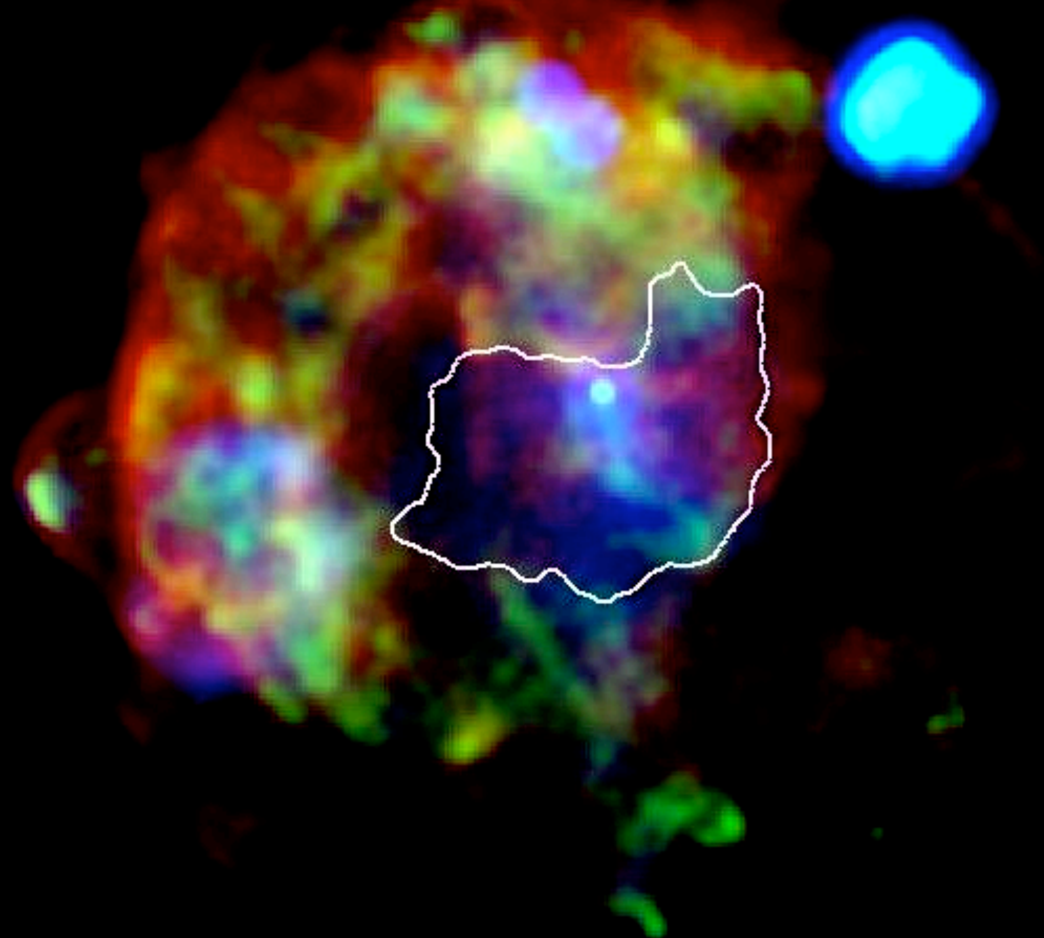
Supernova Remnants and Pulsar Wind Nebulae



in the Fermi Era

Collaborators:
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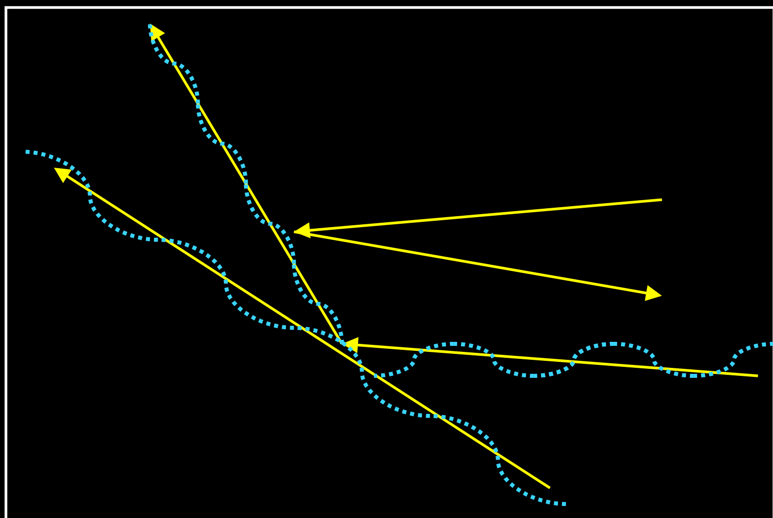
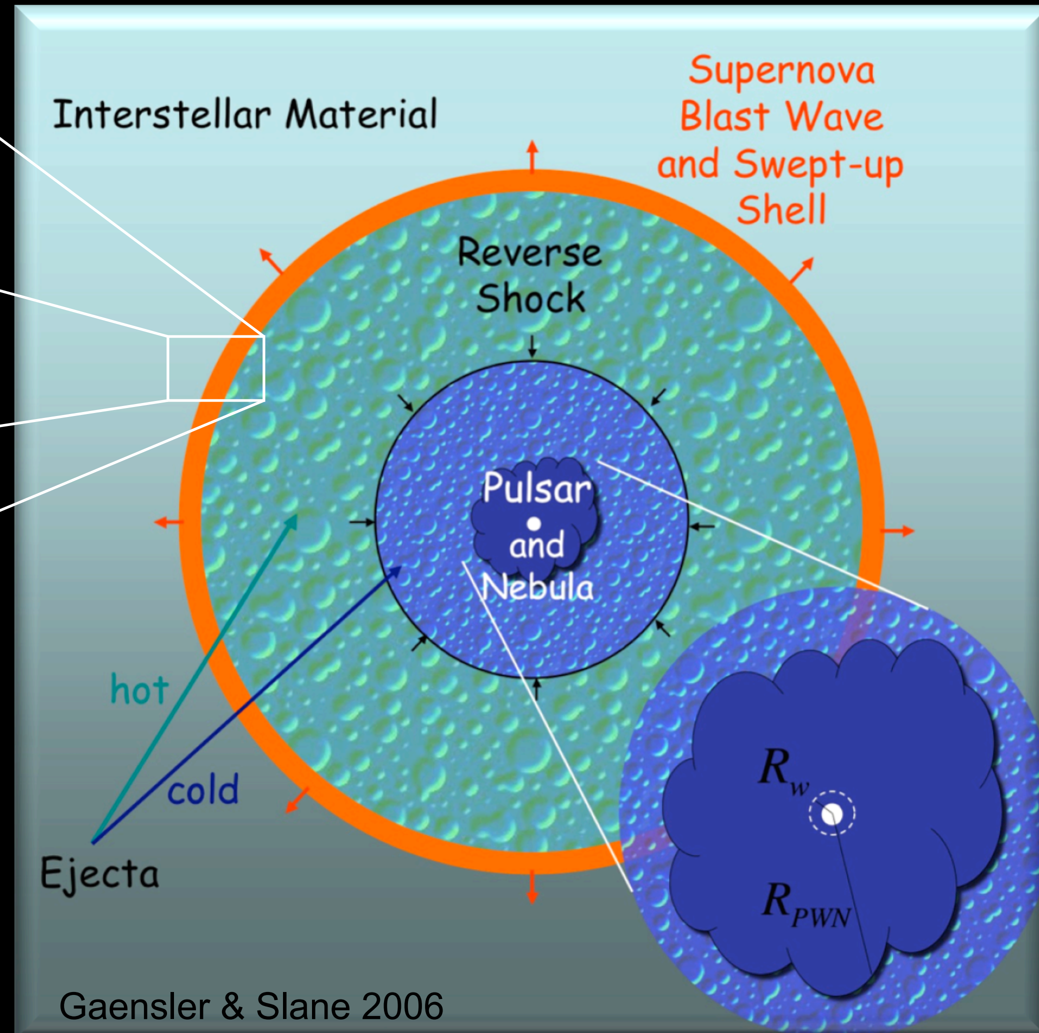
A. Lemiere
and others...

