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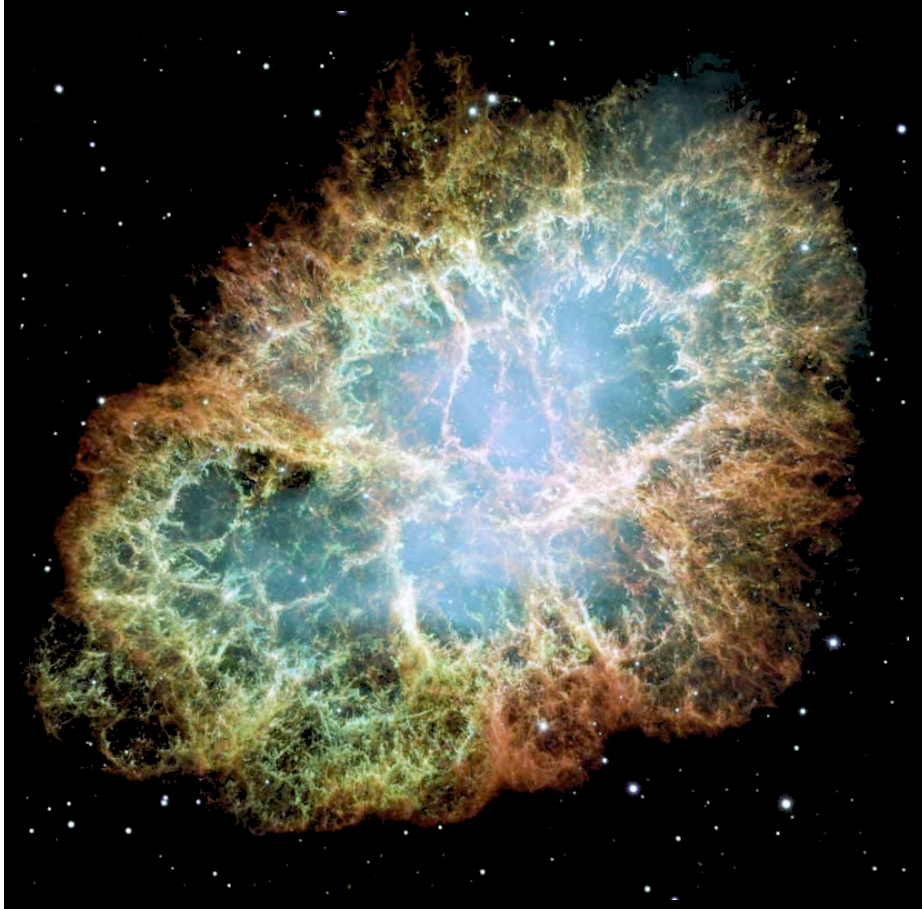

GLAST Observations of Supernova Remnants and Pulsar Wind Nebulae

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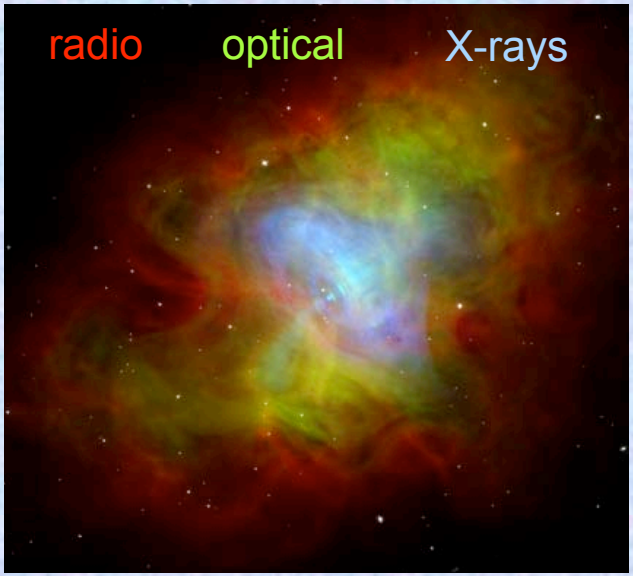
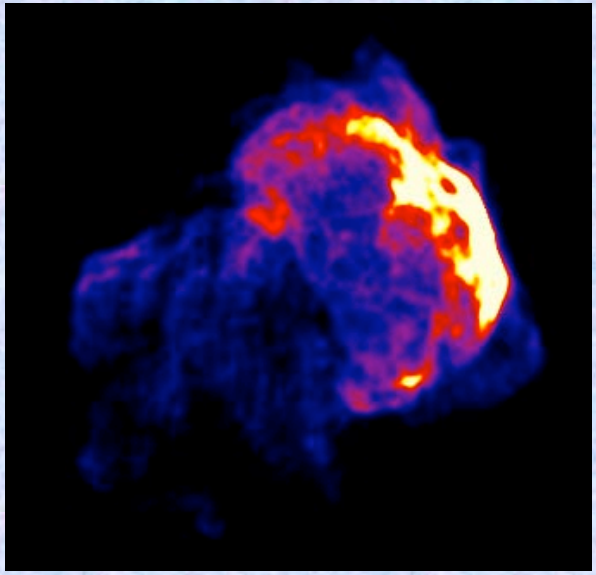
Introduction

- Supernova remnants (SNRs) & pulsar wind nebulae (PWNe)
  - broadband synchrotron emitters
    - → shock acceleration of electrons to above ~10^{14} eV
    - → are ions accelerated also? origin of cosmic rays up to "the knee"?
  - accelerated particles propagated via turbulence, winds, jets
  - emission traces interaction with surrounding gas
  - nearby laboratory for understanding AGN, μ-QSOs, clusters, GRBs
- *GLAST* + (radio ⇔ TeV): direct measure of acceleration sites, mechanisms



