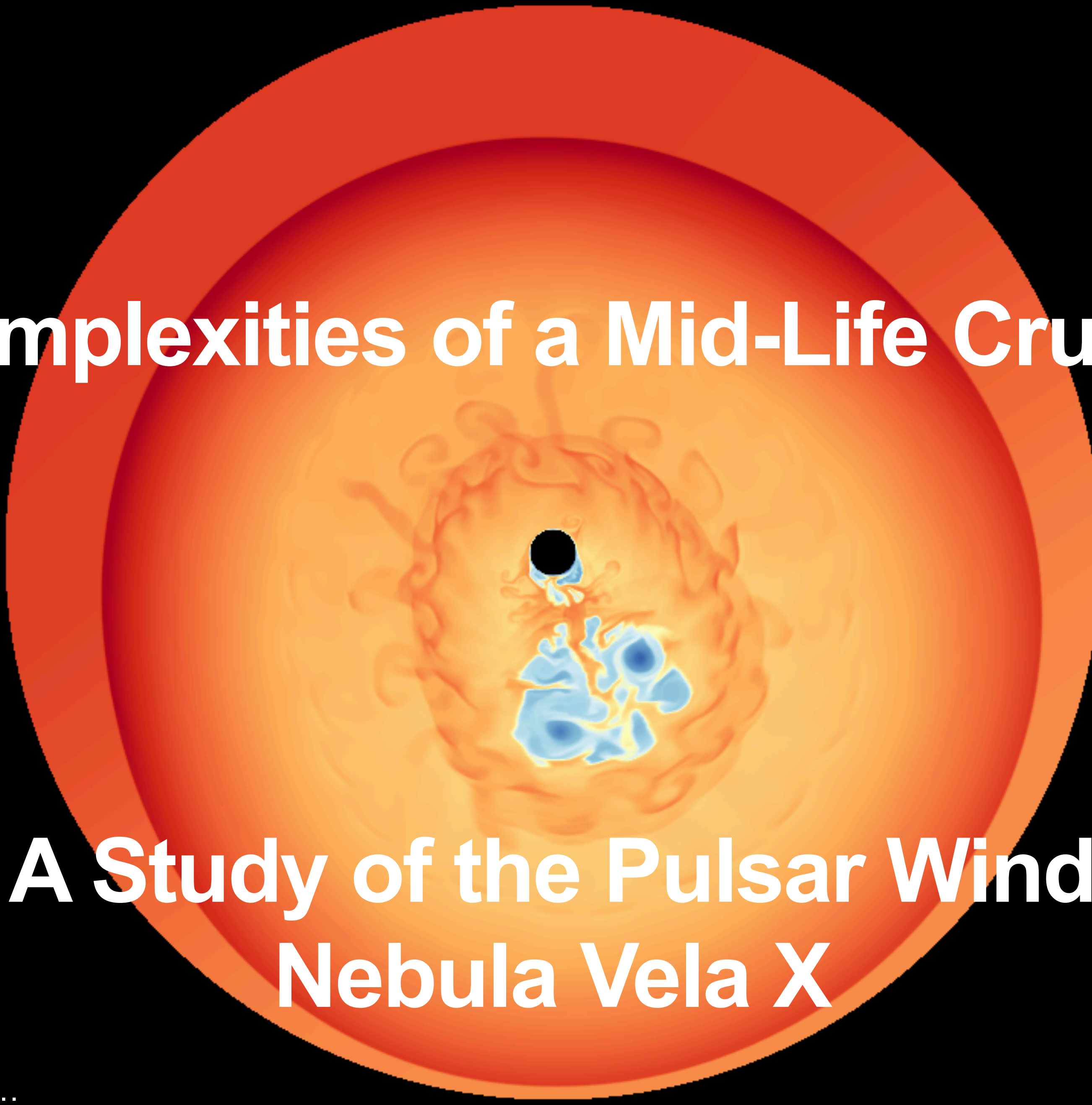
Complexities of a Mid-Life Crush:

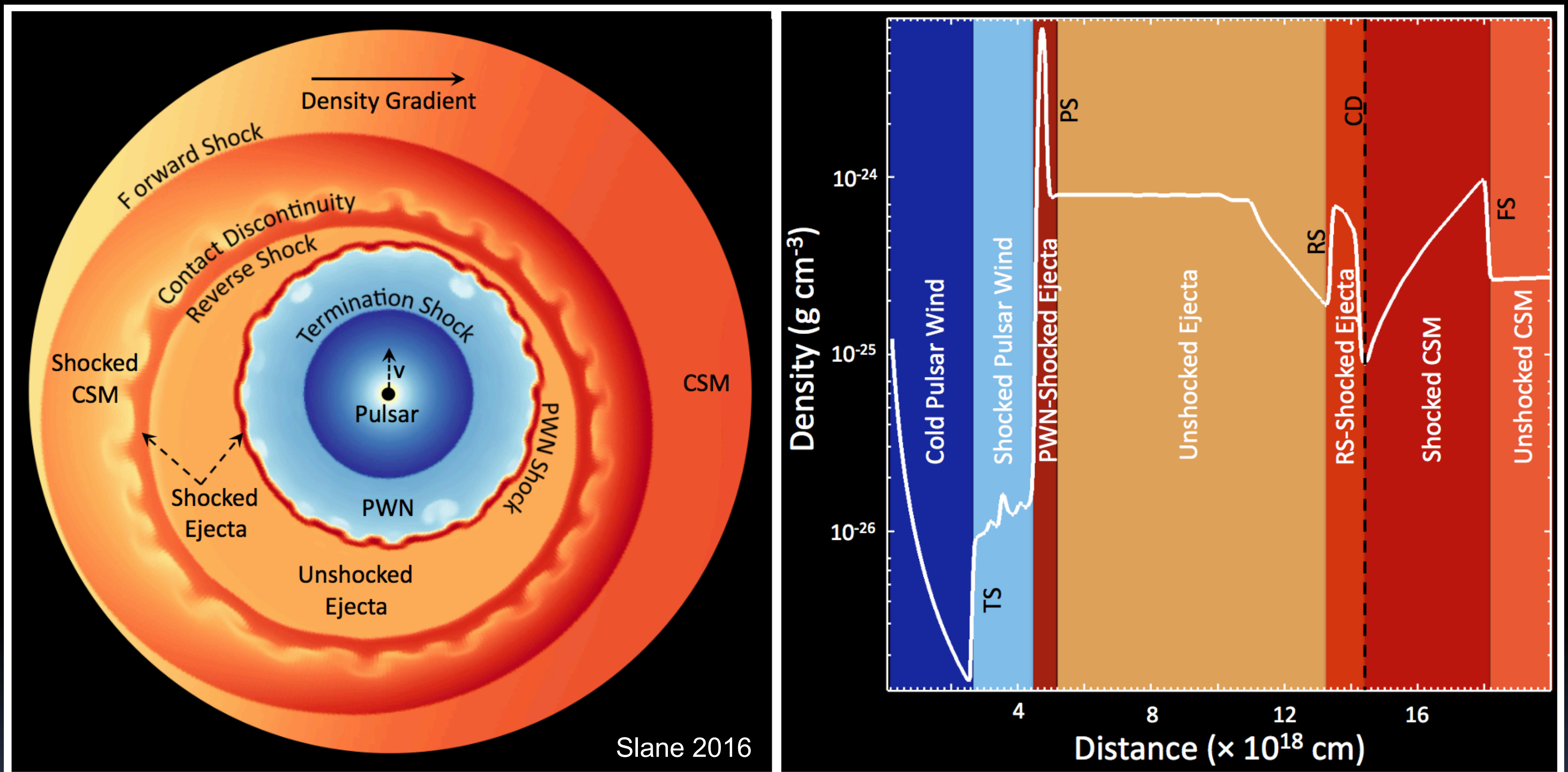


A Study of the Pulsar Wind Nebula Vela X

Collaborators:

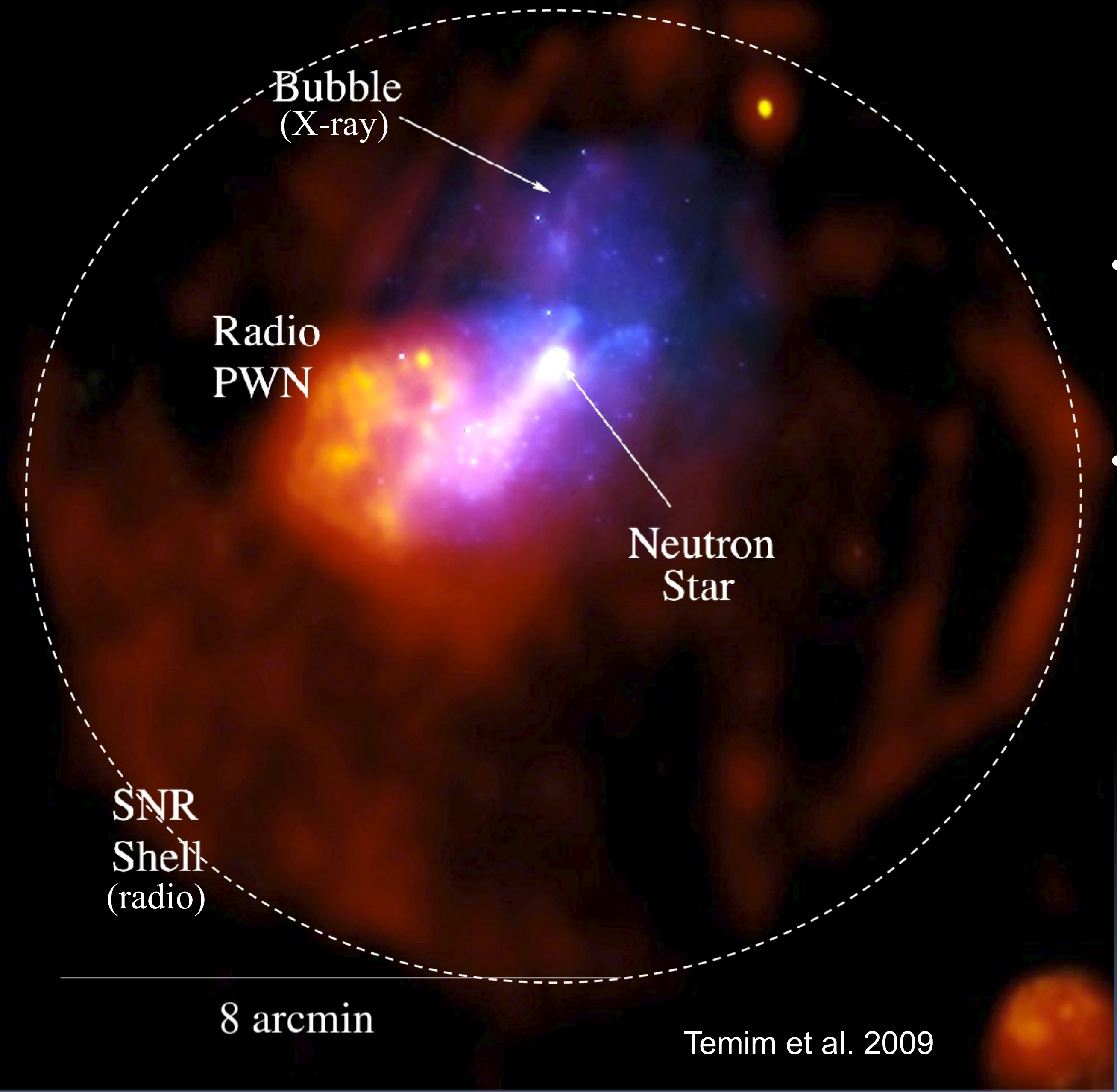
J. Blondin
C. Kolb
T. Temim
and many others…

Composite SNRs: Shock Structure



See, also, Kolb et al. 2017

G327.1-1.1: SNR RS Interaction



- Radio morphology suggests PWN interaction with SNR reverse shock.
- Chandra observations show offset compact source w/ trail of nonthermal emission extending to radio PWN.
  - Compact source shows extent and is embedded in bow shock structure

