# Observations of Pulsar Wind Nebulae

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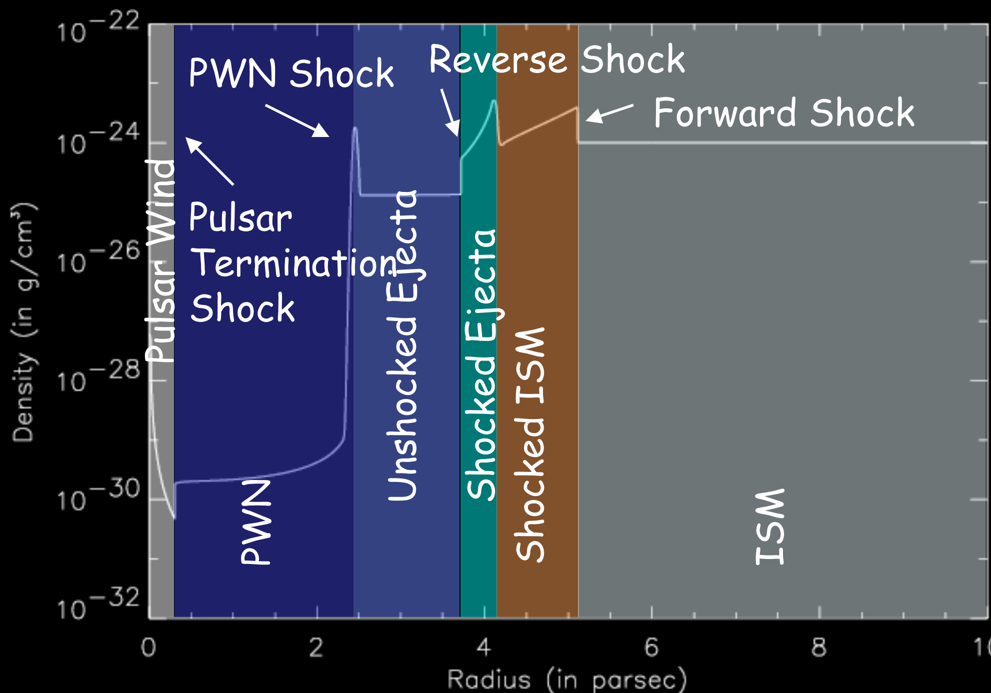
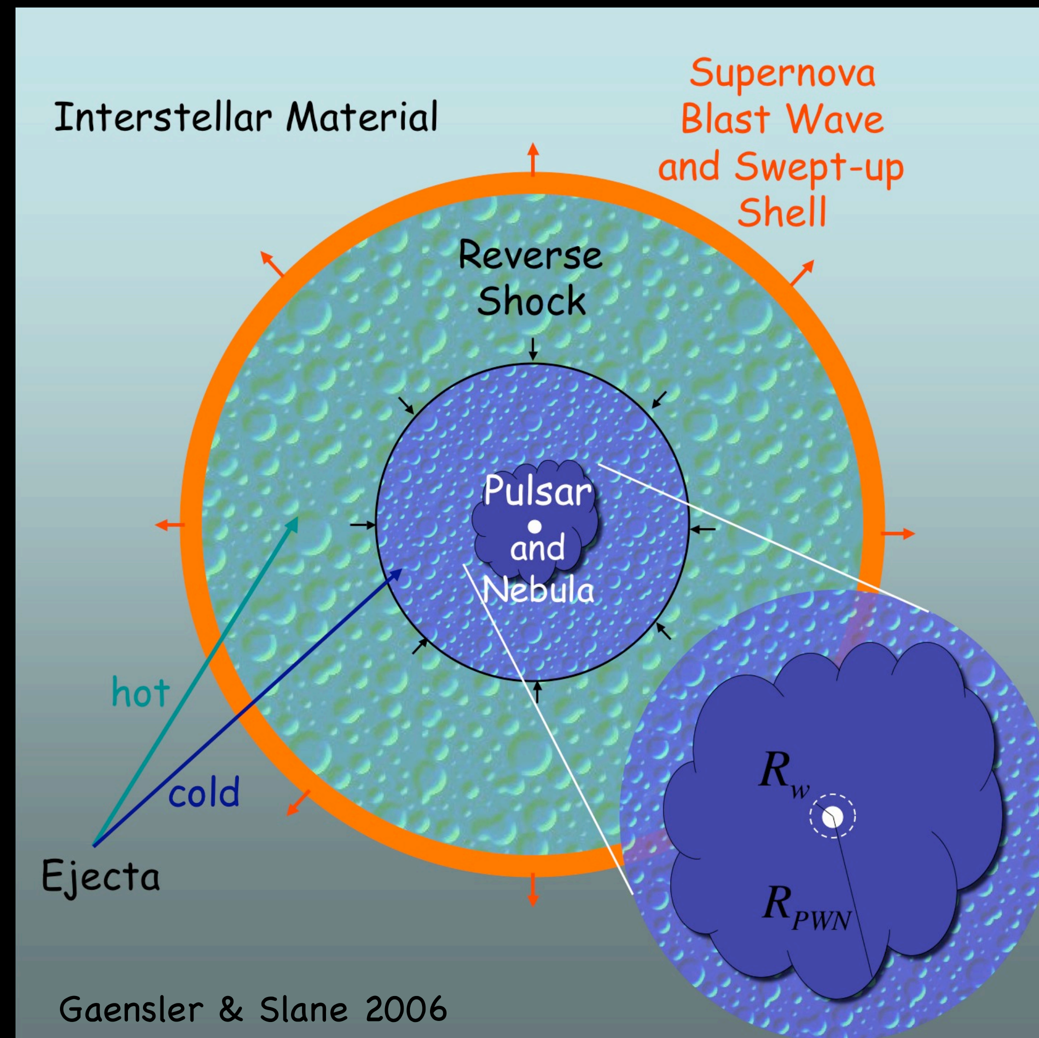
I. Spatial Structure

II. Spectral Structure

III. Evolution

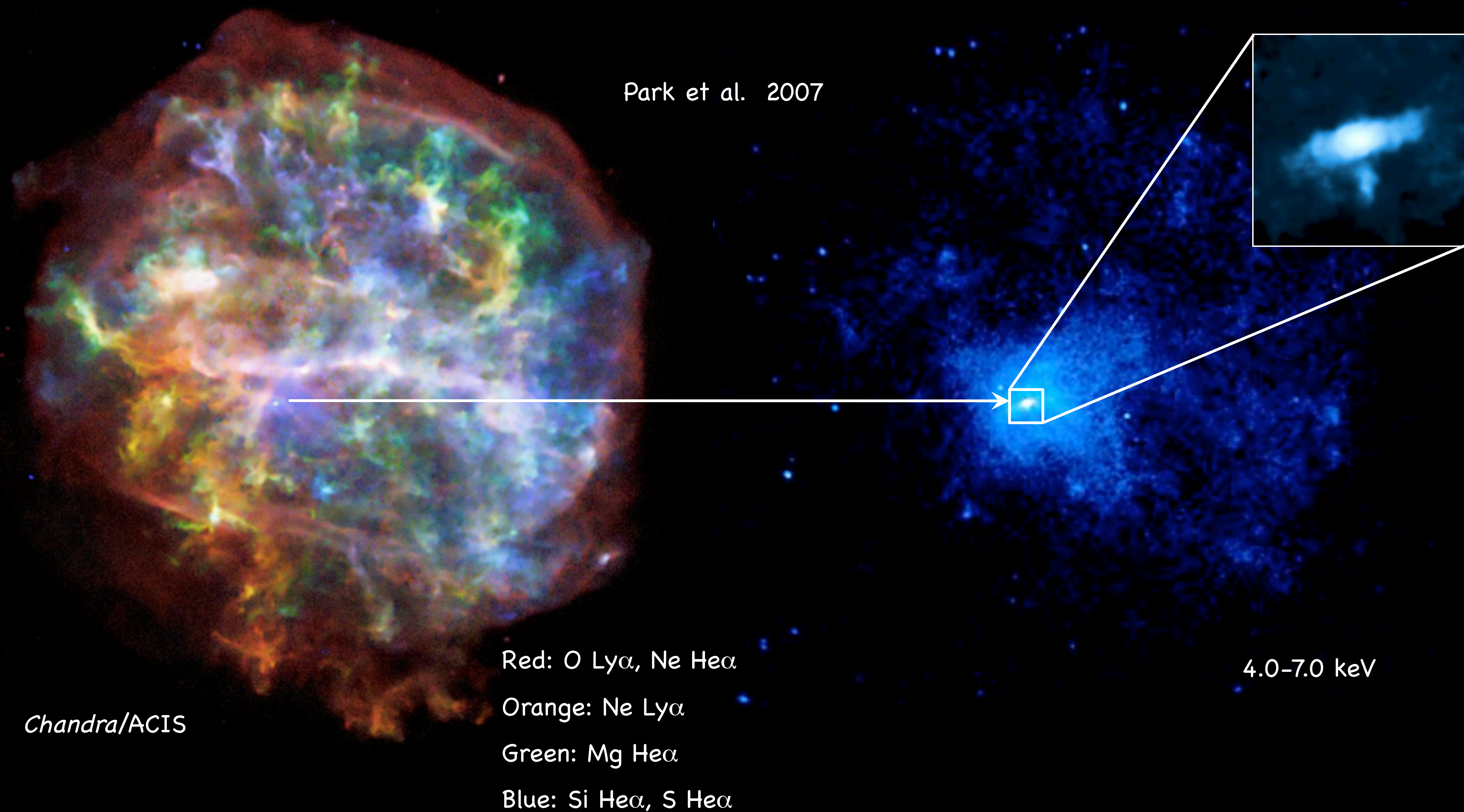
# PWNe and Their SNRs



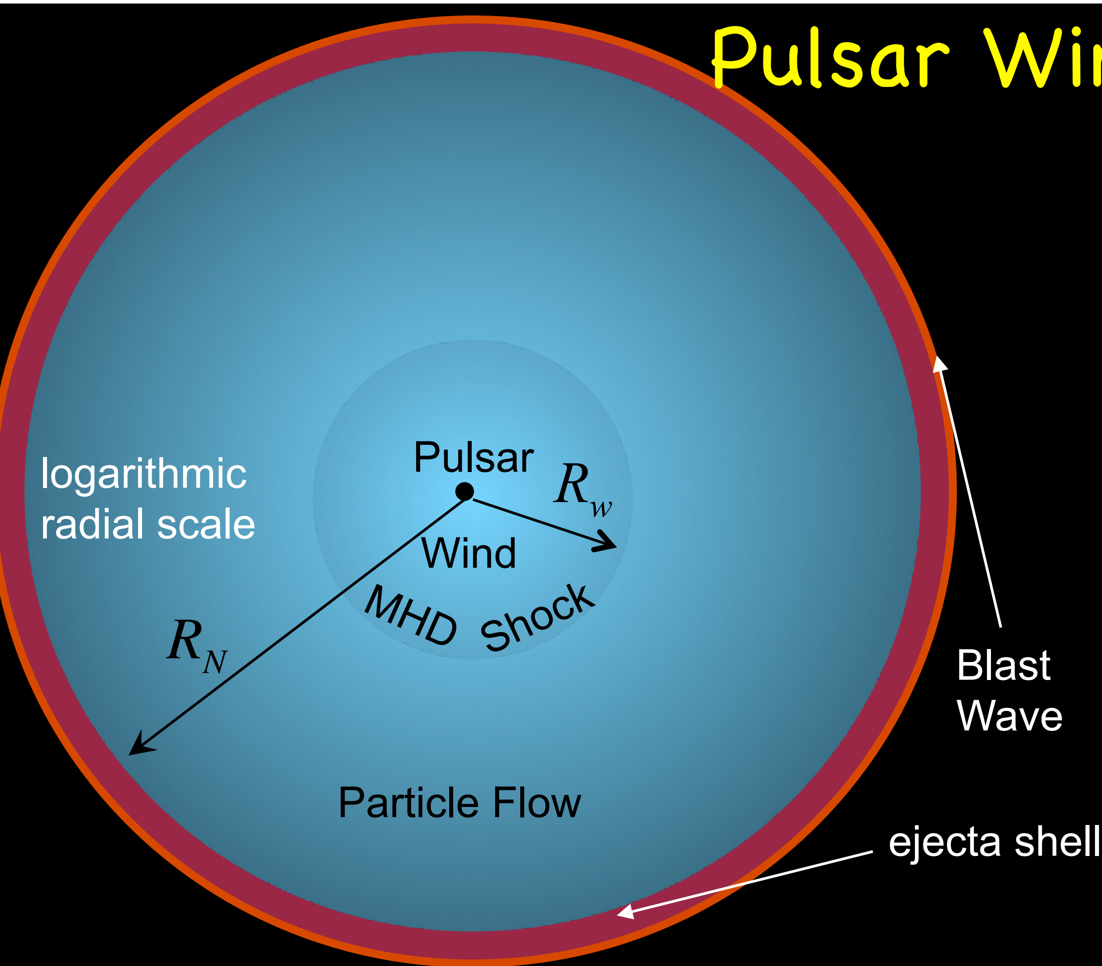




- Pulsar Wind
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms
- Supernova Remnant
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; energy distribution of particles in nebula tracks evolution; instabilities at PWN/ejecta interface may allow particle escape

# G292.0+1.8: A Prototypical Composite SNR



# Pulsar Wind Nebulae




- Pulsar accelerates particle wind
  - wind inflates bubble of particles and magnetic flux
  - particle flow in B-field creates synchrotron nebula

- Expansion boundary condition at $R_w$ forces wind termination shock at $R_N$
  - wind goes from $v = c/3$ inside $R_w$ to $v = R_N/t$ at outer boundary

