Observations of Pulsar Winds and Jets

Collaborators:

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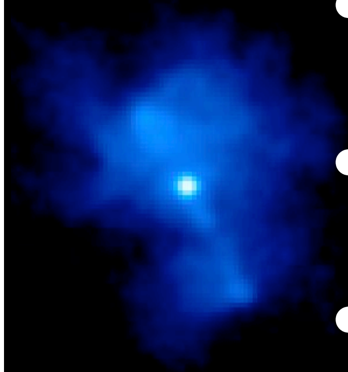
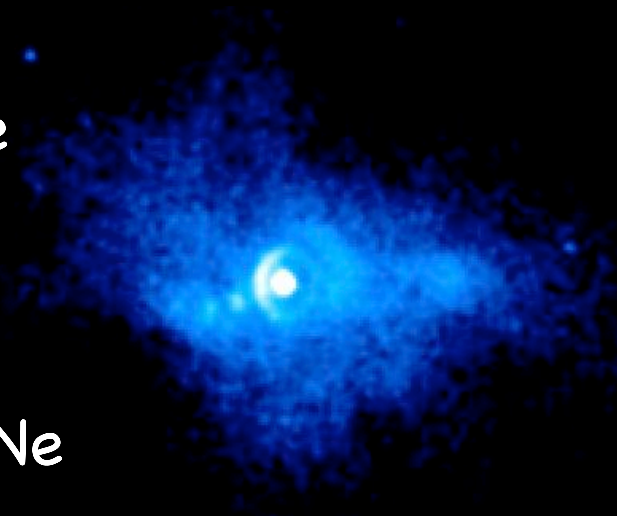
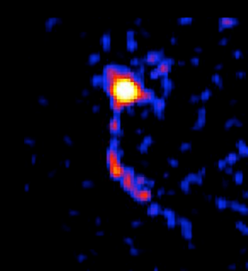
Anne Lemiere
Okkie de Jager
Stephanie LaMassa
Jack Hughes

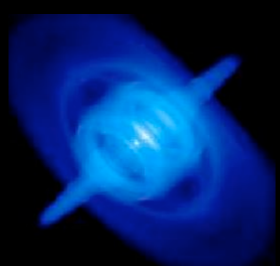
Outline



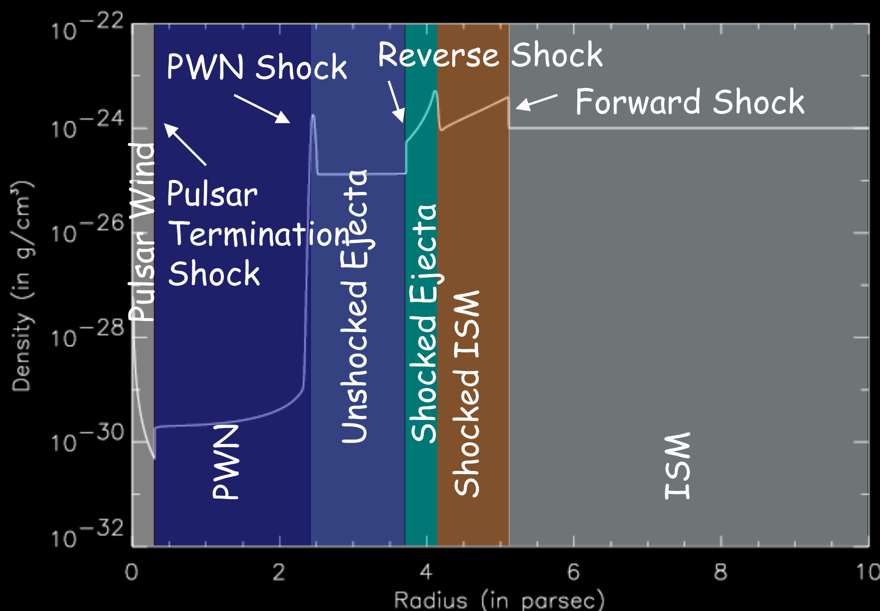
- Observed Structure of PWNe
- Properties of Pulsar Jets
- Broadband Emission from PWNe
- Evolution of PWNe in SNRs

