X-Ray and Radio Connections

Santa Fe, New Mexico, 3-6 February 2004

Broad-Band Photon Emission from Shock Acceleration in SNRs

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with Anne Decourchelle & Jean Ballet (CEA, Saclay)

► **If SNR shocks accelerate cosmic rays efficiently** **(via diffusive shock acceleration), then:**

► **Thermal properties of the shocked heated gas (X-ray lines and continuum) depends importantly on the production of superthermal particles**

► **Emission from radio to X-rays to TeV gamma-rays is interconnected**

This is true for forward and reverse shocks, but reverse shocks are particularly interesting

FERMI SHOCK ACCELERATION in SNRs

► In **collisionless** plasmas, charged particles are coupled by **magnetic fields** → strongly **non-equilibrium particle spectra** possible.

► **Shocks** set up converging plasmas making **acceleration rapid and efficient**

► We know collisionless **shocks exist and accelerate particles efficiently !!** → Direct observation of efficient shock acceleration in the **Heliosphere**

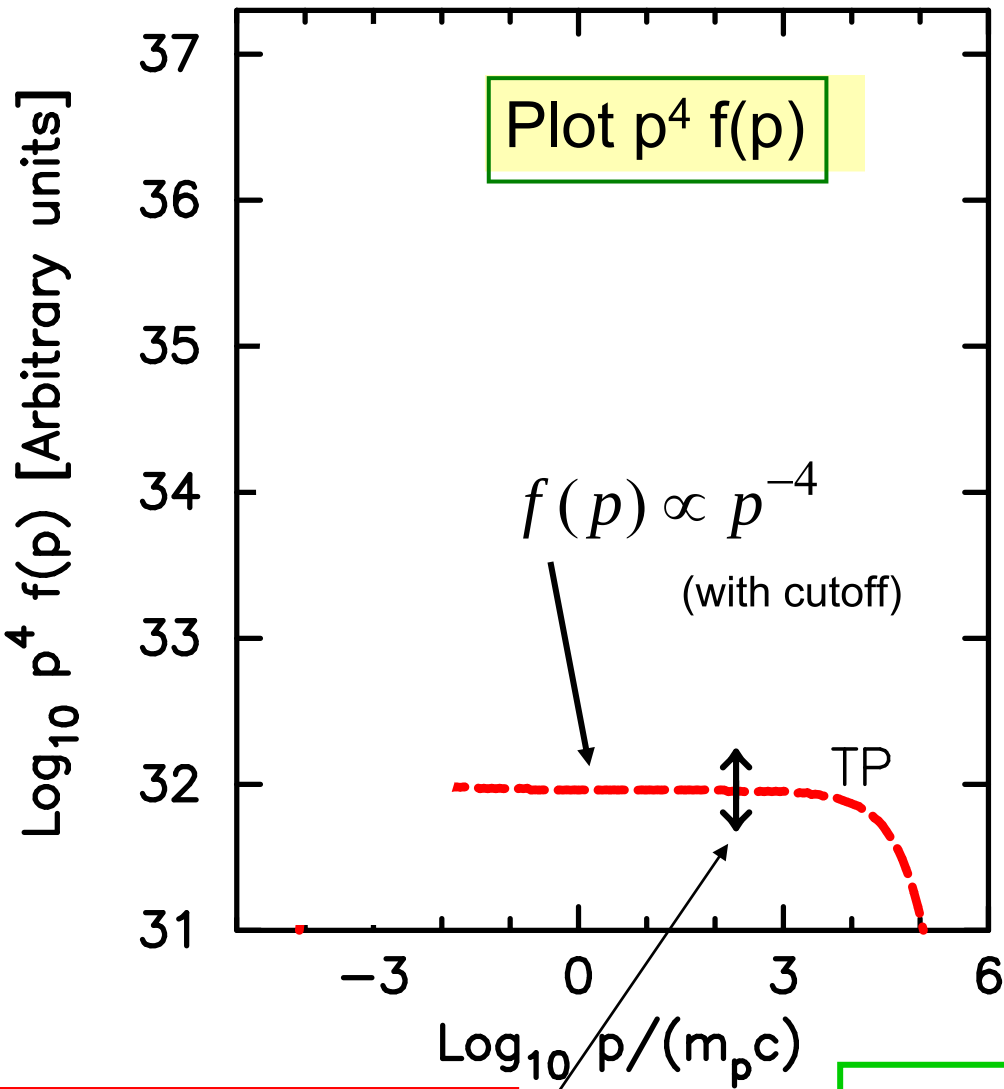
► Much stronger **SNRs shocks <u>should</u> be efficient ION accelerators** (at least in Q-parallel regions of shocks)

The efficient acceleration of CR ions impacts:

1) <u>Thermal properties</u> of the shock heated, X-ray emitting gas,
2) <u>SNR evolution</u>, and 3) <u>broad-band emission</u>

Test Particle Power Law

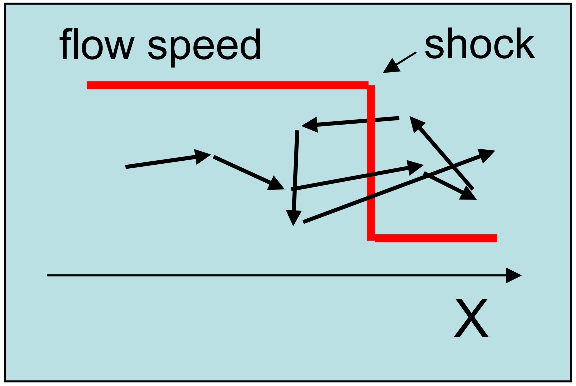
Krymsky 77, Axford at al 77, Bell 78,
Blandford & Ostriker 78



Plot p^4 $f(p)$

$f(p) \propto p^{-4}$

(with cutoff)



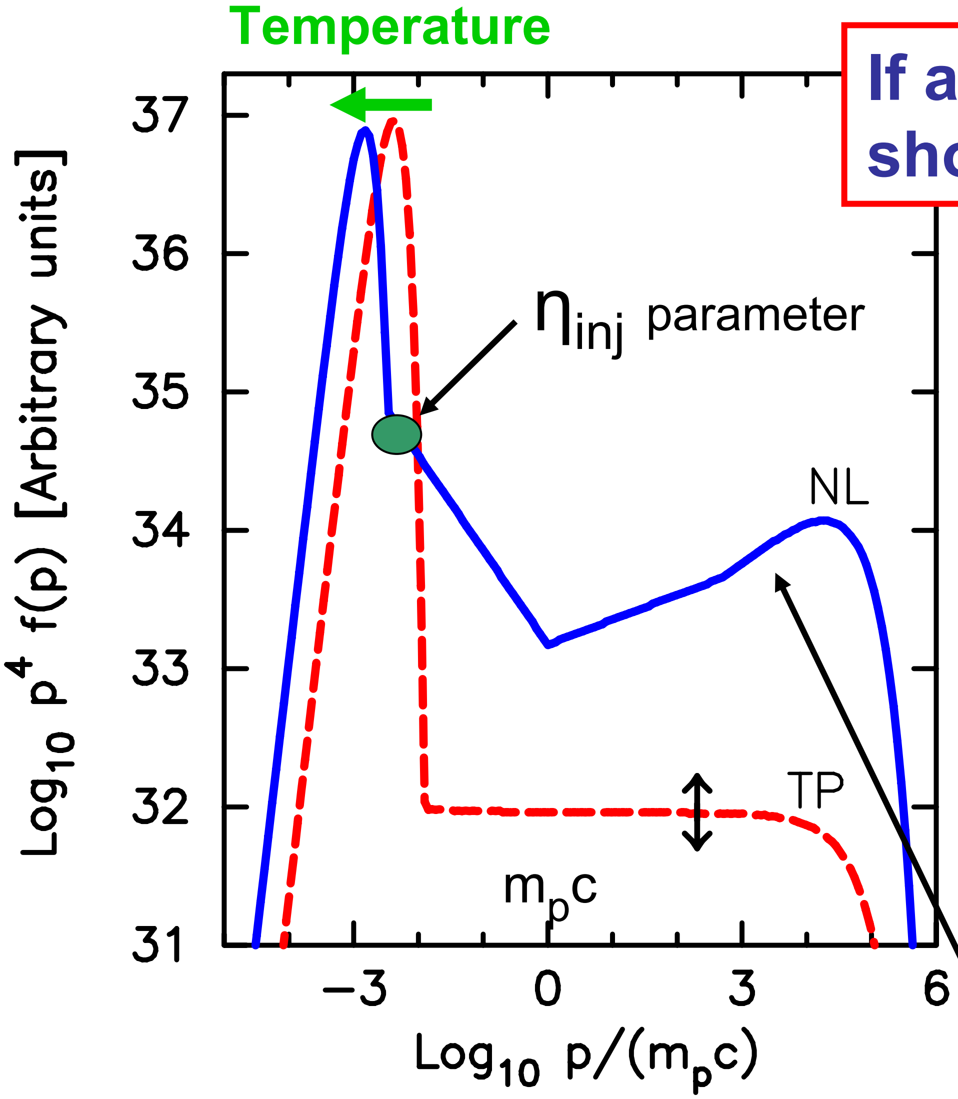
$f(p) \sim p^{-3r/(r-1)}$ where **r** is compression ratio, $f(p)\, d^3p$ is phase space density

