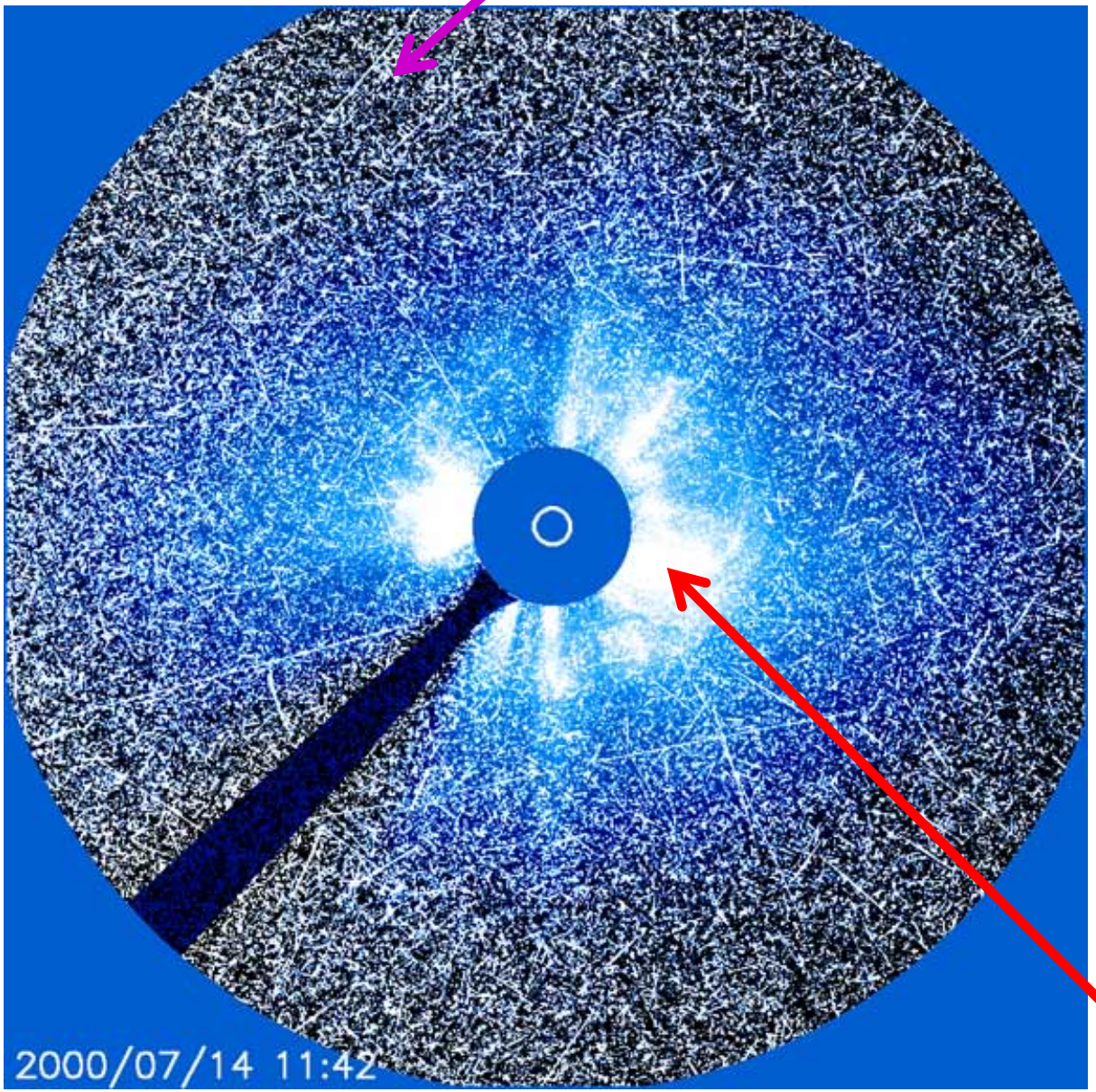
Solar Energetic Particles:
Theory, observations, and coupling SEP transport to MHD/CME models

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LWS Heliophysics Science Technical Interchange Meeting:
NASA/Ames 5/21/14

Solar-energetic particles, or SEPs (the “snow”)



CME

What are the physical processes involved in accelerating and transporting SEPs throughout the inner heliophere?

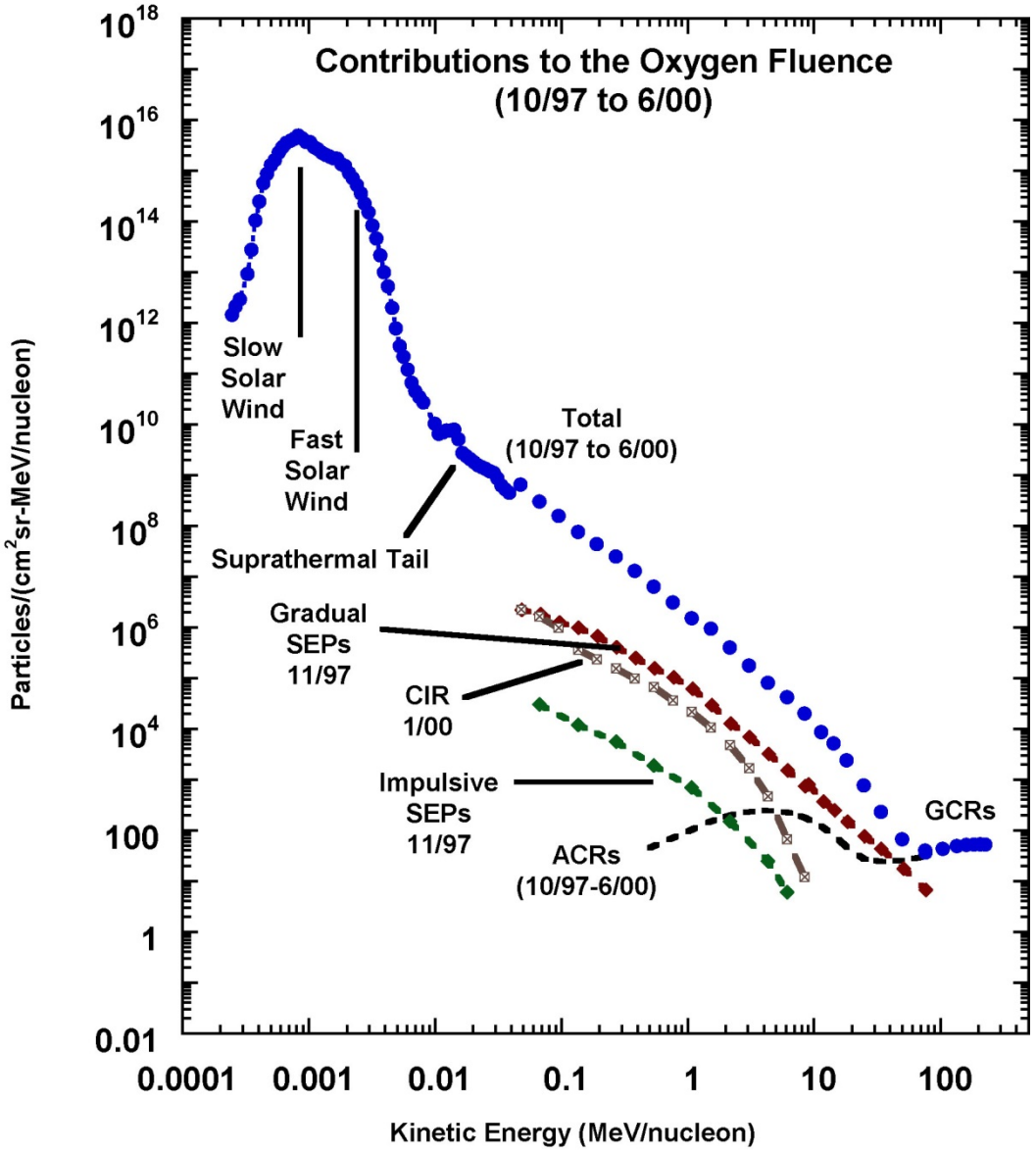
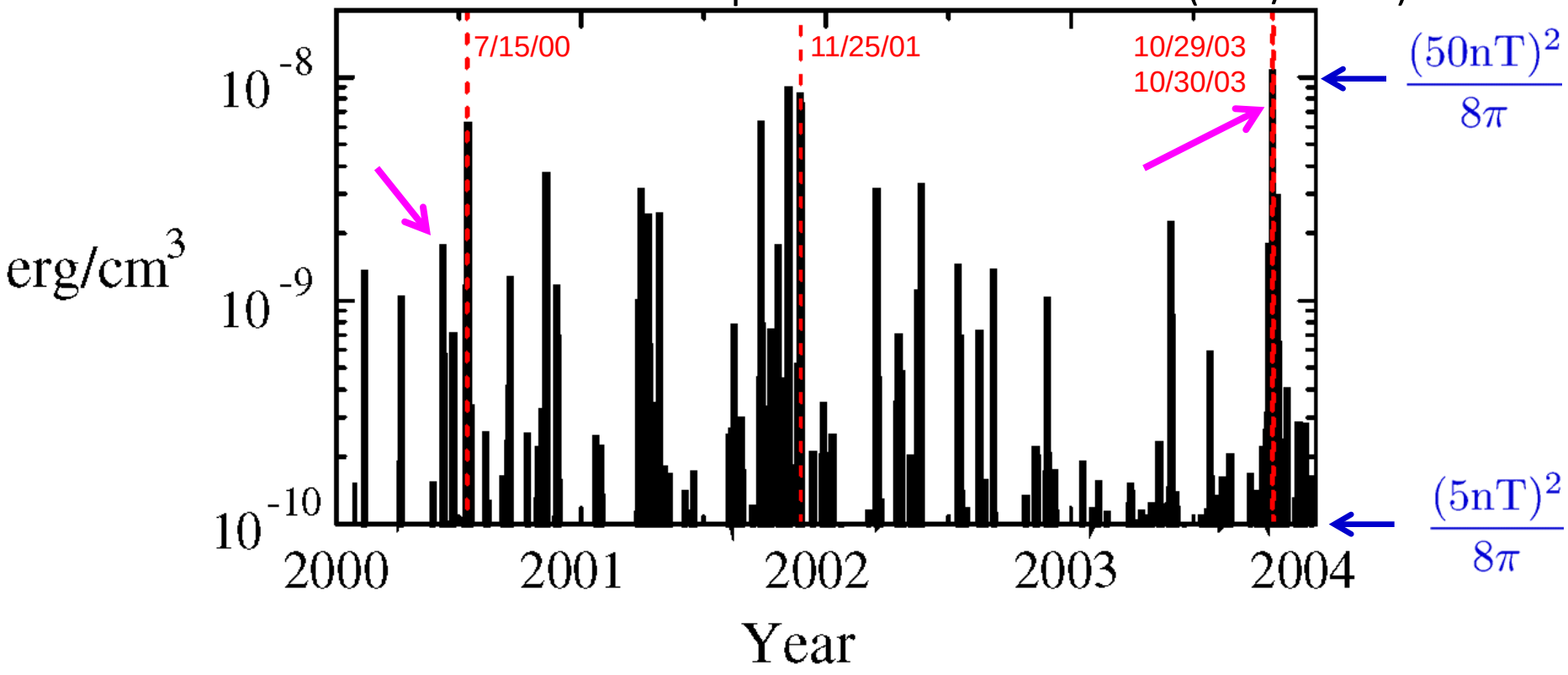


Figure from Caltech's ACE web page

- Large energy range of SEPs implies a large range in spatial and temporal scales involved.
  - The smallest scales are associated with thermal-ion gyroradii (100m for a 1000km/s proton moving in a 1G magnetic field)
  - The largest scales are those associated with the mean-free path of high-energy SEPs (0.1-1 AU or more).
  - Time scales vary from 10^{-4} seconds to days.
- **This huge dynamic range represents a significant modeling challenge**

There is a significant amount of energy density in large SEP events, and there is considerable variability between them.

Partial Pressure of 47 keV -4.75 MeV protons from 2000-2004 (ACE/EPAM).



Red dashed lines are the times of the 4 fastest solar wind speeds measured during this period (all over 1000 km/s). Note that 2 of them occurred during the Oct. 2003 period (there are 2 lines close together).

