Particle Acceleration Mechanisms in Astrophysics

Don Ellison, North Carolina State Univ.

Nonthermal particle distributions are ubiquitous in diffuse plasmas in space → result of low densities and large magnetic fields

Possible acceleration mechanisms →

1) Magnetic reconnection

2) Charge separation (double layers)

3) Pulsar mechanisms (rotating B-fields, Poynting fluxes, jets)

4) Second-order Fermi acceleration

5) Shock acceleration (first-order Fermi mechanism, also called Diffusive Shock Acceleration - DSA)

Particle Acceleration in Collisionless Shocks

What are collisionless shocks?

Why are shocks important?

How does particle acceleration occur in collisionless shocks?

Applications of Diffusive Shock Acceleration (DSA) in astrophysics.

In diffuse regions of space have large bulk speeds compared to typical thermal speeds → supersonic flows and, therefore, shocks:

$$\boxed{\text{Mach\#} = M_S = \sqrt{\frac{3\rho V^2}{5P}}, \quad V = 200\frac{km}{s}, \quad T = 10^6 K, \quad M_S = 1.7}$$

Note: solar wind speed ~400 km/s, $T_{sw} < 10^6$ K

In diffuse space plasmas, particle-particle collisions are rare.

$$\lambda \propto \frac{1}{n\sigma_C}$$ collision mean-free-path

Coulomb cross-section is small ($\sigma_C \sim 10^{-12}$ cm^{2}) and densities are low, n ~ 1 cm^{-3}

For solar wind, $\lambda \sim 1/10$ AU implies no collective effects, like planetary bow shocks, if only particle-particle collisions take place

But shocks with very small length scales are observed → collective effects from charged particles interacting with background magnetic turbulence replaces particle-particle collisions ($\lambda_B \ll \lambda_{coll}$) and produces dissipation

The important difference between particle-particle collisions and B-field-particle interactions is that B-field interactions are nearly elastic: energetic particles don't share energy

In collisionless plasmas, strongly nonthermal particle distributions can persist for long times.

The most extreme case: Galactic Cosmic Rays

Jones_&_Ellison_review_paper_SSR91.pdf

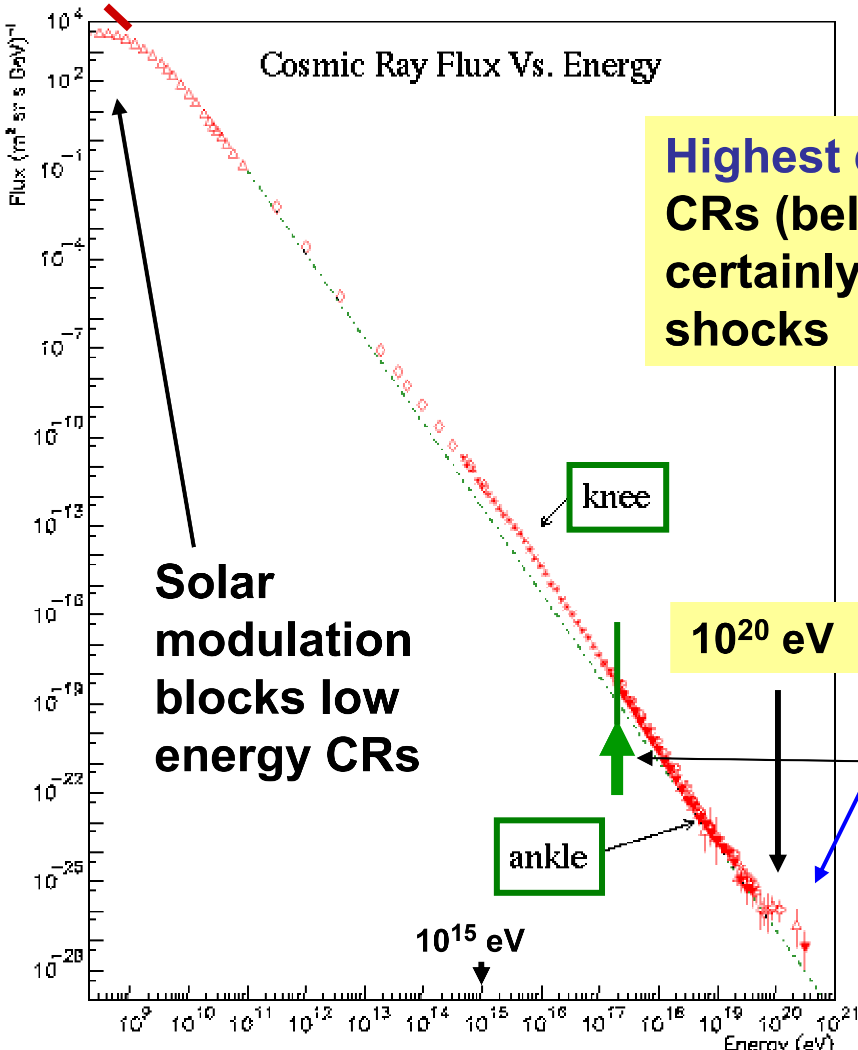
Galactic Cosmic Ray all particle spectrum

Flux spans ~40 decades

10^{10}

Flux

10^{-28}



10^9 eV   Energy [eV] 10^{21} eV

Solar modulation blocks low energy CRs

Highest energy particles ever observed!
CRs (below 10^{15} eV at least) almost certainly accelerated in collisionless shocks

GRBs, extra-galactic radio jets, "strange" particles ???

LHC 10 TeV proton ~ 2 x 10^{17} eV cosmic ray energy

Hillas_Rev_CRs_JPhysG2005.pdf

Don Ellison, NCSU

We know collisionless shocks exist – directly observed by spacecraft in heliosphere

We know, from direct observations in the heliosphere, that they can accelerate particles with high efficiency

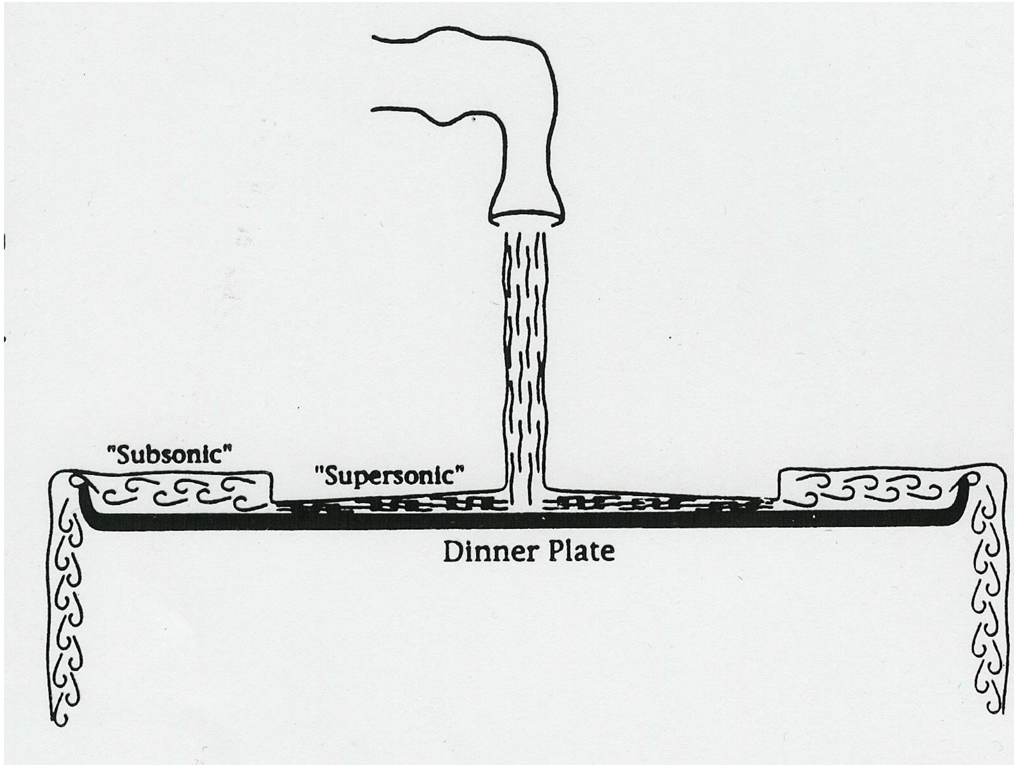
Indirect observations show that shocks occur at all scales in the universe

Generally, where shocks are seen or inferred, nonthermal particle populations are also seen

There is a well-developed theory for accelerating particles in shocks – Diffusive Shock Acceleration

No other astrophysical acceleration mechanism is so well developed or so universal

Clear evidence that DSA is efficient → more than 50% of total ram kinetic energy can be put in to relativistic particles



Analog to solar wind flowing into interstellar medium. The termination shock is the jump between supersonic and subsonic flow.

Axford & Suess 94

This is collisional shock → No particle acceleration

In diffuse astrophysical environments, plasmas are collisionless, particles interact through B-fields

Heliosphere

Many collisionless shocks, ALL accelerate particles !

Can study shock accel. In detail with in-situ spacecraft observations

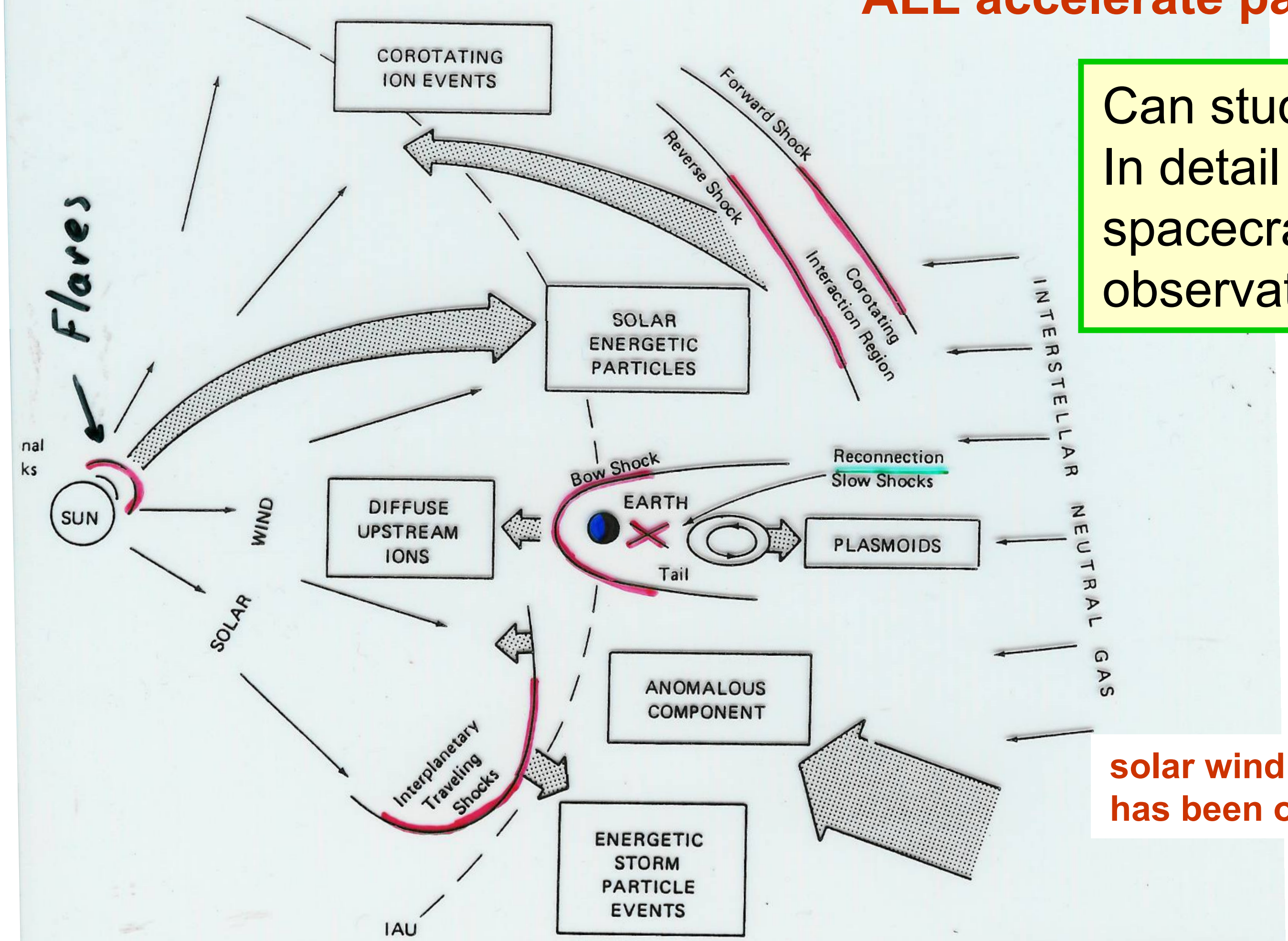
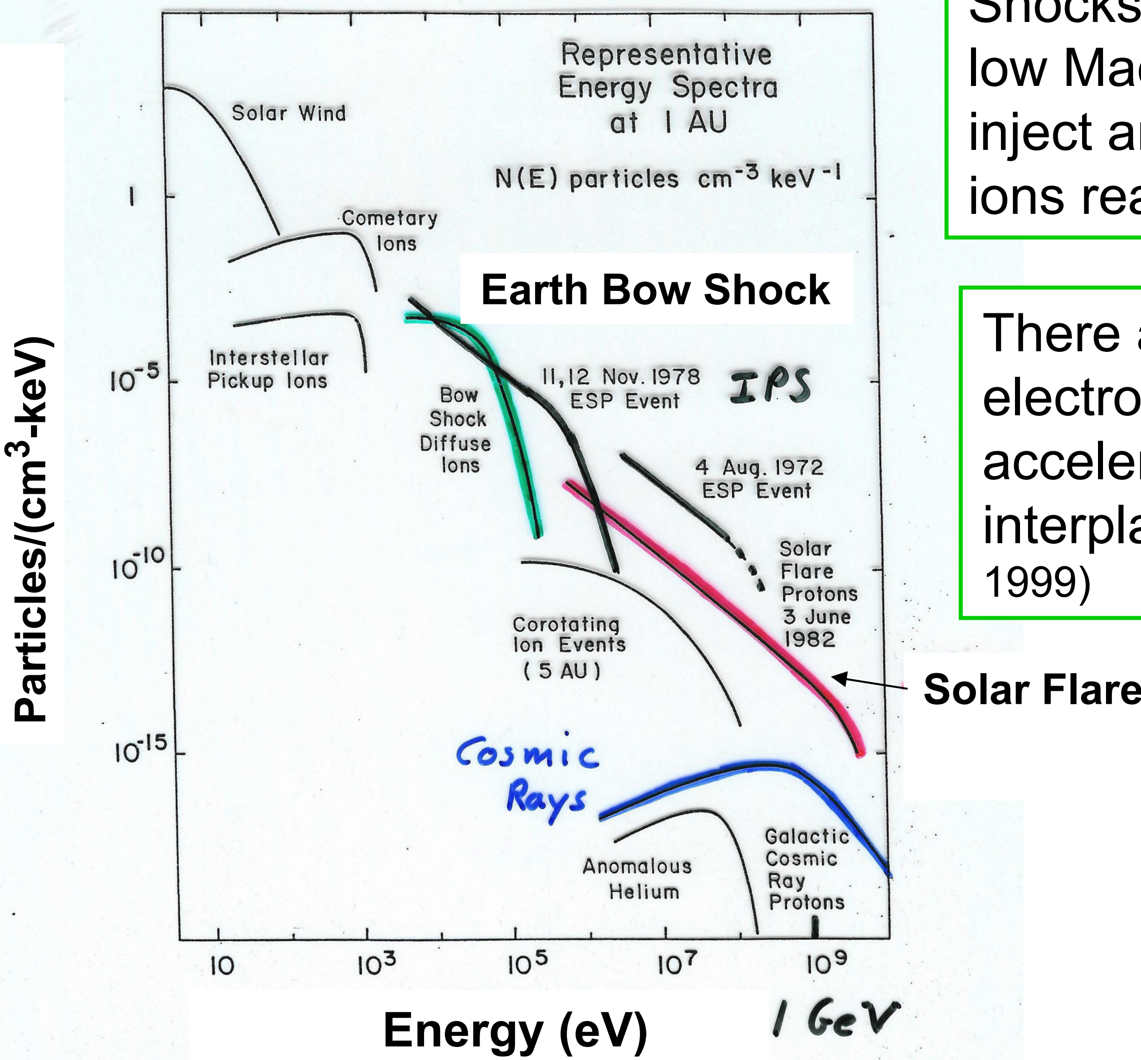


Fig. 2. Various particle acceleration sites within the heliosphere (adapted from [262]).

