Stochastic Shock Drift Acceleration of Electrons: Monte Carlo Simulations

Seve Nyberg[1,*], Rami Vainio[1], Laura Vuorinen[1], Alexander Afanasiev[1]
[1] Department of Physics and Astronomy, University of Turku, Finland
* email: shonyb@utu.fi

Online Presentation

This presentation participates in OSPP
Outstanding Student & PhD candidate Presentation contest

A Small Introduction

As acceleration mechanisms for electrons in shocks from low energies (less than keV) to high energies (more than MeV) are still poorly understood, we investigate stochastic shock drift acceleration (SSDA) (see, e.g., Amano 2022) as a potential mechanism for sufficient particle acceleration and electron beam formation. Diffusive shock acceleration (DSA) is capable of accelerating particles to high energies, but is inefficient at accelerating lower energy particles. Incorporating an efficient low energy particle acceleration mechanism, such as shock drift acceleration, bridges the gap between the energies of thermal electrons (less than 1 keV) and the required energies for efficient acceleration in DSA (100s of keV).

The Model

The 1D Monte Carlo model (Fig. 1) assumes a shock with a thickness of the order of an ion inertial length (d_i) and a hyperbolic tangent profile for the magnetic field at the shock. The turbulent region around the shock has approximately the same width as the shock ramp. The simulation has a finite box size corresponding to the estimated diffusion length of the injected particle population with free escape boundaries in the upstream and downstream. Particles are injected monoenergetically and isotropically to the plasma rest frame at the upstream simulation box boundary and traverse along the magnetic field lines.

Input Parameters

The physical input parameters of the shock for the simulation are estimated from radio observations of the 2023-10-03 coronal mass ejection and magneto-hydrodynamic modeling of the coronal magnetic field. The input parameters of the simulation are:

Upstream flow speed in the shock frame along the shock normal	u_{x1} = 1400 km/s
Upstream Alfvén speed	V_A = 150 km/s
Shock obliquity	θ_{Bn} = 87°
Plasma beta	β = 0.1
Particle density	$n = 9 \cdot 10^7$ cm^{-3}
Particle injection energy	E_{inj} = 1 keV

Results

Fig. 2a shows the energy spectra of the upstream and downstream particle populations, where we can see particle acceleration from the injected 1 keV to more than 100 keV, hinting at SSDA being capable of accelerating electrons from low energies to high energies. Fig. 2b shows the residence times of particles in the simulation box, resulting in acceleration time scale of tens of seconds. Fig 3. shows time integrated histograms of particle energies parallel, anti-parallel, and perpendicular to the magnetic field. An electron beam away from the shock towards the upstream can be seen in Fig. 3c and 3d in the energy range of 2-10 keV. The simulation results in a bump-in-tail energy distribution upstream of and away from the shock shown in Fig. 3d.

References

Amano, T.: Electron Injection via Stochastic Shock Drift Acceleration: Theory, Simulation, and Observation, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-3277, https://doi.org/10.5194/egusphere-egu22-3277, 2022.

