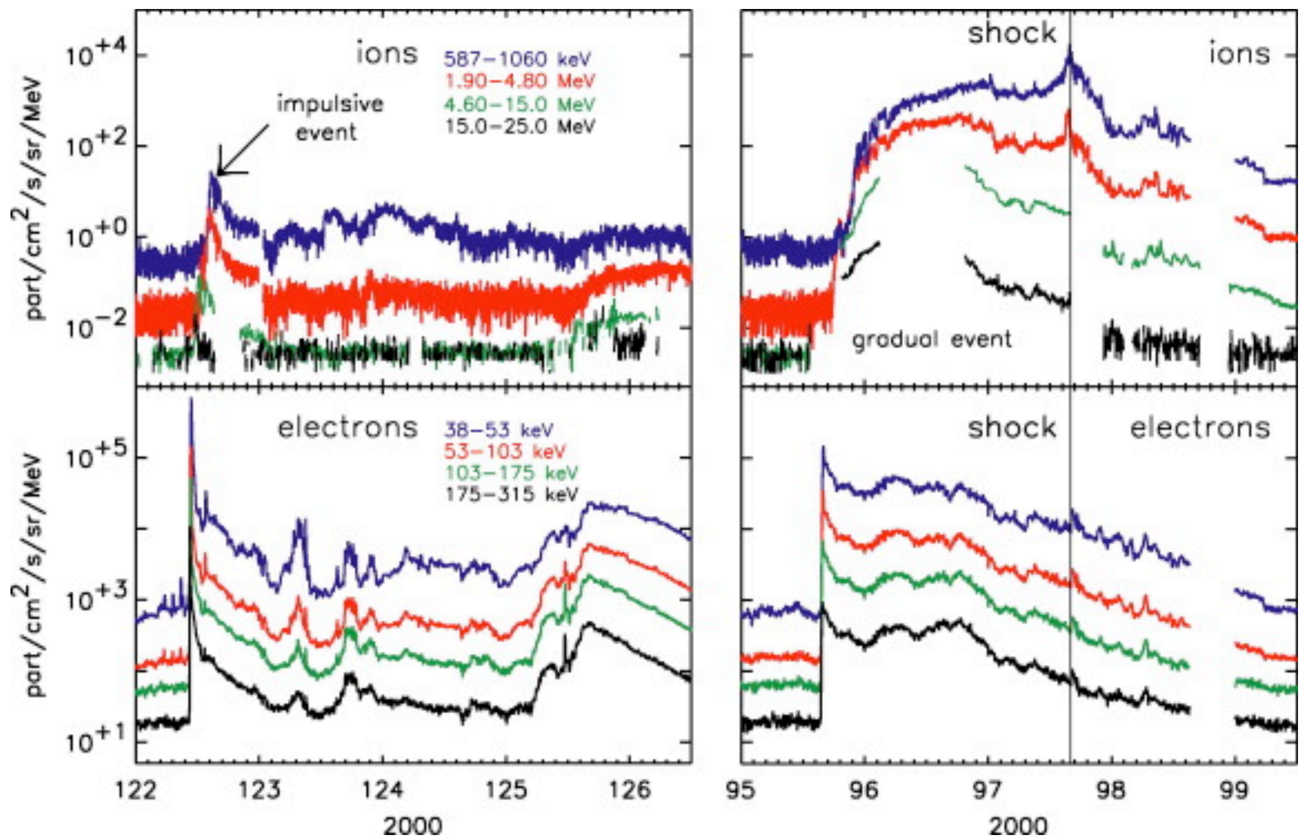
Particle acceleration in coronal and interplanetary shocks: quasi-linear and hybrid-Vlasov simulations

R. Vainio, A. Afanasiev, M. Battarbee,
University of Turku, Finland
U. Ganse,
University of Helsinki, Finland
M. Palmroth, Y. Kempf
Finnish Meteorological Institute, Helsinki, Finland
S. von Alfthan
CSC – IT Centre for Science, Espoo, Finland

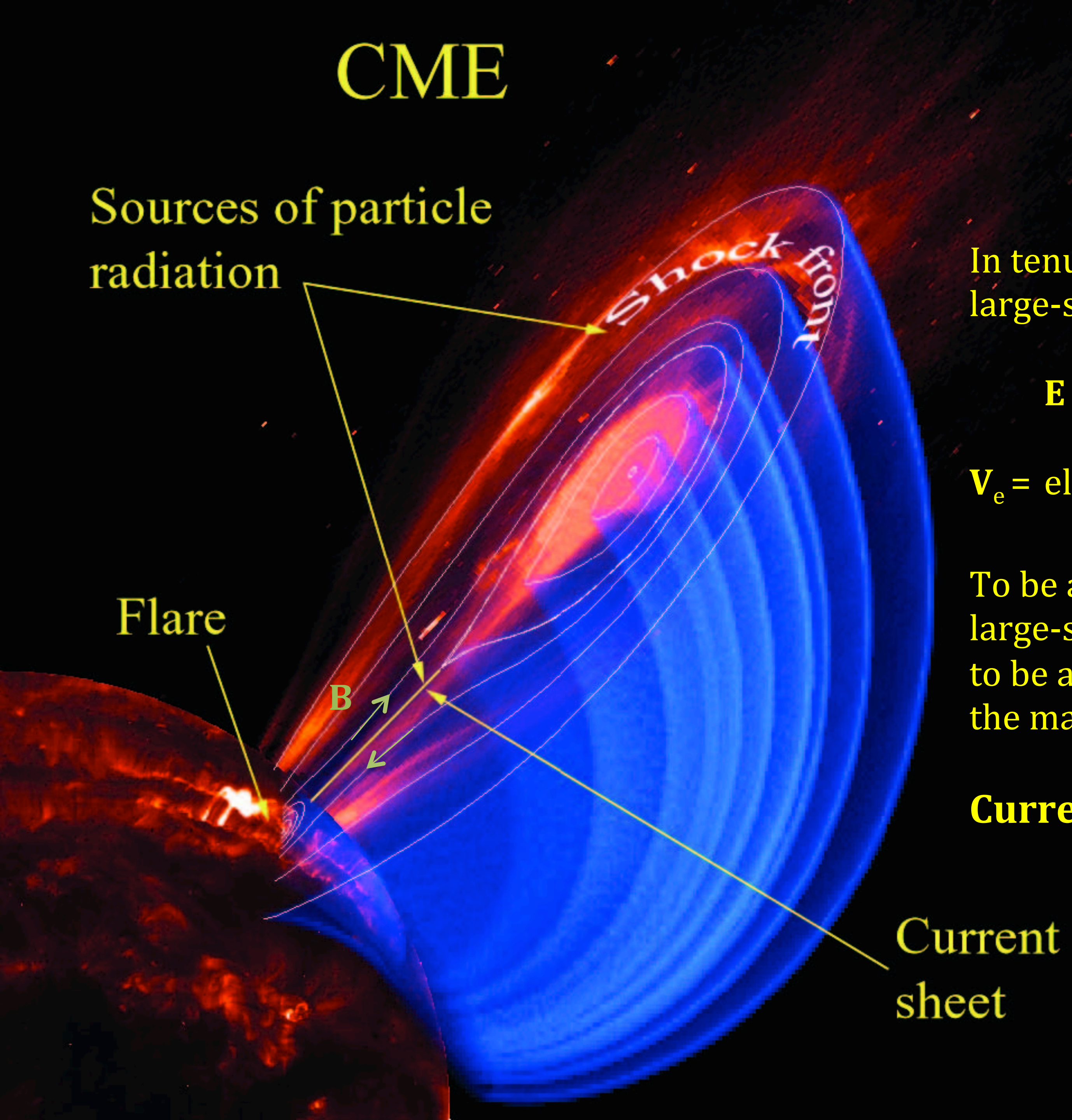
Solar Energetic Particle (SEP) events: Directly detected accelerated particles



1-AU observations from ACE and SOHO spacecraft (Lario 2005)

Impulsive events:
- Electron and heavy-ion rich
- Duration up to a day
- Low ion intensities and max. energies (100 MeV)
- Related to impulsive flares

Gradual events:
- Electron-poor, nominal ion abundances
- Duration up to a week
- High ion intensities and max. energies (10 GeV)
- Related to fast coronal mass ejections



In tenuous space plasmas, large-scale electric field

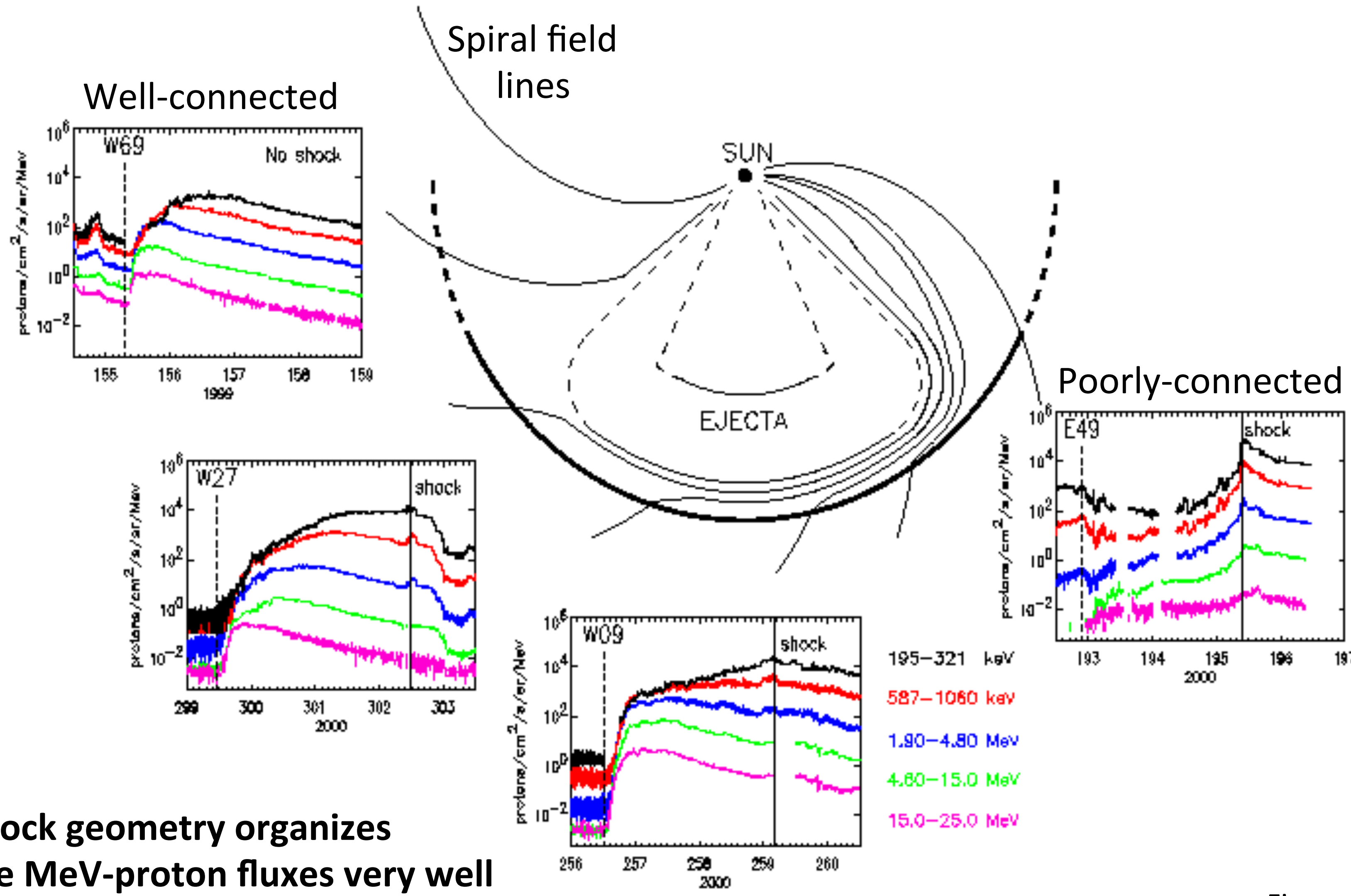
$$\mathbf{E} = -\mathbf{V}_e \times \mathbf{B}$$

$\mathbf{V}_e$ = electron bulk velocity

To be accelerated by the large-scale field, particles have to be able to propagate across the magnetic field.

Current sheets and shocks

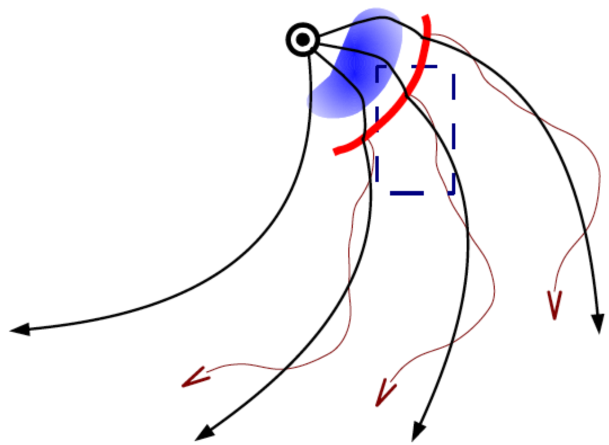
Effect of heliolongitude (gradual events)

