Transport and Acceleration of Solar Energetic Particles from Coronal Mass Ejection Shocks

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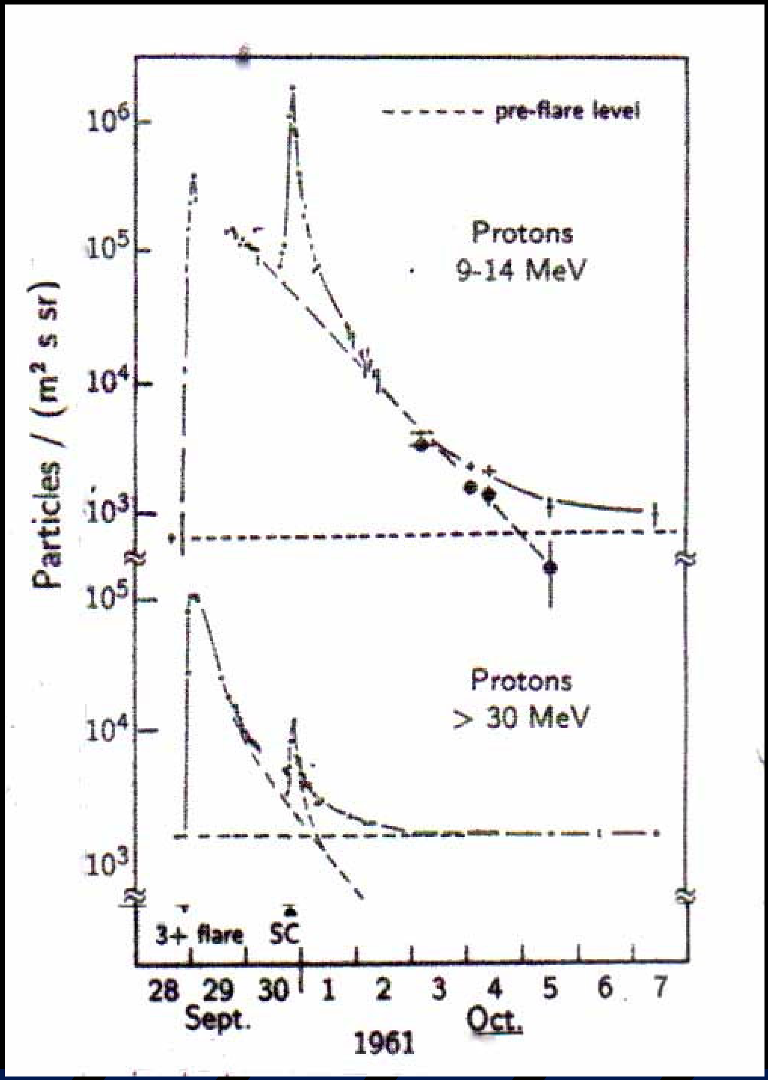
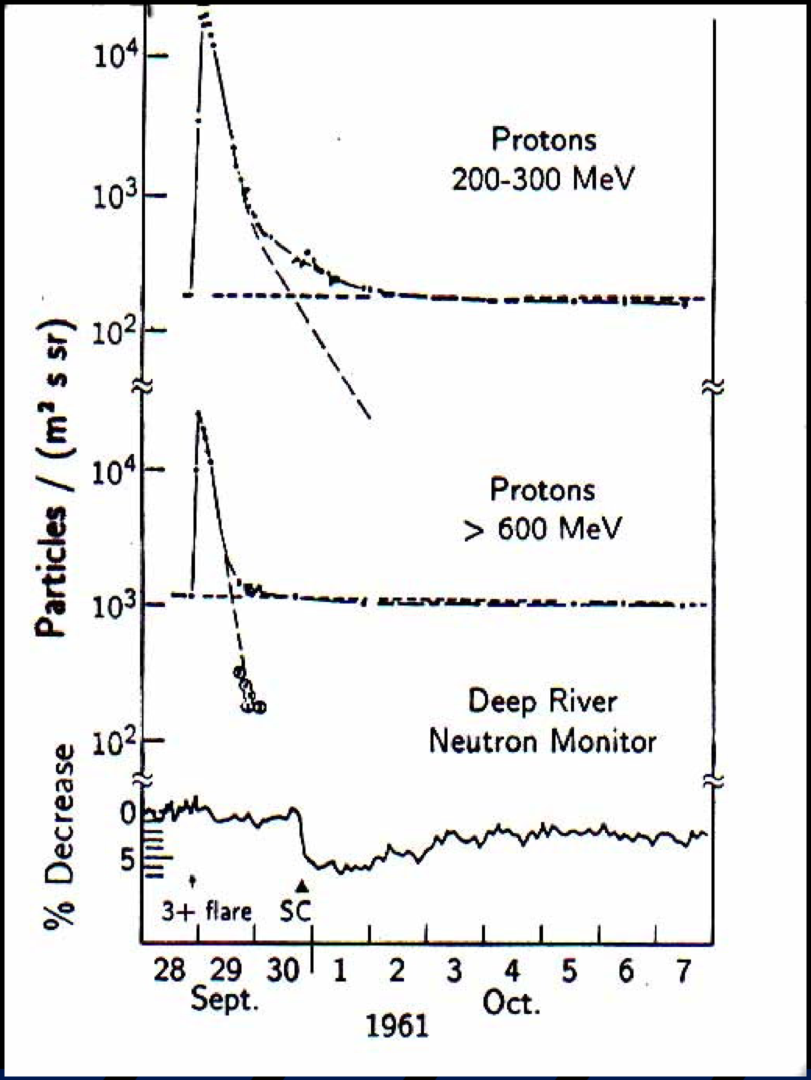
Outline

1. Overview
2. SEP Transport
3. SEP Acceleration

Overview of observations [Bryant et al. 1962]





Solar energetic particles

Impulsive flares	CME shocks (gradual events) near Sun	CME shocks (gradual events) interplanetary
^{3}He enhanced, electron-rich high ion Q	Up to high E, dispersive onset	At low E, non-dispersive peak
(stochastic acceleration)	(shock acceleration)	

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Precision modeling → Transport
→ Injection

Pitch-angle transport equation [DR 1995, ApJ, 442, 861] 6

$$\frac{\partial F(t,\mu,z,p)}{\partial t} = -\frac{\partial}{\partial z}\mu v F(t,\mu,z,p) \qquad \text{(streaming)}$$

$$-\frac{\partial}{\partial z}\left(1-\mu^2\frac{v^2}{c^2}\right) v_{\rm sw}\sec\psi F(t,\mu,z,p) \qquad \text{(convection)}$$

$$-\frac{\partial}{\partial \mu}\frac{v}{2L(z)}\left[1+\mu\frac{v_{\rm sw}}{v}\sec\psi-\mu\frac{v_{\rm sw}v}{c^2}\sec\psi\right]$$

$$\cdot(1-\mu^2)F(t,\mu,z,p) \qquad \text{(focusing)}$$

$$+\frac{\partial}{\partial \mu}v_{\rm sw}\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu(1-\mu^2)$$

$$\cdot F(t,\mu,z,p) \qquad \text{(differential convection)}$$

$$+\frac{\partial}{\partial \mu}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial \mu}F(t,\mu,z,p) \qquad \text{(scattering)}$$

$$+\frac{\partial}{\partial p}p v_{\rm sw}\left[\frac{\sec\psi}{2L(z)}(1-\mu^2)+\cos\psi\frac{d}{dr}\sec\psi\mu^2\right]$$