The energy content in SEP events is often dominated by the intensity at high energies

- The pressure tensor for particles with a distribution *f* is given by:

$$P_{i,j} = \int d^3\mathbf{p}\ w_i\ p_j\ f(\mathbf{p})$$

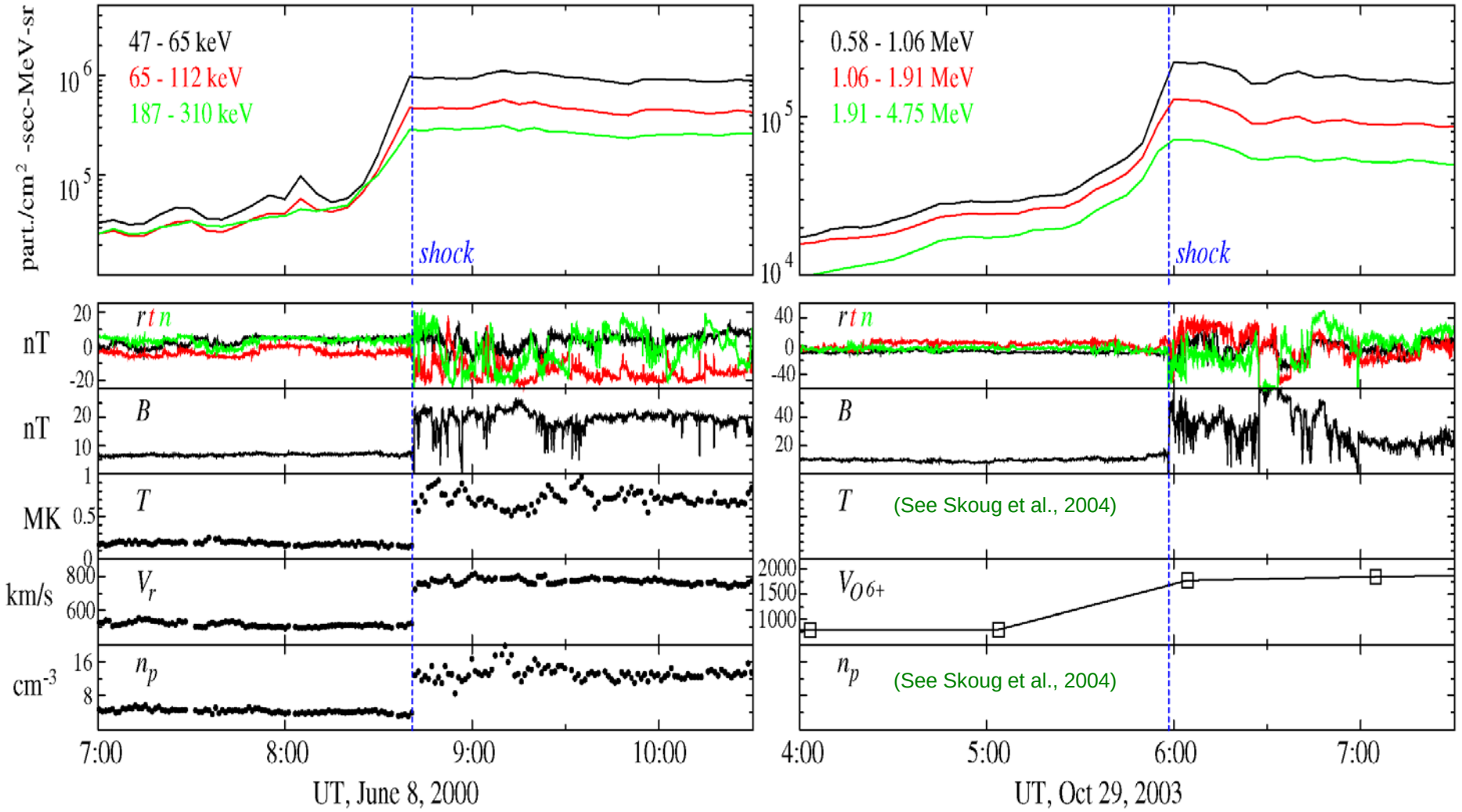
- Thus, the scalar pressure of an isotropic, power-law distribution of non-relativistic energetic particles, with spectral index γ, (i.e. $f = Ap^{-\gamma}$) reduces to

$$P_{e.p.}(p_1, p_2) = \frac{4\pi A}{3m} \int_{p_1}^{p_2} p^{4-\gamma} dp$$

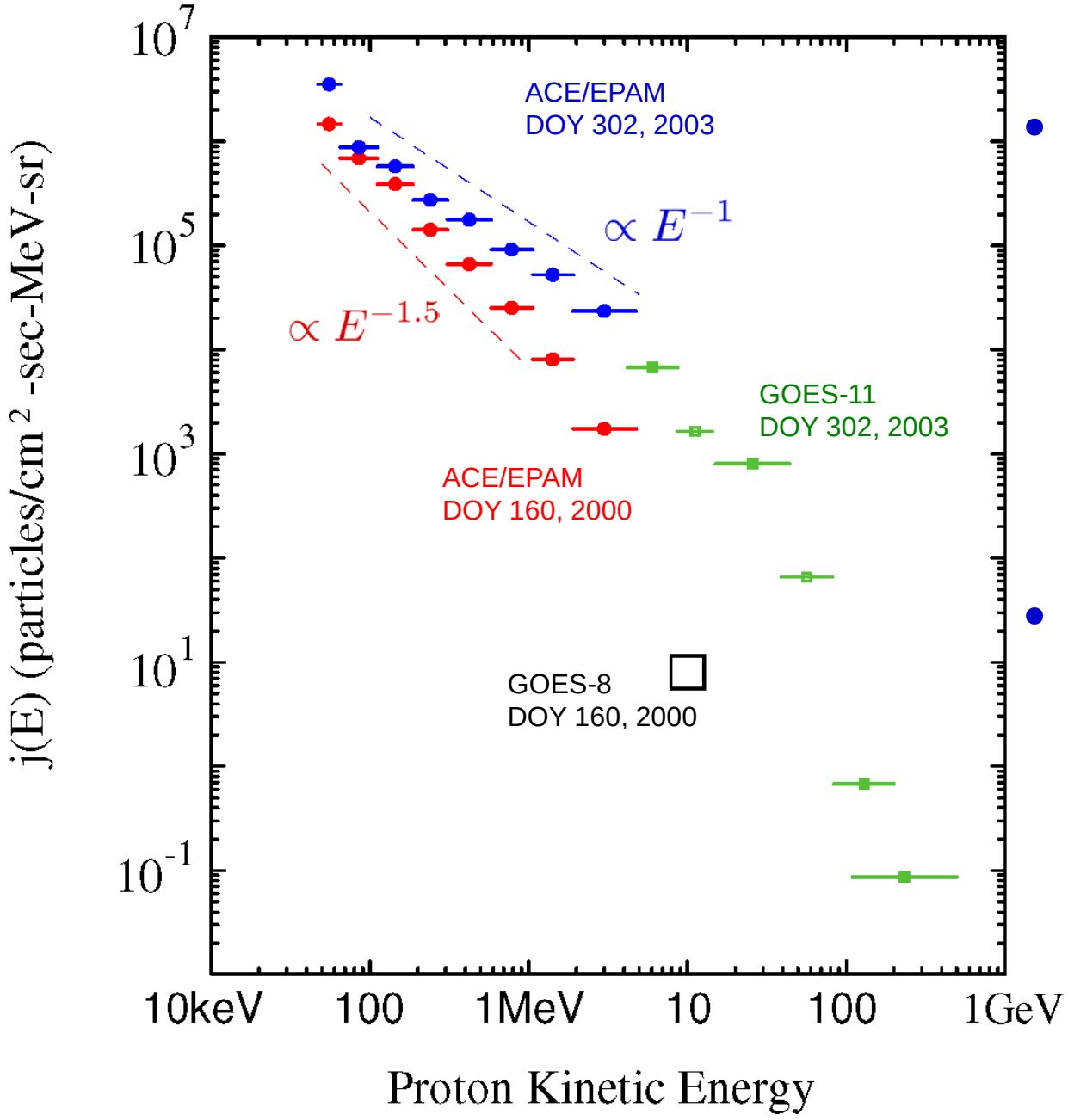
- For momentum spectra that are flatter than p^{-4} (energy spectra flatter than E^{-1}), the partial pressure is dominated by the higher-energy particles

4-hour periods around each of the highlighted events

In both events, the energetic-particle intensities peak at the passage of a strong interplanetary shock and closely resemble the predictions of diffusive shock acceleration theory



Energy spectra at the shock for the 2 events highlighted

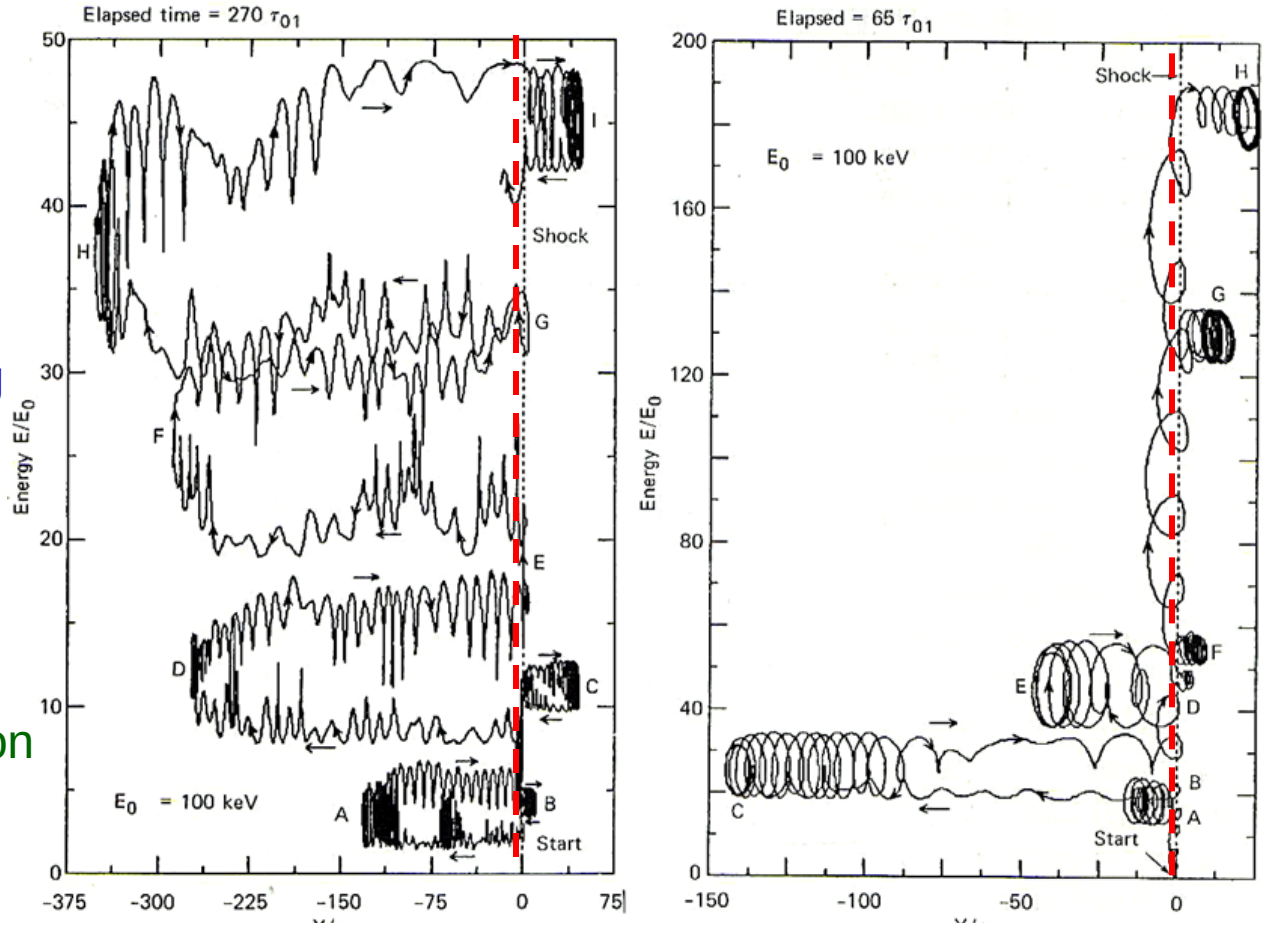


- What determines the shape of the energy spectrum at the shock (which is where the peak intensity occurs)?
- How does this depend on both space and time for traveling interplanetary shocks?

