High Energy Emission from Composite Supernova Remnants
• **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 **diffusive shock acceleration** of electrons and ions to energies exceeding 10-100 TeV

*Gaensler & Slane 2006*
SNRs in Dense Environments

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

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

where $\theta$ 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 $\gamma$-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}
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- PWN expands into surrounding ejecta, powered by input from pulsar:

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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...
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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
  - $B_{\text{PWN}}$, $E_e$, reverse-shock interaction

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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
• 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

Slane et al. 2008
• 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)
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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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$^{-1}$ $\Rightarrow \dot{E} \sim 10^{36.7}$ erg s$^{-1}$
  - X-ray and TeV spectrum well-described by leptonic model with $B \sim 6$ $\mu$G and $t \sim 15$ kyr
  - example of late-phase of PWN evolution: X-ray faint, but $\gamma$-ray bright
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- Fermi LAT reveals emission associated with source

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• 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 $\gamma$-rays,

And...
Probing Composite SNRs With Fermi

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

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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)?