

SHINE 2004 Meeting, Big Sky, MT, June 2004

Modeling SEP Acceleration and Transport at CME driven Shocks: Toward a Realistic CME

*J Kóta, W.B. Manchester, D.L. DeZeeuw, J.R. Jokipii,
and T.I. Gombosi*

*The University of Arizona, Tucson, AZ 85721-0092
The University of Michigan, Ann Arbor, MI 48109*

kota@lpl.arizona.edu

- Outline -

- *Motivation: to model (and forecast) SEP acceleration in realistic CME models*
- *CME structure: what features are important ?*
- *Fokker-Planck Equation for SEP Acceleration & Transport*
 - *co-moving (Lagrangian) frame*
- *Numerical Illustrations*
- *Relevance to composition*
- *Summary/Conclusions*

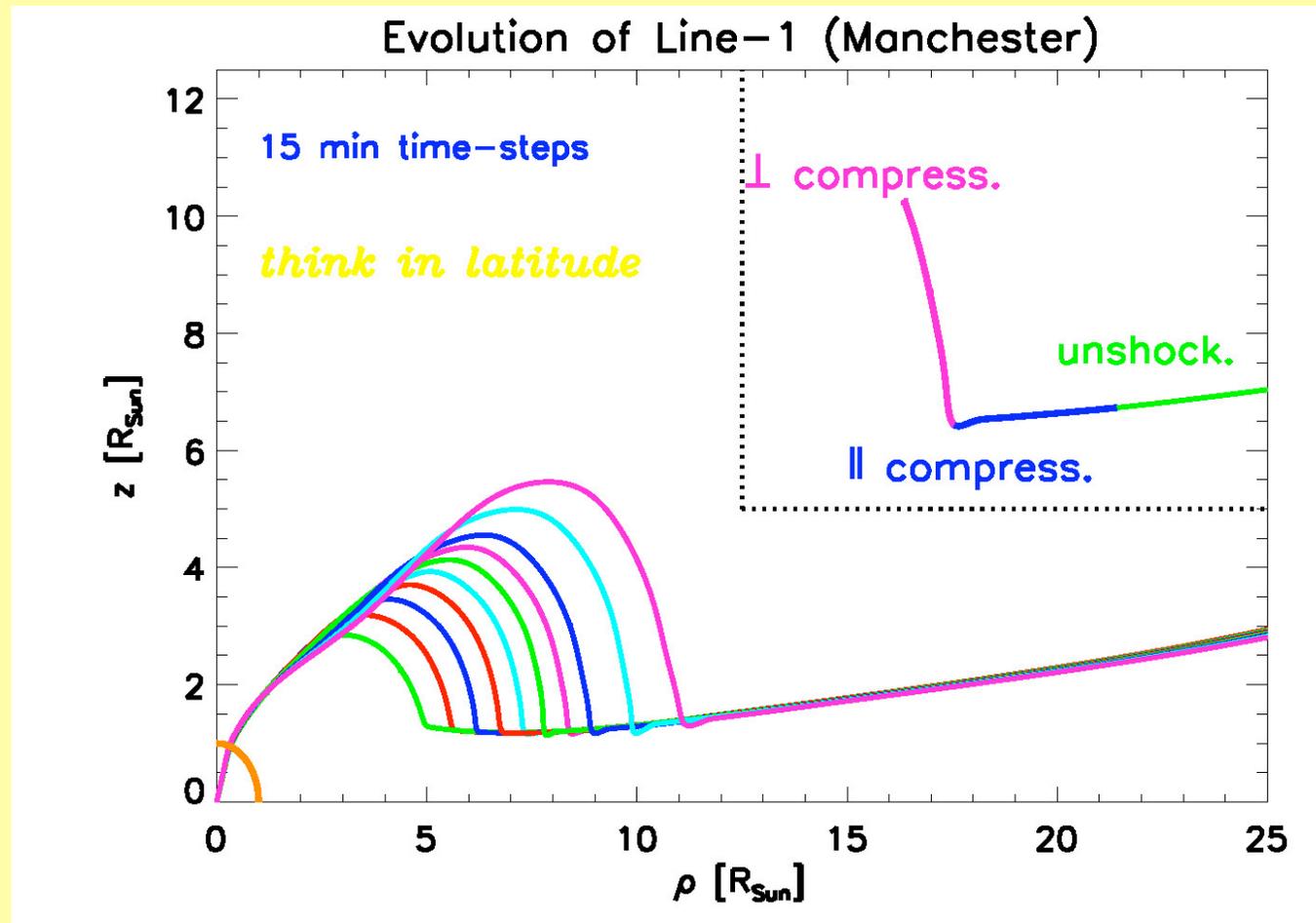
Understand – Model -Forecast

- _ Acceleration is likely to occur at shocks driven by CMEs -- mechanism is not fully understood*
- _ Theoretical challenges:
 - Shock geometry: parallel vs perpendicular*
 - Single shock or **more** ?**
- _ Try to combine **realistic CME** simulations from Michigan as input to SEP acceleration and transport model.*

Evolution of Field Line around the CME (Manchester)

Follow one field line in time (15 min Increments)