The basic physics of particle acceleration at shocks

Quasi-parallel shock

Quasi-perpendicular shock



Increasing Particle Energy

Slower Acceleration case

More rapid acceleration

Position relative to the shock

Decker, 1988

Quantitative predictions of **Diffusive Shock Acceleration** can be obtained by solving the cosmic-ray transport equation (*Parker, 1965*) (which assumes isotropy)

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

advection ***diffusion*** ***drift*** ***energy change***

When applied to a simple, planar shock-like discontinuity, the resulting distribution has the form

$$f(x,p) = \begin{cases} f_0\left(\frac{p}{p_0}\right)^{-\gamma} \exp\left(-\frac{U_1|x|}{\kappa_{xx,1}(p)}\right) & x < 0 \\ f_0\left(\frac{p}{p_0}\right)^{-\gamma} & x \geq 0 \end{cases}$$

where $\gamma = 3U_1/(U_1 - U_2) = 3r/(r-1)$

Thus, strong shocks produce flatter energy spectra than weaker shocks.

Coupling the Parker Eq. to MHD/CME models

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

This a simpler version of the equation used by the NSF / "Sun to Ice" team, as well as the "PATH" model used by the University of Alabama, and others, to solve for SEP acceleration and transport

It assumes that SEPs are isotropic. This is not really a bad approximation, except in the early part of the event.

While the focused-transport equation, and PATH-model approach, are a good way to go for MHD/CME/SEP calculations, especially if large anisotropies are expected, some insight can also be gained by solving this equation for propagating shocks.

It is **conceptually** straightforward to couple this (and similar) eq.'s to MHD, but hard to do, in practice.

Coupling the Parker Eq. to MHD/CME models

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

advection *diffusion* *drift* *energy change* *source*

The drift velocity due to the large scale curvature and gradient of the average magnetic field is:

The magnetic field enters here

$$\mathbf{V_d} = \frac{pcw}{3q}\,\nabla \times \left[\frac{\mathbf{B}}{B^2}\right]$$

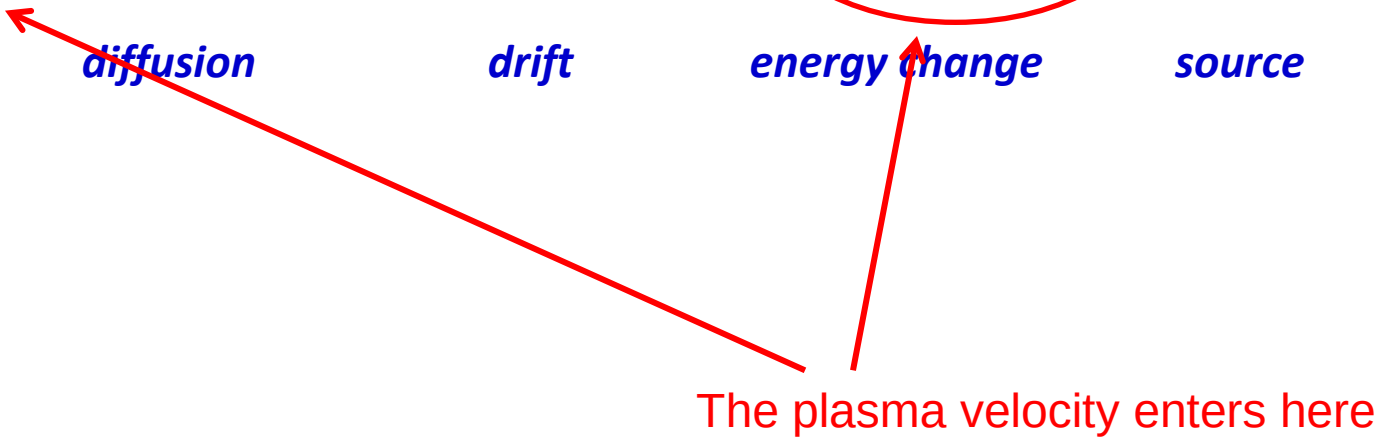
And the symmetric part of the diffusion tensor is:

$$\kappa_{ij}^{(S)} = \kappa_\perp \delta_{ij} + (\kappa_\parallel - \kappa_\perp)\frac{B_i B_j}{B^2}$$

Coupling the Parker Eq. to MHD/CME models

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

advection ***diffusion*** ***drift*** ***energy change*** ***source***

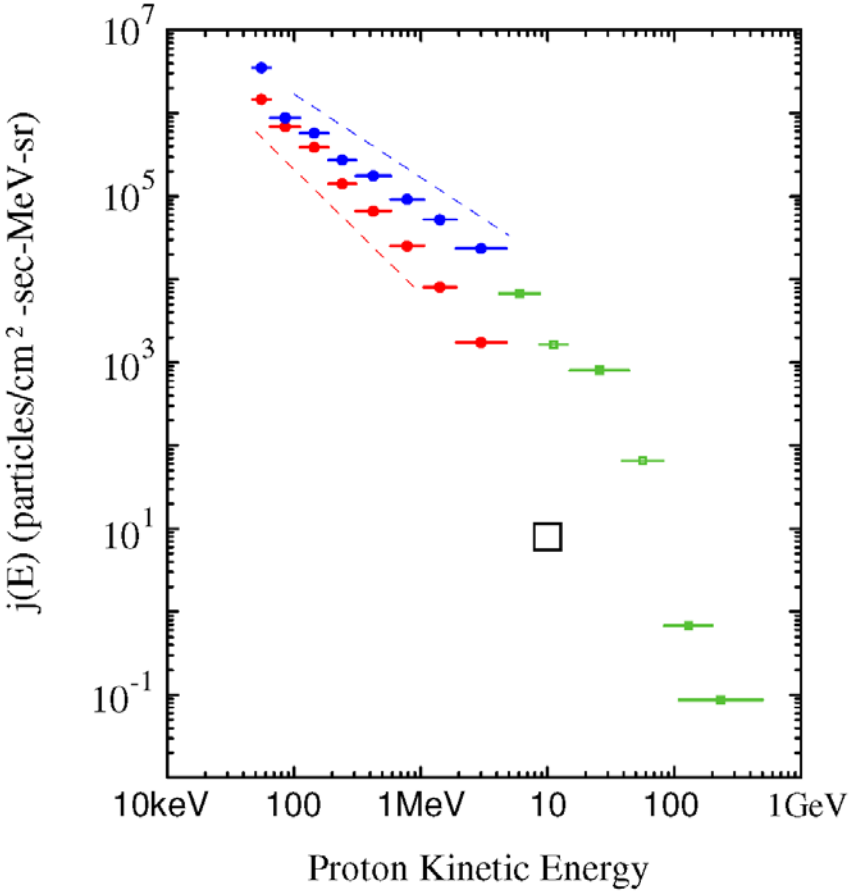


The intensity of high-energy particles accelerated by a shock depends on …

a) The flux of "source" particles – which controls the intensity at lower energies, and …

b) the strength of the shock (density compression ratio) – which determines the slope of the power-law part of the spectrum seen primarily at lower energies, and …

c) losses and/or time dependence, which can lead to spectral breaks at higher energies



Variations in any of these with time or space (e.g. caused by turbulence, or unusual shock/magnetic-field geometries) can lead to other spectral variations as well.

Acceleration Time in Diffusive Shock Acceleration

- For a planar shock, one can theoretically determine the time to accelerate particles to an energy *E* from a smaller energy E_0. *It is given by*

$$\tau_{acc} = \frac{(3/2)}{U_1 - U_2} \int_{E_0}^{E} \left(\frac{\kappa_{xx,1}(E')}{U_1} + \frac{\kappa_{xx,2}(E')}{U_2} \right) \frac{dE'}{E'}$$

where

$$\kappa_{xx} = \kappa_{\perp} \sin^2 \theta_{Bn} + \kappa_{||} \cos^2 \theta_{Bn}$$

Is the diffusion coefficient normal to the shock front (kappa is formally a tensor). θ_{Bn} is the angle between the shock normal and magnetic field

The acceleration time depends on …

1. the (upstream) diffusion coefficient.
   - Smaller diffusion coefficient means faster acceleration
   - For a given time which to accelerate particles, more-rapid acceleration leads to higher maximum energy
   - Perpendicular shocks are faster accelerators than parallel shocks because $K_{perp} << K_{parallel}$.
   - The diffusion coefficient depends on the intensity of the magnetic field turbulence
   - Some versions of shock-acceleration theory require the turbulence to be significantly enhanced upstream of shocks. This is not commonly seen at 1 AU.

and 2. U_1-U_2, the ***difference*** in plasma speed across the shock.

- This is not the same as the speed of the shock.

The evolution of the spectral break with distance from the Sun for a traveling shock

- As we discussed, the time to accelerate depends on the diffusion coefficient.
- The diffusion coefficient likely is proportional to the gyroradius of the particles which is considerably shorter in the strong magnetic fields near the Sun.

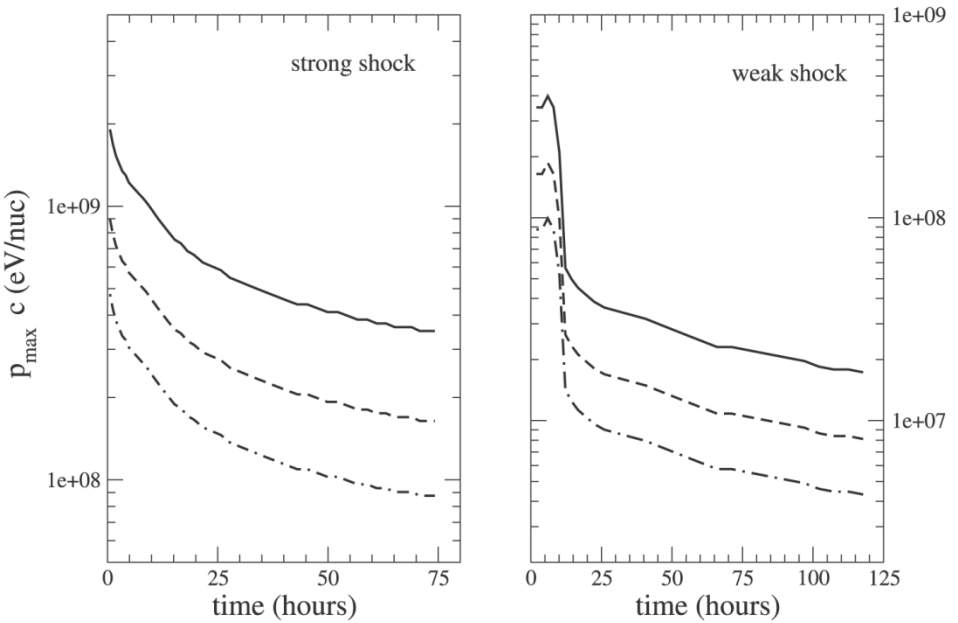


Figure 2. The maximum particle momentum per nucleon at the shock front. The solid lines are for protons, the dashed lines are for CNO particles, and the dash-dotted lines are for iron.

