Heavy ion spectral breaks in large SEP events

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Scenario check

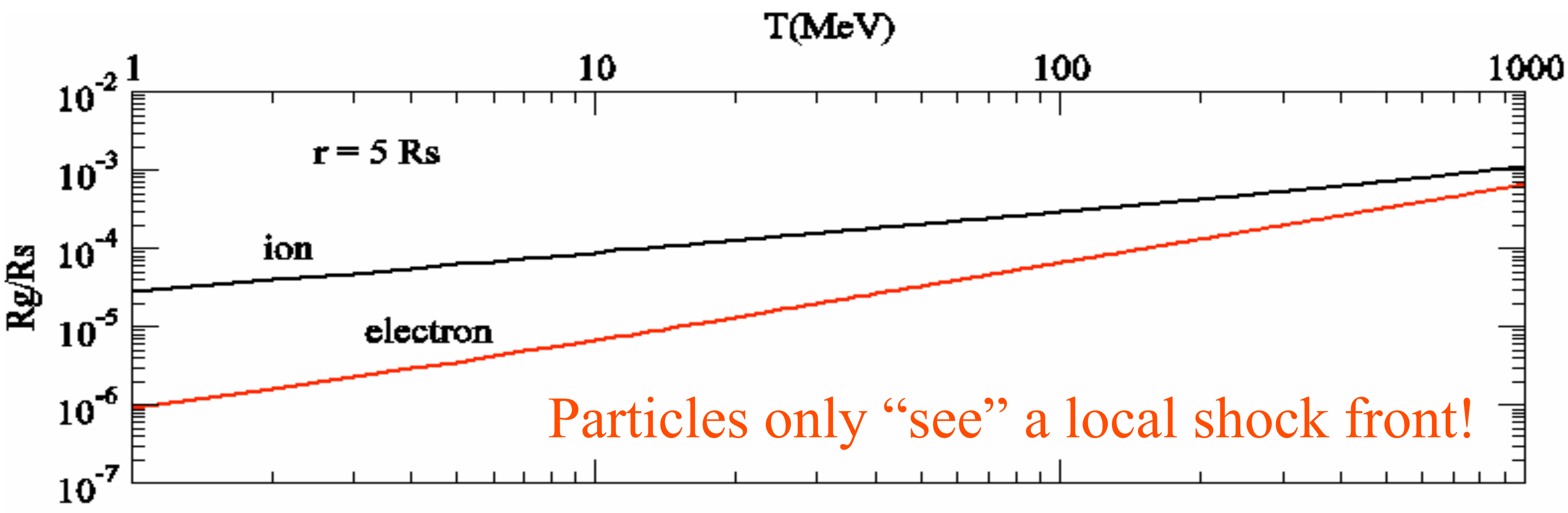
Close to the sun, where the acceleration occurs …

Comaring shock scale with particle length scale.

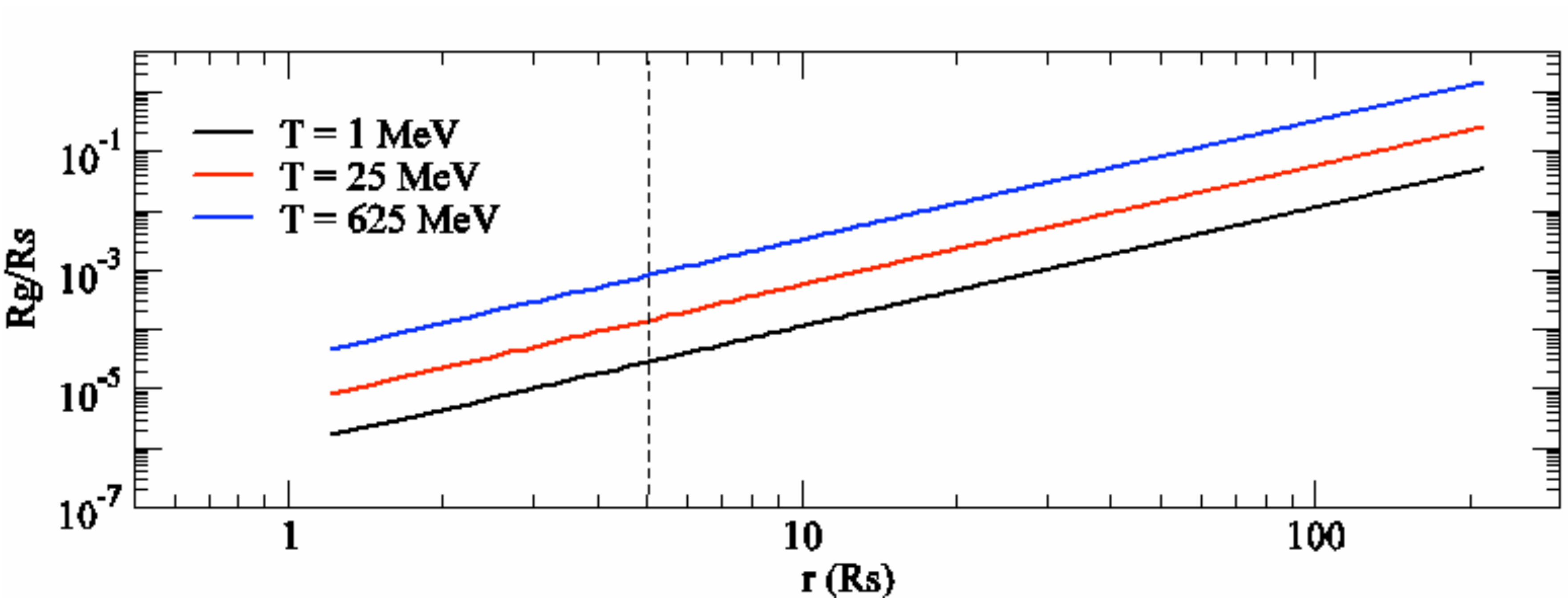
In a magnetic field, this length scale is given by Rg, the gyroradius.