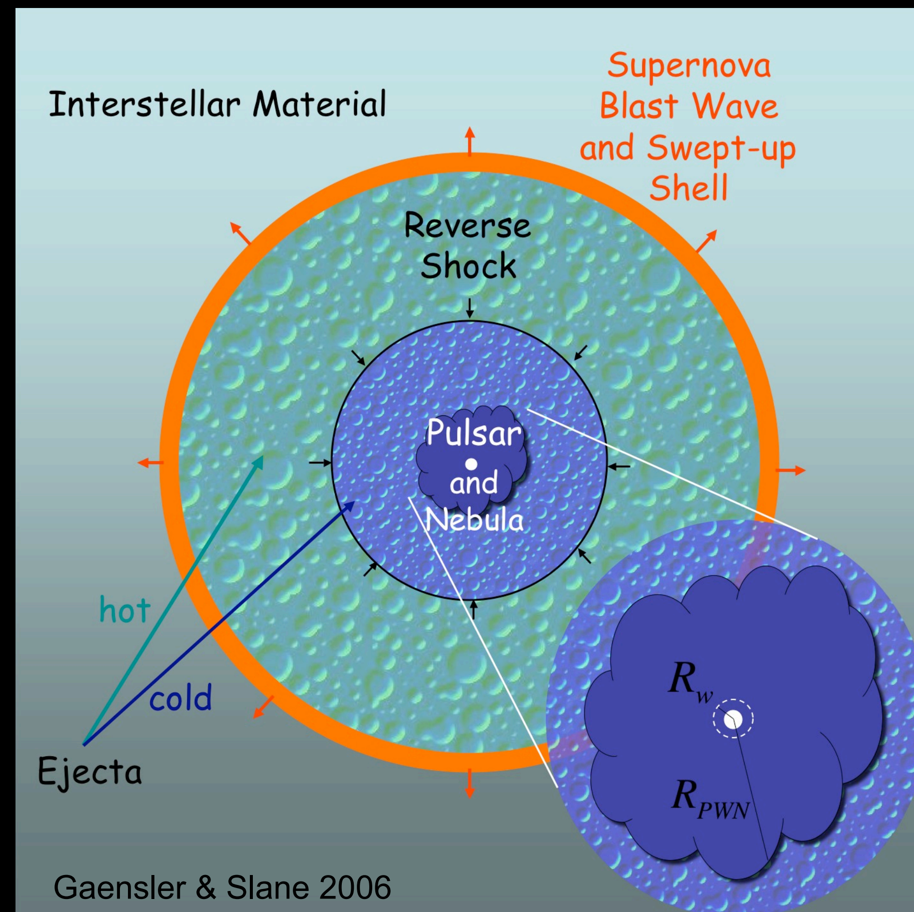






PWNe and Their SNRs

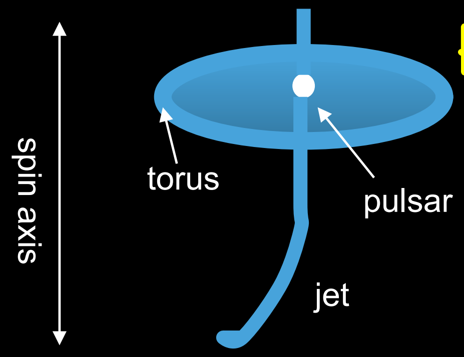




- Pulsar Wind
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms

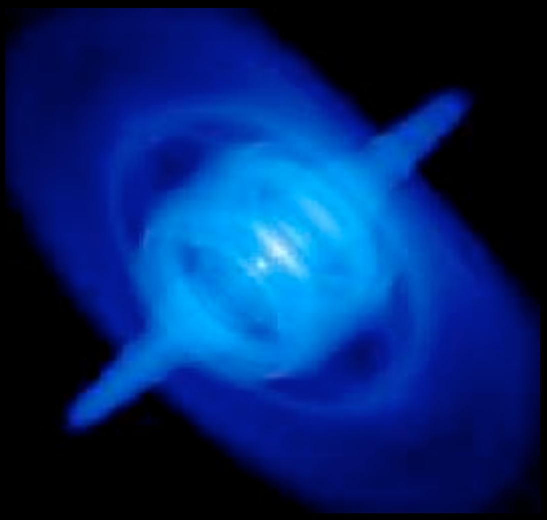
- Supernova Remnant
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; particles accelerated at forward shock generate magnetic turbulence; other particles scatter off this and receive additional acceleration

PWN Jet/Torus Structure



- Poynting flux from outside pulsar light cylinder is concentrated in equatorial region due to wound-up B-field
  - termination shock radius decreases with increasing angle from equator (Lyubarsky 2002)

- For sufficiently high latitudes, particle flow is deflected back inward
  - collimation into jets may occur
  - asymmetric brightness profile from Doppler beaming



Del Zanna et al. 2006

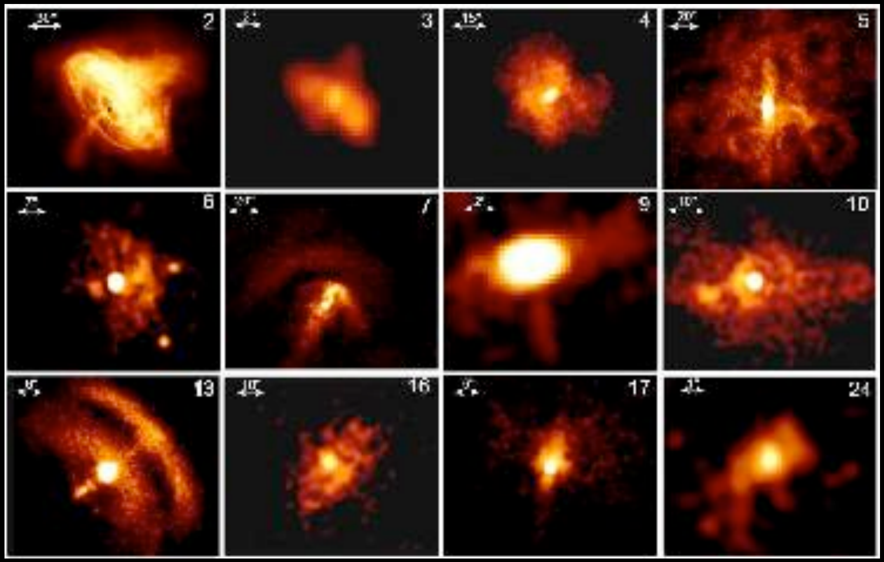
- Collimation is subject to kink instabilities
  - magnetic loops can be torn off near TS and expand into PWN (Begelman 1998)
  - many pulsar jets are kinked or unstable, supporting this picture

See talk by N. Bucciantini

Pulsar Jets – and Lots of Them

- Jets or jet-like structures are observed for ~20 young pulsar systems
  - the more we look the more we find, though evidence is weak for some

Kargaltsev & Pavlov 2008



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  - many more show toroidal structures or extended tails (possibly also jets)

- Sizes vary from <0.1 pc (CTA 1) to >10 pc (PSR B1509-58)
  - no strong connection with dE/dt

- Jet luminosity ranges are huge:

$$5\times10^{-7} - 6\times10^{-3}\dot{E}$$

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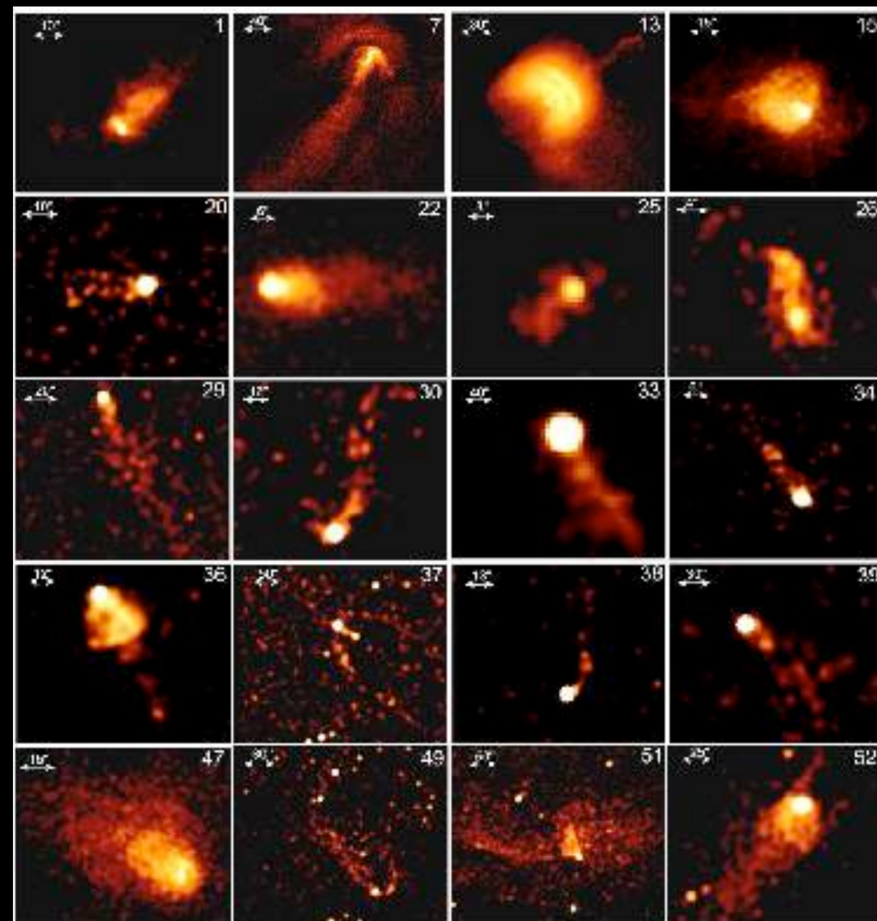

