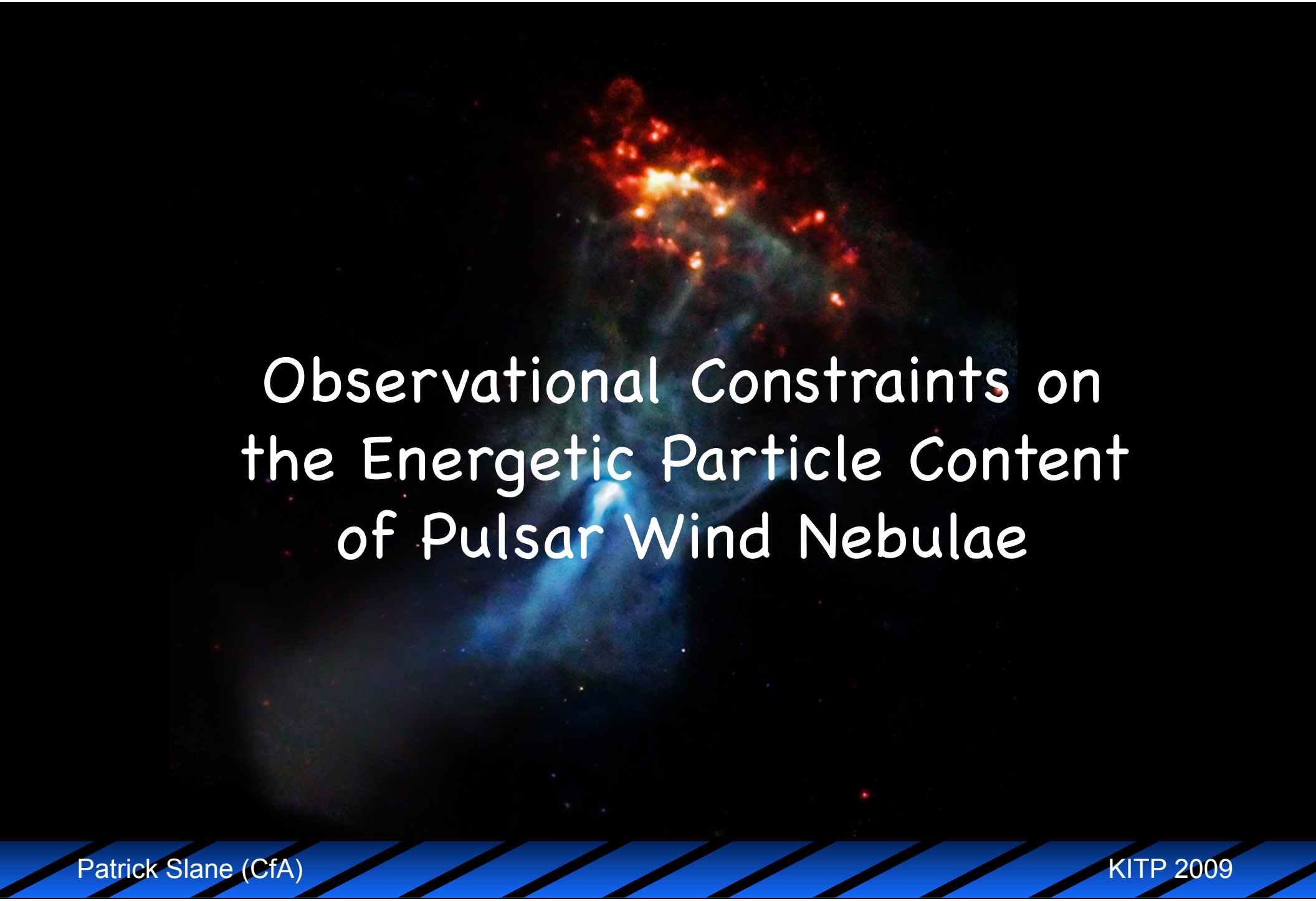


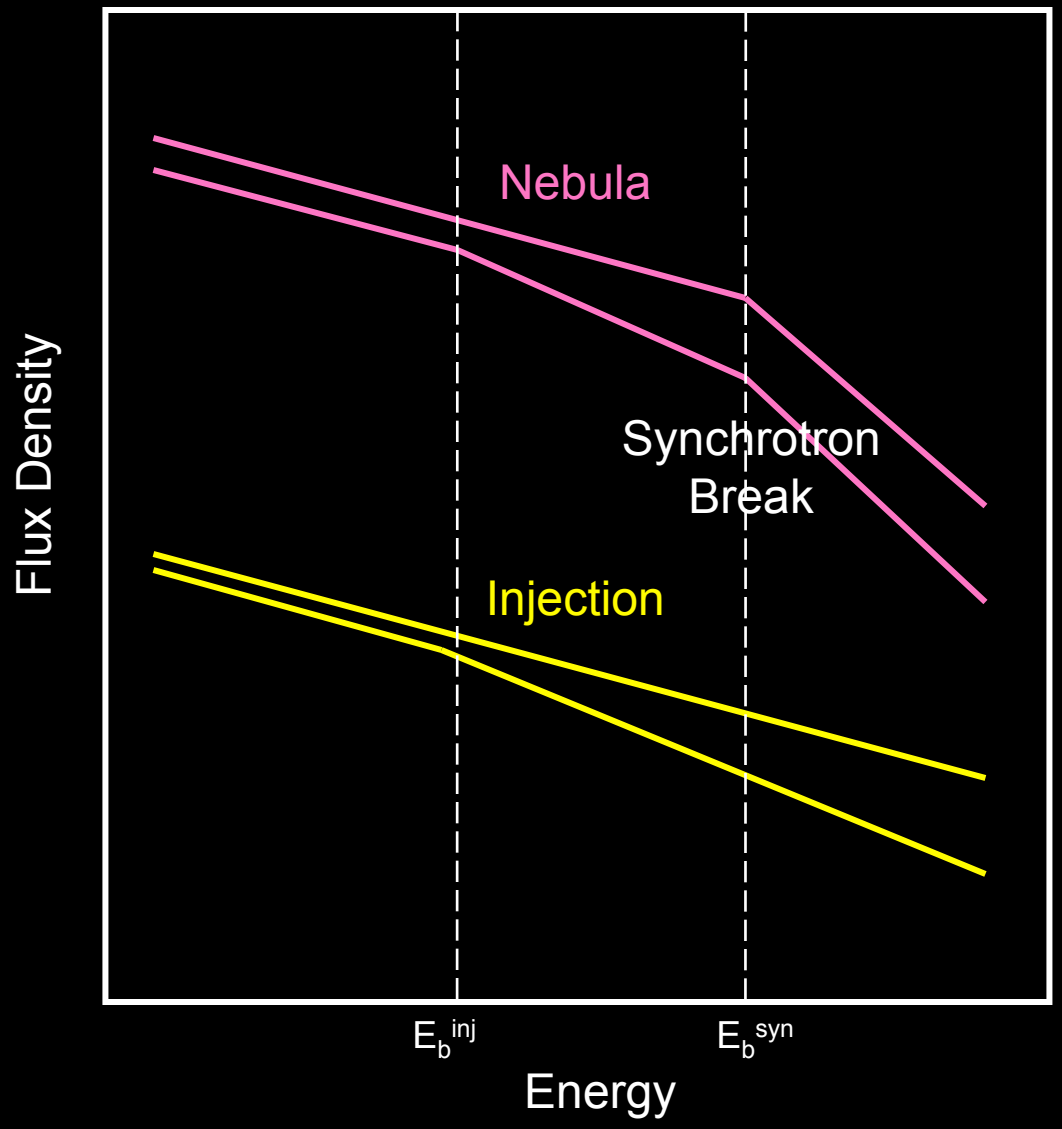
Observational Constraints on the Energetic Particle Content of Pulsar Wind Nebulae

