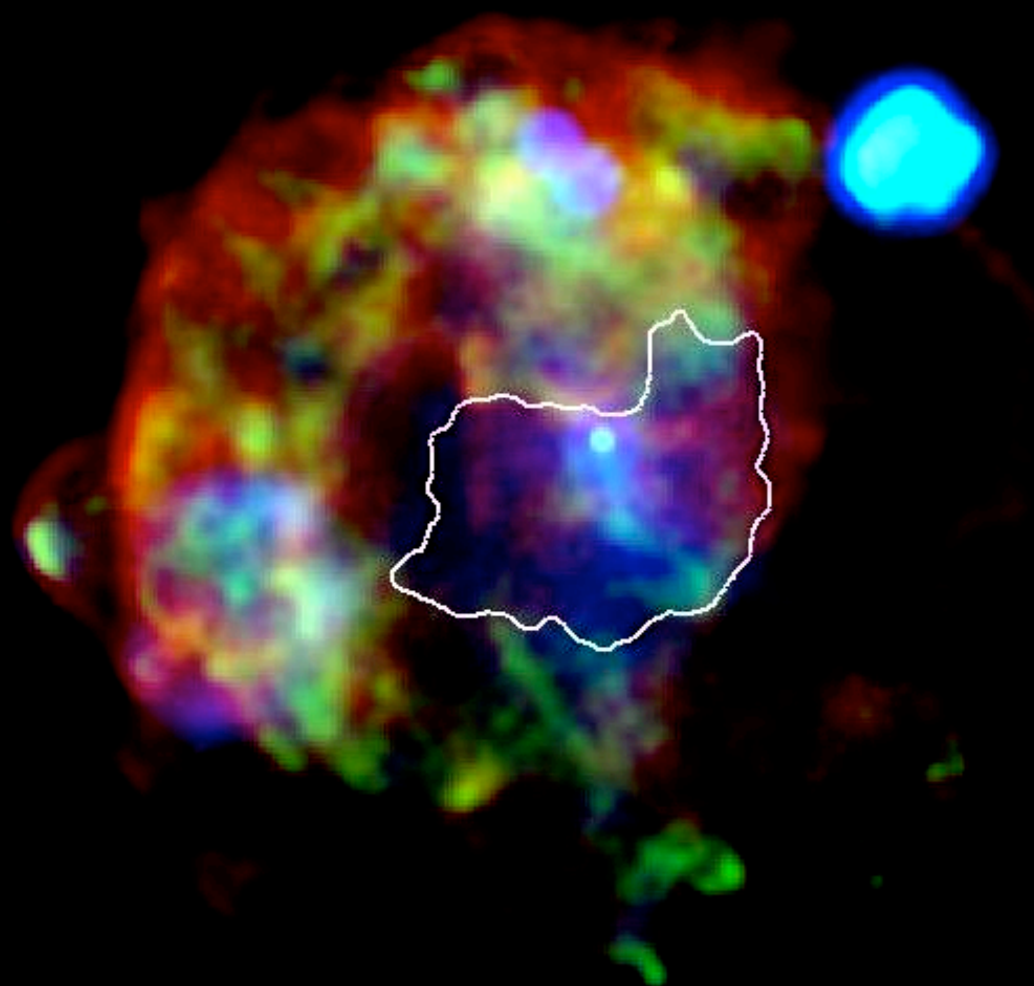
Gamma-rays From Supernova Remnants



and Pulsar Wind Nebulae

Start With a Caveat

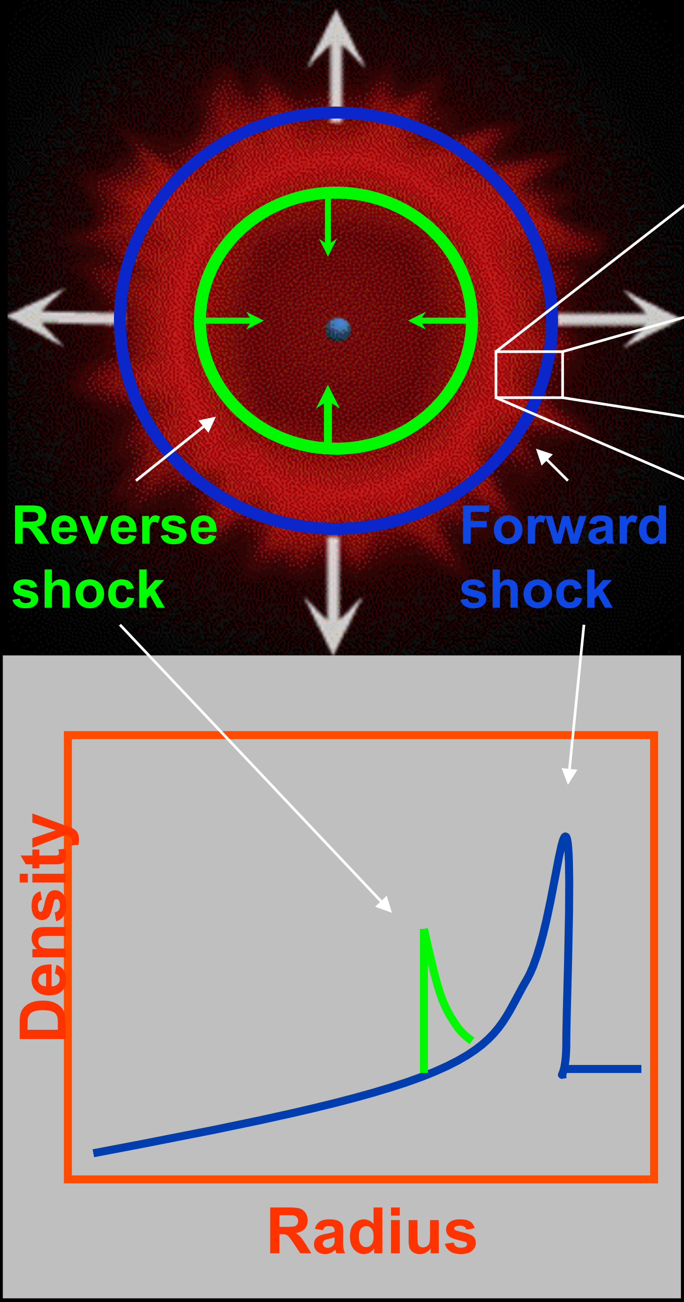
This is not a literature review. There is a huge body of work on both theoretical and observational areas in these fields, and I haven't tried to capture or summarize that here.

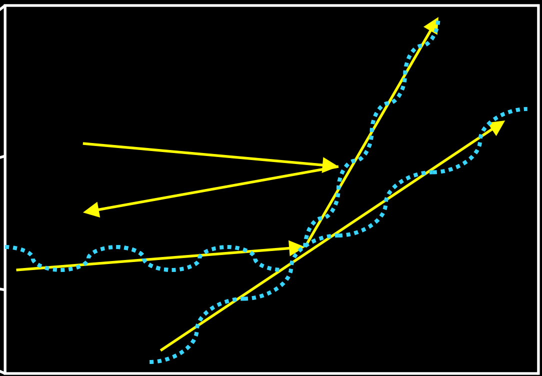
Sorry.

As a starting point, see ARAA reviews by Reynolds (2008) and Gaensler & Slane (2006) for a pretty good list of references to work backward. Note that these are both pre-Fermi! To work forward to recent work, use ADS to study newer citations to those references. There are a lot.

Now for some background and highlights...

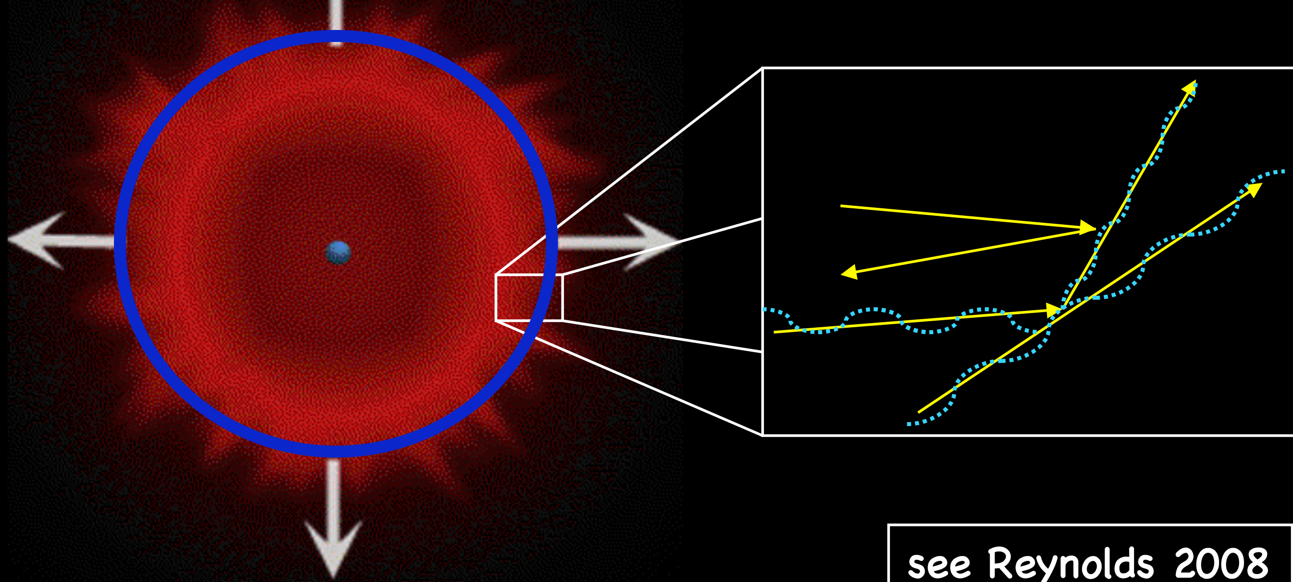
Supernova Remnants





- Explosion blast wave sweeps up CSM/ISM in forward shock
  - spectrum shows abundances consistent with solar or with progenitor wind
- As mass is swept up, forward shock decelerates and ejecta catches up; reverse shock heats ejecta
  - spectrum is enriched w/ heavy elements from hydrostatic and explosive nuclear burning
- Streaming particles create turbulence, off of which other particles scatter and return to shock
  - build up population of accelerated electrons and ions
  - maximum energy depends on acceleration age, losses, and escape

Diffusive Shock Acceleration



- Particles scatter from MHD waves in background plasma
  - pre-existing, or generated by streaming ions themselves

see Reynolds 2008

- Maximum energies determined by either:

  age – finite age of SNR (and thus of acceleration)

  $$E_{\max}(\text{age}) \sim 0.5 v_8^2 t_3 B_{\mu G} (\eta R_J)^{-1}\,\text{TeV}$$

  radiative losses (synchrotron; electrons)

  $$E_{\max}(\text{loss}) \sim 100 v_8 (B_{\mu G} \eta R_J)^{-1/2}\,\text{TeV}$$

  escape – scattering efficiency decreases w/ energy

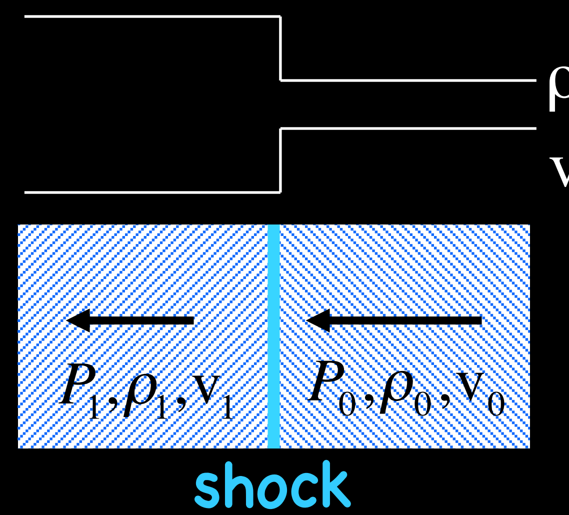
  $$E_{\max}(\text{escape}) \sim 20 B_{\mu G} \lambda_{17}\,\text{TeV}$$

Electrons:
- large B lowers max energy due to synch. losses

Ions:
- large B increases max energy (needed to get to hadrons to knee of CR spectrum)

<u>Current observations suggest high B fields</u>

Shocks in SNRs



- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with γ=5/3)

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

$$v_1 = \frac{\gamma-1}{\gamma+1} v_0 = \frac{v_0}{4}$$

$$v_{ps} = \frac{3 v_s}{4}$$

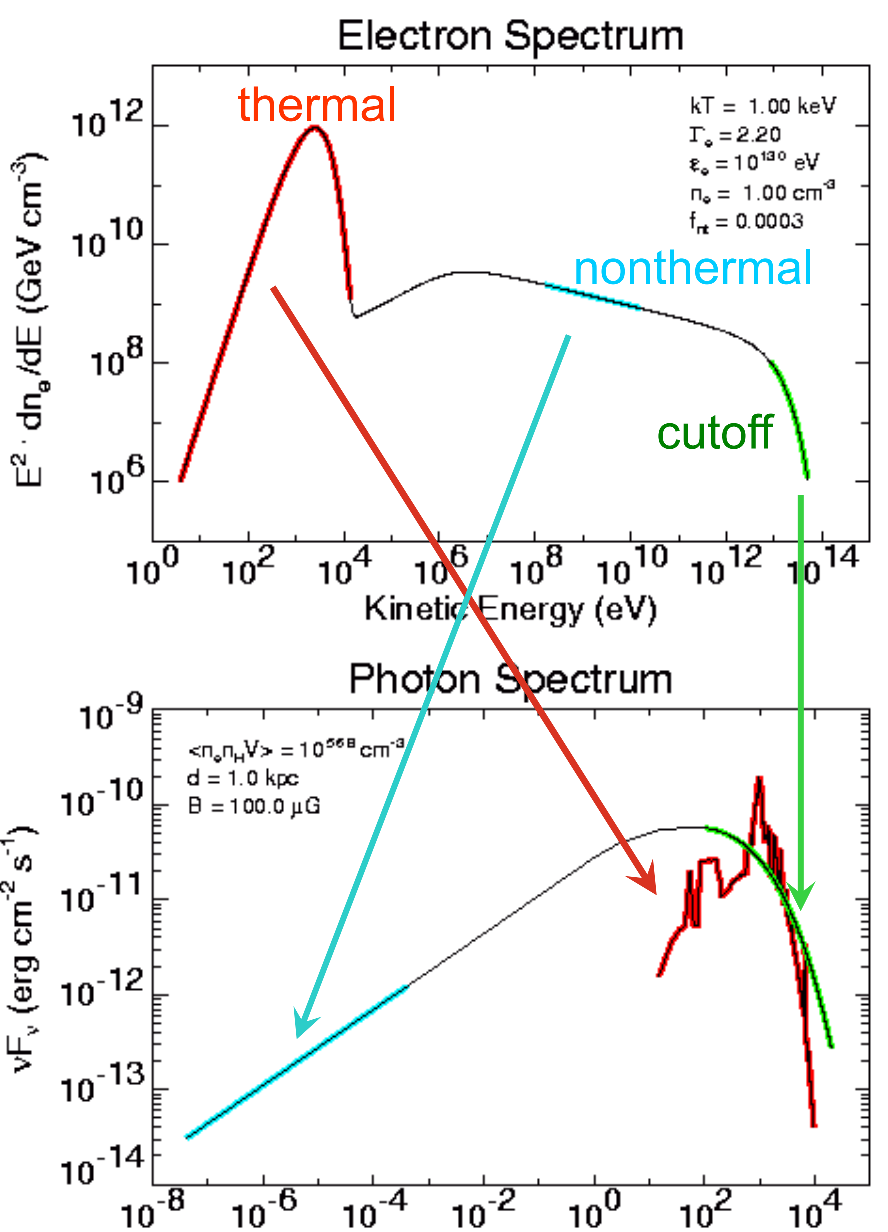
$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k} m_H v_0^2 = 1.3 \times 10^7 \, v_{1000}^2 \text{ K}$$

X-ray emitting temperatures

- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales

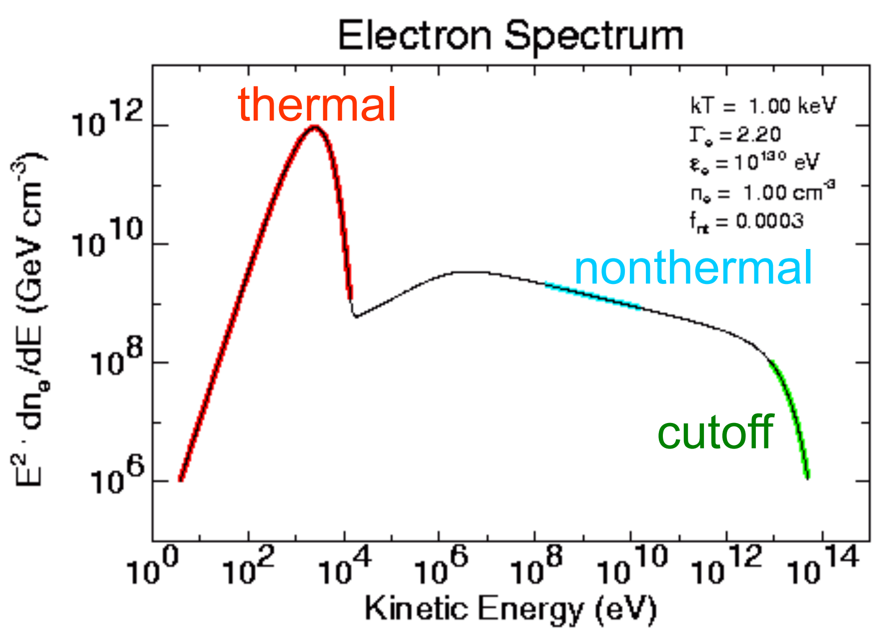
- If another form of pressure support is present (e.g., cosmic rays), <u>the temperature will be lower than this</u>

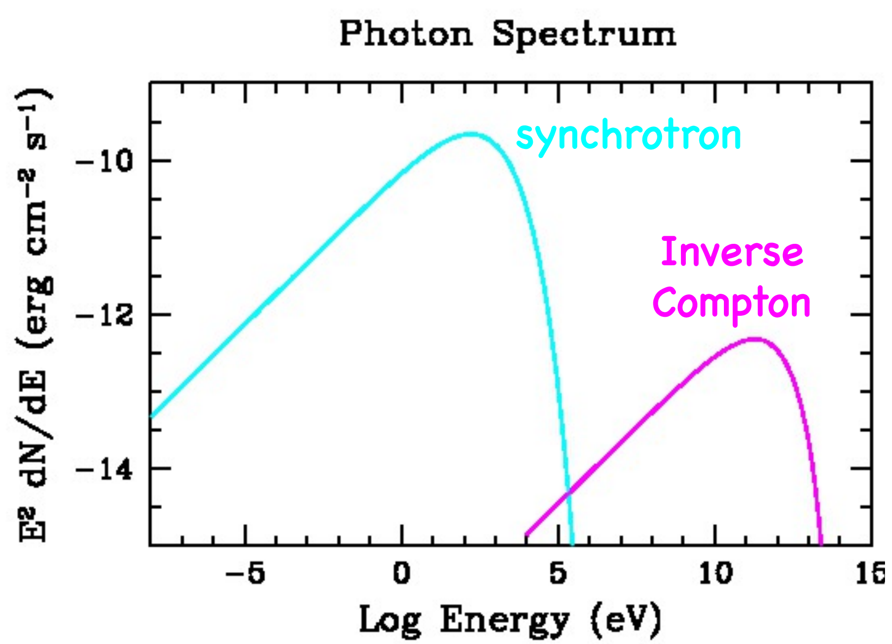
Shocked Electrons and their Spectra



Allen 2000

- Thermal electrons produce line-dominated x-ray spectrum with bremsstrahlung continuum
  - yields kT, ionization state, abundances
- nonthermal electrons produce synchrotron radiation over broad energy range
  - responsible for radio emission
- high energy tail of nonthermal electrons yields x-ray synchrotron radiation
  - rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and limits on energy of associated cosmic rays
  - large contribution from this component modifies dynamics of thermal electrons





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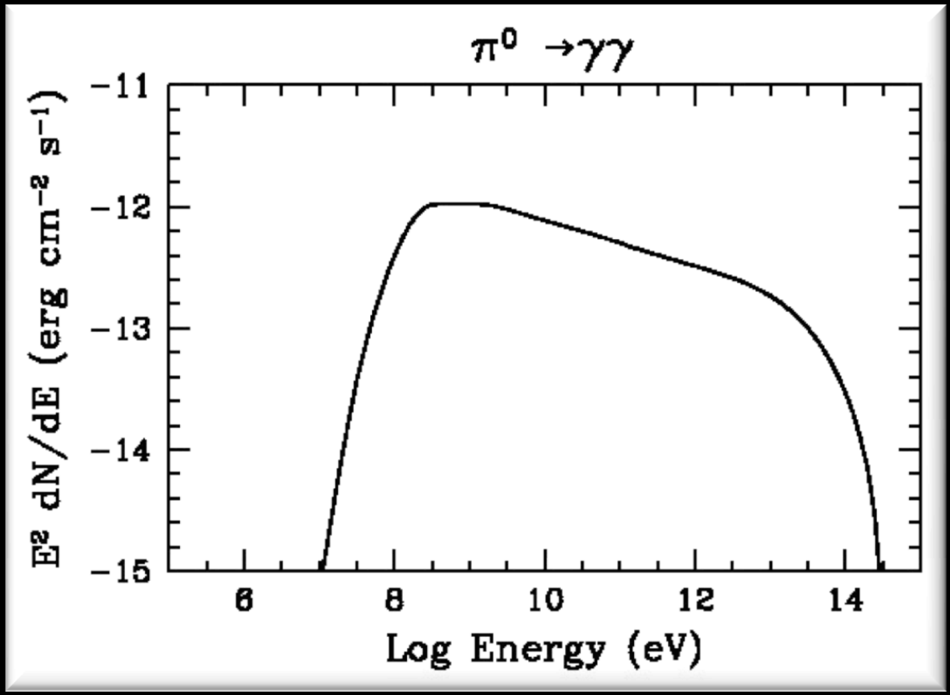
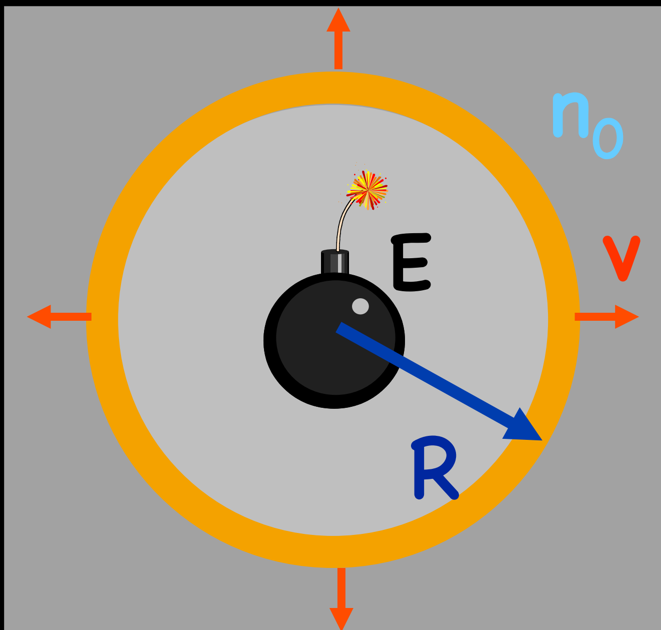
- energetic electrons upscatter ambient photons through inverse-Compton scattering
  - source of GeV/TeV γ-rays
  - field photons include CMB, starlight, dust IR