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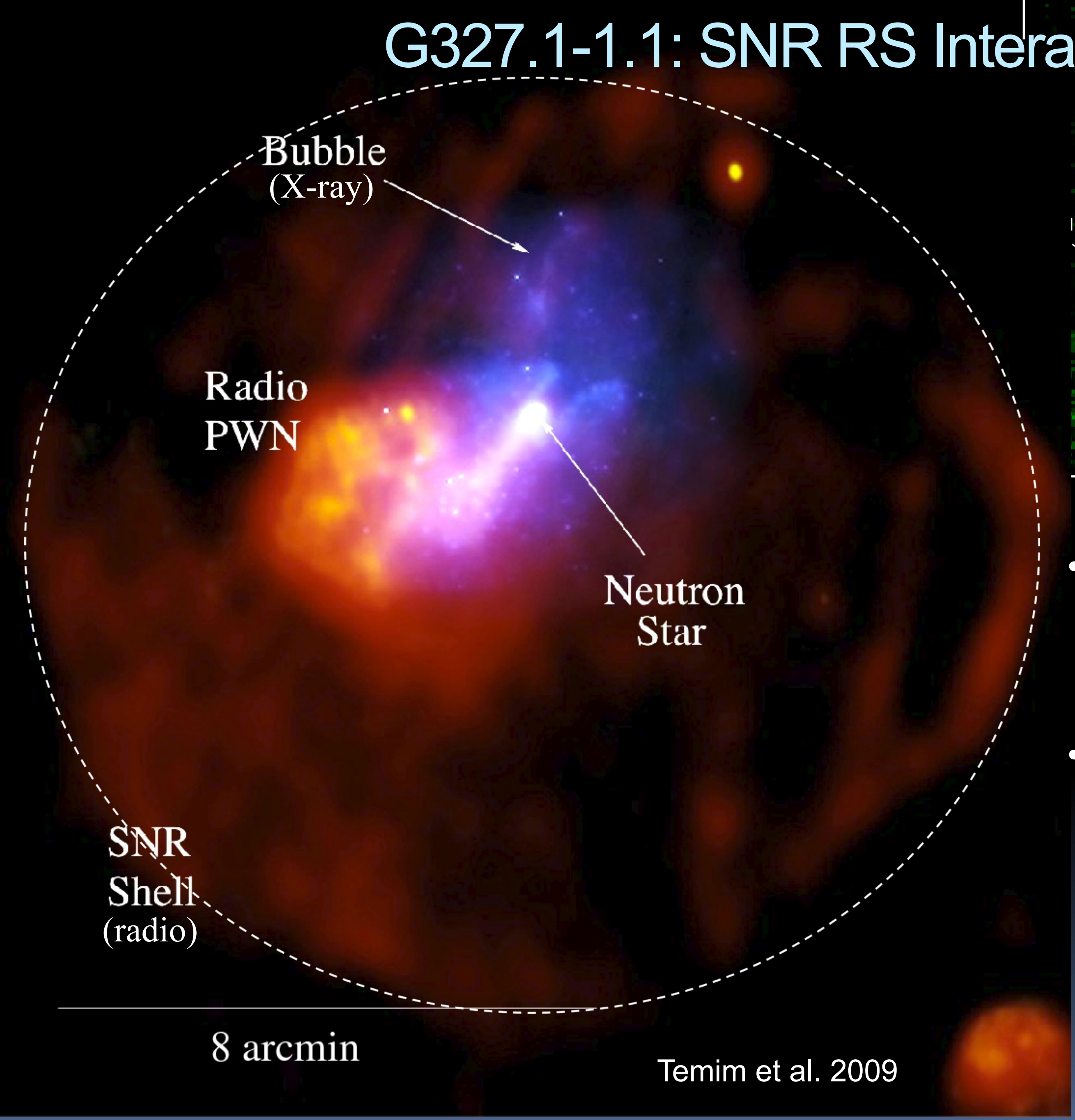

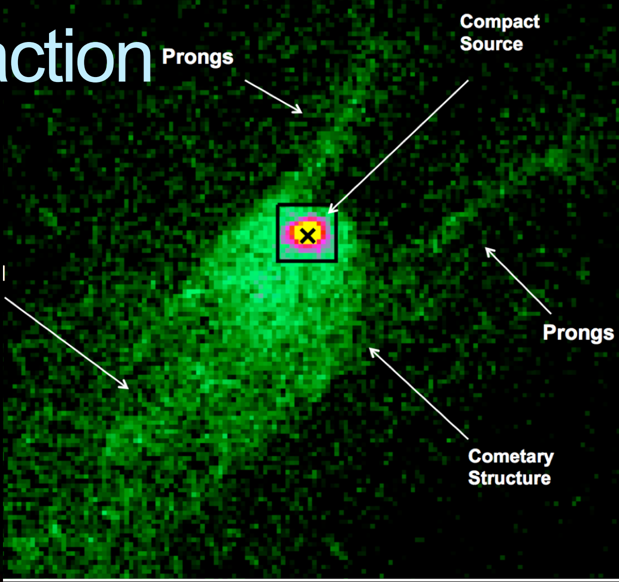

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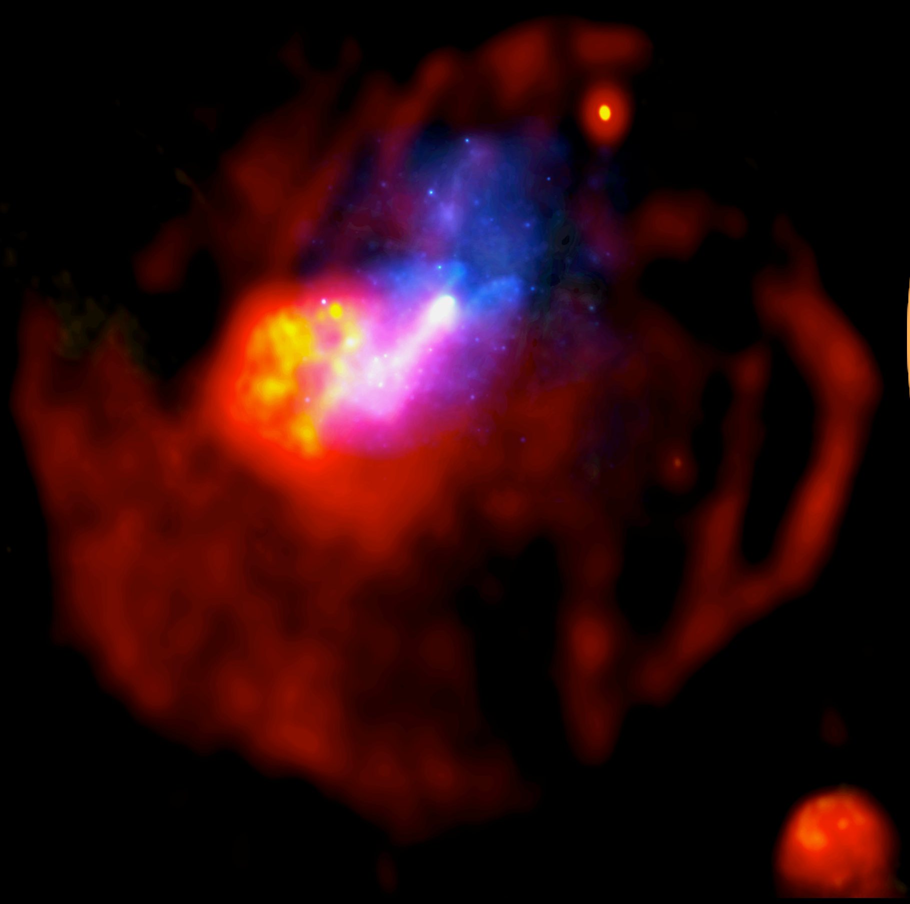
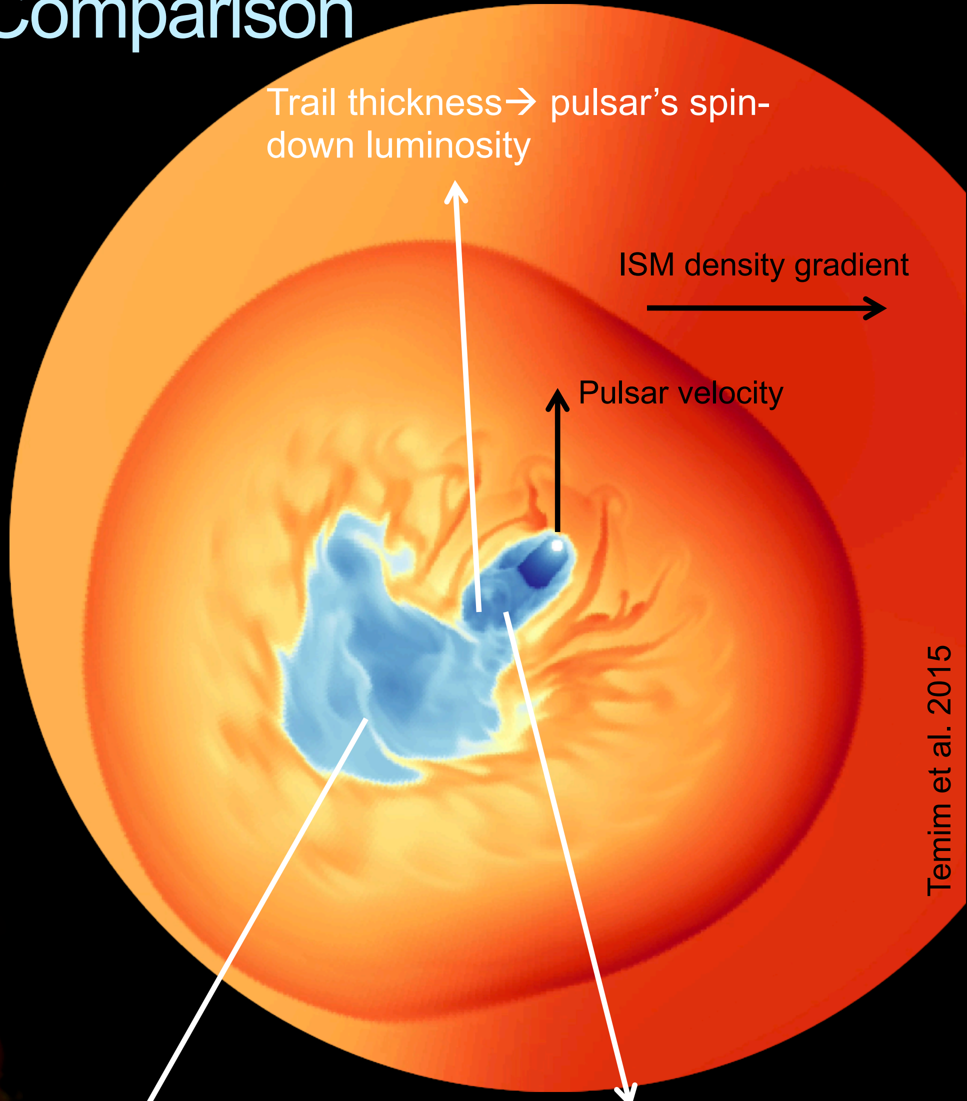
Morphology Comparison

