Particle Acceleration at Strong Shocks from the Sun to 1AU: The Importance of the Magnetic Field

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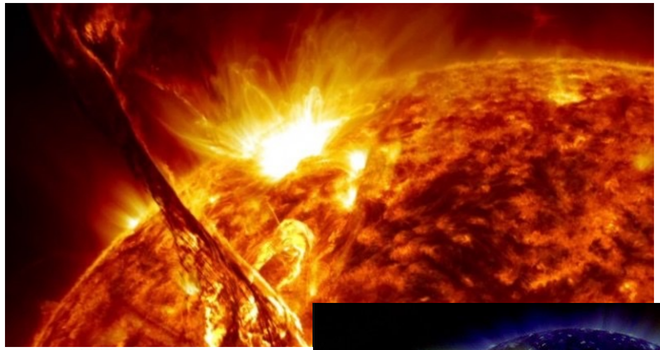
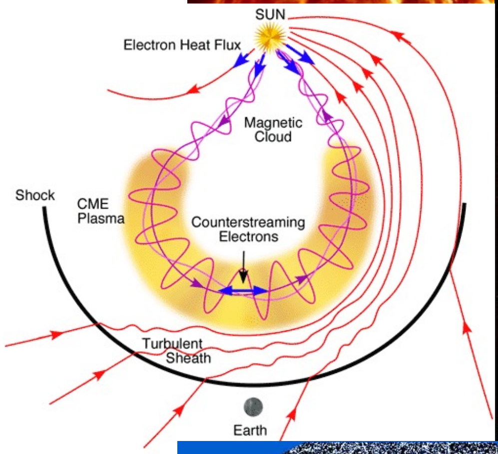
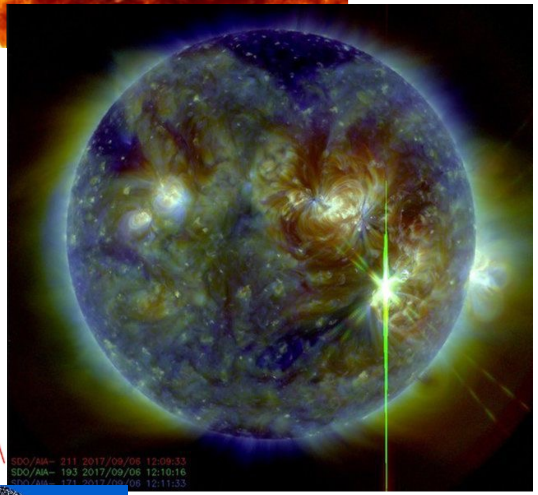
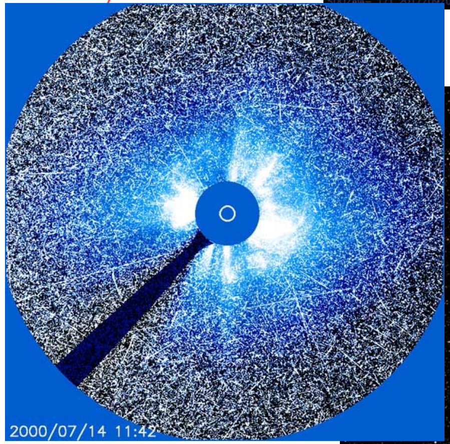
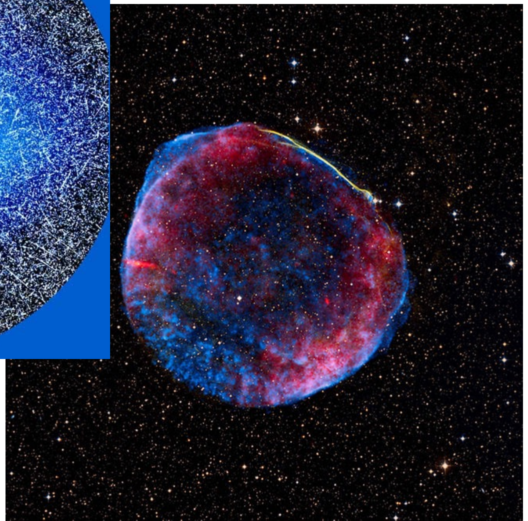
Why Study Particle Acceleration at Shocks in the Inner Heliosphere?

- The Sun is significant source of energetic particles and provides an excellent target for studying the underlying physics of particle acceleration in shock waves.
- This physics has significant overlap and application to astrophysical shocks, such as supernovae remnants, which produce the majority of GCRs, but for which we cannot study *in situ*.
- Characteristic energies at IP shocks can exceed a few MeV, with maximum energies up to a few GeV.   Sufficient to study diffusive transport.

