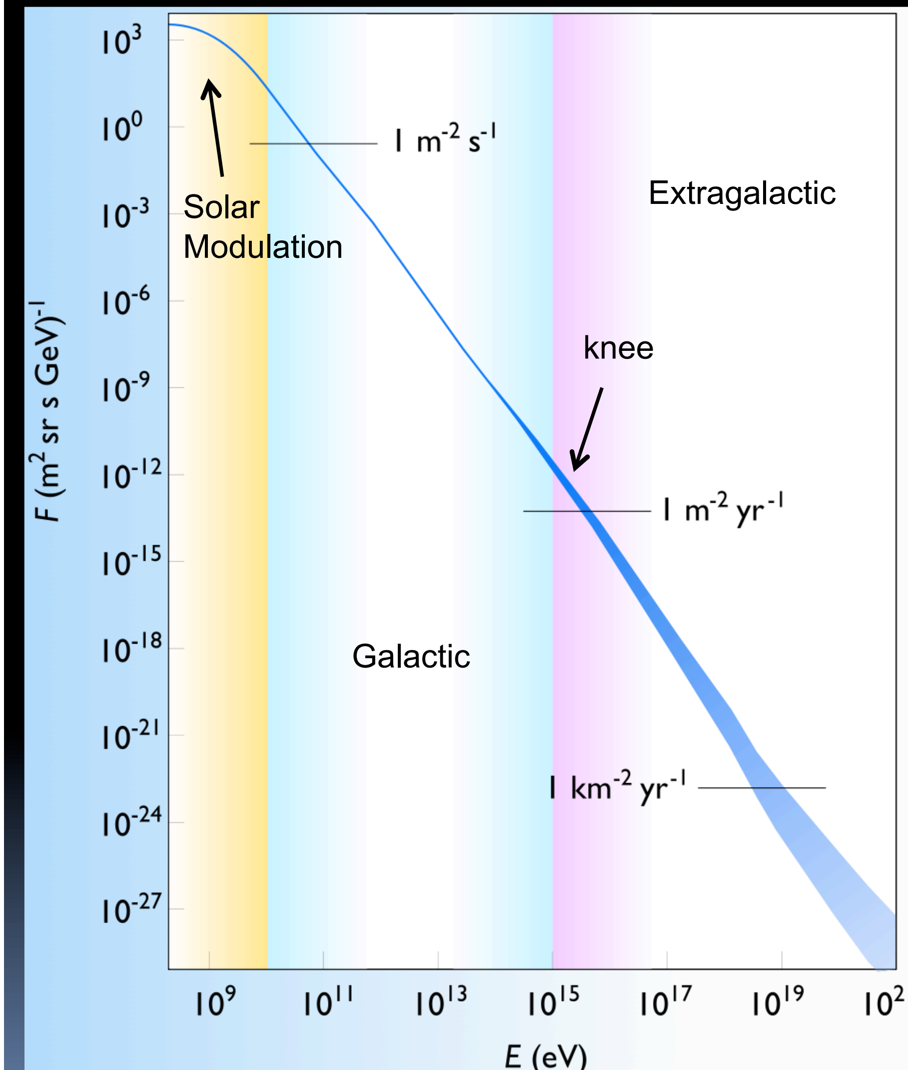
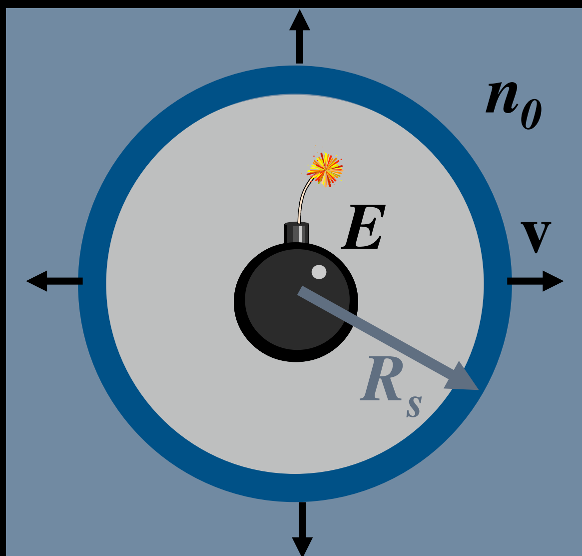
Cosmic-Ray Acceleration in Supernova Remnants

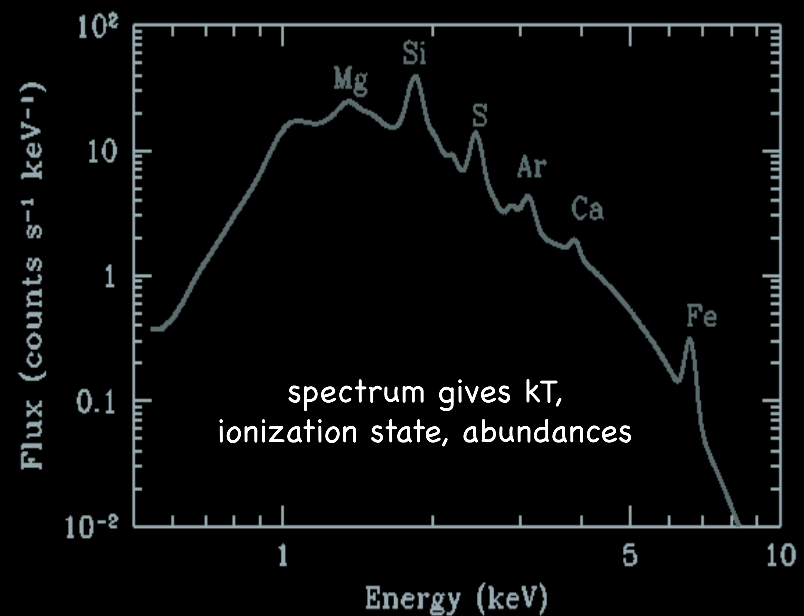
Cosmic Rays and SNRs



- CR spectrum is a power law covering more than 10 decades in energy.
  - "knee" in spectrum at ~10^{15-16} eV
  - CRs below knee thought to be Galactic in origin
- Composition of Galactic CRs similar to well-mixed ISM; energy density ~1 eV cm^{-3}
  - consistent w/ production in SNRs
- Direct evidence of CR acceleration in SNRs provides opportunity to constrain acceleration physics and address source of CRs

SNR Evolution: The Ideal Case





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

$$v_s = \frac{2}{5}\frac{R_s}{t}$$

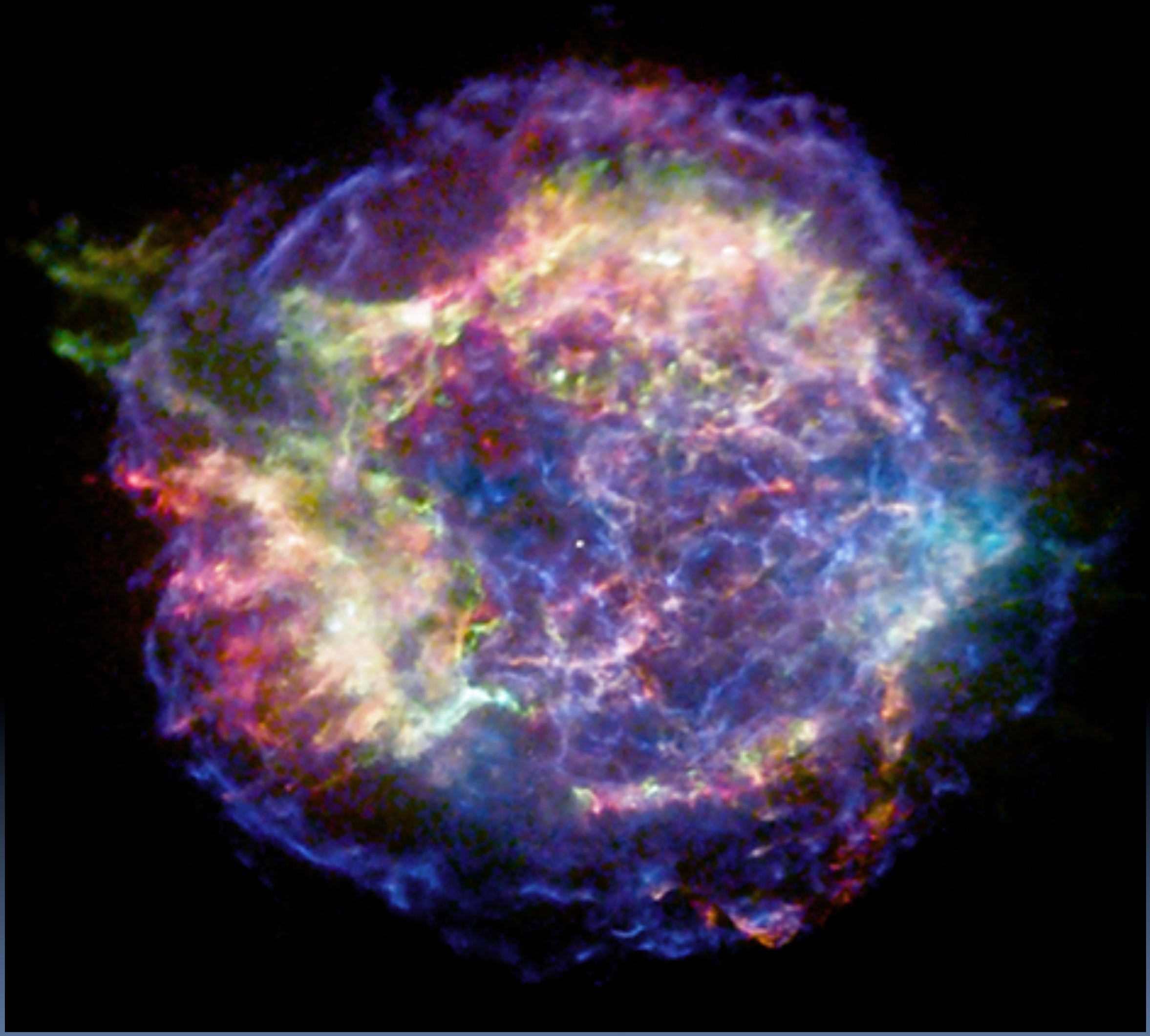
$$\frac{E_{51}}{\rho_0} = 0.49 R_s^5 t^{-2}$$

- X-ray measurements can provide temperature and density:

$$T_x = 1.28 T_{shock}$$

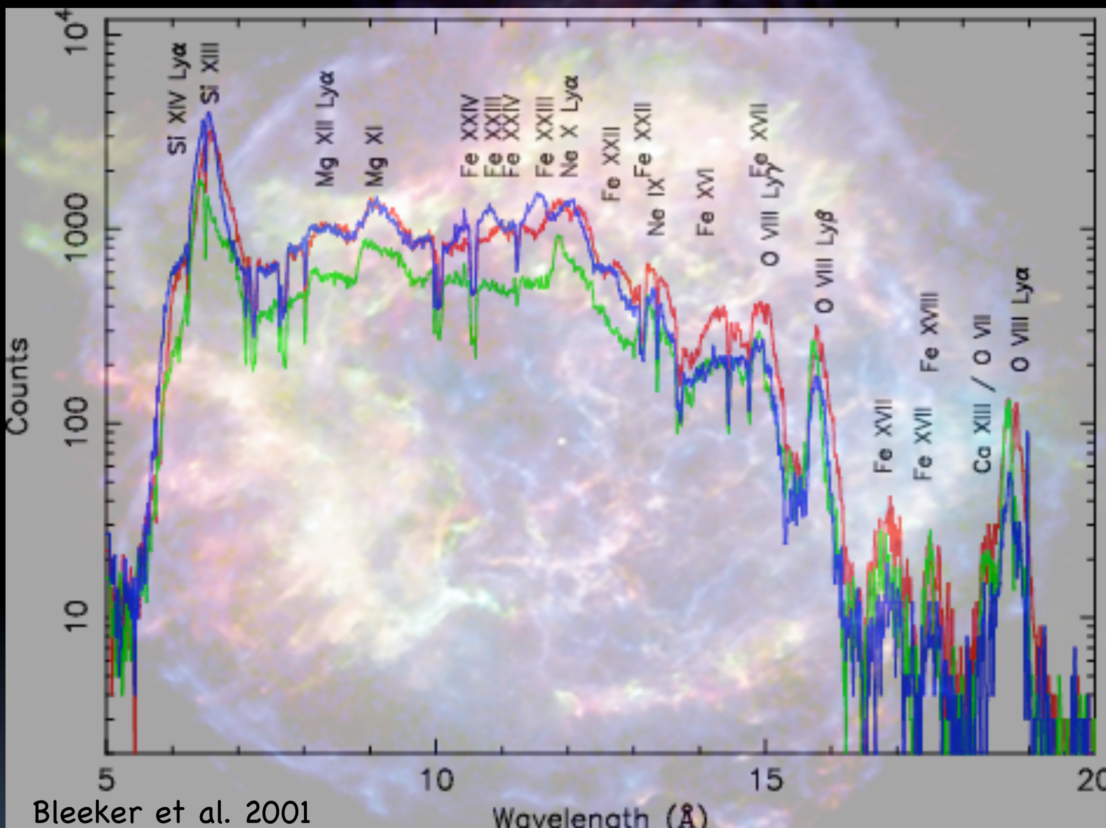
$$EM = \int n_H n_e dV$$

SNR Evolution: The Real Case



- At early ages, expansion is more rapid
- Ejecta emission can dominate flux
- X-ray spectrum is complicated
- For core-collapse SNRs, CSM is never uniform
- Cosmic-ray acceleration modifies the picture

SNR Evolution: The Real Case



Bleeker et al. 2001

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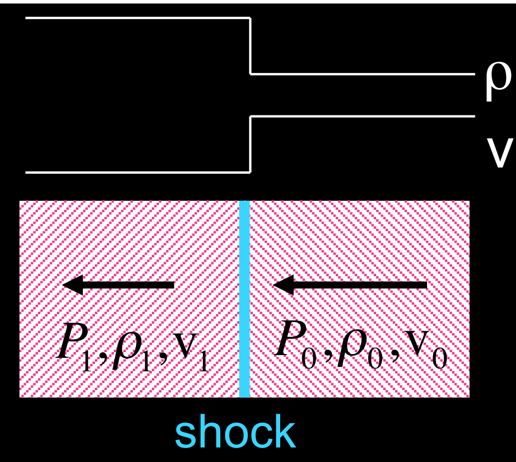
Shocks in SNRs



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

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

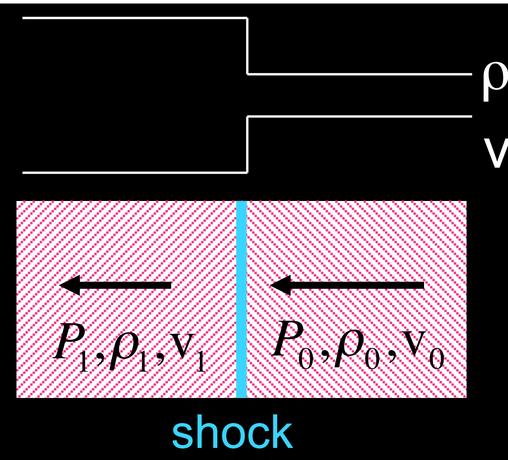
$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

