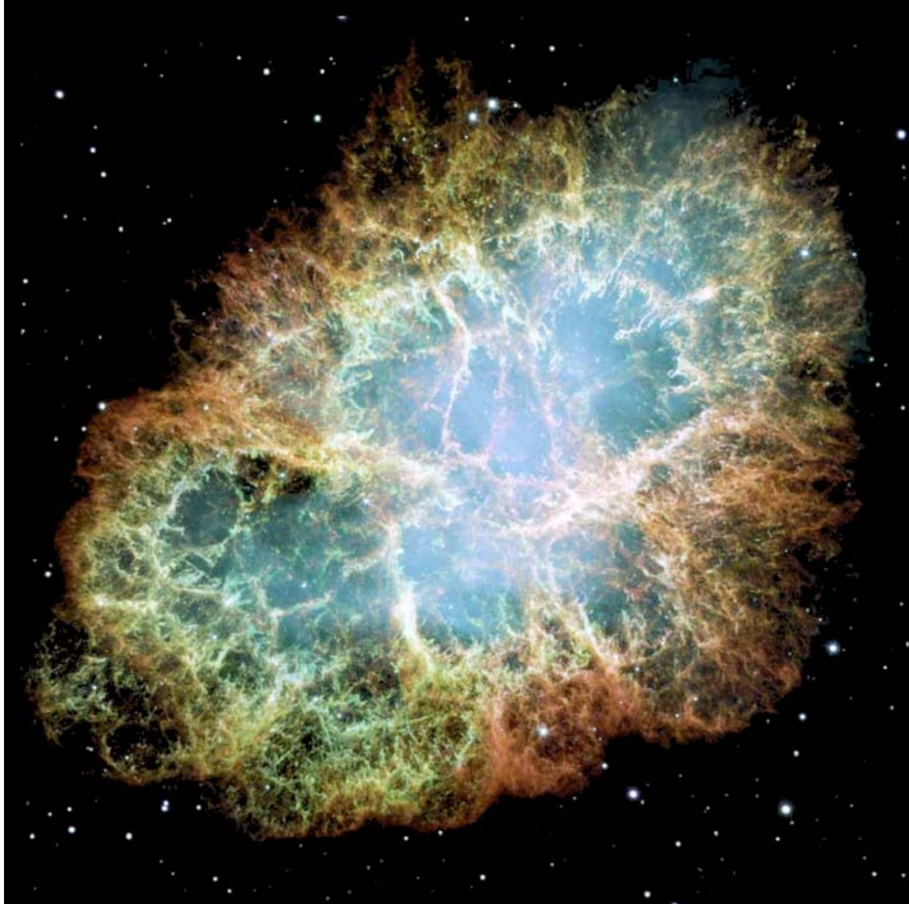
NASA / ESA / J. Hester / A. Loll / ASU



New Views of Pulsar Winds in TeV Gamma-rays

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Pulsar Wind Nebulae

- **All pulsars are slowing down**

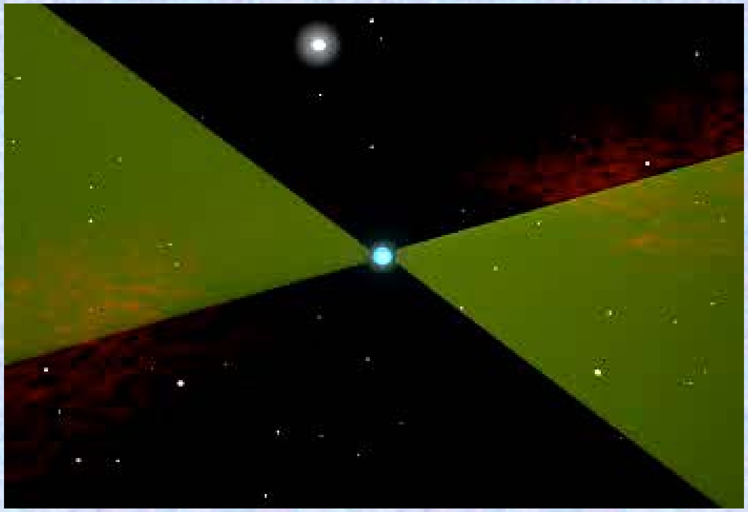
$$\dot{E} = I\omega\dot{\omega} = 10^{32} - 10^{39} \text{ ergs s}^{-1}$$

- **Where does this energy go?**
  - usually negligible energy in pulses
  - relativistic magnetized particle wind

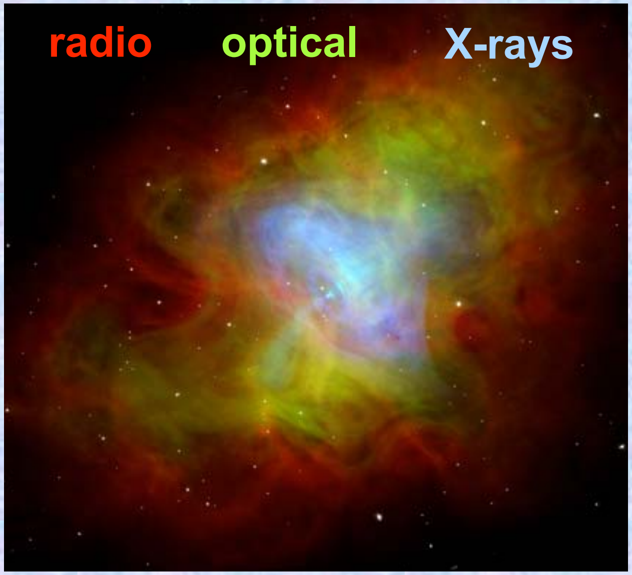
- **Shock where wind terminates**

→ ***pulsar wind nebula*** (PWN)

- direct calorimeter for energy loss processes
- laboratory for studying relativistic shocks & interaction with surroundings (GRBs, AGN)
- unambiguous signpost for young, energetic neutron stars



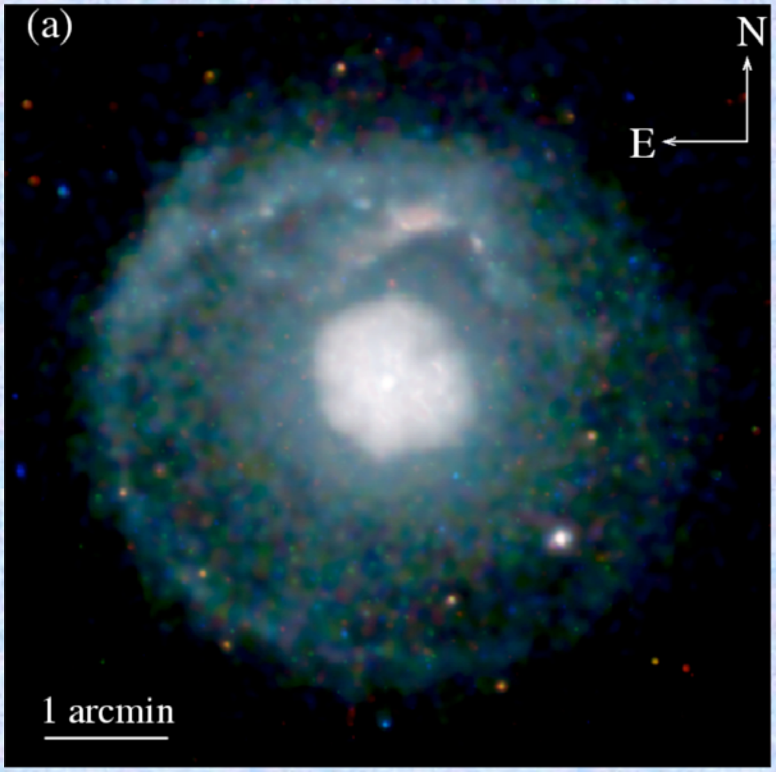
NASA / CXC



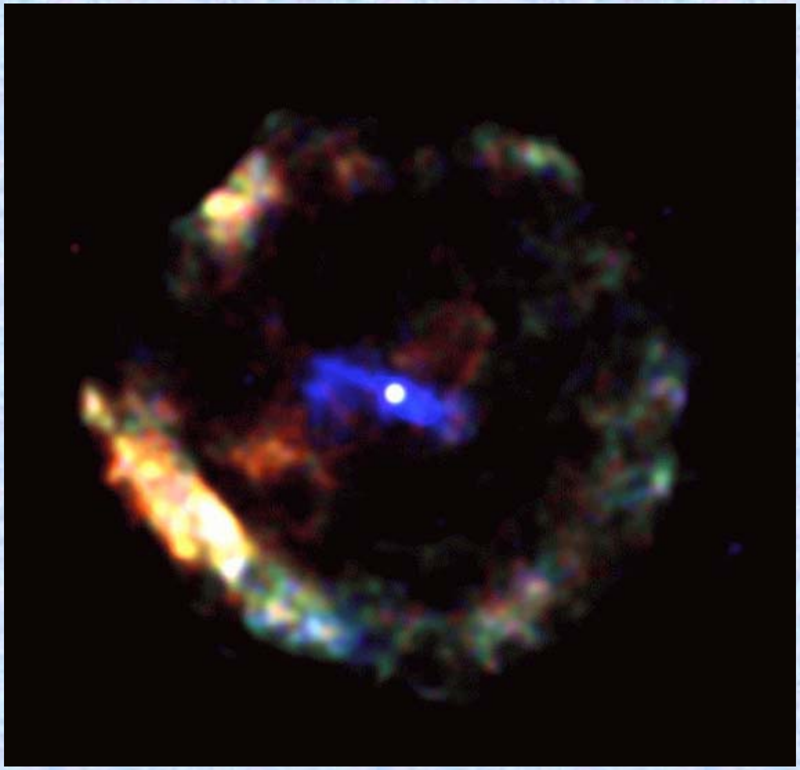
Crab Nebula (Hester et al. 2002)