I. Injection Spectrum

II. Low Energy Particles

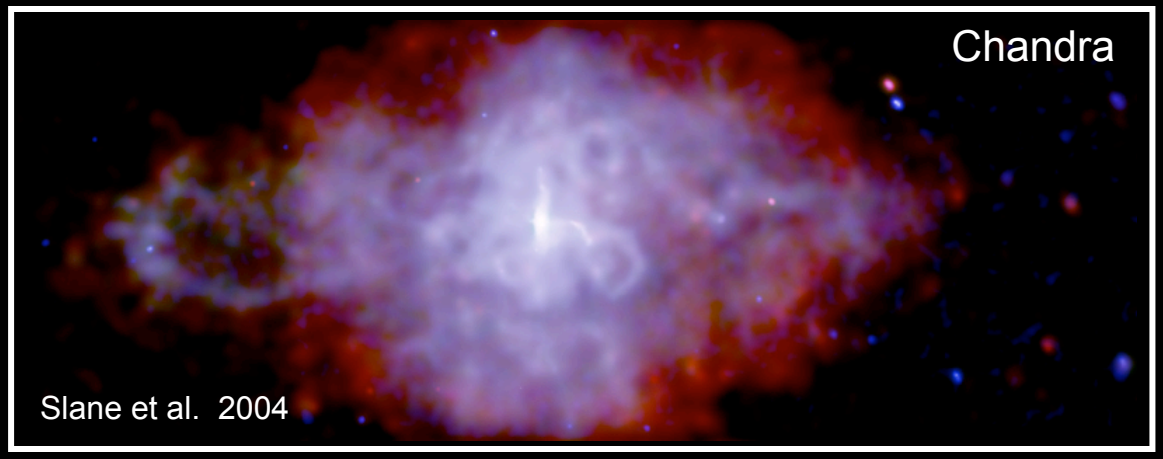
III. Late-Phase Evolution

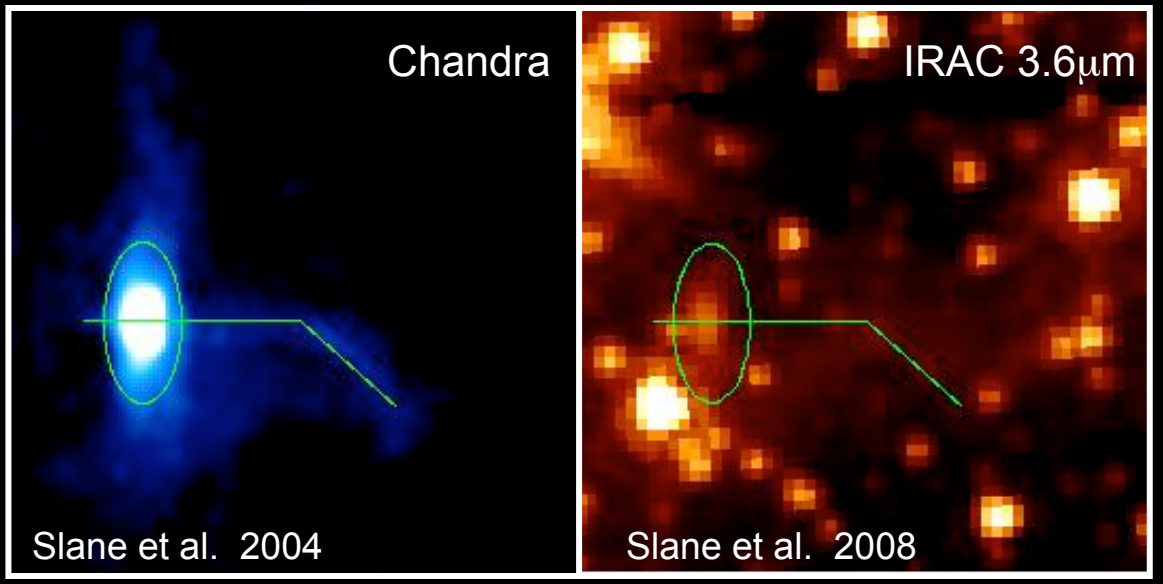
A Point About Injection



- 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

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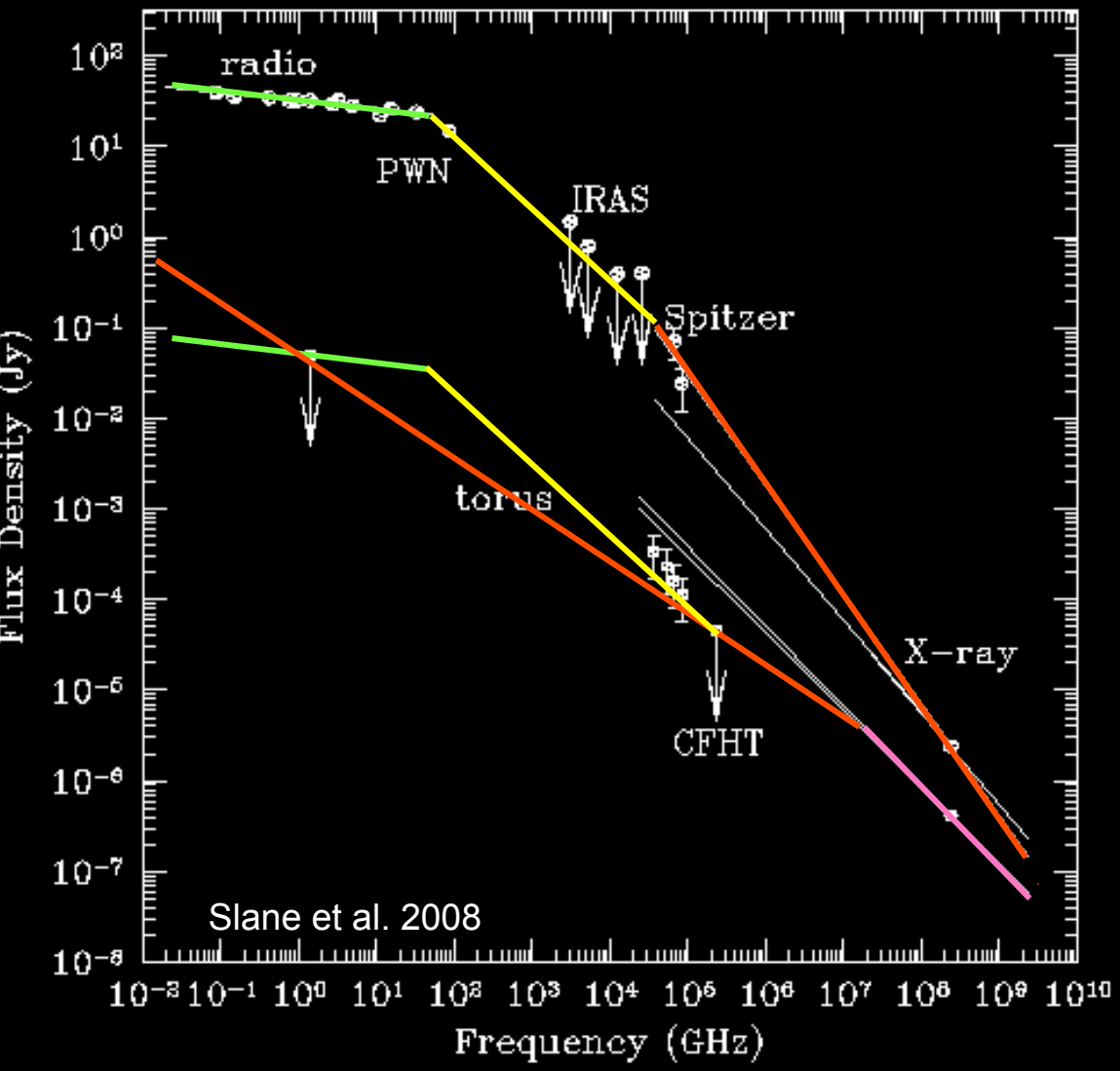

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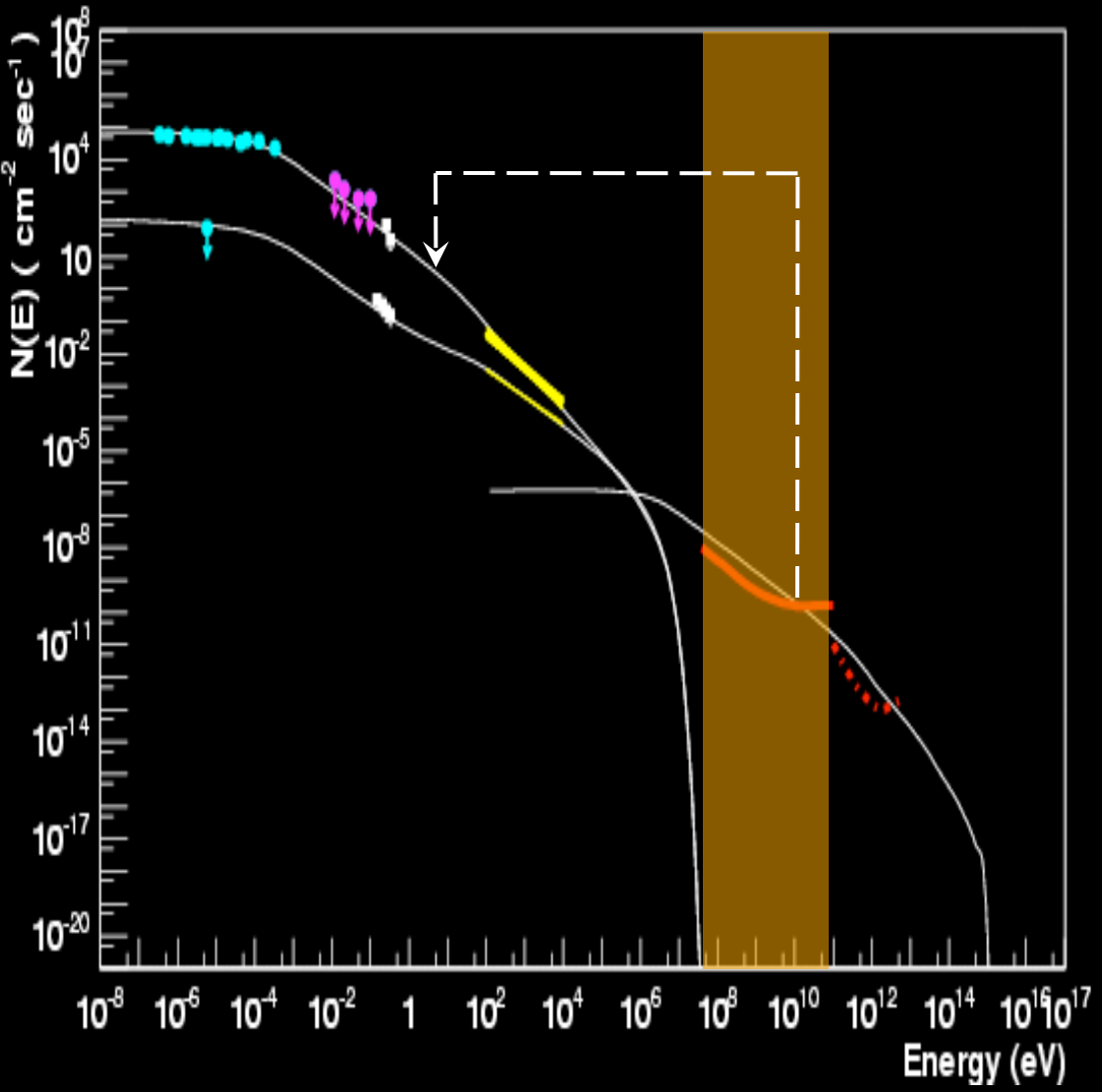
  - indicates single break just below IR
- Torus spectrum requires change in slope between IR and X-ray bands
  - challenges assumptions for single power law for injection spectrum

