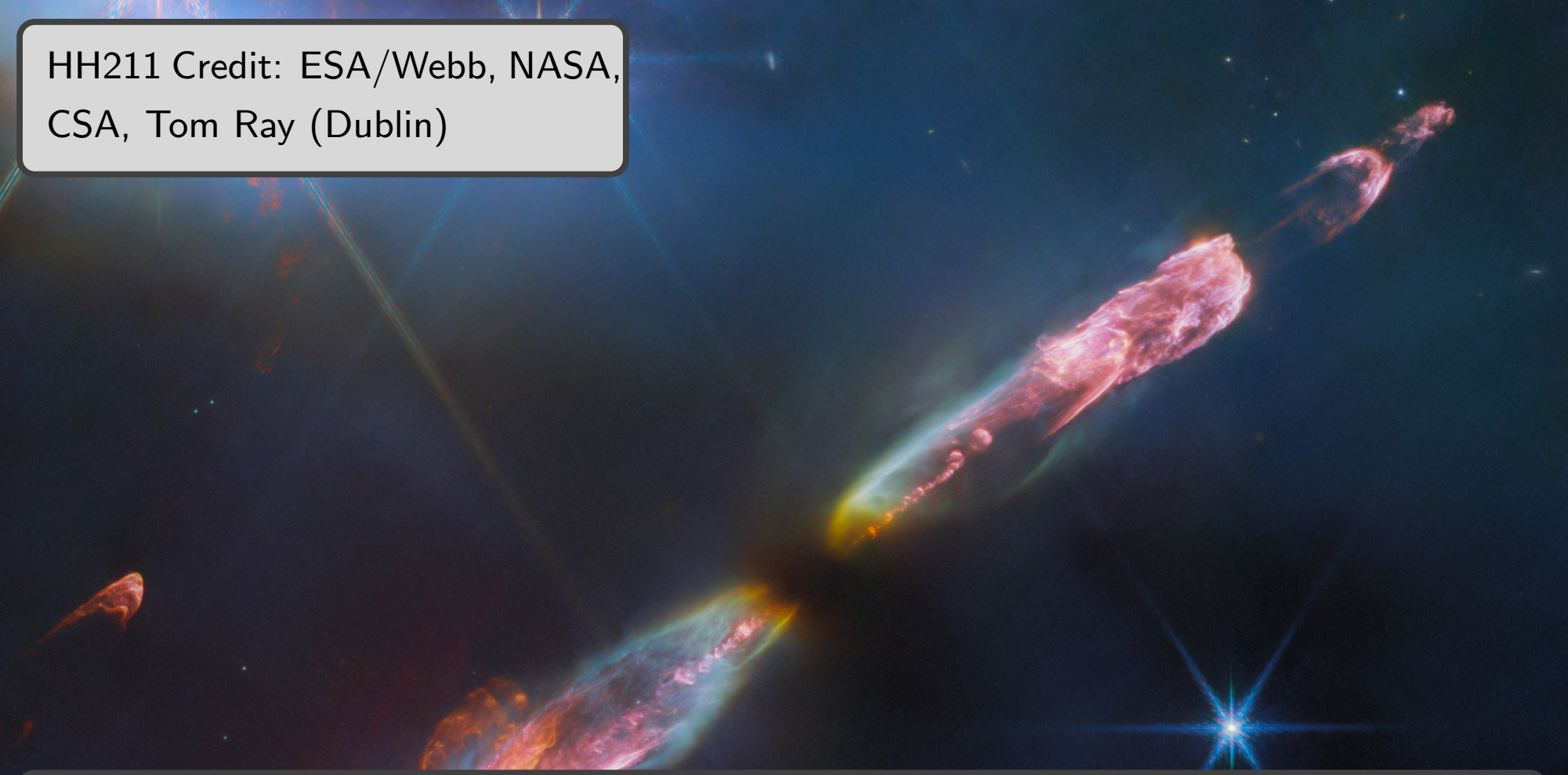

HH211 Credit: ESA/Webb, NASA, CSA, Tom Ray (Dublin)

Kinetic study of shock formation in protostellar jets

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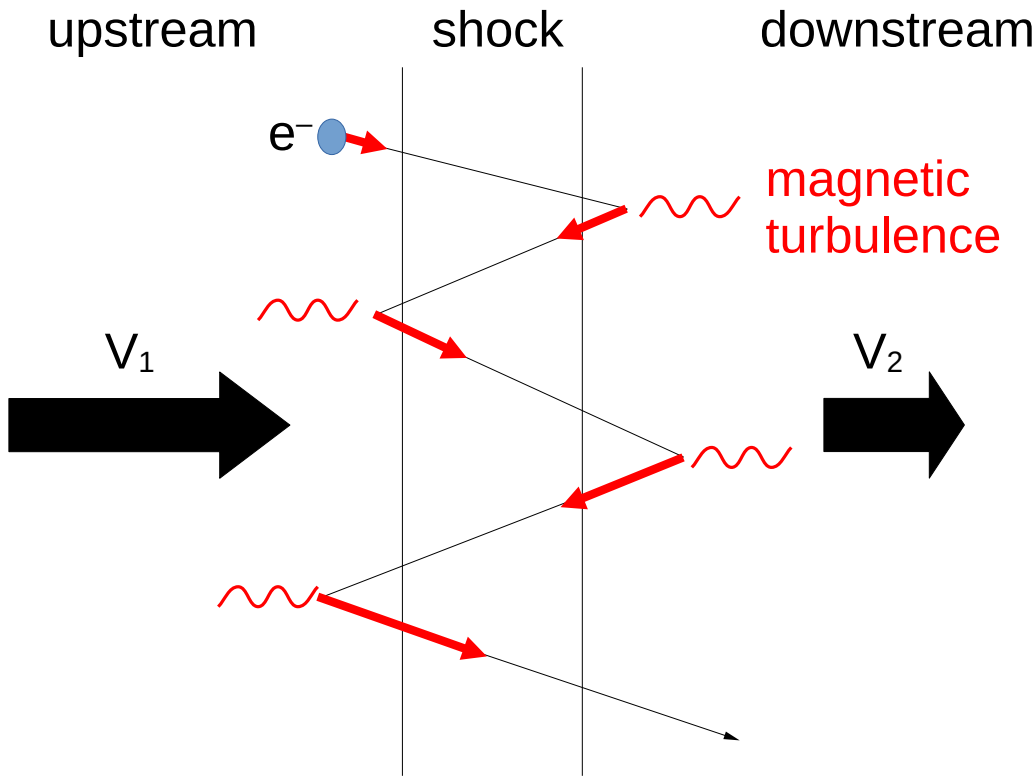
Young Stellar Objects with rotating accretion disk launch jets (300–1500 km/s) that impact surrounding medium producing termination shocks.

