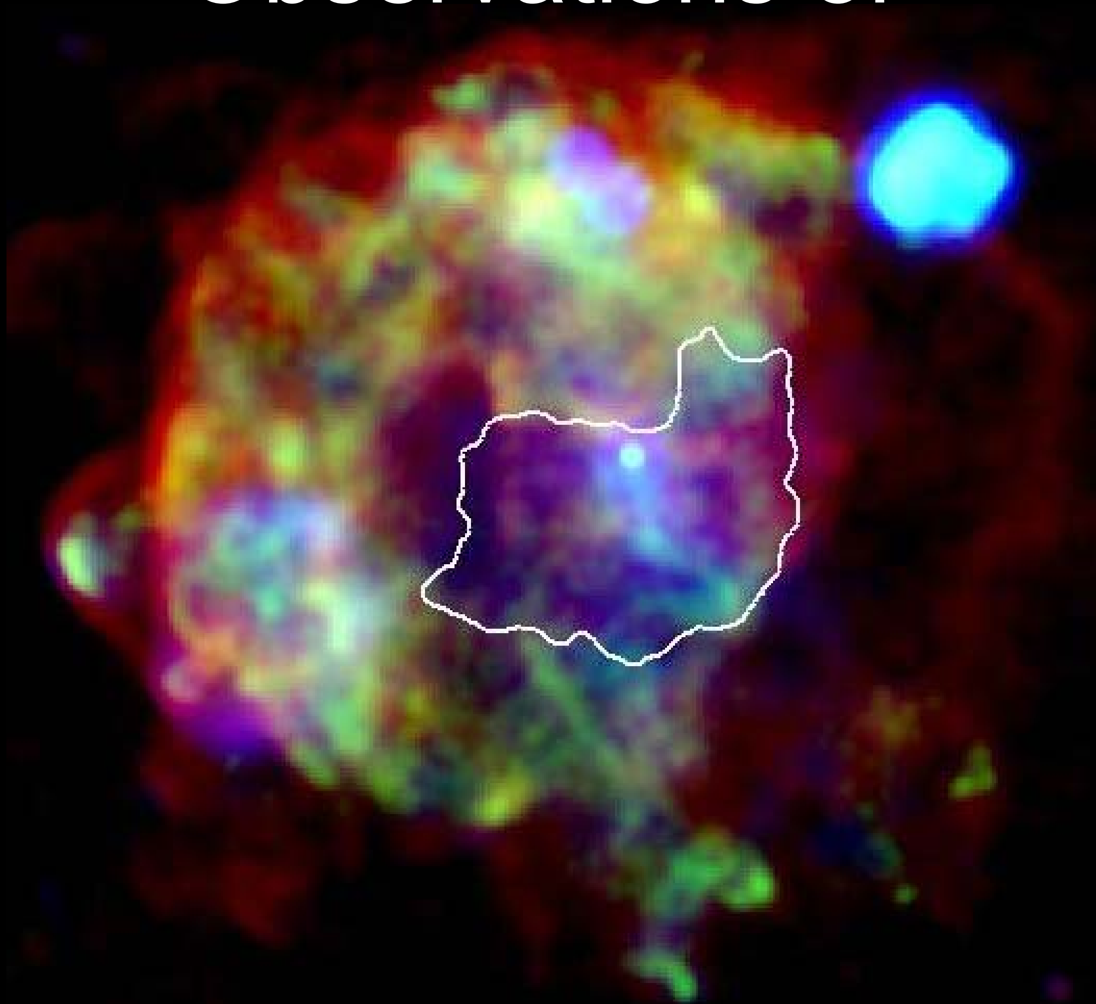
Observations of



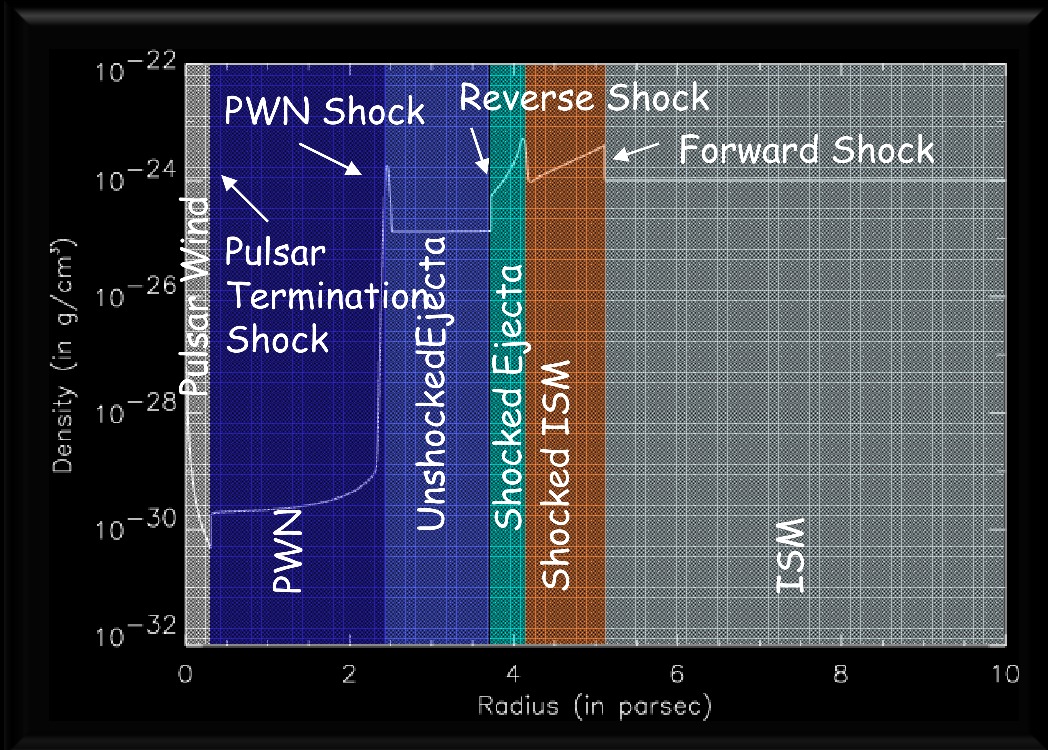
Pulsar Wind Nebulae

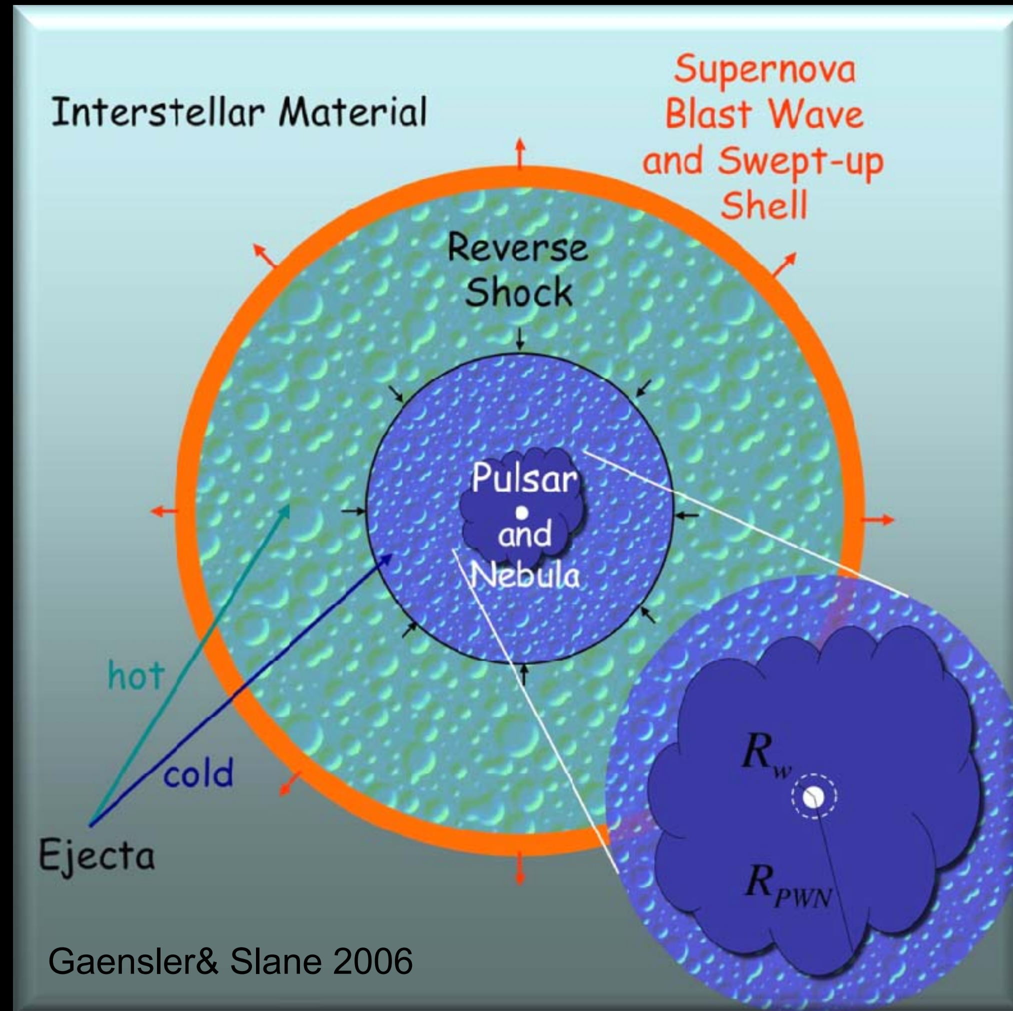
I. Injection Spectrum

I. Late-Phase Evolution

II. PWNe and Magnetars

PWNe and Their SNRs





- Pulsar Wind

- sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms

- Supernova Remnant

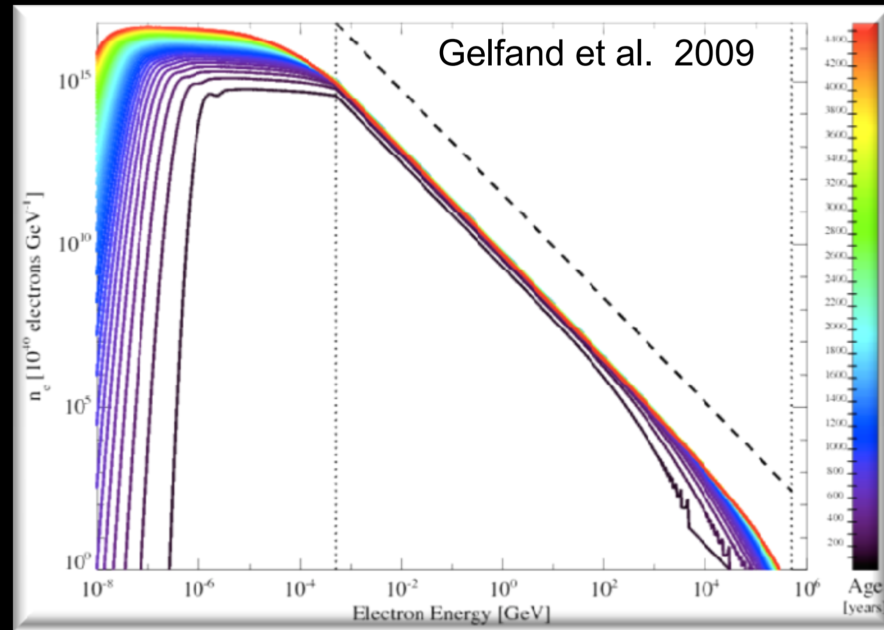
- sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; energy distribution of particles in nebula