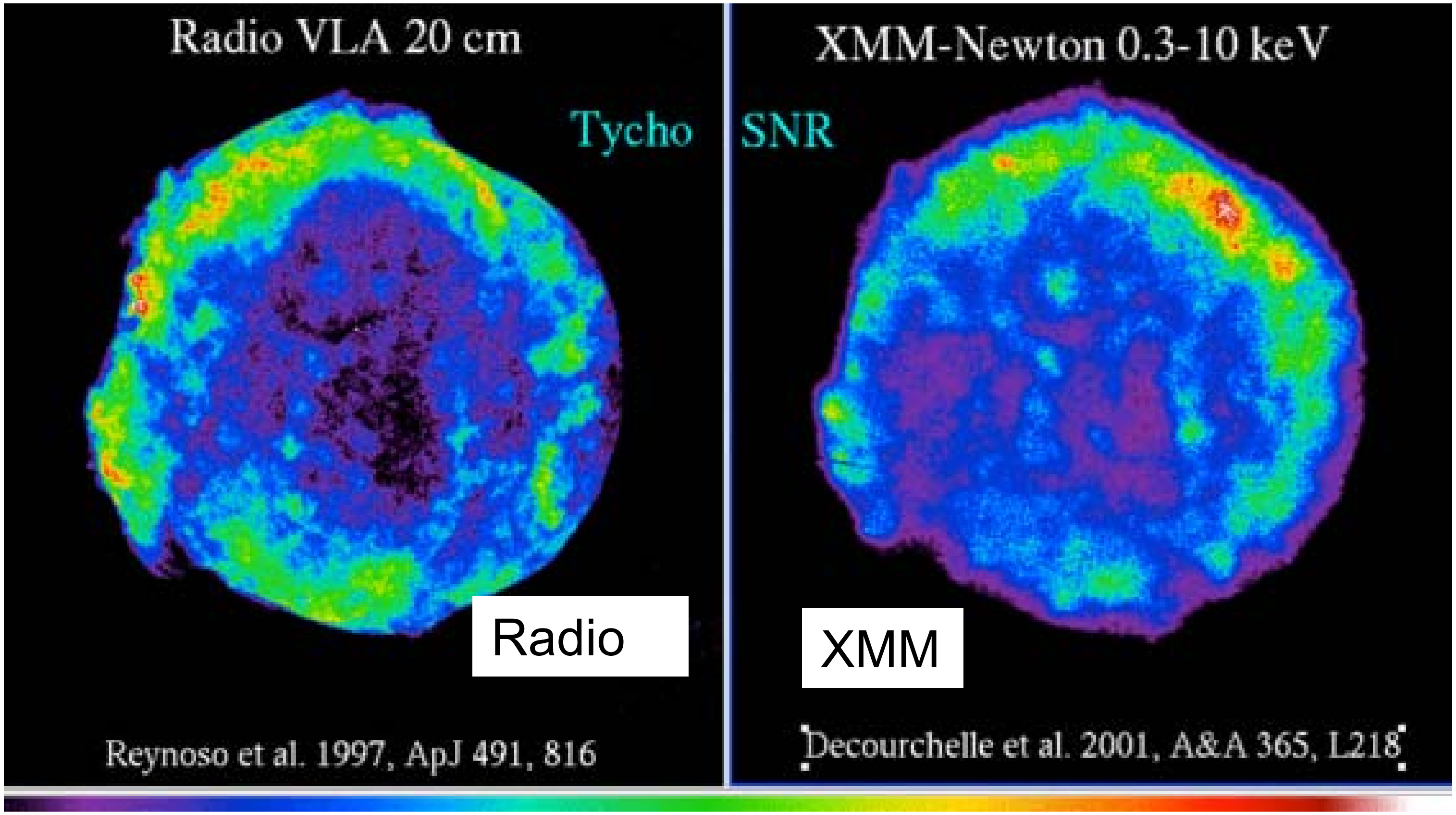
Cosmic Rays and Supernova Remnants

Don Ellison (North Carolina State Univ)

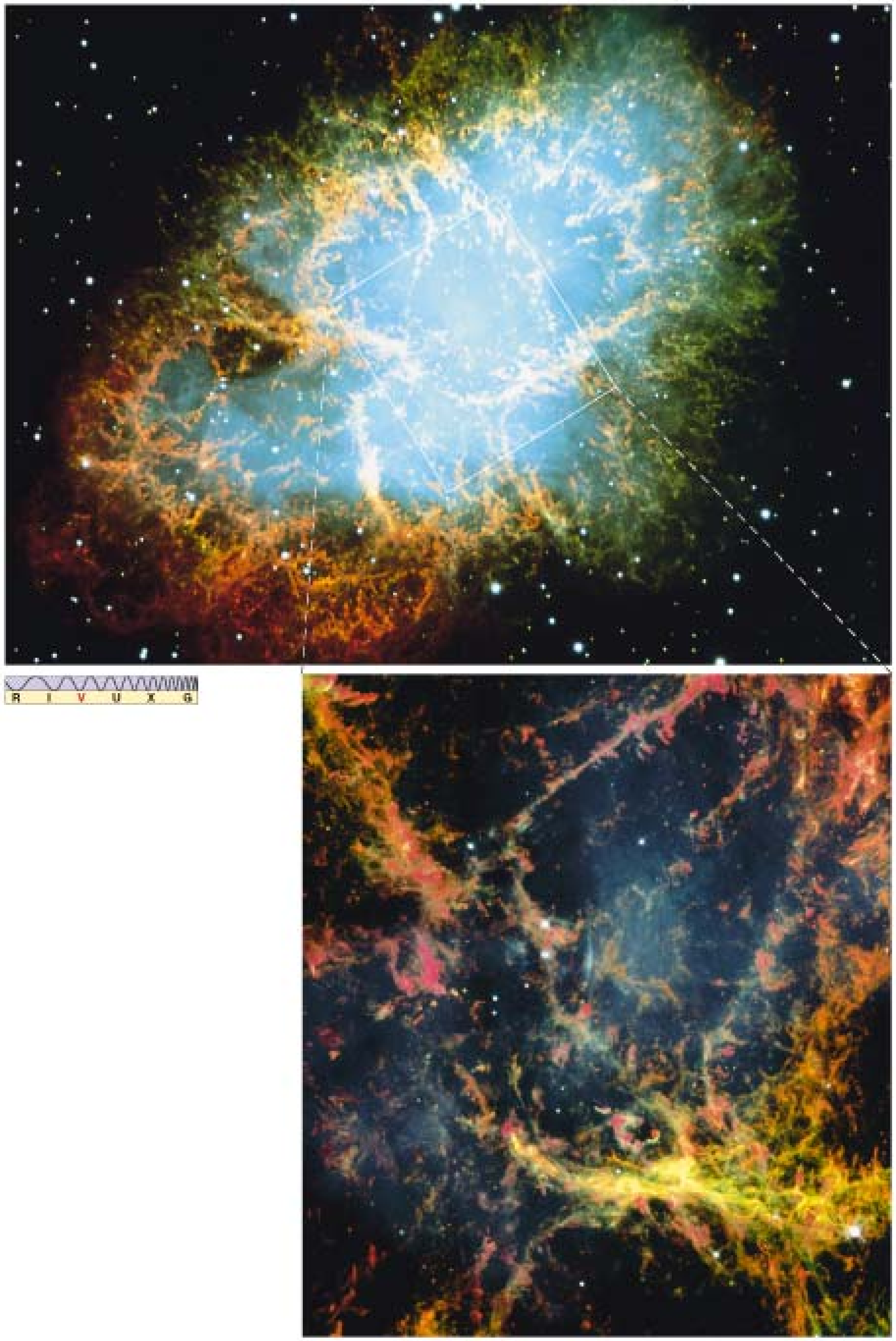
SNRs are believed to be the main source of CRs with energies ≤ 10^{15} eV

Tycho's SNR

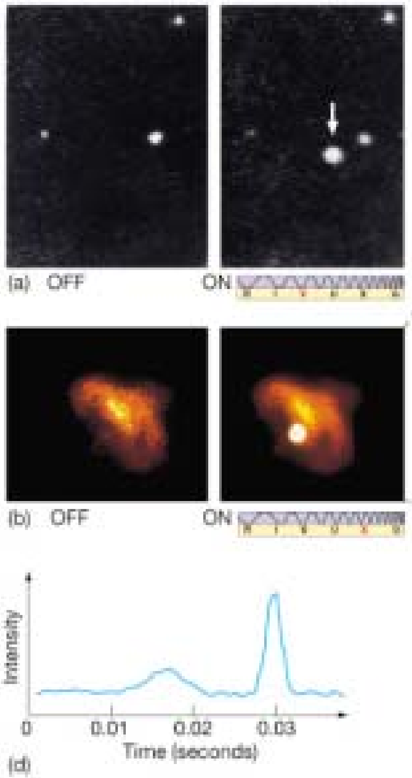


Supernova explosion observed by Tycho Brahe in 1572

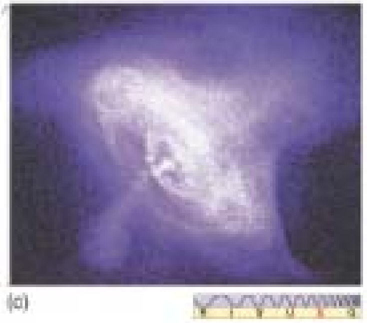
Crab supernova remnant
– observed by Chinese in
A.D. 1054



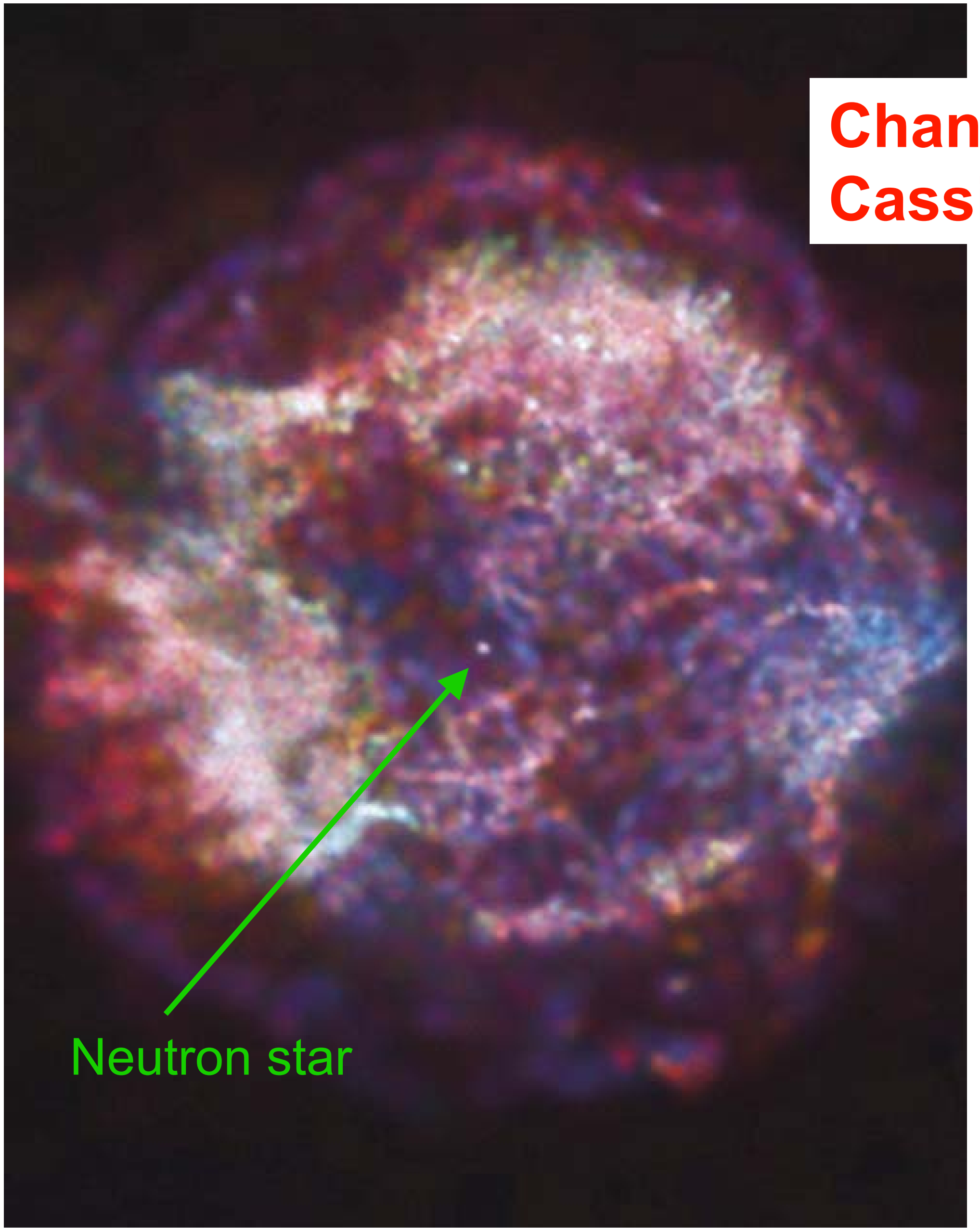
Pulsar (NS)



Disk and
jets (X-rays)



Chandra X-ray image of Cassiopeia A SNR

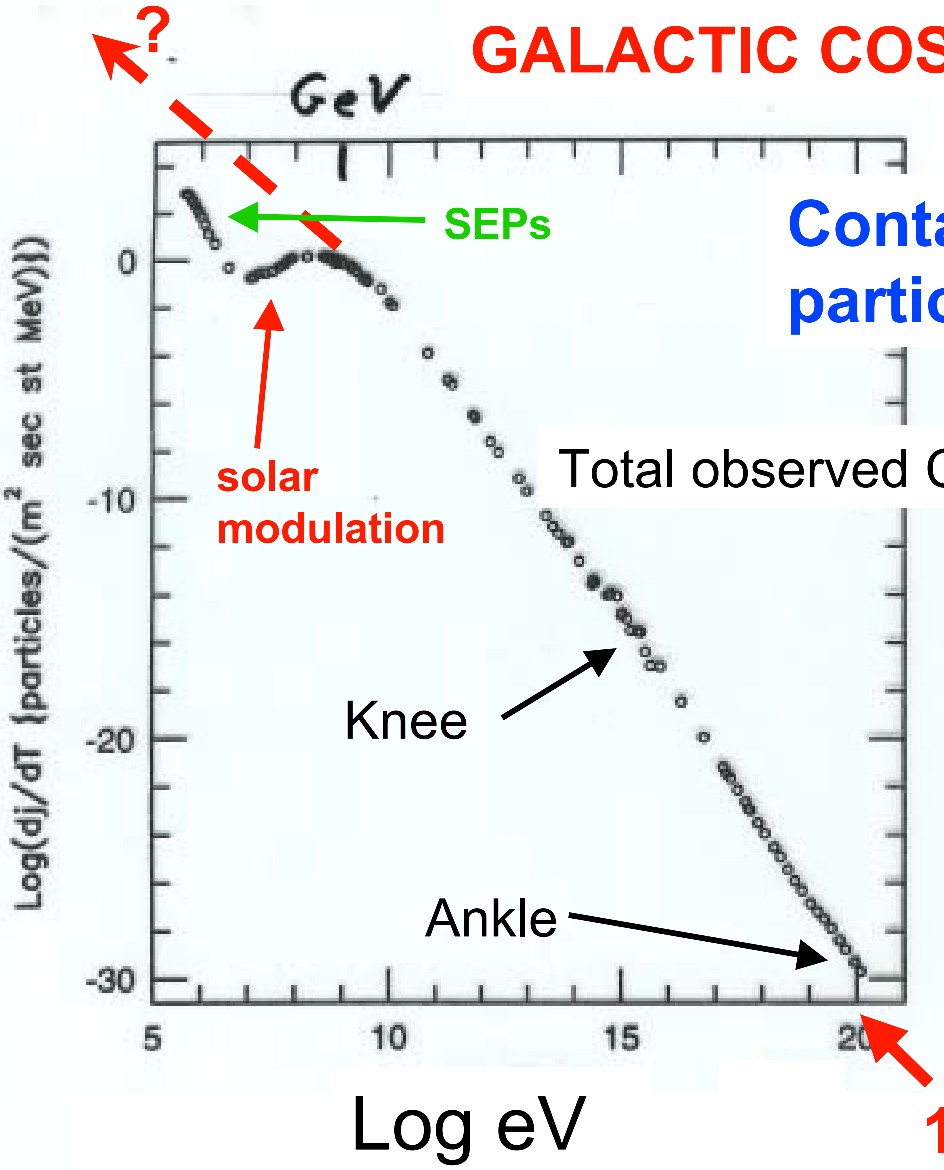


Different colors indicate different energy X-rays, cloud enriched in Si, S, and Fe

All elements heavier than Boron produced in stars and supernovae !

