Mildly relativistic shocks at high magnetisation

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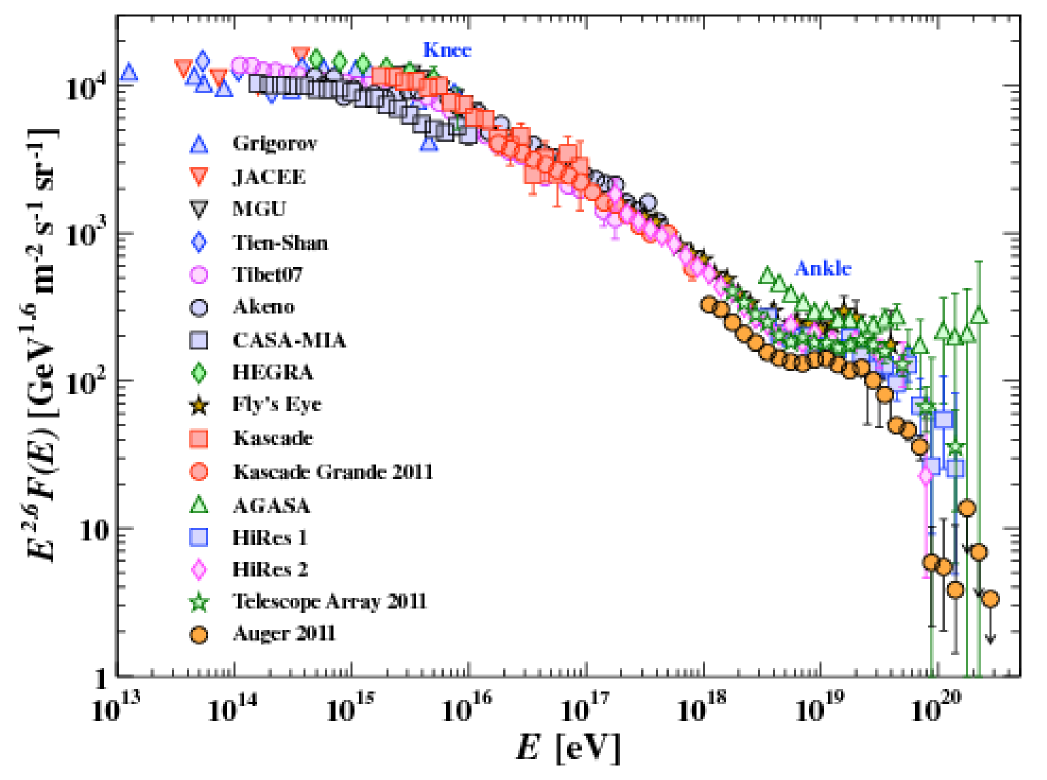
What are cosmic rays?

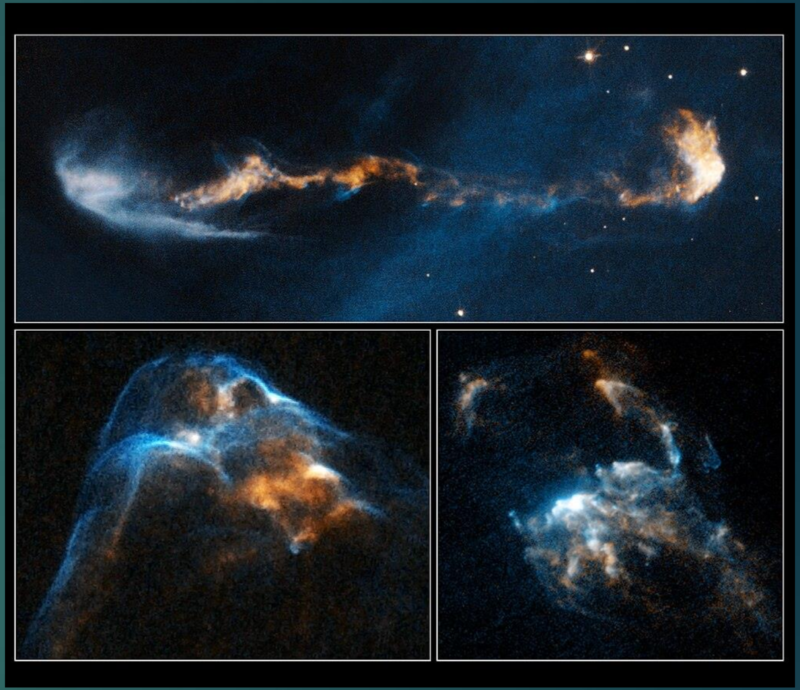
- Cosmic rays are high-energy particles that reach Earth from many different astrophysical sources.
- High-energy particles include protons, electrons and ions.
- One of the main sources of cosmic rays are plasma shocks.
- Particles can reach energies higher than 10^{20} eV. That is **SEVEN** orders of magnitude more than LHC achieved.



Spectrum of Cosmic Rays
(CERN)

Introduction to plasma shocks

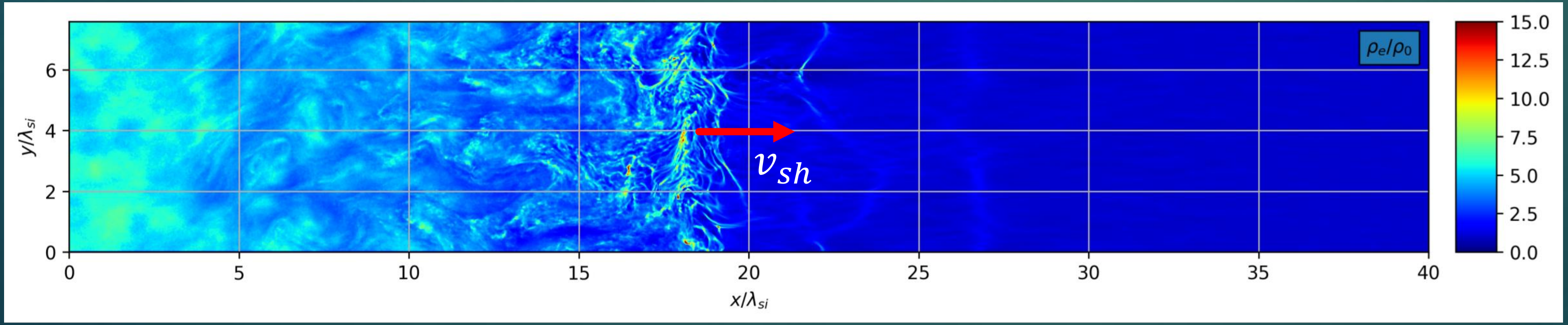
- Plasma is the most abundant state of matter in the universe. Commonly, astrophysical plasmas are collisionless.
- A plasma shock represents a transition layer between two plasmas at different conditions.
- Plasma originated from astrophysical sources interact with an external medium and produce a shock
- Within a plasma shock, plasma instabilities arise due to complex wave-wave or particle-wave interactions that can cause particle acceleration.
- High-energy particles might leave the plasma and travel across the universe. Some of them will end up on Earth as cosmic rays.