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

$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k}m_H v_0^2 = 1.3\times10^7 v_{1000}^2 \text{ K}$$

X-ray emitting temperatures

Shocks in SNRs



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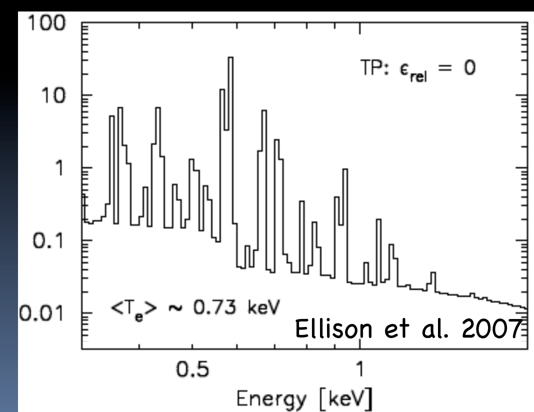
- Shock velocity gives temperature of gas
  - can get from X-rays (modulo T_e/T_p equilibration)



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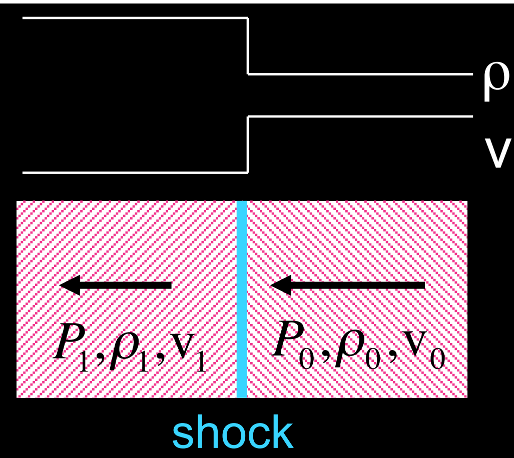

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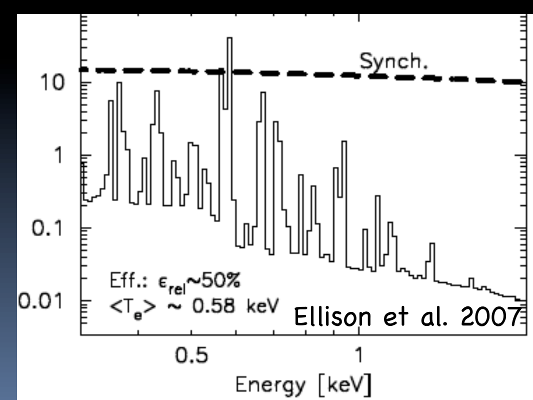
- If cosmic-ray pressure is present <u>the temperature will be lower than this</u>



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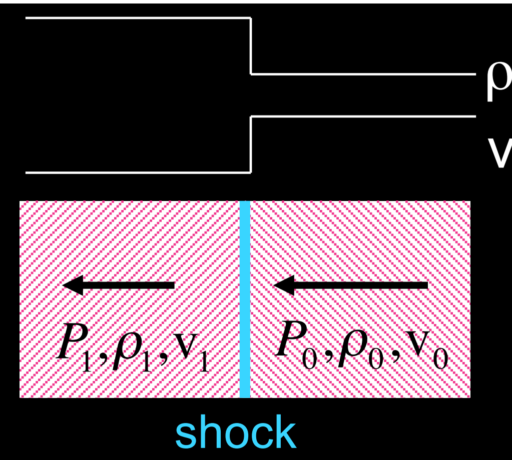

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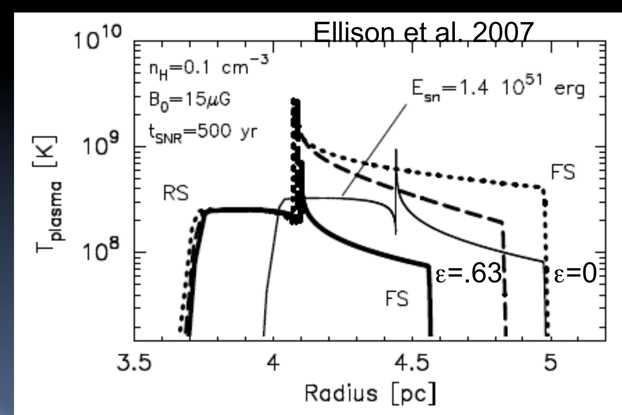
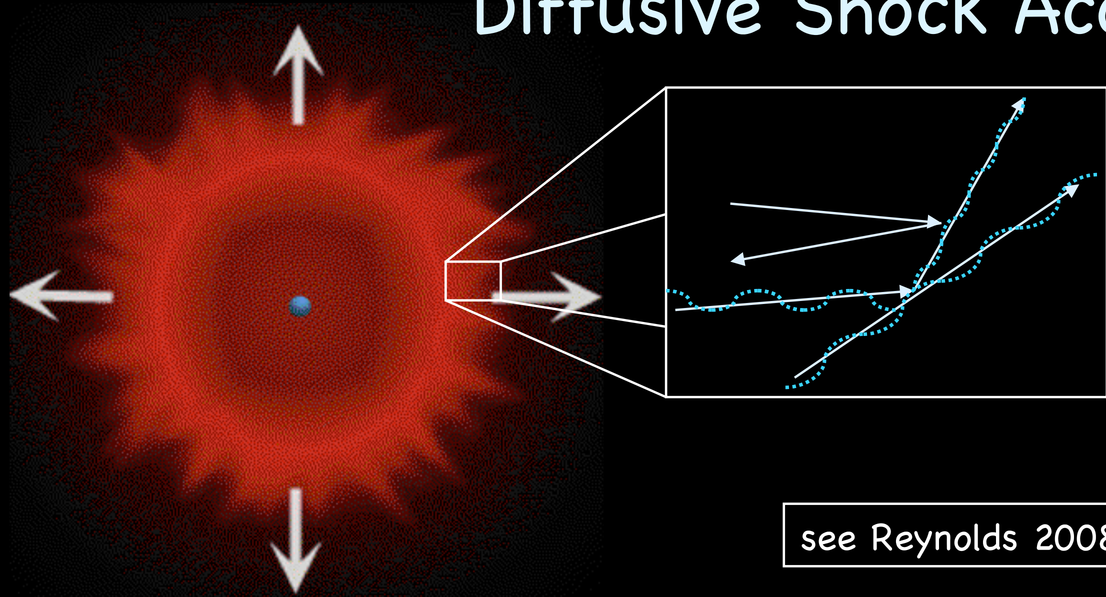
X-ray emitting temperatures

- Shock velocity gives temperature of gas
  - can get from X-rays (modulo NEI effects)
- If cosmic-ray pressure is present <u>the temperature will be lower than this</u>
  - radius of forward shock affected as well (e.g., Decourchelle et al. 2000)



Diffusive Shock Acceleration



see Reynolds 2008

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

$$\lambda \propto r_g = E / eB$$

(i.e., most energetic particles have very large λ and escape)

- Maximum energies determined by either:

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

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

High B ➔ High E_{max}

radiative losses (synchrotron; electrons)

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

High B ➔ Low E_{max} for e^{+-}

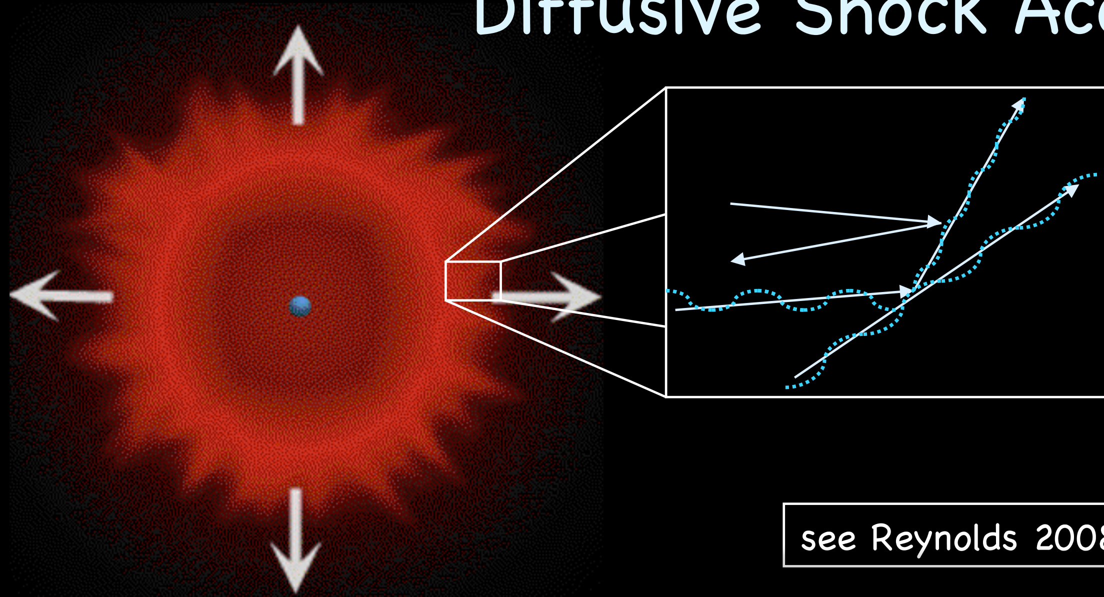
escape – scattering efficiency decreases w/ energy

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

High B ➔ High E_{max}

magnetic field amplification important!

Diffusive Shock Acceleration



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(i.e., most energetic particles have very large λ and <u>escape</u>)

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>

- Maximum energies determined by either:

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

$$E_{\max}(\mathrm{age}) \sim 0.5 \mathrm{v}_8^2 t_3 B_{\mu G} (\eta R_J)^{-1} \mathrm{TeV}$$

radiative losses (synchrotron; electrons)

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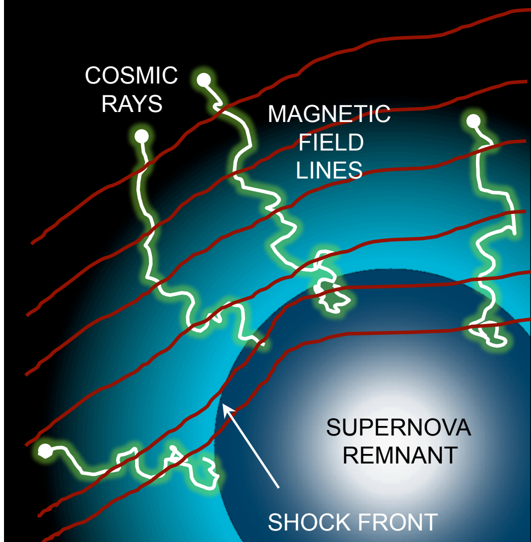
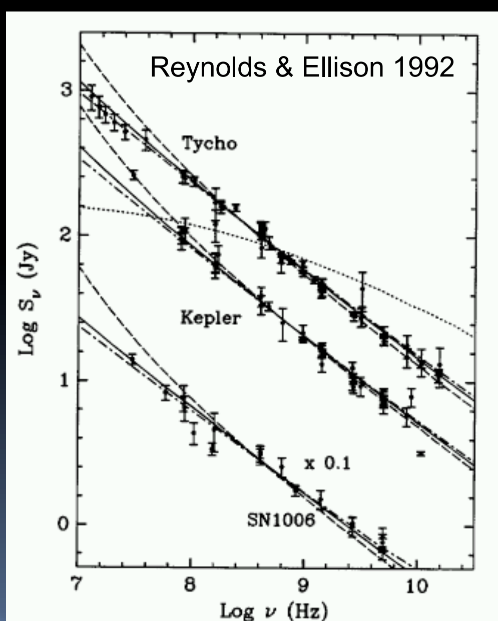




Radio Emission from SNRs

- Synchrotron Radiation: $$E_{e,GeV} = \left[\frac{\upsilon}{16\text{ MHz}} B_{\mu G}^{-1}\right]^{1/2}$$

  - for typical fields, radio emission is from GeV electrons (Hint: for X-rays, $\nu > 10^{18}$ Hz → >TeV electrons)

  - Power law photon spectra imply power law particle spectra:

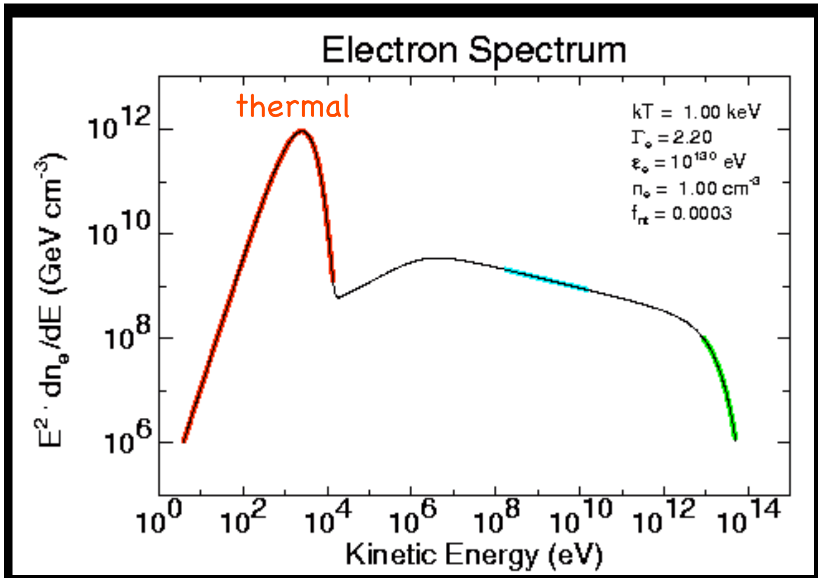
$$dN = KE^{-\alpha} dE$$

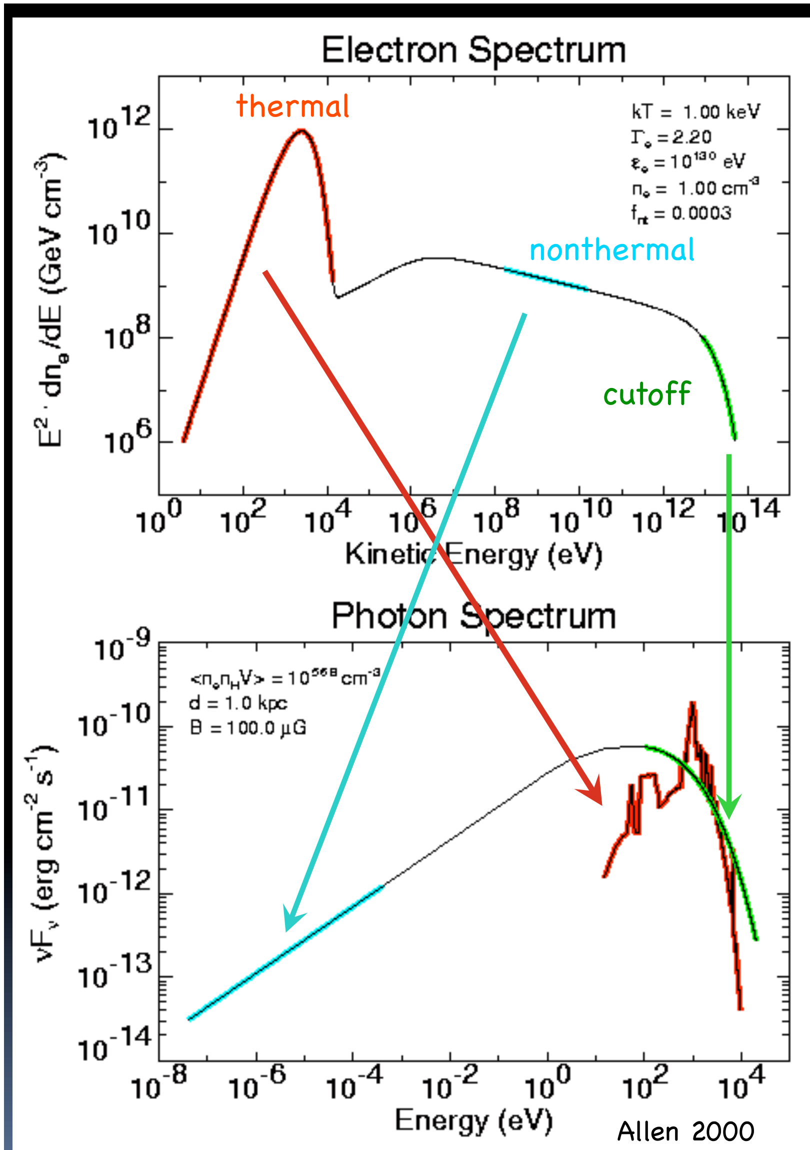
which gives

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

  - shell-type SNRs have $S_\nu = A\nu^{-0.6}$ or $\alpha = 2.2$, similar to CR spectrum

