Particle acceleration

How are particles energized during solar eruptions?

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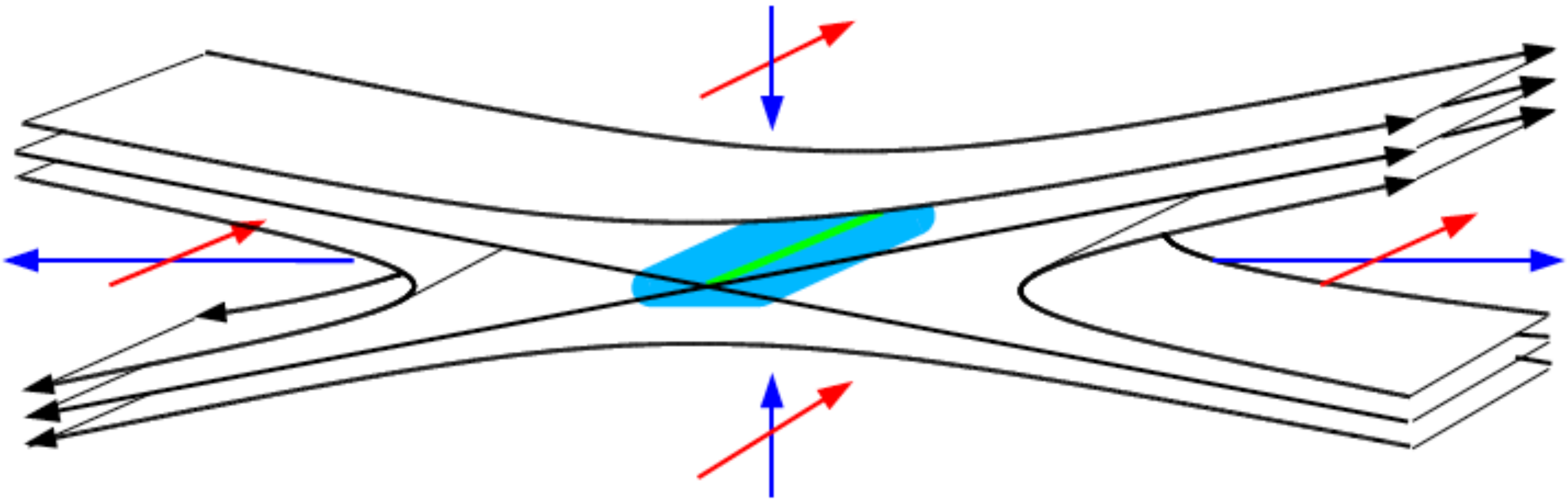
Solar energetic particle events

- Energetic particle events are associated with both flares and coronal mass ejections
  - Impulsive flares without CMEs able to generate impulsive SEP events
    - Electron rich
    - 3-He rich
    - Heavy-ion rich
  - Prominence eruptions (and resulting CMEs) without flares able to generate gradual SEP events
    - Electron poor
    - ”Normal” ion abundances
  - A typical large SEP event would be associated with both a CME and a flare
- Acceleration of particles up to relativistic energies:
  - Ions: 10 GeV/n
  - Electrons: 100 MeV
- Spectral shapes
  - Ions: variable (exponential, power laws, double power laws, power laws with exponential cutoff)
  - Electrons: power laws / double power laws
- How can we understand energy spectra and abundances?
- Note: usually an SEP event is associated with both a flare and a CME

Particle acceleration mechanisms in flares

- Direct electric field models (current sheets)
- Collapsing trap models (flare loops)
- Stochastic acceleration models

Direct electric field acceleration



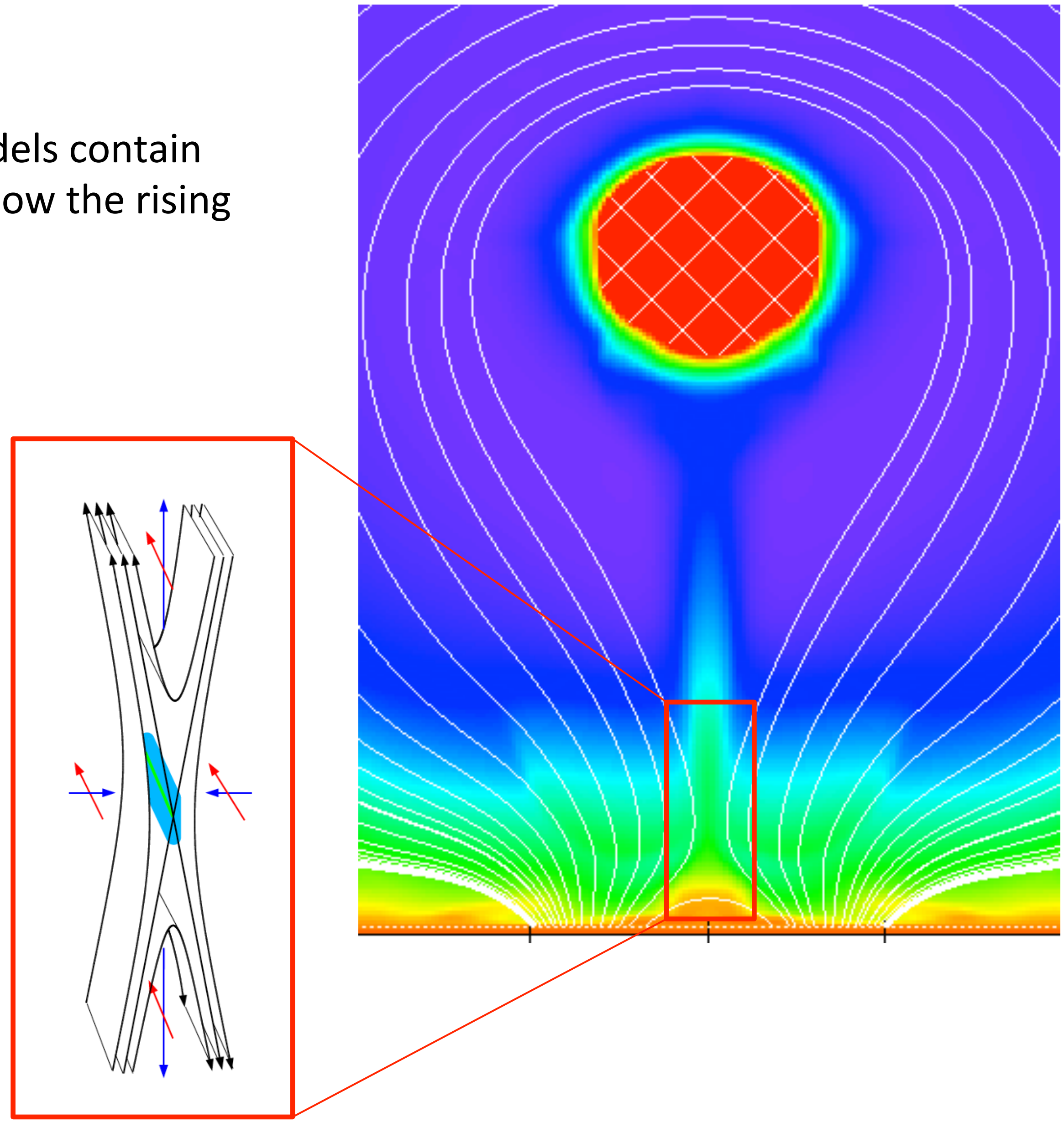
Infinitely conducting plasma → **E** = − **V** × **B** ⊥ **V**, **B**

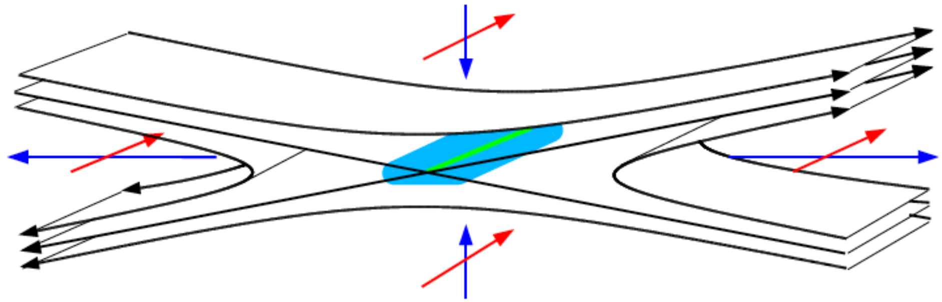
Particle acceleration by DC electric field requires either

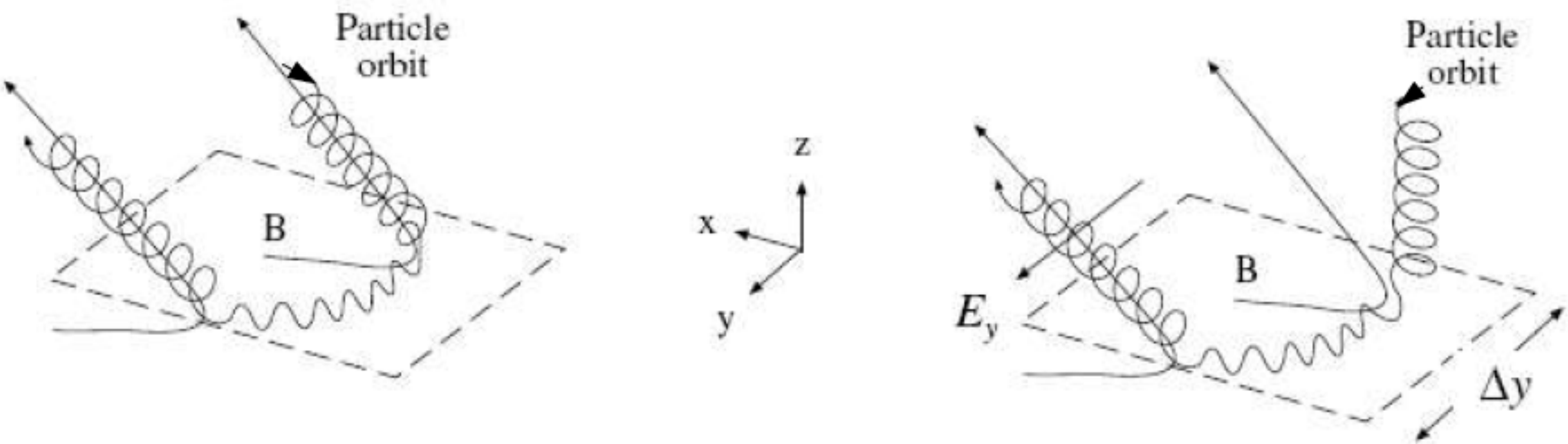
- **E** · **B** ≠ 0 (resistive plasma),
- **B** ≈ 0 (magnetic null point / line), or
- Strong curvature / gradient drifts across the magnetic field

