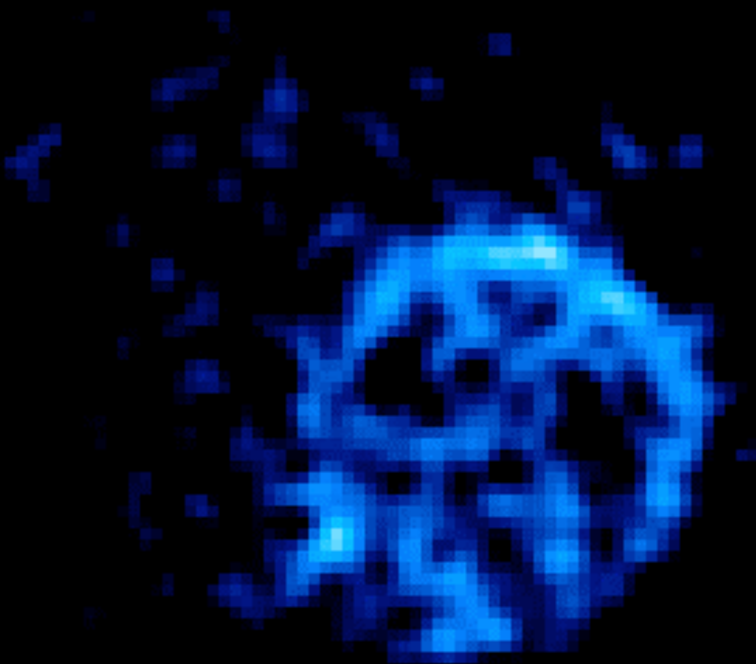
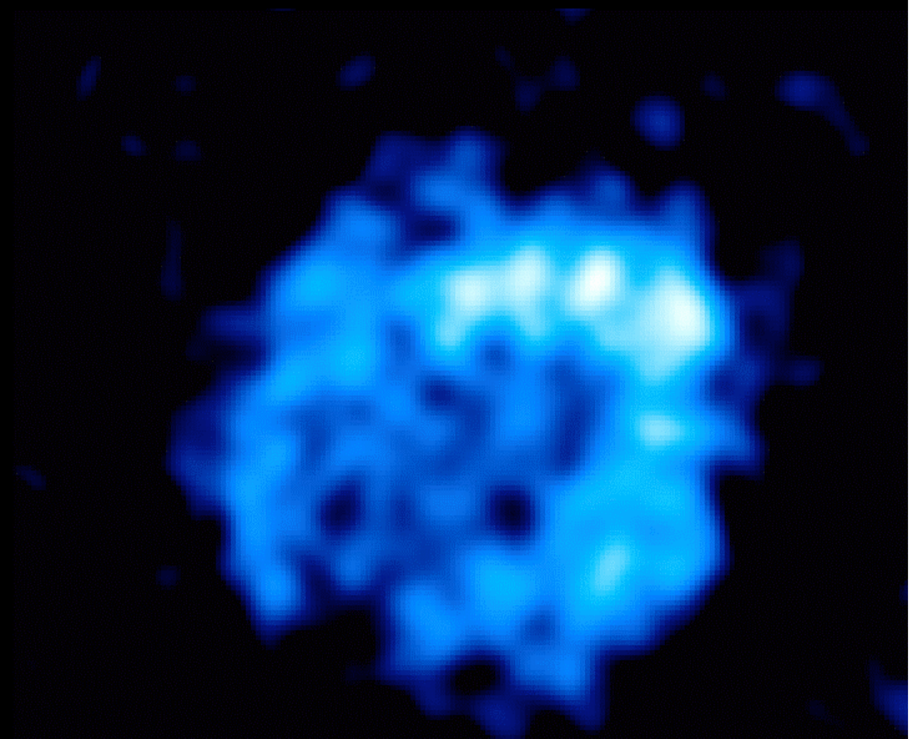
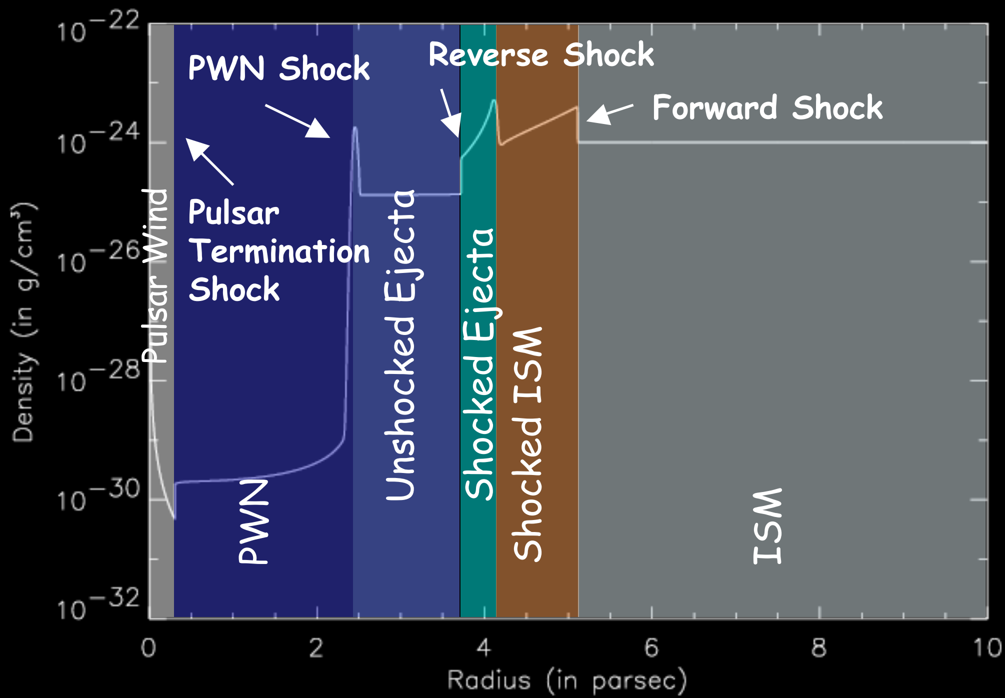
High Energy Emission

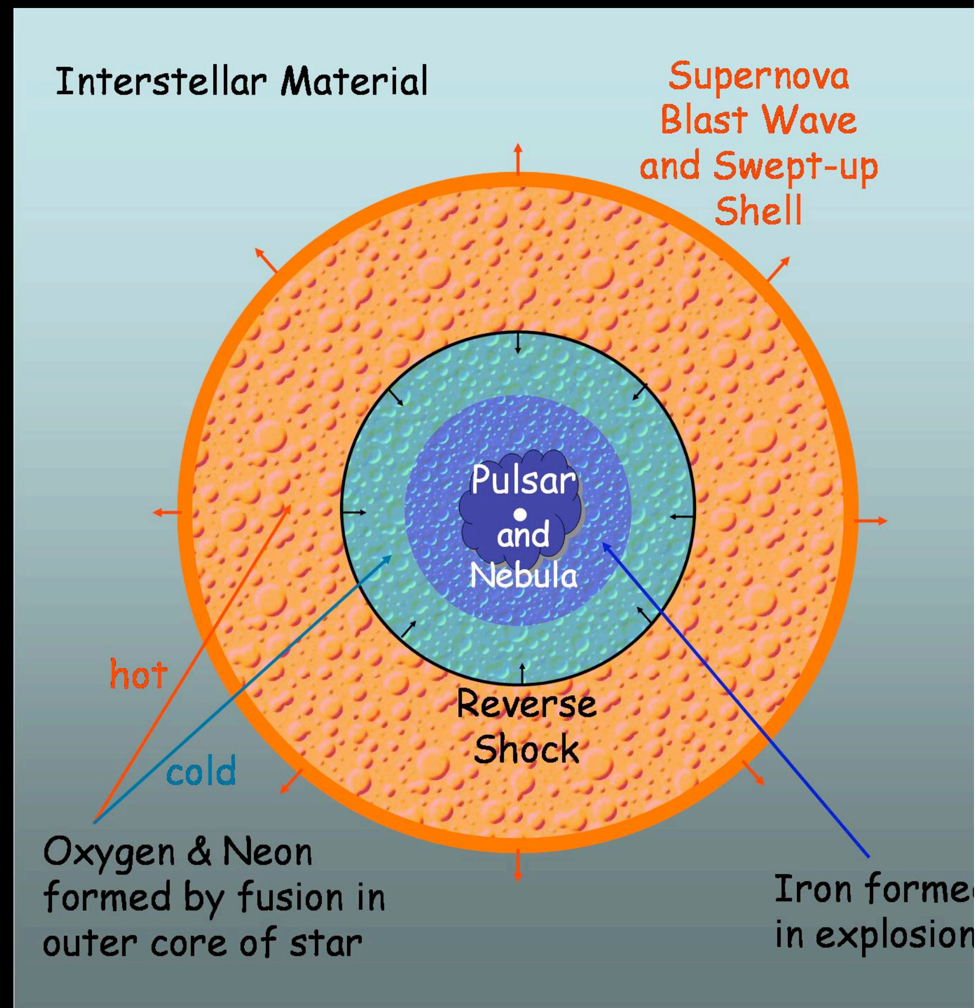




from Supernova Remnants

SNRs: The (very) Basic Structure

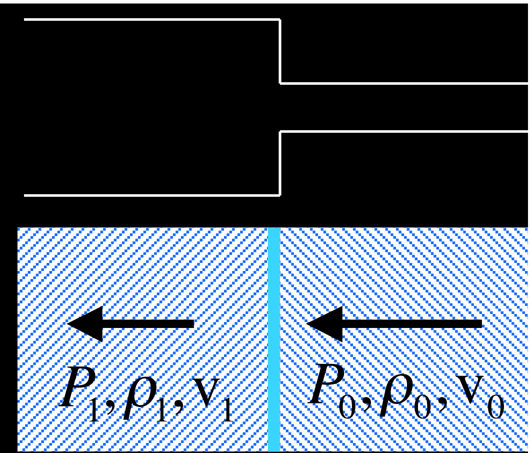




- **Pulsar Wind**
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms

- **Supernova Remnant**
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; particles accelerated at forward shock generate magnetic turbulence; other particles scatter off this and receive additional acceleratio

