Collisionless Shocks in 12 minutes or less

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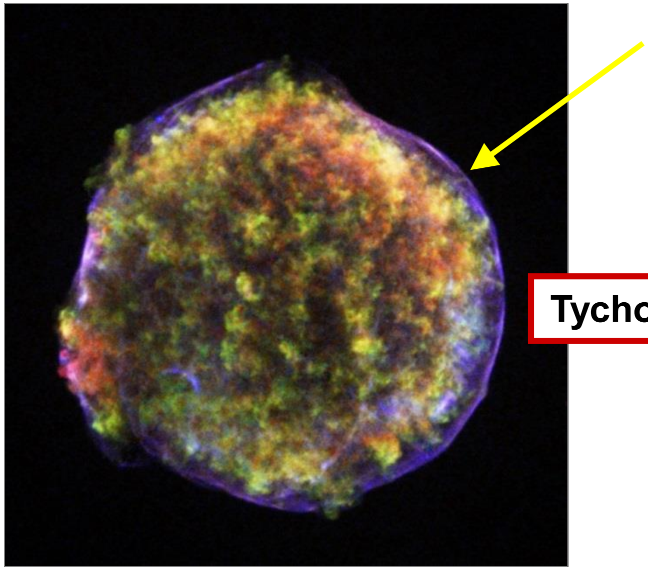
Strong collisionless shocks are important sources of TeV particles

- ➔ **Supernova remnant shocks**
- ➔ **Gamma Ray Bursts**
- ➔ **AGNs**
- ➔ **Large-scale shocks in galaxy clusters – Probably**



No doubt that TeV electrons are produced by this non-relativistic shock.

Evidence for TeV ions is less direct but very strong.

Tycho's Supernova Remnant (Type Ia SN)

Some references:

Pelletier, Lemoine & Marcowith 2009; Bykov, Osipov & Ellison 2011; Bykov & Treumann 2011; Plotnikov, Pelletier & Lemoine 2013; Ellison, Warren & Bykov 2013, 2016; Warren et al. 2017

➔ Particle acceleration (vs. heating) occurs in shocks as charged particles (CRs) scatter "elastically" off converging plasmas ➔ Fermi shock acceleration

a) This is a kinetic process fundamentally different from energization by "coherent" electric fields

b) Can tap sizable fraction of bulk kinetic energy of massive flows ! ←

c) Heavy particles (i.e., protons) gain more energy then light ones (i.e., electrons) in converging glows ➔ hard to accelerate electrons in relativistic shocks ! ←

➔ Despite continuing questions, it is certain that thermal particles are injected and accelerated at collisionless shocks

a) Observational evidence for non-rel. shocks

b) Particle-In-Cell (PIC) simulations show injection and acceleration at relativistic shocks

Non-relativistic shocks: shock speed Vsk << c

- ➔ Compression ratios R ~ 4 or greater

- ➔ CR acceleration can be extremely efficient: > 25% of ram kinetic energy can be put into relativistic CRs ➔ nonlinear models essential

- ➔ CR spectrum can be hard, i.e., harder than $\frac{dN}{dE} \propto E^{-2}$ i.e. $f(p) \propto p^{-4}$

- ➔ When particle speed v_p >> Vsk , diffusion approximation can be made simplifying semi-analytic descriptions

- ➔ As maximum CR energy increases, precursor scale and acceleration time become large ➔ limits E_{max}

- ➔ How particles scatter off B-field turbulence is critical factor. Turbulence must be self-generated ➔ highly nonlinear ➔ PIC & hybrid sims essential

- ➔ In semi-analytic (and Monte Carlo) modeling, often assume Bohm scattering: particle mfp: $\lambda \propto p$ (momentum)

Self-consistent (i.e., Not test-particle) result for non-relativistic shock (using Monte Carlo techniques)

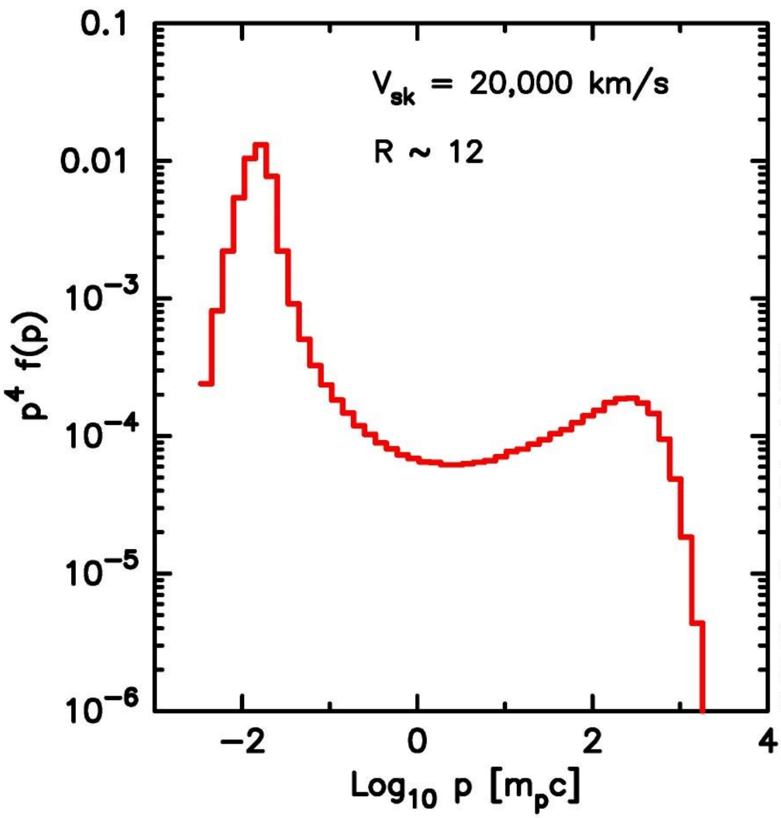


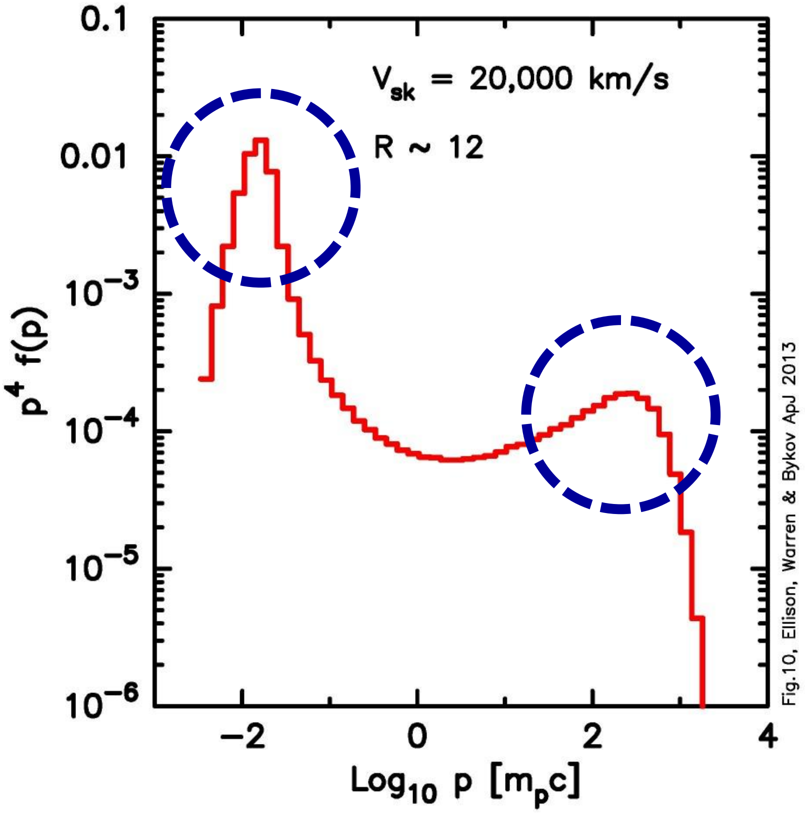
Fig.10, Ellison, Warren & Bykov ApJ 2013

