2013年9月4日
宇宙線研究所

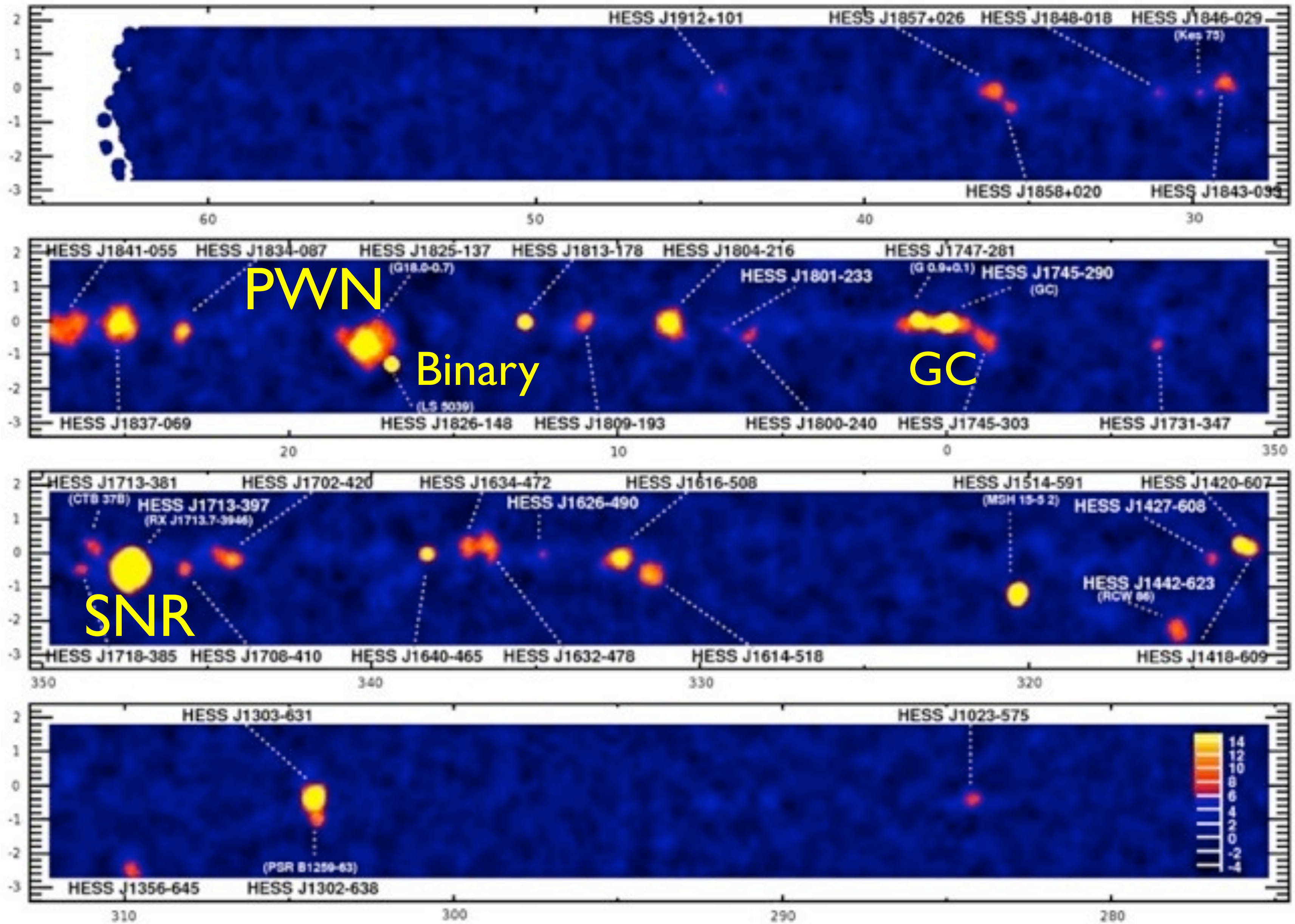
フェルミ衛星による銀河系TeVガンマ線天体の研究

内山 泰伸 (立教大学)

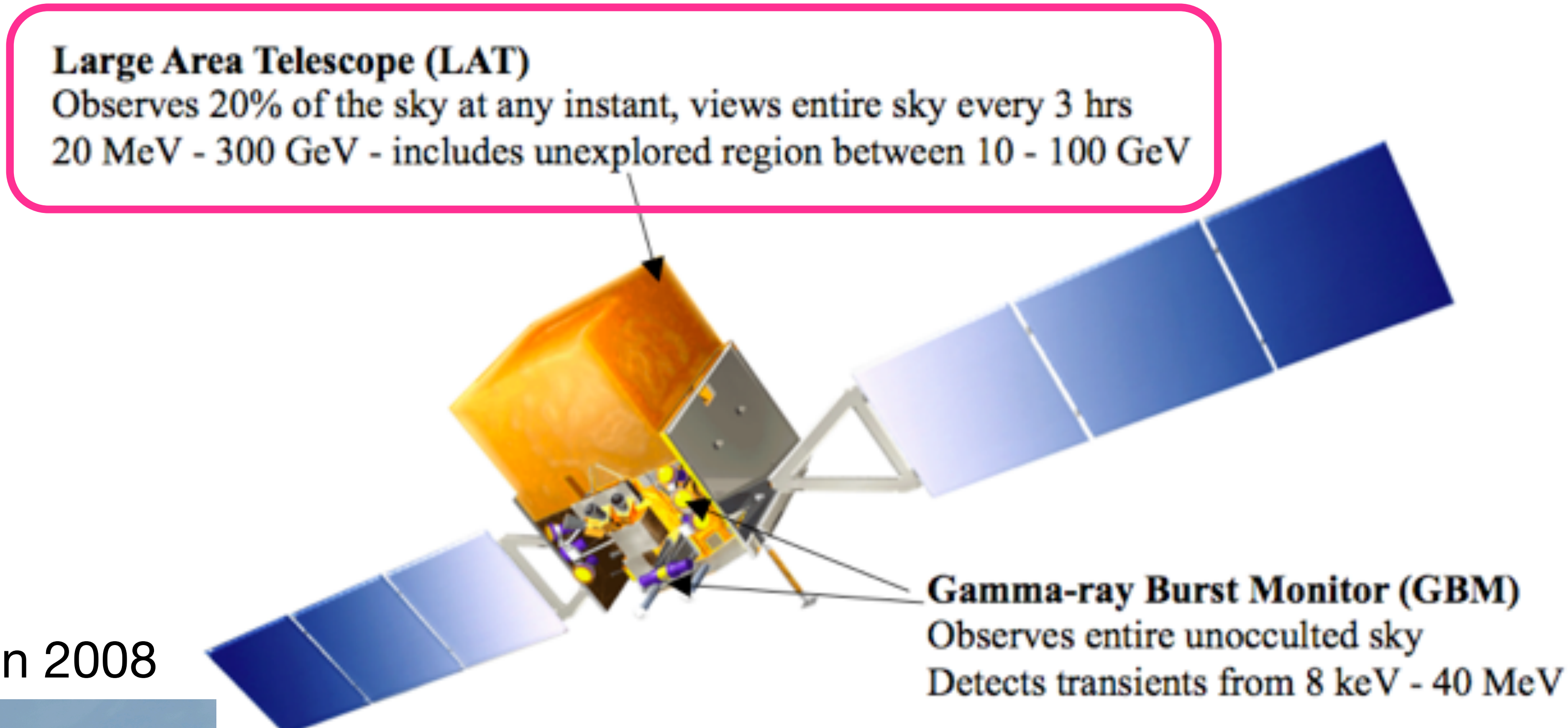
On behalf of Fermi-LAT Collaboration

Milky Way in TeV Gamma-ray: H.E.S.S.

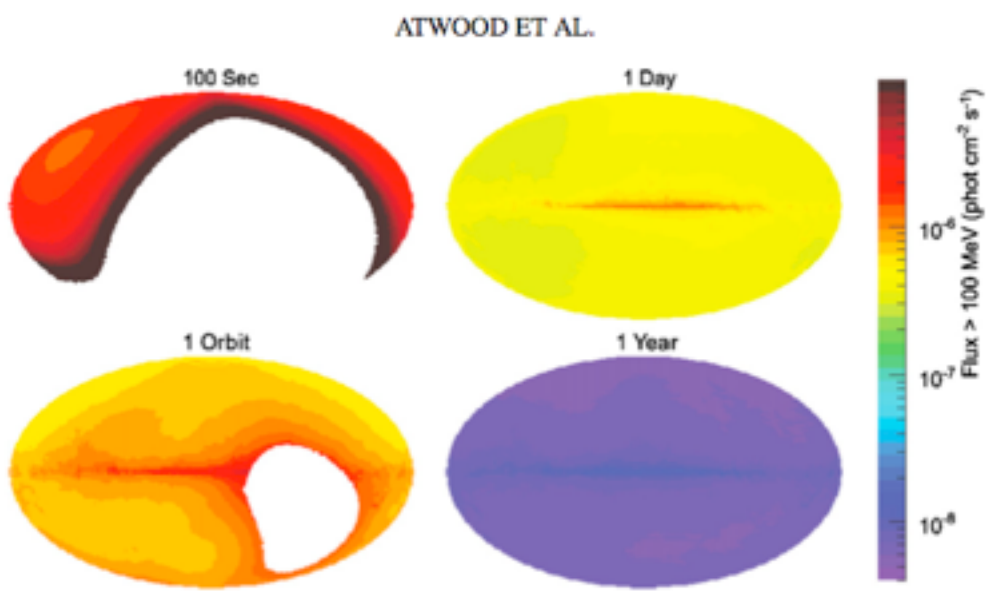
H.E.S.S. (imaging air Cherenkov telescopes, ~1 TeV γ-rays) has revealed various TeV sources along the Milky Way in 2005



Fermi Gamma-ray Space Telescope



Launch in 2008

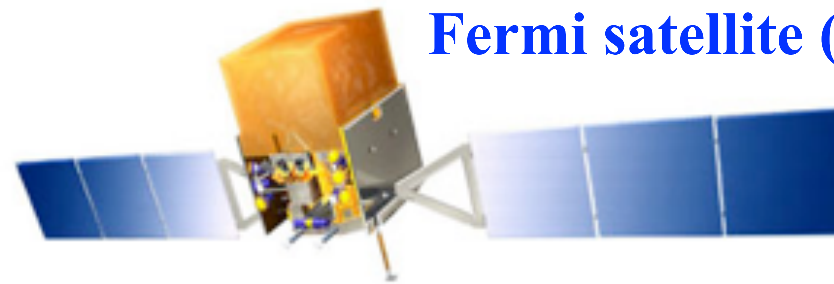


← LAT sensitivity

for various exposures

Large Area Telescope (LAT) onboard Fermi

Fermi satellite (2008-)

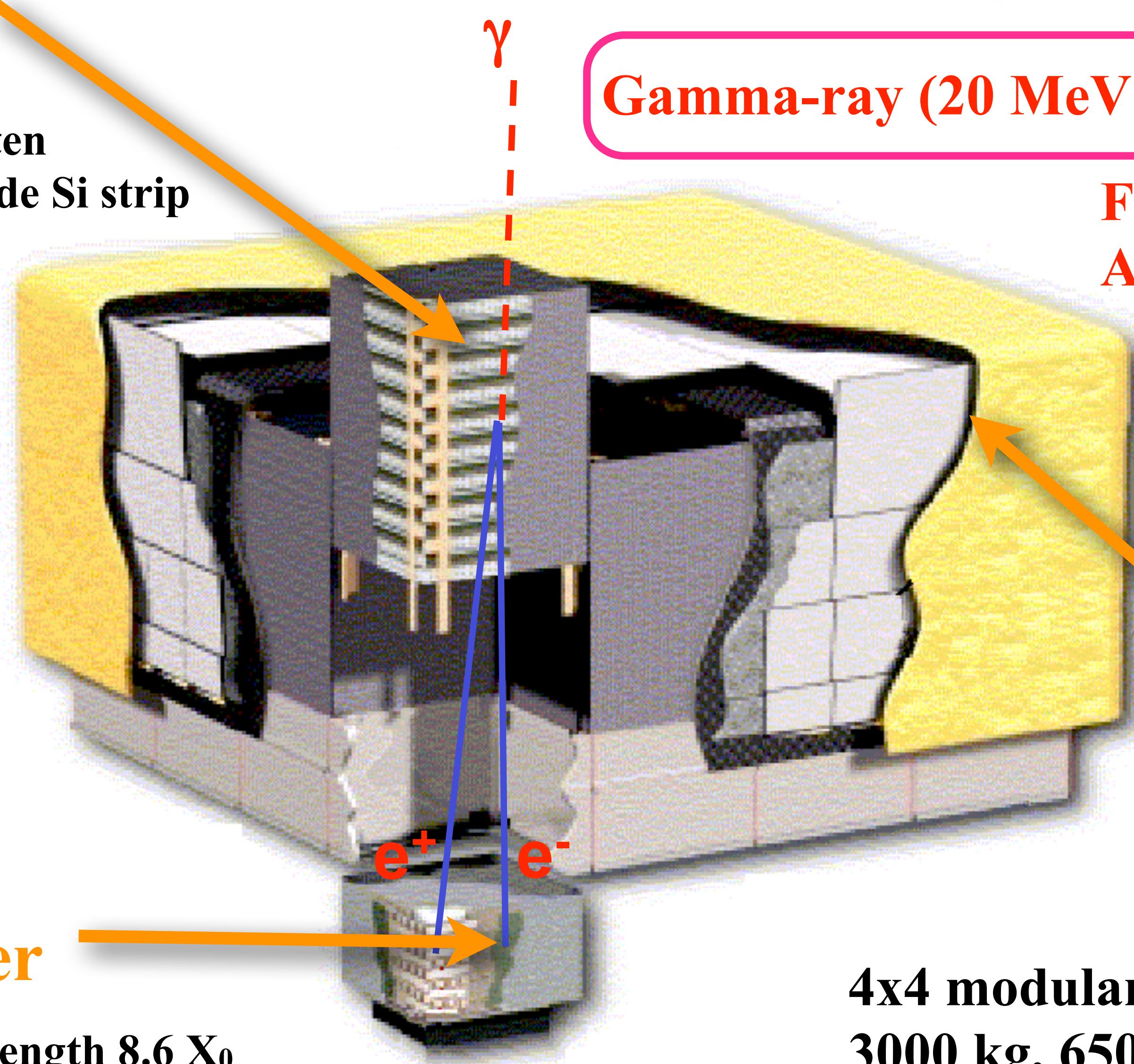


Si Tracker (18 planes)

converter: tungsten
tracker: single-side Si strip

Gamma-ray (20 MeV - 300 GeV)

Field of view: 2.4 str
Angular resolution:
~ 1 deg at 1 GeV
~0.1 deg > 10 GeV



Anti Coincidence Detector

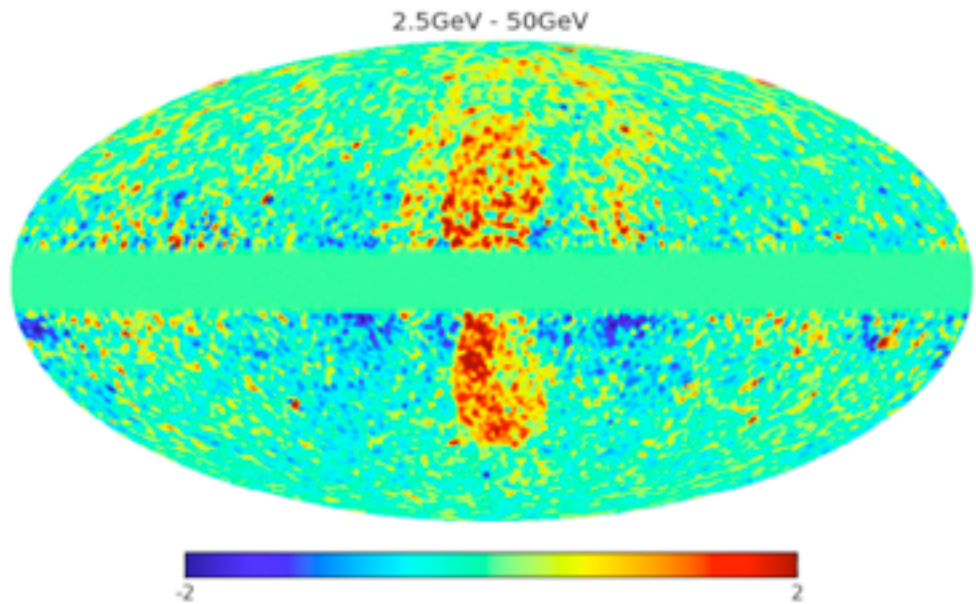
CsI Calorimeter

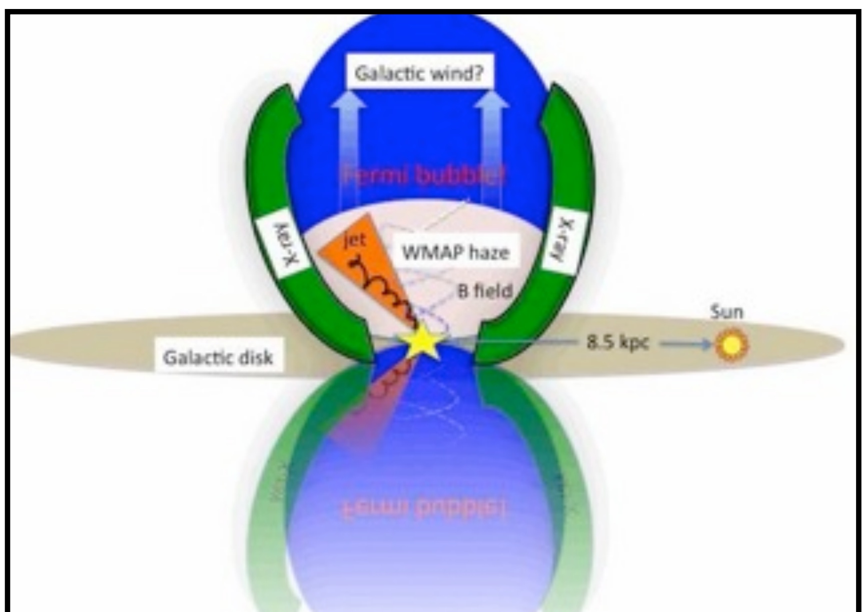
total radiation length 8.6 X_0

4x4 modular array
3000 kg, 650 W

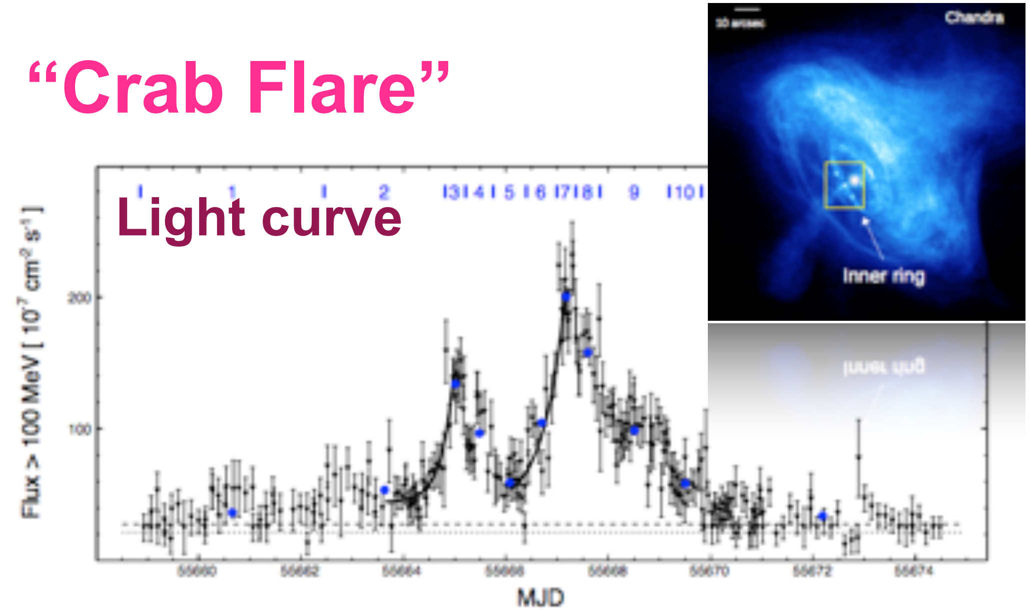
銀河系内 GeV ガンマ線源：サプライズ

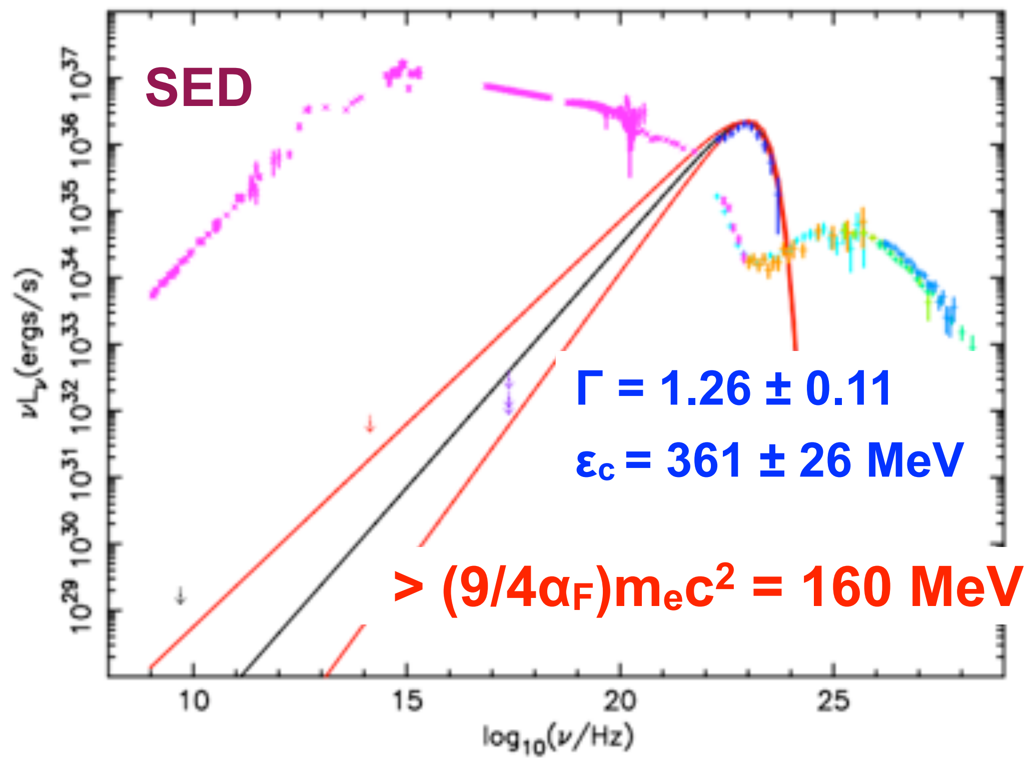
"Fermi Bubble"



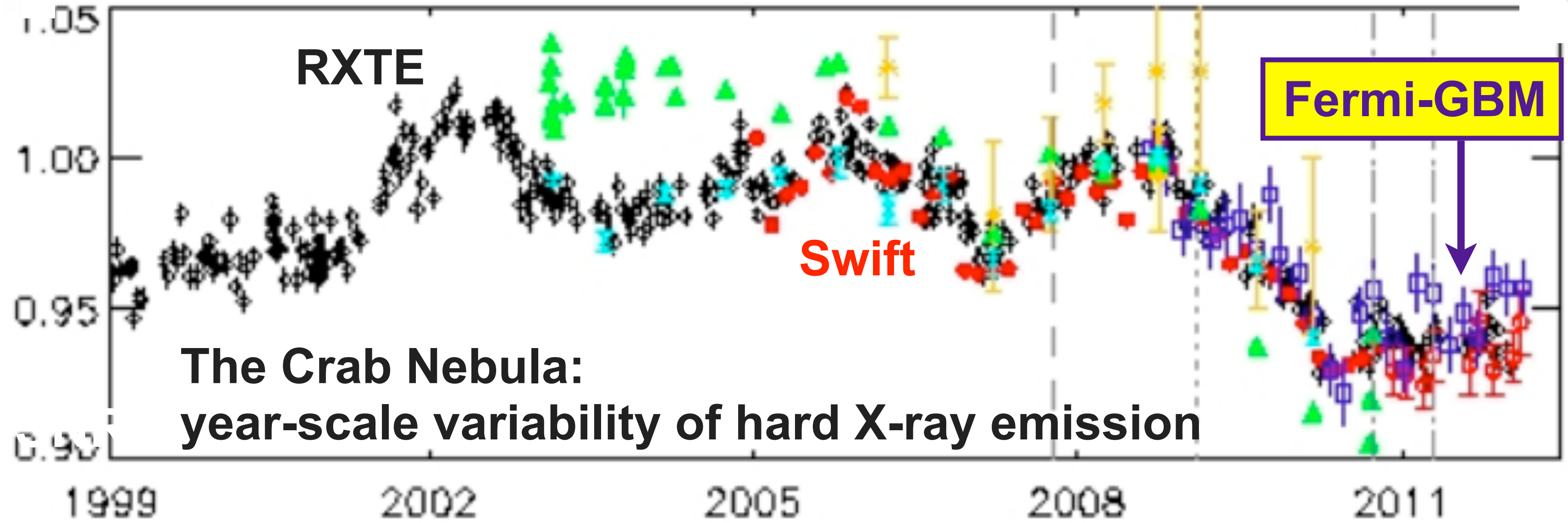


"Crab Flare"

