



# Ion and electron acceleration in strongly magnetised mildly relativistic shocks

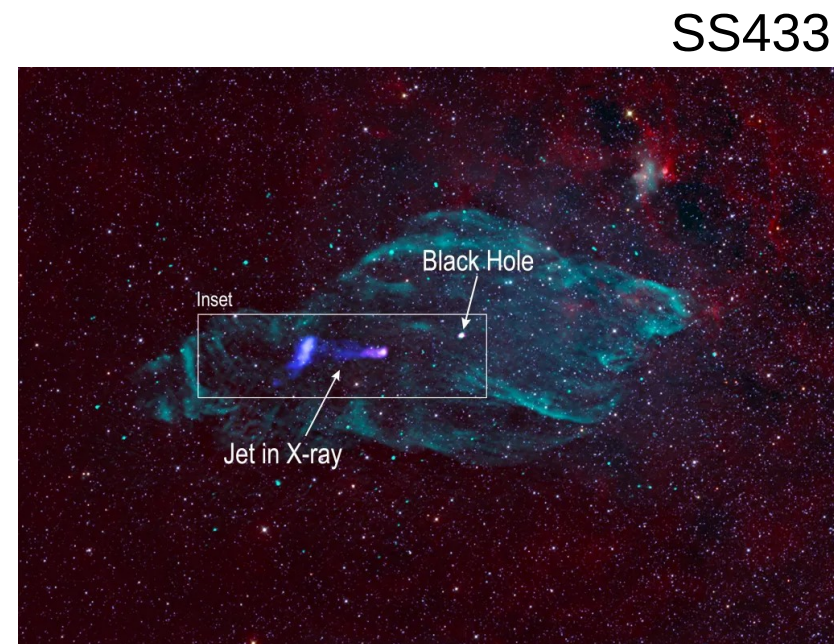
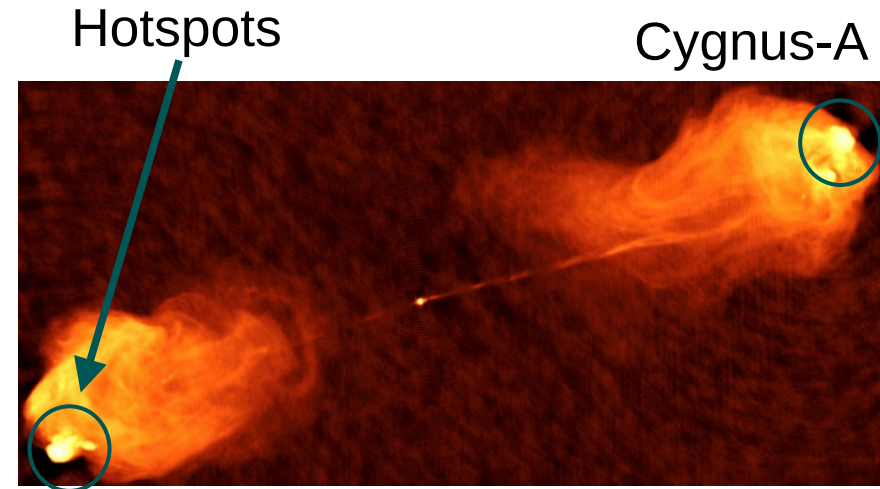


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# Mildly relativistic (MR) shocks in jets



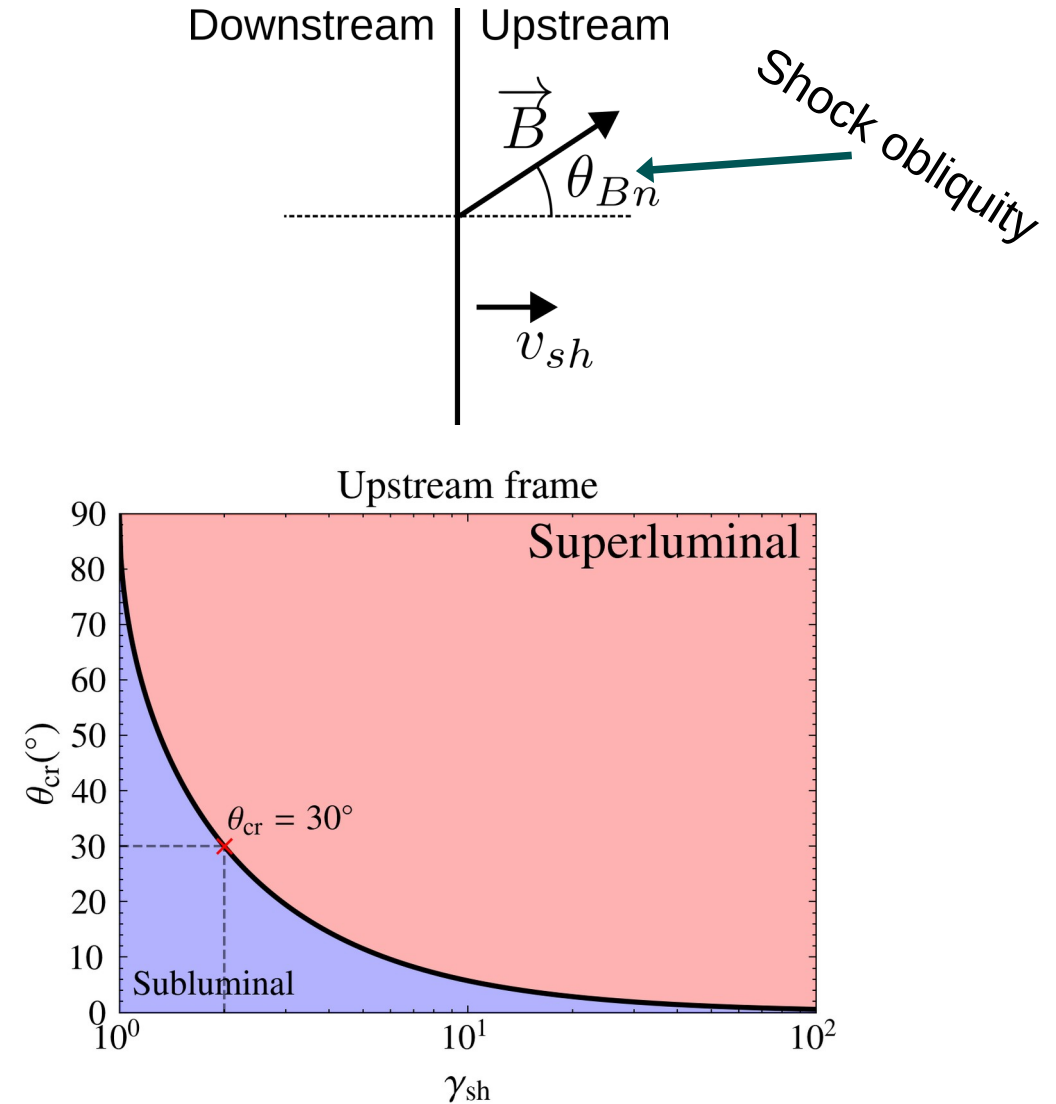
- Strong X-ray or  $\gamma$ -ray emission observed from jets of AGN and MQ
  - Indicates **particle acceleration**
- We expect mildly relativistic shocks in
  - **AGN hotspots**
  - **Standing shock** at base jet of MQ
- Mildly relativistic means  $\gamma_{\text{bulk}} \approx 2-5$
- Plasma in these jets is expected to be **magnetised**



# Superluminal and subluminal shocks



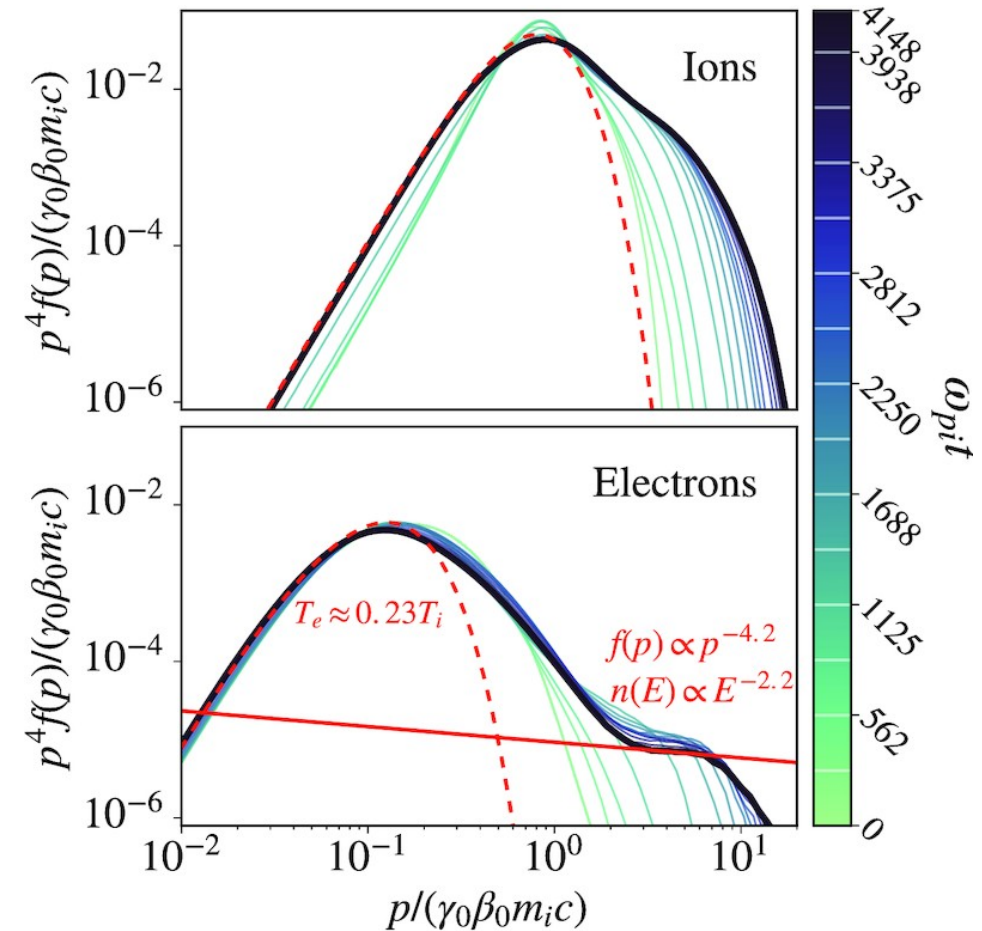
- In magnetised shocks, there exists an obliquity angle,  $\theta_{cr}$ , defined as:
  - Shock frame:  $\tan(\theta_{cr}) = c/v_{sh}$
  - Upstream frame:  $\cos(\theta_{cr}) = v_{sh}/c$
- Depending on the obliquity angle, the shock behaves differently:
  - $\theta_{Bn} < \theta_{cr}$  : particles can reflect off the shock-compressed magnetic field back upstream (subluminal)
  - $\theta_{Bn} > \theta_{cr}$  : particles are ultimately advected downstream (superluminal)



# Already studied mechanisms in MR shocks

## Diffusive shock acceleration (DSA)

- DSA is a very well-known mechanism
  - A particle is specularly reflected on each side of the shock (due to e.g. waves, turbulence, ...) and gains energy for each shock crossing
- Efficient in the non-relativistic regime
- Generally not efficient in ultra-relativistic (UR) shocks
- Efficient in MR shocks work for subluminal weakly or un-magnetised shocks