tracks evolution; instabilities at PWN/ejecta interface may allow particle escape

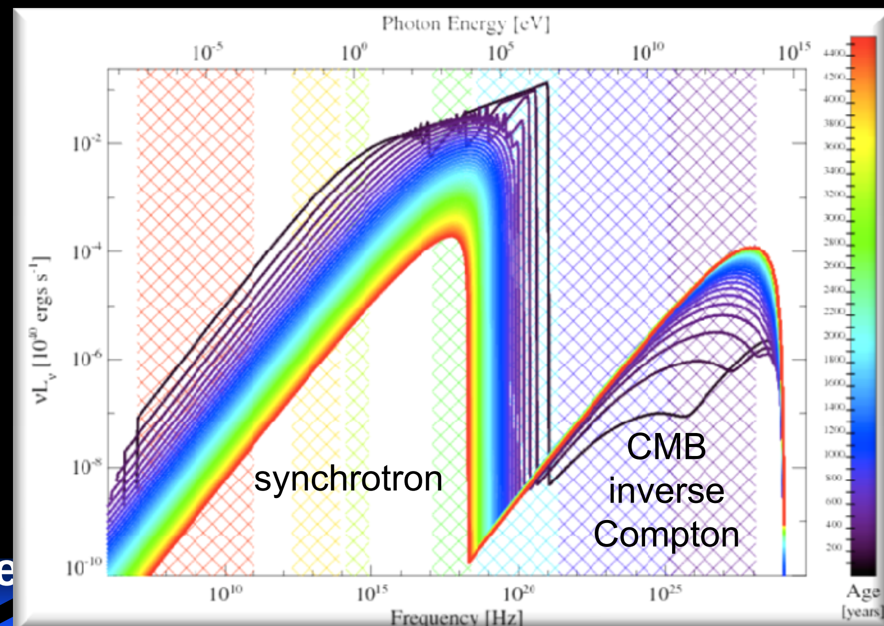
Broadband Emission from PWNe

- Spin-down power is injected into the PWN at a time-dependent rate

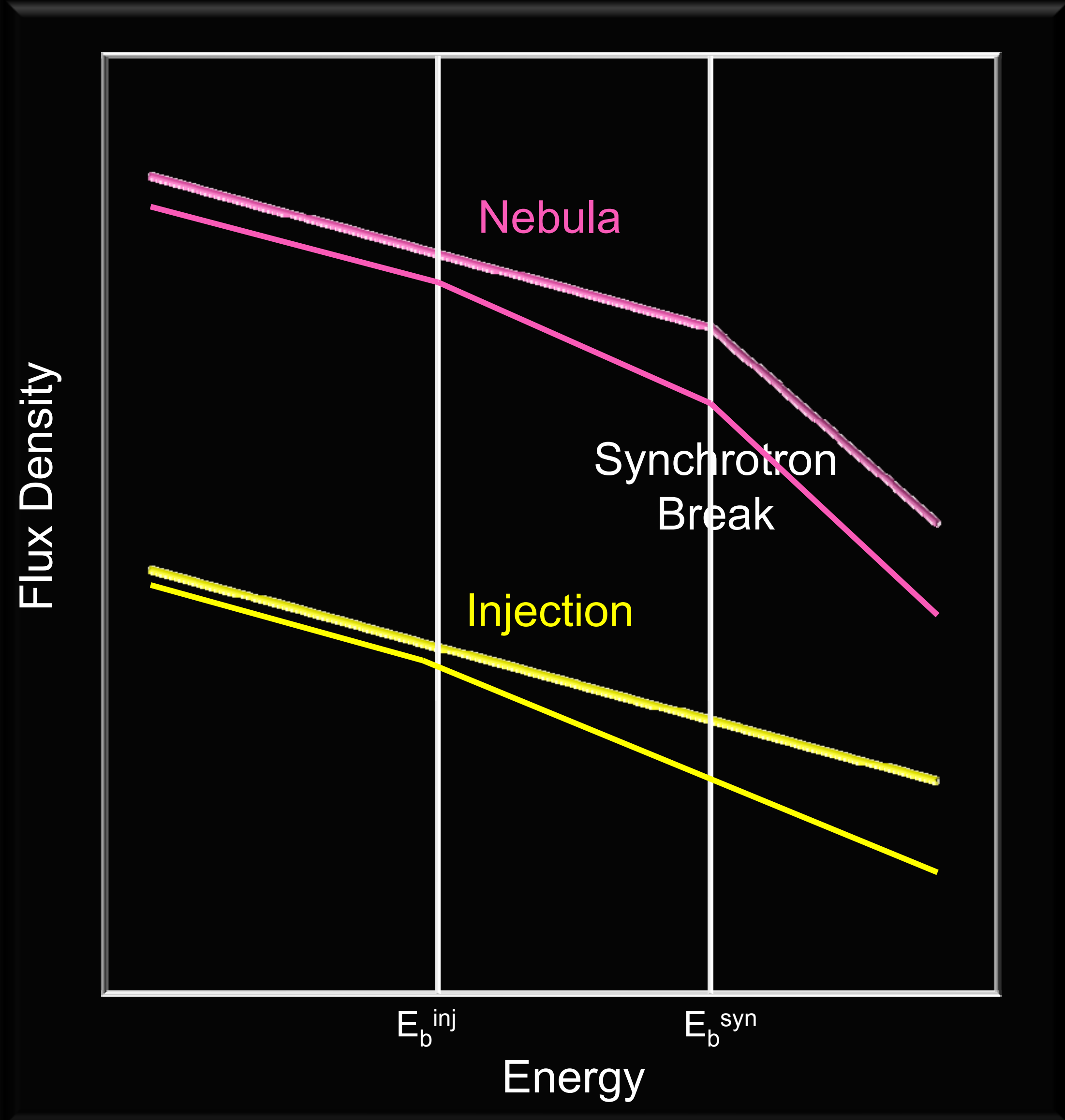
- Assume power law input spectrum:

- Get associated synchrotron and IC emission from electron population evolved nebula
  - note X-ray synchrotron losses beyond cooling break
  - joint fitting of synchrotron and IC spectra give B