Expansion into Unshocked Ejecta

- Assume continuous energy injection produces synchrotron nebula
- PWN expands supersonically into low-P environment, $R_{\mathrm{PWN}} \propto t^{6/5}$
- Sound speed high: PWN stays centered on pulsar

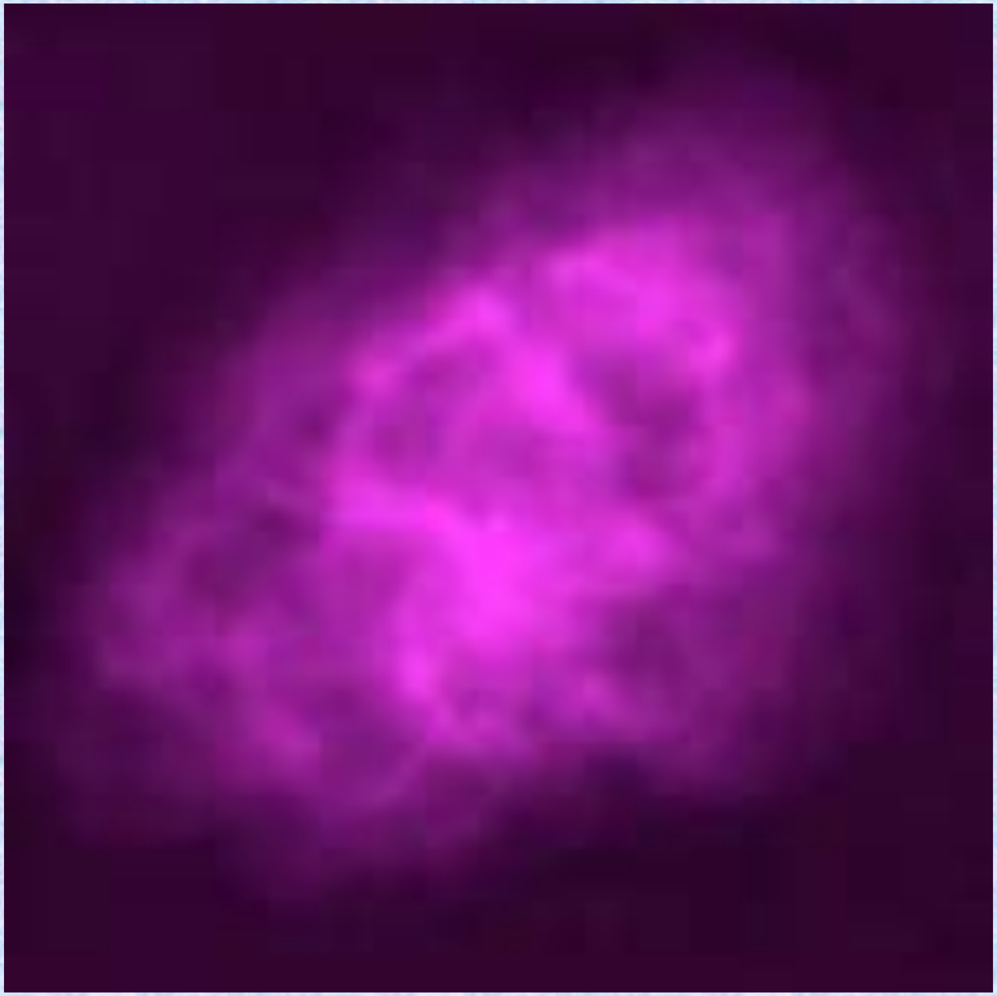


SNR G21.5-0.9 with PWN and pulsar
(X-rays; Matheson & Safi-Harb 2005)



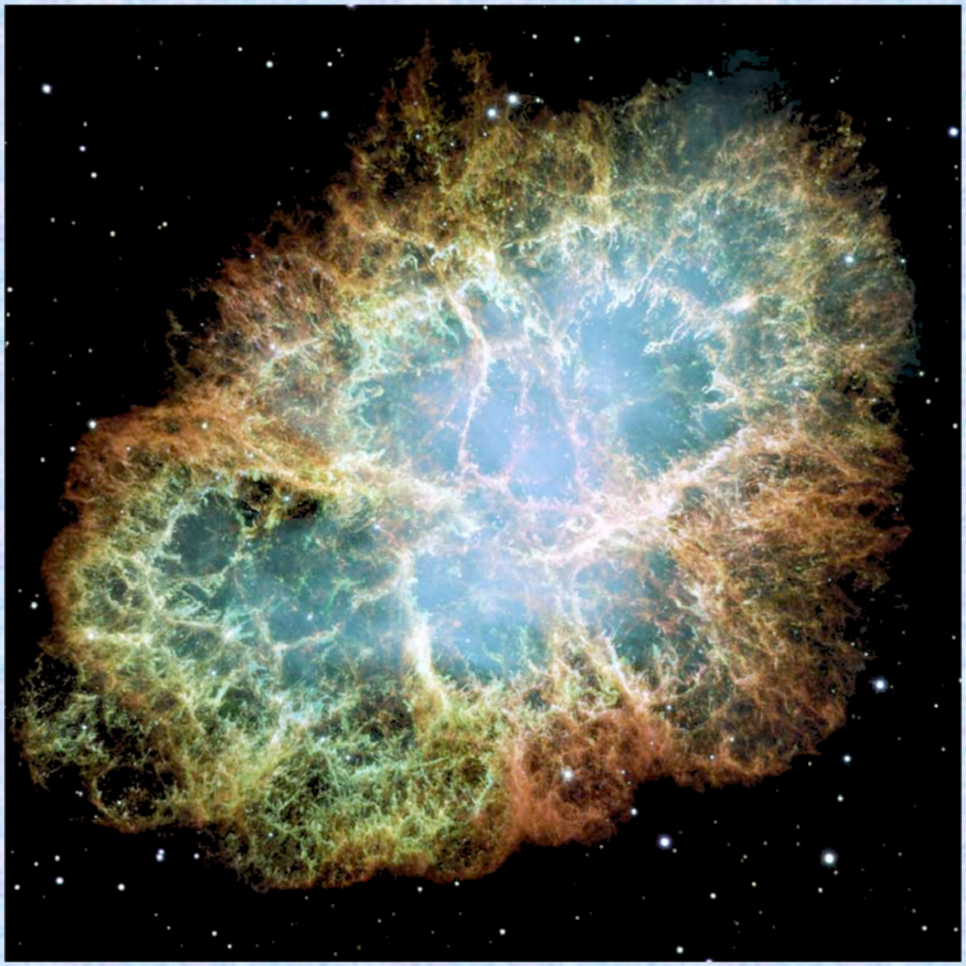
SNR G11.2-0.3 with PWN and pulsar
(X-rays; Kaspi et al. 2001)