Observations with Giant Metrewave Radio Telescope (GMRT) Ainsworth et al. (2014) report fit of spectral index $\alpha = -0.89$ indicative of synchrontron radiation produced by a population of relativistic electrons.

What is accelerating the electrons?

Fermi acceleration

produces non-thermal high energy particles

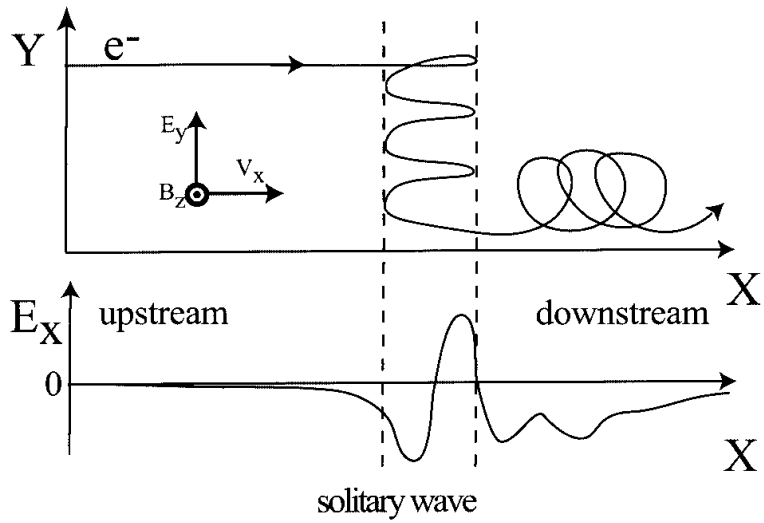


finite shock width $\approx$ mean free-path of thermal protons/ions
$\gg$ mean free-path of thermal electrons
$\Rightarrow$ thermal electrons cannot cross shock, acceleration impossible

Injection problem

Thermal electrons need pre-acceleration to enter Fermi regime

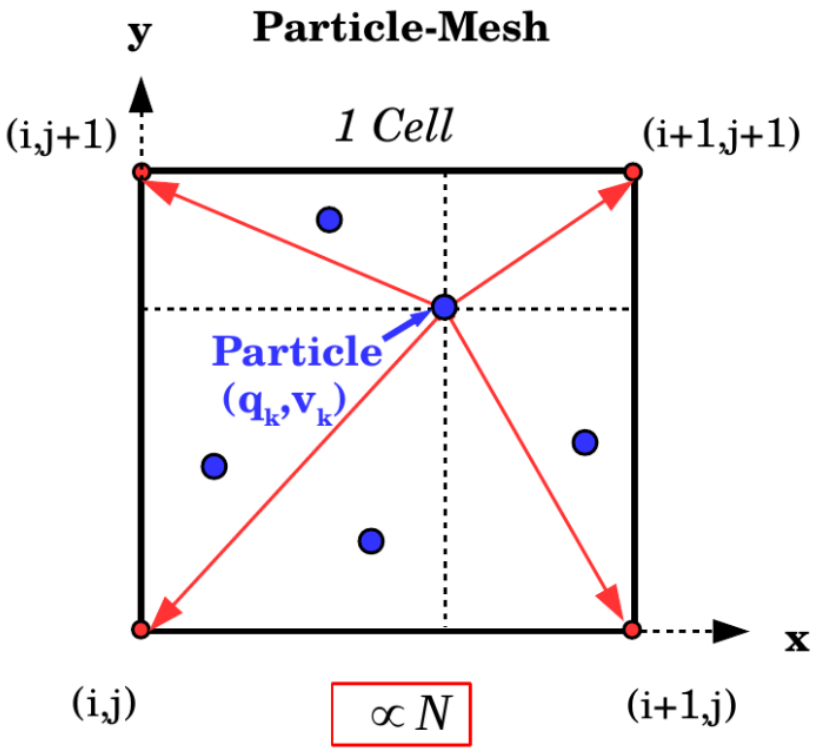
1. Shock Surfing Acceleration (SSA)
Hoshino and Shimada (2002)
Electrons trapped and accelerated in strong localised electrostatic waves (ESW)

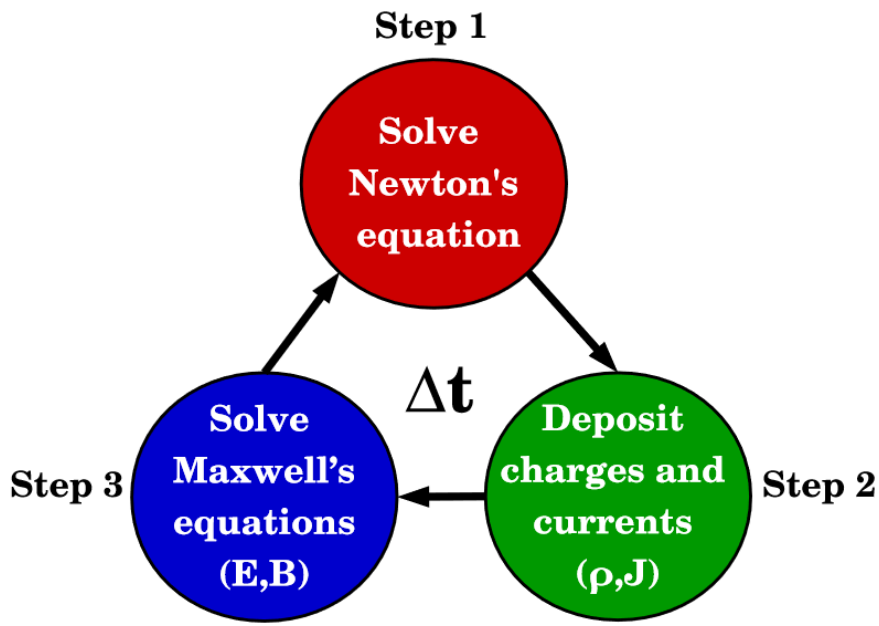


2. Stochastic Shock Drift Acceleration (SSDA)
Katou and Amano (2019)
Electrons gain energy from gradient-B drift due to compression of magnetic field at shock

