Cosmic Ray Production in Young Supernova Remnants (SNRs)

Don Ellison (North Carolina State Univ.)

Origin of Galactic Cosmic Rays (CRs)

► Main problems:

Source of energy **??**

Source of material **??**

Acceleration of bulk of CRs (i.e., those below ~10^{16} eV) **??**

Origin of highest energy CRs (those above ~ 10^{19} eV) **??**

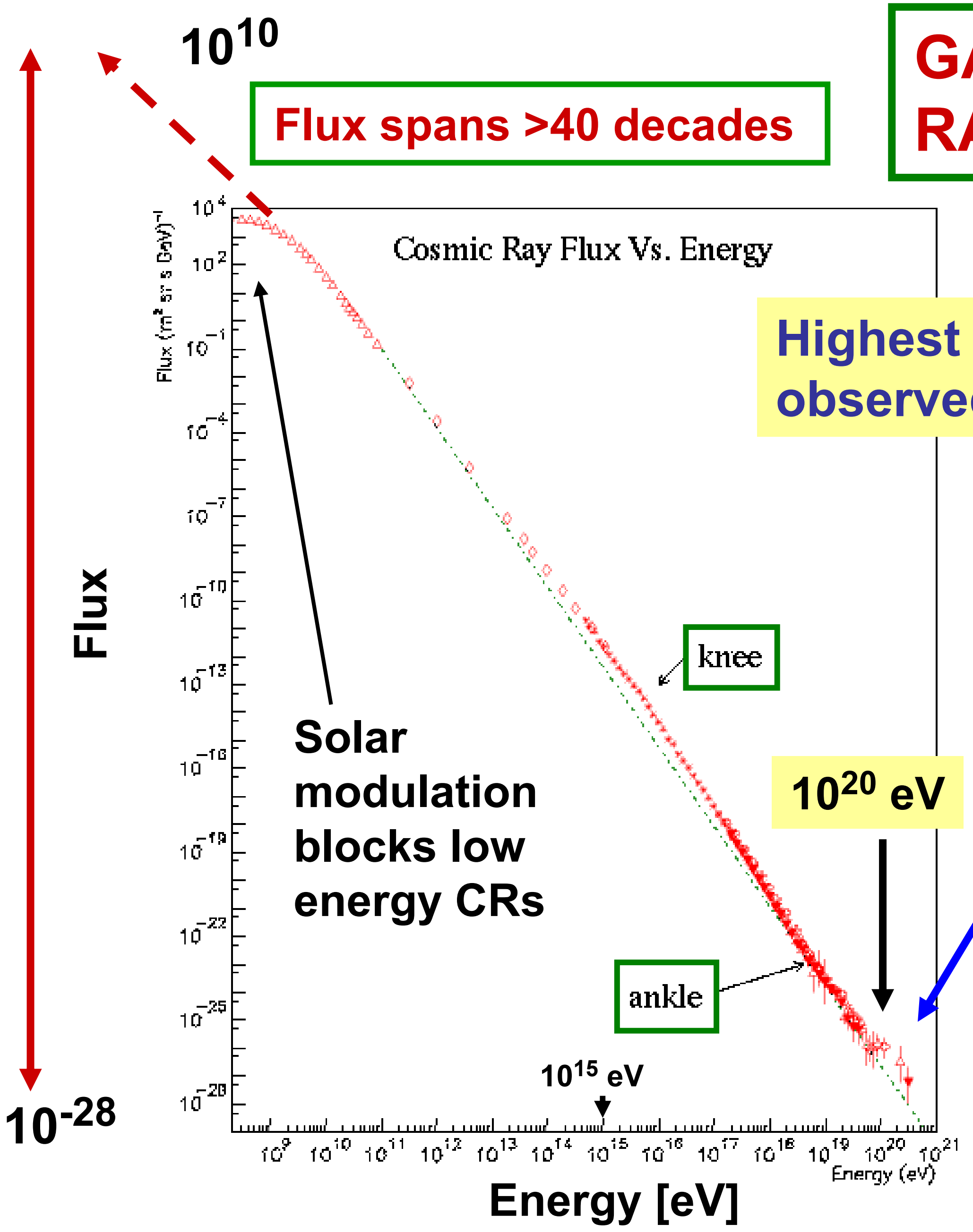
If restrict discussion to CRs below the `knee' near 10^{15} eV

Source of energy ► supernovae ✓

Source of material ► Gas & dust from well-mixed interstellar medium ✓

Acceleration ► Diffusive Shock acceleration (DSA) (a.k.a. First-order Fermi mechanism) in outer blast wave in supernova remnants ??

GALACTIC COSMIC RAY SPECTRUM



10^{10}

10^{-28}

Flux

Energy [eV]

Flux spans >40 decades

Solar modulation blocks low energy CRs

10^{15} eV

Highest energy particles ever observed !

10^{20} eV

GRBs ??

Here, just worry about CRs below the knee near 10^{15} eV

Kinetic energy of supernova ejecta material can power CRs BUT:

► May need 10% or more efficiency of conversion in SNR shocks to power CRs ! Is ≥ 10% acceleration efficiency possible ?

► Diffusive shock acceleration (DSA) mechanism can easily be this efficient

► BUT, **nonlinear effects** must be taken into account if acceleration is efficient

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► Nonlinear diffusive shock acceleration of ISM gas and dust provides a quantitative explanation for cosmic ray composition (Ellison et al. 1997; Meyer et al. 1997)

Acceleration of Cosmic Rays in SNR Blast Waves

Theory Issues:

- ► Maximum energy – Magnetic field amplification?
- ► Spectral shape – Steepness of CR source spectrum, break at knee?
- ► Efficiency and nonlinear effects – are NL effects important?
- ► Electrons and e/p ratio – shocks put most energy into ions?

These are the same issues facing relativistic shocks in GRBs:

- ► Can internal or external shocks accelerate electrons with high efficiency?
- ► Is the electron spectrum consistent with the γ-ray emission?
- ► What fraction of shock energy goes into protons vs. electrons?
- ► Is the ambient magnetic field amplified by large factors?

The difference is that there is some hope of actually answering these questions with observations of young supernova remnants

Acceleration of Cosmic Rays in SNR Blast Waves

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Observations:

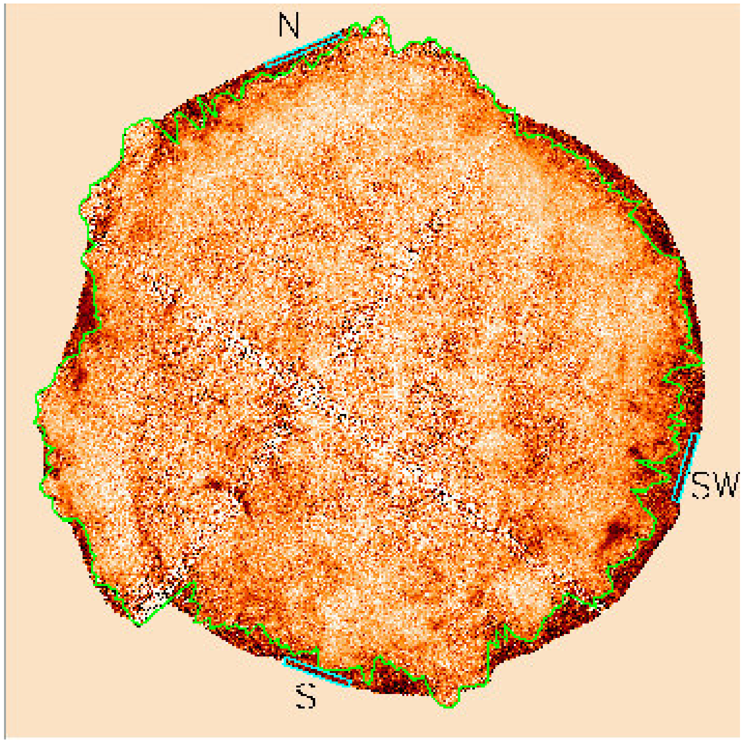
- ► Cosmic rays observed at Earth
- ► Photons from particular SNRs
- ► Photons from diffuse galactic emission

Detailed models of individual SNRs (nonlinear shock acceleration coupled to remnant hydrodynamics) may offer best way to address these issues → non-thermal, broad-band continuum emission

► Impact on interpretation of thermal X-ray observations – NL shock acceleration modifies SNR evolution and shock heating

Use Tycho's SNR as a test case because of the excellent Chandra observations of the large-scale morphology (Warren et al. 2005)

Other young SNRs show similar features

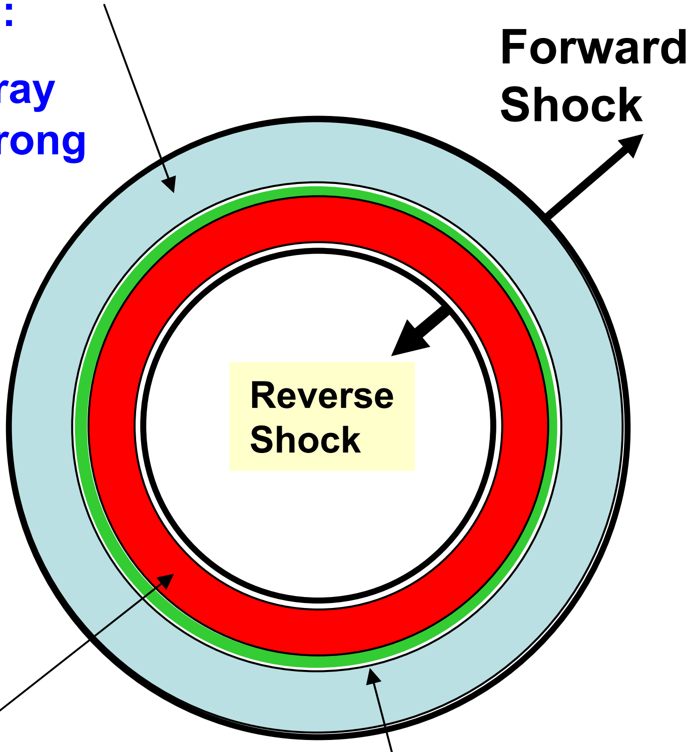


X-ray emission

In addition to large-scale morphology, we have:

- ► **broadband continuum emission – radio, X-rays, TeV gamma-rays (upper limits)**
- ► **Constraints on forward shock X-ray precursor**
- ► **Thermal X-rays**

1-D CR-hydro model couples eff. DSA to SNR hydrodynamics



Shocked ISM material :

Weak X-ray lines; Strong Radio

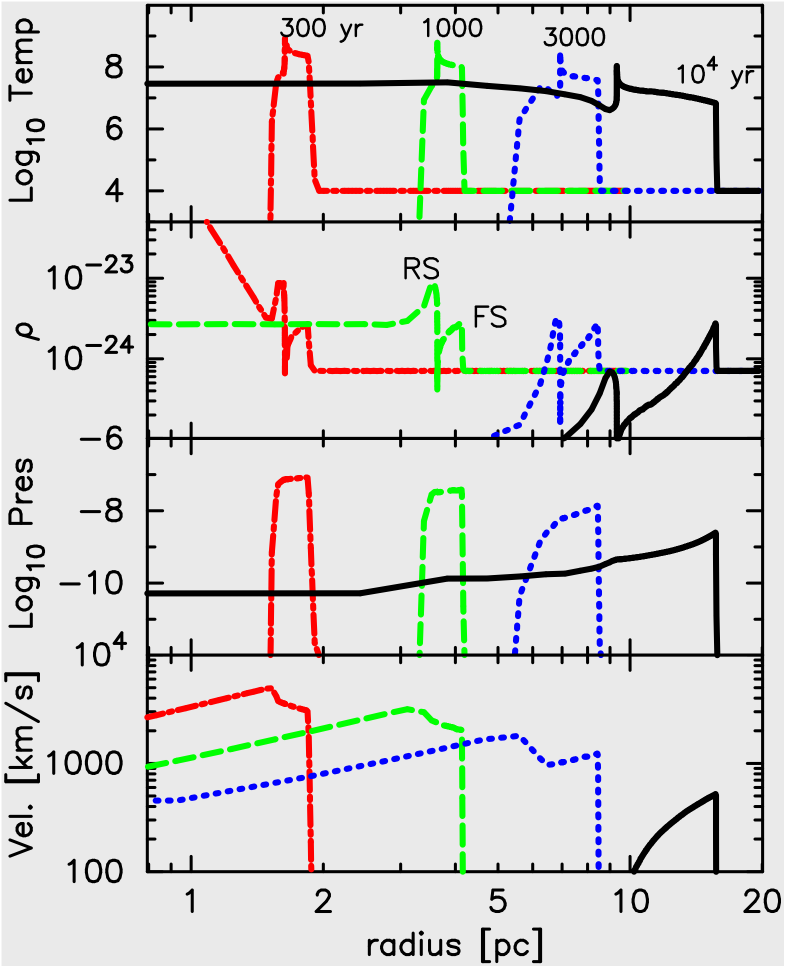
Forward Shock

Reverse Shock

Contact Discontinuity

Shocked Ejecta material : Strong X-ray emission lines, but expect no radio if B is diluted progenitor field

hydro simulation – NO Shock Accel. or Test-particle acceleration



e.g. Ellison, Decourchelle Ballet 2004

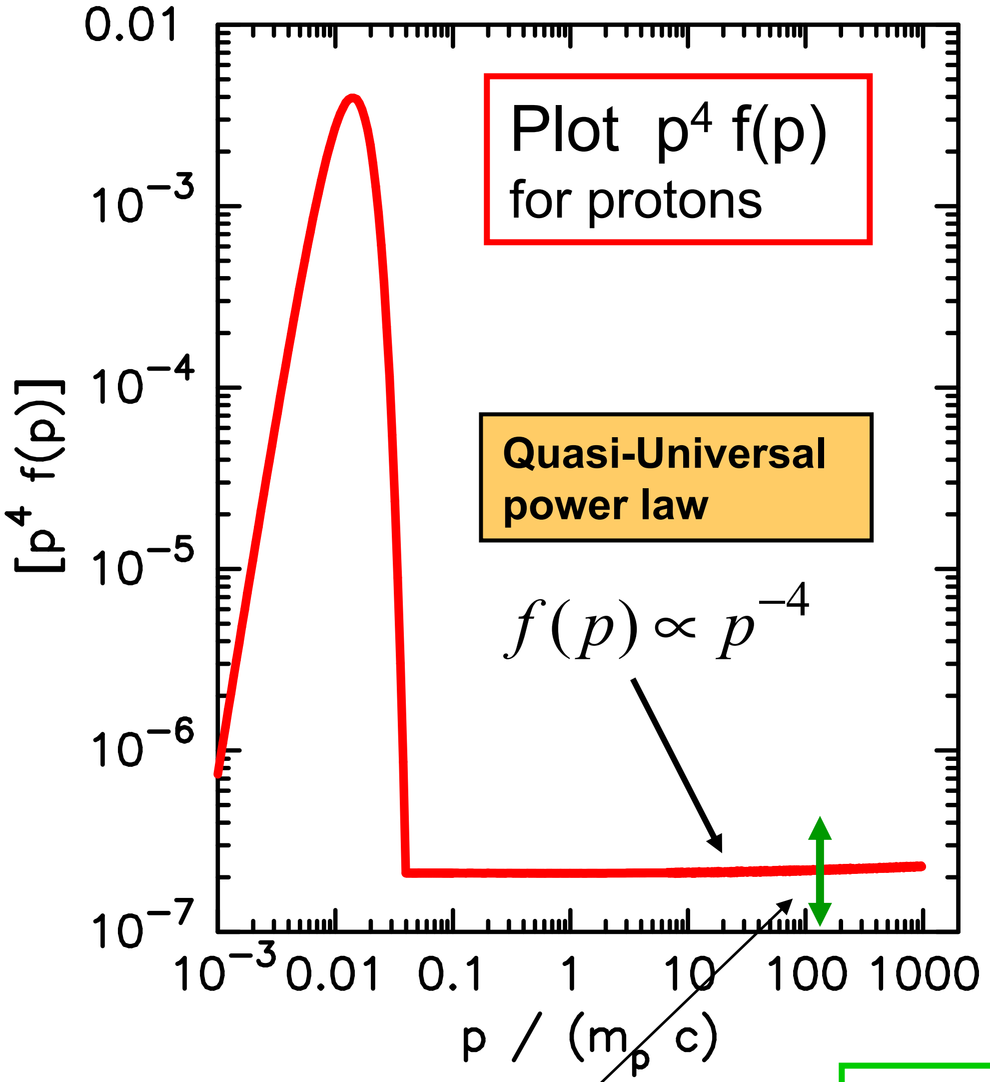
Brief description of Diffusive Shock Acceleration (DSA)

(also called first-order Fermi mechanism)

in non-relativistic shocks

Test Particle Power Law in diffusive shock accel.

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



Plot p^4 f(p) for protons

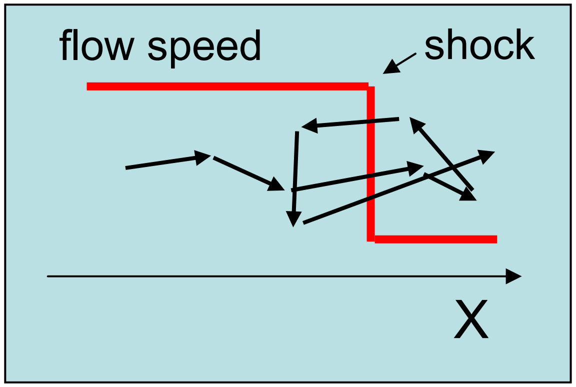
Quasi-Universal power law

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

Normalization of power law not defined in test-particle approximation

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

If r = 4, & γ = 5/3, f(p) ~ p^{-4}



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

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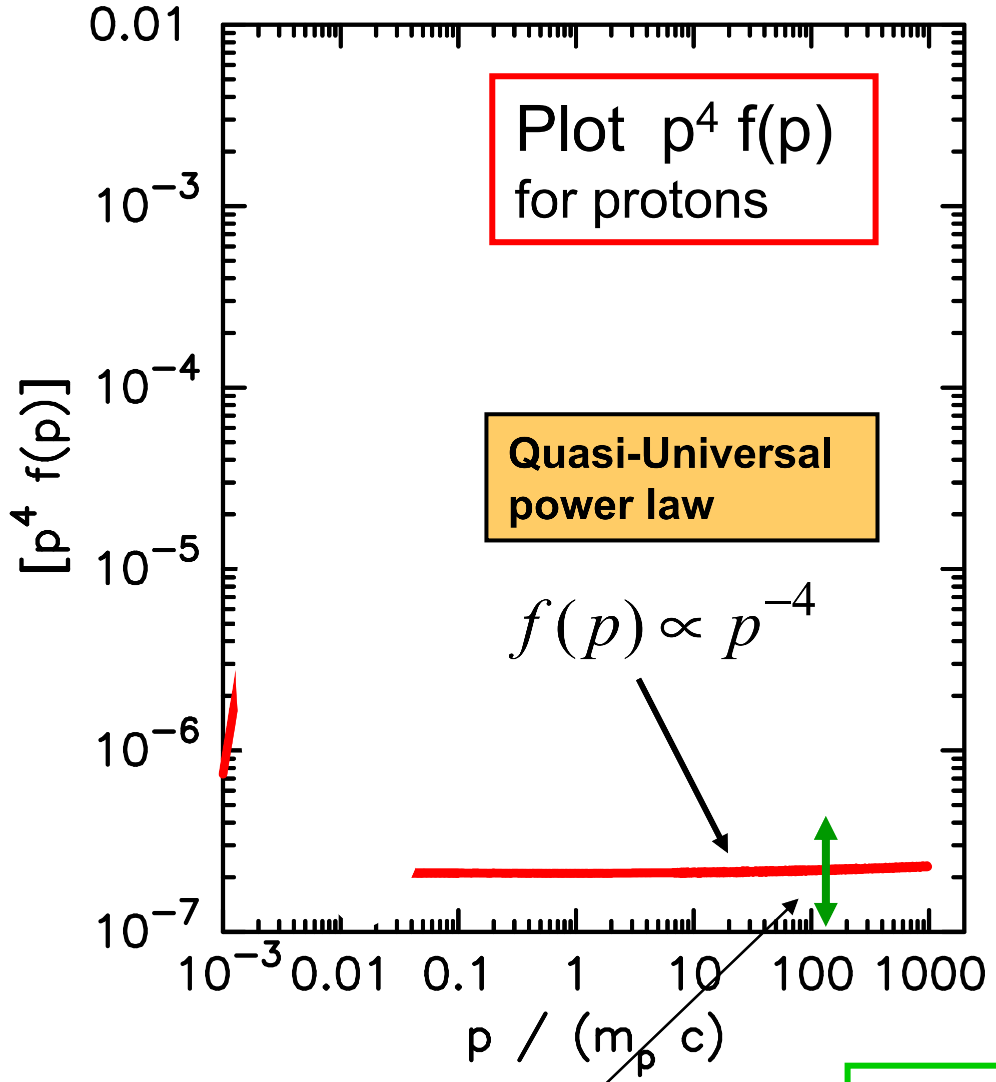

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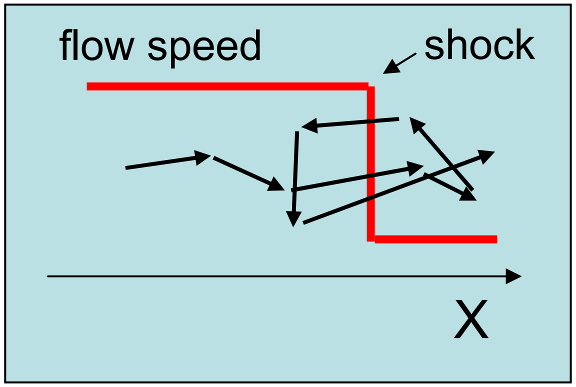