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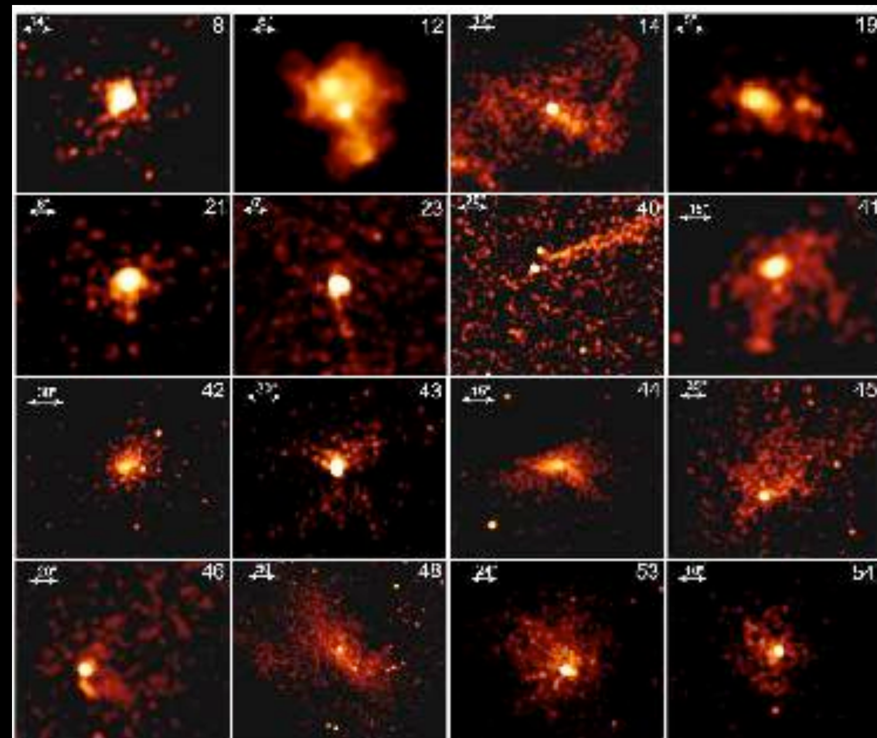

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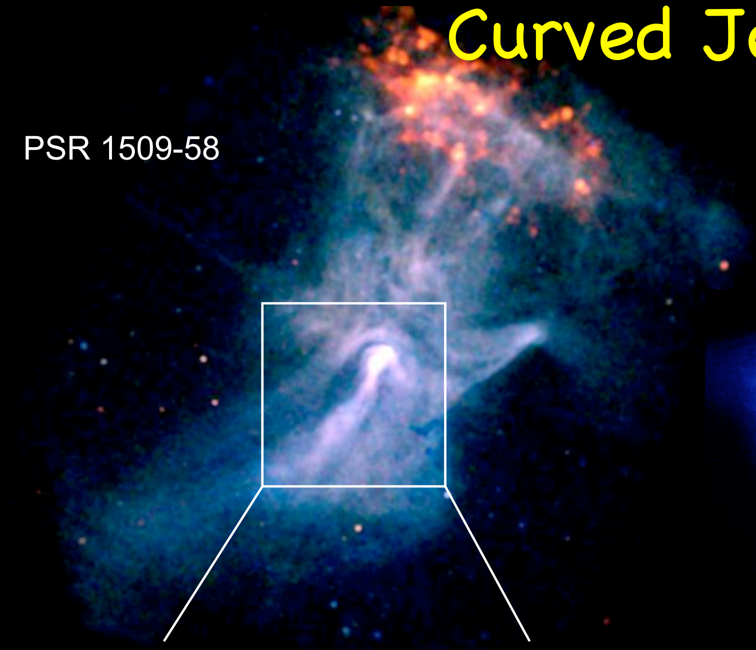
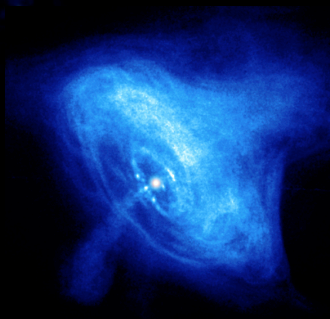
- Typical photon index Γ ~ 1.6 - 2
  - generally, uncooled synchrotron spectrum (Vela jets appears even harder)

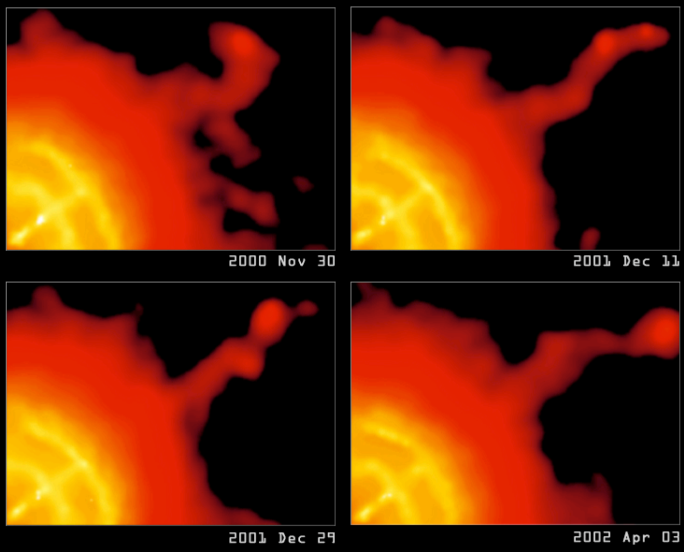
- Where known, outflow velocities are subsonic: $v_{flow} \approx 0.1 - 0.5c$