Fermi Studies of 3C 58



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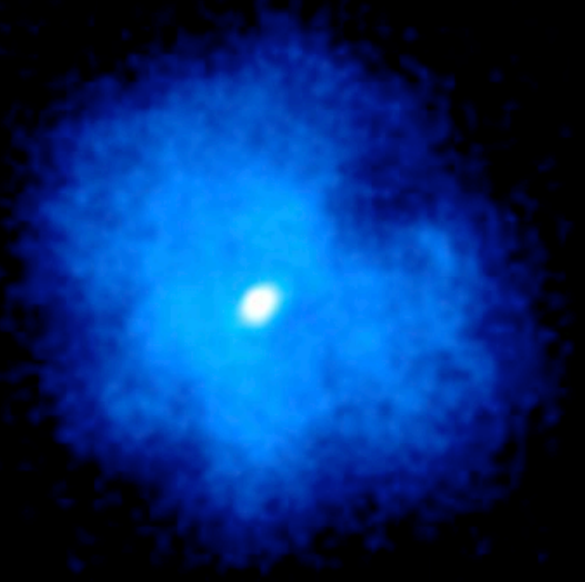
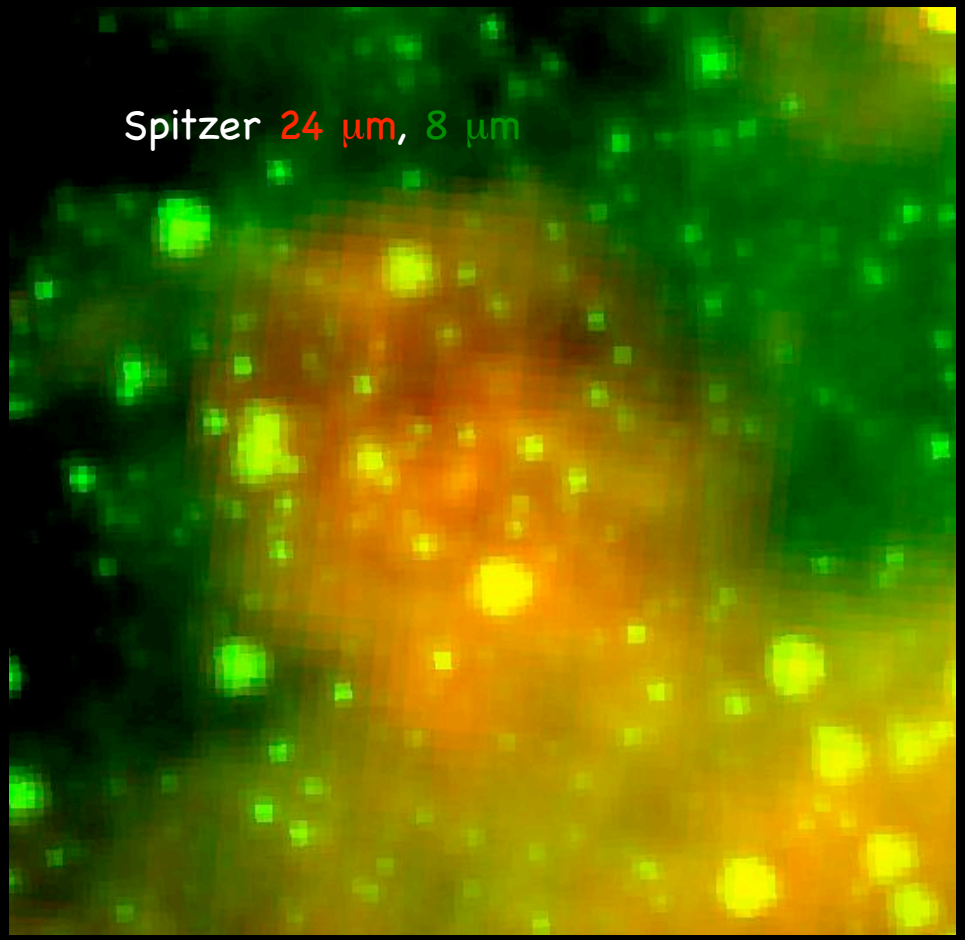
- Fermi LAT band probes CMB IC emission from ~0.6 TeV electrons
  - this probes electrons from the unseen synchrotron region around E^{syn} = 0.4 eV where injection is particularly complex

Broadband Observations of G21.5-0.9

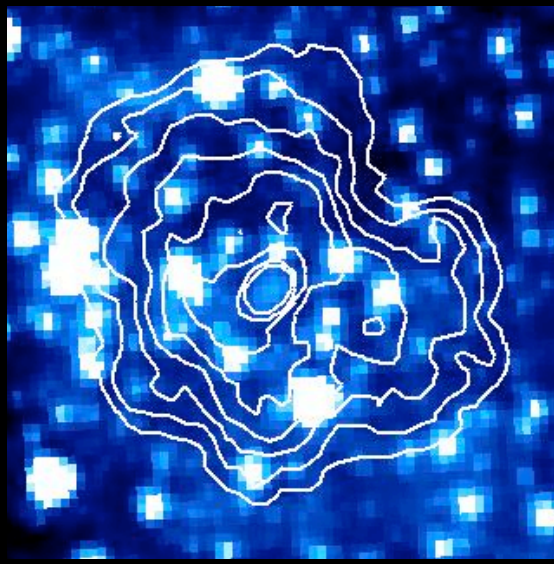
Chandra



Spitzer 24 μm, 8 μm



Spitzer 5.8 μm



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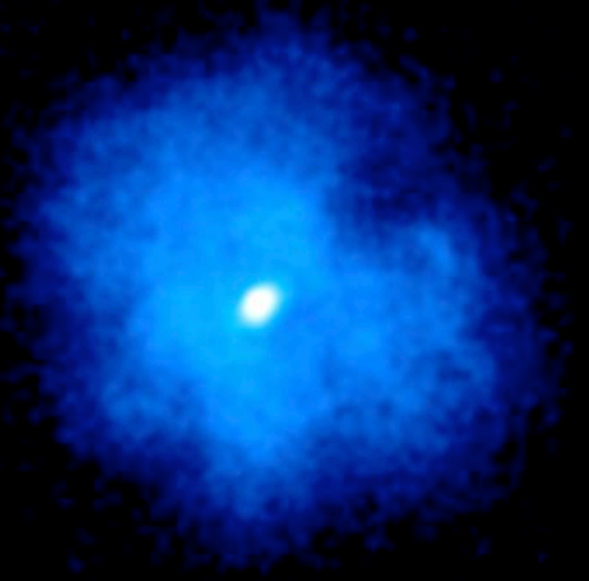