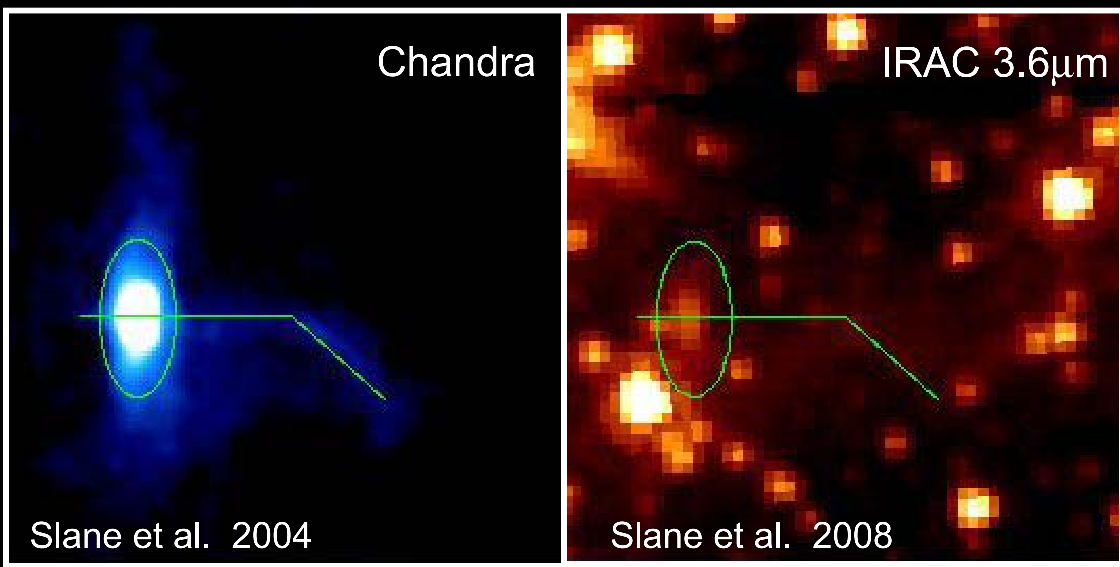
A Point About Injection



- Standard assumption is a power law input electron spectrum
  - this produces synchrotron break where synchrotron lifetime of particles equals age of PWN

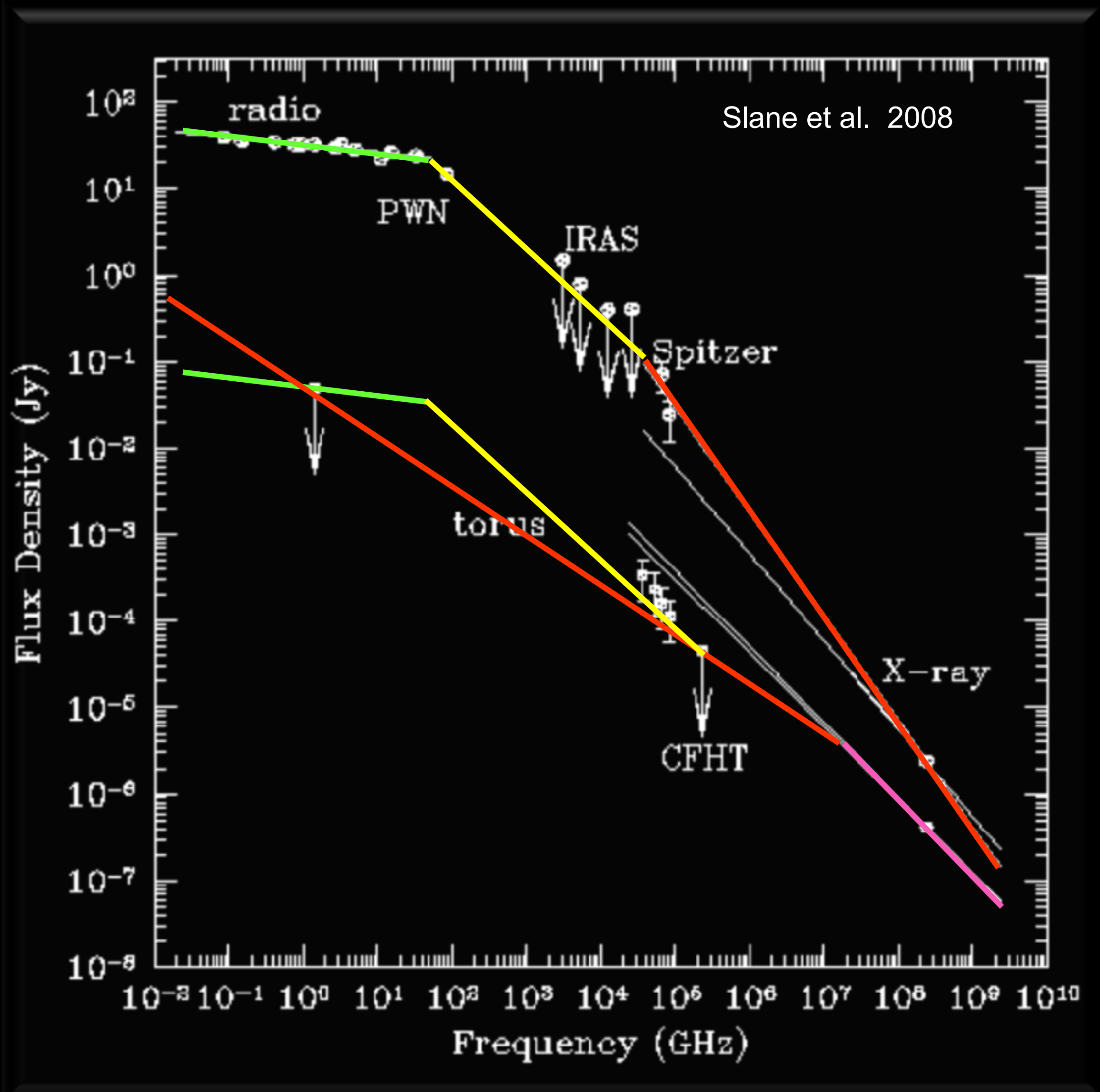
- **If injection spectrum has additional structure (e.g. lower energy break), this imprints itself onto the nebula spectrum**
  - get PWN spectrum with multiple breaks

Broadband Observations of 3C 58



- **3C 58 is a bright, young PWN**
  - morphology similar to radio/x-ray; suggests low magnetic field
  - PWN and torus observed in Spitzer/IRAC

Broadband Observations of 3C 58

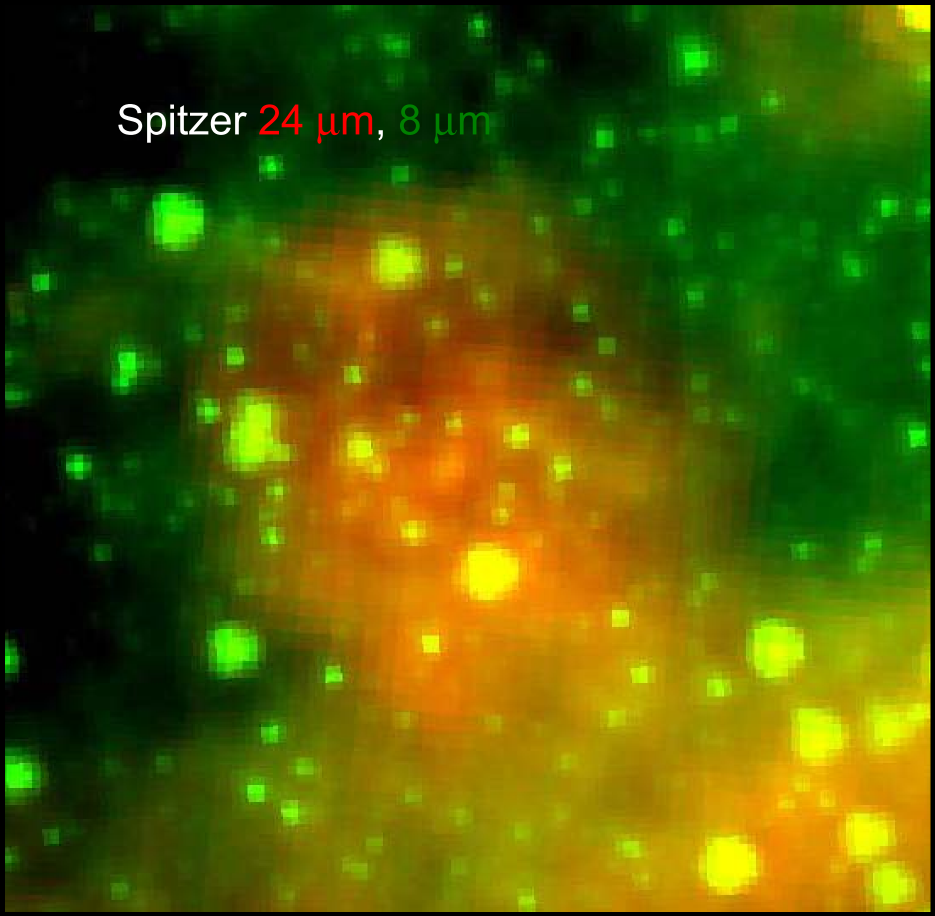


- **3C 58 is a bright, young PWN**
  - morphology similar to radio/x-ray; suggests low magnetic field
  - PWN and torus observed in Spitzer/IRAC
- **Low-frequency break suggests possible break in injection spectrum**
  - IR flux for entire nebula falls within the extrapolation of the X-ray spectrum
  - indicates single break just below IR
- **Torus spectrum requires change in slope between IR and X-ray bands**
  - challenges assumptions for single power law for injection spectrum