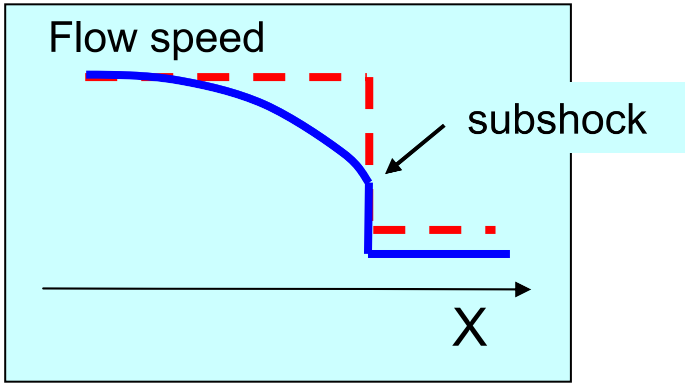
If r = 4, & $\gamma = 5/3$
f(p) ~ $\mathbf{p^{-4}}$

Normalization of power law not defined in TP acceleration

Test particle results: ONLY for superthermal particles, no information on thermal particles

If acceleration is efficient, shock becomes smooth

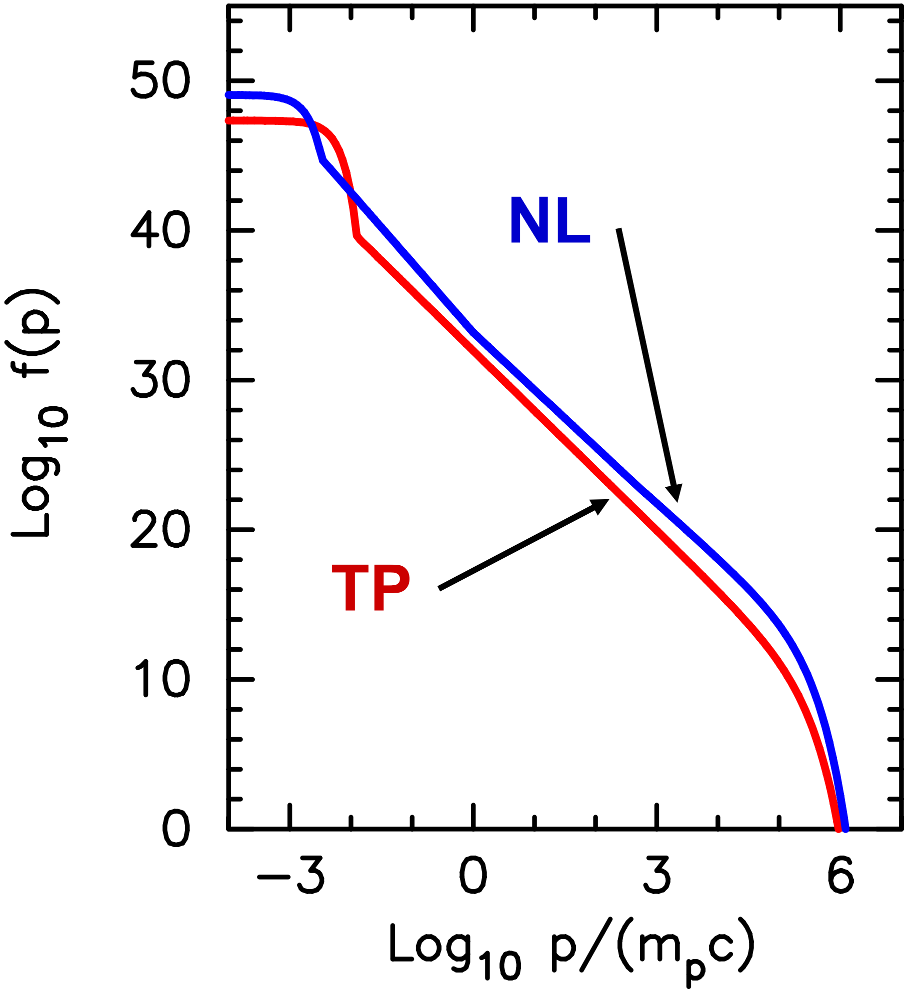




- ► Concave spectrum
- ► Compression ratio, $r_{tot} > 4$
- ► Lower shocked temp. $r_{sub} < 4$
- ► Nonthermal tail on electron & ion distributions

In efficient accel., entire spectrum must be described consistently connects Radio and X-ray emission

Here show `Simple' model of Berezhko & Ellison 99



Without p^4 factor, nonlinear effects much less noticeable

Efficient vs. Test-Particle Acceleration and Temperature of shock heated gas:

If NO acceleration (or Test-particle acceleration), then compression ratio, r ~ 4, and:

$$T_p \approx \frac{3}{16} \frac{m_p}{k_B} V_{sk}^2$$

Shocked proton temperature (for typical young SNR shocks) extremely high !!

e.g., V_{sk} = 2000 km/s → $T_p \approx 10^8$ K !! This may force assumption

$T_e << T_p$ to explain X-ray lines in some SNRs

If accel. occurs, some Internal energy goes into superthermal particles → Must reduce energy in thermal population → **Lower shocked proton temp**. **Can be large effect, i.e., factor of 10**

The greater the acceleration efficiency, the lower the shocked proton temperature → may not need $T_e << T_p$

Hydrodynamic simulation of Supernova remnant evolution with efficient particle acceleration

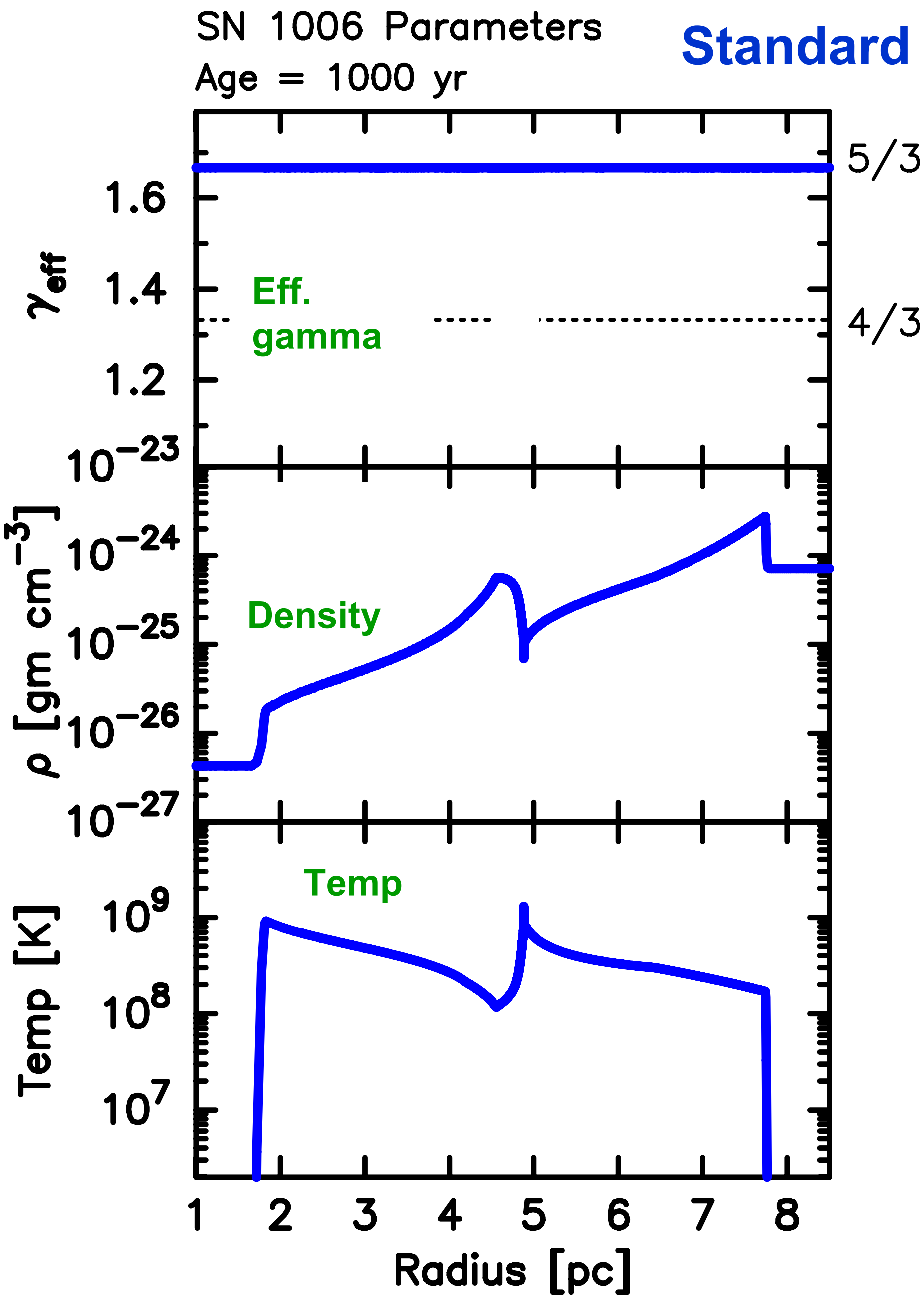
with Anne Decourchelle and Jean Ballet, CEA-Saclay

