Particle Acceleration at Shocks: The Role of Turbulence, Magnetic Field, and Shock Morphology

- Energetic particles in space share one common characteristic: they have energy spectra that are usually ***power laws*** (below a characteristic energy imposed by losses or finite acceleration time).

- Any acceleration mechanism must reproduce this feature ***naturally*** without having to rely on unknown quantities, or one in which the power-law index depends on quantities that vary by orders of magnitude

- Many mechanisms have been proposed, but the one that has received the most attention is acceleration by shocks

Joe Giacalone, University of Arizona KITP Astro Plasmas Conf
Sep 28, 2009

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

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

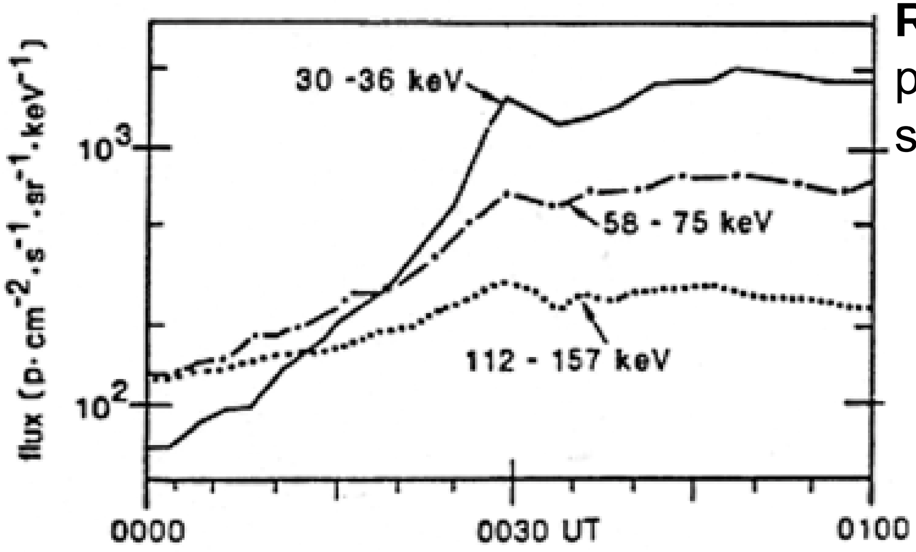
advection ***diffusion*** ***drift*** ***energy change***

- The steady-state solution for a 1D shock (with an infinite upstream region), is given by

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

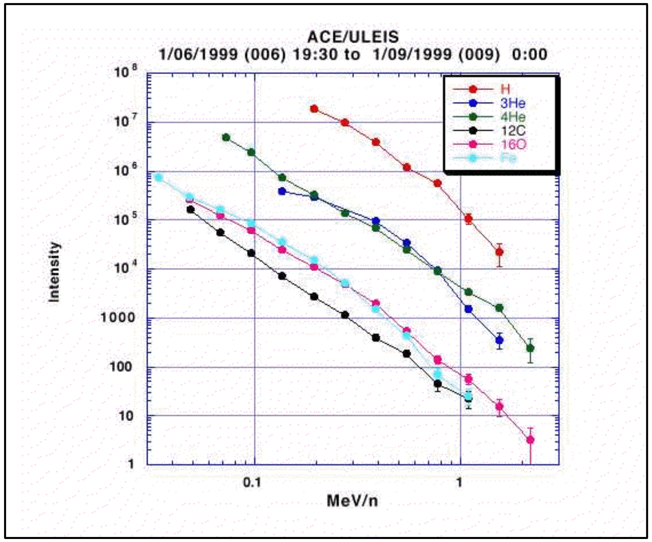
where $\gamma = 3U_1/(U_1 - U_2) \;=\; 3r/(r-1)$

r= plasma density jump across shock

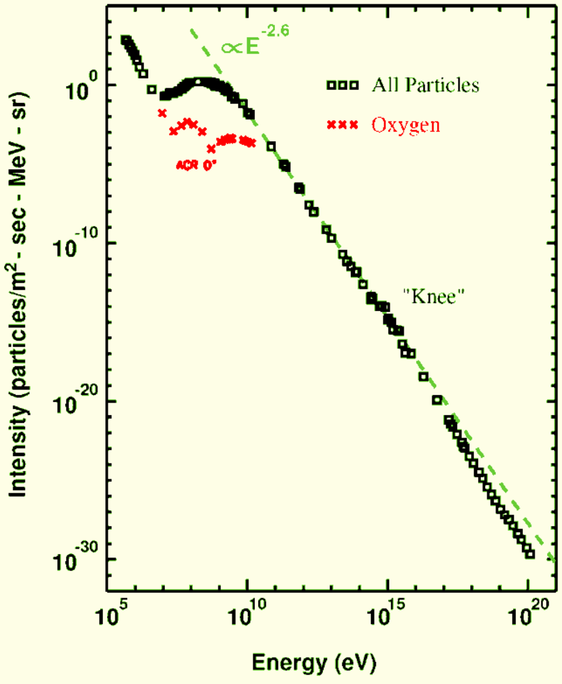


Rare observation of energetic particles at a traveling interplanetary shock

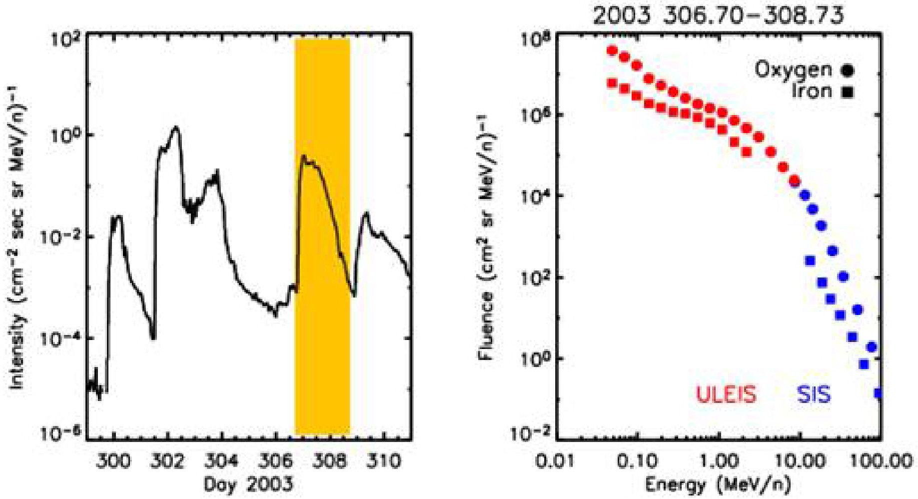
Impulsive SEPs



Cosmic-Ray Spectrum



Gradual SEPs



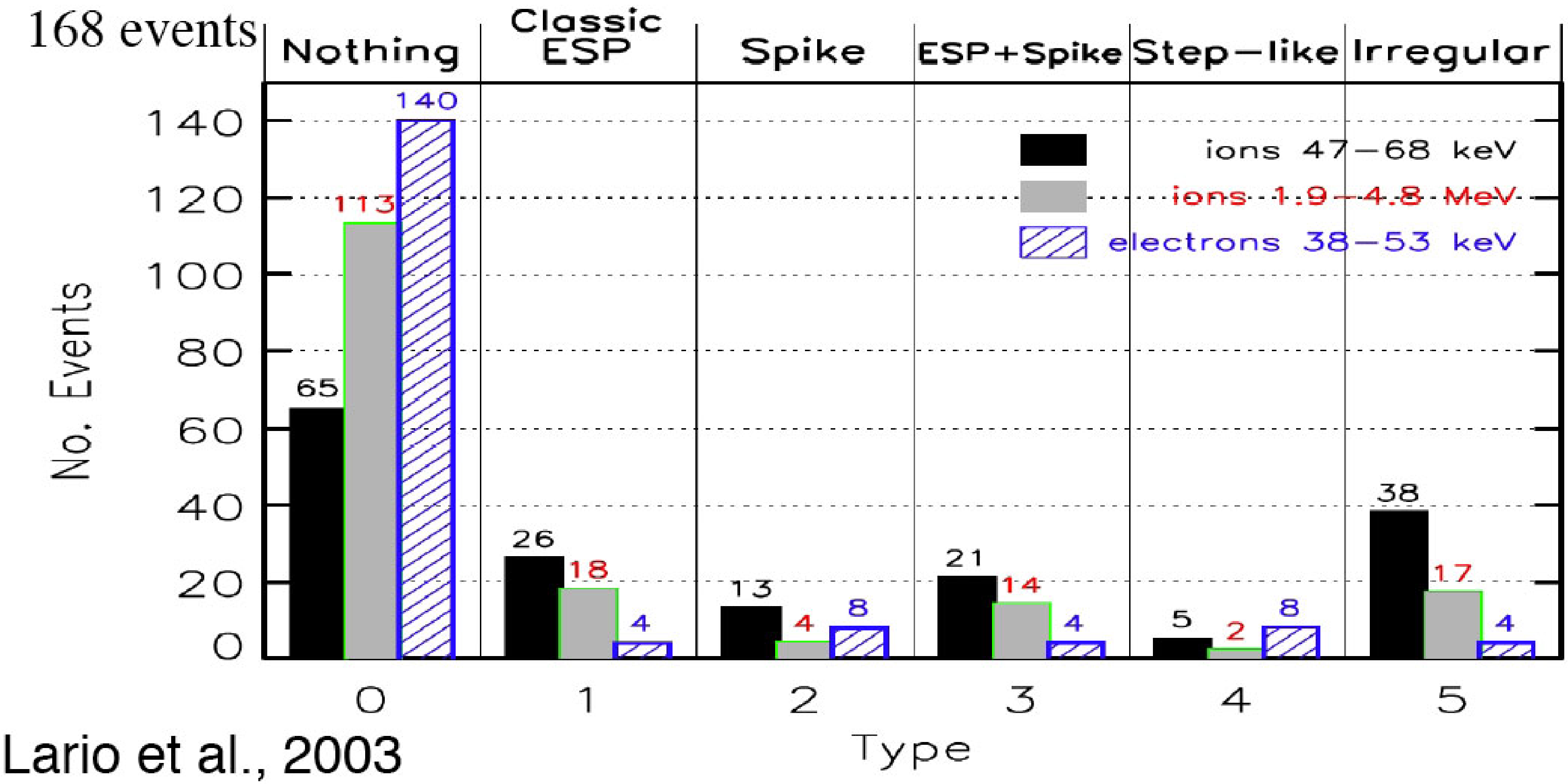
Shocks and Energetic Particles: Some Lessons from the Heliosphere

- Energetic particles don’t often peak at the shock
  - Termination shock: high-energy ACRs did not peak until well downstream
  - Most interplanetary shocks have no associated energetic particles
- Large mean-free paths and anisotropies
  - At 1 MeV $\lambda_{||} > 100 r_G$ $\kappa_{||} \gg \kappa_{\perp}$
- Energetic-particle induced magnetic fluctuations not often seen upstream of shocks

- **Pre-existing large-scale plasma and magnetic-field turbulence play an important role**
- **Magnetic–field direction and morphology is also important**

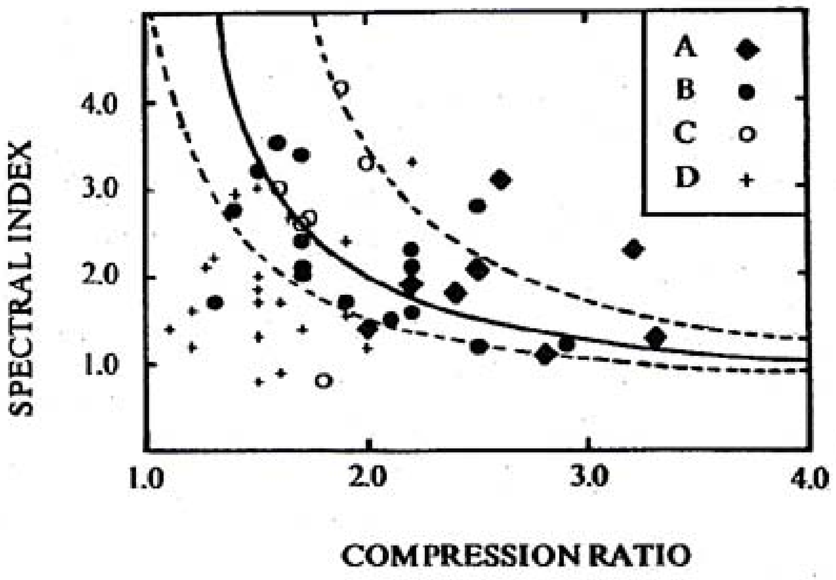
Most interplanetary shocks in the heliosphere are not seen to be associated with energetic particles.