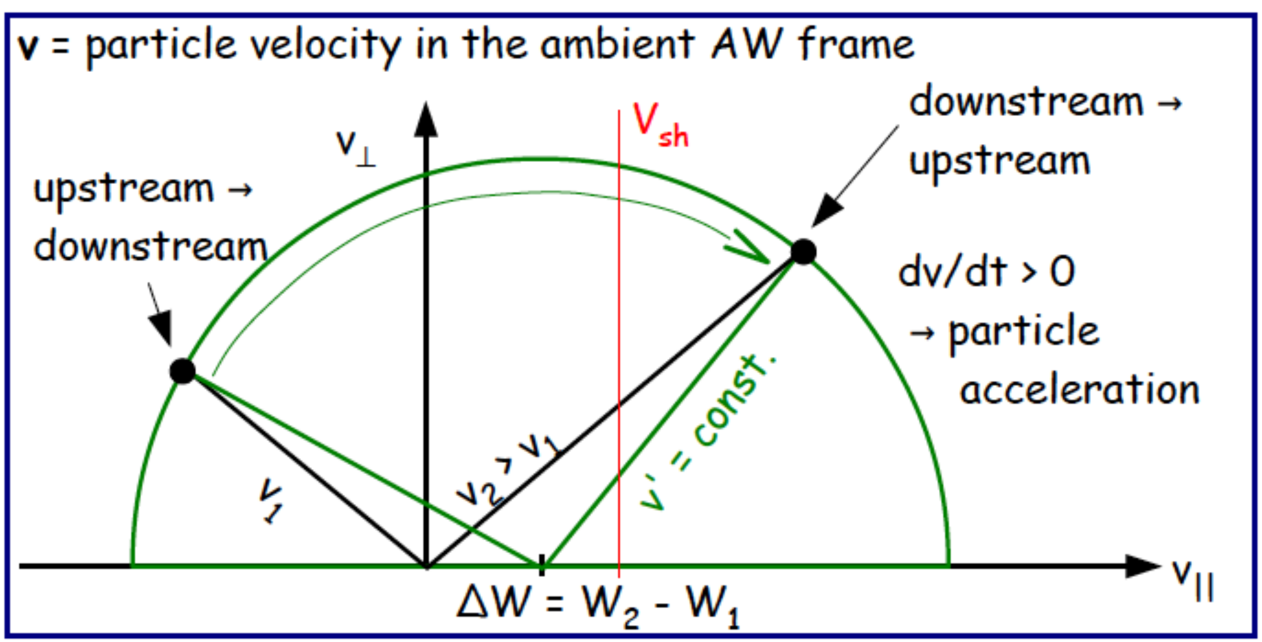


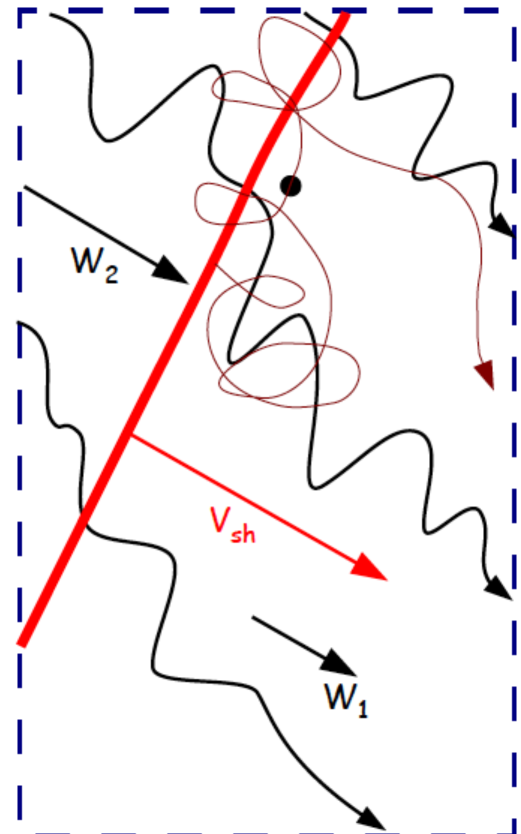
Shock geometry organizes the MeV-proton fluxes very well

Figure: D. Lario

How do shocks accelerate particles? Diffusive shock acceleration

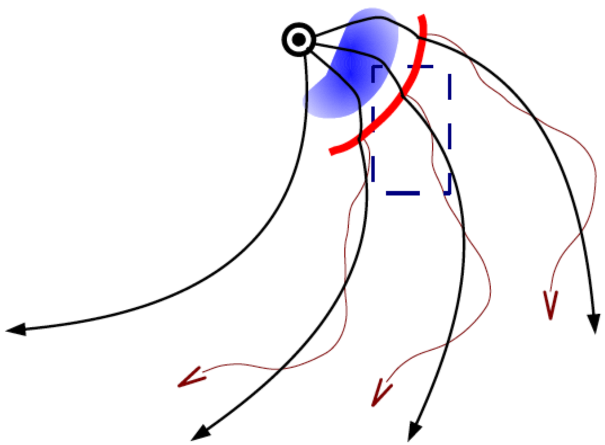


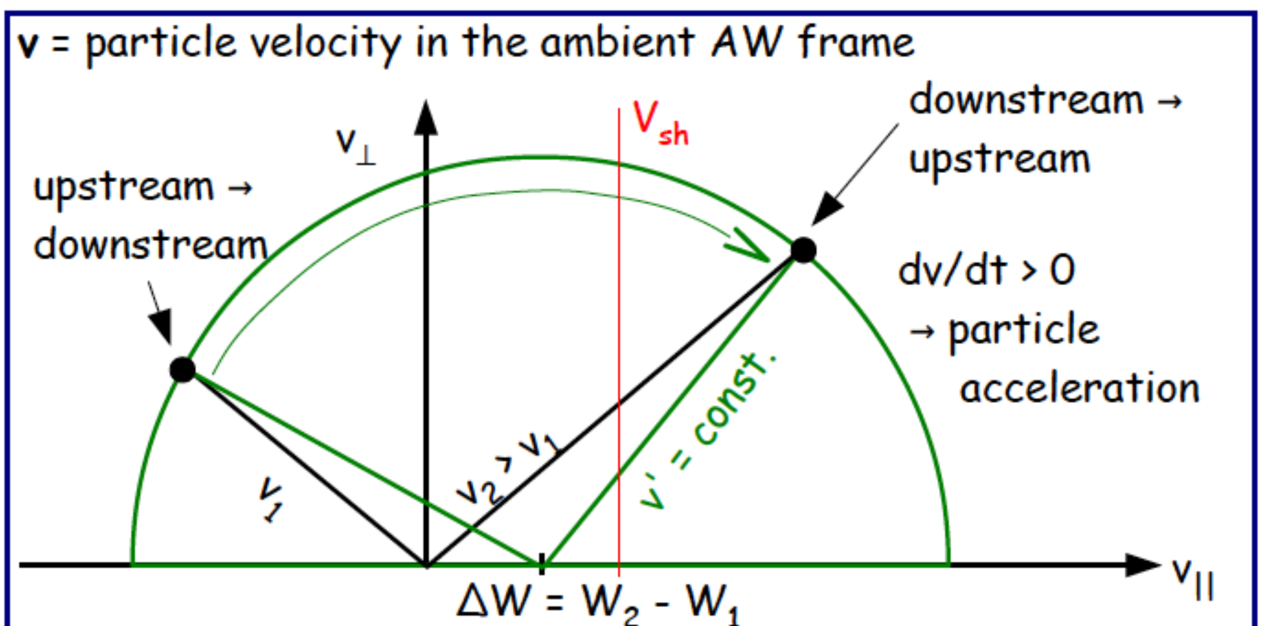


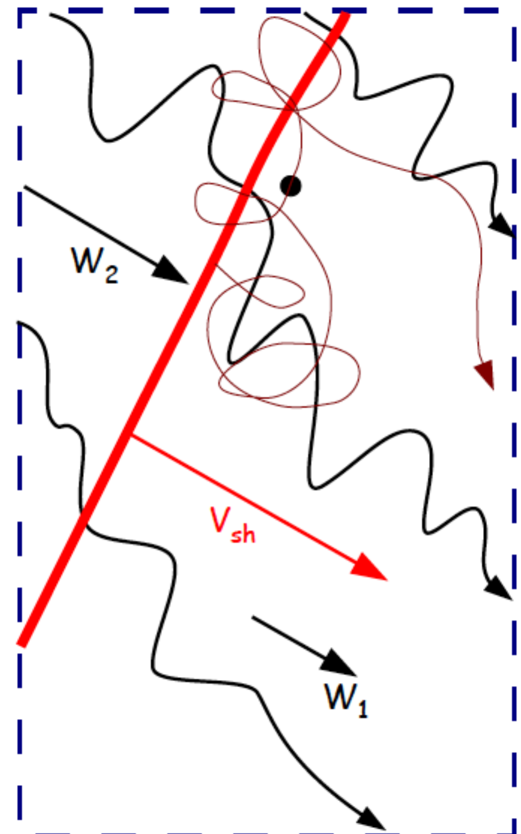


Repeated shock crossings produce a power-law in momentum

How do shocks accelerate particles? Diffusive shock acceleration



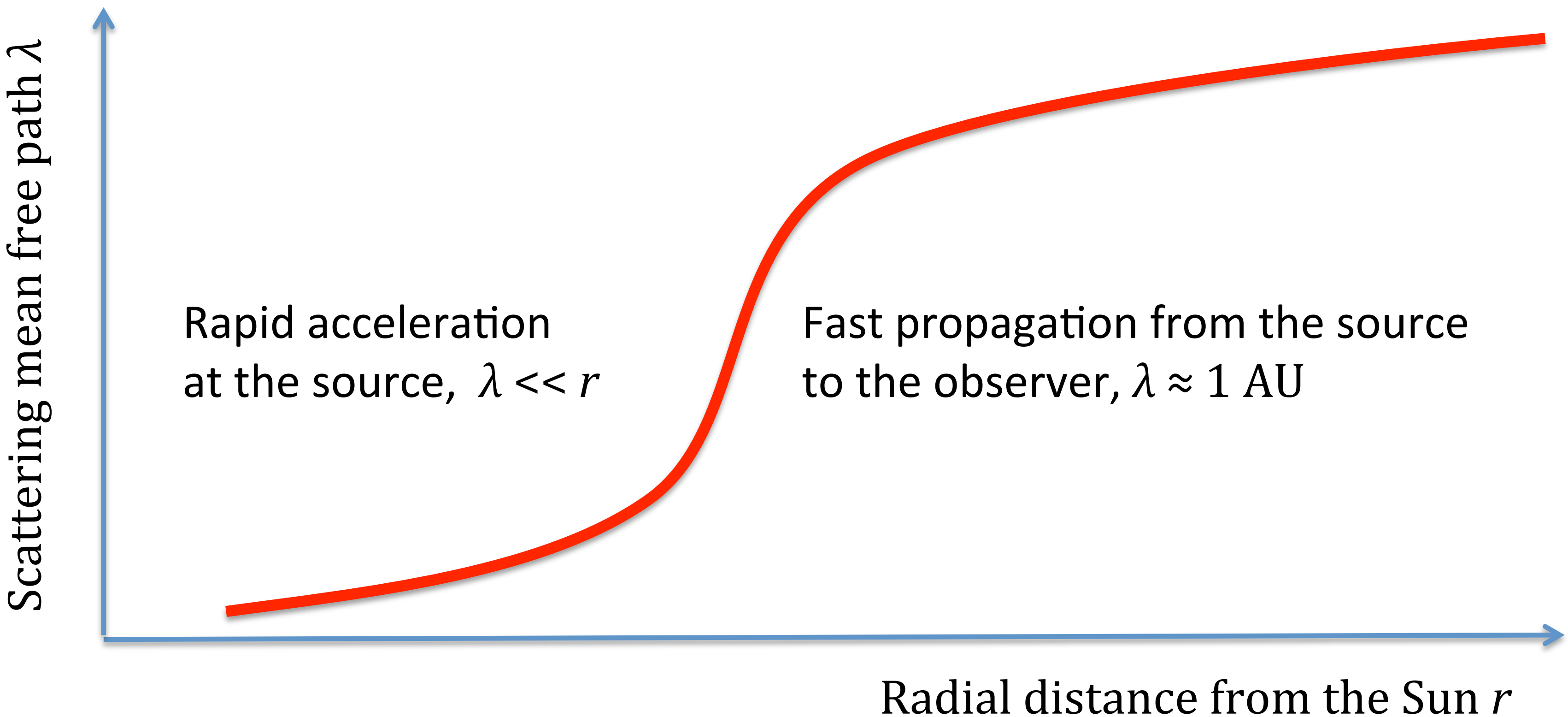




$$D_{\mu\mu} = \frac{\pi}{4}\omega_c(1-\mu^2)\frac{f_r P(f_r)}{B^2}$$

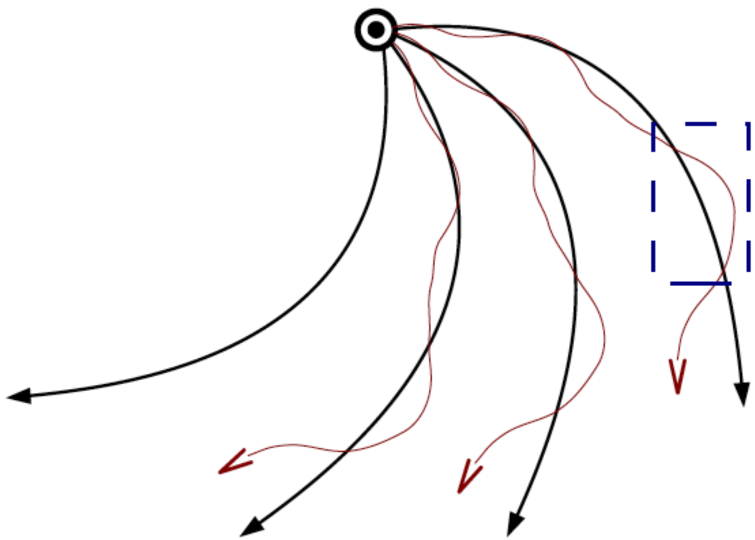
$$f_r = \frac{\omega_c}{2\pi}\frac{W}{v\mu}$$

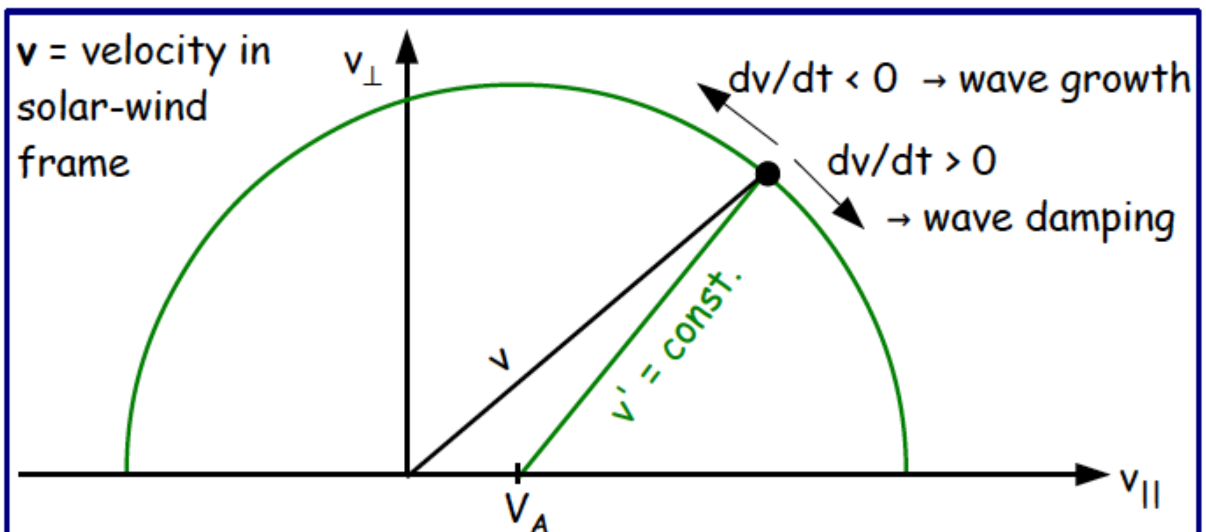
Main problem of standard DSA for SEP events

