Modeling the Dynamical and Radiative Evolution of a Pulsar Wind Nebula inside a Supernova Remnant

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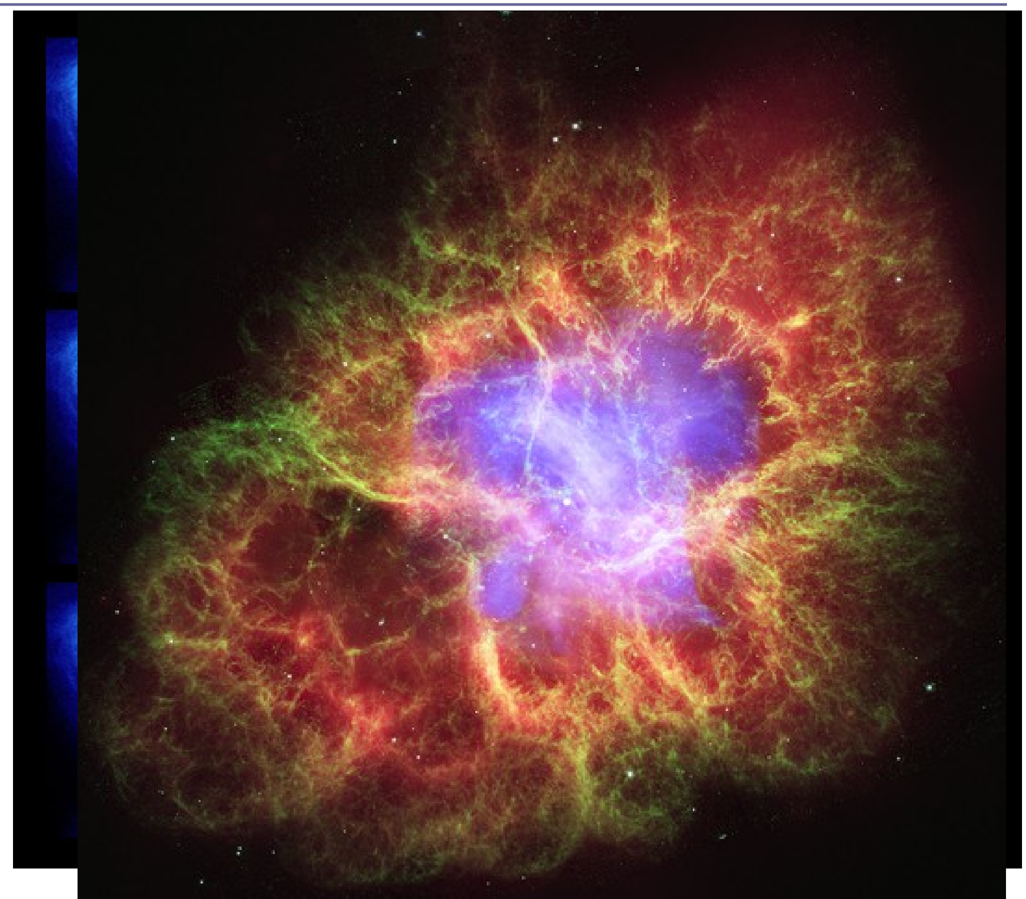
What is a Pulsar Wind Nebula?

