Accelerating Particles from Scratch

David Eichler

Nature distributes energy very unequally among particles.

How to share the wealth?

1) Democratic Capitalism (equal opportunity, but the rich get richer and eventually dominate)

4) Groomed nobility (some particles born to be energetic)

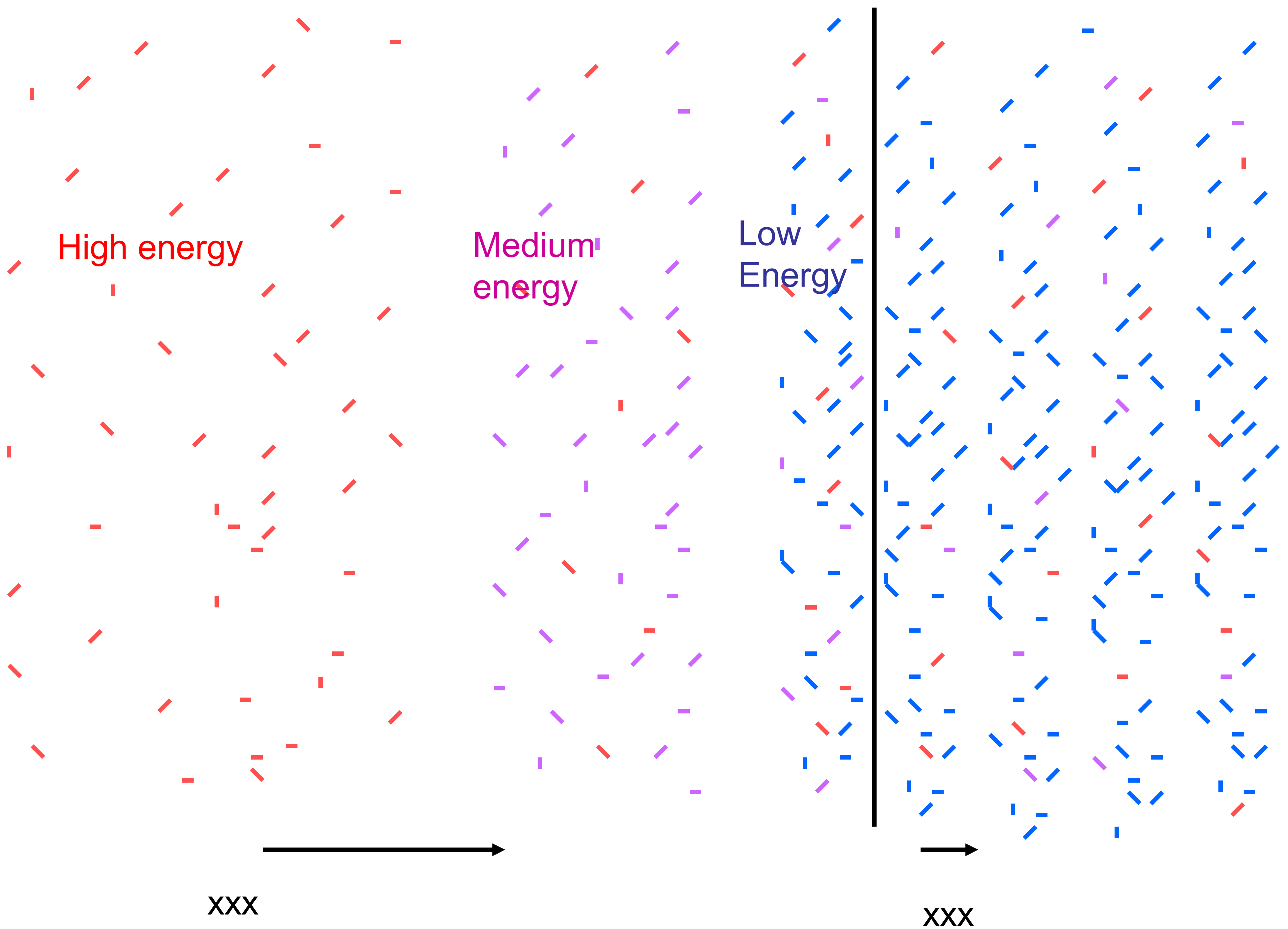
6) Entrance Exams (everyone beyond some high score)

