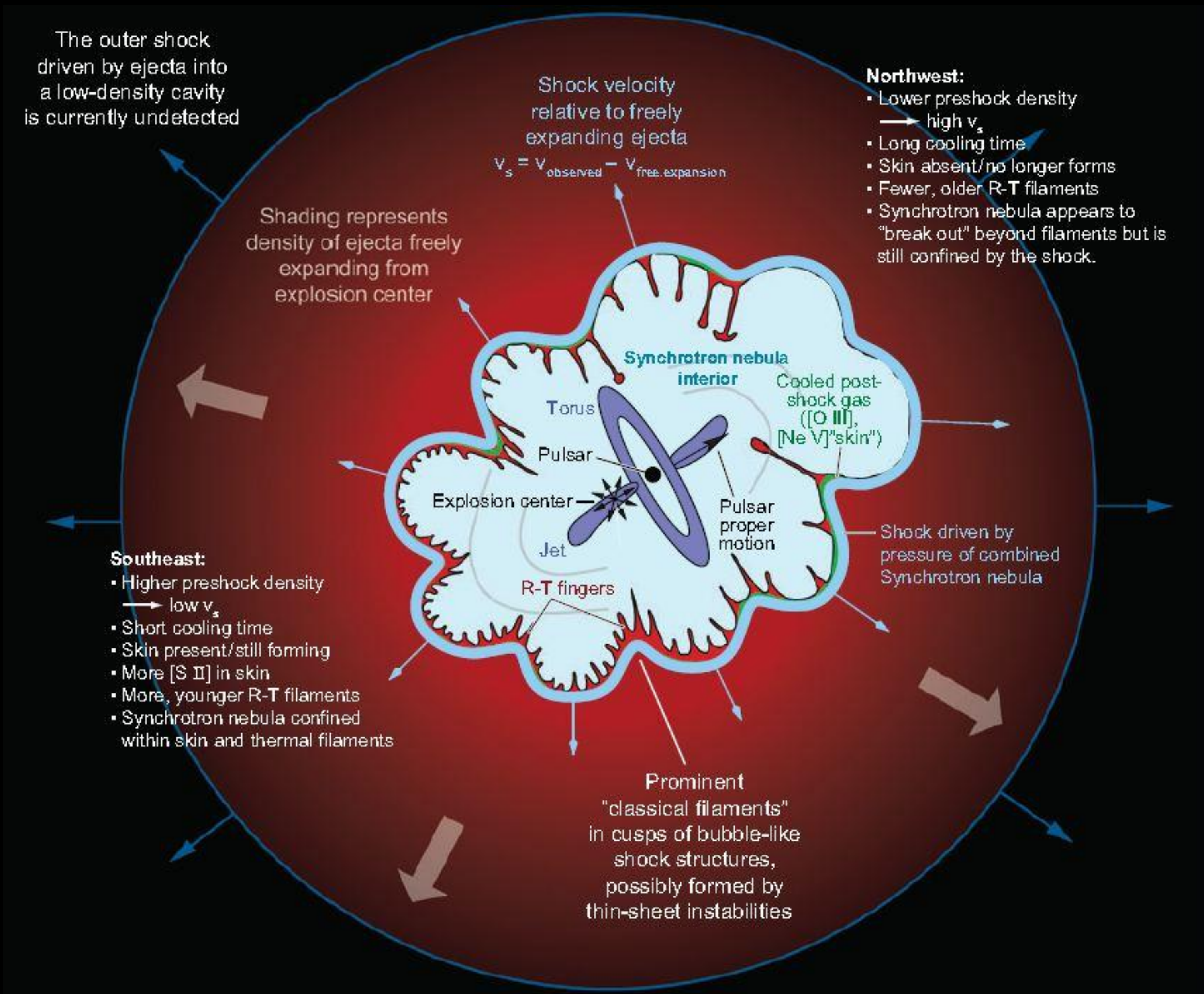
- **particle acceleration preceding (1-2 days) jet launching**



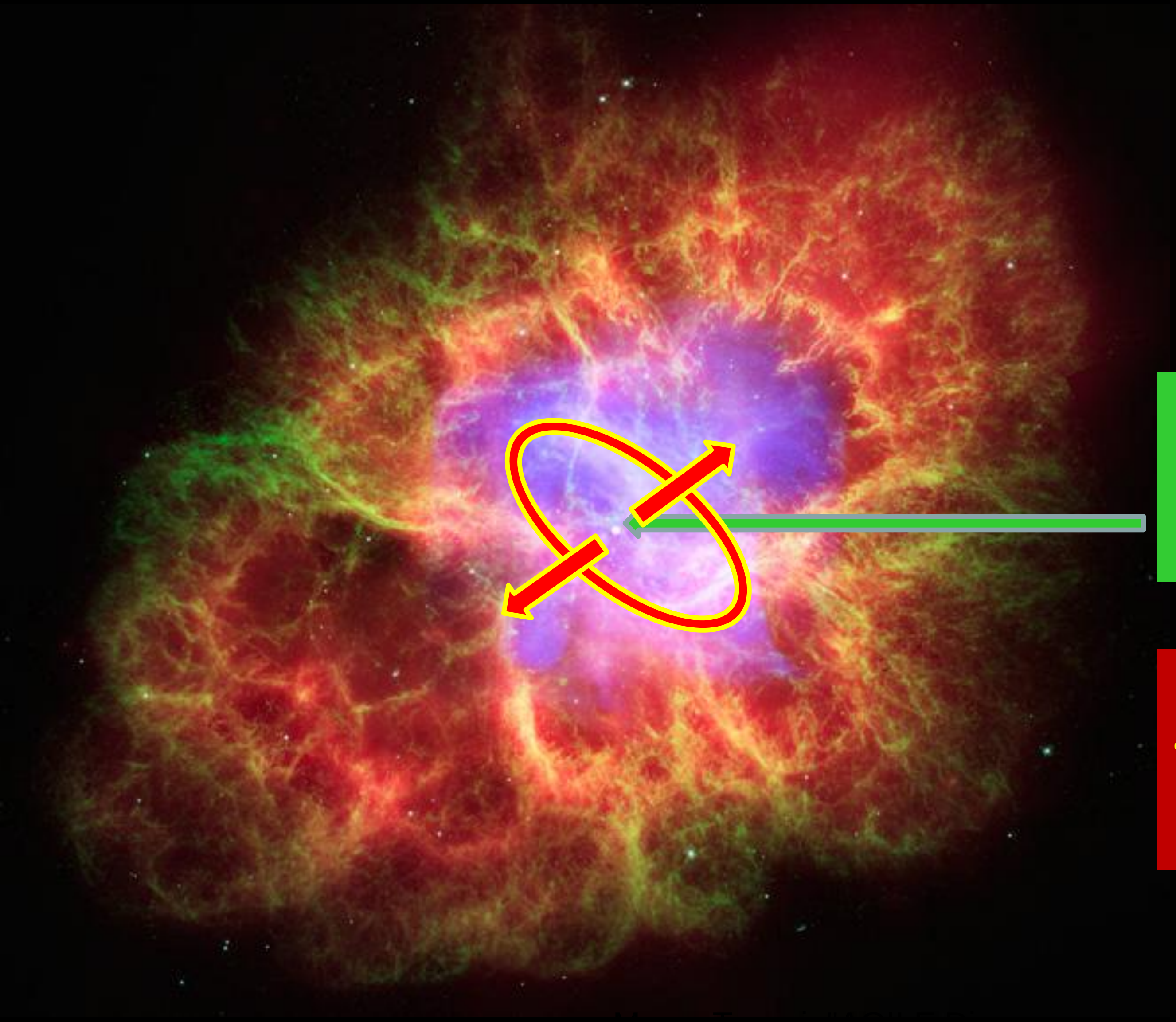
Piano, Vittorini, M.T., 2011


凡十一日沒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
法犯次將歷屛星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九



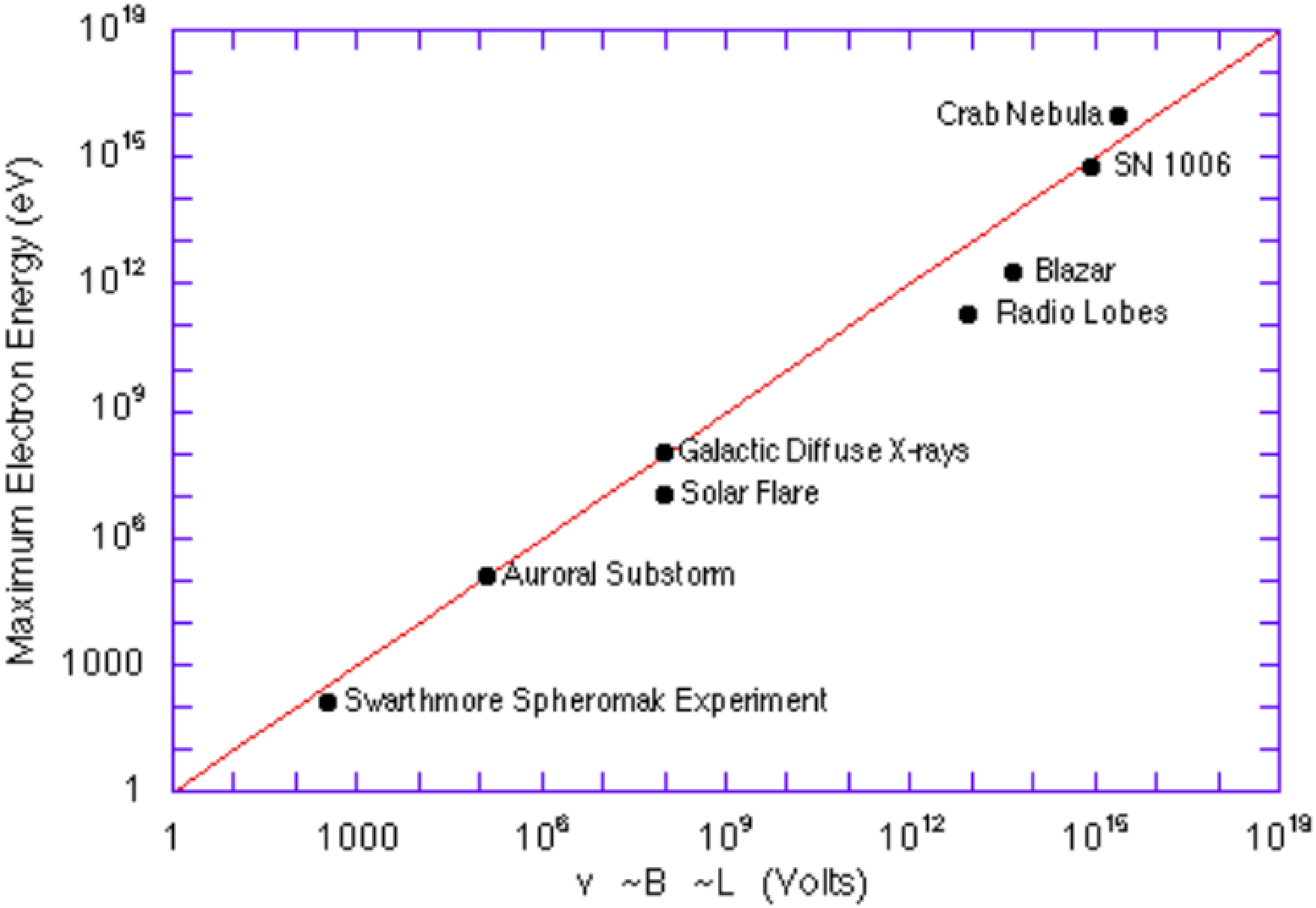

The outer shock driven by ejecta into a low-density cavity is currently undetected
Shock velocity relative to freely expanding ejecta
$v_s = v_{observed} - v_{free.expansion}$
Northwest:
• Lower preshock density → high v_s
• Long cooling time
• Skin absent/no longer forms
• Fewer, older R-T filaments
• Synchrotron nebula appears to "break out" beyond filaments but is still confined by the shock.
Shading represents density of ejecta freely expanding from explosion center
Synchrotron nebula interior
Cooled post-shock gas ([O III], [Ne V]"skin")
Torus
Pulsar
Explosion center
Jet
Pulsar proper motion
R-T fingers
Shock driven by pressure of combined Synchrotron nebula
Southeast:
• Higher preshock density → low v_s
• Short cooling time
• Skin present/still forming
• More [S II] in skin
• More, younger R-T filaments
• Synchrotron nebula confined within skin and thermal filaments
Prominent "classical filaments" in cusps of bubble-like shock structures, possibly formed by thin-sheet instabilities

The Crab Nebula: the best accelerator



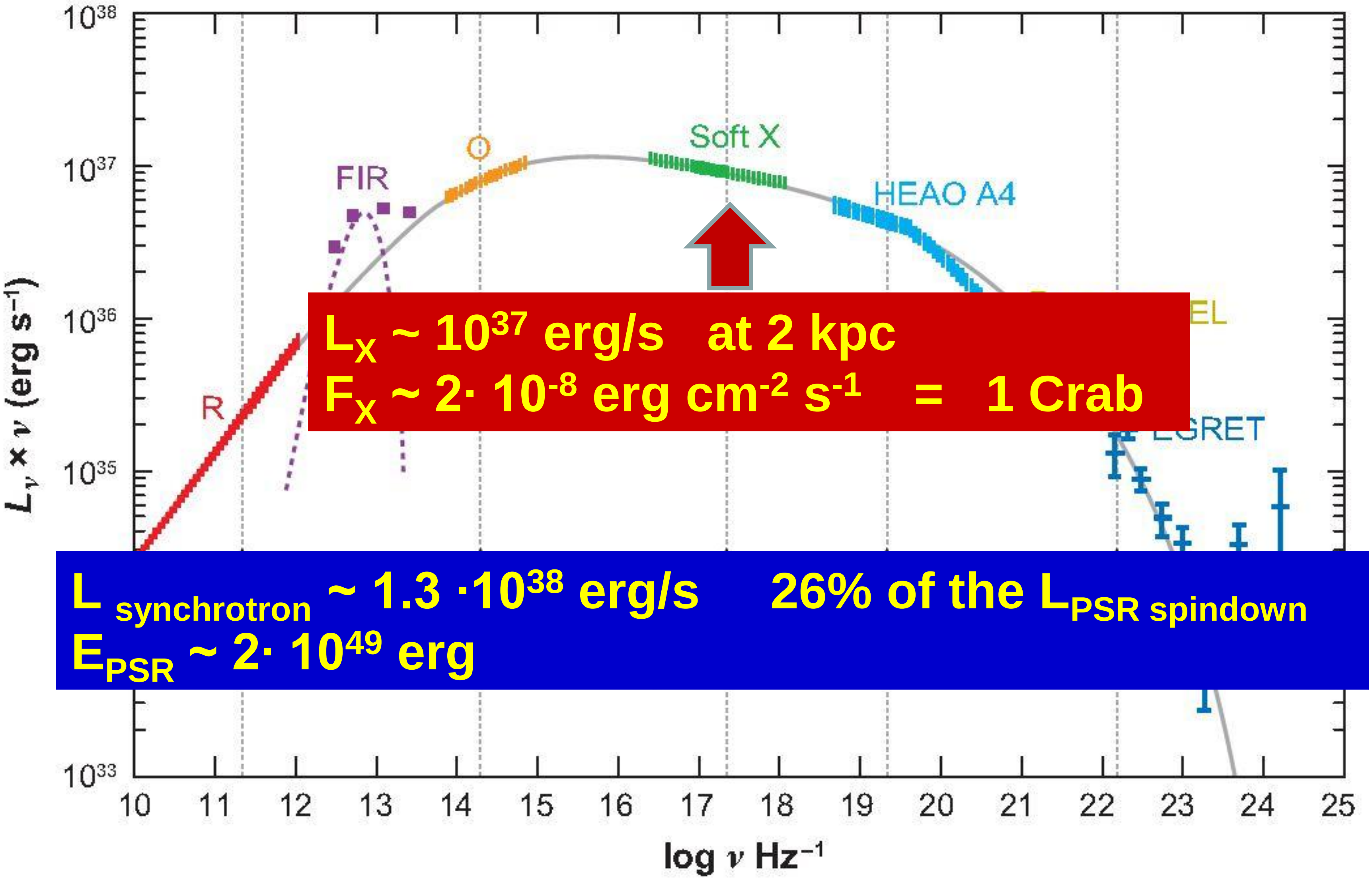
POWERFUL PULSAR (rotating 30 times a second)

NEBULA SHOCKED BY THE PULSAR WIND



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

Crab Nebula spectrum (Hester 2008)



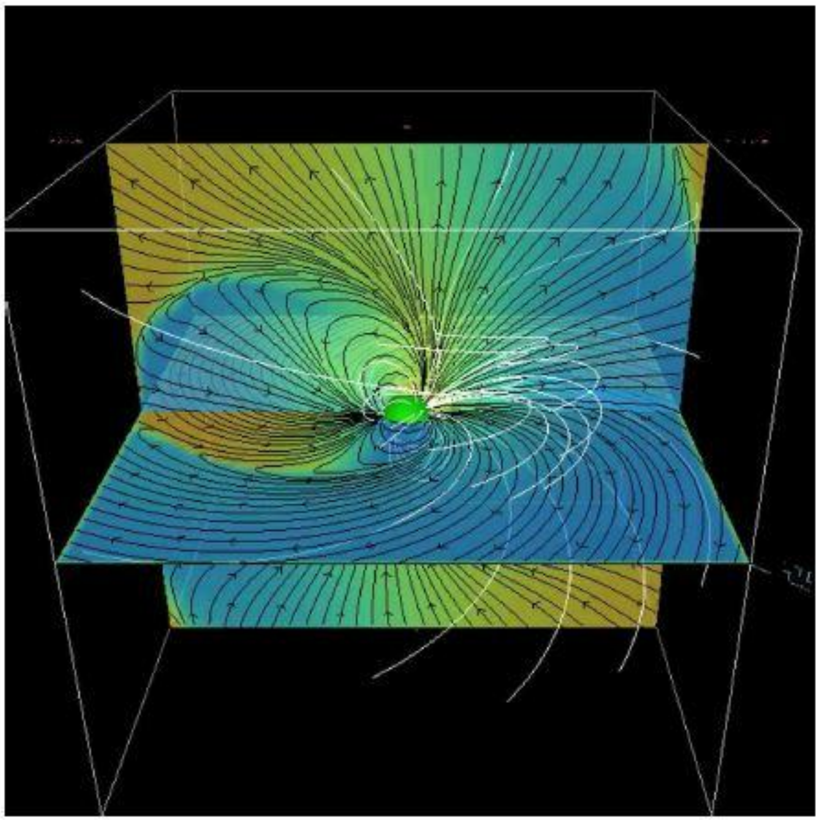
$L_X \sim 10^{37}$ erg/s at 2 kpc

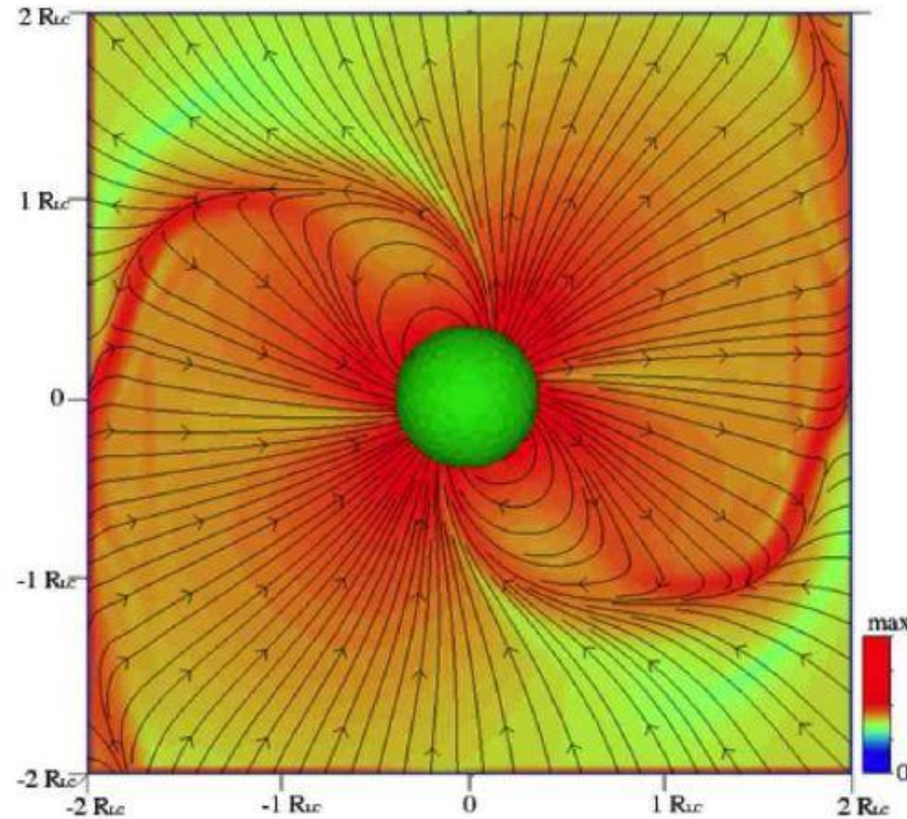
$F_X \sim 2 \cdot 10^{-8}$ erg cm^{-2} s^{-1} = 1 Crab

$L_{synchrotron} \sim 1.3 \cdot 10^{38}$ erg/s 26% of the $L_{PSR\ spindown}$

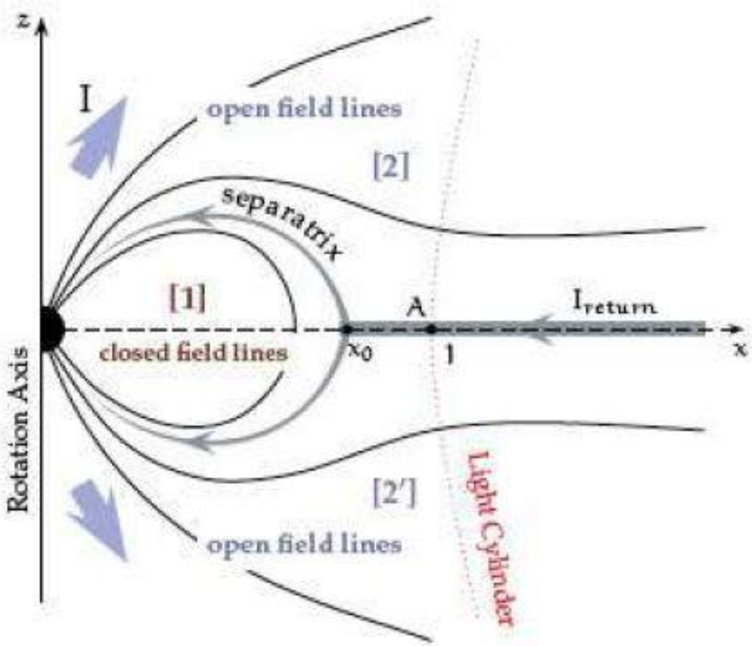
$E_{PSR} \sim 2 \cdot 10^{49}$ erg

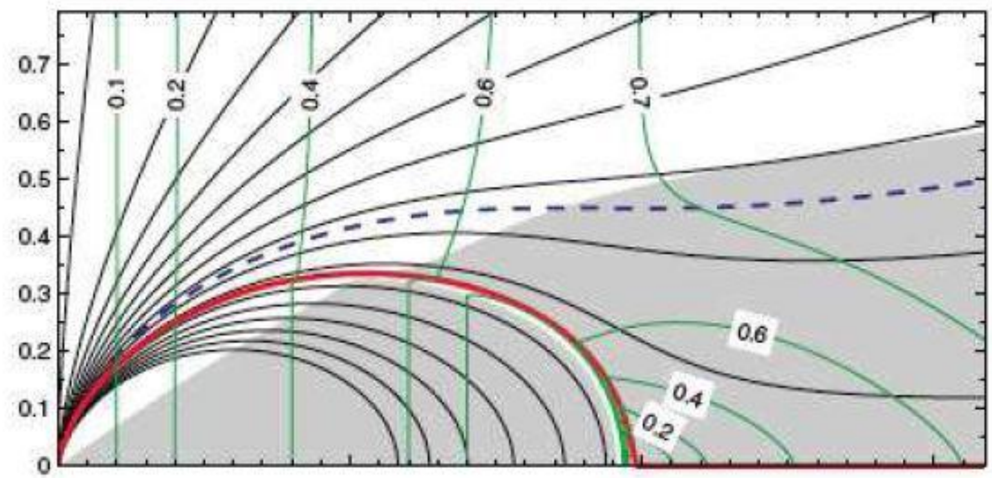
PSR wind modelling (Spitkovsky 2006)





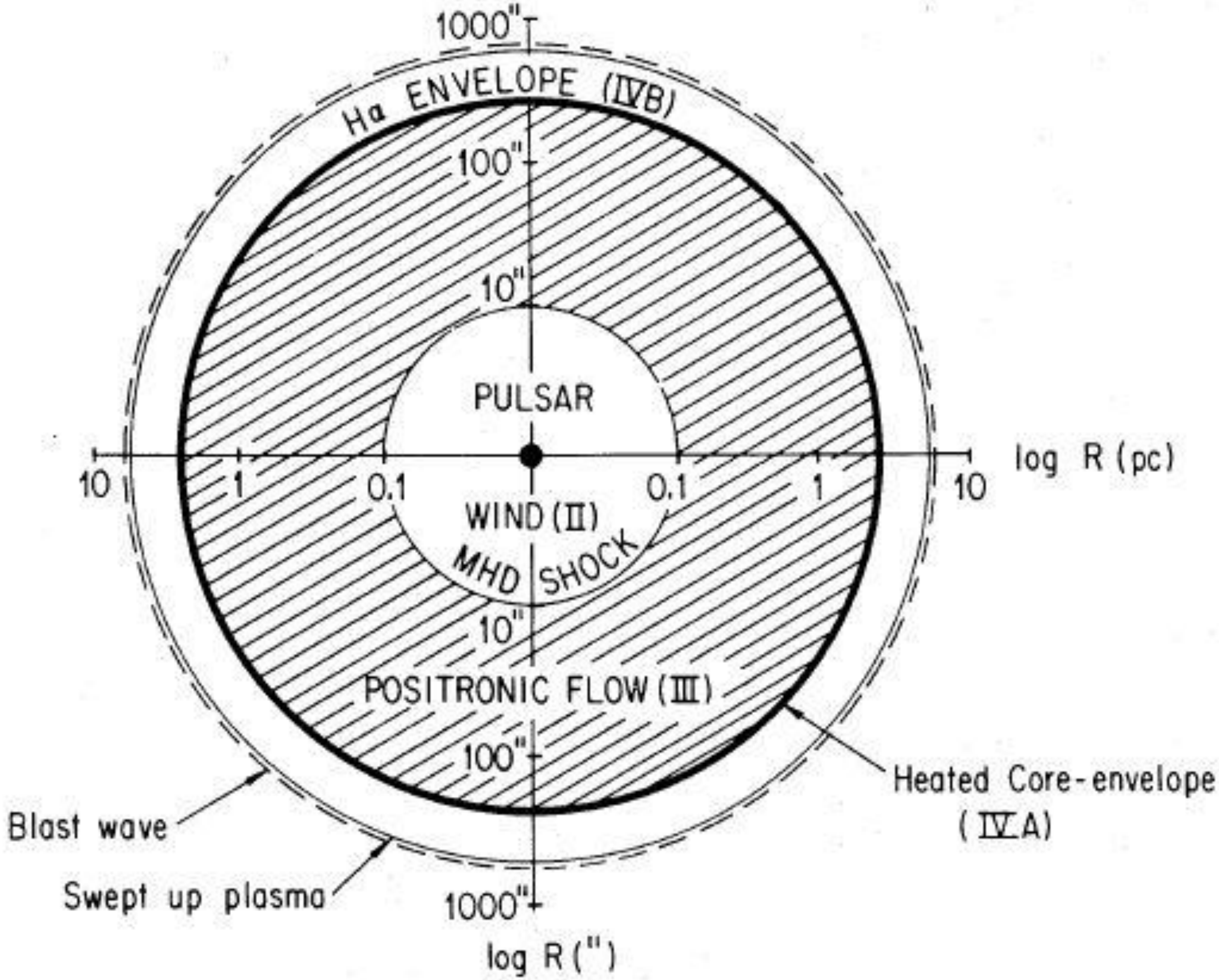
non-symmetric **PSR wind**
(relativistic e+/e-, ions (?), $\gamma_o \sim 10^2$-10^4)





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

Kennel-Coroniti picture of the Crab Nebula



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 emitting particles, **N ~ 2 ·10^{51}**
- many shock accelerating sites in the Nebula
- inner Nebula variability (weeks-months)
  - **Toroidal structures (wisps)**
  - **Jet-like structures (knots)**

possible standard 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.

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

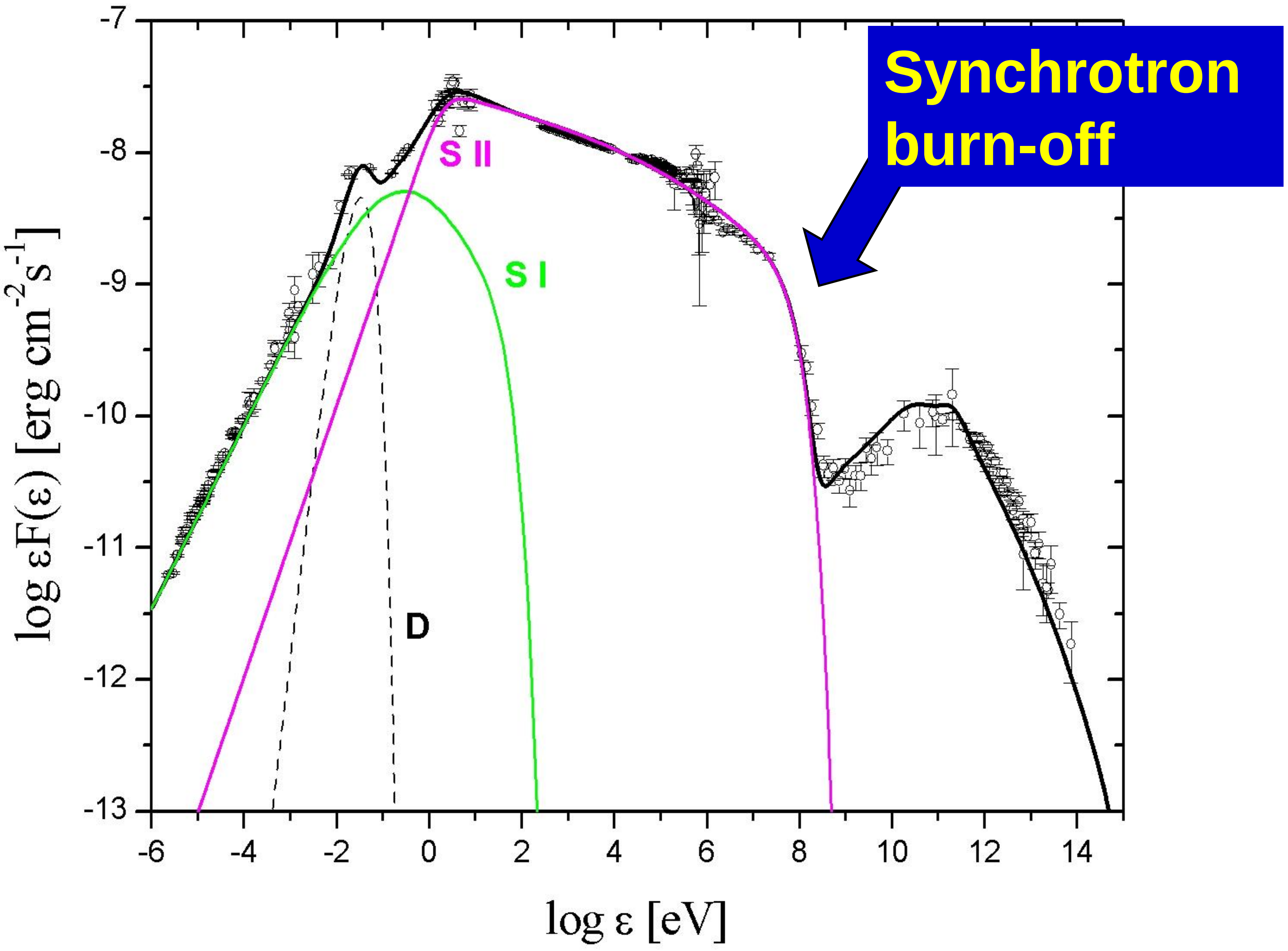
$$\boldsymbol{\gamma_{max} \sim 10^9 (E/B)^{1/2} (\alpha'/\sin^2\theta\, B_{-3})^{1/2}}$$

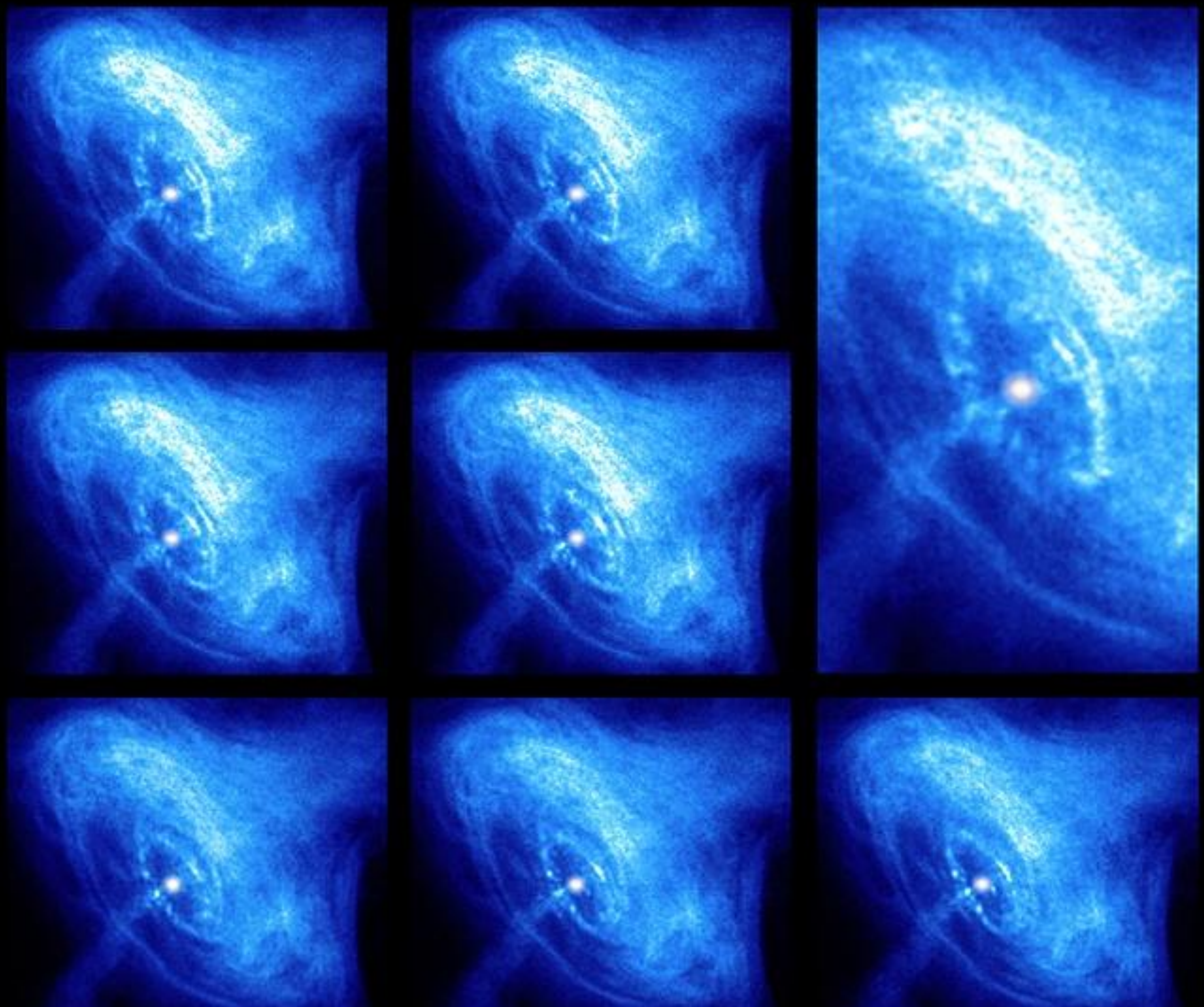
“standard” paradigm for nebular emission
(de Jager, Harding et al. 1996)

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

- **$E_{max} = \hbar\, \omega_B\, \gamma_m^2 \sim$ (100 MeV) ($\delta\, \alpha'/\sin\theta$)**

Crab Nebula spectrum

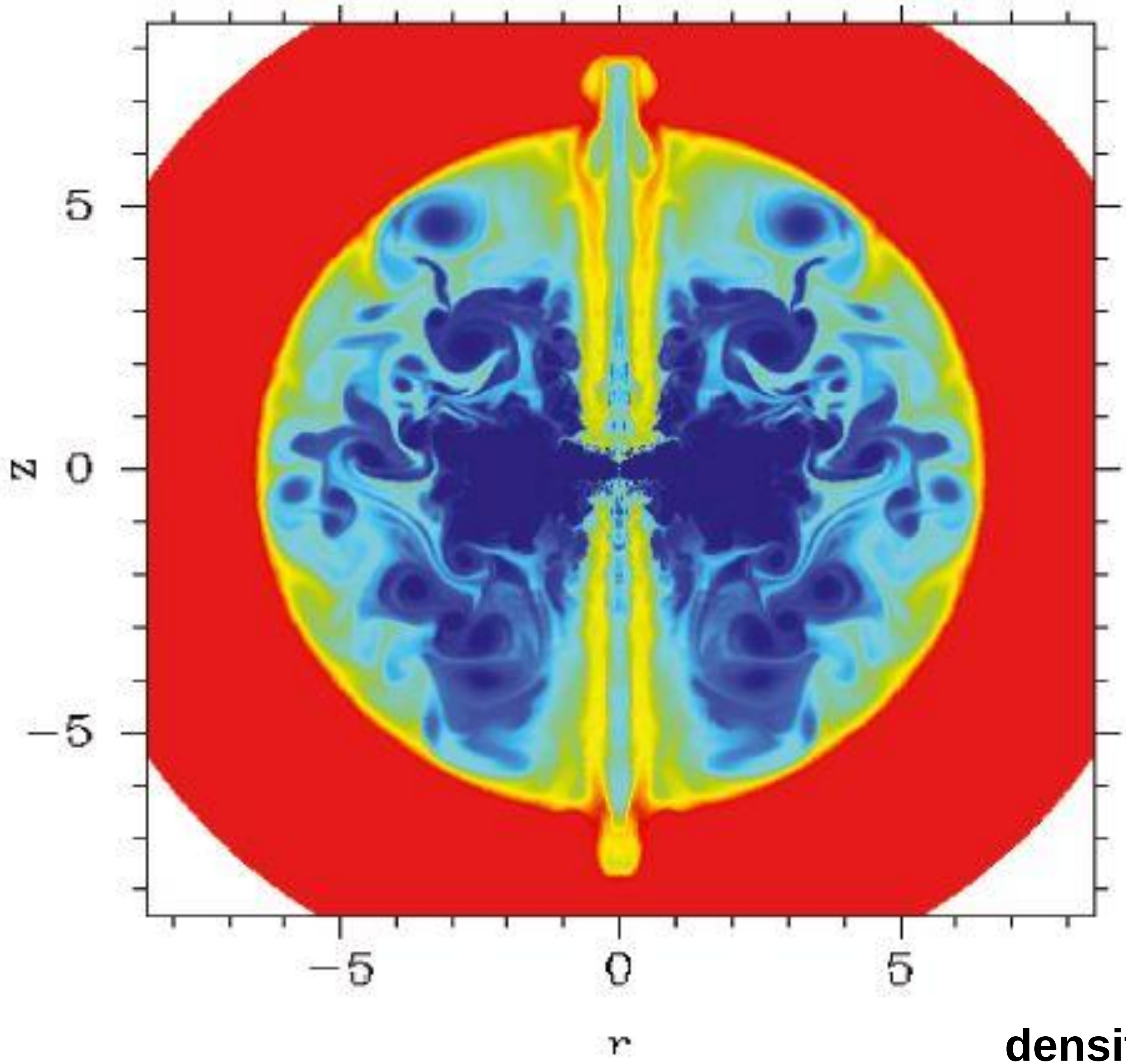




Crab Nebula MHD models

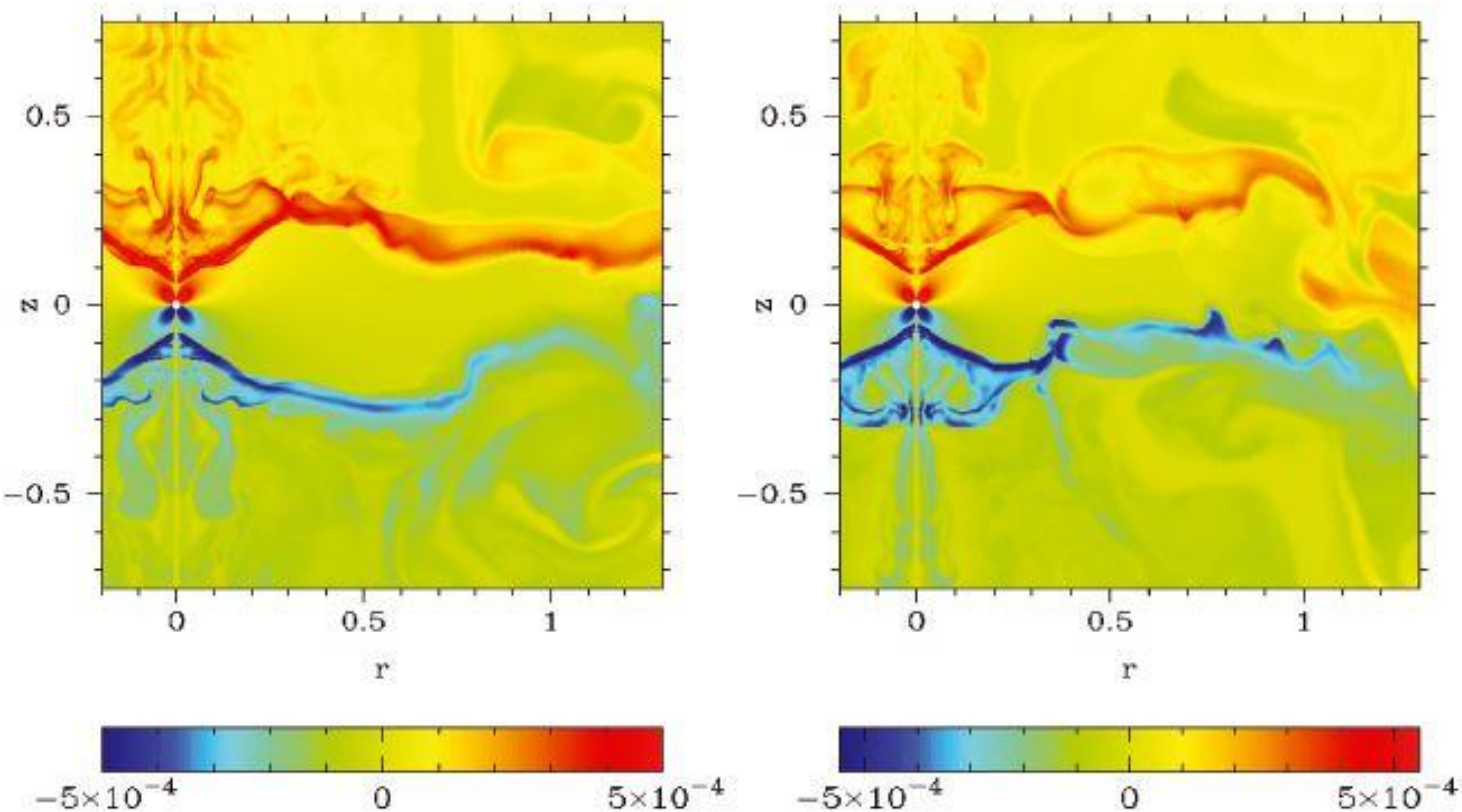
- Arons et al., 1992- 2010
- Komissarov, Lyubarsky, 2003, 2004
- Spitkowsky & Arons, 2004, ApJ, 603, 669
- Del Zanna, Volpi, Amato, Bucciantini, 2006, 2008
- Camus et al., 2009, MNRAS; 400, 1241