- Pulsar wind is confined by pressure in nebula
  - wind termination shock

$$R_w = \left[ \frac{\dot{E}}{4\pi c p_N} \right]^{1/2}$$

obtain by integrating radio spectrum

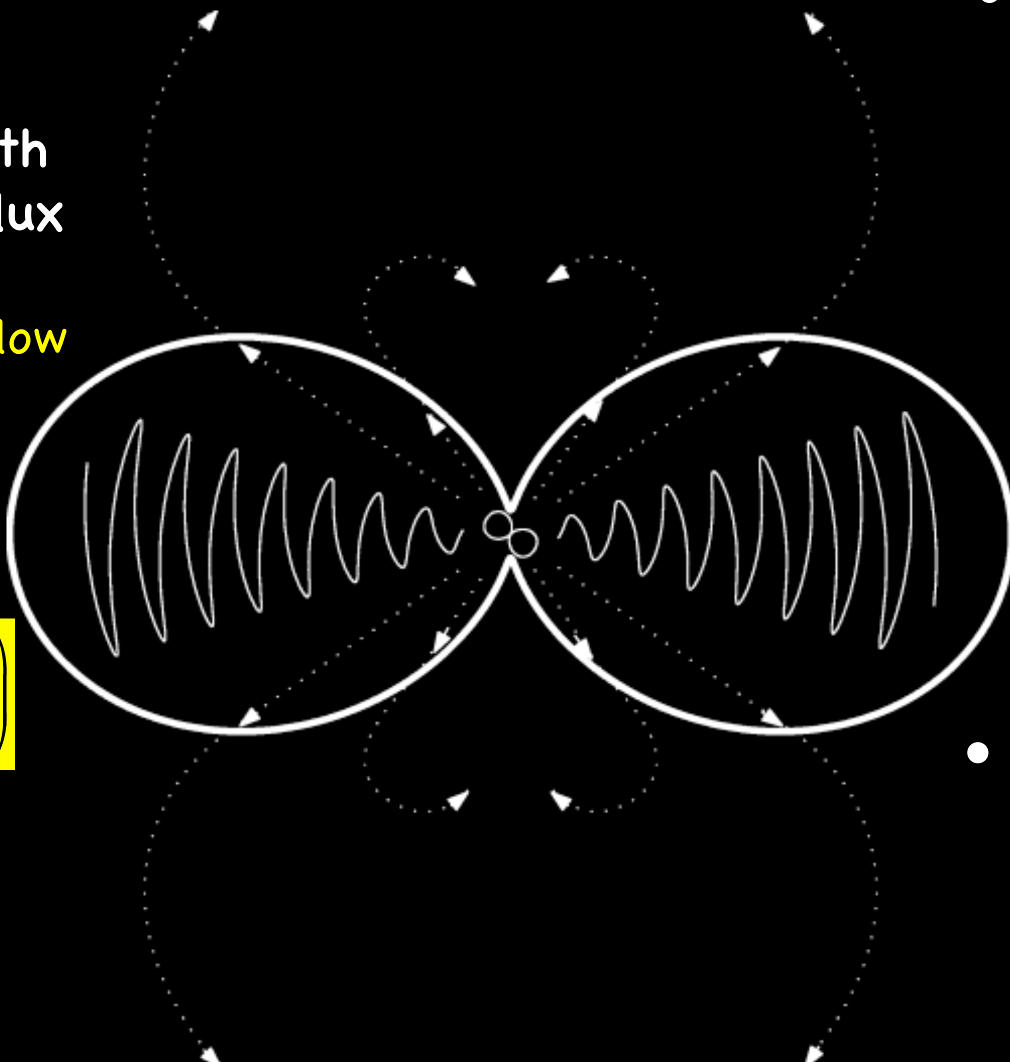
- To meet both flow conditions and X-ray luminosity, upstream wind must be particle-dominated (KC84)

$$\sigma = \frac{B^2}{4\pi\rho\gamma^2 c^2} << 1$$

# Jet/Torus Structure in PWNe

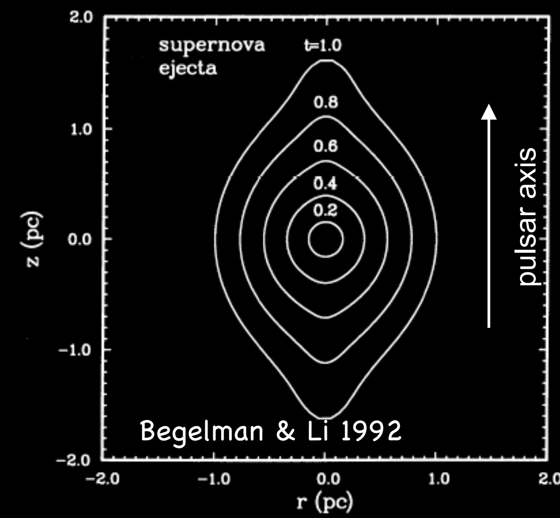
- Anisotropic flux with maximum energy flux in equatorial zone
  - radial particle outflow
  - striped wind from Poynting flux decreases away from equator

$$F \approx \frac{\Omega^2 \psi_0^2}{4\pi c^2 R^2}\left(\sin^2\theta + \frac{1}{\sigma_0}\right)$$

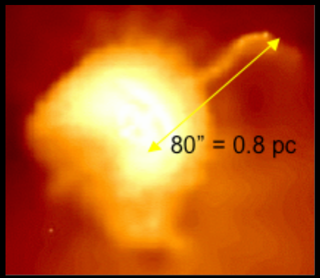


Lyubarsky 2002

- Magnetic tension in equatorial plane results in elongation along rotation axis




- Polar jets form, subject to kink instabilities



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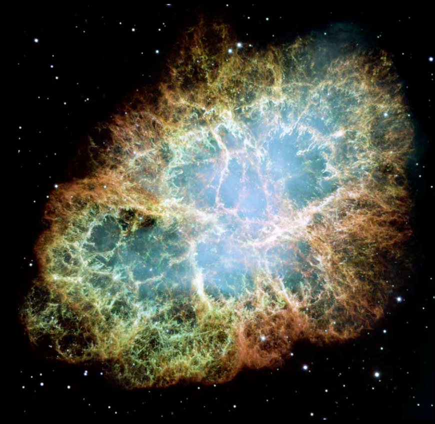

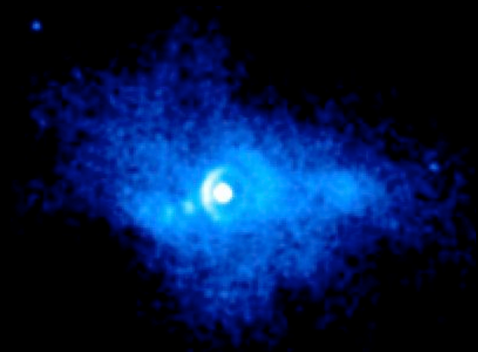

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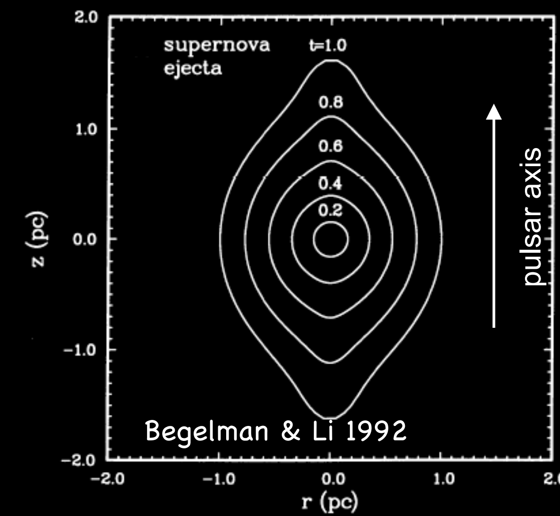


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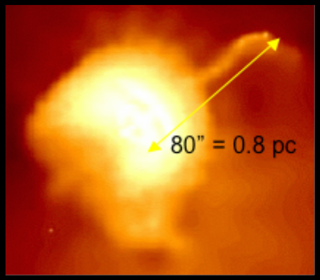
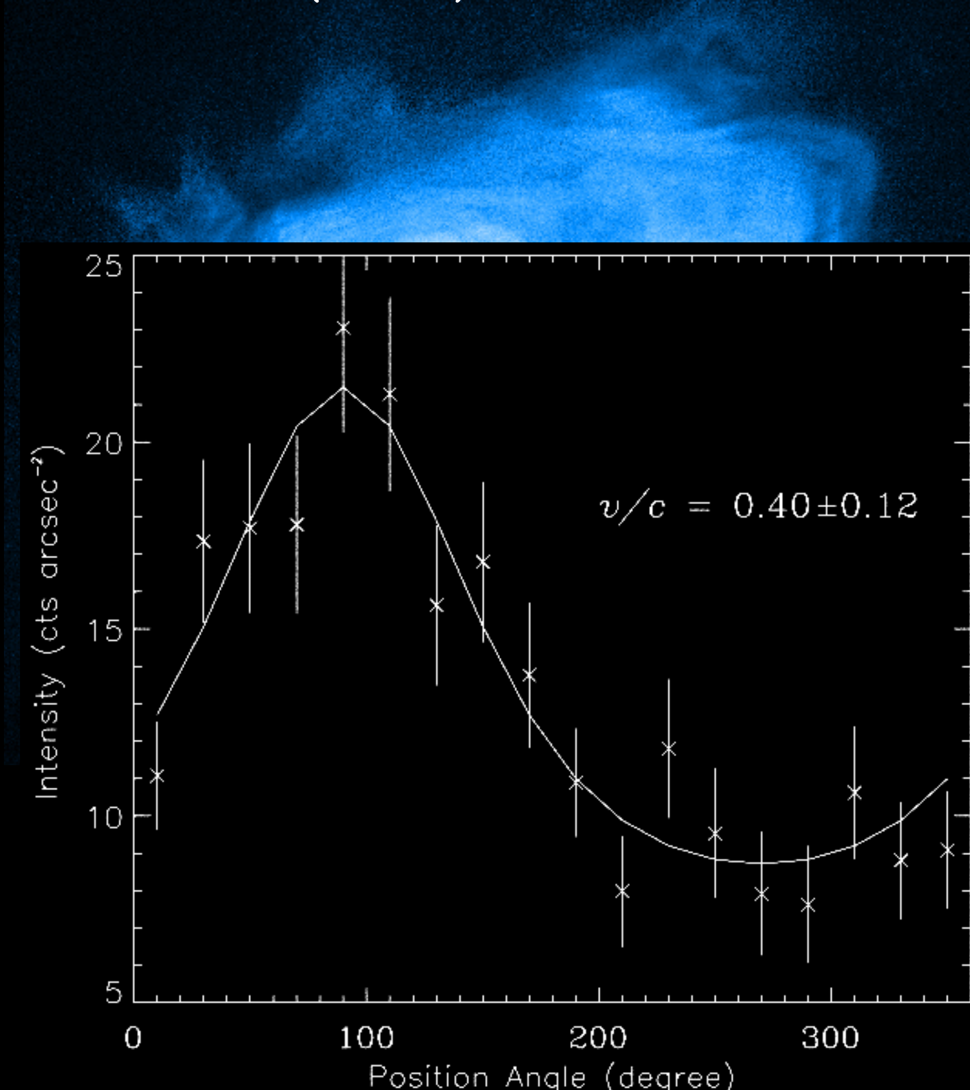
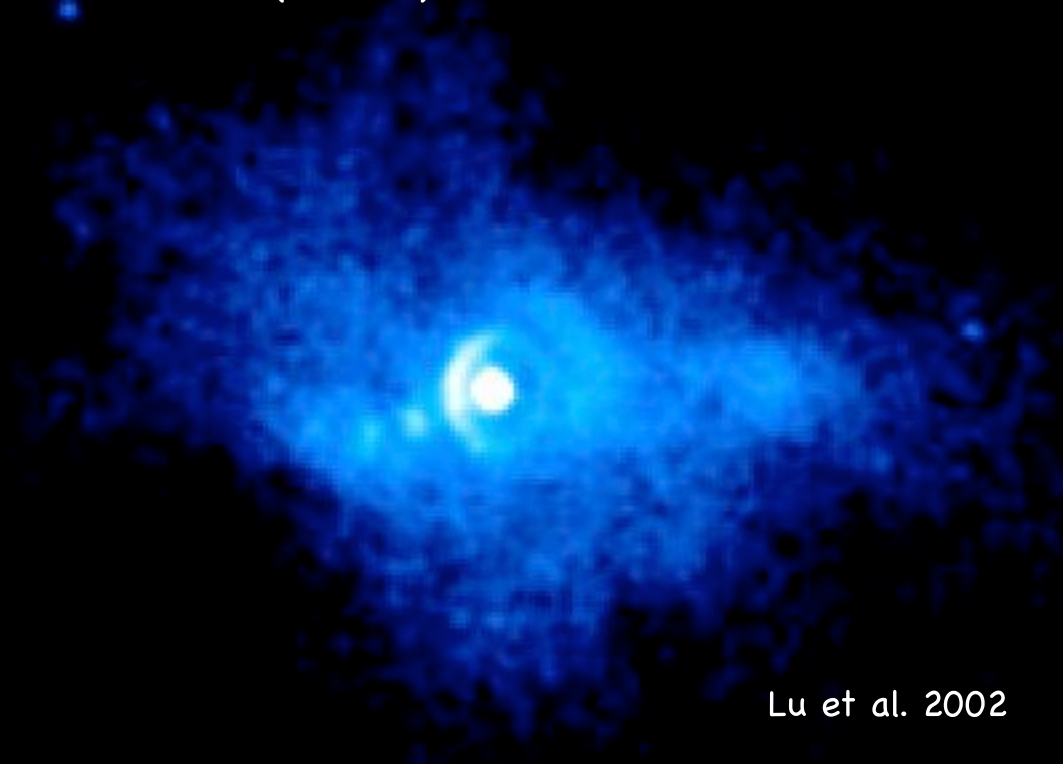


# Jet/Torus Structure in PWNe

Crab Nebula (Chandra)