solar wind termination shock has been observed !

e.g. Scholer 84

Particle spectra (i.e., Ions) in Heliosphere



From M. Lee

Shocks in Heliosphere are all low Mach number (M_S<10), but inject and accelerate thermal ions readily

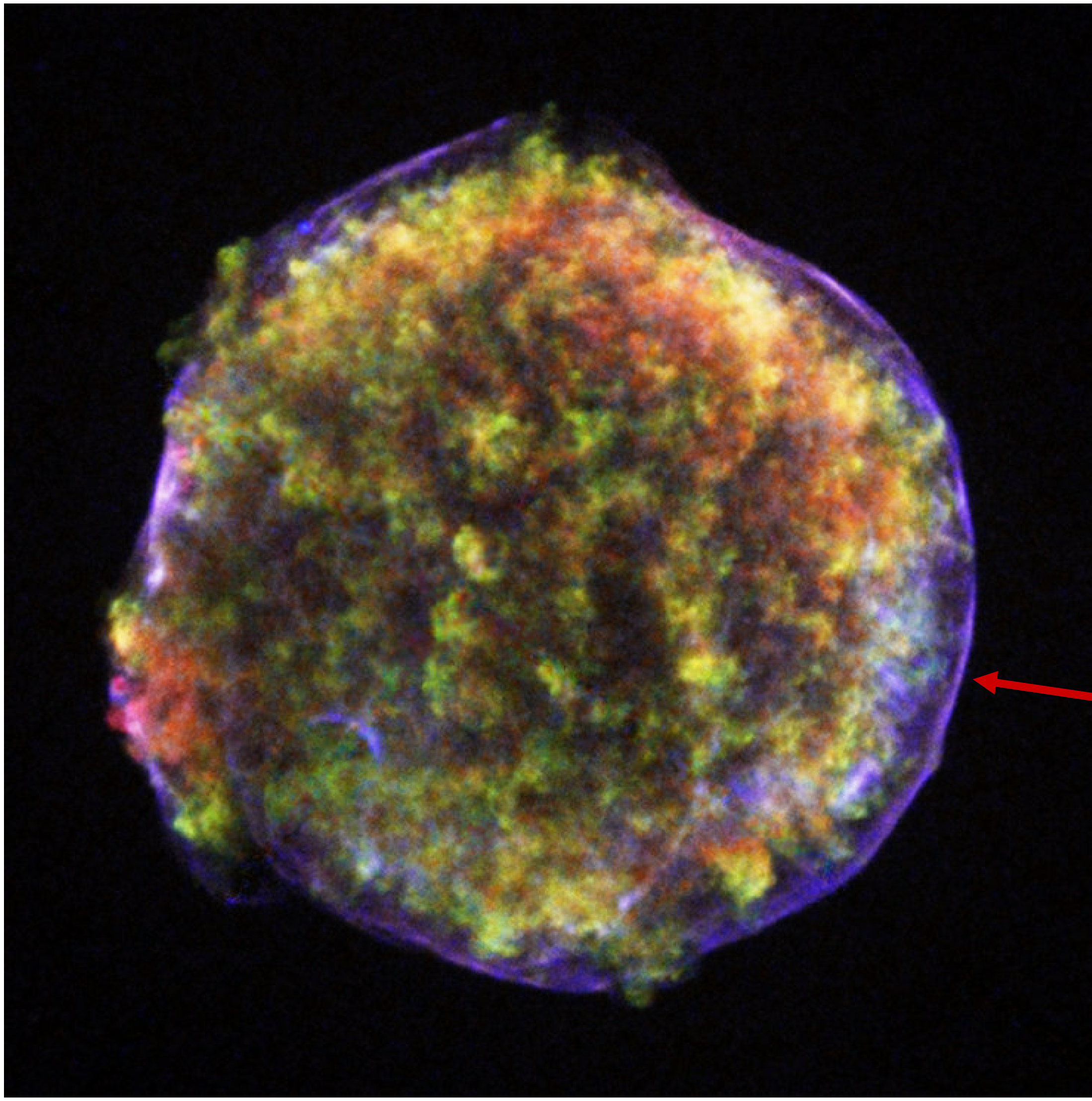
There are some obs. of thermal electrons being injected and accelerated at strong (i.e., M_S~8) interplanetary shocks (Terasawa etal 1999)

Supernova remnants (SNRs):

Outer blast wave is believed to be the main source of cosmic rays below 10^{15} eV

SNRs may accelerate cosmic rays to above 10^{17} eV or even higher

Tycho's Supernova Remnant



http://chandra.harvard.edu/photo/2005/tycho/

Don Ellison, NCSU

Exploded in 1572 and studied by Tycho Brahe

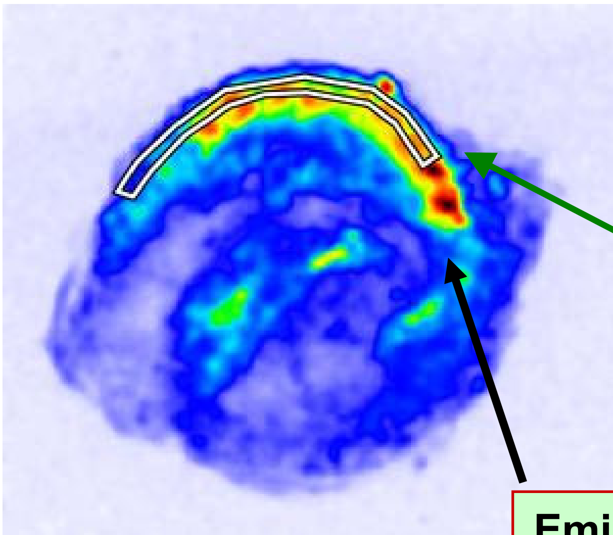
This Chandra X-ray image shows expanding bubble of multimillion degree debris (green and red) inside a more rapidly moving shell of extremely high energy electrons (filamentary blue).

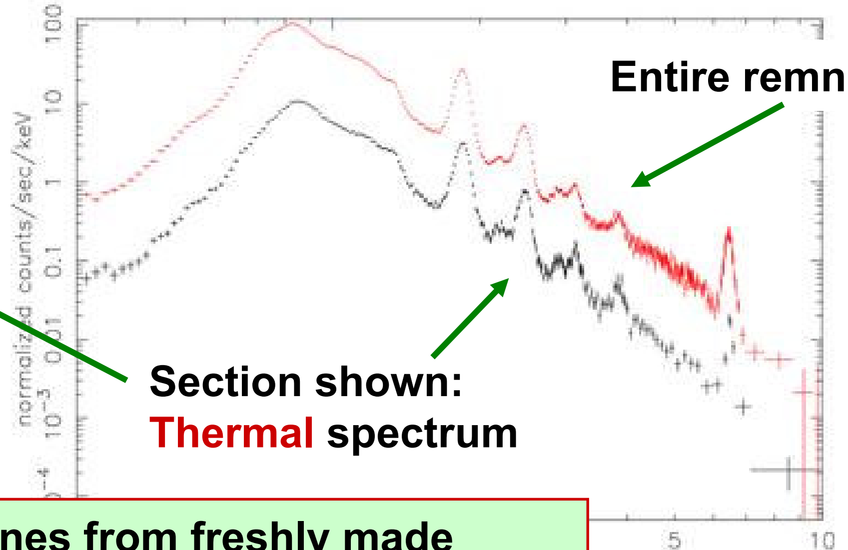
The outer shock wave is moving at about 6 million miles per hour.

Blue is nonthermal X-ray emission (synchrotron) from shock accelerated relativistic electrons.

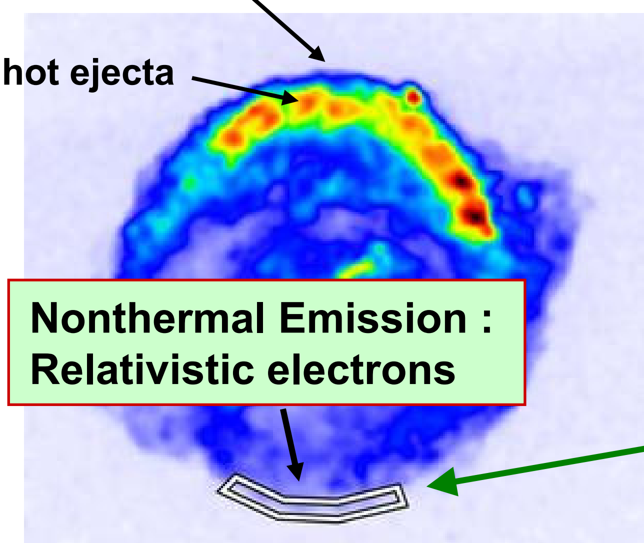
No direct evidence for acceleration of ions !

Chandra obs. of Kepler's Supernova Remnant (discovered Oct 9, 1604)