Shocks in SNRs



shock

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

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

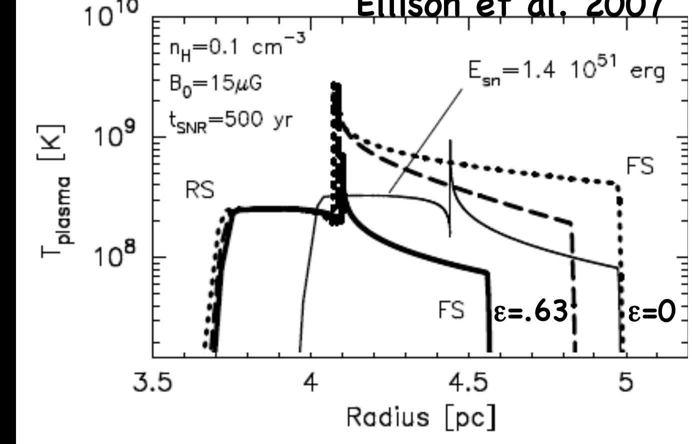
$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

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

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

X-ray emitting temperatures

Ellison et al. 2007



- 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

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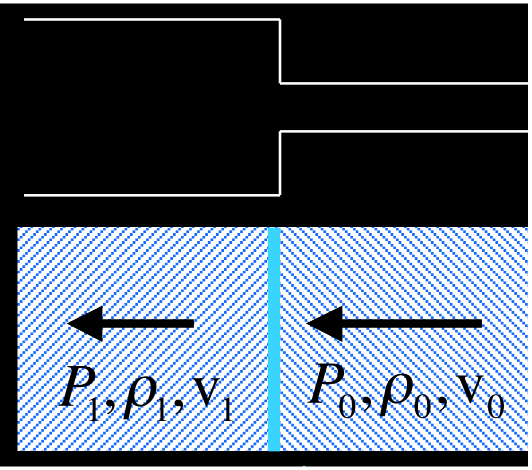
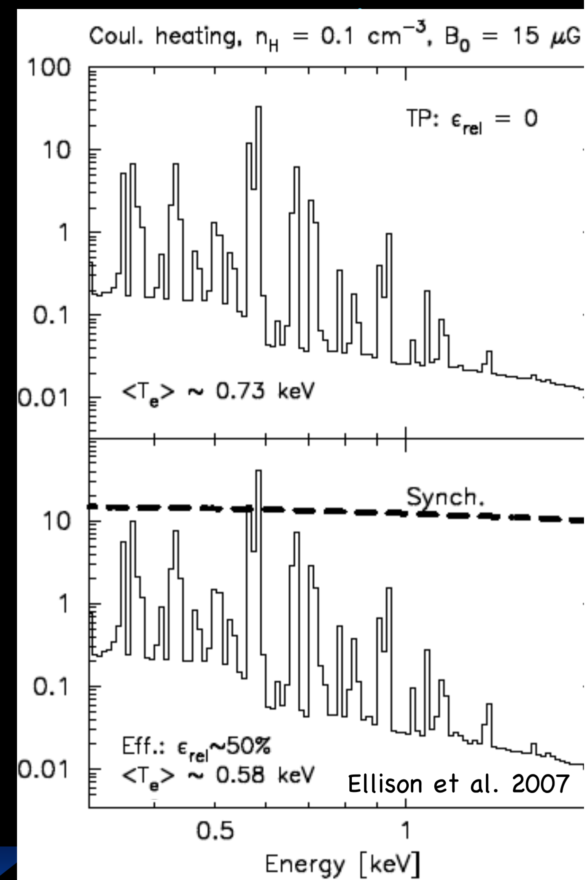
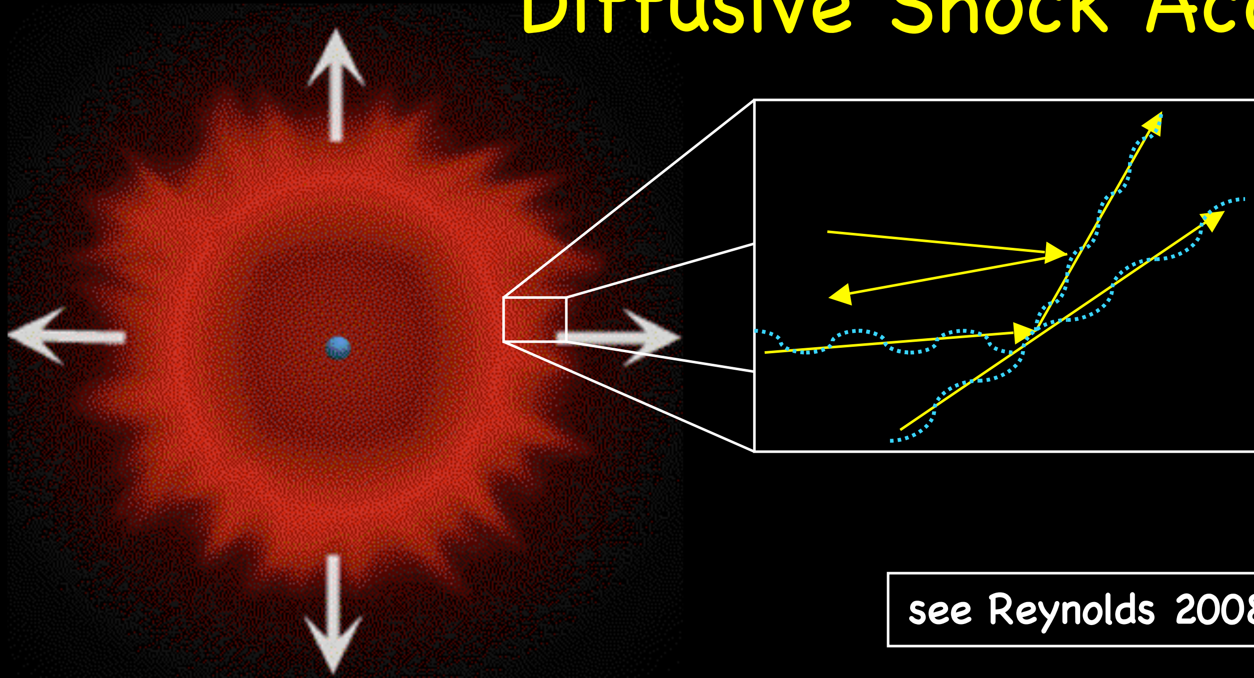




Diffuse Shock Acceleration



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

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

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

$$\eta = \left(\frac{\delta B}{B}\right)^{-2} \geq 1$$

see Reynolds 2008

- Maximum energies determined by either:

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

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

High B => High E_{max}

radiative losses (synchrotron)

$$E_{\max}(\mathrm{loss}) \sim 100 \mathrm{v}_8 (B_{\mu G} \eta R_J)^{-1/2} \mathrm{TeV}$$

High B => Low E_{max} for e^{+-}

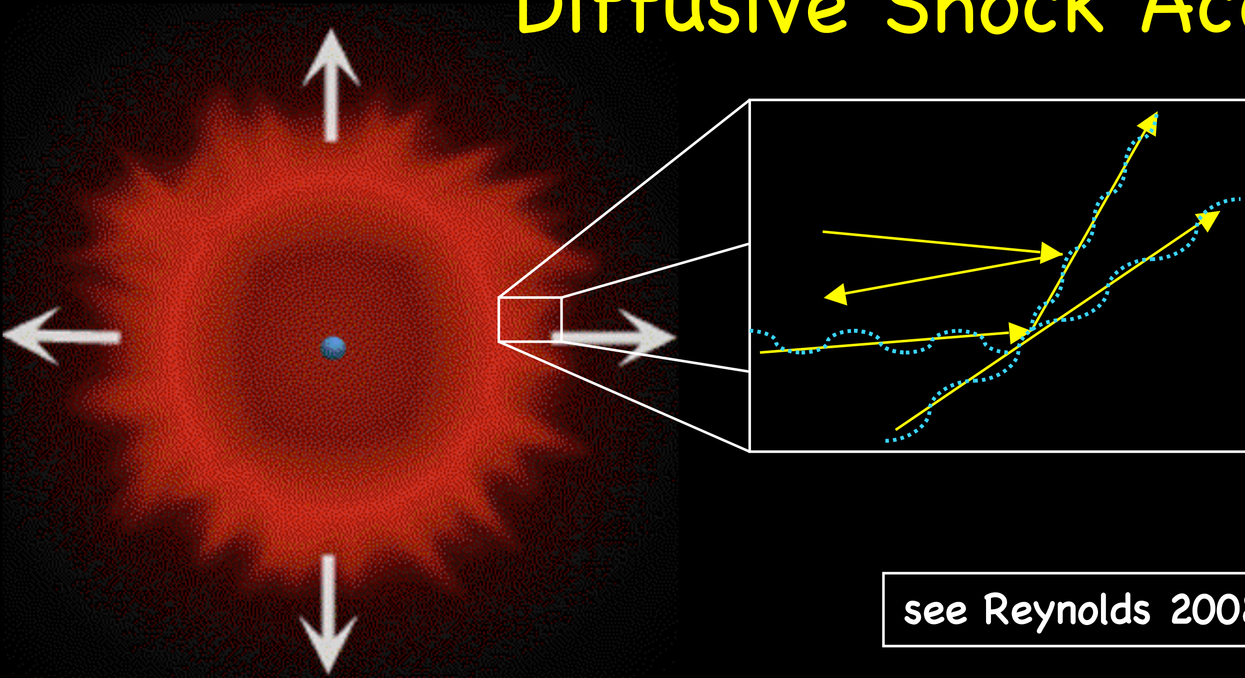
escape – scattering efficiency decreases w/ energy

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

High B => High E_{max}

magnetic field amplification important!