The Multi-Wavelength Crab Nebula



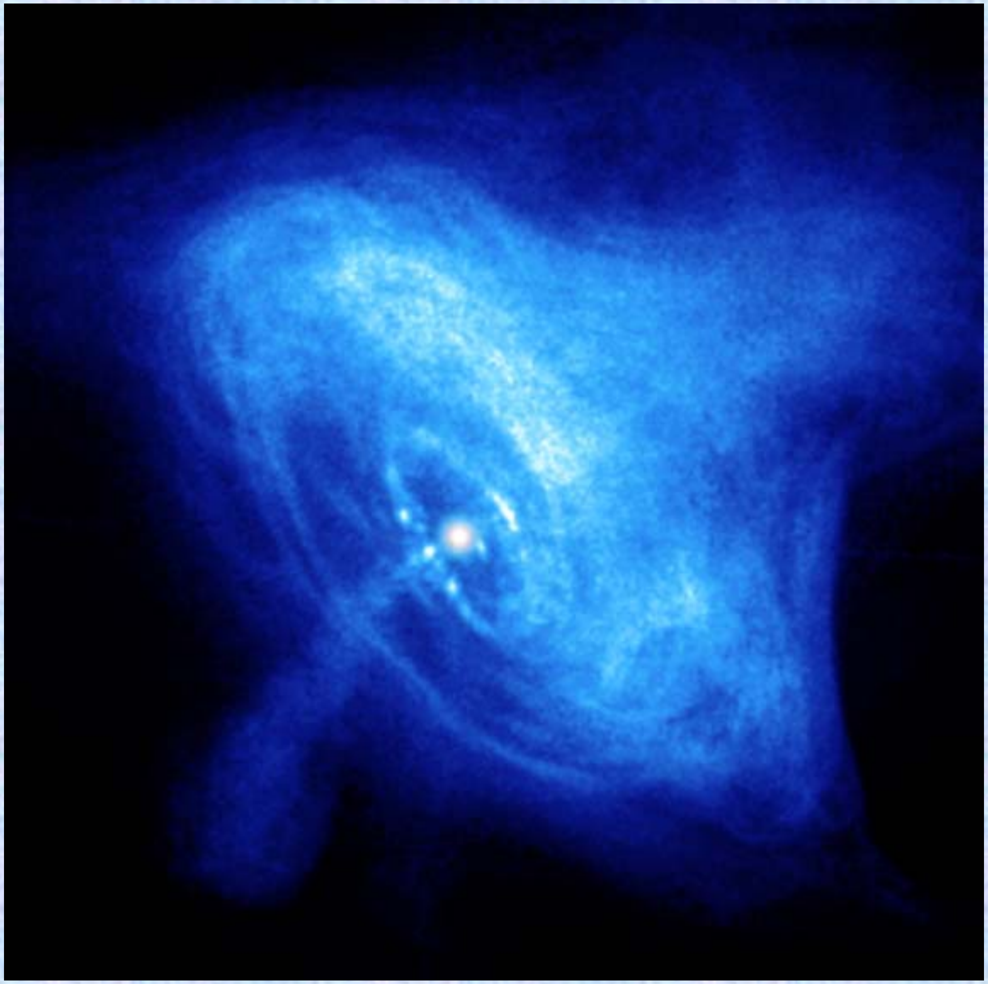
Radio (VLA; NRAO)

The Multi-Wavelength Crab Nebula



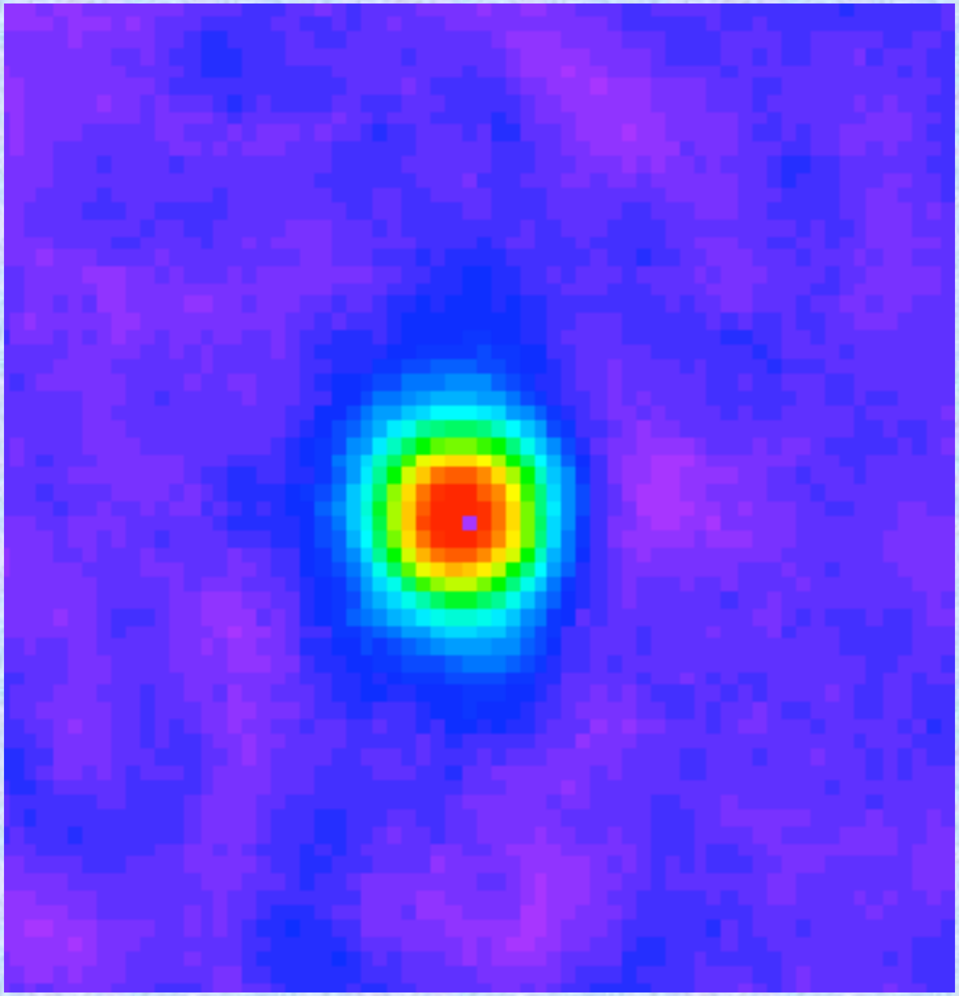
Optical (*HST*; NASA / ESA / J. Hester / A. Loll / ASU)

The Multi-Wavelength Crab Nebula



Soft X-rays (*Chandra*; Weisskopf et al. 2000)

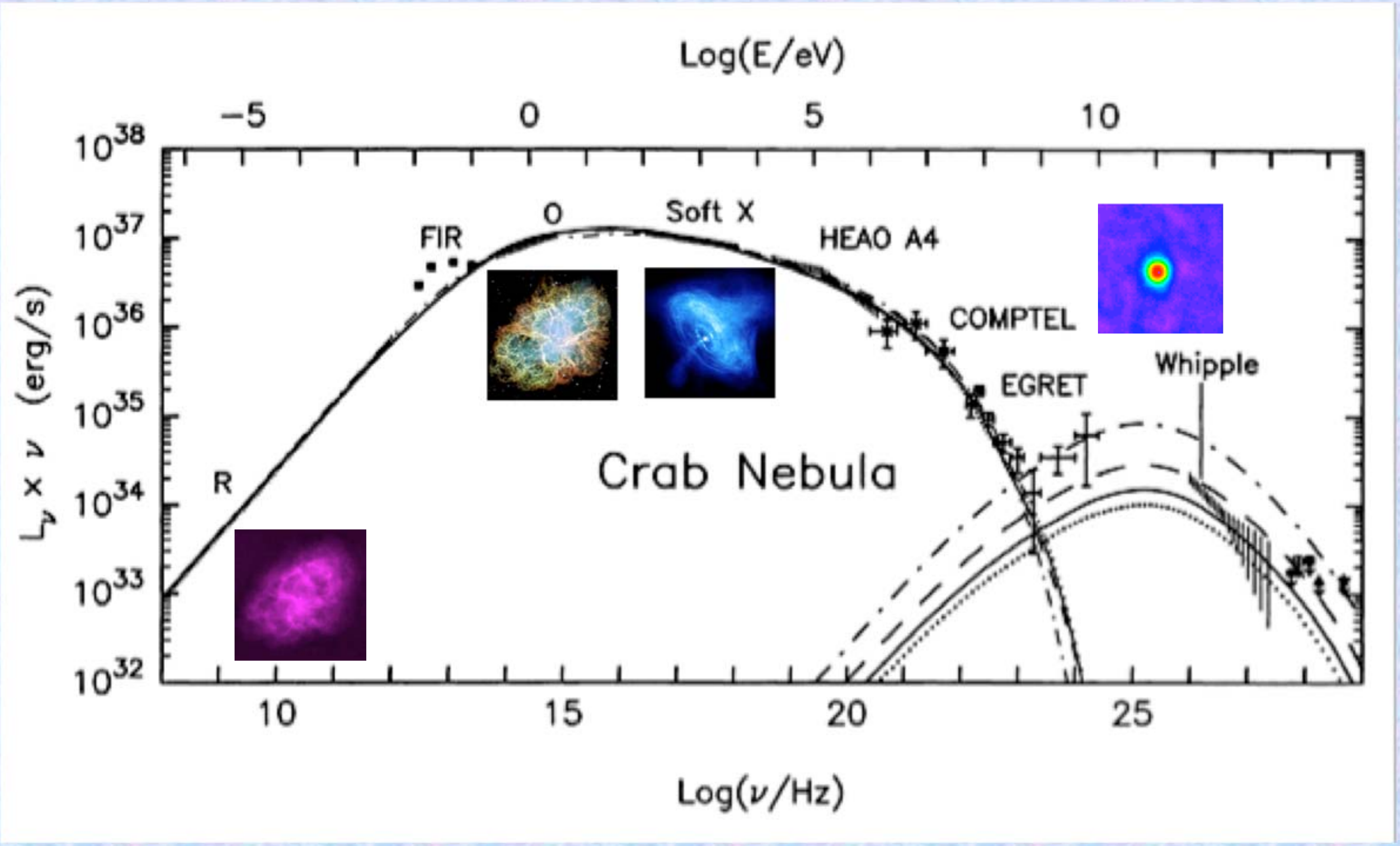
The Multi-Wavelength Crab Nebula



TeV gamma-rays (HESS; Aharonian et al. 2006 / J. Braun)

