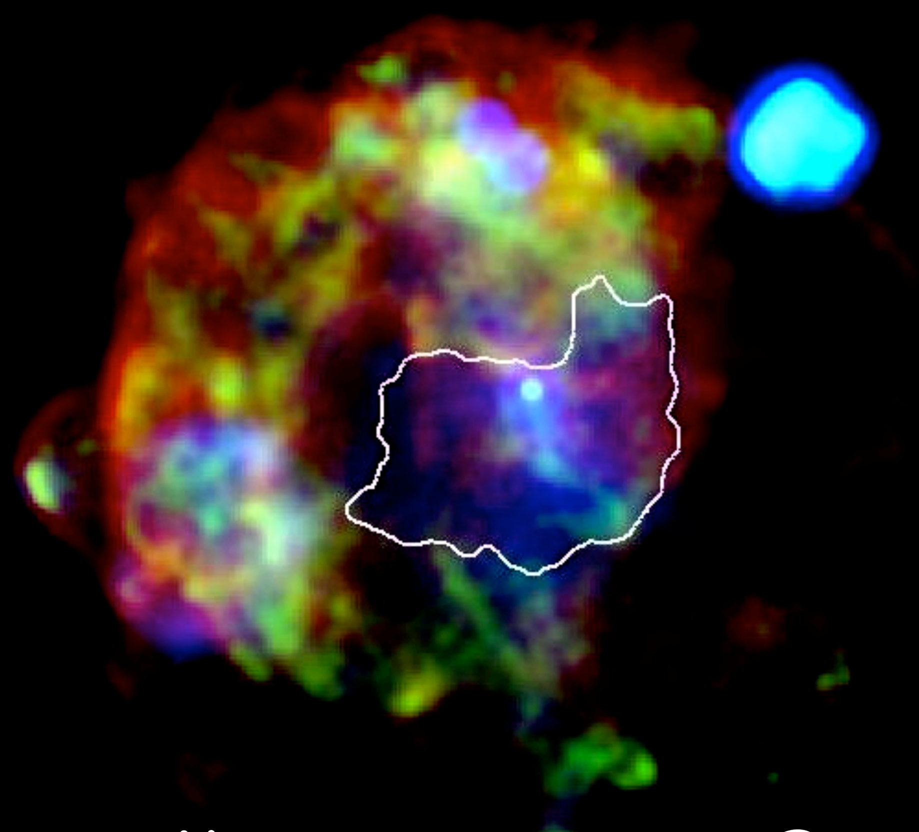
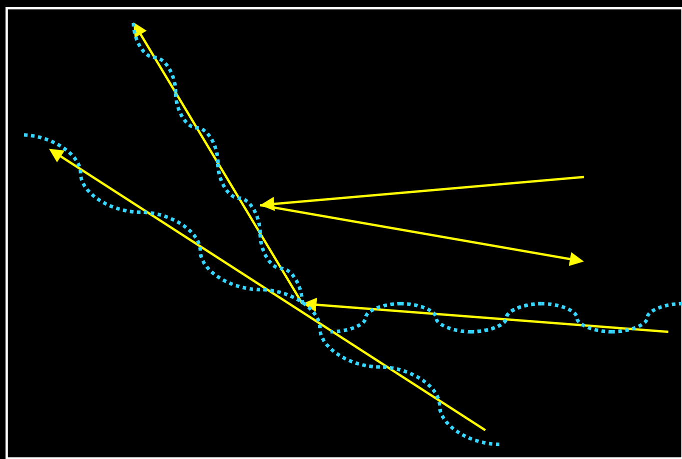
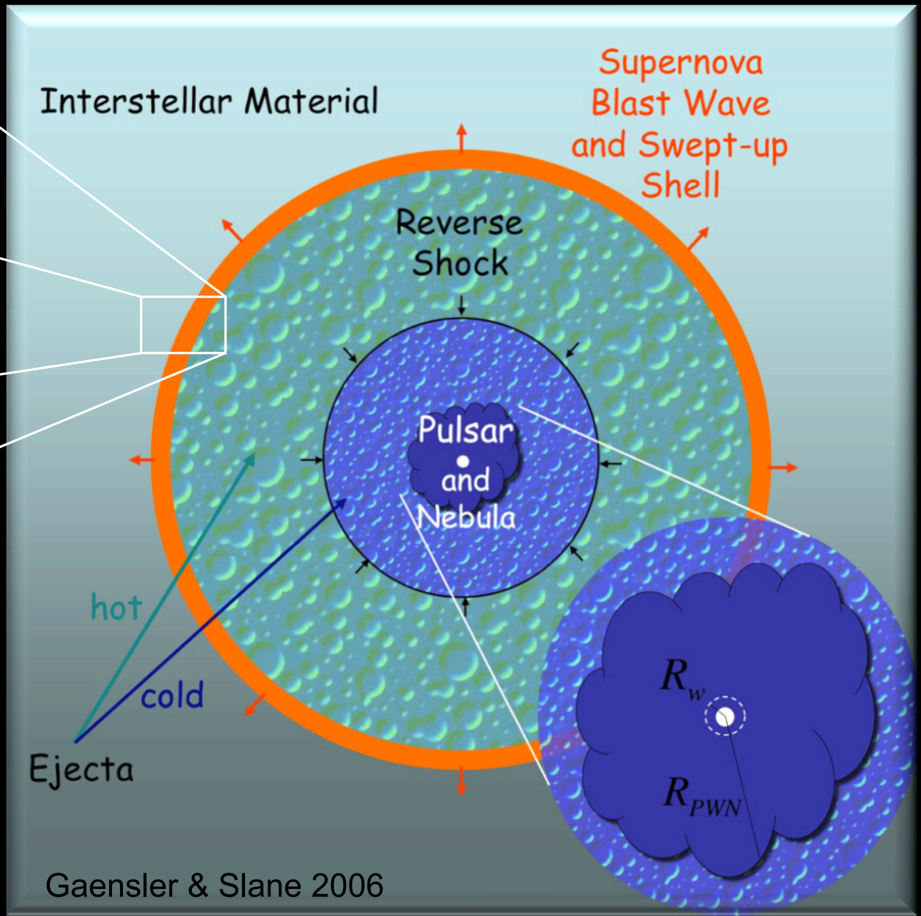
High Energy Emission from



Composite Supernova Remnants

Composite SNRs





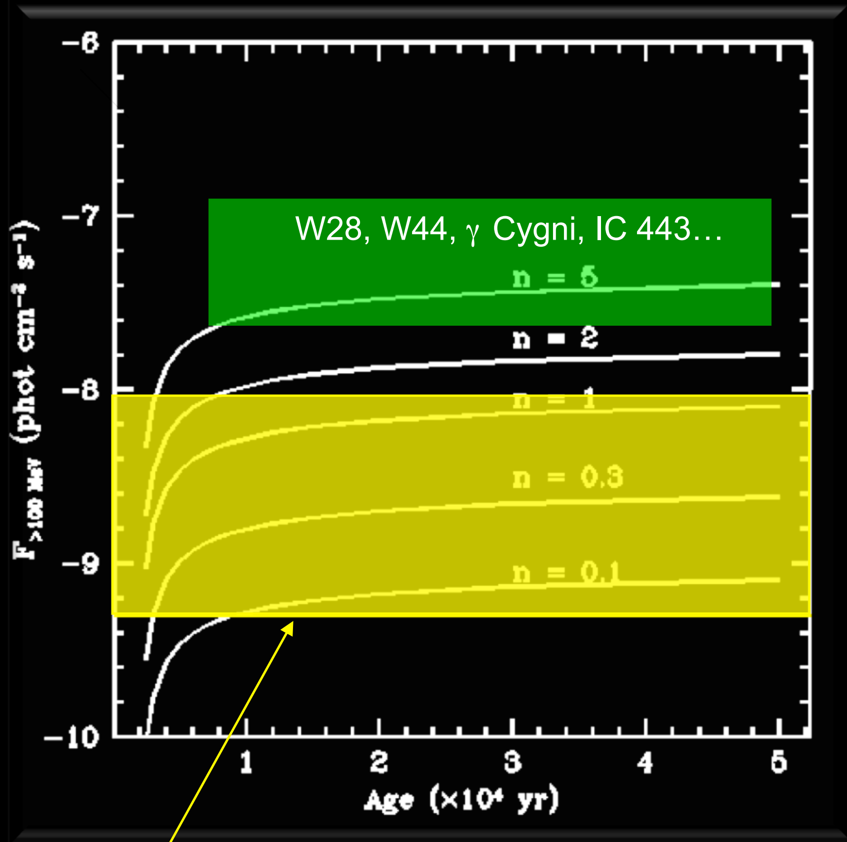
- Pulsar Wind
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms
- Supernova Remnant
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN
  - self-generated turbulence by streaming particles, along with magnetic field amplification, promote <u>diffusive shock acceleration</u> of electrons and ions to energies exceeding 10-100 TeV

SNRs in Dense Environments

- The expected $\pi^0 \rightarrow \gamma\gamma$ flux for an SNR is

$$F(>100MeV) \approx 4.4 \times 10^{-7} \theta E_{51} d_{kpc}^{-2} n \text{ phot cm}^{-2} \text{ s}^{-1}$$

  where θ is a slow function of age (Drury et al. 1994)
  - this leads to fluxes near sensitivity limit of EGRET, but only for large n
- Efficient acceleration can result in higher values for I-C γ-rays
  - SNRs should be detectable w/ Fermi for sufficiently high density; favor SNRs in dense environments or highly efficient acceleration
  - expect good sensitivity to SNR-cloud interaction sites (e.g. W44, W28, IC 443), and indeed these are detected