Typical particle spectrum showing strong nonlinear effects:

➔ Concave spectral shape

➔ R > 4 for highest energy CRs

Self-consistent (i.e., Not test-particle) result for non-relativistic shock (using Monte Carlo techniques)



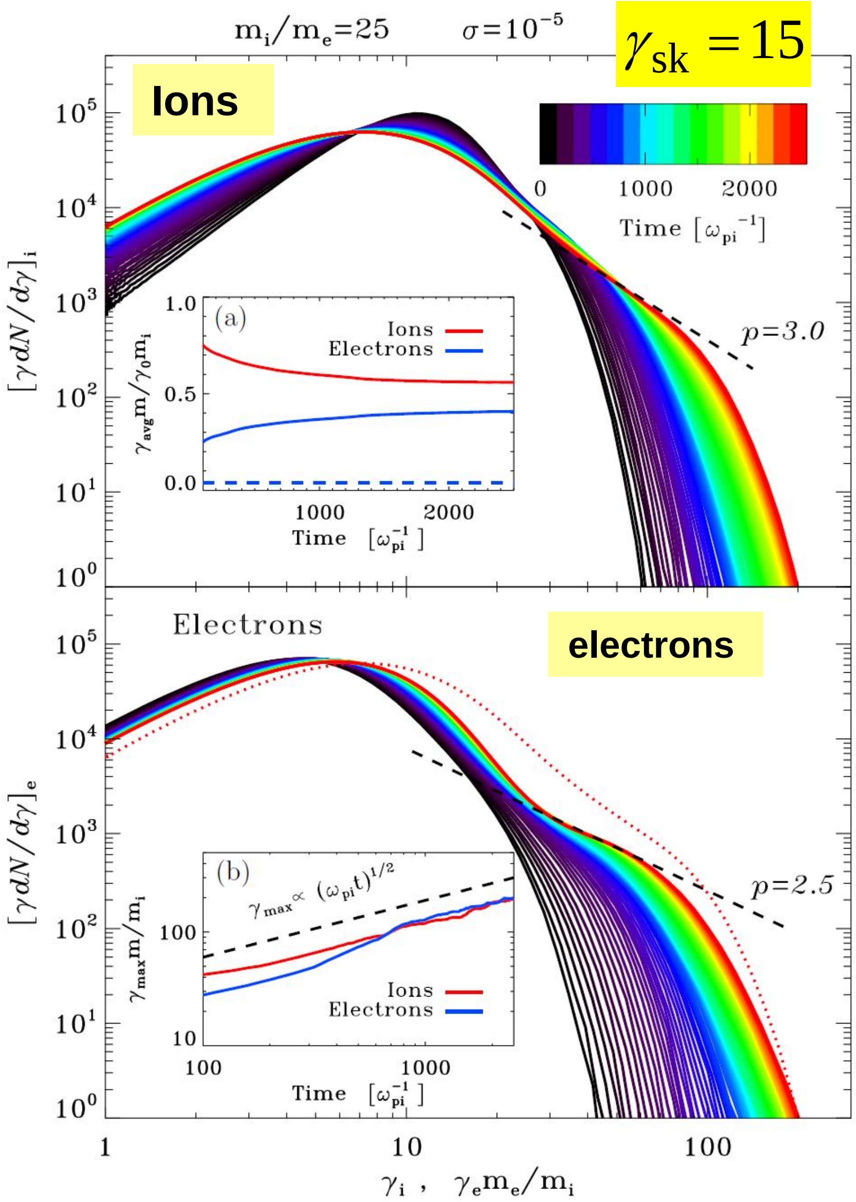
Typical particle spectrum showing strong nonlinear effects:

- ➔ **Concave spectral shape**
- ➔ **R > 4 for highest energy CRs**
- ➔ **Bulk of energy divided between thermal particles and highest energy particles**

Relativistic shocks: Vsk ~ c, Lorentz factor $\gamma_{sk} \geq 5 - 10$

- ➔ Compression ratio R ~ 3
- ➔ Test-particle CR spectrum softer than non-rel. i.e., $f(p) \propto p^{-4.23}$
- ➔ Particle acceleration less efficient but PIC simulations show it may be significant. ➔ Nonlinear effects are still important !
- ➔ Particle speed never >> Vsk ~ c so diffusion approximation cannot be made ➔ Analytic descriptions extremely difficult !
- ➔ Shock precursor scale and acceleration time can be extremely small ➔ possibility of large cosmic ray E_{max} ??
- ➔ **But**, everything depends on self-generated turbulence and turbulence is hard to model in all shocks but particularly in relativistic ones.
- ➔ Do expect $\lambda \propto p^2$ for highest energy CRs

PIC results: Fig 11, Sironi etal. 2013



➔ Thermal particles injected and accelerated in weakly magnetized relativistic shocks !

➔ Acceleration is significant !!

➔ ~40% of energy transferred from protons to electrons in shock precursor !!!

➔ Everything depends on self-generated turbulence.

➔ PIC is only method that can do this consistently but box size is still extremely limited.

At cost of important approximations, Monte Carlo simulations can extend length, time, & energy scales to astrophysically significant values.

Self-consistent (i.e., Not test-particle) Monte Carlo results:

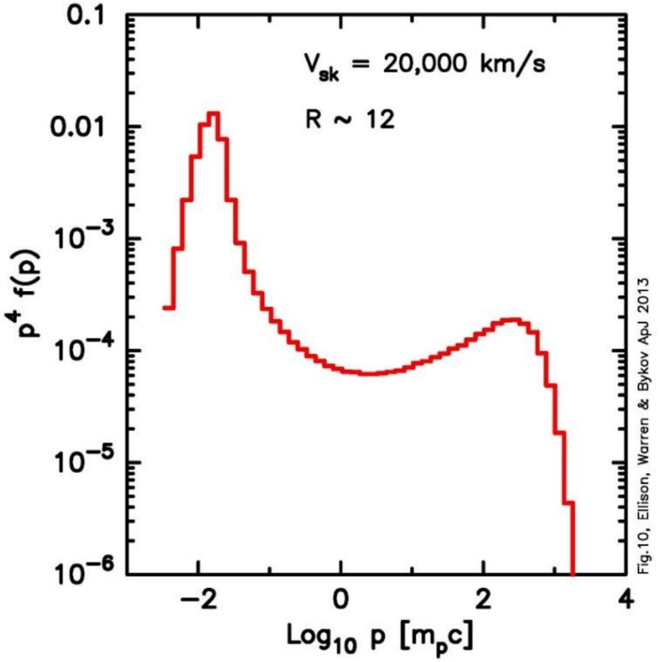


Fig.10, Ellison, Warren & Bykov ApJ 2013

Non-relativistic shock, Vsk = 2 x 10^4 km/s

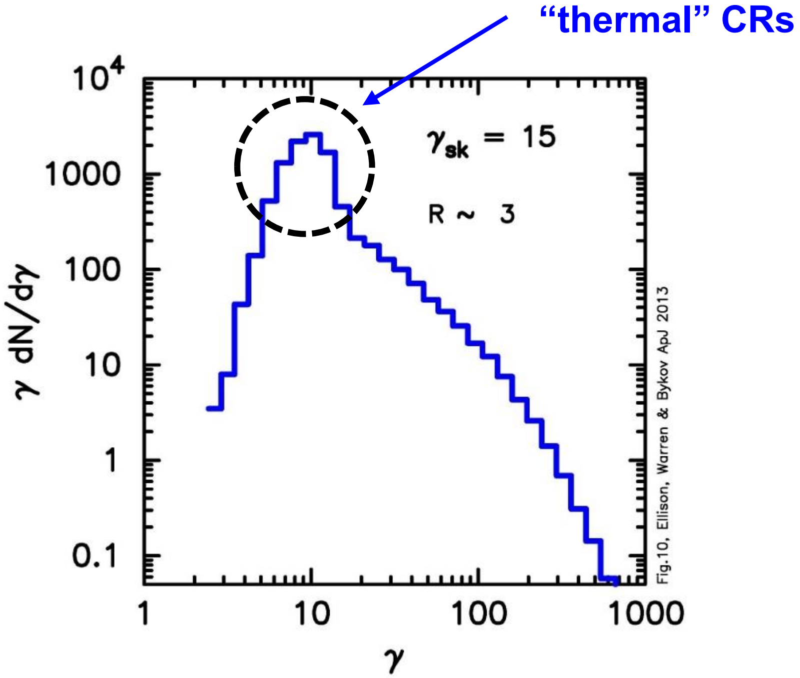


Fig.10, Ellison, Warren & Bykov ApJ 2013

Relativistic shock, $\gamma_{sk} = 15$

Within a single set of assumptions

➔ Monte Carlo simulation gives **full self-consistent distribution function** from thermal particles to maximum energy CRs

➔ MC can do **ions and electrons** self-consistently

➔ Beware of assuming simple power

Regardless of speed, all collisionless shocks are controlled by the same physics ←

- ➔ Charged particles interact with self-generated B-field turbulence

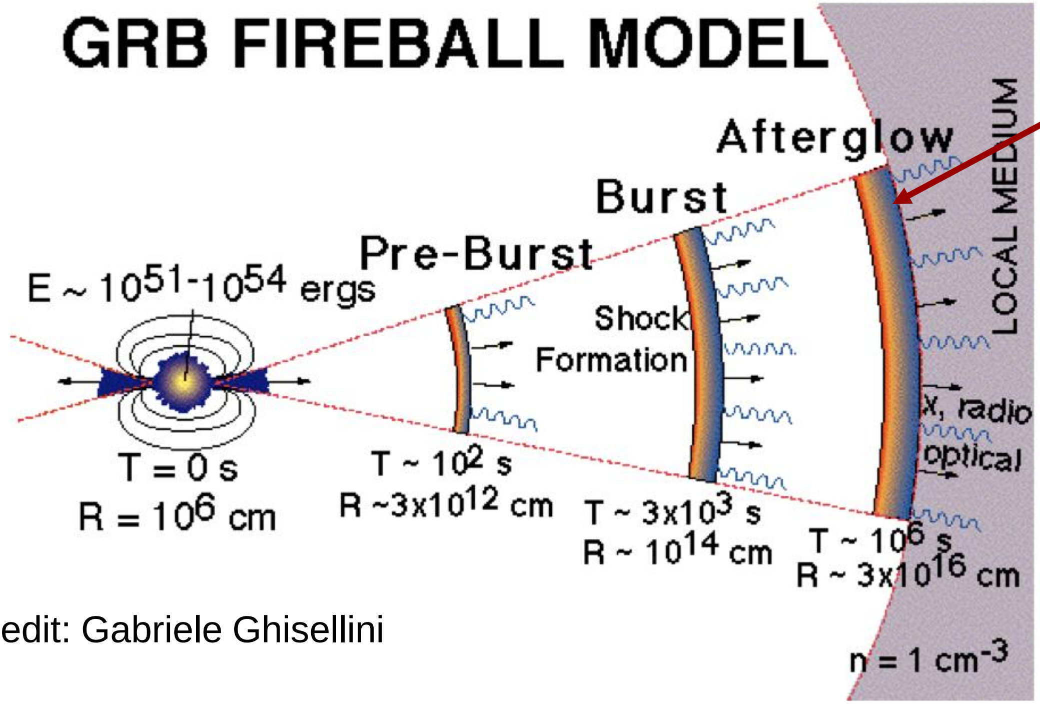
- ➔ Entropy produced as particles scatter "nearly elastically" off background B-field

- ➔ Elastic scattering allows individual particles to be accelerated far beyond simple heating

- ➔ Details (and mathematical description) can depend strongly on shock speed Vsk.

- ➔ Regardless of complications, there must be a continuous transition in shock structure, turbulence generation, and CR production from ultra-relativistic to non-relativistic shocks ←

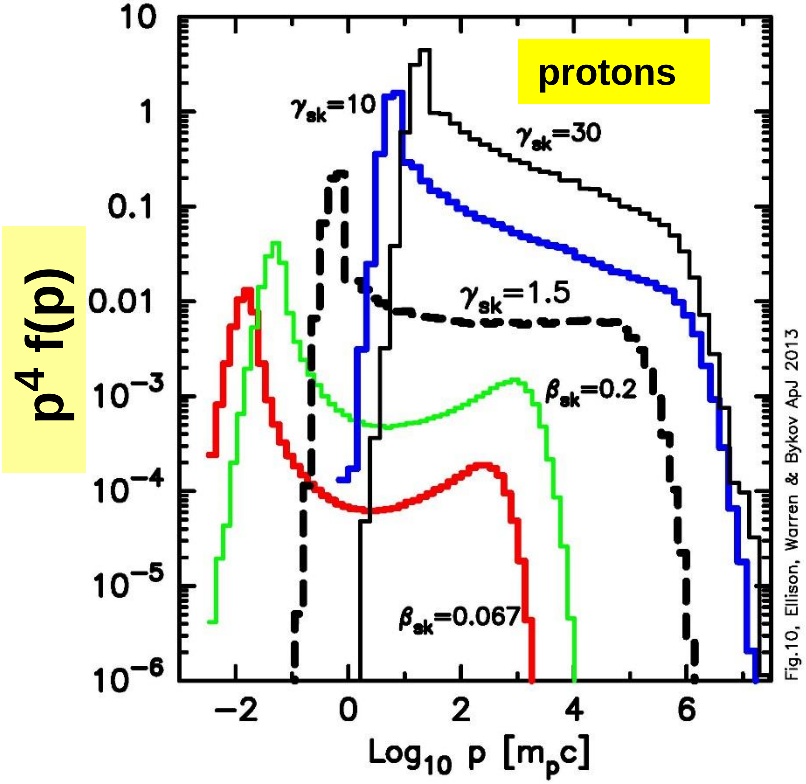
Afterglow shocks in GRBs: shock slows from ultra-rel. to non-rel. as it moves through circumstellar material



Forward shock moving through local medium

Credit: Gabriele Ghisellini

Monte Carlo results for shocks of varying speeds. Snap shot CR spectra:



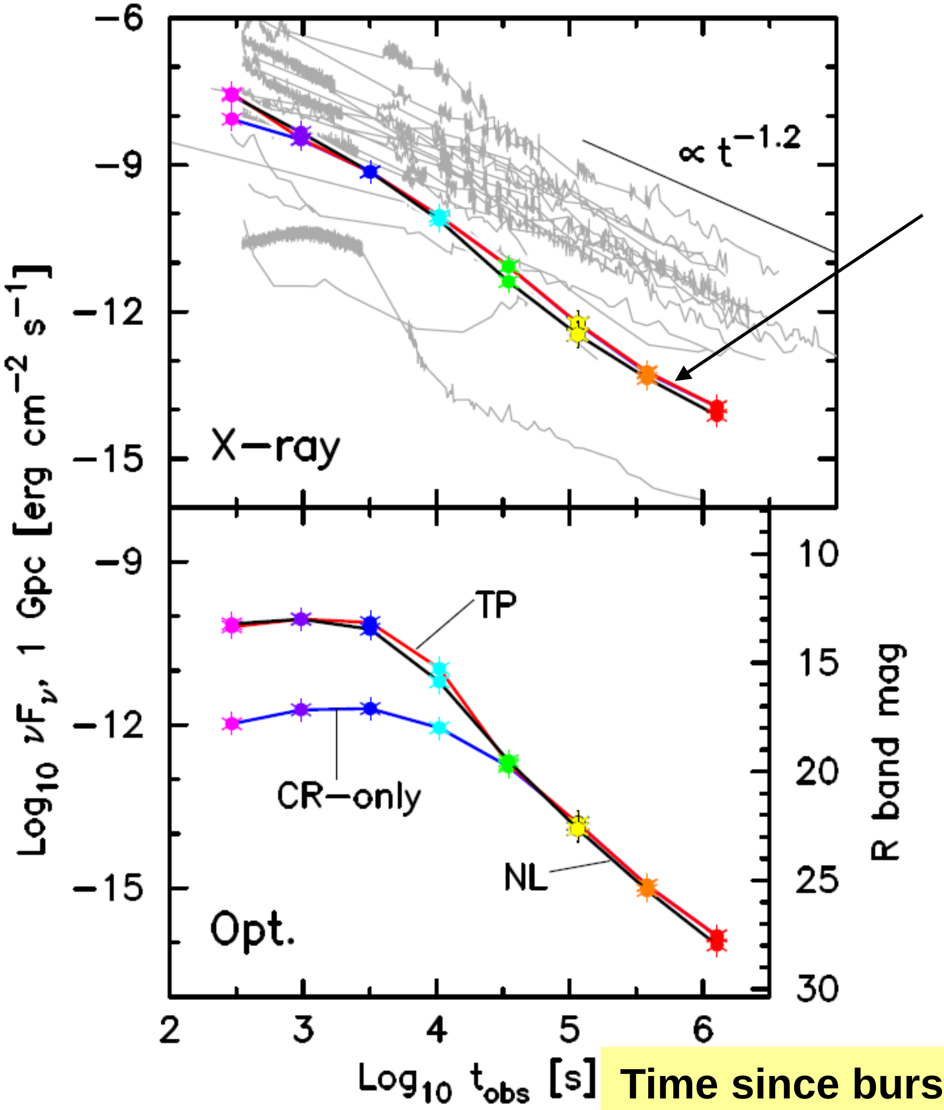
Ellison, Warren & Bykov 2013

- ➔ **As GRB afterglow shock slows it will transition from ultra-relativistic through trans-relativistic to non-relativistic speeds**
- ➔ **Ultra-rel: Softer spectra but dramatic differences in Lorentz transformations of protons and electrons**
- ➔ **Non-relativistic: More pronounced nonlinear effects from efficient CR production**
- ➔ **Evolution in particle spectra ➔ evolution in photon emission**

► **To calculate radiation, must model nonlinear acceleration of protons and electrons together consistently. Even if only radiation from electrons is observed**

Nonlinear model of GRB afterglow evolution using nonlinear Monte Carlo shock acceleration (Warren et al 2017)

photon emission at 1 Gpc



Time since burst [s]

Predictions for afterglow radiation vs. time since burst

➔ This radiation is from CR electrons even though ion acceleration dominates shock physics

See Warren et al 2017 for details

Trans-relativistic shocks with Lorentz factors of a few may be particularly important

- ➔ GRBs, AGNs, Type Ibc SNe, hyper-novae
- ➔ May be important source of PeV CRs and TeV gamma rays

Best of both worlds :

- ➔ CR acceleration faster than non-rel. shocks because Vsk ~ c.
- ➔ Harder spectrum and more efficient CR production than ultra-rel. shocks.
- ➔ BUT trans-relativistic shocks are rare and short-lived compared to non-rel. shocks
- ➔ Must do careful modeling : Role in CR production unclear