If acceleration is done by say, 30 minutes, and shock has a speed of 2000 km/s => r = 3.6 10^6 km ~ 5 Rs (Rs ~ 7.5 10^5 km)

If open angle is 60 degree => shock front has an extension of 5 Rs.



Even at 1AU, particles only see “a local potion of the shock”



Does a shock's geometry change over a length scale of ~ 10 or 100 Rg?

If YES, then all acceleration model need to consider ensemble average of some kind.

If NO, then acceleration may only occur at parallel or perpendicular portion of a shock and acceleration may occur only when favorable condition exist, probably that is why we see large variability.

What geometry is more likely to be responsible for high energy ions? Parallel or Perp?

What decide the break?

0) Equal resonance condition. Li et al 2005 (***parallel shock only***). wave

Break occurs at the same resonant k

1) Equal diffusion coefficient κ condition

Cohen et al. (2003, 2005)

(***parallel shock and/or perp. shock***).

Break occurs at the same κ

2) Equal acceleration time consideration

(***parallel and/or perp. shock***).

Break decided by available amount of time for acceleration

3) Equal Rg condition?

(***parallel and/or perp. shock?)***

The only intrinsic length scale for particle is the gyro-radius. Break occurs at the same Rg

Q/A dependence of κ

- at and near a parallel shock $\kappa \sim v^3 (A/Q)^2 / I(k \cong \Omega/\mu v)$ *Lee (2005)*

If $I(k) \sim k^{\beta}$, $\kappa \sim v^{\beta+3} (A/Q)^{\beta+2}$ $\beta = -1$ => Bohm Approximation

- in quiet solar wind: $\kappa = (1/3)\, v\, \lambda_{\parallel}$, with $\lambda_{\parallel} \sim (r_g)^{\alpha} \sim (A/Q)^{\alpha}$

$\alpha = 1/3$ corresponding to $\beta = -5/3$ *used in Li et al (2003)*

- at a perpendicular shock, $\lambda_{\perp} \sim \lambda_{\parallel}^{1/3}$ so $\kappa_{\perp} \sim v\, (A/Q)^{1/9}$ *Zank et al (2004)*

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the generic form:

$$\kappa = v^{\gamma} (A/Q)^{\delta}$$

→ $\gamma = 2$, $\delta = 1$ => Bohm approx.