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



density profile

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

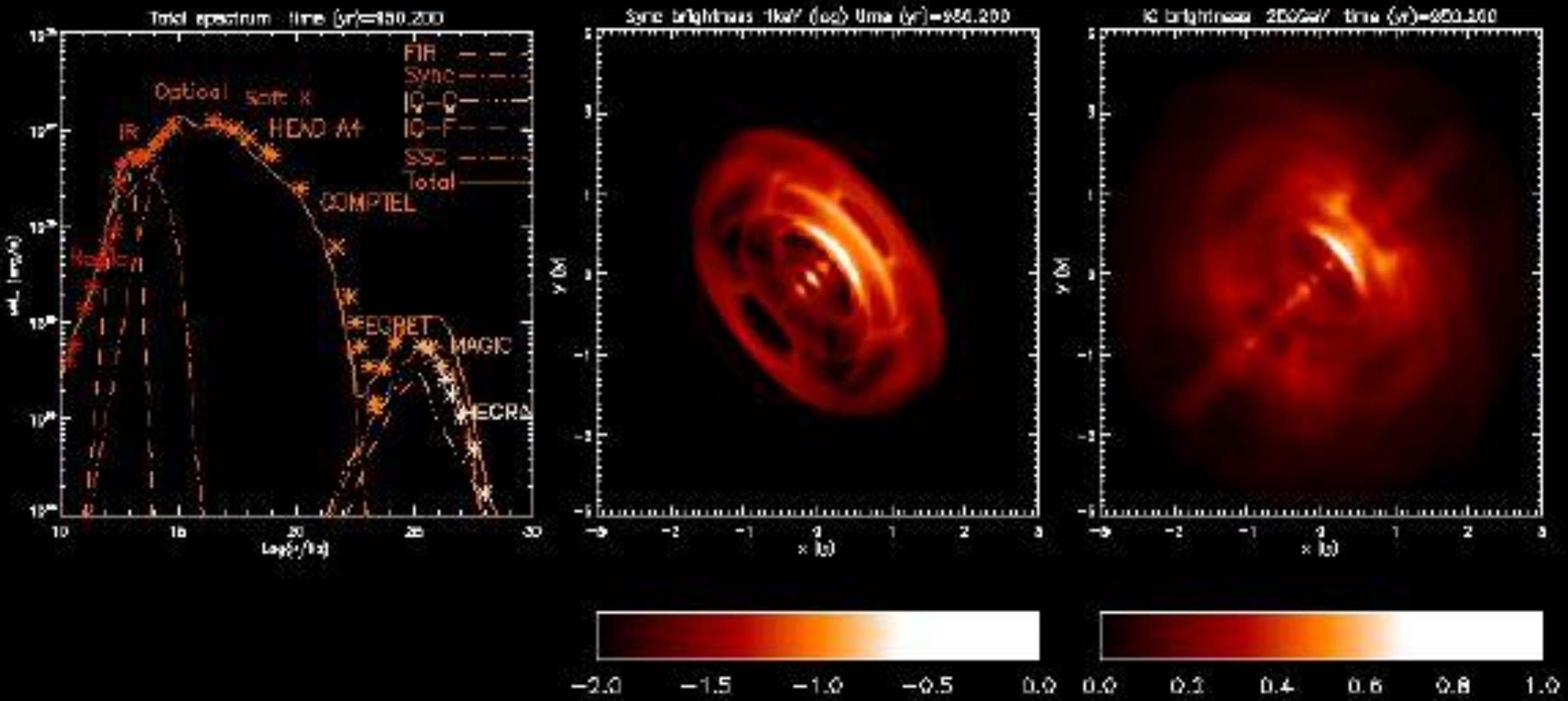


Magnetic field profile at different times

Variability in MHD models

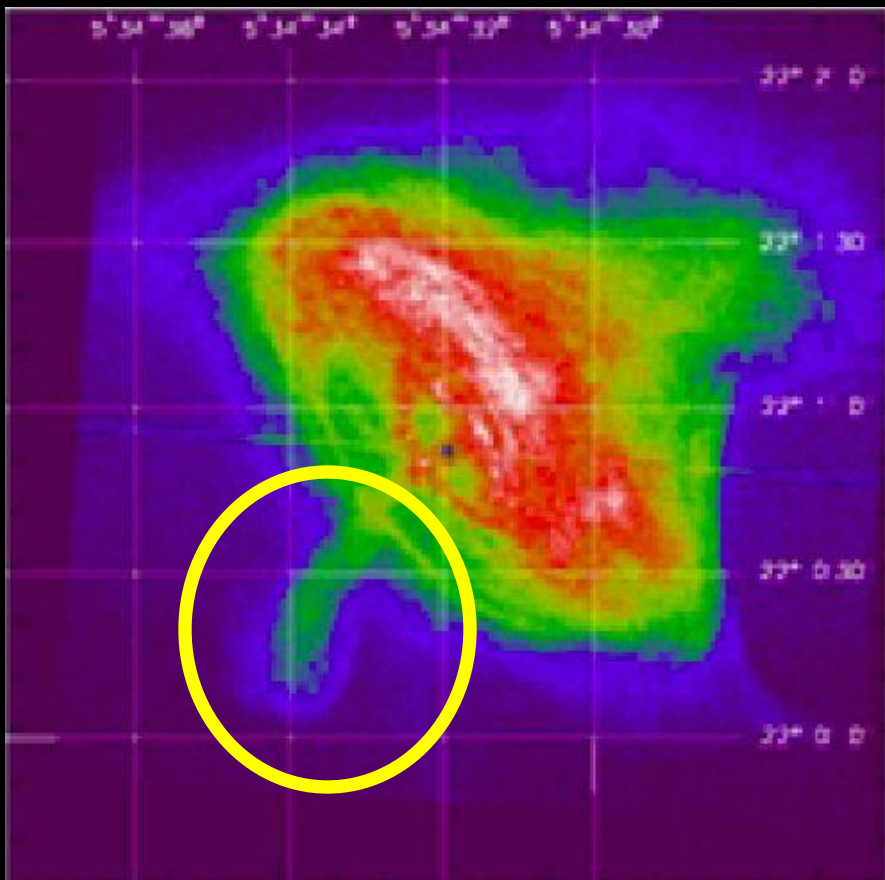
From P.Blasi

Courtesy E. Amato

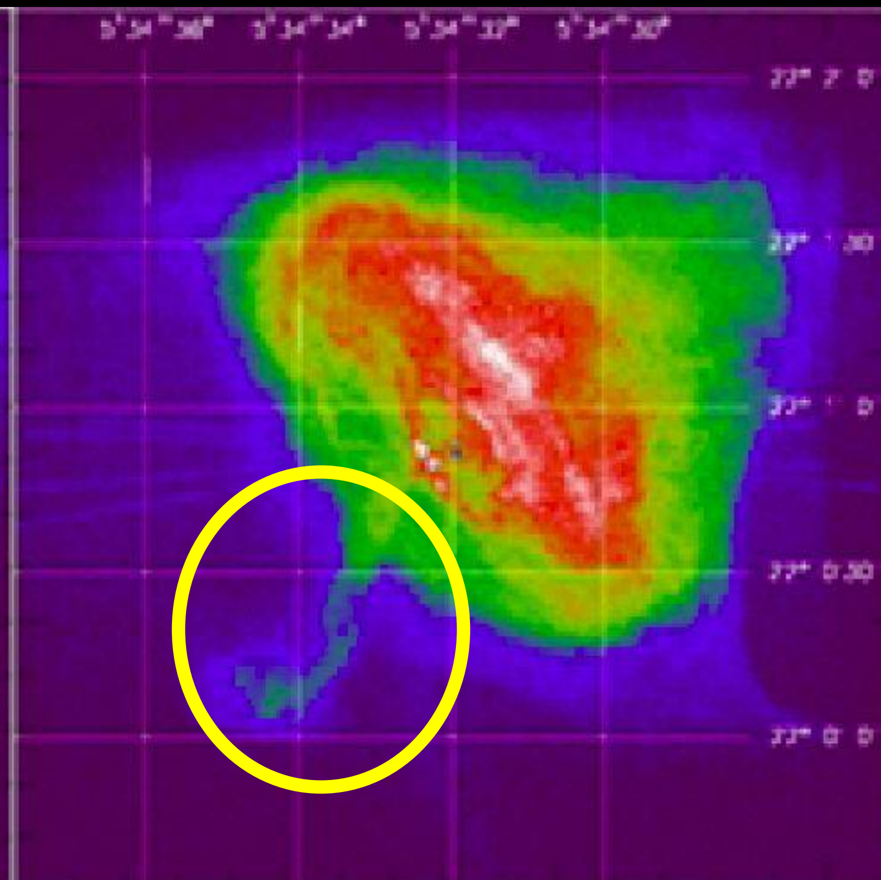


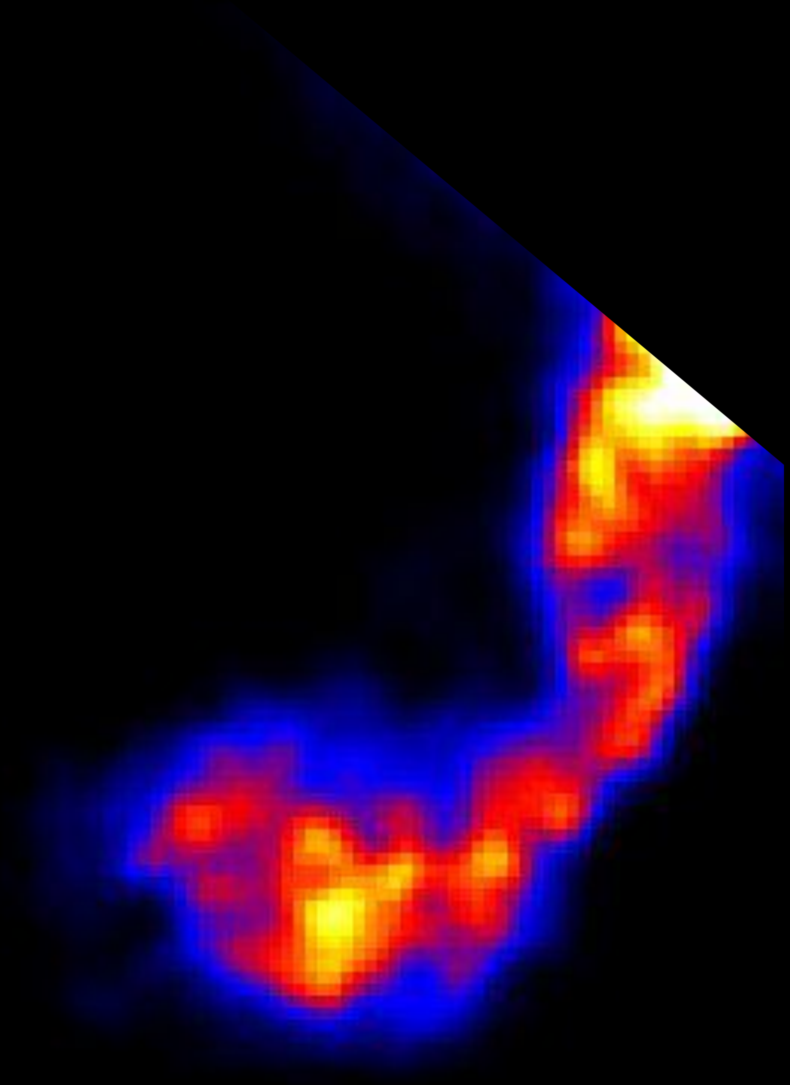
Chandra observations of the Crab Nebula

2001



Sept. 28, 2010



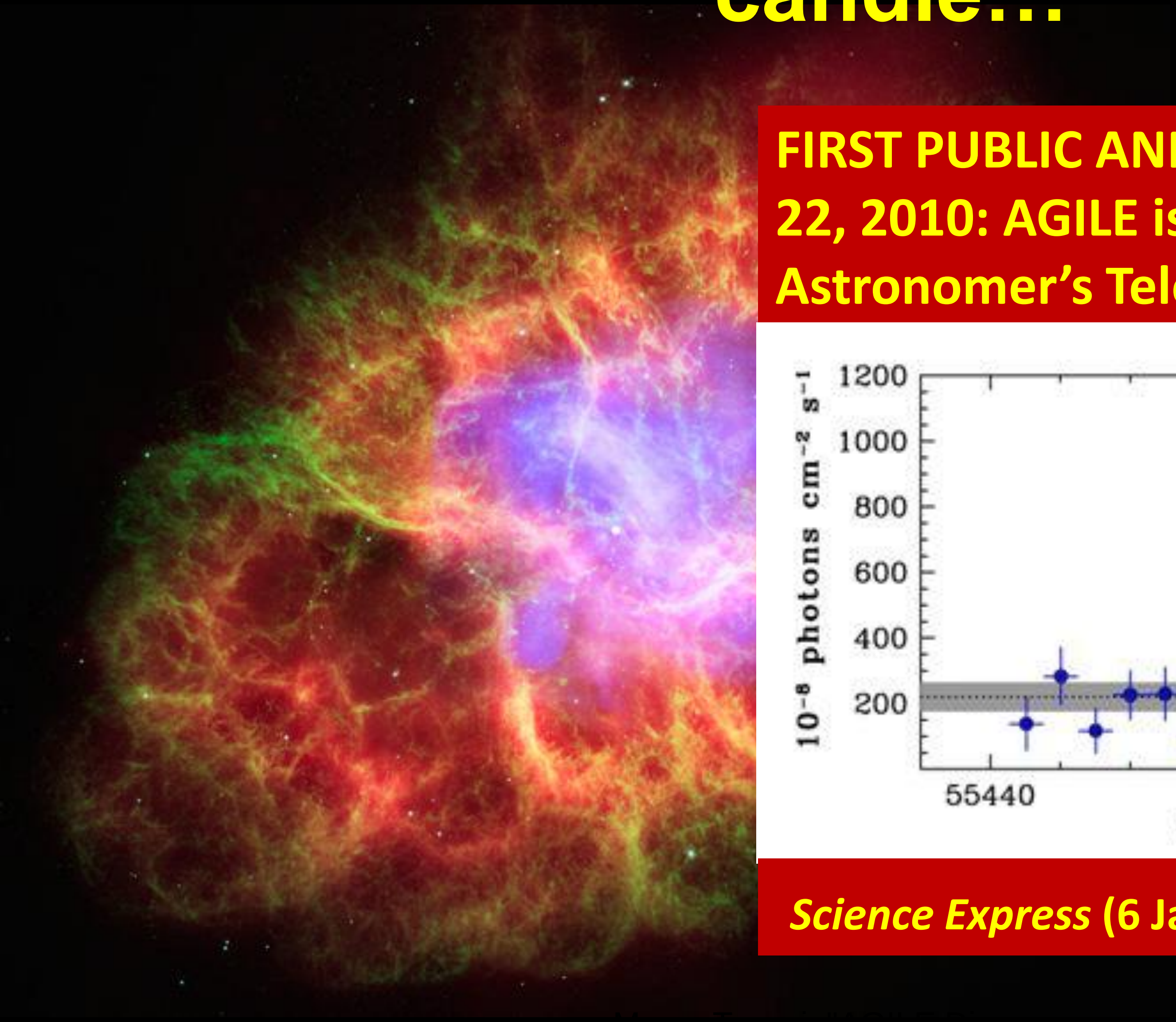


AGILE DISCOVERY OF THE CRAB NEBULA VARIABILITY IN GAMMA-RAYS

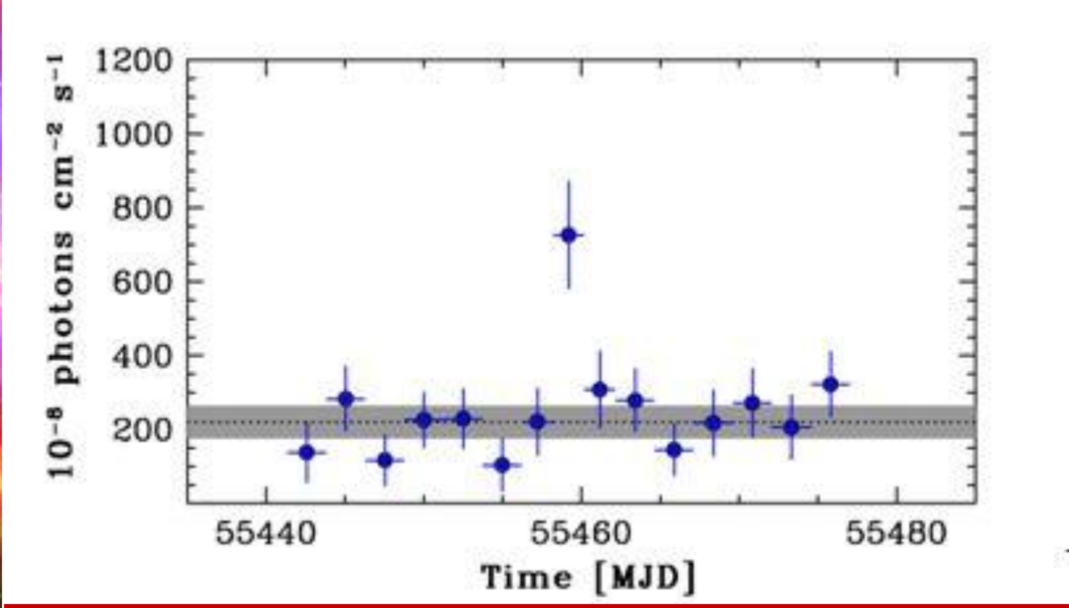
Tavani et al., Science, 331, 736 (2011)

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

The Crab Nebula: a standard candle…

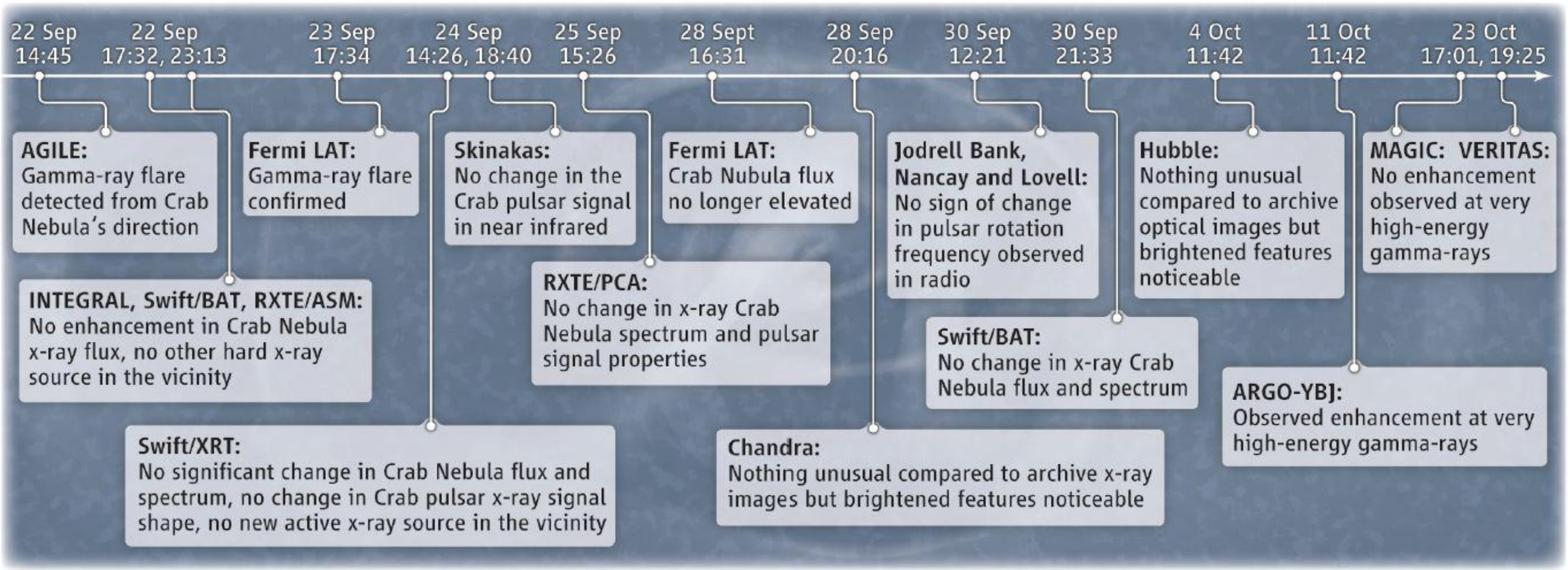


FIRST PUBLIC ANNOUNCEMENT Sept. 22, 2010: AGILE issues the Astronomer's Telegram n. 2855



Science Express **(6 January 2011)**

post-flare excitement



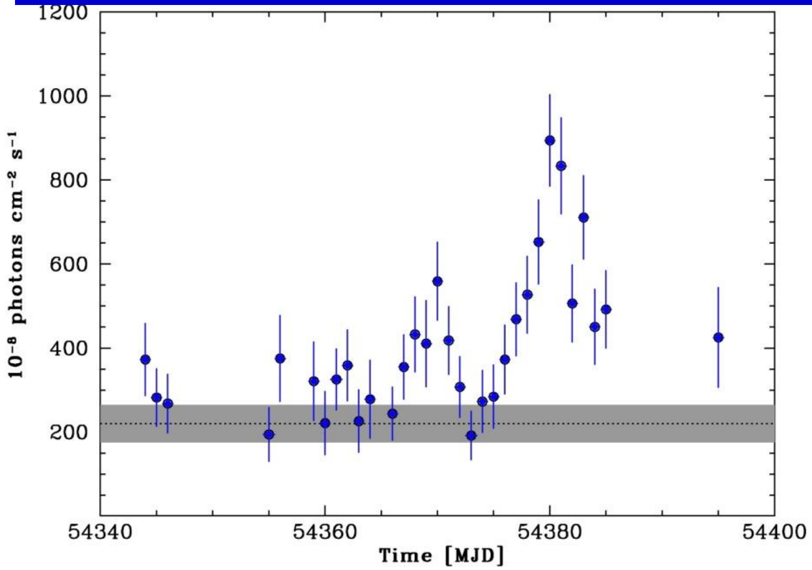
Bernardini E., 2011

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

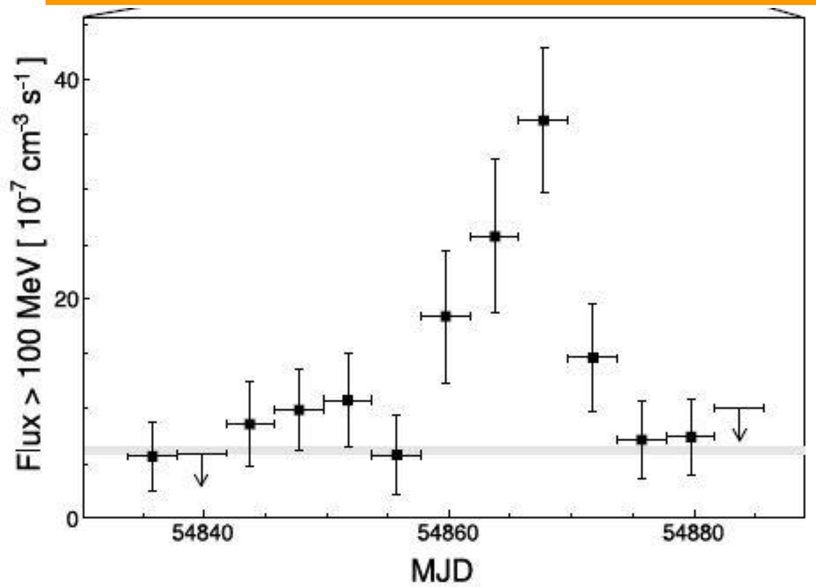
Flare date	Duration	Peak γ-ray flux	Instruments
October 2007	~ 15 days	~ 9 $\cdot 10^{-6}$ ph cm^{-2} s^{-1}	AGILE
February 2009	~ 15 days	~ 7 $\cdot 10^{-6}$ ph cm^{-2} s^{-1}	*Fermi*
September 2010	~ 4 days	~ 7 $\cdot 10^{-6}$ ph cm^{-2} s^{-1}	AGILE, *Fermi*
April 2011	~ 10 days	~ 30 $\cdot 10^{-6}$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

major flare rate: 1-2/year

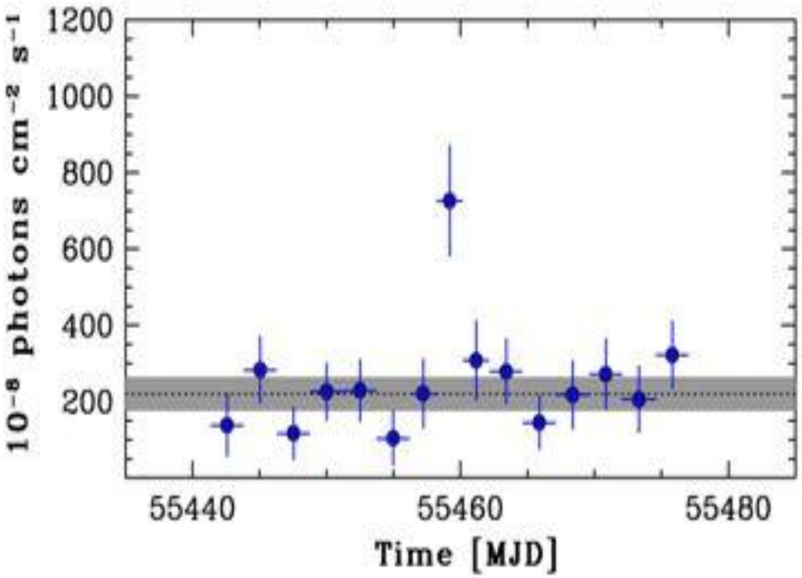
AGILE, 26 Nov. – 13 Oct. 2007



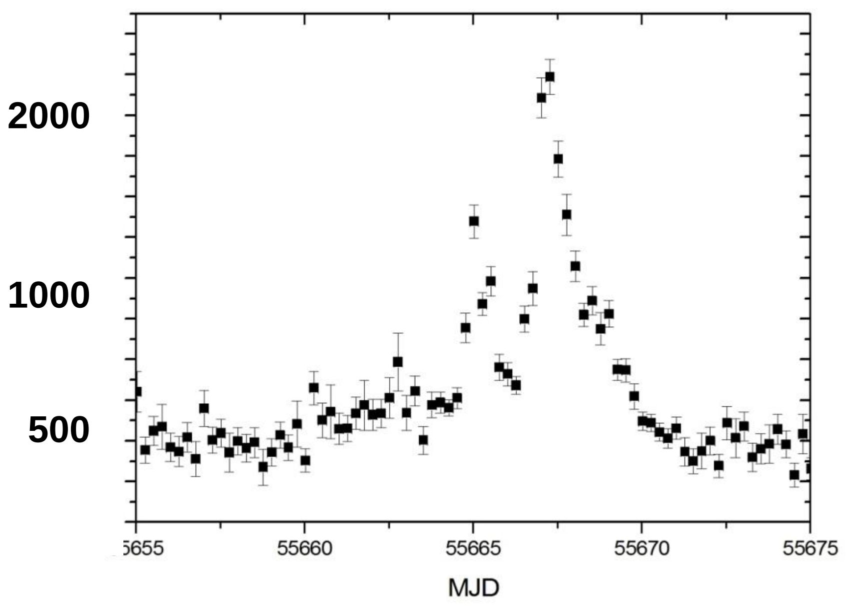
Fermi-LAT, 26 Jan. – 11 Feb. 2009



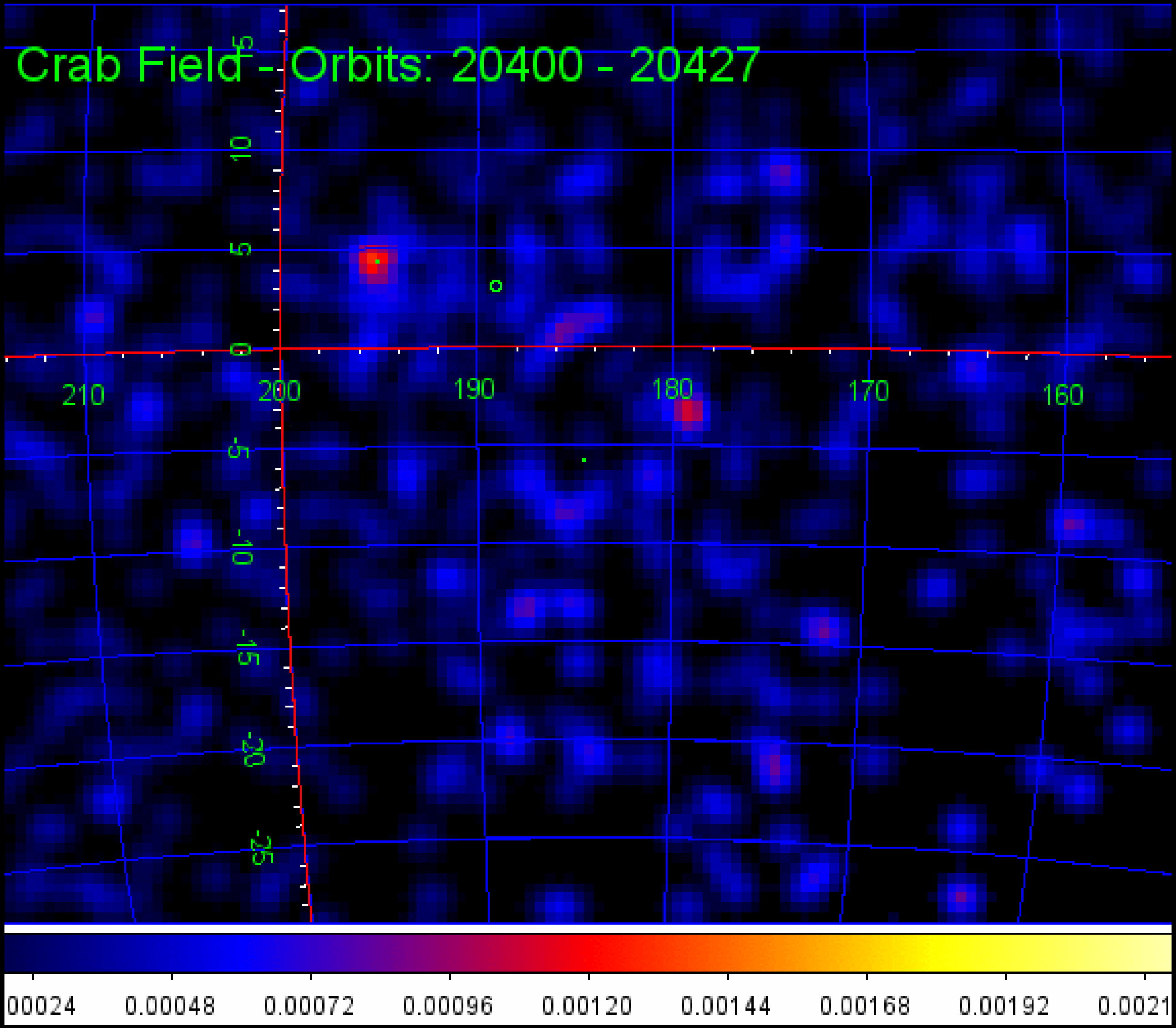
AGILE, 20-22 Sept. 2010



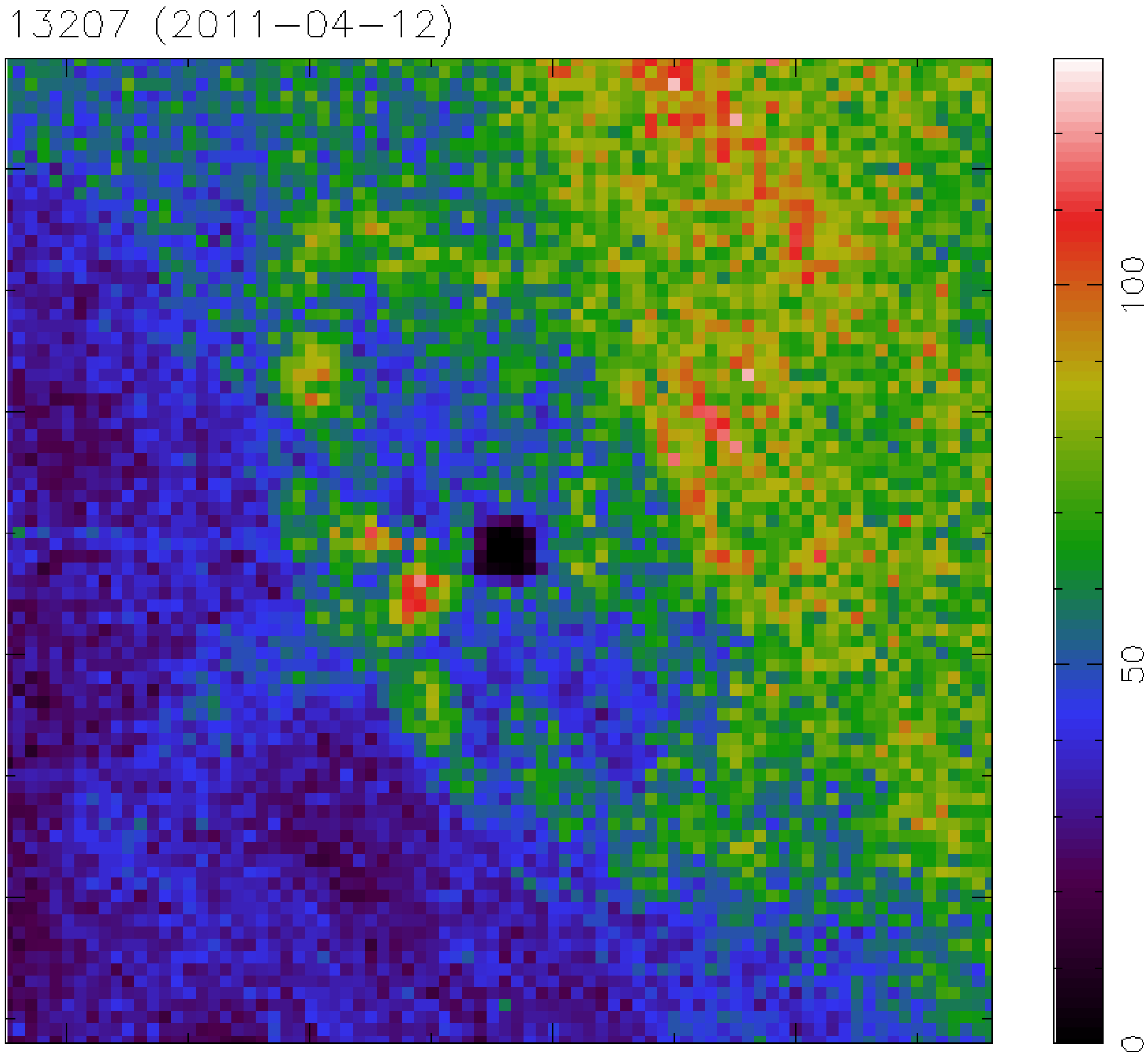
Fermi-AGILE, 12 – 20 Apr. 2011



AGILE monitoring of the Crab (April 2011)



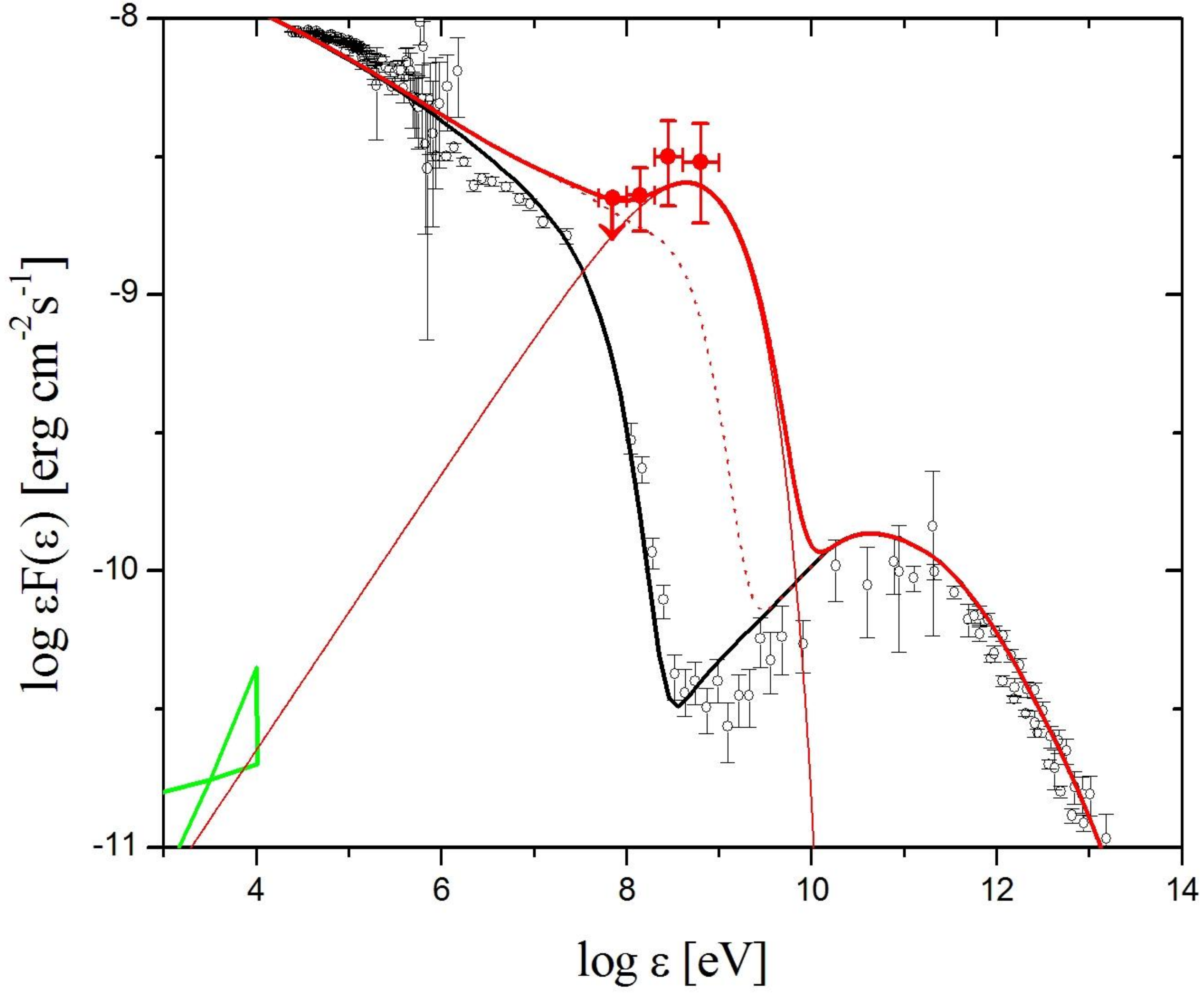
Crab super-flare: Chandra monitoring
(12, 13, 14, 21 Apr. 2011: A. Tennant, M. Weisskopf)



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.