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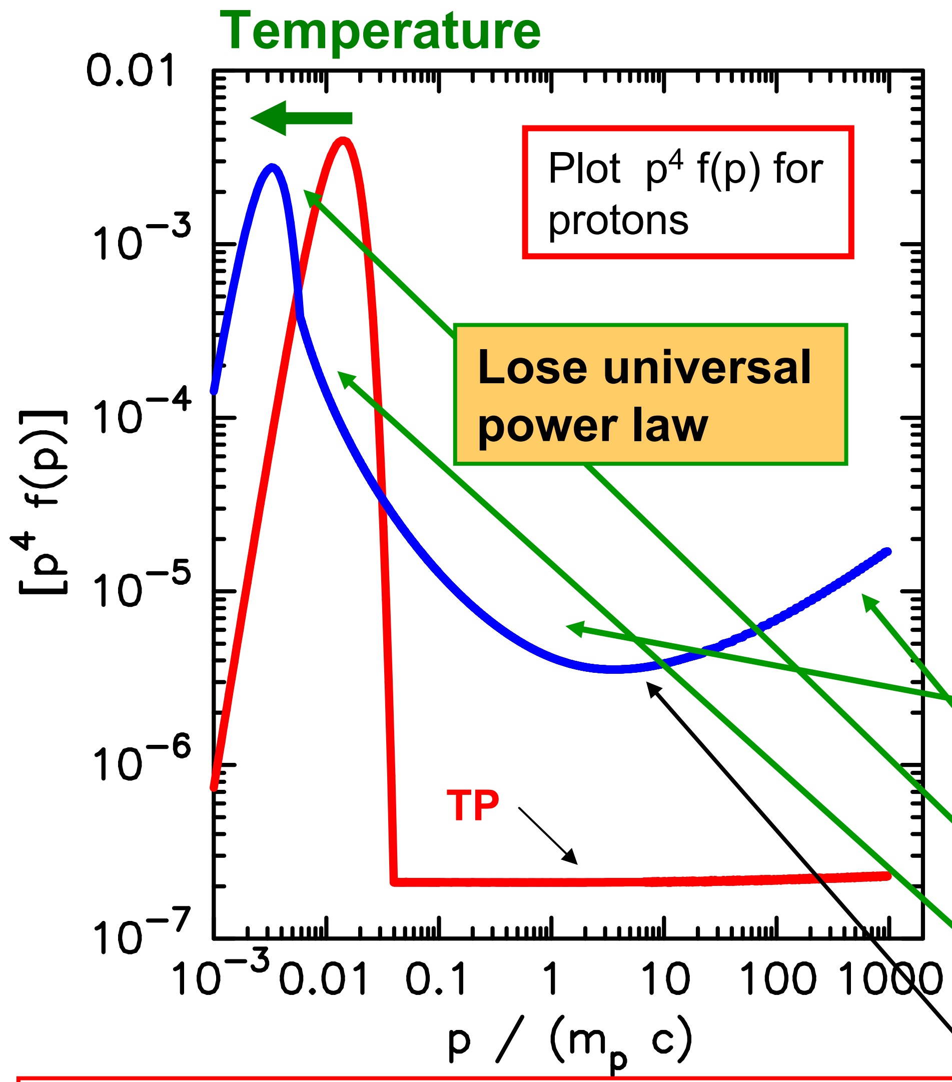
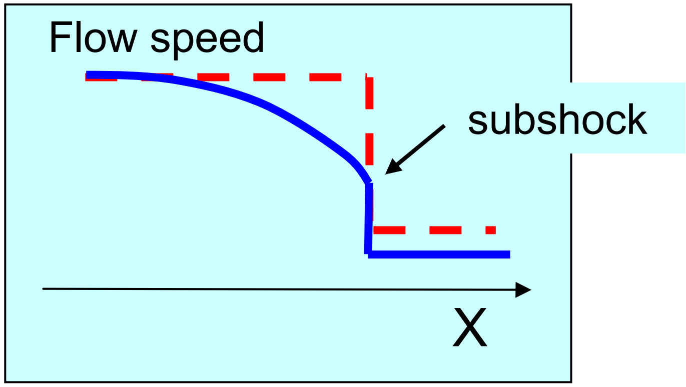


Plot p^4 f(p) for protons

Lose universal power law

If acceleration is efficient, shock becomes smooth from backpressure of CRs



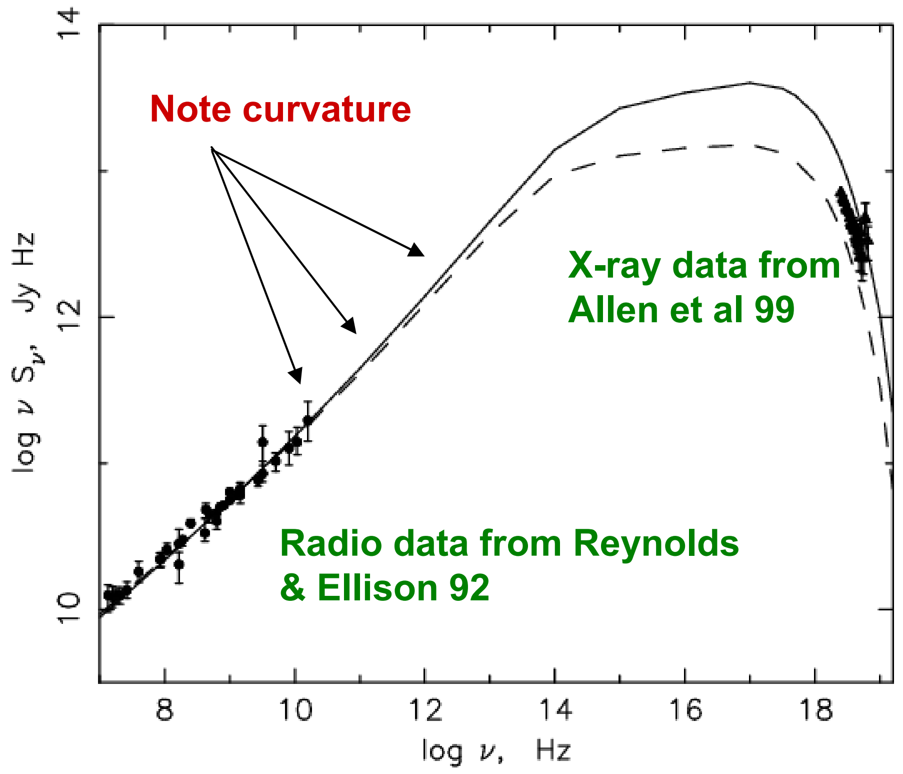
- **Concave spectrum**
- **Compression ratio, $r_{tot} > 4$**
- **Low shocked temp. $r_{sub} < 4$**
- **Nonthermal tail on electron & ion distributions**

In efficient accel., <u>entire spectrum</u> must be described consistently

connects photon emission across spectrum from radio to γ-rays

Here show analytic model of Blasi 02

Tycho: Broadband continuum



Note curvature

X-ray data from Allen et al 99

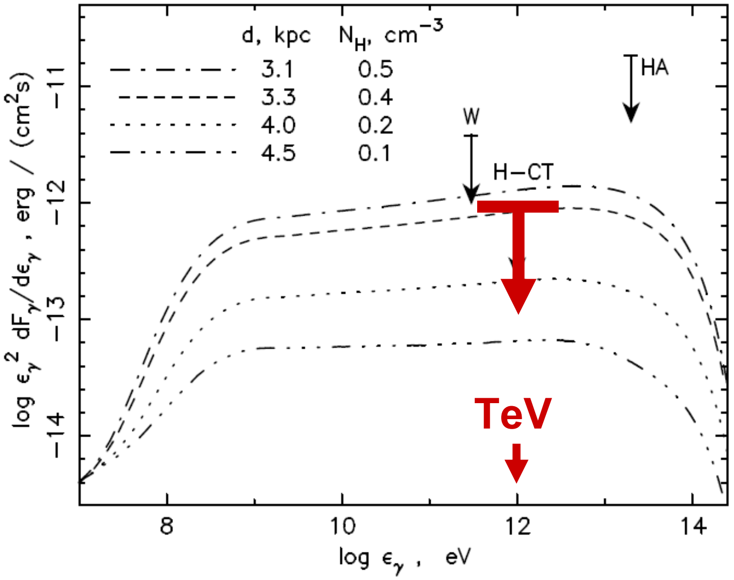
Radio data from Reynolds & Ellison 92

Figure from Volk et al. 2002,2005

Nonlinear DSA model from Volk, Berezhko & Ksenofontov 2002,2005

← synchrotron emission fits to Tycho

HEGRA upper limits on TeV γ-ray emission Volk et al 05



Pion-decay fits: Figure from Volk et al. 2005

Electron and Proton distributions from efficient (nonlinear) diffusive shock acceleration (toy spectra from Blasi et al. accel. model)

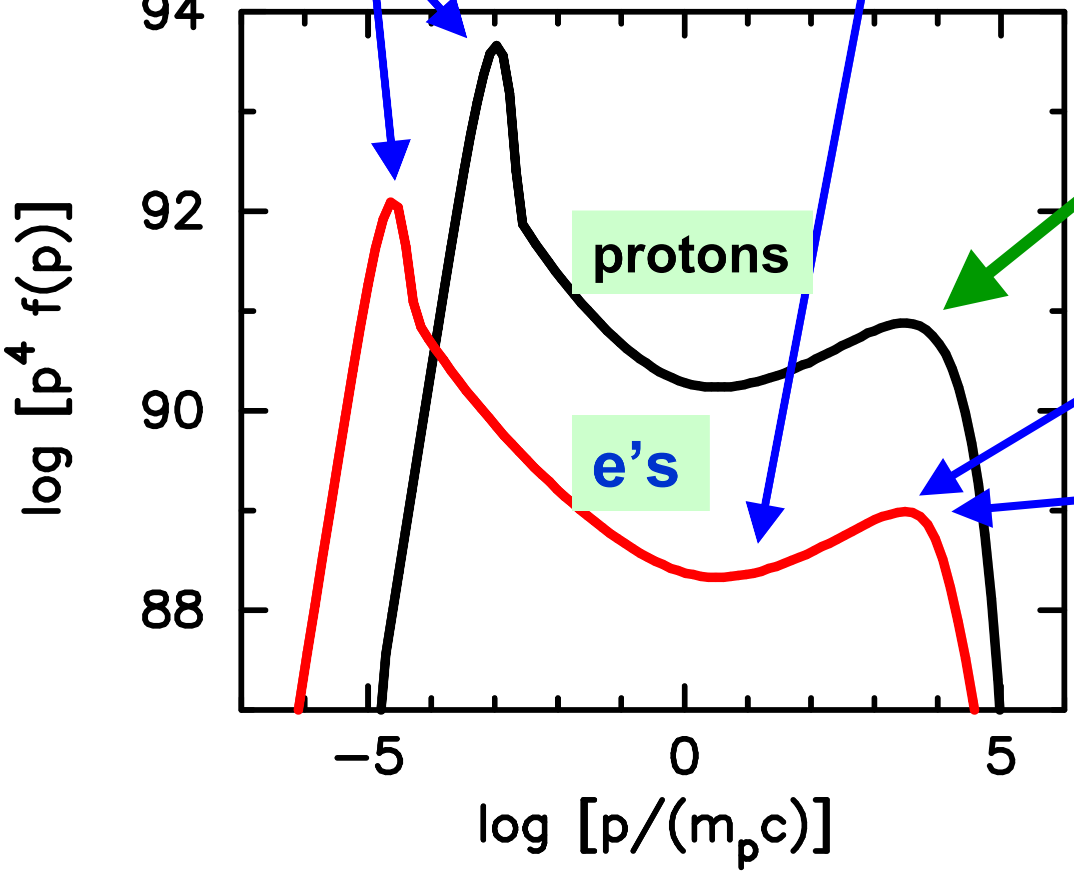
Thermal X-rays (keV)

Radio Synch

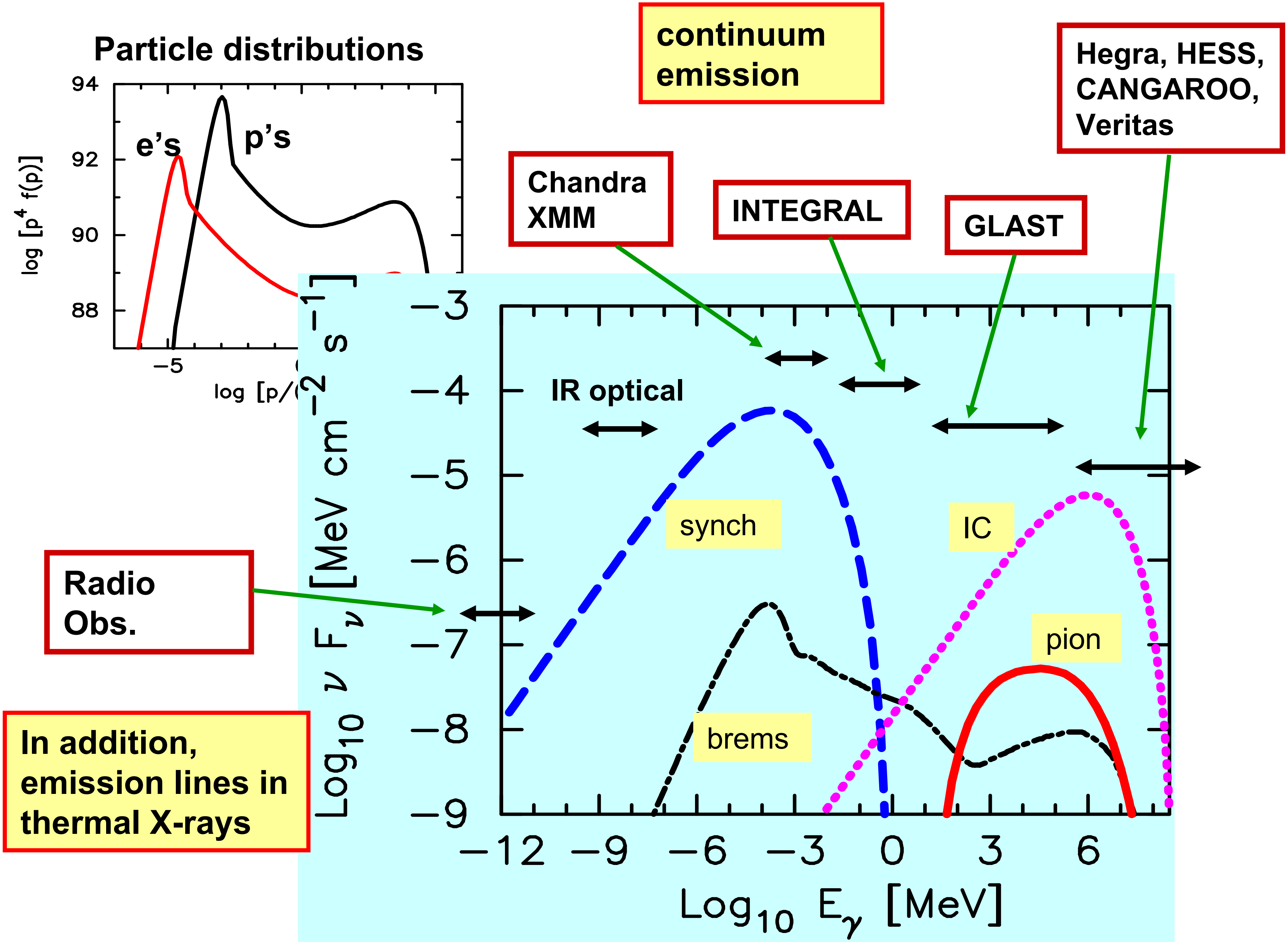
Pion-decay (GeV-TeV) only emission from protons

Non-thermal X-ray Synch (keV)

Inverse Compton (GeV-TeV γ-rays) from electrons



Several free parameters required to characterize particle spectra, including B-field & e/p ratio



continuum emission

Chandra XMM

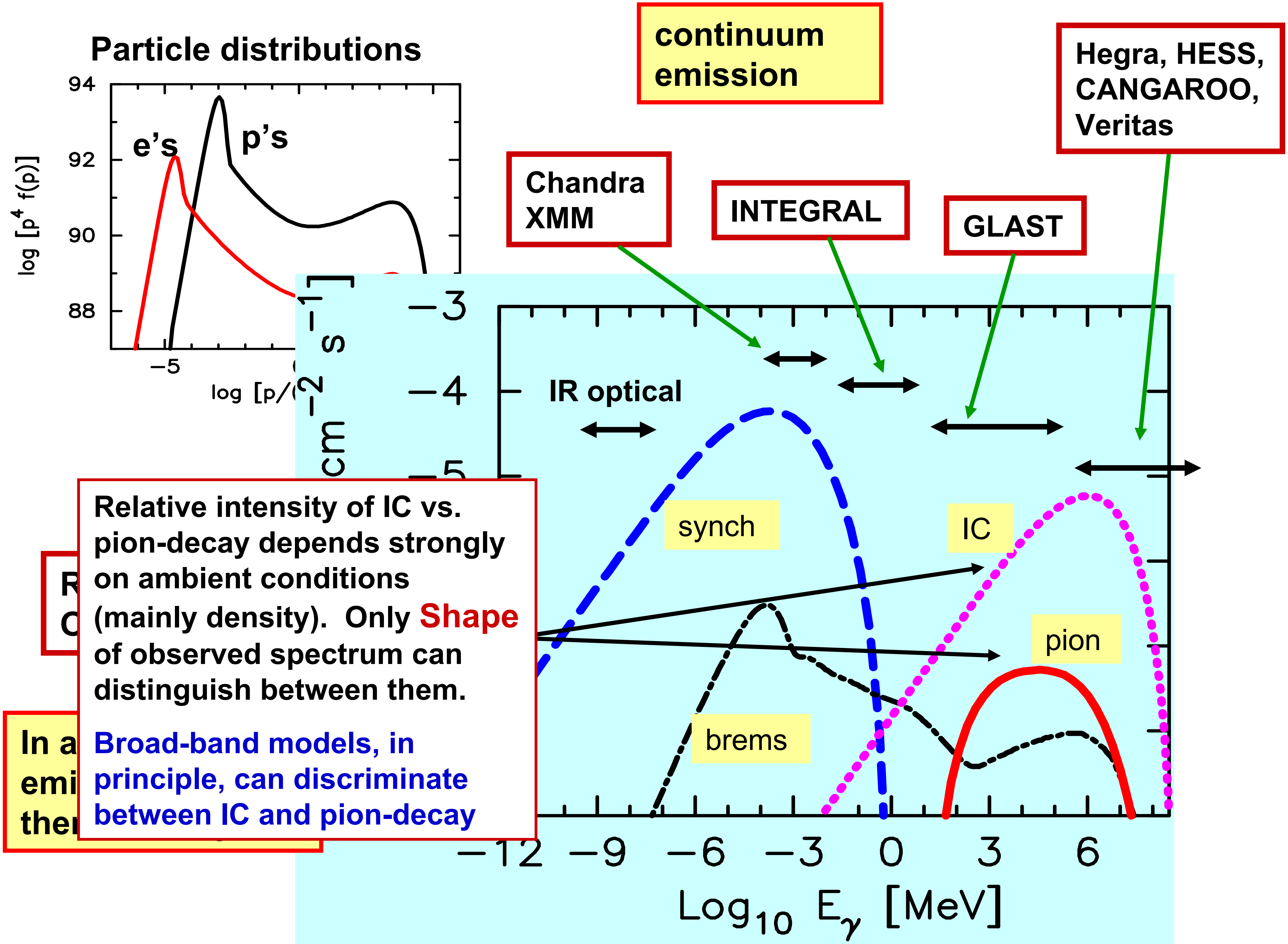
INTEGRAL

GLAST

Hegra, HESS, CANGAROO, Veritas

Radio Obs.

In addition, emission lines in thermal X-rays



continuum emission

Chandra XMM

INTEGRAL

GLAST

Hegra, HESS, CANGAROO, Veritas

Relative intensity of IC vs. pion-decay depends strongly on ambient conditions (mainly density). Only Shape of observed spectrum can distinguish between them.

Broad-band models, in principle, can discriminate between IC and pion-decay

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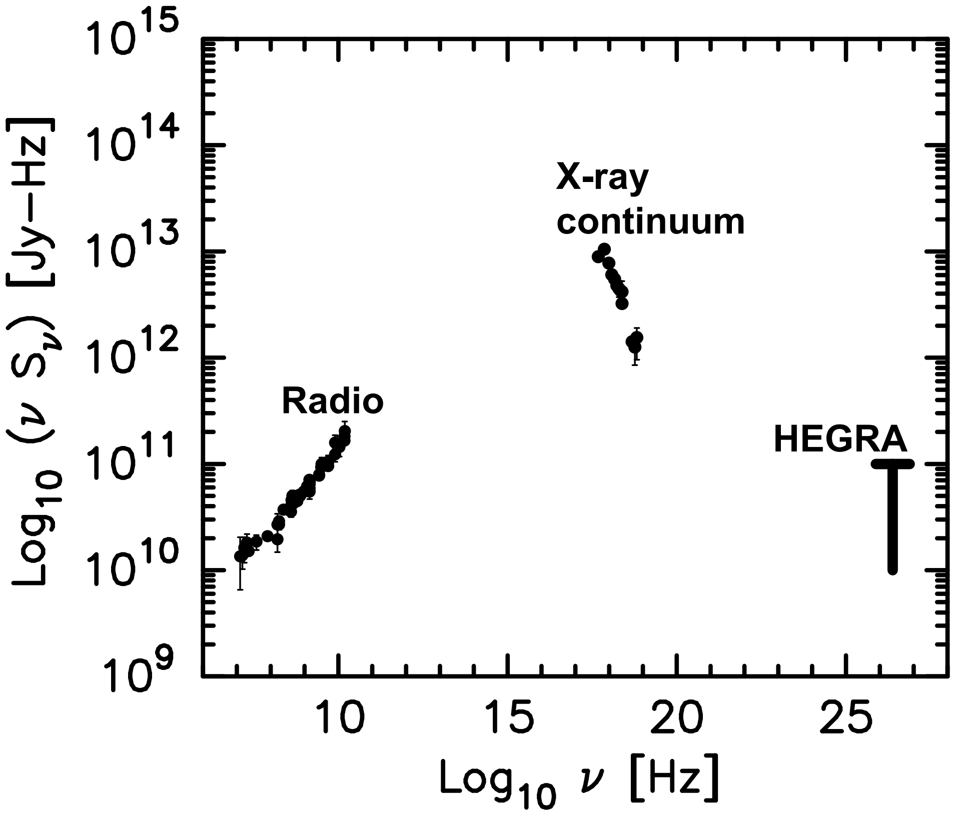
Tycho's SNR – Broad-band continuum

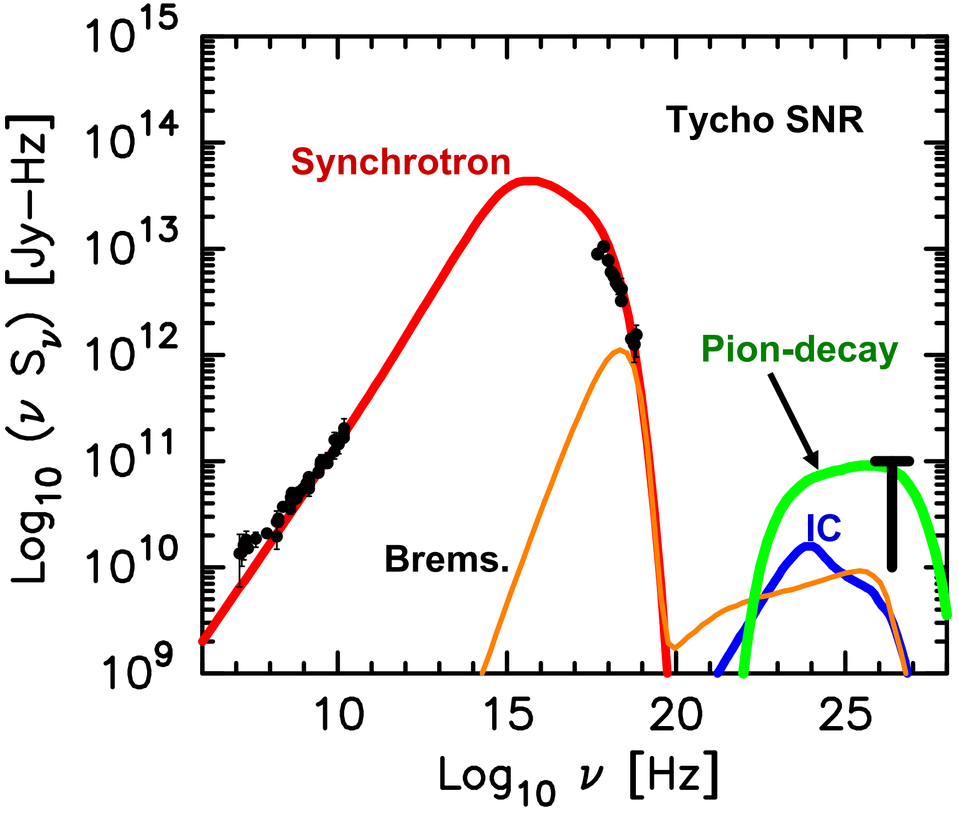


X-ray data from Allen, Gotthelf & Petre, ICRC 99 (>10 keV) and Hwang & Gotthelf, ApJ 97 (low energy)