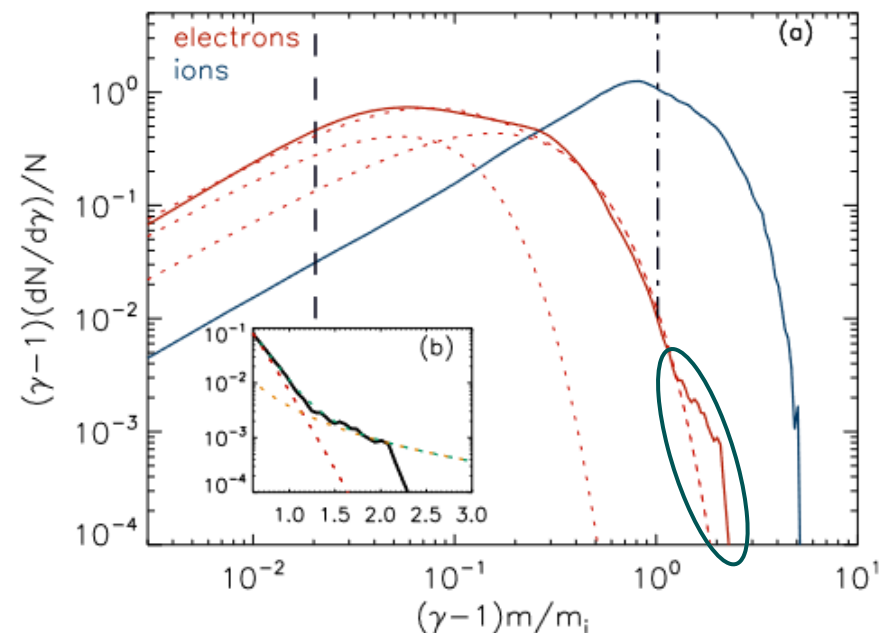
Crumley et al. 2019



# Already studied mechanisms in MR shocks

## Wakefield acceleration (WFA)

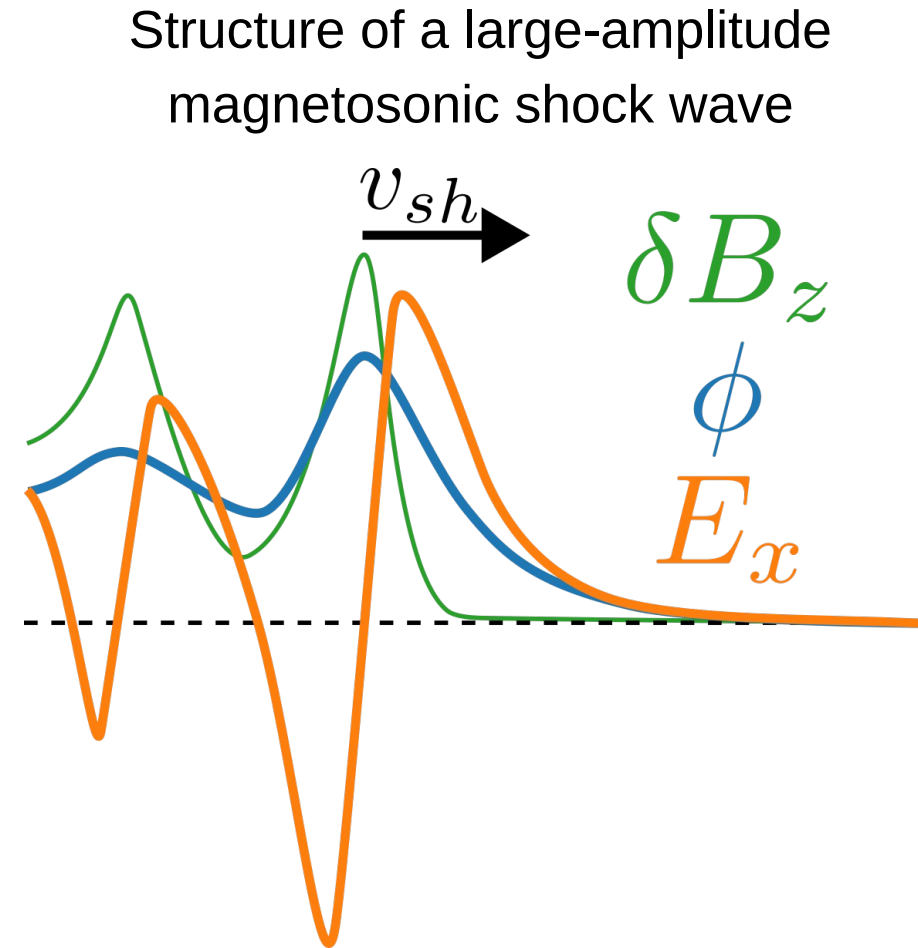
- WFA requires a relativistic plasma beam to occur
  - Synchrotron maser instability (SMI) is excited → Upstream precursor waves → Electrostatic wakefield → Particle acceleration
- Highly efficient in UR shocks (especially for electrons)
- Highly **inefficient** in MR shocks



Ligorini et al. 2021

# An alternative solution

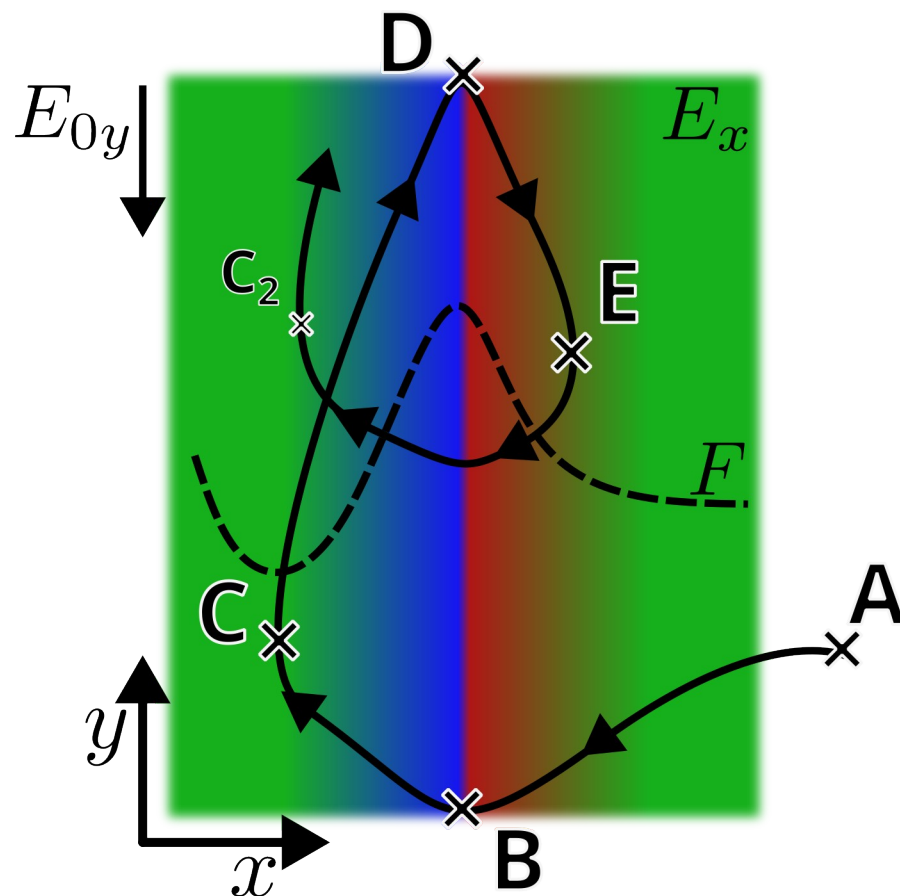
- A **large-amplitude subluminal** magnetosonic shock wave propagating in a magnetised plasma ( $\sigma_e \gtrsim 1$ ) is capable of **reflecting** and **trapping** electrons (Bessho & Ohsawa, 1999).
  - Electrons that follow magnetic field lines can be reflected at potential minima
    - Key quantity: pseudo-potential  $F$  (electric potential along  $\mathbf{B}$ )
  - Large-amplitude waves are highly non-stationary!



# Trapping and acceleration mechanism

## Mechanism cycle

- A: Upstream electron reaches the shock.
- B: Electron attracted by  $\phi$
- C: Electron is **reflected** behind the pulse
- C  $\rightarrow$  D: Electron is **greatly accelerated** by motional electric field  $E_{0y}$
- D  $\rightarrow$  E: Electron is decelerated and is quickly reflected back at E
- C2: Repeat... the electron is **trapped!**
- Efficiency increases for:
  - Faster shocks
  - More oblique shocks (but still subluminal!)



# Trapping and acceleration mechanism

## Energy estimation



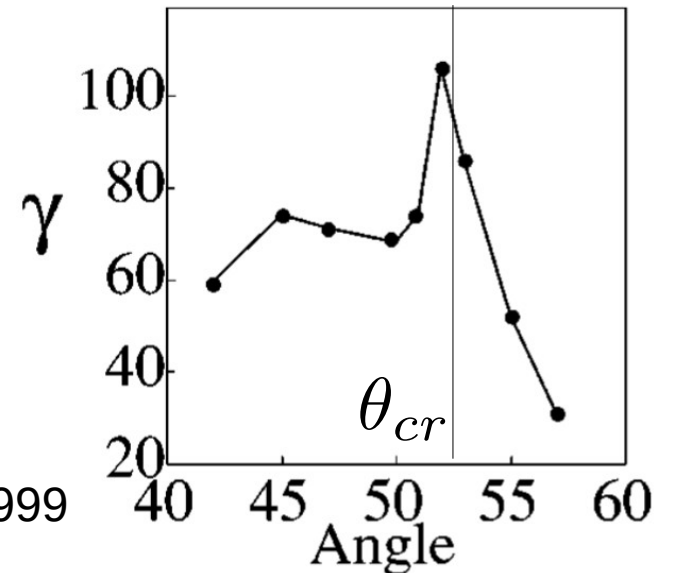
$$\frac{d\gamma}{dt} m_e c^2 = -e \mathbf{E} \cdot \mathbf{v} \rightarrow \Delta \gamma m_e c^2 = e \Delta \phi - e E_{0y} \int v_y dt$$

- Most energetic mechanism section is C→D:

$$\Delta E_{CD} = e (\phi_D - \phi_C) - e E_{0y} \int_C^D v_{\parallel} \frac{B_y}{B} dt + e E_{0y} \int_C^D \frac{E_x}{E_{0y} + v_{\parallel} \frac{B_{0x} B}{B_z}} dx$$

- Assuming ultra-relativistic electron  $v_{\parallel} \sim c$ ,  $B_{z,M} \sim B_M$  and  $\phi_D \gg \phi_C$ :