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



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 (10 times larger than average)**
- **$\gamma_{max} \approx \gamma_{break} \leq 10^9 (E/B)(\delta\, \alpha'/\sin\theta)^{1/2} (B/10^{-3}\ G)^{-1/2}$**
- **$\delta = 2$-3**

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**

issues

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

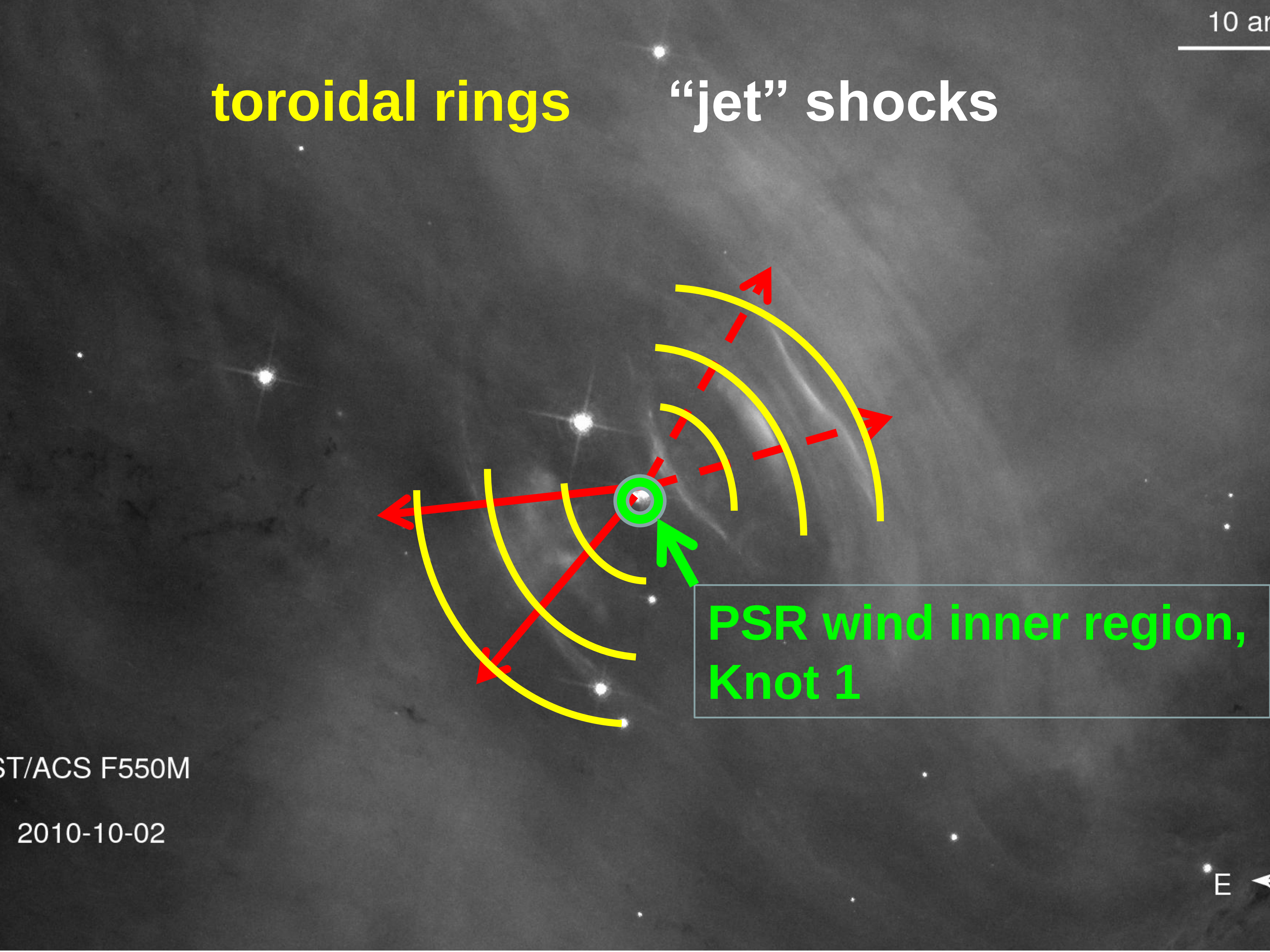
ideas

- **instability: magnetic field reconnection**
  - in the polar jet region

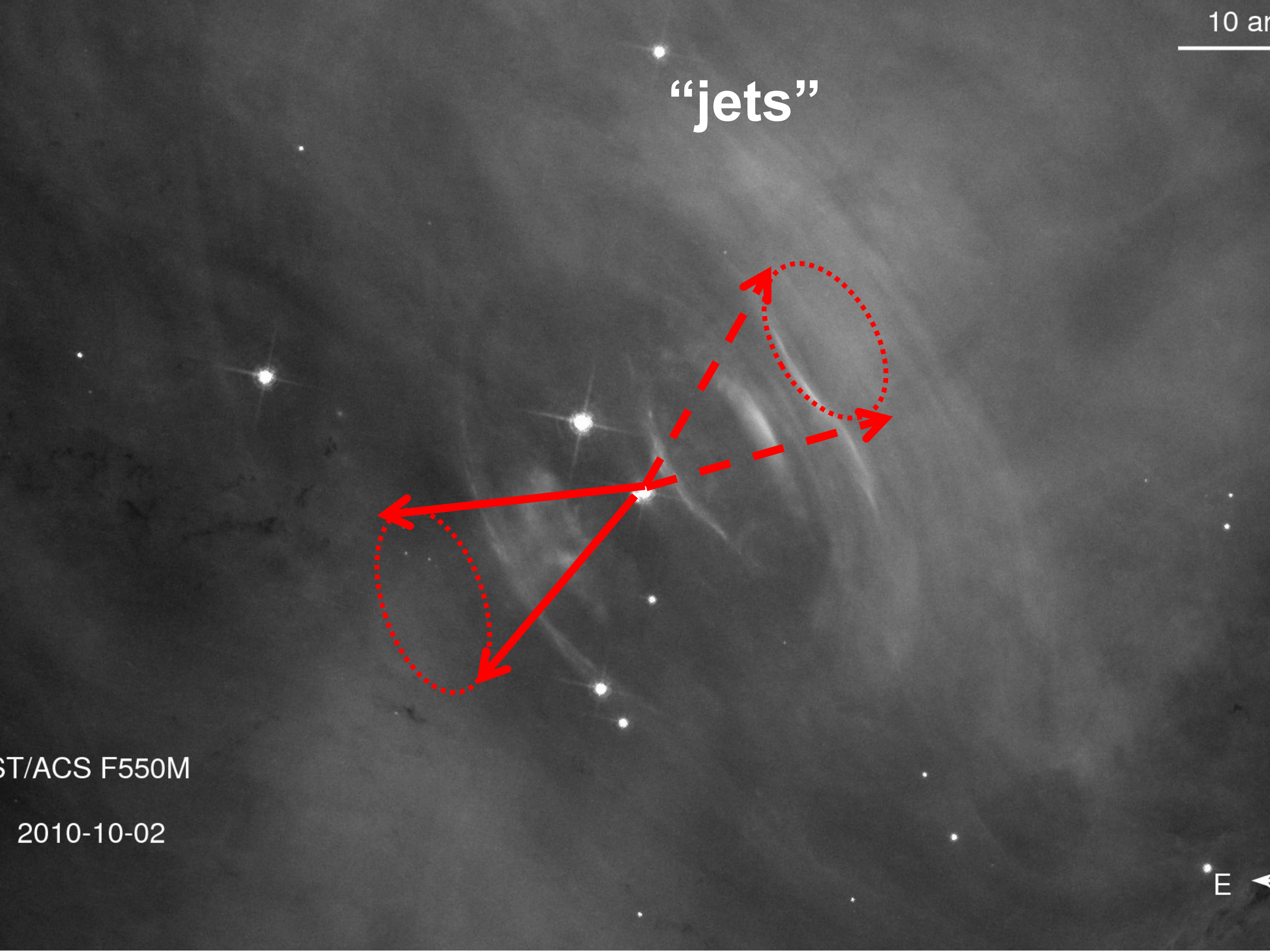
- **current sheet instabilities in rings**

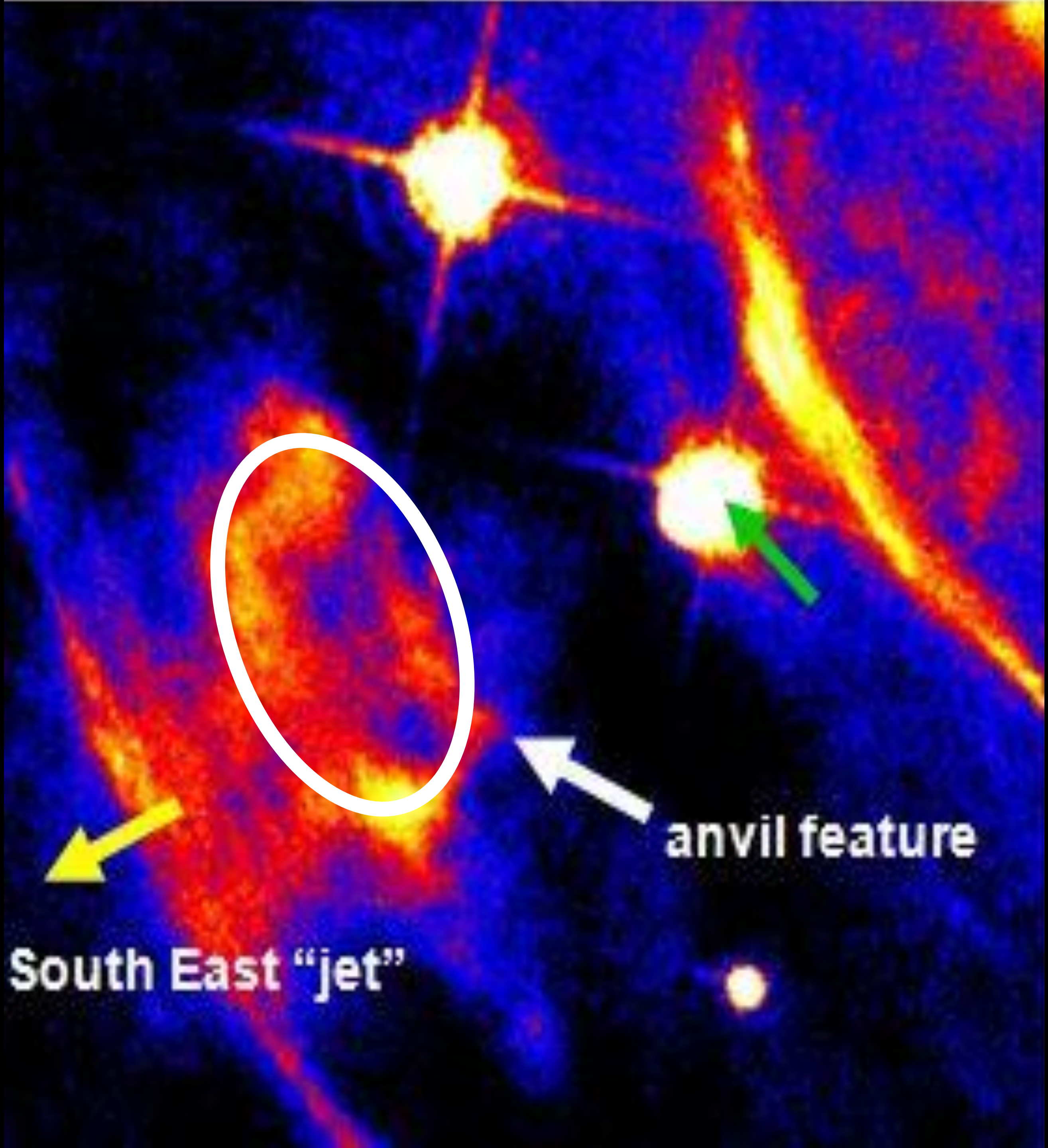
- **relativistic shocks developing E-parallel**

- **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 (?)**



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

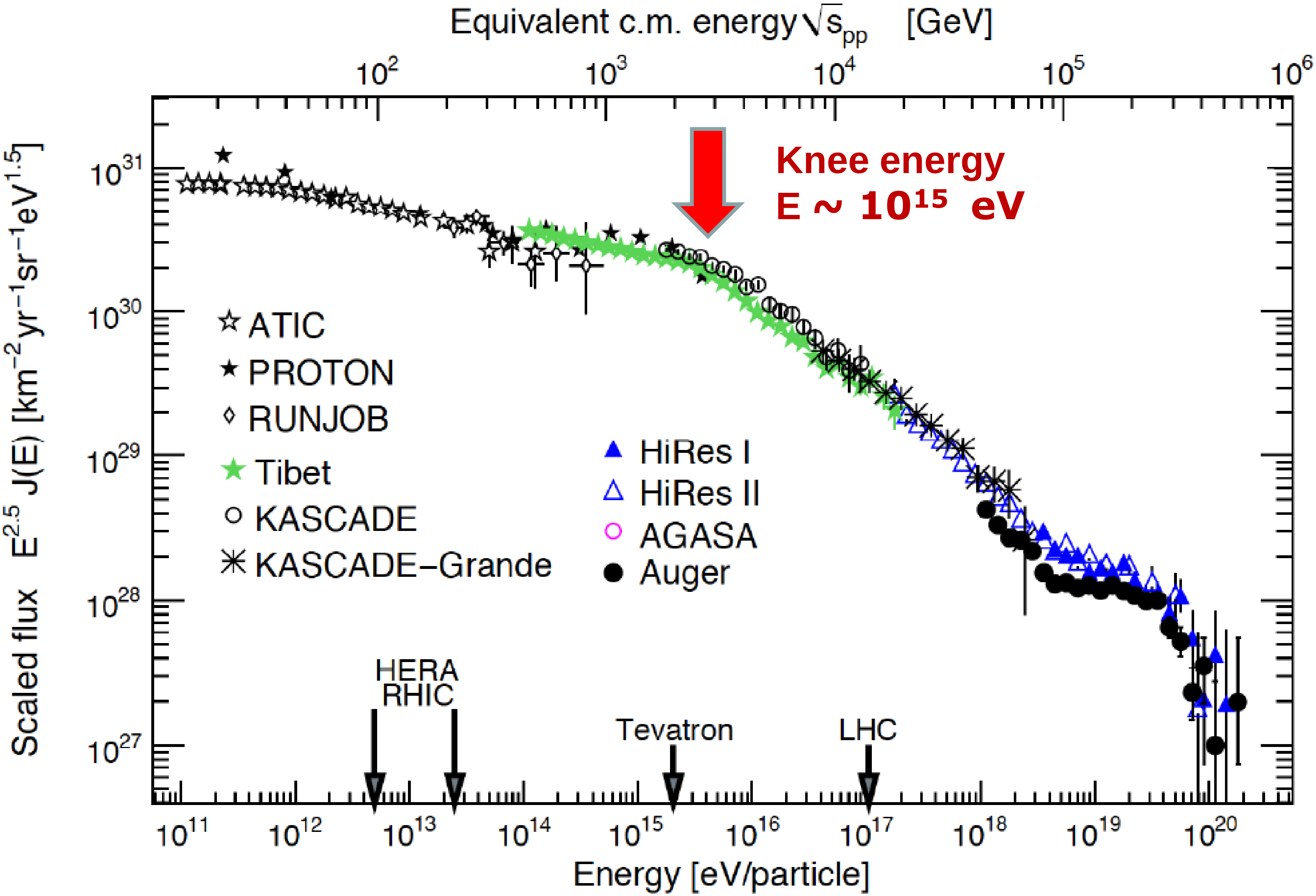

10 ar
“jets”
ST/ACS F550M
2010-10-02
E



HST,
Oct. 2, 1010

on the origin of cosmic rays

Raggi cosmici adronici (CR)



Cosmic-Ray sources and acceleration up to 10^{15} eV

- Supernova explosions and Remnants
- Fast spinning neutron stars
- Relativistic jets (microquasars, NSs)
- Exotic Objects

The big question:

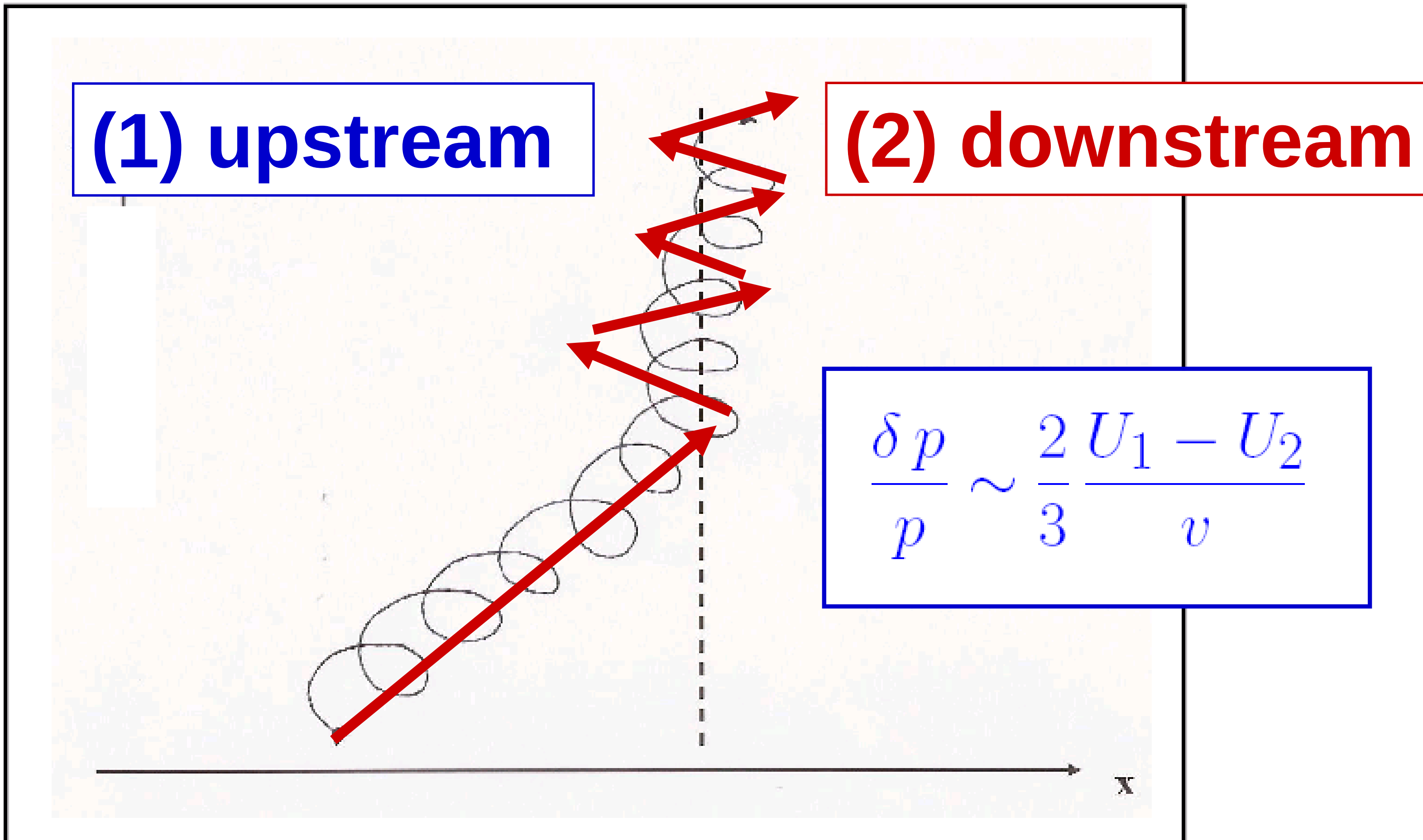
Do SNe produce cosmic-rays ???

V. Ginzburg, Syrovatskii, late 50’s, 1964

F. Hoyle (1960)

….

Diffusive shock acceleration (DSA)
(first-order Fermi acceleration)



$$\frac{\delta p}{p} \sim \frac{2}{3}\frac{U_1 - U_2}{v}$$

- DSA shock acceleration timescale

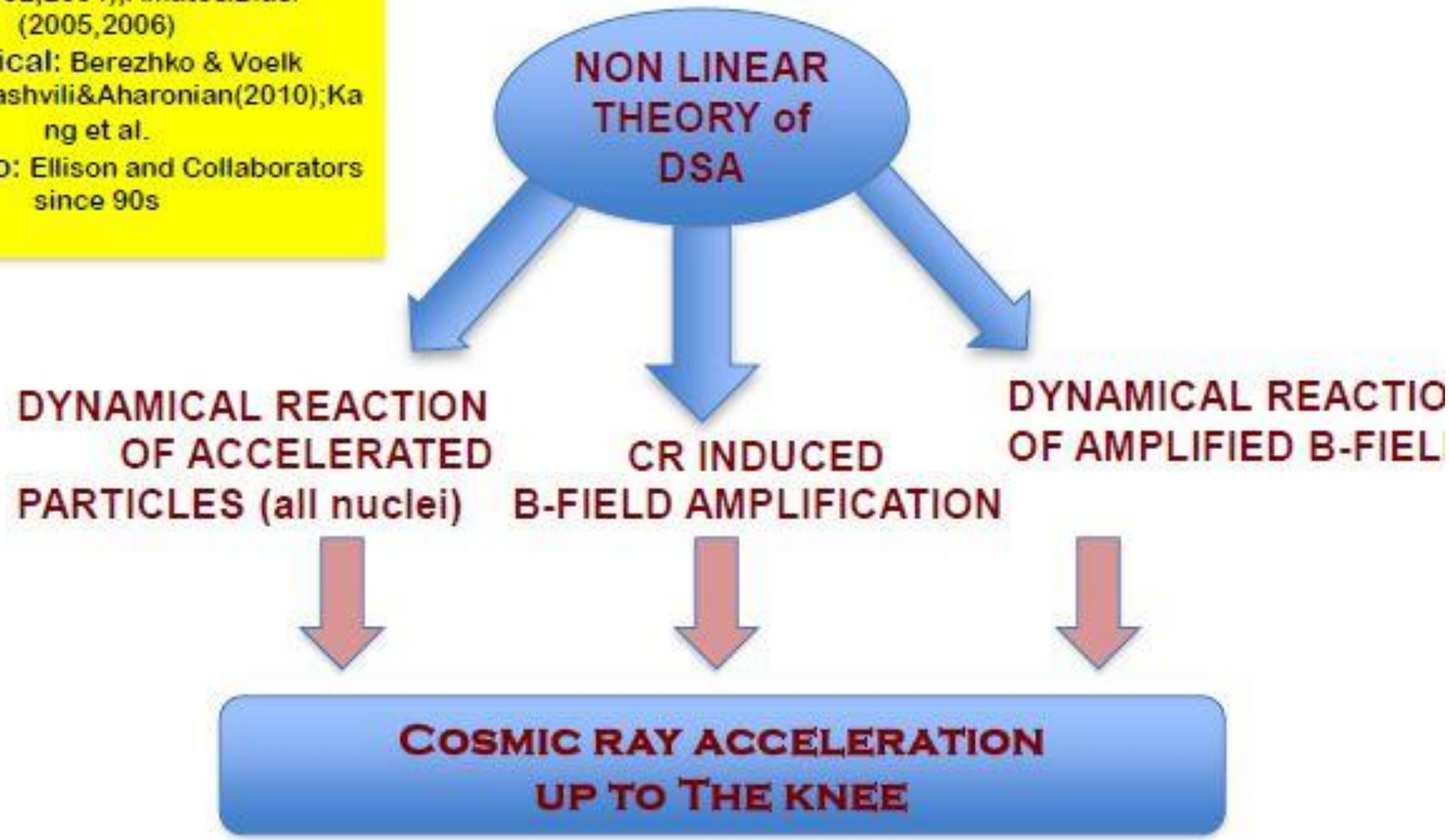
$$\tau_{acc} \sim (10/3)\, \eta\, c\, R_g\, V_s^{-2} \approx 10^3 - 10^4 \text{ yrs}$$

- R_g = cp/eB (gyroradius)
- $\eta \geq 1$ (gyrofactor)
- V_s = shock speed (10^3 km/sec)

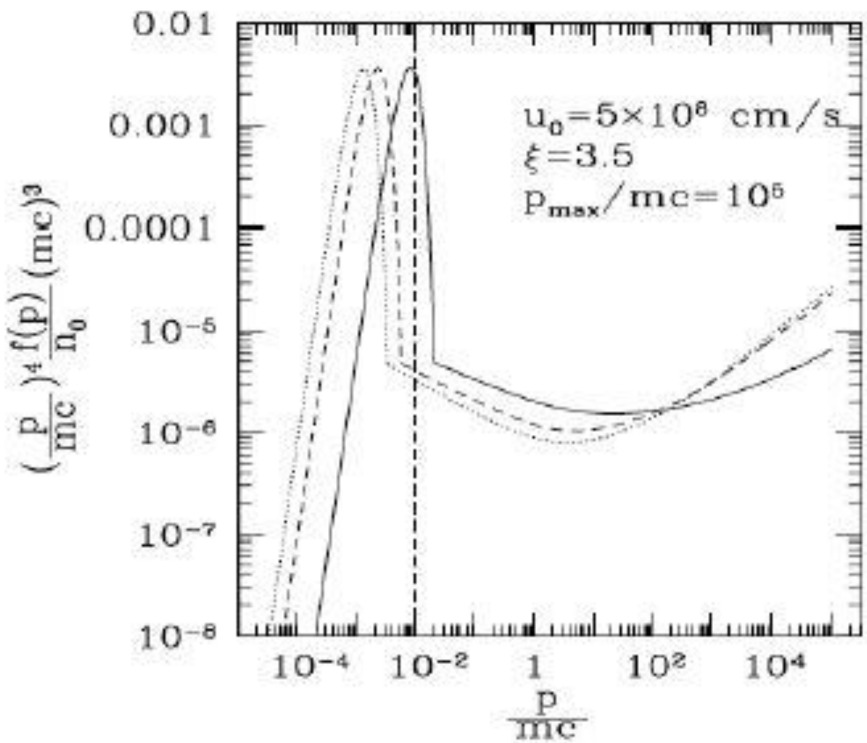
Particle acceleration in SNRs requires a non linear theory

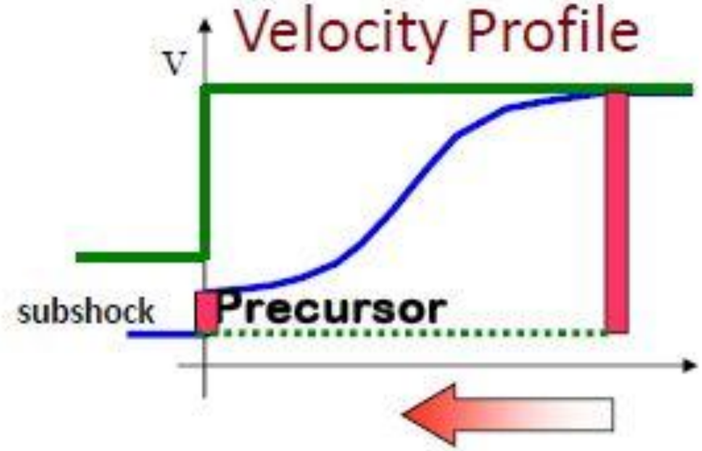
From P.Blasi

Analytical: Malkov(1997,1999), Blasi(2002,2004),Amato&Blasi (2005,2006)
Numerical: Berezhko & Voelk (1997),Zirakashvili&Aharonian(2010);Kang et al.
MonteCarlo: Ellison and Collaborators since 90s



Dynamical Reaction of Accelerated Particles on a collisionless shock





HOT: thermalization behind a collisionless shock

Supernova 1006

(Goumard et al. 2006)

First non-thermal hard X-ray SNR (1995)

Shell-type supernova

distance = 1.8 - 2.2 kpc

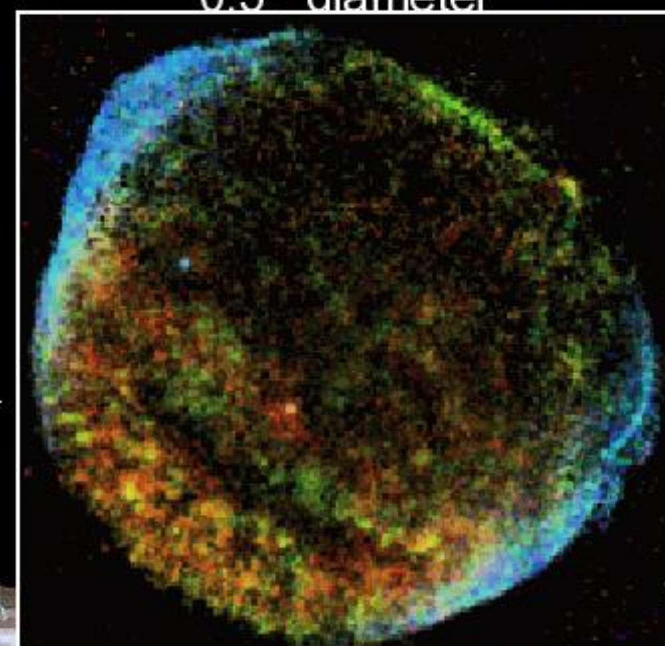
Winkler et al. (2003)

$N_H = 0.05 - 0.3\ cm^{-3}$

Chandra
(X-rays)

50 light years

0.5° diameter



X-Ray Rims

From P.Blasi

TYPICAL THICKNESS OF FILAMENTS: ~ 10^{-2} pc

The synchrotron limited thickness is:

$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

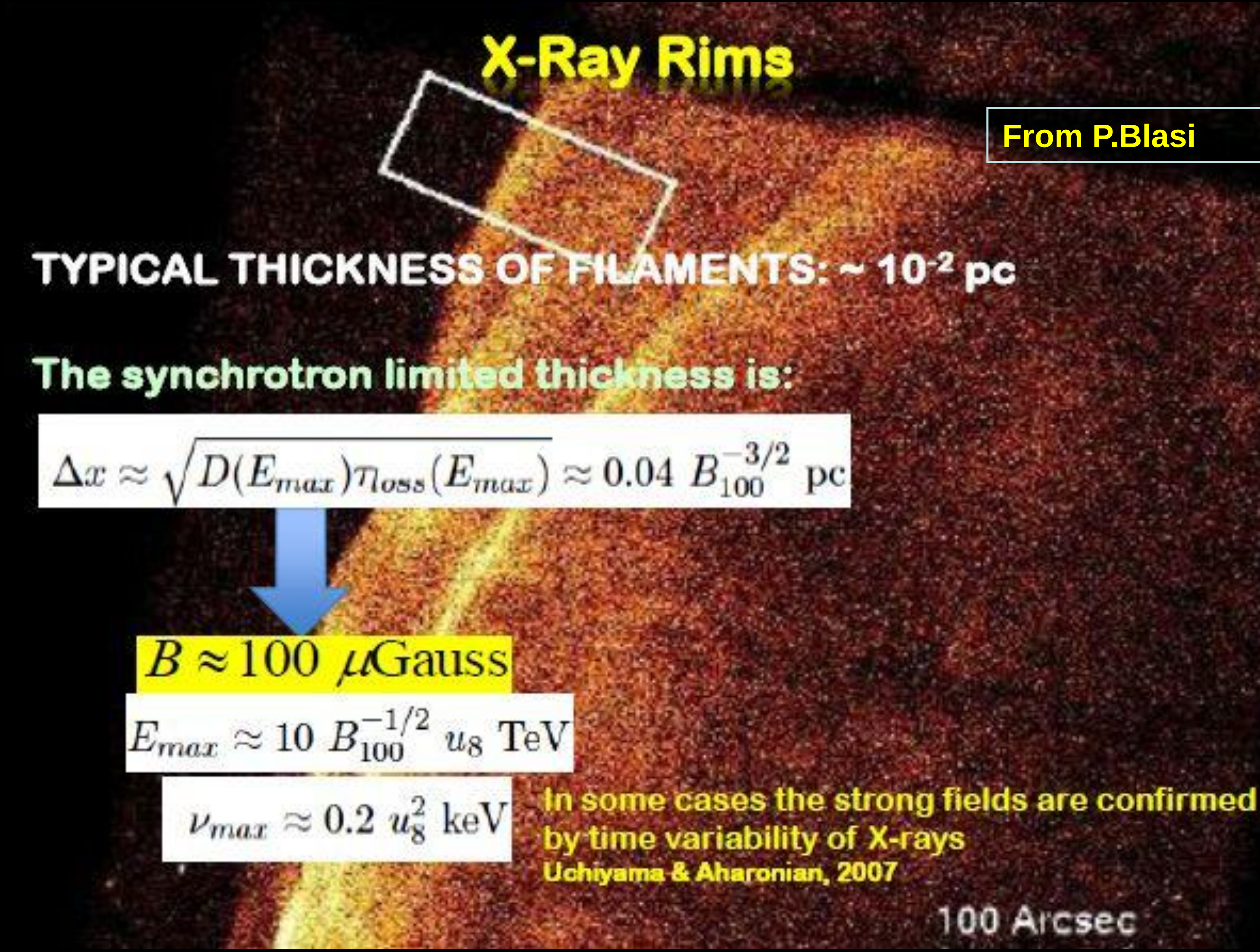
$$B \approx 100\ \mu\mathrm{Gauss}$$

$$E_{max} \approx 10\ B_{100}^{-1/2}\ u_8\ \mathrm{TeV}$$

$$\nu_{max} \approx 0.2\ u_8^2\ \mathrm{keV}$$

In some cases the strong fields are confirmed by time variability of X-rays

Uchiyama & Aharonian, 2007



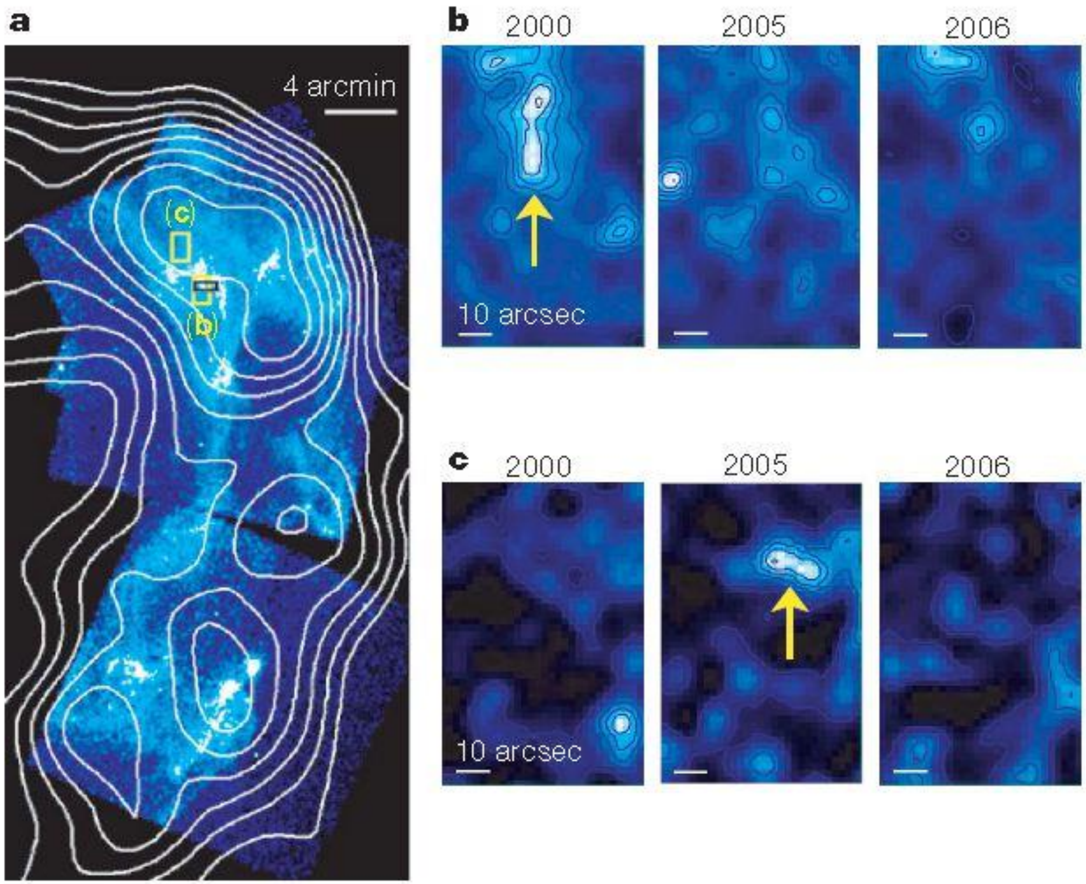


Figure 1 | Chandra X-ray images of the western shell of SNR RX J1713.7−3946. **a**, A Chandra X-ray mosaic image is overlaid with TeV γ-ray contours from HESS measurements[26]. North is up and east is to the

(Uchiyama, Aharonian et al. 2007)

Variable (!) and strongly enhanced X-ray features

large local magnetic field B

B-amplification by CR turbulent processes (Bell,Lucek, 2001)

B = 1 mG

proton-nuclei energies
E = 1 PeV (B/mG) (T/100 yrs)

unambiguous proof of the CR origin in SNRs…

- **Electrons**
  - **Bremsstrahlung (target density)**
  - **Synchrotron emission (magnetic field)**
  - **Inverse Compton (CMB, interstellar photons)**

- **Pion production (target density)**

$$p + p \Rightarrow X + \pi^0$$

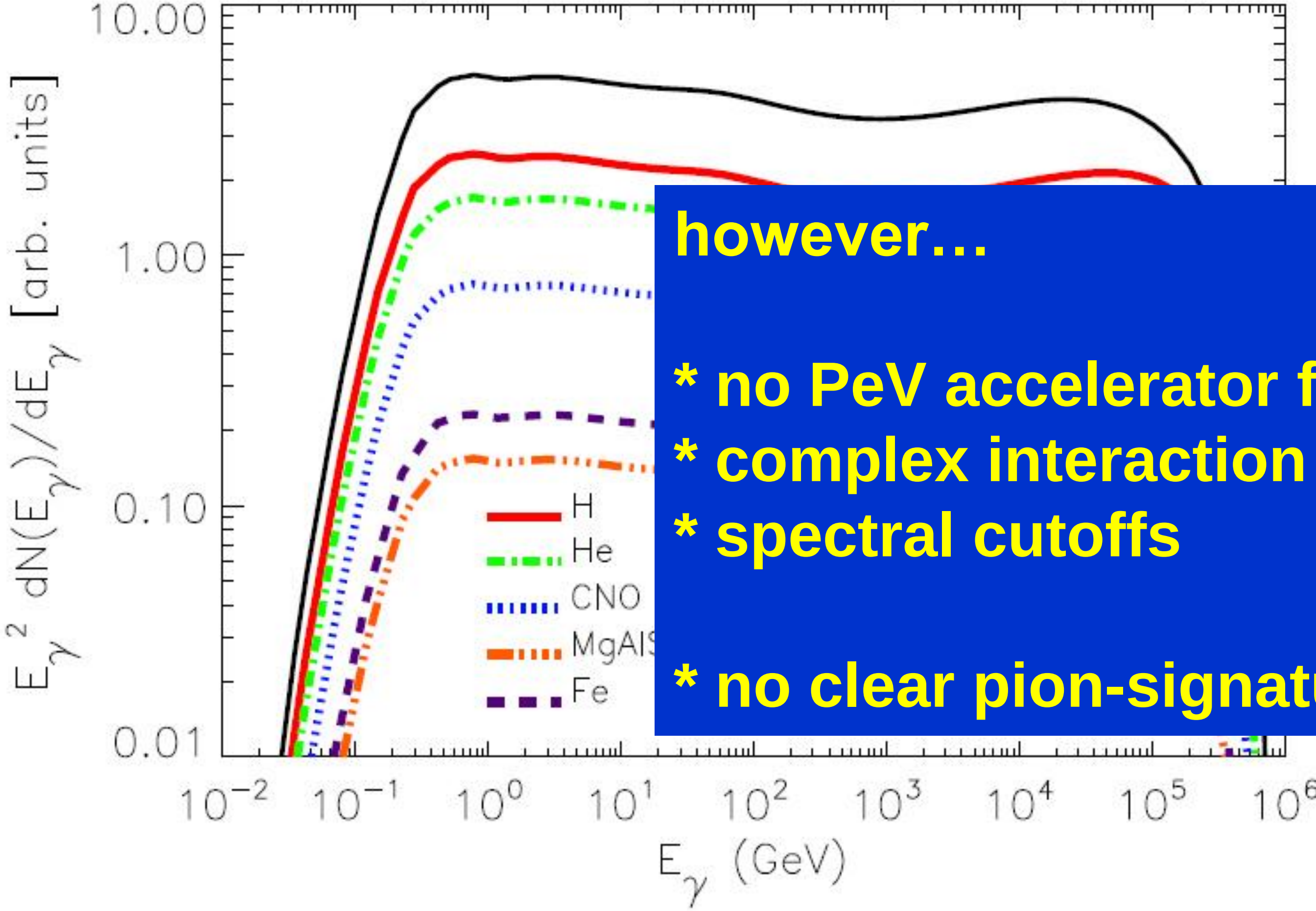
$$\hookrightarrow \gamma + \gamma \quad (\sim 70+70 \text{ MeV})$$

$$\sigma_{pp} \sim 40 \text{ mbarn}$$

$$\tau \sim (\sigma_{pp}\, n\, c)^{-1} \sim (6 \cdot 10^7 \text{ yrs})\, n^{-1}$$

Idealized case: pion emission from accelerated CR in SNR (Caprioli et al. 2010)

the quest for a Pevatron



however…

*** no PeV accelerator found yet**
*** complex interaction**
*** spectral cutoffs**

*** no clear pion-signature**

Cosmic-ray origin in SNRs ?
so far, difficult to prove

- **The ideal SNR:**
  - **energetic**
  - **close to Earth**
  - **with the right dense target (molecolar cloud)**

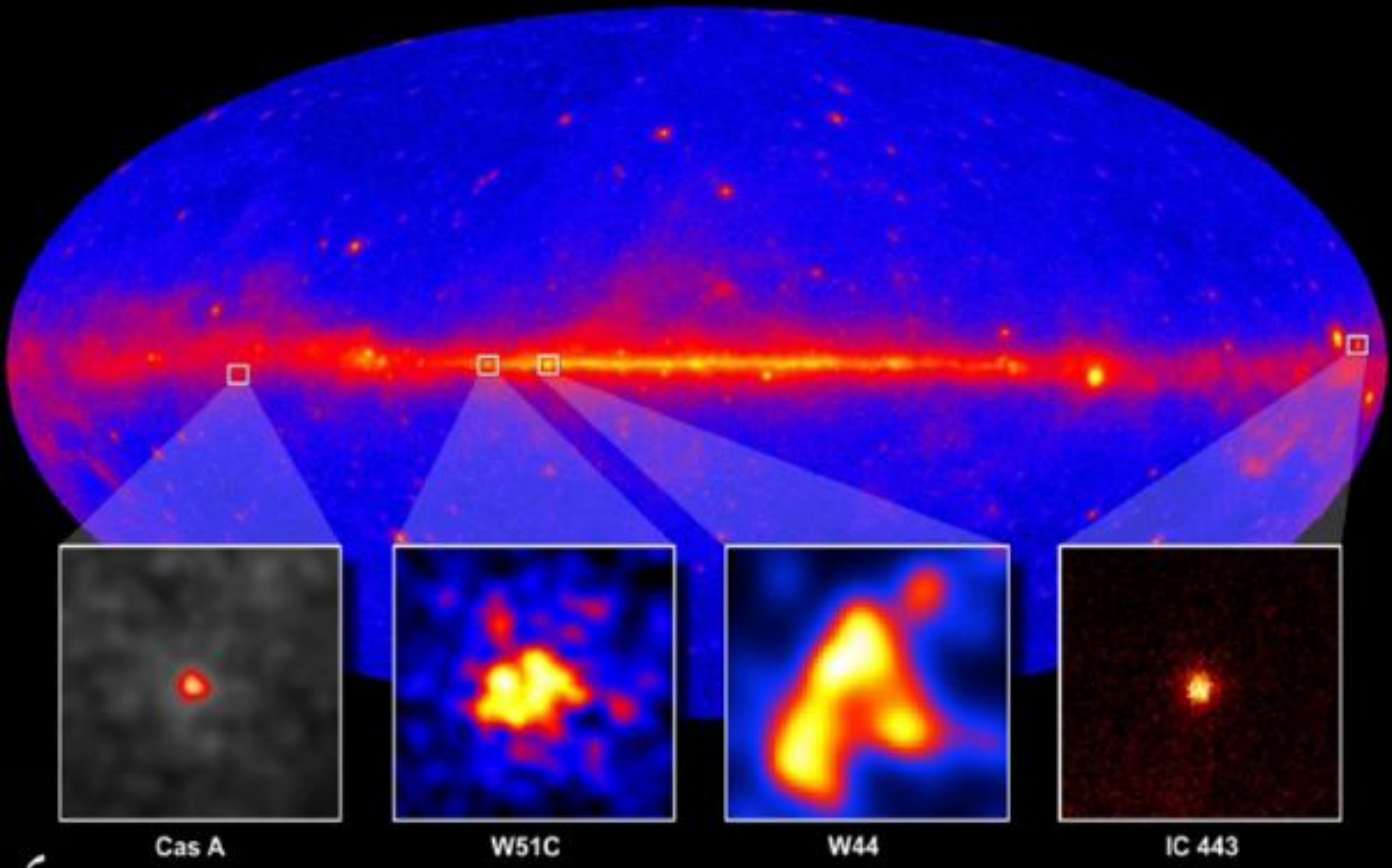
- $f = (W_p \,/\, t_{pp})/4\,\pi\, d^2 \sim (\, n\, W_p\,)/\, d^2$

