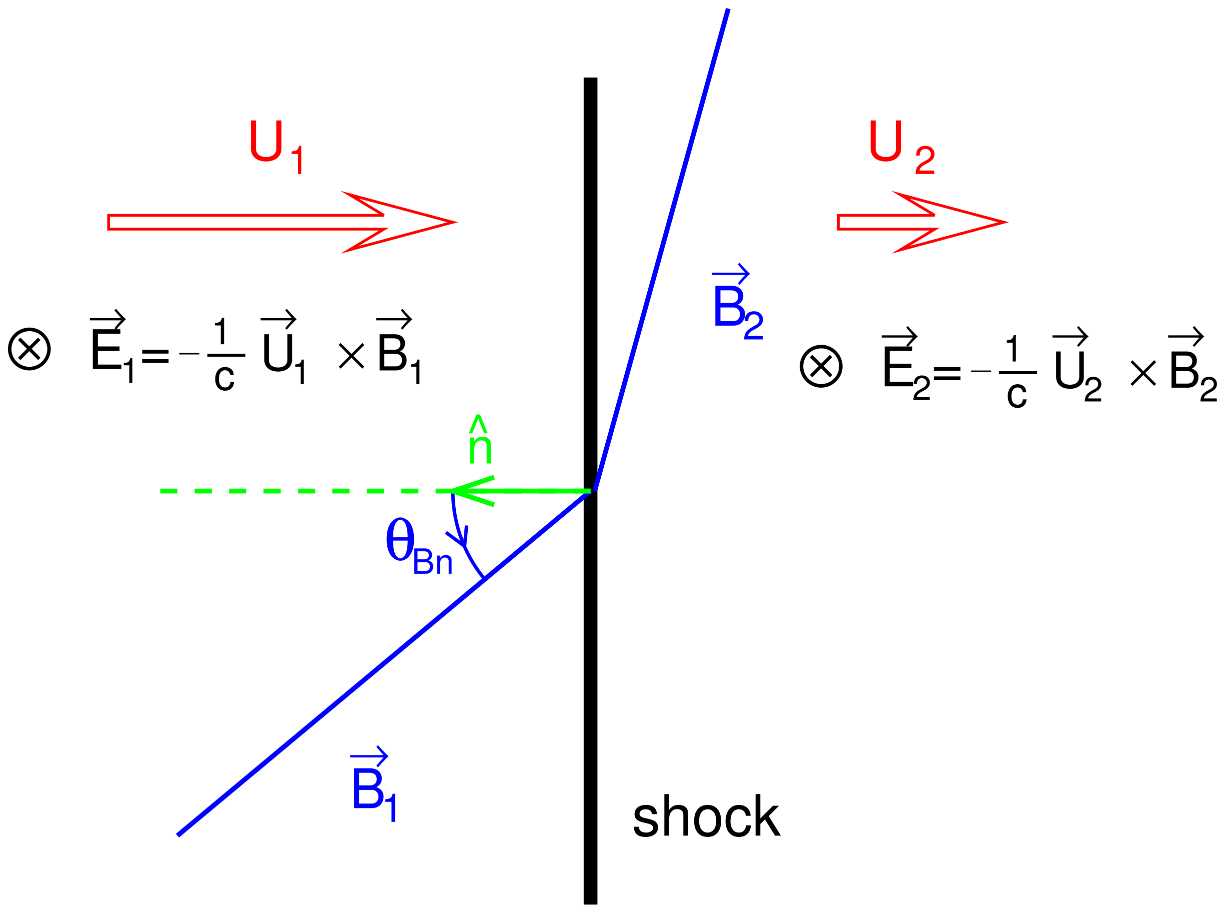
- **What is the Injection Energy Associated with Shock Acceleration?**

- **Does it depend on Shock-Normal Angle?**

- **What is the Acceleration Rate?**

Simplified Shock Geometry



In order for particles to be accelerated by the shock – efficiently – they must remain near the shock.

In the **ABSENCE** of scattering, particles can remain ahead of the shock only if their speed, w is such that

$$w \;>\; V_1 \sec\theta_{Bn}$$

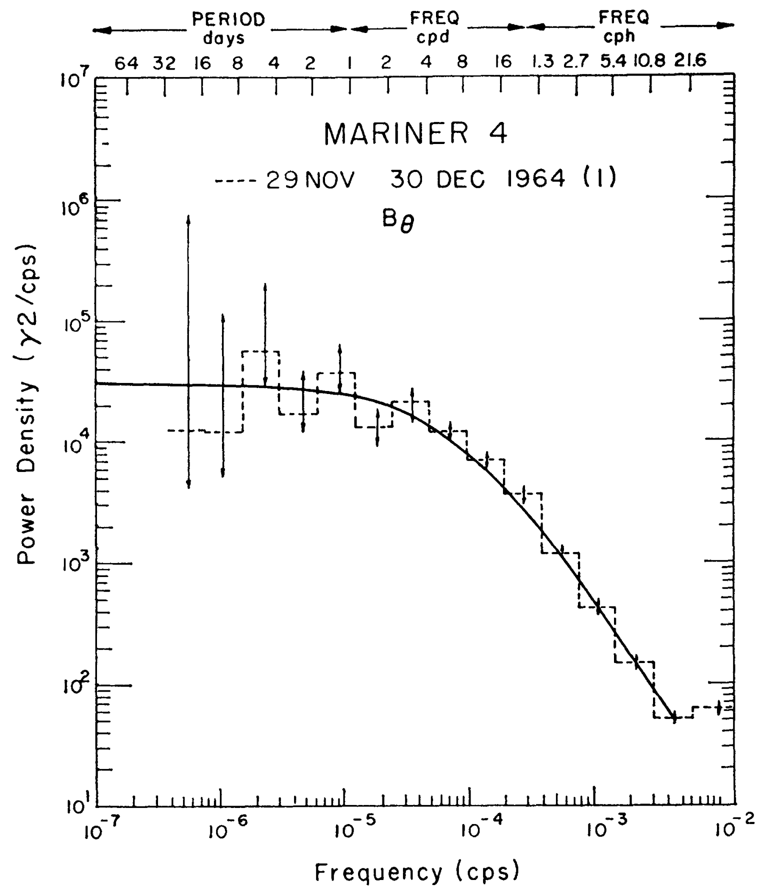
where V_1 is the shock speed.

This implies a STRONG dependence on θ_{Bn}

BUT IS THIS A GOOD APPROXIMATION?