Particle-in-cell method

Detailed description of electromagnetic field and kinematics of charged particles at kinetic scales





Cerutti(2021)

Field Solver:

the time evolution of electromagnetic field and
the particle-field interaction

$$\partial_t \vec{B} = -\nabla \times \vec{E} \qquad \partial_t \vec{E} = \nabla \times \vec{B} - 4\pi \vec{J}$$

Particle Pusher:

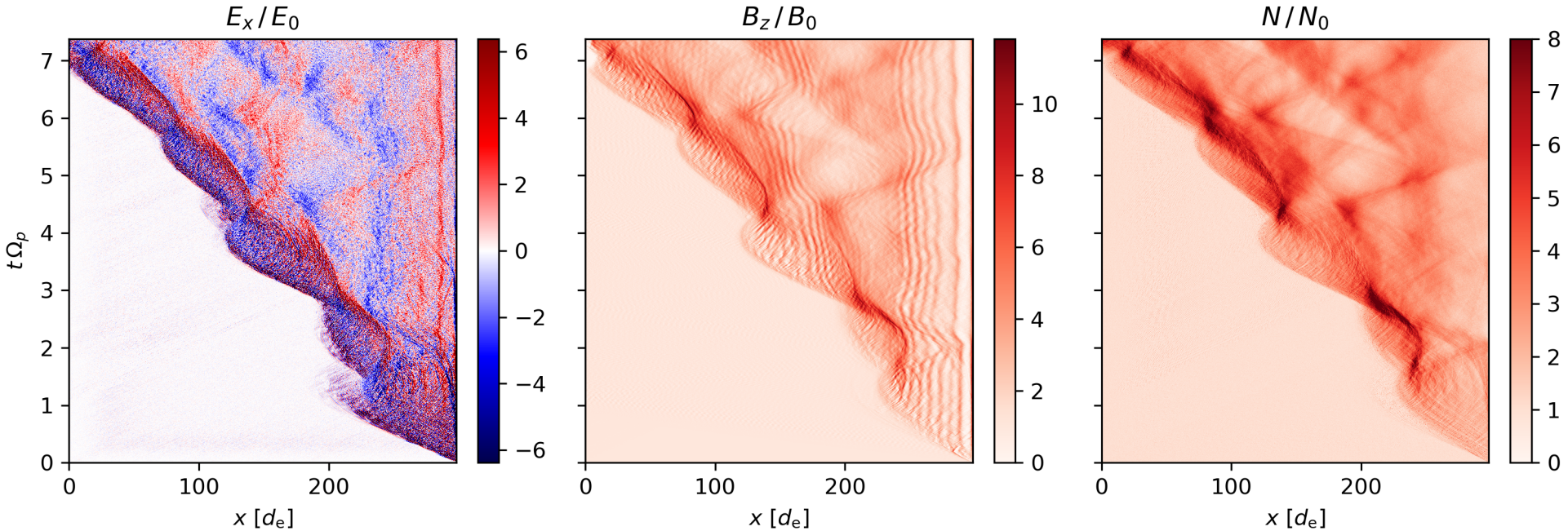
particle movement and field-particle interaction

$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\vec{u}}{\Gamma} \qquad \frac{d\vec{u}}{dt} = \frac{q}{m}\left(\vec{E} + \frac{\vec{u}}{\Gamma} \times \vec{B}\right) \qquad \Gamma = \sqrt{1 + \vec{u}^2}$$

1D simulation using ACRONYM PIC code

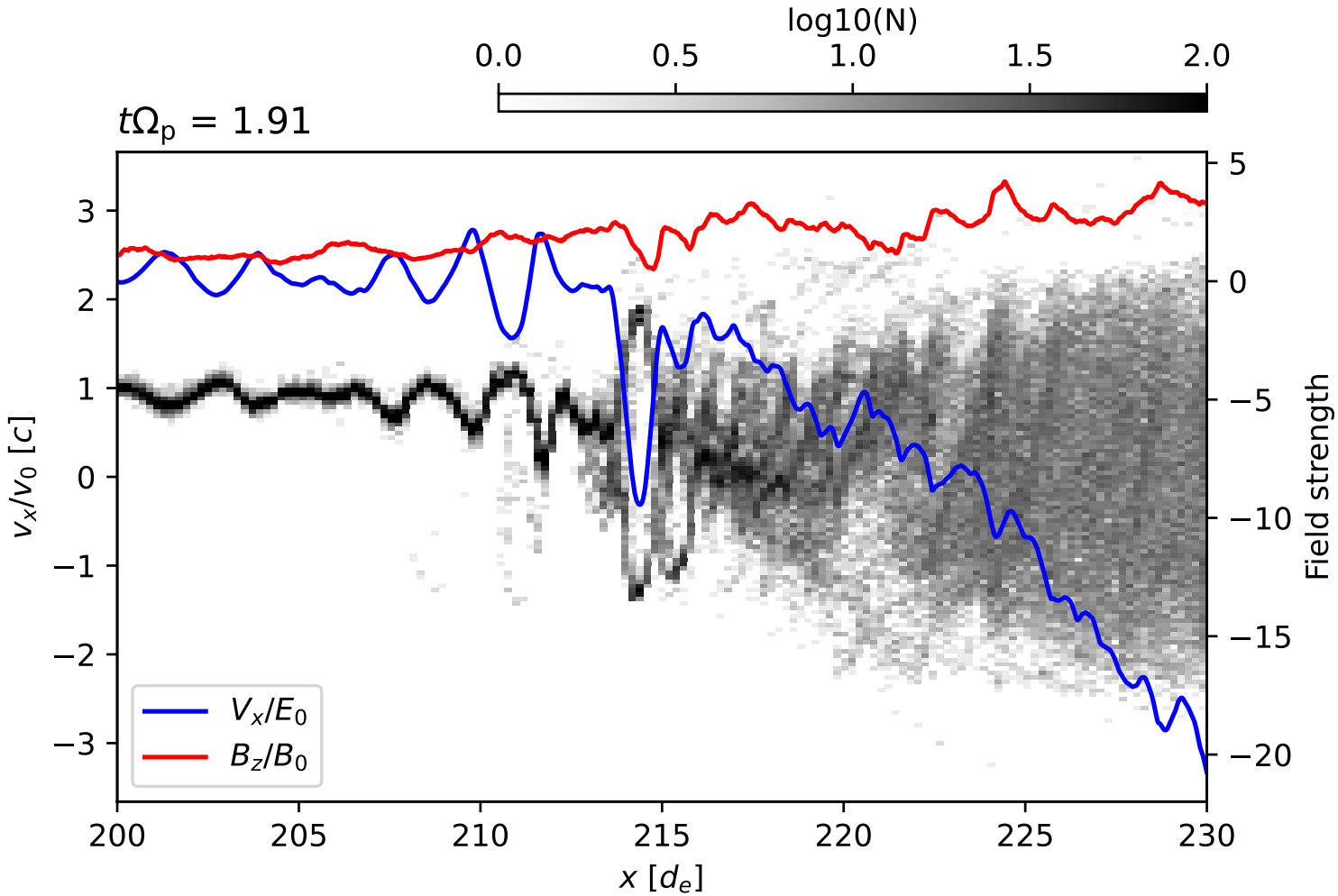
following Hoshino and Shimada (2002)