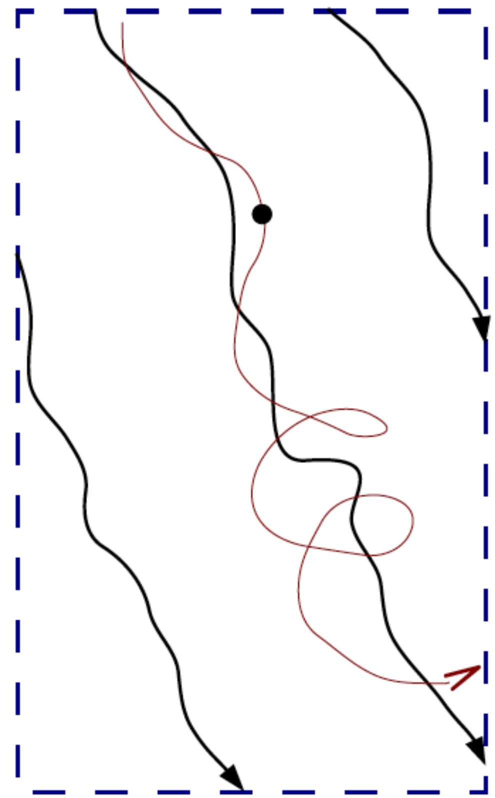


Solution: protons generate their own magnetic fluctuations

Self-generated waves





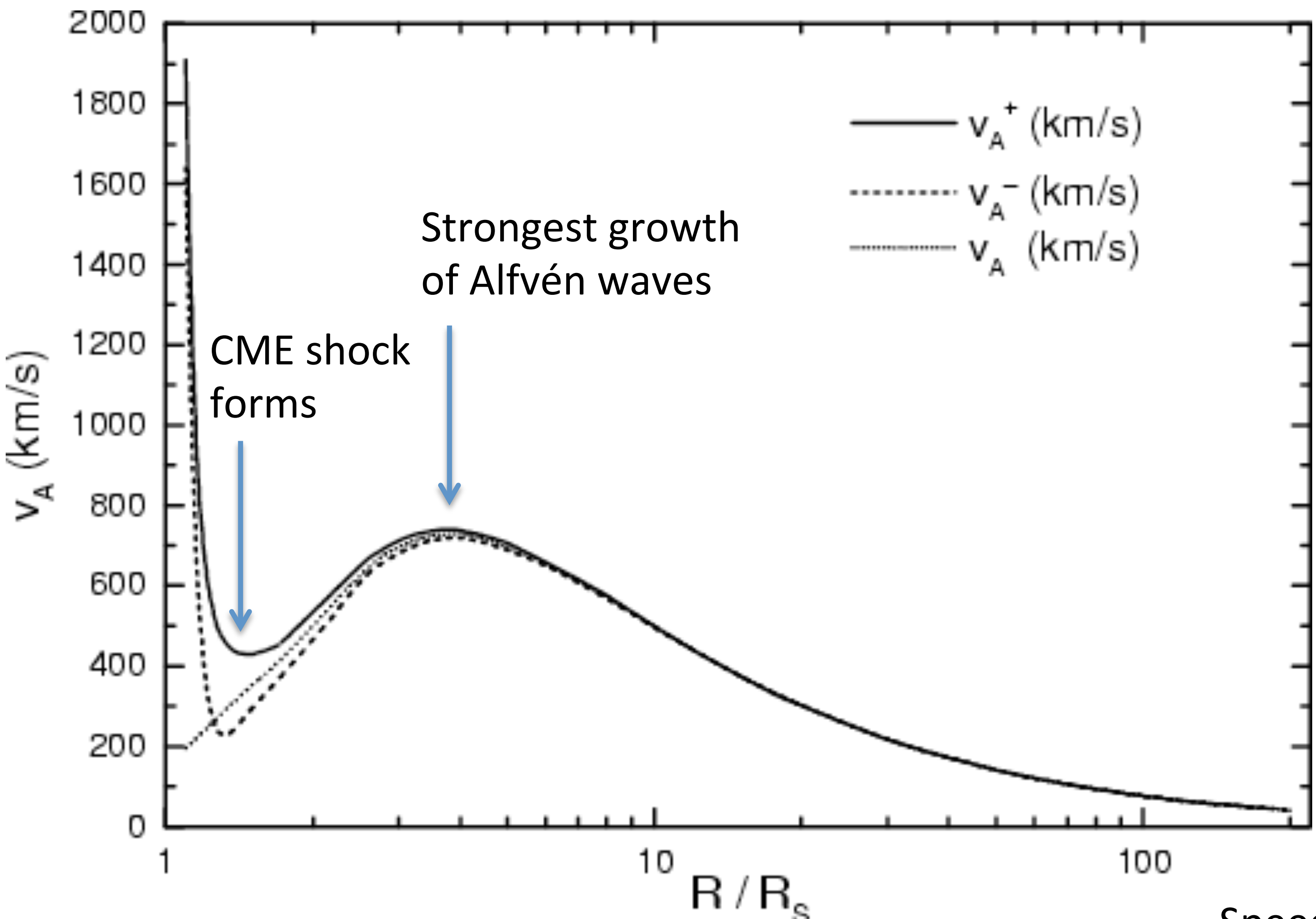


$$\Gamma = \frac{\pi}{2}\omega_{c,p}\frac{p_r S_p(p_r)}{n v_A} \quad \propto B$$

$$p_r = \frac{m_p \omega_{c,p}}{2\pi}\frac{W}{f}$$

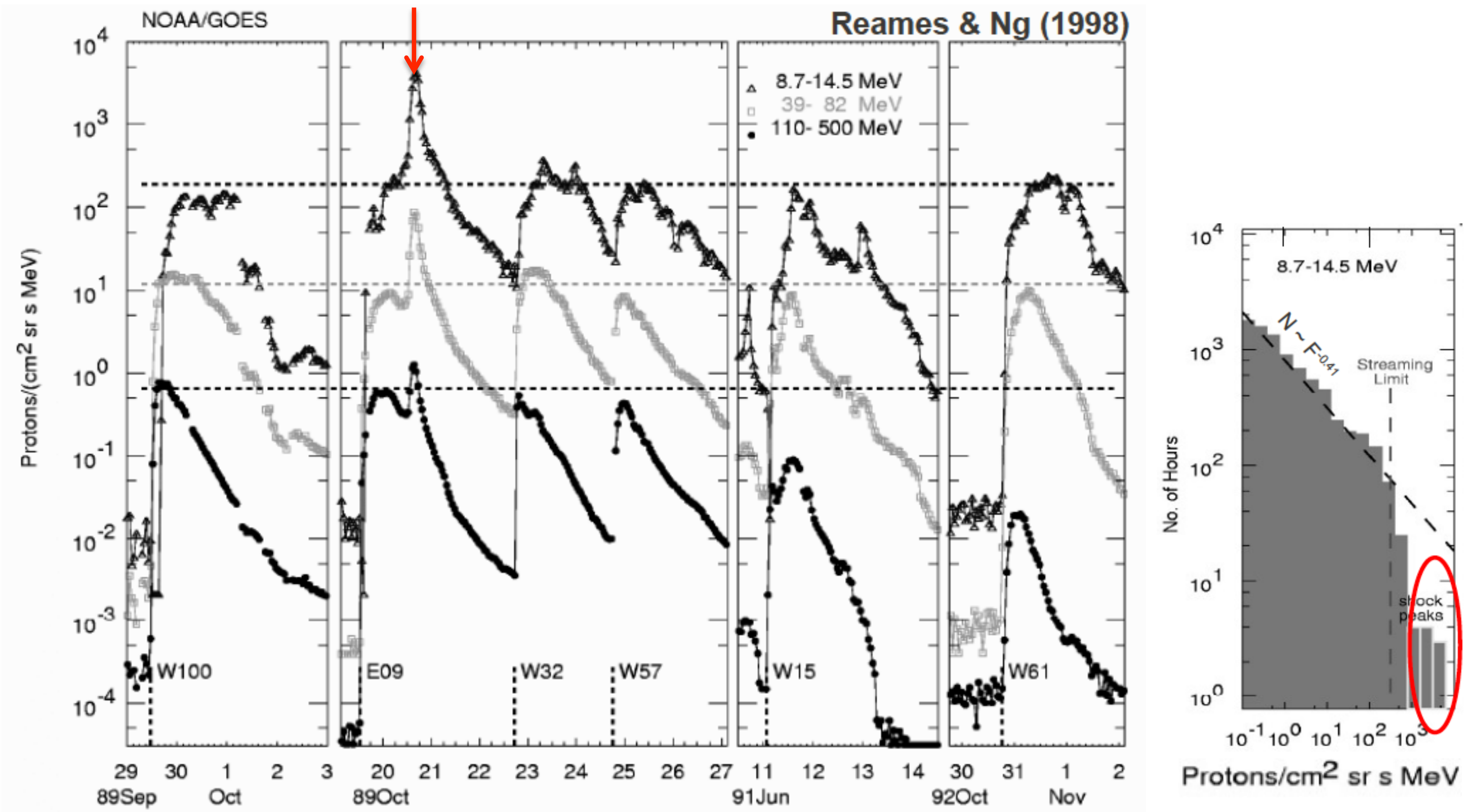
Growth of waves resonant with constant *p* is **strongest where** v_A **has a maximum**

Alfvén speed profile

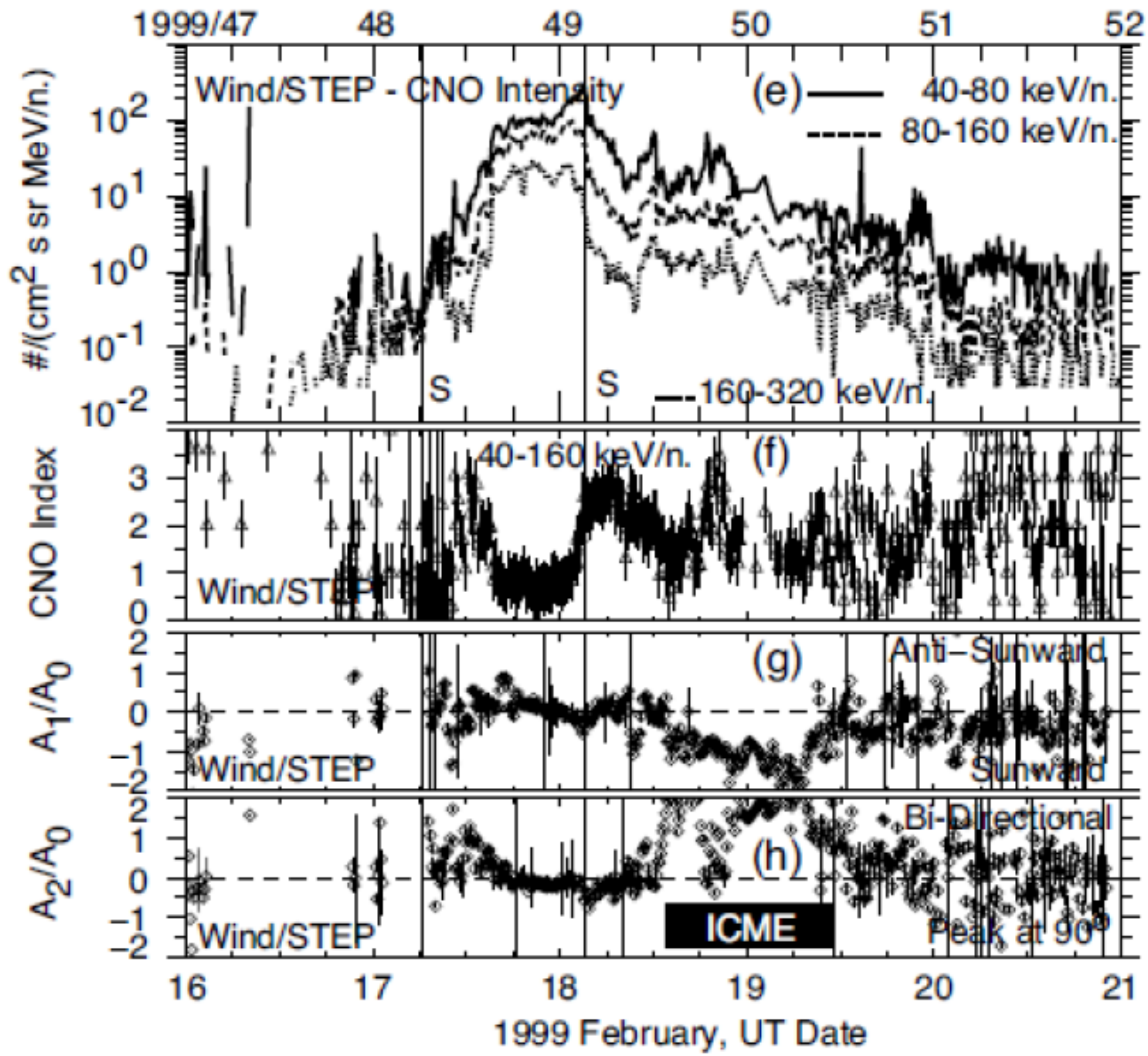


Speed profiles:
Mann et al. (2003)