→ $\gamma = x$, $\delta = x-1$ => parallel shock

→ $\gamma = 1$, $\delta = 1/9$ => perp. shock

Case 0: resonance condition

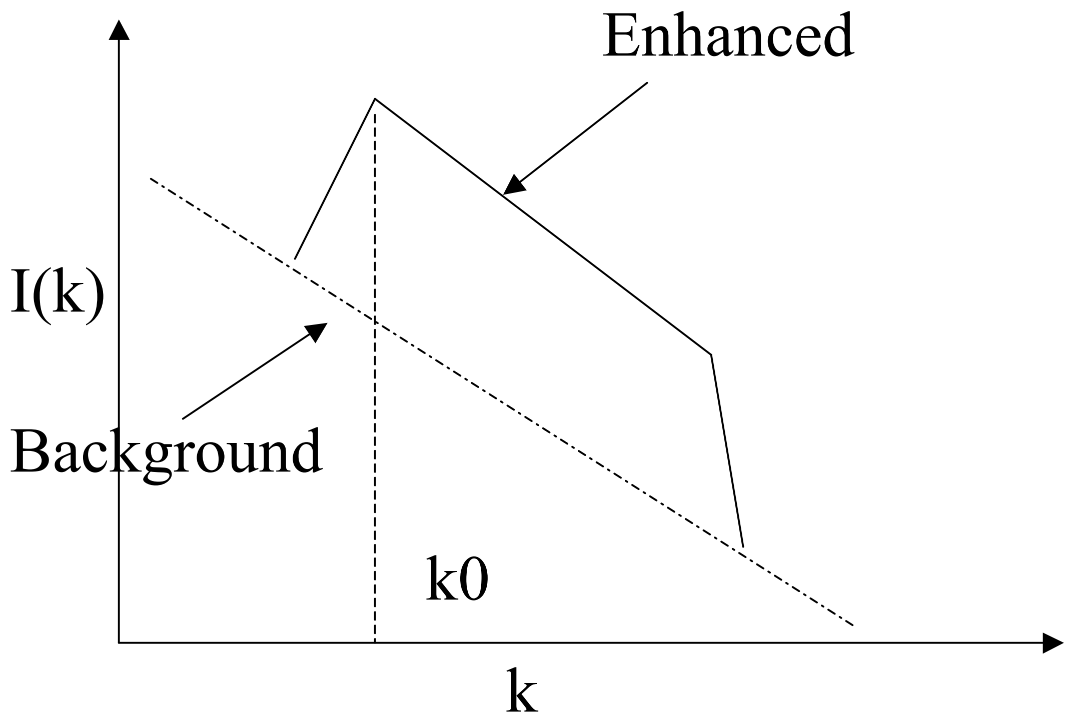
k v = Ω ~ Q/A   (Ω = Q/A [eB/ γmp c])

Break occurs at the same k

E0 ~ v^2 ~ (Q/A)^2

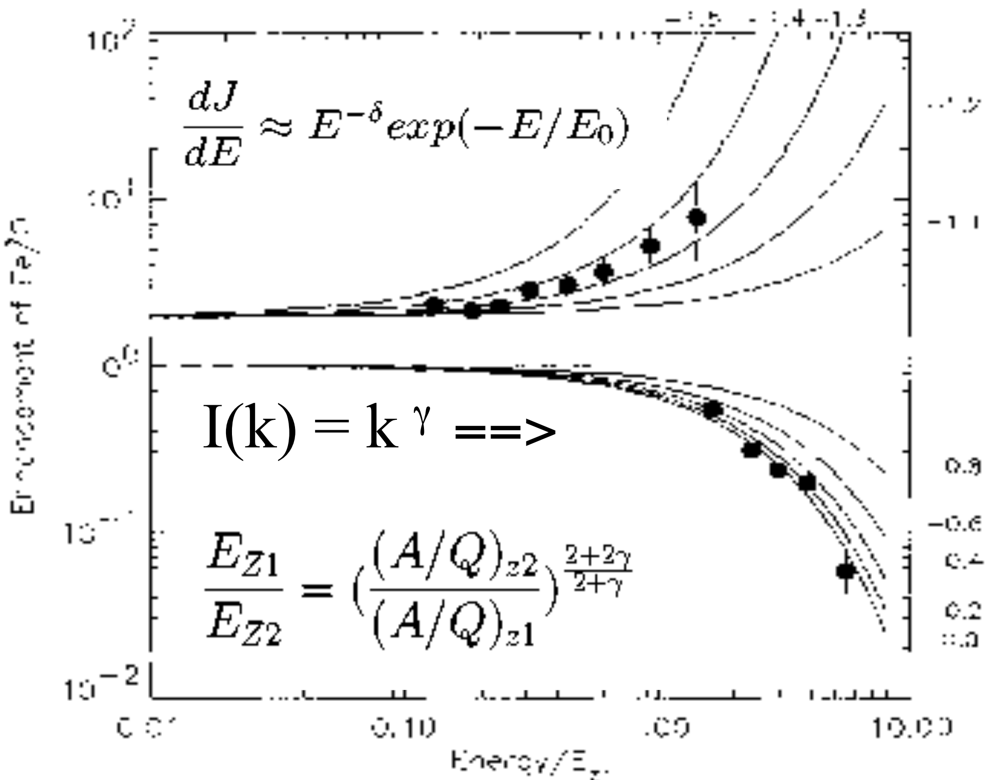
strict (Q/A)^2 dependence

works for parallel shock.