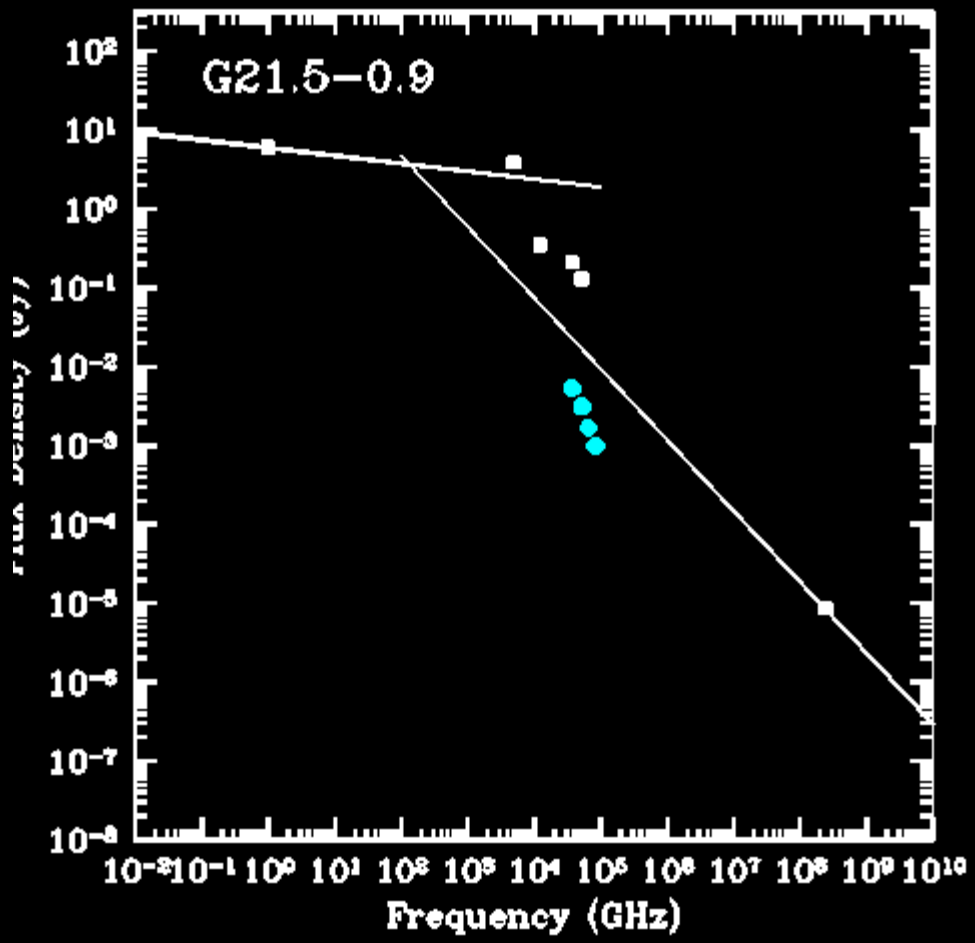

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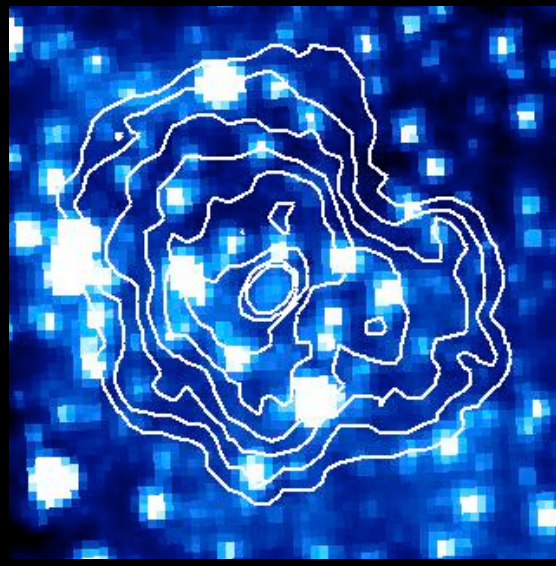

I. Injection Spectrum

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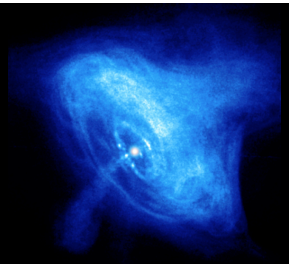


Broadband Emission from PWNe

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

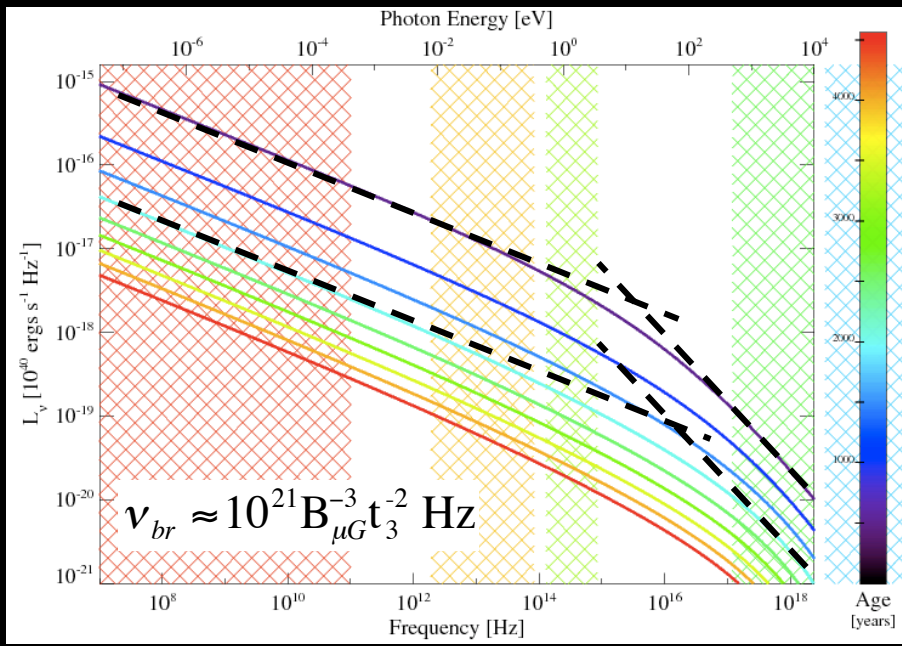
$$\dot{E} = I\Omega\dot{\Omega} = \dot{E}_0\left(1+\frac{t}{\tau}\right)^{-\frac{n+1}{n-1}}$$

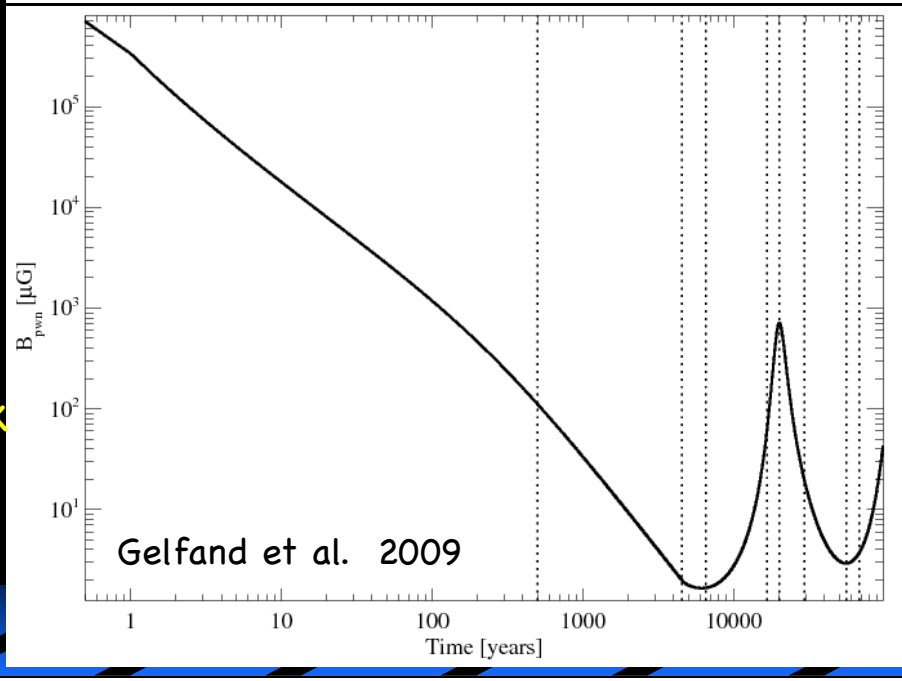
- Assume power law input spectrum:

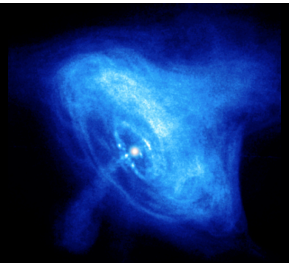
$$Q(t) = Q_0(t)(E_e / E_b)^{-\alpha}$$

  - Note: MHD models require γ=10^6 in upstream wind – too high to explain radio emission; there may be two electron populations

- 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







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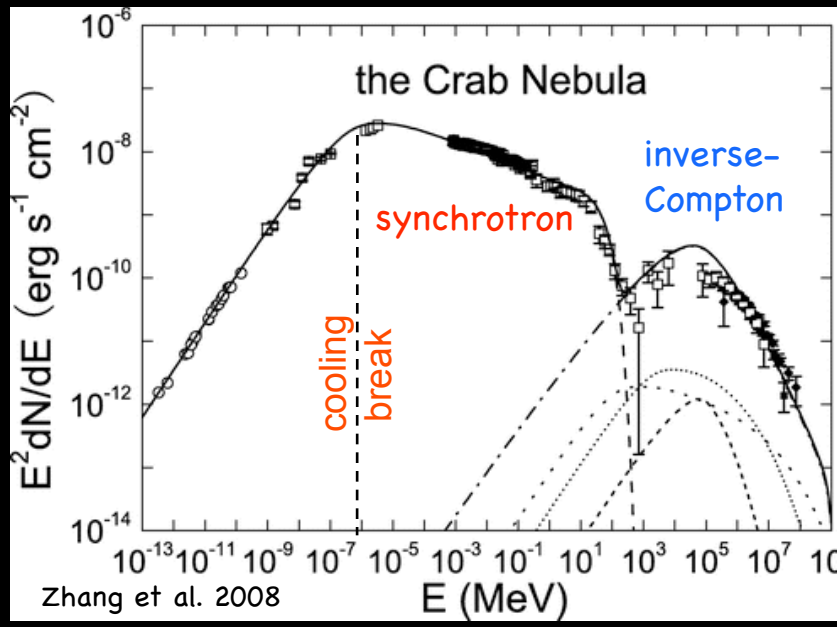