Diffusive Shock Acceleration



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Electrons:

- large B lowers max energ due to synch. losses

Ions:

- small B lowers max energ due to inability to confine energetic particles

Current observations suggest high B fields

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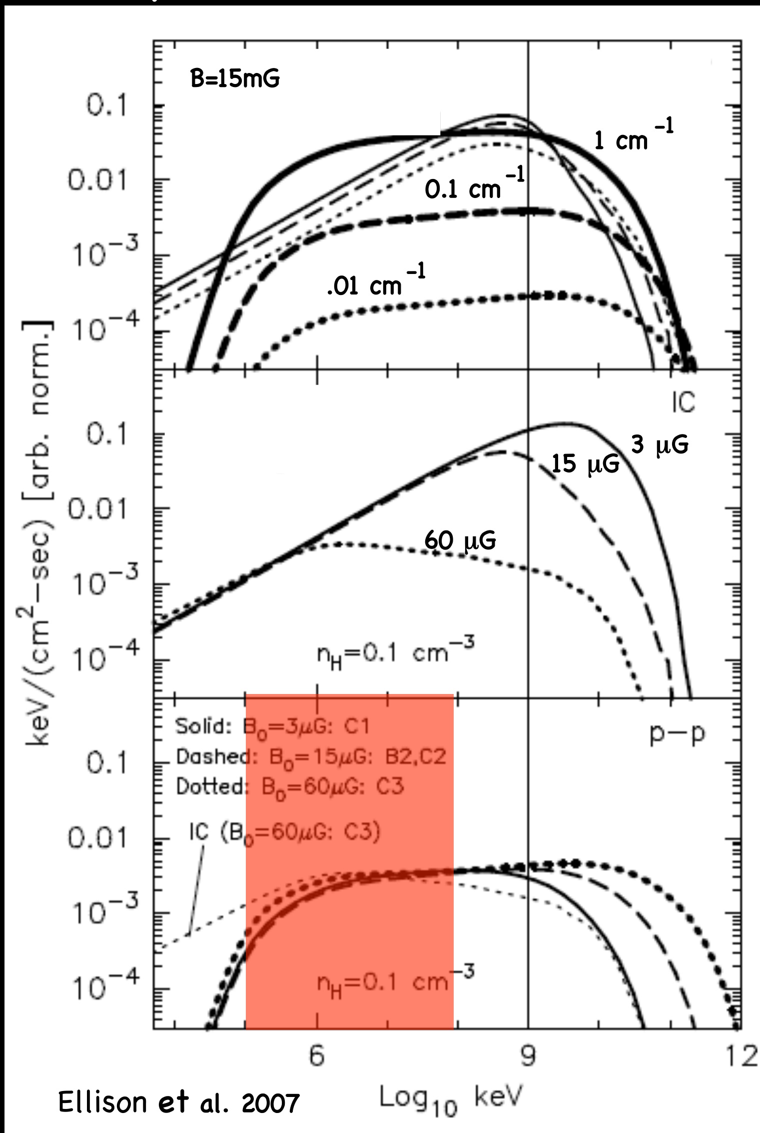
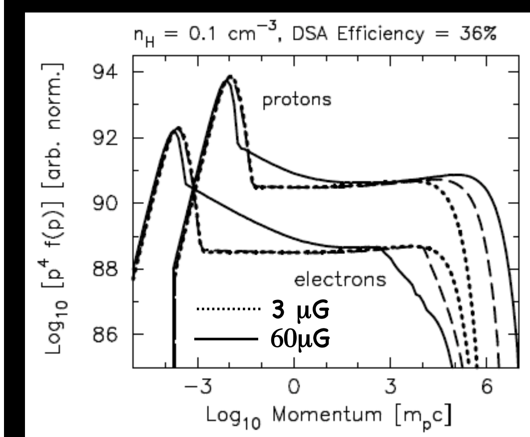
γ-ray Emission from SNRs

t=500y, ε=36%

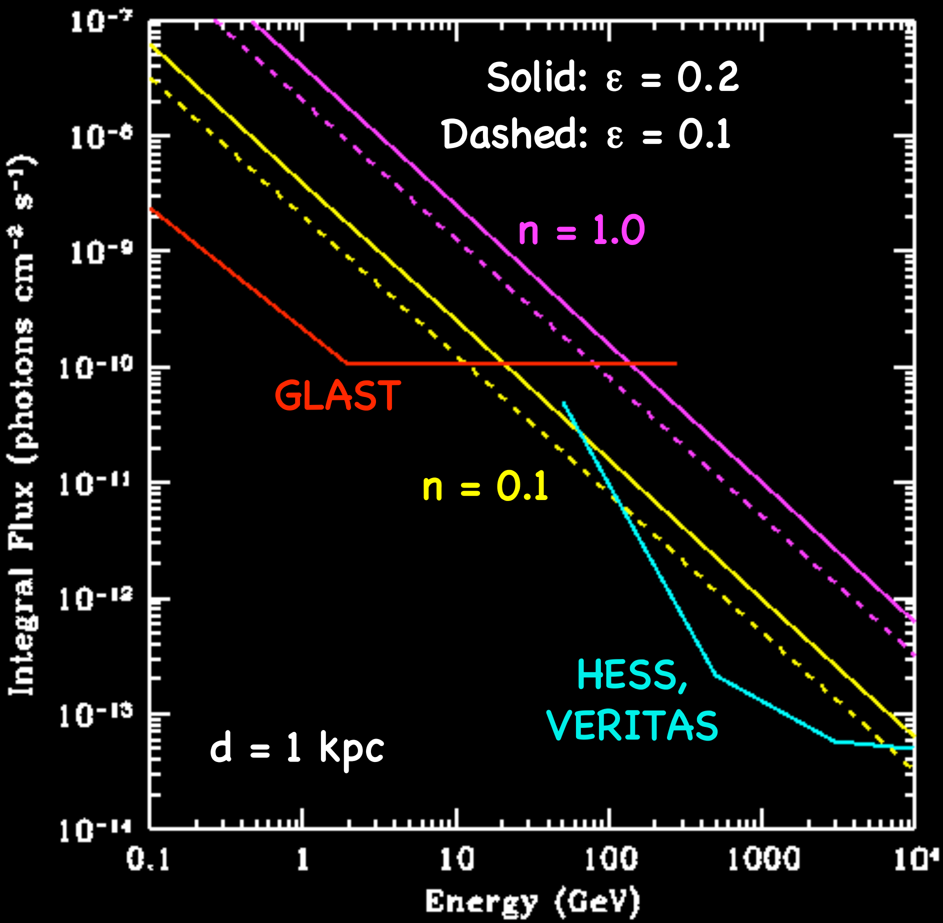


- Neutral pion decay
  - ions accelerated by shock collide w/ ambient protons, producing pions in process: $\pi^o \rightarrow \gamma\gamma$
  - flux proportional to ambient density; SNR-clou interactions particularly likely sites
- Inverse-Compton emission
  - energetic electrons upscatter ambient photon to γ-ray energies
  - CMB, plus local emission from dust and starlig provide seed photons



- High B-field can flatten IC spectrum; low B-field can reduce E_{max} for π^o spectrun
  - difficult to differentiate cases; GLAST observation crucial to combine with other λ's and dynamics

TeV Sensitivity for SNRs



- The expected $\pi^o \longrightarrow \gamma\gamma$ flux for an SNR is

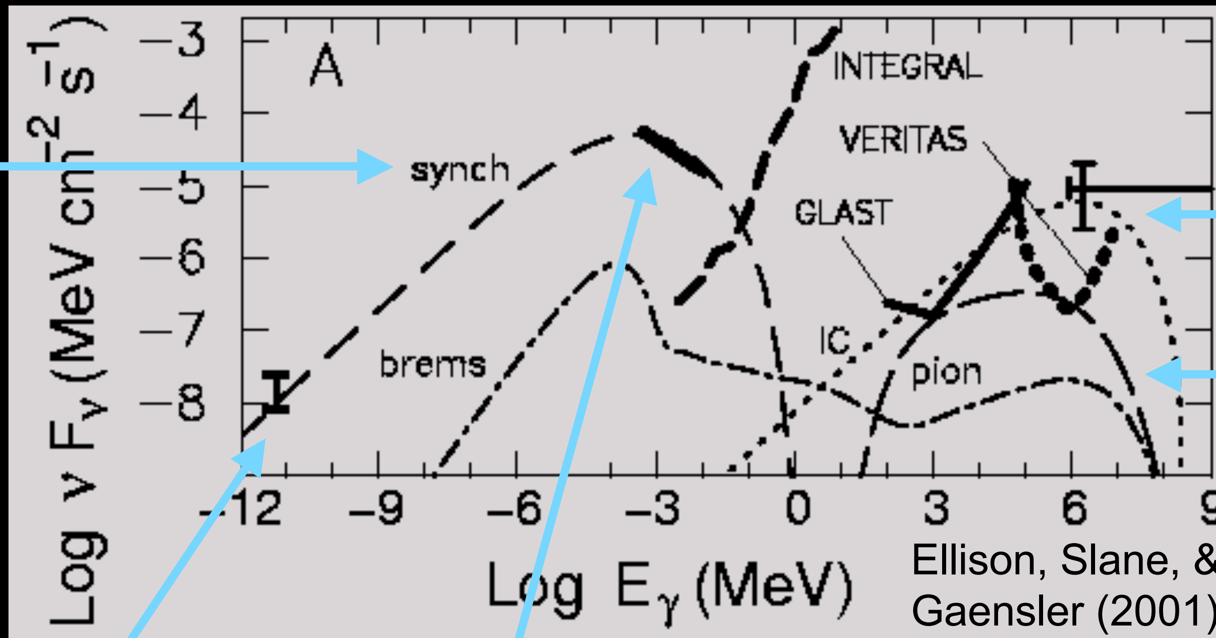
$$F(> E_{TeV}) \approx 5 \times 10^{-11} \varepsilon E_{51} d_{kpc}^{-2} n E_{TeV}^{1-\alpha} \text{ phot cm}^{-2} \text{ s}^{-1}$$