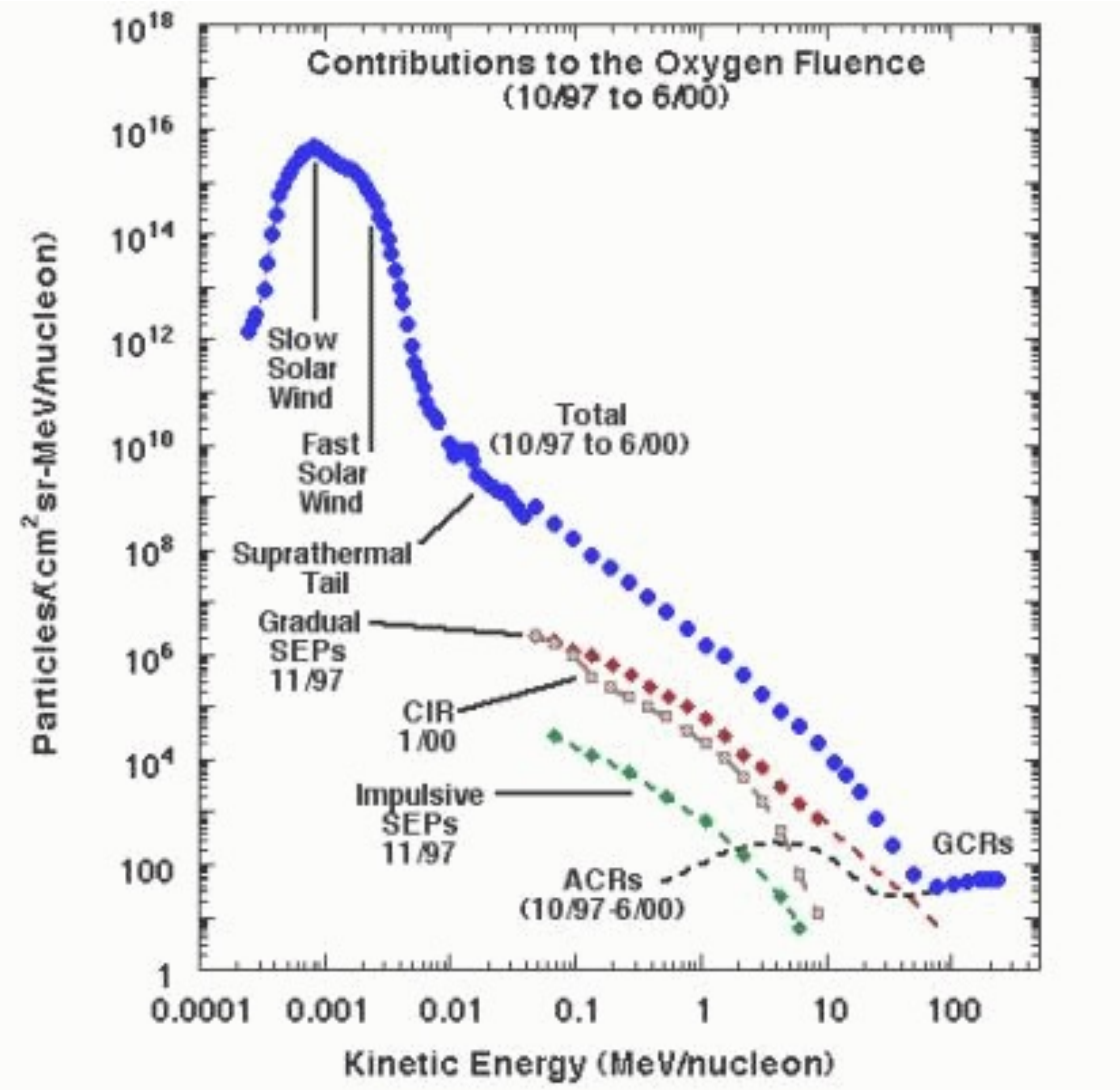



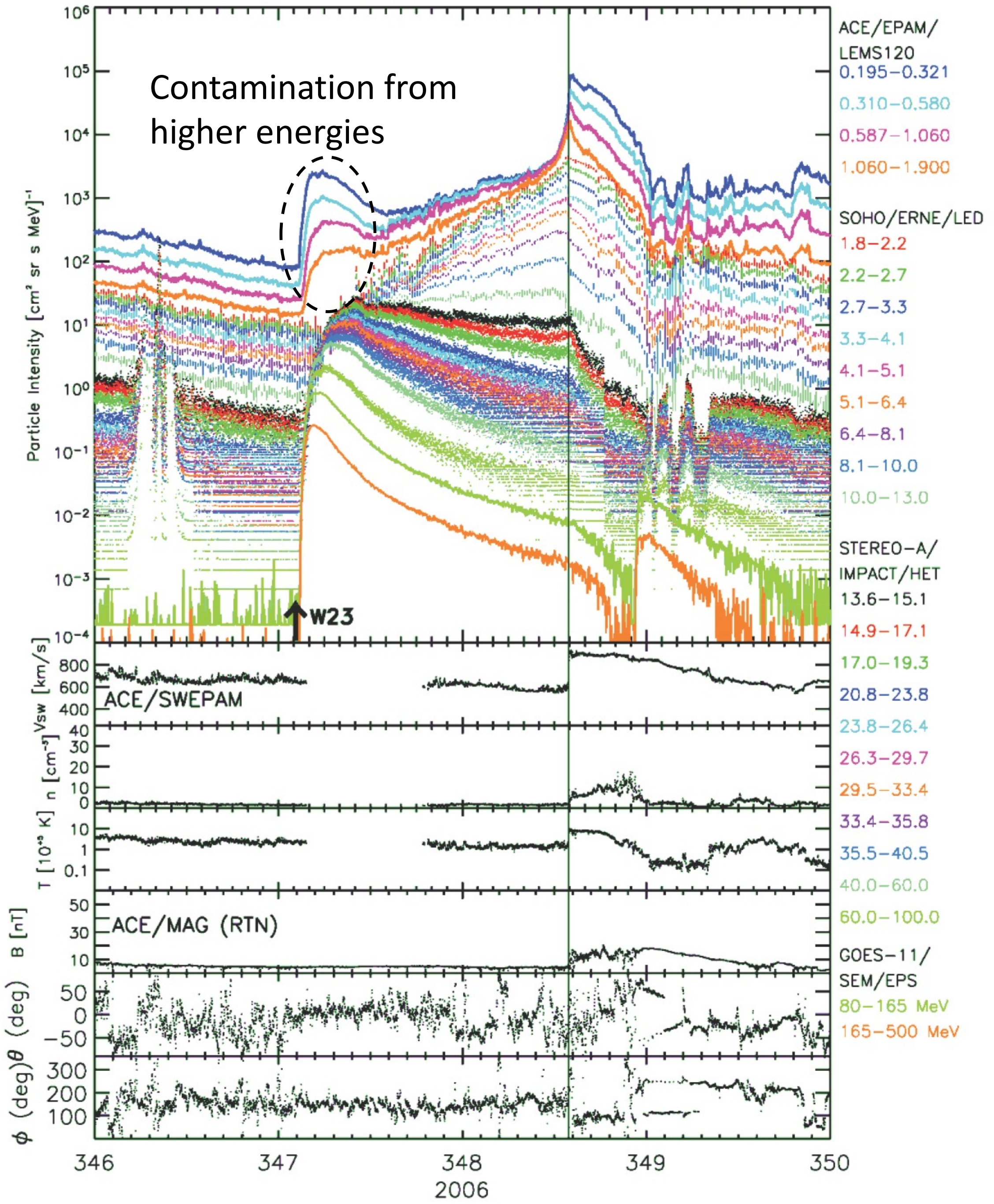


Solar Energetic Particles (SEPs)

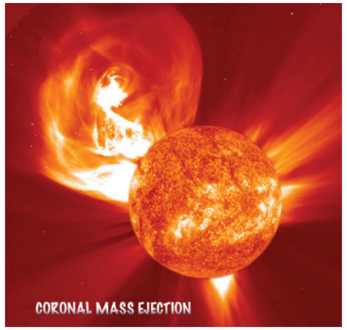
- High-energy component of the plasma distribution originating from processes associated with the Sun.
- What is the acceleration mechanism in producing these particles?
- How are these particles transported in the electric and magnetic fields of the heliosphere?
- SEPs are useful probes of remote processes. Their intensity and spectrum is governed by an equation which is analogous to radiative transfer used in remote sensing.

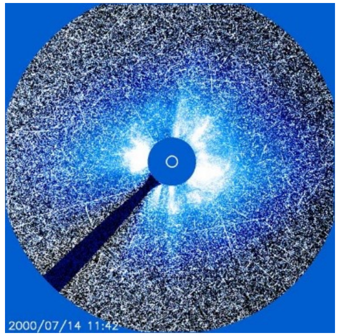


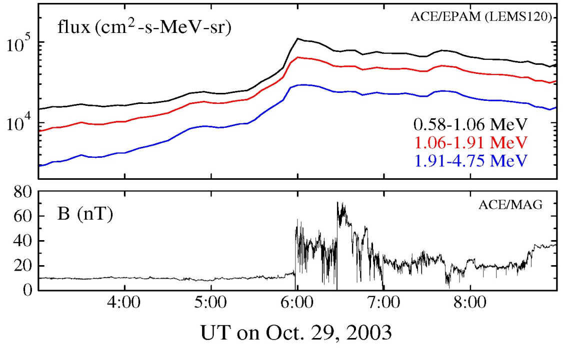
- A typical very large SEP event associated with a fast interplanetary (IP) shock seen by multiple spacecraft (ACE/SOHO/STEREO/GOES) near Earth
- The intensity vs. time depends on energy
- At low energies, the peak intensity is at the IP shock arriving ~1.5 days after the solar event; at high energies, the peak is well before the shock, closer to when the solar event was observed.
- The same shock likely accelerated these particles, but with a rate of acceleration that depends on the location of the shock



A sequence of events:



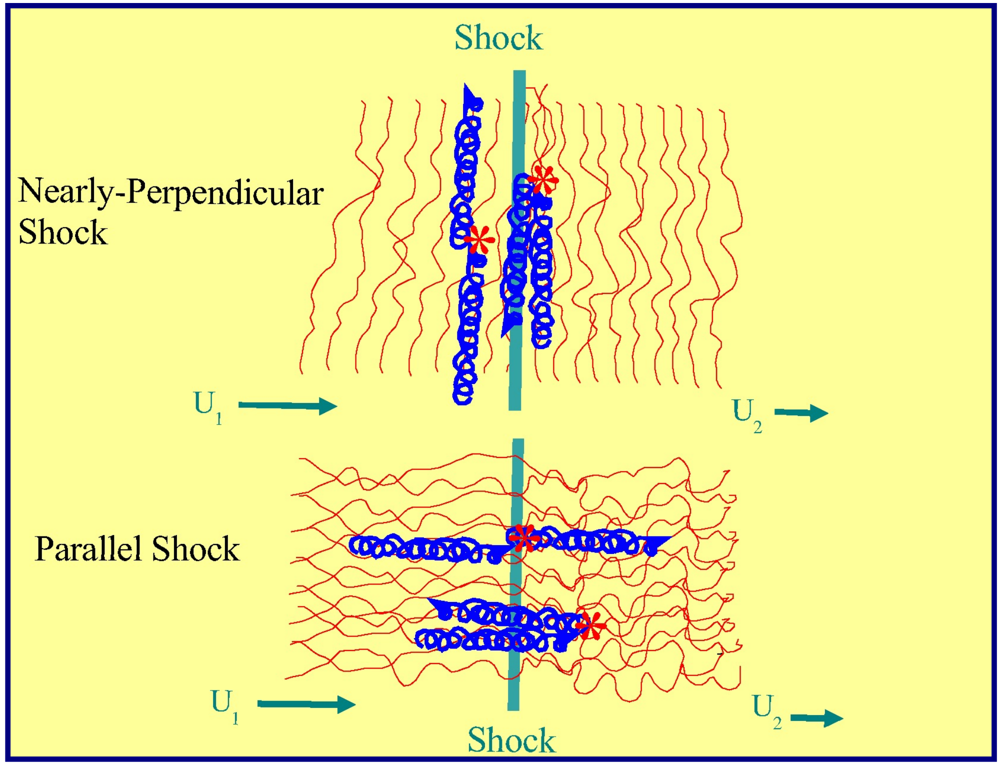




Diffusive Shock Acceleration Theory

Axford et al. (1977), Krymsky, (1977), Bell (1978), Blandford & Ostriker (1978)

- Charged particles that are confined near the strong plasma compression associated with a collisionless shock have a net gain in energy
- The confinement is due to scattering within fluctuating magnetic fields, due either to pre-existing turbulence through which the shock moves, or due to instabilities associated with the shock
  - At a perpendicular shock, most of the energy gain occurs via drifting along the shock, in the same direction as the motional electric field



Quantitative solution for the distribution function of accelerated particles comes from the Parker equation (*Parker*, 1965), which assumes the distribution is isotropic

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

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

Solution to the Parker equation for a planar shock

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

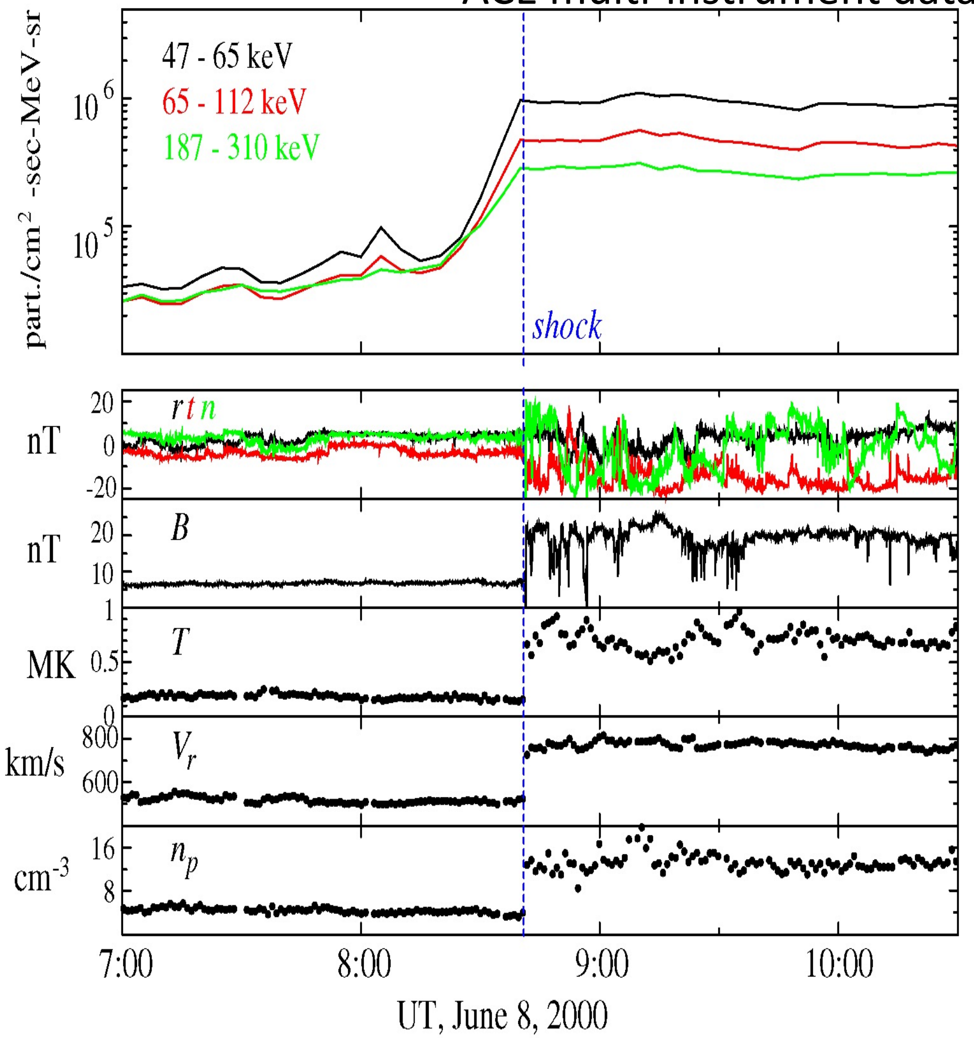
where $\gamma = 3U_1/(U_1 - U_2) \ = \ 3r/(r-1)$