Radio: Reynolds & Ellison 92

γ-ray: HEGRA (Volk et al 05)

CR-Hydro **model fits** (e.g., Ellison, Decourchelle & Ballet)



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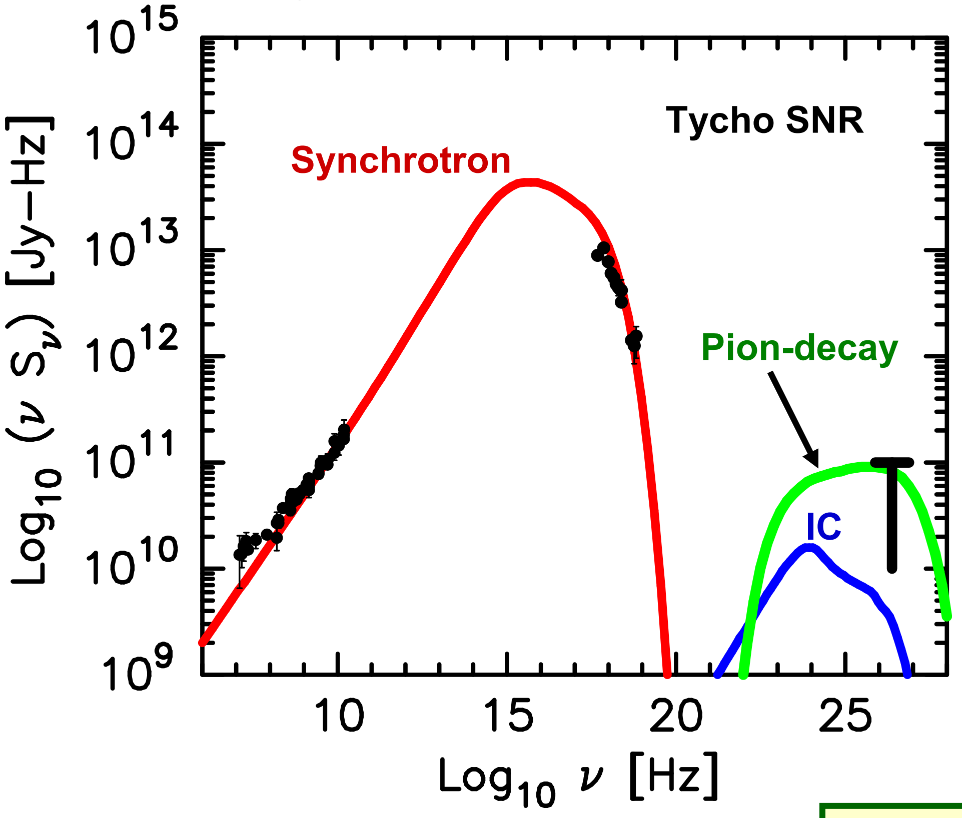


CR-Hydro model similar to results of Volk et al. 2002,2005

parameters almost the same – physics of models pretty much the same.

Main point is that you need a large shocked B-field to fit broad-band continuum observations

$B_2 \geq 200\ \mu G$

Here, $B_2 = 230\ \mu G$ ($B_{ISM} = 60\ \mu G$!!!)

Shock compression ratio, R ~ 5 and B_2 is just compressed B_{ISM}

For this set of parameters, pion-decay from protons is dominant process at TeV energies

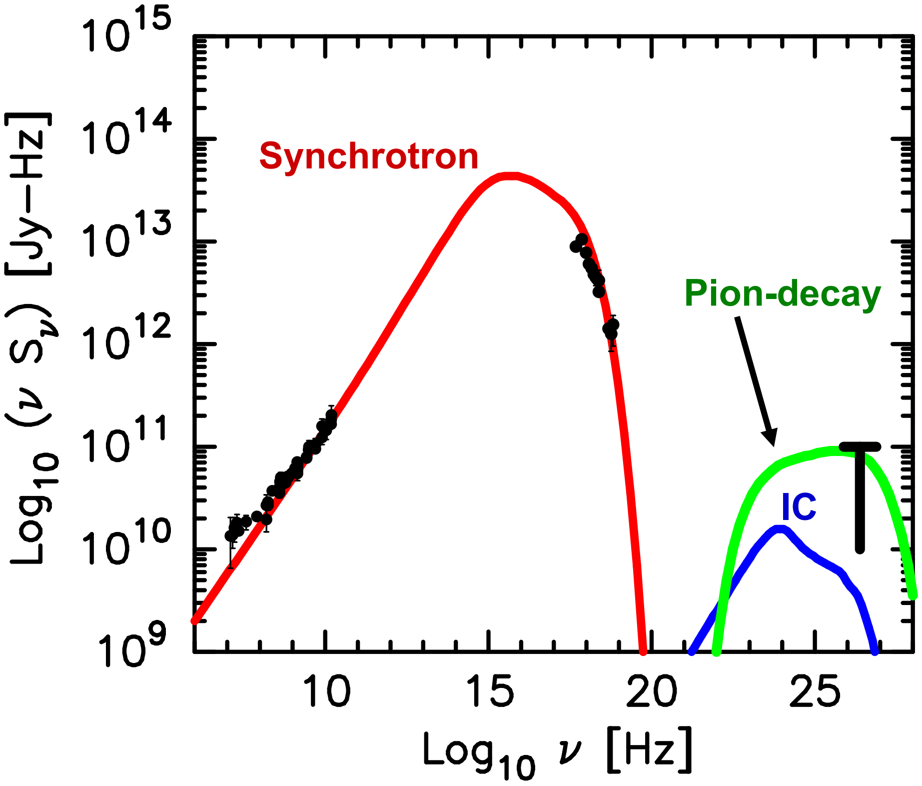
Direct evidence for CR ions in SNRs ??

Decourchelle, Ellison, & Ballet, ApJL, 2000; Blondin & Ellison, ApJ, 01;
Ellison, Decourchelle, & Ballet, A&A, 04,05; Ellison & Cassam-Chenai ApJ 05

Tycho model: B_{ISM} = 60 μG, n_H = 1 cm^{-3}

B_2 = 250 μG Shock comp. ratio, R ~ 5

But, B_{ISM} = 60 μG may be far too high !

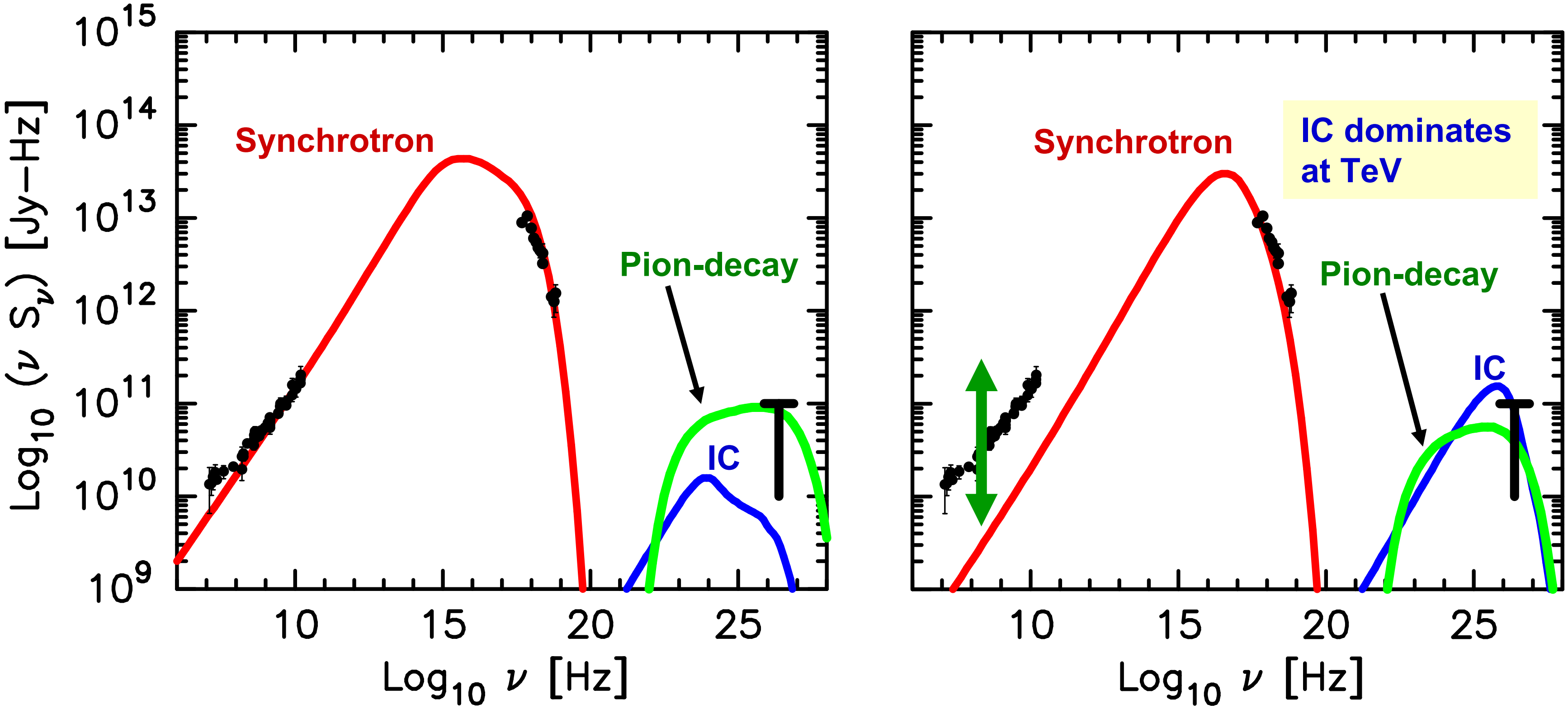


Tycho model: $B_{ISM} = 60\ \mu G$, $n_H = 1\ cm^{-3}$

$B_2 = 250\ \mu G$ Shock comp. ratio, R ~ 5

Here: $B_{ISM} = 15\ \mu G$, $n_H = 0.5\ cm^{-3}$

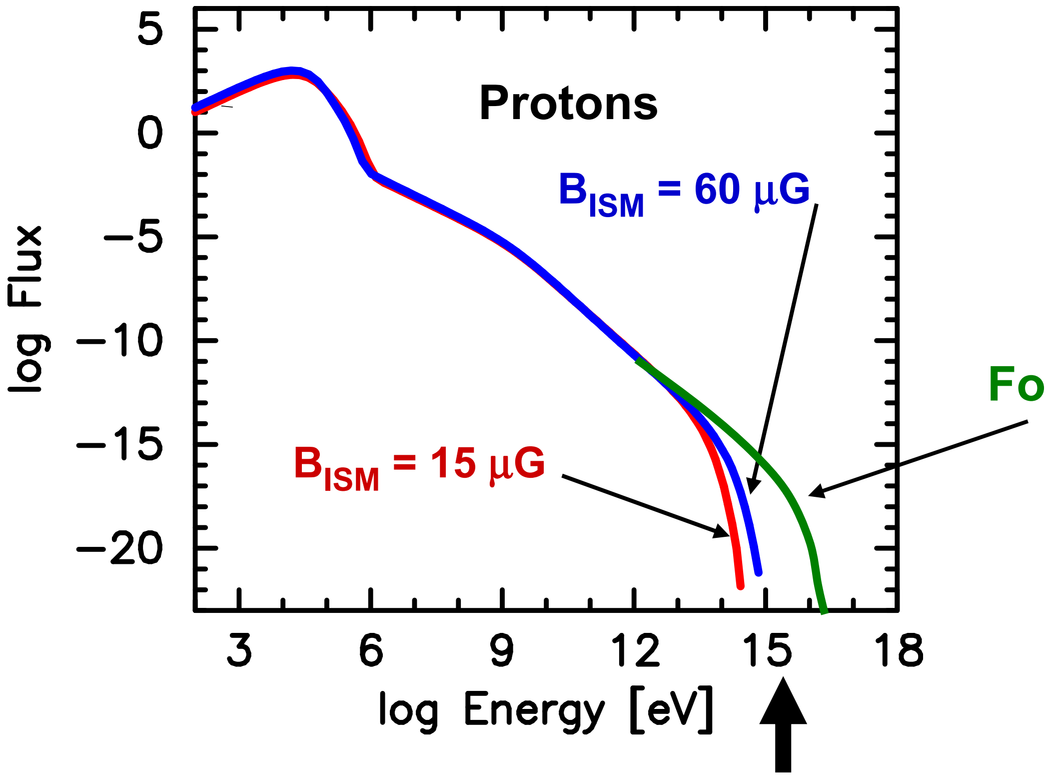
$B_2 = 70\ \mu G$ Shock comp. ratio, R ~ 6



With lower B_{ISM} and n_H, inverse Compton from electrons dominates TeV emission

Emission volumes (and/or electron diffusion lengths) may be different for radio, X-rays, & TeV γ-rays ?

Relative normalization between radio and X-ray continuum is uncertain !!



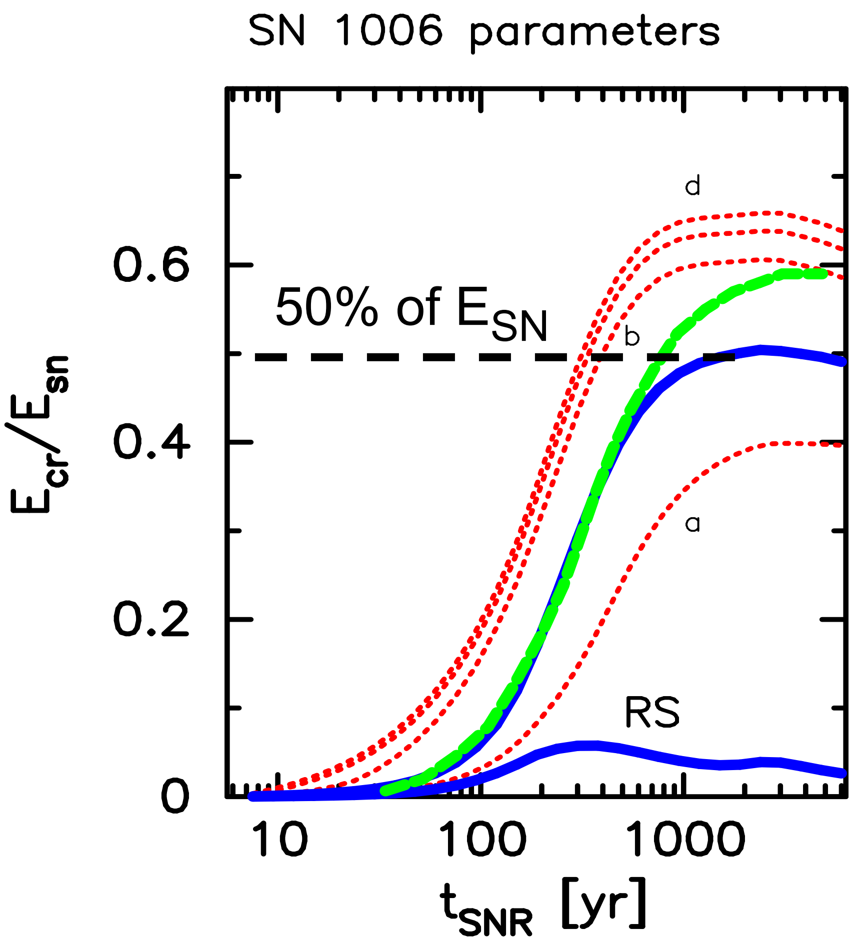
For Fe^{+26} expect

CR Knee

Both models can accelerate Fe^{+26} to above the knee in the observed CR spectrum

And both are highly efficient and can power galactic cosmic rays

Energy in CRs over lifetime of SNR



Berezhko etal 2002

CR-hydro (forward shock)

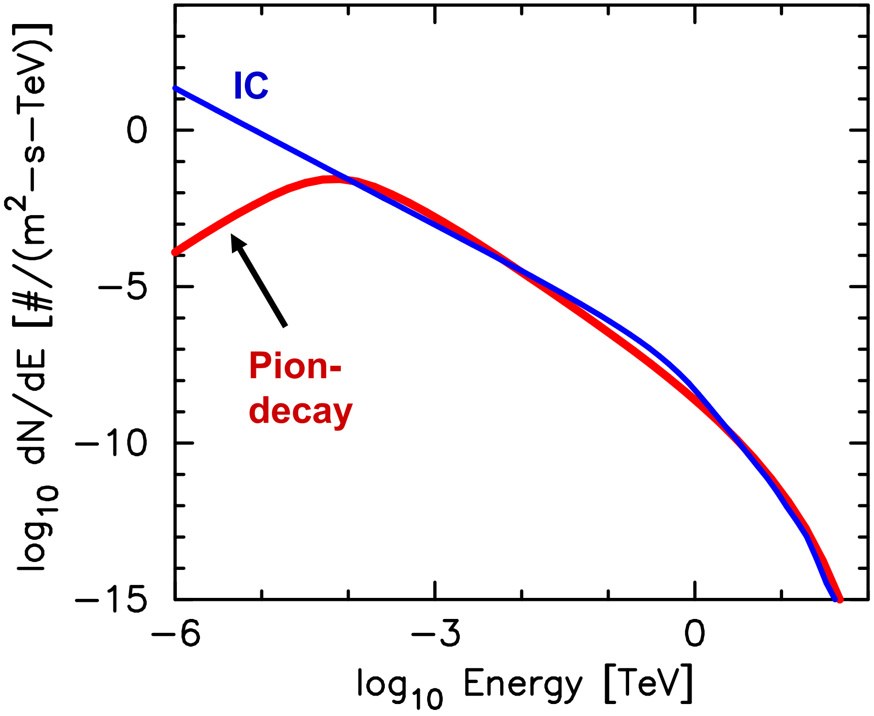
Ellison, Decourchelle, & Ballet 2004

Theory suggests shocks in SNRs can be extremely efficient.

~ 50% of SN explosion energy can easily be put into CRs (e.g. Dorfi etal)

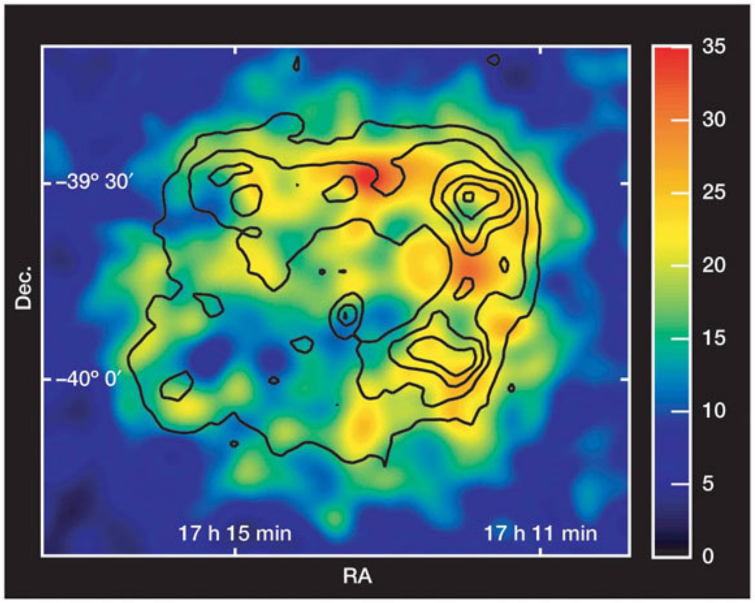
Only need to have efficient accel. over fraction of SNR blast wave to power CRs (e.g. Berezhko etal 2002)

Tycho model with: B_{ISM} = 15 μG, n_H = 0.5 cm^{-3}
B_2 = 70 μG Shock comp. ratio, R ~ 6



First ever Gamma-Ray image of a SNR – H.E.S.S. !!

Aharonian et al *Nature* 2004, 432, 75 - 77



Gamma-ray image of the SNR RX J1713.7 (G347). Linear **color scale** is in units of counts.

The superimposed (linearly spaced) **black contour lines show the X-ray surface brightness** as seen by ASCA in the 1–3 keV range.