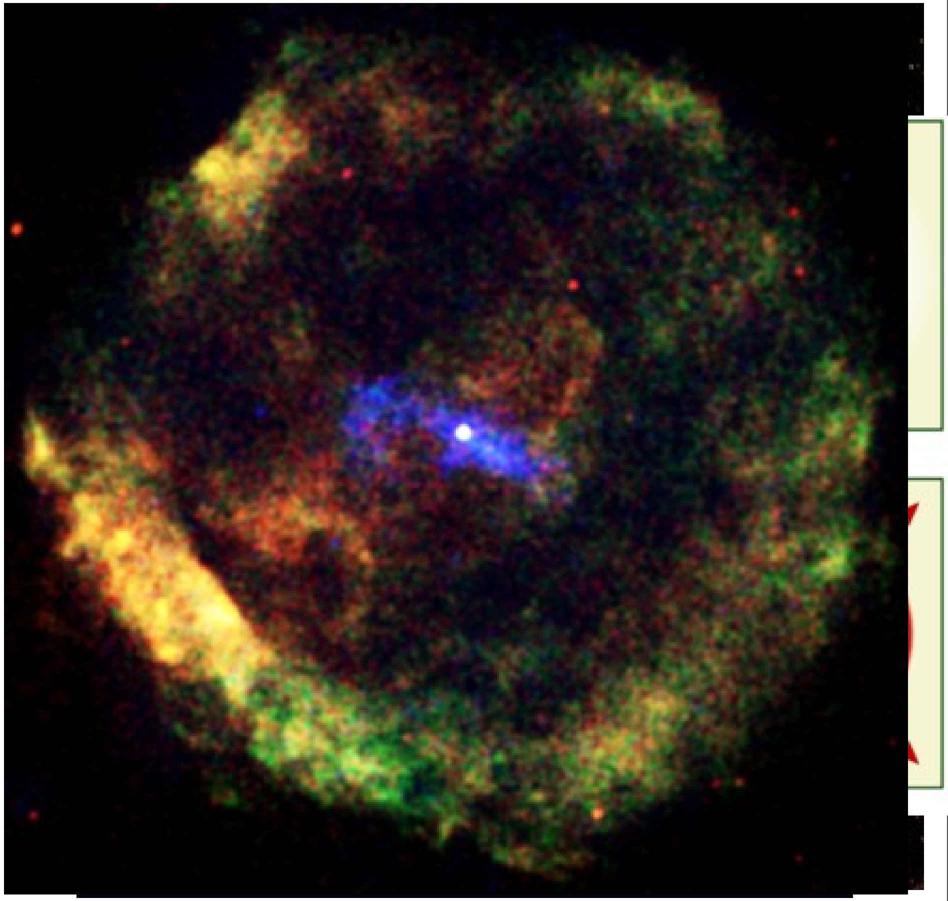
- Electromagnetic forces accelerate charges off neutron star surface (“pulsar wind”)
  - Escape magnetosphere along open field lines
- Confinement by surrounding terminates, shocks wind
- Shocked pulsar wind inflates “Pulsar Wind Nebula”



(Credit: NASA/CXC/ASU/J.Hester et al.; NASA/ESA/ASU/J.Hester & A.Loll; NASA/JPL-Caltech/Univ. Minn./R.Gehrz)

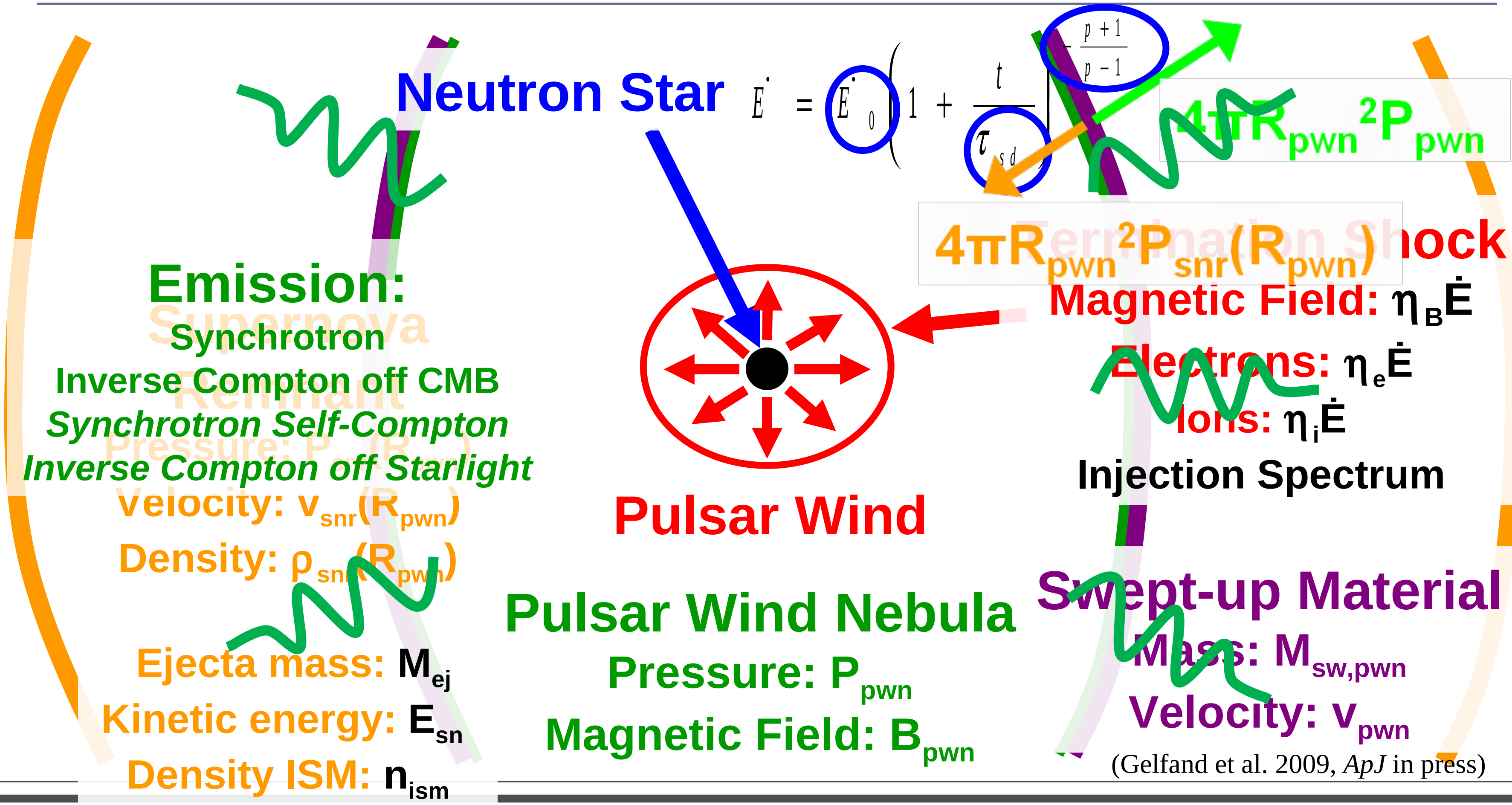
Why study a Pulsar Wind Nebula inside a Supernova Remnant?