Decourchelle, Ellison, & Ballet, ApJL, 2000

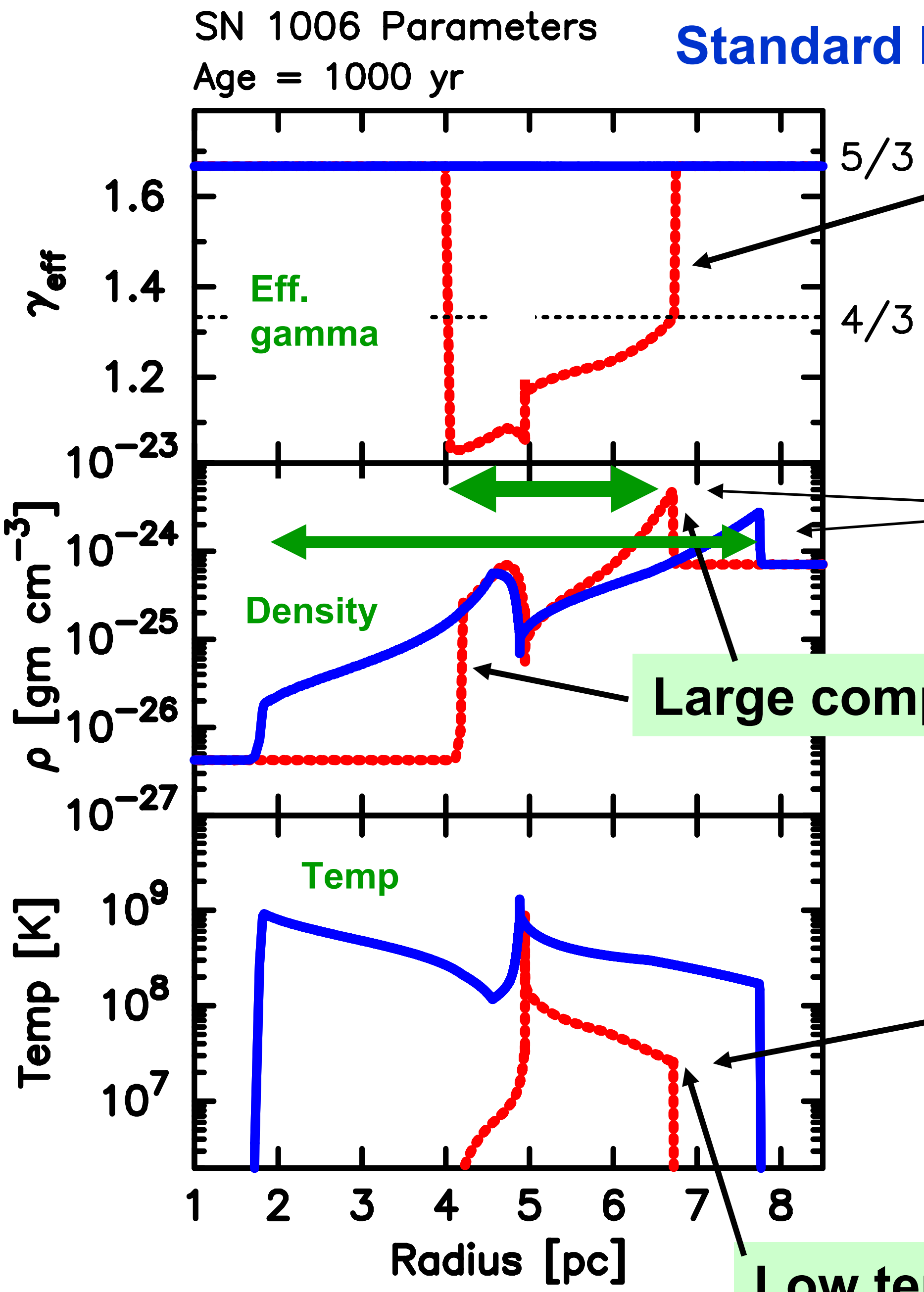
Blondin & Ellison, ApJ, 2001

Ellison, Decourchelle, & Ballet, A&A, 2004

Standard Hydro: NO accel. (Blue)



Standard Hydro: NO accel. (Blue)



Hydro with Efficient accel.

Efficient acceleration (**Red curves**) produces **large compression** ratios and **Low shocked temperatures**

Large comp.

Interaction region between Forward and Reverse shocks is narrower and denser if accel. efficient

For same supernova explosion energy, blast wave shock has slower speed

Low temperature

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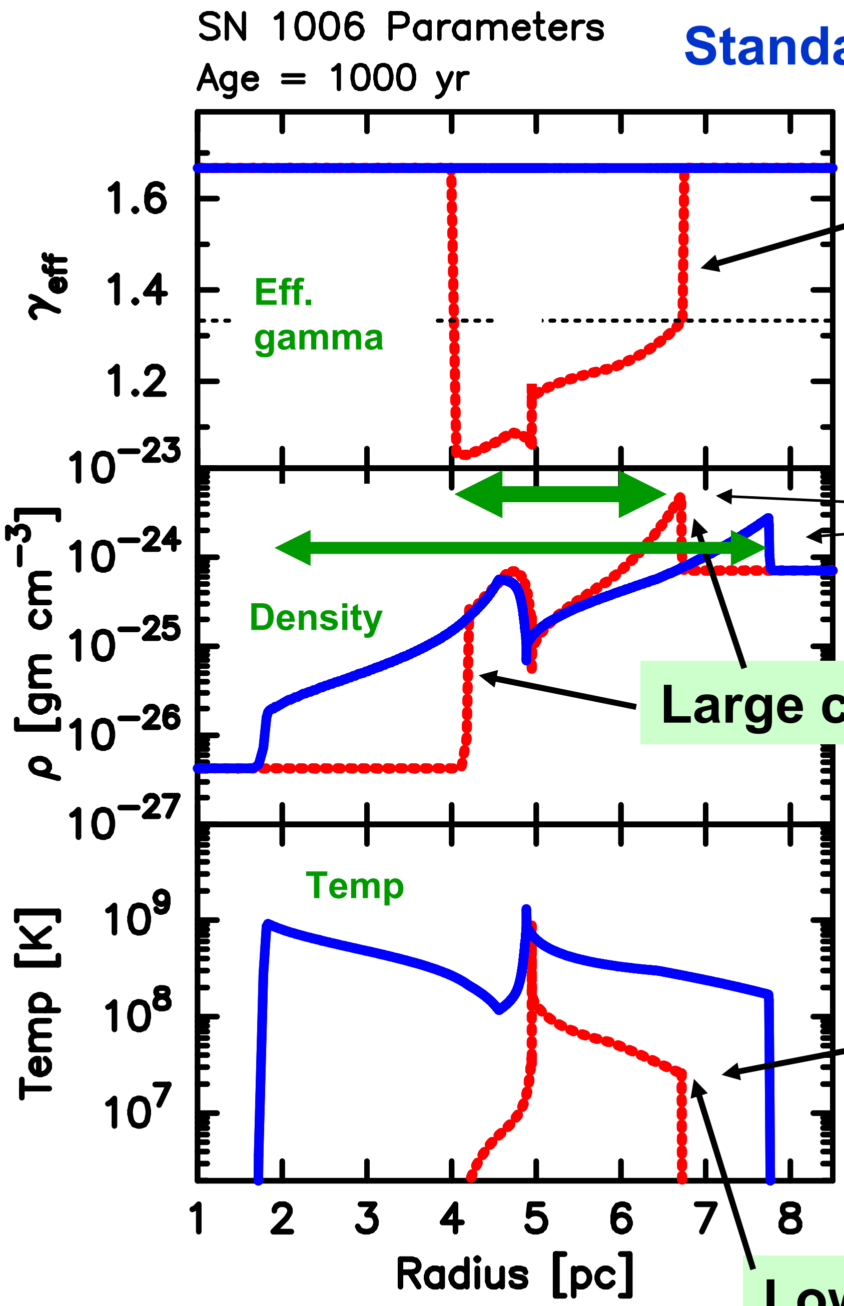