Curved Jets and Instabilities

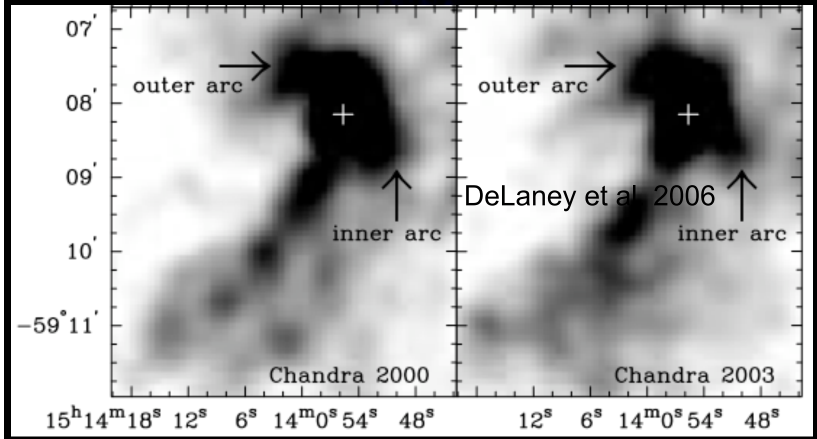
PSR 1509-58







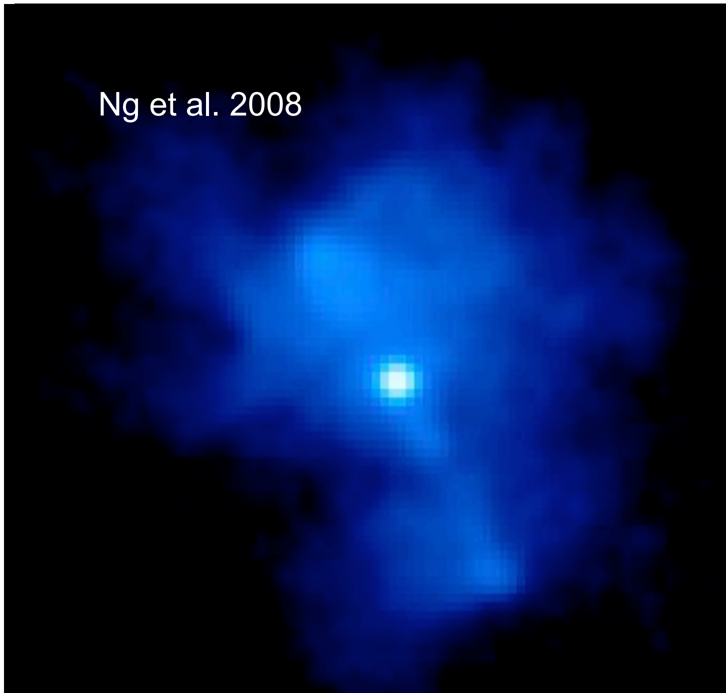
Pavlov et al. 2003

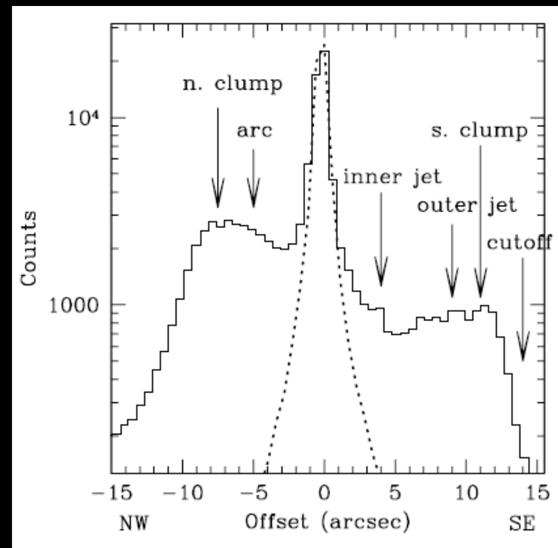


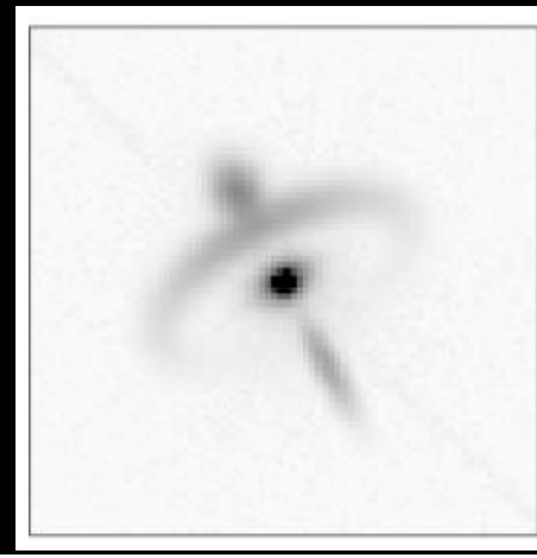
DeLaney et al. 2006

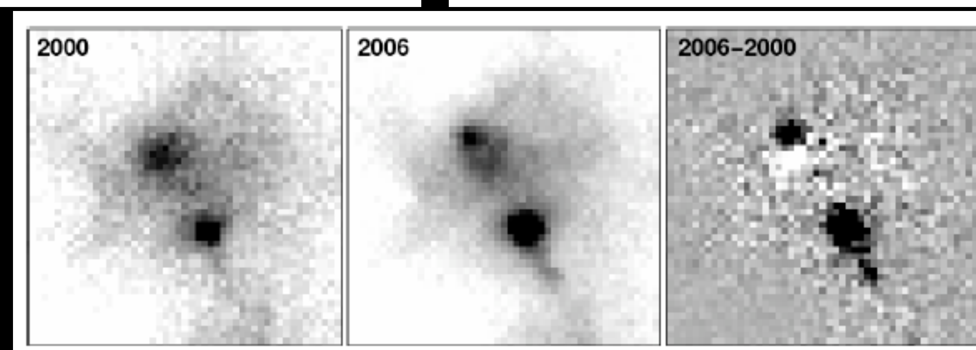
- Jet in PSR 1509-58 is <u>curved</u>, like in Crab
  - variations in structure seen on timescale of several months (v ~ 0.5c)
- Jet in Vela is wildly unstable, showing variations on timescales of weeks to months
  - changes in morphology suggest kink or sausage instabilities (Pavlov et al. 2003)

Kes 75









- Bright wind nebula powered by PSR J1846-0258 ($dE/dt = 10^{36.9}$ erg/s)
  - jet-like structure defines rotation axis

- Deep Chandra observation reveals inner/outer jet features, clump in north, and abrupt jet termination in south
  - jet spectrum is harder than surrounding regions, ➔ high-velocity (uncooled) flow
  - clumps along jet axis vary in brightness over time

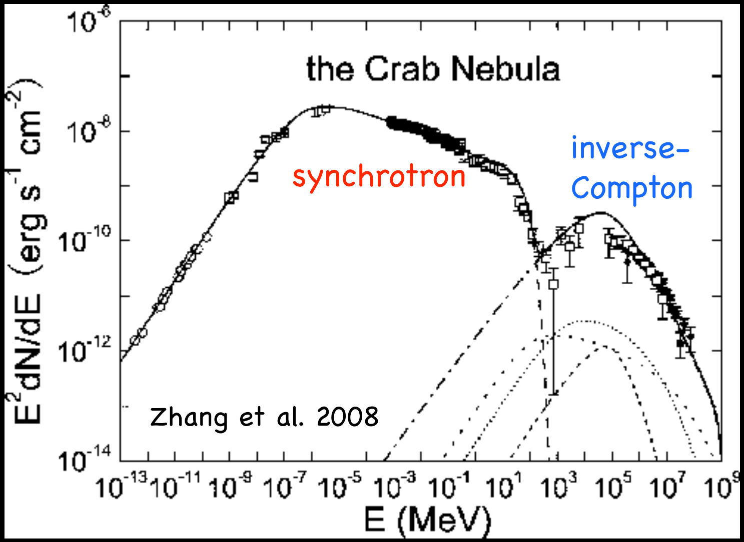
Broadband Emission from PWNe

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

$$L(t) = L_0 \left[1 + \frac{(n-1)P_0^2 L_0 t}{4\pi^2 I} \right]^{-(n+1)/(n-1)}$$

- Based on studies of Crab Nebula, there appear to be two populations – relic radio-emitting electrons and electrons injected in wind (Atoyan & Aharonian 1996)

$$Q(E_e, t) = \begin{cases} Q_0(t)(E_e/E_b)^{-\alpha_1}, & \text{if } E_e < E_b \\ Q_0(t)(E_e/E_b)^{-\alpha_2}, & \text{if } E_e \geq E_b \end{cases}$$



- Get associated synchrotron and IC emission from electron population, and some assumed B field (e.g. Venter & dE Jager 2006