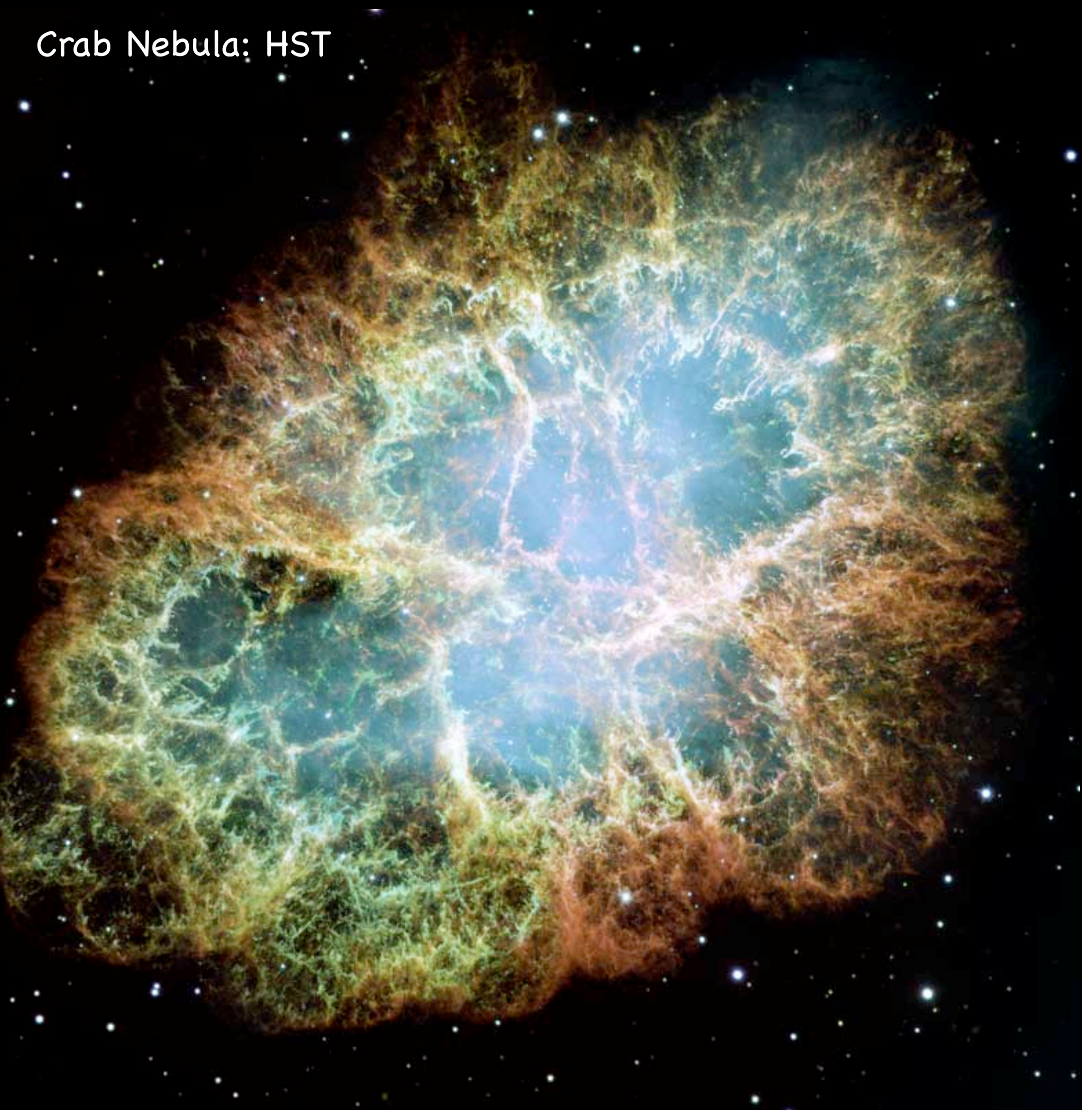

G54.1+0.3 (Chandra)



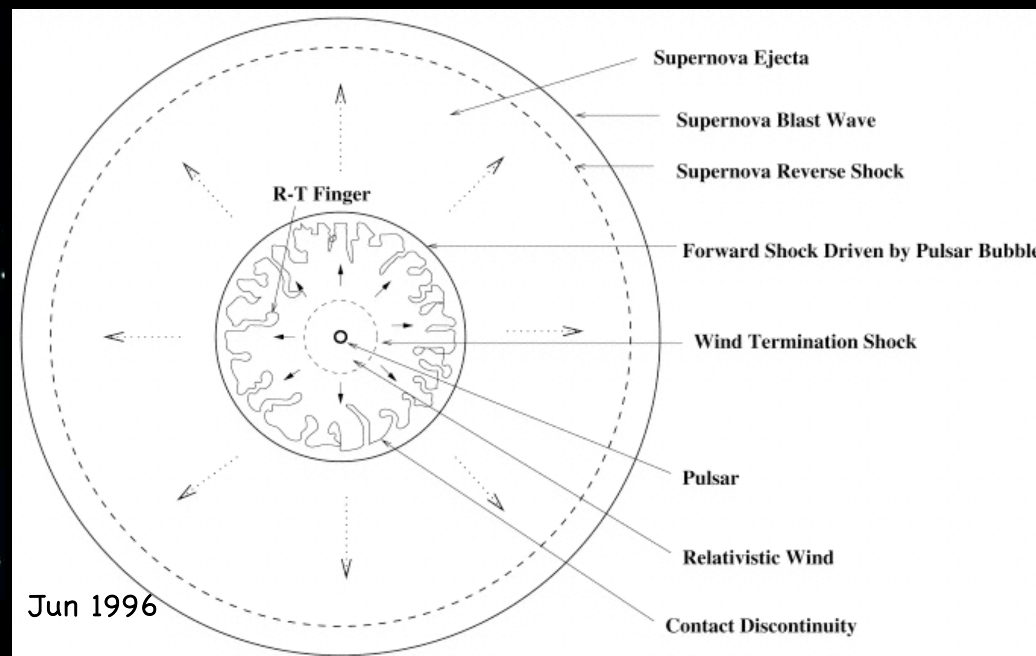
Lu et al. 2002

- Doppler beaming and geometry indicate rapid flows:
  v = 0.4c

# The Surrounding Ejecta: Crab Nebula




- Optical filaments show dense ejecta
  - total mass in filaments is small; still expanding into cold ejecta
- Rayleigh-Taylor fingers produced as relativistic fluid flows past filaments
  - continuum emission appears to reside interior to filaments; filamentary shell



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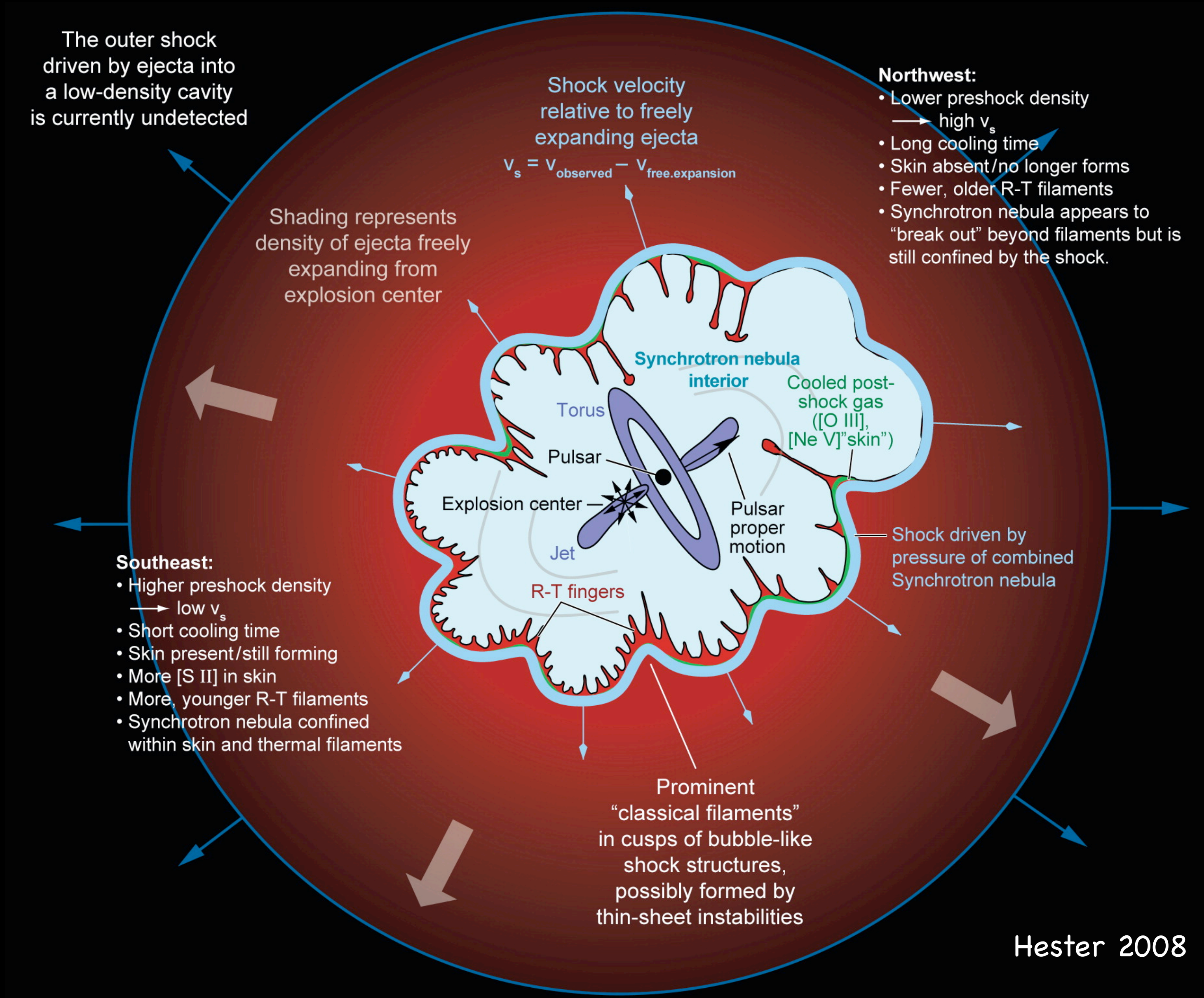
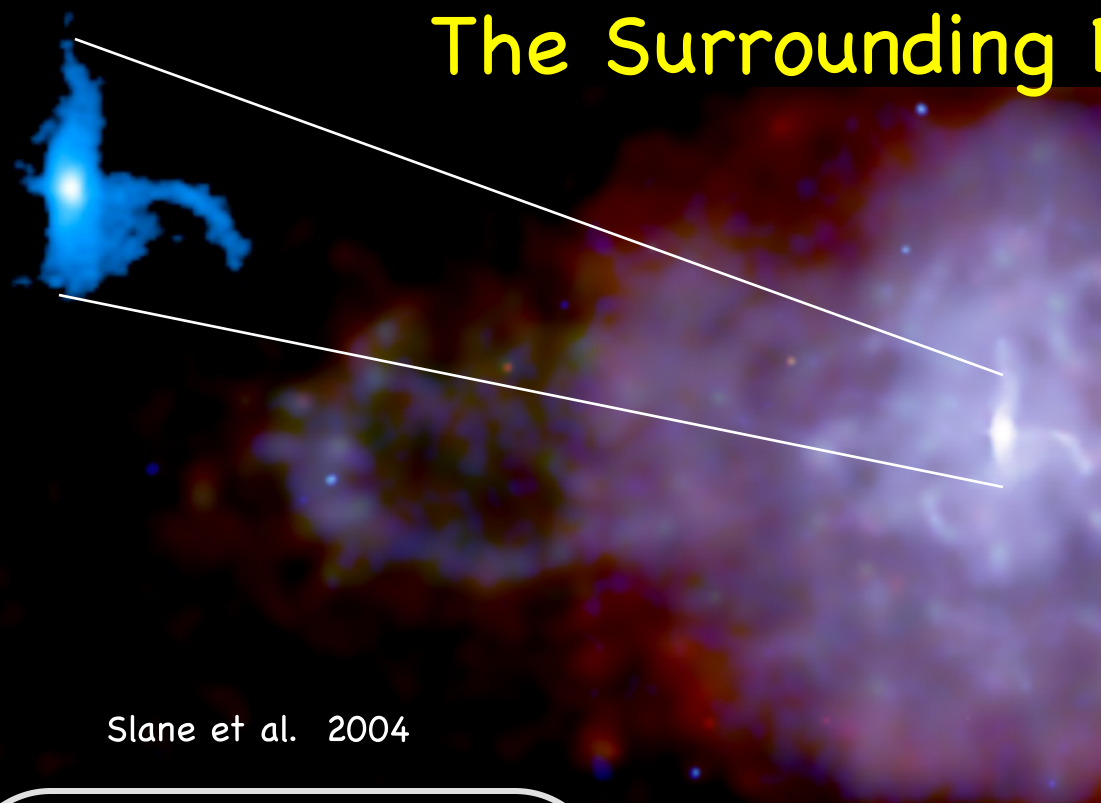
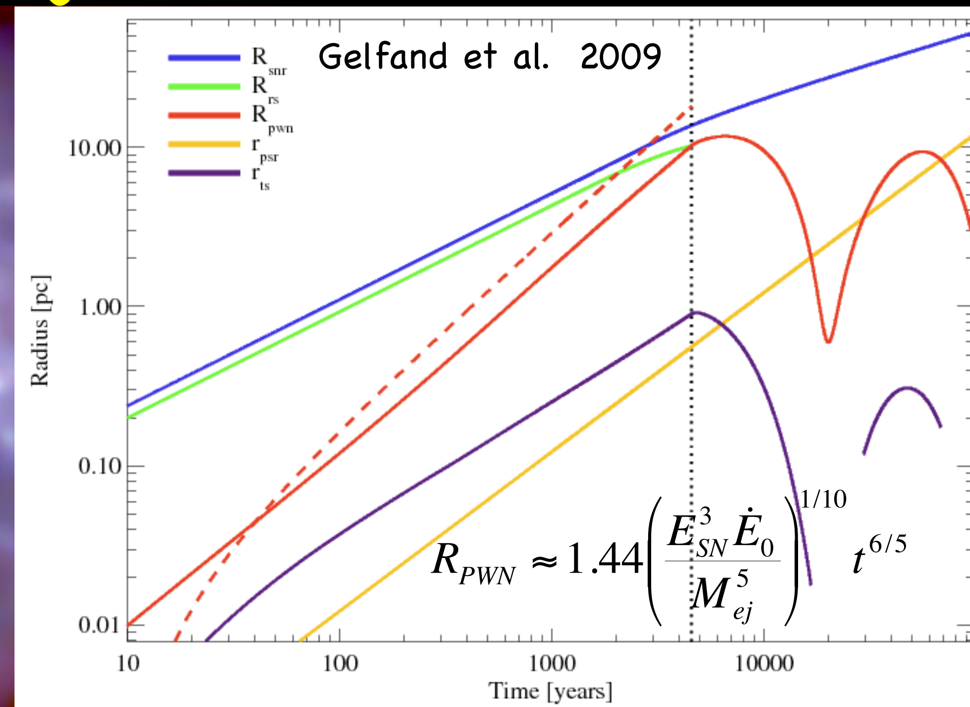



