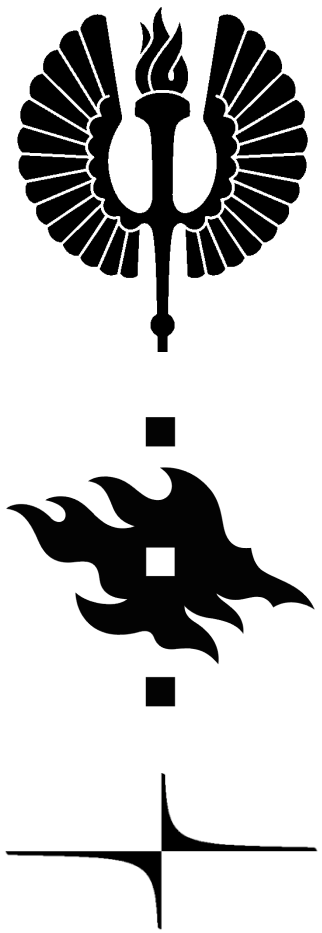

Particle acceleration at collisionless shocks: quasi-linear and hybrid-Vlasov simulations

R. Vainio, A. Afanasiev,
University of Turku, Finland

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University of Helsinki, Finland

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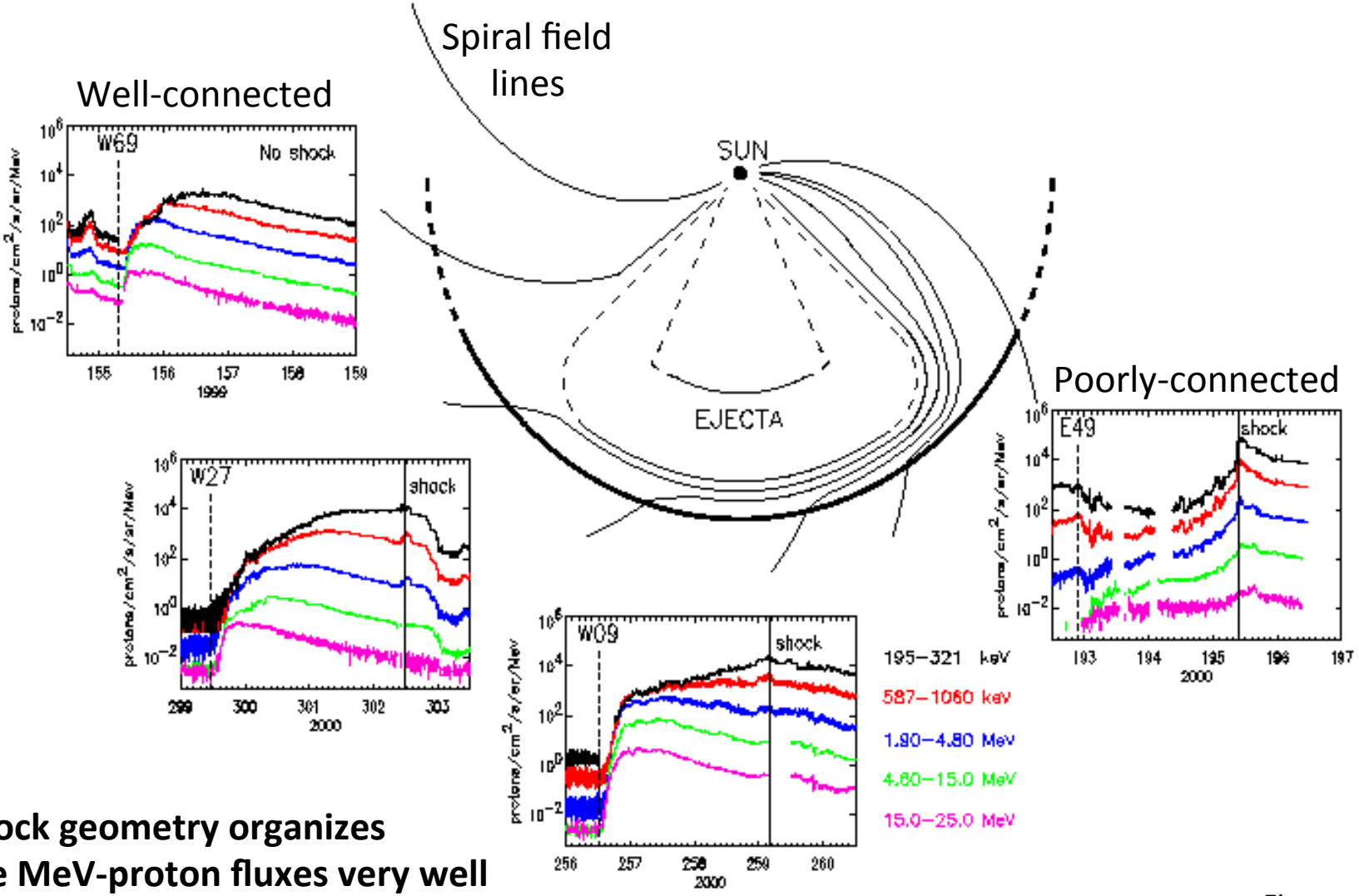
CSC – IT Centre for Science, Espoo, Finland

**also at Finnish Meteorological Institute*

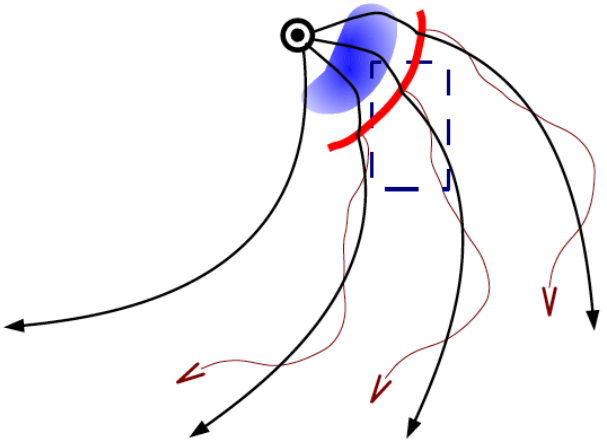
Shock accelerated ions in solar eruptions

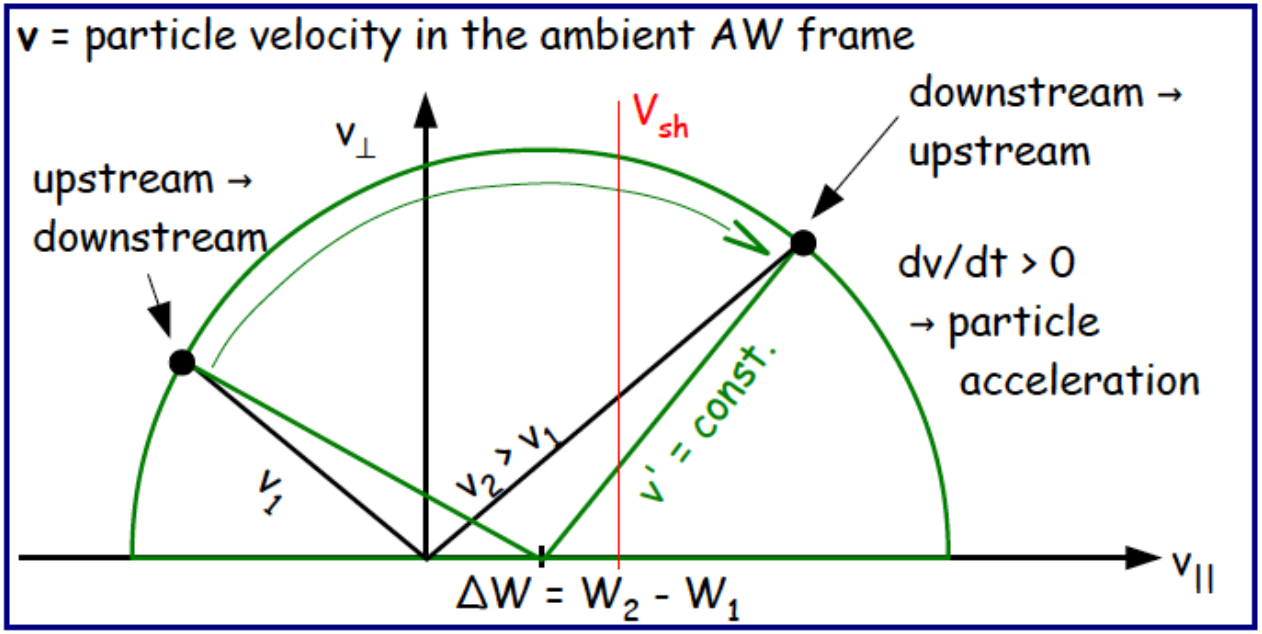


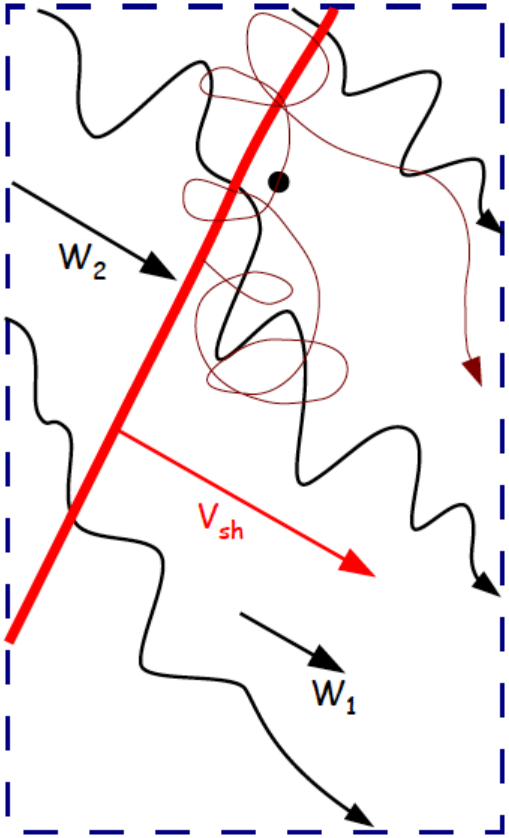
Shock geometry organizes the MeV-proton fluxes very well

Figure: D. Lario

How do shocks accelerate particles? Diffusive shock acceleration

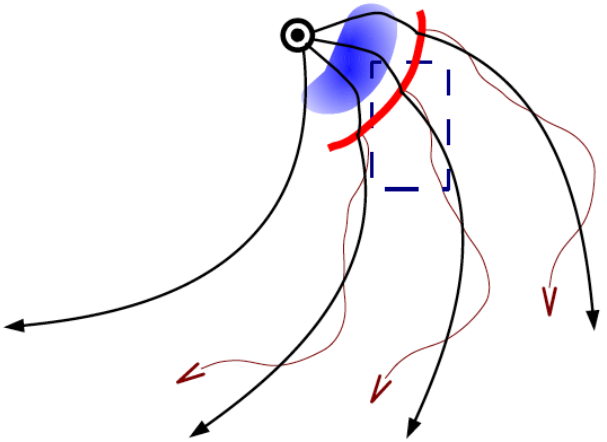


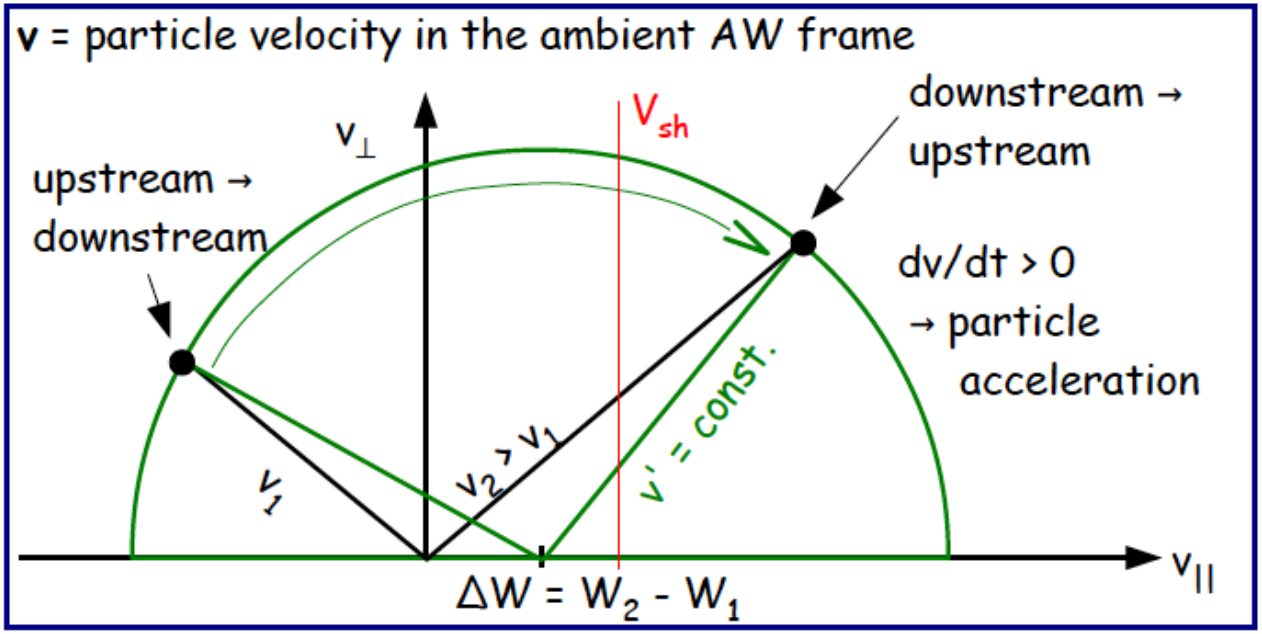


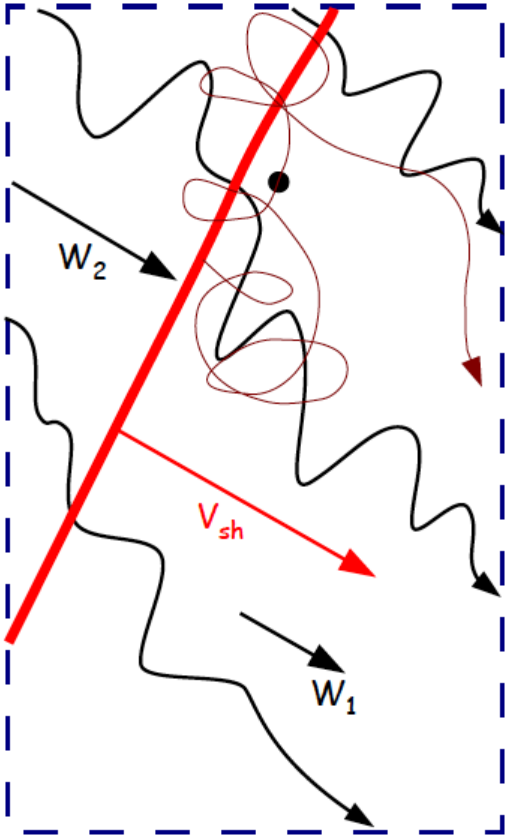


Repeated shock crossings produce a power-law in momentum

How do shocks accelerate particles?
Diffusive shock acceleration



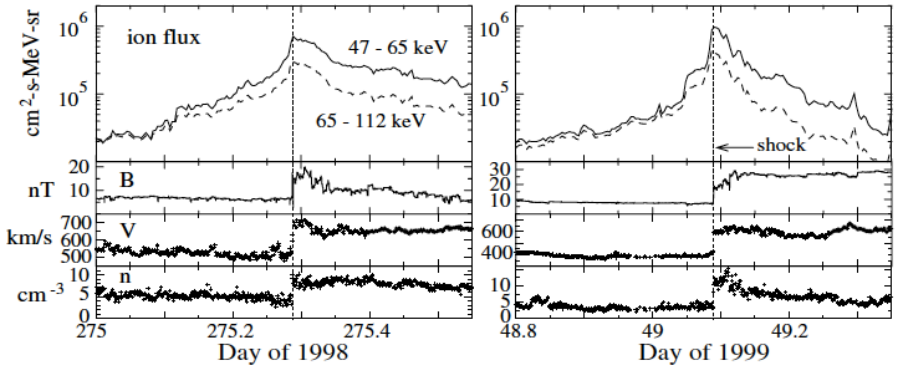


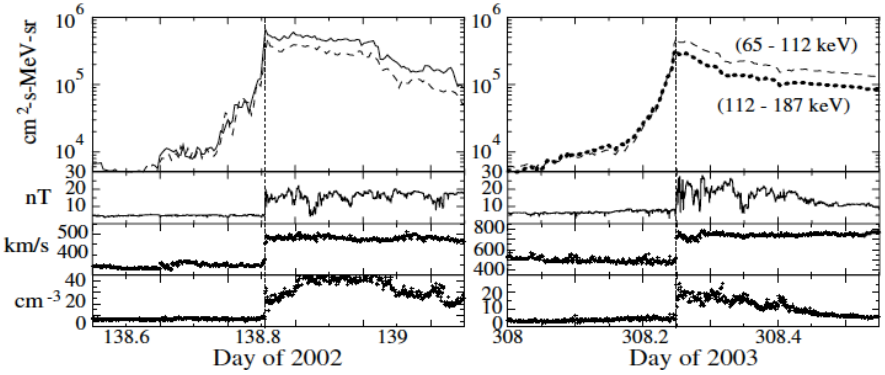


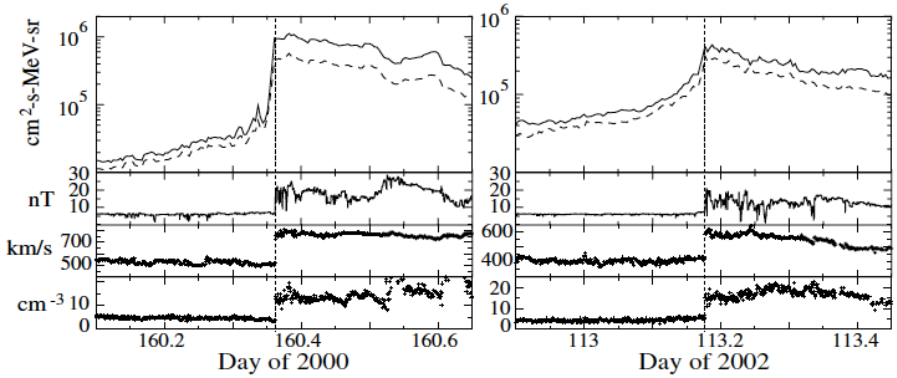
$$D_{\mu\mu} = \frac{\pi}{4}\omega_c(1-\mu^2)\frac{f_r P(f_r)}{B^2}$$