See talk by O.C. de Jager

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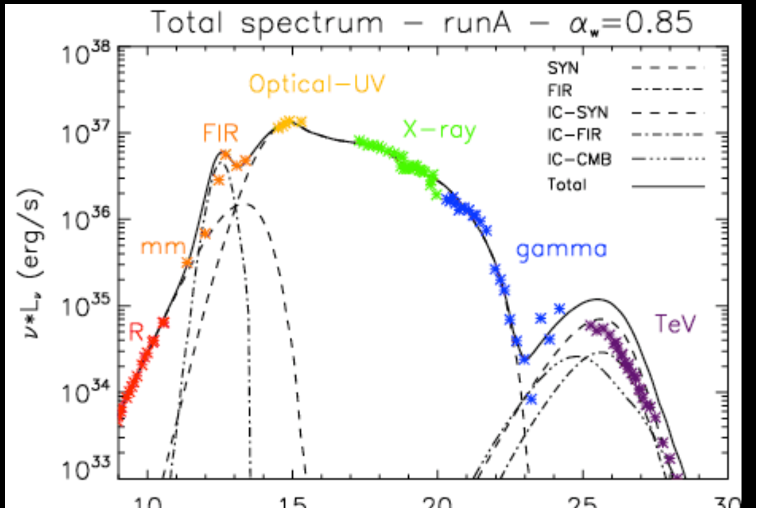

Volpi et al. 2008

- Get associated synchrotron and IC emission from electron population, and some assumed B field (e.g. Venter & dE Jager 2006

- More completely, assume wind injected at termination shock, with radial particle distribution and latitude-dependent magnetic component
  - Evolve nebula considering radiative and adiabatic losses to obtain time- and spatially-dependent electron spectrum and B field (e.g. Volpi et al. 2008)

See talk by O.C. de Jager

A Point About Injection: 3C 58

Slane et al. 2004

- **3C 58 is a bright, young PWN**
  - morphology similar to radio/x-ray; suggests low magnetic field
  - low-frequency spectral break suggests possible injection break
- **PWN and torus region observed in Spitzer/IRAC and CFHT observations**
  - jet structure not seen above diffuse emission

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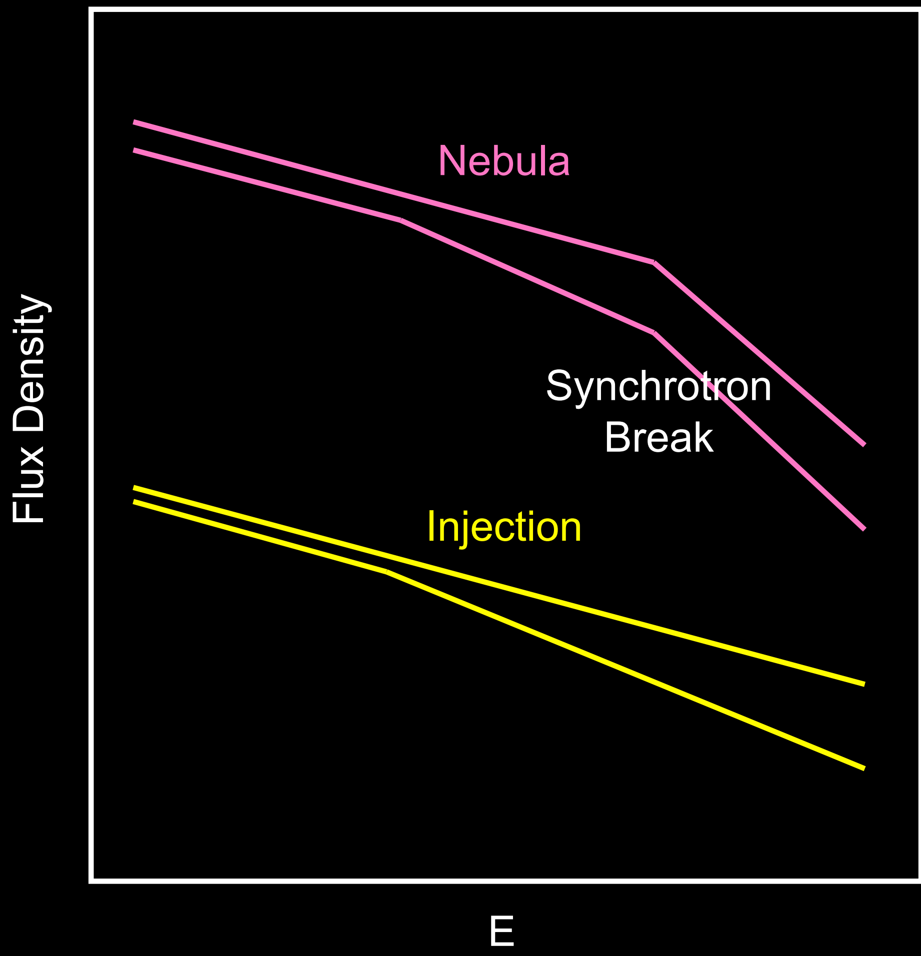

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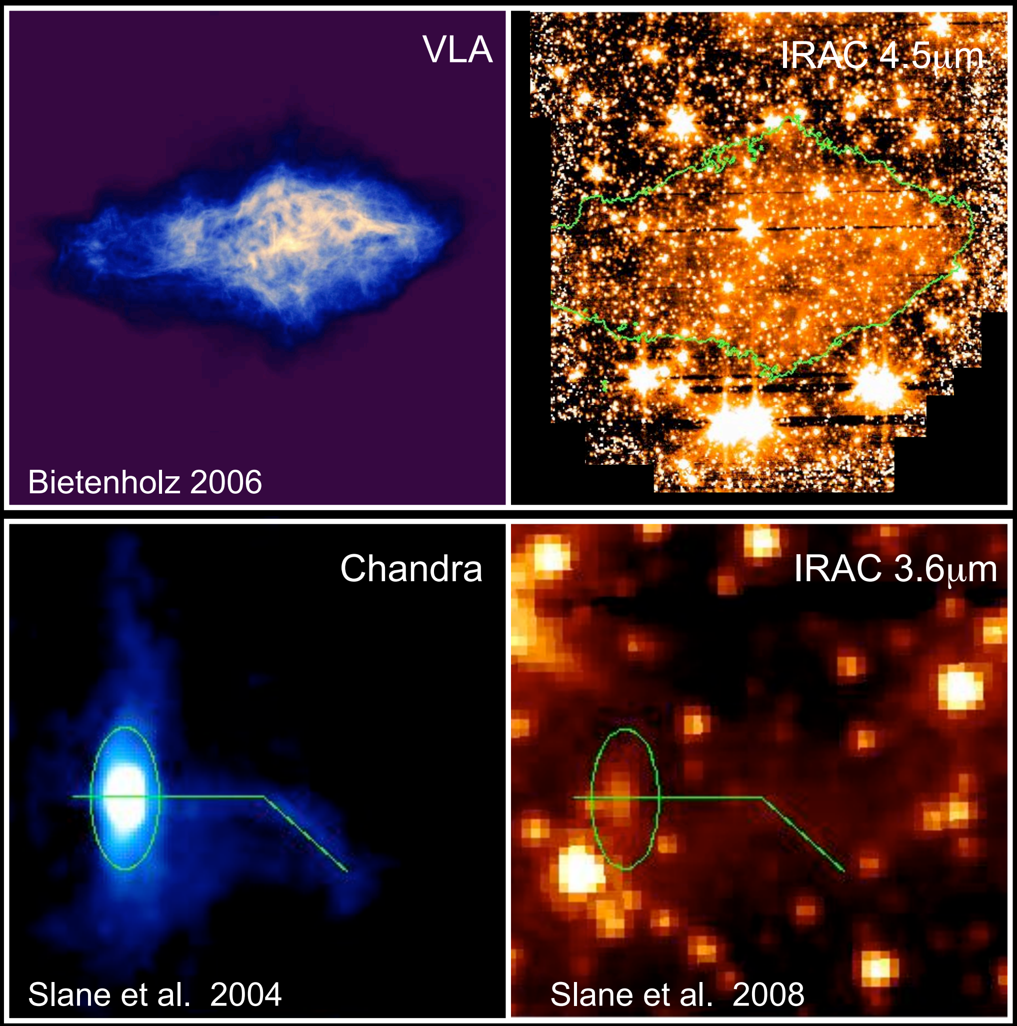