Available, e.g., in reconnection regions

Solar eruption models contain a current sheet below the rising flux rope







static current sheet, **E** = 0

reconnecting current sheet, **E** ≠ 0

$$\Delta W = qE_y \, \Delta y$$

Very model-depedent energy spectrum

Understanding of reconnection electric field still incomplete

Adiabatic invariants

From analytical mechanics: periodic motion in some generalised coordinate *q* always implies the conservation of so-called action variable,

$$\oint p\,\mathrm{d}q = \mathrm{const.}$$

where *p* is the canonical momentum related to *q*. The integral is over one period of *q*.

Consider a system with a parameter (e.g., a scale length, a field strength) λ. When the parameter is kept constant the motion is periodic in *q*.

If now λ is changed slowly, i.e., by a small amount in one period of the motion, it can be shown that the action variable is still an approximately (but to a very high accuracy) conserved quantity, i.e., an adiabatic invariant.

Larmor motion: periodic generalised coordinates (x, y) and canonical momenta (p_x, p_y) = (mv_x+qA_x, mv_y+qA_y), where **A** is the vector potential.

$$J_x = \oint p_x \, \mathrm{d}x; \quad J_y = \oint p_y \, \mathrm{d}y$$

$$J_x + J_y = \oint \mathbf{p}_\perp \cdot \mathrm{d}\mathbf{l} = \gamma m \oint \mathbf{v}_\perp \cdot \mathbf{v}_\perp \, \mathrm{d}t + q \oint \mathbf{A} \cdot \mathrm{d}\mathbf{l}$$

$$= \gamma m v_\perp^2 \frac{2\pi}{\omega_c} + q \int_S (\nabla \times \mathbf{A}) \cdot \mathrm{d}\mathbf{S} = \frac{2\pi}{|q|} \frac{(\gamma m v_\perp)^2}{B} - |q| B \pi r_\mathrm{L}^2$$

$$= \frac{\pi}{|q|} \frac{(\gamma m v_\perp)^2}{B}$$

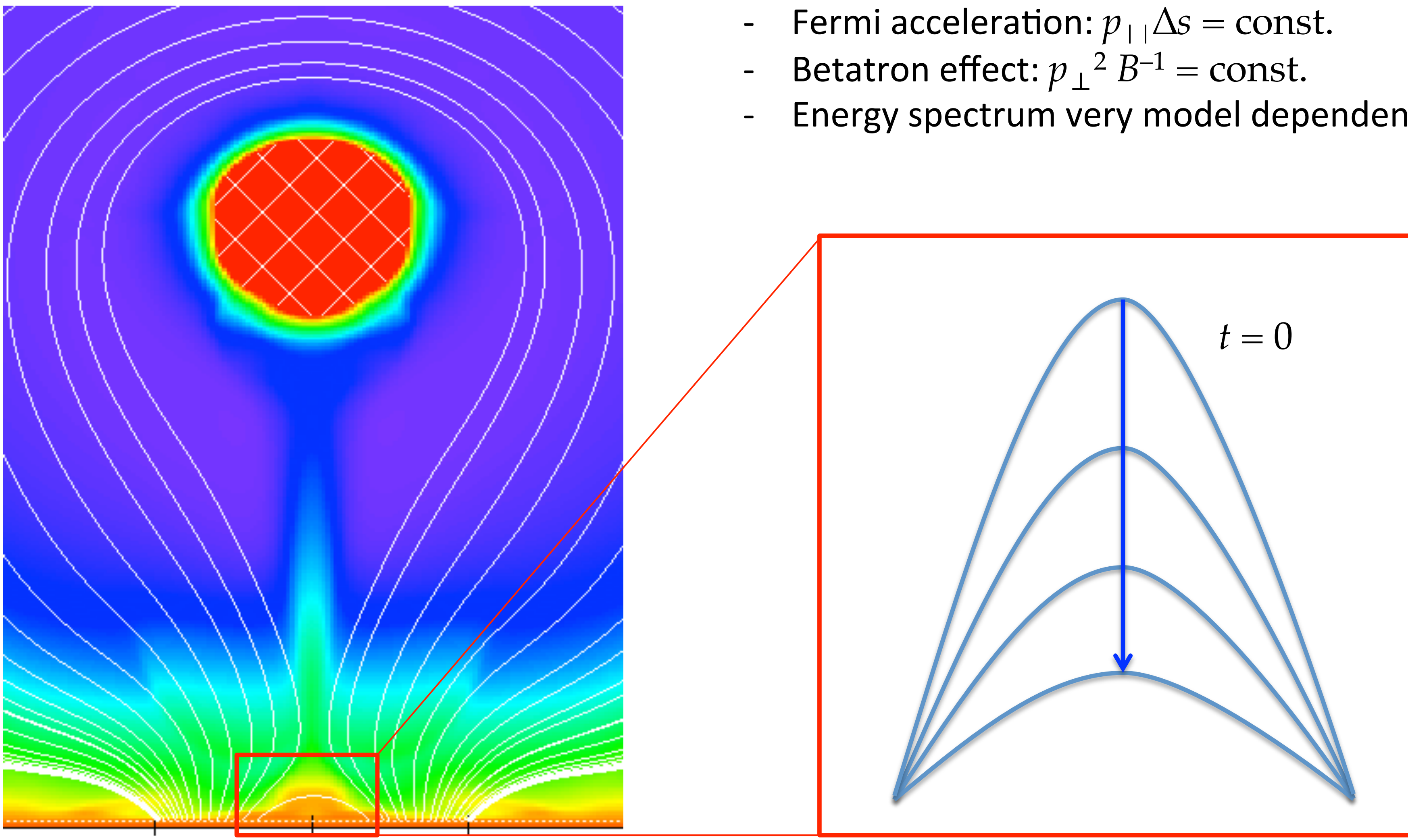
Thus, $\dfrac{(\gamma m v_\perp)^2}{B} = \text{const.} \Rightarrow$ e.g., mirroring

Another example: bounce motion around a minimum in B:

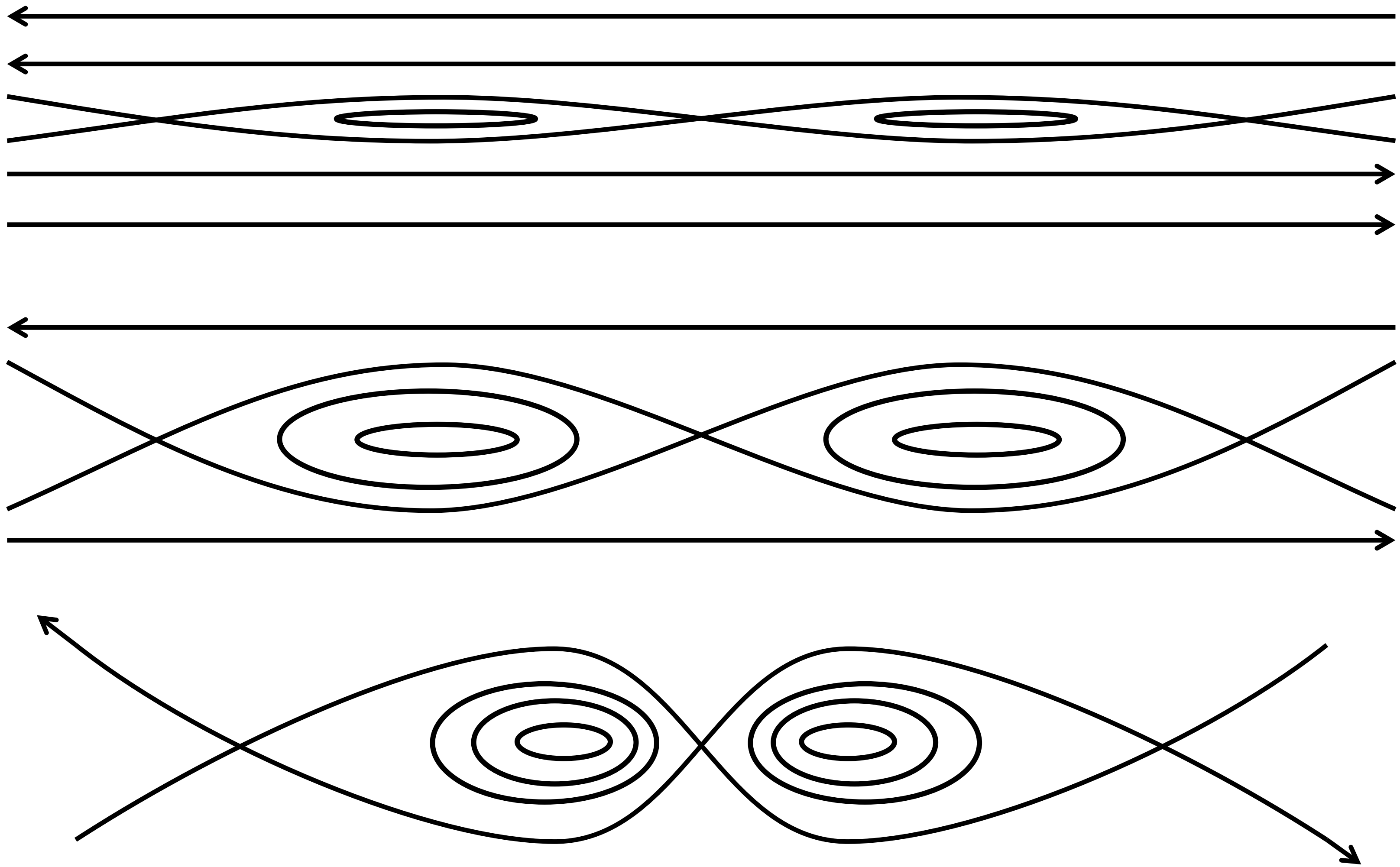
$$\oint p_{||} \, \mathrm{d}s = \text{const.}$$