$$\cdot F(t,\mu,z,p). \qquad \text{(deceleration)}$$

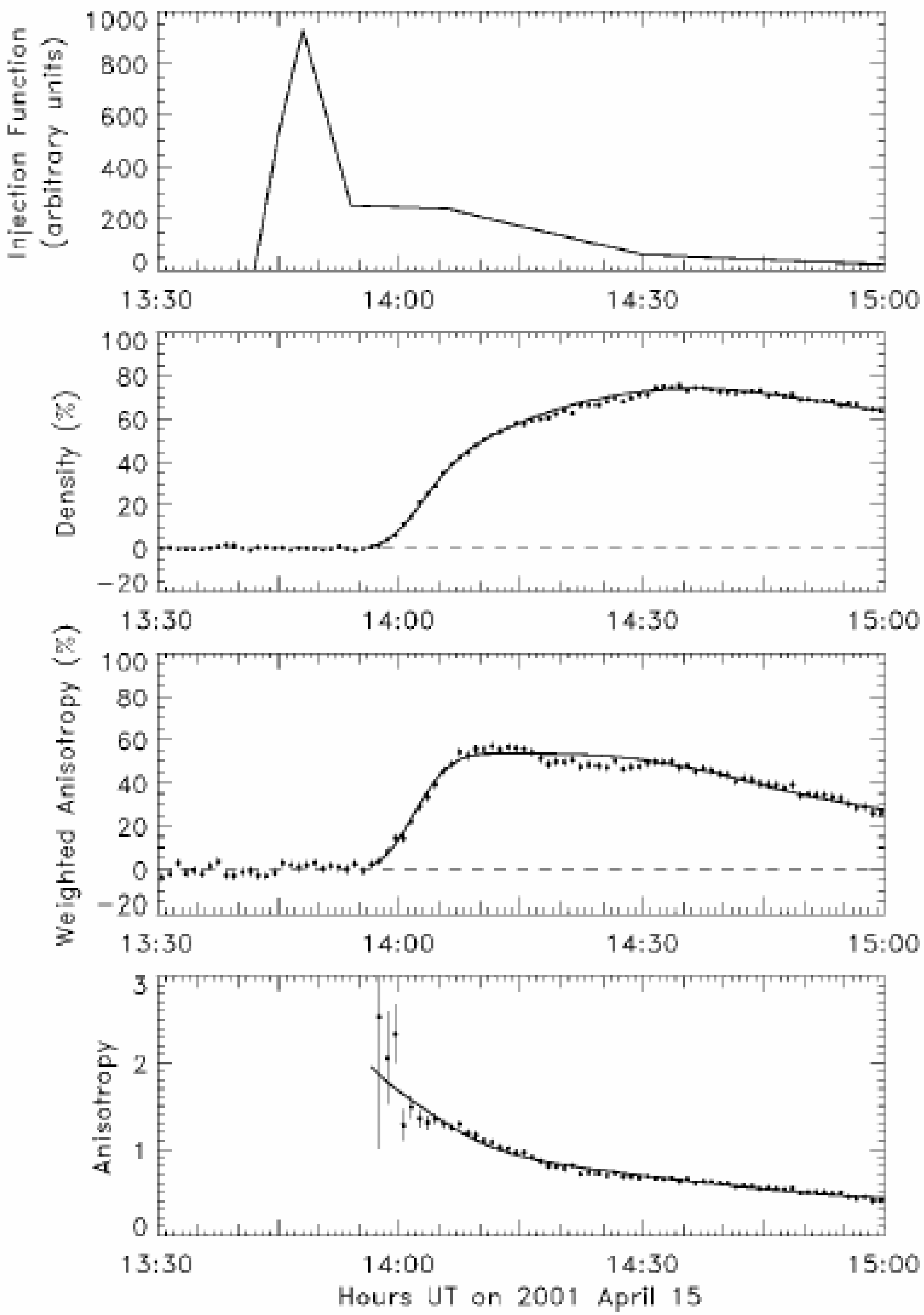
Simulation of interplanetary transport

- Specify magnetic field configuration
- Solve PDE
- Runs in a few minutes [Nutaro et al., Comp. Phys. Comm. ‘01]

Fitting SEP data

- Simultaneous fit to intensity vs. time
  anisotropy vs. time
- Optimal piecewise linear injection (least squares)
- Optimal scattering mean free path, λ

[DR, Khumlumlert, & Youngdee, JGR ‘98]



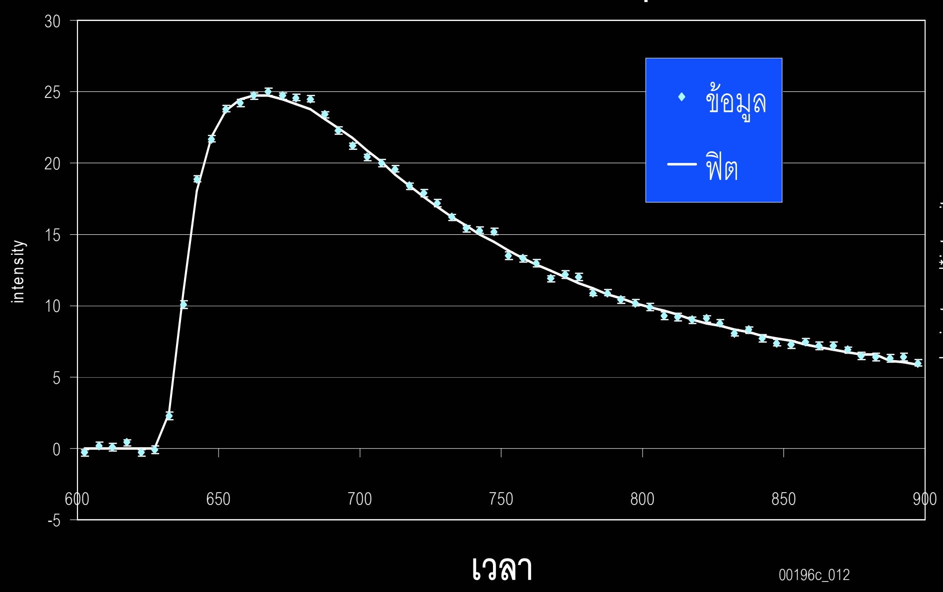
Easter 2001

- Ground Level Enhancement (GLE)
- Observed by neutron monitors (high statistics, precise directionality)
- We can accurately fit the intensity & anisotropy
- Precise timing results (will show shortly)