How well is this really understood?



Lario et al., 2003

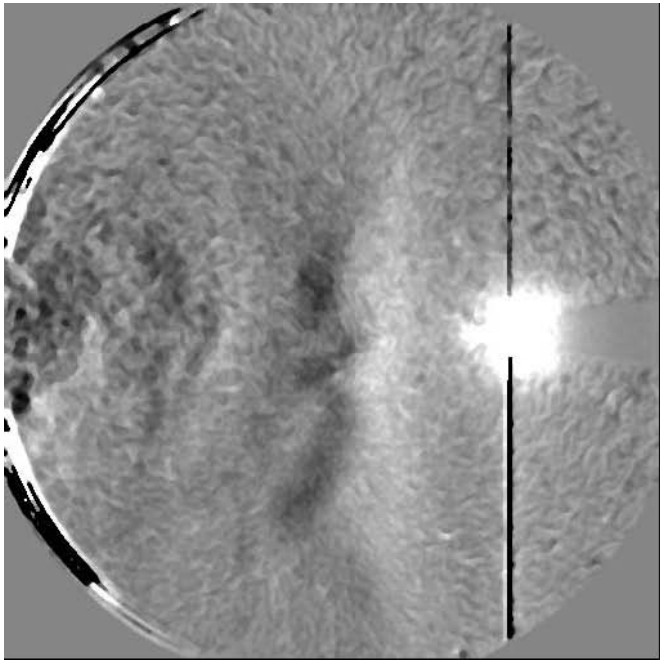
- The predicted simple relationship between the shock strength and spectral index of energetic particles is not well established by *in situ* spacecraft observations



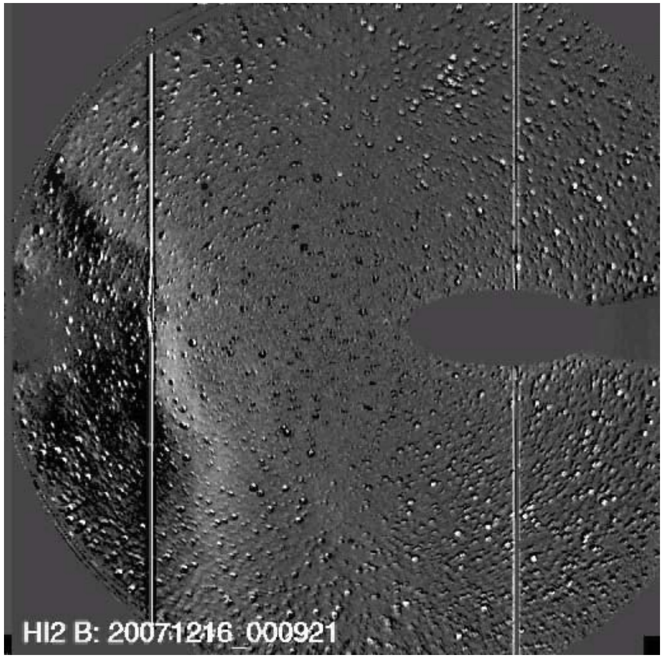
Van Nes et al., 1984

This is most likely caused by the effects arising from interplanetary solar-wind and magnetic-field turbulence

“rippled” interplanetary disturbances (STEREO/HI2 difference images)



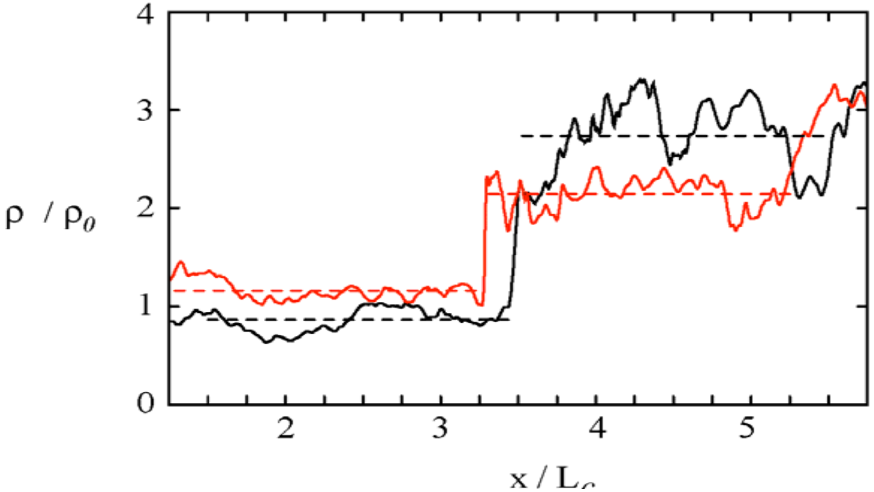
May, 27 2008



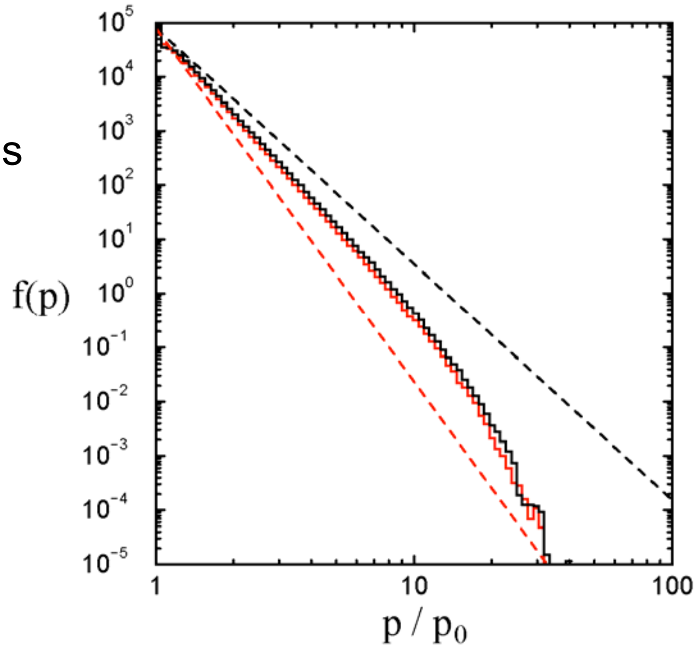
Dec 16 2007

- In addition, Neugebauer & Giacalone (2005) used multi-spacecraft observations to show that interplanetary shock fronts are rippled on a scale similar to the coherence scale of interplanetary turbulence

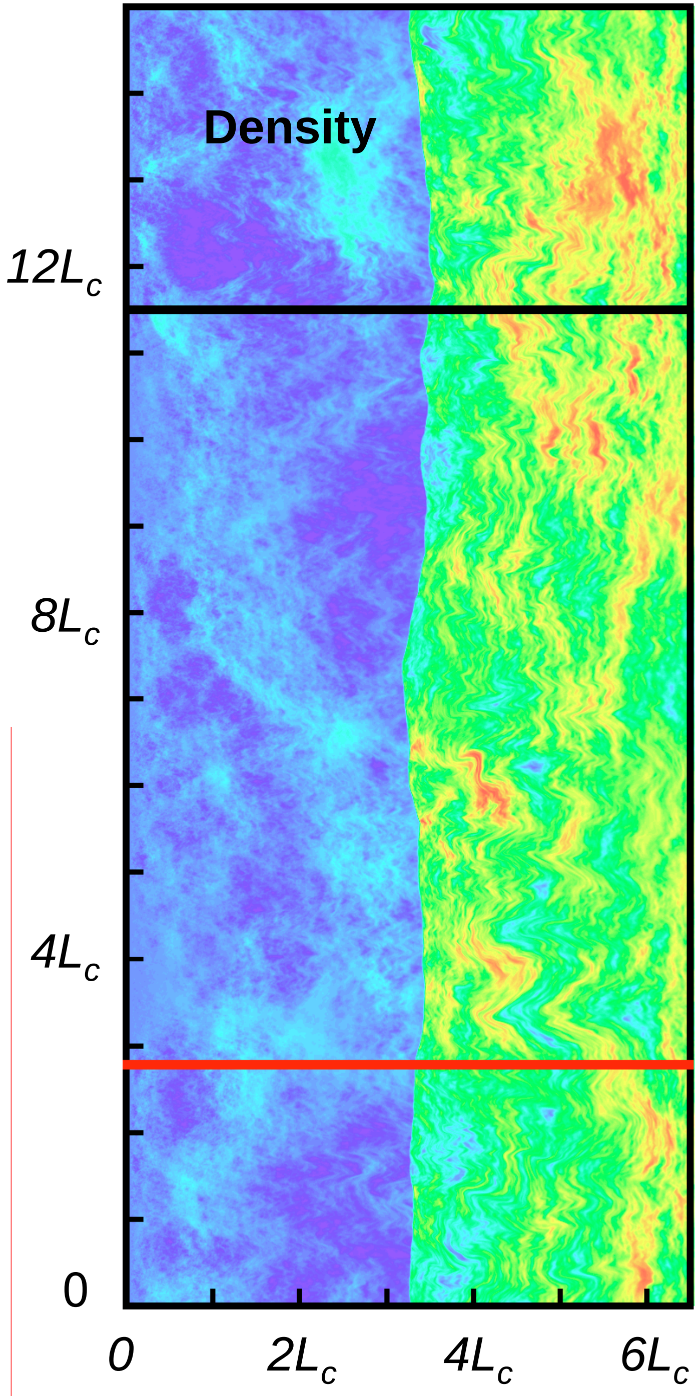
MHD/Energetic-Particle simulation of shock moving through turbulence