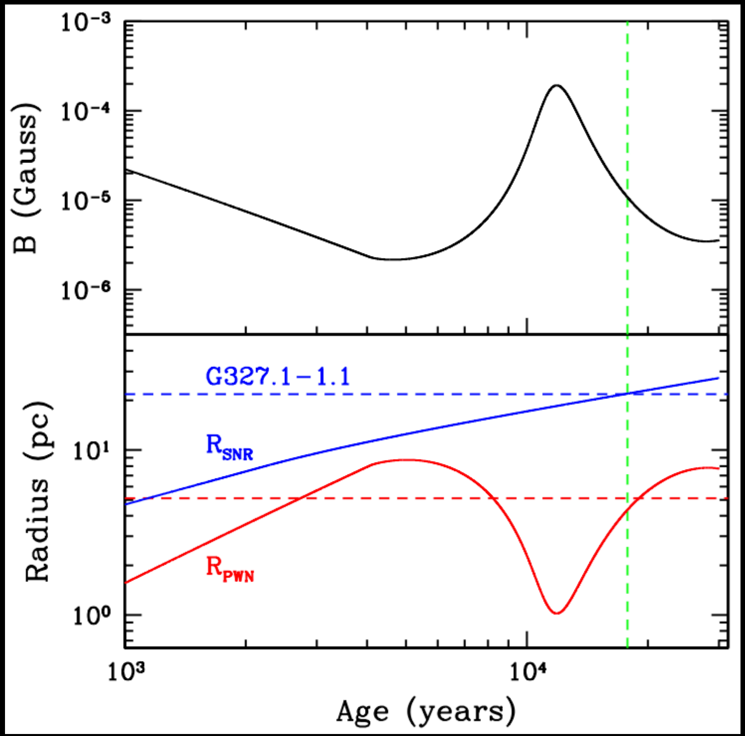


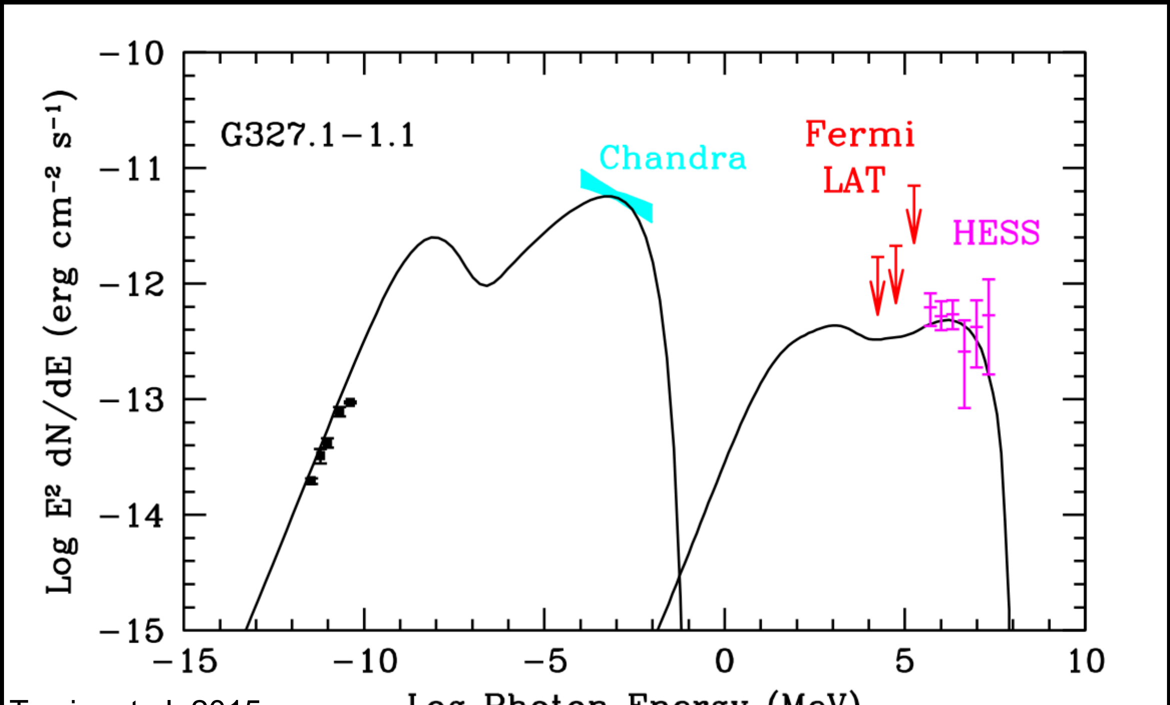


Displacement of "relic" PWN → orientation of density gradient

Orientation of trail → combination of gradient and pulsar motion direction

Broadband Spectrum at 17,000 yrs



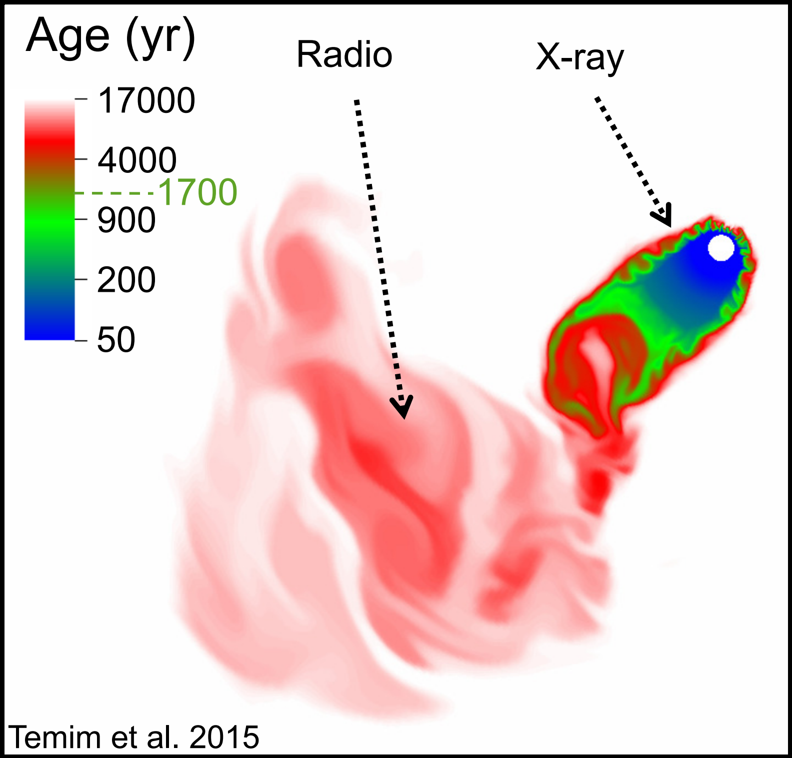


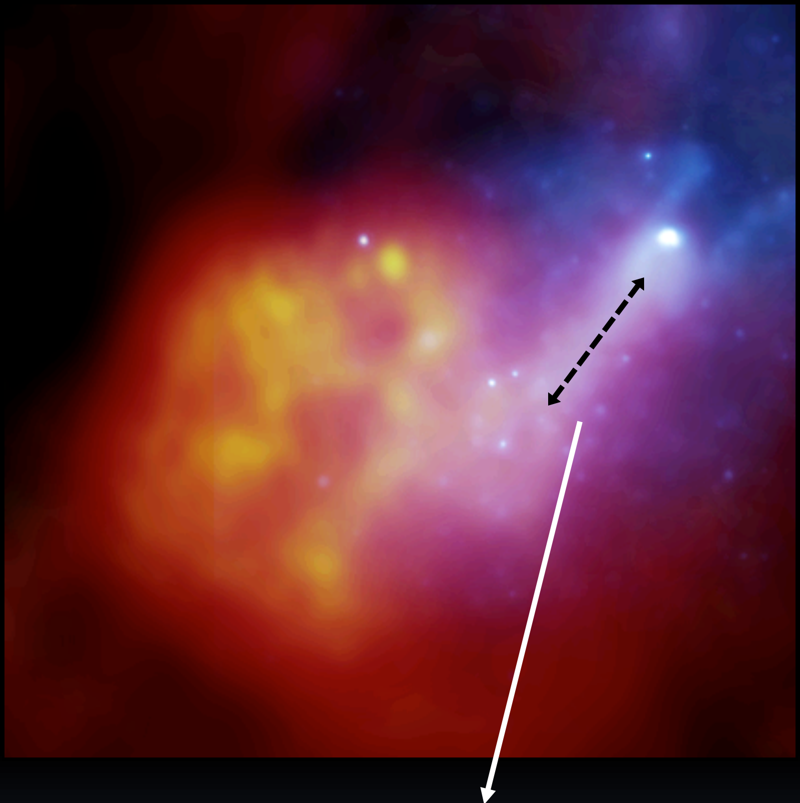
Temim et al. 2015

- Semi-analytic model for radiative evolution of the PWN (Gelfand et al. 2009)
- Input parameters from observational constraints and HD model

→ B = 11 μG and an electron energy break at 300 GeV

Age of Injected Particles at 17,000 yrs





$$\tau_{syn} \approx 820\, E_{e,100}^{-1} B_{10}^{-2}\ \text{yr}$$

∴ Expect spectral steepening

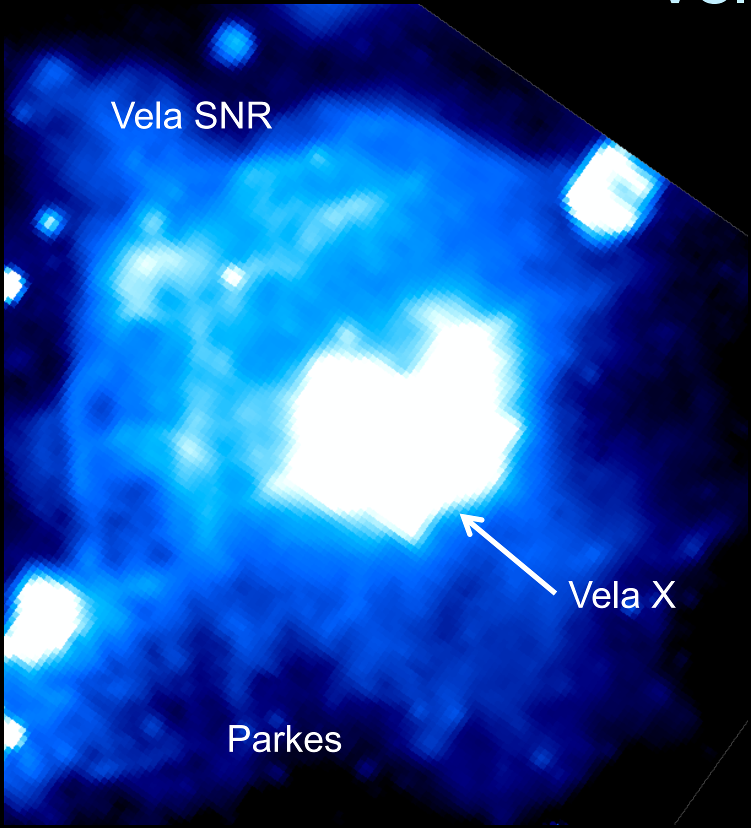
$\Delta\Gamma$ = 0.5

over a synchrotron lifetime

Photon index in the trail steepens from 1.76 to 2.28:

$\Delta\Gamma$ = 0.52 $\pm$ 0.17

Vela SNR and its PWN



- Nearby SNR evolving in density gradient
- Middle-aged pulsar with disrupted PWN (Vela X)

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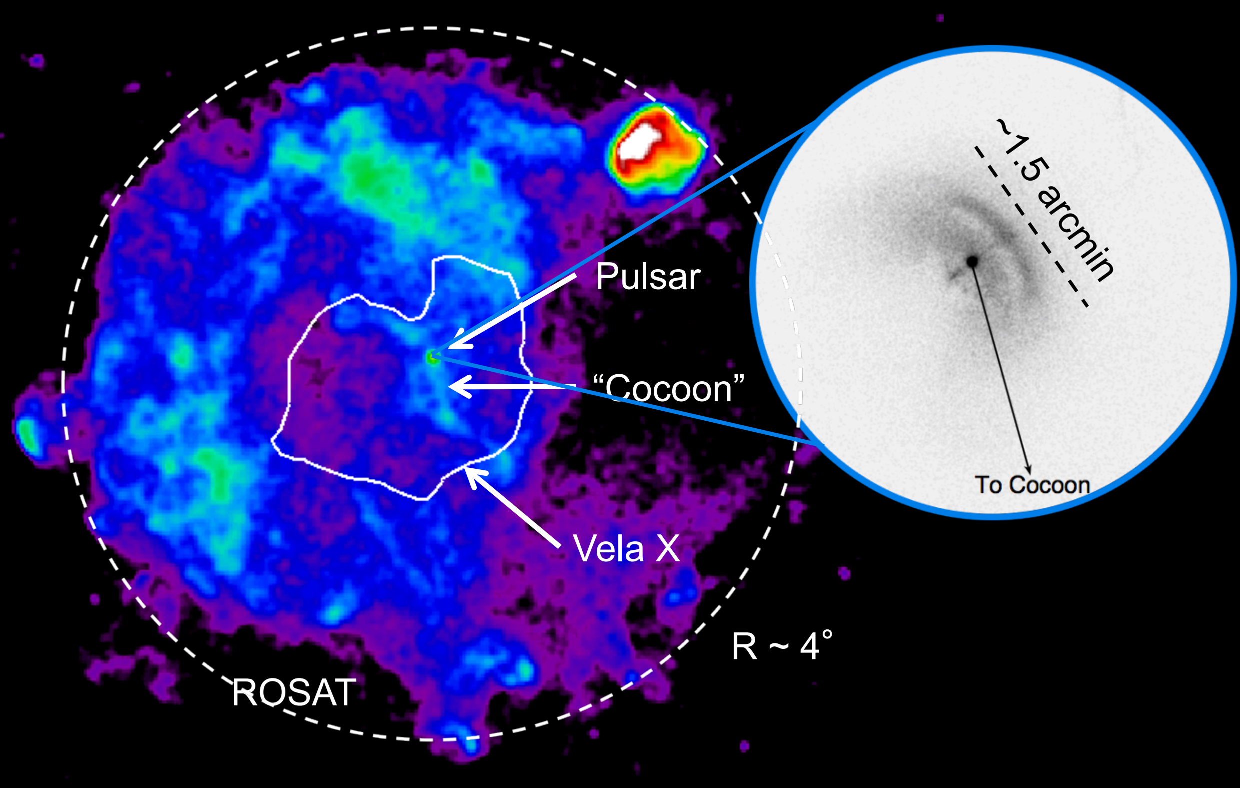

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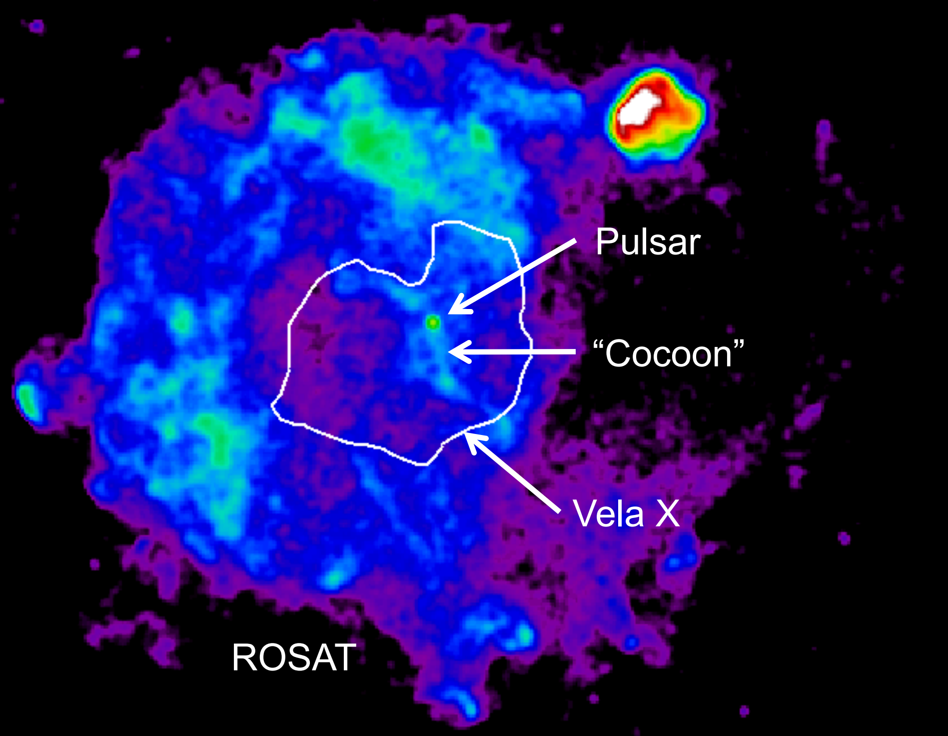