- Neutron Star
  - Initial Spin Period and Spin-down Luminosity
  - Spin-down Timescale
  - Braking Index
- Pulsar Wind
  - Fraction of energy in magnetic field, electrons, and ions
  - Acceleration mechanism: minimum and maximum particle energy, energy spectrum
- Progenitor Supernova
  - Ejecta Mass
  - Initial Kinetic Energy



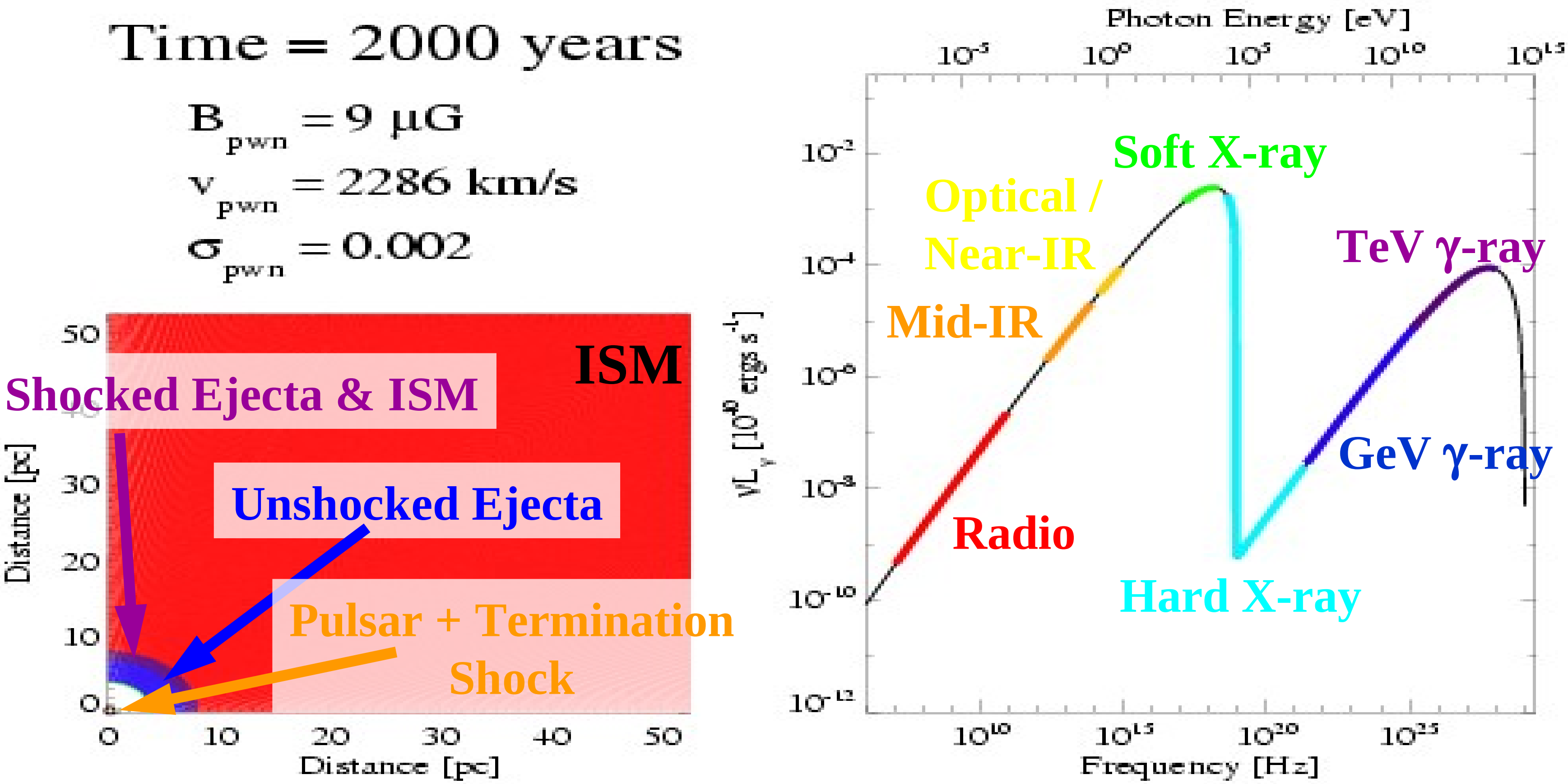
(Credit: NASA/CXC/Eureka Scientific/M.Roberts et al.; NRAO/AUI/NSF)