Most energy in “thermal” CRs

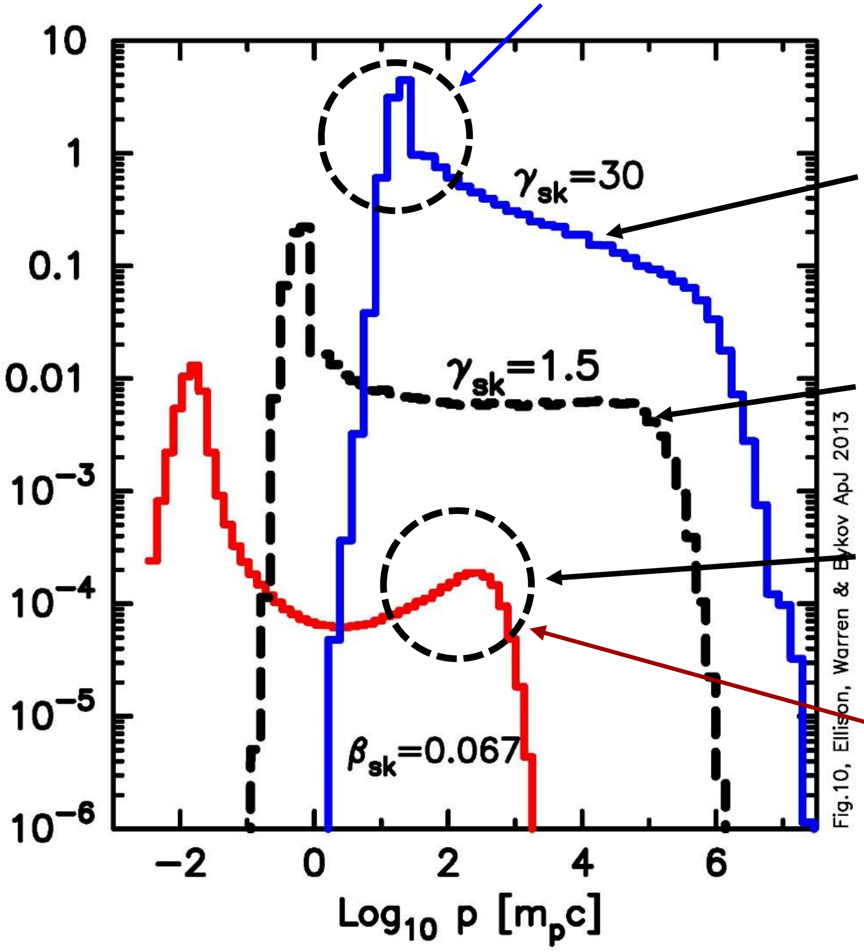


Fig.10, Ellison, Warren & Bykov ApJ 2013

$p^4\ f(p)$

Momentum, p

ultra-relativistic

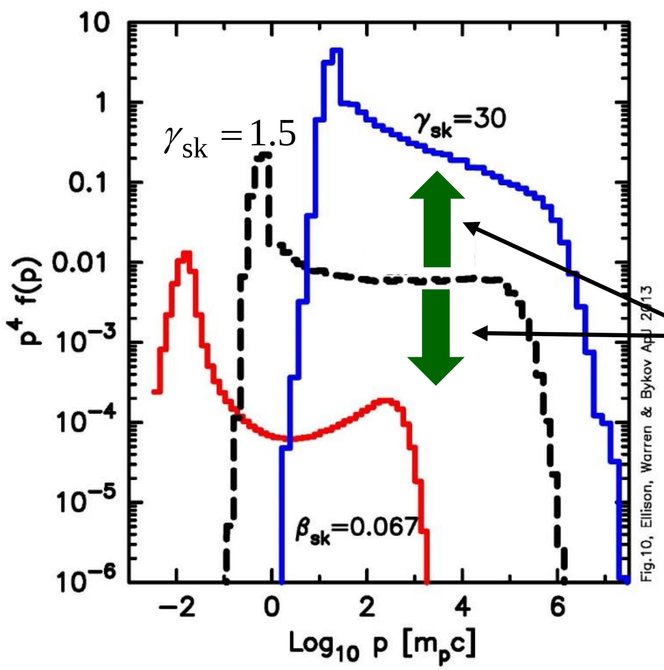
trans-relativistic

non-relativistic

Afterglow or hyper-nova shock slows

Most energy in highest energy CRs

It is challenging to accurately model trans-relativistic shocks:



Slight changes in:

- **Injection efficiency**
- **B-field strength**
- **Shock speed**
- **Shock size, etc.,**

May produce jump from essentially test-particle, ultra-rel. mode, to nonlinear, non-relativistic mode

Small change in parameters may result in large change in CR acceleration efficiency, spectral shape, maximum CR energy, and e/p ratio

Warning ➔ PIC results may depend critically on PIC box size and run time

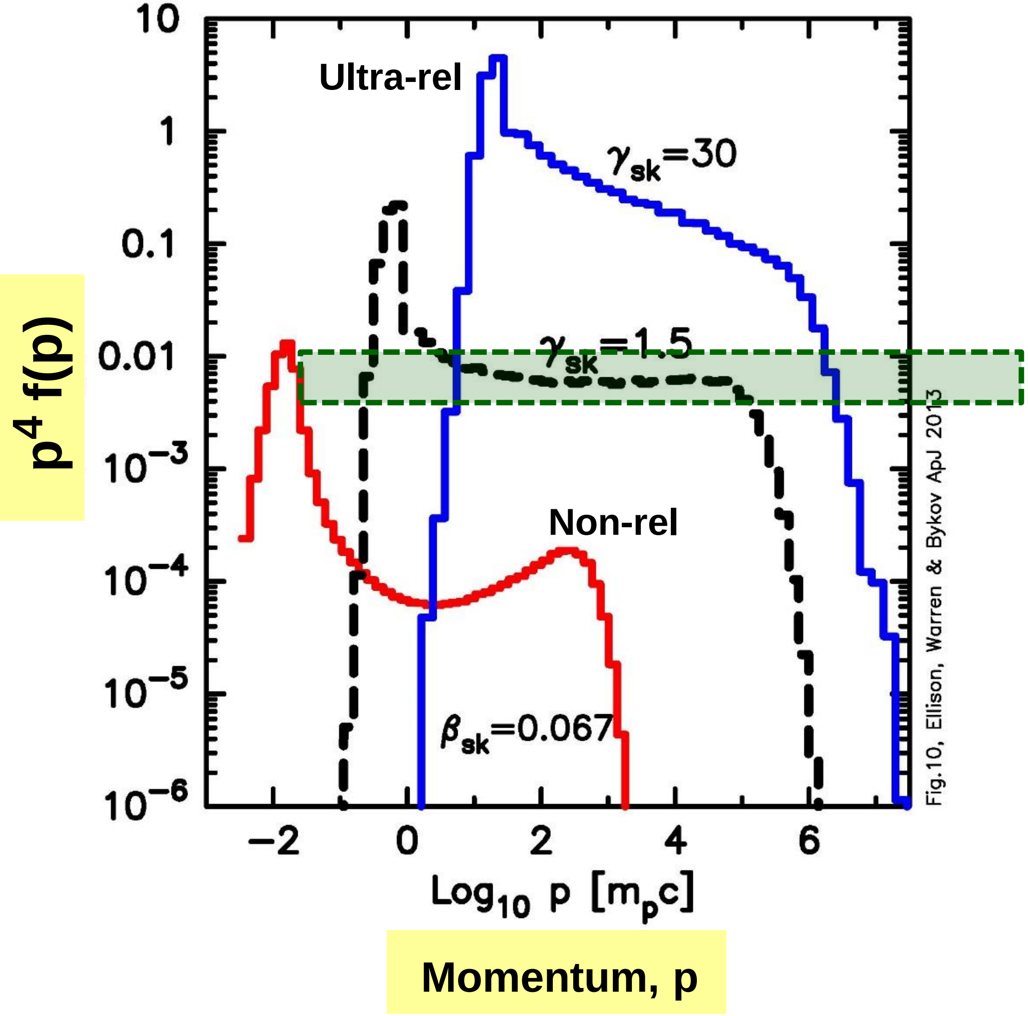


Fig.10, Ellison, Warren & Bykov ApJ 2013

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

Gives equal energy per dLog(p)

➔ **Critical slope: E.g. slight drop in γ_{sk} can cause R to increase.**

➔ **Put larger fraction of energy in highest energy particles**

➔ **Strong nonlinear effects**

Conclusions for Fermi acceleration in collisionless shocks:

1) **Nonlinear effects may be important regardless of shock speed**
    a) Smooth shock structure from pressure of CRs
    b) Self-generation of B-field turbulence
    c) Depends on thermal injection efficiency

2) **Physics is continuous from ultra-relativistic to non-relativistic shocks. BUT, critical differences in:**
    a) Applicability of diffusion approximation: cannot use when Vsk ~ c
    b) Predicted CR spectral shapes: Non-rel. hard; ultra-rel. soft
    c) Efficiency of CR production
    d) Electron / proton ratio: zero-order prediction: faster shock = smaller e/p

3) **Trans-relativistic shocks:**
    a) Important in some objects: GRB afterglows, Type Ibc SNe, radio jets
    b) Have Vsk ~ c but can still produce relatively hard CR spectra ➔ TeV-PeV CRs
    c) Hard to deal with analytically or with PIC simulations
    d) Monte Carlo techniques well-suited for trans-rel. shocks

4) **Current work using Monte Carlo model:**
    a) Extend magnetic field amplification (MFA) to trans- and ultra-relativistic shocks (led by Andrei Bykov & Sergei Osipov)
    b) Generalize GRB afterglow model (led by Don Warren)

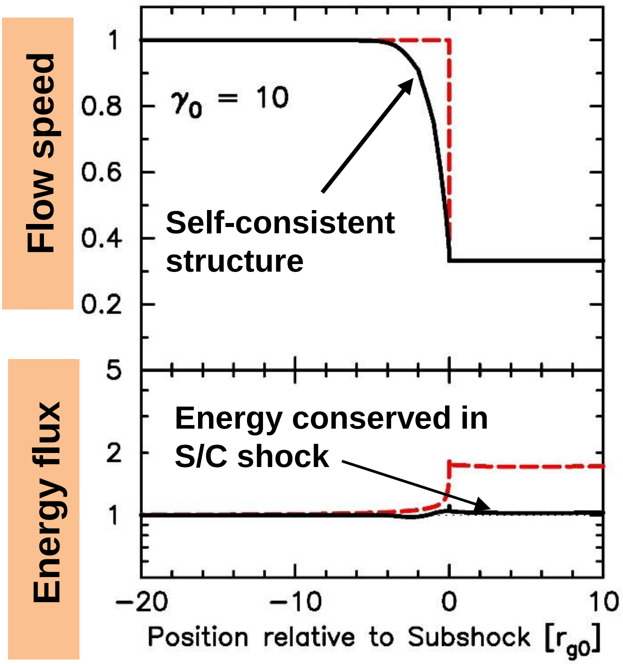
Extra Slides

Monte Carlo results for Lorentz factor $\gamma_0 = 10$ shock:

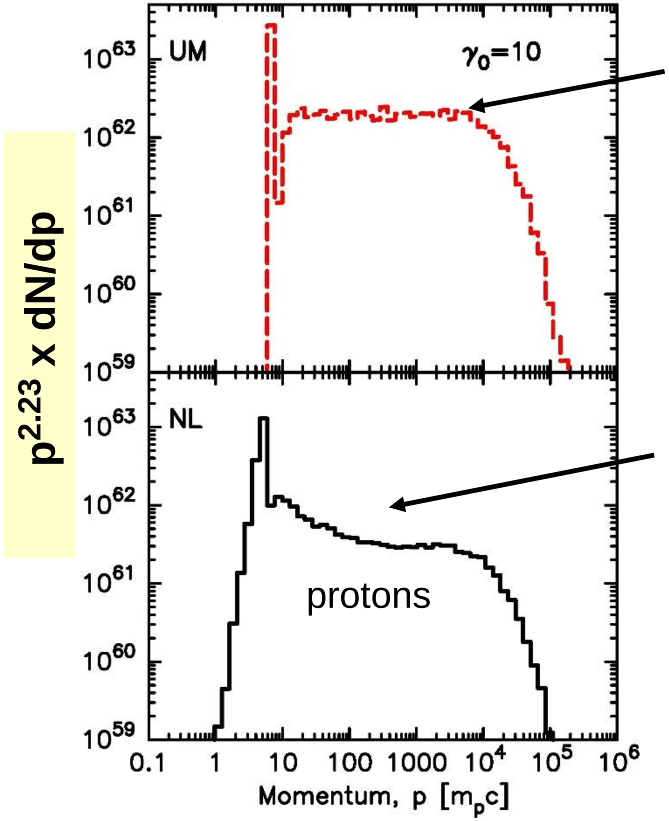
If acceleration is efficient, shock structure must be modified.

If diffusion length increasing function of momentum, p, get concave spectral shape (Eichler 79, 84)

Shock structure



Shock Lorentz factor $\gamma_0 = 10$

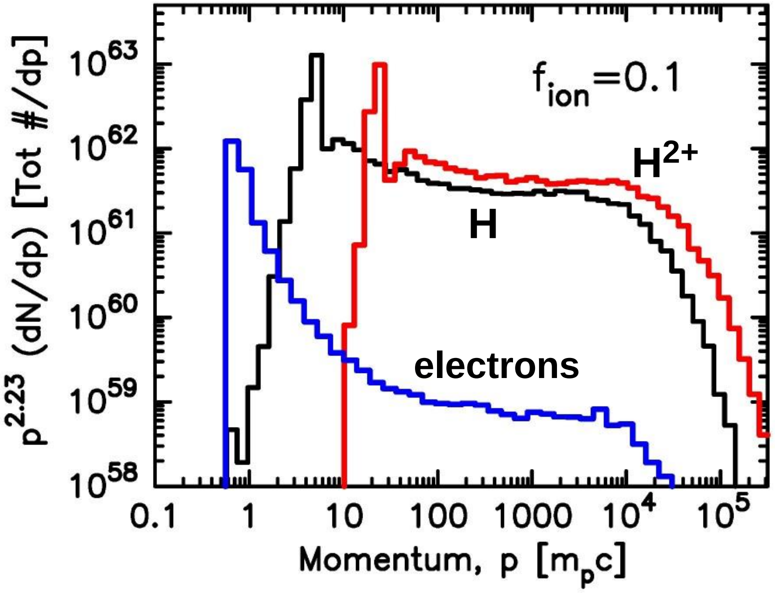


Unmodified: Not self-consistent : $p^{-2.23}$ power law before cutoff

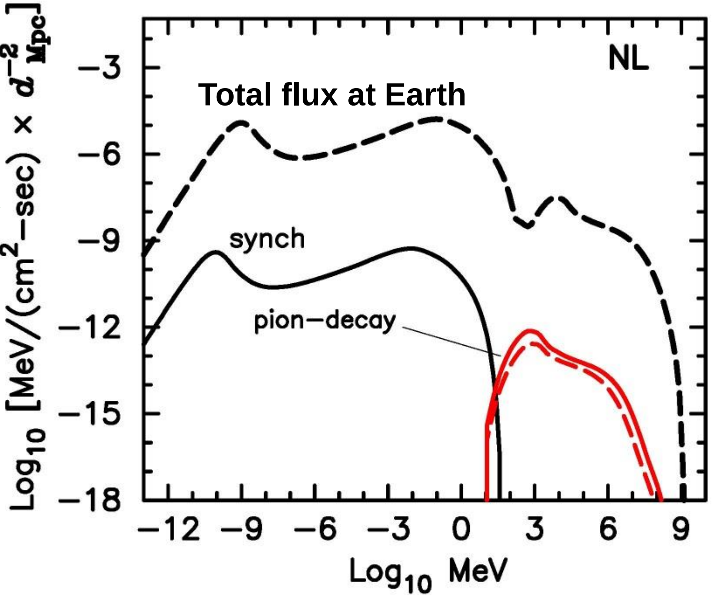
Self-consistent shock
Concave shape from smooth shock:
differs importantly from power law

Warren et al 2015

S/C particle spectra



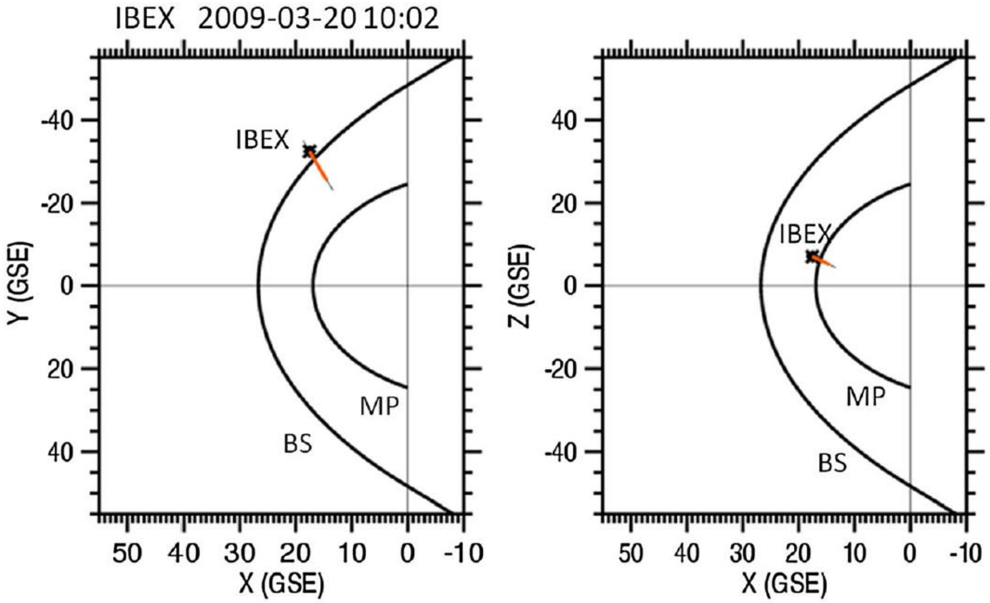
Photons



The free escape continuum of diffuse ions upstream of the Earth's quasi-parallel bow shock

