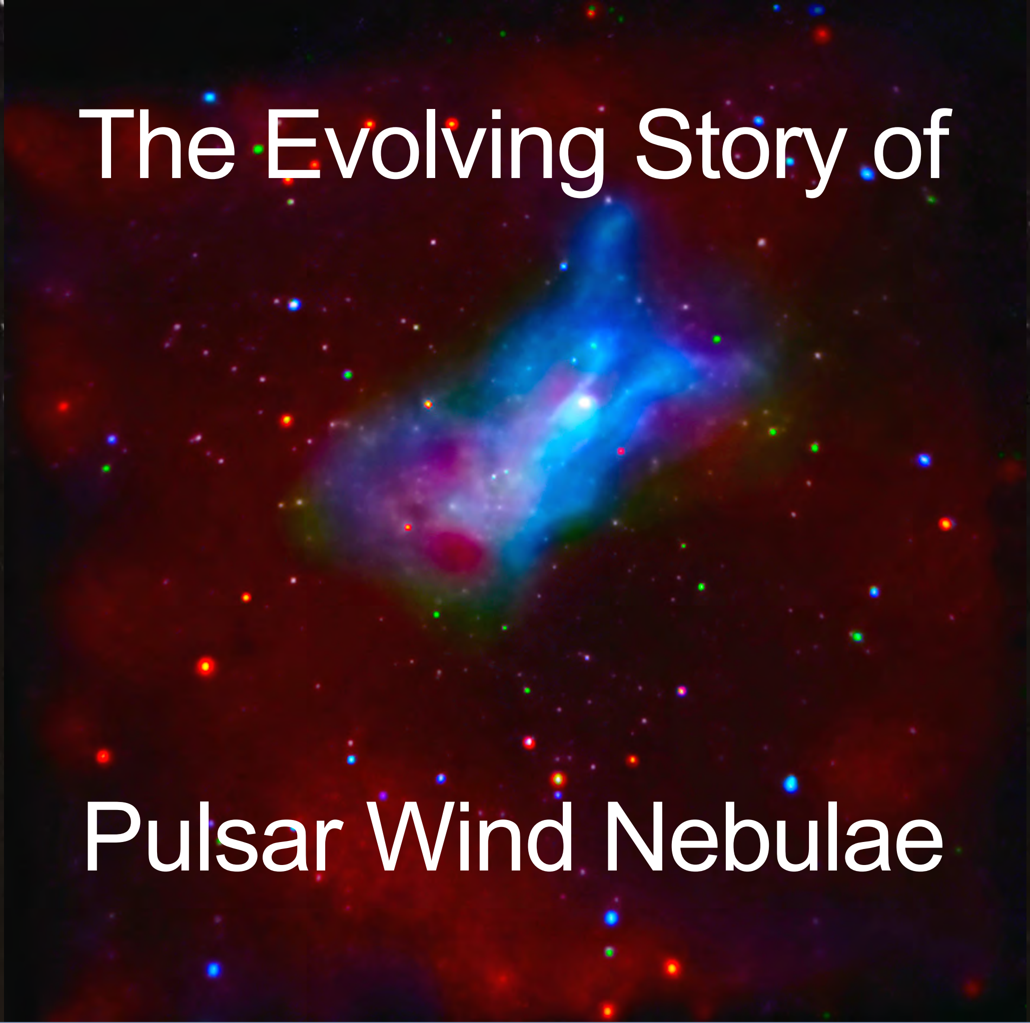
The Evolving Story of Pulsar Wind Nebulae

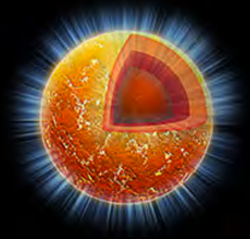


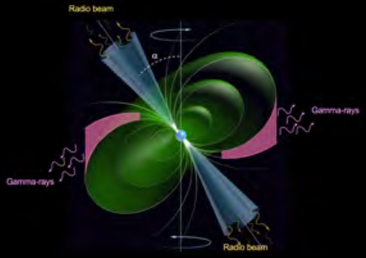
Collaborators:

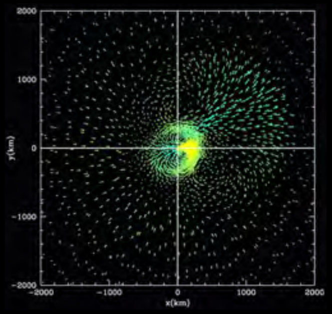
T. Temim
J. Gelfand
C. Kolb
J. Blondin
and more…

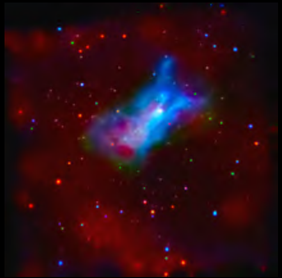
What Can We Learn From Composite SNRs?