Patrick Slane (CfA)

2009 Fermi Symposium, Washington, DC

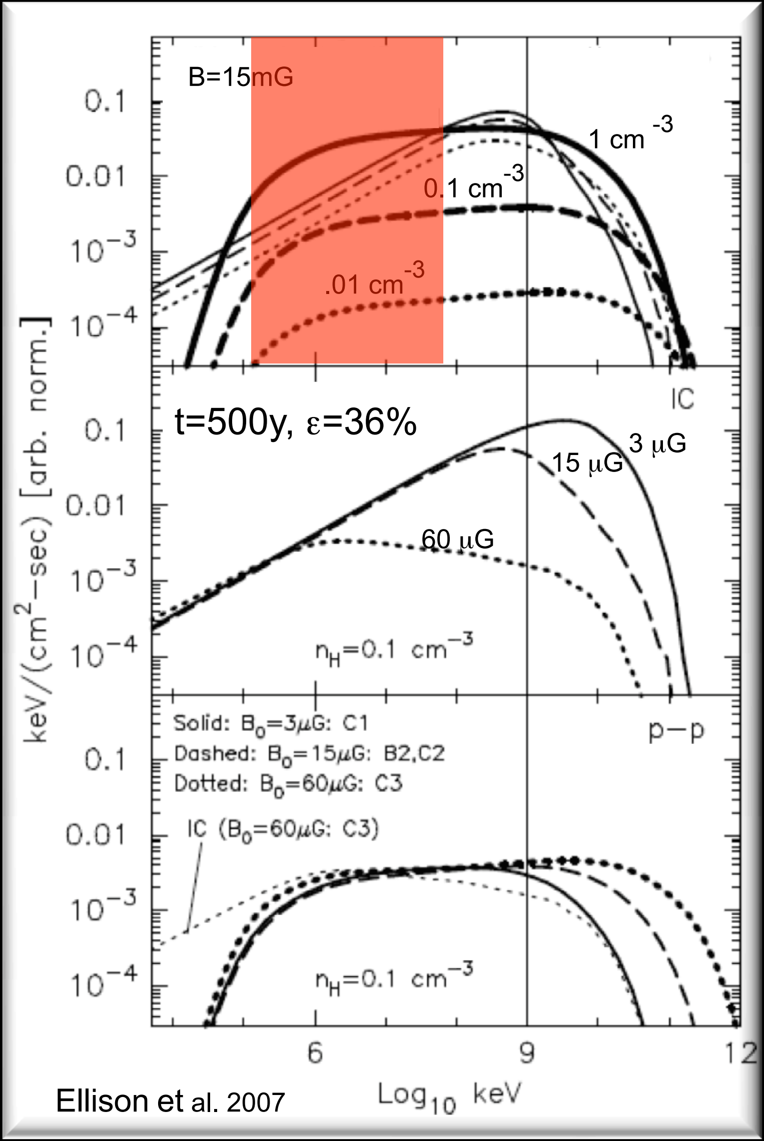
PWNe and SNRs





- 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 diffusive shock acceleration of electrons and ions to energies exceeding 10-100 TeV

Gamma-Ray Emission from SNRs



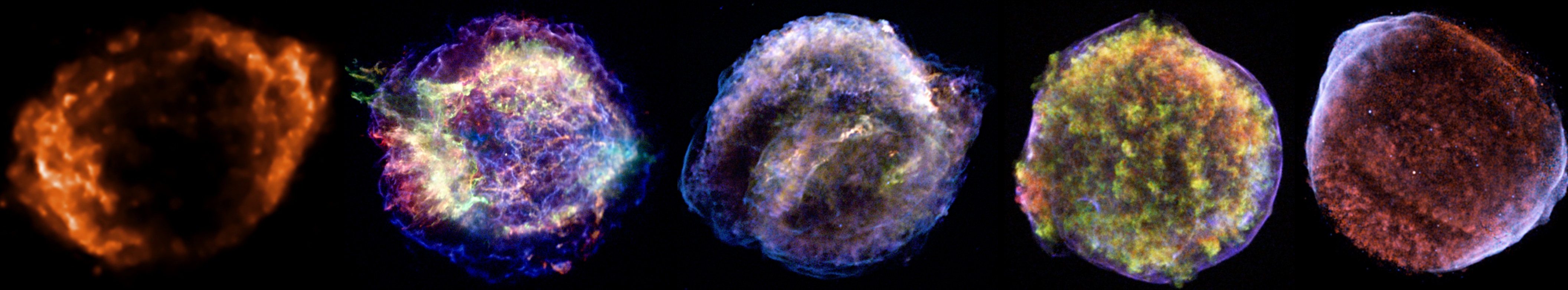
- Neutral pion decay
  - ions accelerated by shock collide w/ ambient protons, producing pions in process: $\pi^0 \rightarrow \gamma\gamma$
  - flux proportional to ambient density; SNR-cloud interactions particularly likely sites
- Inverse-Compton emission
  - energetic electrons upscatter ambient photons to γ-ray energies
  - CMB, plus local emission from dust and starlight, provide seed photons
- Fermi observations, in combination with multi-λ data, will help differentiate between the two different mechanisms

Gamma-Ray Emission from SNRs

Gamma-ray emission depends on (and thus constrains):

- SNR age (need time to accumulate particles)
- acceleration efficiency (can be extremely high)
- electron-proton ratio in injection
- magnetic field (evidence suggests large amplification)
- ambient density (large density increases π^0-decay emission)
- maximum energy limits (age, escape, radiative losses)

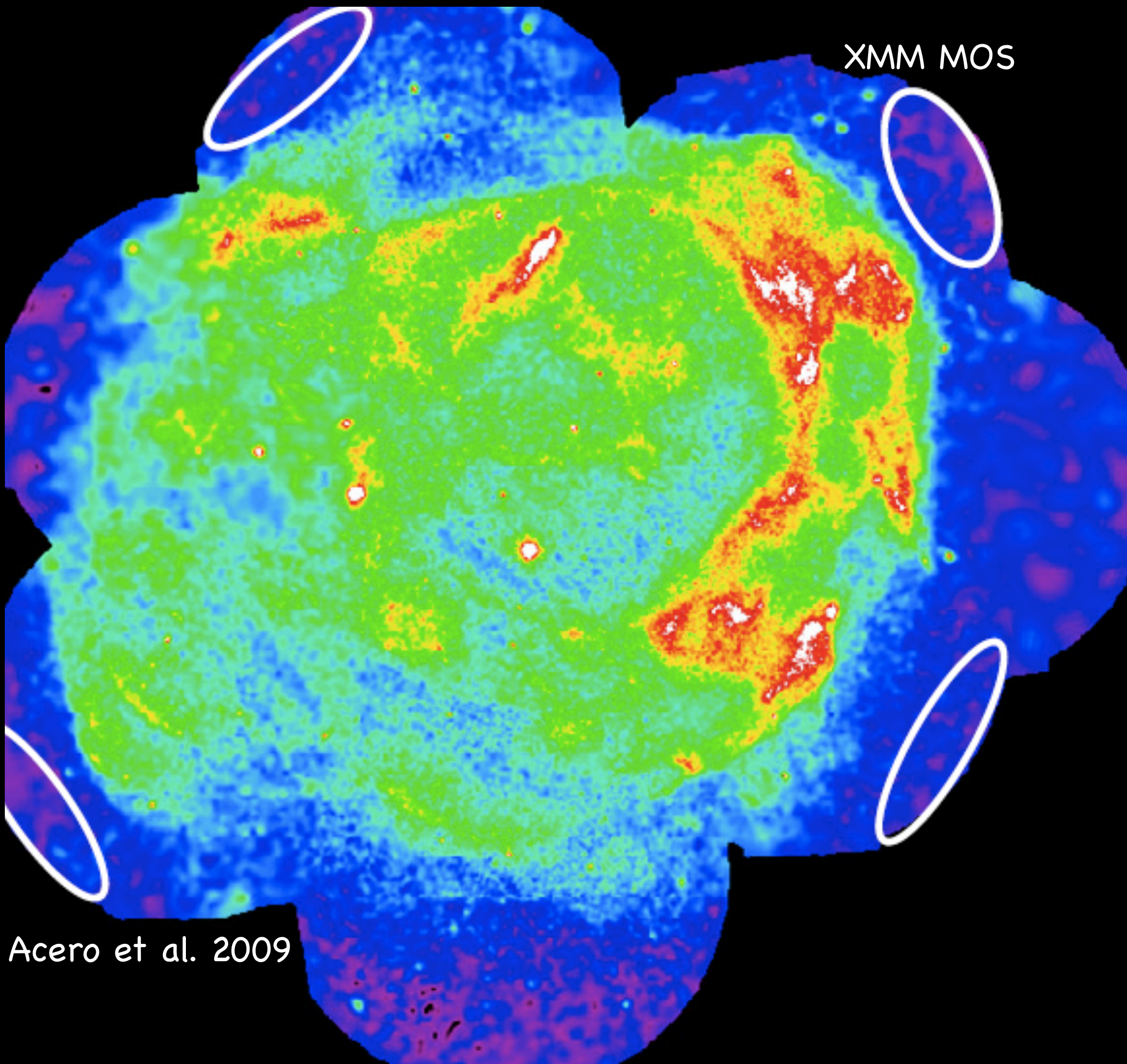
Young SNRs



- Young SNRs have fast shocks that clearly accelerate particles to high energies
  - X-ray observations reveal multi-TeV electrons, and dynamical measurements imply efficient acceleration of ions as well
- But...
  - young SNRs generally haven't encountered high densities
  - maximum energies may be age-limited
- Thus, while very young SNRs should be γ-ray sources, they are not likely to be exceptionally bright