We expect the "maximum energy" to be larger near the Sun than at 1AU (e.g. *Li & Zank*, 2005, as shown above)

A (relatively) simple calculation

- We solve the Parker transport equation using a spherically-symmetric geometry, for a shock moving radially outward from the Sun.

$$\frac{\partial f}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa_{rr}\frac{\partial f}{\partial r}\right) - U\frac{\partial f}{\partial r} + \frac{1}{3r^2}\frac{\partial (r^2 U)}{\partial r}\frac{\partial f}{\partial \ln p} + Q = 0$$

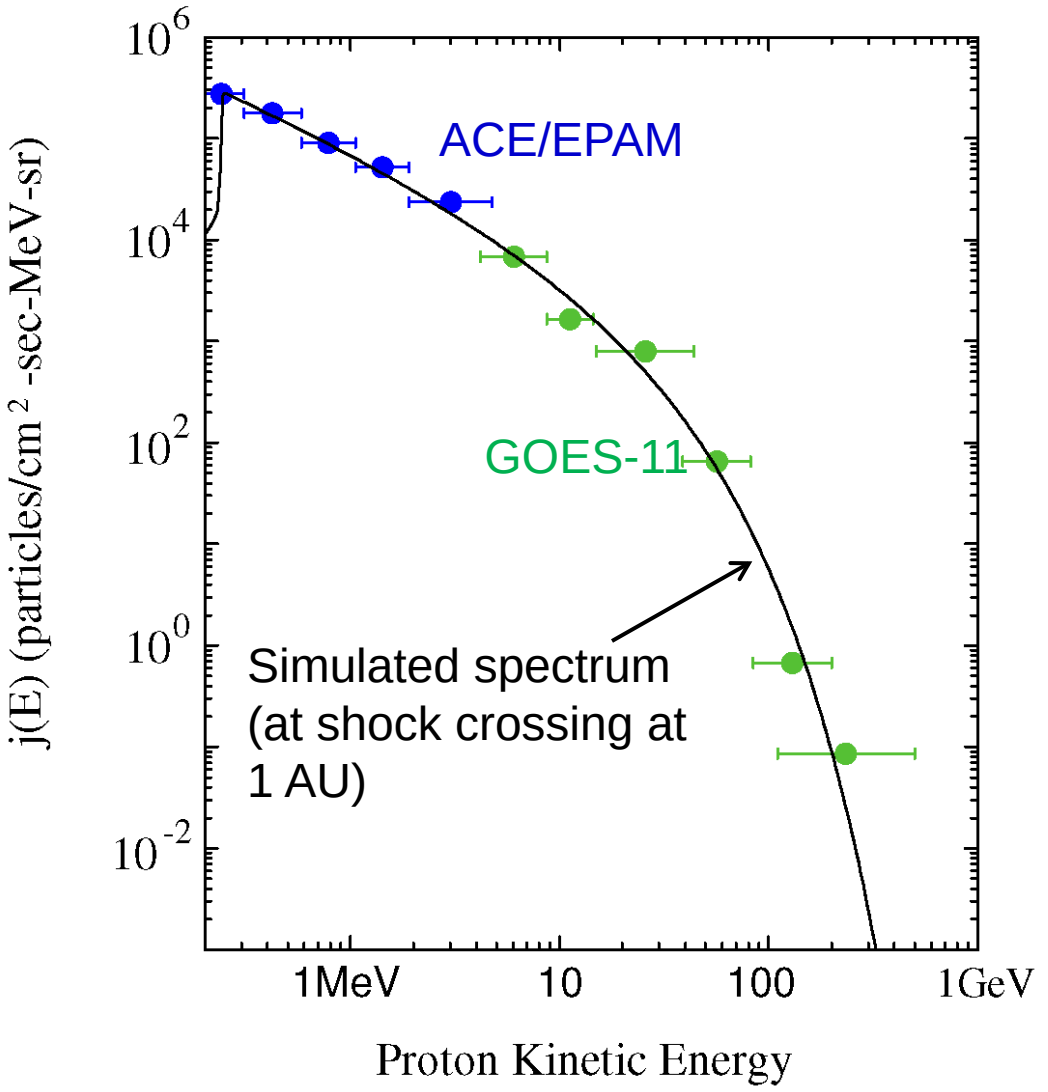
- Solved using a standard finite-difference approach.
- The plasma speed is determined kinematically (consistent with that expected for a radially propagating interplanetary shock).
- The diffusion coefficient is assumed as follows:

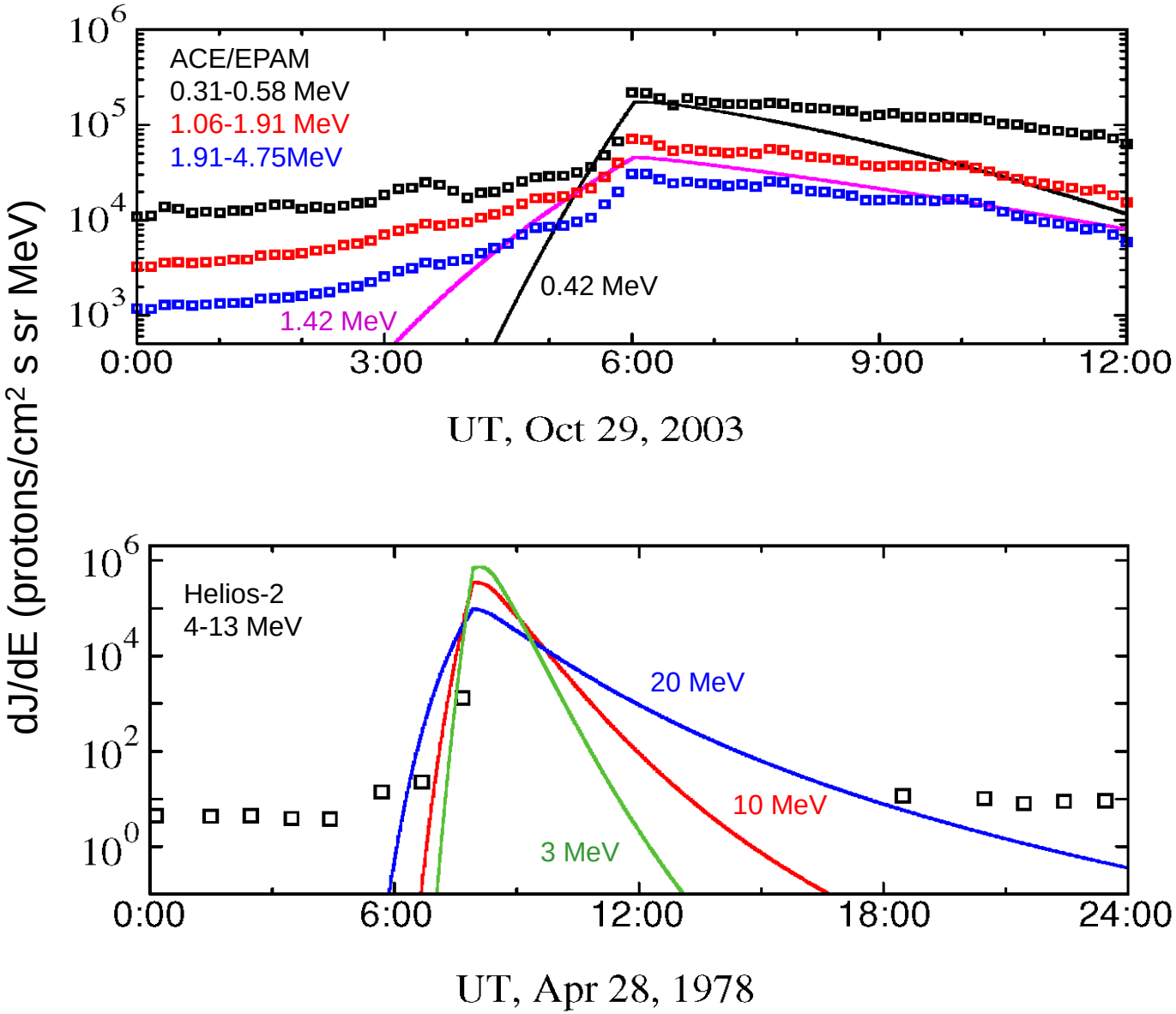
$$\kappa_{rr} = \kappa_0 (E/1\ \mathrm{MeV})^{\gamma} (r/1\ \mathrm{AU})^2$$

- Where K_0 and γ are input parameters. K_0 is about 2×10^{19} cm^2/s, and γ =0.75 based on SEP observations at 1 AU. The dependence on *r* given above is simply an assumption. It is not well constrained, but reasonably, one would expect K_{rr} to scale roughly inversely with the mag. field strength *B*.

Simulation of the large SEP event seen on DOY 302, 2003 (Halloween event)

- Shock speed taken to be that seen at 1AU
- $n_{ep} = 10^{-4}$ was assumed (related to injection efficiency)
- K_0 and γ determined from 1 AU observations
- Spectrum shown is that right at the shock

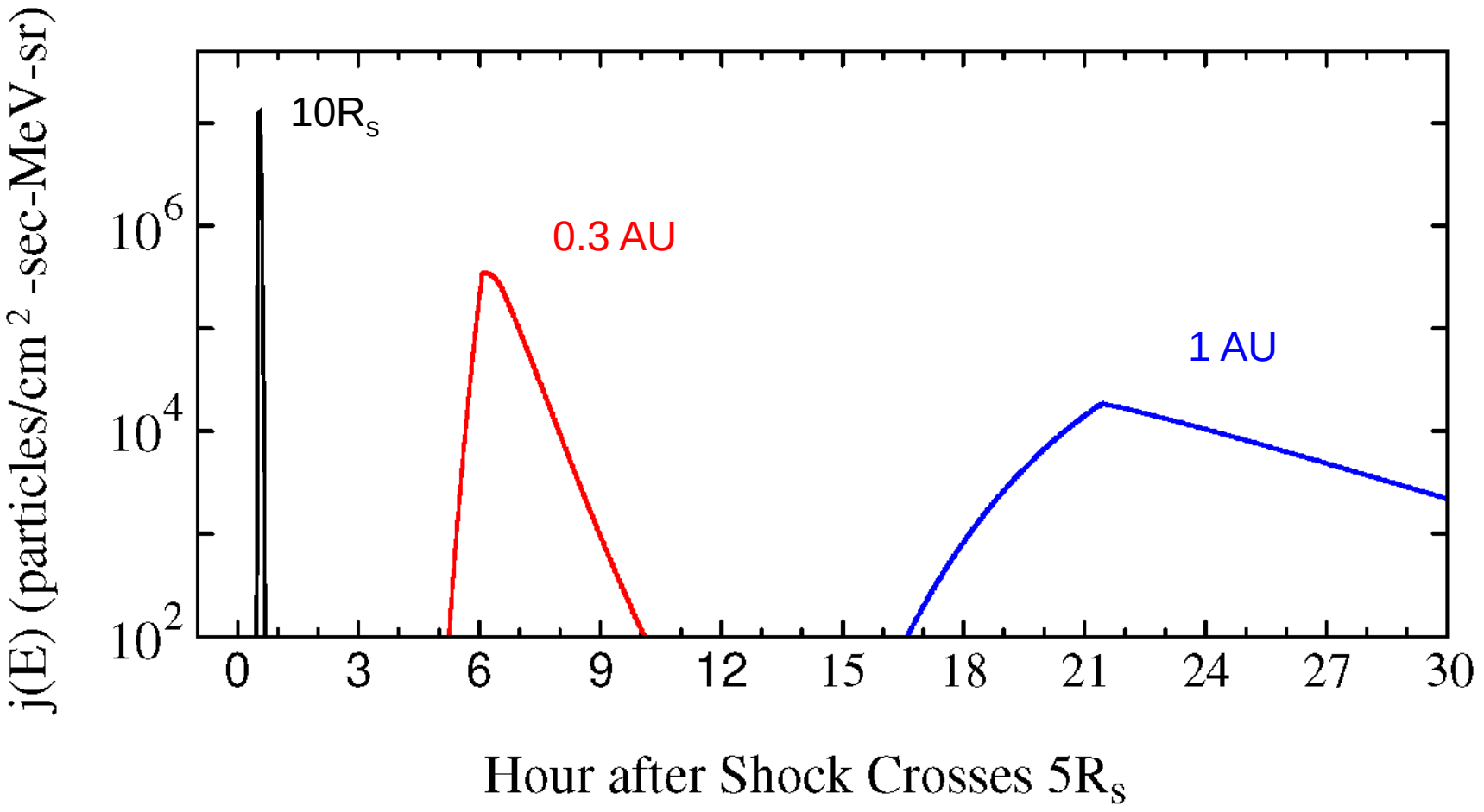




1 AU

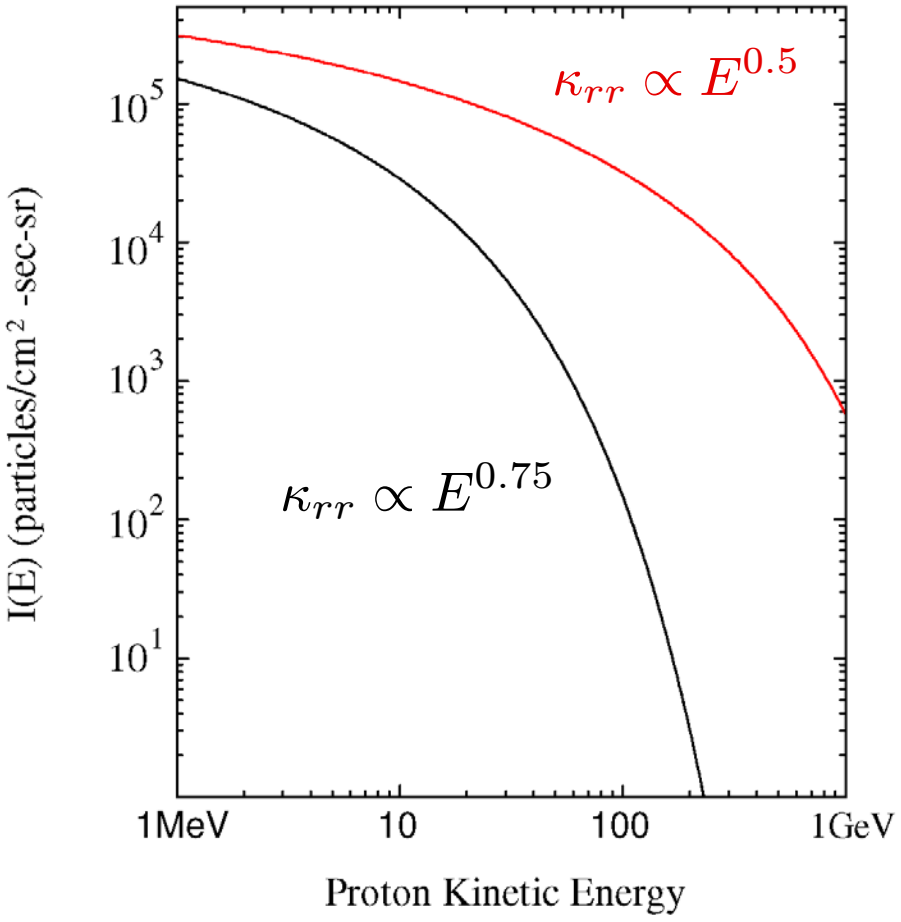
The same event at 0.3 AU and comparison with the largest SEP event (seen at 0.3 AU) by Helios-2