Schematic of a Pulsar Wind Nebula inside a Supernova Remnant



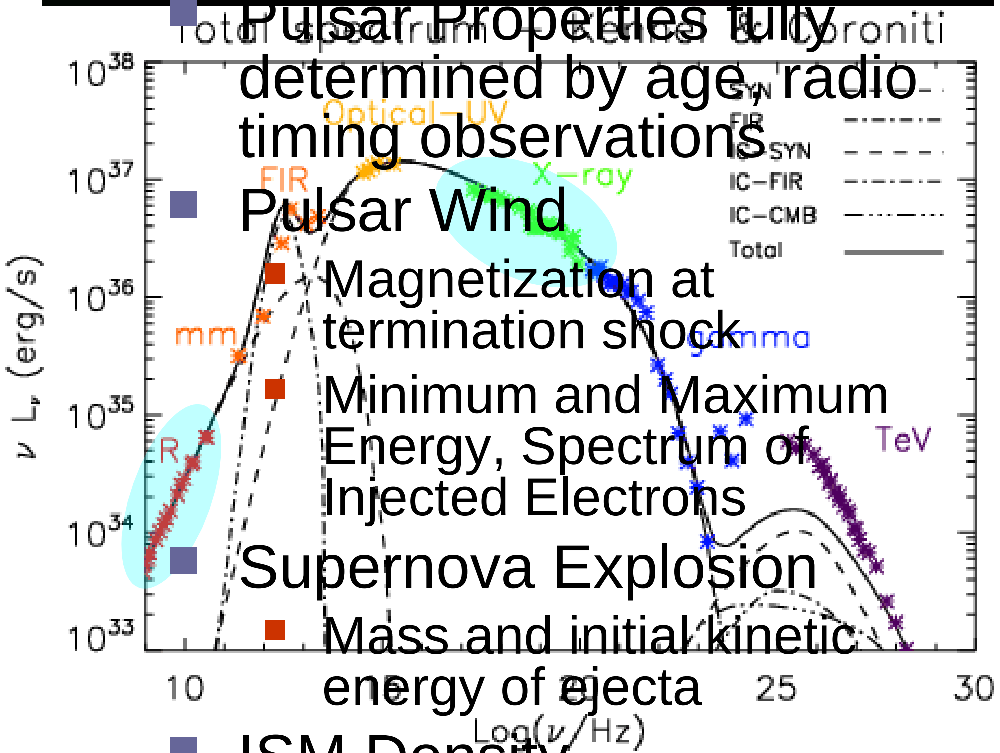
(Gelfand et al. 2009, *ApJ* in press)

Model Output



Example: Crab Nebula

- Dynamical Properties
  - PWN Radius
  - Expansion Velocity
  - Termination Shock Radius
- Radiative Properties
  - Radio Luminosity and Spectral Index
  - X-ray Luminosity and Spectral Index



(Figure 1; Volpi et al. 2008)

- Pulsar Properties fully determined by age, radio timing observations
- Pulsar Wind
  - Magnetization at termination shock
  - Minimum and Maximum Energy, Spectrum of Injected Electrons
- Supernova Explosion
  - Mass and initial kinetic energy of ejecta
- ISM Density

Best Fit: Single Power-law Injection Spectrum

- Best-fit parameters from MCMC fit
  - Pulsar Wind Properties

    Magnetization $\eta_B = 0.05_{-0.03}^{+0.1}$

    Electron Injection Energy **60 GeV – 600 TeV**

    Injection Power Law index **2.5 ± 0.2**
  - Supernova Explosion

    Ejecta Mass = $8 \pm 1\ M_{\odot}$

    Initial KE = $0.6_{-0.2}^{+2.0} \times 10^{51}$ **ergs**
  - Low density (**$n < 1\ cm^{-3}$**) environment

