Electron Acceleration by Collisionless Shocks containing Large-scale turbulence

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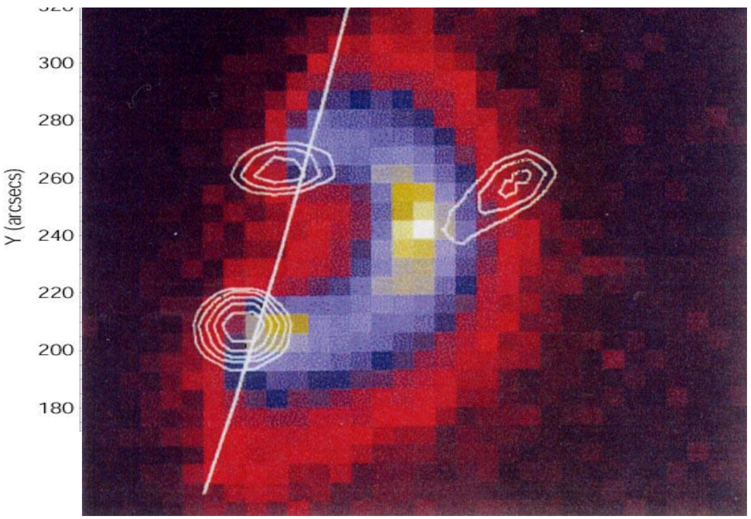
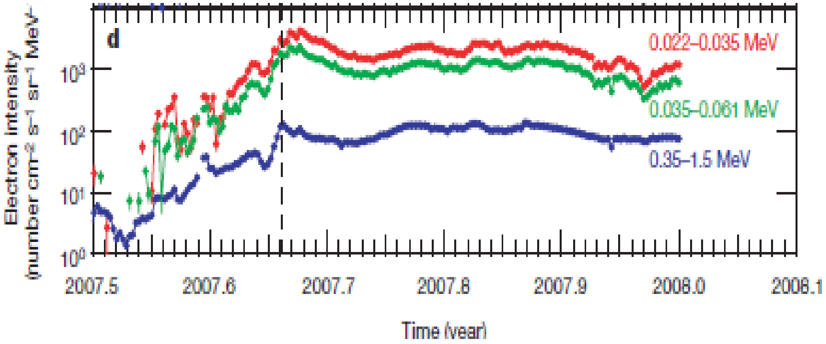
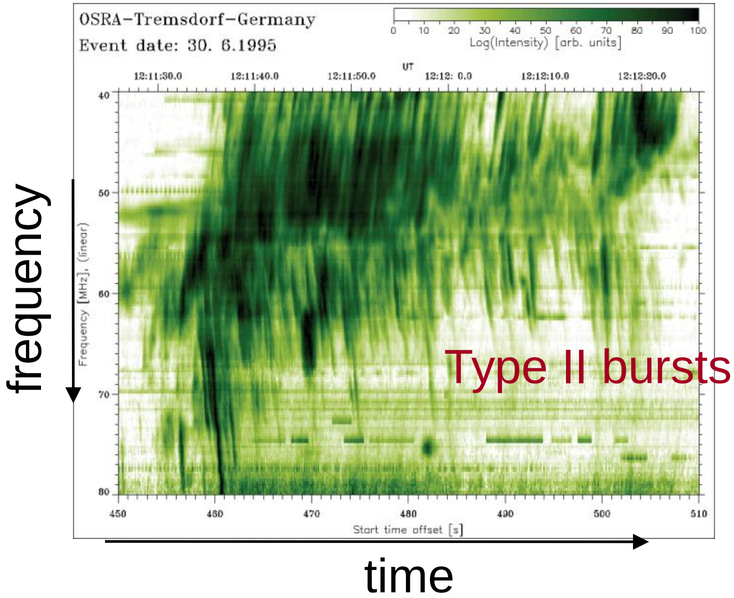
Electron acceleration throughout the universe

Hard X-ray from Flares

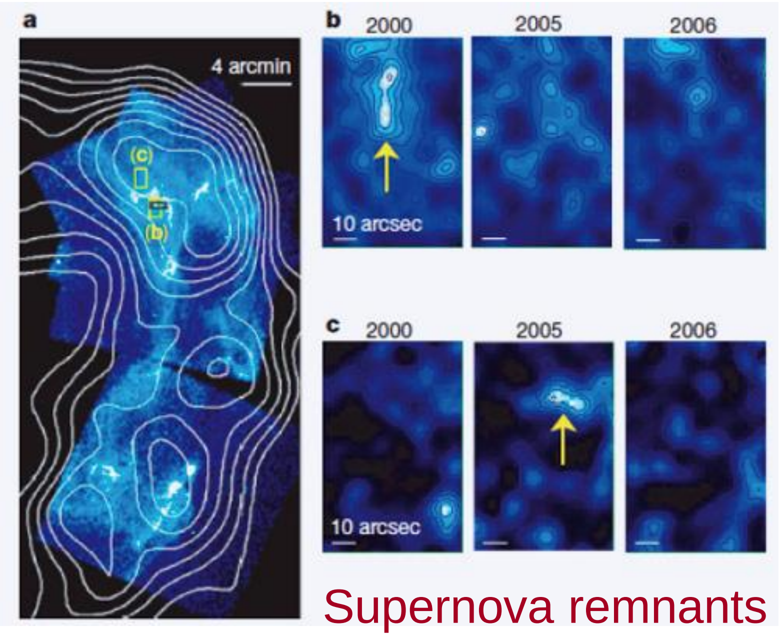


In-situ observation at the Heliospheric Termination shock



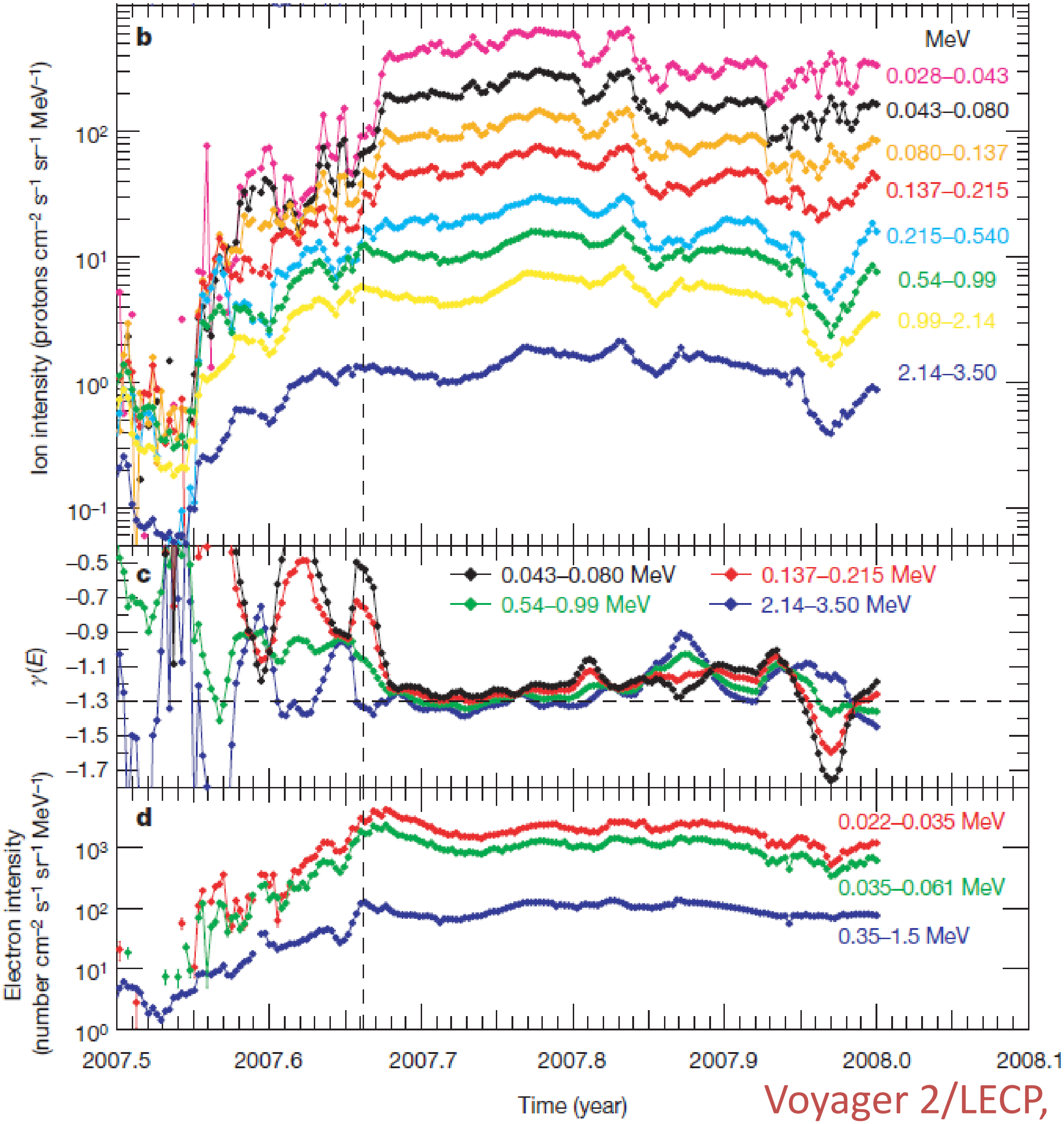


Type II bursts



Supernova remnants

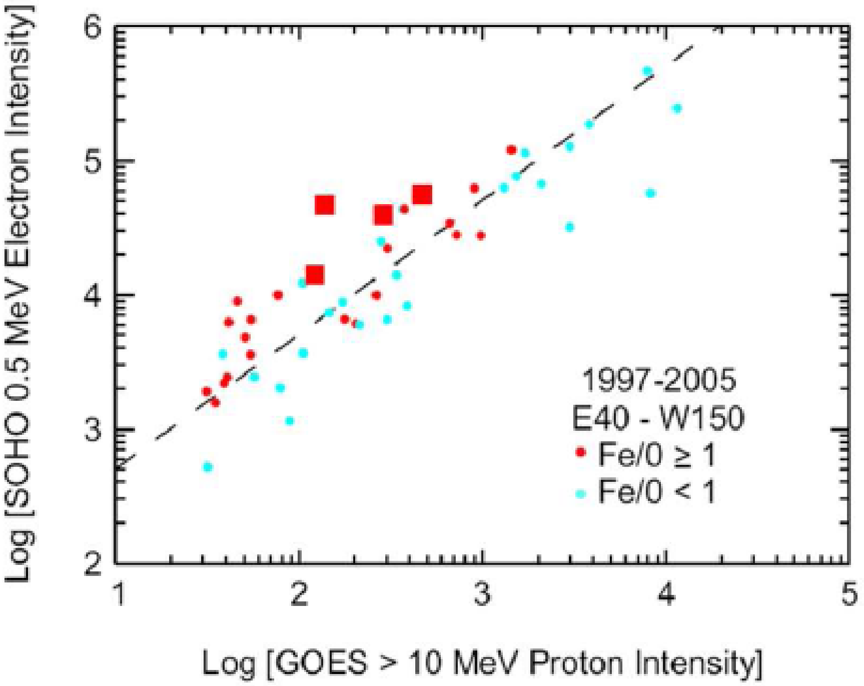
Complicated intensity profile in the turbulent termination shock