Shocked Protons and Their Spectra

- Protons (and other ions) are inefficient radiators
  - large mass reduces synchrotron and IC emission relative to electrons
  - difficult to detect (but hugely important, because they carry virtually all of the energy!)
- proton-proton collisions produce pions; neutral pions decay to γ-rays
  - for regions of high density, this component can dominate γ-ray emission, providing "direct" evidence of energetic hadrons
  - note that this has consequences for thermal X-ray emission as well



SNR Evolution: The Ideal Case



- Once sufficient mass is swept up (> 1-5 M_{ej}) SNR enters Sedov phase of evolution

$$t_{yr} = 470 R_{pc} T_7^{-1/2}$$

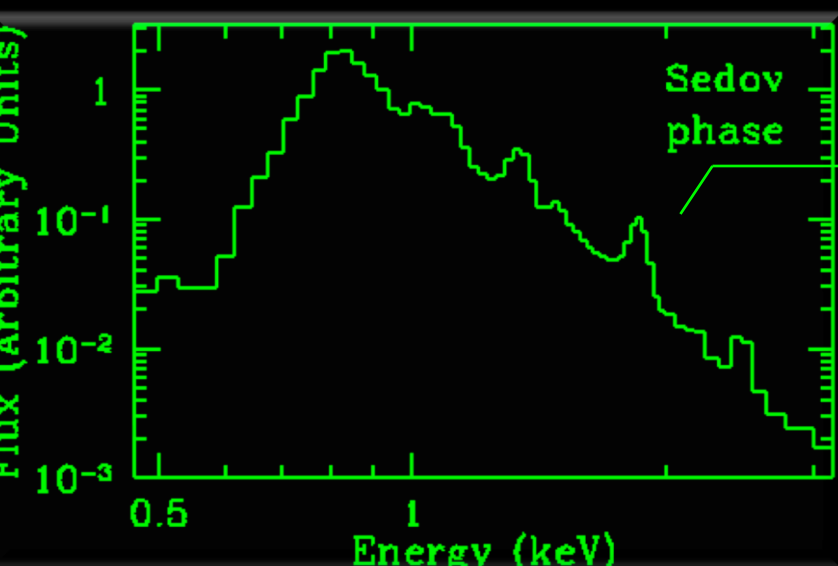
$$\frac{E_{51}}{n_0} = 340 R_{pc}^5 t_{yr}^{-2}$$

- X-ray measurements can provide temperature and density

$$EM = \int n_H n_e dV$$

$$T_x = 1.28 T_{shock}$$

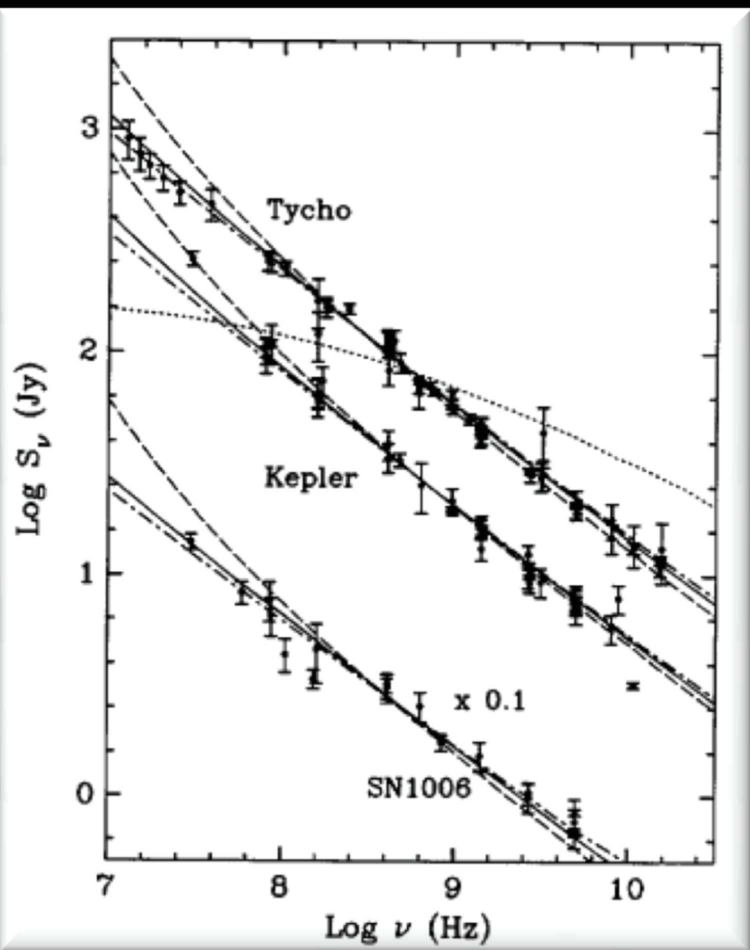
from spectral fits



- Sedov phase continues until kT ~ 0.1 keV

$$t_{rad} \approx 2.4 \times 10^4 \left(\frac{E_{51}}{n_0} \right)^{1/3} yr$$

Radio Emission from SNRs



- Synchrotron Radiation: $E_{GeV} = \left[\frac{\upsilon}{16\text{MHz}} B_{\mu G}^{-1}\right]^{1/2}$
  - for typical fields, radio emission is from GeV electrons
    Hint: for X-rays, $\nu > 10^{18}$ Hz ➔ >TeV electrons
  - PL spectra imply PL particle spectrum

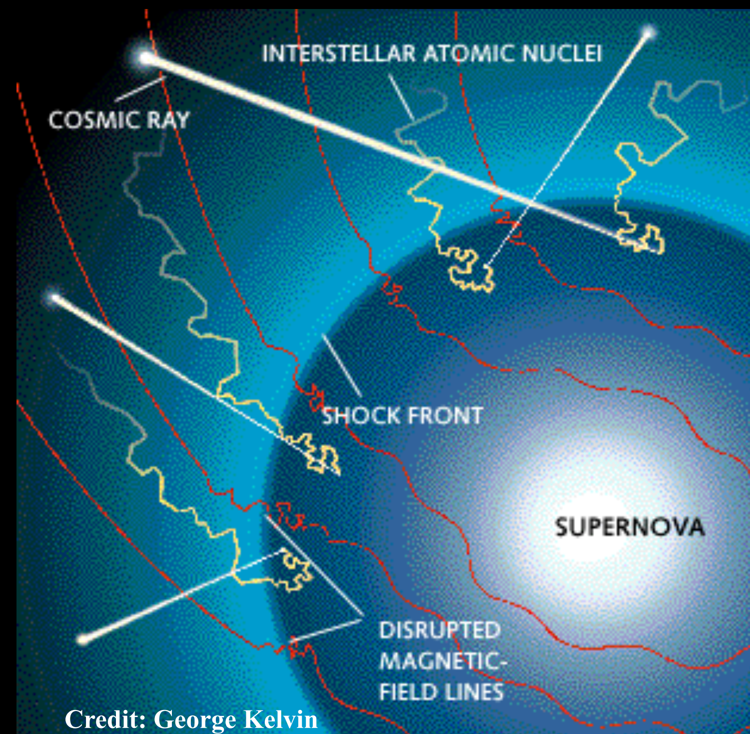
    $$dN = KE^{-\alpha} dE$$

    which gives

    $$f_\upsilon \propto \upsilon^{\left(-\frac{\alpha-1}{2}\right)}$$

  - shell-type SNRs have

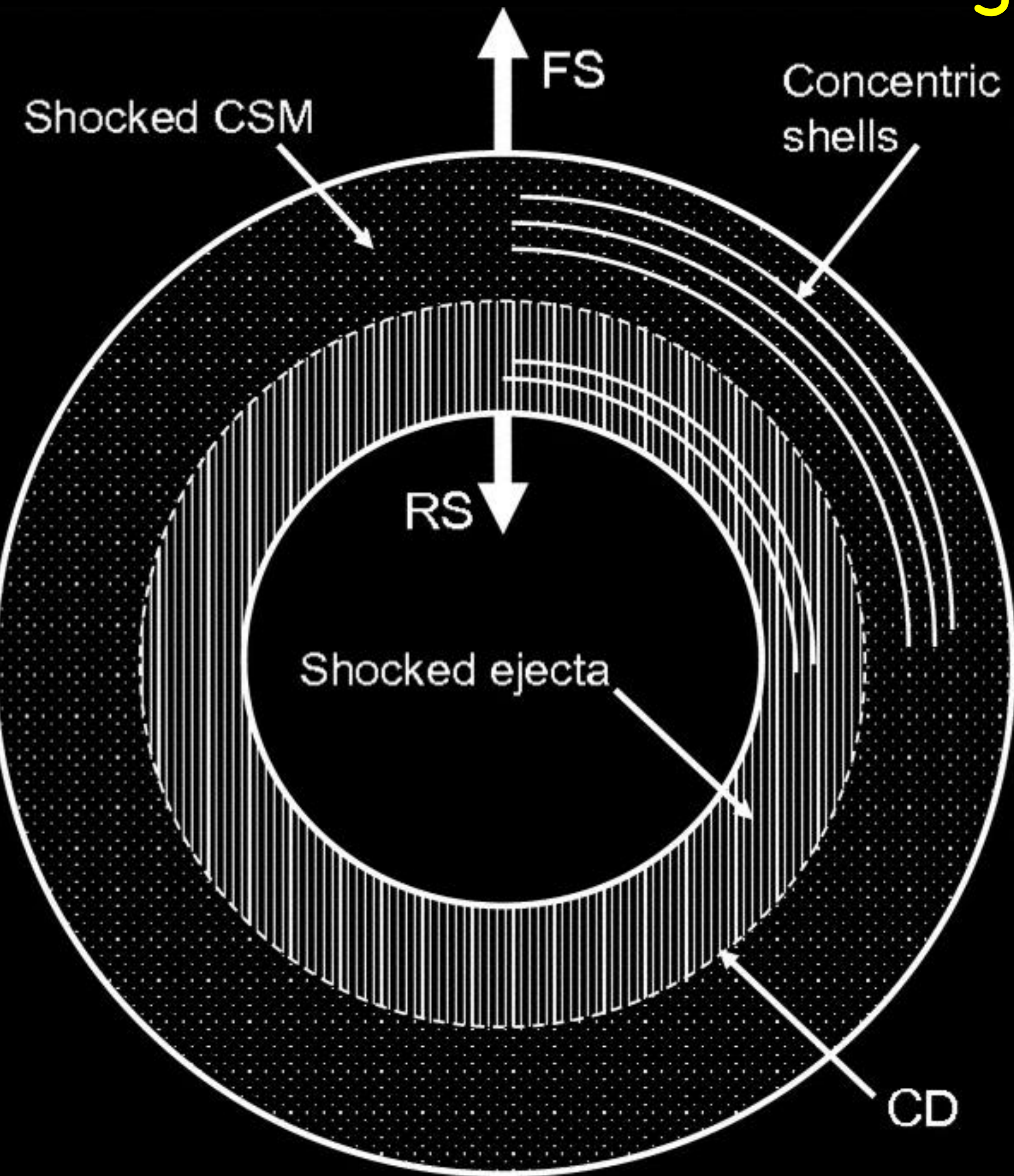
    $$f_\upsilon \propto \upsilon^{(-0.6)}$$



Credit: George Kelvin

or α = 2.2, similar to CR spectrum

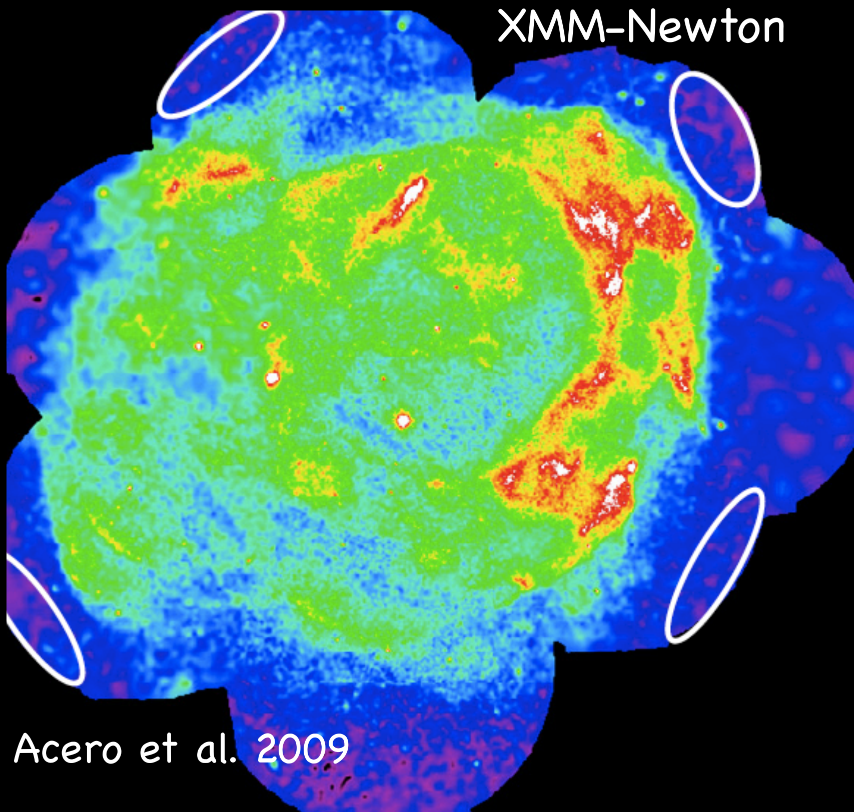
Modeling: CR-Hydro

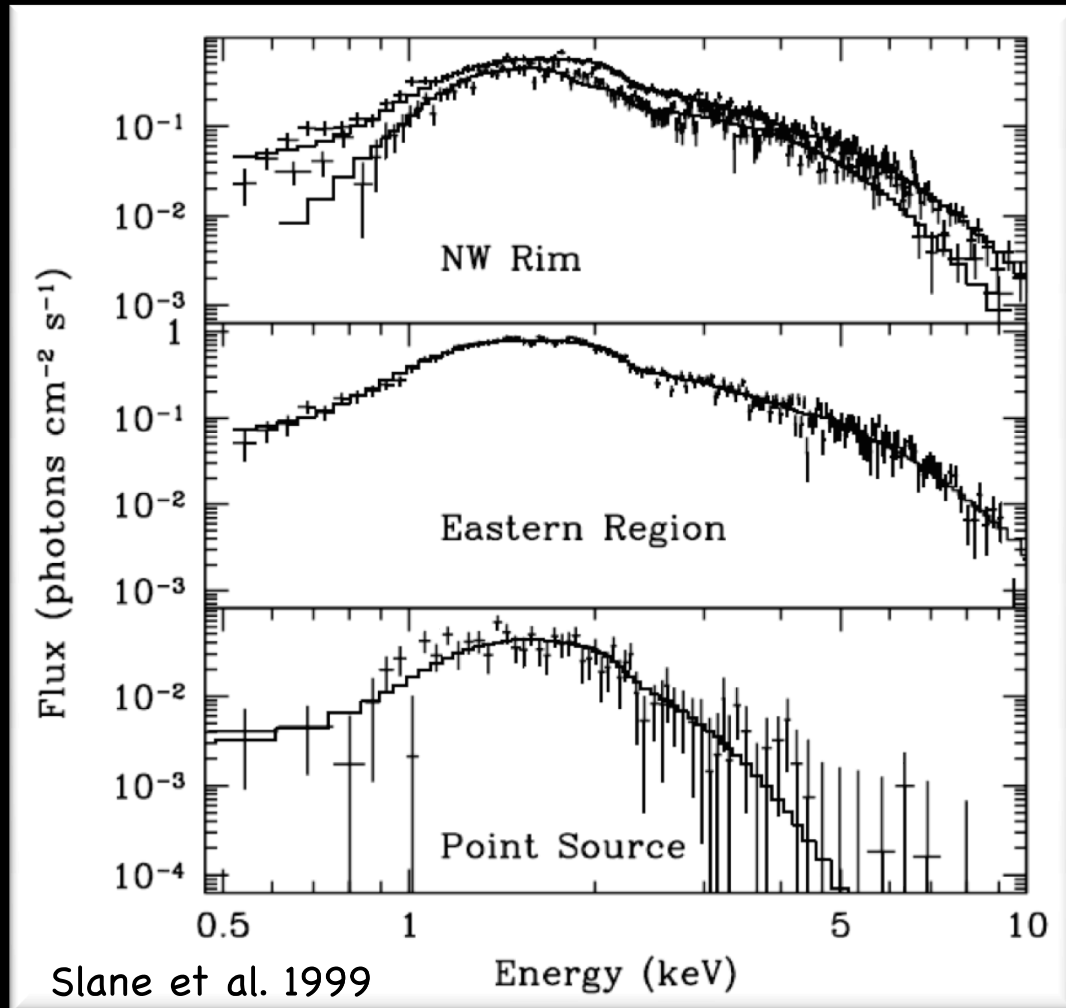


- semi-analytical calculation of DSA
- VH-1 hydrodynamics code to follow SNR evolution
- NEI calculation of ionization fractions from hydro
- plasma emissivity code for spectra
- emission from superthermal/relativistic particles
  - synchrotron
  - inverse Compton
  - nonthermal bremsstrahlung
  - pion-decay

Ellison et al. 2007
Patnaude et al. 2009
Ellison et al. 2010
Patnaude et al. 2010

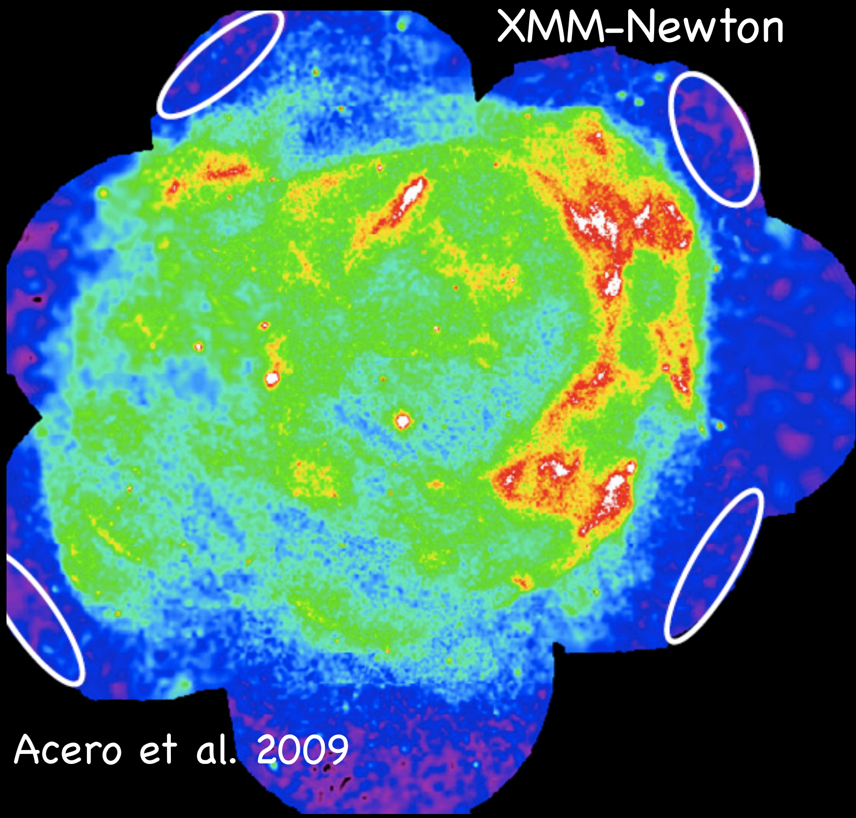
G347.3-0.5/RX J1713.7-3946

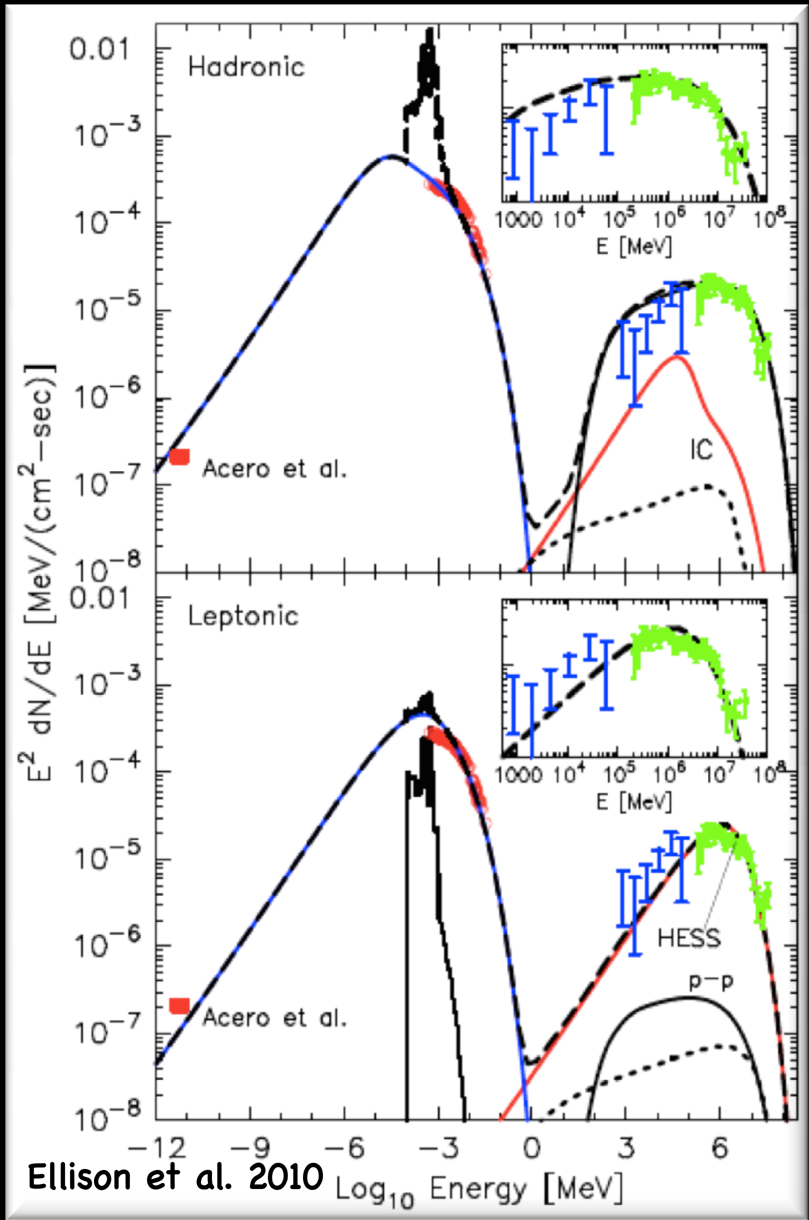




- X-ray spectrum from SNR is completely nonthermal
  - upper limits on thermal emission place strong constraints on density