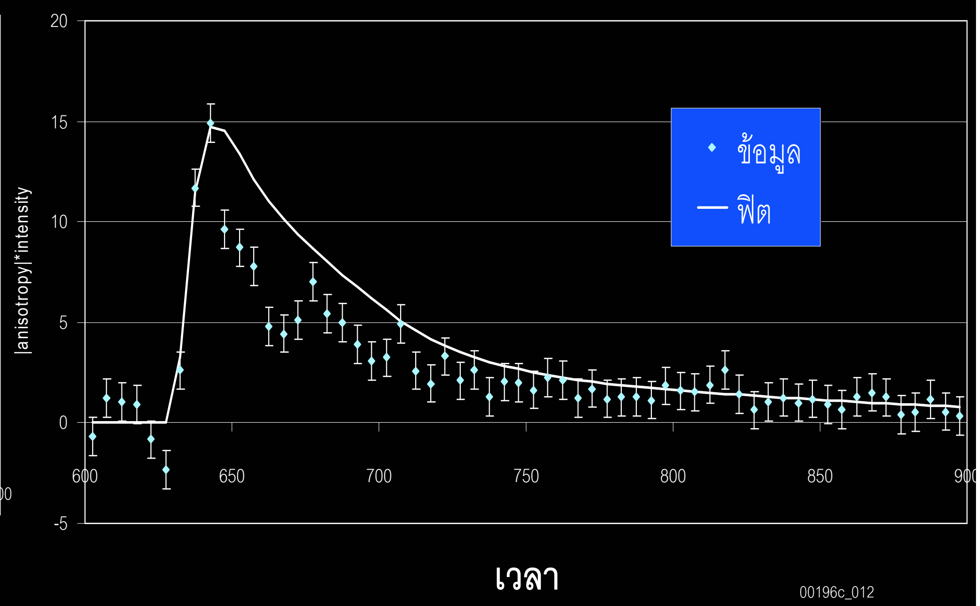
[Bieber et al., ApJL, 2004]

GLE of Bastille Day 2000: Initial Fit ...

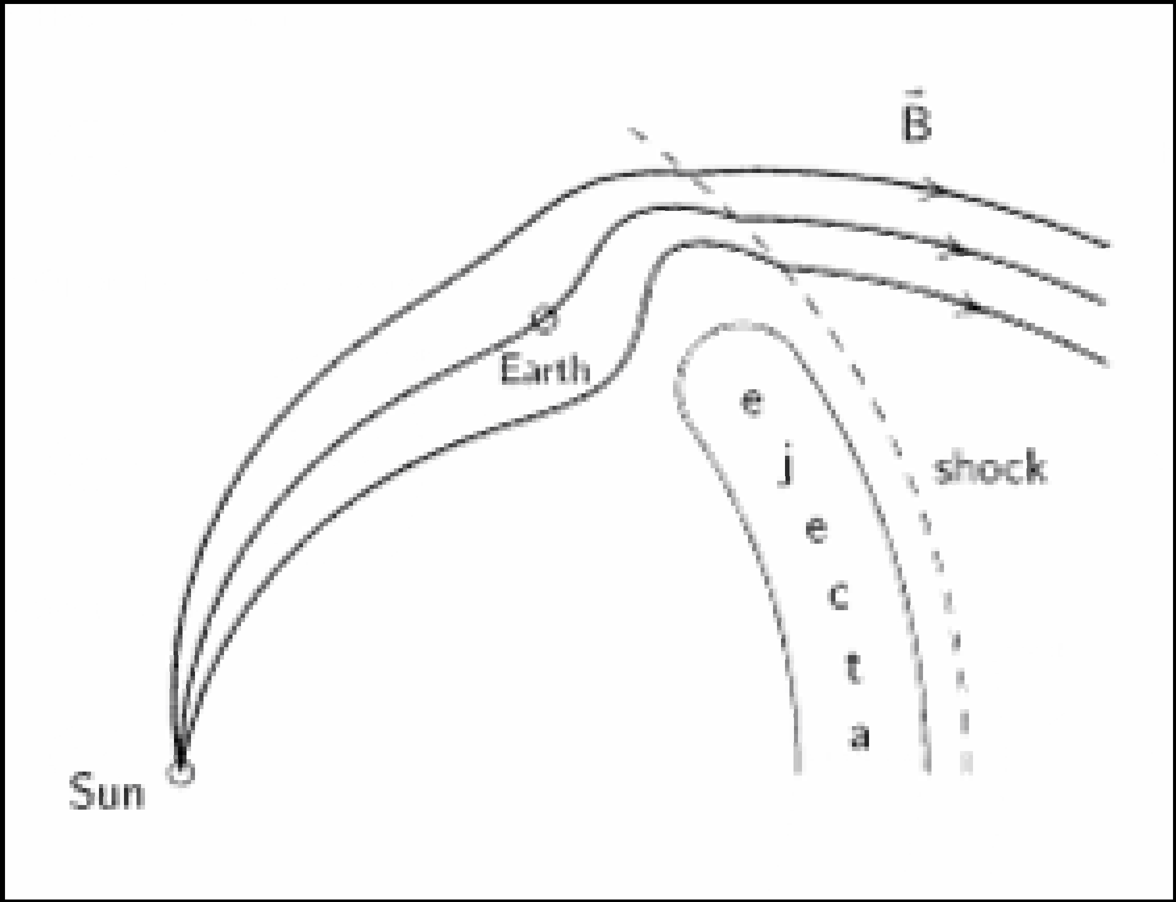
intensity (ความหนาแน่นอนุภาค)



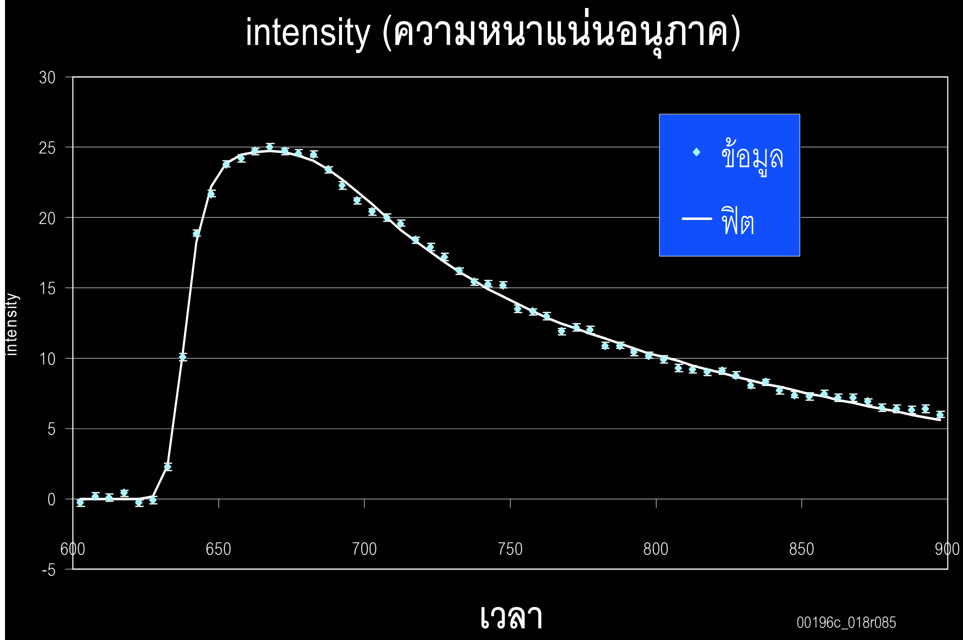
anisotropy (อัตราไหลออก -- อัตราไหลเข้า)