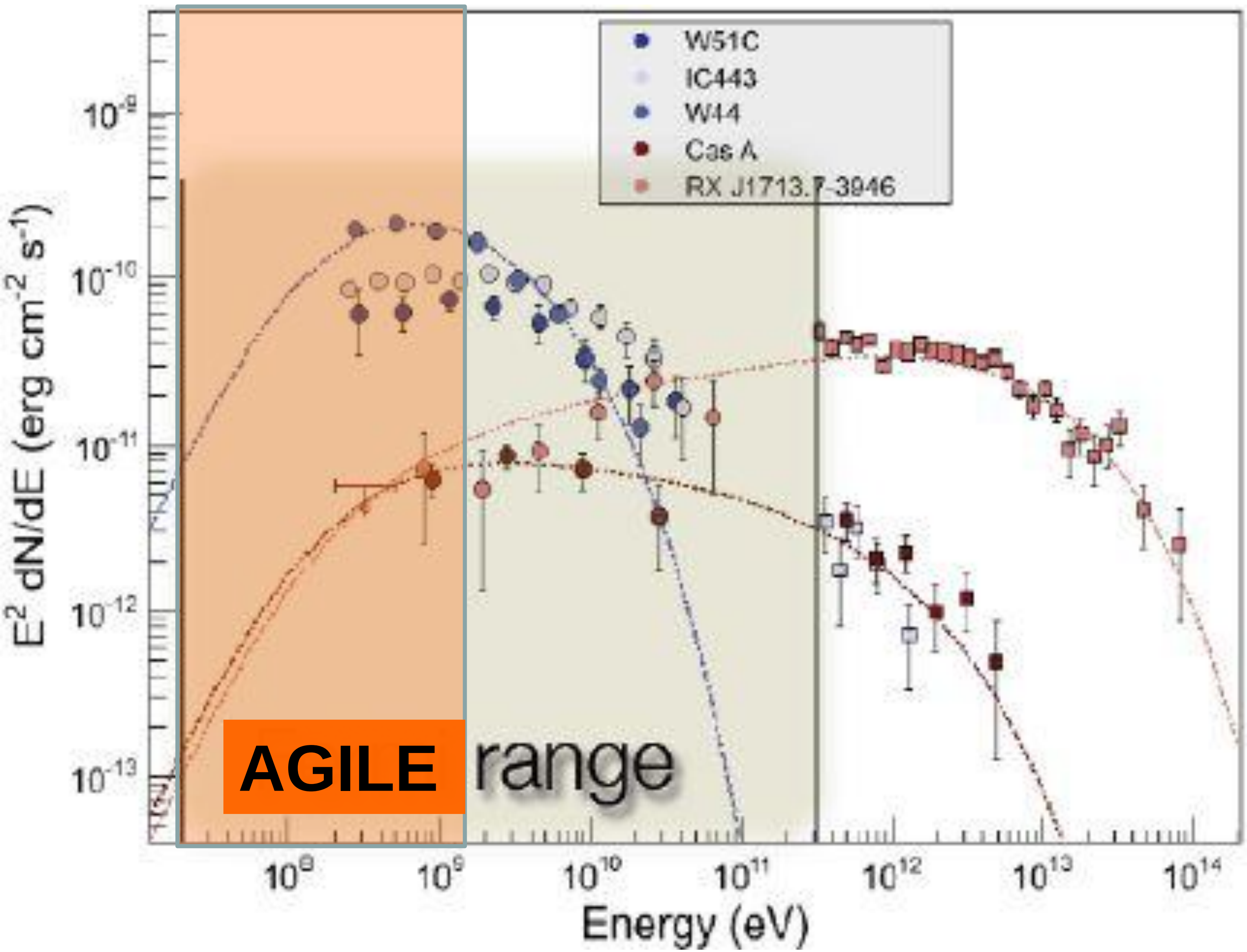
- **possibly low-background**

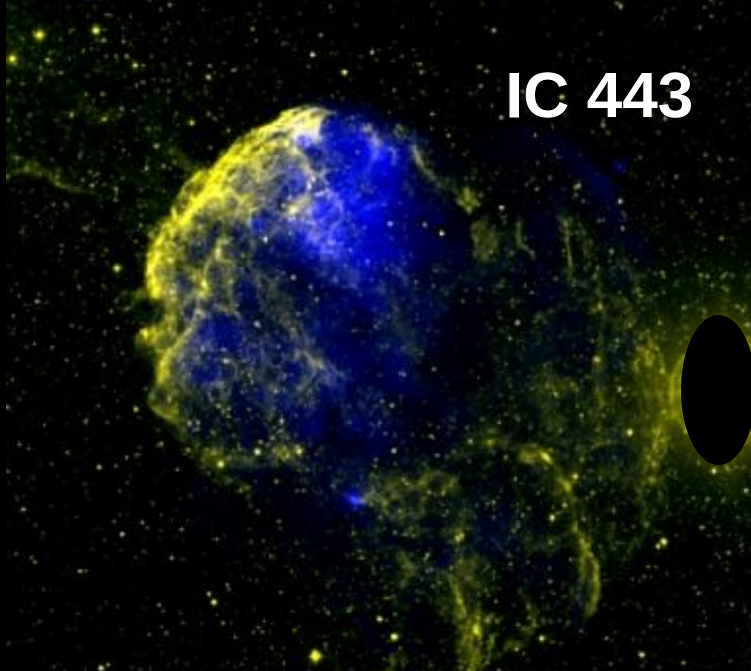
- **not that easy…**

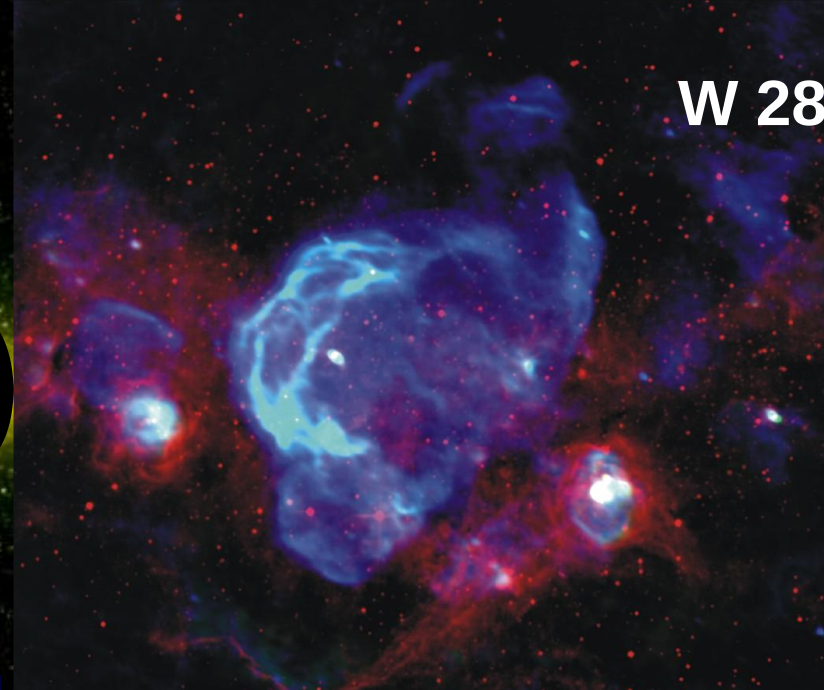
gamma-ray detected SNRs

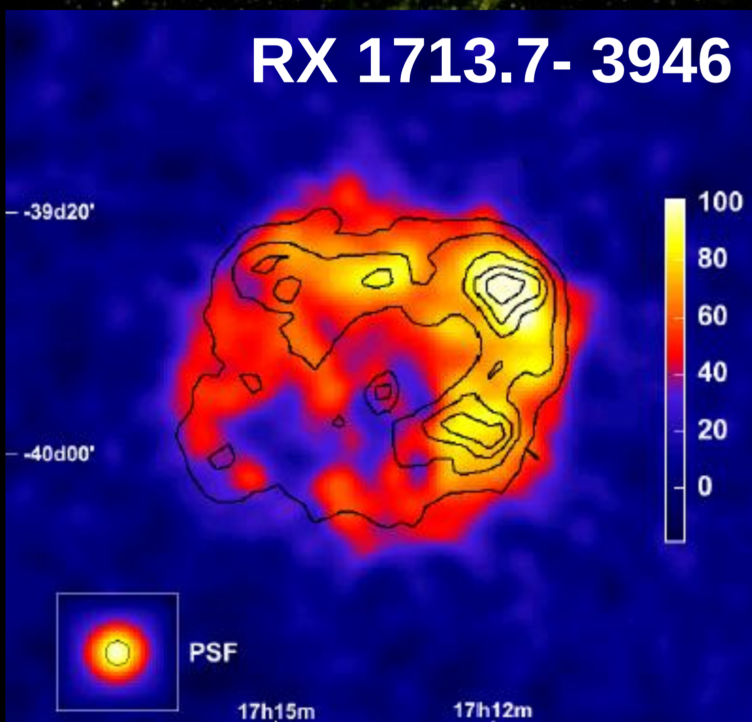
SNR (l,b)	AGILE	Fermi-LAT	age[yrs]
CAS A (111.7,-2.1)	no	yes	~300
SN 1006 (327.6,+14.6)	no	no	~1,000
RXJ1713 (347.3,-0.5)	in prep.	yes	~1,600
W49B (G43.3-0.2)	no	yes	1,000-4,000
γ-**Cygni** (78.2,+2.1)	in prep.	no	~7,000
W51 (49.5,-0.4)	no	yes	~10,000
W44 (34.7,-0.4)	in prep.	yes	~20,000
IC443 (189.1,+3)	yes	yes	20,000-30,000
W28 (6.71,-0.05)	yes	yes	35,000-45,000


Cas A
W51C
W44
IC 443

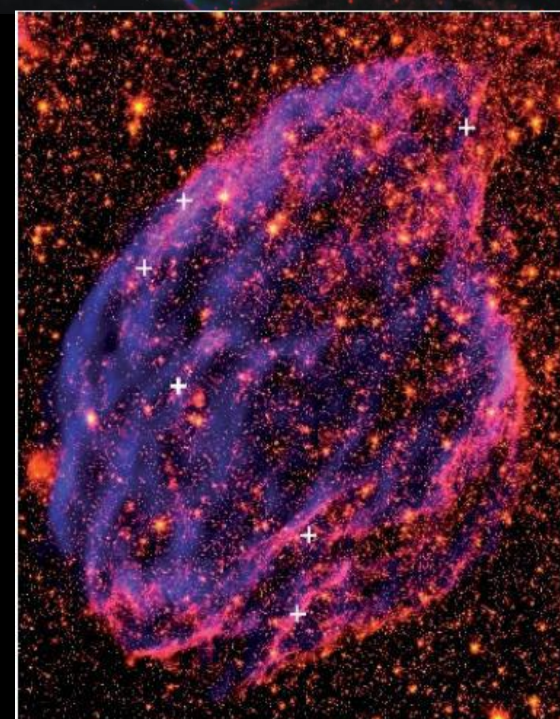

W51C
IC443
W44
Cas A
RX J1713.7-3946
AGILE range
E^2 dN/dE (erg cm^{-2} s^{-1})
Energy (eV)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}


IC 443

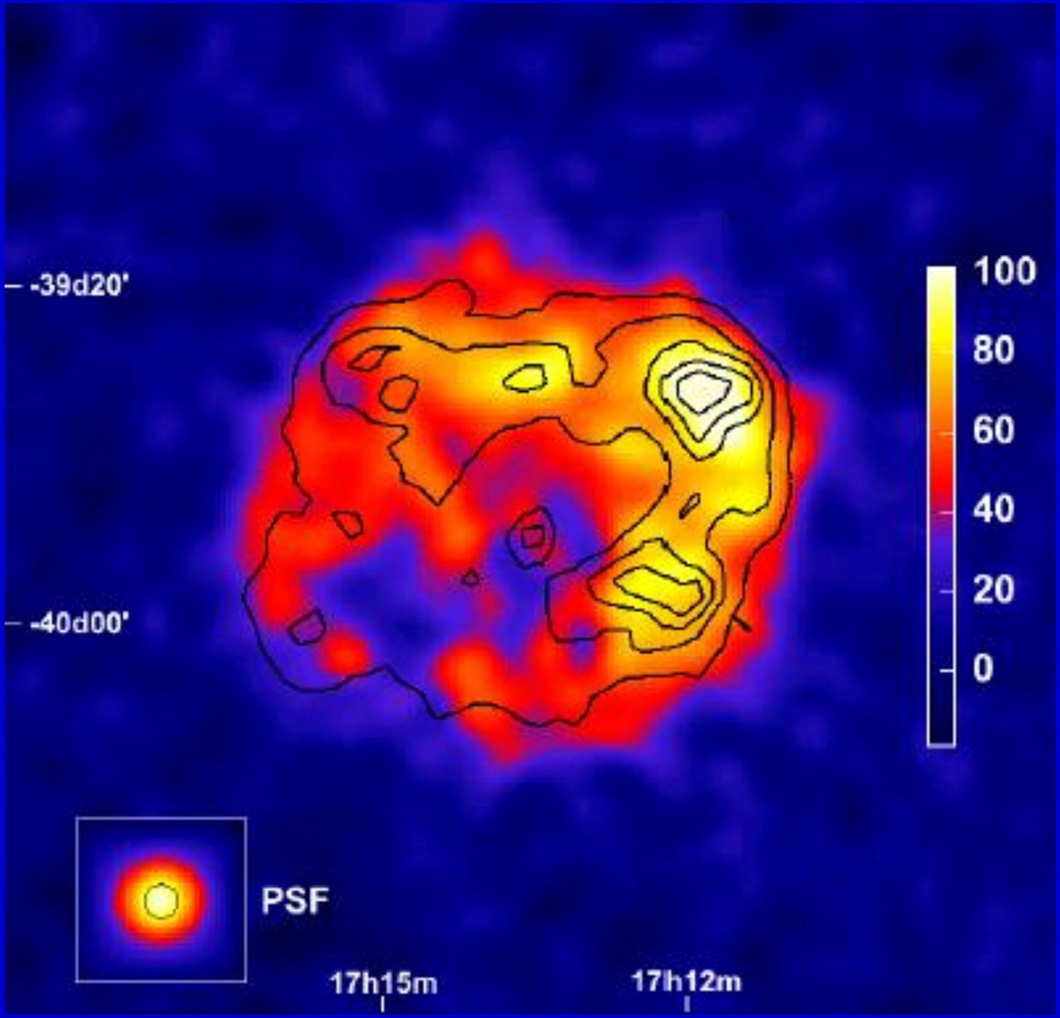

W 28


RX 1713.7- 3946
-39d20'
-40d00'
100
80
60
40
20
0
PSF
17h15m
17h12m

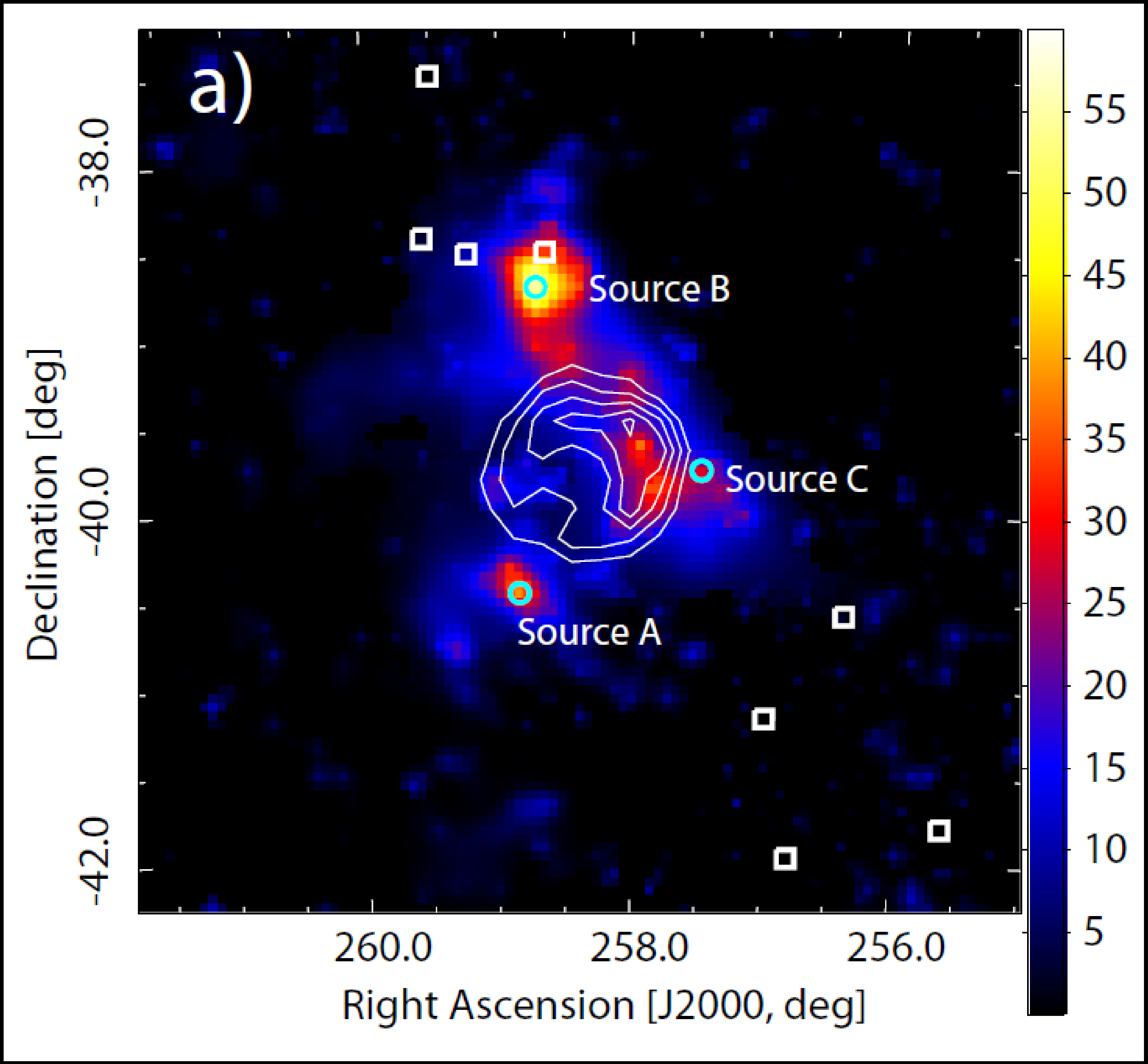
W 44



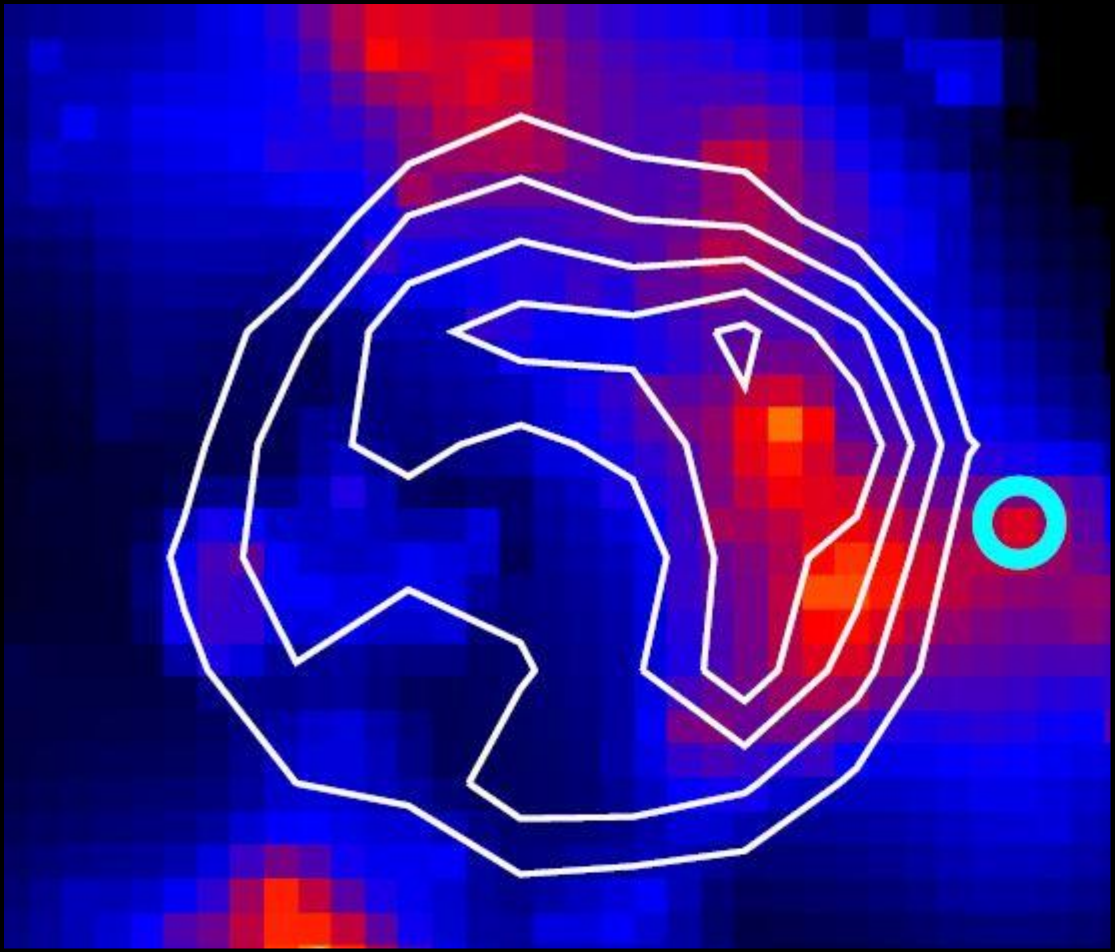
Good X-ray-TeV correlation (~80%)
ASCA-HESS data of RX 1713.7-3946 (Goumard et al. 2006)



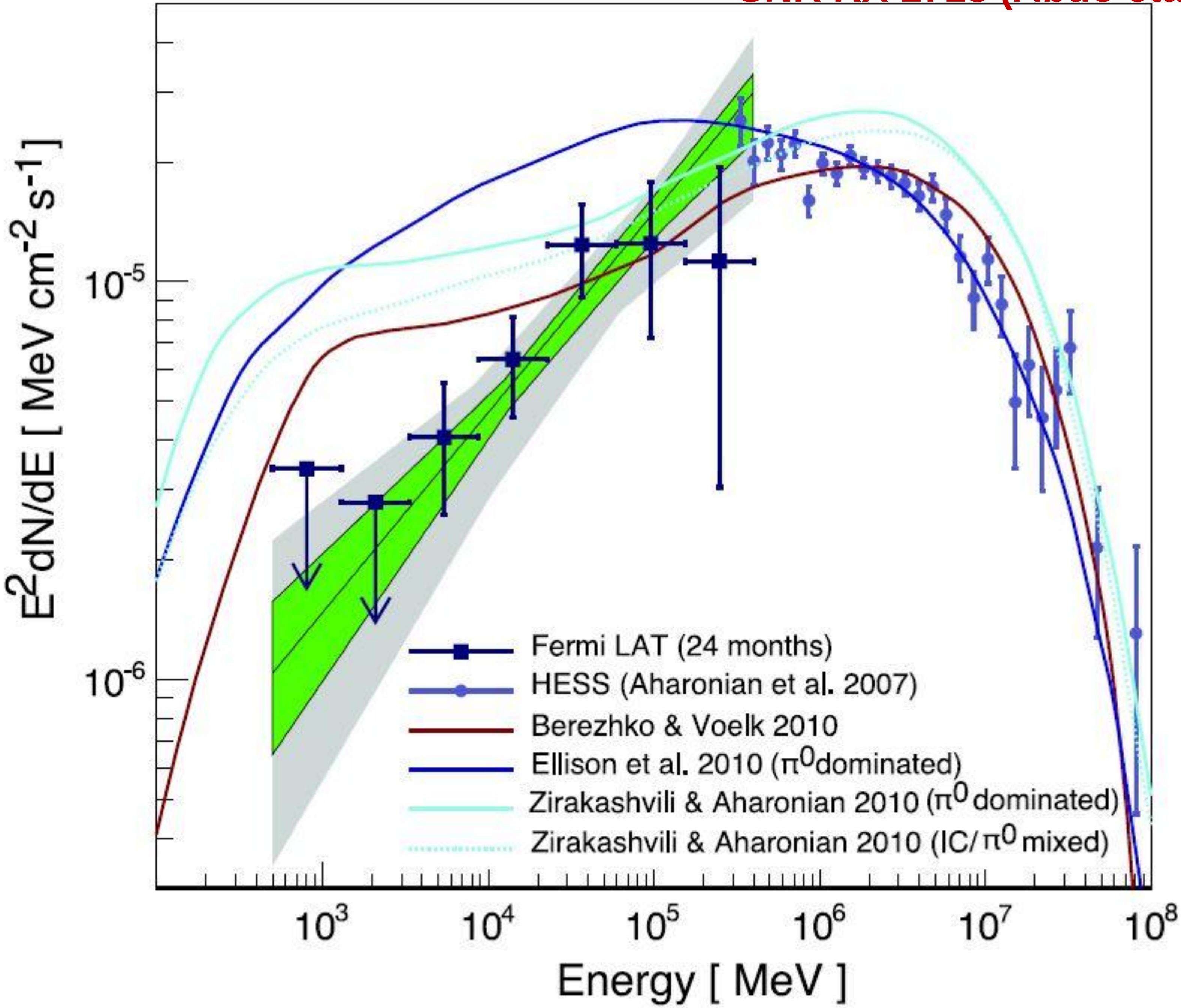
SNR RX 1713 (Abdo etal. 2011)



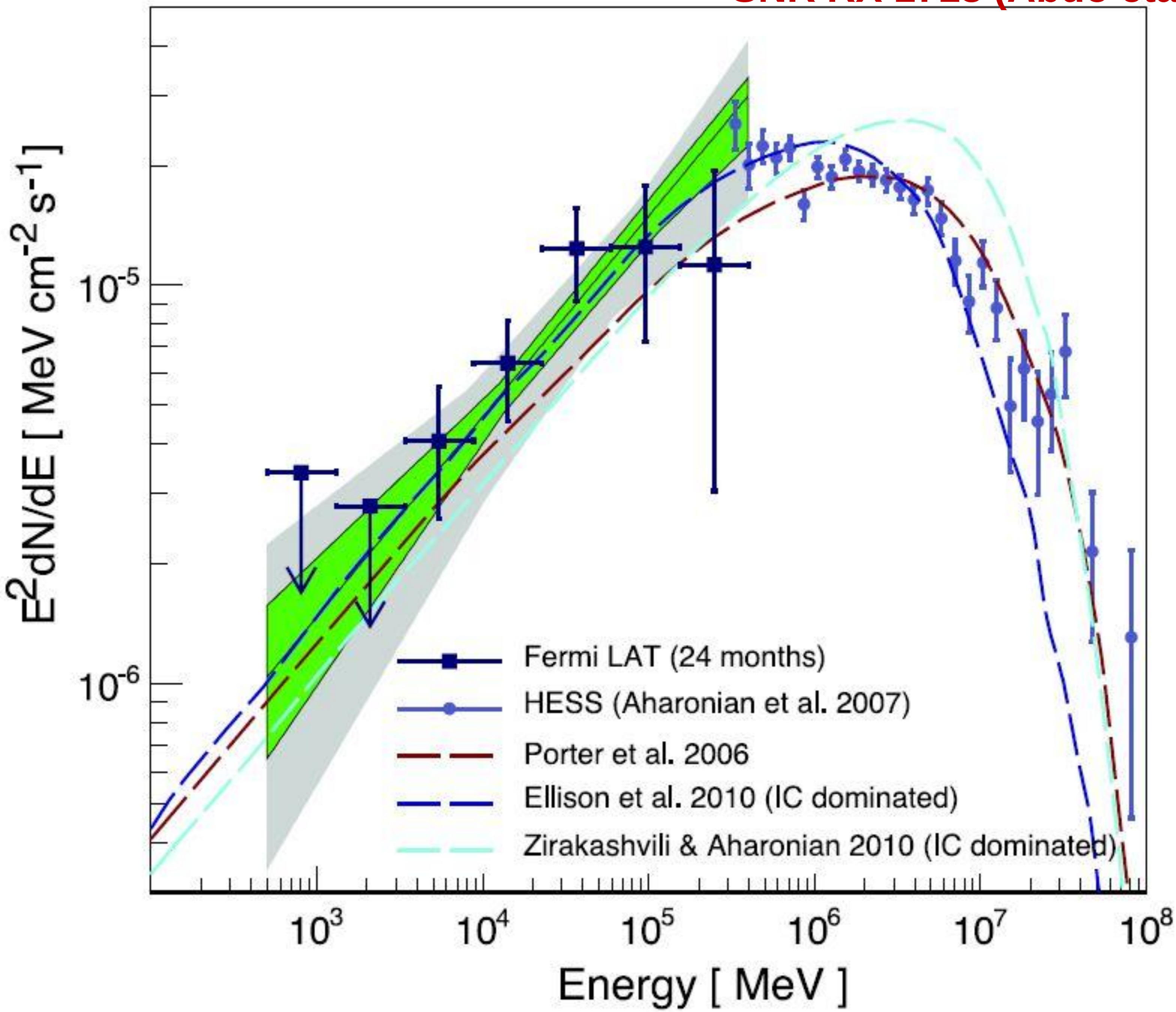
SNR RX 1713 *Fermi* 1-100 GeV (Abdo etal. 2011)



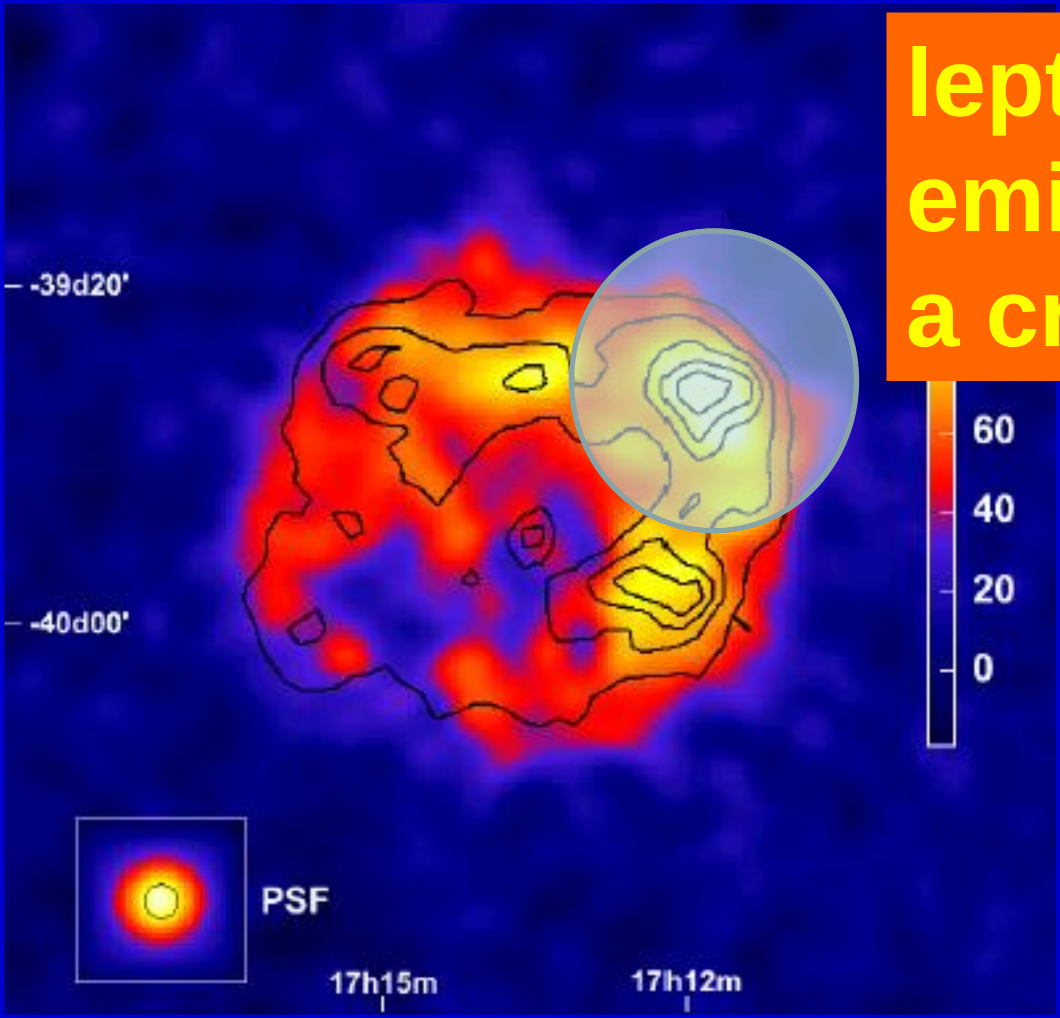
SNR RX 1713 (Abdo etal. 2011)



SNR RX 1713 (Abdo etal. 2011)

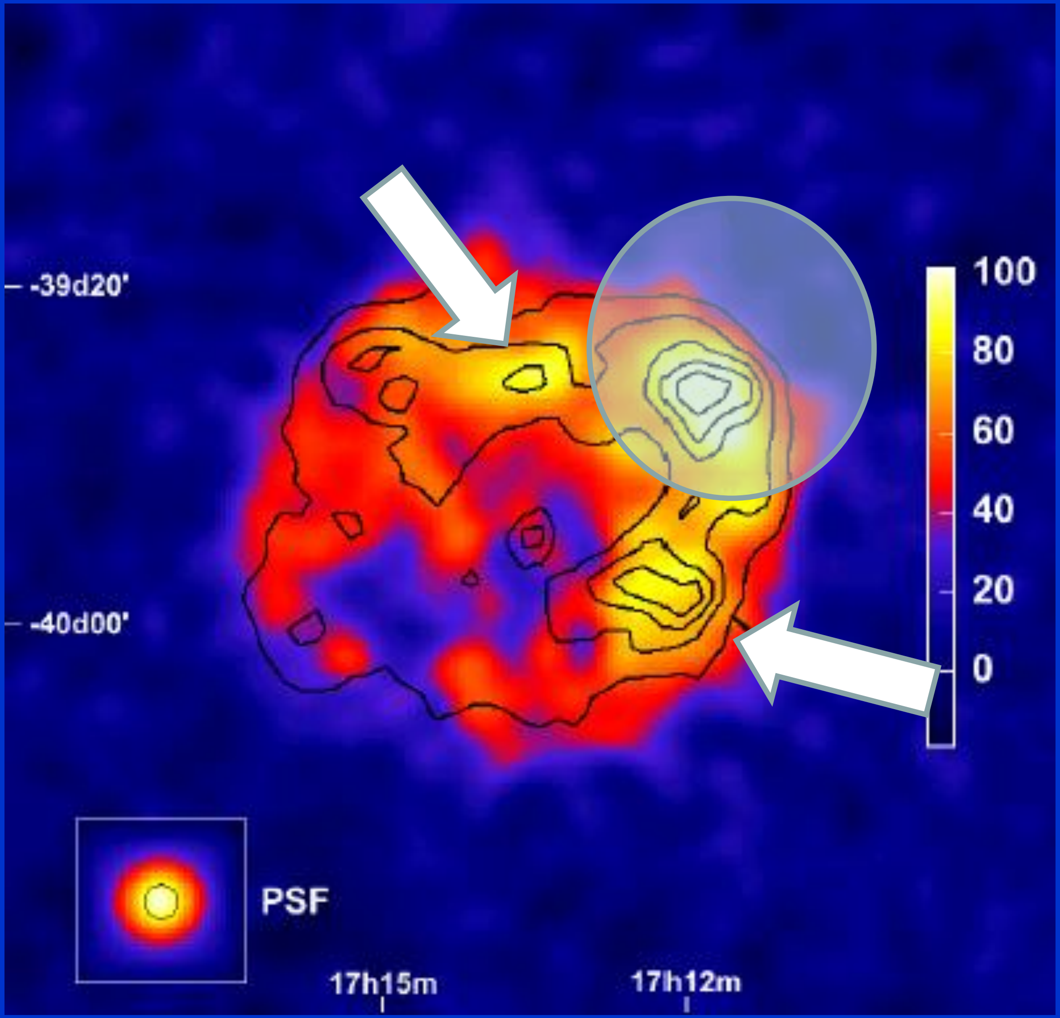


RX 1713.7-3946

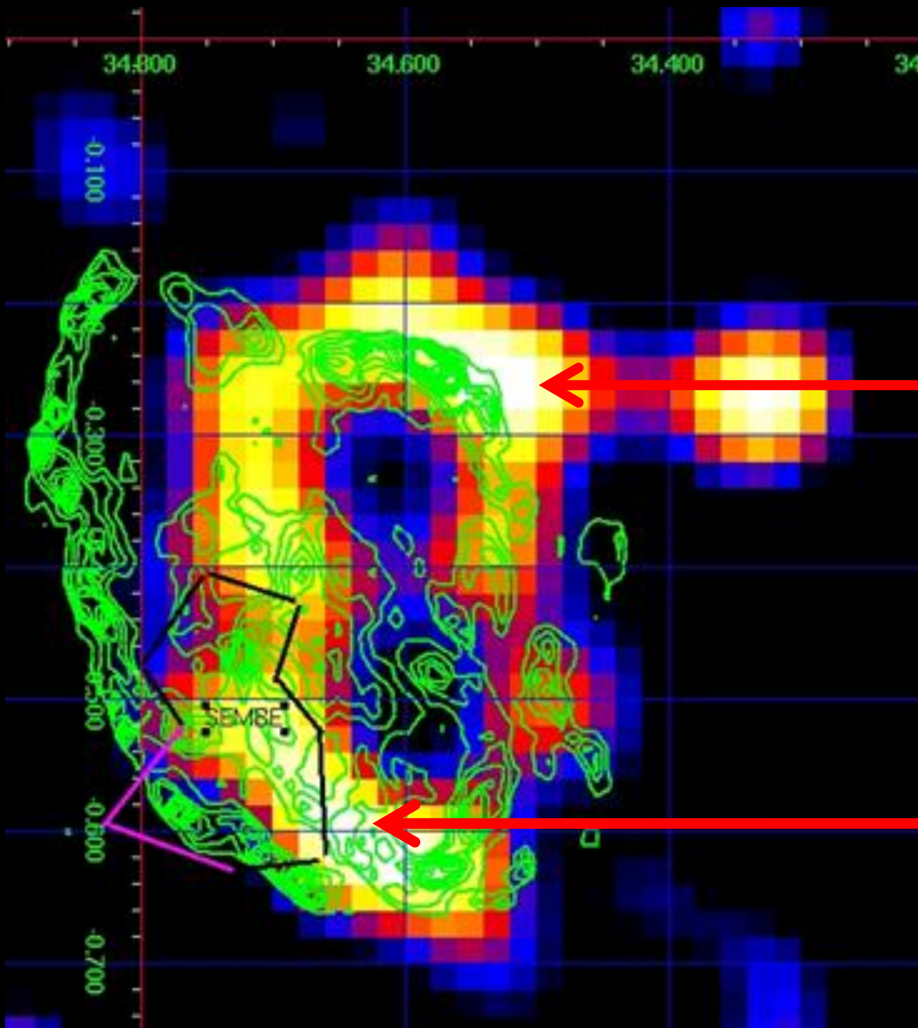


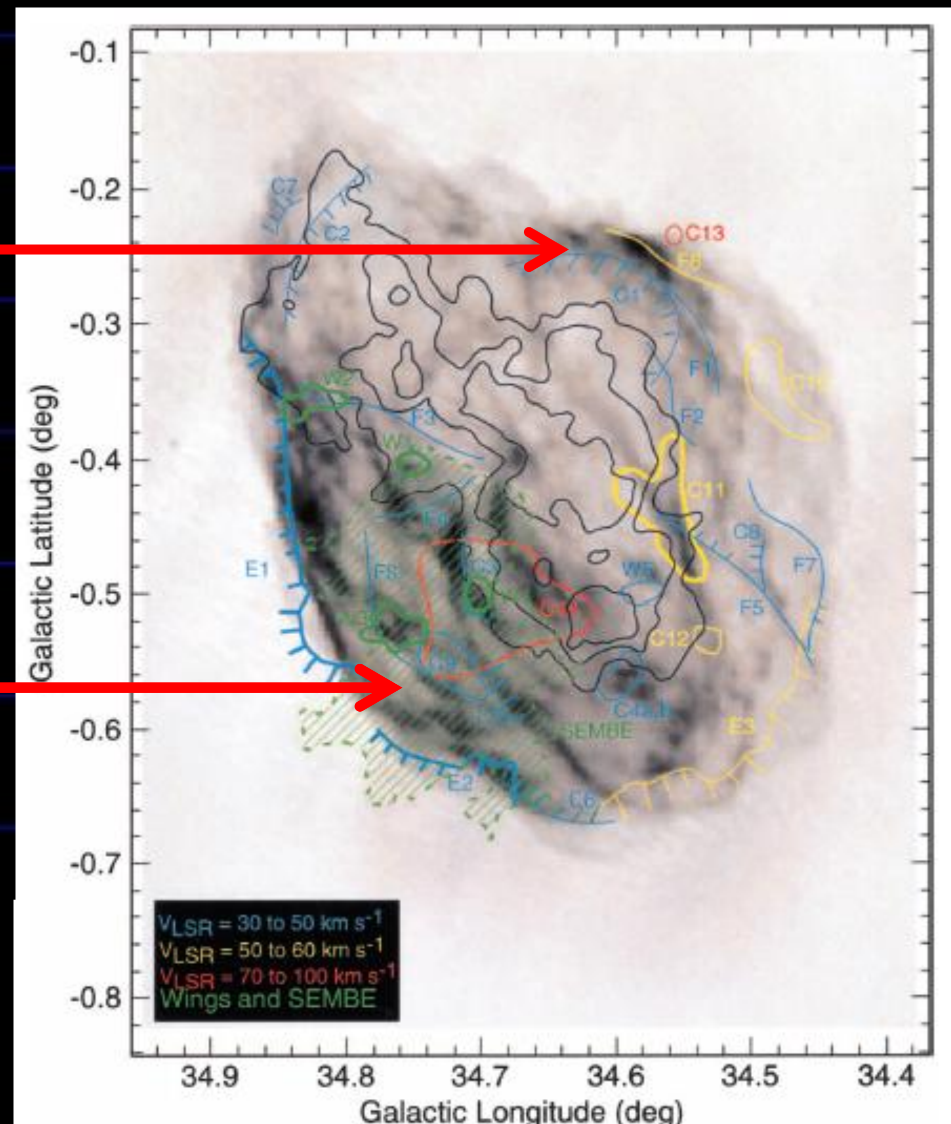
leptonic (?) emission: a crisis ?