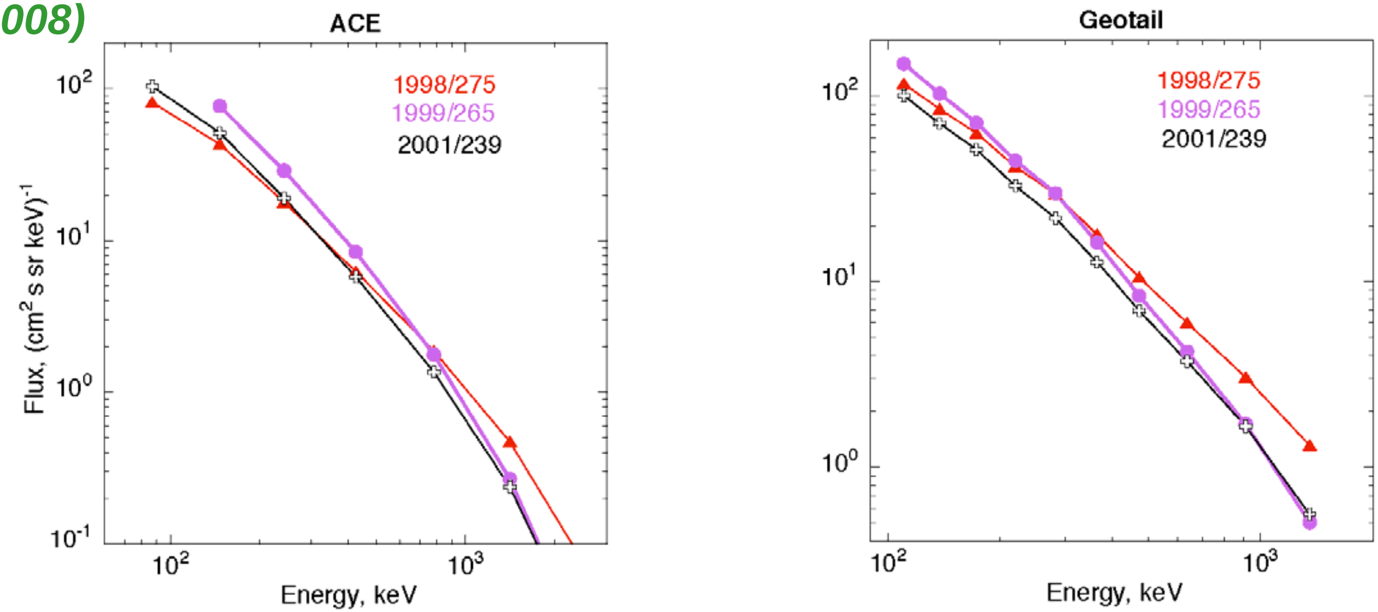
Distribution of energetic particles along these two slices

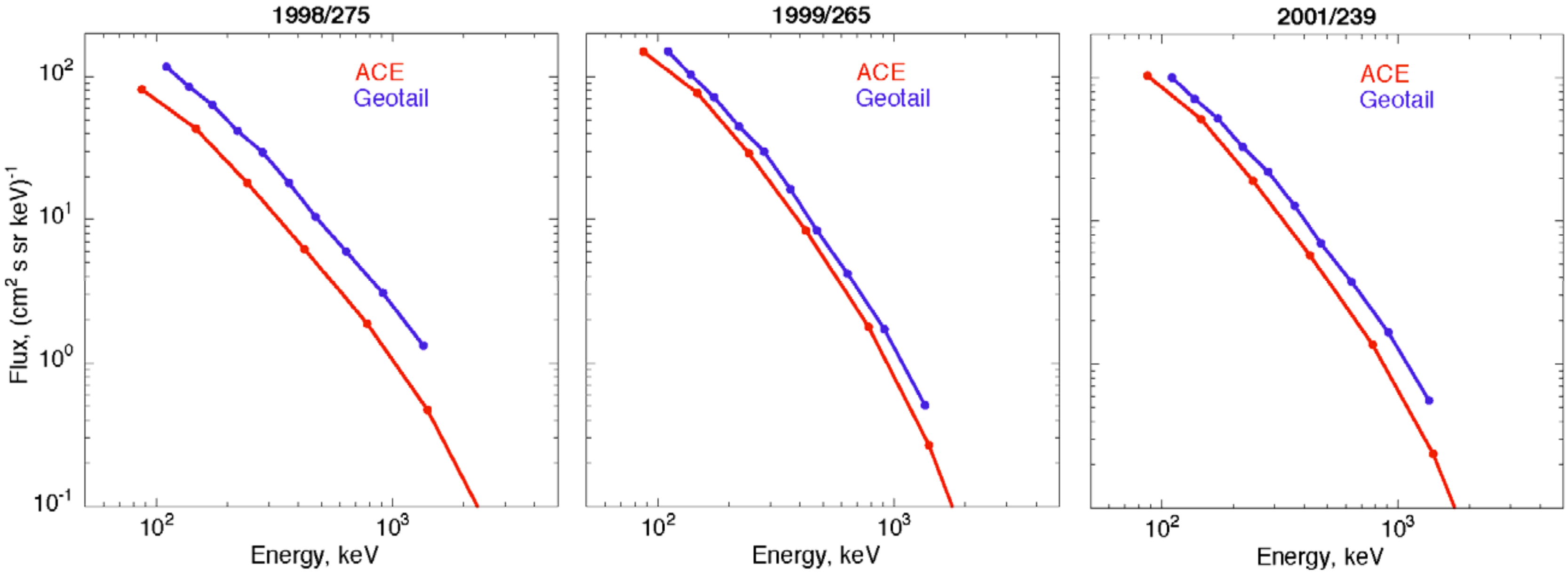


Giacalone & Neugebauer (2008)



Giacalone & Neugebauer (2008)





Importance of Magnetic-Field Angle in Shock Acceleration

- The maximum energy in diffusive shock acceleration is limited either by geometry (size of shock) or by a finite time.

  Acceleration takes time. The ideal power law energy spectrum is not created instantly.

- The maximum energy over a given time interval strongly depends on the shock-normal angle

  Parallel shocks → slow

  Perpendicular shocks → fast

- Hence, for any given situation (e.g. age of shock), a perpendicular shock will yield a larger maximum energy than a parallel shock.

Acceleration Rate as a Function of Shock-Normal Angle:

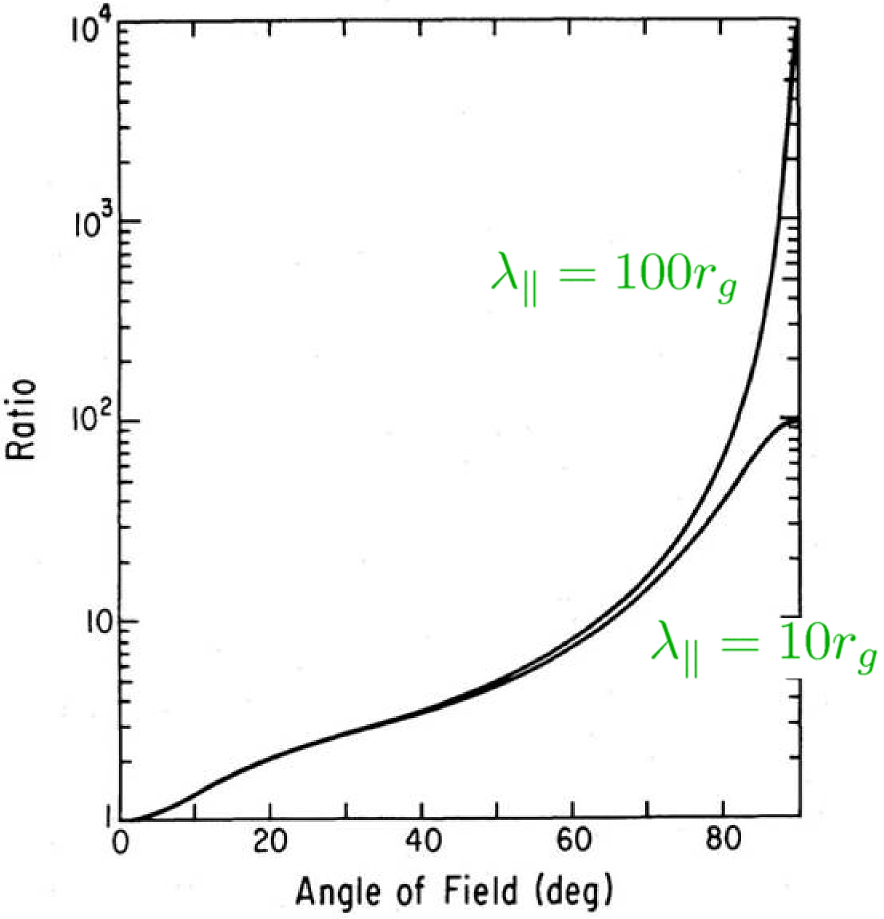
Rate of acceleration at momentum p_c

$$\frac{1}{p_c}\frac{dp_c}{dt} \propto \frac{U_{sh}}{\kappa_{xx}}$$

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

billiard-ball-like scattering assumed
in the figure at the right

$$\kappa_\perp = \left(\frac{r_g}{\lambda_\|}\right)^2 \kappa_\|$$



Jokipii (1987)

The “injection problem”

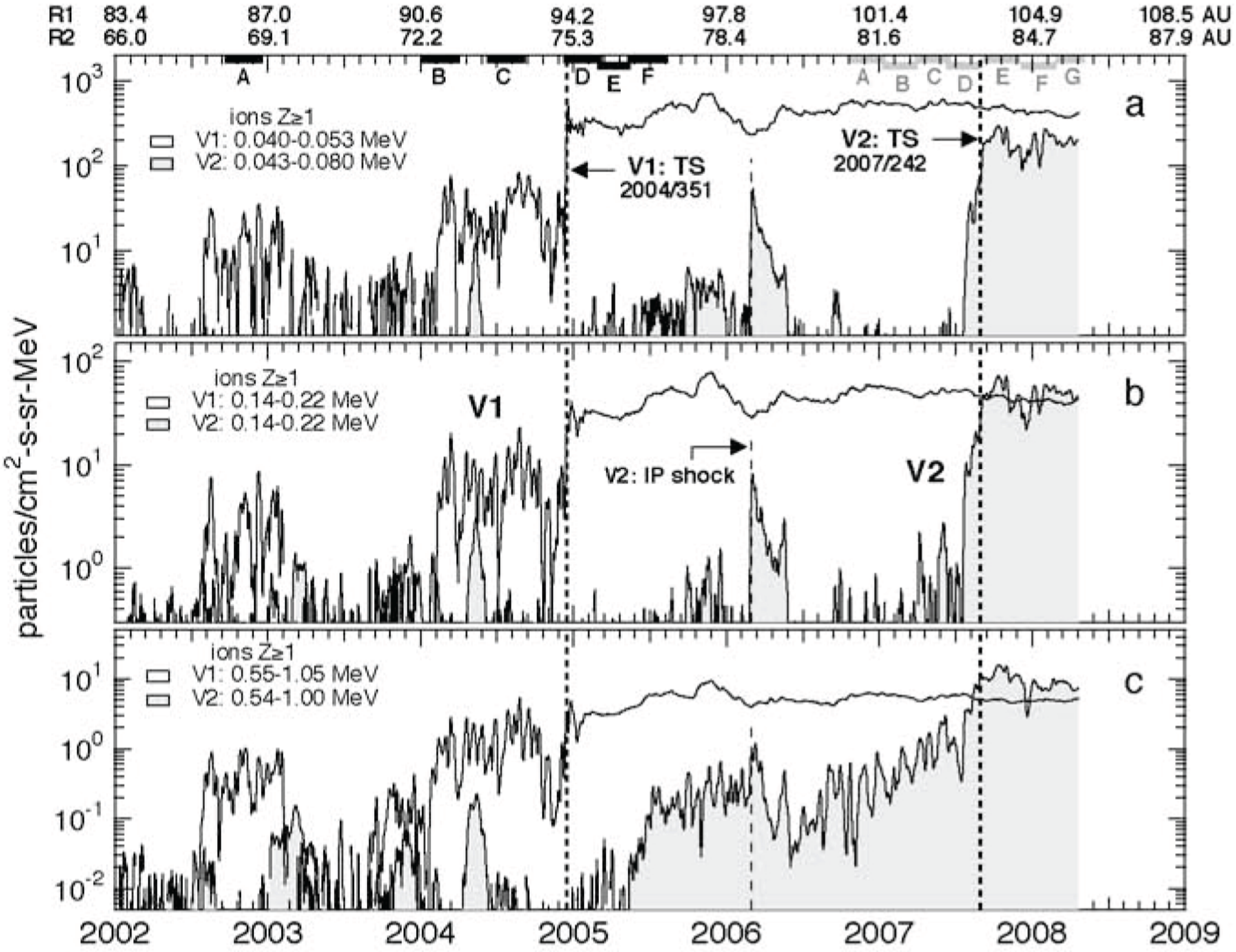
(the problem of accelerating low-energy ions)