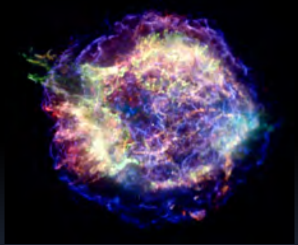
- Neutron star ages ⇒ cooling
- NS velocities ⇒ SN kicks
- Ejecta composition/mass ⇒ progenitor type/mass
- Properties of circumstellar material ⇒ progenitor type/history
- Pulsar spin-down power/history ⇒ magnetic field history
- Particle injection composition/spectrum ⇒ acceleration process
- PWN magnetic field ⇒ particle history and fate
- Pulsar particle diffusion/escape ⇒ e^+/e^- cosmic rays

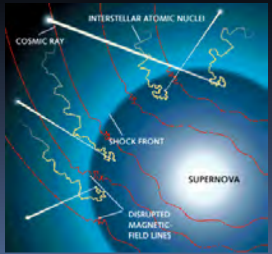




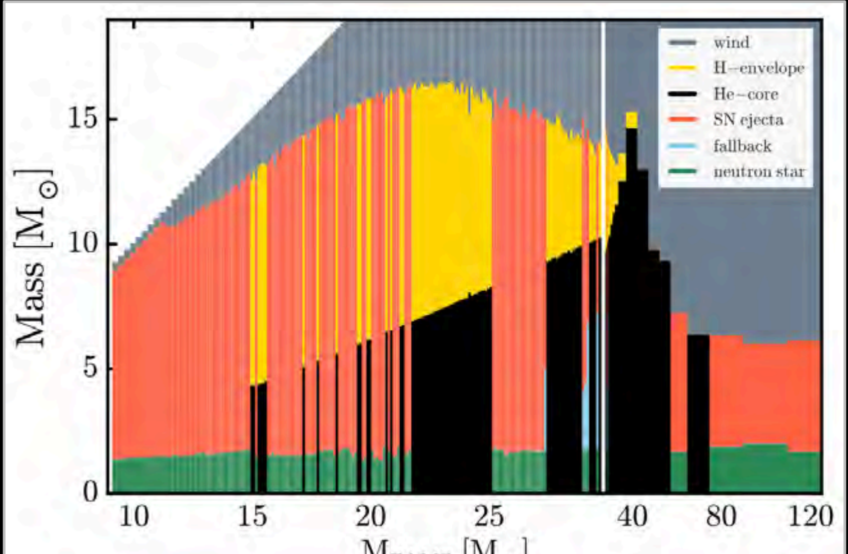




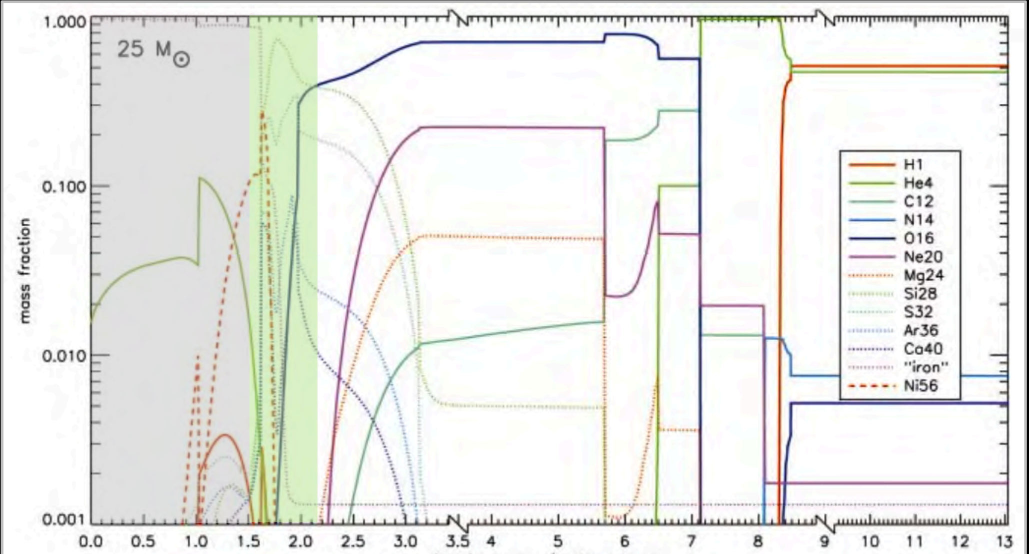