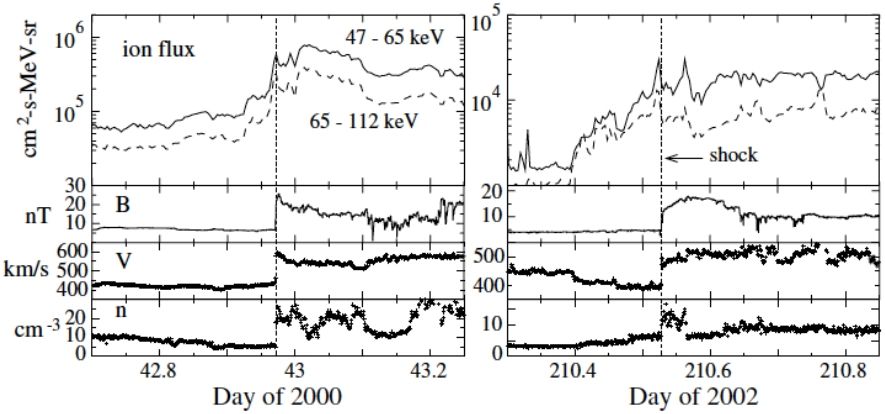
$$f_r = \frac{\omega_c}{2\pi}\frac{W}{v\mu}$$

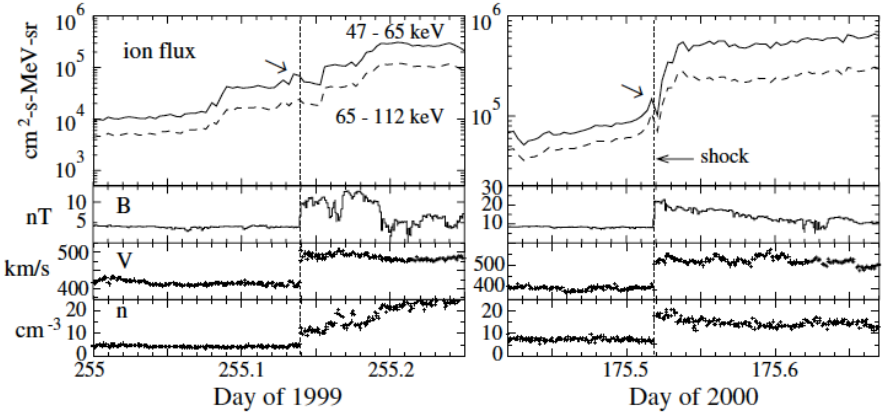
Ions at supercritical shocks ($M_A > 3$, $r > 2.5$)









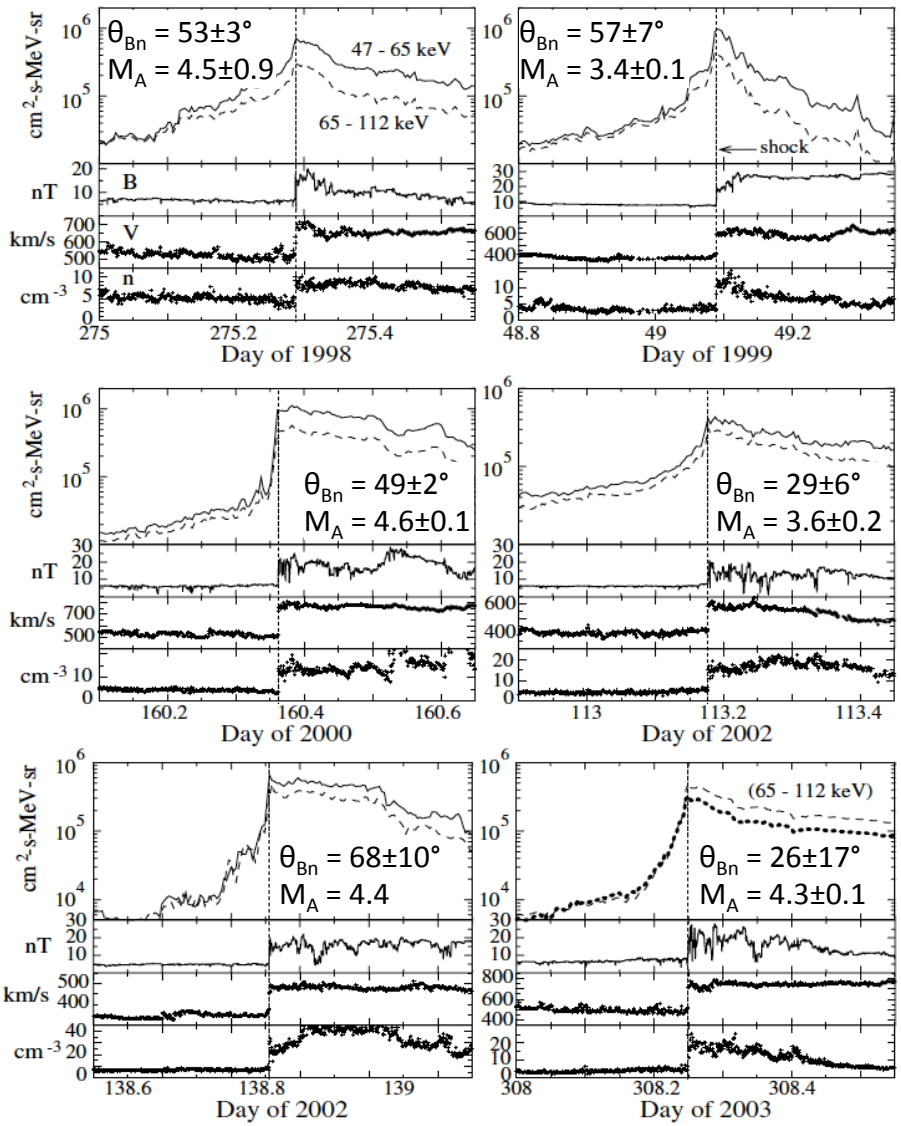


Giacalone (2102)

- 18 cases in ACE shock lists, <u>all</u> have ion acceleration

Diffusive shock acceleration

Giacalone (2012)

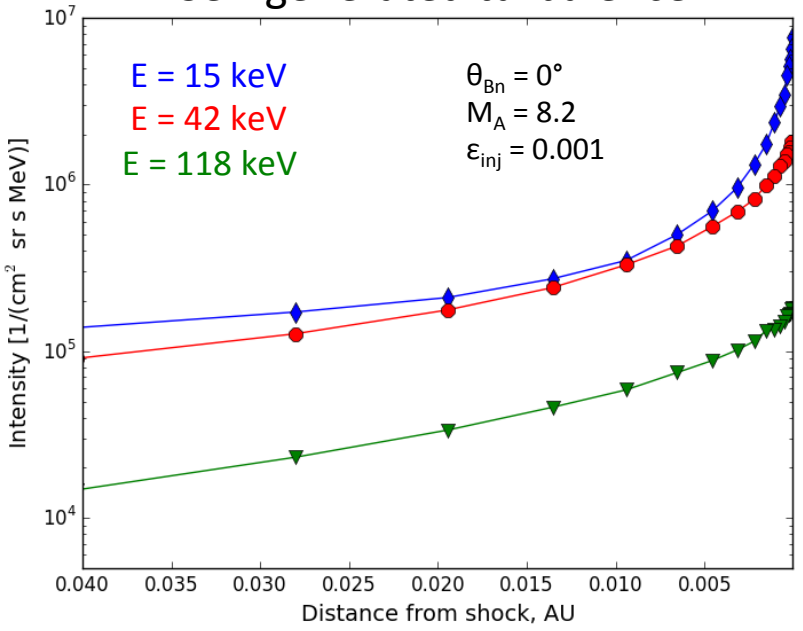


Date	UT	M_A	n_2/n_1	θ_{Bn} (°)
98/275	6:53	5.4 (3.6)	3.2 (2.6)	124 (50)
99/049	2:09	3.3 (3.4)	2.6 (2.9)	63 (50)
00/160	8:41	4.7 (4.5)	3.5 (4.1)	47 (50)
02/113	4:15	3.4 (3.7)	3.9 (3.0)	23 (35)
02/138	19:19	4.4 (4.4)	2.8 (3.0)	102 (59)
03/308	5:59	4.2 (4.4)	4.2 (3.1)	171 (43)

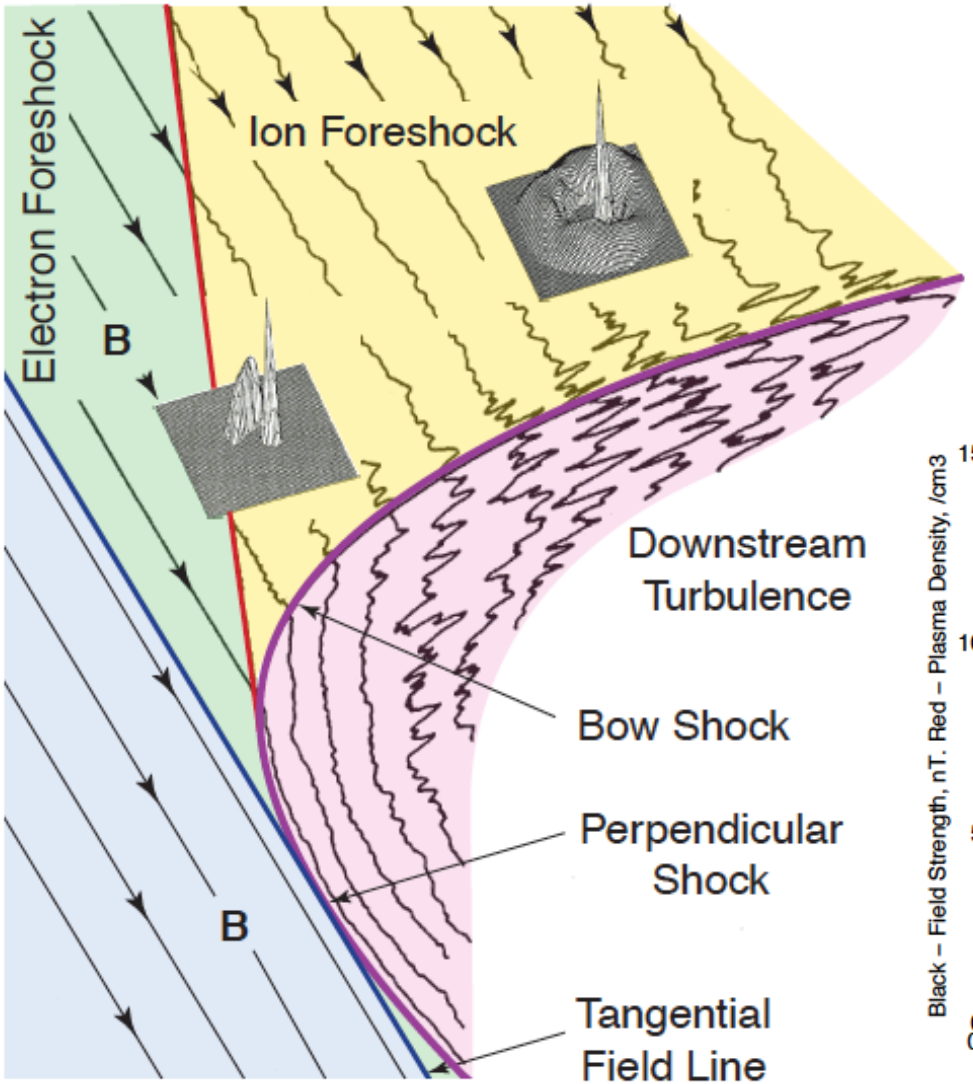
$$I = I_0 \exp\left\{\int_0^x \frac{u_x\,\mathrm{d}x}{\kappa_{xx}}\right\}, \quad x < 0$$

But: increases non-exponential

Self-generated turbulence

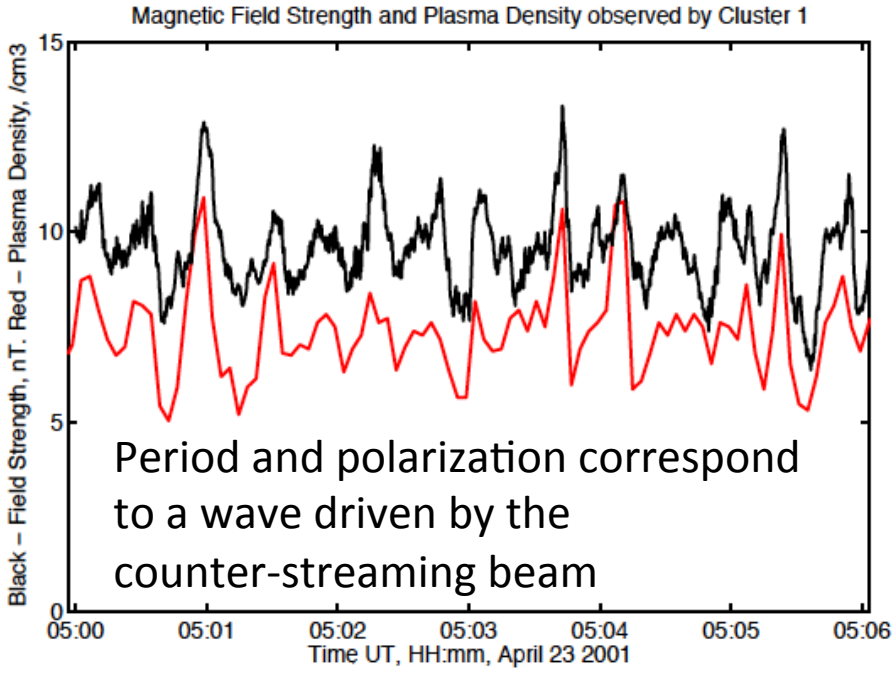


Earth's bow shock



Eastwood et al. (2005)

Foreshock: quasi-periodic
30-sec compressive fluctuations



Period and polarization correspond to a wave driven by the counter-streaming beam

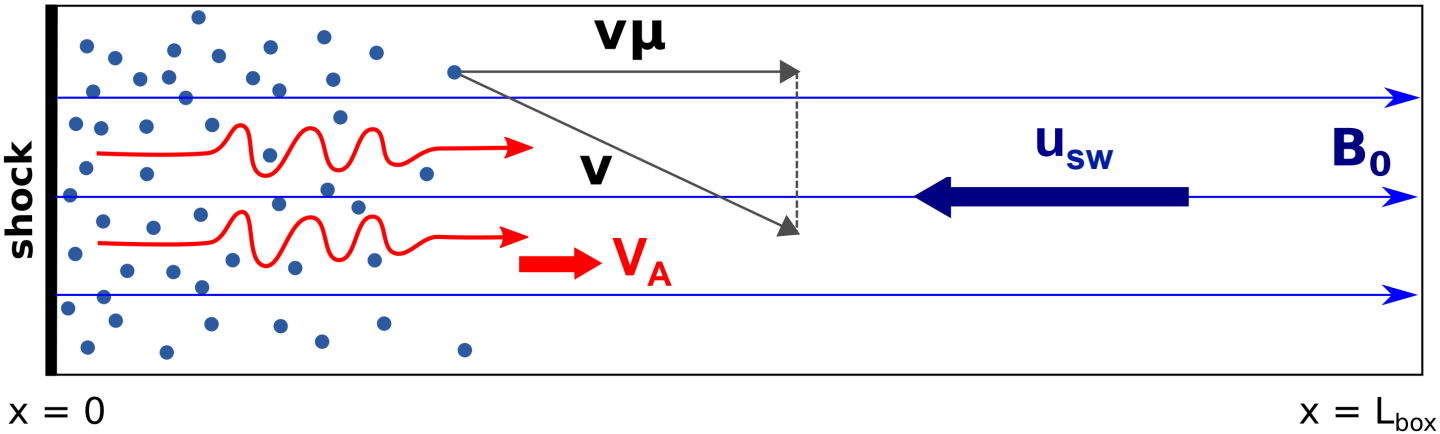
SIMULATION MODELLING

Monte Carlo simulations

SOLar Particle Acceleration in Coronal Shocks (SOLPACS) code

- traces energetic protons upstream of a parallel shock in the GC approximation
- computes interactions of particles with slab-mode Alfvénic turbulence **self-consistently** based on quasi-linear theory
- uses the quasi-linear resonance condition $k_{\mathrm{res}} = \Omega/(v\mu)$
- does local simulations (upstream plasma density and mean magnetic field are taken constant)

