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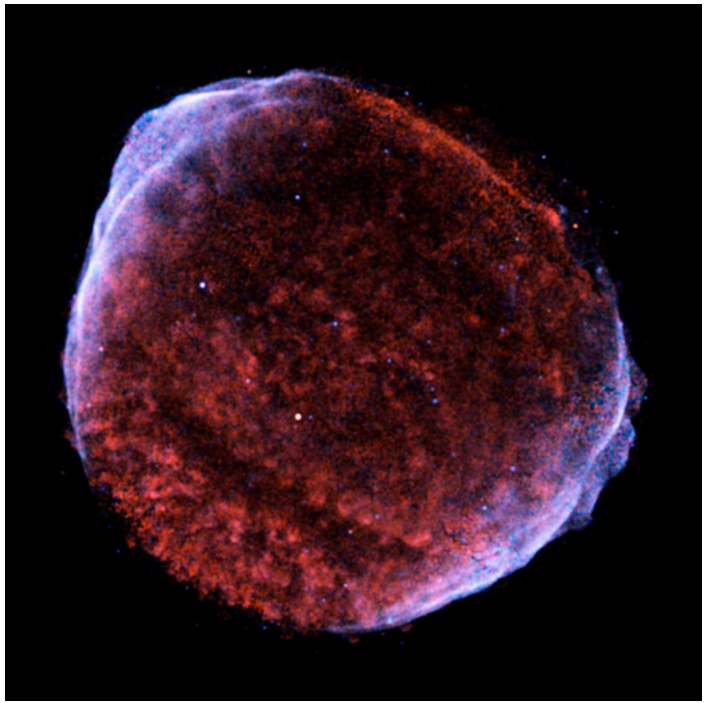
Kinetic simulations of oblique high-Mach number shocks propagating in Alfvénic turbulence

Eloise Moore

Collaborators: Karol Fulat, Mahmoud Al-Awashra, Michelle Tsirou, Martin Pohl

Discussions and synergies on astrophysical plasma with PIC simulations | Prague 2026

Supernova remnants



Chandra X-ray image of SN1006. Exposure: 61 hours
Red: 0.5-0.91 keV, Cyan: 0.91-1.34 keV, Blue: 1.34-3.00 keV
Credit: NASA/CXC/Rutgers/J.Hughes et al.

- Supernova remnants candidate for galactic cosmic rays (see e.g. Reynolds 2008 for a review)
- Fast shocks $(v_{sh} \gtrsim 1000$ km/s$)$ suitable sites for particle acceleration via diffusive shock acceleration (DSA)
- Shocks are collisionless and propagate with high sonic Mach numbers
- Signals of electron acceleration: non-thermal X-ray shells indicating synchrotron emission (e.g. Reynolds & Chevalier 1981)

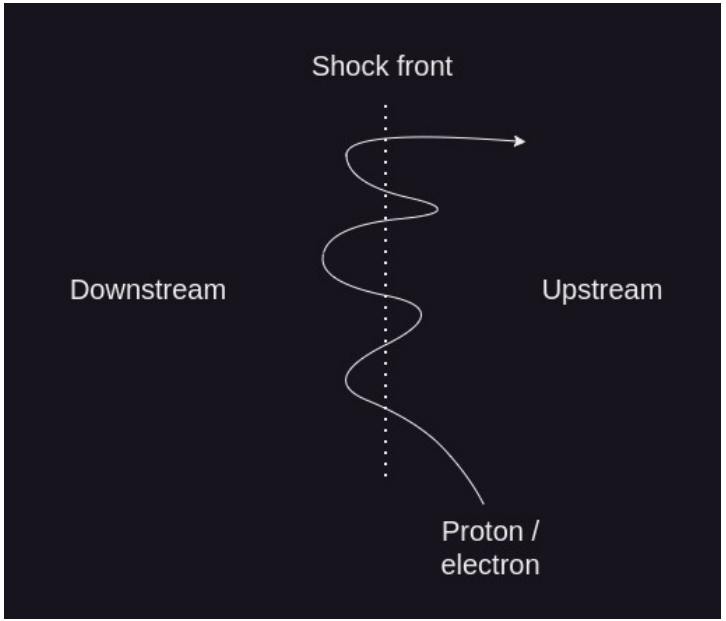
Particle acceleration at shocks

Acceleration to high energies via DSA

- Simplest case: shock modelled as infinitesimally thin discontinuity
- Energy gain ~ v/c with each crossing of the shock
- To enter DSA, particle Larmor radius should be larger than the shock thickness

$$\frac{mv}{|q|B} \gtrsim d_{\mathrm{sh}}$$

- Thermal electrons cannot participate in DSA – the **electron injection problem**



Electron dynamics at oblique shocks

Oblique shocks: **turbulent foreshock region** where various **beam instabilities** are driven



Electron density Bohdan et al. (2022)

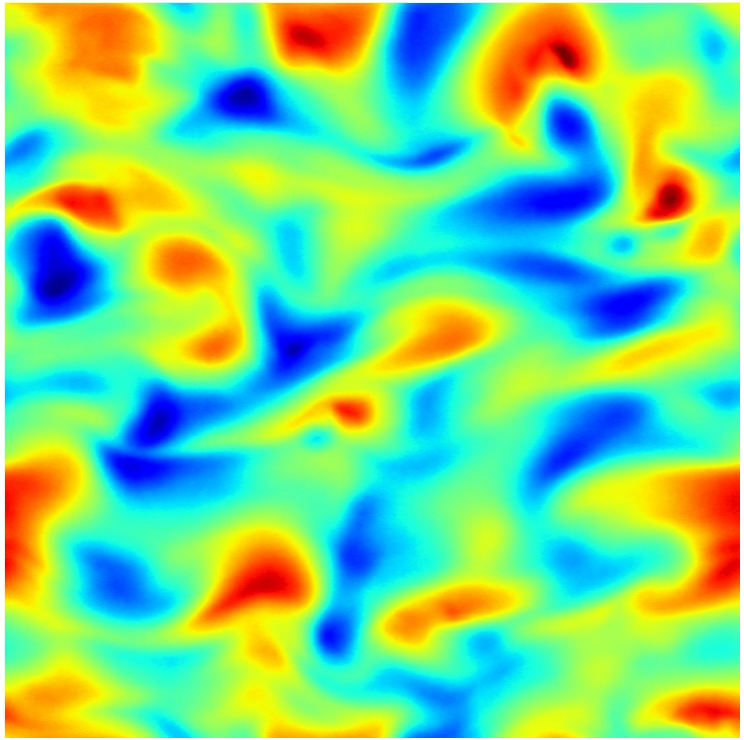
m_i/m_e	n_0	v_0/c	$v_{th,e}/c$	θ_{bn}	λ_{se}	Ω_i^{-1}
50	40	-0.2	0.0444	60	8	$13000\,\delta t$

Simulation parameters

- Bohdan et al. (2022) investigated the nature of beam instabilities within the foreshock from PIC simulations of collisionless oblique shocks propagating towards **homogeneous upstream plasma**

- Instabilities & non-linear structures **modify electron dynamics** – provides scattering and are capable of providing heating & acceleration

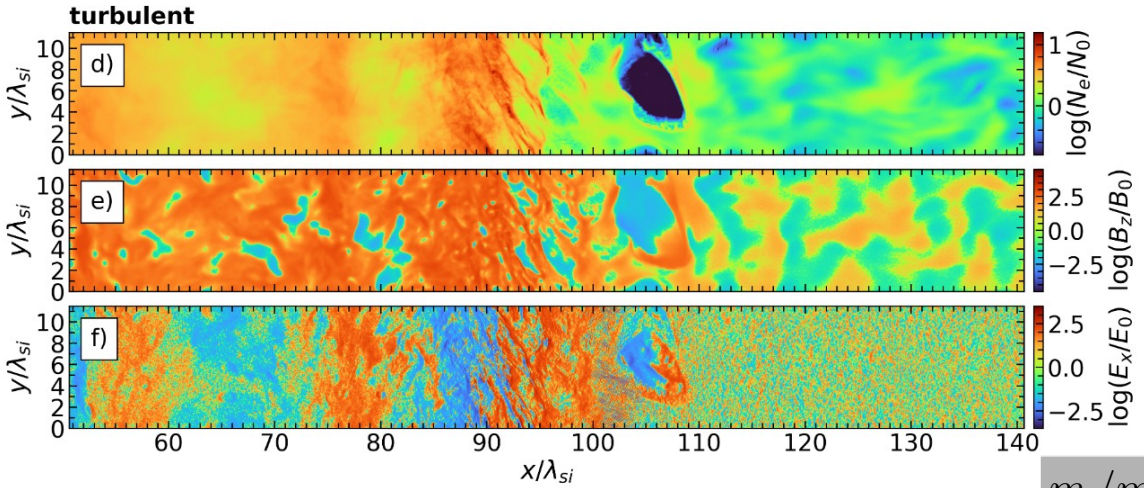
… so what's missing?