See talk by Stefan Funk

G347.3-0.5/RX J1713.7-3946



Acero et al. 2009

- X-ray observations reveal a nonthermal spectrum everywhere in G347.3-0.5
  - evidence for cosmic-ray acceleration
  - based on X-ray synchrotron emission, infer electron energies of >50 TeV
- SNR detected directly in TeV γ-rays
  - γ-ray morphology very similar to X-rays; suggests I-C emission
  - spectrum suggests π^0-decay, but lack of thermal X-rays is problematic

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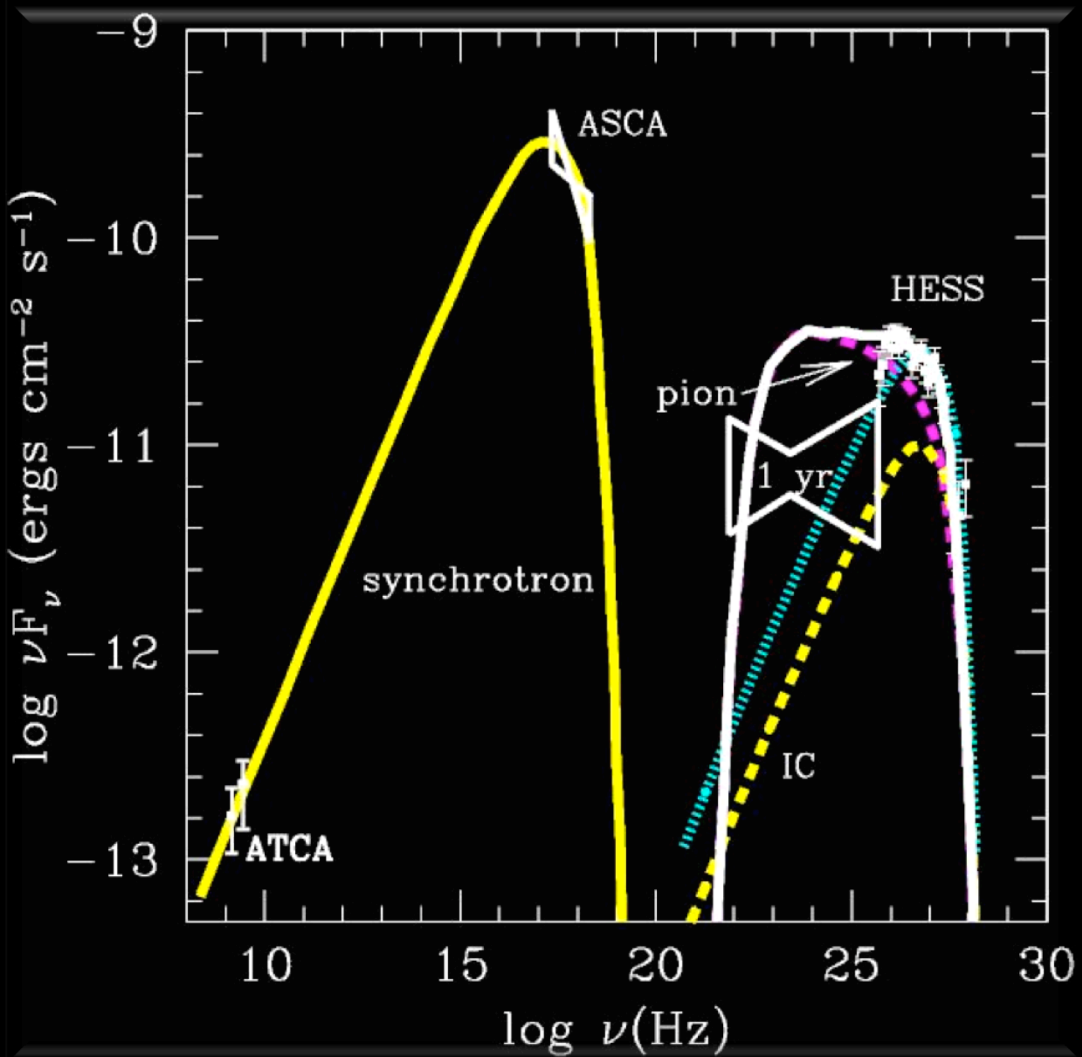

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  - γ-ray morphology very similar to X-rays; suggests I-C emission
  - spectrum suggests π^0-decay, but lack of thermal X-rays is problematic
- Spectrum in Fermi band very different for leptonic and hadronic scenarios
  - if the γ-rays are hadronic in origin, the emission in the Fermi LAT should be bright; weak or non-detection will favor a leptonic origin

See talk by Stefan Funk

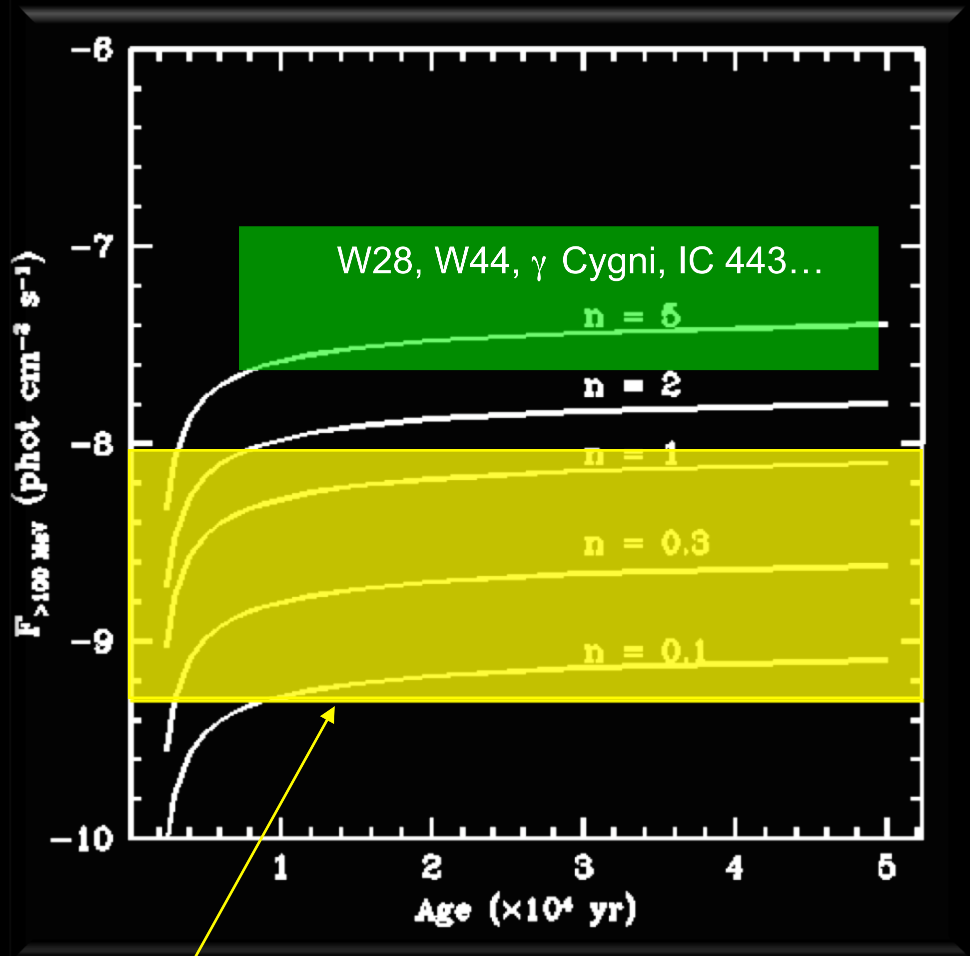
SNRs in Dense Environments

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

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

  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)