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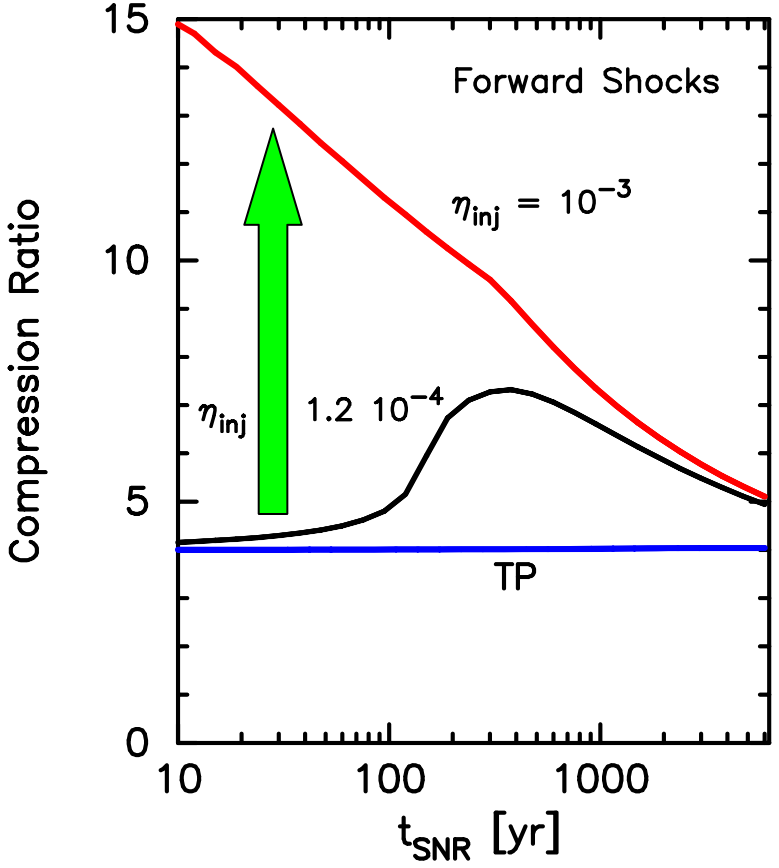
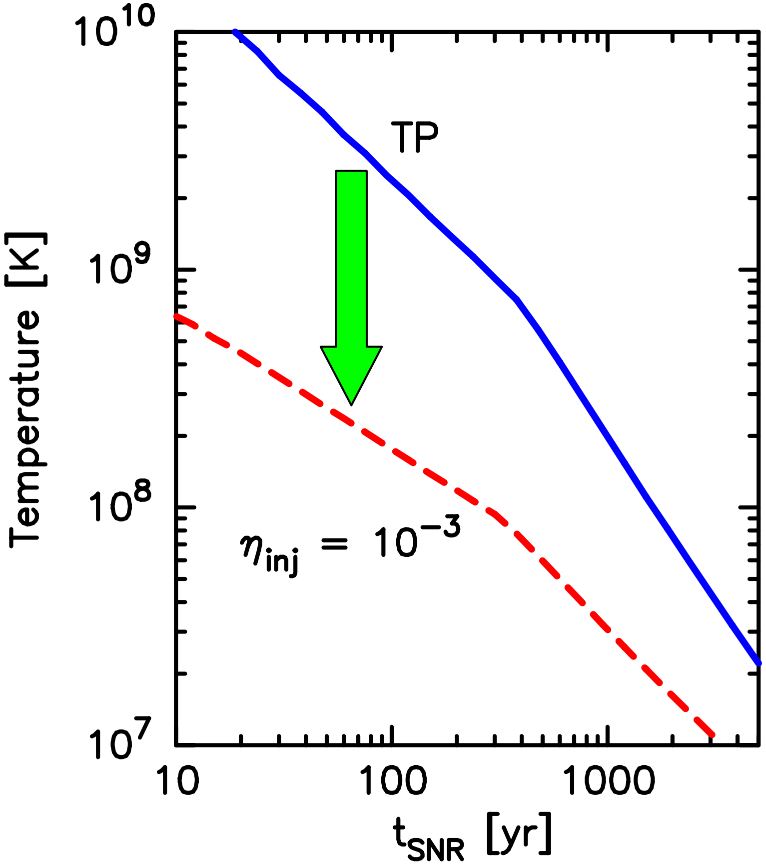
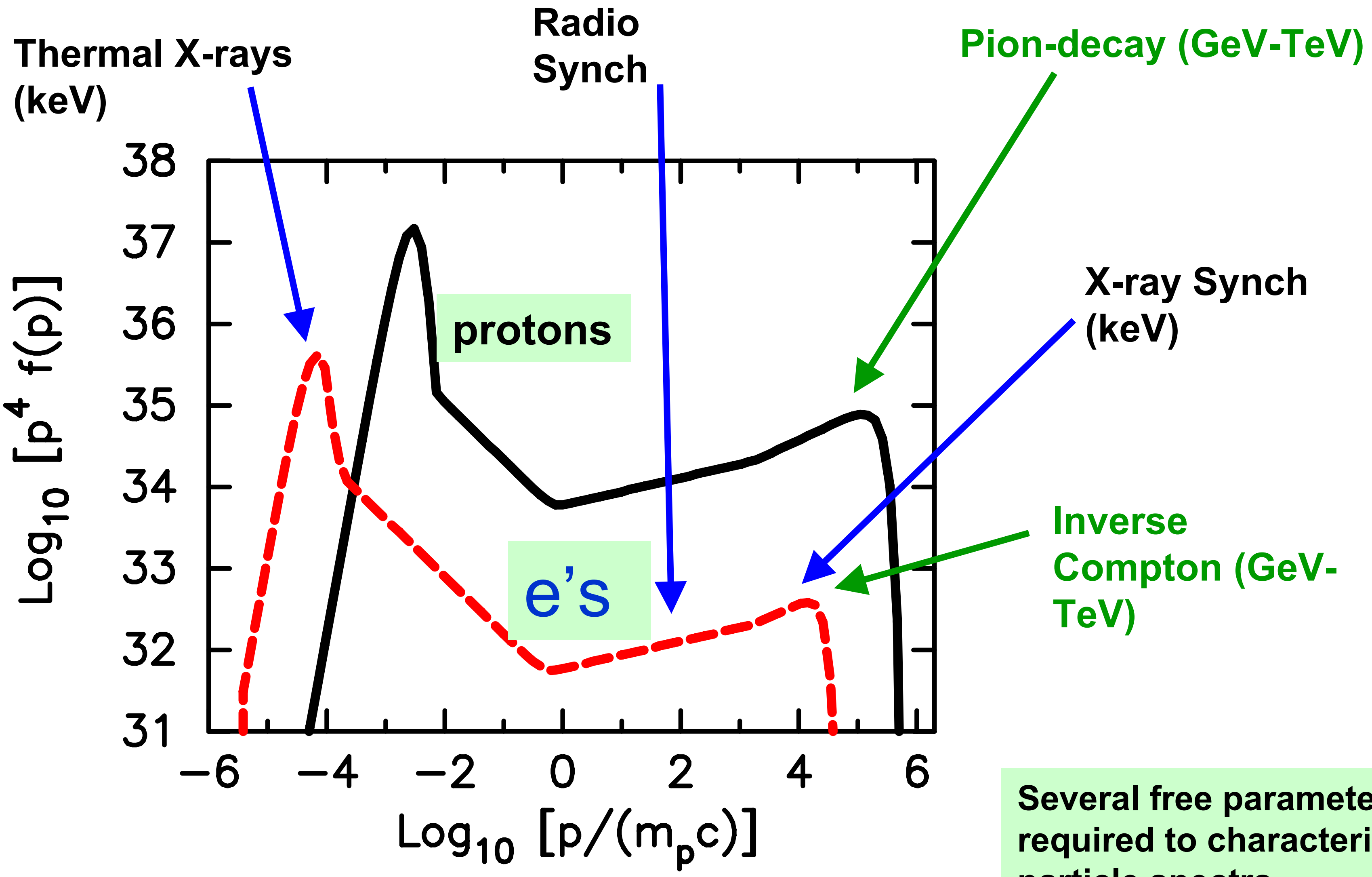

Compression ratios


Shocked temperature

η_{inj} **is parameterized injection efficiency: i.e., fraction of thermal protons that end up superthermal**

Electron and Proton distributions (from B & E model)



Thermal X-rays (keV)

Radio Synch

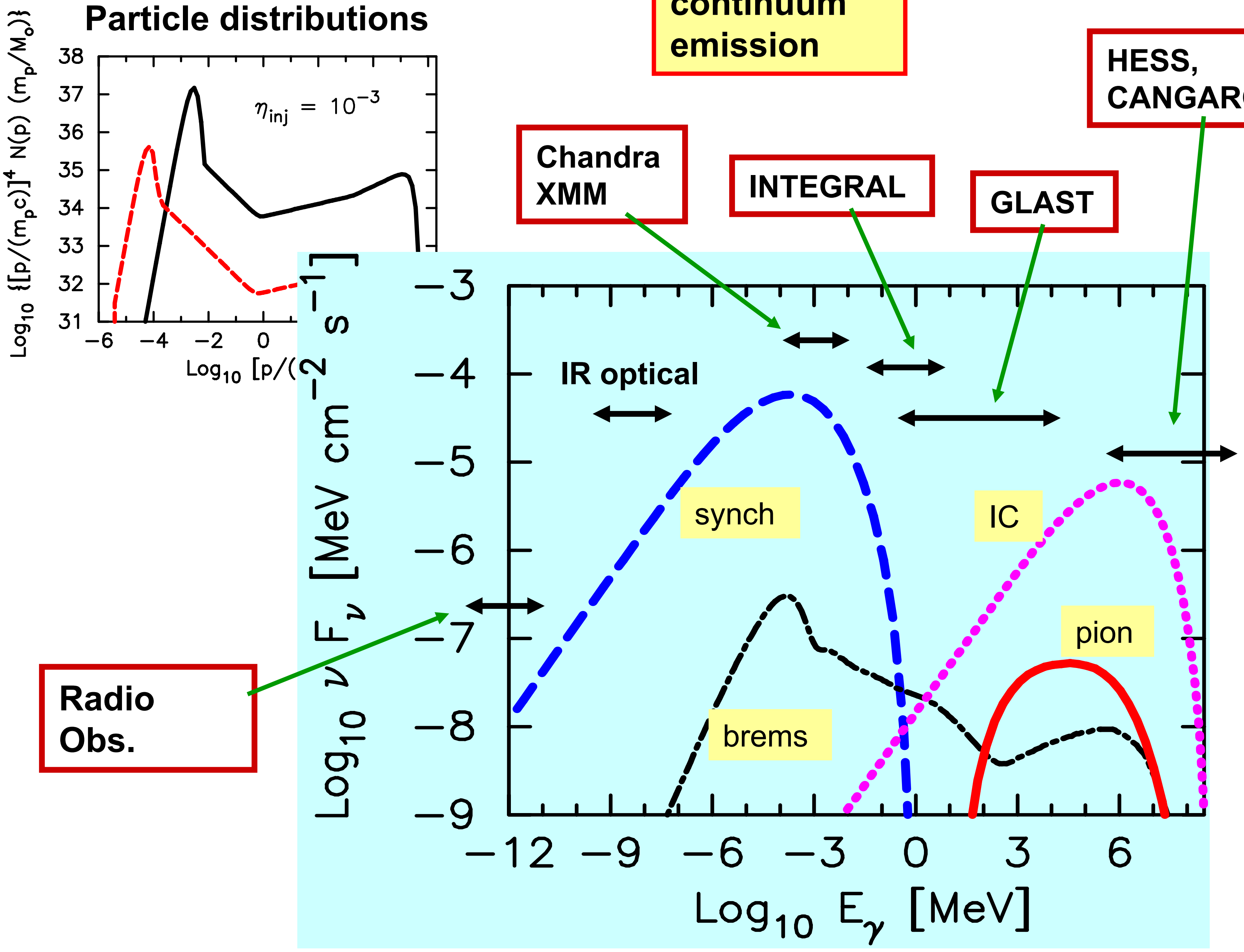
Pion-decay (GeV-TeV)

X-ray Synch (keV)

Inverse Compton (GeV-TeV)

Several free parameters required to characterize particle spectra

continuum emission



Chandra XMM

INTEGRAL

GLAST

HESS, CANGAROO

Radio Obs.