Collapsing trap models

Two mechanisms:
- Fermi acceleration: $p_{||}\Delta s = \text{const.}$
- Betatron effect: $p_{\perp}{}^{2}\, B^{-1} = \text{const.}$
- Energy spectrum very model dependent



Which processes are able to accelerate particles in a tearing-unstable current sheet?



a) DC electric field acceleration?
b) Betratron acceleration?
c) Fermi acceleration?

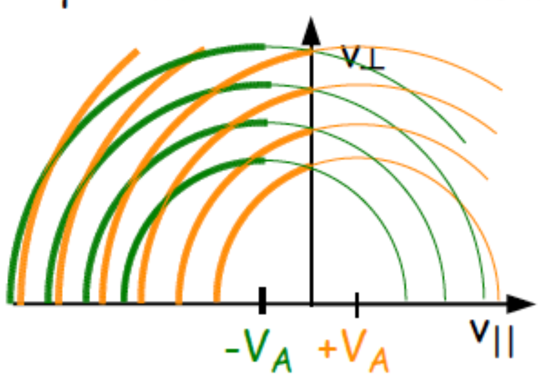
Stochastic acceleration

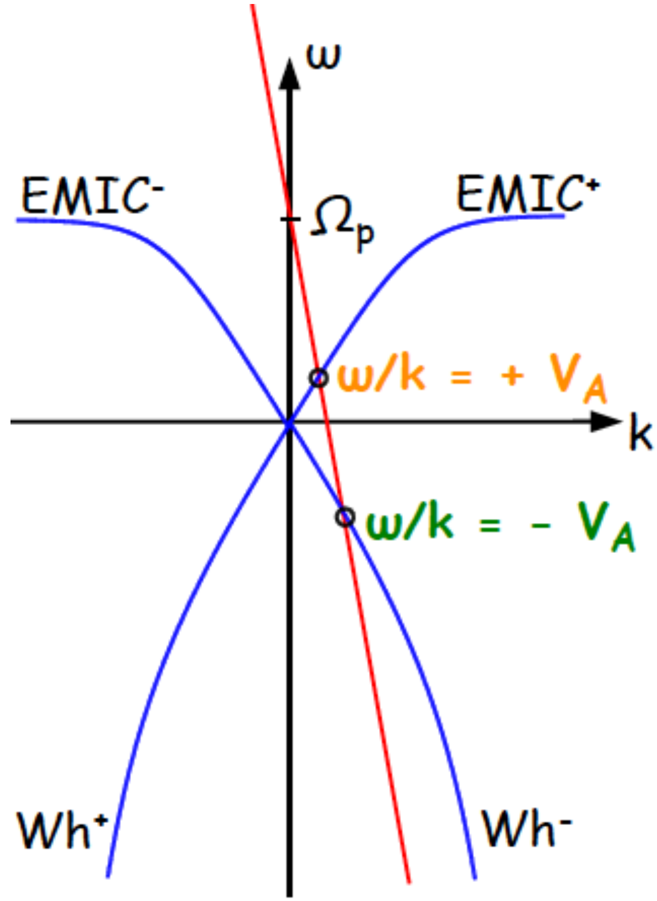
Wave-particle interactions with EM plasma waves

- Cyclotron resonance condition $\omega = v_{||} k + n \Omega$ where $n \in \mathbb{Z}$
- Dispersion relation: $\omega = v_p(k)\, k$

Multiple resonances → acceleration possible

- Faraday's law: $-\omega\, \mathbf{B}_w = \mathbf{k} \times \mathbf{E}_w$
  → wave-frame ($\omega = 0$):
  $\mathbf{k} \,||\, \mathbf{E}_w$ (electrostatic wave), or
  $\mathbf{E}_w = 0$ (electromagnetic wave)
- multiple EM resonances → **momentum diffusion**





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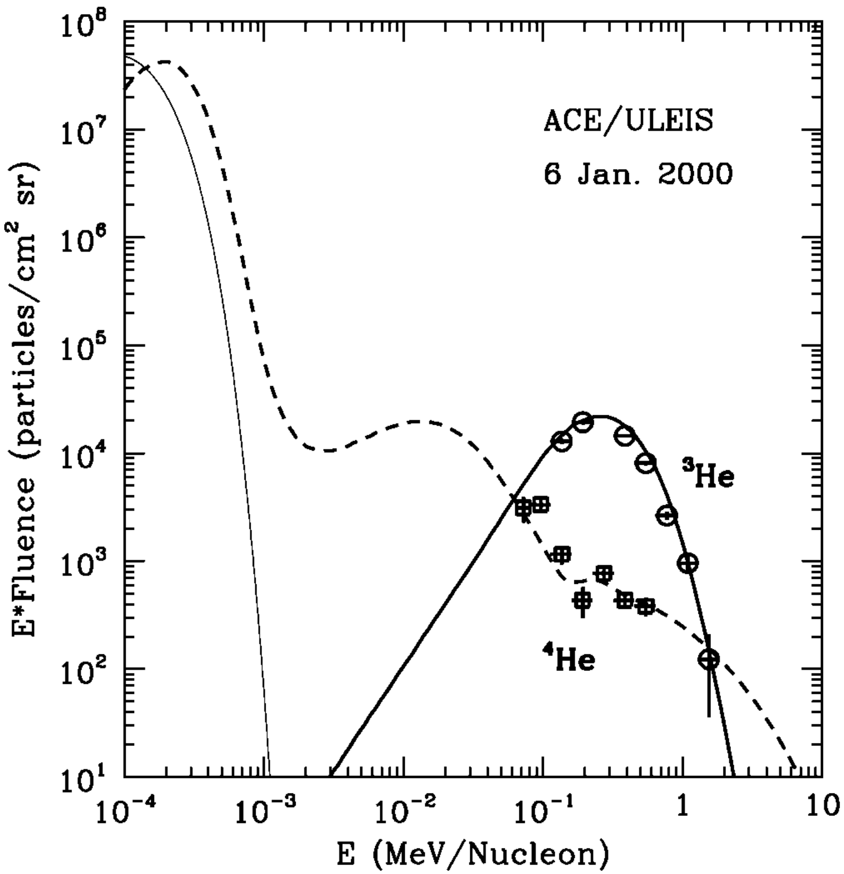
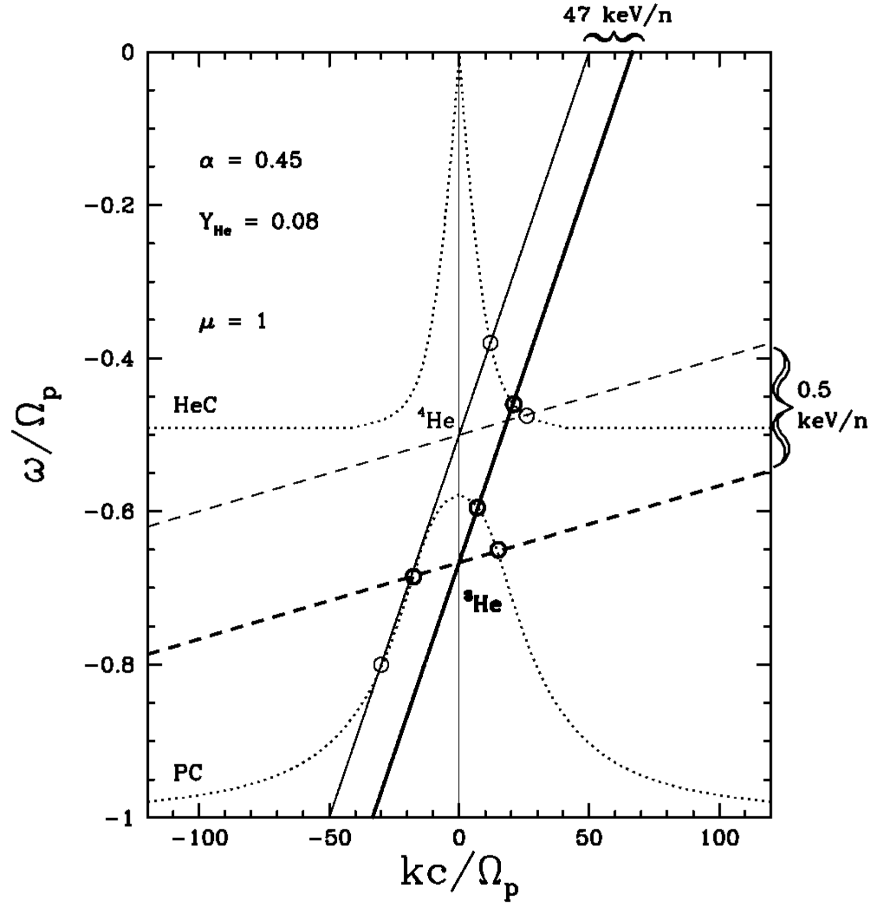
SUMMER SCHOOL HESPERIA