Hester 2008

# The Surrounding Ejecta: 3C 58




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

$$\frac{dM}{dt} = 4\pi R^2 \rho_{SN} (\mathrm{v} - R/t)$$

energy input and swept-up ejecta mass

Measurements of PWN evolution and swept-up mass constrain initial spin and its evolution

$$\frac{d\left(\frac{4}{3}\pi R^3 p_i\right)}{dt} = \dot{E} - p_i 4\pi R^2 \frac{dR}{dt}$$

$$M\frac{d\mathrm{v}}{dt} = 4\pi R^2 \left[p_i - \rho_{SN}(\mathrm{v} - R/t)^2\right]$$

PWN evolution

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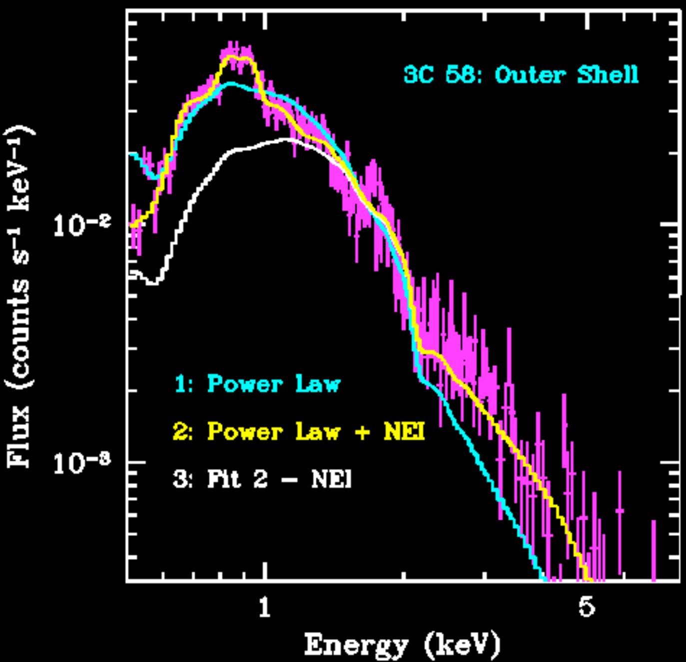
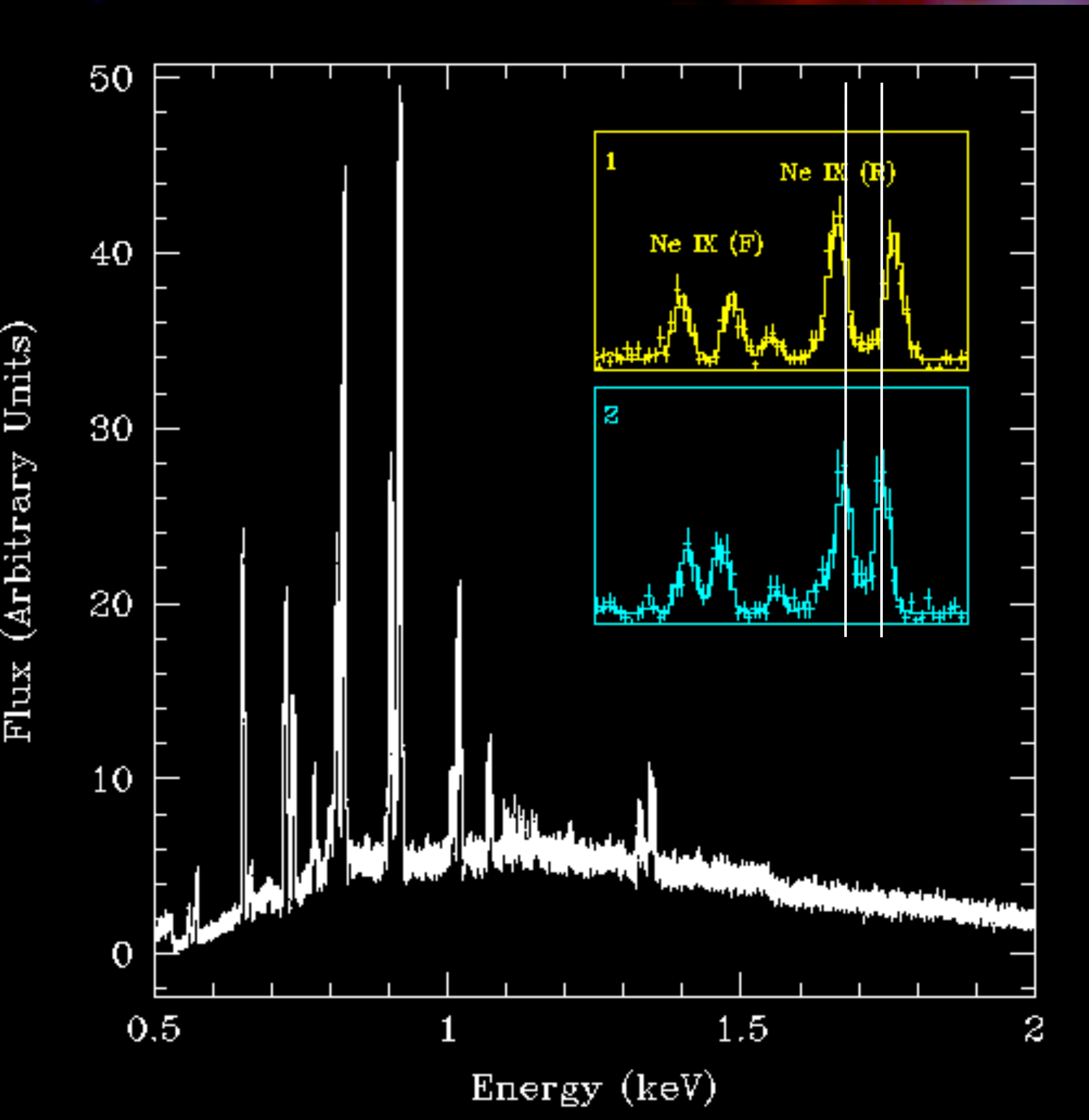
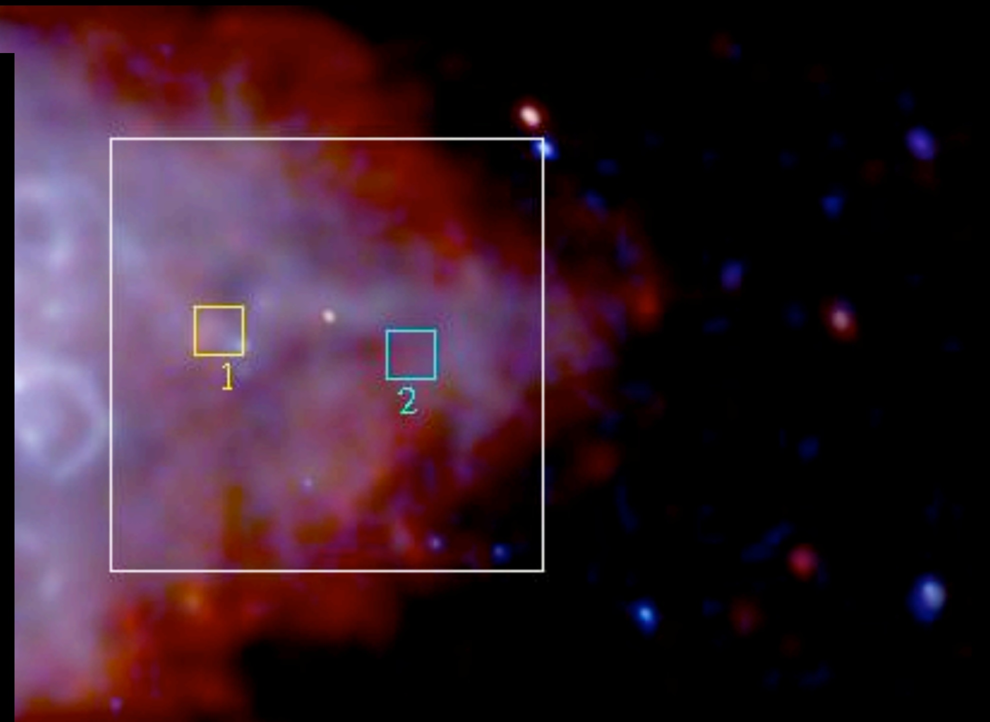



- Chandra reveals complex structure of wind shock zone and surroundings
- Spectrum reveals ejecta shell with enhanced Ne and Mg
  - PWN expansion sweeps up and heats cold ejecta
- Mass and temperature of swept-up ejecta suggests an age of ~2400 yr and a Type IIP progenitor, similar to that for Crab (Chevalier 2005)
- Temperature appears lower than expected based on radio/optical data

# 3C 58 Expansion w/ IXO




- Measure velocity broadening to determine age based on size
  - connect with evolution to determine initial spin and spindown properties
- Maximum velocities in optical are 900 km $s^{-1}$
  - with 2.7 eV resolution, we will resolve back and front shells and measure v

I. Spatial Structure

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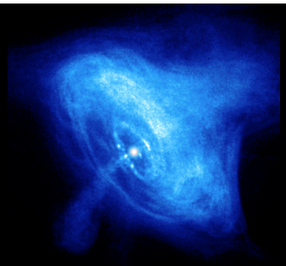


# Broadband Emission from PWNe

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

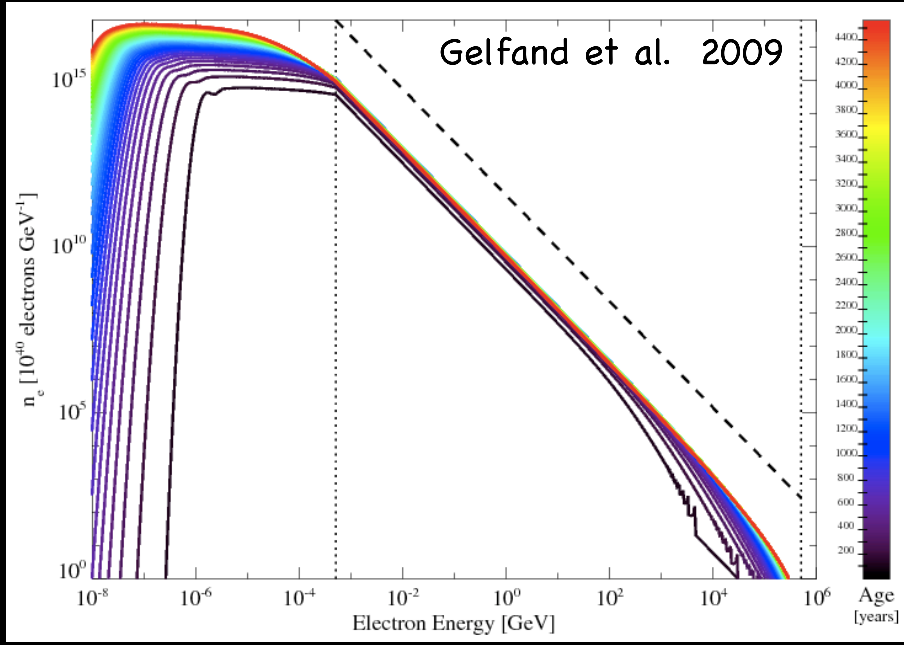
$$\dot{E} = I\Omega\dot{\Omega} = \dot{E}_0\left(1+\frac{t}{\tau}\right)^{-\frac{n+1}{n-1}}$$

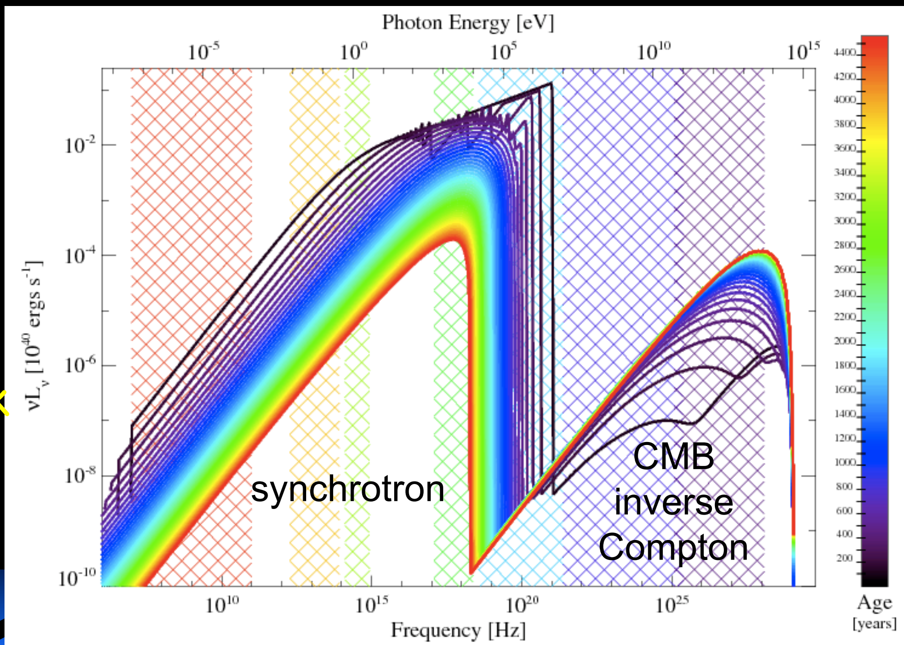
- Assume power law input spectrum:

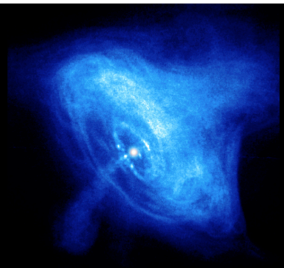
$$Q(t) = Q_0(t)(E_e/E_b)^{-\alpha}$$

  - Note: MHD models require $\gamma=10^6$ 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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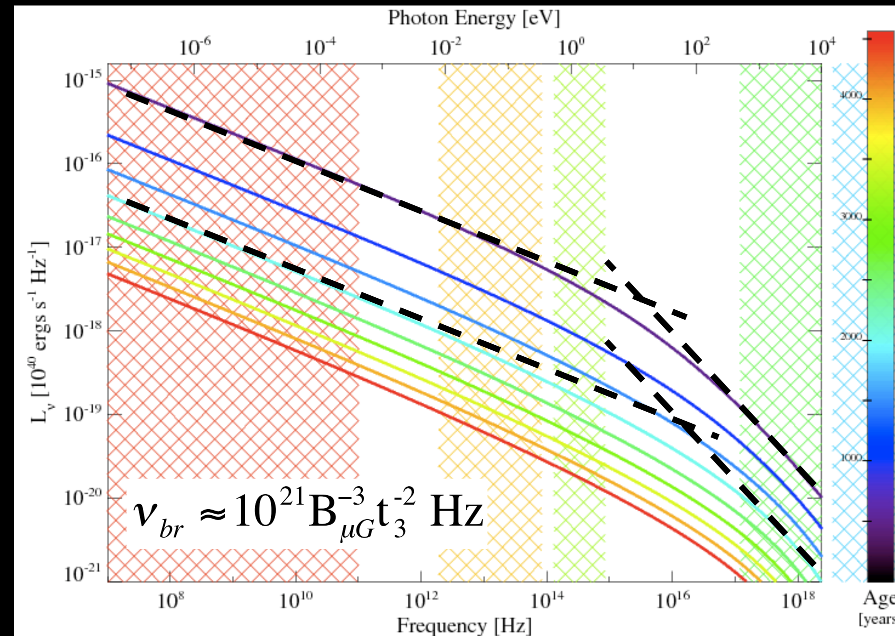


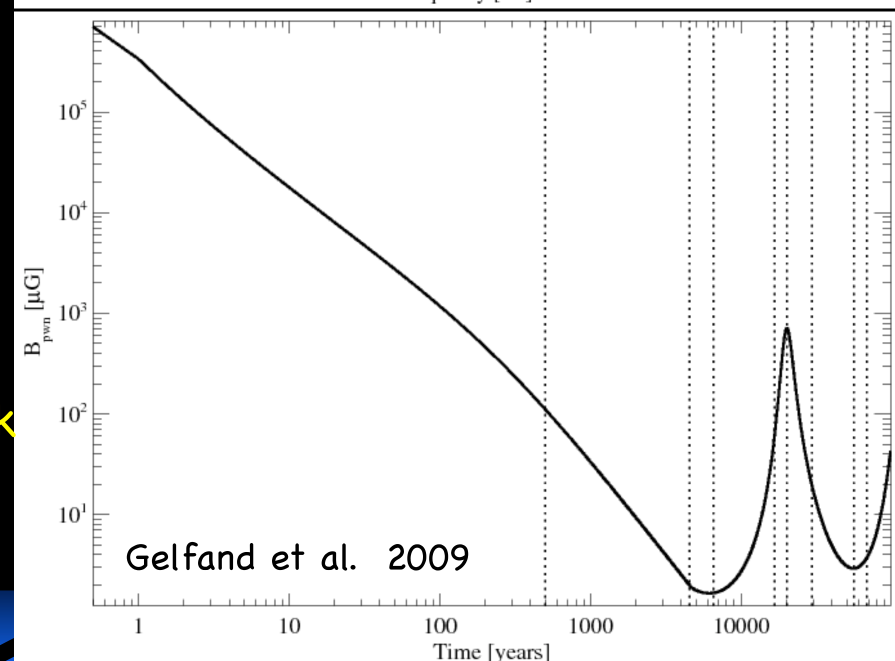

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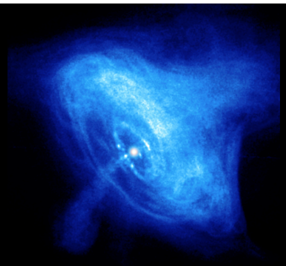

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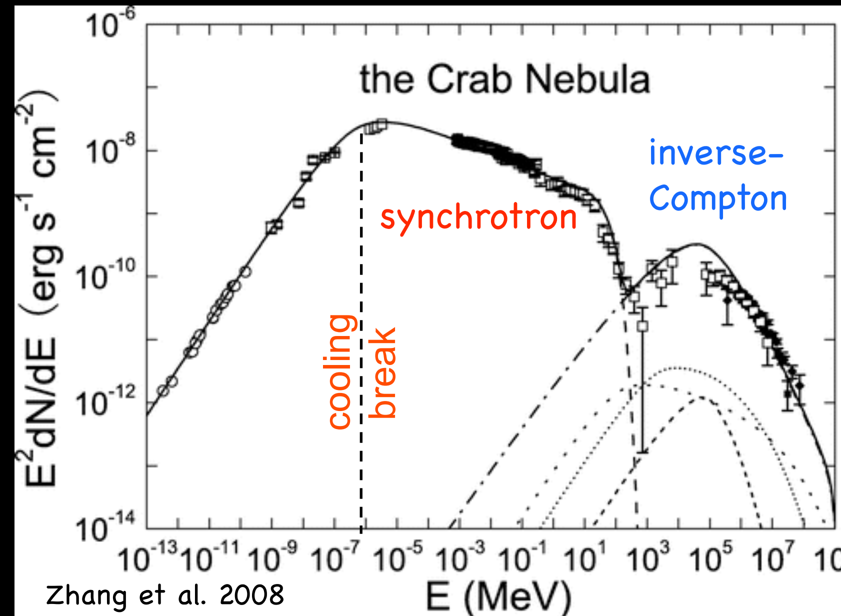
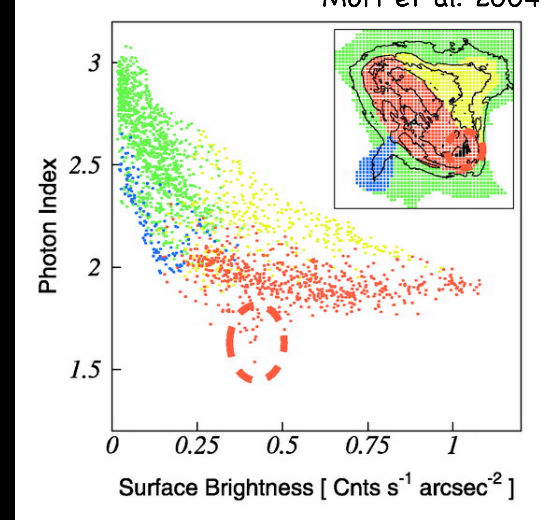
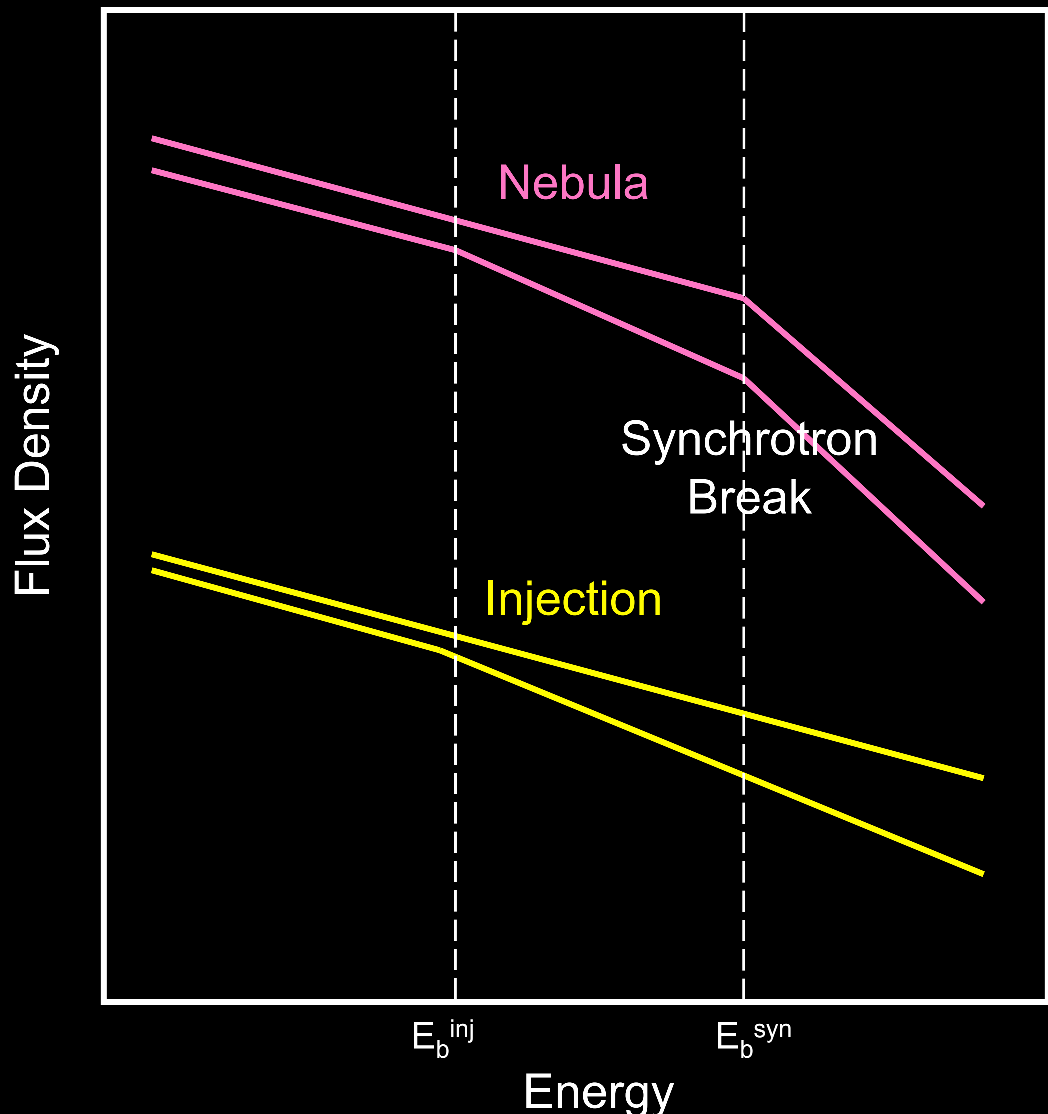



Zhang et al. 2008

Mori et al. 2004

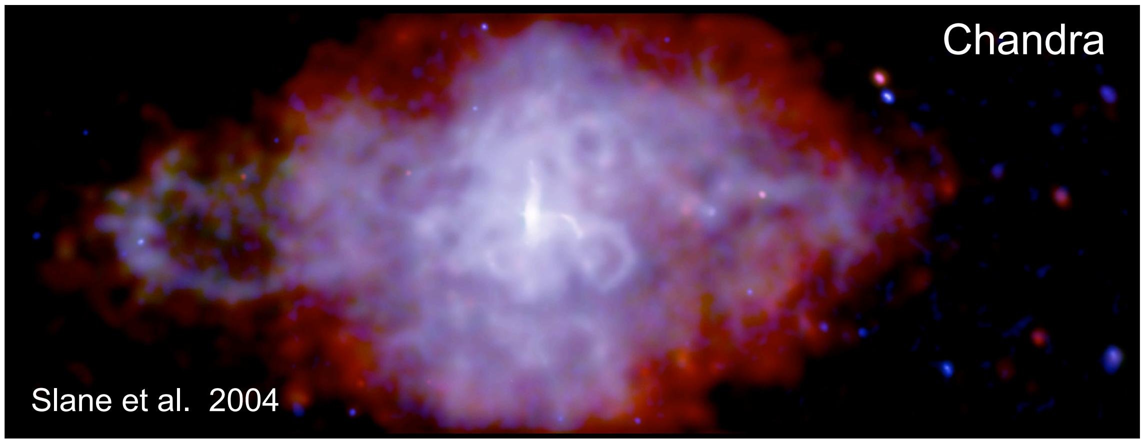


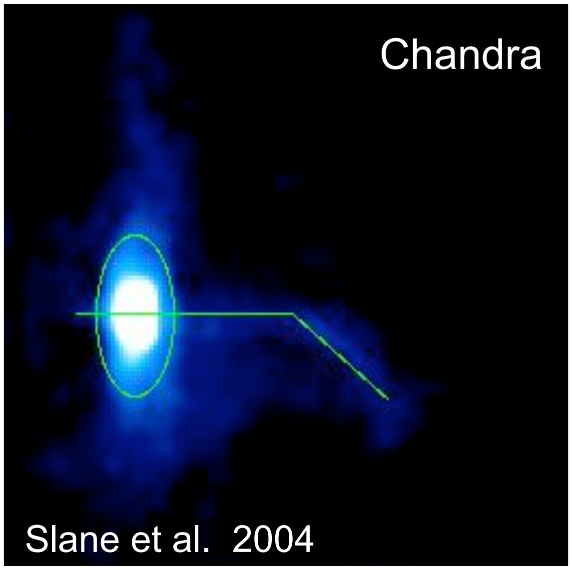
# A Point About Injection

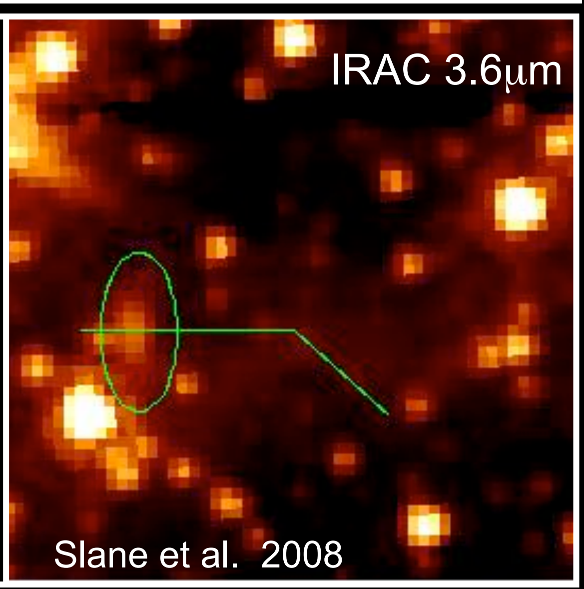



- Standard assumption is a power law input electron spectrum
  - this produces synchrotron break where synchrotron lifetime of particles equals age of PWN
- **If injection spectrum has additional structure (e.g. lower energy break), this imprints itself onto the nebula spectrum**
  - get PWN spectrum with multiple breaks