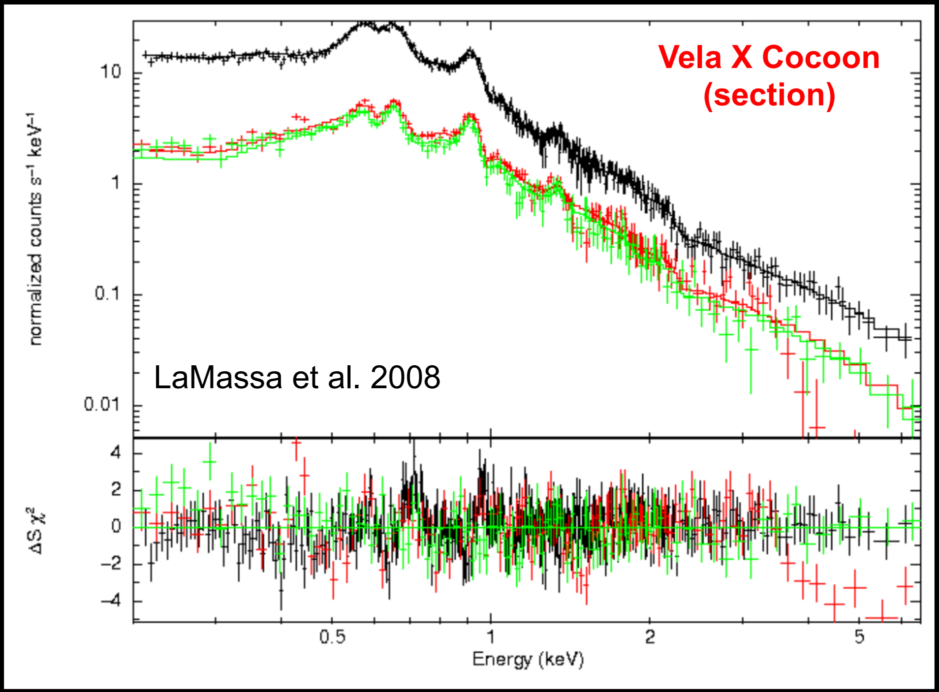

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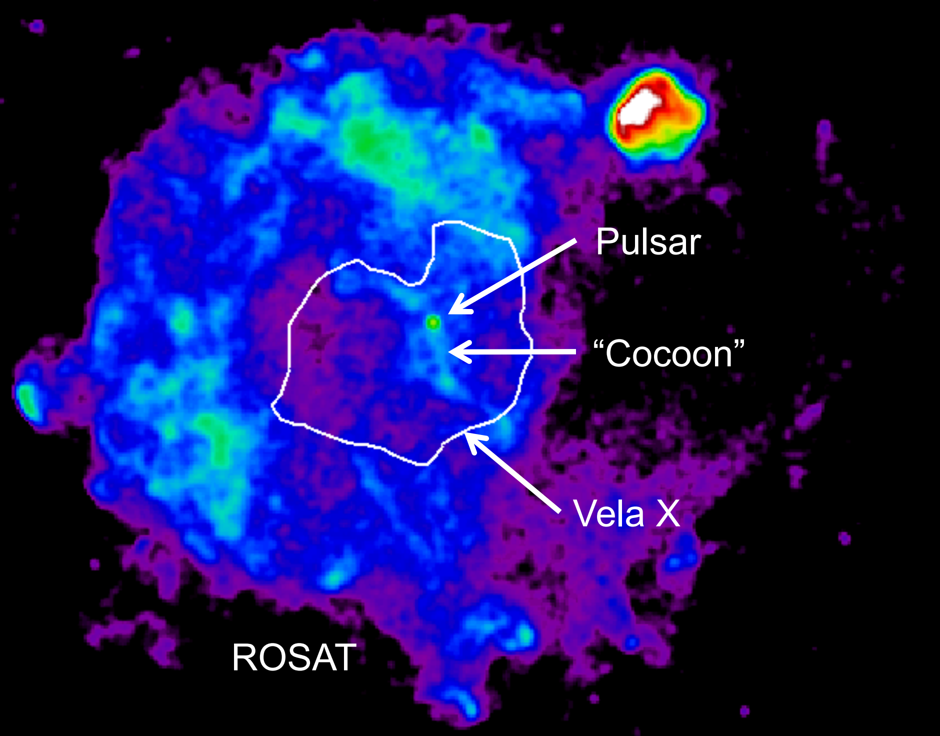

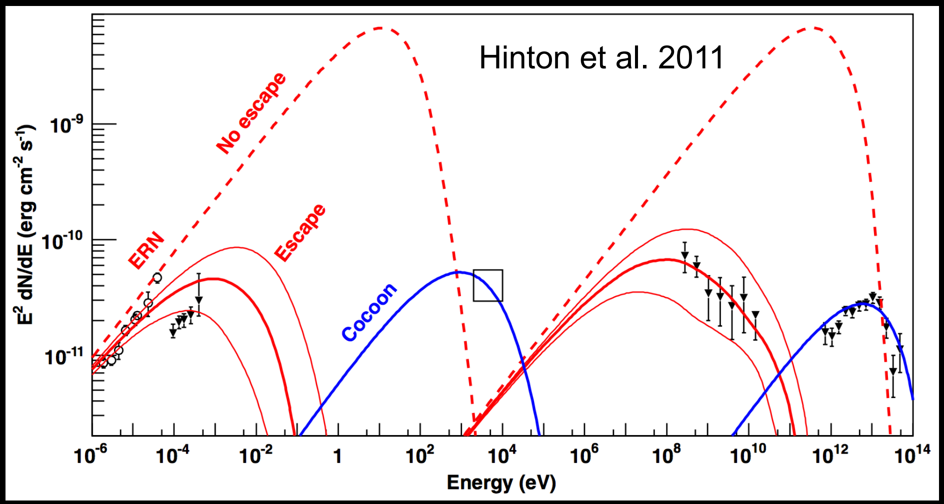

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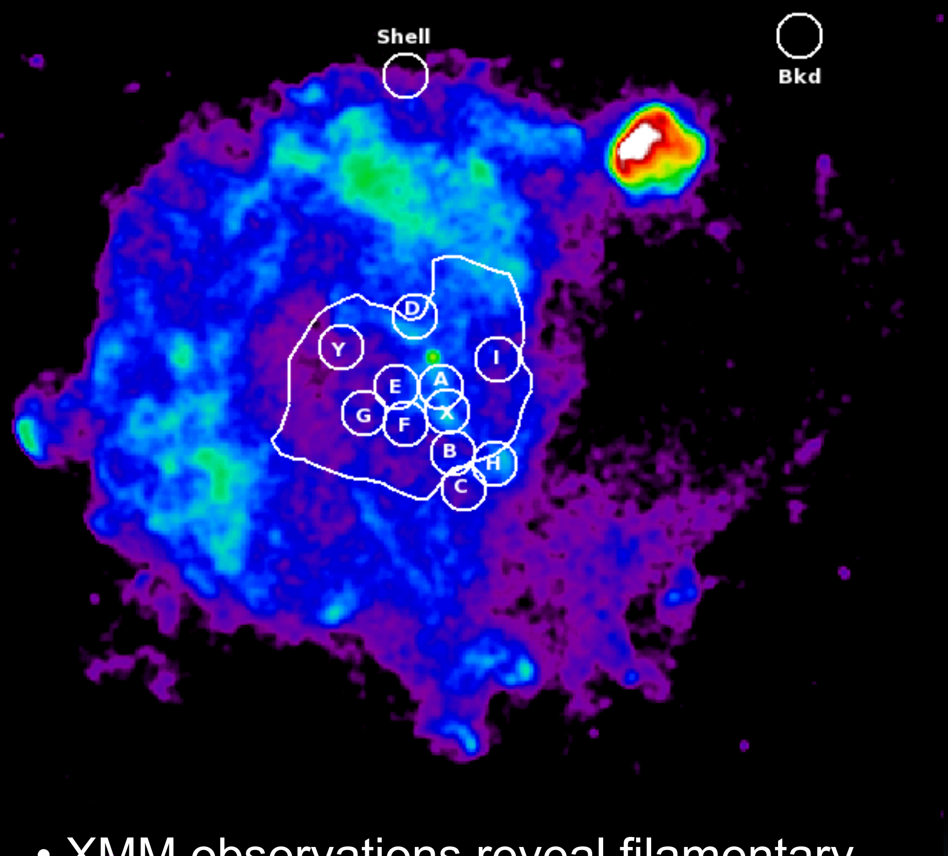
- Possible breaks or particle escape
  - Possibly more rapid diffusion from radio nebula than from cocoon

Vela X: XMM Observations



- XMM observations reveal filamentary structure along cocoon
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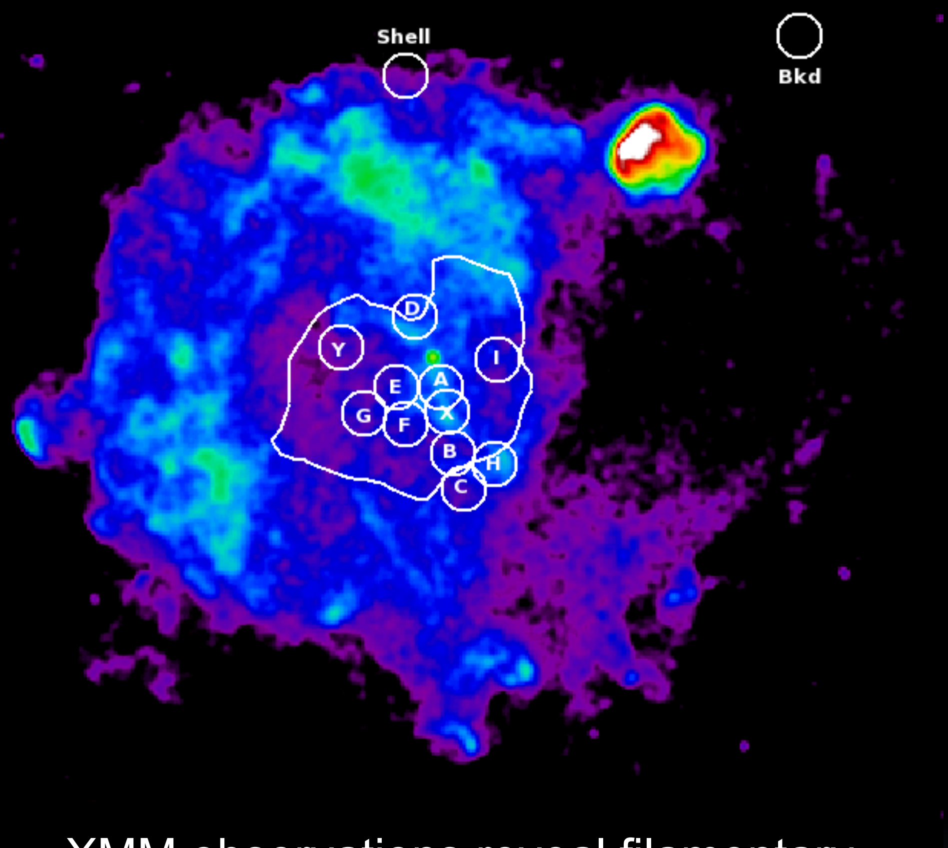