Best Fit: Single Power-law Injection Spectrum

Quantity	*Observed*	*Predicted*
R_{pwn}	**1.5-2.0 pc**	**1.3 pc**
v_{pwn}	**1125 –1500 km/s**	**1570 km/s**
Termination Shock Radius	**0.14 pc**	**0.12 pc**
Radio Luminosity	**1.8×10^{35} ergs/s**	**1.76×10^{35} ergs/s**
Radio Spectral Index	**-0.26**	**+0.1**
X-ray Luminosity	**1.3×10^{37} ergs/s**	**1.0×10^{37} erg**
X-ray Photon Index	**2.1 (1.8 – 3)**	**2.26**

Crab Nebula: Maxwellian + Power-Law Injection Spectrum

Quantity	*Observed*	*Predicted*
R_{pwn}	**1.5-2.0 pc**	**1.3 pc**
v_{pwn}	**1125 –1500 km/s**	**1600 km/s**
Termination Shock Radius	**0.14 pc**	**0.12 pc**
Radio Luminosity	**1.8×10^{35} ergs/s**	**1.83×10^{35} ergs/s**
Radio Spectral Index	**-0.26**	**-0.30**
X-ray Luminosity	**1.3×10^{37} ergs/s**	**1.4×10^{37} erg**
X-ray Photon Index	**2.1 (1.8 – 3)**	**2.2**

Crab Nebula: Maxwellian + Power-Law Injection Spectrum

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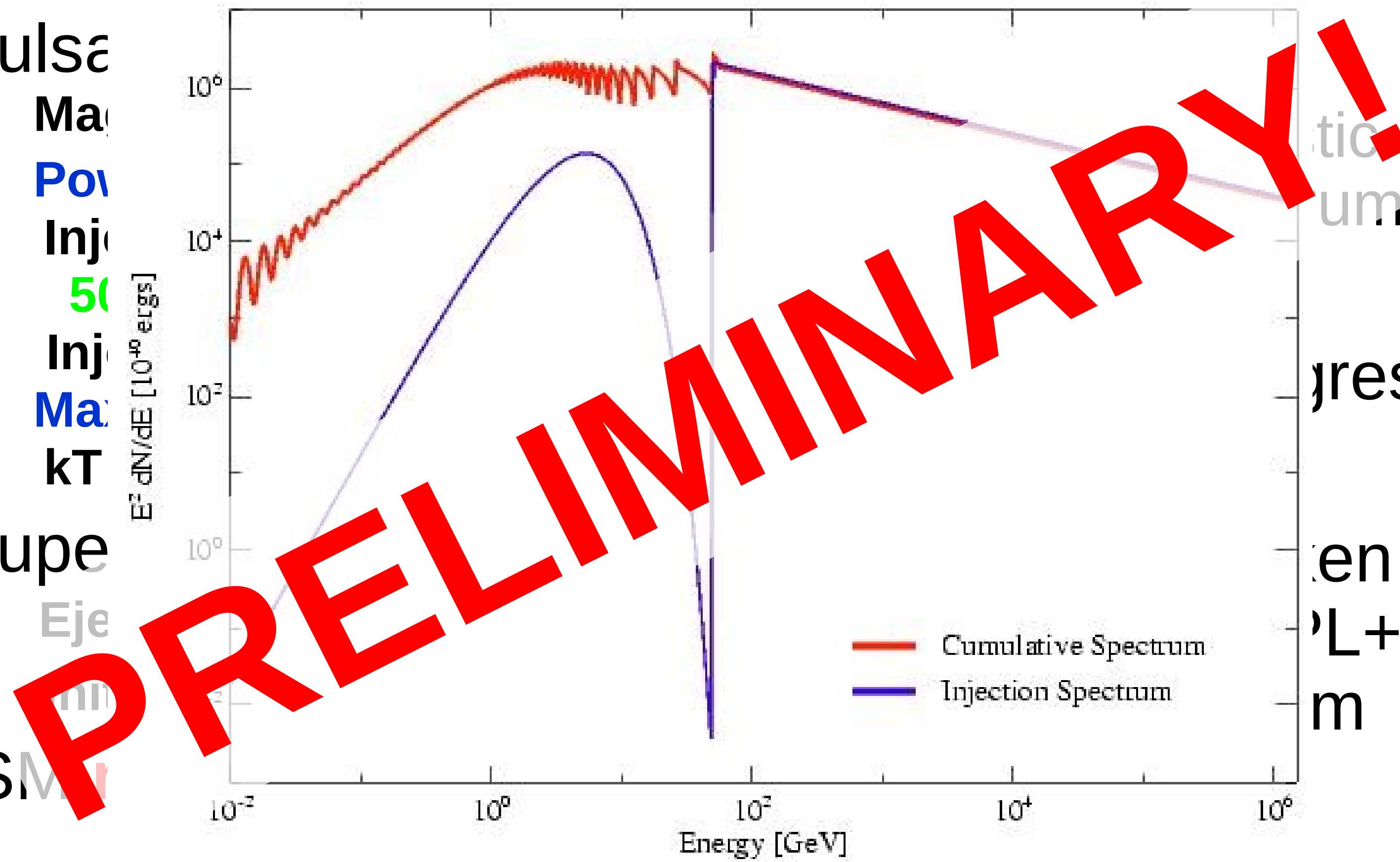