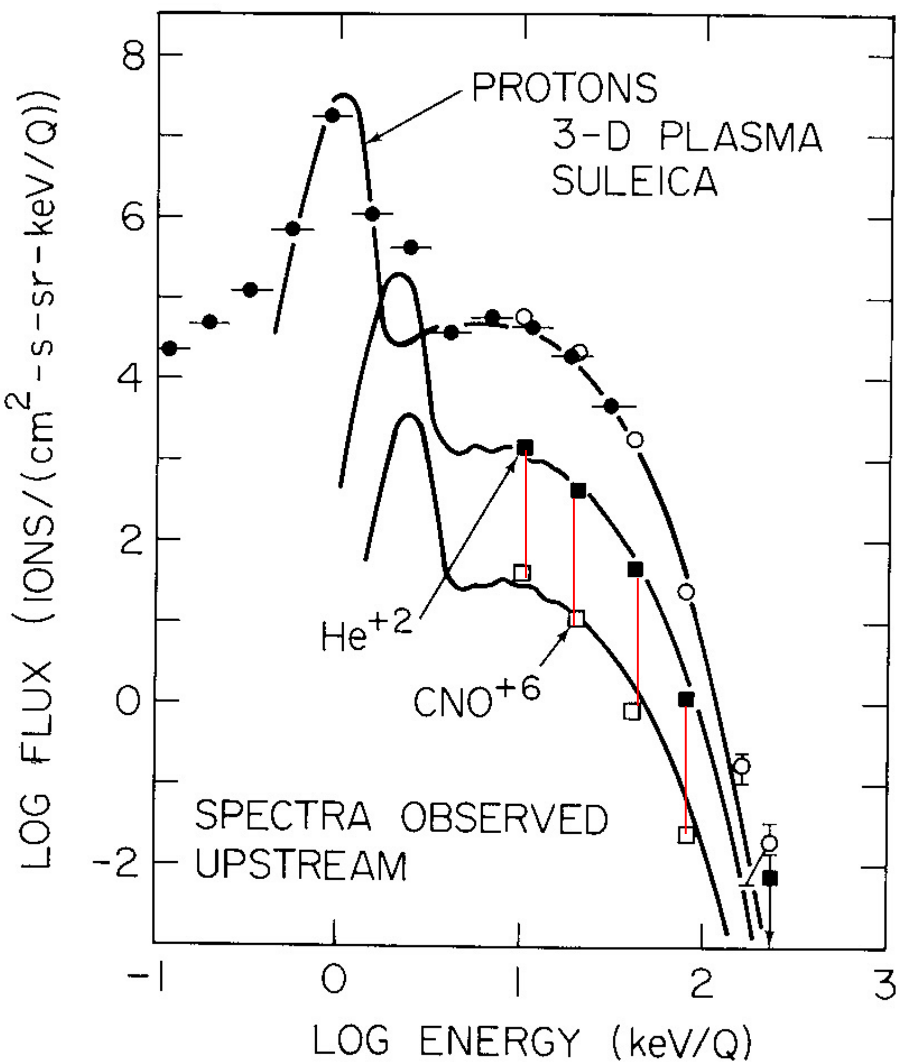
8) Affirmative action (unequal opportunity, but equality enforced, whatever it takes)

Shock Acceleration

Ion species about equally represented in Galactic CR, Solar Flares, Earth's bow shock (FIP effect seems to be in thermal plasma)

This smacks of equal opportunity, democratic capitalism


High energy
Medium energy
Low Energy
xxx
xxx


PROTONS
3-D PLASMA
SULEICA
He+2
CNO+6
SPECTRA OBSERVED
UPSTREAM
LOG FLUX (IONS/(cm2-s-sr-keV/Q))
LOG ENERGY (keV/Q)
8
6
4
2
0
-2
-1
0
1
2
3

Groomed Nobility

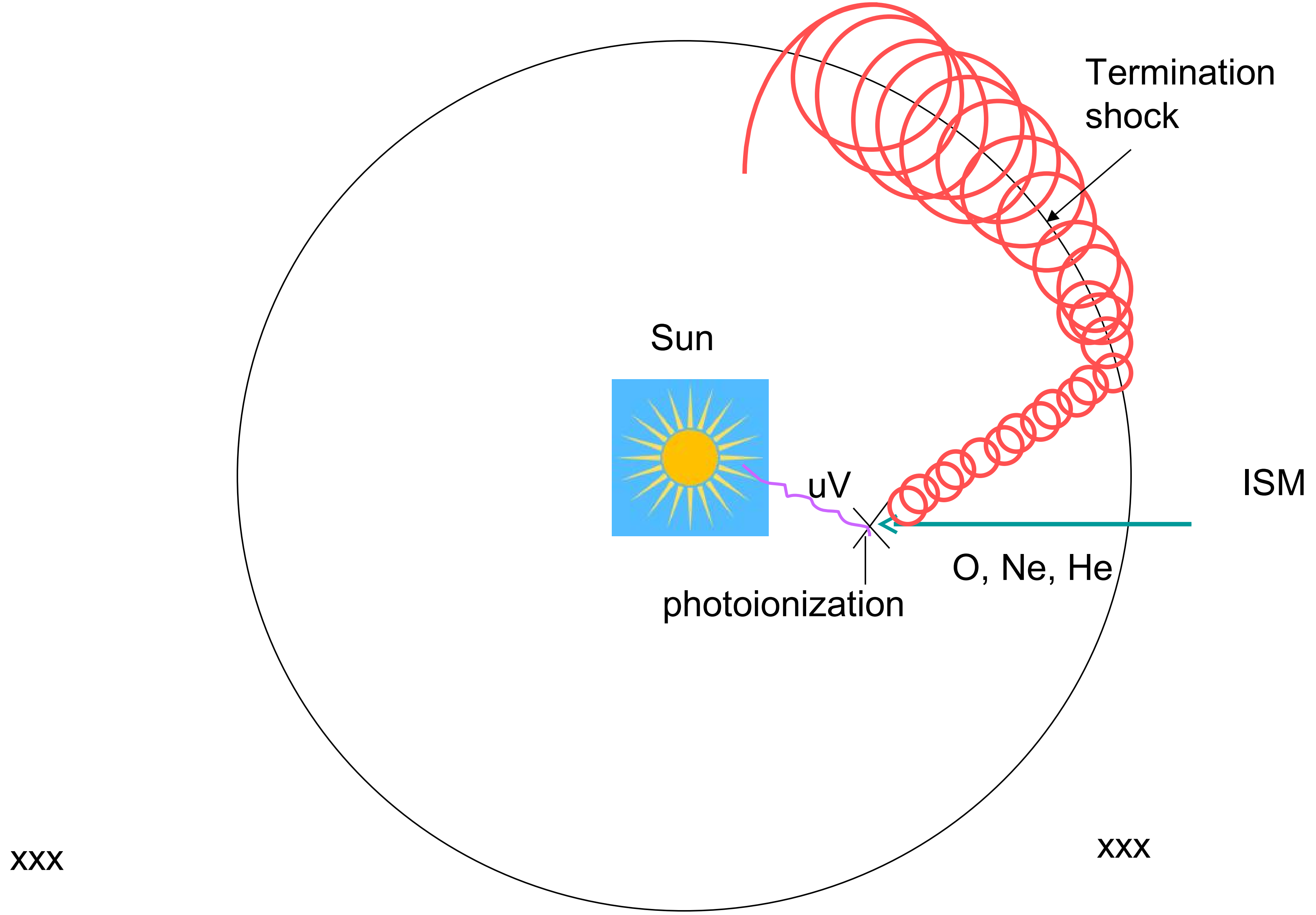
Anomalous Cosmic Rays : Mostly He, Ne, O, some H

Why are these species privileged?