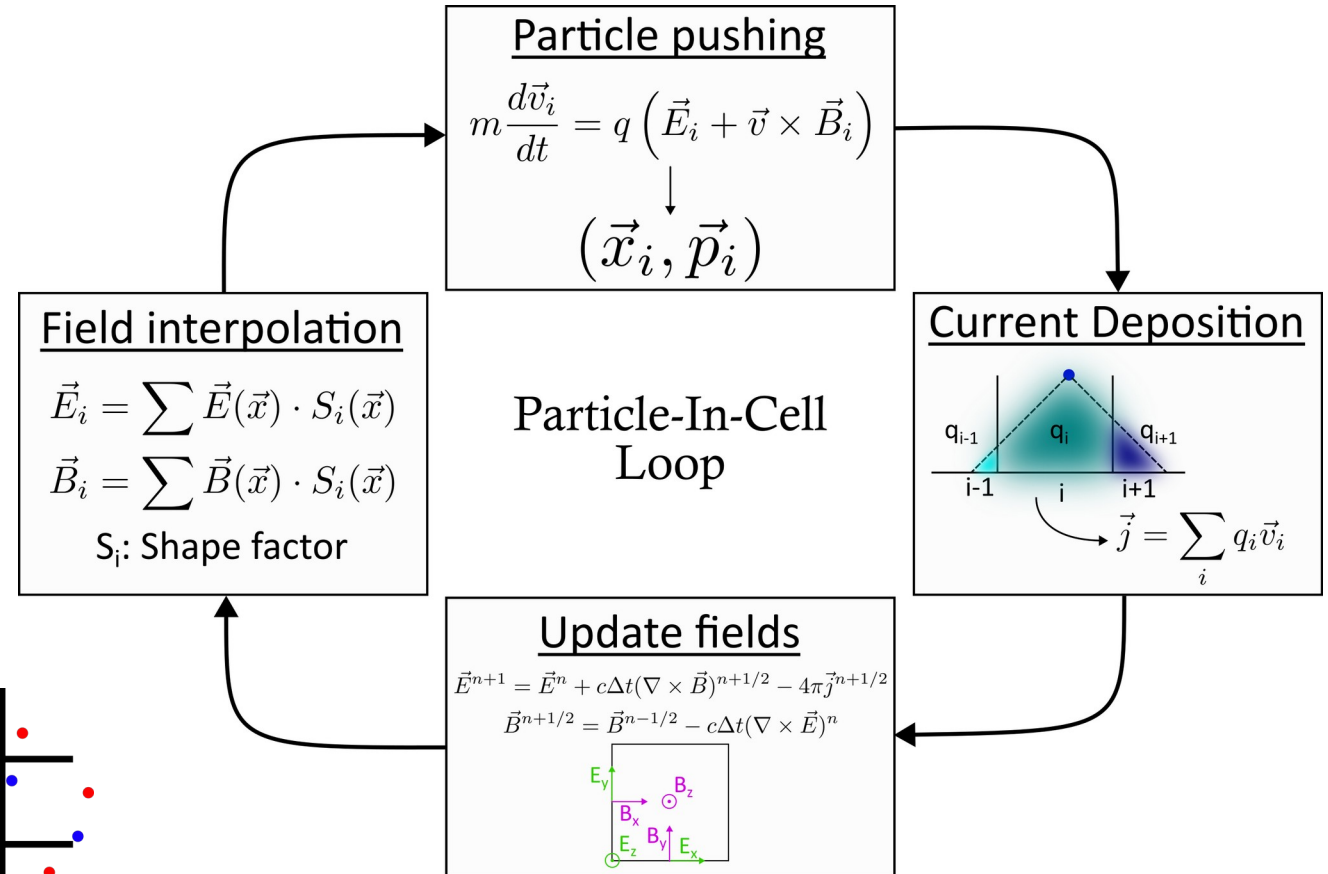
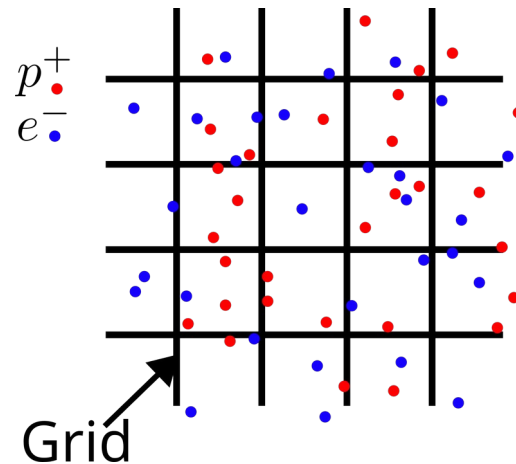
$$\Delta E_{CD} \approx e \phi_D + \frac{-e \phi_D}{1 + \frac{c B_{0x}}{E_{0y}}} = \frac{e \phi_D}{1 - \frac{v_{sh}}{c} \frac{B_{0z}}{B_{0x}}} = \frac{e \phi_D}{1 - \frac{\tan \theta_{Bn}}{\tan \theta_{cr}}}$$



Bessho & Ohsawa, 1999

# Simulation method

- To understand electron acceleration, we require a kinetic-based approach.
- We use the **particle-in-cell** (PIC) method
  - Follow charged particles (continuous) + self-consistent evolution of electromagnetic field (defined on a grid)



# Simulation setup

- $\gamma_0 = \sqrt{5} \approx 2.24$
- $\sigma^{-1} = \sigma_i^{-1} + \sigma_e^{-1} = 1.0$ 
  - $\sigma_i \approx 1, \sigma_e \approx 100$
- $M_s \rightarrow \infty, M_A \gtrsim 1$
- Reflecting wall setup

$$\lambda_{se} = 40\Delta (\text{high resolution})$$

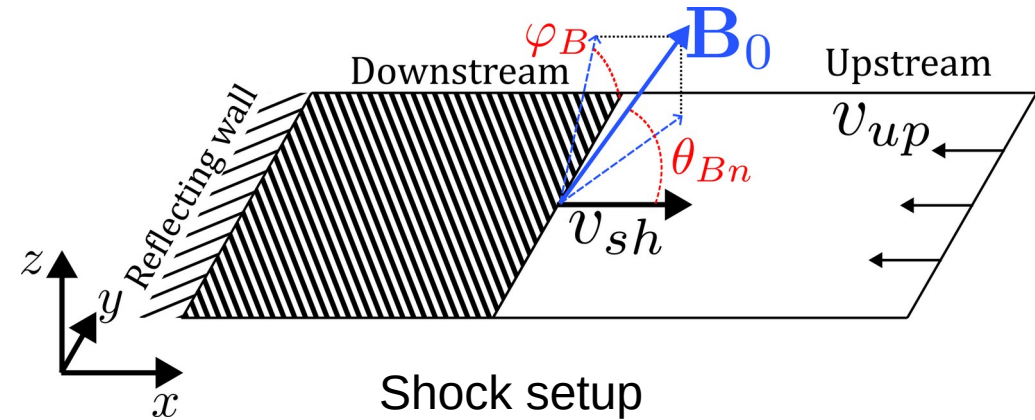
$$\phi_B = 90^\circ (\text{out-of-plane } \mathbf{B})$$

$$m_i/m_e = 100$$

$$T_{\max} = 250,000\Delta t$$

$$\approx 314\Omega_i^{-1} \approx 314\omega_{pi}^{-1}$$

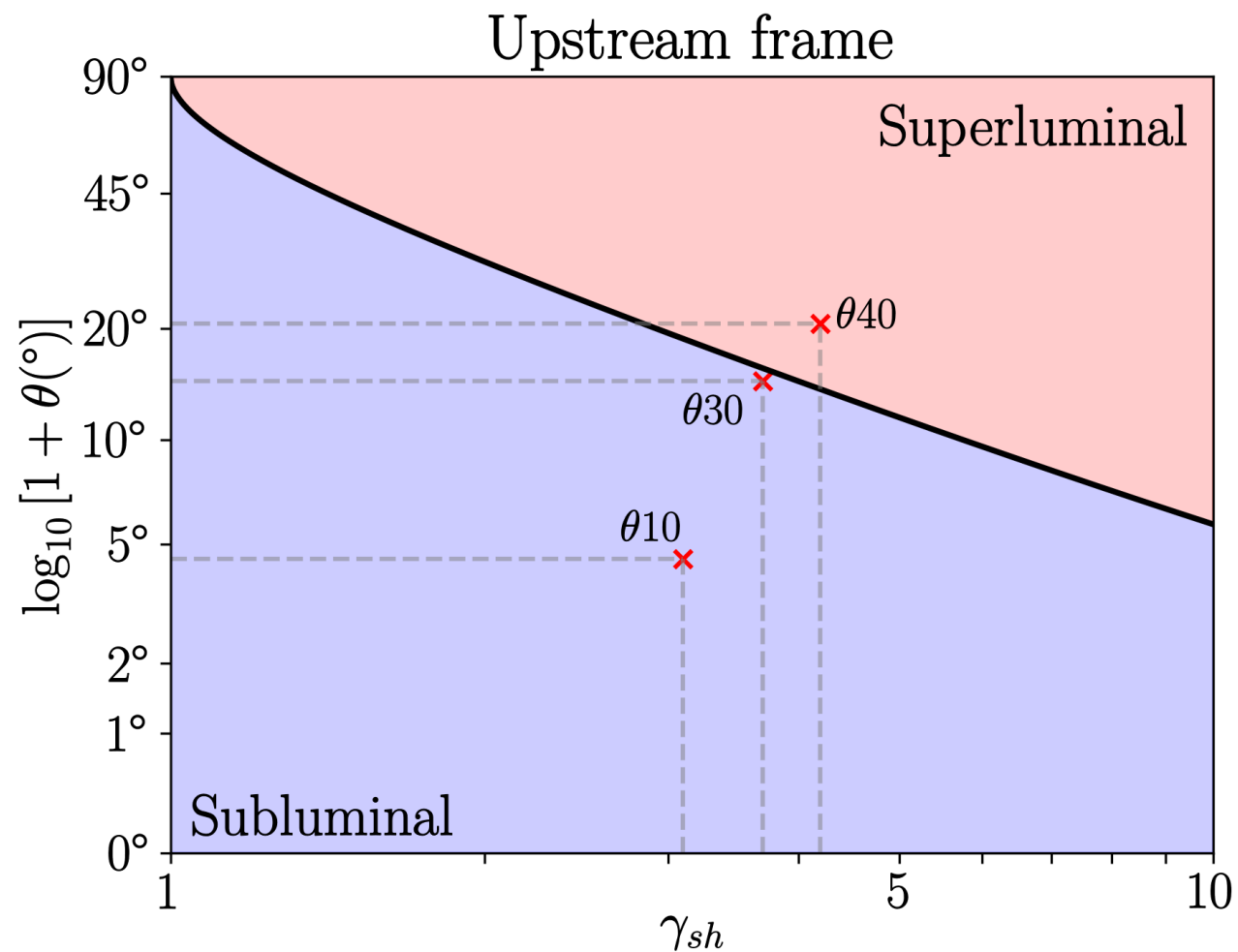
| Sim.        | Type of shock        | $\theta_{Bn}$ | $\gamma_{sh,up}$ | $M_{A,up}$ |
|-------------|----------------------|---------------|------------------|------------|
| $\theta 30$ | Oblique subluminal   | $30^\circ$    | 3.7              | 1.077      |
| $\theta 40$ | Oblique superluminal | $40^\circ$    | 4.2              | 1.106      |
| $\theta 10$ | Quasi-parallel       | $10^\circ$    | 3.1              | 1.035      |



Magnetisation:  $\sigma_j \equiv \frac{\Omega_j^2}{\omega_{pj}^2}$

# Simulation setup

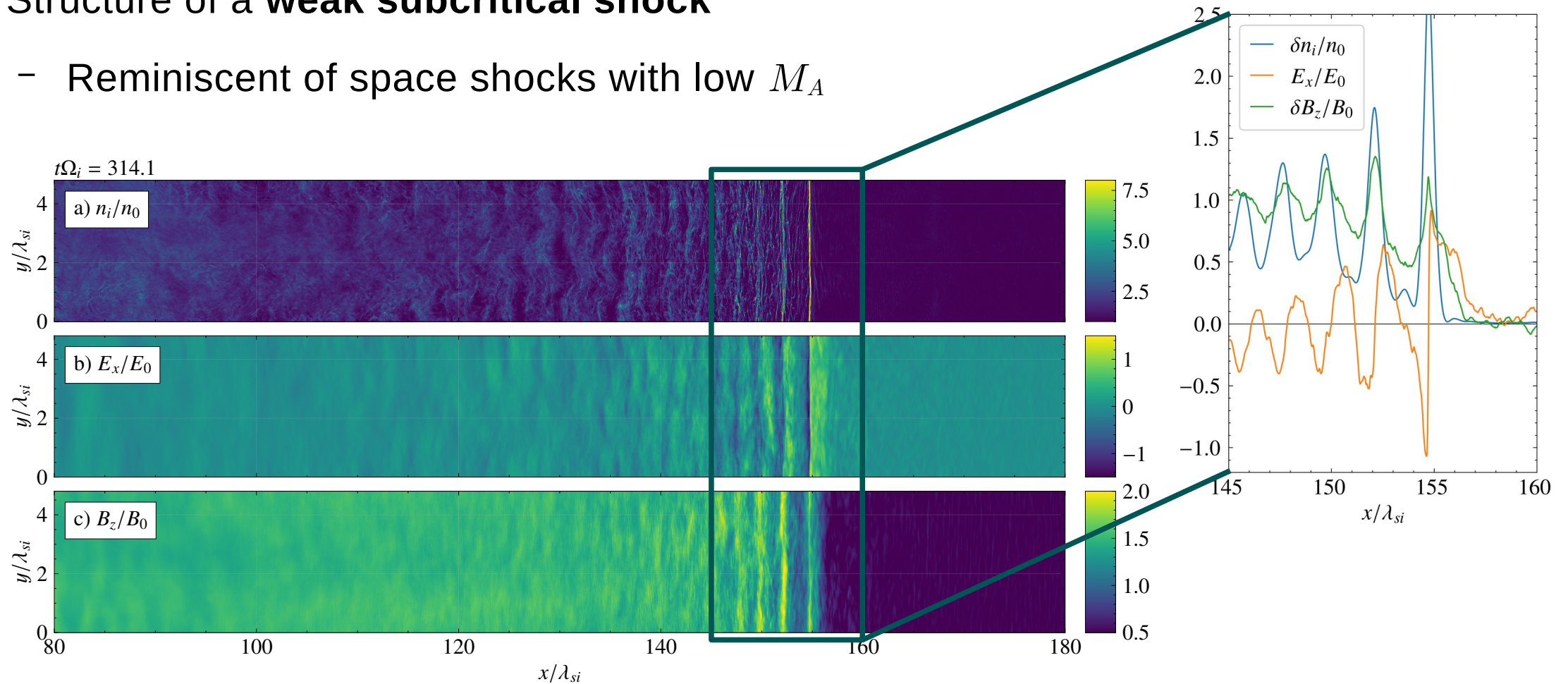
Setup location in  $\theta$  vs.  $\gamma$  space



# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Structure

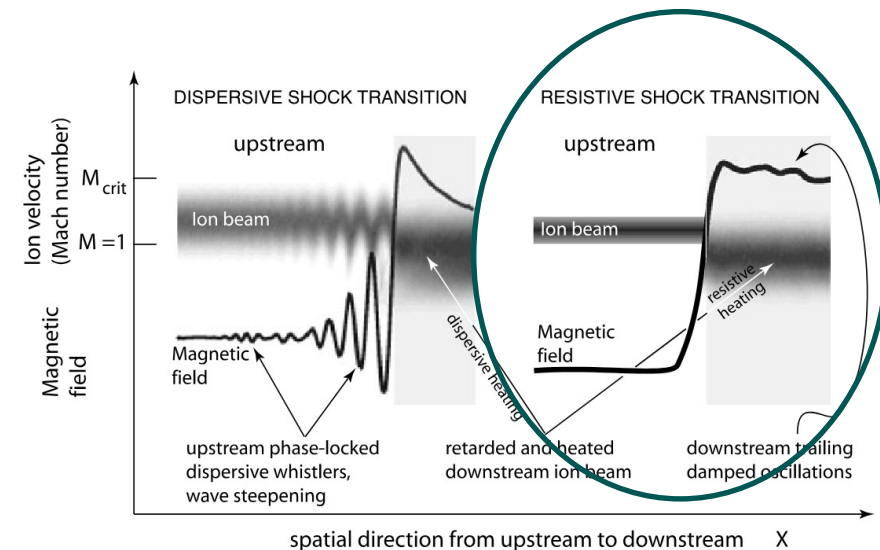
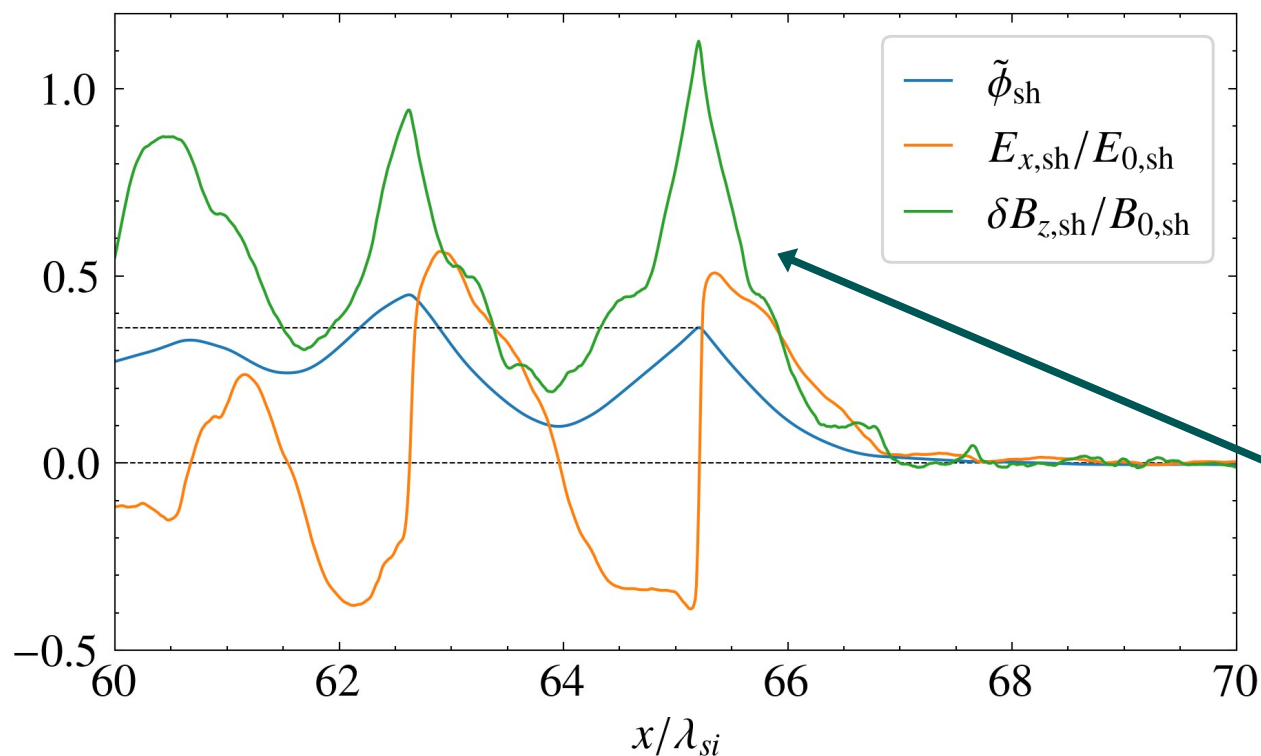
- Structure of a **weak subcritical shock**
  - Reminiscent of space shocks with low  $M_A$



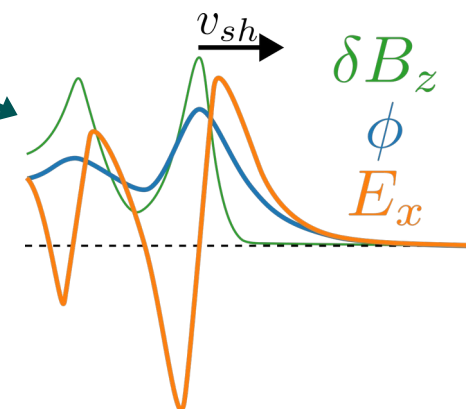
# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Shock potential

- Shock potential =  $\mathbf{E} \times \mathbf{B}$  electron drift + electron motion parallel to  $\mathbf{B}$  (Miyahara et al. 2003) + ion current contribution (Nakawawa and Ohsawa 1997)
- Resistive processes regulate the shock steepening



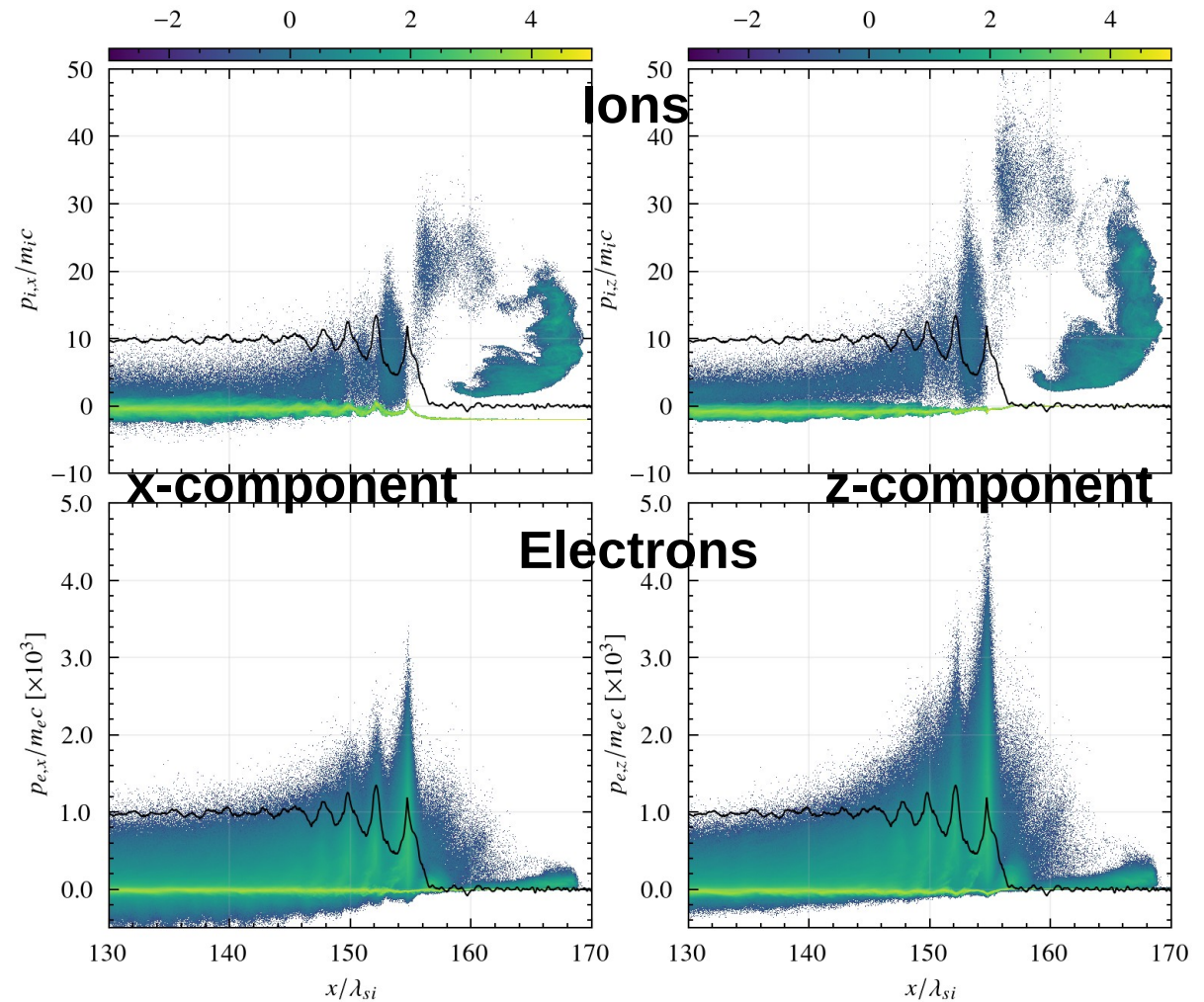
Balogh and Treumann, 2013



# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Phase-space

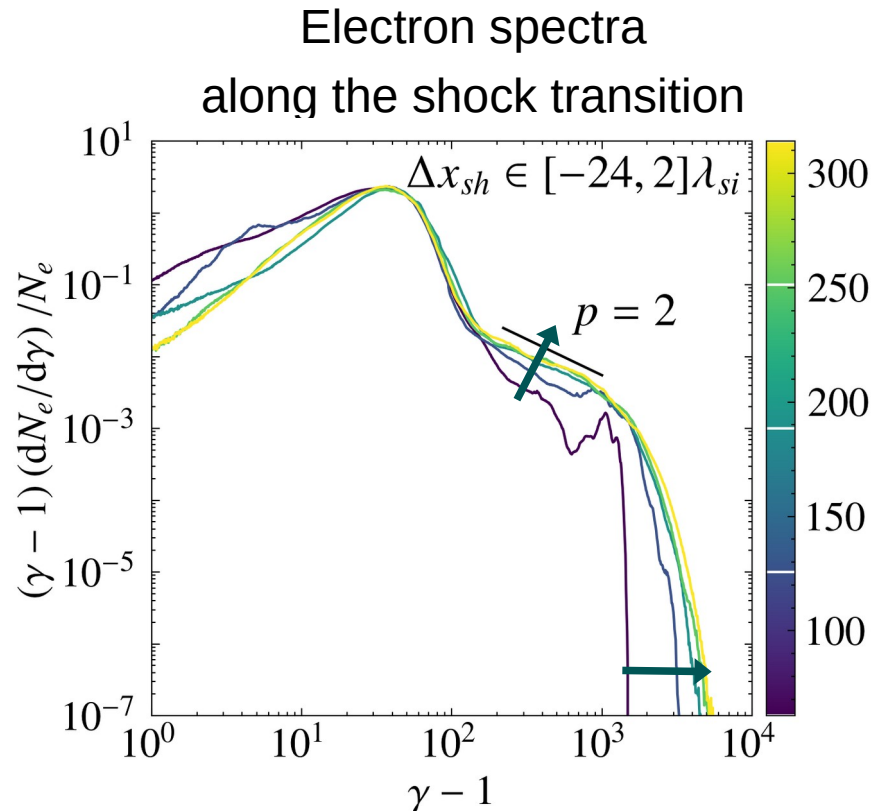
- Large momenta for both ions and electrons
  - Electrons reach  $p_{e,z}/m_e c \sim 5 \times 10^3$  (!)
  - Prominent energisation at the location of the magnetosonic shock wave
    - Electrons at **maxima** of **B**
    - Ions at **minima** of **B**