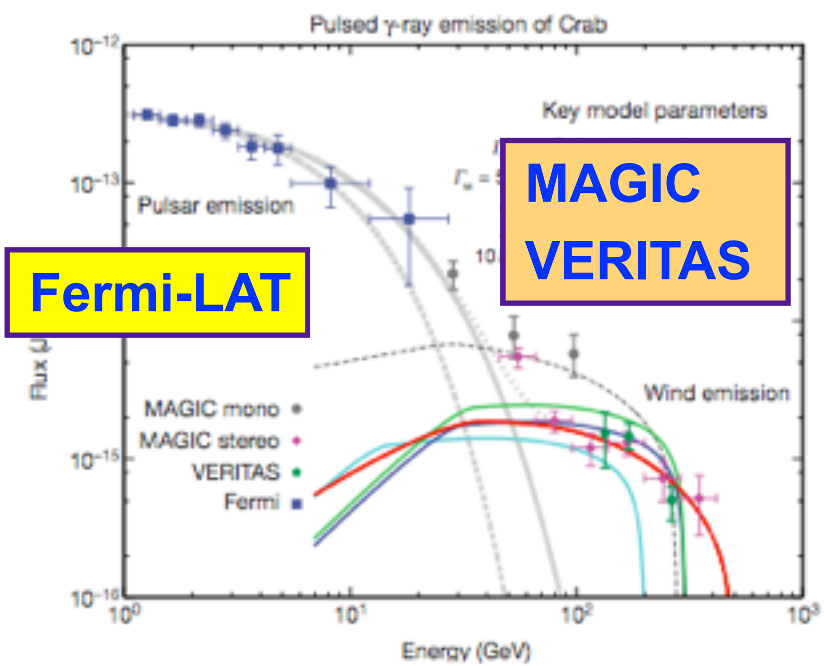




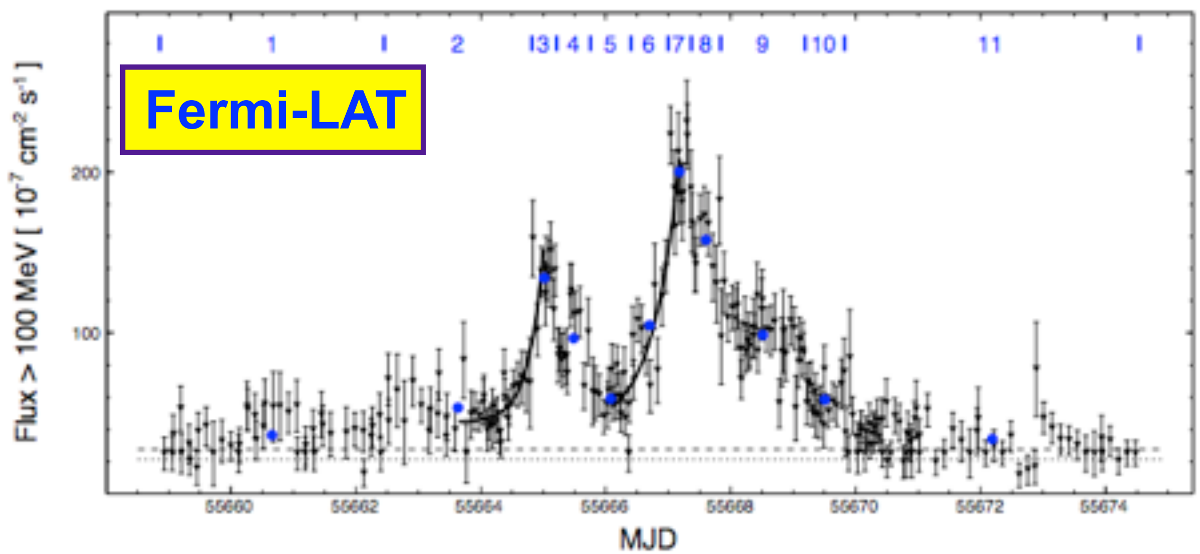
The Crab: Full of Surprises



The Crab pulsar: extra TeV emission

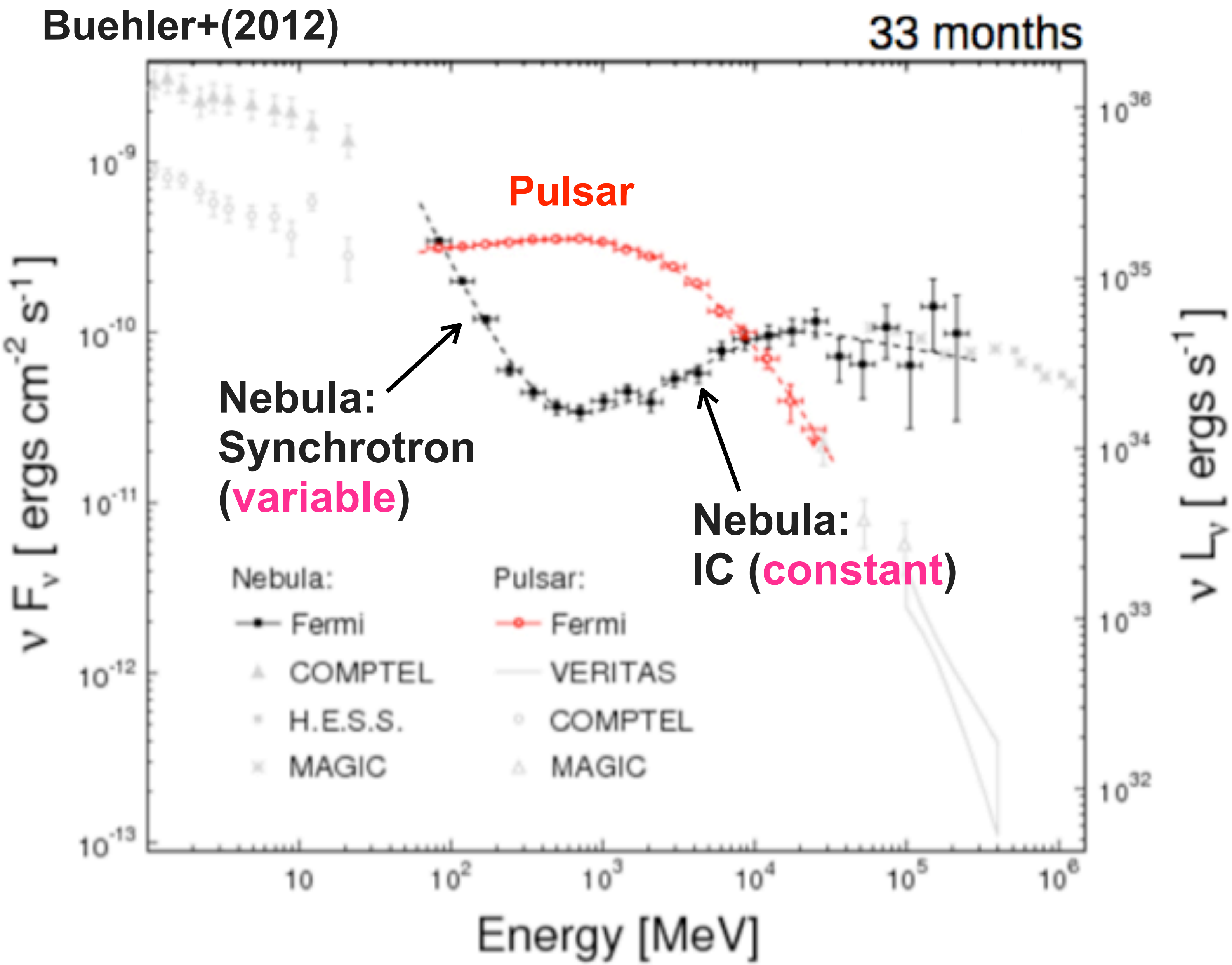


The Crab Nebula: GeV flares

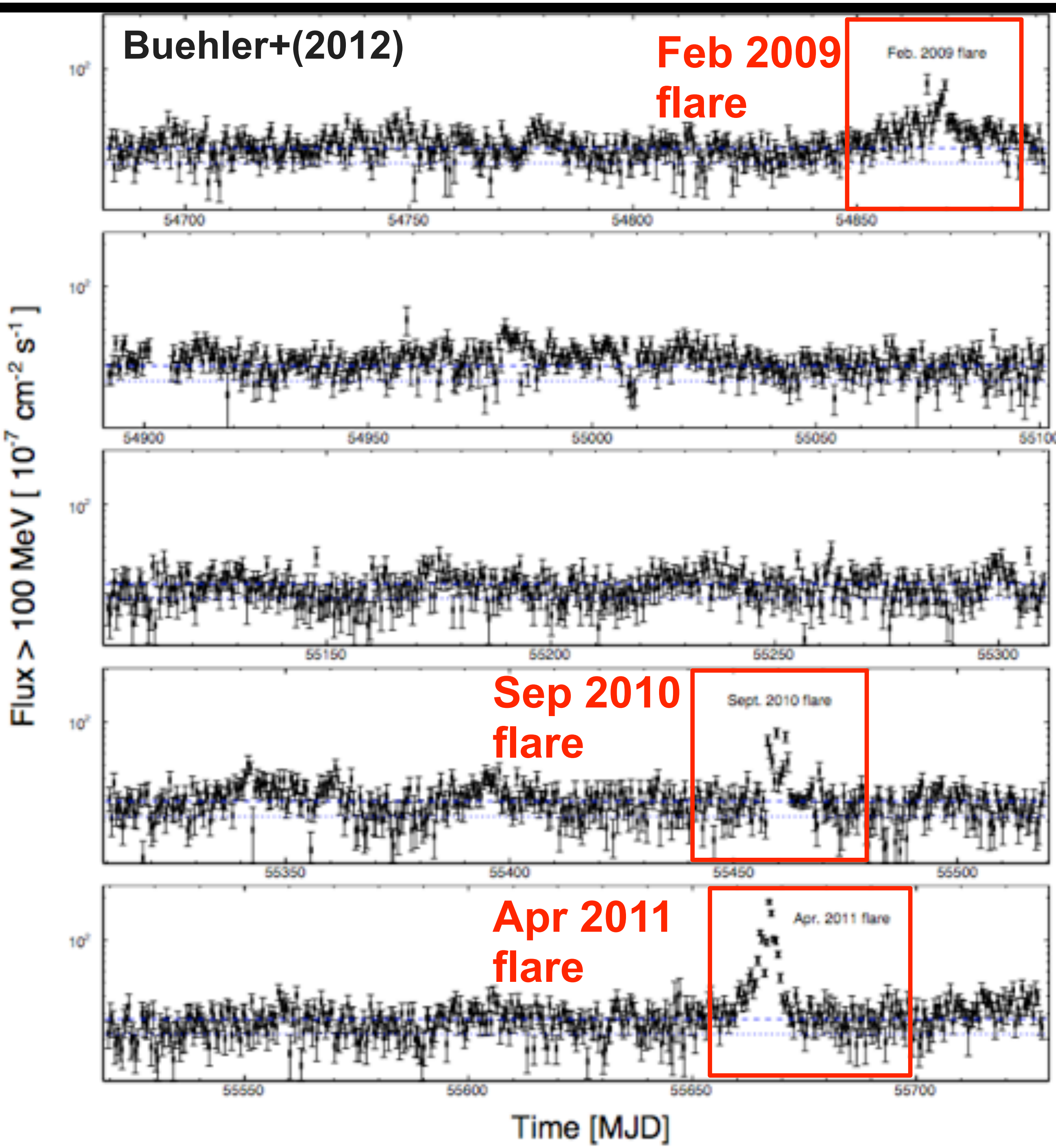


The Crab Seen by Fermi-LAT

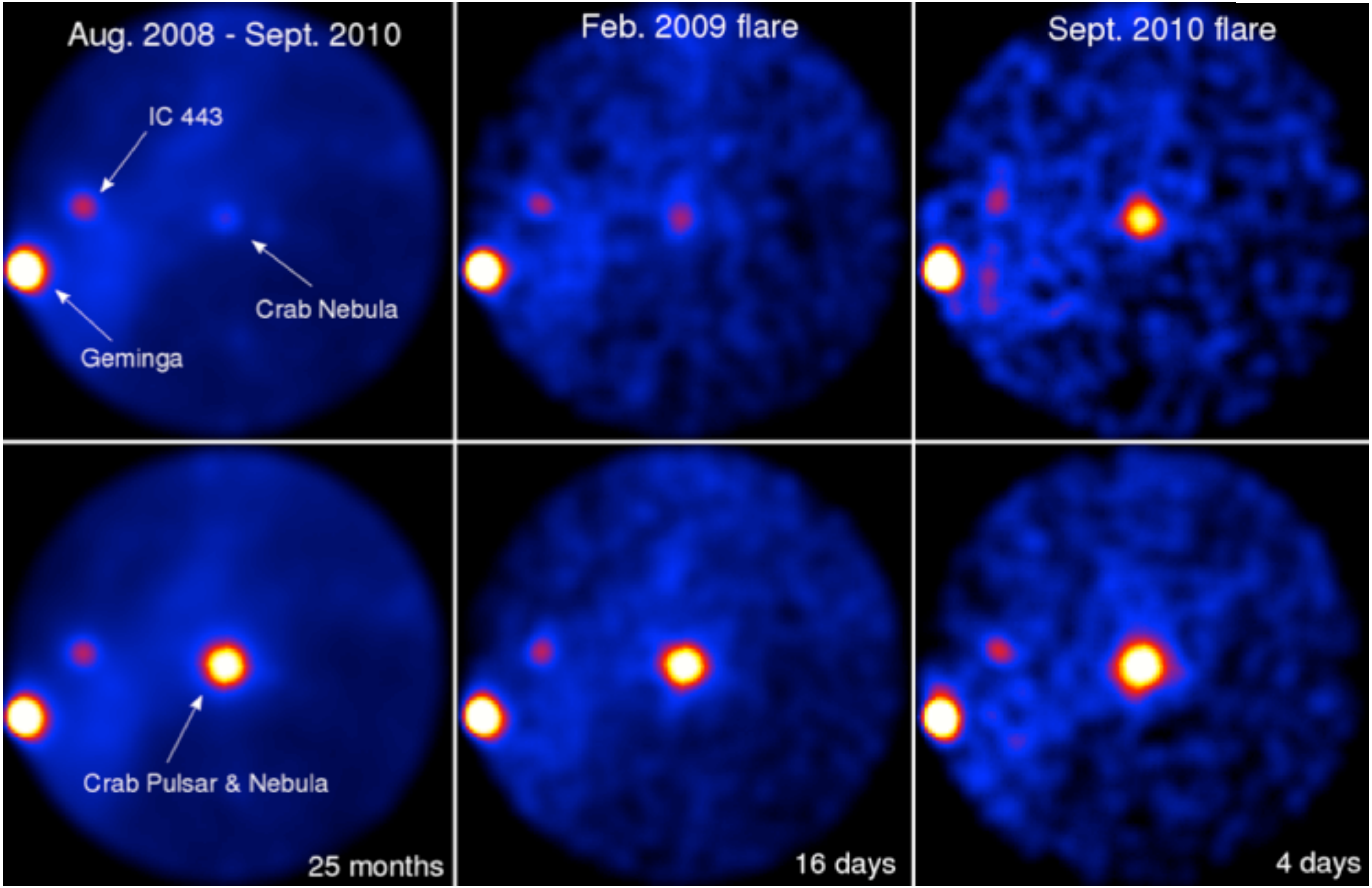
Average gamma-ray spectra



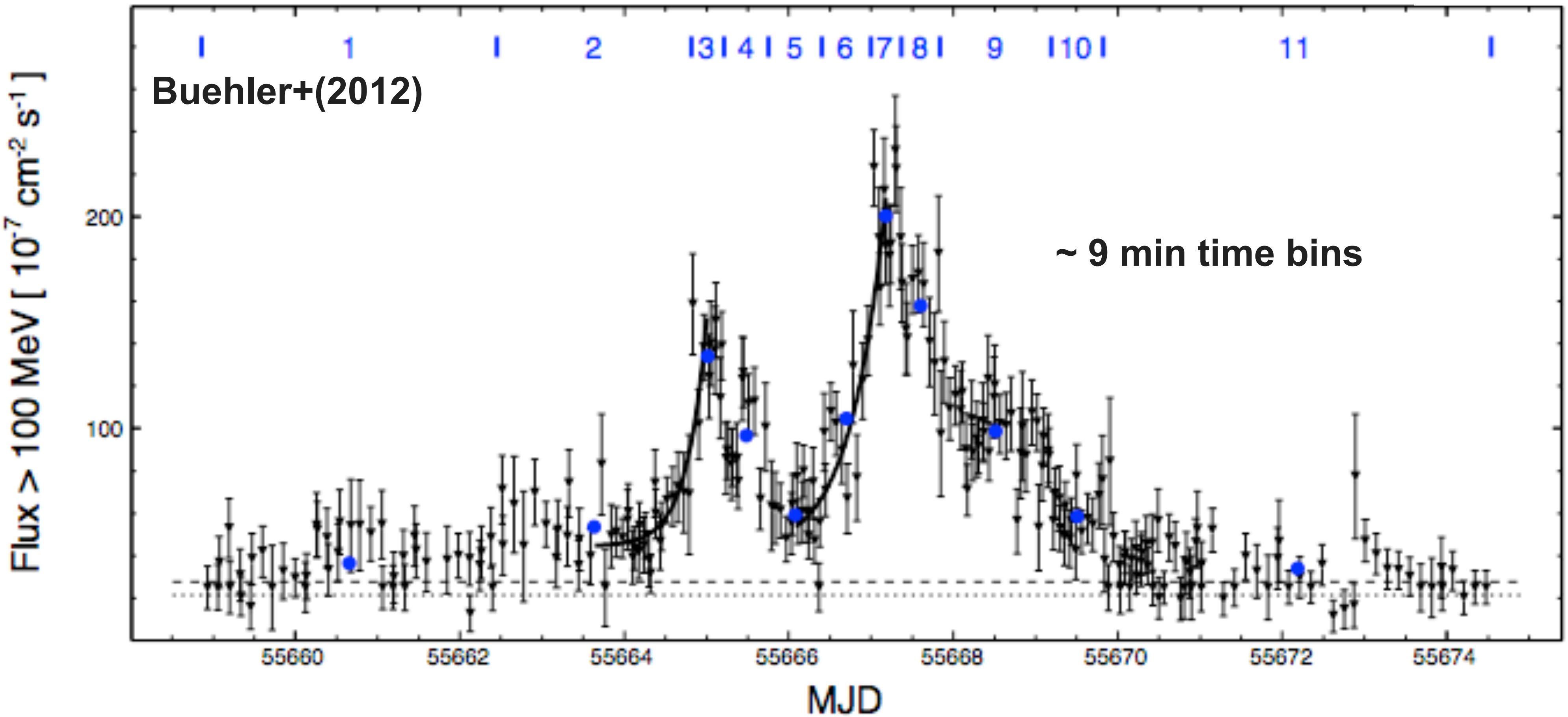
Long Term Lightcurve



The Crab Flares: LAT Images

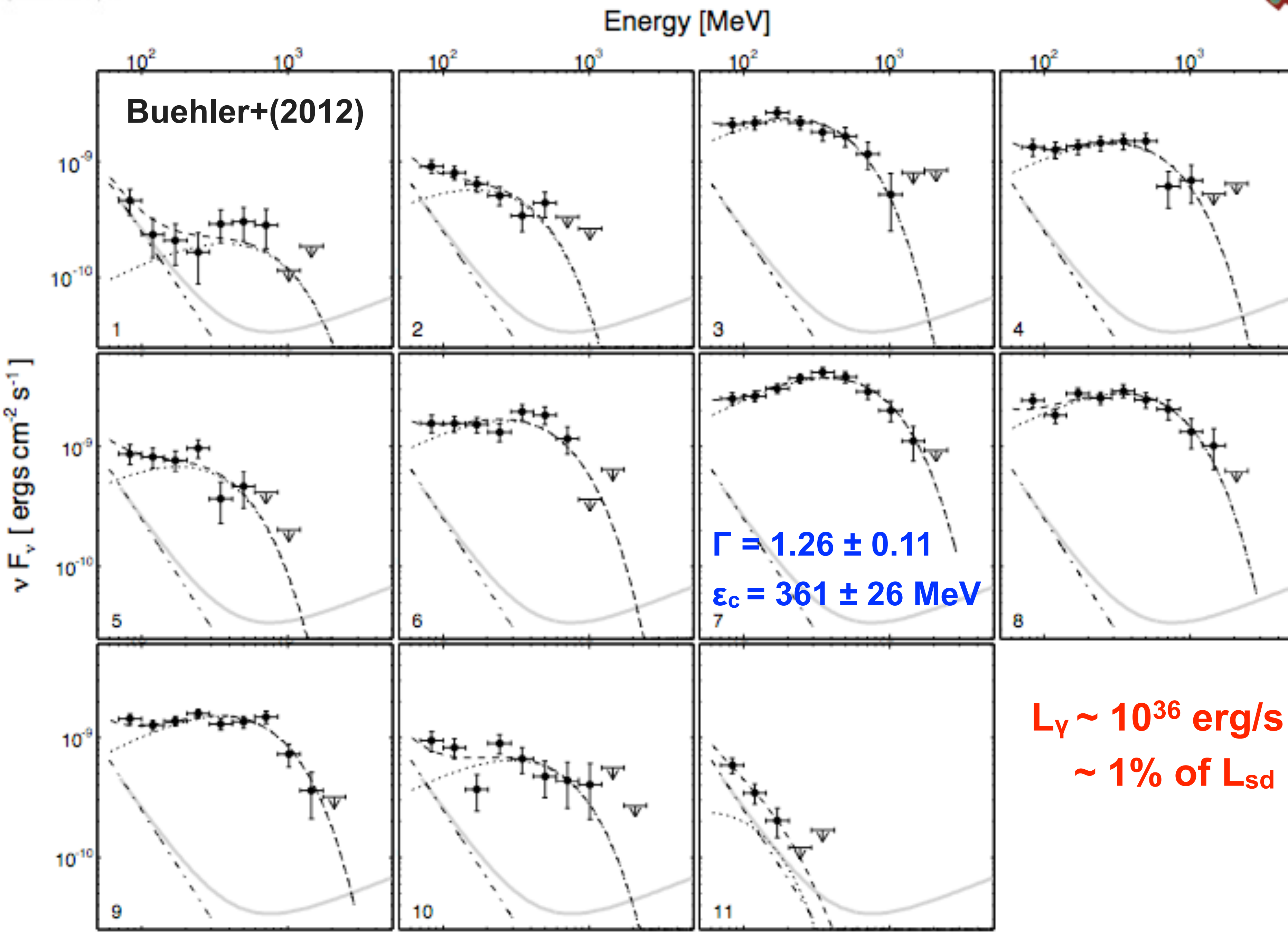


The April 2011 Flare



- Synchrotron nebula brightened by a factor of ~30
- Flux doubling time : 4-8 hours
- No change in pulsar flux and phase

The April 2011 Flare: Spectral Evolution

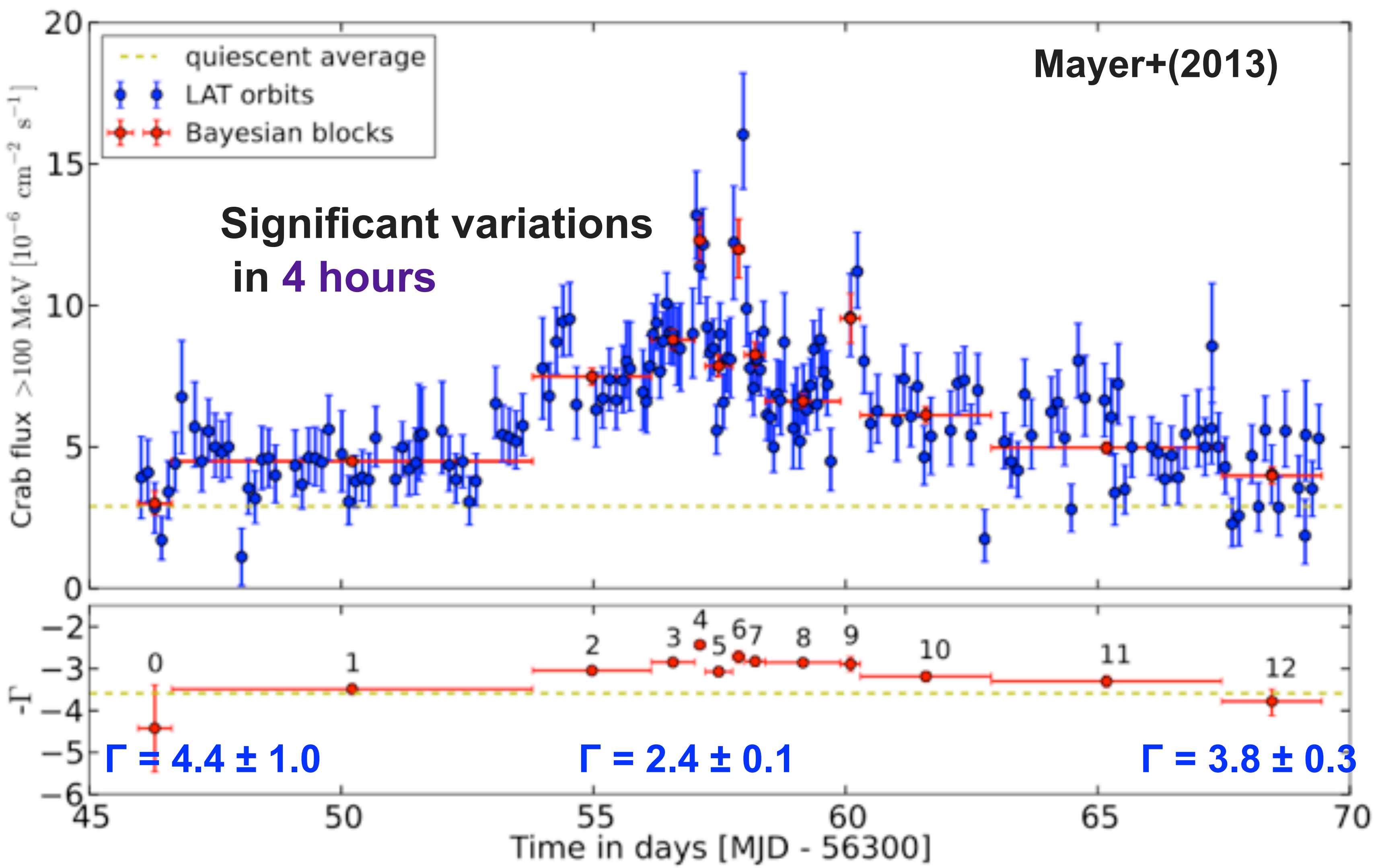


$L_\gamma \sim 10^{36}$ erg/s

$\sim 1\%$ of L_{sd}

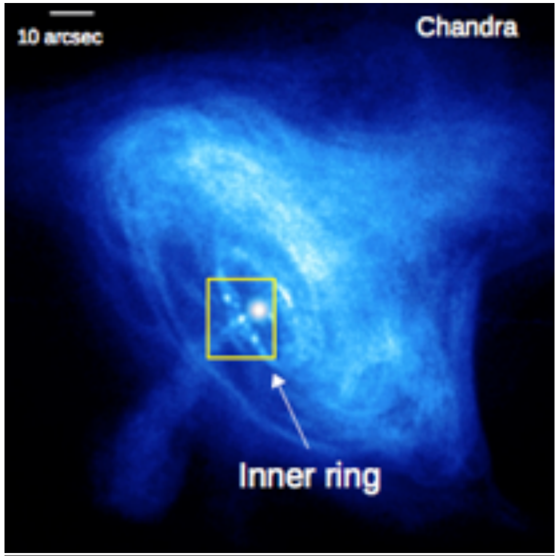
A New Flare in March 2013

The second strongest flare so far.