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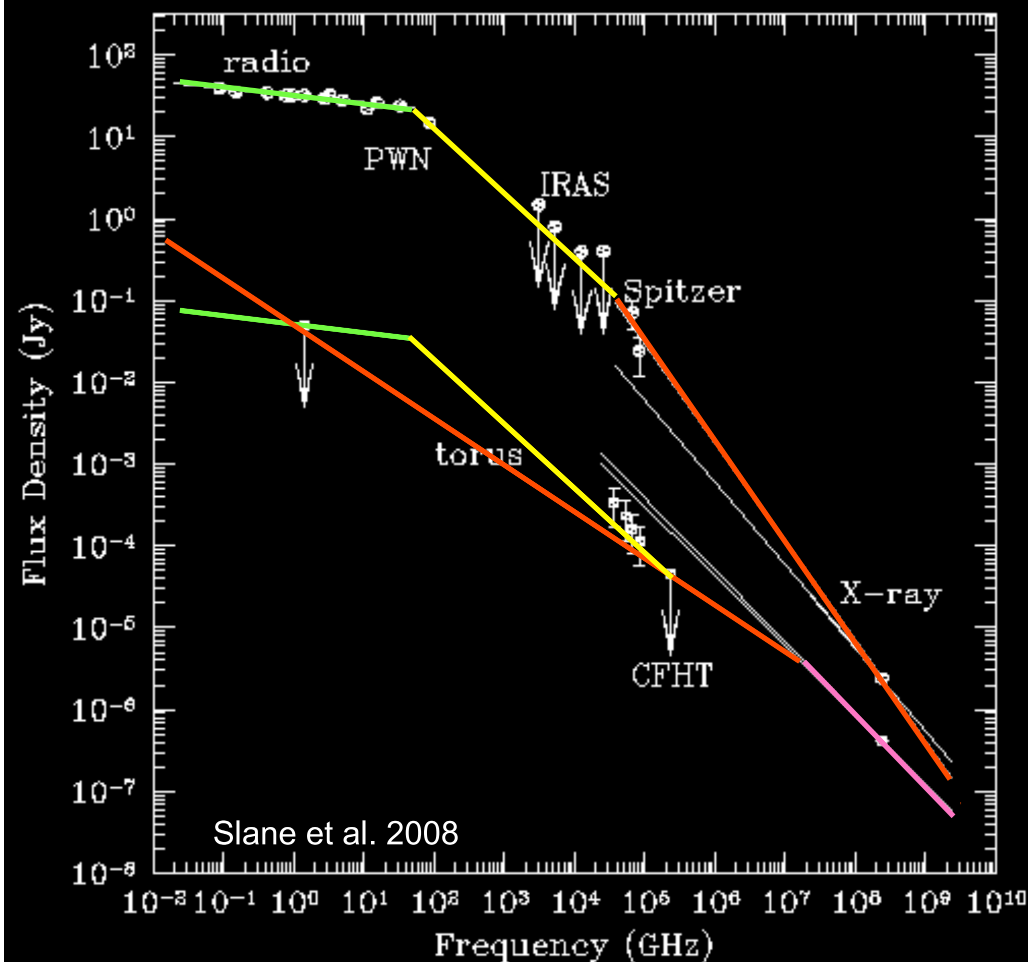

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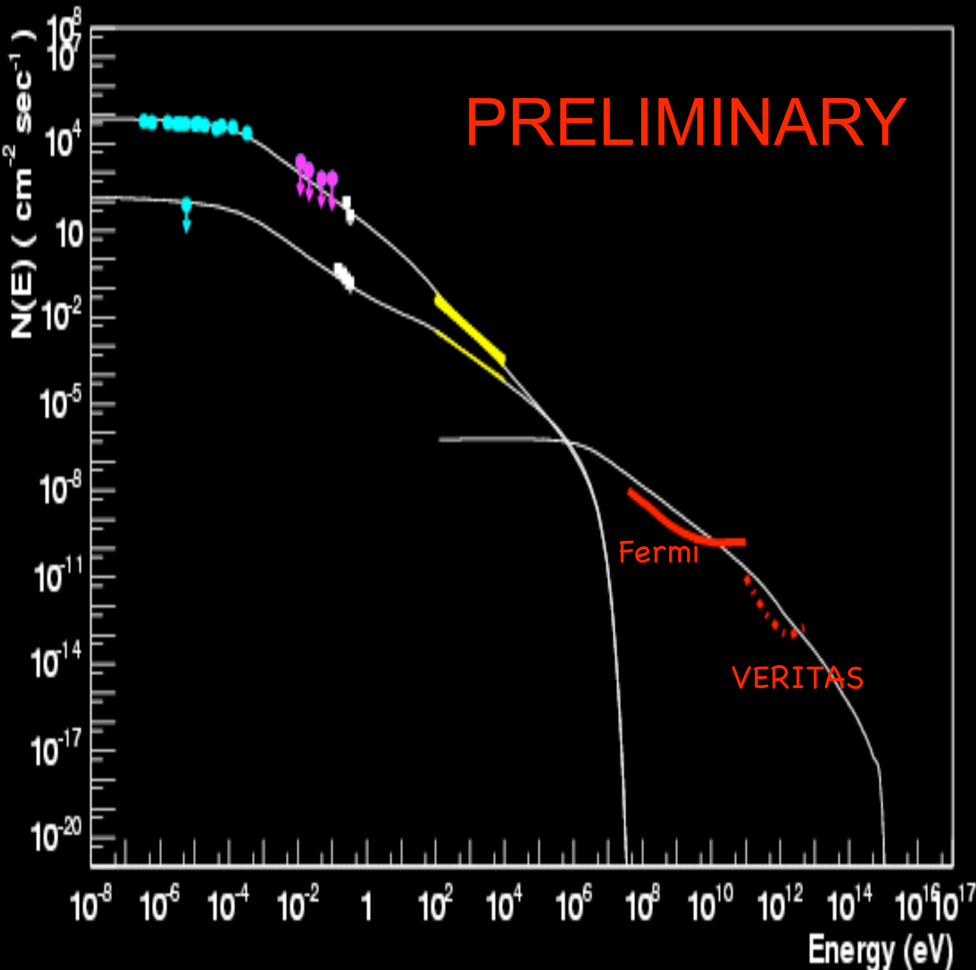