- An often-invoked injection (lower limit) criterion is

$$v_{inj} > U_{sh} \sec \theta_{Bn}$$

- This assumes, for no good reason, that there is NO motion normal the average magnetic field
- This expression has led to a *widely held misconception* that perpendicular shocks are inefficient accelerators of particles
- In astrophysical plasmas, large-scale magnetic turbulence leads to cross-field diffusion, which increases the motion of low-energy particles allowing them to remain near the shock and be accelerated, thereby overcoming the problem of injection

Voyager Observations of Energetic Ions at the Termination Shock

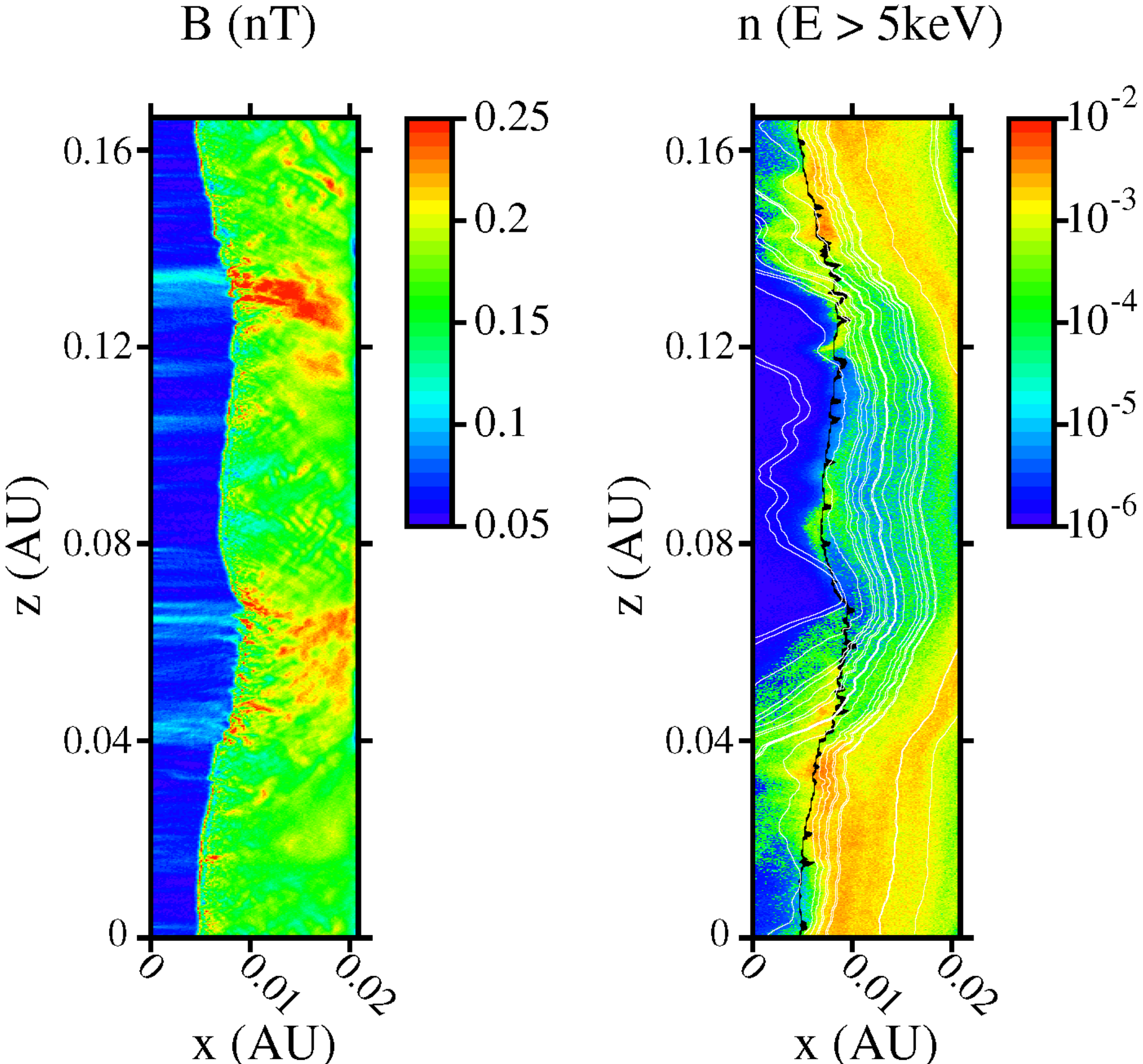


Decker et al. (2008)

No injection problem at the nearly perpendicular termination shock!

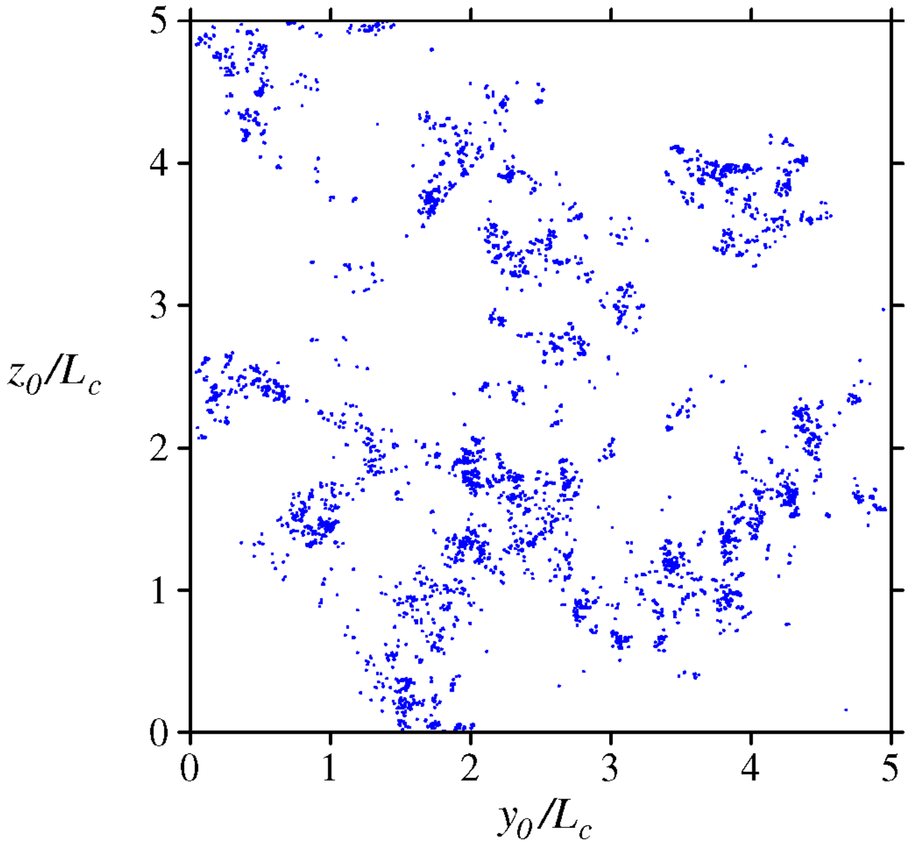
Hybrid simulations of a perpendicular shock moving through large-scale turbulence: efficient acceleration of low-energy ions

Simulation of pickup-ion acceleration at the solar-wind termination shock (Giacalone & Decker, 2009)



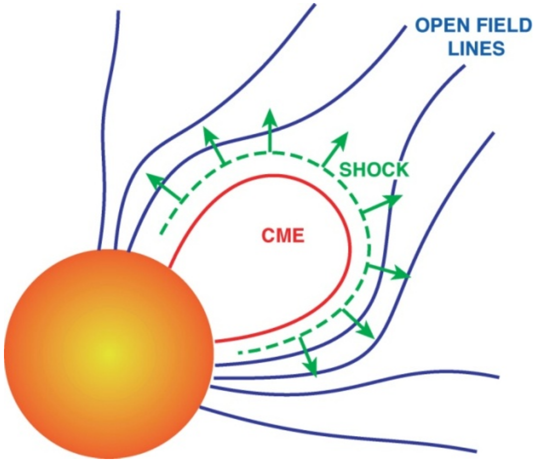
Non-uniform injection arising from large-scale turbulence

- Locations of particles (projected onto the plane normal to the unit shock normal) that eventually become energetic particles, when they first encountered the shock,

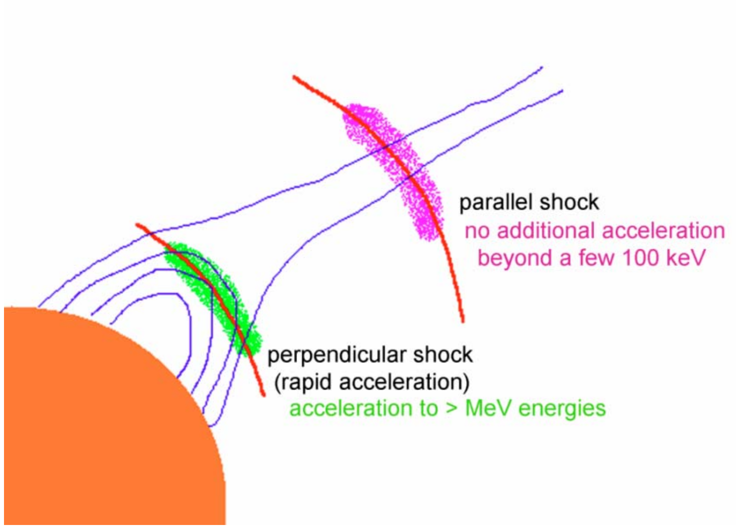


Giacalone & Jokipii, ApJ, 2009

Importance of magnetic field direction and shock morphology



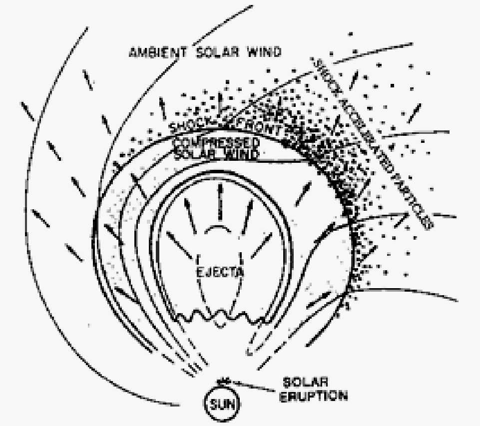
In the solar corona


parallel shock

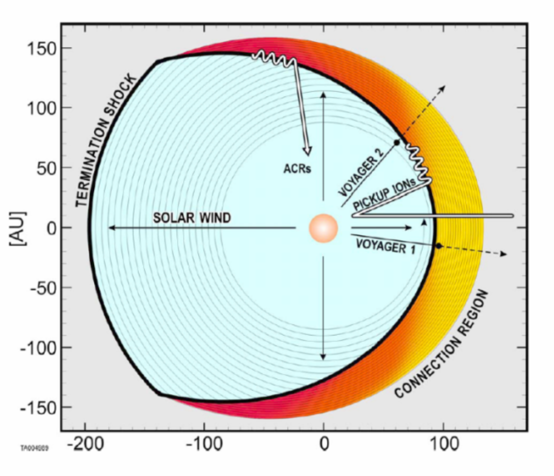
no additional acceleration beyond a few 100 keV

perpendicular shock (rapid acceleration)