Hydrogen and helium produced in big bang, Li, Be, B produced by CRs

GALACTIC COSMIC RAYS



SEPs

solar modulation

Total observed CR nuclei

Knee

Ankle

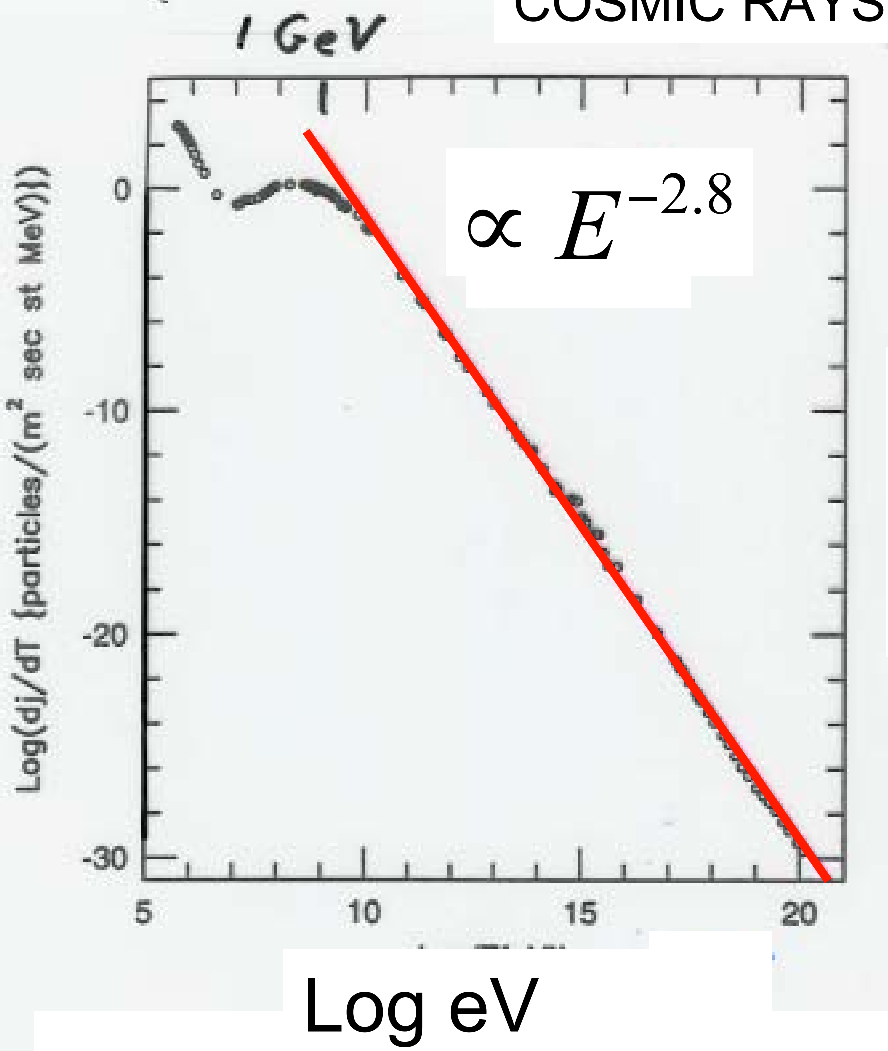
10^{20} eV

Contain highest energy particles ever observed !

Full spectrum may span 50 decades in flux !

From R. Jokipii EOS 95

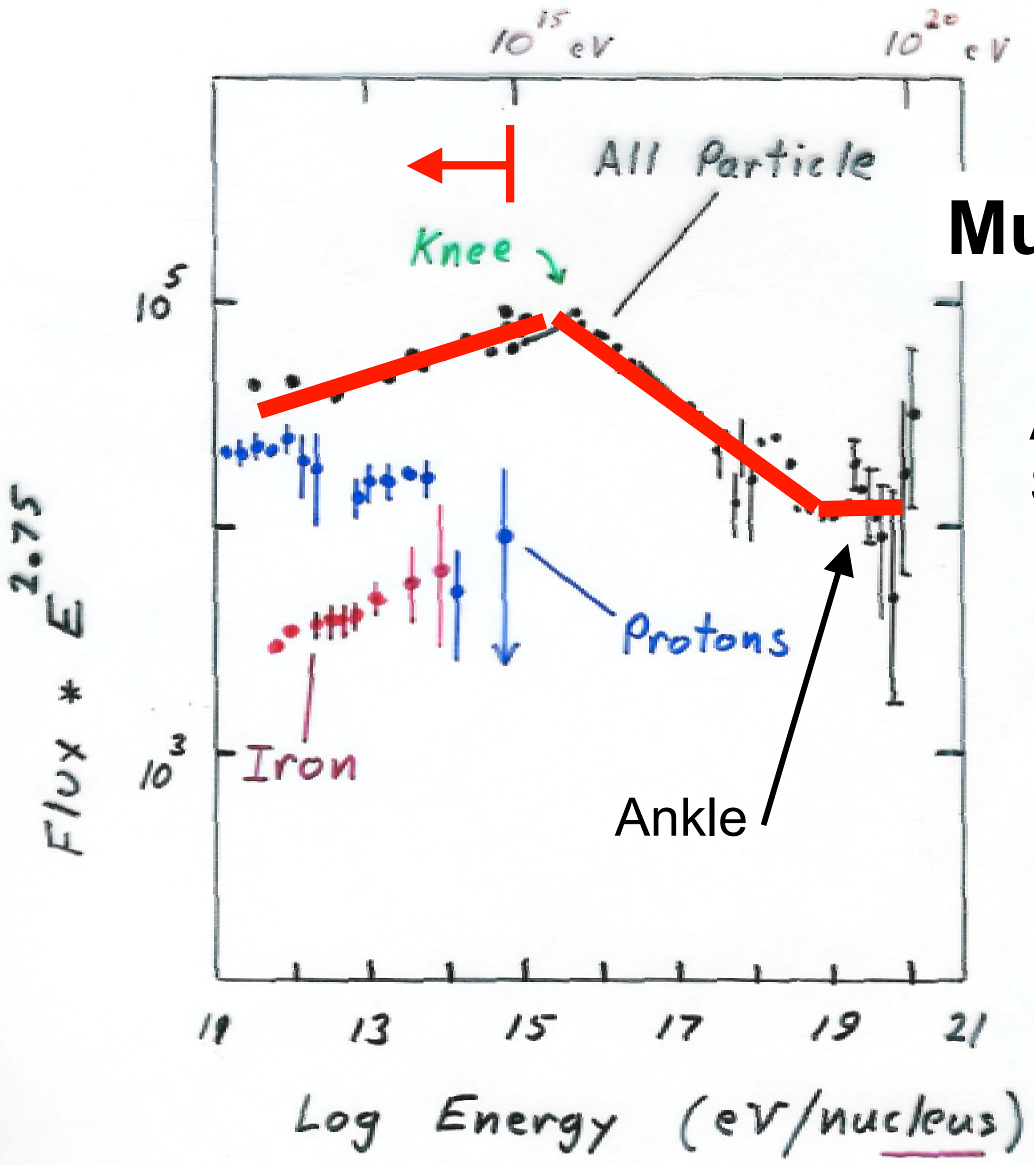
COSMIC RAYS



dJ/dE ~ $E^{-2.8}$ over ~ 10 decades

After propagation in galaxy,

expect CR Source spectrum dJ/dE ~ $E^{-2.2}$ at energies below ~ 10^{15} eV



Multiply by $E^{2.75}$

Above ~ 10^{15} eV,
Source of CRs unknown

Only concerned here with CRs of $E < 10^{15}$ eV where SNRs are almost certainly the source

Cosmic Ray Acceleration in Supernova Remnants

Don Ellison (North Carolina State Univ)

SNRs believed to be main source of CRs with energies ≤ 10^{15} eV because:

_ SNRs have enough total power

_ Strong shocks in SNRs provide ideal acceleration site _ First-order Fermi shock accel., Radio emission _ relativistic electrons

_ Composition of bulk of CRs **NOT exotic -- typical of mixed ISM** _ accel. of ISM GAS and DUST by SNR blast waves

_ Some young SNRs known to produce TeV electrons - if synch. interpretation of nonthermal X-ray observations correct

BUT . . . .

_ Unambiguous **evidence for Cosmic Ray ION production** in SNRs still **lacking _** Cannot do CR astronomy below $\leq 10^{19}$ eV because of galactic magnetic fields !

_ SNRs have trouble accelerating **particles above 10^{15} eV**

_ Energetic particle **spectra** from individual SNRs (assuming first-order Fermi) may be **too flat** – even with liberal interpretation of galactic propagation models _ complex models

ALSO, basic questions concerning Fermi acceleration:

_ Is Fermi acceleration efficient enough in SNRs for nonlinear effects to be important? – Still not clear how injection occurs, or how it varies with shock obliquity

_ Not known how shocks inject electrons relative to protons

Modeling of thermal X-ray and broad-band emission from young SNRs may help answer these questions

SNRs _ Nonthermal X-rays (not from compact object) - partial (and outdated) list

G156.2+5.7 (ASCA: Tomida etal 2000) - line & nonthermal features, spatially extended

G315.4-2.3 (ASCA: Tomida etal 2000) - line & nonthermal features, spatially extended

Kepler's SNR (ASCA & XTE: Decourchelle & Petre; Hwang etal; Kinugasa & Tsunemi) - lines & nonthermal tail

Tycho's SNR (The 1998) - shell emission – lines

SN1006 (ASCA: Ozaki & Koyama 1998) - shell-like emission in hard X-rays - TeV detection

Cas A (ASCA, XTE, BeppoSAX, OSSE, CAT, Whipple: many refs.) - hard tail extending to 100 keV, TeV upper limits

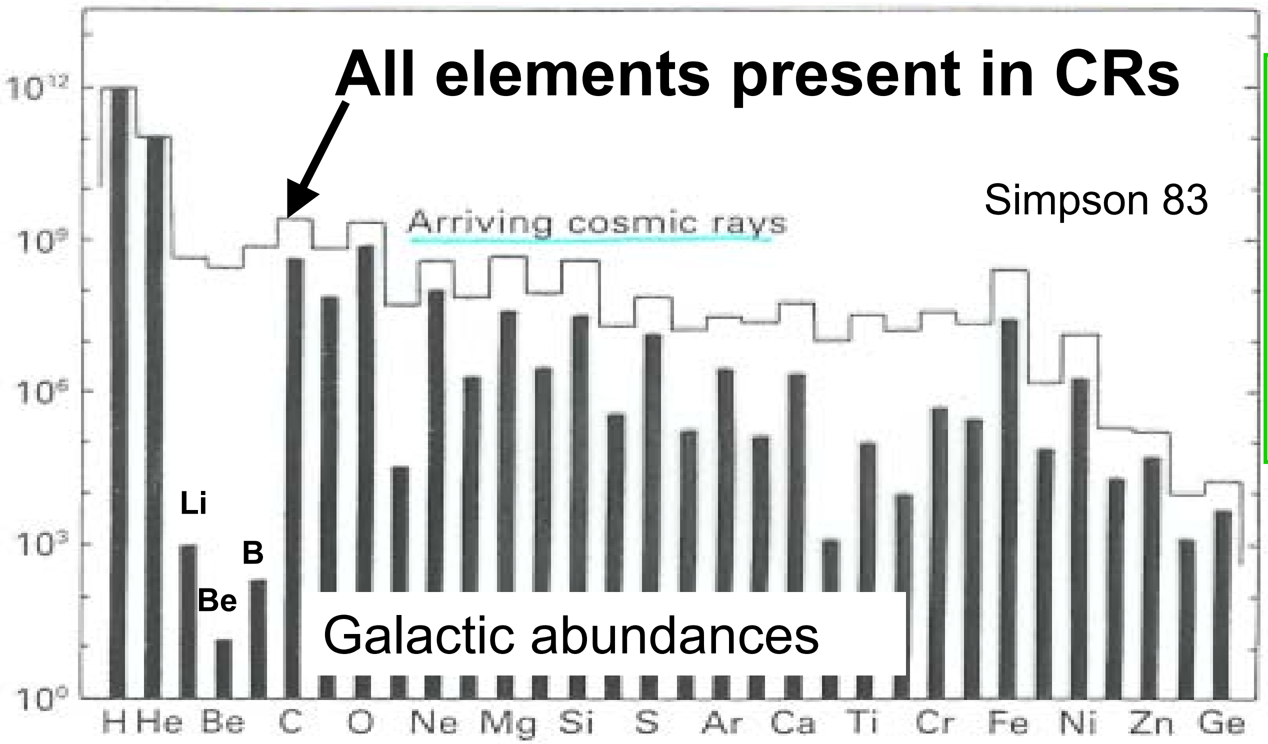
G266.2-1.2 (RXJ0852.0-0462) (ASCA: Slane etal 2000) - featureless, power law

RCW 86 (G315.4-2.3) (ASCA: Borkowski etal 2000; Bamba etal) - weak lines, strong nonthermal synch. component, shell-like SNR

G347.5-0.5 (RX J1713-3946): Radio - Ellison, Slane, & Gaensler etal 2001; X-rays - Slane etal 1999; GeV gamma-rays - Hartman etal 1999 (unidentified EGRET source); TeV gamma-rays - Muraishi etal 2000, Enomoto \etal\ 2002; Evidence for efficient accel. of ions

(a)

Galactic Cosmic Ray Composition


All elements present in CRs

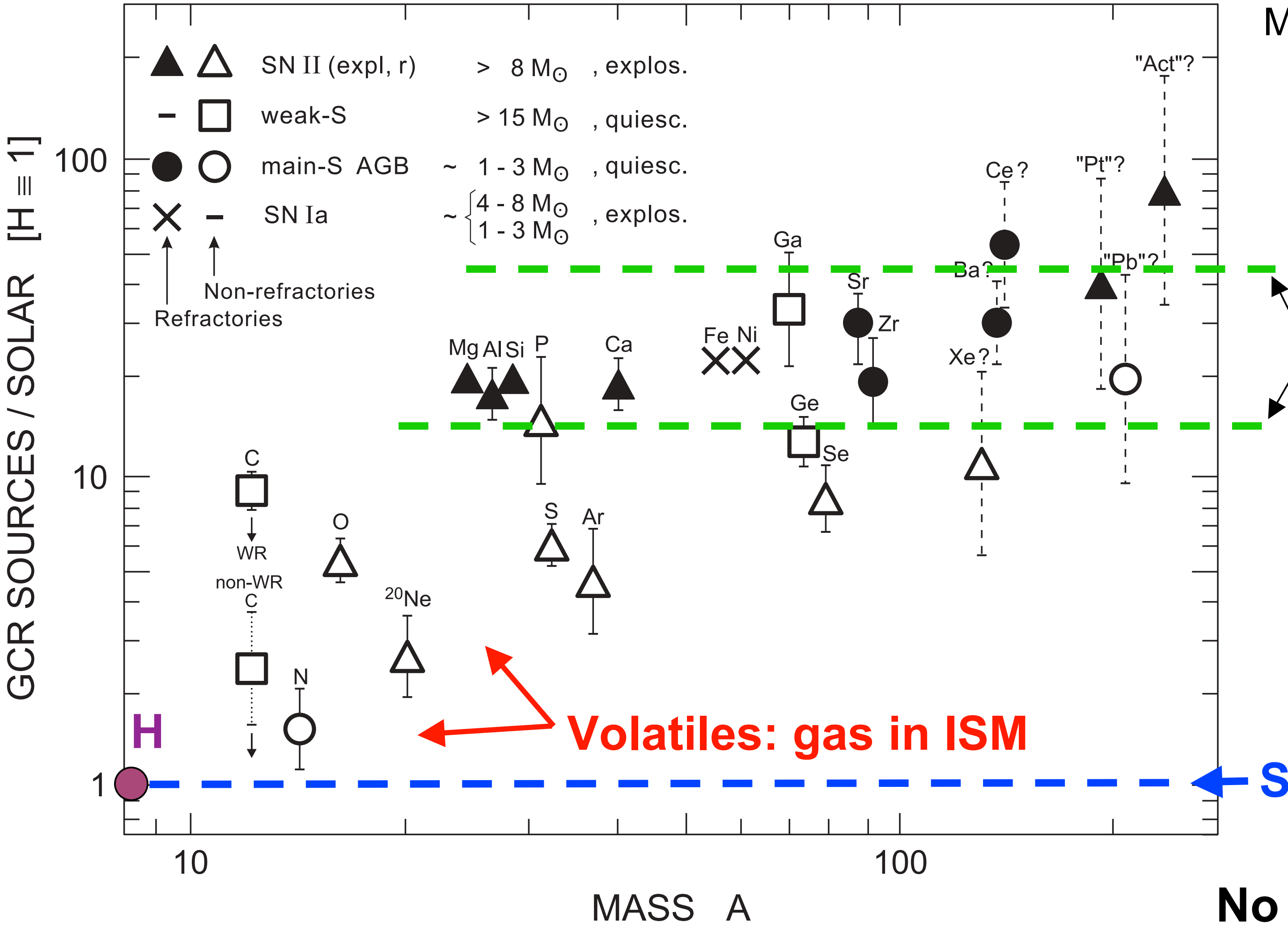
Simpson 83

Consistent explanation of CR source material: **SNRs accelerating mixed ISM gas and dust**

_ **Main effect is enhancement of heavy elements relative to Hydrogen & Helium,**

_ **Secondary effect is enhancement of refractory elements (Dust) relative to volatile ones (Gas)**