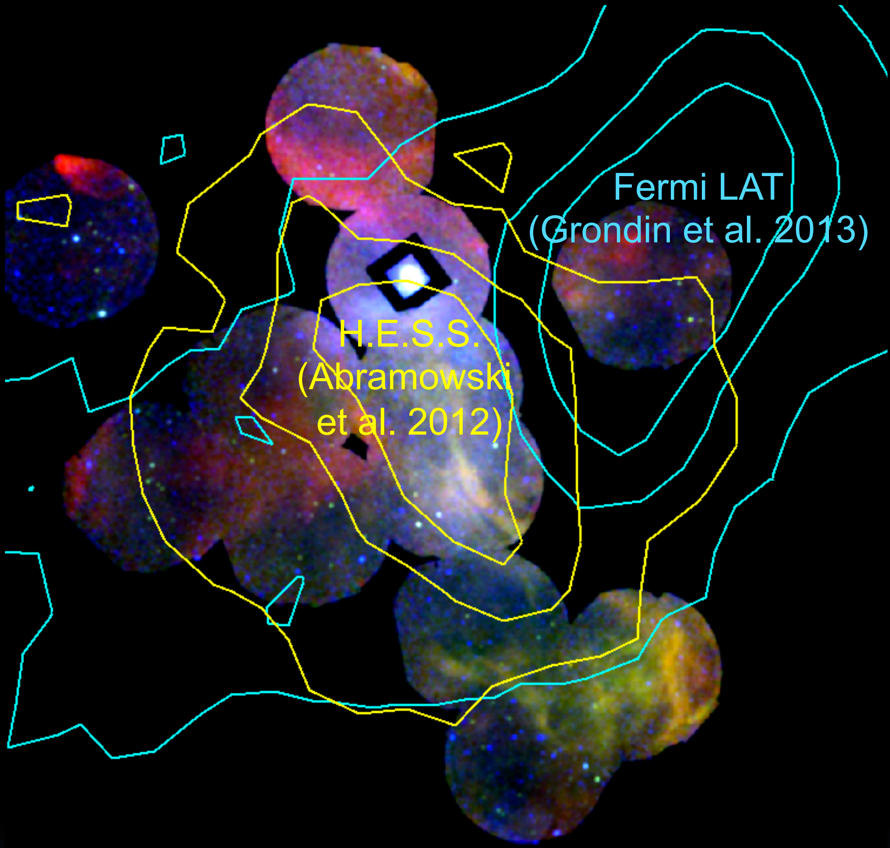

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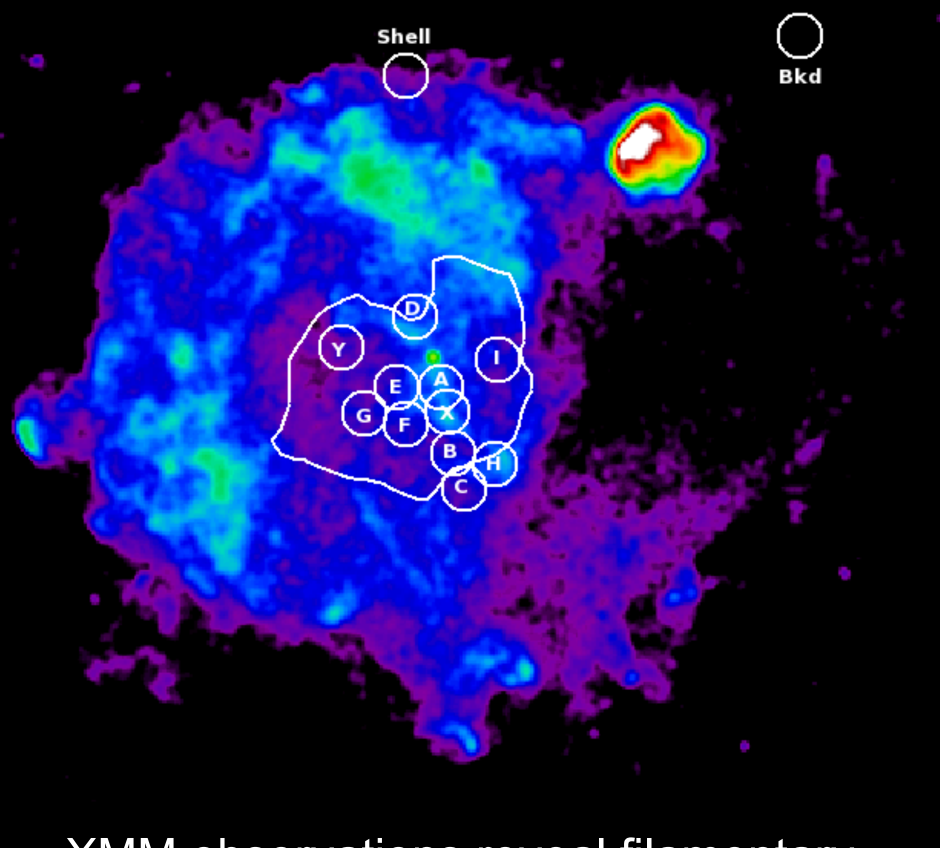

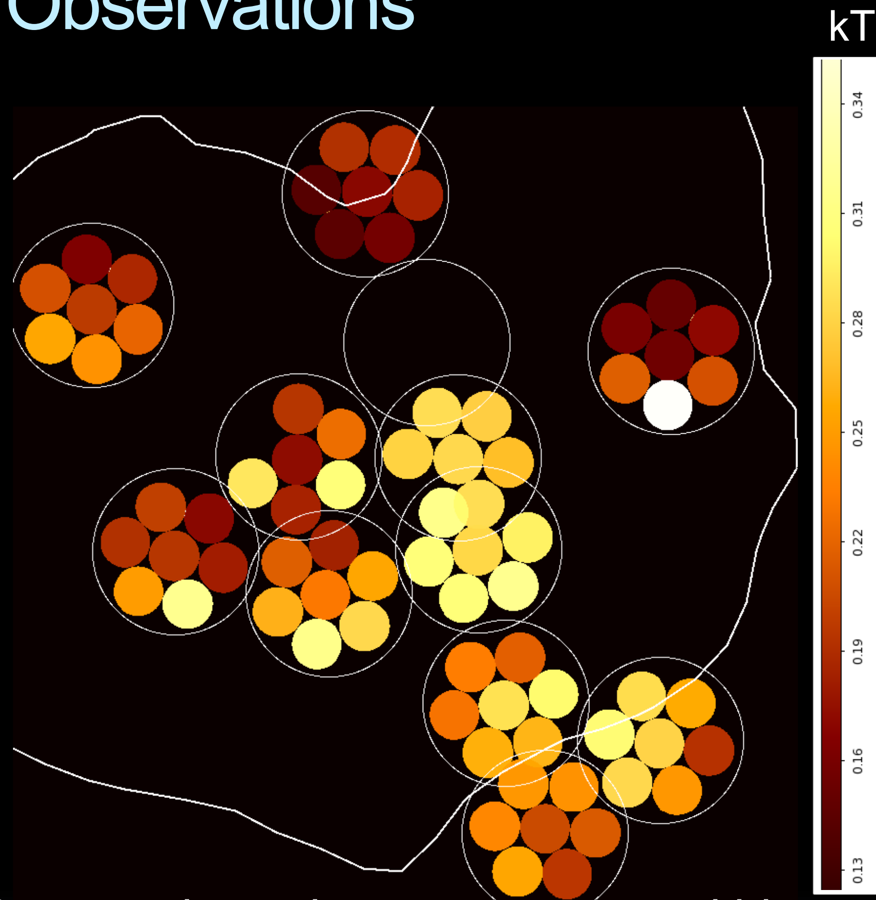

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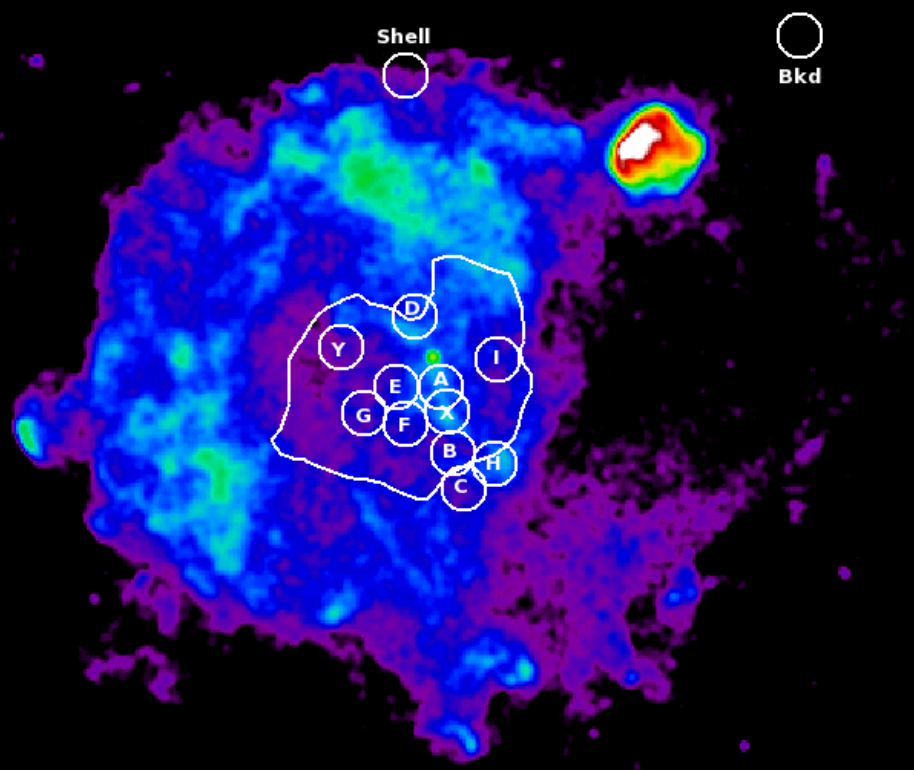

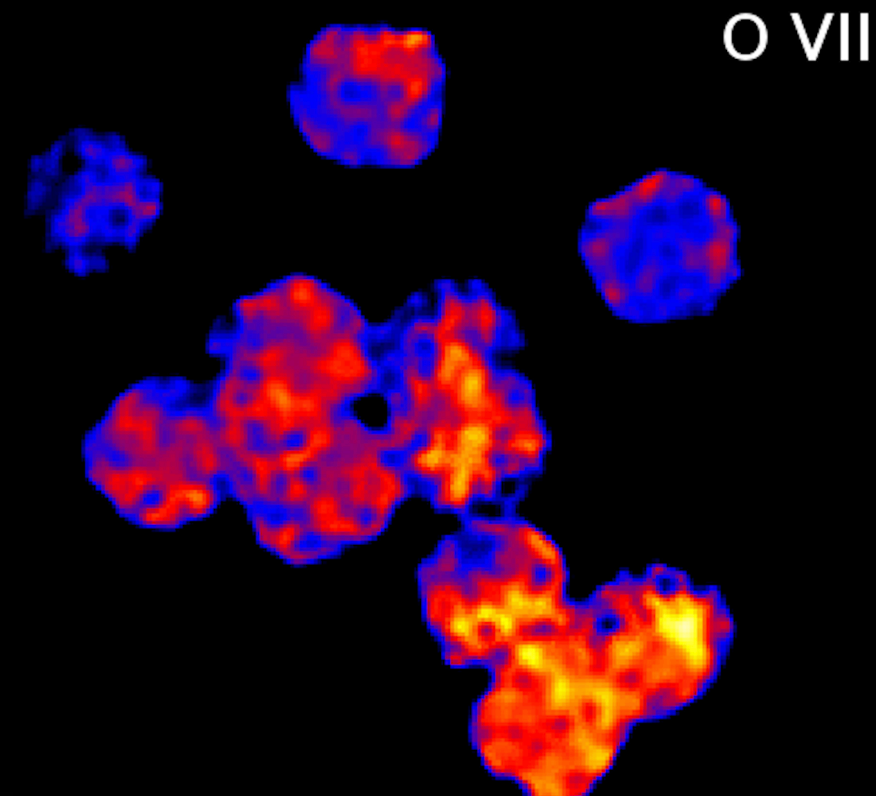

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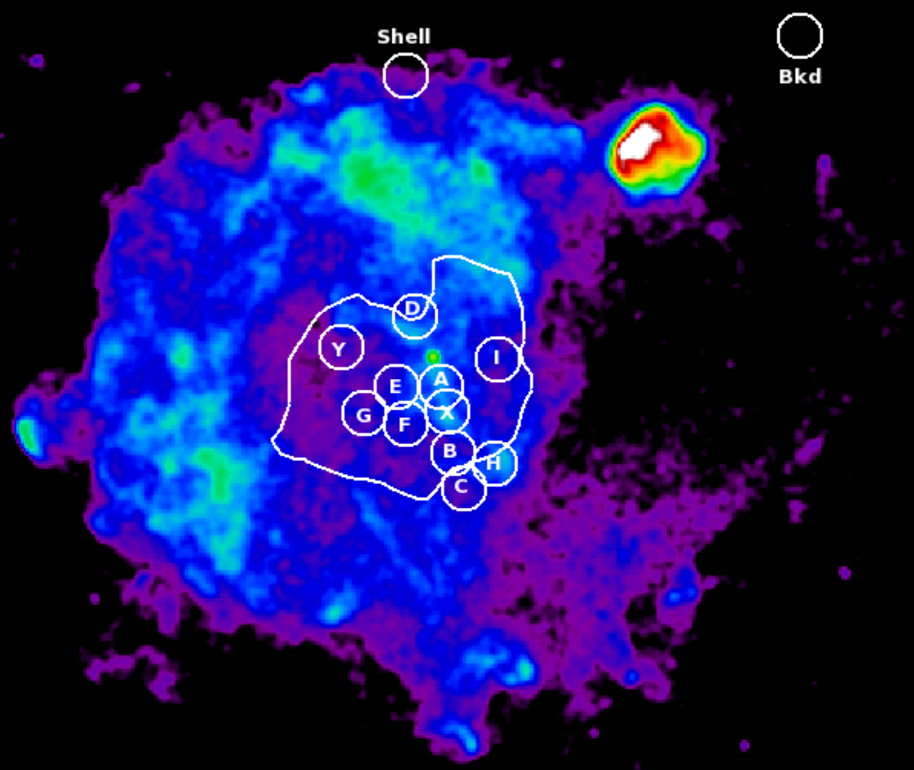