STOCHASTIC ACCELERATION OF ^{3}He AND ^{4}He BY PARALLEL PROPAGATING PLASMA WAVES

SIMING LIU,[1] VAHÉ PETROSIAN,[1,2] AND GLENN M. MASON[3]





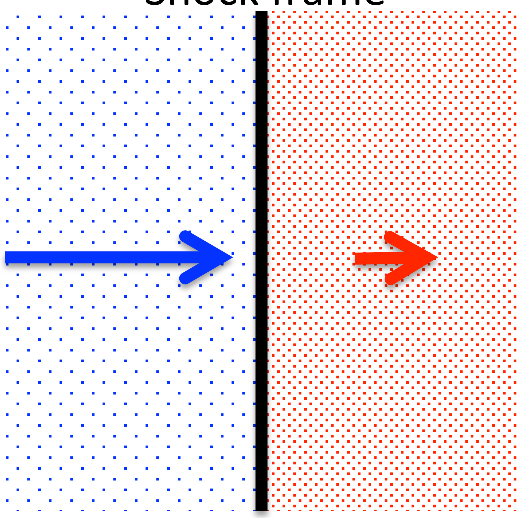
$$\frac{\partial N}{\partial t} = \frac{\partial^2}{\partial \epsilon^2}(D_{\epsilon\epsilon}N) + \frac{\partial}{\partial \epsilon}\{N[\dot{\epsilon}_L - A(\epsilon)]\} - \frac{N}{T_{esc}} + Q,$$

Particle acceleration in CME-driven shock waves

Shocks

Transitions of flow from super(magneto)sonic to sub(magneto)sonic flow with compression and dissipation.

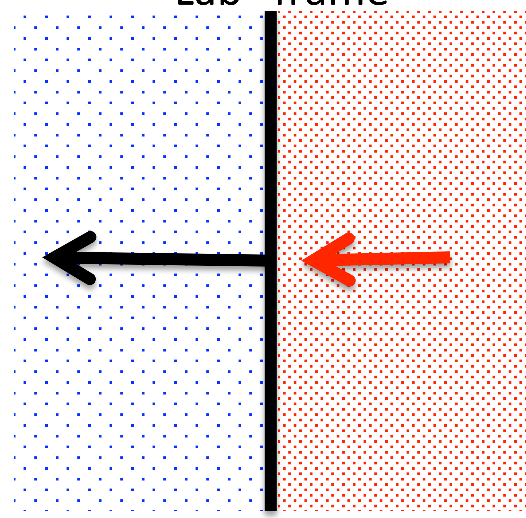
Shock frame



Upstream:
– cool
– dilute
– faster

Downstream:
– hot
– dense
– slower

“Lab“ frame



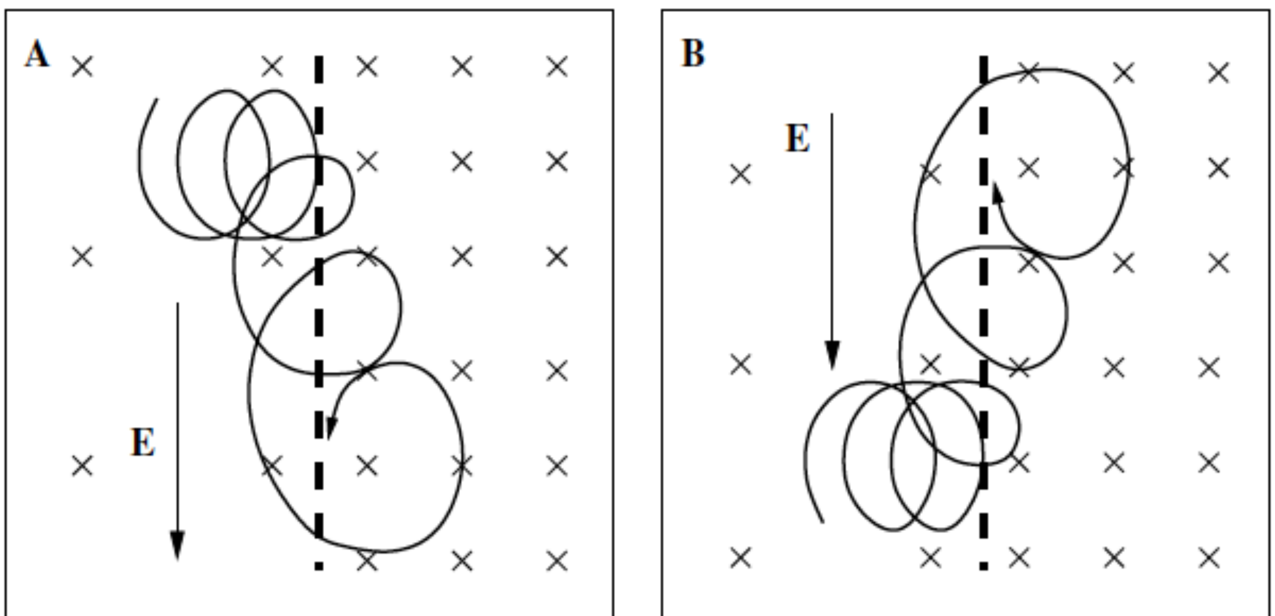
Upstream:
– cool
– dilute
– at rest

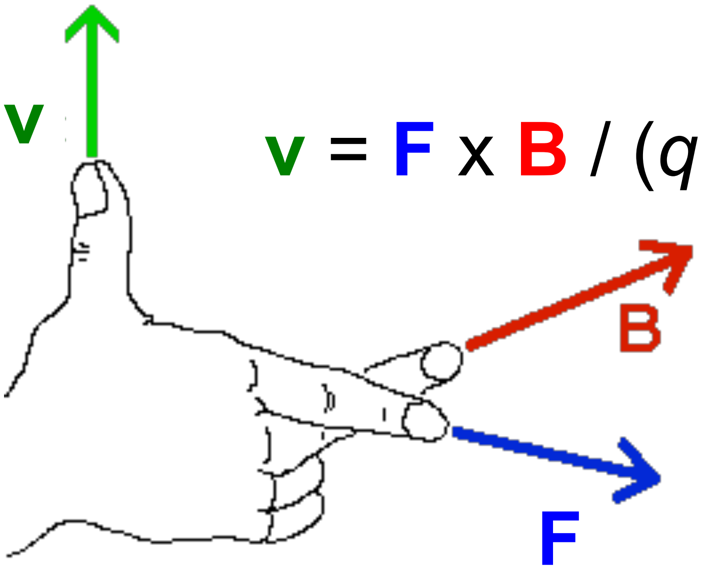
Downstream:
– hot
– dense
– in motion

Scatter-free shock acceleration

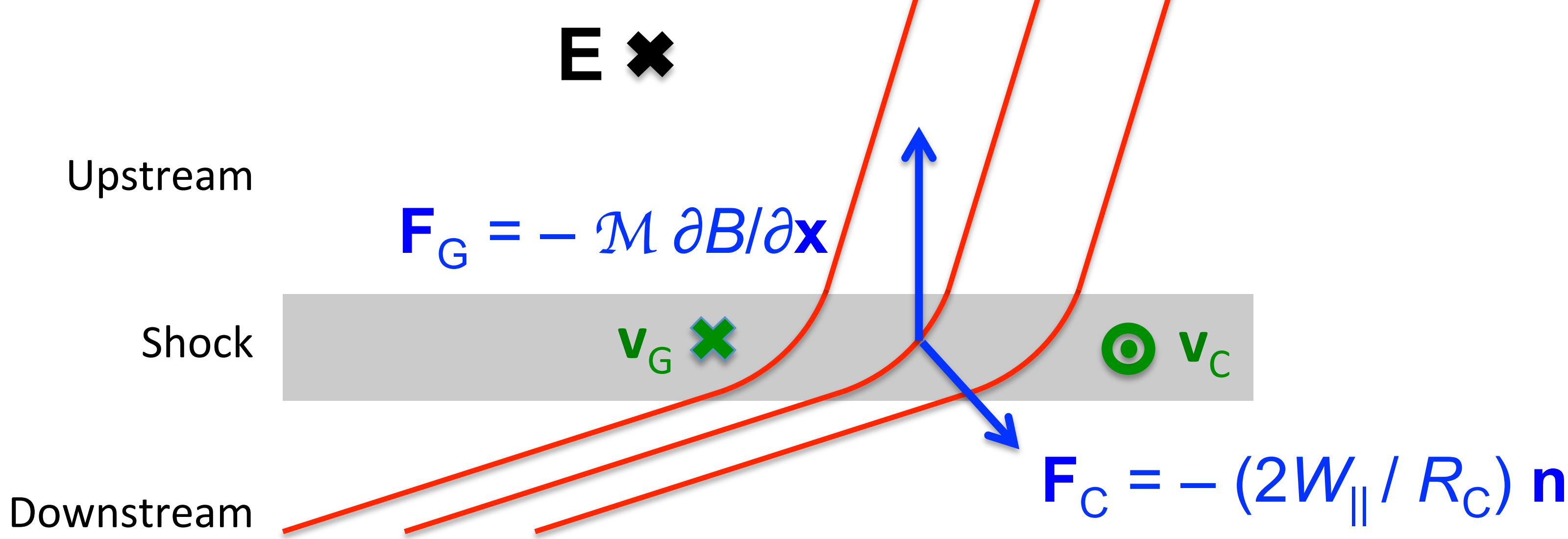
Shock-drift acceleration

- particles energized by the convective electric field
- net gradient + curvature drift along the E-field for ions and against the E-field for electrons
- single interaction provides only a small energy gain, $W_2 \sim (B_2/B_1) \cdot W_1$