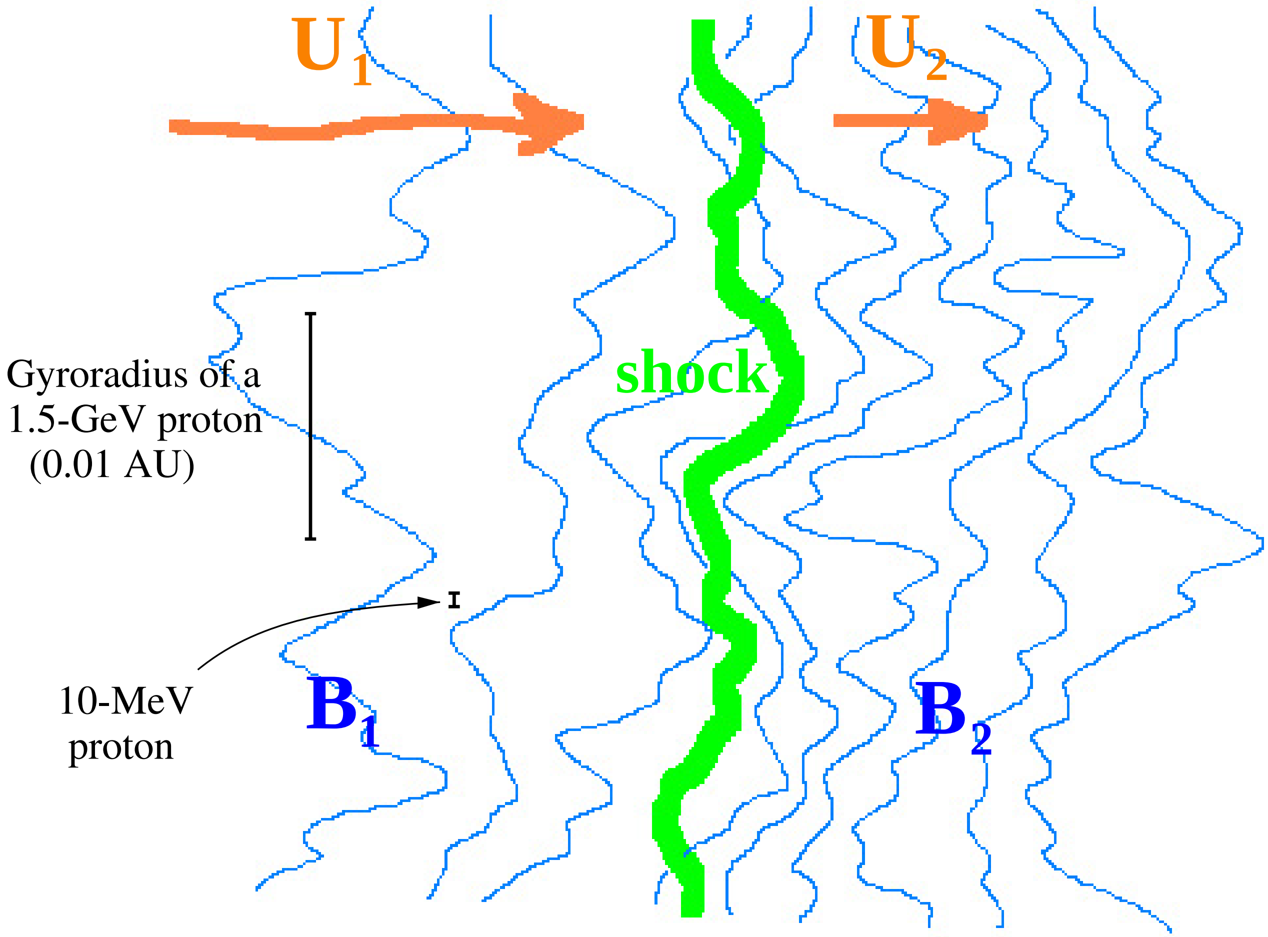
AMBIENT FLUCTUATIONS

The coherence scale of the interplanetary magnetic field is about 0.01 AU (determined from power spectra)



Jokipii & Coleman, 1968

A picture of the fields & flow near a shock at 1 AU



The Limit of Diffusive Shock Acceleration

Diffusive shock-acceleration theory is valid if the anisotropy is small. The general expression is:

$$|\delta_i| = \frac{3U_1}{w}\left\{1 + \frac{\left(\frac{\kappa_A}{\kappa_\|}\right)^2 \sin^2\theta_{Bn} + \left(1 - \frac{\kappa_\perp}{\kappa_\|}\right)^2 \sin^2\theta_{Bn}\cos^2\theta_{Bn}}{\left[\left(\frac{\kappa_\perp}{\kappa_\|}\right)\sin^2\theta_{Bn} + \cos^2\theta_{Bn}\right]^2}\right\}^{\frac{1}{2}}$$

$\ll 1 \quad \Rightarrow \quad$ Diffusive Shock Acceleration is applicable

The Limit of Diffusive Shock Acceleration (cont.)

Case 1. Parallel shock ($\theta_{Bn} \rightarrow 0$)

$$\frac{3U_1}{w} \ll 1$$

Case 2. Perpendicular Shock ($\theta_{Bn} \rightarrow 90$)

$$\frac{3U_1}{w}\left[1 + \left(\frac{\kappa_A}{\kappa_\perp}\right)^2\right]^{\frac{1}{2}} \ll 1$$

The Limit of Diffusive Shock Acceleration (cont.)

Classical-scattering theory gives

$$\frac{\kappa_A}{\kappa_\perp} = \frac{\lambda_\parallel}{r_g} \gg 1 \qquad \text{(for most astrophysical applications)}$$

Thus, the classical-scattering theory predicts

$$w_{inj} \gg 3U_1(\lambda_\parallel / r_g)$$

The Limit of Diffusive Shock Acceleration (cont.)

Classical-scattering theory gives

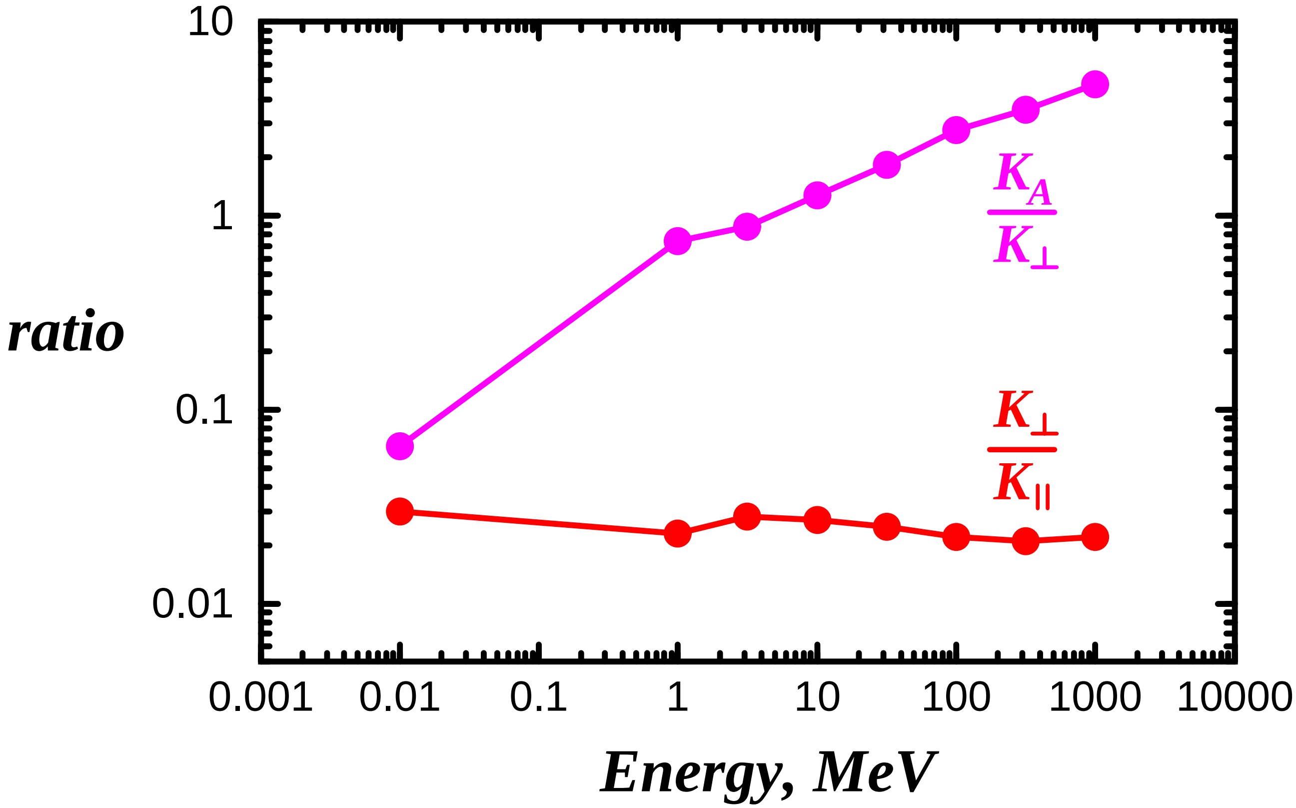
$$\frac{\kappa_A}{\kappa_\perp} = \frac{\lambda_\parallel}{r_g} \gg 1 \qquad \text{(for most astrophysical applications)}$$

