Mildly relativistic shocks at high magnetization using PIC simulations

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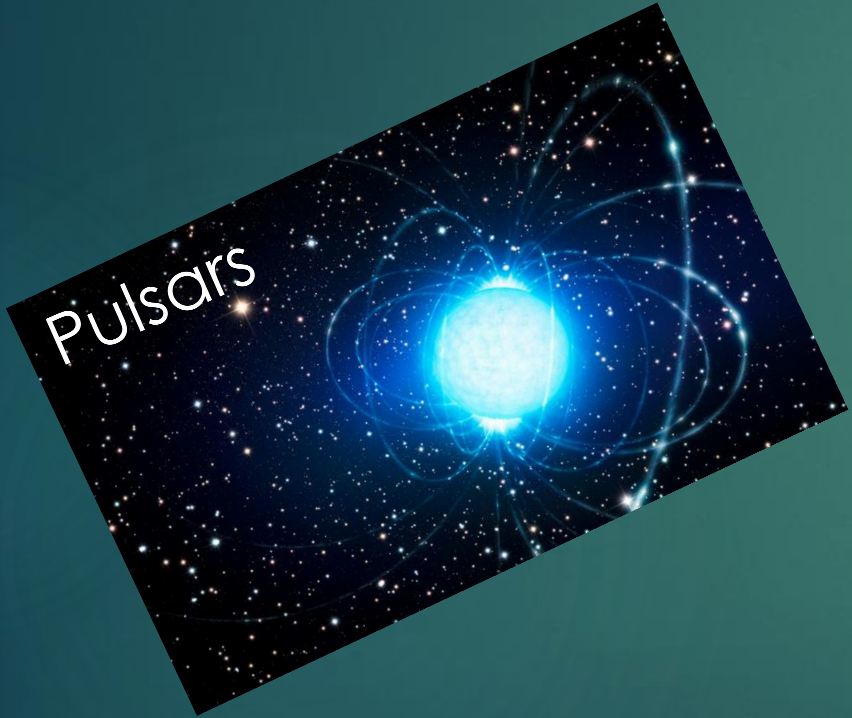
Ultra-relativistic shocks: an overview

Three main sites:



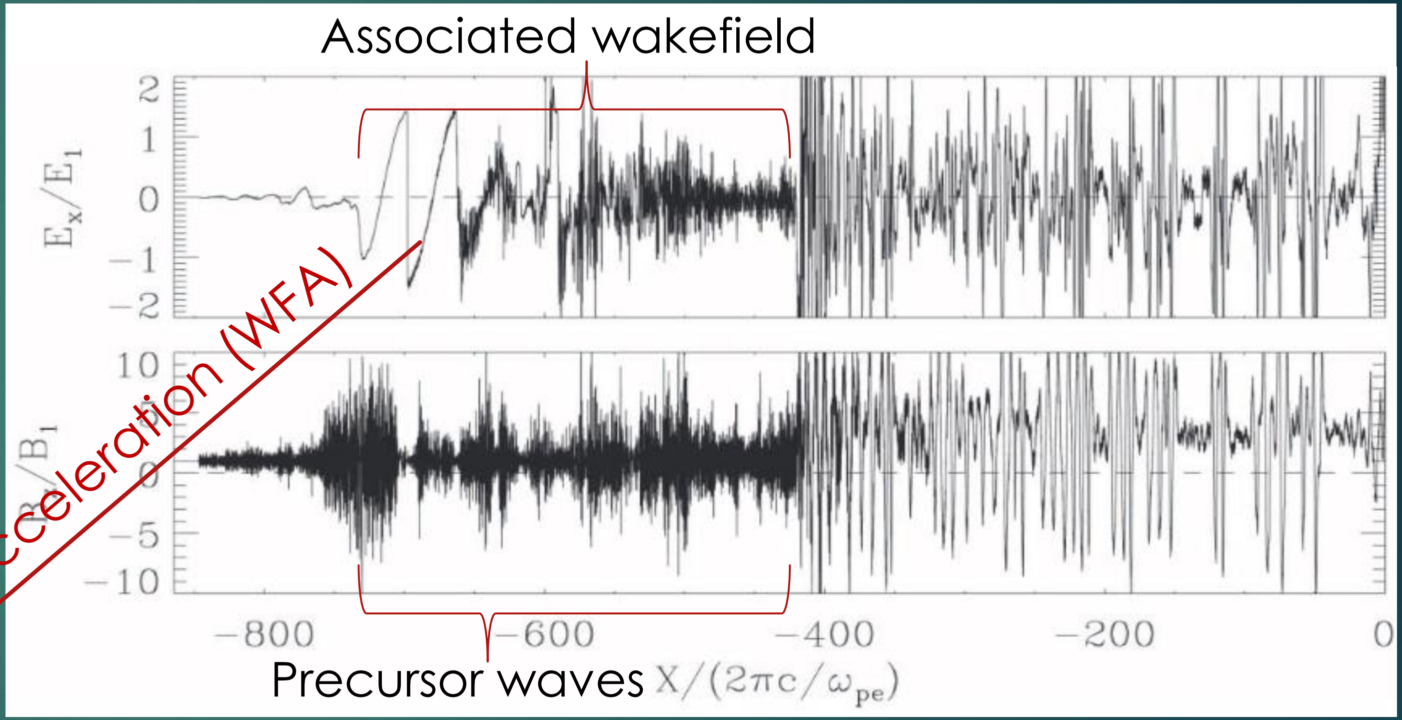
Galactic sources

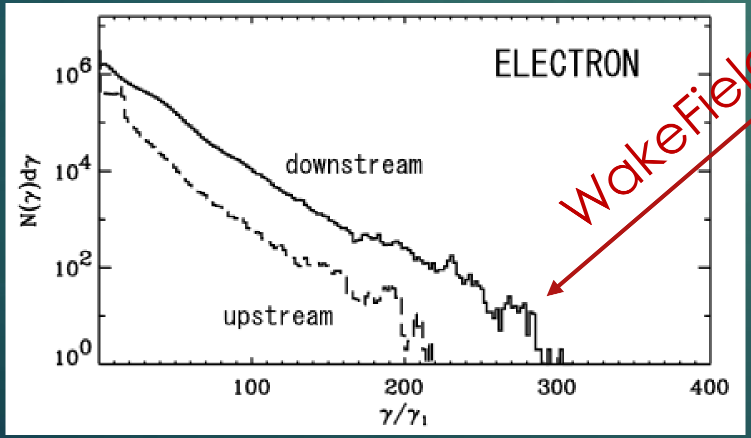
Extragalactic sources

Ultra-relativistic shocks: an overview

- $\gamma_{sh} \gtrsim 10$
- Intrinsic <u>superluminal</u> conditions
- Inherent precursor waves
  - Electric wakefield → Electron acceleration!