Ejecta/Wind Mass



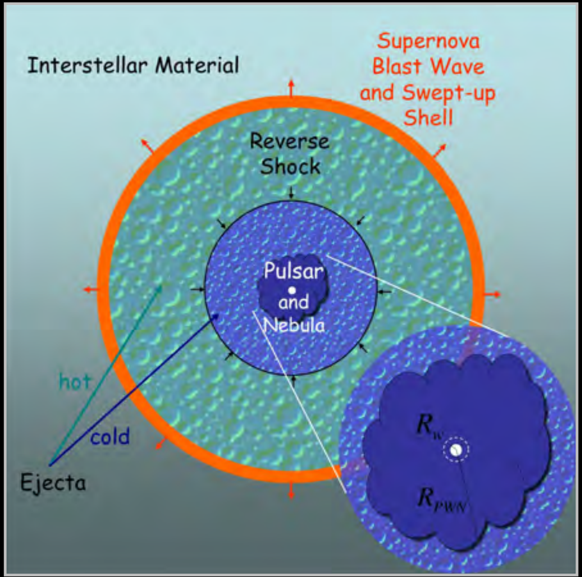
Sukhbold et al. 2016

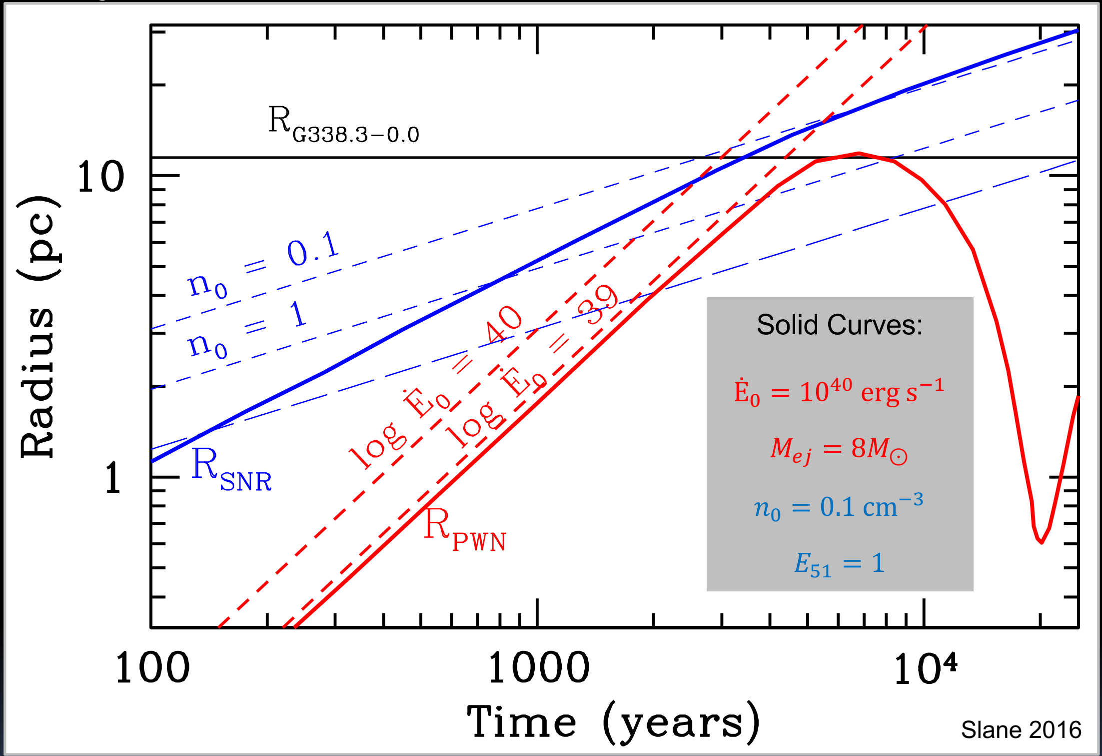


Woosley et al. 2002

- Ejecta and wind mass constrains progenitor mass.
  - X-ray studies (spectra, brightness profiles) can "measure" both.
- Wind profile impacts development of SNR.
- Composition of ejecta probes explosion details.
  - Explosive nucleosynthesis, turbulence/mixing.
- Measurements of shocked ejecta reveals details of progenitor.
  - Inner ejecta particularly important for probing core.