RX 1713.7-3946

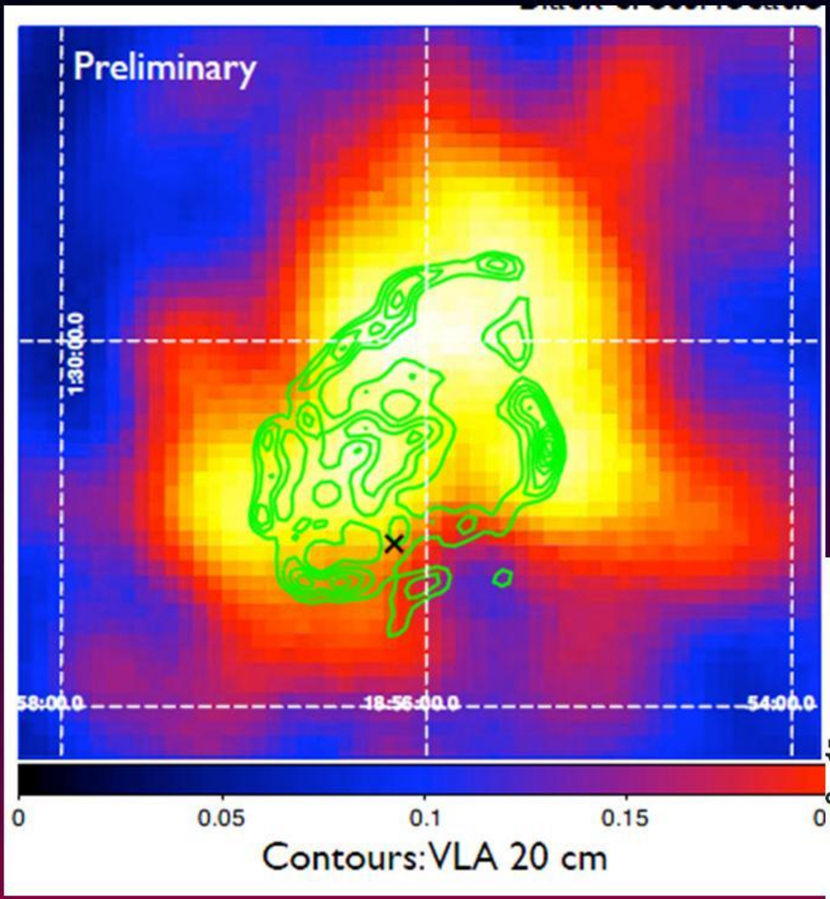


o SNR W44

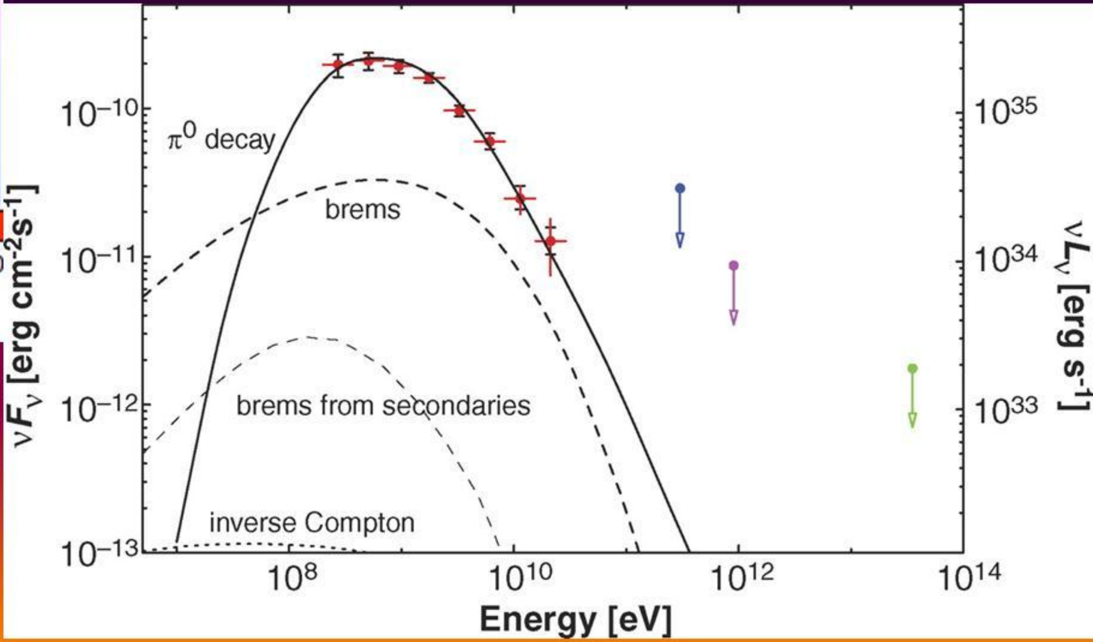

34.800
34.600
34.400
34
-0.100
-0.300
-0.500
-0.600
-0.700
SEMBE

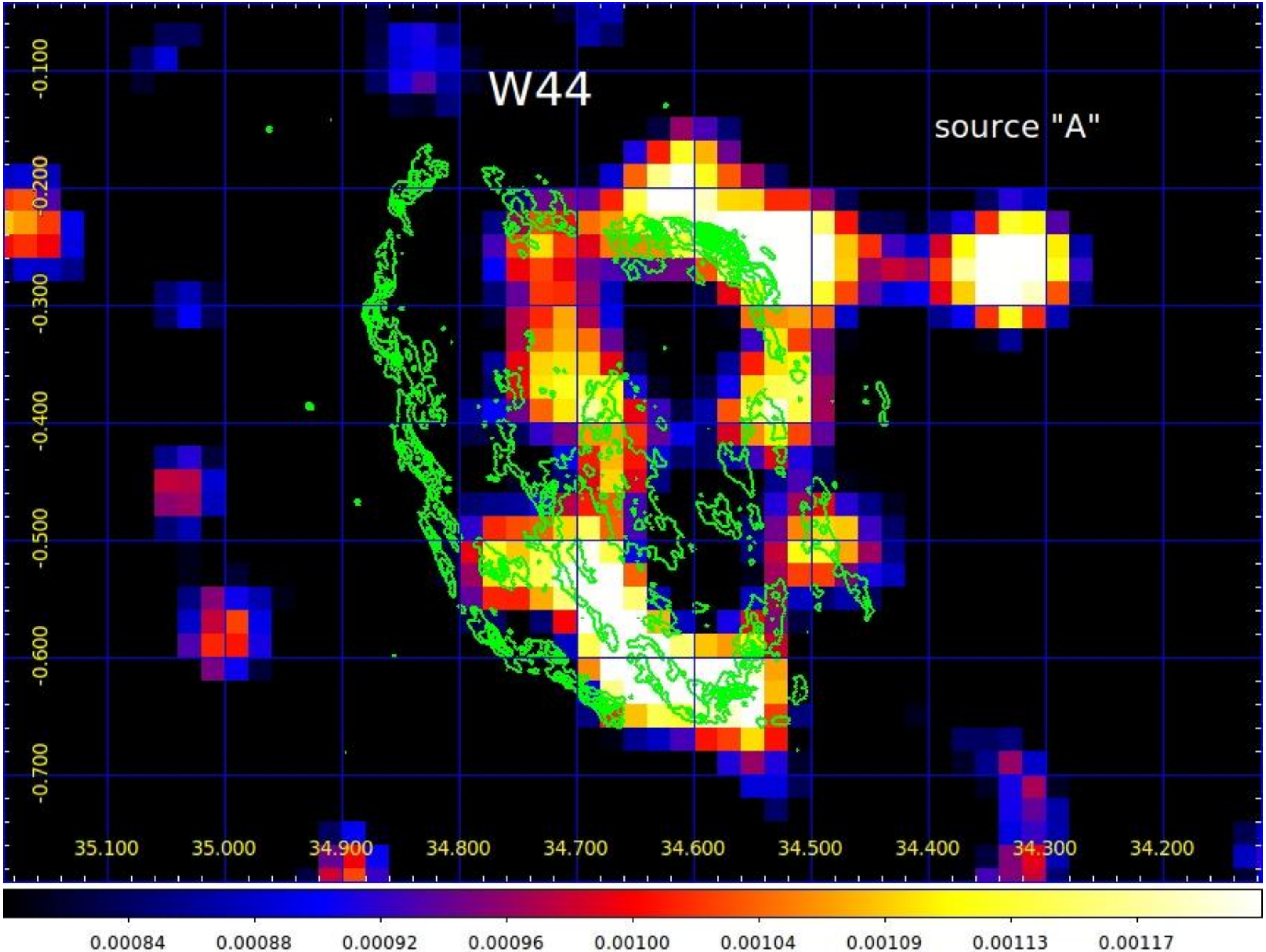

-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
Galactic Latitude (deg)
34.9
34.8
34.7
34.6
34.5
34.4
Galactic Longitude (deg)
C13
C2
C1
F8
F1
F2
F3
C11
C8
F7
F5
E1
C12
E3
E2
C6
SEMBE
V_{LSR} = 30 to 50 km s^{-1}
V_{LSR} = 50 to 60 km s^{-1}
V_{LSR} = 70 to 100 km s^{-1}
Wings and SEMBE

The SNR W44: Fermi-LAT



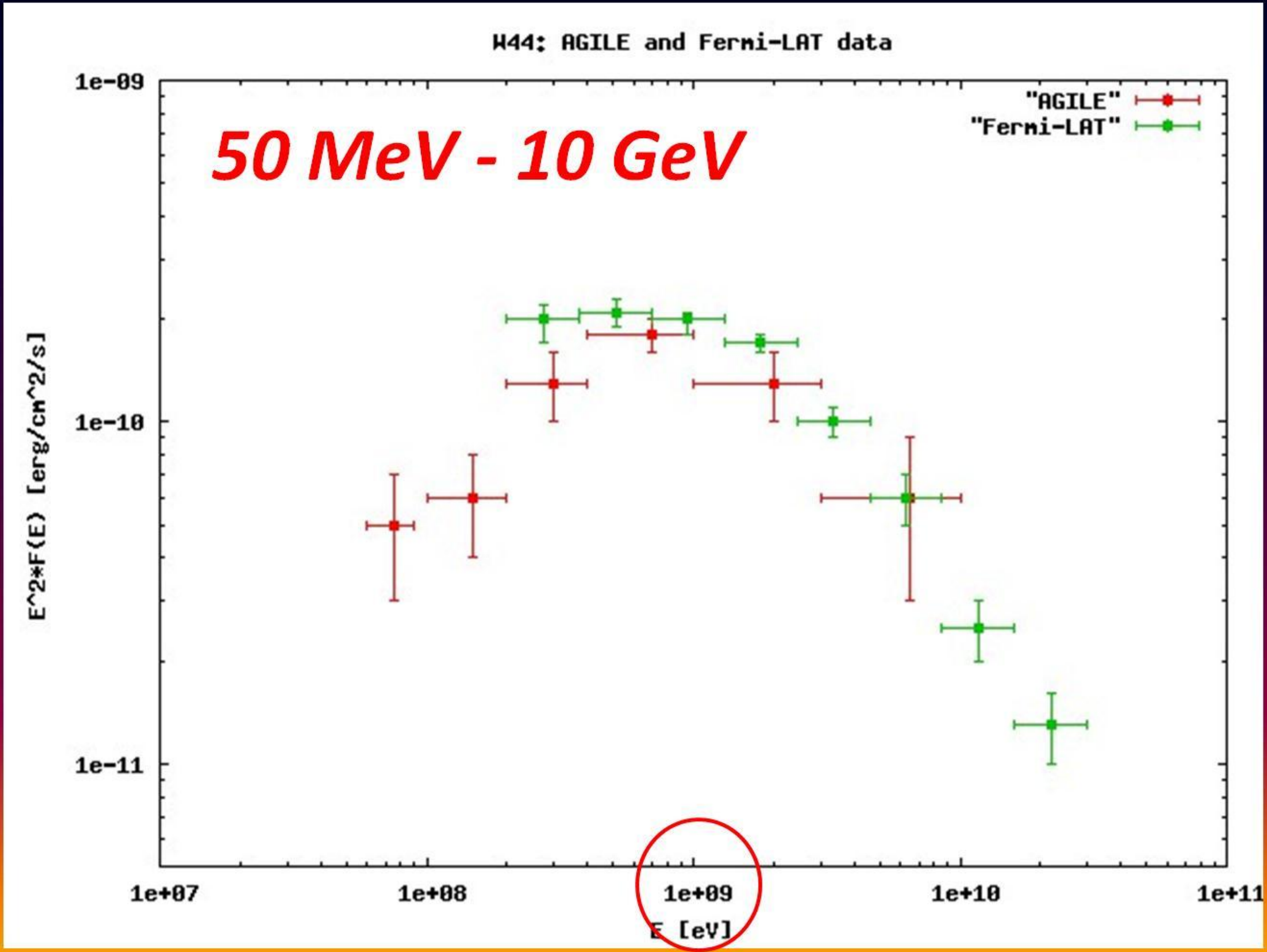
Abdo et al, 2010



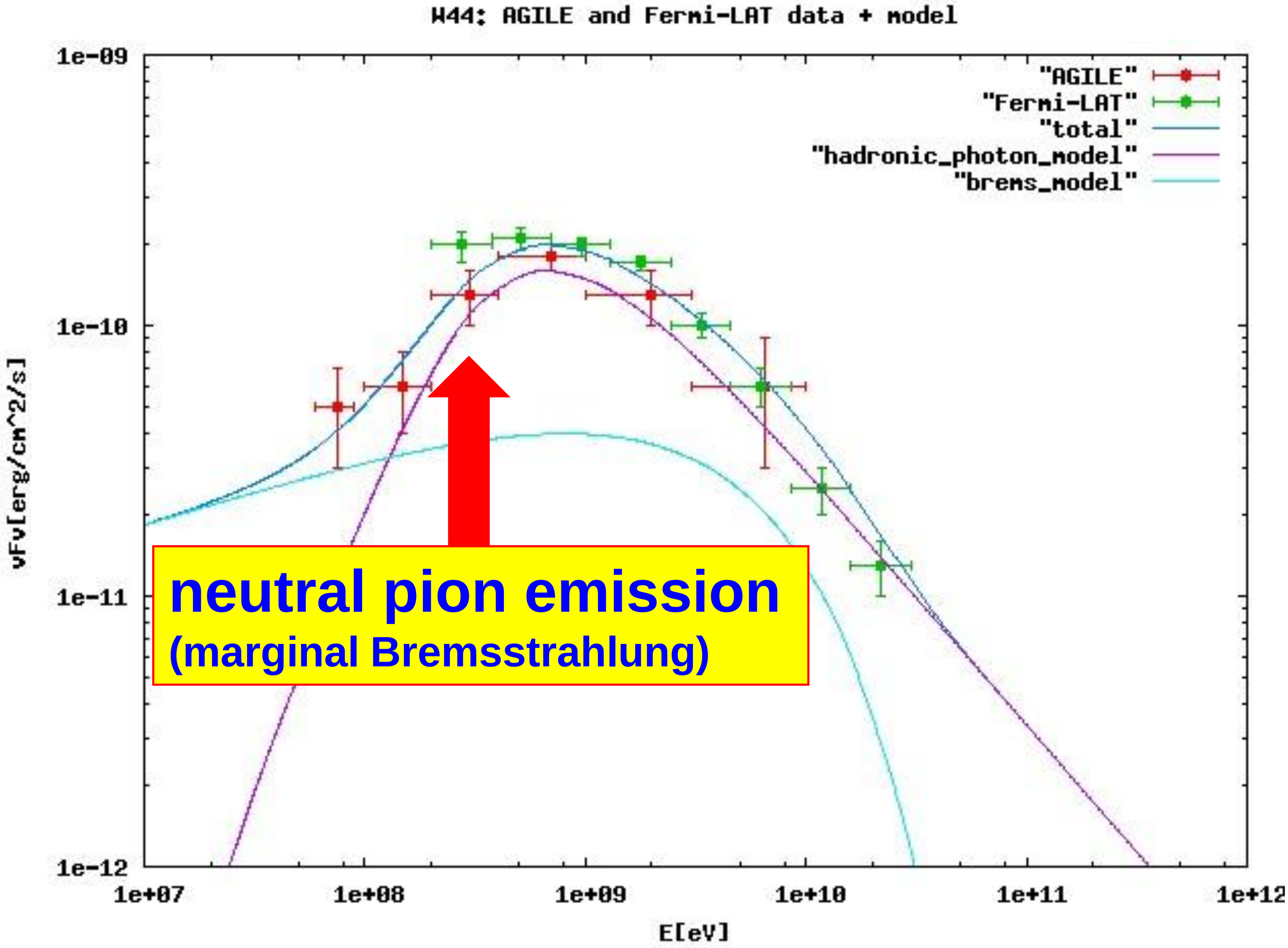

W44
source "A"
-0.100
-0.200
-0.300
-0.400
-0.500
-0.600
-0.700
35.100
35.000
34.900
34.800
34.700
34.600
34.500
34.400
34.300
34.200
0.00084
0.00088
0.00092
0.00096
0.00100
0.00104
0.00109
0.00113
0.00117

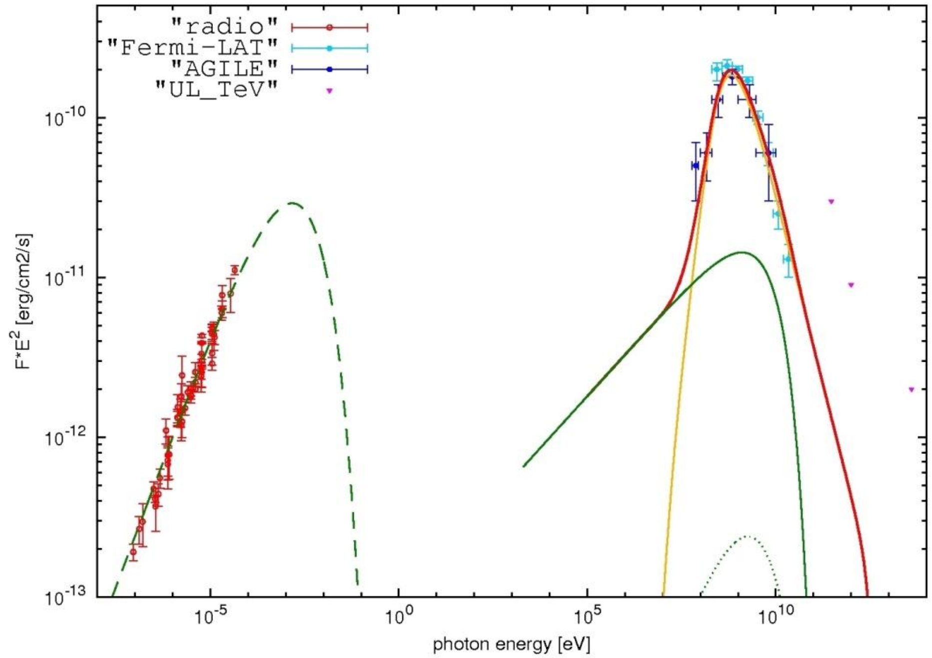
The SNR W44: AGILE

(Giuliani et al. 2011)

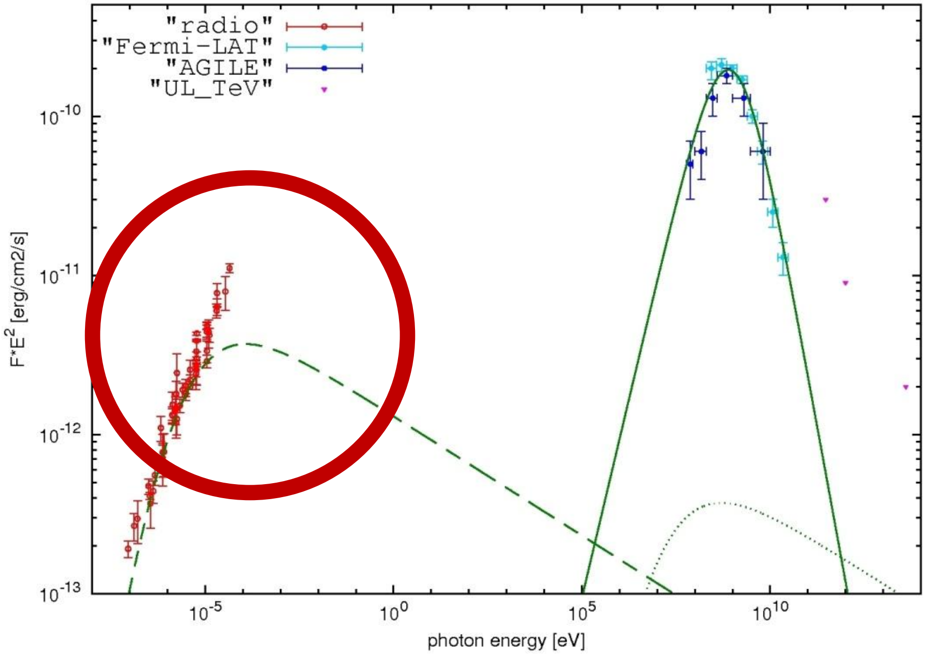


(Giuliani, Cardillo et al. 2011)





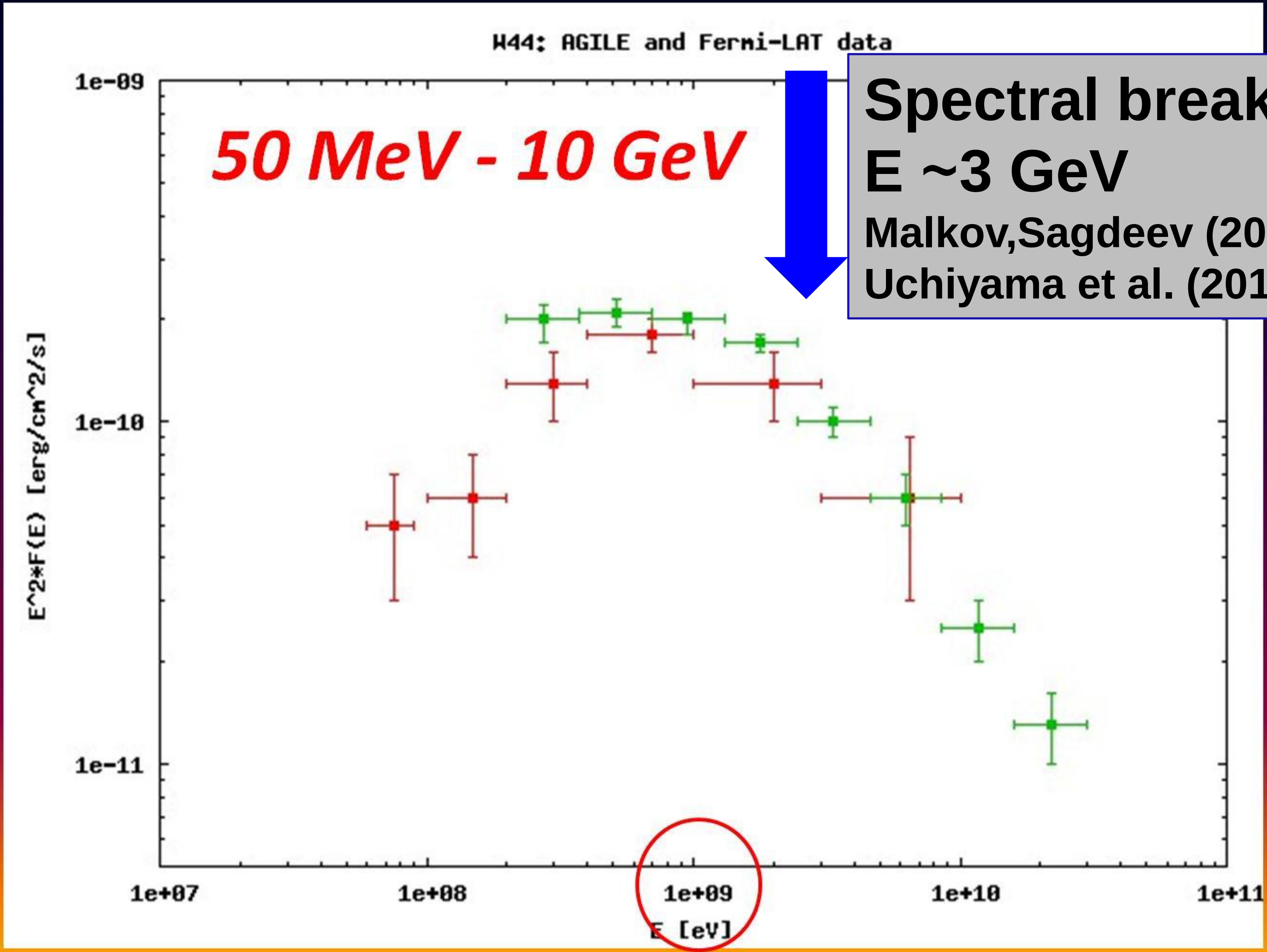
hadronic model,
B = 20 μG,
n = 100 cm^{-3}



"ad hoc" e-Brems. model,
B = 20 μG,
n = 300 cm^{-3}

The SNR W44: AGILE

(Giuliani et al. 2011)



Spectral break, E ~3 GeV

Malkov,Sagdeev (2010)

Uchiyama et al. (2010)

Theoretical challenges and conclusions

- a lot of progress, but also a lot of challenge for models
- Probably magnetic energy storage and pre-jet launching in Cygnus X-3, very efficient particle acceleration during pre-jet-launching, “corona modes”
- the surprising Crab Nebula gamma-ray flares: in contradiction with MHD models and DSA, probably a fast reconnection, a big challenge
- study of SNRs: direct evidence of hadronic acceleration, with challenges for current models

- **Gamma-400** is a Russian project dedicated to the study of high-energy electrons and gamma rays, up to energies of ~ 3 TeV.

- The project is currently in Phase A in Russia. Key requirements of the original mission are, for gamma rays @ 100 GeV, an angular resolution of 0.01° and an energy resolution of ~ 1%.

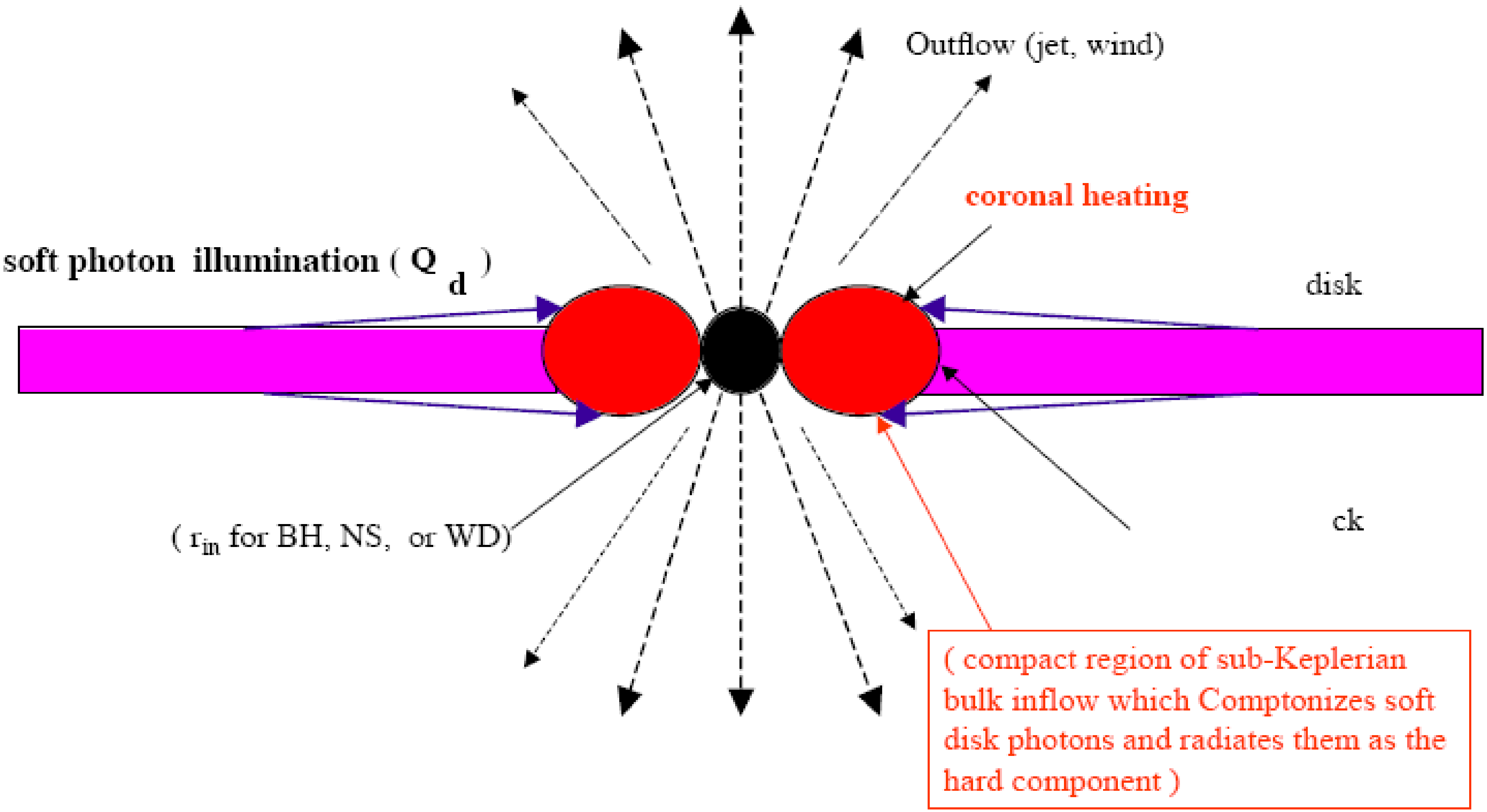
- Italian researchers have been invited since 2009 to consider participation in the project. PAMELA groups from the INFN Units of Trieste, Roma 2 and Florence (joined by groups from INFN Pisa/University of Siena and IASF/University of Roma 2) have felt that the mission had a great scientific potential and started to interact with the Russian colleagues since 2009.

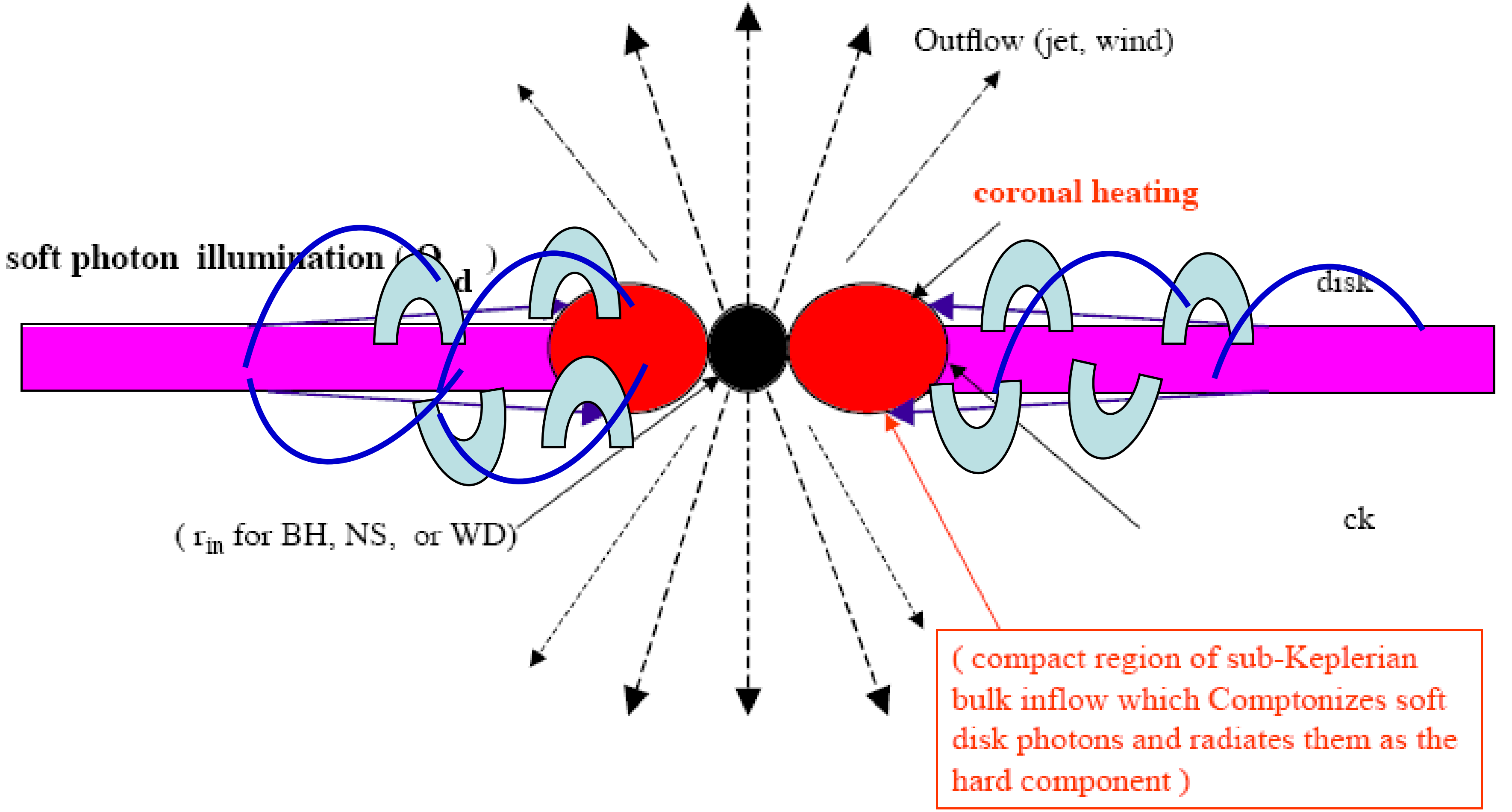
- Possible modification of the original physical scheme of the apparatus are under study, in order (while maintaining, or even improving, the original objectives) to achieve other extremely important physics tasks, namely:
  - to extend the GAMMA-400 measuring capabilities for low- and medium-energy gamma rays in the range 30-300 MeV
  - to achieve a total GF for nuclei exceeding 1 m^2sr, thus enabling the measurement, in a few years, of the proton flux beyond 1 PeV and the helium flux beyond 0.5 PeV/nucleon

- An official proposal to INFN is being submitted to support the Italian participation to the project.

back-up slides

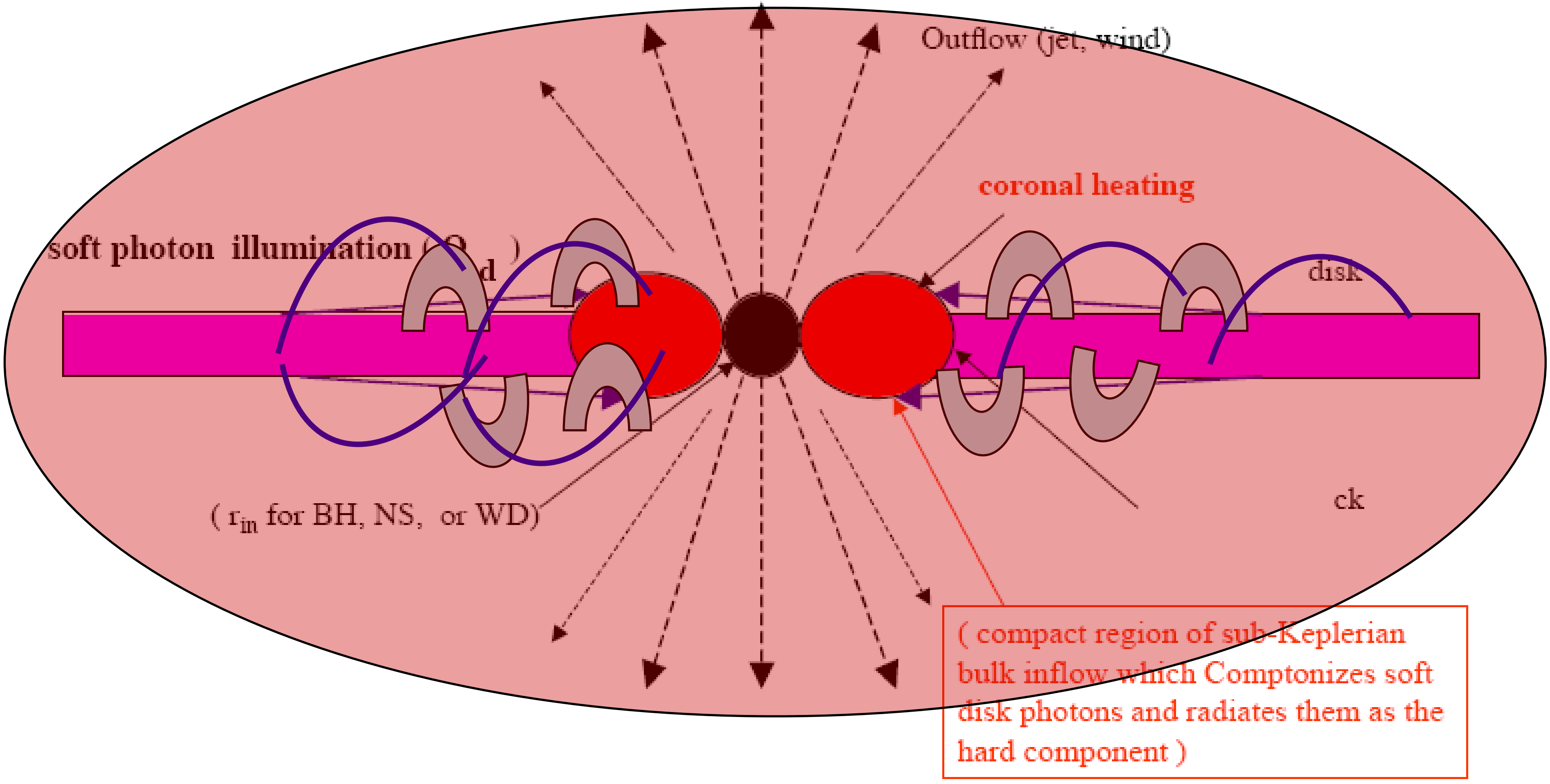
Plasma diagnostics in Cyg X-3

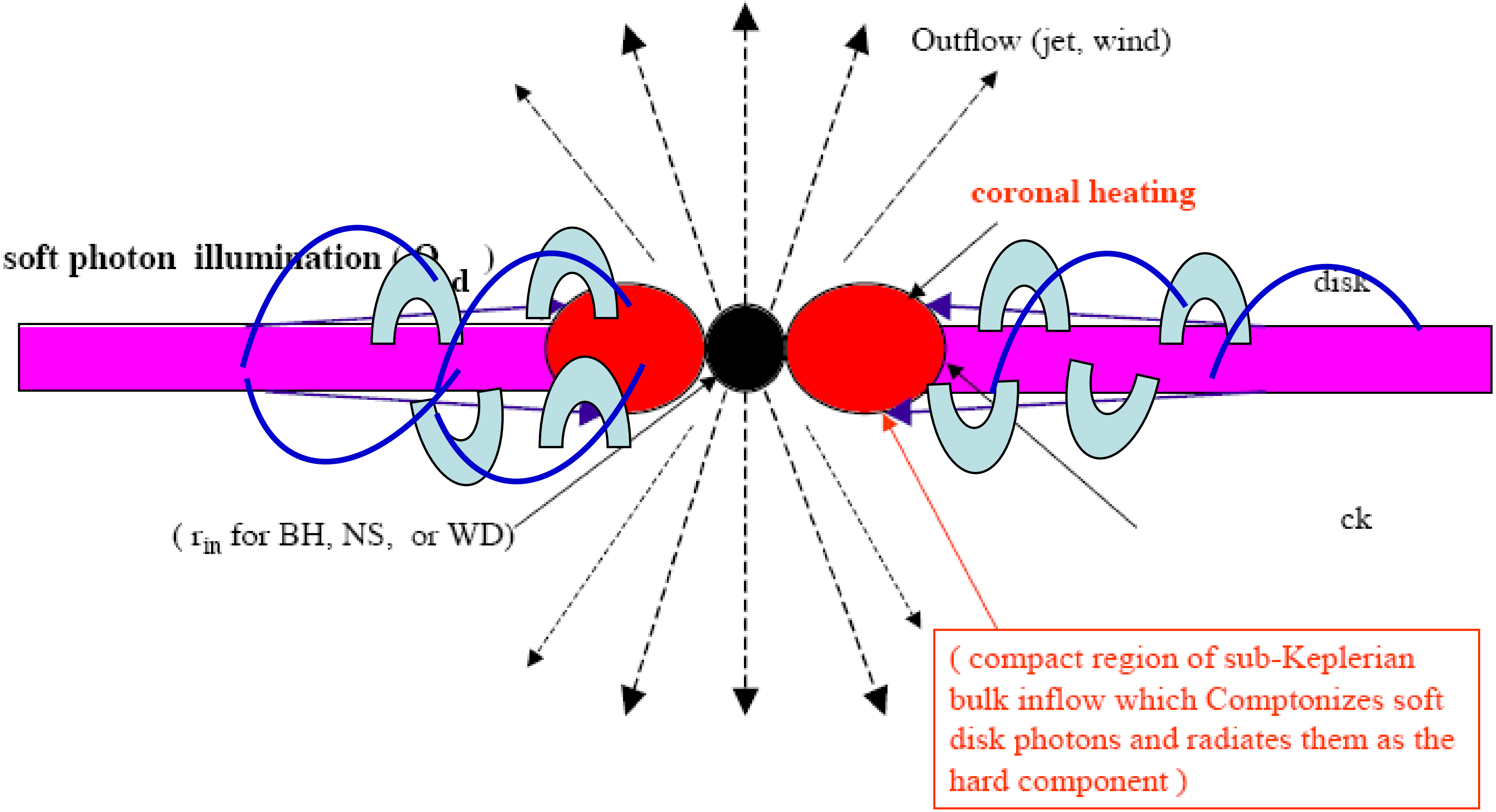



Outflow (jet, wind)
coronal heating
soft photon illumination (Q_d)
disk
(r_in for BH, NS, or WD)
ck
(compact region of sub-Keplerian bulk inflow which Comptonizes soft disk photons and radiates them as the hard component)

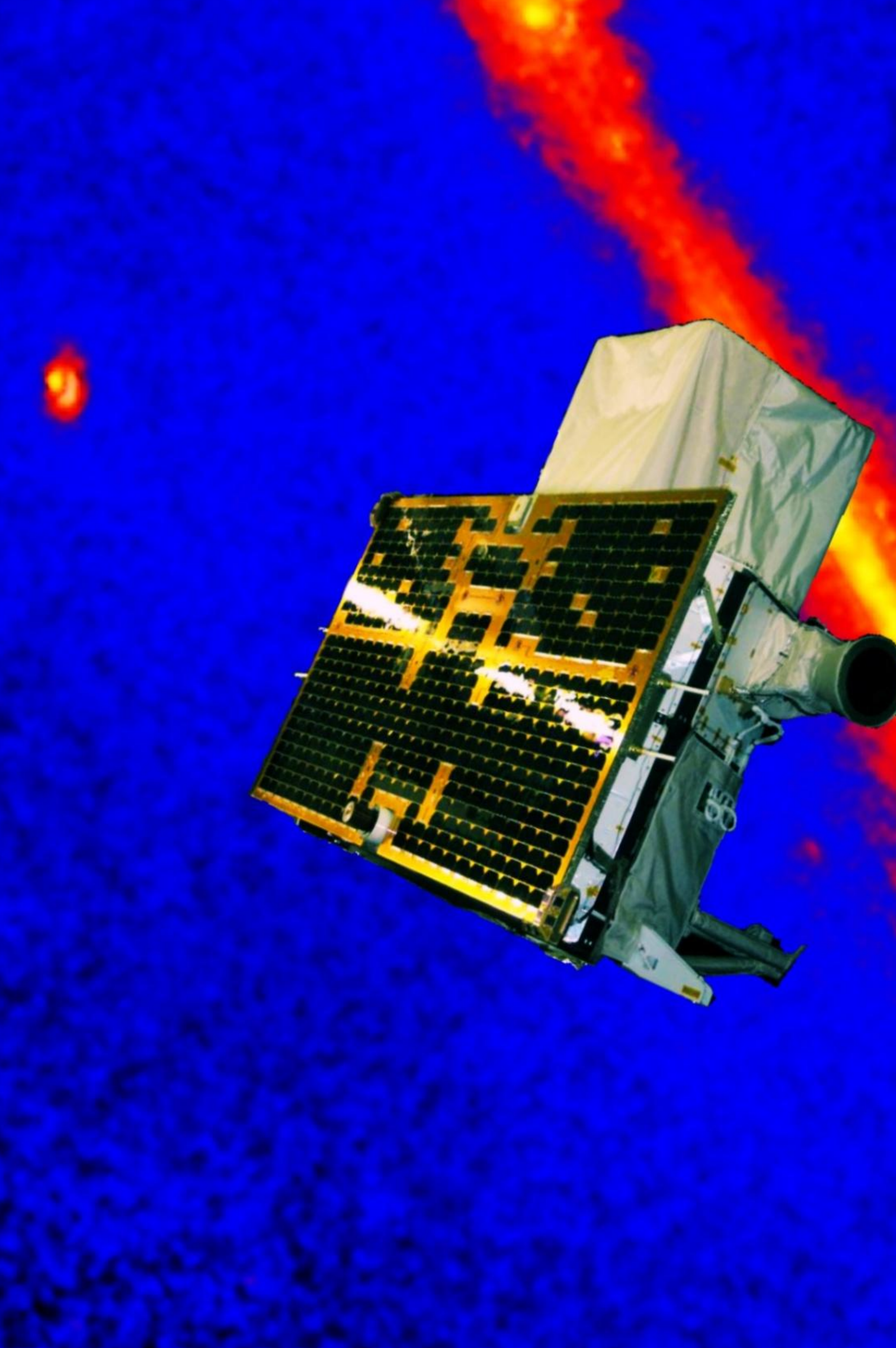
Comptonizing cloud

Compton-thick, $\tau = \sigma_T\, n\, R \sim 1\text{-}10$ **$n \sim (10^{15}\ \mathrm{cm}^{-3})\, R_8^{-1}$**





Outflow (jet, wind)
coronal heating
soft photon illumination (Q_d)
disk
(r_{in} for BH, NS, or WD)
ck
(compact region of sub-Keplerian bulk inflow which Comptonizes soft disk photons and radiates them as the hard component)



•discovery that the Crab Nebula is variable in gamma-rays !!!

• optimal sensitivity at “low” energies (E < 200 MeV)

• VERY EFFICIENT ALERT SYSTEM FOR TRANSIENTS

A quick comparison

	AGILE-1	FERMI/LAT
A_{eff} (100 MeV) (cm^2)	~ 400	~ 400-800
A_{eff} (1 GeV) (cm^2)	~ 500	~ 4000 - 8000
FOV (sr)	2.5	2.5
sky coverage	1/5	whole sky
Energy resolution (~ 400 MeV)	50 %	10 %
PSF (68 % cont. radius) 100 MeV 1 GeV	 3^o - 4^o < 1^o	 4^o - 5^o < 1^o

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.