Meyer & Ellison 99



Volatiles: gas in ISM

Mainly refractory: locked in dust in ISM

Solar system

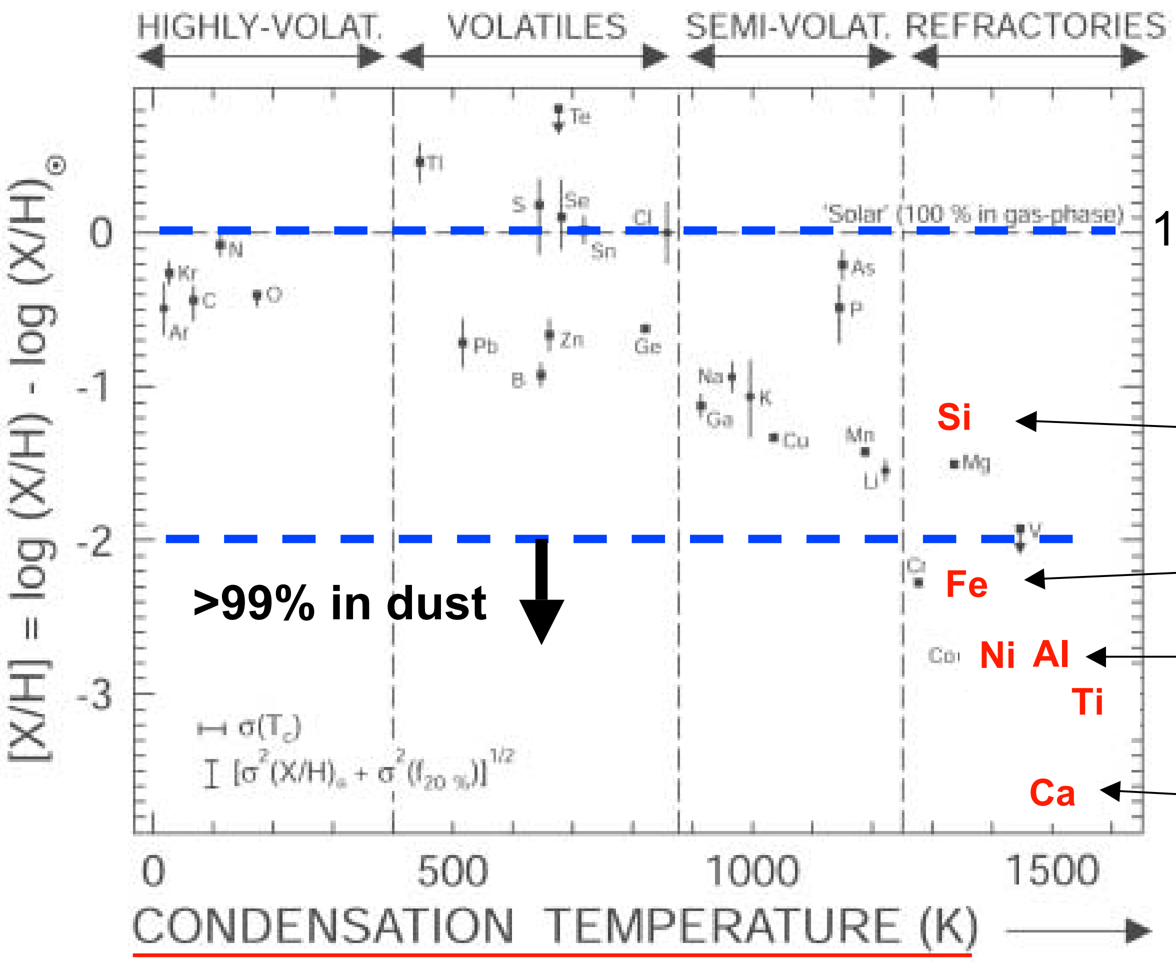
_ SN type II, r-proc.   _ main-S process

☐ weak–S process   X SN type Ia

No seperation by progenitor!

Mixed ISM with enhancement of refractories

ISM gas-phase abundances



100% in gas phase

>99% in dust

Si ← Silicon

Fe ← Iron

Ni **Al** ← Aluminum

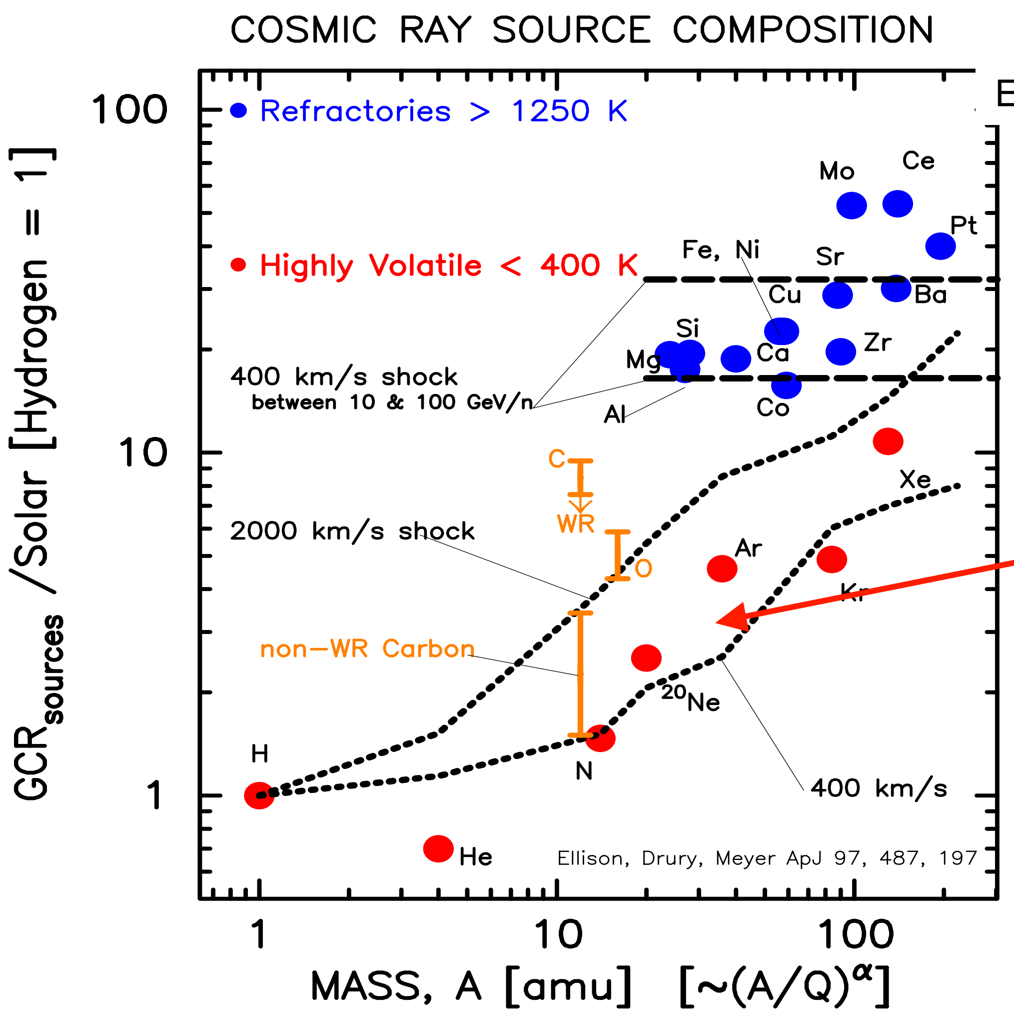
Ti

Ca ← Calcium

→ **Dust**

Meyer, Drury, & Ellison 97

Elements that are most abundant in CRs are locked in dust in ISM



Ellison, Drury, Meyer ApJ 97, V487, p182, p197

Elements locked in dust

Gaseous elements

High Oxygen from dust (15-20%)

High ^{22}Ne _ Wolf-Rayet contr._ high Carbon (carbon also in dust)

_Efficient Fermi accel. of ISM Gas and Dust by SNR shocks gives consistent explanation of CR elemental composition

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**

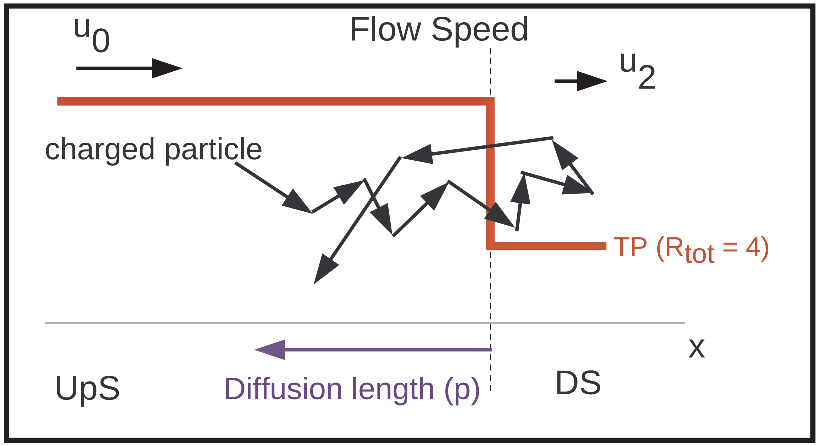
_ We know collisionless **shocks exist and accelerate particles efficiently !!** _ Direct observation of efficient shock acceleration in the Heliosphere

_ 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) the thermal properties of the shock heated, X-ray emitting gas, (2) the SNR evolution, and (3) broad-band emission

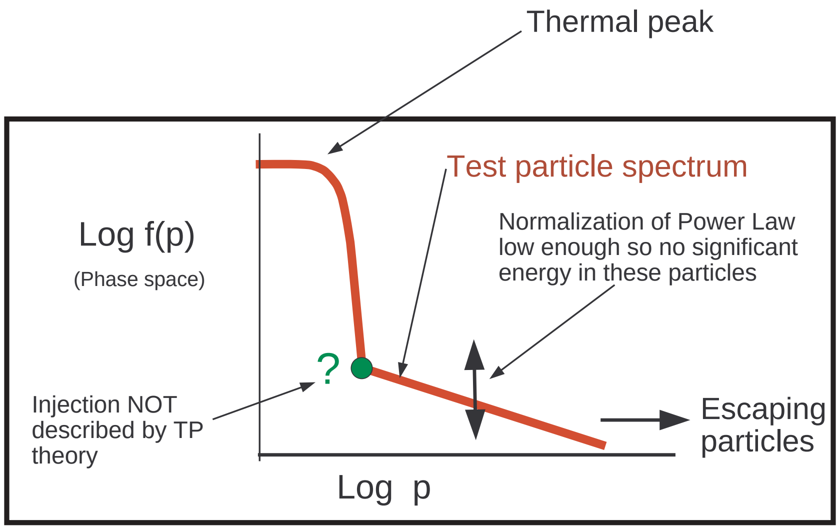
TEST PARTICLE ACCEL.

Test-Particle Shock Acceleration (1st-order Fermi)



Compression ratio, $R_{tot} = u_0/u_2$ ~ 4 for strong shock

Strong heating plus Power Law tail, $f(p) \sim p^{-4}$



$4\pi p^2 f(p)\,dp = (\#/cm^3)$ in dp

Test-particle
power law

$$\boxed{f(p) \propto p^{-3r/(r-1)}}$$

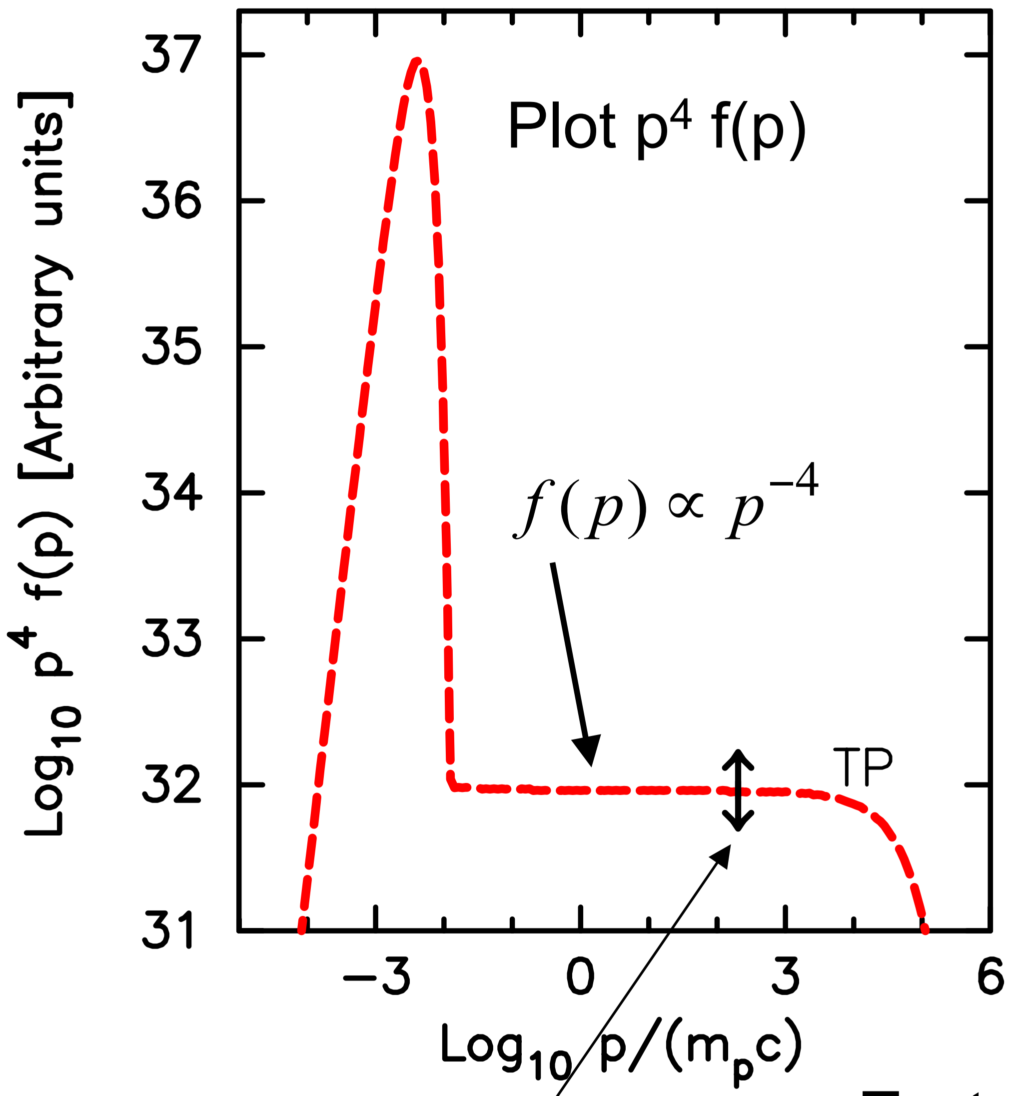
r is compression ratio, f(p) is phase space distr.

As long as shock can be treated as PLANE, all details of scattering drop out !

For strong shock, r ≈ 4 (if _ = 5/3) get $f(p) \sim p^{-4}$

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

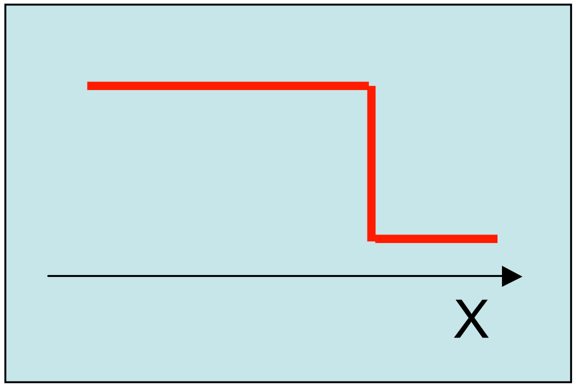
Test Particle Power Law



Normalization of power law not defined in TP acceleration

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

If r = 4, $f(p) \sim p^{-4}$



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

BUT Not so simple

Consider **energy in accelerated particles** assuming NO maximum momentun cutoff and **r ~ 4** (i.e., high Mach #, non-rel. shocks)

$$\int_{p_{inj}}^{\infty} E p^2 p^{-4} dp \propto \int_{p_{inj}}^{\infty} dp / p$$

$$N(p) \propto p^2 f(\vec{p})$$

$$= \ln p \,\Big|_{p_{inj}}^{\infty}$$

Diverges!