Thus, the classical-scattering theory predicts

$$w_{inj} \gg 3U_1(\lambda_\parallel / r_g)$$

HOWEVER, classical-scattering theory is **<u>NOT</u>** a good approximation for perpendicular transport!

Test-particle simulations using synthesized magnetic turbulence (Giacalone and Jokipii, ApJ, 1999 + one extra point)



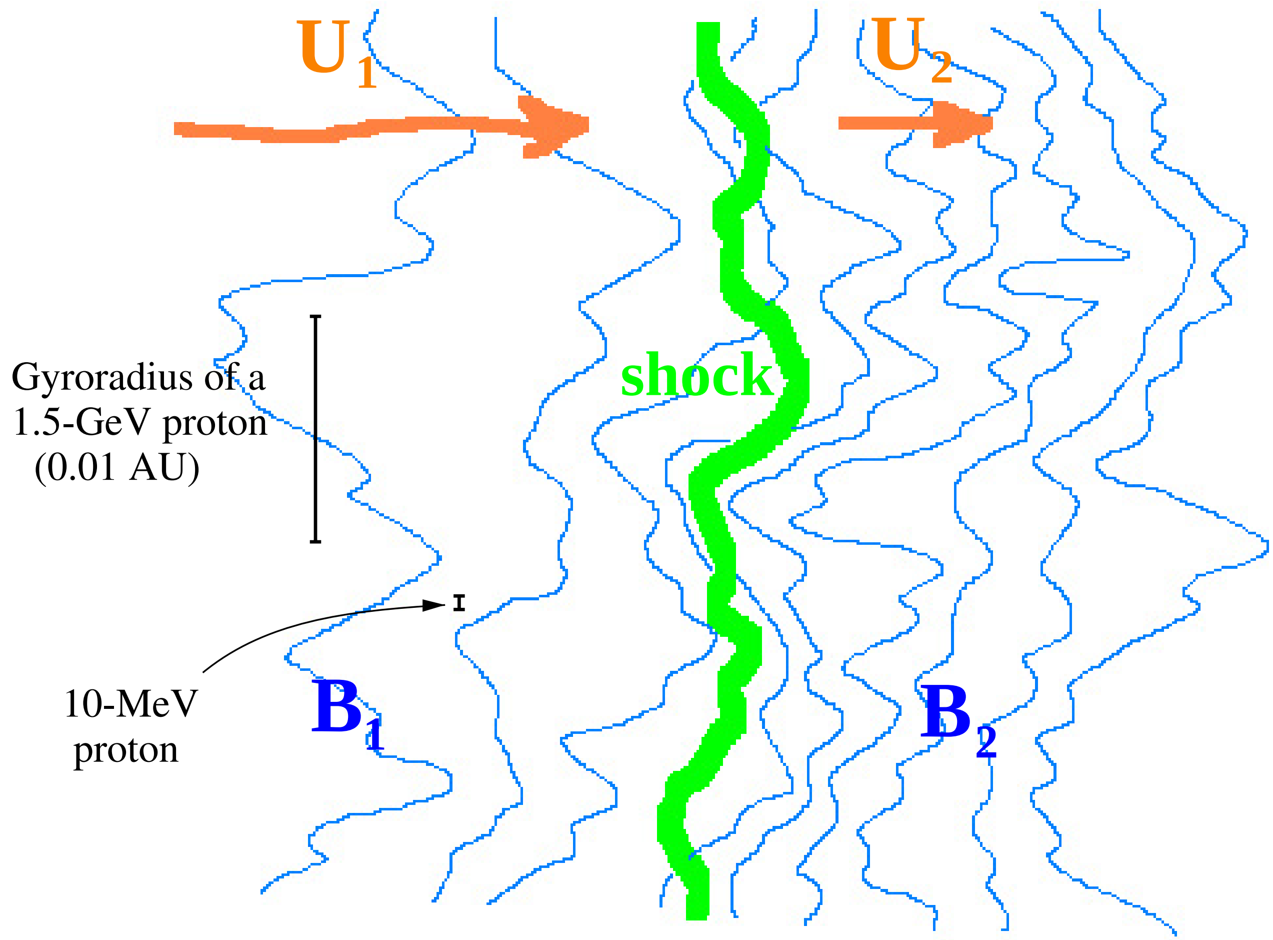
For a perpendicular shock, the injection velocity is given by

$$w_{inj} = 3U_1\left[1 + \left(\frac{\kappa_A}{\kappa_\perp}\right)^2\right]^{\frac{1}{2}}$$

$$\approx 3U_1$$

$\Rightarrow$ The SAME as for a parallel shock.

The Physics of self-excited waves is also affected by large-scale fluctuations – the time scale for wave growth and upstream scale length depend on the local geometry.



We wish to study particle acceleration and transport near a shock without invoking diffusive transport

In order to do this, we need to *synthesize* the turbulent fields.