SNR/PWN Dynamical Evolution



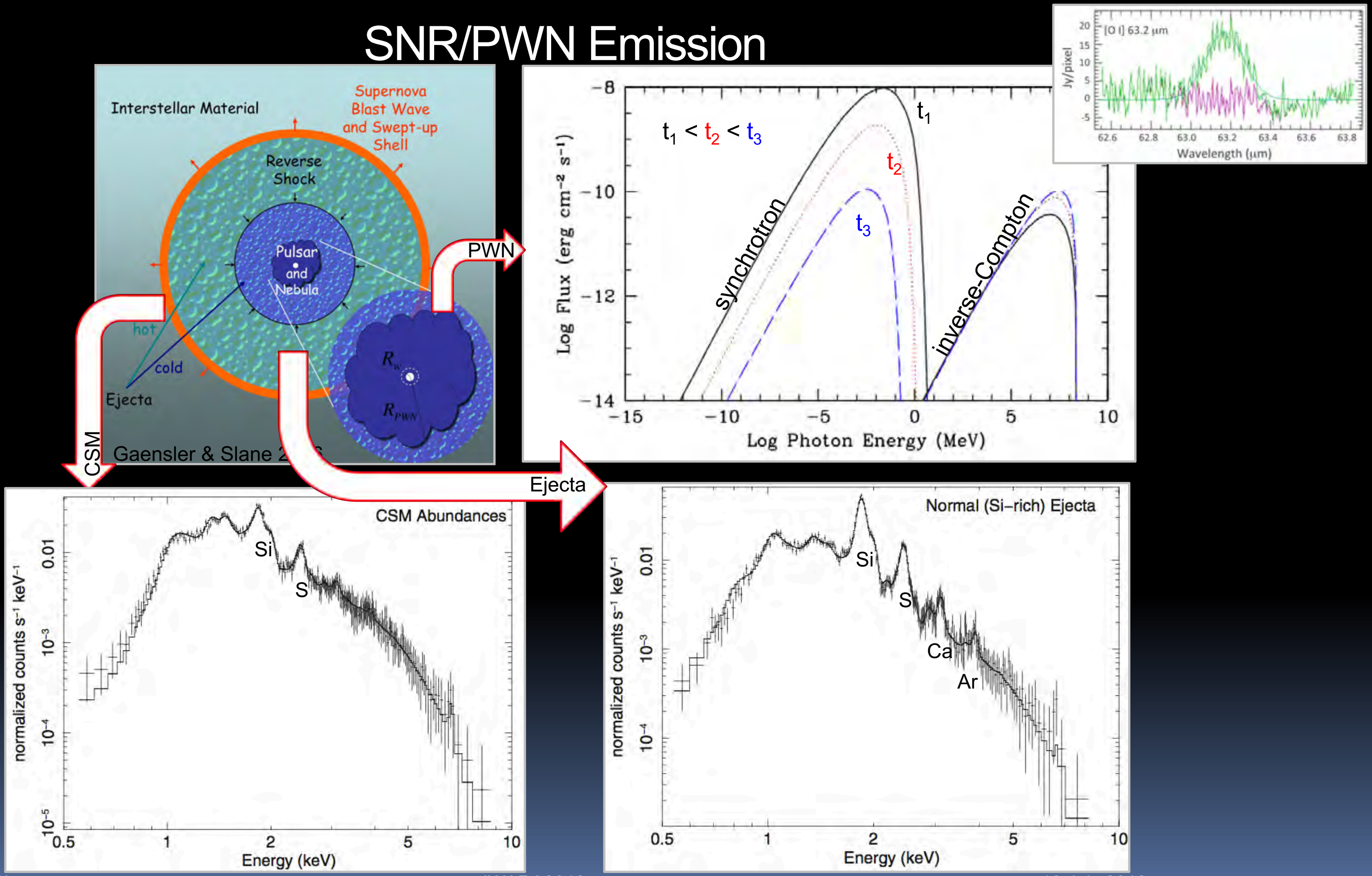


- PWN evolution constrained by pulsar input and SNR evolution
- Derived properties can be used to calculate spectrum and compare w/ multiwavelength observations.
- But… spherical symmetry, uniform medium, etc.

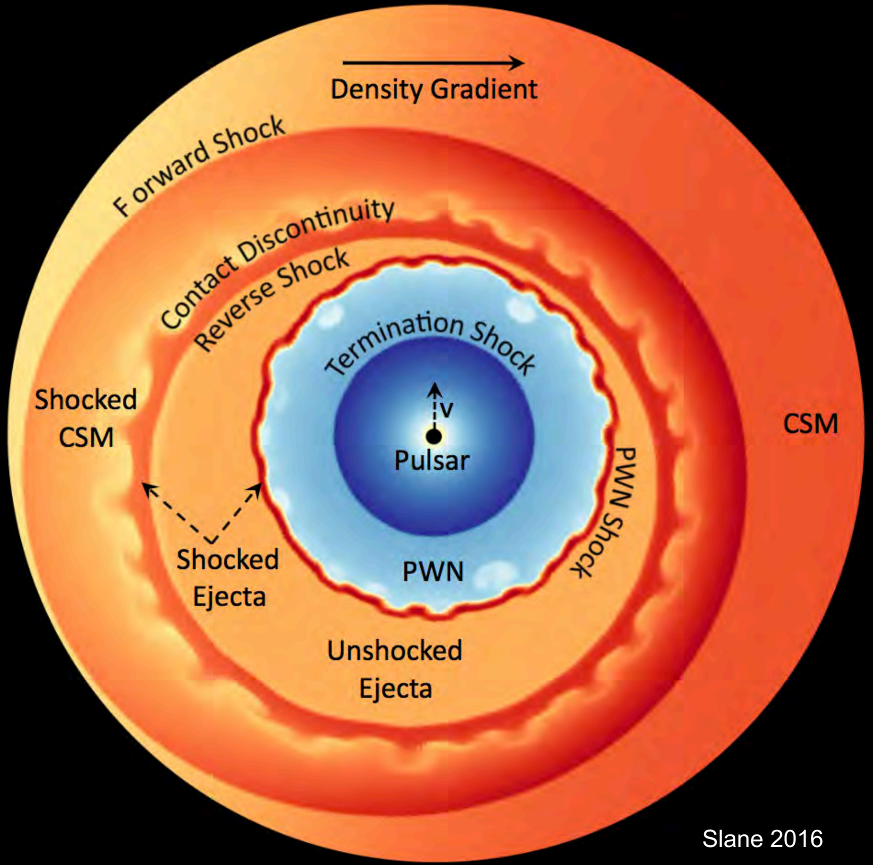
$$R_{SNR} \approx 6.2 \times 10^4 \left(\frac{E_{SN}}{n_0}\right)^{1/5} t^{2/5}$$