Because they were neutral most of their lives back in their old neighborhood.

They enter the acceleration process (solar wind termination shock) already having more energy than a typical particle in the thermal plasma.

Ex-neutral pickup



Exit Exams

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Particles accrete into last stable orbit around Black Hole, each releasing about $0.1\ mc^2$.

Of these , less than 1 in 1000 emerge from inner accretion disk with Lorentz factors of 10^2 or more.

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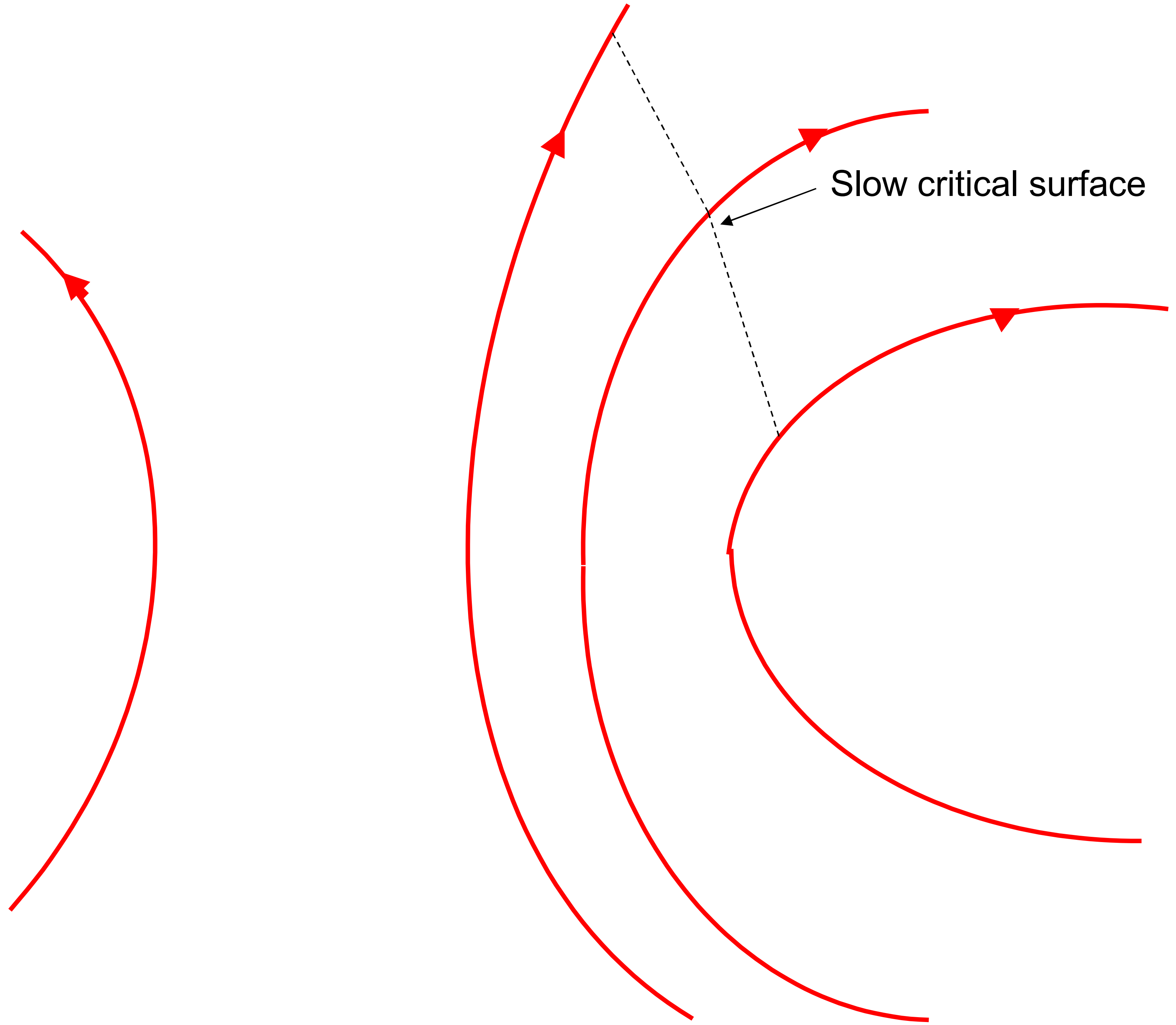
Slow critical surface