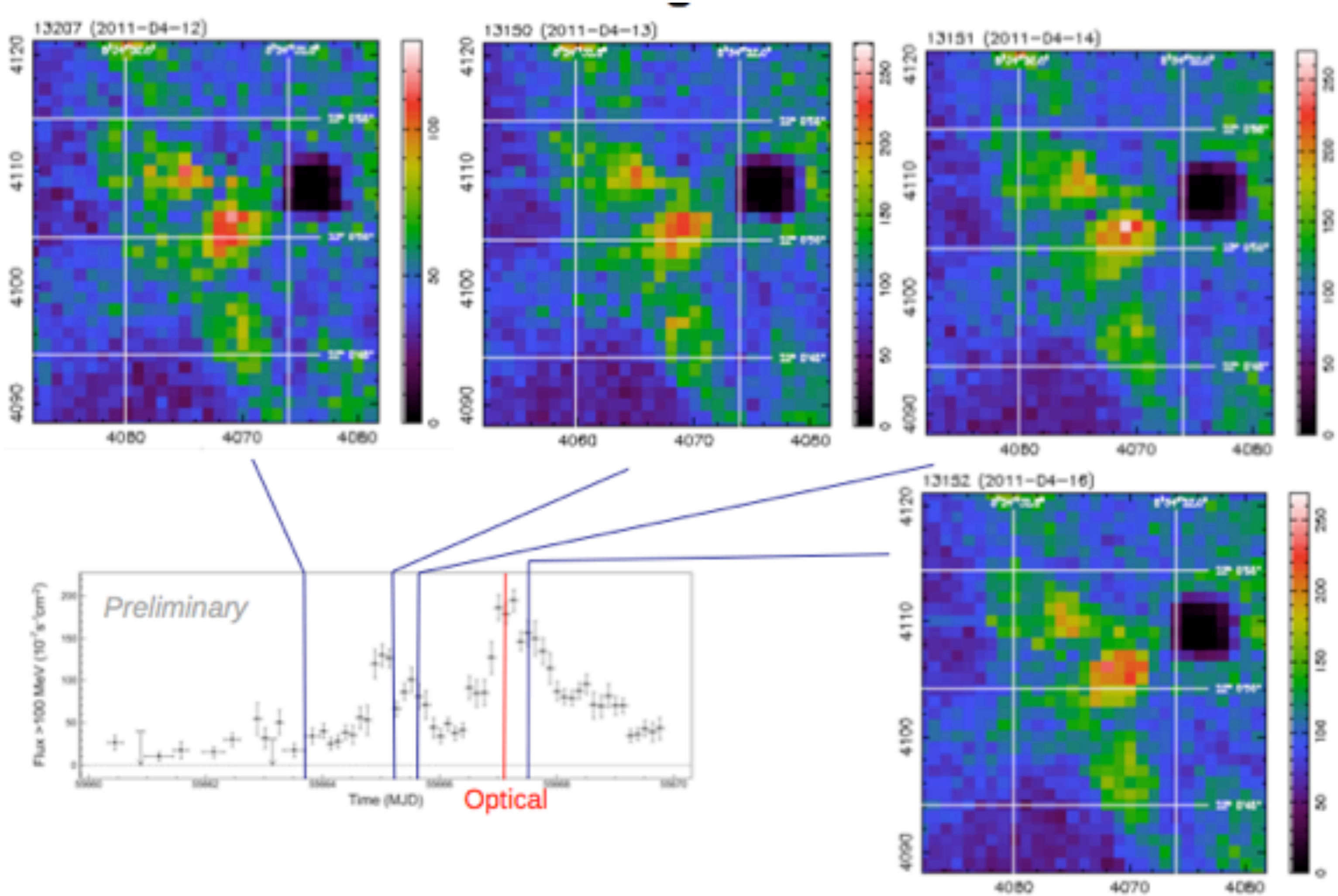


X-ray Images During the Flare

Weisskopf+(2013) inc. Uchiyama



- Chandra observations during the April 2011 flare
- No correlated activities in the inner ring region



Why Puzzling?

- **Compactness**

  Doubling time $t \sim$ 4-8 hours ➜ Emission region < $ct \sim 3\times10^{-4}$ pc

  (Inner ring ~ 0.1 pc)

  Large luminosity (~ 1% of spindown power) from a compact region

- **Spectrum**

  $\Gamma = 1.26 \pm 0.11$: Flare energy is carried by the highest energy electrons

  $\varepsilon_c = 361 \pm 26$ MeV: Appears to violate the radiation reaction limit

  Balance between acceleration (E<B) and synchrotron cooling

  ➜ Cutoff of synchrotron spectrum must be:

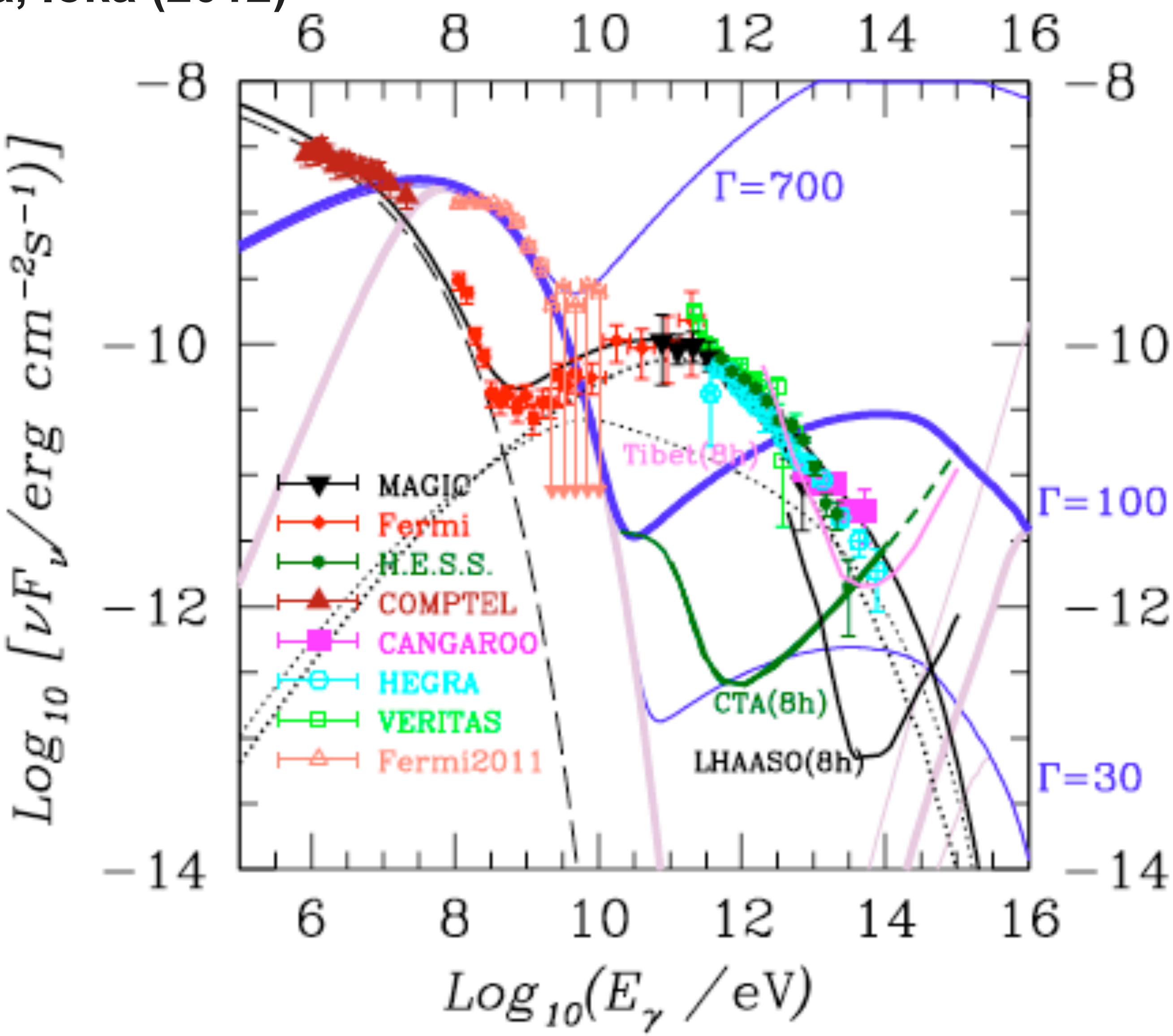
  $$\varepsilon_c < (9/4\alpha_F) m_e c^2 = 160 \text{ MeV}$$

At least, relativistic beaming is necessary ($\delta \sim$ a few or more)
(But HST/Chandra images show only a mildly relativistic flow of ~0.5c)

Prospect for CTA

Counterpart in the TeV bandpass (IC) would be detectable with CTA

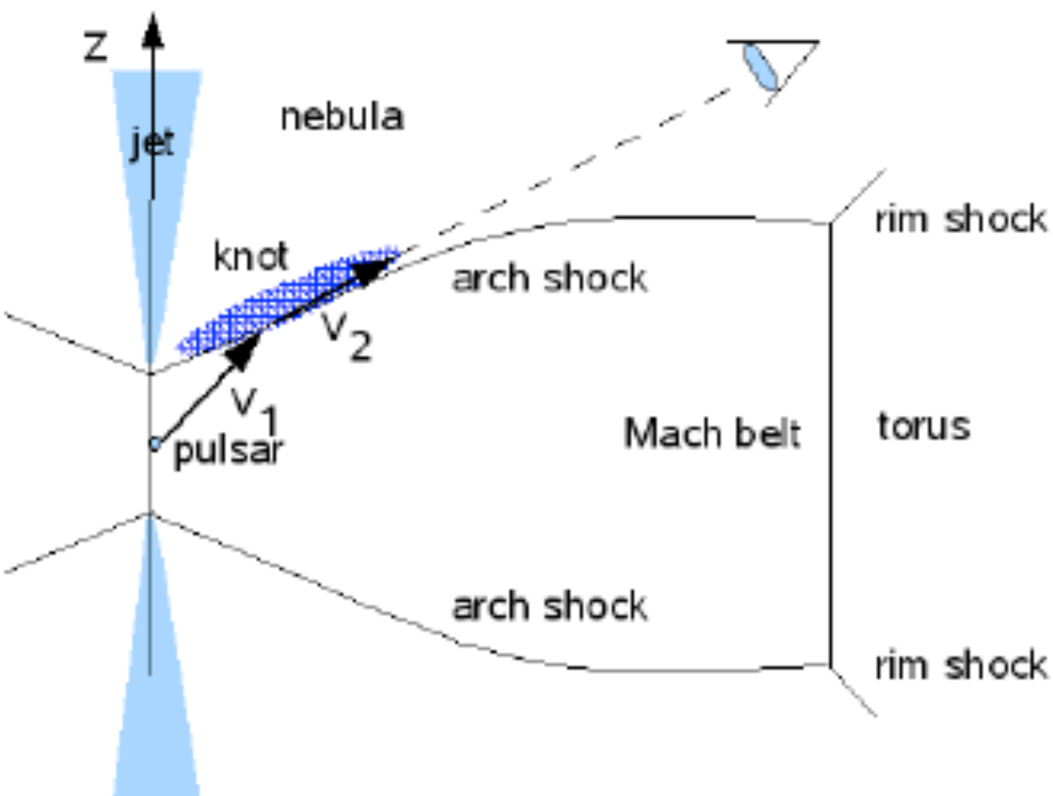
Kohri, Ohira, Ioka (2012)

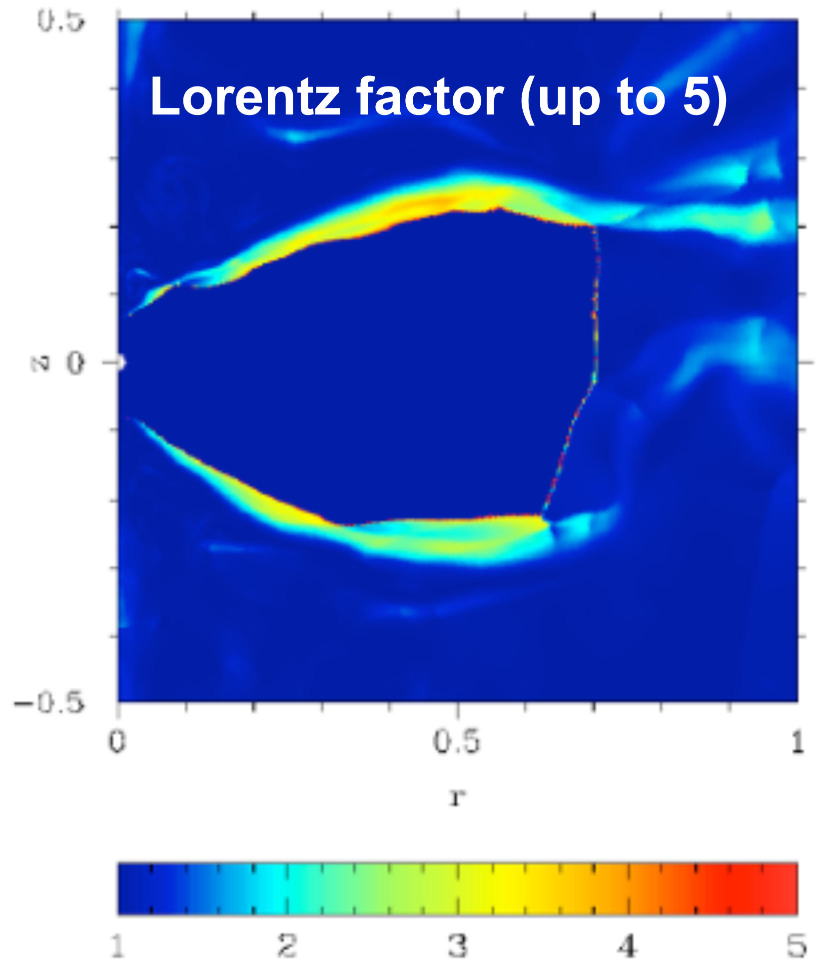


Highly Relativistic Post-shock Flow?

✚ **Komissarov & Lyutikov (2012)**

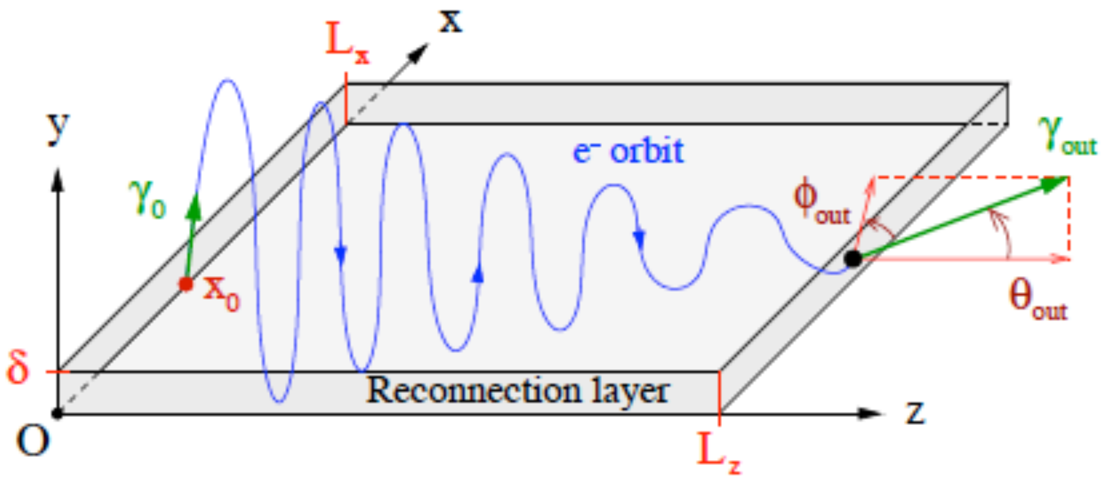
- RMHD simulations suggest highly relativistic flows near termination shock (Komissarov & Lyubarsky 04).
- High resolution simulations suggest variability of termination shock (Camus+09).





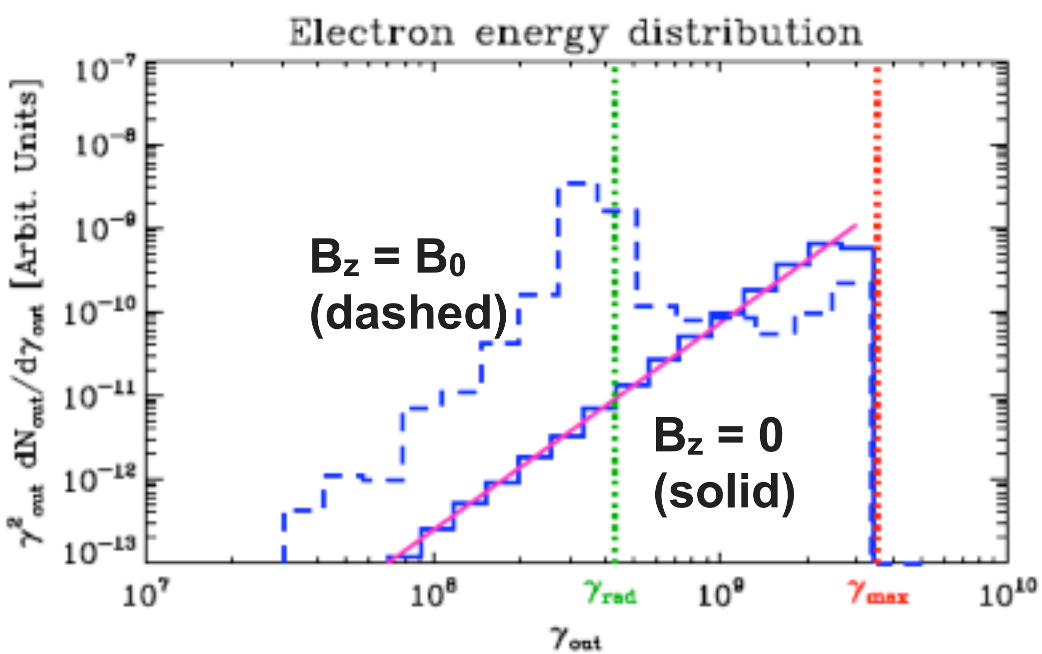
Magnetic Reconnection?

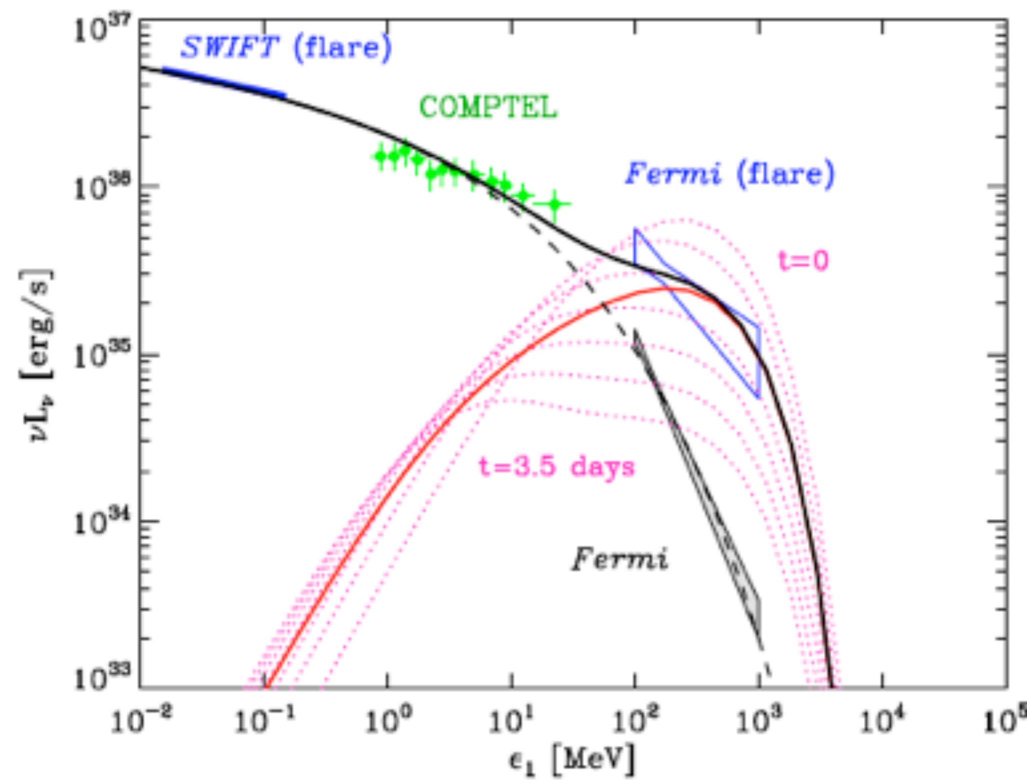
- Cerutti, Uzdensky, & Begelman (2012)



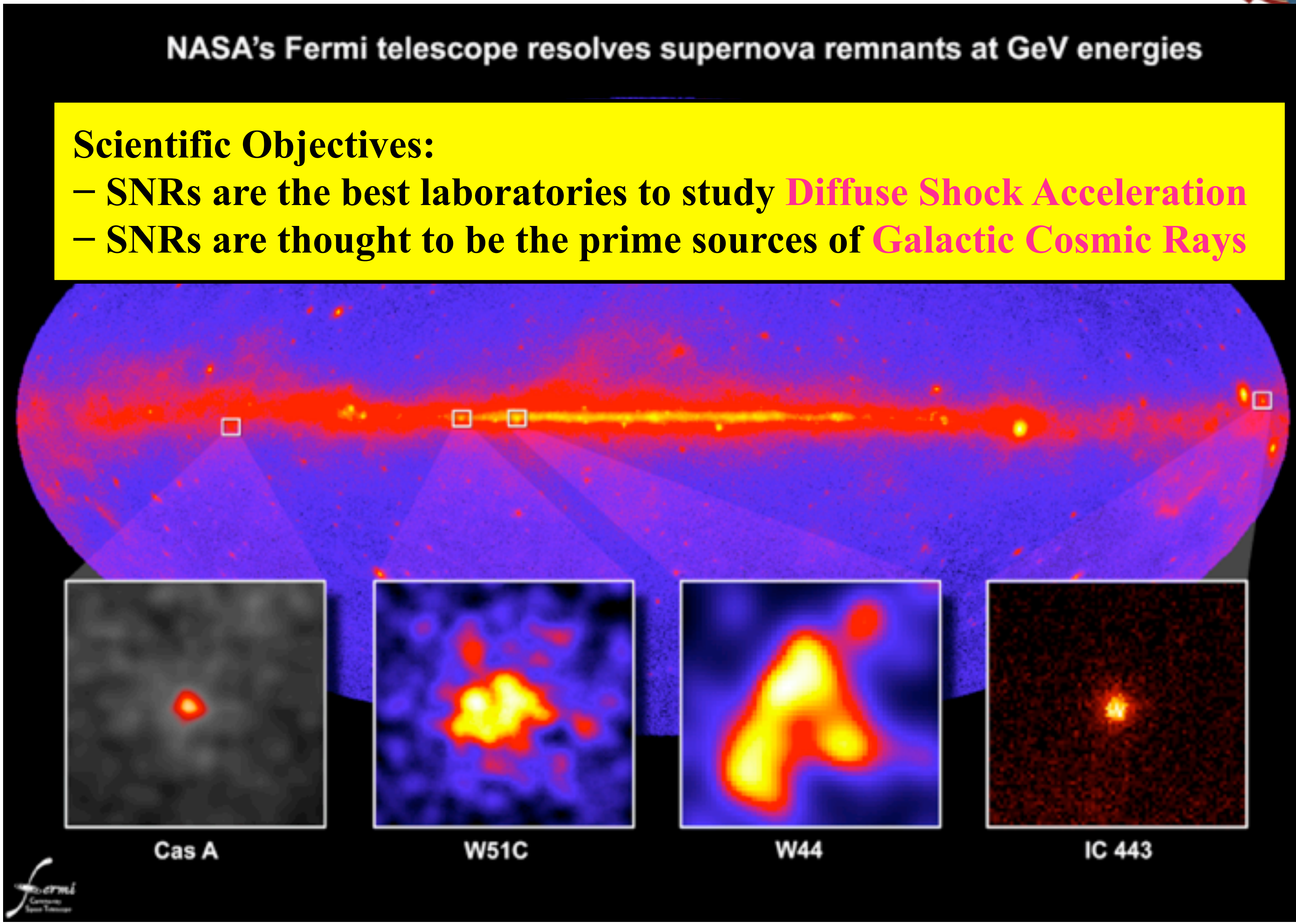
Magnetic reconnection:

- electrons accelerated by reconnection electric field
- focused inside the current layer where B field is small (E>B)
- a beam of PeV electrons