Crab Nebula (Hester et al. 2002)

PSR B1509-58 (X-rays; Slane et al. 2006)



SNR 3C 391 (radio; Moffett & Reynolds 1994)

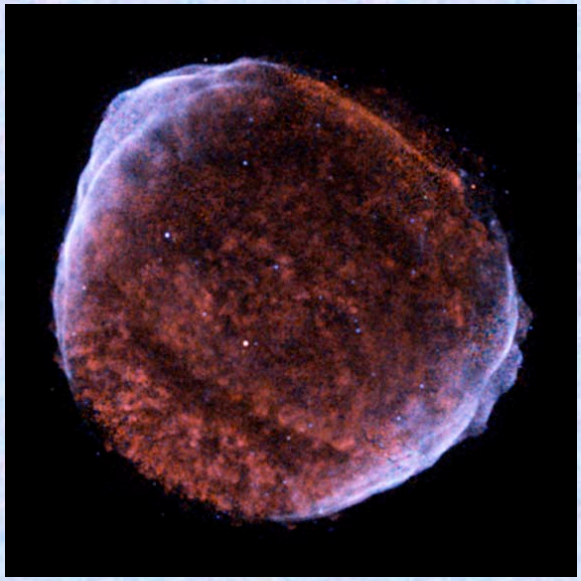
Particle Acceleration in SNRs

- Emerging class of young SNRs emitting synchrotron X-rays
  - e.g., SN 1006, G347.3-0.5, Vela Jr., G330.2+1.0, RCW 86
  - direct evidence of electron acceleration up to ~50-100 TeV

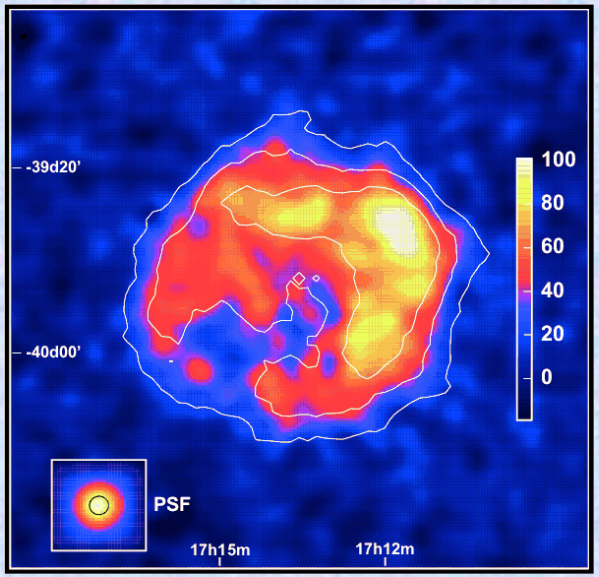
  (Koyama et al. 1995, 1997; Slane et al. 1999, 2001; Vink et al. 2006; Torii et al. 2006)

- G347.3-0.5 & Vela Jr.: now seen at E > 100 GeV

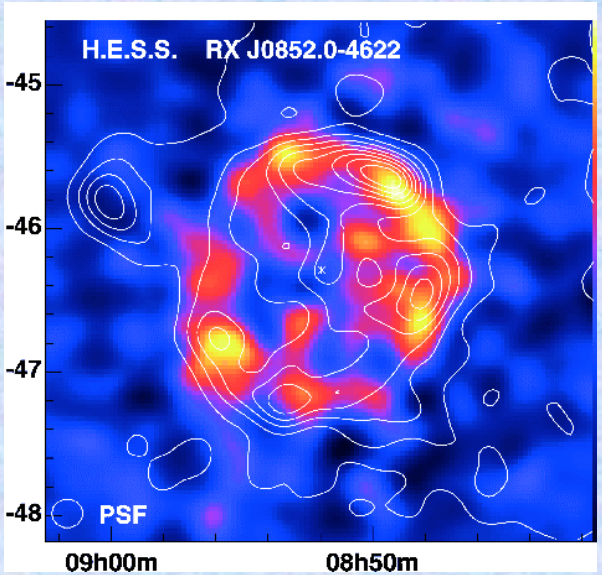
  (Muraishi et al. 2000; Aharonian et al. 2004, 2005; Katagiri et al. 2005)



SN 1006 (X-rays; NASA/CXC/ Rutgers/J.Hughes et al.)



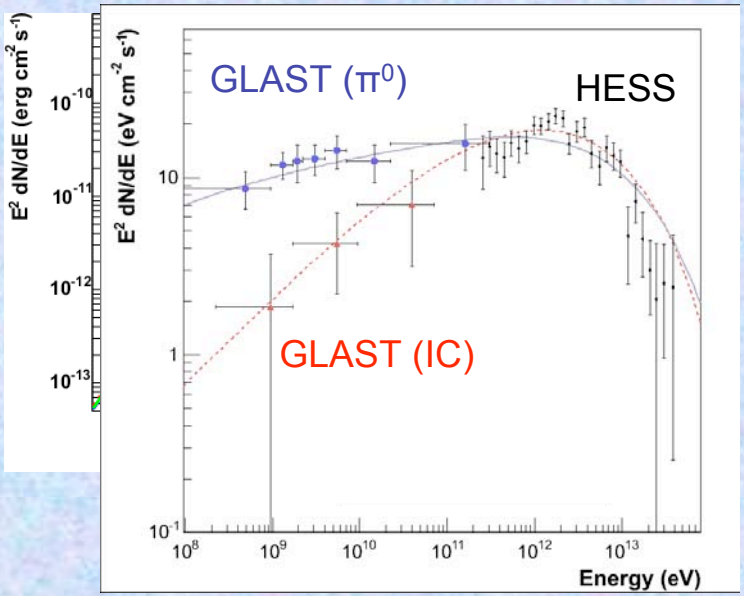
G347.3-0.5 (TeV; Aharonian et al. 2006)