# Broadband Observations of 3C 58

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  - PWN and torus observed in Spitzer/IRAC

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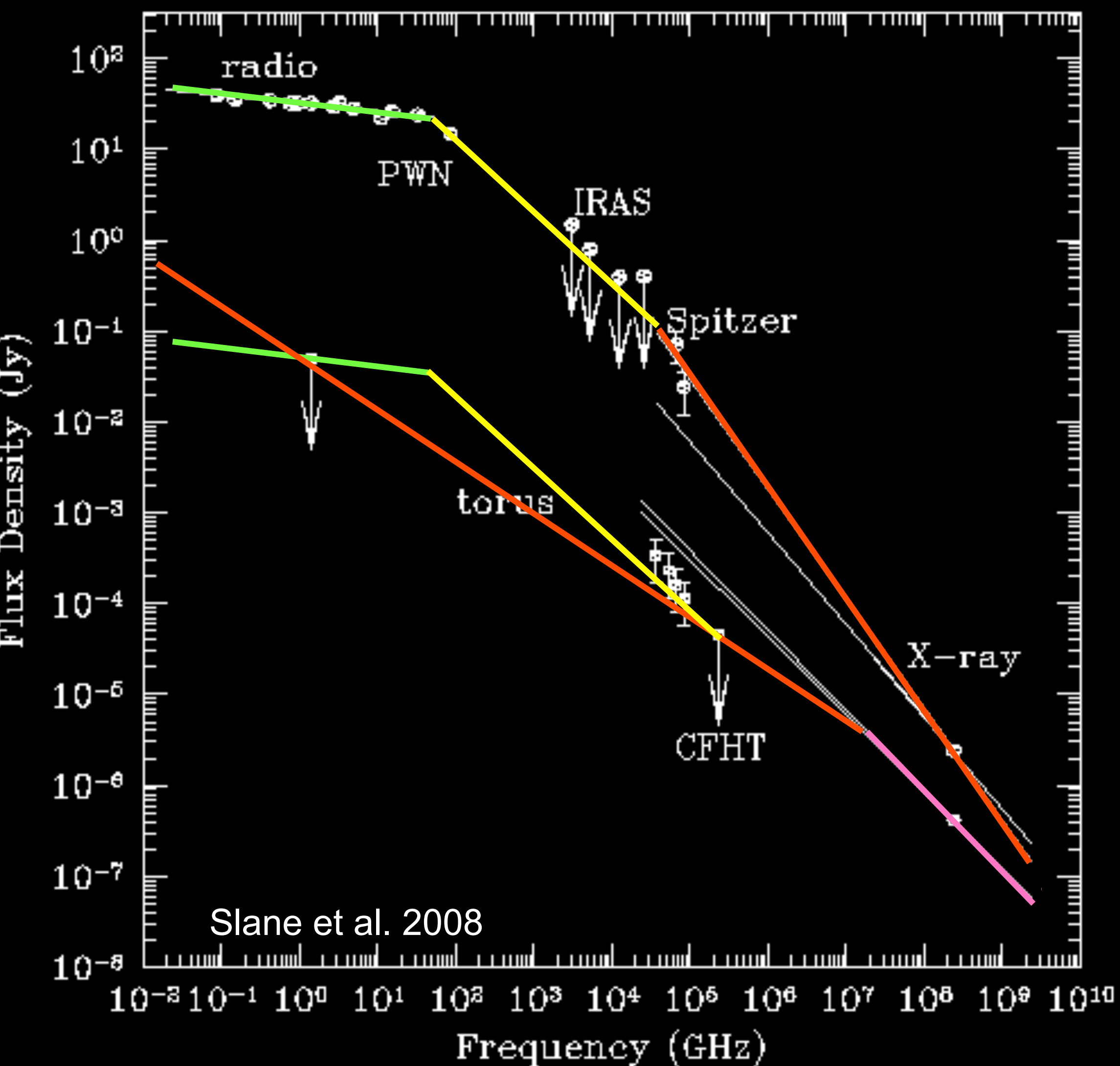


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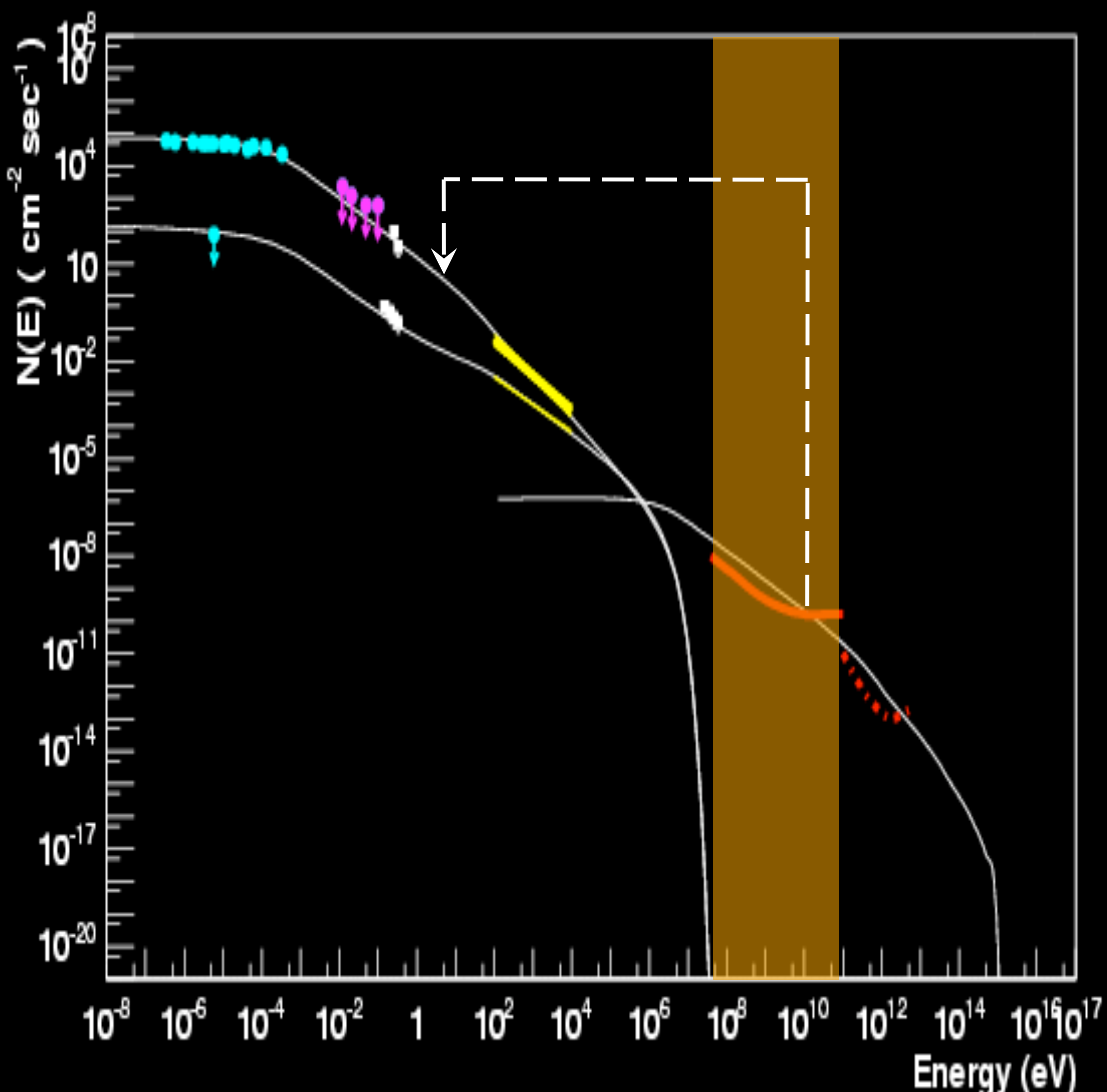
- Low-frequency break suggests possible break in injection spectrum
  - IR flux for entire nebula falls within the extrapolation of the X-ray spectrum
  - indicates single break just below IR
- Torus spectrum requires change in slope between IR and X-ray bands
  - challenges assumptions for single power law for injection spectrum

# Fermi Studies of 3C 58

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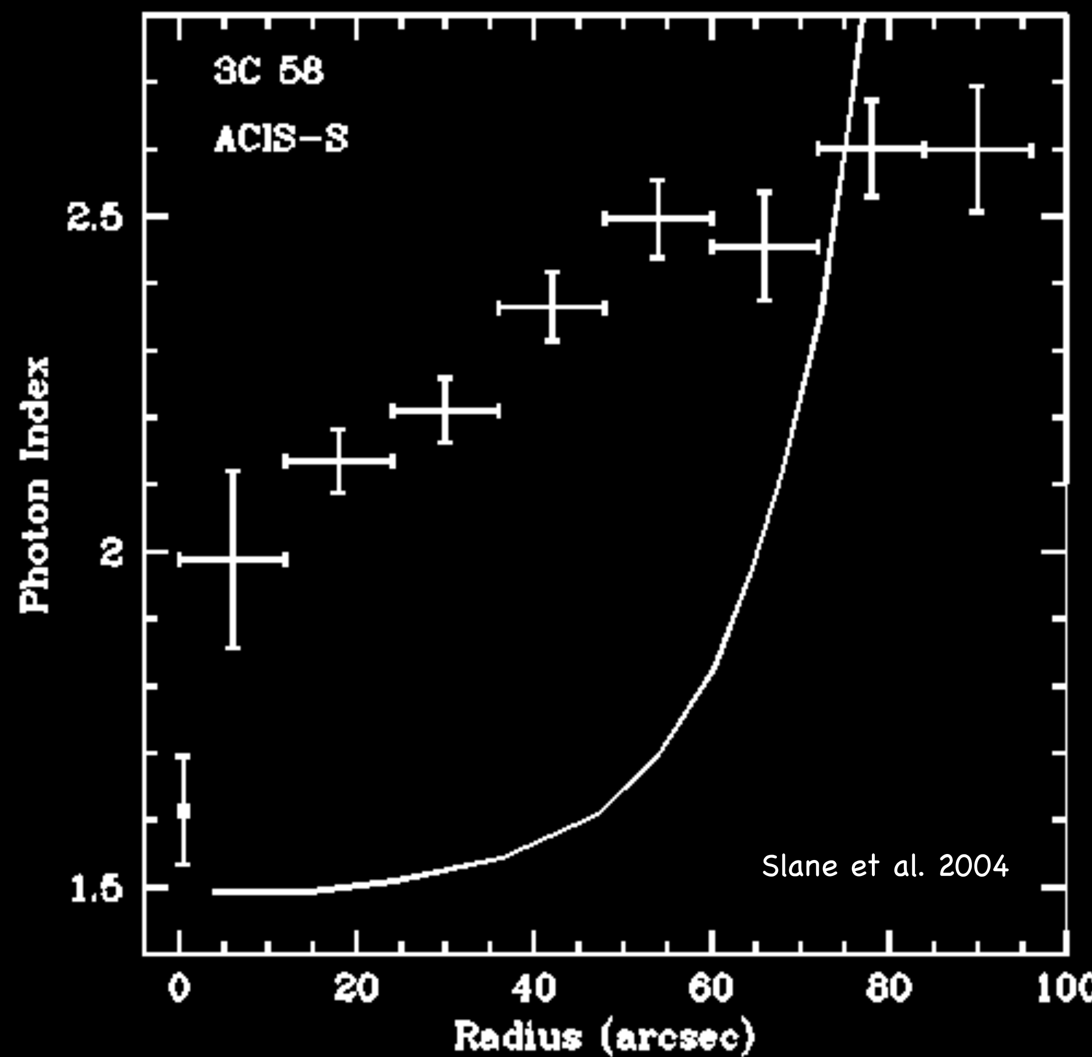
  - challenges assumptions for single power law for injection spectrum
- Fermi LAT band probes CMB IC emission from ~0.6 TeV electrons
  - this probes electrons from the unseen synchrotron region around $E^{syn}$ = 0.4 eV where injection is particularly complex