The diffusion coefficient in this illustrative example is normal to the shock, which is related to the magnetic field

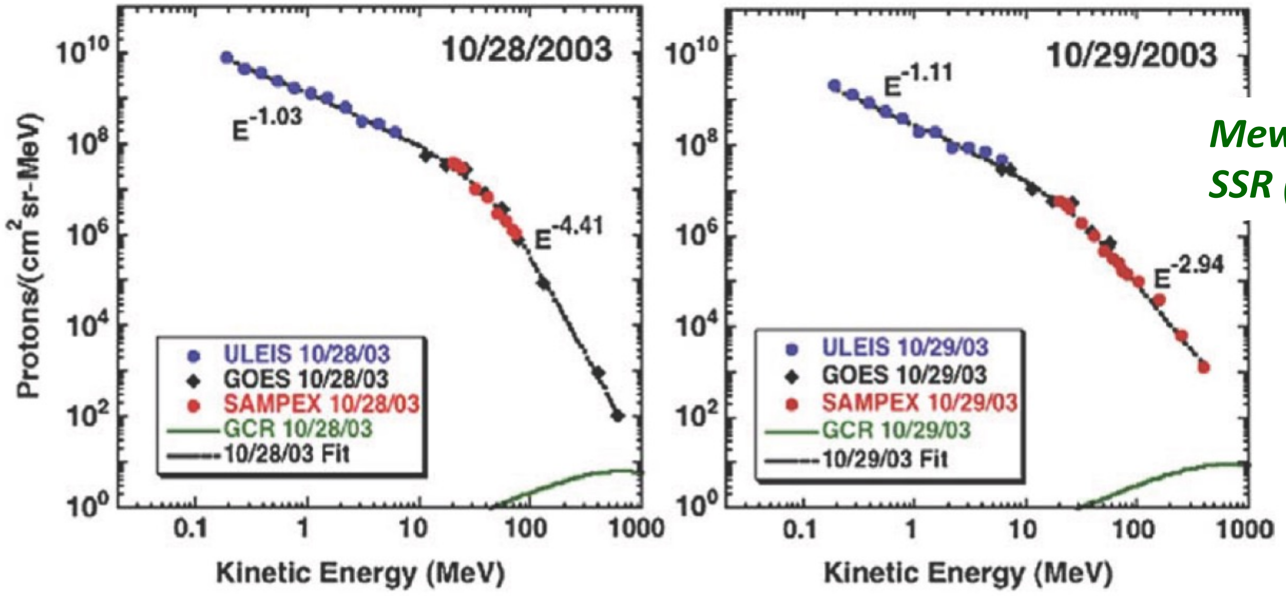
$$\kappa_{xx} = \kappa_\perp \sin^2\theta_{Bn} + \kappa_\| \cos^2\theta_{Bn}$$

Qualitatively consistent with spacecraft observations

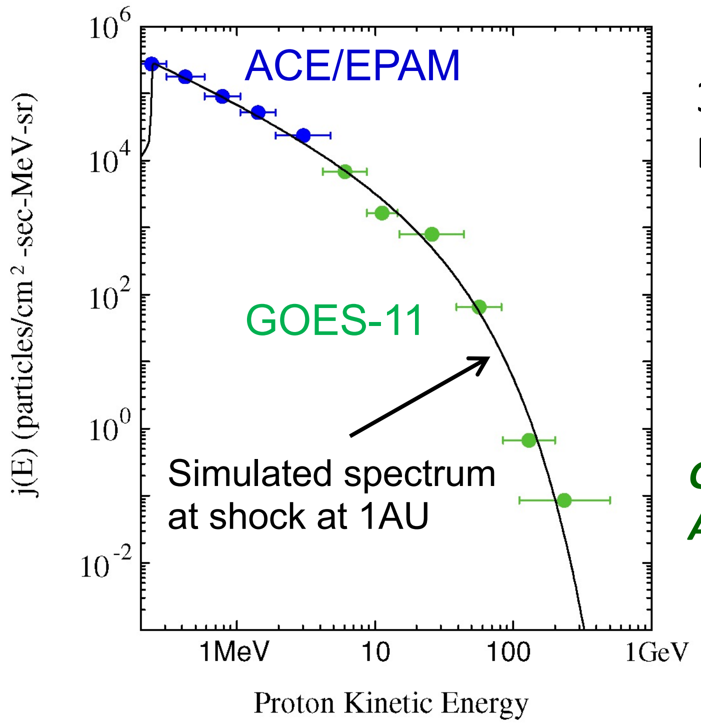
ACE multi-instrument data



Spectral breaks in SEP events

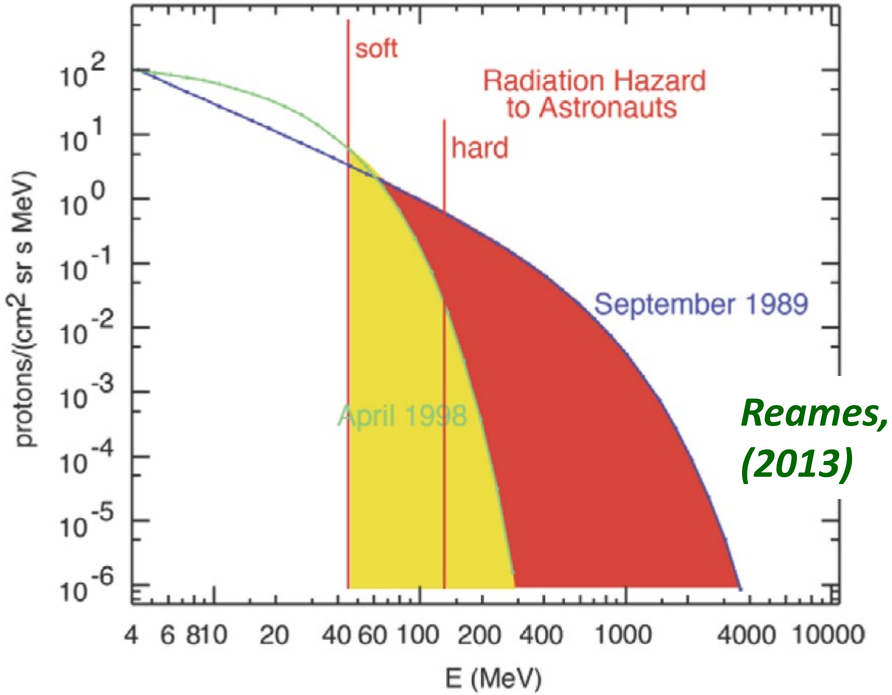


Mewaldt et al., SSR (2012)



302/2003
Event

Giacalone, ApJ, (2015)



Reames, (2013)

- **Large SEP events reveal hard power-law spectra at energies below a “cut-off” energy, (or spectral break energy)**
- **The spectrum is steeper at higher energies, sometimes even to another softer power law.**
- **The break energy is critical with regards to the energy content in SEPs.**
- **The precise cause of this is not well established**
  - Particle transport in IP space, or properties of local acceleration at the shock (finite age of the shock)?
  - “energy budget” and the local injection rate of particles at the shock?

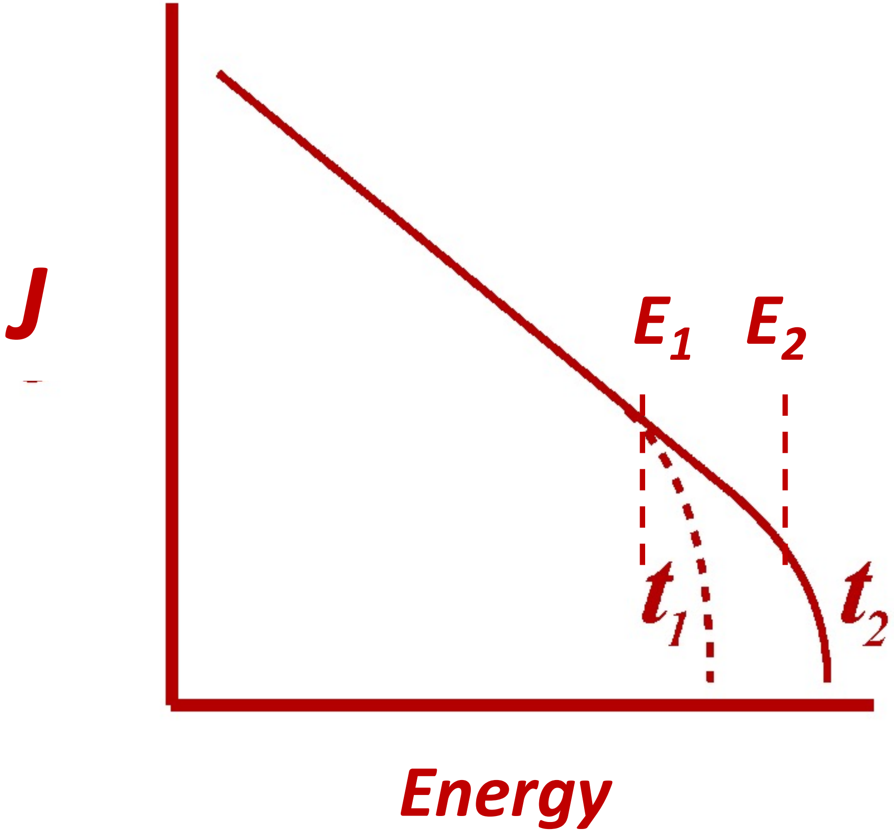
Acceleration time scale in DSA

For a planar shock, the time to accelerate particles from E_0 to E is

$$\tau_{acc} = \frac{(3/2)}{U_1 - U_2} \int_{E_0}^{E} \left(\frac{\kappa_1(E')}{U_1} + \frac{\kappa_2(E')}{U_2} \right) \frac{dE'}{E'}$$

Where κ is the diffusion coefficient normal to the shock front. The subscripts refer to upstream (1) and downstream (2) of the shock