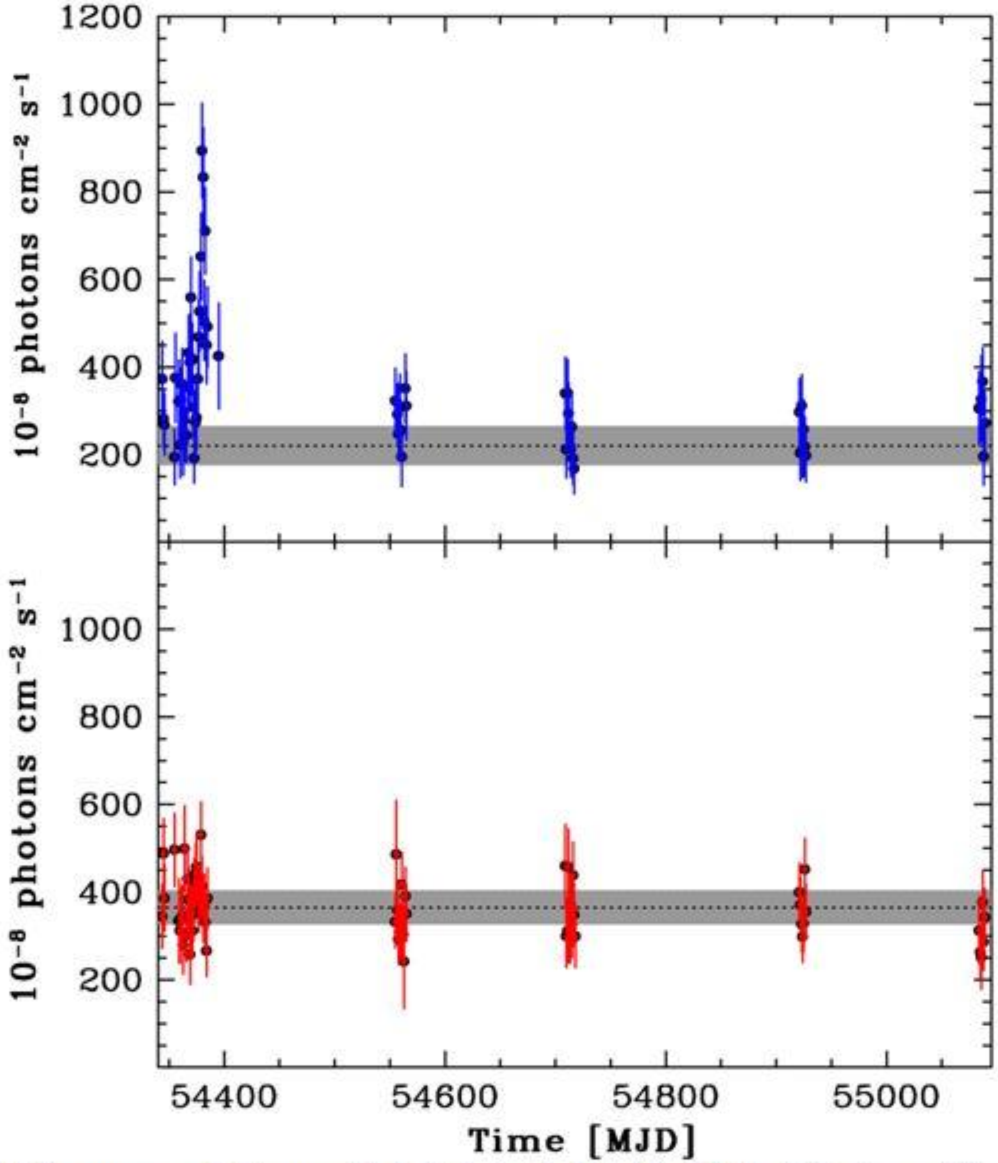


Fig. S1 – The AGILE gamma-ray light curve (1-day binning) of the Crab Pulsar/Nebula and Geminga above 100 MeV during the period **2007-09-01 – 2009-09-15** with the satellite pointing **within 35 degrees** from the source. Gaps in the light curve are due to the satellite pointing at fields different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

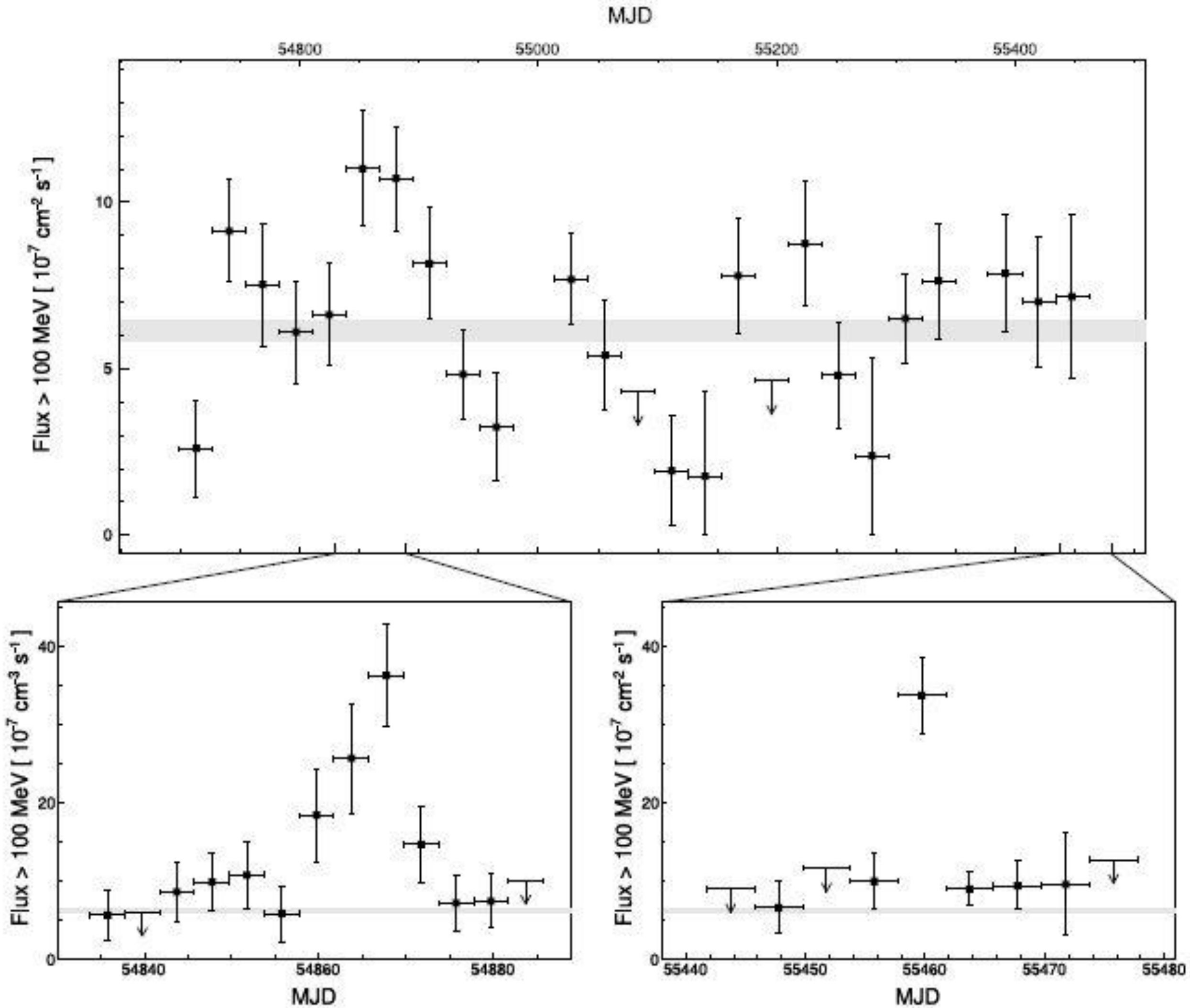
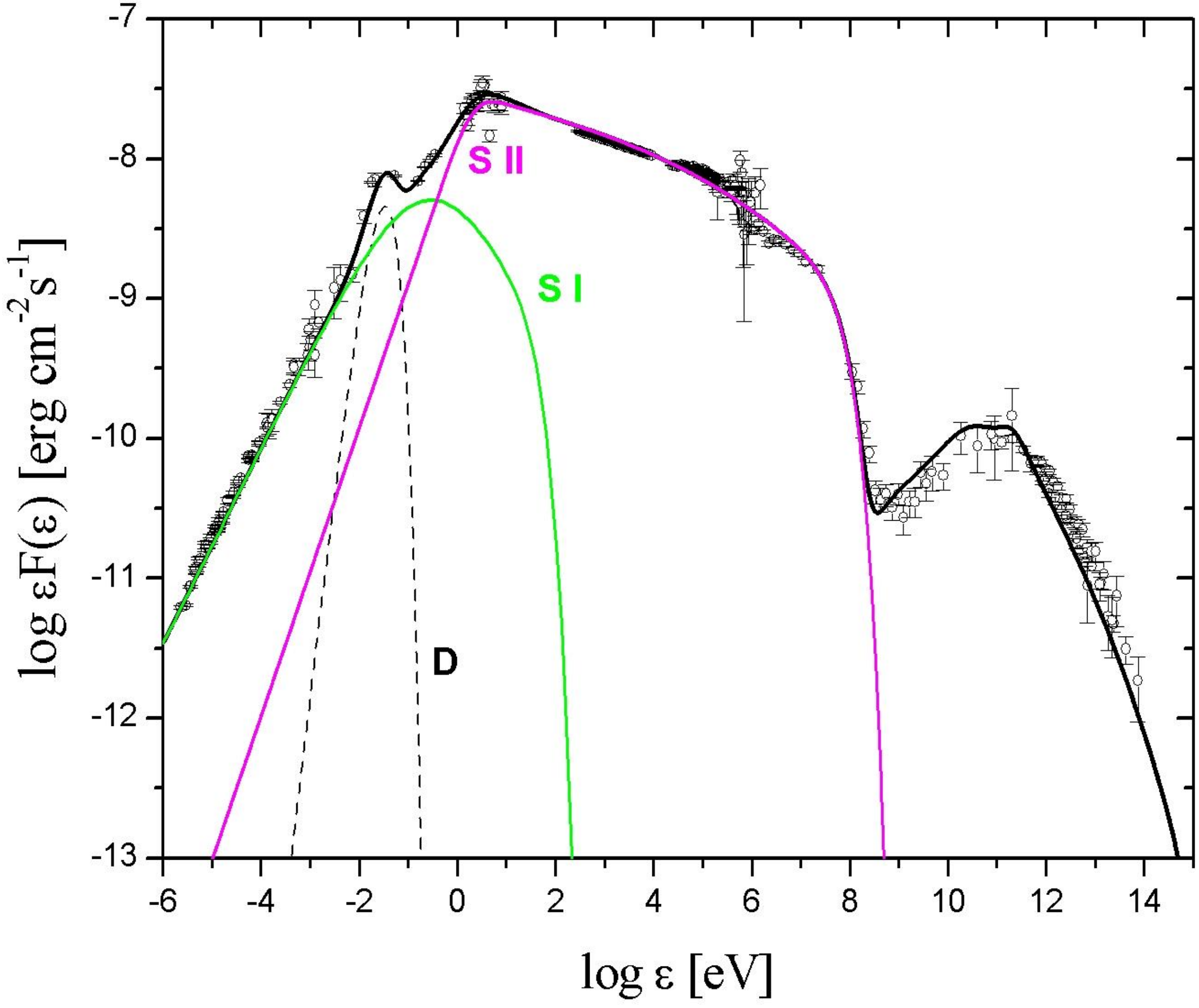


Figure 2: Gamma-ray flux above 100 MeV as a function of time of the synchrotron component of the Crab Nebula. The upper panel shows the flux in four-week intervals for the first 25 month of observations. Data for times when the sun was within 15° of the Crab Nebula have been omitted. The gray band indicates the average flux measured over the entire period. The lower panel shows the flux as a function of time in four-day time bins during the flaring periods in February 2009 and September 2010. Arrows indicate 95% confidence flux limits.

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

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

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

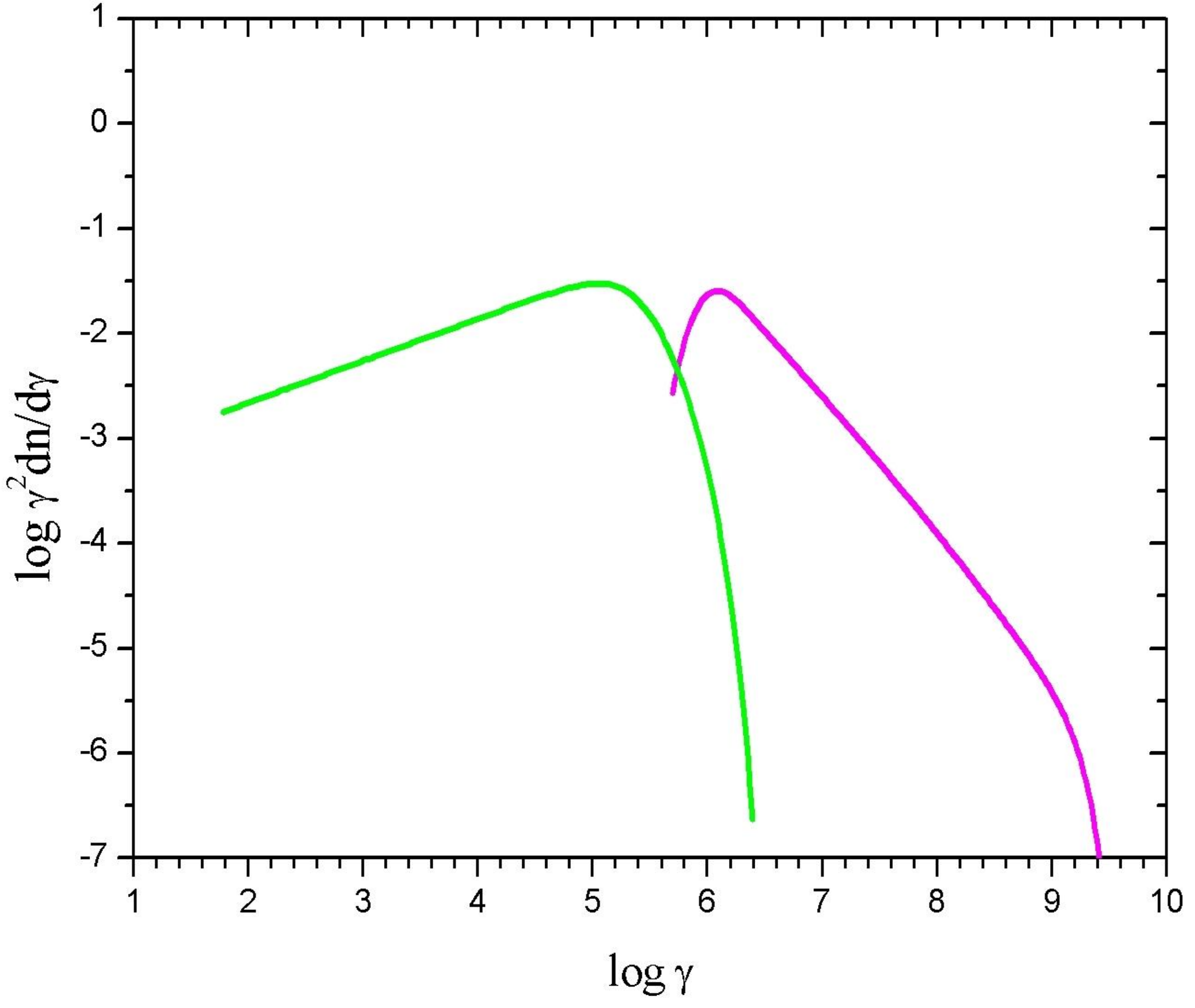
L=3e36 erg/s

T=100 °K

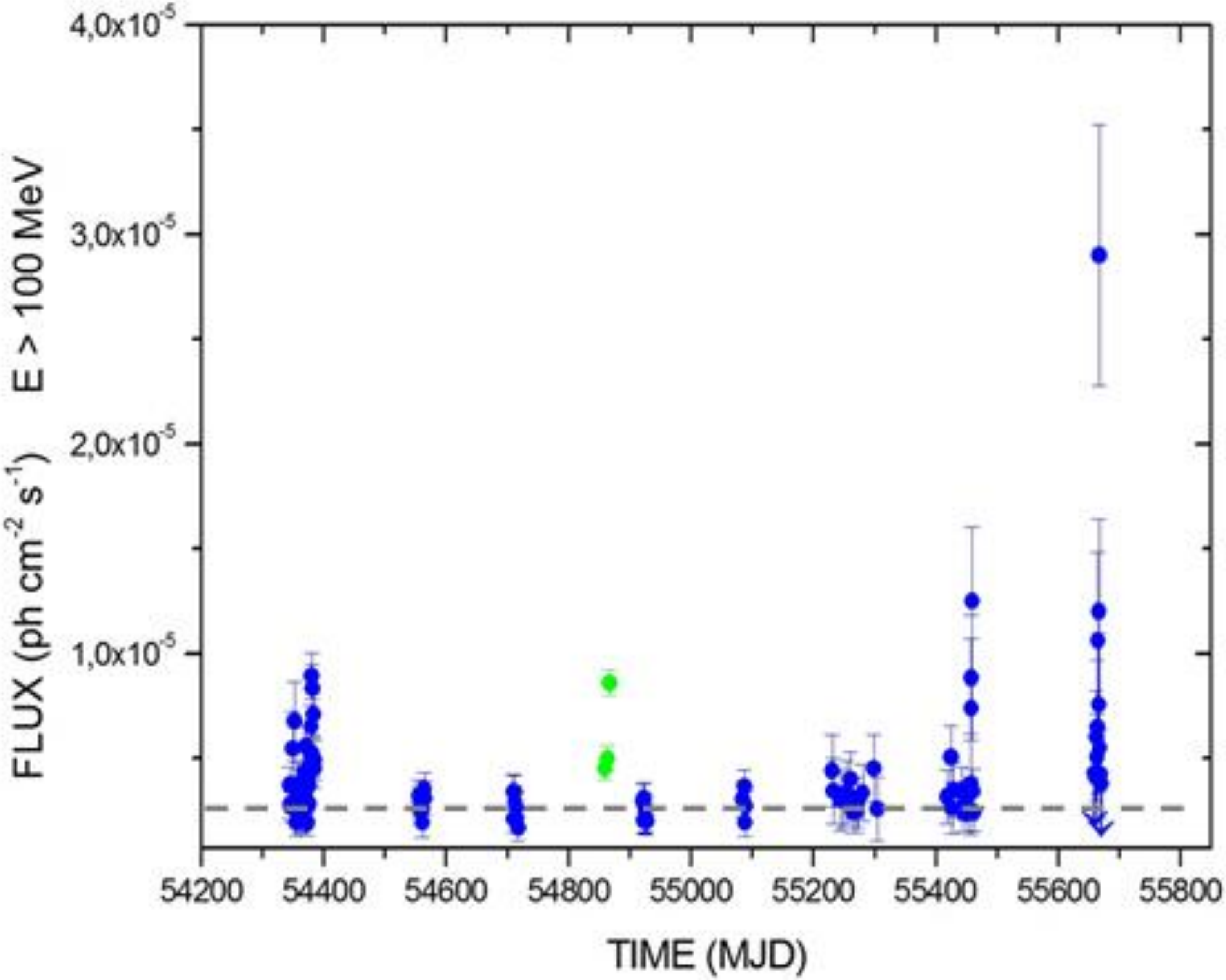
Average magnetic field

B=200 μGauss

Vittorini & M.T. 2011



10 arc
T/ACS F550M
2010-10-02
E


4,0x10^-5
3,0x10^-5
2,0x10^-5
1,0x10^-5
FLUX (ph cm^-2 s^-1) E > 100 MeV
54200
54400
54600
54800
55000
55200
55400
55600
55800
TIME (MJD)

KC MHD modelling: RH eqs.

$$n_1 u_1 = n_2 u_2 \,,$$

$$E = \frac{u_1 B_1}{\gamma_1} = \frac{u_2 B_2}{\gamma_2} \,,$$

$$\gamma_1 \mu_1 + \frac{E B_1}{4\pi n_1 u_1} = \gamma_2 \mu_2 + \frac{E B_2}{4\pi n_1 u_1} \,,$$

$$\mu_1 u_1 + \frac{P_1}{n_1 u_1} + \frac{B_1^2}{8\pi n_1 u_1} = \mu_2 u_2 + \frac{P_2}{n_1 u_1} + \frac{B_2^2}{8\pi n_1 u_1}$$

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

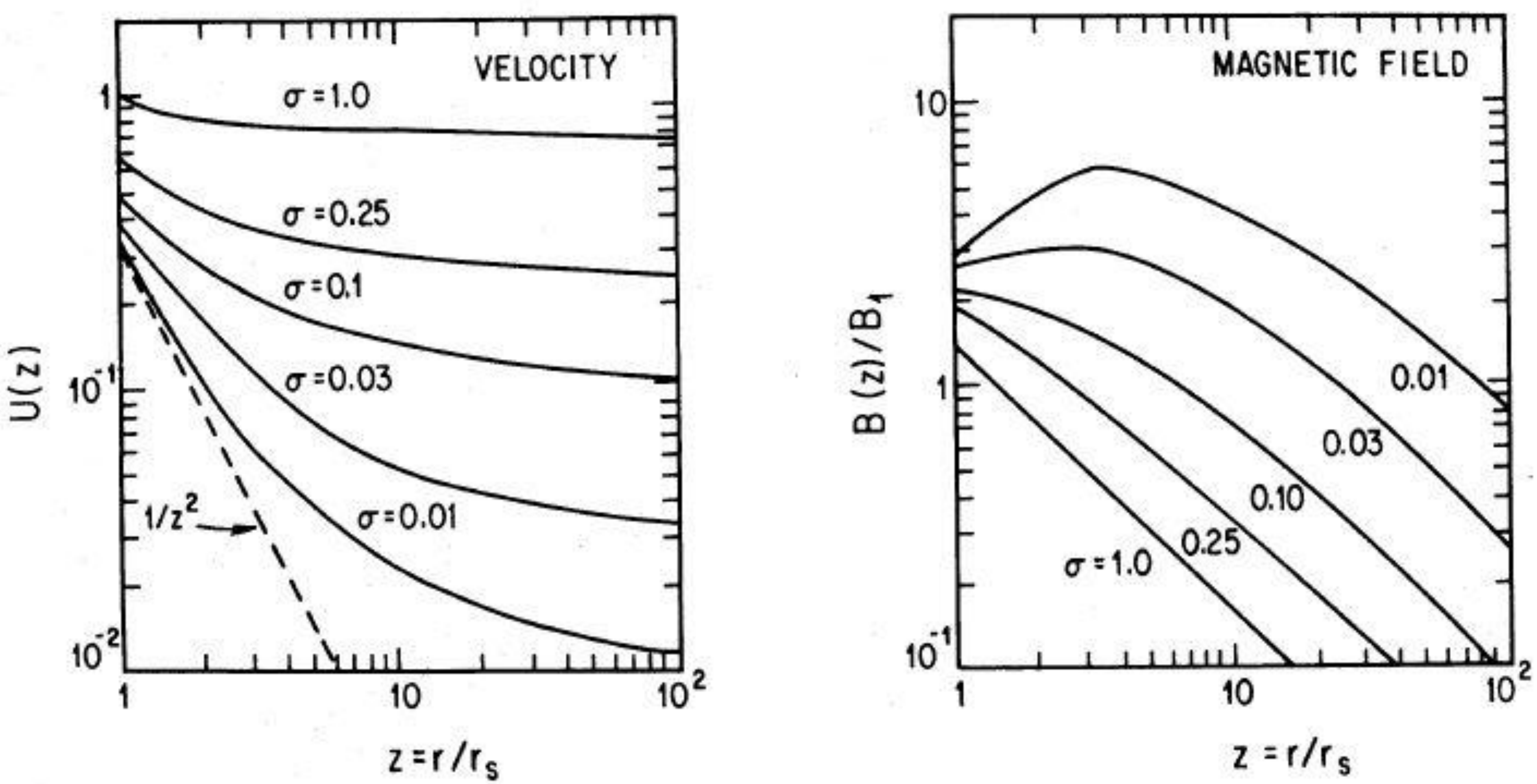
KC MHD modelling: RH eqs. solution

$$u_2^2 \approx \frac{1 + 9\sigma}{8}, \qquad \gamma_2^2 \approx \frac{9 + 9\sigma}{8}, \qquad \beta_2 = \frac{u_2}{\gamma_2} \approx \frac{1}{3}(1 + 4\sigma),$$

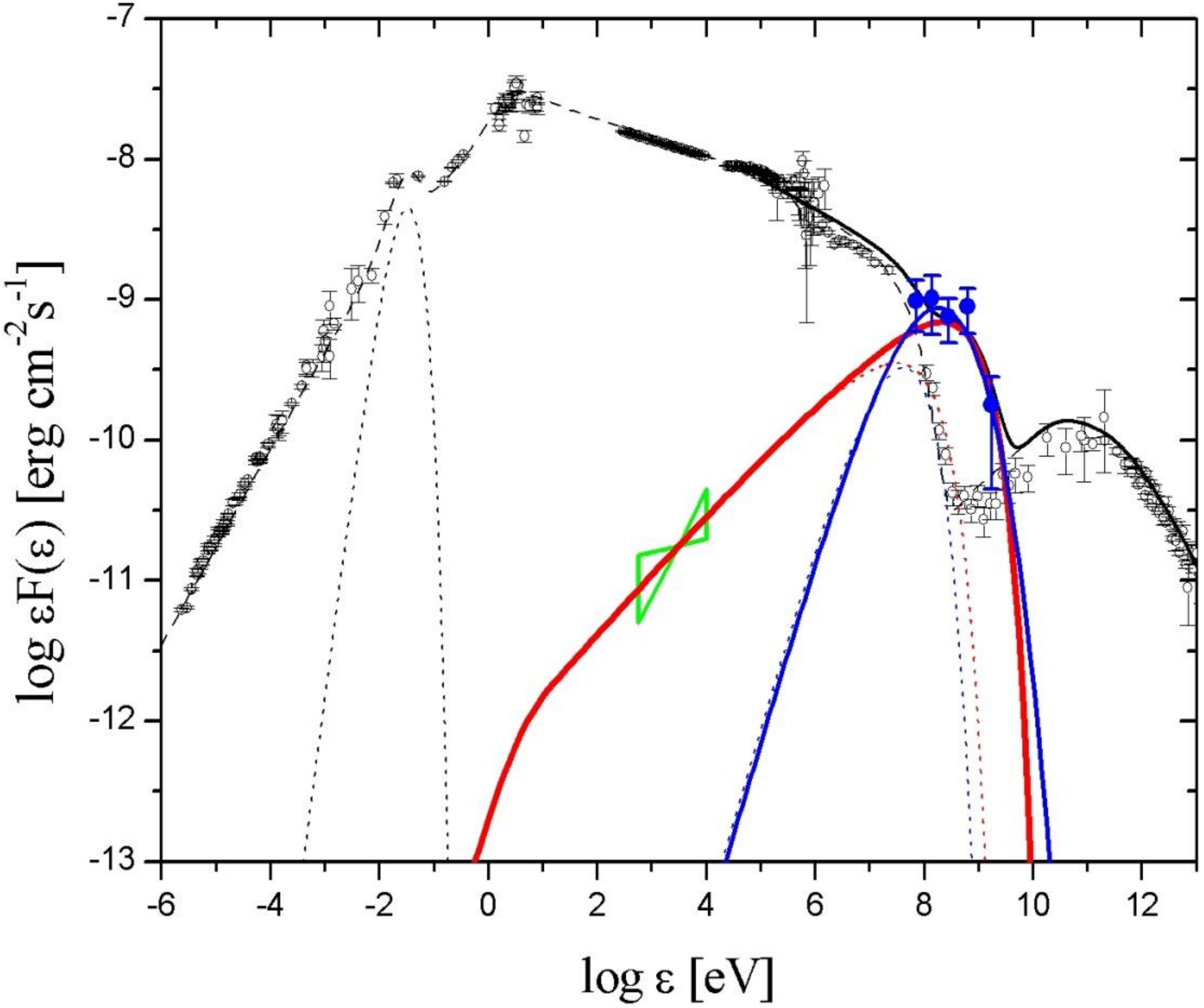
$$\frac{B_2}{B_1} = \frac{N_2}{N_1} \approx 3(1 - 4\sigma),$$

$$\frac{P_2}{n_1 mc^2 u_1^2} \approx \frac{2}{3}(1 - 7\sigma).$$

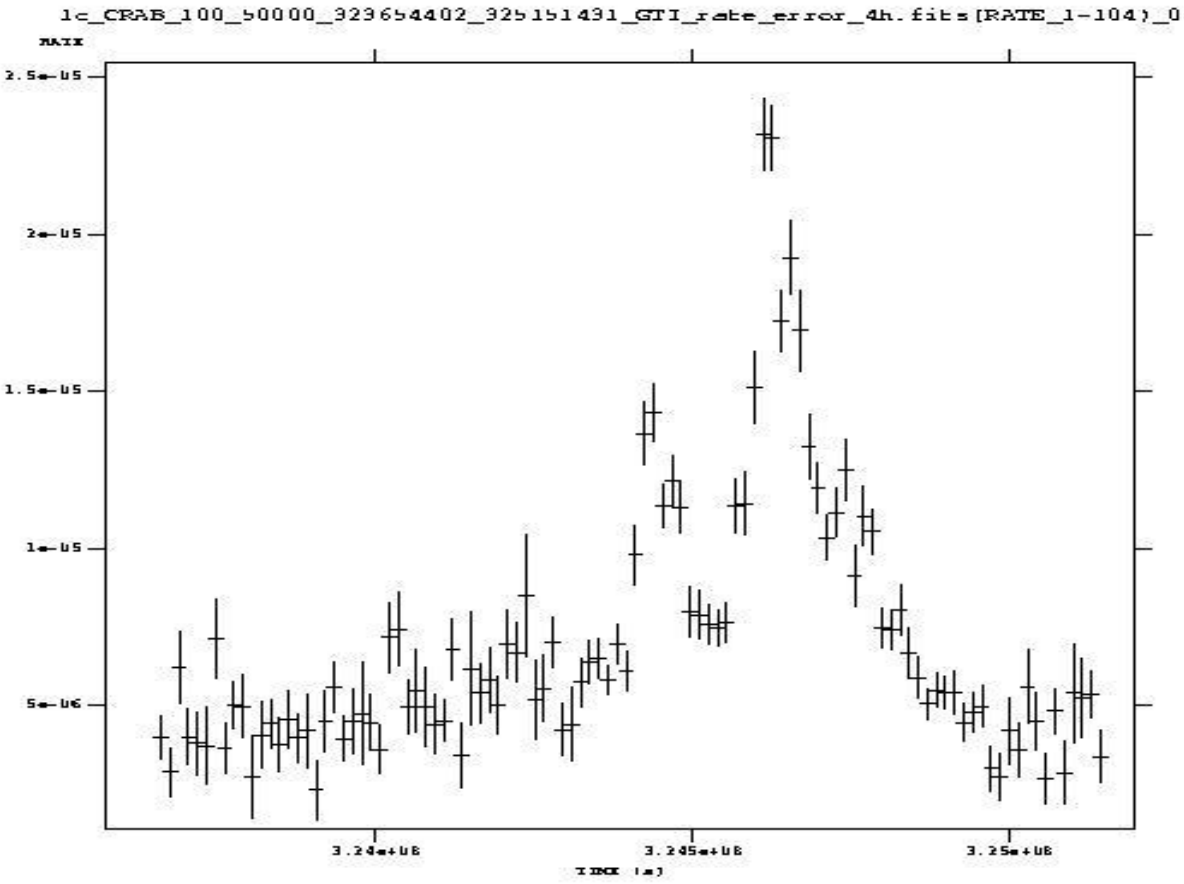
KC MHD modelling: RH eqs. solution



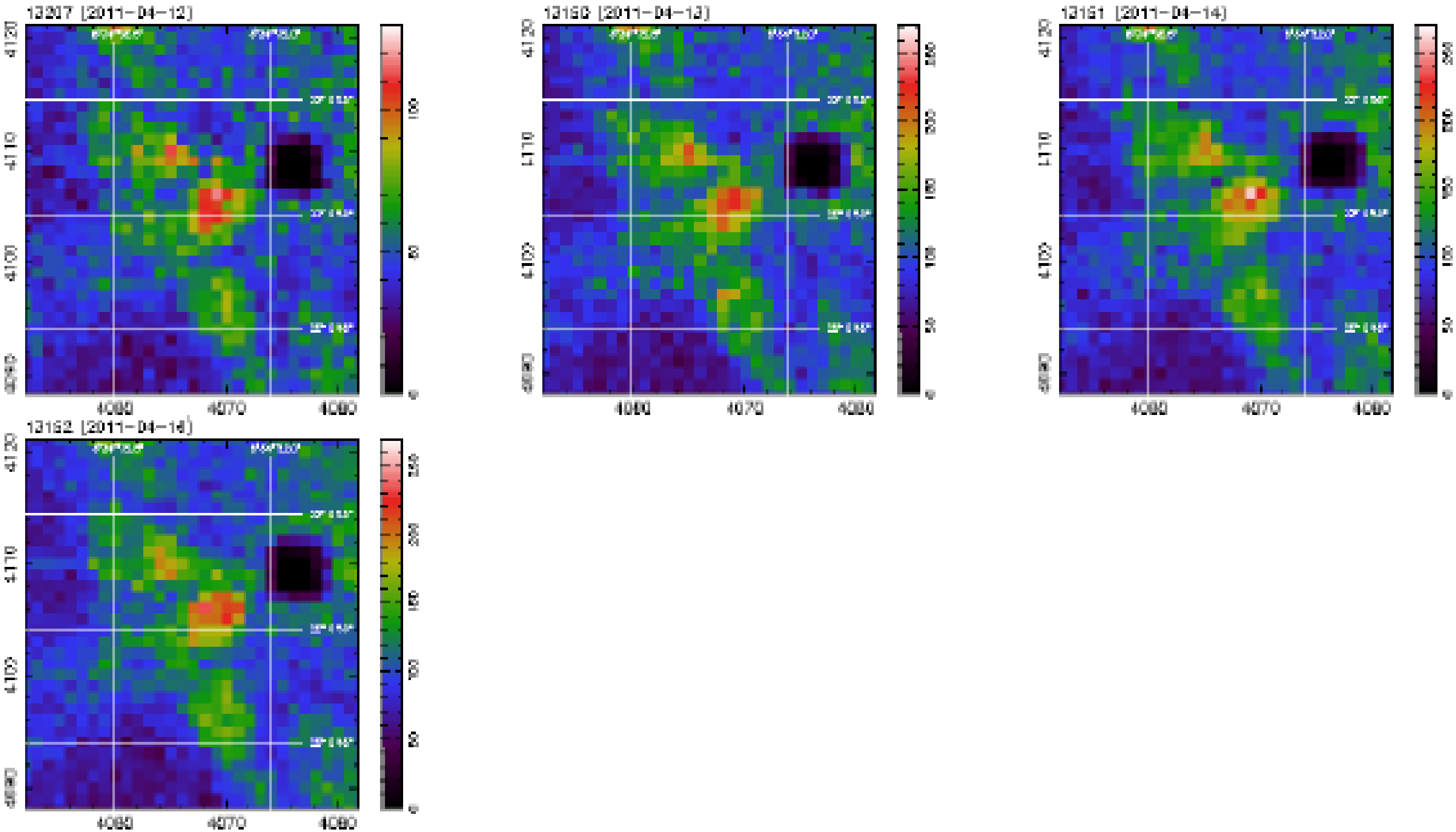
AGILE-GRID spectrum at the peak (Sept. 2010)



fermi, 4 hr.



lc_CRAB_100_50000_323654402_325151431_GTI_rate_error_4h.fits[RATE_1-104]_0
RATE
2.5e-05
2e-05
1.5e-05
1e-05
5e-06
3.24e+08
3.245e+08
3.25e+08
TIME (s)


13207 [2011-04-12]
13160 [2011-04-13]
13161 [2011-04-14]
13162 [2011-04-14]

and also…

- X-ray (secular) variations 1-100 keV (Wilson-Hodge 2010)
- 2-3 year timescale
- a few % / year variation,
  10% decrease in 4 years

Wilson-Hodge et al. 2010

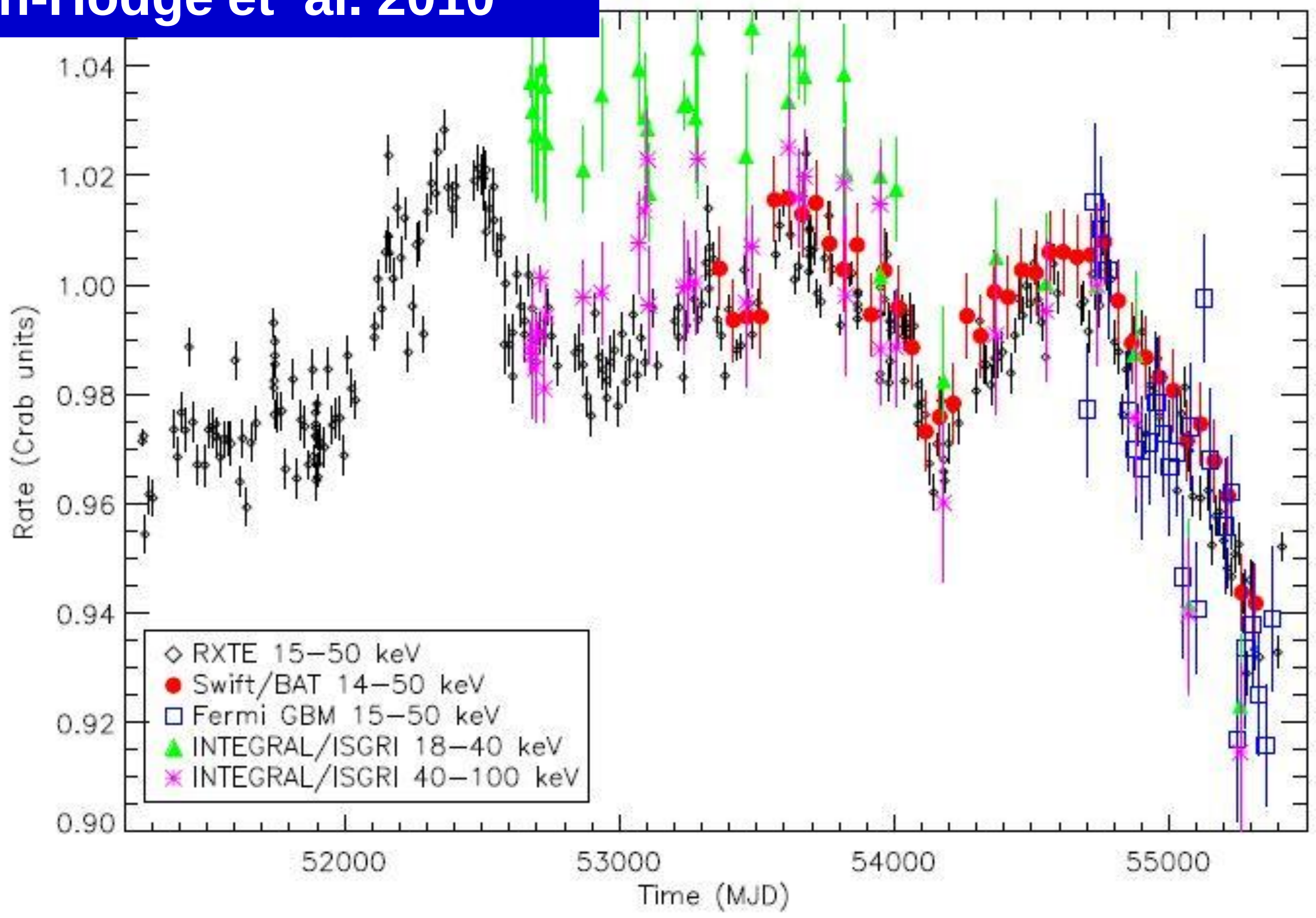
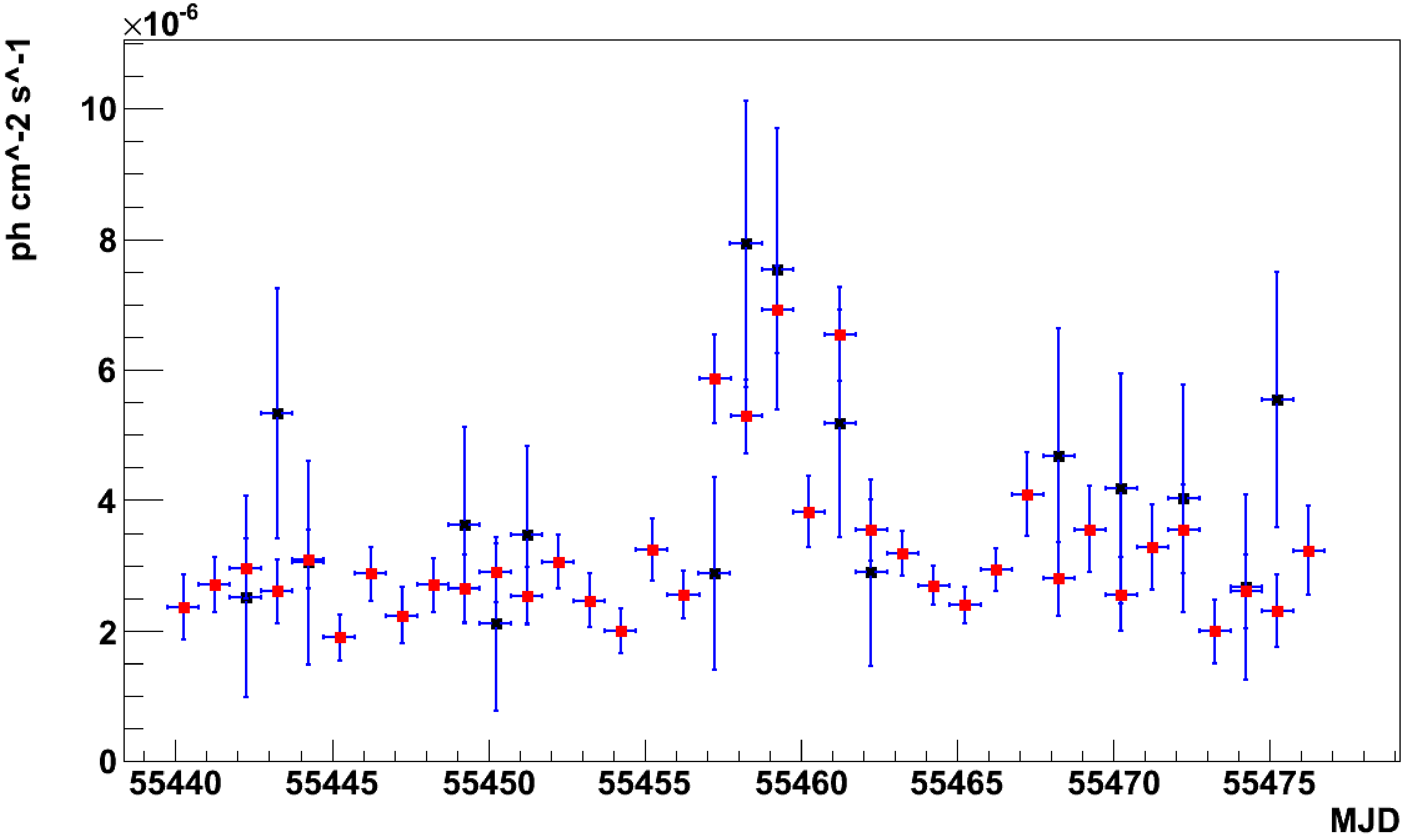


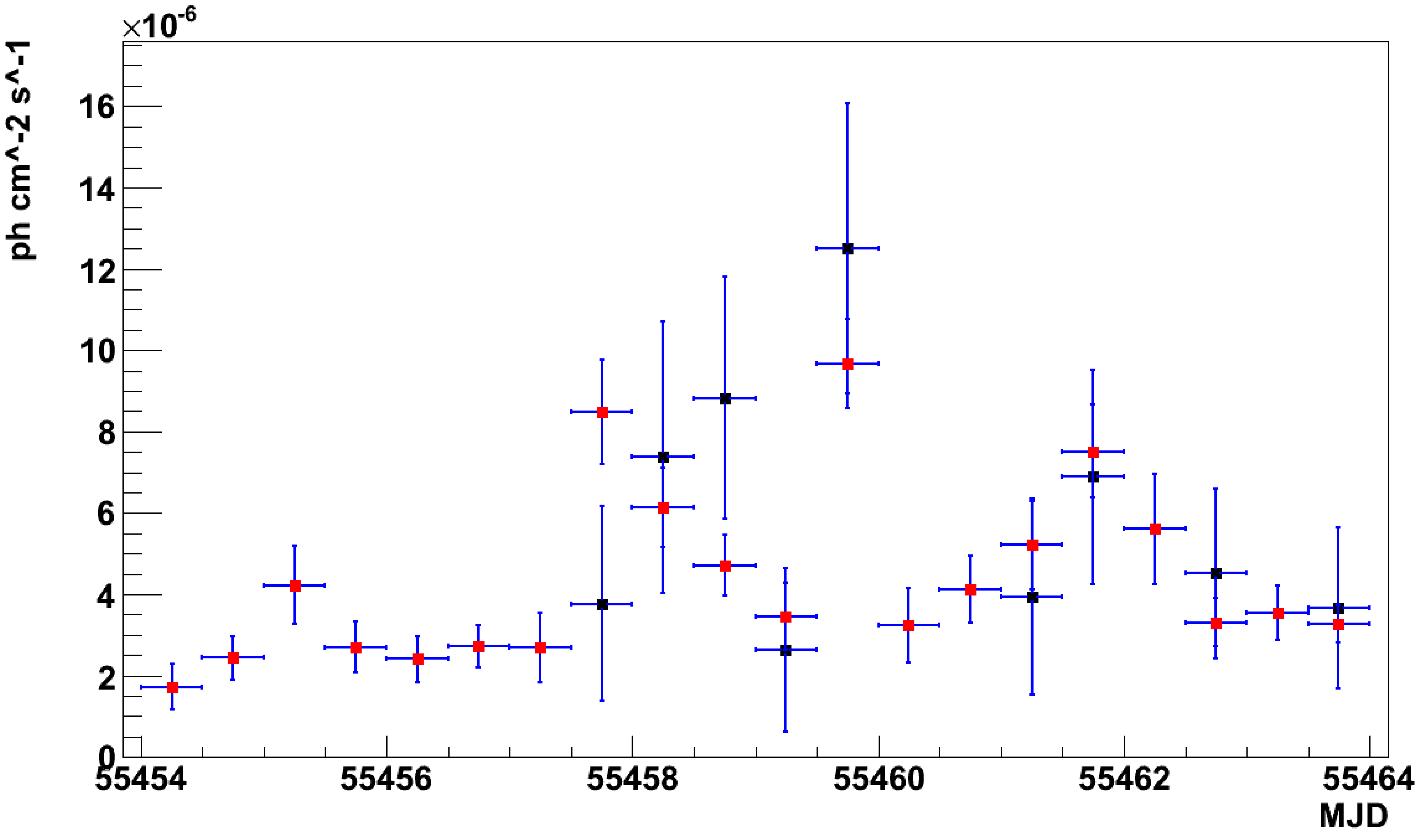
Fig. 5.— Composite Crab light curve for *RXTE*/PCA (15-50 keV - black diamonds), *Swift*/BAT (14-50 keV - red filled circles), *Fermi*/GBM (15-50 keV - open blue squares), *INTEGRAL*/ISGRI (18-40 and 40-100 keV - green triangles and purple asterisks, respectively.) Each data set has been normalized to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