Streaming limit and
Energetic Storm Particle (ESP) peaks

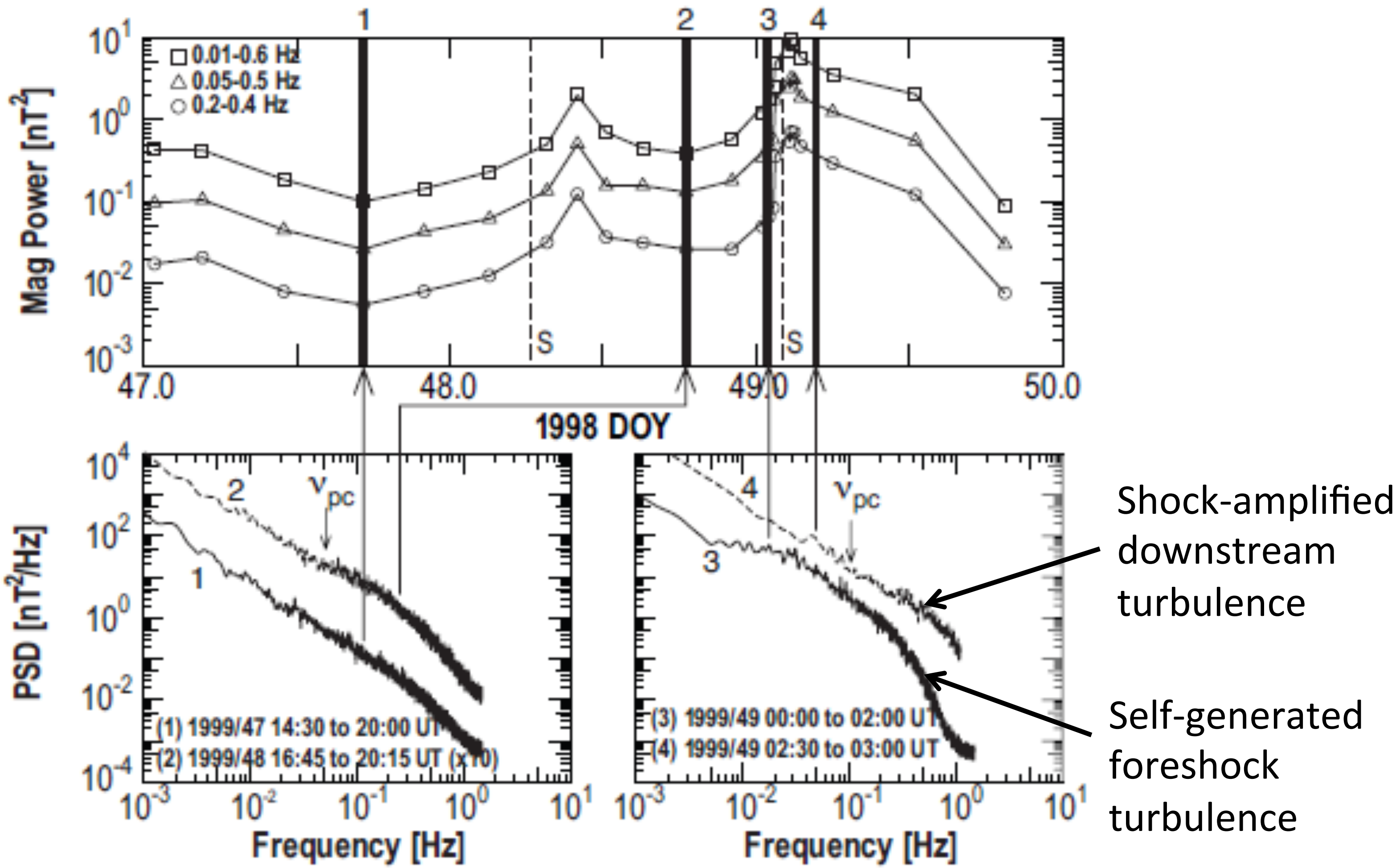


ESP event

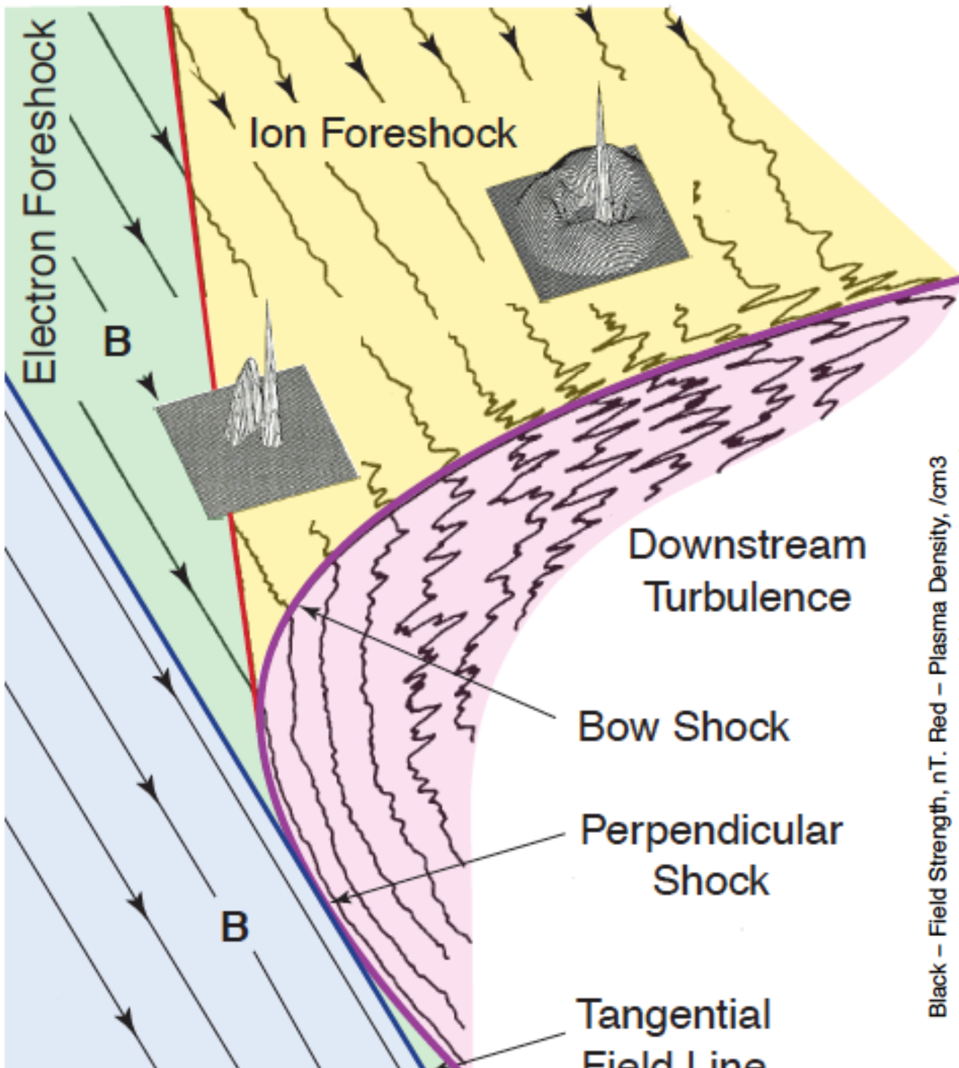


1999/47
48
49
50
51
52
Wind/STEP - CNO Intensity
(e)
40-80 keV/n.
80-160 keV/n.
160-320 keV/n.
#/(cm^2 s sr MeV/n.)
S
S
40-160 keV/n.
(f)
CNO Index
Wind/STEP
(g)
Anti−Sunward
Sunward
A_1/A_0
Wind/STEP
Bi-Directional
(h)
A_2/A_0
ICME
Peak at 90°
Wind/STEP
16
17
18
19
20
21
1999 February, UT Date

Spectral density of fluctuations

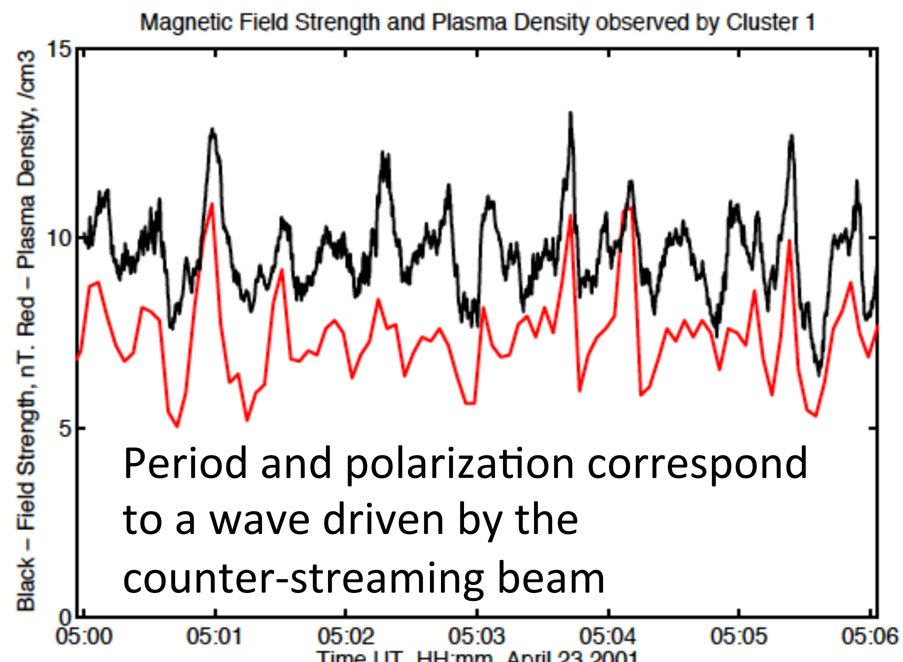


Earth's bow shock



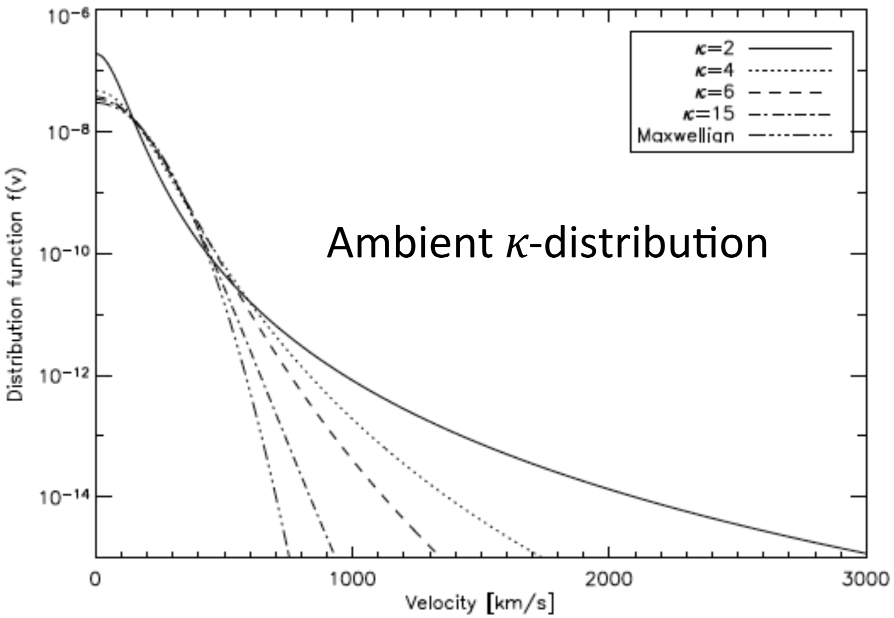
Eastwood et al. (2005)

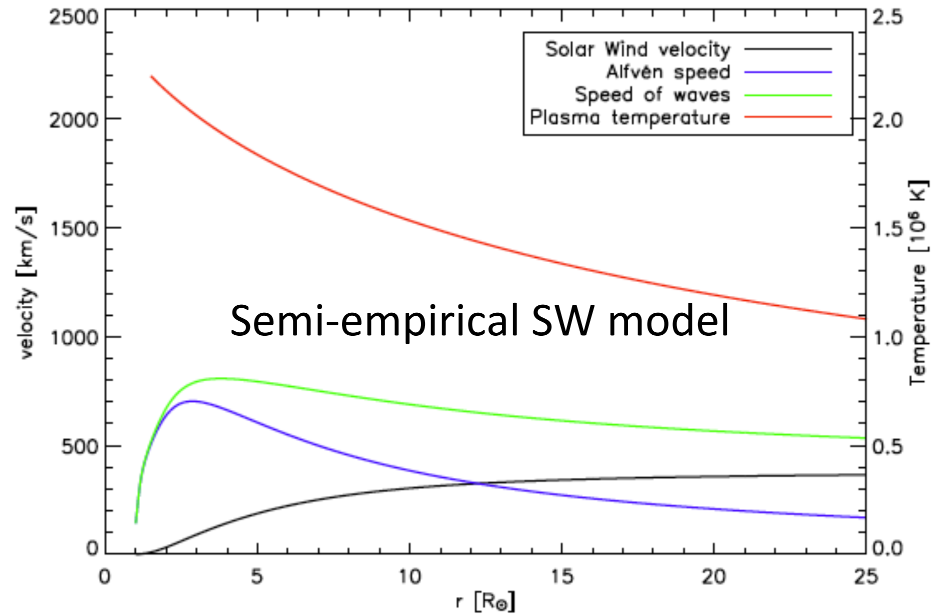
Foreshock: quasi-periodic
30-sec compressive fluctuations

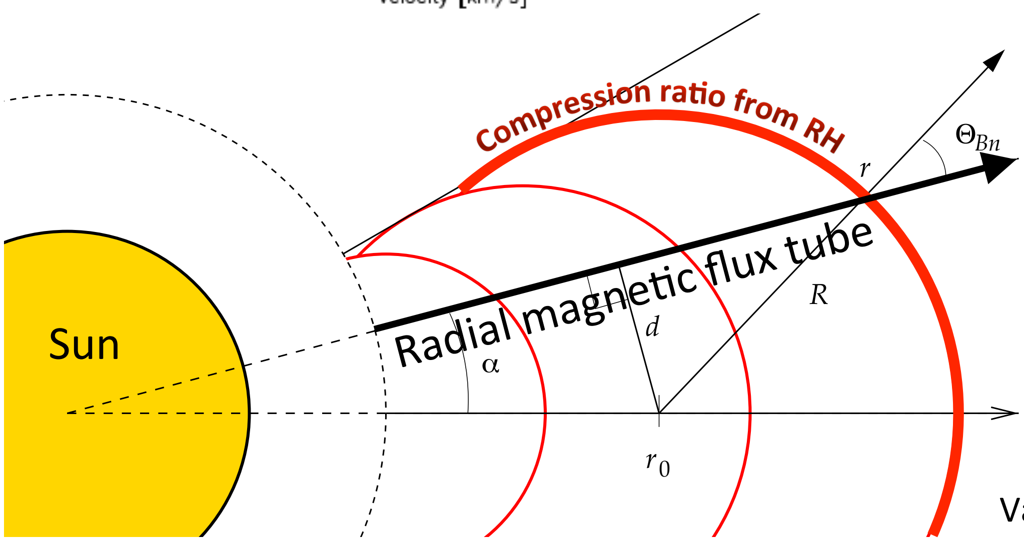


SIMULATION MODELLING

Coronal Shock Acceleration (CSA) code







Self-consistent Monte Carlo approach:

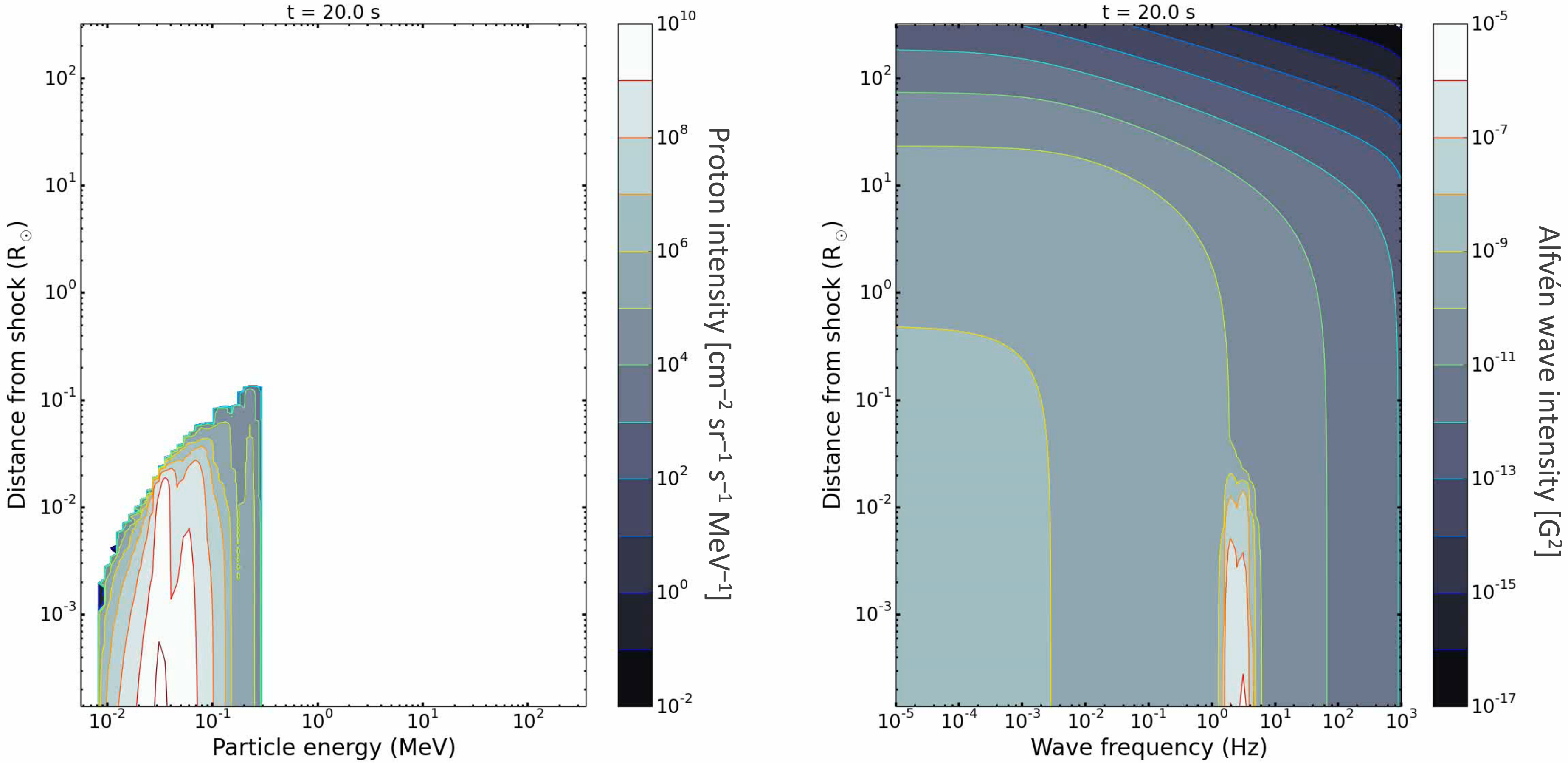
- Ions and resonant Alfvén waves

Ion scattering ↔ Wave growth resonance

$$k = 1/r_{\mathrm{L}}$$

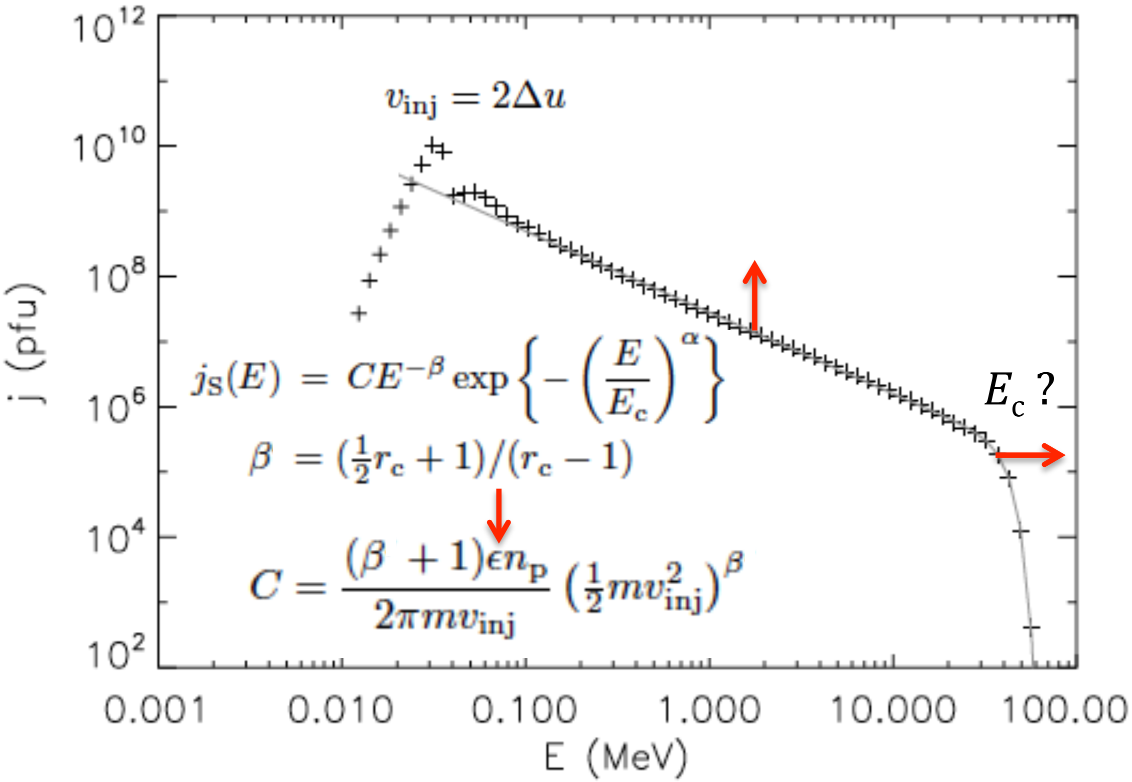
Vainio & Laitinen (2007, 2008); Battarbee et al. (2011)

Ion and Wave Distributions



Distance of the shock from the Sun = 14 – 22 $R_\odot$

Proton spectra at the shock



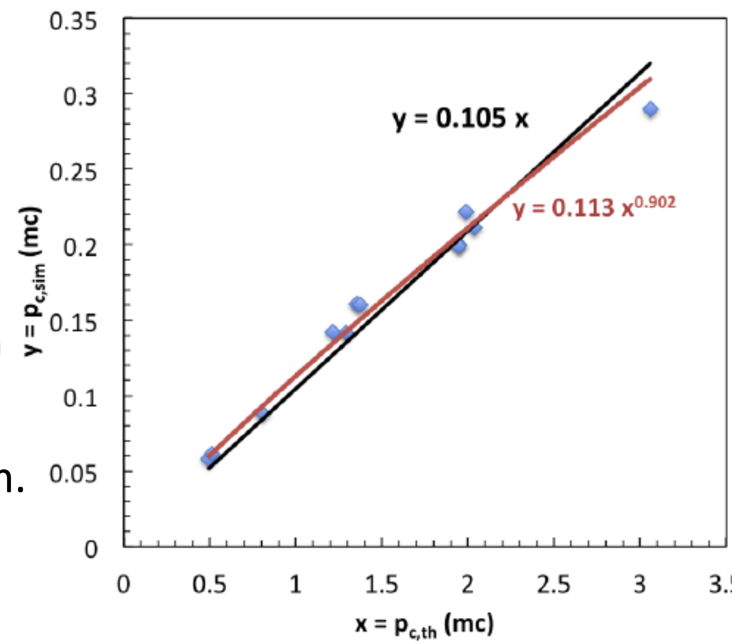
Simulations reproduce the canonical power-law spectrum.

DSA theory:

$$\dot{p} = p\frac{u_{1n}(u_{1n} - u_{2n})}{3D_{nn}}$$

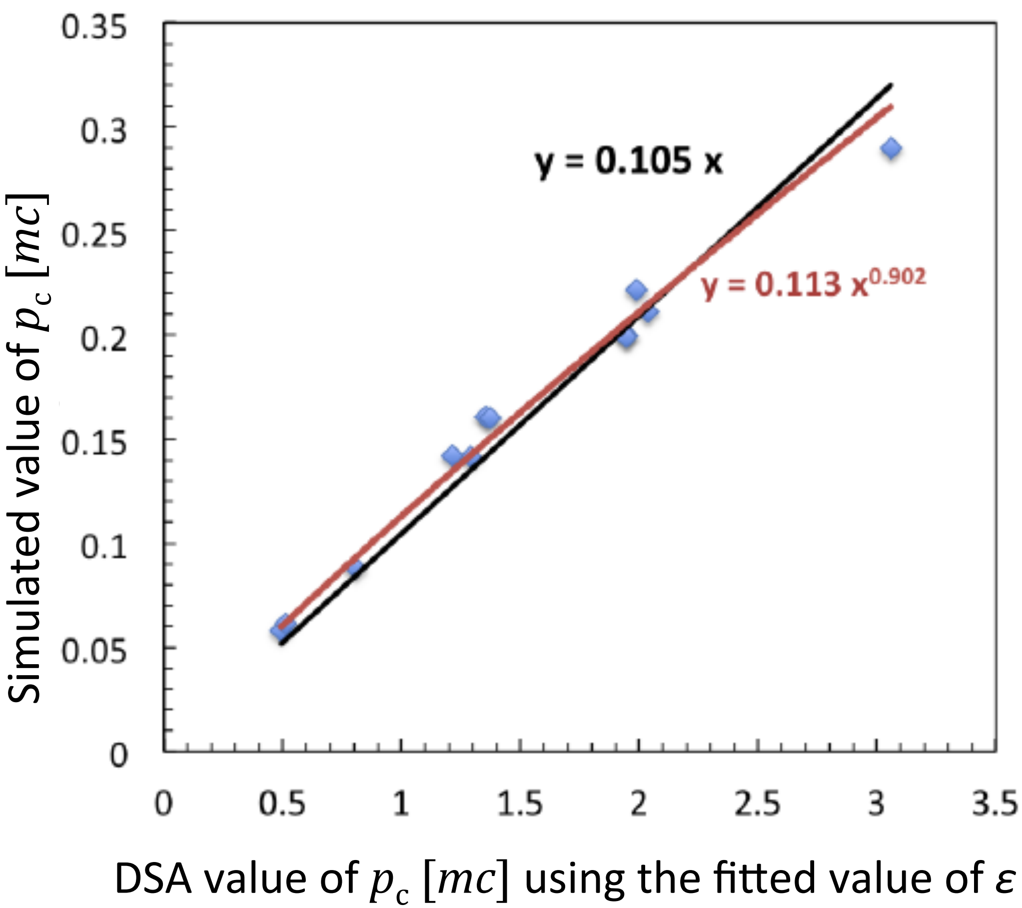
$$p_c^{\sigma-3} = p_{\rm inj}^{\sigma-3}\left[1 + \frac{u_1 \cos\Theta_{Bn}}{V_{\rm S} r_{\rm g}} \frac{\pi\epsilon\sigma}{2} \frac{\Omega_{\rm p}}{v_{\rm A}} R_{\rm S} \ln\frac{R_{\rm S}}{R_{\rm S0}}\right]$$

$$\sigma = 2\beta + 2$$



Vainio et al. (2014)

Cut-off momentum



DSA theory:

$$\dot{p} = p\frac{u_{1n}(u_{1n} - u_{2n})}{3D_{nn}}$$

$$p_{\mathrm{c}}^{\sigma-3} = p_{\mathrm{inj}}^{\sigma-3}\left[1 + \frac{u_1\cos\Theta_{Bn}}{V_{\mathrm{S}}r_{\mathrm{g}}}\frac{\pi\epsilon\sigma}{2}\frac{\Omega_{\mathrm{p}}}{v_{\mathrm{A}}}R_{\mathrm{S}}\ln\frac{R_{\mathrm{S}}}{R_{\mathrm{S0}}}\right]$$

$$\sigma = 2\beta + 2$$

$$\beta = (\tfrac{1}{2}r_{\mathrm{c}} + 1)/(r_{\mathrm{c}} - 1)$$

N.B. Cut-off momentum observable remotely:

$$p_{\mathrm{c,th}} = \frac{p_{\mathrm{c,emp}}}{0.105} = 9.52\,p_{\mathrm{c,emp}}$$

$$\epsilon = \left[\left(\frac{p_{\mathrm{c,th}}}{p_{\mathrm{inj}}}\right)^{\sigma'-3} - 1\right]\frac{2V_{\mathrm{S}}r_{\mathrm{g}}v_{\mathrm{A}}}{u_1\cos\Theta_{Bn}\sigma\pi\Omega_{\mathrm{p}}R_{\mathrm{S}}\ln(R_{\mathrm{S}}/R_{\mathrm{S0}})}$$

DSA theory over-predicts p_c by an order of magnitude
if the steady-state value of D_{nn} (Bell 1978) at the shock is used.