Meridional section

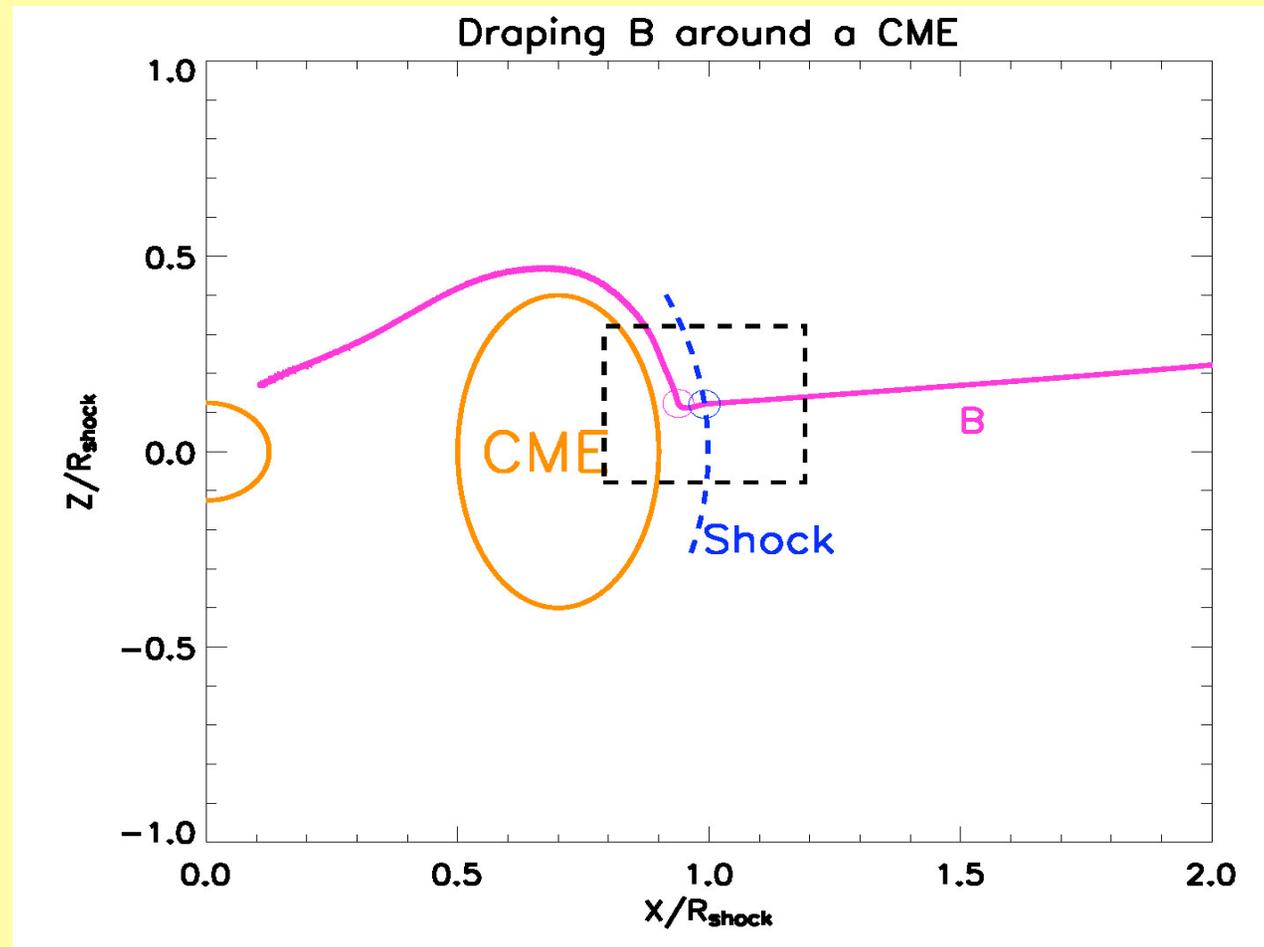


Schematic view of CME & Magnetic Field (meridional cut)

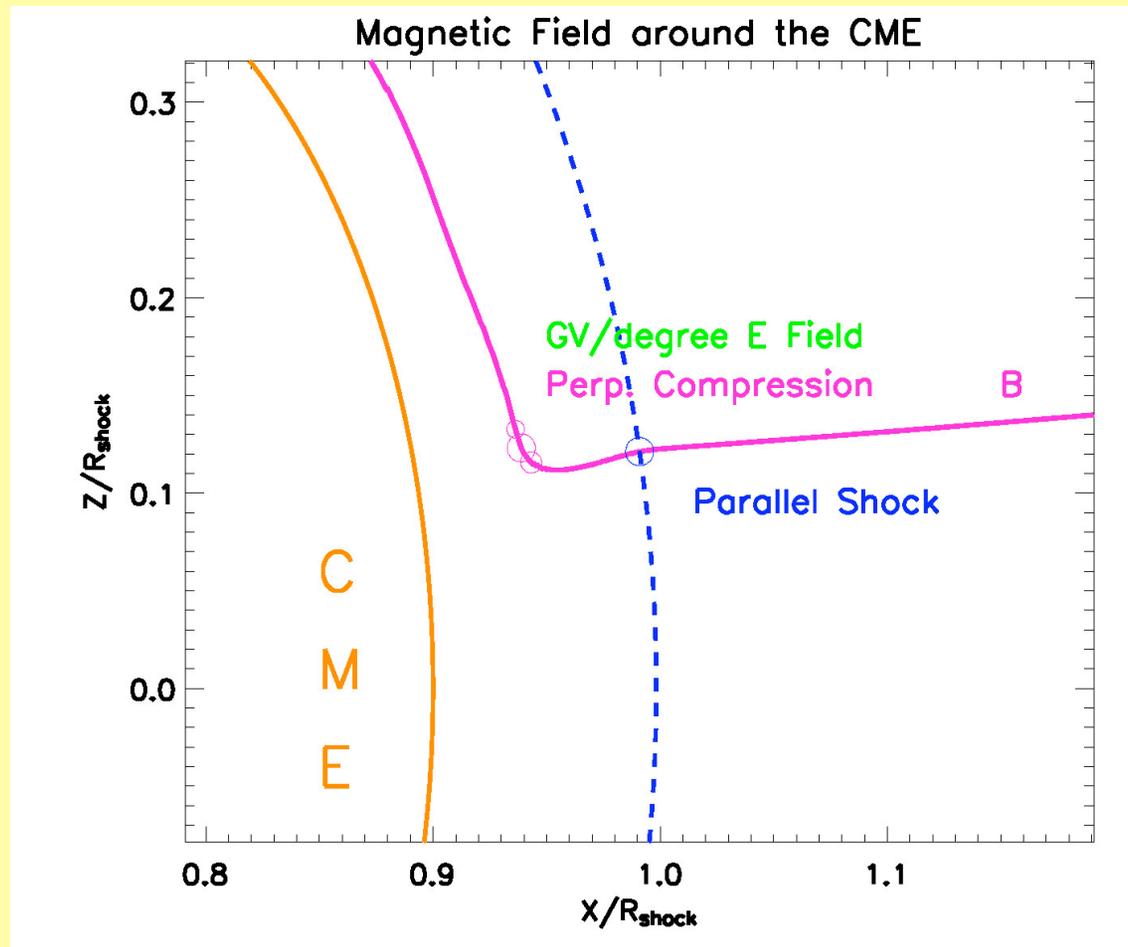
Two important sites:

Quasi-parallel Shock

Quasi *perp.* compression as field line drapes around the CME

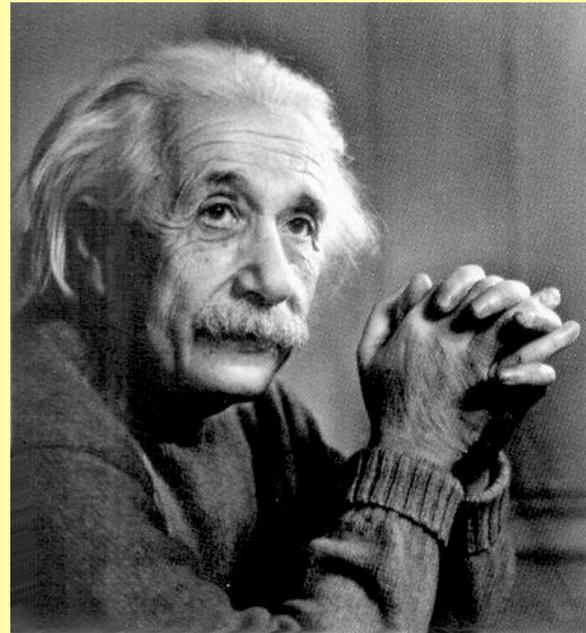


B & n around the shock



Concept:

— *“Make everything as simple as possible, but not simpler”*



Mathematics:

— Numerical solution of Fokker-Planck Equation for

$$f(r, E, _, t)$$

(position, energy, pitch-angle, time)

following one field line

- *Injection at 5-10 keV*
- *Including: acceleration, transport (convection, focusing), scattering*
- *Yields: time-profile, energy-spectrum, pitch-angle distribution, spatial dependence*

Field-aligned Transport

Skilling (1970), Ruffolo 1995), Isenberg (1997) Kóta & Jokipii (1997):

Fokker-Planck equation:

$$\frac{\partial f}{\partial t} + \left\langle \frac{\Delta x_i}{\Delta t} \right\rangle \frac{\partial f}{\partial x_i} + \left\langle \frac{\Delta \mu}{\Delta t} \right\rangle \frac{\partial f}{\partial \mu} + \left\langle \frac{\Delta w}{\Delta t} \right\rangle \frac{\partial f}{\partial w} = \frac{\partial}{\partial \mu} \left(\frac{\mathbf{D}_{\mu\mu}}{2} \frac{\partial f}{\partial \mu} \right) + q$$

Coefficients:

$$\left\langle \frac{\Delta x_i}{\Delta t} \right\rangle = V_i + w \mu b_i$$

$$\left\langle \frac{\Delta \mu}{\Delta t} \right\rangle = \frac{(1 - \mu^2)}{2} \left[\frac{w}{L} - \frac{2}{w} b_i \frac{DV_i}{Dt} + \mu(\delta_{ij} - 3b_i b_j) \frac{\partial V_i}{\partial x_j} \right]$$

$$\left\langle \frac{\Delta w}{\Delta t} \right\rangle = -\mu b_i \frac{DV_i}{Dt} + w \mu^2 b_i b_j \frac{\partial V_i}{\partial x_j} + \frac{w(1 - \mu^2)}{2} (\delta_{ij} - b_i b_j) \frac{\partial V_i}{\partial x_j}$$

Net compression
divided into parallel
and perpendicular
components

inertial

parallel

perpendicular

d/dt (ln n/B)

d/dt(ln B)

Co-moving with Solar Wind

Derivatives expressed with quantities on one field line
(Lagrangian):

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + V_j \frac{\partial}{\partial x_j}$$

$$\delta_{ij} \frac{\partial V_i}{\partial x_j} = -\frac{\partial \ln n}{\partial t}$$

compression

Frozen in B !!!

$$(\delta_{ij} - b_i b_j) \frac{\partial V_i}{\partial x_j} = -\frac{\partial \ln B}{\partial t}$$

**Perpendicular
compression**

$$b_i b_j \frac{\partial V_i}{\partial x_j} = \frac{\partial \ln \Delta s}{\partial t} = \frac{\partial \ln(B/n)}{\partial t}$$

**Parallel
compression**

Field-aligned Equation in Co-moving Frame

Equation in co-moving (Lagrangian) frame:

no convection term

$$\frac{Df}{Dt} + w\mu \frac{\partial f}{\partial s} + \left\langle \frac{\Delta\mu}{\Delta t} \right\rangle \frac{\partial f}{\partial \mu} + \left\langle \frac{\Delta w}{\Delta t} \right\rangle \frac{\partial f}{\partial w} = \frac{\partial}{\partial \mu} \left(\frac{\mathbf{D}_{\mu\mu}}{2} \frac{\partial f}{\partial \mu} \right) + q$$

focusing

$$\left\langle \frac{\Delta\mu}{\Delta t} \right\rangle = \frac{(1 - \mu^2)}{2} \left[\frac{w}{L} - \frac{2}{w} b_i \frac{DV_i}{Dt} + \mu \frac{D \ln(n^2/B^3)}{Dt} \right]$$

*Acceleration
cooling*

$$\left\langle \frac{\Delta w}{\Delta t} \right\rangle = -\mu b_i \frac{DV_i}{Dt} + w\mu^2 \frac{D \ln(n/B)}{Dt} + \frac{w(1 - \mu^2)}{2} \frac{D \ln B}{Dt}$$