Afanasiev et al. (2015)



Interplanetary shock simulation using SOLPACS

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

Interplanetary shock simulation parameters:

Magnetic field $B_0 = 5$ nT

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

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

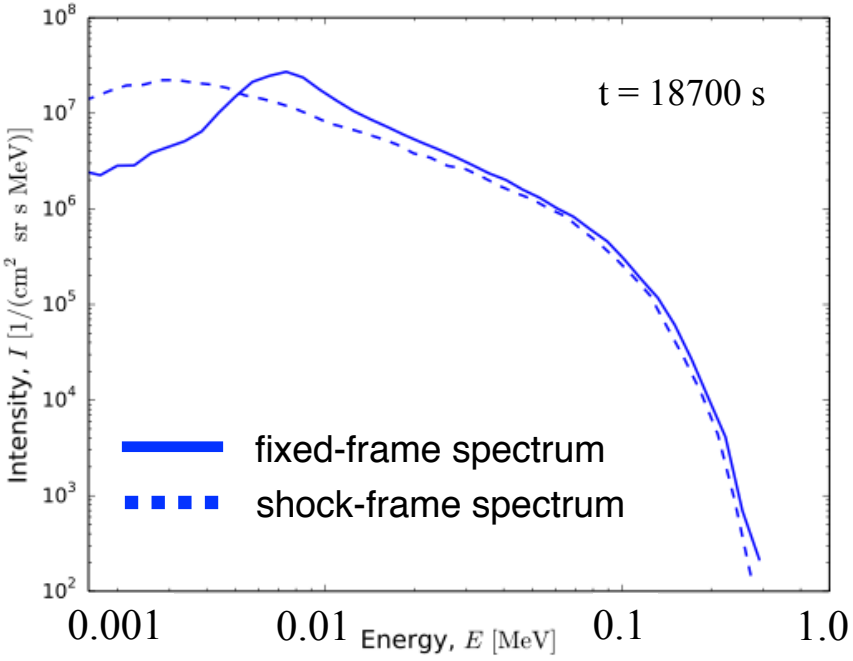
Shock speed $V_{shock} = 800$ km s^{-1} ($u_1 = 400$ km s^{-1})

Scattering-centre compression ratio $r_c = 3.25$

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

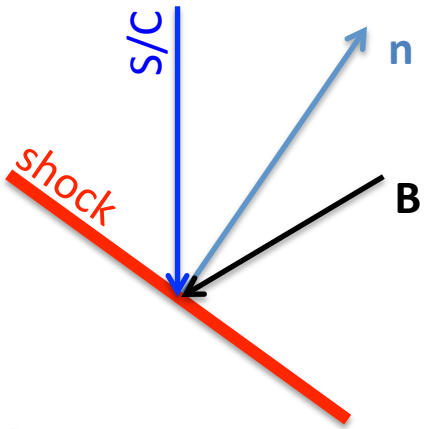
Initial wave-spectral index $q_0 = 5/3$

Simulation time $t_{sim} = 5.2$ h

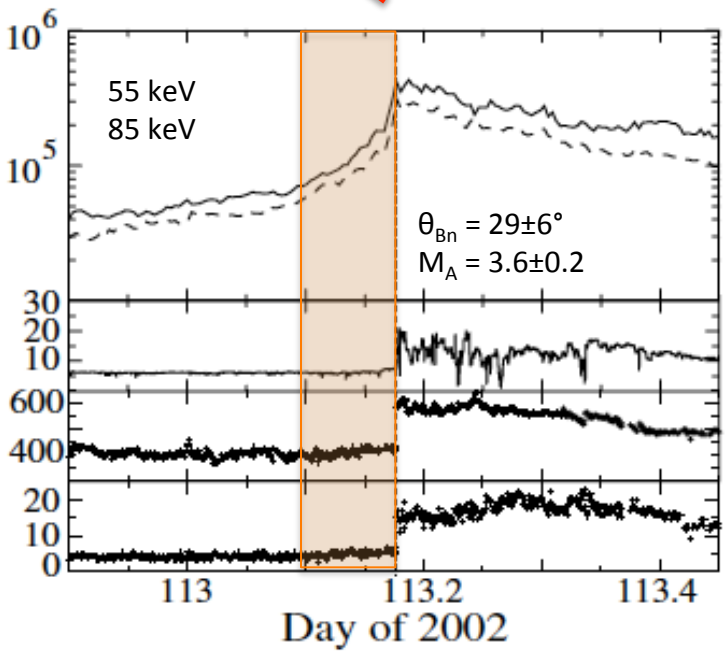


Diffusive shock acceleration

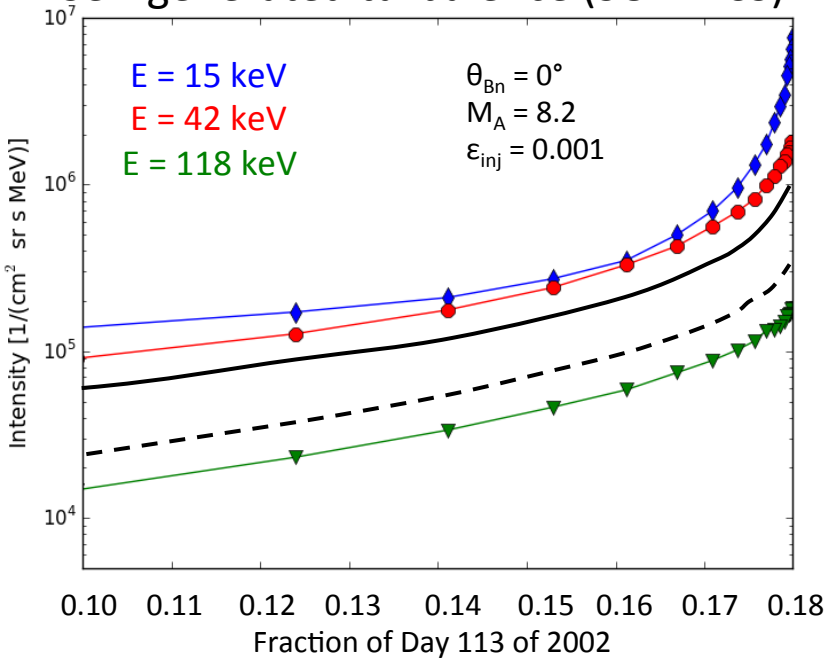
Date	UT	M_A	n_2/n_1	θ_{Bn} (°)
02/113	4:15	3.4 (3.7)	3.9 (3.0)	23 (35)



At least qualitative, if not quantitative, agreement achieved between theory and observations.
However, DSA has a free parameter: ε_{inj}.
In fact, **injection controls what happens at all energies**!

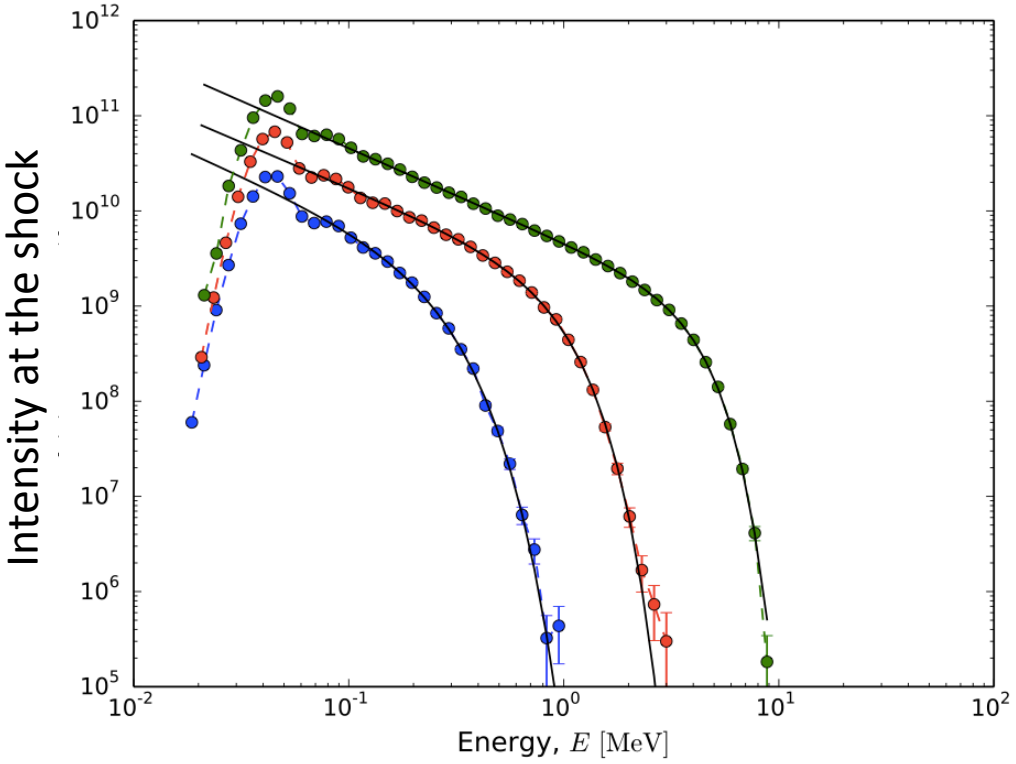


Self-generated turbulence (SOLPACS)



Scaling of intensity at the shock as a function of injection strength

Results of quasi-linear simulations of coronal shocks (Afanasiev et al. 2015)

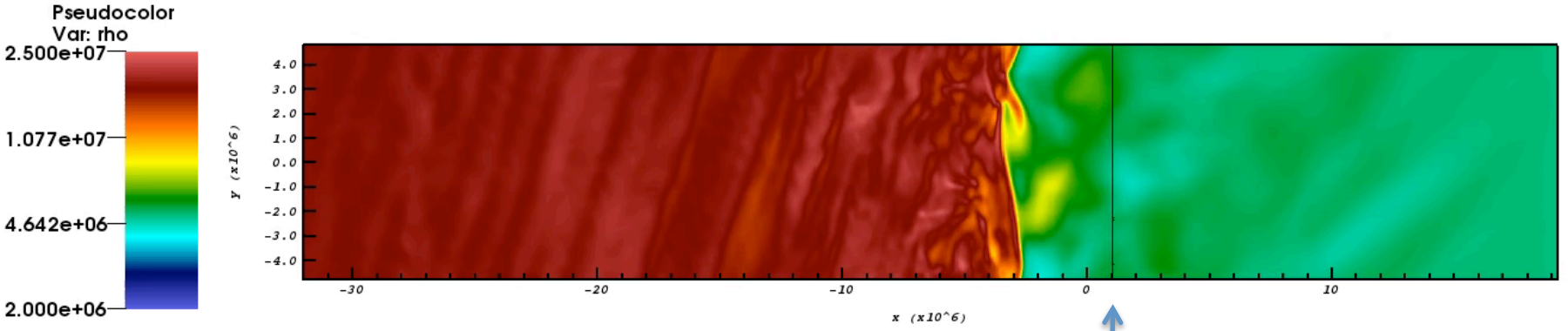


N_{inj} = $5.1 \cdot 10^{16}$ m^{-2}
$1.7 \cdot 10^{16}$ m^{-2}
$5.1 \cdot 10^{15}$ m^{-2}

E_c = 4.04 MeV
0.89 MeV
0.23 MeV

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

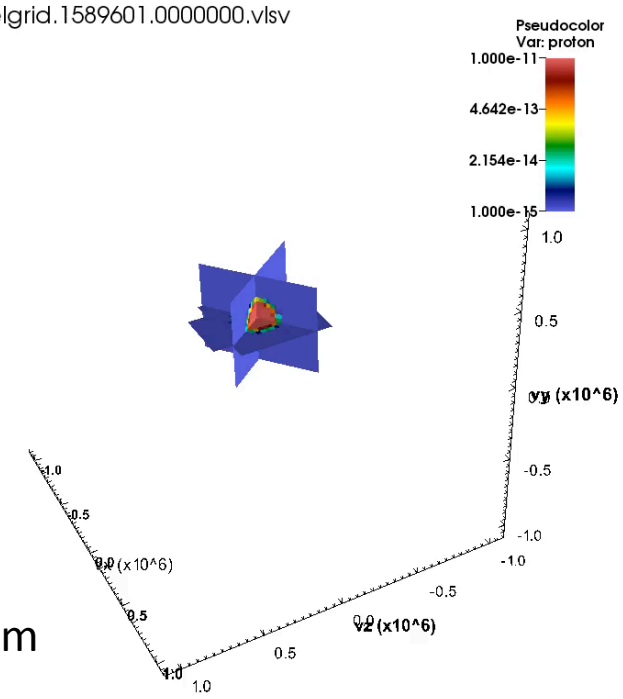
Hybrid Vlasov simulation of an interplanetary shock (HT frame)