JGR, 2013

K. J. Trattner,[1] F. Allegrini,[2,3] M. A. Dayeh,[2] H. O. Funsten,[4] S. A. Fuselier,[2] D. Heirtzler,[5]
P. Janzen,[6] H. Kucharek,[5] D. J. McComas,[2,3] E. Möbius,[5] T. E. Moore,[7] S. M. Petrinec,[1]
D. B. Reisenfeld,[6] N. A. Schwadron,[5] and P. Wurz[8]

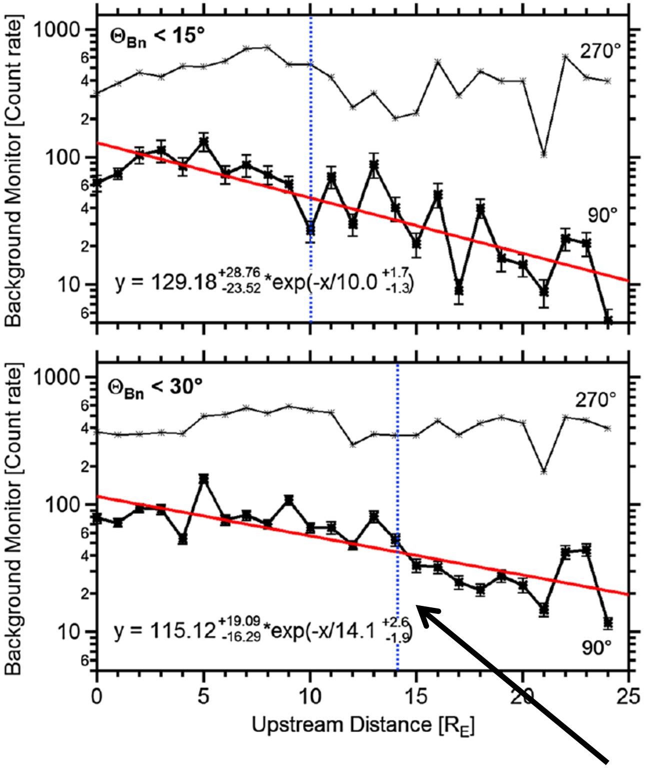


IBEX satellite observations at **quasi-parallel** Earth bow shock

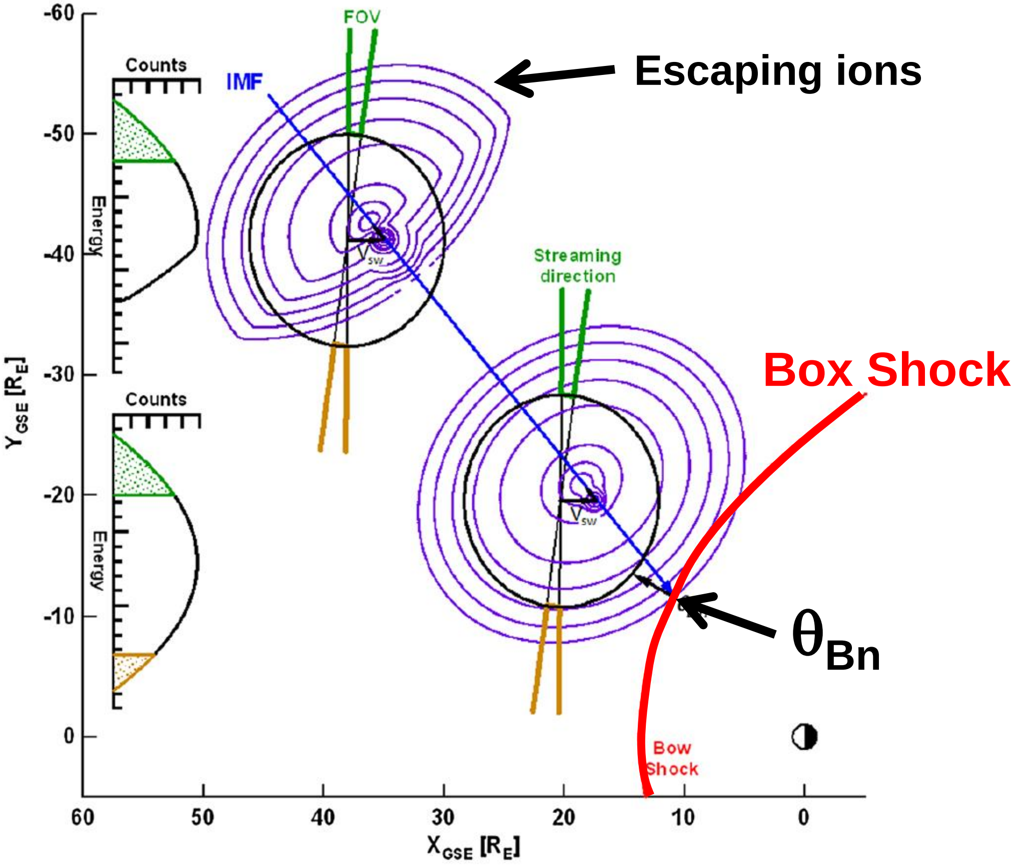
Figure 1. The location of the IBEX satellite in front of the Earth's bow shock (BS) and the magnetopause (MP) on 20 March 2009. The line connecting the satellite with the bow shock represents the direction of the IMF observed by the ACE satellite during the observation time. The IMF data are convected to the BS position. The red section of the IMF line highlights the distance from IBEX to the BS along the magnetic field direction used in the study.

Spacecraft observations of particle escape from a Q-parallel shock

IBEX satellite Observations:



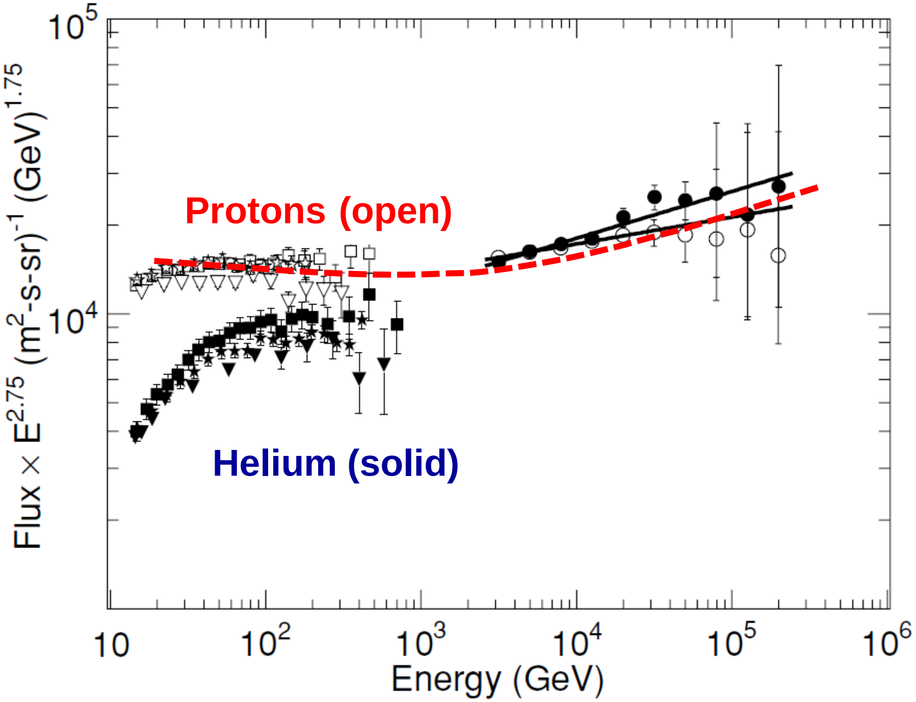
Can define gradual "Free Escape Boundary"