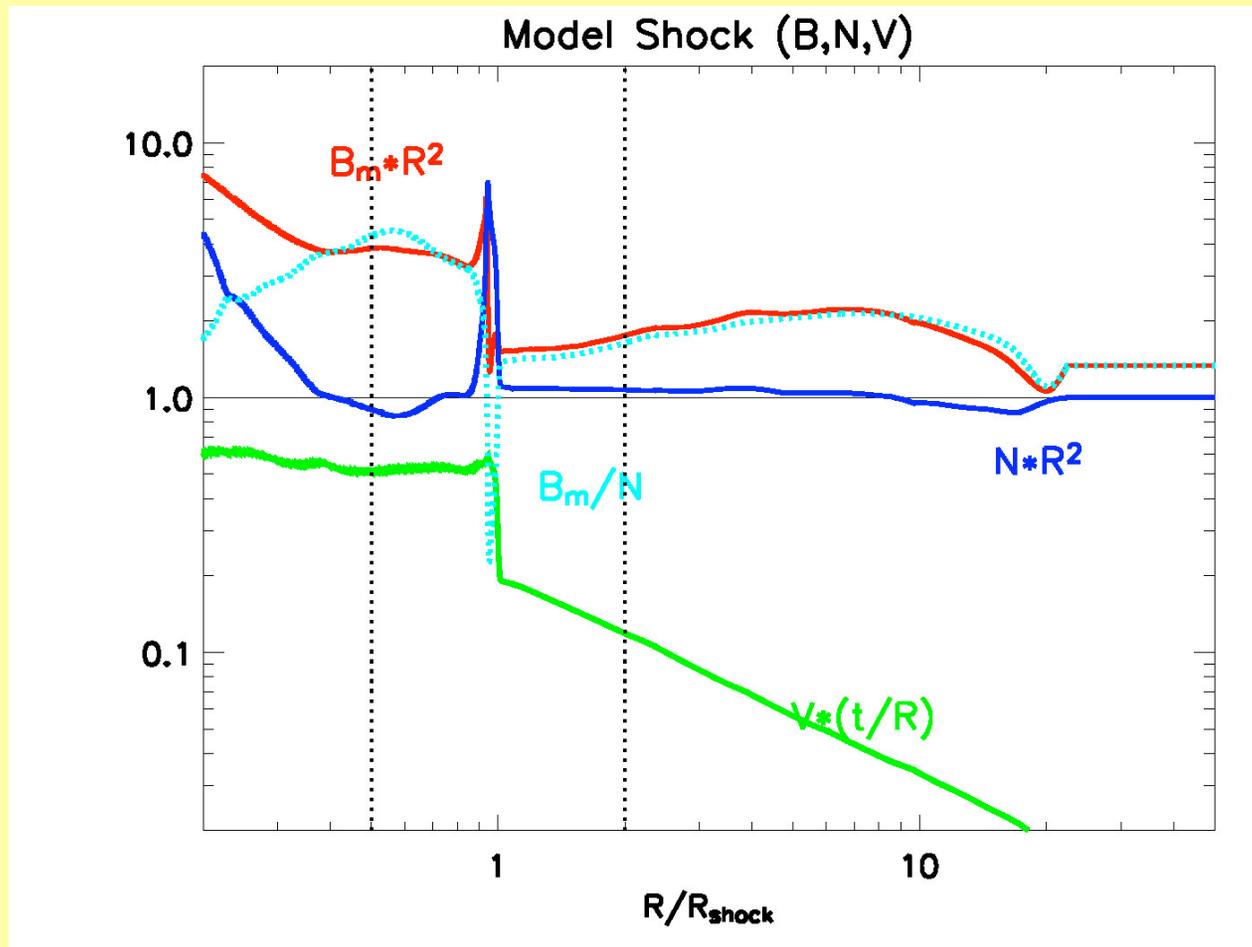
inertial

parallel

perpendicular

Acceleration w/o $\text{div}V < 0$

B, N, & V along one Field Line CME simulation (Manchester)

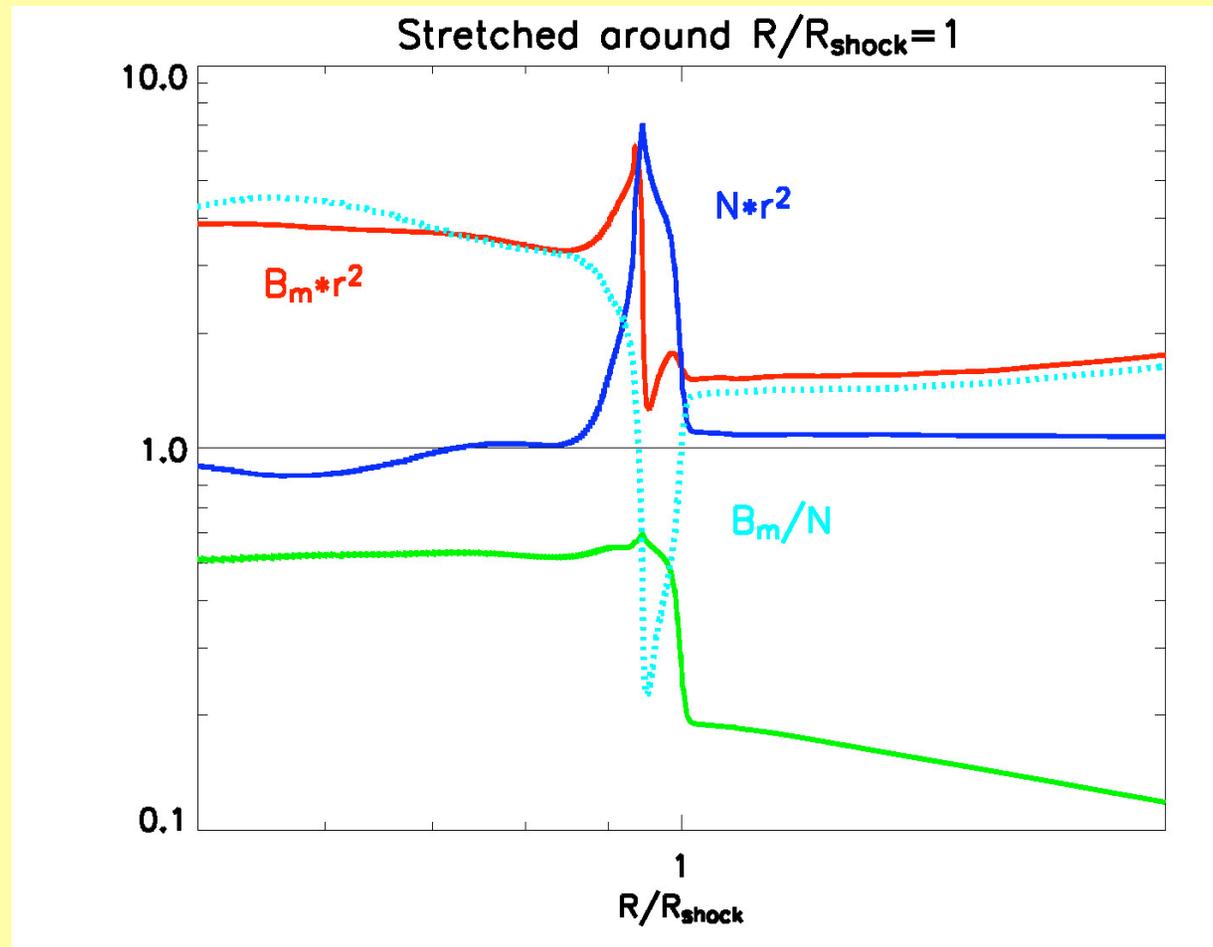


Note: N and B jump at different places

B, N, & V around the Shock(s)