1 yr sensitivity for high latitude point source

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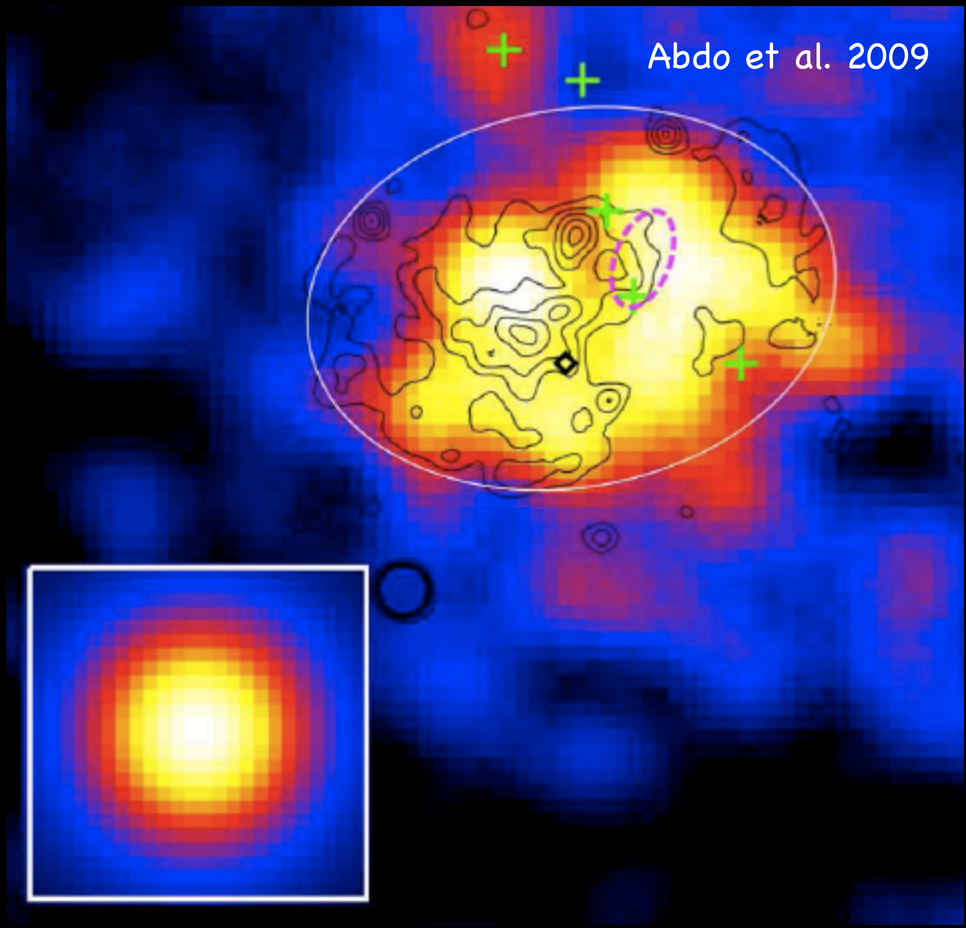
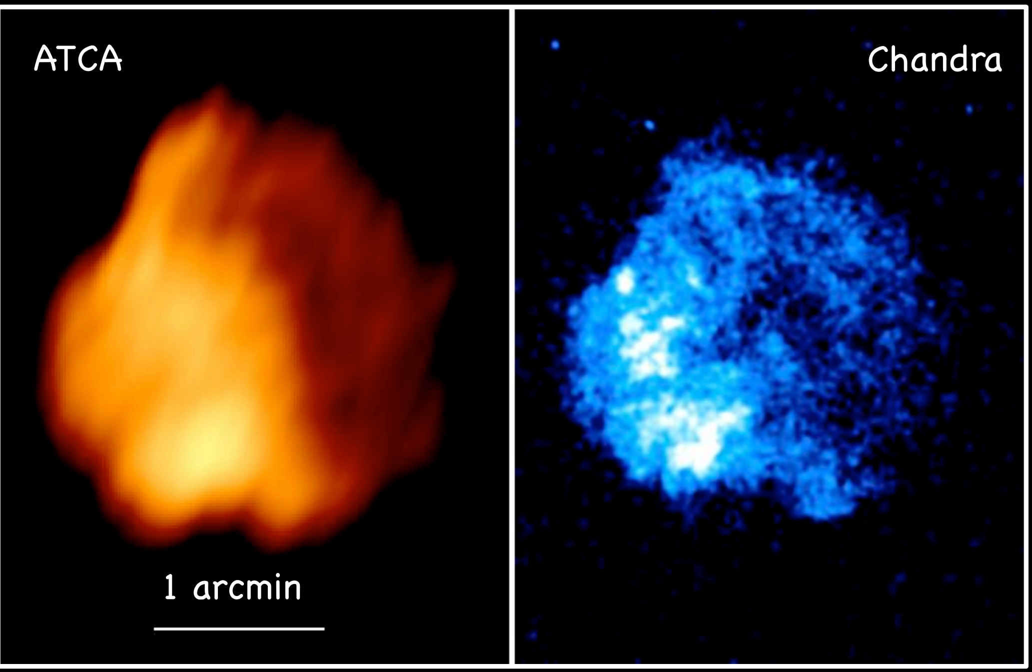
Example: W51C



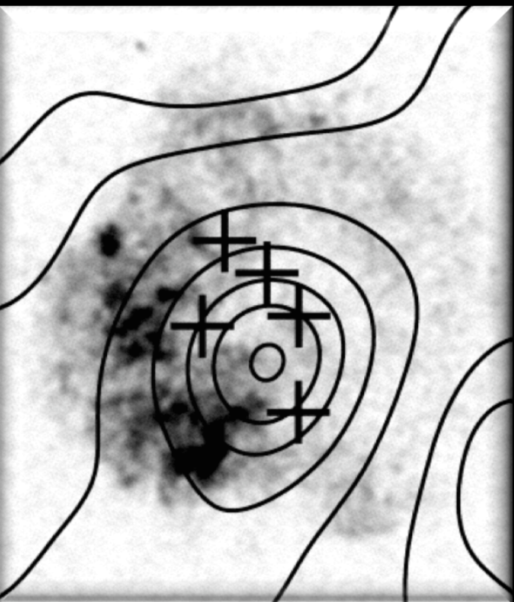
See talk by Takaaki Tanaka

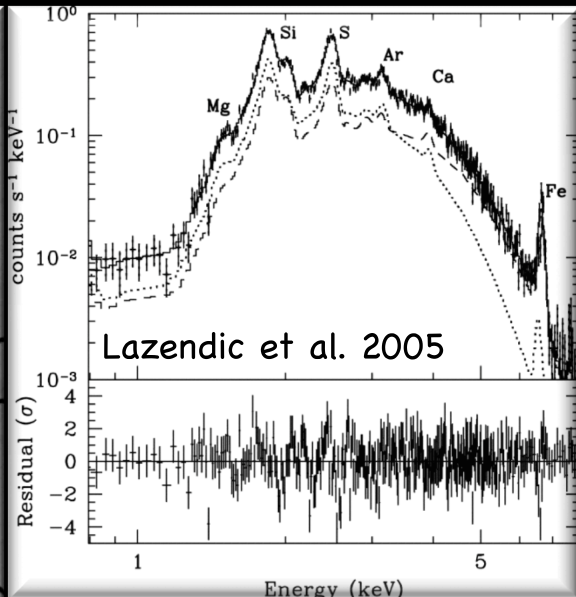
G349.7+0.2



- G349.7+0.2 is a small-diameter SNR with high radio surface brightness
- HI absorption measurements indicate a distance of 22 kpc
  - one of the most luminous SNRs in the Galaxy