Shocked Electrons: Radio & X-ray Spectra

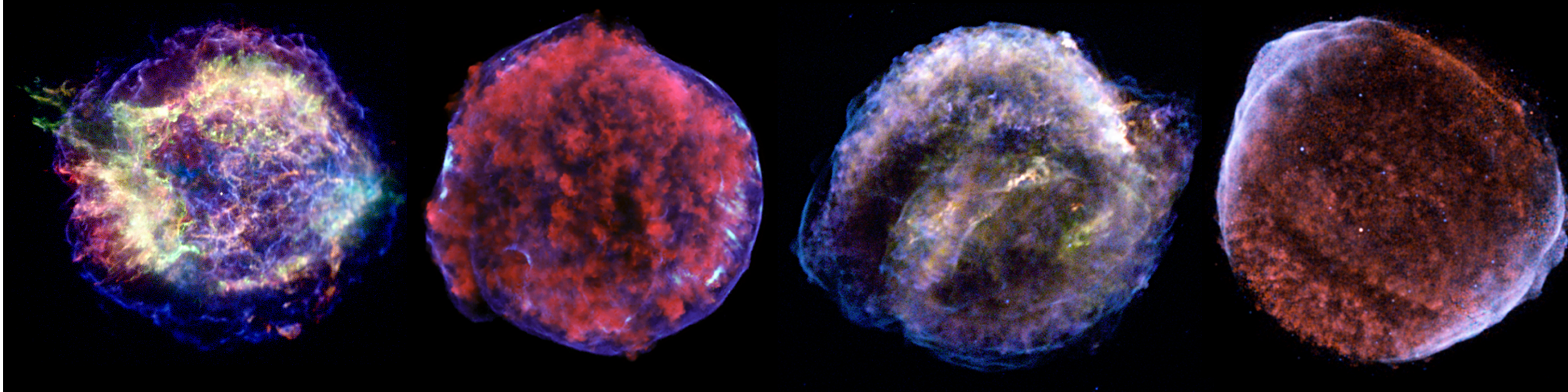




Shocked Electrons: Radio & X-ray Spectra

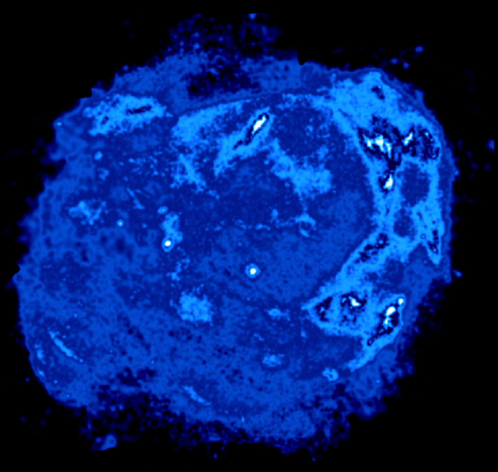
- Thermal electrons produce line-dominated x-ray spectrum with bremsstrahlung continuum
  - yields kT, ionization state, abundances
- nonthermal electrons produce synchrotron radiation over broad energy range
  - responsible for radio emission
- high energy tail of nonthermal electrons yields x-ray synchrotron radiation
  - rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and a limit to the energy of the associated cosmic rays

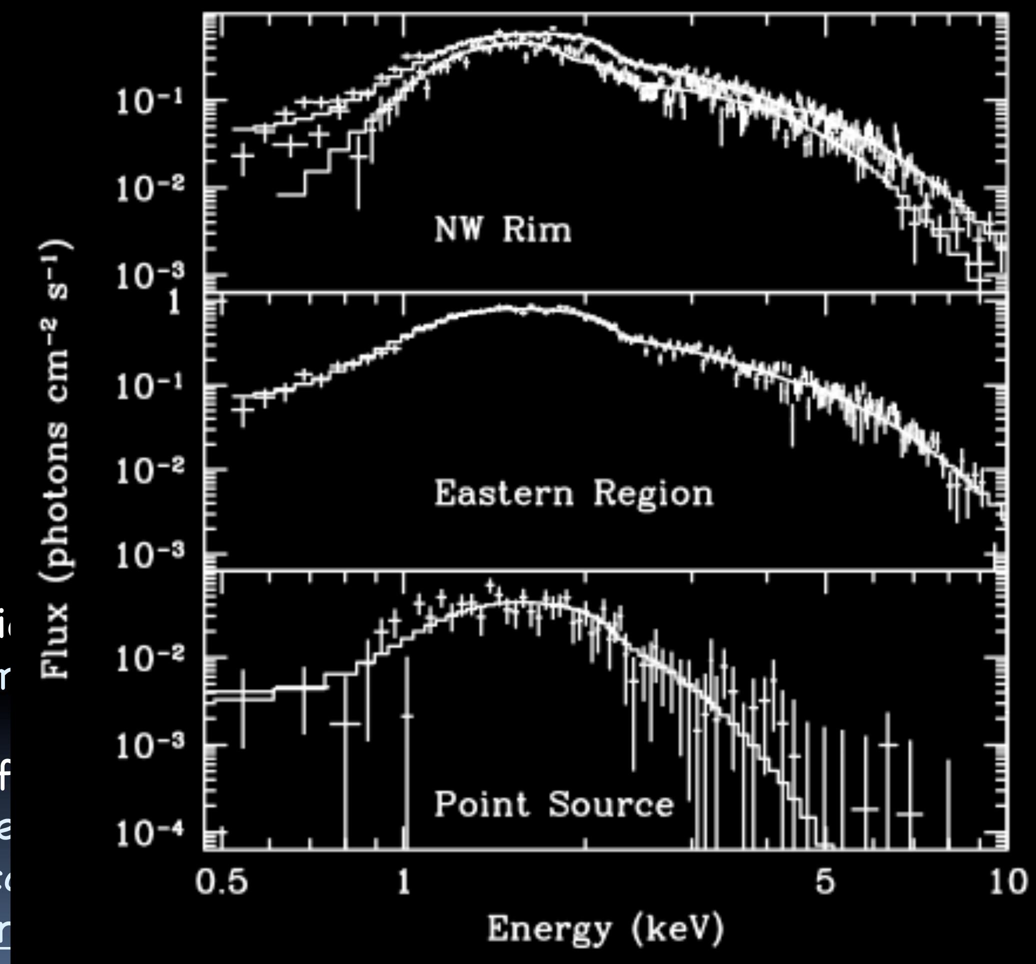
X-ray Signatures of Energetic Particles



- X-ray synchrotron emission implies electrons with energies of 50-100 TeV or higher
  - for some remnants, X-ray emission is dominated by synchrotron radiation
- Is there also evidence of energetic protons? YES!
  - Conditions exist: magnetic field amplification
  - Dynamics imply significant energy in protons
  - Thermal X-ray emission (both its absence and its presence) also provides constraints

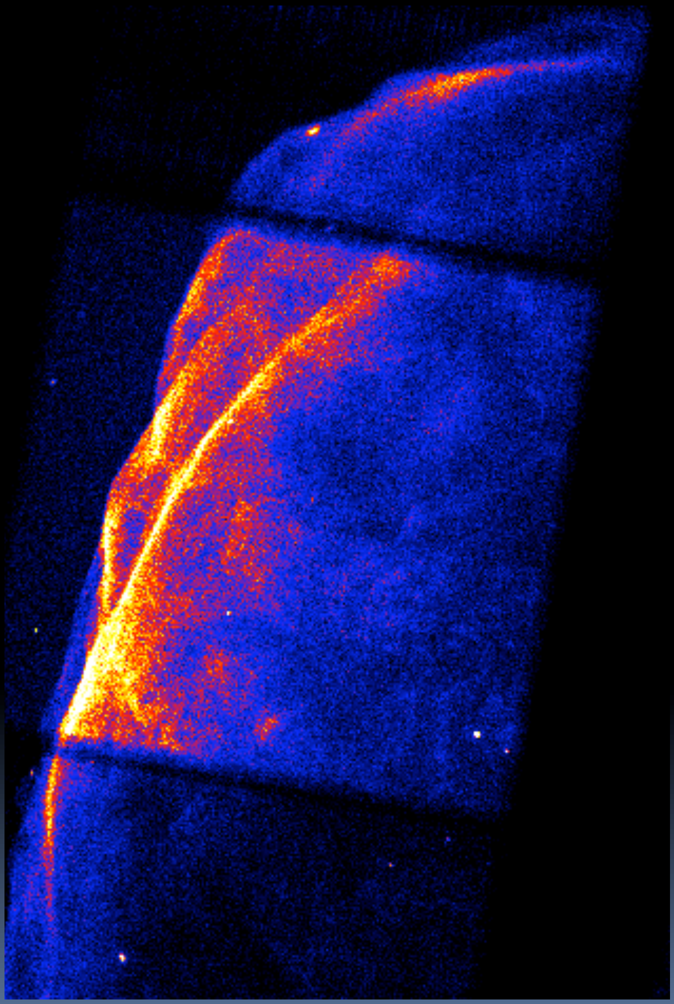
X-ray Signatures of Energetic Particles





- X-ray synchrotron emissi… gher
  - for some remnants, X-r…
- Is there also evidence of…
  - Conditions exist: magne…
  - Dynamics imply signific…
  - Thermal X-ray emission… straints

B Amplification: Thin Filaments



- Thin nonthermal X-ray filaments observed in many SNRs
- Vink & Laming (2003) and others argue that this suggests large radiative losses in a strong magnetic field:

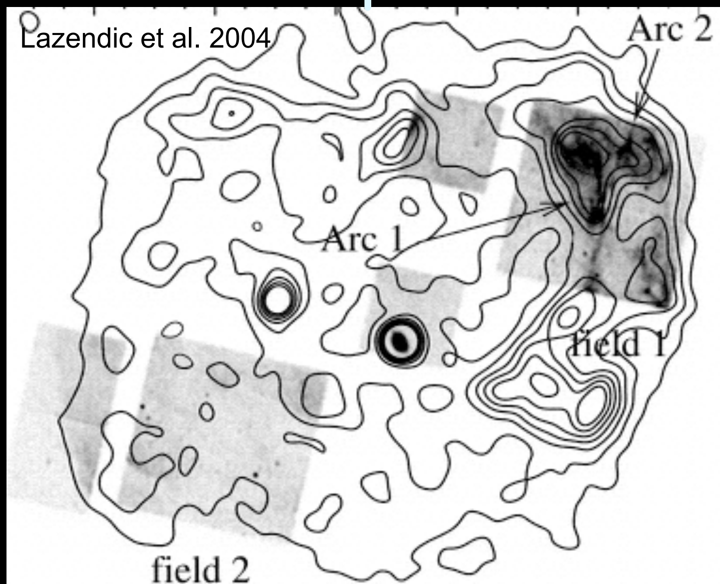
$$B \sim 200 v_8^{2/3} \left(\frac{l}{0.01 pc} \right)^{-2/3} \mu G$$

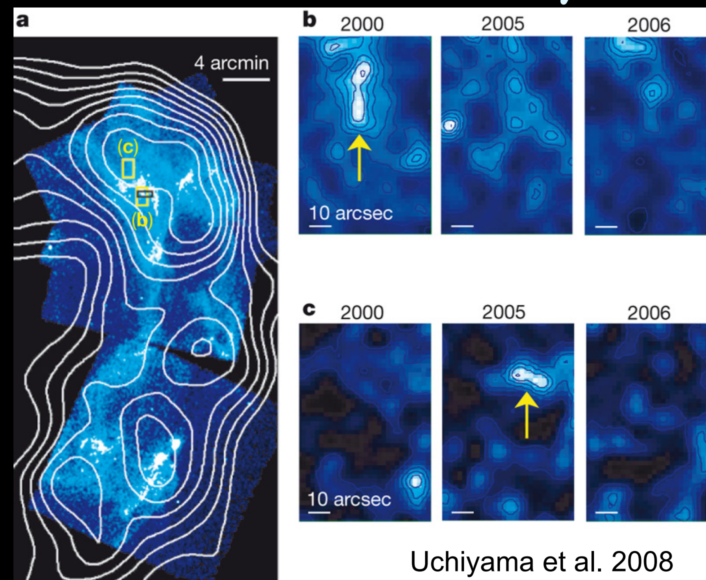
- Diffusion length upstream appears to be very small as well (Bamba et al. 2003)
  - we don't see a "halo" of synchrotron emission in the upstream region