Voyager 2/LECP, Decker et al. (2008)

Strong electron-ion correlation in large SEP events

- In SEP events, ions and electrons show strong correlation.
- Electron acceleration has to be considered.
- The most popular scenario to explain SEP events (Tylka et al. 2005) is based on the argument that injection threshold for perpendicular shock is high, which cannot explain this observation. Parallel shocks are known having troubles accelerating electrons



Cliver 2009, Dietrich & Tylka 2010, Haggerty 2011

Shock acceleration

- **Diffusive shock acceleration** (DSA) (*Krymsky 1977, Axford et al. 1977, Bell 1978, Blandford & Ostriker 1978*)

1. The energy comes from upstream and downstream velocity difference
2. The theory predicts a power-law spectrum $f(p) \propto p^{-3r/(r-1)}$
3. The acceleration rate depends on shock normal angle (*Jokipii 1987*)

Quantitative results of DSA can be calculated by solving Parker 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 transport equation is valid when the anisotropy of particles is small enough! → injection problem

Particle Acceleration by Collisionless Shock

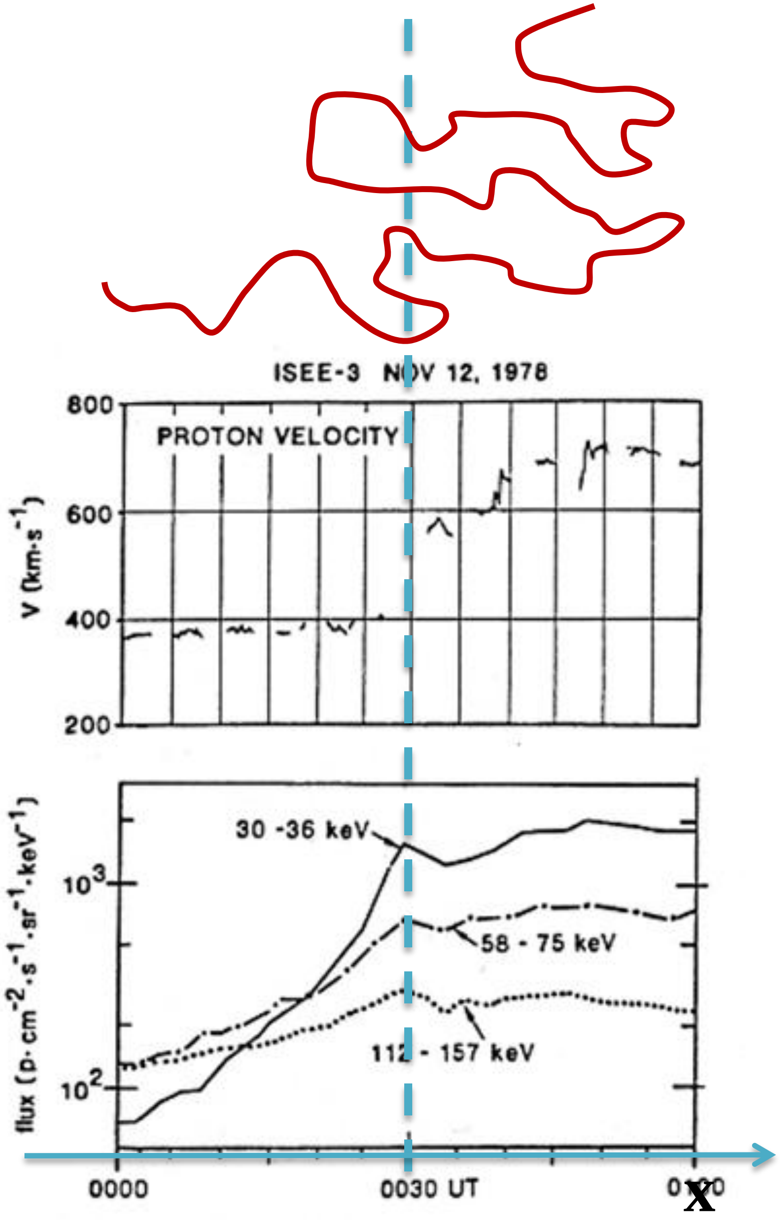
- Solve Parker equation for a compressive discontinuity, in 1-D infinite space and steady state:

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

$$\gamma = 3U_1/(U_1 - U_2)$$

- Diffusive shock acceleration is thought to be the main mechanism for acceleration of cosmic rays

Krymsky 1977, Axford, Leer and Skadron 1977, Bell 1978, Blandford & Ostriker 1978

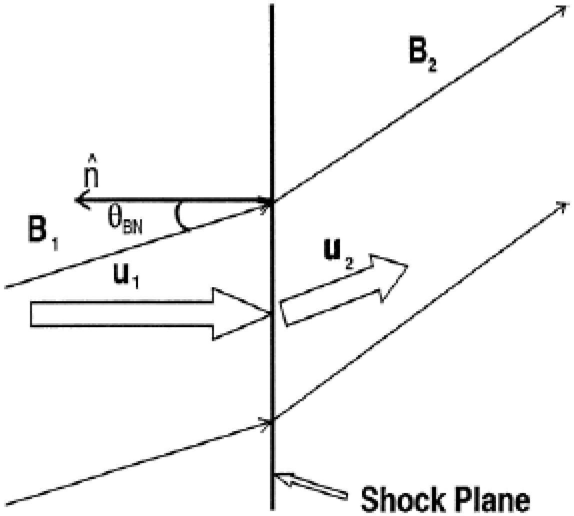


shock drift acceleration (in scattering free limit)

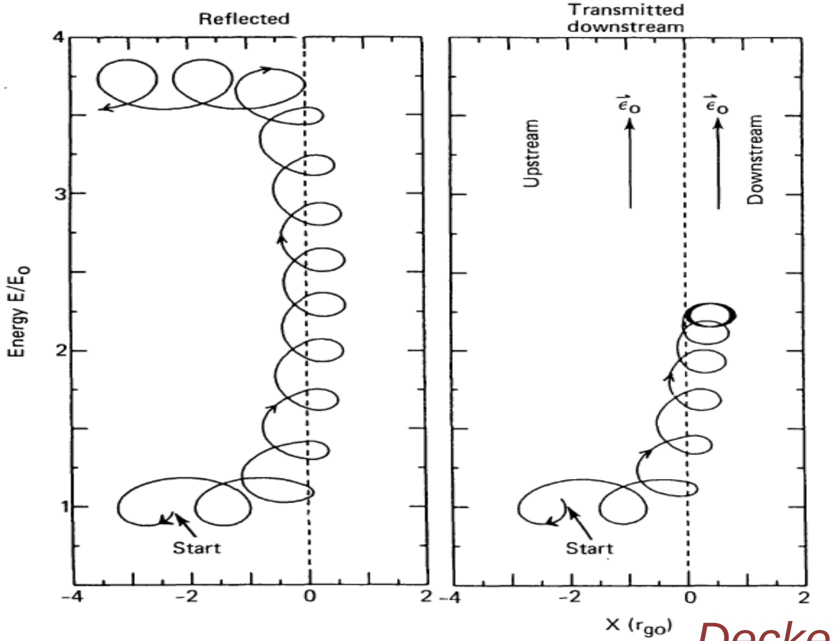
- **Shock drift acceleration** (SDA; or fast-fermi acceleration)

  (Wu [1984], Leroy & Mangeney [1984] discussed electrons)

1. The energy comes from particle drift in -**v** x **B**/c electric field
2. In a planar shock, scattering-free limit, the acceleration is limited (*e.g. Ball 2001*)
3. In a perpendicular shock, diffusion process, shock drift acceleration is the same process as diffusive shock acceleration (*Jokipii 1982*)