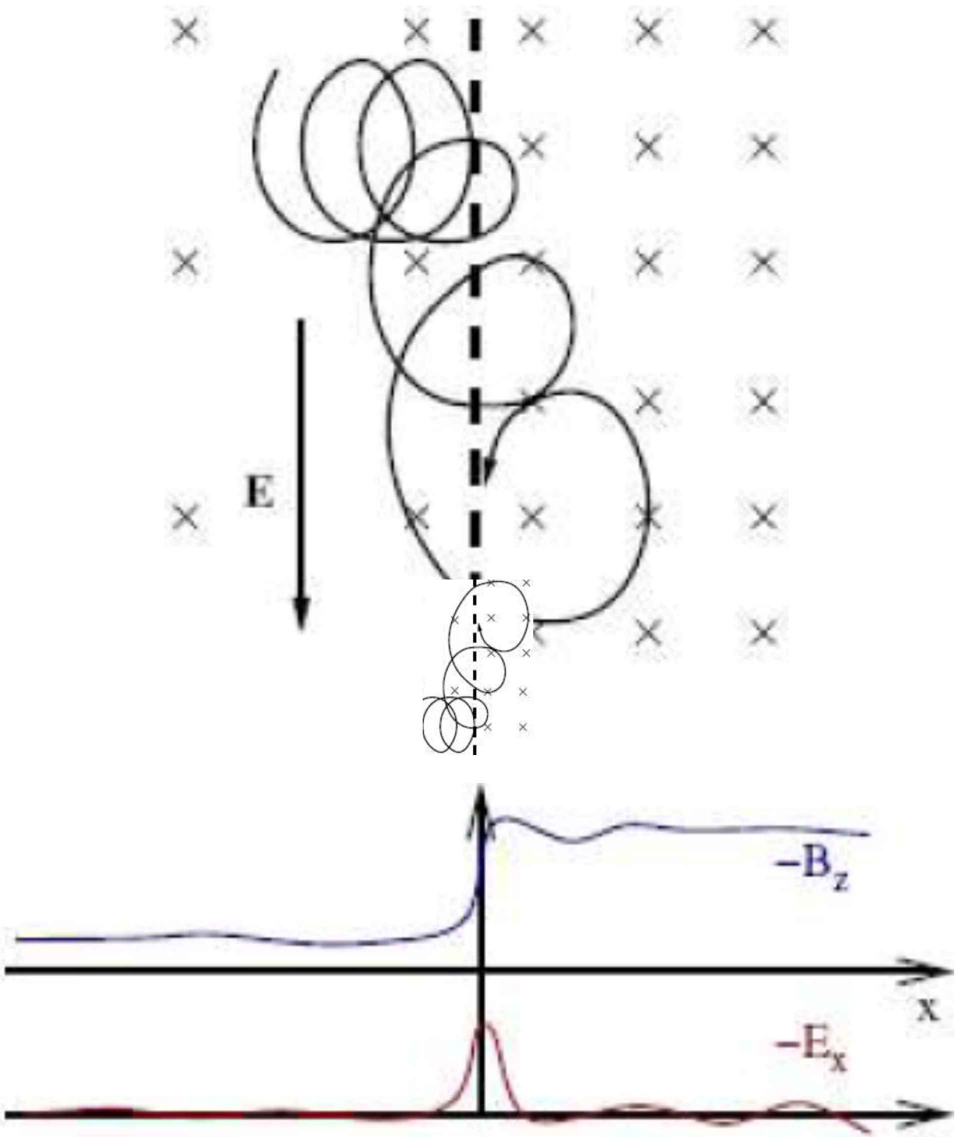




$$\mathbf{v} = \mathbf{F} \times \mathbf{B} / (q B^2)$$



Cross-shock potential

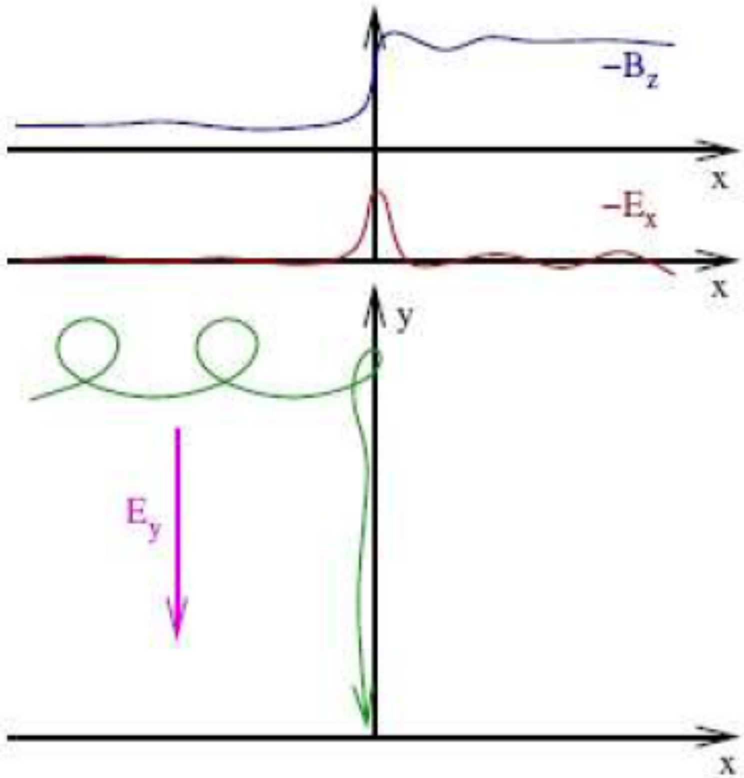


Difference in gyroradii of ions and electrons

➔ Charge separation

➔ Cross-shock potential

Shock surfing (ions)



- $E_x = -d\phi/dx \Rightarrow$ Particles reflected
- Turned back by upstream B_z
- Eqs. of motion

$$\begin{aligned}\dot{p}_x &= q(E_x + v_y B_z)\\ \dot{p}_y &= q(E_y - v_x B_z)\end{aligned}$$

- Ass. v_x small

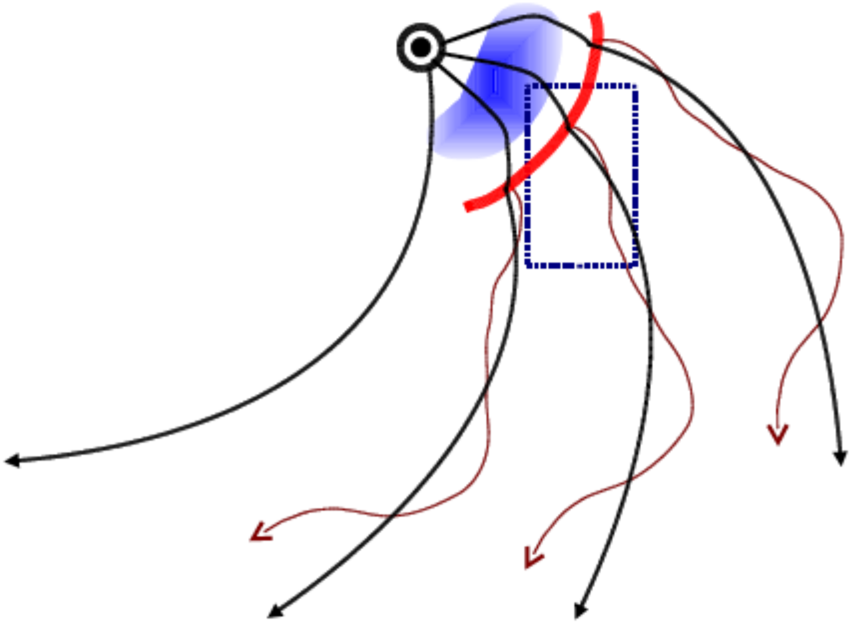
  $\Rightarrow$ Acceleration along $-y$
- particles trapped until

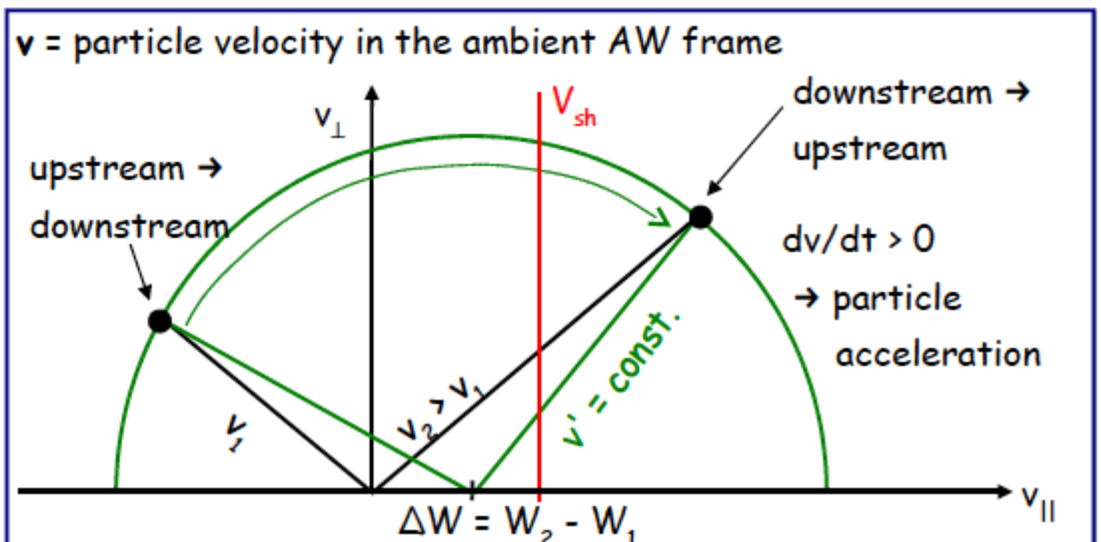
$$v_y \sim -\frac{E_x}{B_z} \ll -\frac{m_i^{1/2}}{m_e^{1/2}} M_A\, V_1 \quad \Rightarrow \quad \text{MeV energies (injector?)}$$