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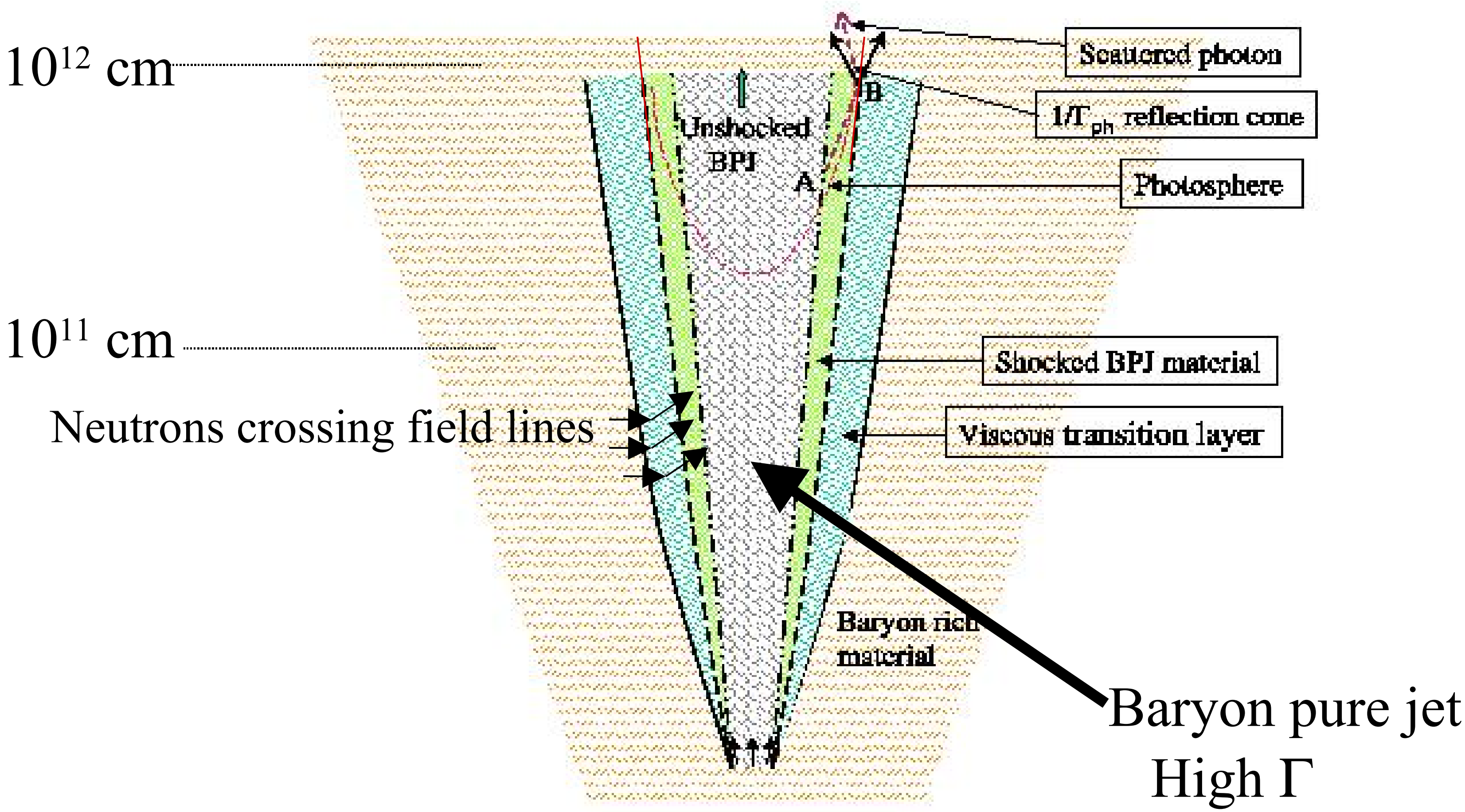
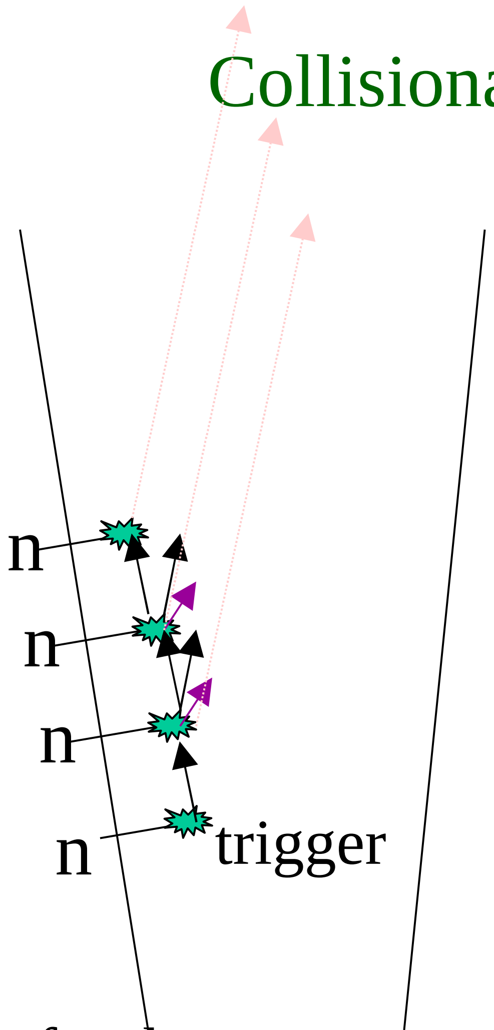
Or, maybe they transferred in from a less selective streamline (Eichler and Levinson, 1999, Levinson and Eichler 2003,…).