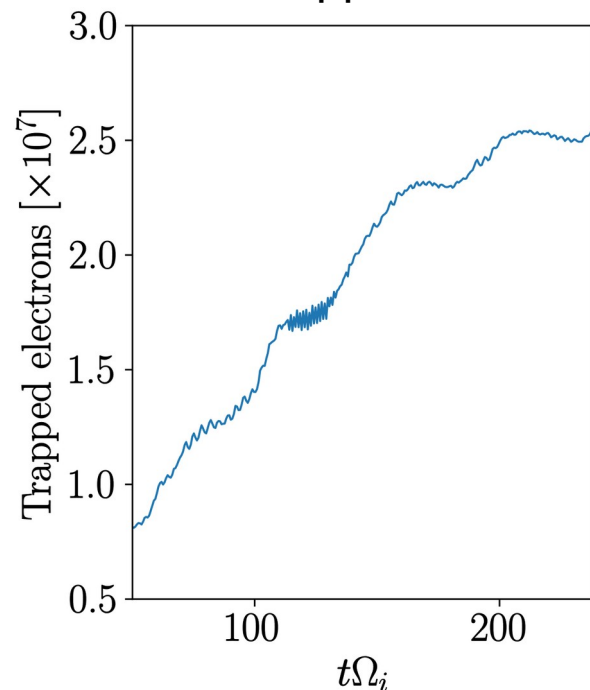
# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Electron energy spectra

- High-energy power-law-like tail with index  $p=2$ 
  - Number of high-energy electrons **increases over time**
  - Maximum energy increases over time



## Number of trapped electrons

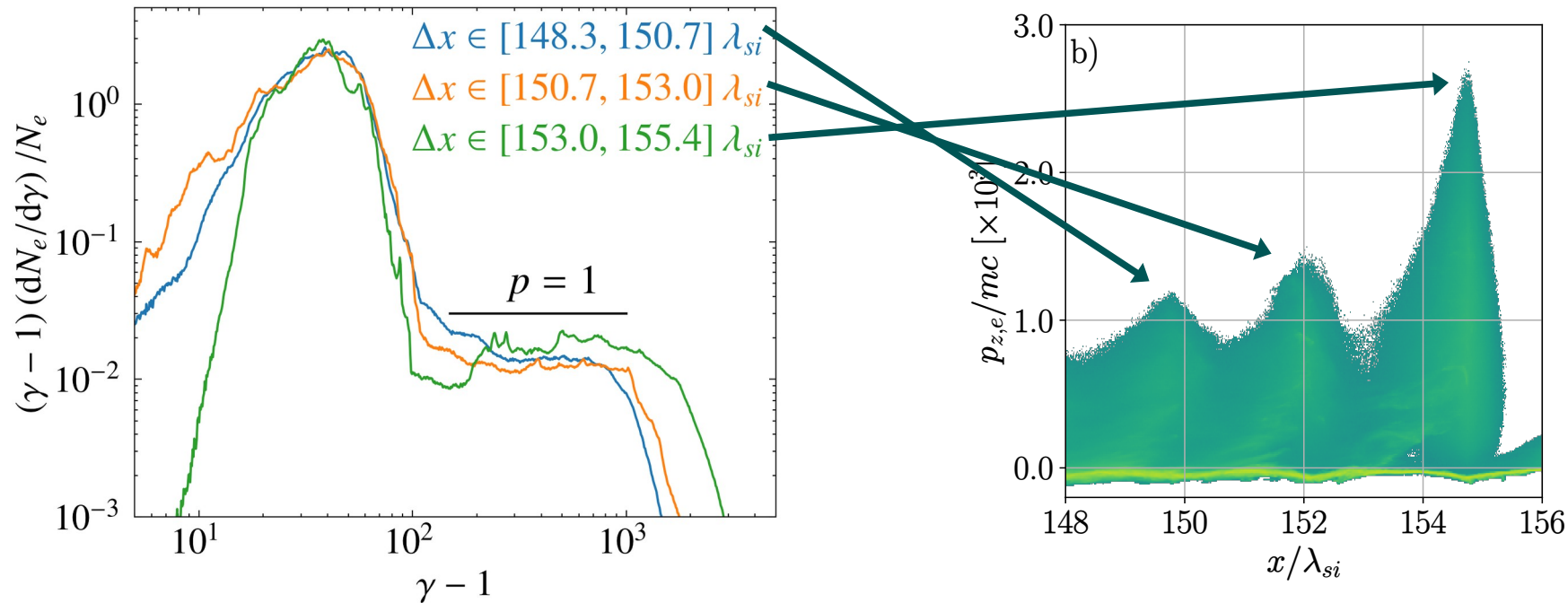


# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Individual pulse spectra

- The trapping mechanism occurs separately for each pulse
- Individual pulses show an index of  $p=1$

Electron spectra  
for individual consecutive pulses

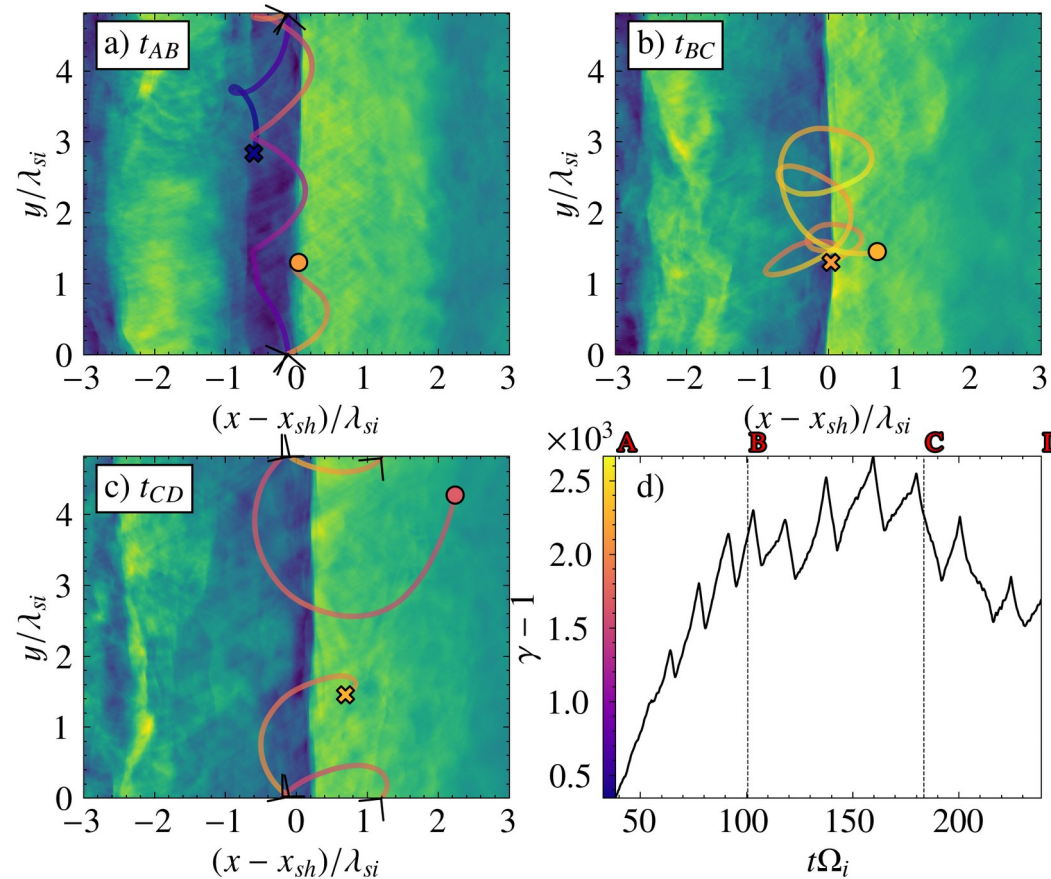


# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Electron tracing

Representative high-electron

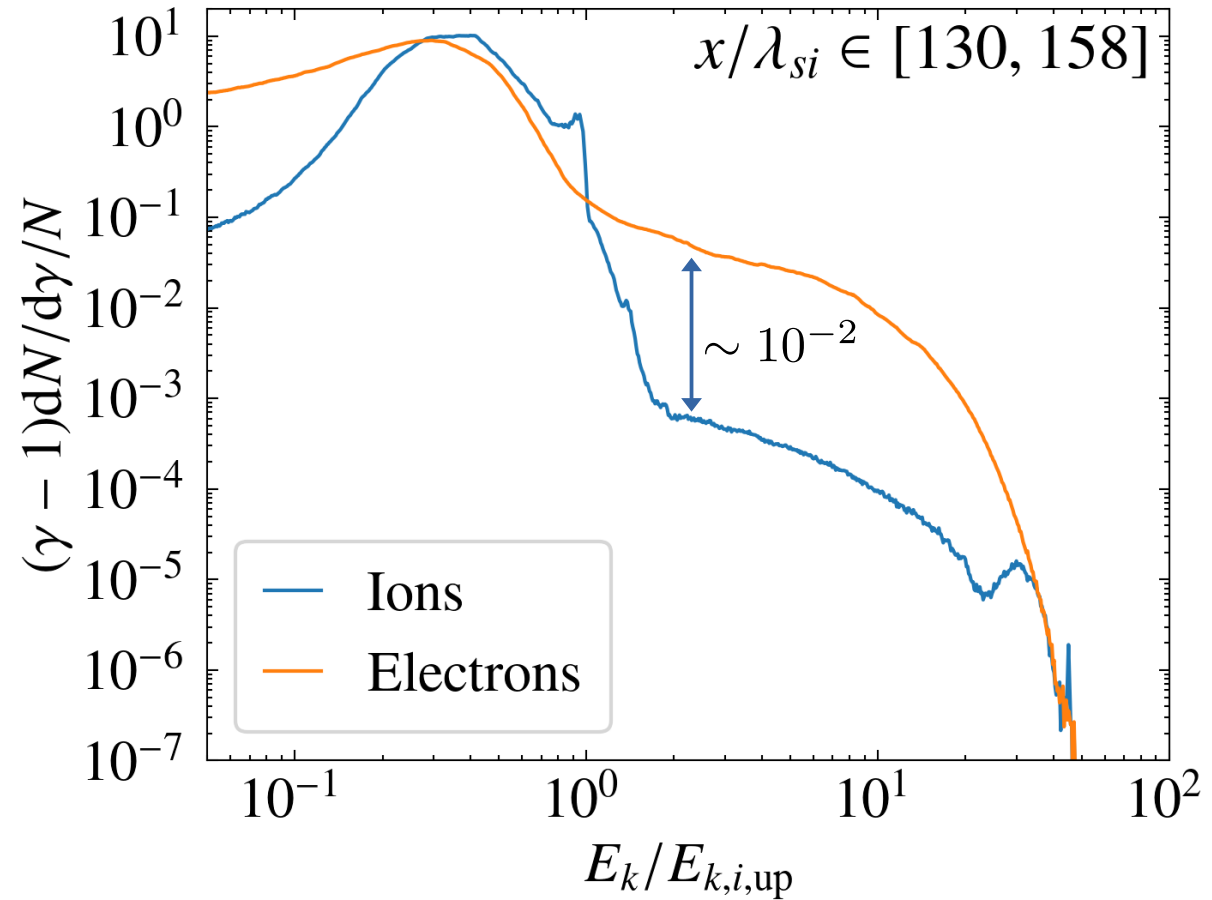
- $t_{AB}$ : the electron is **trapped** and gains energy by the **motional electric field**
- $t_{BC}$ : the electron scatters off magnetic field fluctuations and suddenly changes direction
- $t_{CD}$ : the electron loses energy as it moves in the opposite direction, but remains trapped



# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Ion spectra

- Ions also undergo trapping
  - They are instead trapped within **potential troughs**
- Lower efficiency than electrons
  - Steeper high-energy tail and less trapped ions
  - Ions easily escape the confinement region
  - Potential troughs are shallower than peaks

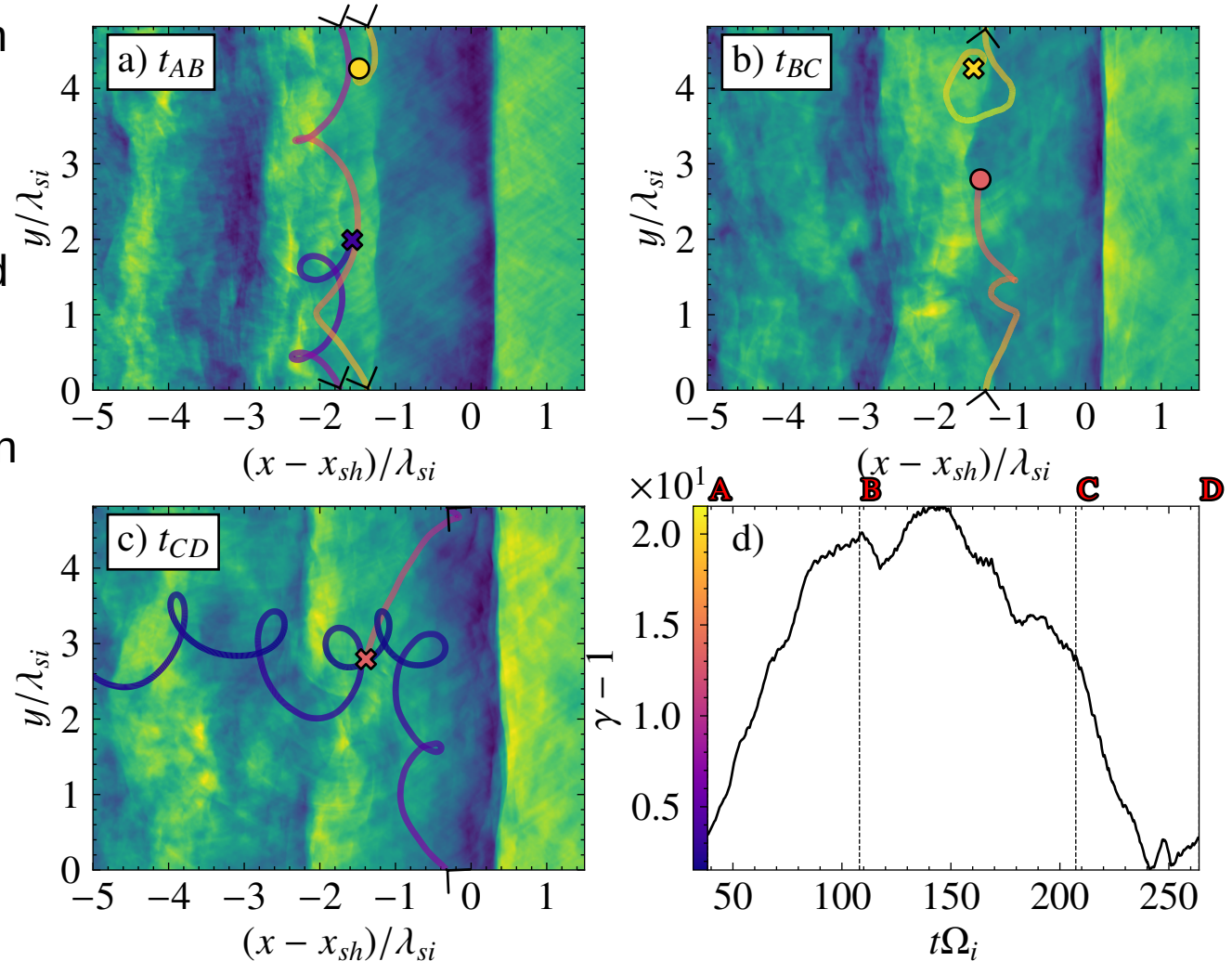


# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Ion tracing (downstream-going)

Representative downstream-escaping ion

- $t_{AB}$ : the ion is trapped and is accelerated by  $E_{0y}$
- $t_{BC}$ : the ion scatters off magnetic field fluctuations and suddenly changes direction
- $t_{CD}$ : the ion loses energy as it moves in the opposite direction and eventually escapes towards downstream



# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

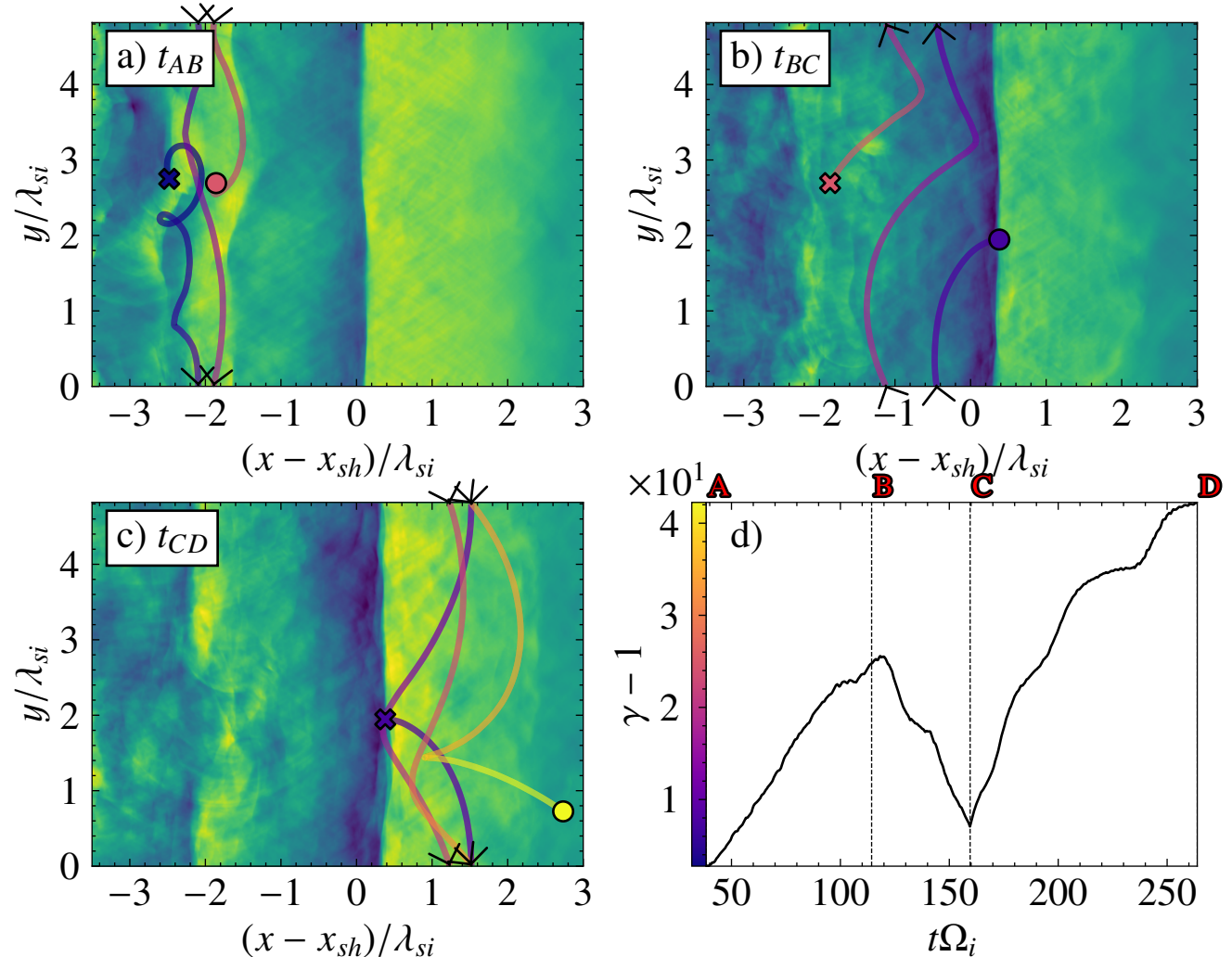
## Ion tracing (upstream-going)



Representative upstream-escaping ion

- $t_{AB}$ : the ion is trapped and is accelerated by  $E_{0y}$
- $t_{BC}$ : the ion starts moving in the opposite direction, but at some point it crosses the shock front
- $t_{CD}$ : the ion undergoes SSA. Bounces off the shock potential while being accelerated. It will eventually escape upstream or be advected downstream

The supra-thermal bump in the ion spectrum is due to upstream-escaping ions undergoing SSA



# Oblique subluminal shock ( $\theta_{Bn}=30^\circ$ )

## Maximum particle energy

- Maximum electron energy scales with mass ratio
  - For a given  $\sigma_i$ , the electric potential  $\phi$  scales linearly with the ion mass
  - Confirmed by a simulation with higher-mass ratio ( $m_i/m_e=400$ )
- Upper limit given by the confinement region i.e. shock width:
  - $\Delta x_{\text{sh}} \sim r_{g,i}$