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

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

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

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

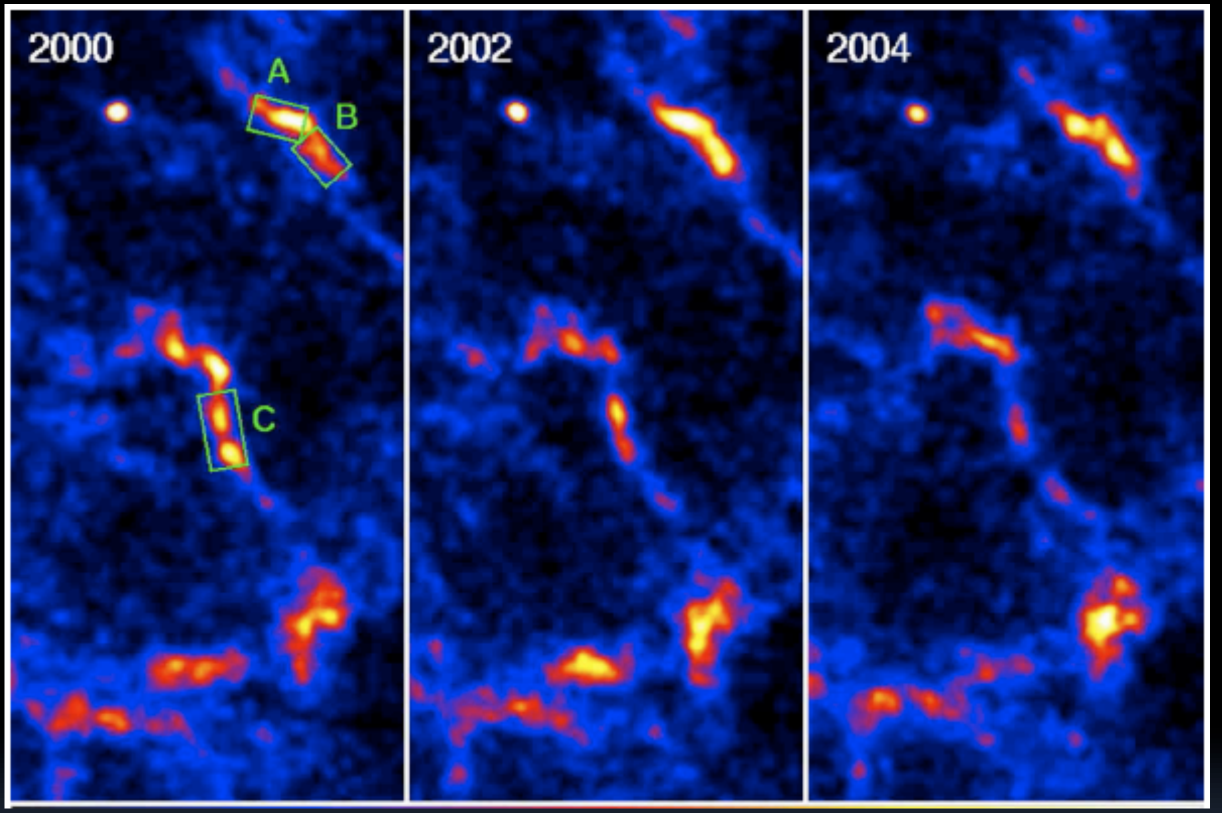
$$t_{acc} \sim 9 B_{mG}^{-3/2} \varepsilon_{keV}^{1/2} \mathrm{v}_{1000}^{-2} \mathrm{yr}$$

  - may support magnetic field amplification => 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: Time Variations in Cas A

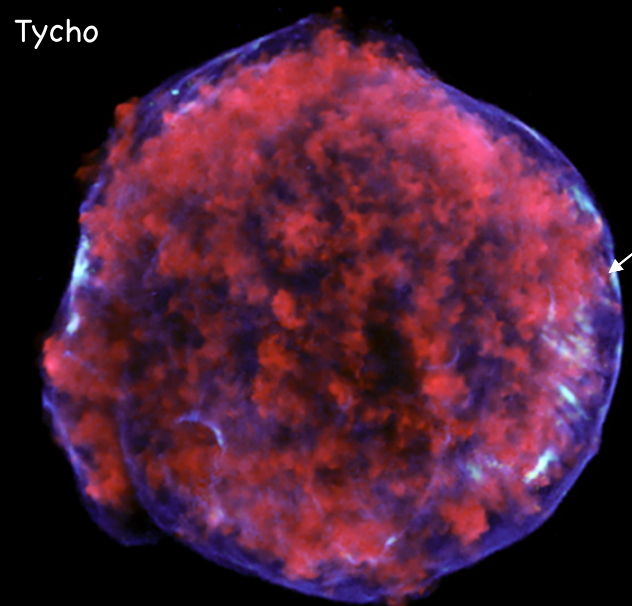
- Cas A is expanding rapidly
- Significant brightness variations are seen on timescales of years
  - ejecta knots seen lighting up as reverse shock crosses
- Variability seen in high energy continuum as well
  - similar to results from RX J1713.7-3946



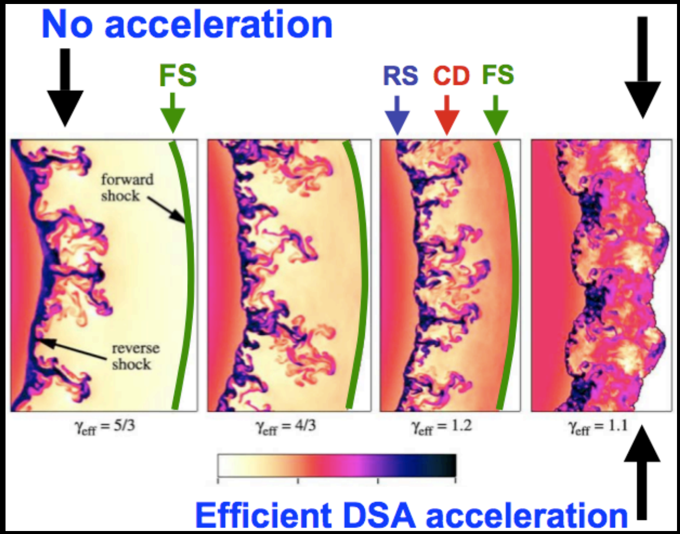
Uchiyama & Aharonian 2008

Overall evidence is that magnetic field amplification is occurring and is important for particle acceleration in SNRs

Dynamical Evidence for CR Ion Acceleration



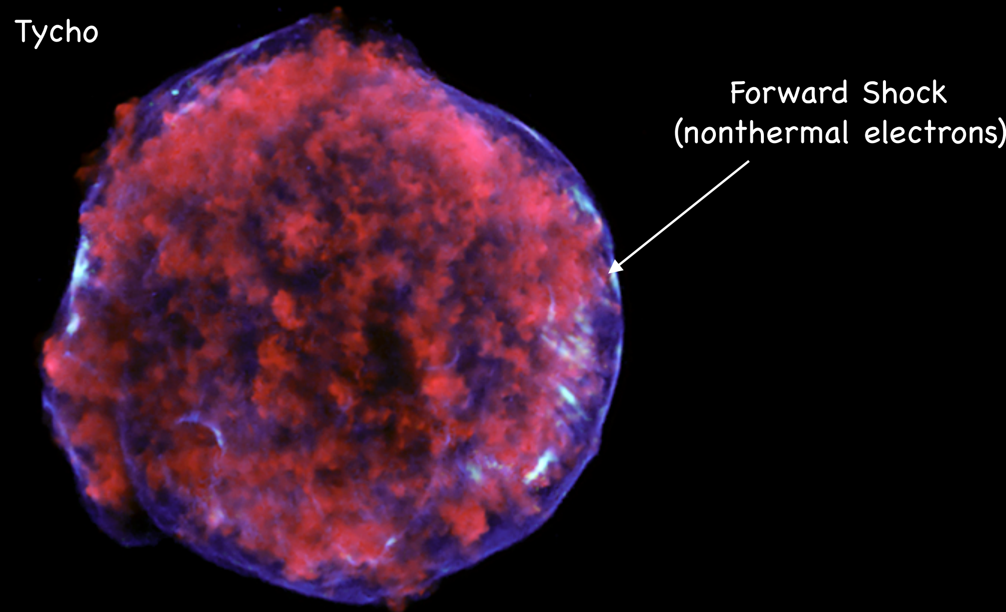
Warren et al. 2005

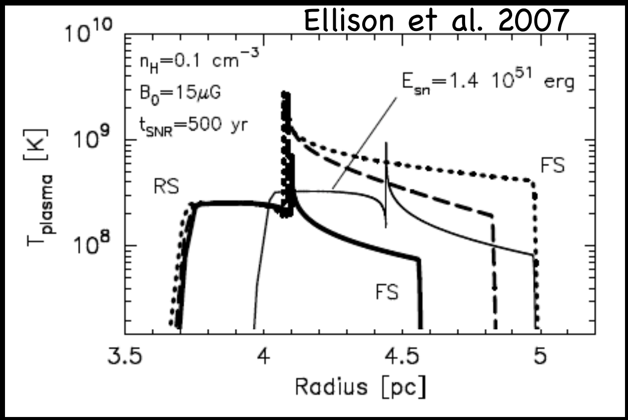


Blondin & Ellison 2001

- 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

Dynamical Evidence for CR Ion Acceleration





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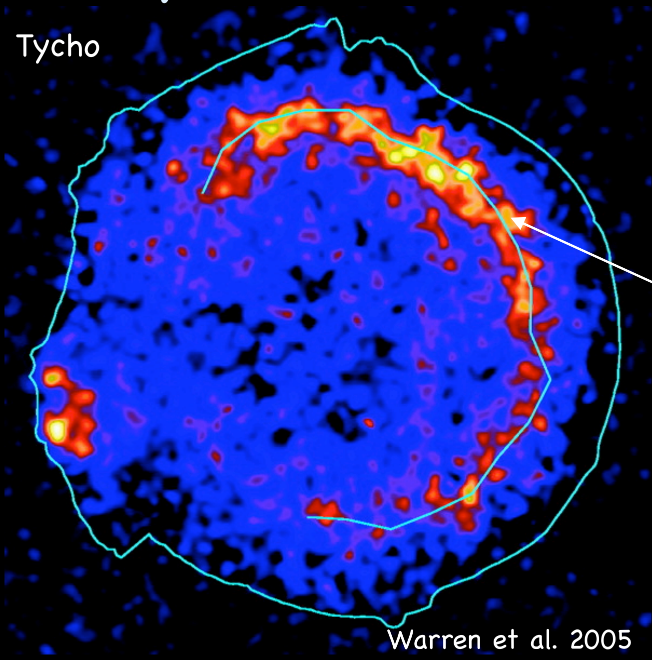
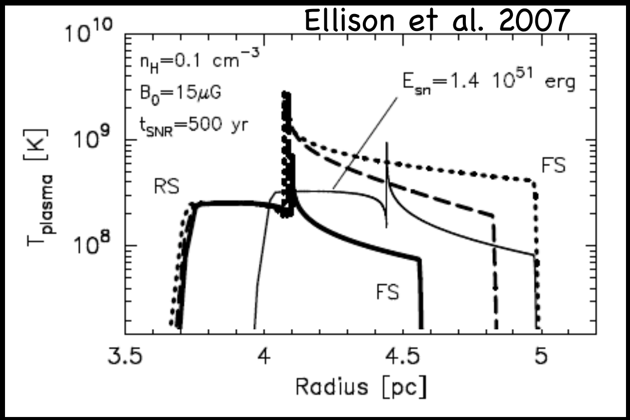


Reverse Shock
(ejecta - here Fe-K)



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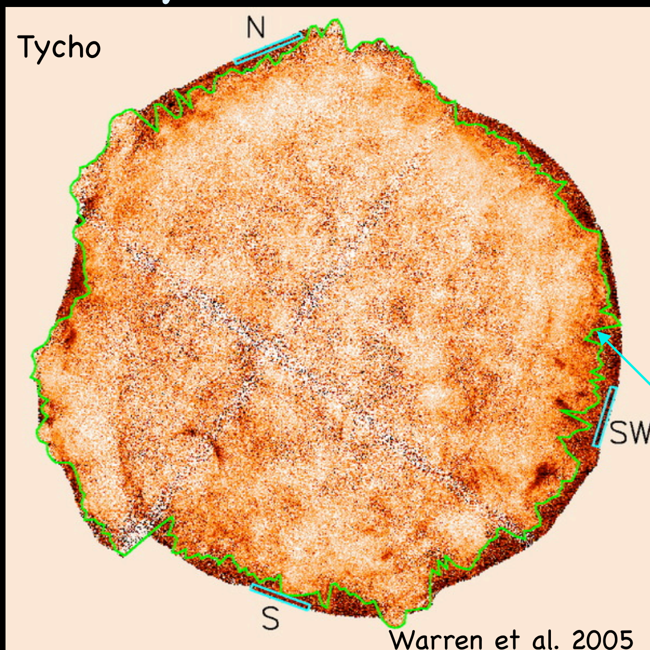
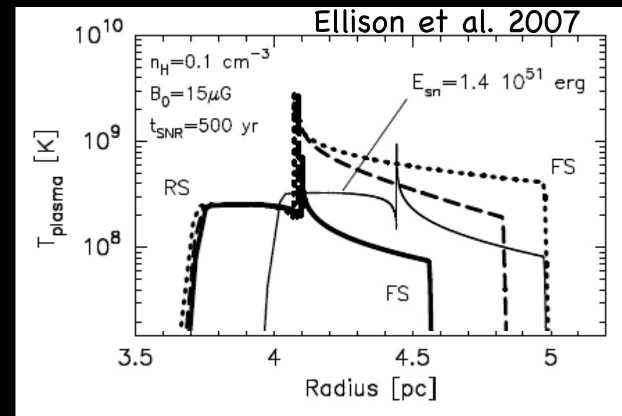
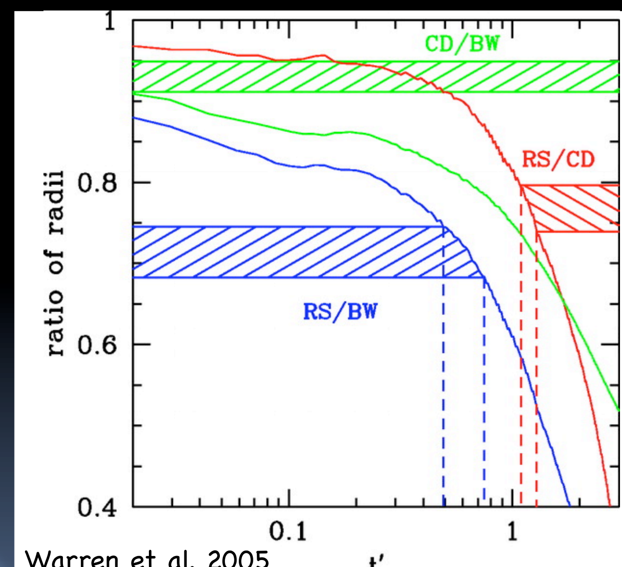