1 yr sensitivity for high latitude point source

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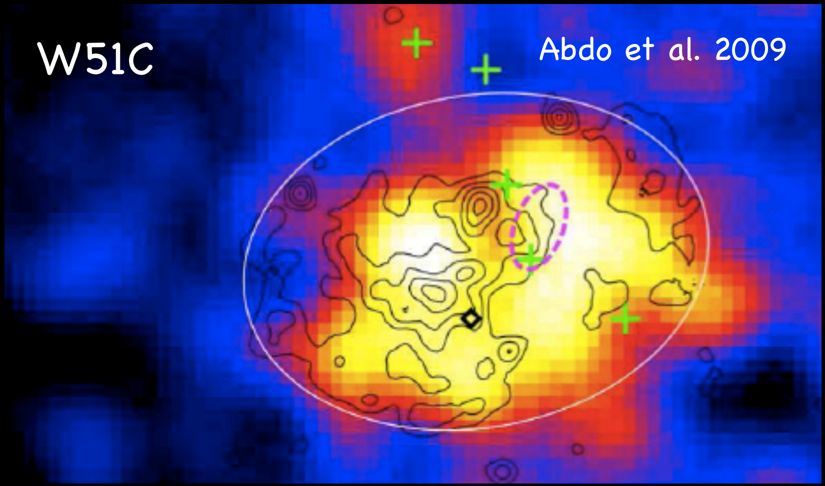
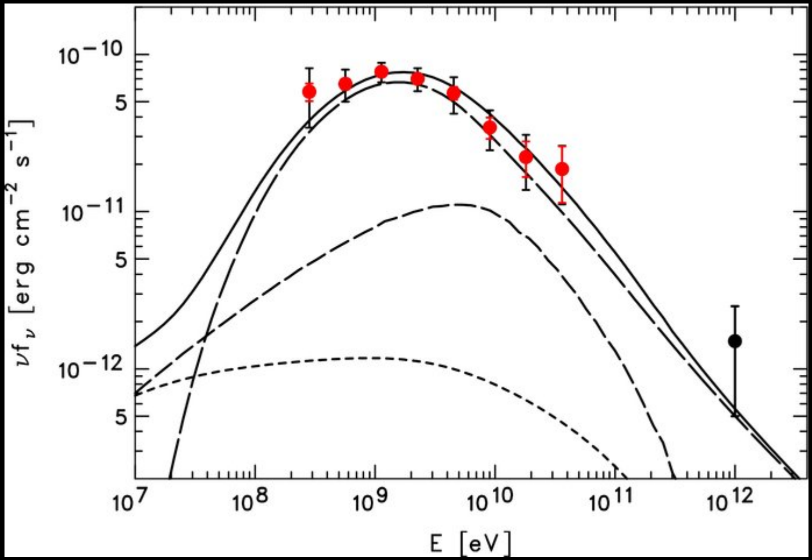
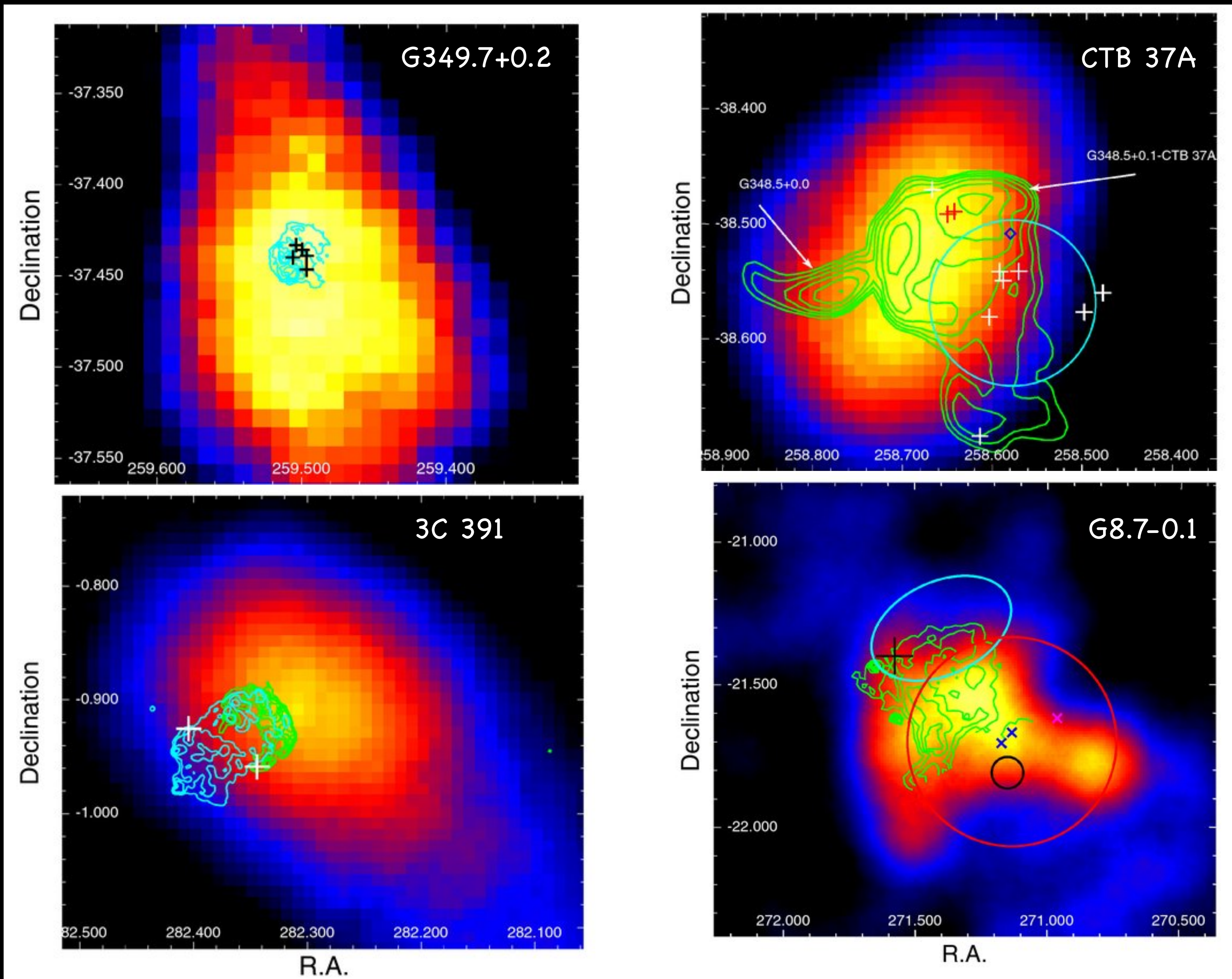




SNRs in Dense Environments



- SNRs with maser emission are sources of GeV emission (Castro & Slane 2010)
- Since composite SNRs are likely to be found in dense regions, one might expect GeV emission from the remnant itself

Evolution of a Composite SNR

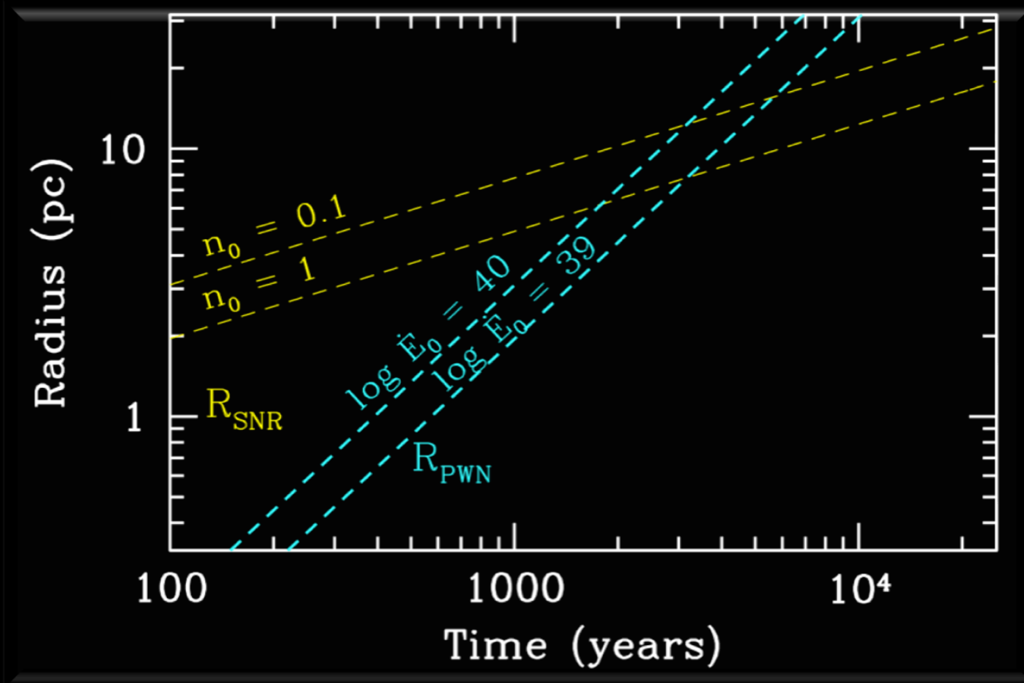
- SNR expands into surrounding CSM/ISM. In Sedov phase,

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

- PWN expands into surrounding ejecta, powered by input from pulsar:

$$R_{PWN} \approx 1.44 \left(\frac{E_{SN}^3 \dot{E}_0}{M_{ej}^5} \right)^{1/10} t^{6/5}$$

- In principle, PWN can overtake SNR boundary
  - In reality, SNR reverse shock will first interact w/ PWN