Model calculation:
Time-intensity of 3-MeV protons at 3 locations

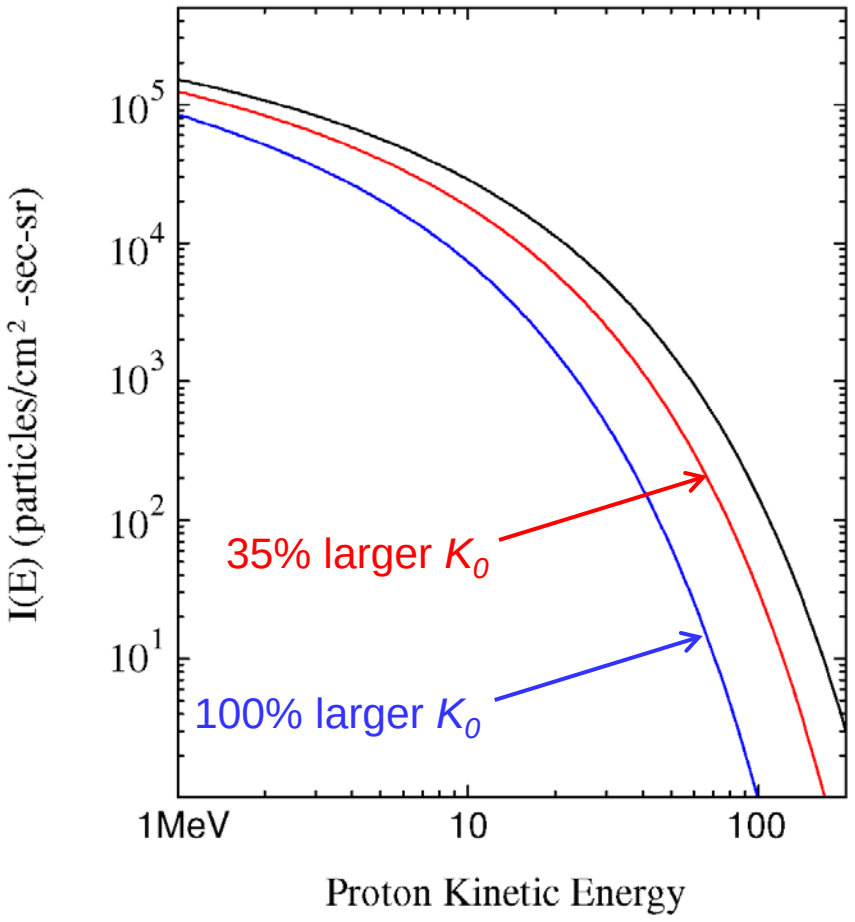


Integrated spectra, at the time of passage of the shock at 1AU: The dependence on the diffusion coefficient is considerable

Fixed K_0 *(fixed field strength)*



Fixed Energy dependence of *K*

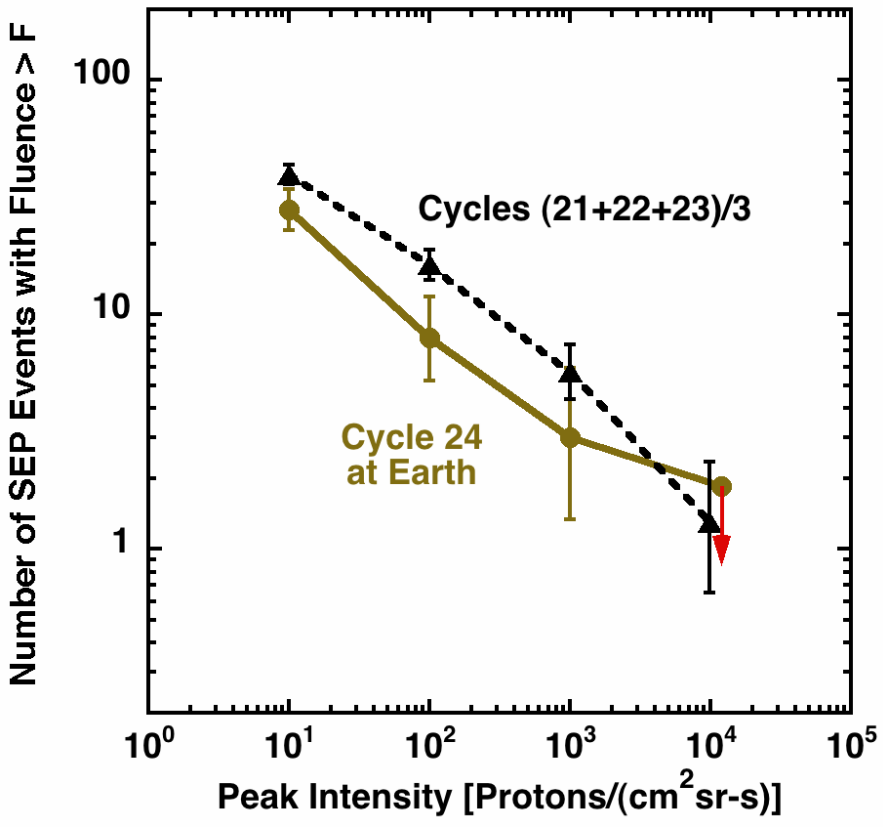


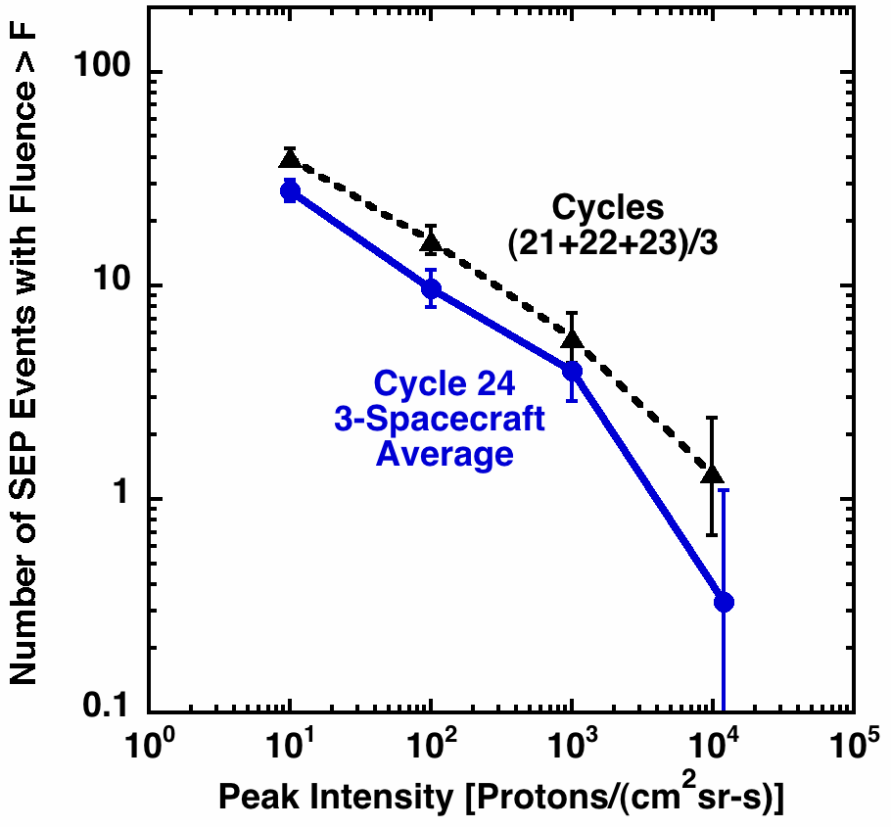
$$I(E) = \int_E^\infty \left(\frac{dJ(E')}{dE} \right) dE'$$

SEP Peak Intensity Distributions
Compare Cycle 24 with cycles 21-23 over first 5 years

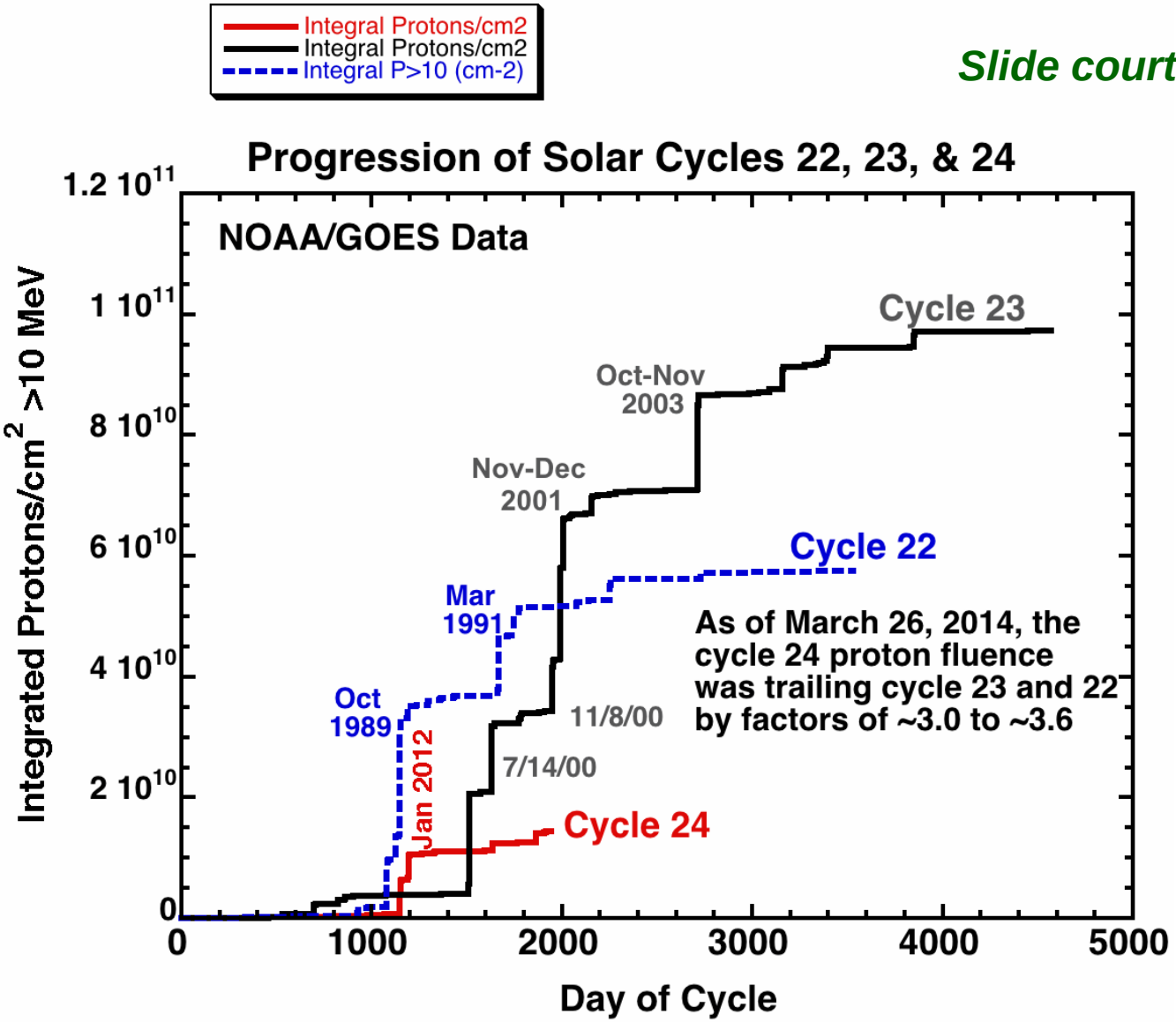
Cycle 24 has had fewer events of all sizes than Cycles 21-23, but especially for events with >10,000 Protons/(cm^{2}sr-s), where cycles 21-23 averaged 4 events and cycle 24 has had only one event (July 23, 2012 at STEREO-A).