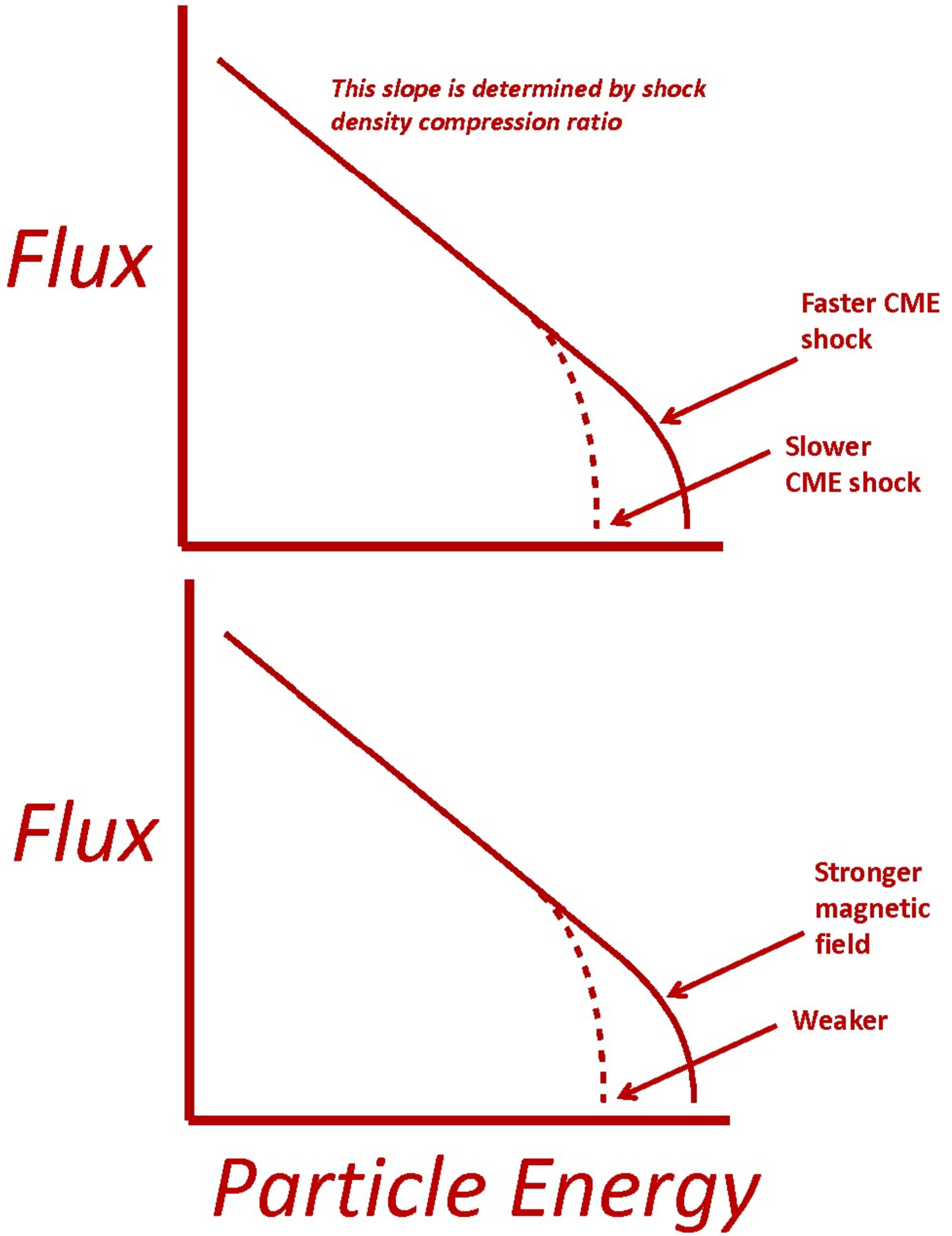
For a CME-driven, propagating shock, E is the "spectral break energy". Below this, the spectrum is power law, and above this it is steeper (sometimes to another power law).



The intensity at the highest energies depends critically on the spectral break energy, and, therefore, on the acceleration time scale (or rate).

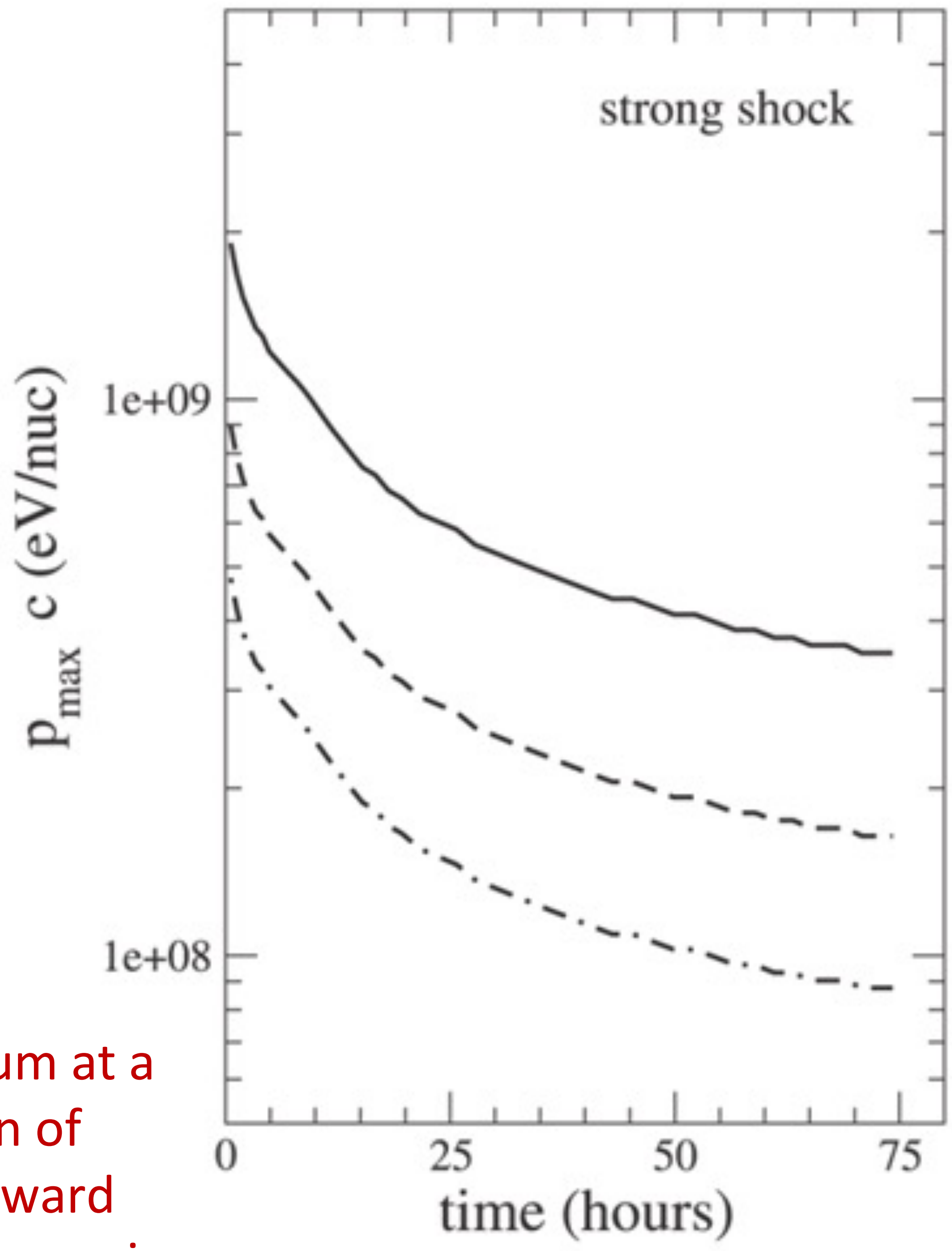
- A slower CME shock does not create as many high-energy particles as a faster one

- When the solar magnetic field is weaker, shocks do not create as many high-energy particles compared to when it is stronger



The spectral break energy likely evolves with distance from the Sun for a traveling shock

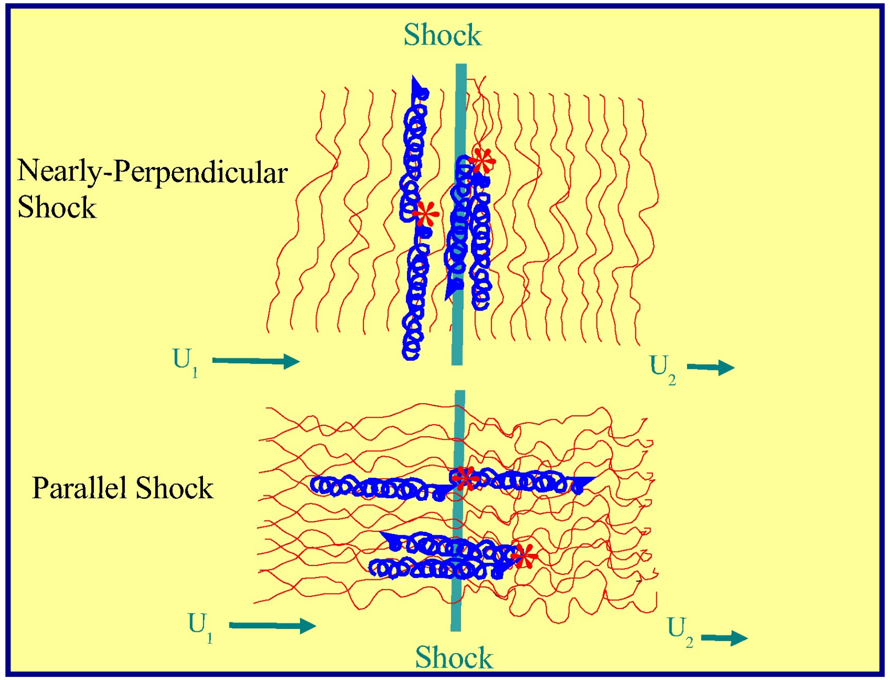
- The diffusion coefficient is likely considerably smaller (more rapid scattering) in the strong magnetic field near the Sun.
- Thus, the high-energy cutoff in the spectrum at the shock (represented by p_{max} in the plots shown) decreases with the shock's distance from the Sun
- This is due to the fact that B decreases with heliocentric distance