Parallel Shock:
- jump in N
- no jump in B

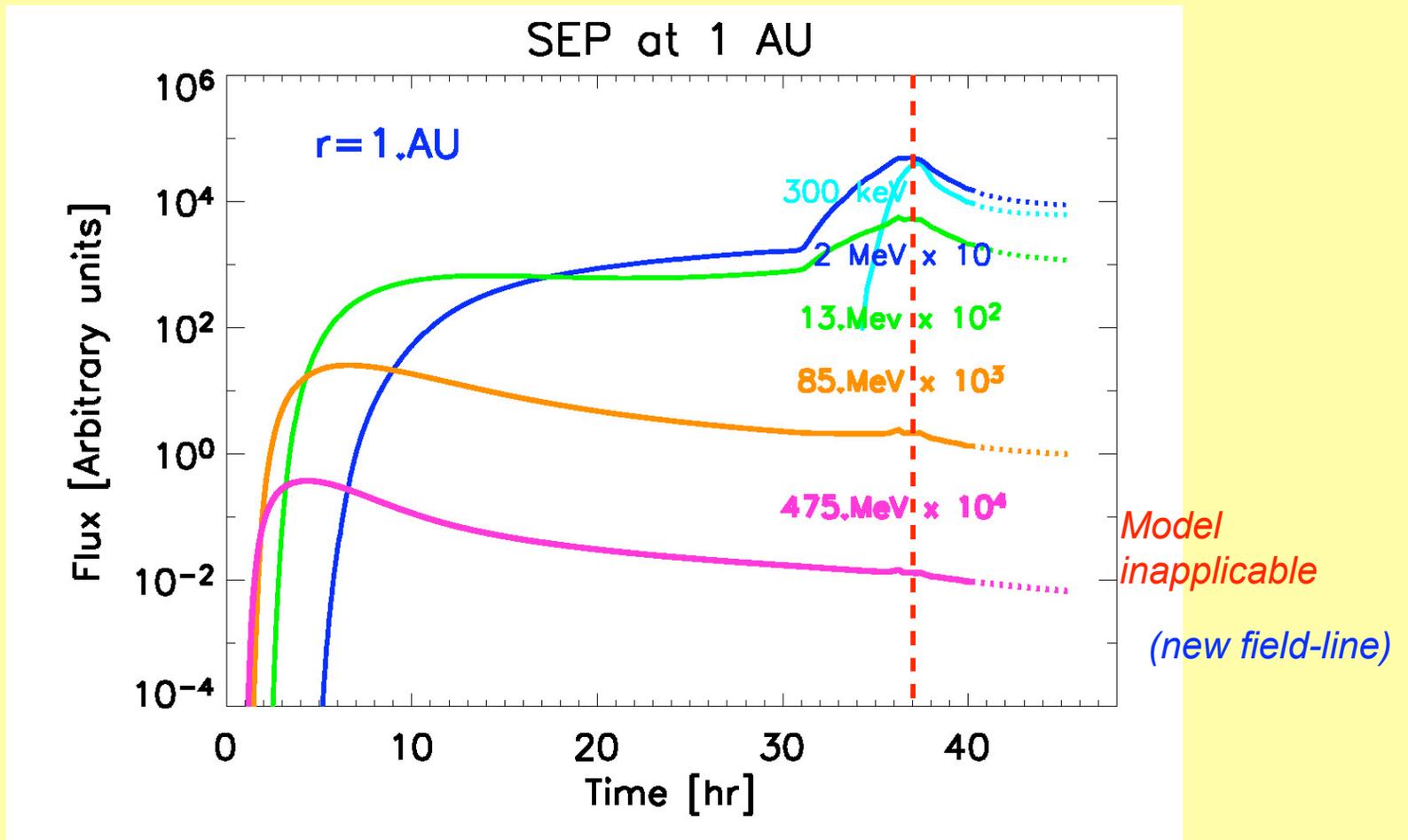
Perpendicular Shock:
- no jump in N/B
- jump in B



Numerical Illustrations

- *We use CME-simulations as input to our SEP acceleration/transport model*
- *Fokker-Planck equation cast in co-moving Lagrangian frame*
- *Present work: takes one snapshot of CME simulation and continues as a similarity solution*
 - *full coupling later (see Ilia Roussev talk)*