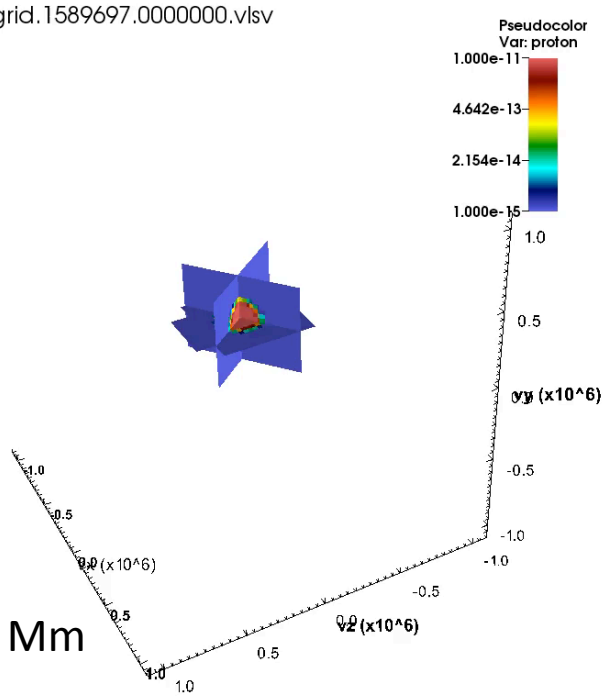
Maxwellian test-particle population

θ_{Bn} = 38.2°
M_A = 6.5
r_n = 3.5
r_B = 2.4

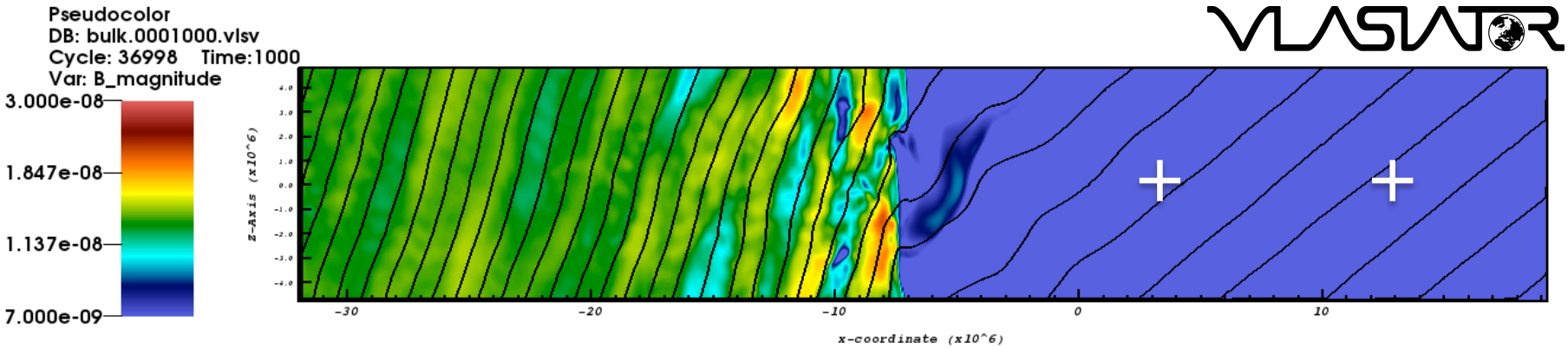
Upstream velocity distributions



X = 3.25 Mm



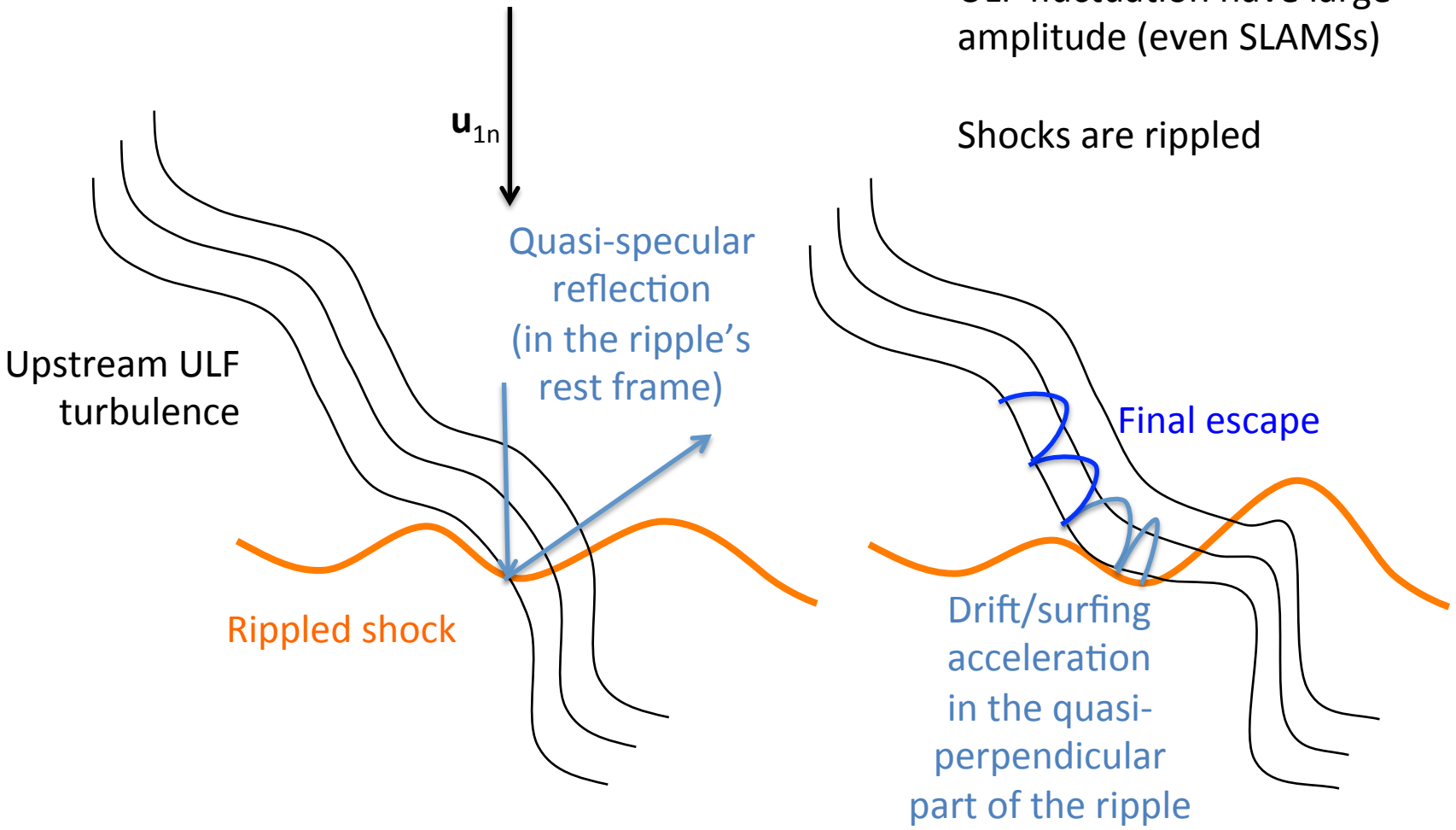
X = 12.85 Mm



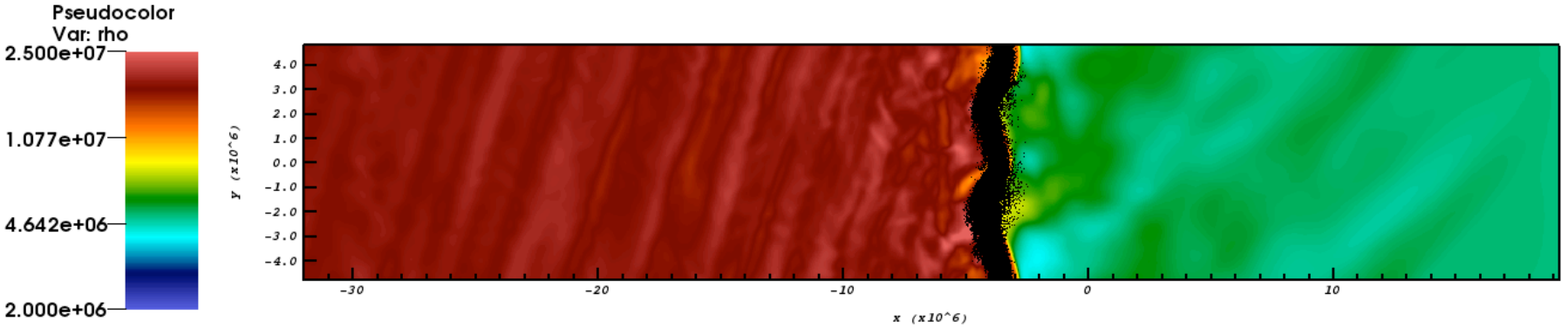
Fully kinetic ion physics crucial for injection

ULF fluctuation have large amplitude (even SLAMSs)