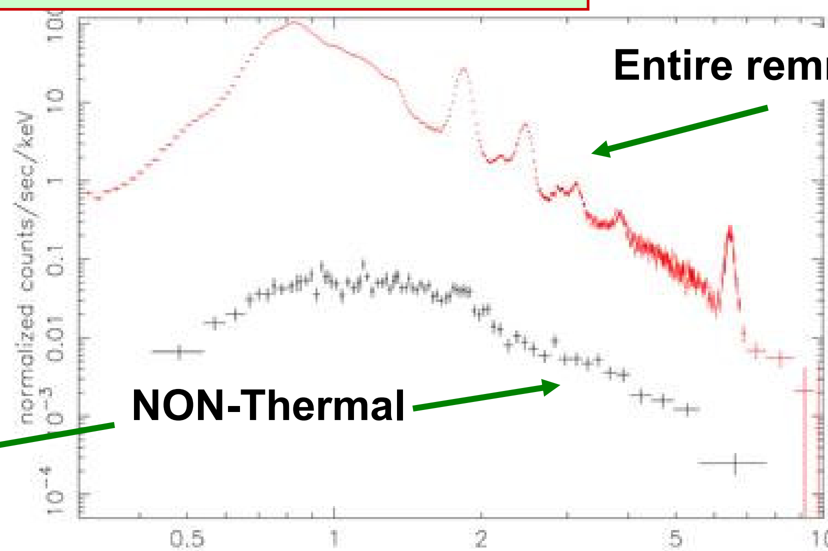




Emission lines from freshly made elements ► Hot ejecta from explosion

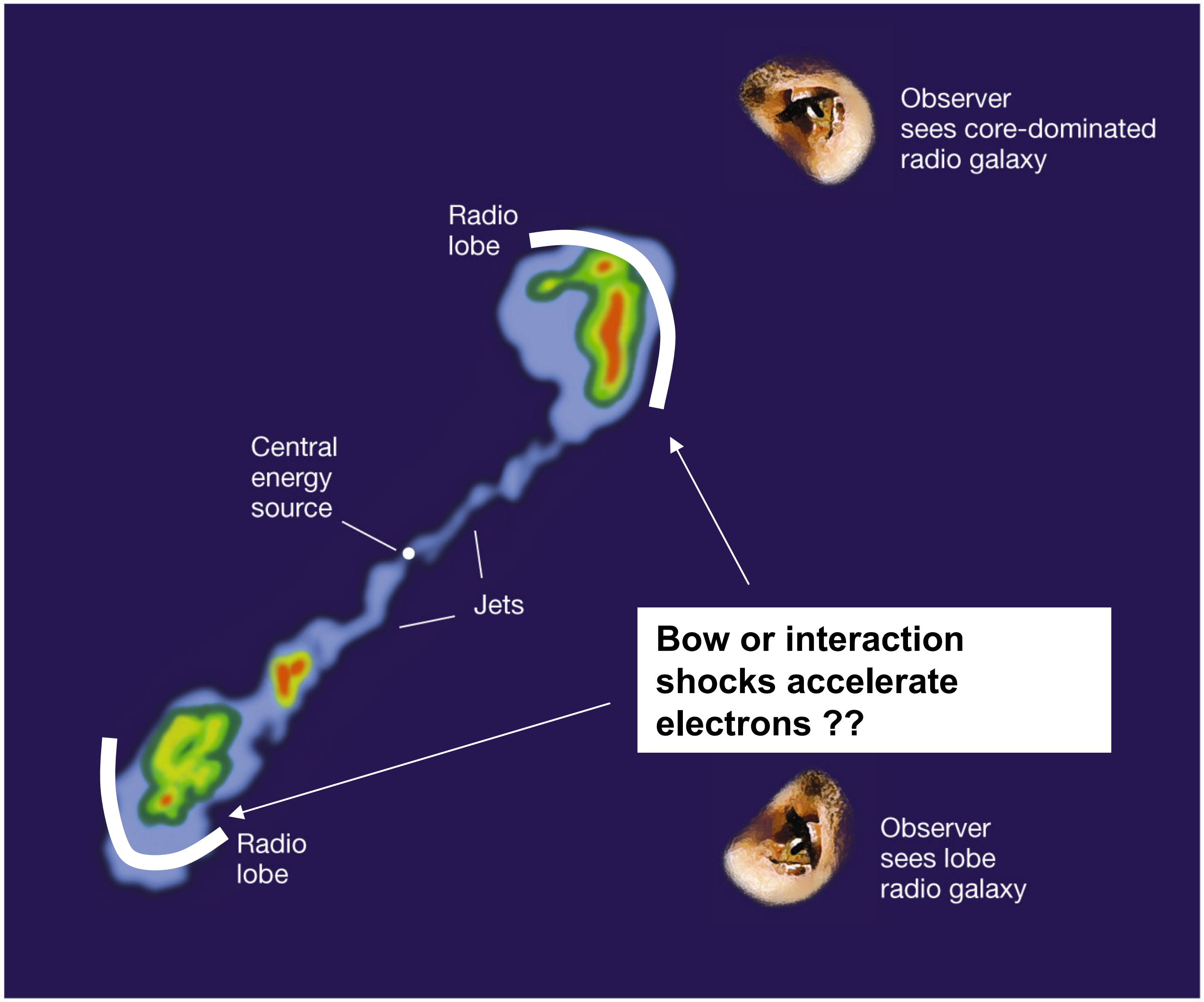


Nonthermal Emission : Relativistic electrons



NASA/Archive

Don Ellison, NCSU

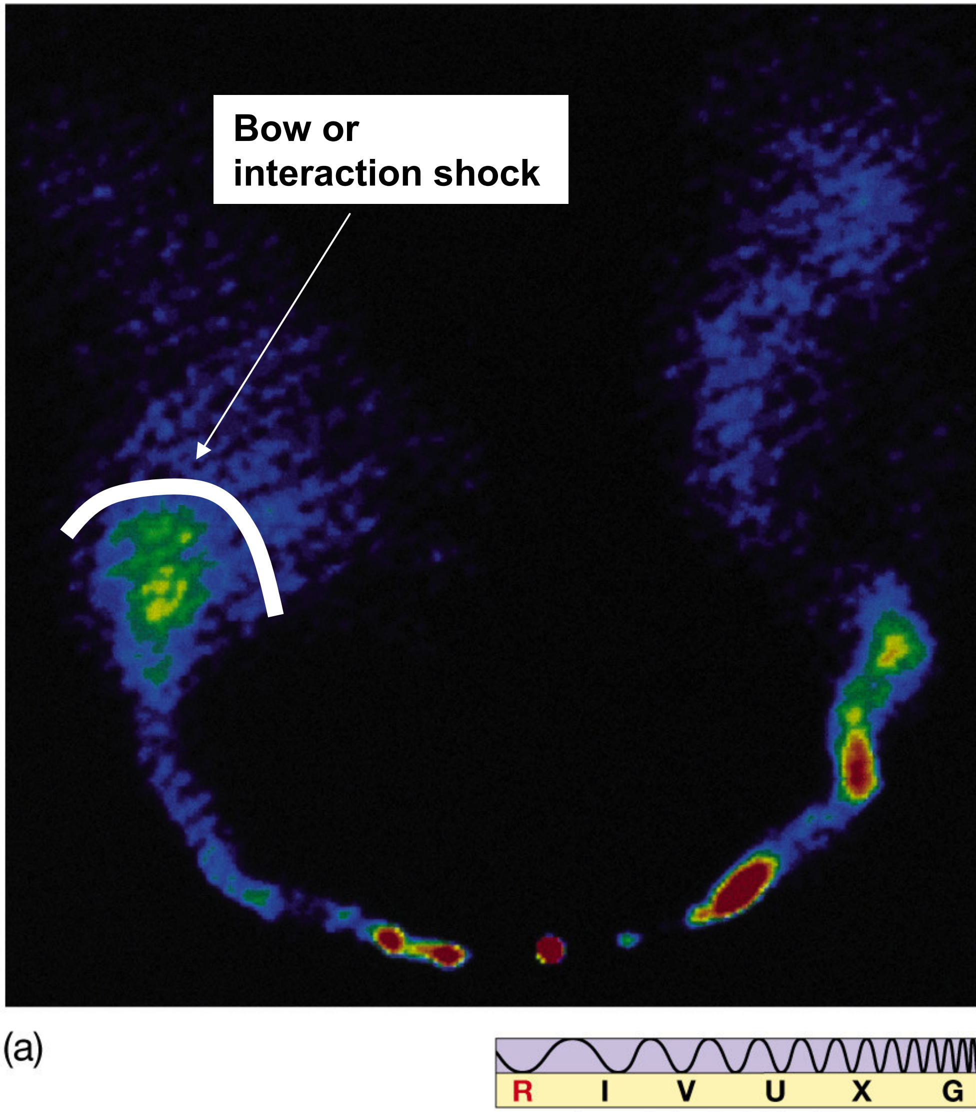


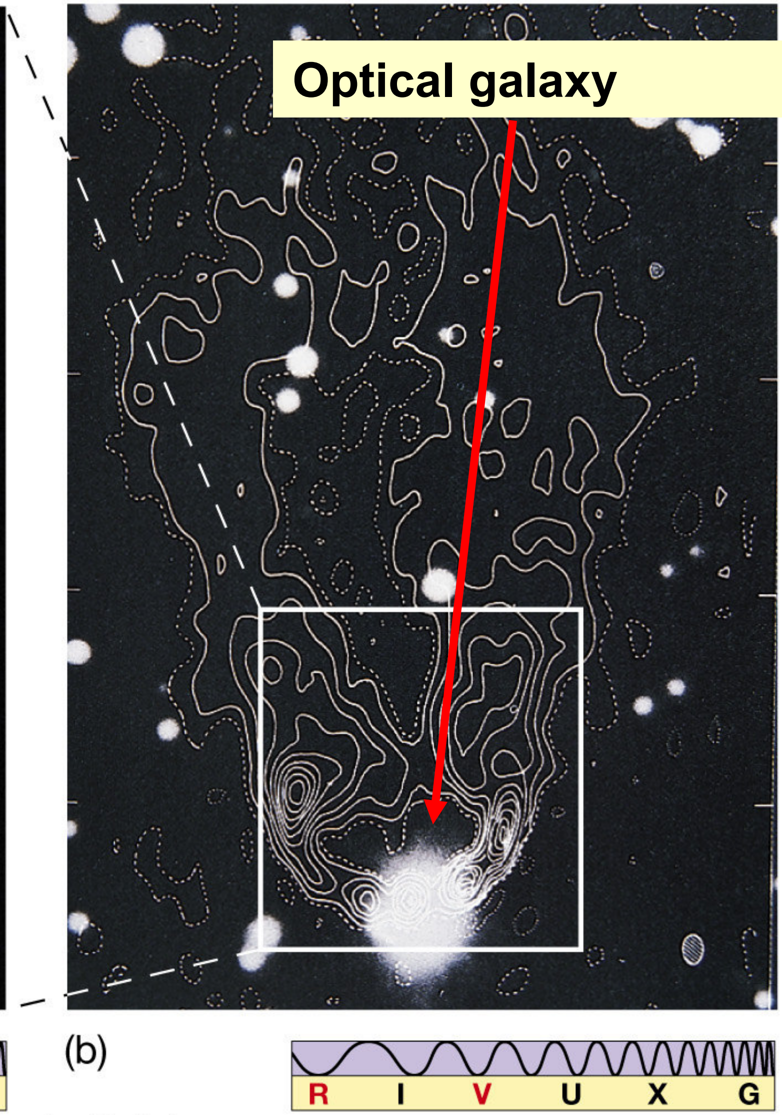
Extra-galactic radio jets

Radio emission produced by relativistic electrons accelerated by interaction shock between jet and intergalactic medium

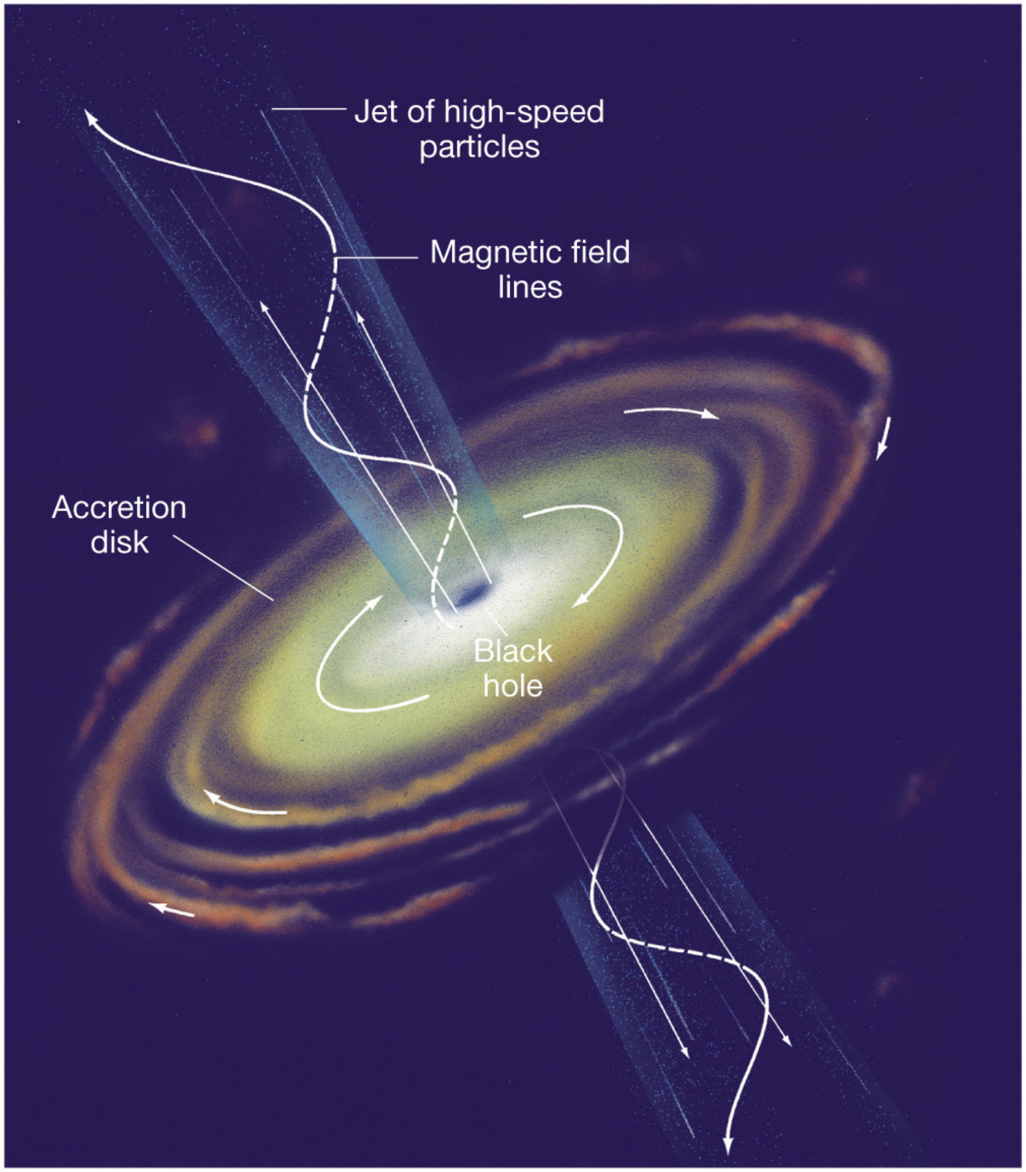
Don Ellison, NCSU

Head-Tail Radio Galaxy, NGC 1265





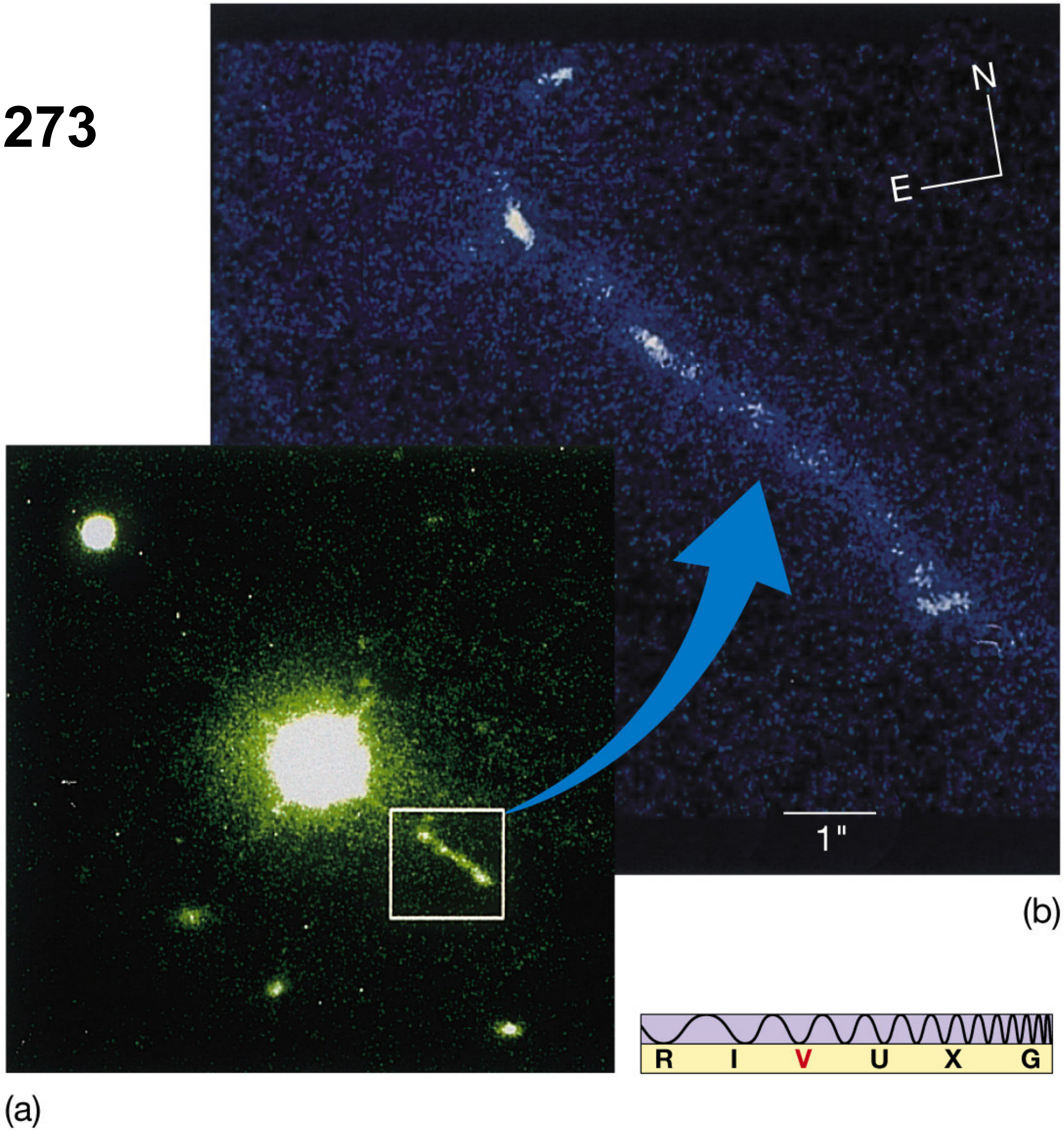
Don Ellison, NCSU



Jets in Active Galactic Nuclei

Don Ellison, NCSU

Quasar 3C 273



Don Ellison, NCSU

Jet from quasar 3C 273

Bow shock where jet interacts with IGM

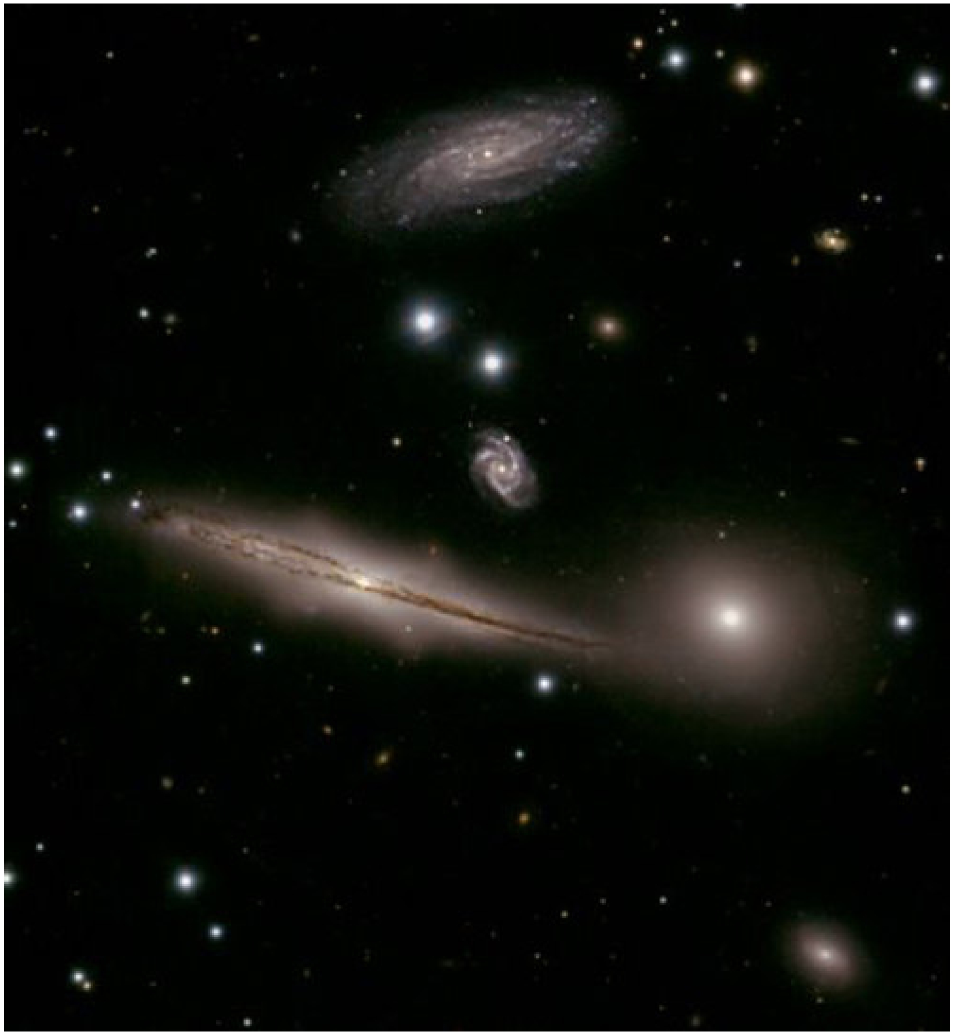
Radio contours and optical image of jet from quasar 3C 273.
(Bahcall et al., 1995)

Radio emission means relativistic electrons. Short lifetimes show these electrons must be accelerated locally, presumably at jet-IGM shock-interface

Expect shocks to form when galaxies collide

Don Ellison, NCSU

Galaxy clusters. Shocks may heat cluster gas to X-ray emitting temperatures

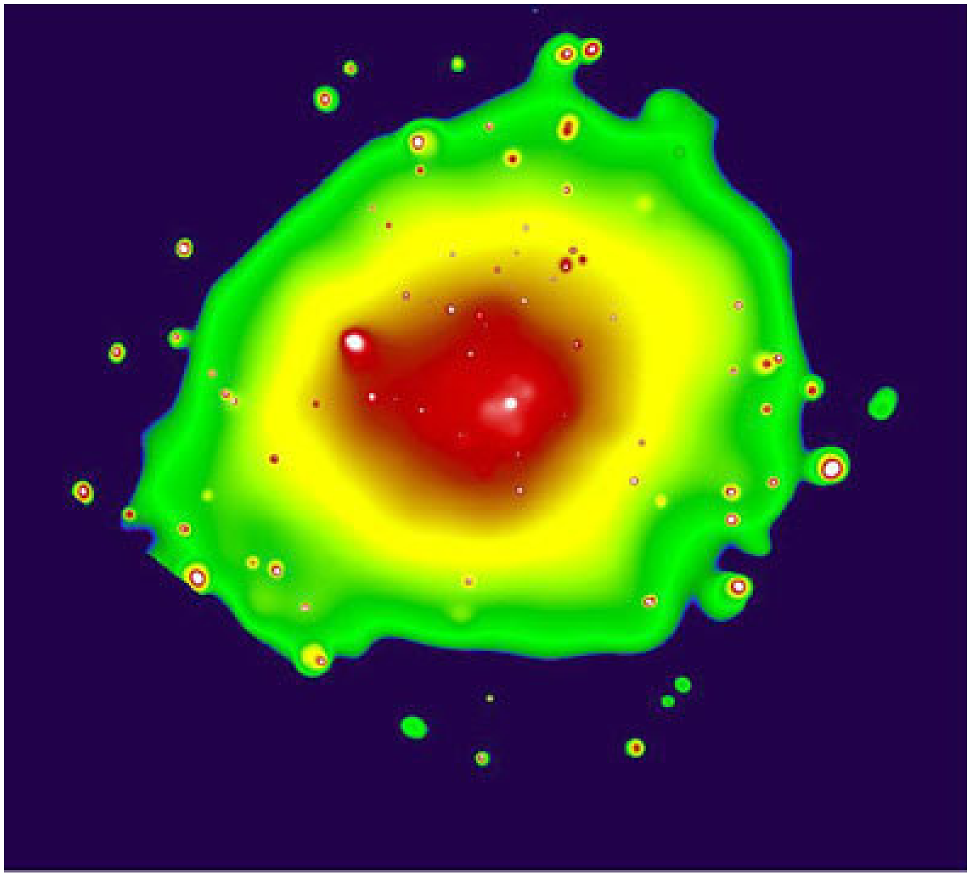


The galaxies of HCG (Hickson Compact Group) 87, about four hundred million light-years away.