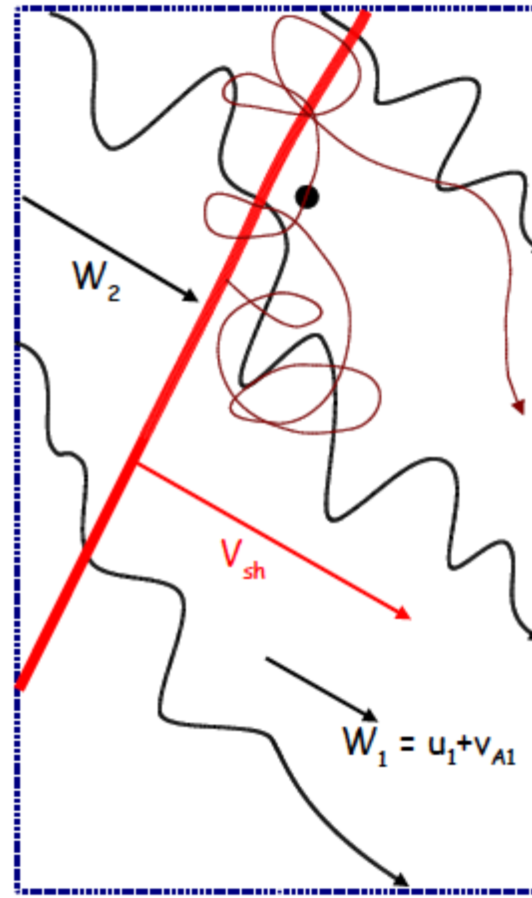
But: surfing requires an almost exactly perpendicular shock

Note: the accelerating field is E_y

Diffusive shock acceleration







Particles crossing the shock many times (because of strong scattering) get accelerated

Particle motion near the shock

Particle energy conserved in the frame of the plasma

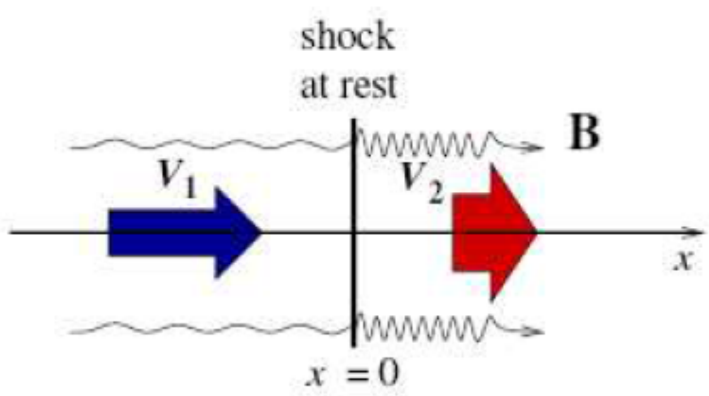
Consider a particle incident on the shock from upstream, scattering downstream and coming back

- change of kinetic energy is

$$\Delta T = \Delta V\, p(\mu_{1\to 2} - \mu_{2\to 1});\quad \Delta V = V_1 - V_2$$

- isotr. → average value of each $|\mu|$ is 2/3
- Thus,

$$\Delta p = \frac{\Delta V\, p(\mu_{1\to 2} - \mu_{2\to 1})}{v} = \frac{4\Delta V}{3v}\, p$$



Probability of return to the shock from downstream

$$P_{\mathrm{ret}} = \frac{\text{flux from downstream to upstream}}{\text{flux incident from upstream}} = \left(\frac{v - V_2}{v + V_2}\right)^2 \approx 1 - 4\frac{V_2}{v}$$

assume isotropy

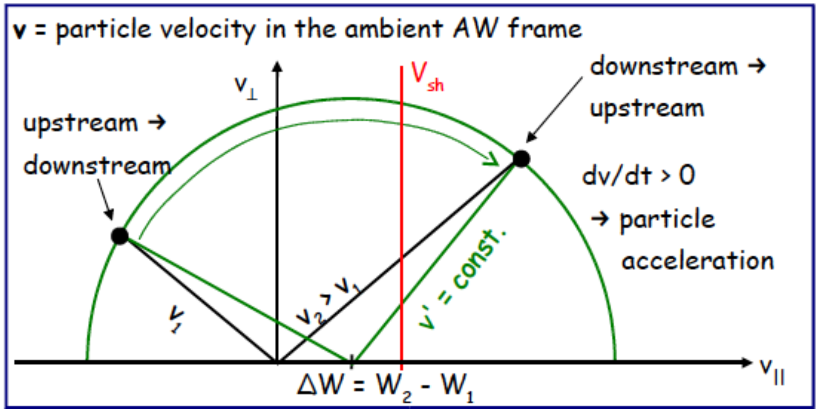
Spectrum in diffusive shock acceleration

Momentum gain per crossing cycle 1 → 2 → 1: $\Delta p = \frac{4\Delta V}{3v} p$

Probability of return from downstream: $P_{ret} = 1 - \frac{4V_2}{v}$

Particle momentum after N cycles:

$$p_N = p_0 \prod_{j=1,N} \left(1 + \frac{4\Delta V}{3v_j}\right)$$



Probability of surviving at least N cycles:

$$P_N = \prod_{j=1,N} \left(1 - \frac{4V_2}{v_j}\right)$$

Thus,

$$\ln P_N = \sum_{j=1,N} \ln\left(1 - \frac{4V_2}{v_j}\right) = \sum_{j=1,N} \left(\frac{-4V_2}{v_j}\right) = \frac{-3V_2}{\Delta V} \ln(p_N / p_0)$$

$$N(p > p_N) = N_0 (p_0 / p_N)^{3/(X-1)}; \quad X = \frac{V_1}{V_2}$$

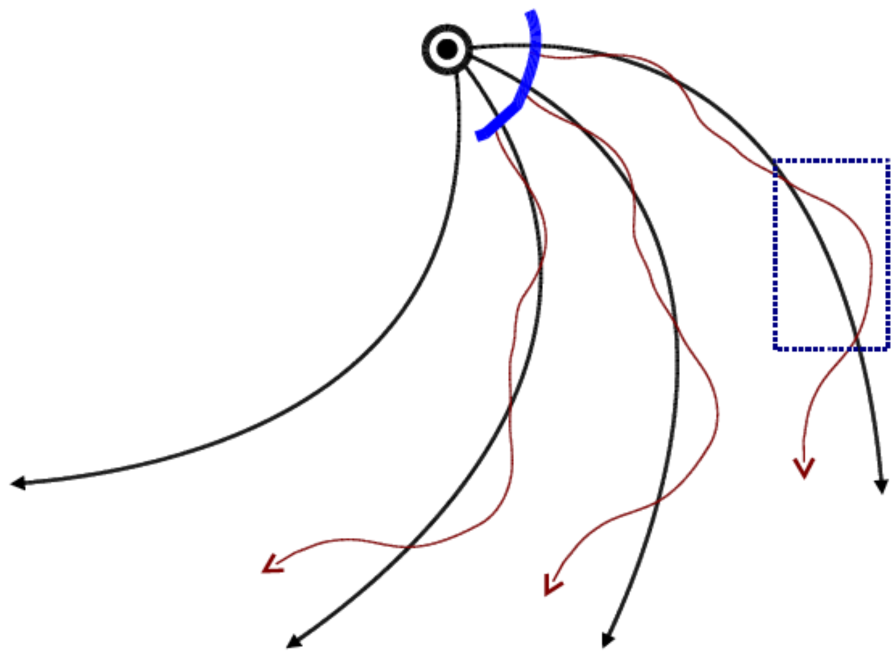
$$\frac{dN}{dp} = \frac{3N_0}{X-1} \left(\frac{p_0}{p}\right)^{(X+2)/(X-1)}$$

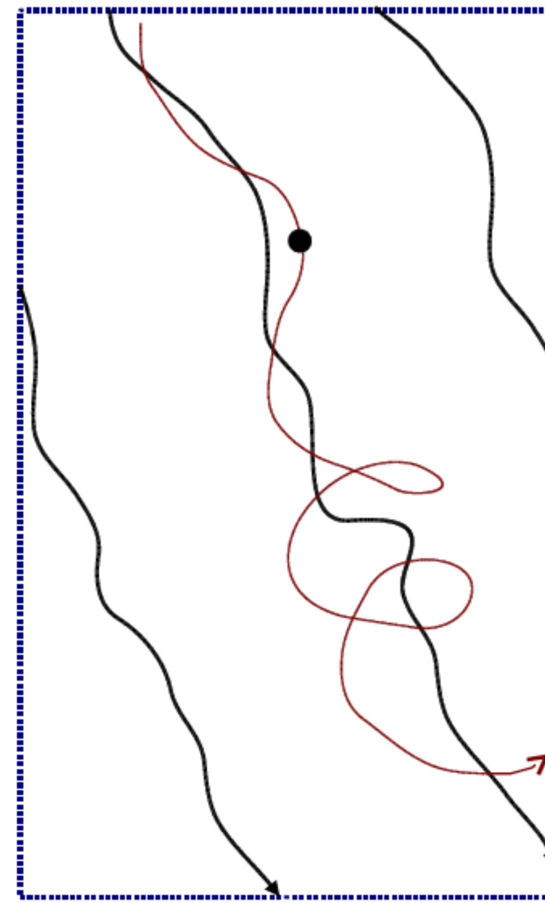
"Canonical" power-law spectrum! Matches observations of ion spectra very well at low energies.