Neutron Leakage into Baryon-Pure Fireball



Collisional Avalanche



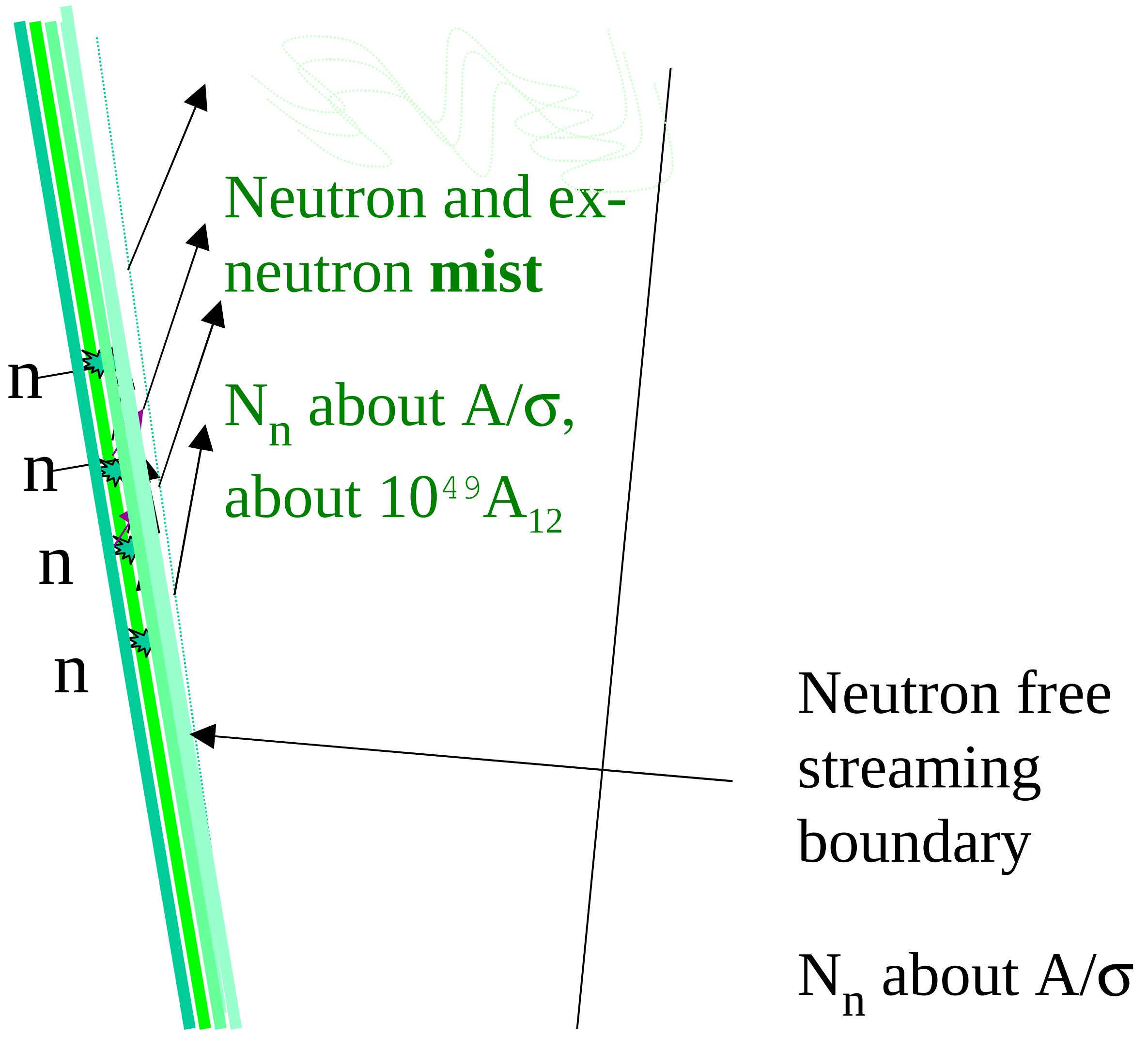
Neutrons converted to protons + neutrons + pairs + neutrinos. This happens ***quickly***, near the walls.

Typical γ_p for emergent protons is about Γ^2

neutrons of order

(area/cross section)x(r/mfp)$^{1/2}$ roughly 10^{50}

Collisional Avalanche



Affirmative Action

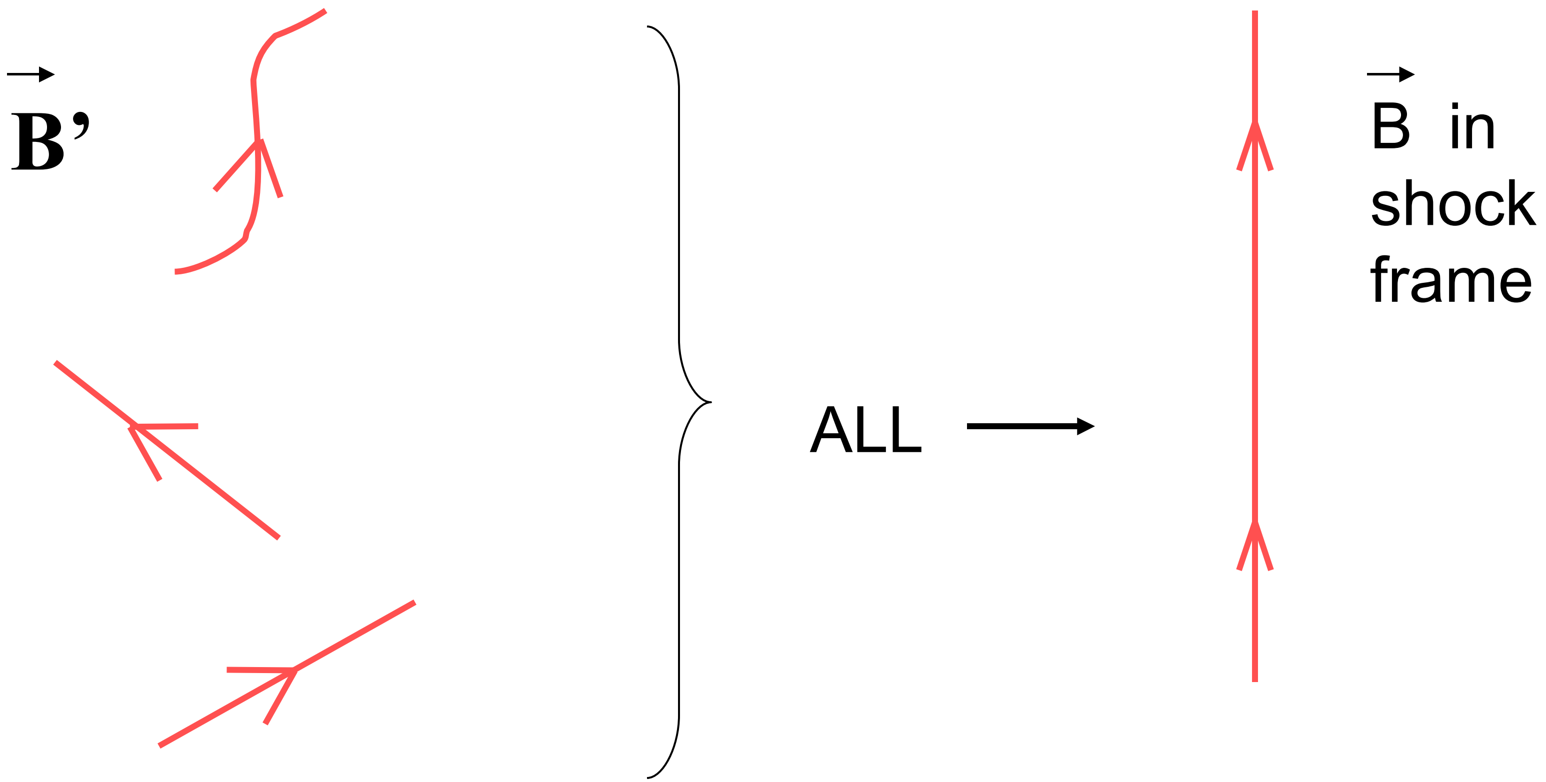
Electron Heating in Ultrarelativistic shocks.