But $r \approx \dfrac{\gamma + 1}{\gamma - 1}$

Produce relativistic particles _ _ < 5/3 _ compression ratio increases (r _)

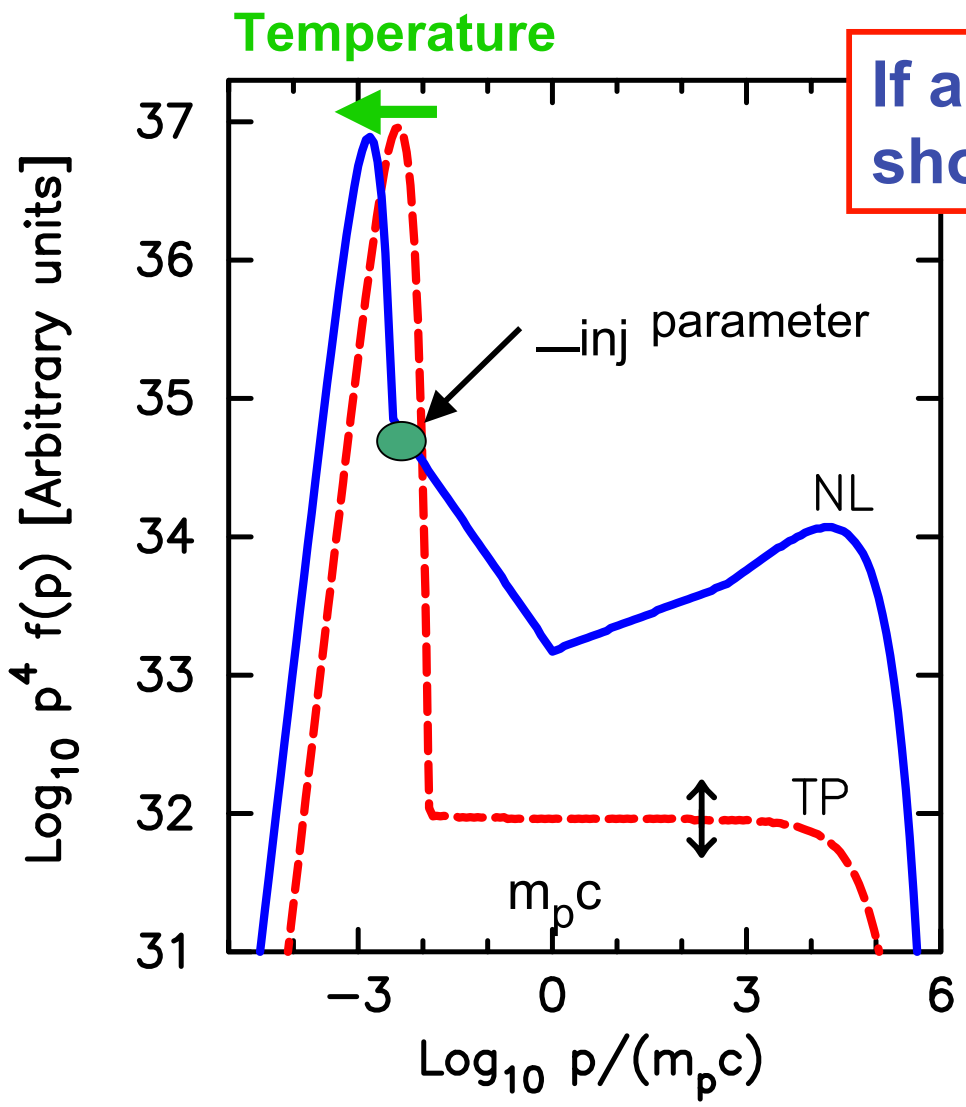
Spectrum flatter _ Worse energy divergence _ Must have high energy cutoff in spectrum to obtain steady-state _ particles escape

But, if particles escape, compression ratio increases even more **. . . .**

Acceleration becomes strongly nonlinear

_Strong shocks will be efficient accelerators even if injection occurs at modest levels (1 ion in 10^4)

If acceleration efficient, shock becomes smooth

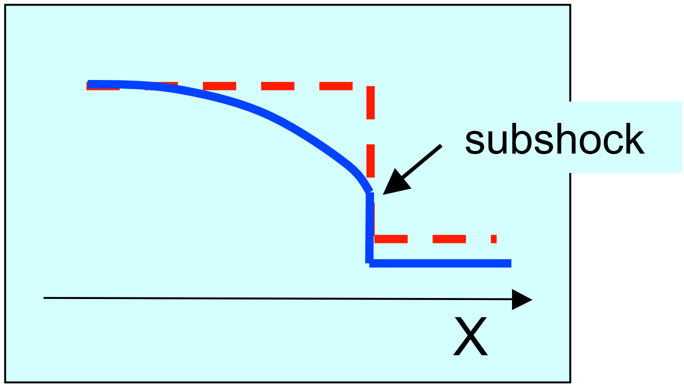


_ Concave spectrum

_ Compression ratio, $r_{tot} > 4$

_ Lower shocked temp.

_ Nonthermal tail on electron & ion distributions



In efficient accel., entire spectrum must be described consistently

Here show `Simple' model of Berezhko & Ellison 99

Simple Model for NL Shock Acceleration

Berezhko & Ellison 99; Ellison, Berezhko, Baring 2000

Approximate concave momentum spectrum with broken power law plus thermal peak – Alfven wave heating is included

After input (shock speed, Mach numbers, etc) only 3 parameters for PROTON spectrum. (NOTE: more complete models have many parameters as well)

Injection rate, _$_{inj}$, i.e., fraction of thermal protons accelerated

Maximum momentum, p_{max}

Shape of cutoff at p_{max}

Add Electron spectrum with 2 additional parameters:

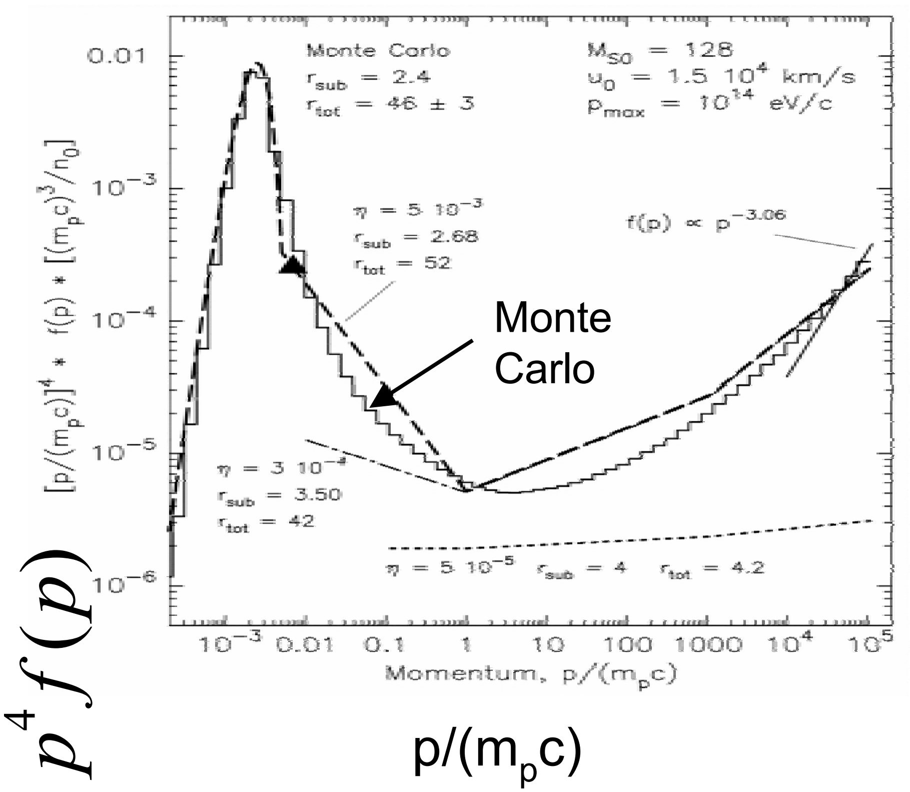
T_e/T_p Shocked elec. Temperature (e's are test-particles)

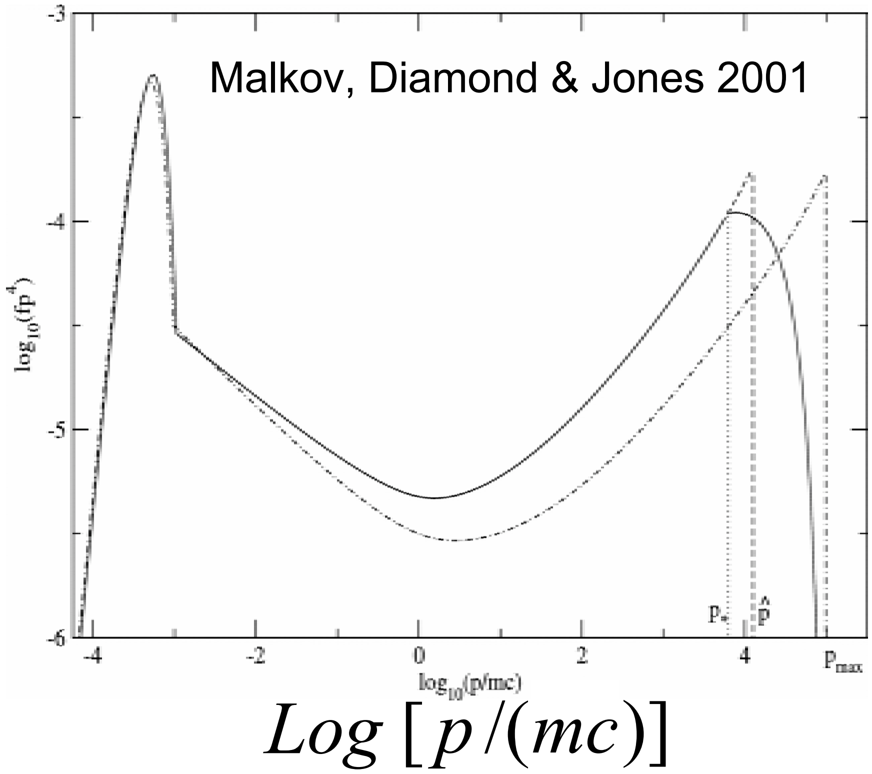
$(e/p)_{rel}$ electron to proton ratio at rel. energies

Advantage: Allows rapid calculation _ incorporate in Hydro simulation _ make parameter searches possible

Concave spectra, High compression ratios

Berezhko & Ellison 99

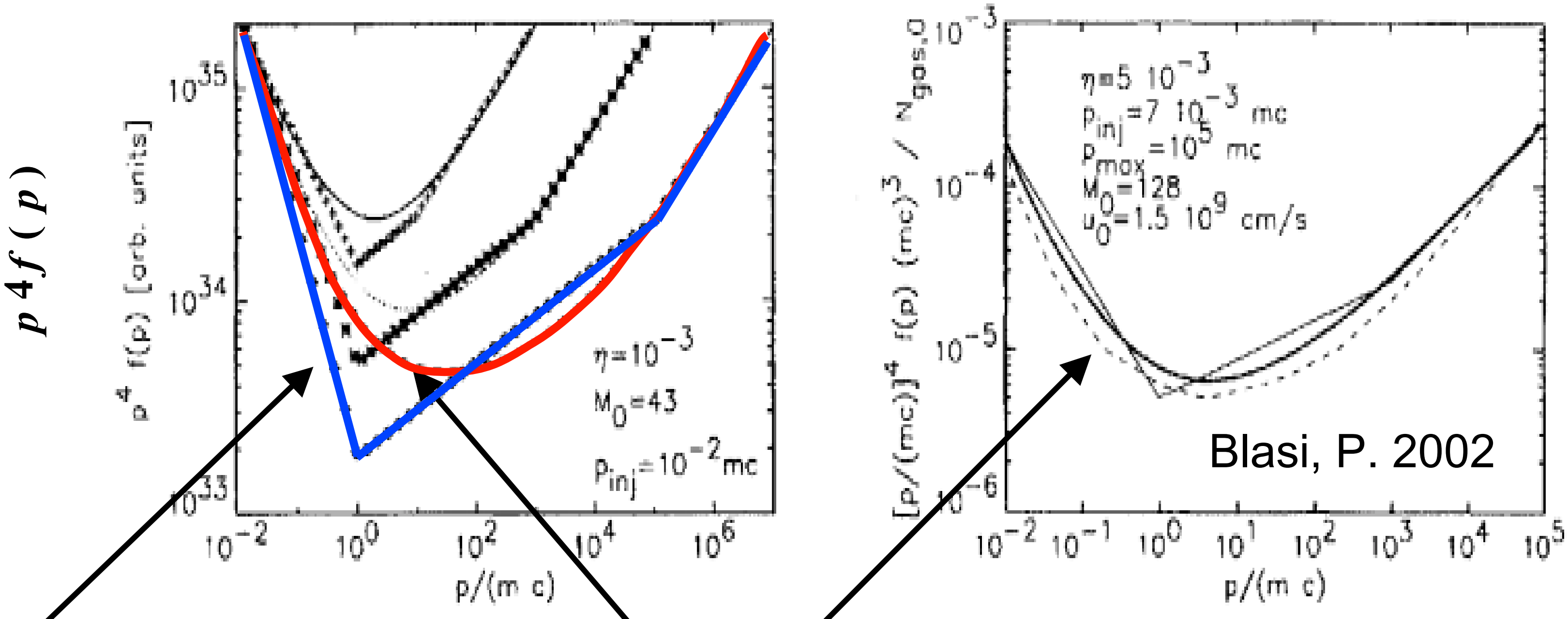




Malkov, Diamond & Jones 2001

Concave spectra and compression ratios greater than 4 predicted by SEVERAL independent derivations of NL Fermi accel.: e.g., Eichler 84; Ellison & Jones 81-91; Berezhko etal 96; Malkov 96-01; Blasi 2002

P. Blasi/Nuclear Physics B (Proc. Suppl.) 110 (2002) 475–477 477



Blasi, P. 2002

Berezhko & Ellison ApJ 99

Blasi

Concave spectra and compression ratios greater than 4 predicted by SEVERAL independent theories – effect softened by B-field effects

Eichler 84; Ellison & Eichler 84

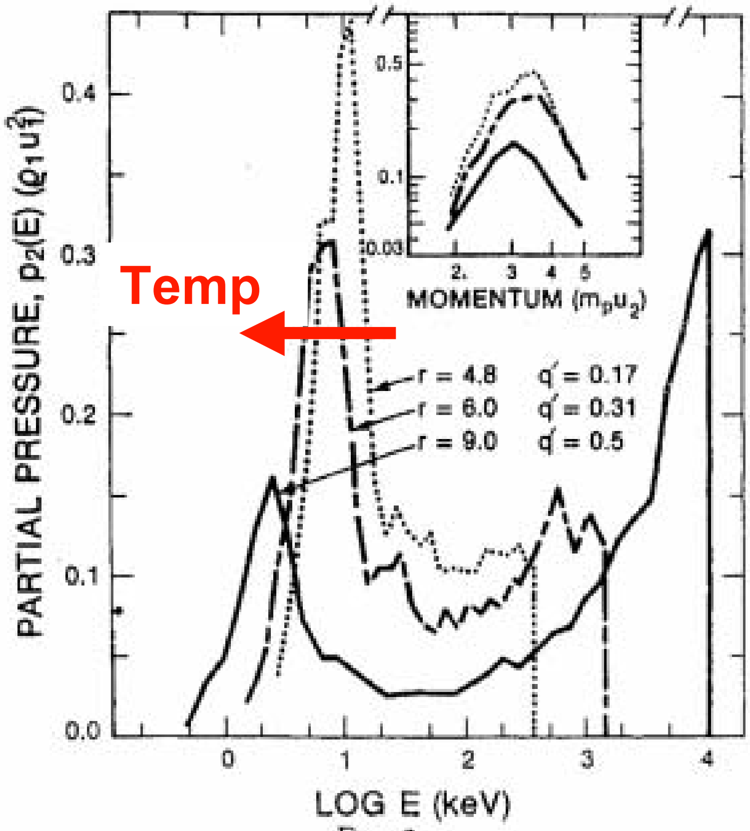


FIG. 3

Temp

As acceleration eff. increases, temperature of shocked gas drops

Concave spectra and compression ratios greater than 4 predicted by SEVERAL independent theories.

Only requires D(p) increasing function of p

EFFICIENT VS. TEST-PARTICLE ACCEL.