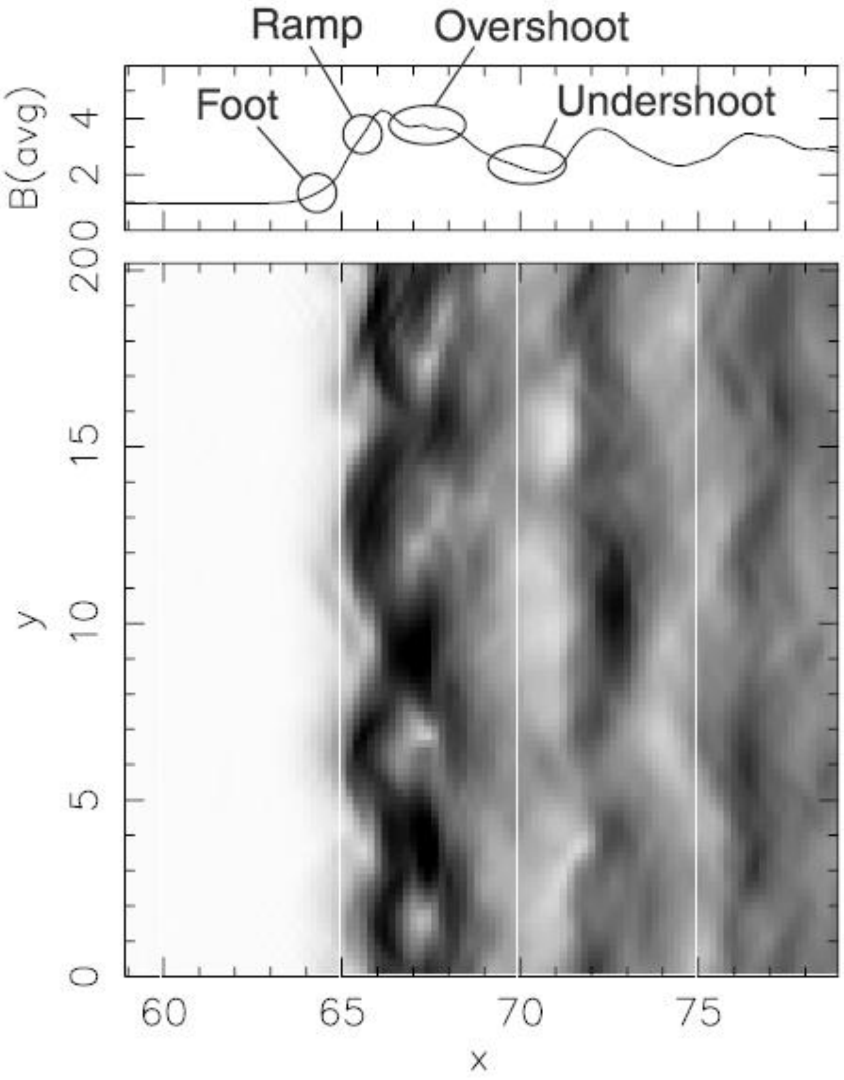


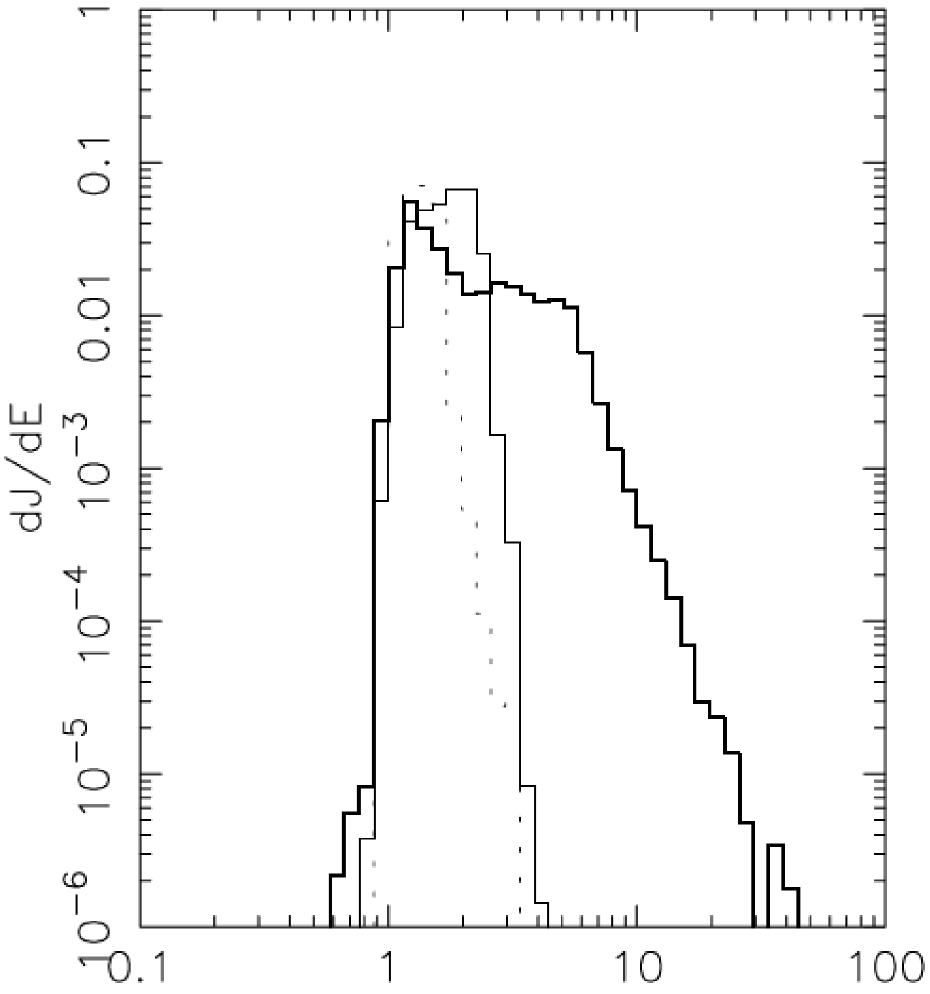
Normal Incidence frame



Decker (1988)

Electron acceleration: Effect of ion-scale ripples



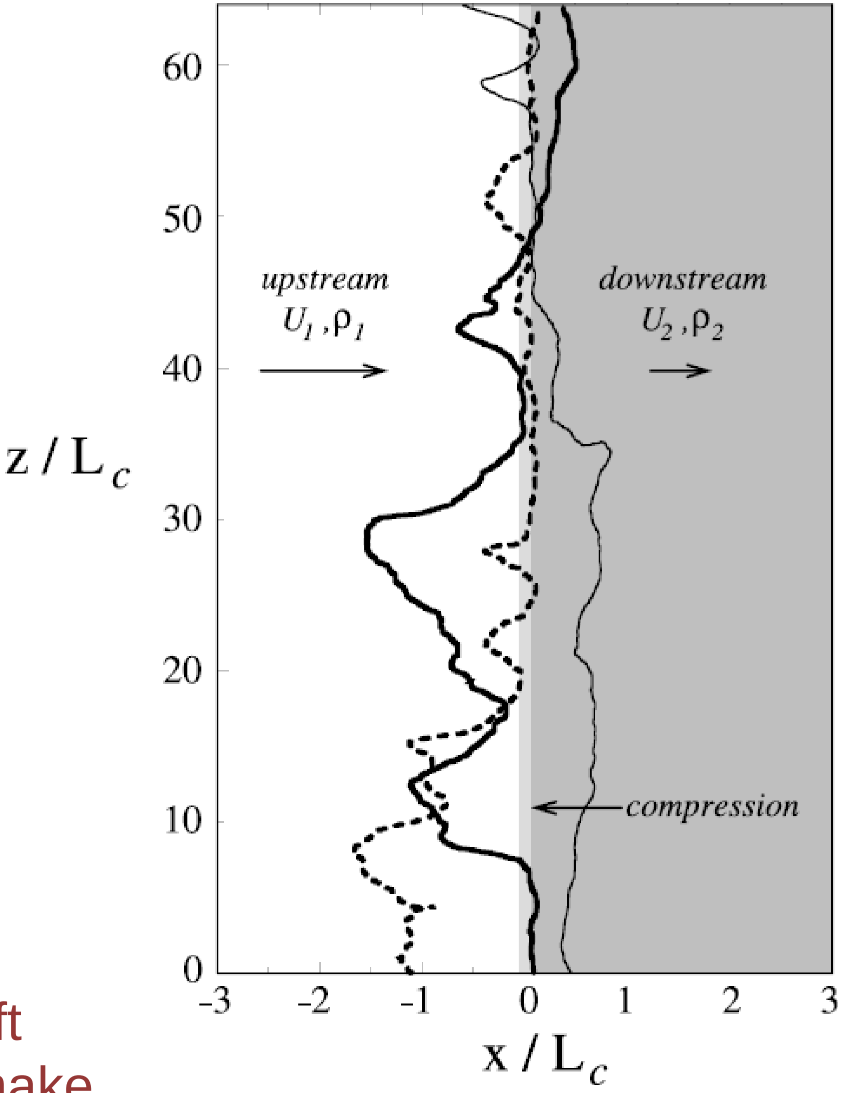


Burgess 2006 ApJ

Electron Acceleration by Collisionless Shocks

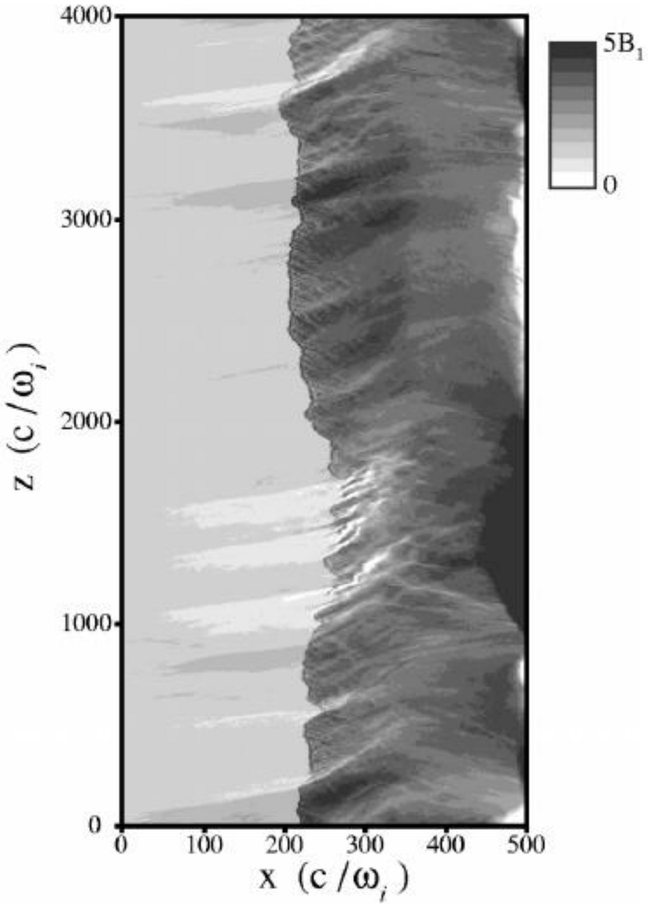
- Jokipii & Giacalone (2007) provided an interesting solution for electron acceleration at perpendicular shocks
- Electrons can travel along meandering magnetic field lines, and cross shock many times…
- The energy is from the difference between upstream and downstream velocities.

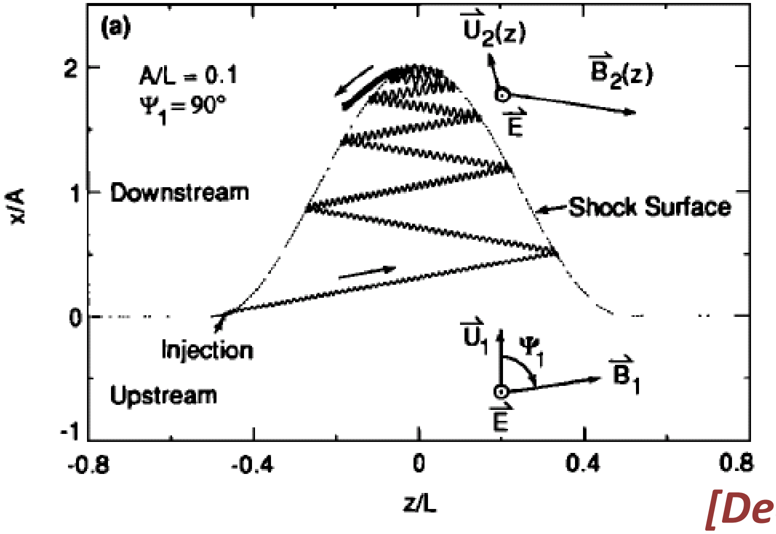
Note: This process does not include drift acceleration at shock front, which will make the acceleration more efficient.



Jokipii & Giacalone (2007)

Effect of shock ripples





[Decker 1990]

Shock is rippled in a variety of scales (by magnetic field or density fluctuations)

Interplanetary shocks have the characteristic irregular structure in the same scale with the coherence length of the interplanetary turbulence *Neugebauer & Giacalone(2005).*

The shock ripples in different scales may contribute to the acceleration of particles.

Our approach to study this problem

- Consideration: Interaction between magnetic turbulence and collisionless shock is very complicated. There is no way to capture all the physics analytically.
- Suitable self-consistent simulation has to be used. The scale has to be large enough to include large scale pre-existing turbulence, and the resolution has to be small enough to capture shock microphysics (ion scale).

- Approach: 2-D Hybrid simulation + electron test particle
- hybrid simulation (kinetic ions, fluid electron) gives electric and magnetic fields
- Test particle electrons: assume no feed back on the electric and magnetic field. (*Krauss-Varban, Burgess and Wu 1989, Burgess 2006*)

Hybrid simulation

- The simplified 1-D magnetic fluctuations are assumed for the pre-existing turbulence.
- The fluctuating component contains an equal mixture of right- and left-hand circularly polarized, forward and backward parallel-propagating Alfven waves. The amplitude of the fluctuations is determined from a 1D Kolmogorov power spectrum:

$$P_{\text{input waves}}(k) \propto \frac{1}{1 + (kL_c)^{5/3}}$$

- $\langle \Delta B^2 \rangle = 0.3 B_0^2$

Note: In 1-D or 2-D hybrid simulations, the particles are tied on their original field lines! (Jokipii 1993)

Test Particle simulation

- Integrate the equation of motion for an ensemble of test-particle electrons with non-relativistic motions assumed

- Use second order interpolation of fields to make sure the smoothness and avoid artificial scattering

- Bulirsh-Stoer method (see *Numerical Recipes*):

  Highly accurate and conserves energy well

  Fast when the fields are smooth

  Adaptive time-step method based on the evaluation of local truncation error. Get better accuracy when the change of EM field is fast.