Time-variation of SEP fluxes

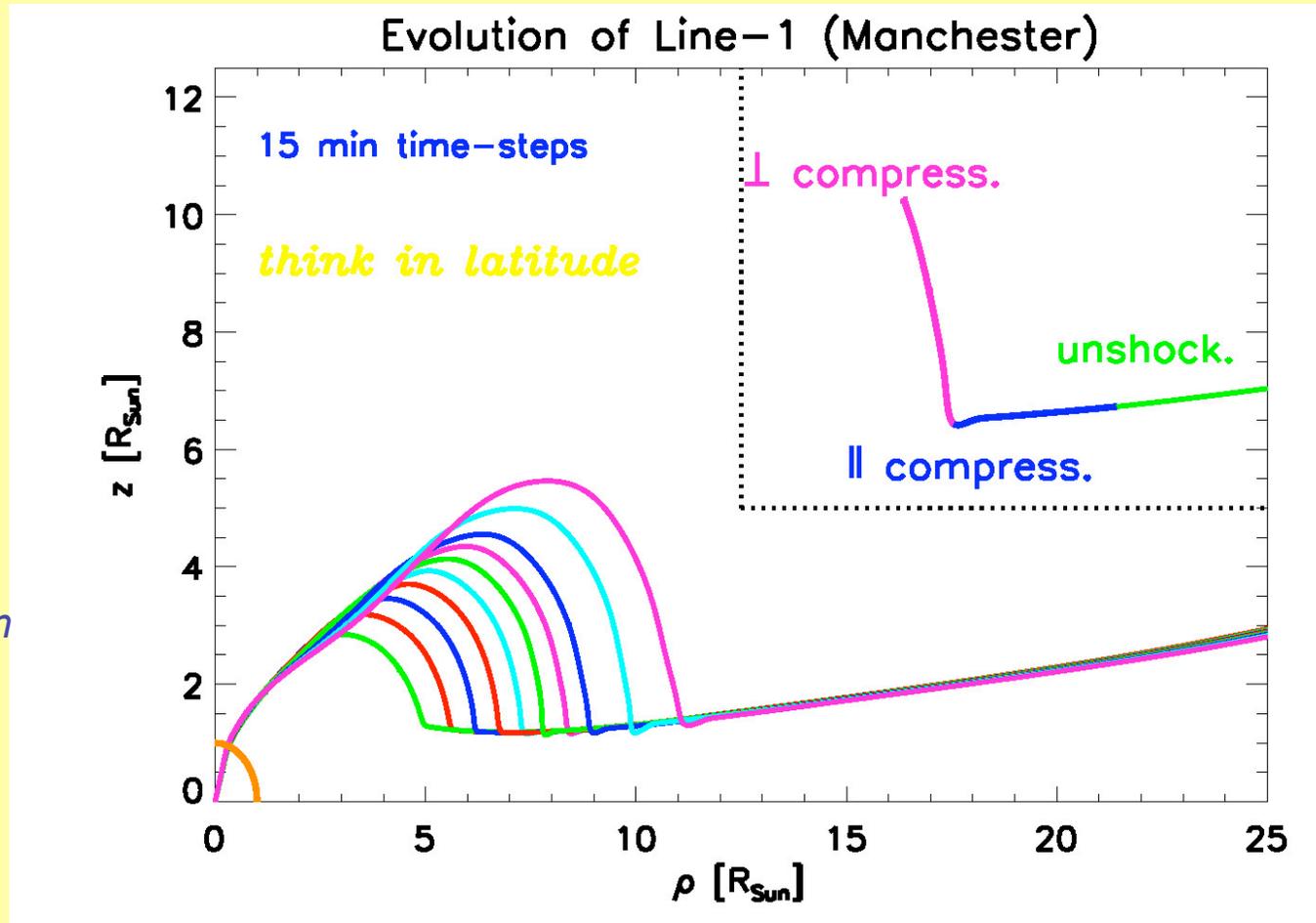


Evolution of Field Line around the CME

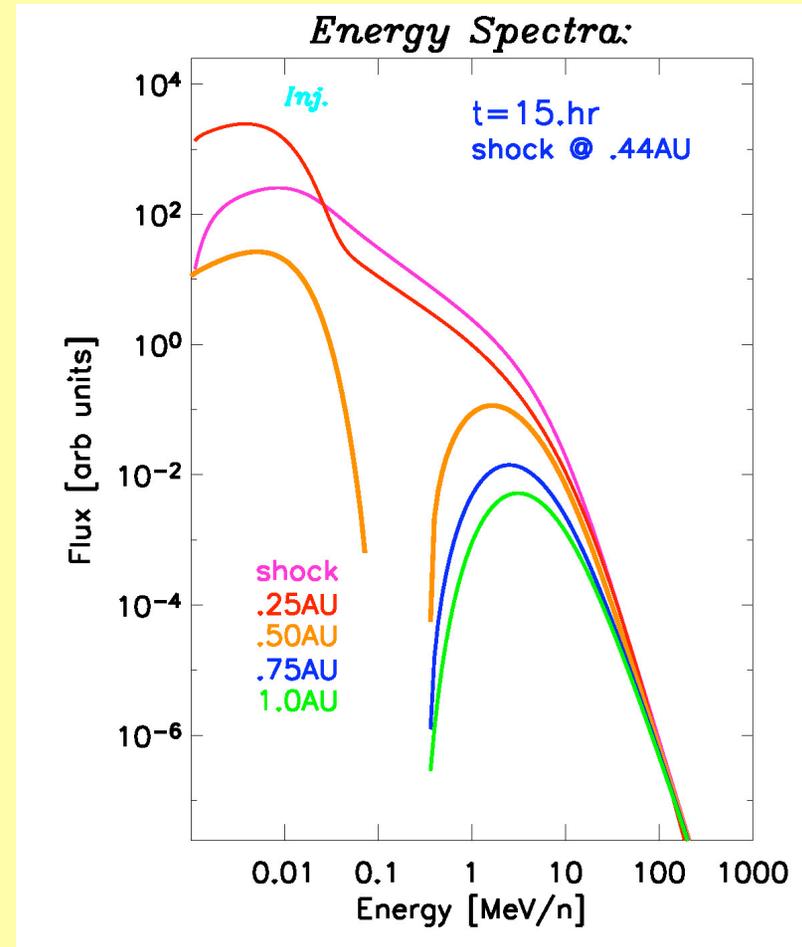
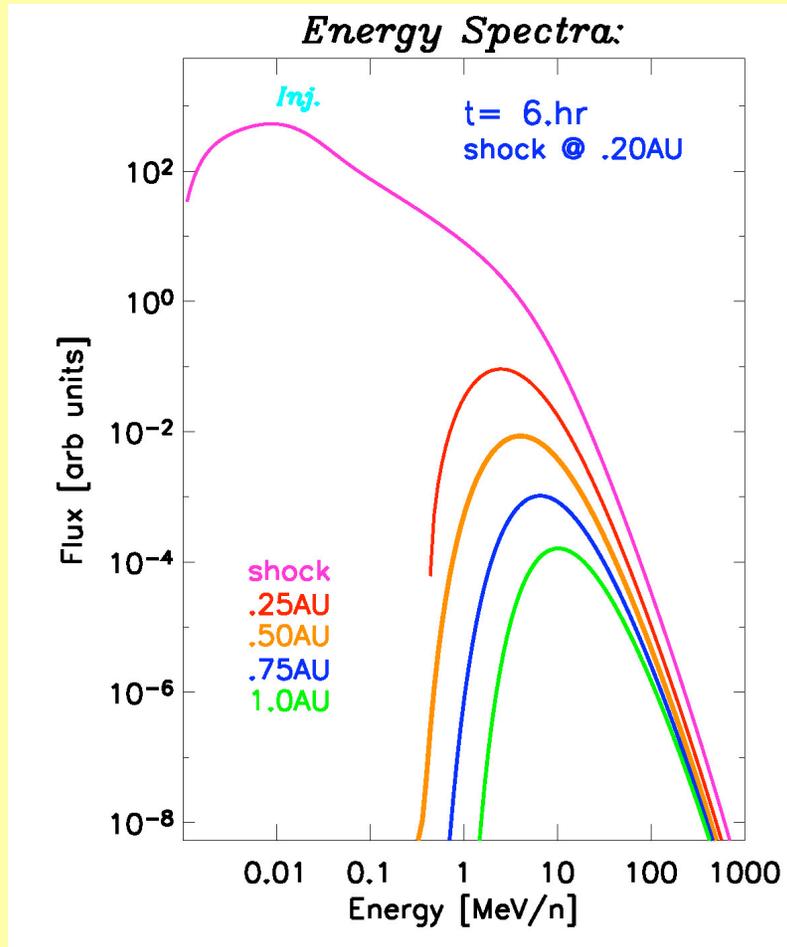
Follow **one field line** in time (15 min Increments)