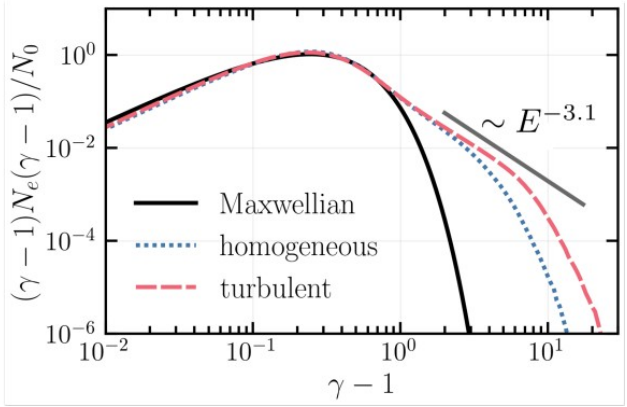
- Plasma is ubiquitous in astrophysical environments, but is **rarely homogeneous**, especially on kinetic scales
  - We need to include turbulence in the upstream region of shock simulations!
- Turbulence can:
  - Provide additional **particle scattering** towards & around the shock
  - Modify the **shock structure**
  - Modify properties of **instabilities** and **non-linear structures** in the foreshock region

Oblique shock simulations with compressive turbulence

- Previous work by Karol Fulat has shown that electrons are accelerated more efficiently with pre-existing compressive turbulence in the upstream



PIC simulation of oblique high-Mach number shocks with compressive turbulence.
(Fulat, **Moore** et al. 2026 accepted)



m_i/m_e	n_0	v_0/c	$v_{th,e}/c$	θ_{bn}	λ_{se}	Ω_i^{-1}
100	20	-0.2	0.05722	60	20	$48000\,\delta t$

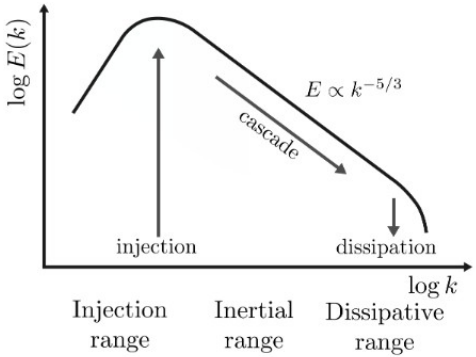
Simulation parameters

Alfvénic turbulence

- One of the main forms of electromagnetic turbulence
- Transverse, non-compressive turbulence resulting from the interaction between counter-propagating Alfvén waves
  - Wavepackets are deformed non-linearly when they collide ⇒ generates turbulence!



Propagation of Alfvén wave packets (Galtier 2022)



Source: Karol Fulat (2024, thesis)

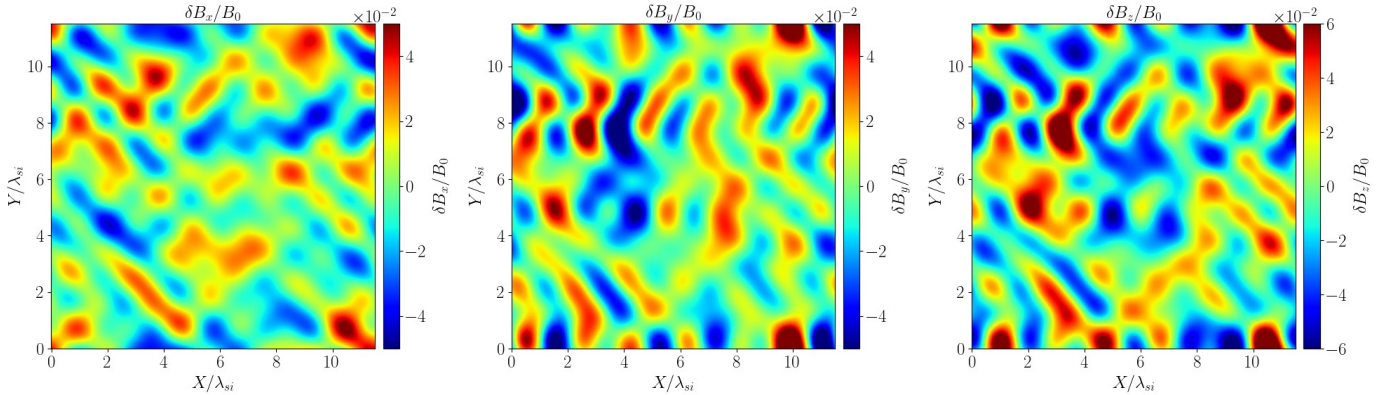
Alfvén waves propagate parallel to the direction of the magnetic field ⇒ perturbations transverse to direction of propagation resulting in anisotropic energy cascade $(k_\perp \gg k_{||})$

Implementation of EM turbulence

- **Decaying** electromagnetic turbulence similar to that of **kinetic Alfvén wave** turbulence
- Consider 50 perturbations in the magnetic field each of a given wavenumber and phase inserted in upstream rest frame

m_i/m_e	n_0	v_0/c	$v_{th,e}/c$	θ_{bn}	λ_{se}	Ω_i^{-1}
100	20	-0.2	0.05722	60	20	$48000\,\delta t$

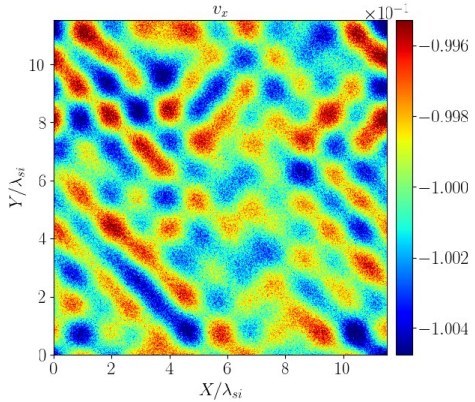
Simulation parameters

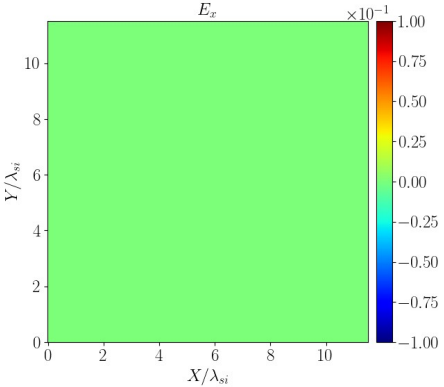


Initial magnetic field perturbations at $t = 0\,\Omega_i^{-1}$

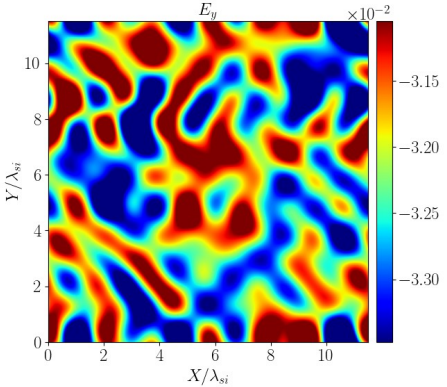
Implementation of EM turbulence

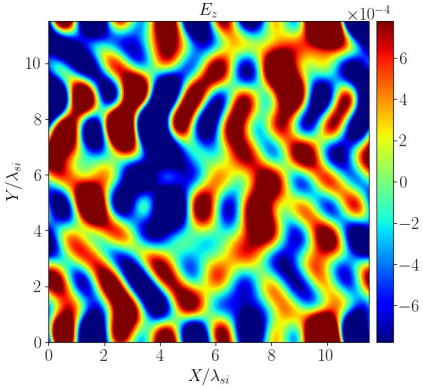
- Self-consistent current initialised by shifting the ion distribution by $\nabla \times \delta \boldsymbol{B}$ in the upstream rest frame to avoid rapidly growing electric field
- Motional electric field carried by electrons $\boldsymbol{E} = -v_0 \times (\boldsymbol{B}_0 + \delta \boldsymbol{B})$ initialised in simulation frame