Gamma-rays From Crab Nebula

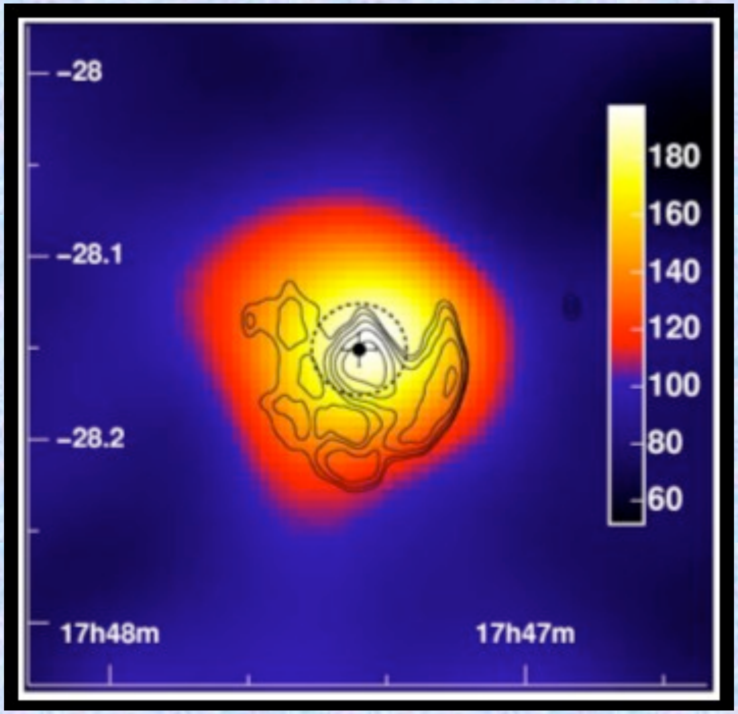
- EGRET spectrum of Crab Nebula shows upturn at E ~ 1 GeV
  - modelled as synchrotron + synchrotron-self-Compton



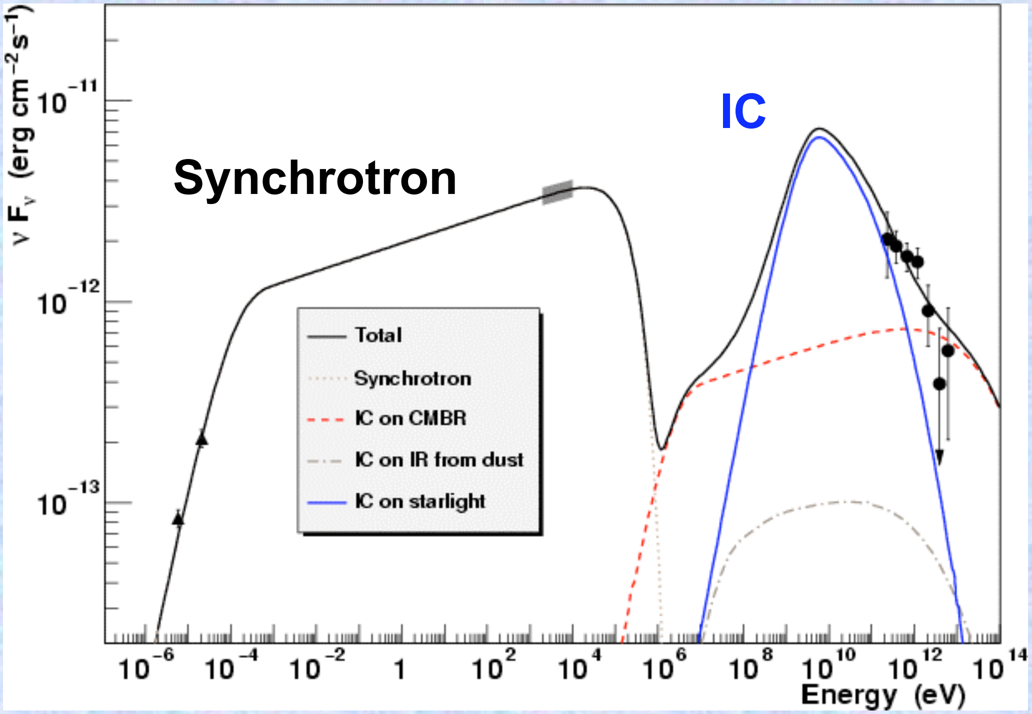
Atoyan & Aharonian (1996)

Gamma-rays from Other PWNe

- Several pulsar wind nebulae now seen in TeV gamma-rays
  - inverse Compton emission from CMB, starlight, IR from dust



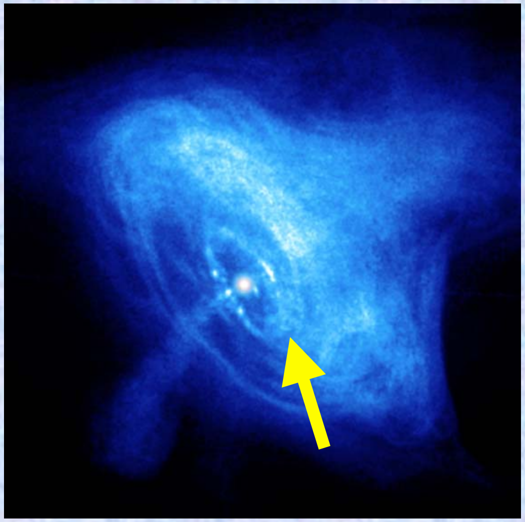
PWN G0.9+0.1 (HESS/VLA; Aharonian et al. 2005)



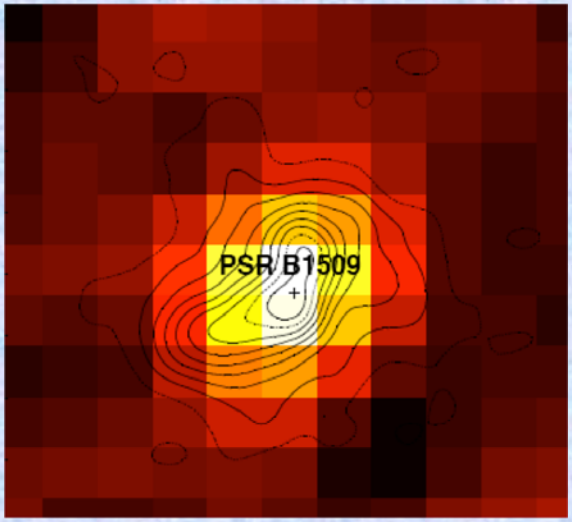
Broadband spectrum of G0.9.+0.1 (Aharonian et al. 2005)

How Do Pulsars Accelerate Particles?