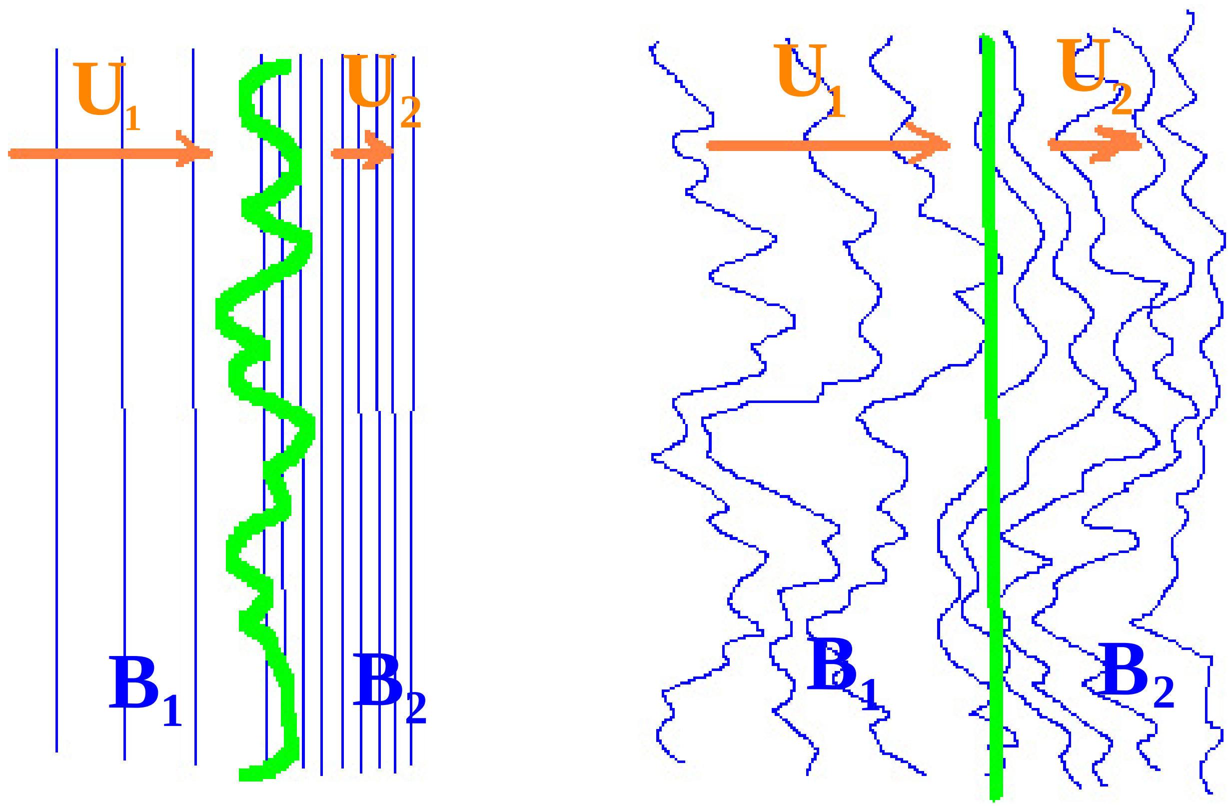
<u>There are two obvious ways to proceed:</u>