Magnetic bottleneck in space



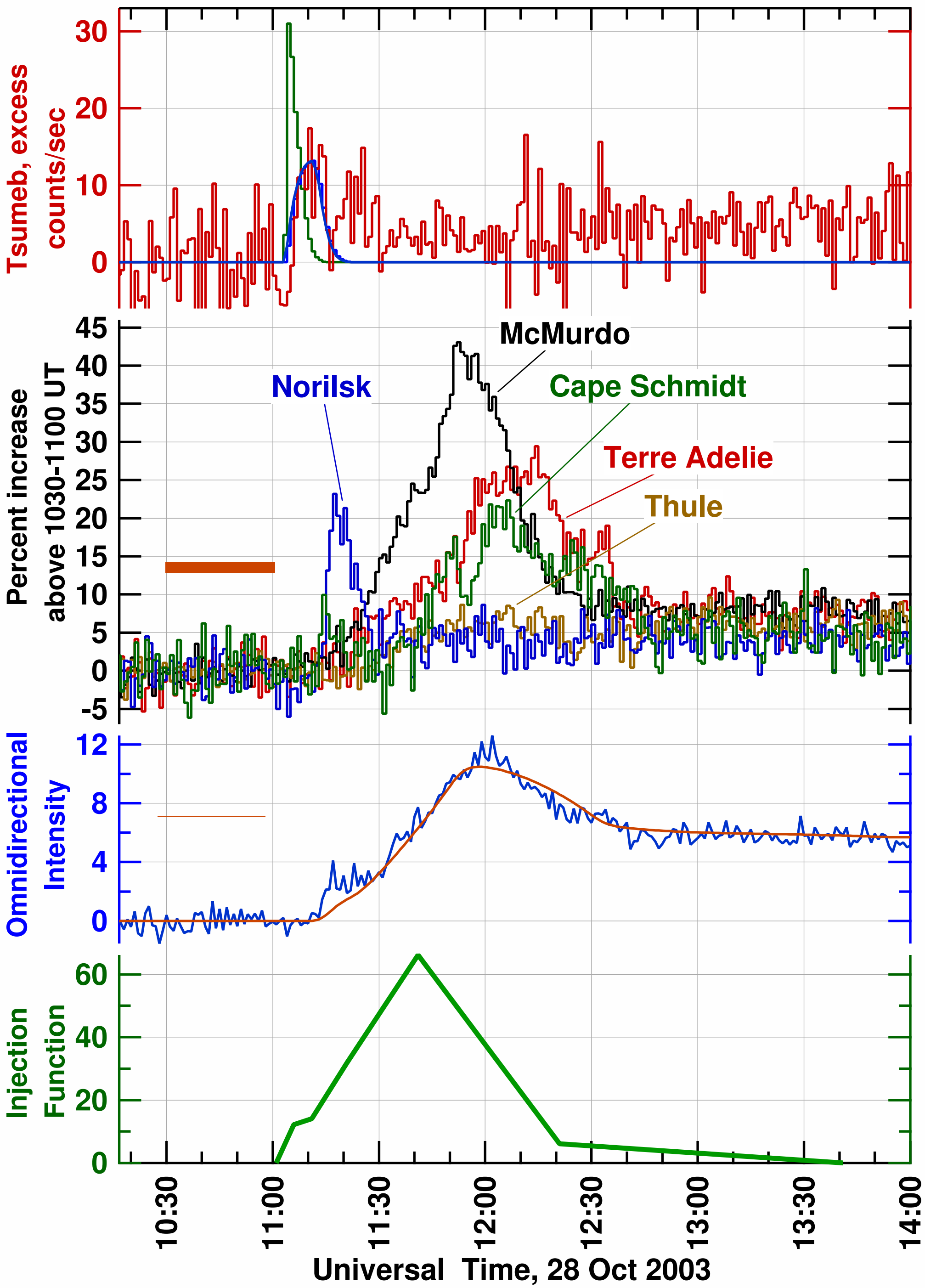
… Final Fit



Thus we have convincing evidence for interplanetary magnetic mirroring of energetic particles.

[Bieber et al., ApJ, 2002]

Closed magnetic loop?



Oct. 28, 2003

- Solar neutrons: from interacting SEP
- Mysterious fast peak
- Slow decay implies loop geometry
- Timing of main peak of escaping SEP: onset at soft X-ray maximum (like Easter 2001)

[Bieber et al., sub. to GRL]

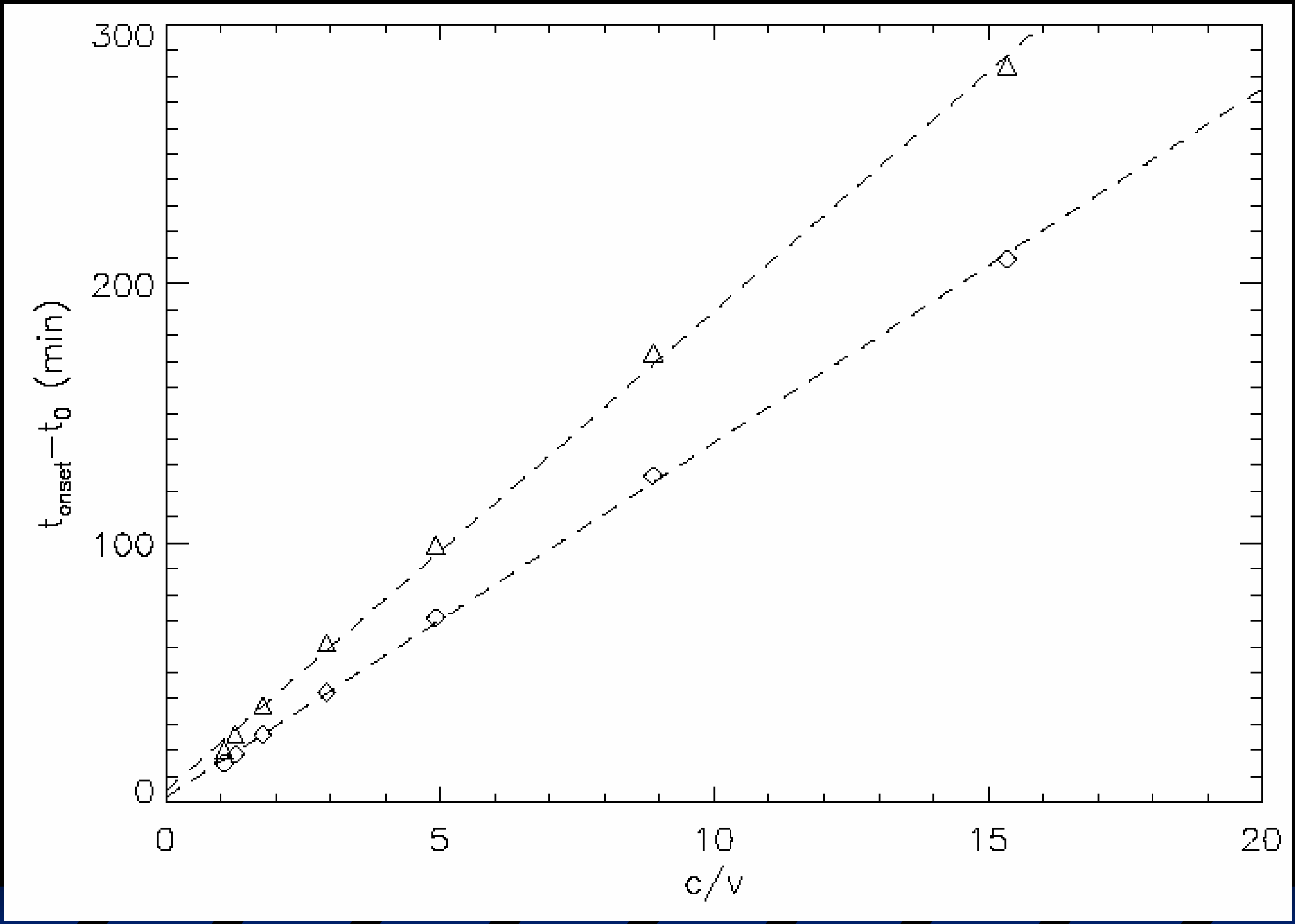
Comparison with EM timing

EMISSION	APR. 15, 2001			OCT. 28, 2003		
	START	PEAK	END	START	PEAK	END
Relativistic Protons	**13:42**	13:48		**11:03**	11:41	
Soft X-rays	13:11	**13:42**	13:47	10:52**	**11:02**	11:16
H-alpha	13:28	13:41	15:27	09:53	11:57	14:12
Type III radio burst	13:36		13:38	-		-
CME liftoff*	*13:24-31*			*10:53-58*		
Type II radio burst	13:40		13:47	10:54		11:03
Type IV radio burst	13:44		14:57	10:25		15:23