Tycho model with: B_{ISM} = 15 μG, n_H = 0.5 cm^{-3}
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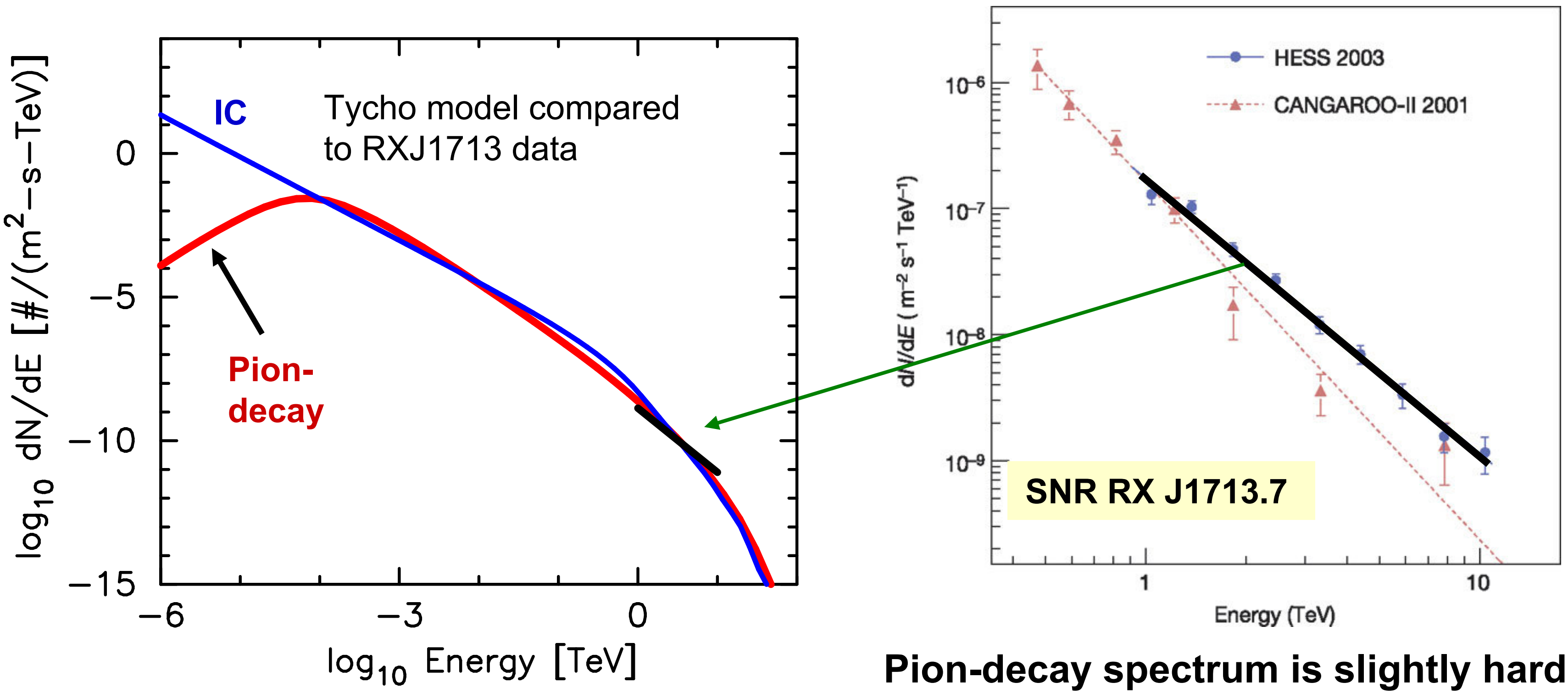
Aharonian et al *Nature* 2004, 432, 75 - 77



Pion-decay spectrum is slightly harder than inverse Compton in 1-10 TeV range – HESS spectra are pretty hard

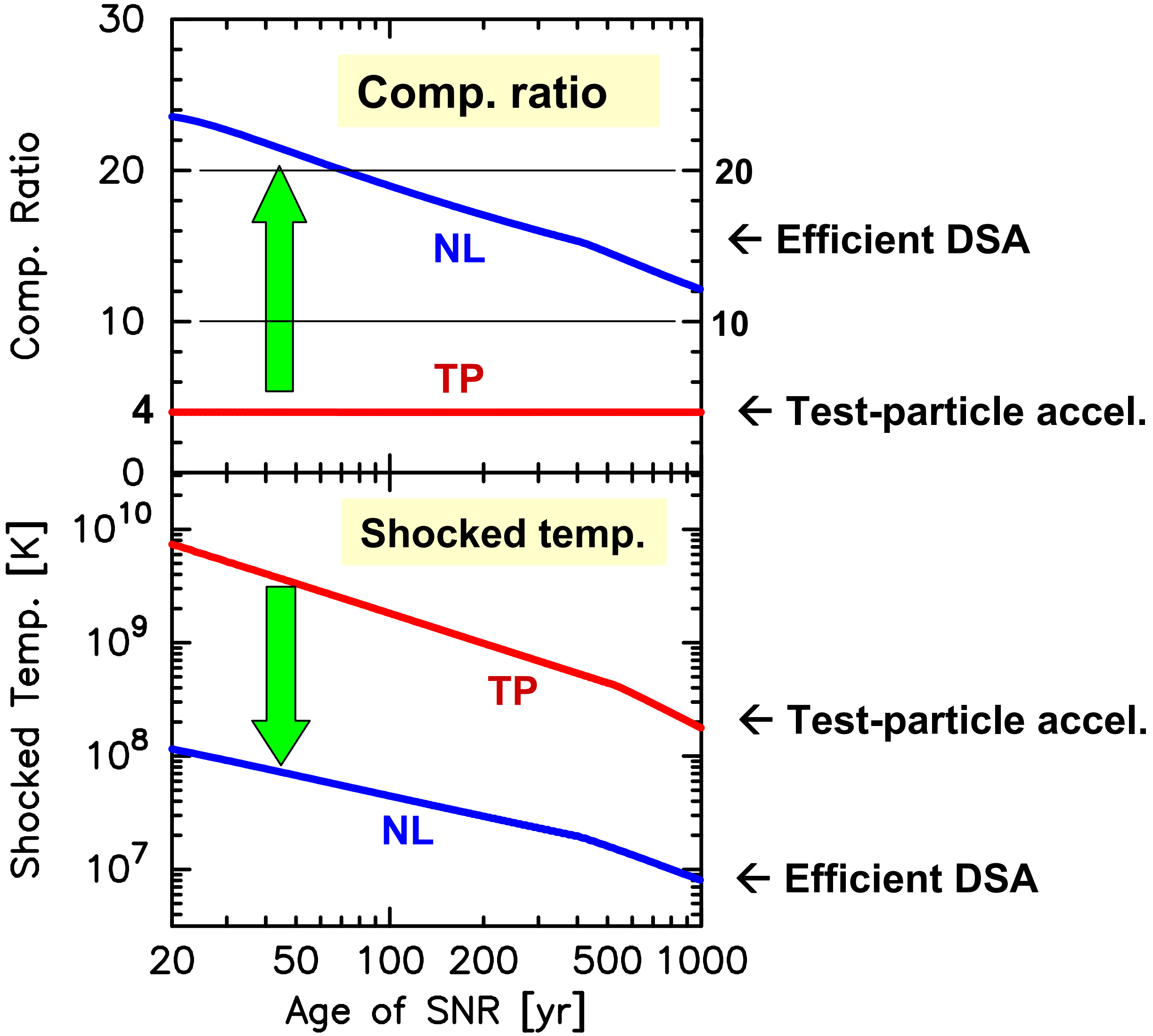
Are young SNRs accelerating IONs efficiently?

What is the electron/proton ratio of accelerated particles?

Is the B-field large and amplified by large factors over B_{ISM}?

Indirect evidence may come from morphology of SNRs

Forward shock values in CR-hydro simulation for low B_{ISM} models with just B-field compression

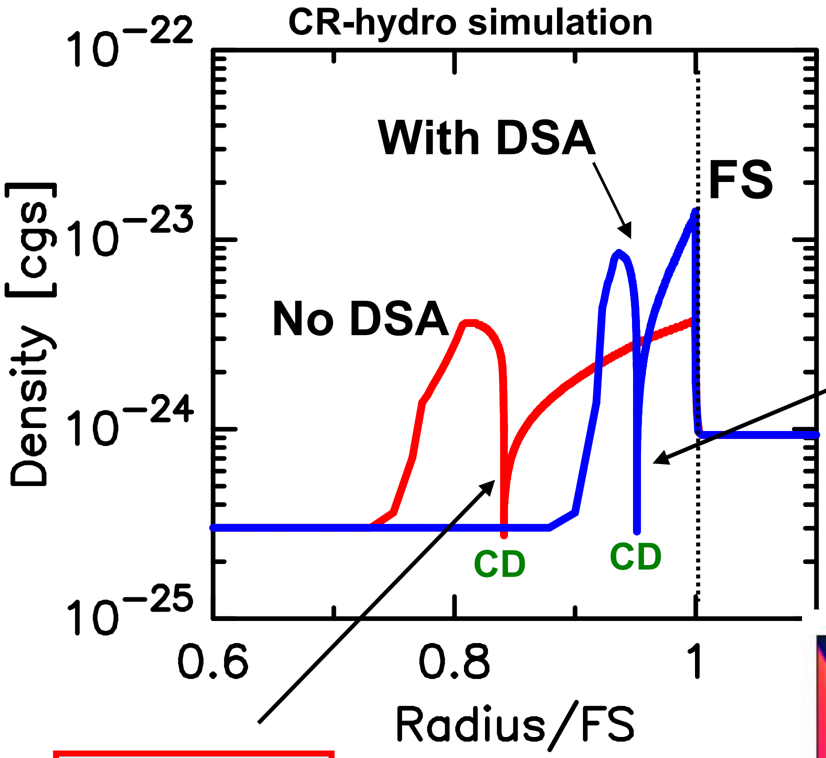


Increase in compression ratio and

Decrease in shocked temperature with efficient CR acceleration

These are large effects when B_{ISM} is low

Compression ratios >> 4 should clearly show in morphology



Power law ejecta distribution with no pre-SN stellar wind

Ellison, Decourchelle & Ballet 2004

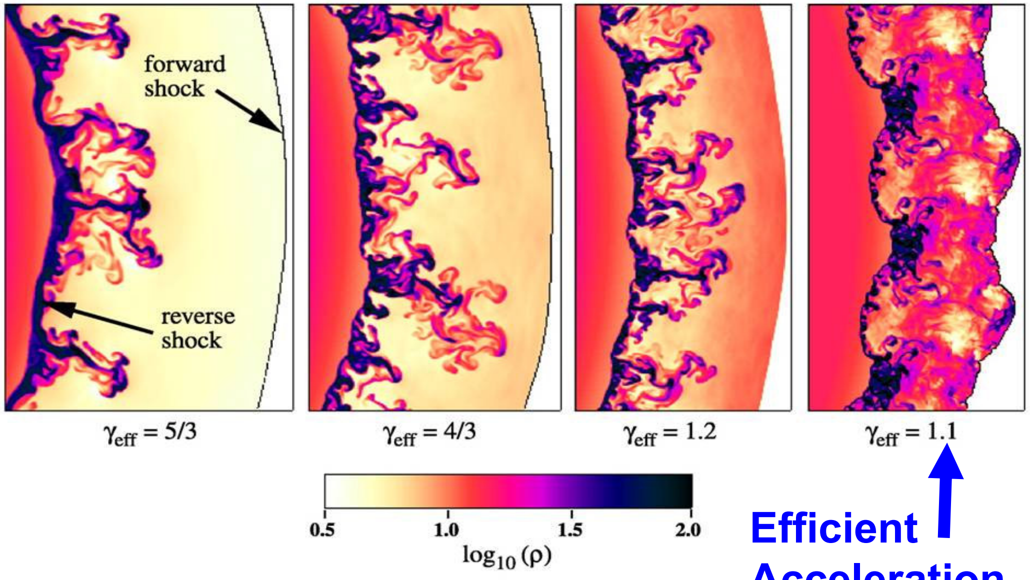
1-D, spherically symmetric hydro simulation of SNR with nonlinear DSA coupled to hydrodynamics

$$\frac{R_{CD}}{R_{FS}} > 0.95$$

$$\frac{R_{CD}}{R_{FS}} \sim 0.85$$

vary γ_{eff} effective

No acceleration



Efficient Acceleration

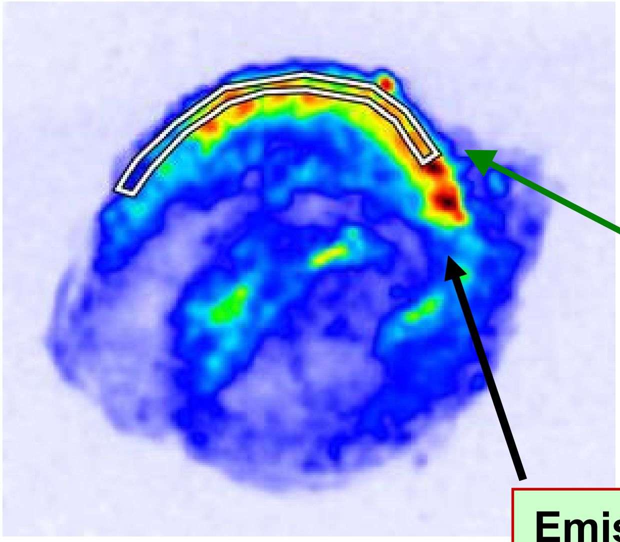
2-D Hydro simulation Blondin & Ellison 01

Signature of efficient diffusive shock acceleration:

Interaction region between RS and FS narrower & denser than expected

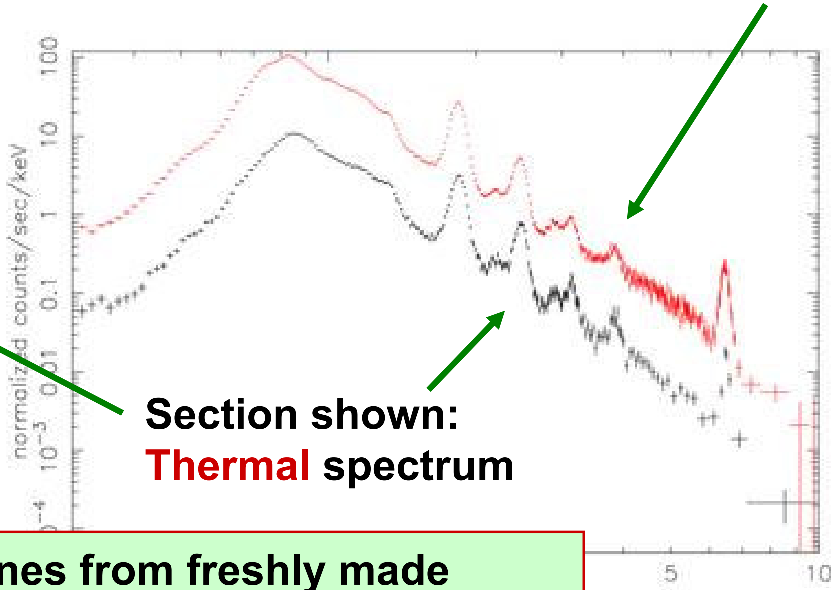
Shocked proton temperature less than expected

Chandra obs. of Kepler's SNR



Entire remnant

counts/sec/keV



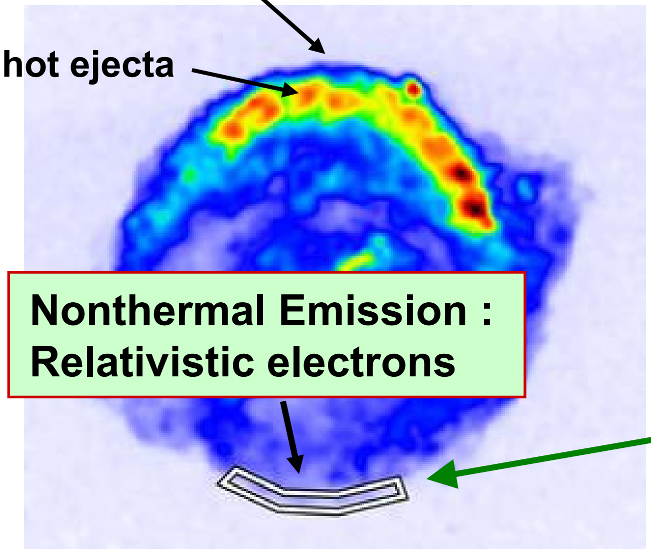
Section shown:
Thermal spectrum

Emission lines from freshly made elements ► Hot ejecta from explosion

energy, keV

non-thermal

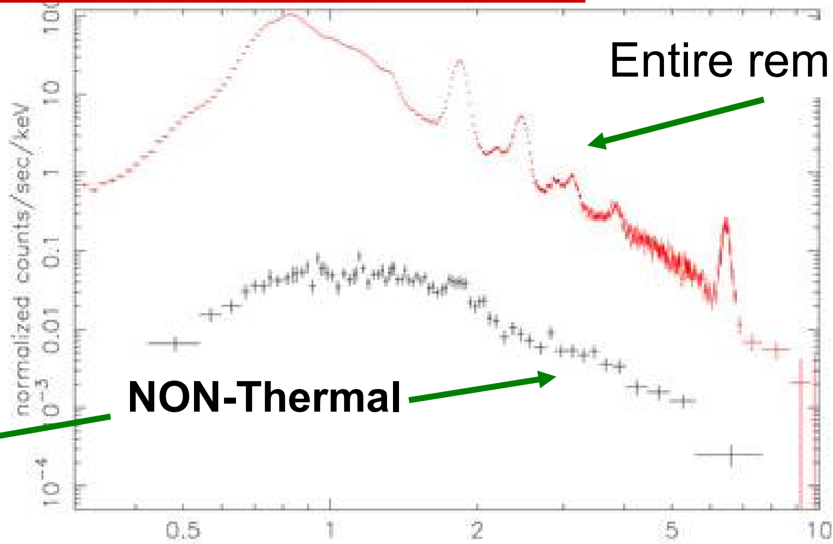
hot ejecta



Nonthermal Emission : Relativistic electrons

Entire remnant

counts/sec/keV



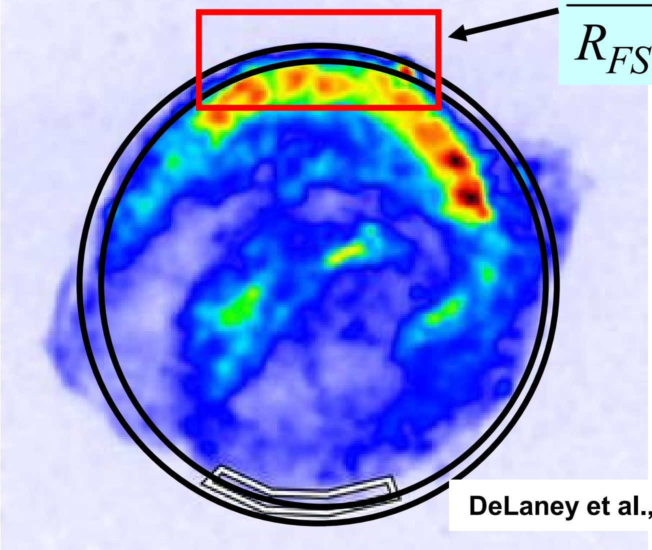
NON-Thermal

energy, keV

DeLaney et al., 2002, ApJ 580, 914

Morphology of Young Supernova Remnants (SNRs)

Kepler's SNR



$$\frac{R_{CD}}{R_{FS}} \geq 0.9$$

DeLaney et al., 2002

In some young SNRs, **outer blast wave shock is extremely close to inner shocked ejecta material** or contact discontinuity (CD).

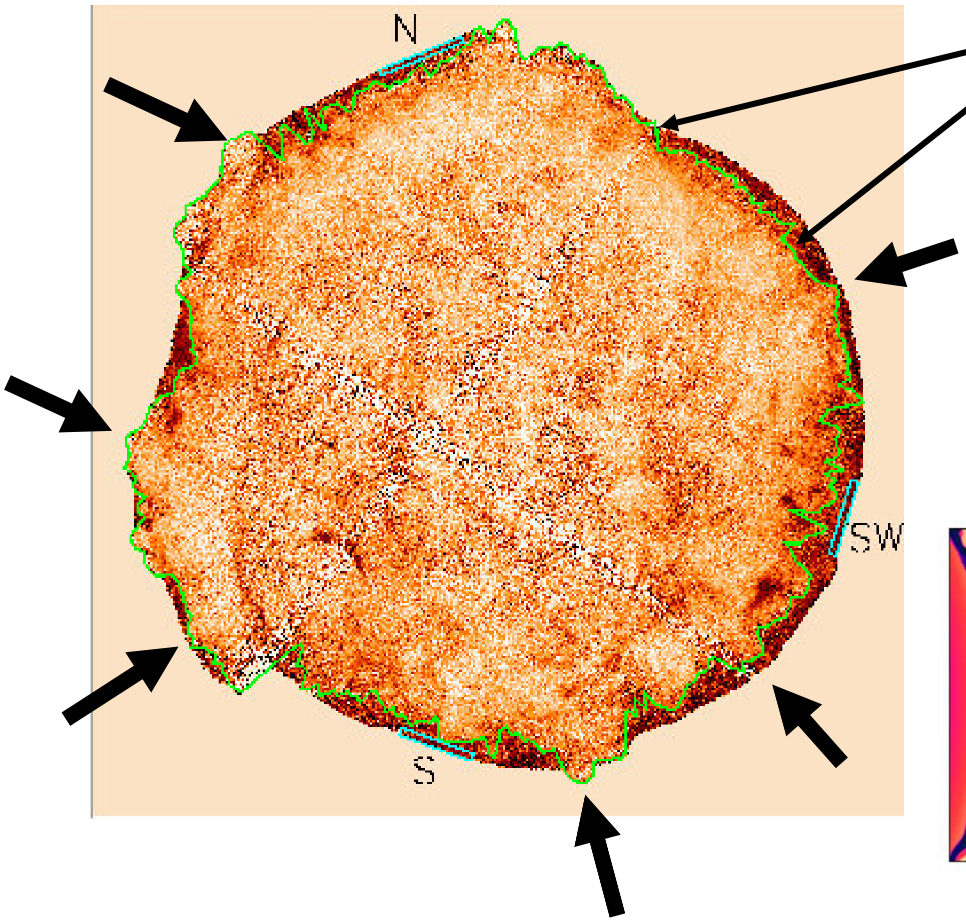
In **hydro models without efficient CR production**, the outer, **forward shock (FS) is well separated from the ejecta or CD**.