Vainio et al. (2014)

SOLar Particle Acceleration in Coronal Shocks (SOLPACS) model

SOLPACS uses the full resonance condition:

$$k_{\text{res}} = \frac{\Omega}{v\mu}$$

Note that

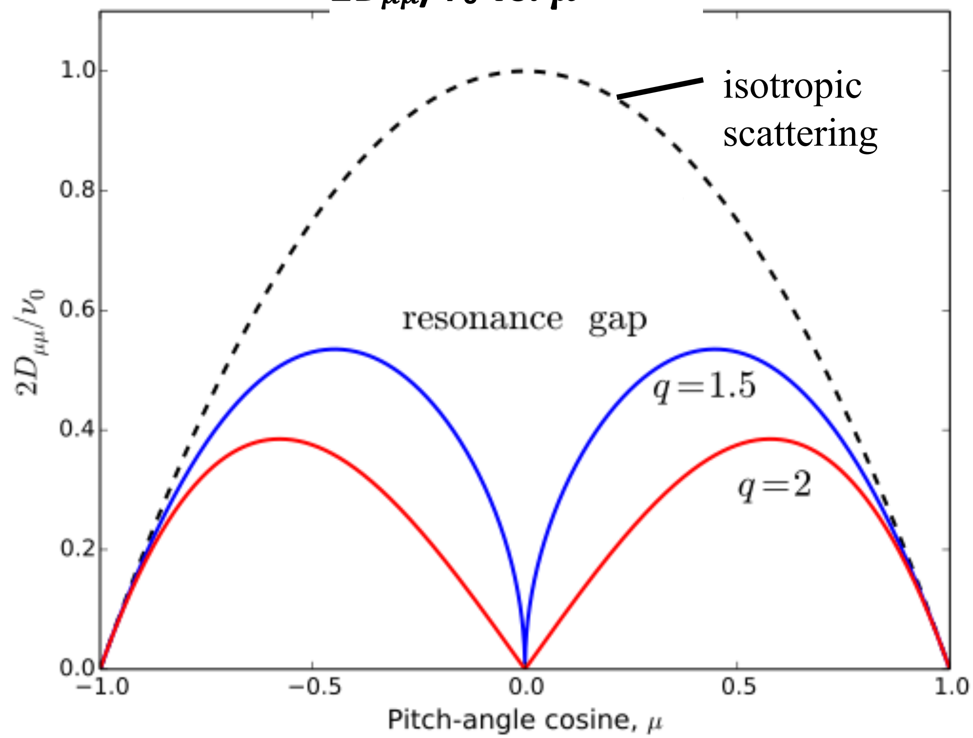
$$k_{\text{res}} = \frac{\Omega}{v} \Rightarrow D_{\mu\mu}(\mu) = \frac{1}{2}\nu_0(1-\mu^2)$$ isotropic scattering

$$k_{\text{res}} = \frac{\Omega}{v\mu} \Rightarrow \text{if } I(k) \propto k^{-q} \Rightarrow$$

$$\Rightarrow D_{\mu\mu} = \frac{1}{2}\nu_0|\mu|^{q-1}(1-\mu^2)$$

anisotropic scattering

2D$_{\mu\mu}$/ν$_0$ vs. μ



Simulation setup

Goal: To explore the effect of the resonance condition

We assume:

- Constant background plasma (n_0, B_0, u_{sw} parameters)
- Anti-sunward propagating Alfvén waves with the initial spectrum $I_w \propto k^{-q_0}$
- Particle injection at shock at constant rate $Q = \epsilon_{inj} n_0 u_1$
- Exponential velocity spectrum of injected protons:

$$\frac{dN_{inj}}{dv} \propto \exp\left(-\frac{v - u_1}{v_1}\right)$$

Coronal shock simulation parameters:

Magnetic field $B_0 = 3.4 \times 10^{-5}$ T

Plasma density $n_0 = 3.6 \times 10^6$ cm^{-3}

Solar-wind speed $u_{sw} = 12.4$ km s^{-1}

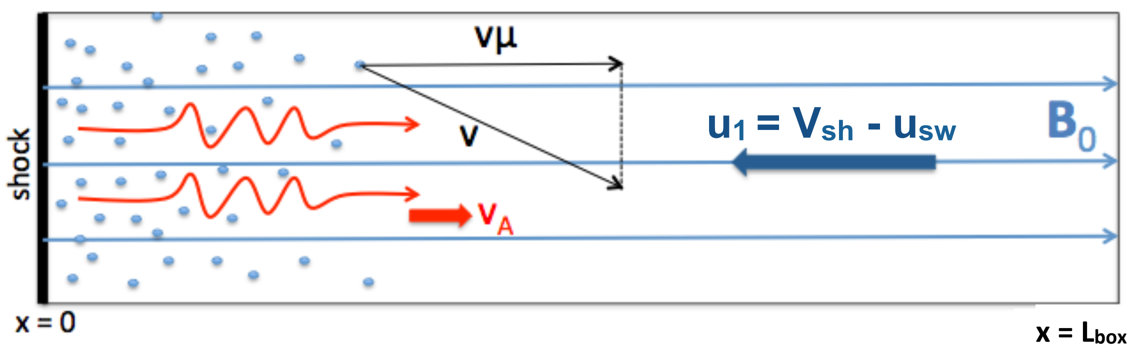
Shock speed $V_{shock} = 1500$ km s^{-1}

Scattering-centre compression ratio $r_c = 4$

Simulation box length $L_{box} = 1 R_\odot$

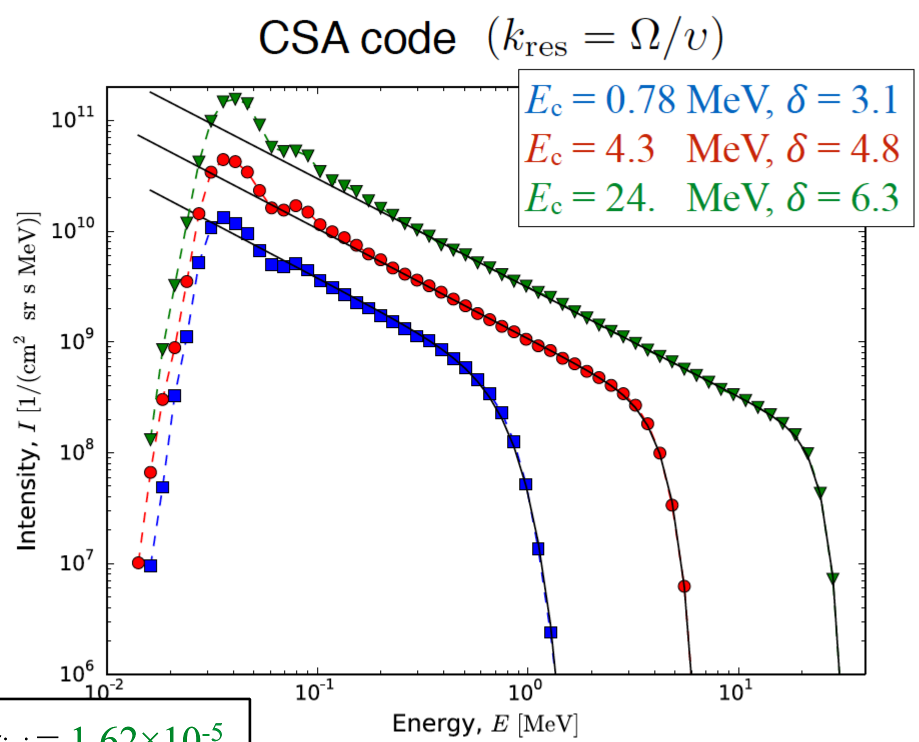
Initial wave-spectral index $q_0 = 3/2$

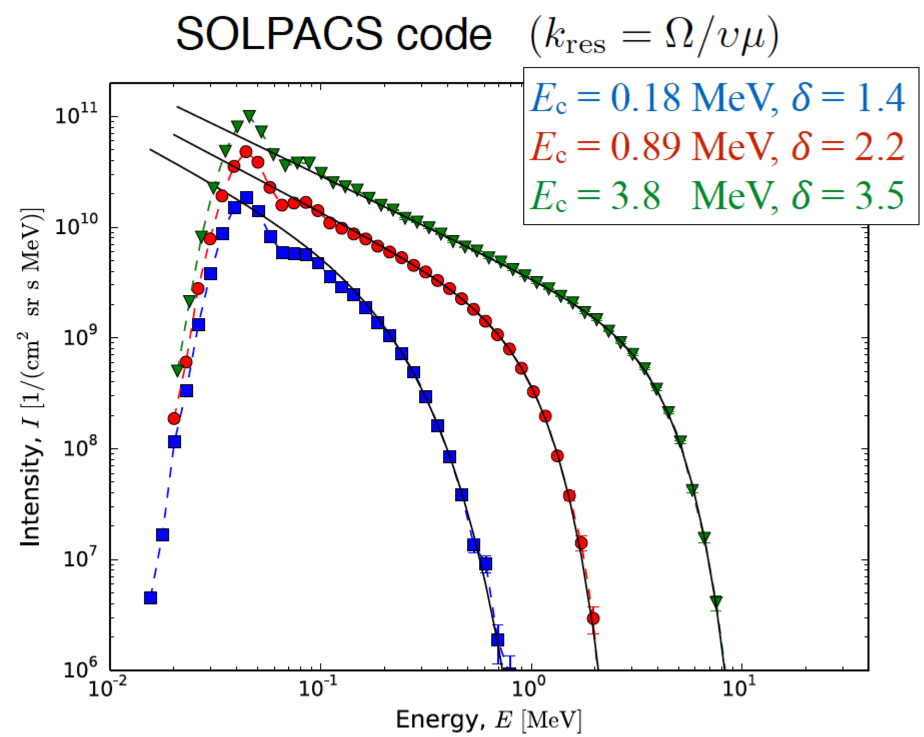
Simulation time t_{sim} = 580 s



Proton spectrum at a coronal shock

for different injection strengths $\epsilon_{\rm inj}$ (at t = 580 s)



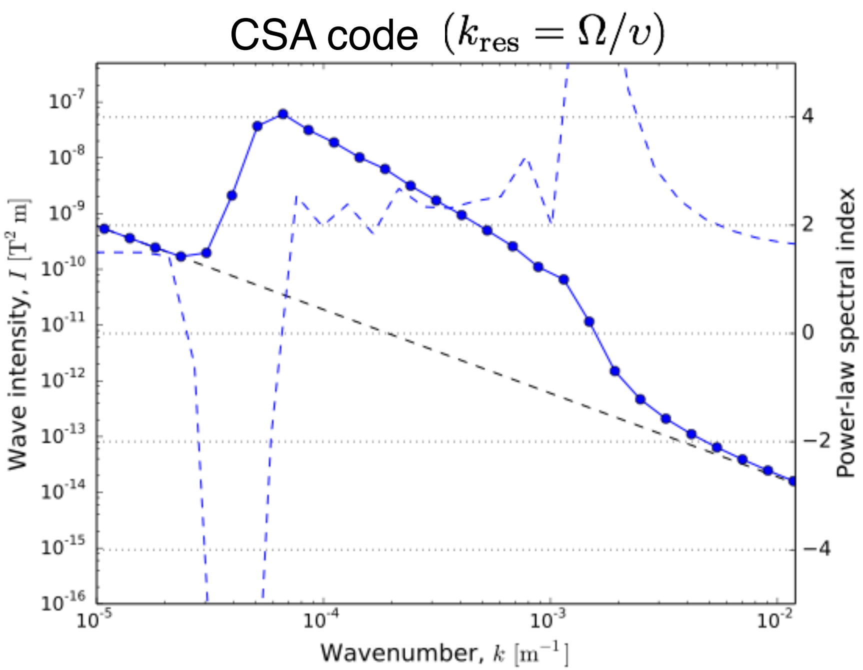


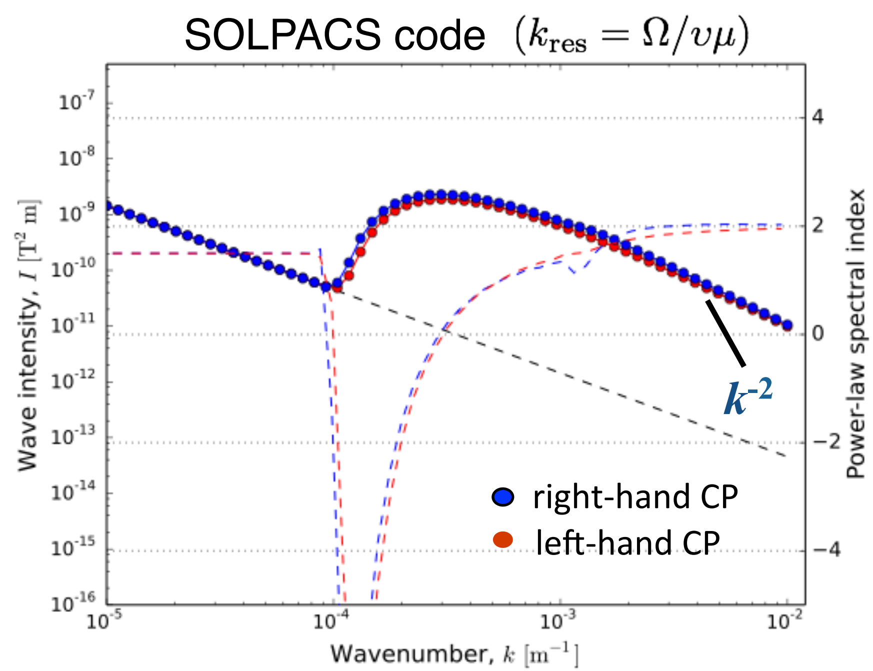
$\epsilon_{\rm inj} = 1.62\times10^{-5}$
5.40×10^{-6}
1.62×10^{-6}

Fitting function: $$I(E) = CE^{-\beta}\exp\{-(E/E_c)^\delta\}$$

Corresponding spectrum of waves

for $\epsilon_{\rm inj}$ = 1.62×10^{-5} (strongest injection), t = 580 s



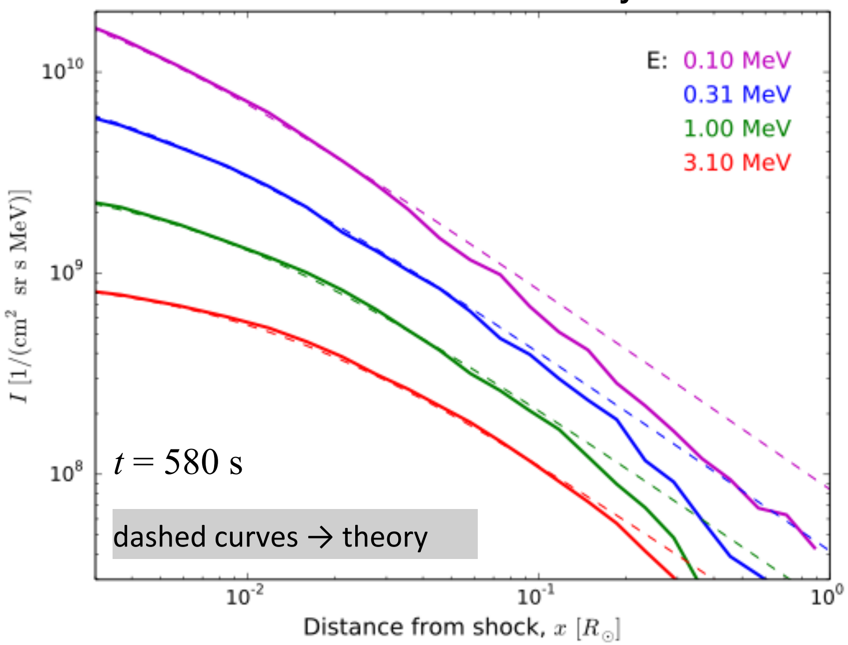


The SOLPACS spectrum is smoother and less intense at low wavenumbers than the CSA one (corresponds to the lower particle cut-off energy E_c).