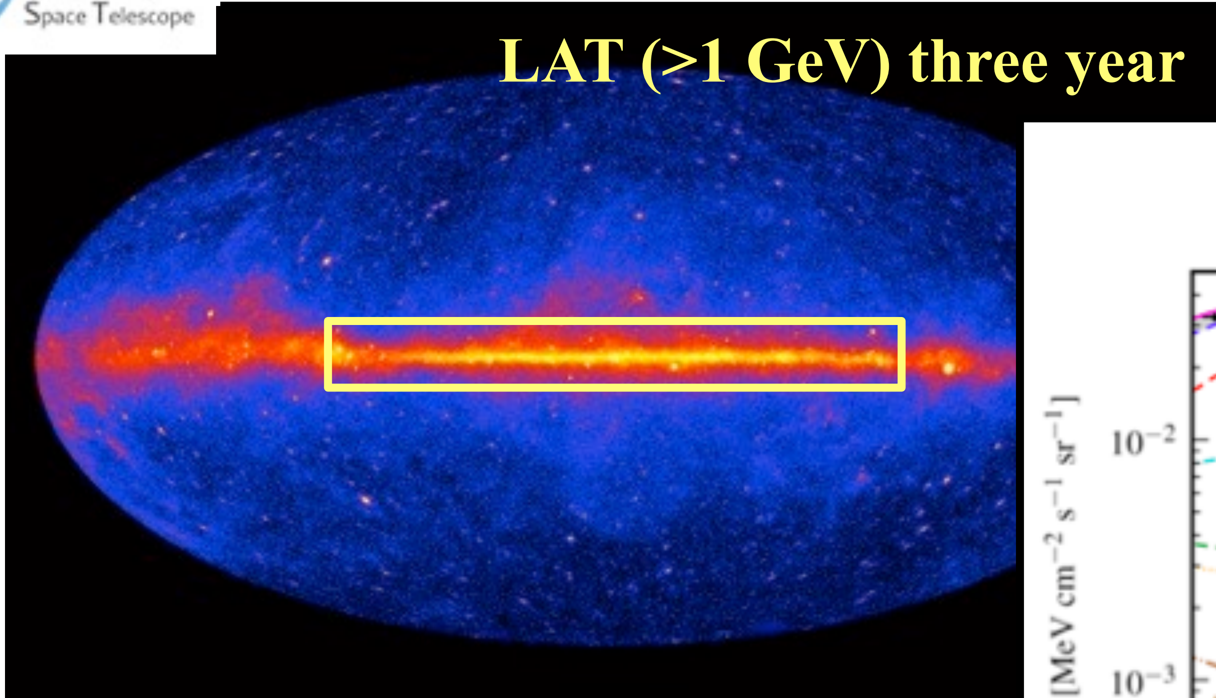


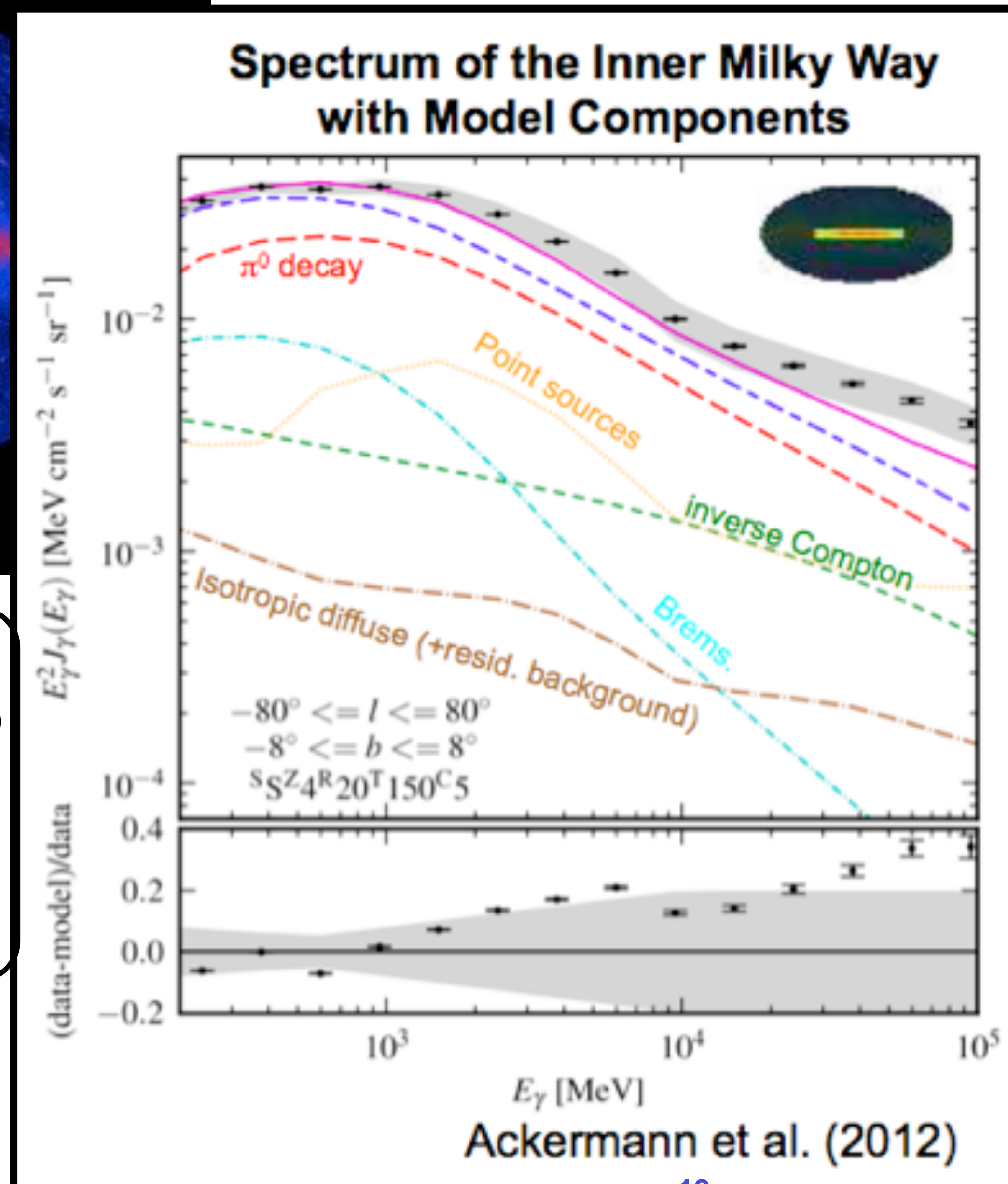


Fermi Observations of SNRs



Galactic Diffuse Background





Hadronic:

π^0-decay γ-rays (CR p + H → π^0 → 2γ)

Leptonic:

bremsstrahlung (CR e + H → γ)

Inverse Compton (CR e + γ → γ)

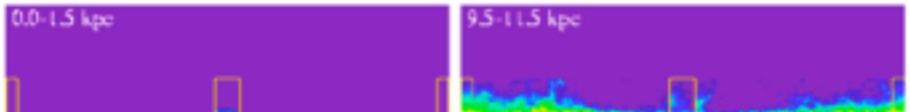
Galactic diffuse emission

– the distribution of interstellar gas; and

– the distribution of Galactic cosmic rays

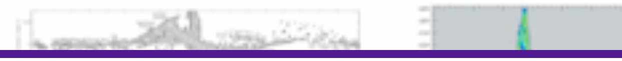
Modeling Diffuse Background

All-sky H I 'Ring' maps*



CO (molecular gas) distribution

- Dame, Hartmann, & Thaddeus (2001) composite survey



The diffuse gamma-ray emission is modeled as a linear combination of templates of gas tracers and other diffuse components

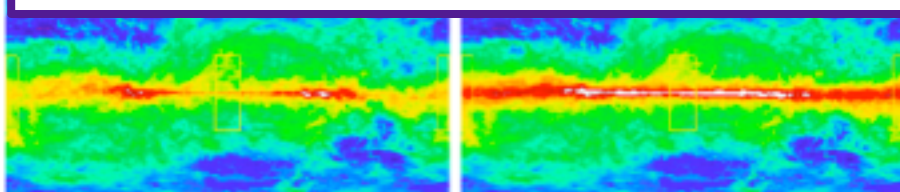
$$N_{pred}(l,b) = \iint d\Omega_k \Big(\sum_{i=rings} [q_{HI,i} N_{HI}(r_i,l_k,b_k) + q_{CO,i} W_{CO}(r_i,l_k,b_k)] + q_{EBV} E(B-V)_{res}(l_k,b_k) + q_{IC} I_{IC}(l_k,b_k) + I_{iso}(l_k,b_k) \Big) \epsilon(l_k,b_k)\, PSF(l,b,l_k,b_k) + \sum_{j=sources} F_j\, \epsilon(l_j,b_j)\, PSF(l_j,b_j,l,b)$$

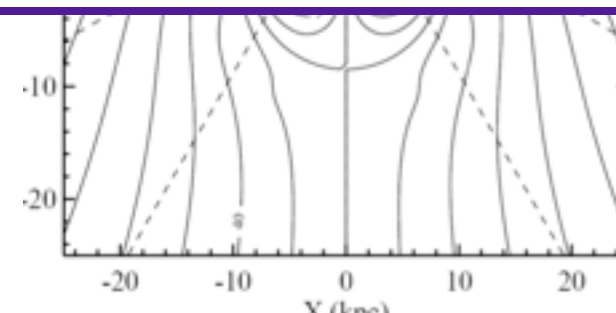
Model for diffuse gamma-ray intensity (q_{HI} is the emissivity, related to cosmic-ray intensities)

Exposure

Effective point-spread function

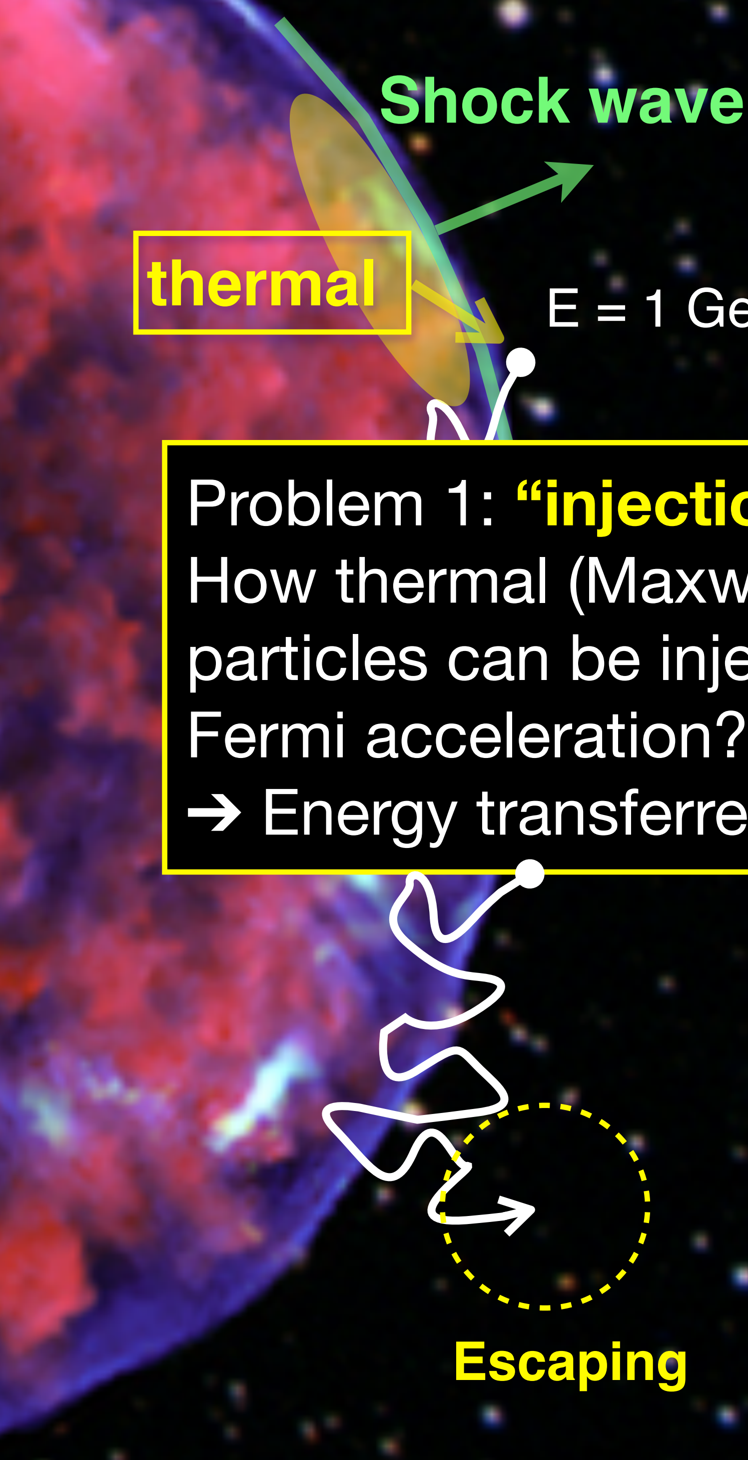
Point sources





*These are not currently-used rings.

Diffusive Shock Acceleration



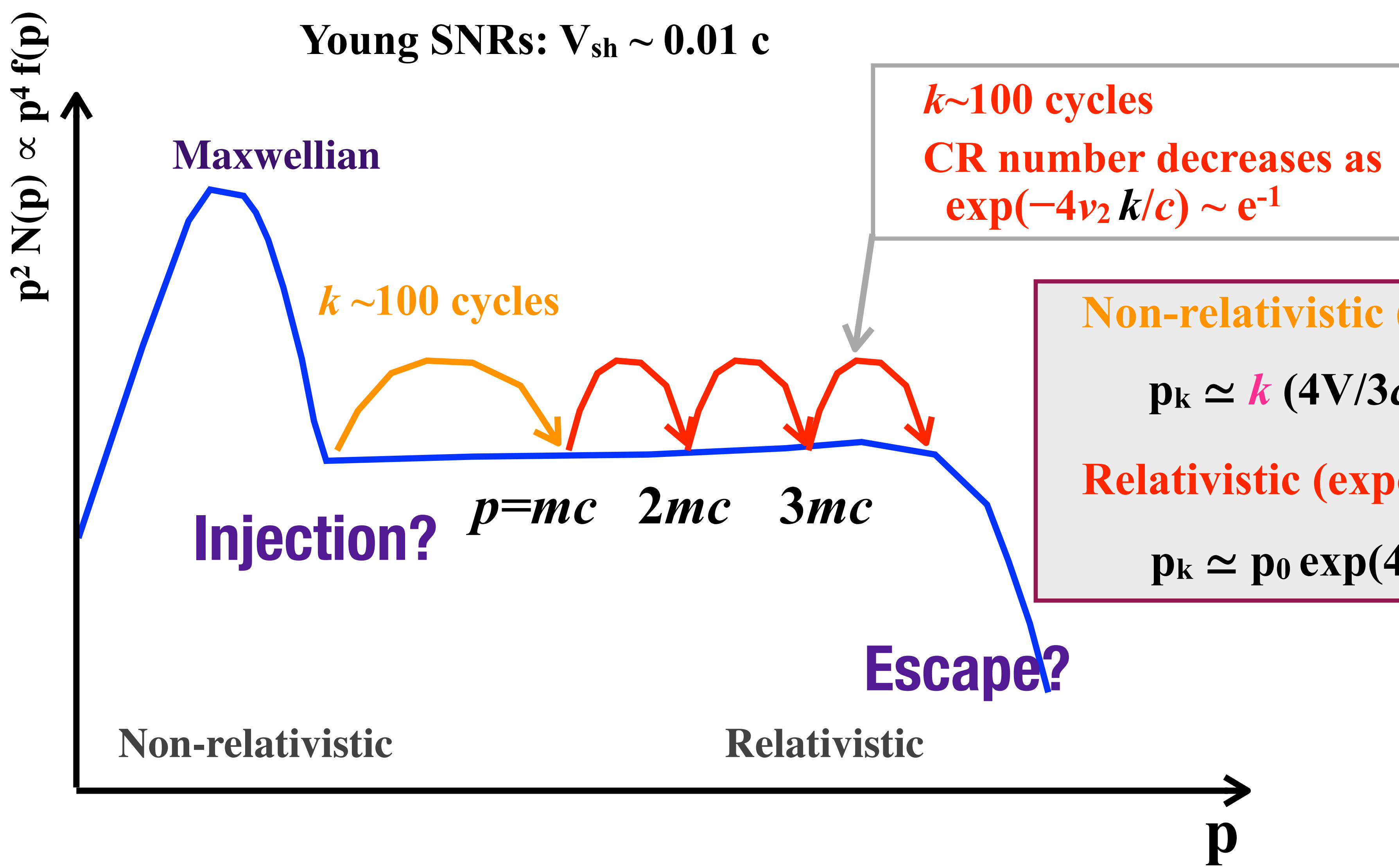
Problem 1: **"injection"**
How thermal (Maxwellian) particles can be injected into Fermi acceleration?
➔ Energy transferred to CRs

Problem 2: **"escape"**
How highest energy particles escape from a shock?
➔ Maximum attainable energy

Shock crossing ➔ energy gain
Energy gain per one round trip:
$\Delta E/E \sim V/c \sim 1\%$ for young SNRs. After 1000 round trips:
e.g. 1 GeV ➔ 20 TeV
Energy distribution (test particle approximation):
$N(E)dE \propto E^{-2}\,dE$

NB:
- ✔ **Non-linear effects**
- ✔ **Magnetic field amplification**

Diffusive Shock Acceleration



Non-relativistic (linear)

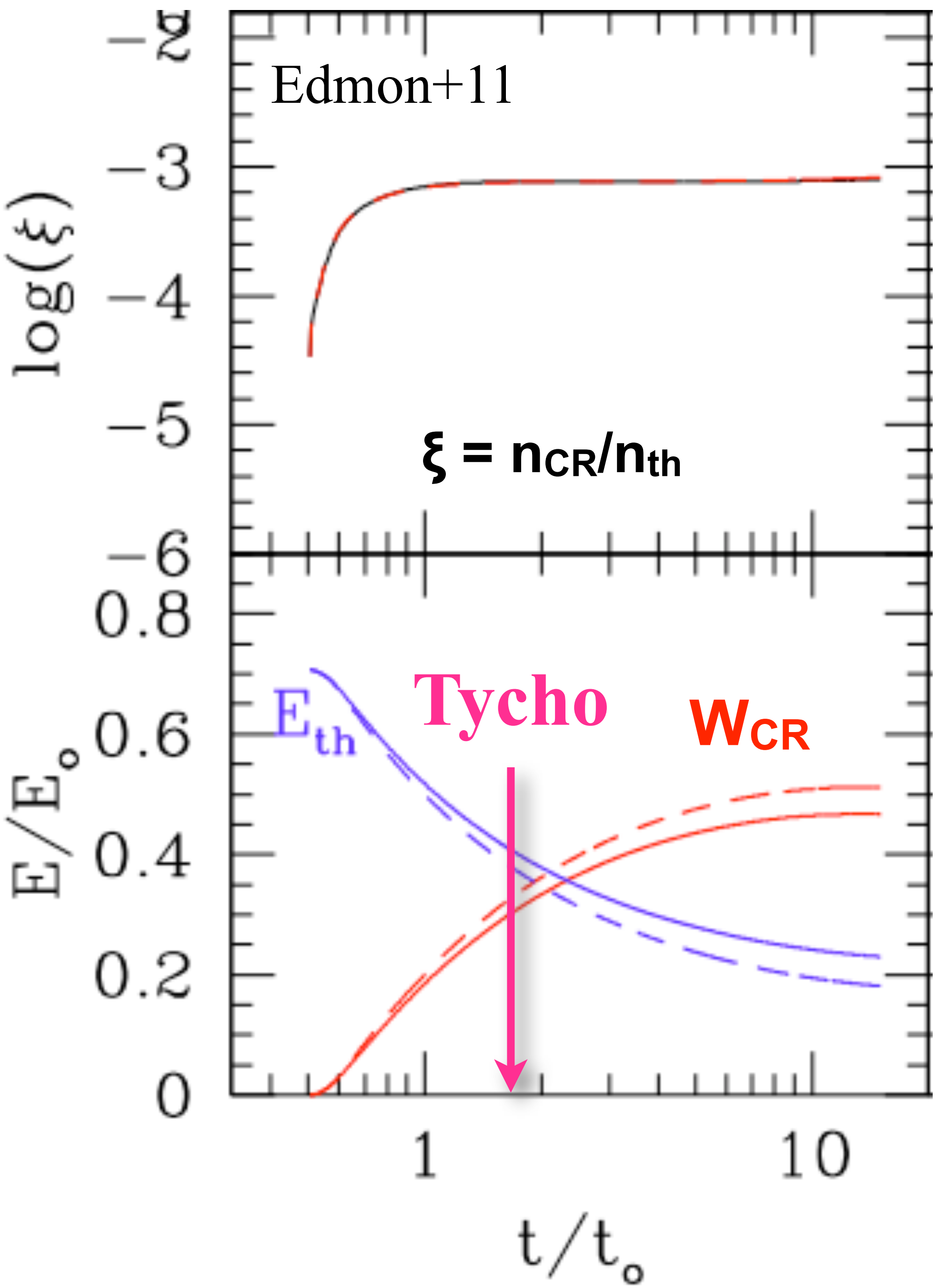
$$p_k \simeq k\,(4V/3c)\,mc$$

Relativistic (exponential)

$$p_k \simeq p_0 \exp(4kV/3c)$$

$N(p) \propto p^{-s}$ with s = 2 for strong shock

(1) "Injection" → Energy transferred to CRs



$$\xi = n_{CR}/n_{th} = \frac{\text{CR particles}}{\text{thermal particles}}$$

ξ is assumed to be constant

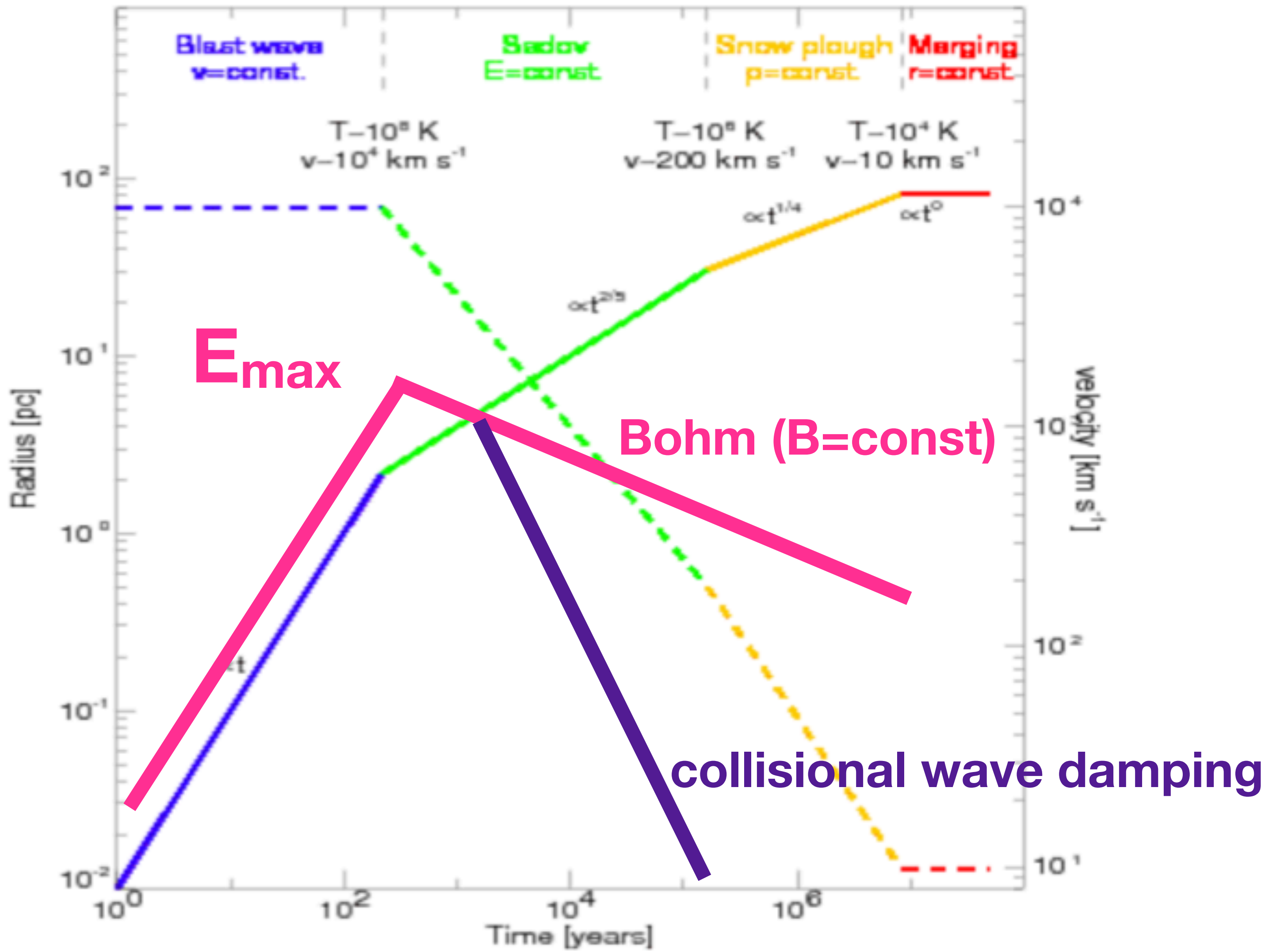
From the gamma-ray data, the amount of CRs in Tycho's SNR at its age of t = 439 yr is:
$W_{CR} \sim 7\%$ of E_{SN}

↓

W_{CR} will reach 14% of E_{SN}

Supporting SNR origin of Galactic CRs

(2) "Escape" → Maximum Energy



Cutoff from ion-neutral wave damping (e.g. Drury+ 1996)

$$E_{\max} \approx u_{0,7}^{3} T_4^{-0.4} n_n^{-1} n_i^{0.5} \xi_{\mathrm{CR},-1}\ \mathrm{GeV}$$

Origin: loss of CR trapping power → enhanced escape in partially ionized medium

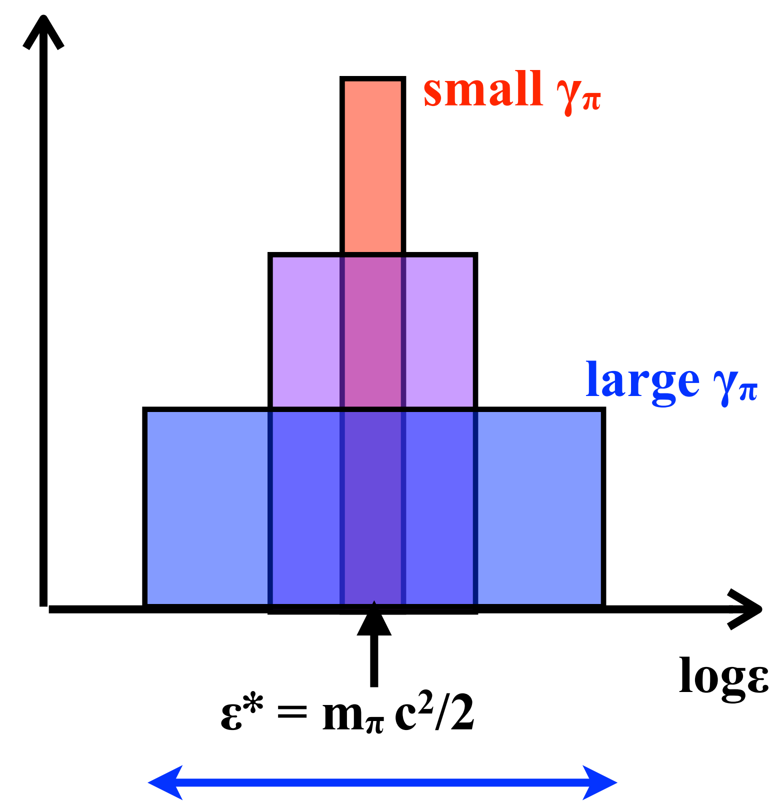
π^0-decay γ-rays: Direct Probe of Accelerated Protons