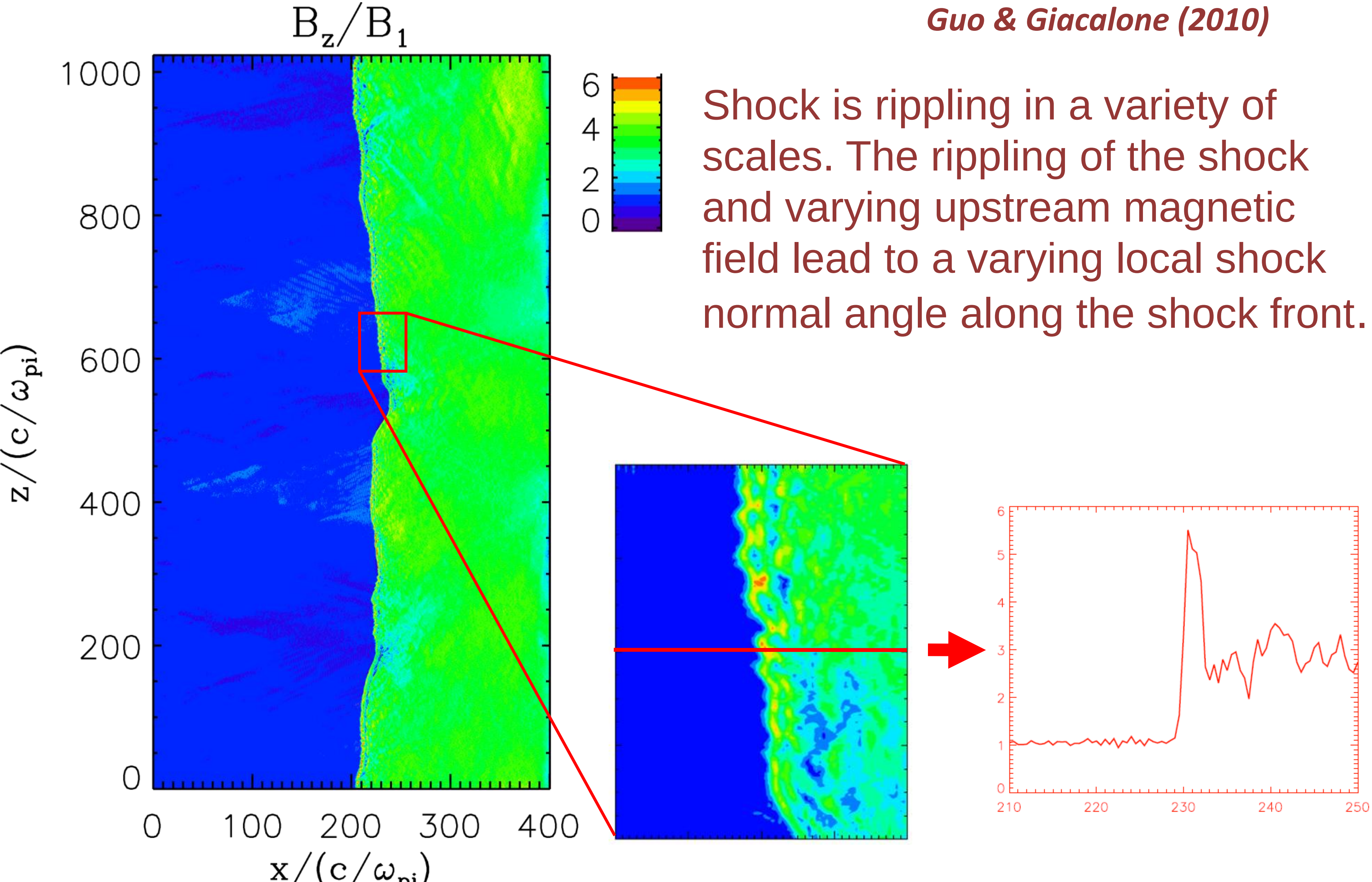
- Test-particle electron

  release ~10^6 test particles uniformly upstream with a isotropic mono-energetic distribution (100eV) after the shock is fully developed

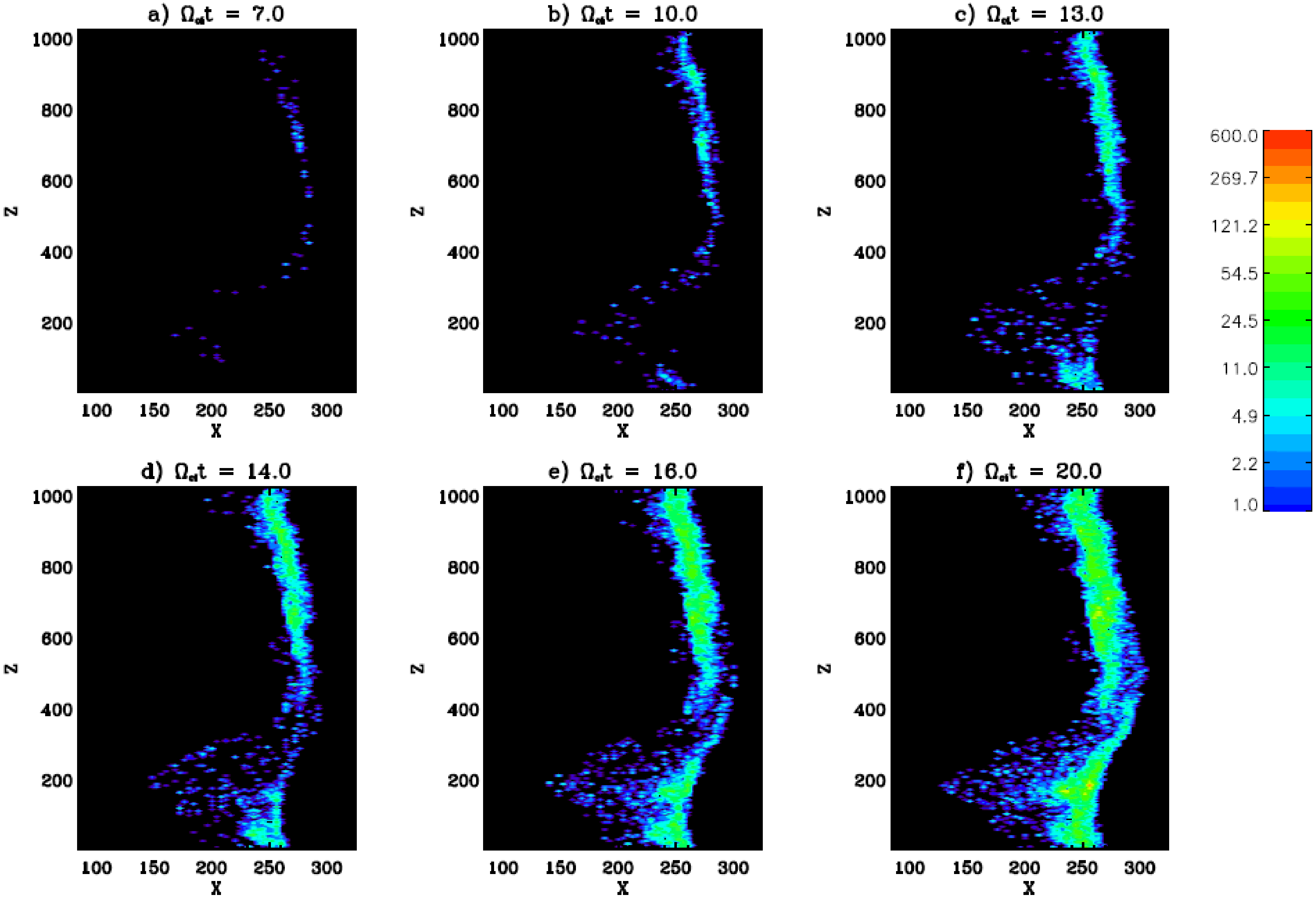
Hybrid simulation + test particle

Guo & Giacalone (2010)

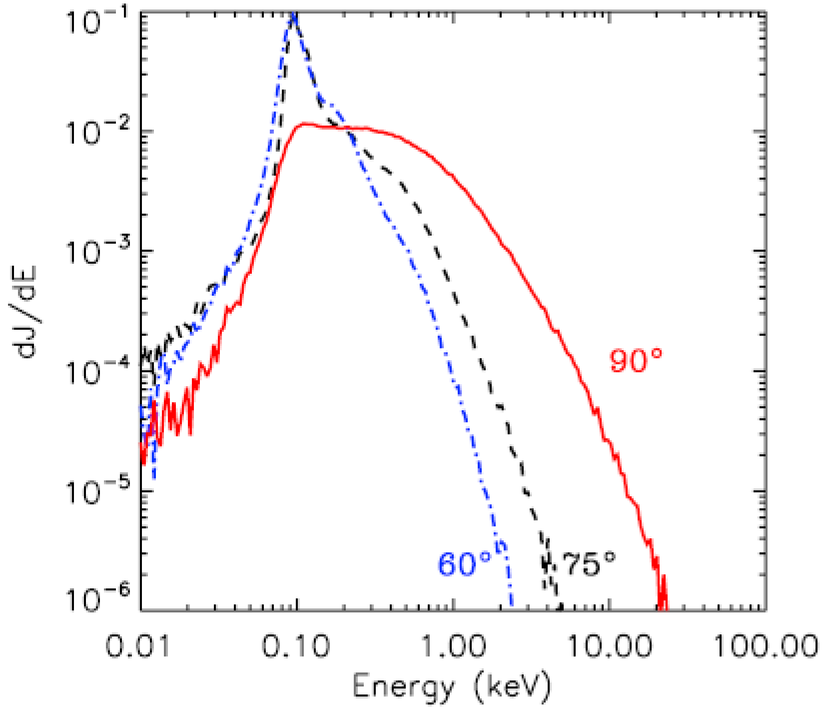
Shock is rippling in a variety of scales. The rippling of the shock and varying upstream magnetic field lead to a varying local shock normal angle along the shock front.