- electron–proton plasma beam
- low-temperature ($v_{\mathrm{th}} = 0.0037\,\mathrm{c}$)
- bulk velocity $v_x = v_0 = 0.25\,\mathrm{c}$
- perpendicular background magnetic field $B_z = B_0$
- motional electric field $E_y = E_0 = v_0 B_0$
- particles are reflected at right boundary

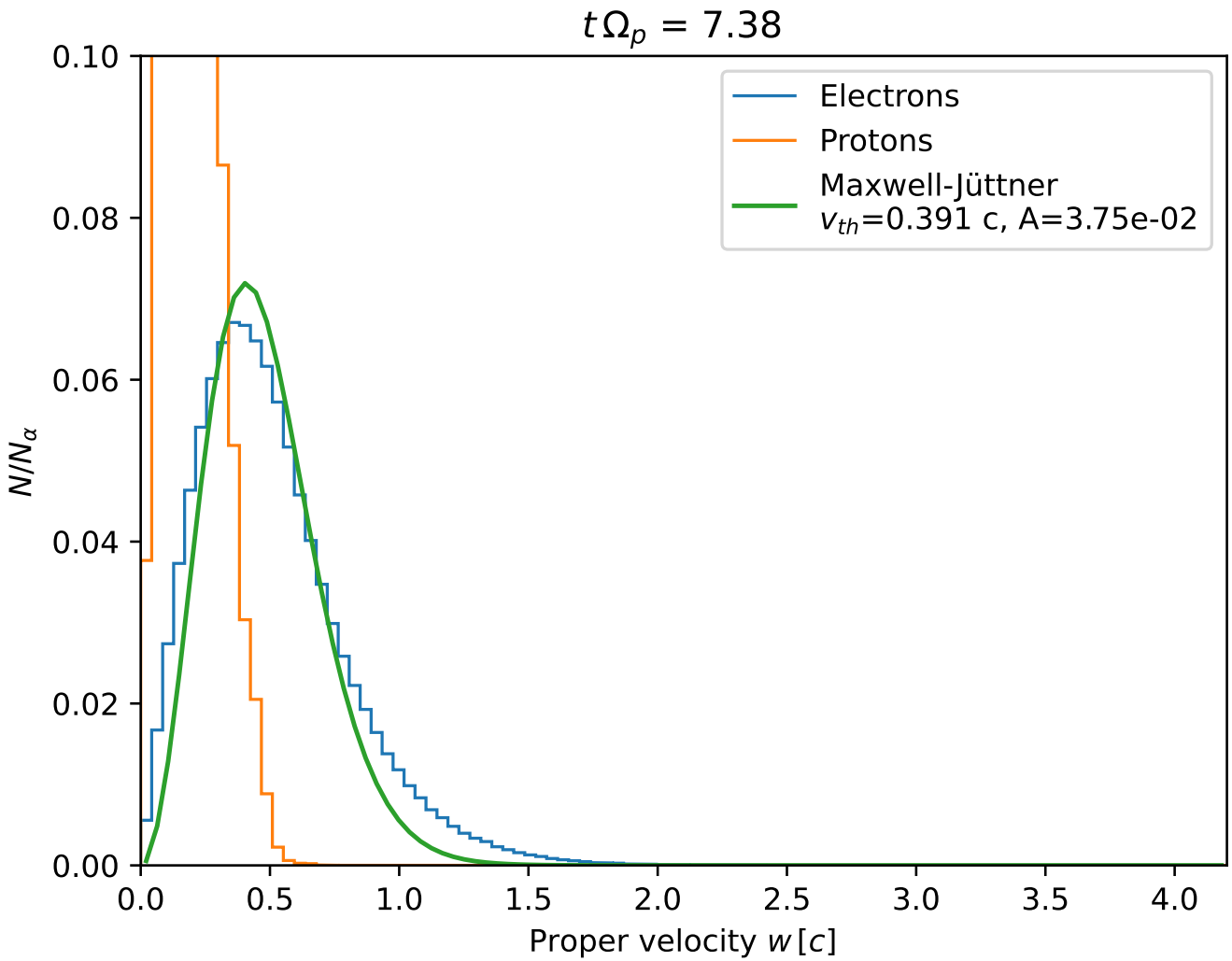


Phase space, electric potential, magnetic field

Snapshot at 1.9 $t\,\Omega_p$ zoomed in around the shock front region. An electron hole at around $x = 215\ d_e$ associated with ESW in the electric field and a dip in amplitude of the magnetic field.