Composite of shock structures (Hubble telescope)

Simulation of collisionless plasma shocks

- Although plasma shocks can be generated at the laboratory, the conditions and lifetime of such differ significantly from real astrophysical shocks.
- Computer simulations are required to study these shocks in-depth.
- Particle-In-Cell (PIC) simulations reproduce plasma shocks at kinetic scales:
  - Particles e.g. ions and electrons, are simulated in a self-consistent electromagnetic field + background magnetic field
- Many other kind of simulations exist to study different regimes of shocks.



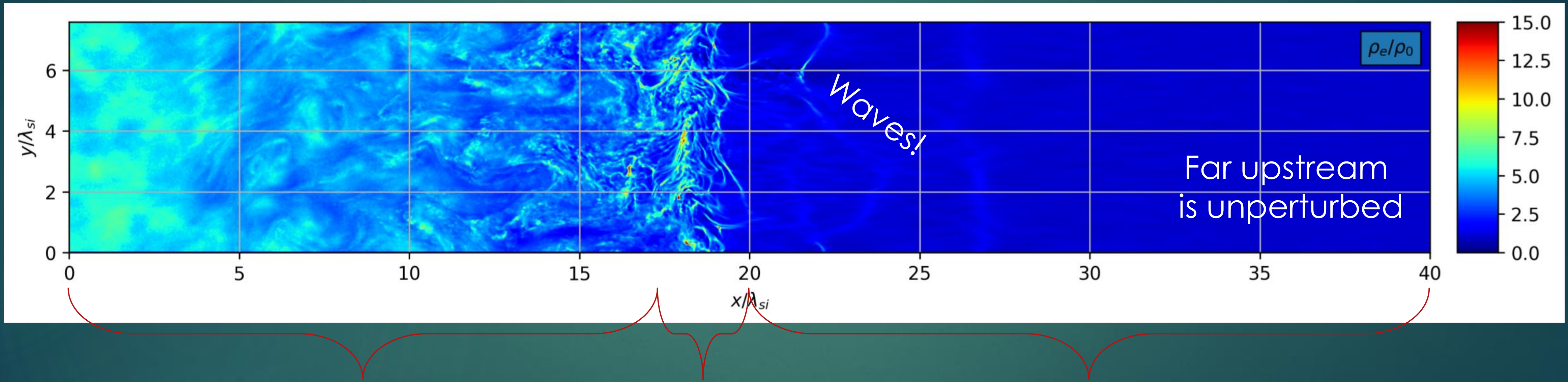
Electron density of a plasma shock. Notice the difference between both sides

Plasma shock overview

The magnetic field
and the density
are compressed downstream

Shocks can be corrugated

Near upstream is usually filled
with a reflected population



Far upstream
is unperturbed

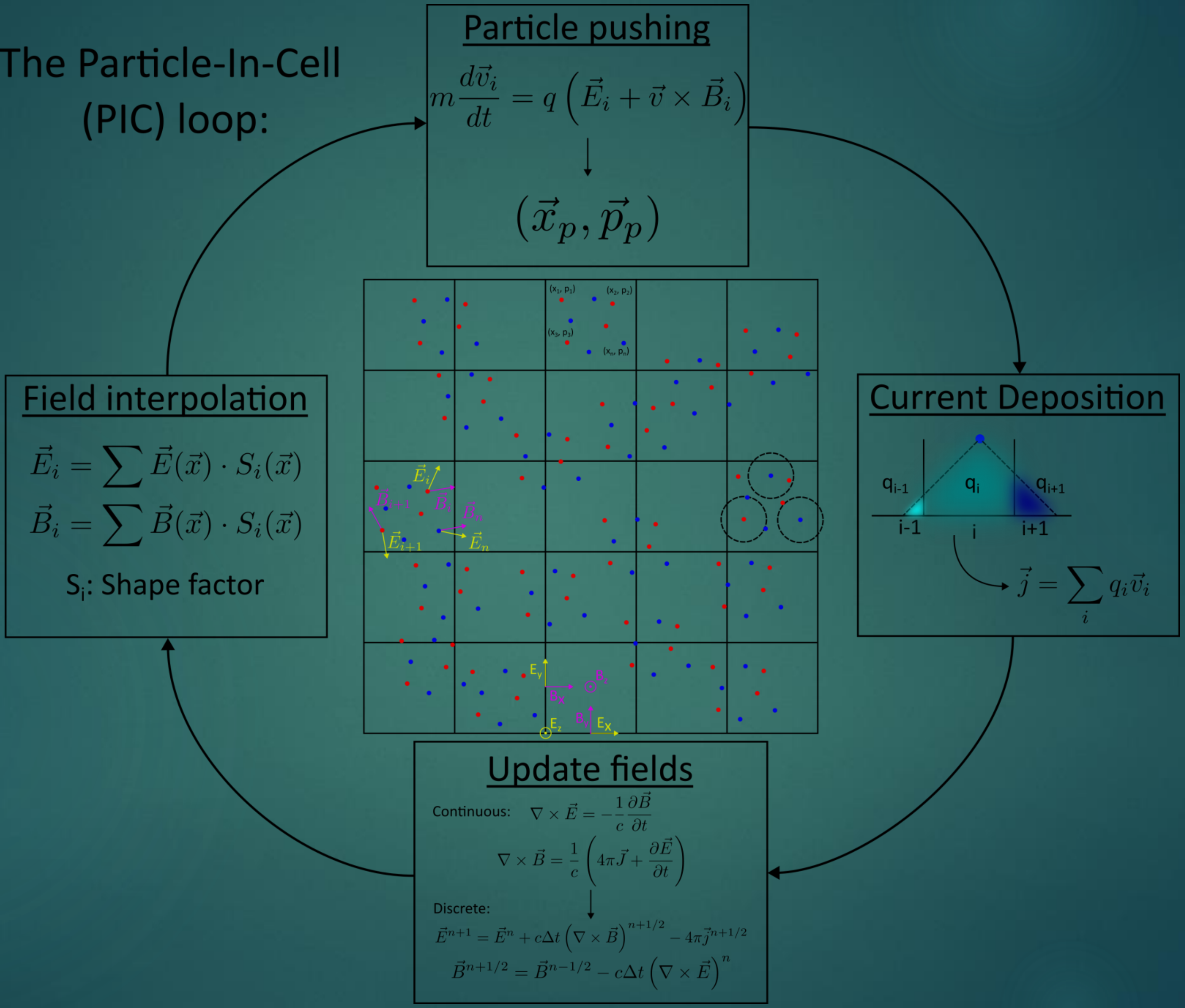
Downstream

Shock

Upstream

The medium gets compressed
and produces a shock

The Particle-In-Cell (PIC) loop:



Particle pushing

$$m\frac{d\vec{v}_i}{dt} = q\left(\vec{E}_i + \vec{v} \times \vec{B}_i\right)$$

$$\downarrow$$

$$(\vec{x}_p, \vec{p}_p)$$

Current Deposition

$$\vec{j} = \sum_i q_i \vec{v}_i$$

Update fields

Continuous: $\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$

$$\nabla \times \vec{B} = \frac{1}{c}\left(4\pi \vec{J} + \frac{\partial \vec{E}}{\partial t}\right)$$

$$\downarrow$$

Discrete:

$$\vec{E}^{n+1} = \vec{E}^n + c\Delta t\left(\nabla \times \vec{B}\right)^{n+1/2} - 4\pi \vec{j}^{n+1/2}$$

$$\vec{B}^{n+1/2} = \vec{B}^{n-1/2} - c\Delta t\left(\nabla \times \vec{E}\right)^n$$