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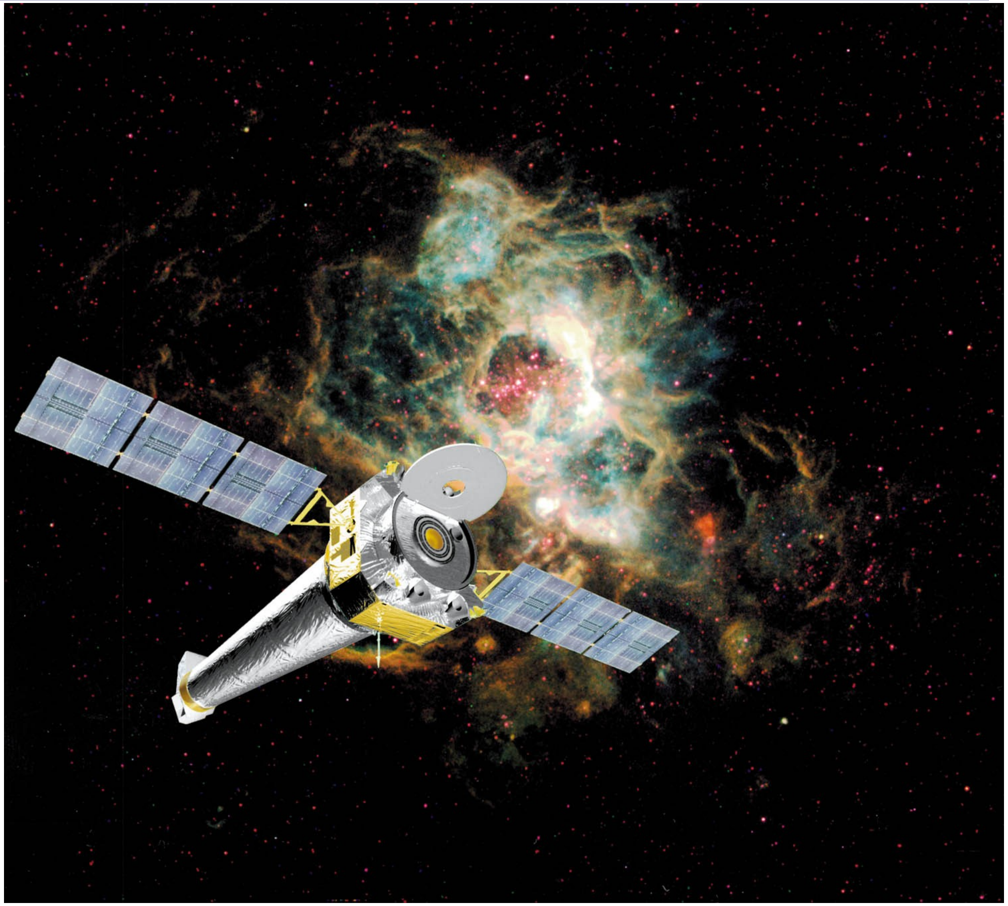
Future Directions

- Distinguish between injection scenarios
- Better incorporate results form multi-D simulations
  - Magnetic field structure
  - Growth and effect of instabilities
- Apply model to other systems
  - Thank you *Chandra*!