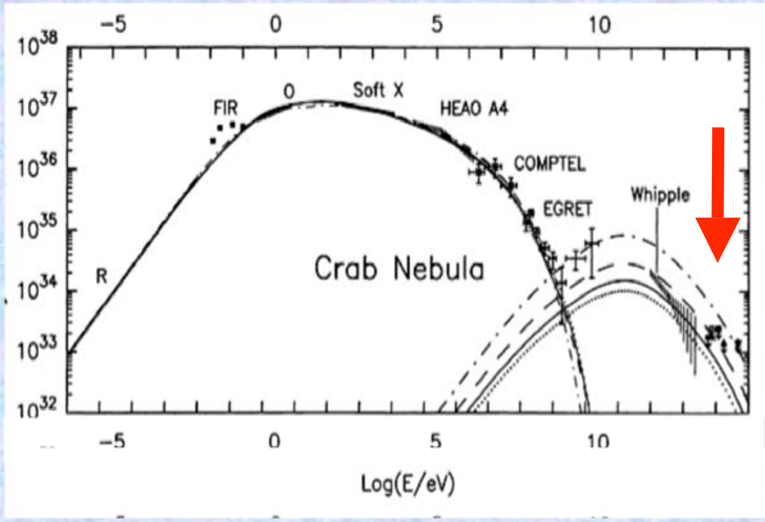
- Theory says unshocked wind has $\gamma \sim 10^6$
- X-ray & γ-ray synchrotron emission in PWNe
  - termination shock accelerates particles to $\gamma > 10^9$
- Data at E > 100 TeV needed to measure IC roll-off
  - knowing γ_{max} as fn. of pulsar parameters constrains mechanism



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



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

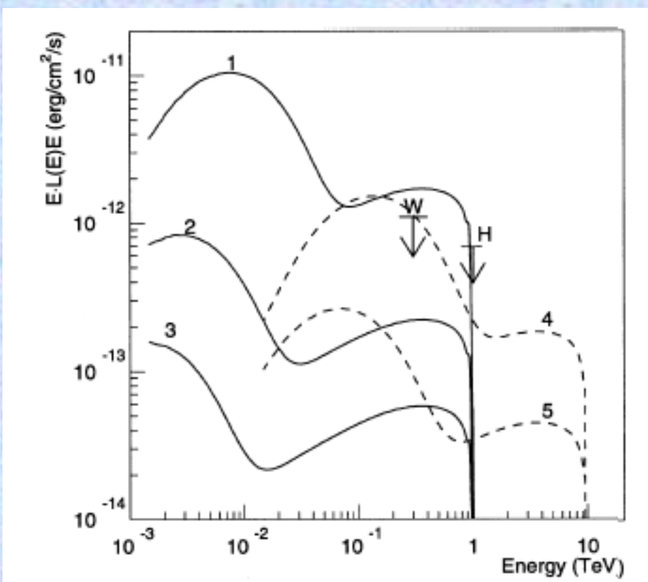


Spectrum of Crab Nebula
(Atoyan & Aharonian 1996)

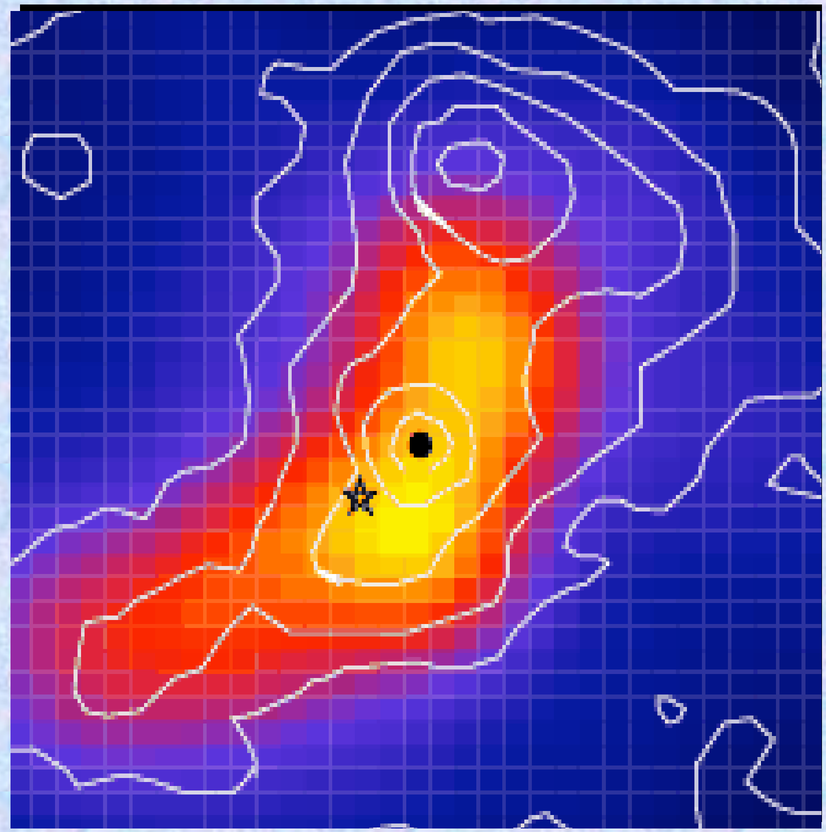
Inverse Compton in PWNe

- 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)



Crab Nebula
(Bogovalov & Aharonian 2000)

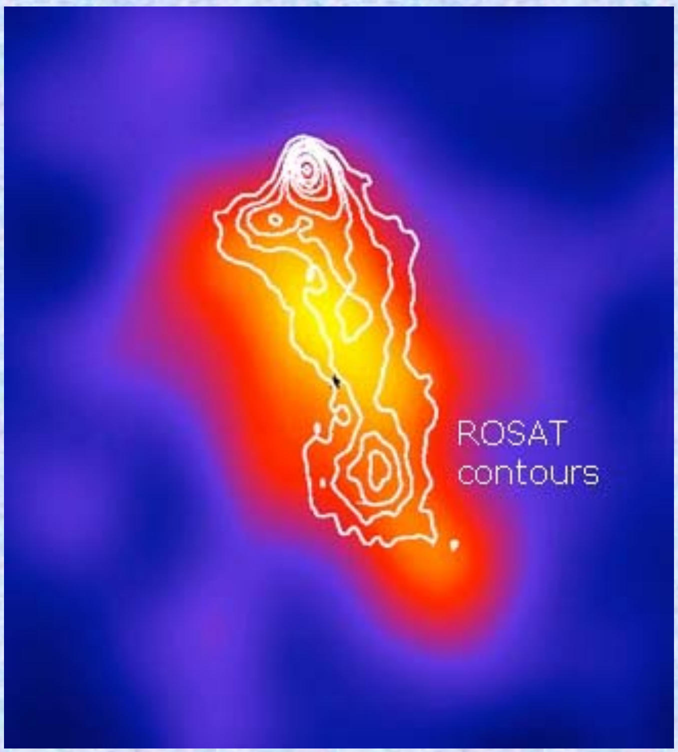


B1509-58 (*Chandra*; Slane et al. 2006)
B1509-58 (HESS; Aharonian et al. 2005)

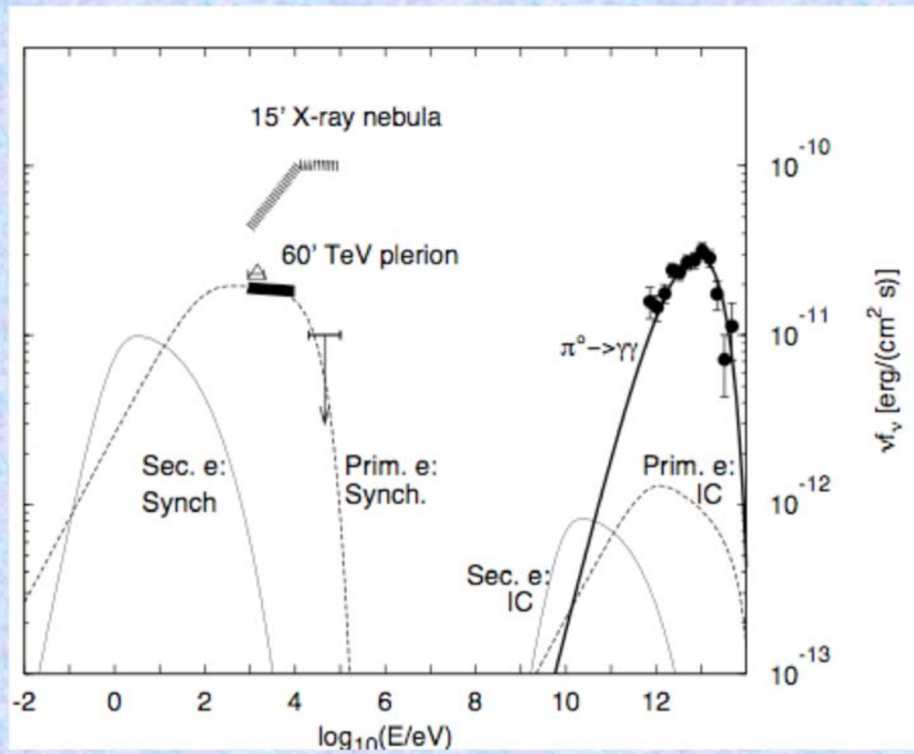
Nucleons in Pulsar Winds

- Ions in wind will produce macroscopic shock structure
  - generate magnetosonic waves which can accelerate e^- (Hoshino et al. 1992)
  - may explain appearance and evolution of "wisps" in Crab Nebula & B1509-58 (Gallant & Arons 1994; Spitkovsky & Arons 2004)

- Do we see π^0 decay from relativistic ions accelerated in PWNe?