Meridional section

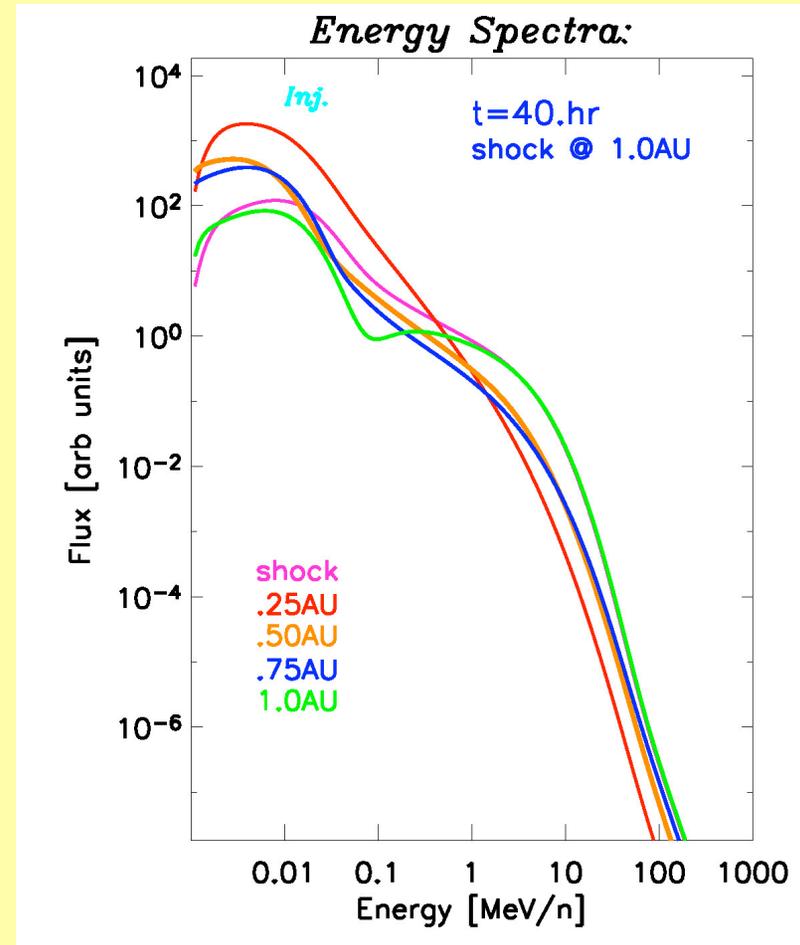
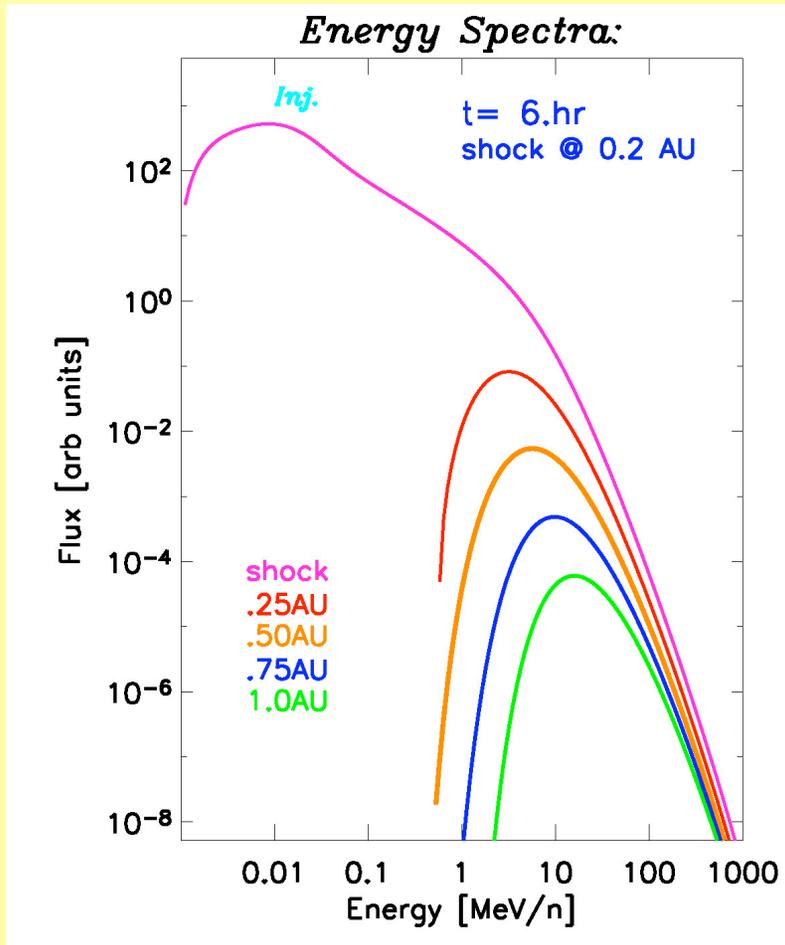
Earth will be on **another field line** after the shock arrival



Energy spectra at early & later phase

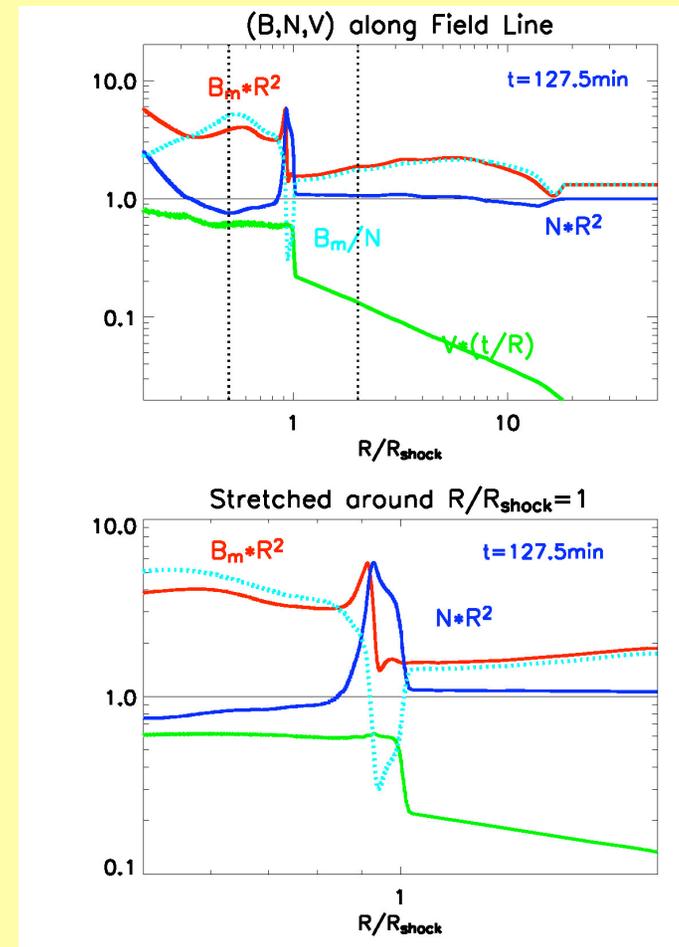
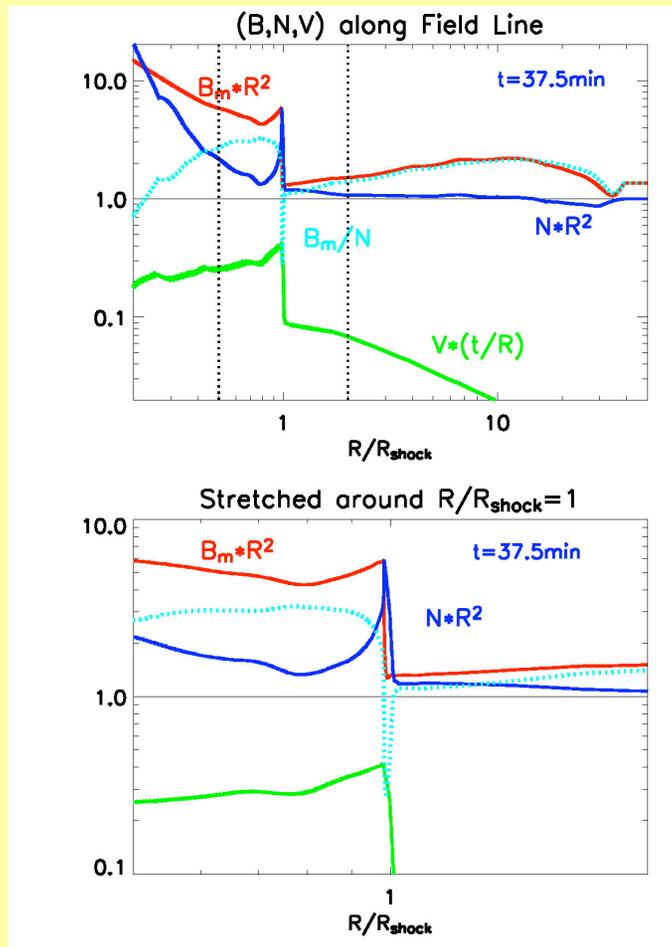