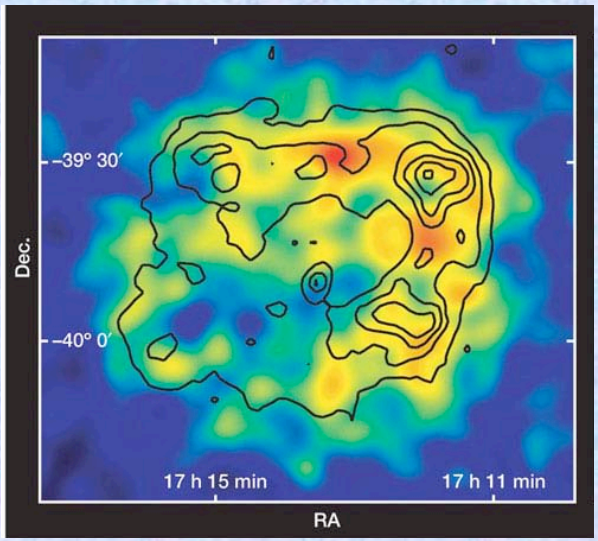
Vela Jr. (TeV; Aharonian et al. 2005)

What Particles Are TeV Emitters?

- π^0 decay from p-p collisions
  (e.g., Enomoto et al. 2002; Aharonian et al. 2006)
  - would be direct evidence for proton acceleration to > 10 TeV
- Inverse Compton (IC) emission
  (e.g., Reimer & Pohl 2002; Lazendic et al. 2004)
  - Synch. e^- scatter CMB, starlight, dust IR
- Spectroscopy can distinguish between p^+ & e^-
  - Cerenkov sees only high-energy tail
  - *GLAST* will measure overall shape
- γ-ray imaging resolves acceleration sites
  - π^0 decay should trace thermal X-rays
  - IC should trace non-thermal radio/X-rays
- *GLAST* targets:
  - SNRs with synch. X-rays / TeV (e.g., RCW 86)
  - SNRs interacting with molec. clouds (e.g., W28)



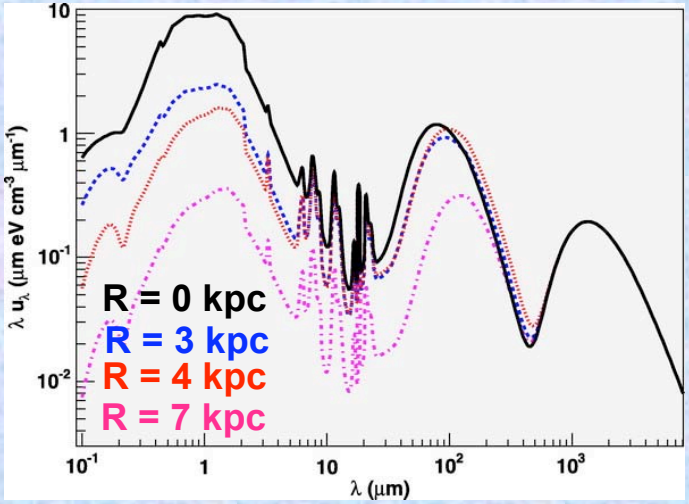
LAT spectrum of G347.3-0.5 (Stefan Funk)



G347.3-0.5 (TeV, X-rays; Aharonian et al. 2004)