Ultra-relativistic shock structure

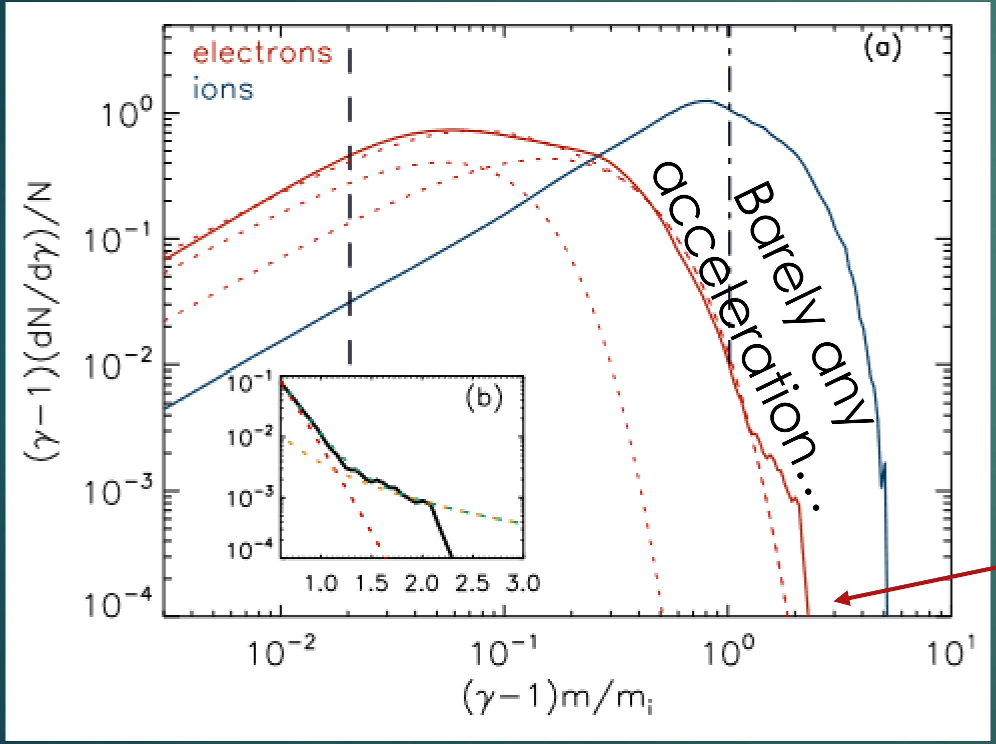


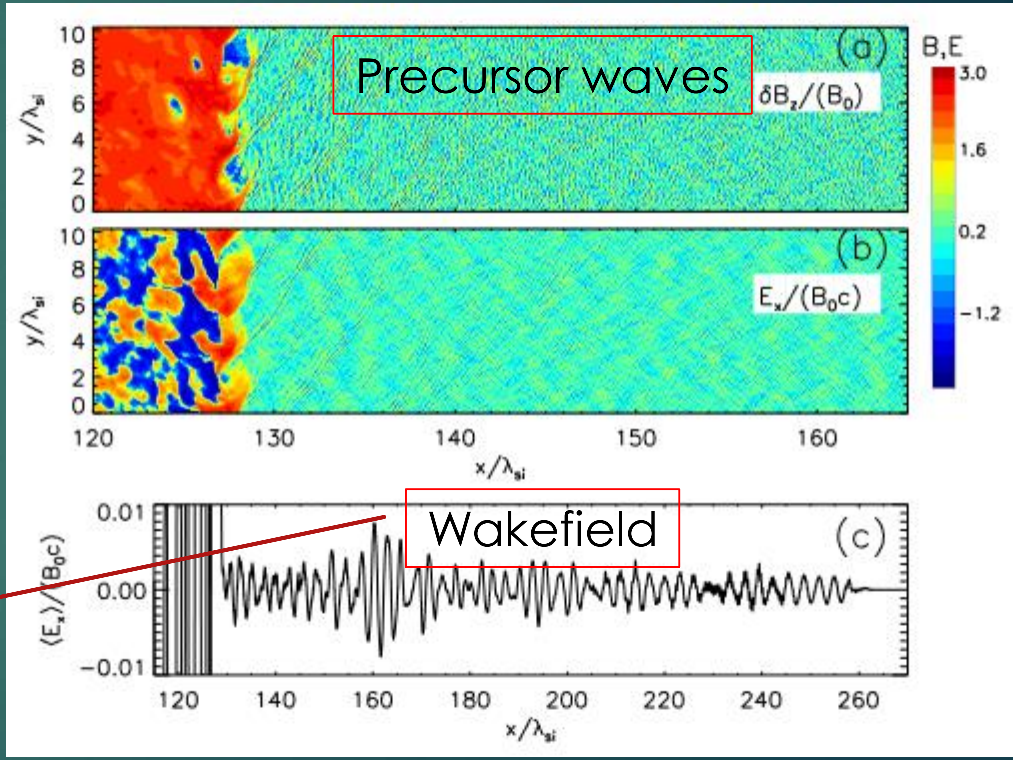


Hoshino, 2008

WFA in mildly relativistic shocks

- Mildly relativistic shocks show precursor waves
- But the WFA efficiency is very low…