Case 1: Equal diffusion coefficient

Break regulated by an escape process and occurs at the SAME κ



Consider a parallel shock, assuming a power law turbulence:

If $\kappa = v^{\gamma} (A/Q)^{\delta}$

==> $E0 \sim (Q/A)^{2\delta/\gamma}$

Can generalize to oblique shock case, where

$$\kappa = \kappa_{\|} \cos^2(\theta) + \kappa_{\perp} \sin^2(\theta)$$

Cohen et al. (2003, 2005)

Case 2: equal acceleration time

time for a particle's momentum to increase from p to p + △p.

$$\Delta t = \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{\Delta p}{p}$$

Drury (1983)

$$t = \int_{p_0}^{p_{\max}} \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{1}{p}\,dp$$

$\kappa = v^{\gamma} (A/Q)^{\delta}$ ==> $E0 \sim (Q/A)^{2\delta/\gamma}$

Same as case 1

Again, oblique shock $\kappa = \kappa_{||} \cos^2(\theta) + \kappa_{\perp} \sin^2(\theta)$

breaking energy E_0 for case 1&2

<u>Case A: Bohm approx.</u>

$\gamma = 2, \delta = 1$

$E_0 \sim (Q/A)$

Seen in observation e.g. *Tylka (2001)*

*<u>Bohm approximation may **NOT** be a bad approximation</u>*

<u>Case B: parallel shock with</u> $I(k) \sim k^{\beta}$

$E_0 \sim (Q/A)^{2(\beta+2)/(\beta+3)}$

$\beta = -2 \quad \Rightarrow \quad E_0 \sim (Q/A)^0$

$\beta = -1.5 \quad \Rightarrow \quad E_0 \sim (Q/A)^{2/3}$

$\beta = 0 \quad \Rightarrow \quad E_0 \sim (Q/A)^{4/3}$

<u>Case C: perpendicular shock:</u> $\gamma = 1, \delta = 1/9$

$E_0 \sim (Q/A)^{2/9}$

→ Not seen yet

<u>Can perp. Shock be responsible for large SEP events?</u>

Oblique shock?

Assume

$$\kappa_{\perp} = \kappa_{\perp 0} v (A/Q)^{1/9}$$

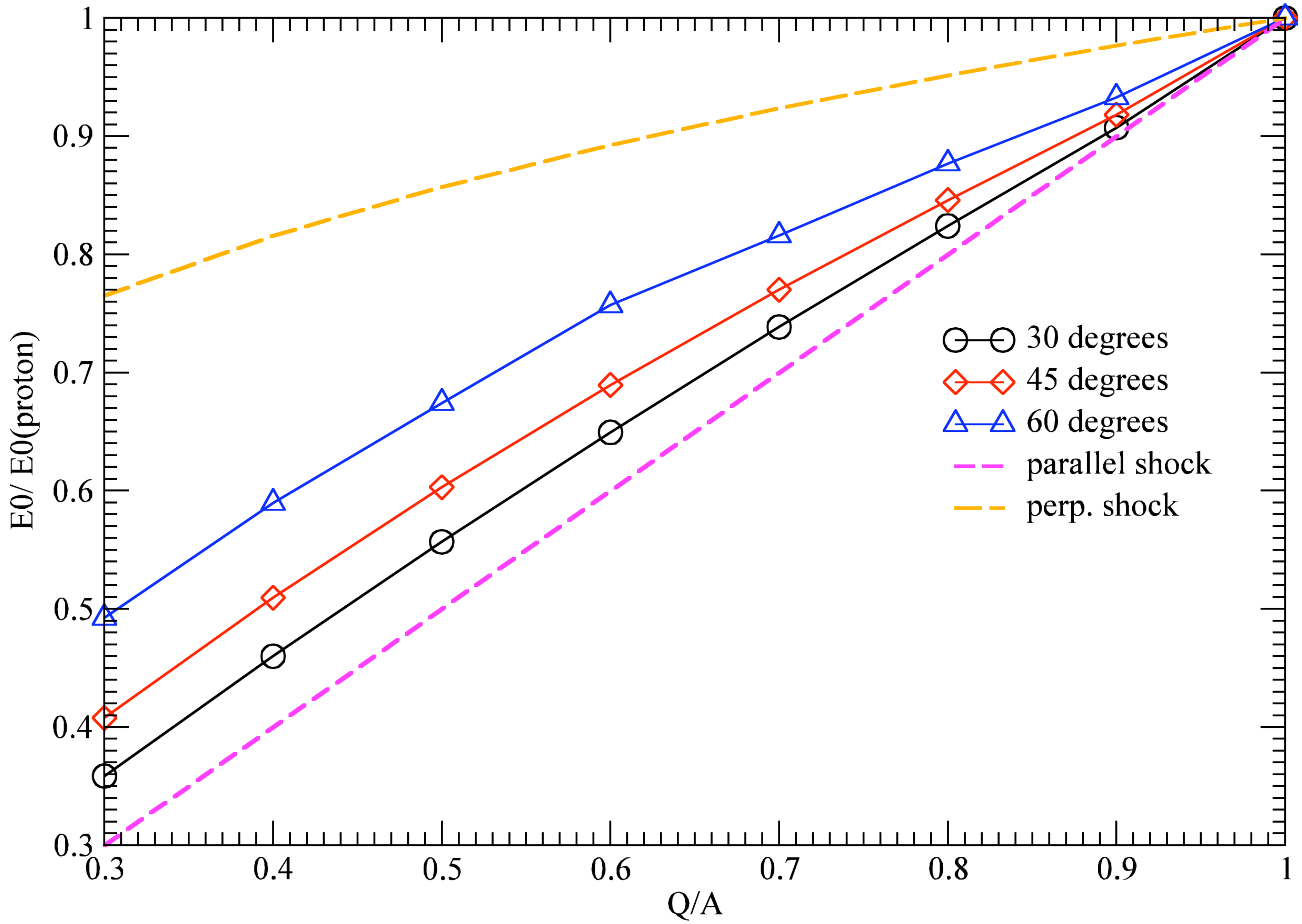
$$\kappa_{\|} = \kappa_{\| 0} v^{\gamma} (A/Q)^{\gamma - 1}$$