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

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

Shocked Temperature (for high Mach #s) extremely high !!

e.g., V_{sk} = 2000 km/s _ $T_p \approx 10^8$ K _ Must assume $T_e << T_p$ to explain X-ray lines in 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 Te << Tp

Supernova remnant evolution with efficient particle acceleration

with Anne Decourchelle and Jean Ballet, CEA-Saclay

A realistic SNR model requires four basic features:

with Anne Decourchelle and Jean Ballet, CEA-Saclay

1) The **SNR evolution**, including the forward and reverse shocks and the temperature and density structure in the interaction region between these shocks, must be **calculated self-consistently with particle acceleration**;

2) Nonlinear particle acceleration must produce **realistic electron and ion distribution functions** at these shocks;

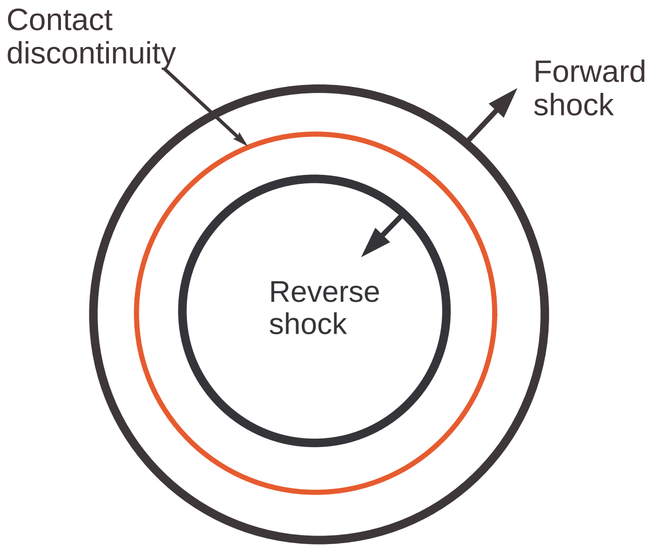
3) A non-equilibrium ionization calculation of **X-ray emission lines** must be done in the **interaction region modified by particle accel.** (e.g. Decourchelle et al. 2000) (thermal X-ray emission); and

4) Some way to deal with **complex morphology**

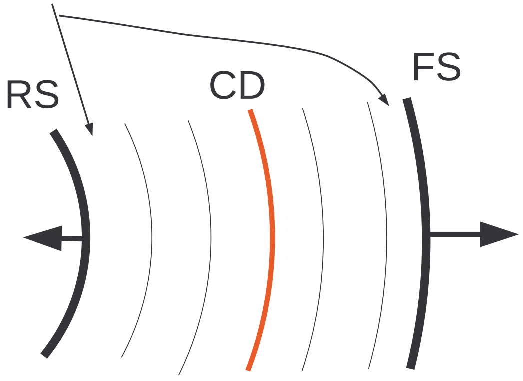
We are developing a CR-Hydro-X-ray model that incorporates NL shock acceleration (i.e., first-order Fermi) into a hydrodynamic simulation of SNR evolution. Here only CR-Hydro connection

1-D HYDRO

(J. Blondin)

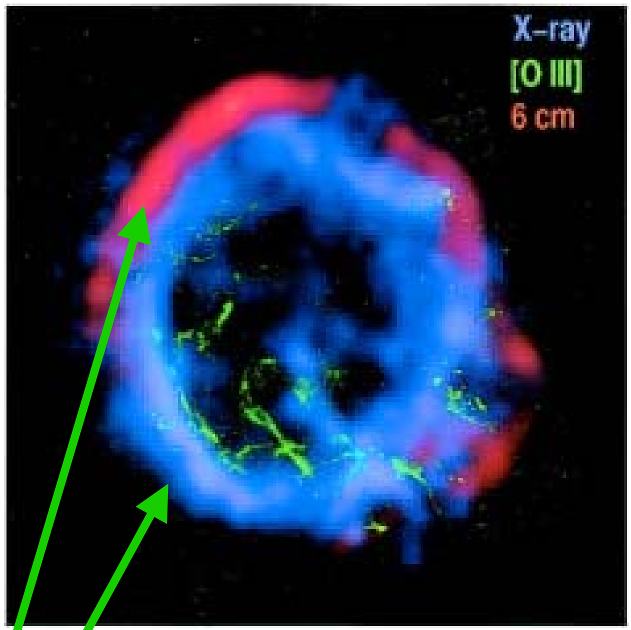


$\square_{eff}$ from accel. calculation used in hydro equations behind shocks



Lagrangian mode - grid stays with mass

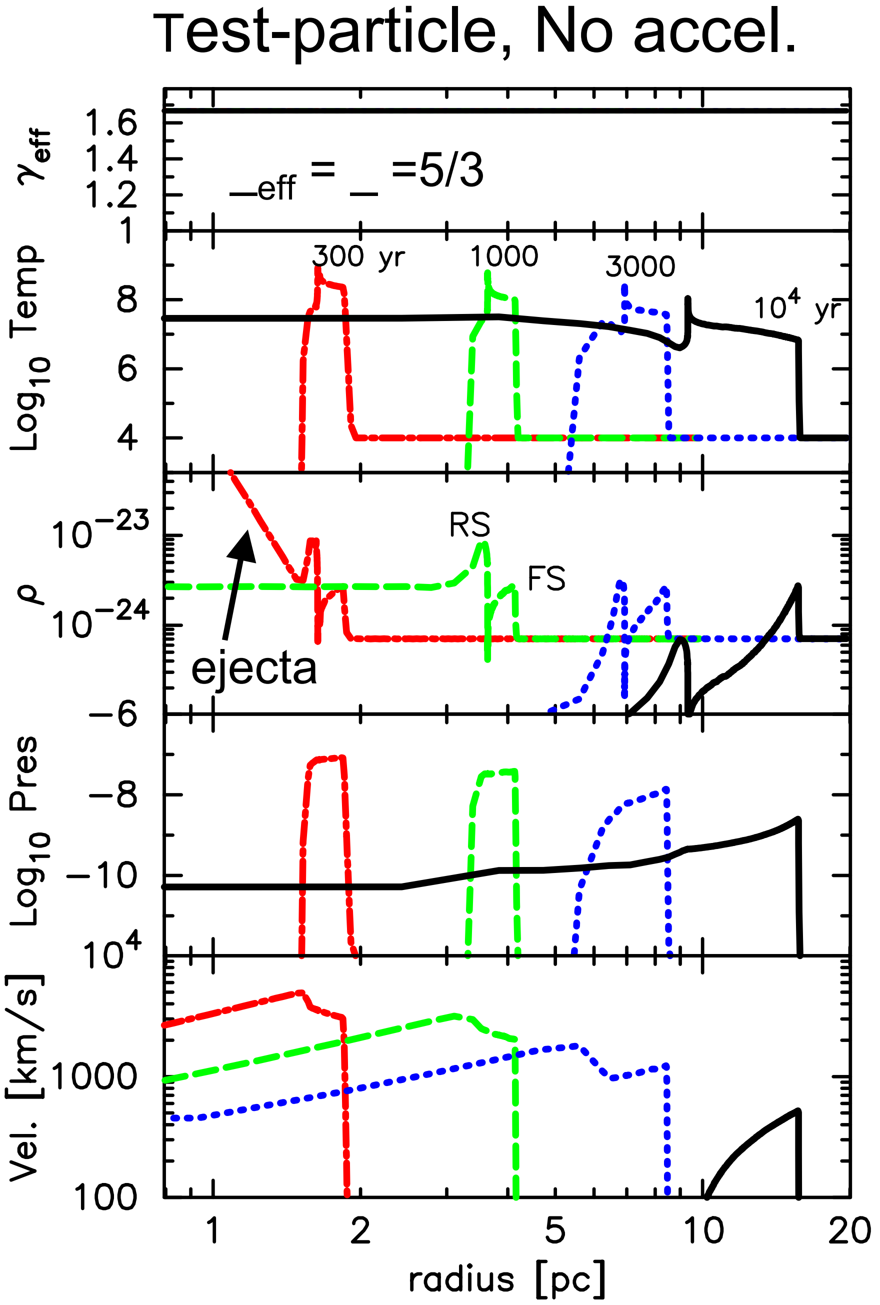
SNR E0102 SMC



Geatz etal 2000

Spherically symmetric model not so bad for general characteristics

Can adjust injection rate to mimic different accel. efficiencies at parallel or perp. regions of shock (e.g. Berezhko etal 2002)



1-D Hydro simulation e.g., Blondin et al.

Obtain standard results with no acceleration

When acceleration occurs, get less pressure for same amount of supernova explosion energy _ SNR evolution is modified

CR-Hydro Coupling (with A. Decourchelle and J. Ballet)

_ **Set up hydro** with exponential or power-law ejecta distribution, constant density ISM, pre-existing wind etc.

_ At each time step, **evolve hydro** and **find Forward Shock (FS) and Reverse Shock** (RS) positions and Mach numbers

_ After each time step, **calculate CR acceleration** in shell behind FS and RS using Berezhko & Ellison (1999) model with parameterized Injection efficiency, _$_{\mathrm{inj}}$ = fraction of thermal ions accelerated

_ Use t_{SNR} and R_{sk} to **set Maximum CR energy, E_{max}** and obtain overall shock compression ratio, **$R_{\mathrm{tot}} > 4$**, from NL accel. calculation

_ **Calculate Effective Gamma**, _$_{\mathrm{eff}}$, using: $\gamma_{\mathrm{eff}} \approx (r_{\mathrm{tot}} + 1)/(r_{\mathrm{tot}} - 1)$

_$_{\mathrm{eff}}$ includes effect of `escaping' particles. Note: _$_{\mathrm{eff}}$ < (Pres/EnDensity) + 1, i.e., can be less than 4/3

_ **_eff** used in equation of state for shocked material near forward and reverse shocks _ **couples hydro to acceleration** _ **modifies evolution of SNR**

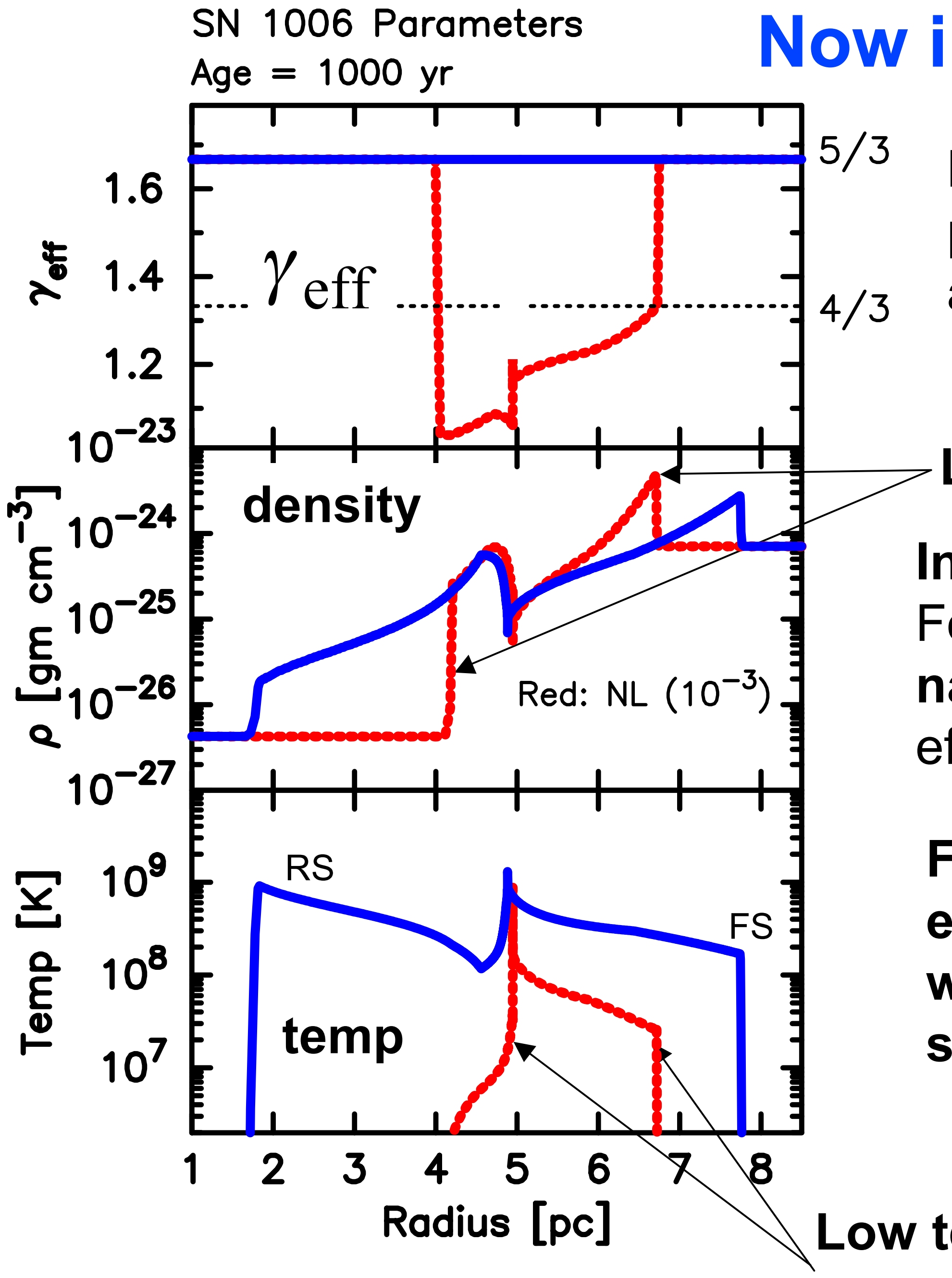
_ Obtain full **electron and proton distribution functions**, f(p), for shell behind shock _ **Broad-band photon emission**: Brems, Synch, IC, pion-decay

_ As SNR evolves, f(p) undergoes **adiabatic losses** in each shell

_ At end of simulation, sum particle spectra from all shells in SNR _ **contribution to Galactic cosmic-ray flux**.

_ Use density and temperature structure between FS and RS to **calculate X-ray emission** with **non-equilibrium ionization** calculation (as done in Decourchelle etal 2000)

Now include efficient accel.



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

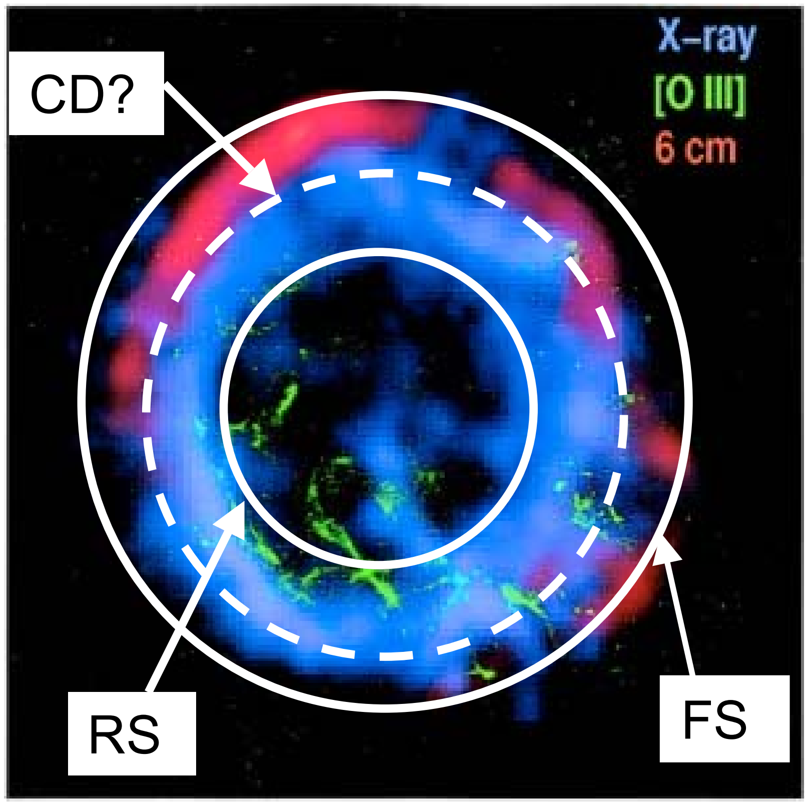
Large compression

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

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

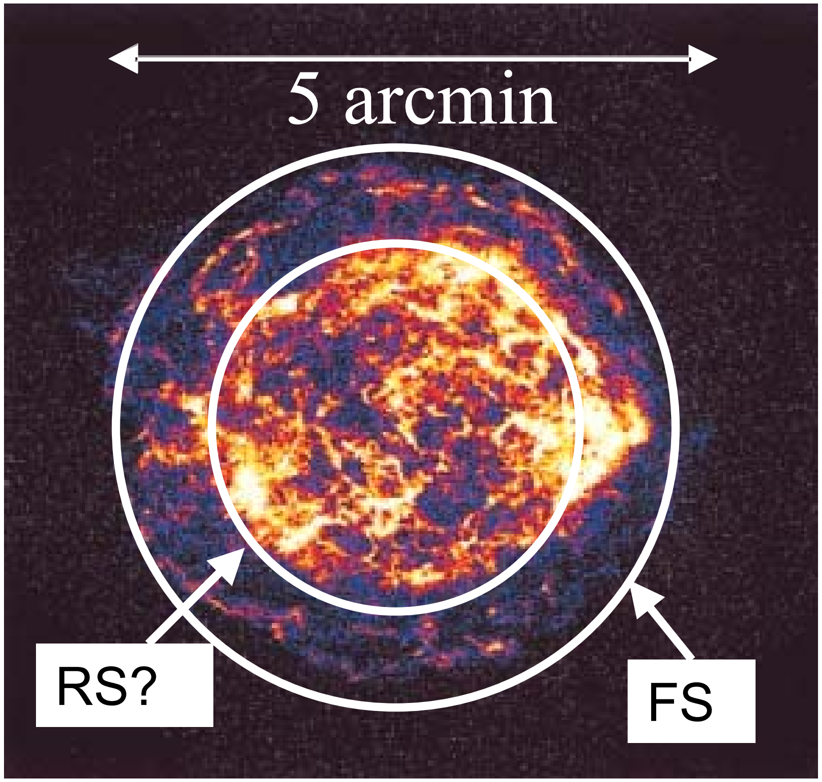
Low temperature

SNR E0102 SMC



X-ray and radio (Geatz etal 2000)