Spectra with smaller diffusion



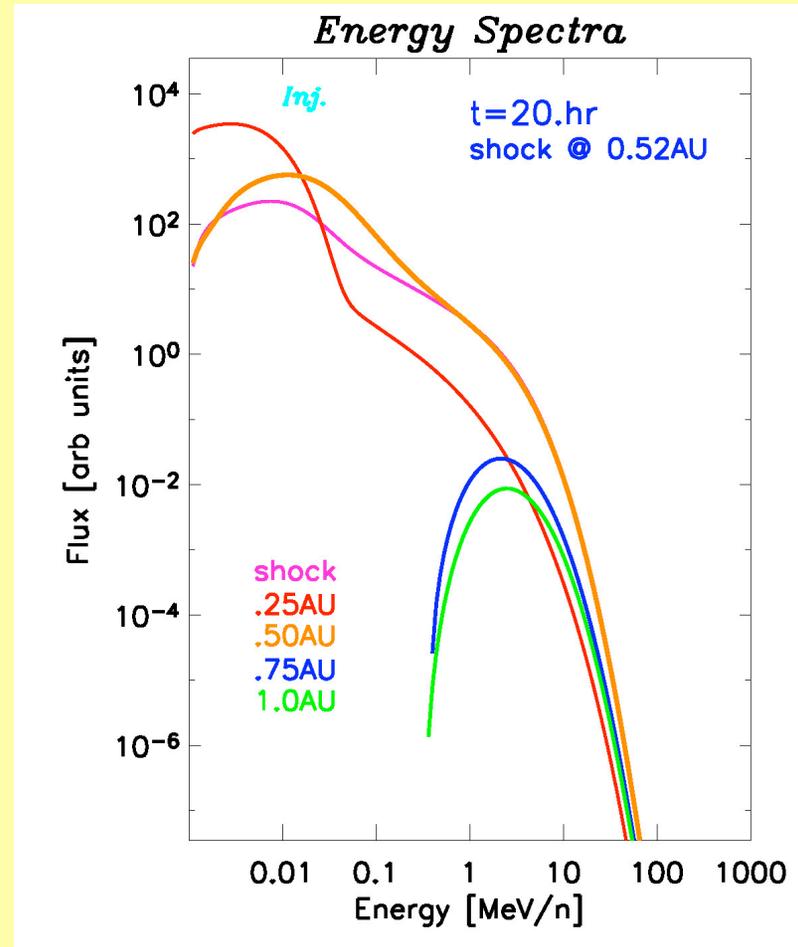
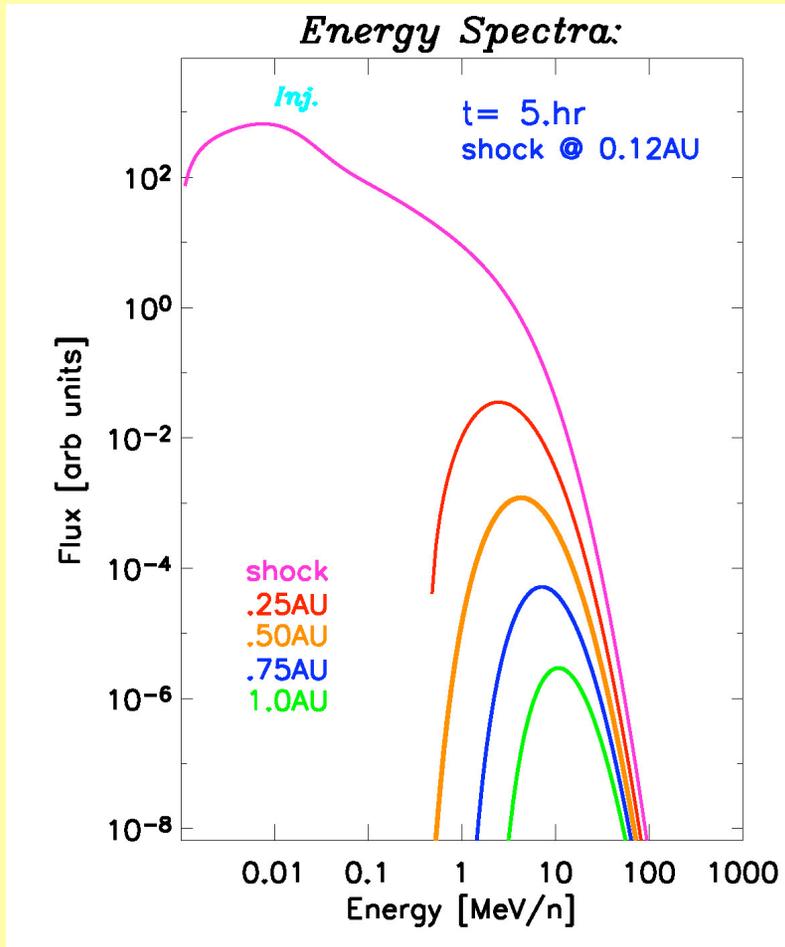
Note: twofold change in D_{\perp} has quite small effect

Evolution of parallel & perpendicular shock structure



Separation (relative) is *smaller earlier* and increases as CME evolves

Same with more separation between parallel & perpendicular shocks



Note much *less efficient* acceleration to high energies

Relevance to Composition

- *Acceleration to high energies is sensitive to the shock-structure. Larger separation between the parallel and perpendicular shocks/compressions is less effective.*
- *The relative separation is smaller at early phase. A small difference in the injection may lead to large differences in the composition at high energies*
- *At present this is a guess only. Need simulations with full coupling between CME and SEP codes.*

Summary / Conclusions :

- *Our model including both parallel and perpendicular compressions is capable to accelerate SEP from 5 keV to hundreds of MeV*
- *We find that perpendicular shocks can accelerate faster and more effectively*
- *Acceleration efficiency seems to depend on the distance between the parallel and perpendicular compressions, which increases as the CME evolves – this may be relevant for composition.*
- *There are still outstanding theoretical and technical/numerical questions.*
- *Next step: full coupling between CME and SEP codes*

Where do we stand now ?

- *Understanding?*
- *Modeling?*
- *Forecasting?*

Trying to put all pieces in place