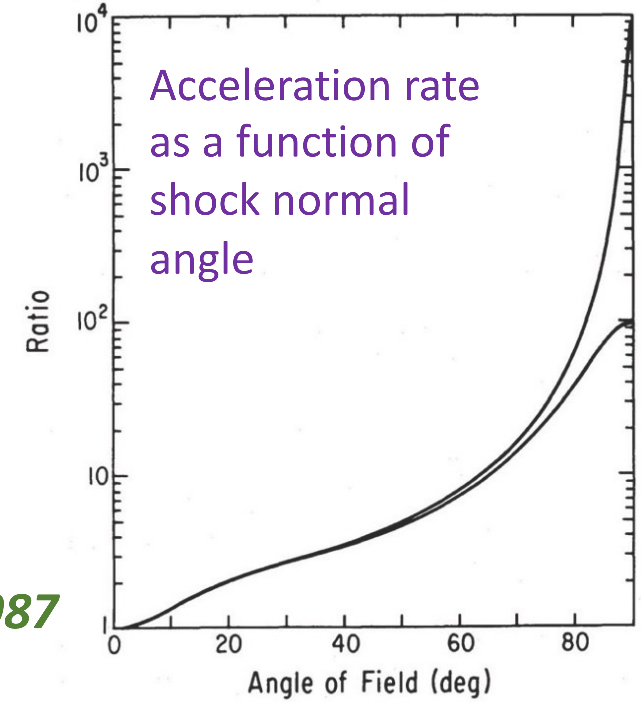
Cutoff energy in the spectrum at a traveling shock as a function of time. The shock moves outward from the Sun. The cutoff energy is highest close to the Sun

Li & Zank, 2005

Rate of acceleration depends strongly on the angle between magnetic field and unit normal to the shock



Highest maximum energies are attained at a "perpendicular shock"

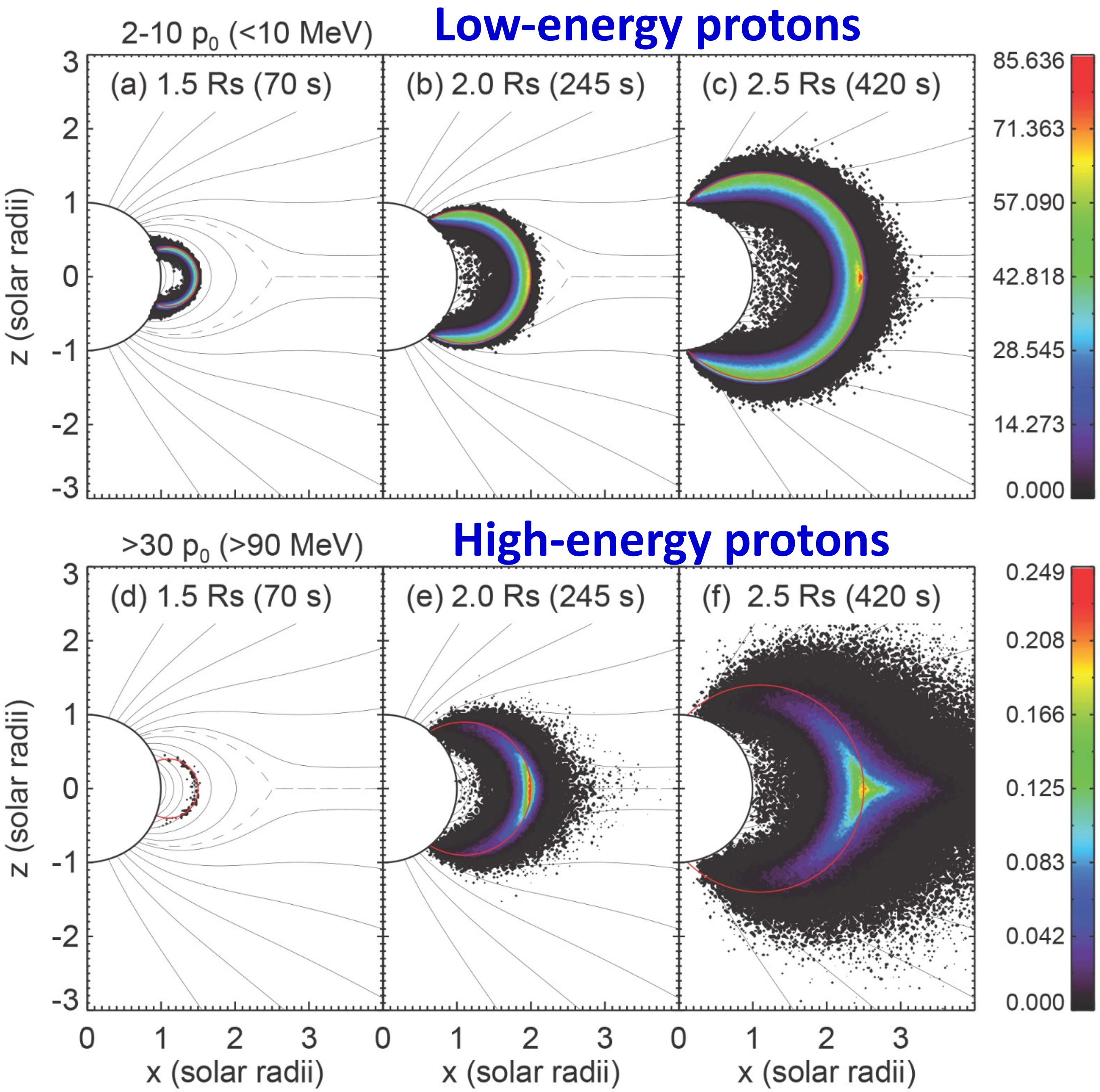


Jokipii, 1987

Particle acceleration at shocks in the low corona that move through closed-magnetic field loops (Kong et al., 2017, ApJ)

Highest energy particles most intense where the field is normal to the shock normal. Most rapid acceleration.

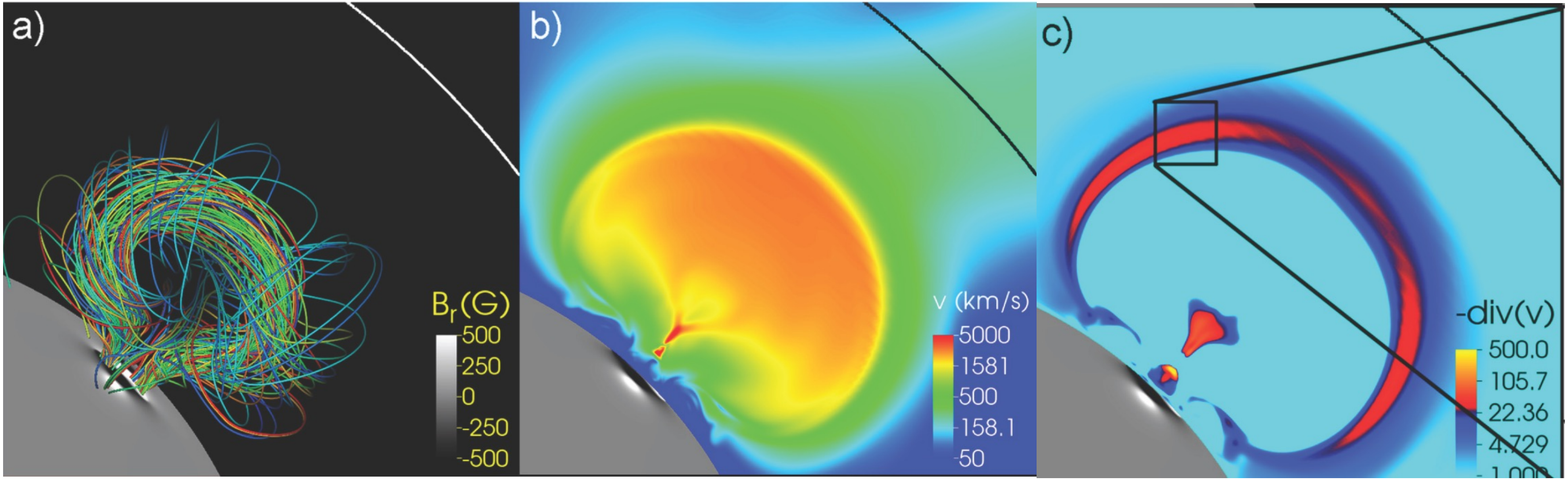
There is a variation in the intensity and spectrum along the shock



Variations along the shock can also result from variations in the plasma compression

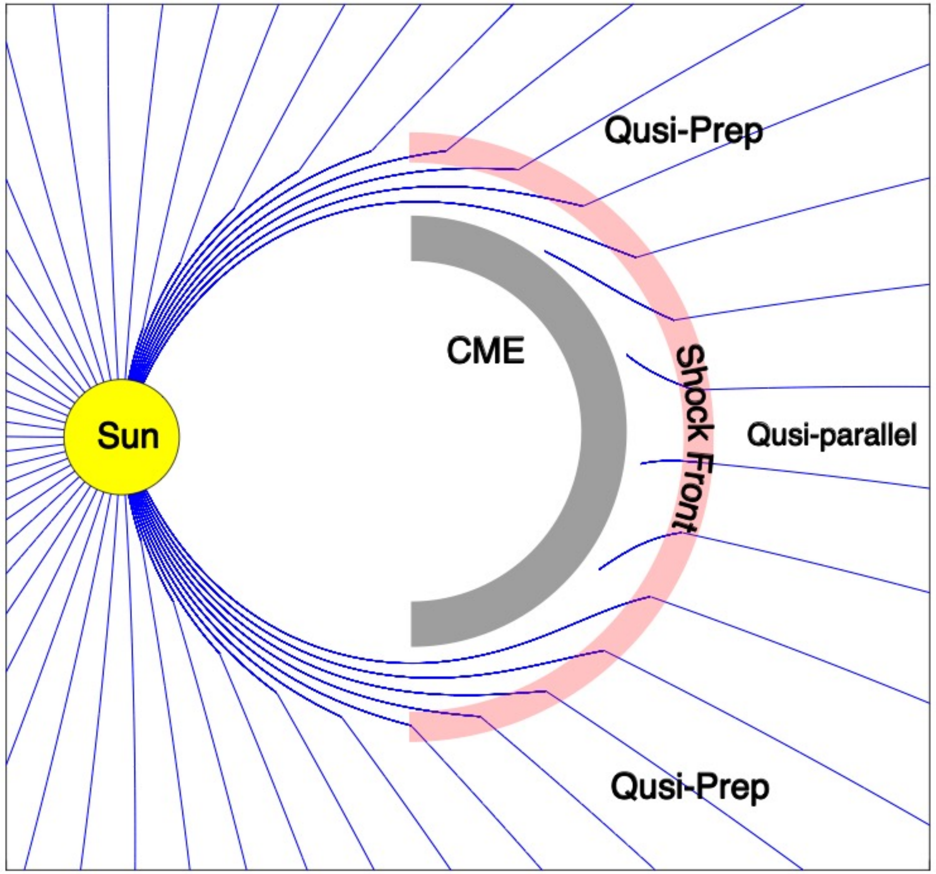
- In shock acceleration theory, the acceleration rate depends on div(U).