Field interpolation

$$\vec{E}_i = \sum \vec{E}(\vec{x}) \cdot S_i(\vec{x})$$

$$\vec{B}_i = \sum \vec{B}(\vec{x}) \cdot S_i(\vec{x})$$

S_i: Shape factor

Disclaimer: PIC simulations are quite harder than this

Parameters of the simulations

- The parameters that are used in the code e.g. magnetic field, density, …, are always given in code units.
- Derived physical parameters show accurately the properties of the shock:
  - $\gamma_{up} = 2.24 \rightarrow \gamma_{sh} \approx 3.3$ (upstream and shock Lorentz factor)
  - $m_i/m_e = 10$ (ion-to-electron mass ratio)
  - $\lambda_{se} = 40,\ \lambda_{si} = 126.5$ (skin depth in units of cells)
  - $\beta_p = 0$ (plasma beta)
  - $\sigma = 0.1, 1.0$ (magnetic energy density over plasma bulk energy)
  - $\theta = 30°, 40°$ (angle between background **B** and the shock normal)
  - $\varphi = 90°$ (angle of background **B** with respect to the simulation plane)

The effect of parameters

- Lorentz factor (γ_{up}):
  - Relativistic shocks usually have large obliquities (relativistic contraction).
  - Magnetised relativistic shocks emit precursor waves via SMI.
  - Relativistic shocks appear in extragalactic sources or even around neutron stars or black holes.
- Ion-electron mass ratio (m_i/m_e):
  - The realistic mass ratio would be $m_i/m_e = 1836$.
  - In simulations, this corresponds to extremely short physical time, but requiring very long simulation times.
  - Usually, simulations use a smaller mass ratio while maintaining the physics of the shock.

The effect of parameters

- Electron skin depth ($\lambda_{se} = \frac{c}{\omega_{pe}}$):
  - Determines the resolution of the simulation.
  - Larger λ_{se} → Better resolution albeit larger simulation size.
  - There is always a **trade-off**.
- Plasma beta (β_p):
  - Plasmas have a certain temperature that can affect the results.
  - We quantify it by the plasma beta $\beta_p = \frac{nk_BT}{P_B}$, the ratio of thermal pressure to magnetic pressure $P_B = \frac{B^2}{2\mu_0}$.
  - Ultimately, the temperature is just the <u>random motion</u> of particles.

The effect of parameters

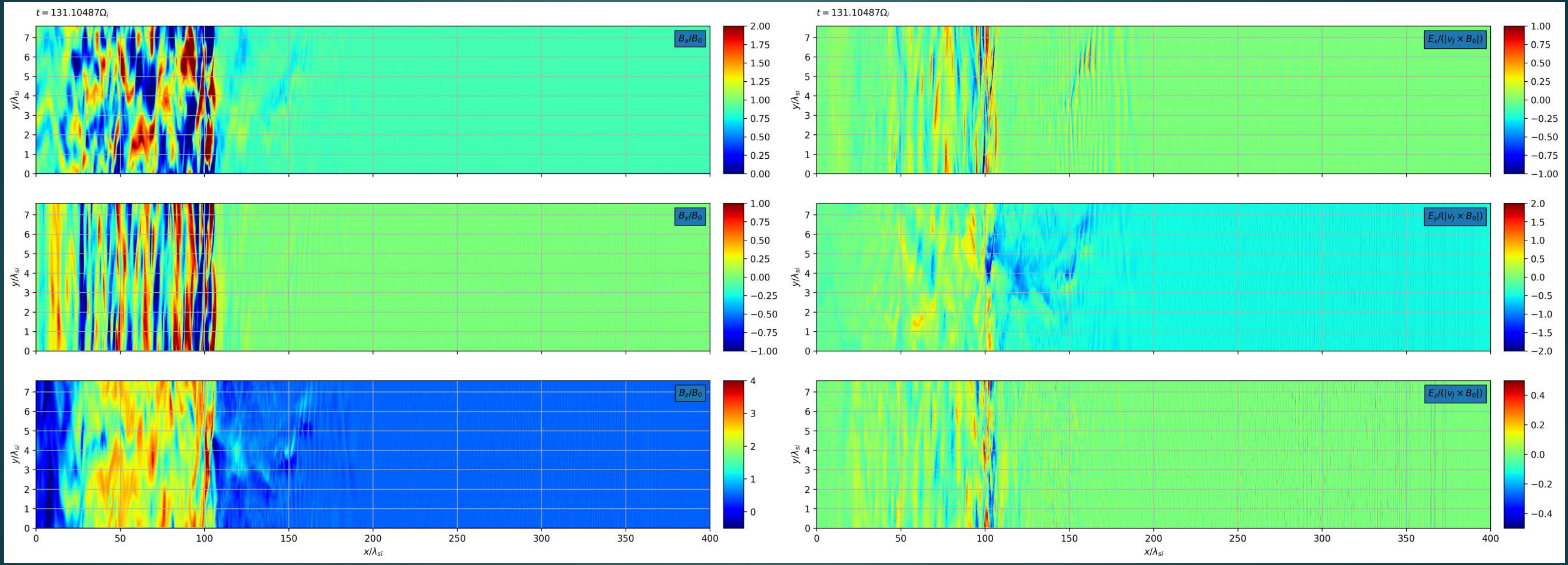
- Magnetisation ($\sigma = \frac{u_p}{P_B}$):
  - To compare the magnetic field and the plasma velocity, we use both energy densities:
    - Magnetic energy density, which is also the magnetic pressure P_B
    - Plasma bulk energy: $u_p = n\gamma_0 mc^2$
  - Large magnetisation will cause electrons to likely follow magnetic lines.
- Obliquity angle (θ):
  - Direction of the magnetic field with respect to the shock normal.
  - The obliquity divides the shock in two different regimes: sub and superluminal shocks.
  - This angle is of great importance in terms of particle acceleration.

The effect of parameters

- Simulation plane angle (φ):
  - Our simulations are performed in 2 spatial dimensions due to computational constraints.
  - The angle of the magnetic field with respect to the simulation plane can play an important role.
  - Sometimes, the physics do not change whether the magnetic field is in-plane or out-of-plane.

- A small change in the initial parameters can lead to great differences.
- Plasma evolution can be highly non-linear.