  where ε is the efficiency, α is the spectr index of the particles, and n is the ambie density (Drury et al. 1994)
  - nearby SNRs should be strong TeV sources, particularly in regions of high density

- Efficient acceleration can result in higher values for I-C γ-rays
  - spectra in TeV band can constrain the emission mechanism
  - high sensitivity needed for distant SNR

(Note that efficiency can be >>0.1)

Broadband Emission from SNRs



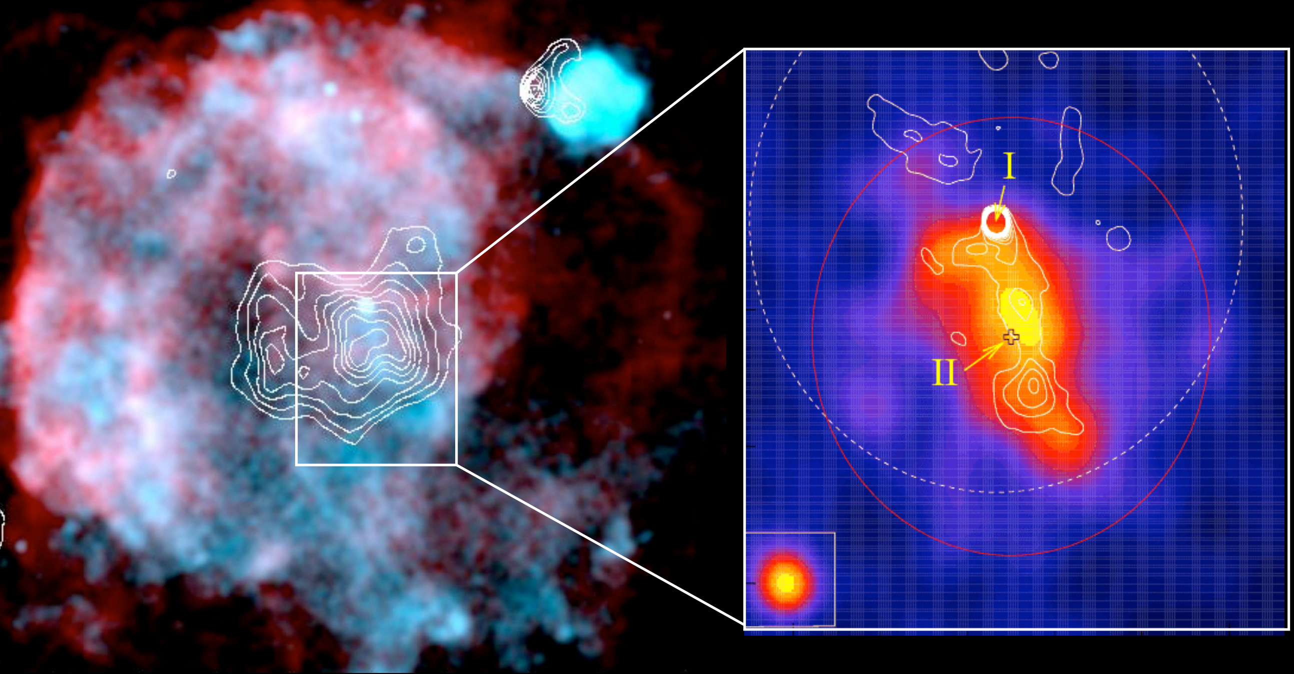
- synchrotron emission dominates spectrum from radio to x-rays
  - shock acceleration of electrons (and protons) to > 10^{13} eV

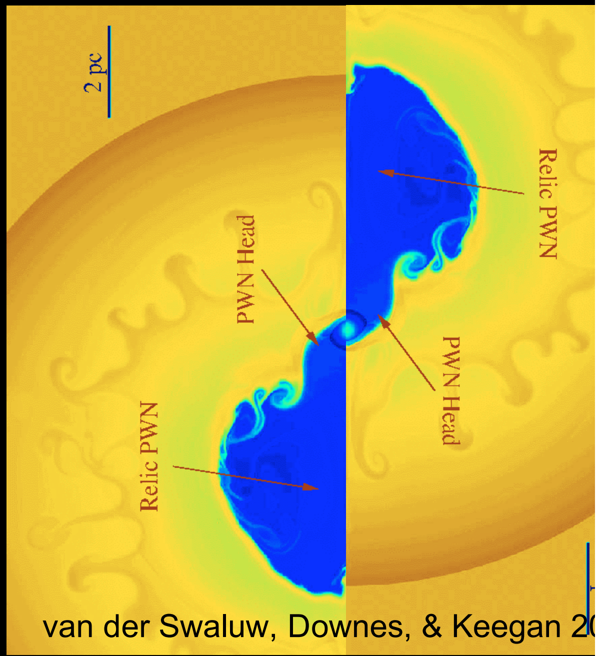
E_{max} set by age or energy losses
- observed as spectral turnover

- inverse-Compton scattering probes same electron population; need self-consistent model w/ synchrotron

- pion production depends on density
  - GLAST/TeV observations required

Contributions from PWNe: Vela X





- Elongated hard X-ray structure extends southward of pulsar
  - clearly identified by HESS
  - this is not the pulsar jet (which is known to be directed to NW)
  - presumably relic nebula that has been disturbed by (asymmetric) passage of reverse shock

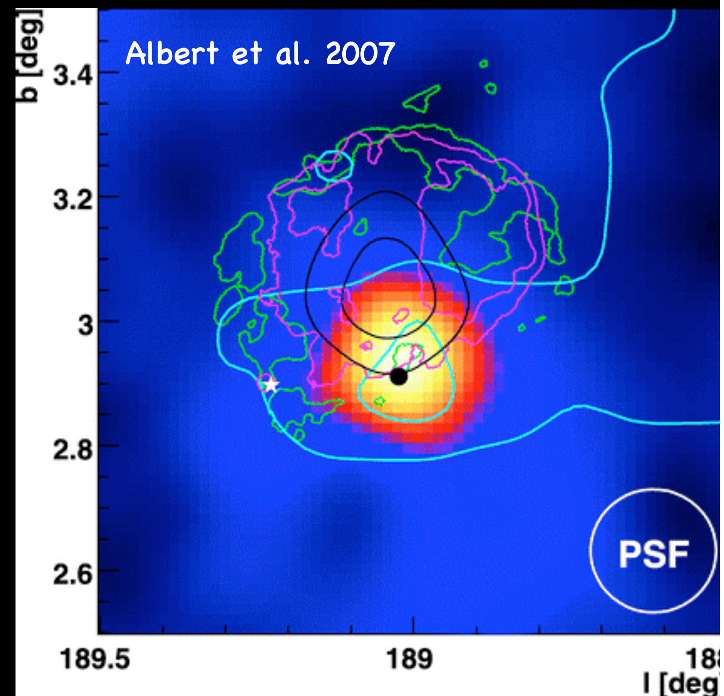
- Similar extended structures seen offset from field pulsars
  - deep TeV studies needed

VHE Emission from SNRs

Name	$Flux_{TeV}$ ($cm^{-2}s^{-1}TeV^{-1}$)	Γ	Comments
RX J1713.7-3946	$2.0x10^{-11}$	2.32 +/- 0.01	G347.3.-0.5; nonthermal X-rays
RX J0852.0-4622	1.9×10^{-11}	2.2 +/- 0.3	Vela Jr.; nonthermal X-rays
Cas A	$1x10^{-12}$	2.4 +/- 0.2	Nonthermal X-ray filaments
IC443	$5.8x10^{-13}$	3.1 +/- 0.3	PWN? SNR? MC interaction?
RCW 86	$2.7x10^{-12}$	2.5 +/- 0.1	Nonthermal X-rays
W28	$7.5x10^{-13}$	~2.6	MC interactions; masers
CTB 37A	$8.7x10^{-13}$	2.3 +/- 0.1	PWN? MC interaction?
CTB 37B	$6.5x10^{-13}$	2.65 +/- 0.19	
HESS J1834-087	$3.7x10^{-12}$	2.5 +/- 0.2	SNR W41?
HESS J1804-216	$5.2x10^{-12}$	2.7	SNR?
HESS J1745	$2.5x10^{-12}$	2.7	MC interaction?
G0.9+0.1	$8.1x10^{-13}$	2.4	PWN?

IC443: What is the Source of Emission?