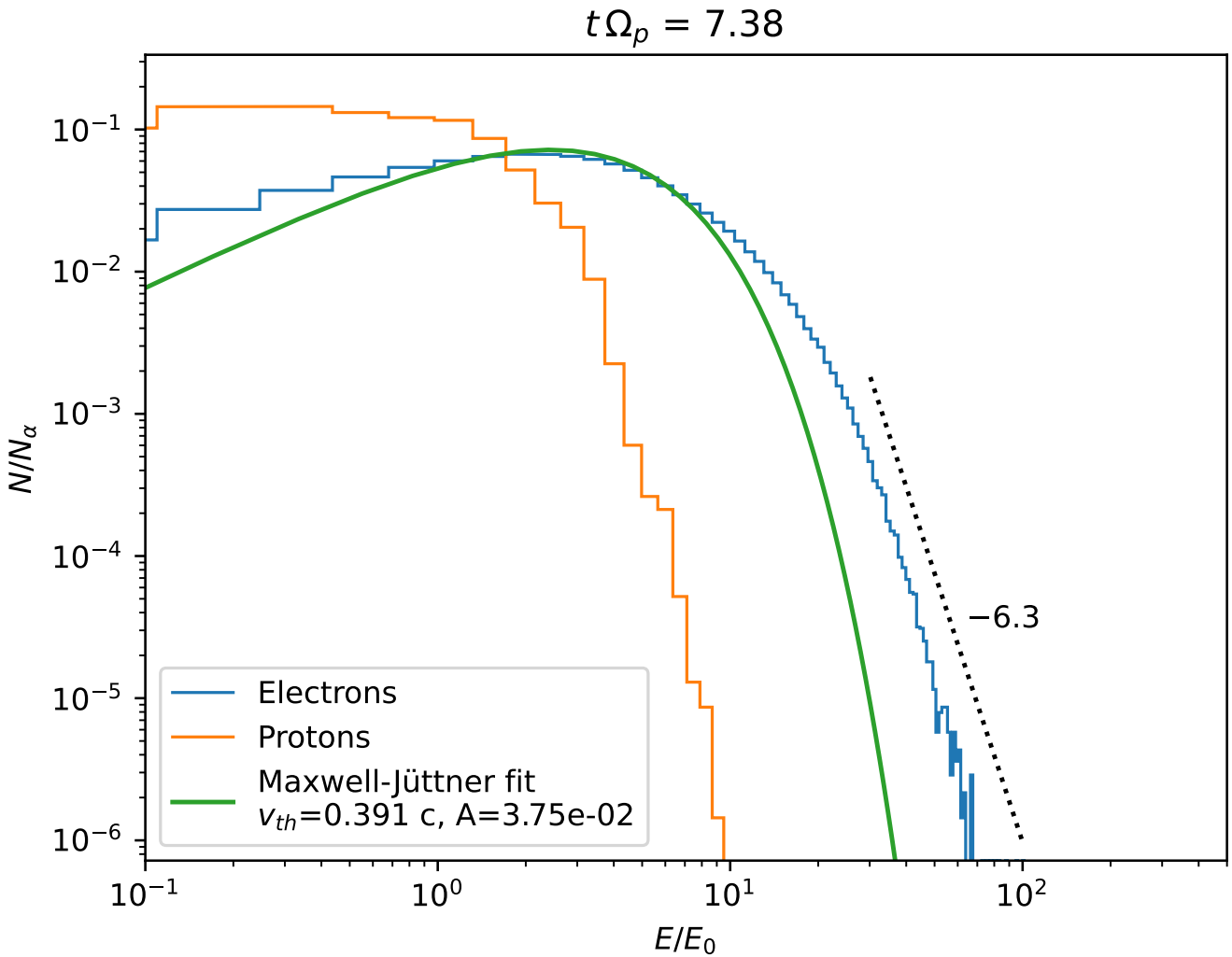


Particle velocity spectra



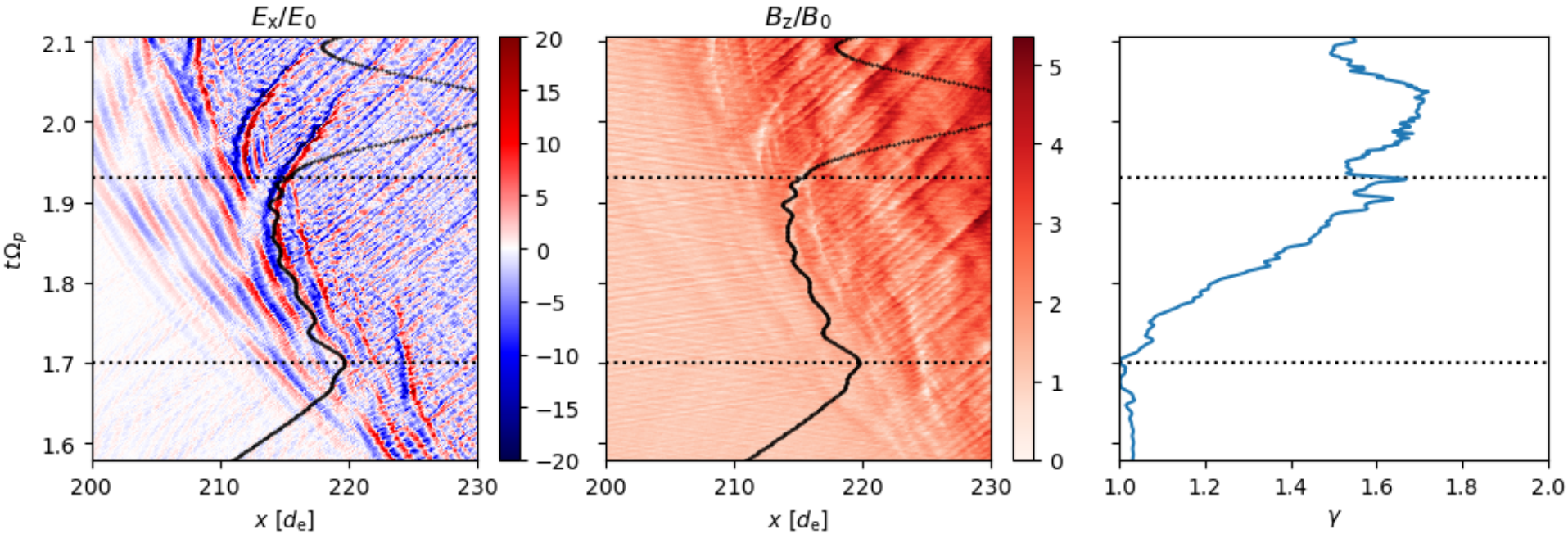
Particle energy spectra

fitted by Maxwell-Jüttner distribution reveals non-thermal population.