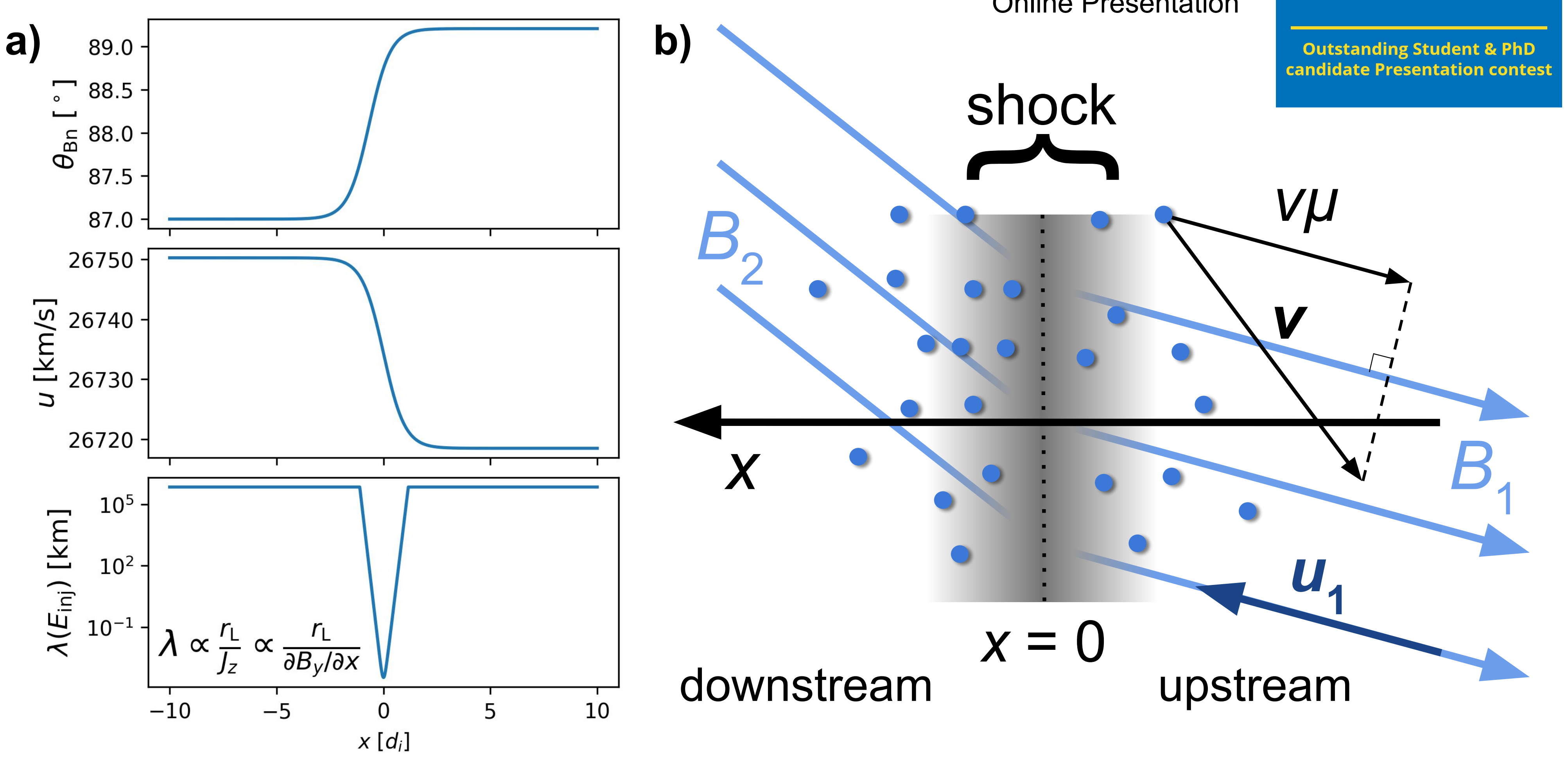

Figure 1: **a)** The shock obliquity θ_{Bn} profile, the flow speed u in the de Hoffmann–Teller frame (HTF) profile, and the mean free path λ profile of the simulation close to the shock assuming a hyperbolic tangent profile for the magnetic field. **b)** The one-dimensional stochastic shock drift acceleration Monte Carlo model geometry depicting the shock normal line x along which the 1D simulation is calculated, the magnetic field vectors $\boldsymbol{B}$, the HTF upstream flow speed u_1, the particle velocity $\boldsymbol{v}$ and pitch angle cosine μ, and the finite-thickness shock midpoint at x = 0.