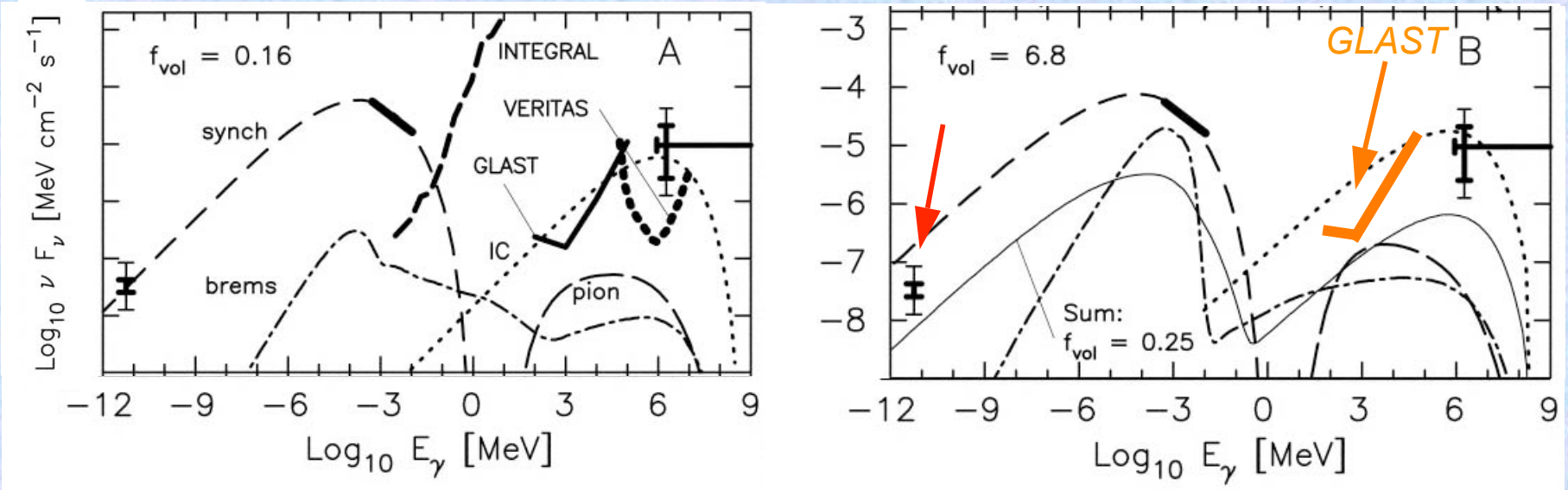
Probes of SNR Environments

- For inverse Compton emission, γ-rays probe photon field (Helfand et al. 2005; Porter et al. 2006)
- For π^0 decay, γ-rays probe ambient density



Interstellar radiation field (Moskalenko et al. 2006)

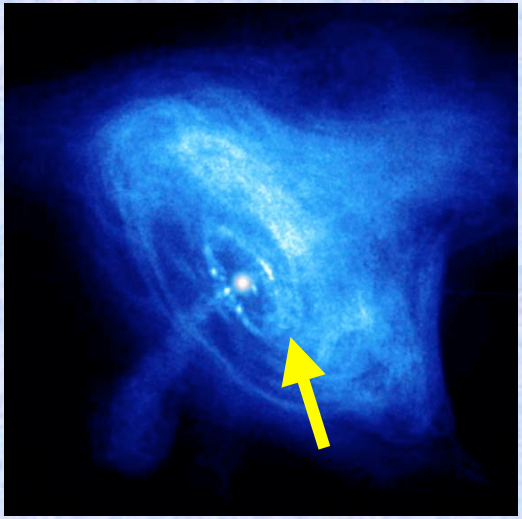
- Broadband fitting from radio to VHE γ-rays gives age, explosion energy, magnetic field, shock efficiency, $E_{max,e-}$, $E_{max,p+}$, etc.



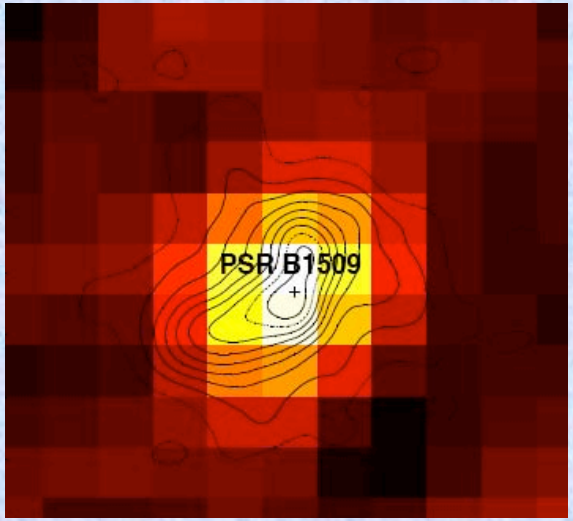
G347.3-0.5 (Ellison et al. 2001)

How Do Pulsars Accelerate Particles?

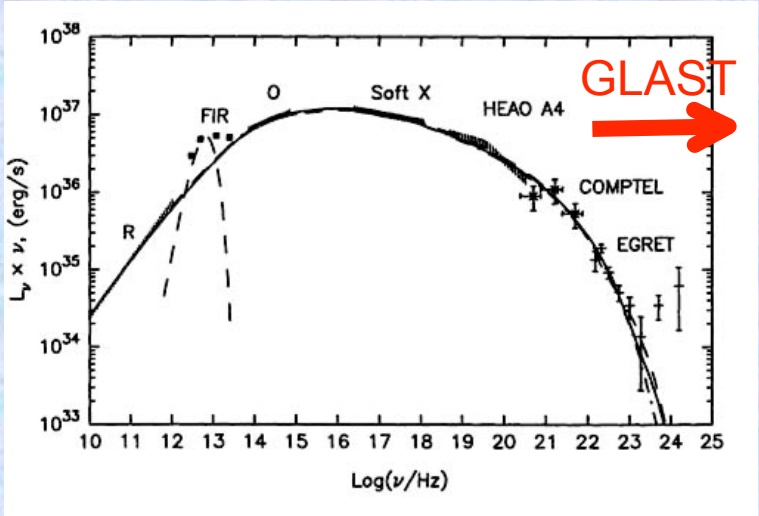
- Theory says unshocked wind has $\gamma \sim 10^6$
- X-ray & γ-ray synchrotron emission in PWNe
  - termination shock accelerates particles to $\gamma > 10^9$
- *GLAST* bandpass needed to measure synch. roll-off
  - knowing γ_{max} as fn. of pulsar parameters constrains mechanism



Crab Nebula
(*Chandra*; Weisskopf et al. 2000)