G349.7+0.2

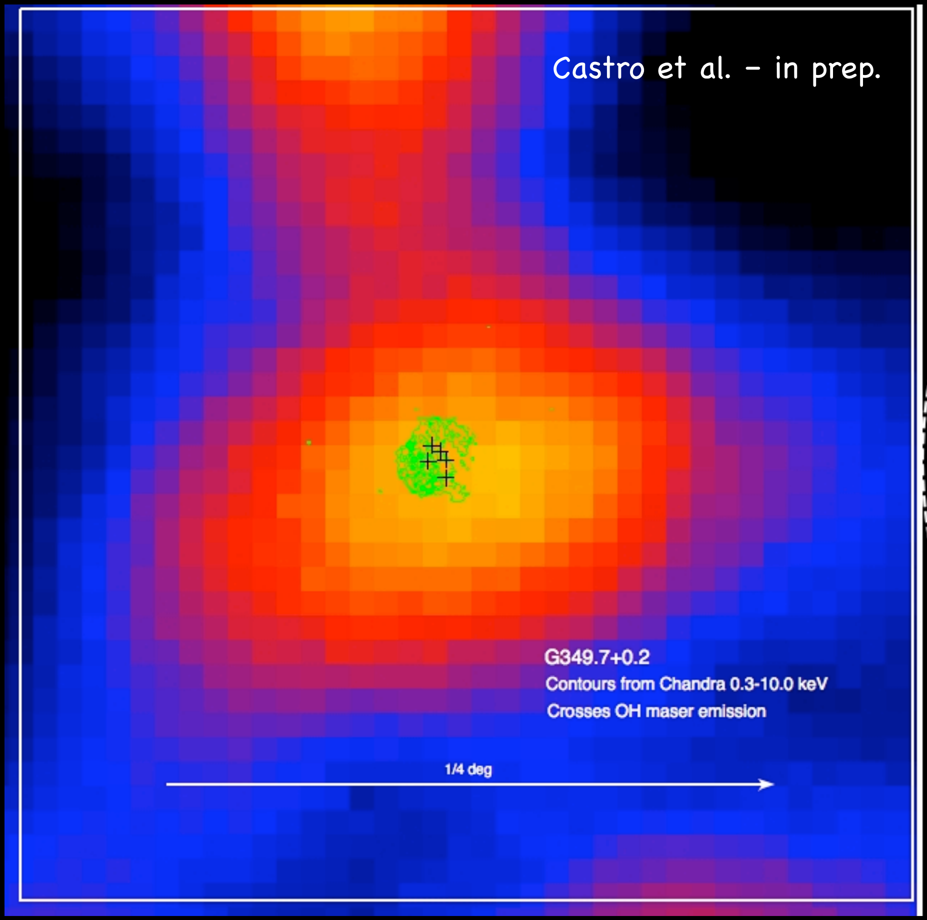


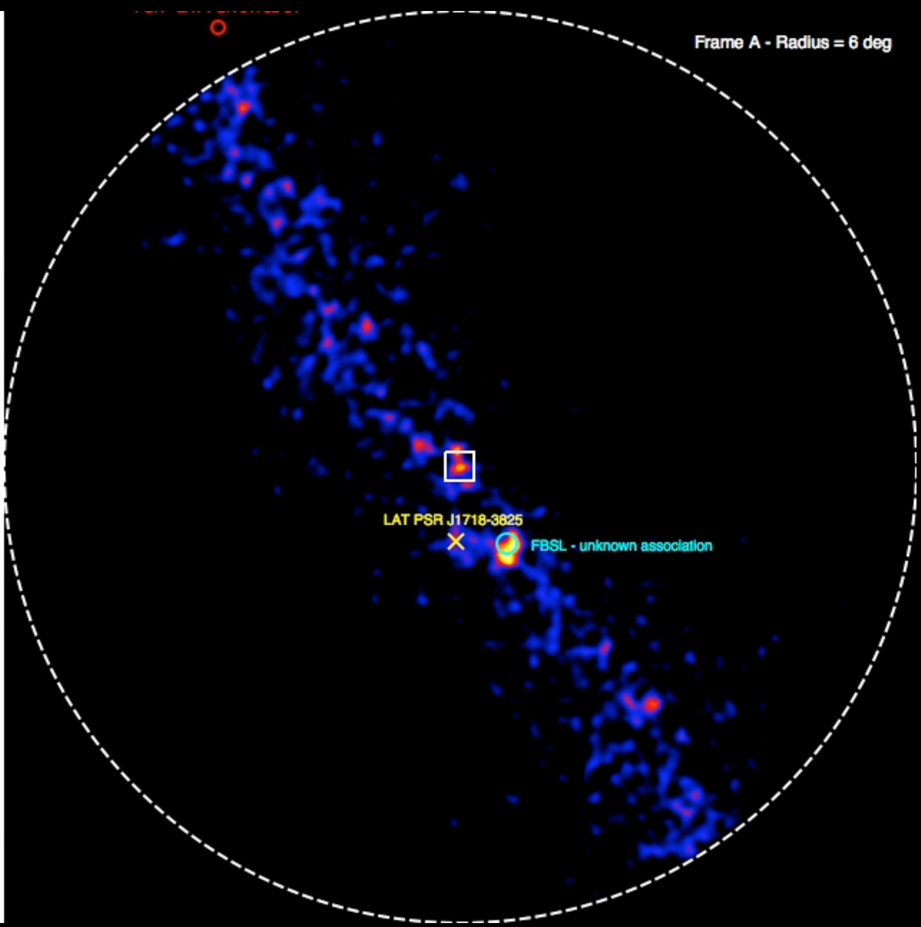


- G349.7+0.2 is a small-diameter SNR with high radio surface brightness
- HI absorption measurements indicate a distance of 22 kpc
  - one of the most luminous SNRs in the Galaxy
- CO emission reveals nearby MC
  - OH masers at v = 16 km s^{-1} confirm SNR shock-cloud interactions

- X-ray spectrum is dominated by bright thermal emission (Lazendic et al. 2005)
  - consistent with interaction with high density surroundings
  - high temperature suggestions fast shocks ⇒ efficient particle acceleration

G349.7+0.2



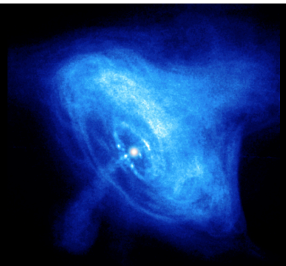


- Fermi LAT detects emission associated with G349.7+0.2 (Castro et al. – in prep)
  - likely evidence of π^0-decay γ-rays from p-p collisions in molecular cloud

Gamma-Ray Emission from PWNe

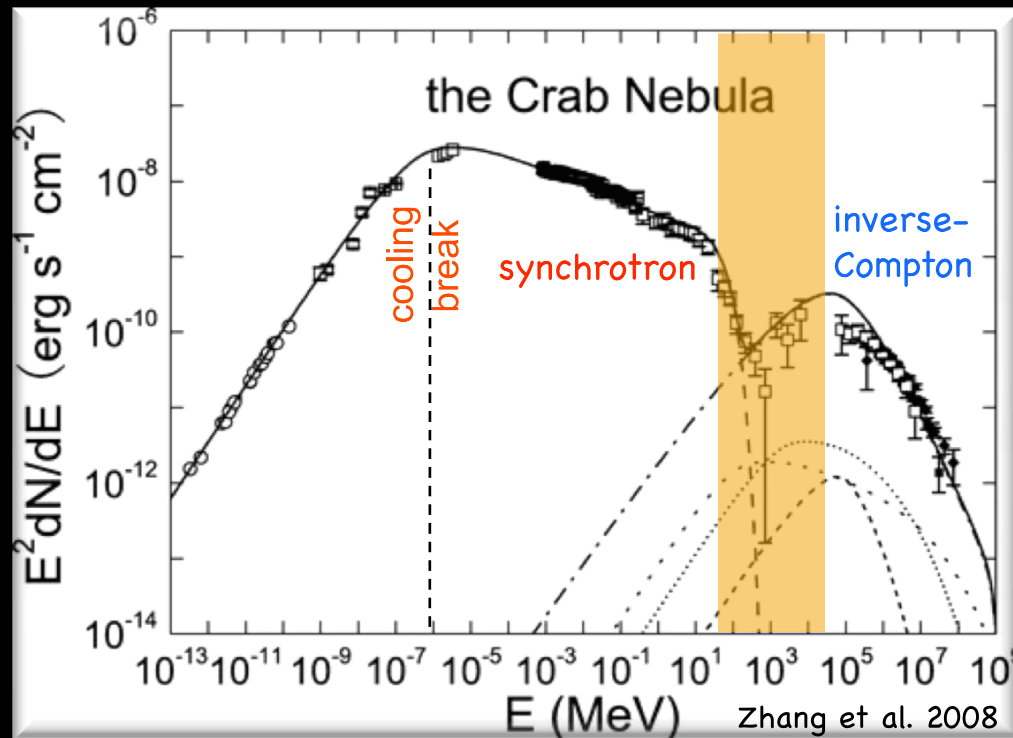
Gamma-ray emission depends on (and thus constrains):

- PWN age
- maximum particle energy (depends on properties of both pulsar and nebula)
- magnetic field (decreases with time, allowing high-E particles injected at late phases to persist; also introduces loss breaks)
- ambient photon field (synchrotron self-Compton can be important)
- breaks in injection spectrum



Broadband Emission from PWNe

- Get synchrotron and IC emission from electron population & evolved B field
- Spin-down power is injected into PWN at time-dependent rate
  - results in spectral break that propagate to lower energy with time
- Based on studies of Crab Nebula, there may be two distinct particle populations
  - relic radio-emitting electrons and those electrons injected in wind



- Fermi observations can provide constraints on maximum particle energies via synchrotron radiation, and on lower energy particles via IC emission

Connecting the Synchrotron and IC Emission

- Energetic electrons in PWNe produce both synchrotron and inverse-Compton emission
  - for electrons with energy E_{TeV},

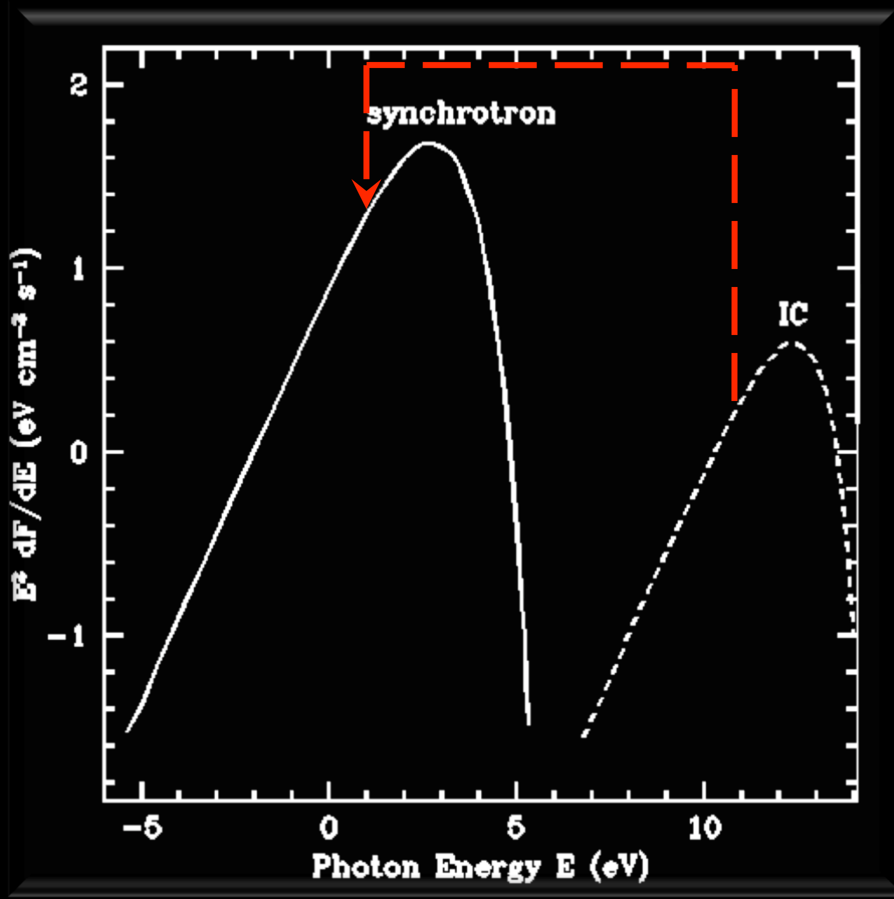
$$\varepsilon^{s}_{keV} \approx 2\times 10^{-4} E^{2}_{TeV} B_{-5}$$ synchrotron