$$R_{PWN} \approx 1.5 \dot{E}_0^{1/5} E_{SN}^{3/10} M_{ej}^{-1/2} t^{6/5}$$

SNR/PWN Emission



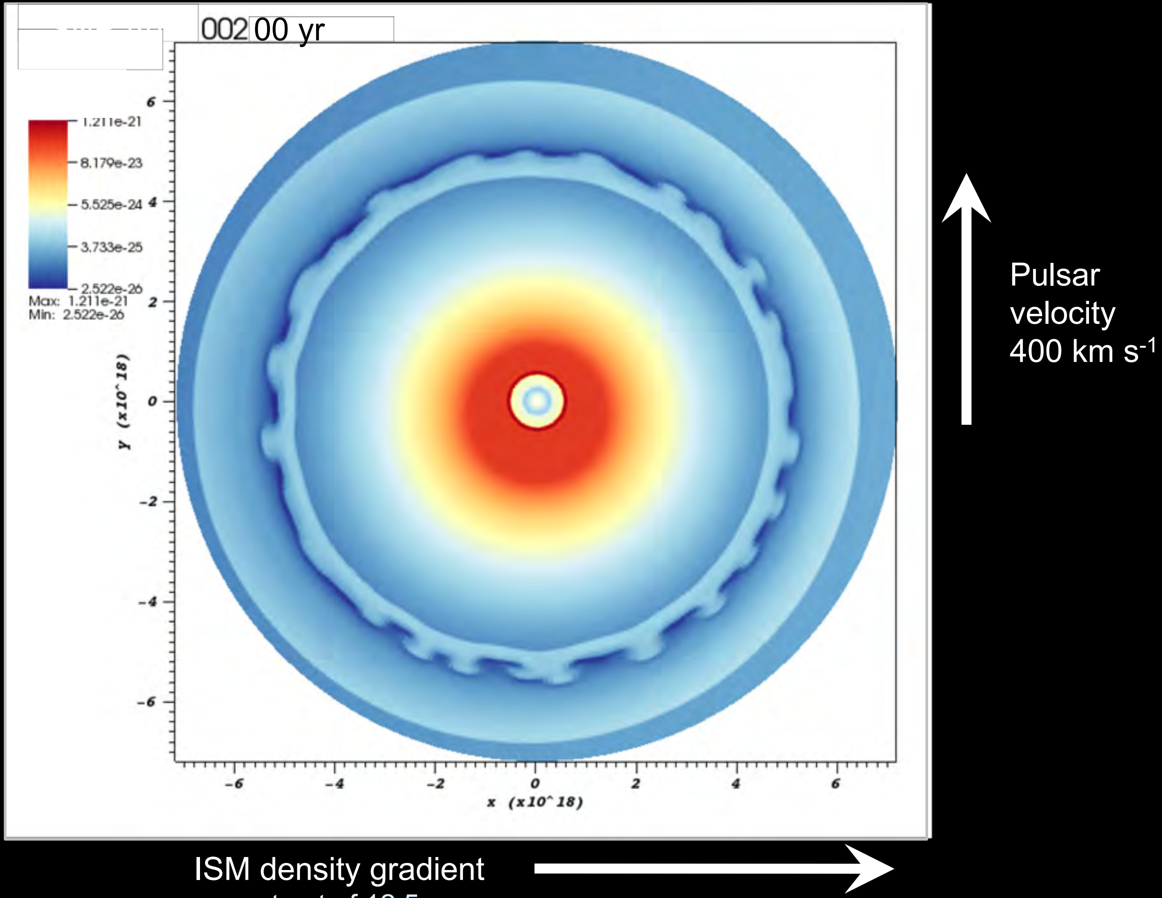
Modeling Composite SNRs: Hydro Simulations



Slane 2016

- Hydrodynamical model (VH1)
  - Uniform-composition ejecta imparts explosion energy
  - Expansion into CSM with optional density gradient
- Pulsar at center of grid
  - Optional pulsar motion by moving grid
  - Inject γ = 4/3 wind w/ parameterized synchrotron/IC/adiabatic losses
- Track particle composition, age, and effective γ of cells.

Modeling Composite SNRs



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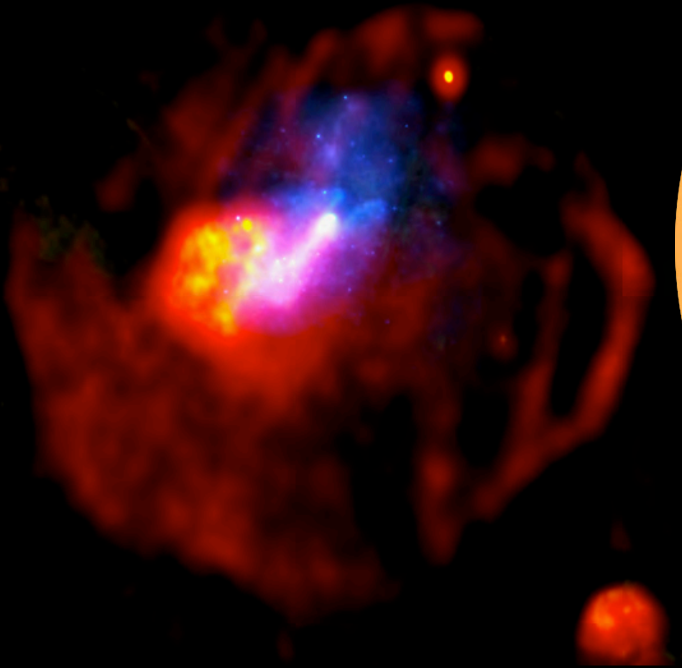
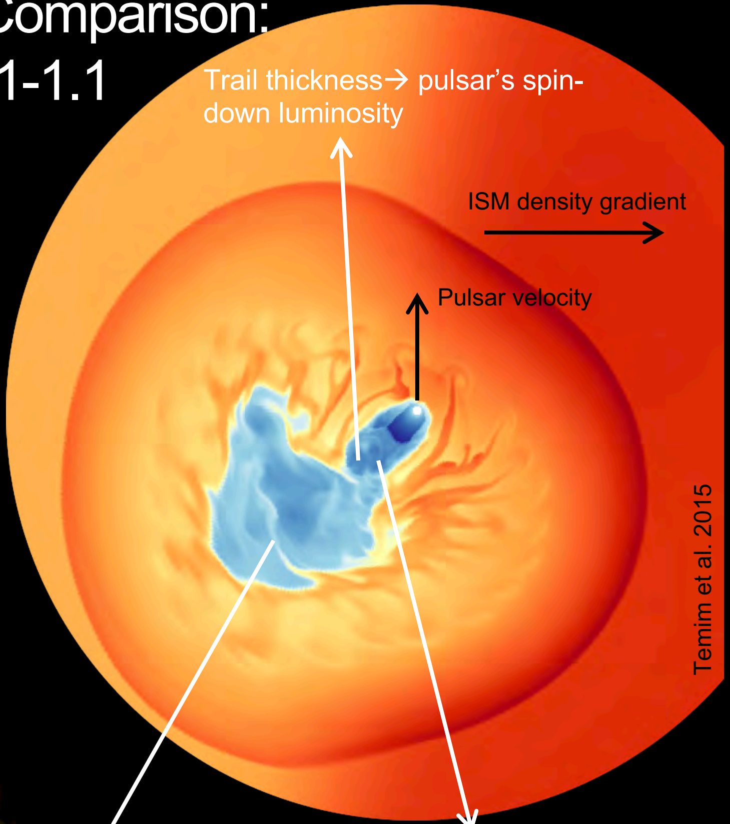
Morphology Comparison: G327.1-1.1