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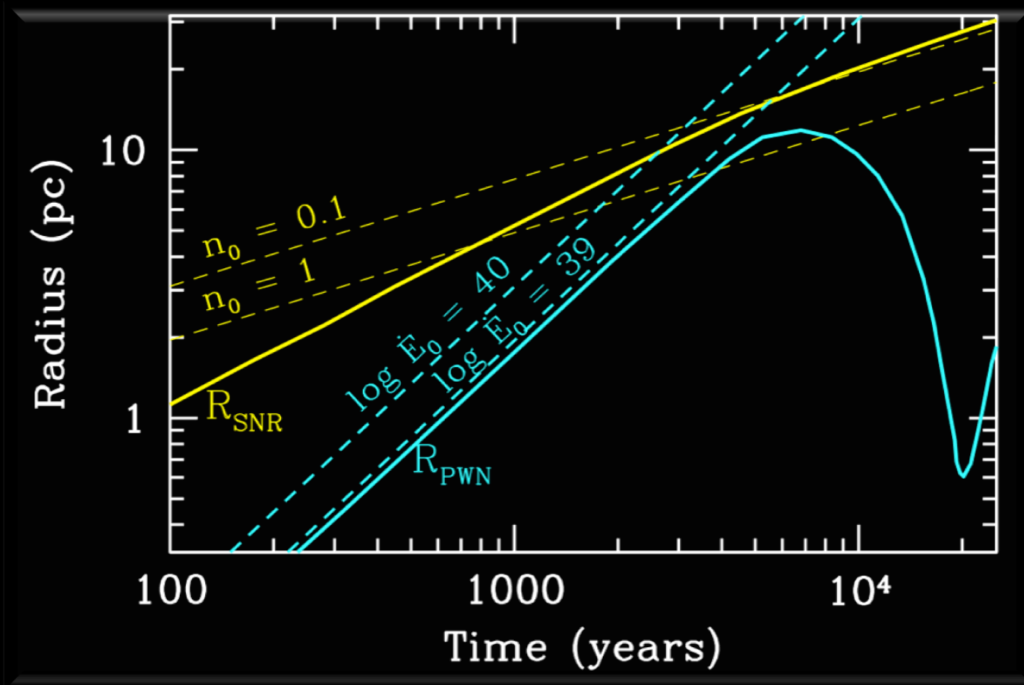
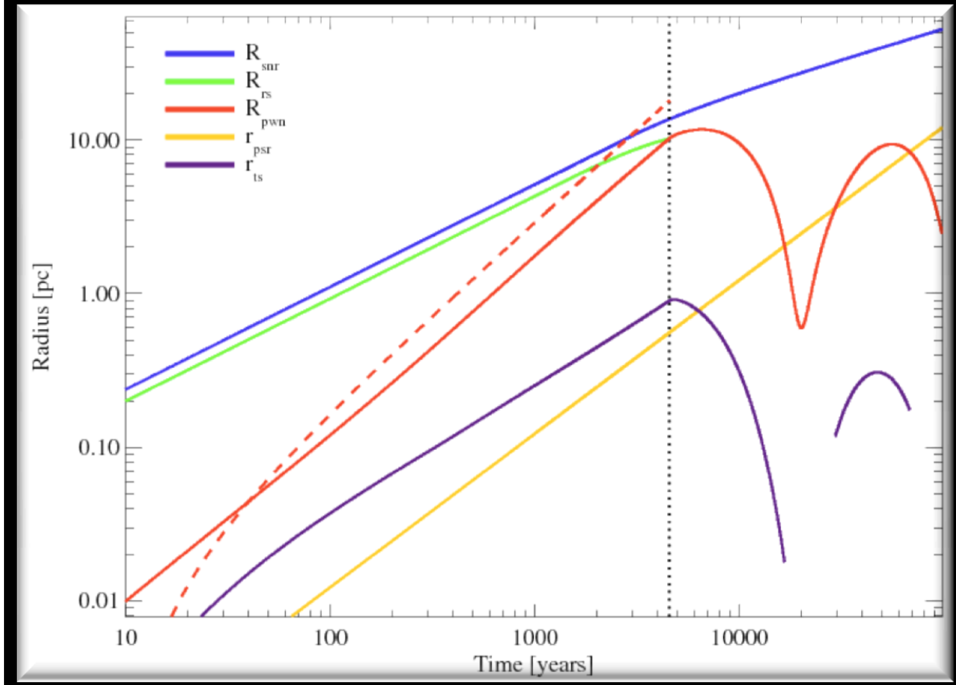
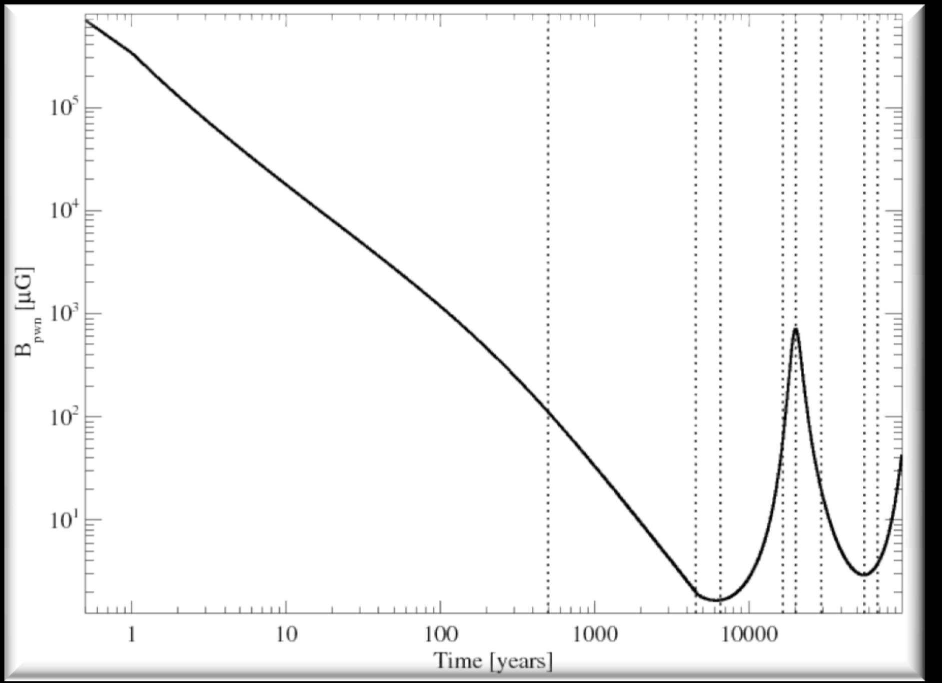


- Treating evolution self-consistently, with rapid initial SNR expansion, and evolution of PWN and SNR reverse shock through common ejecta distribution reveals more details…

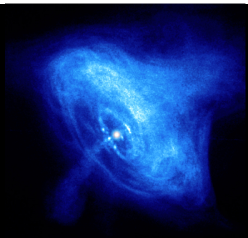
Evolution of a Composite SNR





- Forward shock behavior (primarily, as far as we understand) determines γ-ray emission from the SNR
  - DSA, B_0, n_0
- Pulsar input plus confinement by ejecta determines γ-ray emission from the PWN
  - B_{PWN}, E_e, reverse-shock interaction

Evolution of PWN Emission



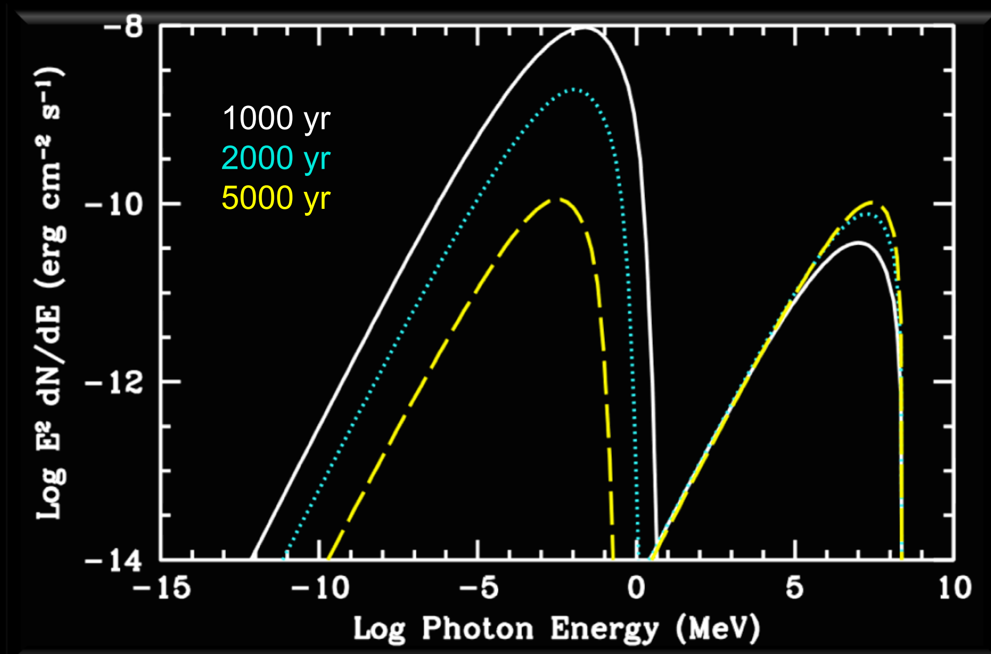
- Spin-down power is injected into the PWN at a time-dependent rate

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

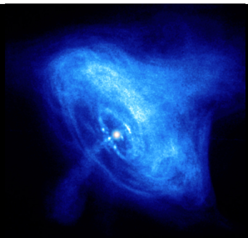
- Assume power law input spectrum:

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

- note that studies of Crab and other PWNe suggest that there may be multiple components



- Get associated synchrotron and IC emission from electron population in the evolved nebula
  - combined information on observed spectrum and system size provide constraints on underlying structure and evolution



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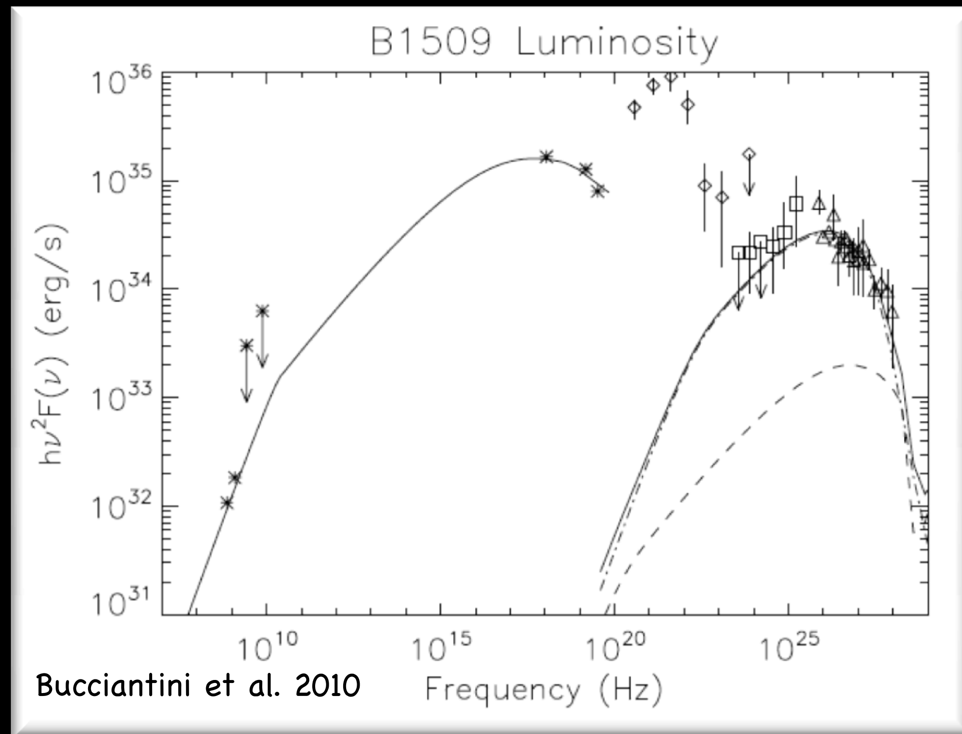