Initial ion x- velocity at $t = 0\,\Omega_i^{-1}$





Initial electric field at $t = 0\,\Omega_i^{-1}$

Shock simulation setup

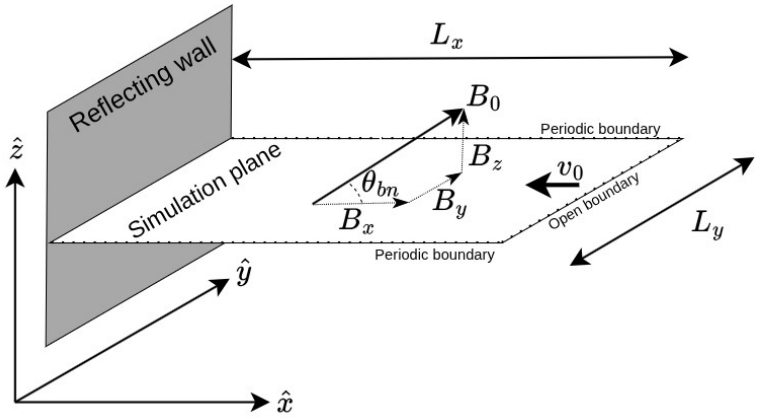
2D3V particle-in-cell code THATMPI, based on TRISTAN

Reflecting wall setup to create a shock

4 simulations:
- Homogeneous
- Turbulent (fluctuations $\delta B/B \sim [5\%, 20\%, 80\%]$)

Aim to run for $\sim 15\,\Omega_i^{-1}$, currently at $13.65\,\Omega_{ci}{}^{-1}$

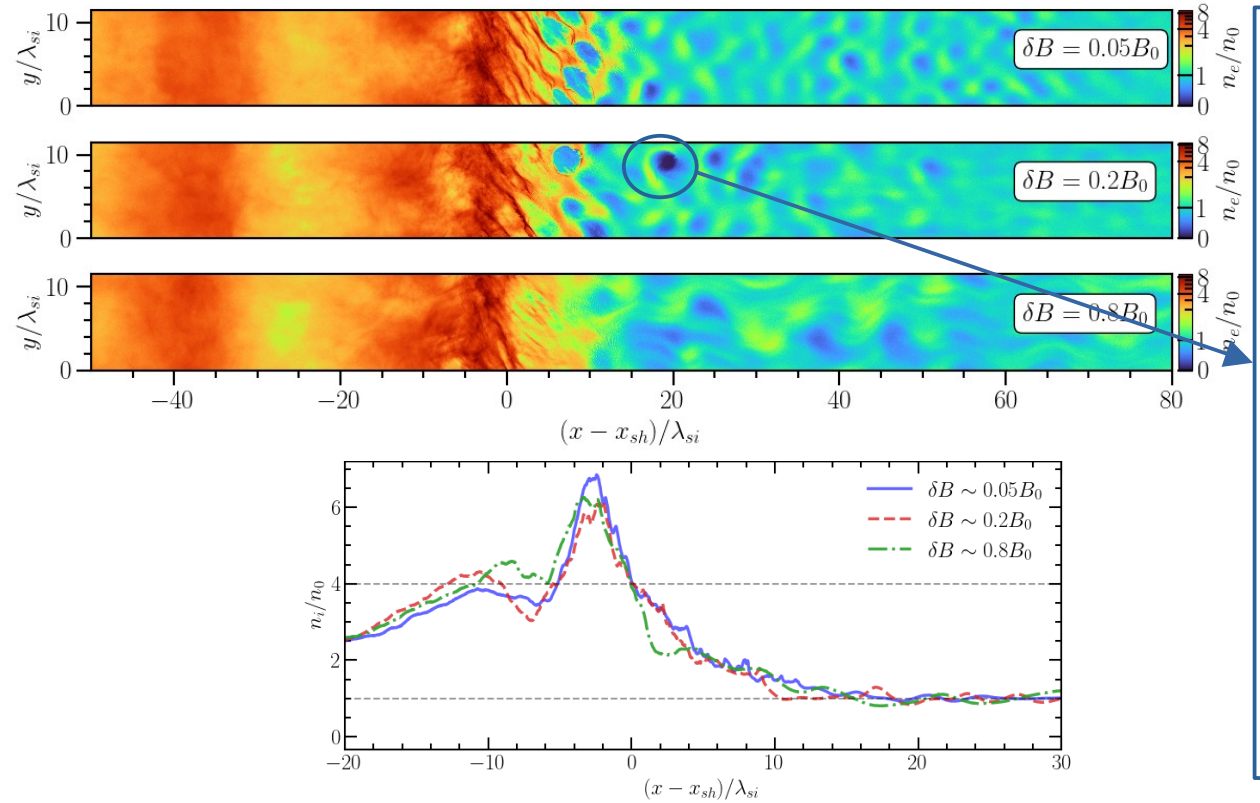
Simulation schematic

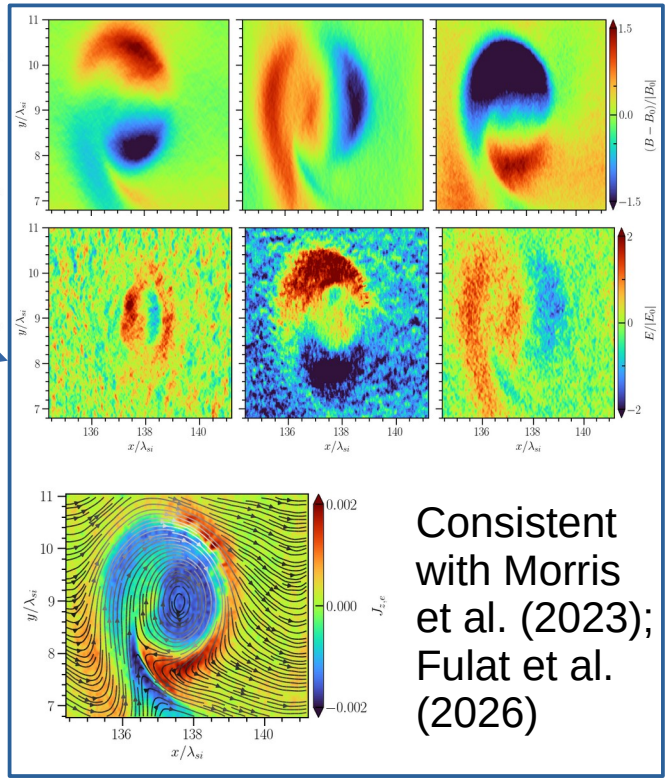


Simulation parameters

m_i/m_e	n_0	v_0/c	θ_{bn}	L_y	λ_{se}	M_s	M_A	Ω_i^{-1}
100	20	-0.2	60	12	20	36	32	$48000\,\delta t$

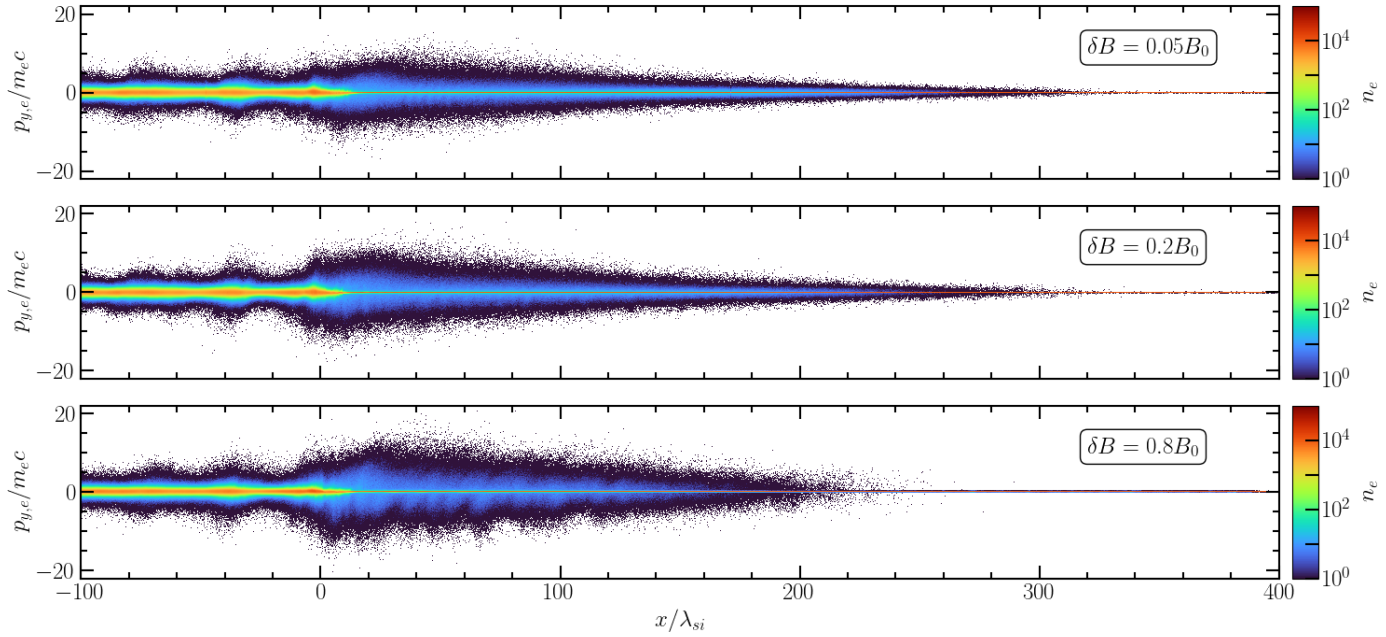
Shock structure: density





Consistent with Morris et al. (2023); Fulat et al. (2026)