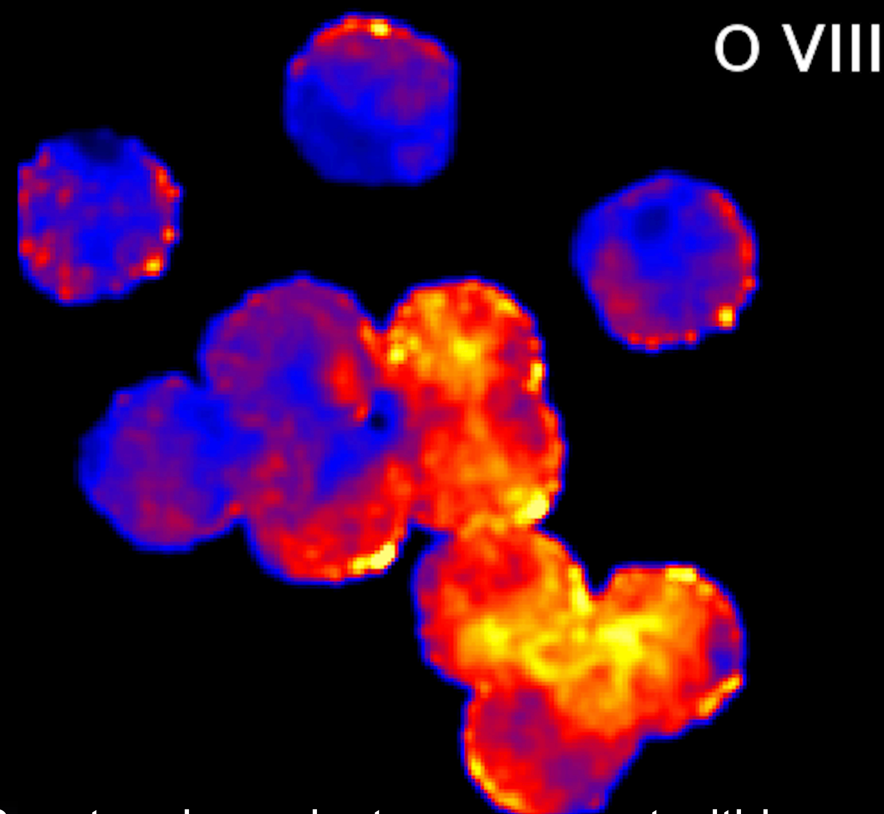

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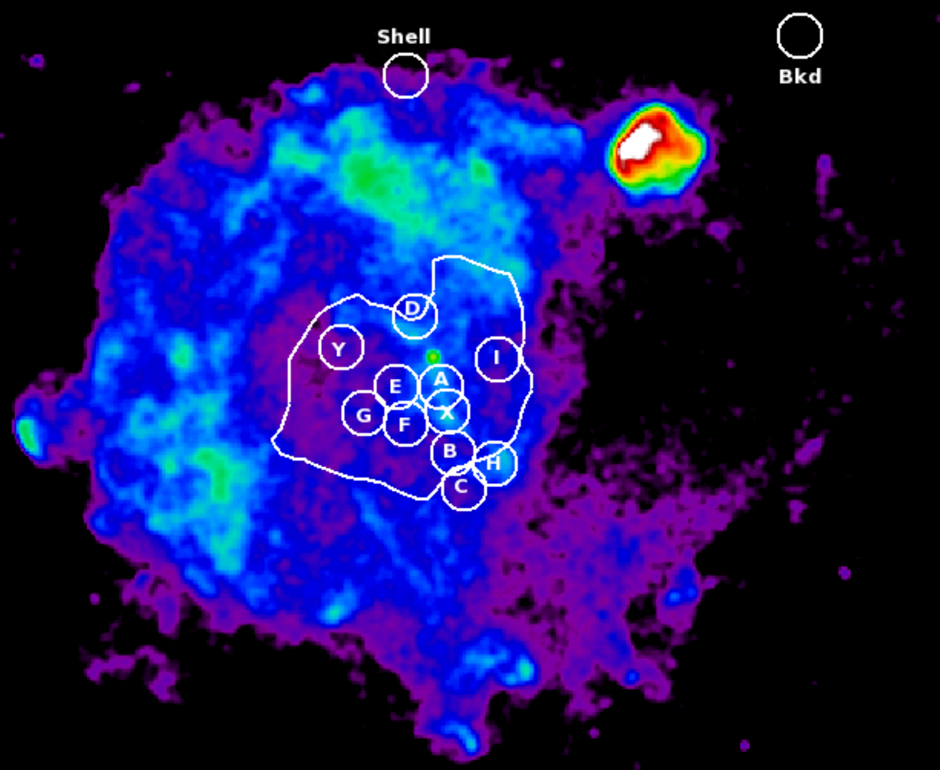

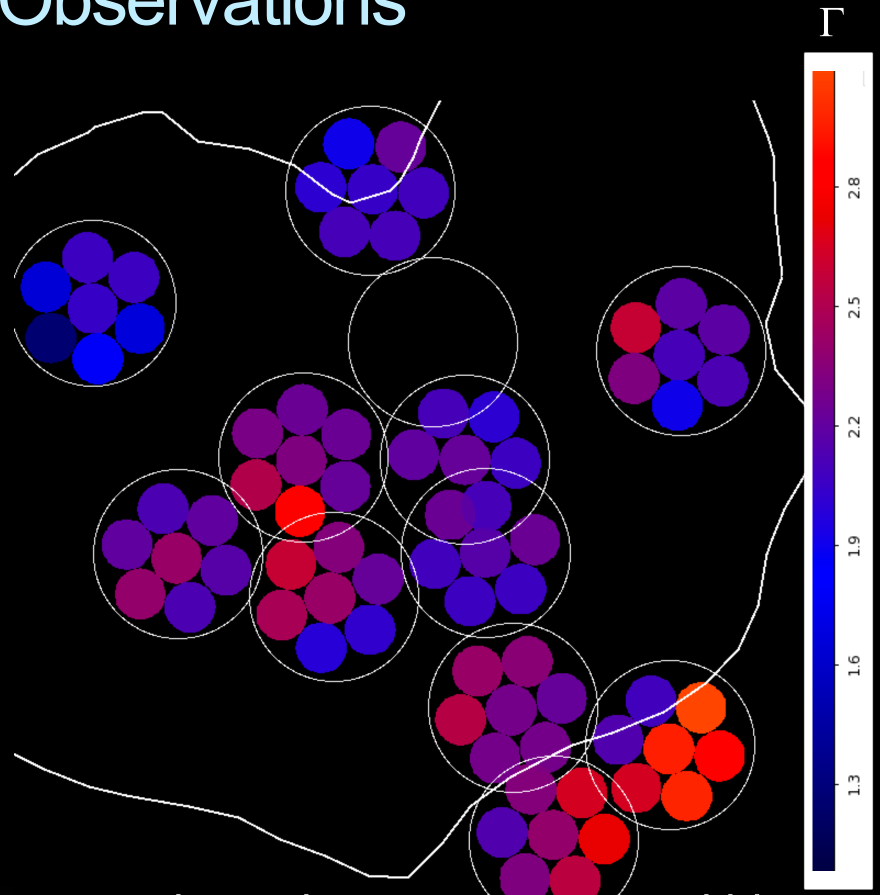

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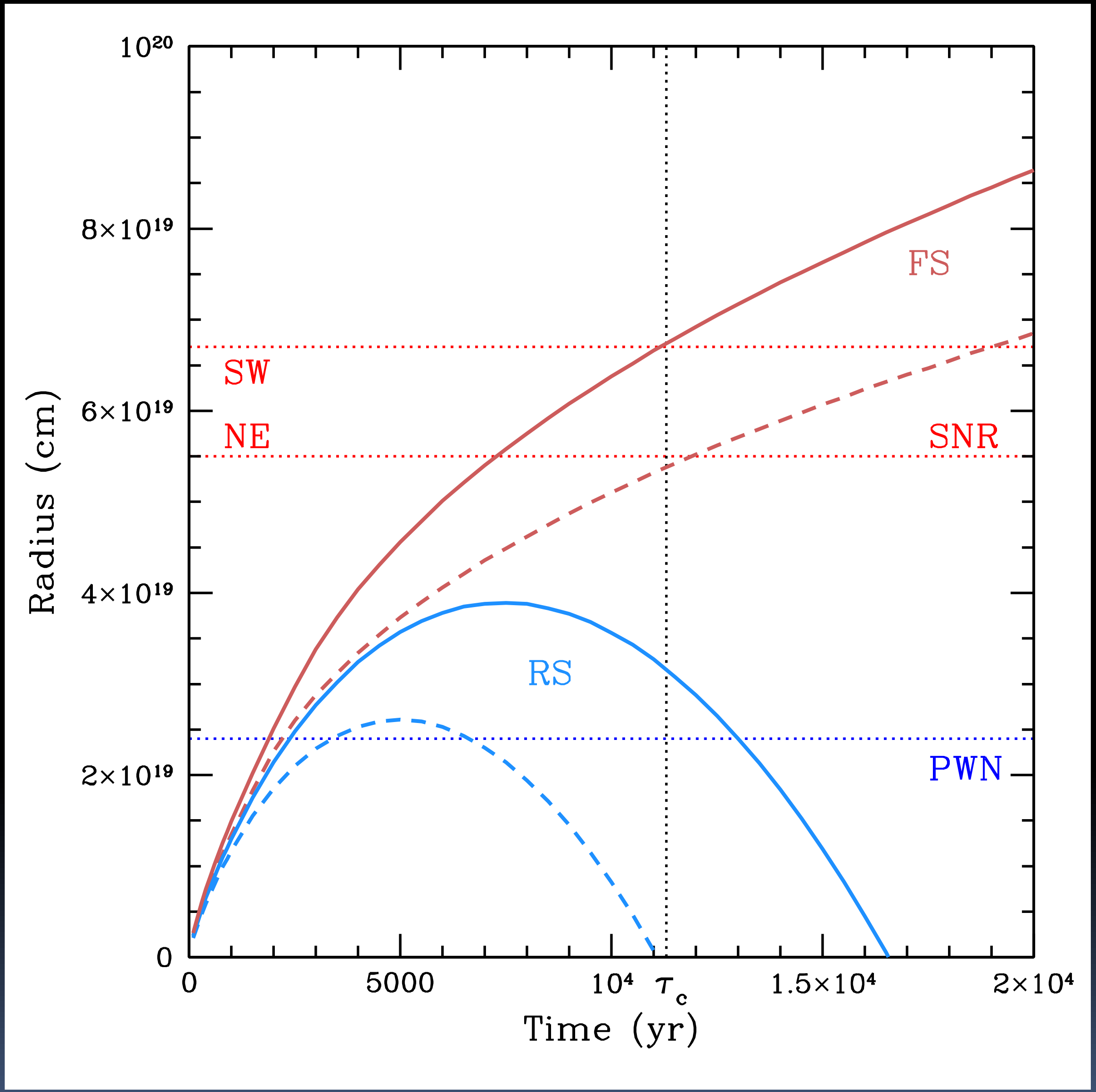
- Spectra show ejecta component within Vela X has higher kT along cocoon
  - distribution of O VII and O VIII is consistent with this picture
- Power law index steepens with distance from pulsar, though slowly along cocoon
  - emission at Fermi peak somewhat harder

Progression of FS/RS



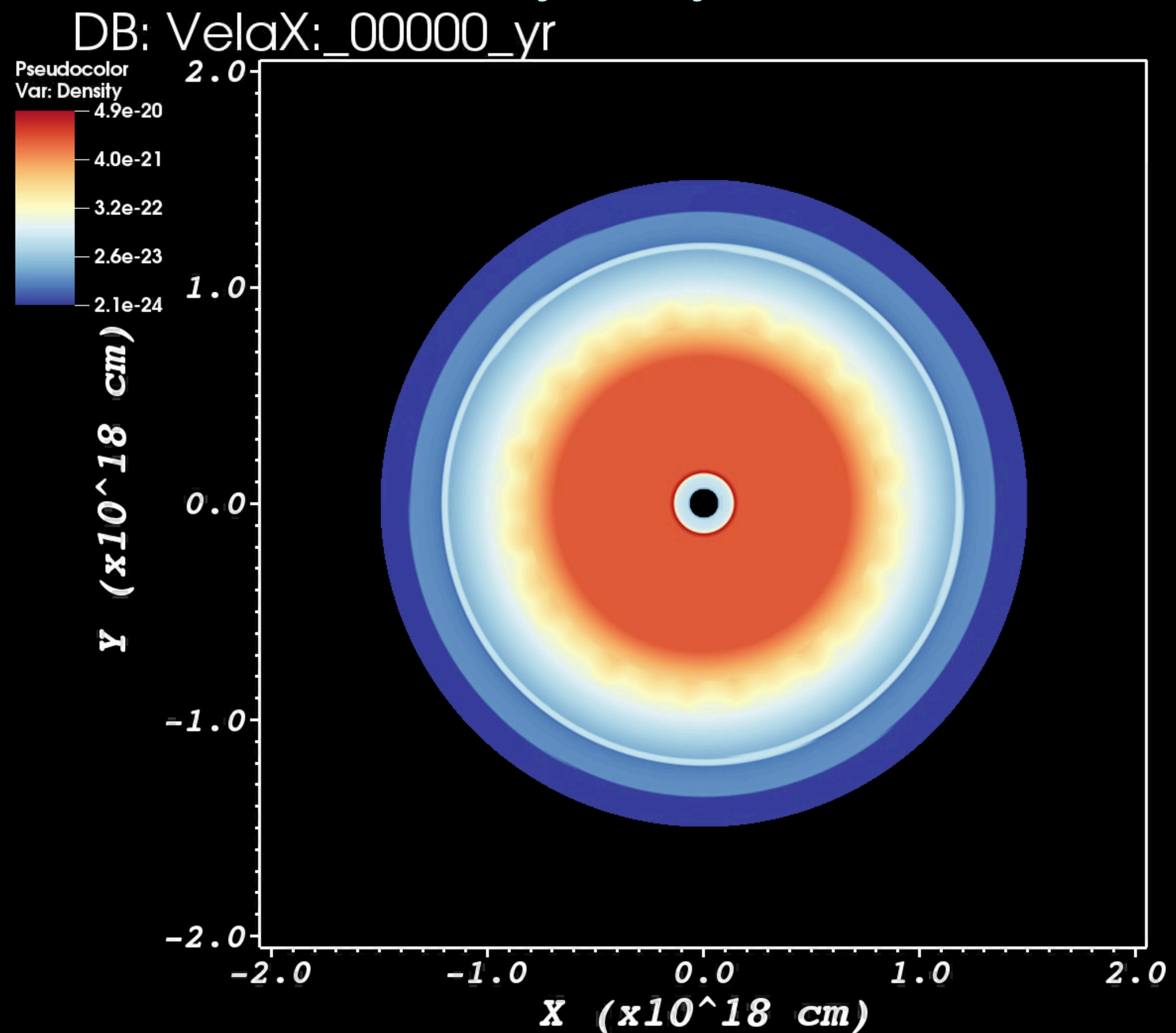
- Solutions by Truelove & McKee (1999) show evolution of FS/RS radius for different values of explosion energy, ambient density, and ejecta mass/profile.
- Explore parameter space to arrive at scenario for Vela SNR