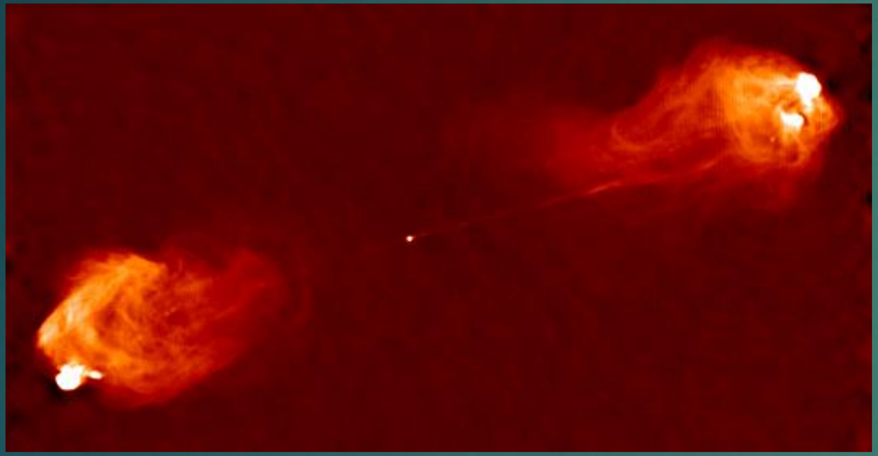




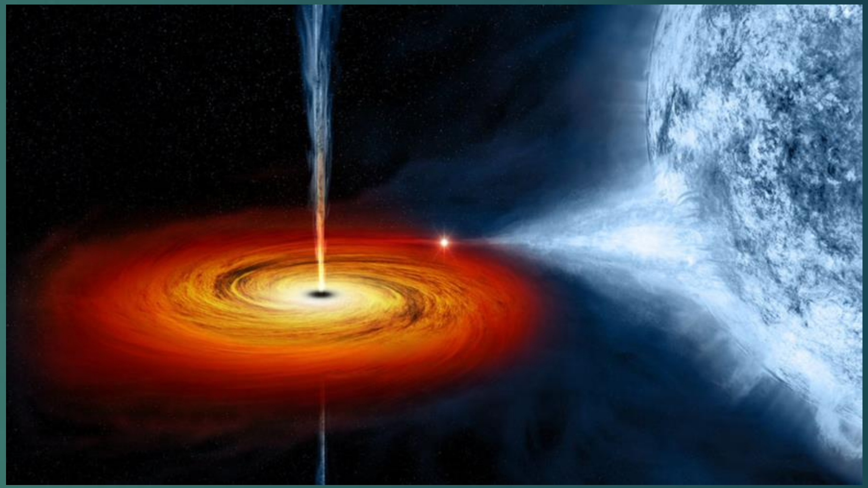
PIC simulation of a strictly perpendicular mildly relativistic shock. Taken from Ligorini, A., et al. 2021.

Mildly relativistic shock sites

Where can we find these?



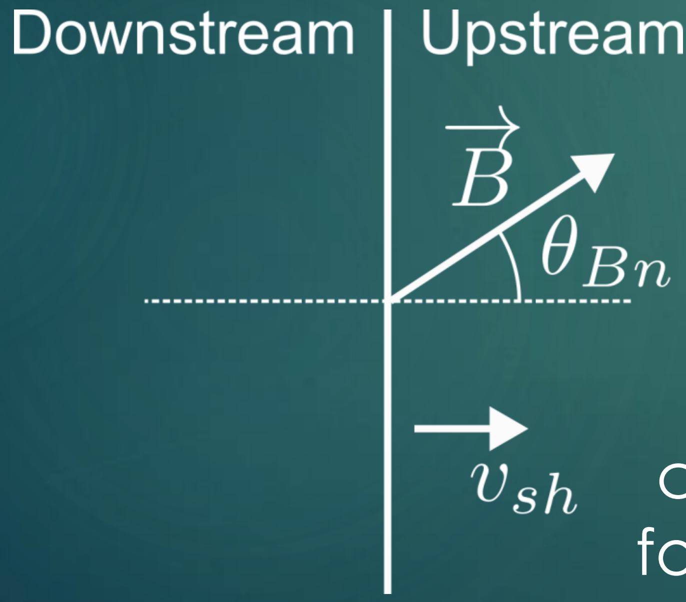
- AGN jets / AGN hot spots
  - $\gamma_{bulk} \sim a\ few$
  - Strong X-ray emission
  - Magnetic field structure?



- X-ray binaries / Microquasars
  - Jets (mildly rel. locations)
  - Quite strong B field
  - Classic example: SS 433

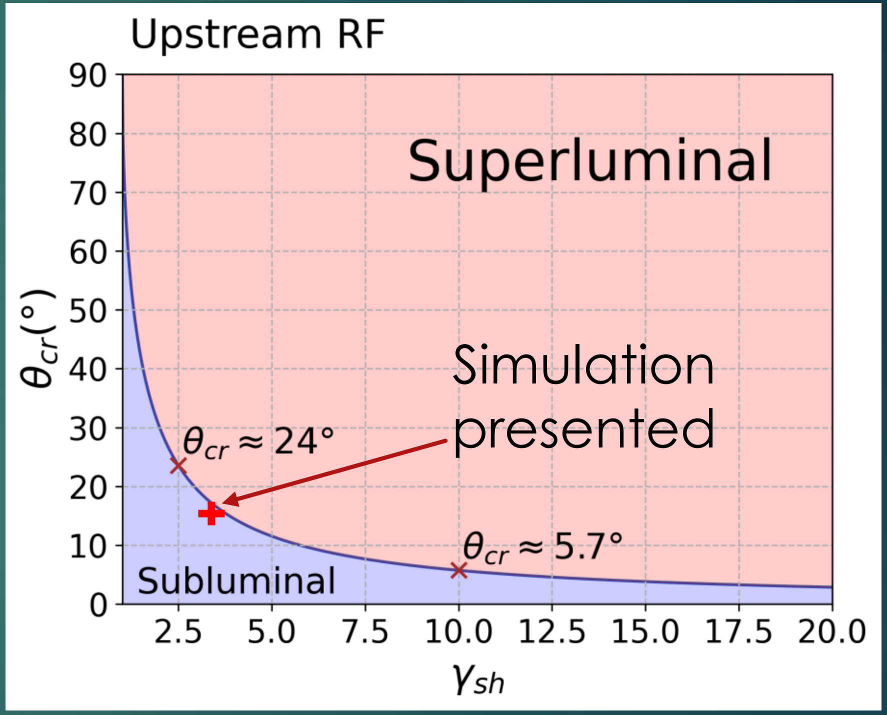
Mildly relativistic shocks offer more!