Vela X (HESS; Aharonian et al. 2006)



Vela X (Horns et al. 2006)

Expansion into Unshocked Ejecta

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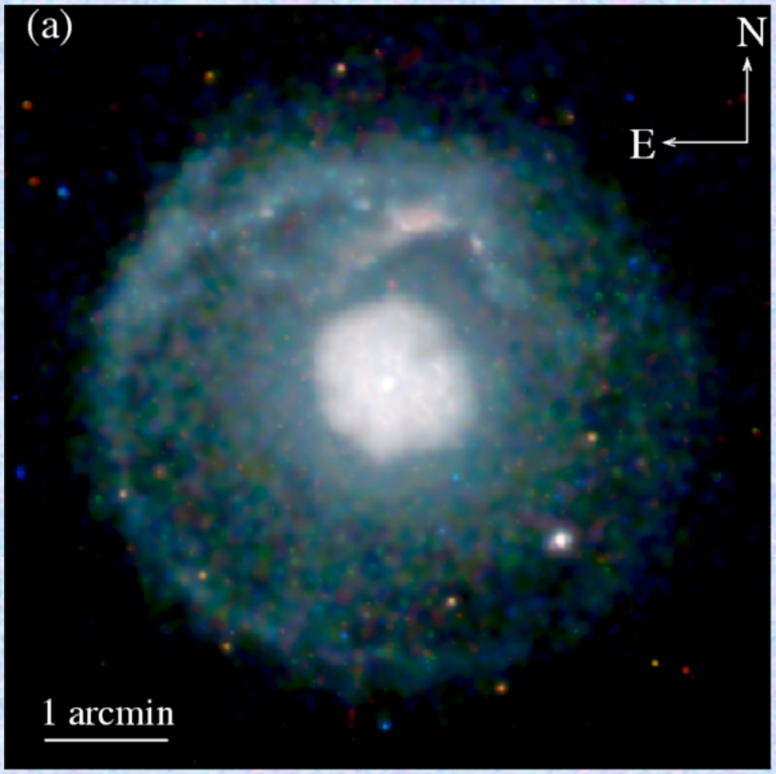
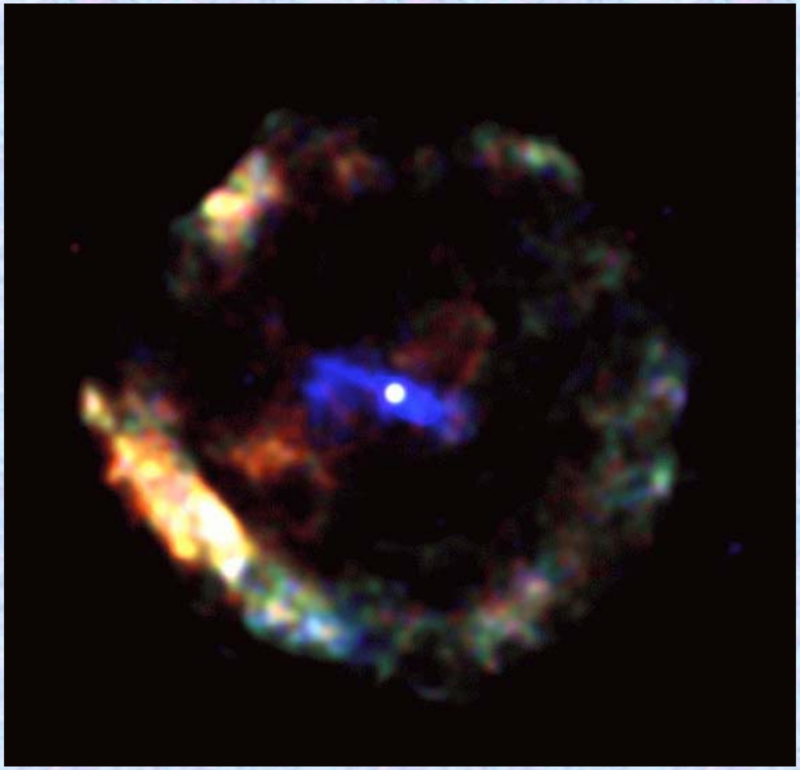


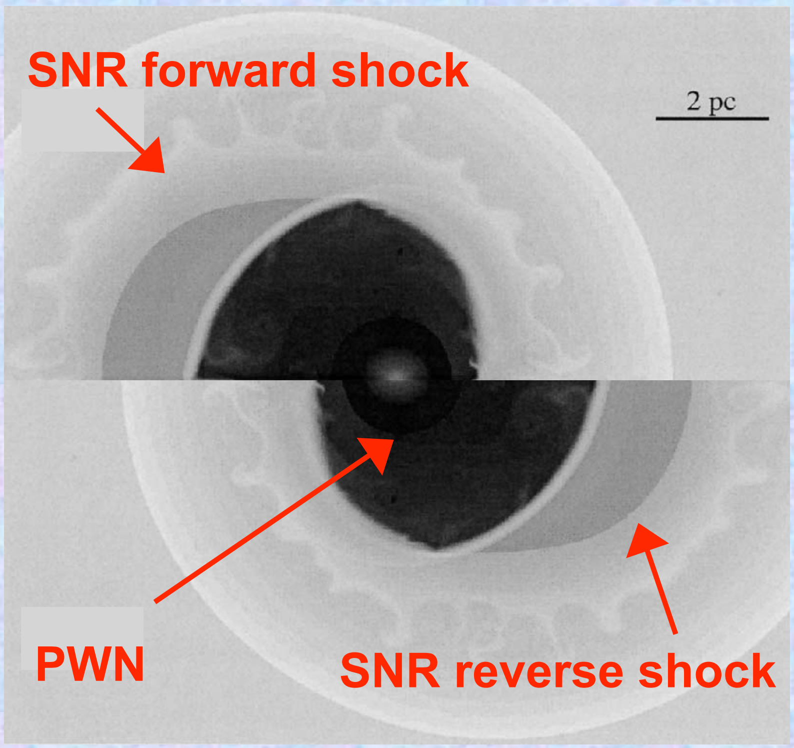
SNR G21.5-0.9 with PWN and pulsar
(X-rays; Matheson & Safi-Harb 2005)



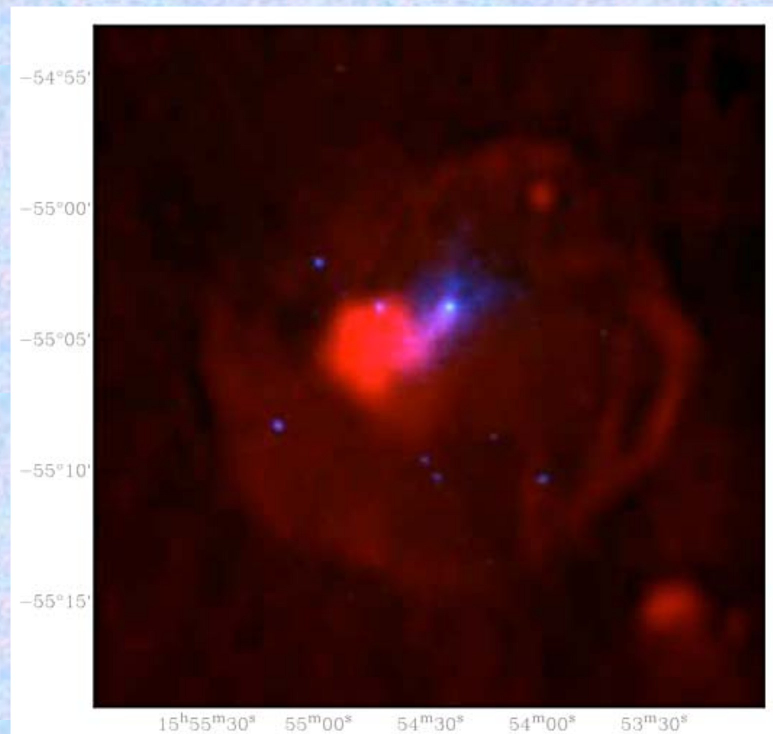
SNR G11.2-0.3 with PWN and pulsar
(X-rays; Kaspi et al. 2001)

Interaction with SNR Reverse Shock

- Reverse shock crushes PWN after time $t \sim 7 M_{10M_{sun}}^{5/6} E_{51}^{-1/2} n_0^{-1/3}$ kyr
- Compression & reverberation; synchrotron burn-off at high energies
- Asymmetric collision for moving pulsar or ISM gradient
- Pulsar now at one edge of “relic” radio PWN



van der Swaluw et al. (2004)