Explanation: SNR shock is efficiently accelerating cosmic rays, i.e., ~50% of shock ram K.E. goes into relativistic IONS producing large shock compression ratios

This may be most direct evidence for the efficient production of Cosmic Ray Ions in SNRs

Some references for large compression ratios ($r>7$) in DSA: Eichler 84; Ellison & Eichler 84; Jones & Ellison 91; Berezhko & Ellison 99; Decourchelle etal 2000; Ellison etal 2004

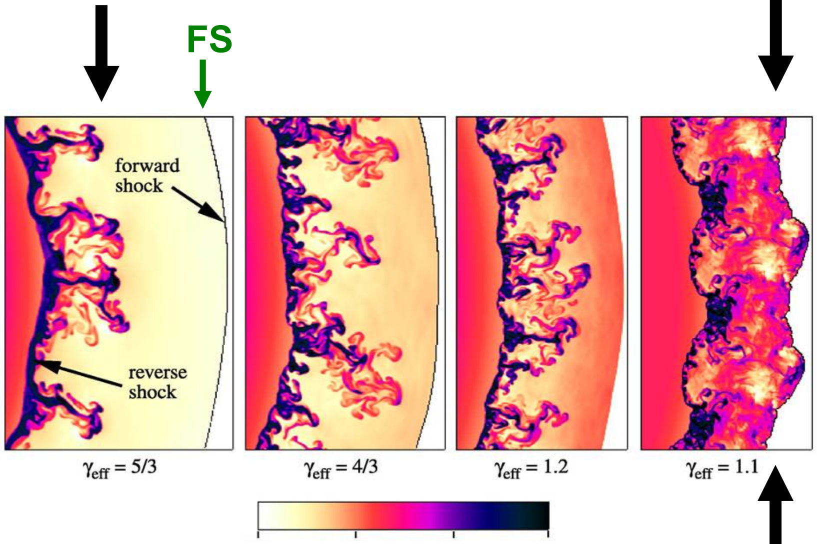
Chandra observations of Tycho's SNR
(Warren et al. 2005)



Green line is contact discontinuity (CD)

CD lies close to outer blast wave determined from 4-6 keV (non-thermal) X-rays

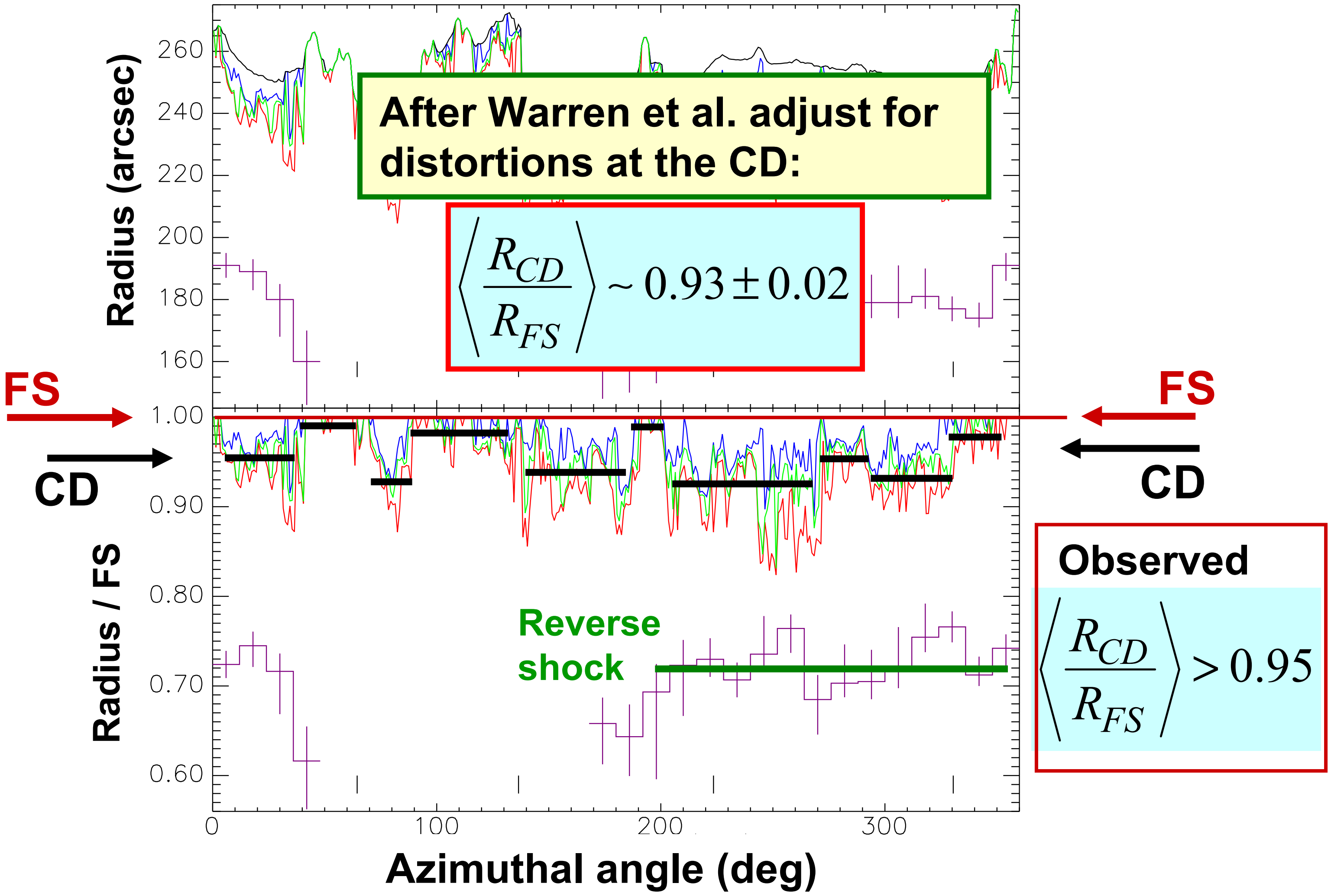
No acceleration



Efficient DSA acceleration

2-D Hydro simulation **Blondin & Ellison 2001**

Chandra observations of Tycho's SNR (Warren et al. 2005)



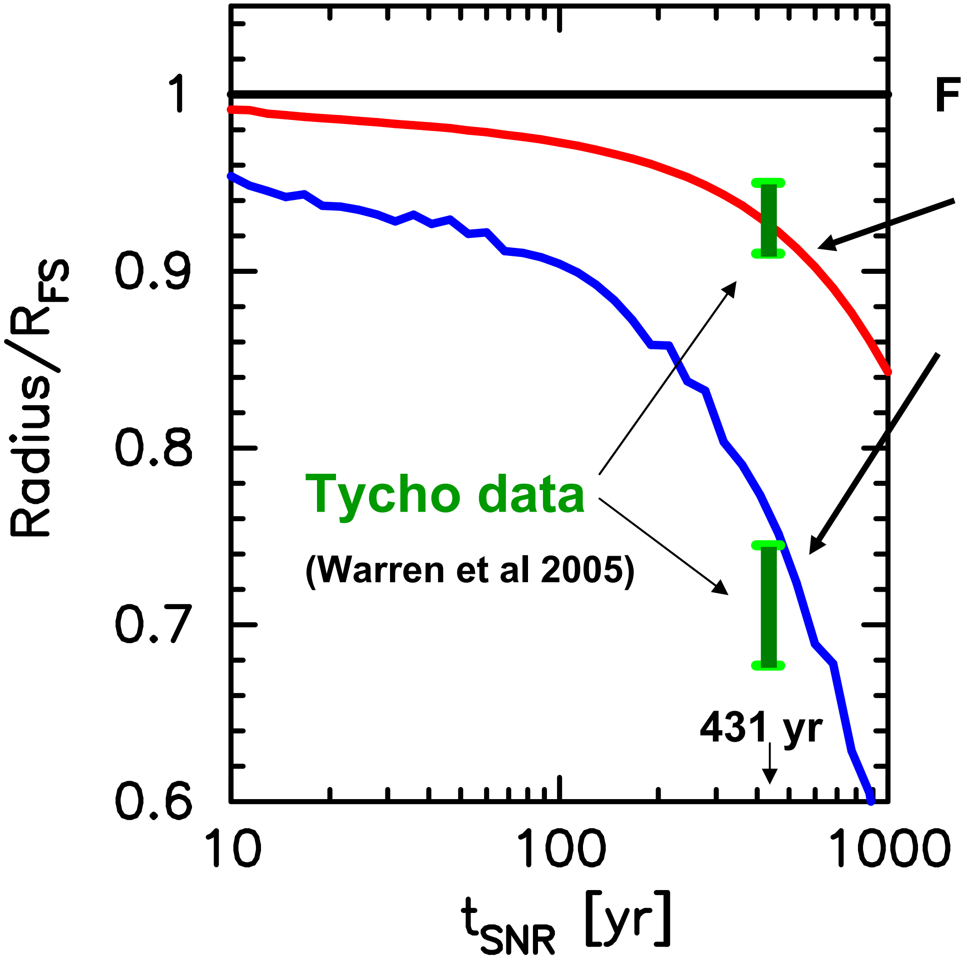
After Warren et al. adjust for distortions at the CD:

$$\left\langle \frac{R_{CD}}{R_{FS}} \right\rangle \sim 0.93 \pm 0.02$$

Observed

$$\left\langle \frac{R_{CD}}{R_{FS}} \right\rangle > 0.95$$

Tycho's SNR



SNR model with efficient shock accel.

(Ellison, West, Butt, Blasi et al. in preparation)

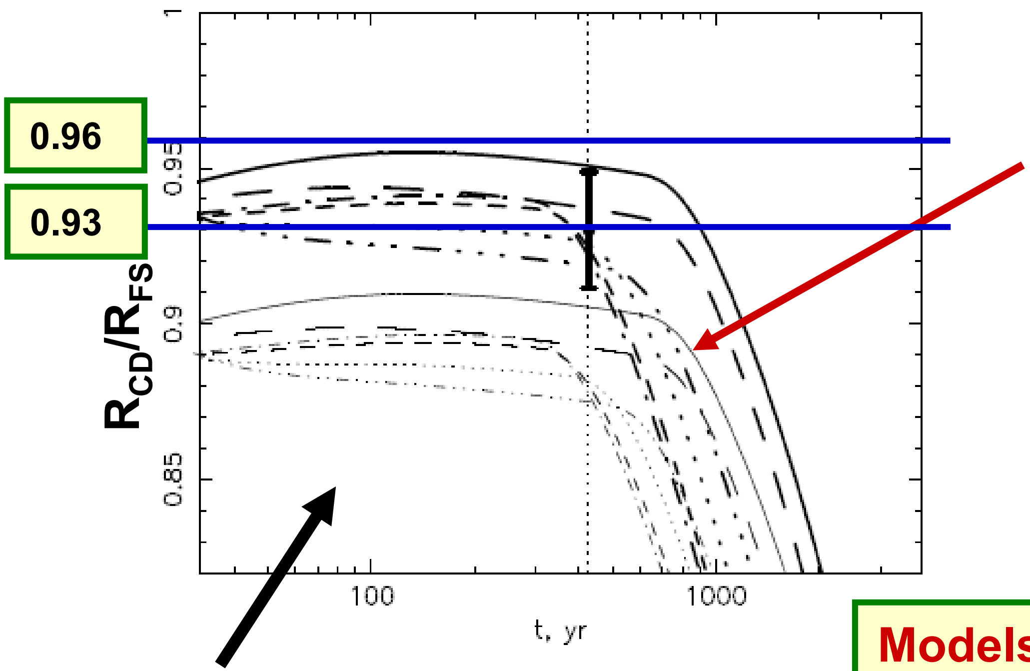
Efficient diffusive shock acceleration of IONs can easily explain data,

Test-particle acceleration cannot

BUT shock compression ratio must be fairly high: $R_{tot} \geq 10$

$r_{tot} \sim 6$ will not fit !!

Volk, Berezhko & Ksenofontov astro-ph/0512086



This model assumes high B-field, $B_{ISM} \sim 40\text{-}50\ \mu G$

High B gives comp. ratio $r_{tot} \sim 6$

Model R_{CD}/R_{FS} outside of error bars

NOTE: $R_{CD}/R_{FS} \approx 0.93$ already has correction for distorted contact discontinuity.

Without correction $R_{CD}/R_{FS} \approx 0.96$

Volk, Berezhko & Ksenofontov 2005 model for morphology of Tycho – I believe that the distortions of CD are corrected for twice by VBK

Models (Volk et al. or Ellison et al.) with r = 6 don't fit observed R_{CD}/R_{FS} !!

Assumption in models is that CRs produce Alfvén wave turbulence in the shock precursor (e.g., McKenzie & Volk 82).

The turbulence saturates and heats the cold, incoming plasma transferring energy from CRs to heat. This heating weakens the subshock and damps the acceleration. The B-field is not determined self-consistently in this model

The larger B_{ISM}, the greater the heating, the less efficient the acceleration' and the smaller r_{tot}.

Dilemma:

Morphology (R_{CD}/R_{FS}) requires large compression ratios ($r > 10$) which requires small $B_{ISM} \sim 3 - 10\ \mu G$

Broad band fits require large $B_{shocked} > 240\ \mu G$ but, if only compression of the B-field occurs, must start with $B_{ISM} \sim 50\ \mu G$ and this produces smaller compression ratios $r \sim 6$

Assumption in models is that CRs produce Alfvén wave turbulence in the shock precursor (e.g., McKenzie & Volk 82).

The turbulence saturates and heats the cold, incoming plasma transferring energy from CRs to heat. This heating weakens the subshock and damps the acceleration. The B-field is not determined self-consistently in this model

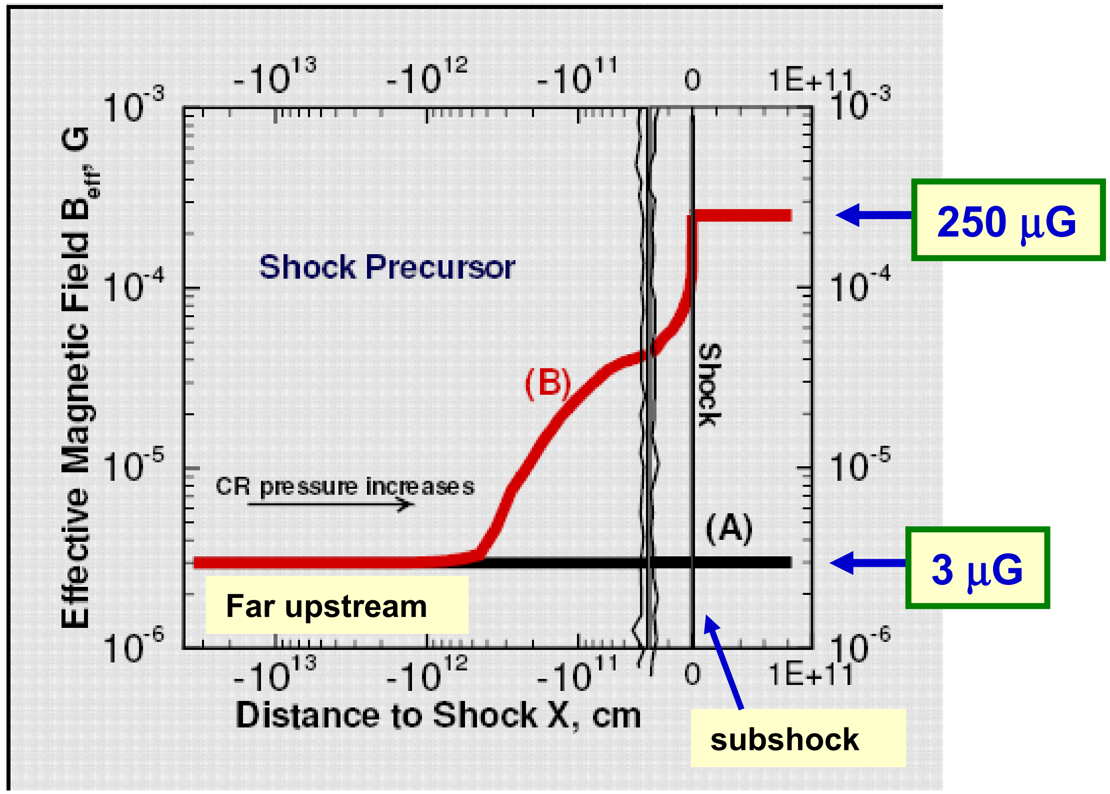
The larger B_{ISM}, the greater the heating, the less efficient the acceleration' and the smaller r_{tot}.

Is there a way to start with $B_{ISM} \sim 3\ \mu G$ and end up with $B_{shocked} > 200\ \mu G$?

Magnetic field amplification may be the answer ??

Note difference between B-field compression in shock and B-field amplified by DSA process (Bell & Lucek scheme)

Poster: Andrey Vladimirov, Ellison & Bykov



This **preliminary** result is for a parallel shock with NO compression of the B-field.

The increase from B_{ISM}=3 μG to B_{shock}=250 μG is <u>amplification</u> by nonlinear processes.

Generalized Bell & Lucek approach for B-field amplification is imbedded in a Monte Carlo simulation of nonlinear shock acceleration.

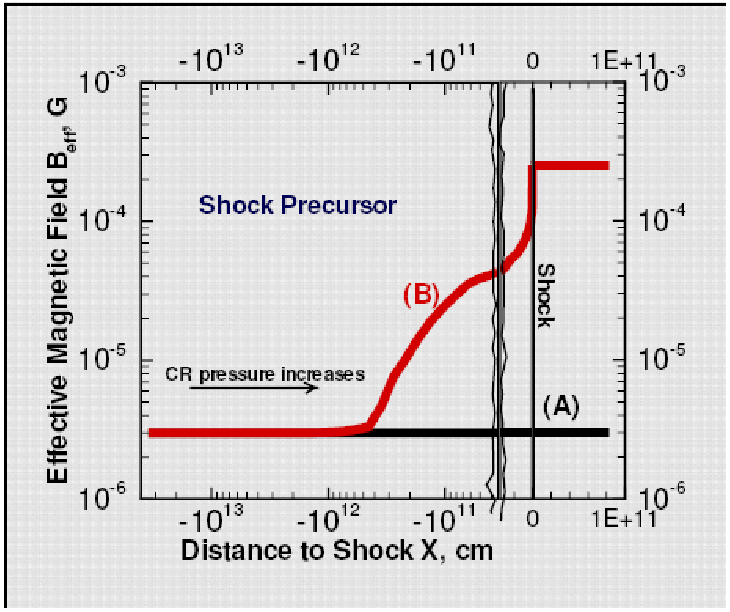
Aim is to derive the

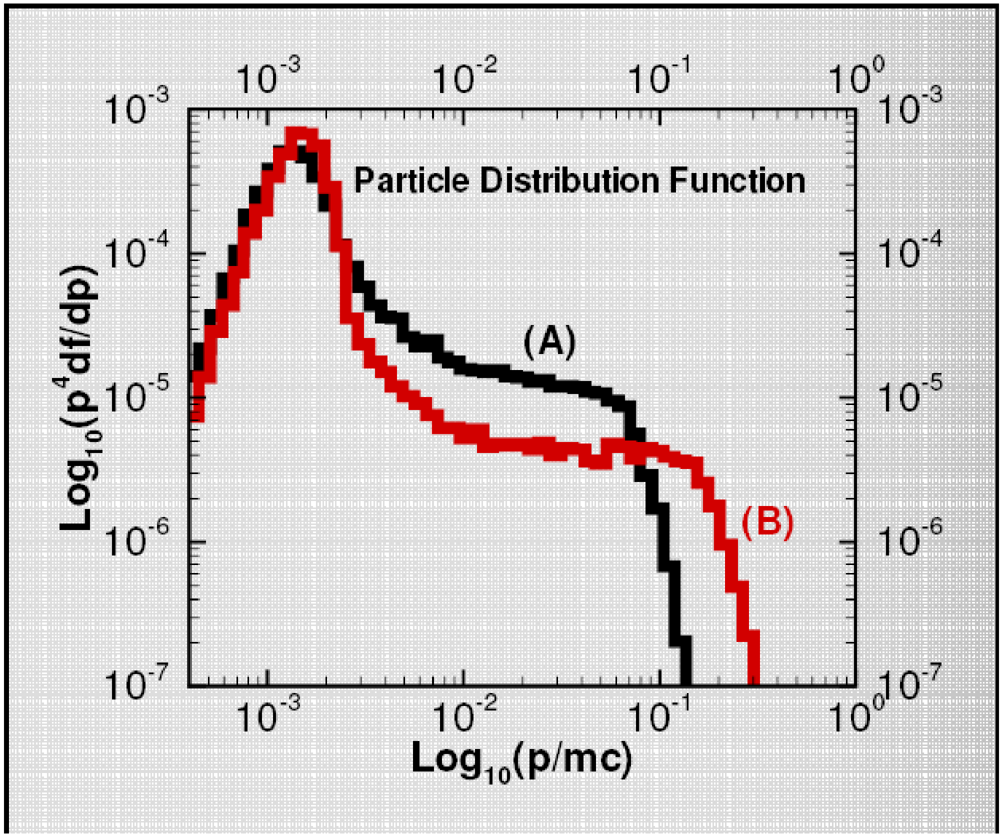
(a) particle distribution,

(b) nonlinear shock structure, and

(c) self-generated stochastic fields

self-consistently without assuming that $\Delta B/B < 1$



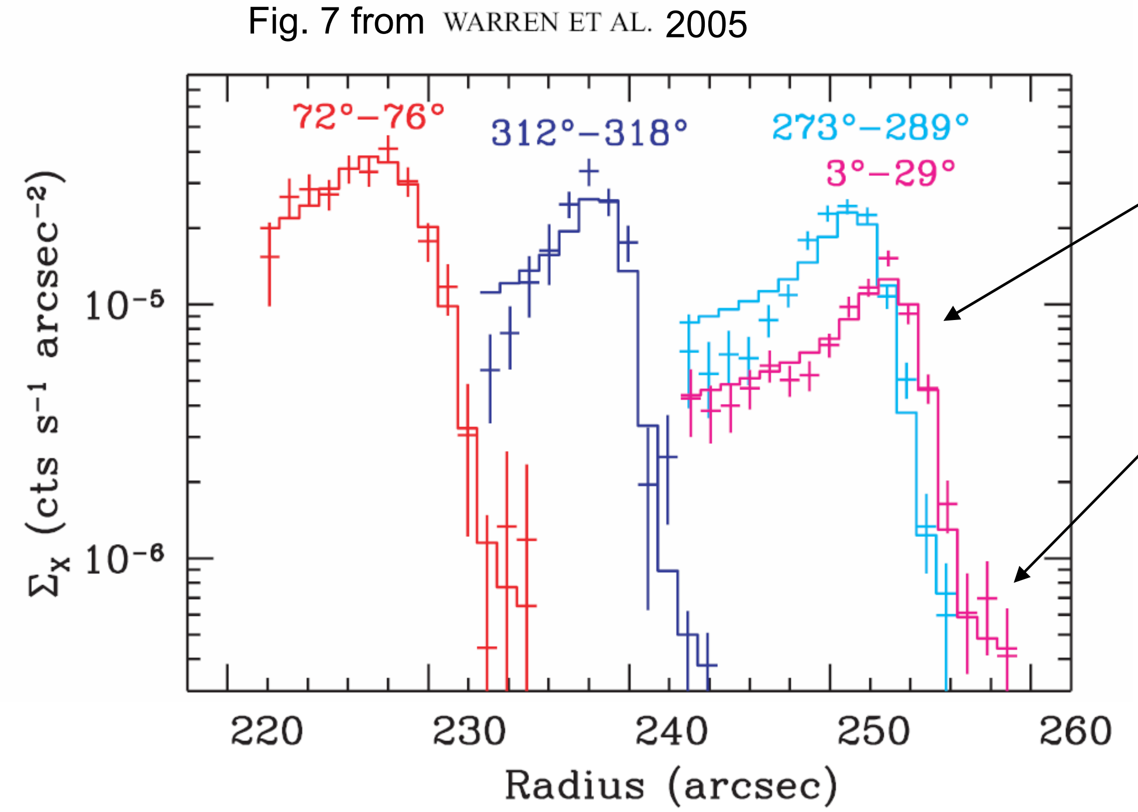


B-field amplification translates to higher energy cosmic rays

These are preliminary results: stay tuned for latest developments

Additional constrains on magnetic field come from observations of synchrotron emission in forward shock precursor

Fig. 7 from WARREN ET AL. 2005



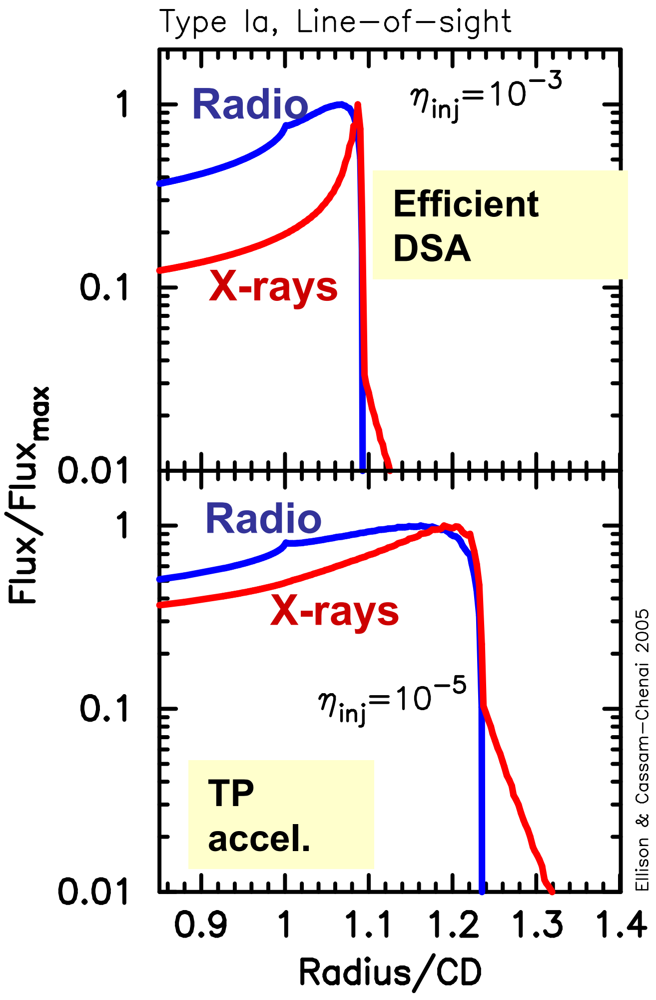
line-of-sight projection effect, NOT precursor

Precursor in front of forward shock (below Chandra sensitivity?)