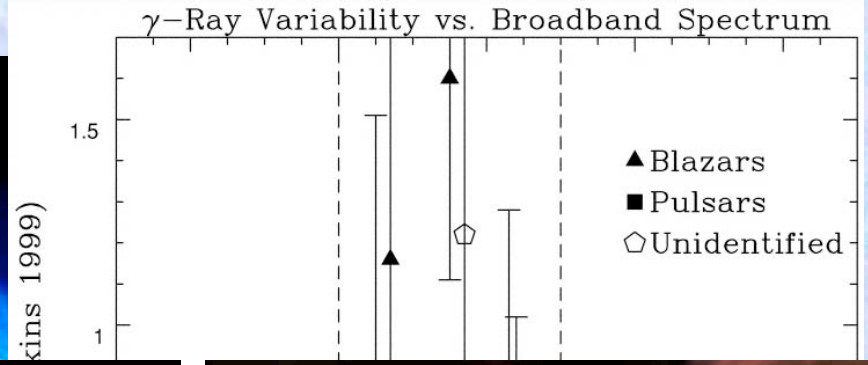
PWN around PSR B1509-58
(*INTEGRAL*; Forot et al. 2006)

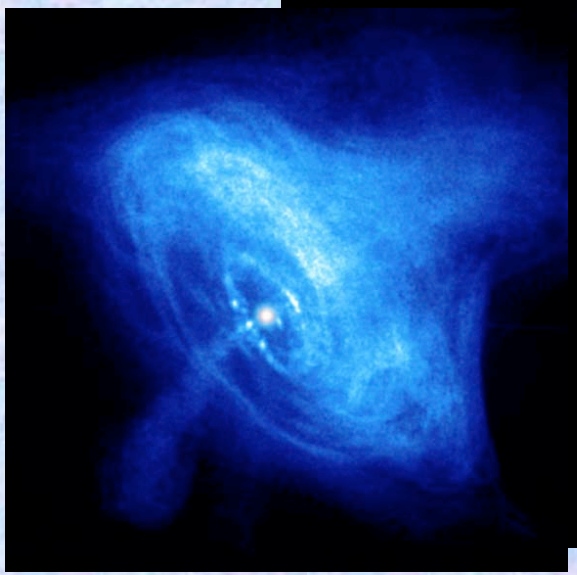


Synchrotron spectrum of Crab
(Atoyan & Aharonian 1996)

Variability in Gamma-Ray PWNe

- Gamma-ray emission from PWNe is variable, $\delta t \sim$ months
  (de Jager et al. 1996; McLaughlin et al. 1996; Roberts et al. 2001; Ling & Wheaton 2003)
- Synchrotron rather than IC
- Simultan
  - meas
  - probe

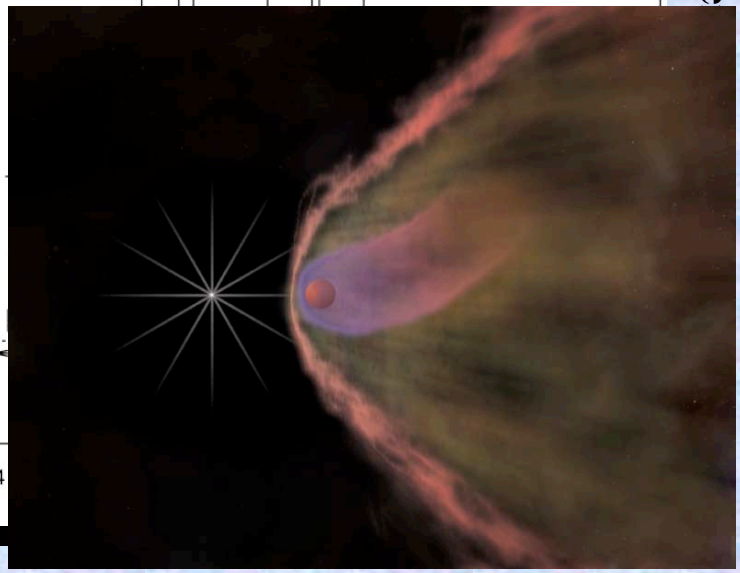




Crab Nebula (Weisskopf et al. 2000)

The Mouse (Gaensler et al. 2004)

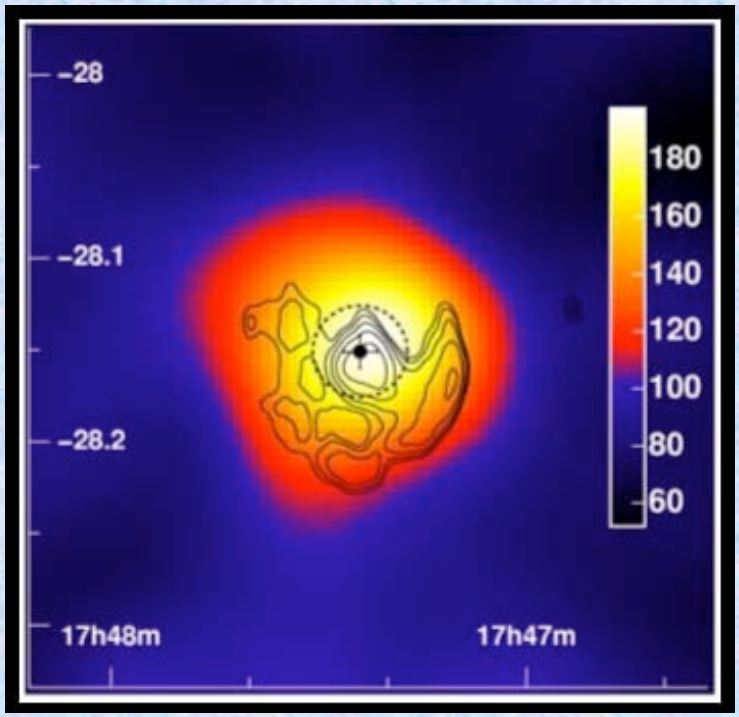
NASA/CXC/ASU/J.Hester et al.