Slide courtesy D. Mewald



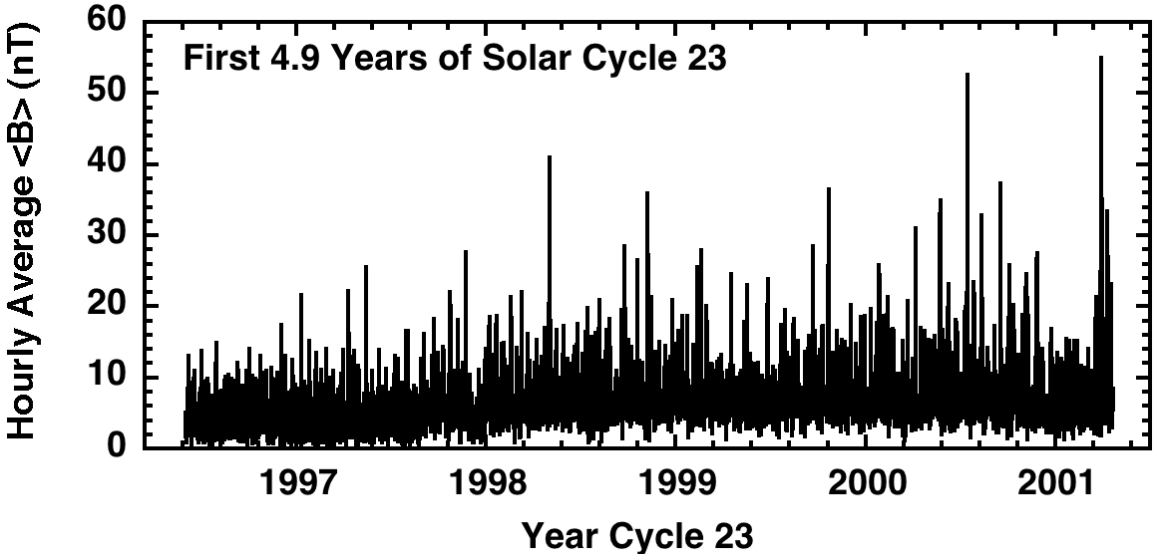


Slide courtesy D. Mewaldt

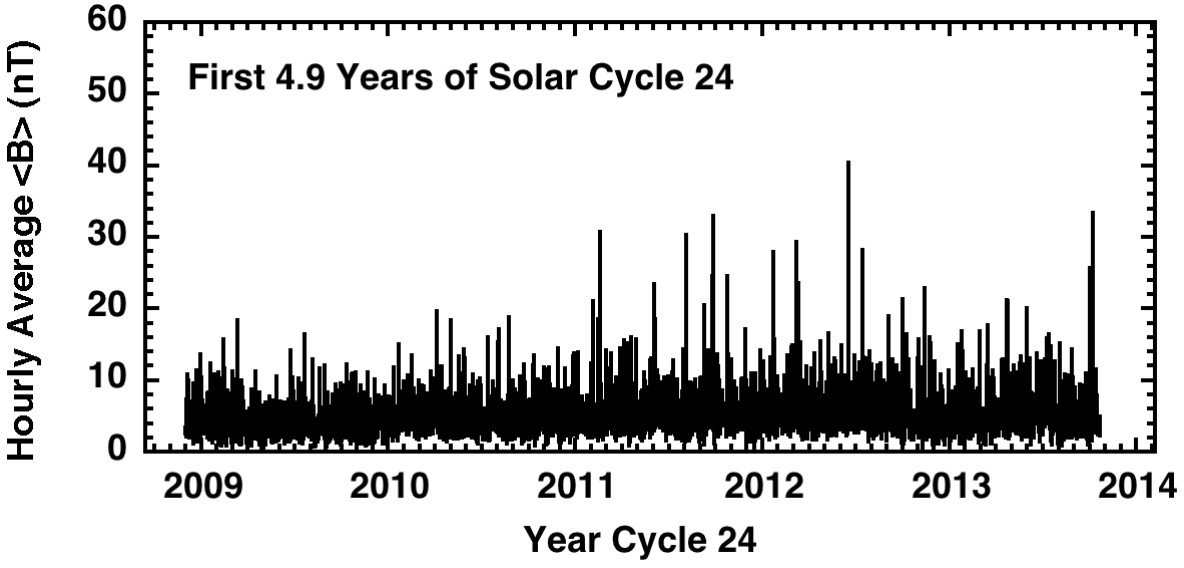


Daily Fluences of >10 MeV protons from NOAA's Goes satellites were integrated, starting with the beginning of cycles 22 (Sept 1986), 23 (June 1996) and and 24 (December 2008). As of 2/24/14, the cycle 24 proton fluence was trailing cycle 23 and 22 by factors of ~2.4 and ~3.6, respectively. The dates of large SEP events are indicated. There have been few large events at Earth this cycle.

The interplanetary magnetic field is significantly weaker during the rise to maximum of cycle 24 - a pattern that was also very evident during the extended solar minimum.



<B> = 6.48 nT



<B> = 4.97 nT

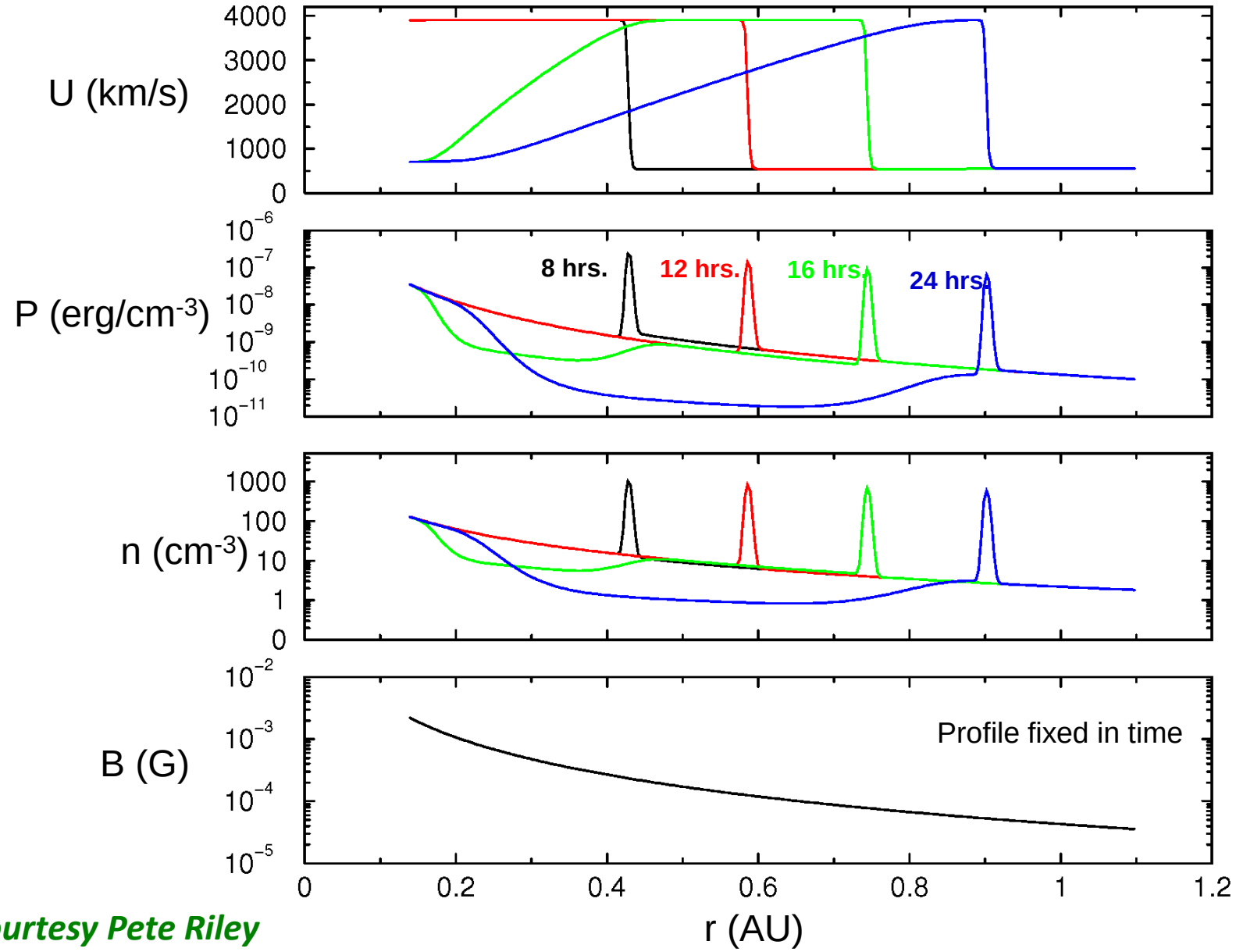
Slide courtesy D. Mewaldt

Is a shock required for efficient acceleration?

- In terms of the Parker equation, the answer is “no” – the acceleration only depends on the divergence of the flow speed. Thus, **any** compression can accelerate particles – but the larger the compression, the higher the acceleration rate

- **A caution, though**: when coupling SEP transport to MHD/CME models, one must be sure the MHD compression is physically reasonable!

Very simple 1-D MHD/CME calculation of a large plasma disturbance (no shock – the adiabatic approximation was used)

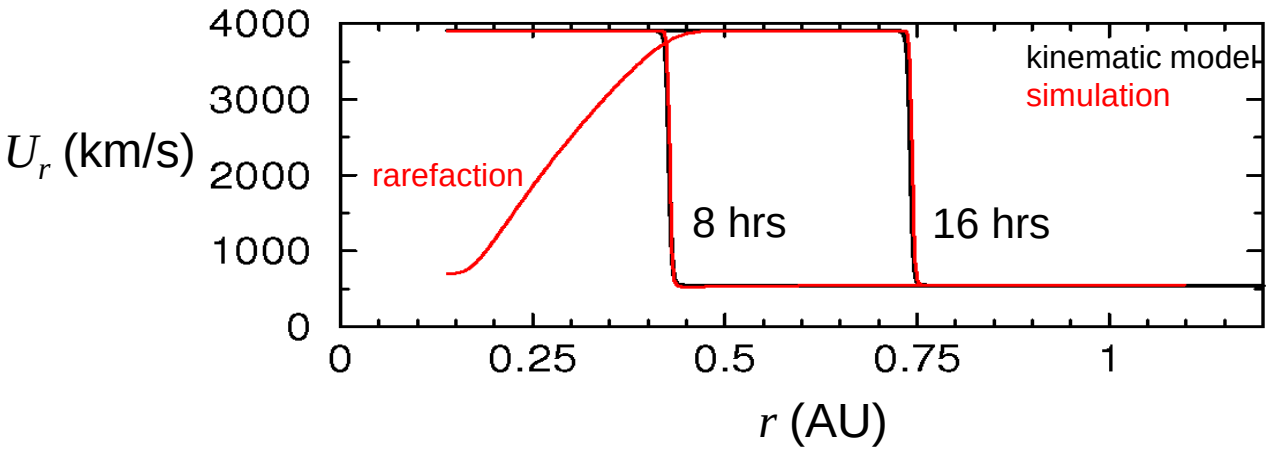


Courtesy Pete Riley

A kinematic representation of U_r that is consistent with that from the 1D/HD simulation