$$\kappa = \kappa_{\|} \cos^2(\theta) + \kappa_{\perp} \sin^2(\theta)$$

What is the Q/A dependence now?

worst case scenario

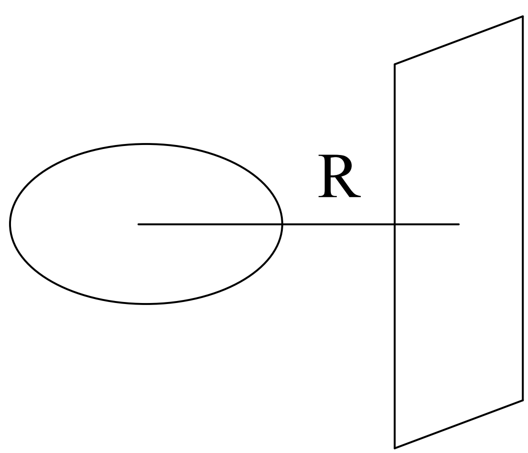
$$\frac{\kappa_{\perp}}{\kappa_{\|}} \ll 1$$



Case 3: Equal Rg

Suppose turbulence is strong, and no wave signatures show up, then what? $\delta B \sim B$ Gyro-motion is not well defined!

The break in this case may be decided by equaling its intrinsic length scale, Rg to some external length scale R.



E = (Q/A)^2

This becomes case zero.

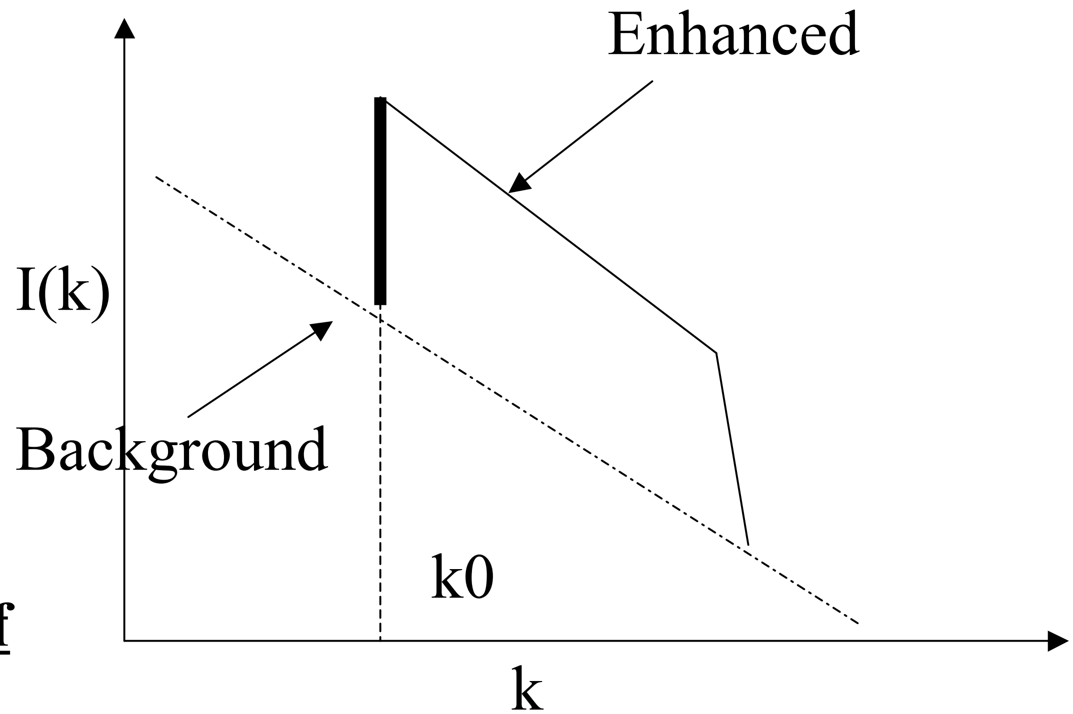
With a very turbulent B, no point of talking parallel or perp. B.