acceleration to > MeV energies



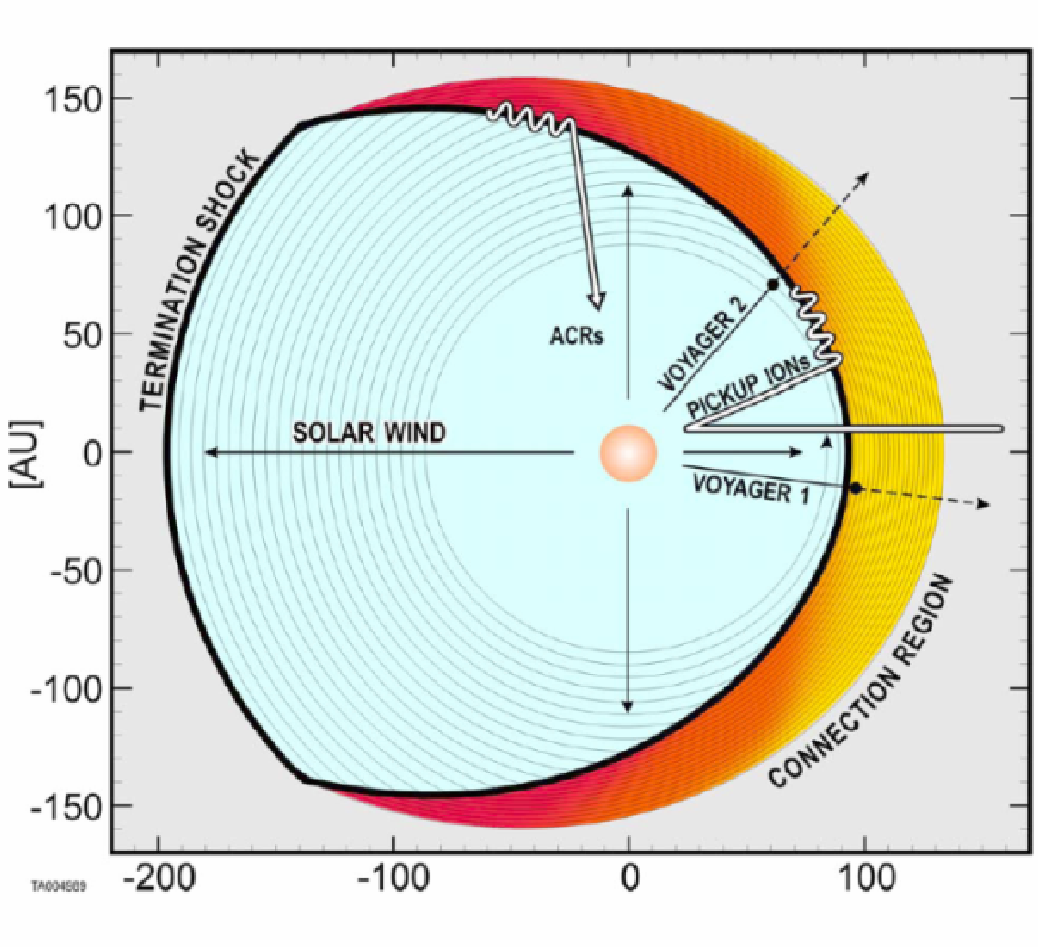
In interplanetary space

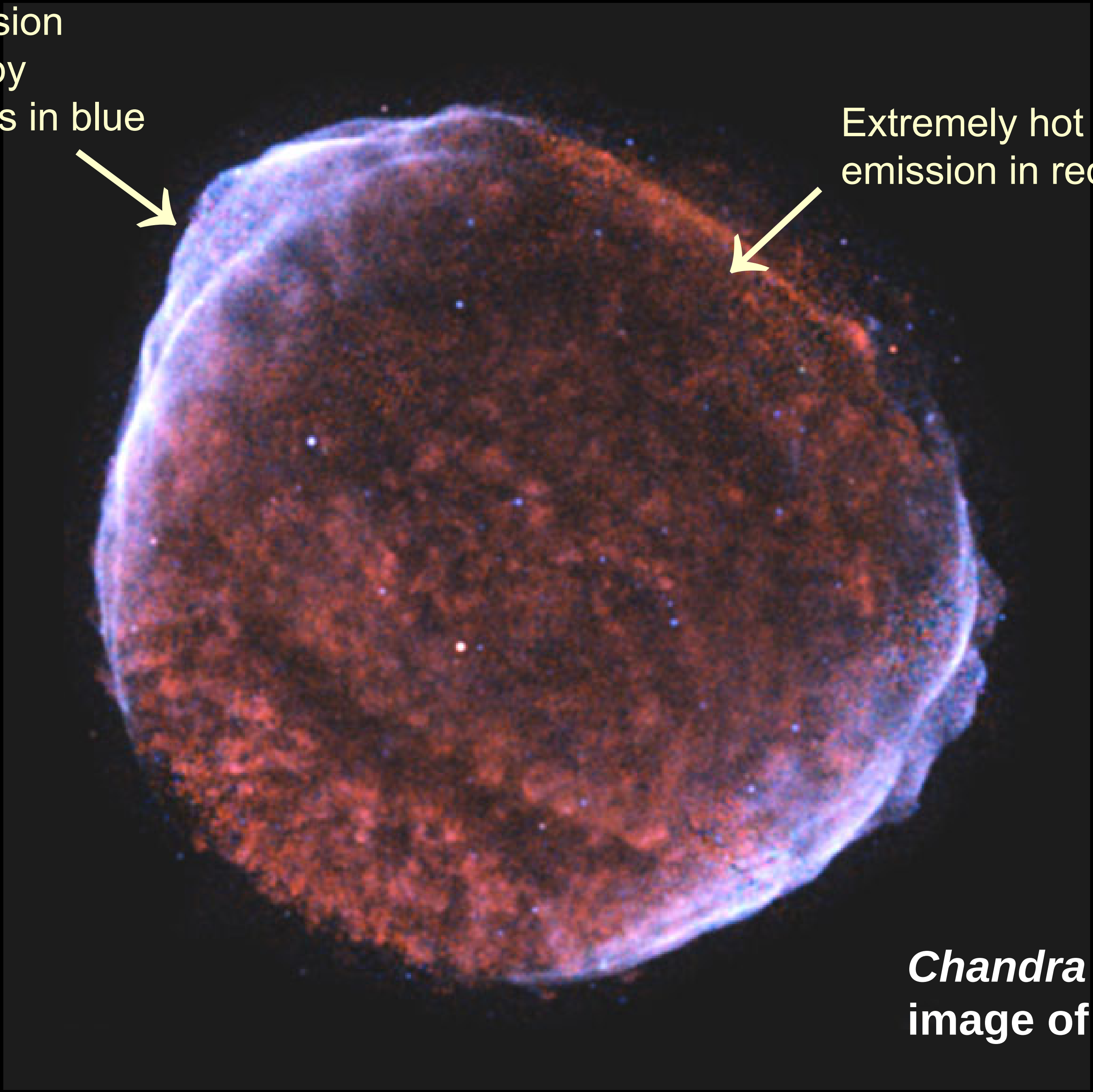


Termination shock

Morphology of ACRs at the termination shock

- Both Voyagers found that the ACR spectrum did not “unroll” to the expected power law until well behind the shock
    - Highest-energies did not peak at the shock
- McComas & Schwadron (2006) suggested that this is due to the morphology of energetic particles at a blunt termination shock
- Field lines at the “flanks” have been connected to the shock the longest. High-energy ACRs come from there