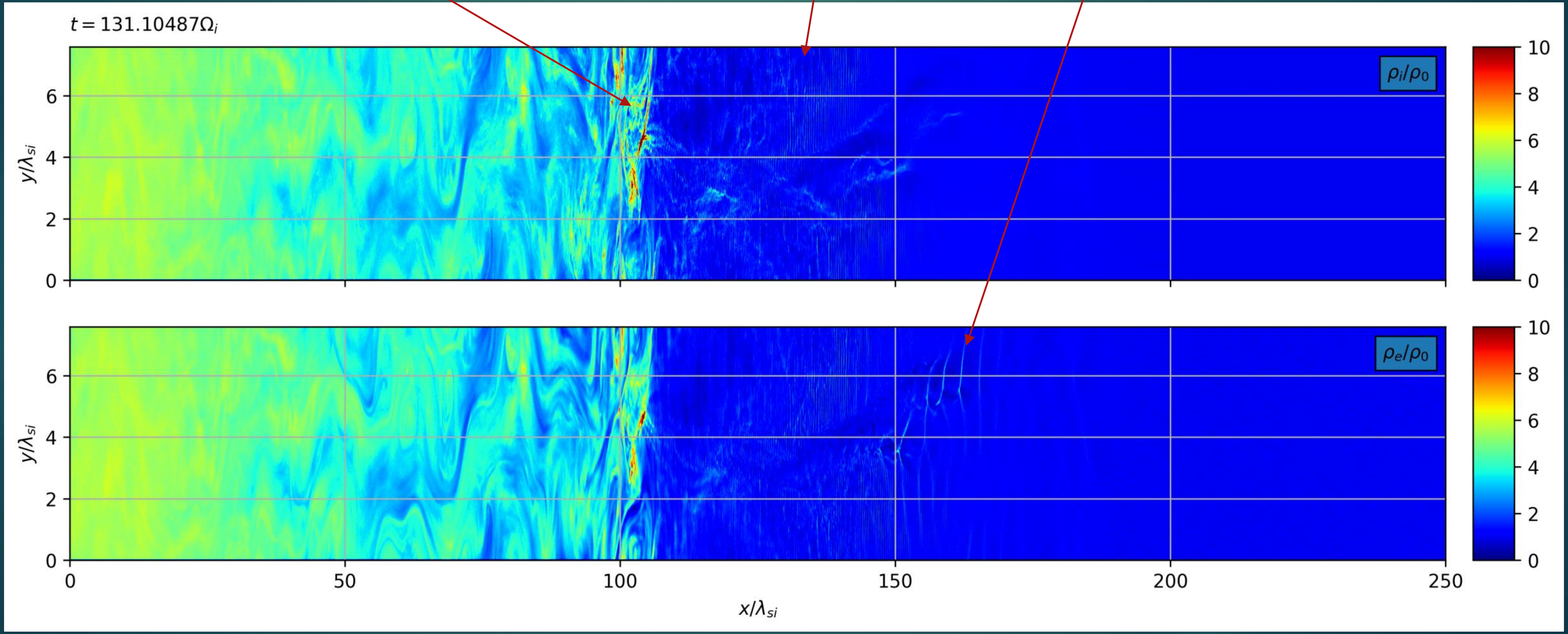
Results (σ = 0.1, θ=30°)



Magnetic field

Electric field

Density



Shocks do not necessarily have to be laminar

Small scale density waves in front of the shock

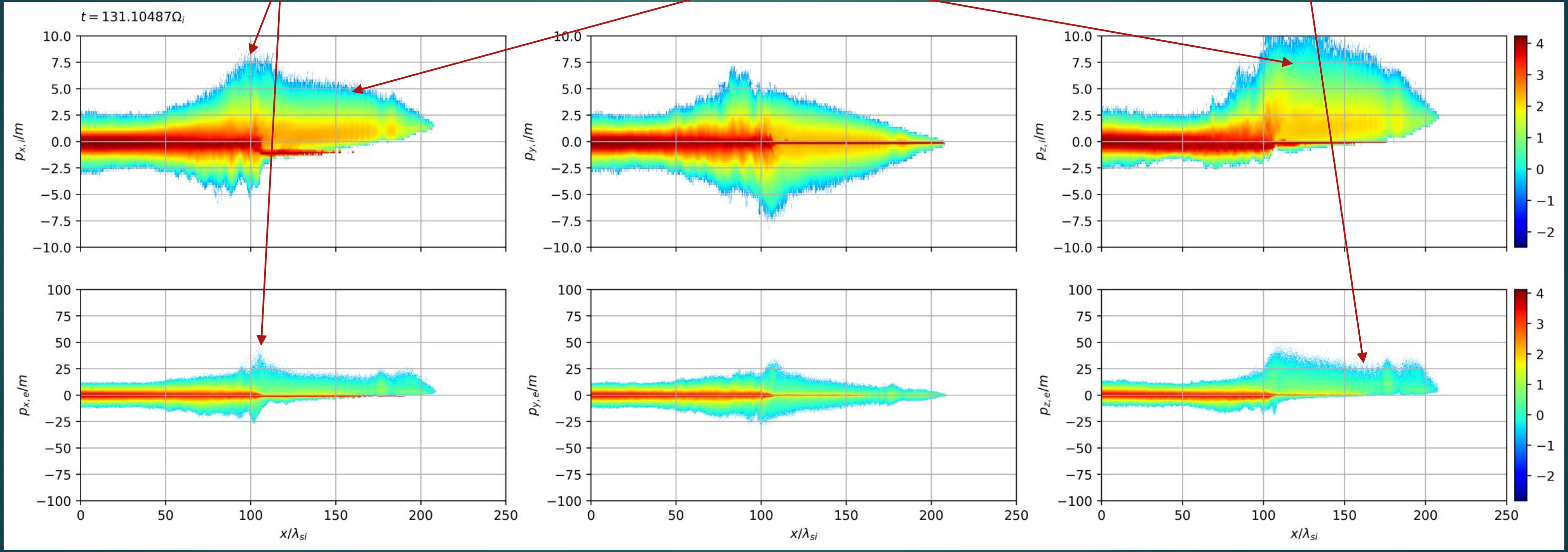
Mid-scale waves associated with accelerated electrons

Phase space

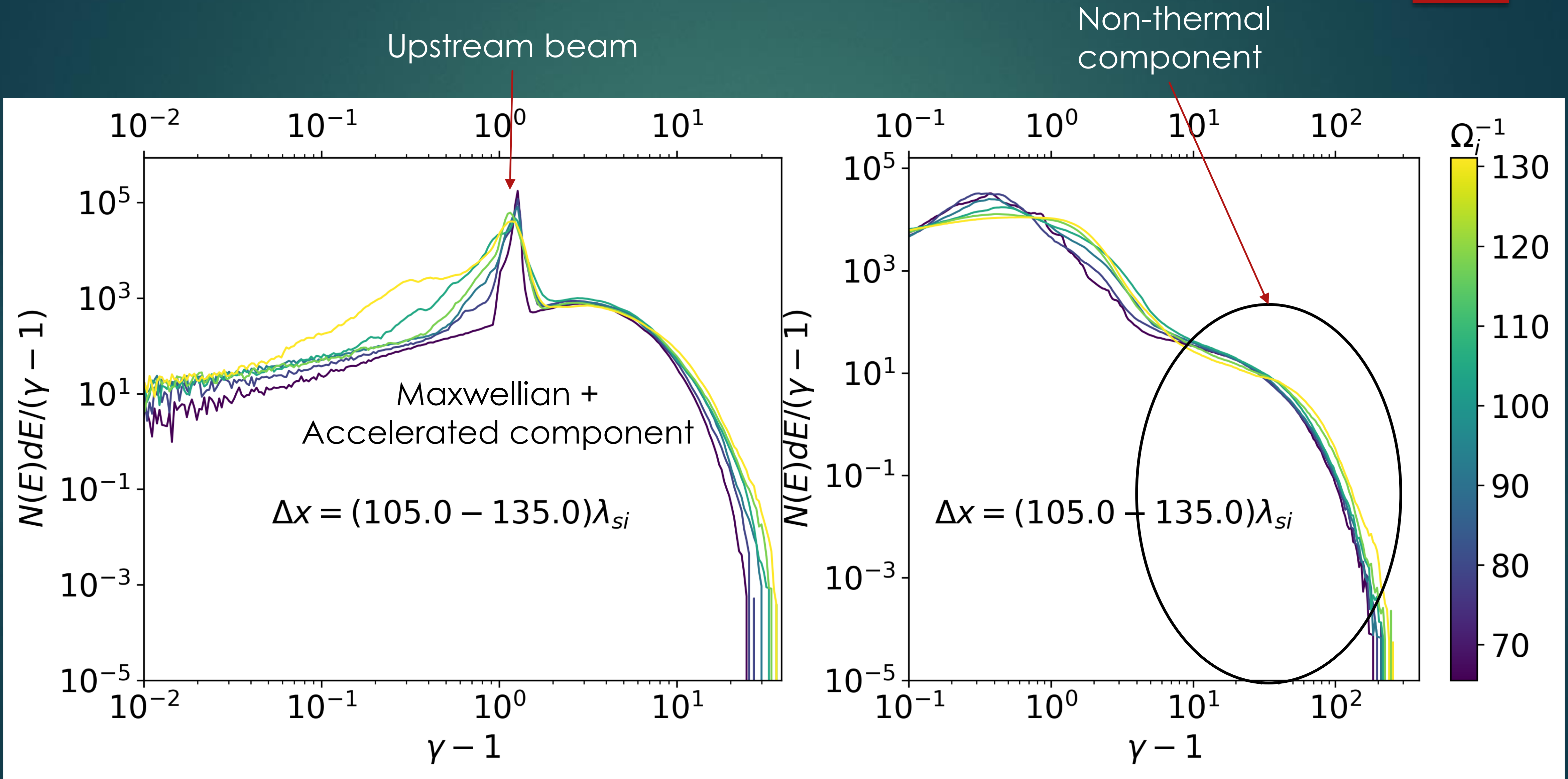
Protons and electrons
get accelerated and reflected