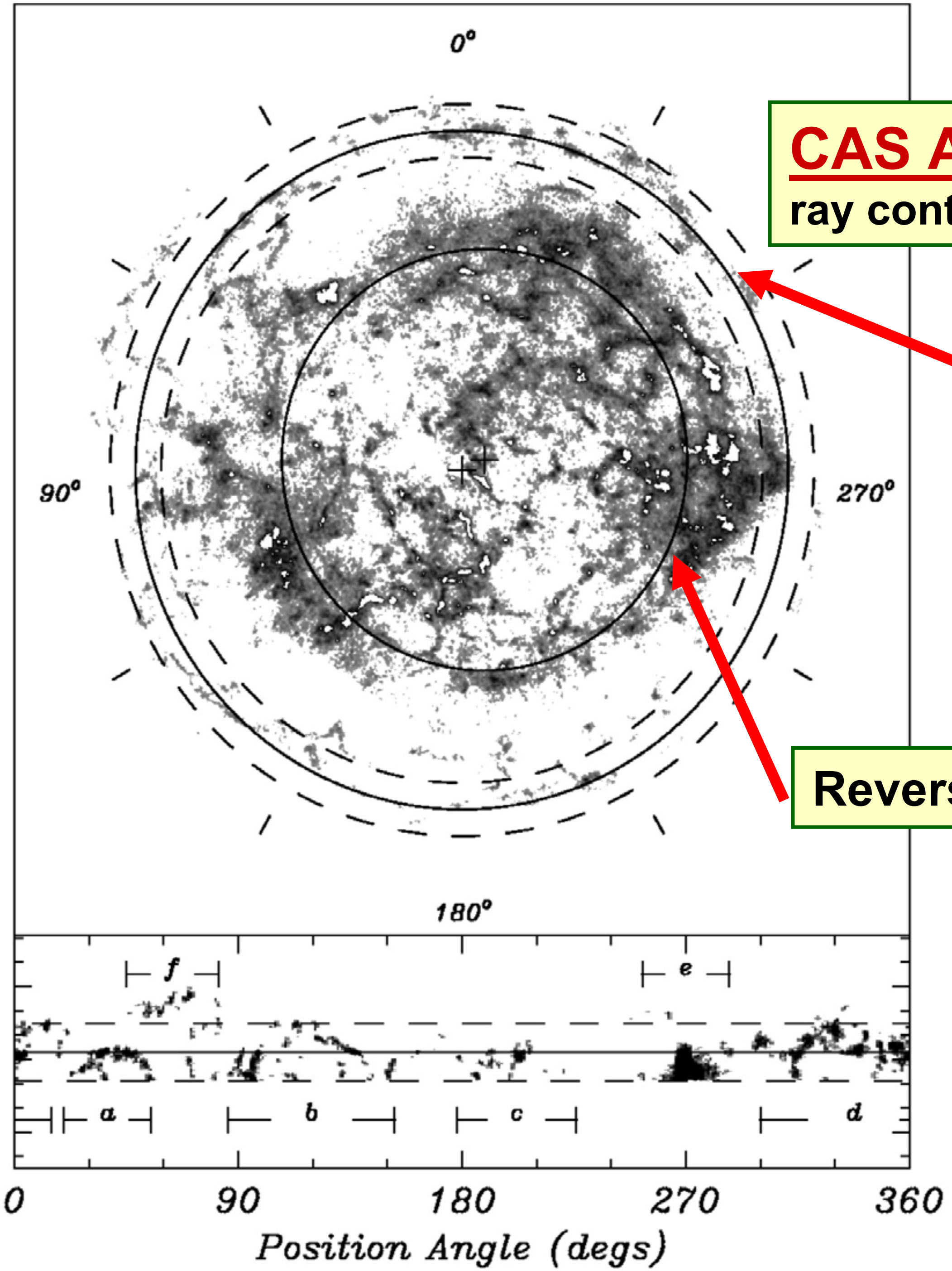
Do reverse shocks in SNRs accelerate electrons to radio emitting energies ??

Suggestions that reverse shocks CAN produce relativistic electrons: Cas A (Gotthelf et al 2001), Kepler (DeLaney et al 2002), & RCW86 (TeV e's !) (Rho et al 2002)

In ejecta, any progenitor B-field will be vastly diluted by expansion and flux freezing → After << 100 yr will fall below levels necessary to support particle acceleration to radio emitting energies.

Ejecta bubble may be lowest magnetic field region anywhere!

If radio emission is clearly associated with reverse shocks, may be sign that ejecta B-field has been strongly amplified by diffusive shock acceleration (e.g., Bell & Lucek)



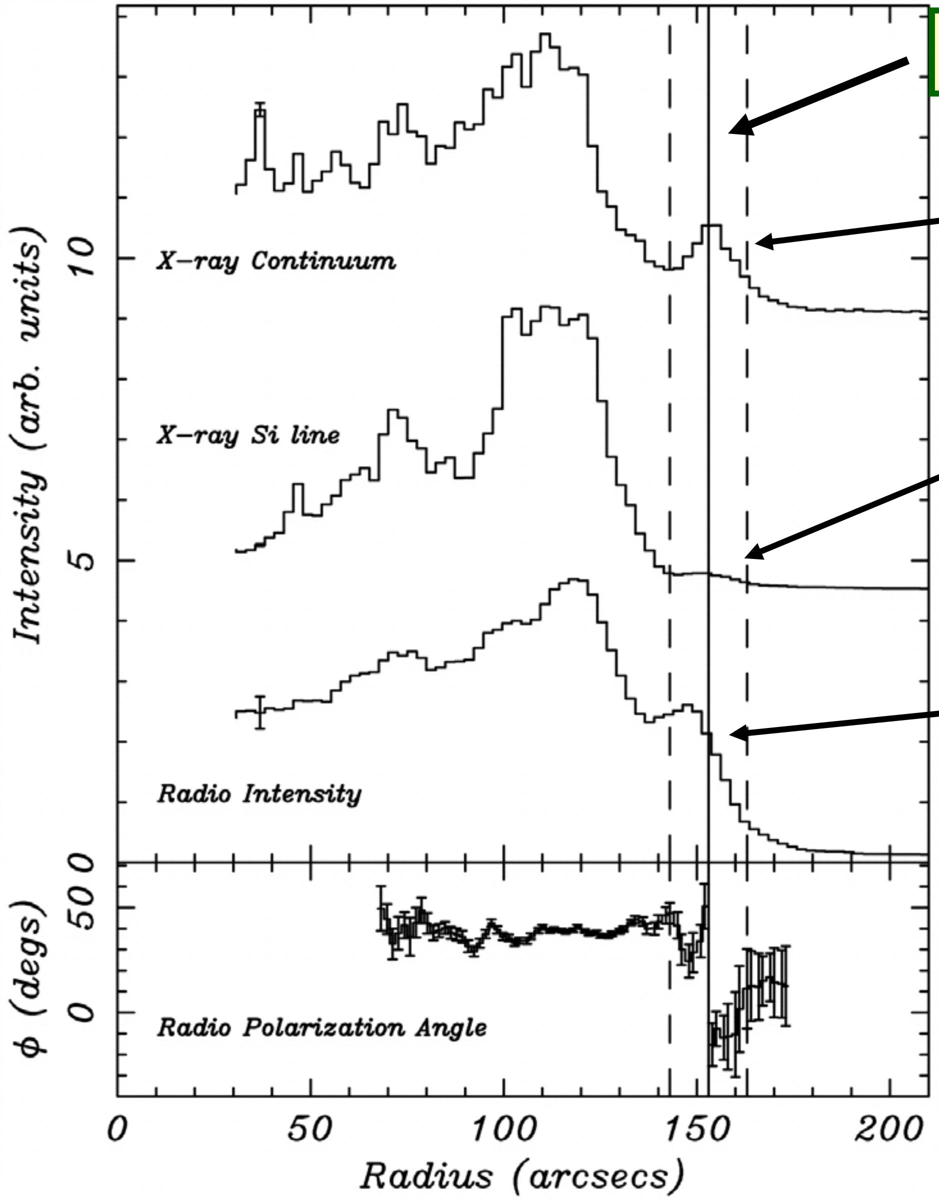
CAS A: 4-6 keV high-energy X-ray continuum map

Forward Shock

Reverse shock?