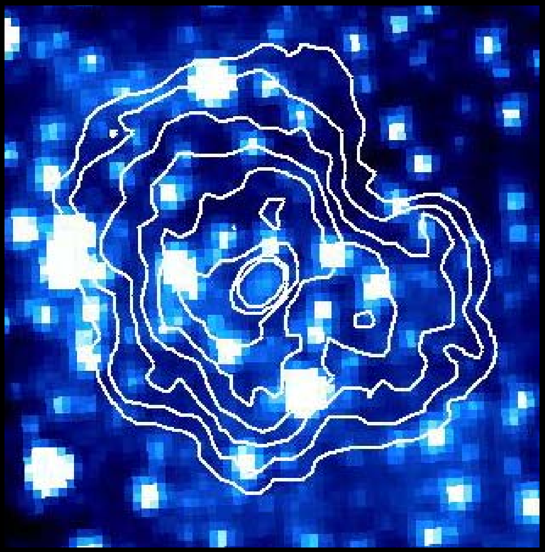
Broadband Observations of G21.5-0.9

Chandra

Spitzer 24 μm, 8 μm



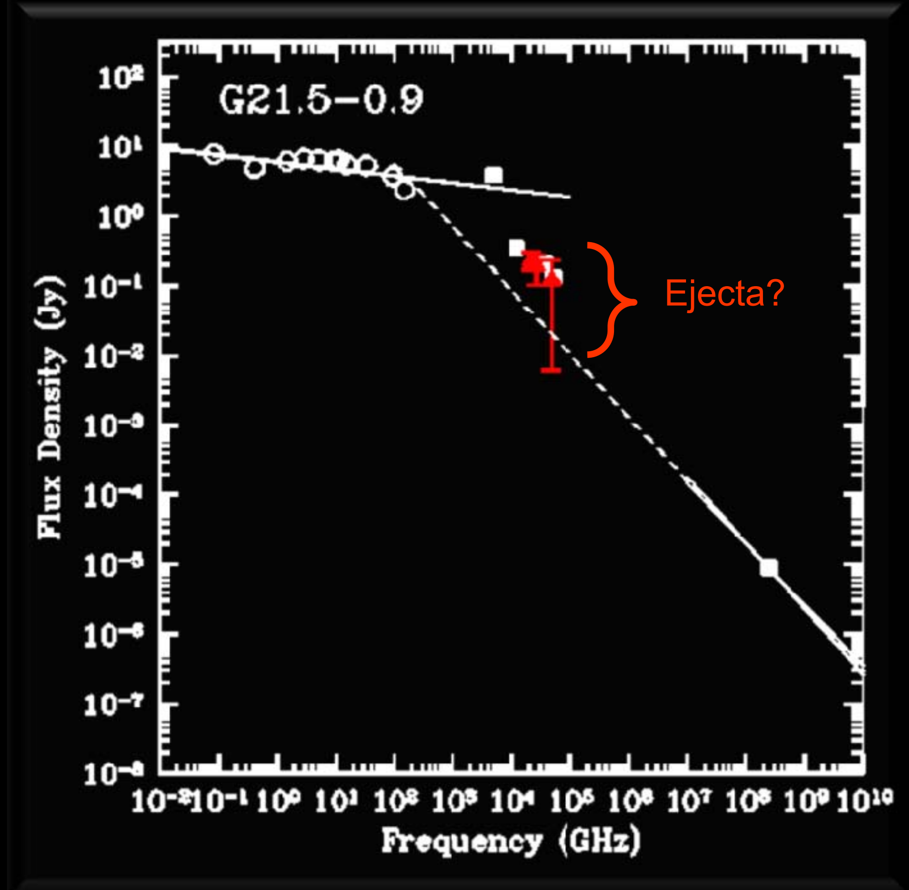
Spitzer 5.8 μm



- PWN and core also seen by Chandra and Spitzer

Broadband Observations of G21.5-0.9

Chandra



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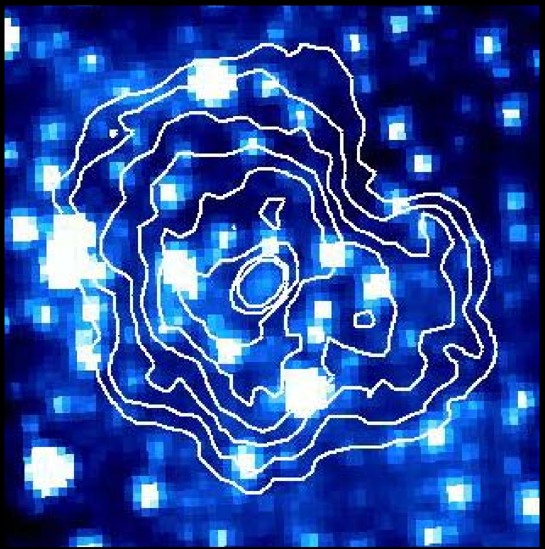

- PWN and core also seen by Chandra and Spitzer

- Broadband spectrum shows distinct low-frequency break, like 3C 58
  - excess in IR may be indicative of ejecta component (Zajczyk et al. in prep)

Broadband Observations of G21.5-0.9

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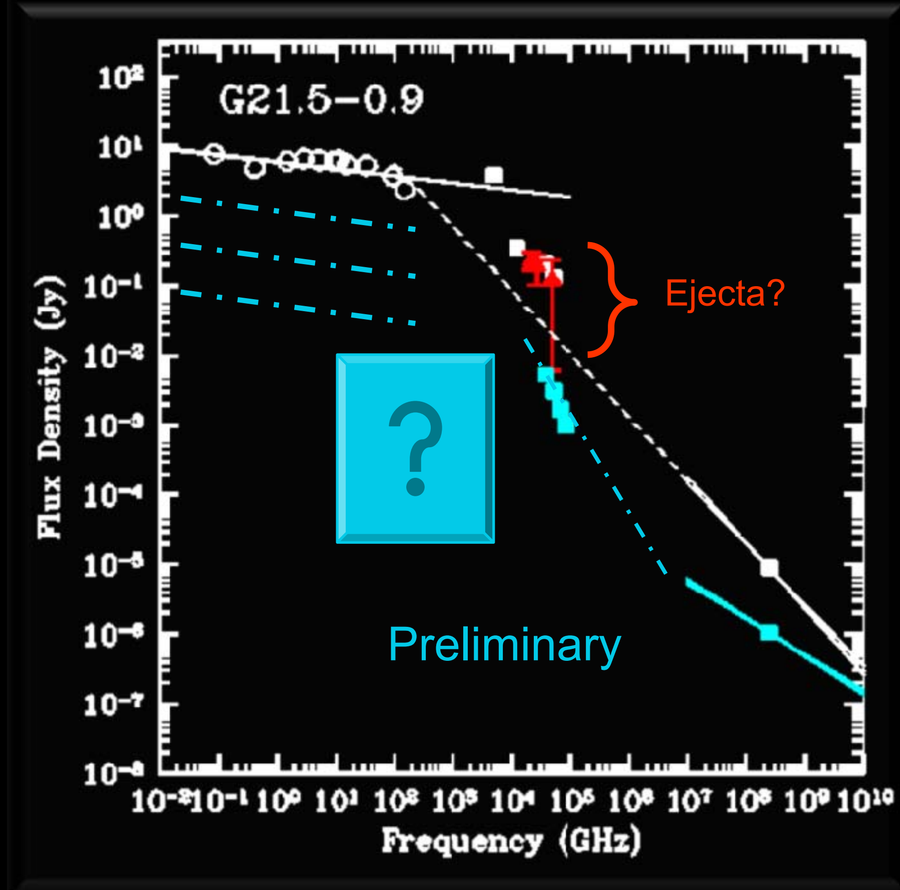