* Linear - quadratic fits ** Sudden onset of intense emission

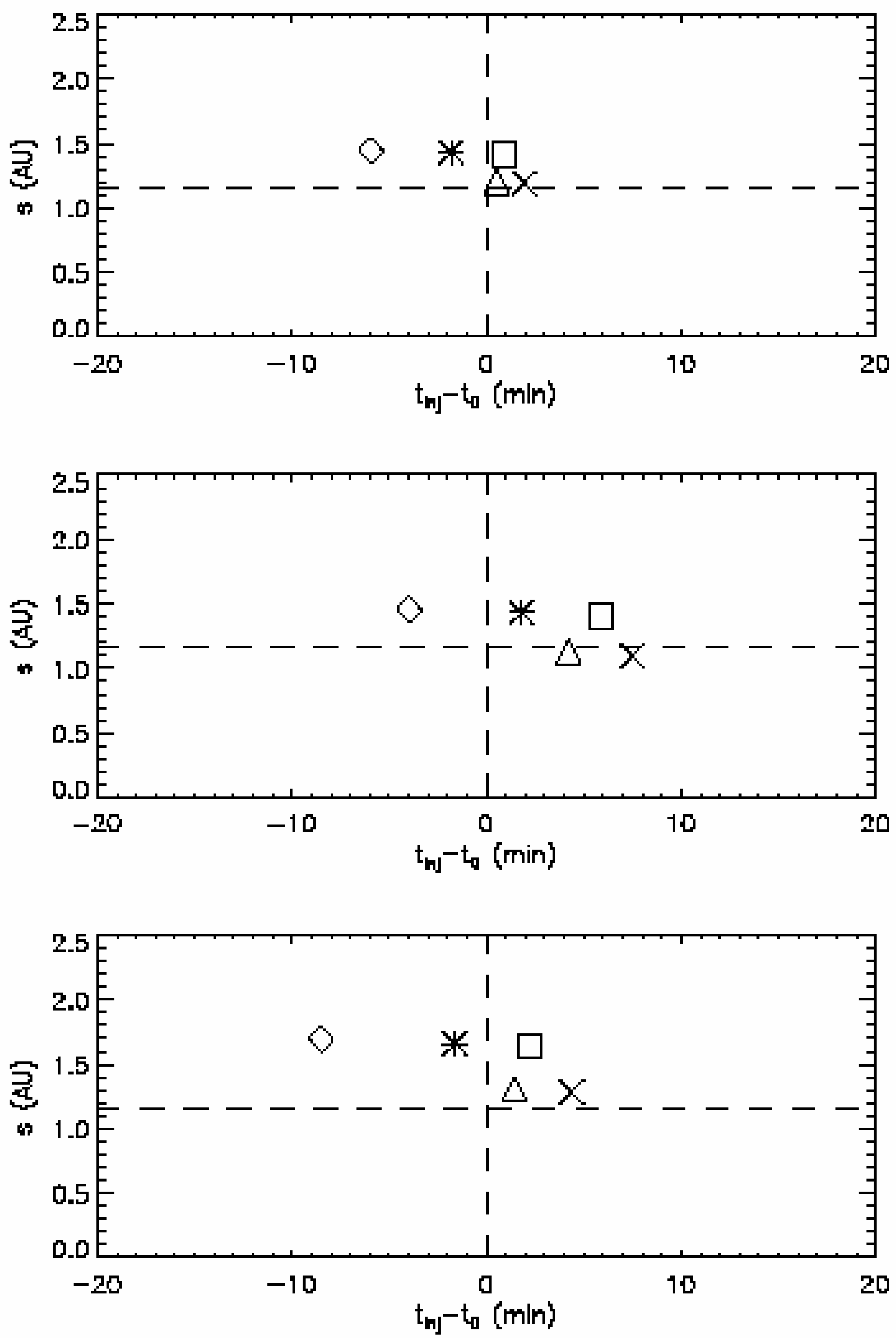
All times are "Solar Time" or UT minus 8 min. for EM emissions

How accurate is the injection timing derived from linear fits to onsets?



$$t_{onset} \stackrel{?}{=} path / v + t_0$$

[Sáiz, Evenson, & DR, in preparation]



There is some spread in the injection start times and pathlengths derived from straight-line fits, depending on the mean free path and duration of injection:

- Injection timing: several minutes
- Pathlength: ~ 50 %

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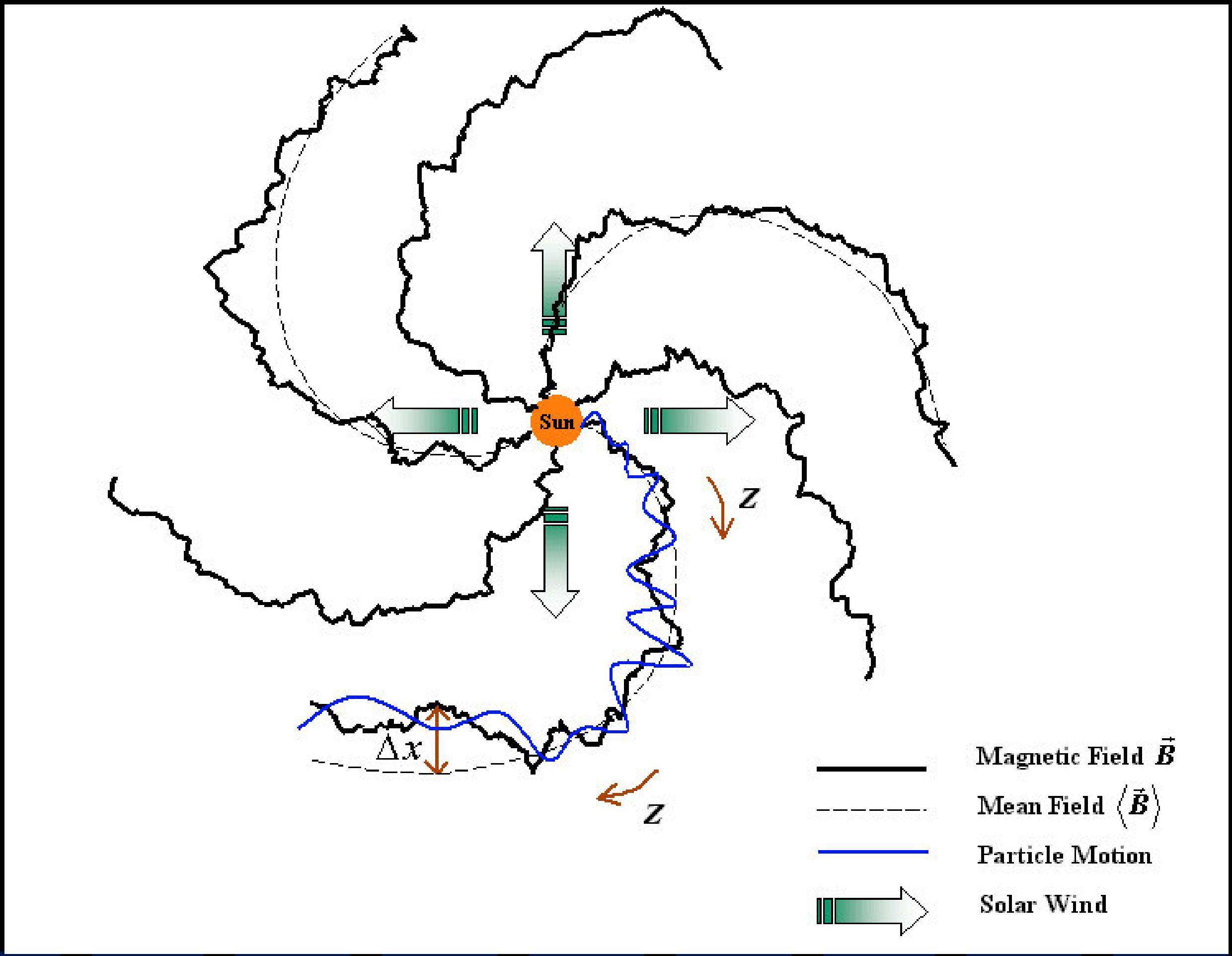
Difficult to separate acceleration & transport