This image is from the Gemini Observatory's South Telescope at Cerro Pachon, Chile.

http://antwrp.gsfc.nasa.gov/apod/ap030731.html

Chandra X-ray image of galaxy cluster Abell 160 (observation includes 29 galaxies) Colors indicate temperature



X-ray image of Abell 160 from Chandra. Credit: David Acreman

Galaxy clusters are filled with gas.

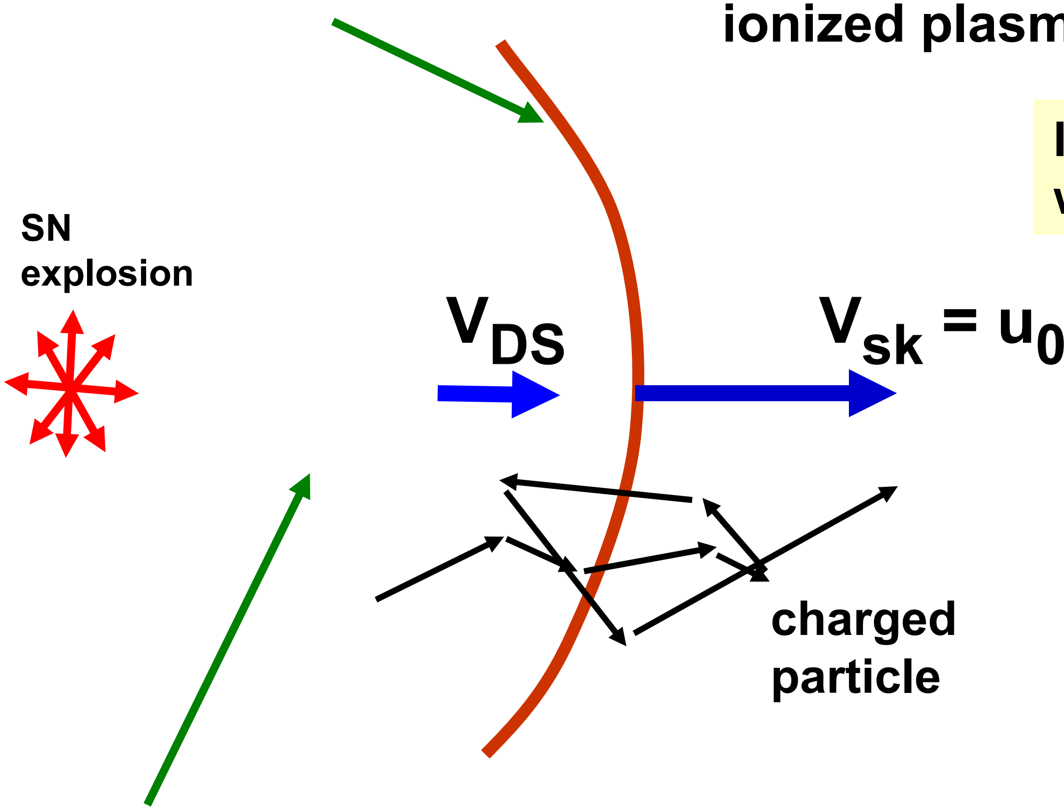
The galaxies move through this gas at a few thousand kilometers per second.

This is supersonic and shocks form and heat the gas to X-ray emitting temperatures

http://spaceflightnow.com/news/n0304/12supersonic/

Don Ellison, NCSU

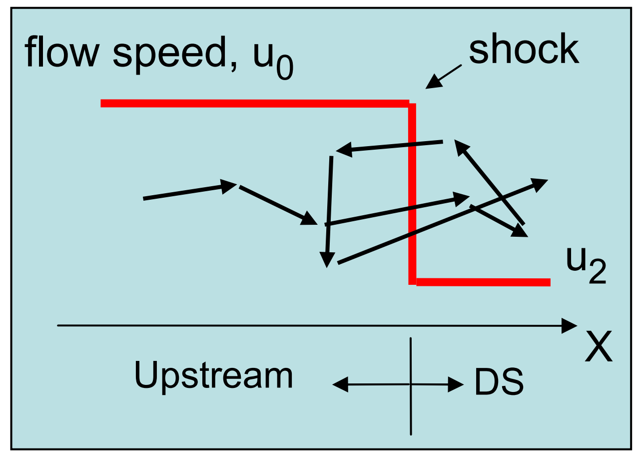
Shocks set up converging flows of ionized plasma



Interstellar medium (ISM), cool with speed $V_{ISM} \sim 0$

Post-shock gas → Hot, compressed, dragged along with speed $V_{DS} < V_{sk}$

shock frame



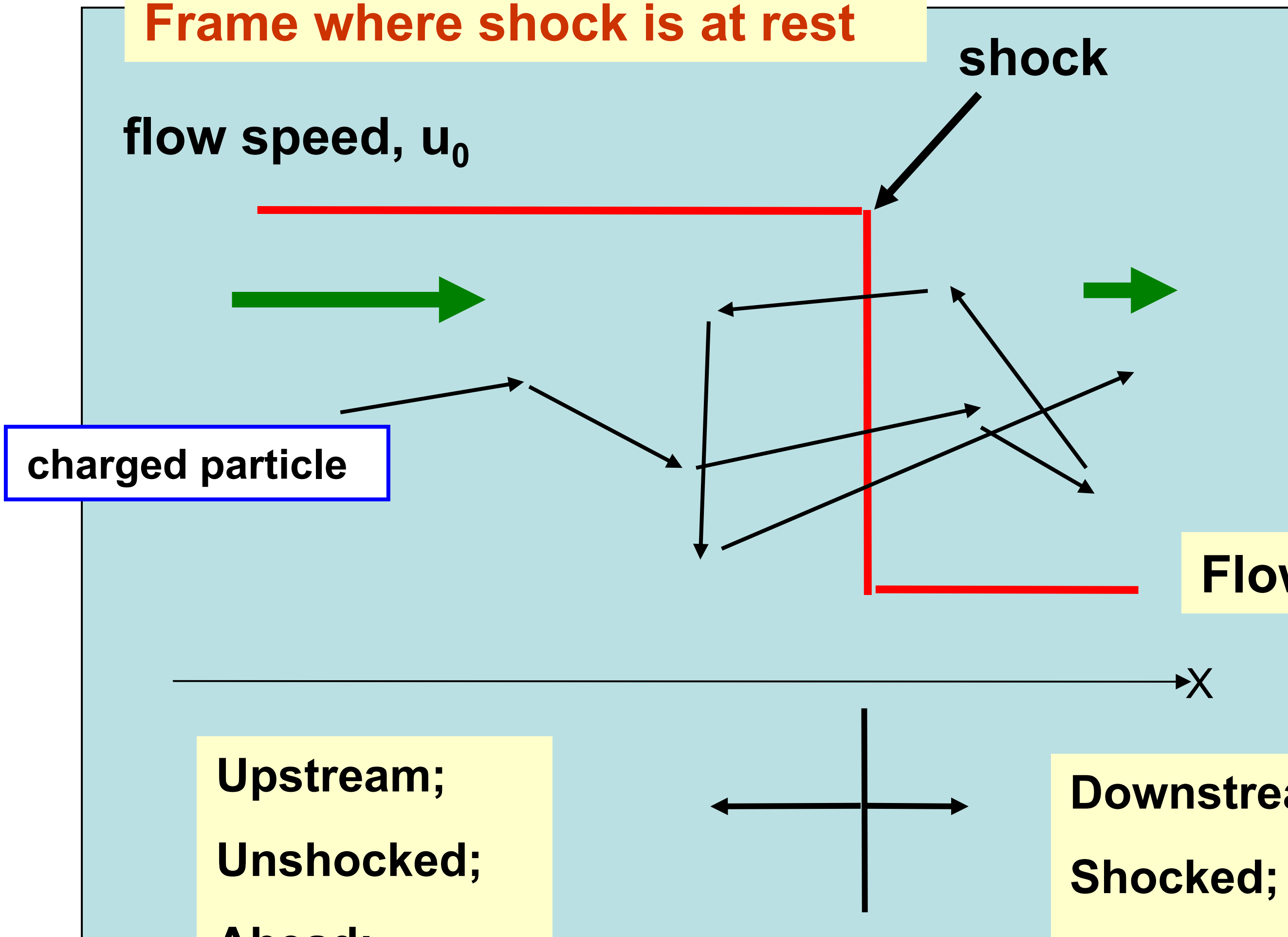
$u_2 = V_{sk} - V_{DS}$

Particles make nearly elastic collisions with background plasma → gain energy when cross shock → bulk kinetic energy of converging flows put into individual particle energy

Don Ellison, NCSU

Collisionless shocks

Frame where shock is at rest



compression ratio:

$r = u_0/u_2$ **or**

$r = \rho_2/\rho_0$

Upstream;	**Downstream;**
Unshocked;	**Shocked;**
Ahead;	**Behind;**
low density & temperature	**high density & temperature**

Don Ellison, NCSU

Shocks can accelerate particles because interactions are nearly elastic

Elastic scattering makes sense in <u>collisionless</u> plasmas

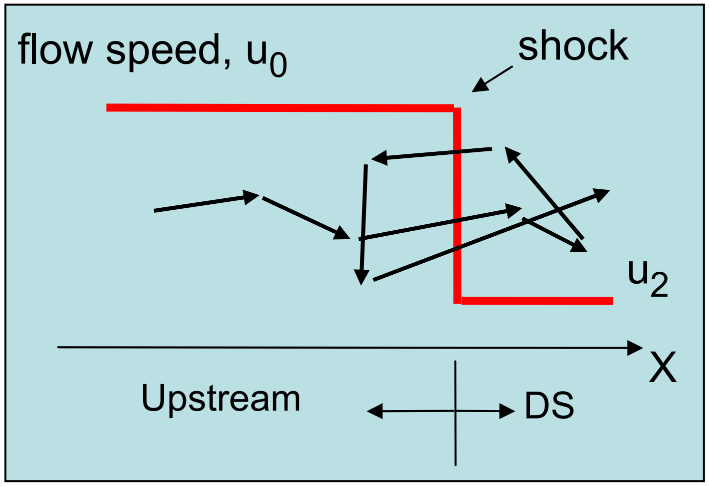
A charged particle interacts with background magnetic field → field is "frozen-in" to plasma since conductivity is so high.

Effectively, have one proton scattering off of Avogadro's number of particles moving as one.

"Collisions" on either side of shock are nearly elastic. In an interaction with B-field, speed doesn't change. If particle crosses shock and interacts, it gains the velocity of converging flows – clear evidence for this in solar wind

In collisional plasmas, fast particles collide inelastically and share energy with slower particles. Get shock heating and compression, but no acceleration. Once downstream, particles never recross the shock back into upstream region

Diffusive Shock Acceleration (DSA) in test-particle limit



$$u_0 = \text{shock speed}$$

$$u_2 = \text{downstream flow speed}$$

$$\boxed{r = \frac{u_0}{u_2} = \frac{\rho_2}{\rho_0} = \text{compression ratio}}$$

When particles are non-relativistic, only speed governs test-particle DSA

In a shock crossing, a particle gains an increment in speed: $\Delta u \sim u_0 - u_2$

But holds for relativistic particles as well if work in momentum space

Don Ellison, NCSU

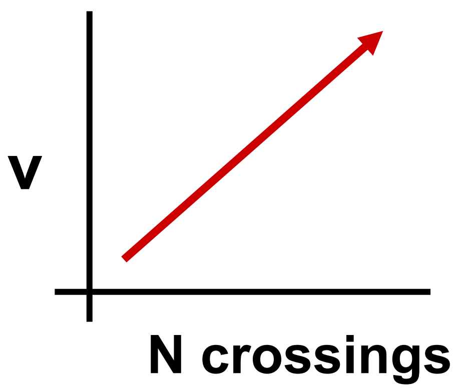
Test particle result: Power law in momentun: $f(p) \propto p^{-3r/(r-1)}$

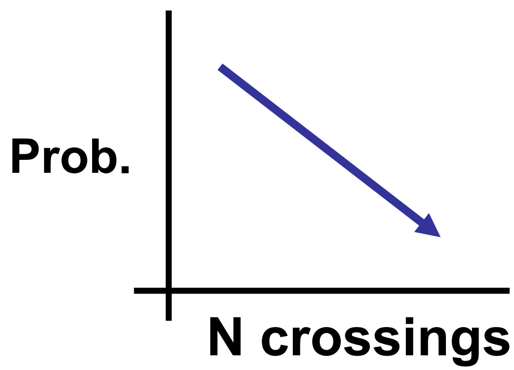
Consider non-relativistic particles with $v \gg u_0$.
On each shock crossing gain $\Delta u \sim u_0 - u_2$

Works for rel. particles as well

To obtain some speed, v, must make N crossings of shock

But, particle can be lost downstream after any crossing.
Have some probability to make N crossings





If $v \gg u_0$ (near isotropic distr.), can fold these together. Result only depends on compression ratio, r

When folded together, find power law $f(p) \propto p^{-3r/(r-1)}$

Note, assumption that $v \gg u_0$ only needed to calculate a pitch angle average for particles crossing the shock. The "Injection problem" is a mathematical problem!

Can describe DSA with transport equation (i.e., diffusion-convection equation) Requires assumption that $v \gg u_0$ to calculate the pitch angle average for particles crossing the shock

Original references: Krymskii 1976; Axford, Leer & Skadron 1977; Blandford & Ostriker 1978; Bell 1978

$$\boxed{\frac{\partial}{\partial x}\left[D(x,p)\frac{\partial}{\partial x}f(x,p)\right] - u\frac{\partial f(x,p)}{\partial x} + \frac{1}{3}\left(\frac{du}{dx}\right)\ p\ \frac{\partial f(x,p)}{\partial p} + Q(x,p) = 0}$$

D(x,p) is diffusion coefficient

f(x,p) is phase distribution function

u is flow speed

Q(x,p) is injection term

x is position

p is particle momentum

Modern papers with latest work and references:

Amato & Blasi 2006; Blasi 2002

Kang & Jones 2005

Berezhko and co-workers

Ellison and co-workers

Malkov & Drury 2001

Basic idea: Charged particles gain energy by diffusing in converging flows. Bulk K.E converted into random particle energy. Peculiar nature of shocks gives power law with index depending only on compression ratio.

For shock acceleration to work, diffusion must occur and this results from charged particles moving through turbulent magnetic field.

All complicated plasma physics contained in diffusion coefficient D(x,p). But, in test-particle limit, power law doesn't depend on D(x,p) !

Also, magnetic turbulence ($\Delta B/B$) must be self-generated by accelerated particles for shock acceleration to produce power law over wide momentum range.

If acceleration is efficient, energetic particles modify shock structure and results do depend on details of plasma interactions.