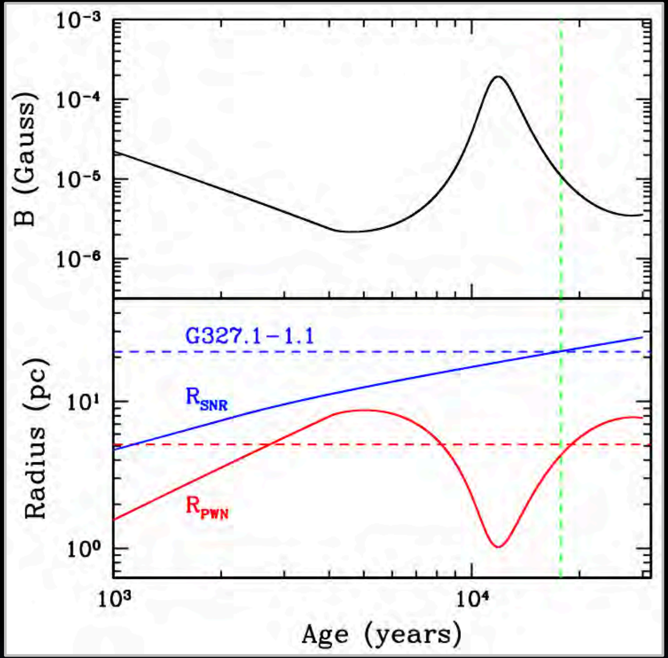


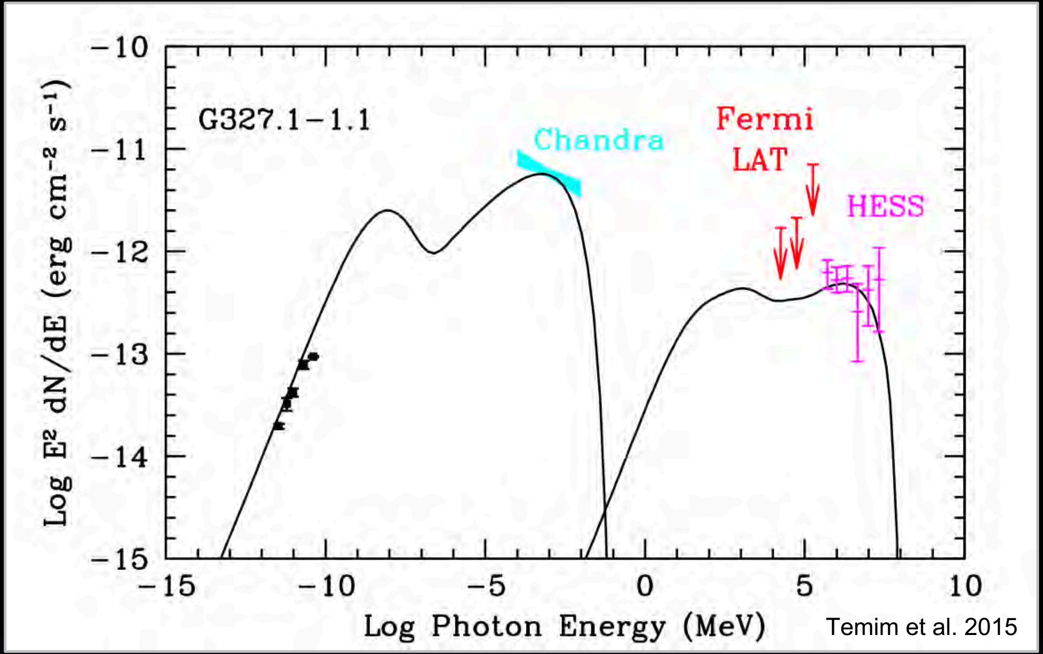


Displacement of "relic" PWN → orientation of density gradient

Orientation of trail → combination of gradient and pulsar motion direction

Broadband Spectrum at 17,000 yrs



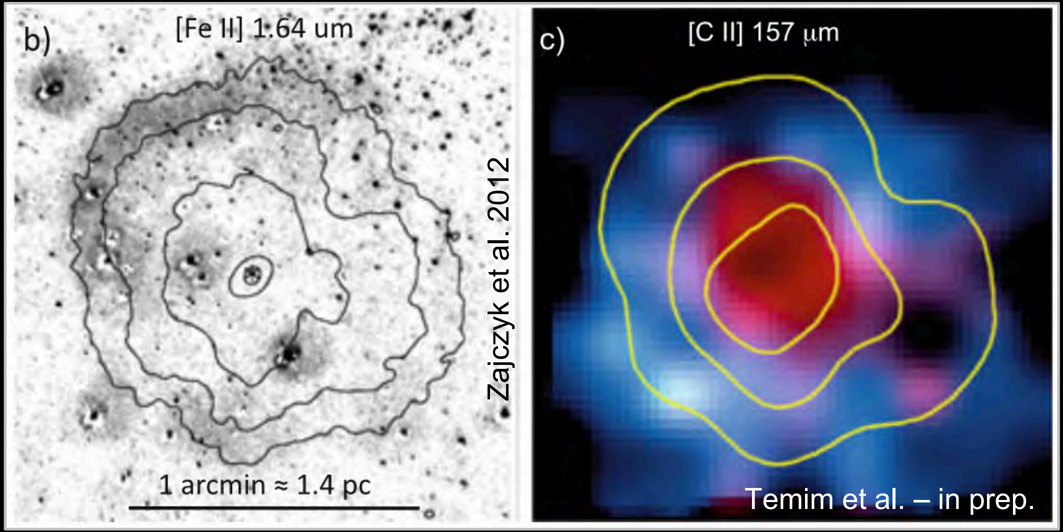