Contact Discontinuity





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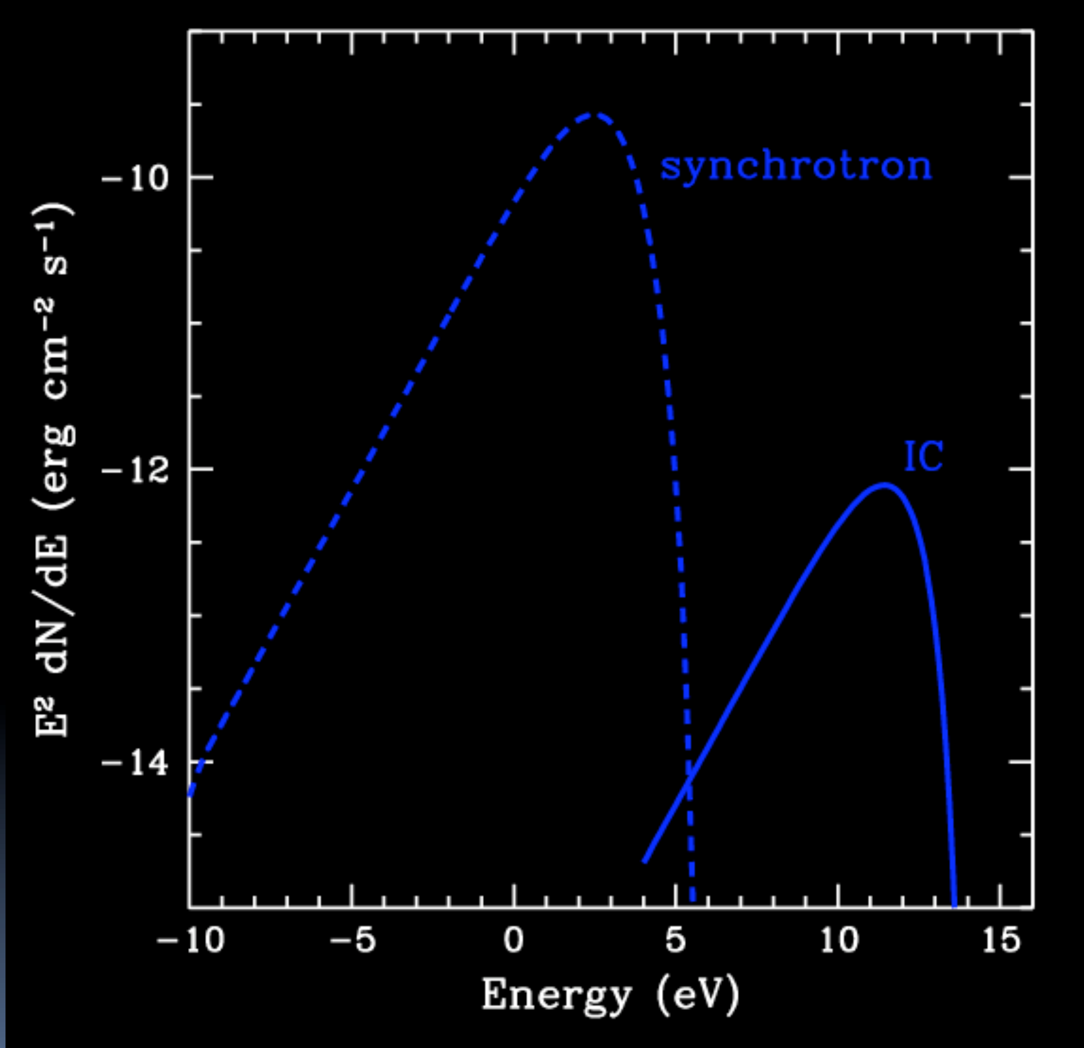
Gamma-Ray Emission from SNRs



- Inverse-Compton
  - energetic electrons upscatter ambient photons to γ-ray energies

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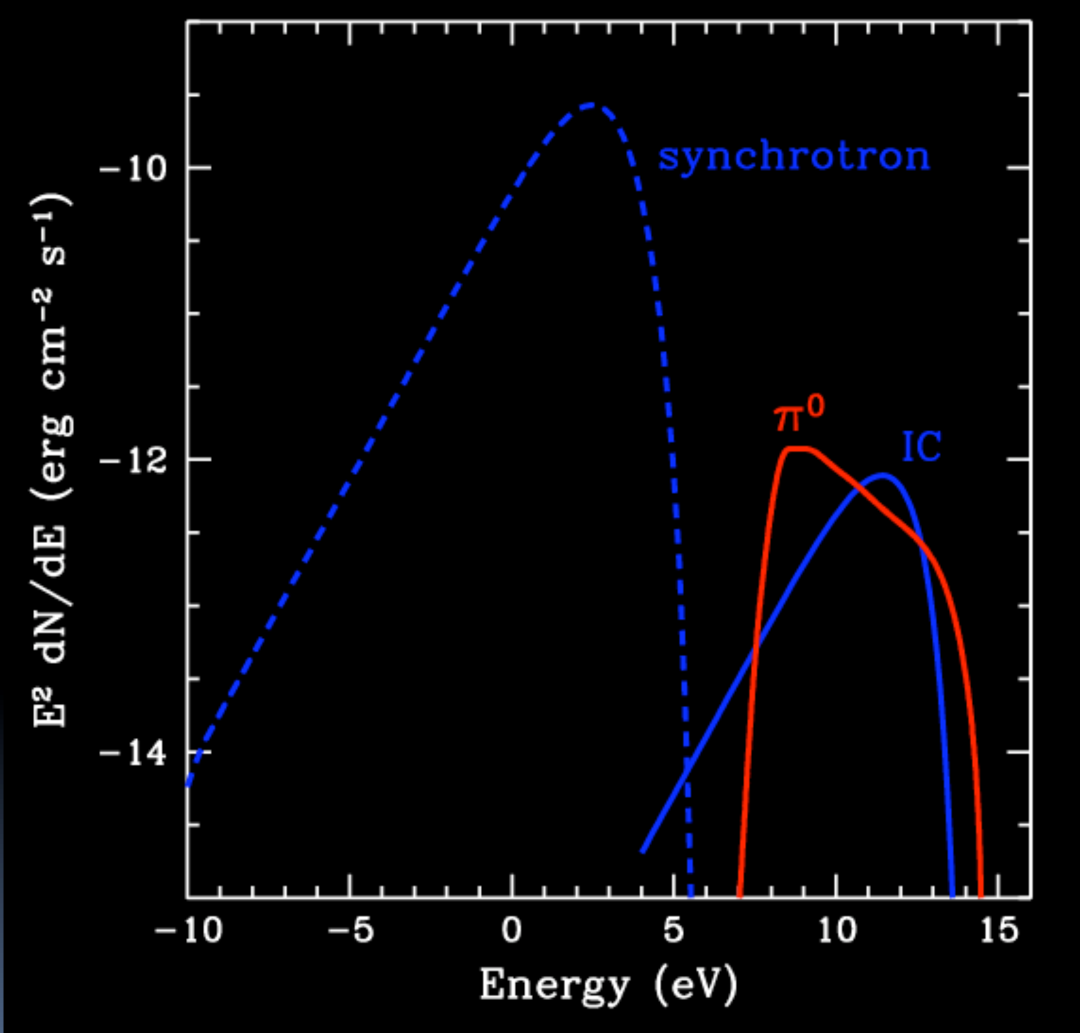
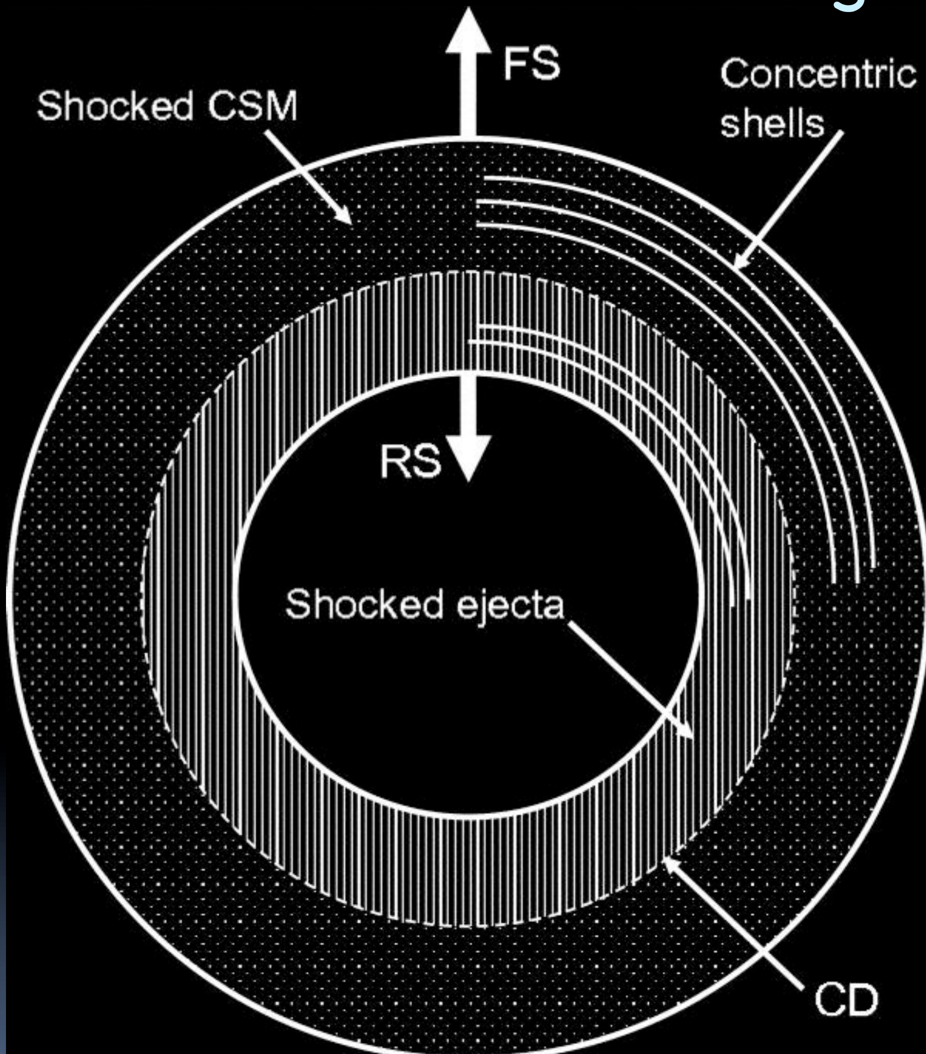


- Inverse-Compton
  - energetic electrons upscatter ambient photons to γ-ray energies
- Neutral pion decay:

  $\pi^0 \rightarrow \gamma\gamma$

  - flux proportional to ambient density; SNR-cloud interactions particularly likely sites
- Multi-λ data differentiate between these, but full modeling required

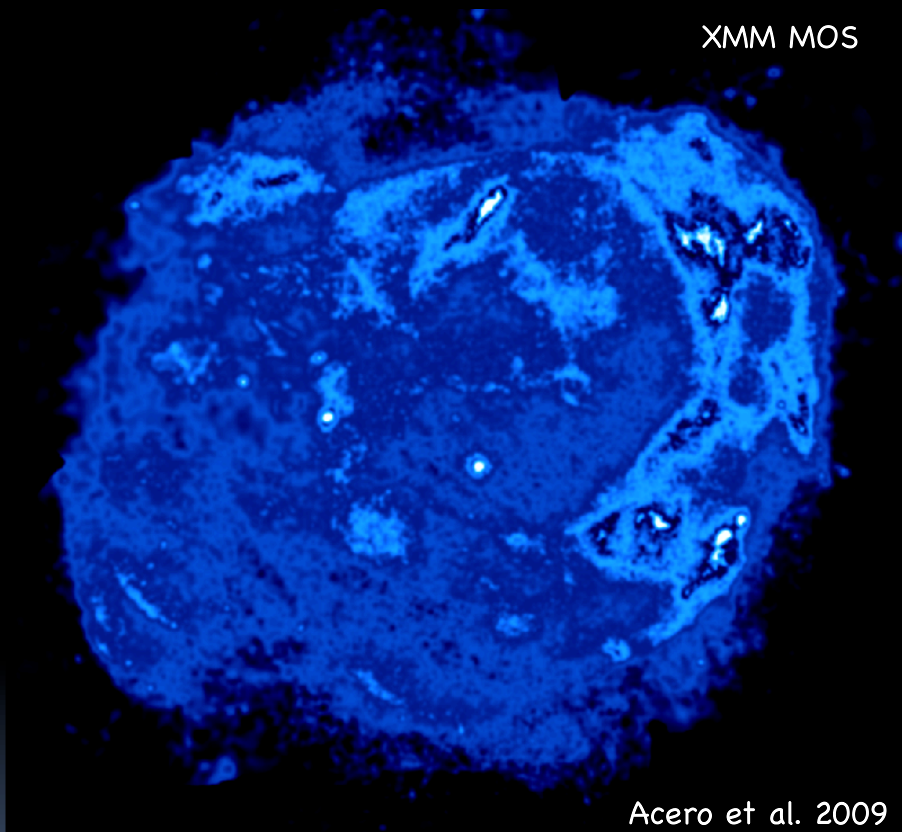
Modeling: CR-Hydro



- 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



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- SNR detected directly in TeV γ-rays
  - γ-ray morphology very similar to X-rays; I-C?
  - spectrum suggests π^0, but lack of thermal X-rays problematic

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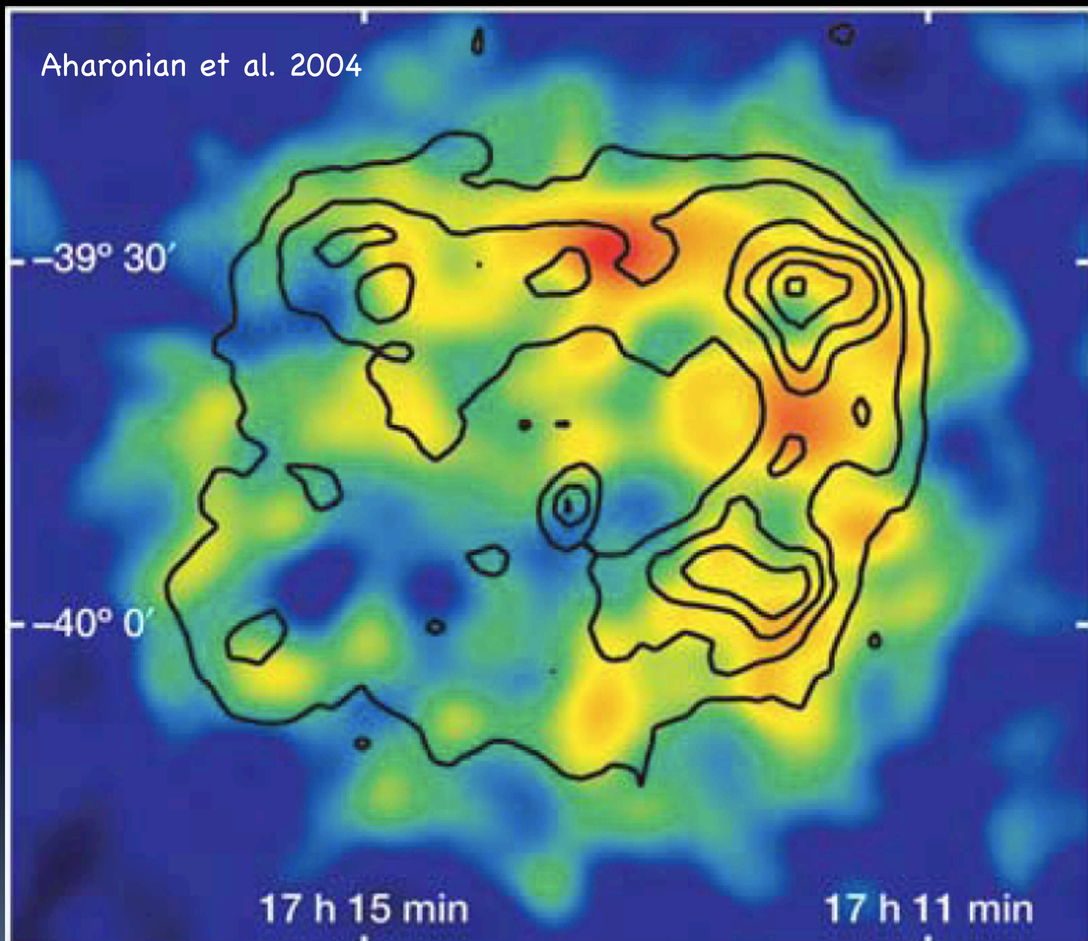