They are reflected
following magnetic lines

The mid-scale waves are
seen here in phase space!



Spectra



Upstream beam

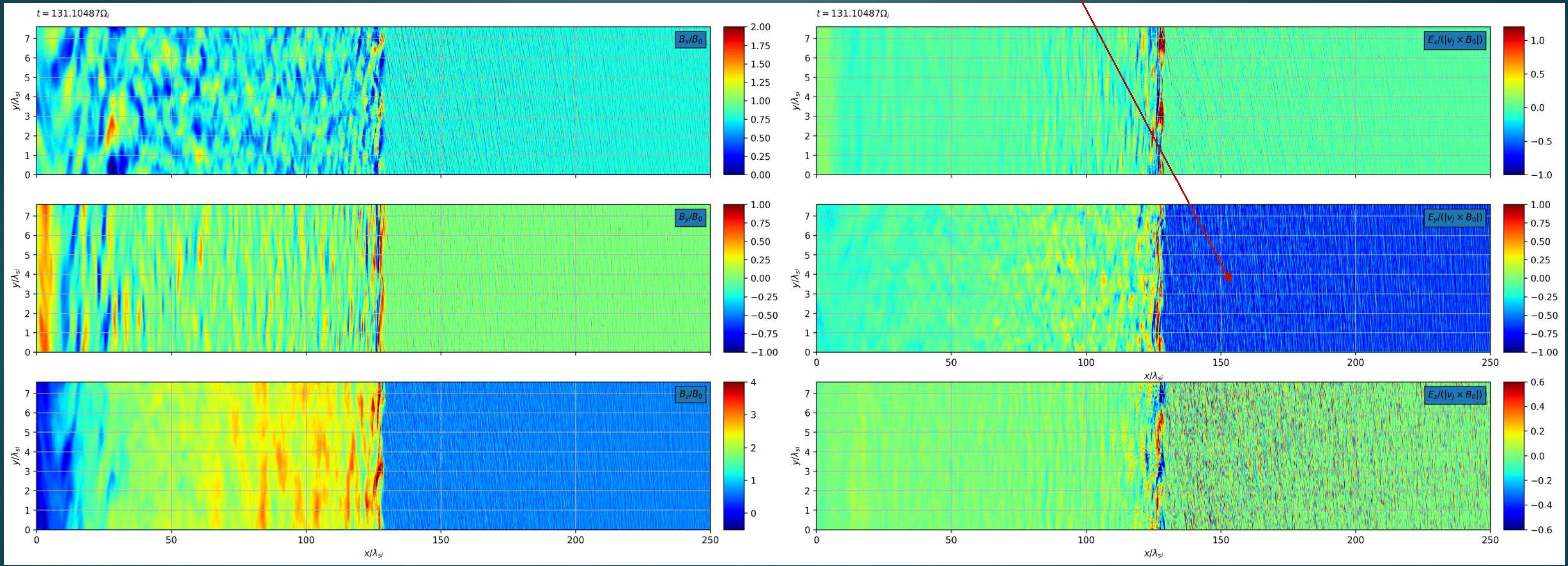
Non-thermal component

Maxwellian + Accelerated component

Results (σ = 0.1, θ=40°)