$$\varepsilon^{ic}_{TeV} \approx 3\times 10^{-3} E^{2}_{TeV}$$ inverse-Compton

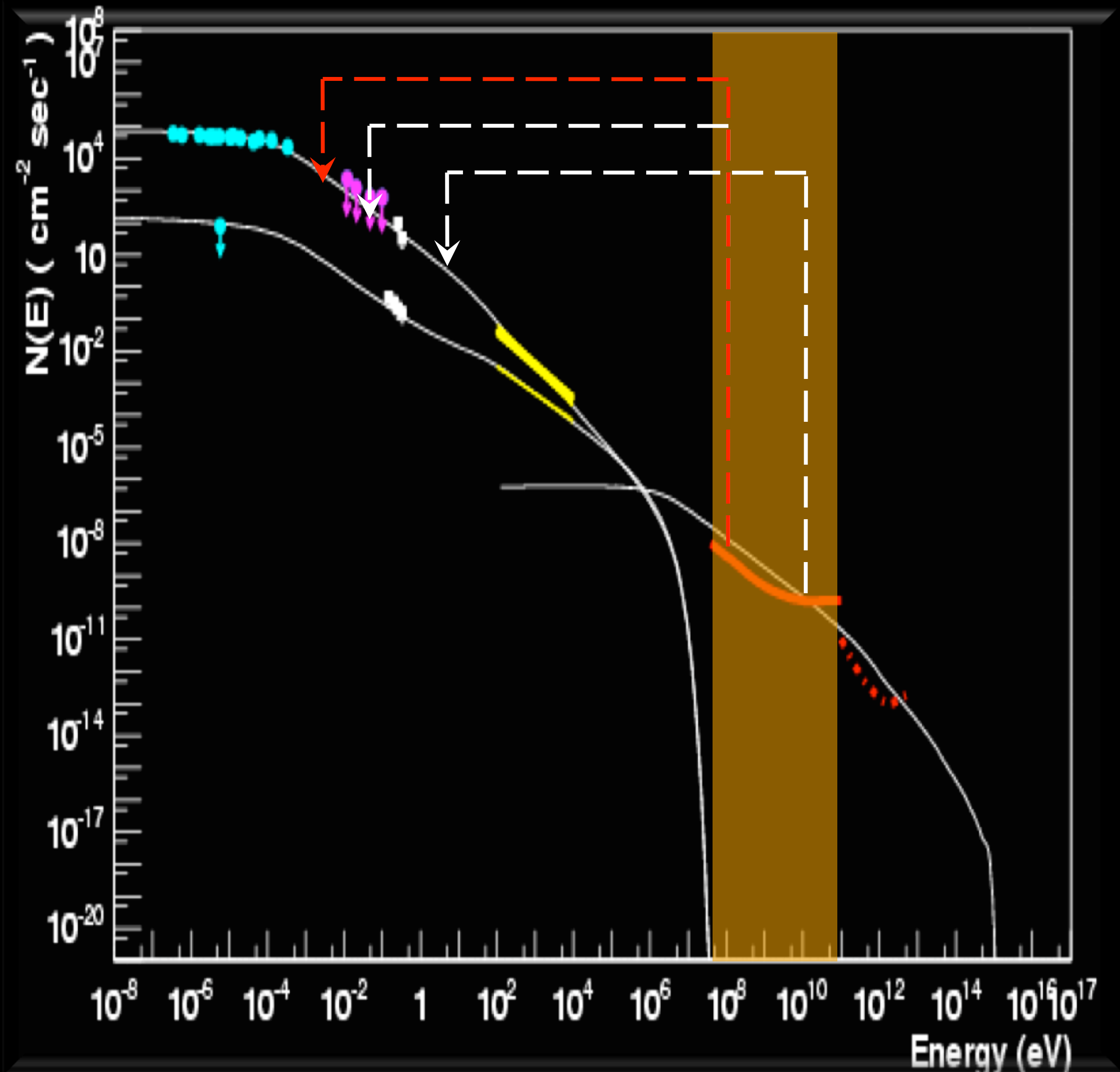
- Magnetic field strength links IC photons with synchrotron photons from same electrons

$$\varepsilon^{s}_{keV} \approx 0.06 \varepsilon^{ic}_{TeV} B_{-5}$$

- For low B, γ-ray emission probes electrons with lower energies than those that produce X-rays
  - γ-ray studies fill crucial gap in broadband spectra of PWNe

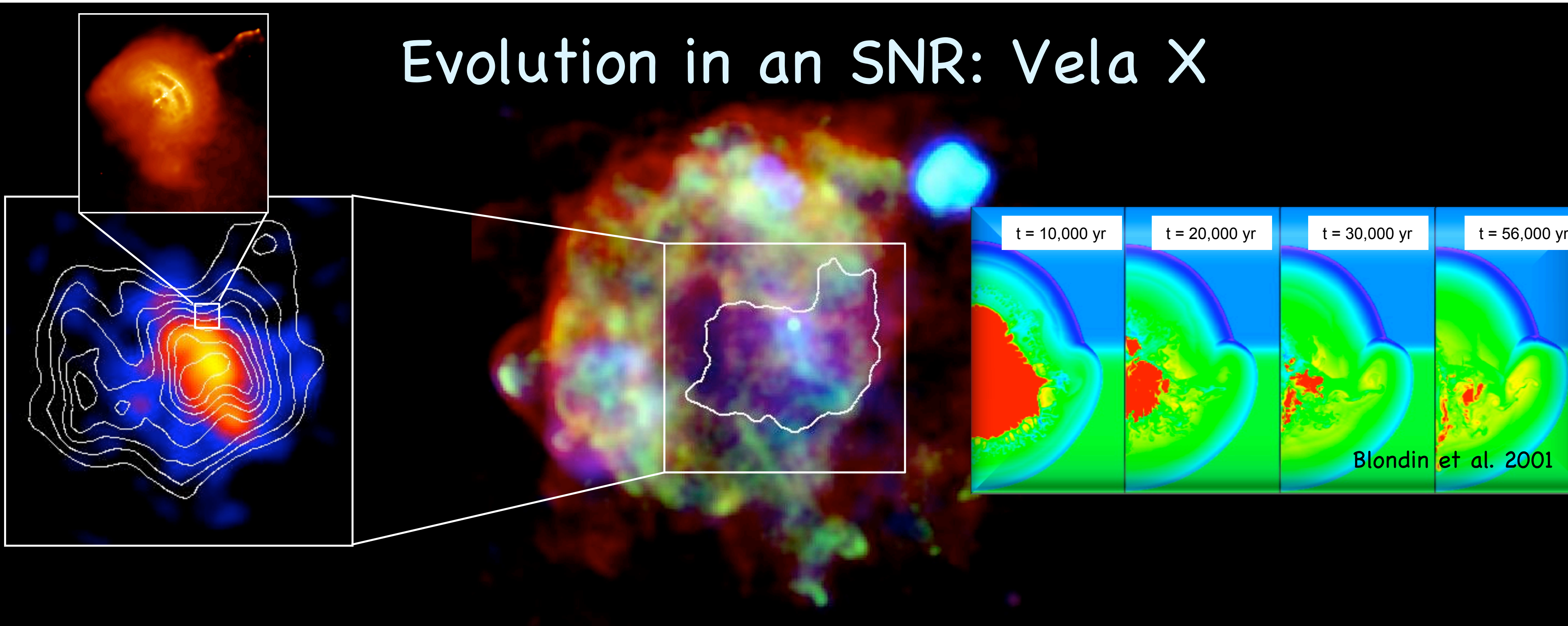


Fermi Studies of 3C 58



- Low-frequency break suggests possible break in injection spectrum
- Torus spectrum requires change in slope between IR and X-ray bands
  - challenges assumptions for single power law for injection spectrum
- Fermi LAT band probes CMB IC emission from ~0.6 TeV electrons
  - this probes electrons from the unseen synchrotron region around E^{syn} = 0.4 eV where injection is particularly complex