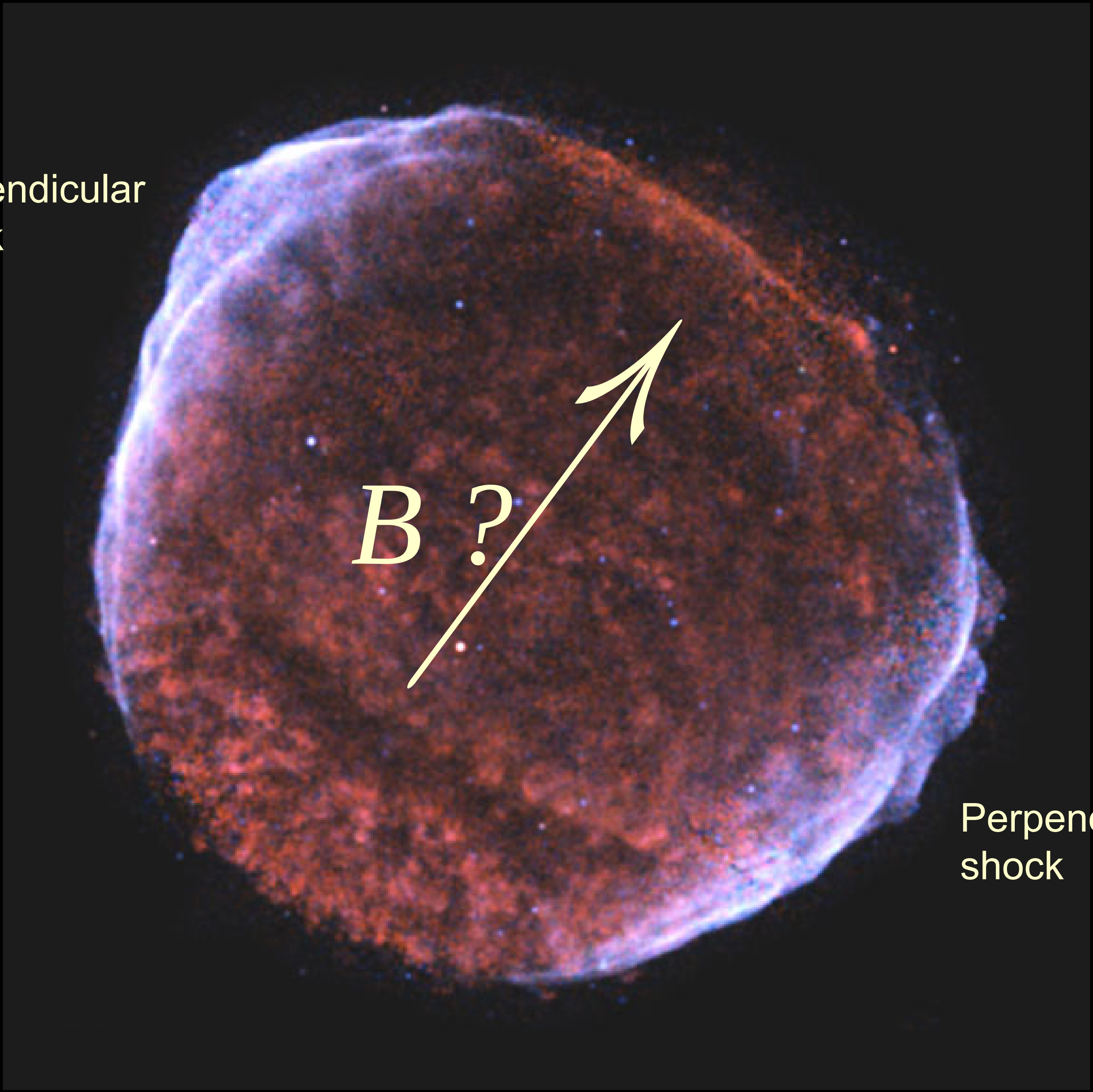


x-ray emission
produced by
cosmic rays in blue

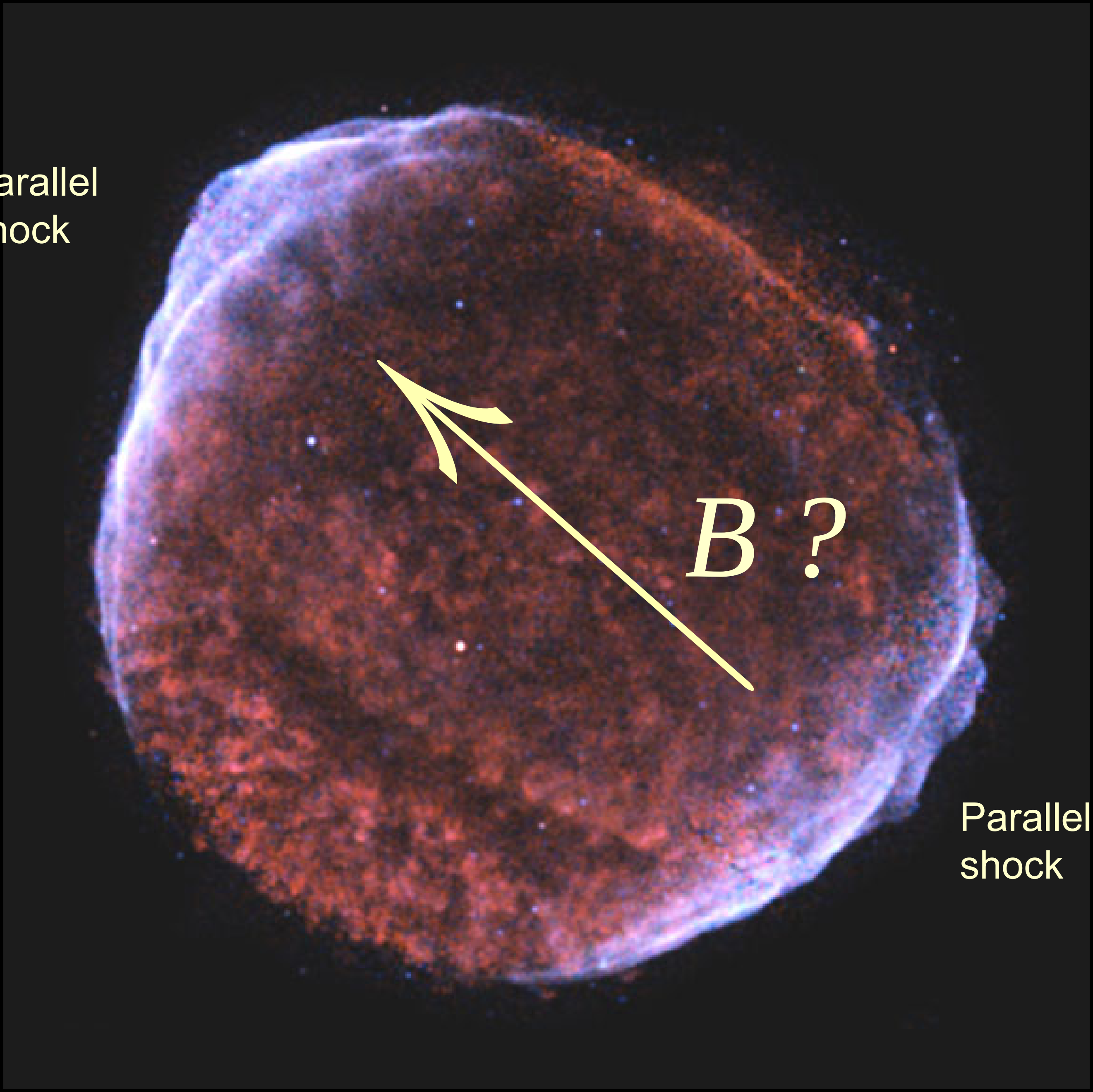
Extremely hot gas
emission in red

***Chandra* x-ray**
image of SN1006

Perpendicular shock



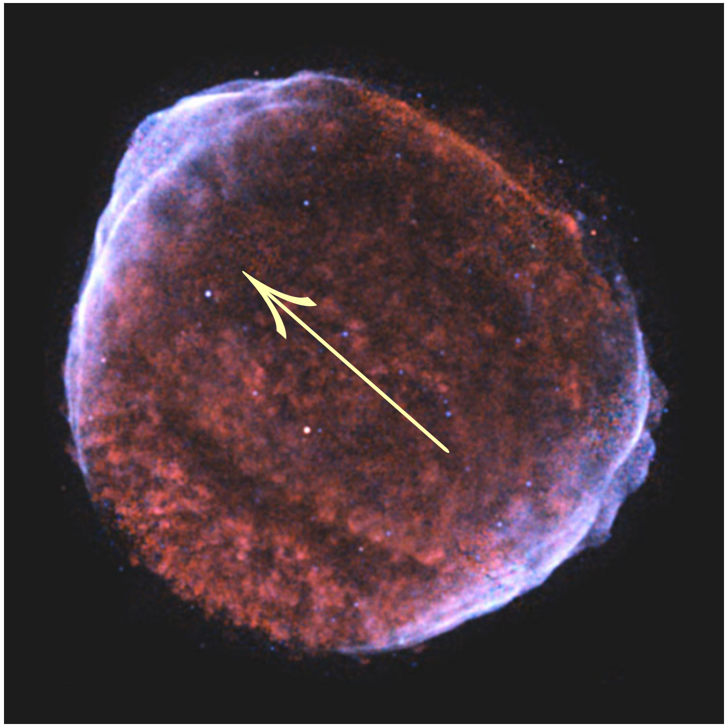
Perpendicular shock



Parallel
shock

Parallel
shock

- *Rothenflug et al.* (2004) carefully analyzed the 1006 x-ray emission and concluded that it is most likely "polar caps" and not the sides of a barrel.



- Thus, if the asymmetry is produced by the magnetic field, the particles likely exist near the parallel shock

- But the max. energy at a parallel shock has been shown to be too low to be consistent with observations (*Legage & Cesarsky*, 1983)

- If the acceleration occurs locally, the magnetic field must be very strong (to reduce the acceleration time at a parallel shock)
  - Strong fields are observed (*Berezhko et al.*, 2003) and theorized to exist
    - Cosmic-ray current-driven instability (*Bell & Lucek*, 2004)
    - Shock-generated turbulent dynamo *(Giacalone & Jokipii*, 2007)

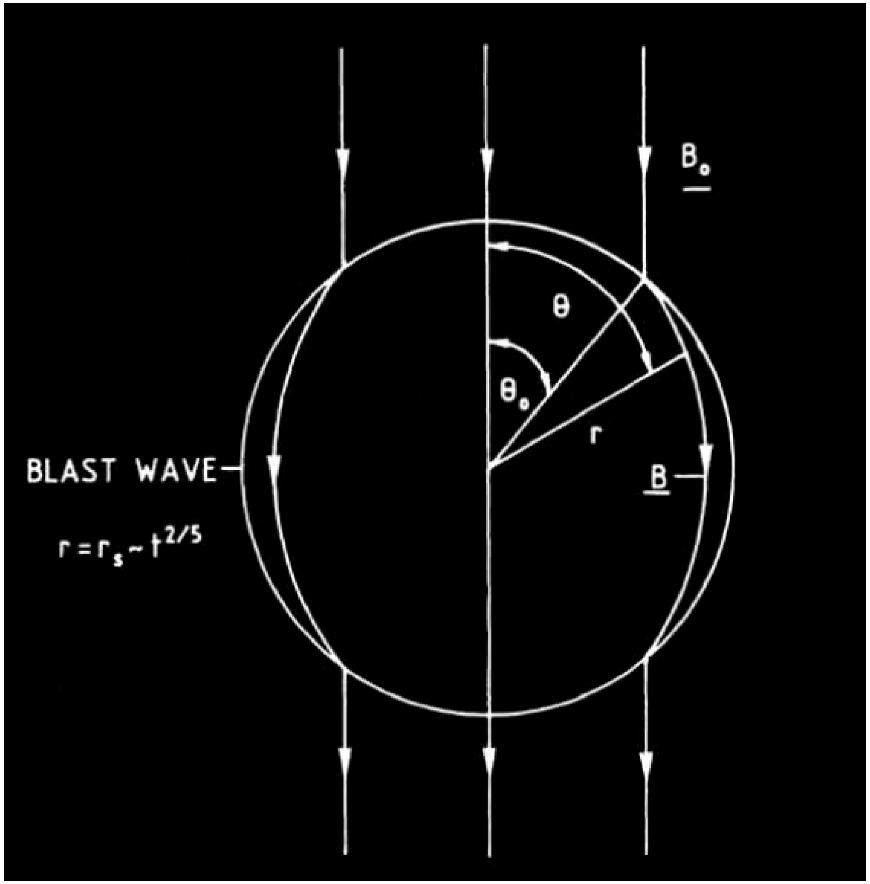
- But the amplified fields are only seen behind the blast wave. It is not known if it is amplified upstream of it too.
  - If downstream only, then acceleration at a parallel shock is still ia problem.

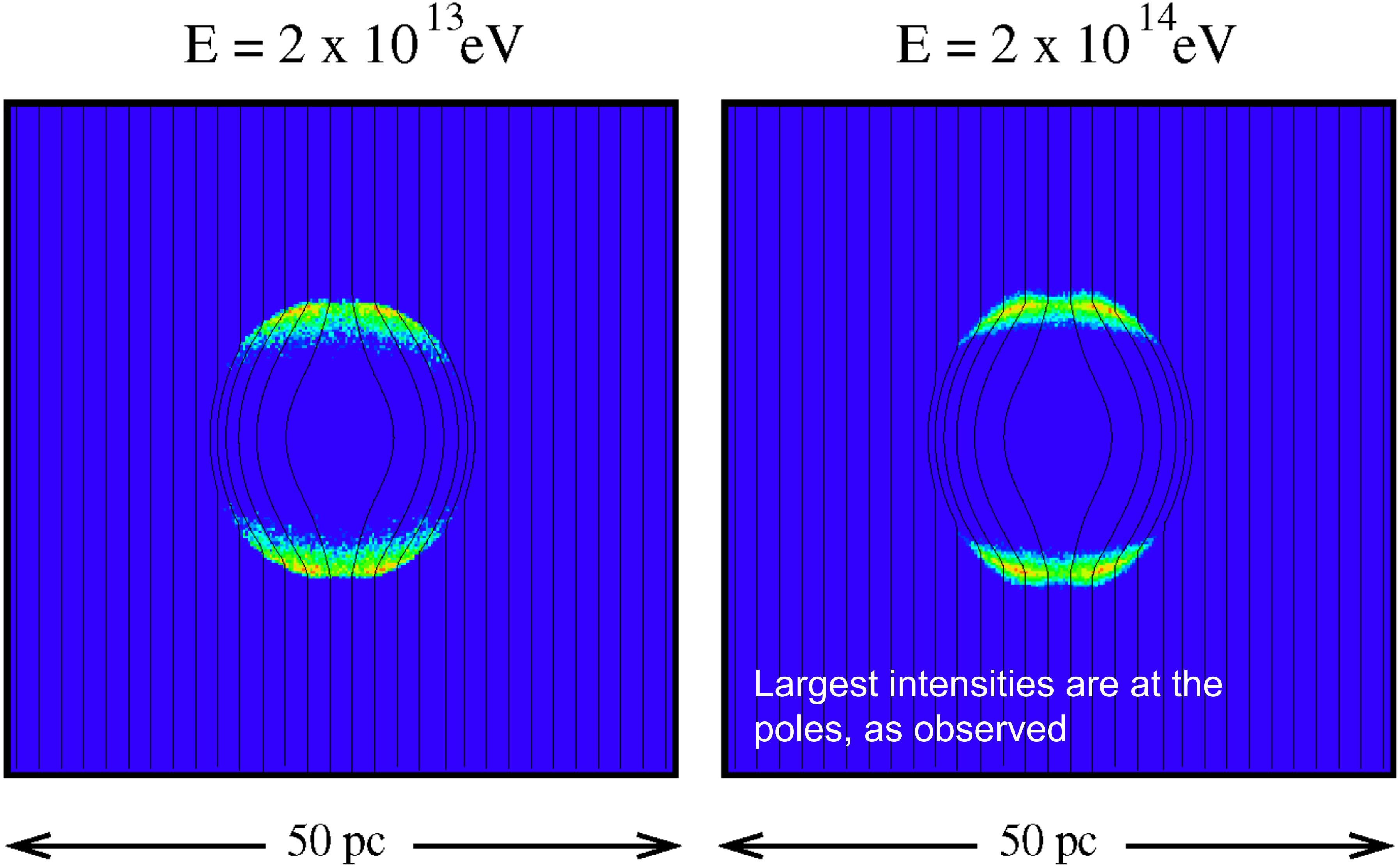
- **Must do a global cosmic-ray calculation**