# 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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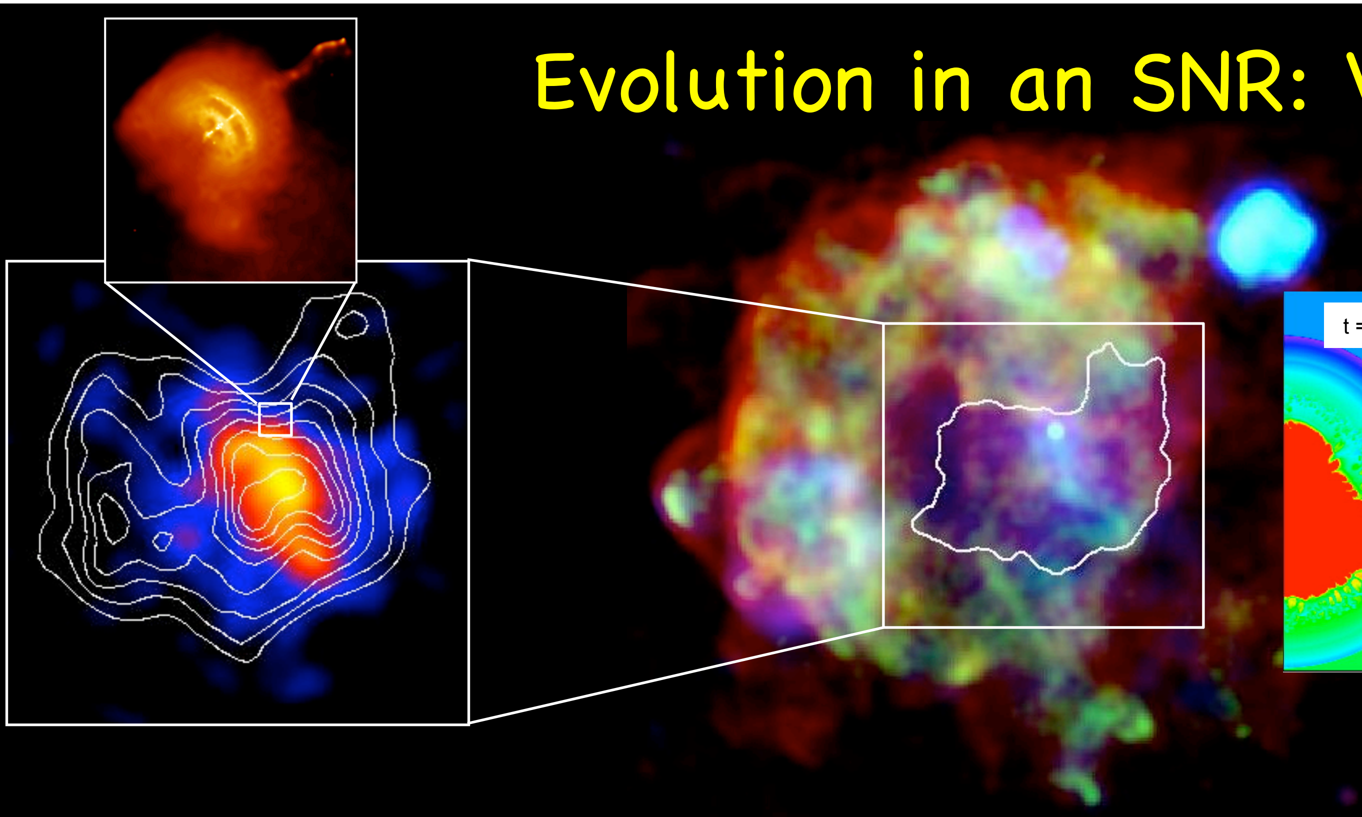
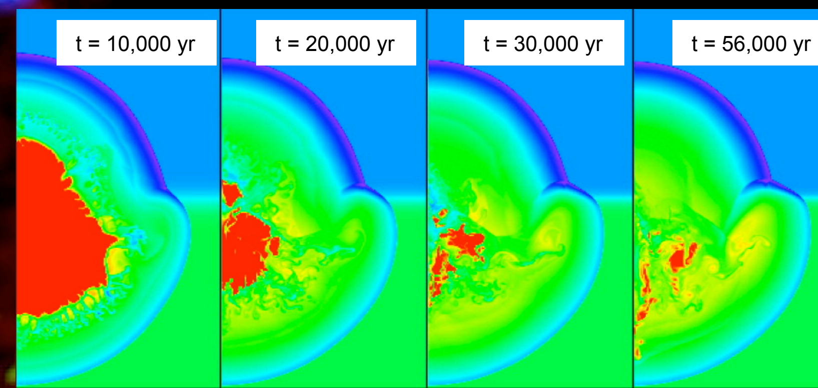
# Evolution in an SNR: Vela X






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

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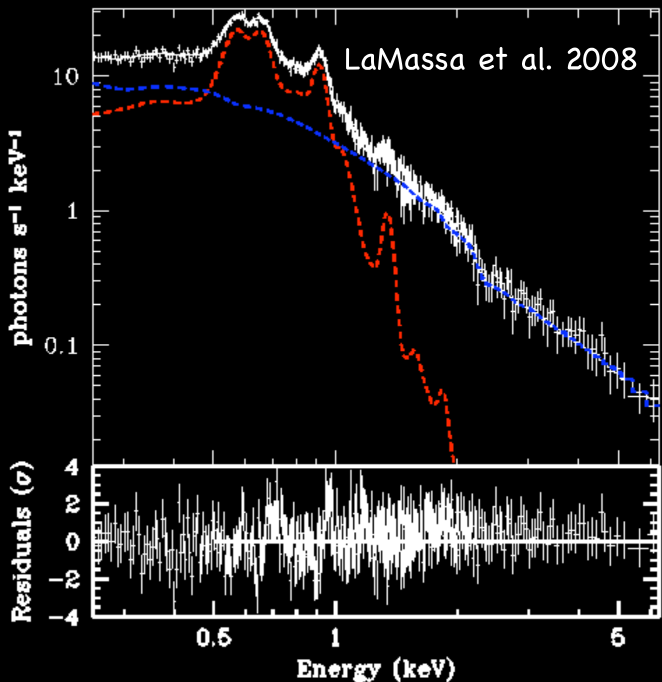
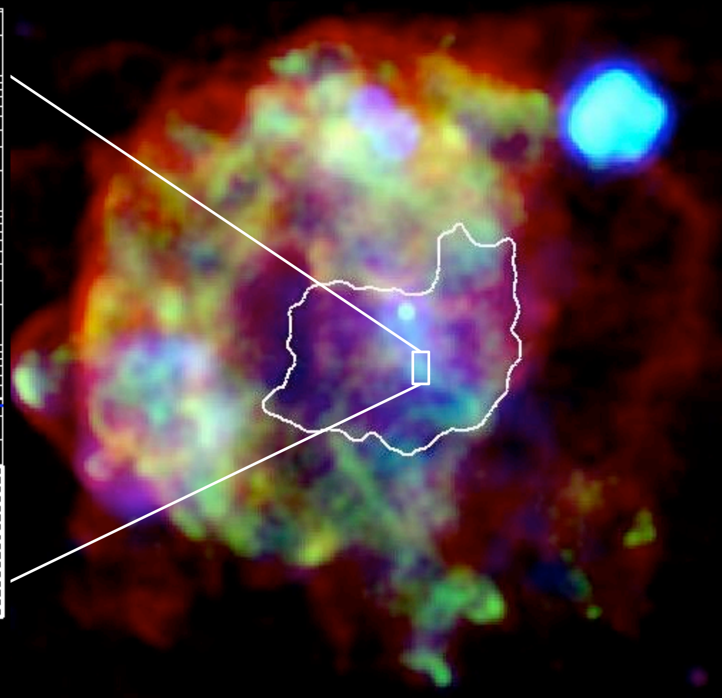
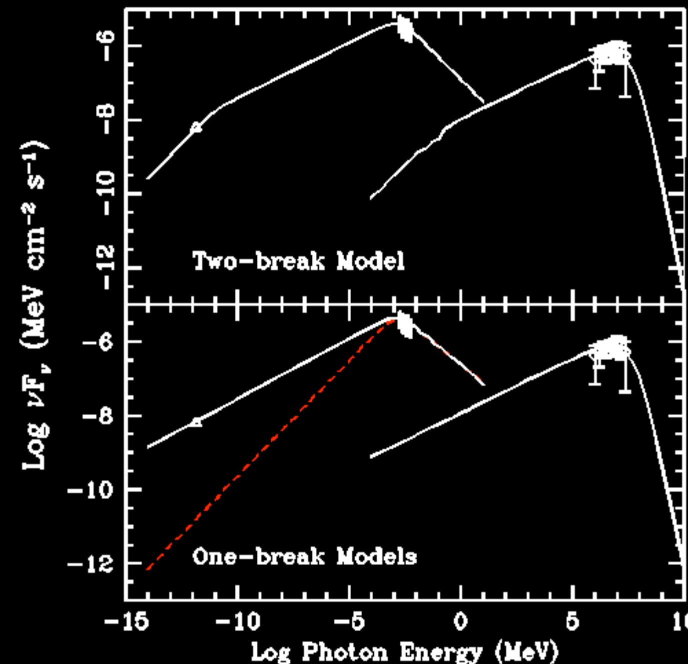


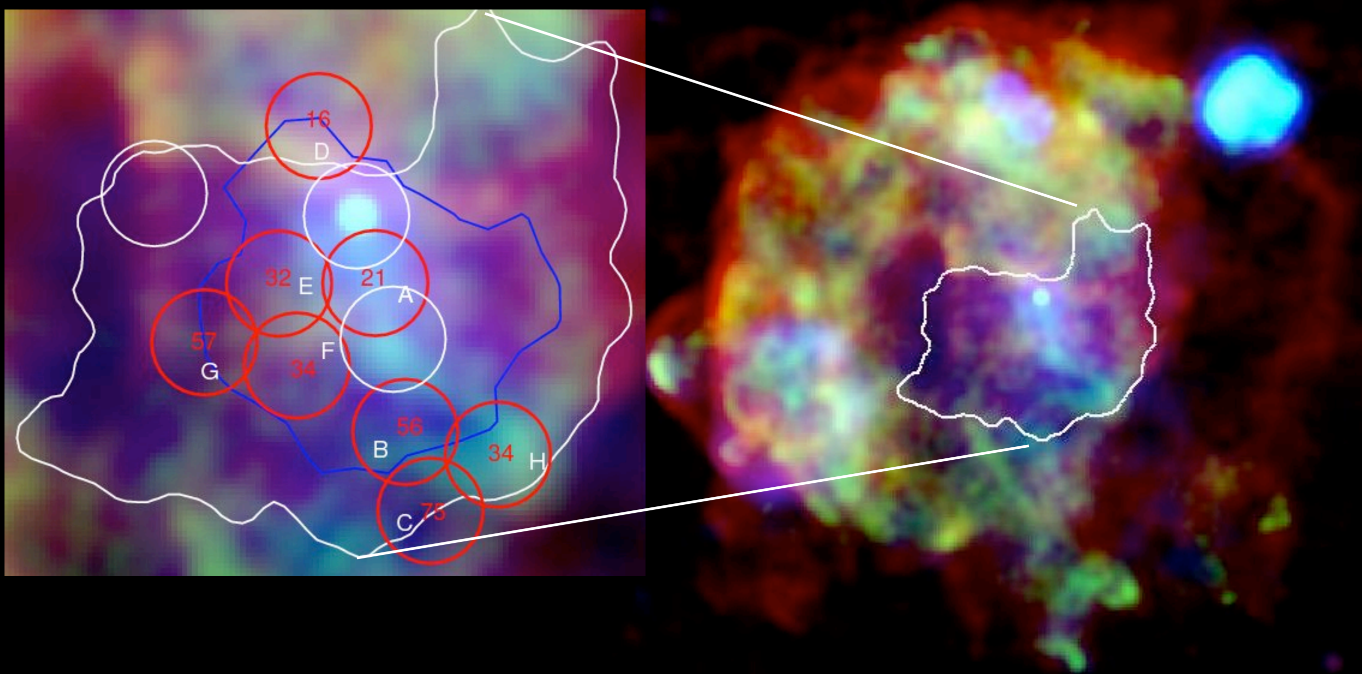






- XMM spectrum shows nonthermal <u>and</u> ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta? R-T filaments providing radial B field?