Tycho's SNR, 4-6 keV surface brightness profiles at outer blast wave

More evidence of eff. Accel.

Line-of-sight profiles for parameters typical of SN1006

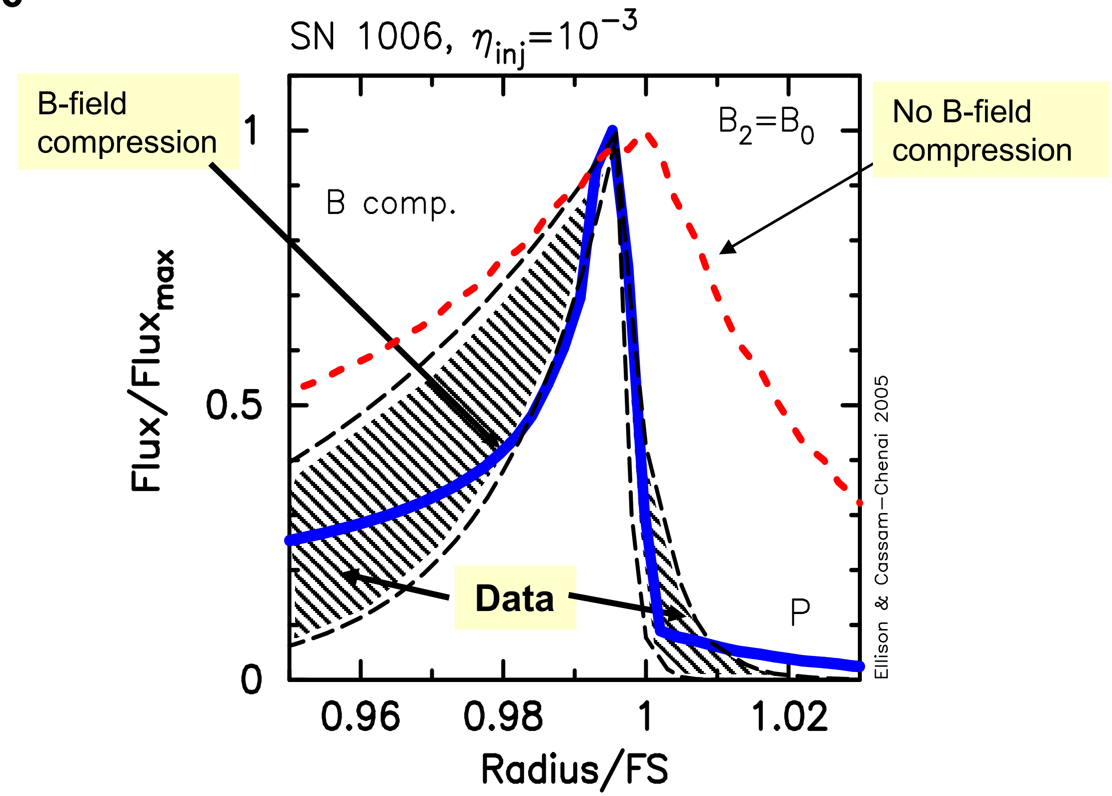


Efficient DSA

TP accel.

Ellison & Cassam-Chenai 2005

Comparison with SN1006 data (Bamba etal 03)



B-field compression

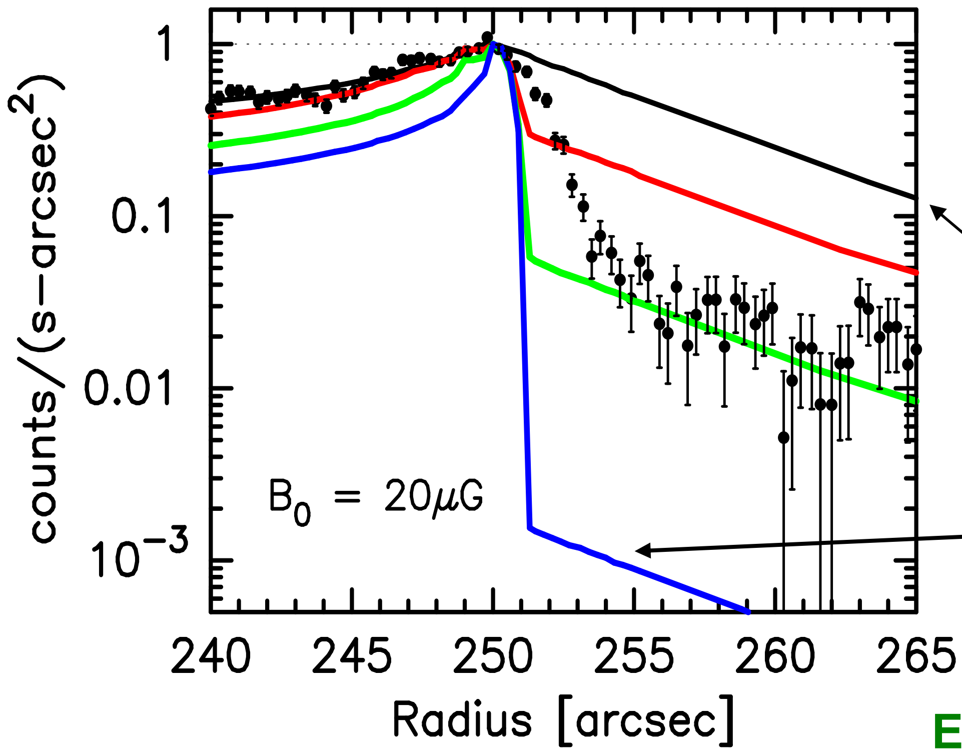
No B-field compression

Data

Sharply peaked X-rays at forward shock is evidence that B-field increases fairly sharply at shock.

See also Berezhko, Ksenofontov & Volk 02; and Vink & Laming 03

Tycho's SNR X-ray Precursor



Only difference in these models is the assumed compression of the B-field (preliminary results; models not folded through Chandra response)

$B_2 = B_0$ (no compression)

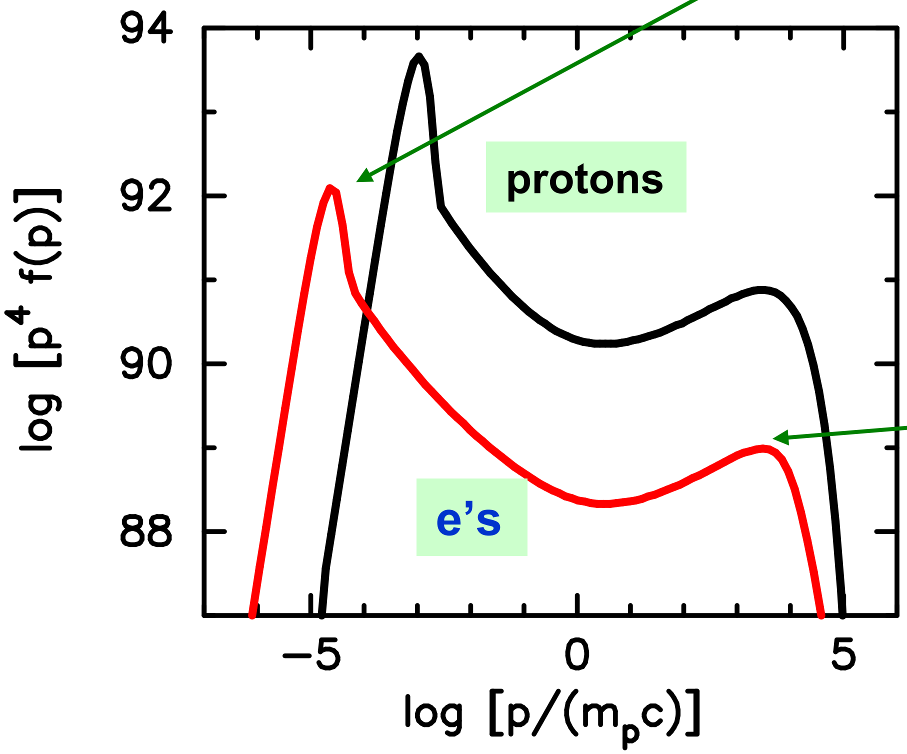
$B_2 = r_{tot} * B_0$ (maximum compression)

with Y. Butt & J. West (in preparation)

These models do not include magnetic field amplification

Even upper limits on X-ray precursor should provide important constraints on magnetic field compression and/or amplification in precursor

Thermal X-ray emission (with Dan Patnaude & Pat Slane; in preparation)



CR acceleration modifies shocked density and temperature from test-particle values,

modifies $\int n_e dt$ in interaction region between forward and reverse shocks

→ thermal X-ray emission depends on DSA

DSA produces TeV electrons → nonthermal X-ray synch. Matching thermal X-ray data may give [e/p] injection ratio

DSA = diffusion shock acceleration

Few words on Fermi acceleration in relativistic shocks

Relativistic Shocks: Shock speed approaches c ($V_{sk} = u_0 \sim c$)

Main applications in

1) gamma-ray bursts – fireball, internal shocks, afterglow
2) Pulsar winds
3) Radio jets

More difficult to understand than non-relativistic shocks because:

1) Particle speed never >> shock speed. Can't use diffusion approx.
   → No simple test-particle power law derivable from first principles
2) Acceleration, even in test-particle limit, depends critically on scattering properties (i.e., self-gen. B-field), which are unknown
3) No direct observations of relativistic shocks in heliosphere
4) PIC simulations are harder – must be 3-D
5) Afterglow models require simultaneous accel. of electrons with ions
6) Second-order Fermi likely to be important (e.g., Ostrowski et al; Virtanen)

Relativistic Shocks: Shock speed approaches c ($V_{sk} = u_0 \sim c$)

Peacock (1981): One of the first looks at relativistic shock acceleration

Kirk & Schneider (1987): Monte Carlo methods applied to Fermi acceleration in relativistic shocks (TP, parallel shocks)

Heavens & Drury (1988): (TP, parallel shocks)

Ellison, Jones, & Reynolds (1990): Monte Carlo results (TP, parallel shocks)

Kirk & Heavens (1989); Ballard & Heavens (1991); Ostrowski (Oblique shocks) (1991,93): First attempts to study Fermi accel. in oblique, rel. shocks (TP only)

Vietri (1995): application to gamma-ray bursts

Bednarz & Ostrowski (1996);

Achterberg, Gallant, Kirk & Guthmann (2001)

Ellison & Double (2002): First calculation of NL DSA in rel. shocks.

Meli & Quenby (2003) (TP)

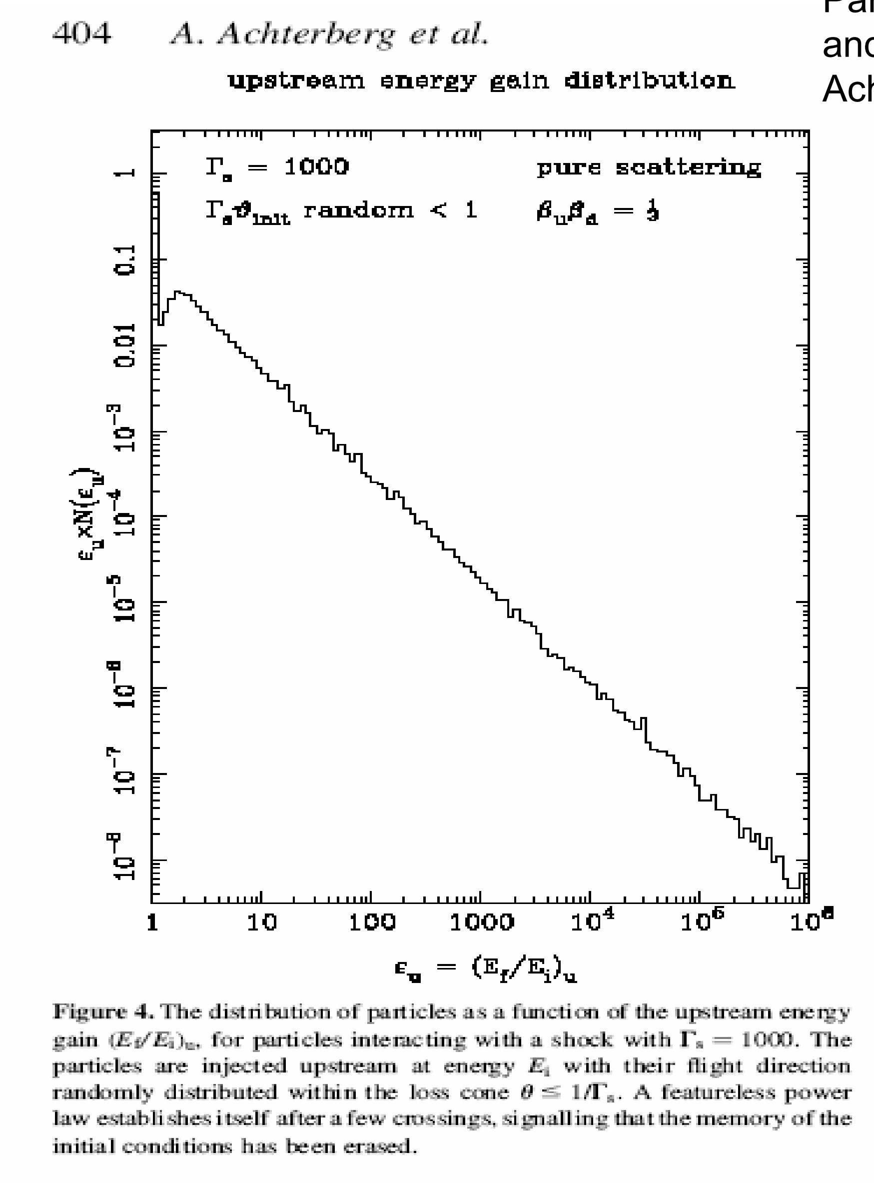
Niemiec & Ostrowski (2004): trajectories integrated in assumed magnetic field turbulence (TP)

Double et al. (2004): Relativistic jump conditions

Issues for GRBs:

In fireball model, assumption is that internal shocks in expanding fireball convert, via DSA, bulk motion of cold plasma into internal energy of electrons. Electrons then radiate

- **Because of energy budget requirements, DSA is assumed to be efficient → TP approx. not good enough**
- **Internal shocks likely to be only mildly relativistic → Non-linear effects important**
- **Unless fireball is lepton dominated, must consider partition of energy between electrons and ions. Standard shock acceleration should put most energy into heavy particles, not electrons**
- **Afterglow comes from relativistic fireball expanding into interstellar medium → Have to confront acceleration of mixed plasma & shock will slow and go through a mildly rel. phase where NL effects will be important**
- **If want to accelerate UHECRs with GRBs (e.g., Waxman …) than must accelerate ions together with electrons**
- **Shape of accelerated electron spectrum – interpretations of GRB spectra suggest that electron spectrum has a low energy cutoff → $E_{min}(e^-) \sim \gamma\, m_p\, c^2$, NOT $\gamma\, m_e\, c^2$ this is not easy to obtain in standard models of DSA**



404 *A. Achterberg et al.*

Figure 4. The distribution of particles as a function of the upstream energy gain $(E_f/E_i)_u$, for particles interacting with a shock with $\Gamma_s = 1000$. The particles are injected upstream at energy E_i with their flight direction randomly distributed within the loss cone $\theta \le 1/\Gamma_s$. A featureless power law establishes itself after a few crossings, signalling that the memory of the initial conditions has been erased.

Particle acceleration by ultrarelativistic shocks: theory and simulations
Achterberg, Gallant, Kirk & Guthmann 2001

Find so-called “universal power law”

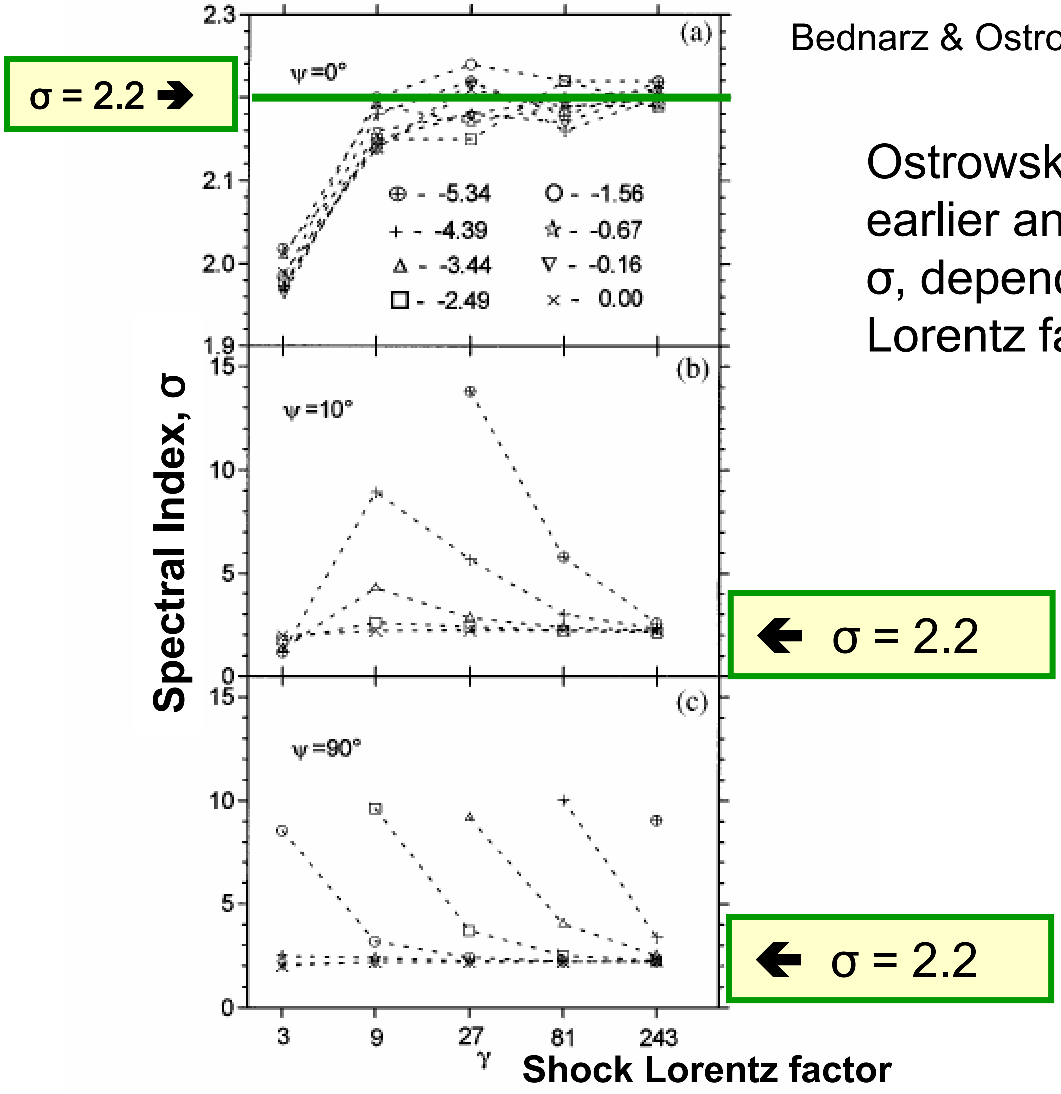
$$f(p) \propto p^{-4.2} \quad \left(N(E) \propto E^{-2.2}\right)$$

This result is for ultra-relativistic and

“fine” scattering limits

(also for parallel shocks)

Bednarz & Ostrowski 98



σ = 2.2 ➔

🡐 σ = 2.2

🡐 σ = 2.2

FIG. 1. The simulated spectral indices σ for particles accelerated at shocks with different Lorentz factors γ. Results for a given $\kappa_\perp/\kappa_\parallel$ are joined with lines; the respective value of $\log_{10}\kappa_\perp/\kappa_\parallel$ is marked by the point shape (see upper panel). The results for different magnetic field inclinations ψ are given in the successive panels: (a) $\psi = 0°$, (b) $\psi = 10°$, and (c) $\psi = 90°$.