Gotthelf, Koralesky, Rudnick, Jones, Hwang & Petre 2001

Cas A



Forward shock

X-ray continuum

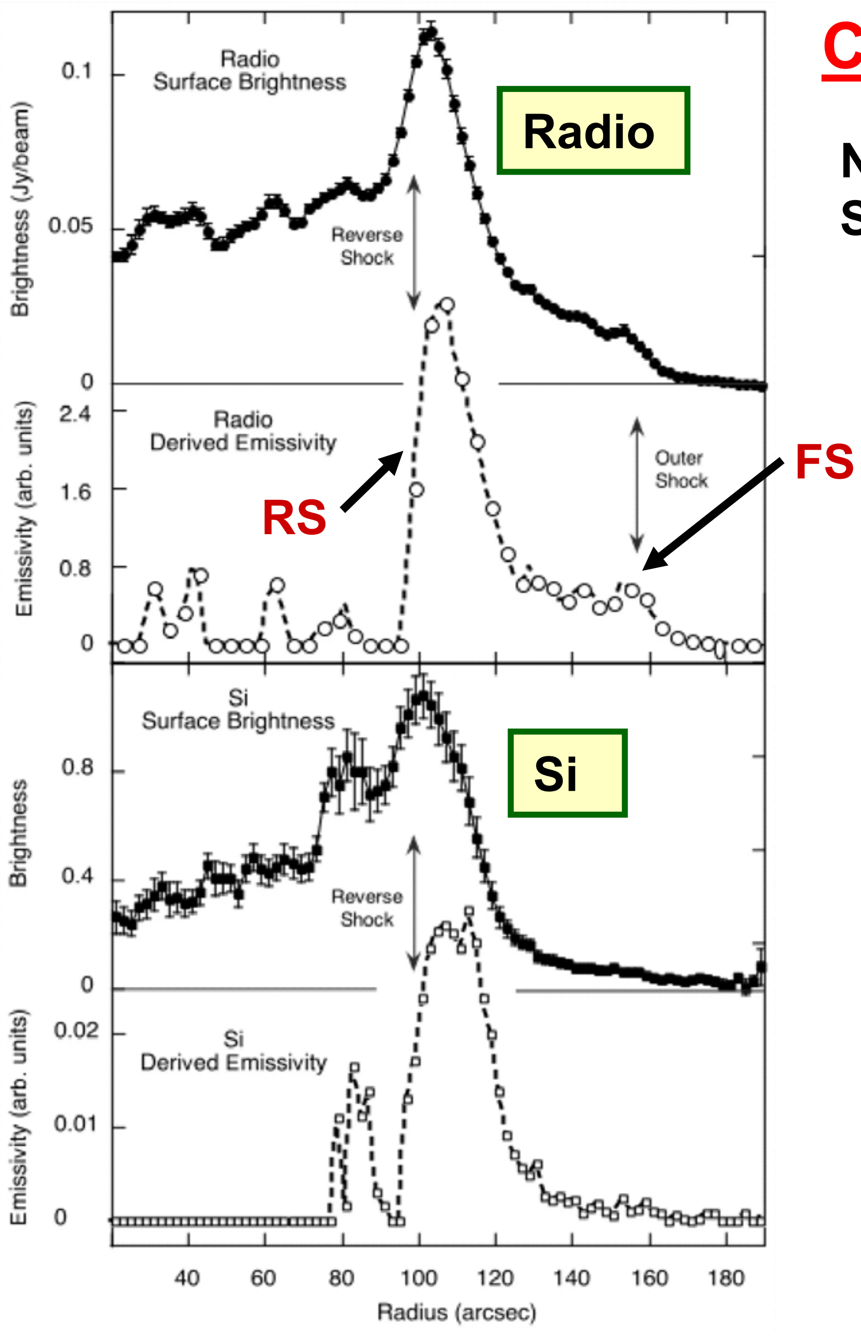
Nothing in Si line

Radio

Averaged over the northwestern quadrant between -5° and -60° centered on the wisps

Gotthelf, Koralesky, Rudnick, Jones, Hwang & Petre 2001

Cas A – Reverse shock



Normalized surface brightness, Spatial decomposition

Gotthelf et al 2001

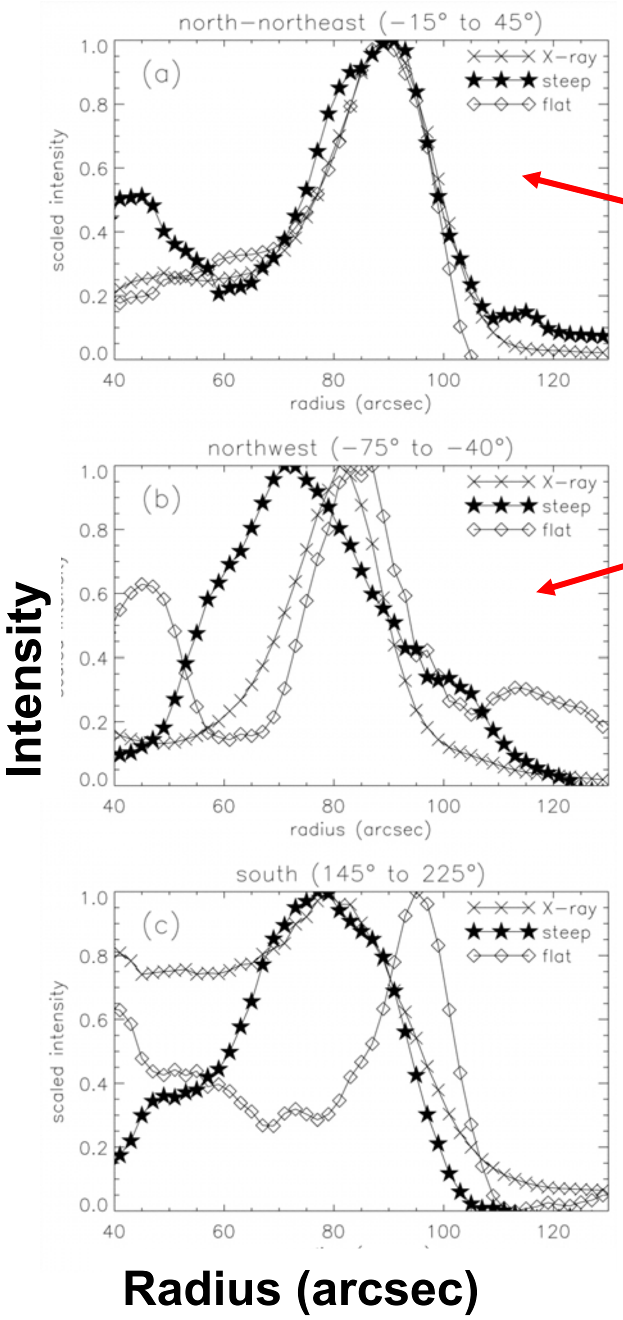
Convincing evidence in radio,

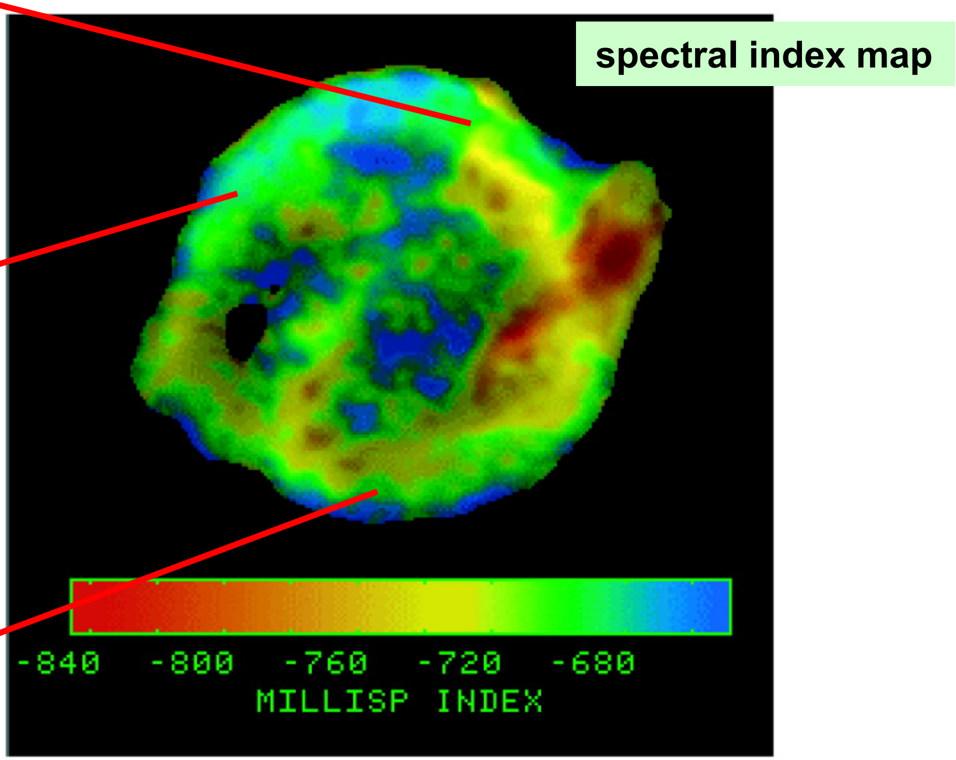
marginal evidence at 4-6 keV

Is the RS accelerating these relativistic electrons ??