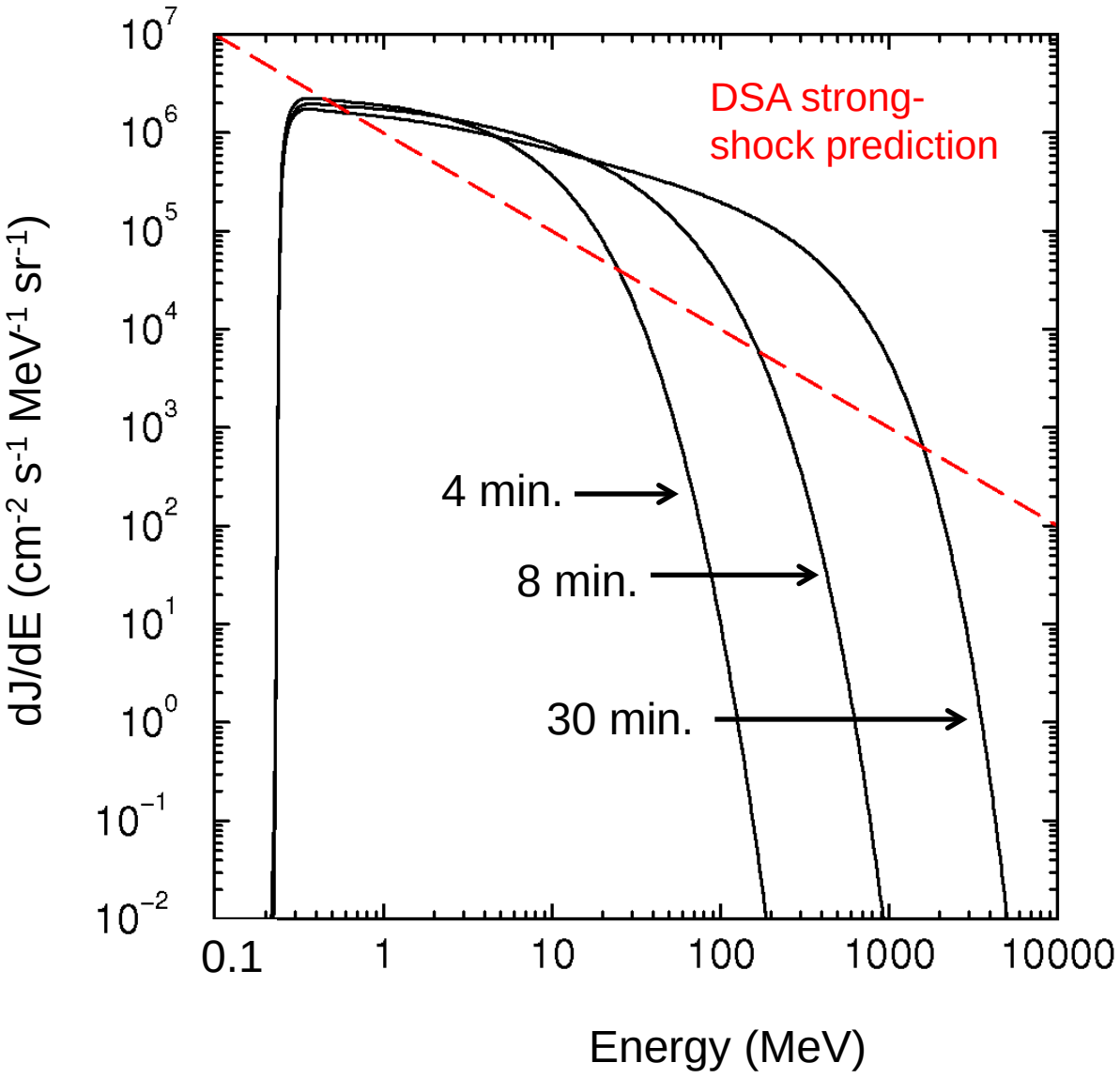
$$U_r(r,t) = \frac{1}{2}\left(V_w + V_f\right) + \frac{1}{2}\left(V_w - V_f\right)\tanh\left(\frac{r - r_d(t)}{\Delta r_d}\right)$$

- Where V_w is the solar wind speed upstream of the disturbance, V_f is the wind speed behind it, r_d is the location of the disturbance and Δr_d is its thickness.
- $r_d = r_{min} + V_d\, t$, where V_d is the velocity of the disturbance. V_d is taken to be constant (about 1600 km/s), which is pretty close to the simulation result (except near 1 AU).
- The rarefaction behind the disturbance late in the event is neglected here



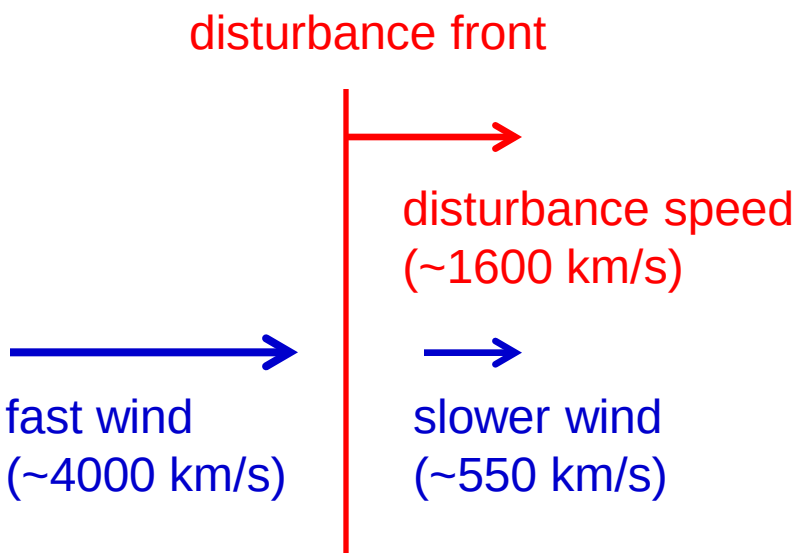
SEP transport/acceleration simulation result for this case.

- Accelerated spectrum (at the shock) is extremely flat
- Very rapid
- **Not realistic!**

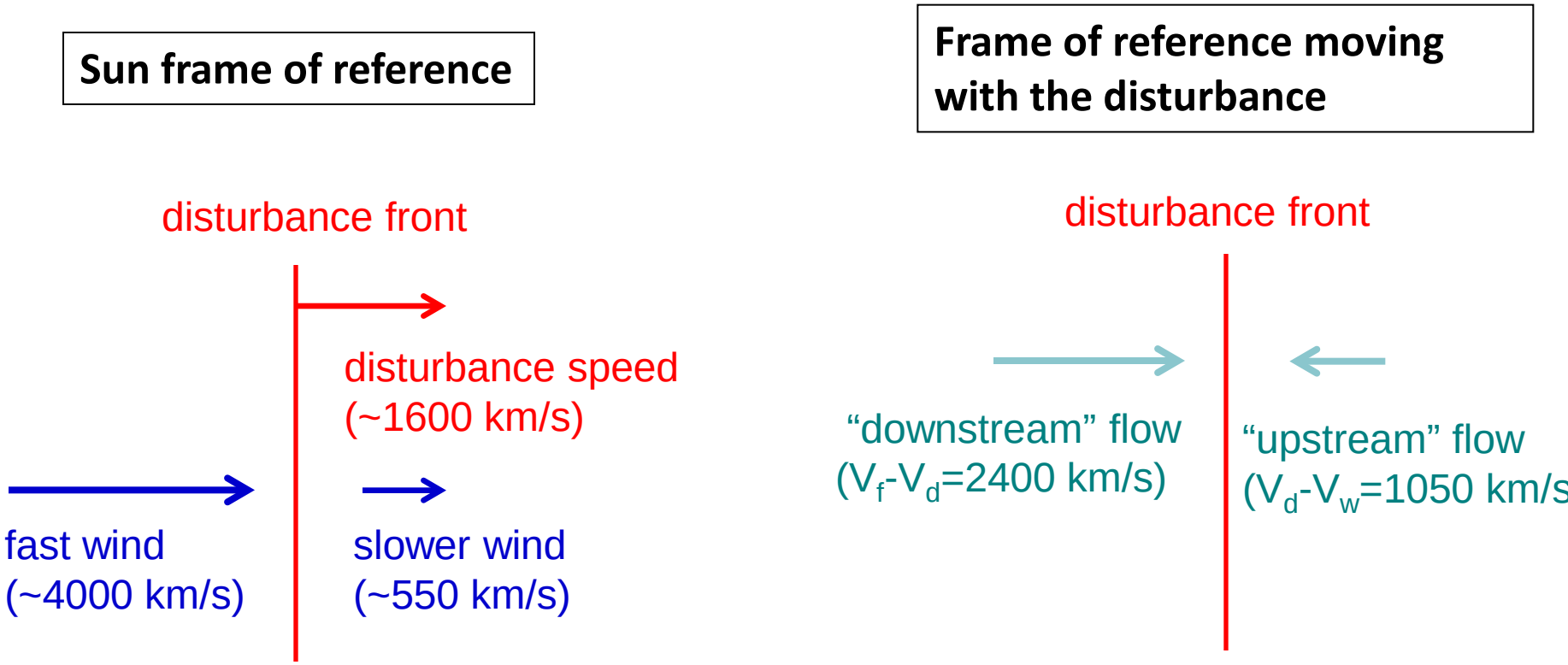


For this (unphysical) case, the acceleration is way too efficient. The reason is as follows …

Sun frame of reference

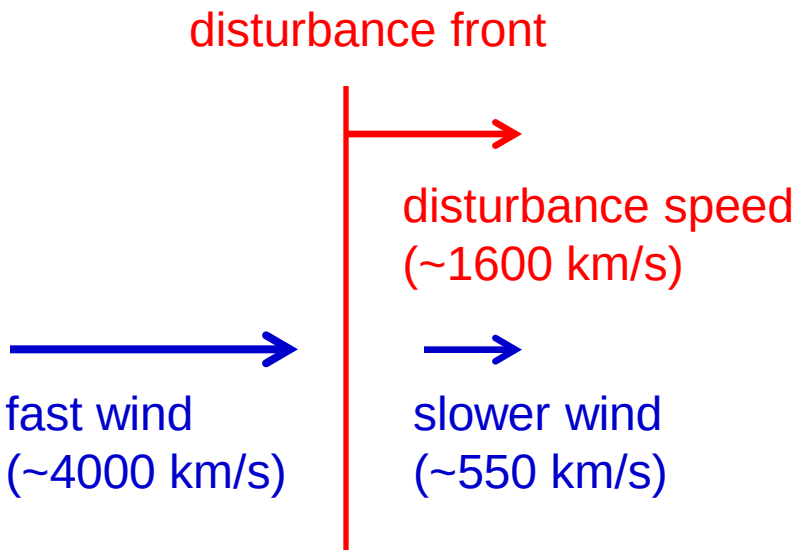


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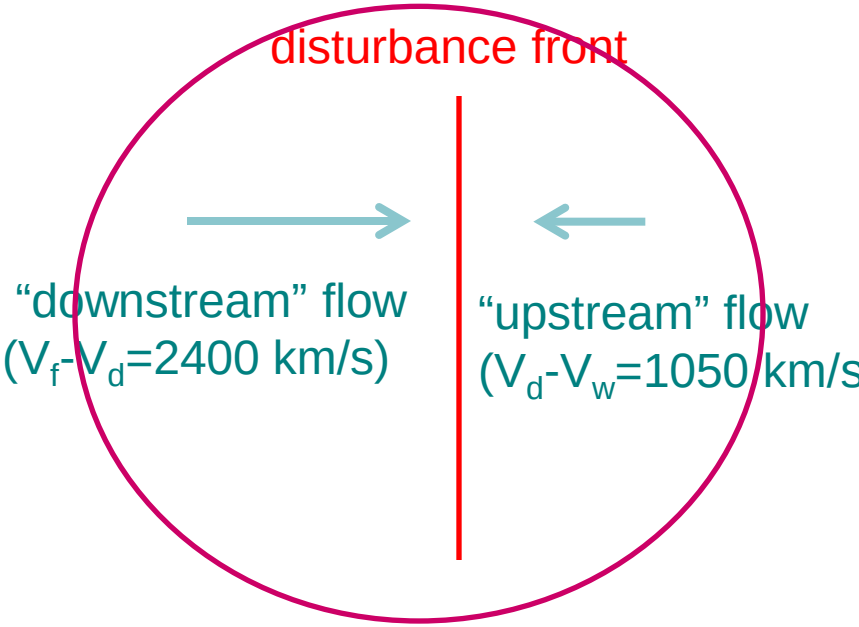