- **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 ?**

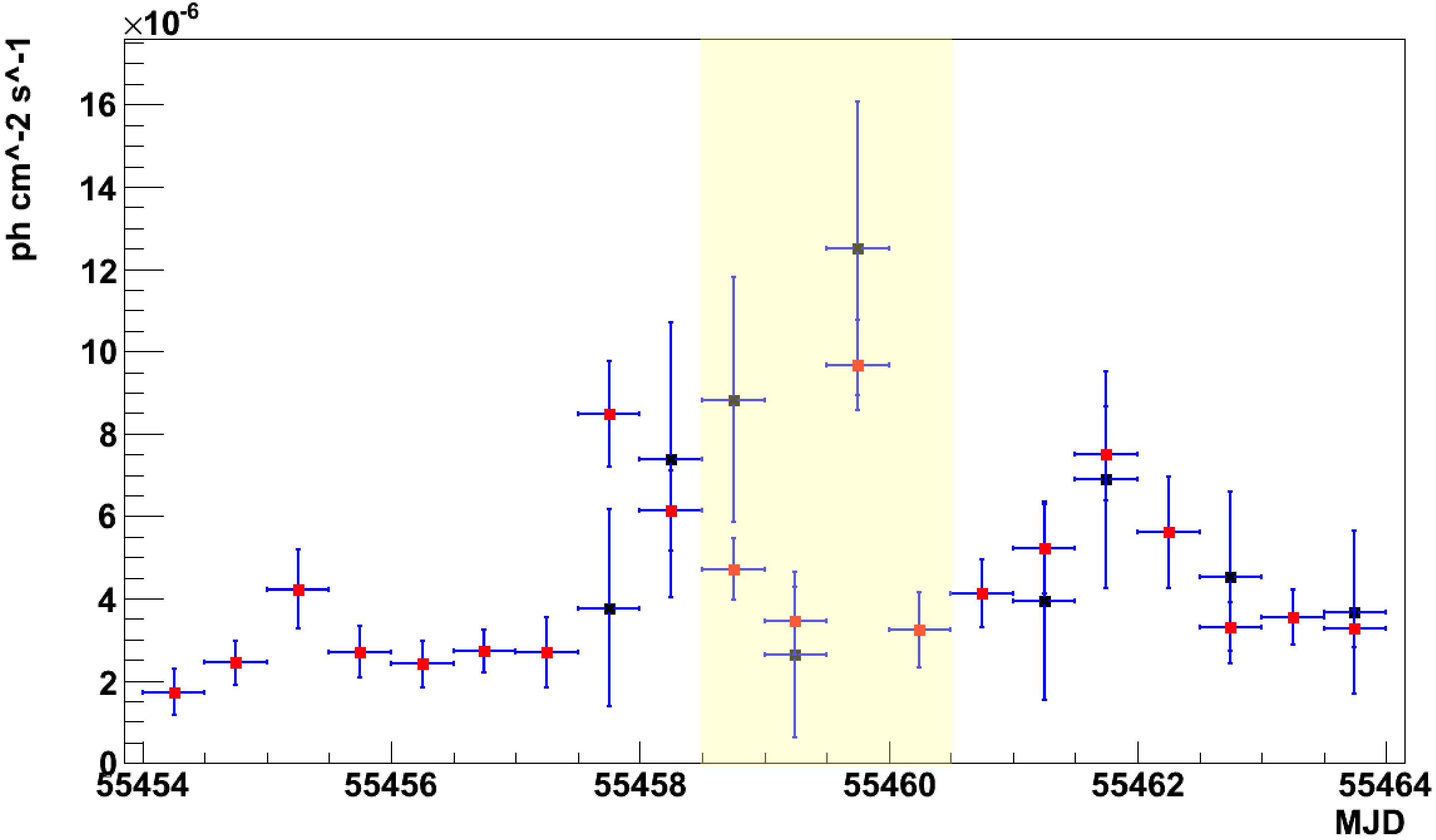
1-day bin lightcurves (AGILE and Fermi)



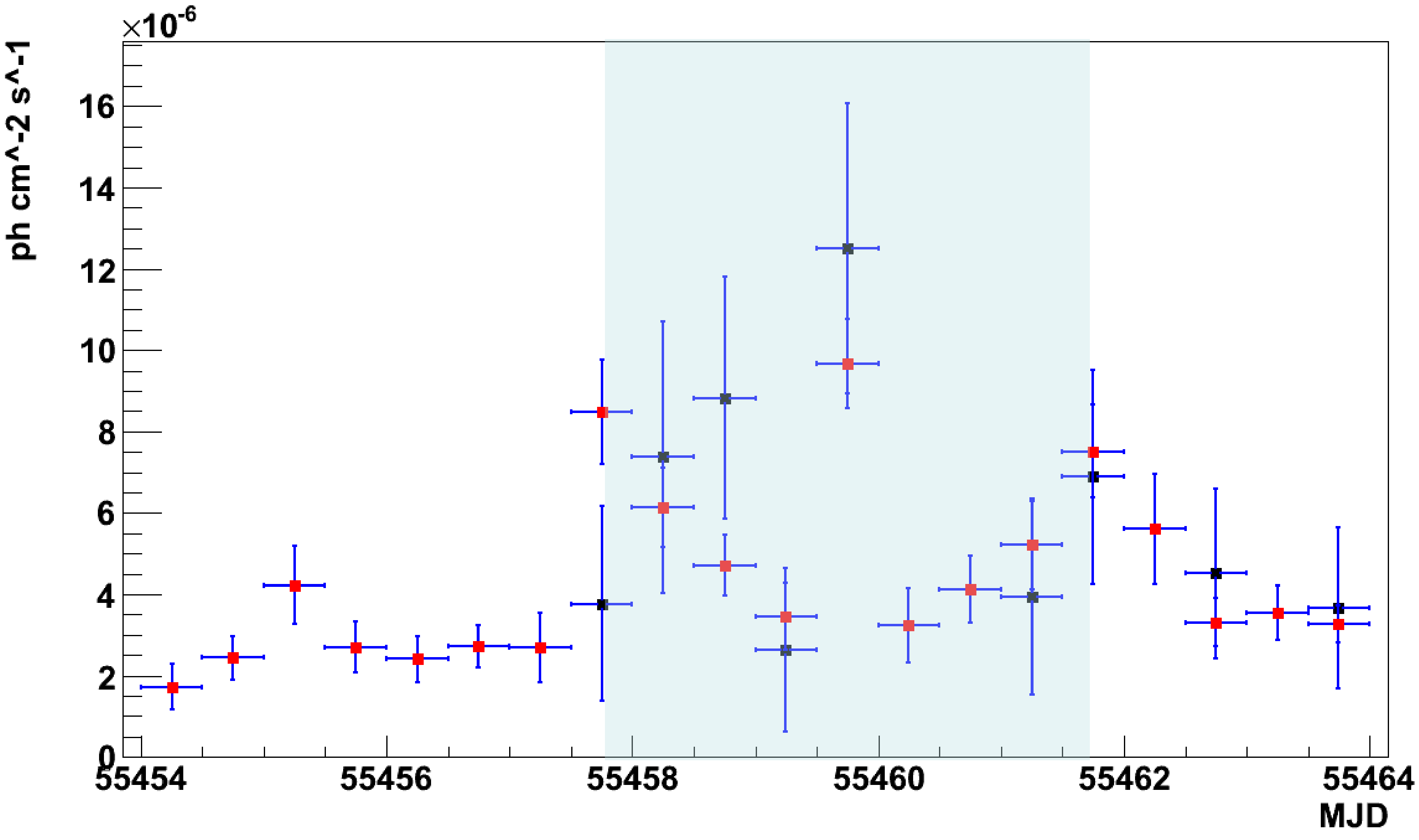
12-hr bin lightcurves (AGILE and Fermi)



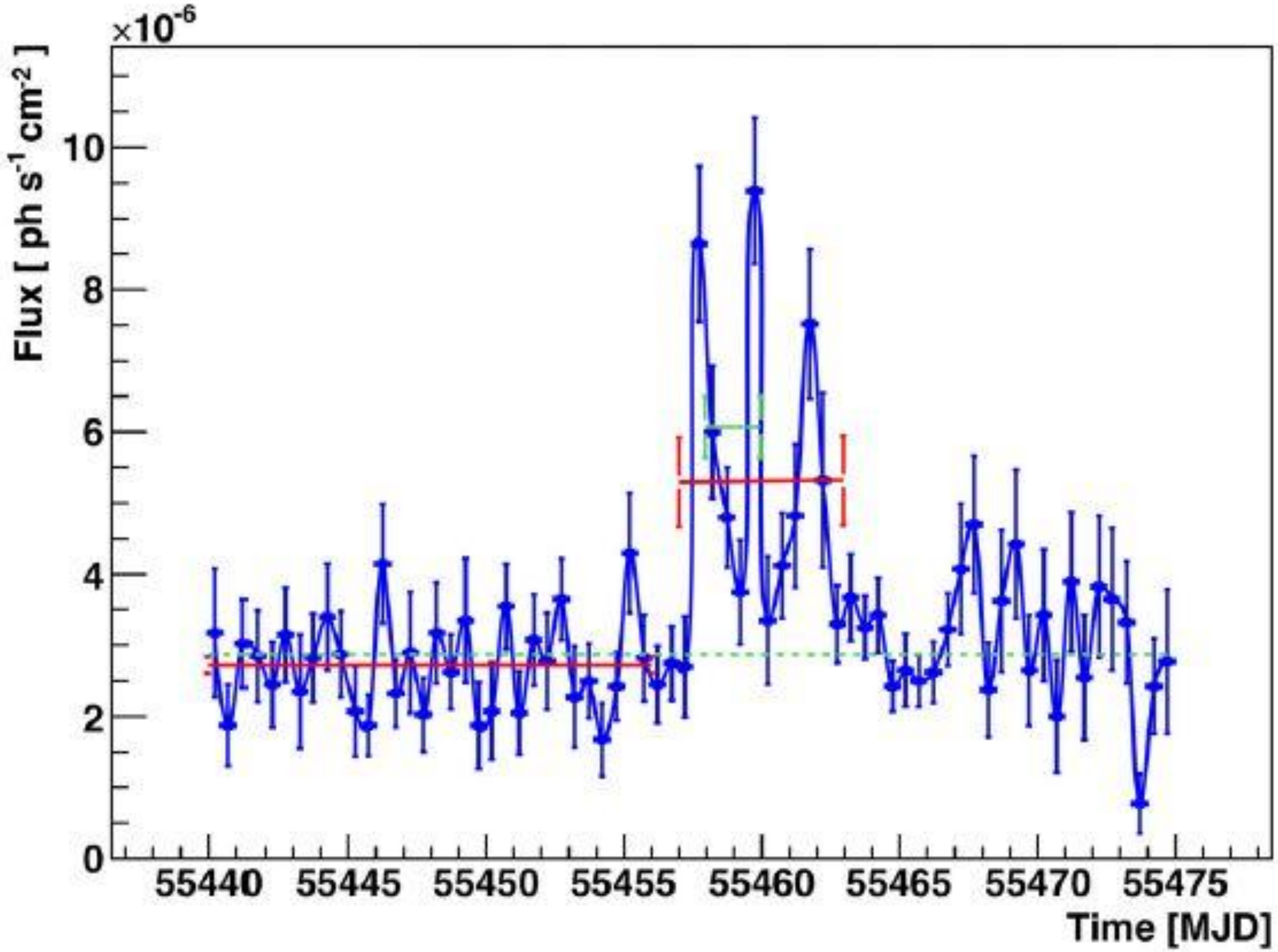
12-hr bin lightcurves (AGILE and Fermi)



12-hr bin lightcurves (AGILE and Fermi)



independent Fermi data analysis (Balbo et al., A&A, 527, L4, 2011)



- evidence for very short (12 hrs or less) variability detected both by AGILE and Fermi

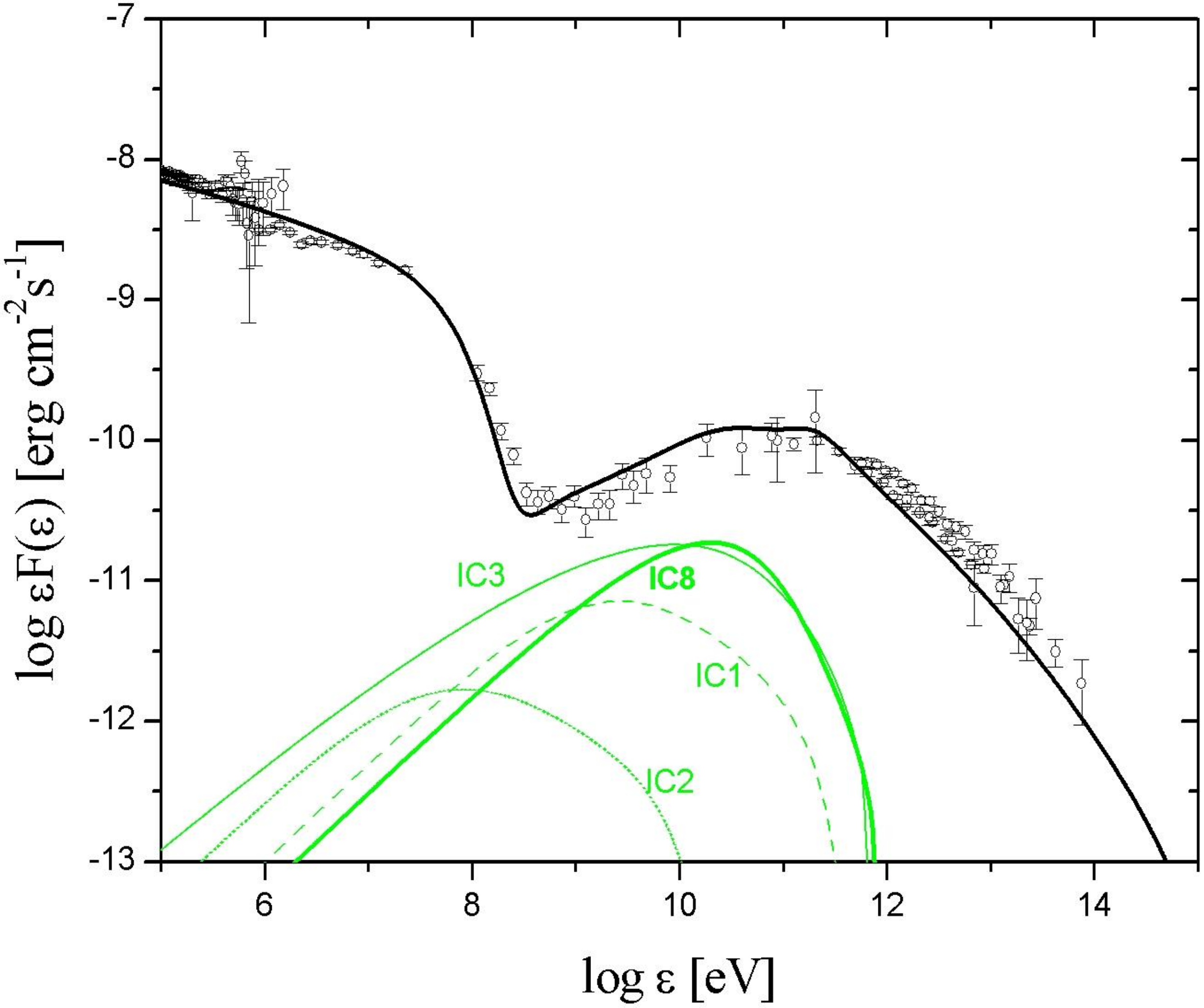
- **not the end of the story…**

still more surprises..!

- **TeV observations and ARGO-YBJ detection in Sept. 2010 (ATEL 2921)**

- **see also ATELs by VERITAS and MAGIC**

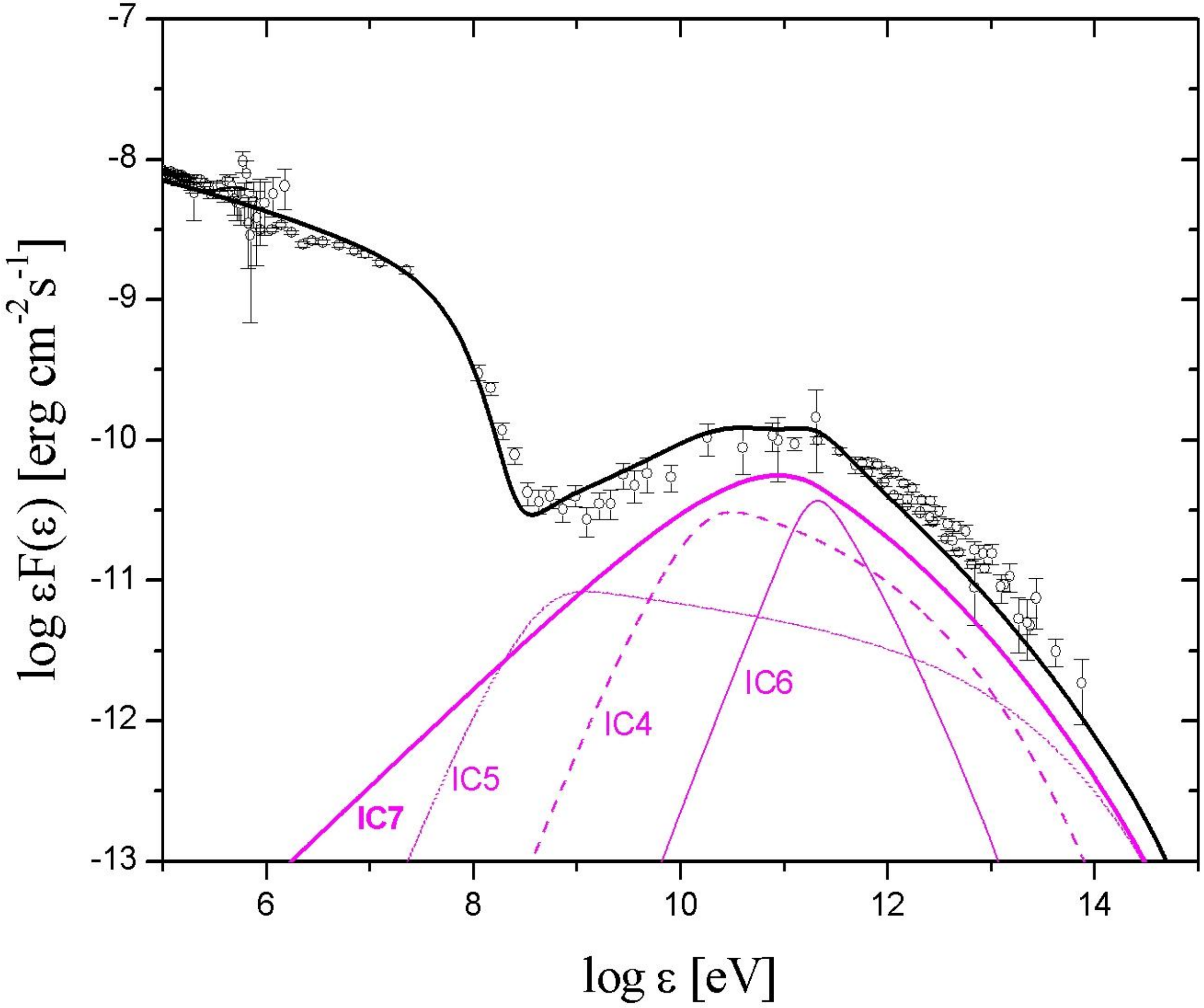
TeV nebular emission



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

IC1 dust ph
IC2 CMB ph
IC3 syn ph from **pop I**
IC8 syn ph from **pop II**

TeV nebular emission



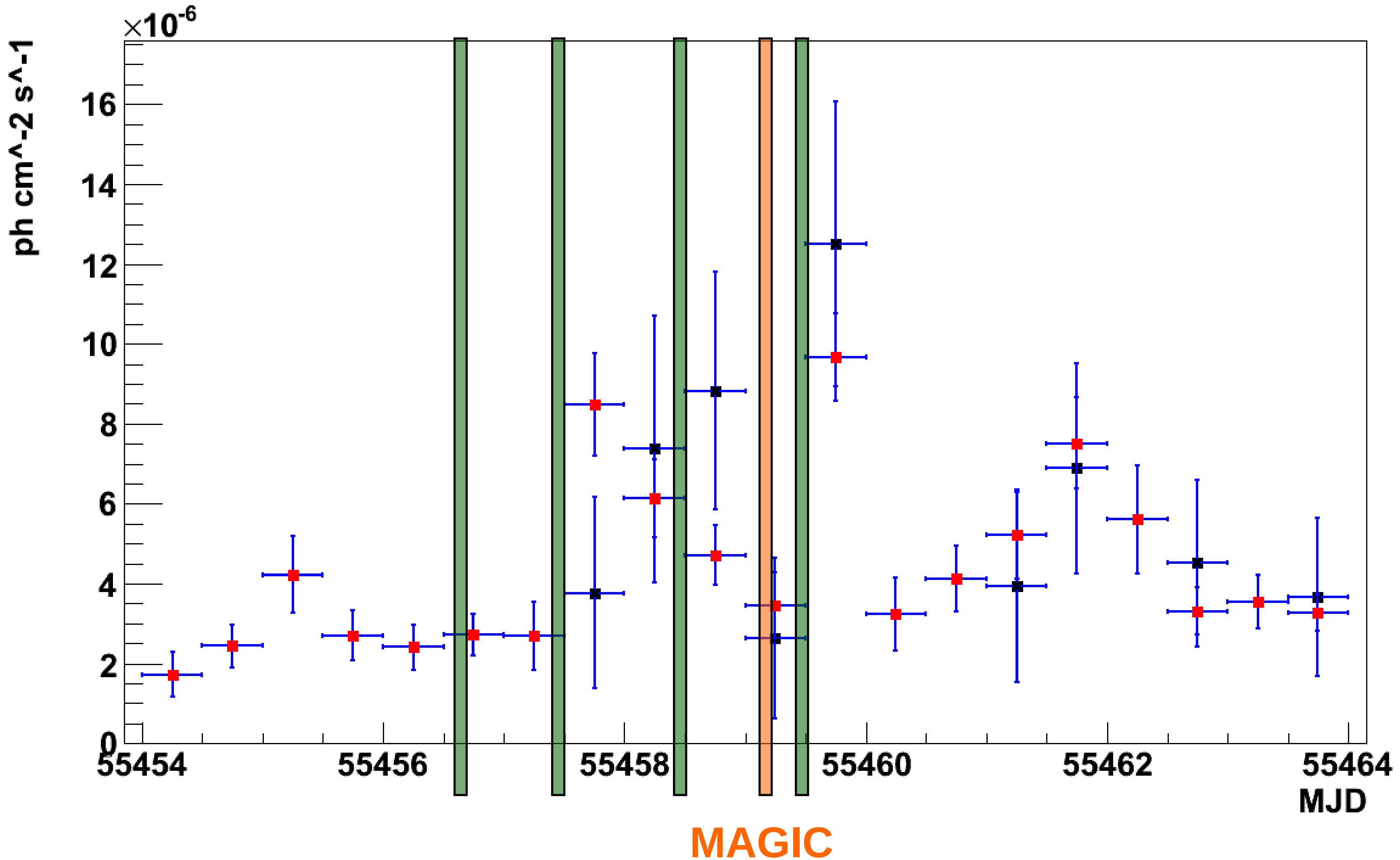
Inverse Compton contribution from **pop II** electrons scattering:

IC4 dust ph
IC5 CMB ph
IC6 syn ph from **pop II**
IC7 syn ph from **pop I**

post-flare TeV observations (ATel's: 2921, 2967, 2968)

Instrument	Epoch (MJD)	Duration	
VERITAS	55456.44	20 min.	no variation
	55456.47	20 min.	
	55457.47	20 min.	
	55458.45	20 min.	
	55458.47	20 min.	
	55459.47	20 min.	
MAGIC	55459.20	58 min.	no variation
ARGO-YBJ	55456-55461	5 days	3-4 times enhancement
	55456-55466	10 days	possible enhancement

12-hr bin lightcurves (AGILE and Fermi)



post-flare TeV observations

Instrument	Epoch (MJD)	Duration	
VERITAS	55456.44	20 min.	no variation
	55456.47	20 min.	
	55457.47	20 min.	
	55458.45	20 min.	
	55458.47	20 min.	
	55459.47	20 min.	
MAGIC	55459.20	58 min.	no variation
ARGO-YBJ	55456-55461	5 days	3-4 times enhancement
	55456-55466	10 days	possible enhancement

exciting prospects

- **room for possible short timescale TeV emission**

- **test VERITAS data during the first peak of emission (MJD 55458.5)**

- **search for similar episodes in the past ?**

- **TeV emission requires enhancement !**
  - **favorable Doppler beaming**

- **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**

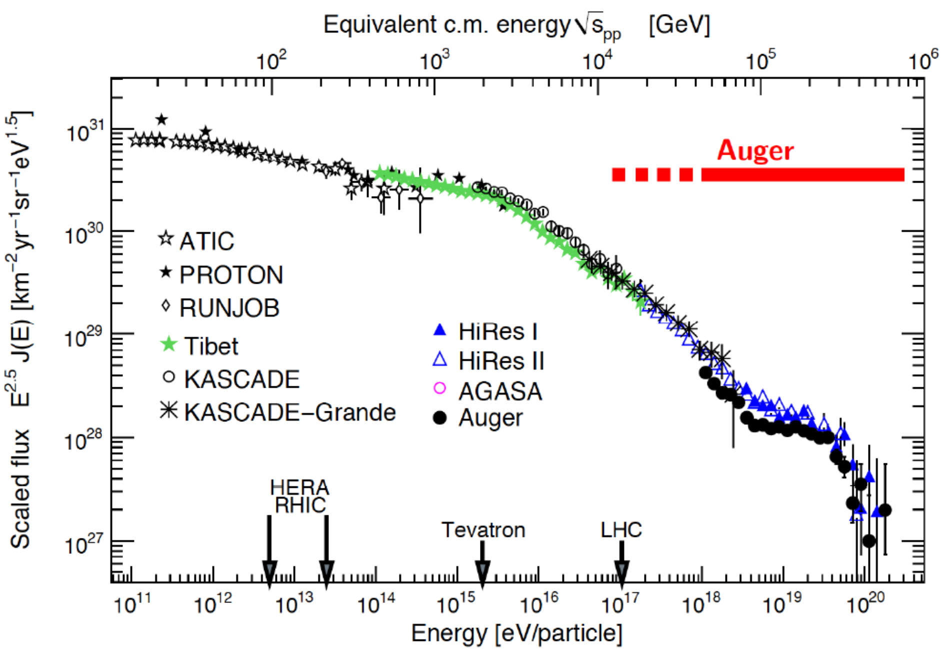
Conclusions

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

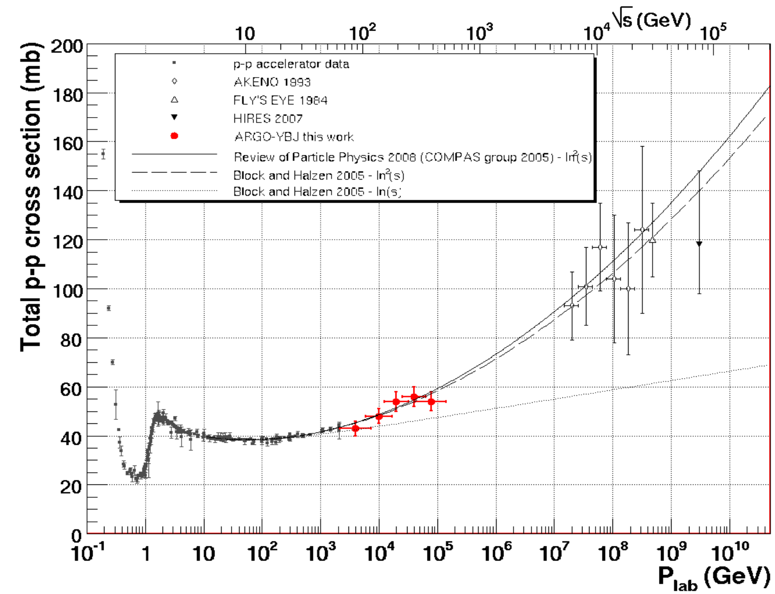
- **a big theoretical challenge**
  - **shock acceleration + magnetic field reconnection ?**
  - **current sheet and MHD instabilities**
  - **Doppler boosting ?**

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

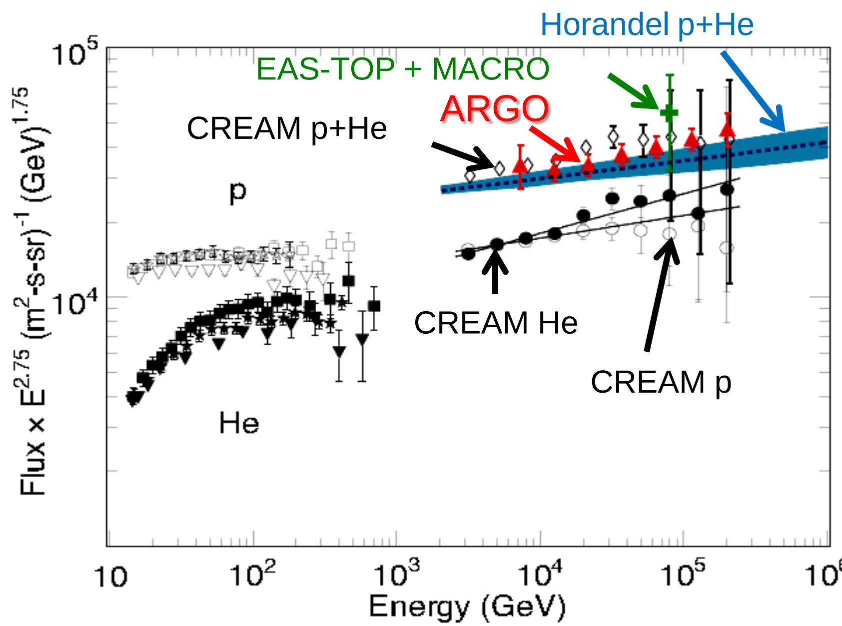
CR physics



Equivalent c.m. energy √s_pp [GeV]
Auger
ATIC
PROTON
RUNJOB
Tibet
KASCADE
KASCADE–Grande
HiRes I
HiRes II
AGASA
Auger
HERA
RHIC
Tevatron
LHC
Scaled flux E^2.5 J(E) [km^-2 yr^-1 sr^-1 eV^1.5]
Energy [eV/particle]

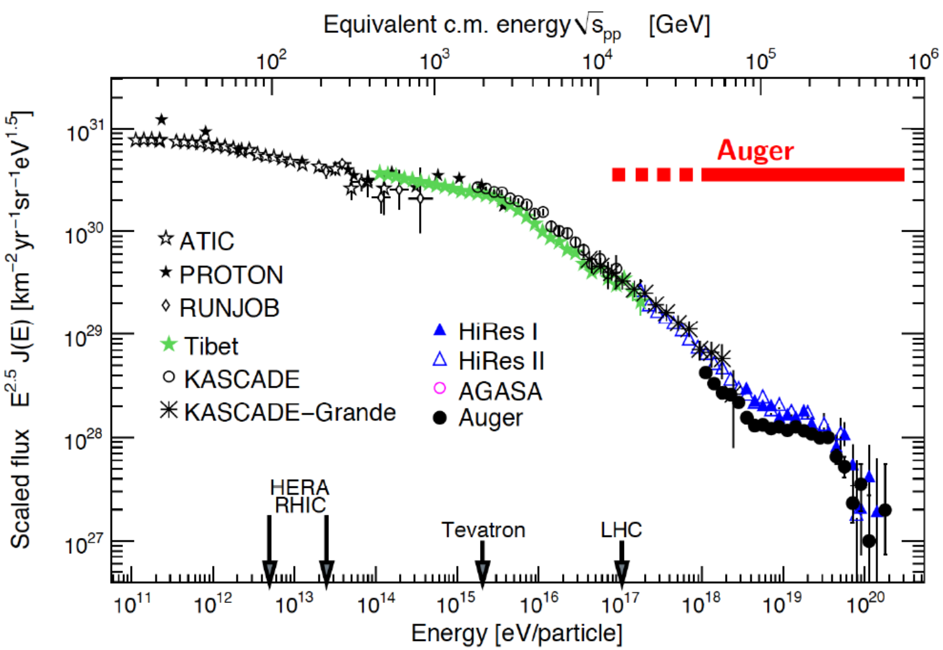


√s (GeV)
Total p-p cross section (mb)
p-p accelerator data
AKENO 1993
FLY'S EYE 1984
HIRES 2007
ARGO-YBJ this work
Review of Particle Physics 2008 (COMPAS group 2005) - ln²(s)
Block and Halzen 2005 - ln²(s)
Block and Halzen 2005 - ln(s)
P_lab (GeV)

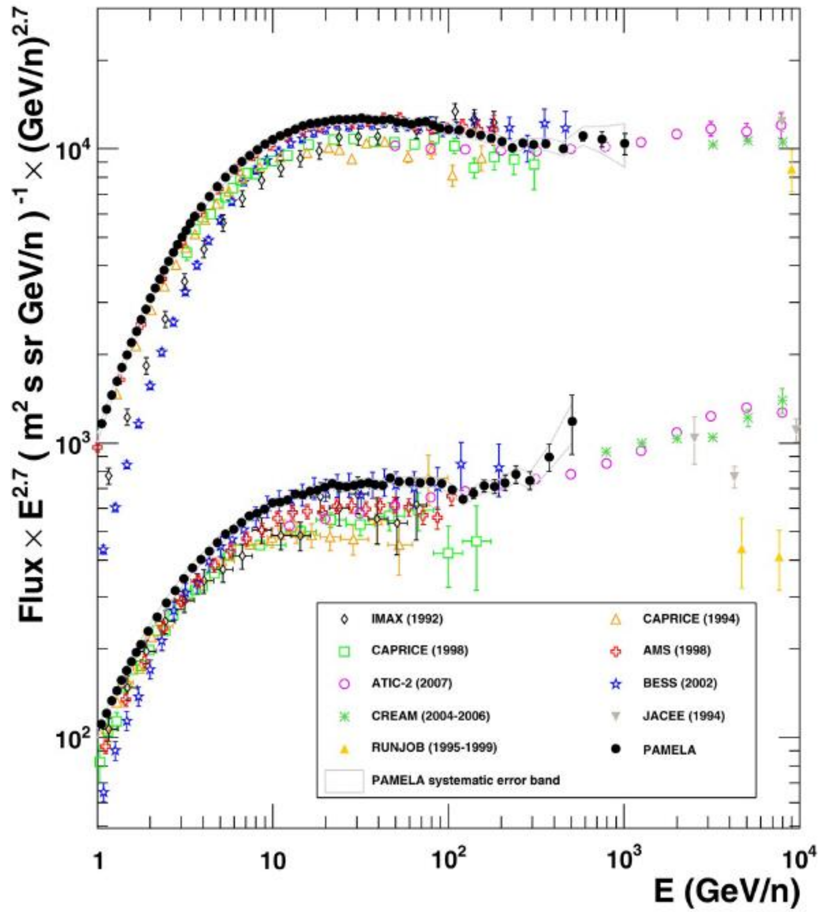


Horandel p+He
EAS-TOP + MACRO
ARGO
CREAM p+He
p
He
CREAM He
CREAM p
Flux × E^2.75 (m²-s-sr)^-1 (GeV)^1.75
Energy (GeV)

CR physics



PAMELA



$$\frac{\partial f}{\partial t} + U\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\kappa\frac{\partial f}{\partial x} + \frac{1}{3}\frac{\partial U}{\partial x}p\frac{\partial f}{\partial p}$$

$$U(x) = \begin{cases} -u_1, & \text{if} \quad x > 0 \\ -u_2, & \text{if} \quad x \le 0 \end{cases}$$

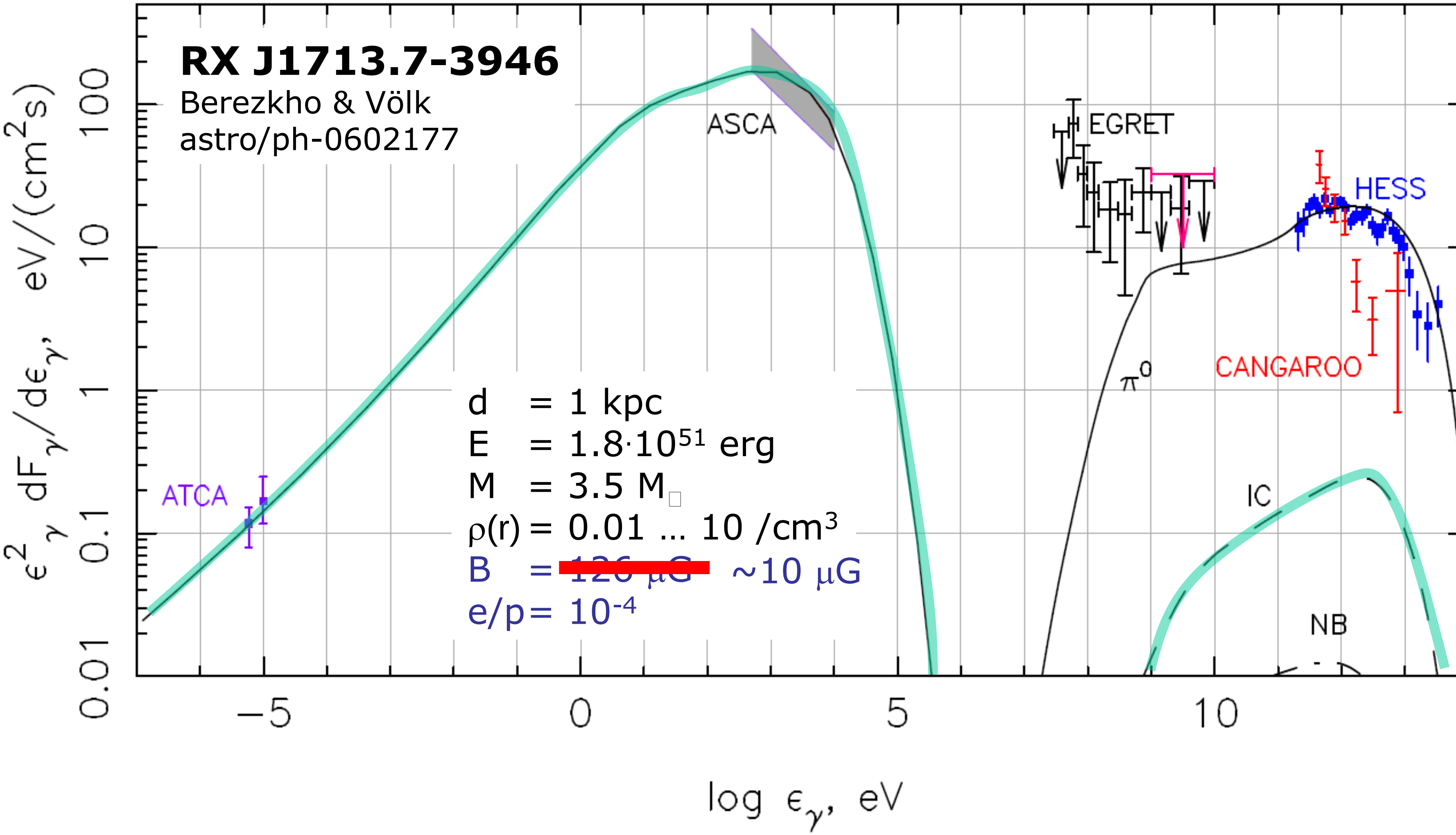
$$f = f_0(p)\exp(-u_1 x/\kappa)$$

$$\text{compression ratio, } r = \frac{u_1}{u_2}$$

$$f_0 = Q_{inj}\, p^{-q} \quad \text{where} \quad q = \frac{3r}{r-1}$$

$$t_{acc}(p) = \frac{3}{u_1 - u_2} \int_{p_0}^{p} \left(\frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2} \right) \frac{dp}{p}$$

Spectral Modelling…



composite scenario of gamma-ray emission: forward shock in dense clouds and reverse shock