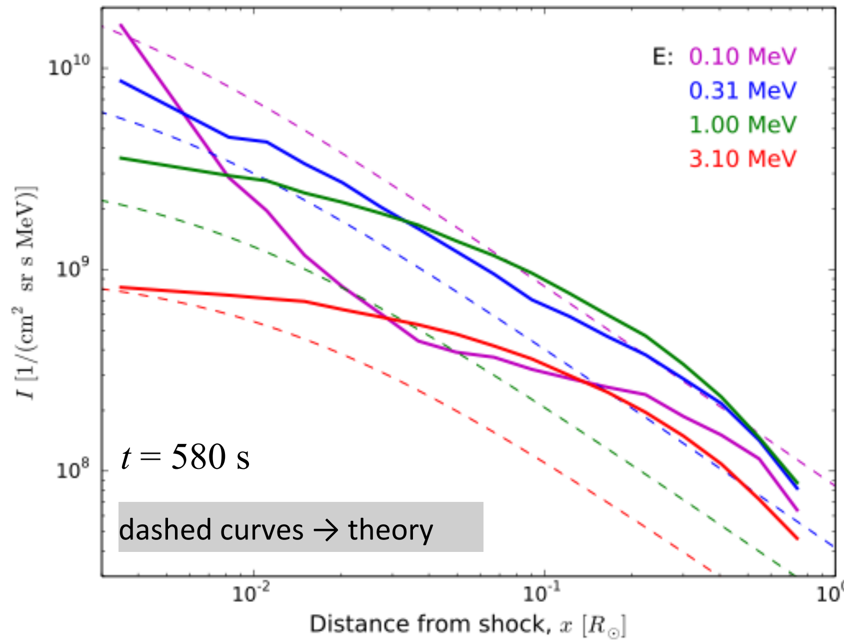
Note also the differences in the high-k spectrum

Distribution of protons in the foreshock

CSA vs. Bell's theory



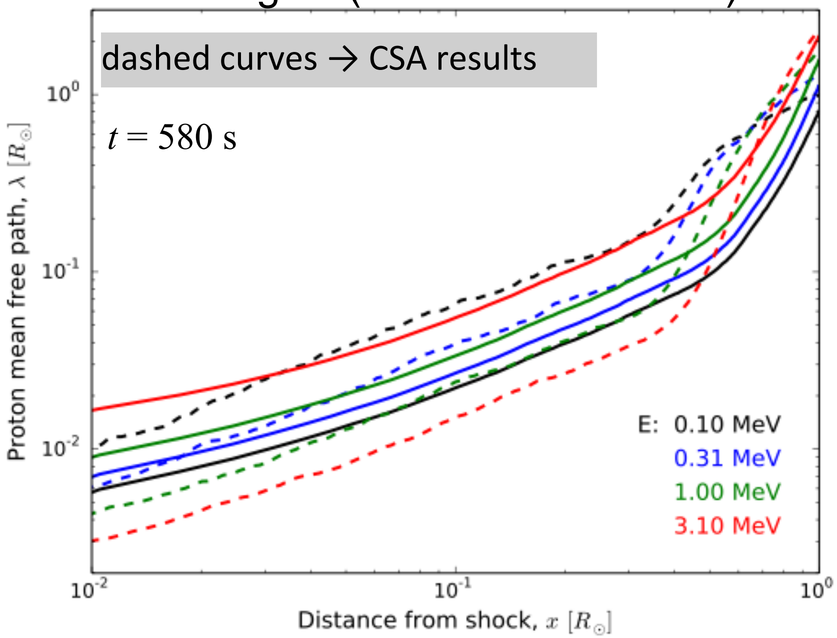
SOLPACS vs. Bell's theory



Bell's steady-state theory (1-D): $I(x,p) \propto \dfrac{x_0}{x+x_0}, \quad x_0 = x_0(p)$

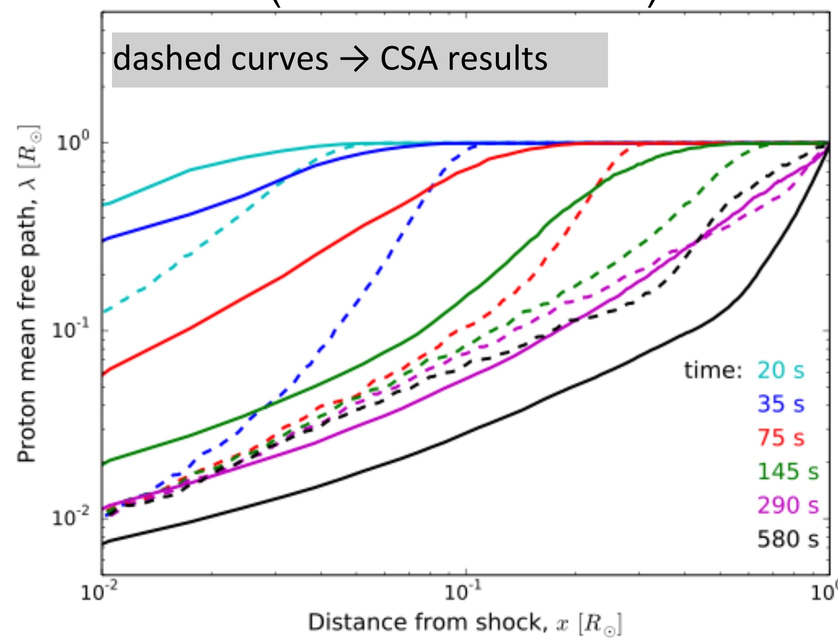
Proton mean free path in the foreshock

Spatial distribution at different energies (SOLPACS vs. CSA)



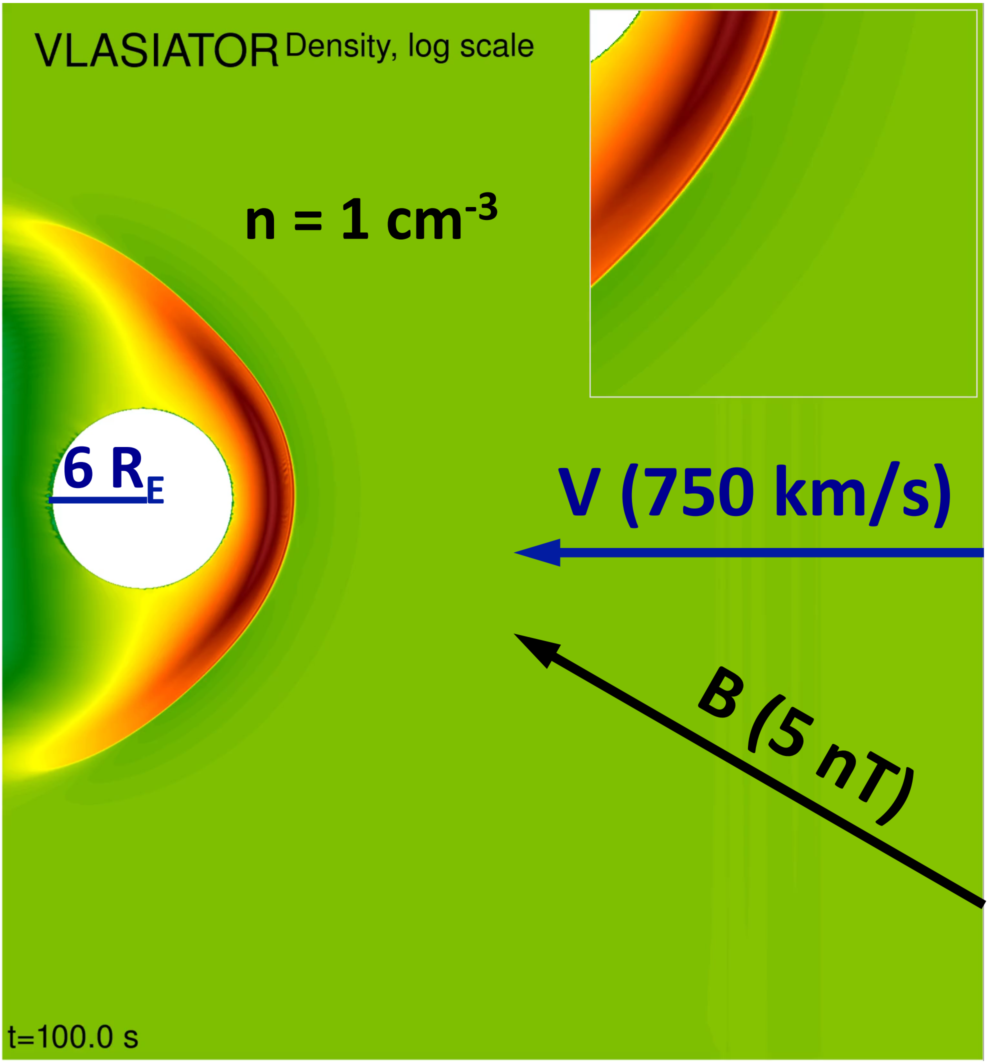
SOLPACS produces a mean free path increasing a function of energy.

Temporal evolution at E = 0.1 MeV (SOLPACS vs. CSA)



The CSA mean free path reaches a steady state, but the SOLPACS one does not.

Future: beyond quasi-linear physics?



Example: Vlasiator

- Hybrid-Vlasov model, 2D+3V
- Developed at FMI for Earth's magnetosphere (Palmroth et al. 2012)
- Vlasov eq. for protons
- Neutralizing cold electron fluid
- Ampère's, Faraday's and Hall-MHD Ohm's laws

Interplanetary shock case using SOLPACS

$\epsilon_{\text{inj}} = 10^{-3}$

Interplanetary shock simulation parameters:

Magnetic field $B_0 = 5$ nT

Plasma density $n_0 = 5$ cm^{-3}

Solar-wind speed $u_{\text{sw}} = 400$ km s^{-1}

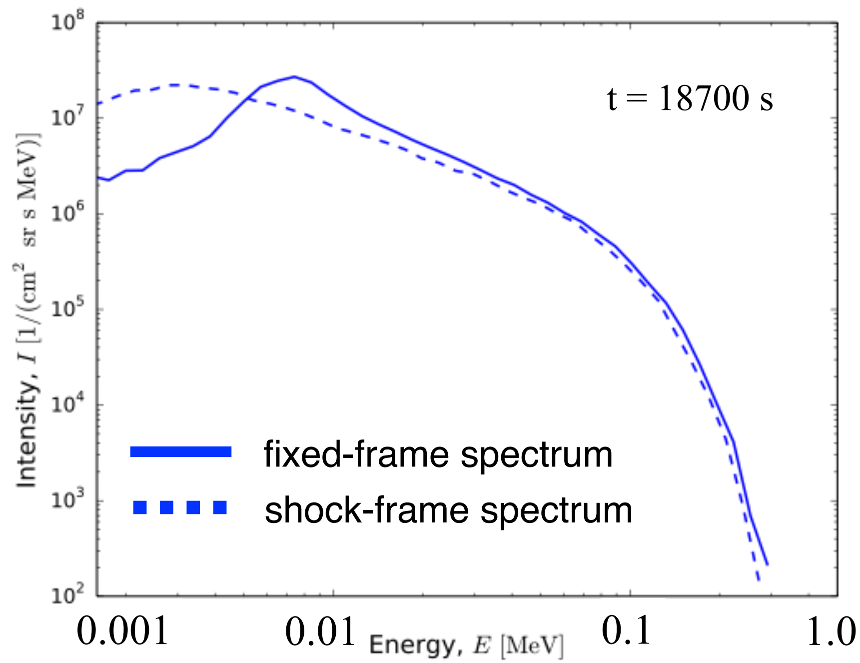
Shock speed $V_{\text{shock}} = 800$ km s^{-1} ($u_1 = 400$ km s^{-1})