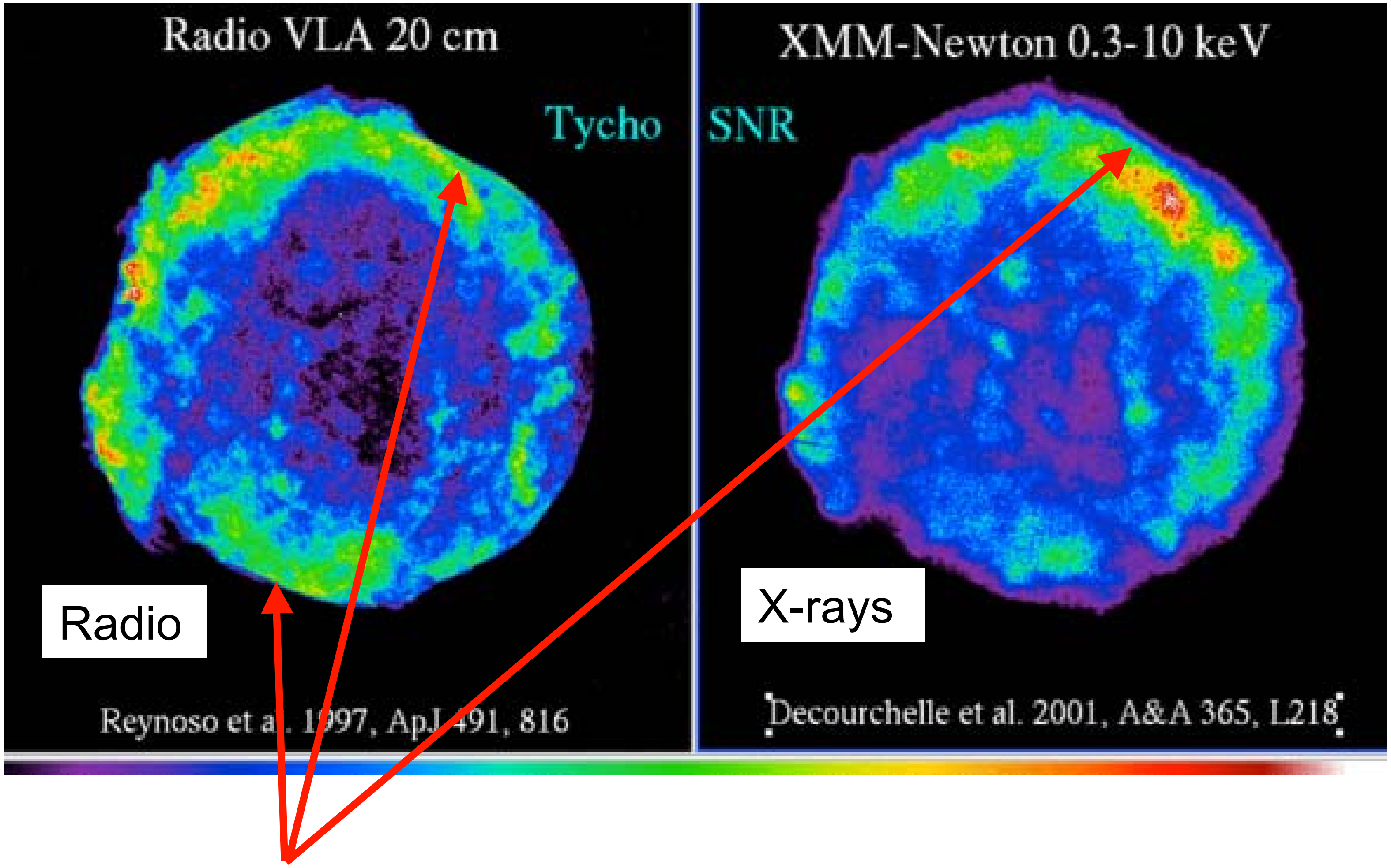
Cassiopeia A



4-6 keV continuum (Gotthelf etal 2001)

Is morphology of SNRs consistent with efficient shock acceleration?

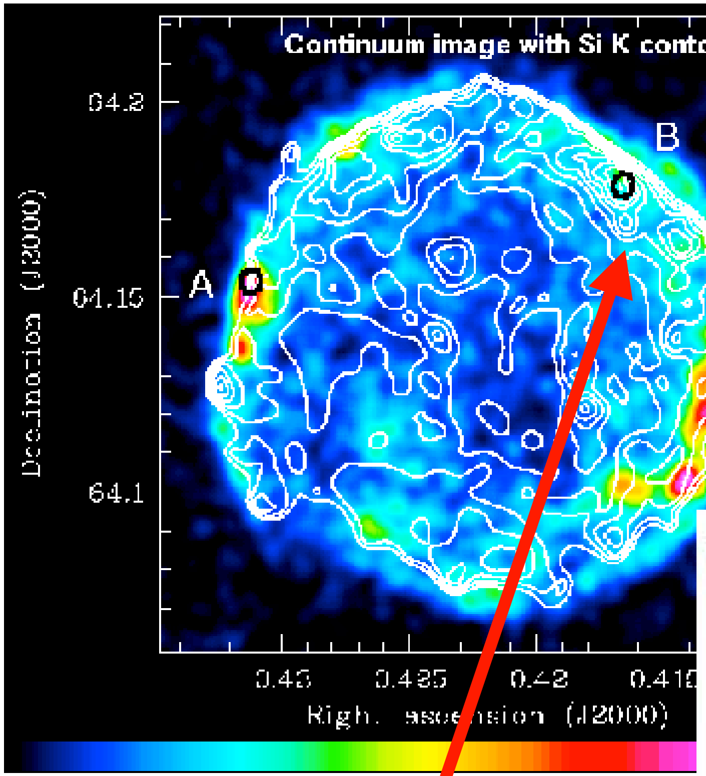
Tycho's SNR



Radial distance between outer shock and contact discontiunity seems extremely small in some cases

Tycho's SNR, XMM-Newton

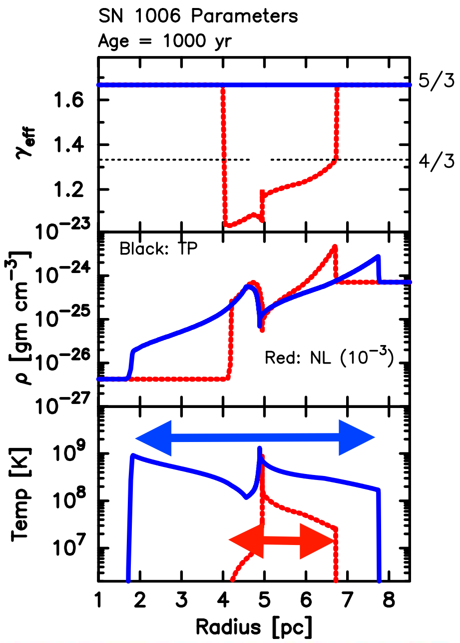
(Decourchelle etal 2001)



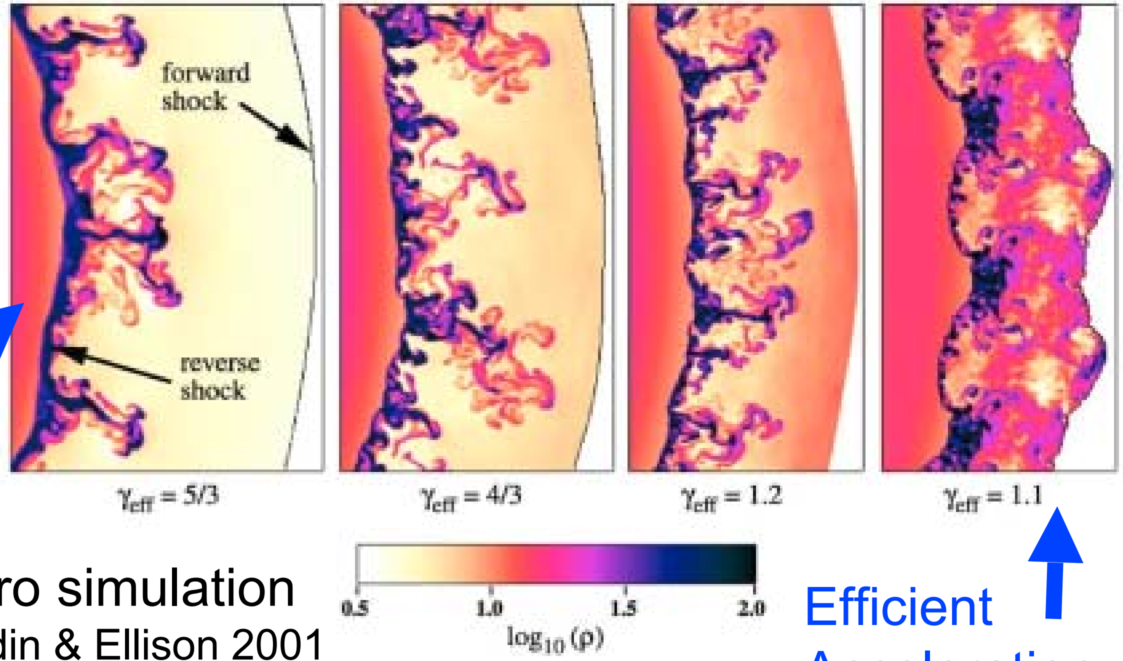
4.5-5.8 keV X-ray continuum: FS??

Si XIII contours: CD?

Reverse shock ??



vary gamma effective



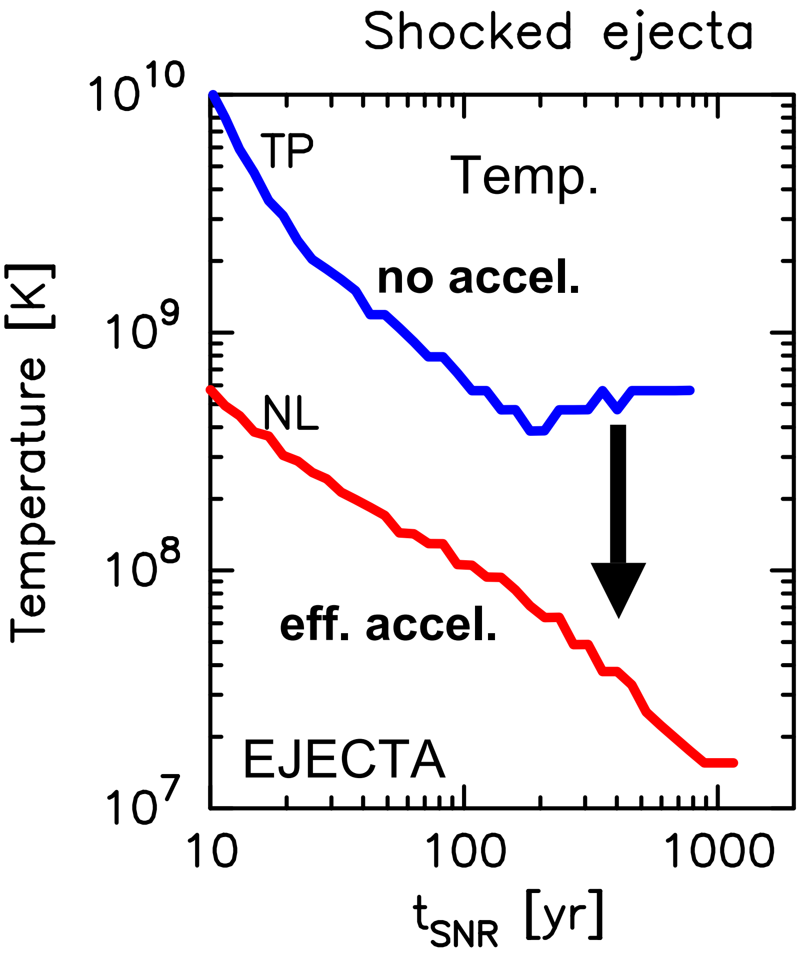
No acceleration

Hydro simulation

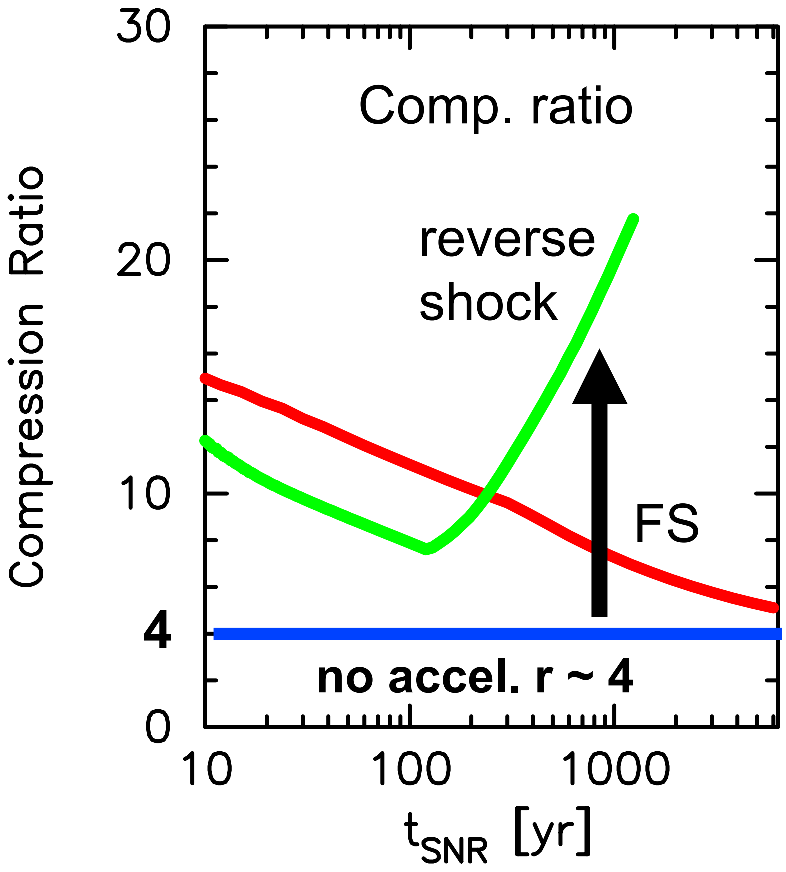
Blondin & Ellison 2001

Efficient Acceleration

Temperature & compression ratio time history



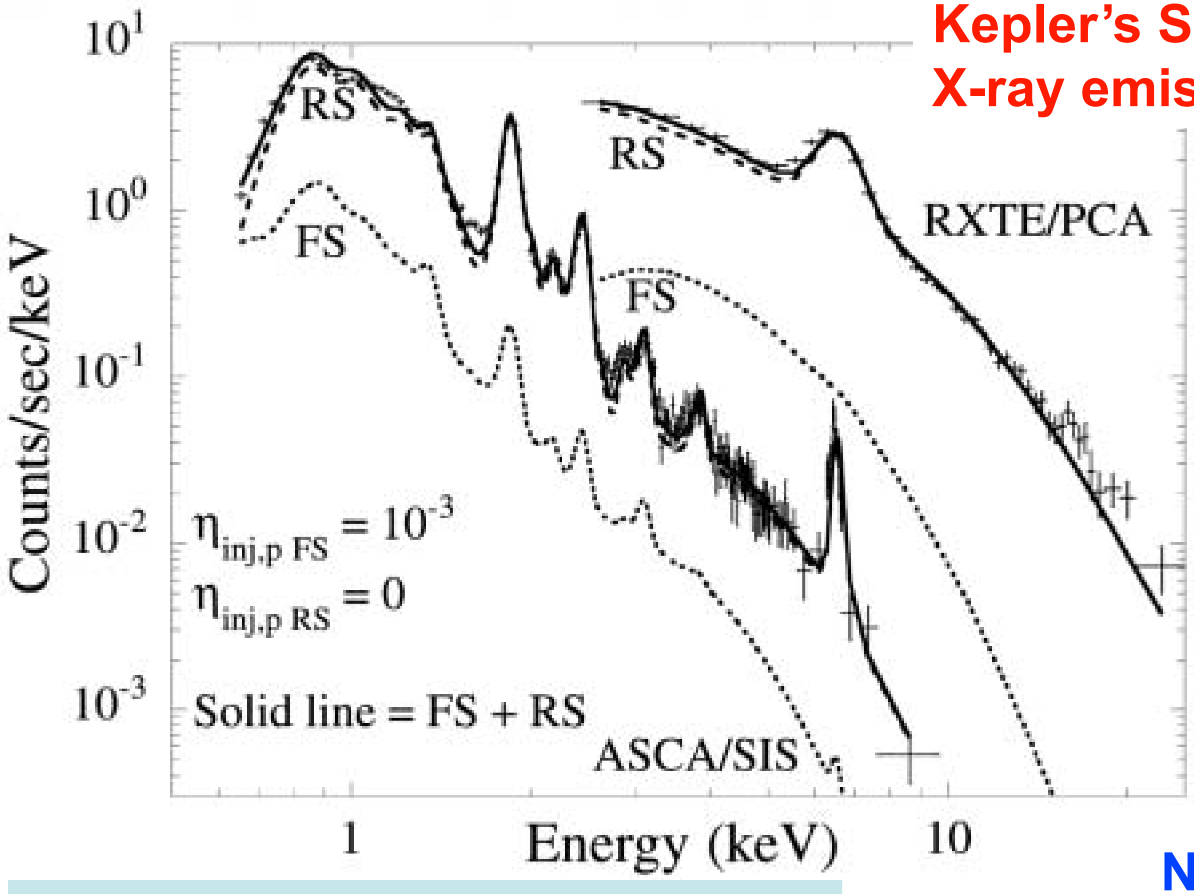
More than a factor of 10 reduction in proton temperature when CRs are produced

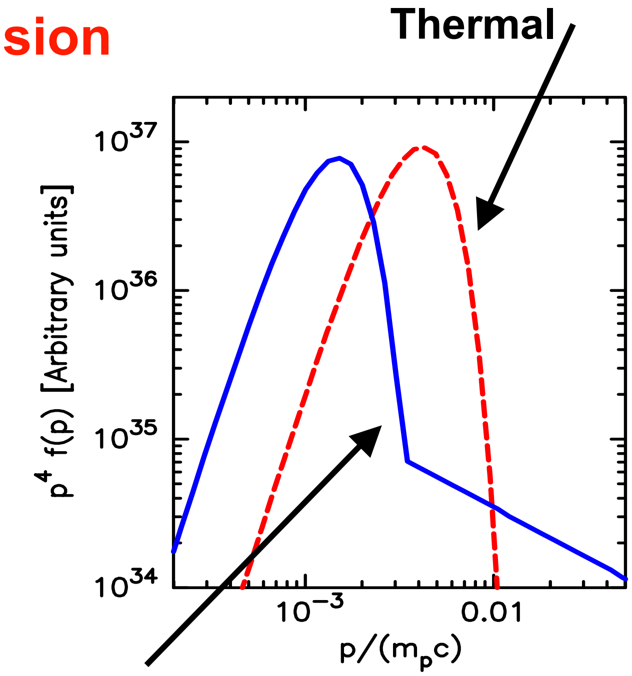


Comp. ratio at RS increases as ejecta B-field drops

Analytic model coupling NL acceleration with self-similar hydro – Two-fluid approximation (Decourchelle etal 2000)

Kepler's SNR THERMAL X-ray emission





Thermal

Nonlinear accel.