1. Turbulent ("rippled") shock + magnetic field

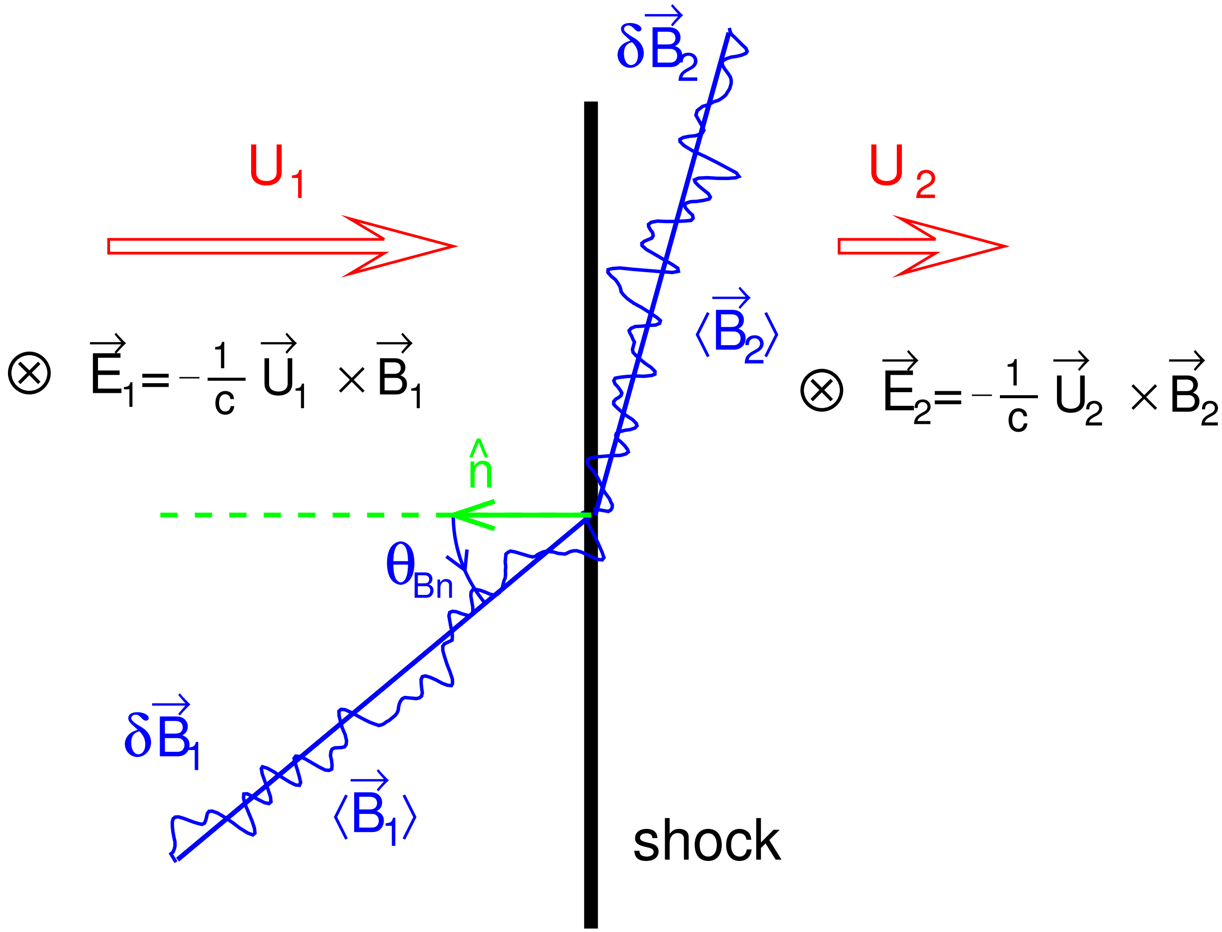
   turns out to be difficult

2. Planar (or spherical) shock + turbulent magnetic field

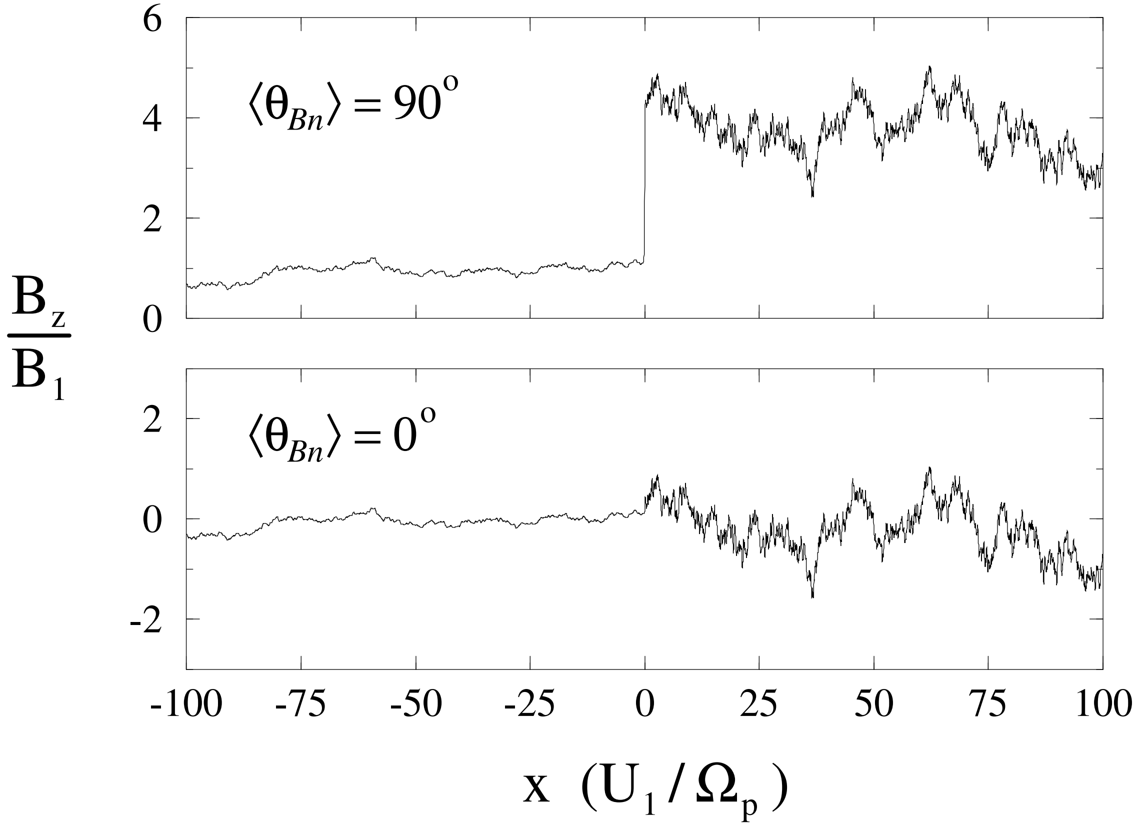
Modeling a shock moving through a turbulent medium