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

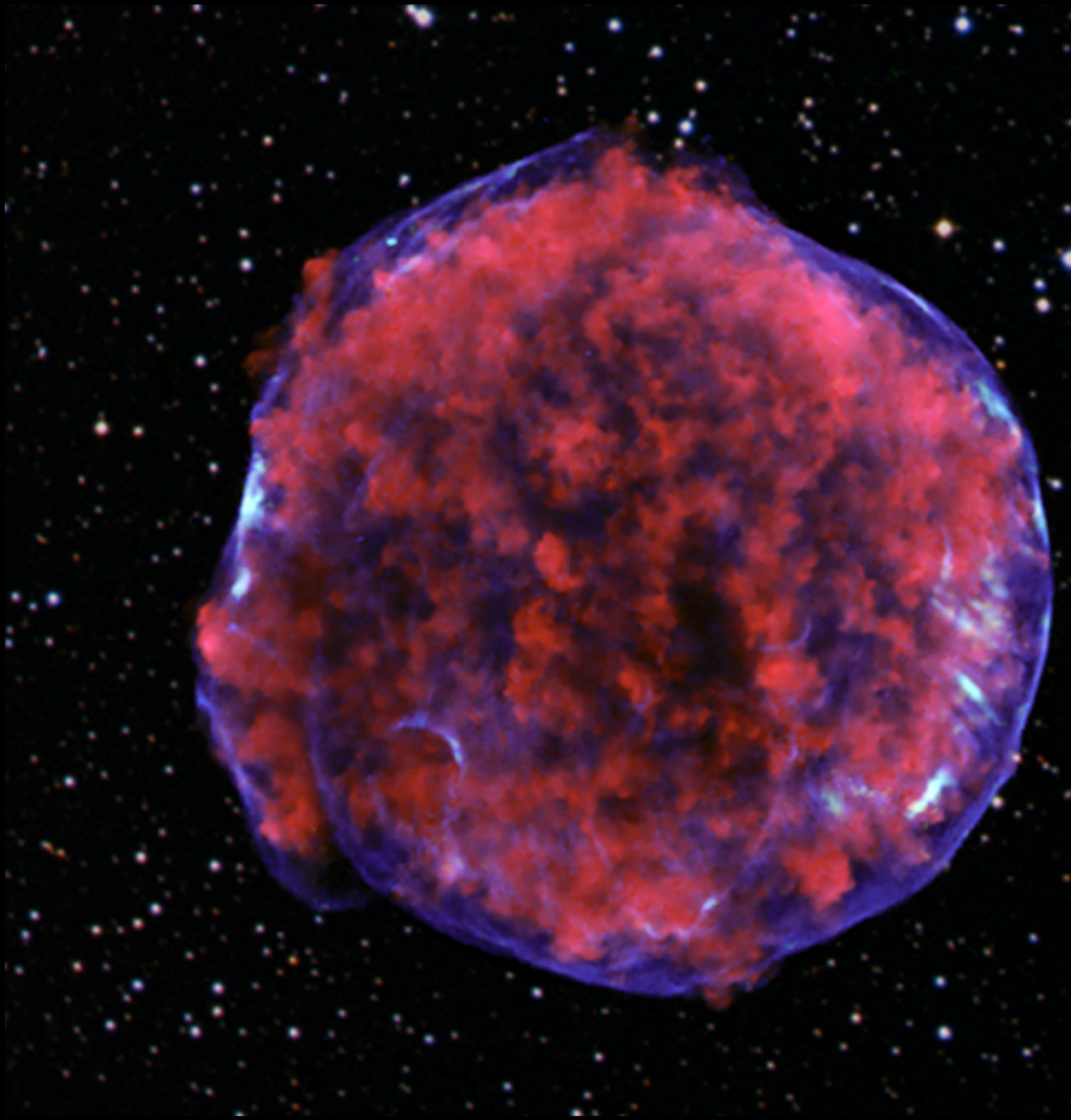




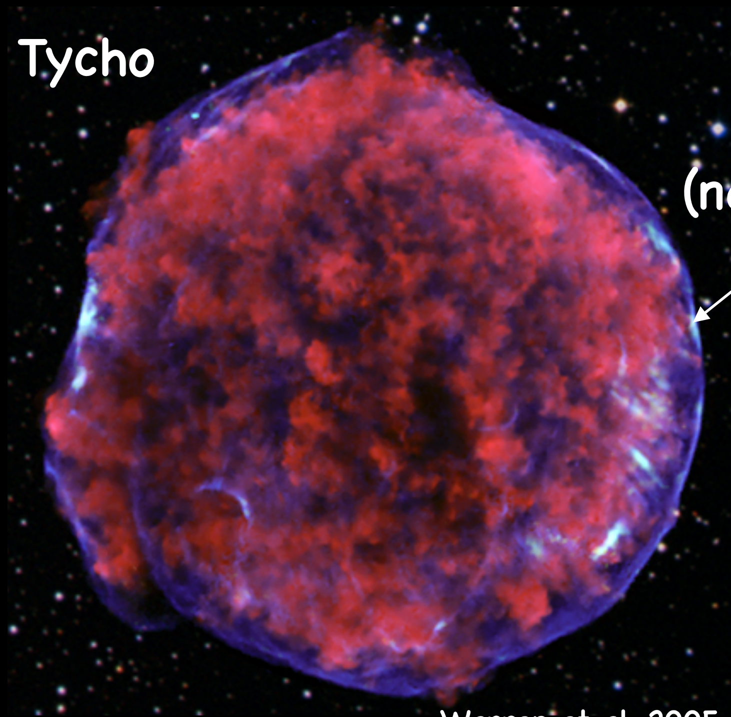
- Broadband modeling shows that, for expansion into a uniform ISM, γ-ray emission must be leptonic in origin
  - NOTE: This does NOT mean that energetic hadrons are not produced in such a model; they ARE!

Cosmic Rays from Tycho?

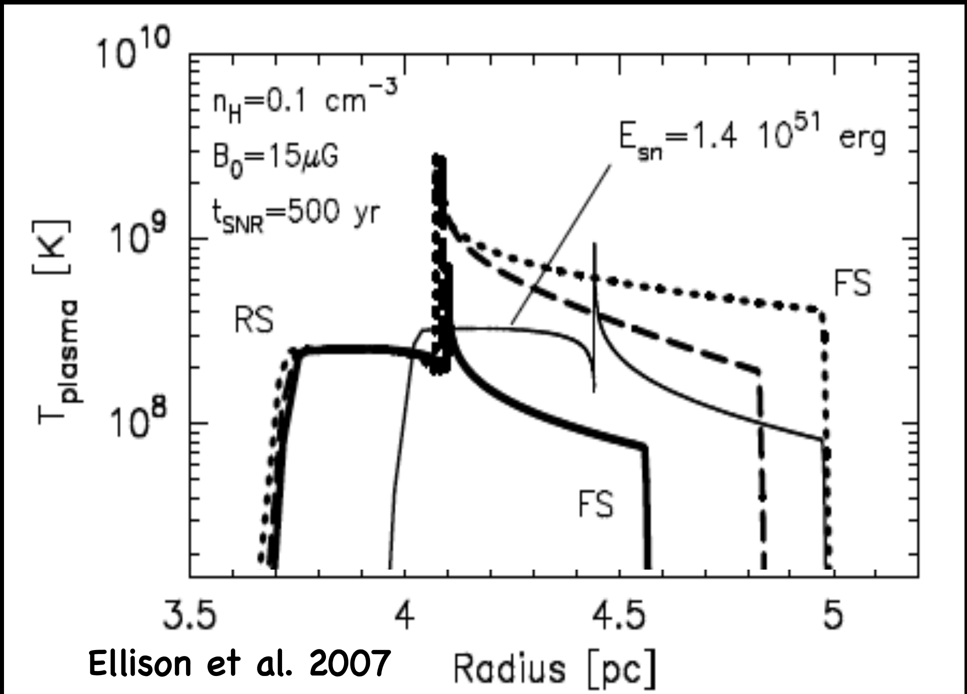
- X-ray observations show thin synchrotron rims surrounding SNR
  - electrons with E > 100 TeV
- Dynamical measurements of shocks show effects of particle acceleration
  - efficient acceleration of <u>protons</u>



Dynamical Evidence for CR Ion Acceleration



Warren et al. 2005



Ellison et al. 2007

- Efficient particle acceleration in SNRs affects dynamics of shock
  - for given age, FS is closer to CD and RS with efficient CR production

- This is observed in Tycho's SNR
  - "direct" evidence of CR ion acceleration

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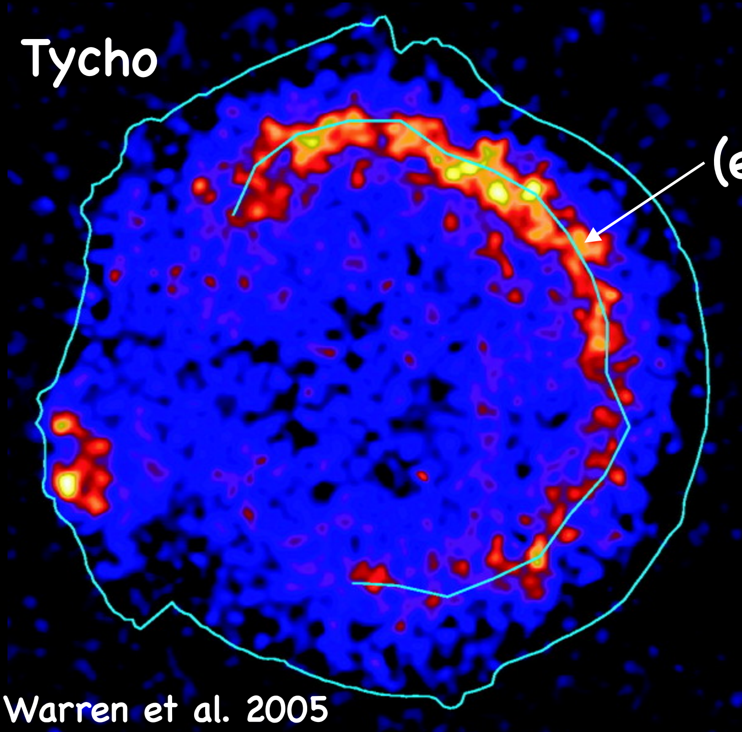

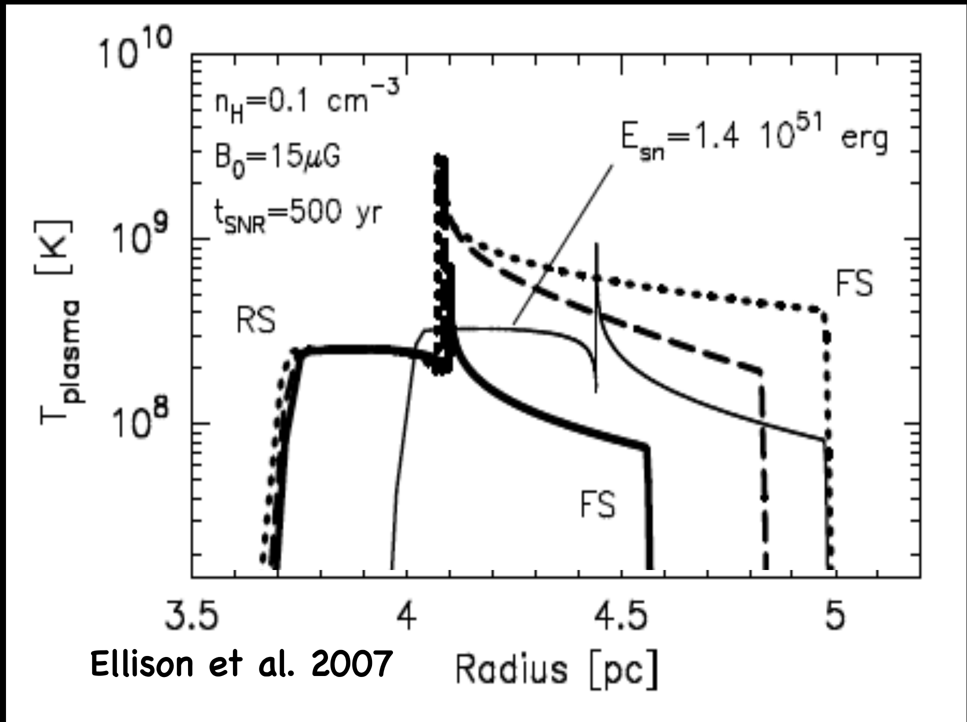

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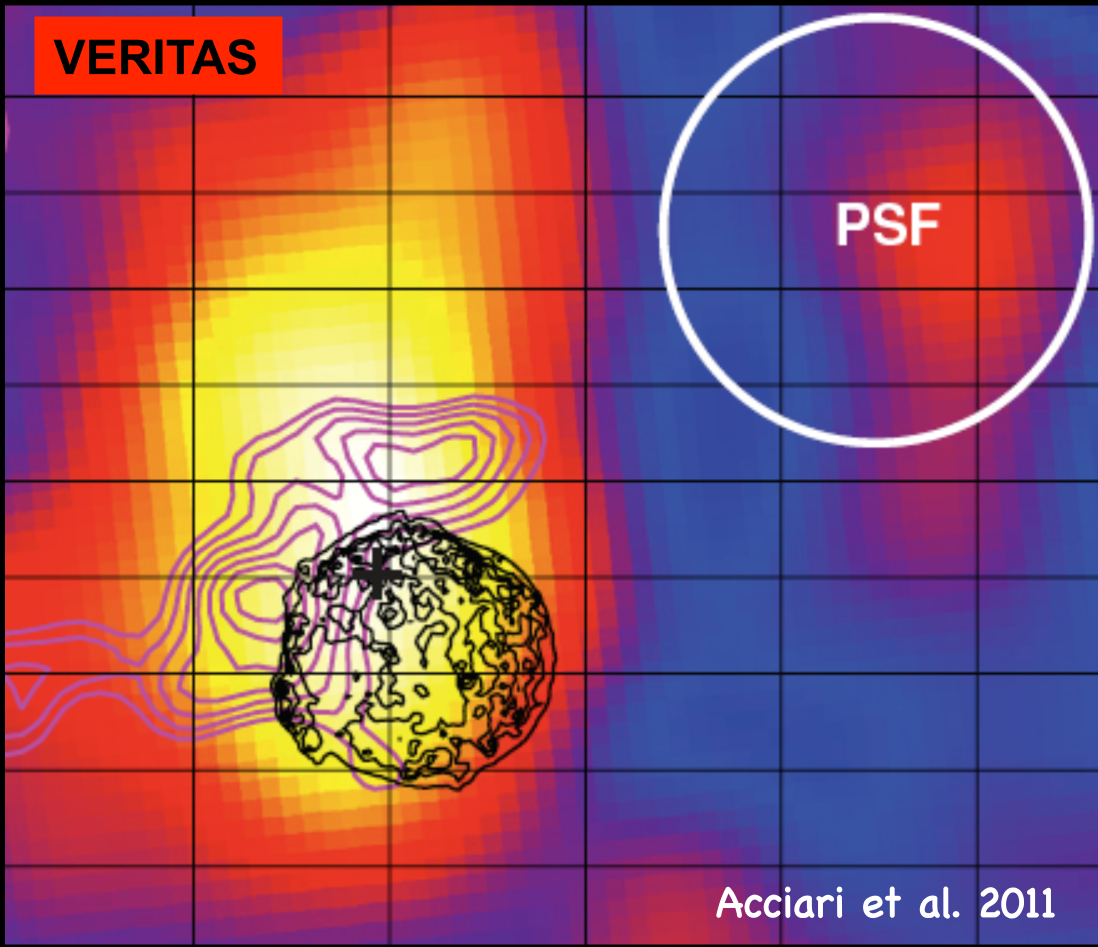
- TeV gamma-rays observed by VERITAS
  - centroid may be offset in direction of molecular cloud
  - escaping particles interacting with cloud?



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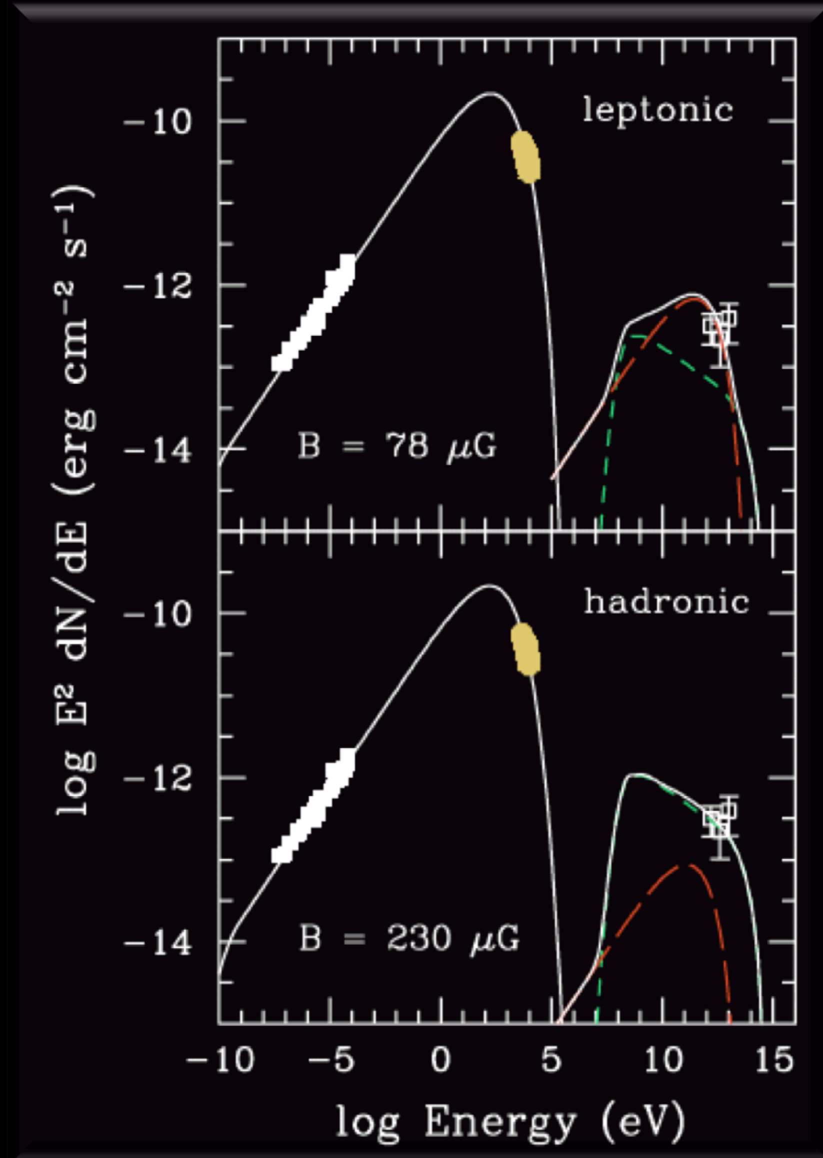