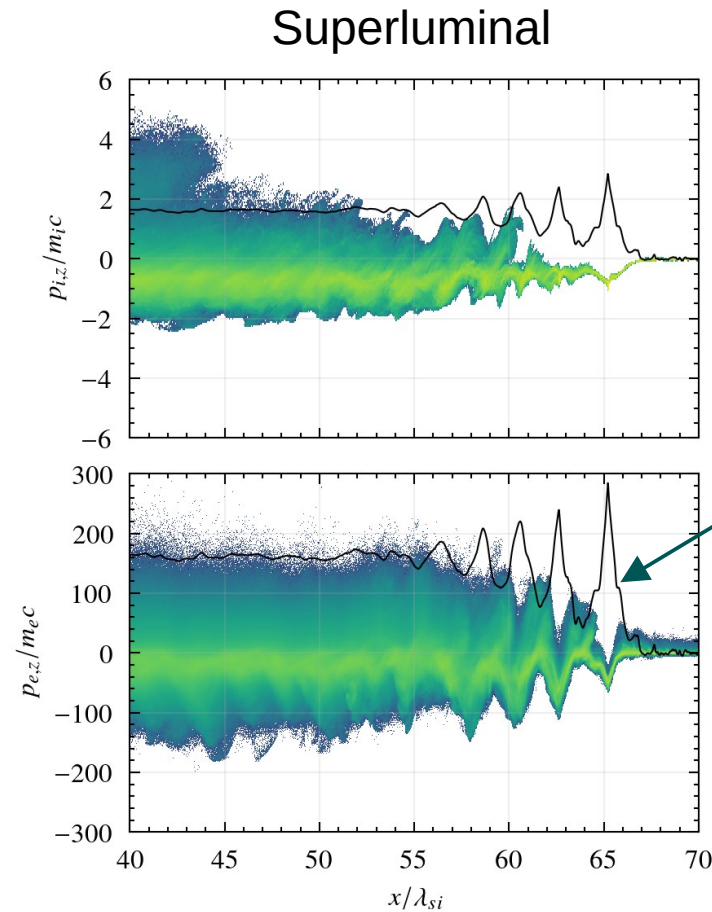
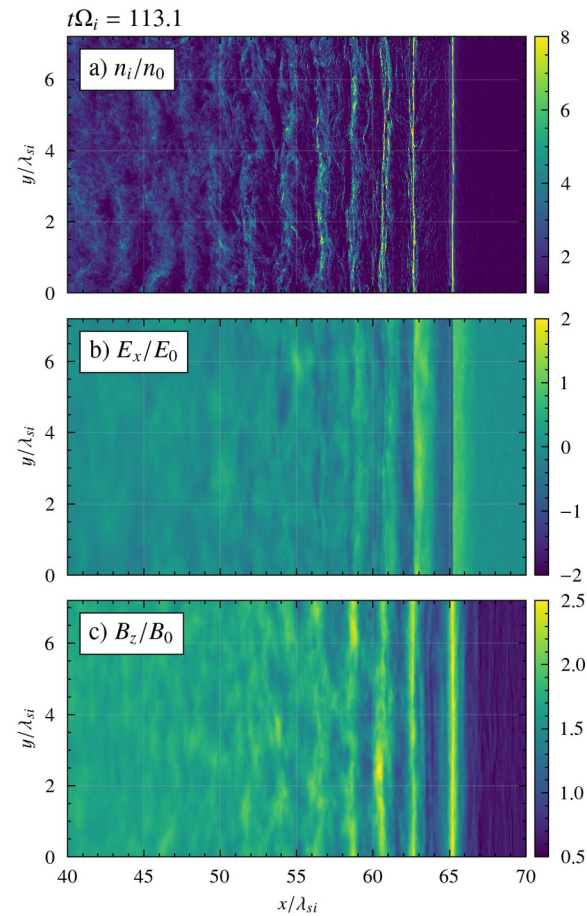
- Electrons require a lot of energy to escape

$$r_{g,e,\text{max}} \approx \frac{\gamma_{\text{max}} m_e c}{eB} \approx \Delta x_{\text{sh}} \rightarrow \gamma_{\text{max}} \propto \frac{m_i}{m_e}$$

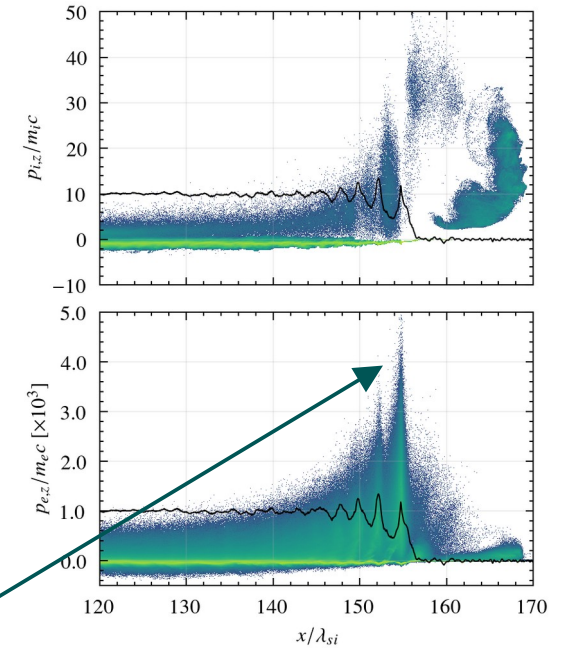
- Ions easily escape since their gyroradii is already of the order of the shock width

# Oblique superluminal shock ( $\theta_{Bn}=40^\circ$ )

- Similar structure, **inefficient** acceleration
  - Superluminal conditions prevent electrons from being trapped



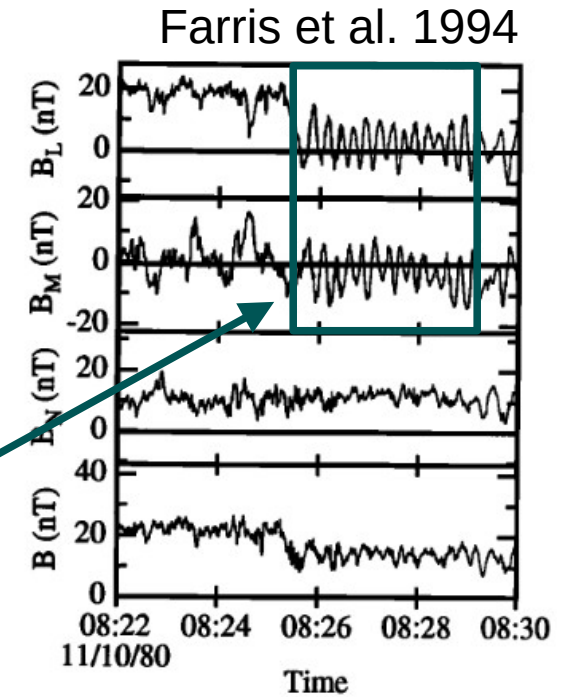
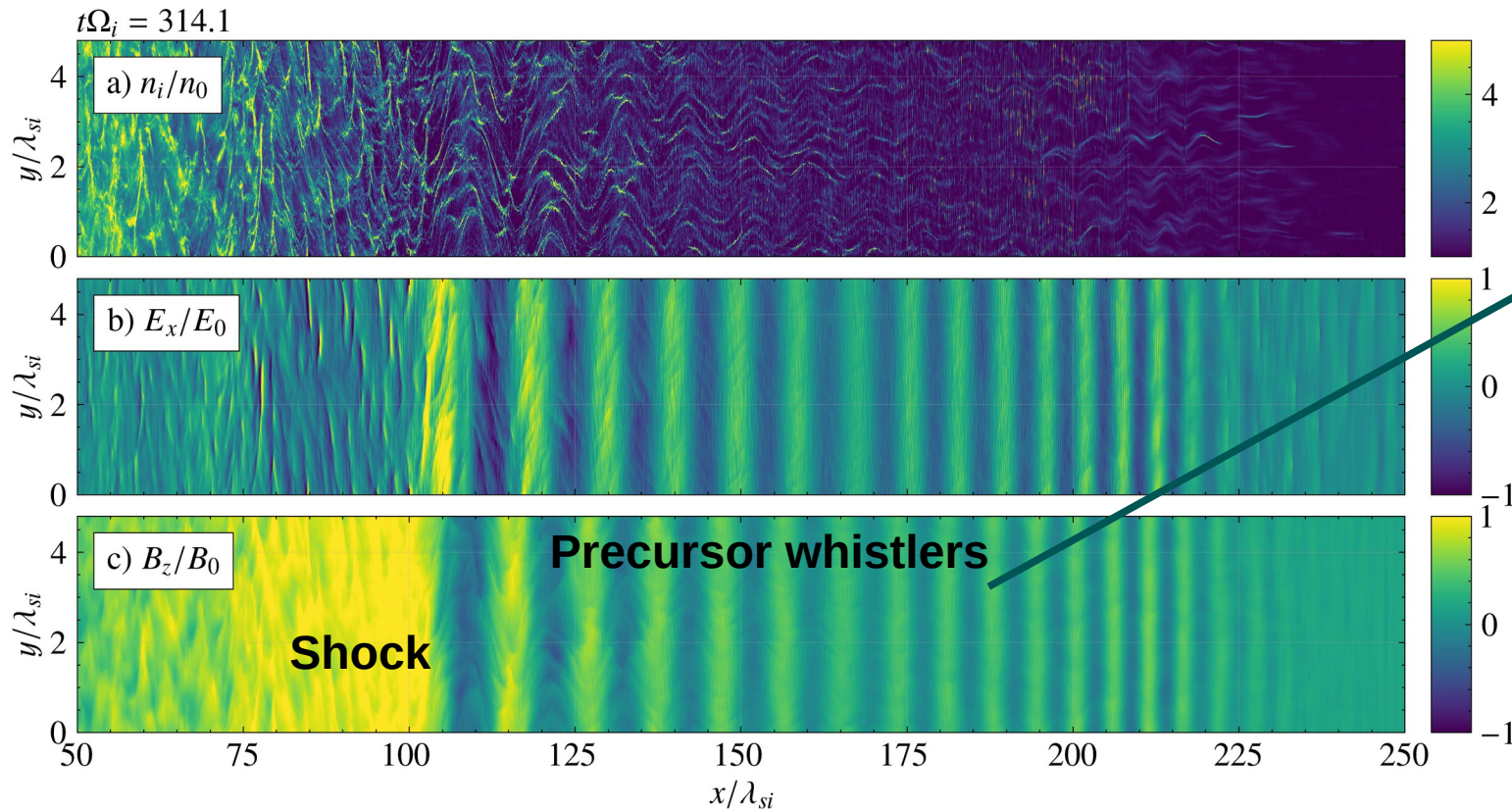
Subluminal



# Quasi-parallel shock ( $\theta_{Bn}=10^\circ$ )

## Structure

- Vastly different structure
- Shock at  $x \approx 105\lambda_{si}$ , followed by precursor whistlers
- Similar structure observed in space shocks