- Mildly relativistic shocks have a wider range of subluminal conditions!
- Subluminal? You may ask…



Subluminal configurations allow for particle reflection!

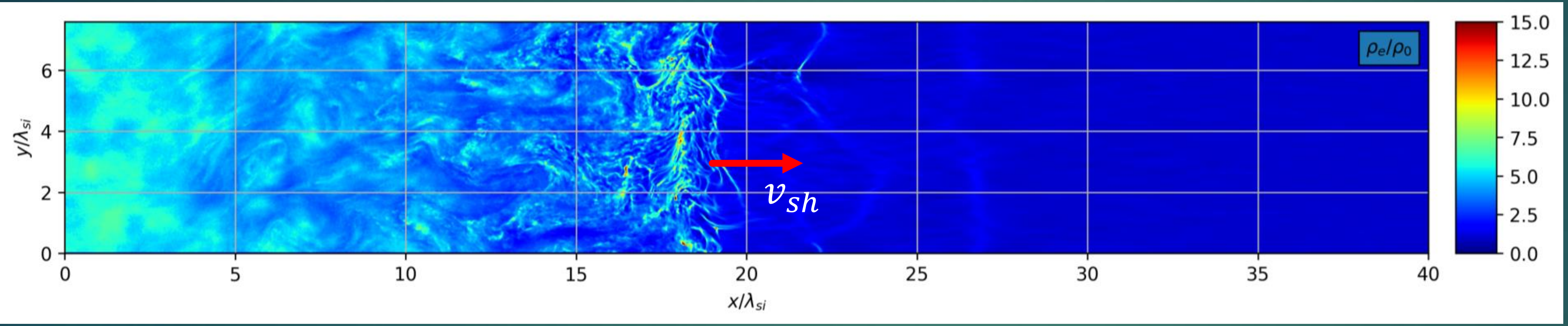
$$v_{sh} = c\cos\theta_{cr}$$



Critical angle vs. Shock Lorentz factor with two examples.

Particle-In-Cell (PIC) simulations

- Plasma shocks can be studied using PIC simulations.
- They require a lot of computational power.



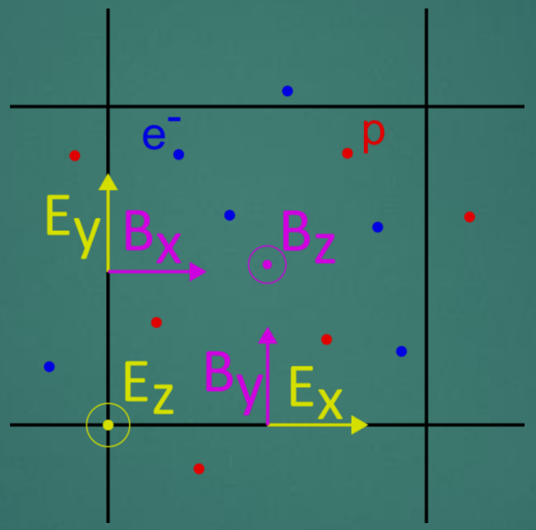
Typical PIC simulation plot: electron density ρ_e.

- Resources (for one simulation):
  - Cluster: Ares at ACK Cyfronet AGH (CPU partition)
  - Max. number of processes used: 1440 (30 nodes)
  - Time: 129 h, 121795 CPUh
  - Storage: 6 TB

Particle-In-Cell method

Particles are pushed (Lorentz force):

$$\frac{d^2\boldsymbol{x}}{dt^2} = \frac{q}{m}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$



Particles deposit the current in a discrete grid:

$$\boldsymbol{j} = \sum_i q_i v_i$$

Current density → E and B field:

$$\boldsymbol{\nabla} \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} \quad \boldsymbol{\nabla} \times \boldsymbol{B} = \frac{1}{c}\left(4\pi \boldsymbol{j} + \frac{\partial \boldsymbol{E}}{\partial t}\right)$$

E and B interpolation at particle i:

$\boldsymbol{E}_i, \boldsymbol{B}_i$

Subluminal mildly relativistic shocks

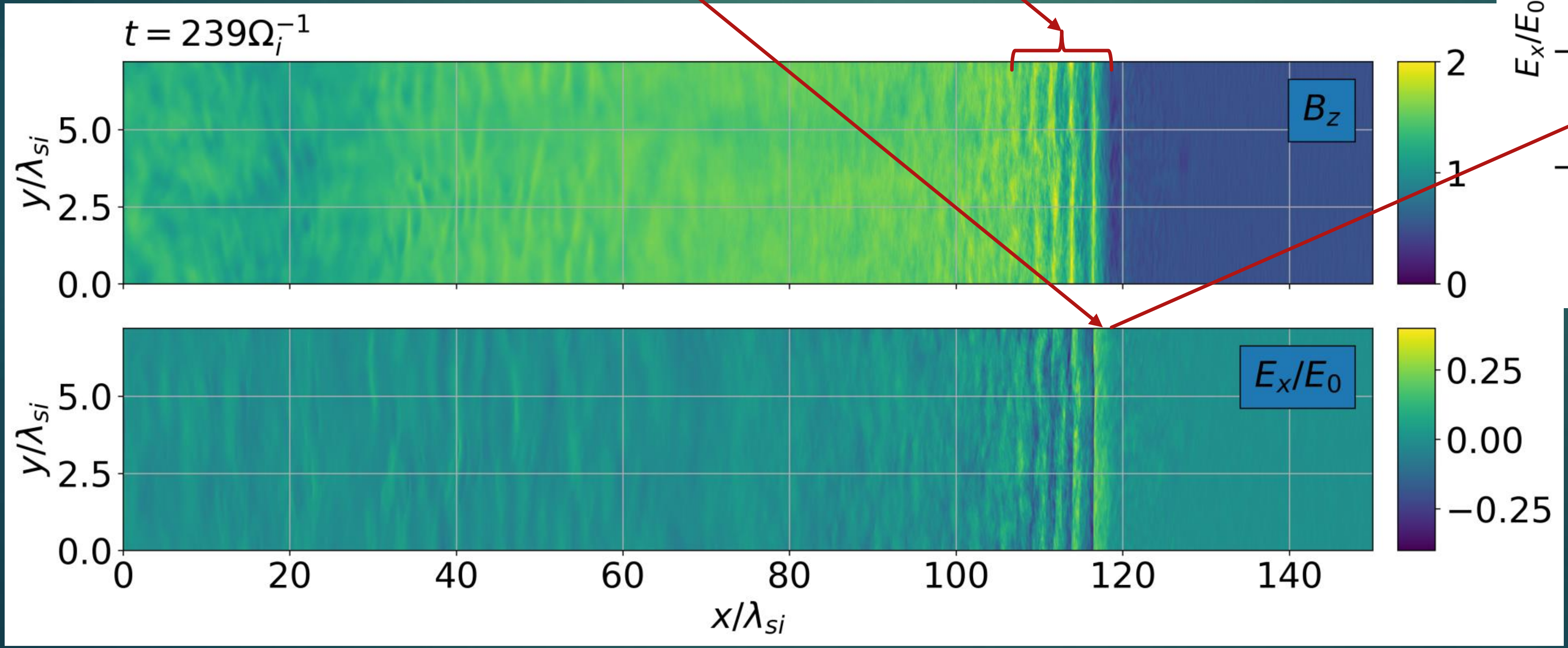
- Mildly relativistic[1] strongly magnetised[2] oblique[3] shocks:

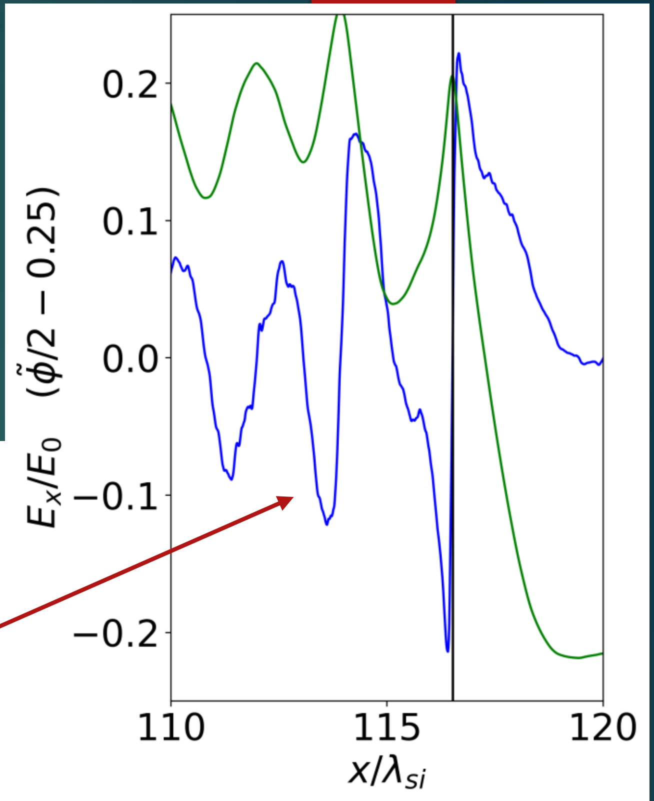
1. Shock speed: $v_{sh} \approx 0.953c$
   or Lorentz factor $\gamma_{sh} \approx 3.3$
2. Magnetisation $\sigma = 1$
   $$\sigma = \frac{\Omega_c^2}{\omega_p^2} = \frac{B^2}{\mu_0 \gamma n m c^2}$$
3. Obliquity $\theta_{Bn} = 30°$

- This "middle ground" of mildly rel. shocks looks promising!

Shock structure at Θ=30°

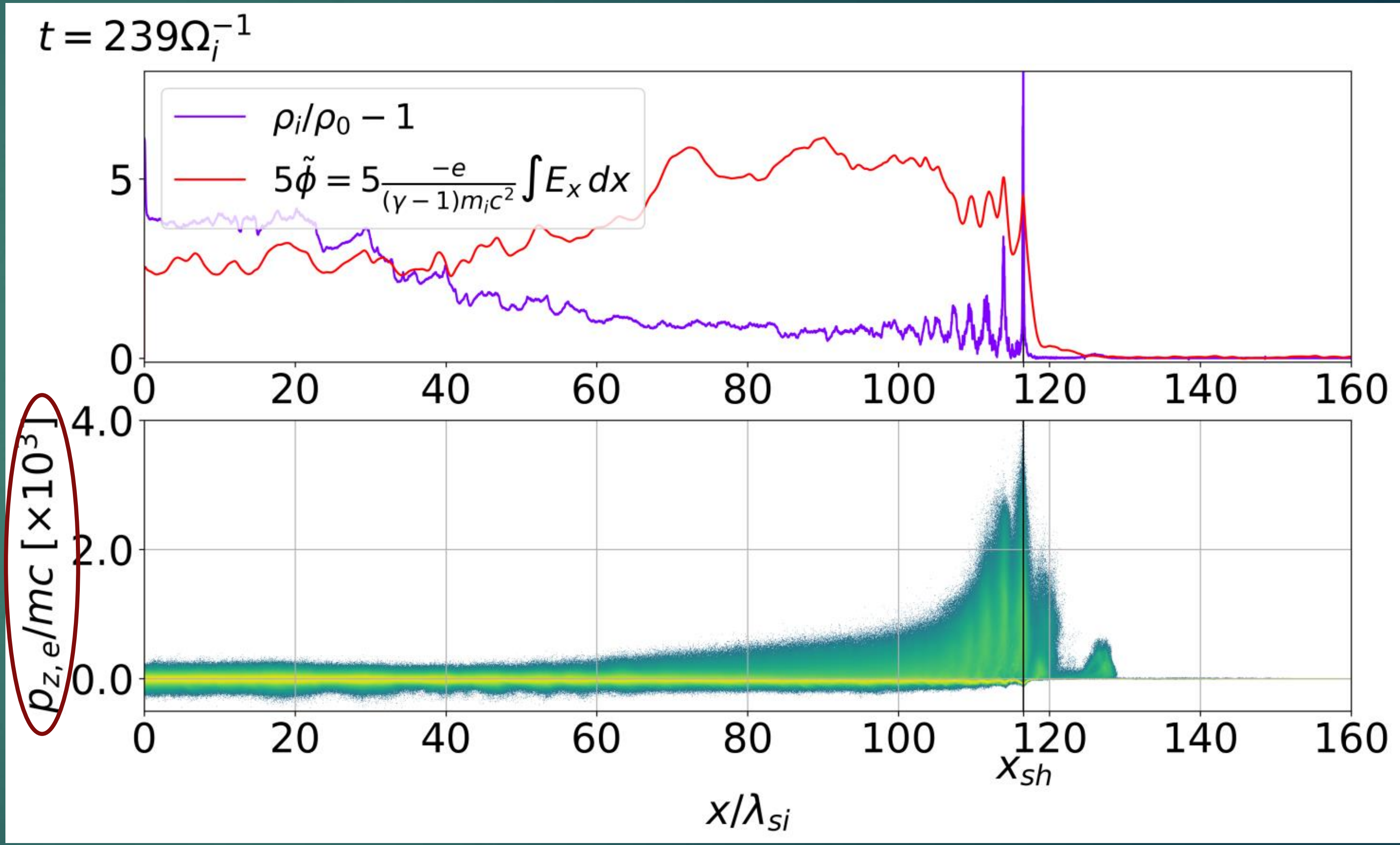
- Atypical shock
  - Series of magnetosonic waves.
  - Strong E_x gradient.