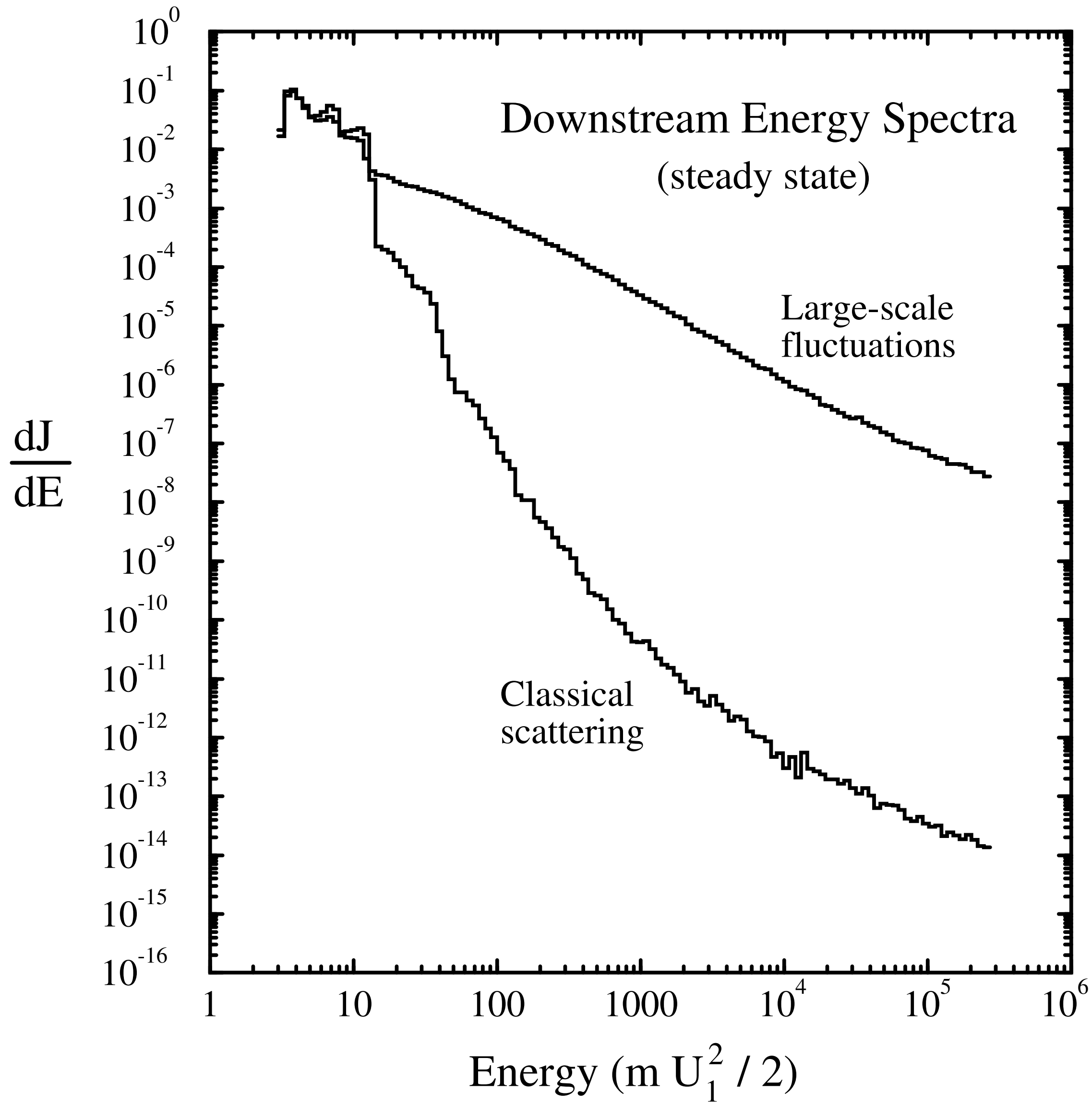
Model Geometry



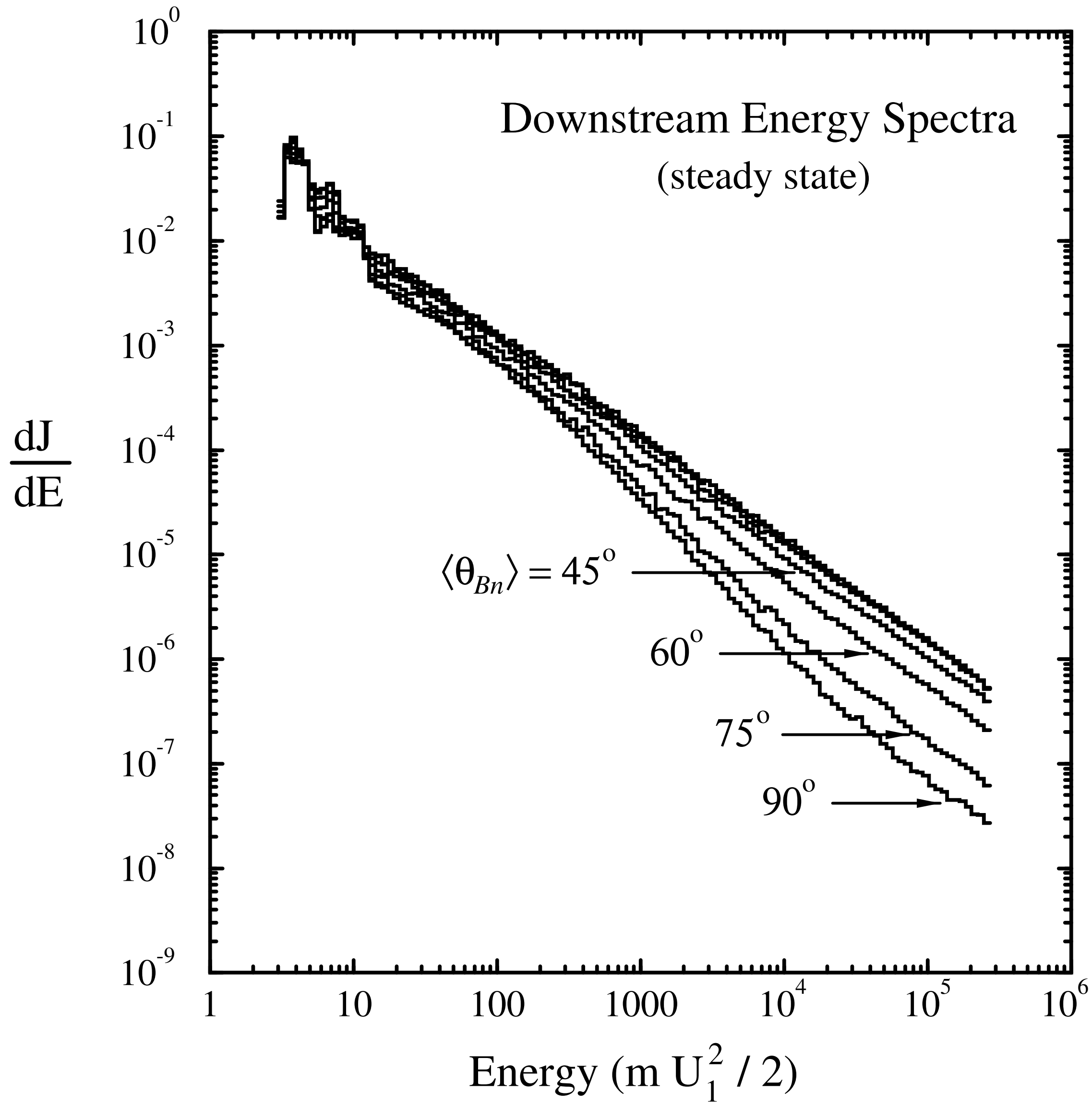
Model Fields



Model Results

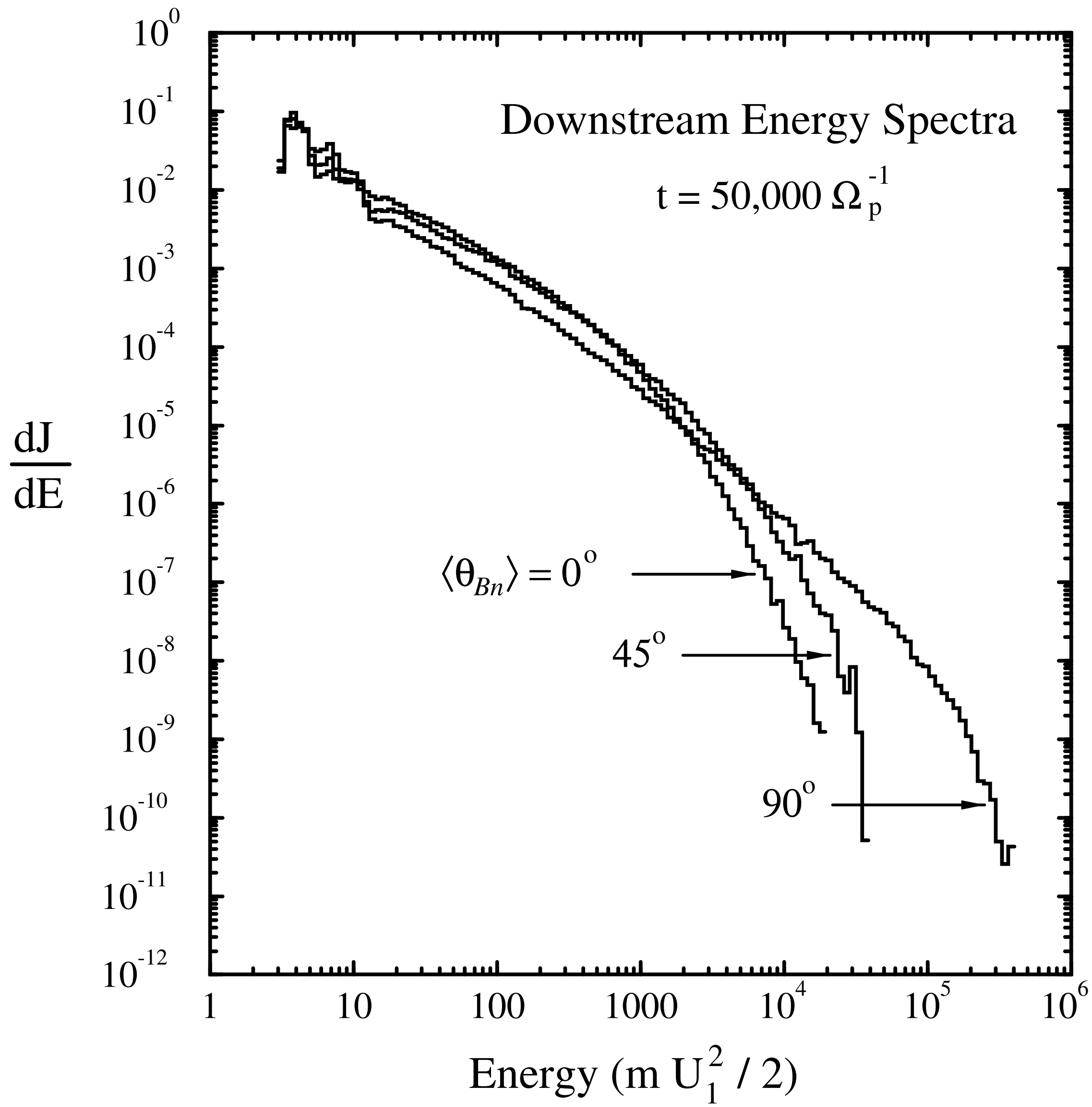


Model Results

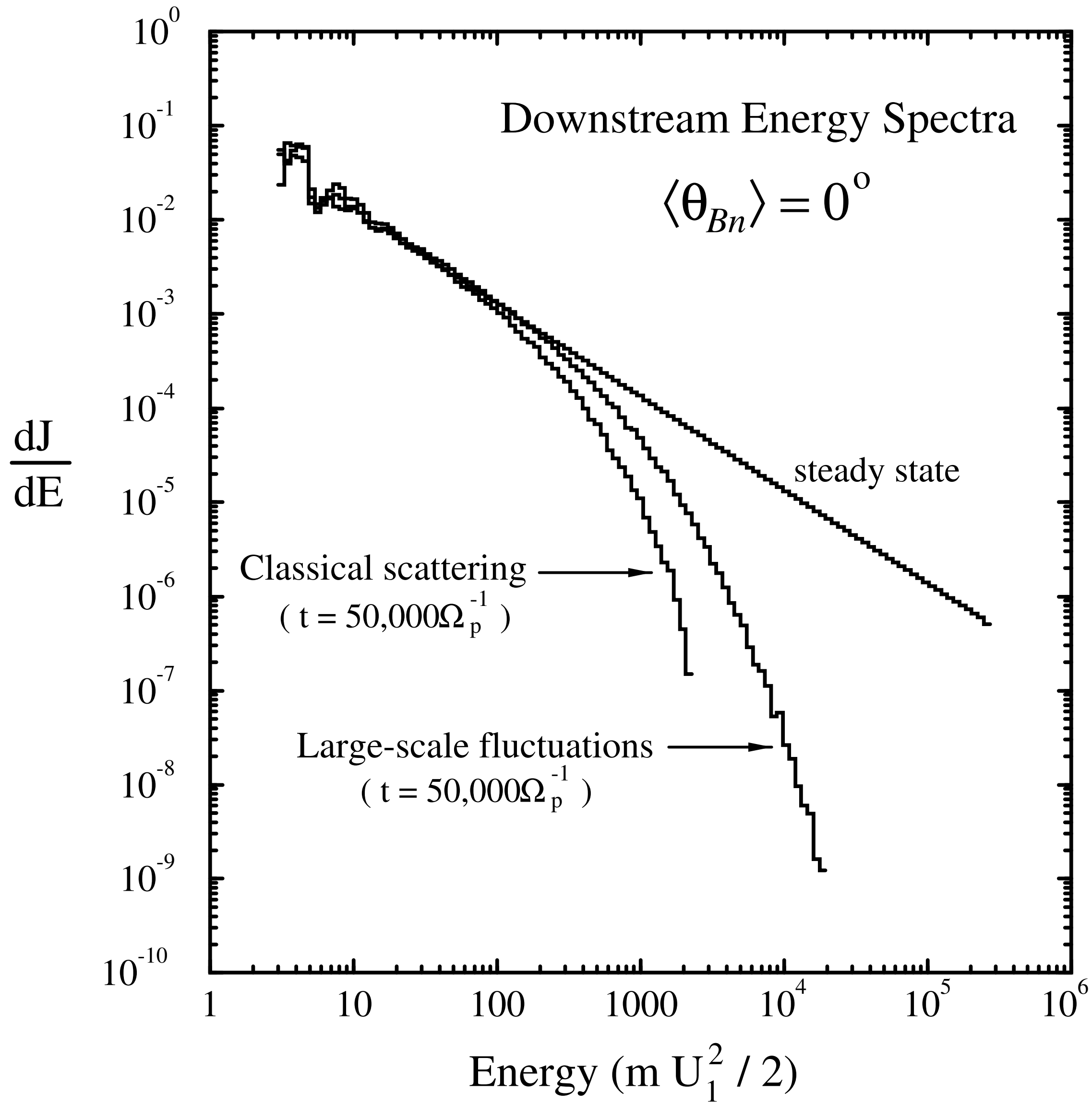


Model Results