Schwadron et al., 2015

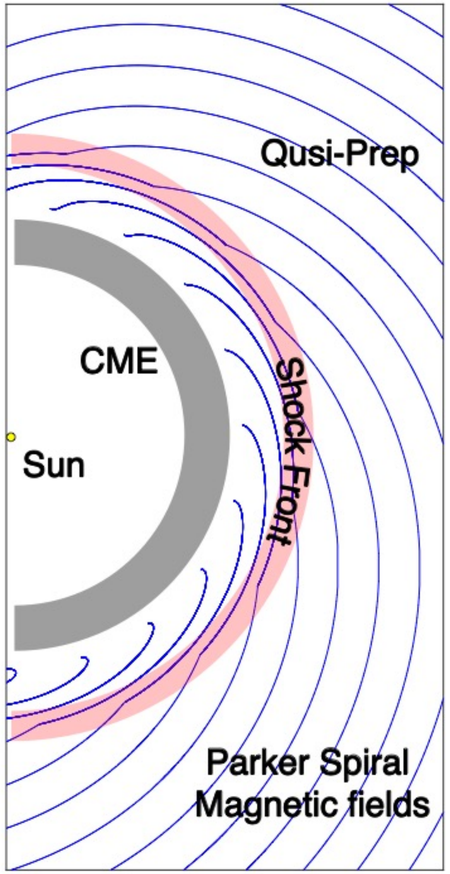


Particle acceleration at a shock in which the local magnetic-field / unit-shock-normal vary along the shock. This is the case of a CME-shock

Near the sun



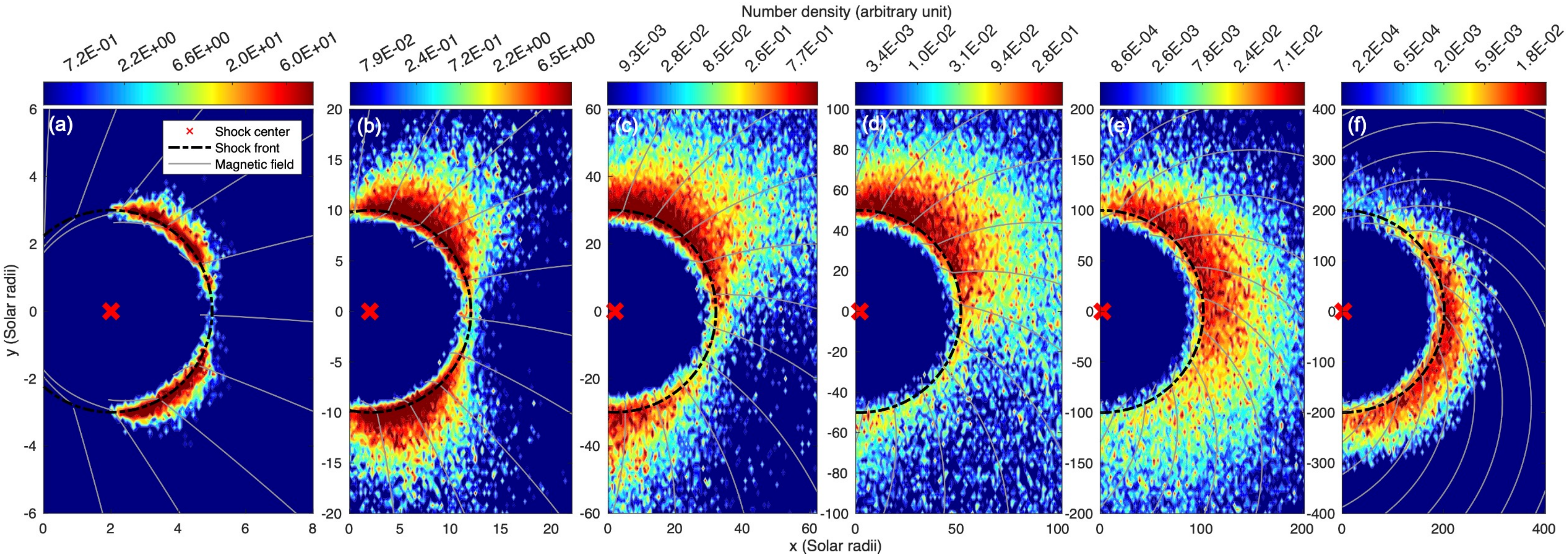
Far from sun



- The magnitude of IMF will decrease with the distance from the sun which is related to the cross-field diffusion.
- The direction of IMF will change from nearly radial to azimuthal as the increase of distance and the shock normal angle will also vary accordingly.
- The origin of the CME is offset from the center of the sun.

Work by Xiaohang Chen, University of Arizona, publication in preparation

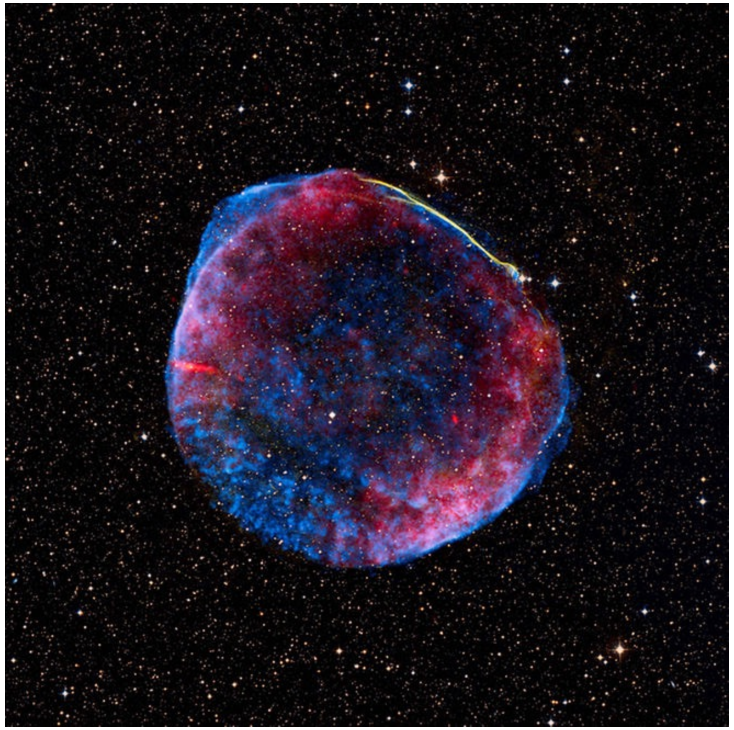
Particle acceleration at a shock in which the local magnetic-field / unit-shock-normal vary along the shock. This is the case of a CME-shock



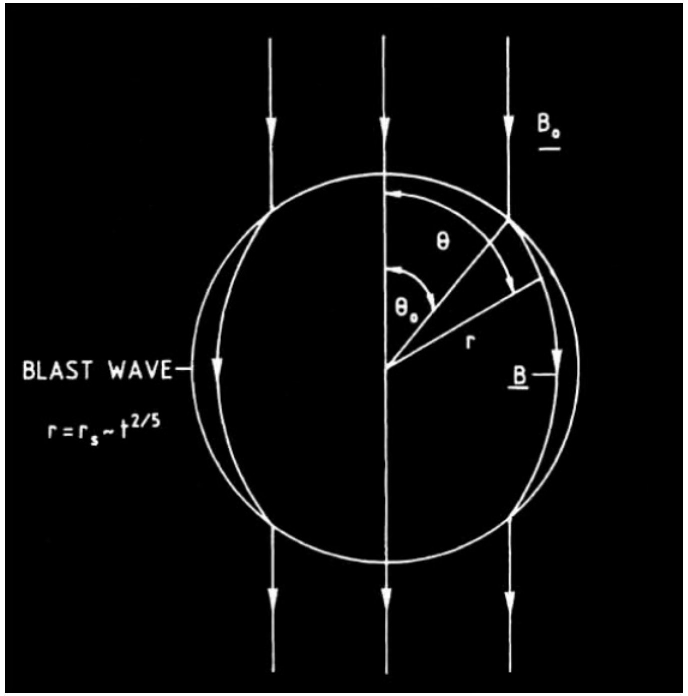
Work by Xiaohang Chen, University of Arizona, publication in preparation