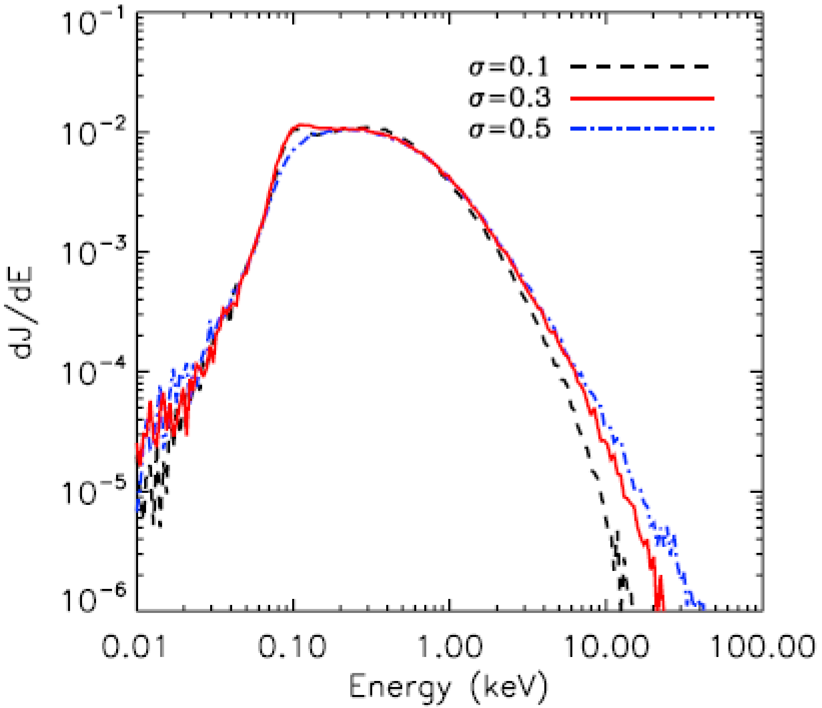


Electron distribution ($E>10E_0$) after the initial release

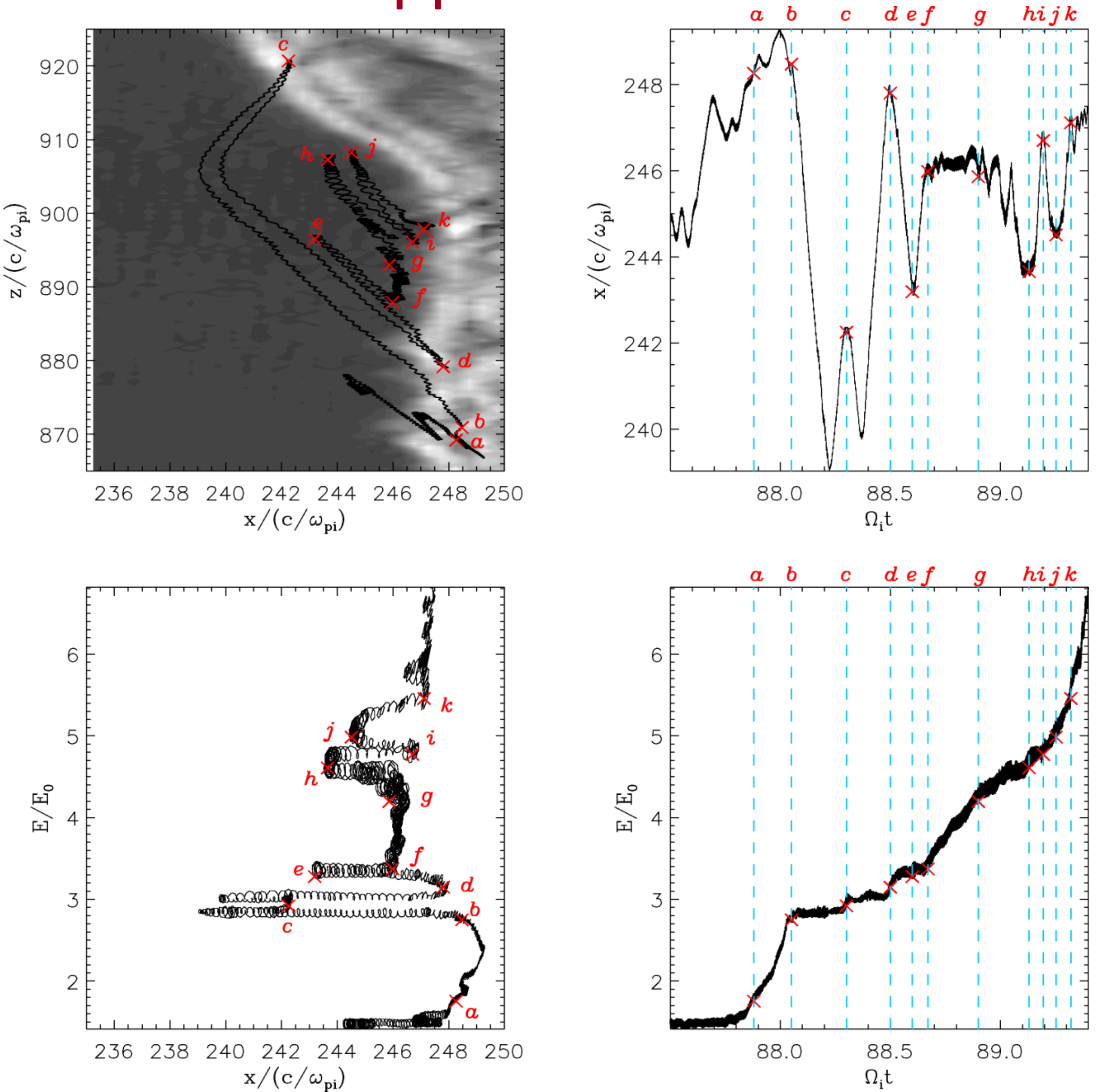


Effect of shock angles and turbulence amplitude

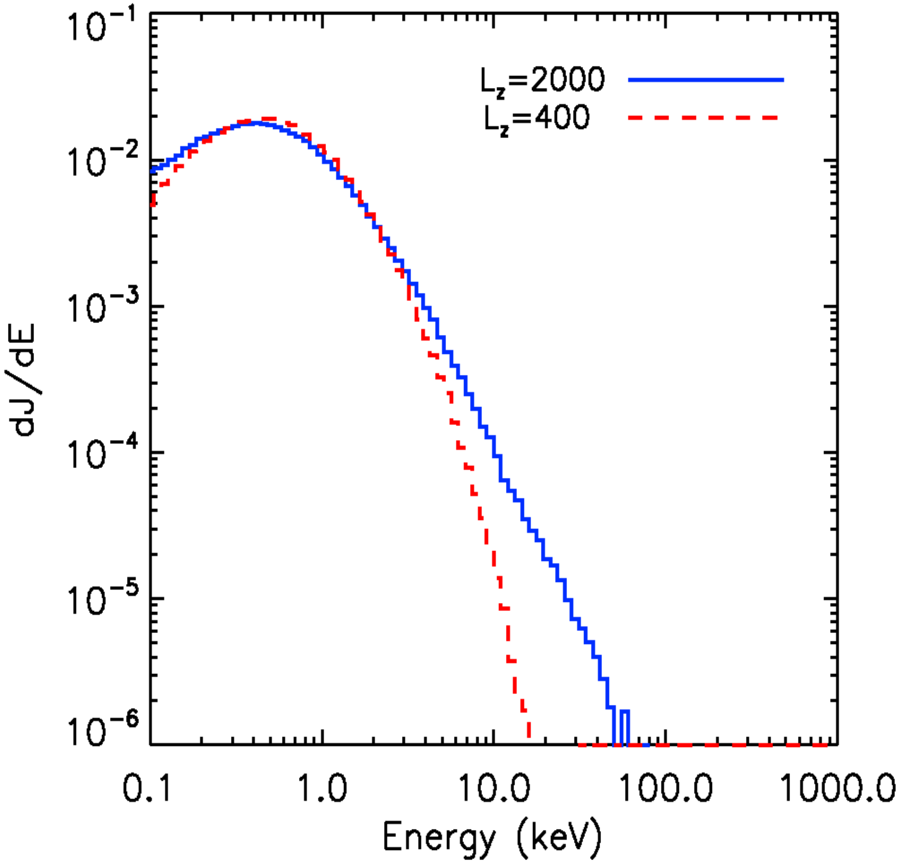


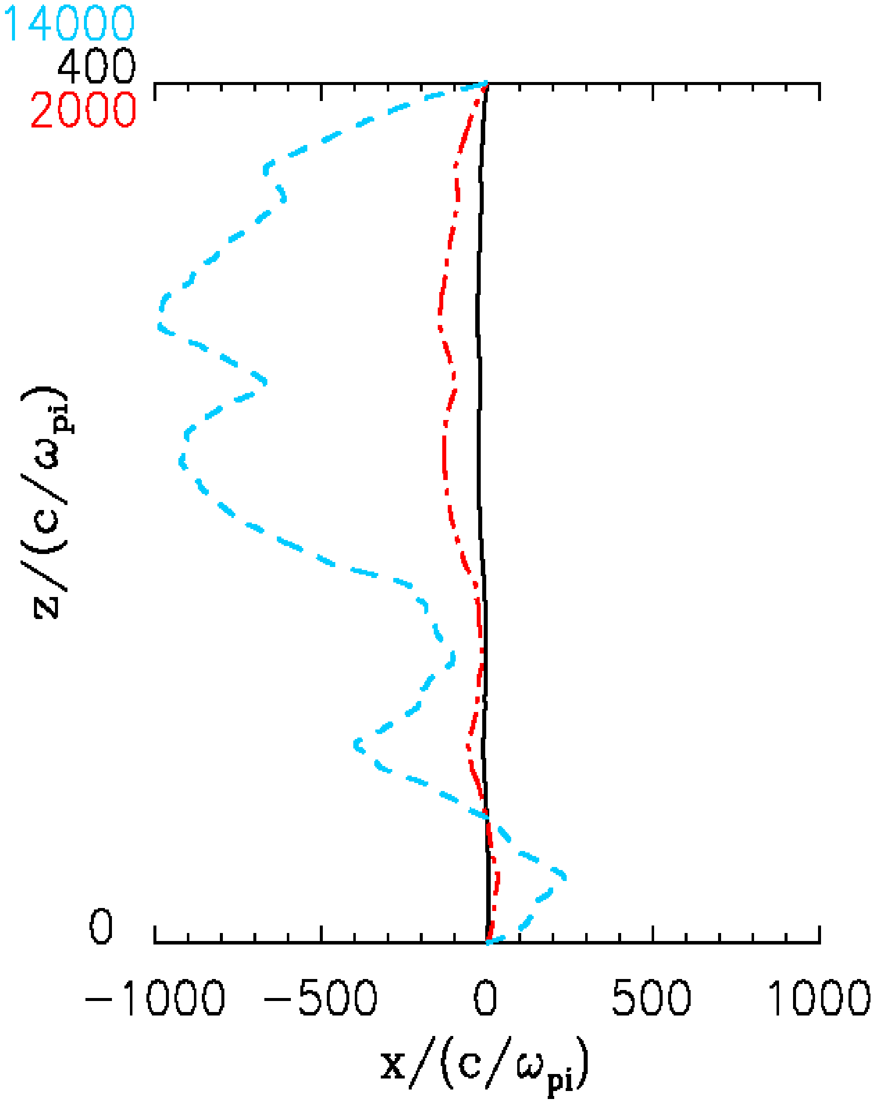


Effect of shock ripples on electron acceleration



Effect of turbulence length (recent results)