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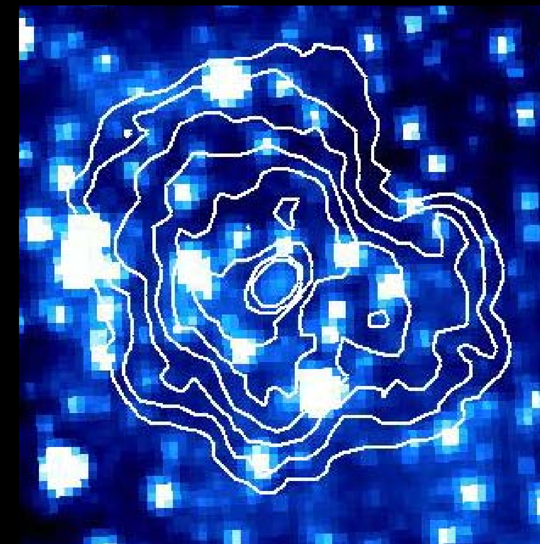
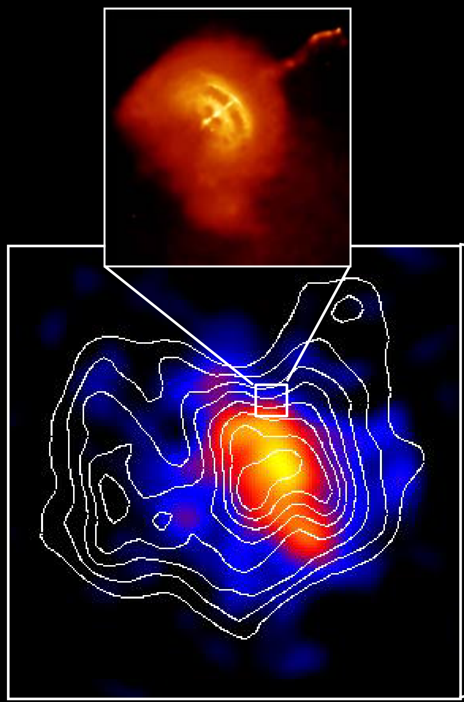


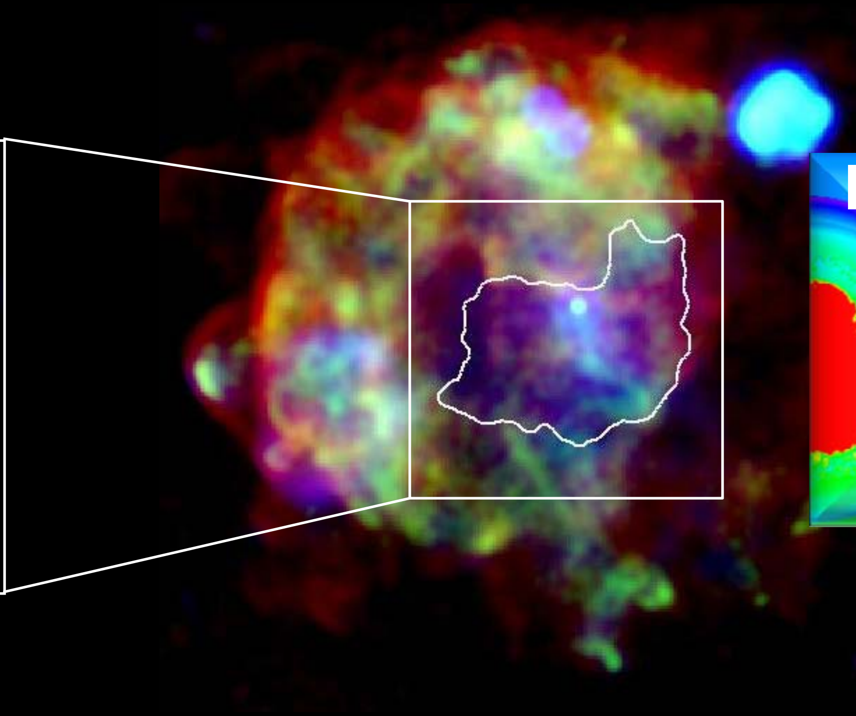
- PWN and core also seen by Chandra and Spitzer

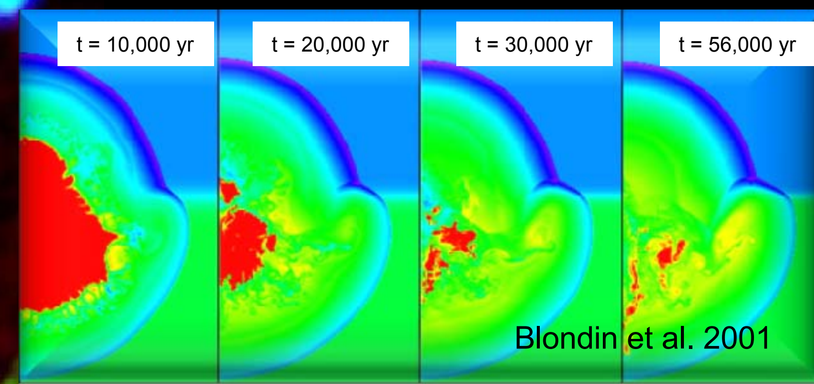
- Broadband spectrum shows distinct low-frequency break, like 3C 58
  - excess in IR may be indicative of ejecta component (Zajczyk et al. in prep)

- Emission from core complicated
  - appears to require multiple changes in curvature

Evolution in an SNR: Vela X



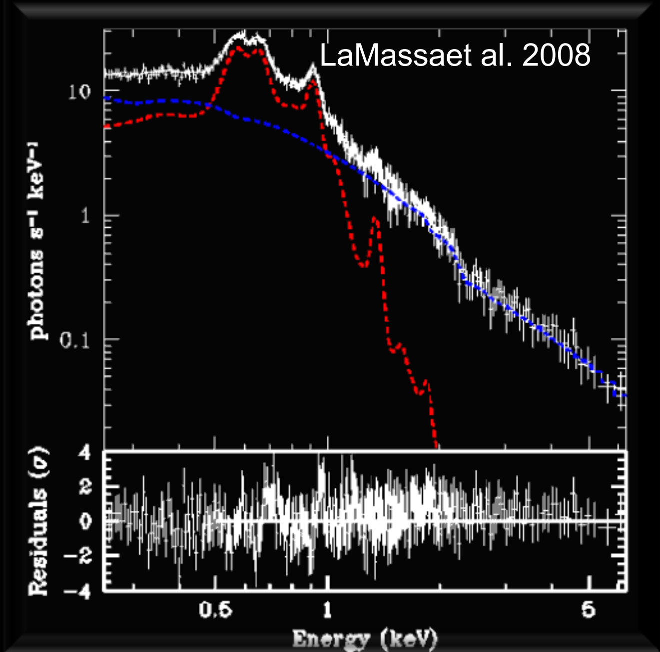


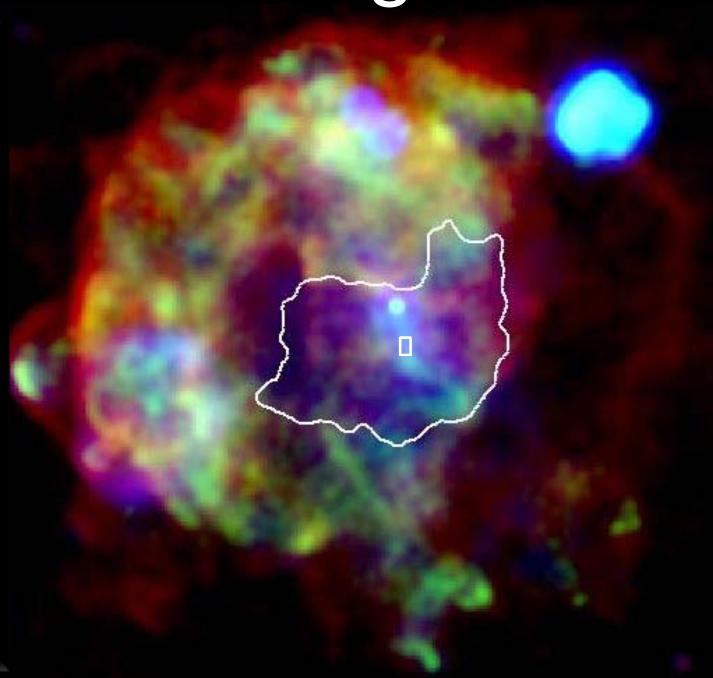


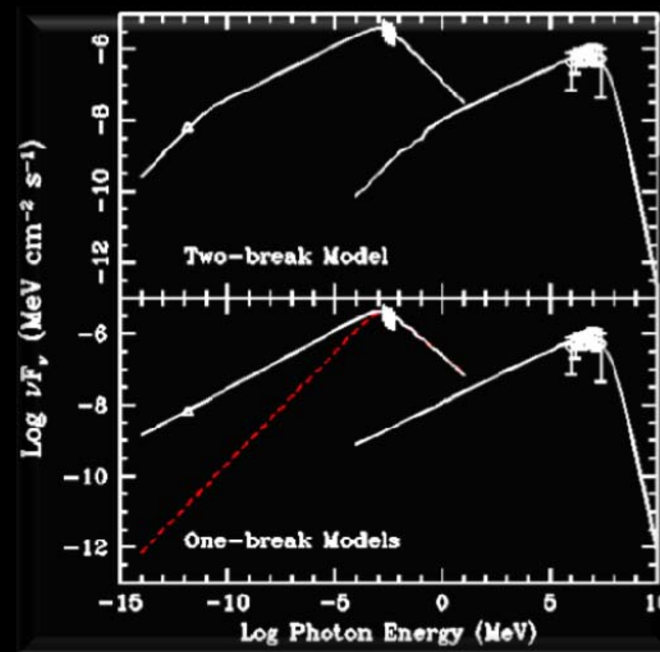
- **Vela X is the PWN produced by the Vela pulsar**
  - **apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock**