Kepler's SNR

DeLaney, Koralesky, Rudnick, & Dickel ApJ, 580, 914, 2002



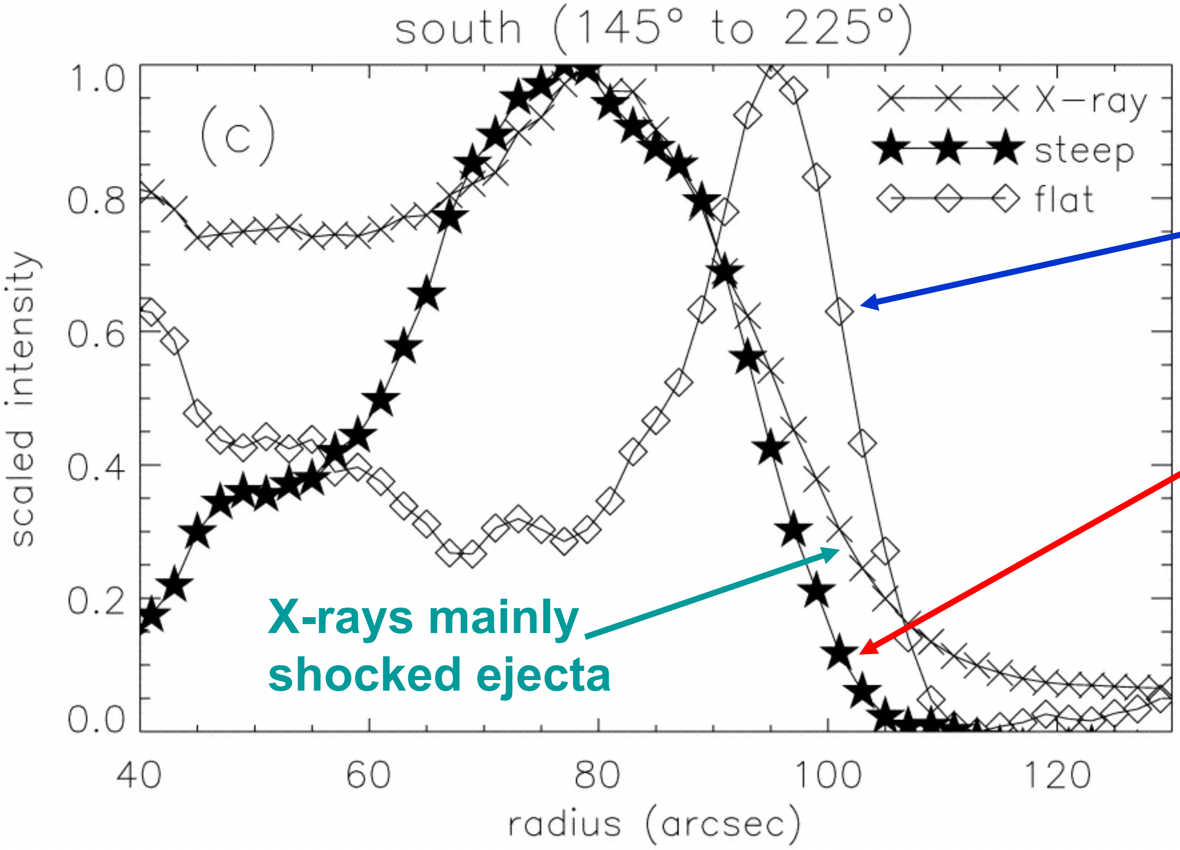


← Steep Radio Flat Radio →

May see a partial decoupling of forward and reverse shocks in southern part of SNR

Kepler's SNR

DeLaney etal. ApJ, 580, 914, 2002



Flat radio: FS ?

Steep radio: RS ?

X-rays mainly shocked ejecta

Indirect evidence that RS is accelerating electrons

The fact that ejecta magnetic fields may be much lower than B_{ISM} opens the possibility that the dampening effects of the magnetic field become insignificant.

A high magnetic field damps Fermi acceleration because:

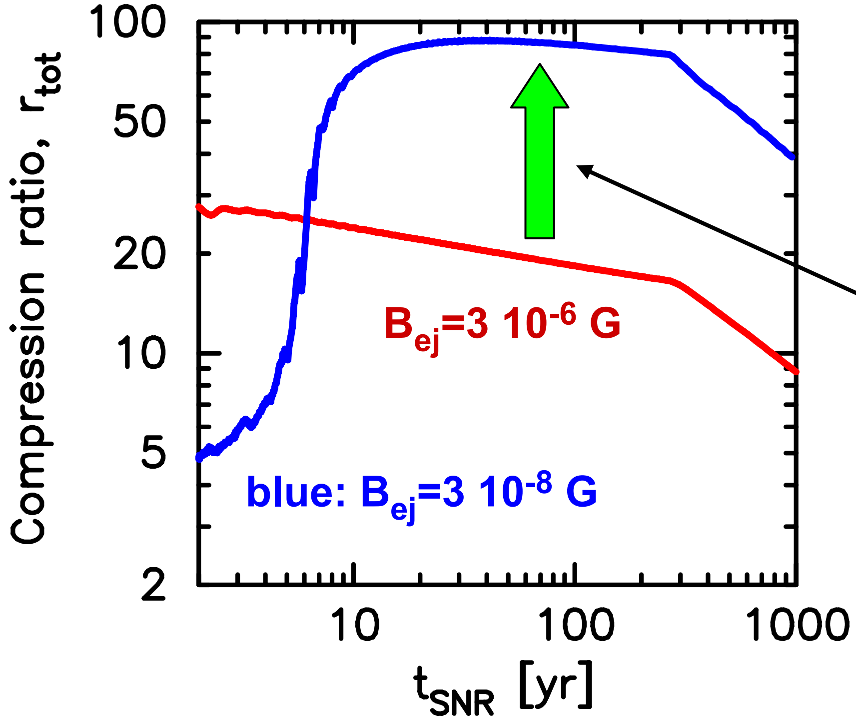
- ► **Energy from superthermal particles is efficiently transferred to magnetic turbulence and then to heat, lowering the subshock Mach number and lowering the injection rate**
- ► **Magnetic scattering centers move through fluid at the Alfven speed, lowering the effective compression ratio**

Normal ISM magnetic fields ($B_{ISM} \geq 3\ 10^{-6}$ G) are large enough to damp acceleration

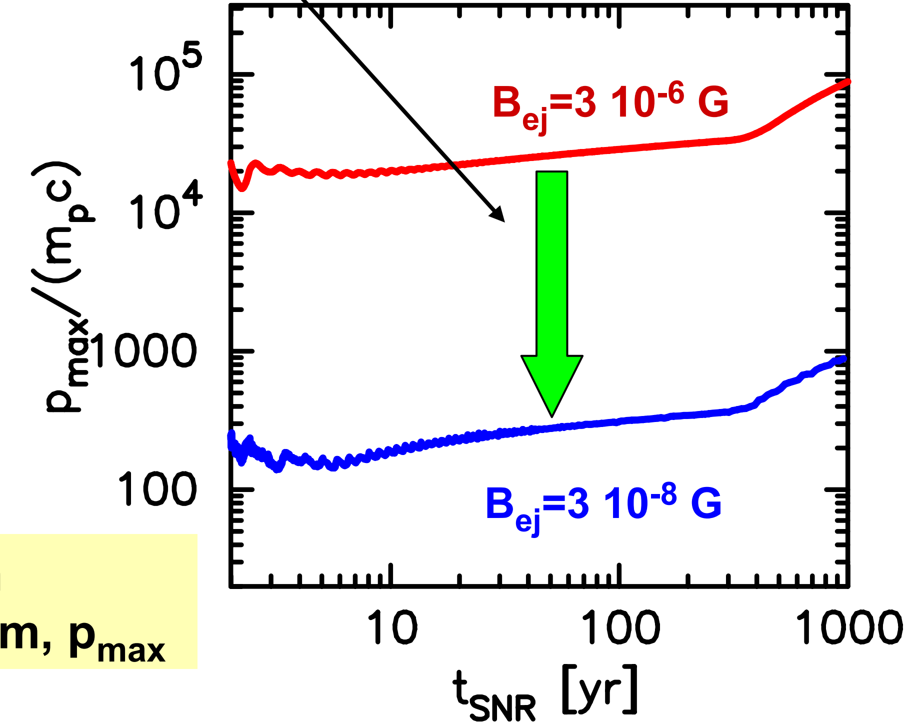
A range of $B_{ej} << B_{ISM}$ may exist where B_{ej} is high enough so electrons are trapped near the shock long enough to be accelerated to radio emitting energies,

But low enough so the full nonlinear effects of efficient Fermi acceleration of ions occurs.

Reverse shock compression ratio in Low B-fields



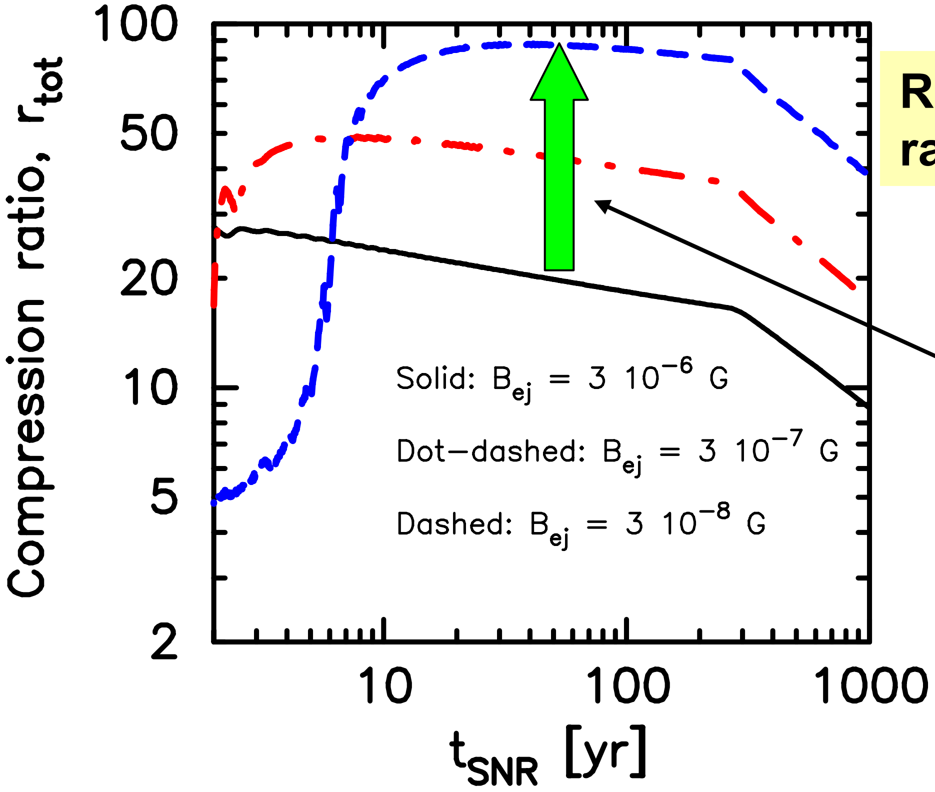
r_{tot} increases and p_{max} deceases as ejecta B-field drops