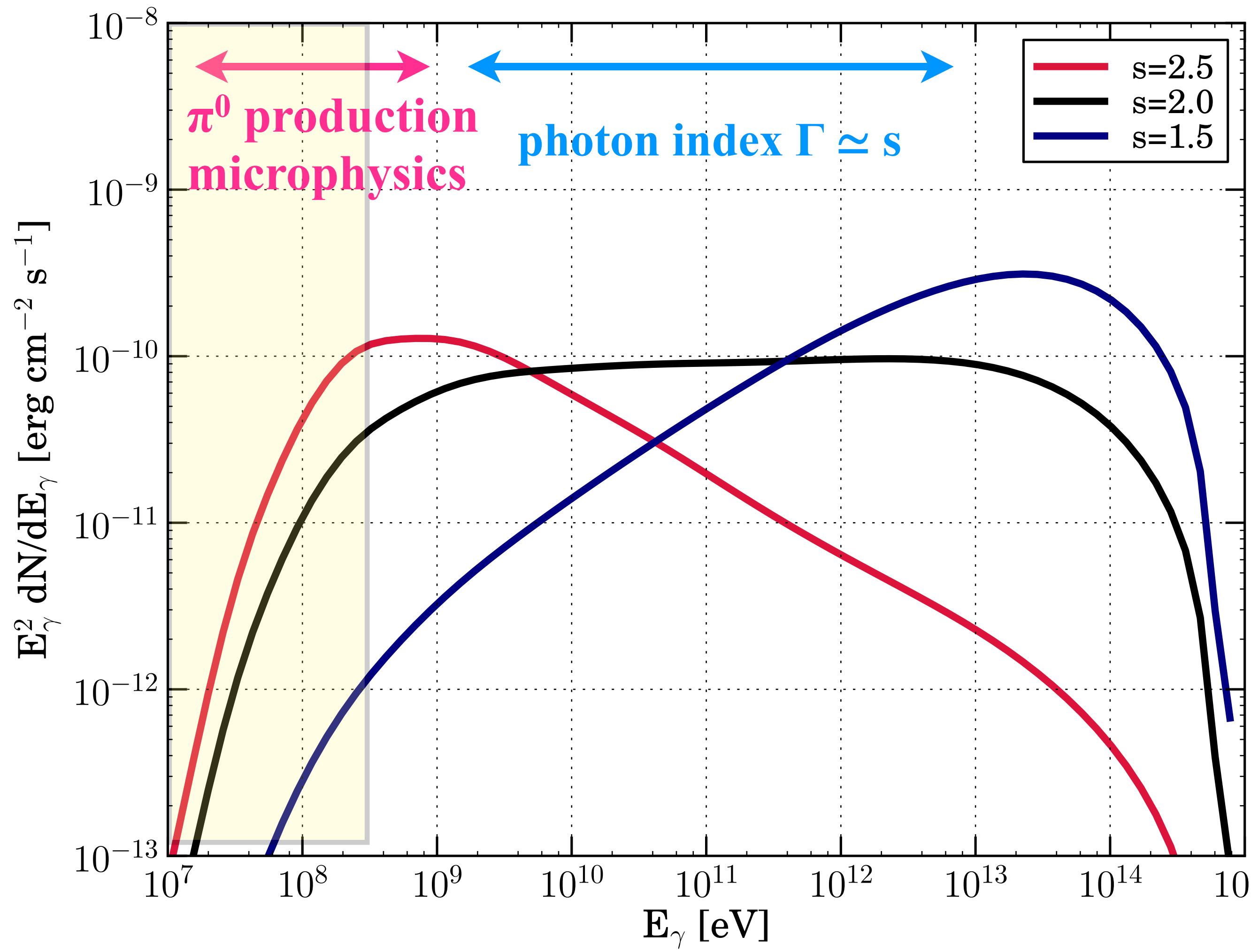
$dN_\gamma/d\varepsilon$:
symmetric about 68 MeV

→

$\varepsilon^2\, dN_\gamma/d\varepsilon$:
hard spectrum below 300 MeV

γ-ray spectrum: dN/dε





Very hard spectrum below 300 MeV for any reasonable proton index

Detection of the Characteristic Pion-Decay Signature in Supernova Remnants

CA: Funk, Tanaka, Uchiyama

M. Ackermann,[1] M. Ajello,[2] A. Allafort,[3] L. Baldini,[4] J. Ballet,[5] G. Barbiellini,[6,7] M. G. Baring,[8] D. Bastieri,[9,10] K. Bechtol,[3] R. Bellazzini,[11] R. D. Blandford,[3] E. D. Bloom,[3] E. Bonamente,[12,13] A. W. Borgland,[3] E. Bottacini,[3] T. J. Brandt,[14] J. Bregeon,[11] M. Brigida,[15,16] P. Bruel,[17] R. Buehler,[3] G. Busetto,[9,10] S. Buson,[9,10] G. A. Caliandro,[18] R. A. Cameron,[3] P. A. Caraveo,[19] J. M. Casandjian,[5] C. Cecchi,[12,13] Ö. Çelik,[14,20,21] E. Charles,[3] S. Chaty,[5] R. C. G. Chaves,[5] A. Chekhtman,[22] C. C. Cheung,[23] J. Chiang,[3] G. Chiaro,[24] A. N. Cillis,[14,25] S. Ciprini,[13,26] R. Claus,[3] J. Cohen-Tanugi,[27] L. R. Cominsky,[28] J. Conrad,[29,30,31] S. Corbel,[5,32] S. Cutini,[33] F. D'Ammando,[12,34,35] A. de Angelis,[36] F. de Palma,[15,16] C. D. Dermer,[37] E. do Couto e Silva,[3] P. S. Drell,[3] A. Drlica-Wagner,[3] L. Falletti,[27] C. Favuzzi,[15,16] E. C. Ferrara,[14] A. Franckowiak,[3] Y. Fukazawa,[38] S. Funk,[3]* P. Fusco,[15,16] F. Gargano,[16] S. Germani,[12,13] N. Giglietto,[15,16] P. Giommi,[33] F. Giordano,[15,16] M. Giroletti,[39] T. Glanzman,[3] G. Godfrey,[3] I. A. Grenier,[5] M.-H. Grondin,[40,41] J. E. Grove,[37] S. Guiriec,[14] D. Hadasch,[18] Y. Hanabata,[38] A. K. Harding,[14] M. Hayashida,[3,42] K. Hayashi,[38] E. Hays,[14] J. W. Hewitt,[14] A. B. Hill,[3,43] R. E. Hughes,[44] M. S. Jackson,[30,45] T. Jogler,[3] G. Jóhannesson,[46] A. S. Johnson,[3] T. Kamae,[3] J. Kataoka,[47] J. Katsuta,[3] J. Knödlseder,[48,49] M. Kuss,[11] J. Lande,[3] S. Larsson,[29,30,50] L. Latronico,[51] M. Lemoine-Goumard,[52,53] F. Longo,[6,7] F. Loparco,[15,16] M. N. Lovellette,[37] P. Lubrano,[12,13] G. M. Madejski,[3] F. Massaro,[3] M. Mayer,[1] M. N. Mazziotta,[16] J. E. McEnery,[14,54] J. Mehault,[27] P. F. Michelson,[3] R. P. Mignani,[55] W. Mitthumsiri,[3] T. Mizuno,[56] A. A. Moiseev,[20,54] M. E. Monzani,[3] A. Morselli,[57] I. V. Moskalenko,[3] S. Murgia,[3] T. Nakamori,[47] R. Nemmen,[14] E. Nuss,[27] M. Ohno,[58] T. Ohsugi,[56] N. Omodei,[3] M. Orienti,[39] E. Orlando,[3] J. F. Ormes,[59] D. Paneque,[3,60] J. S. Perkins,[14,21,20,61] M. Pesce-Rollins,[11] F. Piron,[27] G. Pivato,[10] S. Rainò,[15,16] R. Rando,[9,10] M. Razzano,[11,62] S. Razzaque,[22] A. Reimer,[3,63] O. Reimer,[3,63] S. Ritz,[62] C. Romoli,[10] M. Sánchez-Conde,[3] A. Schulz,[1] C. Sgrò,[11] P. E. Simeon,[3] E. J. Siskind,[64] D. A. Smith,[52] G. Spandre,[11] P. Spinelli,[15,16] F. W. Stecker,[14,65] A. W. Strong,[66] D. J. Suson,[67] H. Tajima,[3,68] H. Takahashi,[38] T. Takahashi,[58] T. Tanaka,[3,69]* J. G. Thayer,[3] J. B. Thayer,[3] D. J. Thompson,[14] S. E. Thorsett,[70] L. Tibaldo,[9,10] O. Tibolla,[71] M. Tinivella,[11] E. Troja,[14,72] Y. Uchiyama,[3]* T. L. Usher,[3] J. Vandenbroucke,[3] V. Vasileiou,[27] G. Vianello,[3,73] V. Vitale,[57,74] A. P. Waite,[3] M. Werner,[63] B. L. Winer,[44] K. S. Wood,[37] M. Wood,[3] R. Yamazaki,[75] Z. Yang,[29,30] S. Zimmer[29,30]

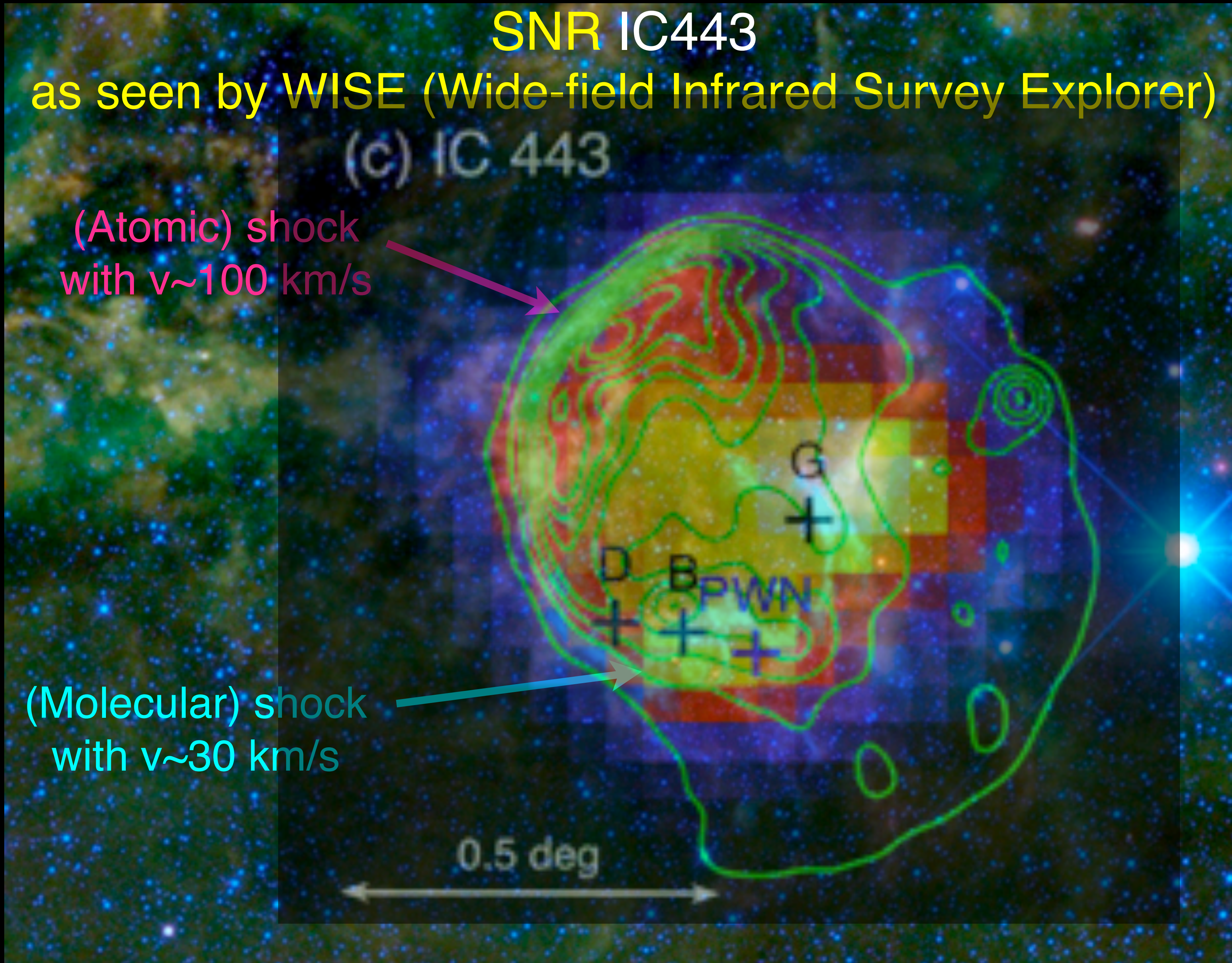
Cosmic rays are particles (mostly protons) accelerated to relativistic speeds. Despite wide agreement that supernova remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking. When accelerated protons encounter interstellar material, they produce neutral pions, which in turn decay into gamma rays. This offers a compelling way to detect the acceleration sites of protons. The identification of pion-decay gamma rays has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering. We detected the characteristic pion-decay feature in the gamma-ray spectra of two SNRs, IC 443 and W44, with the Fermi Large Area Telescope. This detection provides direct evidence that cosmic-ray

ejecta and is then transferred to kinetic and thermal energies of shocked interstellar gas and relativistic particles. The shocked gas and relativistic ... hermal ...). The ... (DSA) can explain the production of relativistic particles in SNRs (*1*). DSA generally predicts that a substantial fraction of the shock energy is transferred to relativistic protons. Indeed, if SNRs are the main sites of acceleration of the galactic cosmic rays, then 3 to 30% of the supernova kinetic energy must end up transferred to relativistic protons. However, the presence of relativistic protons in SNRs has been mostly inferred from indirect arguments (*2*–*5*).

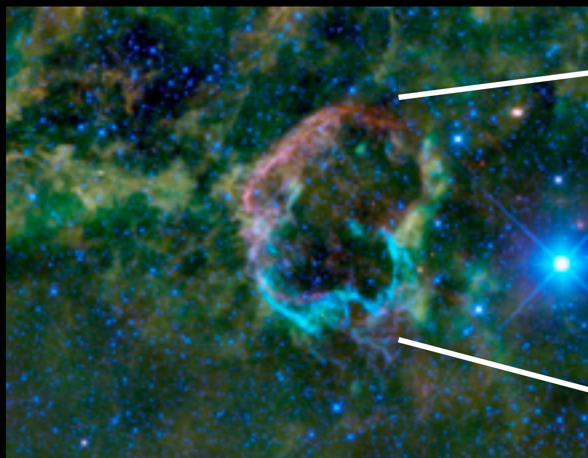
A direct signature of high-energy protons is provided by gamma rays generated in the decay of neutral pions (π^0); proton-proton (more generally nuclear-nuclear) collisions create π^0 mesons, which usually quickly decay into two gamma rays (*6*–*8*) (schematically written as $p + p \rightarrow \pi^0$ + other products, followed by $\pi^0 \rightarrow 2\gamma$), each having an energy of $m_{\pi^0}c^2/2 = 67.5$ MeV in the rest frame of the neutral pion (where m_{π^0} is the rest mass of the neutral pion and c is the speed of light). The gamma-ray number spectrum, $F(\varepsilon)$, is thus symmetric about 67.5 MeV in a log-log representation (*9*). The π^0-decay spectrum in the usual $\varepsilon^2 F(\varepsilon)$ representation rises steeply below ~200 MeV and approximately traces the energy distribution of parent protons at energies greater than a few GeV. This characteristic spectral feature (often referred to as the "pion-decay bump") uniquely identifies π^0-decay gamma rays and thereby high-energy protons, allowing a measurement of the source spectrum of cosmic rays.

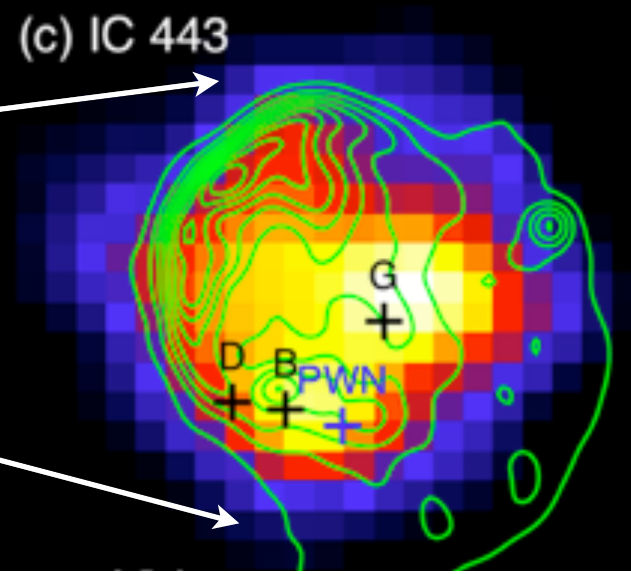
Massive stars are short-lived and end their lives with core-collapse supernova explosions. These explosions typically occur in the vicinity of molecular clouds with which they in-

Fermi Telescope Revealed Cosmic-ray Protons



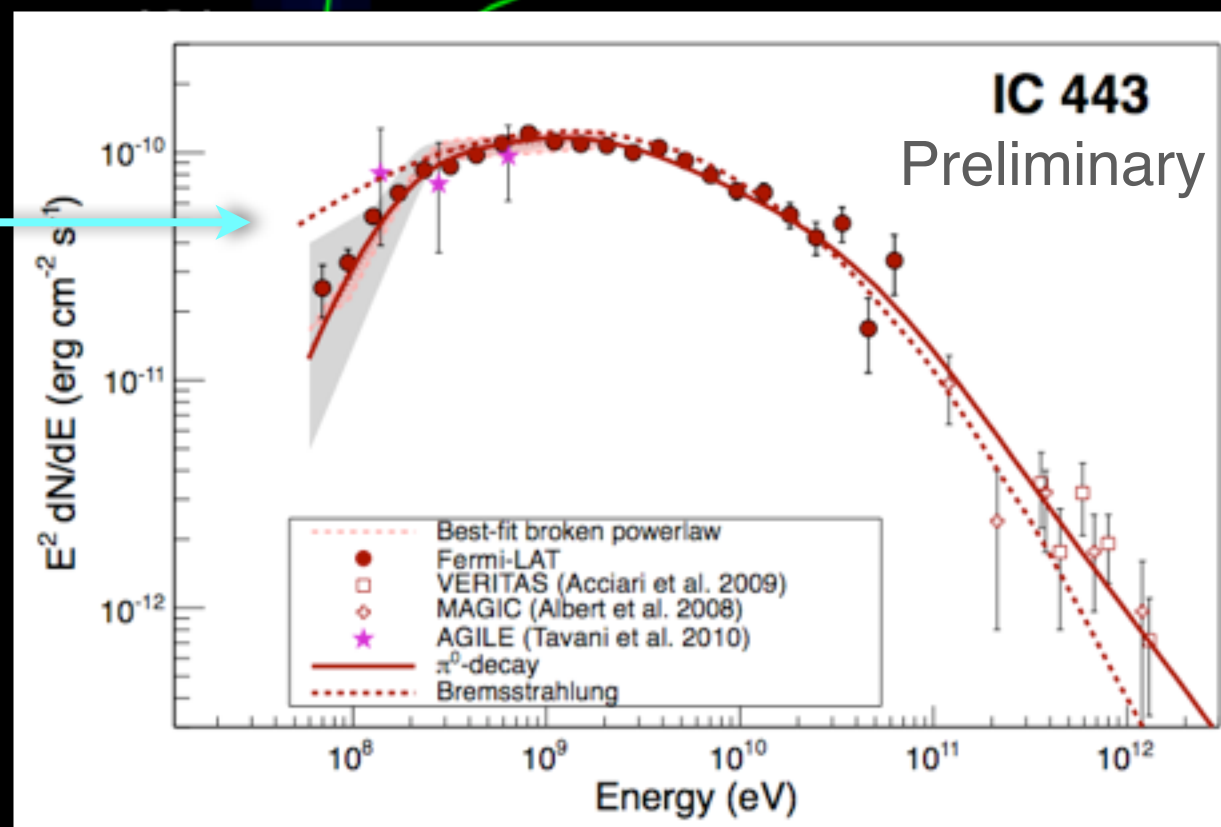
Fermi Telescope Revealed Cosmic-ray Protons



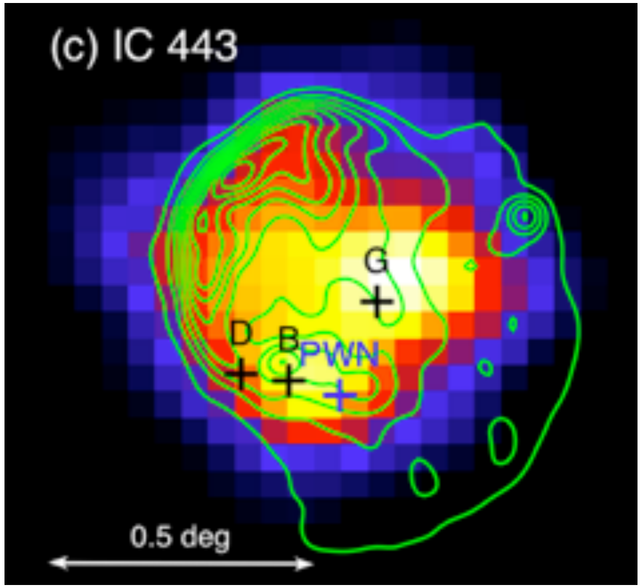


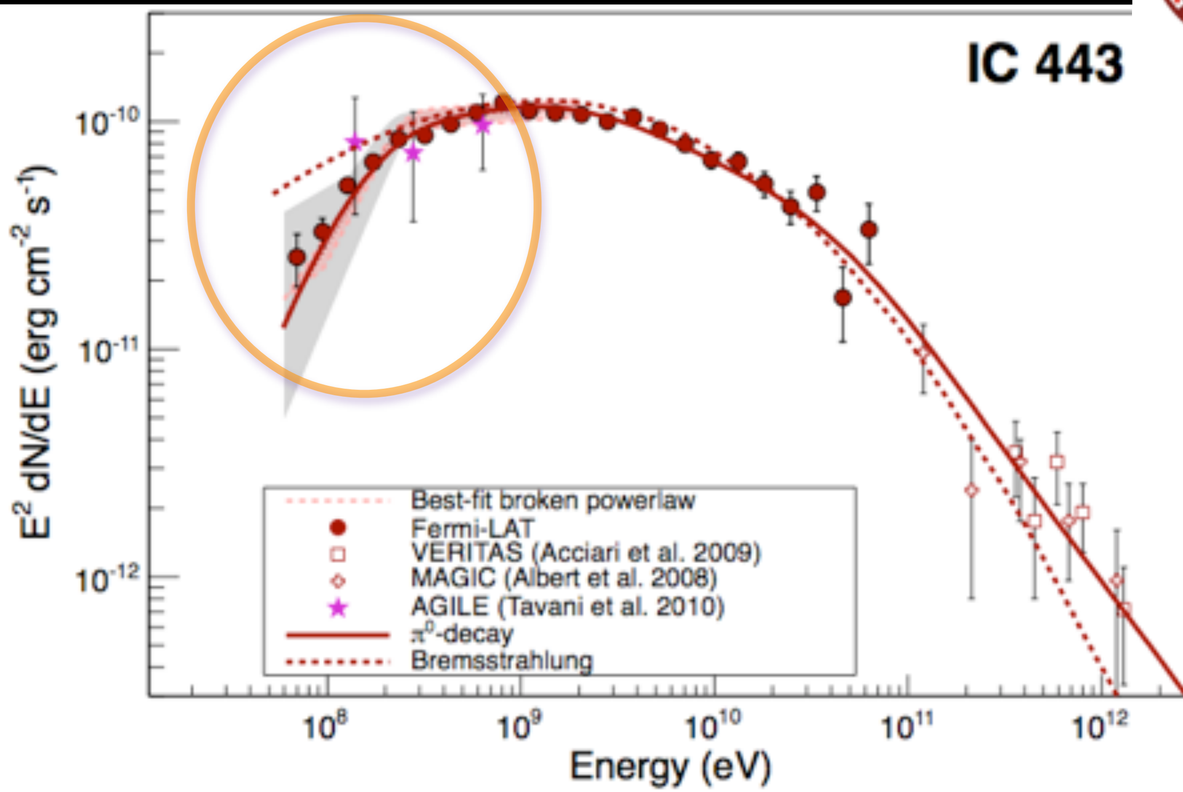
Gamma-ray map measured with Fermi Large Area Telescope

Gamma-ray spectrum measured with Fermi ➜ consistent with π^0 decay



Signature of π^0-decay Gamma-rays

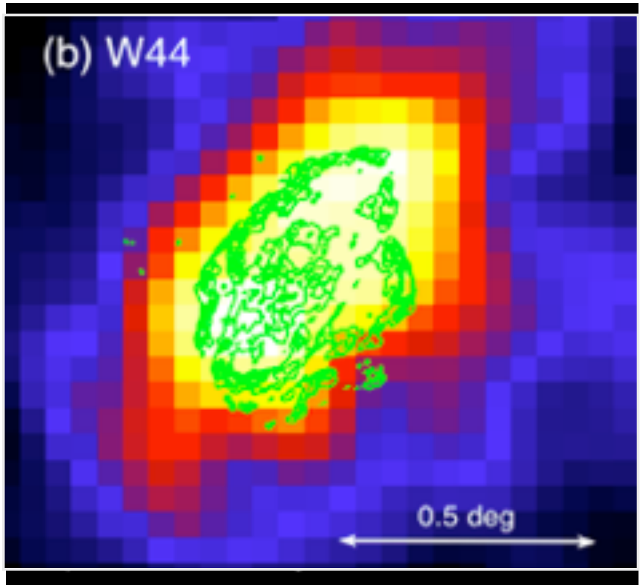


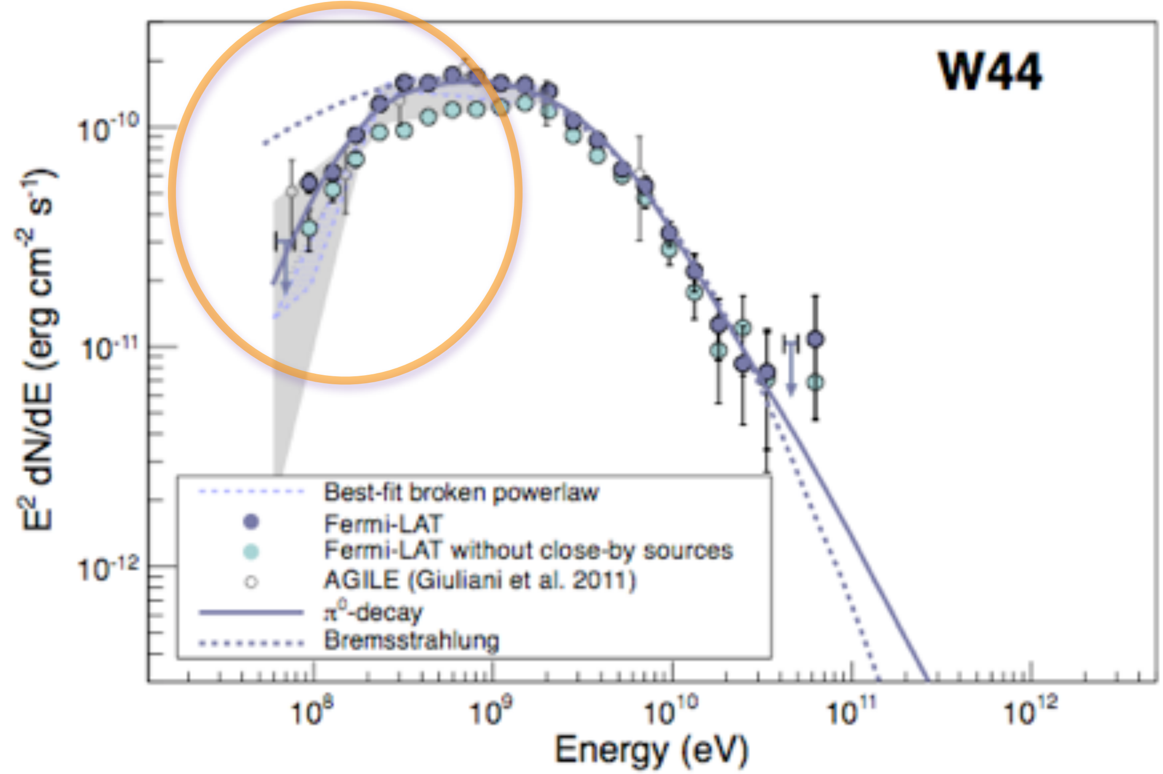


- ☑ Our previous papers reported spectra only >200 MeV.
- ☑ Here we report spectra **down to 60 MeV** thanks to:
  - ✱ Recent update ("Pass-7") of event reconstruction, which largely improved effective area at low energies.
  - ✱ Increased exposure time: 1 yr ➜ 4 yr

Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra.