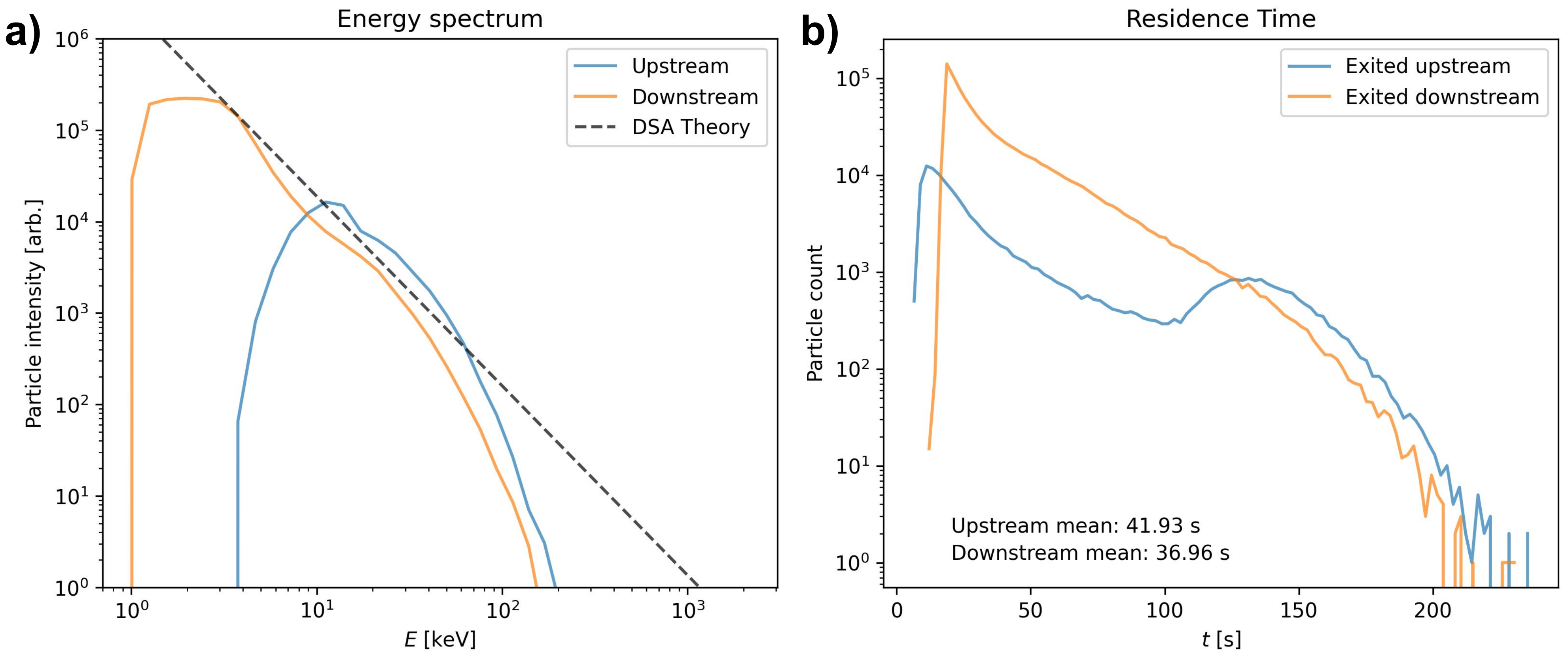

Figure 2: **a)** The particle intensity as a function of energy at the end of the simulation separately for particles that have escaped either upstream or downstream in the plasma rest frame. A theoretical power law distribution predicted by diffusive shock acceleration (DSA) for the input parameters is plotted for comparison. **b)** The particle residence time within the simulation box distribution separately for particles that have escaped either upstream or downstream.