- SNR age is ~30 kyr; large diameter suggests modest shock speeds
  - probably not highly efficient accelerator at present, so leptonic emission may be weak
- A molecular cloud lies at the edge of the remnant
  - enhanced density provides significant target material for γ-rays from π^0 decay



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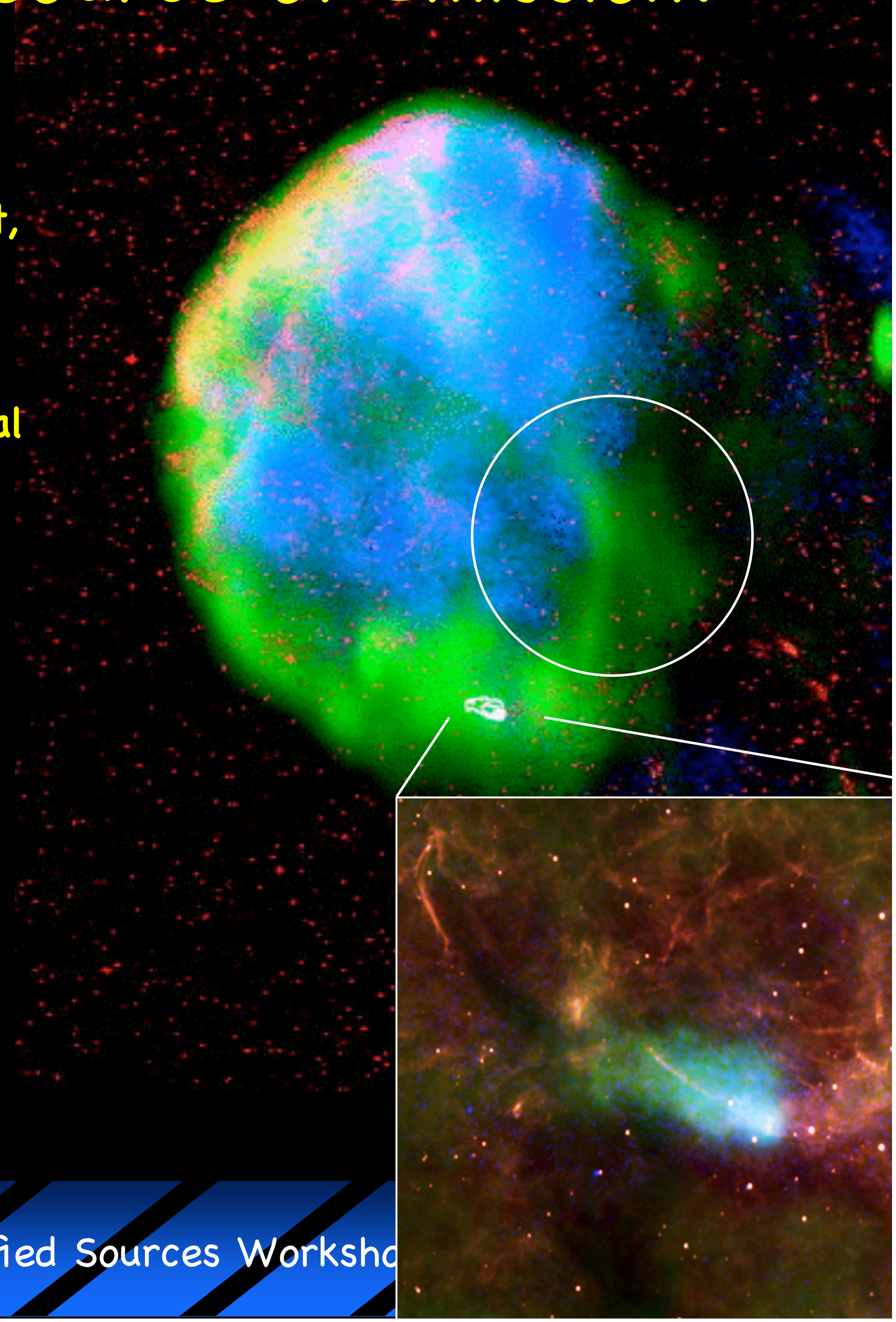
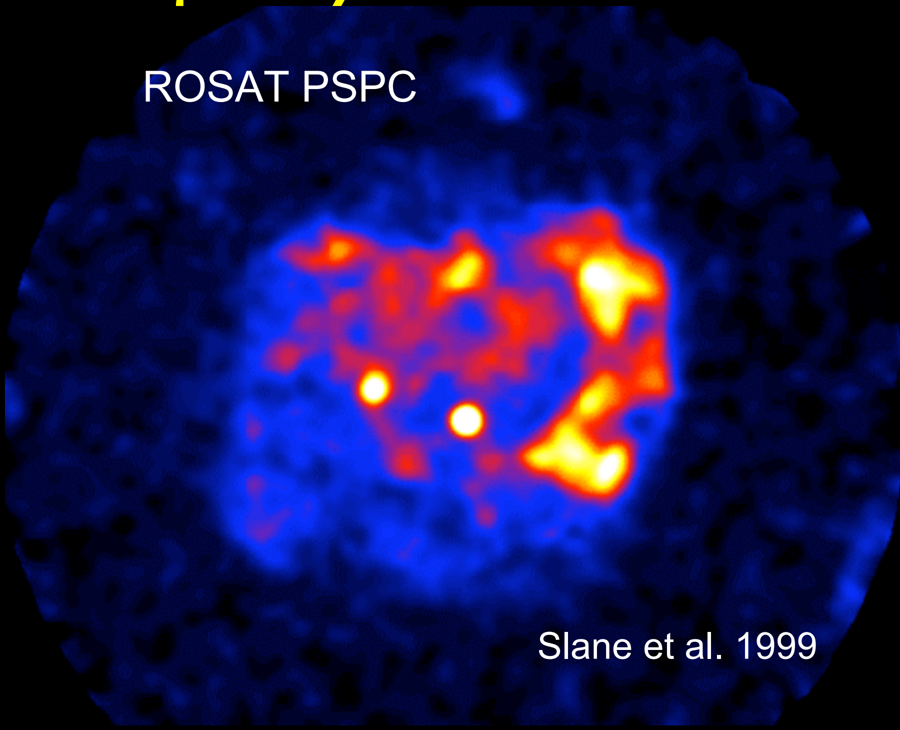
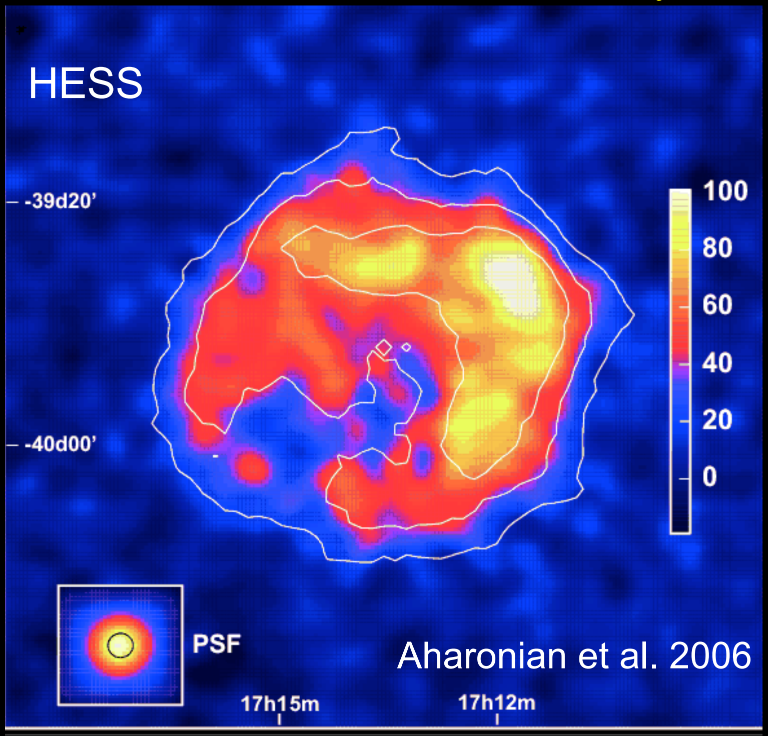
- SNR contains PWN which could be a source of TeV emission
  - PWN is outside of γ-ray error circle, and X-ray tail points away from γ-ray source, so not likely candidate



γ-rays from G347.3-0.5 (RX J1713.7-3946)





- 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

- This SNR is detected directly in TeV gamma-rays, by HESS
  - γ-ray morphology very similar to x-rays; suggests I-C emission
  - spectrum seems to suggest π^0-decay