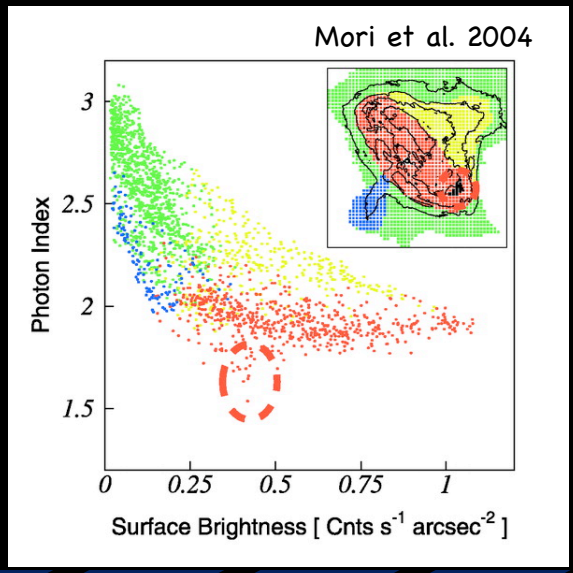

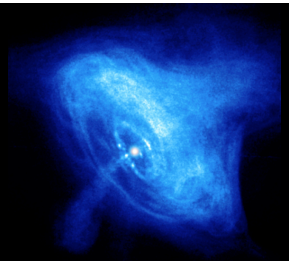

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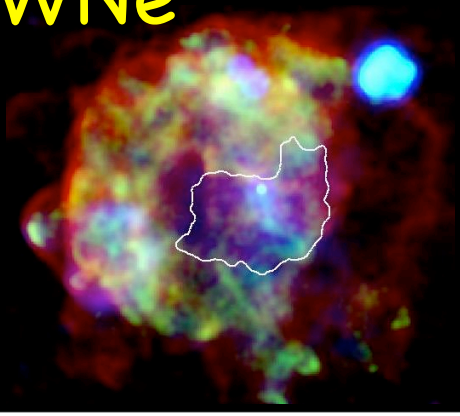

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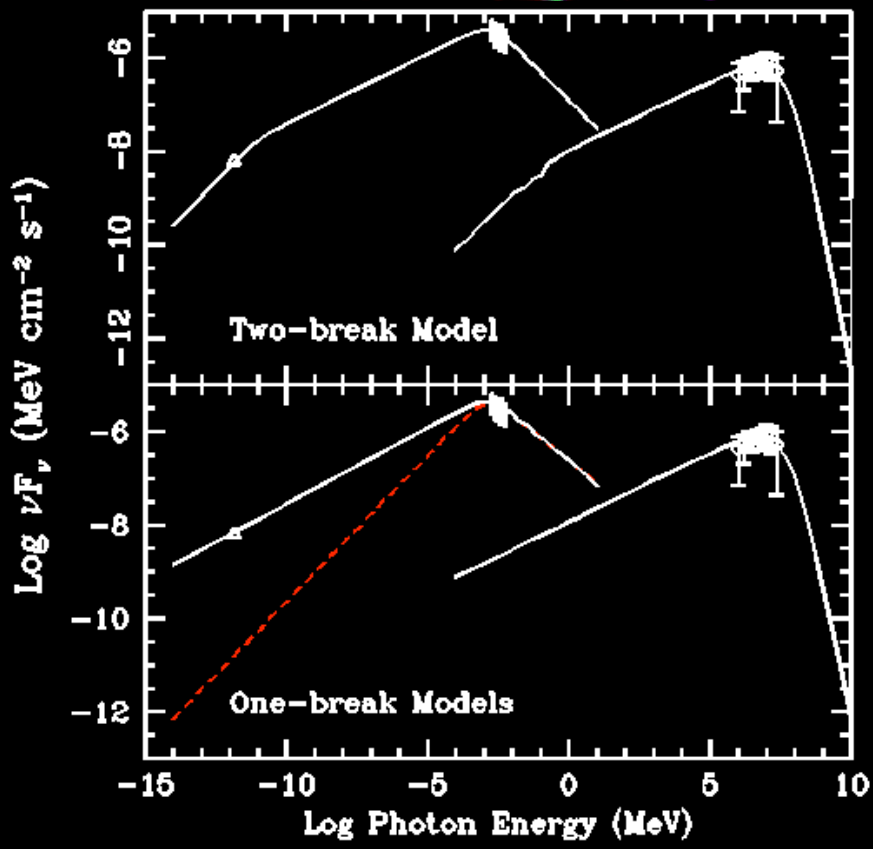

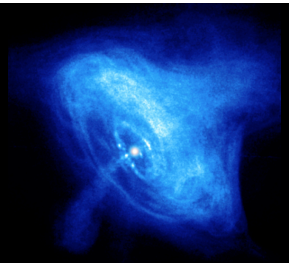

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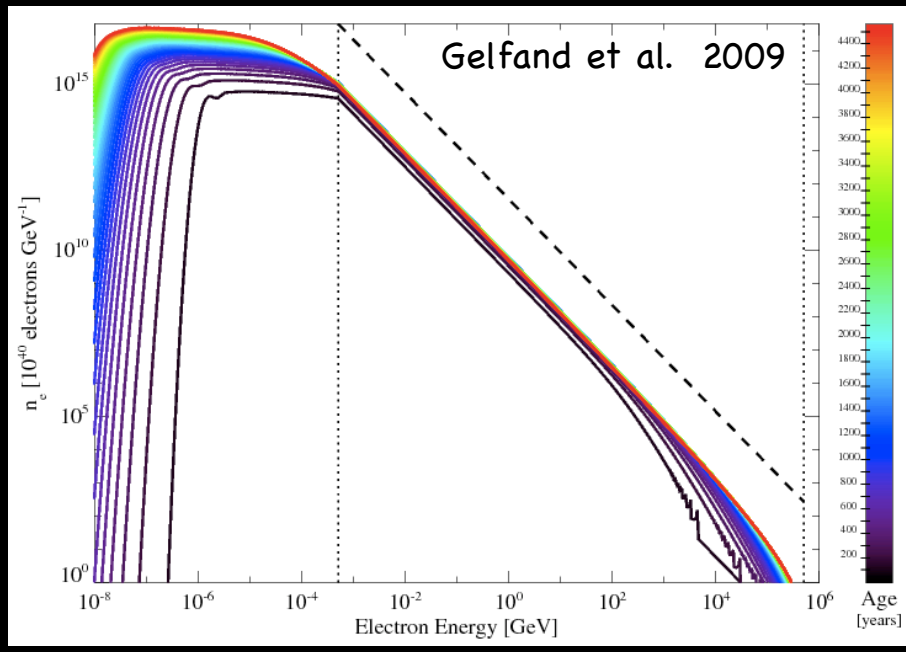
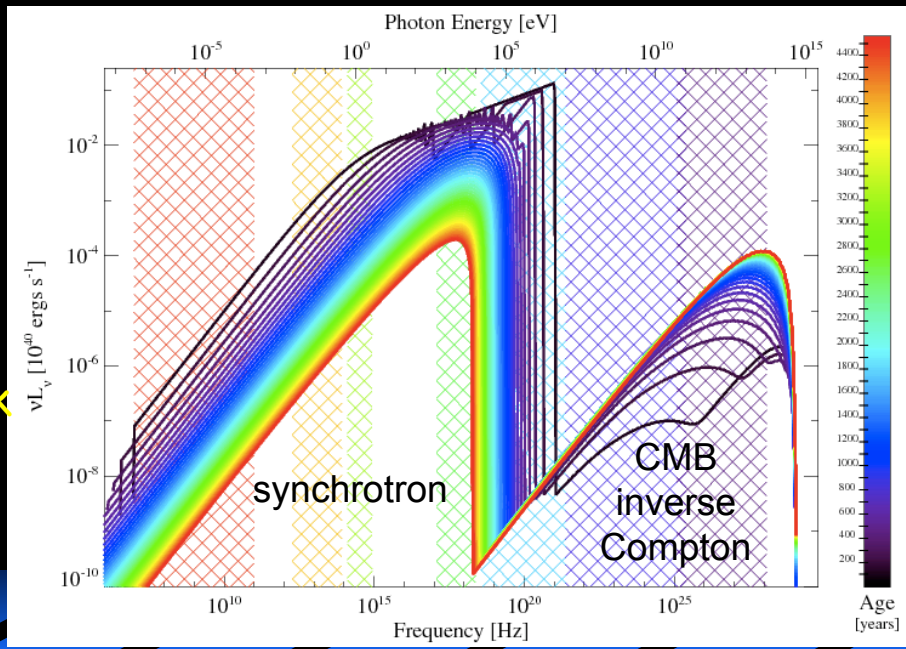
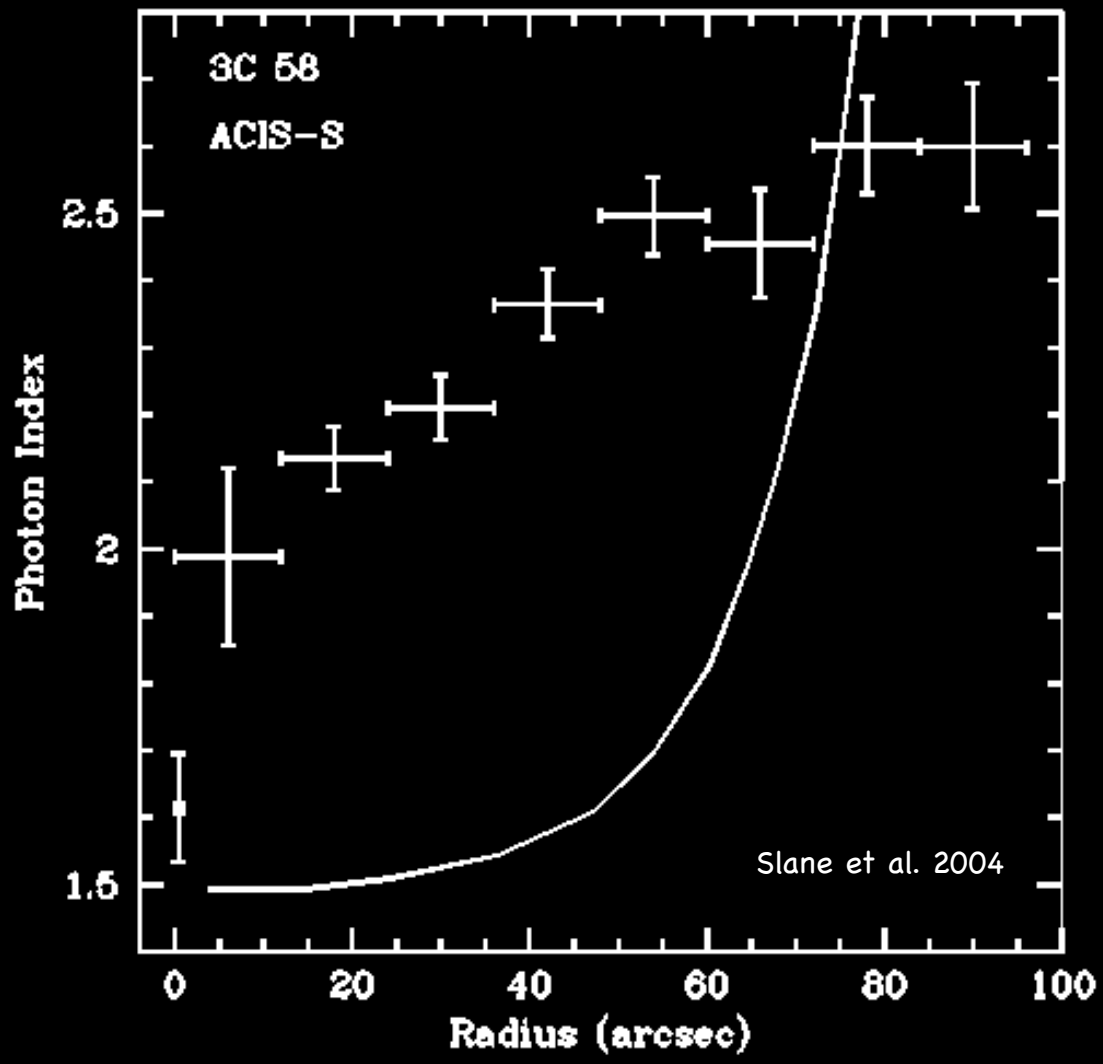