A related, instructive, analogy: particle acceleration at a supernova blast wave

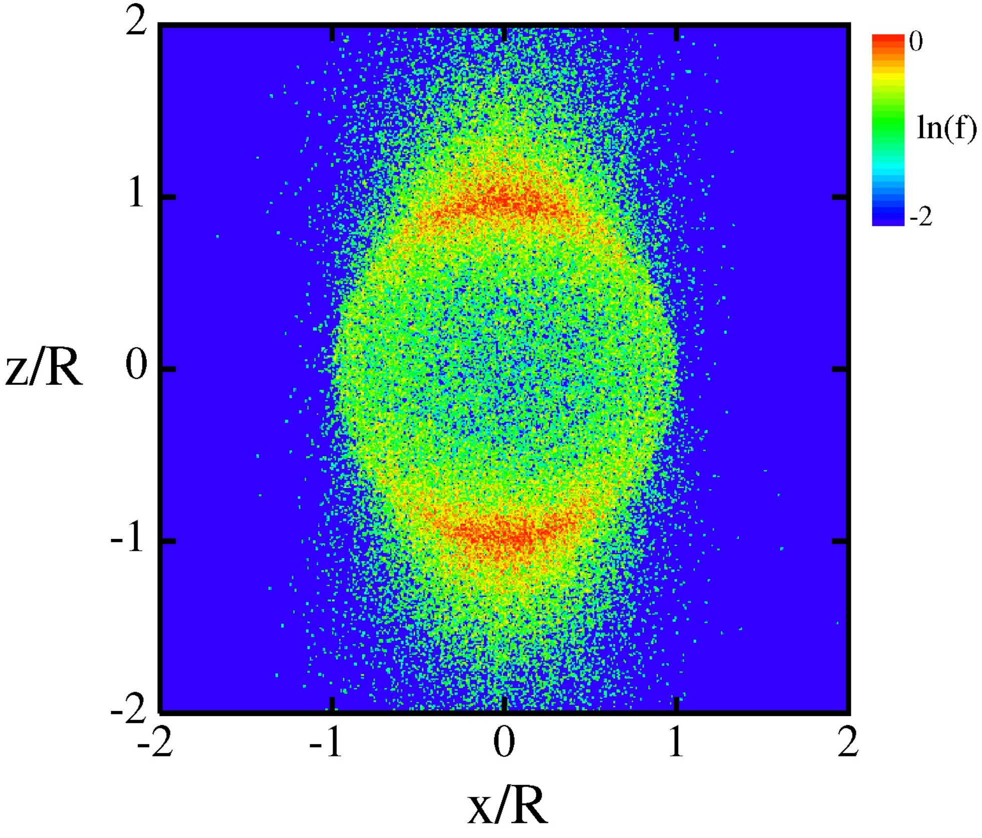
X-rays from SN1006



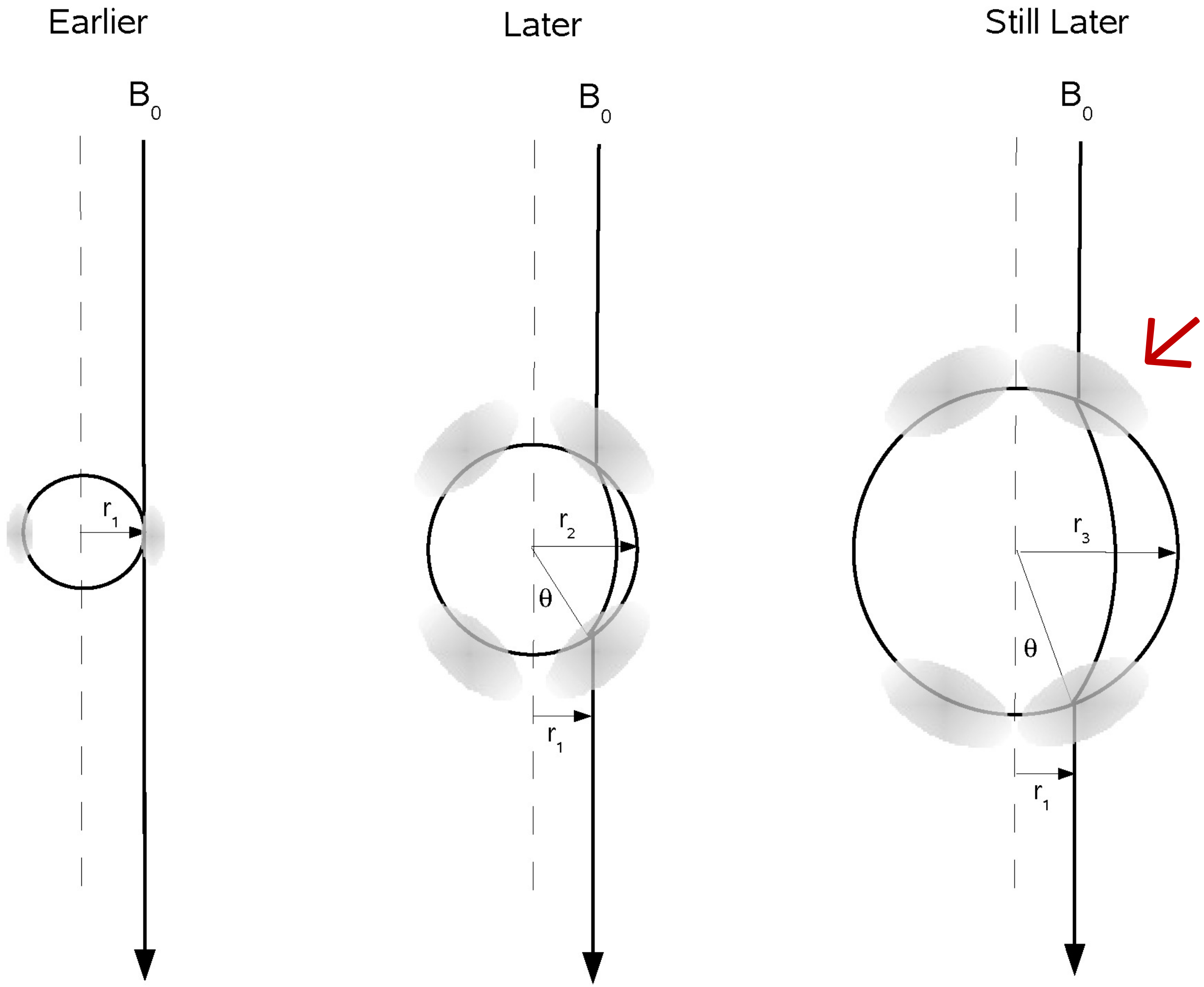
Basic picture



Numerical simulation (Giacalone, 2017)



A physical interpretation



The lines of force here have been connected to the shock the longest

MULTI-SPACECRAFT OBSERVATIONS

Combined SEP modeling at surface-fitting-models of observed CME shocks, evolving in the solar corona

Joint project between Xiaohang Chen, University of Arizona, and D. Lario, NASA/Goddar, publication in preparation

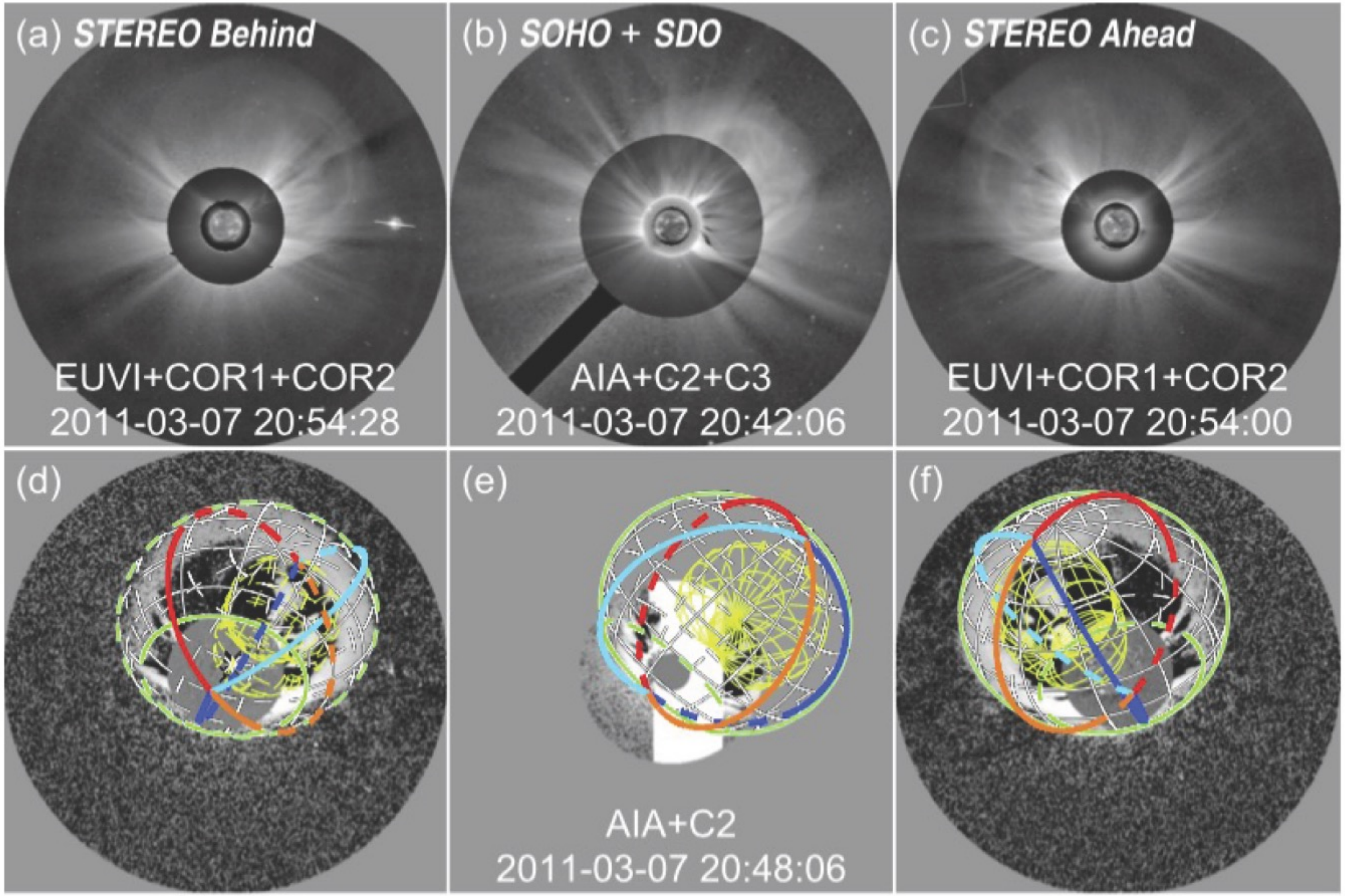
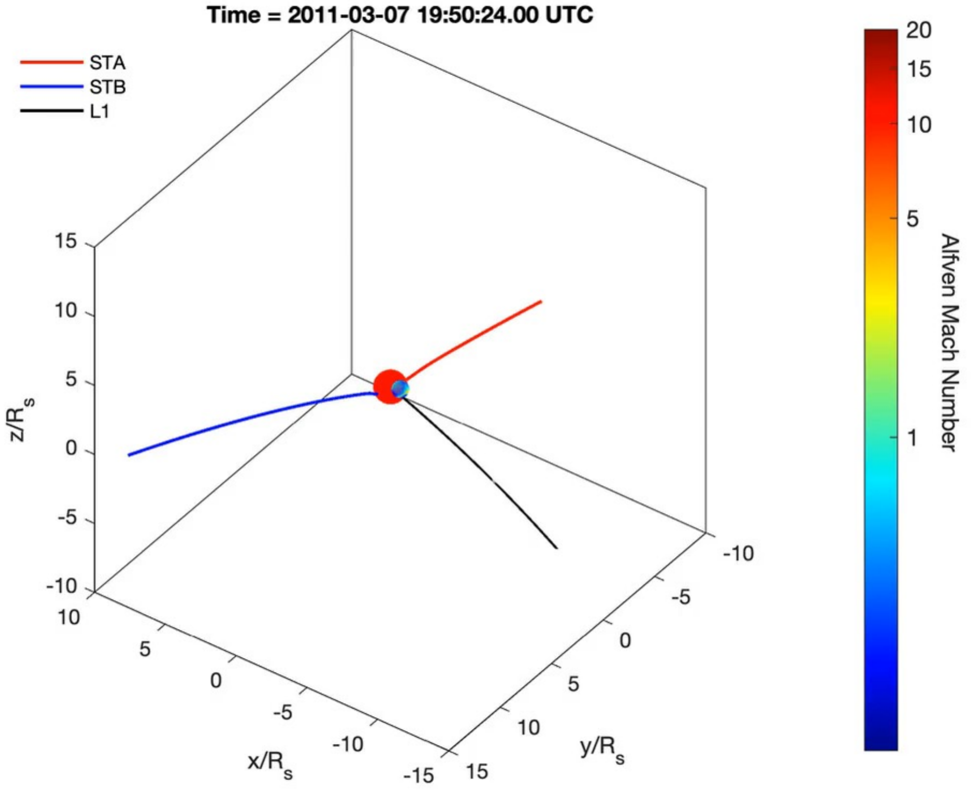
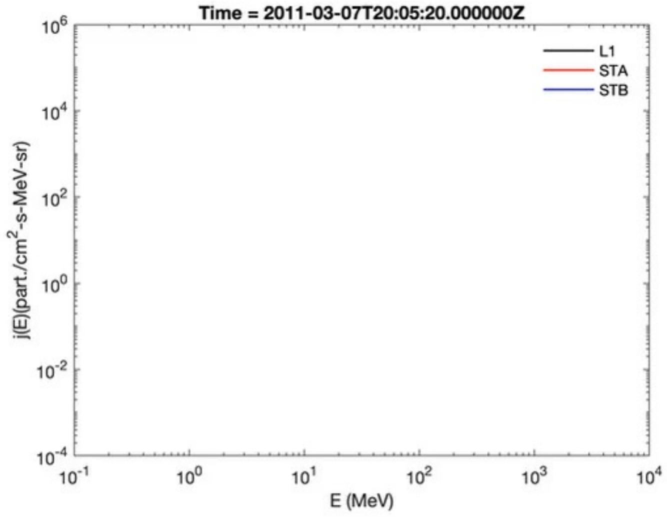