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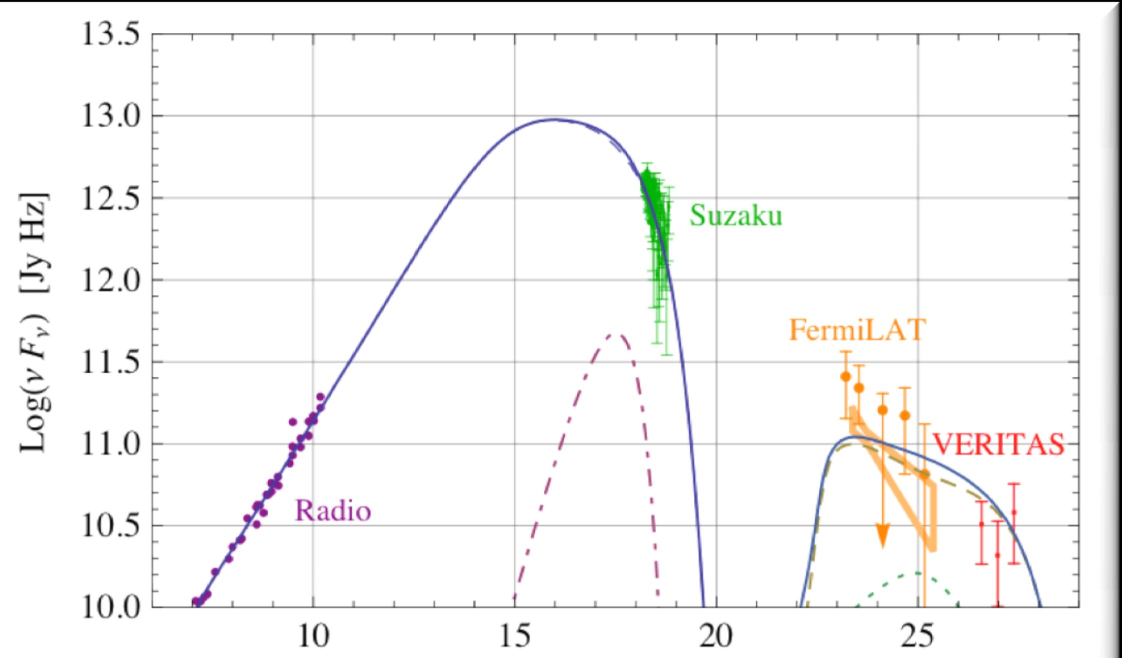
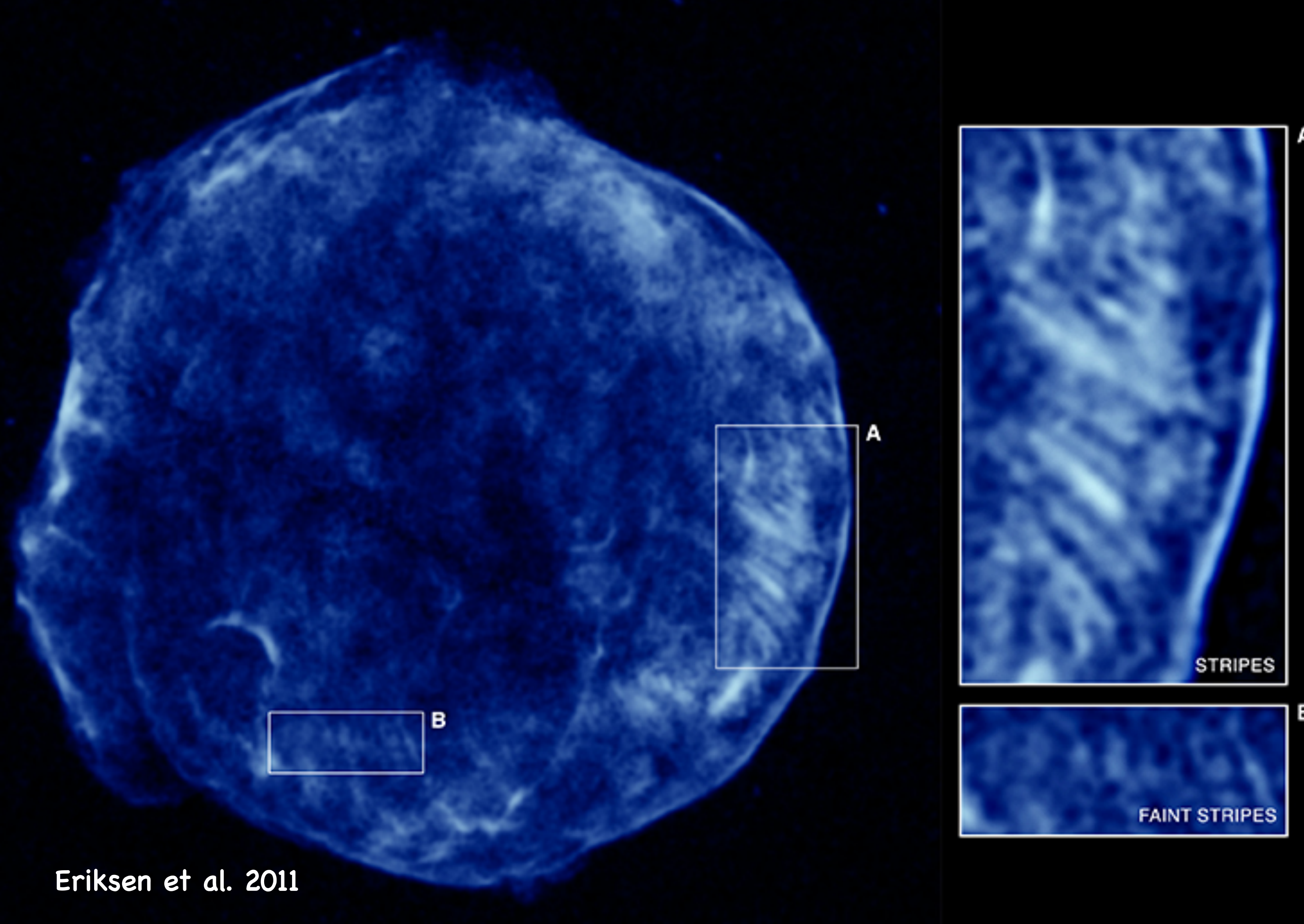
- Modeling including Fermi LAT data suggests γ-ray emission is dominated by hadrons



Morlino & Caprioli 2011

Cosmic Rays from Tycho?



Eriksen et al. 2011

- Stripe features seen in X-rays may correspond to gyro-radii of 10^{15} ev protons

SNRs in Dense Environments

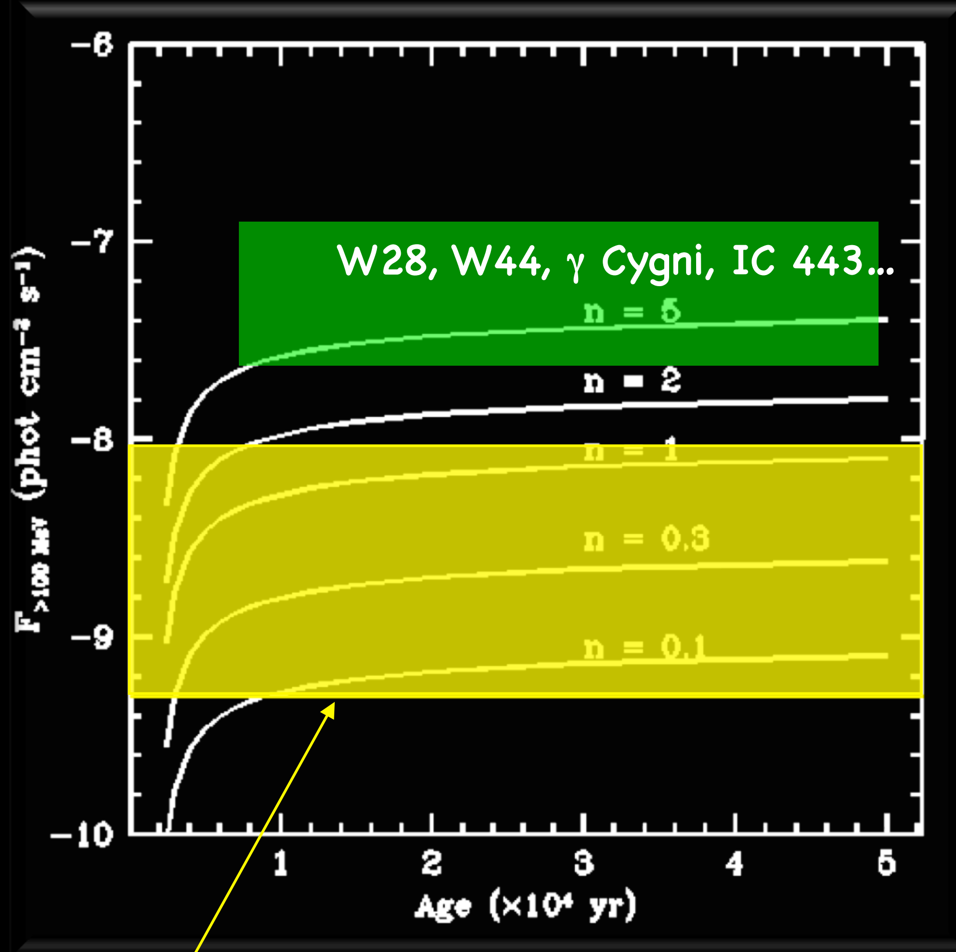
- The expected $\pi^0 \rightarrow \gamma\gamma$ flux for an SNR is

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

where θ is a slow function of age (Drury et al. 1994)
  - for large values of n, one thus expects to see γ-rays from accelerated hadrons

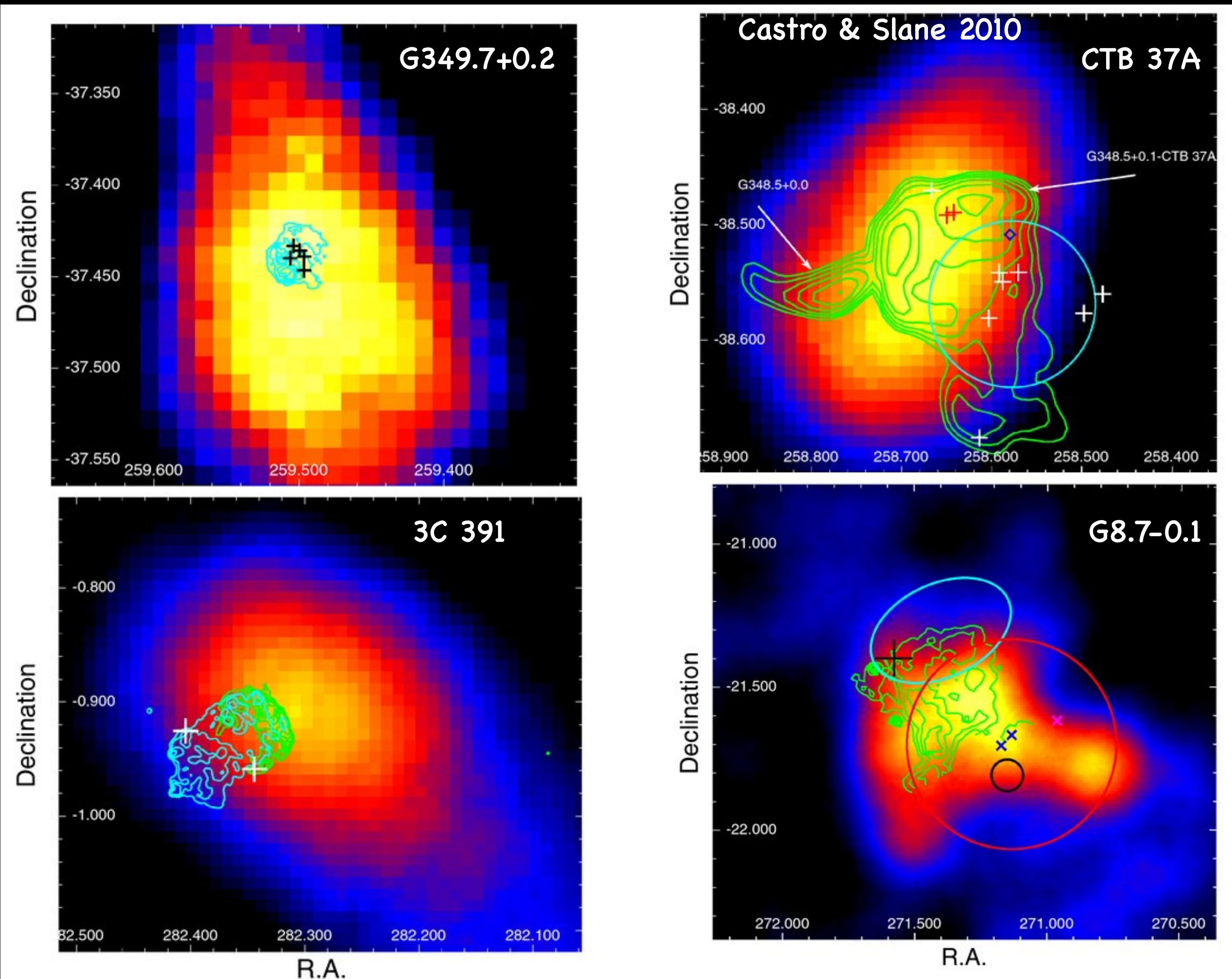
- SNRs in dense environments are good candidates for γ-ray emission
  - e.g., remnants interacting with molecular clouds should be strong γ-ray emitters

- Fermi LAT detects emission from above, as well as W51C, W49B, and more



1 yr sensitivity for high latitude point source

SNRs in Dense Environments



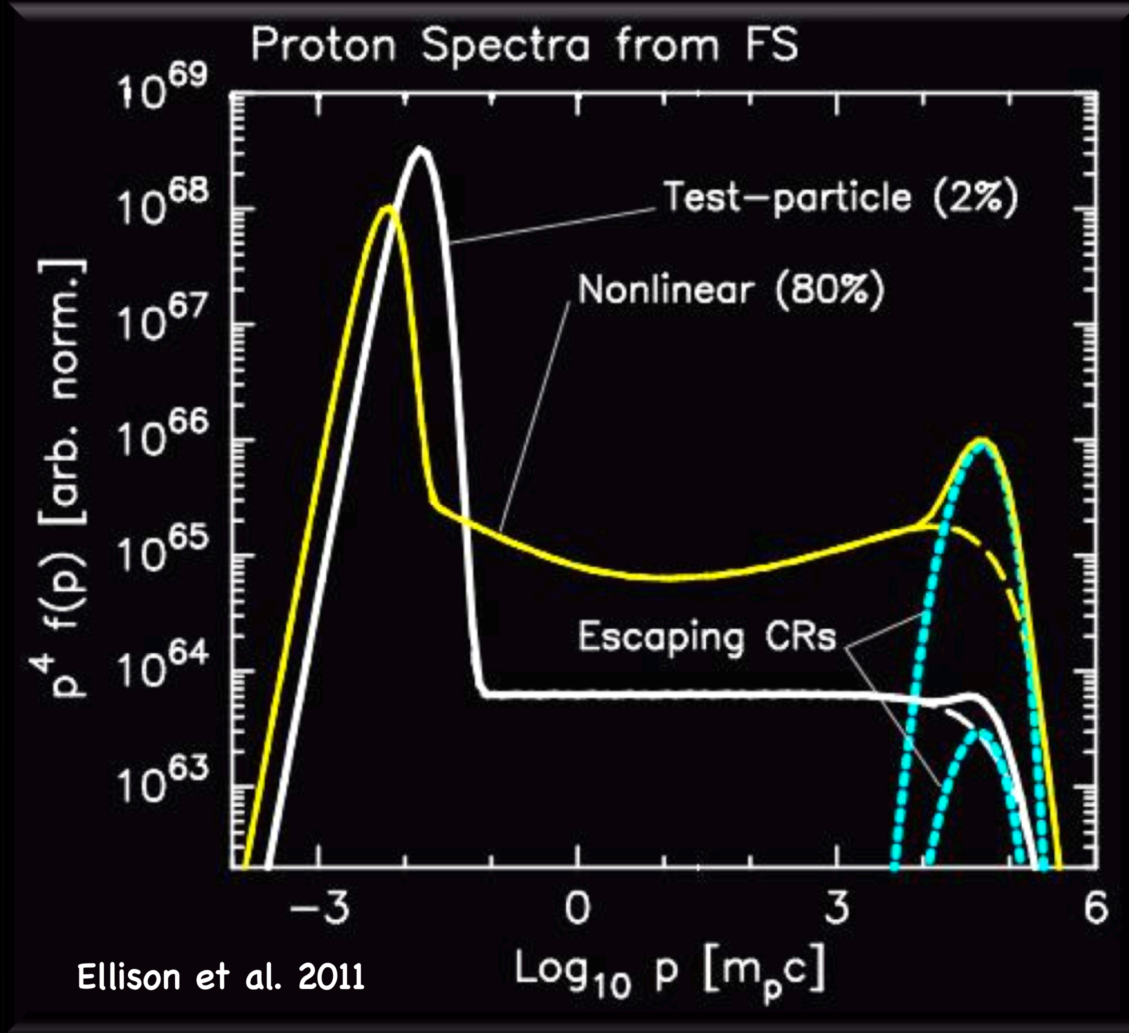
- SNRs with maser emission interacting with molecular clouds
  - likely sources of γ-ray emission
- Fermi/LAT detects GeV emission from several maser-emitting SNRs
  - inferred density is much higher than that suggested by thermal X-ray data
  - may imply clumping or escaping cosmic-ray population that is interacting with nearby clouds

Particle Escape and Diffusion

- Some fraction of particles escape acceleration region
  - fraction depends on acceleration efficiency

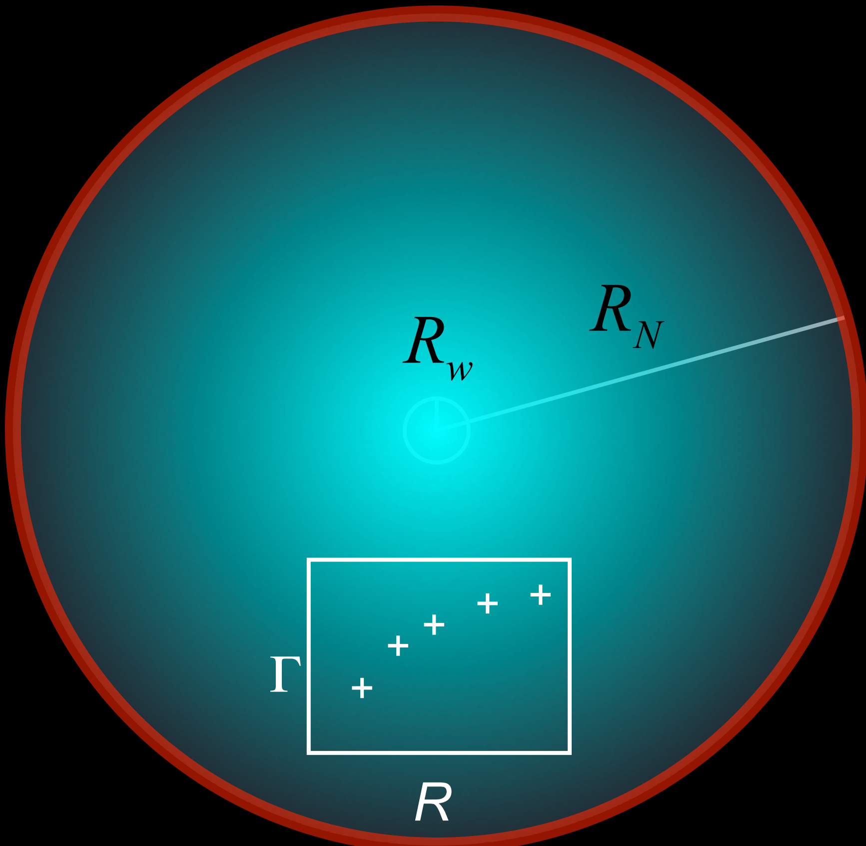
- Only the most energetic particle escape
  - largest gyroradii
  - determines gamma-ray spectrum for upstream interactions

- Particles diffuse from shock region
  - diffusion behavior depends on:
    - > energy
    - > magnetic turbulence
    - > losses
  - ambient medium makes a big difference



Ellison et al. 2011

Pulsar Wind Nebulae



- Pulsar wind inflates bubble of energetic particles and magnetic field
  - pulsar wind nebula
  - synchrotron radiation; at high frequencies, index varies with radius (burn-off)

- Expansion boundary condition at R_N forces wind termination shock at R_w
  - **nebula confined by surrounding ejecta**
  - wind goes from $v = c/3$ inside R_w to $v \approx R_N/t$ at outer boundary

- Pulsar wind is confined by pressure in nebula

$$\frac{\dot{E}}{4\pi R_w^2 c} = P_{neb}$$

obtain by integrating radio spectrum

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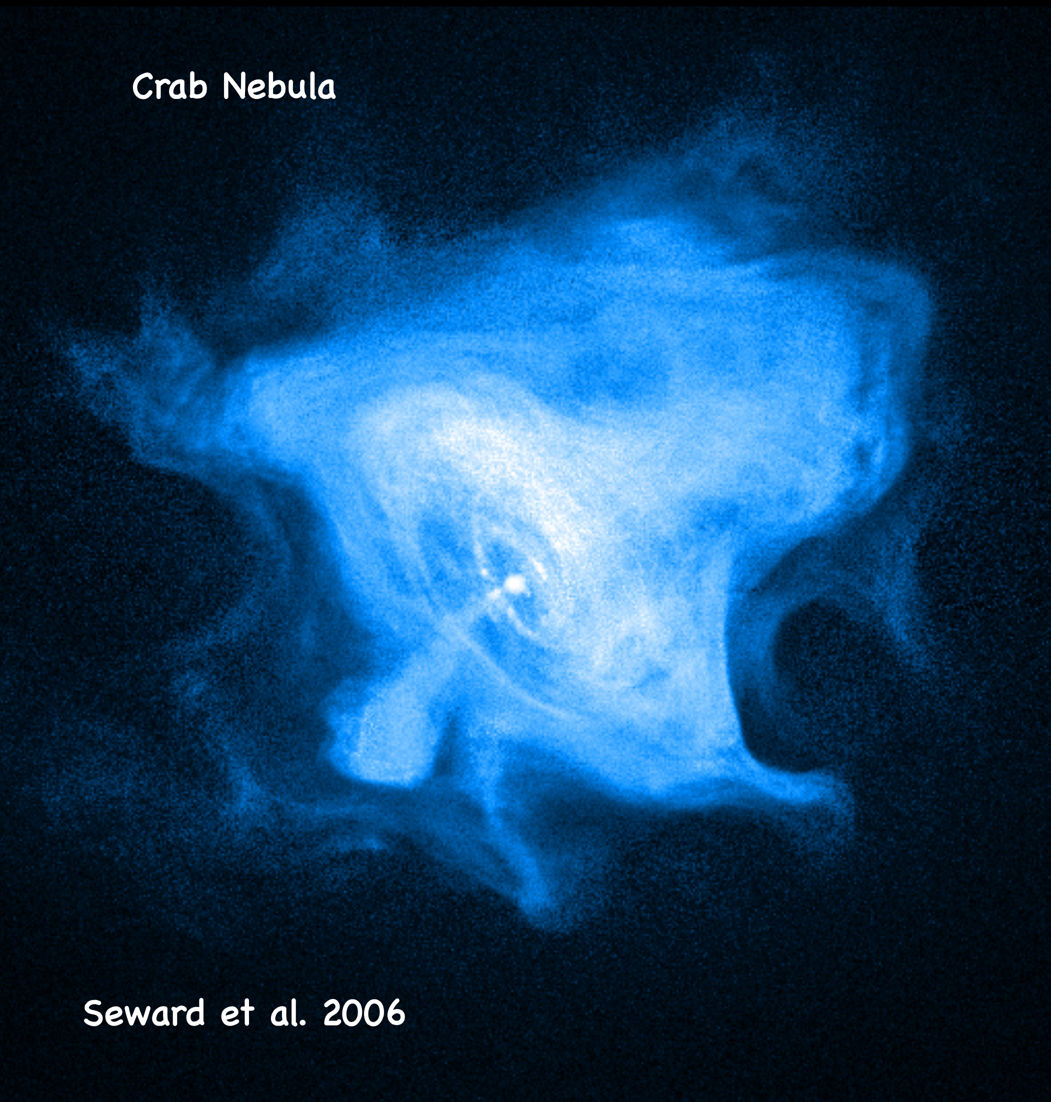