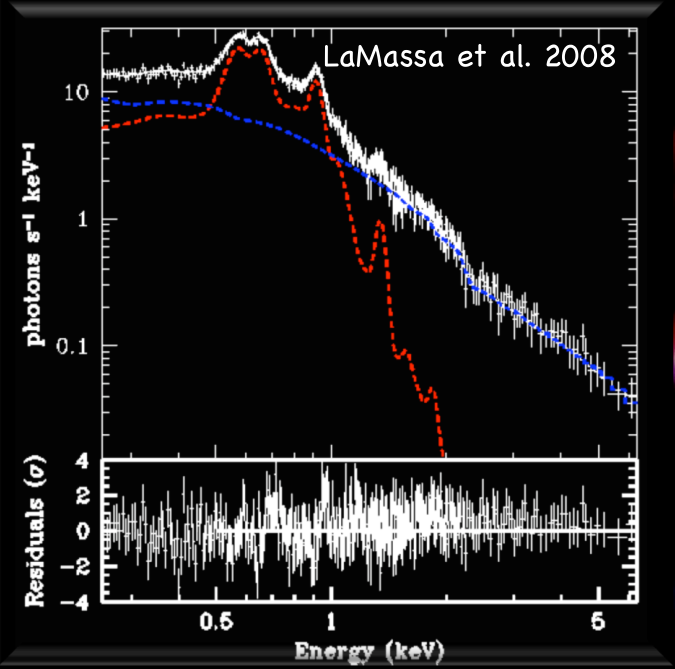
Evolution in an SNR: Vela X

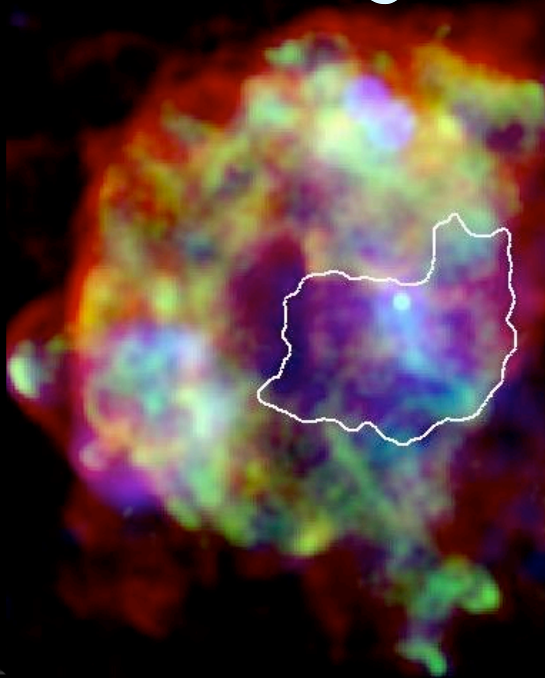


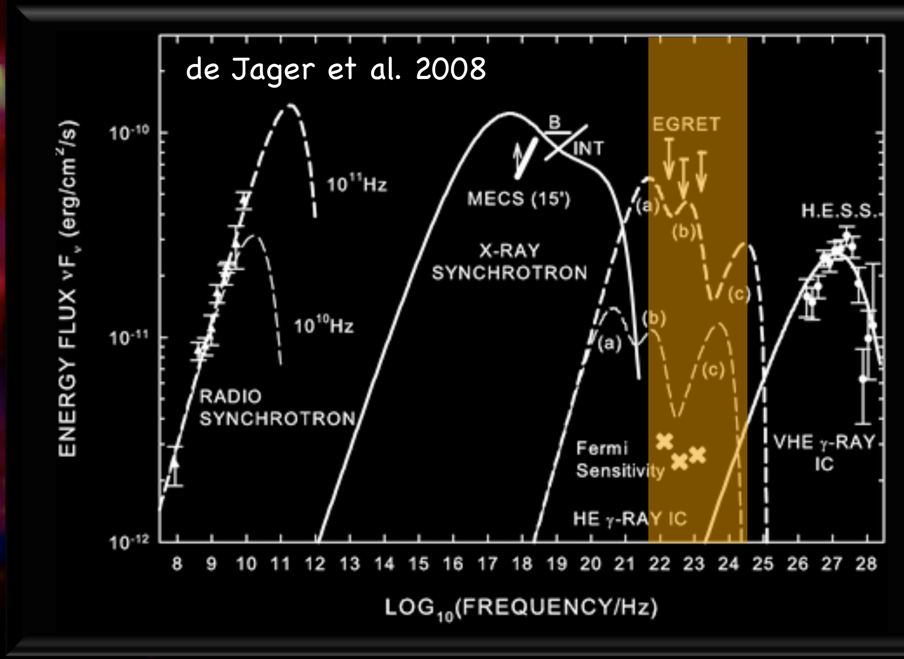
- Vela X is the PWN produced by the Vela pulsar
  - apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock

- Elongated "cocoon-like" hard X-ray structure extends southward of pulsar
  - clearly identified by HESS as an extended VHE structure
  - this is not the pulsar jet

Understanding Vela X: Fermi



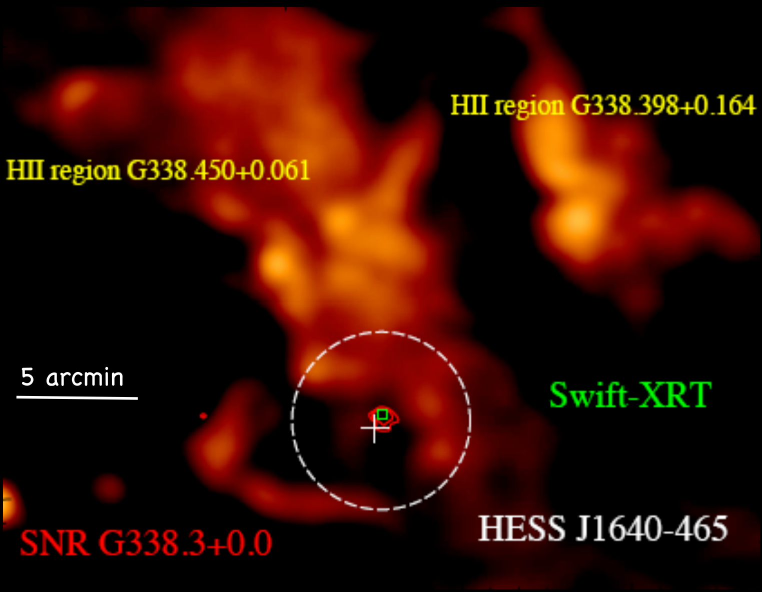


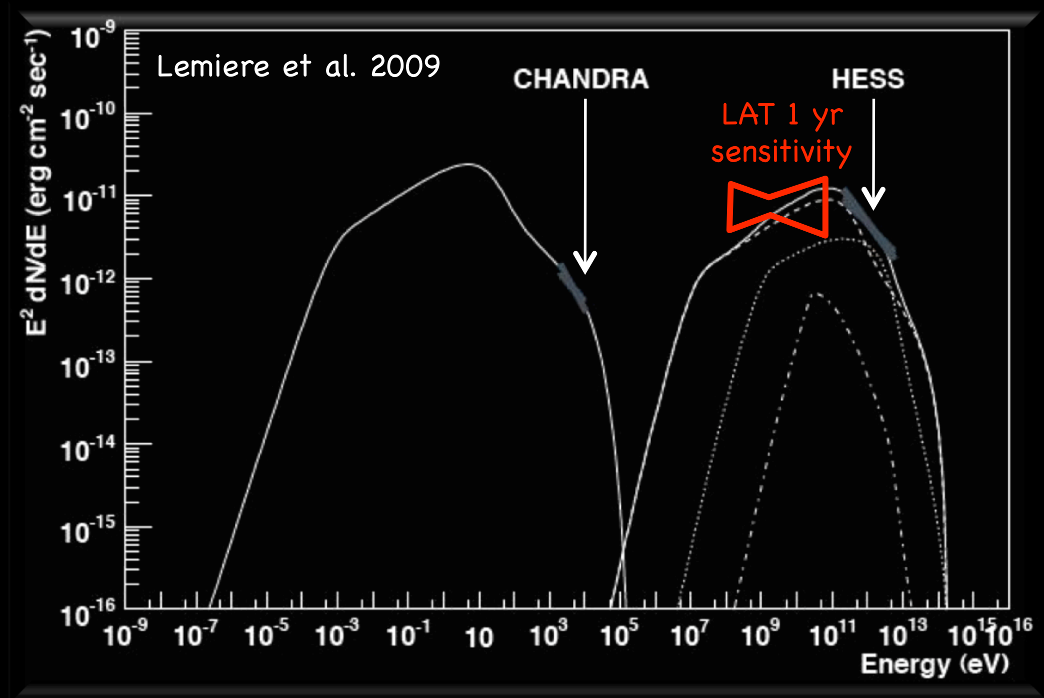


- Broadband spectrum for PWN suggests two distinct electron populations and very low magnetic field (~5 μG)
  - radio-emitting population will generate IC emission in LAT band
  - spectral features may identify distinct photon population and determine cut-off energy for radio-emitting electrons

See Talk by Marianne Lemoine-Goumard

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
  - example of late-phase of PWN evolution: X-ray faint, but γ-ray bright