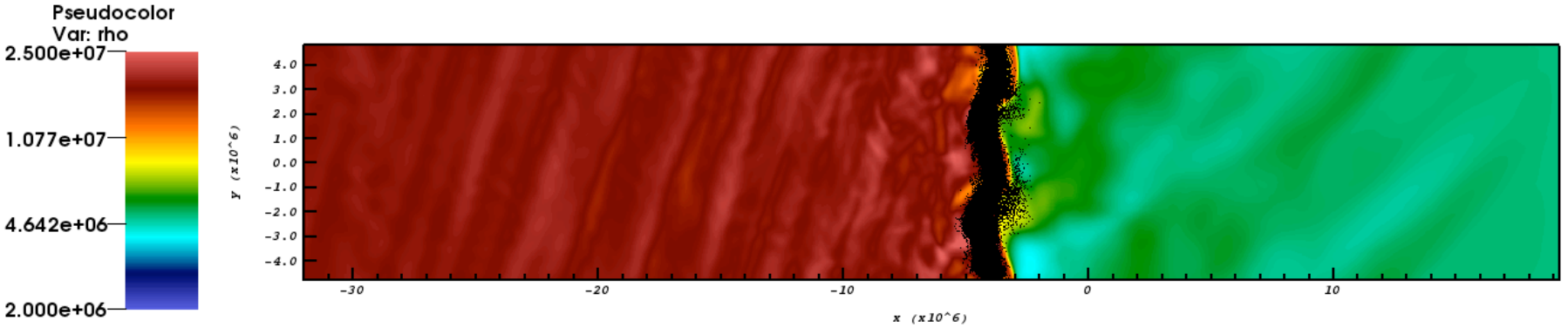
Shocks are rippled



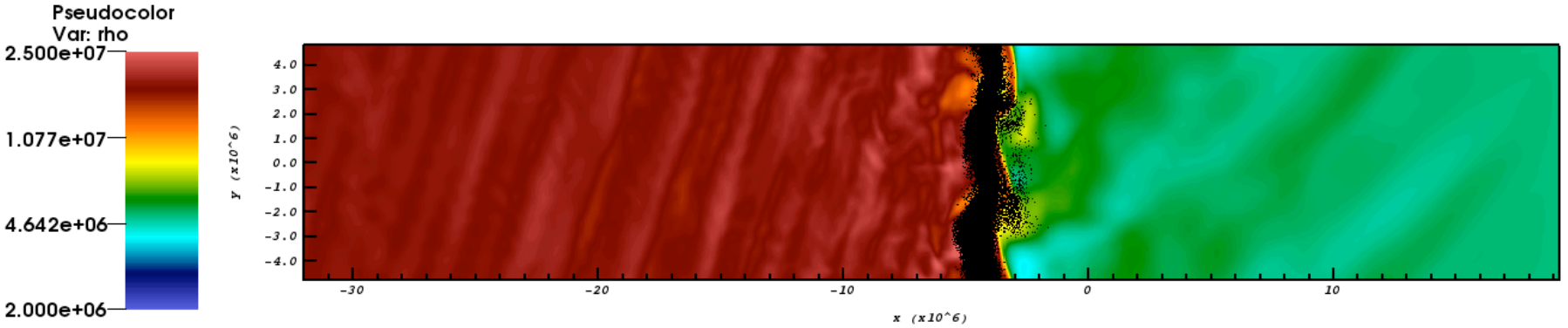
Injection from ripples



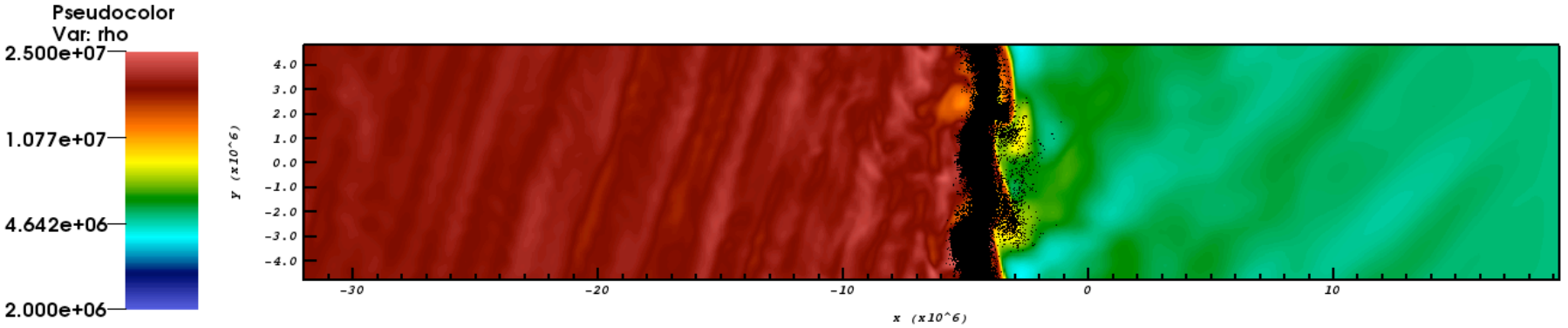
Injection from ripples



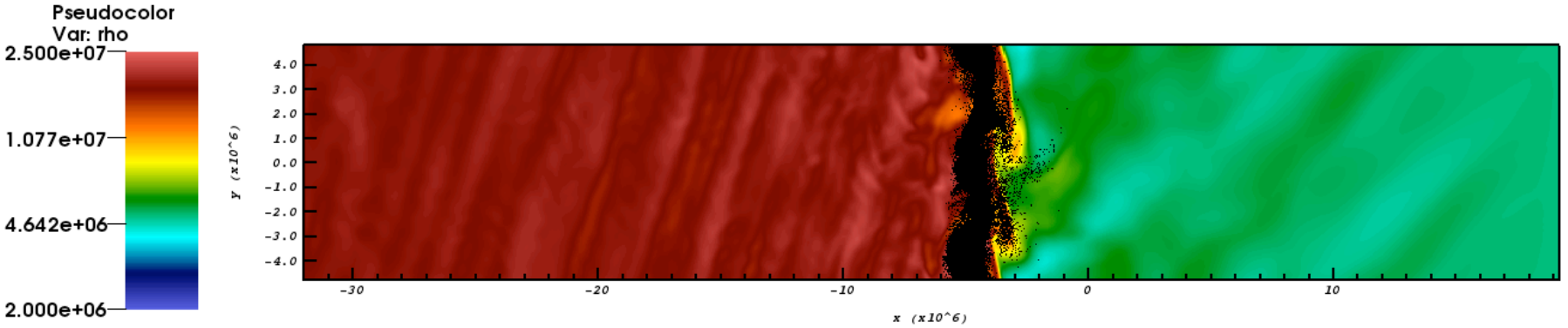
Injection from ripples



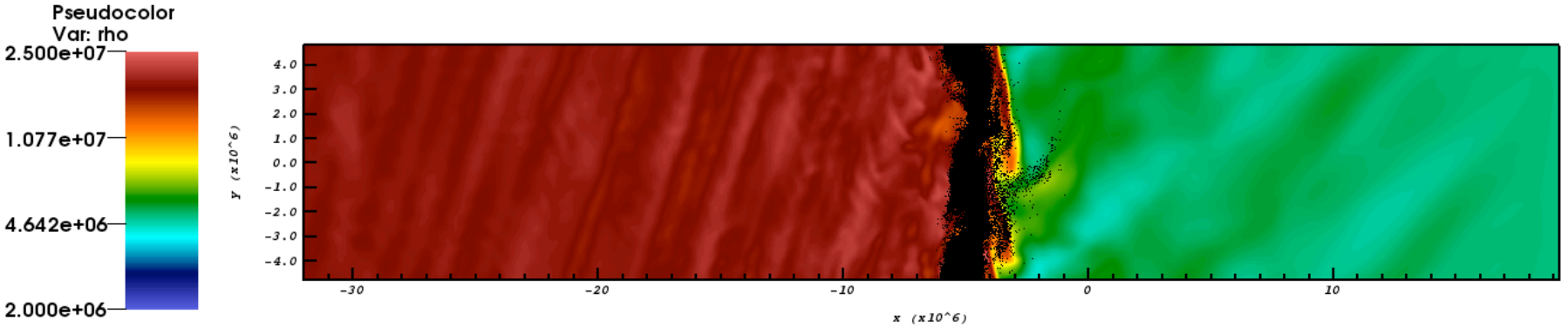
Injection from ripples



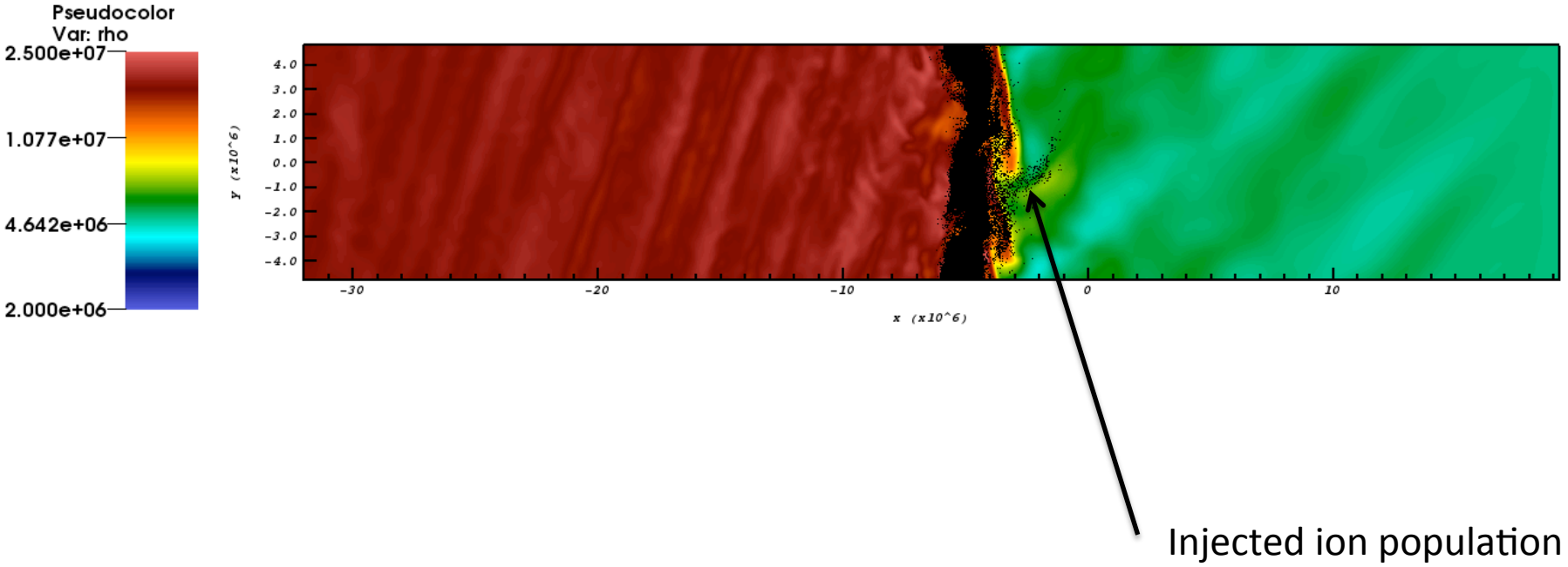
Injection from ripples



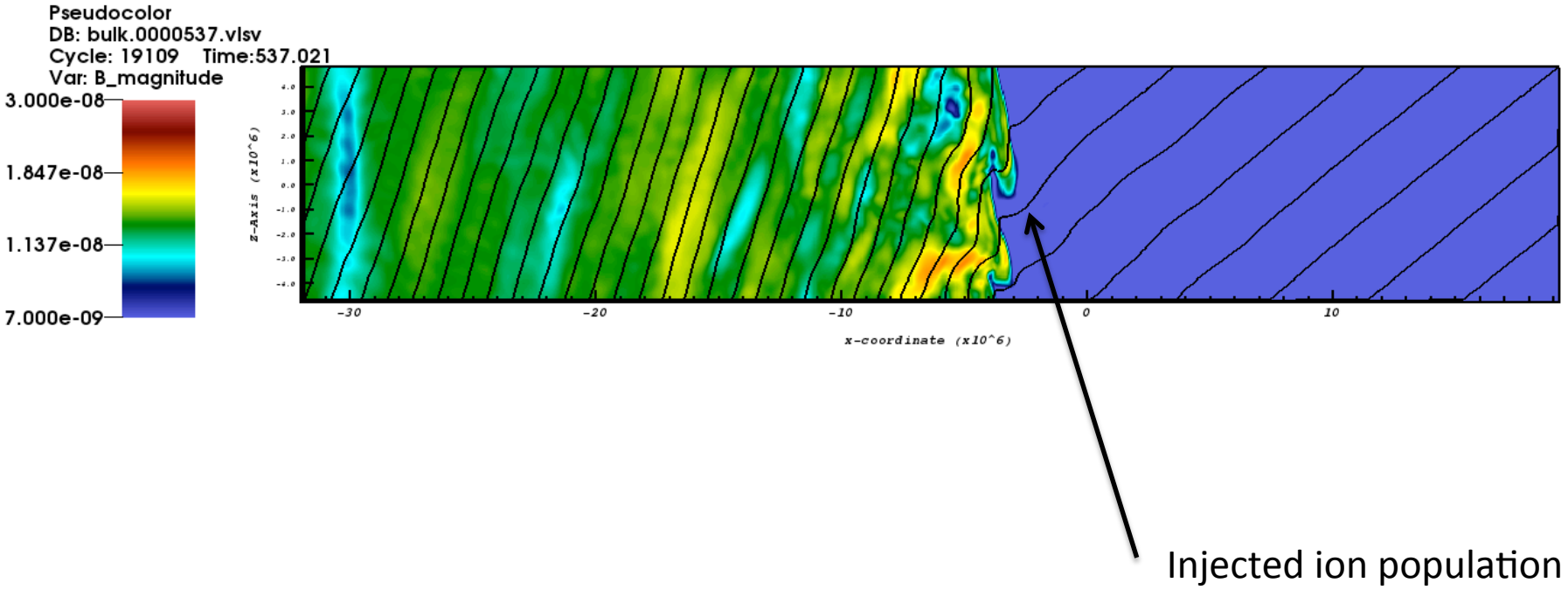
Injection from ripples



Injection from ripples

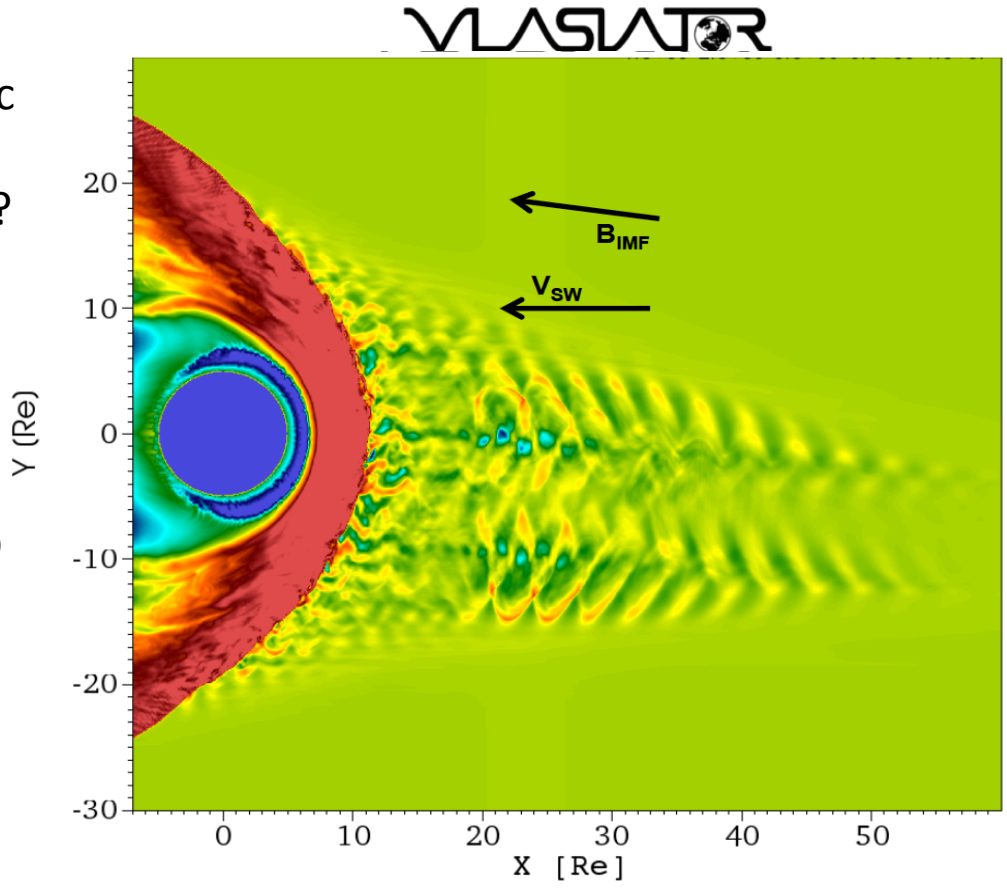


Injection from ripples



Comparison of SOLPACS to a Vlasiator simulation

If injection is obtained from a local kinetic simulation, can we model the acceleration at higher energies with DSA?

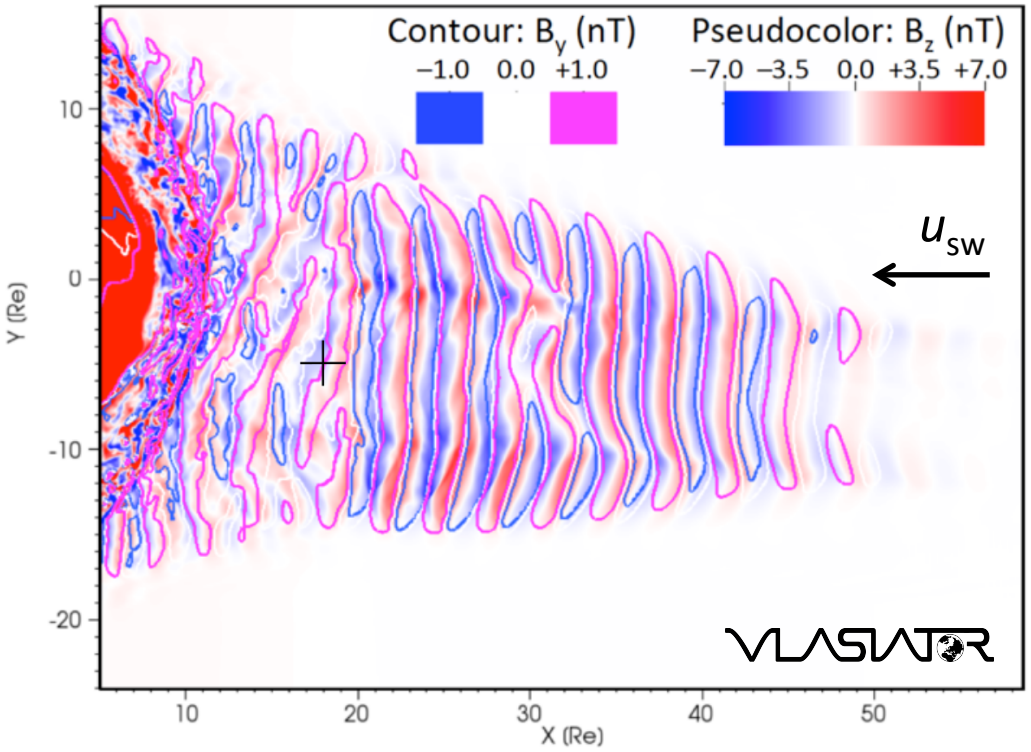


Run setup

- 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 simulation

Magnetic ULF foreshock at t = 450 s



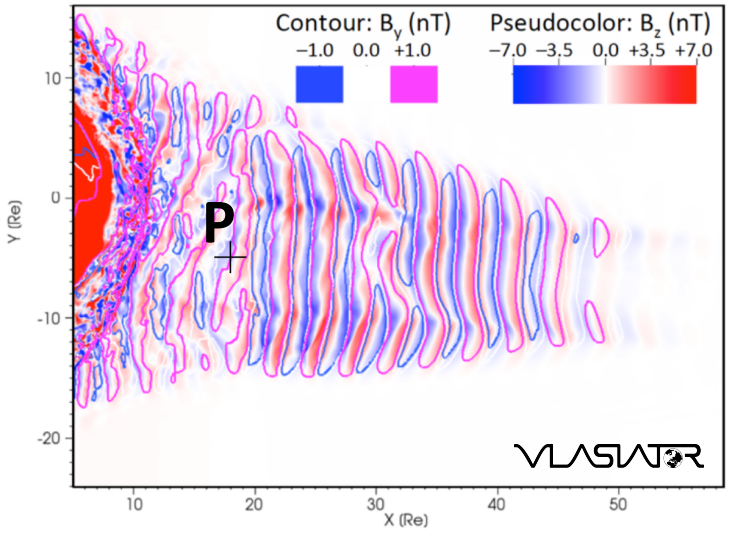
- **Quasi-parallel shock** (clock angle 5 deg.)
- Incident solar wind parameters:

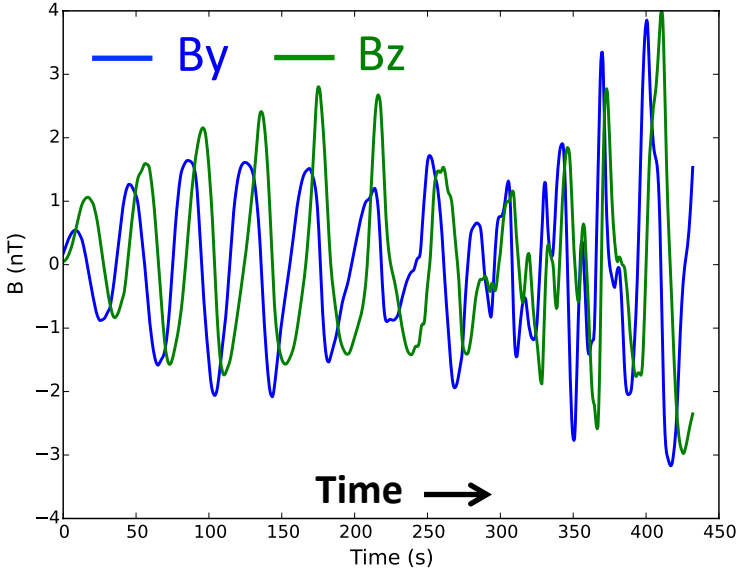
  plasma density **3.3 cm^{-3}**

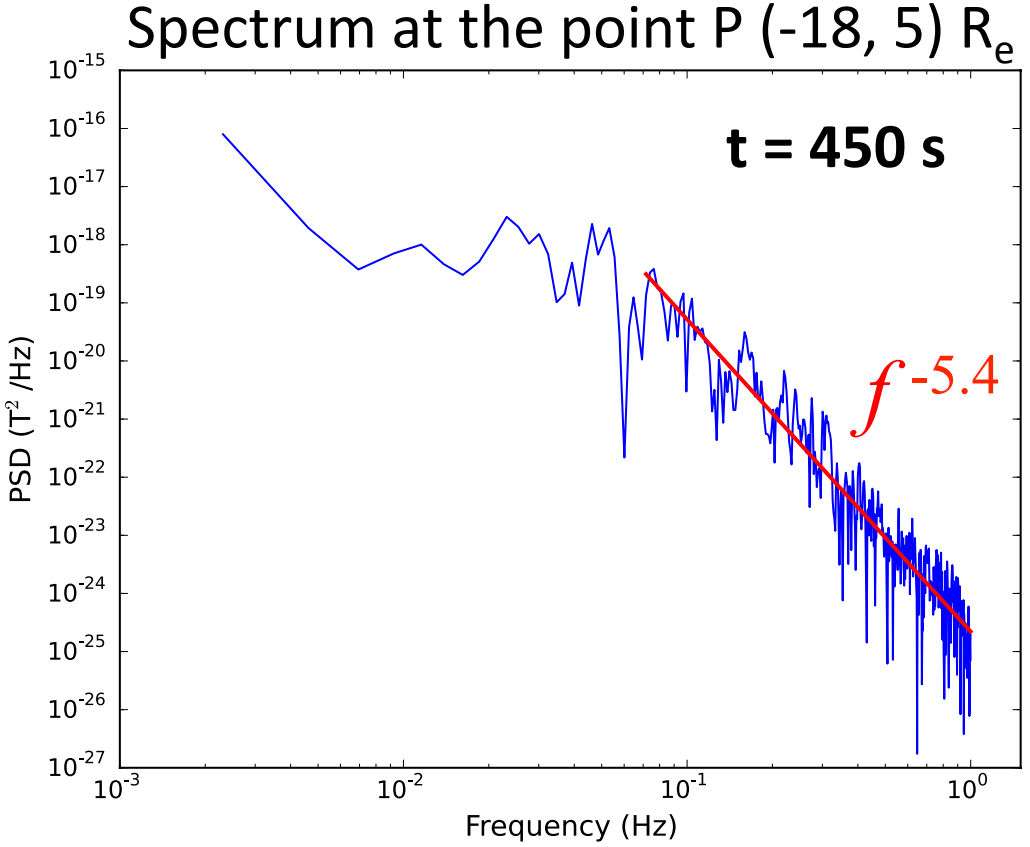
  magnetic field **5 nT**

  solar wind speed **600 km/s**

Wave power spectrum in Vlasiator

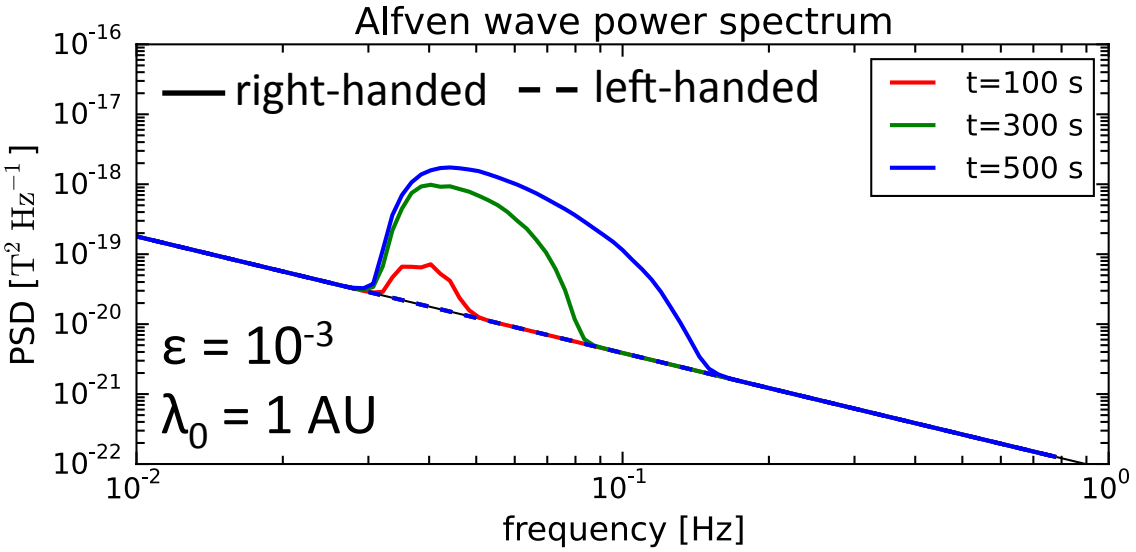


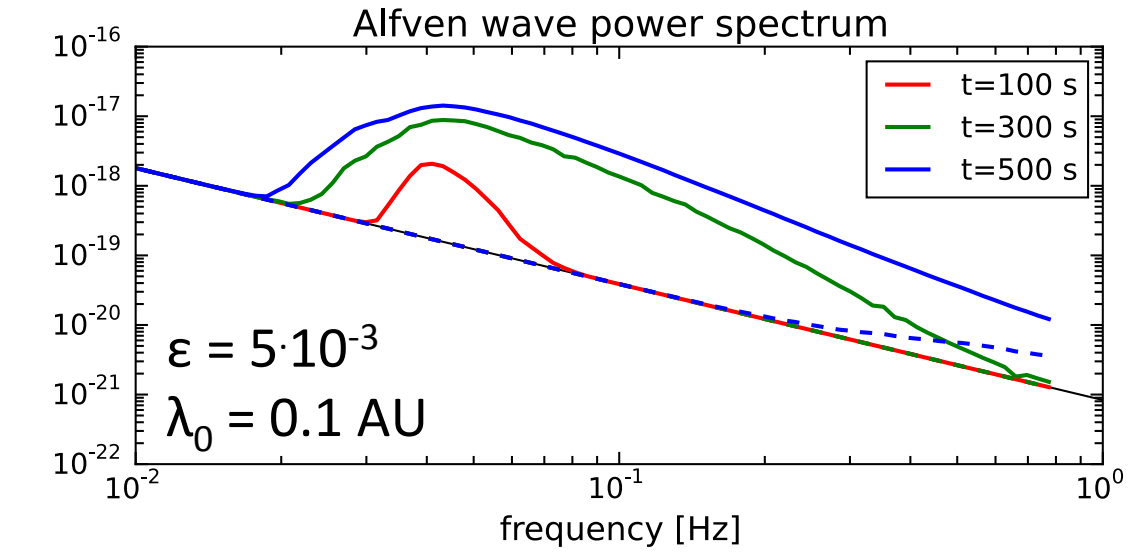




The waves are right-handed (in plasma frame)