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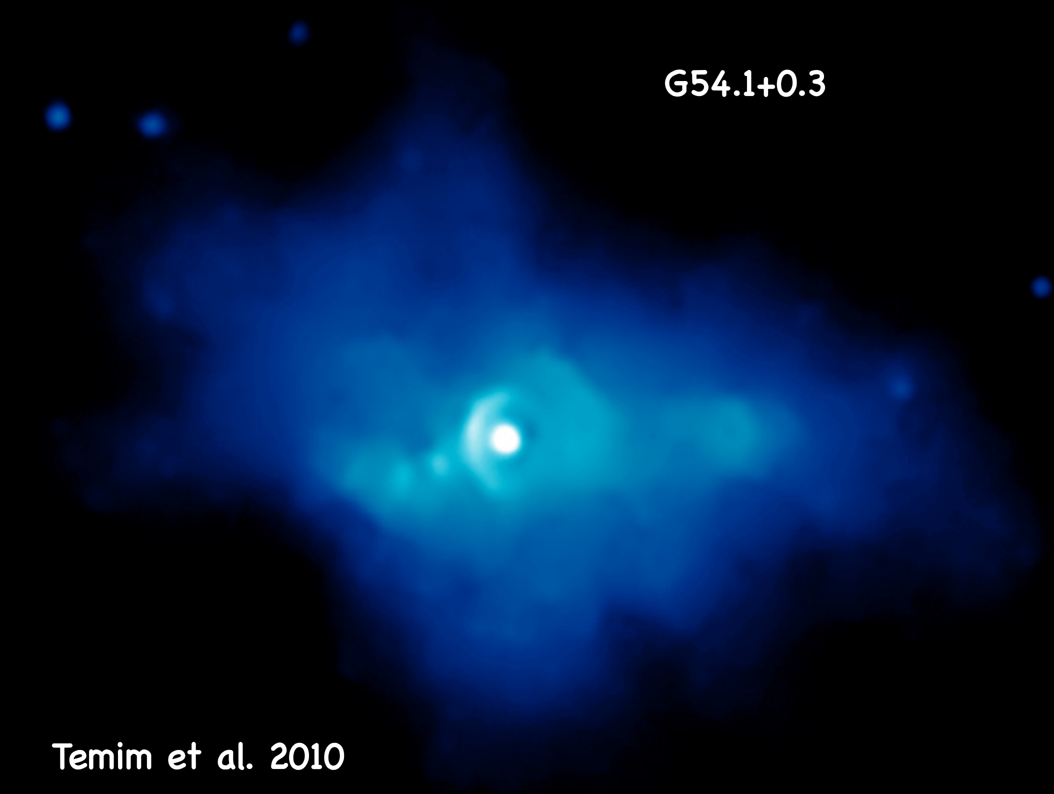

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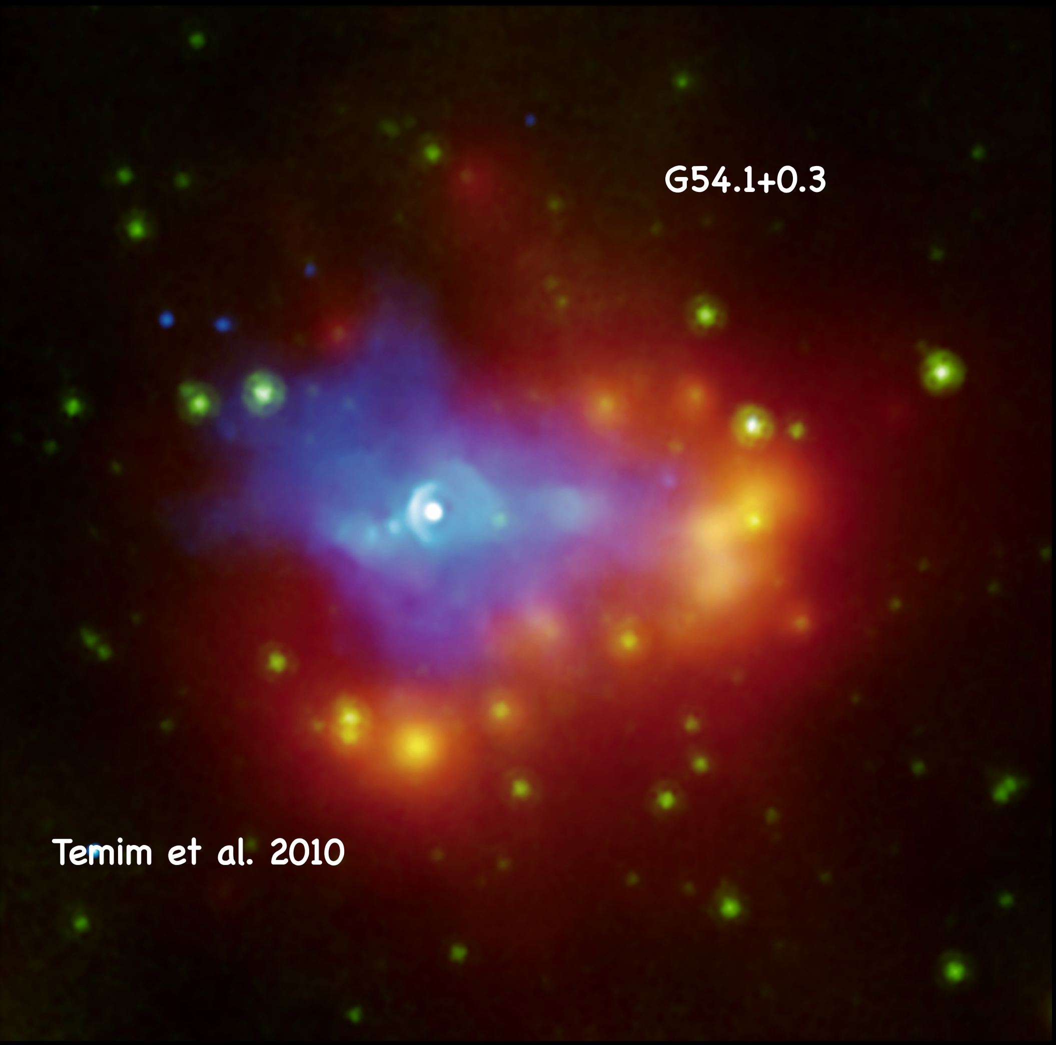

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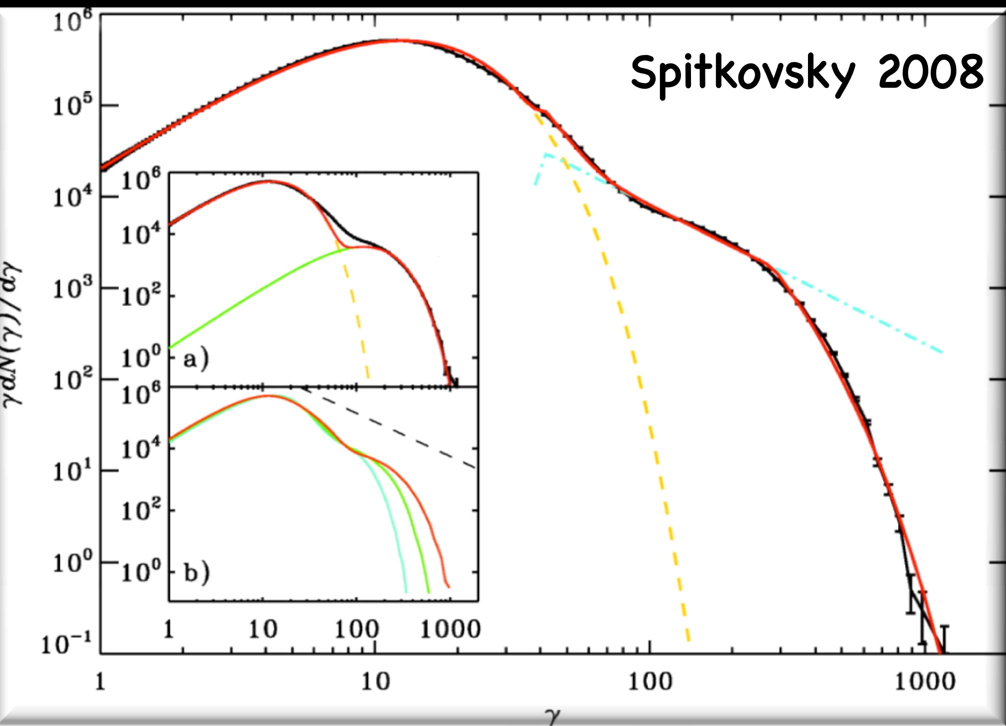
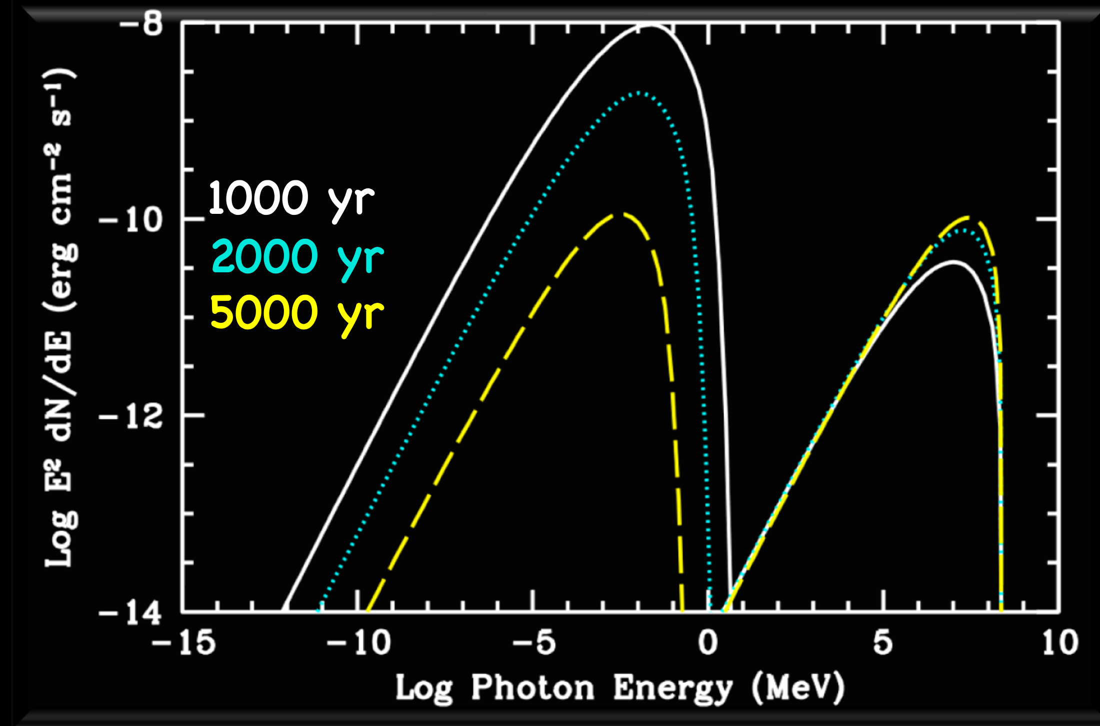
Evolution of PWN Emission

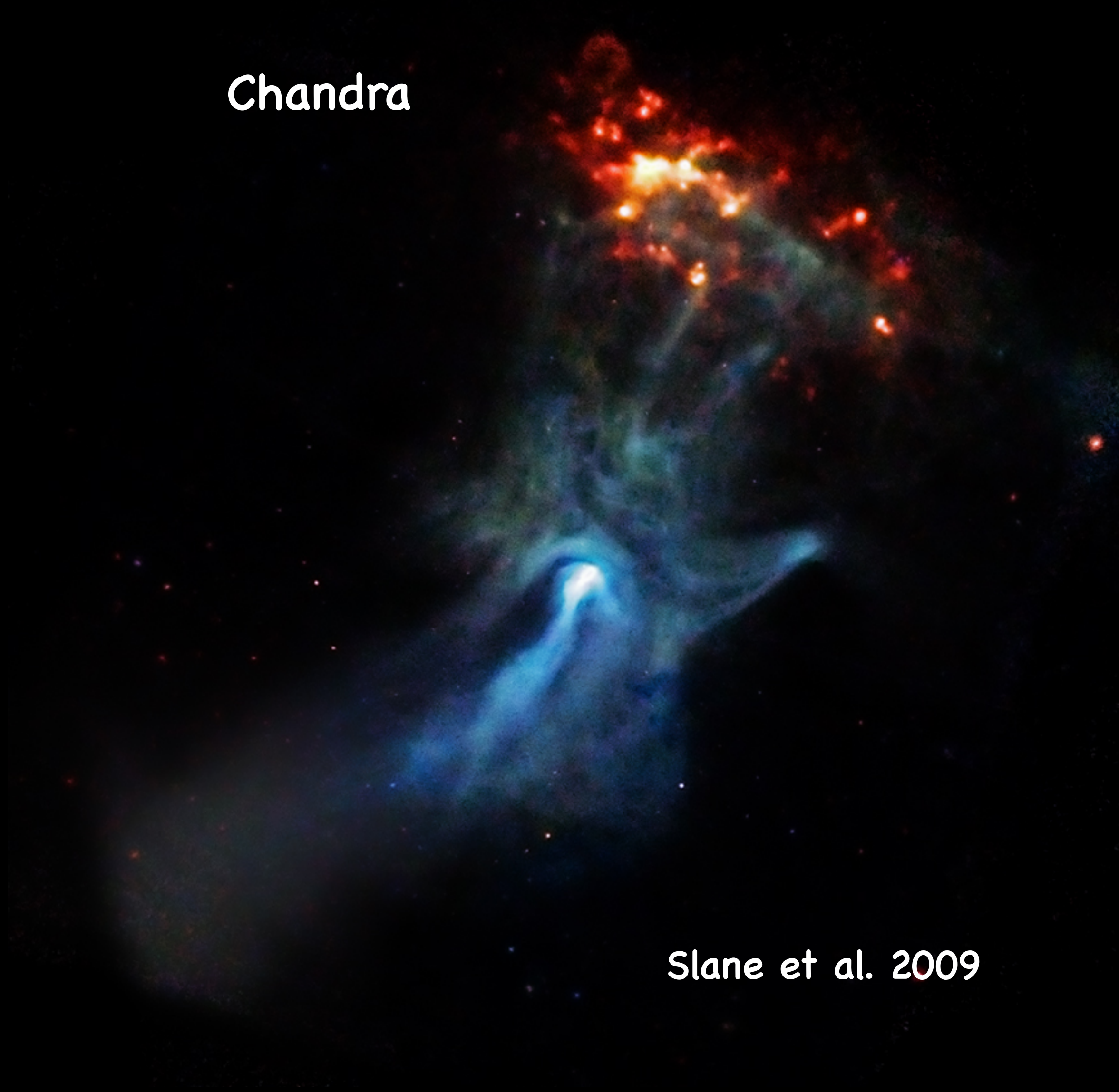




- Injected spectrum is expected to be Maxwellian w/ nonthermal tail
  - note that Maxwellian has never been definitively detected
- E_{max} and fraction of energy in PL likely to vary within PWN
- Energetic electrons produce synchrotron emission in X-ray band, and IC emission in γ-ray band
- Note that X-ray emission decreases with time, while γ-ray emission increases

High Energy Emission from MSH 15-52

- Powered by energetic young pulsar (actually discovered in X-rays)
- X-ray images reveal complex nebula with distinct jet/torus morphology (and more…)



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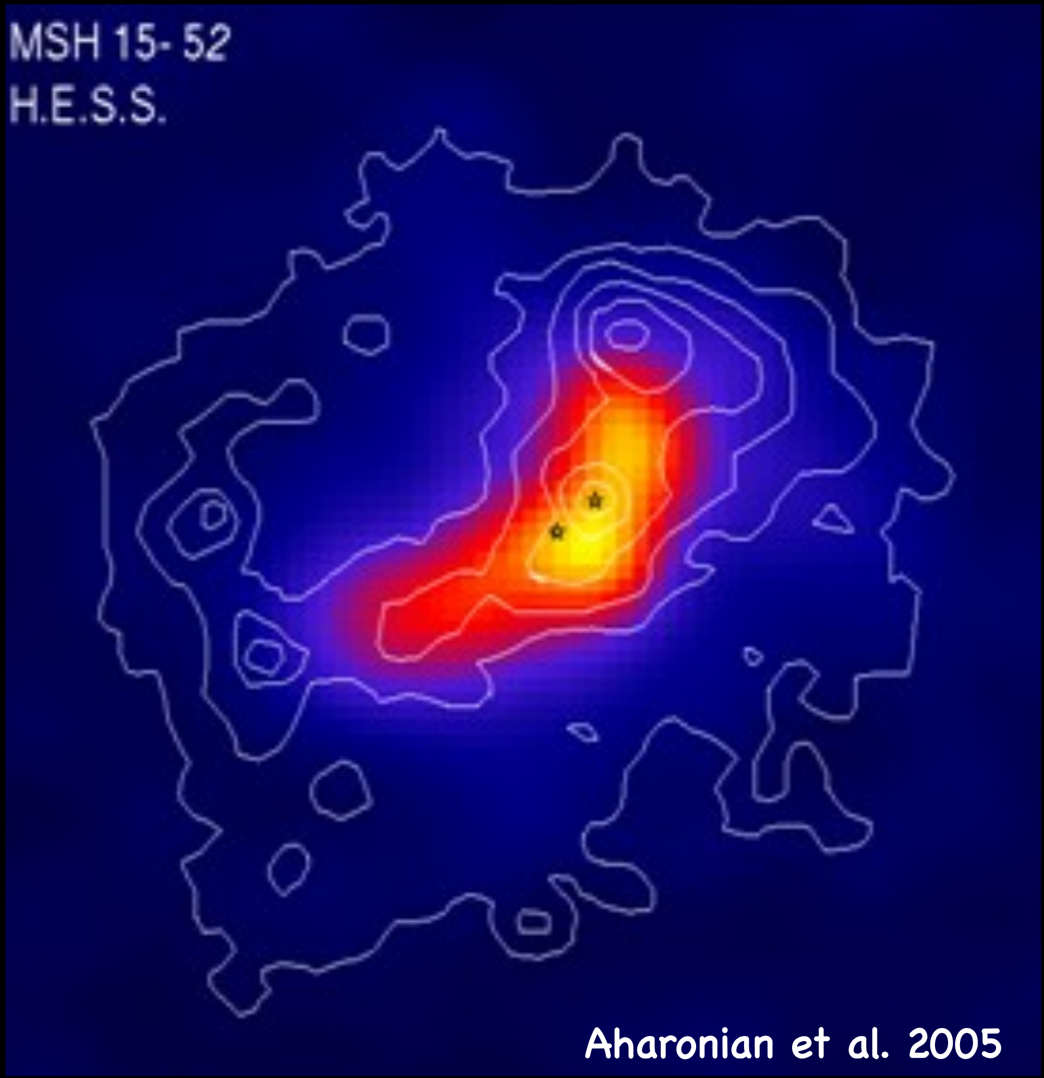

Aharonian et al. 2005

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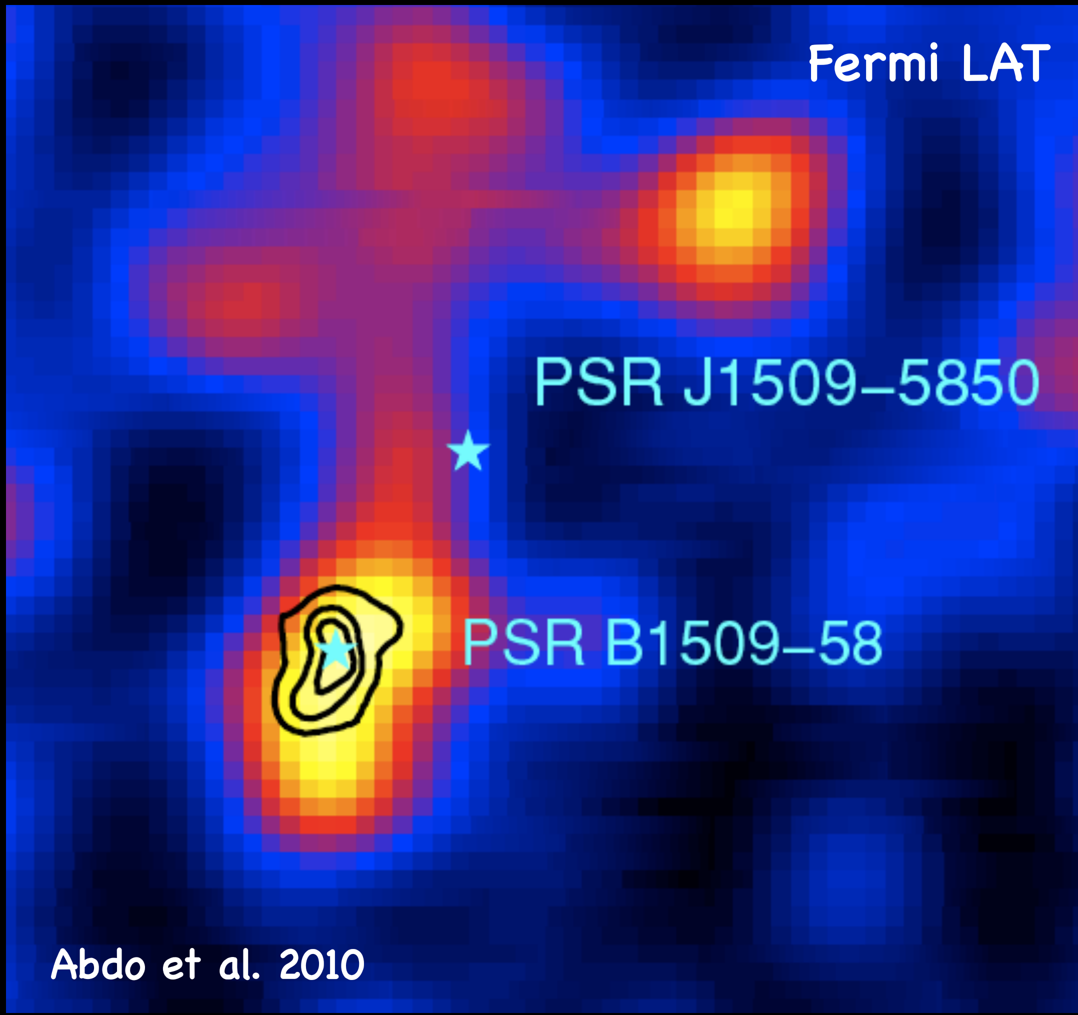