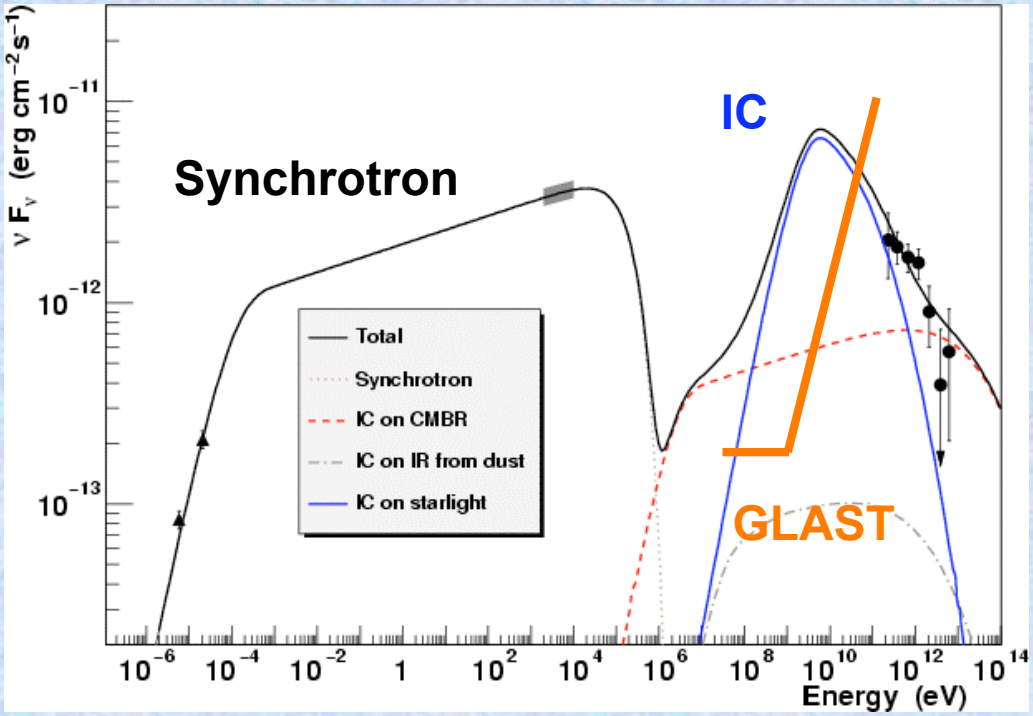
Black Widow (NASA/CXC/M.Weiss)

Inverse Compton Emission in PWNe

- Several pulsar wind nebulae now seen with HESS
  - inverse Compton emission from CMB, starlight, IR from dust
  - Cerenkov detectors usually see high-energy tail
  - *GLAST* will see spectral peak + overlap with synchrotron



PWN G0.9+0.1 (HESS/VLA; Aharonian et al. 2005)

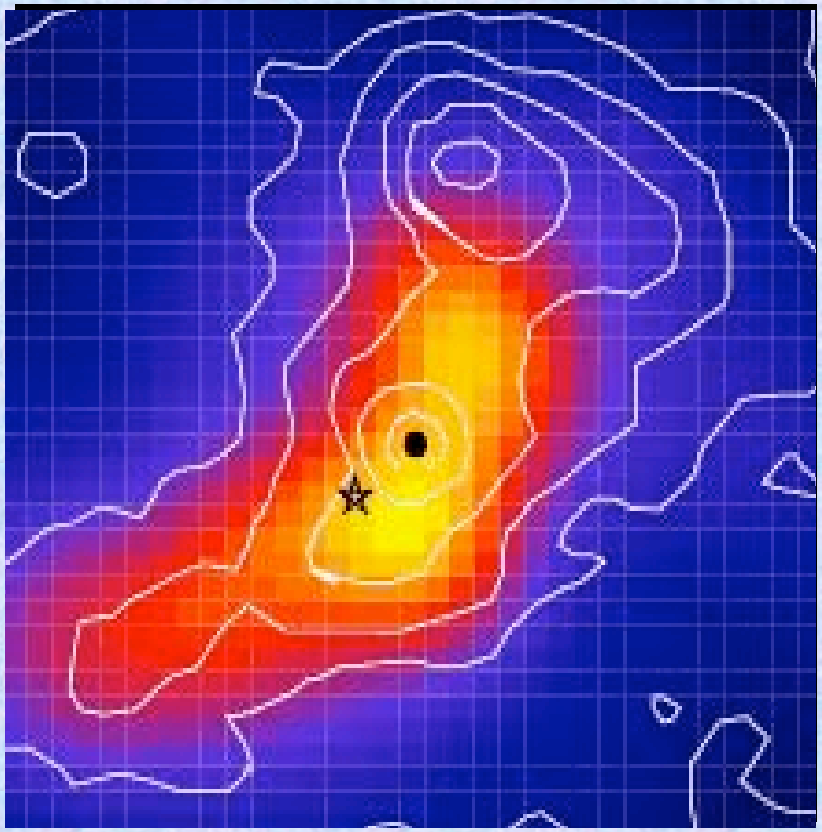


Broadband spectrum of G0.9.+0.1 (Aharonian et al. 2005)

Inverse Compton in PWNe (cont.)