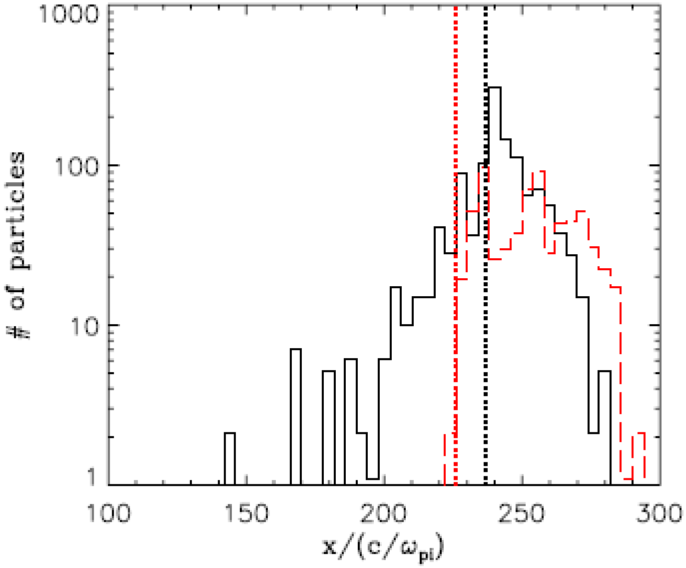




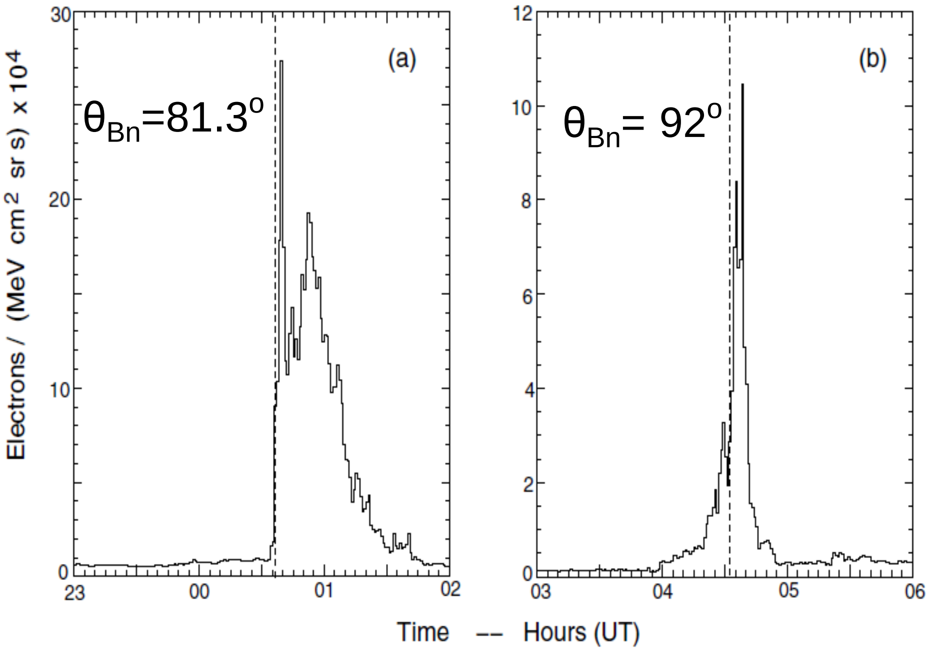
Upstream electron: compared with the observations

simulation

observation



Guo & Giacalone (2010)

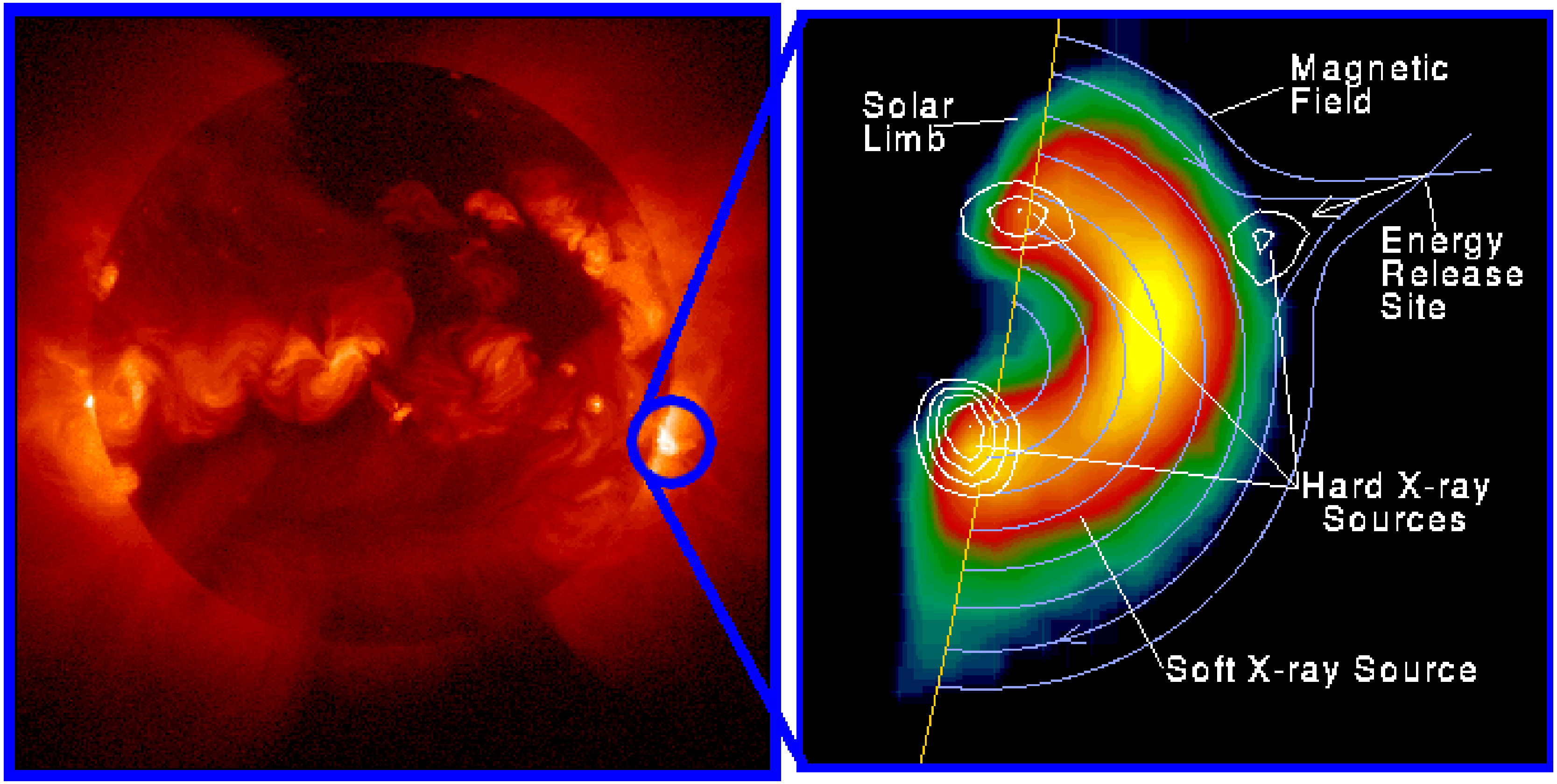


Simnett et al. (2005)

- Profile of number of accelerated electrons shows similar features with observations.
- $D_{perp} = \frac{<\Delta x^2>}{<\Delta z>} = 0.44$ Lc (Giacalone&Jokipii 1999), use

$$\mathrm{Vs} = 800\ \mathrm{km/s},\ \mathrm{Lc} = 0.01\ \mathrm{AU},\ \Delta z \sim Lc,\ \ \tau \sim \frac{\sqrt{<\Delta x^2>}}{\mathrm{Vs}} \sim 20\mathrm{min}.$$

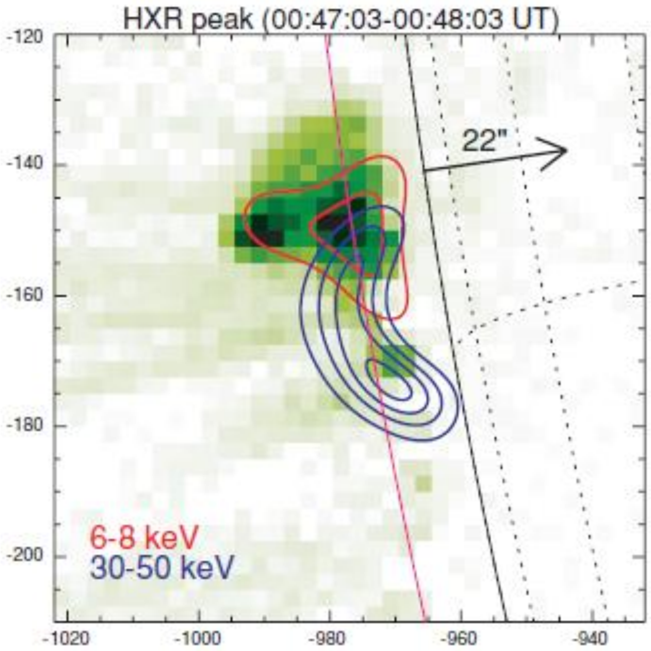
Possible electron heating and acceleration by shocks in solar flares



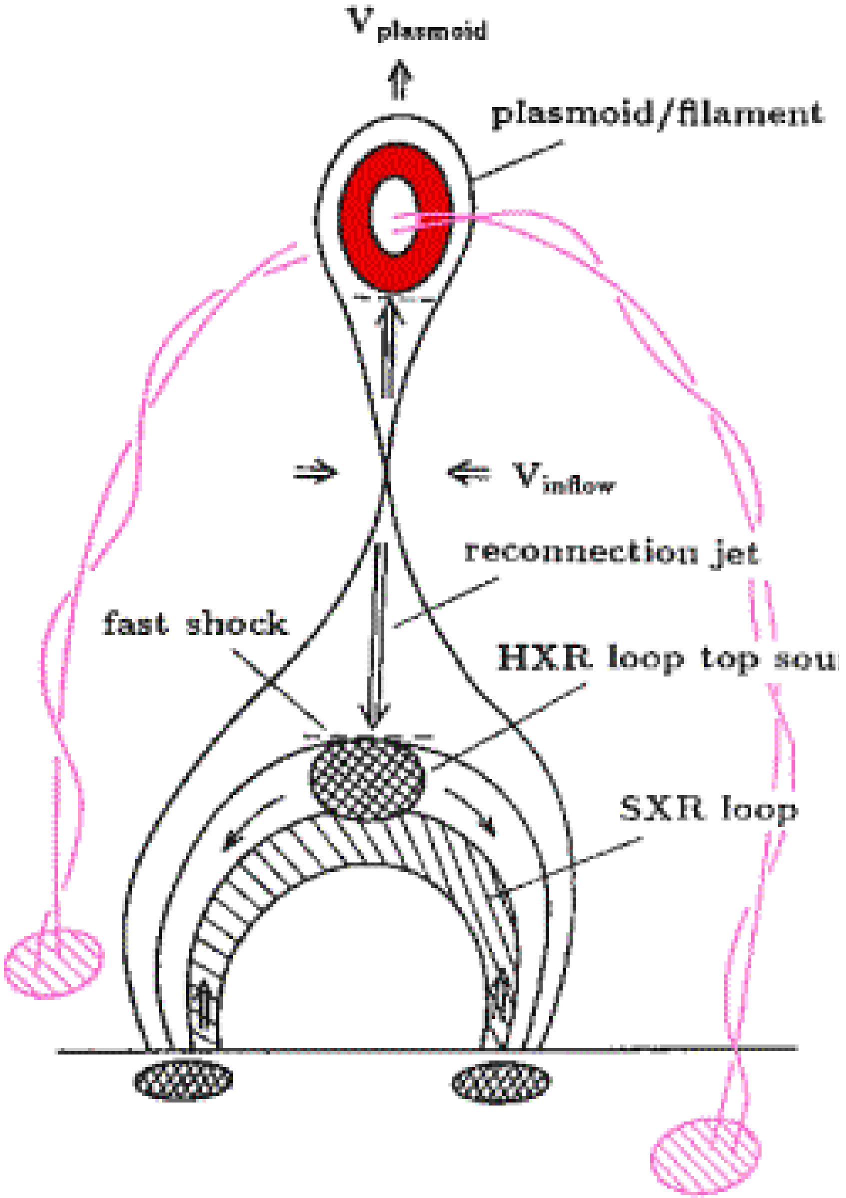
Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