- **Elongated "cocoon-like" hard X-ray structure extends southward of pulsar**
  - **clearly identified by HESS as an extended VHE structure**
  - **this is not the pulsar jet**

Understanding Vela X: Fermi

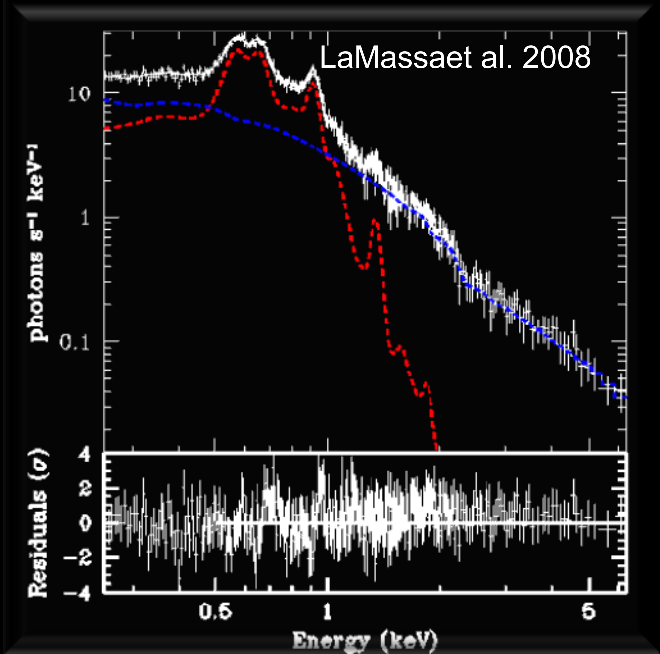


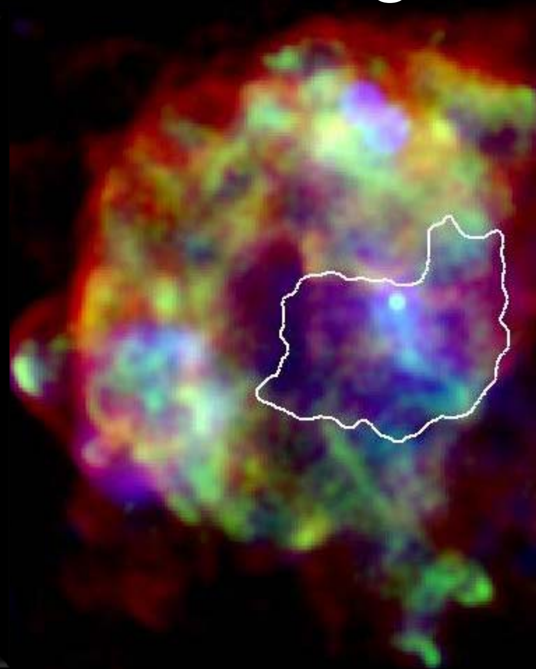


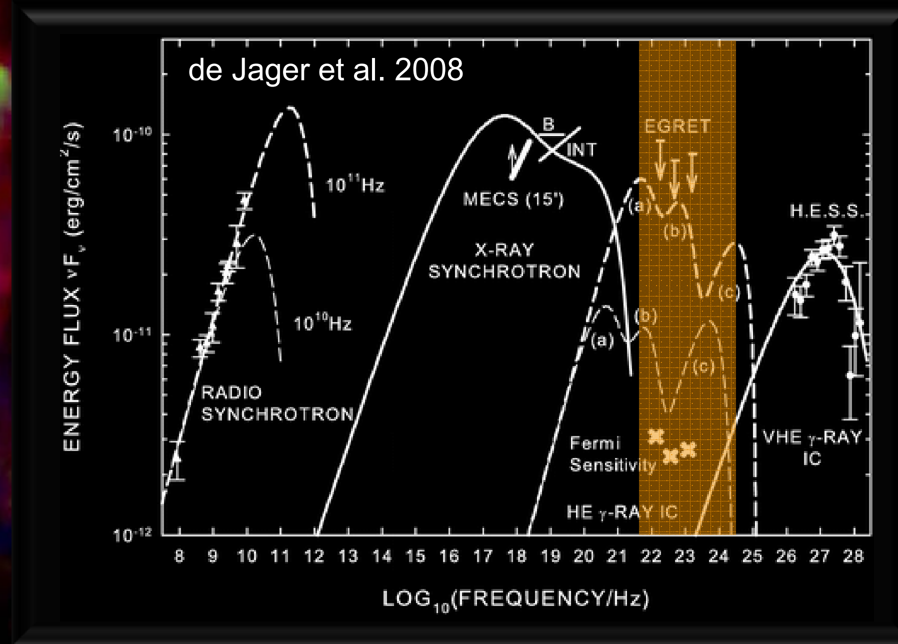


- **Broadband spectrum for PWN suggests two distinct electron populations**
  - **radio-emitting population will generate IC emission in LAT band**
  - **spectral features will identify distinct photon population and determine cut-off energy for radio-emitting electrons**

Understanding Vela X: Fermi







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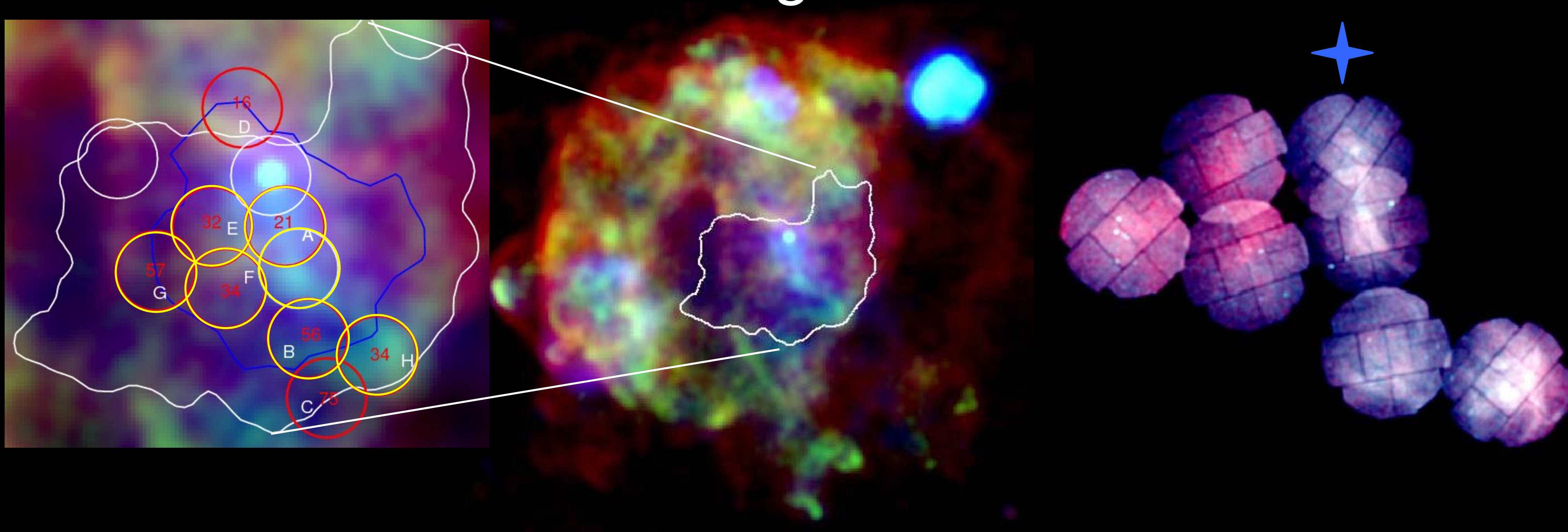
Understanding Vela X: XMM