Particle trajectories

shows acceleration in the region of the ESW



1D shock simulation in protostellar jet environment

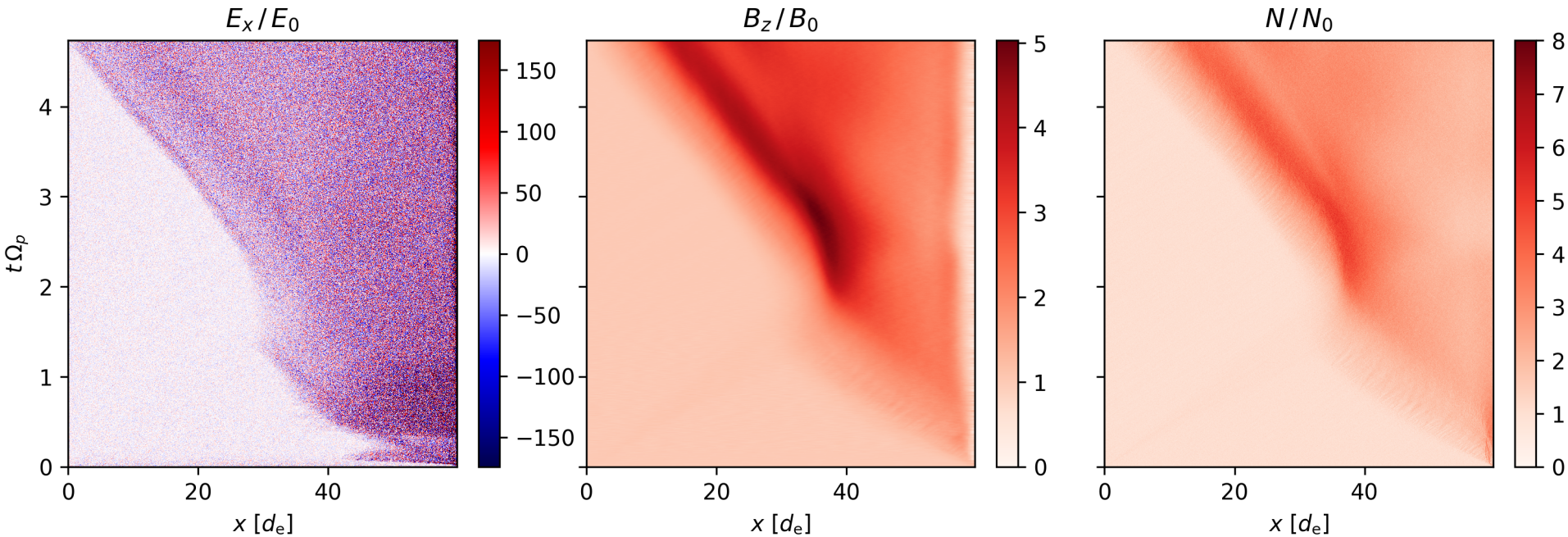
Previous studies by Bohdan et al. (2024) focus on high-velocity shocks (SNR)

Taking physical parameters from Araudo, Padovani, and Marcowith (2021):

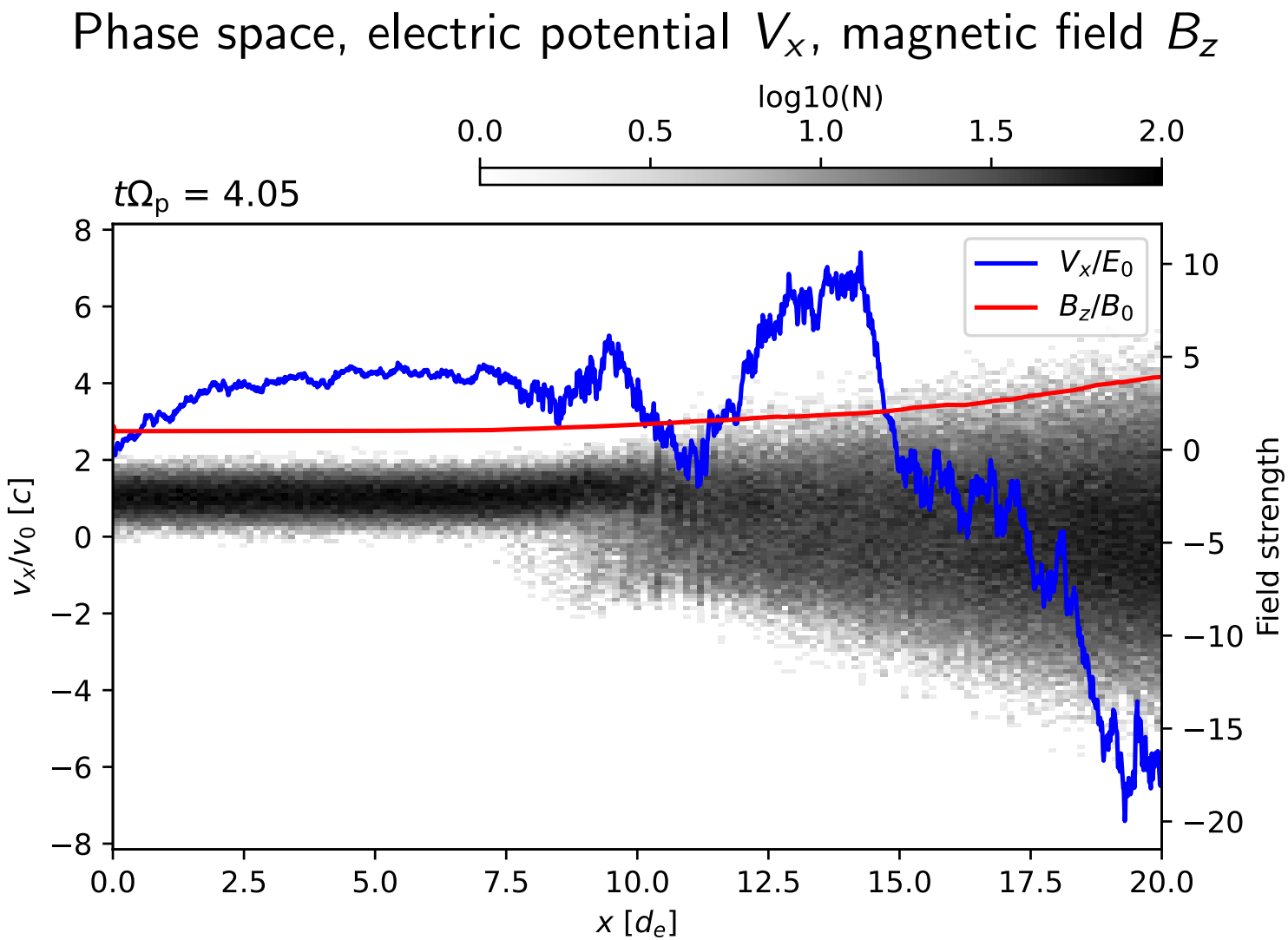
$v_0 = 1000\,\mathrm{km/s} = 0.003\,\mathrm{c}$