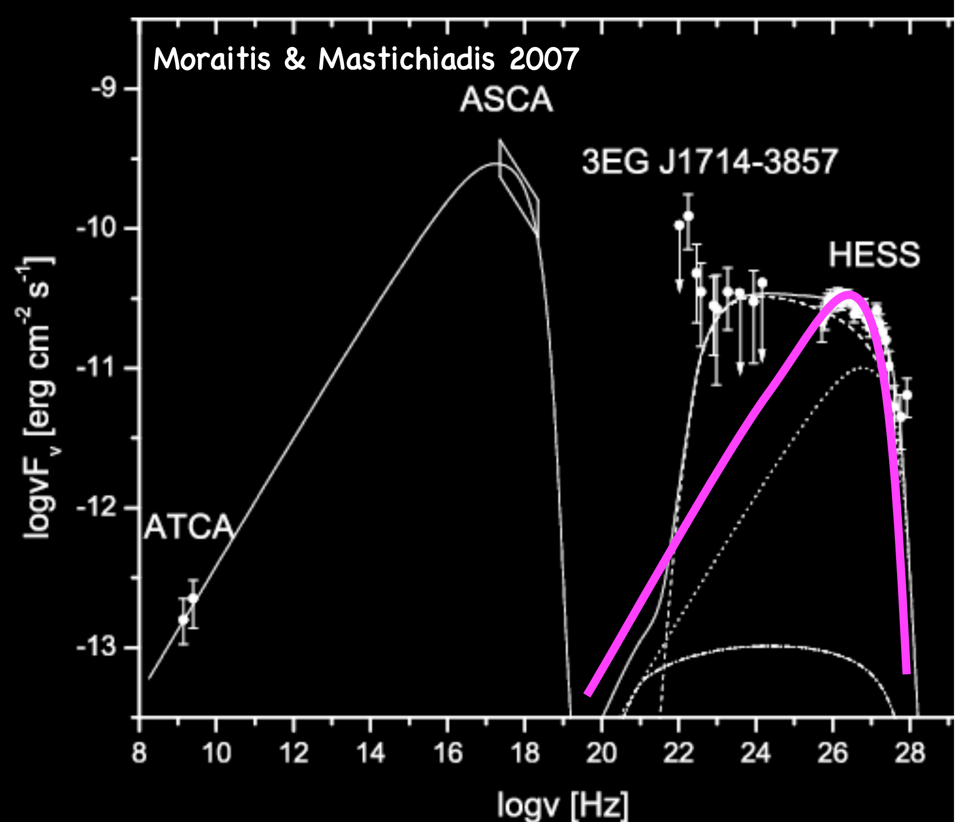
WHAT IS EMISSION MECHANISM?

Modeling the Emission

- Joint analysis of radio, X-ray, and γ-ray data allow us to investigate the broad band spectrum
  - data can be accommodated by synch. emission in radio/X-ray and pion decay (with some IC) in γ-ray
  - however, two-zone model for electrons fits γ-rays as well, without pion-decay component

- Pion model requires dense ambient material
  - but, implied densities appear in conflict with thermal X-ray upper limits

- Origin of emission NOT YET CLEAR



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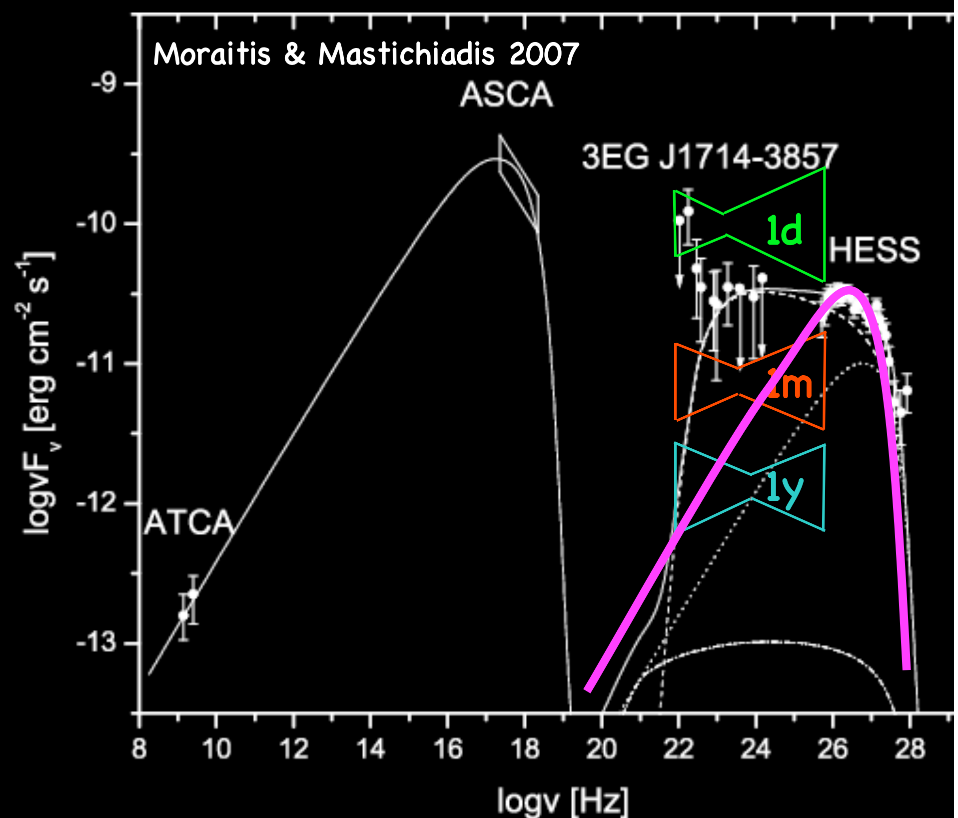
  - NEED GLAST



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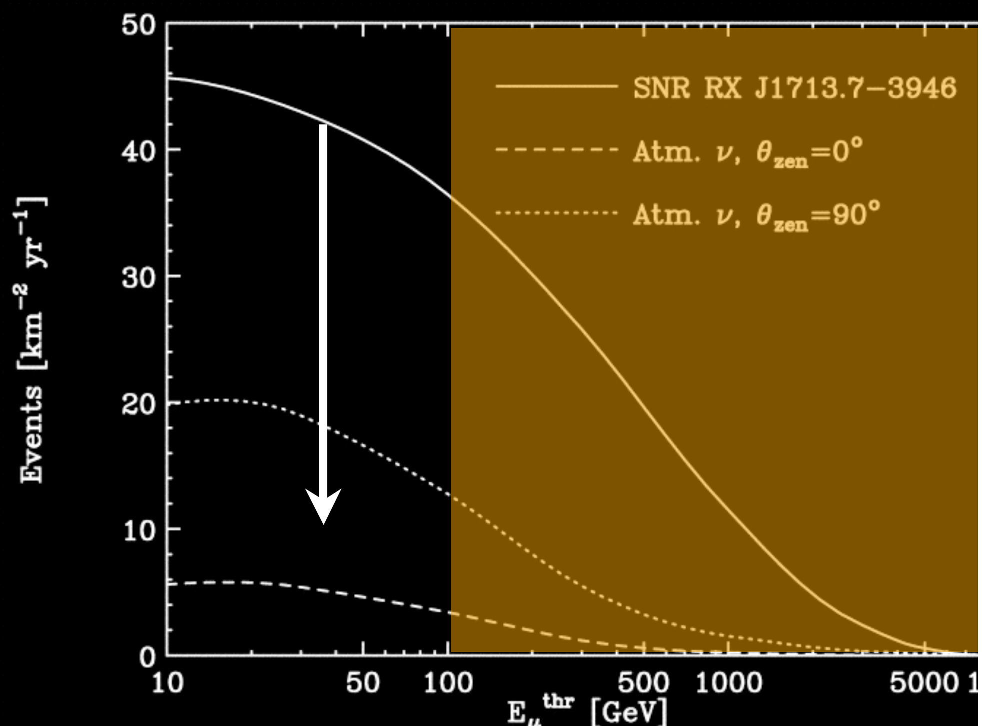
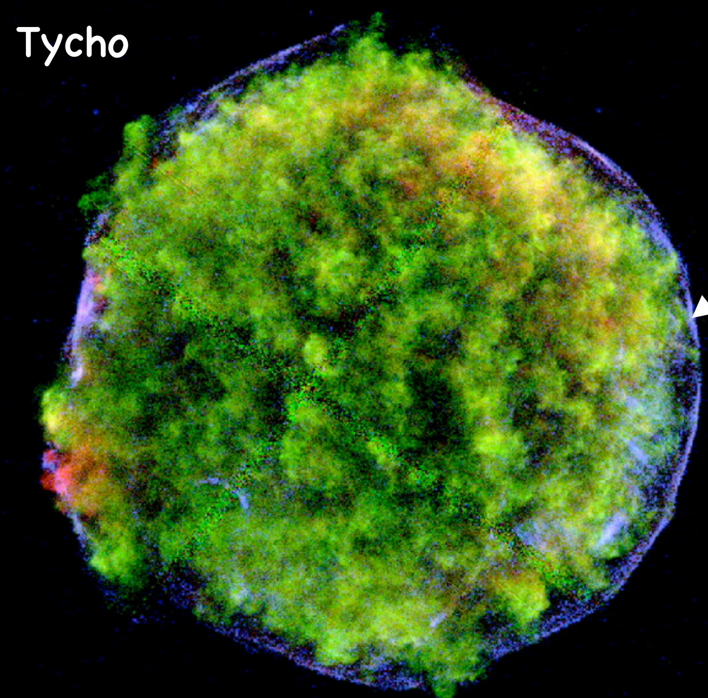
or a Northern IceCube...