$E_{51} = 1$, $M_{ej} = 8\ M_{\odot}$, $n = 12$

$n_{0,SW} = 0.05\ cm^{-3}$
$n_{0,NE} = 0.15\ cm^{-3}$

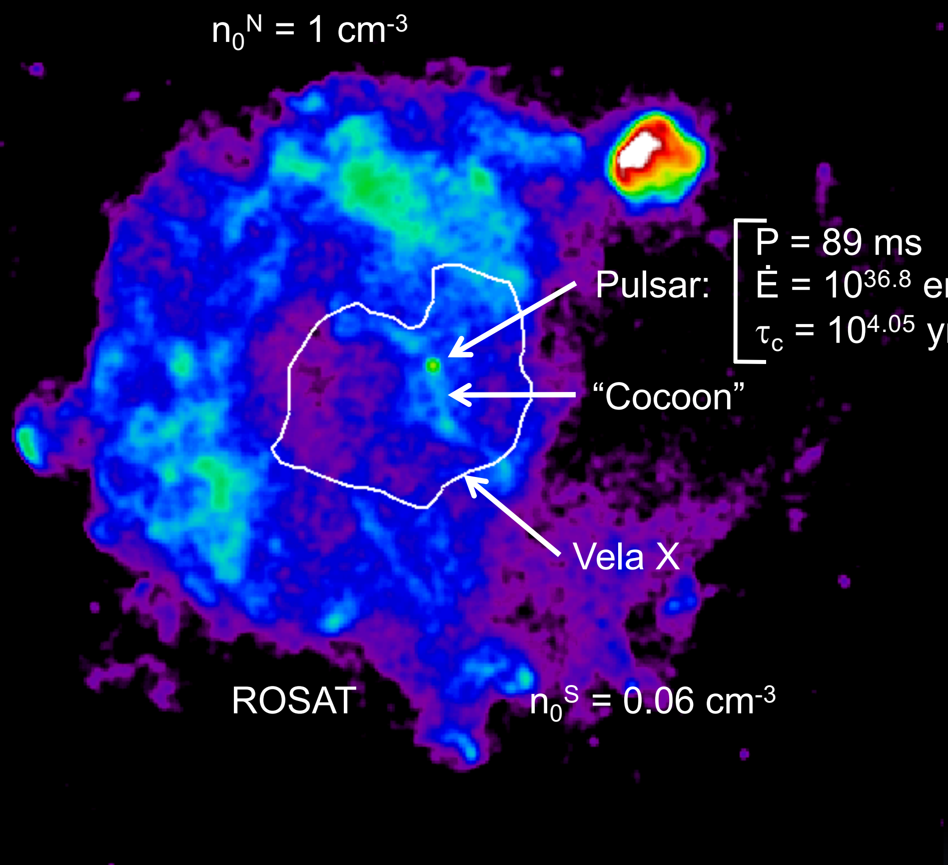
Note: actually, evidence of engulfed clouds suggests a higher mean density.

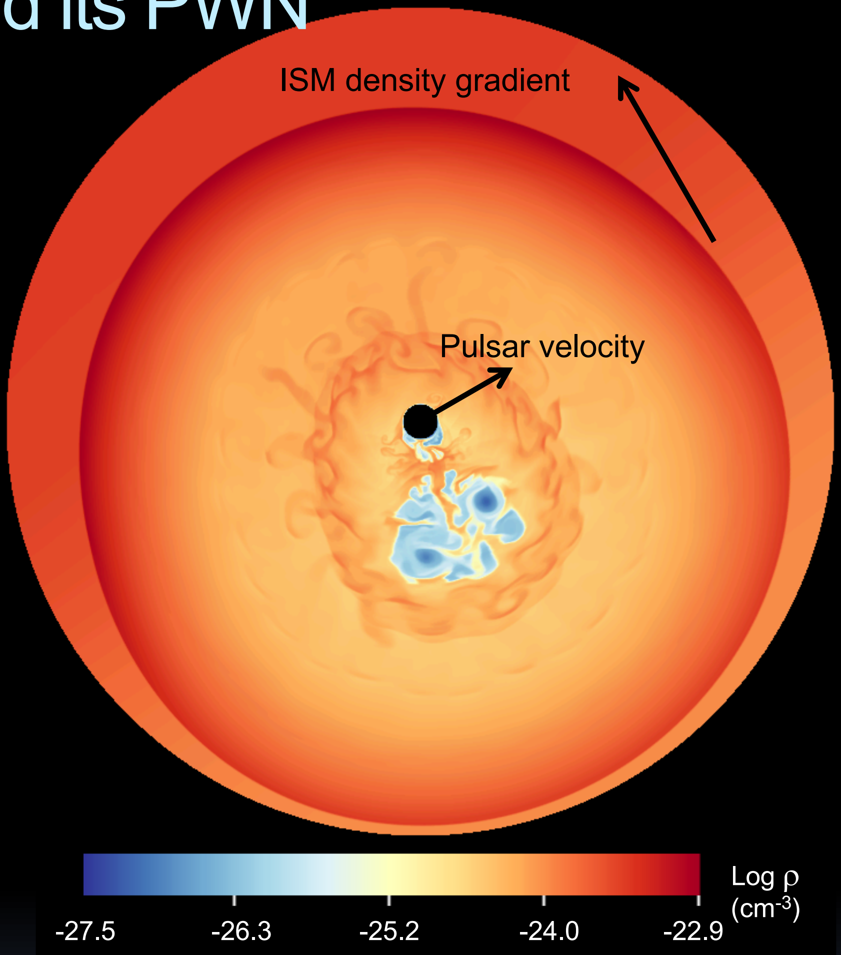
Hydrodynamical Simulations



- Evolution of SNR into density gradient with contrast of ~4 results in asymmetric crushing similar to that observed in Vela X.
  - As RS sweeps over pulsar, a channel of ejecta-rich material is formed, similar in structure to cocoon.
  - Rapid advection may explain hard spectrum in cocoon.

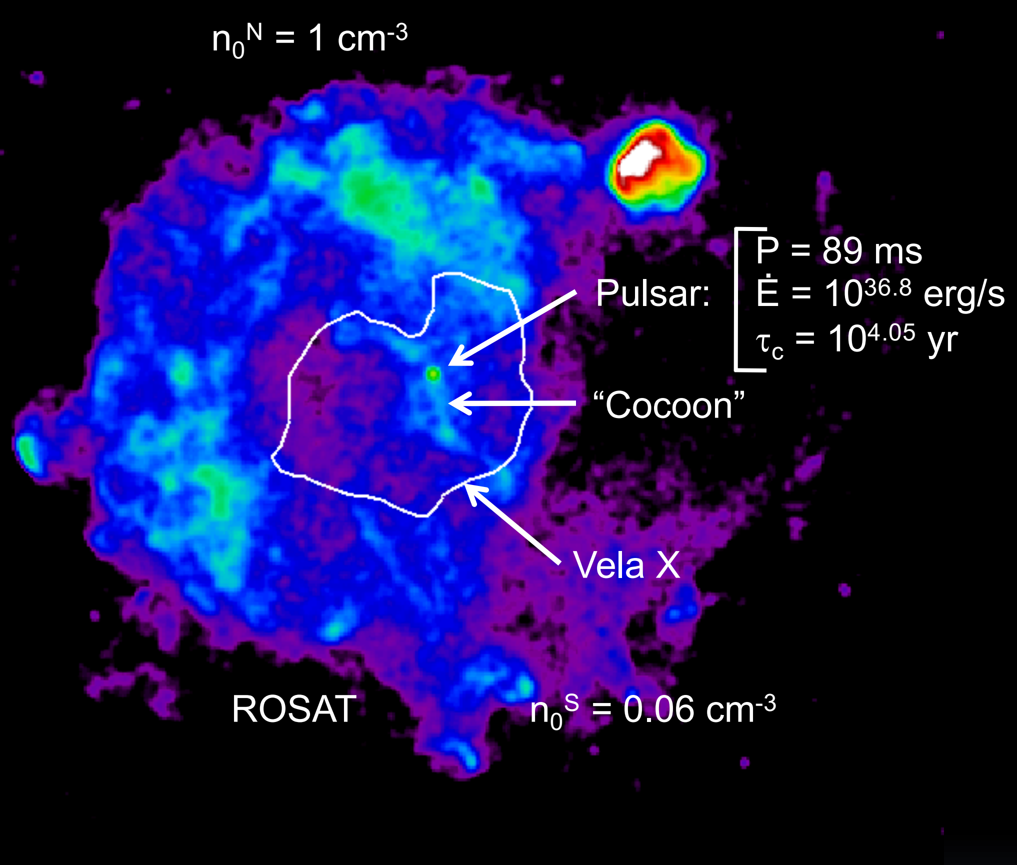
Vela SNR and its PWN

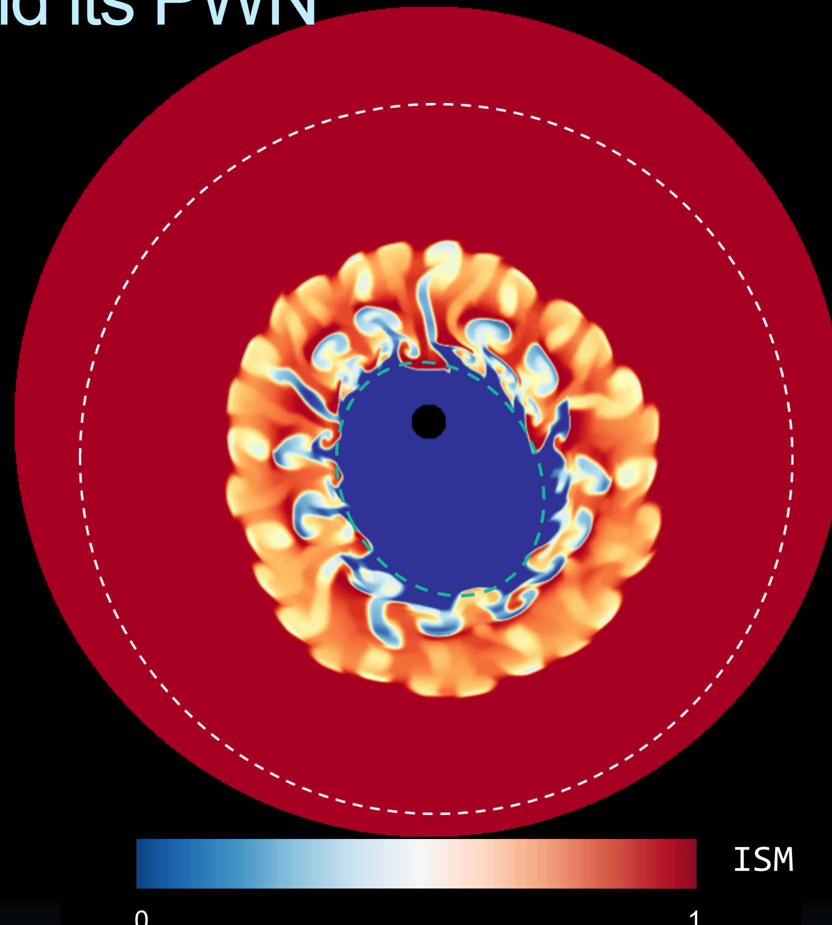




- Hydro simulations reproduce overall structure
- "Cocoon" created by RS interaction
  - RS sweeps ejecta into PWN, creating channel of mixed gas
- PWN gas still fills much of nebula, but ejecta mixing occurs throughout
  - consistent w/ observations, though fast diffision may be required
- 3D modeling and study of broadband emission in progress