Signature of π^0-decay Gamma-rays

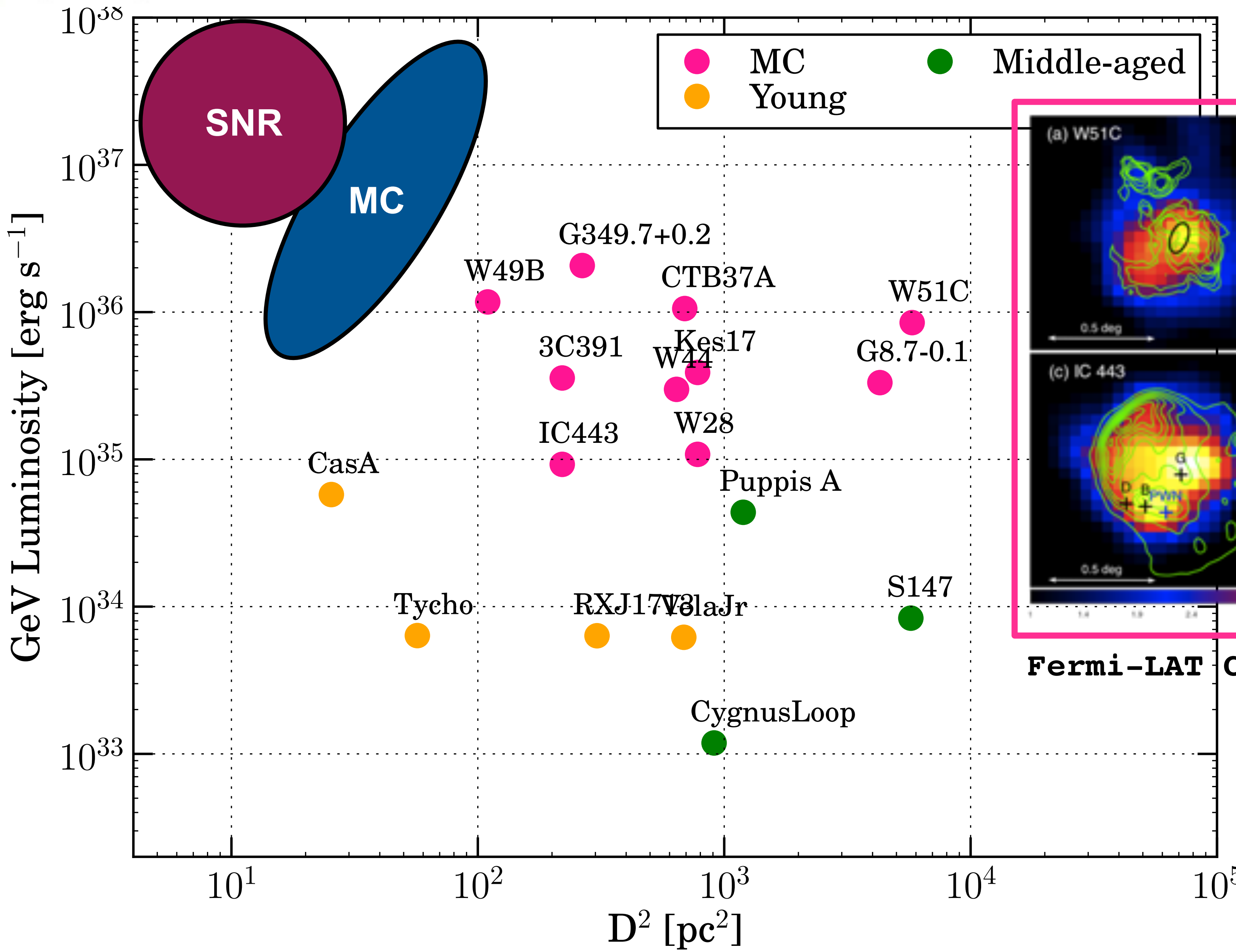


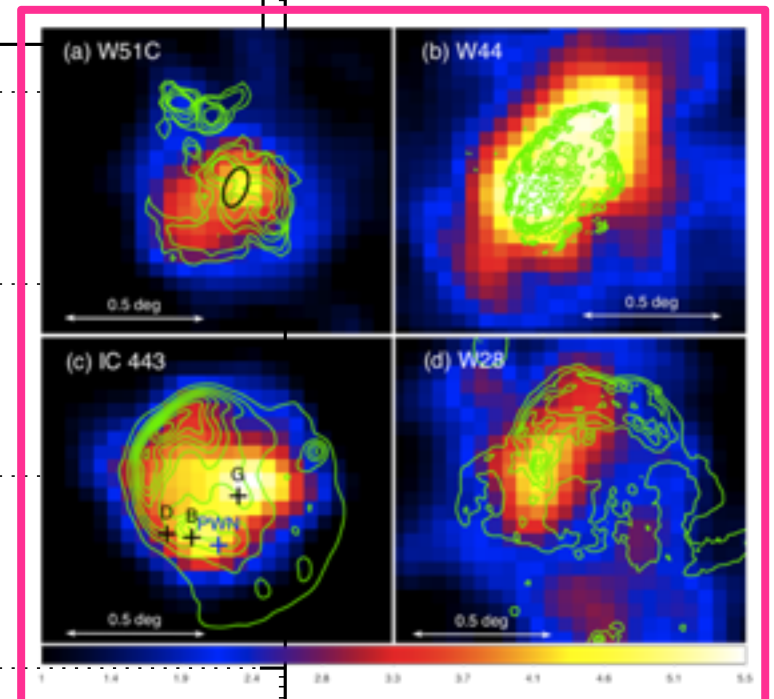


- ☑ Our previous papers reported spectra only >200 MeV.
- ☑ Here we report spectra down to 60 MeV thanks to:
  - ✱ Recent update (“Pass-7”) of event reconstruction, which largely improved effective area at low energies.
  - ✱ Increased exposure time: 1 yr ➜ 4 yr

Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra.

SNRs Detections with Fermi

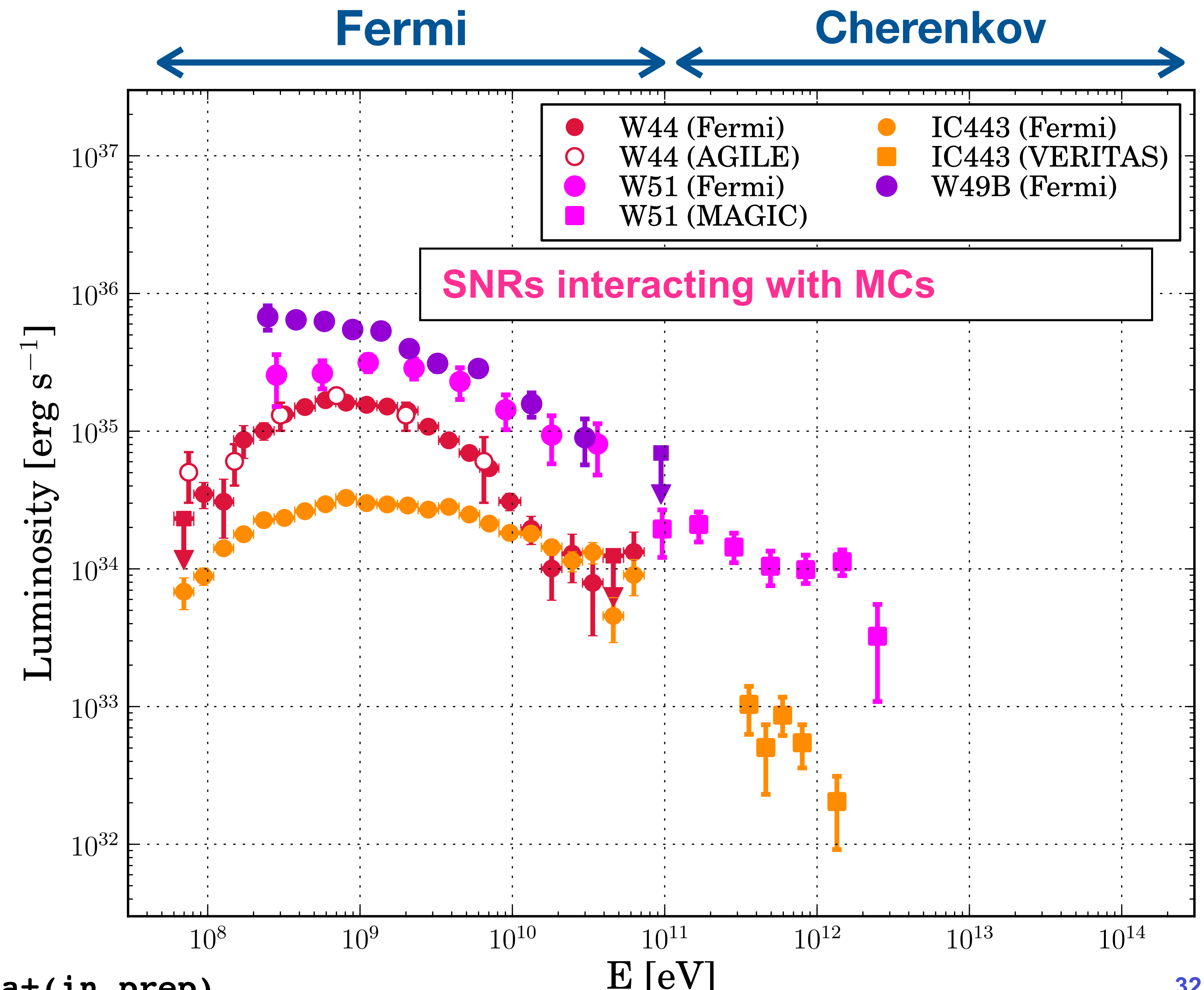




Fermi-LAT Coll(Uchiyama+)2011

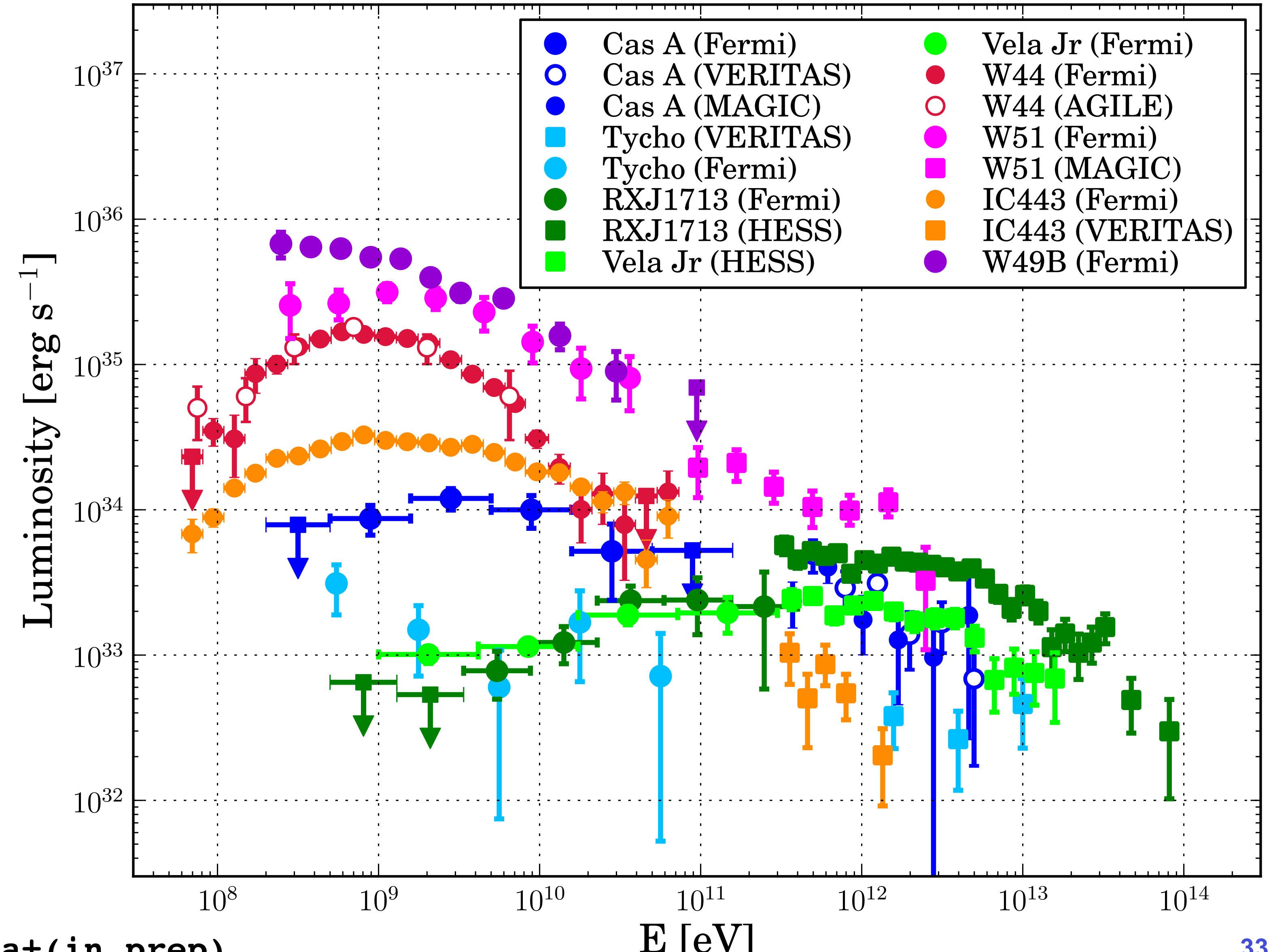
Updated from Thompson,Baldini,Uchiyama(2012)

Gamma-ray Spectra of Fermi-Detected SNRs



Uchiyama+(in prep)

Gamma-ray Spectra of Fermi-Detected SNRs



Uchiyama+(in prep)

Young SNR: Tycho's SNR

Fermi-LAT Detection (5σ)

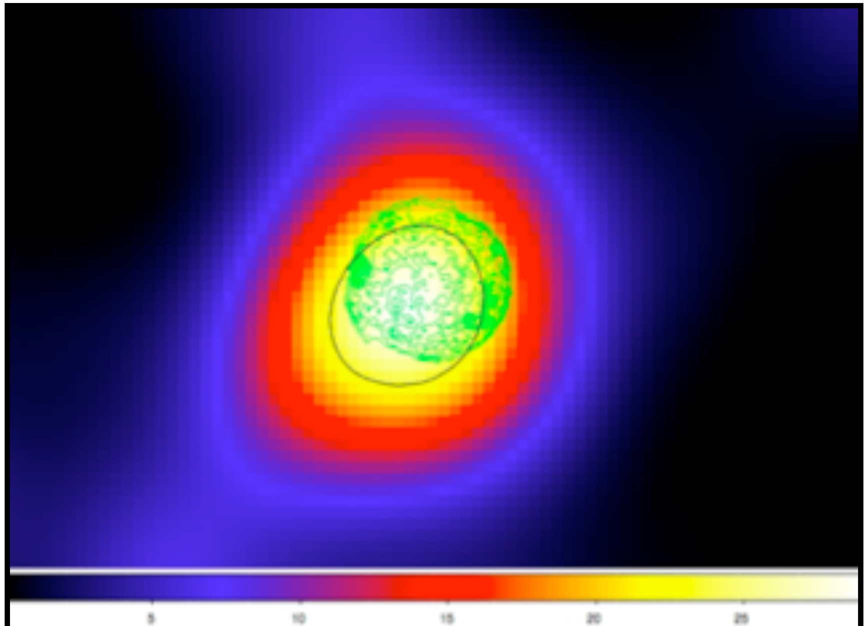
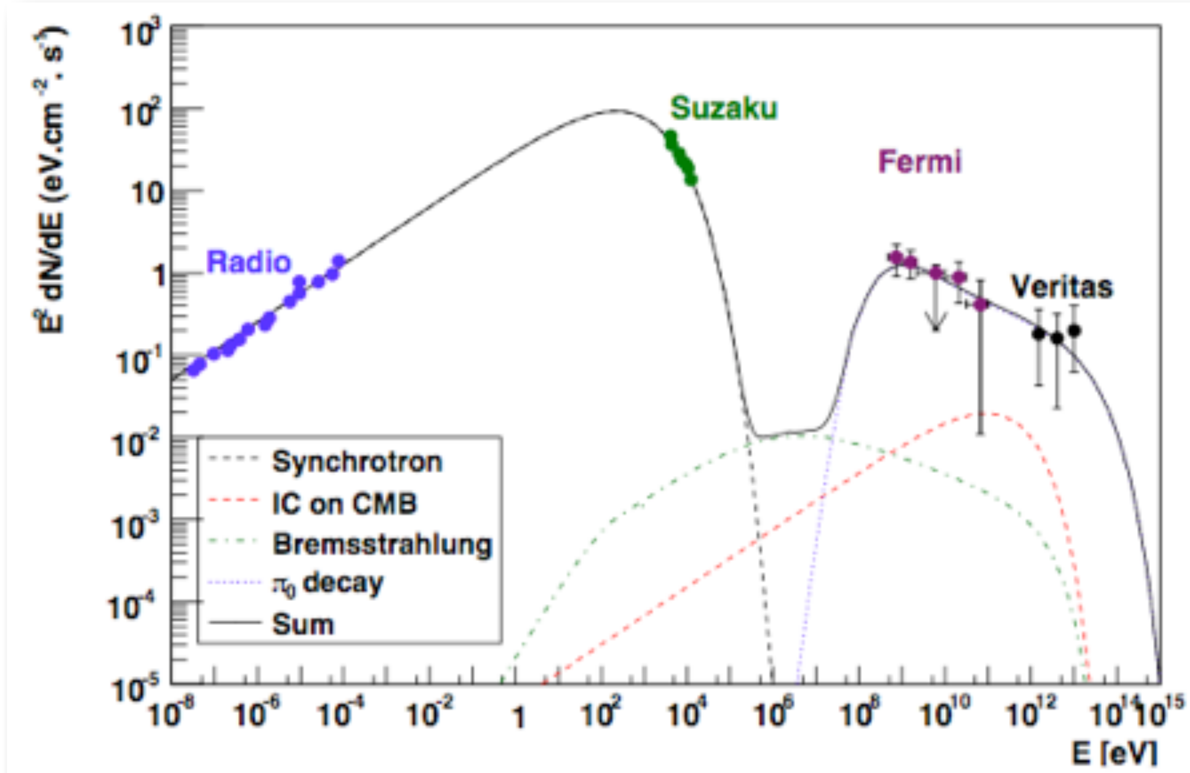


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*



Case	D_{kpc}	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{51}erg]	K_{ep}
Far	3.50	0.24	2.0	0.150	4.5×10^{-4}
Nearby	2.78	0.30	1.0	0.061	7.0×10^{-4}

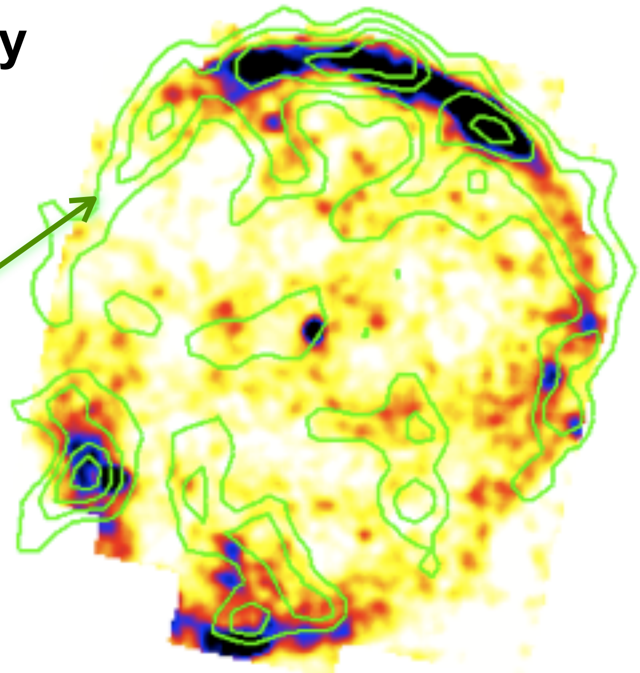
Photon index = 2.3 ± 0.1 (favors hadronic origin)

6-8% of E_{SN} transferred to CRs.

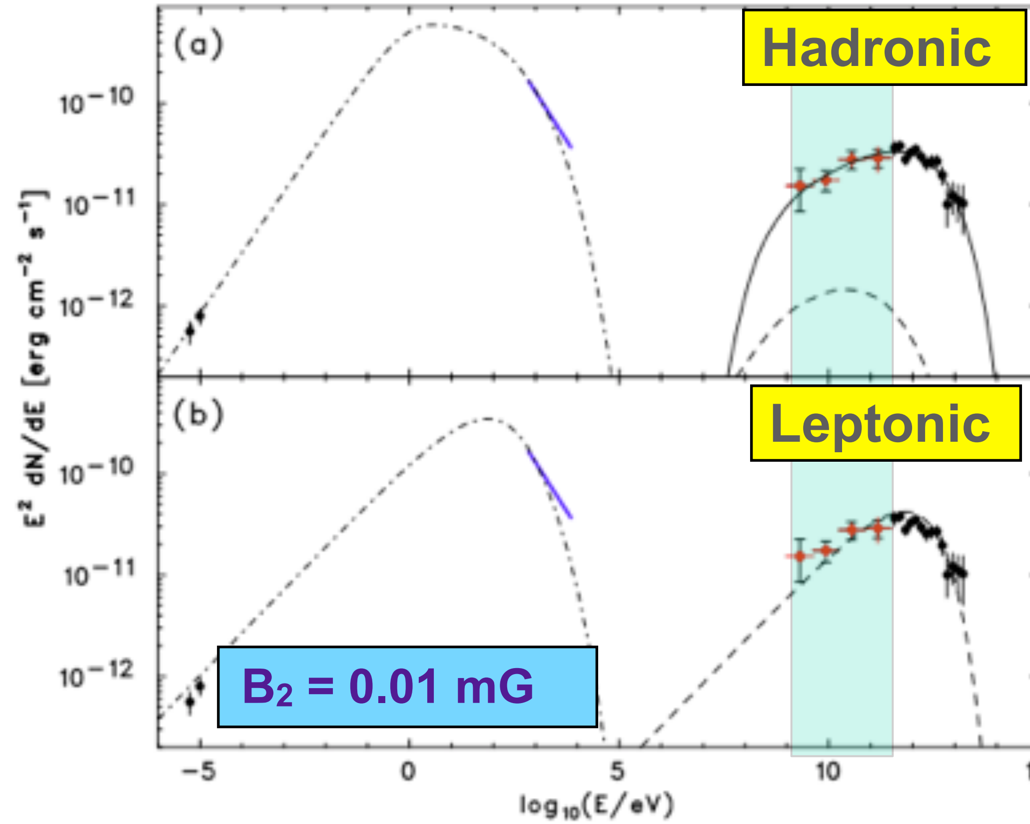
Synchrotron-dominated SNR: Vela Jr.