From test-particle theory, in Non-relativistic shocks (Krymskii 76; Axford, Leer & Skadron 77; Bell 78; Blandford & Ostriker 78):

$$f(p) \propto p^{-3r/(r-1)} \quad \text{if} \quad v_p \gg u_0 = V_{sk}$$

$f(p)$ is phase space density
r is compression ratio

Power law index is:

- **Independent of any details of diffusion**
- **Independent of shock Obliquity** (geometry)
- **But, for Superthermal particles only**

u_0 is shock speed

Ratio of specific heats, γ, along with Mach number, determines shock compression, r

For high Mach number shocks: $r \sim \dfrac{\gamma+1}{\gamma-1} = \dfrac{(5/3)+1}{(5/3)-1} = 4$!

$$\boxed{f(p) \propto p^{-3r/(r-1)} = p^{-4}, \quad \left(\text{or, } N(E) \propto E^{-2}\right)}$$

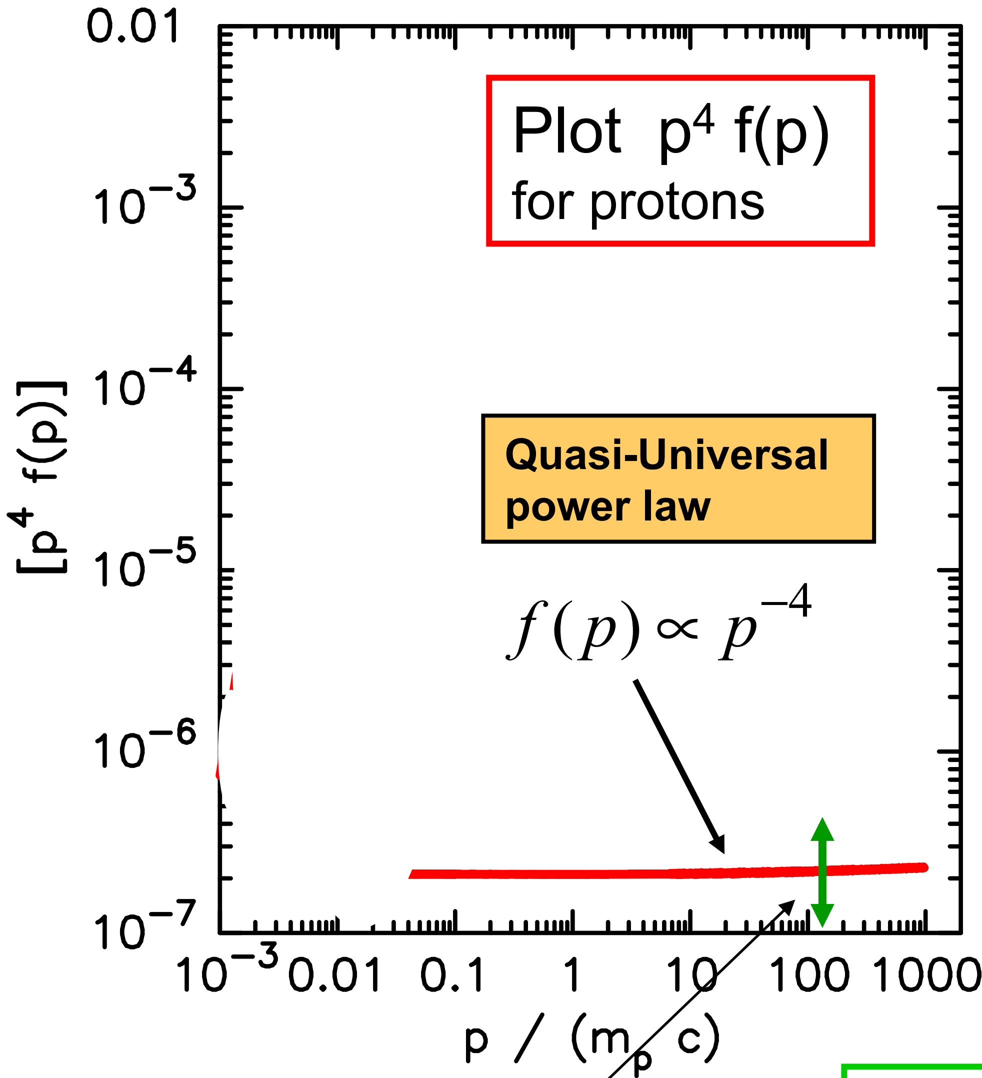
So-called "Universal" power law from shock acceleration

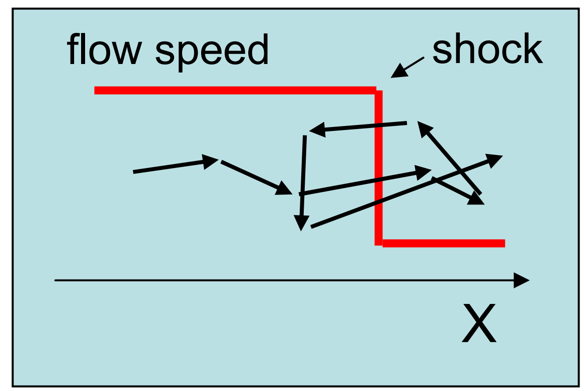
Test Particle Power Law in diffusive shock accel.

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

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

If r = 4, & γ = 5/3, $f(p) \sim p^{-4}$





Normalization of power law not defined in test-particle approximation

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

Don Ellison, NCSU

BUT clearly Not so simple!

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

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

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

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

Diverges if r = 4

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

If produce relativistic particles → $\gamma < 5/3$ → **compression ratio increases**

If $\gamma < 5/3$ the spectrum is flatter → Worse energy divergence → **Must have high energy cutoff in spectrum** to obtain steady-state → **particles must escape at cutoff**

But, if particles escape, compression ratio increases even more . . . Acceleration becomes strongly nonlinear !!

►Bottom line: Strong shocks will be <u>efficient</u> accelerators <u>with large comp. ratios</u> even if injection occurs at modest levels (1 ion in 10^4)

Large compression ratio ➔ hard spectrum

$$\text{For} \quad r = \infty, \quad f(p) \propto p^{-3} \quad \text{vs.} \; f(p) \propto p^{-4} \quad \text{for} \quad r = 4$$

Shock structure must adjust to conserve momentum and energy

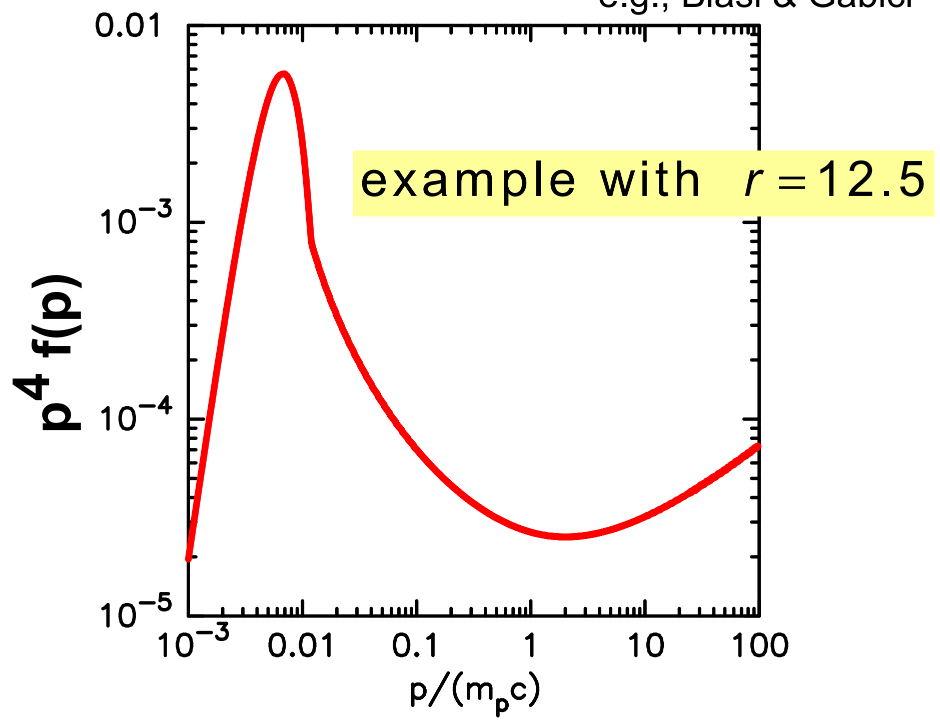
If diffusion coefficient is an increasing function of momentum, the superthermal spectrum will be curved:

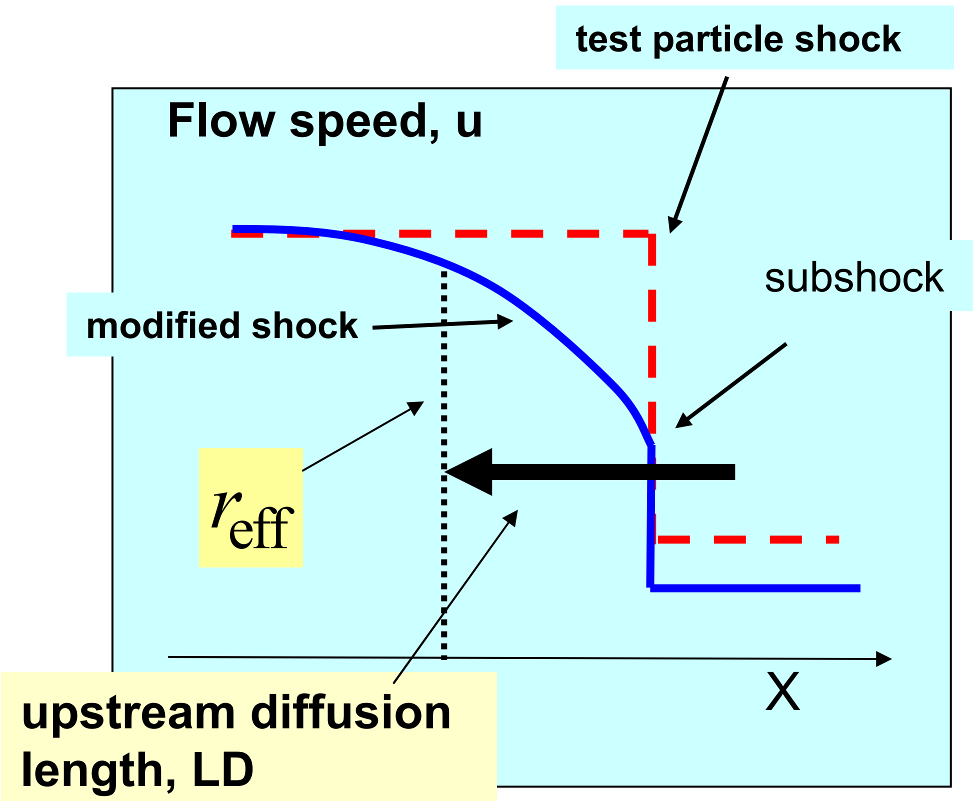
Note: If solve DSA with diffusion coefficient <u>independent</u> of momentum,

superthermal spectrum will be a power law even if r > 4.

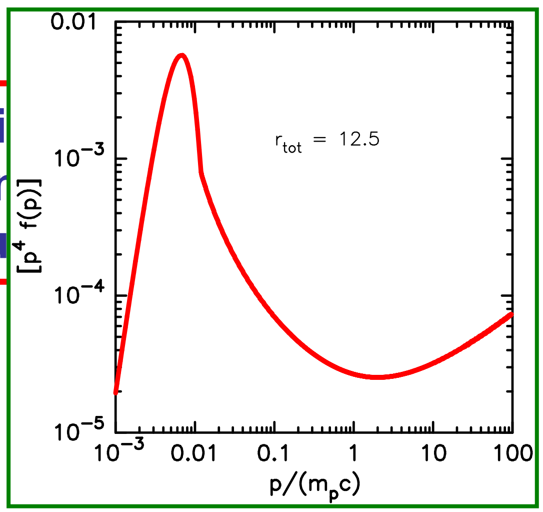
Lose important physical effects

e.g., Blasi & Gabici





If accelerati
becomes sr
backpressu



Upstream diffusion length, $L_D \sim D/u$

$D \propto \lambda v$, λ is diffusion mean free path. Take proportional to gyroradius, $r_g = p/(eB)$

$L_D \propto vp/B$

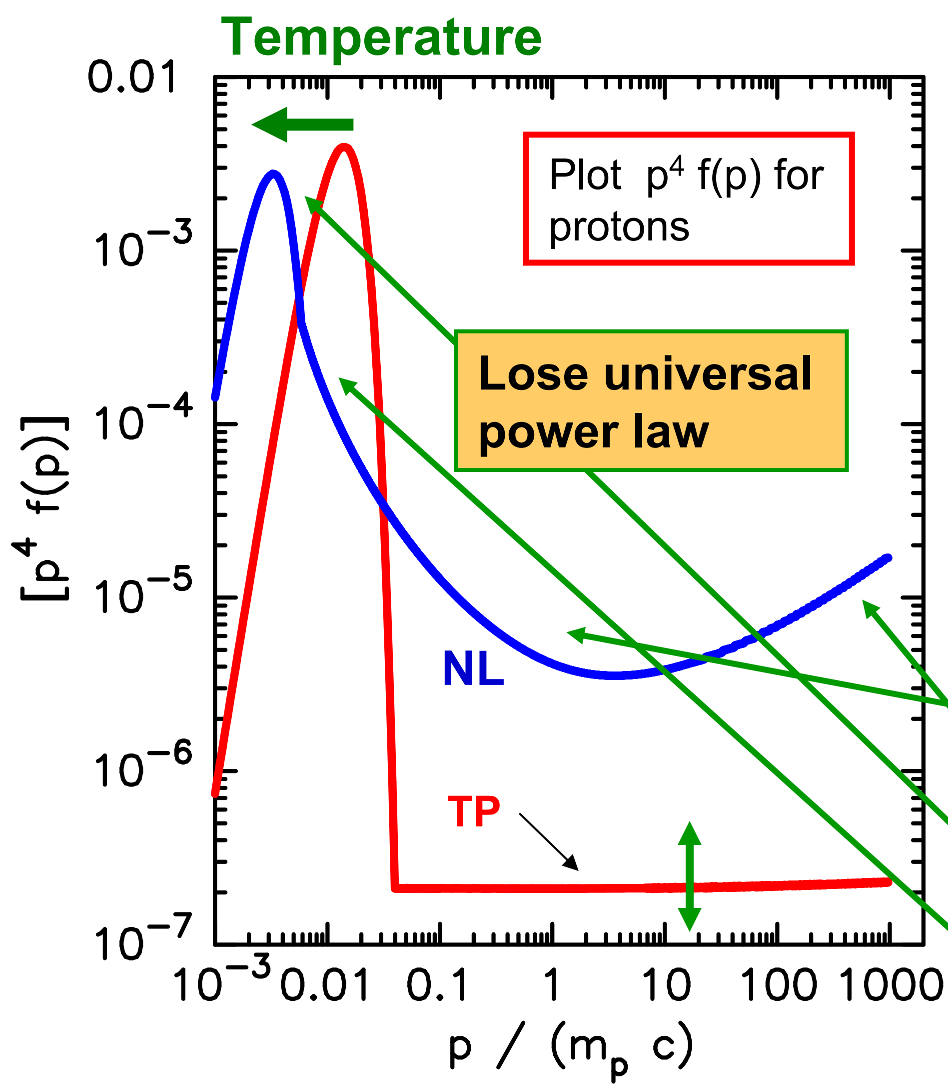
High momentum particles diffuse farther upstream than low p particles.

High p particles "feel" a larger compression ratio in modified shocks → get accelerated more.

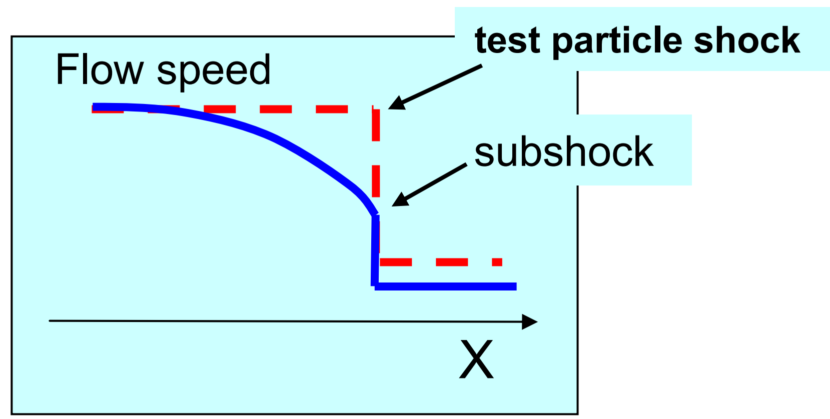
This produces a concave spectrum.