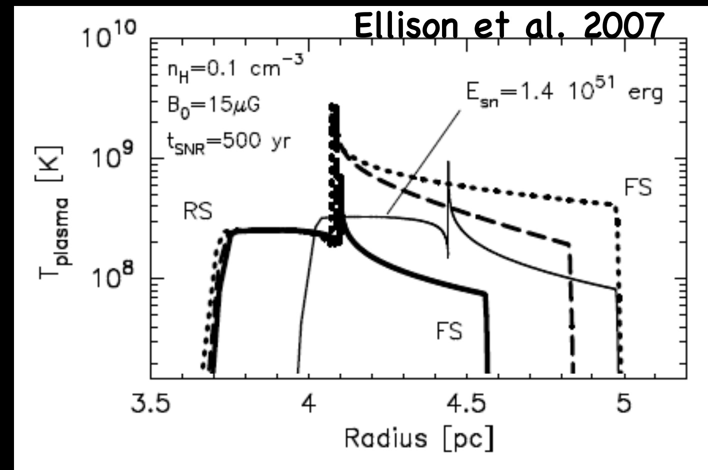
Alvarez-Muniz & Halzen 2002



Aside: Evidence for CR Ion Acceleration



Warren et al. 2005



- 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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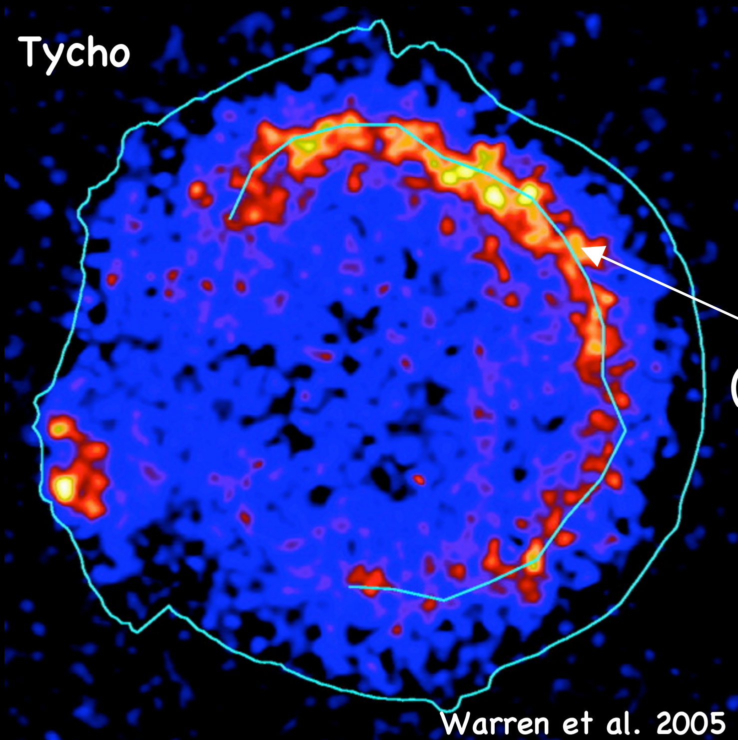

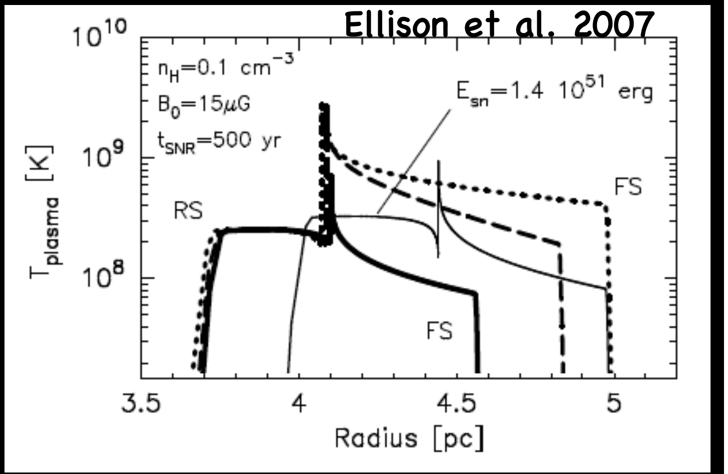

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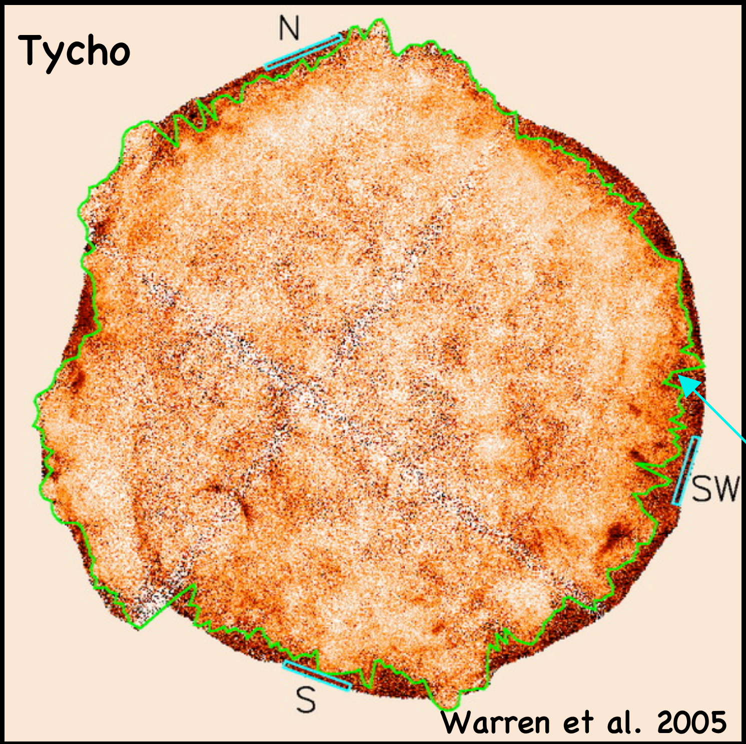

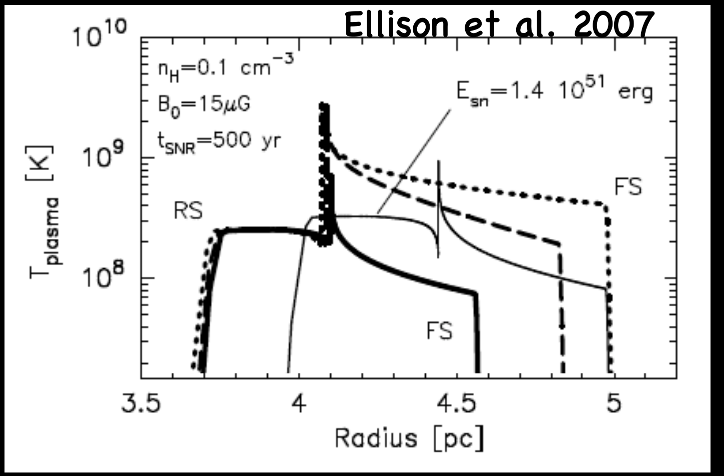

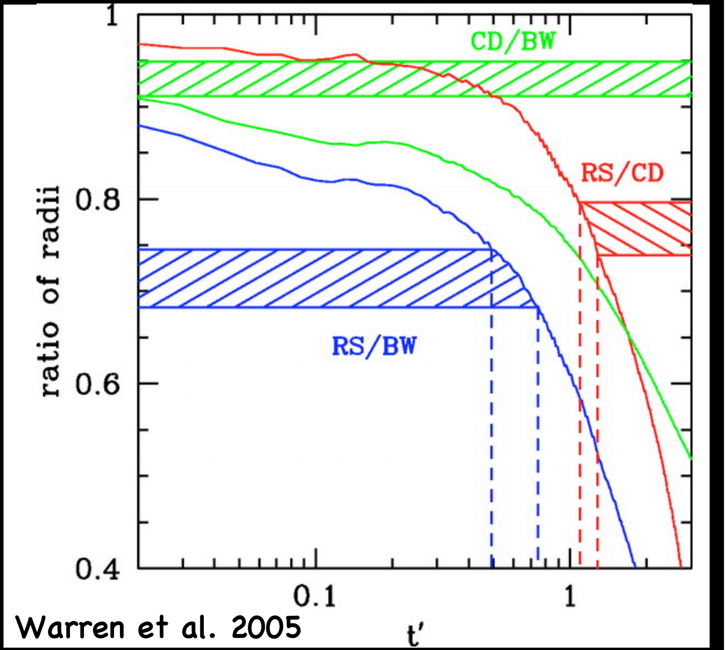

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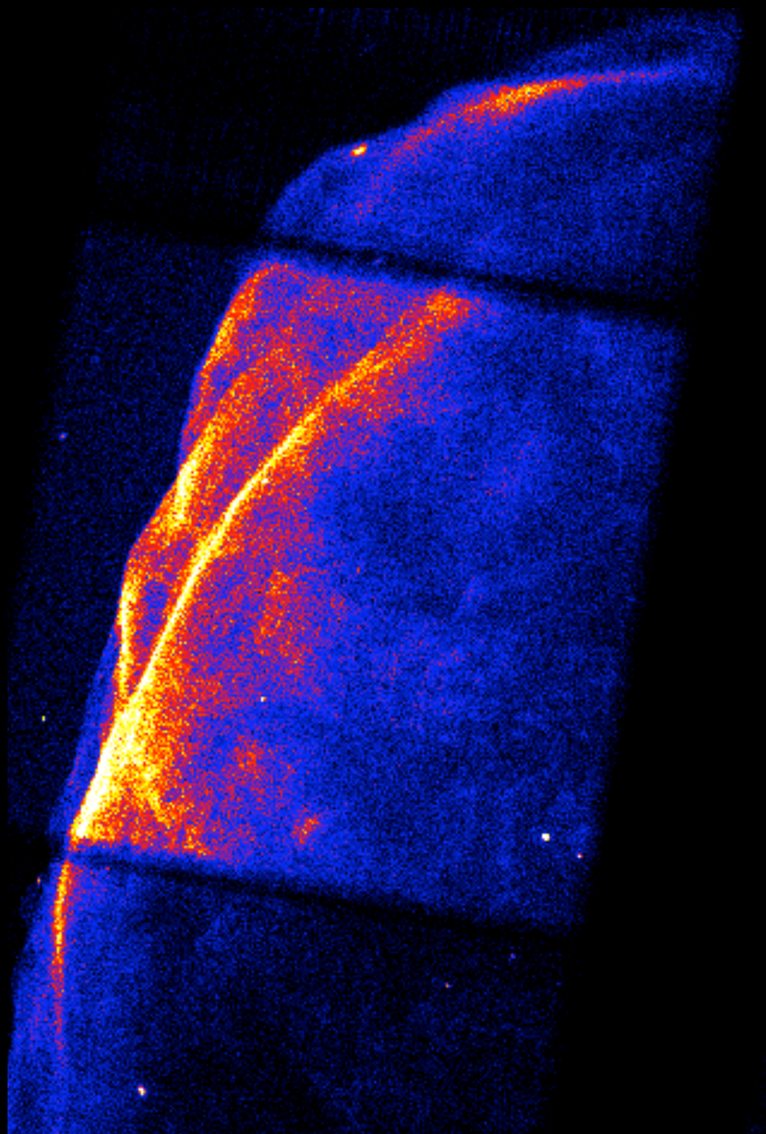
Thin Filaments: B Amplification?