The problem: If electrons are magnetized, they merely drift, no matter how hard you try to accelerate them.

Ultrarelativistic Shocks

Gedalin, Eichler and Balikhin (2006)

1) Almost always $\perp$



Ultrarelativistic shocks:

3) Transverse current can be reduced by acceleration along the shock normal because γ increases and p_y conserved.

In other words, you can slow a particle down in a particular direction merely by accelerating it in a different direction. (This is a purely relativistic effect.)

Ultrarelativistic shocks:

3) Mass ratio can be changed by heating or accelerating electrons

Significance: May enable Weibel instability, which is disabled by high proton/electron mass ratio (Lyubarskii and Eichler, 2006).

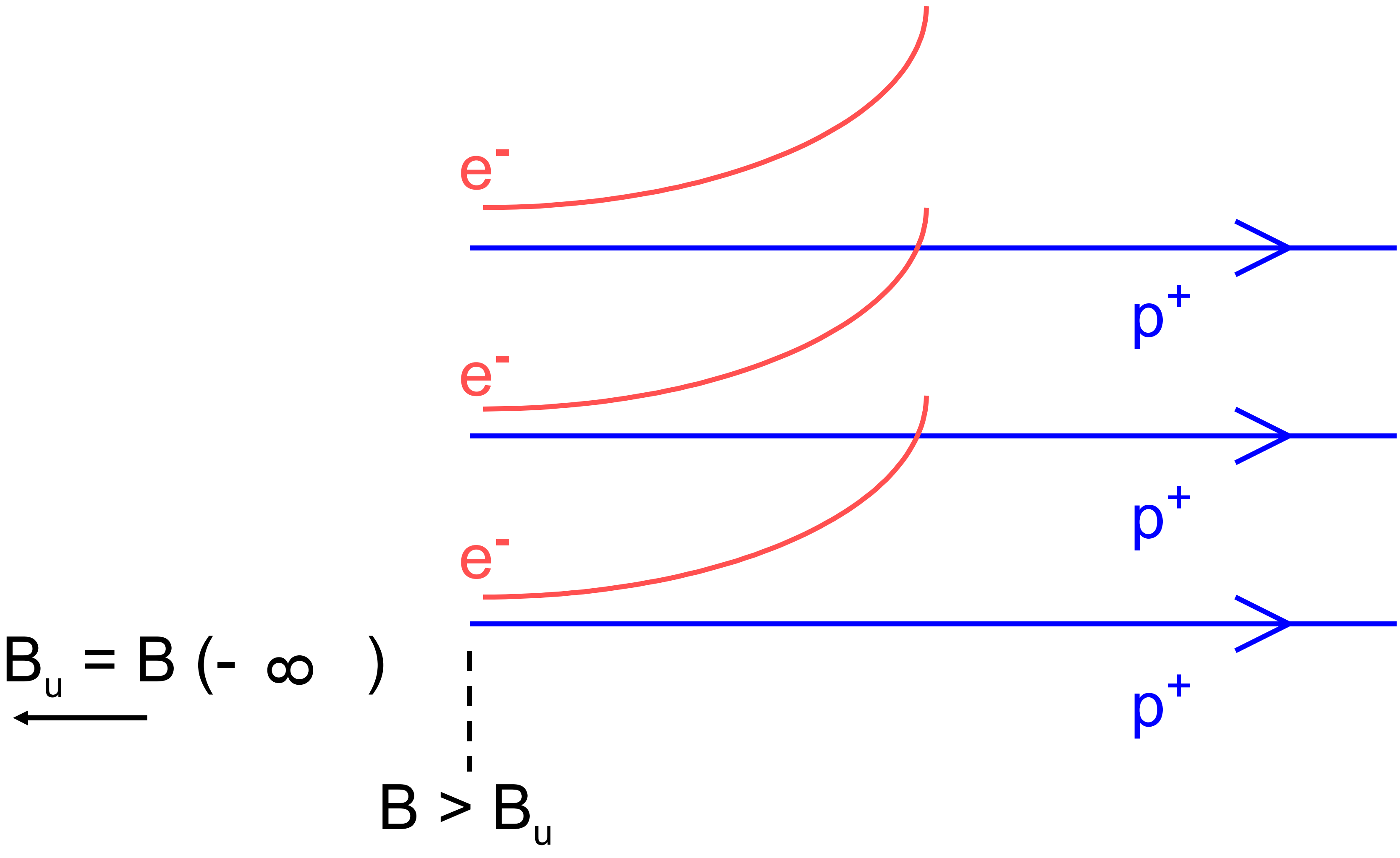
GRB external shocks:

4) Very weakly magnetized because ion velocity in shock frame so large

($> [m_i/m_e]V_{Alfven}$) .