$B_z = 1\,\mathrm{mG}$

$T = 10^4\,\mathrm{K} \rightarrow v_{\mathrm{th}} = 0.0013\,\mathrm{c}$

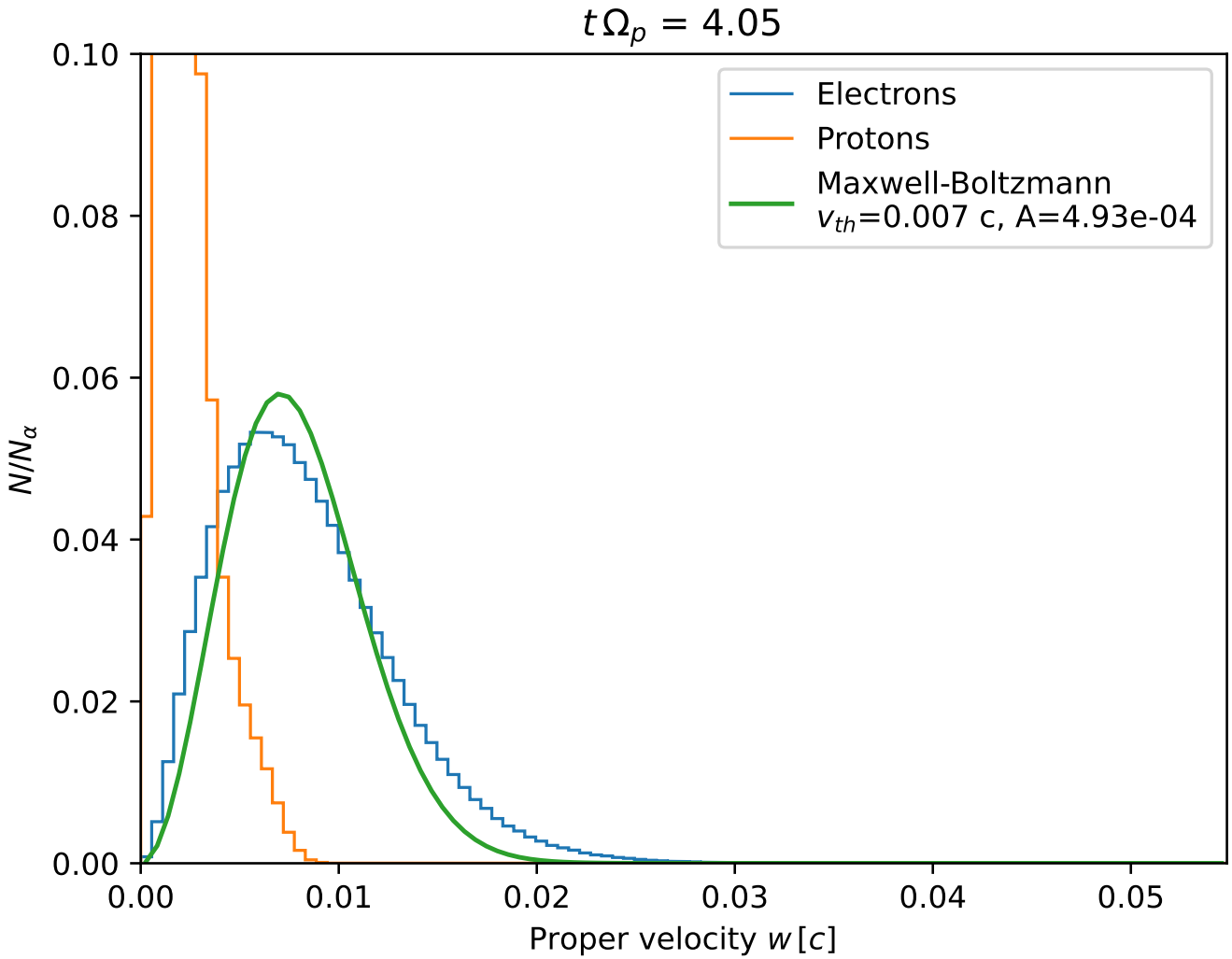


Preliminary results



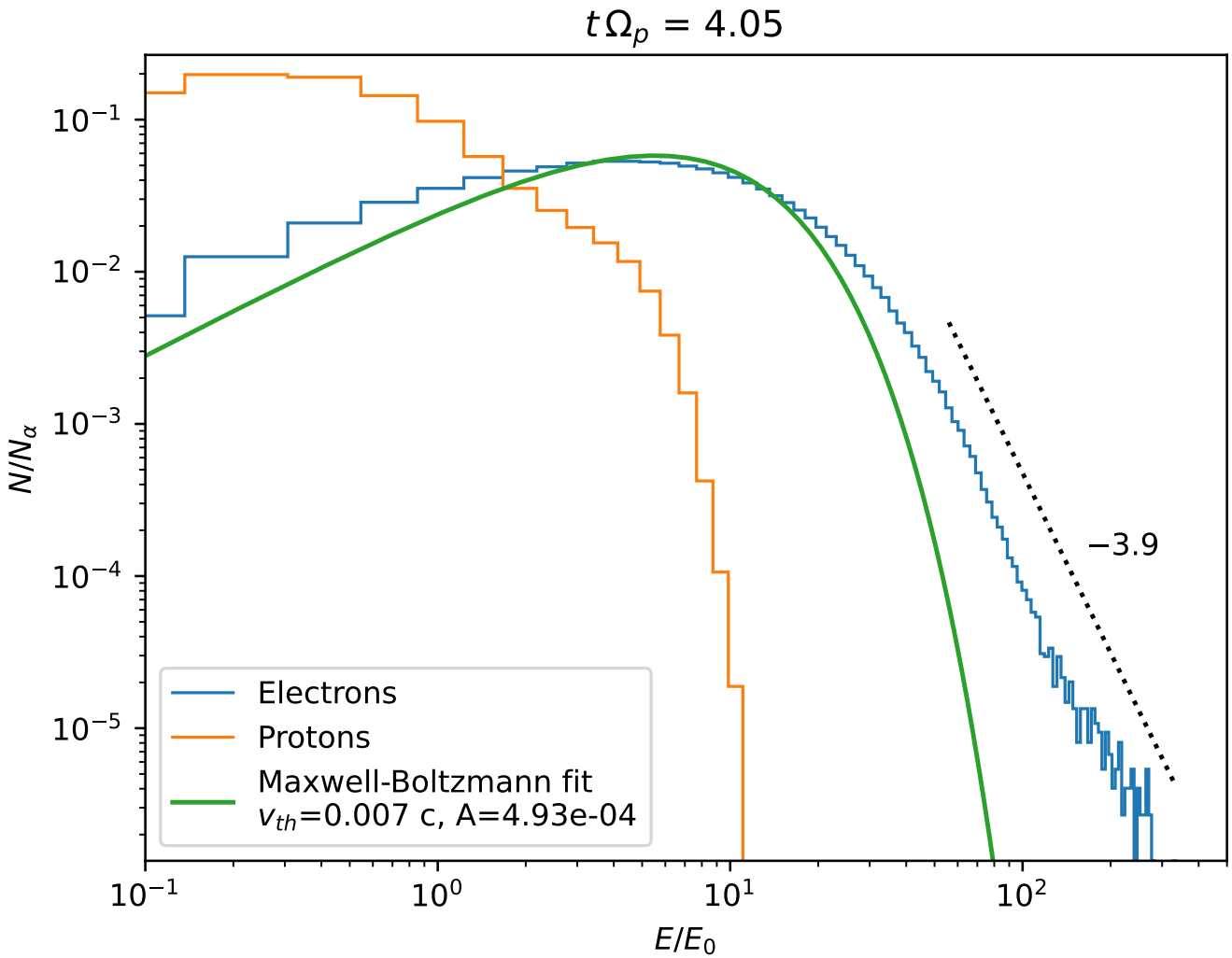
Preliminary results

Particle velocity spectra



Preliminary results

Particle energy spectra



Summary

Reproduced results of Hoshino and Shimada (2002) showing

- the formation of strong ESWs accompanied by holes in the electron phase-space
- non-thermal population of electrons accelerated by the shock
- particle trajectories indicating acceleration by the ESW

Follow-up studies focus on high-velocity shocks

Preliminary 1D simulations of protostellar jet environment to test setup, explore shock evolution