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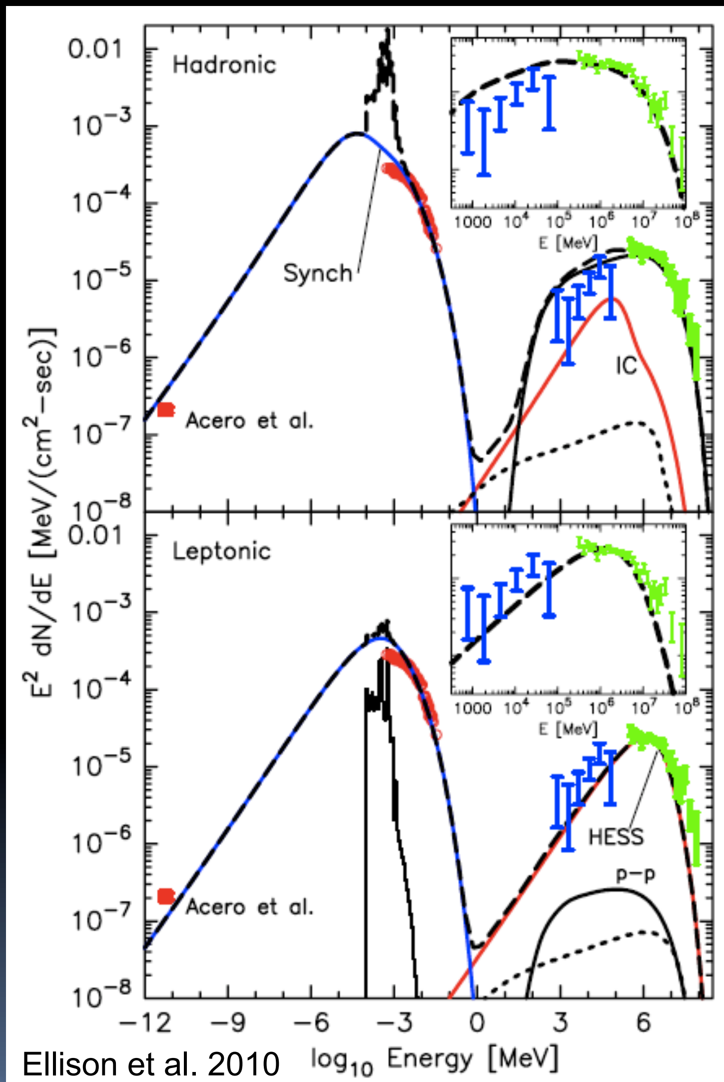

Ellison et al. 2010

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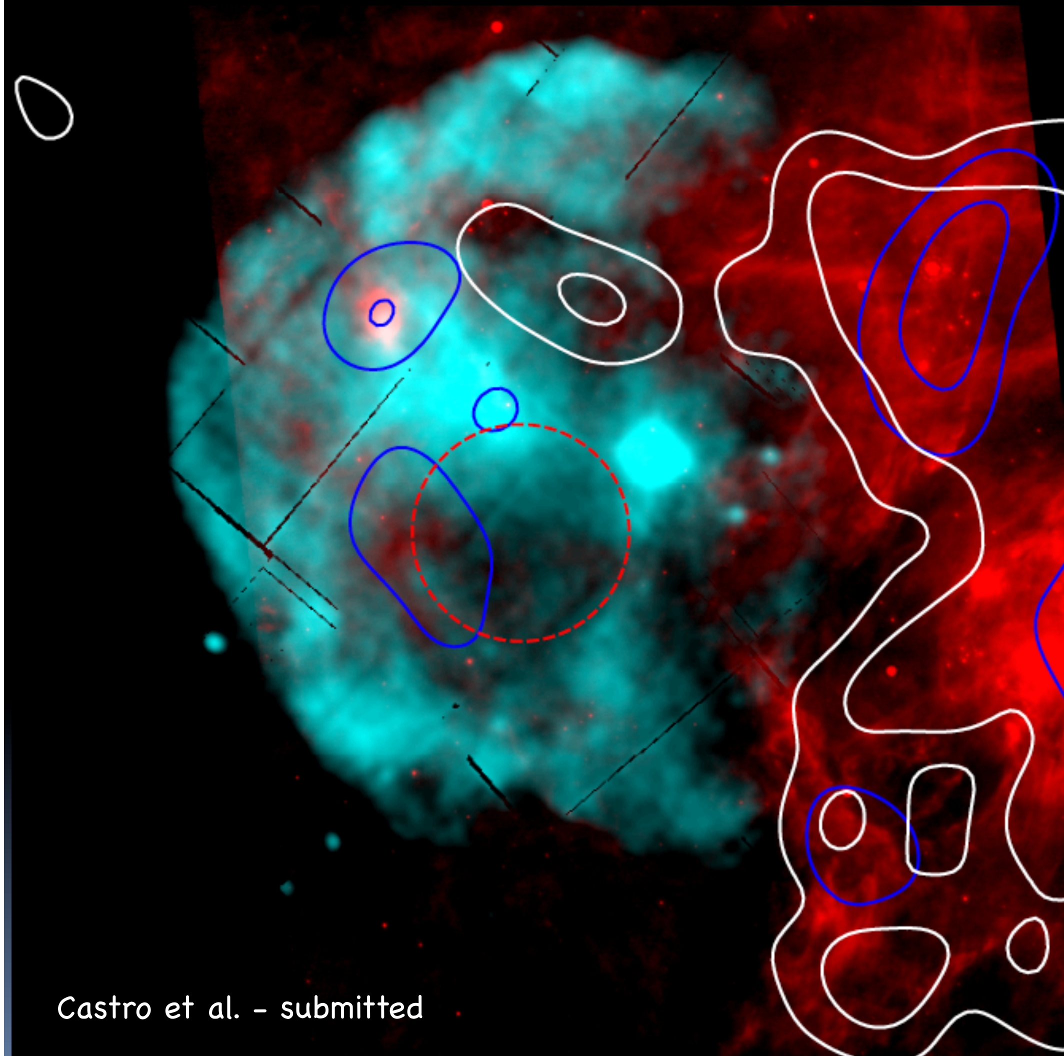
- SNR detected directly in TeV γ-rays
  - γ-ray morphology very similar to X-rays; I-C?
  - spectrum suggests π^0, but lack of thermal X-rays problematic
- Broadband modeling shows γ-rays leptonic in origin

NOTE: This does NOT mean energetic hadrons are not produced. They ARE, and dominate the total energy.

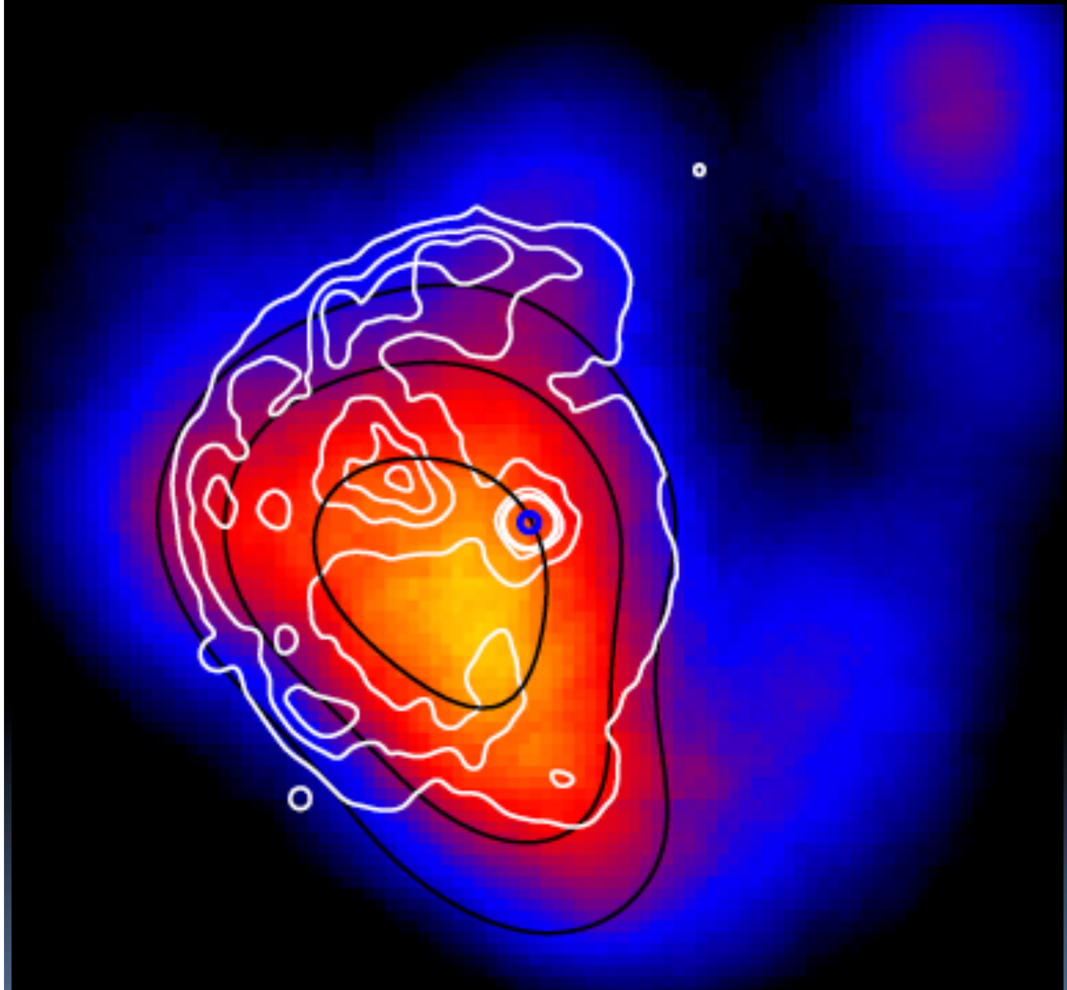
Particle Acceleration in CTB 109



Castro et al. – submitted

- CTB 109 is interacting with a massive molecular cloud
  - small cloud interactions as well
  - no nonthermal X-ray emission

Particle Acceleration in CTB 109

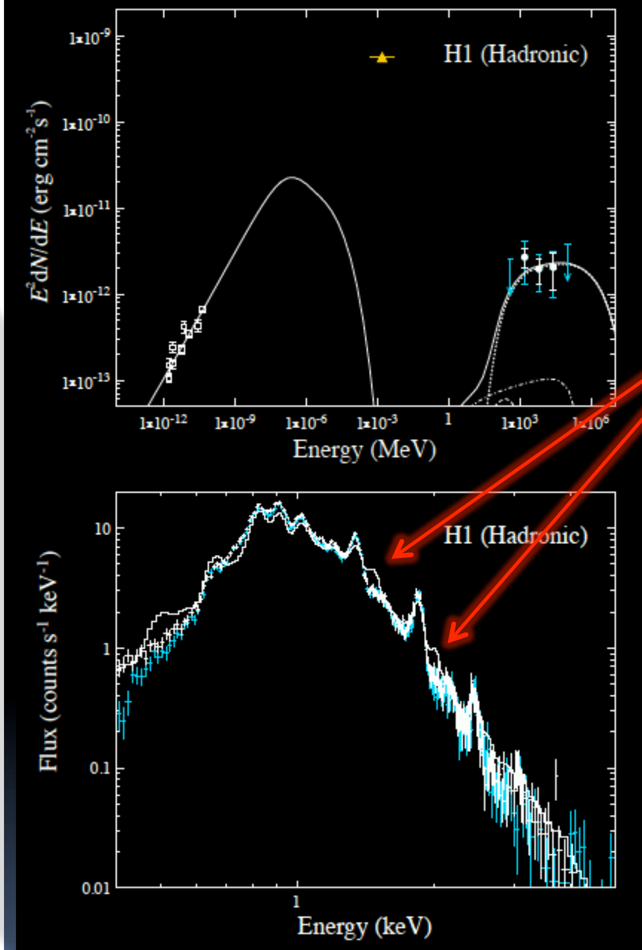


Castro et al. - submitted

- CTB 109 is interacting with a massive molecular cloud
  - small cloud interactions as well
  - no nonthermal X-ray emission
- SNR is detected in Fermi LAT
  - emission concentrated on SNR, not from western MC region
- GeV emission can be fit by both hadronic and leptonic models
  - self-consistent modeling that includes thermal X-ray emission solves the problem

Particle Acceleration in CTB 109

Castro et al. - submitted



- Hadronic model requires high density and small distance
  - high ionization states overpredicted due to high density

Particle Acceleration in CTB 109

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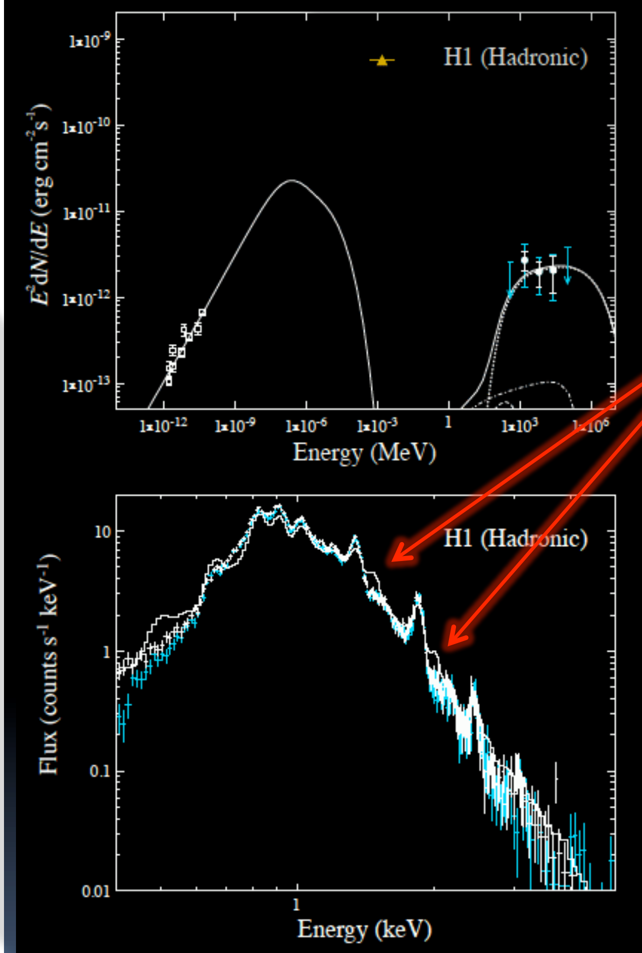
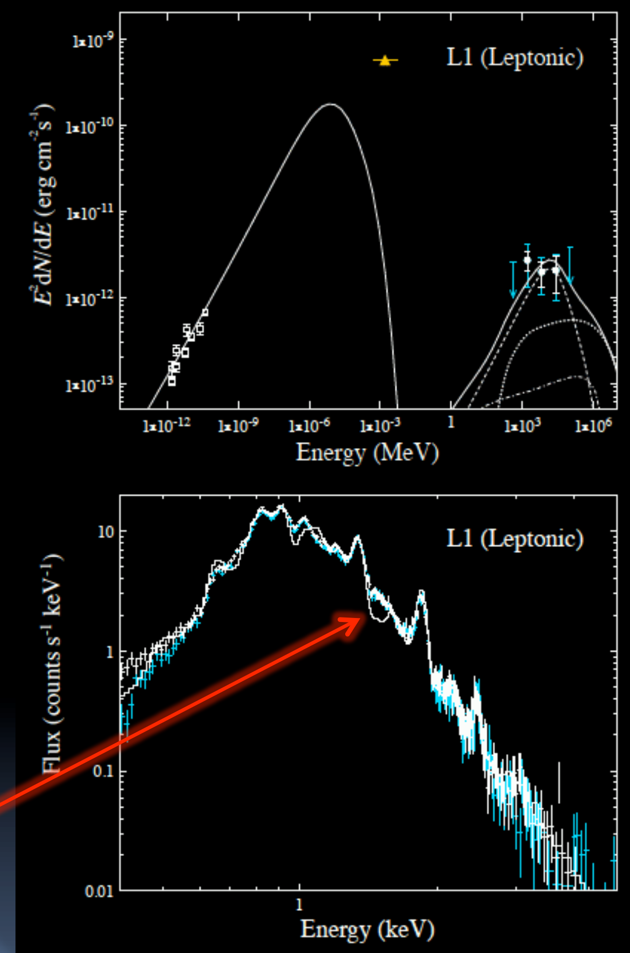