- 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 fie

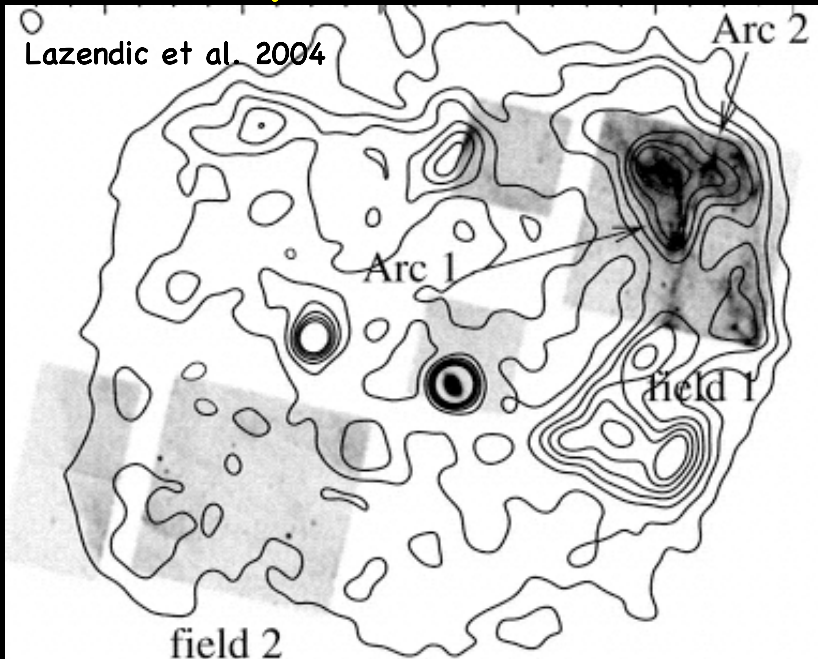
$$B \sim 200 v_8^{2/3} \left(\frac{l}{0.01 pc} \right)^{-2/3} \mu G$$

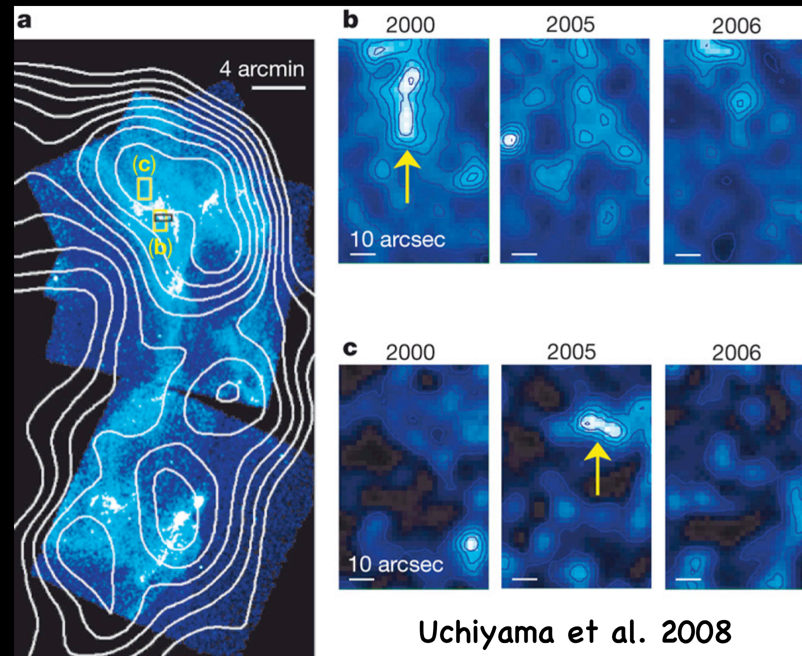
- Diffusion length upstream appears to be very small as well (Bamba et al. 2003)
  - we don't see a "halo" of synchrotron emission in the upstream region

$$l_D \sim \sqrt{\kappa t_{syn}} \propto B^{-3/2}$$

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

Rapid Time Variability: B Amplification?





- 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

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

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

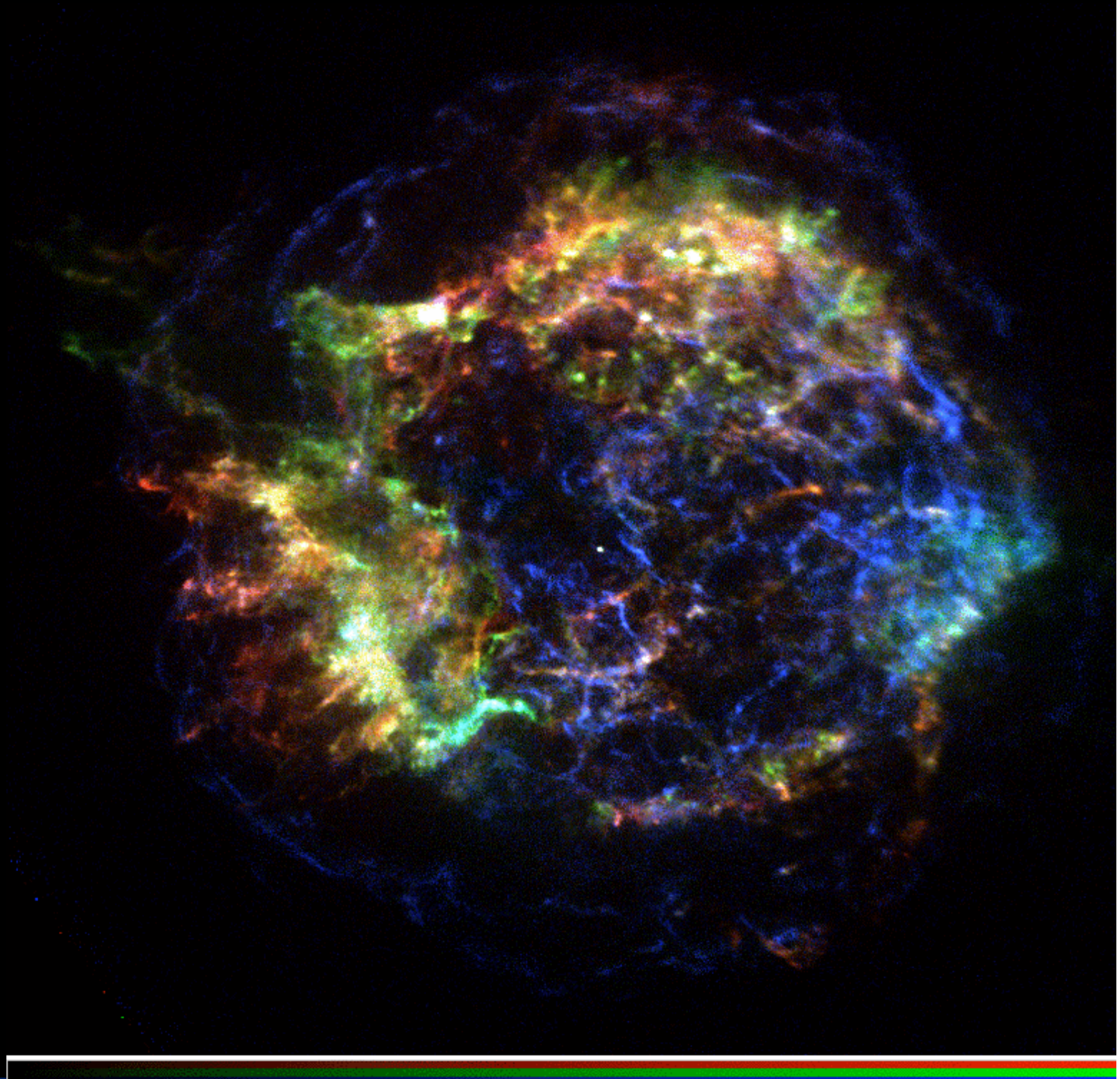
- This, along with earlier measurements of the nonthermal spectrum in Cas A, may support the notion of magnetic field amplification => potential high energies for io

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

Time Variations in Cas A

Patnaude & Fesen 20

- 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
- Uchiyma & Aharonian (2008) identify variations along region of inner shell, suggesting particle accelerations at reverse shock
  - many more observations needed to understand this!



Summary

- SNRs are efficient accelerators of cosmic ray electrons and ions
  - X-ray spectra reveal multi-TeV electrons
  - X-ray dynamics indicated strong hadronic component

- Several lines of argument lead to conclusion that the magnetic field is amplified to large values in shock
  - thin filaments
  - rapid variability

    ==> this could allow acceleration of hadrons to ~knee

- Other explanations for above exist, without large B
  - further study needed
  - GeV/TeV studies will help resolve question of hadron acceleration
  - neutrino observations will weigh in on this as well