Unique and robust prediction for efficient, nonlinear DSA

Don Ellison, NCSU

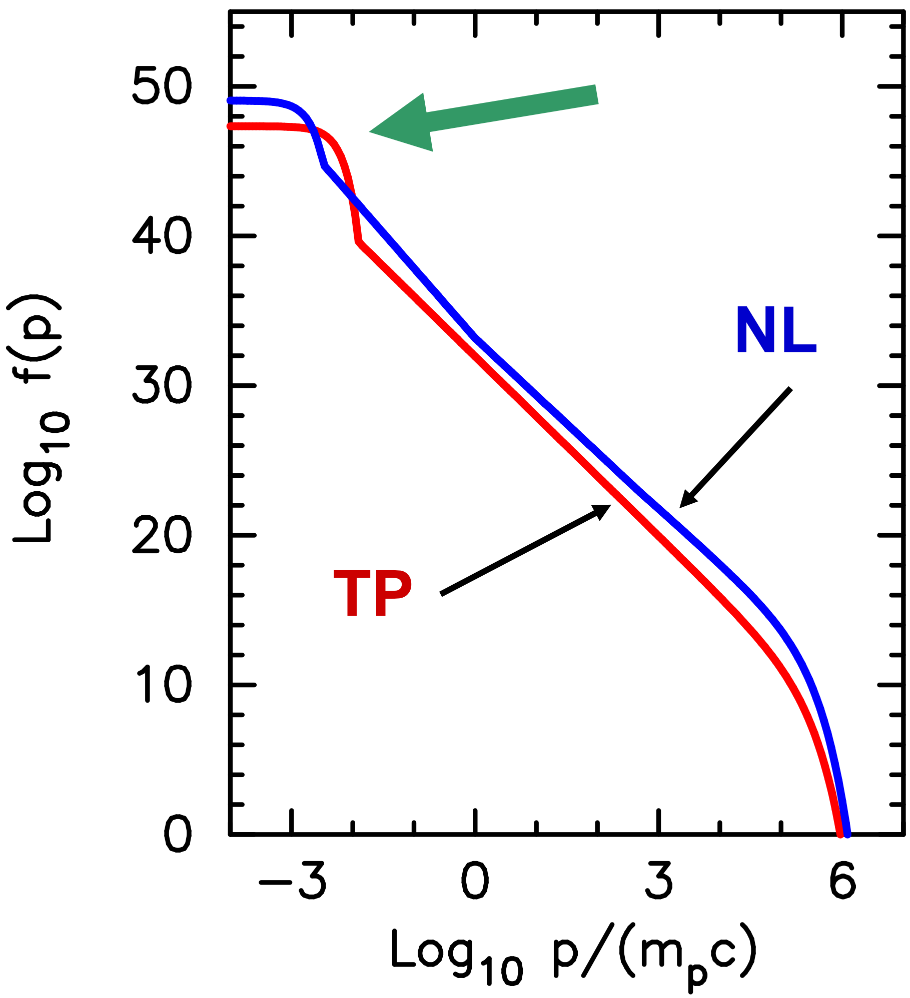


If acceleration is efficient, shock becomes smooth from backpressure of CRs



- **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 → much harder mathematically
BUT, connects photon emission across spectrum from radio to γ-rays → more information and more constraints on models



Without p^4 factor in plot, nonlinear effects much less noticeable → hard to see in cosmic ray obs.

Most important point for X-ray observations: the more efficient the cosmic ray production, the lower the shocked temperature. This is a large effect

Compression ratios, $r_{tot} > 4$ result from: (1) contribution to pressure from rel. particles (γ=4/3, $r_{tot} \rightarrow$ 7) and (2) particle escape ($r_{tot} \rightarrow$ infinity)

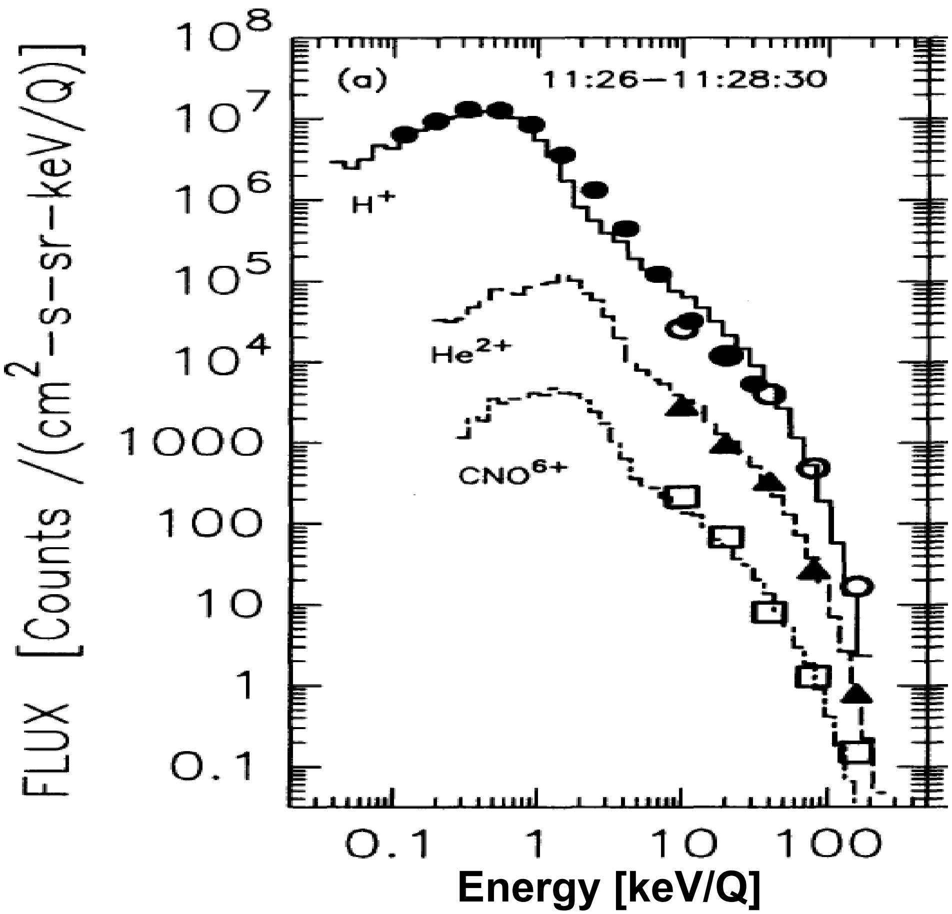
Are shocks, in fact, efficient? So far all theory.

There is clear observational evidence that shocks can put ~50% of ram kinetic energy into superthermal particles.

Direct evidence from spacecraft observations of Earth Bow Shock:

Modeling and observations of Earth Bow Shock

Ellison, Mobius & Paschmann 90



AMPTE observations of diffuse ions at Q-parallel Earth bow shock

Thermal leakage with NL shock modification matches H+, He2+, & CNO6+ spectra with single set of parameters

Matched predictions of A/Q enhancement

Indication of NL effects and R > 4.

Scholer, Trattner, Kucharek 1992 found similar results with hybrid PIC simulations

Modeling of Earth Bow Shock

Ellison, Mobius & Paschmann 90

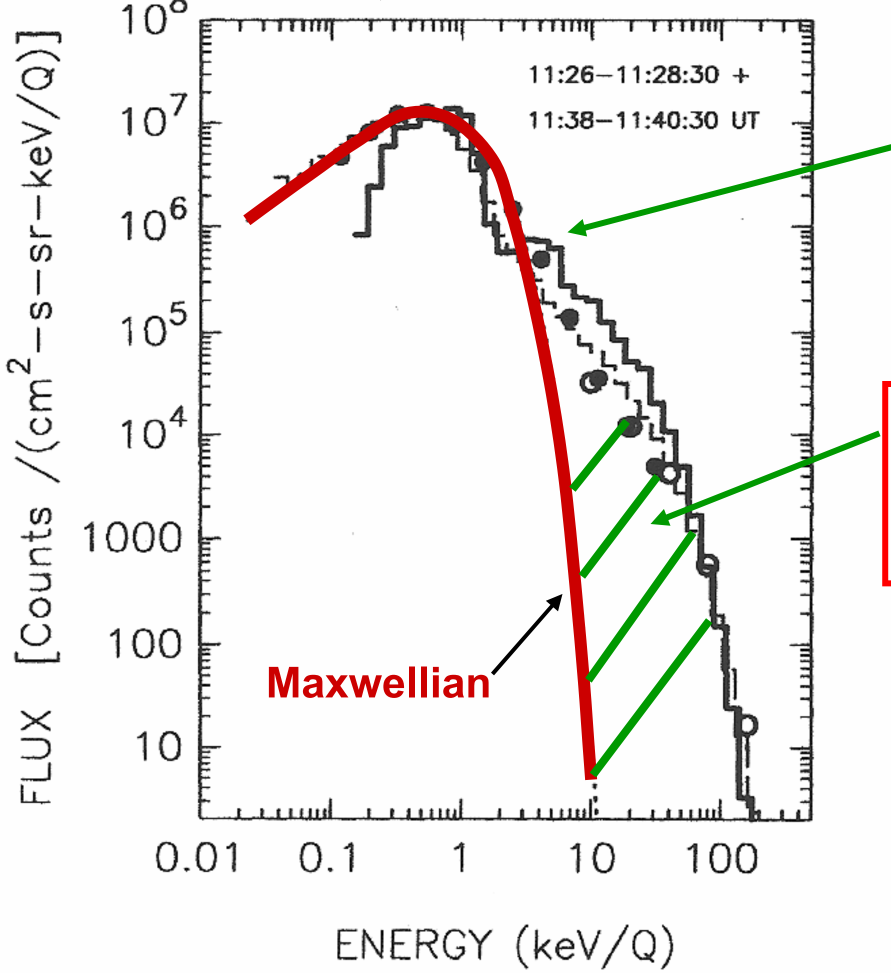


FIG. 13.—Downstream spectra (*points plus dashed line*) compared to a thermal distribution (*dotted line*). The thermal distribution has a temperature of 6×10^6 K, a density of 5.7 cm^{-3}, and a velocity of 115 km s^{-1}. Also shown is the Monte Carlo simulation result for a discontinuous shock transition (dotted line in Fig. 9). The heavy solid line shows the best fit obtainable for the given solar wind conditions when no upstream slowing of the solar wind is assumed.

Observed acceleration efficiency is quite high:

Dividing energy ~4 keV

gives ~2.5% of proton density in superthermal particles, and

>25% of energy flux crossing the shock in superthermal protons

Note: Acceleration of thermal electrons much less likely in heliospheric shocks

Superthermal electrons routinely seen to be accel. by heliospheric shocks

Are shocks, in fact, efficient? So far all theory.

There is clear evidence that shocks can put ~50% of ram kinetic energy into superthermal particles.

Direct evidence from spacecraft observations of Earth Bow Shock:

Indirect evidence from broad-band fits to emission from SNRs:

Broad-band continuum emission from SNRs

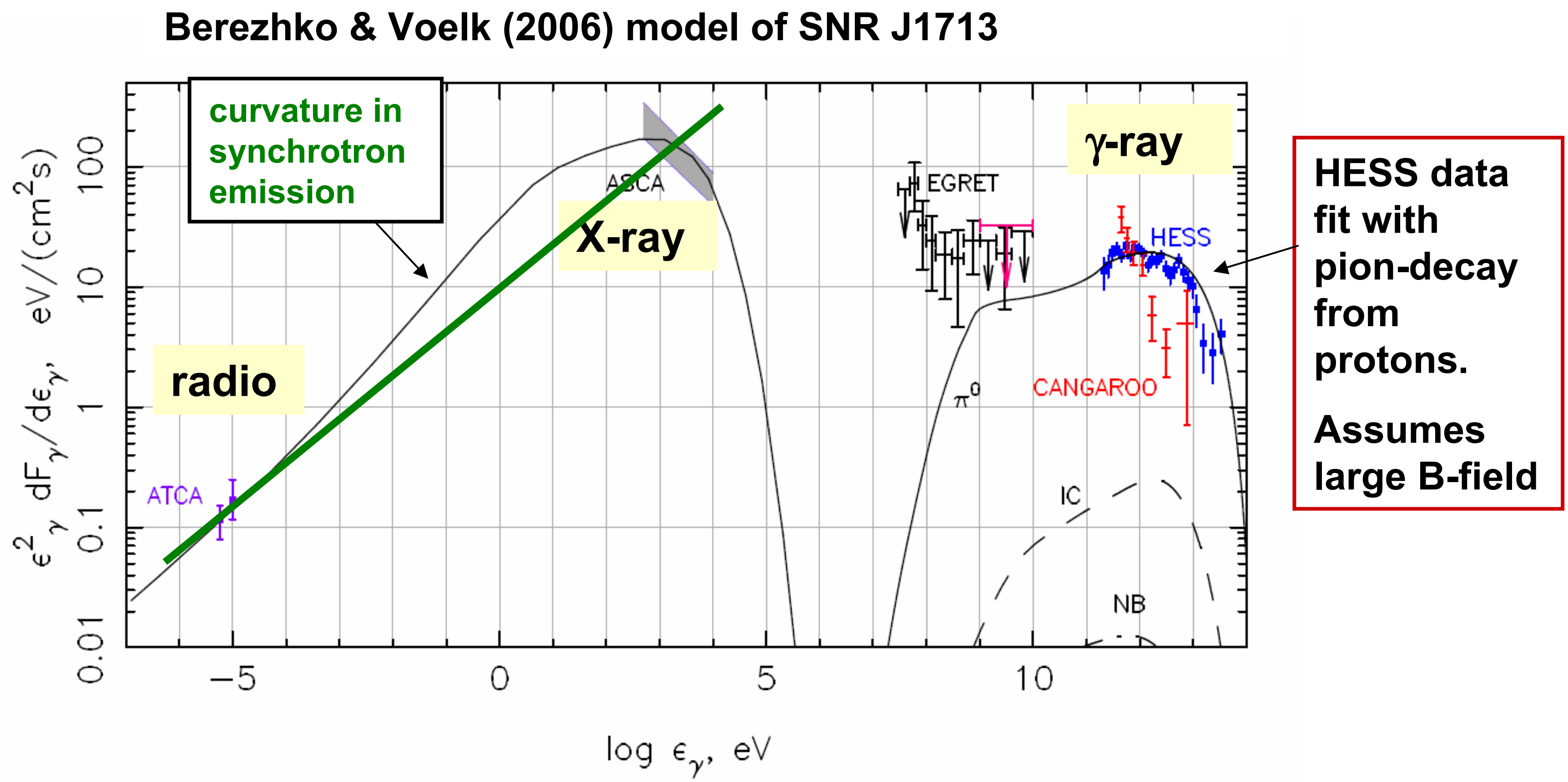
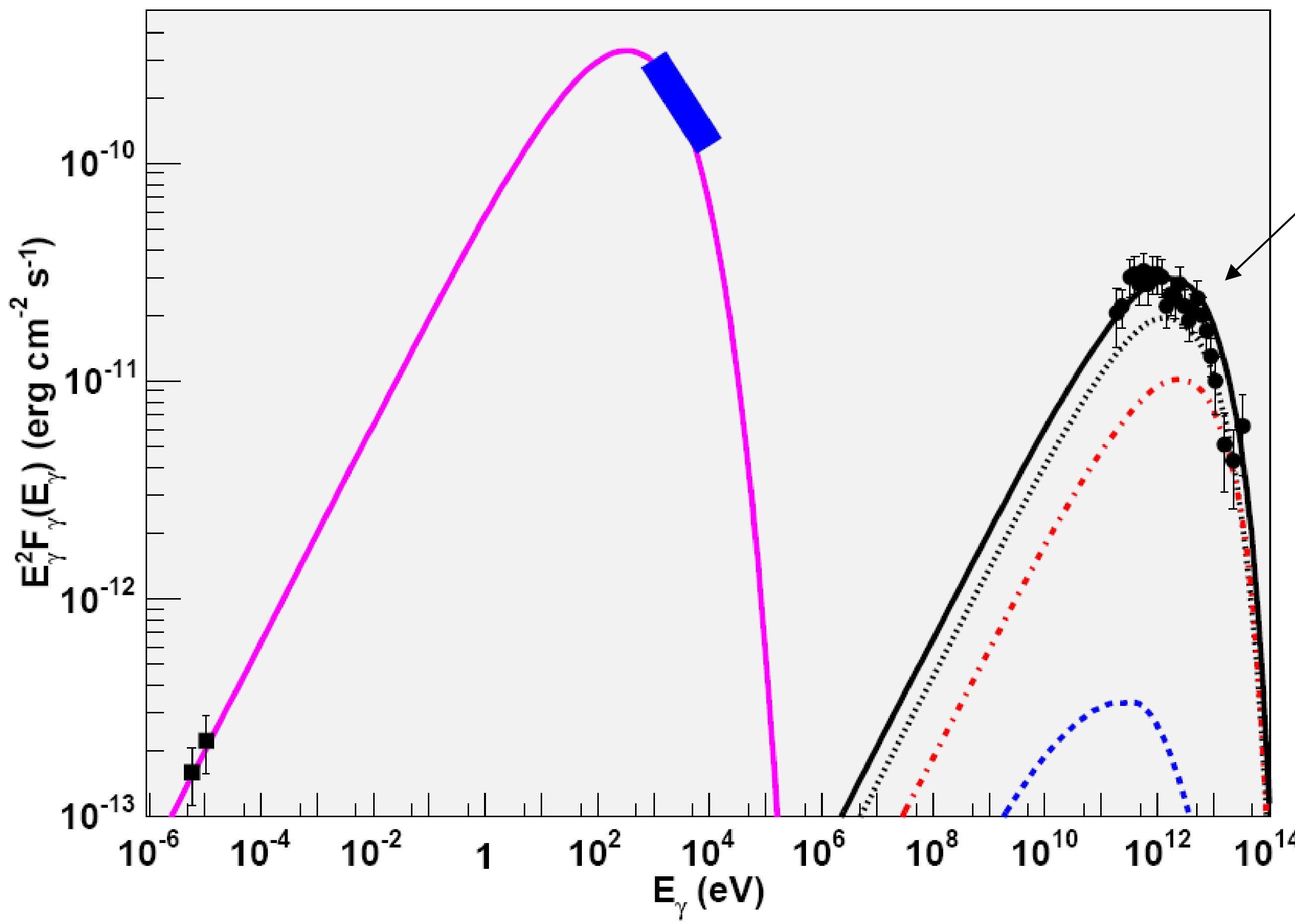


Fig. 3. Spatially integrated spectral energy distribution of RX J1713.7-3946 . The ATCA radio data (cf. Aharonian et al. 2005), ASCA X-ray data (cf. Aharonian et al. 2005), EGRET spectrum of 3EG J1714-3857 (Reimer & Pohl 2002), CANGAROO data (Enomoto et al. 2002), in red color) and H.E.S.S. data (Aharonian et al. 2005), in blue color) are shown. The EGRET upper limit for the RX J1713.7-3946 position (Aharonian et al. 2005) is shown as well (red colour). The solid curve at energies above 10^7 eV corresponds to π^0-decay γ-ray emission, whereas the dashed and dash-dotted curves indicate the inverse Compton (IC) and Nonthermal Bremsstrahlung (NB) emissions, respectively.