- Hadronic model requires high density and small distance
  - high ionization states overpredicted due to high density
- Leptonic model requires low density and larger distance
  - high ionization states now underpredicted



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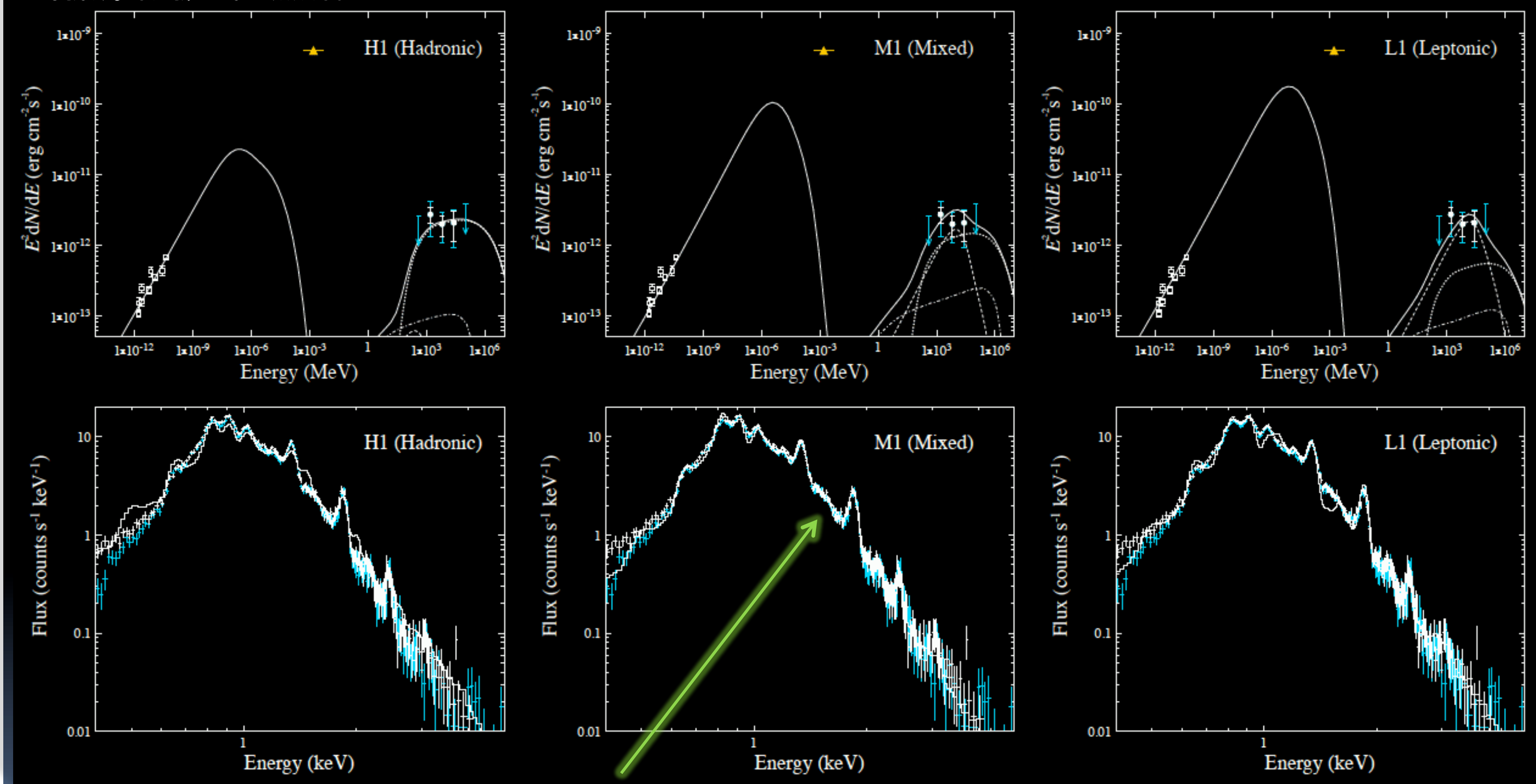
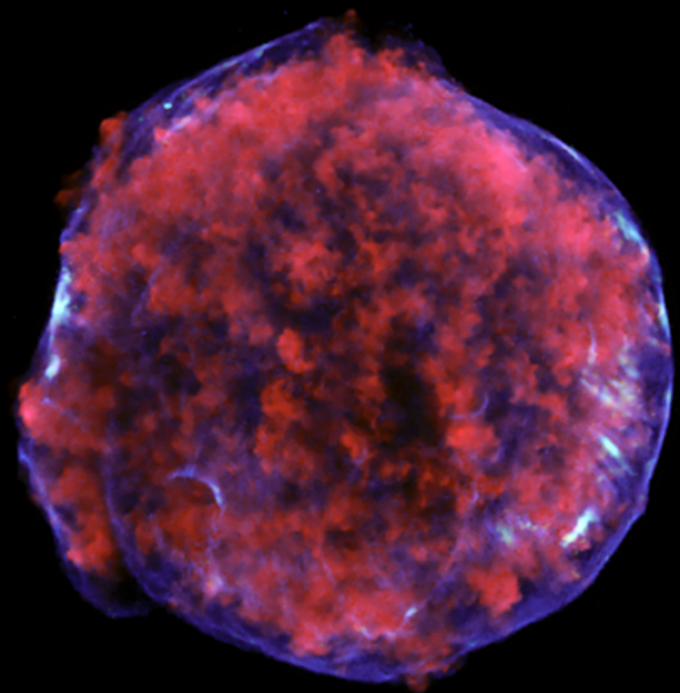


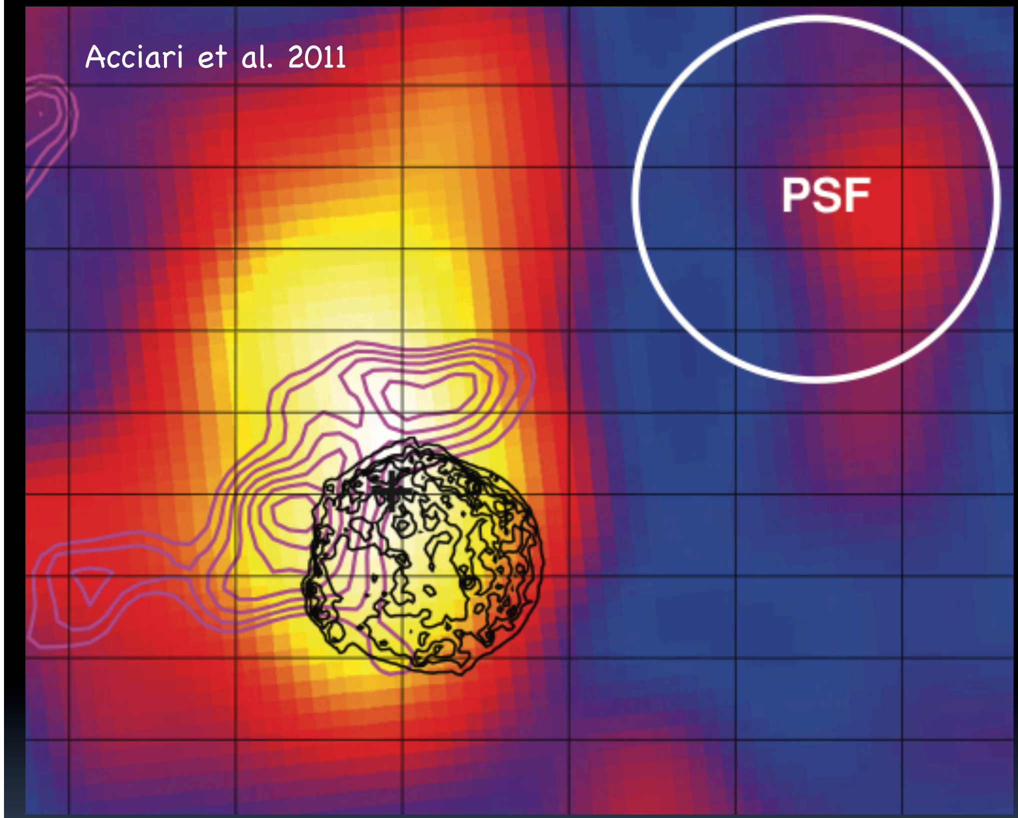
- Mixed leptonic/hadronic scenario provides excellent fit to spectra.

Gamma-Rays from Tycho's SNR



- Tycho's SNR is also detected in γ-rays
  - VERITAS centroid appears shifted slightly toward molecular cloud

Gamma-Rays from Tycho's SNR



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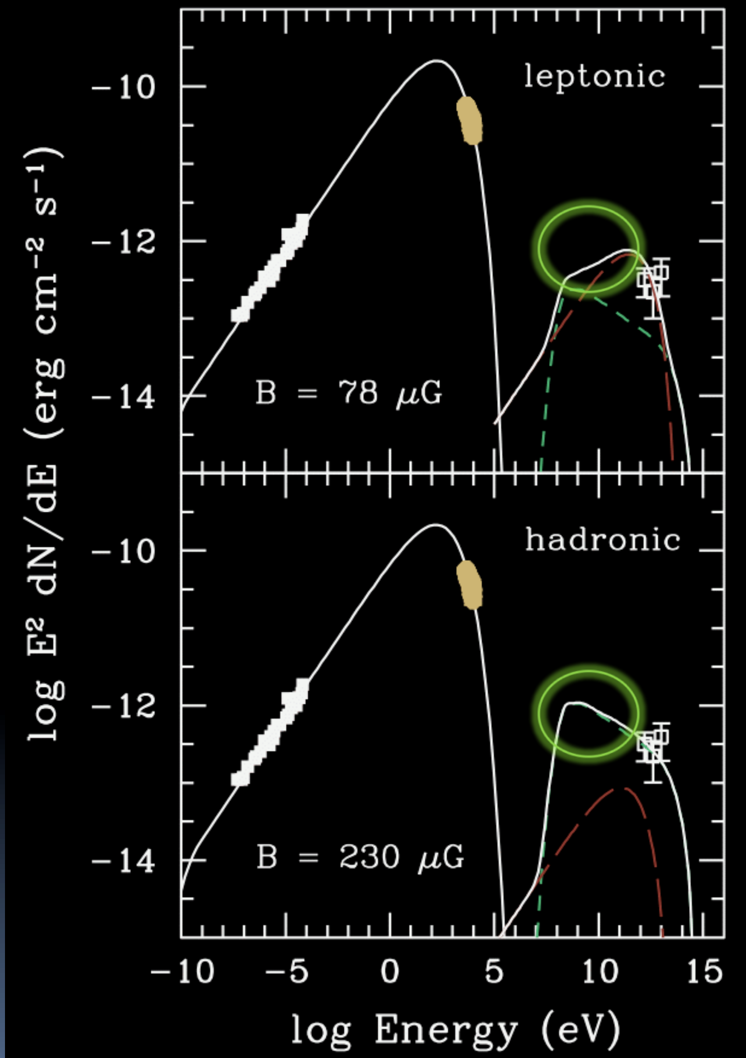
Gamma-Rays from Tycho's SNR

Acciari et al. 2011



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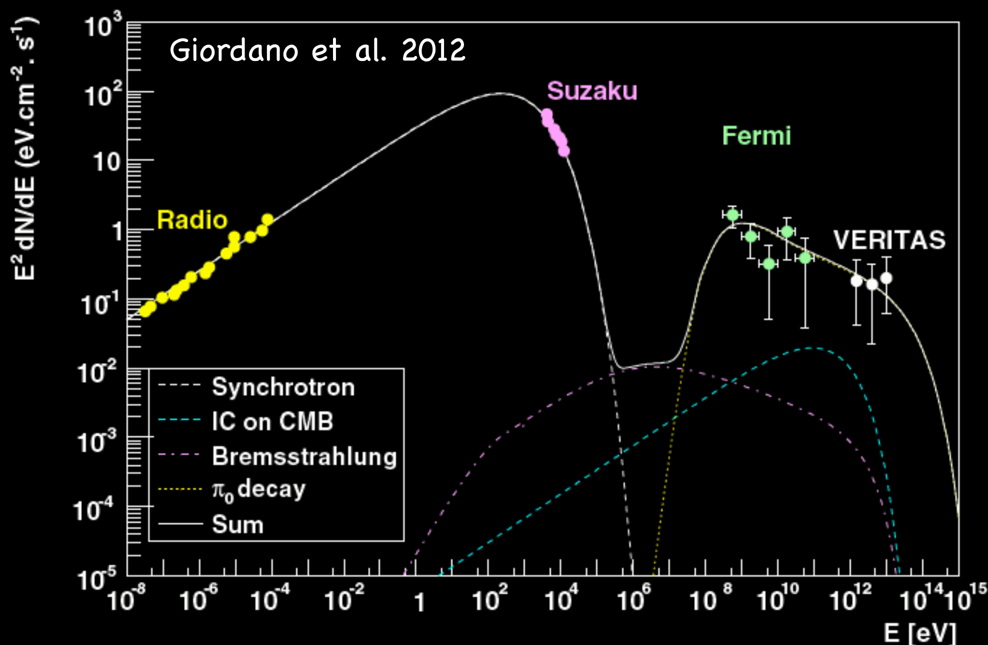
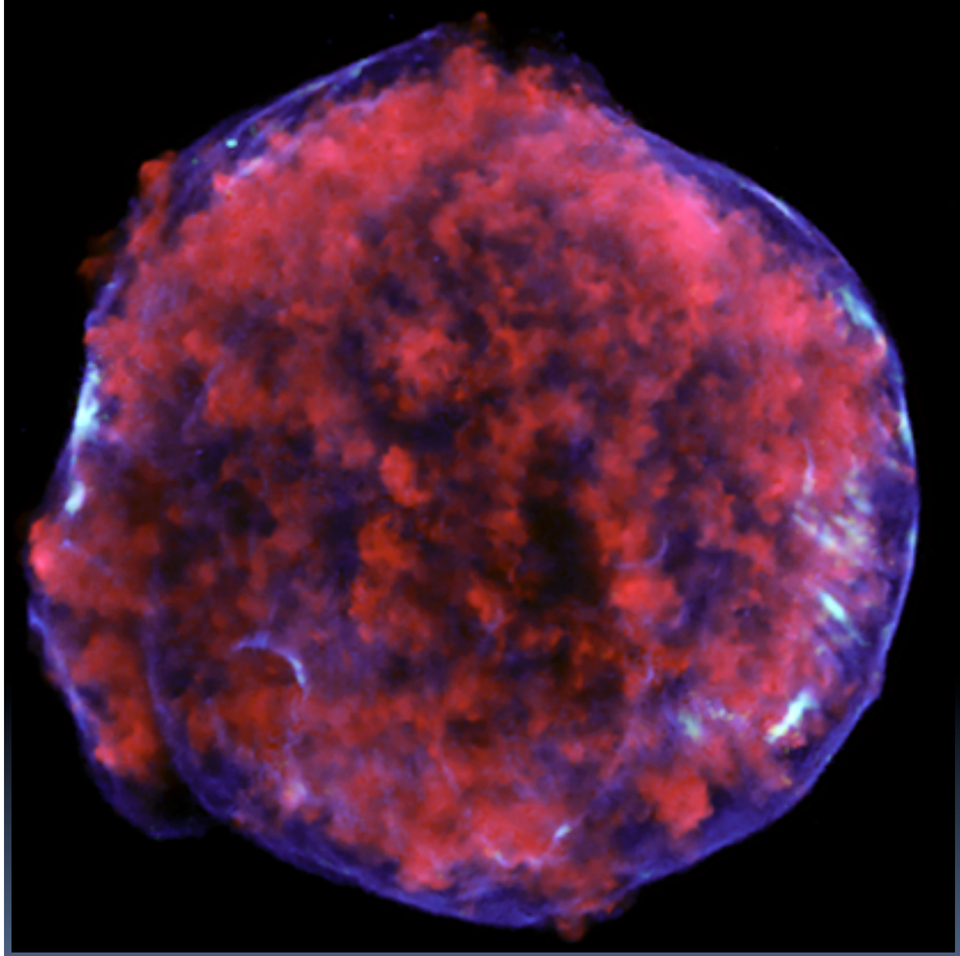