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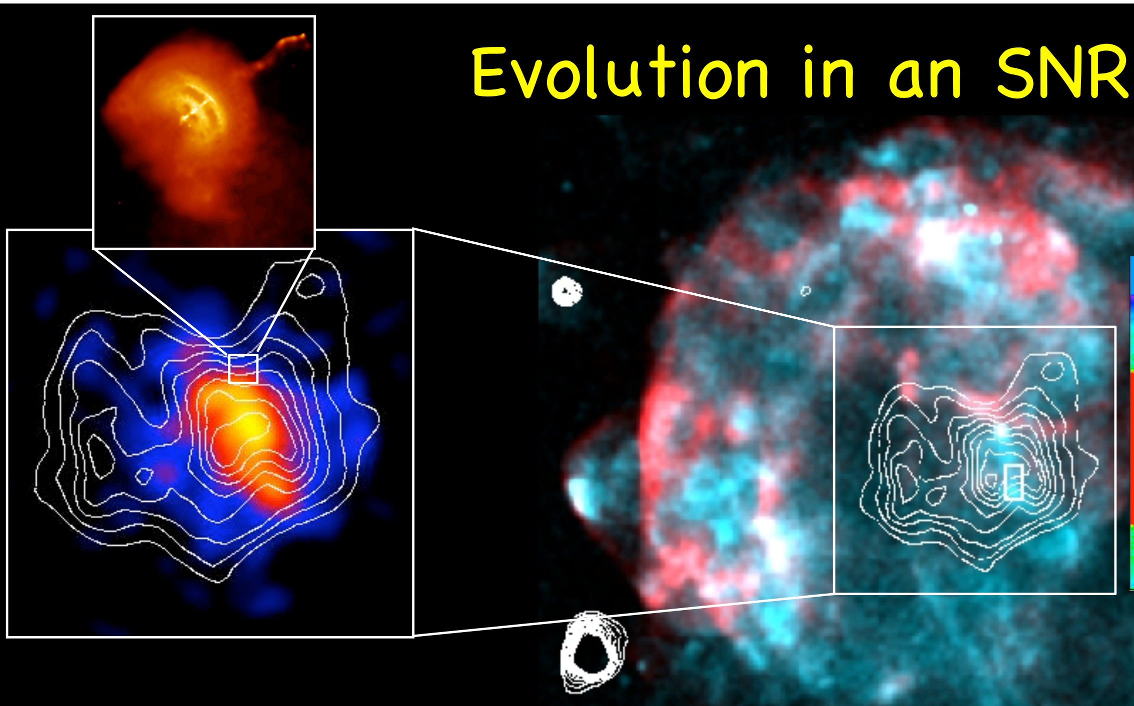
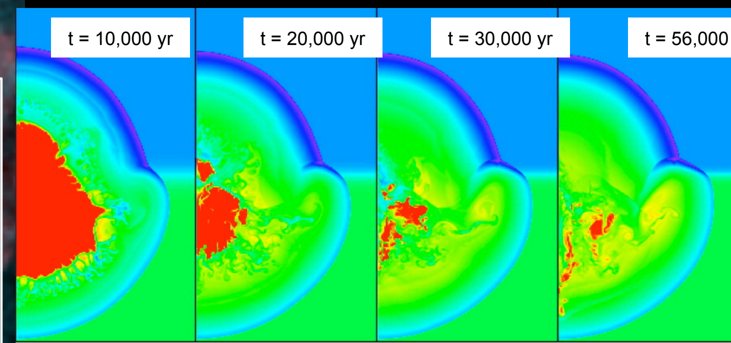
Evolution in an SNR: Vela X





Blondin et al. 2001

- Vela X is the PWN produced by the Vela pulsar
  - located primarily south of 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 (which is known to be directed to NW); presumably the result of reverse shock interaction

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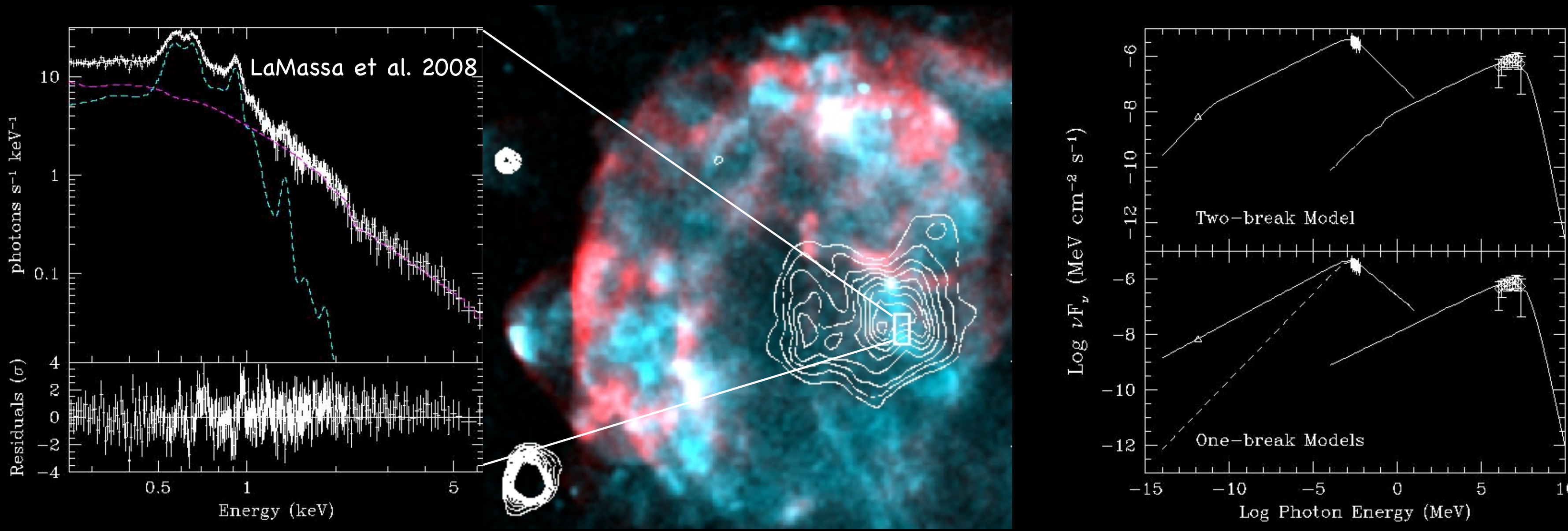
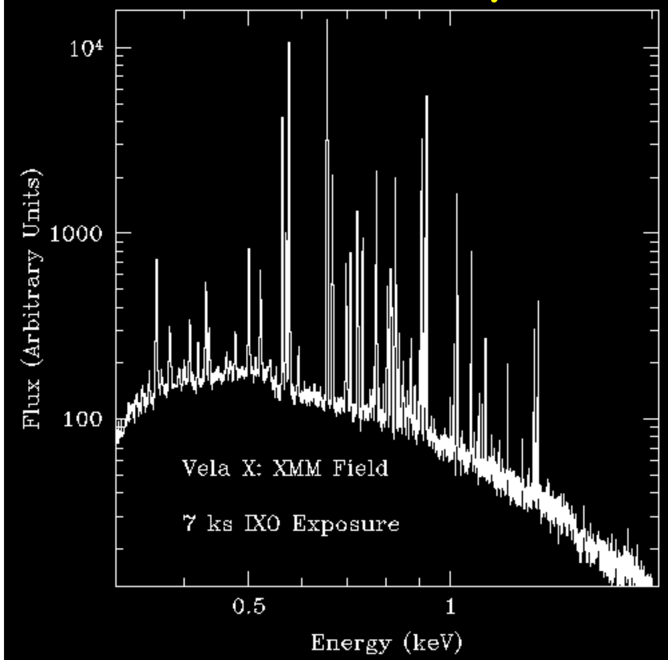
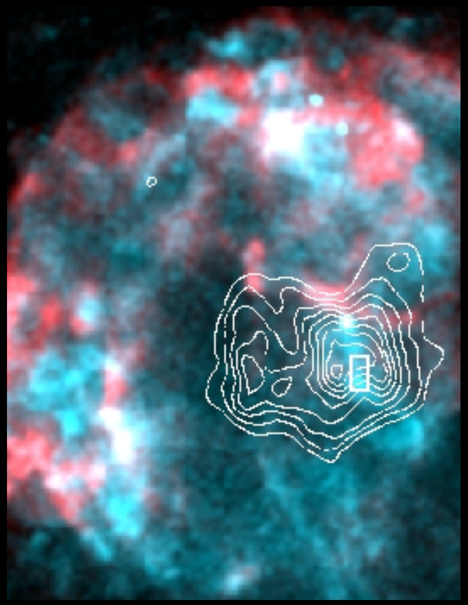