The Fate of Particles in PWNe

- Simple MHD flow fails to properly account for distribution of energetic particles inferred from X-rays
  - synchrotron cooling much faster than flow for energetic particles
  - somehow, energetic particles are transported to larger radii than predicted

- Flow pattern appears to be more complex than revealed in 1-D and 2-D hydro/MHD simulations
  - more extensive modeling required, including effects of diffusion and geometry of magnetic field



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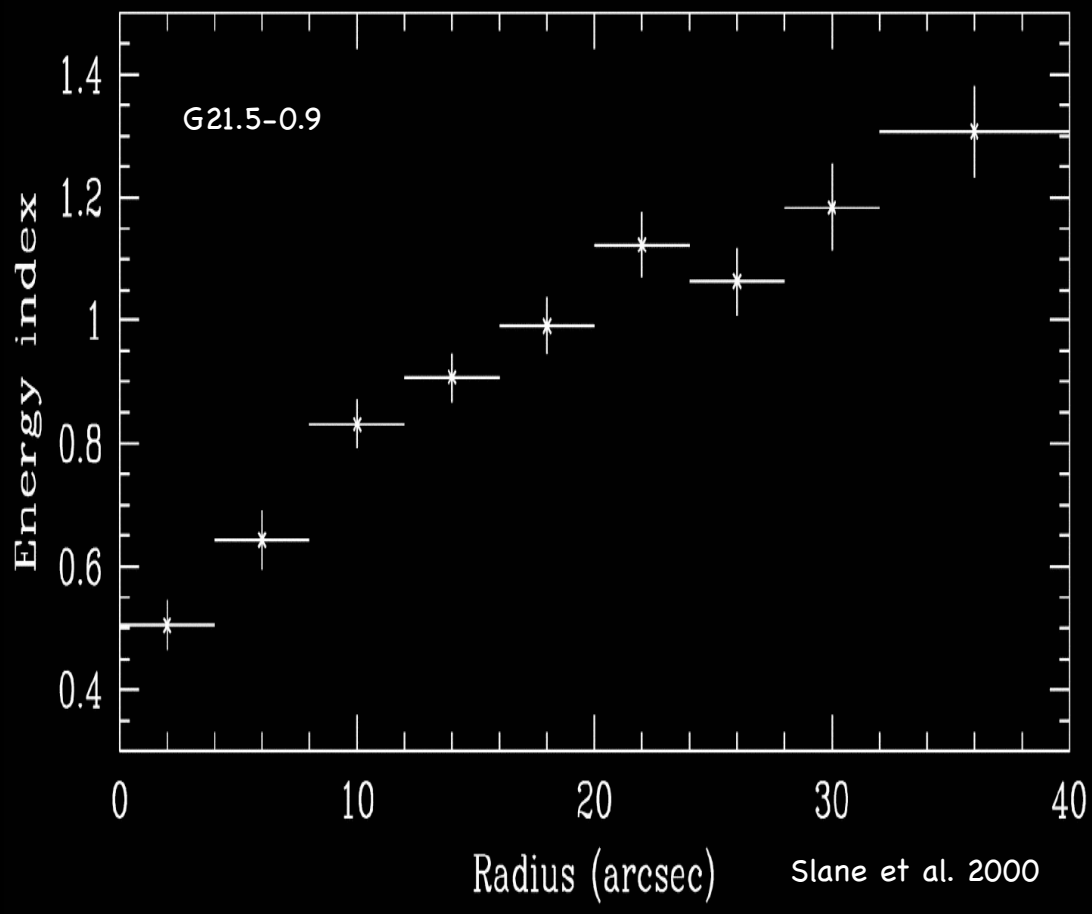