Figure 1. Observations of the H-CME on 2011 March 7 modeled with the ellipsoid model by Kwon and Vourlidas (2017).

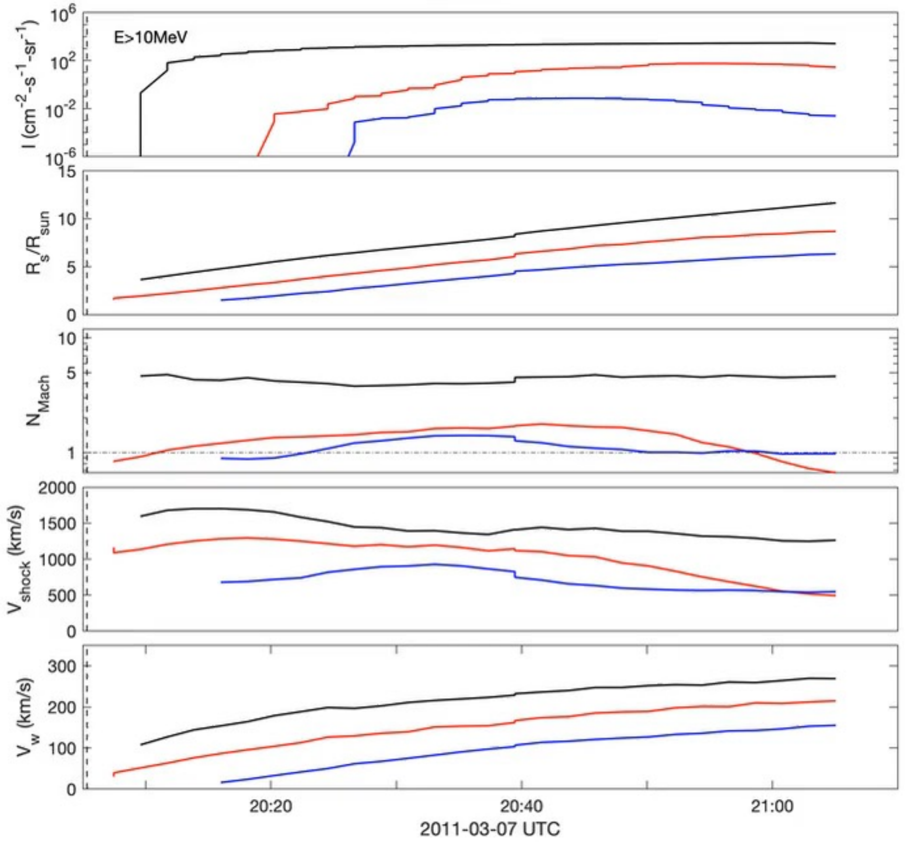
Variation of Mach number along the shock surface with time



Energetic particle spectra as a function of time



Various shock parameters as a function of time along the 3 connections at the left



The 3 paths represent the connection of the shock surface to 1AU observations (STA,STB,L1) along a nominal parker-spiral field

Conclusions

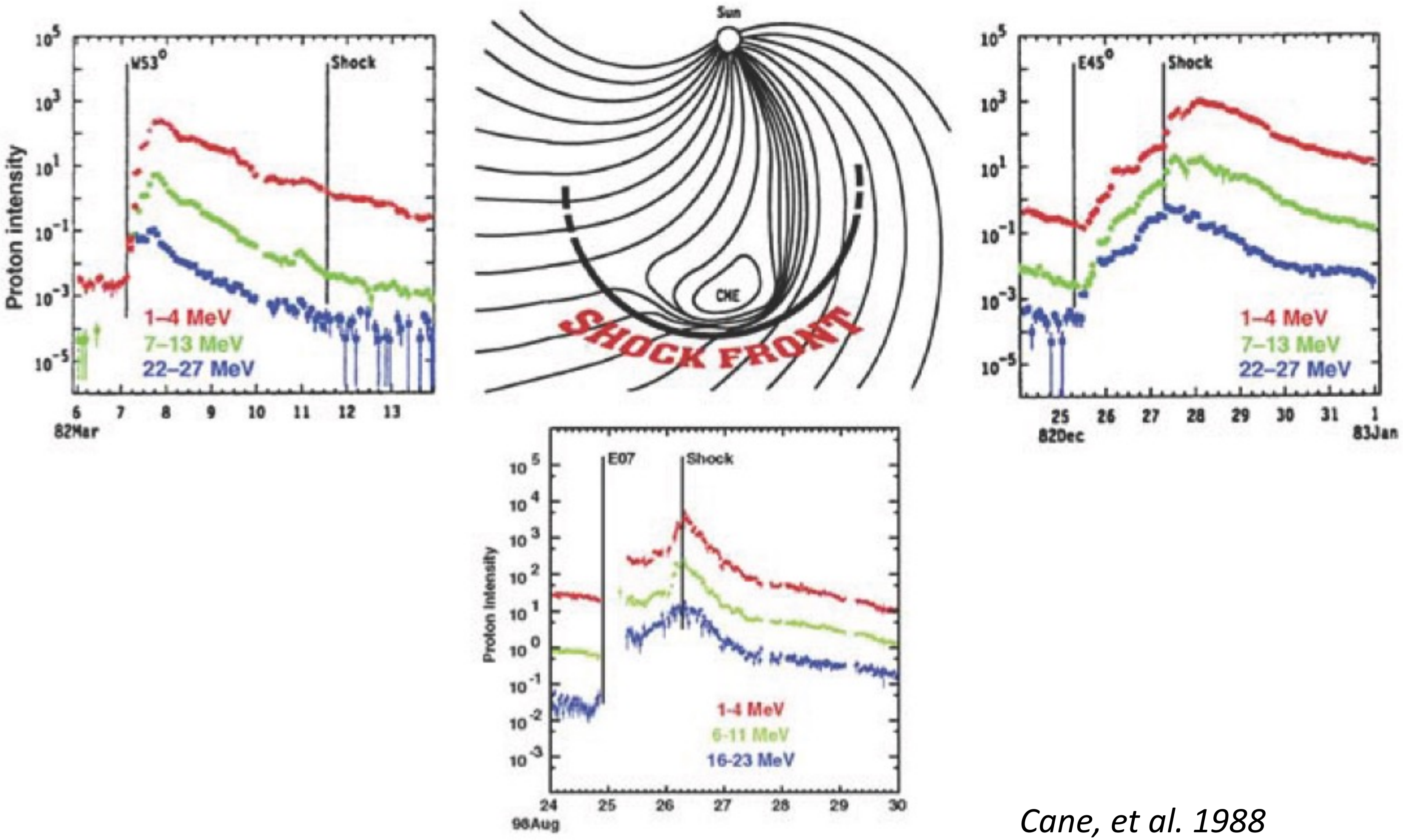
- Understanding SEPs associated with CME-driven shocks – which are among the largest SEP events we observe – would benefit greatly from knowing the evolution of the magnetic field along the shock front as the shock moves from near the Sun to 1AU.
- Theory (& numerical simulations) predict that there should be variation in the intensity and spectrum of SEPs along the shock front as it moves outward from the Sun, in a non-trivial way and depends on the morphology of the shock front and magnetic field, and speed of the shock.
- Coordinated observations from PUNCH along with PSP, SO, and STA, and others will be extremely beneficial.

In addition to the variation in energy an radial distance, the intensity and spectra of SEPs depends on longitude as well.

This is mostly determined by the magnetic-field-line-connection between the observer and shock.

Variations along the shock front may also occur.

This has almost exclusively been studied with a single spacecraft. STEREO could provide such observations, but the separation changes with time, and there have been other complications (STB unavailable, no or few events to study, etc.)



Cane, et al. 1988