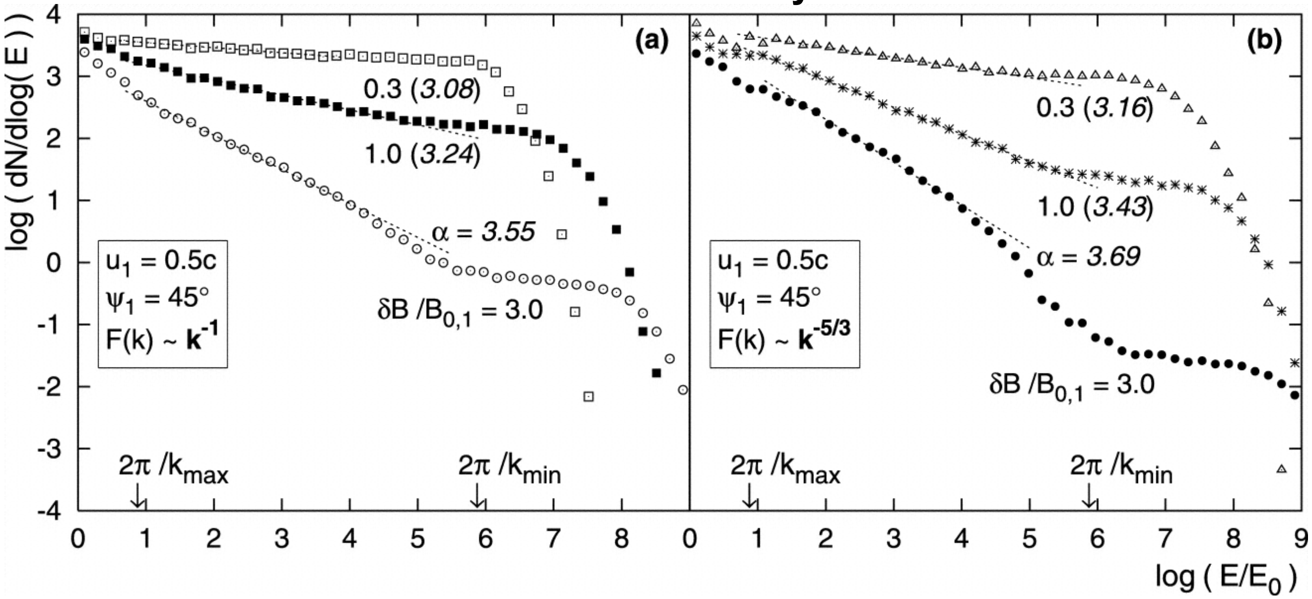
Ostrowski and co-workers found this earlier and showed that spectral index, σ, depended on shock obliquity and Lorentz factor

$$f(p) \propto p^{-4.2} \quad \left(N(E) \propto E^{-2.2}\right)$$

This result is for ultra-relativistic and “fine” scattering limits (also for parallel shocks)

Niemiec & Ostrowski 2004

Density distributions



V_{sk} = 0.5c

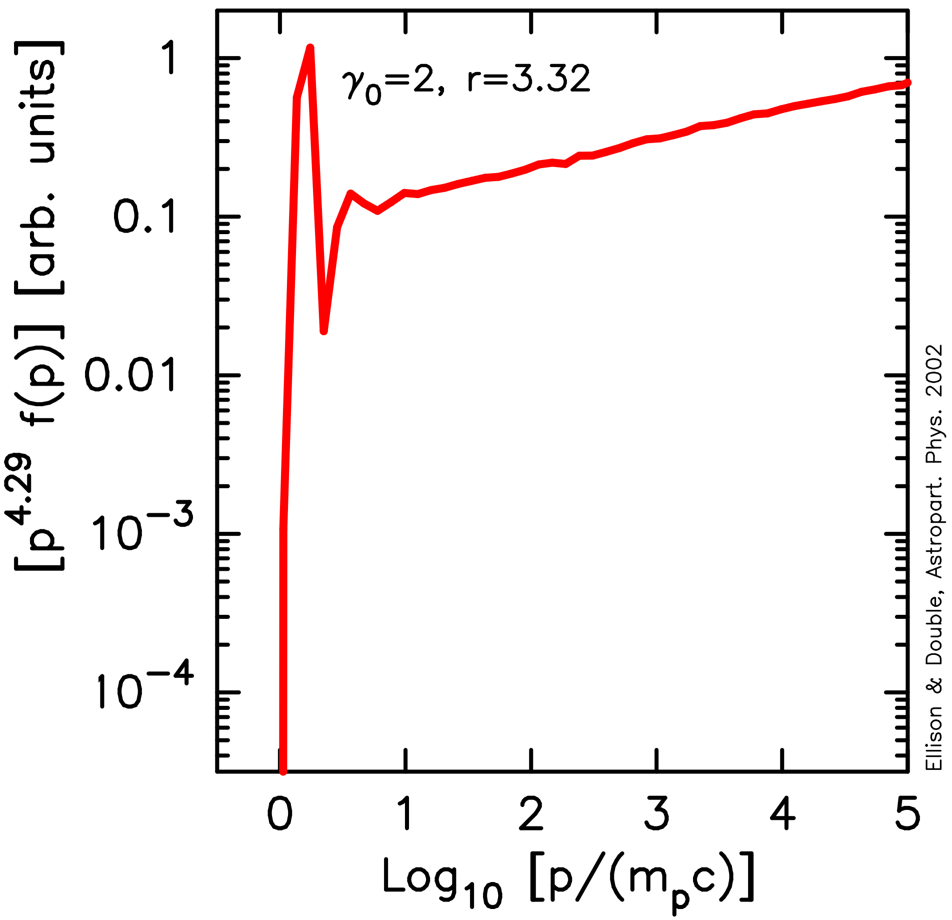
θ_{Bn} = 45°

Spectrum also depends on how particles scatter. Here, Niemiec & Ostrowski calculate particle trajectories in various magnetic field configurations, F(k).

➔ Spectrum not necessarily a power law

➔ Cutoffs if no magnetic turbulence at relevant scales

Remember: Acceleration in relativistic shocks depends critically on details of diffusion and details of diffusion are unknown



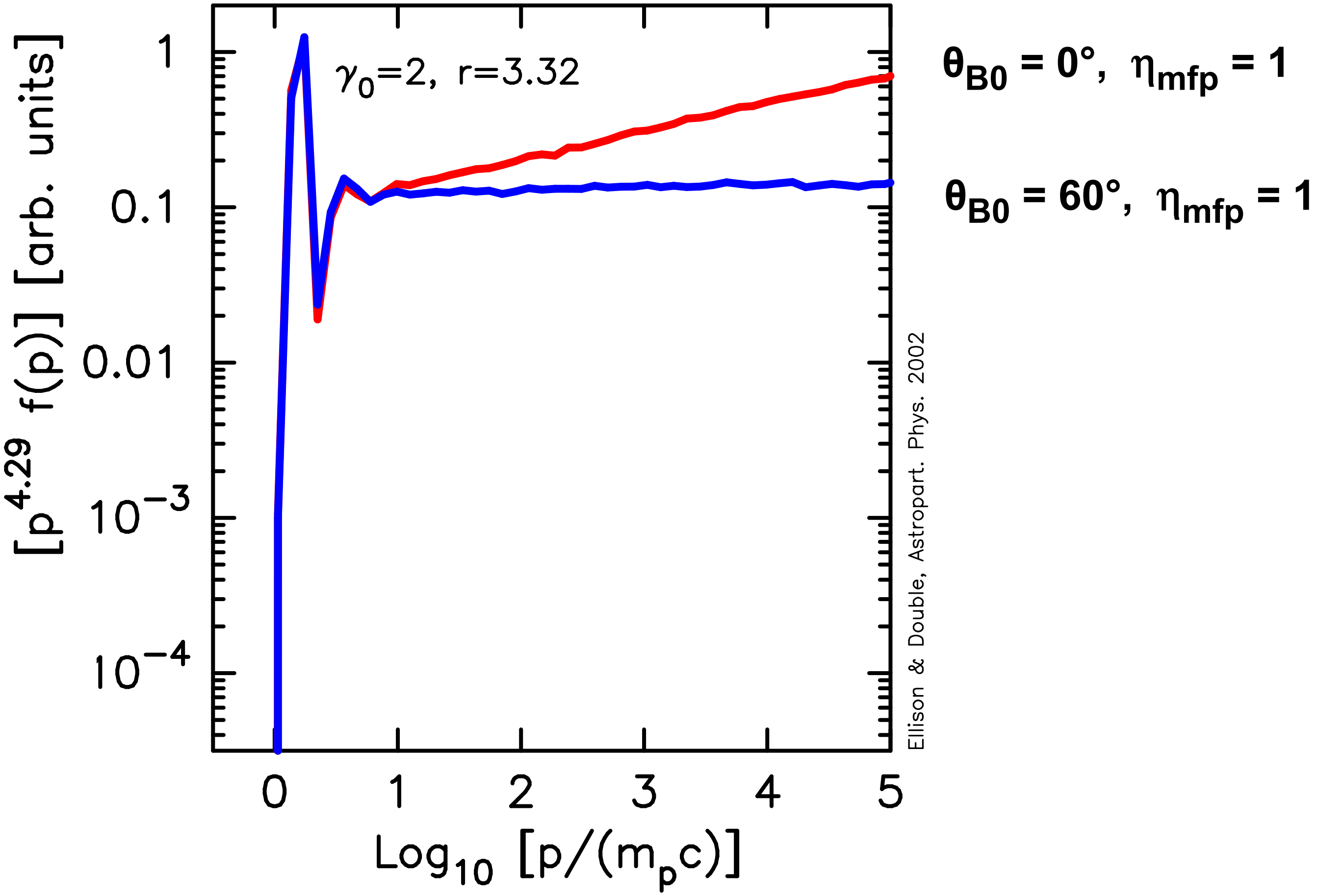
Ellison & Double, Astropart. Phys. 2002

$\theta_{B0} = 0°$, $\eta_{mfp} = 1$

Shock Lorentz factor, γ_0 = 2

Trans-rel. shock

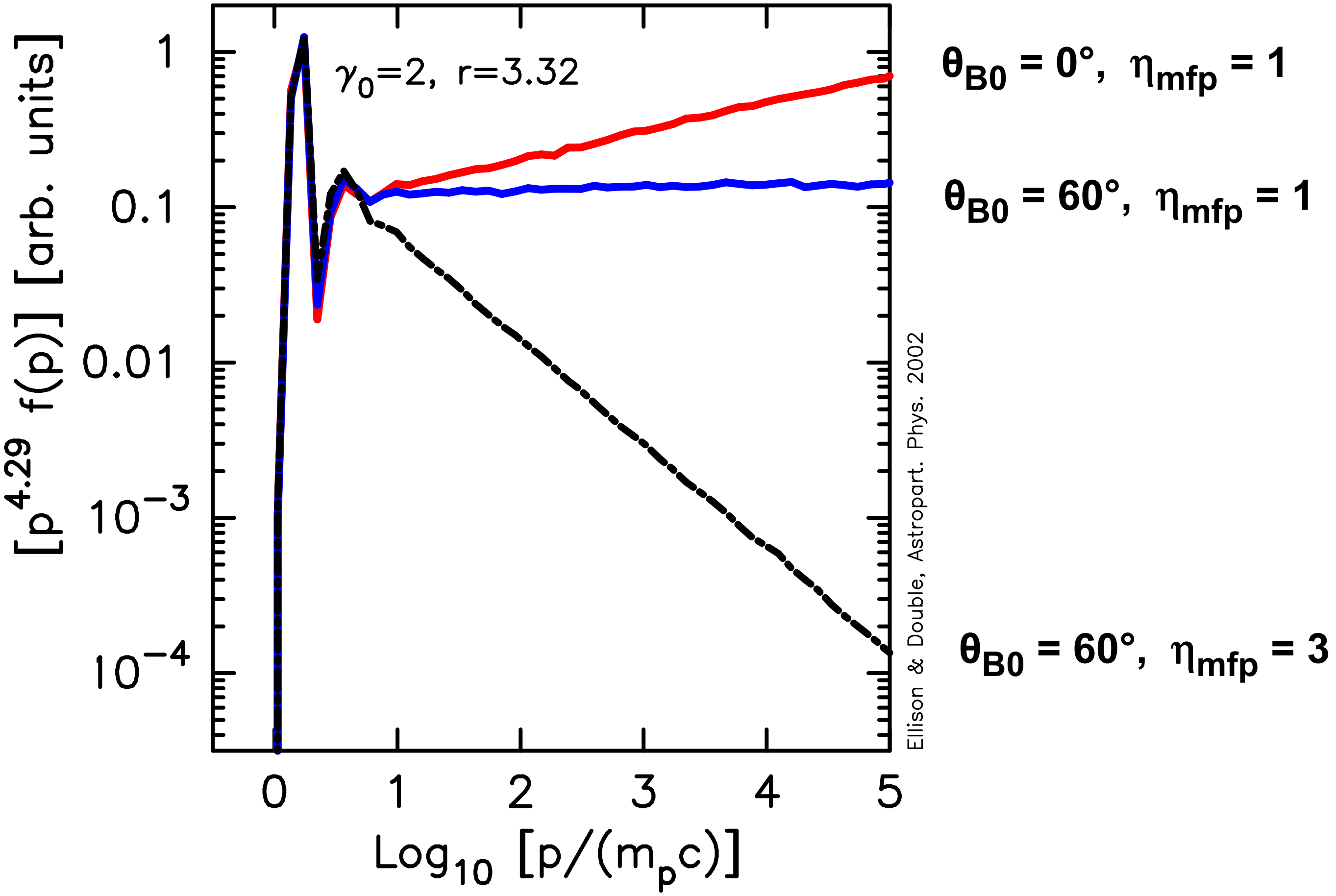
Test-particle results



Ellison & Double, Astropart. Phys. 2002

Shock Lorentz factor, γ_0 = 2

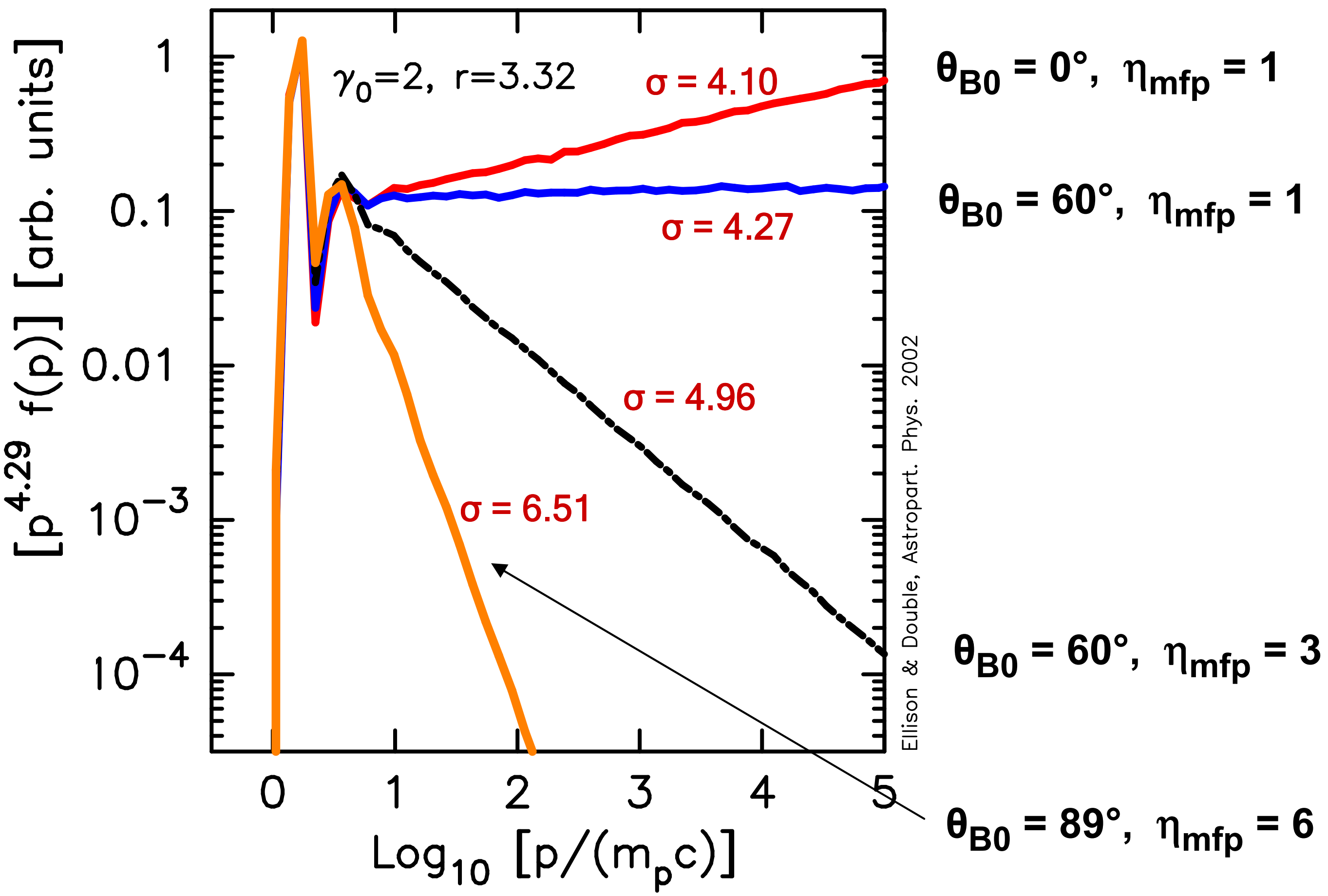
Test-particle results



Shock Lorentz factor, γ_0 = 2

Test-particle results

Test-particle results (Ellison & Double 04)

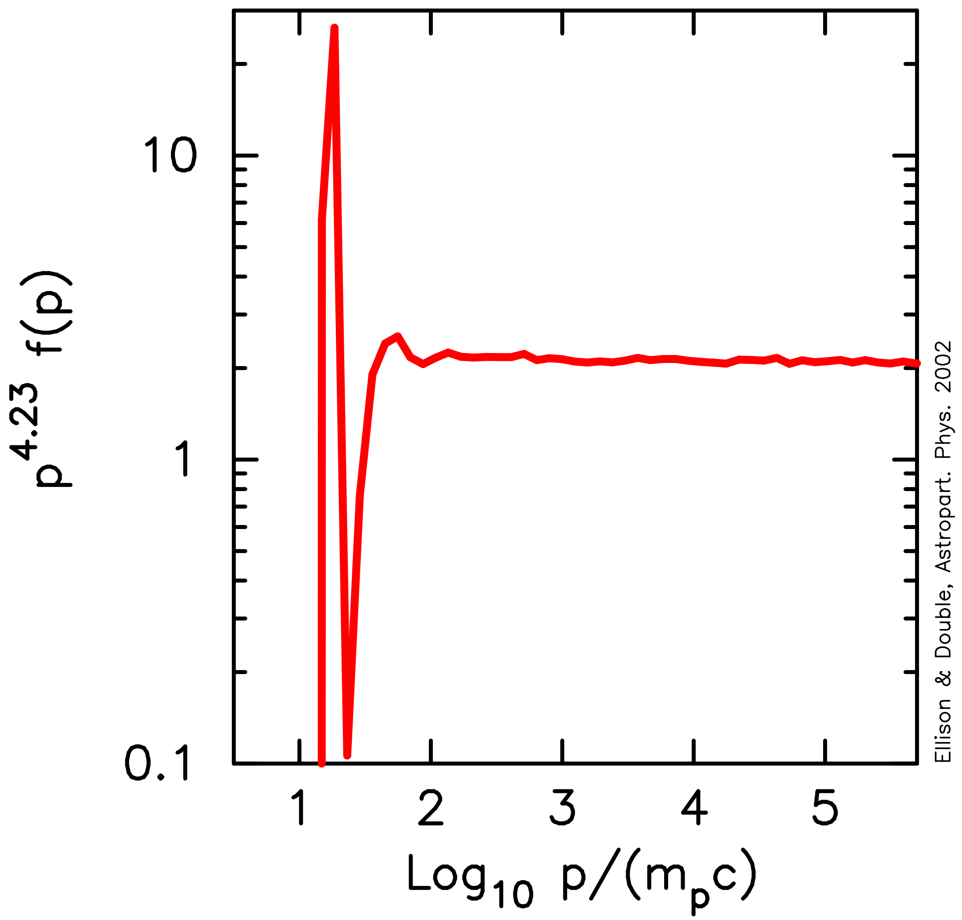


More oblique, weaker scat.

Shock Lorentz factor, γ_0 = 2

Power law depends on shock obliquity, θ_{B0} and amount of cross-field diffusion, η_{mfp}

In all cases, N_g large enough for convergent results (fine scattering)



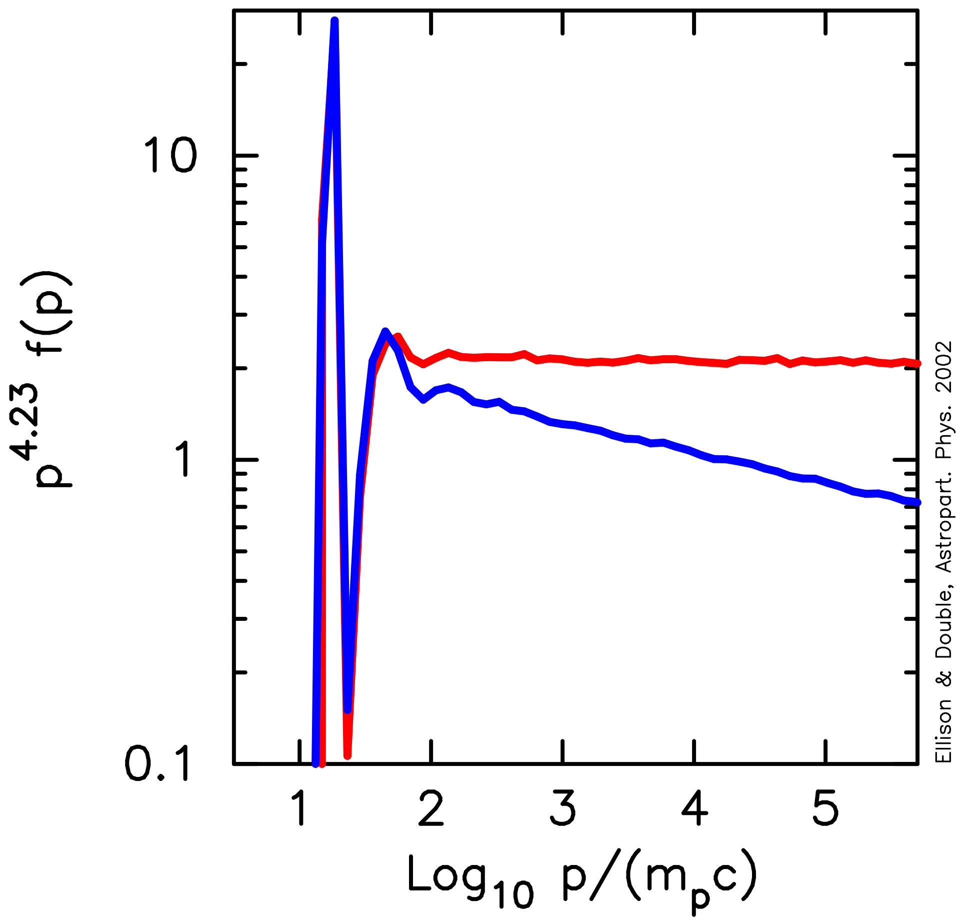
θ_{B0} = 0°, η_{mfp} = 1

$f(p) \propto p^{-4.23}$ is standard result

Shock Lorentz factor, γ_0 = 20

Fully relativistic shock

Test-particle results



Ellison & Double, Astropart. Phys. 2002

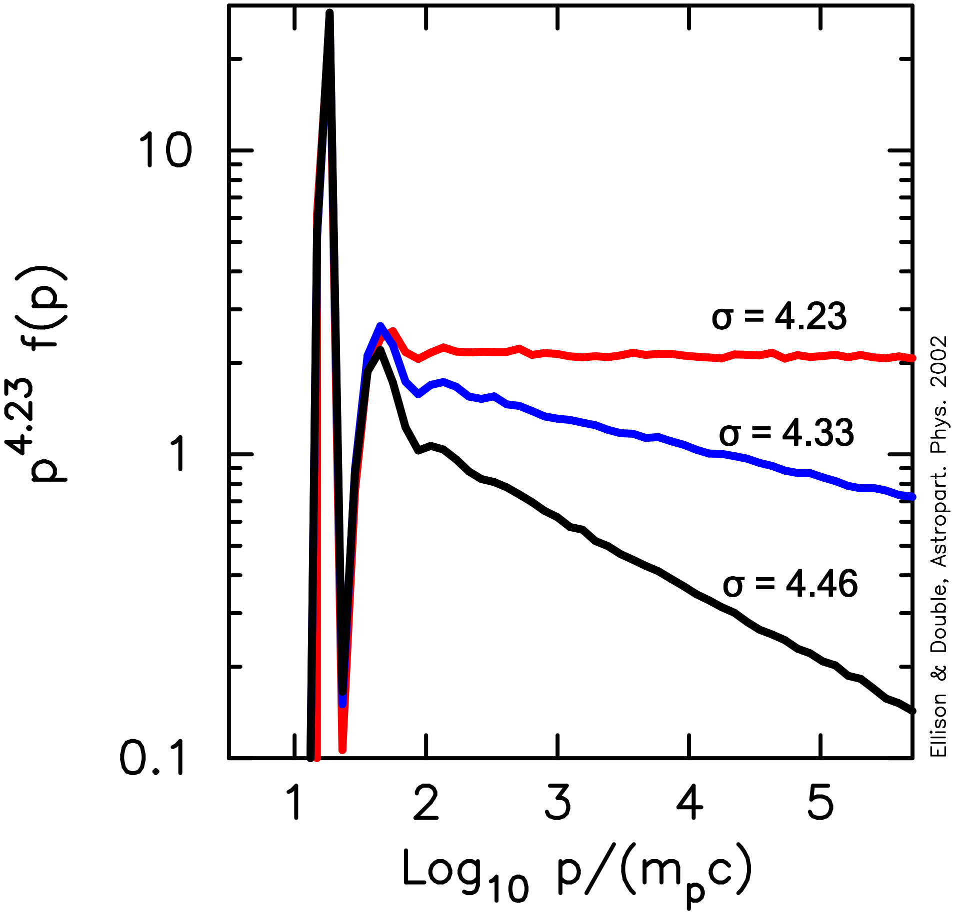
$f(p) \propto p^{-4.23}$ is standard result

θ_{B0} = 0°, η_{mfp} = 1

θ_{B0} = 60°, η_{mfp} = 3

Shock Lorentz factor, γ_0 = 20

Test-particle results



Ellison & Double, Astropart. Phys. 2002

$f(p) \propto p^{-4.23}$ is standard result

θ_{B0} = 0°, η_{mfp} = 1

θ_{B0} = 60°, η_{mfp} = 3

θ_{B0} = 89°, η_{mfp} = 6

More oblique, weaker scat.