Electron phase space



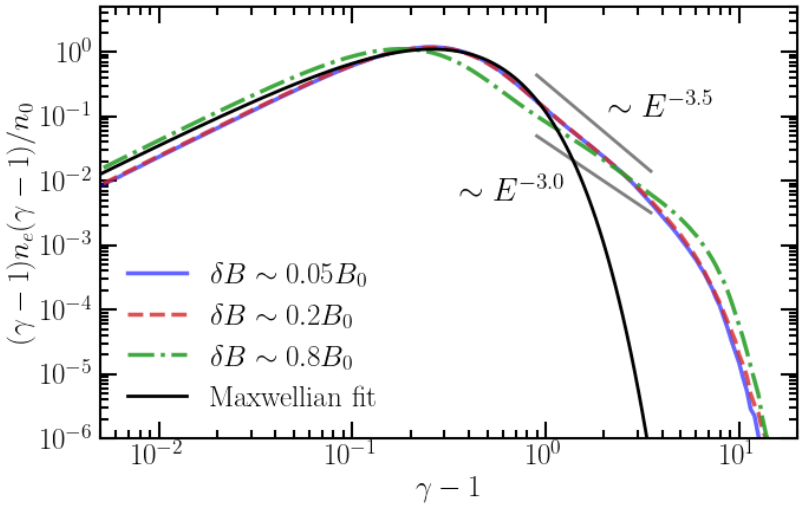
Shorter foreshock in $\delta B \sim 0.8B_0$ but **wider distribution**

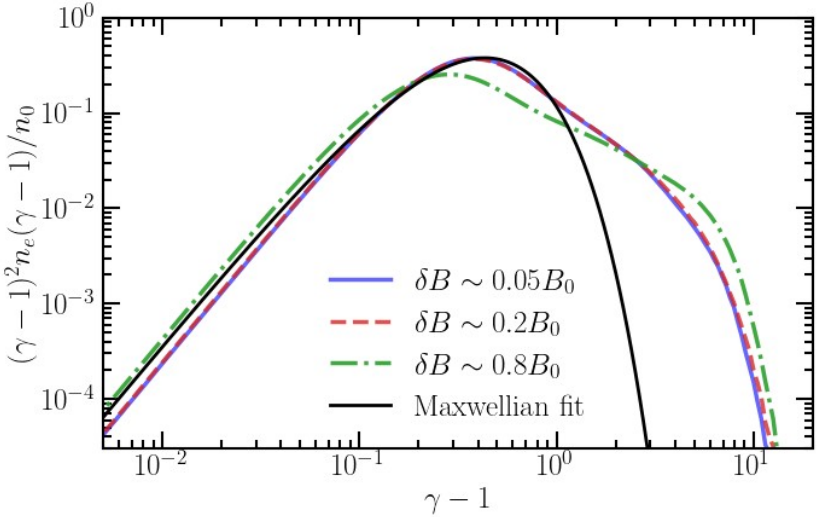
Wider spread in **core distribution** between $(x - x_{sh}) \in [0, 20]\,\lambda_{si}$ for $\delta B \sim [0.05, 0.2]B_0$

Narrower core distribution in **downstream** for $\delta B \sim 0.8B_0$

Electron energy spectrum

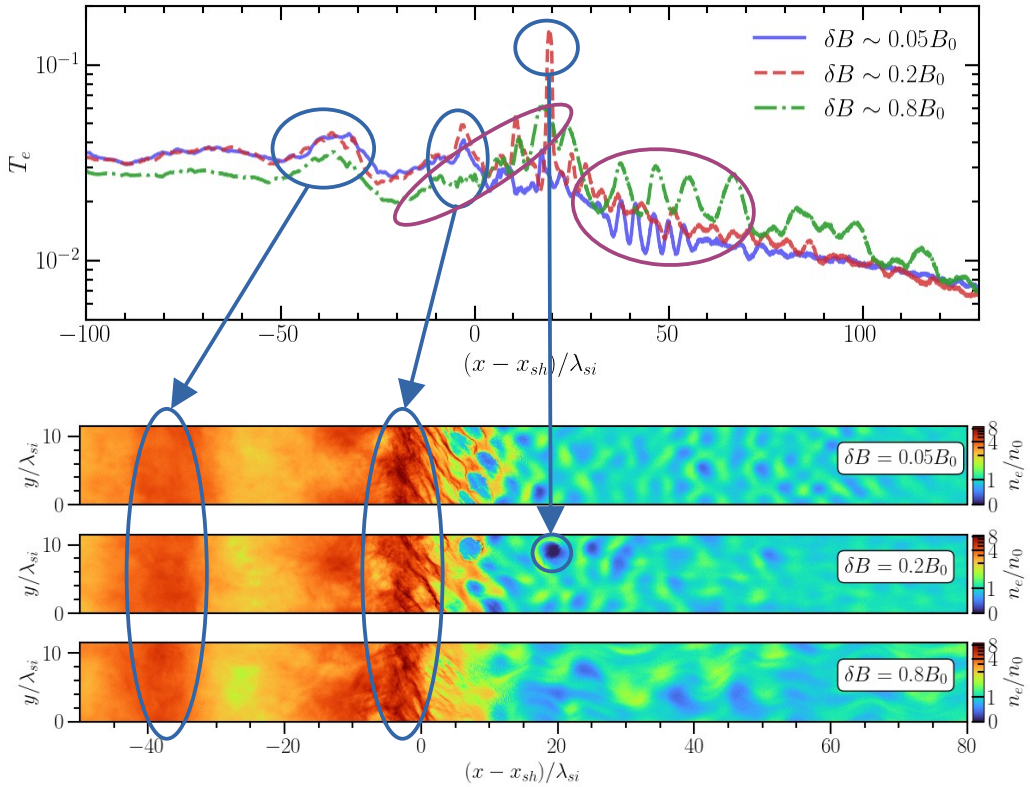
Energy spectrum taken in the downstream (region $40-80\,\lambda_{si}$ behind shock)



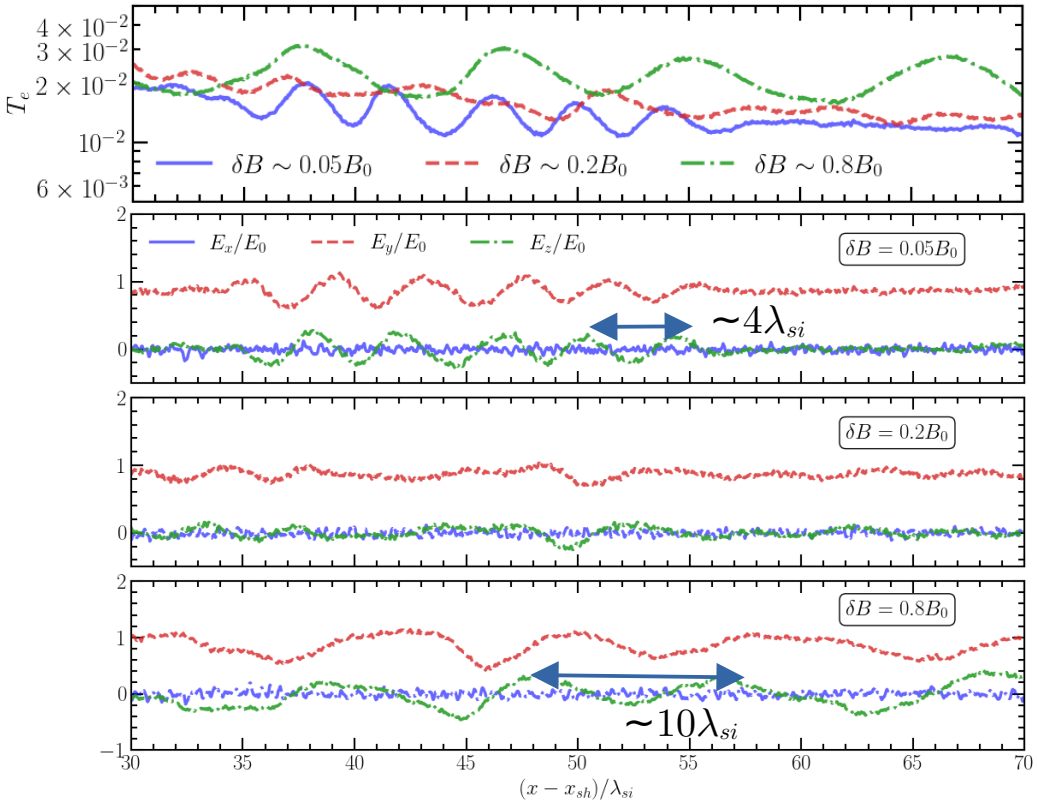


Electrons are accelerated **more efficiently and to slightly higher energies** in $\delta B \sim 0.8B_0$ but the downstream temperature is lower