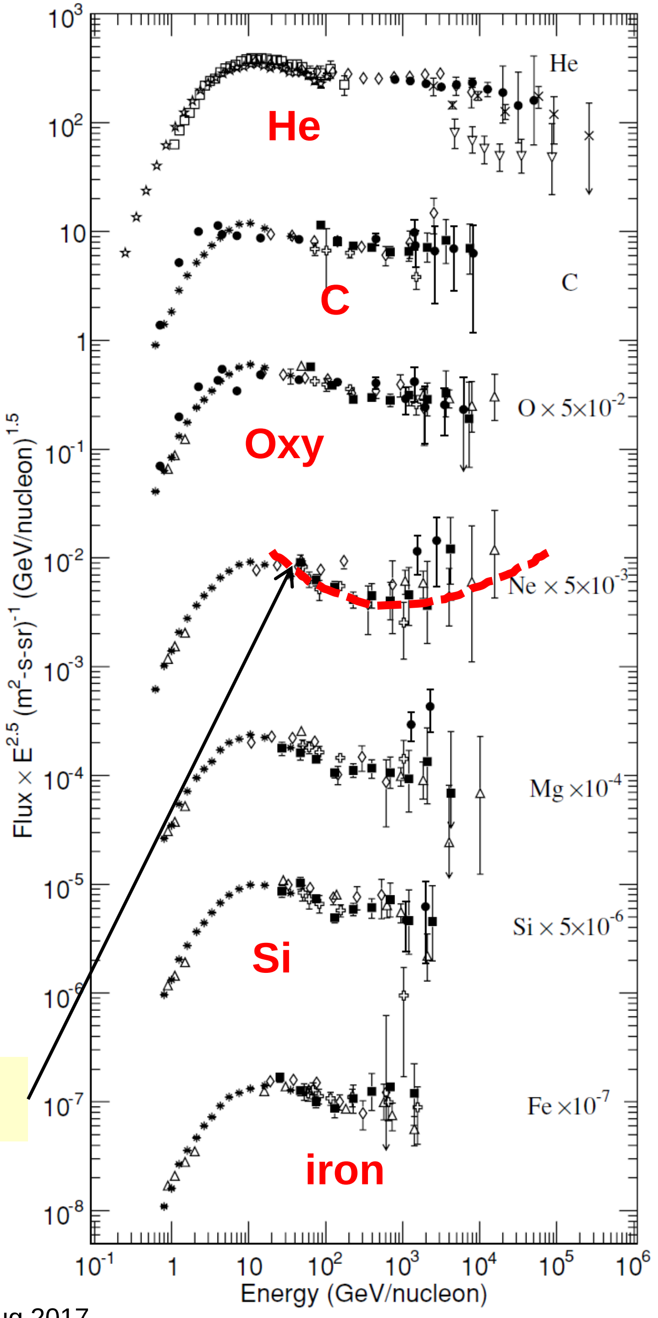
Trattner et a; (2013): "Somewhere in the upstream region of a quasi-parallel shock, the shock-accelerated **diffuse ions decouple** from the acceleration region and stream away, which lets them **escape from the region where Fermi acceleration occurs**."

Spacecraft observations of particle escape from a Q-parallel shock

Different shape for H and He spectra &
Hint of curvature in CR spectra seen at Earth !?



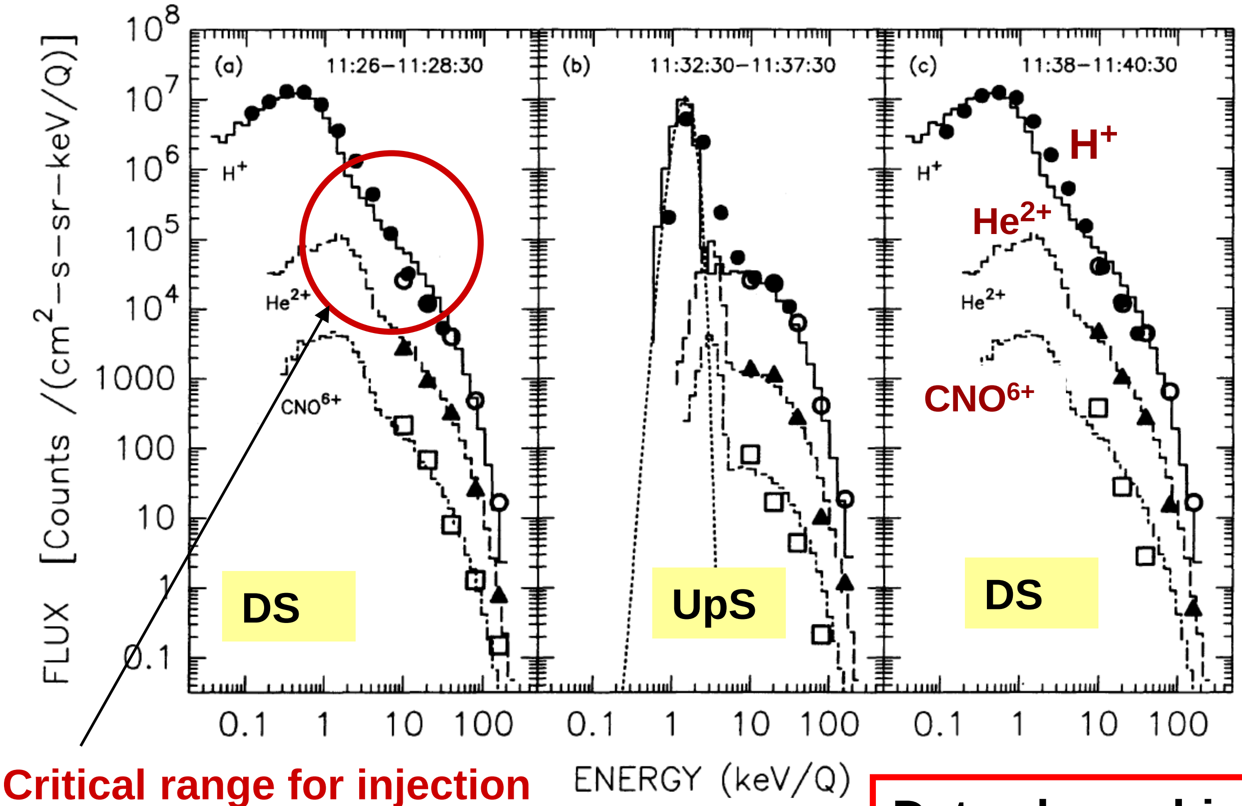
CREAM data from Ahn et al 2010



Concave curvature?

Quasi-parallel Earth Bow Shock

Ellison, Mobius & Paschmann 90



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

H$^+$, He^{2+}, & CNO^{6+}

Observed during time when solar wind magnetic field was nearly radial.

Critical range for injection

Modeling suggests nonlinear effects important

Data shows high A/Q solar wind ions injected and accelerated preferentially. These observations are consistent with A/Q enhancement in nonlinear DSA (Eichler 1979)