Wave power spectra in SOLPACS

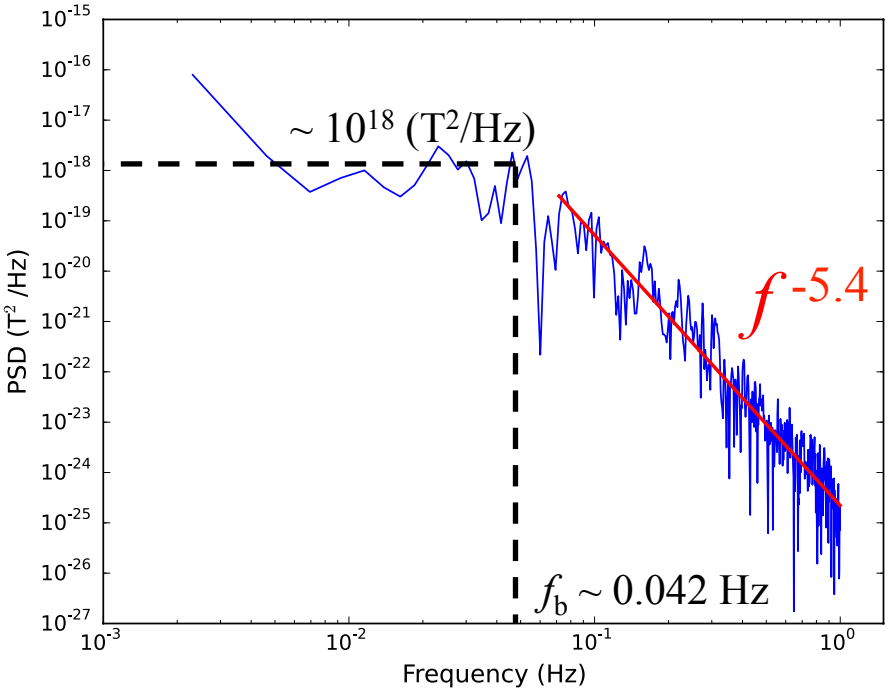


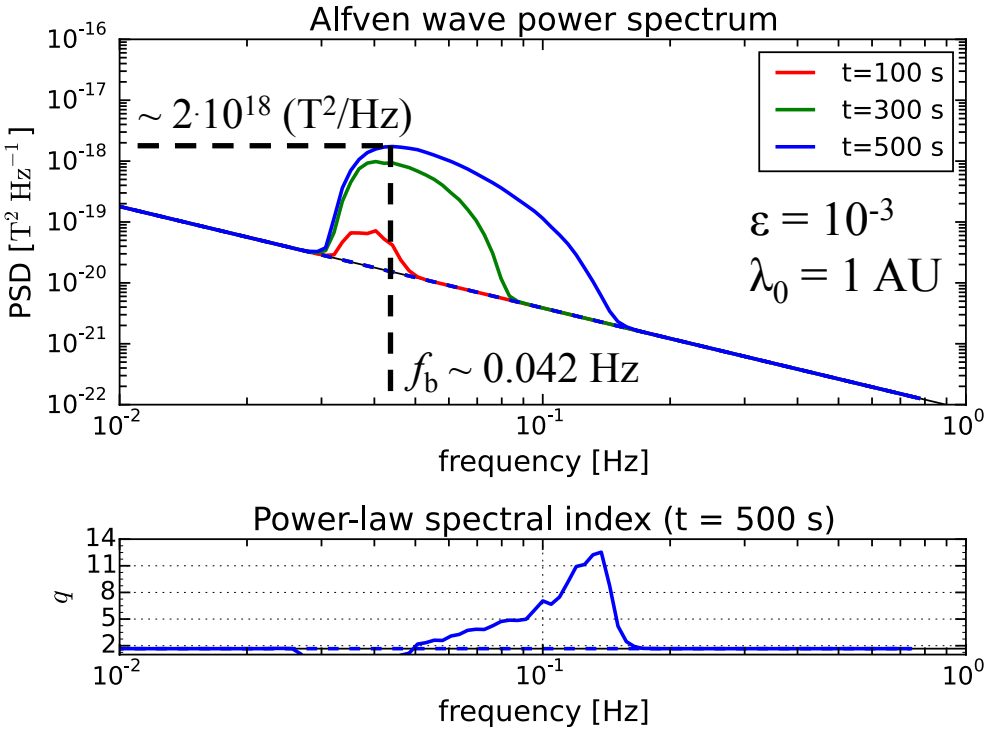


- **Initial wave power spectrum:**
  - has a power-law form
  - Its level is determined by the mean free path λ_0 of 100 keV protons
  - both right-handed and left-handed waves are equally presented
- **The evolution is governed by λ_0 and the proton injection efficiency ε**

Note that right-handed polarization dominates!

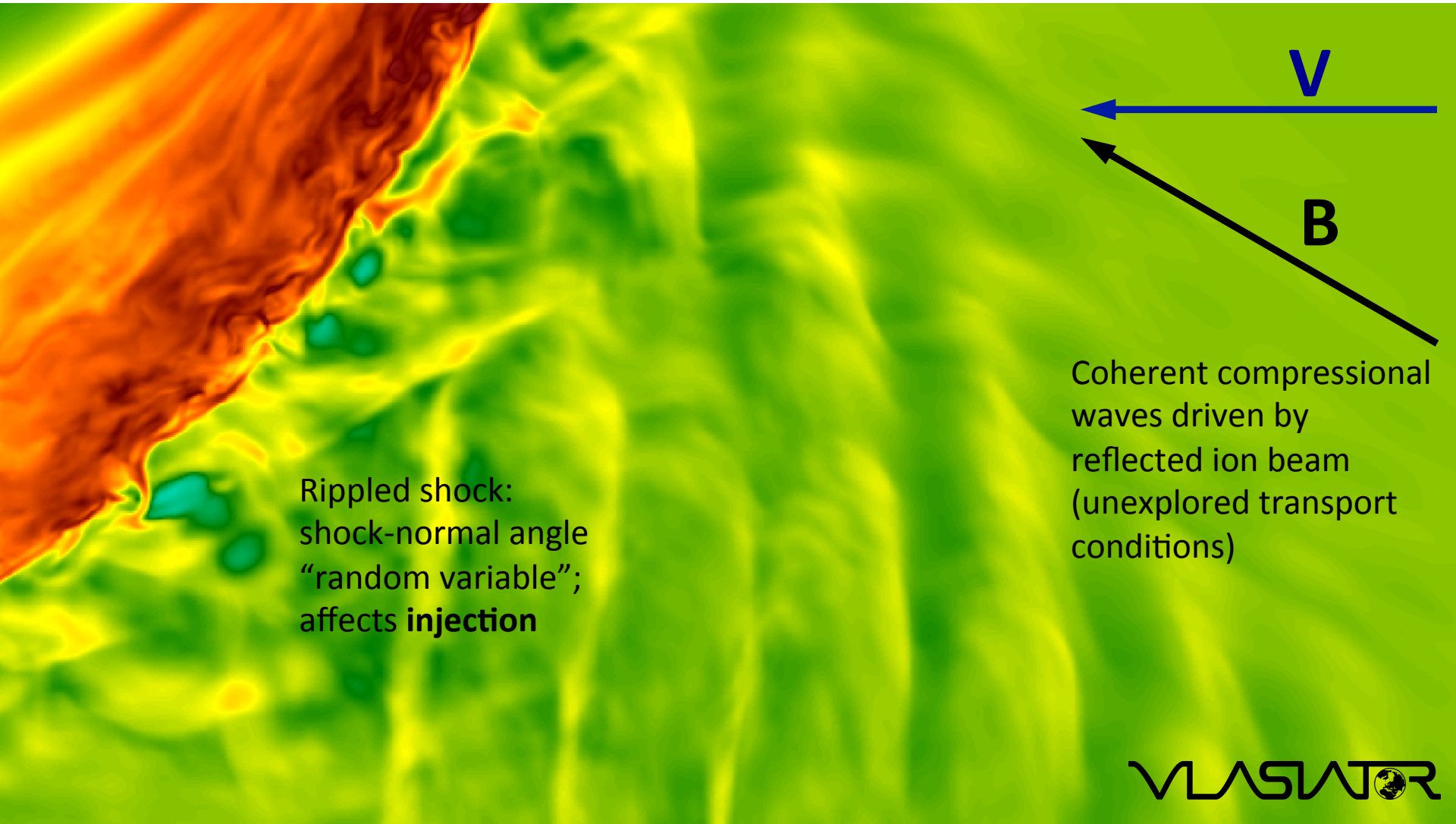
Detailed comparison of the spectra



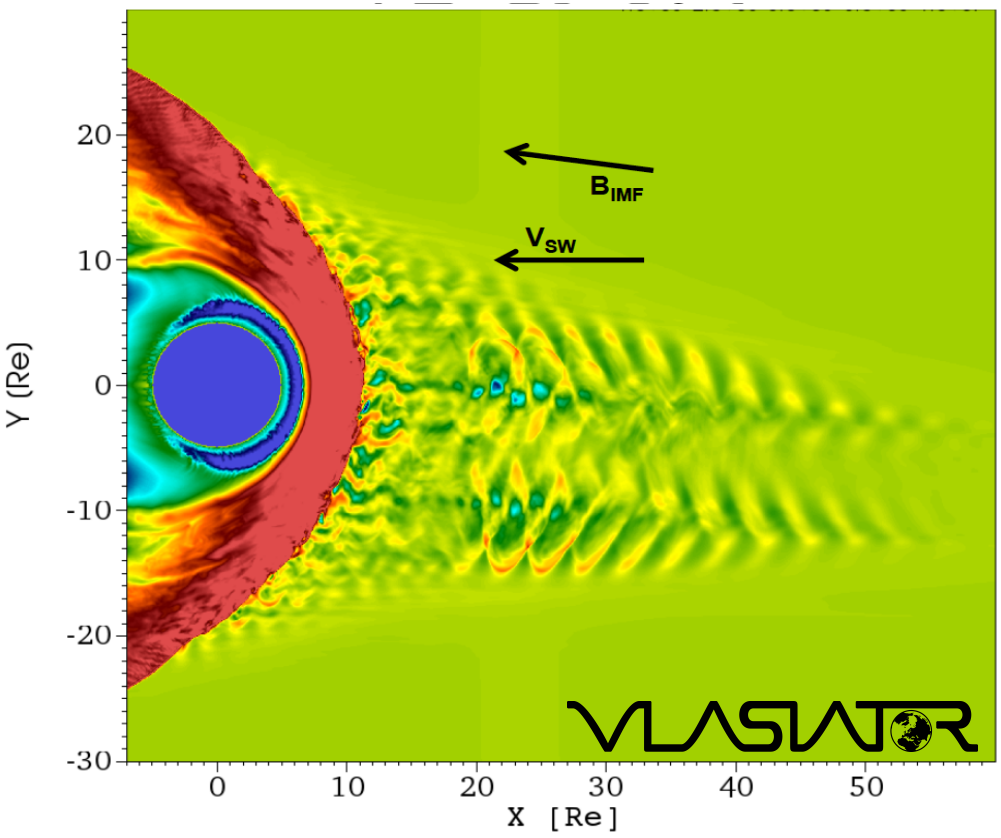


The power spectra have comparable values ($\sim 10^{-18}$ T^2/Hz) at the beam-resonant frequency $f_b \sim 4.2 \cdot 10^{-2}$ Hz. However, there is a difference in the spectral shape. Why?

Future: beyond quasi-linear physics



Christmas tree structure

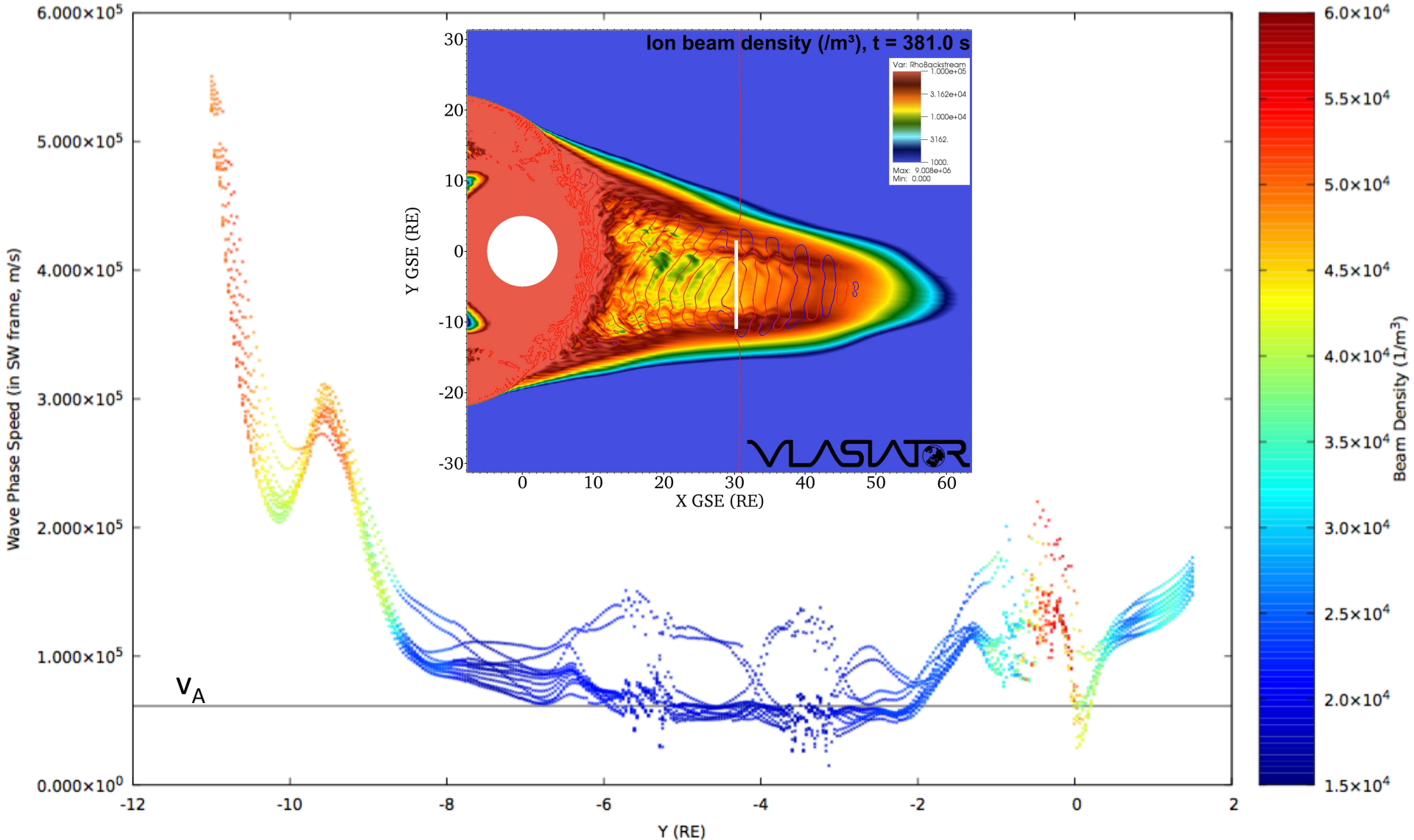


Vlasiator foreshock is not filled with parallel propagating Alfvén waves even in a quasi-radial IMF. Instead, waves often get more and more oblique as the simulation proceeds.