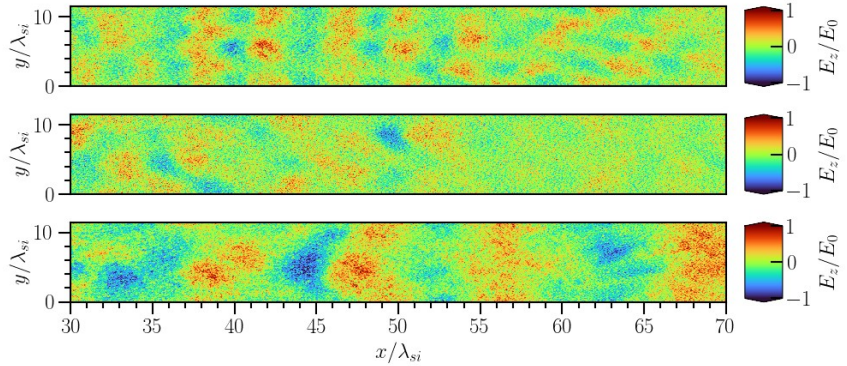
Electron temperature profile



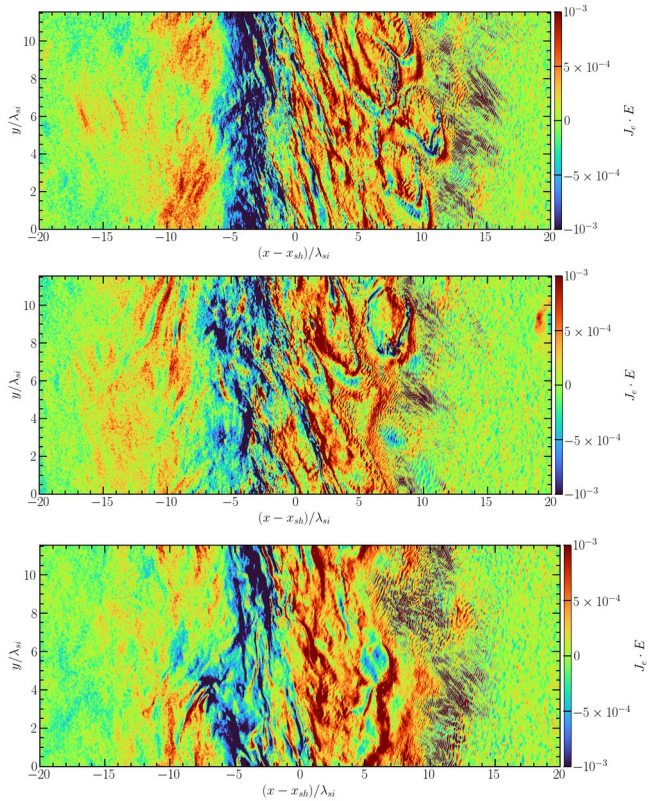
Feature at $(x - x_{sh}) \sim 30 - 70\,\lambda_{si}$



Wavelike fluctuations in temperature for $\delta B \sim 0.05B_0$ and $\delta B \sim 0.8B_0$ correlate with polarised wavelike fluctuations in E & B

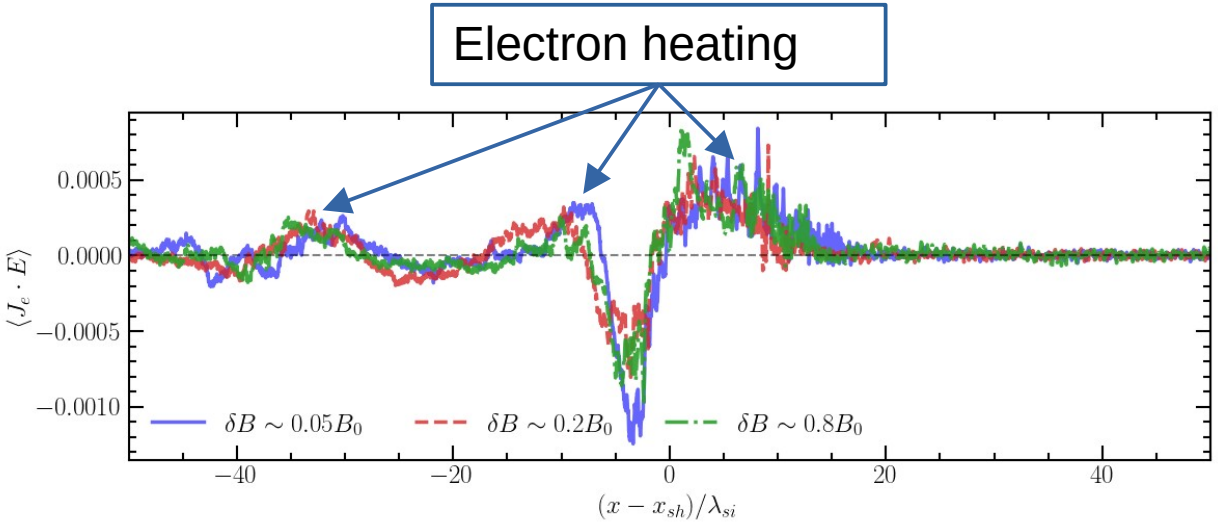


Electron heating

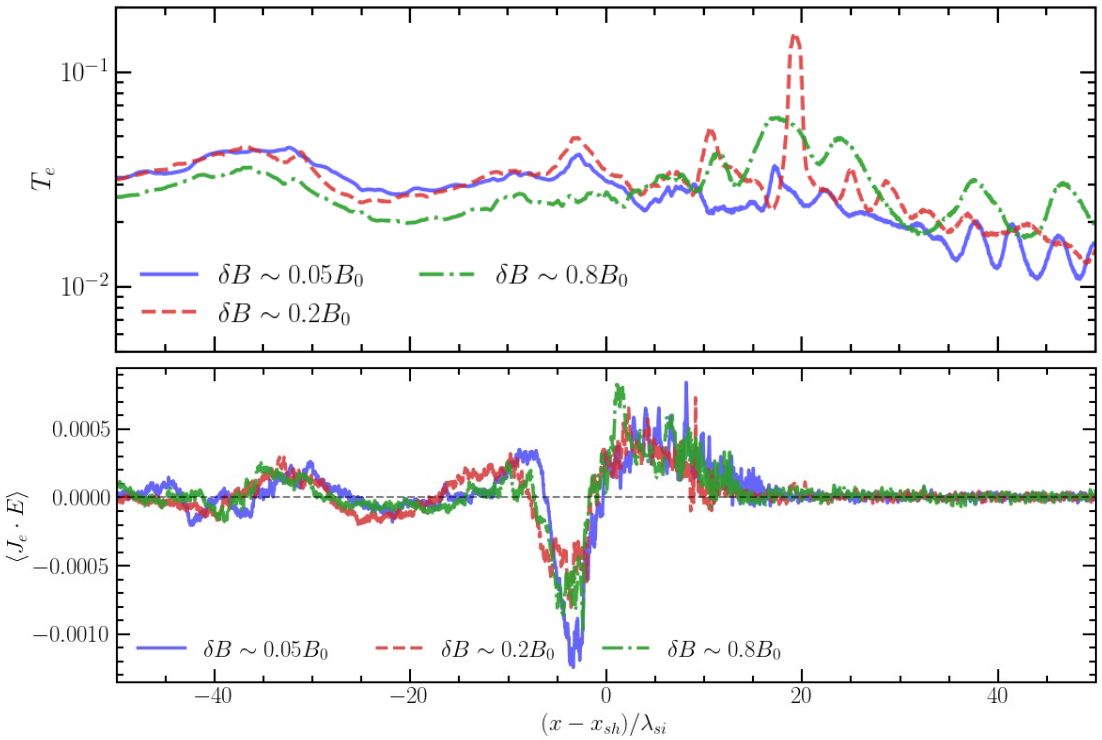


$J_e \cdot E > 0$: Electric field does work on the electrons

$J_e \cdot E < 0$: Electrons do work on the field



Electron ~~heating~~ (?)