at 10 $R_\odot$, 50,000 $\Omega_p^{-1} \approx 6$ minutes



Model Results

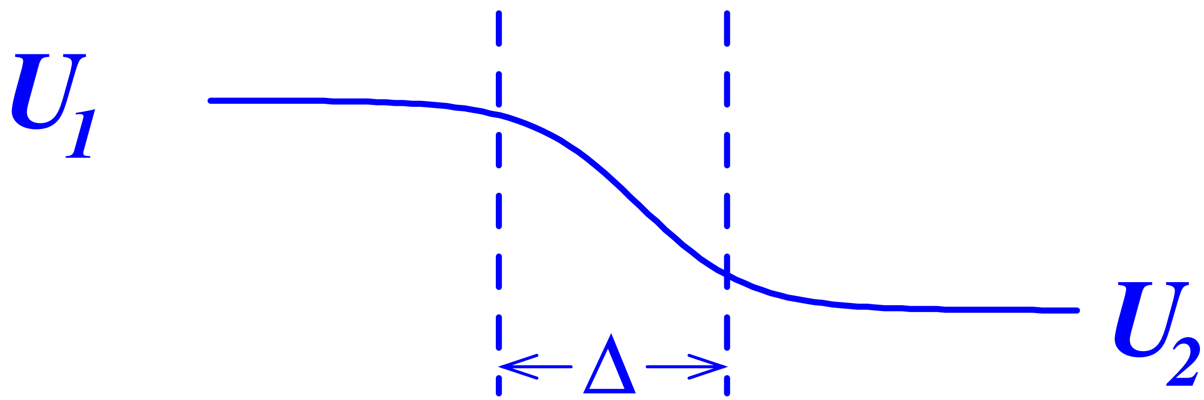


CAN SHOCK ACCELERATION THEORY EXPLAIN THOSE EVENTS IN WHICH FE/O INCREASES WITH ENERGY?

CAN SHOCK ACCELERATION THEORY EXPLAIN THOSE EVENTS IN WHICH FE/O INCREASES WITH ENERGY?