Bucciantini et al. 2010

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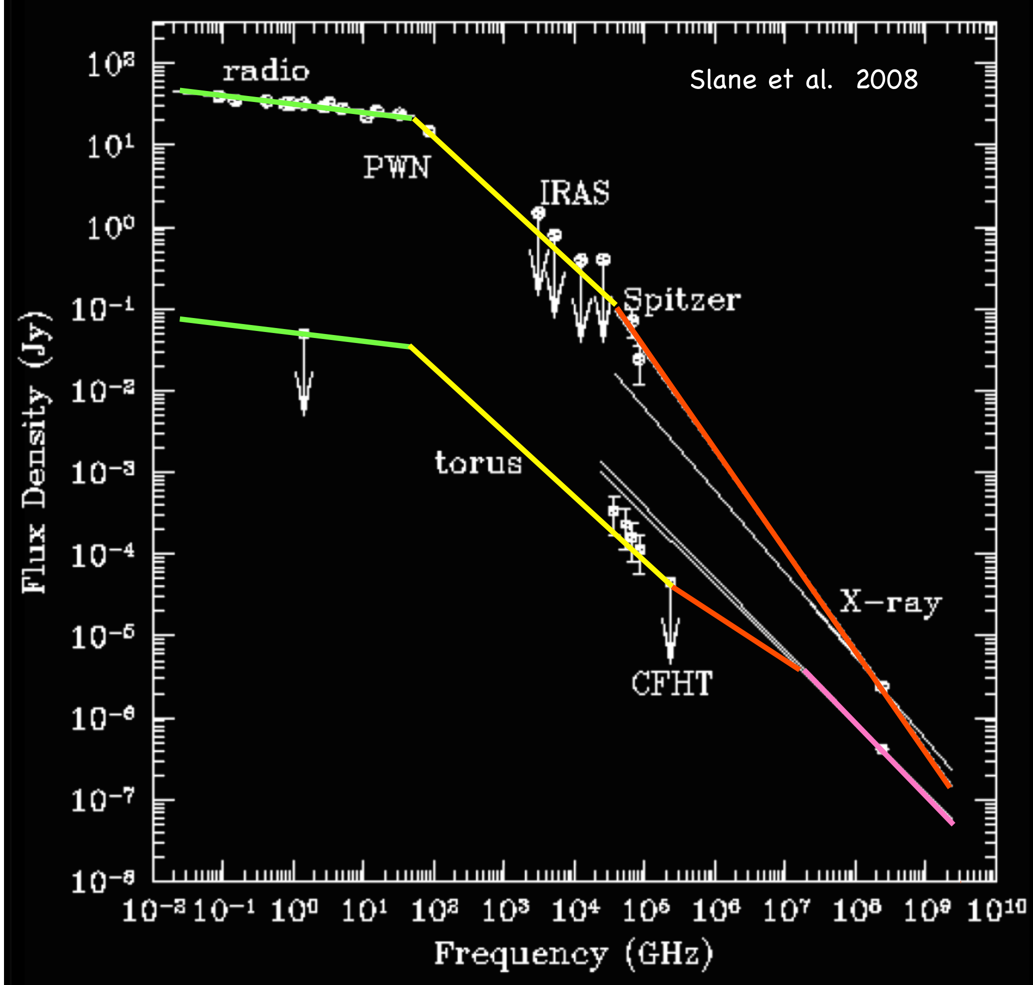
Broadband Observations of 3C 58



- 3C 58 is a bright, young PWN
  - morphology similar to radio/x-ray; suggests low magnetic field
  - PWN and torus observed in Spitzer/IRAC
- 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

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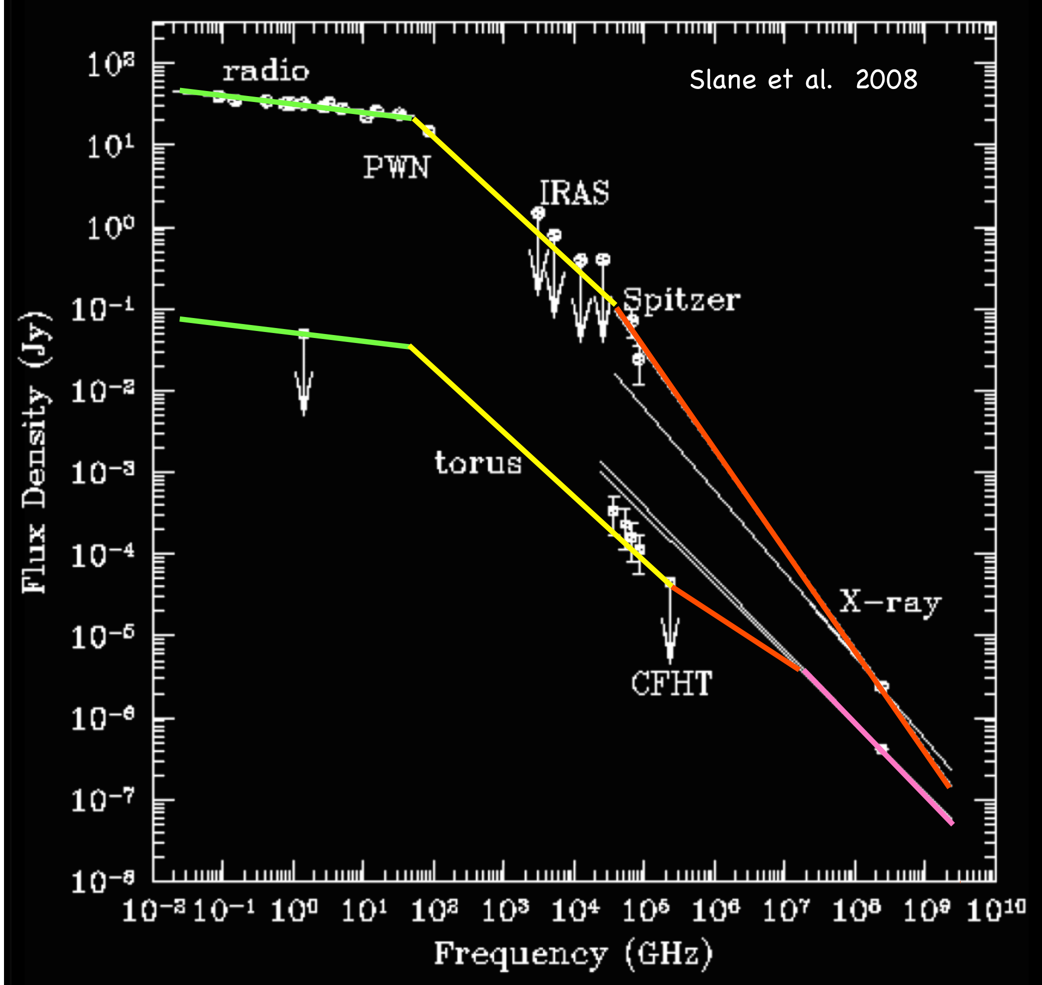
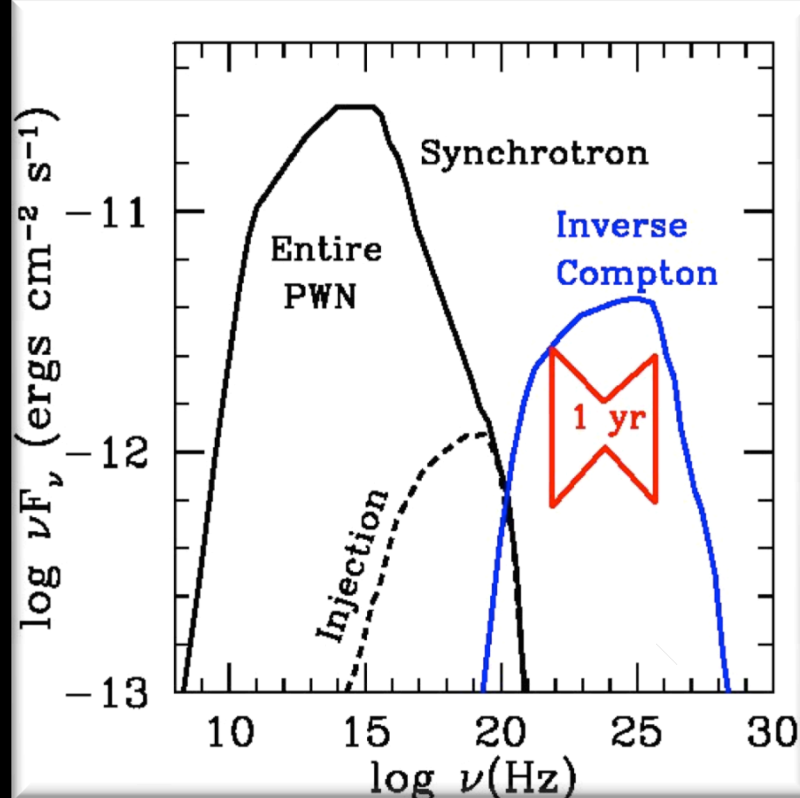
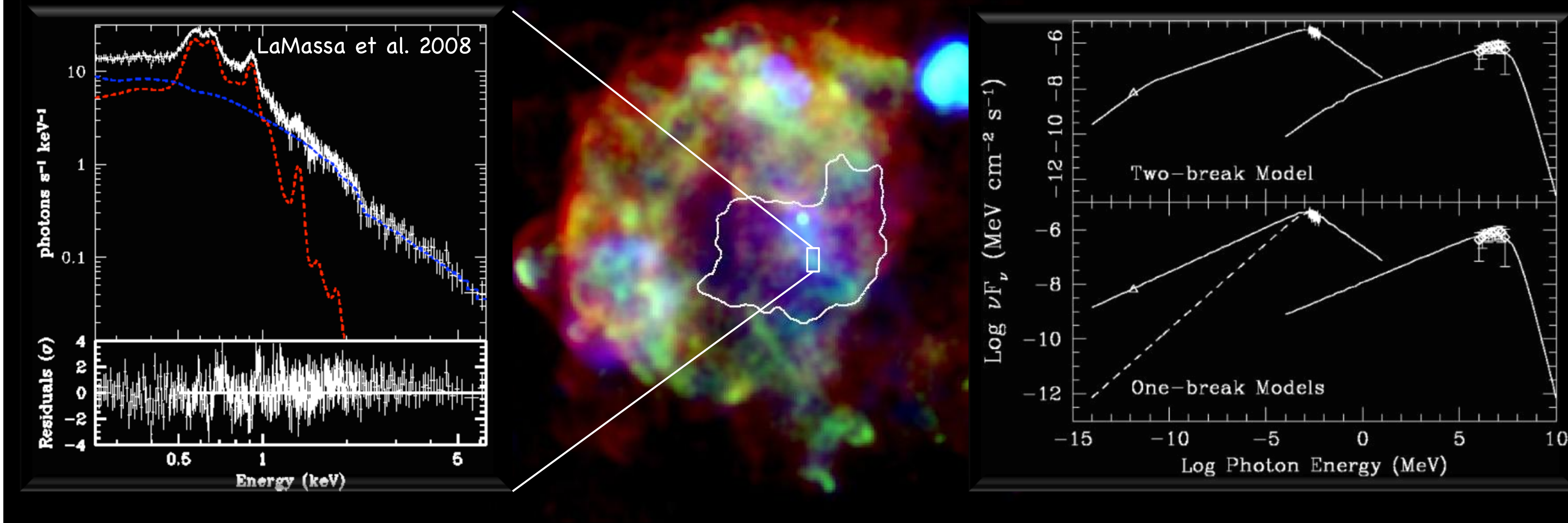