Reduction in temperature for $\delta B \sim 0.8 B_0$ is not explained by $J_e \cdot E$ maps & profiles

Some other transfer of energy process that is not present in lower turbulence amplitudes?

Summary

- I have developed a framework for stable, self-consistent electromagnetic turbulence for use in Particle-In-Cell shock simulations

- Currently running shock simulations with electromagnetic turbulence of varying turbulence amplitudes (fluctuations $\delta B/B_0 \sim [5\%, 20\%, 80\%]$)
  - Whistler waves (+ cavities) and Weibel filaments present in the foreshock, but are weakened in higher amplitude turbulence
  - Higher amplitude turbulence results in a **higher maximum electron energy** and has a **harder spectrum** comparable to compressive turbulence but a **lower downstream temperature**
  - Investigating source of reduction of electron temperature in downstream

Thanks for listening!

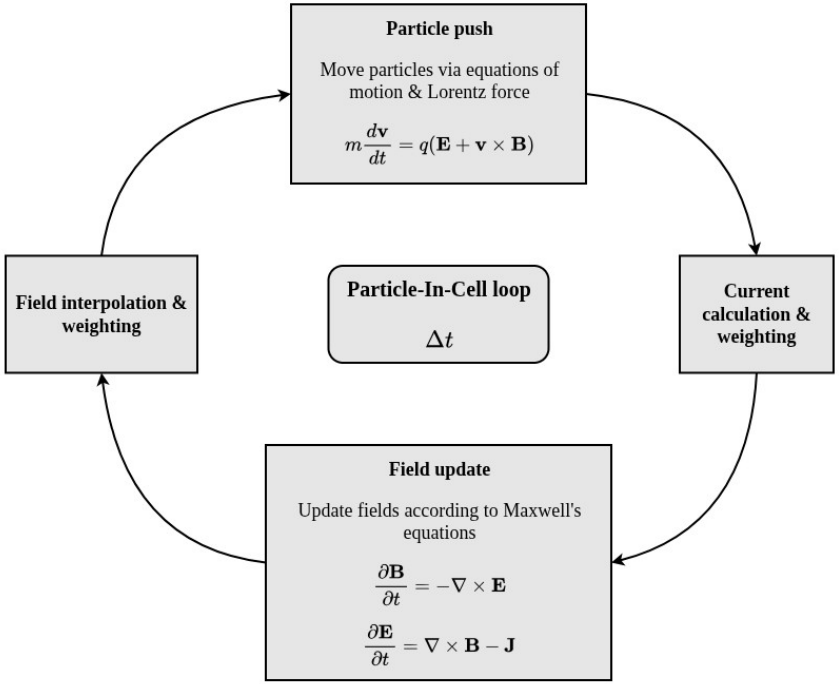
BACKUP SLIDES

Driven vs. decaying turbulence

- Driven turbulence
  - Turbulent energy continuously injected at larger scales to mimic MHD cascade
  - May lead to artificial heating of particles and thus enhanced acceleration efficiency
  - e.g. Langevin antenna (Tenbarge et al. 2014)

- Decaying turbulence
  - Wavelike structures imposed by initial condition and left to evolve in the simulation
  - May struggle to reach a steady state
  - e.g. Grošelj et al. 2019, Comisso et al. 2019, Bresci et al. 2022

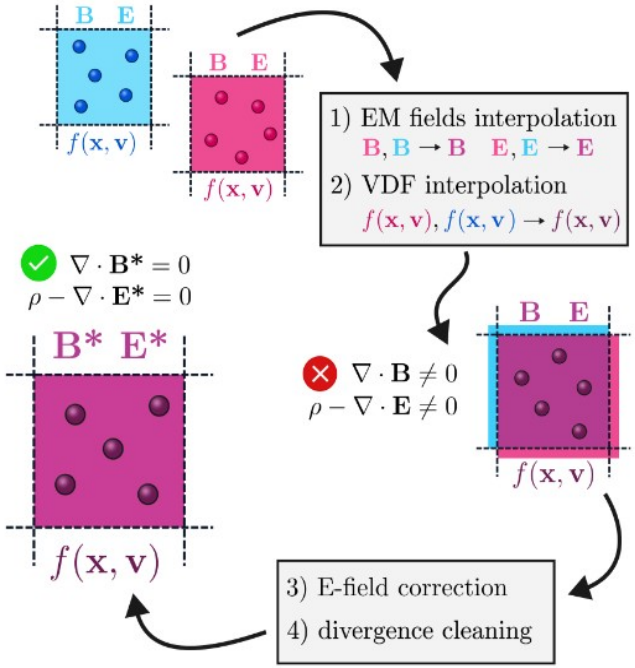
The Particle-In-Cell Method



- Plasma represented by ensemble of macro-particles (representing many particles in a real plasma) injected with an initial distribution function (e.g. Maxwellian)
- Electric & magnetic fields are solved self-consistently via Maxwell's equations
- Particle motion by Lorentz force computed through leapfrog algorithm