- Tycho's SNR is also detected in γ-rays
  - VERITAS centroid appears shifted slightly toward molecular cloud
- Both hadronic and leptonic models can reproduce broadband spectrum
- Fermi detection strongly favors hadrons as primary source of γ-rays
- X-ray emission from shocked ISM introduces additional constraints (e.g., Cassam-Chenai et al. 2007)
  - Efforts to model dynamics and broadband spectrum self-consistently ongoing: STAY TUNED

Summary

- Cosmic ray particles appear to have Galactic component below 10^{15} eV
  - Shock properties and overall energetics suggest SNRs may produce the bulk of these particles
- X-ray observations provide unique information on energetic particles
  - Synchrotron emission from multi-TeV electrons
  - Dynamical evidence of ion acceleration
  - Evidence of magnetic field amplification
  - Strong constraints on ambient density
- Gamma-ray observations constrain underlying particle spectrum
  - Modeling of broadband emission, including thermal X-ray emission, is generally required understand gamma-ray emission
  - SNRs interacting with molecular clouds provide important environment for detection of gamma-ray emission from hadronic component
- Current studies show that SNRs are powerful accelerators of cosmic rays.
  - Question of whether they are the only main contributor still under active investigation

Structural Evidence for CR Ion Acceleration



- Image of nonthermal X-ray emission in Tycho shows distinct stripe features

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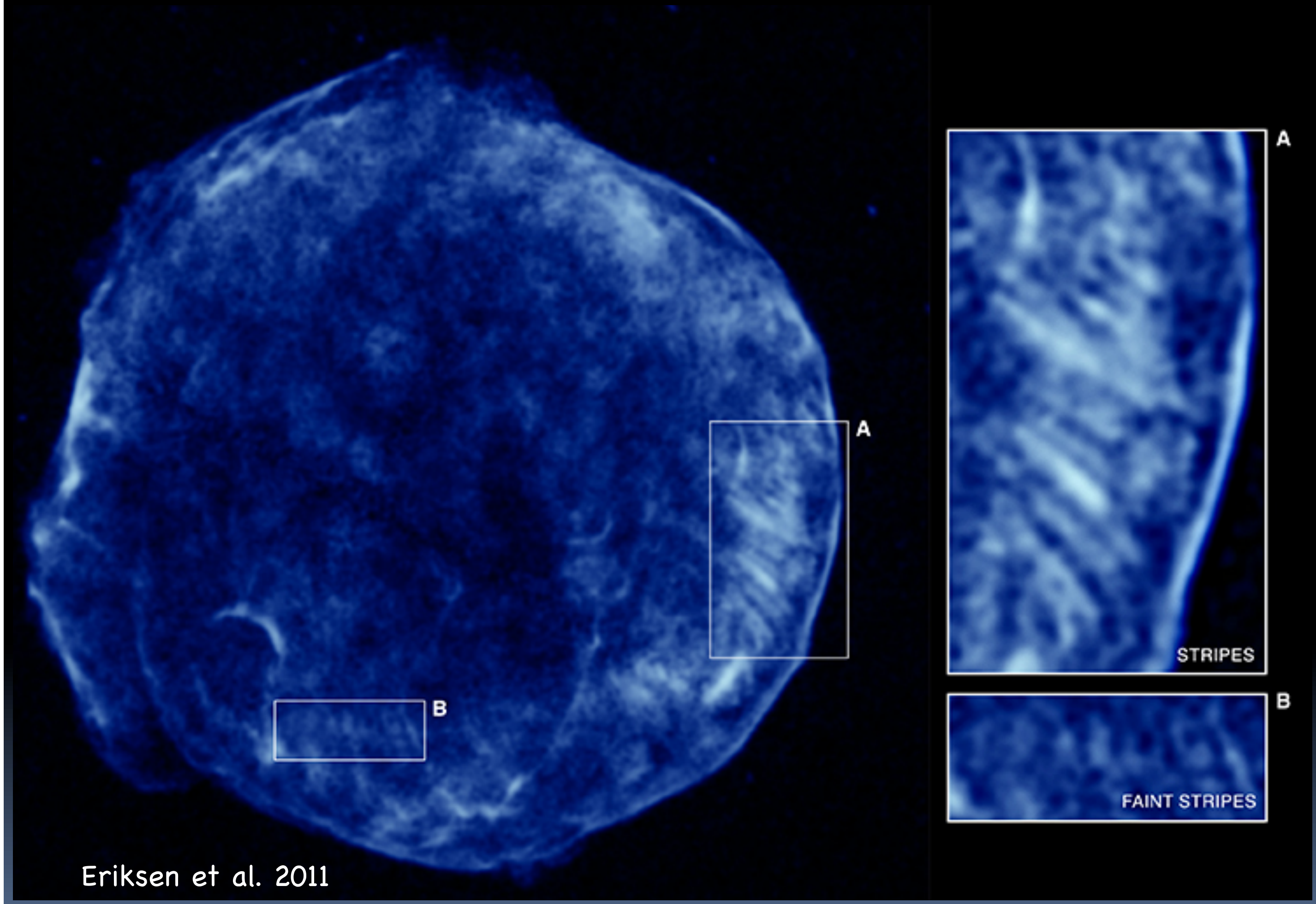

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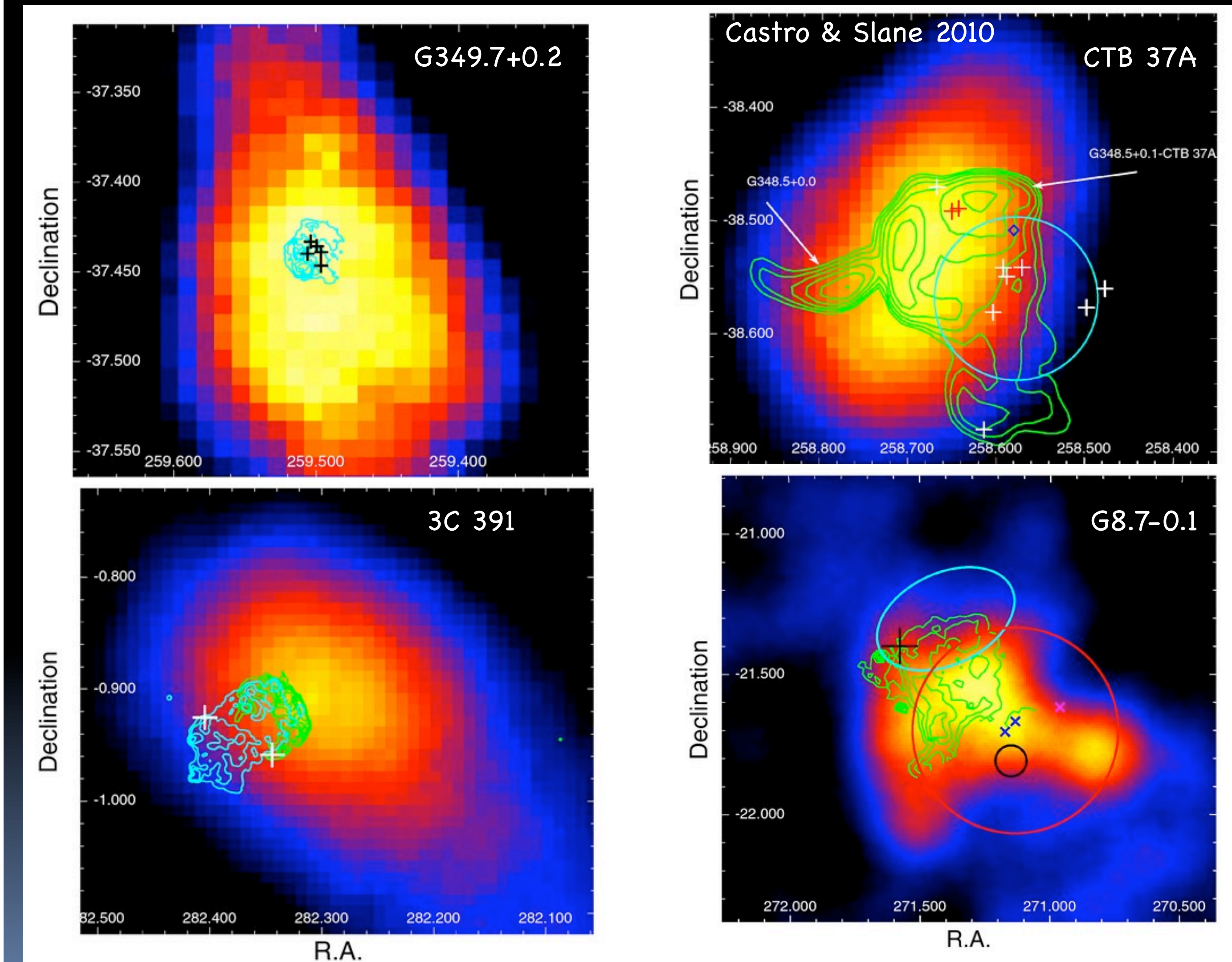
  - may correspond to gyro-radii of 10^{15} eV protons in amplified magnetic field

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 SNRs with masers
  - inferred density much higher than X-rays indicate
  - may imply clumping or escaping cosmic-ray population that is interacting with nearby clouds

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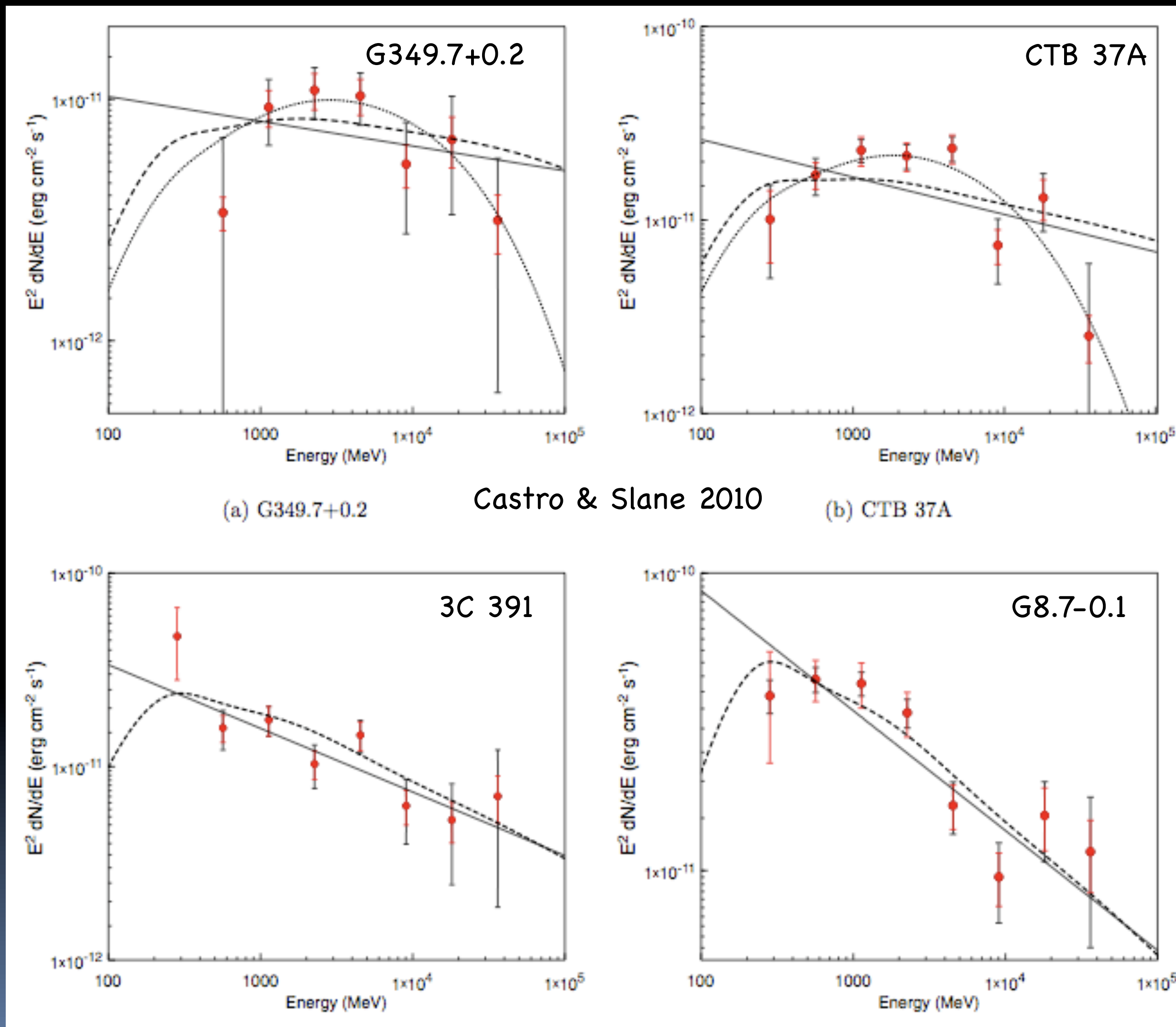

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