- **Broadband spectrum for PWN suggests two distinct electron populations**
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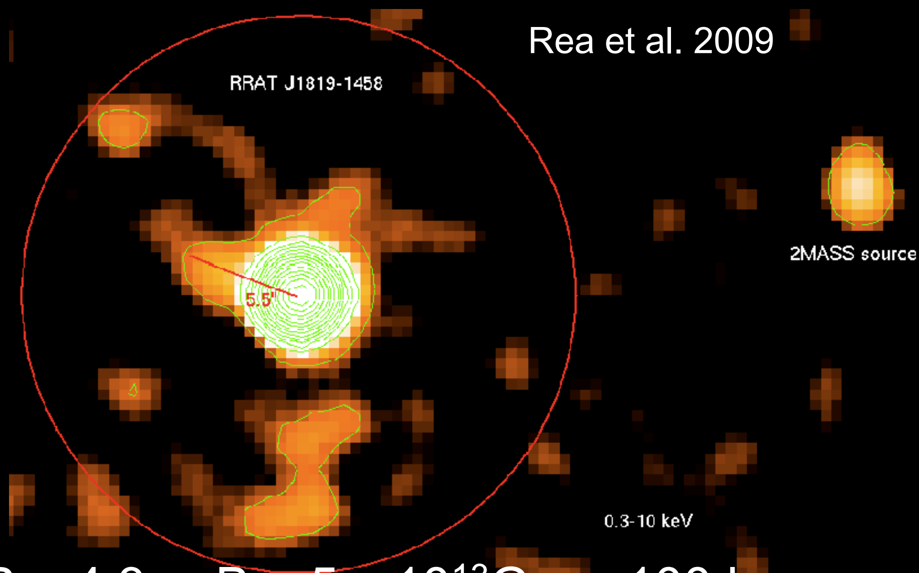
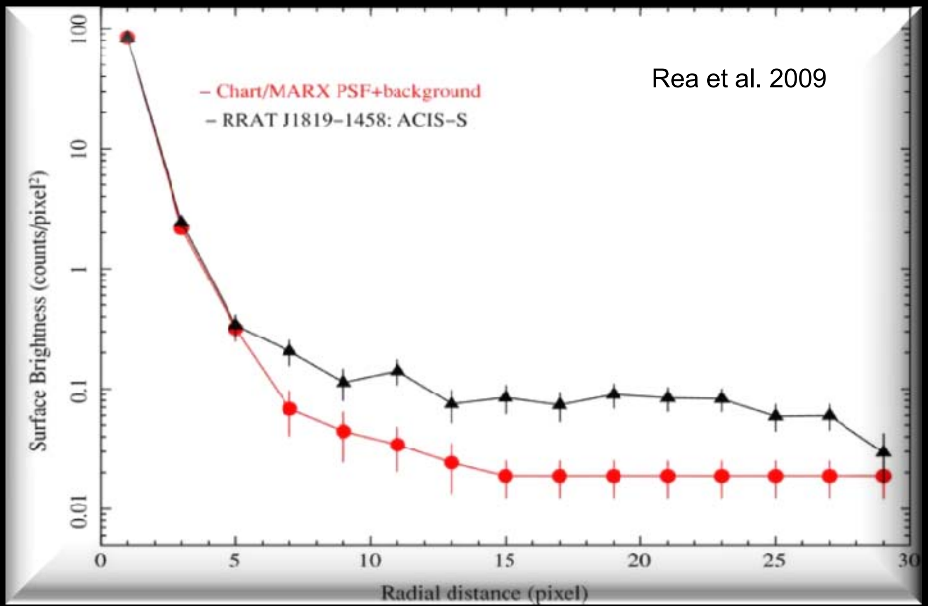
  - **spectral features will identify distinct photon population and determine cut-off energy for radio-emitting electrons**

- **XMM large project (400 ks) to study ejecta andnonthermal emission now underway; images reveal considerable structure and spectral variation**

PWNe around RRAT J1819-1458



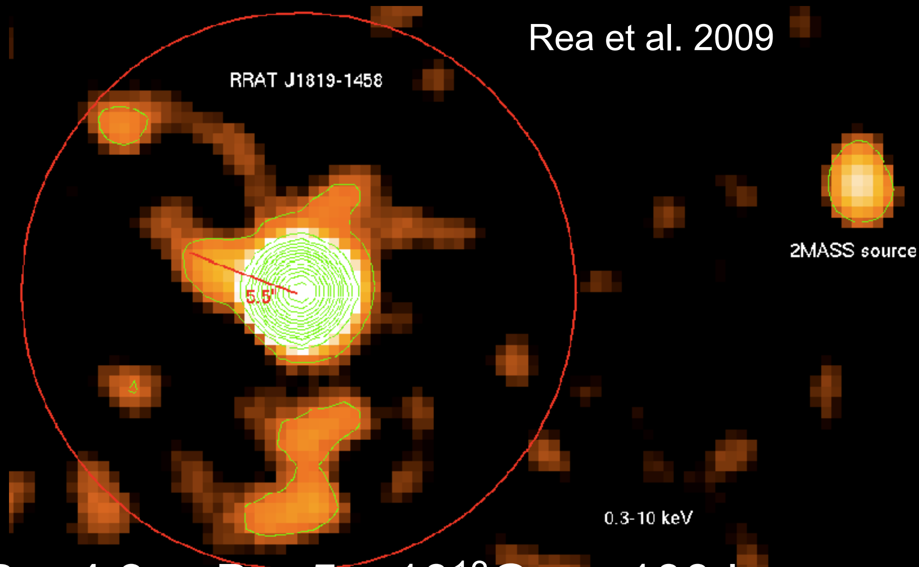


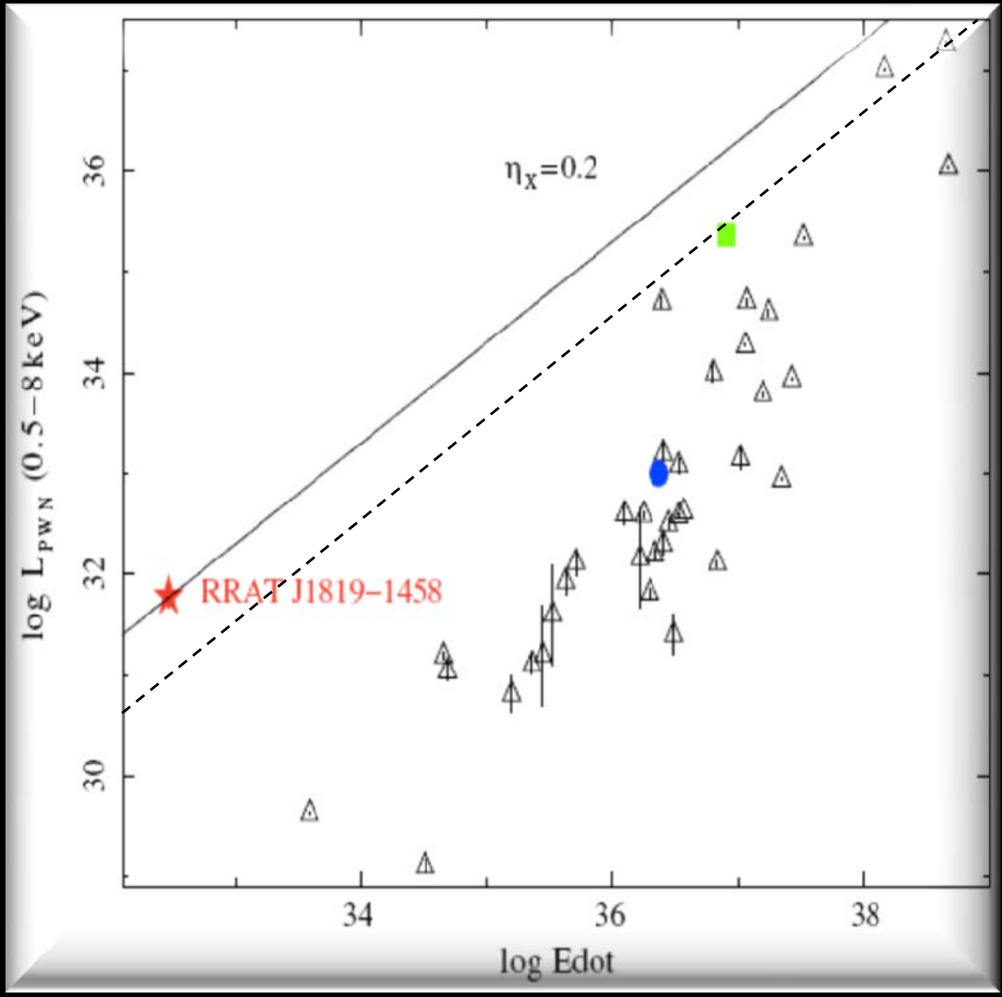
- P = 4.3 s, B = 5 x 10^{13}G, $\tau_c \approx 100$ kyr
  - near magnetars in P-Pdot diagram
  - only known X-ray RRAT; parameters similar to other old pulsars

- $\dot{E}$ = 3 x 10^{32} erg s^{-1} < $0.1 L_{x,psr}$
  - some other energy source for x-rays; magnetically powered?