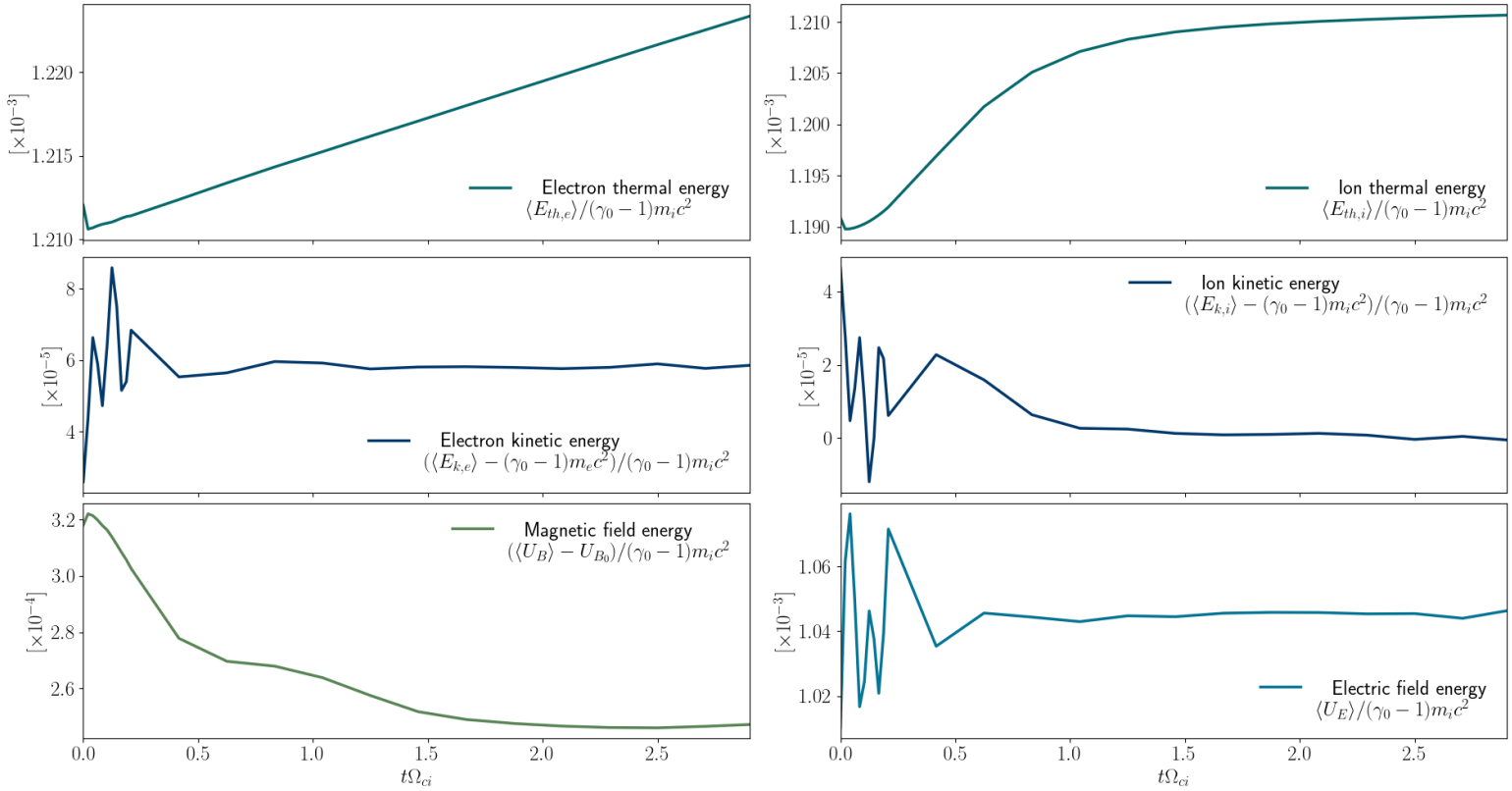
PIC = Particle-In-Cell

Slab matching in THATMPI

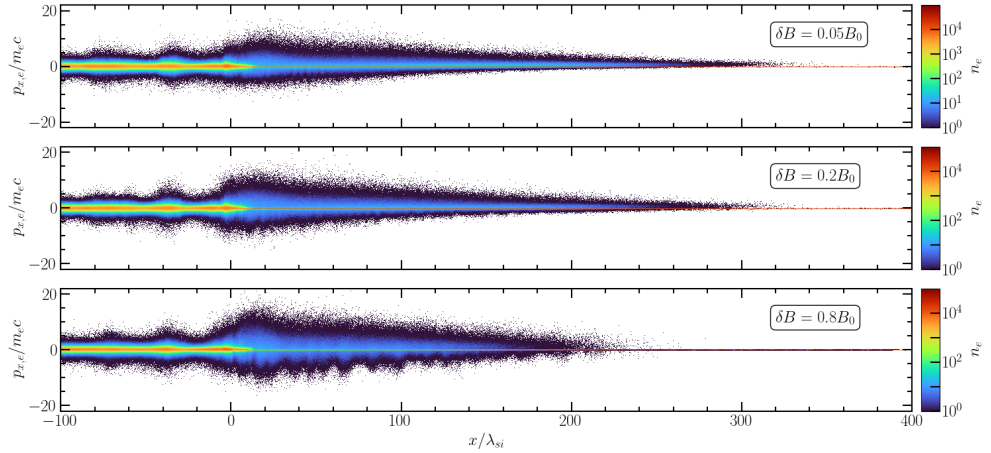


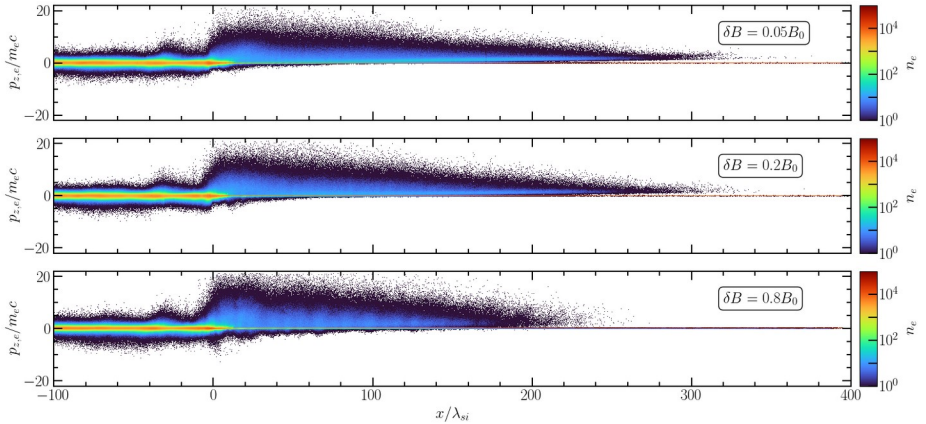
- Pre-generate turbulent slabs using periodic box simulations
- Fields interpolated within a “transition zone” with weights imposed by their position in the simulation grid. Particle distribution functions recomputed using first 3 moments of distribution function
- Corrections made to ensure Gauss’ law satisfied, and $\nabla \cdot \boldsymbol{B} = 0$

Long-term evolution of turbulence

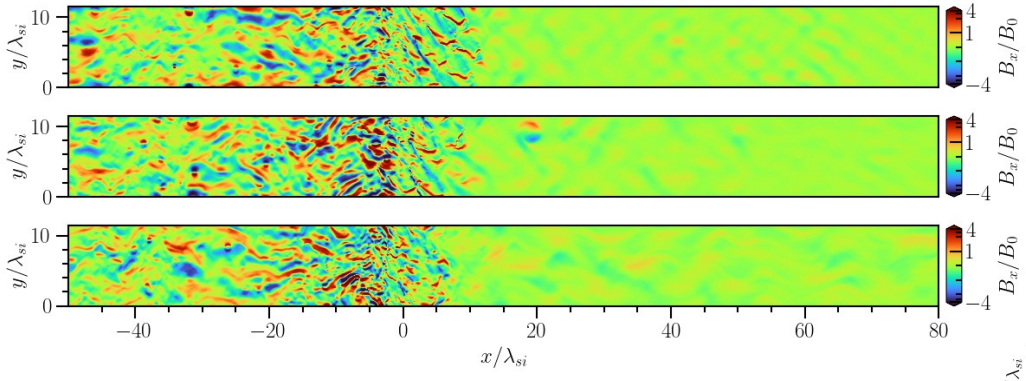


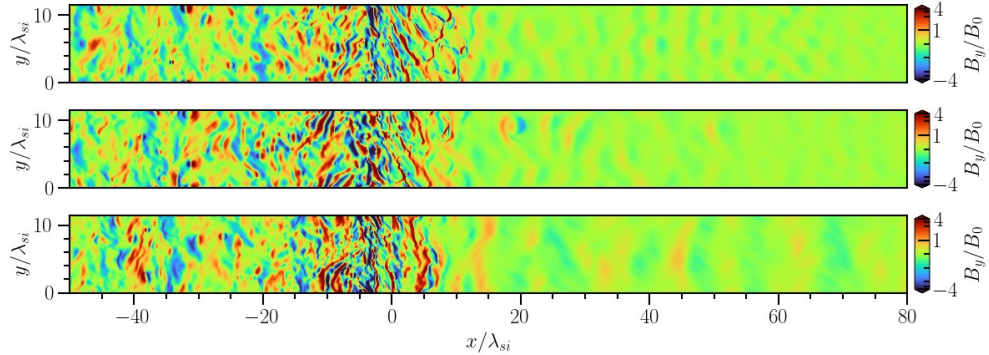
Electron phase space (p_x & p_z)