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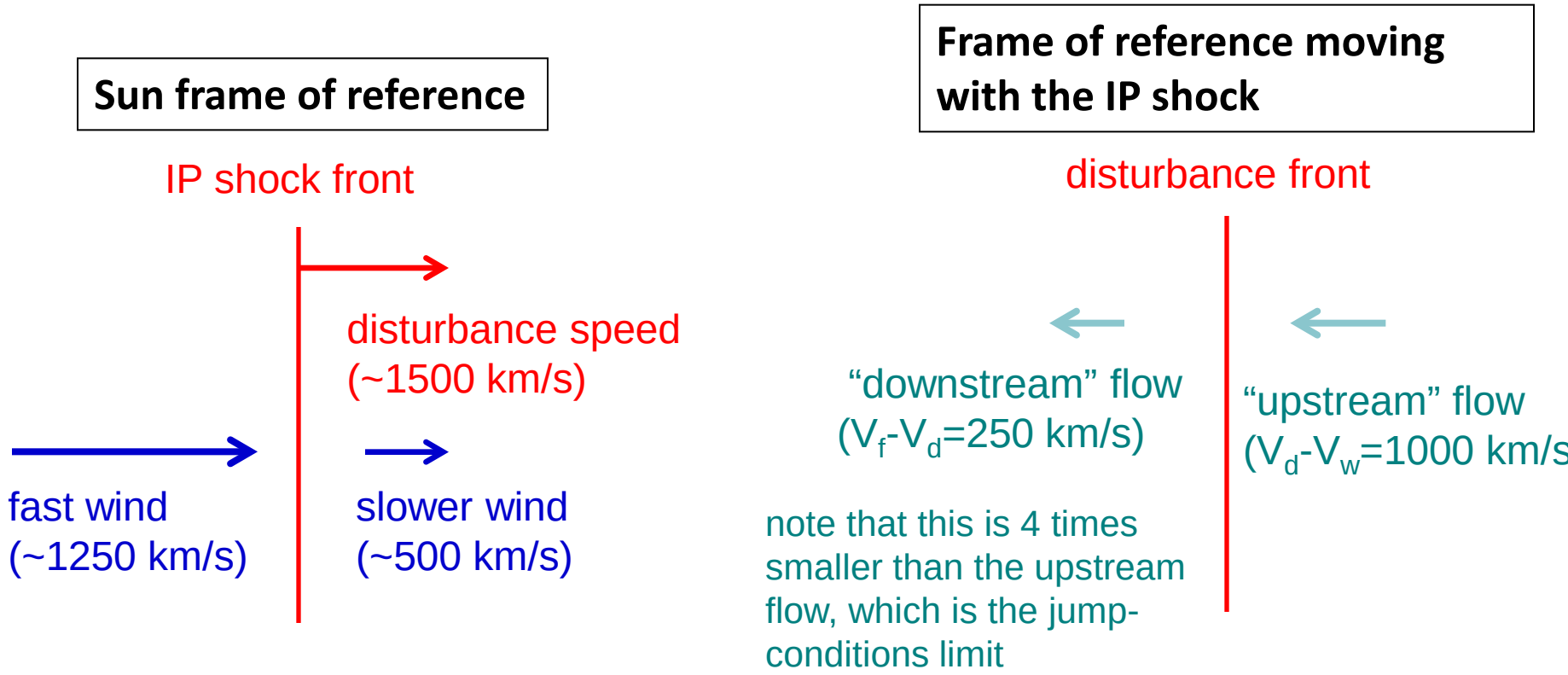


Frame of reference moving with the disturbance



- Note that the flows on both sides of the disturbance flow towards the disturbance!!
- Energetic particles are always brought back to the disturbance for acceleration. No way to escape!

In an interplanetary shock, the shock is moving faster than the fast wind behind it. Thus, when transforming into the frame moving with the shock, the flow upstream (opposite the side of the Sun) enters the shock supersonically, and the flow downstream (Sun side) moves away from the shock sub-sonically



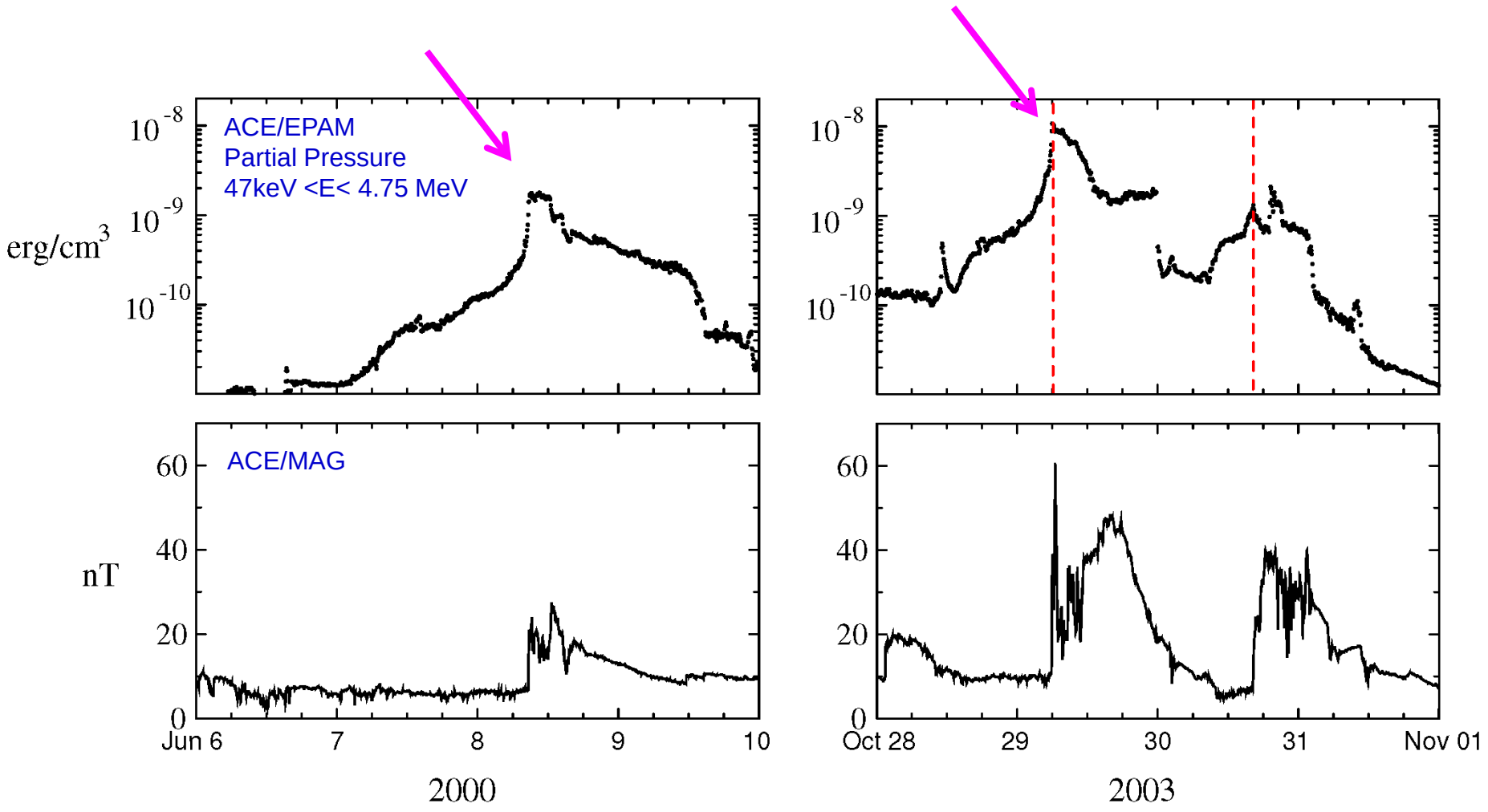
Moral of Story: MHD (or plasma model) should handle the shock correctly. This effects the SEP acceleration efficiency.

Conclusions

- Large SEP events are associated with shocks and, at least, are qualitatively consistent with the predictions of diffusive shock acceleration theory
- The SEPs contain a significant fraction of the overall energy available.
- The variability of the energy content in SEPs likely results from variability in SEP fluxes at the highest energies
- The intensity at the highest energies is strongly dependent on the diffusion coefficient
- Puzzles remain concerning the relationship between the diffusion coefficient and the magnetic-field power spectrum
- Coupling between SEP transport and CME/MHD models is conceptually straightforward, but must be validated carefully!

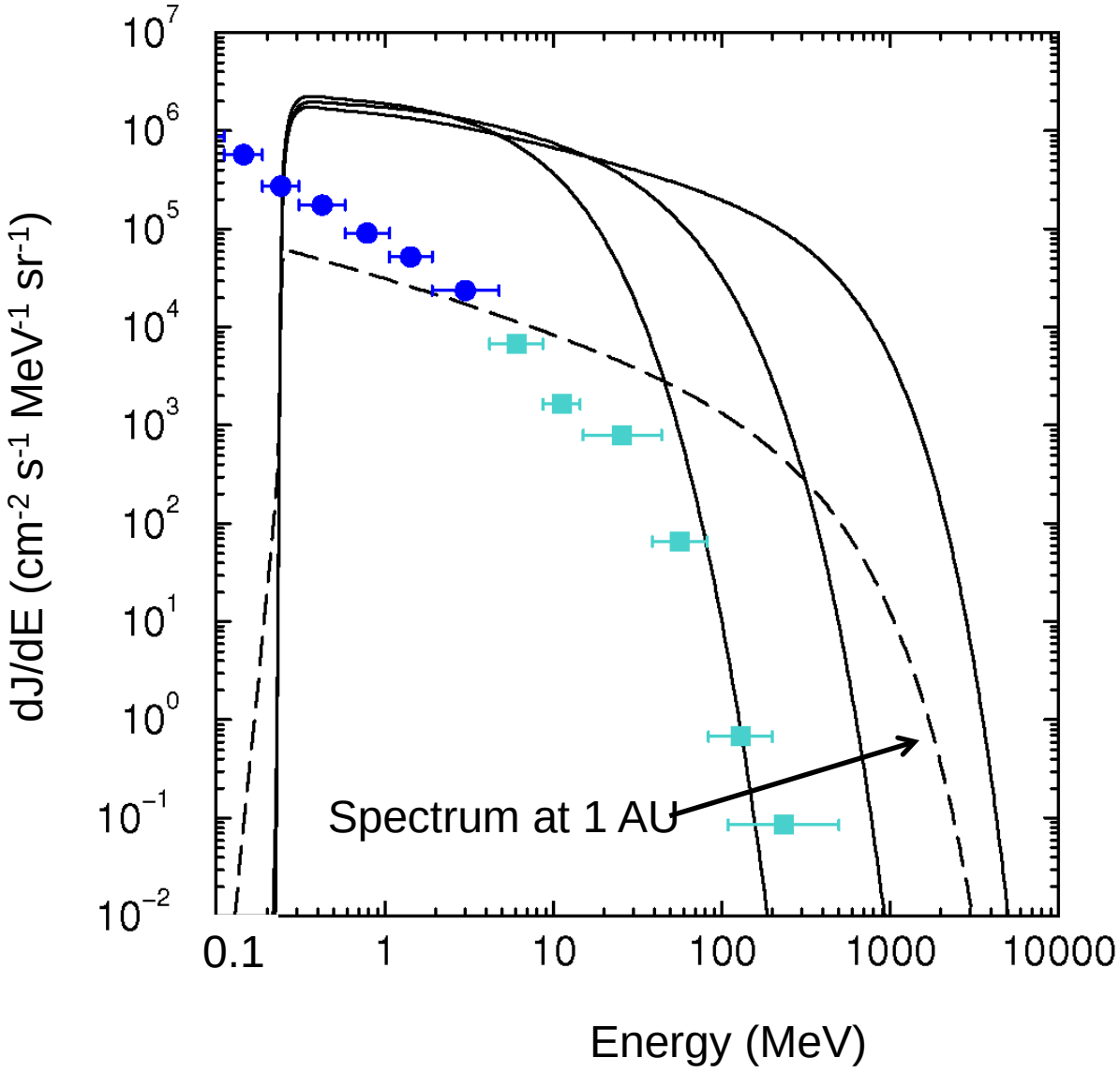
Extra slides

4-day periods around each of the highlighted events



Simulation of event simulated by Pete (using kinematic model)

- Symbols are spectra at strong shock for Halloween event – one of the largest SEP events recorded



Energy budget