In SNR shocks, by contrast , shock velocity V_{shock} is usually less than 10^2 V_{Alfven}

($< [m_i/m_e]V_{Alfven}$) .



Region of negative charge buildup

The Basic Equations

$$m_s v_{sx} \frac{d}{dx}(\gamma_s v_{sx}) = q_s(E_x + v_{sy}B_z/c), \quad (1)$$

Newton + Lorentz

$$m_s v_{sx} \frac{d}{dx}(\gamma_s v_{sy}) = q_s(E_y - v_{sx}B_z/c), \quad (2)$$

$$\gamma_s = (1 - v_{sx}^2/c^2 - v_{sy}^2/c^2)^{-1/2}, \quad (3)$$

$$n_s v_{sx} = \text{const}, \quad (4)$$

continuity

$$E_y = \text{const}, \quad (5)$$

Faraday

$$\frac{dB_z}{dx} = -4\pi \sum_s q_s n_s v_{sy}/c = 4\pi e(n_e v_{ey} - n_i v_{iy})/c, \quad (6)$$

Ampere

$$\frac{dE_x}{dx} = 4\pi \sum_s q_s n_s = 4\pi e(n_i - n_e). \quad (7)$$

Poisson

Notation:

$$\omega_{pe}^2 = \frac{4\pi n_u e^2}{m_e} = \frac{4\pi n_0 \gamma_0 e^2}{m_e}$$

c/ω_{pe} proportional to $\gamma_0^{-1/2}$

Whereas convective ion gyroradius $r_{gyro,conv}$, proportional to γ_0

$$\sigma = \frac{B_u^2}{4\pi n_u m_i c^2 \gamma_u}$$

Typically 10^{-9} for interstellar medium

independent of γ_u.

$$\frac{r_{i,\mathrm{conv}}}{r_{i,\mathrm{inert}}} \approx \frac{1}{\sqrt{\sigma}} = \sqrt{\frac{4\pi n_0 m_i c^2}{B_0^2}} \beta$$

Clearly much greater for relativistic shocks

$$\frac{r_{i,\mathrm{conv}}}{r_{e,\mathrm{inert}}} \approx \frac{1}{\sqrt{\sigma}}\sqrt{\frac{m_i}{m_e}}\ \beta$$

Quasineutrality

$$\delta n = \frac{1}{4\pi e}\frac{dE_x}{dx} \ll n.$$

ENFORCED!..... WHATEVER IT TAKES!

And it takes huge electron acceleration.

$$m_i \gamma_i v_{iy} = -\frac{c m_e \gamma_e}{4\pi e n} \frac{dB_z}{dx}$$

get $$\left(\frac{c^2}{\omega_{pe}^2}\right)\frac{1}{N}\frac{d}{dx}\frac{\gamma_e}{N}\frac{d}{dx}\boldsymbol{b}$$

$$= \frac{(1+\sigma)(b-1) - \sigma b(b^2-1)/2\beta_0^2}{1-\sigma(b-1)}$$

b* =*B*/*B*_**, ***b=1 is asymptotically homogeneous critical point

Note, when γ_e=1, equation of pseudo particle in pseudo potential (e.g. Tidman and Krall, 1968)

But for relativistic shocks, need to solve for γ_e.

The Basic Length Scale of the electrostatic transition is thus

$$l_e \sim \sqrt{\frac{m_e c^2}{4\pi n_0 e^2}} \sqrt{\frac{\gamma_e}{\gamma_0}}$$

Environmental parameter

Shock parameter

Now try solving for γ_e

(not so easy)

$$s \equiv \frac{e\phi}{m_e c^2}, \qquad p \equiv \frac{eA_y}{m_e c}$$

Exact equations:

$$N_e = \frac{1}{v_{ex}} = \left[1 - \frac{1}{(\gamma_0 + s)^2} - \frac{p^2}{(\gamma_0 + s)^2}\right]^{-1/2},$$

$$N_i = \frac{1}{v_{ix}} = \left[1 - \frac{1}{(\gamma_0 - \mu s)^2} - \frac{\mu^2 p^2}{(\gamma_0 - \mu s)^2}\right]^{-1/2},$$

$$l_e^2 \frac{d^2}{dx^2} s = v_0 (N_e - N_i),$$

$$l_e^2 \frac{d^2 p}{dx^2} = \frac{p}{\gamma_0 + s} + \frac{\mu p}{\gamma_0 - \mu},$$

$$v_0^2 = 1 - 1/\gamma_0^2, \qquad l_e^2 = c^2/\omega_{pe}^2, \qquad \mu = \frac{m_e}{m_i}$$

Further approximations:

$$m_i/m_e \longrightarrow \infty$$

Valid for

$$1 \leq \frac{\gamma_e}{\gamma_0} << \frac{m_i}{m_e}$$

$$E_y \to 0 \Rightarrow \text{integrable}$$

$$\frac{E_x}{E_y} \sim \sqrt{\frac{4\pi n_0 m_e c^2}{B_0^2}} \gamma_0^{-1/2} \left(\frac{x}{l_e} \right)$$

Validity of neglecting E_y:

$$x \sim l_e \quad \text{and} \quad E_x/E_y \gtrsim 1 \Rightarrow$$

$$\frac{4\pi n_0 m_i c^2}{B_0^2}\left(\frac{m_e}{m_i}\right)\frac{1}{\gamma_0} \gtrsim 1 \Rightarrow$$

$$\gamma_0 \lesssim 10^6 \quad \text{for shock in the ISM}$$

Easily satisfied

$$\frac{E_x}{E_y} \sim \frac{x}{c/\omega_{pe}} \sqrt{\frac{1}{\sigma}} \sqrt{\frac{m_e}{m_i}}$$

$$\frac{E_x}{E_y} \sim \frac{x}{c/\omega_{pe}} \sqrt{\frac{1}{\sigma}} \sqrt{\frac{m_e}{m_i}} \sim 10^3 \frac{x}{c/\omega_{pe}}$$