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

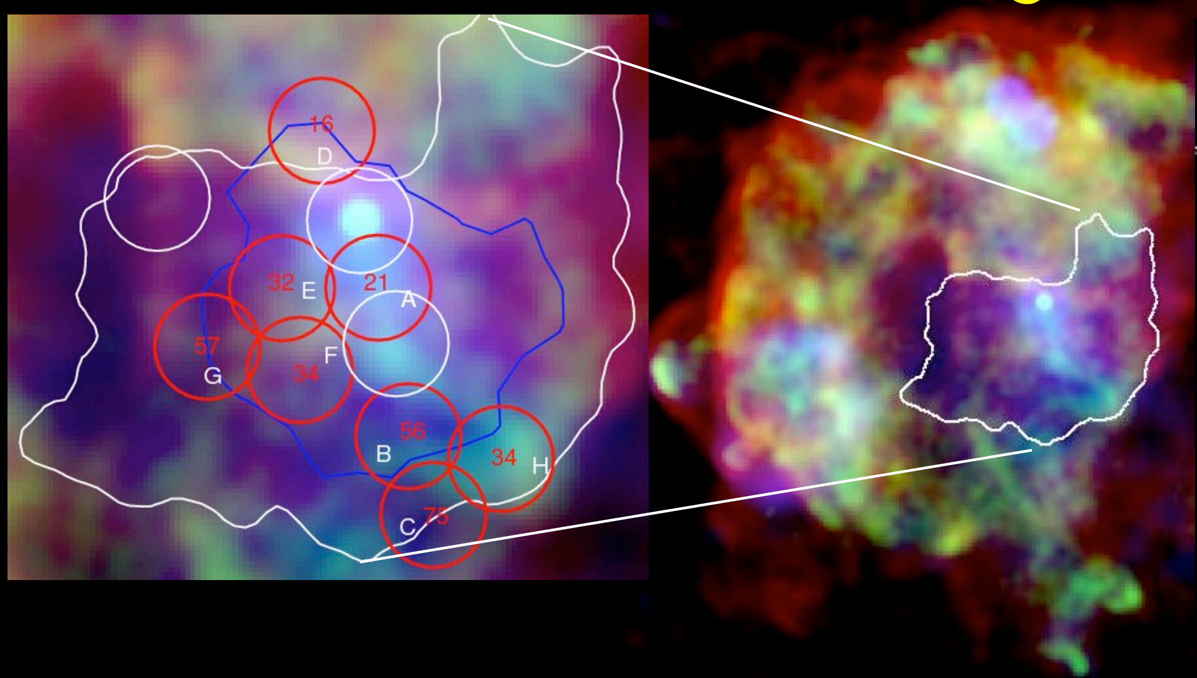
# Understanding Vela X: XMM

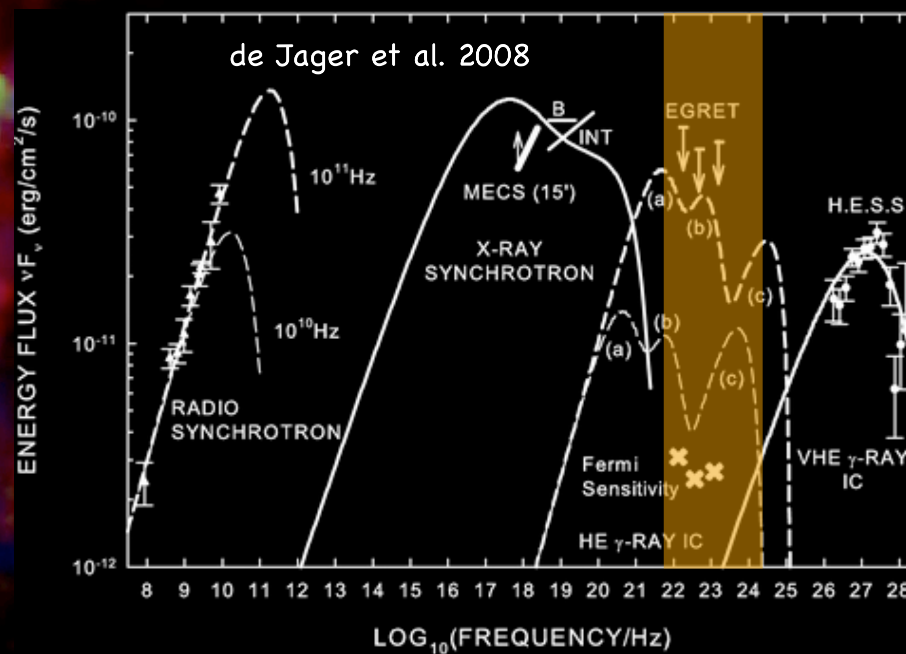



- XMM large project (400 ks) will map Vela X to study ejecta and nonthermal emission

- 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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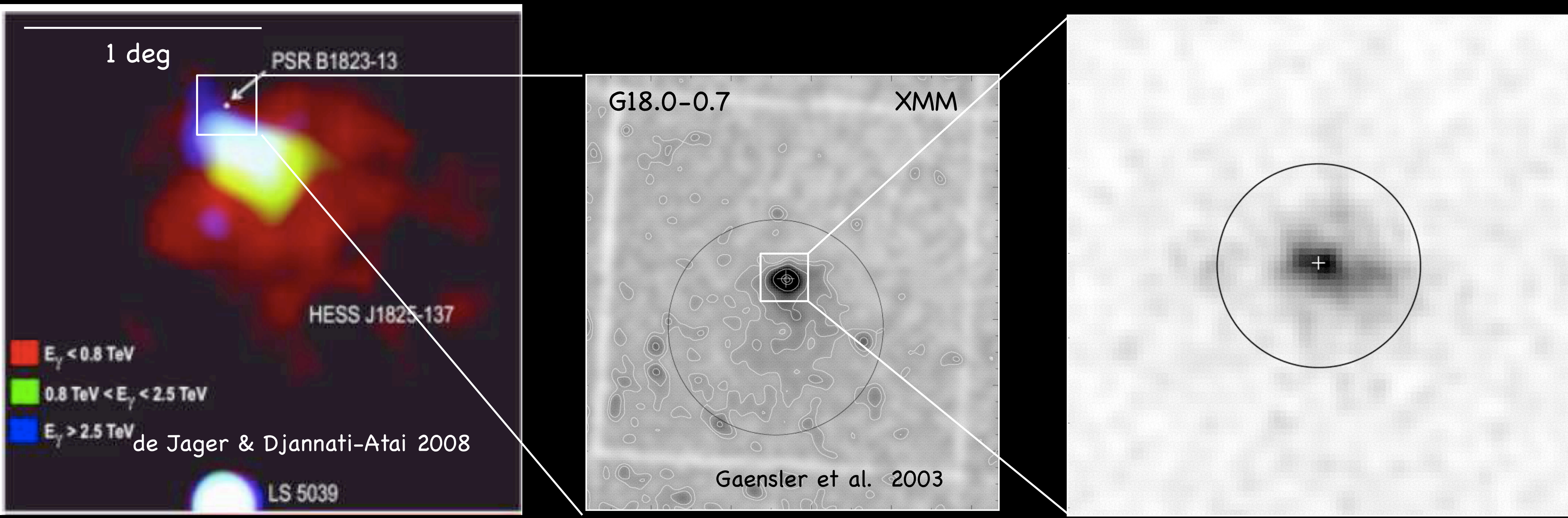
# The End Game: TeV PWNe




- HESS observations have revealed a population of extended TeV sources that appear to be late-phase PWNe
  - large diameter (~1 deg), associated with pulsars or compact X-ray sources, but with small, faint X-ray nebulae

- Modeling indicates very low magnetic fields with loss breaks at low energies
  - these sources may be the signature of PWNe beginning to merge w/ ISM
  - observations in X-ray and lower-energy γ-ray band will test this picture

# Conclusions

## I. Spatial Structure

- Recent observational work has revealed underlying PWN structure that defines the system geometry and identifies PWN shock regions
  - constrain particle flows, field geometry, jet formation

## II. Spectral Structure

- Modeling of broadband emission constrains evolution of particles and B field
  - synchrotron and inverse-Compton emission places strong constraints on the underlying particle spectrum and magnetic field
  - modeling form of injection spectrum and full evolution of particles still in its infancy
  - origin of radio-emitting particles still uncertain

## III. Evolution

- TeV observations have revealed emission from known PWNe as well as identifying a population of large-diameter nebulae not previously seen in other bands
  - late-phase PWNe disrupted by the SNR reverse shock
  - TeV and Fermi observations, and continued radio and X-ray observations promise dramatic results in understanding the lives of PWNe

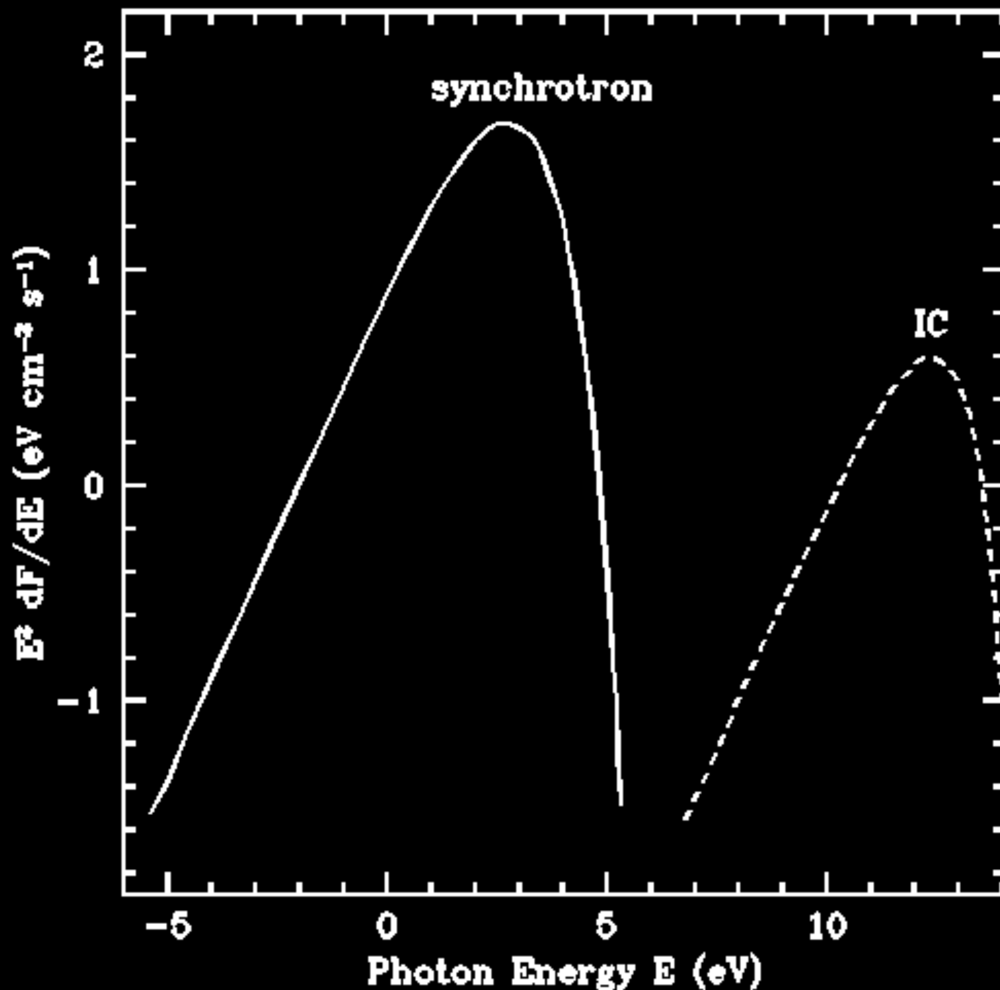
# Connecting the Synchrotron and IC Emission

- Energetic electrons in PWNe produce both synchrotron and inverse-Compton emission

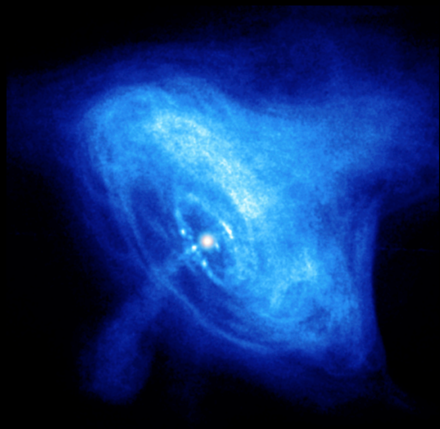
$$\varepsilon^{s}_{\rm keV} \approx 2\times 10^{-4} E^2_{\rm TeV} B_{-5}$$ synchrotron

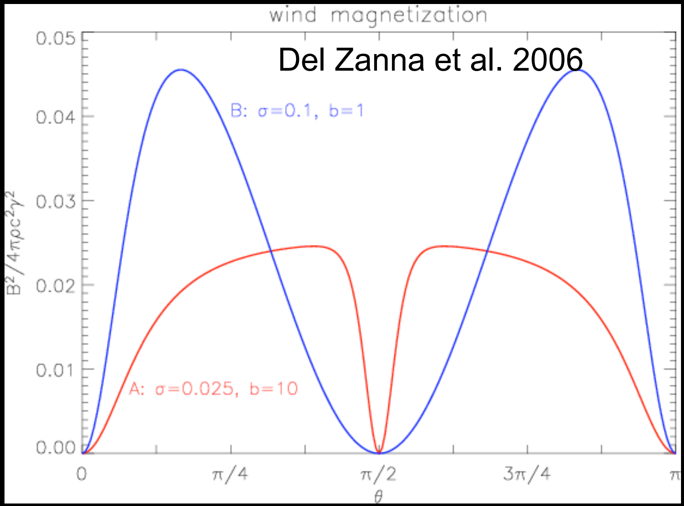
$$\varepsilon^{ic}_{\rm TeV} \approx 3\times 10^{-3} E^2_{\rm TeV}$$ inverse-Compton

- Modeling synchrotron and inverse-Compton emission simultaneously determines B
- For low B, γ-ray emission probes electrons with lower energies than those that produce X-rays
  - γ-ray studies fill crucial gap in broadband spectra of PWNe



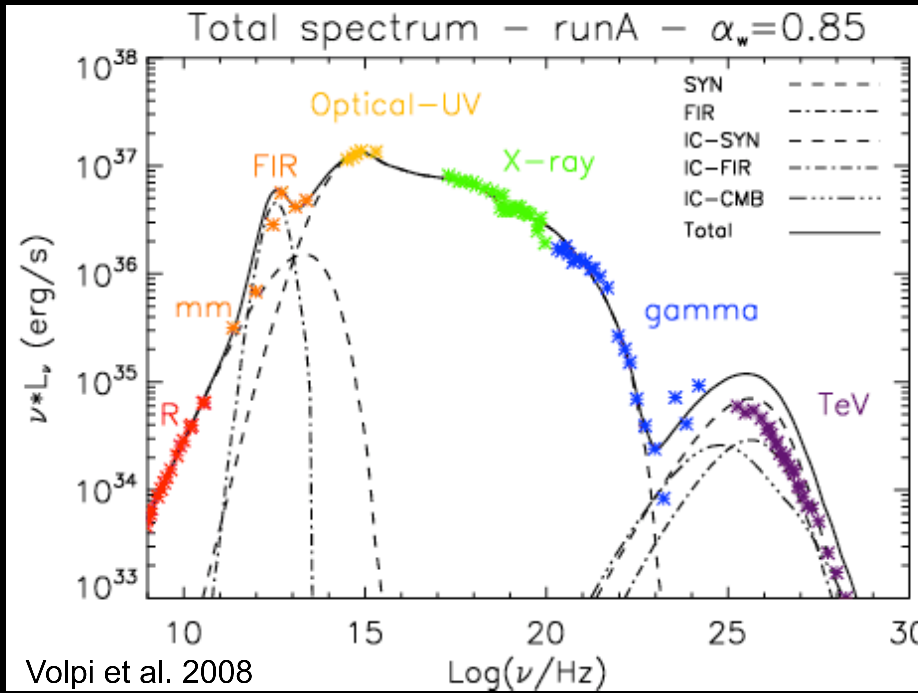
# Broadband Emission from PWNe






- More completely, assume wind injected at termination shock, with radial particle distribution and latitude-dependent magnetic component:

$$\sigma = \frac{B^2}{4\pi\rho\gamma^2 c^2} = \sigma(\theta)$$




- Evolve nebula considering radiative and adiabatic losses to obtain time- and spatially-dependent electron spectrum and B field (e.g. Volpi et al. 2008)