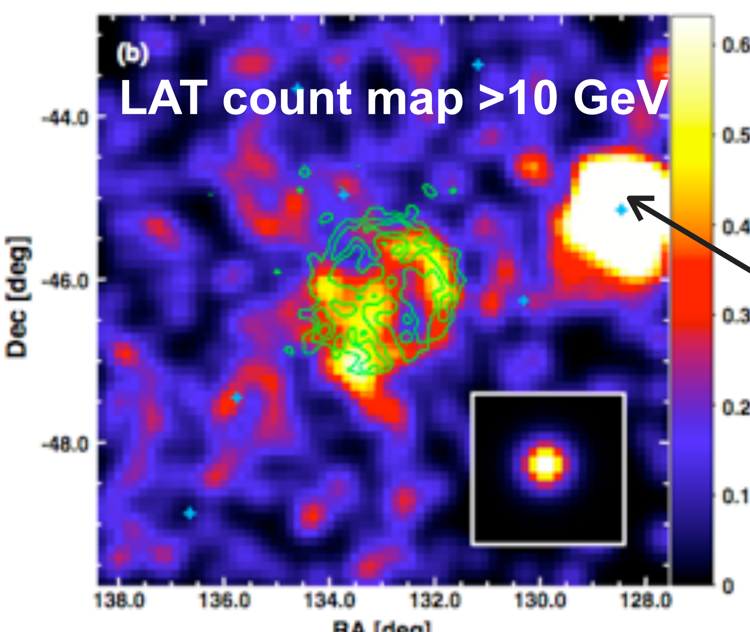
Suzaku X-ray
(Y. Uchiyama)

TeV (H.E.S.S.)



Tanaka+2011





Vela pulsar

LAT Detection at ~15σ level
Γ_{LAT} = 1.87 ± 0.08(sta) ± 0.17(sys)

B_2 = 0.01 mG in leptonic model would be difficult to be reconciled with X-ray measurements.
Hadronic model would require a large CR content (5×10^{50} erg for n=0.1 cm^{-3})

Middle-Aged SNR: Puppis A

Hewitt+2012

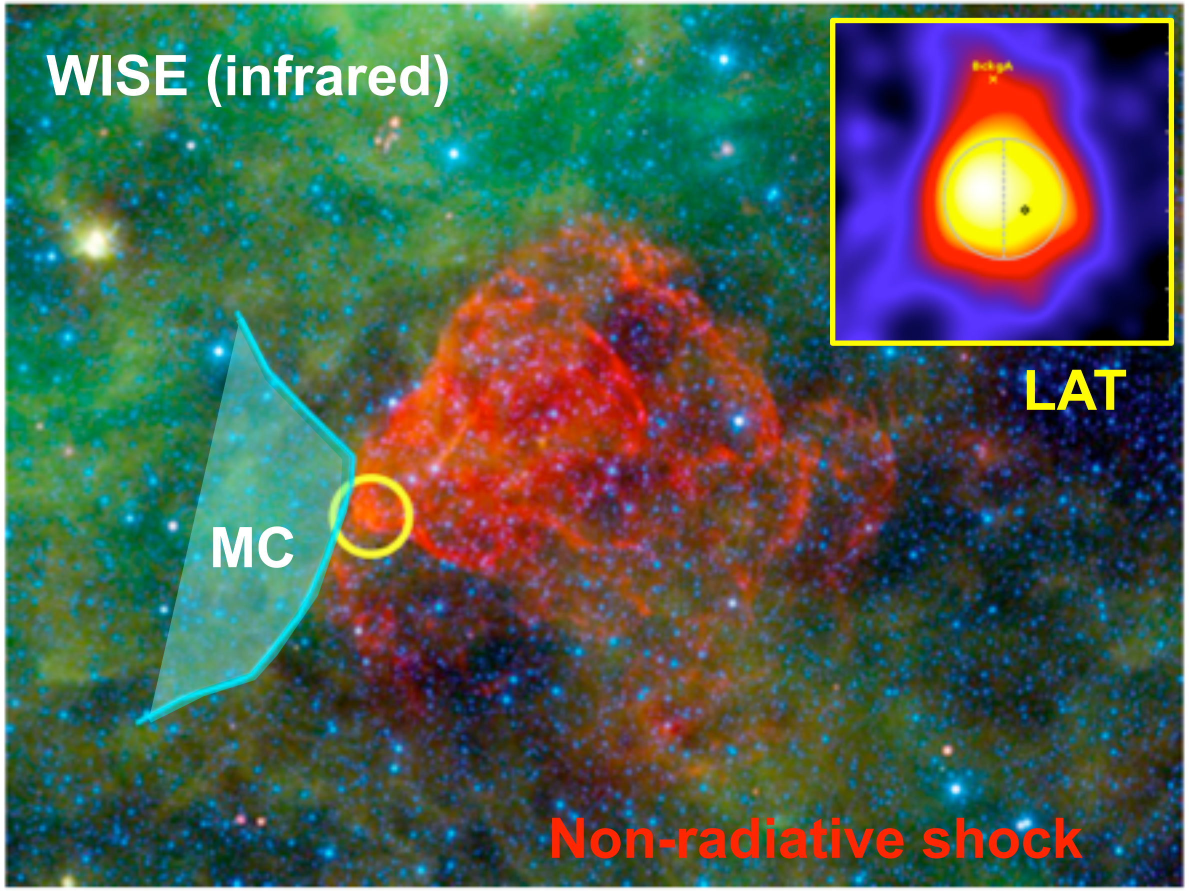
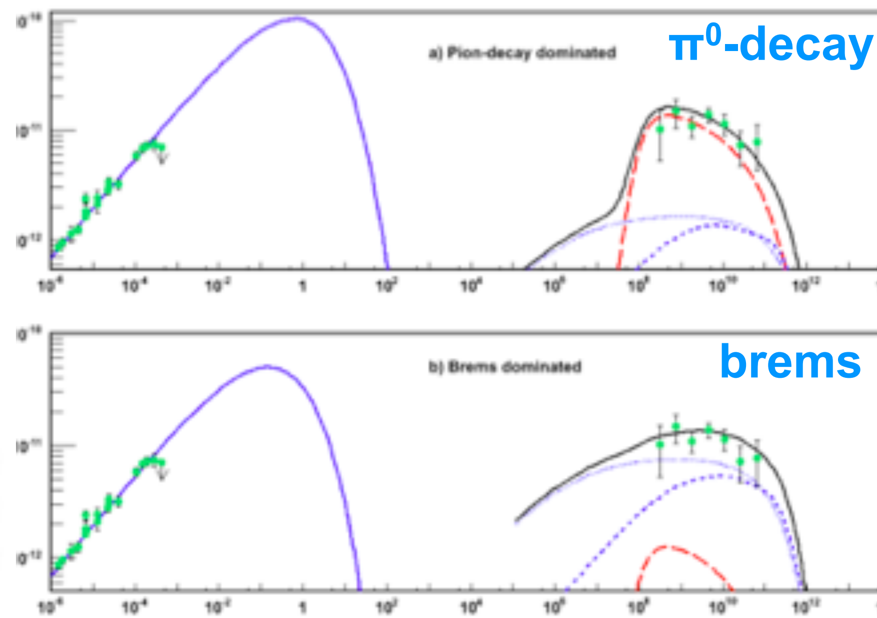


Figure 1: *Infrared emission from dust heated by the expanding shock-wave of Puppis A (courtesy WISE). Yellow circle indicates where the shock has encountered a small cloud. Cyan contours highlight the adjacent molecular cloud, just beyond the SNR.*

Diameter: 30 pc
Age: ~40,000 yr (Sedov phase)
ISM Density: 1 cm^{-3}

LAT Detection at ~13σ level
$\Gamma_{LAT} = 2.10 \pm 0.07$(sta) ± 0.10(sys)



The gamma-ray emission can be modeled either by bremsstrahlung with $W_e = 1\times10^{49}$ erg or by hadronic (π^0-decay) with $W_p = 4\times10^{49}$ erg

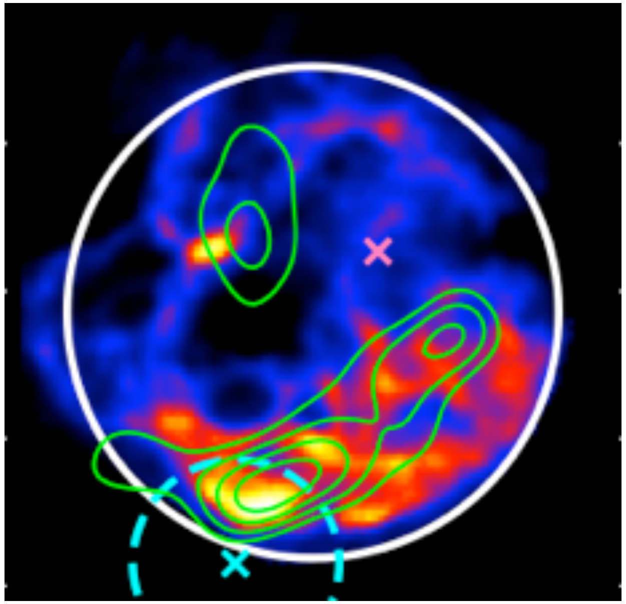
Old SNR: S147

Katsuta, Uchiyama+2012

Hα image (radiative shock)

Diameter: 76 pc (d=1.3 kpc)
Age: ~30,000 yr
ISM Density (2 phases): 4 cm^{-3} / 0.1 cm^{-3}
➜ compression ➜ 400 cm^{-3} / 0.4 cm^{-3}

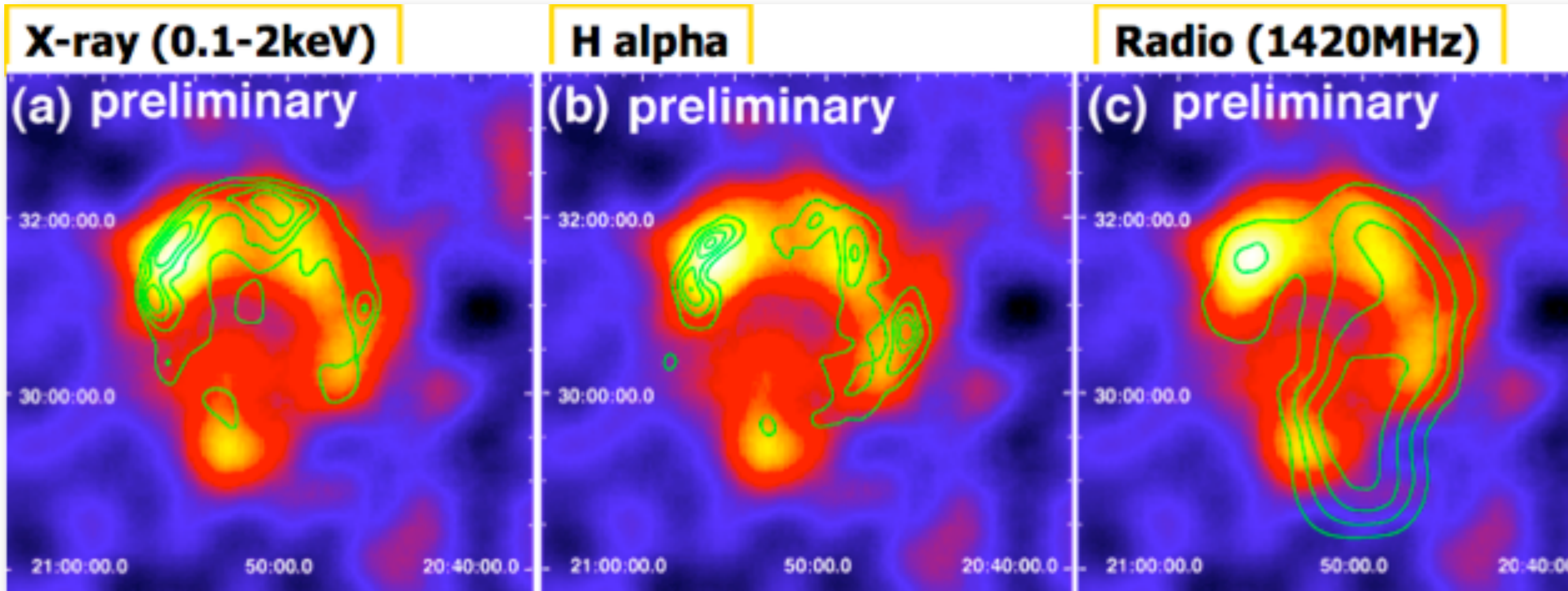
Fermi vs Hα

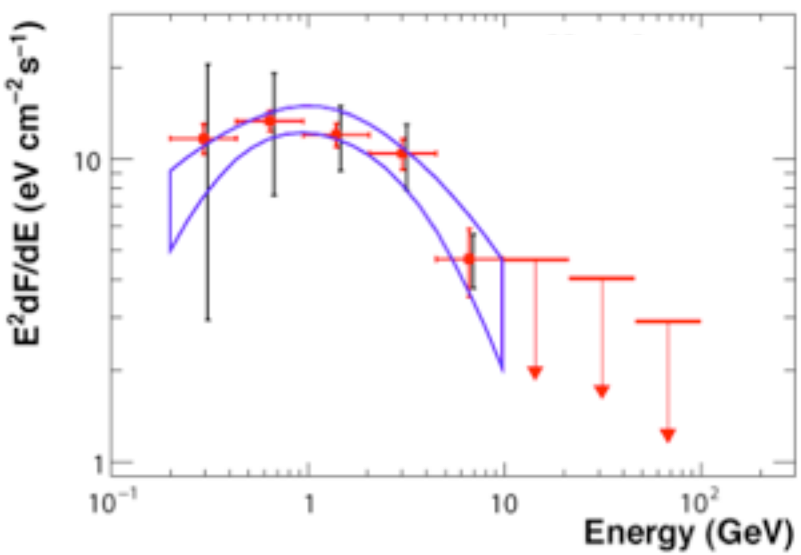


The gamma-ray emission can be explained by re-acceleration of Galactic CRs in optical filaments (Uchiyama+2010).

Cygnus Loop: LAT Results

Katagiri+ (2011)





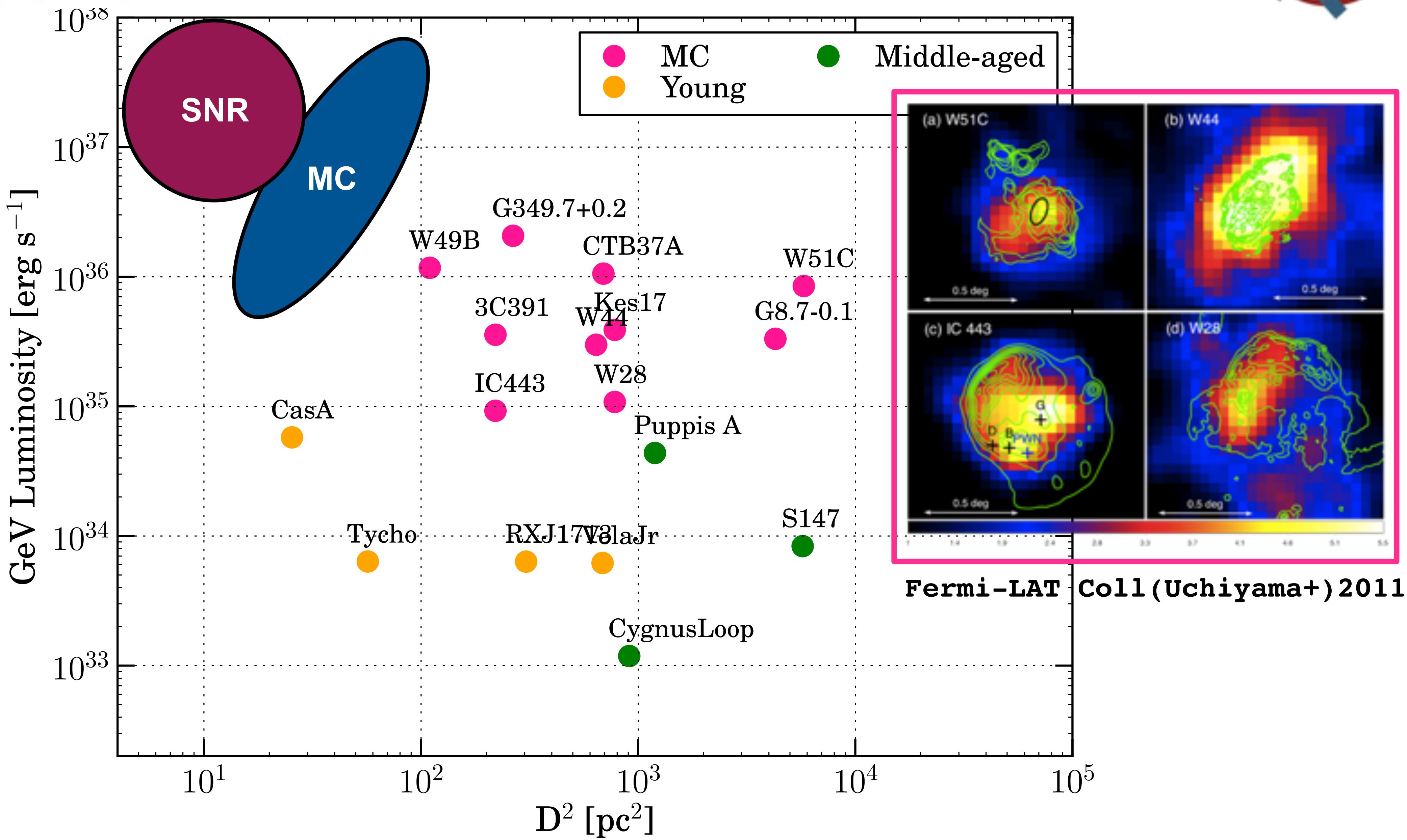
Correlation with X-ray and Hα emissions

→ Gamma-ray-emitting particles distribute near shock waves

NOTE: southern radio emission would be another SNR.

Spectral steepening above ~ 2 GeV.
(simple power-law disfavored at 3.5σ level)
Gamma-ray Luminosity ~ 1×10^{33} erg/s (< other LAT SNRs)

SNRs Detections with Fermi

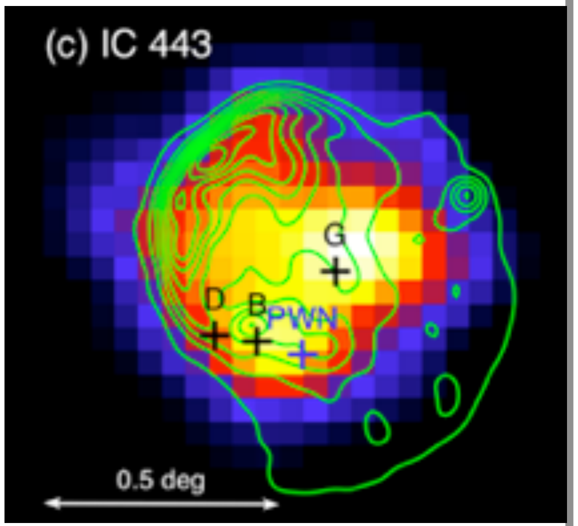


Fermi-LAT Coll(Uchiyama+)2011

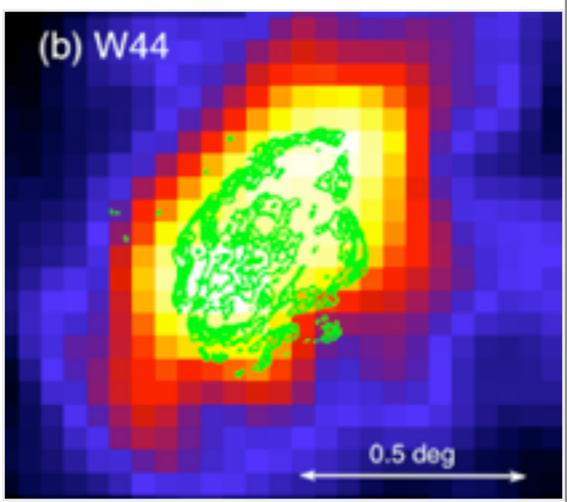
Updated from Thompson,Baldini,Uchiyama(2012)

Growing Examples: MC-SNRs

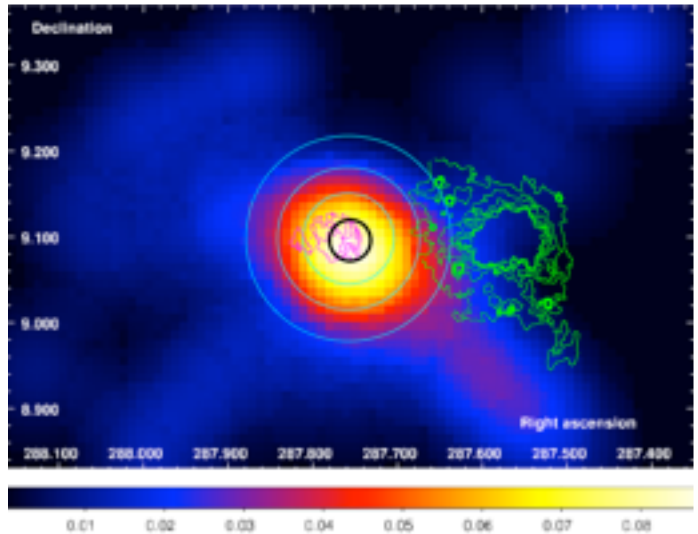
IC 443

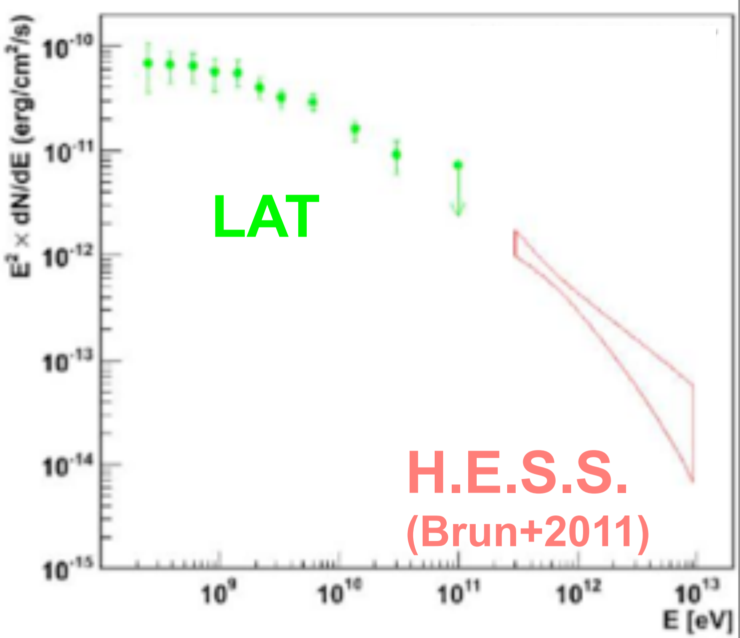


W44

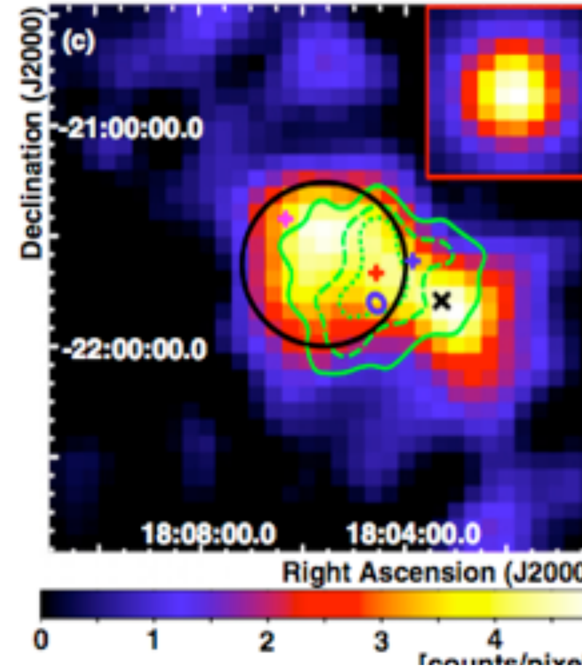


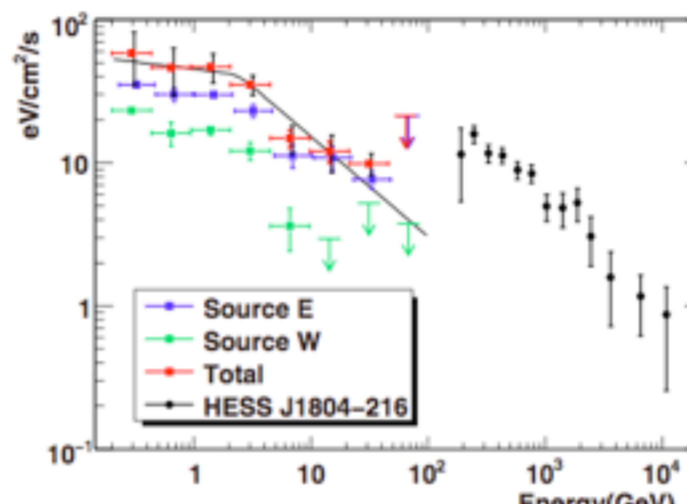
W49B Abdo+2010





W30(G8.7-0.1) Hanabata+

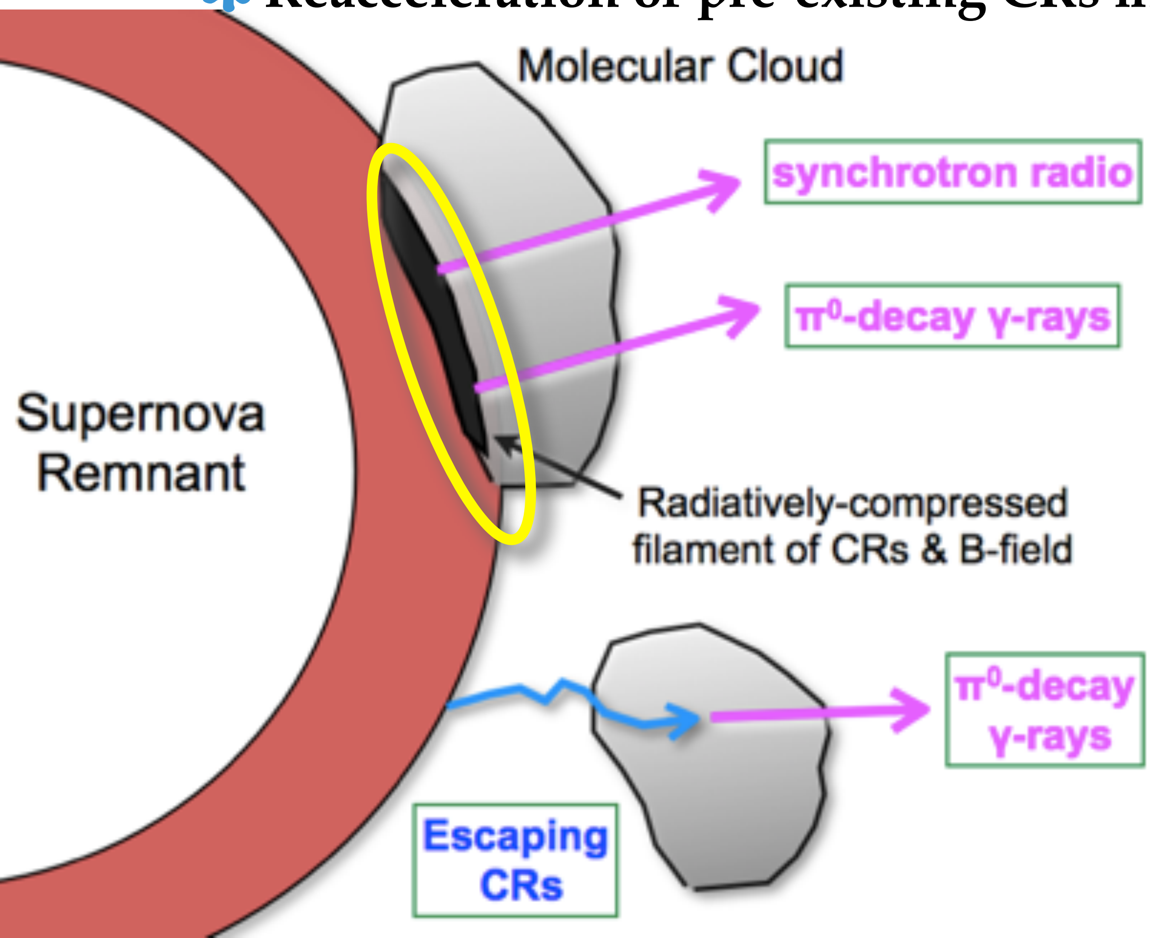




SNR-MC System

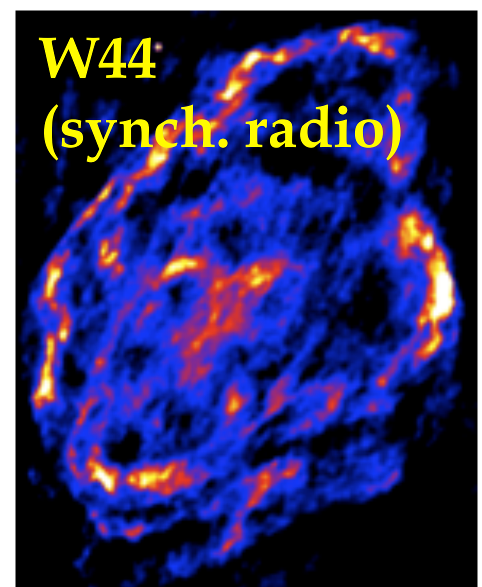
☑ Crushed Cloud model: π^0-decay γ-rays come from shocked molecular clouds   Blandford & Cowie (1982), Uchiyama et al. (2010)