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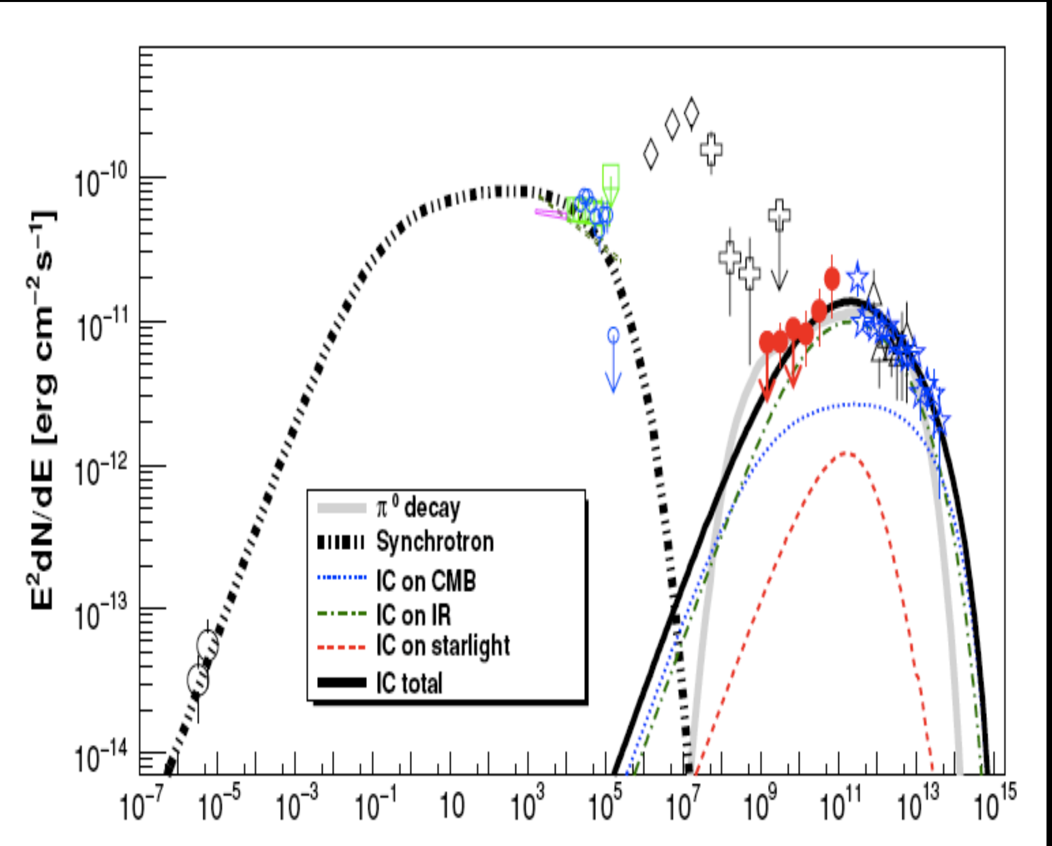
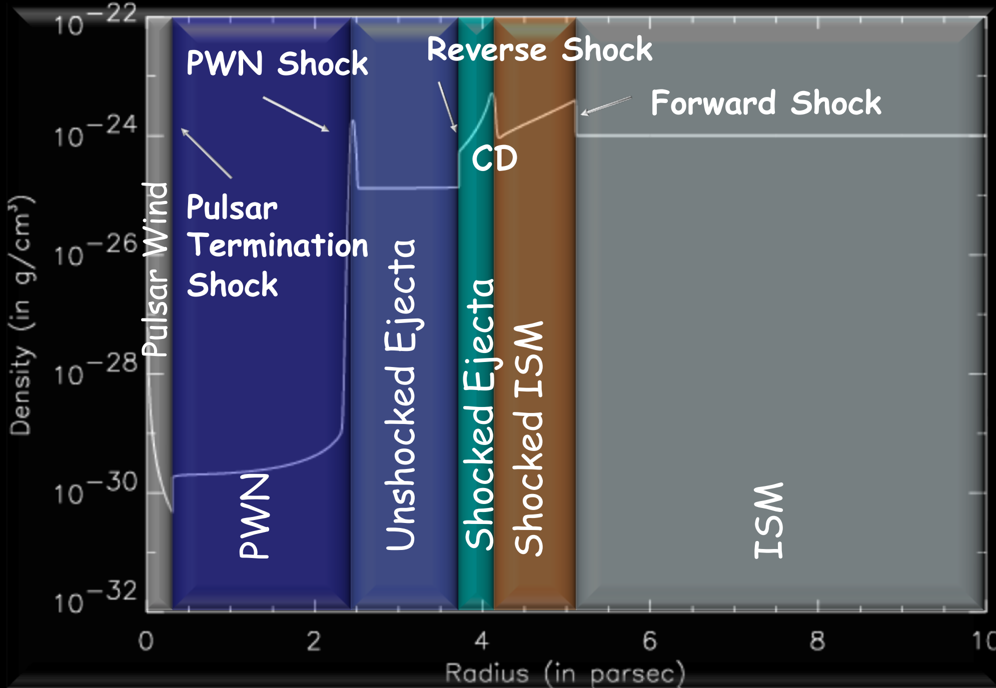
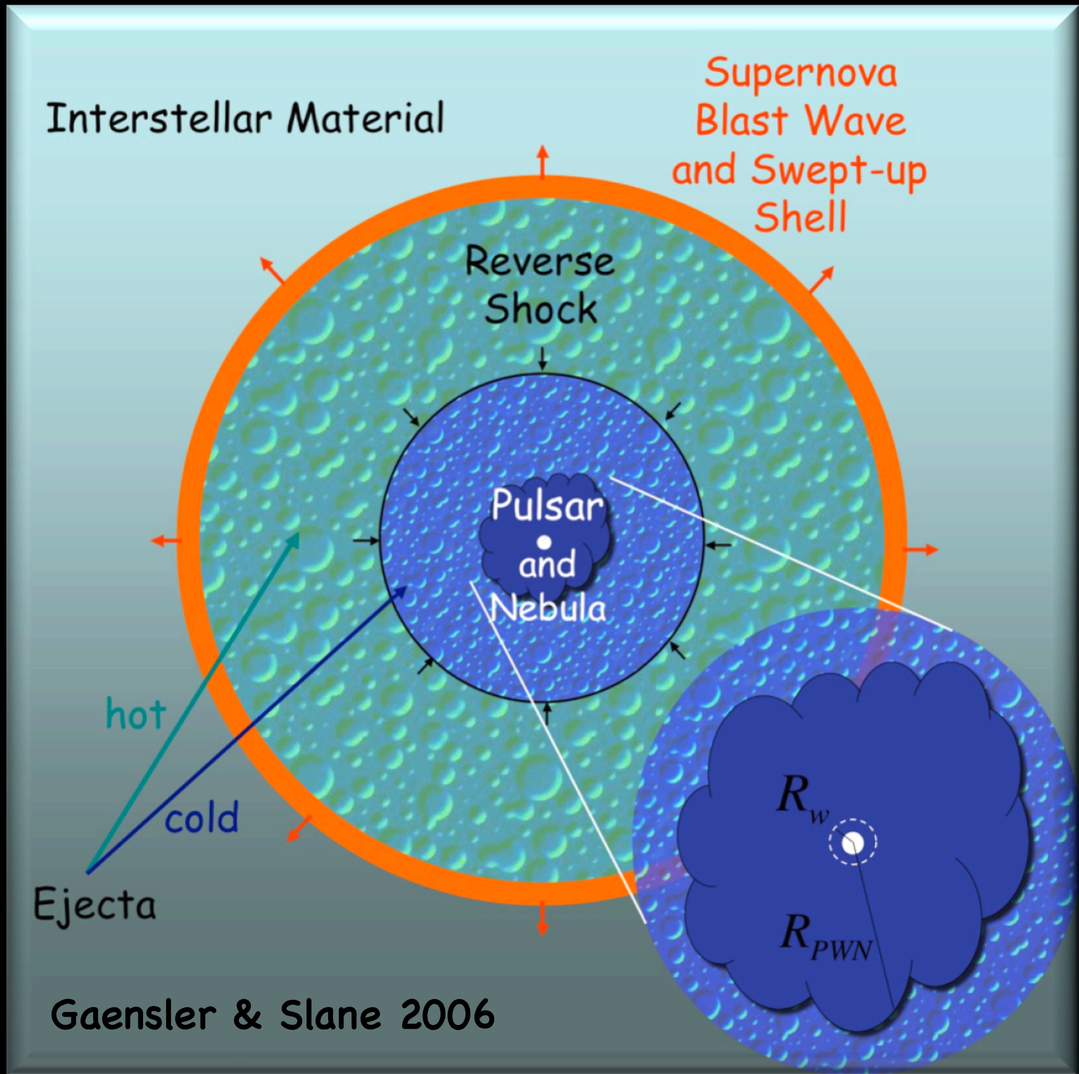
- Broadband modeling provides self-consistent picture of synchrotron/IC emission
  - requires broken power law for electron spectrum



Abdo et al. 2010

Putting it Together: Composite SNRs





- **Pulsar Wind**
  - sweeps up ejecta; termination shock decelerates flow; PWN forms
- **Supernova Remnant**
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN

Composite SNR Evolution

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

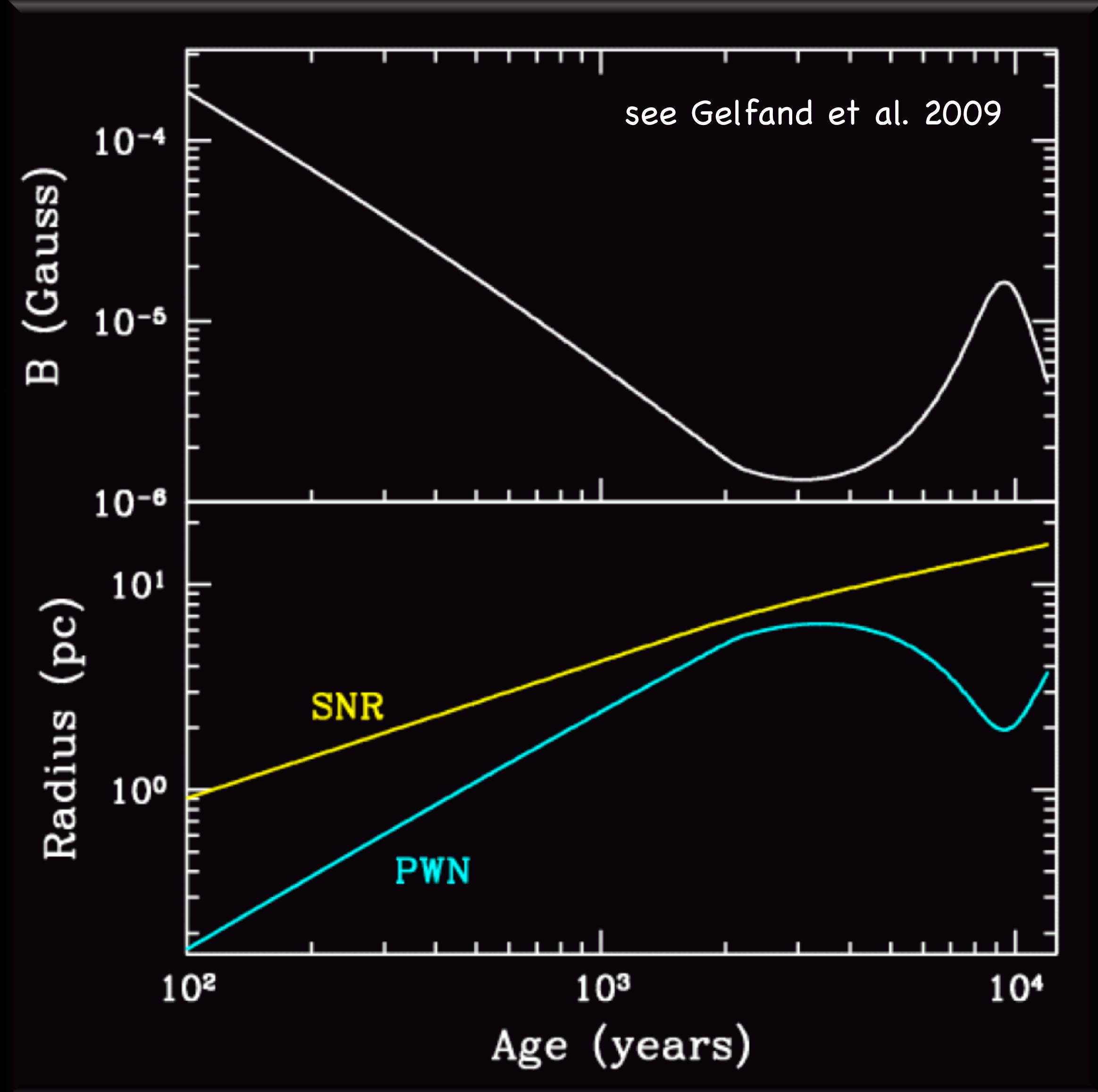
$$\frac{dM}{dt} = 4\pi R^2 \rho_{SN}(\mathrm{v} - R/t)$$

energy input and swept-up ejecta mass

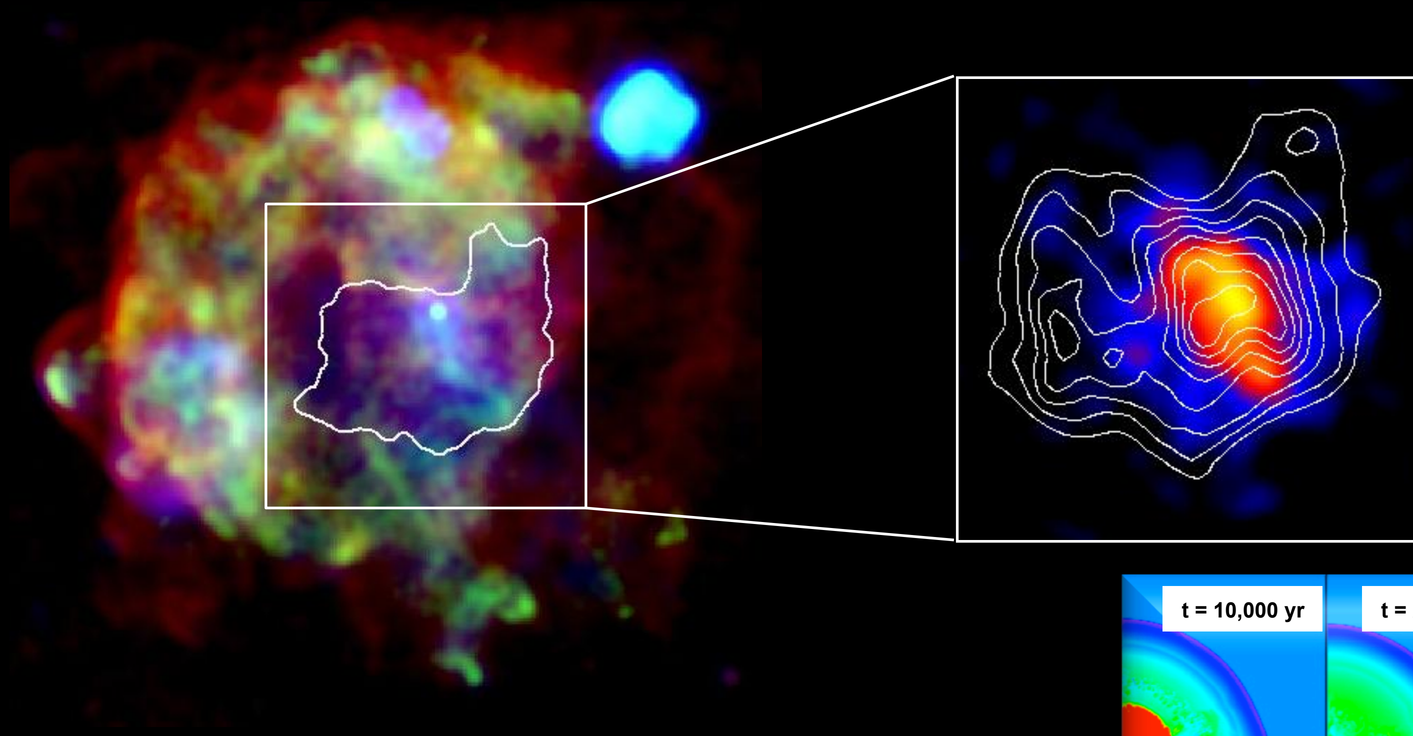
$$\frac{d\left[\frac{4\pi R^3}{3} p_i\right]}{dt} = \dot{E} - p_i 4\pi R^2 \frac{dR}{dt}$$

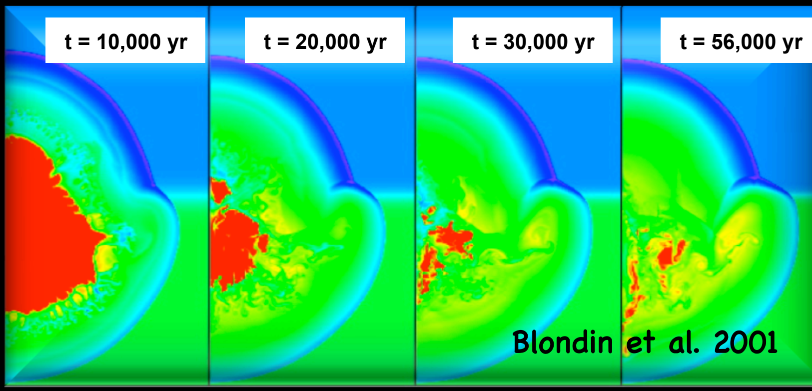
$$M\frac{d\mathrm{v}}{dt} = 4\pi R^2\left[p_i - \rho_{SN}(\mathrm{v} - R/t)^2\right]$$

PWN evolution



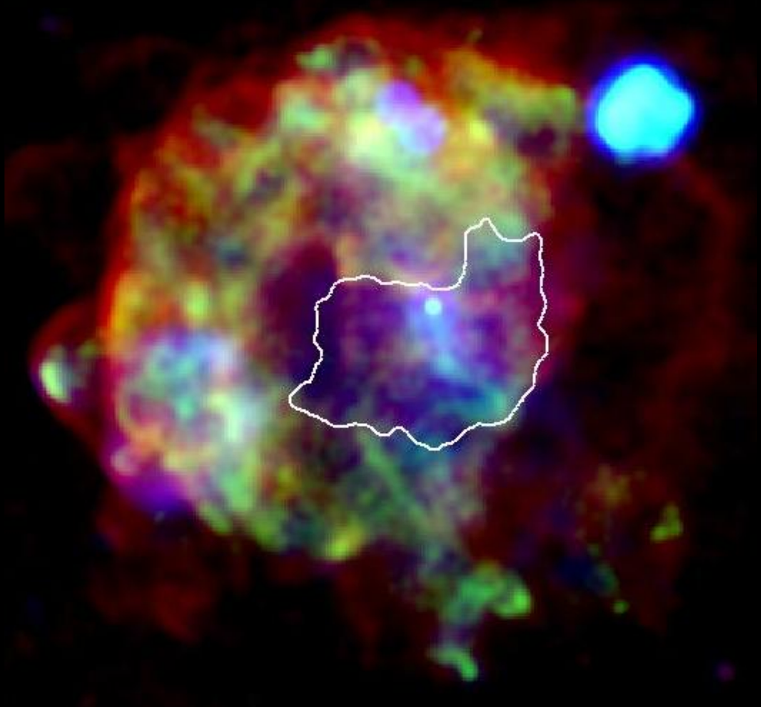
Evolution in an SNR: Vela X

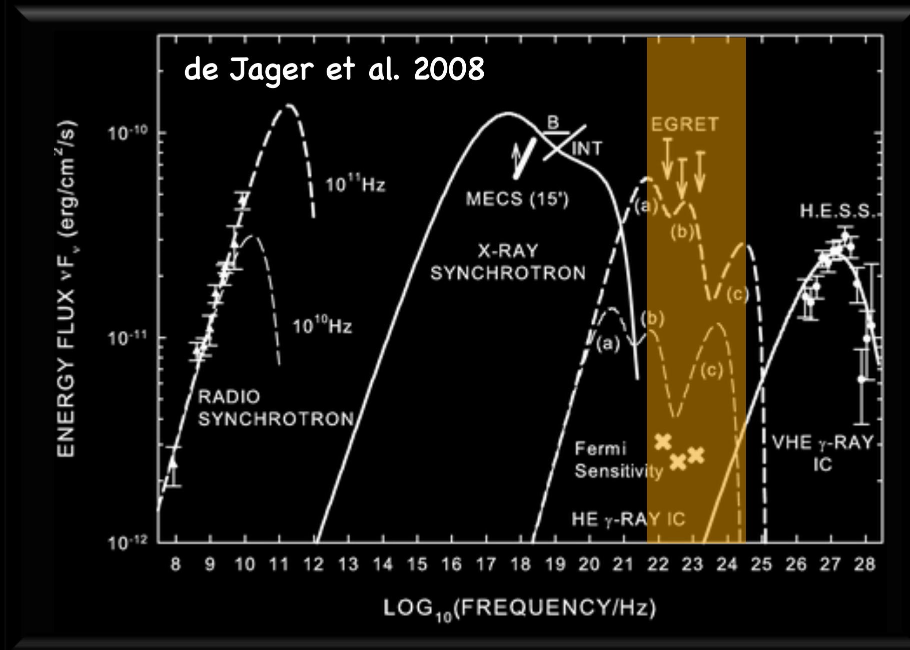




- Vela X is the PWN produced by the Vela pulsar
  - apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock
- Elongated "cocoon-like" hard X-ray structure extends southward of pulsar
  - clearly identified by HESS as an extended VHE structure
  - this is not the pulsar jet