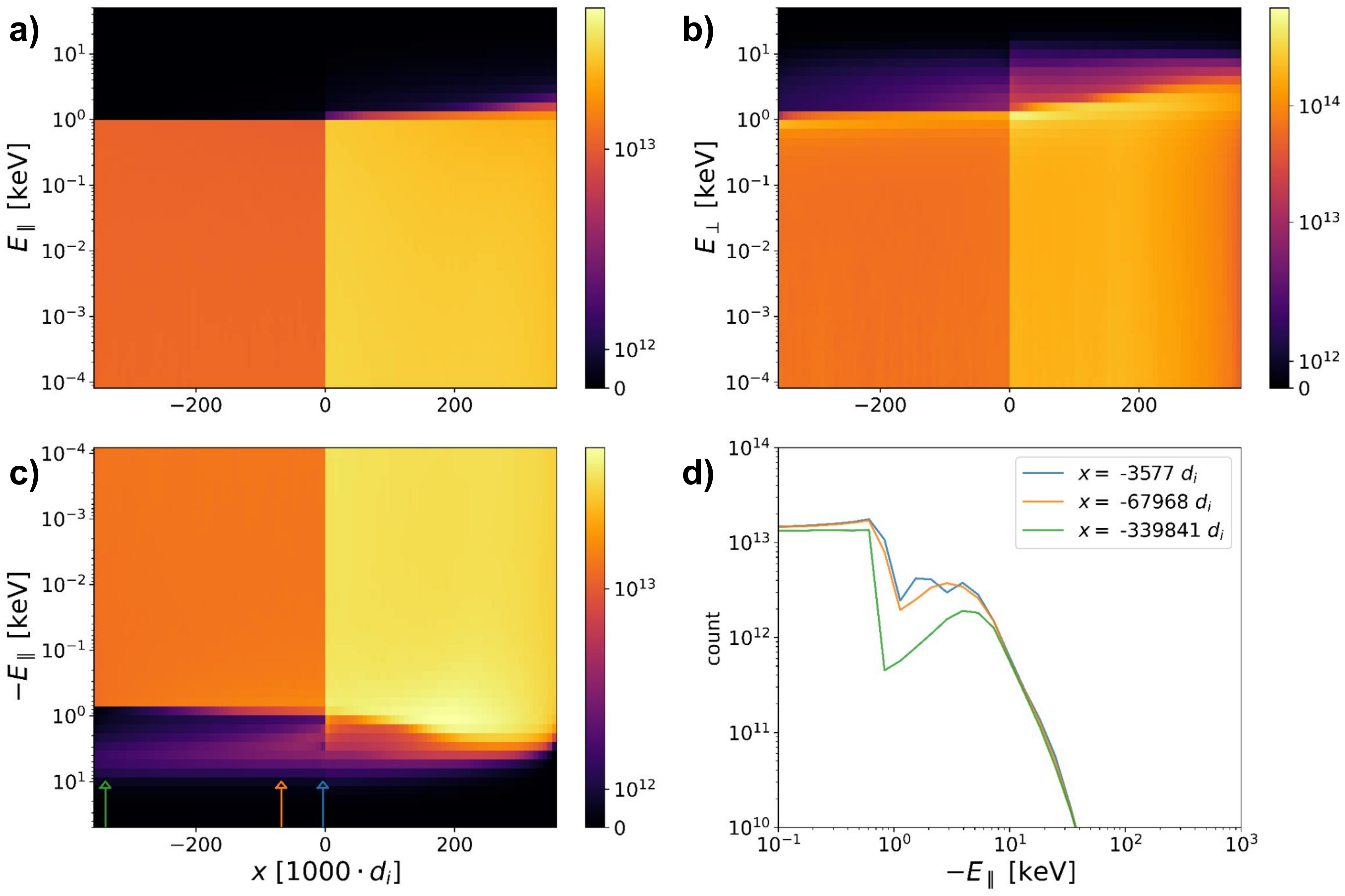

Figure 3: Time integrated distribution of particles as a function of position x along the shock normal and momentum **a)** parallel **b)** perpendicular **c)** anti-parallel to the magnetic field translated to energy in the plasma rest frame. Parallel (positive) direction is towards the positive direction of x. **d)** Time integrated distributions of particles as a function of anti-parallel energy at three locations in the upstream depicted with color-coded arrows in Fig. 3c.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or HaDEA. Neither the European Union nor the granting authority can be held responsible for them.

This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101004159 (SERPENTINE) and from the Finnish Cultural Foundation, Varsinais-Suomi Regional fund. The computer resources of the Finnish IT Center for Science (CSC) and the FGCI project (Finland) are acknowledged.

UNIVERSITY OF TURKU