Don Ellison, NCSU

Porter, Moskalenko &Strong (2006) model of SNR J1713

Same data, different model and different parameters



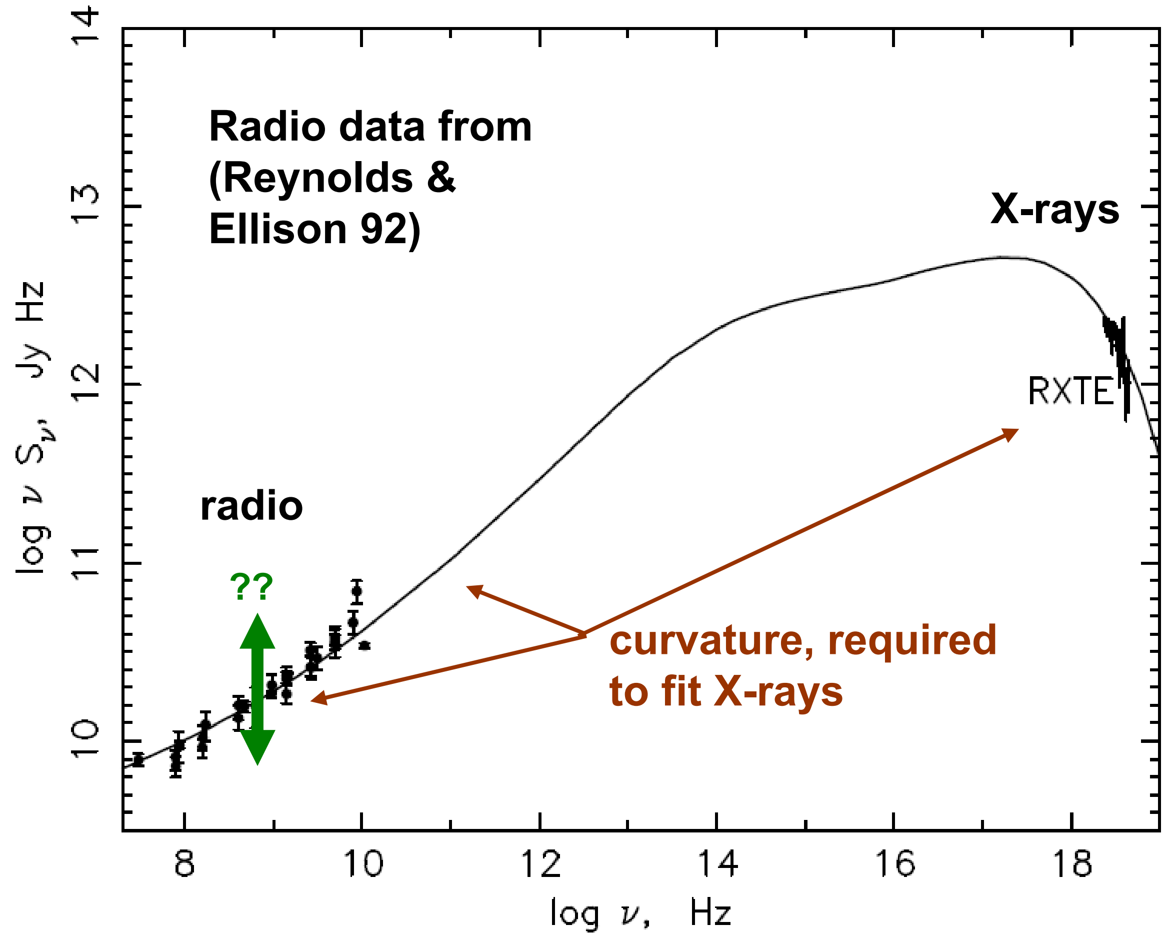
HESS data fit with inverse-Compton emission from electrons.

Assumes small B-field

Still an important open question if TeV emission produced by protons or electrons

Don Ellison, NCSU

Kepler's SNR (nonlinear model by Berezhko, Ksenofontov & Volk astroph2006)



Don Ellison, NCSU

Are shocks, in fact, efficient? So far all theory.

There is clear evidence that shocks can put ~50% of ram kinetic energy into superthermal particles.

Direct evidence from spacecraft observations of Earth Bow Shock:

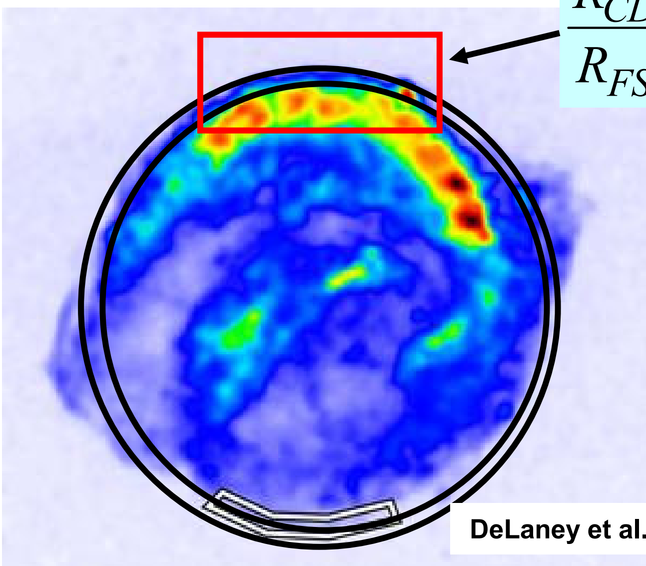
Indirect evidence from broad-band fits to emission from SNRs:

Fairly strong evidence from morphology of SNRs:

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).

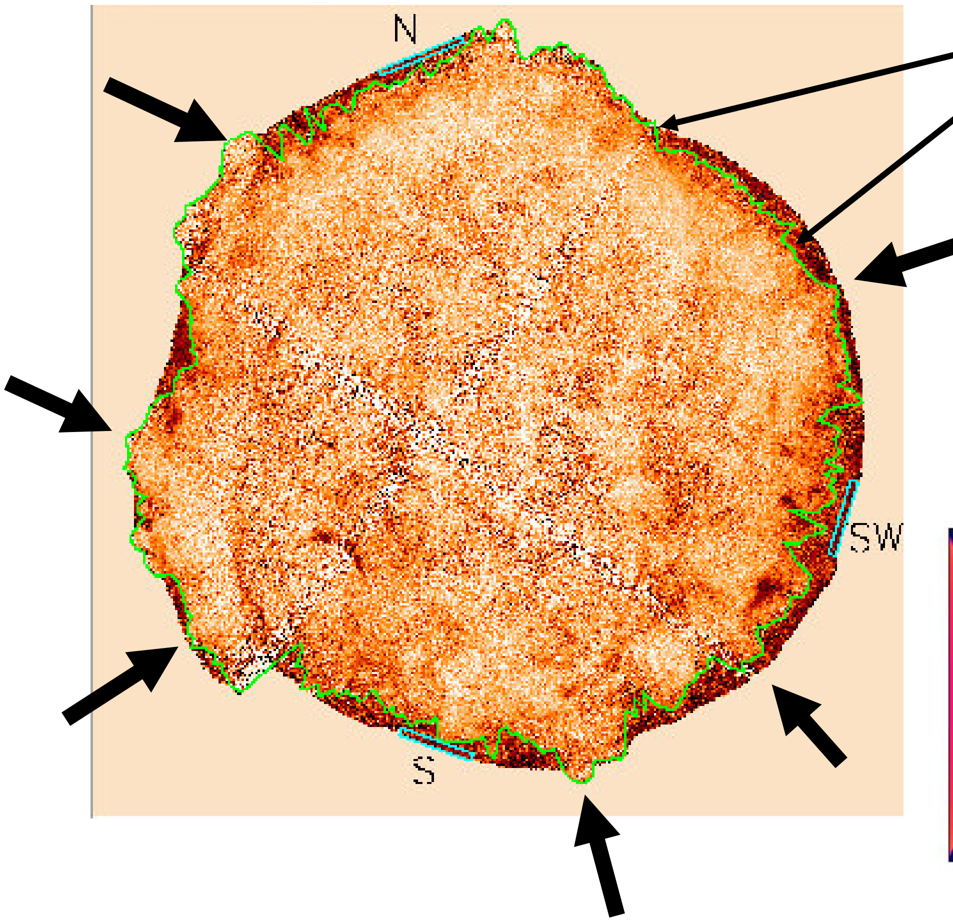
In **hydro models without efficient CR production**, the outer, **forward shock (FS) is well separated from the ejecta or CD**.

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

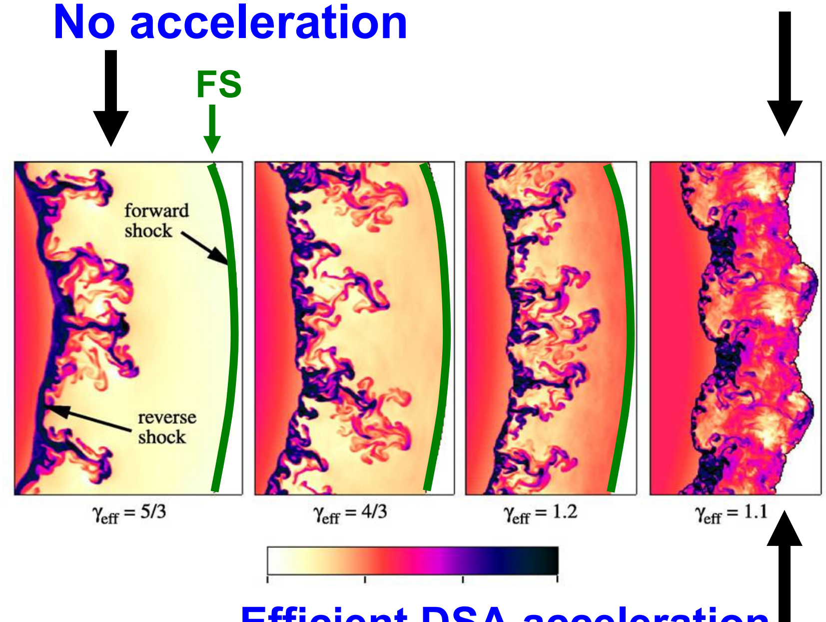
Chandra observations of Tycho's SNR
(Warren et al. 2005)



Green line is contact discontinuity (CD)

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

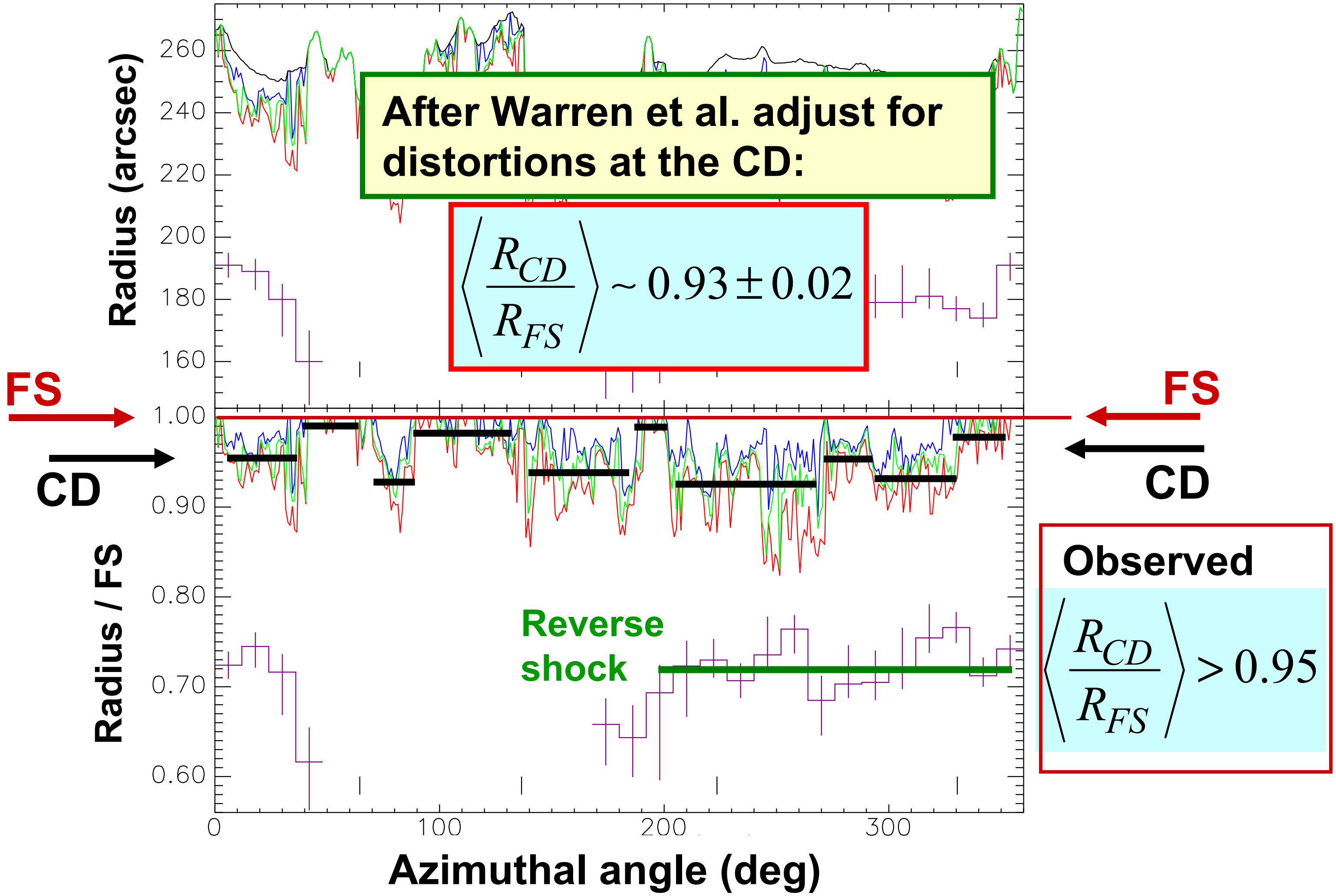
No acceleration



Efficient DSA acceleration

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

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



If shock compression ratio was 4, R_{CD}/R_{FS} ~ 0.85.
Data implies compression ratio r ~ 10

Don Ellison, NCSU

Not only must the particle distribution be calculated self-consistently, the magnetic field turbulence must be done self-consistently as well.

Must have B-field turbulence to scatter particles and particles must self-generate this turbulence.

This is another, strongly nonlinear process if acceleration is efficient.