Maximum momentum, p_{max}

Decourchelle, Ellison, & Ballet, in preparation

BUT: If B_{ej} gets too low, Fermi accel. shuts down & can't produce radio emitting electrons



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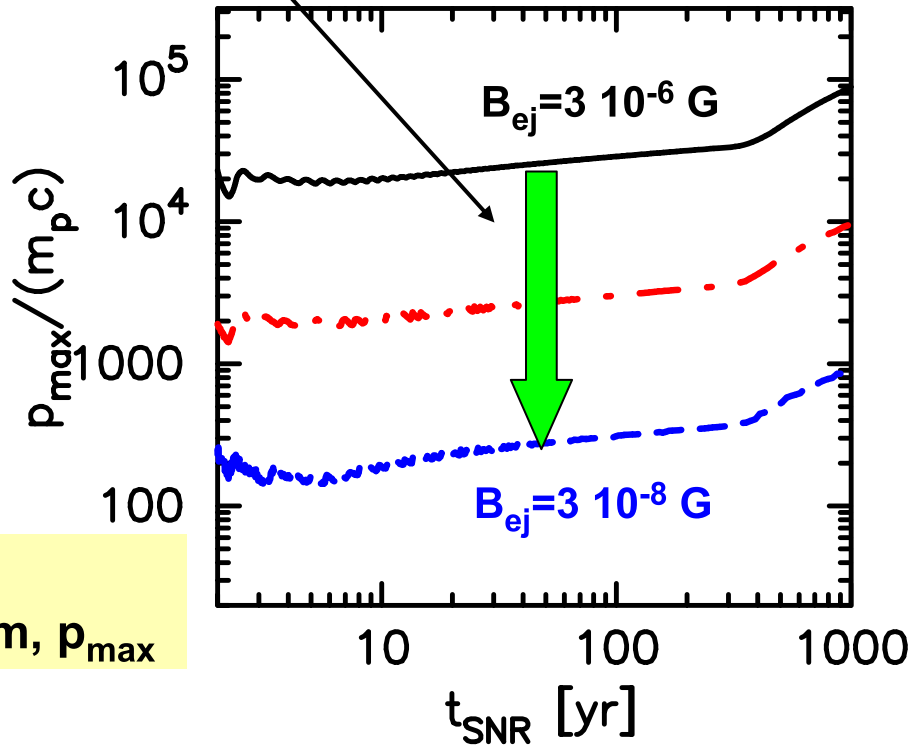
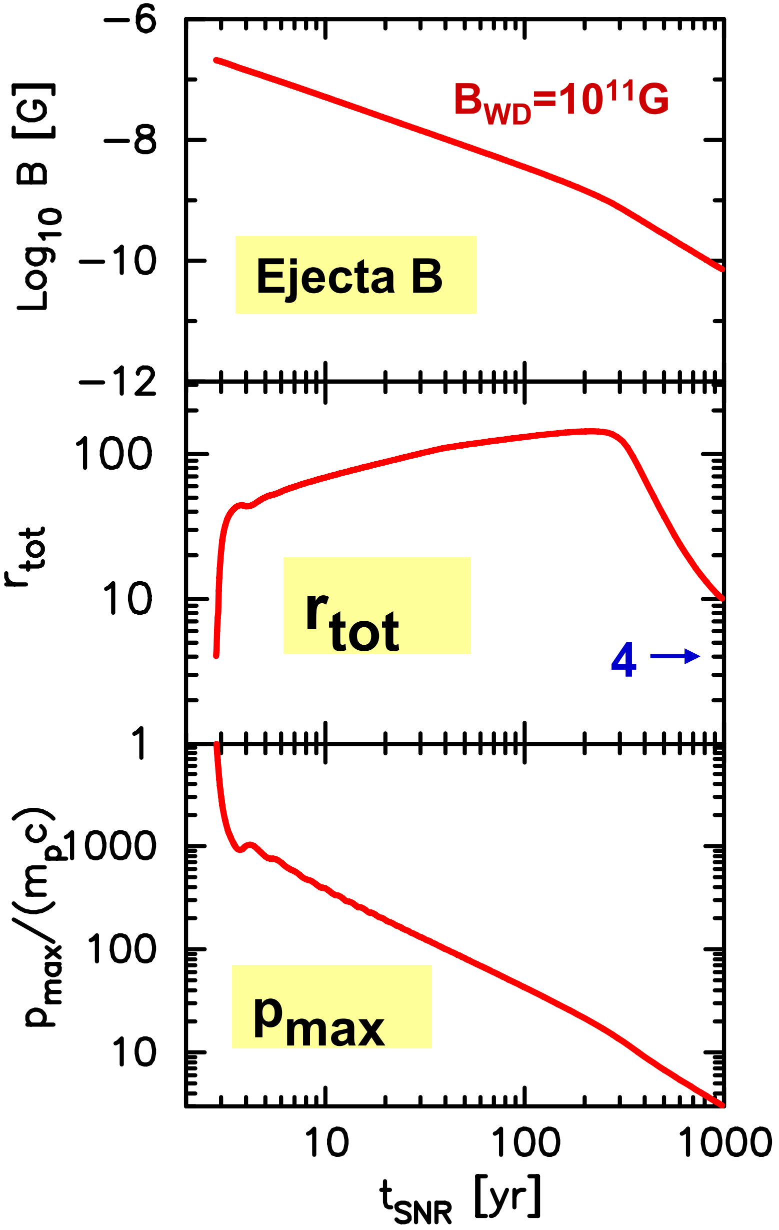
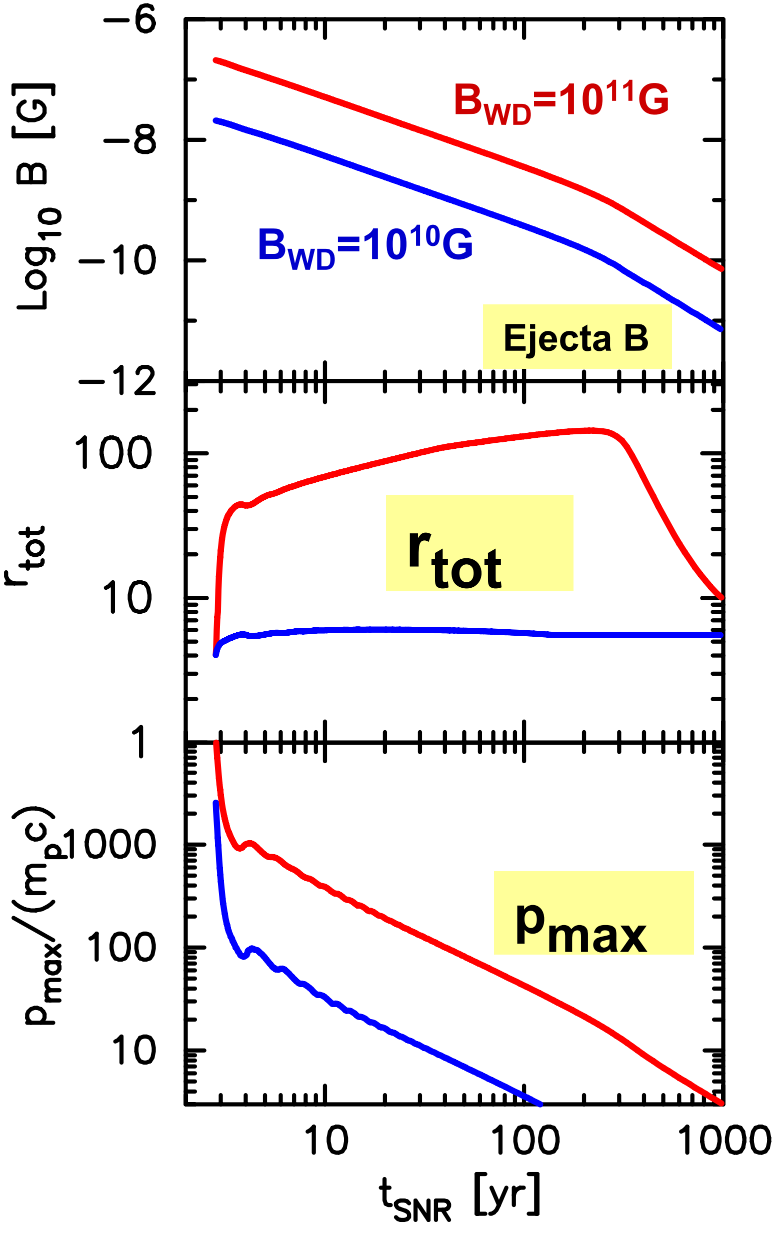




Dilution of B-field in expanding ejecta – assuming magnetic flux stays constant

Maximum possible B_{ej} from white dwarf with initial $B_{WD}=10^{11}$ G !!

This field is large enough to produce efficient acceleration by reverse shock with r_{tot} » 4



For smaller $B_{WD} \leq 10^{10}$ G, p_{max} too small for efficient production of radio emitting electrons

If radio emission is clearly associated with RS, may imply that B_{ej} has been amplified

For normal $B_{WD} \leq 10^9$ G, needed amplification is many orders of magnitude!

If reverse shocks in SNRs are accelerating electrons by diffusive shock acceleration to radio emitting energies or higher, there may be important consequences for:

- ► **magnetic field generation in strong shocks,**
- ► **cosmic-ray production,**
- ► **the structure and evolution of the X-ray emitting interaction region between the reverse shock and contact discontinuity,**
- ► **the likelihood of an early radiative phase in young remnants, and**
- ► **electron equilibration times.**

The efficient production of cosmic rays (superthermal particles) by the Fermi shock mechanism influences the dynamics of supernova remnants and constrains the broad-band photon emission – emission in one band depends on emission in all other bands.

This should apply to other sites undergoing shock acceleration, e,g., colliding stellar winds