Can E_0 scale as $(Q/A)^2$ from case 1&2?

At a parallel shock if $I(k) \sim k^{\beta}$ ==> $E_0 \sim (Q/A)^{2(\beta+2)/(\beta+3)}$

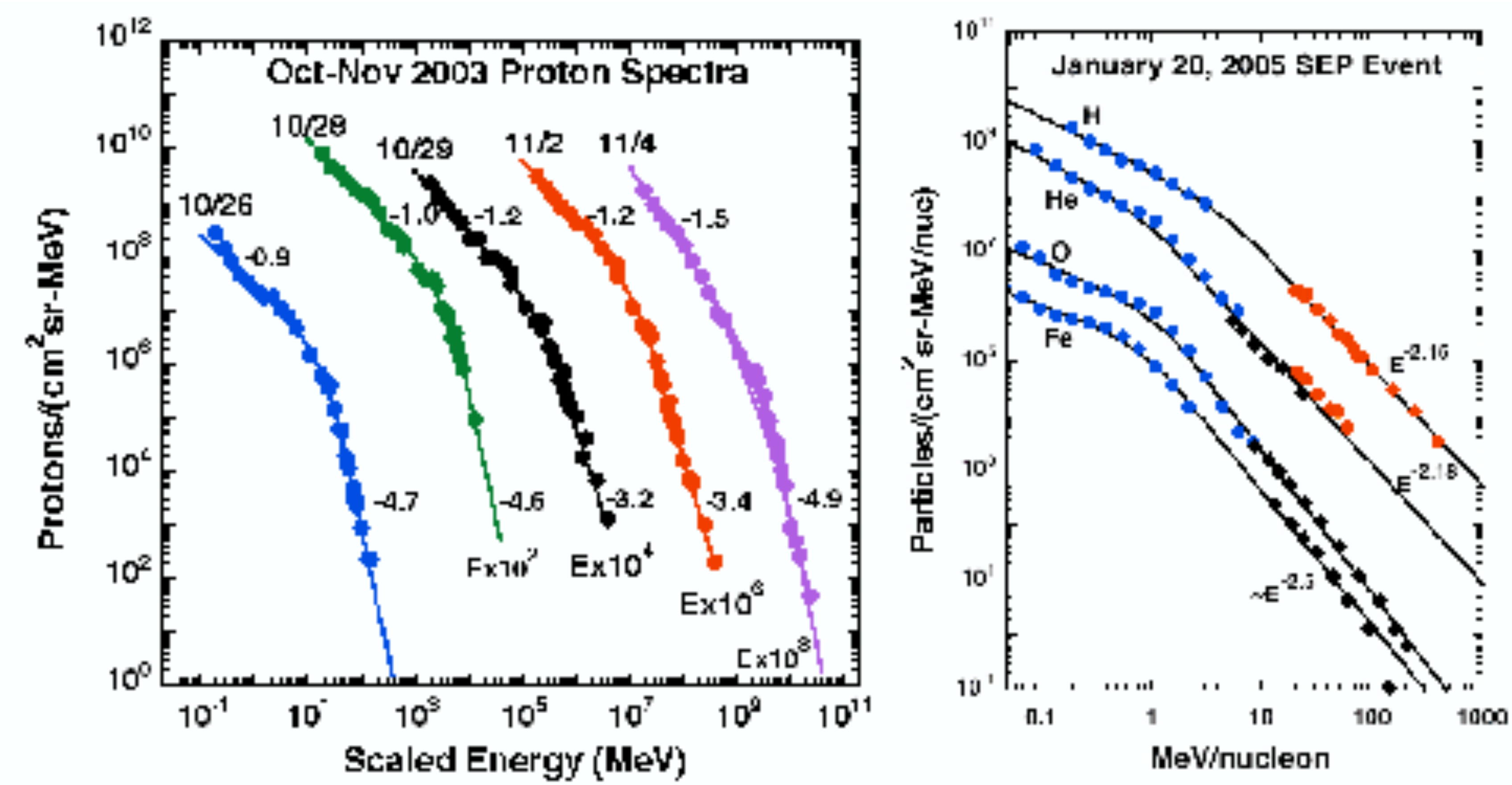
To have a (Q/A)2 dependence, $\beta = \infty$. What does this mean?