Temim et al. 2015

- 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

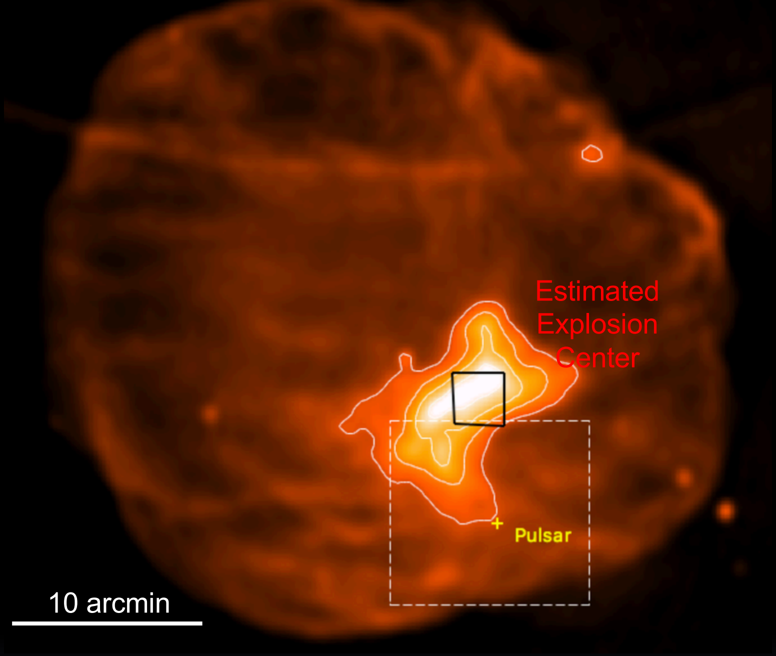
G21.5-0.9

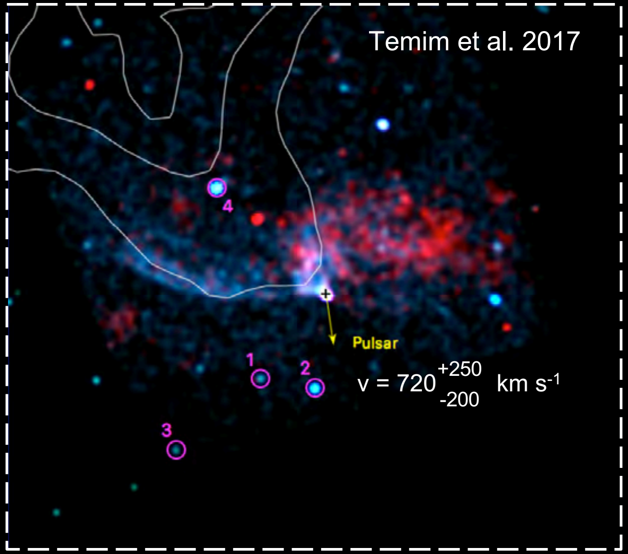


- IR measurements reveal ejecta swept up by PWN.
  - Shell seen in [Fe II] and [C II]

- PWN is probing innermost ejecta from explosion.