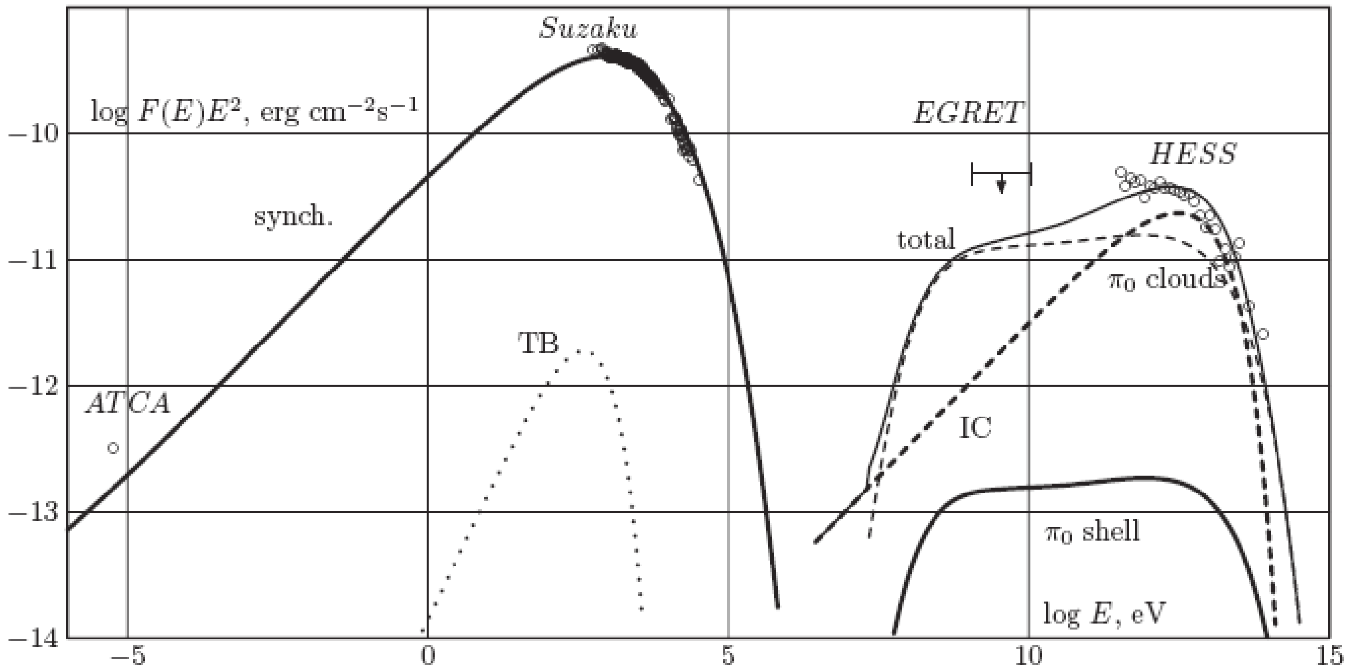
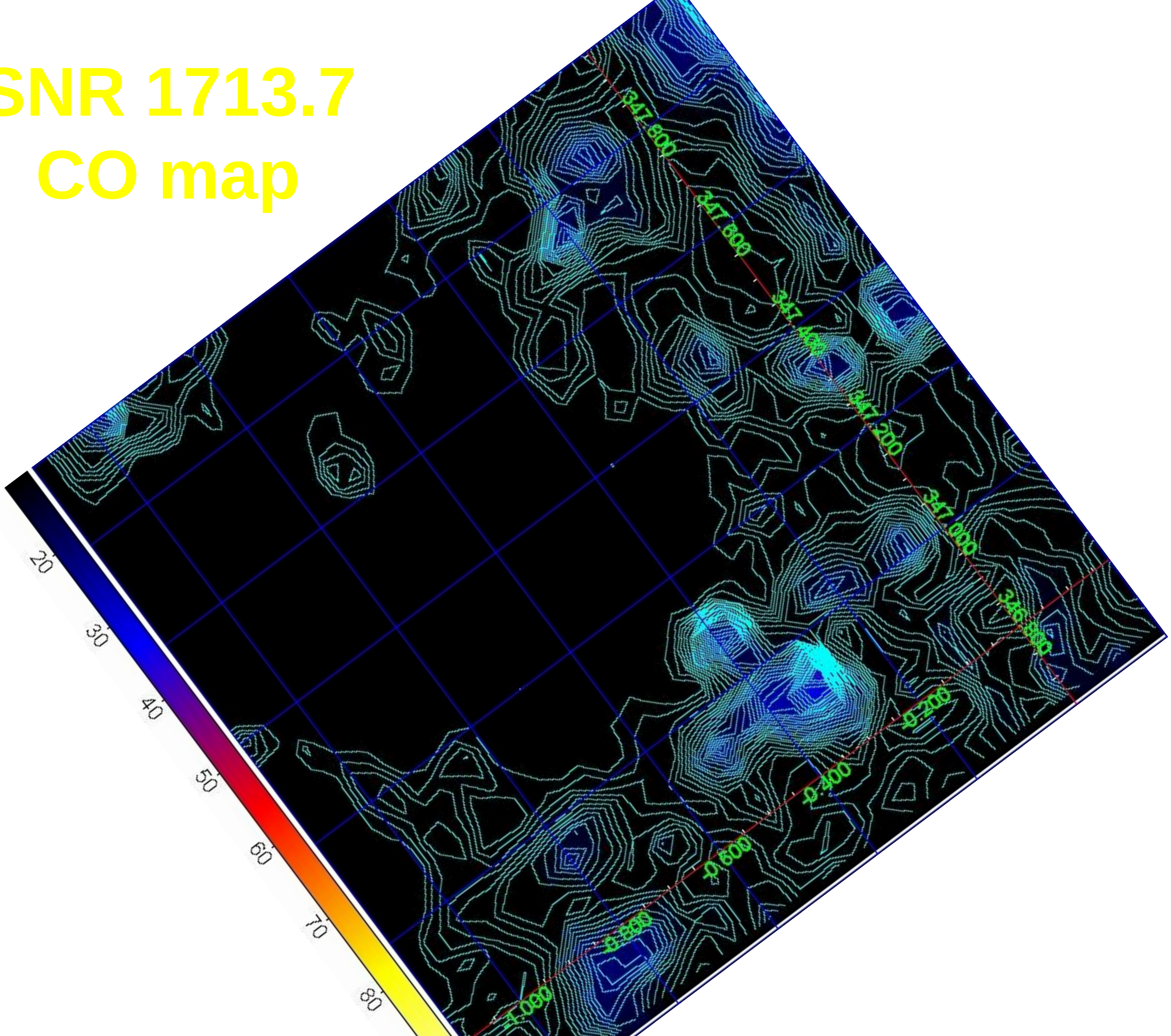
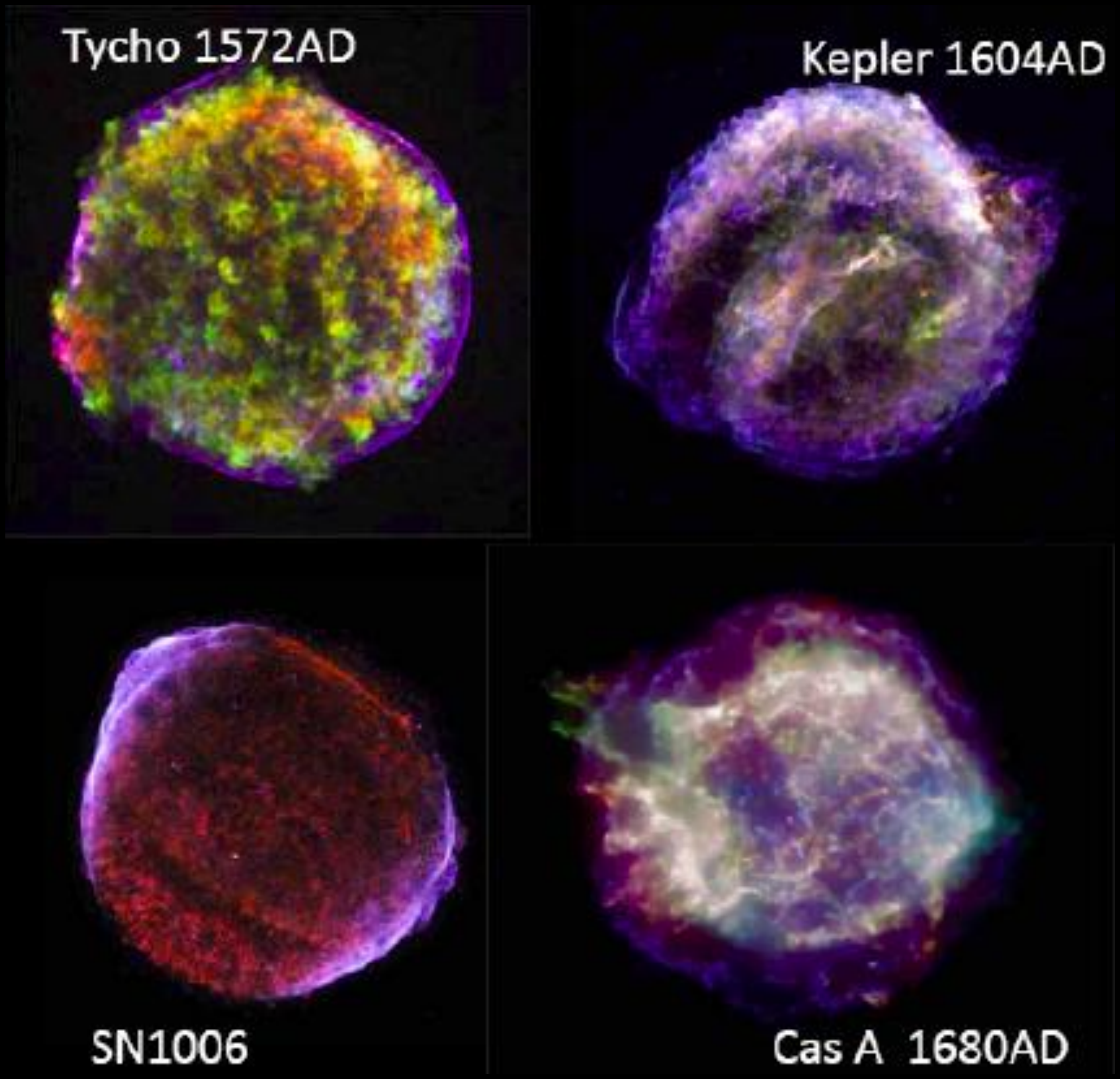


Figure 14. Broadband emission of RX J1713.7−3946 for the composite scenario of gamma rays with a non-modified forward shock and dense clouds. The principal model parameters are: $t = 1620$ yr, $D = 1.5$ kpc, $n_{\rm H} = 0.02\ {\rm cm}^{-3}$, $E_{SN} = 1.2 \times 10^{51}$ erg, $M_{ej} = 0.74\, M_{\odot}$, $M_A^f = 55$, $M_A^b = 10$, $\xi_0 = 0.1$, $K_{ep}^f = 1.4 \times 10^{-2}$, and $K_{ep}^b = 9 \times 10^{-4}$. The calculations lead to the following values of the magnetic fields and the shock speeds at the present epoch: the magnetic field downstream of the forward and reverse shocks $B_f = 22\ \mu$G and $B_b = 31\ \mu$G, respectively, the speed of the forward shock $V_f = 3830\ {\rm km\ s}^{-1}$, and the speed of the reverse shock $V_b = -1220\ {\rm km\ s}^{-1}$. The following radiation processes are taken into account: synchrotron radiation of accelerated electrons (solid curve on the left), thermal bremsstrahlung (dotted line), IC gamma-ray emission of the entire remnant including forward and reverse shocks (dashed line), and hadronic component of gamma-rays from the remnant's shell (solid line on the right), as well as from dense clouds assuming the factor of 120 enhancement of the flux (thin dashed line). We also show the total gamma-ray emission from the entire remnant including the dense clouds (thin solid line).

SNR 1713.7
CO map



young SNRs (X-rays, Chandra)



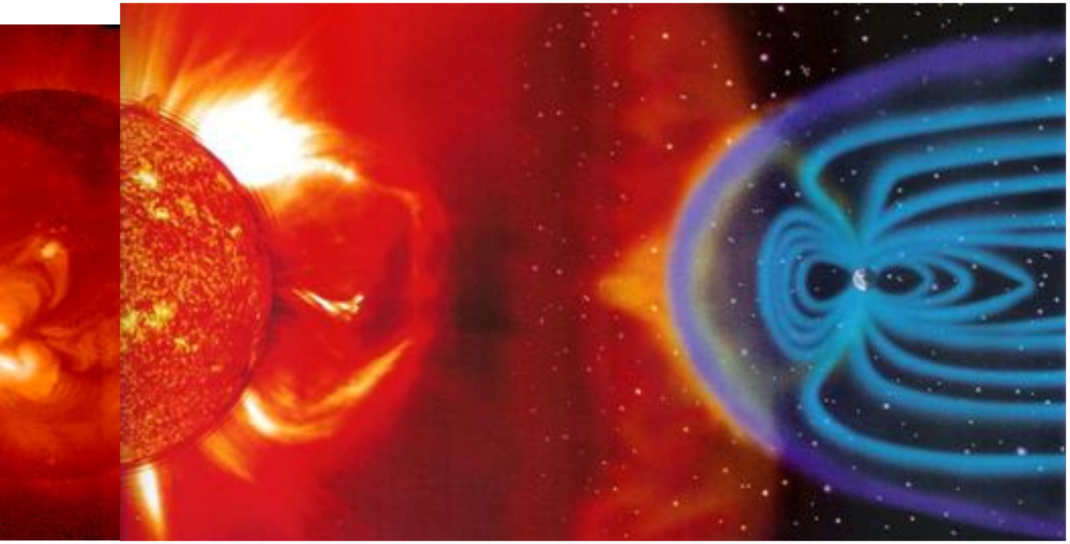
theoretical challenges

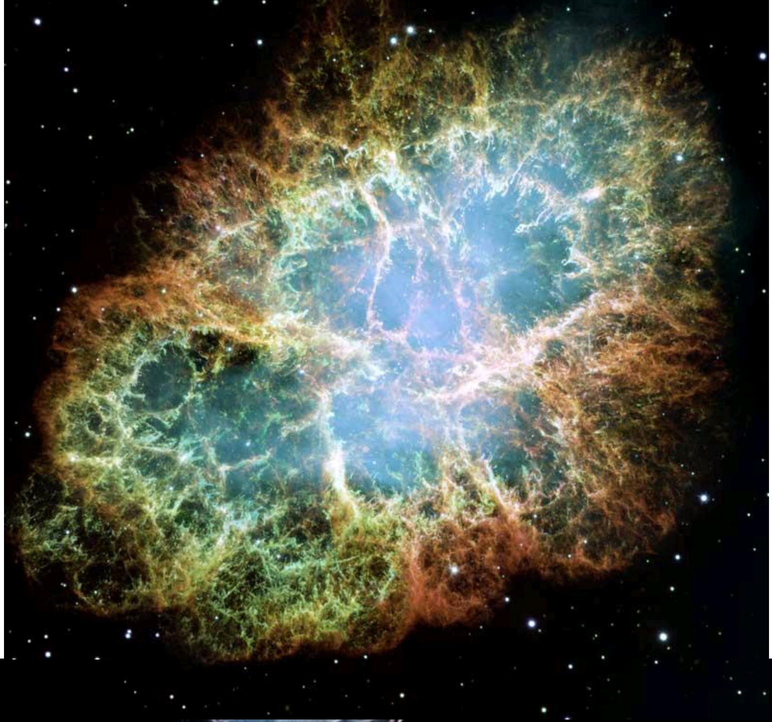
- **spectral breaks near 1-10 GeV for emission associated to molecular clouds**

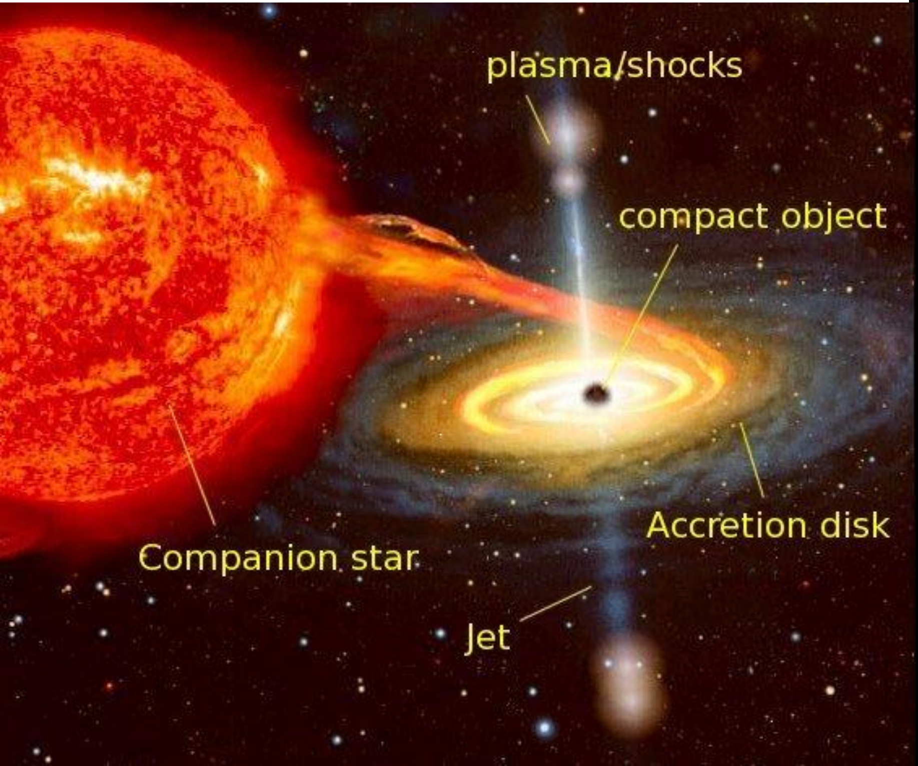
- **co-existence" (?) of *average* low-B and l*ocal* strongly enhanced-B (1 mG): filamentary structure of shocks**

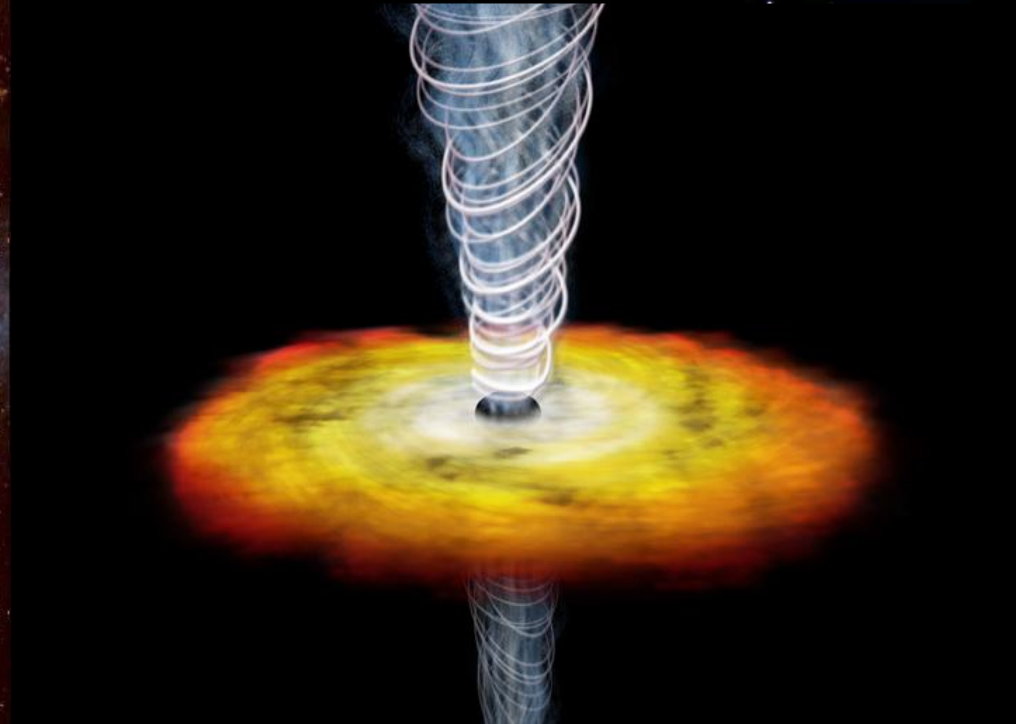
- **no obvious sign of shock-accelerated particle concave spectra (non-linear effect)**

- **"escape" and propagation of hadronic CRs**
- **explain local anisotropies, …**

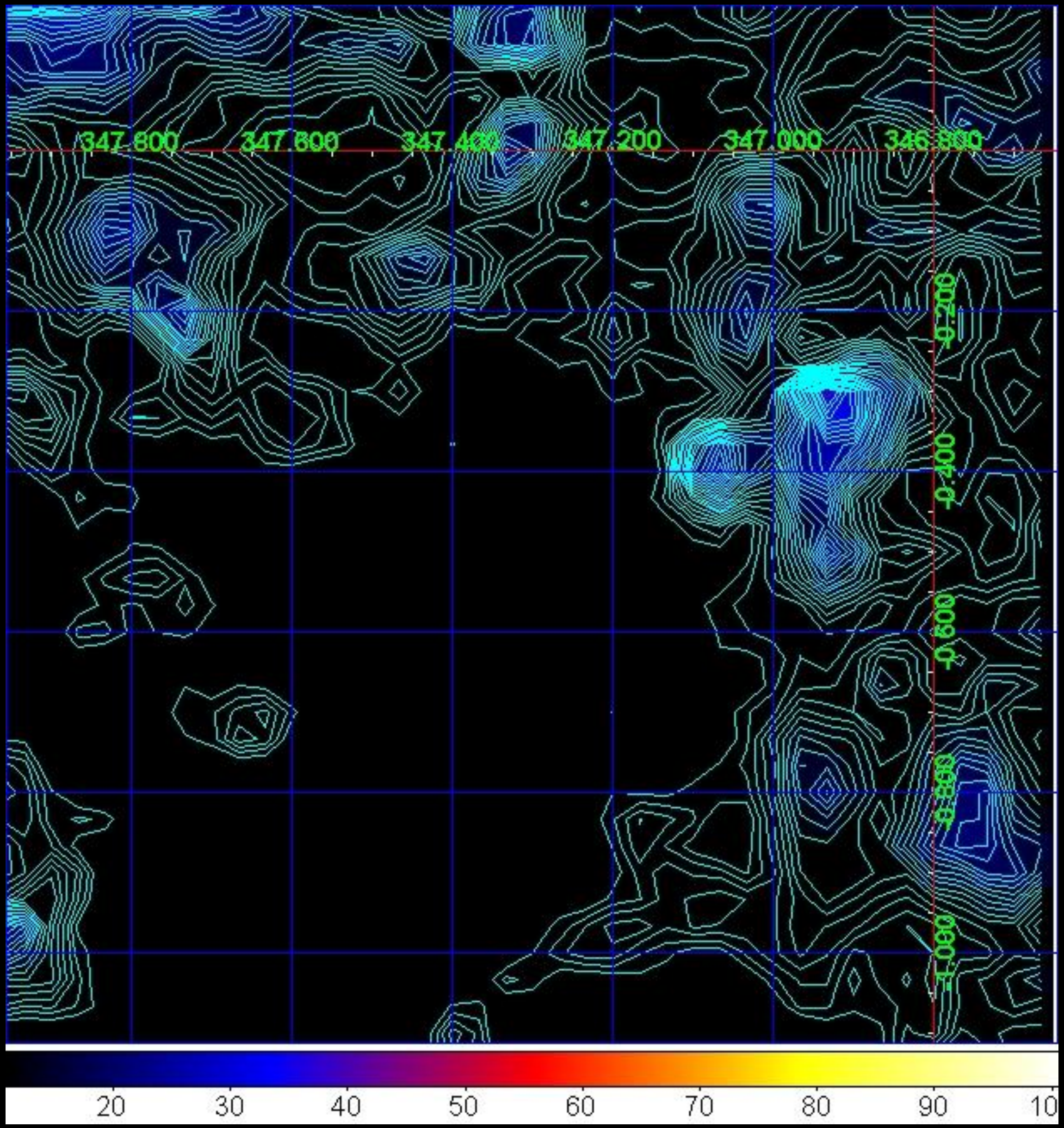




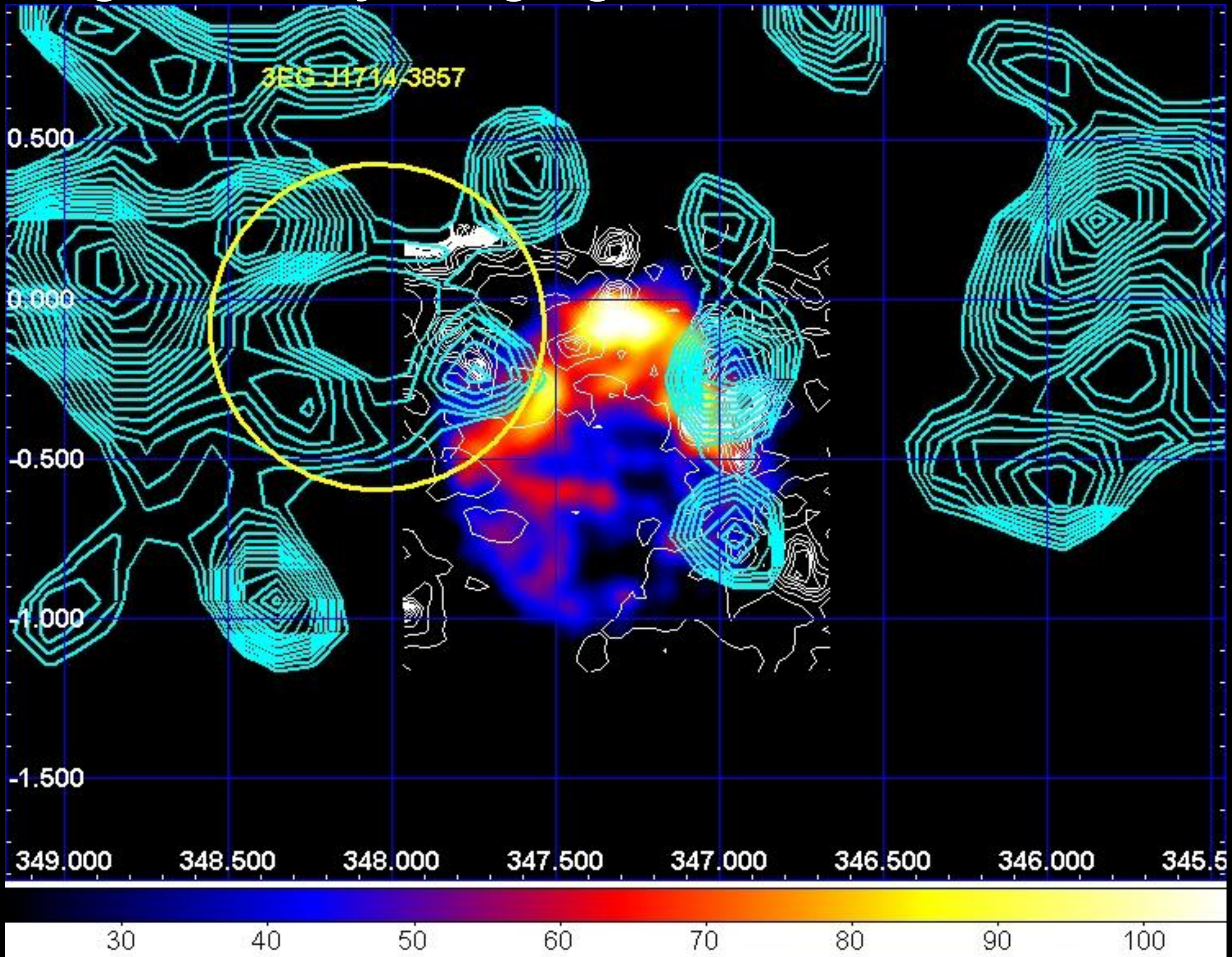

plasma/shocks
compact object
Accretion disk
Companion star
Jet



SNR 1713.7 NANTEN CO map



SNR RX J1713-3946
AGILE gamma-ray imaging,

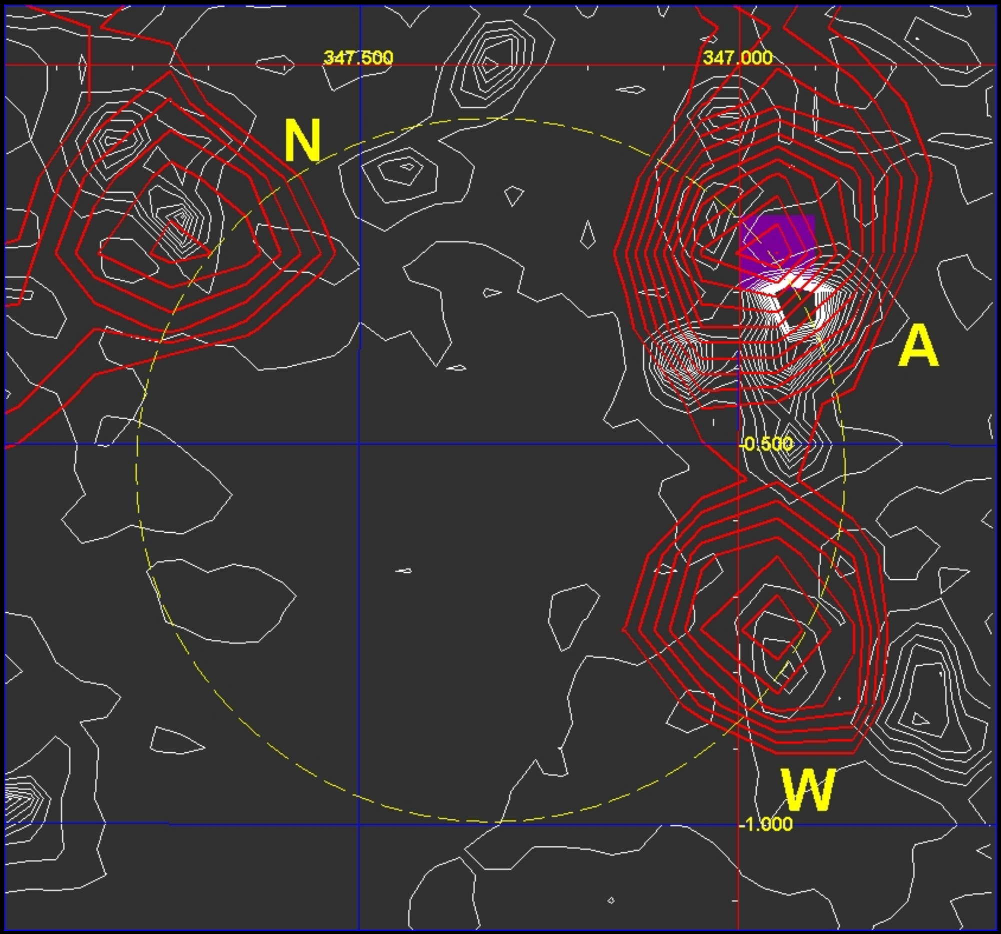


SNR RX J1713-3946

AGILE gamma-ray imaging,

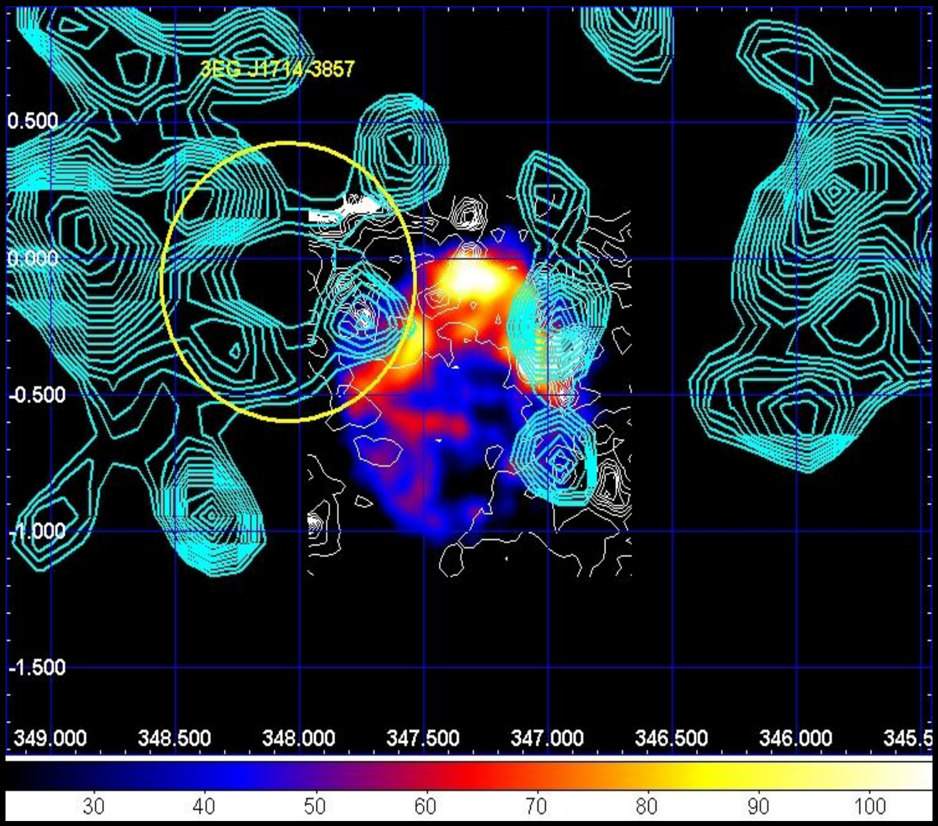
E> 400 MeV

Intensity map



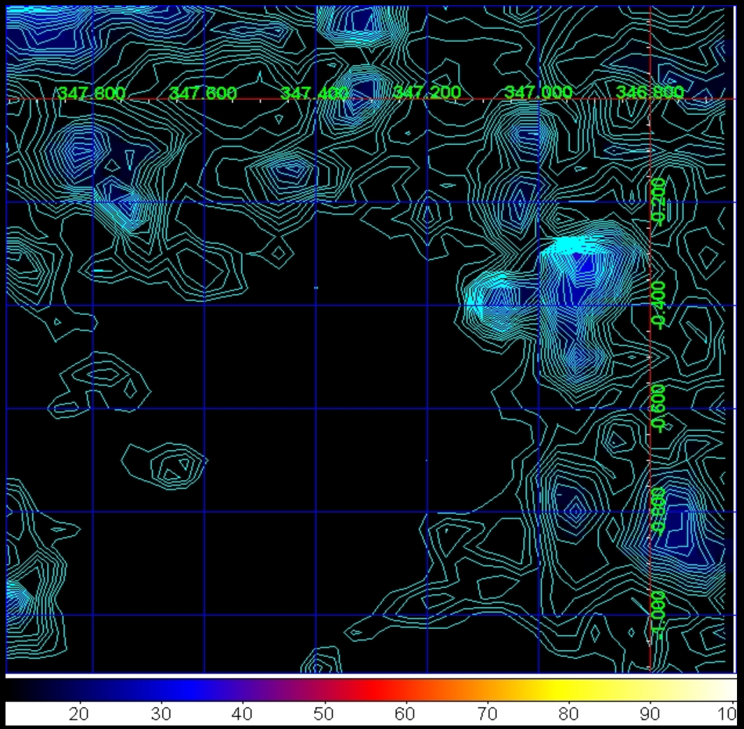
Tavani et al. 2011 in prep.

SNR RX J1713-3946



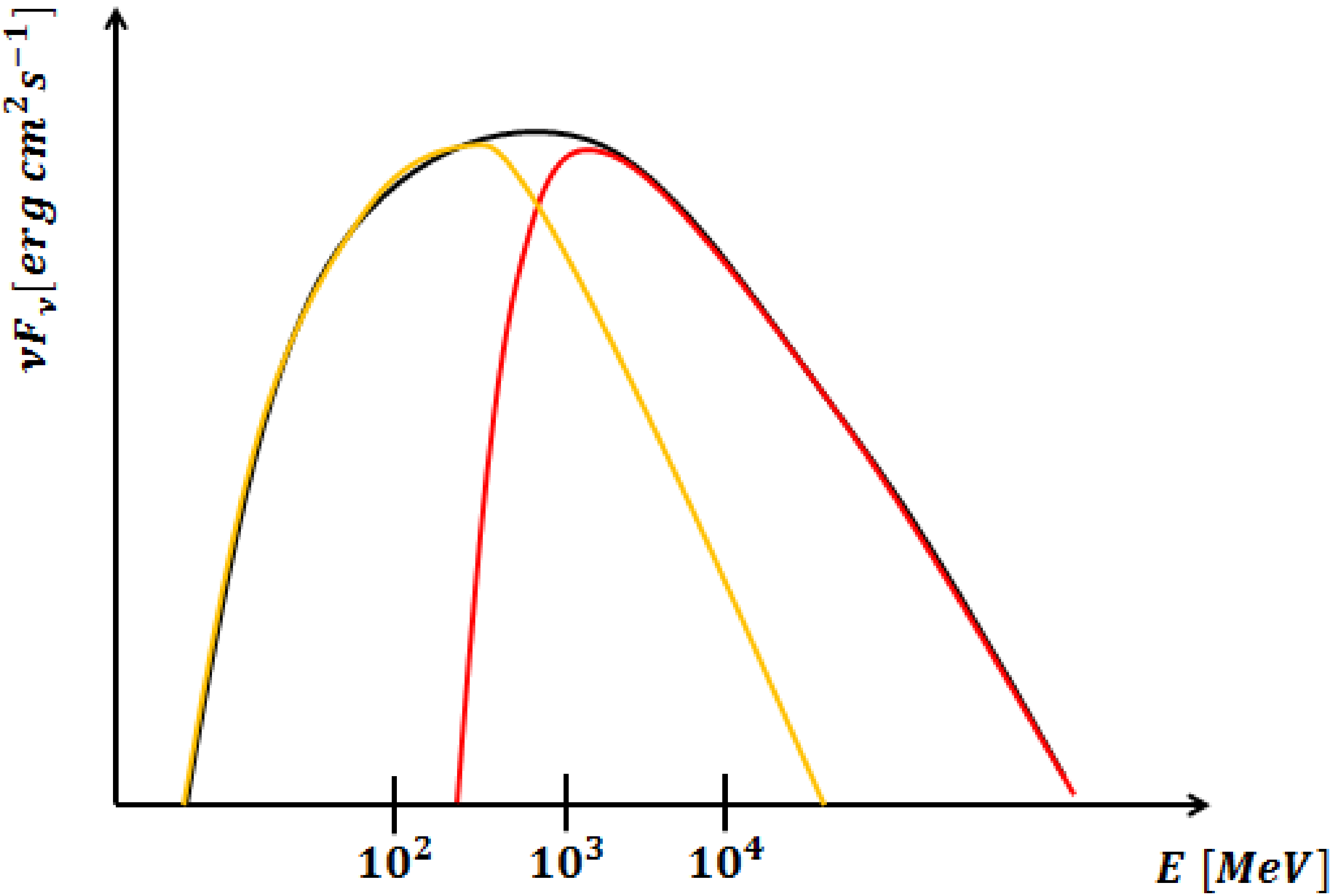
HESS map +

AGILE/GRID contours (E> 400 MeV)



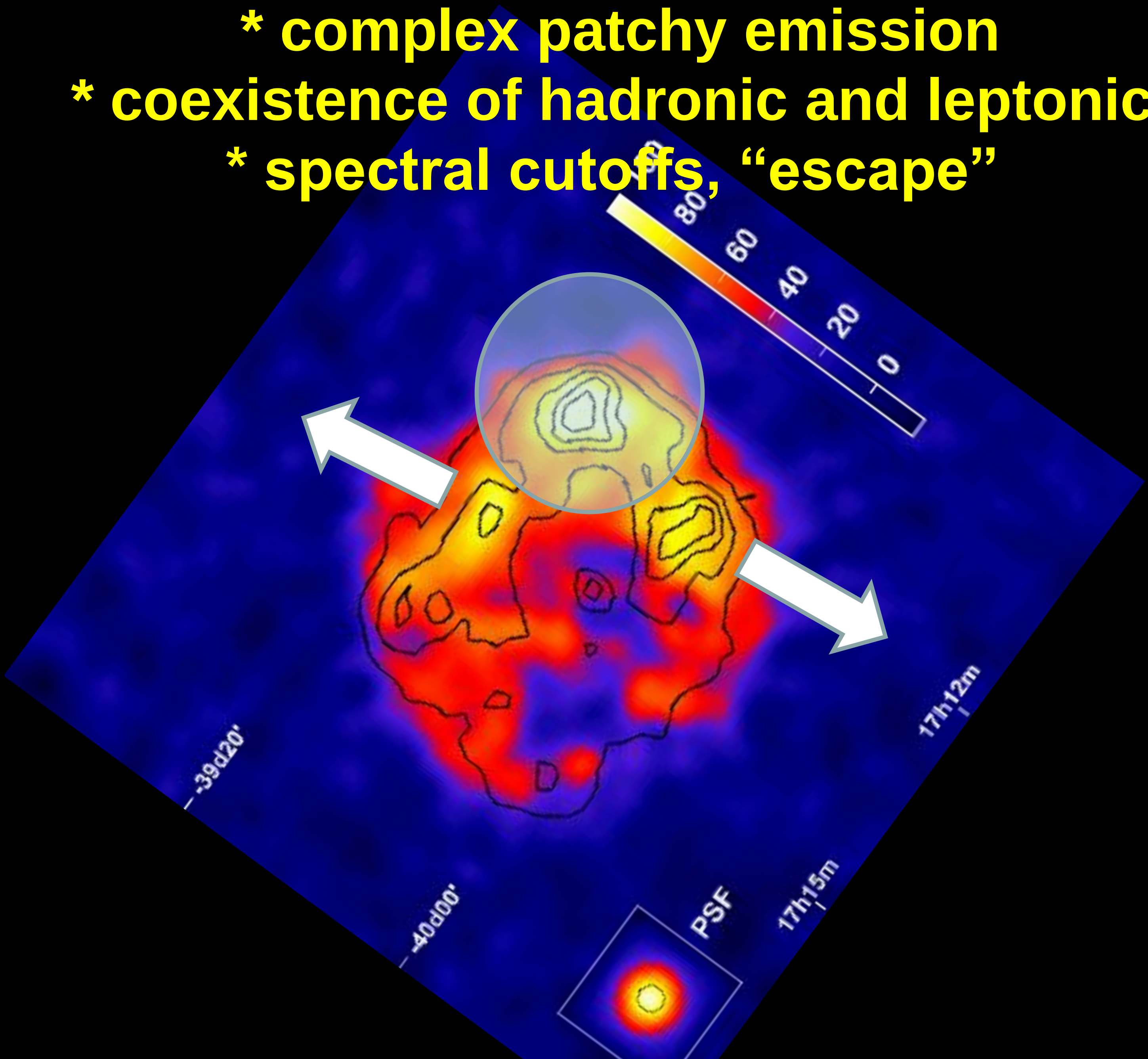
NANTEN

CO map



$\nu F_\nu [erg\, cm^2 s^{-1}]$
10^2
10^3
10^4
$E\ [MeV]$

lessons from RX 1713.7-3946
* complex patchy emission
* coexistence of hadronic and leptonic
* spectral cutoffs, “escape”



DIFFICULT TO PROVE: Fermi paper on W51C, Abdo et al. 2010

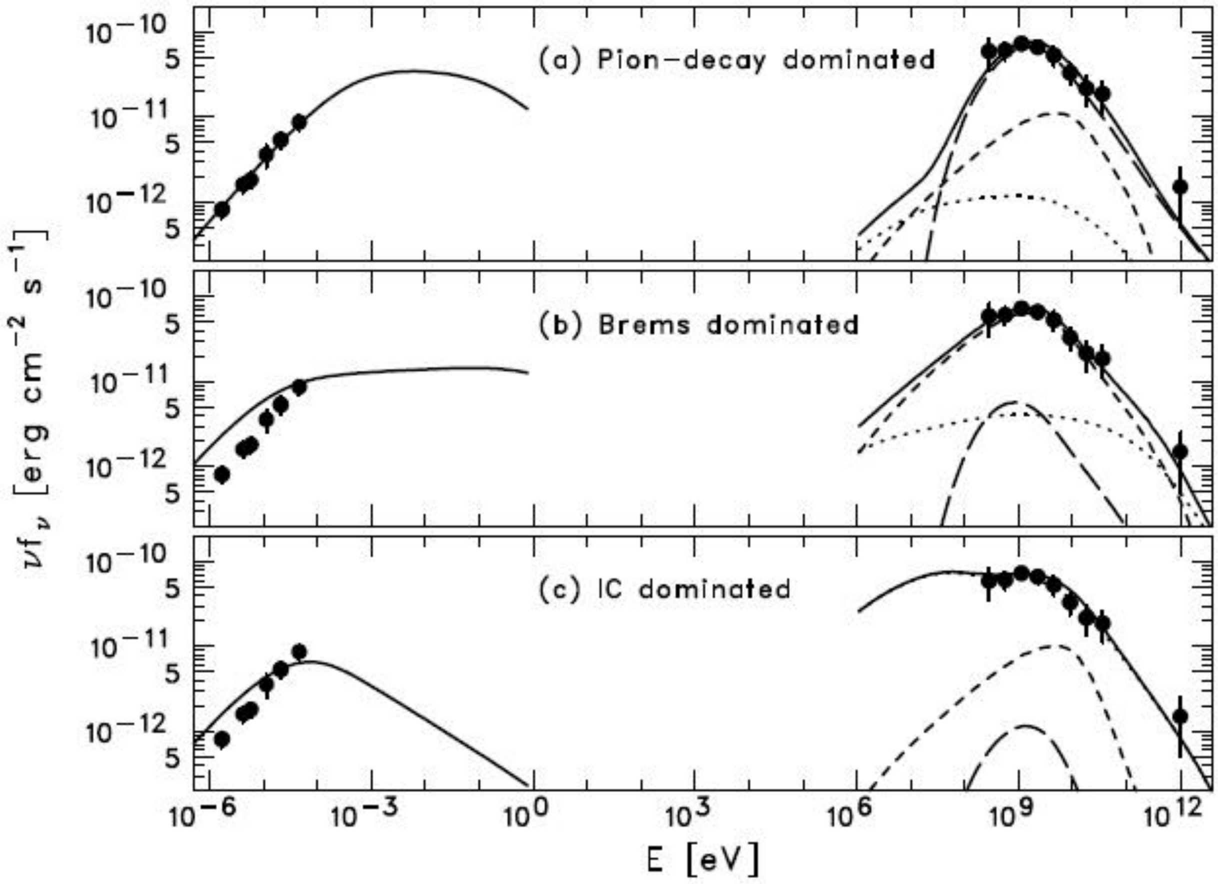


Fig. 4.— Three different scenarios for the multiwavelength modeling (see Table 1). The radio emission (from Moon & Koo 1994) is explained by synchrotron radiation, while the gamma-ray emission is modeled by different combinations of π^0-decay (long-dashed curve), bremsstrahlung (dashed curve), and IC scattering (dotted curve). The sum of the three component is shown as a solid curve.

SNR	Age (yrs)	distance
IC 443	~ 30.000	~ 1.5 kpc
W28	~ 35.000	~ 1.8-3.3 kpc
W44	~ 20.000	~ 3 kpc
1713.7-3946	1.000- 3.000	~ 1 kpc

advancement in CR astrophysics

- about 10 SNRs detected in gamma-rays *Fermi* and AGILE
- complex interaction with the surroundings
- acceleration and “escape” of accelerated CRs play a crucial role
- co-existence of leptonic and hadronic emission
- so far, only 1 case of clear pion emission (W44) unveiled by AGILE

- **Synchrotron cooling timescales**

- 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$)^{-1/2}$