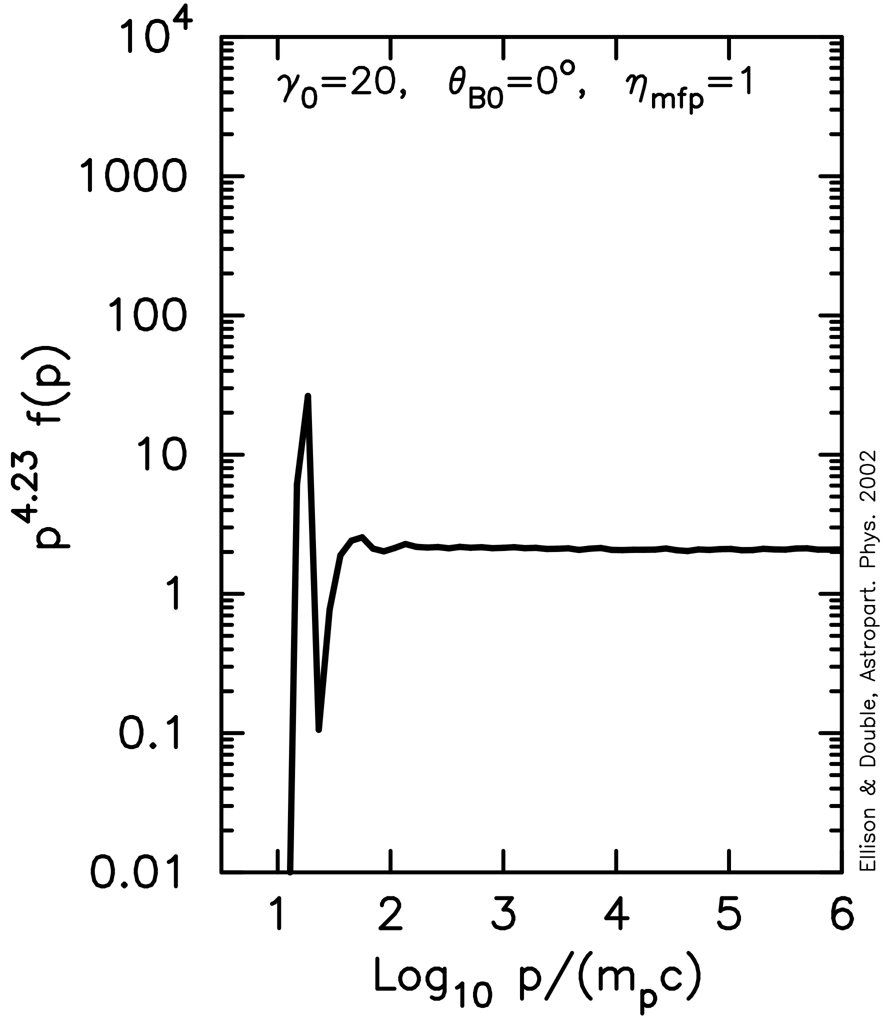
Shock Lorentz factor, γ_0 = 20

Power law index depends on both obliquity and scattering m.f.p

In ultra-relativistic limit get $p^{-4.23}$ result

In all cases, N_g large enough for convergent results

Test-particle results

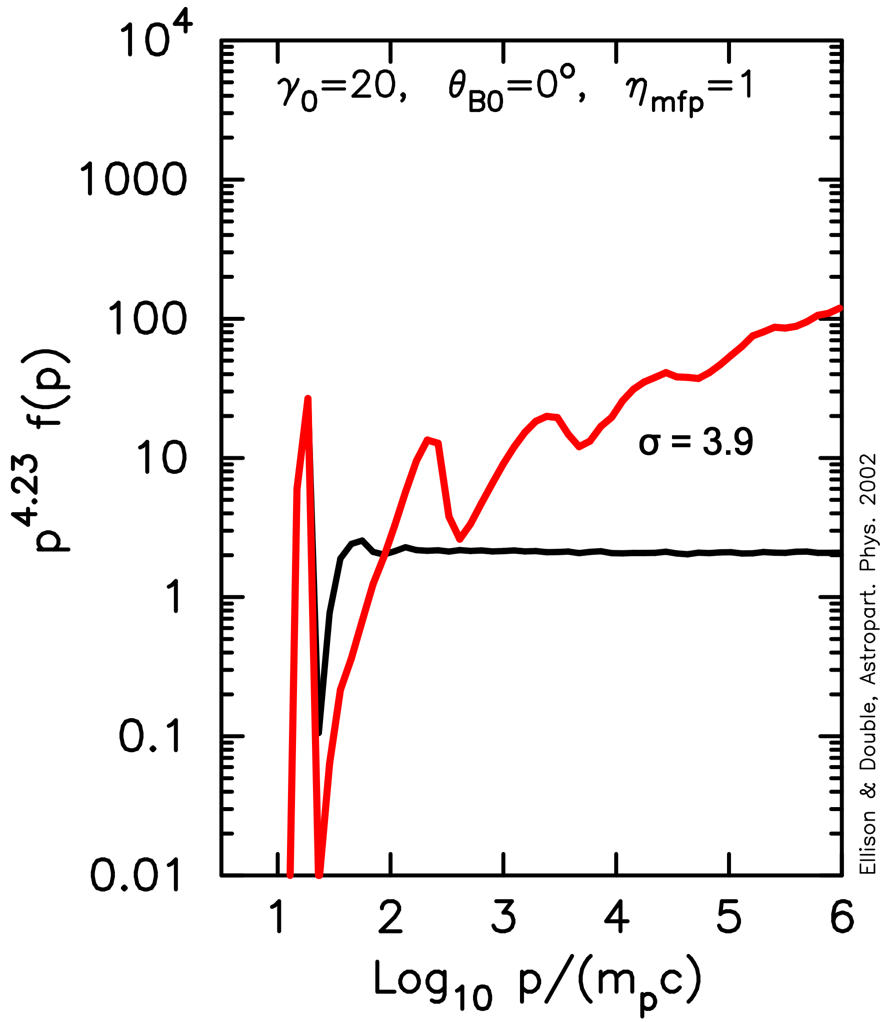


Shock Lorentz factor, γ_0 = 20

N_g = 10^4 (fine scattering, $\delta\theta << 1/\gamma_0$)

Fineness of scattering (N_g) strongly influences the spectrum

Test-particle results



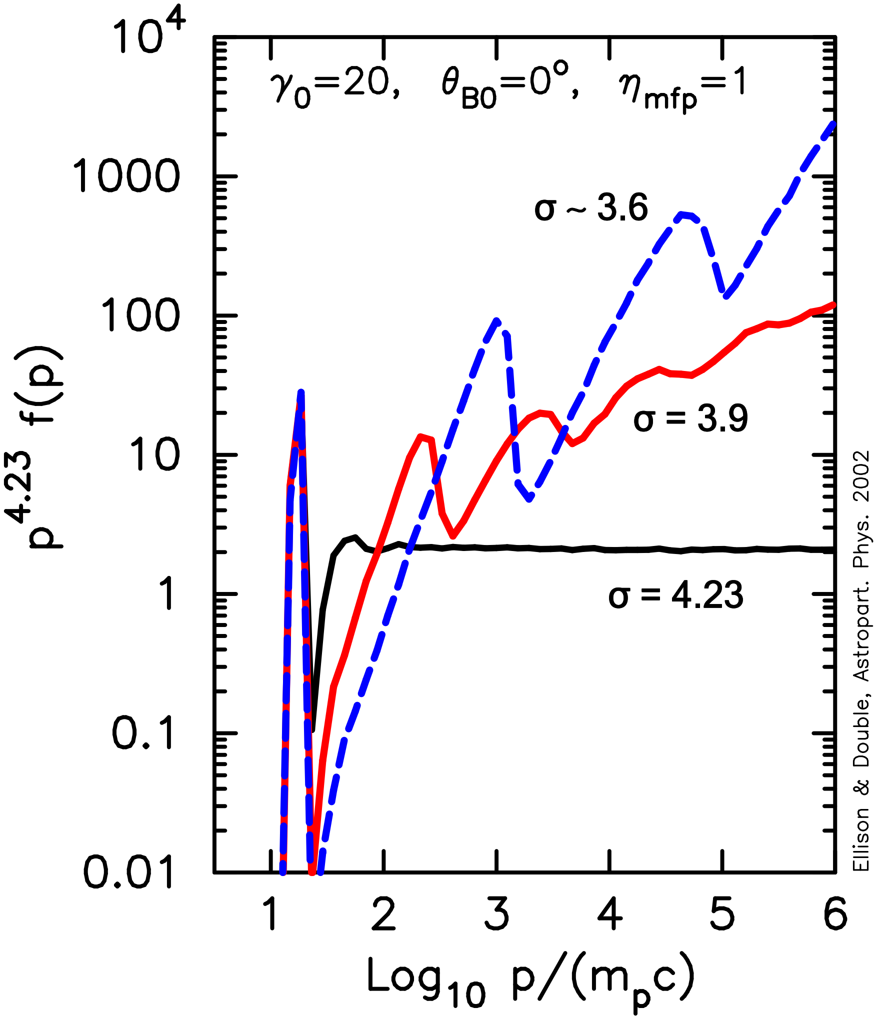
Shock Lorentz factor, γ_0 = 20

N_g = 500

N_g = 10^4 (fine scattering, $\delta\theta << 1/\gamma_0$)

Fineness of scattering (N_g) strongly influences the spectrum

Test-particle results



Ellison & Double, Astropart. Phys. 2002

Shock Lorentz factor, $\gamma_0 = 20$

$N_g = 100$

$N_g = 500$

Coarser scattering

$N_g = 10^4$ (fine scattering, $\delta\theta << 1/\gamma_0$)

This effect does not go away as $\gamma_0 \rightarrow \infty$

Fineness of scattering (N_g) strongly influences the spectrum

Test-particle results

Nonlinear Effects in Relativistic Shocks

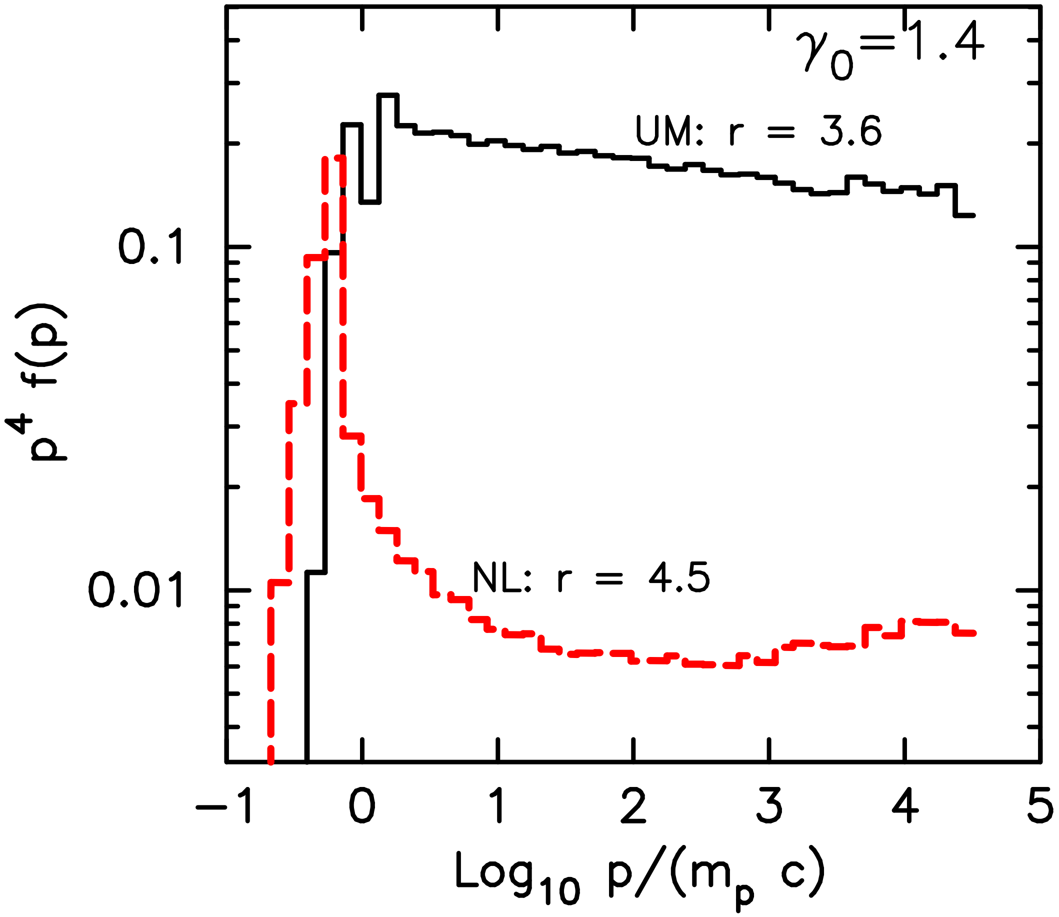
Ellison & Double (2002)

Must conserve momentum and energy, just like in non-relativistic shocks

➔ shocks will be smoothed by backpressure of accelerated particles

➔ In general, NL effects will be less important for ultra-rel. shocks because TP spectrum is steeper, **BUT this will depend on "fineness" of scattering**

Nonlinear effects should be important for mildly relativistic shocks i.e., those in GRBs



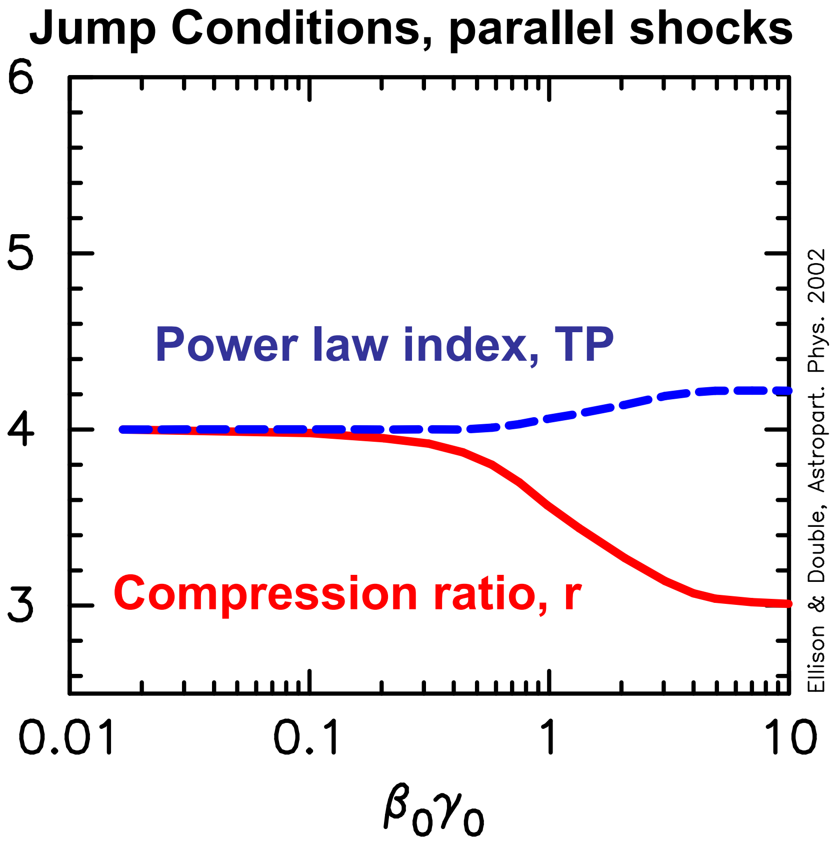
γ_0 = 1.4

Unmodified (TP)

Nonlinear

Shock compression ratio goes from r = 3.6 for TP case to r = 4.5 when NL effects are taken into account

For mildly relativistic shocks, nonlinear effects will be important. Application to Internal shocks in GRBs and late afterglow



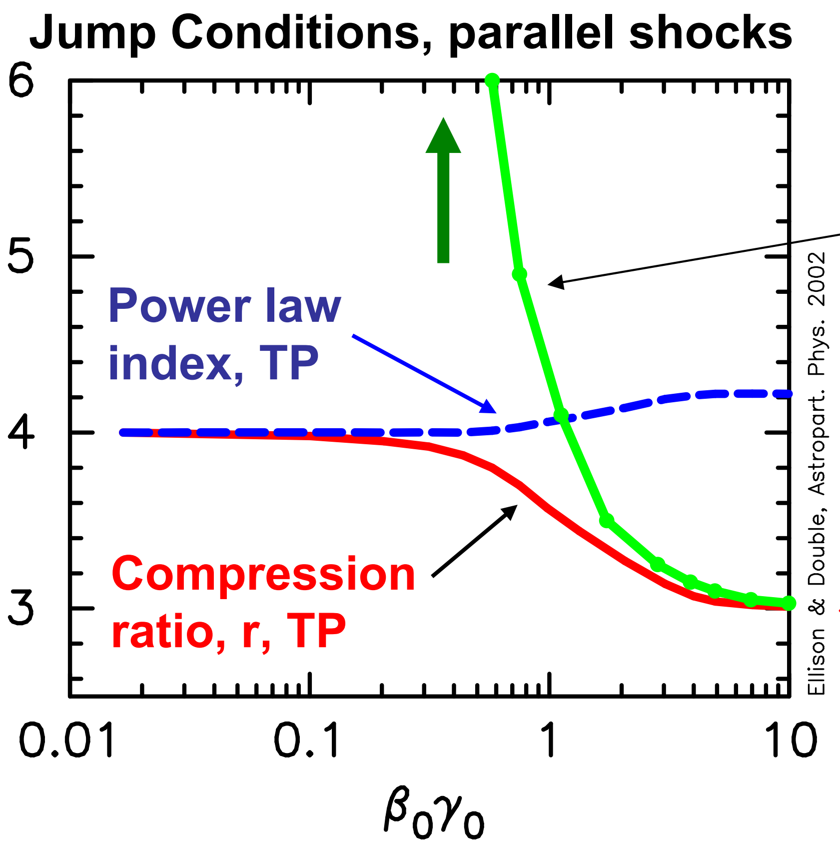
$$\theta_{BN} = 0^\circ$$

Test particle acceleration

← **4.23 index**

← **r = 3**

$\beta_0 = u_0/c$, γ_0 is shock Lorentz factor



Ellison & Double, Astropart. Phys. 2002

$\theta_{BN} = 0°$

Compression ratio, r, for Nonlinear case

4.23 index

r = 3

$\beta_0 = u_0/c$, γ_0 is shock Lorentz factor

When shock becomes mildly relativistic, large increase in compression ratio can occur producing harder spectra

Important points for relativistic Diffusive Shock Acceleration:

a) **Diffusive shock accel. harder to describe AND may be less likely to work than for nonrelativistic shocks**

b) **PIC simulations needed but still long way to go (see poster by Nishikawa et al)**

c) **Spectrum (even test-particle power law) depends on (1) unknown scattering properties, (2) shock Lorentz factor, (3) obliquity**

d) **"Universal" power law index, $f(p) \propto p^{-4.2}$ only a special case**

e) **Application to GRBs has many unsolved problems**

Cosmic Ray Production in Supernova Remnants

1) No doubt that isolated SNRs produce TeV particles
    a) Seems certain this is primarily by diffusive shock acceleration
    b) Still open question if TeV protons are produced (HESS ?) → Non-linear effects in accelerator critical here
    c) SNR morphology → efficient acceleration of IONS
2) Presence of high B-fields (100s of μG) very likely → SNRs can accelerate CRs to well above the knee (~10^{17} eV) (iron nuclei)
    a) Non-linear B-field amplification likely to be important
3) Young SNRs (Kepler, Tycho, Cas A, Vela Jr, etc) offer best place to study details of shock acceleration (injection; e/p ratio, B-field)
    a) Broad-band observations (radio, IR, X-ray (thermal & non-thermal) , gamma-ray) of individual SNRs, combined with broad-band (i.e. nonlinear) models, may answer fundamental questions of DSA and CR origin
    b) Nonlinear DSA makes clear predictions for: Shock compression > 4, Low shocked temperatures, Concave spectral shapes for electrons and protons → connects thermal emission (X-ray lines) to non-thermal (radio, X-ray, TeV)
4) What is learned in SNR shocks helps our understanding of relativistic shocks