Saturation, composition changes [Ng et al. '99]

Seed population, local accelerated spectrum

(stochastic acceleration) — (shock acceleration)

Transport *parallel* or *perpendicular* to the mean magnetic field



Turbulent magnetic field deviates from mean field

↓

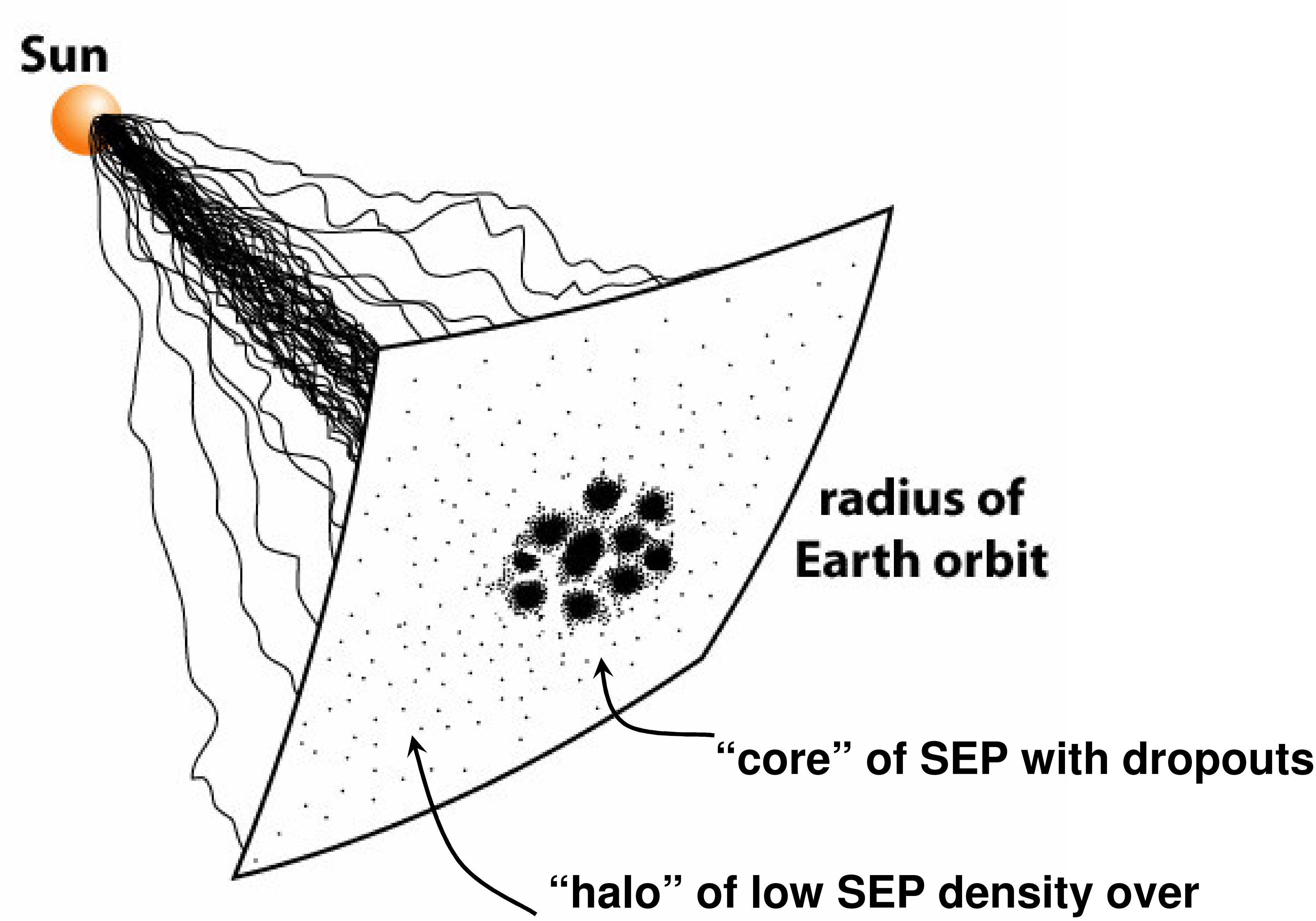
field line random walk

↓

Δx vs. z

Perpendicular transport: Recent ideas

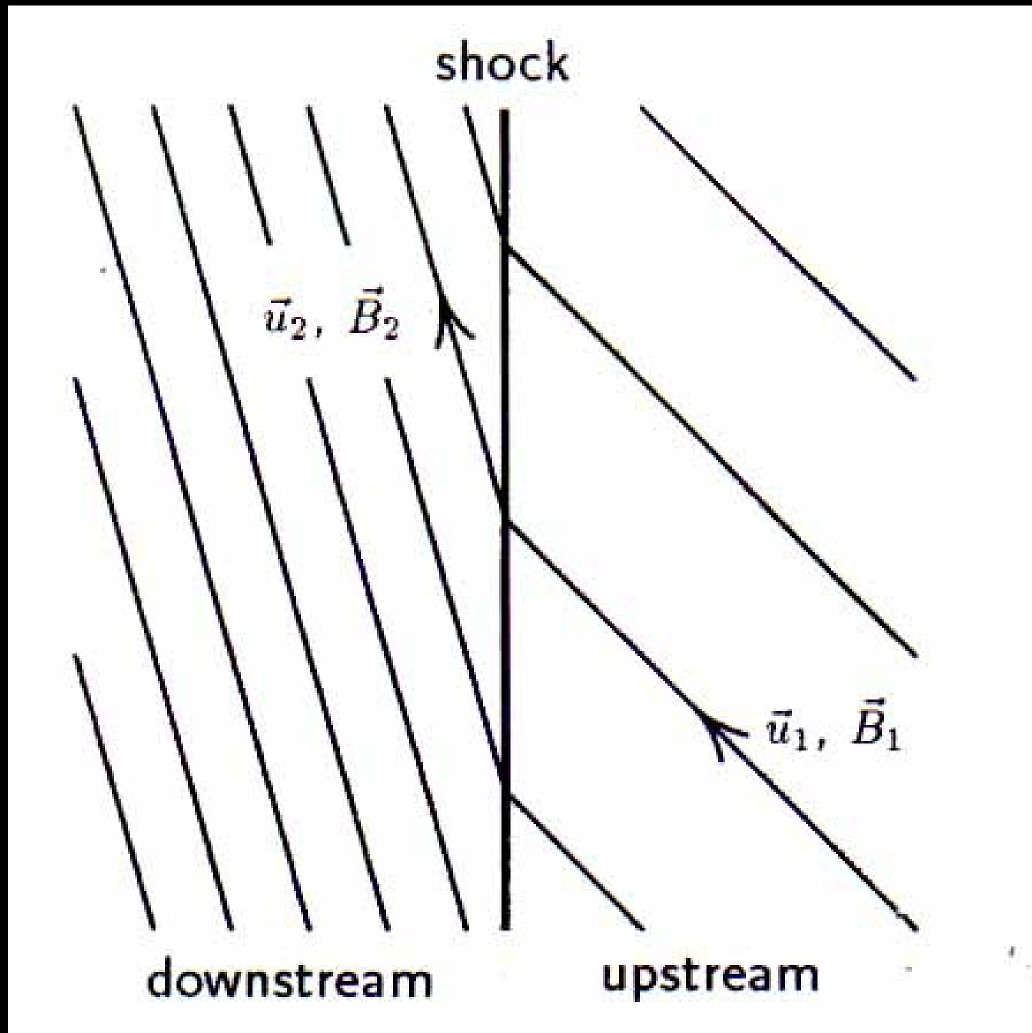
- Dynamical turbulence [Bieber & Matthaeus 1997]