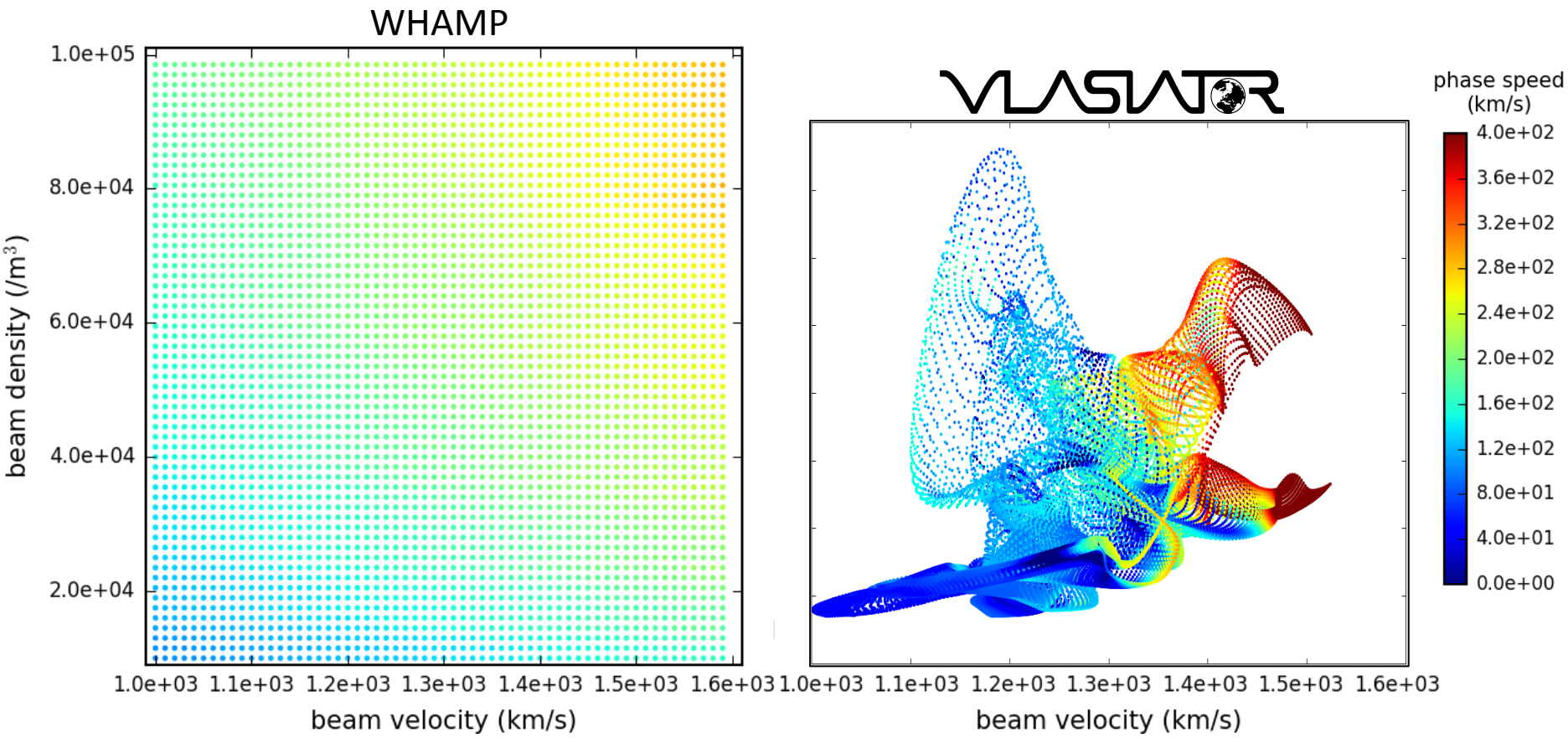
What is the reason for the obliquity? Refraction?

What is the dispersion relation of the beam-driven waves?

Phase speed in a vertical slit



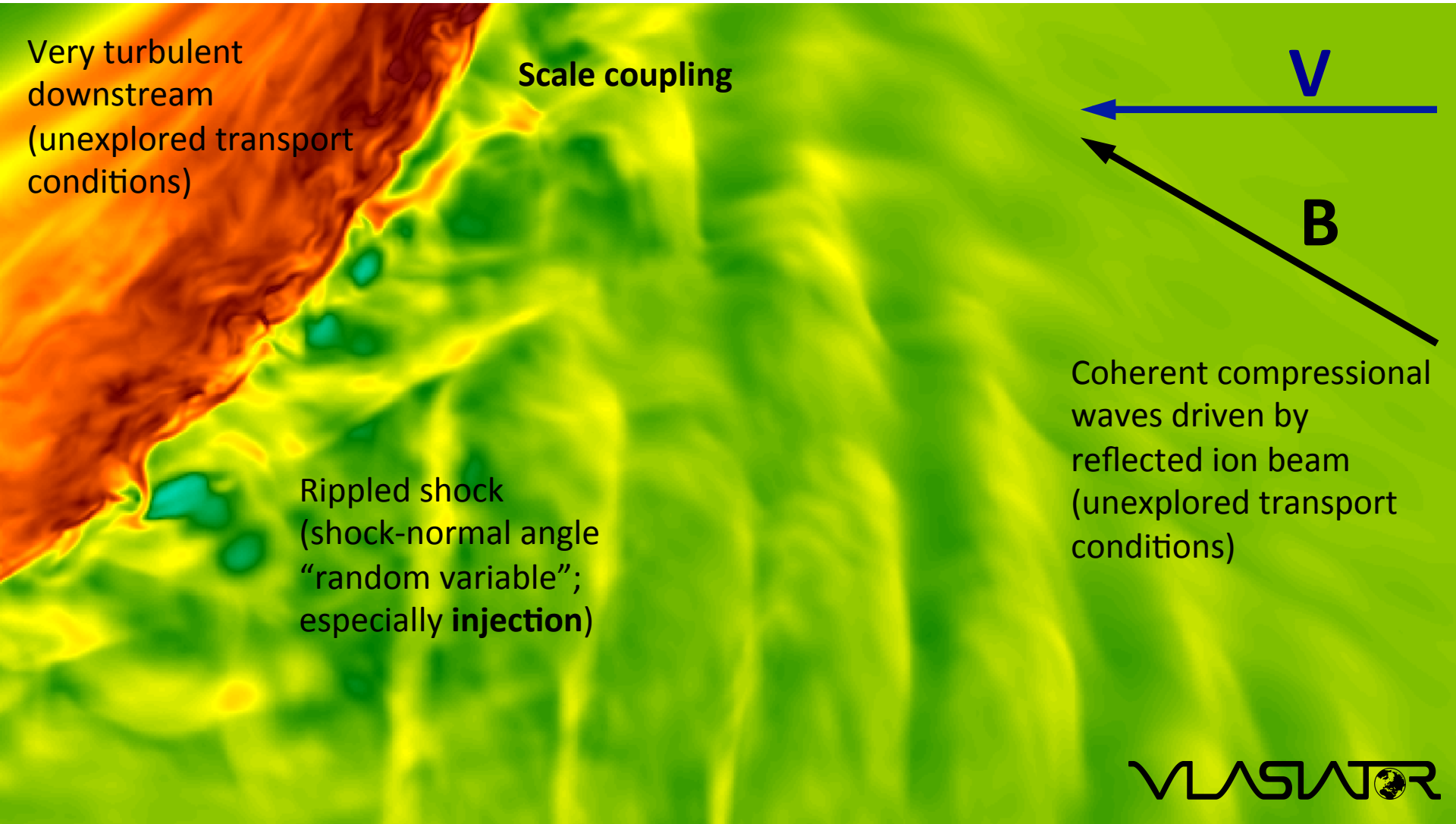
Phase speed of beam-driven waves

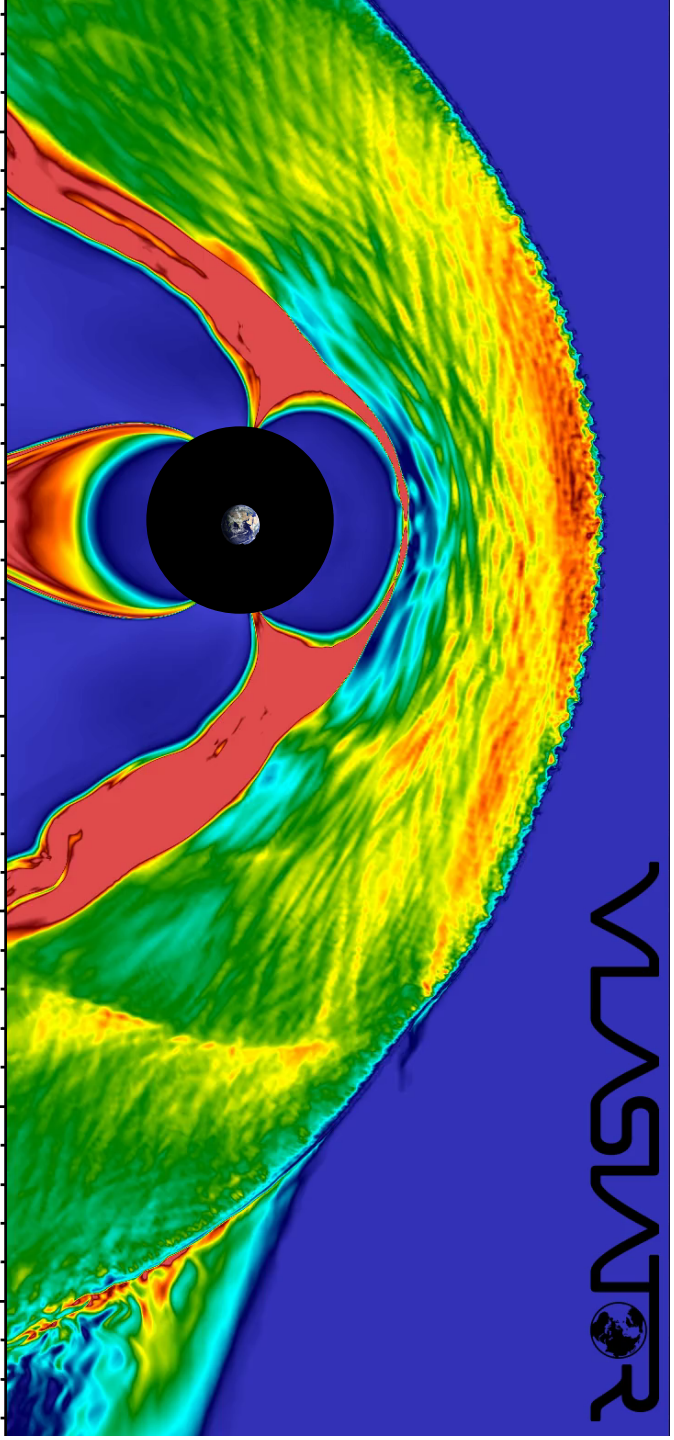


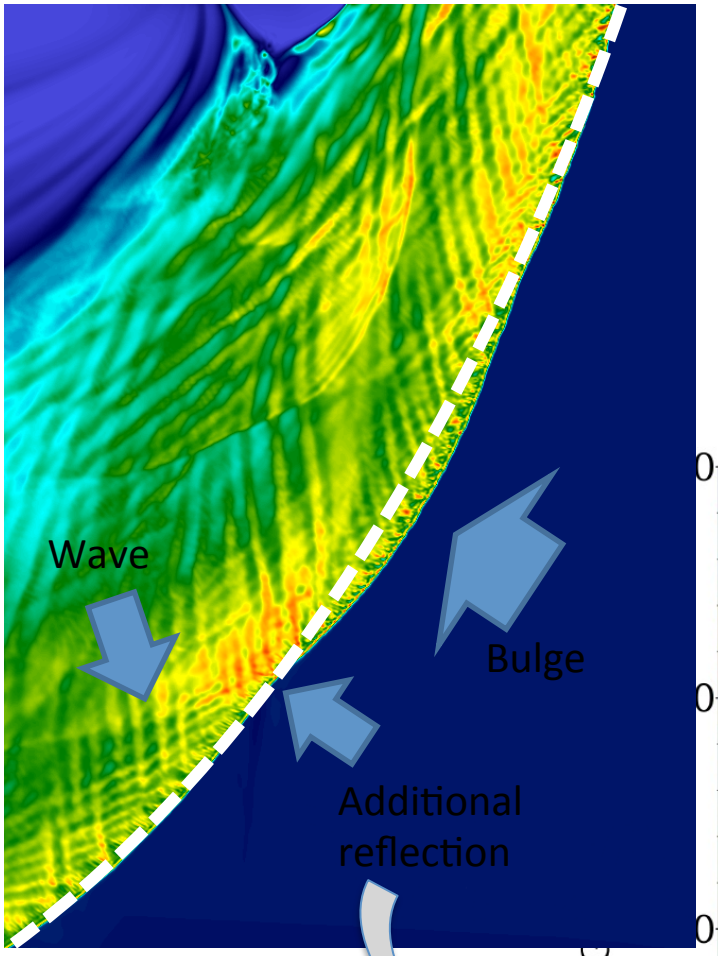
Denser and faster parts of the beam produce a faster phase speed of the beam-driven waves

Note: a counter-propagating wave with phase speed ≈ fluid speed —> strong effect on DSA!