A new global calculation of cosmic-rays accelerated by a supernova blast wave

- We solve the Parker transport equation for a spherical blast wave moving into a uniform magnetic field
  - Stochastic integration method
  - Injection at shock, with a uniform rate

- We assume the modified Sedov solution (to get the shock position and flow behind the shock)

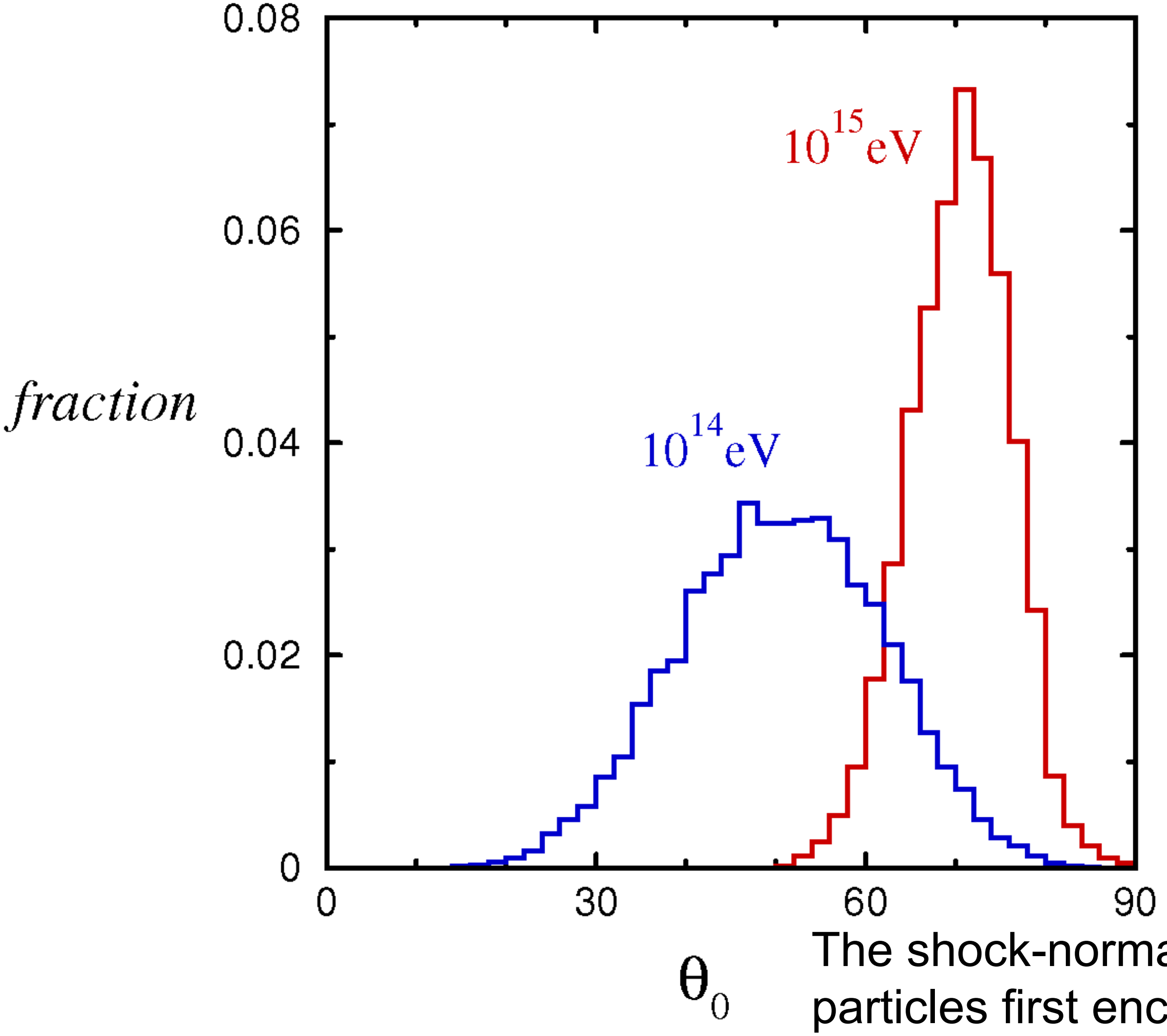




Largest intensities are at the poles, as observed

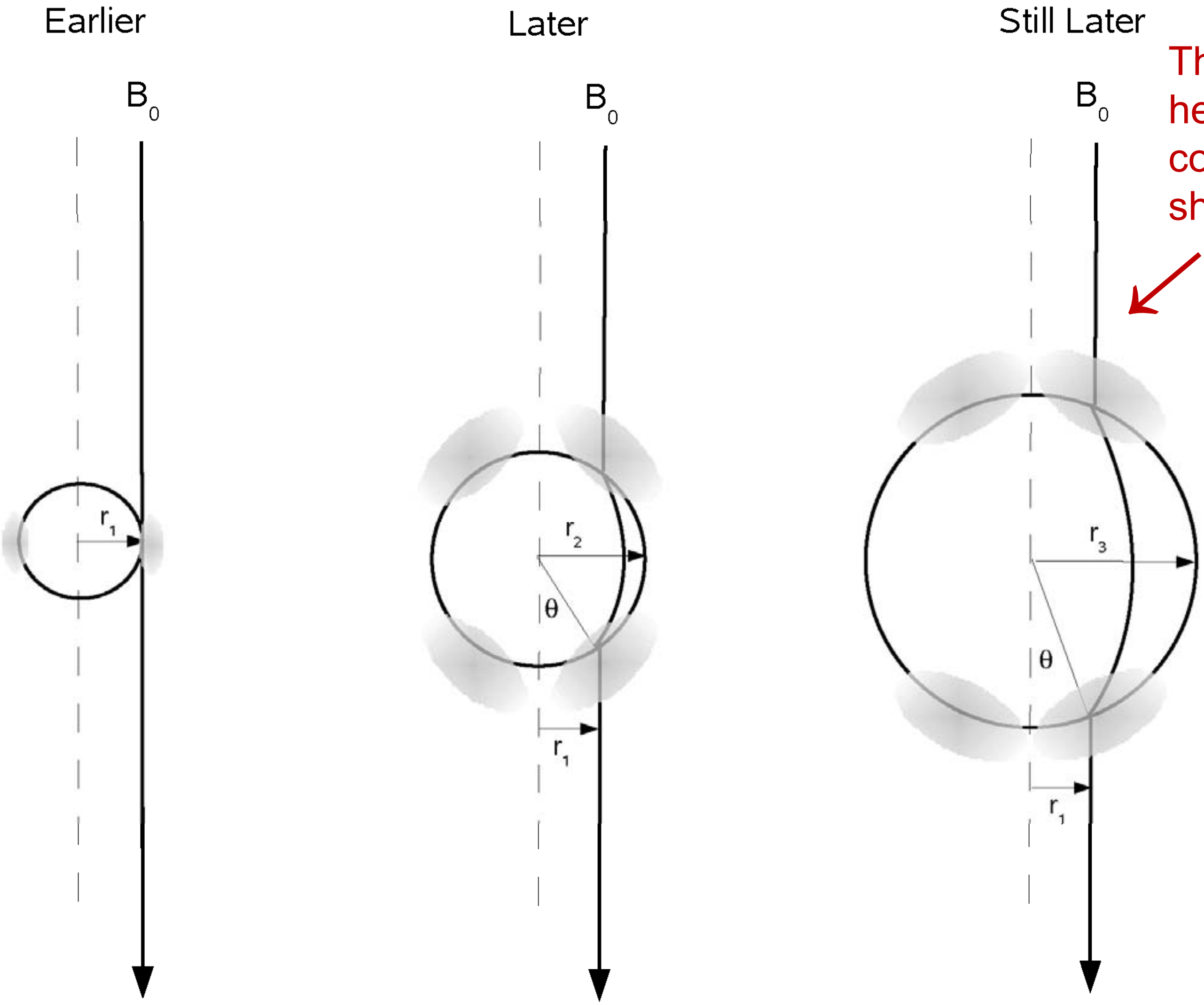
Simulated line-of-sight intensity of cosmic rays of a given energy, 1000 years after the supernova explosion

Even though the cosmic rays collect at the poles, they *originate* closer to the equator, where the shock is quasi-perpendicular,



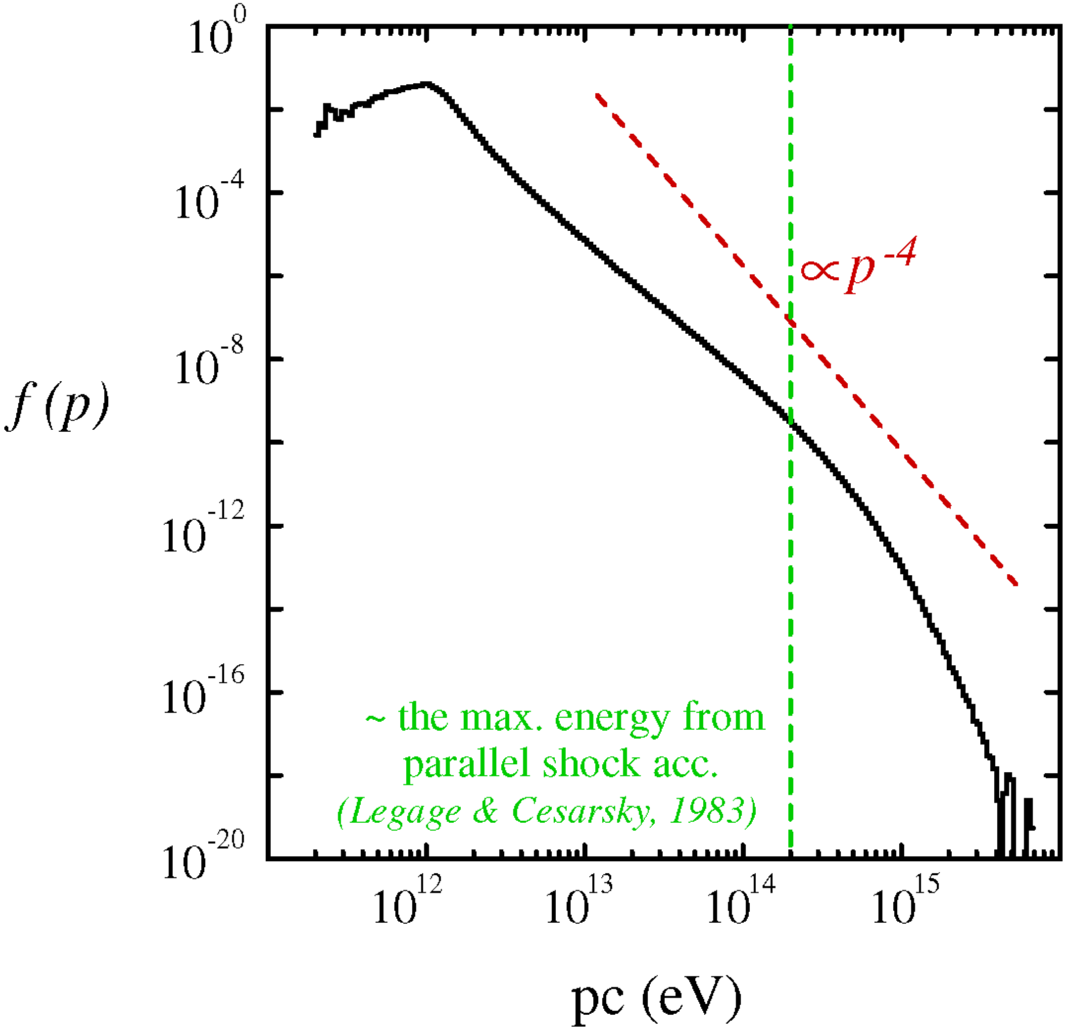
The shock-normal angle where particles first encountered the shock