- Chandra observations reveal extended emission associated with source
  - $L_{x,pwn} = 0.2\dot{E}$ - much higher than for otherPWNe(although distance/flux uncertainties could lower this to somewhat more reasonable values)

PWNe around RRAT J1819-1458





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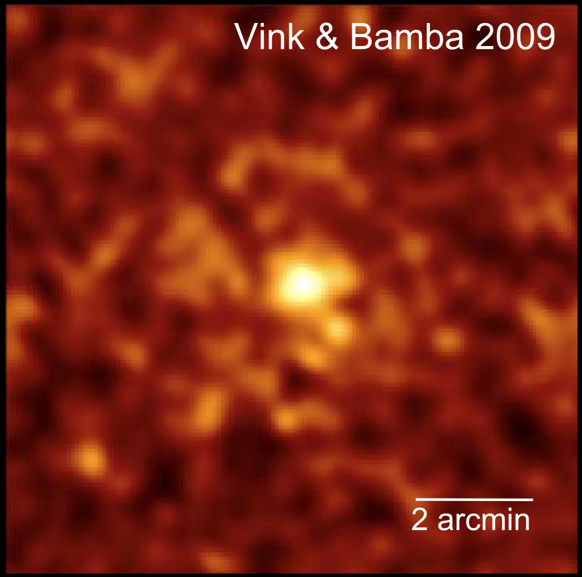
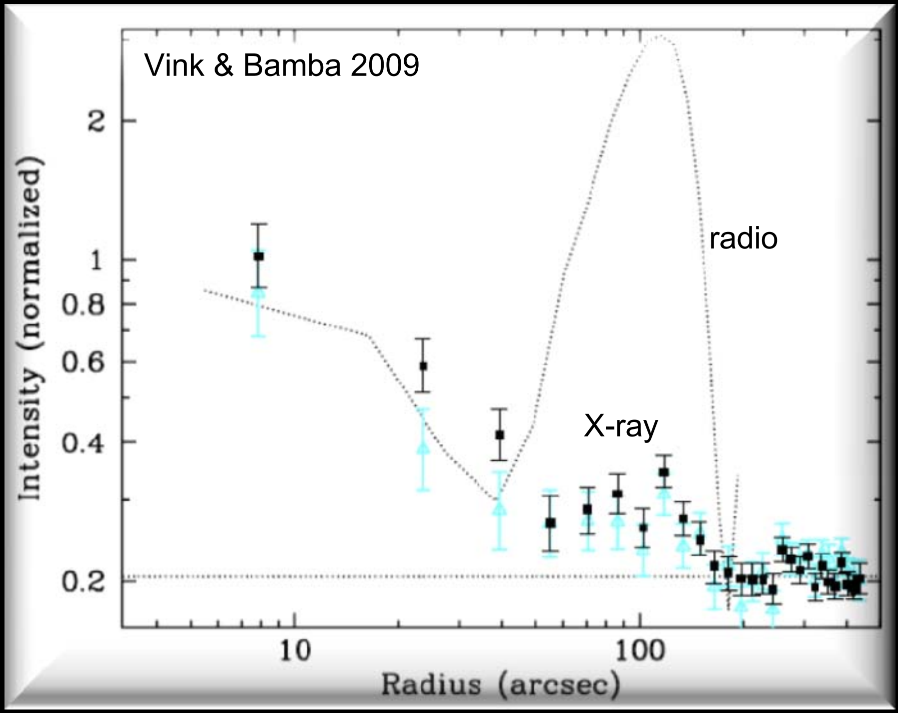
PWNe around 1E 1547.0-5408



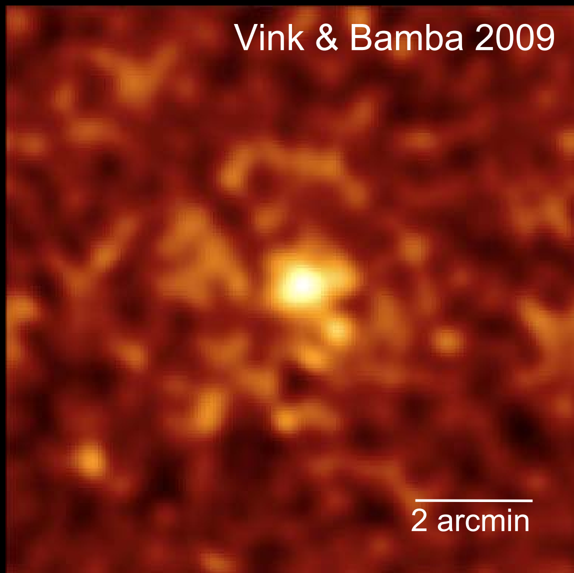


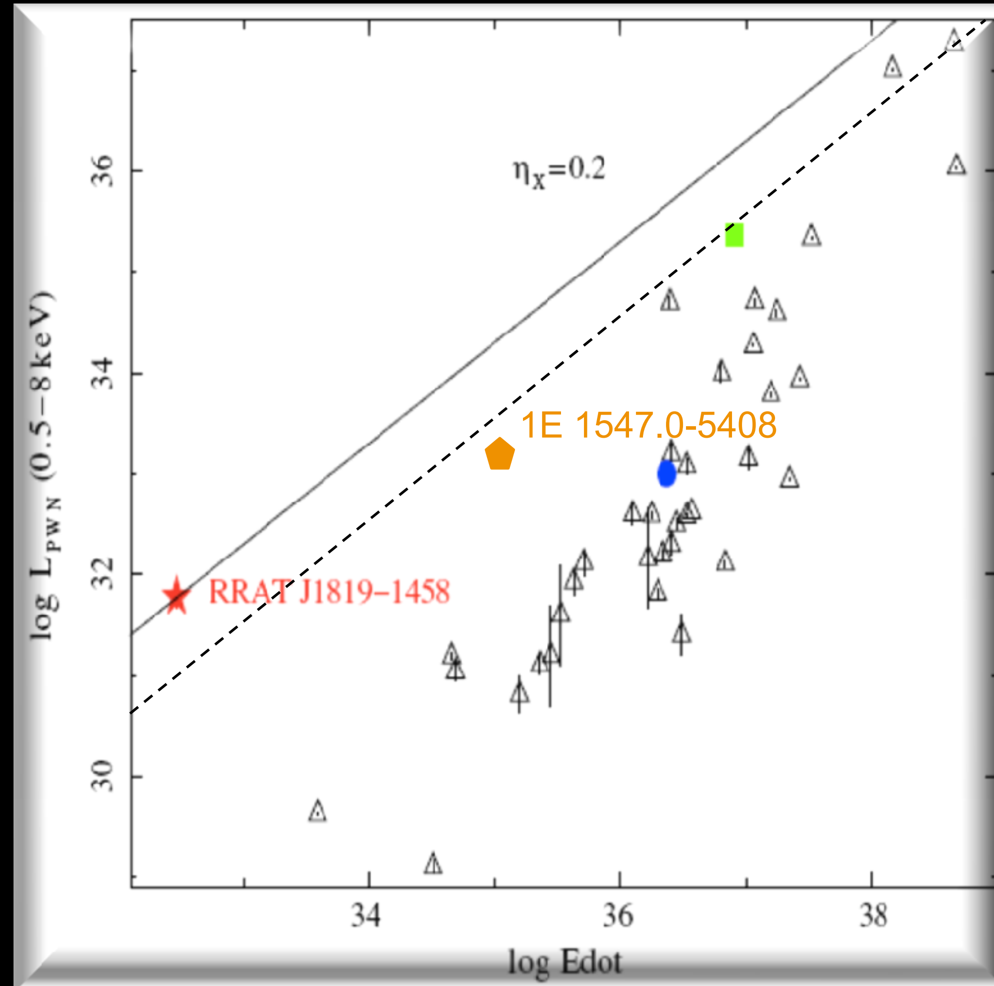
- P = 2.1 s, B = 2.2 x 10^{14} G
- located in SNR; SGR-like bursts confirm source as magnetar; also radio transient

- $\dot{E}$ = 1 x10^{35}erg $s^{-1} \approx L_{x,psr}$
- also magnetically powered?

- Chandra observations reveal extended emission associated with source
  - $L_x/\dot{E}$higher than formost pulsars; how is X-ray nebula nebula produced?
  - does PWN point to a fast initial spin period for magnetars?

PWNe around 1E 1547.0-5408





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Conclusions

I. Injection Spectrum

- PWN are reservoirs of particles that track pulsar evolution, and eventually seed ISM w/ energetic particles
- Spectrum of region near TS appears to deviate significantly from single PL; ramifications for broadband modeling
- Low energy particles may represent a separate population. From where?

I. Late-Phase Evolution

- Late-phase results in mixing of thermal and nonthermal gas, with modification to particle spectrum
- As predicted(?), but not well-studied observationally

II. PWN and Magnetars

- Observations of RRAT J1819-58 and 1E 1547.0-5408 show that magnetar-like objects <u>can</u> have PWNe-like structures.
- Powering by pulsar spin-down energetically feasible, but is that what is going on?