Phase space and acceleration

- Strong electron acceleration.
  - Note the units!
- Clearly, there must be a relation with ϕ.
- Acceleration parallel to **B**.
  - p_x and p_z.



Electrostatic potential and normalised electron momentum in z-direction

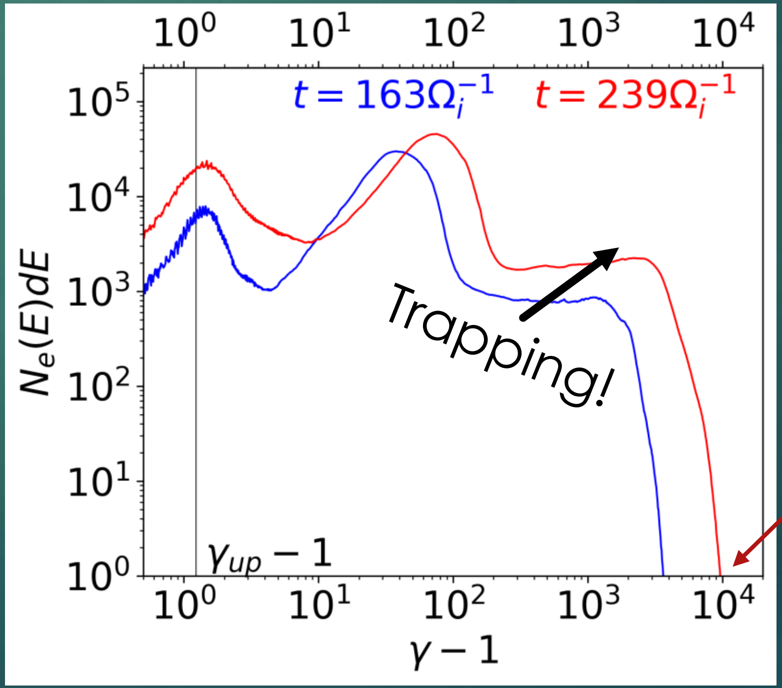
Electron acceleration

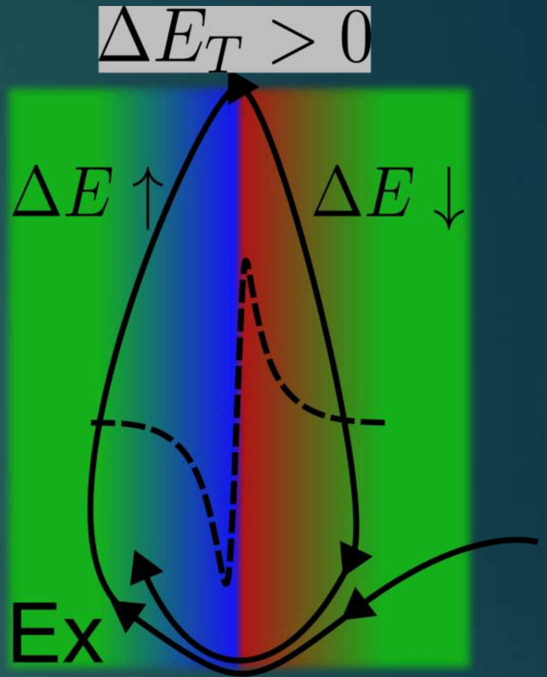
- Following Bessho and Ohsawa 1999, 2002:
  - Strong magnetosonic wave + Oblique magnetic field

    =

    - Electron trapping and acceleration!

1. Electrons get trapped in the large electrostatic potential.
2. Acceleration over many cycles.
3. Net energy increases!





$\gamma_{max} \approx 10{,}000$

Summary

- Mildly relativistic shocks enable particle acceleration mechanisms different than that at ultra-rel. shocks at subluminal configurations.
- Oblique mildly rel. shocks accelerate electrons and ions to very high energies.
- Other subluminal obliquities are currently under research.