ASCA & XTE observations – non-equilibrium, ionization X-ray calculation

Nonthermal electron spectra may substantially change X-ray line calculations

Impact of shock acceleration of cosmic rays on interpretation of X-ray observations of young SNRs:

For inferred electron temperature and density from X-ray obs:

_ Proton temp. may be smaller _ shocked gas closer to equilibrium

_ Inferred shock speed LOWER, less pressure for given energy density

_ Need GREATER supernova explosion energy to produce same X-ray temp.

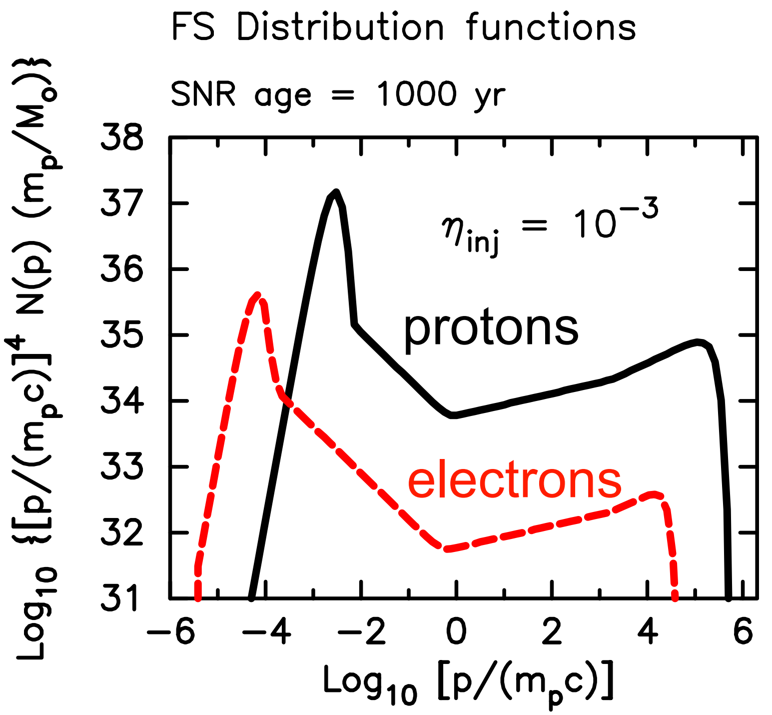
_ SNR evolution modified with different density & temperature structure in interaction region between forward and reverse shocks _ may change inferred density and abundances of ISM and ejecta material

_ ``Thermal'' spectra may not be good approx. for X-ray calculations

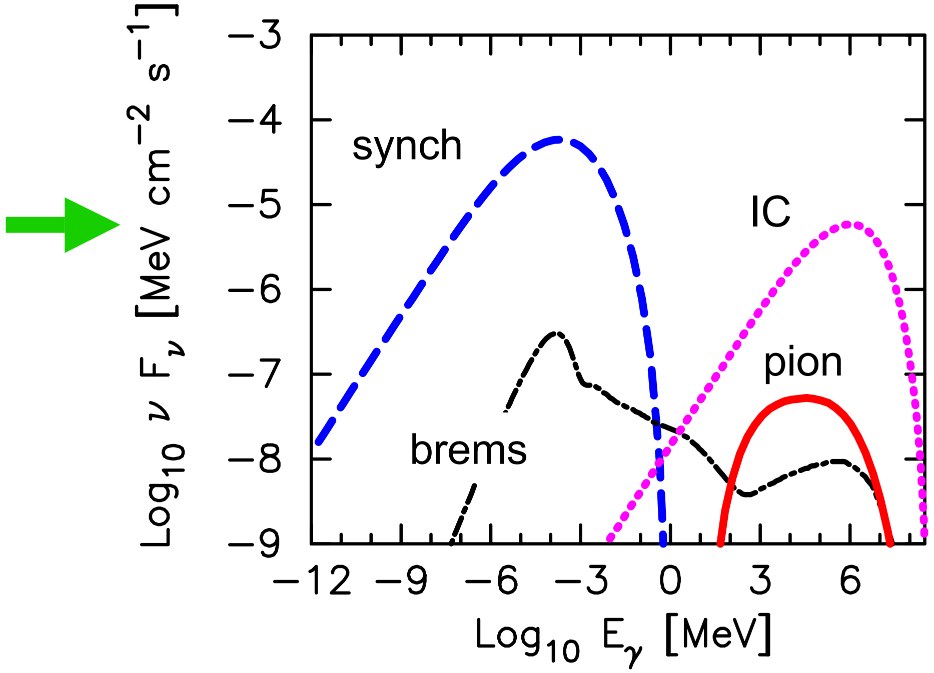
Plan detailed modeling of ``thermal'' X-ray emission and broad-band continuum

Impact of Eff. shock acceleration on broad-band photon emission:

_ Proton and electron spectra are constrained from thermal to highest energies _ broad-band photon emission unified



Must consider B-field, diffusion lengths of different energy electrons, etc

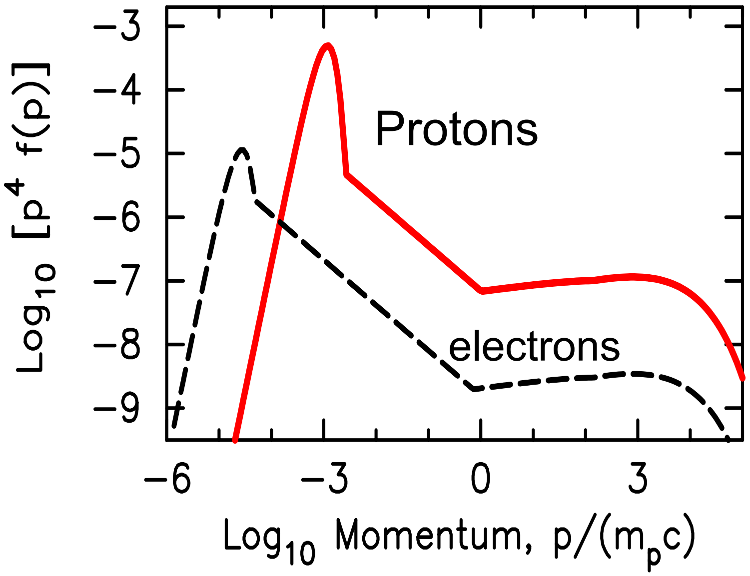


_ Cannot adjust thermal without impacting all other energy photons

_ E.g., adjusting for radio will change TeV from inverse Compton

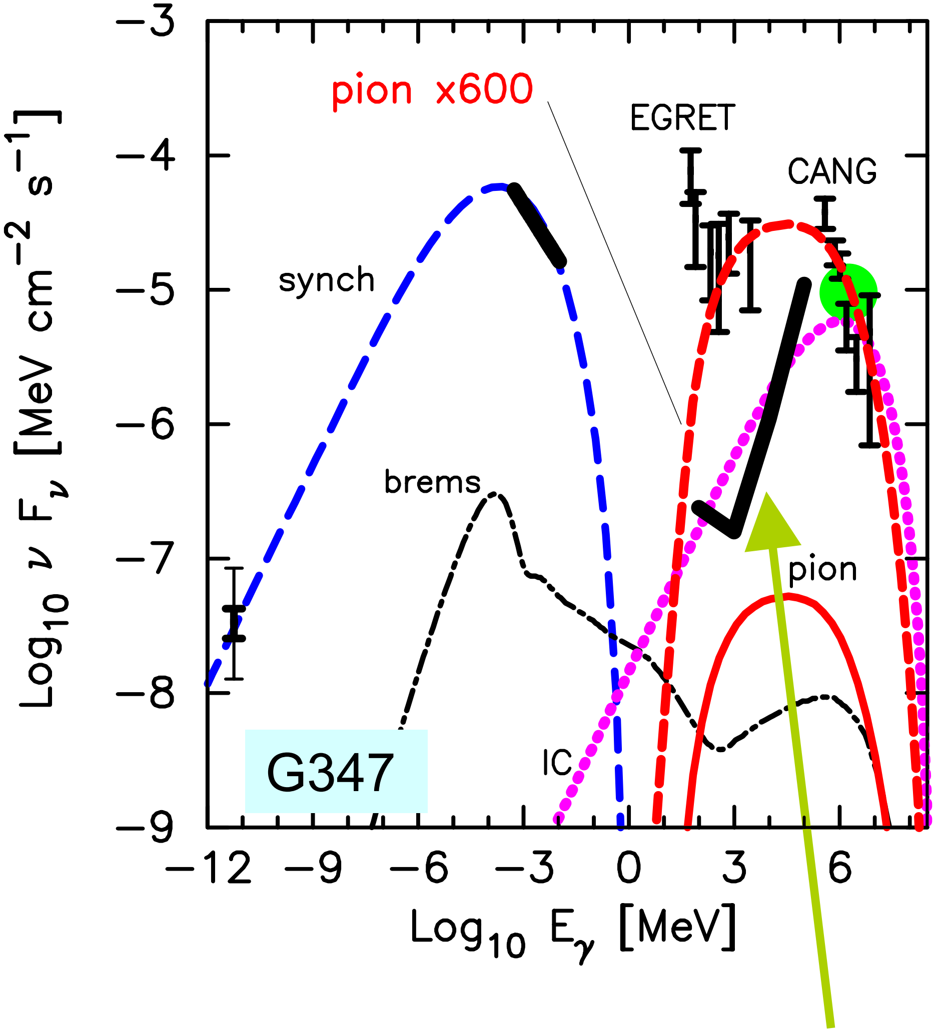
_ GLAST (and INTEGRAL) bands extremely important

SNR: G347 (RX J1713.7)



Are TeV gamma rays produced by ions or electrons? GLAST should help

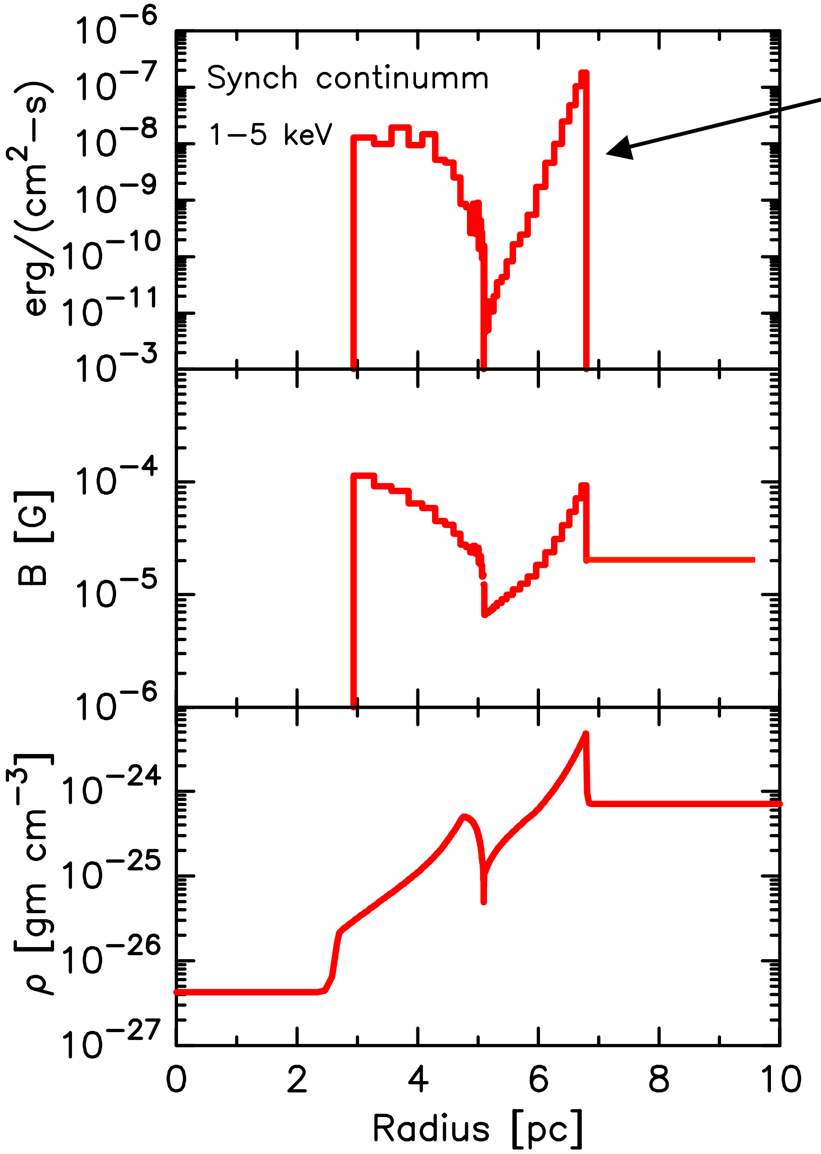
Ellison et al. 2001



GLAST Limits

See, for example, Enomoto etal 2002; Reimer & Pohl 2002; Butt etal 2002 for a discussion of G347 (RX J1713.7)

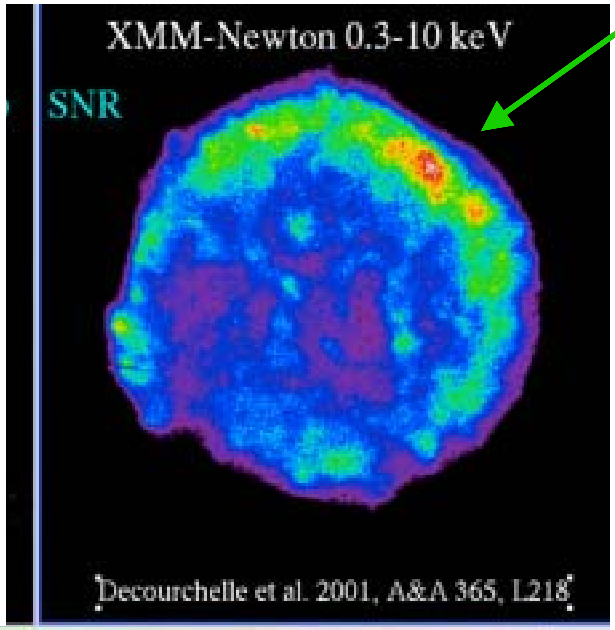
SN 1006 model at 1000 yr



Radial profile of 1-5 keV Synchrotron continuum

Currently, model does NOT include diffusion of TeV electrons upstream of FS (see Reynolds etal; Bamba etal)