- MC simulations [Giacalone & Jokipii 1999]
- Second diffusion: Nonlinear guiding center theory [Qin et al. 2003]
- Trapping by topology of turbulence [DR, Matthaeus, & Chuychai 2003]



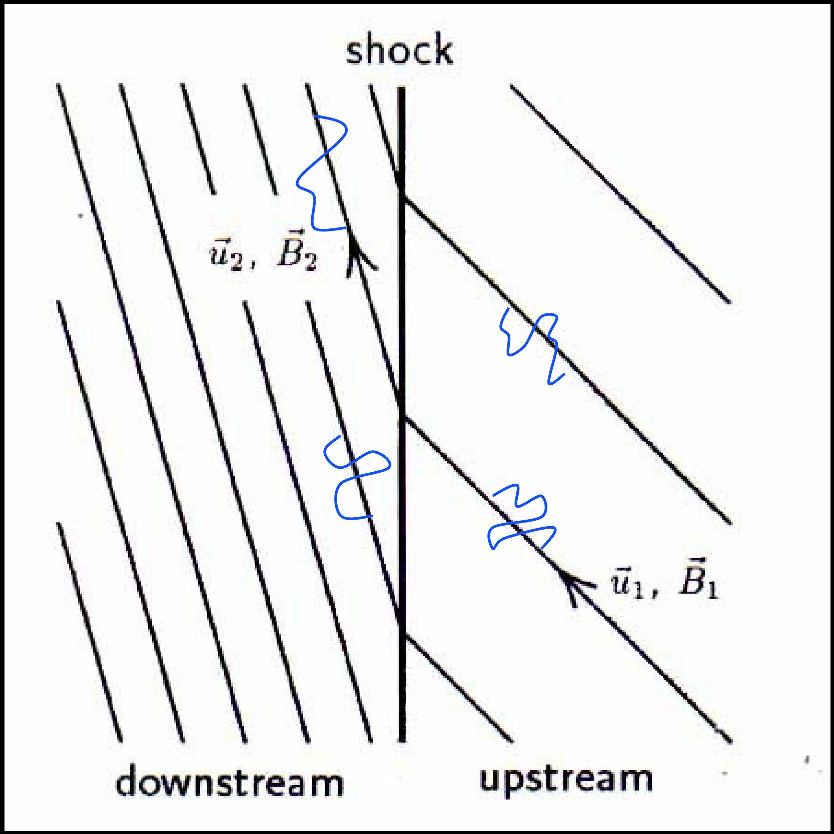
[DR, Matthaeus, & Chuychai 2003]

Acceleration of particles by shocks

A shock front



… and diffusive shock acceleration



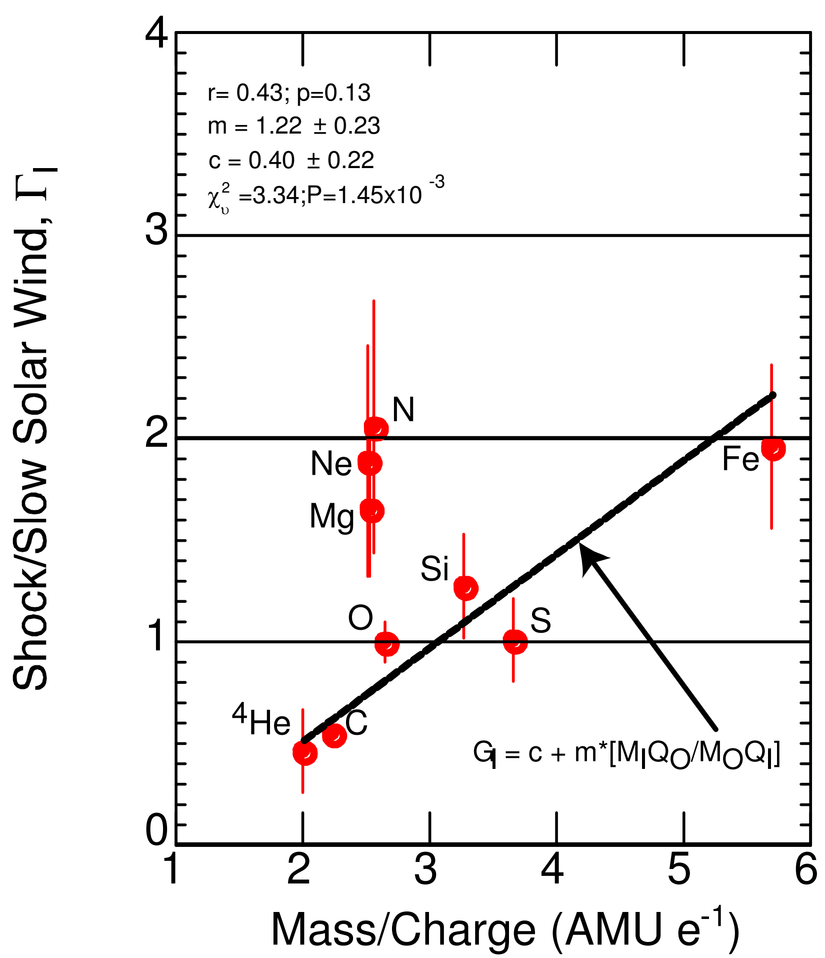
Following collision with a scattering center: lose energy