- Pulsar is detected in Fermi-LAT
  - to date, no detection of PWN in off-pulse data

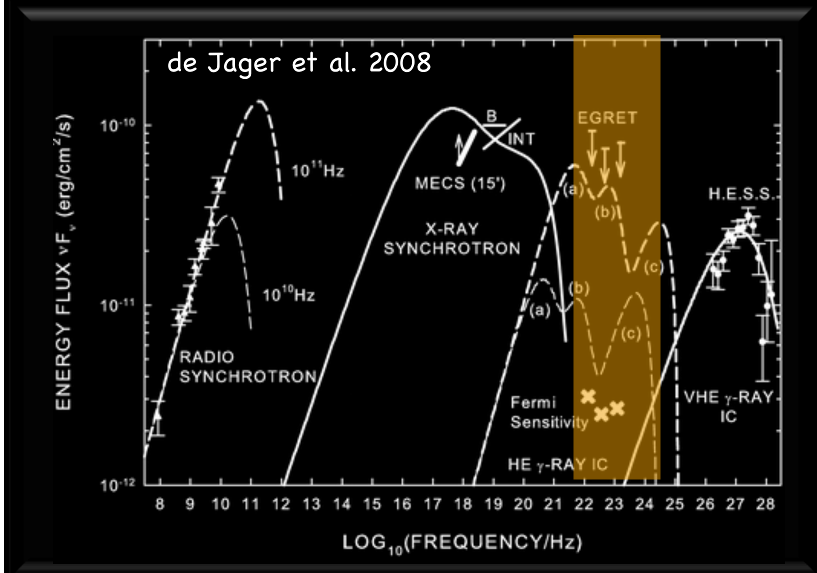
Evolution in an SNR: Vela X

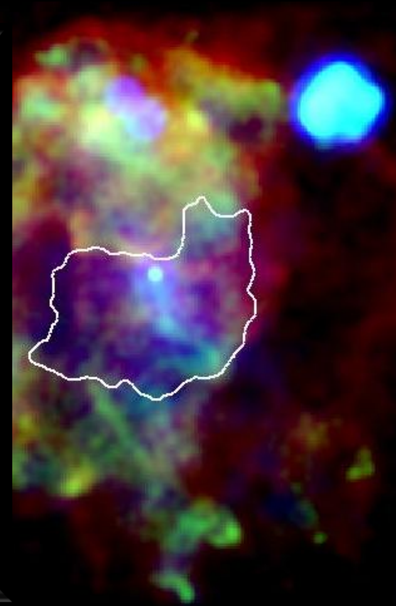


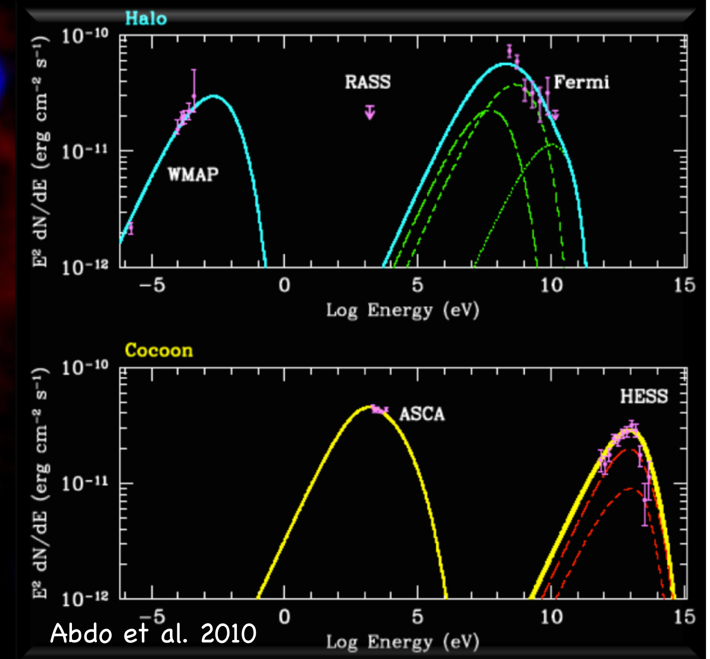
- XMM spectrum shows nonthermal and ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta?

- Broadband measurements consistent with synchrotron and I-C emission from PL electron spectrum w/ two breaks, or two populations
  - density too low for pion-production to provide observed γ-ray flux
  - magnetic field very low (5 μG)

Evolution in an SNR: Vela X







- Treating radio-emitting particles as separate population, flux limits suggest detection of IC component in GeV band
- AGILE and Fermi-LAT measurements confirm these predictions
  - apparent difference between main nebula and cocoon

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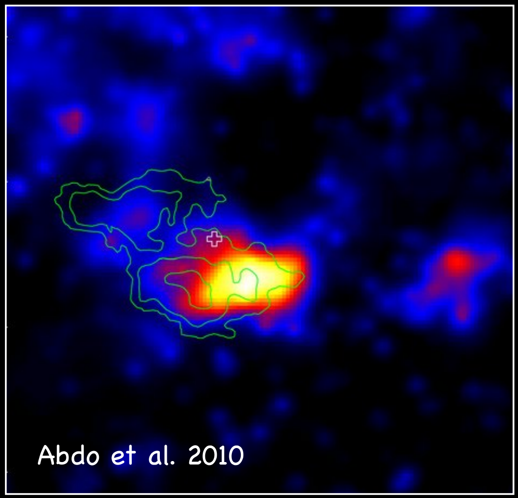
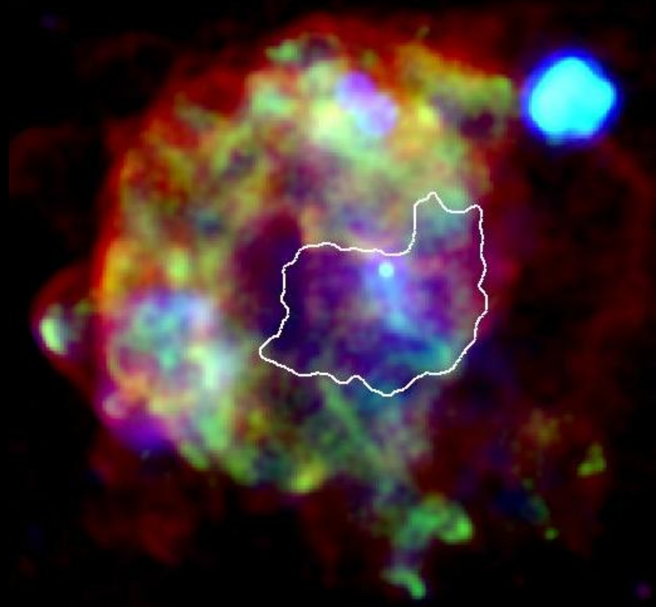
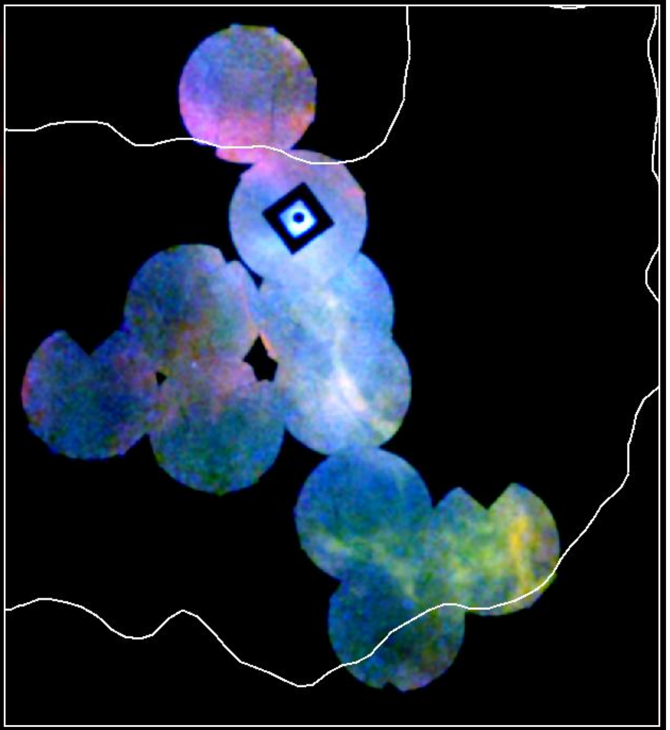
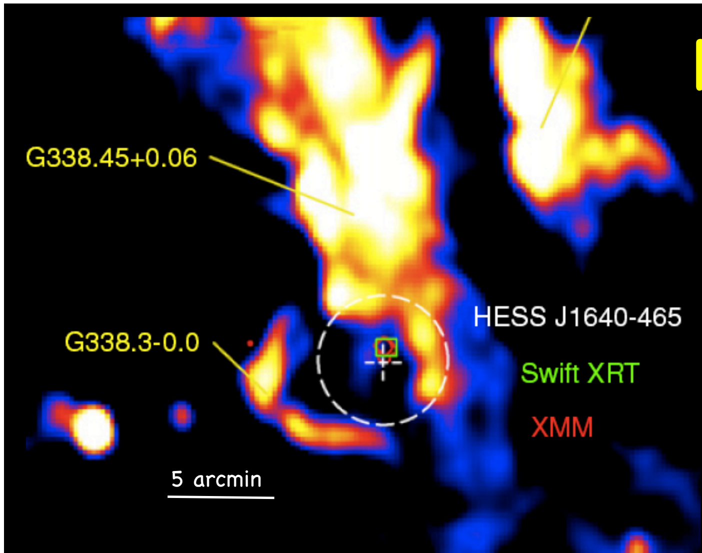