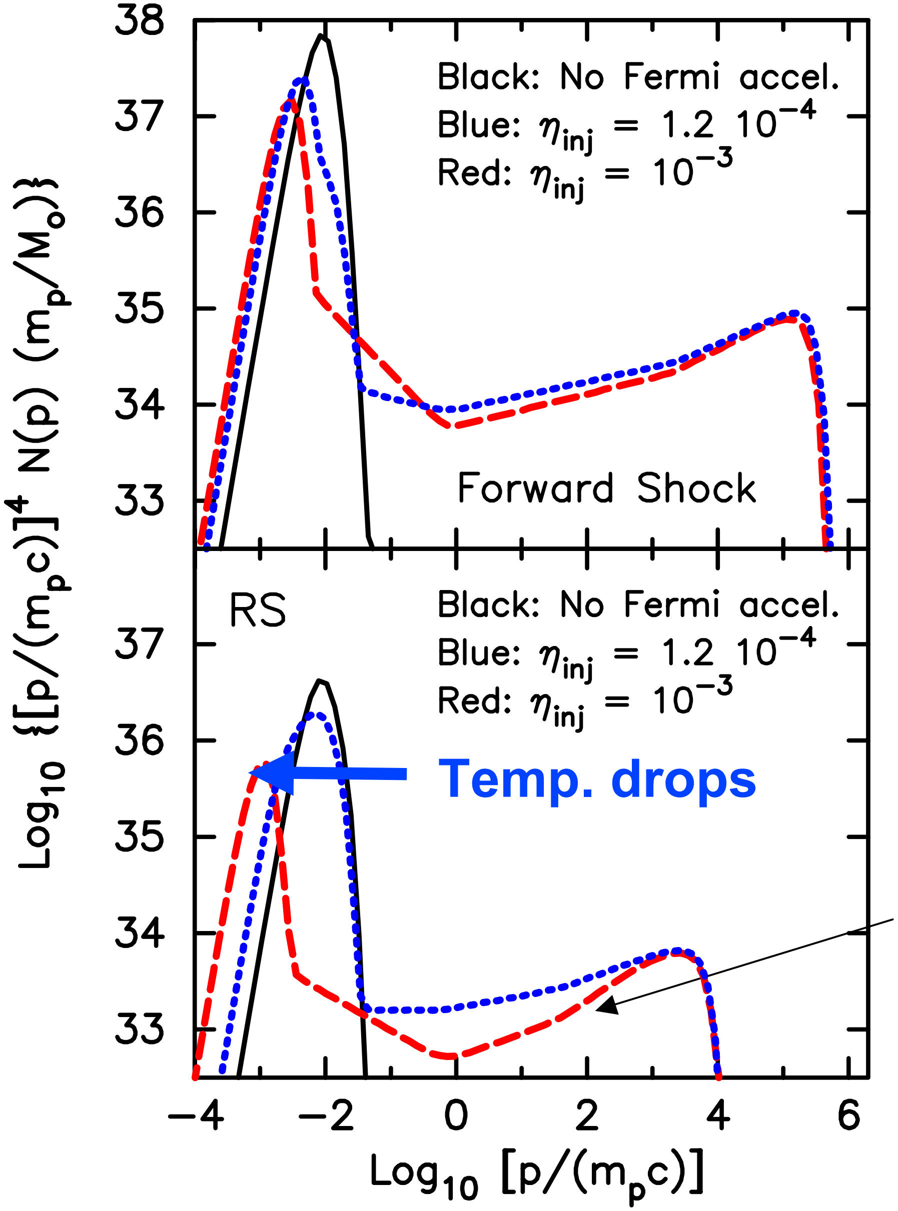
Sharp synchrotron edges at blast wave are important diagnostic



Tycho

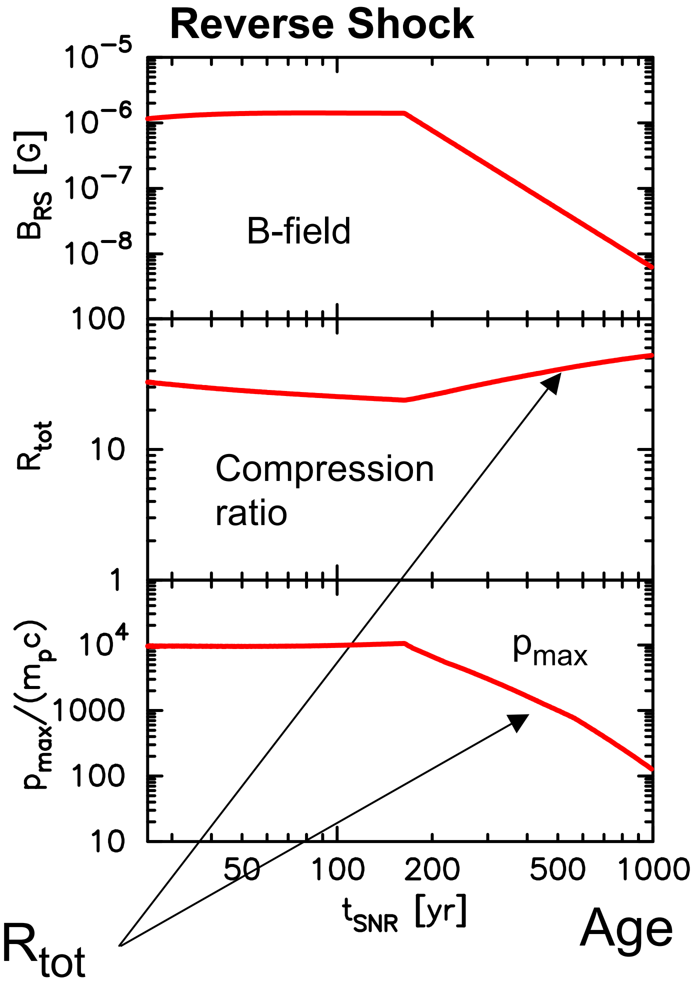
COSMIC RAYS FROM SUPERNOVA REMNANTS

Proton spectra t_{SNR} =1000yr



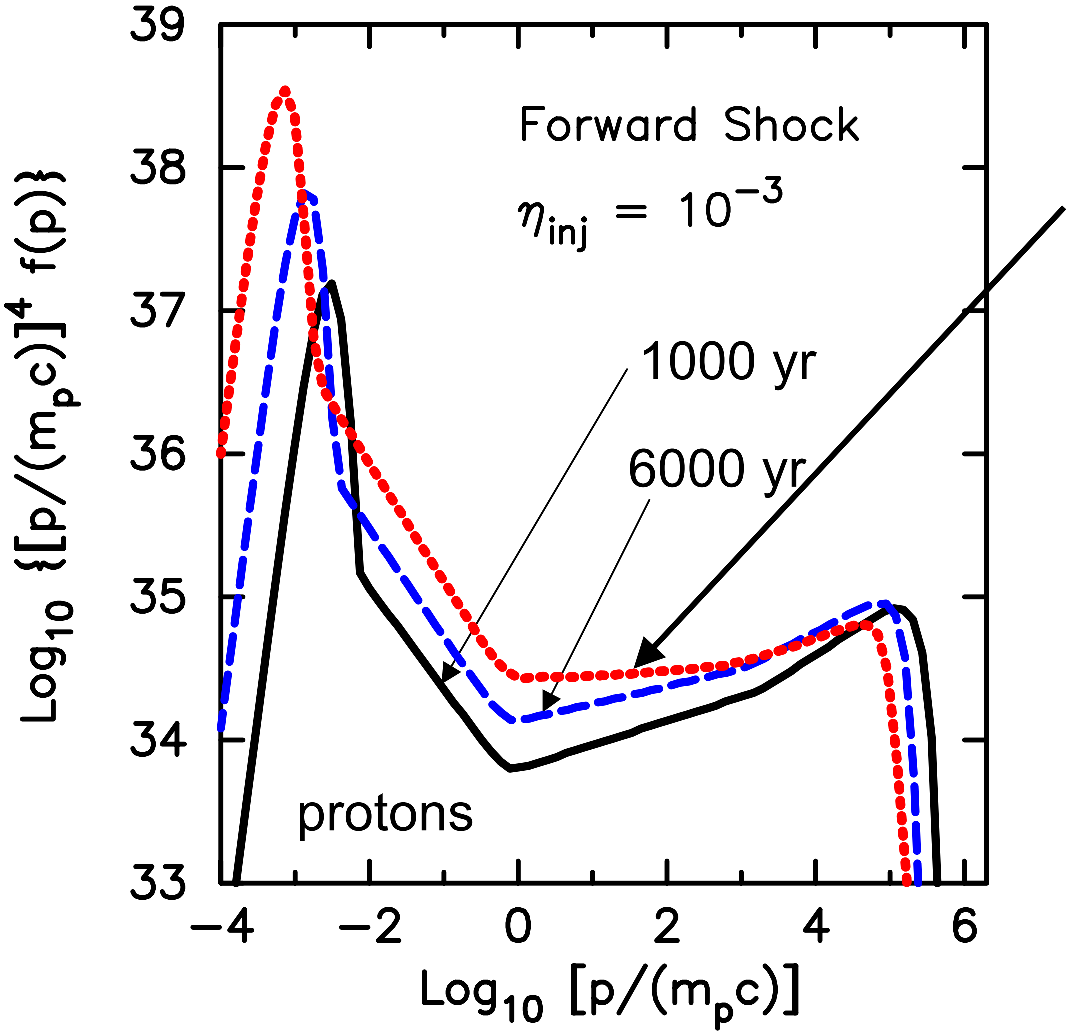
Temp. drops

High R_{tot} but low P_{max}

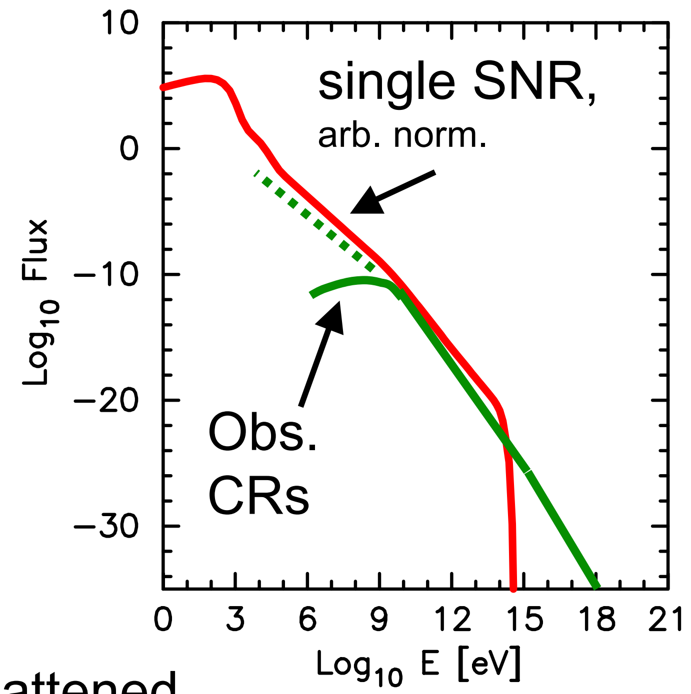


As ejecta B-field drops, acceleration at RS becomes MORE Nonlinear

Total contribution to Cosmic Ray flux after 40,000 yr



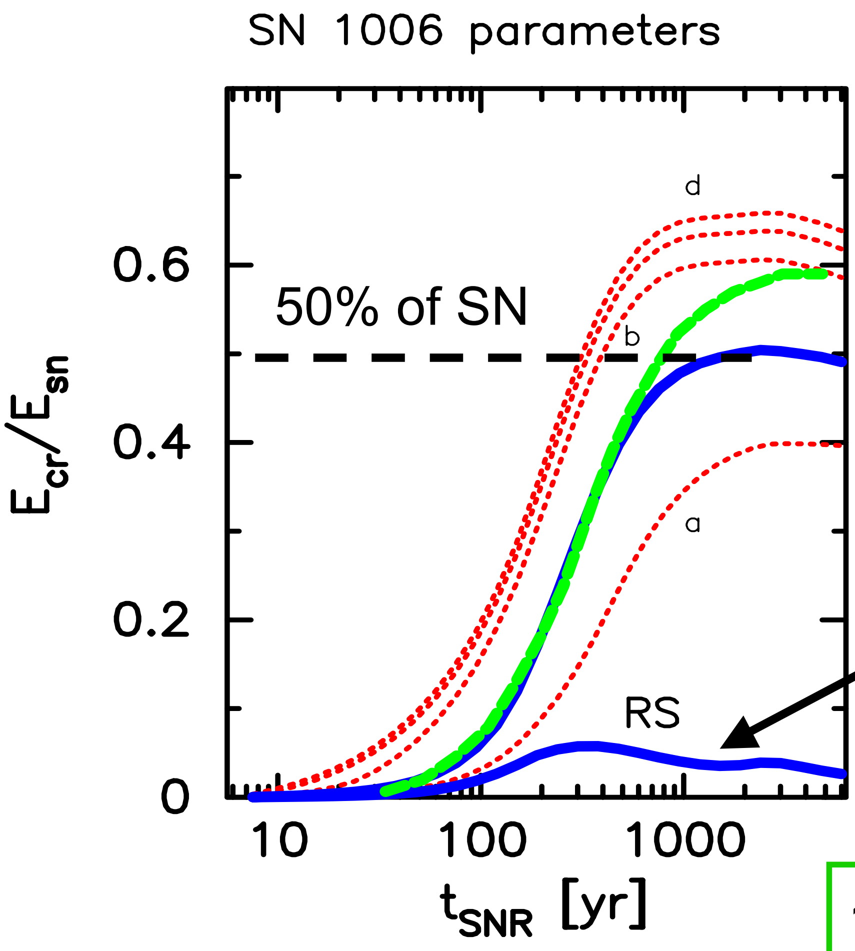
After 4 x10^4 years, total CR spectrum is steepened, BUT still **not steep enough to match observed CR all particle spectrum** !



SN1006
parameters

looks worse when flattened

Energy in CRs over lifetime of SNR



Berezhko etal 2002

CR-hydro

reverse shock

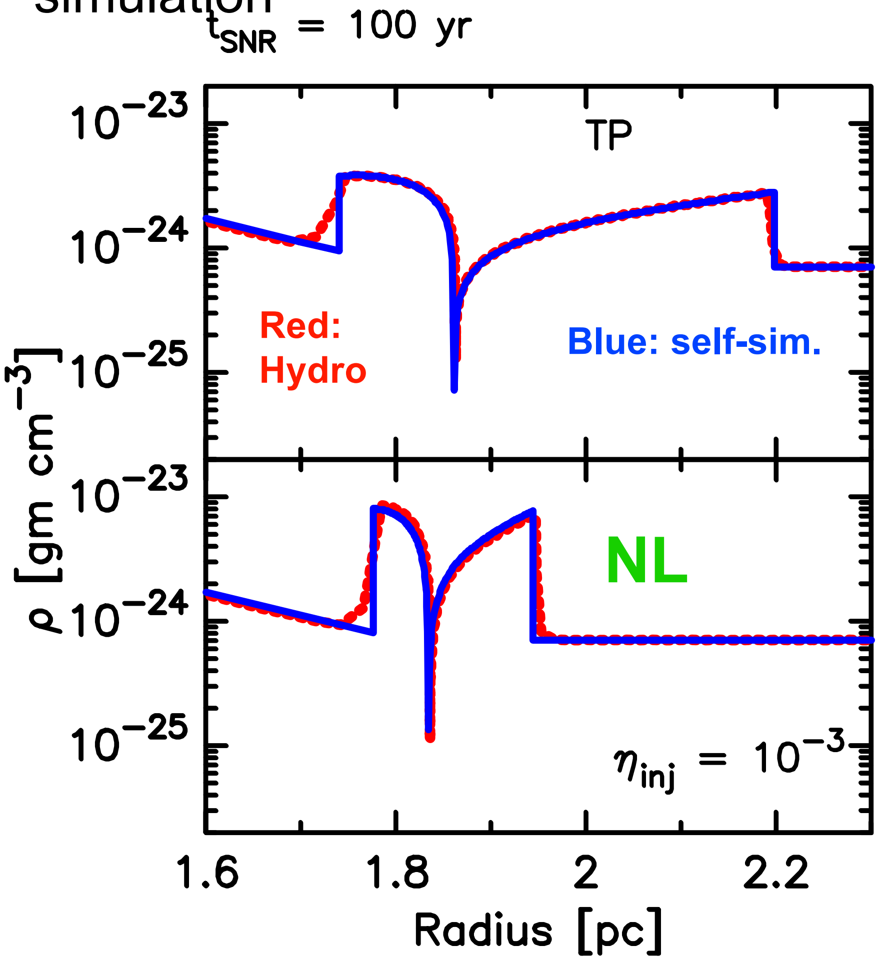
Ellison, Decourchelle, & Ballet 2003

~ 50% of SN explosion energy can easily be put into CRs.

Only need to have efficient accel. over fraction of SNR blast wave to power CRs (e.g. Berezhko etal 2002)

APPROXIMATIONS in CR-Hydro Model

1) Feedback between hydro and Fermi acceleration is accomplished by varying the **effective adiabatic index, _eff**, in the hydro simulation



Effective gamma results are nearly identical to **analytic, self-similar calculation** with NL acceleration (see Ellison, Decourchelle, & Ballet 2003)

2) **Spherical symmetry** is assumed. 1-D precludes the calculation of convective instabilities and other multi-dimensional effects, but does allow modeling of pre-supernova wind-shell interactions

3) **Magnetic field is not explicit** in the hydro simulation. A scalar B field is included for calculating accel. and synch emission

4) For the shock acceleration, we assume **parallel shocks** with strong cross-field diffusion, i.e., the Bohm limit.

5) The **maximum particle energy** is determined from some fraction of the shock radius or the remnant age -- **don't follow individual particles**

6) **Accelerated particles** are assumed to **remain in the mass shell** where they are produced. A 2nd high-energy population, whose pressure is spread out uniformly over the region between the shock and the contact discontinuity, might improve on this approximation

CONCLUSIONS

Cosmic Ray production and photon emission are intimately connected in SNRs if shock acceleration is efficient _ spectrum of relativistic particles linked to Temp. of shock-heated gas and broad-band emission

The **greater the acceleration efficiency, the lower the temperature of the shocked gas** AND, the **larger** the shock **compression ratio.**
This may be a **large effect !! (perhaps factor of 10)**

Nonlinear Fermi models will change the interpretation of SNR obs. _ narrow interaction region, different inferred shock speed, E_{sn}, ISM densities, etc. from TP models

Broad-band photon continuum from Radio to TeV gamma-rays, plus X-ray line obs., can help us understand **Injection process** in Fermi accel. AND help with **origin of Cosmic Rays,** e.g., T_e/T_p largely unknown