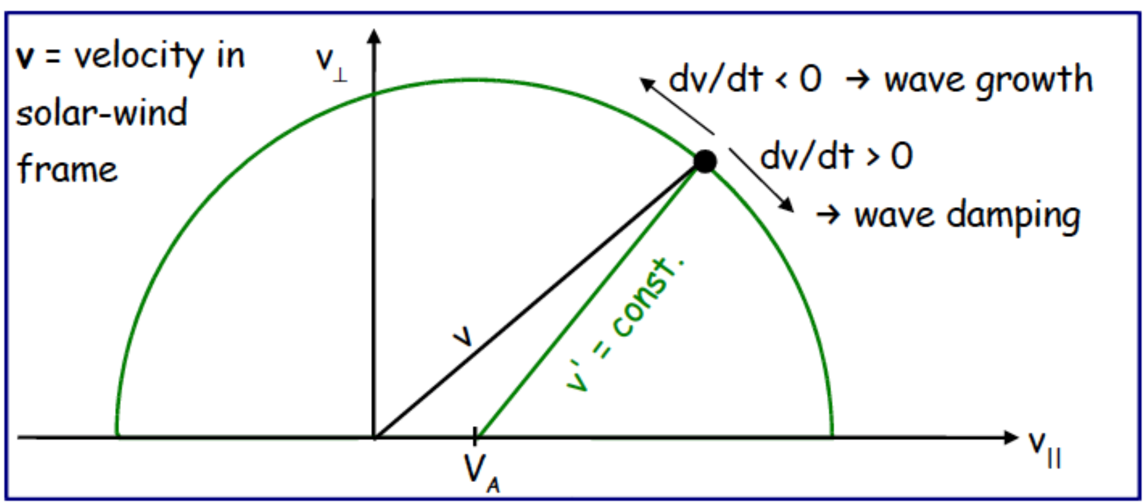
Turbulence around shocks

- Diffusive shock acceleration requires turbulence to scatter particles back and forth across the shock
  - Downstream, turbulence is naturally present (generated by the shock)
  - Upstream, ambient turbulence has to be adjusted to meet two constraints:
    - Fast acceleration (strong turbulence close to the shock)
    - Rapid escape (turbulent sheath not too thick)
- Upstream turbulence can be self-generated
  - Ion distribution upstream is unstable (streaming instability) for growth of Alfvén waves propagating across the flow

Streaming instability and proton transport

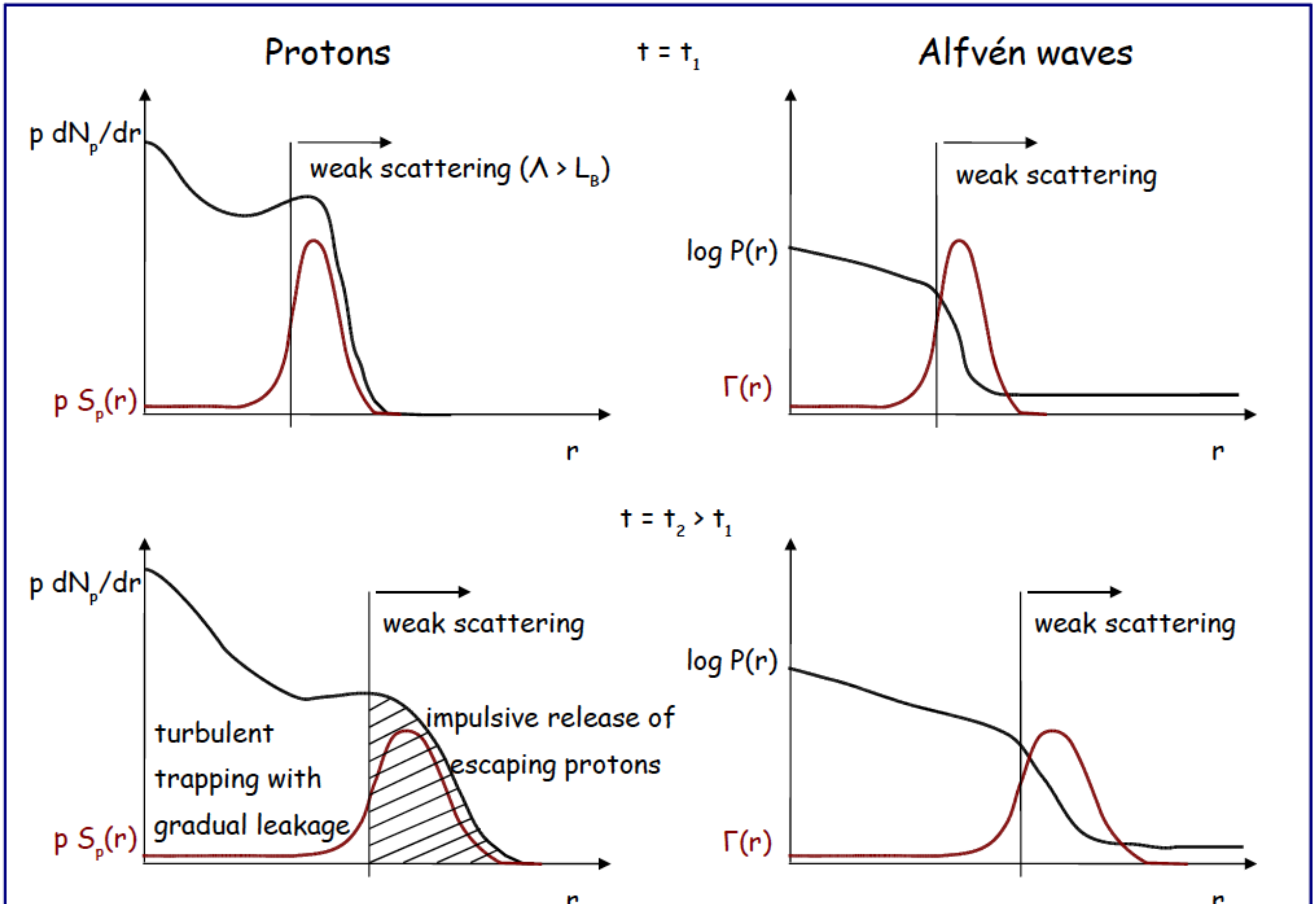




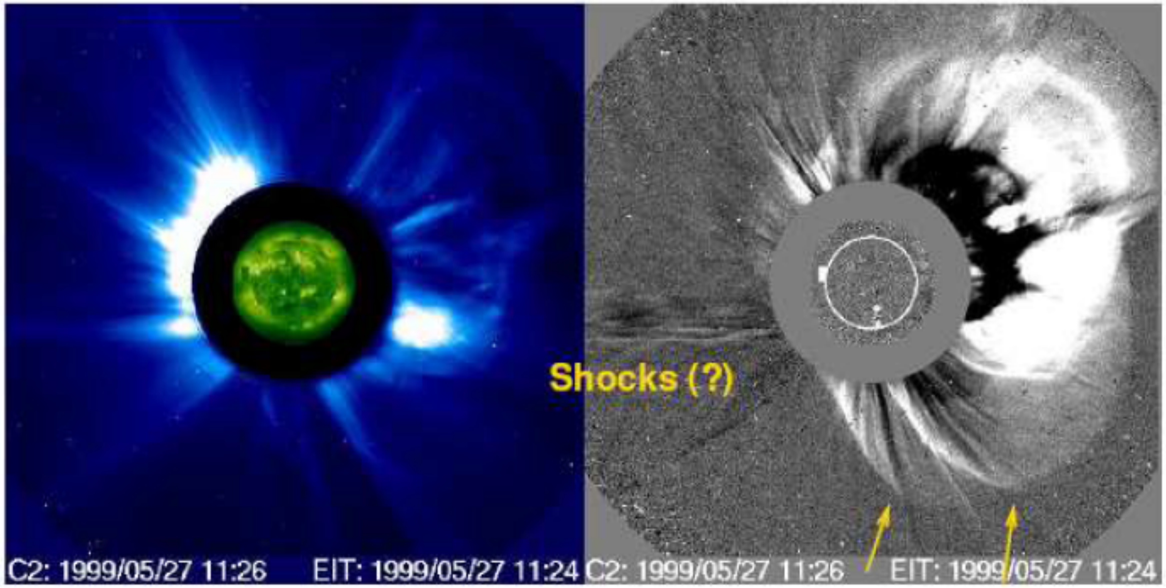


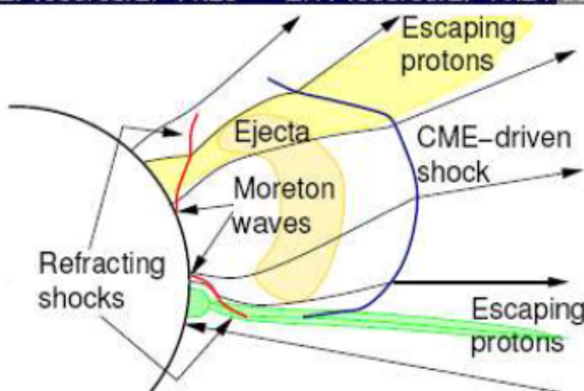
Outward propagating AWs amplified by outward streaming SEPs
→ stronger scattering

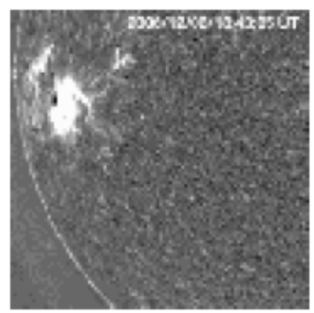
Coupled evolution of particles and waves