Scattering-centre compression ratio $r_c = 3.25$

Simulation box length $L_{\text{box}} = 0.1$AU

Initial wave-spectral index $q_0 = 5/3$

Simulation time $t_{\text{sim}} = 5.2$ h

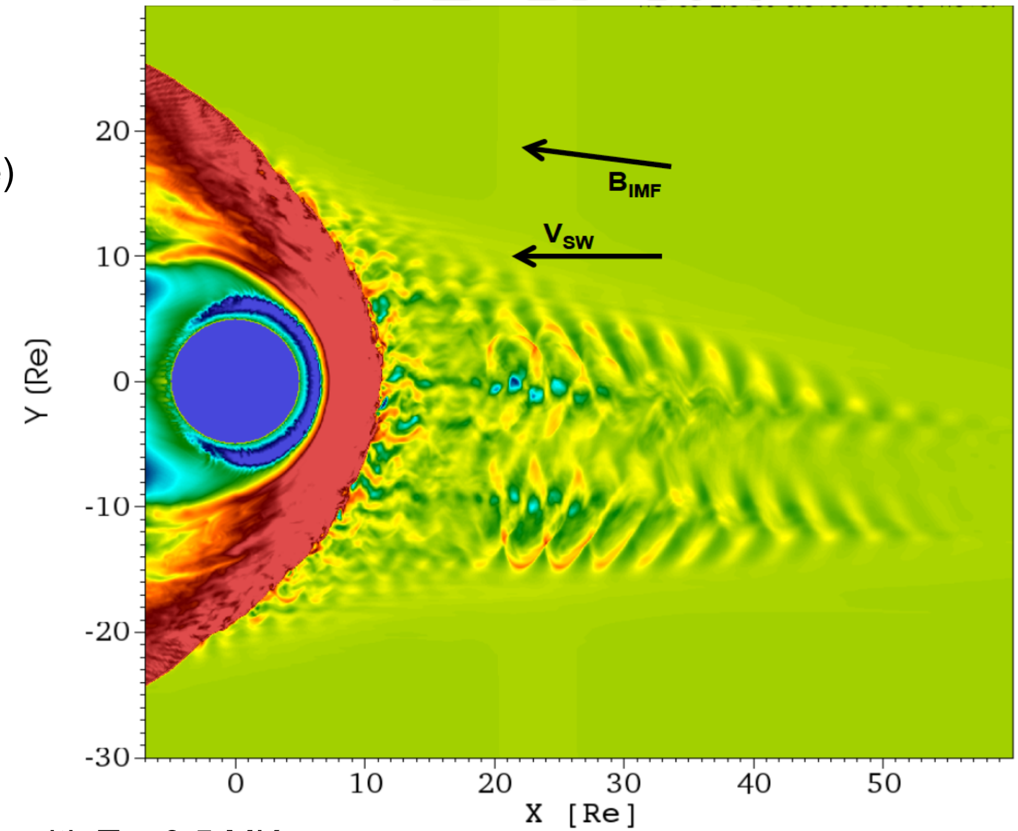


Comparison of SOLPACS to a Vlasiator simulation

Run setup

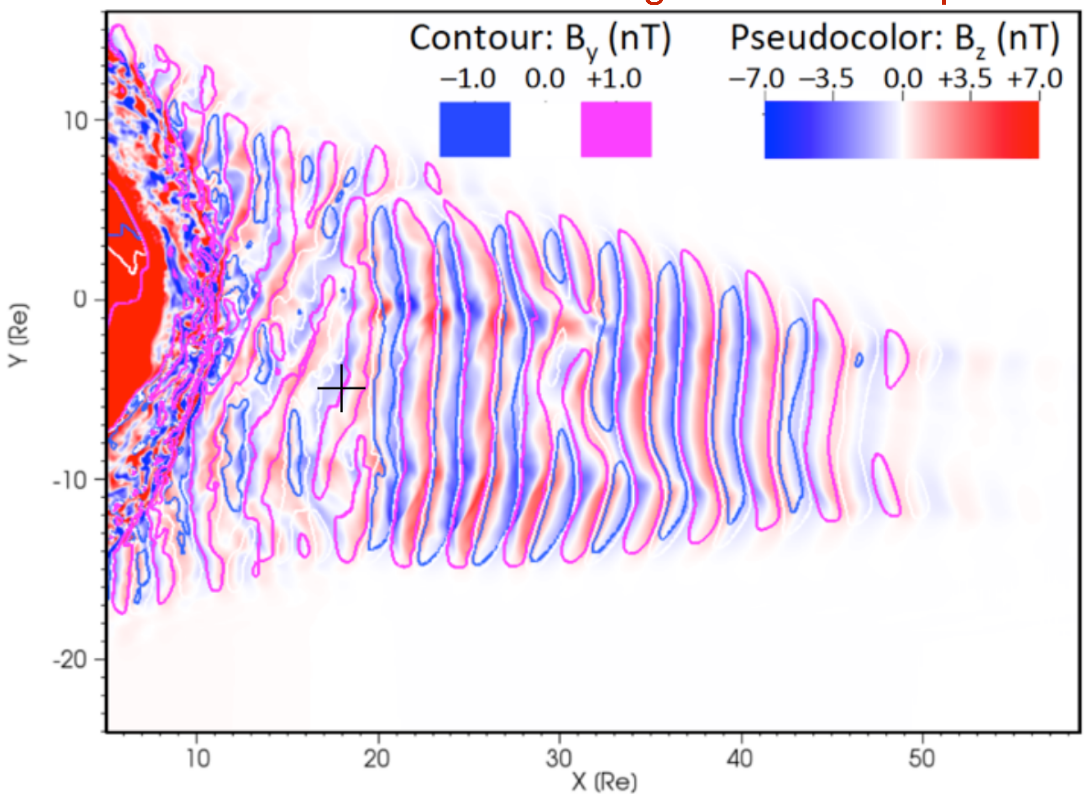
- 5-D run (XY ecliptic plane, 3-D velocity space)
- Resolution: 227 km (ordinary space)
  30 km s^{-1} (velocity space)
- Inner magnetospheric boundary at 5 R_E
- IMF: magnitude 5 nT, radial (cone angle 5°)
- Solar wind velocity: 600 km s^{-1}
- Density: 3.3 cm^{-3}
- Maxwellian velocity distribution of SW protons with T = 0.5 MK.

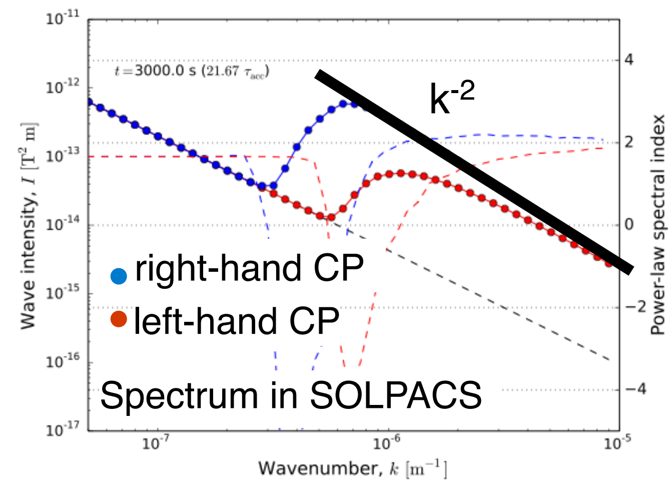
VLASIATOR

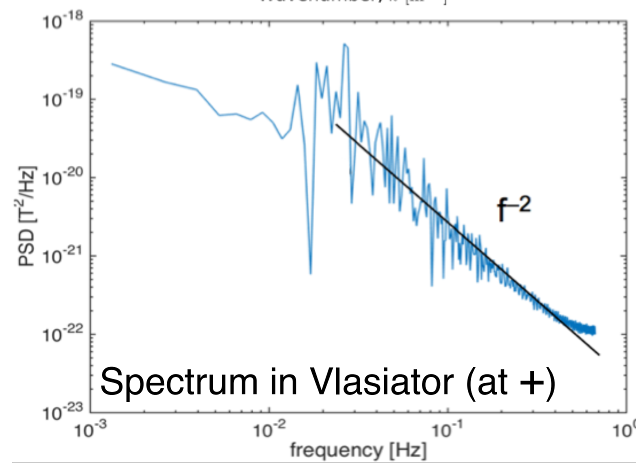


Comparison of SOLPACS to a Vlasiator simulation

Distribution of transverse magnetic field components

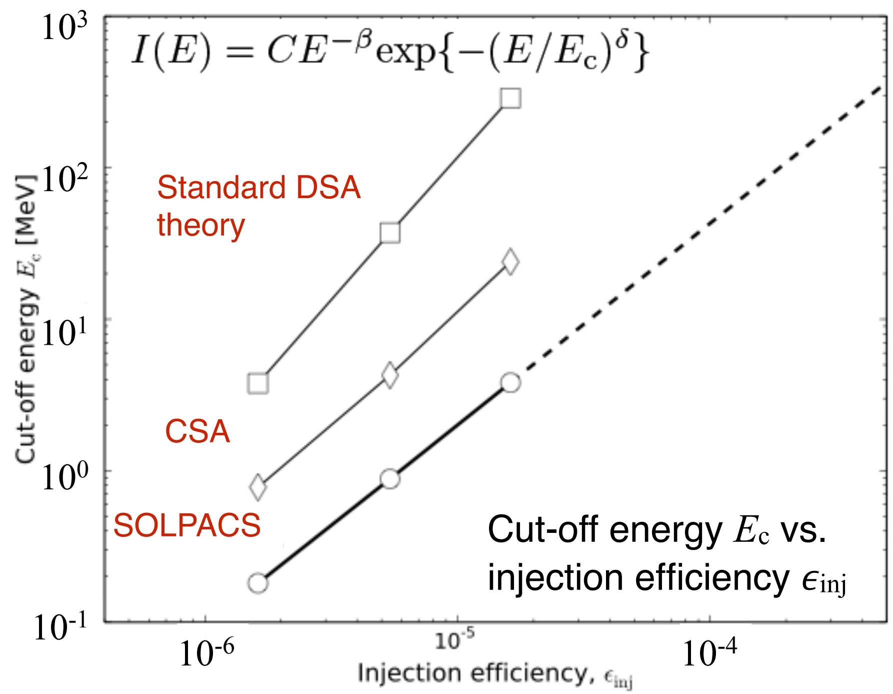




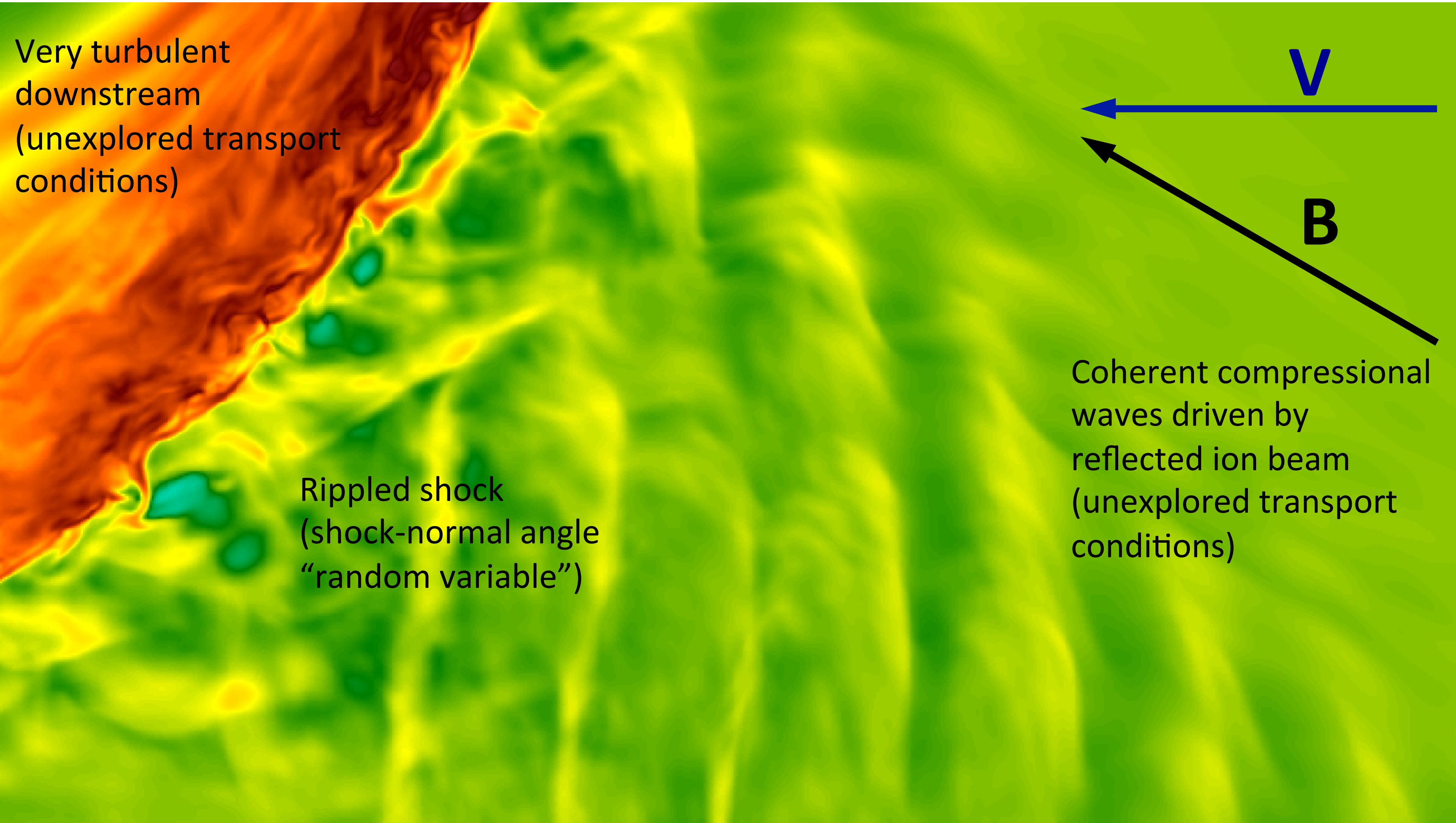


Conclusions on Quasi-linear modeling

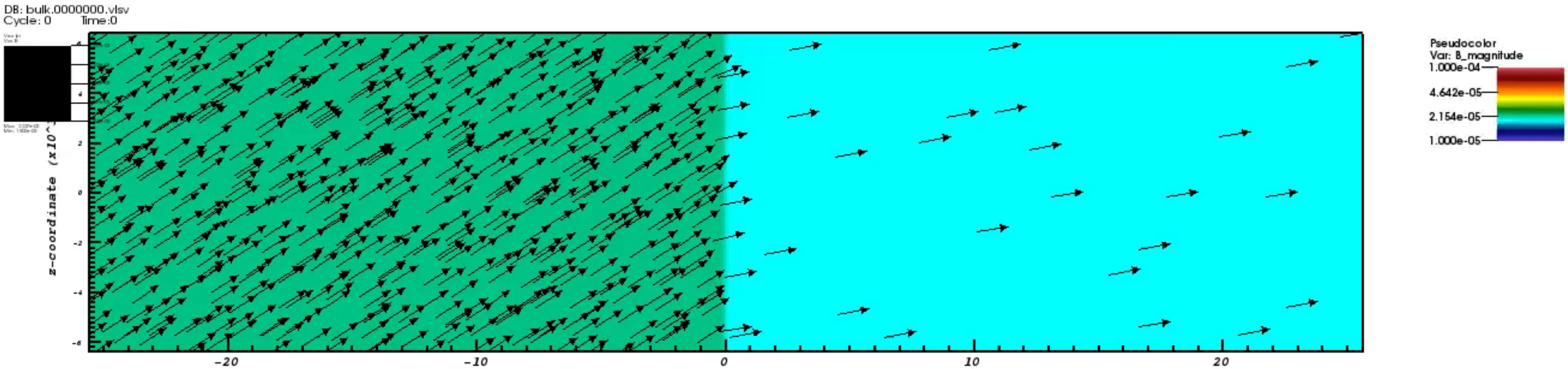
- **The evolution timescale of particles and waves in DSA cannot be neglected!**
- The full quasi-linear resonance condition yields less efficient particle acceleration than the simplified one (cf. the plot ⇒)
- Moreover, it provides a mean free path increasing with energy in contrast to Bell's steady-state theory
- The k^{-2} asymptotic Alfvén wave spectrum agrees with kinetic (hybrid-Vlasov) simulations



Beyond quasi-linear physics?



IP shock simulation / Vlasiator



Conclusions and outlook

- CME-driven shocks are the best candidate to account for the majority of proton fluence in large gradual events beyond 10-MeV energies.
- Acceleration is strongest in the corona but continues in the interplanetary medium
- DSA in solar eruptions is much more complicated than simple, 1D steady-state modelling can account for
  - Time evolution of foreshock
  - Complicated shock structures, both global and local
  - Quasi-linear treatment of DSA may be invalid, at least at supra-thermal energies
- Future modelling efforts should combine local fully kinetic simulations with global Monte Carlo simulations
  - Code Coupling probably not efficient enough (time scale limitation)
  - Statistical analysis of kinetic models with test-particle trajectories may provide the way ahead.