- below a critical k, decided by the maximum proton momentum, I(k) will quickly decrease to the quiet solar wind level.



<u>Such a sudden decrease of I(k) corresponds to $\beta = \infty$.</u>

clear spectral breaks in large SEP Event



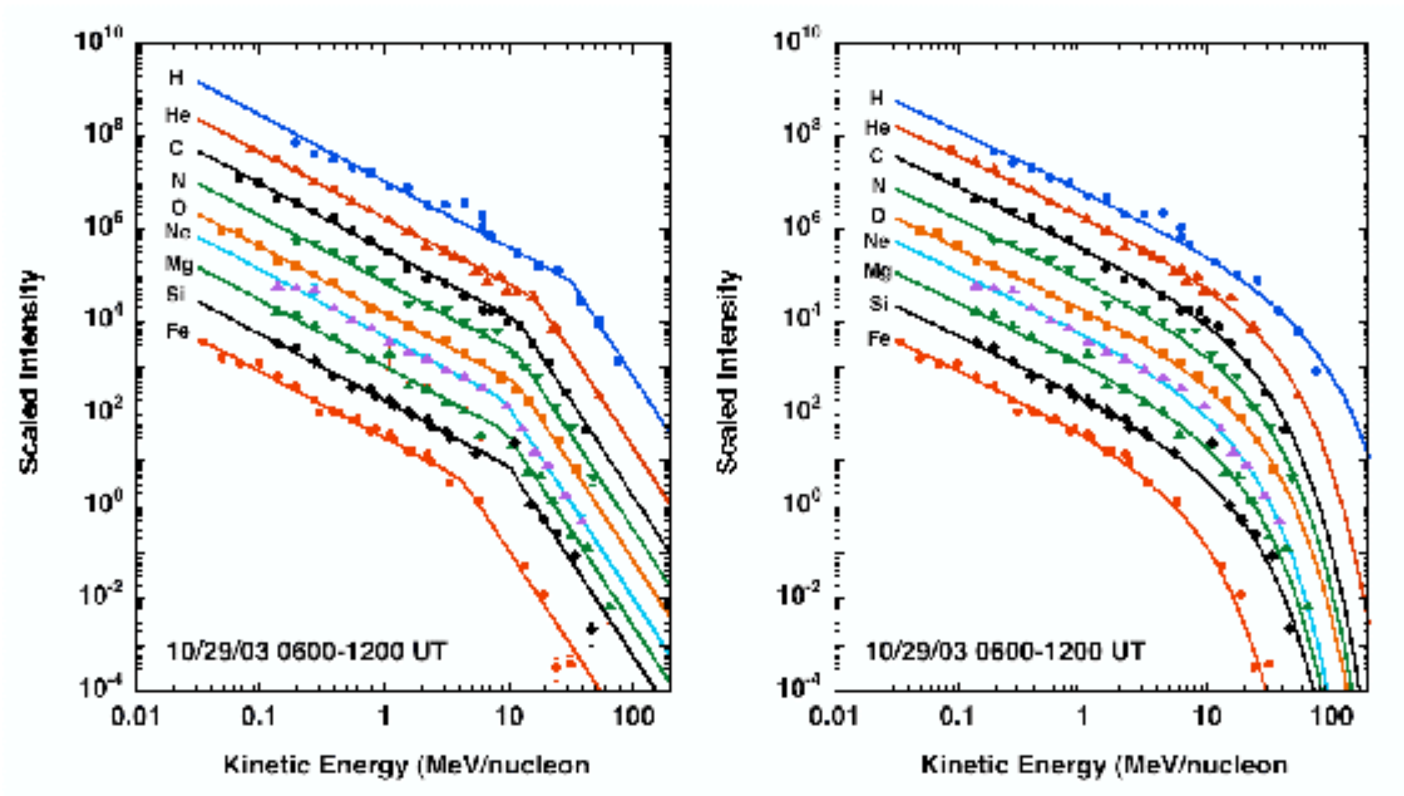
R. Mewaldt et al. 2005

fluence of the Oct-Nov events

• spectra of large SEP events often show broken (or double) power feature.

•Breaking energies seem to be ordered by (Q/M).