Head-on collision with a scattering center: gain energy

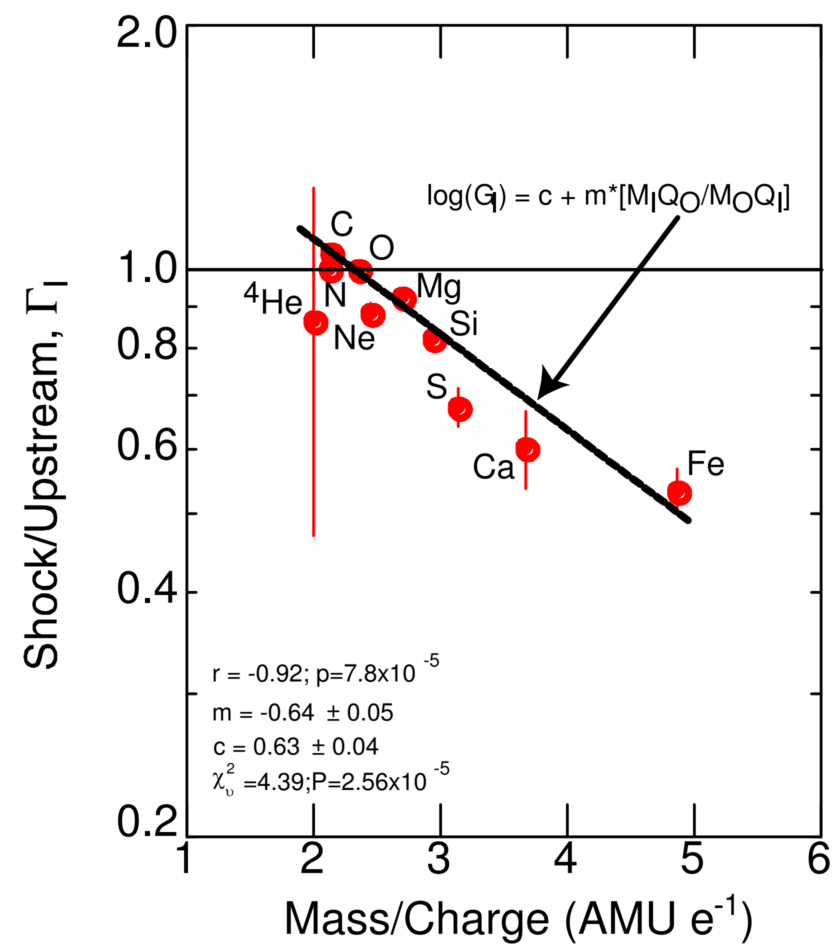
Since $u_1 > u_2$ there is a net gain in energy

(Desai et al. 2003 ApJ 558, 1149).

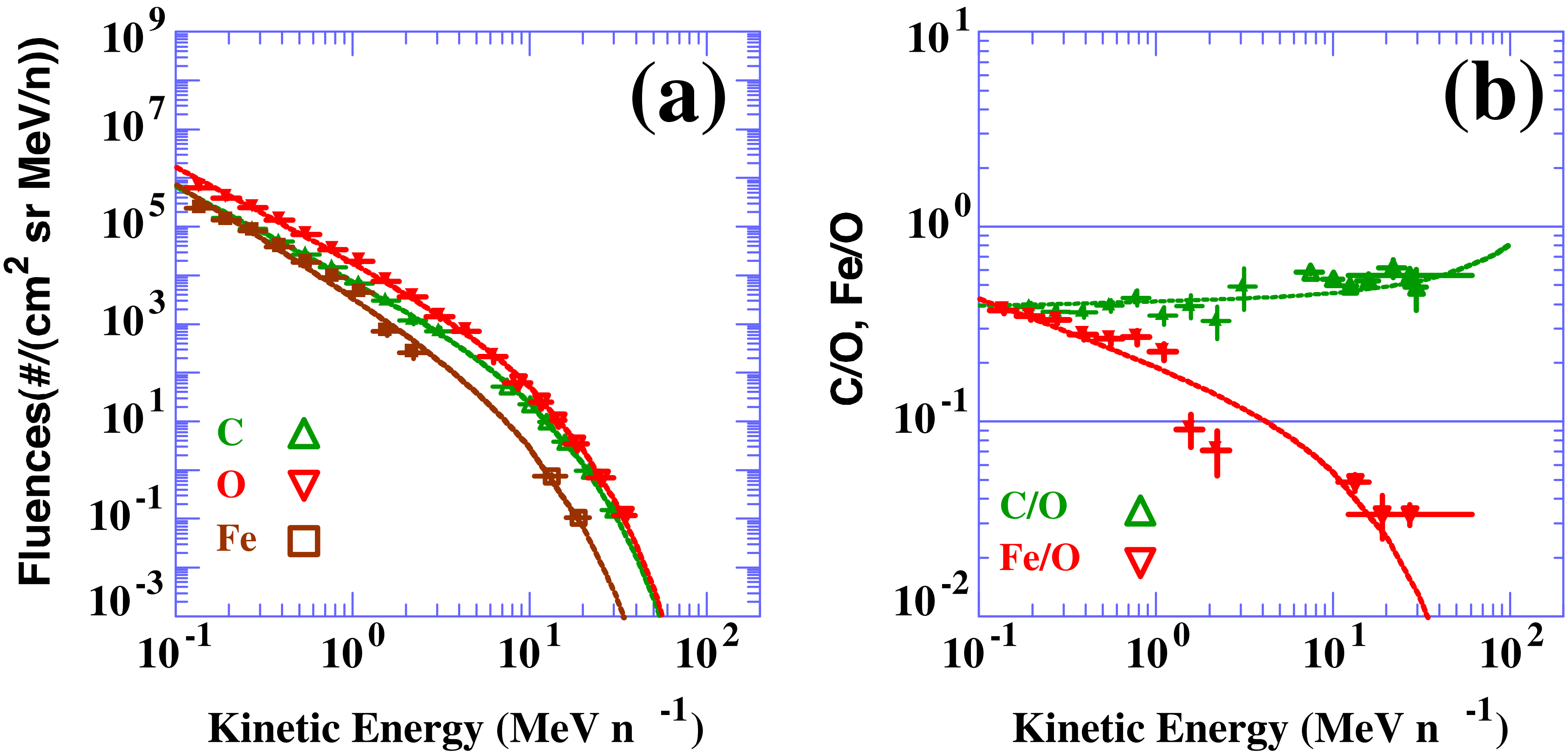
Solar wind & IP shock abundances



Upstream & IP shock abundances



Spectra and abundances for Sep. 7 2002 IP shock



(Desai et al. 2003 to be submitted to ApJ).

Why do the spectra roll over at ~ 0.1 - 10 MeV/n?

(data - see also: Gosling et al. 1981; van Nes et al. 1985)

Possible mechanisms suggested by Ellison & Ramaty (1985)

- shock thickness ~ κ/u → energy is too low
- drift over shock width → rollover at ~ 100 MeV/Q
- finite time for shock acceleration → *considered here*

(see also: Klecker et al. 1981; Lee 1983)

Finite-Time Shock Acceleration

- Probability approach (like Bell 1978, Drury 1983)
- Acceleration rate, $r = 1/t_{acc}$ Escape rate, ε

  Time at present (age of shock), t

  No. of acceleration events, n
- r, ε constant w/ energy - combinatorial model
- r, ε varying - ODE (analytic, numerical)
- Acceleration at interplanetary shocks

Rollover energy (E_c/A)

(well above injection energy)

λ = const.

$$E_c/A \propto t^{2}, \text{ independent of } Q/A$$

$\lambda \propto P^{\alpha}$

$$E_c/A \propto t^{2/(\alpha+1)} \, (Q/A)^{2\alpha/(\alpha+1)}$$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