$\rightarrow$ weaker shock, high thermal noise
Simulation setup needs further consideration

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Araudo, Anabella T, Marco Padovani, and Alexandre Marcowith (June 2021). "Particle acceleration and magnetic field amplification in massive young stellar object jets". In: *Monthly Notices of the Royal Astronomical Society* 504.2, pp. 2405–2419. ISSN: 0035-8711. DOI: 10.1093/mnras/stab635. eprint: https://academic.oup.com/mnras/article-pdf/504/2/2405/37680305/stab635.pdf. URL: https://doi.org/10.1093/mnras/stab635.

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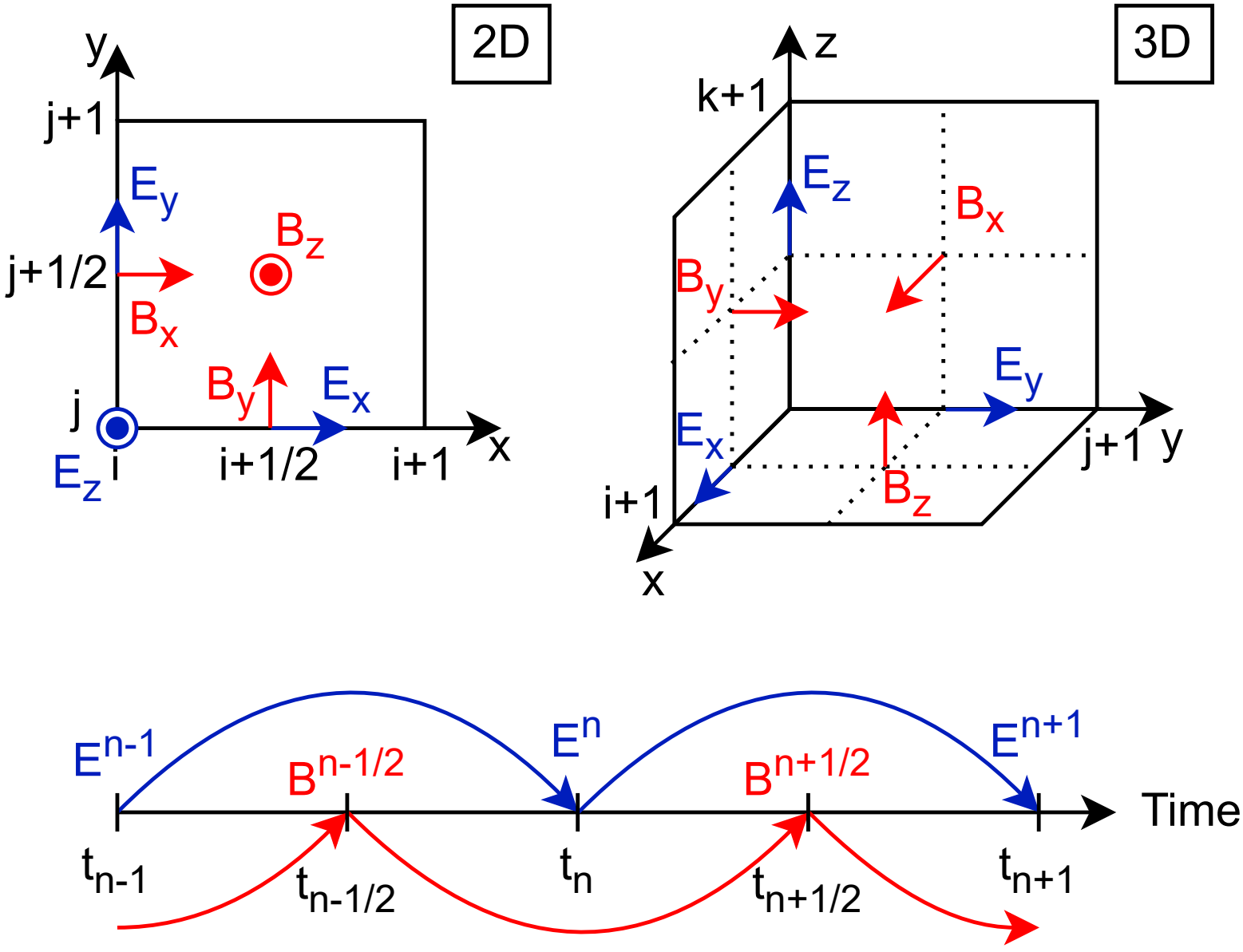
Yee lattice = fields staggered in space and time



Leapfrog scheme