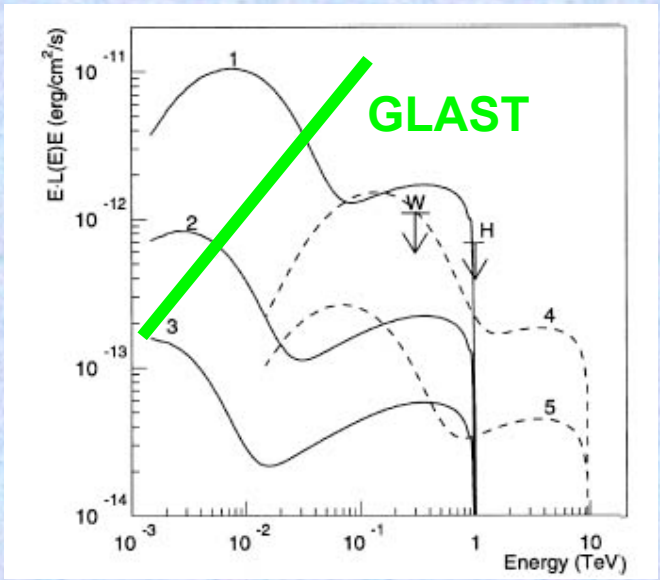
- Synchrotron is convolution of *N(E)*, *B*
- IC depends on *N(E)*, photon field
- Spatial distribution of synch., IC
  - spatially resolved map of *B*
  - particle content, injection rate
  - $\sigma = E_{\text{fields}}/E_{\text{particles}}$
- Pulsed IC from *unshocked* wind?

(Ball & Kirk 1999; Bogovalov & Aharonian 2000)



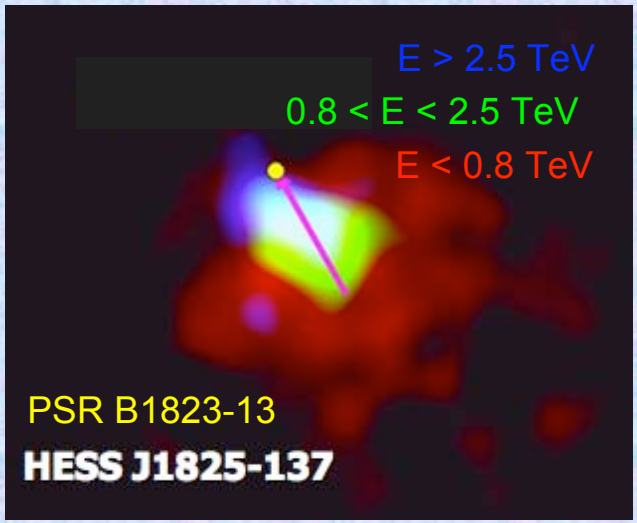
B1509-58 (*CESSdra*; Slane et al. 2006)

Crab Nebula
(Bogovalov & Aharonian 2000)



Offset Gamma-Ray PWNe

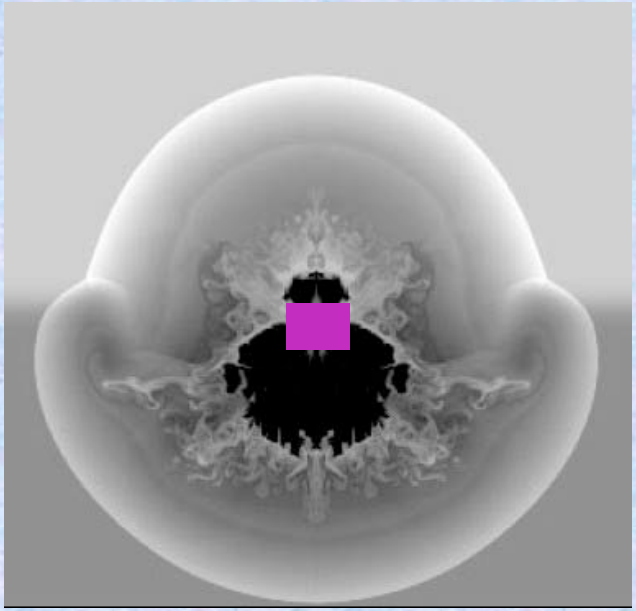
- HESS sees large TeV nebulae to one side of energetic pulsars
  - reverse shock from aspherical SNR? (Gaensler et al. 2003; Aharonian et al. 2005)
  - systems need to expand rapidly, age ~ 5,000 - 20,000 years (e.g., de Jager & Venter 2005)



Aharonian et al. (2006)

- *GLAST* obs. of "Vela-like" pulsars
  - ~25 sources known (Kramer et al. 2003)
  - nebulae will be v. large at E ~ 1 GeV
  - morphology vs. E over five decades

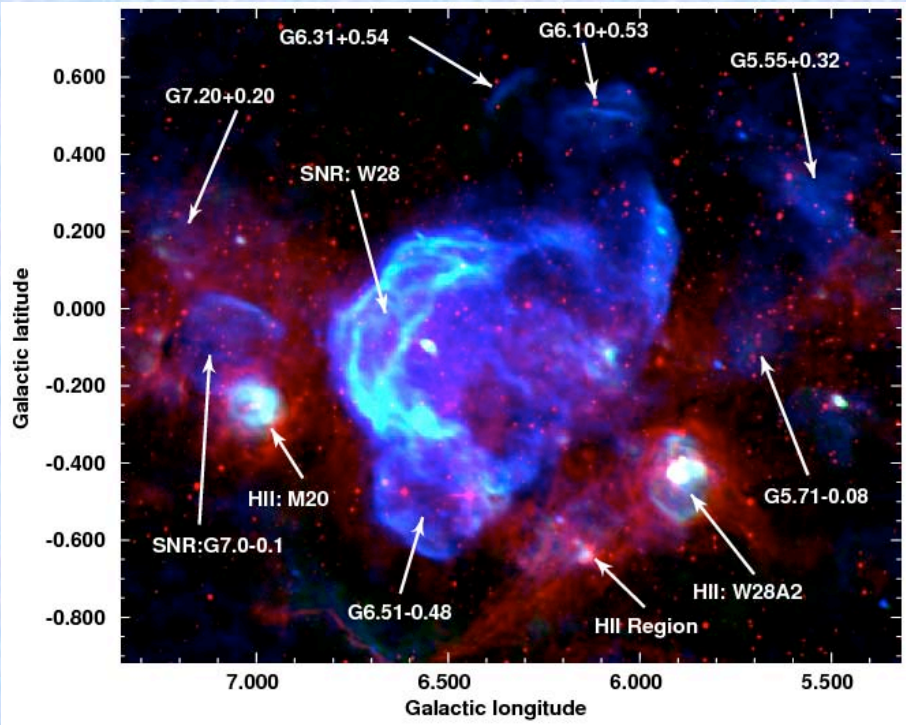
→ particle transport, magnetic fields, diffusion, interaction with ISM/CSM