For a superluminal shock, the wave activity decreases

There are only precursor waves

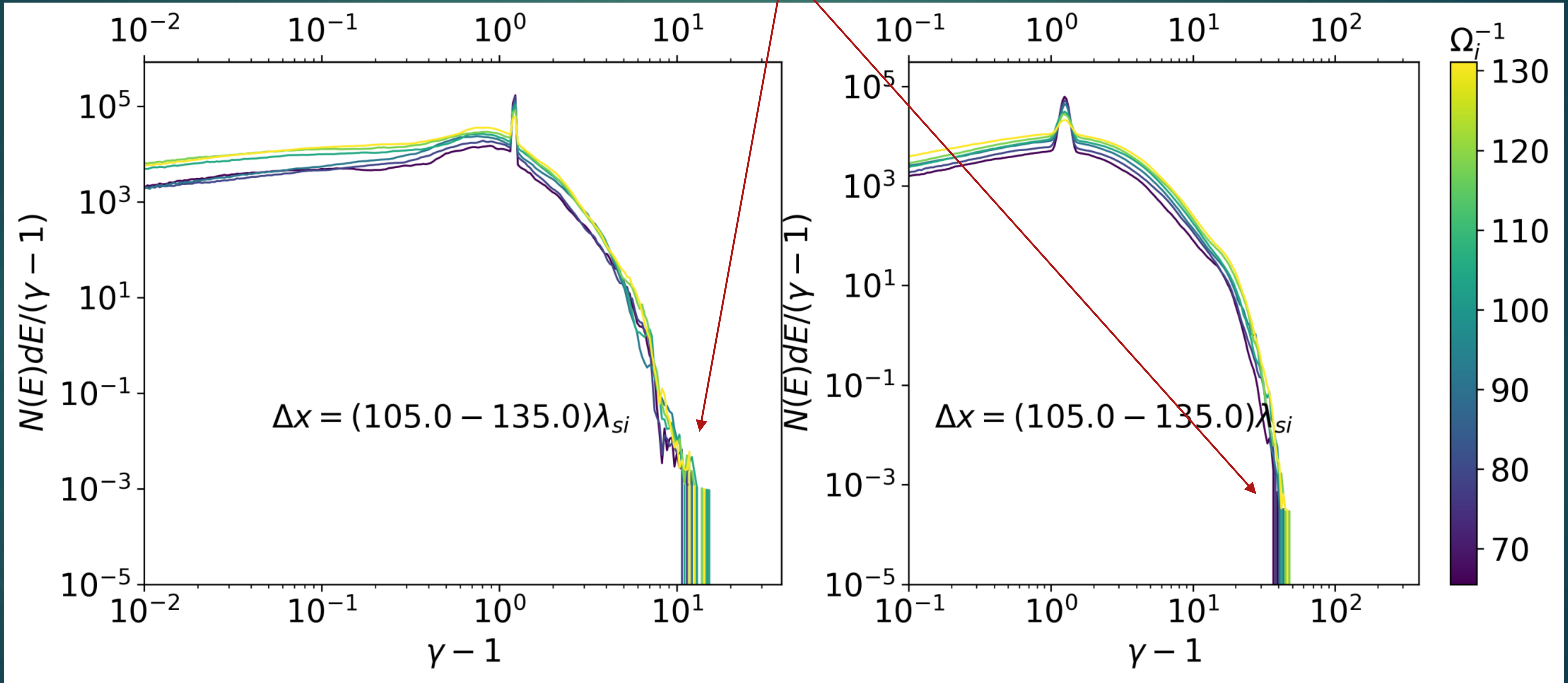


Magnetic field

Electric field

Spectra

Ions and electrons are barely accelerated

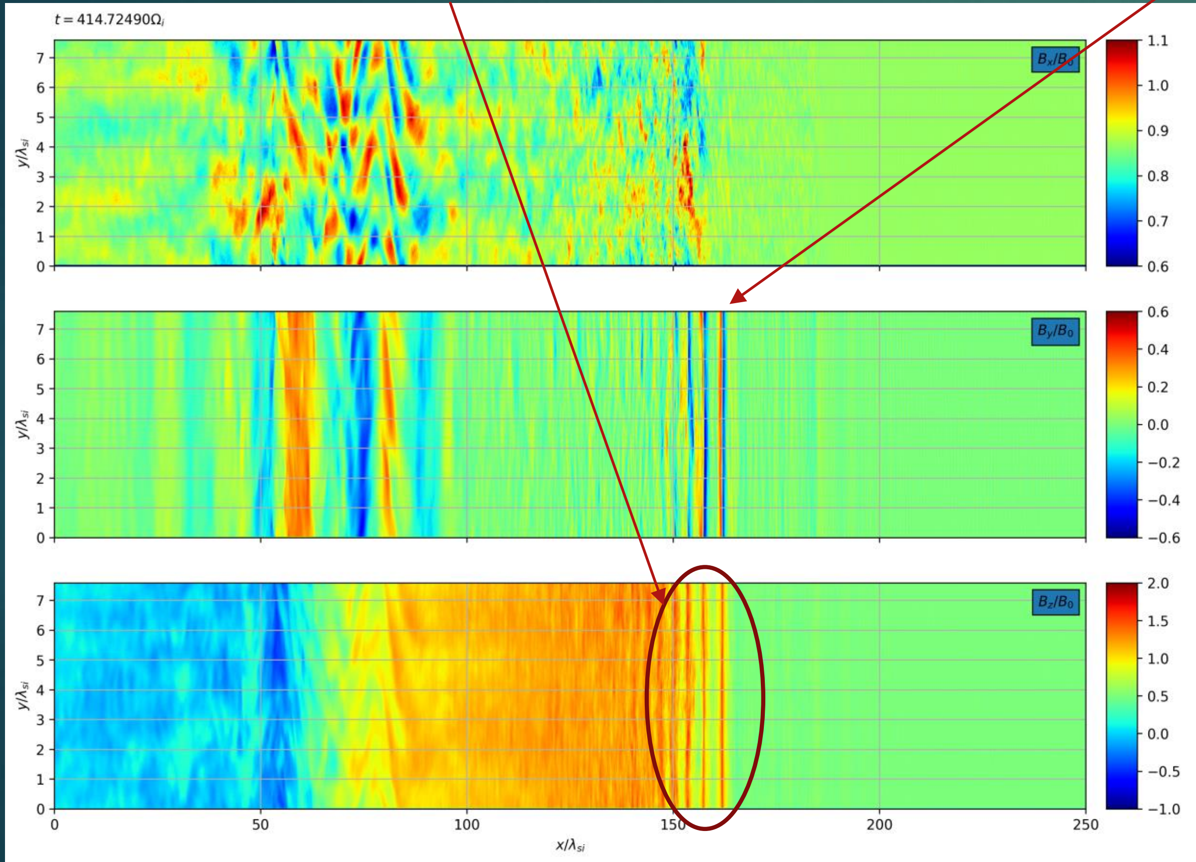


Results (σ = 1.0, Θ=30°)

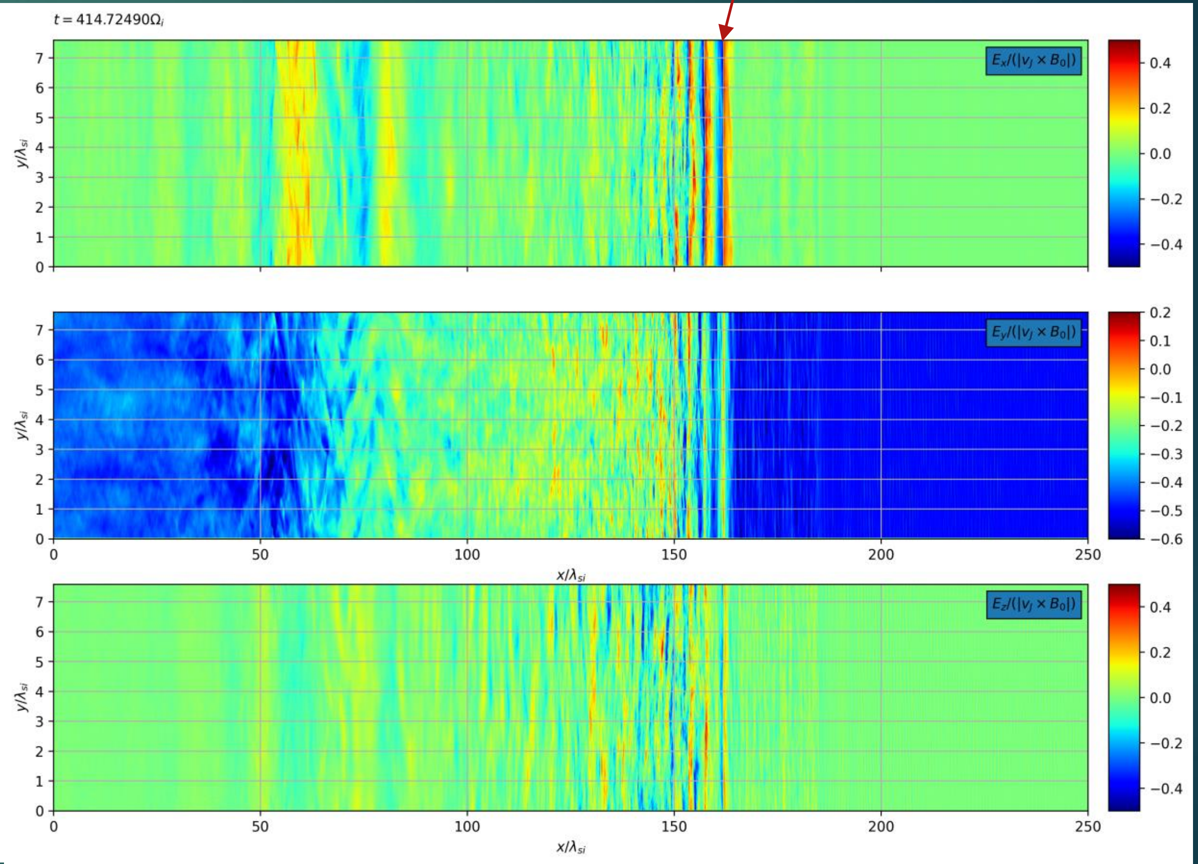
We cannot even call it shock as the transition to the downstream is not yet formed