I. Injection Spectrum

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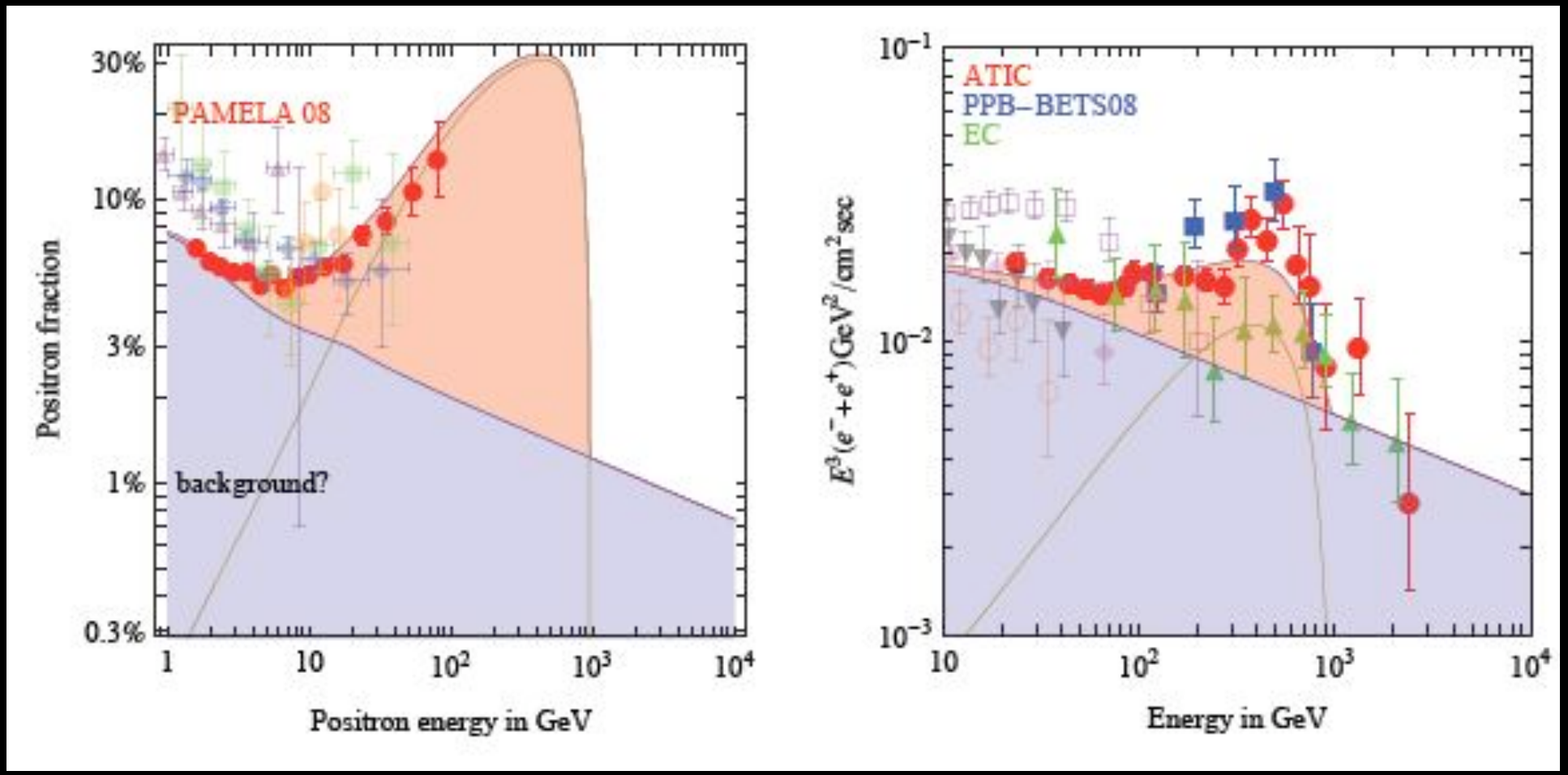
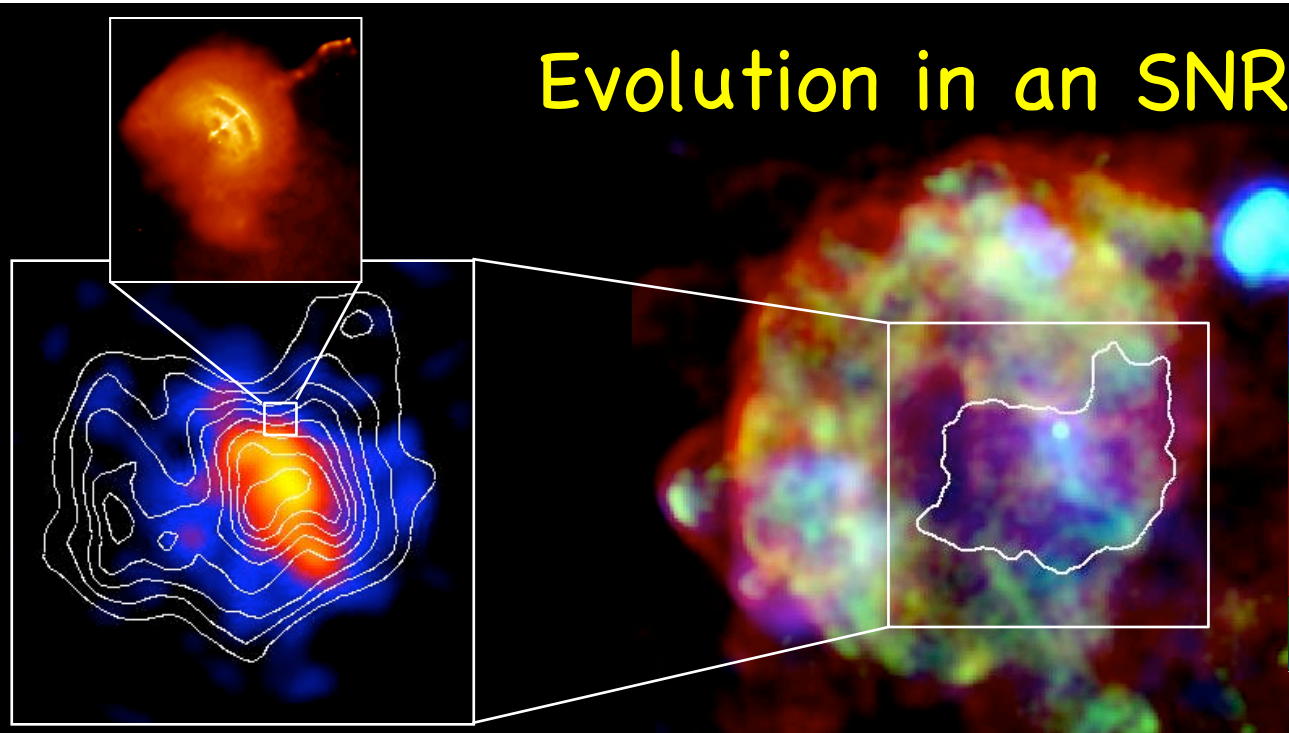
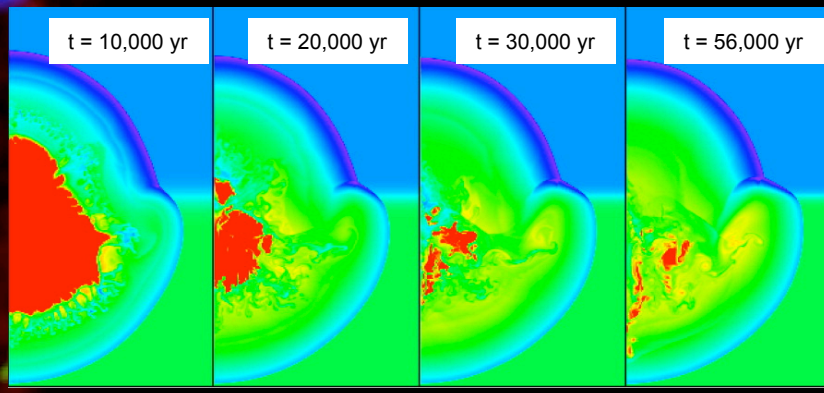
What is the Spectrum at End of Life?



Evolution in an SNR: Vela X



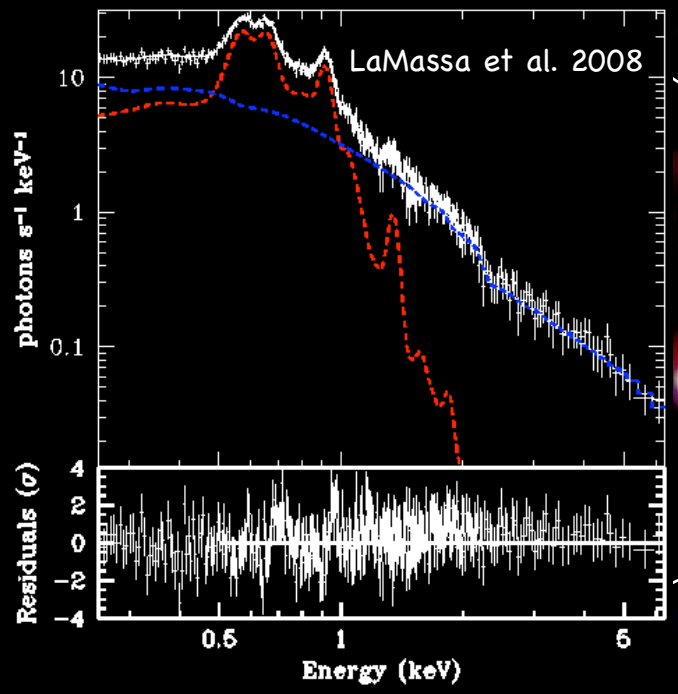


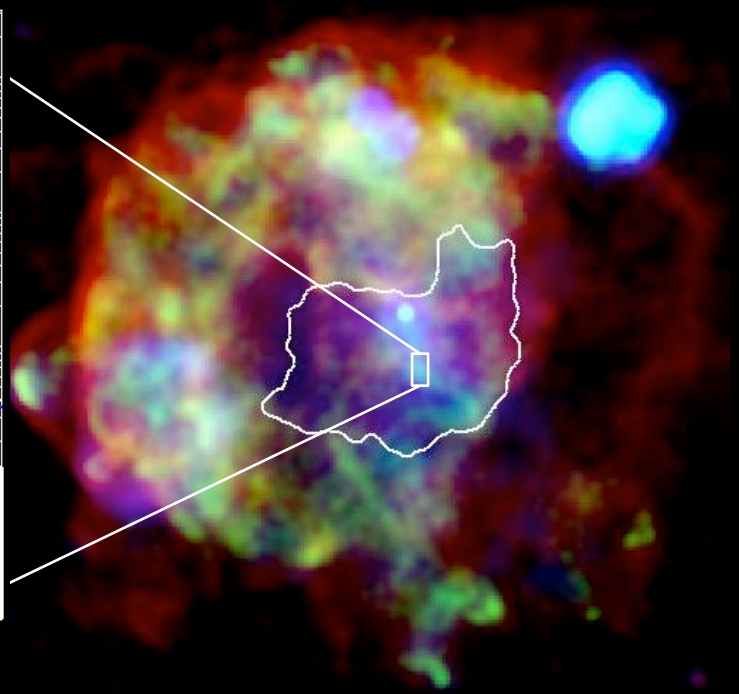
Blondin et al. 2001

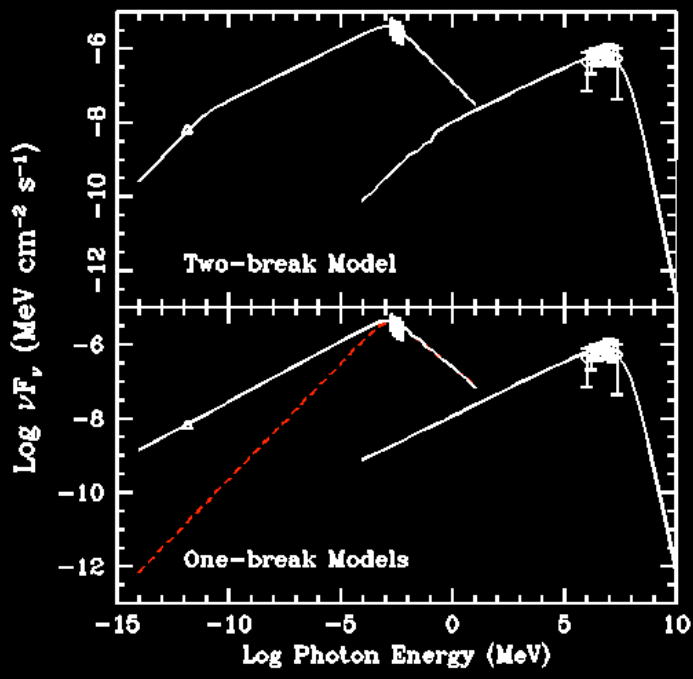
- Vela X is the PWN produced by the Vela pulsar
  - apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock