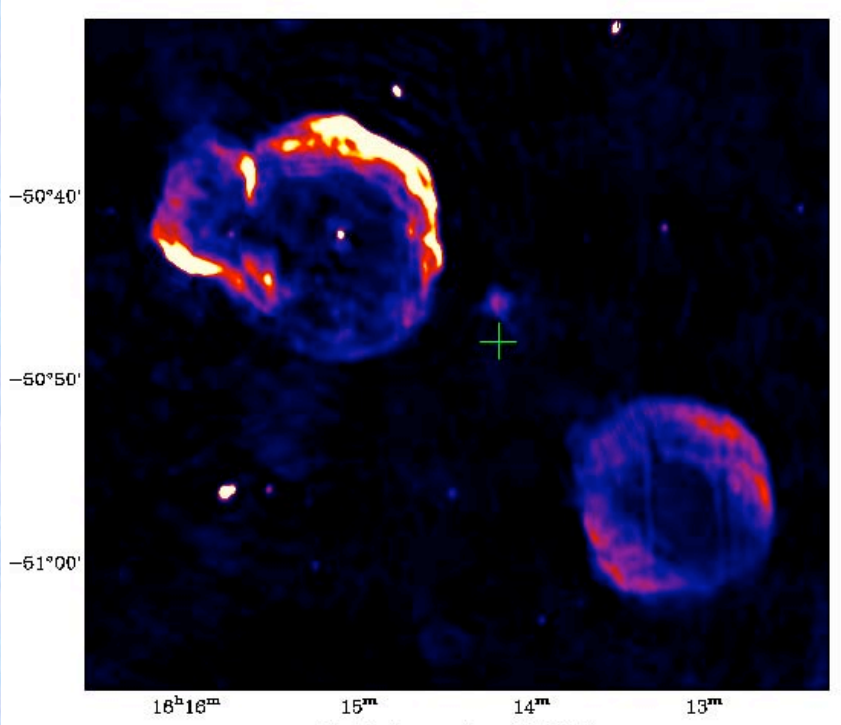
Blondin et al. (2001)

Surveys & Discovery

- > 1000 missing supernova remnants in Galaxy
- Young pulsars without supernova remnants or pulsar wind nebulae
  - invisible in synchrotron if *B* is low
    ... but inverse Compton independent of *B*
- <u>Many</u> new SNRs & PWNe seen w. *GLAST*, especially for $|l| < 45^0$



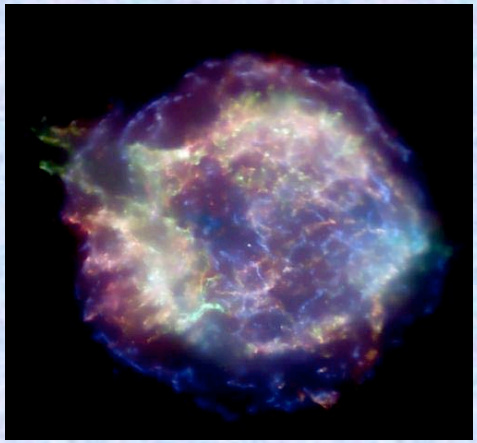
35 new SNRs in 1st Galactic quadrant (Brogan et al. 2006)



7000 year old pulsar B1610-50 (Stappers et al. 1999)

Summary

- *GLAST* will (finally!) reveal sites & products of particle acceleration in SNRs
- *GLAST* will watch pulsars accelerate particles in real time
- GLAST will map distribution, evolutionary history, injection rate of particles and magnetic fields in PWNe
- *GLAST* spectra + multi-wavelength data will tightly constrain evolution, environment, ambient photon field of SNRs & PWNe
- *GLAST* will help complete Galactic sample of SNRs & PWNe



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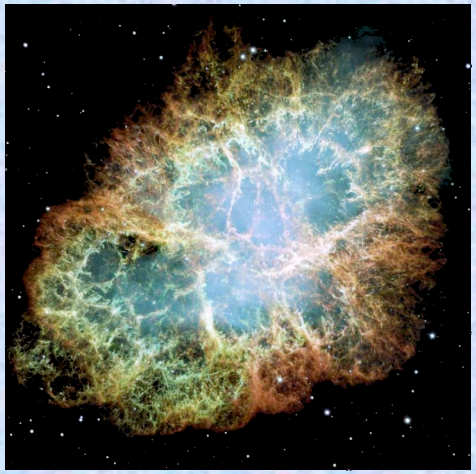

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