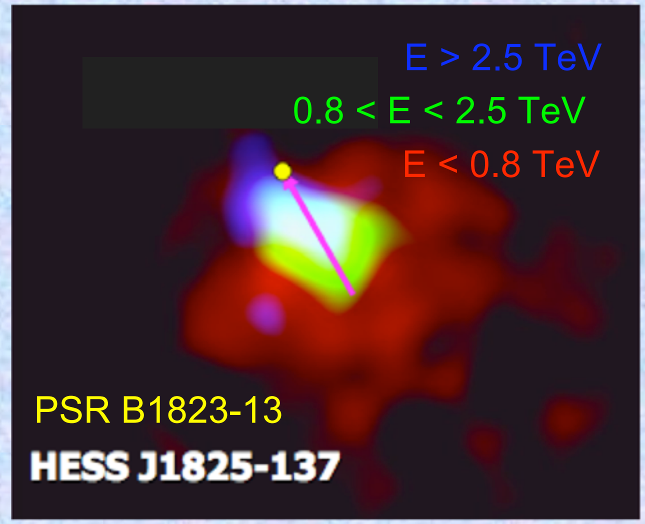
SNR G327.1-1.1 (radio + X-rays; Gaensler & Slane 2006)

Offset Gamma-Ray PWNe

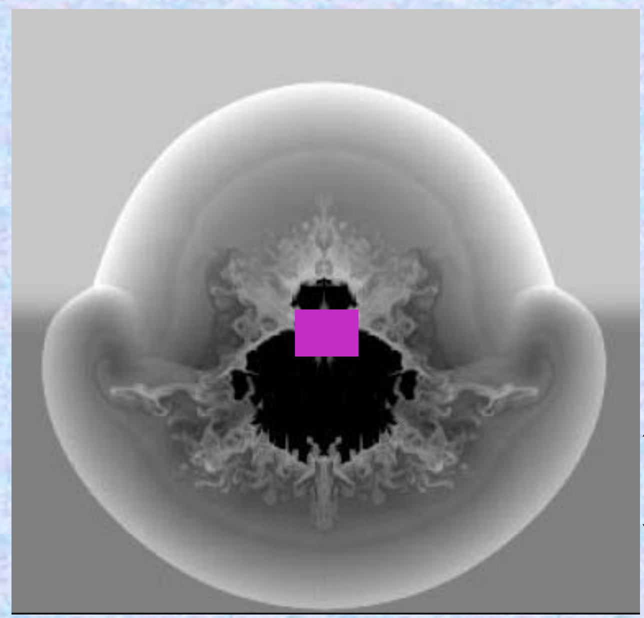
- HESS sees large TeV nebulae to one side of several energetic pulsars
  - energy dependence confirms IC mechanism
  - reverse shock interaction with SNR?
    (Gaensler et al. 2003; Aharonian et al. 2005)
  - TeV systems must have expanded rapidly, age ~ 10,000 - 40,000 years
    (e.g., de Jager & Venter 2005)

- Implies possible molecular cloud interactions?
  - confirmed by ^{12}CO detections (Lemiére et al. 2006)

- Approx. 25 "Vela-like" pulsars known
  (Kramer et al. 2003)
  - expect large number of offset PWNe
  → particle transport, magnetic fields, diffusion, interaction with ISM/CSM

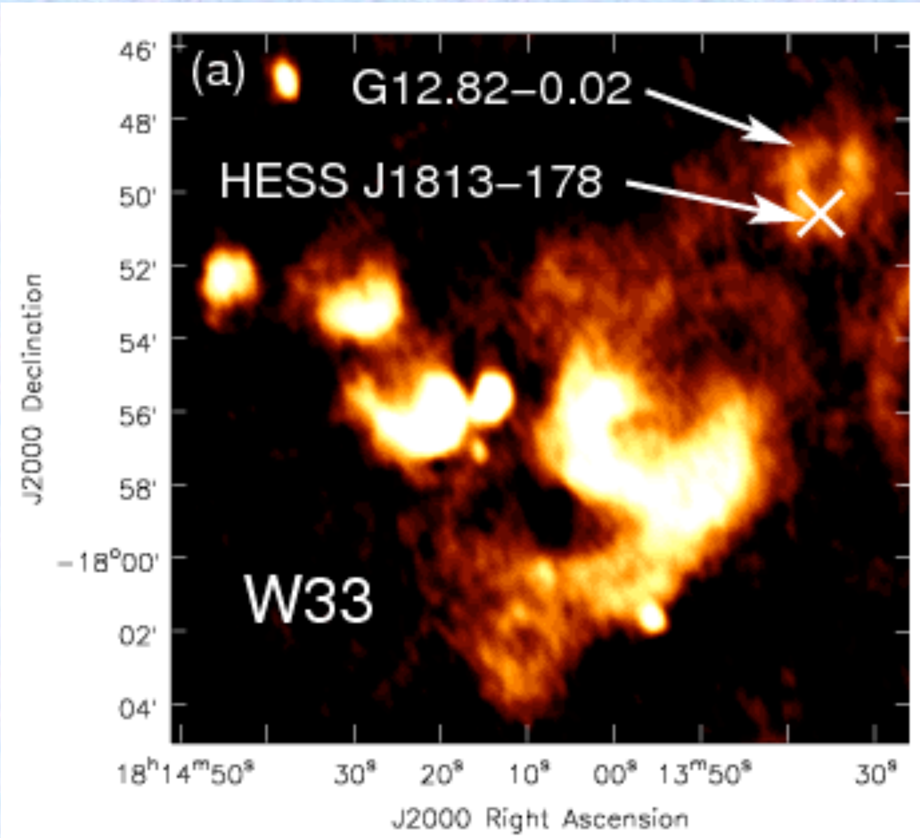


Aharonian et al. (2006)


Blondin et al. (2001)

New Pulsar Wind Nebulae

- Extended TeV source HESS J1813-178
  - radio reveals very young SNR, G12.8-0.0

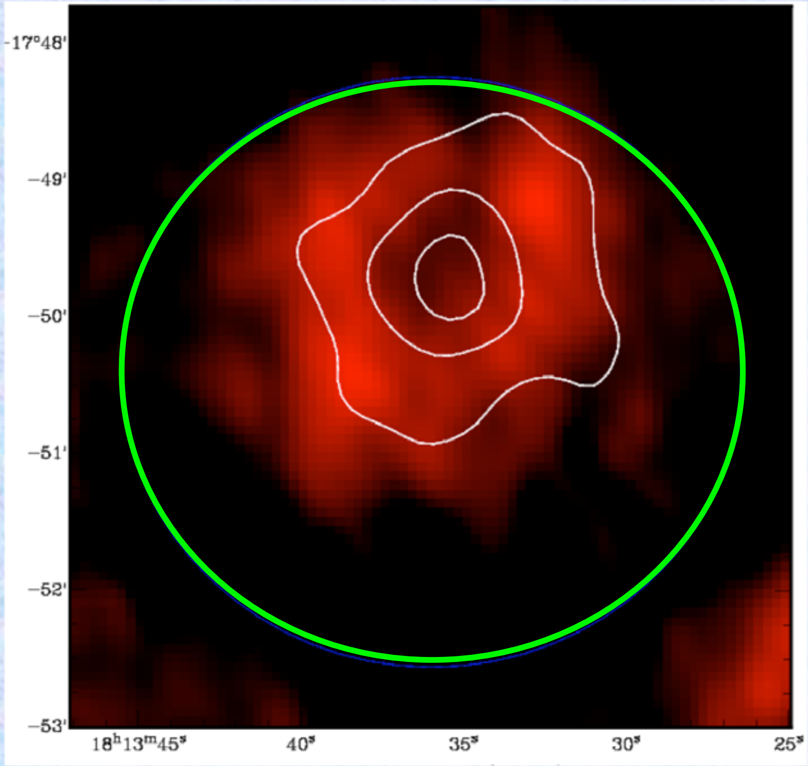


VLA 90cm (Brogan, Gaensler et al. 2005)

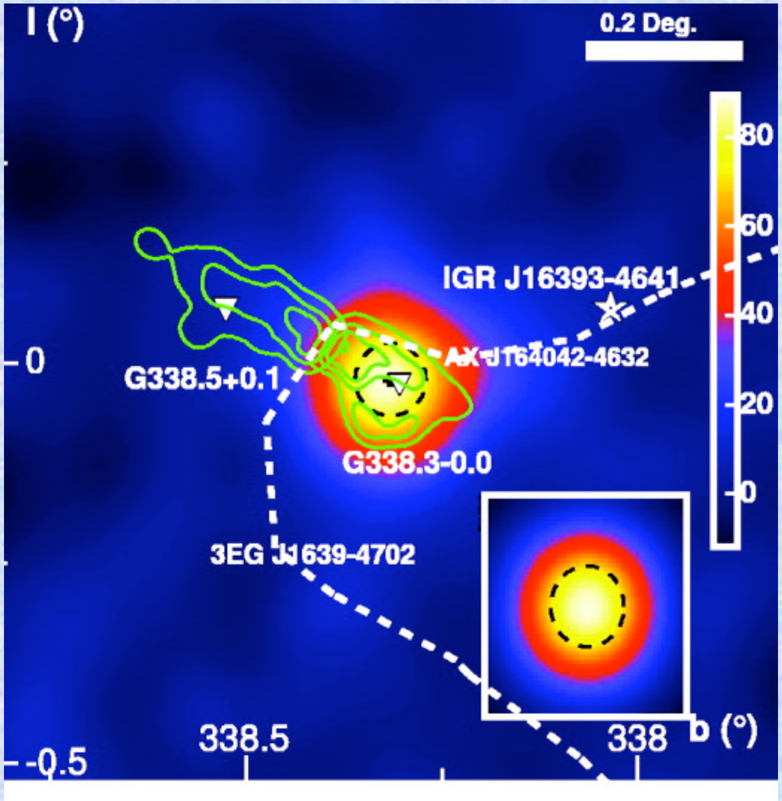
New Pulsar Wind Nebulae

- Extended TeV source HESS J1813-178
  - radio reveals very young SNR, G12.8-0.0
  - matches X-ray source AX J181336-1749
    (Brogan, Gaensler et al. 2005; Ubertini et al. 2005)
  - *XMM* images show central X-ray nebula
    (Funk et al. 2006)