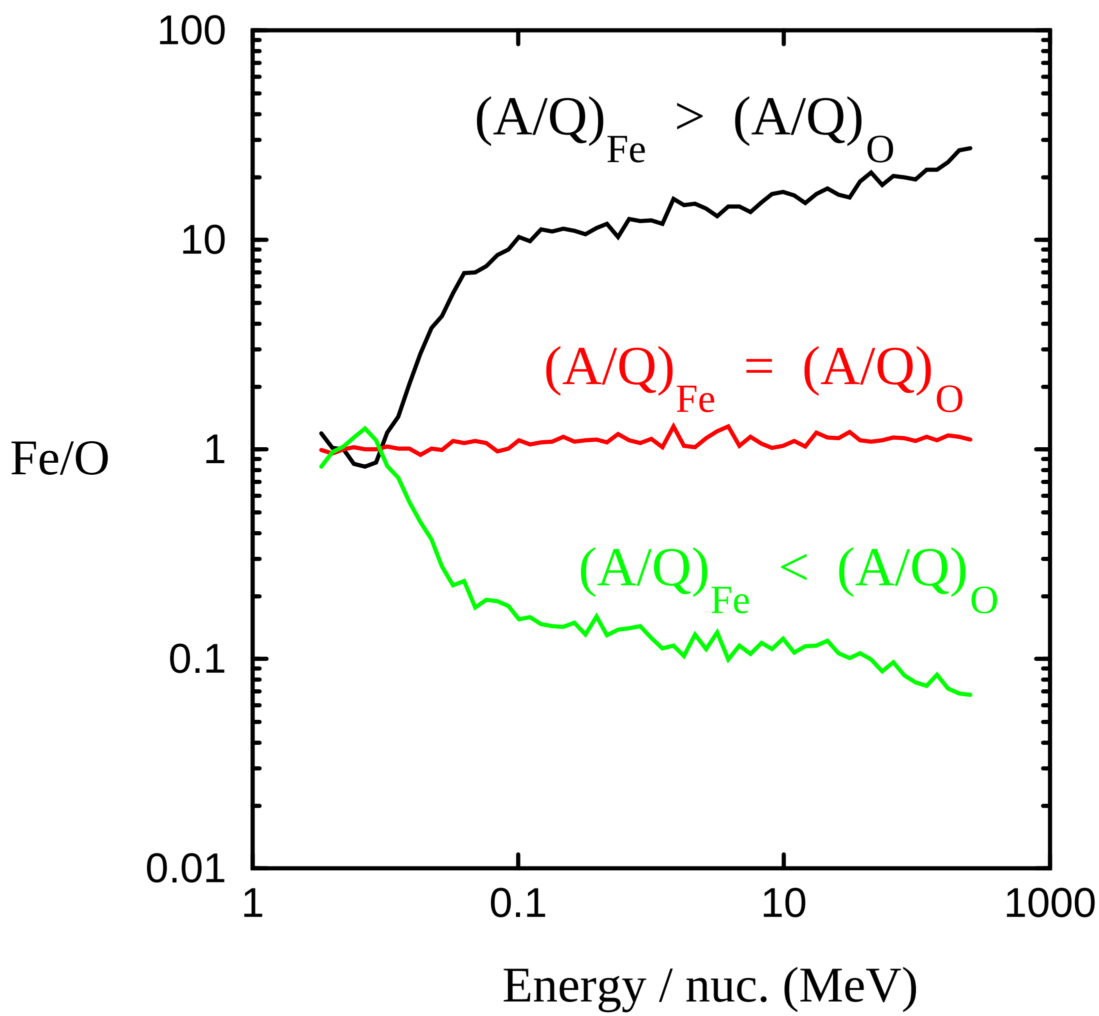
POSSIBLY YES – USING COMPRESSION ACCELERATION

Consider a gradual plasma compression – NOT A SHOCK (e.g. CIRs at 1AU)

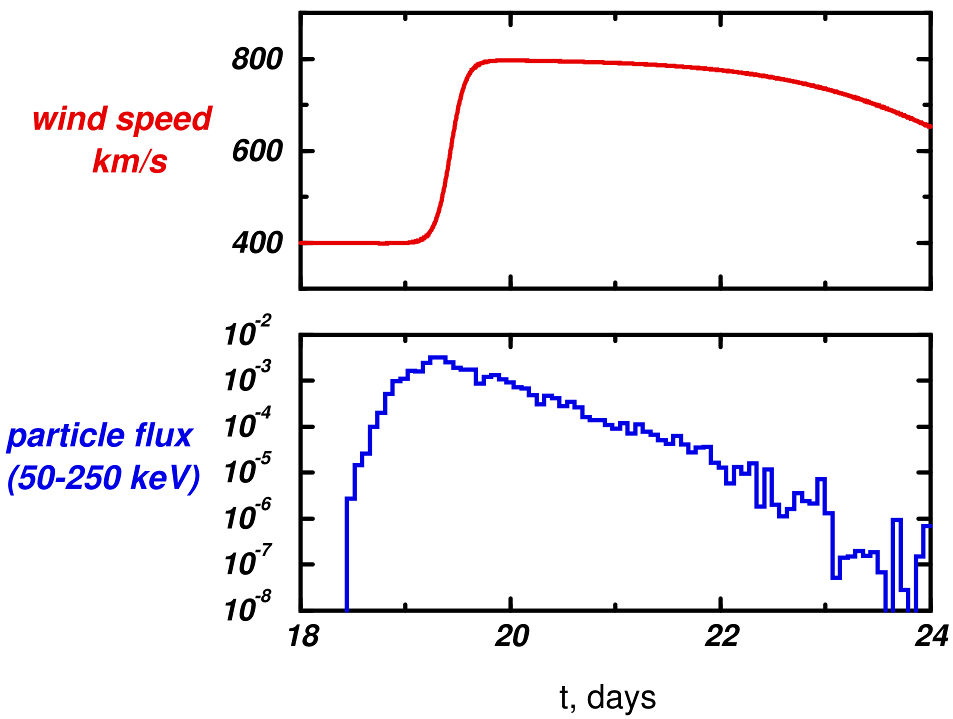


$$\Delta >> c/\omega_i$$

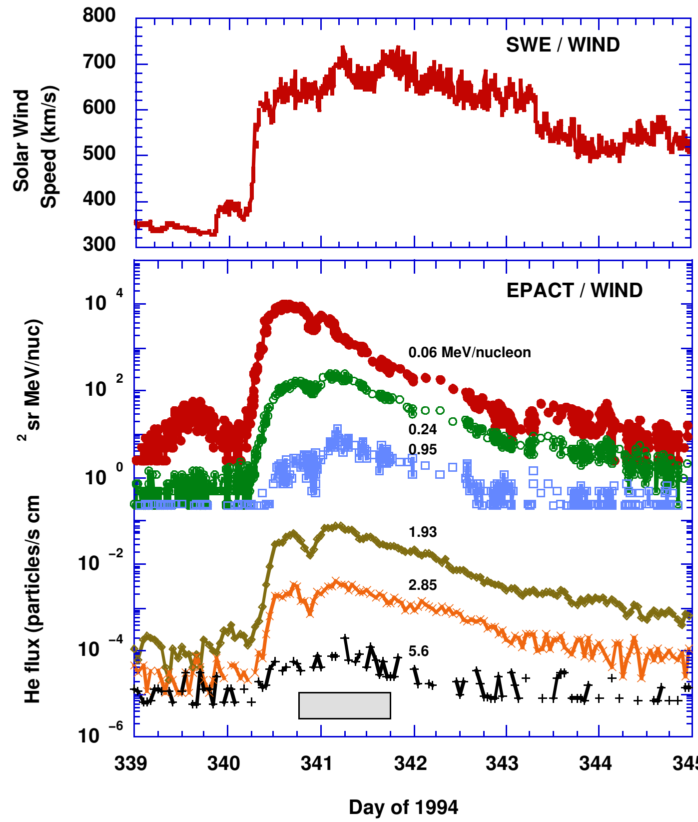
Acceleration of Fe and O at a gradual compression (three different charge states are considered)



Simulations
(Giacalone et al., 2002)



Observations
(Mason, 2000)



Conclusions

1. For the case of strong IMF fluctuations $(\Delta B^2 \sim B)$ with a coherence scale of 0.01 AU, the injection velocity for shock acceleration is WEAKLY dependent on shock-normal angle.

2. Perpendicular shocks are more rapid accelerators of charged particles than parallel shocks – although the acceleration rate at a parallel shock is higher than expected from simple classical scattering theory.

3. Unusual enhancements of Fe/O may be due to acceleration at compression regions.