Magnetic Field Amplification in Nonlinear Shock Acceleration – Non-relativistic shocks only

1) Magnetic field most important parameter for both the acceleration mechanism and for synchrotron radiation from electrons

2) Turbulent magnetic fields must be self-generated for DSA to work

3) Convincing evidence that magnetic fields in acceleration region of young supernova remnants (SNRs) much larger than B_{ISM} or even $r \times B_{ISM}$ (r is shock compression ratio)

4) Particle acceleration process may amplify ambient fields by large factors

5) Both the particle acceleration process, and B-field amplification are strongly nonlinear

Evidence for High magnetic fields in SNRs (all indirect):

1) Broad-band fits: Ratio of radio to TeV emission (radio/TeV) is large. Same distribution of electrons produces synchrotron (radio, X-ray) and TeV (inverse-Compton, IC)

Synchrotron depends directly on B-field, IC and pion-decay do not

High (radio/TeV) implies high B. Extreme case: Cas A where B_{sk} > 500 μG

2) Spectral curvature in continuum spectra

3) Sharp X-ray edges: Sharp edges seen in several young SNRs (e.g., Kepler, Cas A, Tycho, SN1006)

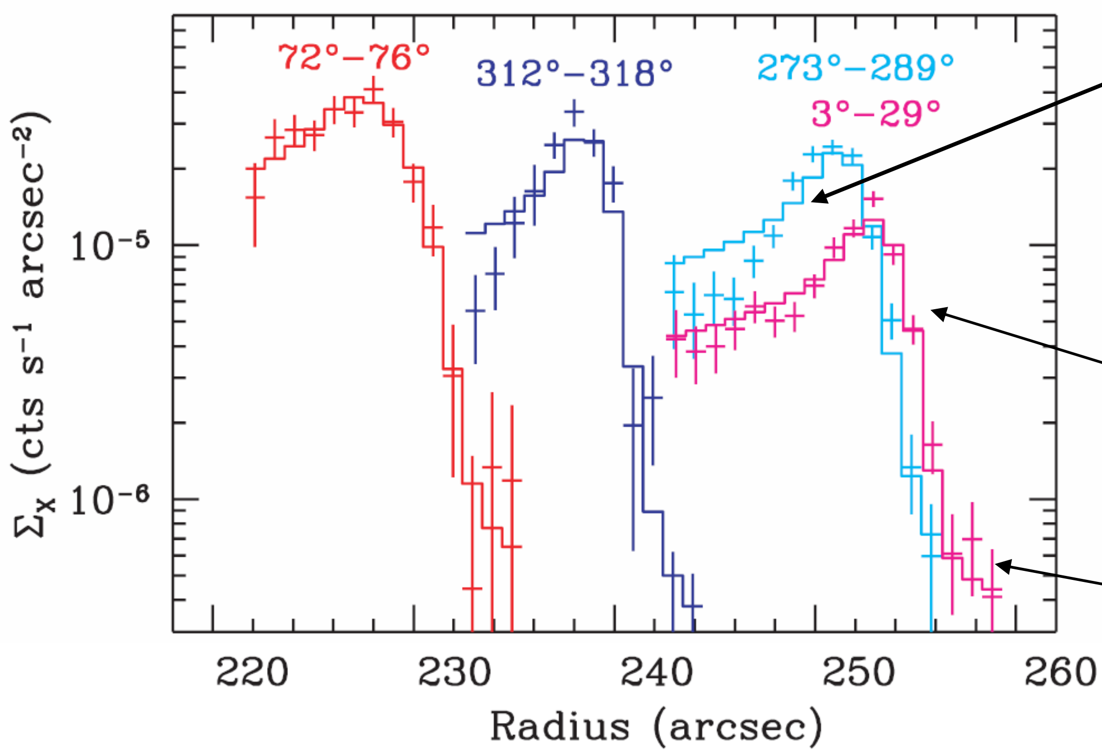
Non-thermal, X-ray synchrotron emission from TeV electrons

High B → large synch losses → short electron lifetime and short diffusion lengths → narrow X-ray structures. Imply B-fields >200μG

→ **Bottom line: Nonlinear effects are important (r_{tot} >> 4) & Inferred B-fields are much larger than can be expected from simple compression of B_{ISM}**

Sharp edges from various radial slices:

Fig. 7 from WARREN ET AL. 2005



Drop in brightness attributed to synchrotron losses in large B-field
(note: alternative explanation is that the B-field decays see Pohl et al 05)

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 (non-thermal emission)

Additional constrains on magnetic field come from synchrotron emission in forward shock precursor → B must increase sharply at forward shock

How do you start with $B_{ISM} \sim 3\ \mu G$ and end up with $B \sim 500\ \mu G$ at the shock?

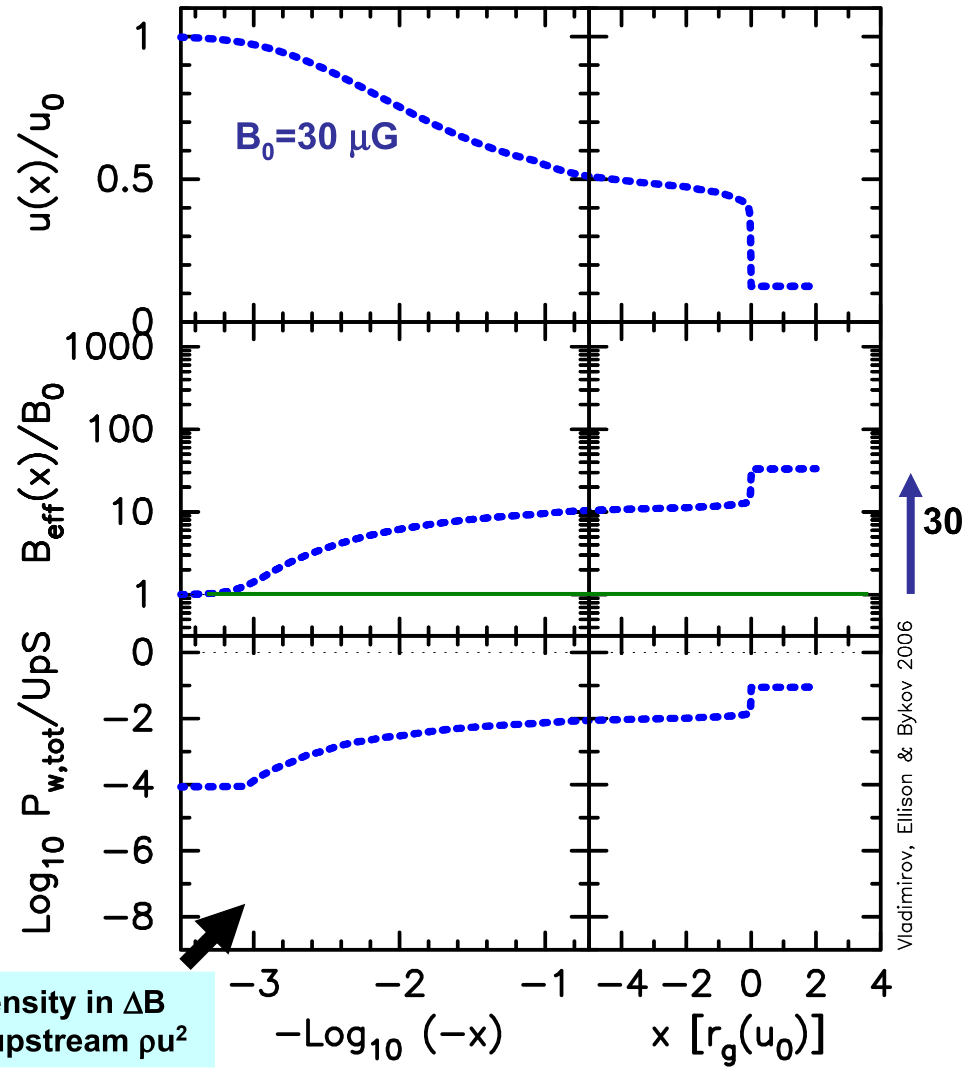
B-field Amplification:

Efficient diffusive shock acceleration (DSA) not only places a large fraction of shock energy into relativistic particles, but also amplifies magnetic field by large factors

Bell & Lucek 2001
Amato & Blasi 2006
Vladimirov, Ellison & Bykov 2006

Basic ideas:

1) Large B-fields exist and shock acceleration produces them
2) Cosmic ray streaming instability must be responsible, but hard to model correctly → difficult plasma physics (non-resonant interactions)
3) Connected to efficient CR production, so nonlinear effects essential
4) Make approximations to estimate effect as well as possible
5) Once basic model is understood, put in more realistic plasma physics

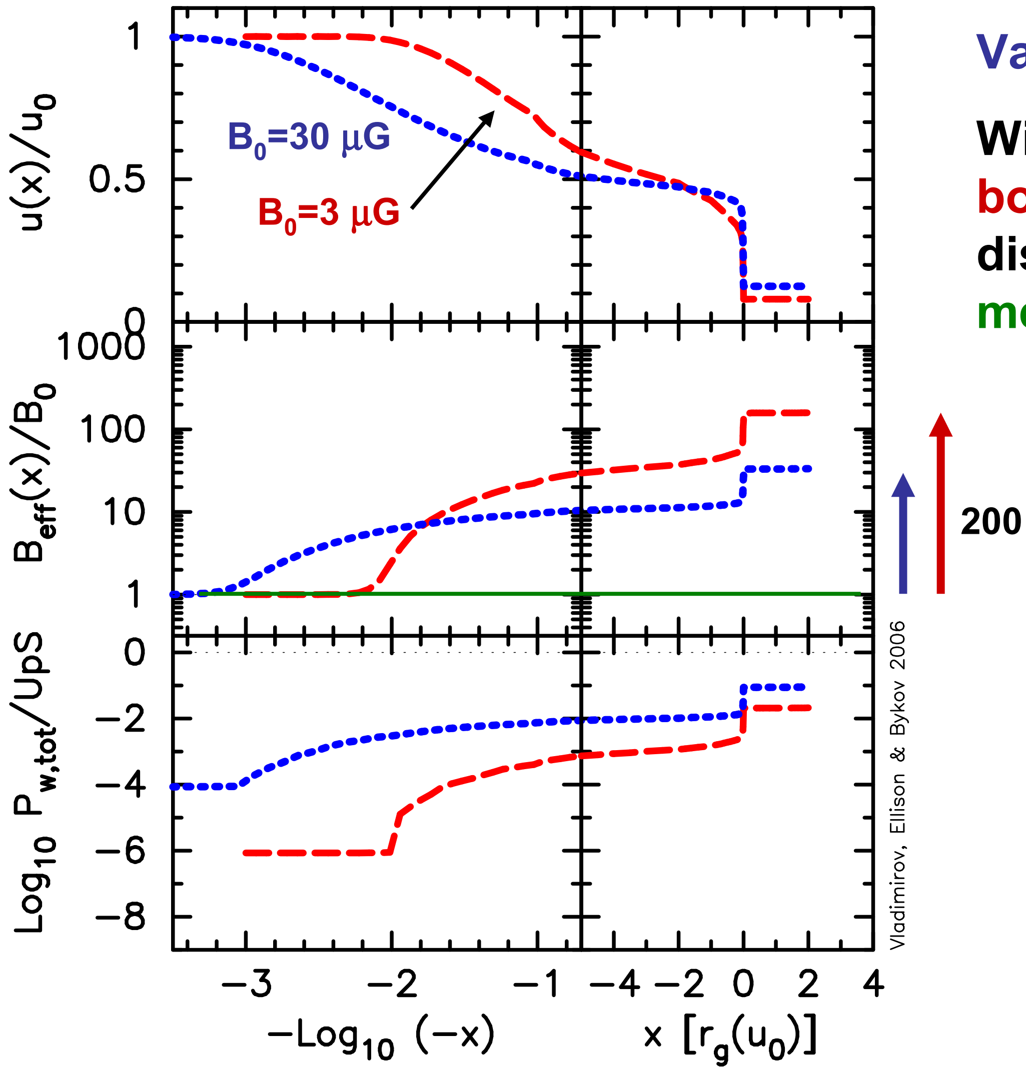


en. density in ΔB over upstream ρu^2

x-scale in units of gyroradius

Vary far upstream field B_0

With the free escape boundary at a fixed distance upstream in meters?



x-scale in units of gyroradius

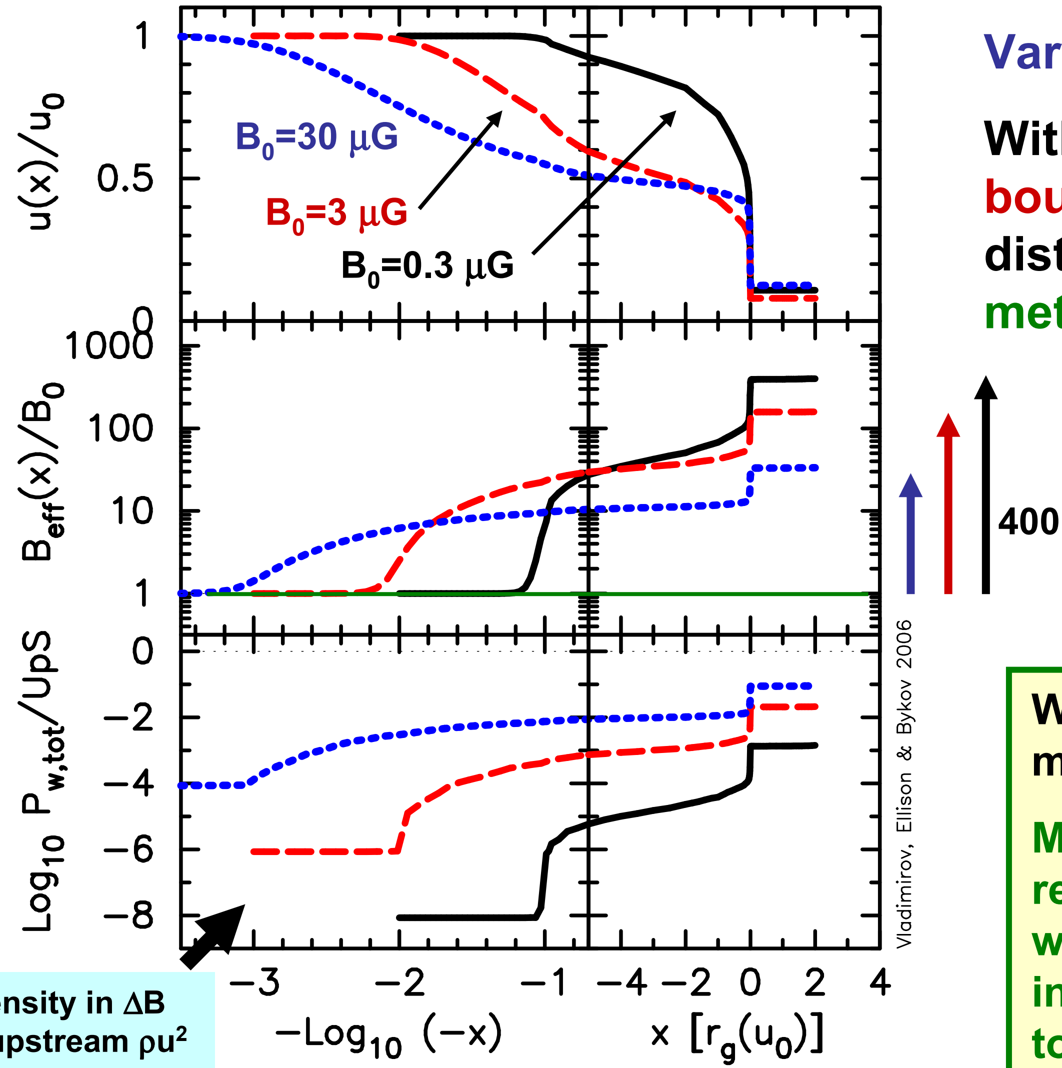
Vary far upstream field B_0

With the free escape boundary at a fixed distance upstream in meters?

Don Ellison, NCSU

Vary far upstream field B_0

With the free escape boundary at a fixed distance upstream in meters?



en. density in ΔB over upstream ρu^2

x-scale in units of gyroradius

Weak fields are amplified more than strong fields

May be important for reverse shocks in SNRs where the un-amplified field in the ejecta material is far too low to support any shock acceleration

Conclusions:

1) Collisionless shocks are ubiquitous and produce nonthermal particles on wide range of astrophysical scales
2) Diffusive shock acceleration well developed mechanism describing acceleration
3) DSA is predicted to be efficient and observational evidence supports this → mainly in supernova remnants
4) Production of energetic particles seems to go hand-in-hand with magnetic field amplification, at least in young SNRs
5) If B-field amplification always accompanies DSA, will have important implications in many astrophysical sites, i.e., radio jets, gamma-ray bursts