- Treating radio-emitting particles as separate population, flux limits suggest detection of IC component in GeV band
- AGILE and Fermi-LAT measurements confirm these predictions
  - apparent difference between main nebula and cocoon
- XMM large project to map cocoon and much of remaining nebula underway

HESS J1640-465



- Extended source identified in HESS GPS
  - no known pulsar associated with source
  - may be associated with SNR G338.3-0.0
- XMM observations (Funk et al. 2007) identify extended X-ray PWN
- Chandra observations (Lemiere et al. 2009) reveal neutron star within extended nebula
  - $L_x \sim 10^{33.1}$ erg s^{-1} ➔ $\dot{E} \sim 10^{36.7}$ erg s^{-1}
  - X-ray and TeV spectrum well-described by leptonic model with B ~6 μG and t ~15 kyr
  - <u>example of late-phase of PWN evolution</u>: X-ray faint, but γ-ray bright

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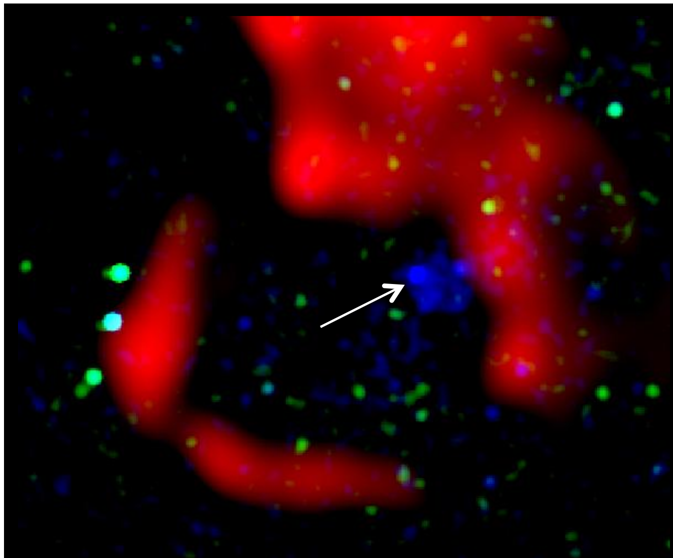

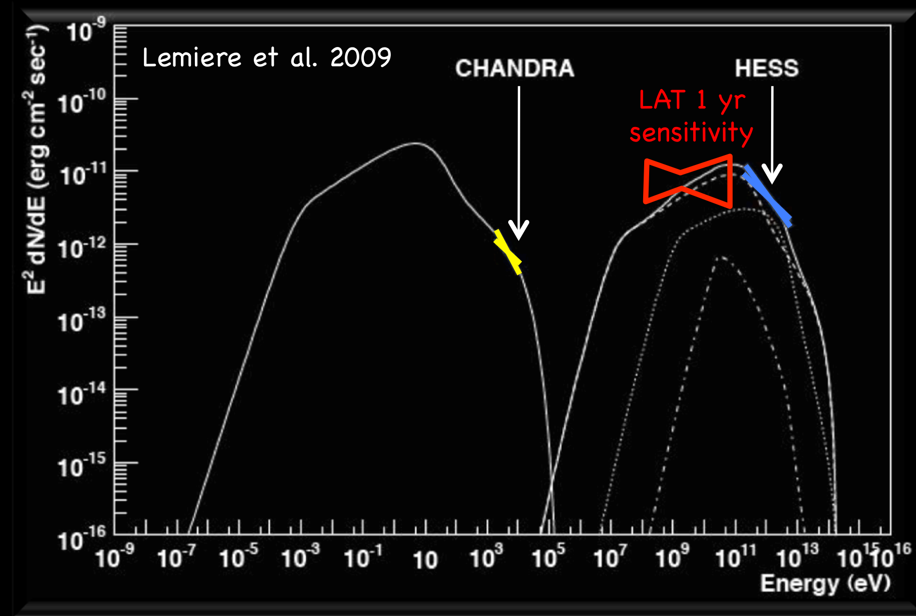

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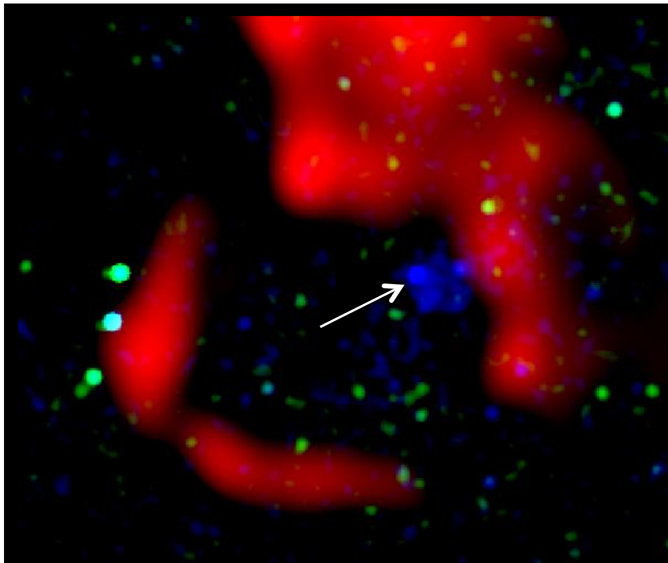