MSH 15-56: A Fast-Moving NS

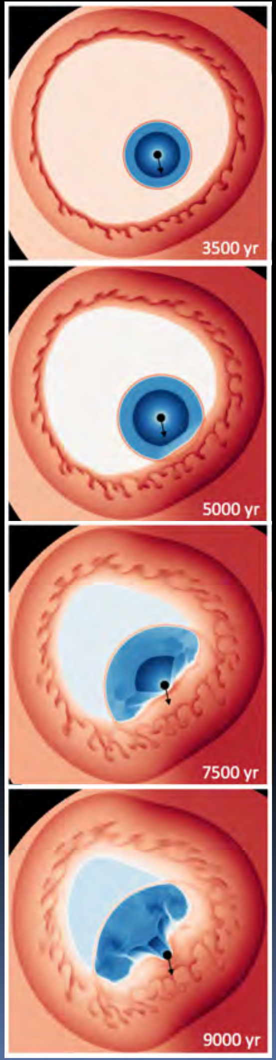


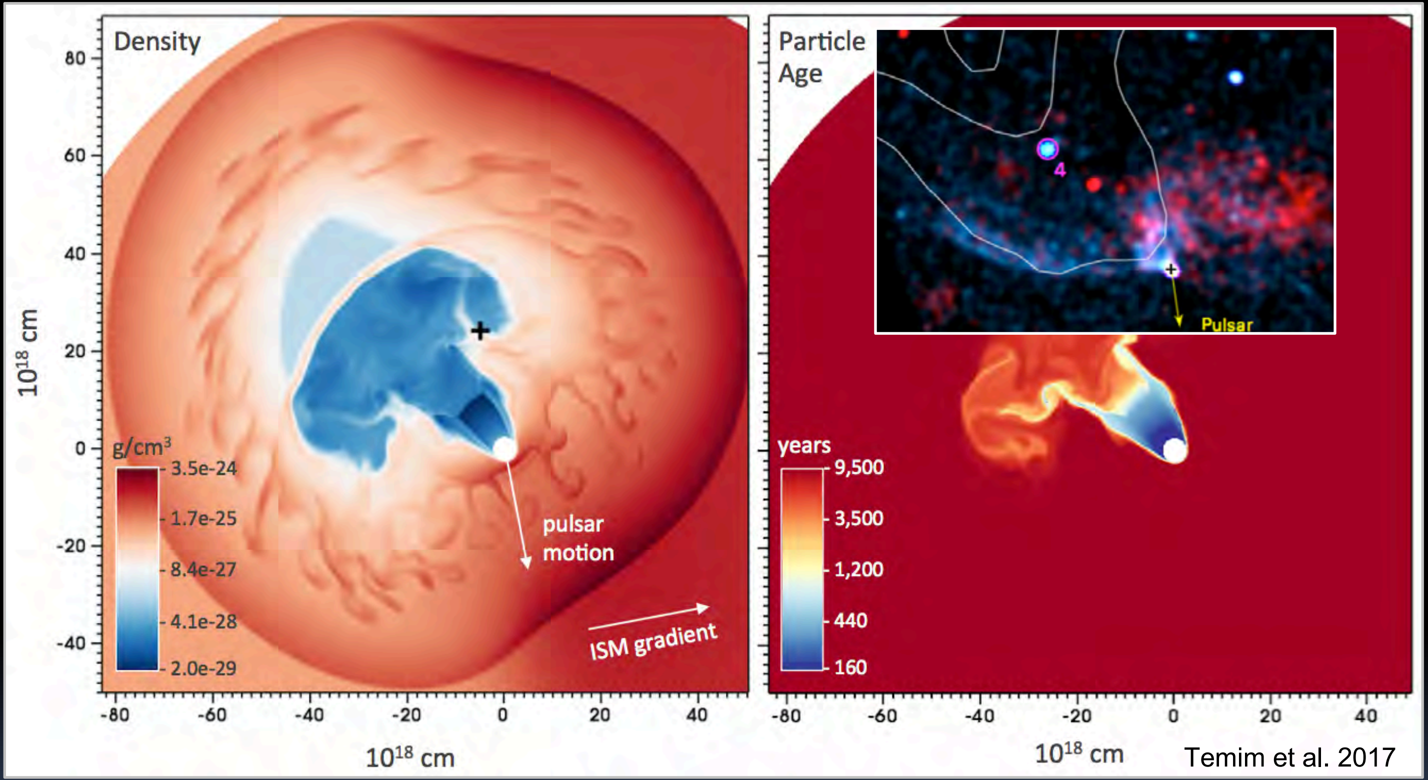


- For MSH 15-56, X-ray observations reveal NS located at edge of disrupted PWN, close to SNR shell.
  - Suggestive of asymmetric RS/PWN interaction.

- Proper motion measured with Chandra.
  - Relatively high velocity in direction of nearby shell (assuming d = 4.1 kpc).
  - Position angle 10° ± 14° W of S.

Pulsar Wind History





- Young electrons flow along edge of disrupted PWN while older particles fill nebula.
  - Consistent with observed X-rays/radio structure.

Summary

- X-ray studies of composite SNRs provide important constraints on
  - Ejecta mass, CSM distribution, history of pulsar injection, pulsar motion…
- Broadband modeling constrains evolution of PWNe and SNRs.
  - Magnetic field, synchrotron burn-off.
  - Pulsar injection, particle history.
- Hydrodynamical modeling crucial in understanding morphology and overall evolution.
  - Reverse shock interactions provide crucial impact on evolution, and on inferences about pulsar velocities.
  - More work on 3D, MHD, and radiation needed.