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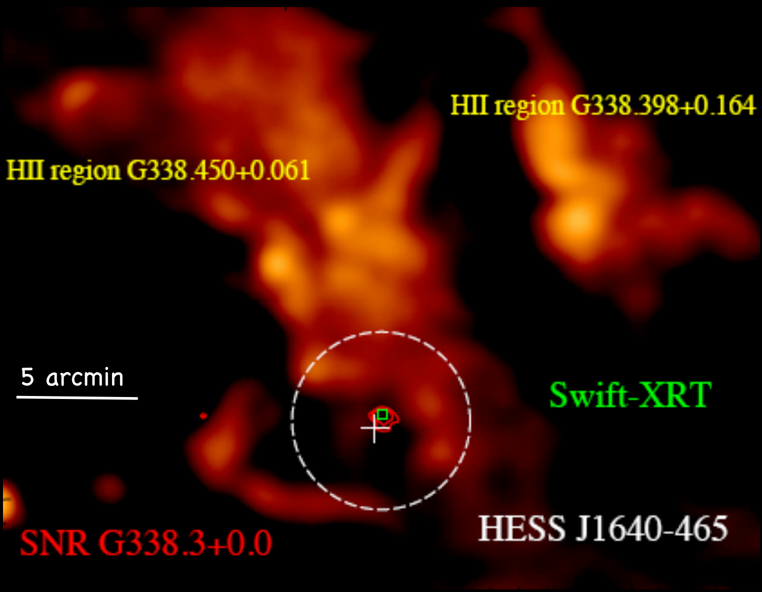

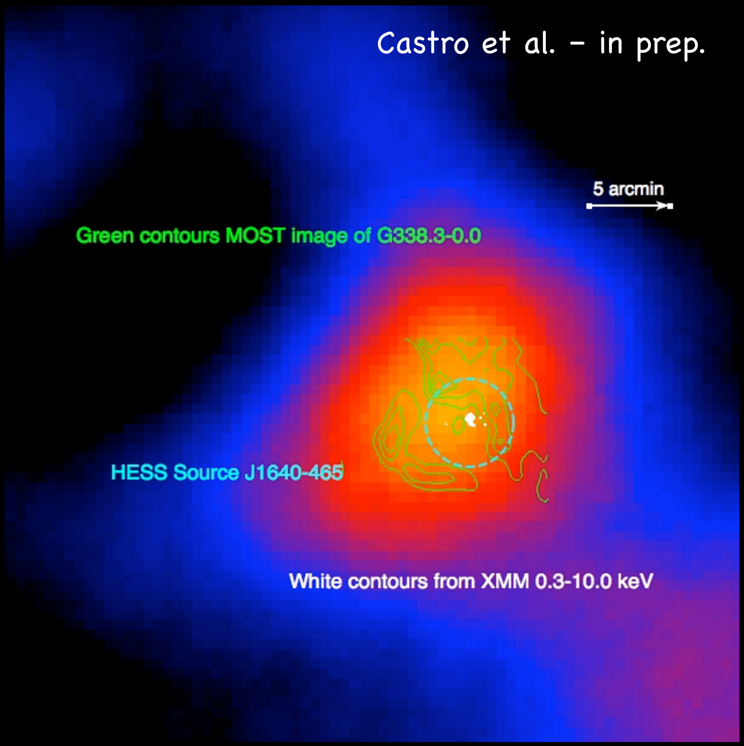

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  - example of late-phase of PWN evolution: X-ray faint, but γ-ray bright
- Fermi LAT reveals extended emission associated with source (Castro et al. – in prep.)
  - flux appears consistent with PWN model predictions

Conclusions

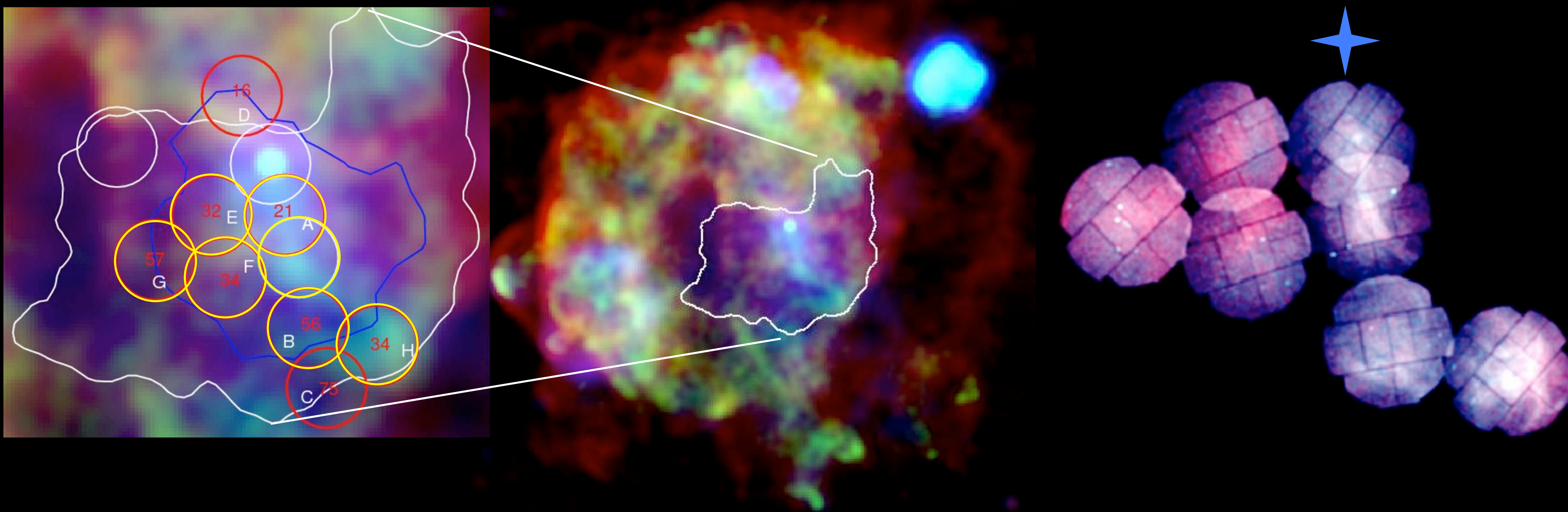
- SNRs are efficient particle accelerators, leading to γ-ray emission from both hadronic and leptonic processes
  - the associated spectra strongly constrain fundamental parameters of particle acceleration processes; Fermi LAT observations will help differentiate between emission mechanisms

- SNRs interacting with dense clouds are particularly strong candidates for γ-ray emission
  - Fermi has already detected several, and more are being uncovered

- PWNe are reservoirs of energetic particles injected from pulsar
  - synchrotron and inverse-Compton emission places strong constraints on the underlying particle spectrum and magnetic field

- Fermi LAT has sensitivity and resolution to probe underlying electron spectrum in crucial energy regimes
  - observations of PWNe will complement multi-λ studies to constrain the structure and evolution of PWNe

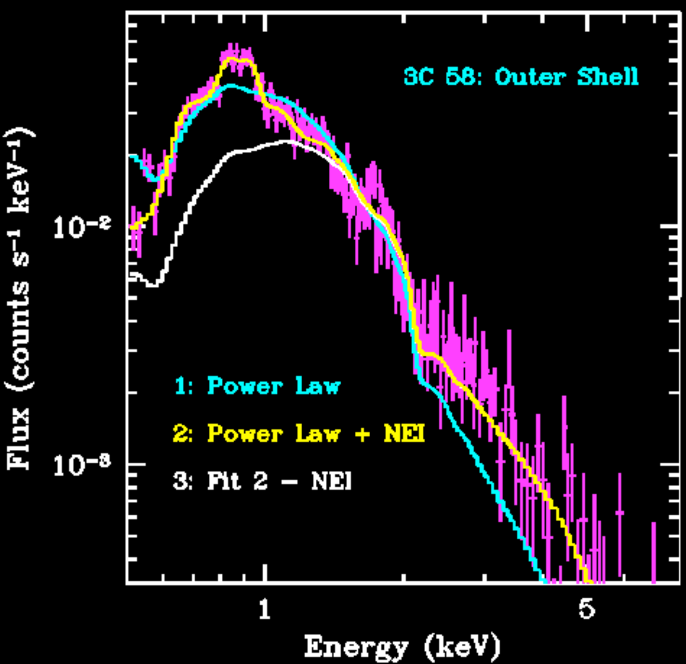
Understanding Vela X: XMM



- Broadband spectrum for PWN suggests two distinct electron populations
  - radio-emitting population will generate IC emission in LAT band
  - spectral features will identify distinct photon population and determine cut-off energy for radio-emitting electrons

- XMM large project (400 ks) to study ejecta and nonthermal emission now underway; images reveal considerable structure and spectral variation

The Surrounding Ejecta: 3C 58



- Chandra reveals complex structure of wind shock zone and surroundings
- Spectrum reveals ejecta shell with enhanced Ne and Mg
  - PWN expansion sweeps up and heats cold ejecta
- Mass and temperature of swept-up ejecta suggests an age of ~2400 yr and a Type IIp progenitor, similar to that for Crab (Chevalier 2005)
- Temperature appears lower than expected based on radio/optical data