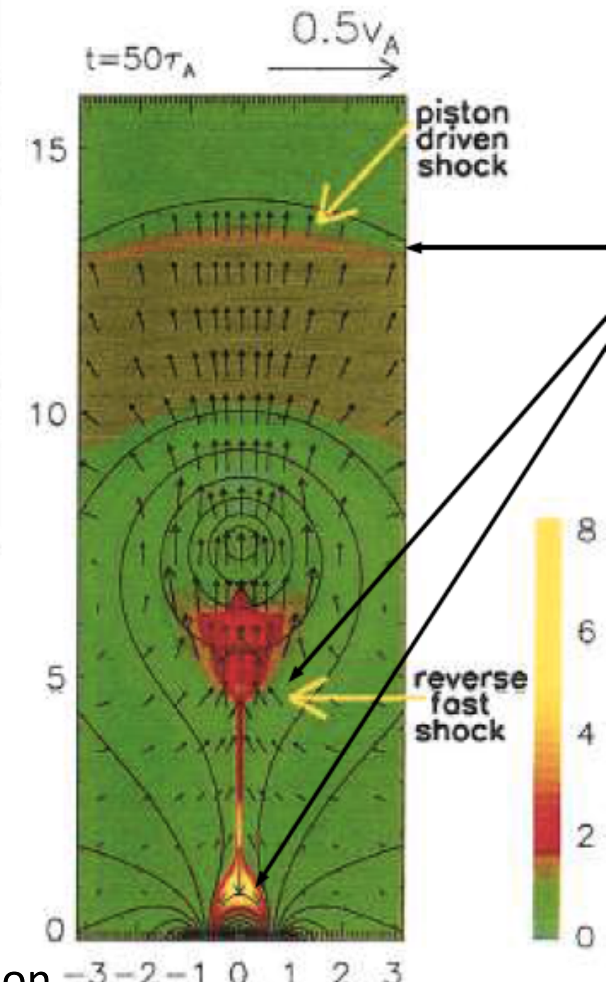


Coronal shocks









Shocks found everywhere where there is fast motion

Explains ubiquitous power laws (with cutoff)

Consistent with ion abundances in gradual events

Summary

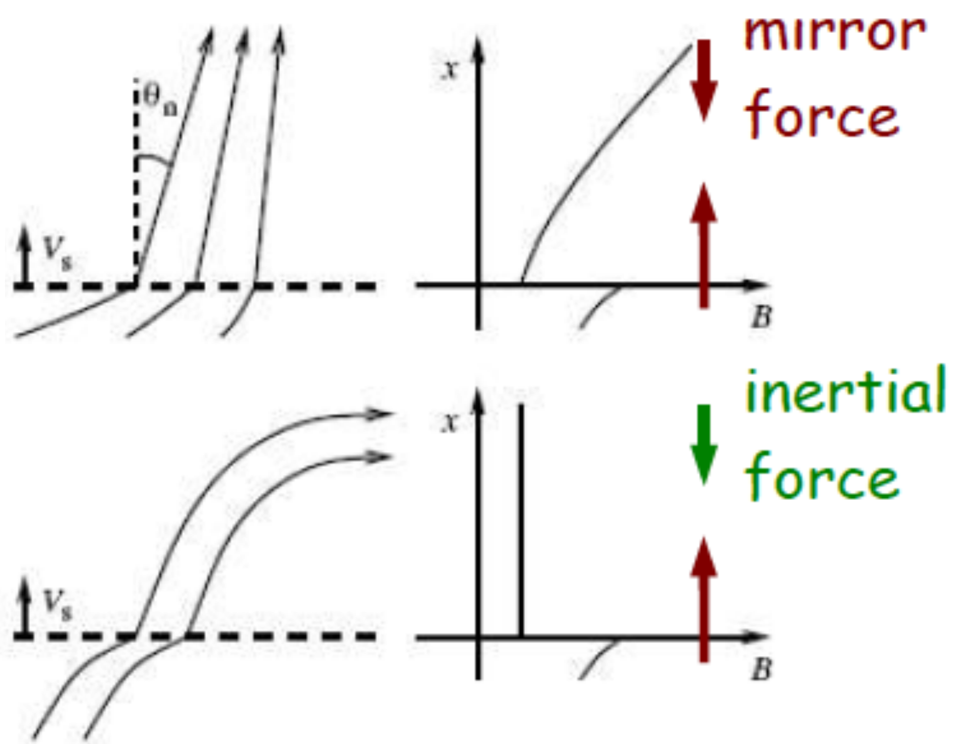
- Particle acceleration during solar eruptions can produce relativistic ions and electrons with power-law energy spectra
- Mechanisms proposed:
  - Direct electric field (current sheets)
  - Collapsing traps (post-flare loops, magnetic islands)
  - Stochastic acceleration (post-flare loops and turbulent sheath regions)
  - Shock acceleration (CME-driven, refracting, flare-jets)
    - Shock-drift mechanism, boosted by inhomogeneous upstream fields
    - Shock surfing
    - Diffusive shock acceleration
- More data analysis efforts needed to pinpoint the actual sources
- Realistic simulation modelling needed to compute the spectra and abundances related to solar eruptions self-consistently

Shock acceleration in inhomogeneous upstream magnetic field

inhomogeneous upstream fields can trap particles close to the shock

trapped particles gain energy if

- $dB_1 / dt > 0$ (W/B_1 = const.), or
- $\Theta_n \rightarrow 90°$ ($v_{||} \sim V_s/\cos\Theta_n \rightarrow c$)



Sandroos & Vainio (2006: A&A **455**, 685)

Acceleration in curved upstream field

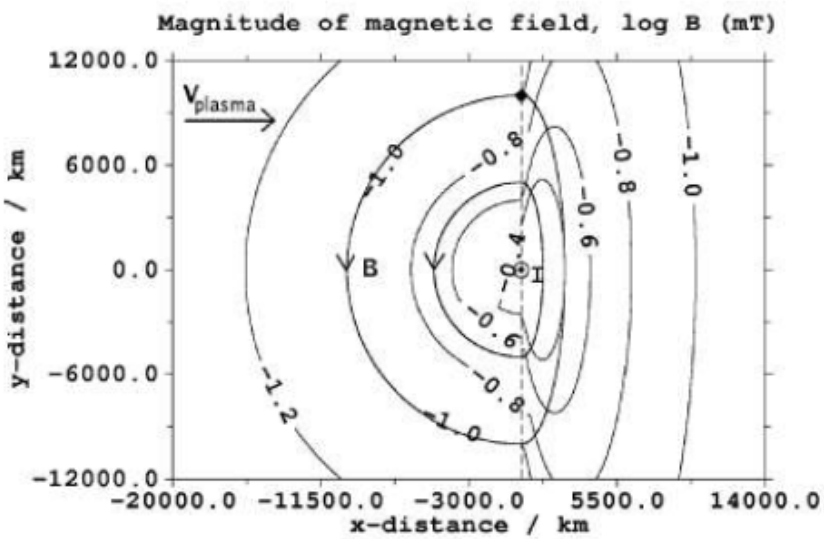


Fig. 2. Setup for line current runs. At $t = 0$ the shock plane is situated at $x = 0$ (dashed line) and moves from right to left with velocity V_s. 10 keV protons are injected to the field line marked with a diamond. Magnitude of $\boldsymbol{B}$ is shown with the contour lines, along with two field lines.

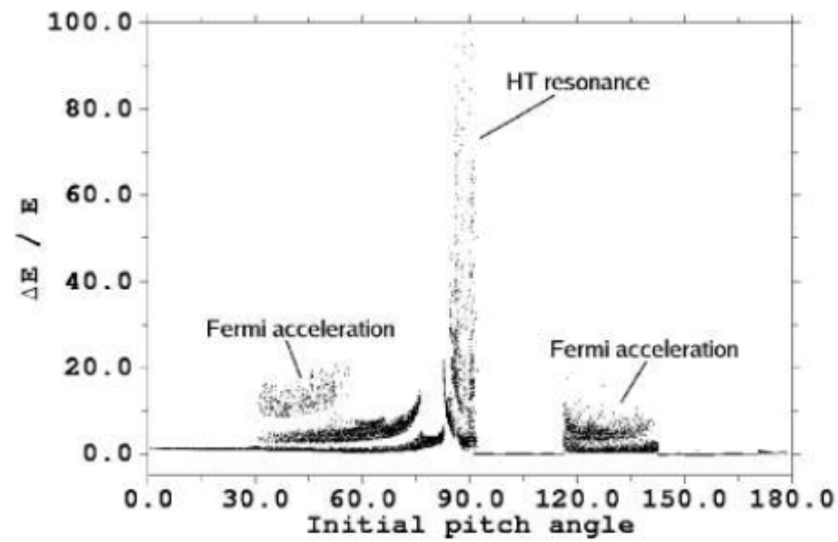


Fig. 3. Initial pitch angle vs. energy gain ratio $\Delta E/E_0$ for a line current run with $V_s = 400\ \mathrm{km\,s^{-1}}$ and $r = 4$. Each dot is one simulated particle.

Sandroos & Vainio (2006: *A&A* **455**, 685)

Effects of shock geometry

Rate of **diffusive shock acceleration** (DSA)

$dp/dt = p\,[(r_{sc}-1)/3r_{sc}] \cdot (u_{1x}^2 / D_{xx})$

$D_{xx} = D\cos^2\theta_n; \quad D = \Lambda v/3$

Time available $t_{acc} = (\Delta s/u_{1x}) \cos\theta_n$

For a given Λ

$$v_{max} \sim (\Delta s/\Lambda) \cdot (u_{1x}/\cos\theta_n)$$

But: Injection of protons requires

$$v_{inj} \sim u_{1x}/\cos\theta_n$$

Thus, quasi-perpendicular shocks

- require higher injection energies but
- accelerate particles to higher energies

than quasi-parallel shocks