Back up slides

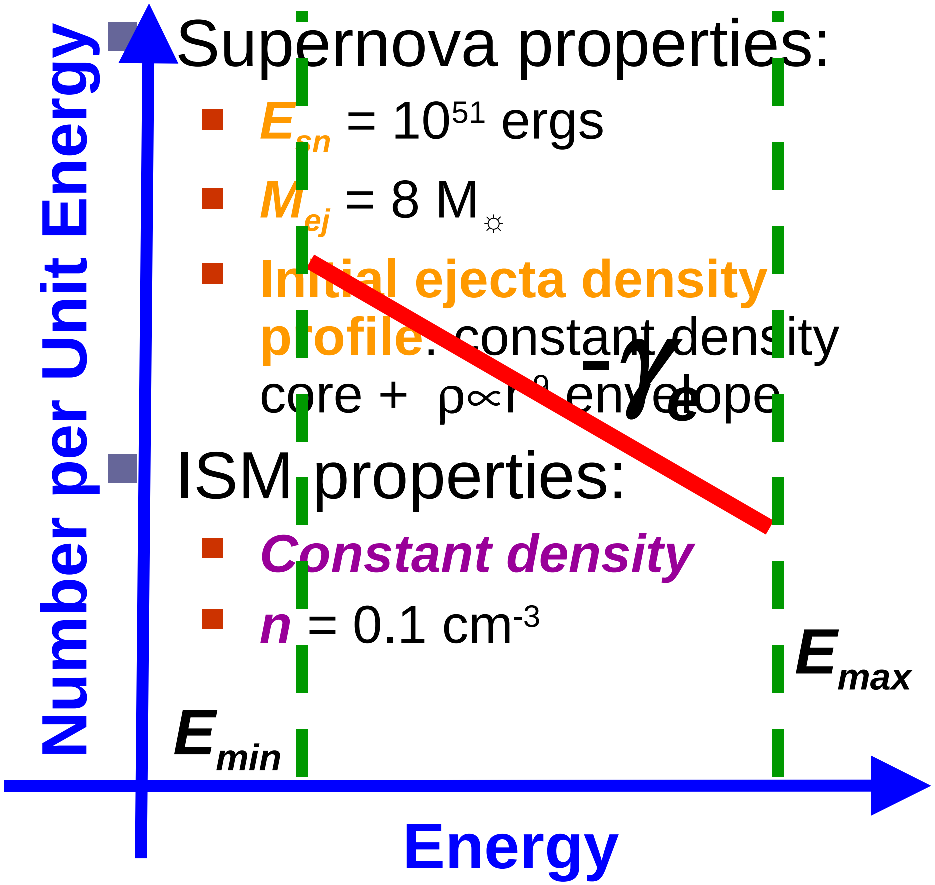
Model Limitations and Advantages

- Model Limitations:
  - Can not reproduce morphological features inside the PWN (e.g. jets and torus)
  - Can not reproduce spectral variations inside PWN
  - Can only estimate effect of instabilities (e.g. Raleigh-Taylor) on PWN.

(Fig

Dynamical and Radiative Evolution for a Trial Set of Parameters

- Neutron Star properties:
  - $\dot{E}_0 = 10^{40}$ ergs/s
  - $\tau_{sd} = 500$ years
  - $p = 3$
  - $v_{psr} = 120$ km/s
- Pulsar Wind properties:
  - $\eta_e = 0.999$, $\eta_B = 0.001$, $\eta_i = 0$
  - $E_{min} = 511$ keV, $E_{max} = 500$ TeV, $\gamma_e = 1.6$
- Supernova properties:
  - $E_{sn} = 10^{51}$ ergs
  - $M_{ej} = 8\ M_{\odot}$
  - **Initial ejecta density profile**: constant density core + $\rho \propto r^{-9}$ envelope
- ISM properties:
  - ***Constant density***
  - $n = 0.1\ cm^{-3}$