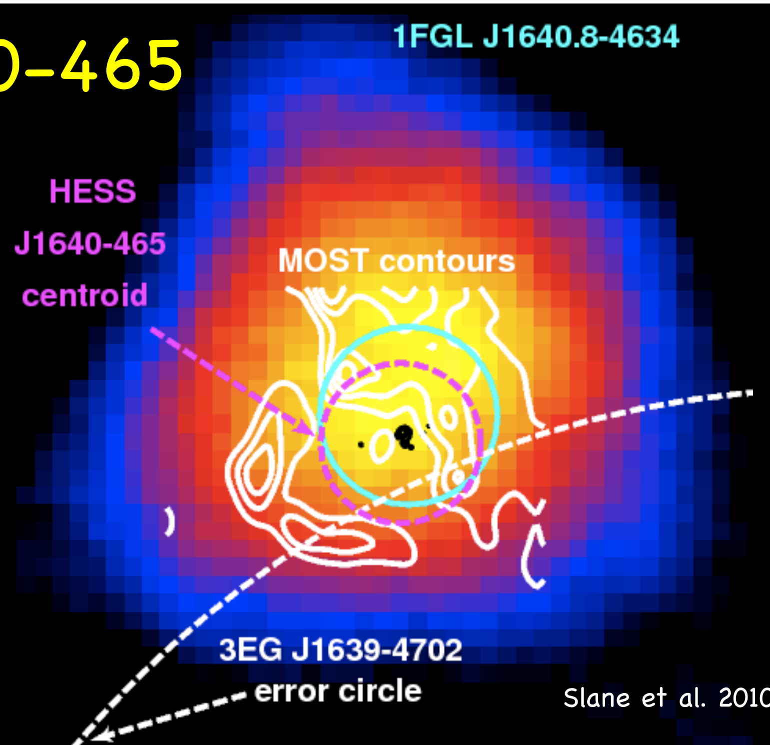

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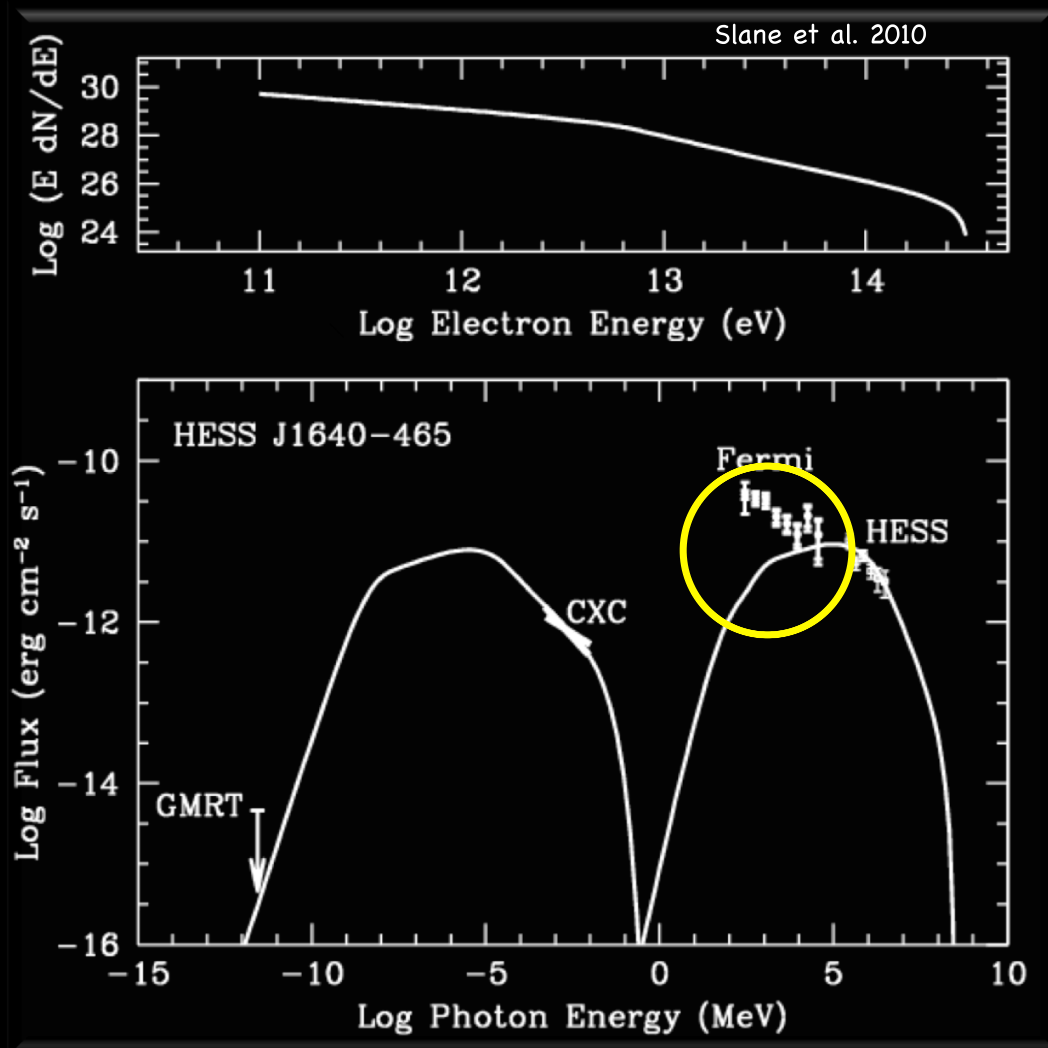
- Fermi LAT reveals emission associated with source

HESS J1640-465

- PWN model with evolved power law electron spectrum fits X-ray and TeV emission
  - Fermi emission falls well above model



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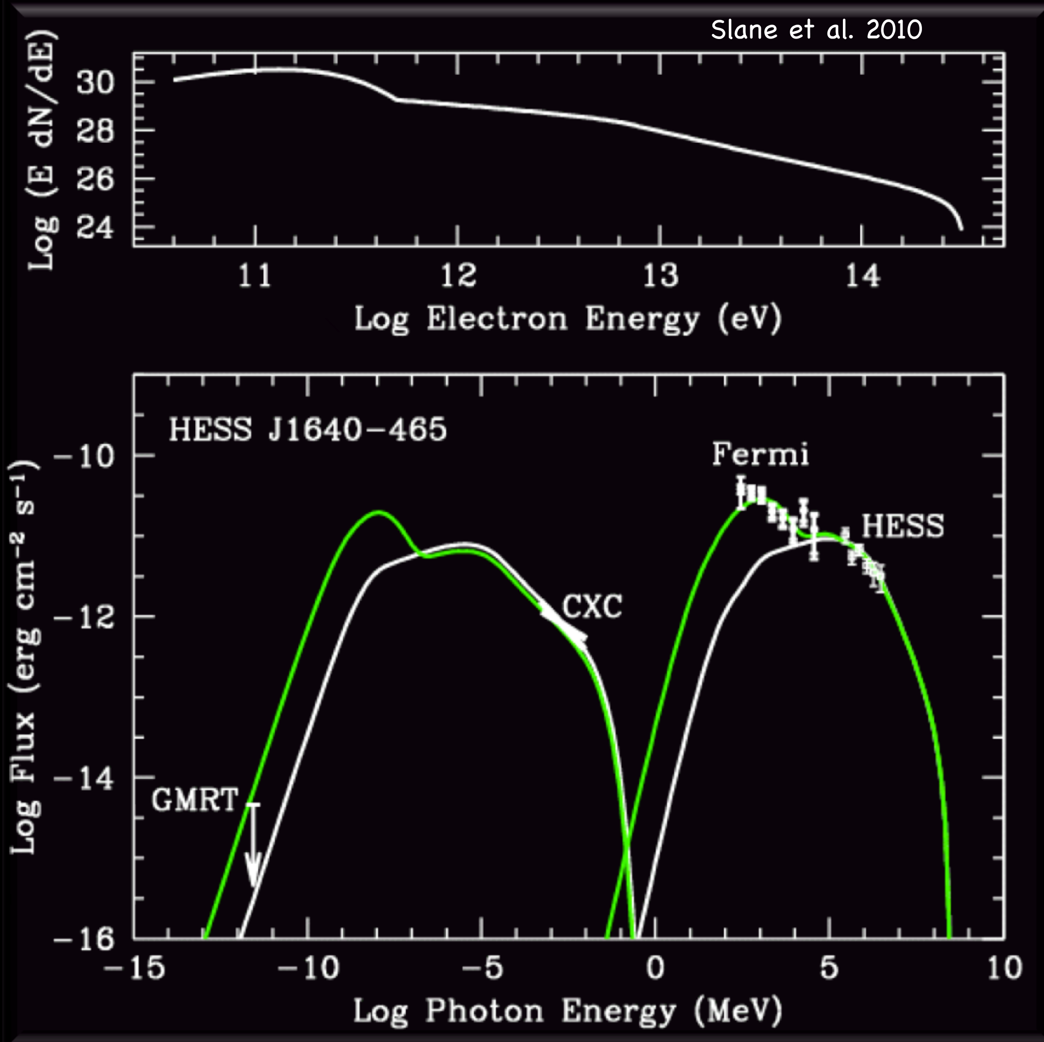
- Modifying low-energy electron spectrum by adding Maxwellian produces GeV emission through inverse Compton scattering
  - primary contribution is from IR from dust (similar to Vela X)
  - mean energy (γ~10^5) and fraction in power law (~4%) consistent w/ particle acceleration models