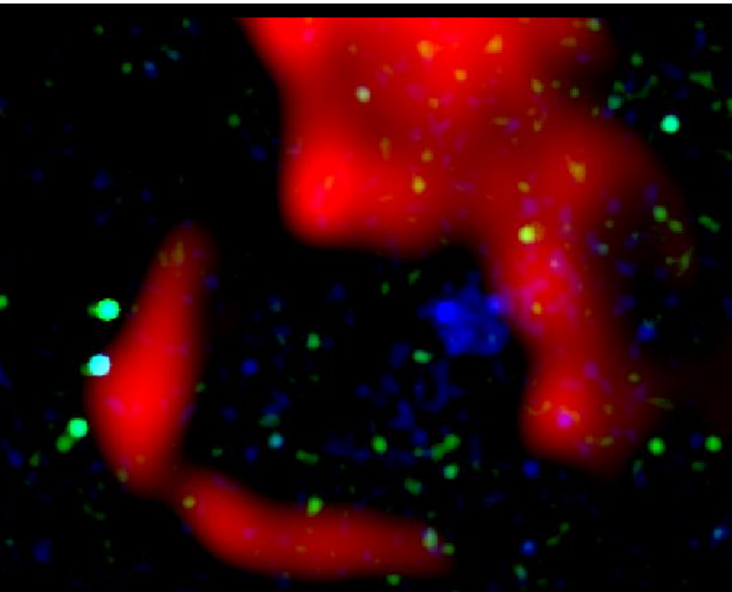
Understanding Vela X: Fermi



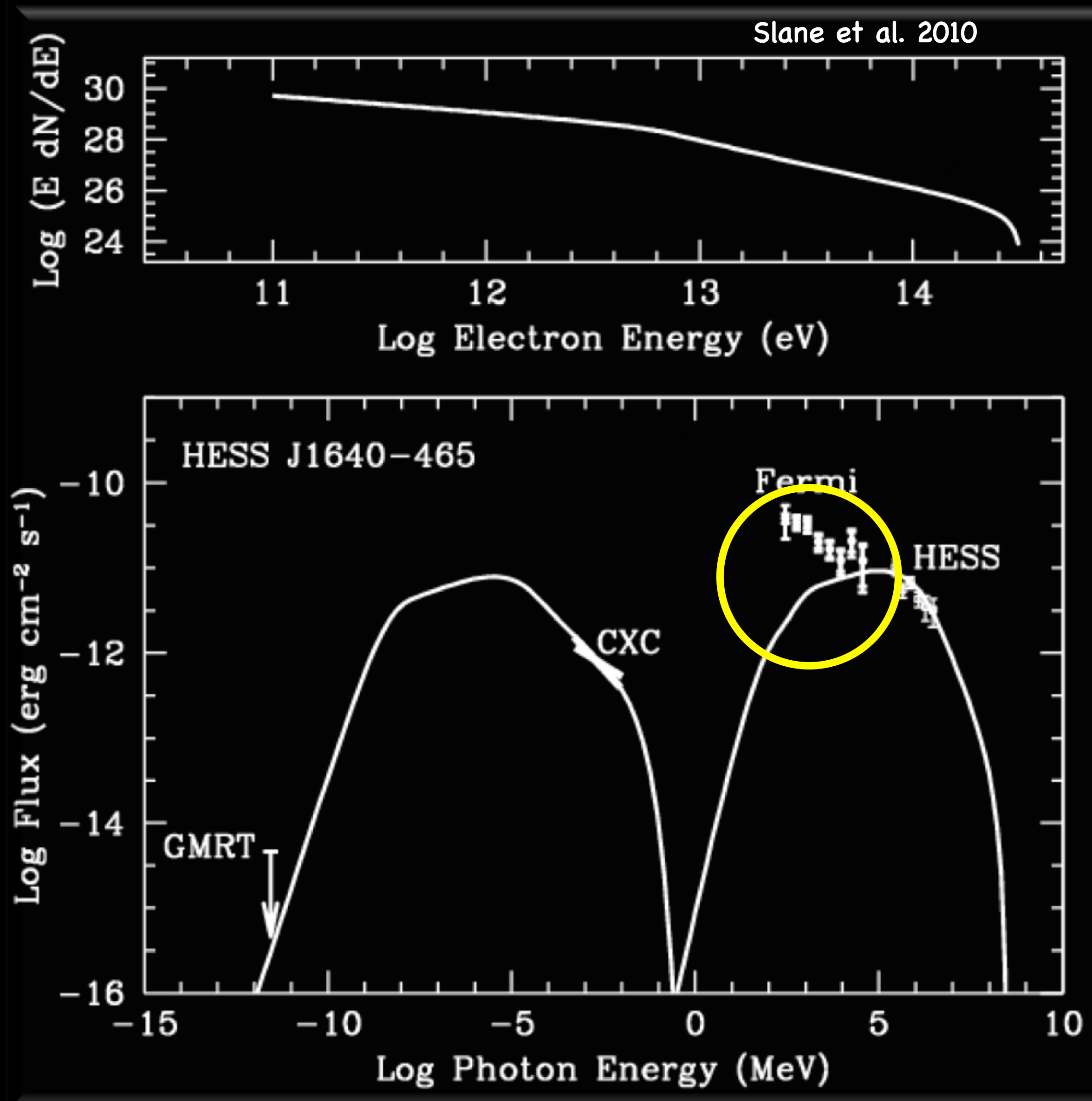


- Broadband spectrum for PWN suggests two distinct electron populations and very low magnetic field (~5 μG)
  - radio-emitting population will generate IC emission in LAT band
  - spectral features may identify distinct photon population and determine cut-off energy for radio-emitting electrons

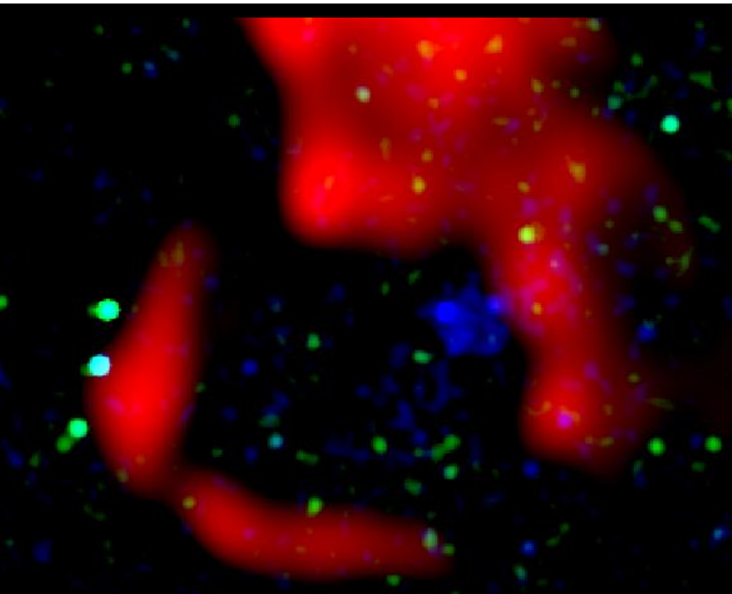
HESS J1640-465

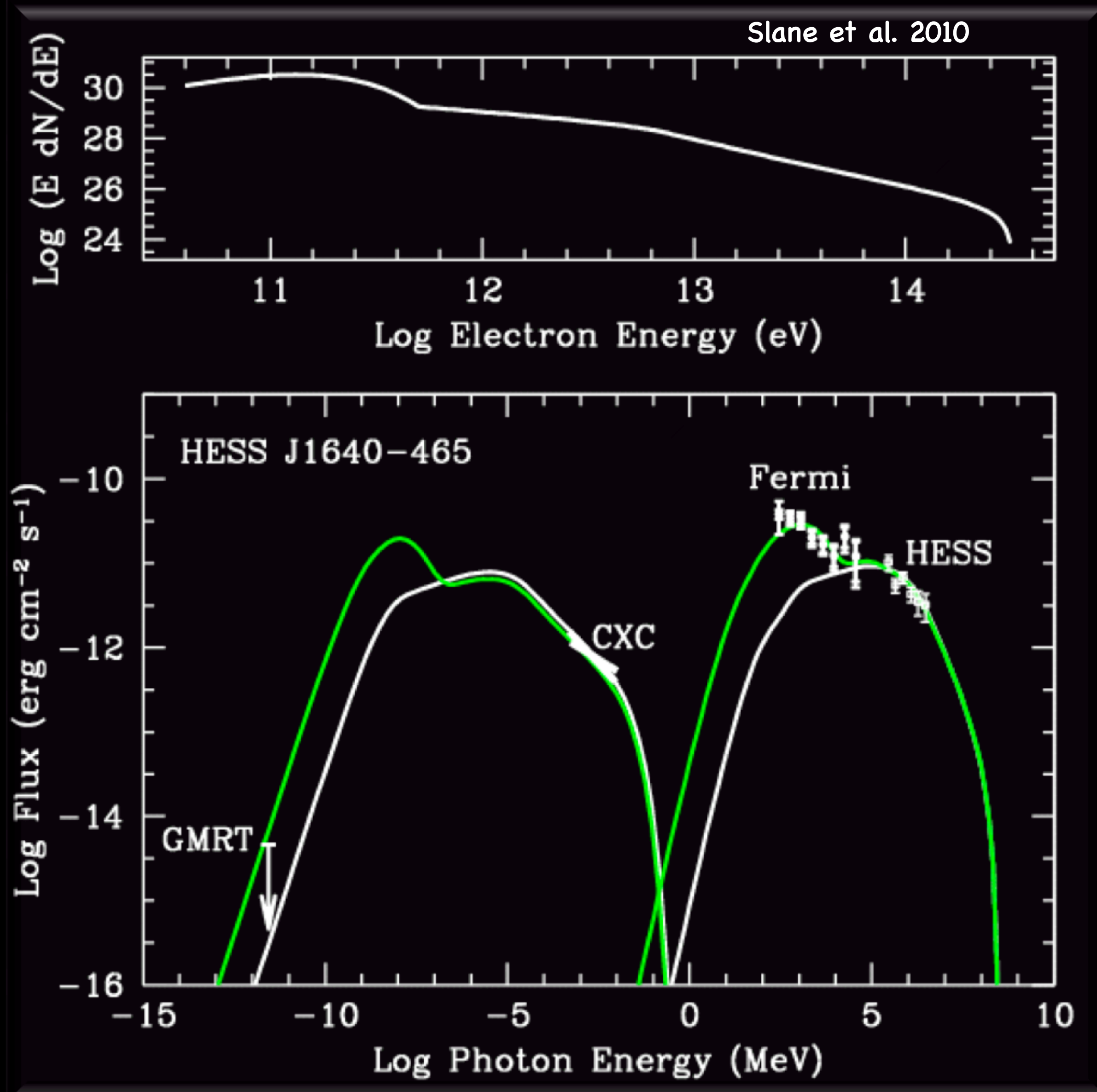


- Composite SNR in late evolution
- PWN model with evolved power law electron spectrum fits X-ray and TeV emission, but not GeV



HESS J1640-465

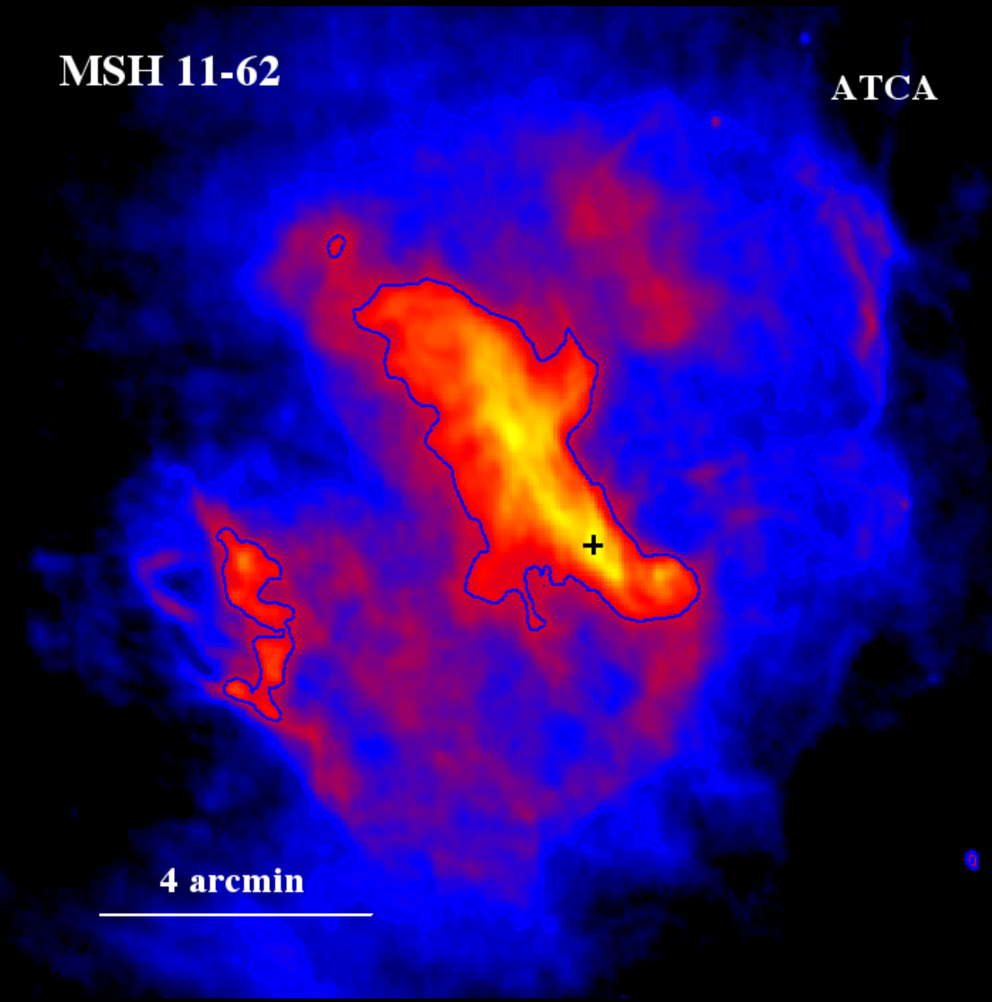




- Composite SNR in late evolution
- PWN model with evolved power law electron spectrum fits X-ray and TeV emission, but not GeV
- Modifying low-energy electron spectrum by adding Maxwellian produces GeV IC emission

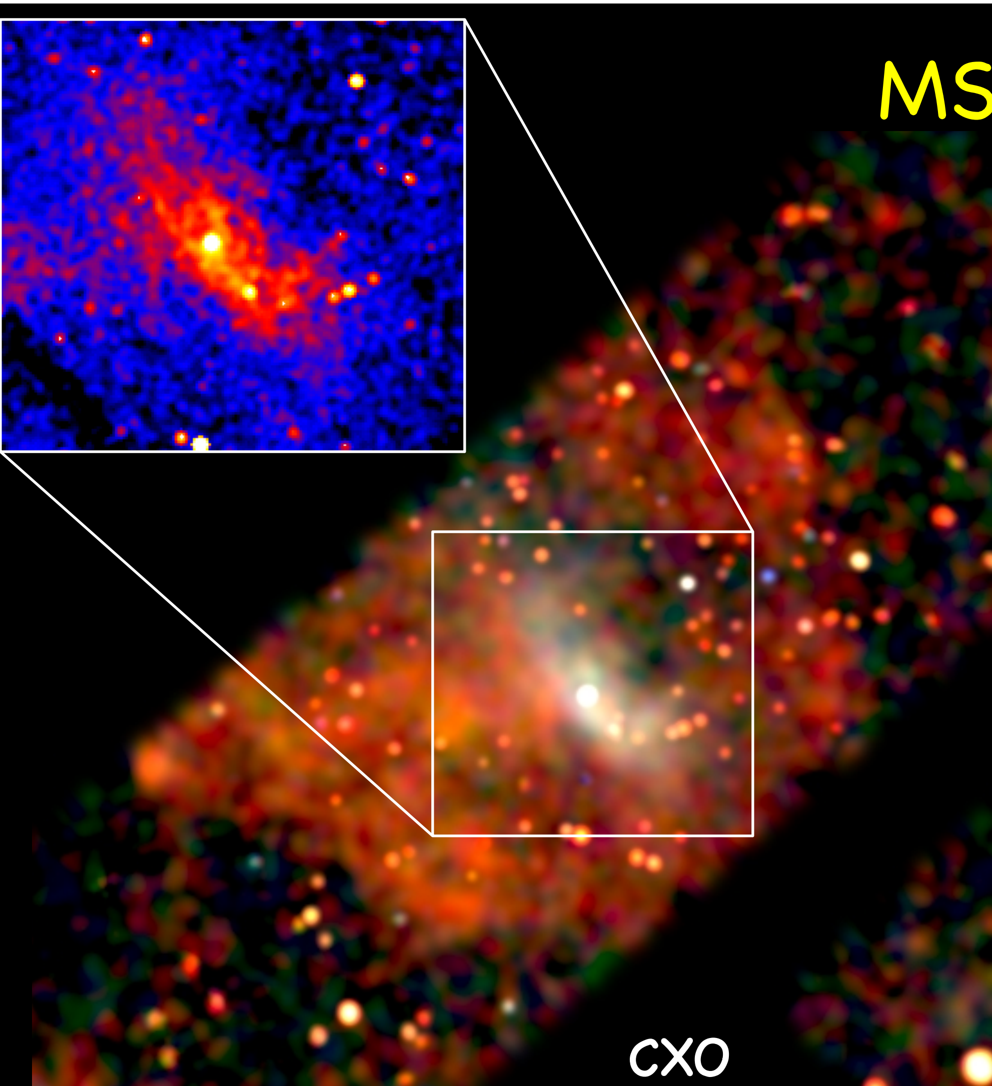
- similar to results from Vela X
- possible evidence of long-sought Maxwellian component expected from shock acceleration models

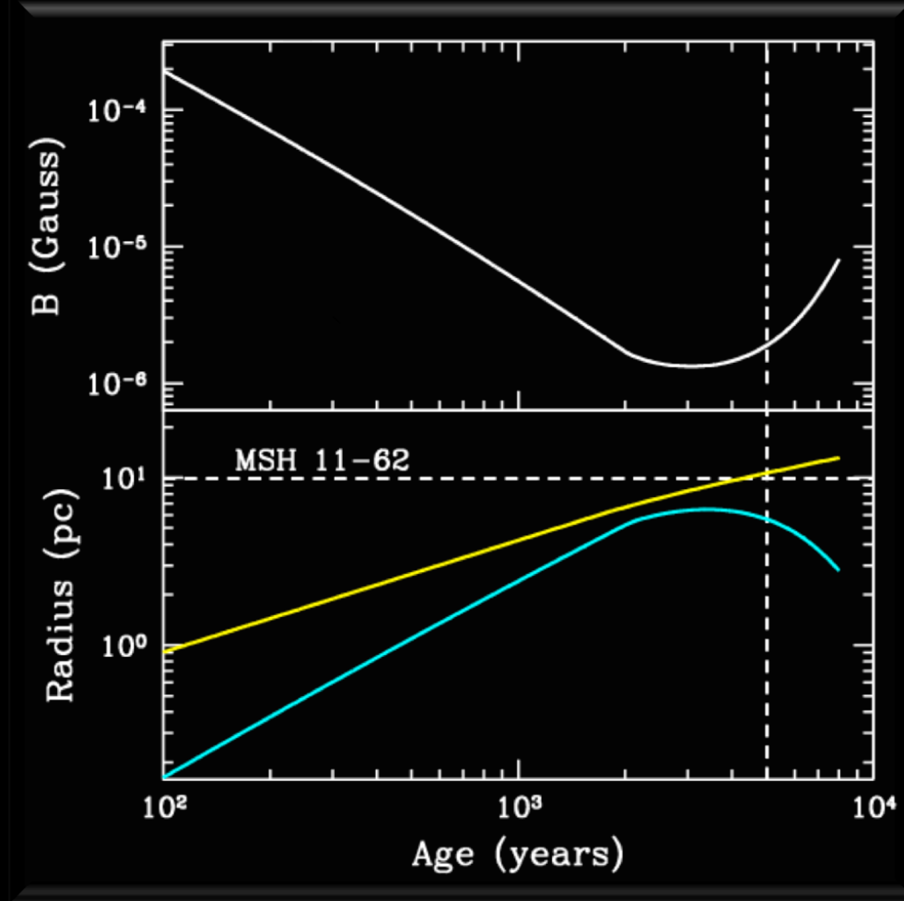
MSH 11-62



- Radio observations reveal shell with bright, flat-spectrum nebula in center
  - no pulsar known, but surely a PWN
- Distance not well known, but ≈5 kpc
  - R ≈ 10.6 pc

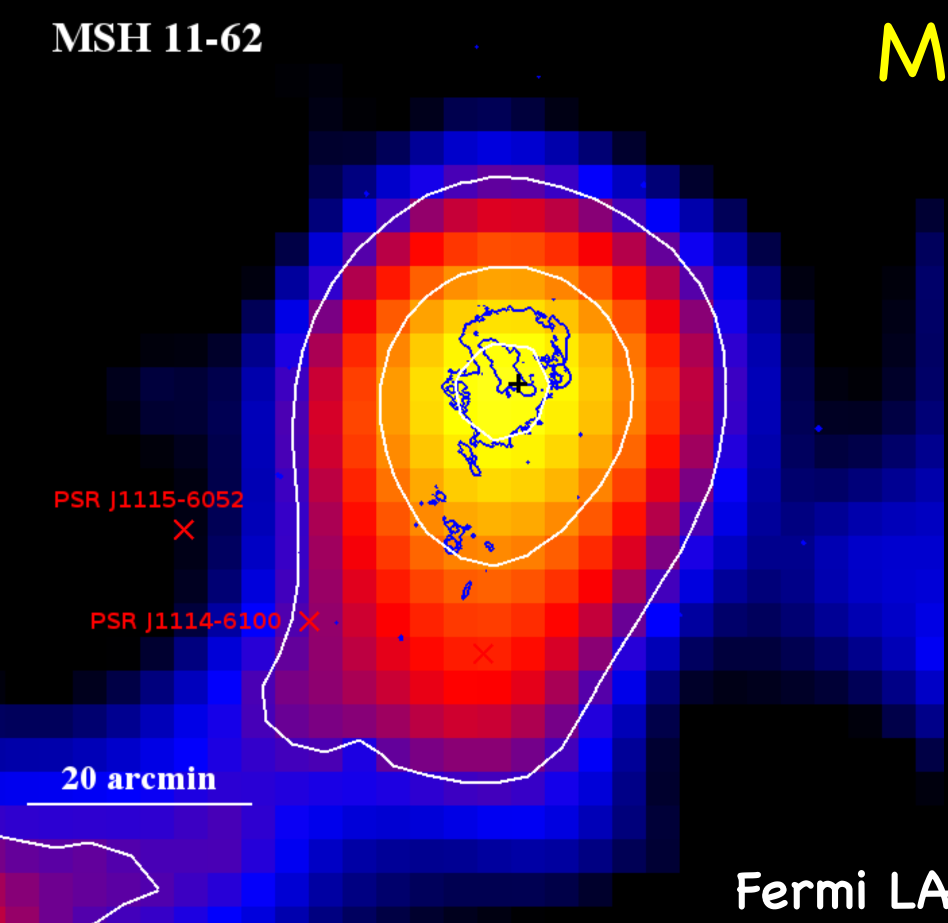
MSH 11-62



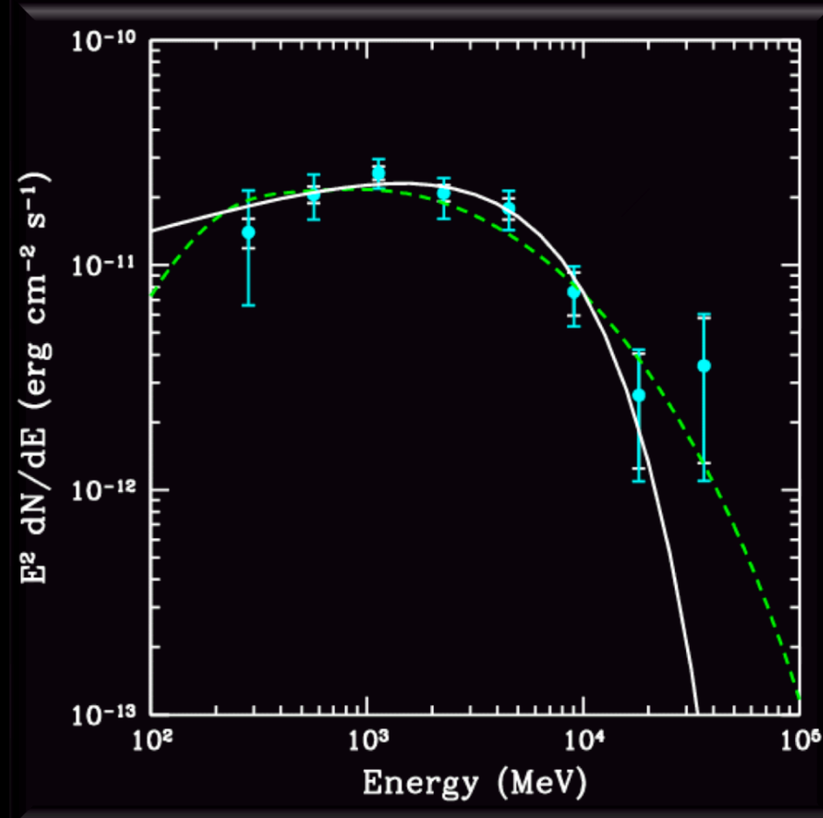


- X-ray studies show thermal shell with a central PWN
  - pulsar candidate seen as hard point source in center of PWN (offset from radio center)
- X-ray spectrum gives $n_0 \approx 0.6\ \mathrm{cm}^{-3}$
- SNR/PWN modeling gives $t \approx 5$ kyr
  - SNR reverse shock has begun to interact with PWN