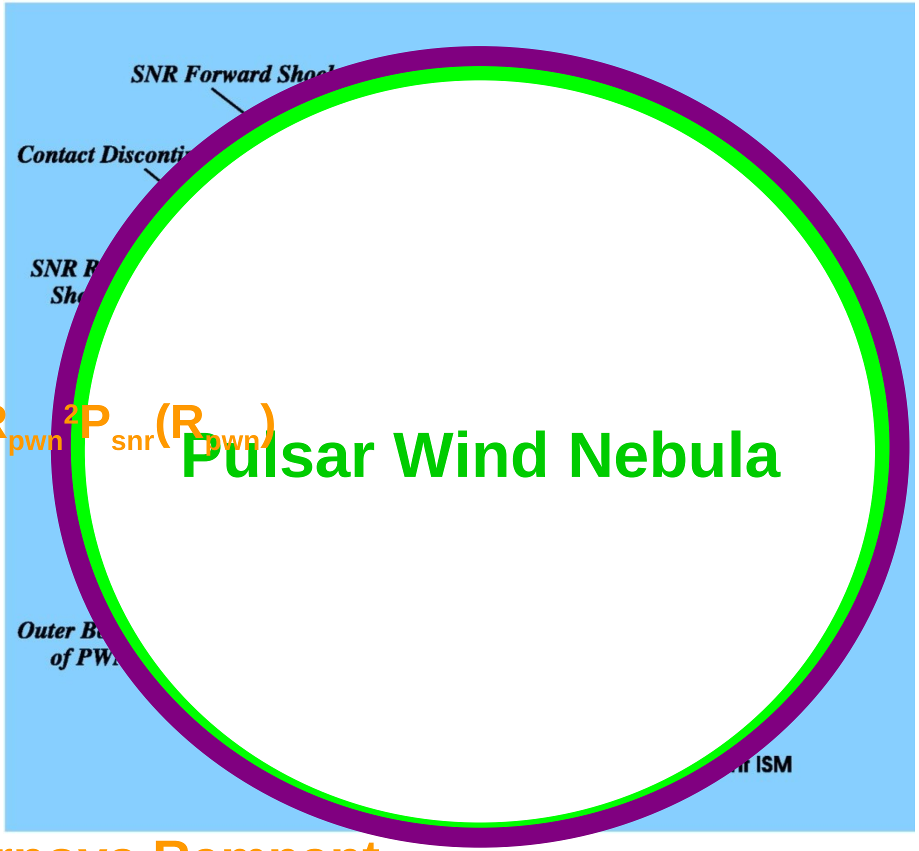


Evolutionary Model for a Pulsar Wind Nebula Inside a Supernova Remnant

- Homogeneous ISM, PWN
  - 1D problem
- Dynamical evolution of PWN determined by dynamics of swept-up material
  - Force result of pressure difference between PWN and SNR
  - Momentum conserved
- PWN's radiative losses dominated by synchrotron, IC scattering off CMB

$4\pi R_{pwn}^{2} P_{pwn}$

$4\pi R_{pwn}^{2} P_{snr}(R_{pwn})$



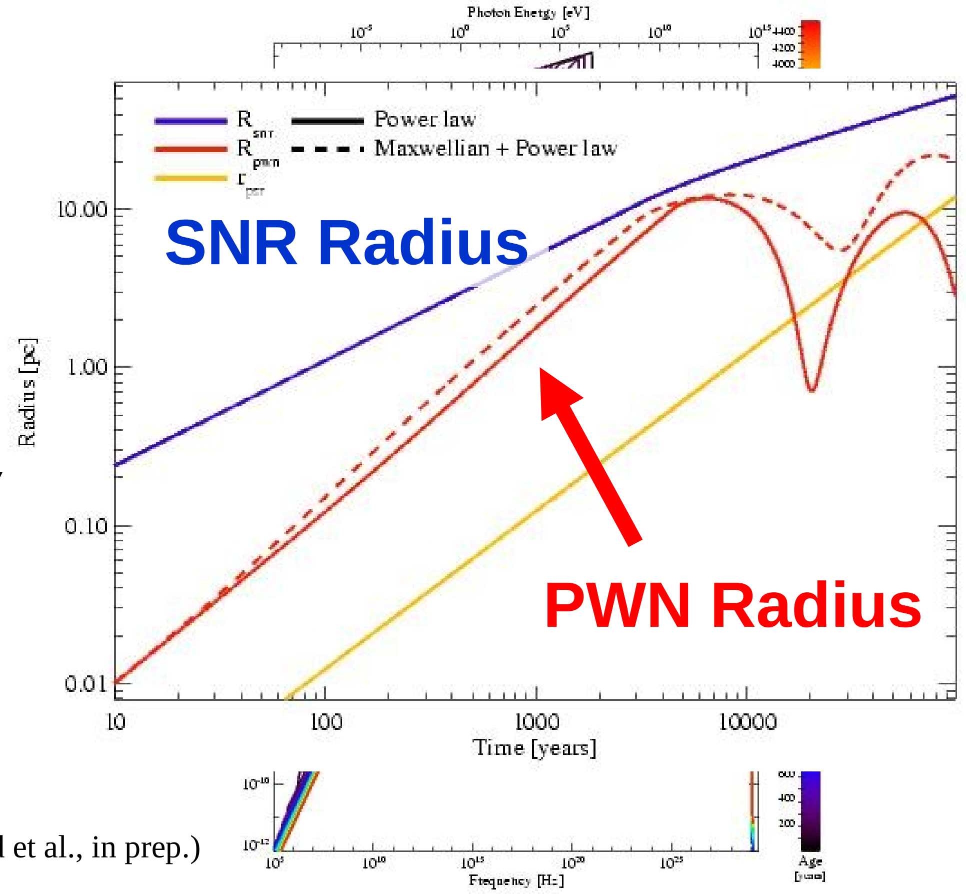
Supernova Remnant

(Gelfand et al. 2009, *ApJ* submitted)

(Figure 6; Gelfand et al. 2007)

Importance of Injection Spectrum

- Single Power Law unlikely to be correct
- Two component models:
  - Broken Power-law
  - *Maxwellian + Power-law*
  - Two power-laws?
- Very different spectral and ***dynamical*** evolution



(Gelfand et al., in prep.)