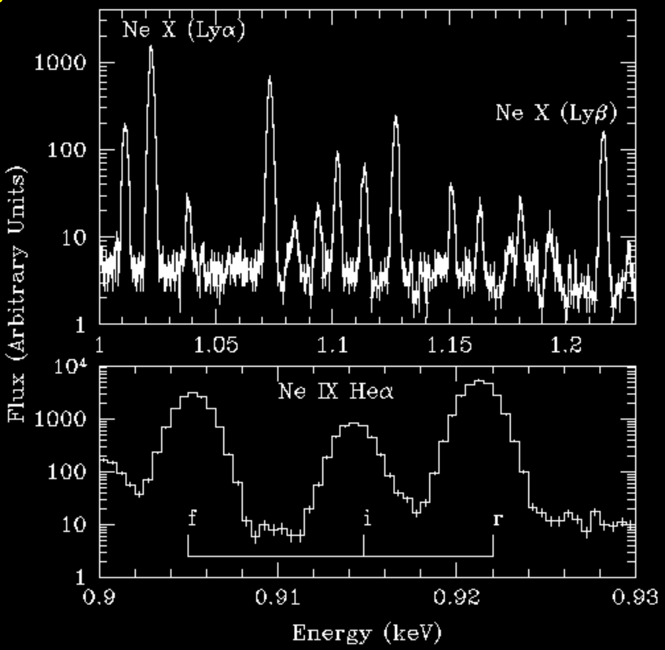
- XMM spectrum shows nonthermal <u>and</u> ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta?

- Radio, X-ray, and γ-ray measurements appear consistent with synchrotron and I-C emission from power law particle spectrum w/ two spectral breaks
  - density derived from thermal emission 10x lower than needed for pion-production to provide observed γ-ray flux
  - <u>much larger X-ray coverage of Vela X is required to fully understand structure</u>

PWN/RS Interactions w/ IXO: Vela X

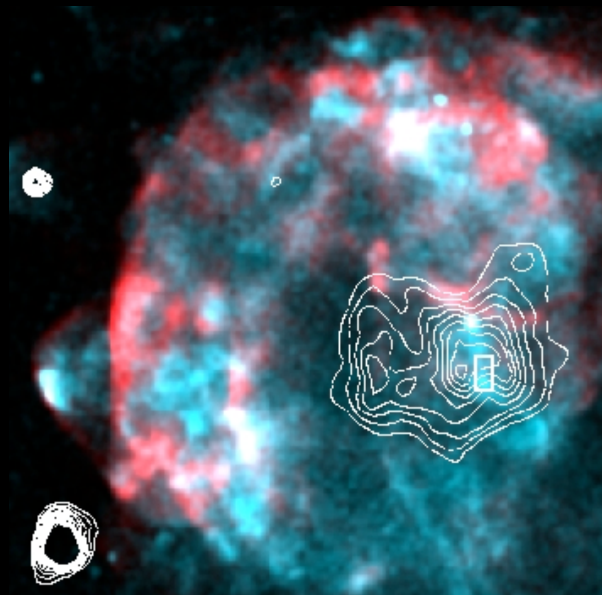


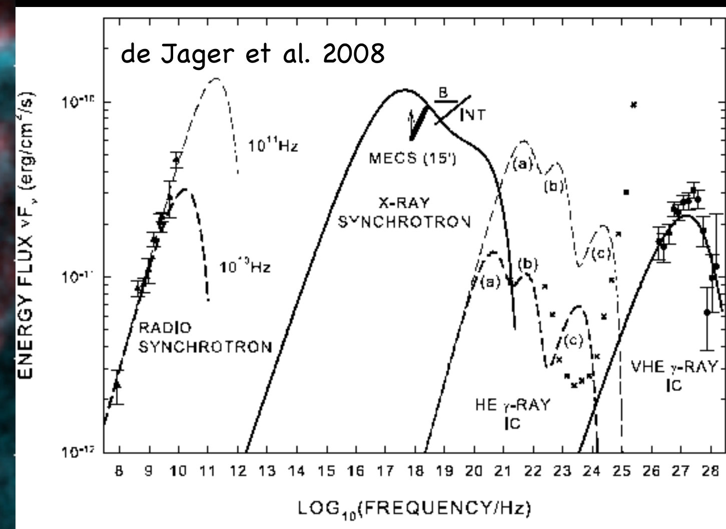




- Thermal properties of ejecta in/around Vela X constrain the PWN/RS interaction
  - expect additional compression and heating as RS meets PWN
- IXO will easily determine plasma parameters (temperature, density, abundances, and ionization state) in short exposures (e.g. Lyβ/Lyα ➔ kT, Heα[F]/[R] ➔ $n_e t$)
  - line diagnostics will trace evolution of ejecta mixed into Vela X
  - similar studies will be enabled for other (much fainter) known systems of this type

Evolution in an SNR: Vela X





- Radio and VHE spectrum for entire PWN suggests presence of two distinct electron populations
  - radio-emitting particles may be relic population, or a complicated injection spectrum...
- Maximum energy of radio-emitting electrons not well-constrained
  - this population will generate IC emission in GLAST band; spectral features will identify indentify emission from distinct up-scattered photon populations and constrain the underlying particle spectrum

Conclusions

- Recent X-ray observations show that jet/torus structures around pulsars are common
  - jet sizes and luminosities span a huge range; structure can be highly variable and unstable

- PWNe are reservoirs of energetic particles injected from pulsar
  - synchrotron and inverse-Compton emission places strong constraints on the underlying particle spectrum and magnetic field

- Modeling of broadband emission constrains evolution of particles and B field
  - modeling form of injection spectrum and full evolution of particles still in its infancy

- Reverse-shock interactions between SNR and PWNe distort nebula and may explain TeV sources offset from pulsars
  - multiwavelength observations needed to secure this scenario (e.g. Vela X)