Vela SNR and its PWN





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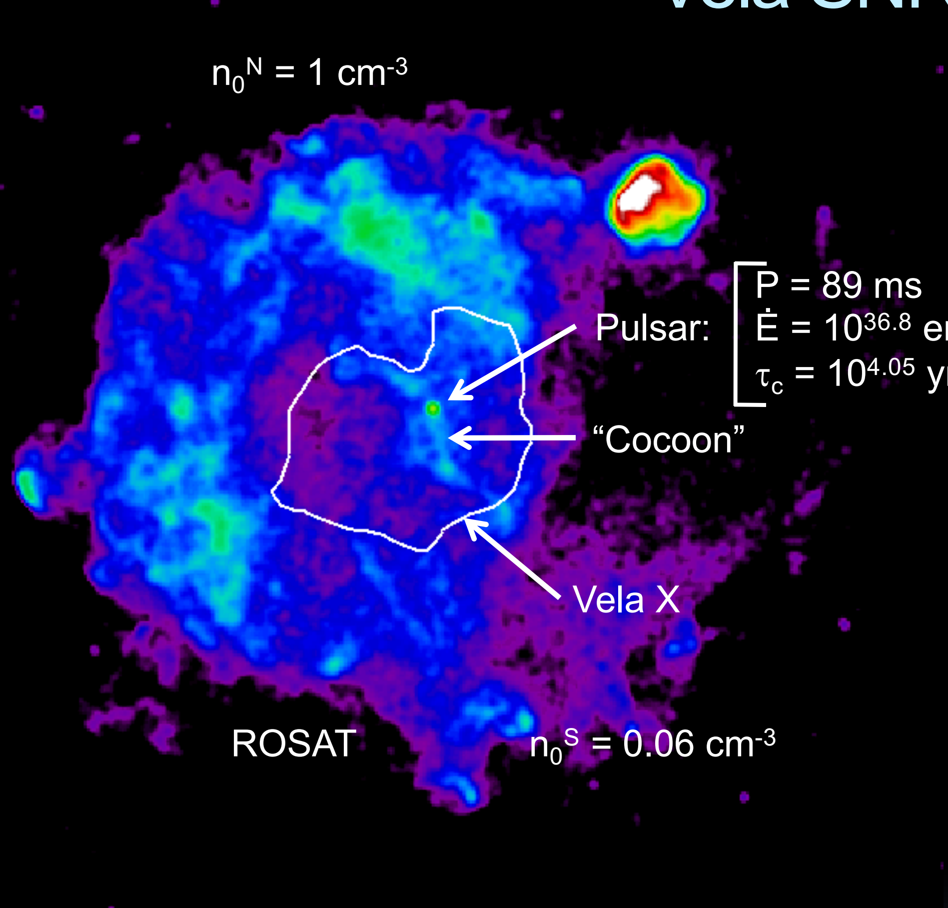
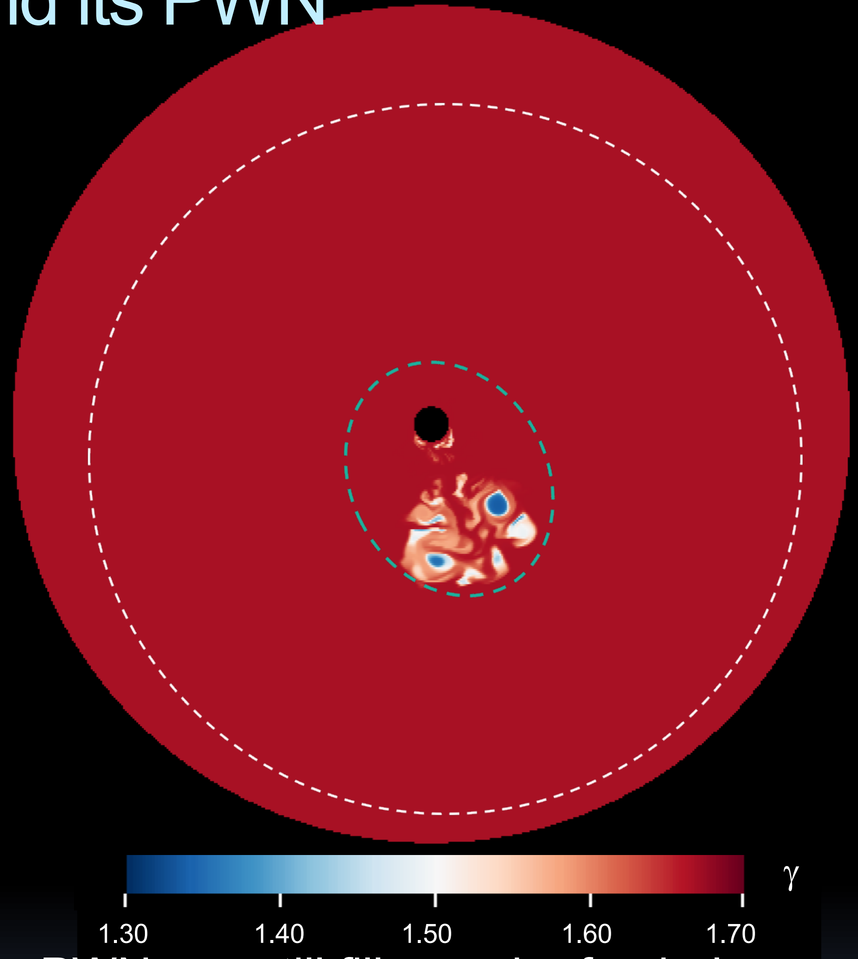




- Hydro simulations reproduce overall structure
- "Cocoon" created by RS interaction
  - RS sweeps ejecta into PWN, creating channel of mixed gas
  - lower ρ in cocoon ⇒ higher kT
- PWN gas still fills much of nebula, but ejecta mixing occurs throughout
  - consistent w/ observations, though fast diffision may be required
- 3D modeling and study of broadband emission in progress

Summary

- Multiwavelength studies of PWNe reveal unique information on the conversion of spin-down power into relativistic outflows, providing views of shocks and interactions with supernova ejecta.
  - Hydrodynamical simulations, constrained by observations, provide important tool for unfolding the evolution and properties of PWNe within SNRs.

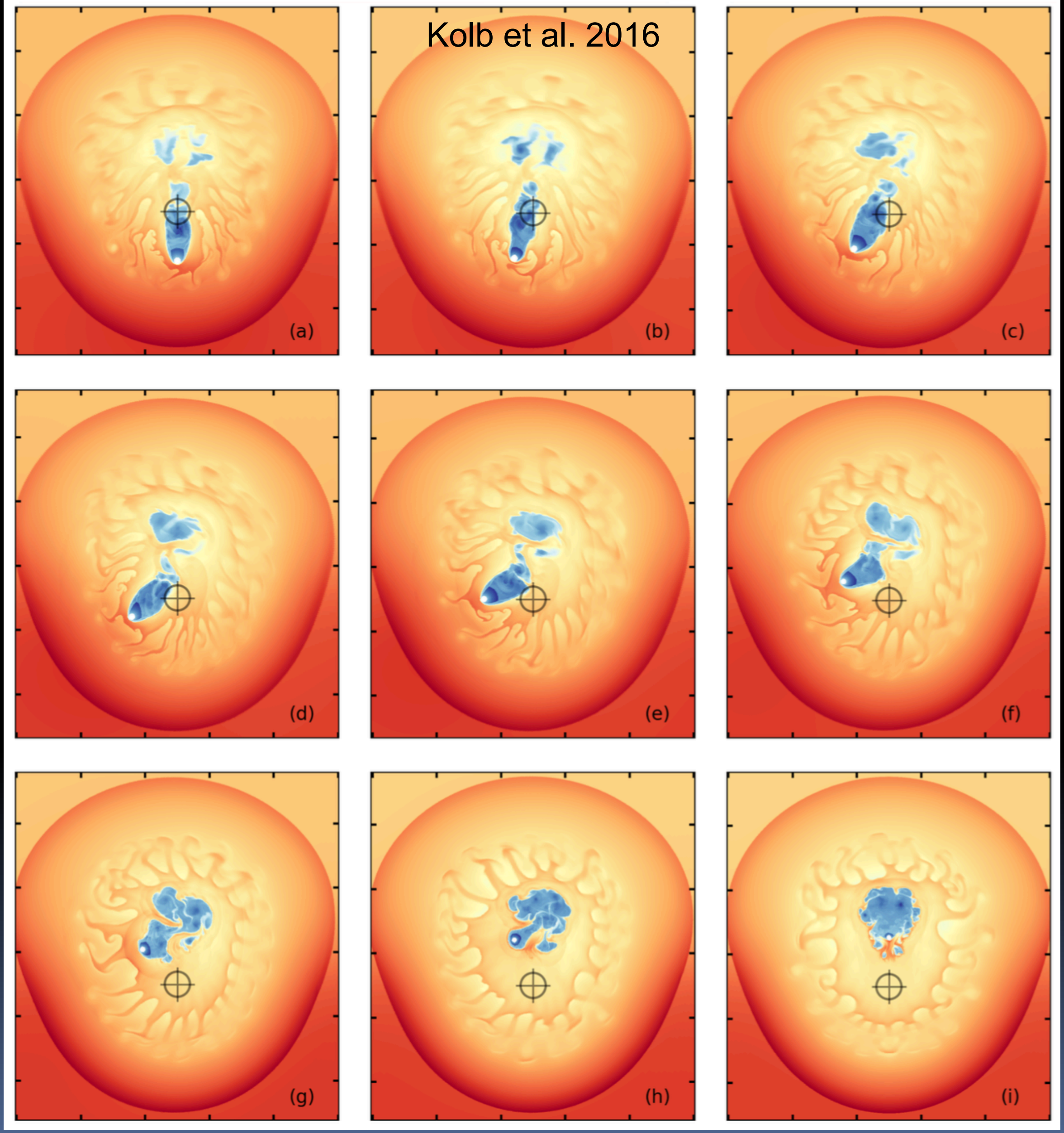
- Vela SNR shows distinct signatures of evolution into a non-uniform CSM, resulting in disruption of its PWN by an asymmetric reverse shock.

- X-ray studies of Vela X reveal ejecta mixed into disrupted PWN.
  - Hard nonthermal X-rays observed along cocoon, and also near GeV peak.
  - Enhanced ejecta observed along cocoon.
  - HD modeling suggests cocoon may result from instabilities dragging ejecta into disrupted PWN.
  - Higher advection speed may reduce synchrotron losses in cocoon region.

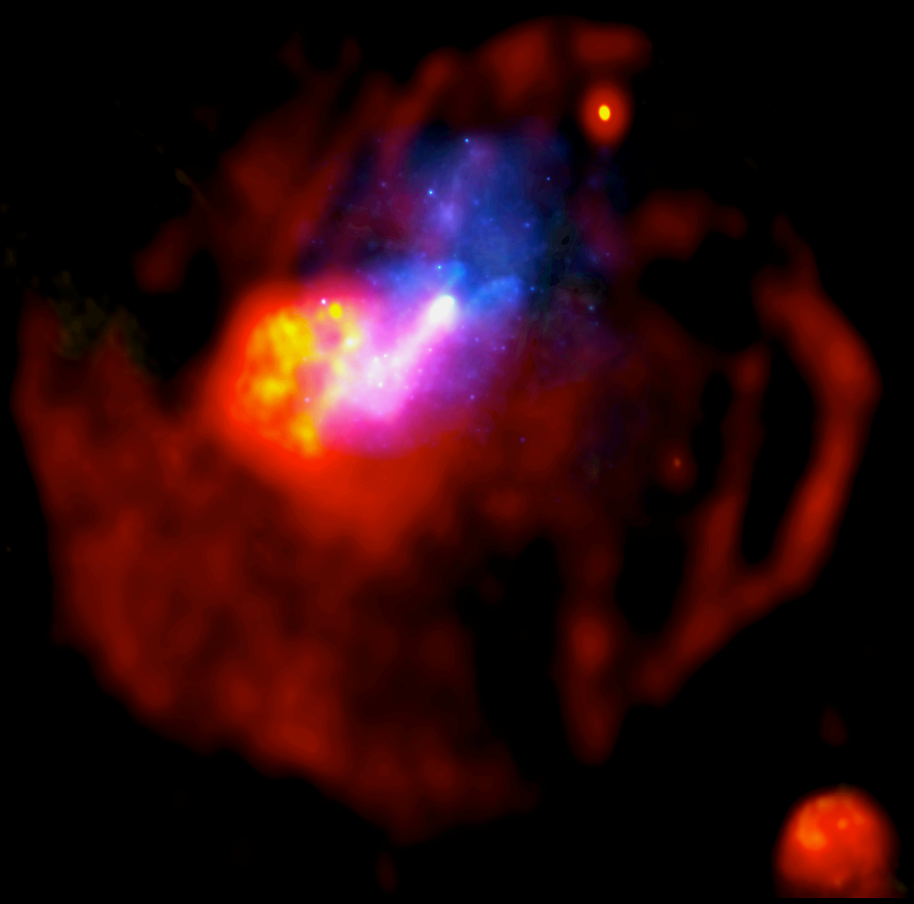
- Ongoing efforts include 3D simulations with post-processed emission characteristics, applied to these and other evolving systems.

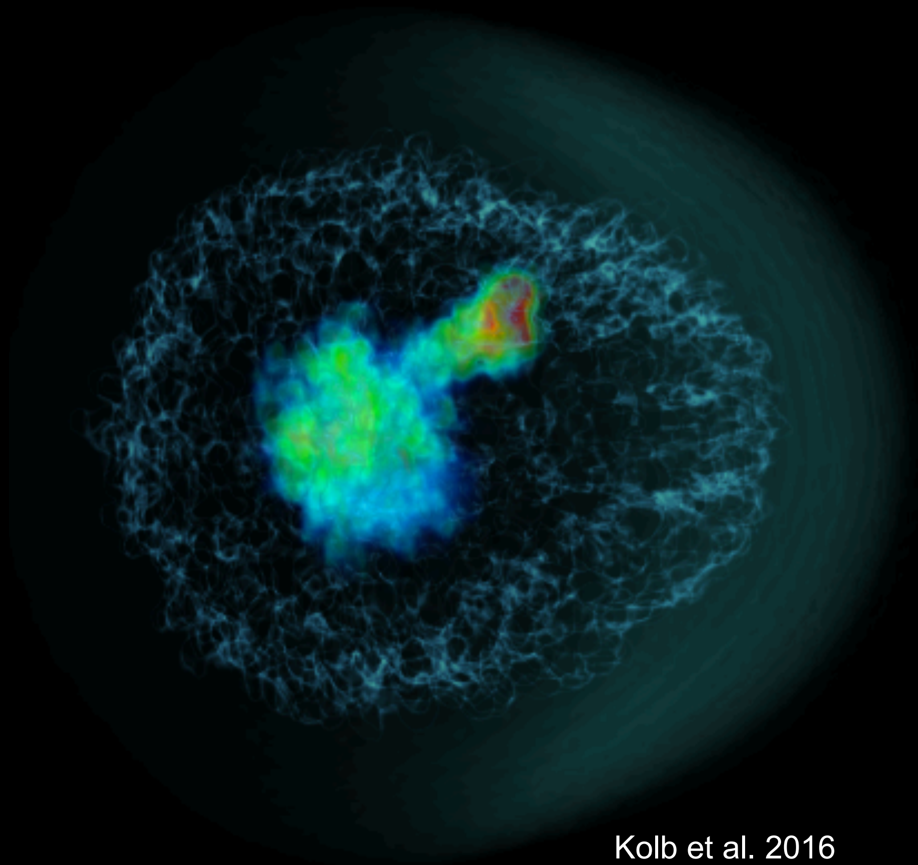
Inferring Pulsar Kicks

- Cross-hair indicates original pulsar position.
- Interpreting pulsar motion based on tail geometry and distance from apparent SNR center is misleading.



Morphology Comparison





Kolb et al. 2016