Future: beyond quasi-linear physics

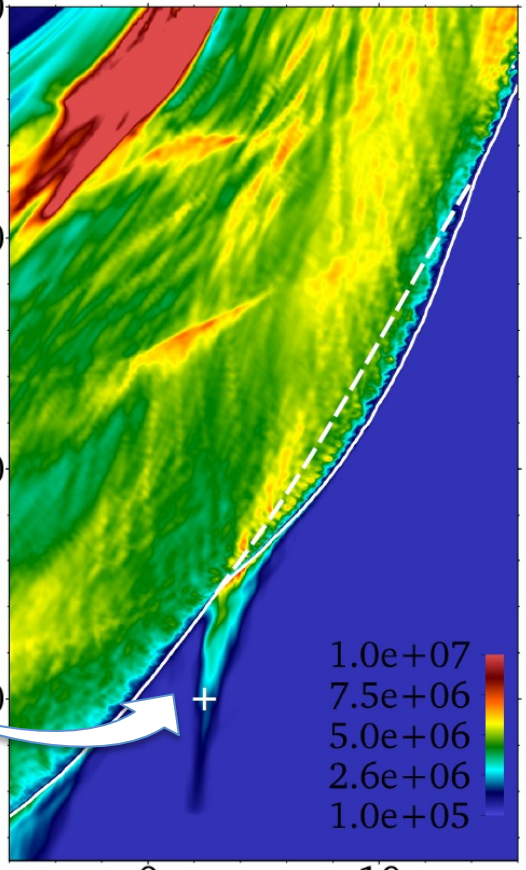






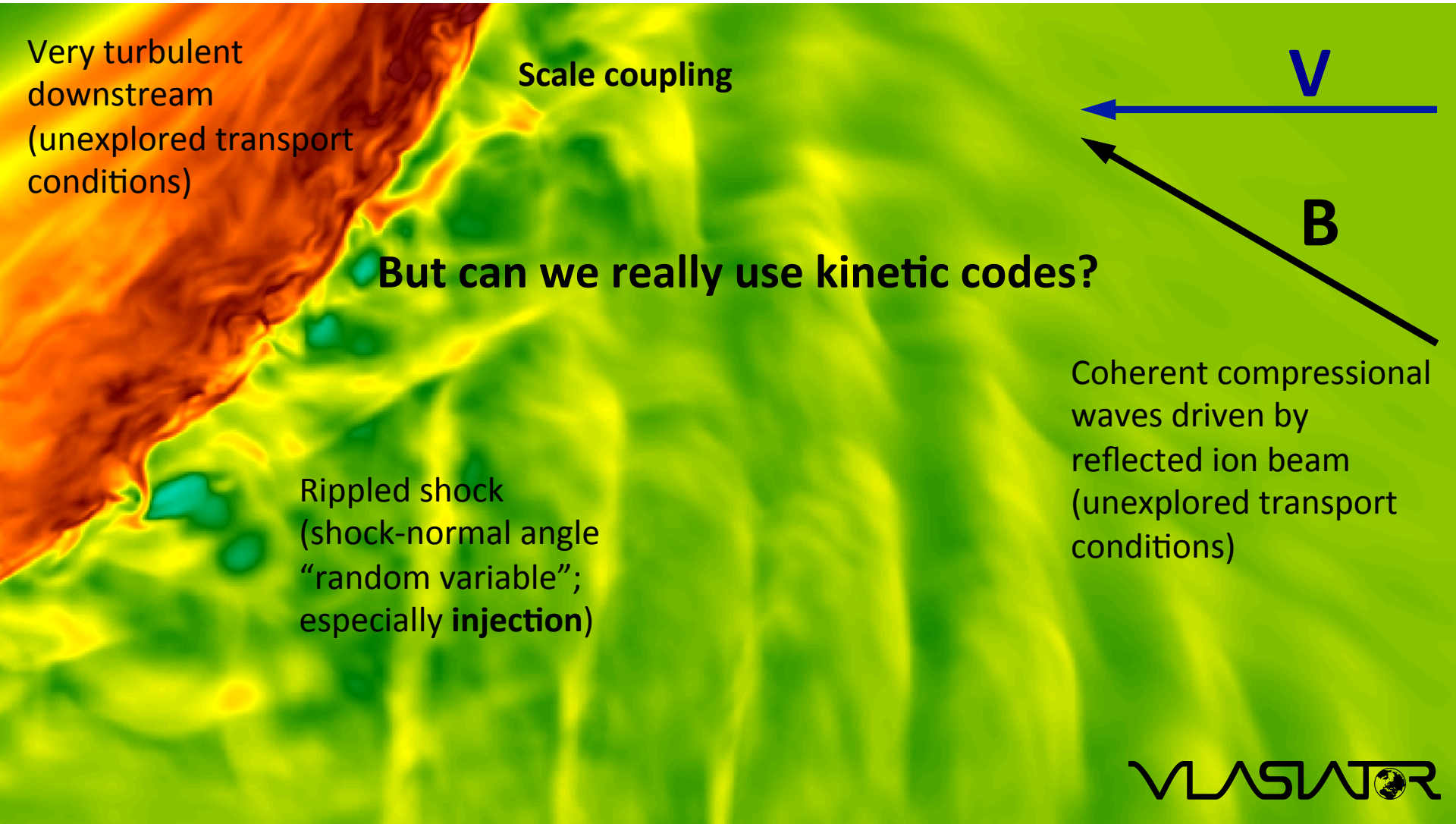
Pfau-Kempf et al., 2016

Transient
foreshock

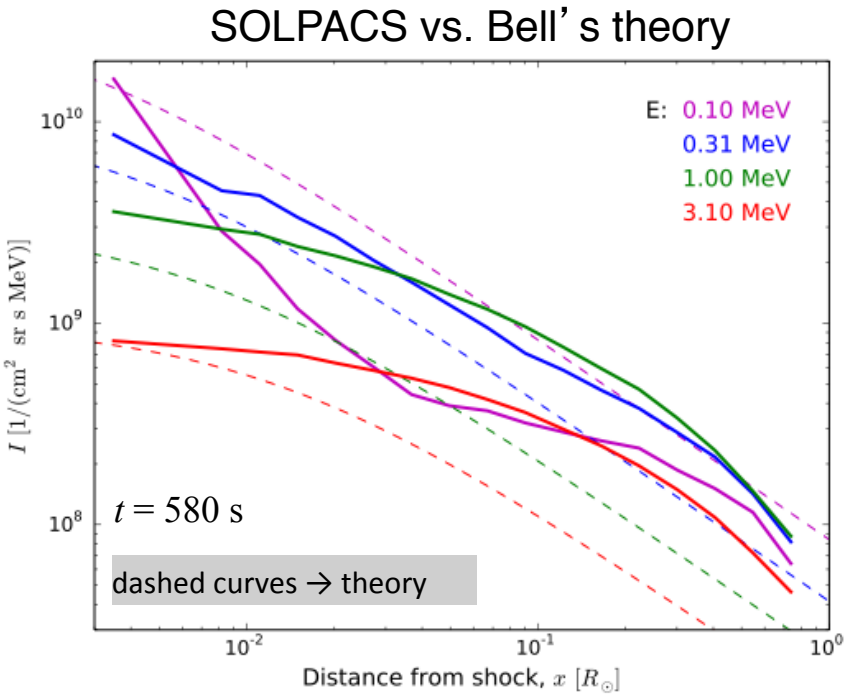


Sheath waves with
precursors

Future: beyond quasi-linear physics



Distribution of protons in the foreshock



Small scales need to be resolved throughout the system!

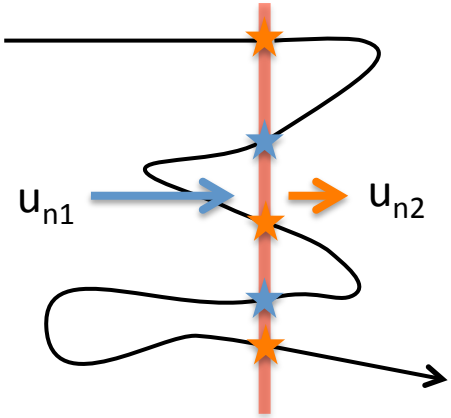
Bell's steady-state theory (1-D): $I(x,p) \propto \dfrac{x_0}{x + x_0}, \quad x_0 = x_0(p)$

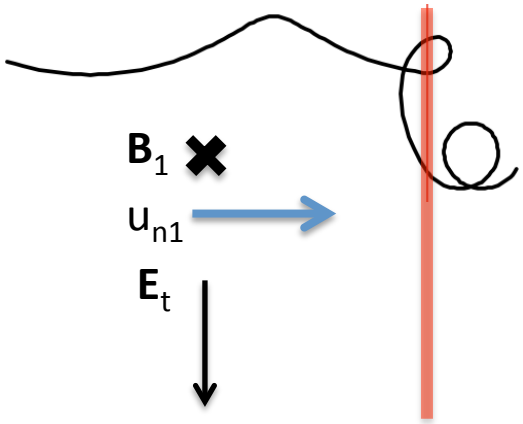
Conclusions

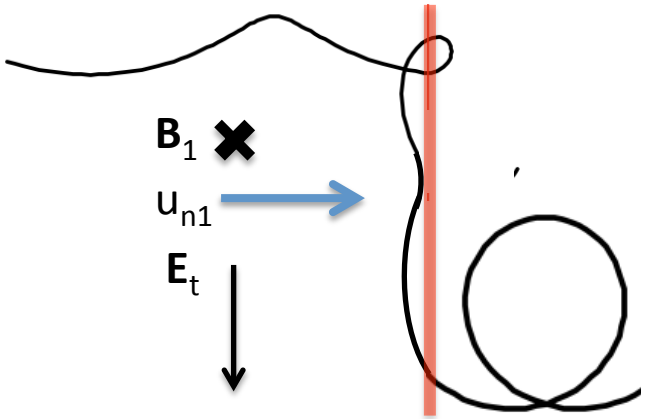
- Diffusive shock acceleration can accelerate particles to high energies in solar wind
  - Super-criticality guarantees ion acceleration
  - Quasi-linear model works reasonably well at moderately strong ($M_A \approx 3–5$) quasi-parallel and oblique shocks in comparison with observations
- Injection efficiency in the acceleration process determines not only the number of accelerated particles but also the maximum energy obtained from the process
  - The higher the particle intensity, the higher the intensity of scattering waves, and the higher the achieved energy in a given time
- Hybrid-Vlasov simulations (and observations) yield a picture of a turbulent environment
  - Injection is determined by local shock structure and its interactions with upstream-generated structures
  - Foreshock wave properties differ from Alfvénic —> DSA affected
- Bow shock is a much more complex system than (planar) IP shocks
  - Scales and physical processes couple to each other
  - Downstream differs from the DSA picture of homogeneous turbulence
- Huge variations of relevant scales in a space-filling manner pose great challenges to the kinetic approach
  - Sub-grid-scale modeling may still be needed

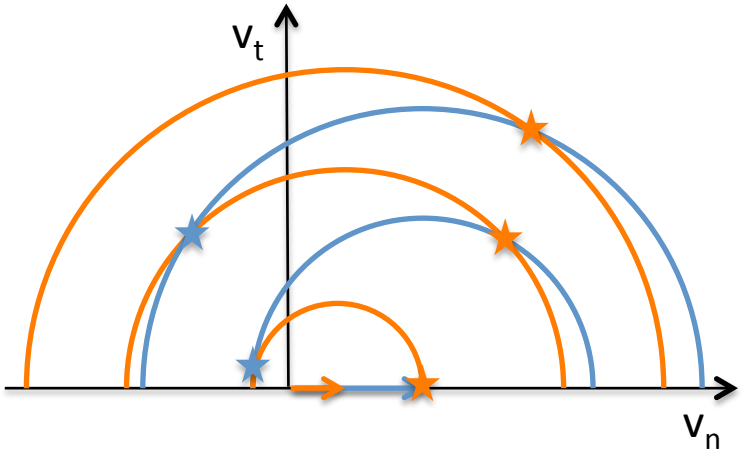
SPARES

Basic Mechanisms







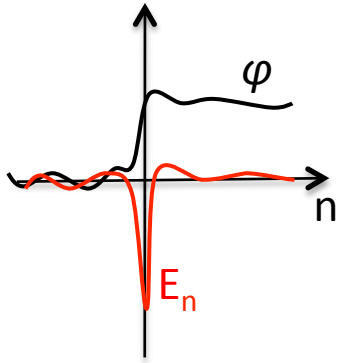


Diffusive Shock Acceleration
Electrons and ions

Included in Vlasiator and SOLPACS

Shock Drift Acceleration
Electrons and ions

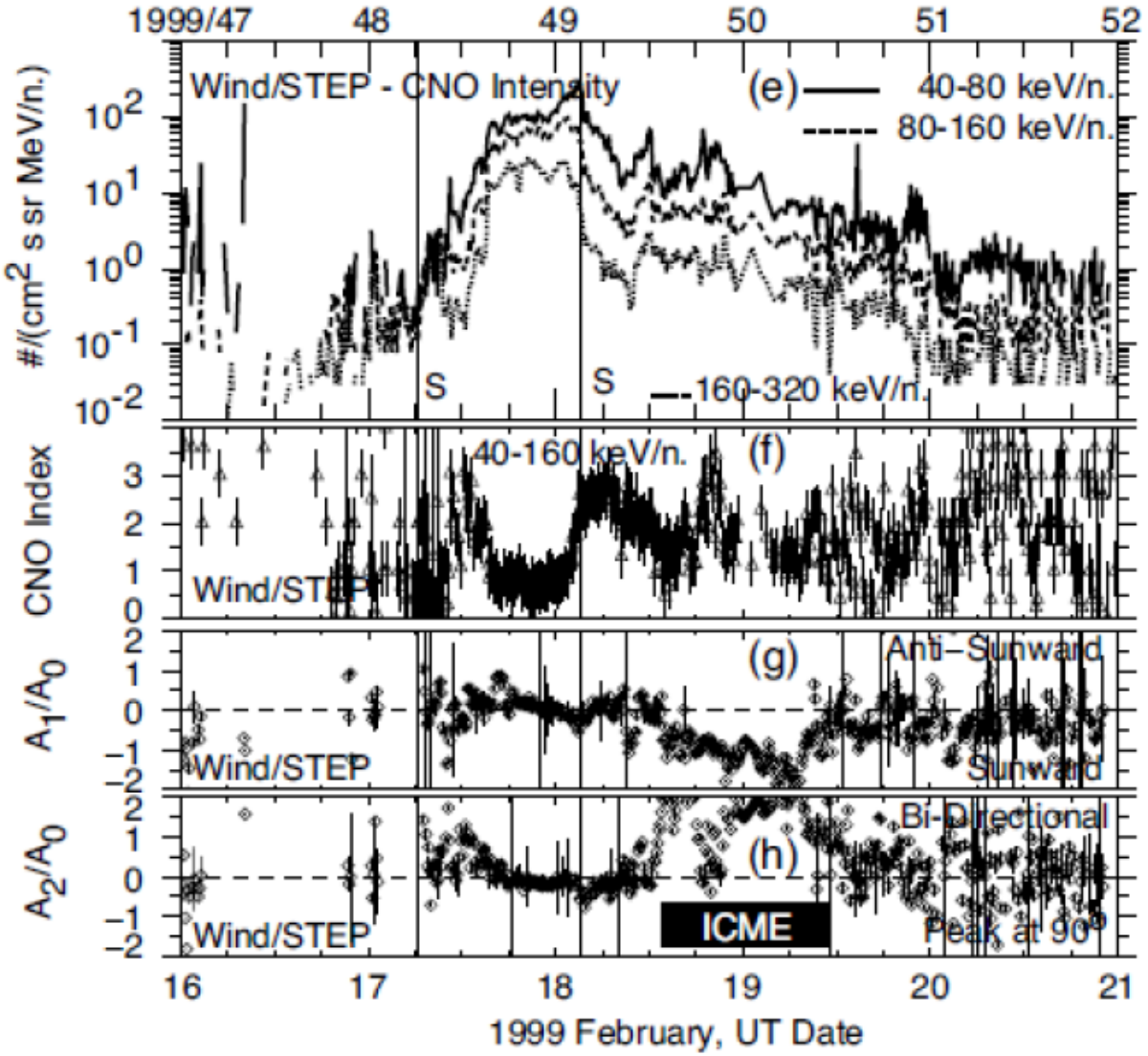
Included in Vlasiator and approximately in SOLPACS



Shock Surfing Acceleration
Ions

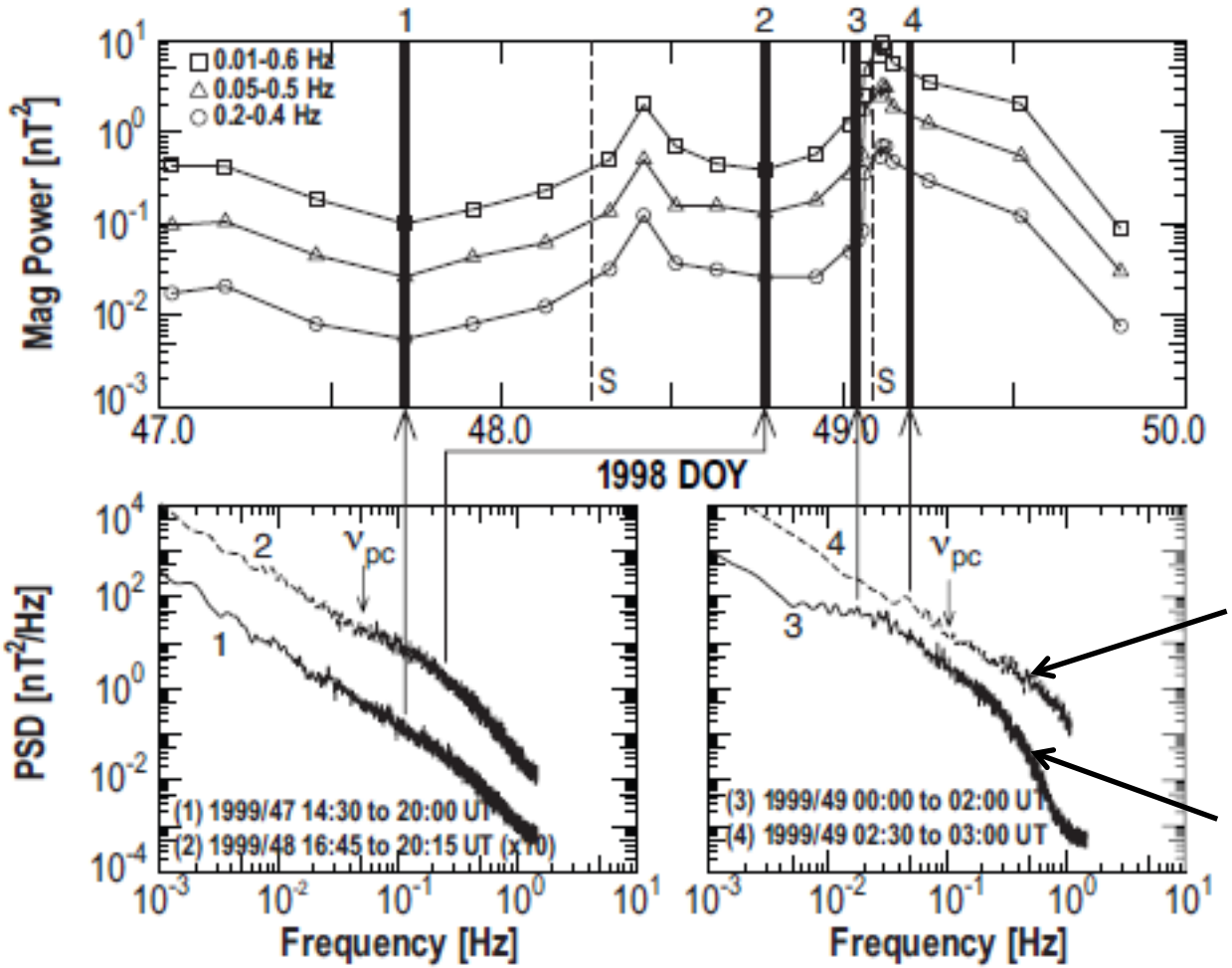
Suppressed in both models

ESP event



Desai et al. (2011)

Spectral density of fluctuations



Shock-amplified downstream turbulence

Self-generated foreshock turbulence

Desai et al. (2011)