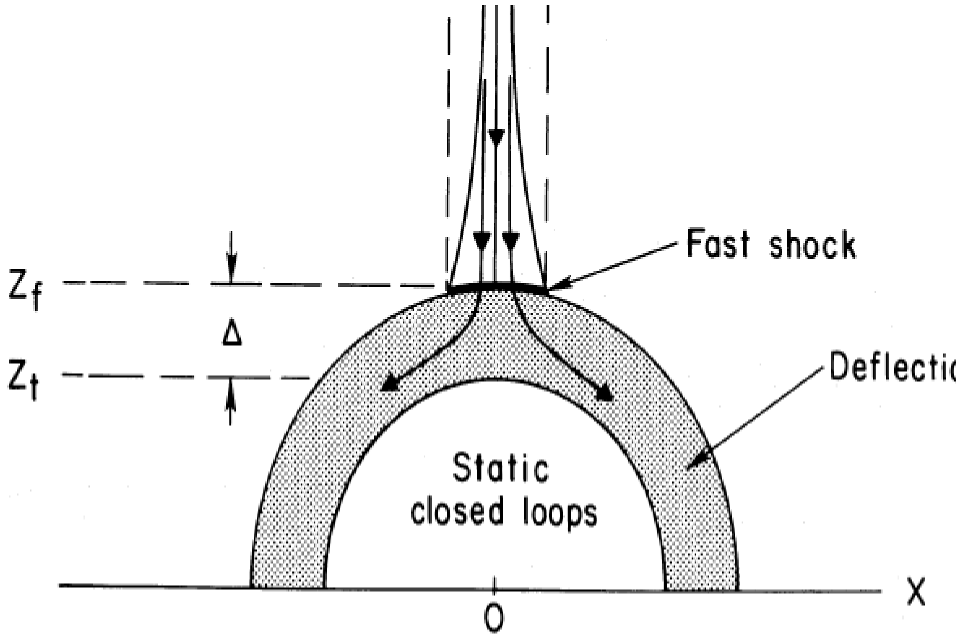
Recent Krucker et al. results

- The accelerated electron distribution is consistent with a power-law distribution.
- Electron are accelerated up to several MeV.
- The non-thermal population $n_e = 2 \times 10^9 [E/16keV]^{-1.35}$
- All particles get accelerated??



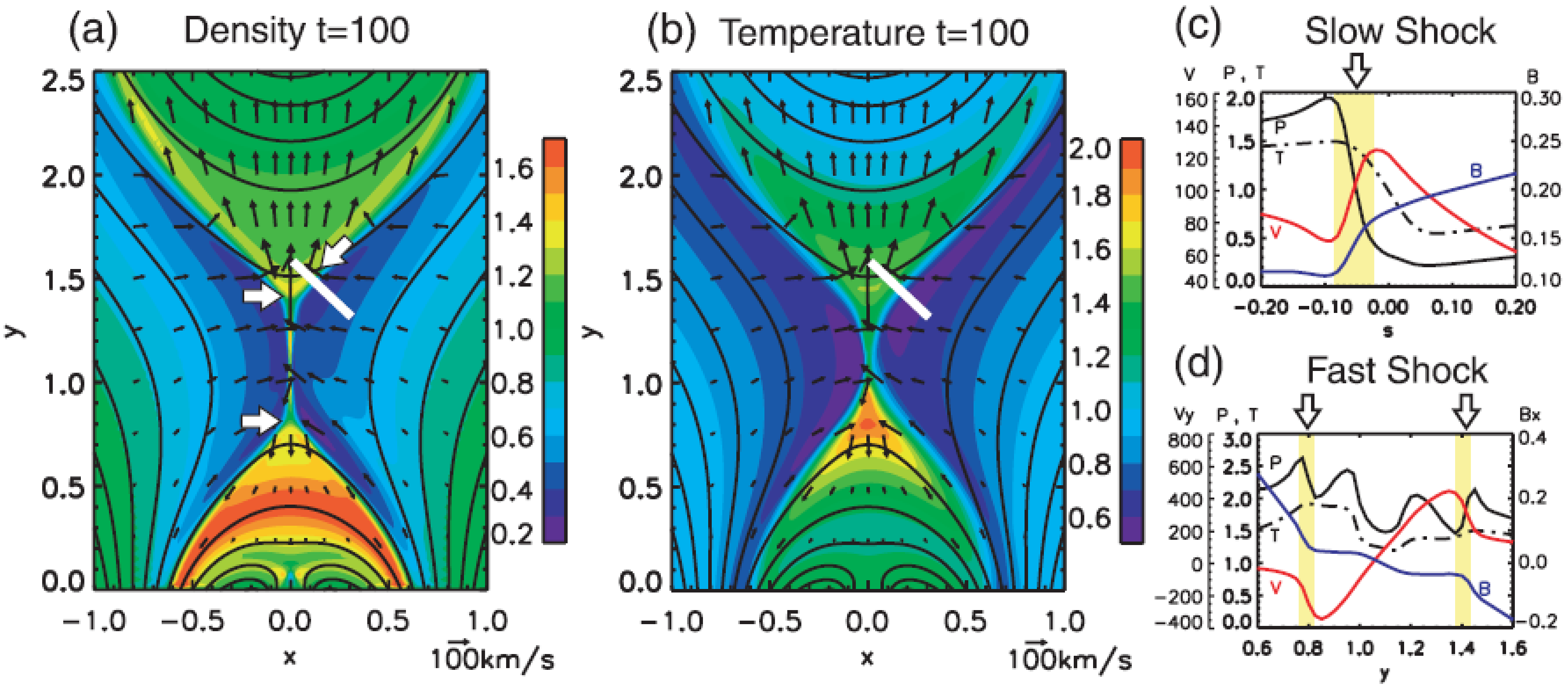
Flare models predict the existence of shocks





Terry Forbes (1986): perpendicular shock driven by reconnection outflow.
Mach number ~ 2.3, Compression ratio ~ 2

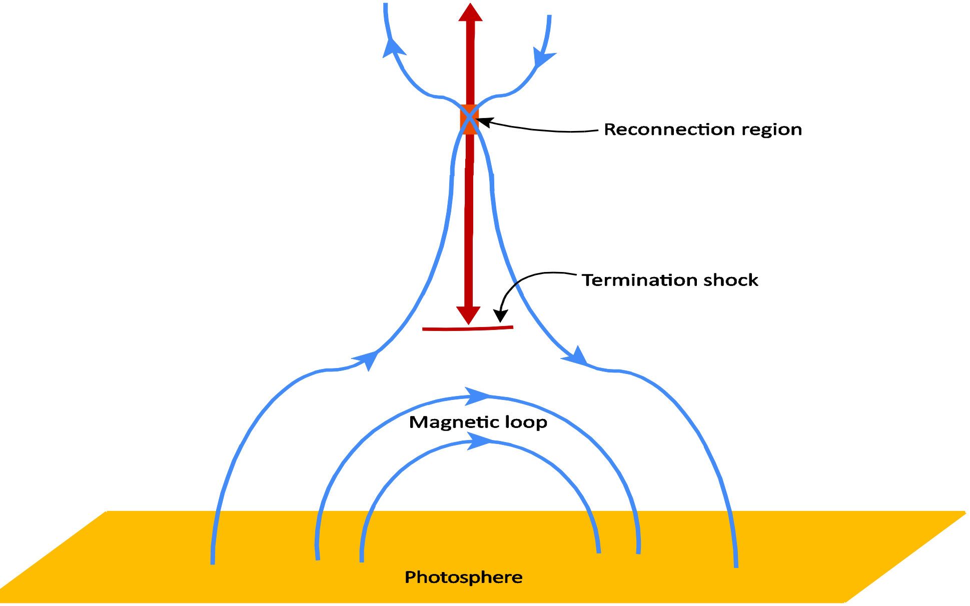
Results from MHD simulations



Shiota et al. 2003

Electron acceleration at flare shocks

Guo & Giacalone (2011 to be submitted)



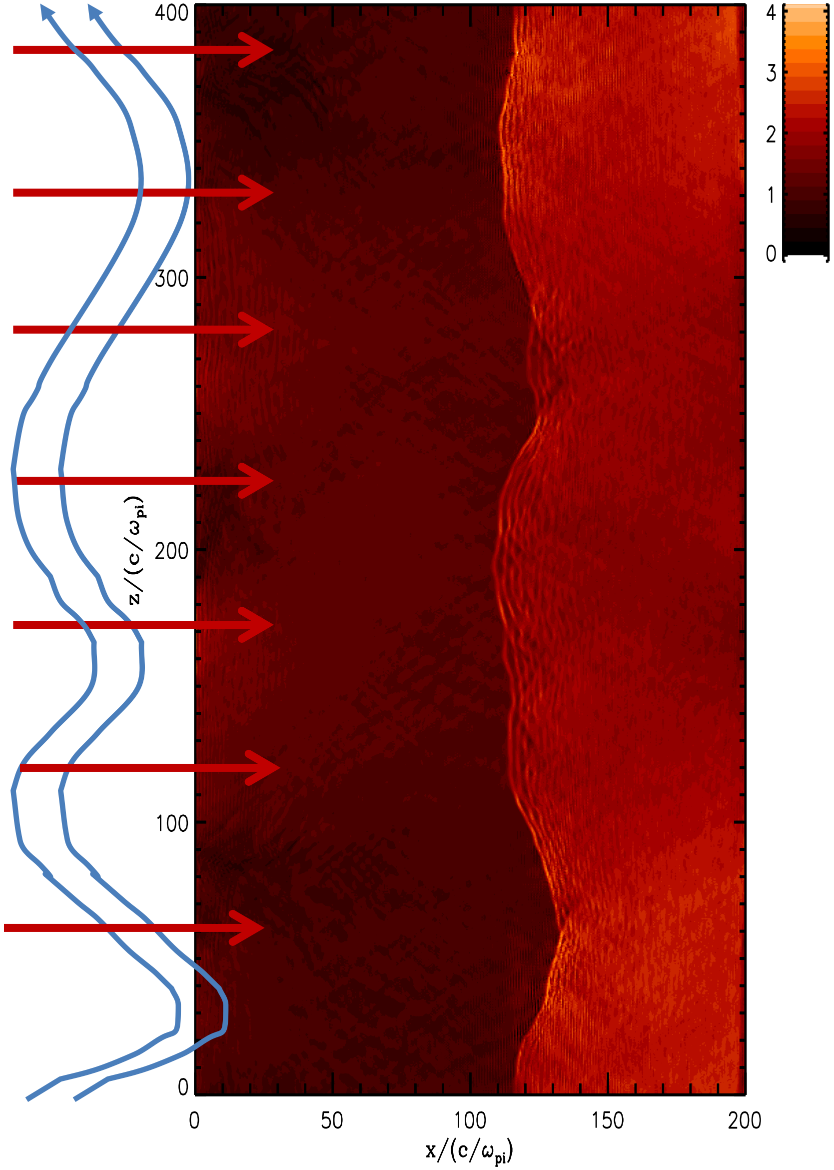
Method: hybrid simulation (kinetic ions, fluid electron) combined with test-particle electron simulation