MSH 11-62

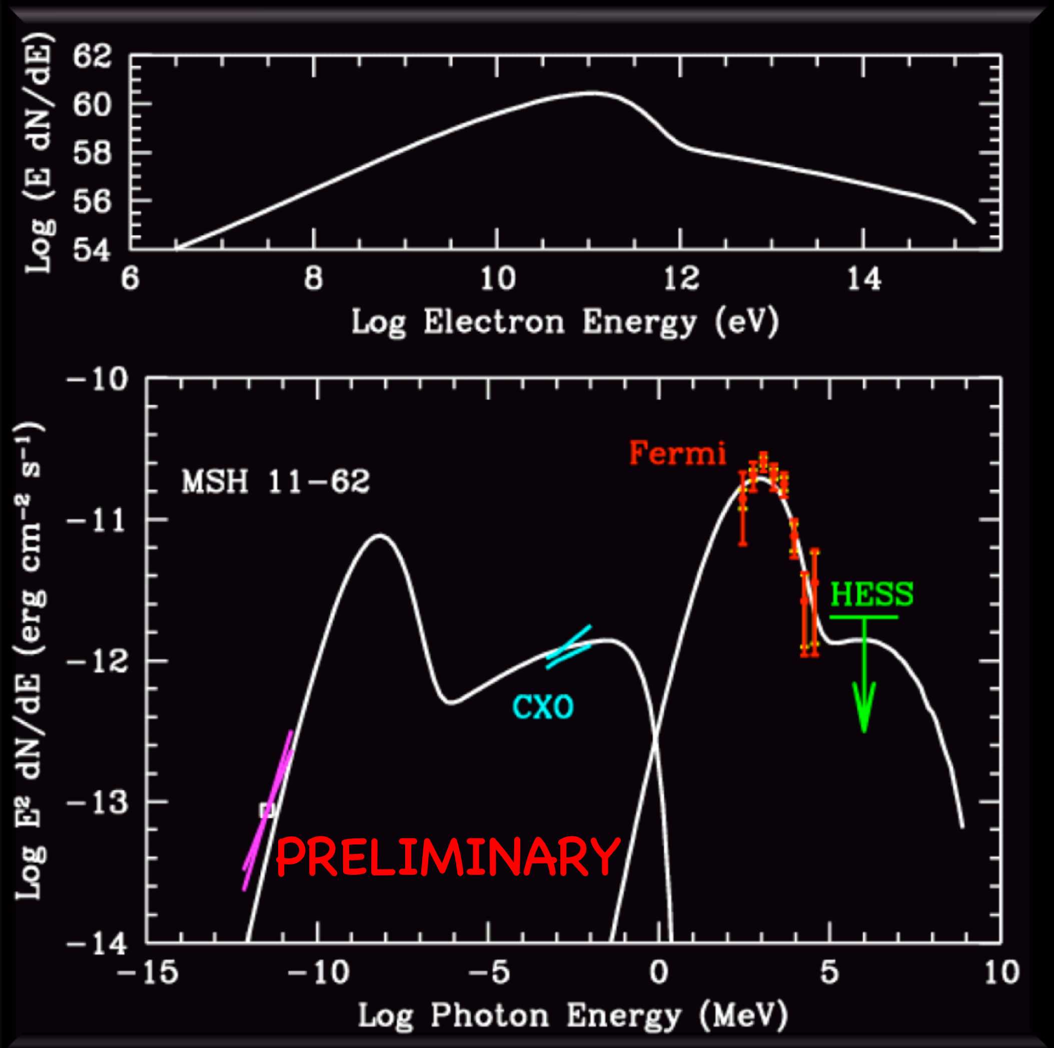


Fermi LAT



- 1FGL J1112.1-6041 is spatially associated with MSH 11-62
  - F(>100 MeV) ≈ 1 x 10^{-10} erg cm^{-2} s^{-1}
- Two nearby pulsars w/ $\dot{E}$ > 10^{33} erg/s
  - neither can yield more than 3% of the flux
- Spectrum well-described by cut-off PL
  - E_{cut} ≈ 5 GeV, consistent w/ pulsar spectra
- Pion model gives acceptable fit
  - requires n_0 = 7 cm^{-3} and E_{cut} = 70 GeV
  - these values are too high and too low, respectively, for a typical SNR scenario

MSH 11-62



- PWN model with PL injection cannot fit broadband spectrum
  - either over-predicts TeV flux or under-predicts GeV flux
  - similar to Vela X and HESS J1640-465
- Model w/ Maxwellian + PL gives good approximation to data
  - $\gamma_e \approx 10^6$, $\Gamma \approx 2.7$; $E_{PL} = 0.01\ E_{Maxwellian}$
  - $B \approx 2\ \mu G$, typical of evolved PWN
- Fermi observations of MSH 11-62 are consistent with emission arising from an evolved PWN
  - if correct, broadband modeling appears to provide additional support for presence of Maxwellian electron component
  - cannot rule out pulsar as origin of GeV emission
  - timing and sub-mm observations important

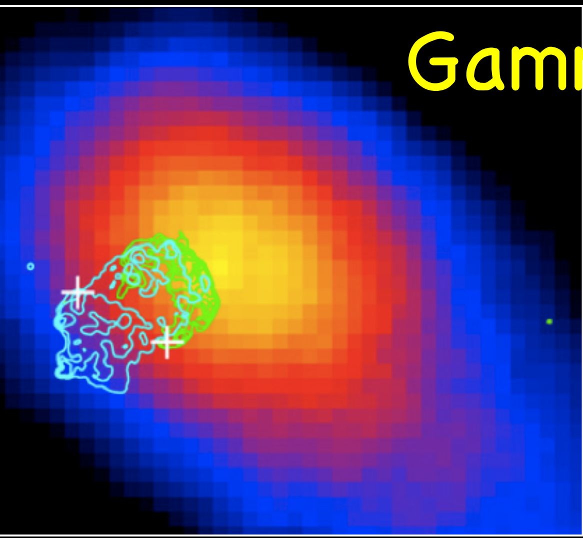
SNRs and PWNe: Summary

- SNRs accelerate electrons and ions to extremely high energies
  - Gamma-ray observations place strong constraints on underlying particle spectrum, providing important information about acceleration process and production of cosmic rays
  - Modeling of broadband emission is generally required understand gamma-ray emission
  - Current studies show that SNRs are powerful accelerators of cosmic rays. Question of whether they are the only main contributor remains open.
  - SNRs interacting with molecular clouds provide important environment for detection of gamma-ray emission from hadronic component

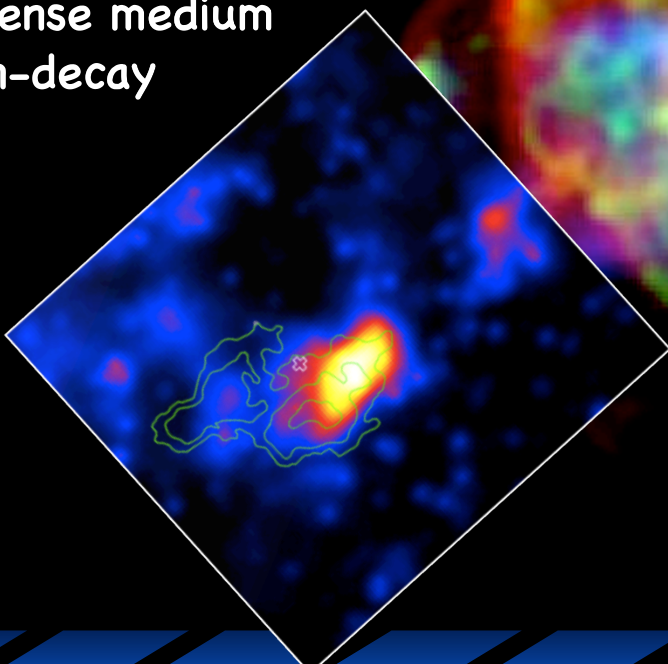
- PWNe contain extremely energetic electrons that produce gamma-rays
  - As PWNe evolve, and magnetic field declines, gamma-ray emission becomes especially important for studying evolution
  - Gamma-rays provide unique probe of underlying electron spectrum, particularly at low energies (where many particles are expected).
  - PWNe that have undergone interaction with SNR reverse shock appear to be strong gamma-ray sources. Evolution? Reacceleration?

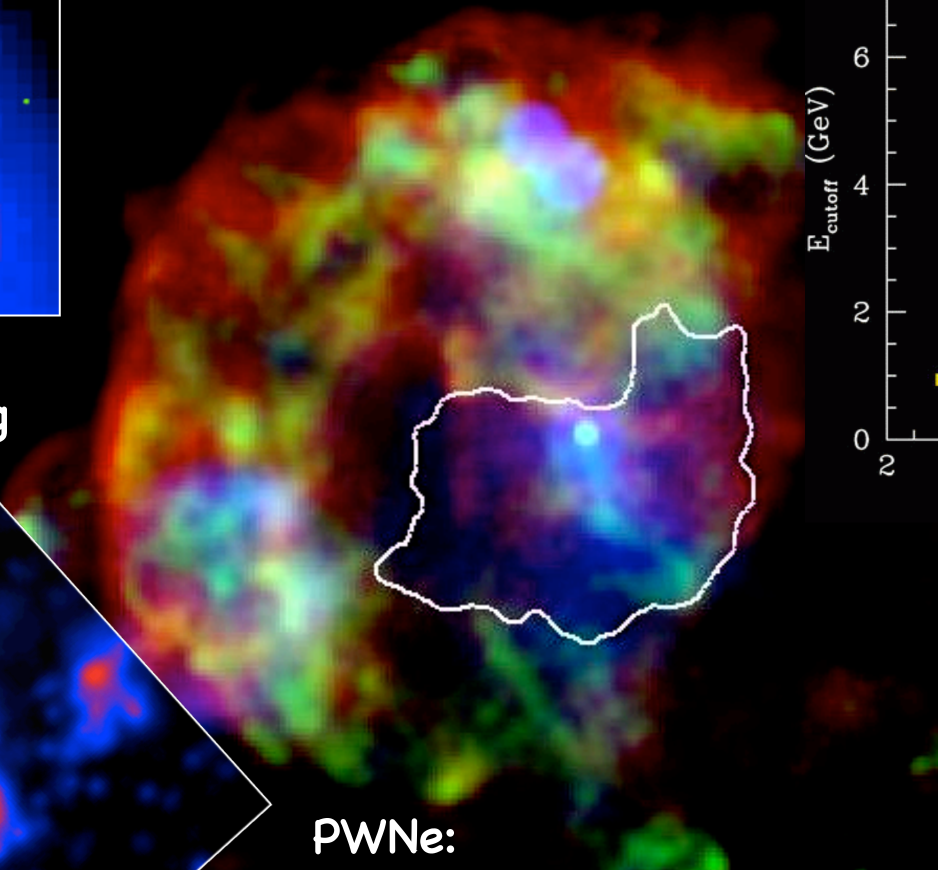
Backup Slides

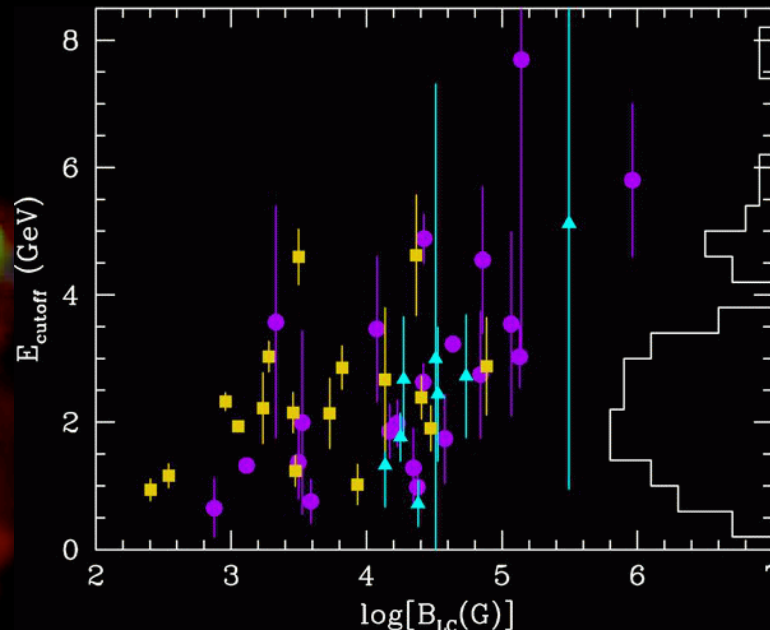
Gamma-Rays from Composite SNRs



SNRs:
- particularly if evolving in dense medium
- pion-decay



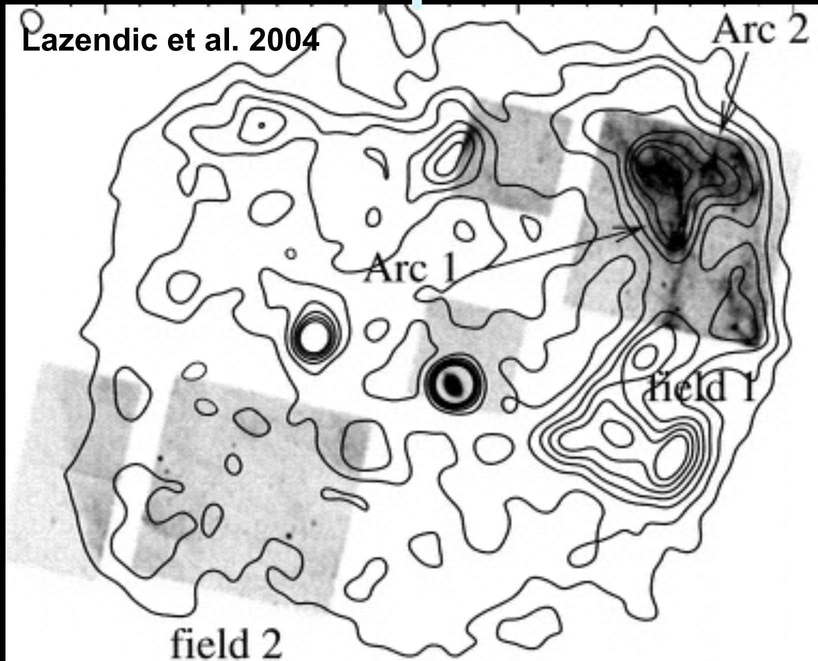


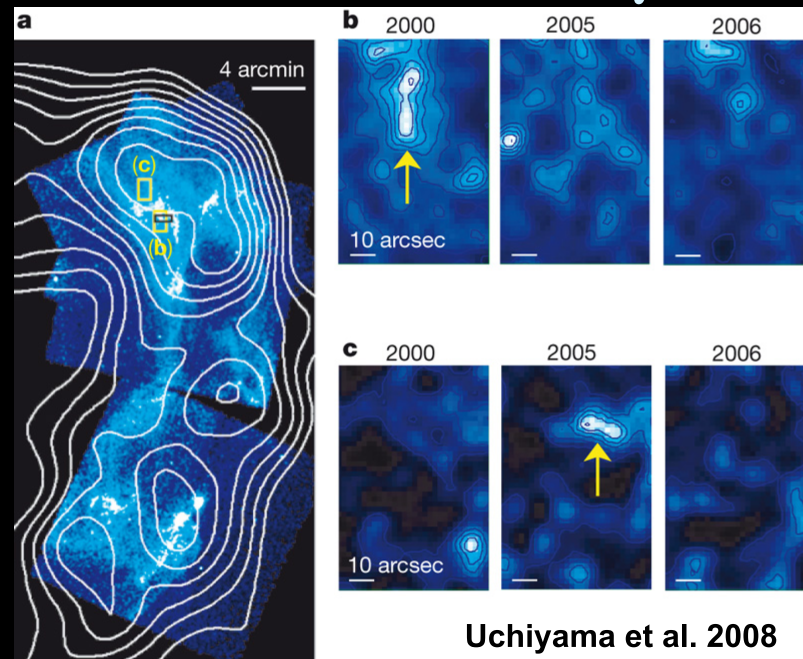


Pulsars:
- PL spectra with cutoffs below 5-6 GeV

PWNe:
- emission highly dependent on evolutionary state
- generally require breaks or multiple electron components

B Amplification: Rapid Time Variability





- Along NW rim of G347.3-0.5, brightness variations observed on timescales of ~1 yr
  - if interpreted as synchrotron-loss or acceleration timescales, B is huge: B ~ 1 mG

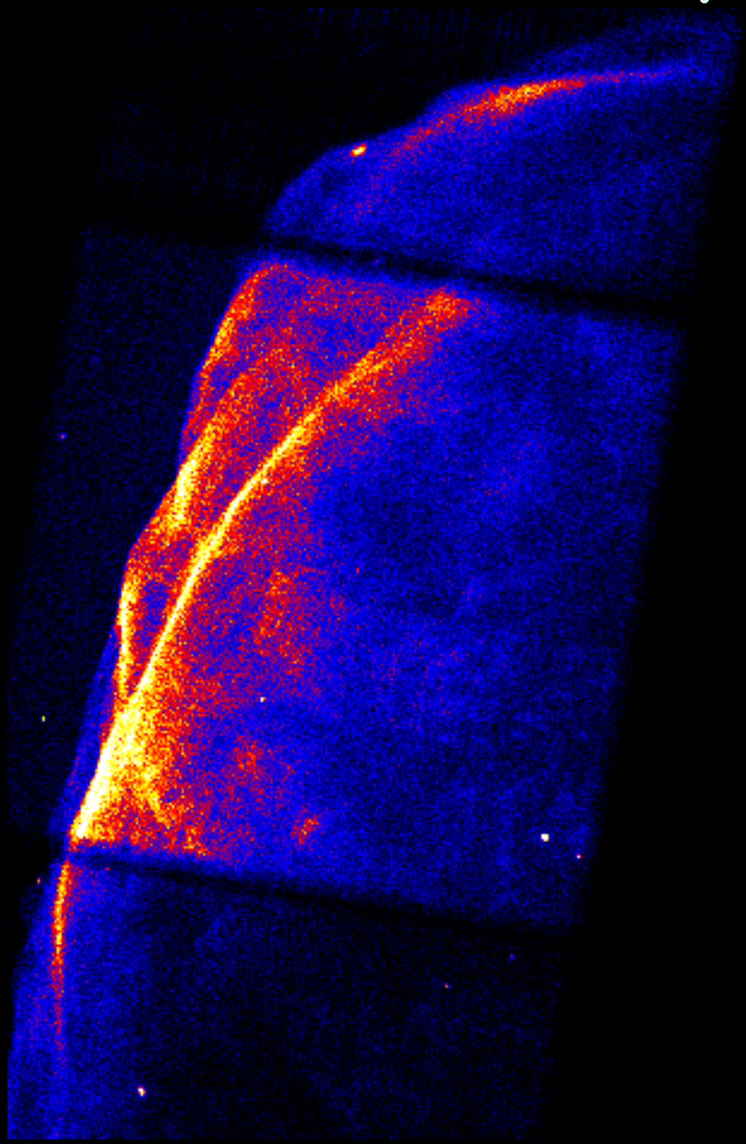
$$t_{syn} \sim 1.5 B_{mG}^{-3/2} \varepsilon_{keV}^{-1/2} \mathrm{yr}$$

$$t_{acc} \sim 9 B_{mG}^{-3/2} \varepsilon_{keV}^{1/2} v_{1000}^{-2} \mathrm{yr}$$

- This, along with earlier measurements of the nonthermal spectrum in Cas A, may support the notion of <u>magnetic field amplification</u> => potential high energies for ions

- Notion still in question; there are other ways of getting such variations (e.g. motion across compact magnetic filaments)

B Amplification: Thin Filaments



- Thin nonthermal X-ray filaments are now observed in many SNRs, including SN 1006, Cas A, Kepler, Tycho, RX J1713, and others
  - observed drop in synchrotron emissivity is too rapid to be the result of adiabatic expansion

- Vink & Laming (2003) and others argue that this suggests large radiative losses in a strong magnetic field:

$$B \sim 200 \mathrm{v}_8^{2/3} \left(\frac{l}{0.01 pc} \right)^{-2/3} \mu G$$

- Diffusion length upstream appears to be very small as well (Bamba et al. 2003)
  - we don't see a "halo" of synchrotron emission in the upstream region

$$l_D \sim \frac{\kappa}{\mathrm{v}}, \text{ but } \kappa \propto B^{-1}$$

- Alternatively, Pohl et al (2005) argue that field itself is confined to small filaments due to small damping scale