With the above approximations:

$$P_y = p_y + qA_y/c = m\gamma v_y + q\int B_z dx/c = \text{const},$$

$$P_t = mc^2\gamma + q\phi = \text{const},$$

$$s \equiv \frac{e\phi}{m_e c^2}, \qquad p \equiv \frac{eA_y}{m_e c}$$

$$l_e^2 \frac{d^2 s}{dx^2} = v_0 \left[1 - \frac{1 + p^2}{(\gamma_0 + s)^2} \right]^{-1/2} - 1,$$

$$l_e^2 \frac{d^2 p}{dx^2} = \frac{p}{\gamma_0 + s}$$

Guess that there is an attractor at large s, p

$$s \gg \gamma_0 \,, p \gg \gamma_0 \Rightarrow \frac{p}{s} \longrightarrow \frac{\sqrt{3}}{2}$$

Numerical solutions confirm

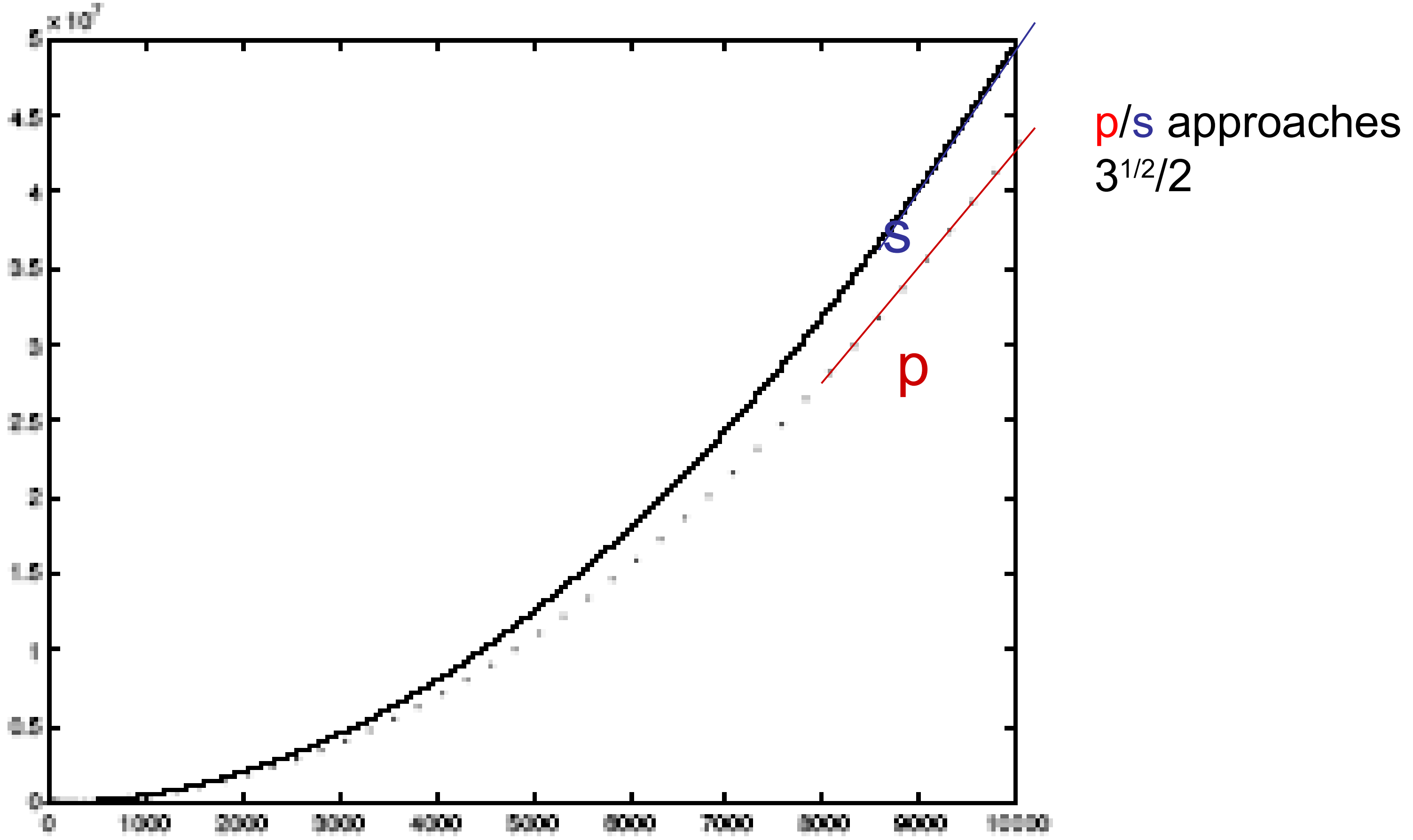


FIG. 1: s (solid) and p (dotted) as a function of X.

The main point:

$$\frac{\sqrt{3}}{2} < 1$$

(Checked numerically)

Hence E>B, electrons are demagnetized, can acquire significant fraction of $\Gamma m_i c^2$ in electrostatic soliton.

But it is questionable whether ultrarelativistic solitons have anything to do with ultrarelativistic shocks in nature, because they have no reflected particles.

So the above calculation should be considered nothing more than an illustrative principle of how enforced quasi-neutrality can produce strong longitudinal electric fields shock-like situations.

It is meant as an advertisement for coming talks (Lyubarsky, ….)

Conclusion:

Nature has all sorts of ways to accelerate particles.