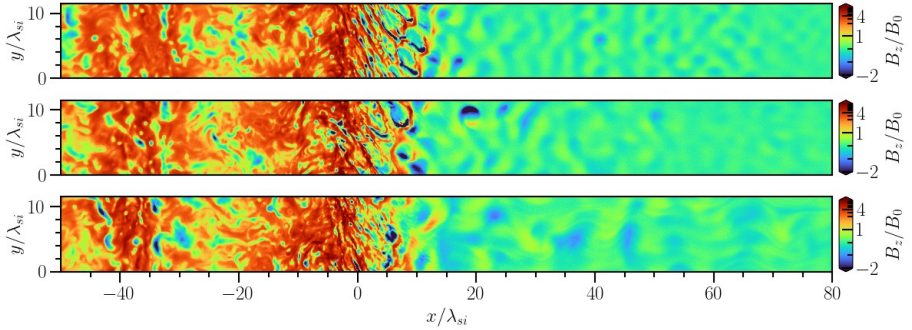




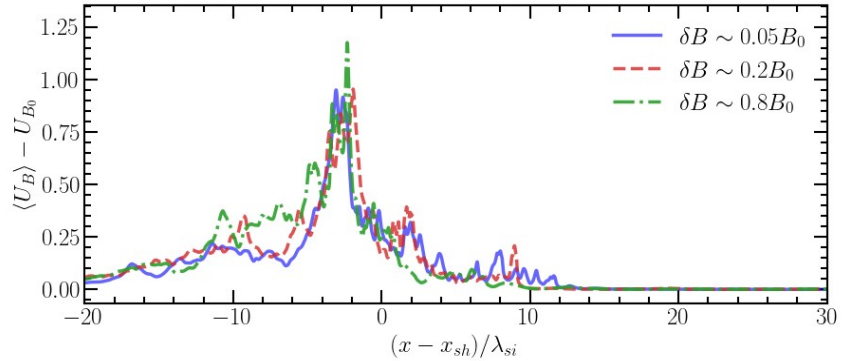
Magnetic field maps

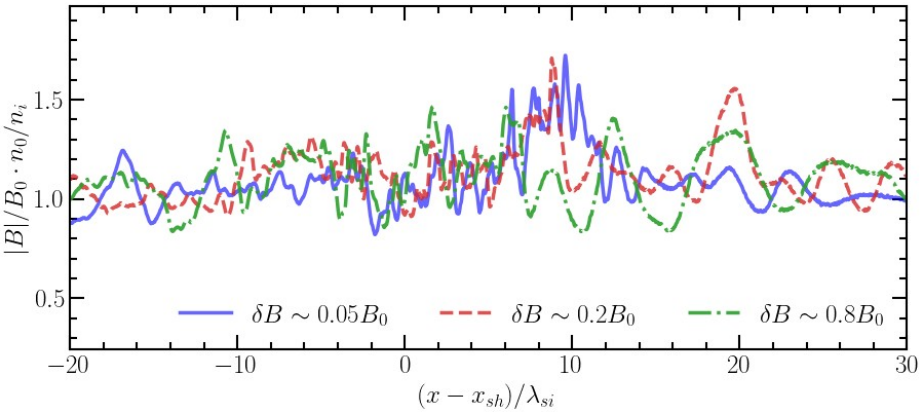


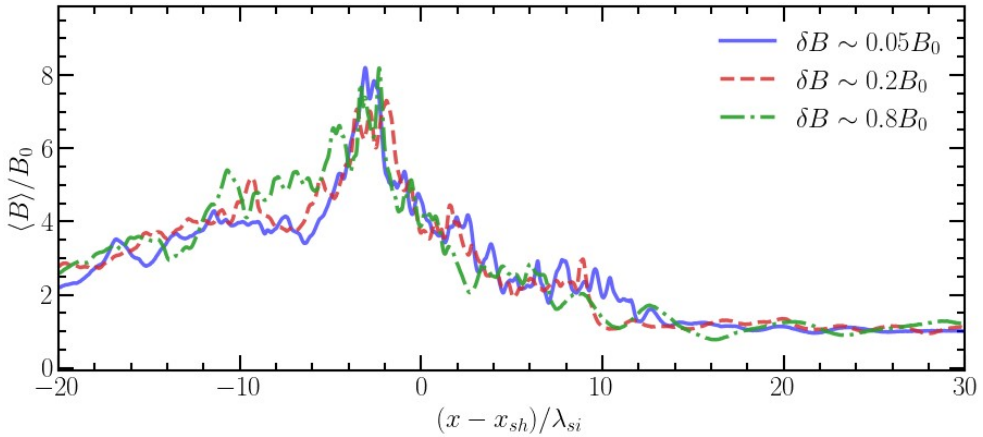




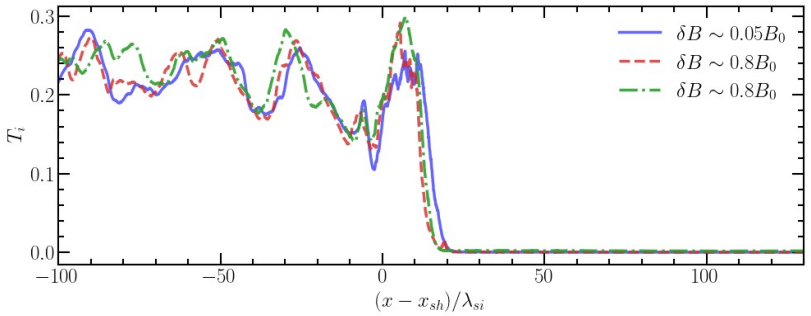
Magnetic field profiles

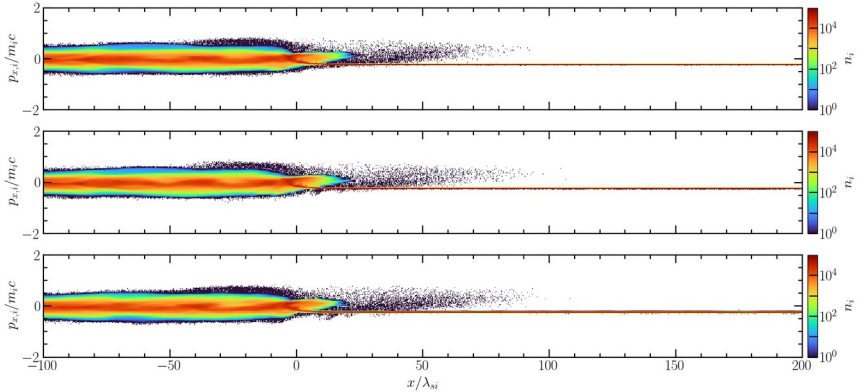


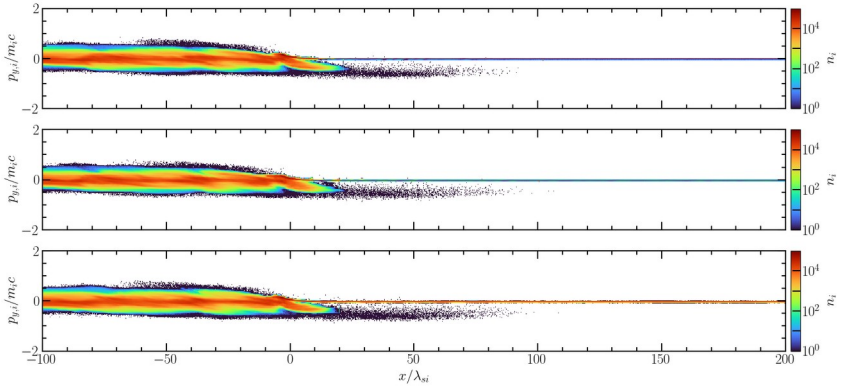


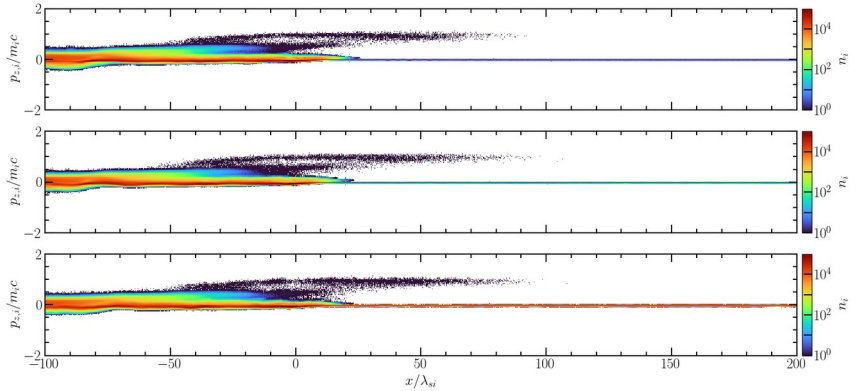


Ion profiles



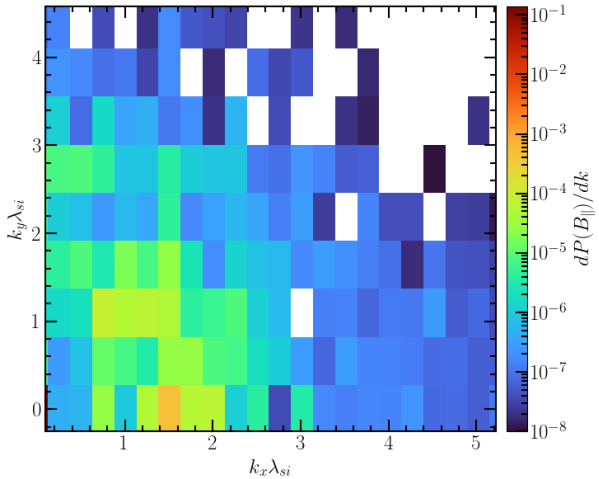






Polarisation - $\delta B \sim 0.05 B_0$

Peak in power at $k_x \lambda_{si} = 1.5$ – consistent with $\lambda \sim 4\lambda_{si}$



$$\epsilon(\mathbf{k}) = \frac{2\Im(\tilde{B}_\parallel(\mathbf{k})\tilde{B}^*_\perp(\mathbf{k})}{|\tilde{B}_\parallel(\mathbf{k})|^2 + |\tilde{B}_\perp(\mathbf{k})|^2}$$

$$\epsilon((1.5, 0)\lambda_{si}) \sim 0.1$$