Very planar shock. No corrugation as for σ = 1.0

Very strong Ex gradient



Magnetic field

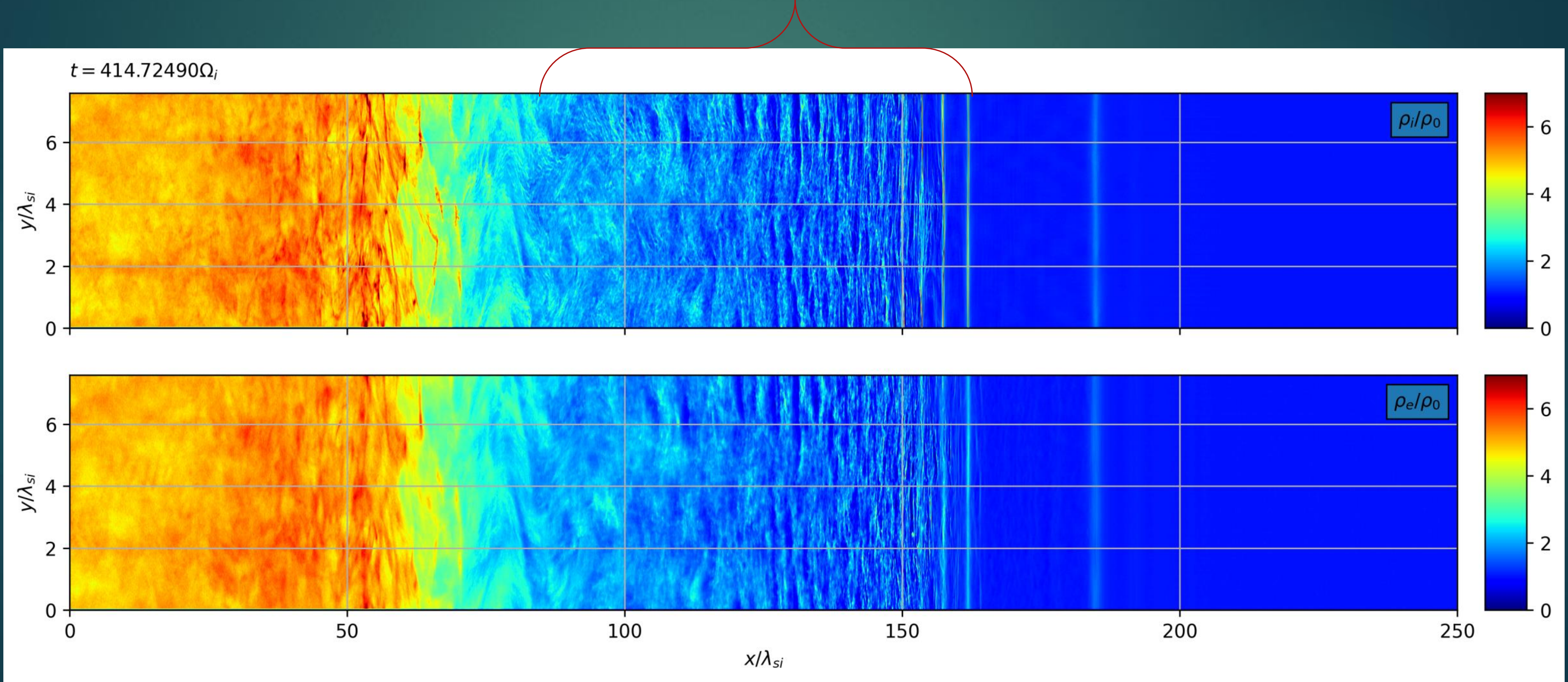


Electric field

Density

The "shock" is more of a series of strong soliton waves

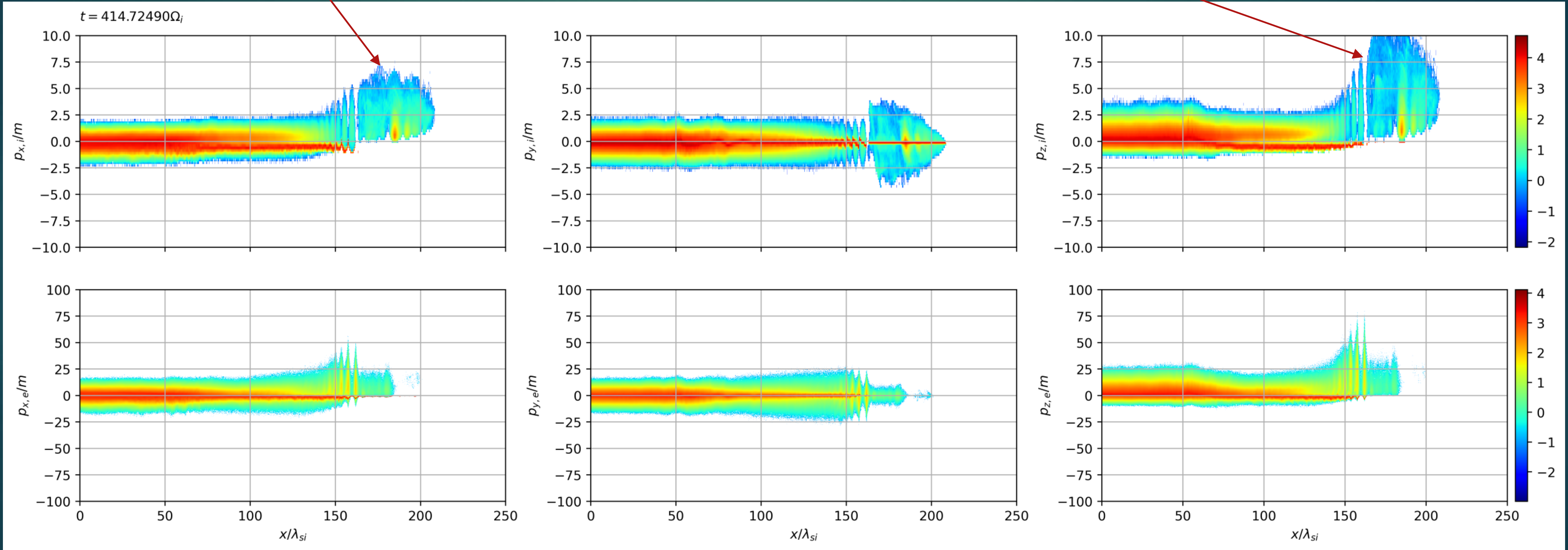
The shock transition spans over a long range