- TeV source HESS J1640-465
  - matches X-ray source AX J164042-4632
  - matches catalogued SNR G338.3-0.0
    (Aharonian et al. 2006)



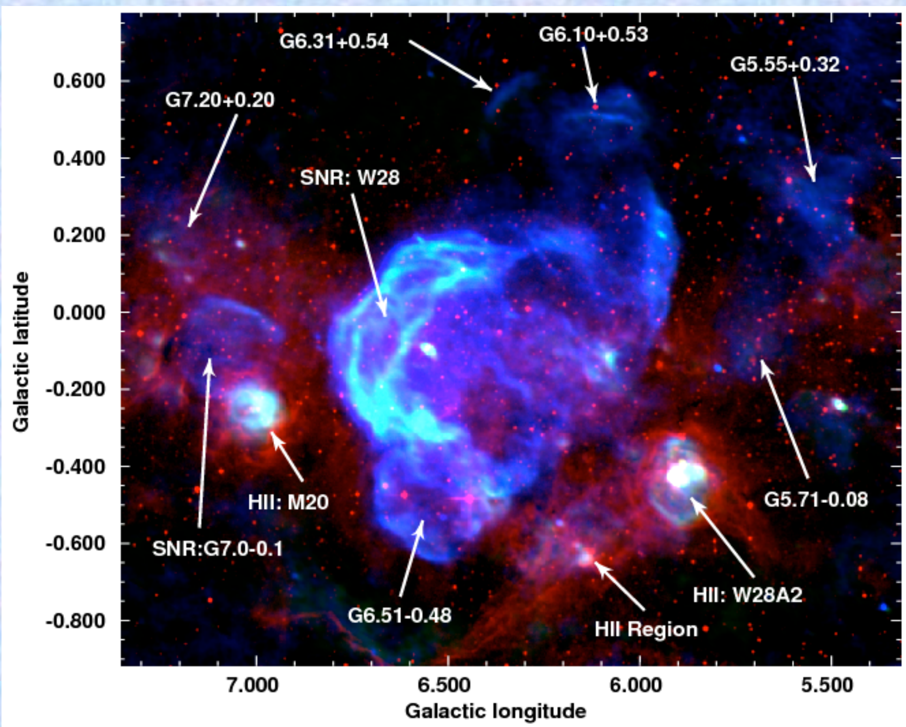
Red: VLA; Blue: HESS; Contours: *ASCA* (Brogan et al. 2005)



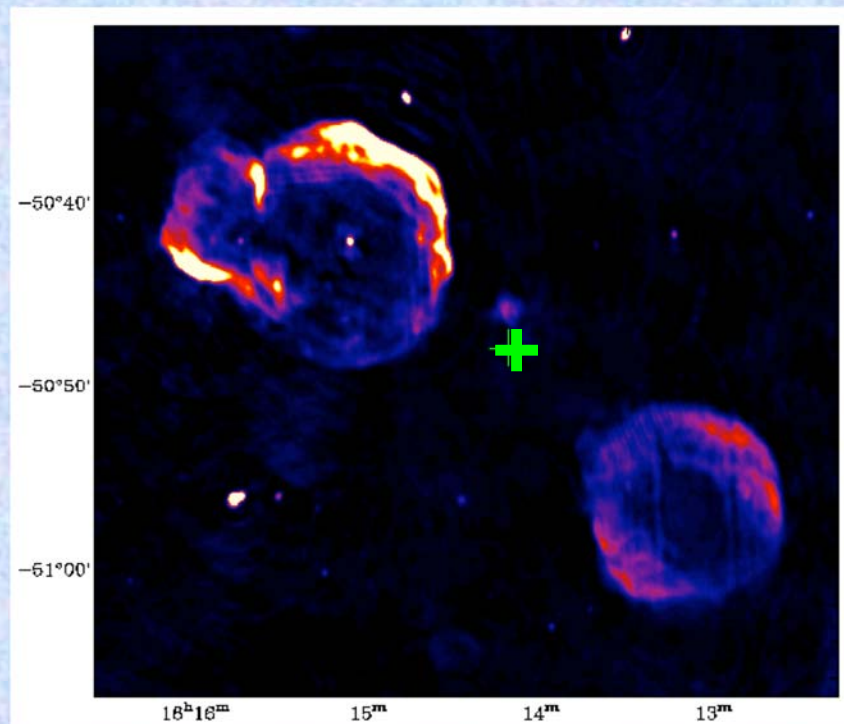
HESS J1640-465 (HESS; Aharonian et al. 2006)

Surveys & Discovery

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



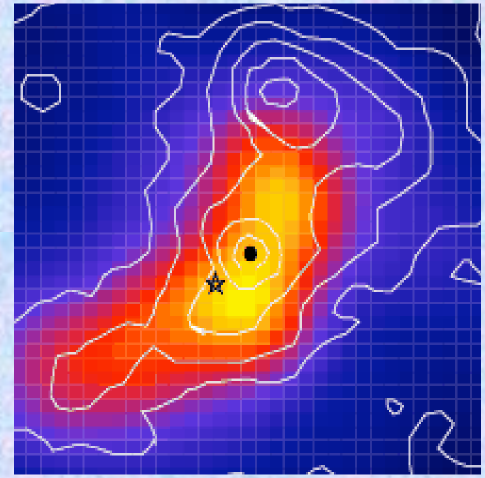
35 new SNRs in 1st Galactic quadrant (Brogan et al. 2006)



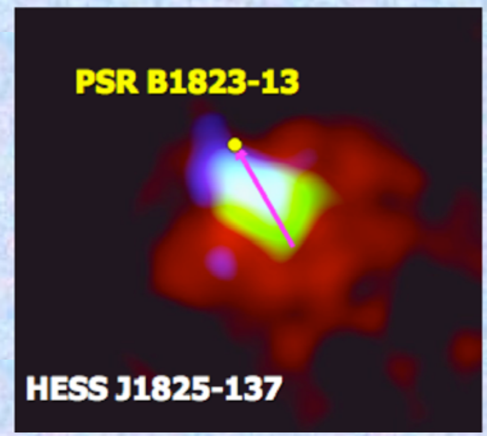
7000 year old pulsar B1610-50 (Stappers et al. 1999)

Summary

- TeV data yield distribution, injection rate, evolutionary history of fields + particles in PWNe
- TeV data reveal later stages of PWN evolution, and probe interaction with ambient gas / photons
- TeV data can help complete Galactic sample of PWNe & SNRs



Aharonian et al. (2005)



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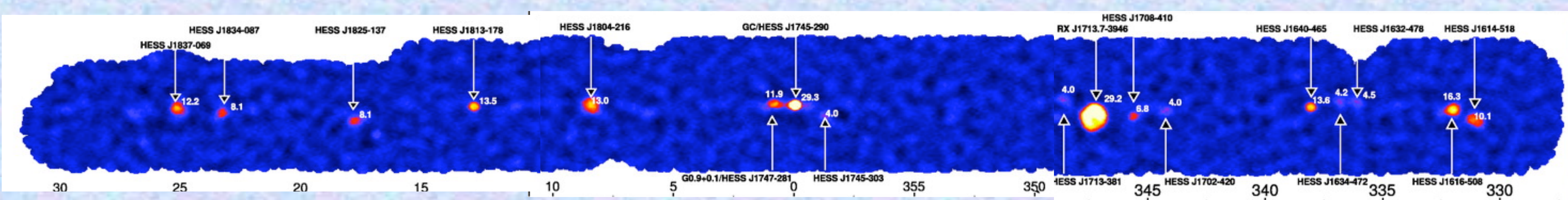

Aharonian et al. (2006)