Parameters: $T_i=T_e=2$MK, $n=8 \times 10^9$ cm^{-3}, B=30G

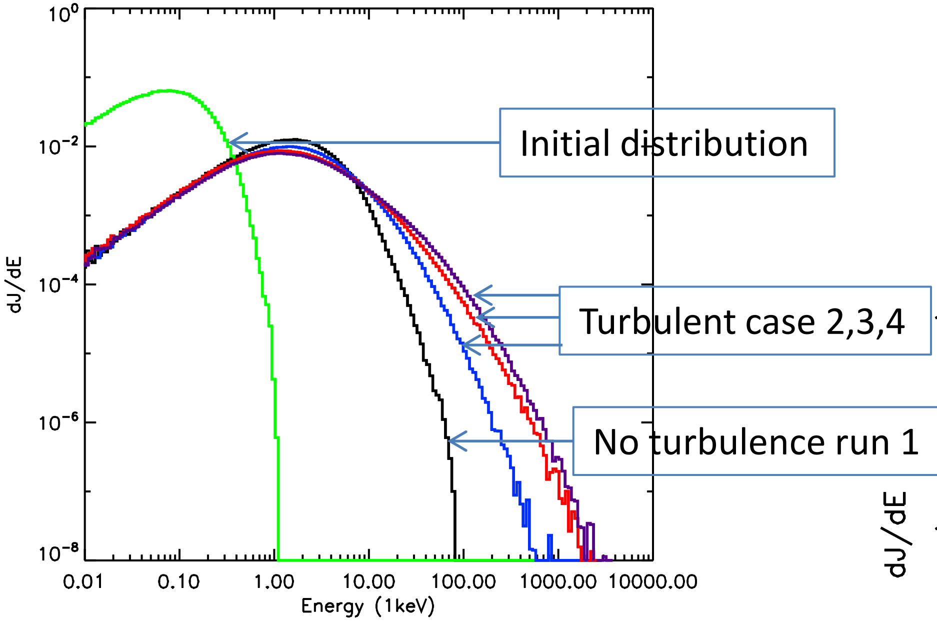
(Adapted from Krucker [2010])

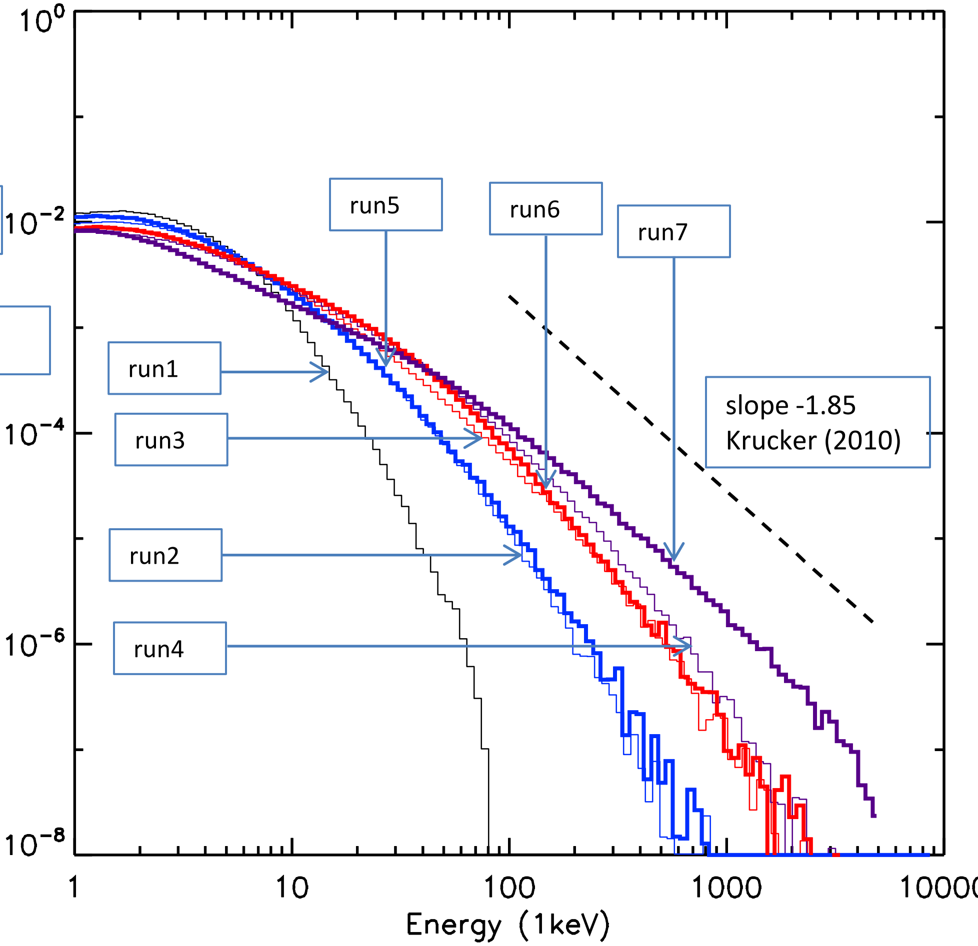
$M_A \sim 2.0$, $\rho_2/\rho_1 \sim 2.0$, $V_{shock}=1460$km/s

In real units: box size: 0.8km X 2.1km.



Electron acceleration at flare shocks



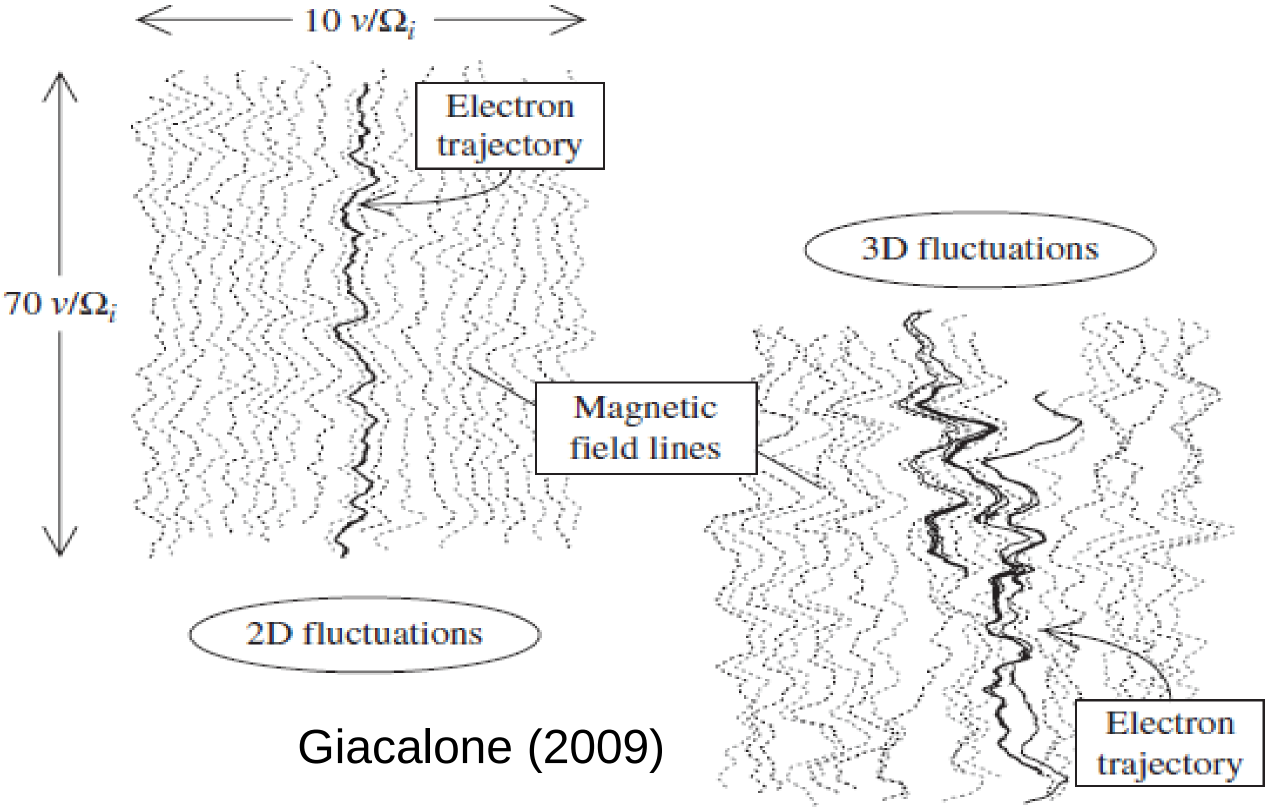


Reference

[1] Guo, F., & Giacalone, J. 2010, ApJ, 715, 406

[2] Krucker, S., Hudson, H. S., Glesener, L., White, S. M., Masuda, S., Wuelser, J.-P., & Lin, R. P. 2010, ApJ, 714, 1108

- **Effect of 3-D collisionless shocks.** In the system with at least one ignorable coordinate, particles are artificially tied on their original field lines. Particle transport normal to the mean magnetic field is suppressed [Jokipii et al. (1993)].



Giacalone (2009)

Conclusions

- After including preexisting turbulence, the electron can be efficiently accelerated by quasi-perpendicular shock.
- The acceleration mechanism is drift acceleration including acceleration by ripples and multiple reflection taken by large scale field line random walk.
- The limitation of drift acceleration is probably associated with the scale of shock and structure in y-direction.
- The diffusive acceleration is suppressed by 2-D calculation, which require the consideration of 3-D magnetic field, or artificial cross-field diffusion.
- When electrons gain sufficient energy, their feedback to the EM field become important. A full particle simulation is desired.