Phase space

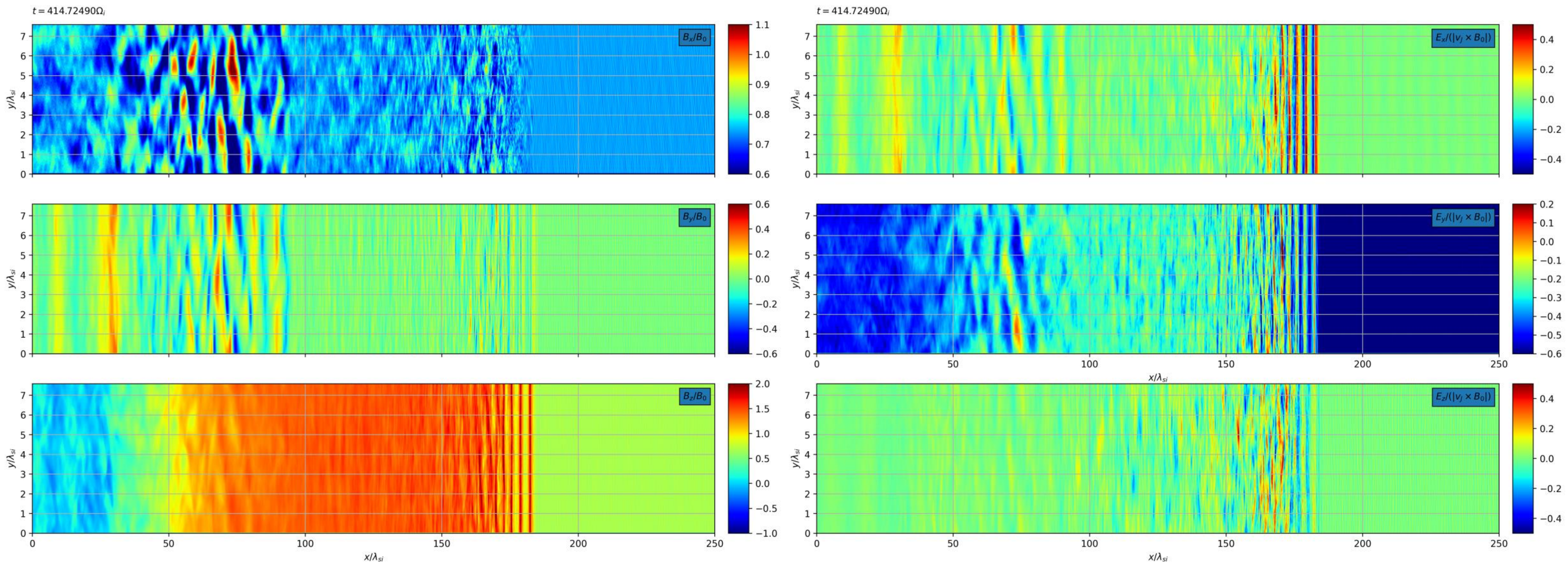
Massive acceleration in front and at the shock

Ions have two clearly separated populations



Results (σ = 1.0, θ=42°)

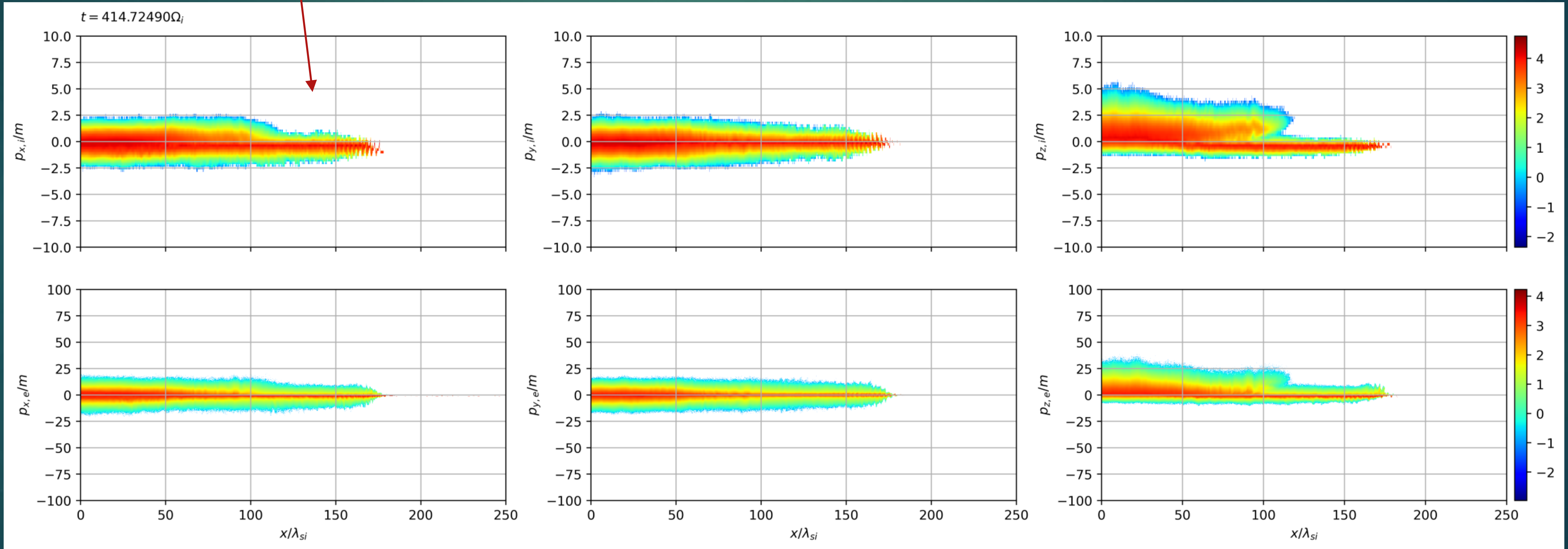
Similar structure to the case of 30°.



Phase space

But contrary to 30°, there is no acceleration.

The shock is in the supercritical regime.



Large-scale simulations

- Previous results show mid-scale simulations.
- We are planning large-scale simulations on LUMI.
- We will search for a broader parameter range, extending simulations up to $T = 250\Omega_i^{-1}$.
- What does large-scale mean?
  - The largest simulation will use up to 192 CPUs or 12,288 cores.
  - A total of storage used of ~360 TB, spanning 2 million files.
  - A total of 20 MCPUh!

LUMI supercomputer
in Finland

Future prospects

- As mentioned, large scale simulations are planned, totalling to 13 simulations.
- Parameter range:
  - $\sigma = 0.1, 1$
  - $\theta = 10°, 20°, 30°, 40°$
  - $\varphi = 0°, 90°$
  - $m_i/m_e = 100, 400$
- To understand how particles get accelerated, particle tracing is required.
- Dispersion relation $\omega(k)$ plots are important to understand the type of waves we observe.

Summary

- We study mildly relativistic shocks for mild and high magnetisations and oblique configurations.
- Strong waves are observed for both magnetisations, as well as a surprising acceleration of particles.
- Spectra show a non-thermal population which might help in understanding the origin of cosmic rays.
- Large-scale simulations are planned in LUMI.
- Research still goes on!