A physical interpretation



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

Simulated energy spectrum (integrated over all space). Energies beyond the "knee" in the cosmic-ray spectrum are achieved in this model



Conclusions

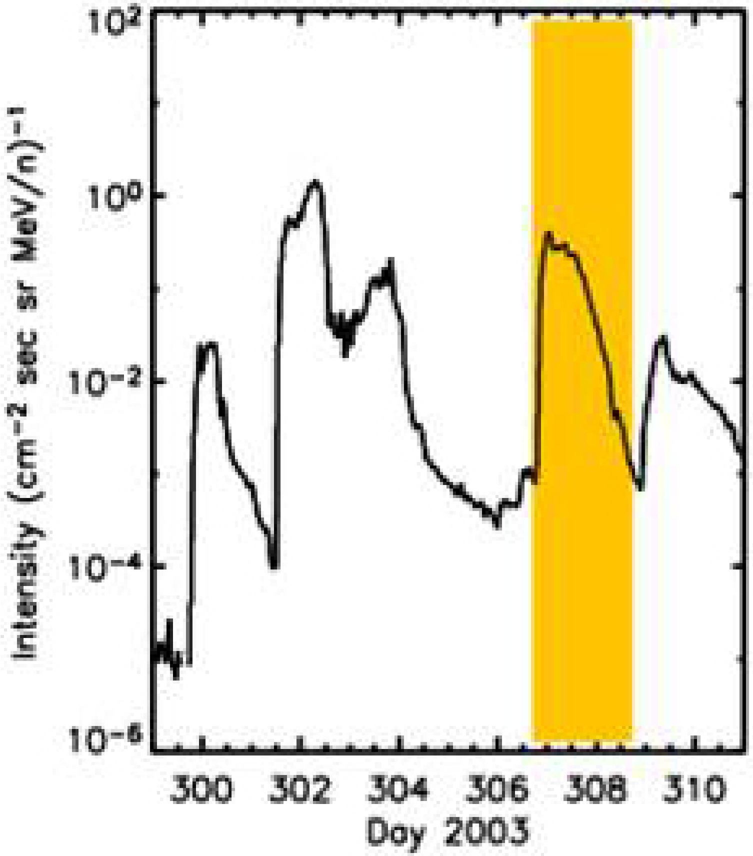
- Understanding *in situ* observations of shocks and energetic particles in heliosphere require an understanding of the role of large-scale turbulence (not shock associated), magnetic-field direction, and morphology.

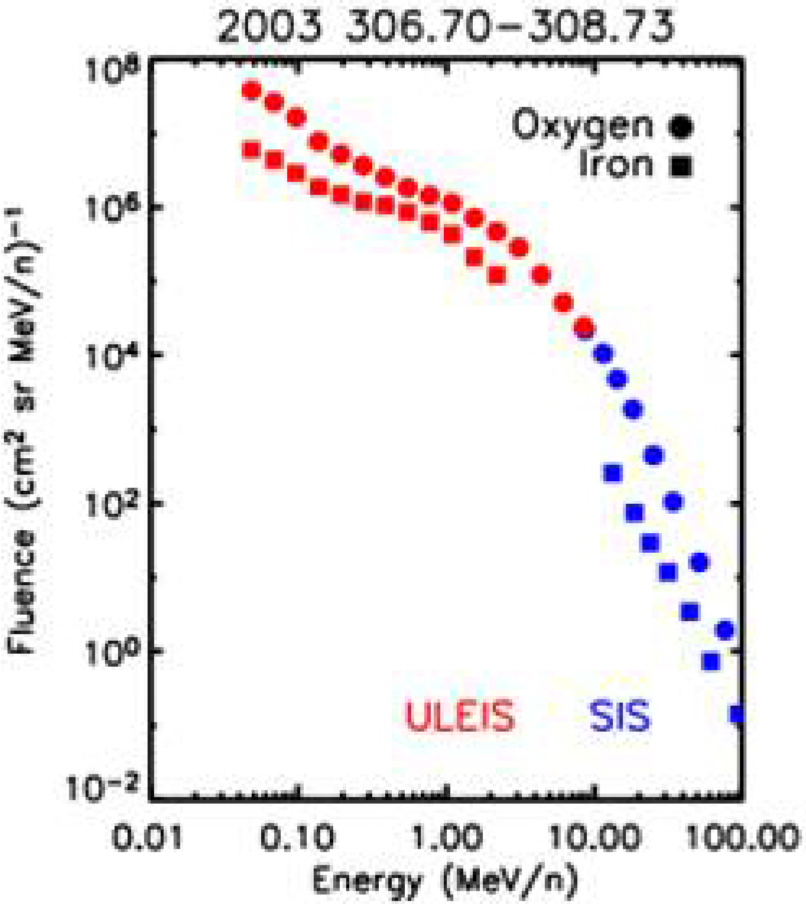
- Acceleration by perpendicular shocks is particularly important for producing the high-energy particles, and they also efficiently accelerate low-energy particles.

- The highest energy particles come from places on the shock where the field lines have been connected to it the longest.

Extra slides

Broken power-law spectra seen in large solar energetic particle events

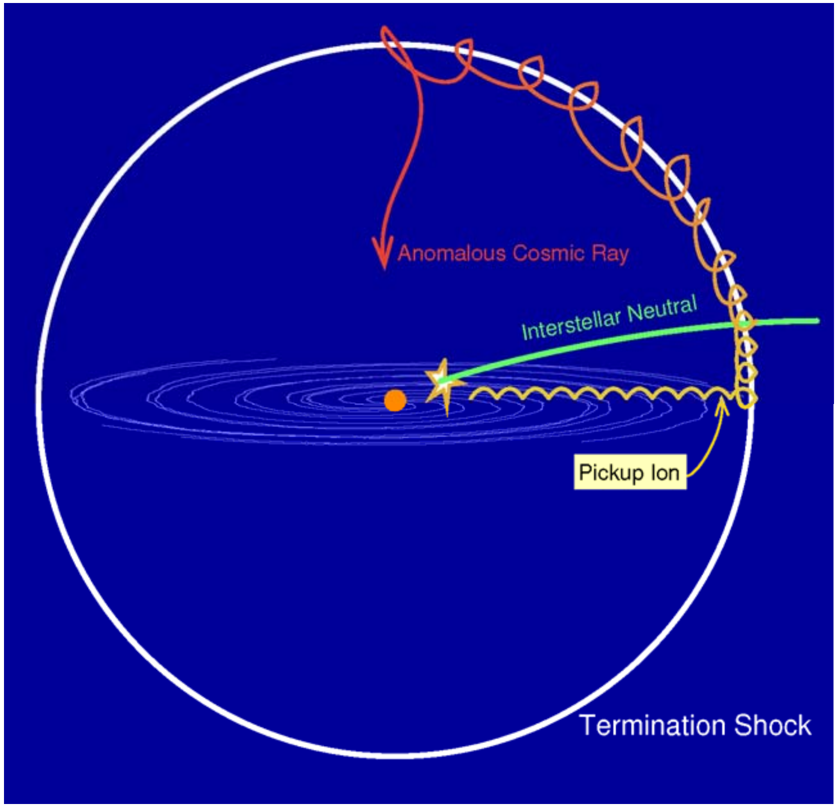




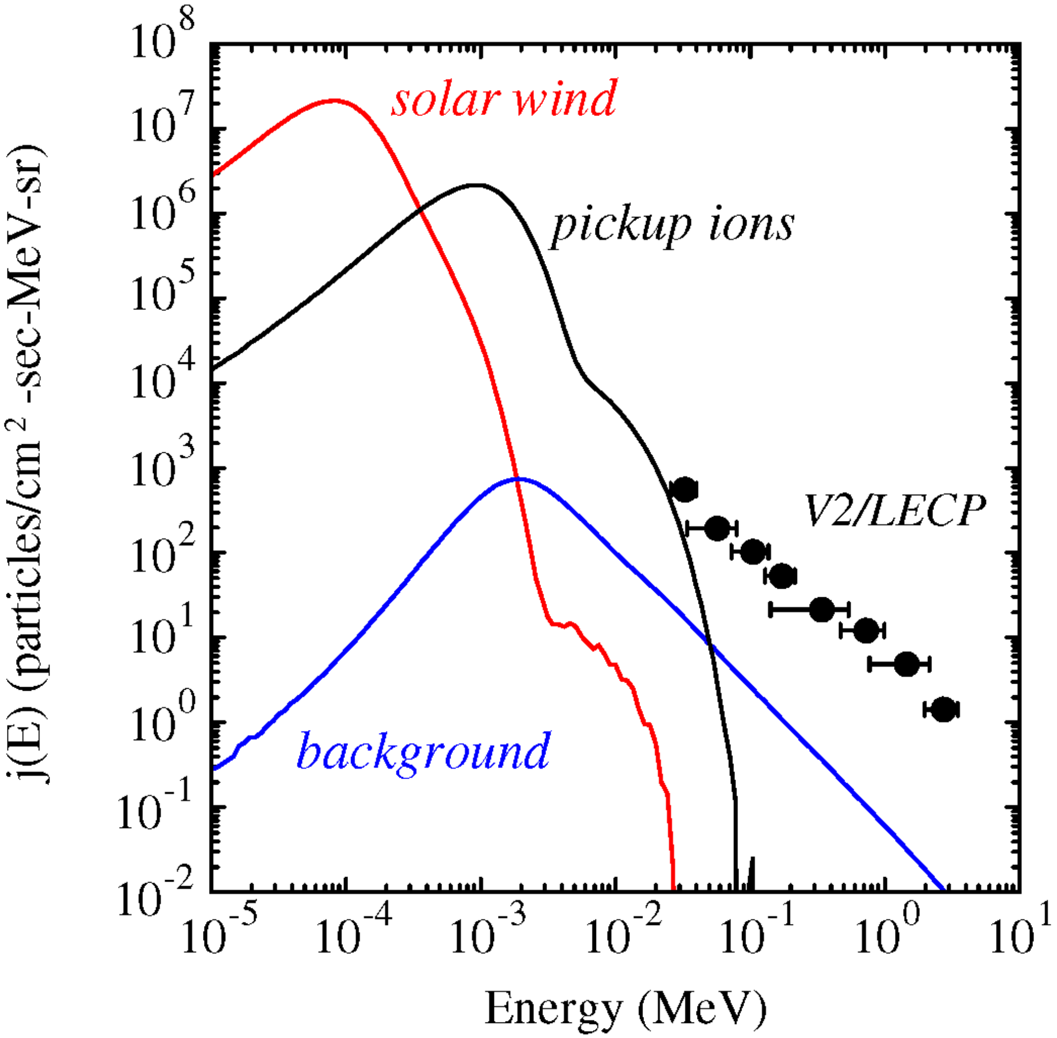
Acceleration of anomalous cosmic rays (ACR) at the termination shock

- Acceleration to ACR energies (~100 MeV) at a *parallel* termination shock would take over 100 years
  - This is inconsistent with the observed charge states of ACRs

- Need acceleration in about a year, which is consistent with a *perpendicular* shock



Downstream distributions of various proton species



- Simulation results reveal that the low-energy ACRs are accelerated core pickup ions