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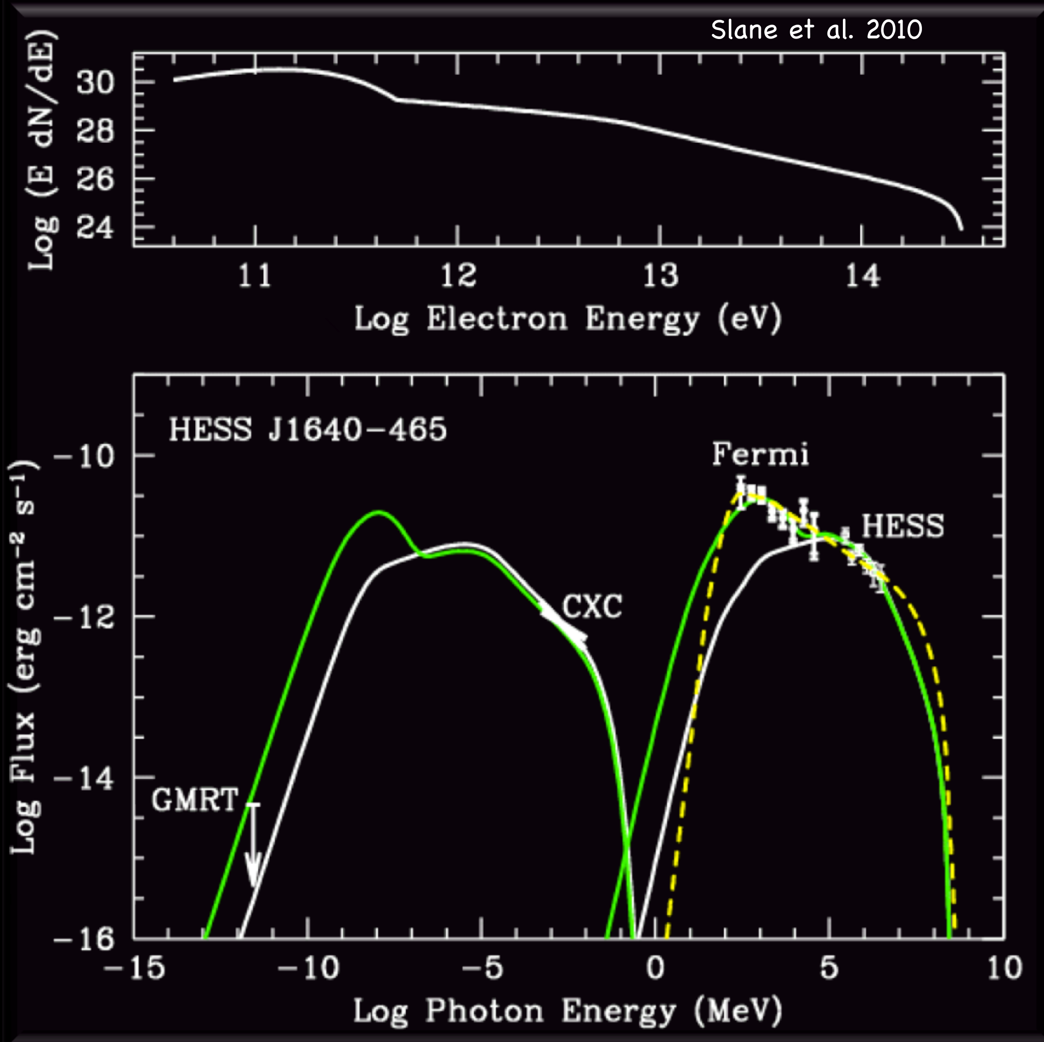
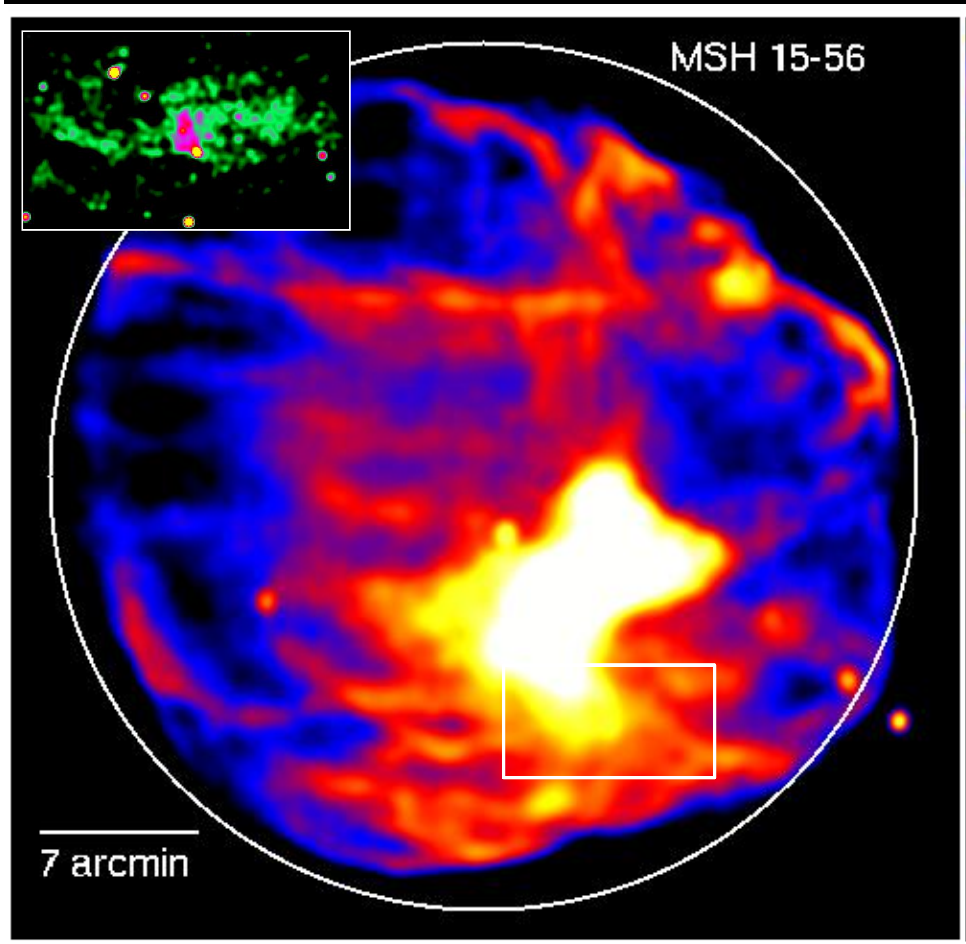
  - primary contribution is from IR from dust (similar to Vela X)
  - mean energy ($\gamma \sim 10^5$) and fraction in power law (~4%) consistent w/ particle acceleration models
- GeV emission can also be fit w/ pion model
  - requires $n_0 > 100\ cm^{-3}$, too large for G338.3-0.3



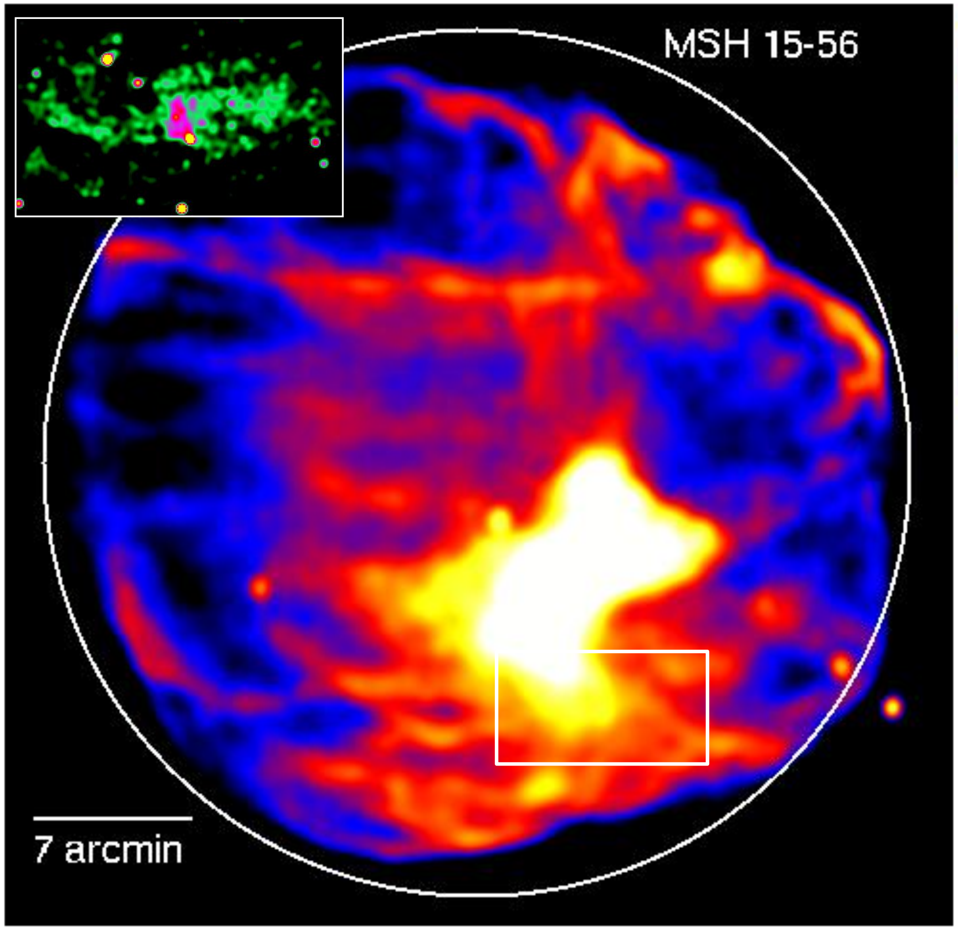
Probing Composite SNRs With Fermi

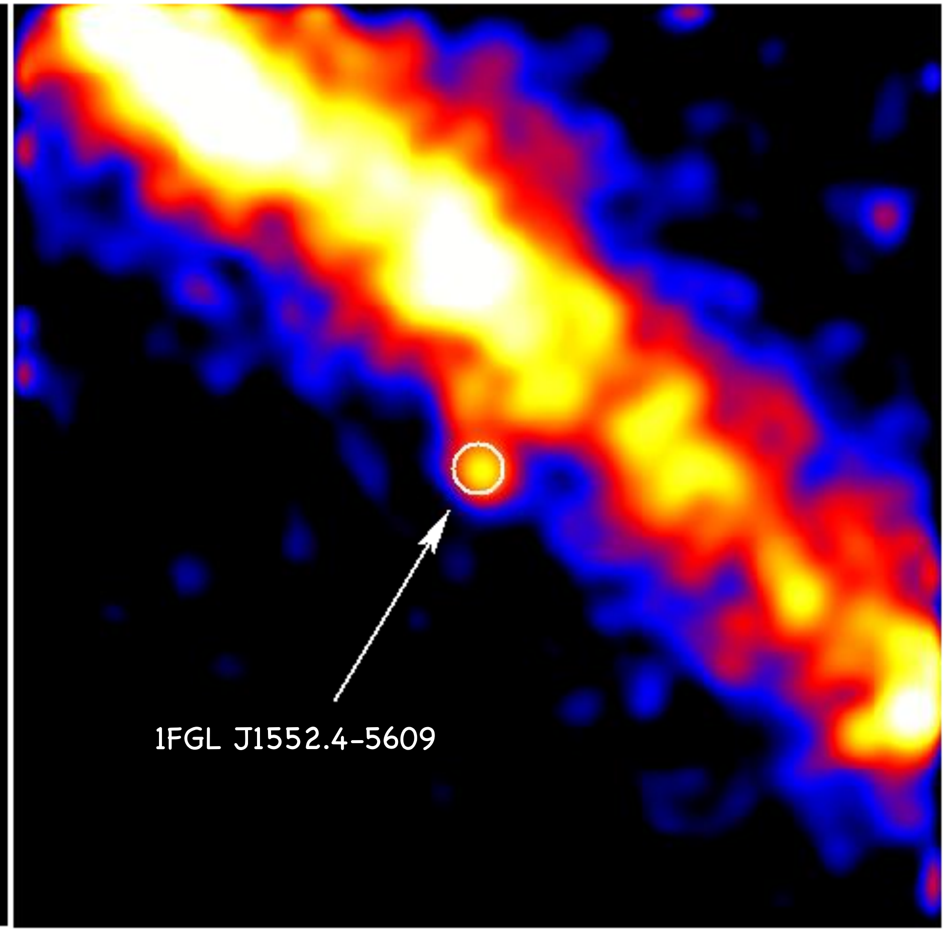


- MSH 15-56 is a composite SNR for which radio size and morphology suggest post-RS interaction evolution
- Chandra and XMM observations show an offset compact source with a trail of nonthermal emission surrounded by thermal emission (Plucinsky et al. 2006) - possibly similar to Vela X
- Good candidate for γ-rays,

And…

Probing Composite SNRs With Fermi





- Watch for studies of this and other such systems with Fermi

Questions

- Is stage of evolution a crucial factor in determining whether or not a PWN will be a bright GeV emitter? In particular, is the reverse-shock interaction an important factor?

- Are multiple underlying particle distributions (if they indeed exist) physically distinct? If so, what do they correspond to?

- How can we best differentiate between PWN and SNR emission in systems we can't resolve (in gamma-rays)?