- Radiative shock ➜ high compression ➜ high CR & gas density
- Shock: slow (~100 km/s), partially ionized ➜ Maximum energy < TeV
- Thin filaments or sheets ➜ Hard to confine CRs at high energies
- Reacceleration of pre-existing CRs may be important



☑ The Case of W44:

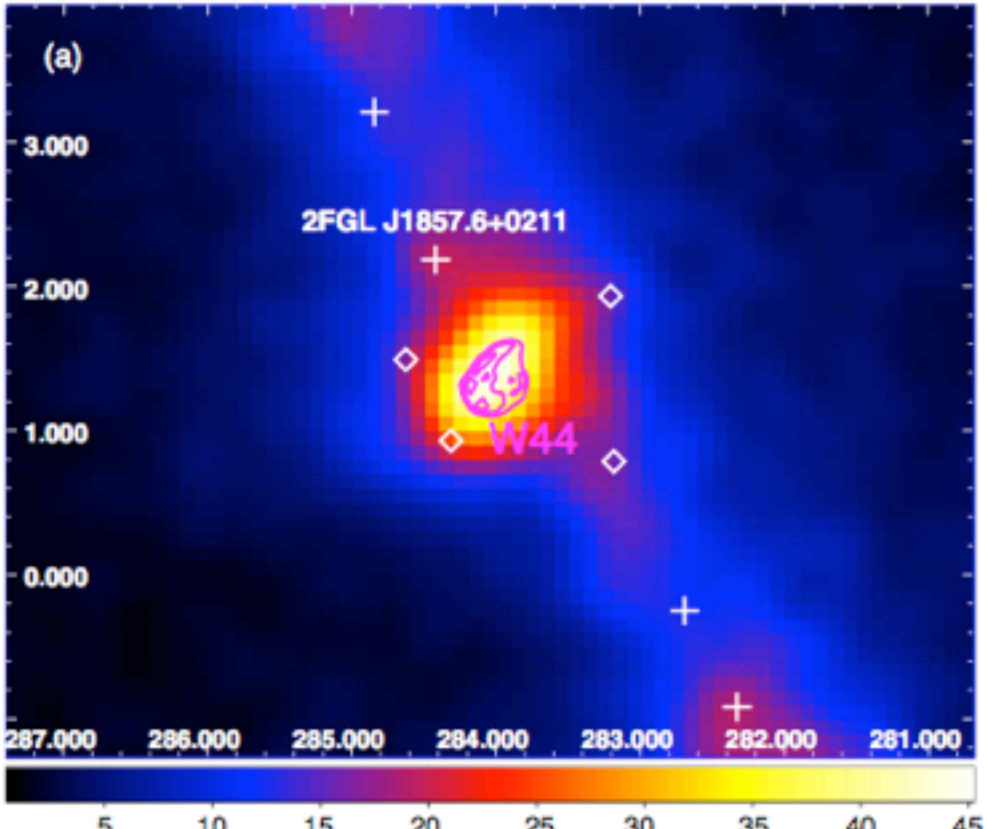
- Shocked MC mass of 5000 $M_\odot$
- Synchrotron radiation correlated with shocked H_2 gas (infrared lines)

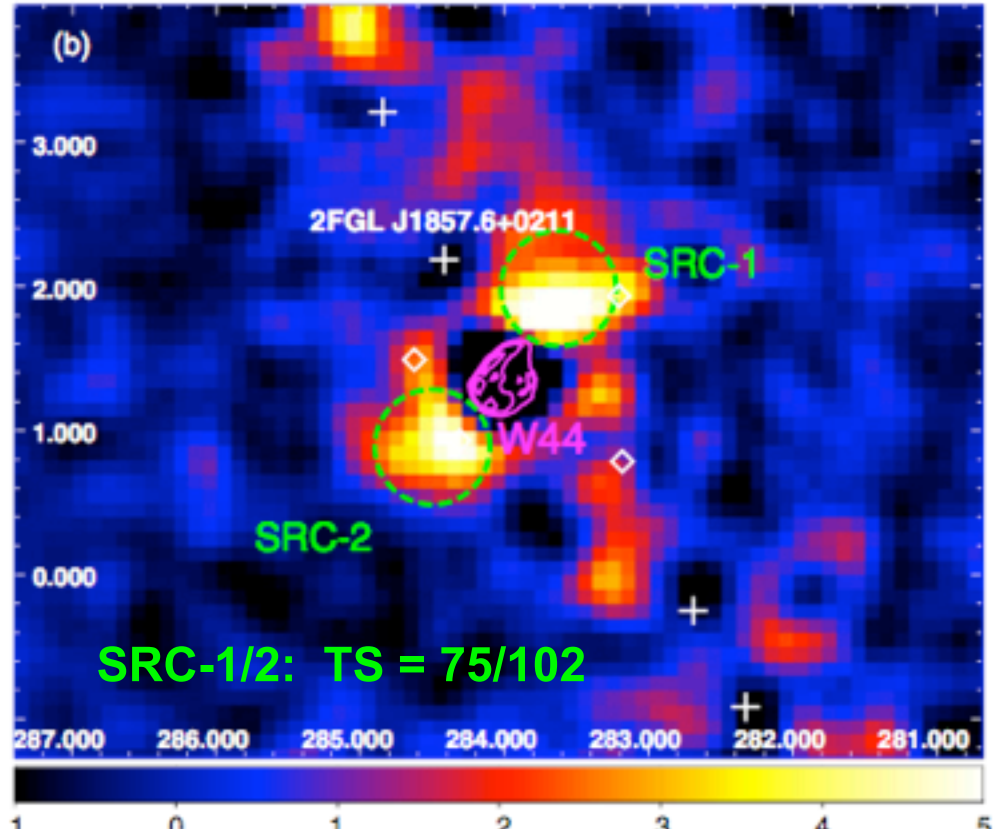


Fermi-LAT Detection of W44 Surroundings

The presence of large-scale GeV emission was found in the vicinity of SNR W44

Uchiyama et al. (2012)

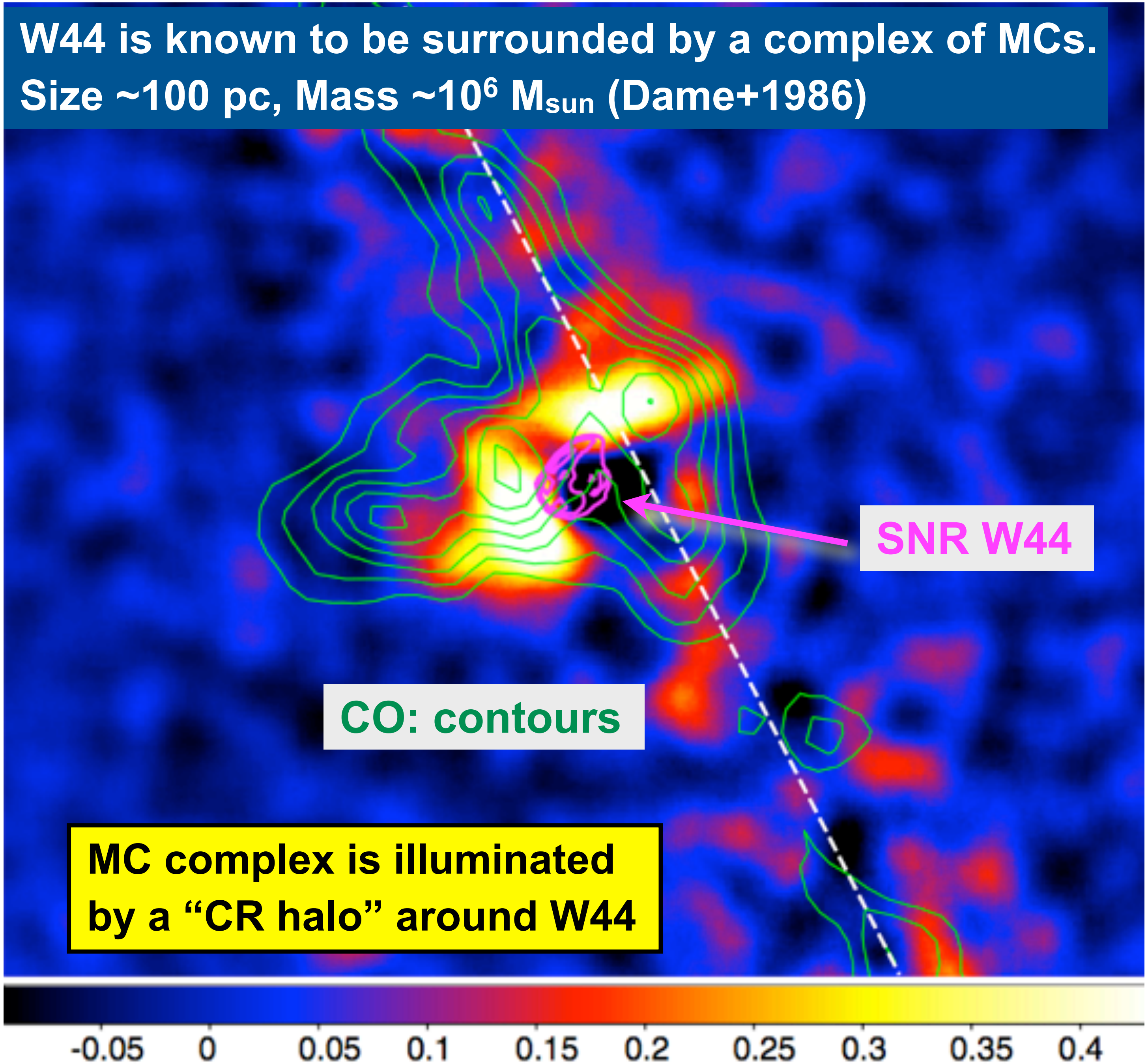




Subtraction of W44

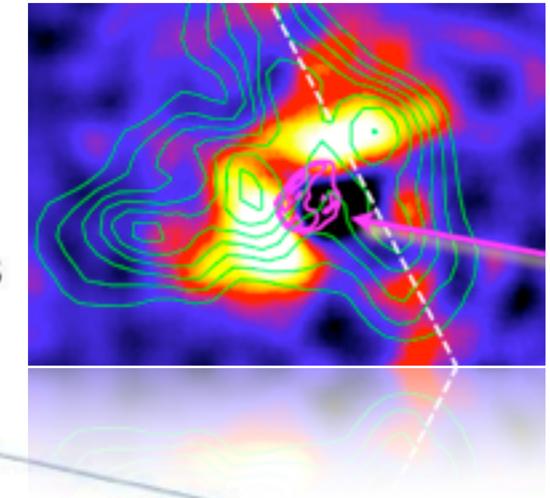
Gamma-rays from W44 itself are subtracted, assuming "radio map = gamma-ray map"

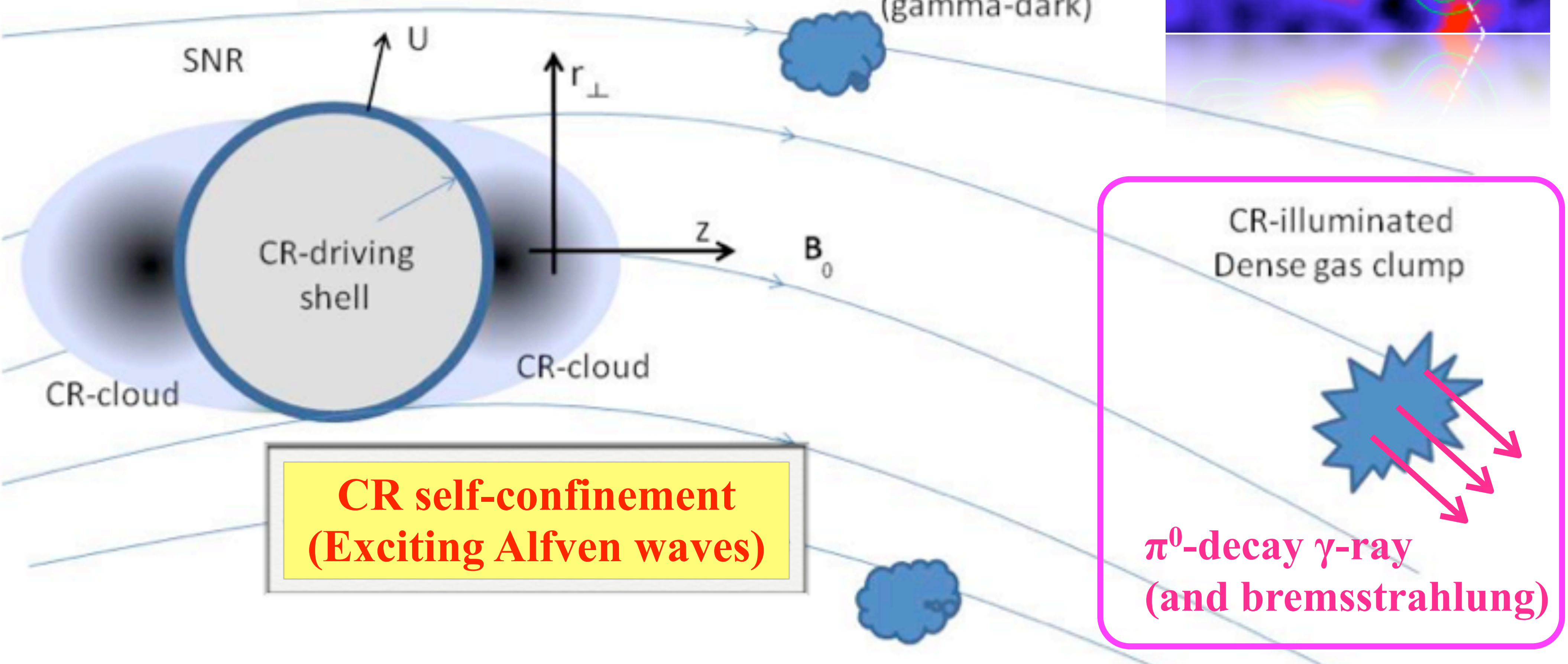
Large-scale GeV γ-rays vs CO map



Gamma-ray Evidence for Leaking CRs

(c) M. Malkov (2012)

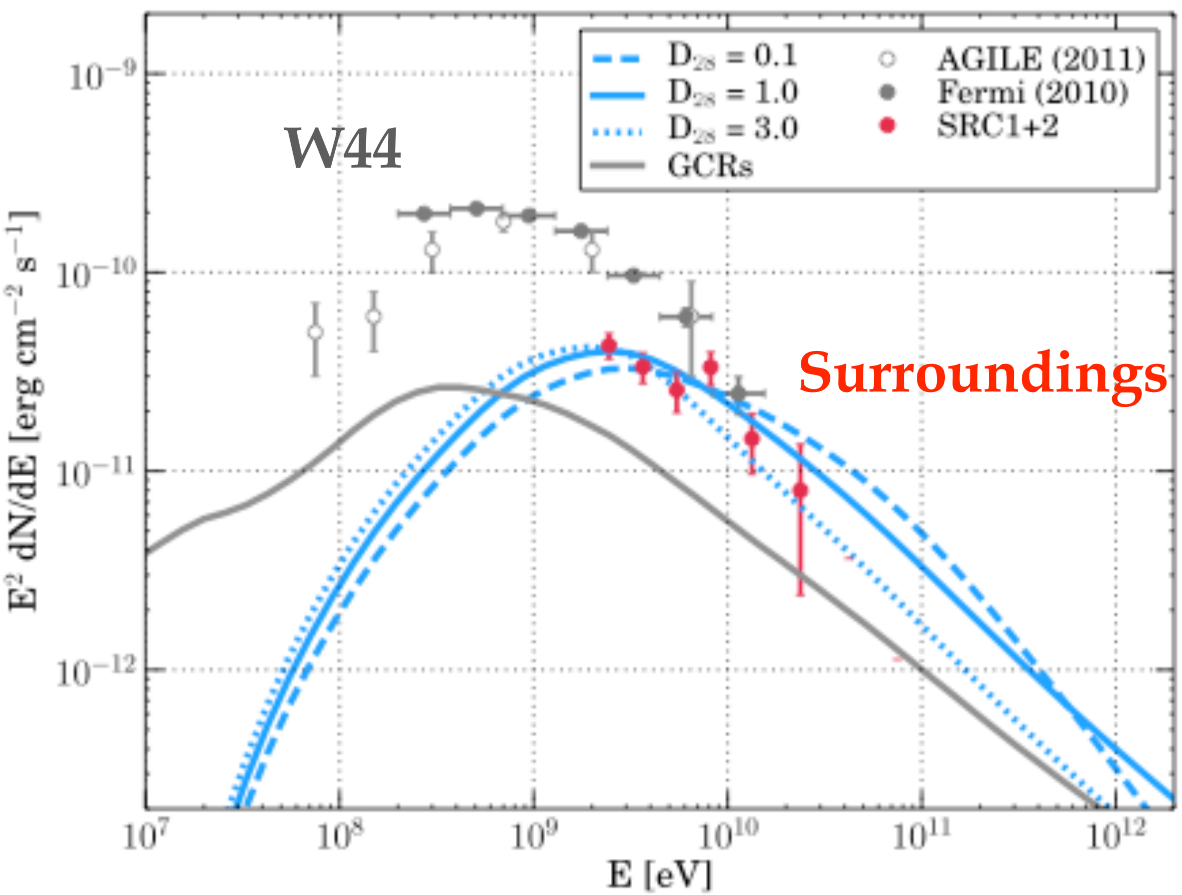




After leaving SNR W44, CRs diffuse along the external B-field direction ➜ bipolar morphology

Amount of CRs Escaped from W44

- ☑ Molecular clouds illuminated by escaping CRs (assumed to be uniform within r<L)
  - ✱ L ~100 pc, Mass = $0.5\times10^5\ M_\odot$
- ☑ Diffusion coefficient of the ISM (isotropic)
  - ✱ $D(p) = D_{28}\ (cp/10\ \mathrm{GeV})^{0.6}\ 10^{28}\ \mathrm{cm^2/s}$



Solving the diffusion equation in the vicinity of W44, we can estimate the energy spectrum of escaping CRs.

✱ **Case 1:**

Slow diffusion ($D_{28} = 0.1$)

$N_{esc}(E) = k\ E^{-2.6}$

$W_{esc} = 0.3\times10^{50}$ erg

✱ **Case 2:**

$D_{28} = 1$

$N_{esc}(E) = k\ E^{-2.0}$

$W_{esc} = 1.1\times10^{50}$ erg

✱ **Case 3:**

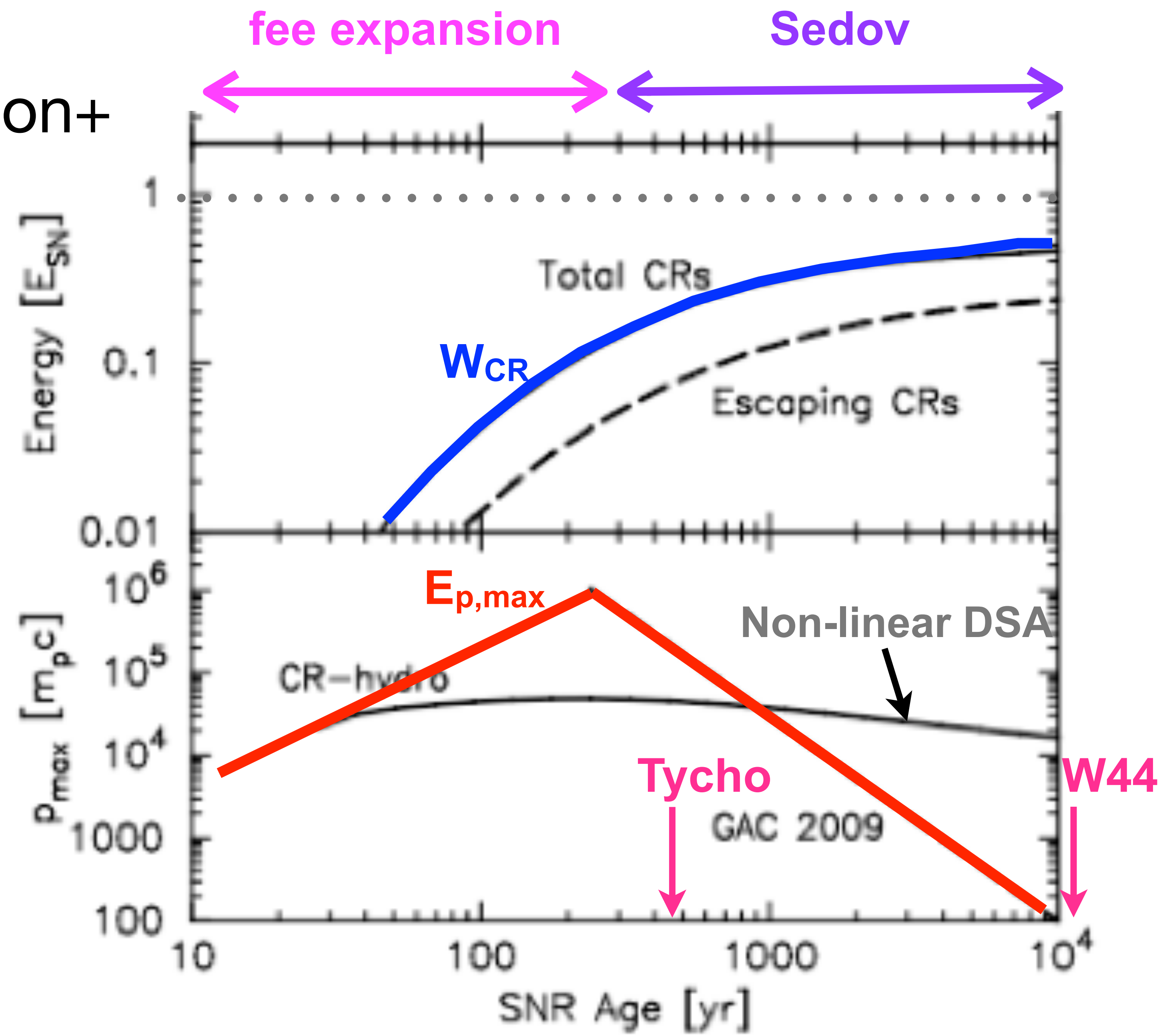
Fast diffusion ($D_{28} = 3$)

$N_{esc}(E) = k\ E^{-2.0}$

$W_{esc} = 2.7\times10^{50}$ erg

CR Content and Maximum Energy as Function of SNR Age

c: Ellison+



Summary

- Fermi-LAT observations of the Crab Nebula:
  - Flares of synchrotron radiation challenge PWN models
  - Very efficient e-e+ acceleration (close to theoretical limit)
  - Change of a beaming factor seems to play a key role

- Fermi-LAT observations of SNRs:
  - Historical SNRs Tycho & Cassiopeia A
    - Hadronic origin, Magnetic field amplification, CR energy content
  - Young TeV-bright SNRs RX J1713.7-3946 & Vela Jr.
    - Leptonic origin? (B-field too low?)
  - SNRs interacting with molecular clouds
    - W51C, W44, IC443, W28, W49B, W30, CTB37A, ...
    - Direct evidence for hadronic origin (IC443, W44)
    - Evidence for Runaway CRs
  - Evolved SNRs without molecular cloud interactions
    - Cygnus Loop, Pup A, S147
    - Hadronic origin? Perhaps from radiative shock (Hα)