- 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

Evolution in an SNR: Vela X



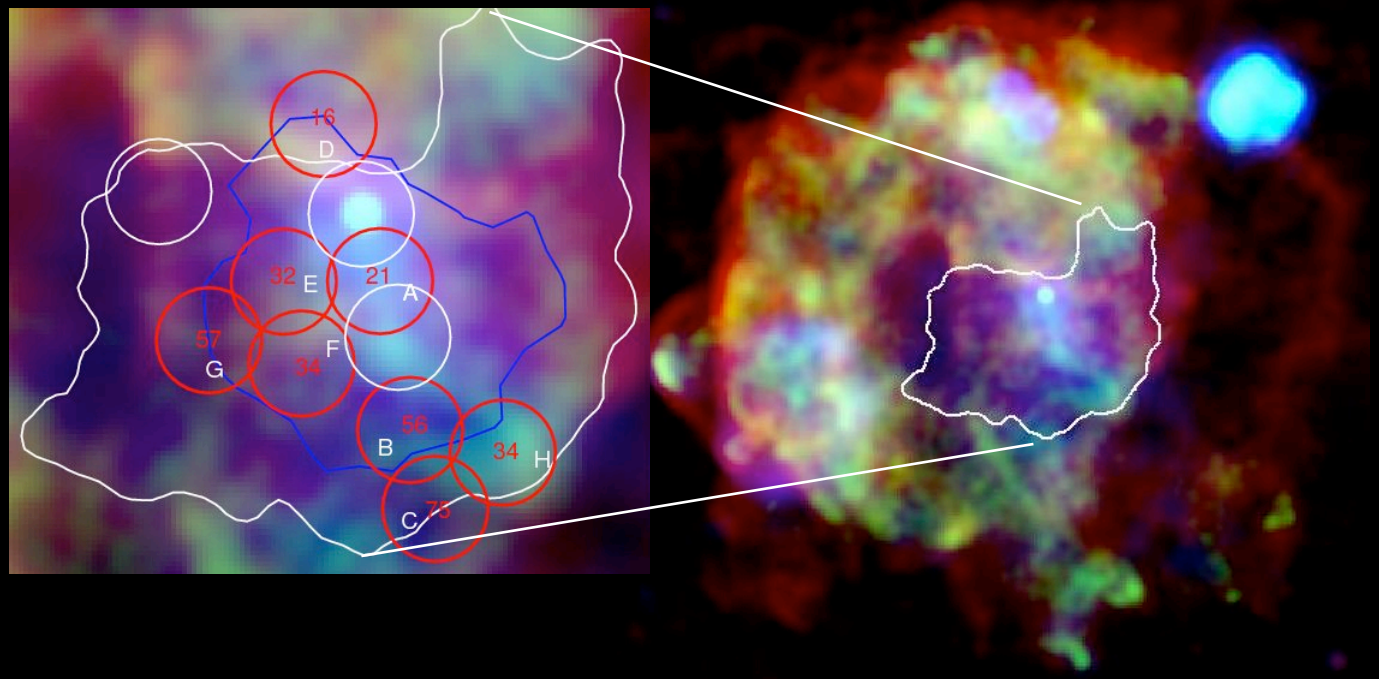




- XMM spectrum shows nonthermal and ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta? R-T filaments providing radial B field?

- Broadband measurements appear consistent with synchrotron and I-C emission from power law particle spectrum w/ two spectral breaks, or two populations
  - density too low for pion-production to provide observed γ-ray flux
  - magnetic field very low (5 μG)

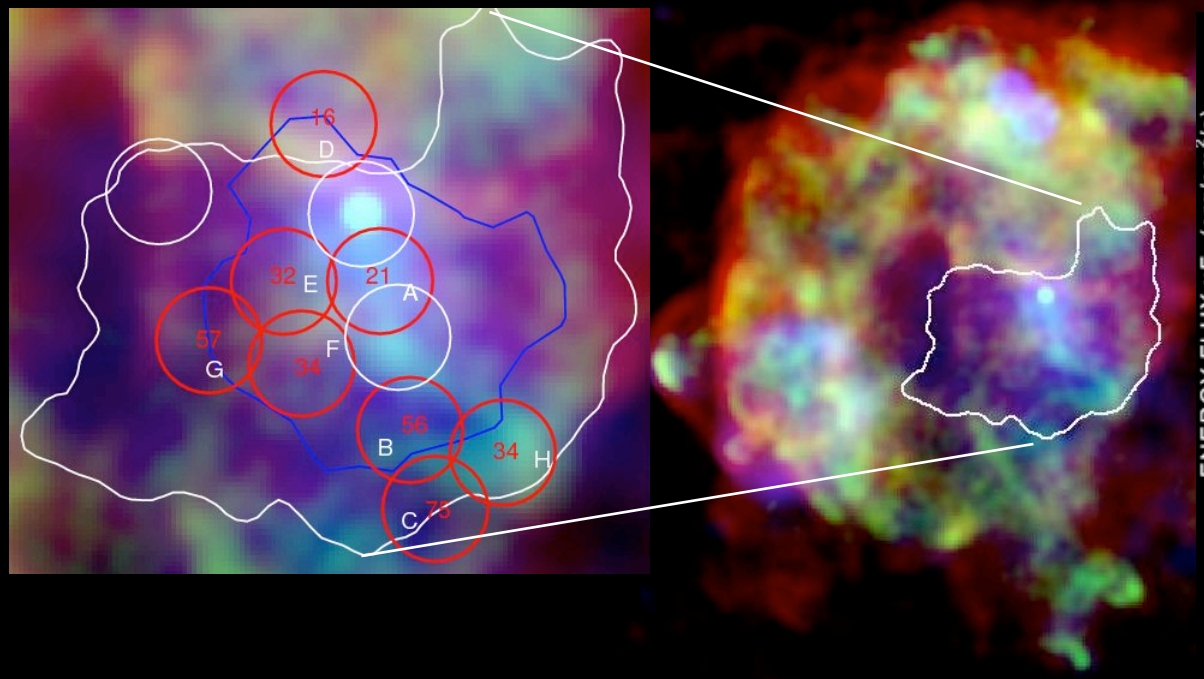
Understanding Vela X: XMM

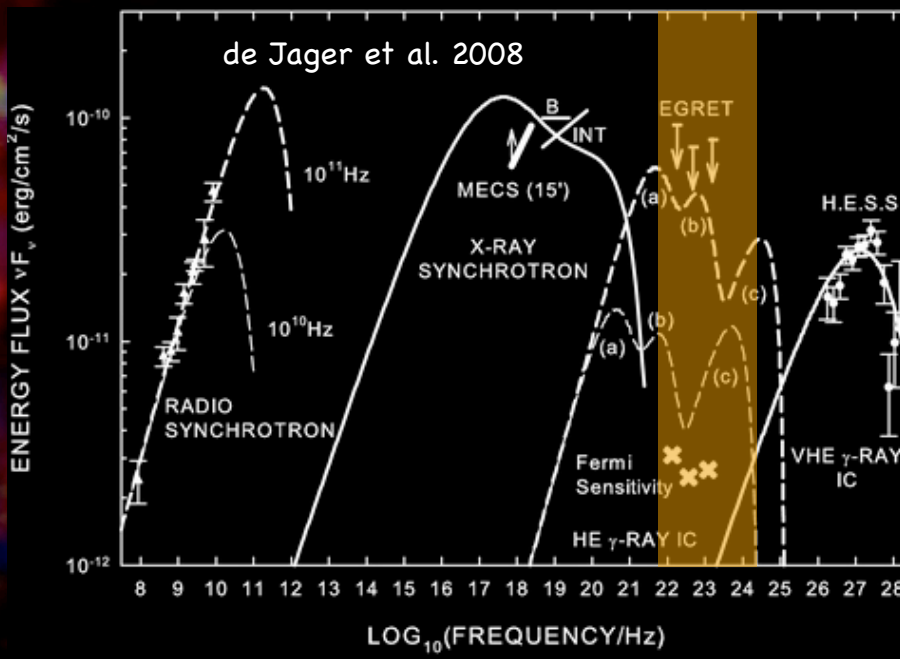


- XMM large project (400 ks) will map Vela X to study ejecta and nonthermal emission

- Radio and VHE spectrum for entire 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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Questions

- What causes the complex spectra of PWNe?
  - it doesn't all appear to be evolution; some structure may be required at injection
- Is there a "relic" population of low-energy electrons?
  - maybe not; does a small thermal component combined with evolutionary losses explain the radio emission?
- Why does the X-ray spectral index vary so slowly with radius?
  - is this just from flows in 3-D that the models haven't accounted for, or is it something more complex (e.g. re-acceleration)?
- What is the long-term fate of the particles in PWNe?
  - when do the particles leave the PWN, and what is the spectrum at this point?