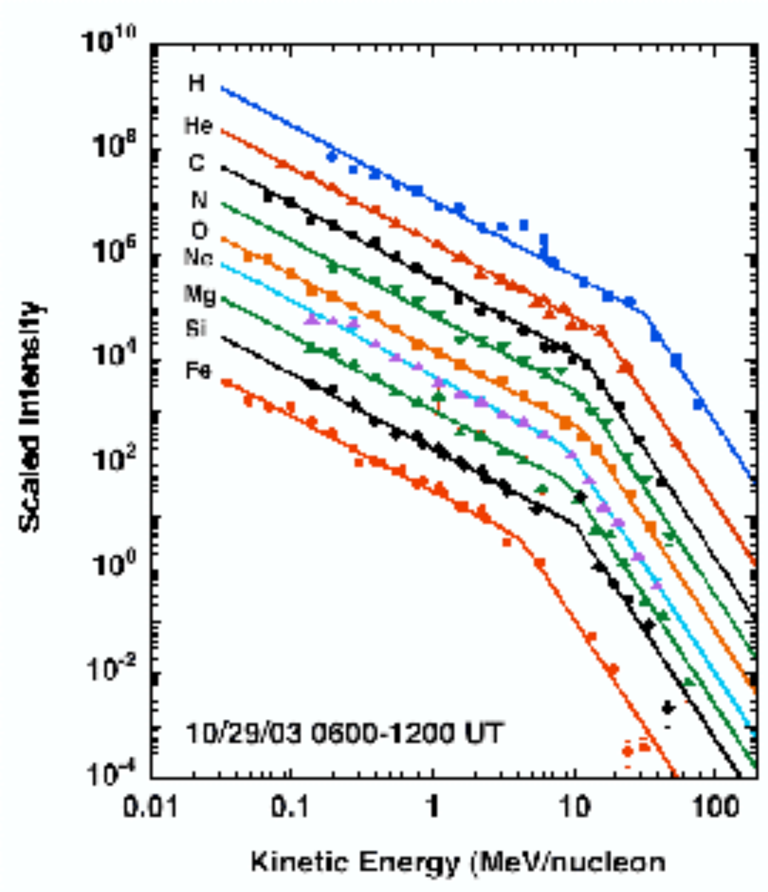
Spectrum form beyond the break

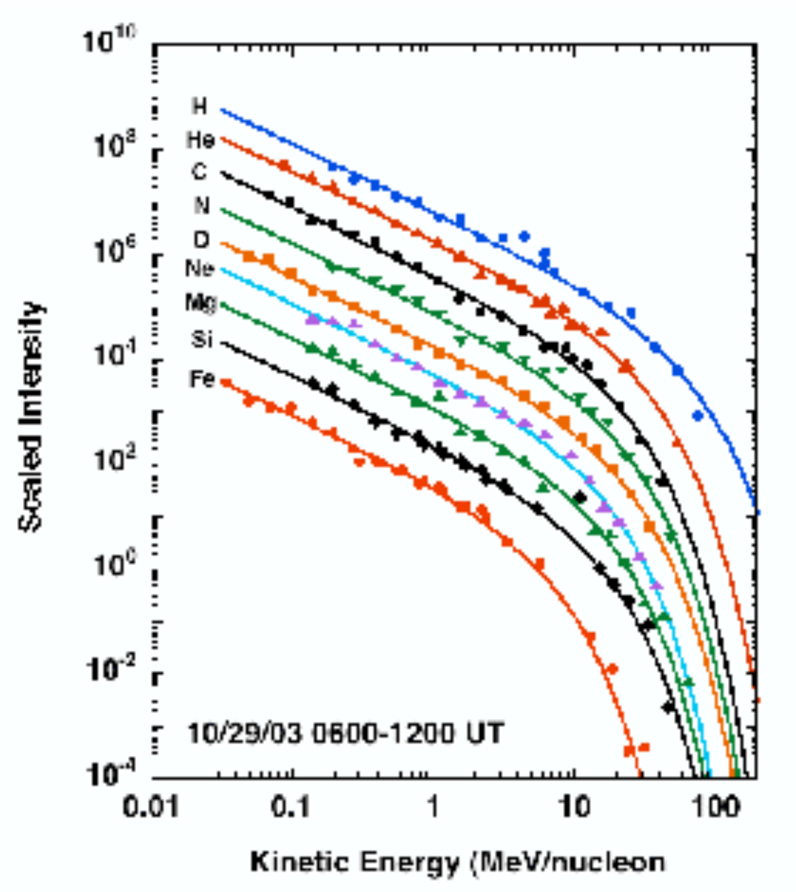


Not necessary double power law, but if the shifting technique works, then the physical process for this part of the spectrum also has the SAME (Q/A) dependence of the break.

Should examine Marty's idea on relating E0 and the shape beyond the break.

The October 29th, 2003 event





spectra right after the shock

R. Mewaldt et al. 2005

•Similar spectral indices for different heavy ions

•Double power law or exponential roll over