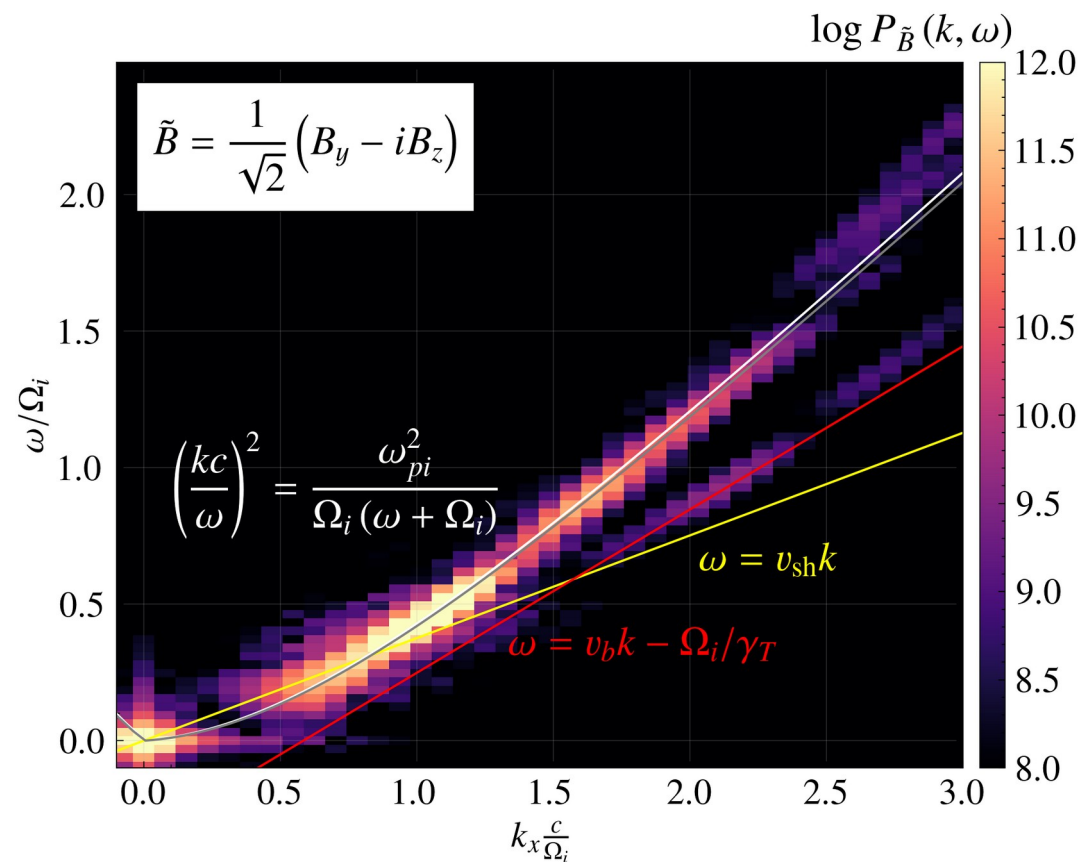


ISEE 1 measurements  
November, 1980

# Quasi-parallel shock ( $\theta_{Bn}=10^\circ$ )

## Precursor wave train

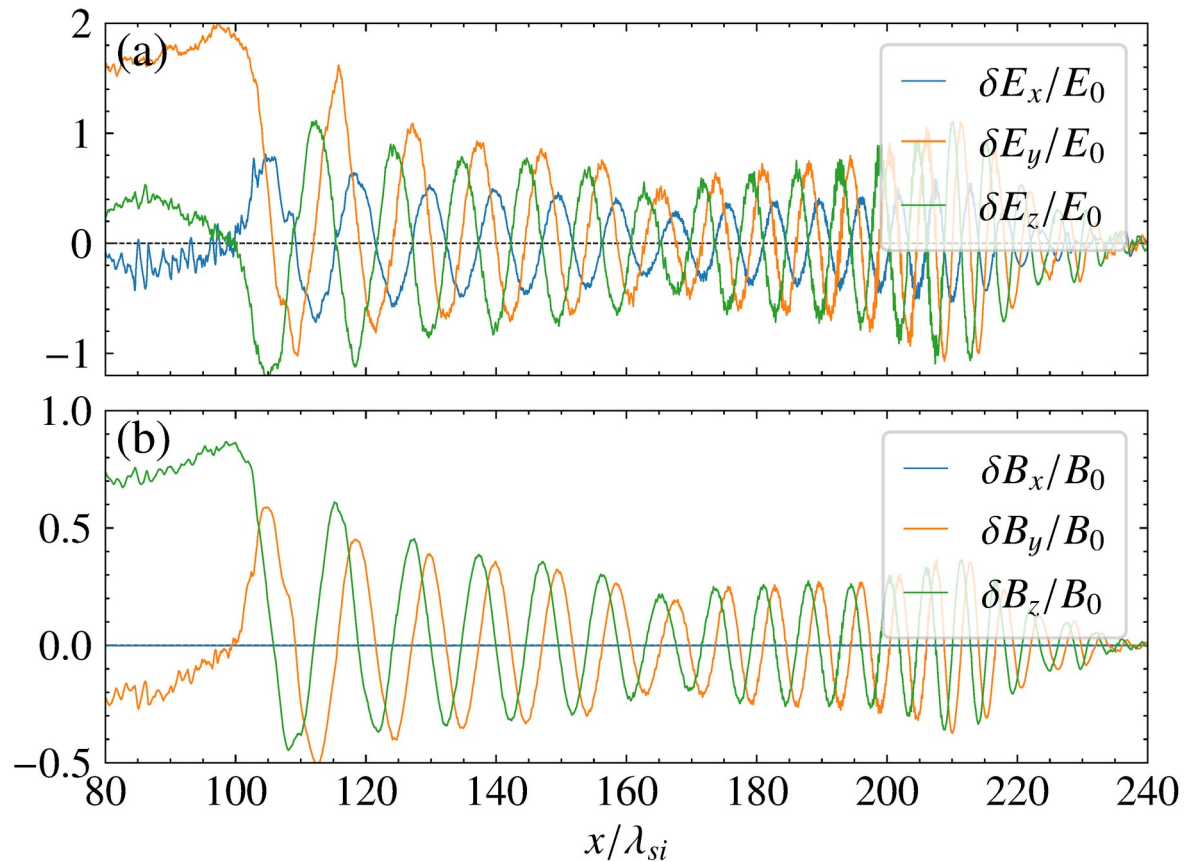
- The waves in front of the shock are whistler waves. Confirmed by:
  - $M_{A,\text{up}} < M_{w,\text{up}}$
  - Analysis in Fourier space
- The waves are excited downstream by the ion-ion right-hand resonant instability
- Sustained only by background upstream ions
  - Compare grey line (full dispersion relation) and white line (only cold ions contribution)



# Quasi-parallel shock ( $\theta_{Bn}=10^\circ$ )

## Structure

- Whistlers propagate along the shock normal
  - But magnetic field obliquity is finite!
  - Not circularly, but rather elliptically polarised
- As a consequence of quasi-parallel propagation,  $E_x$  wave appears
  - Similar amplitude as transverse electric field
  - Same  $k$  and  $\omega$

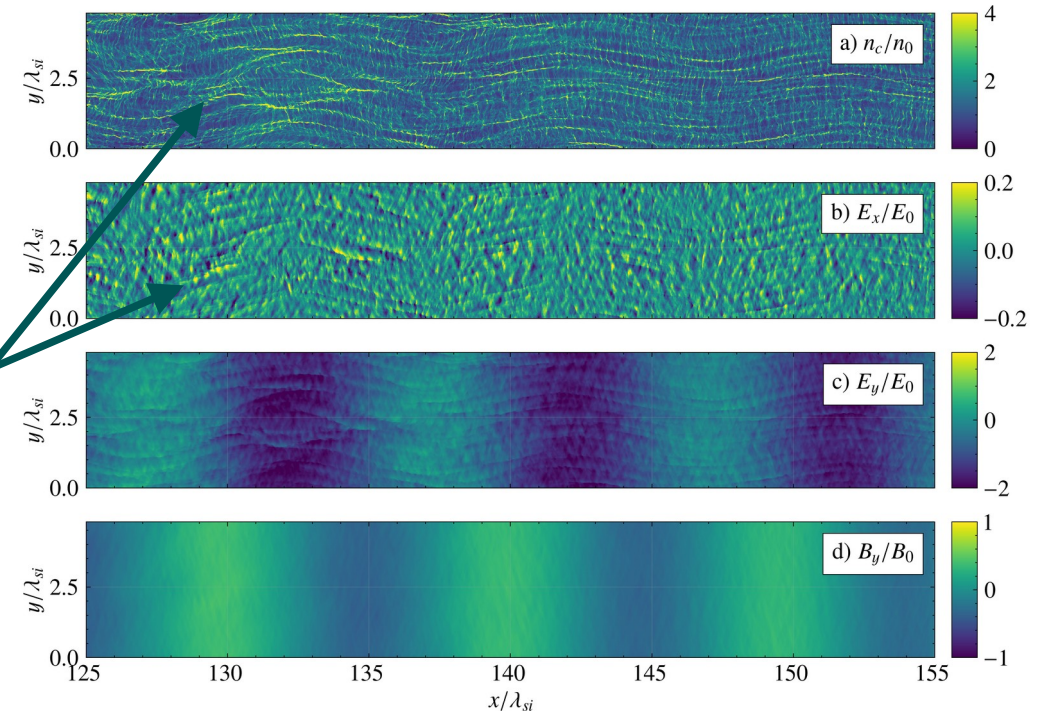
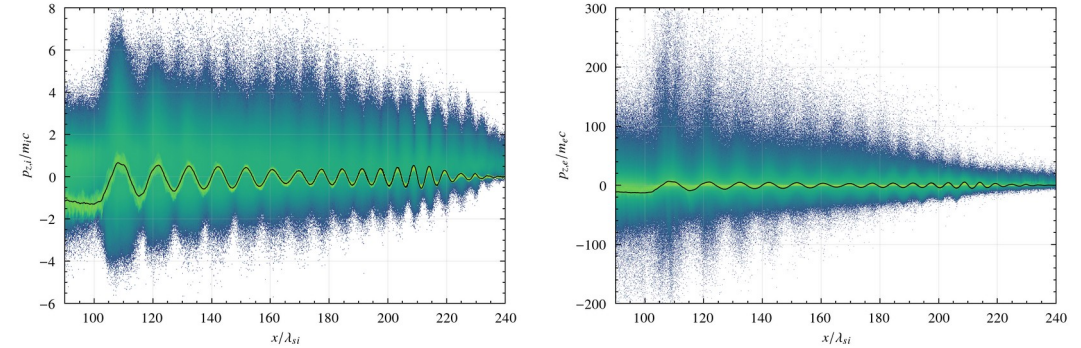


# Quasi-parallel shock ( $\theta_{Bn}=10^\circ$ )

## Modified two-stream instability (MTSI)

- Particles perform a quiver motion in the precursor whistler region.
  - Perpendicular velocity given by the Walén relation (Hollweg et al. 1993):
    - $$v_{j,\perp} = -v_{ph} \frac{\Omega_j}{\omega \pm \Omega_j} \frac{\delta B_\perp}{B_0}$$
- Ions and electrons have different perpendicular velocities
  - A current drift is generated, and the modified two-streaming instability (MTSI) is excited
- The MTSI produces oblique waves in  $E_x$
- Density filaments as a non-linear outcome of MTSI

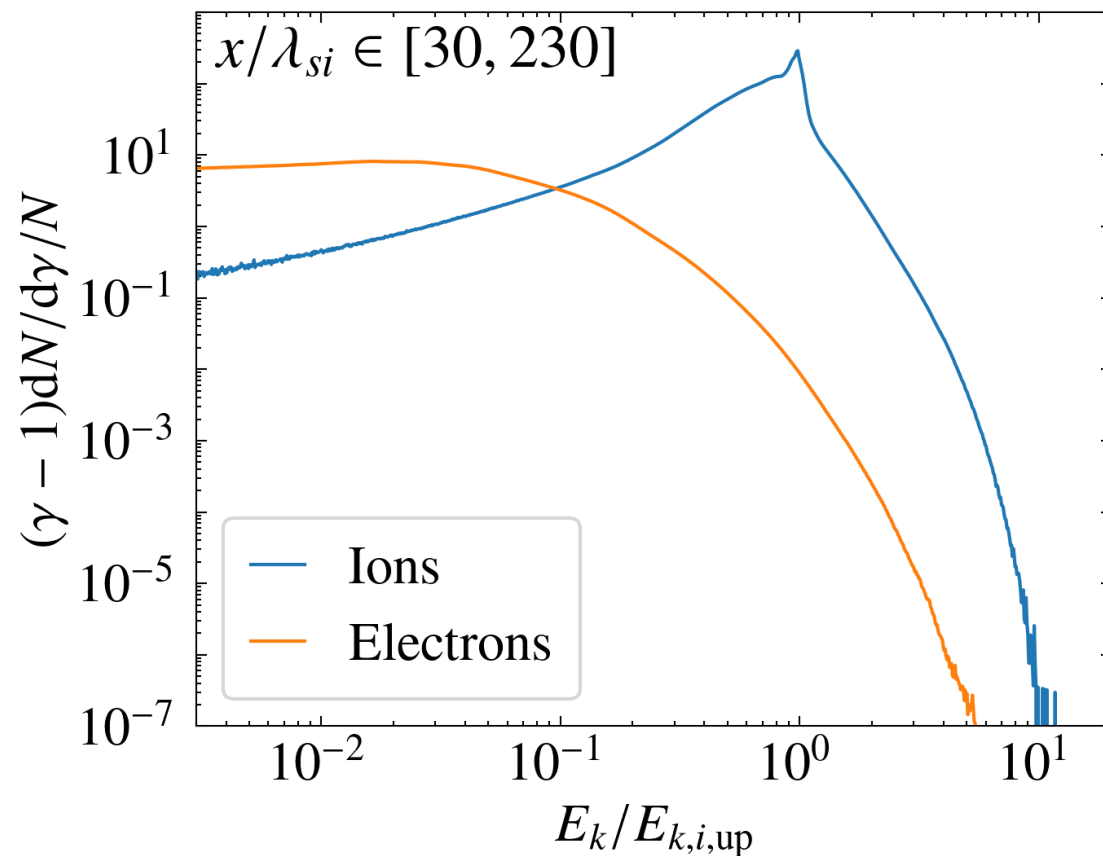
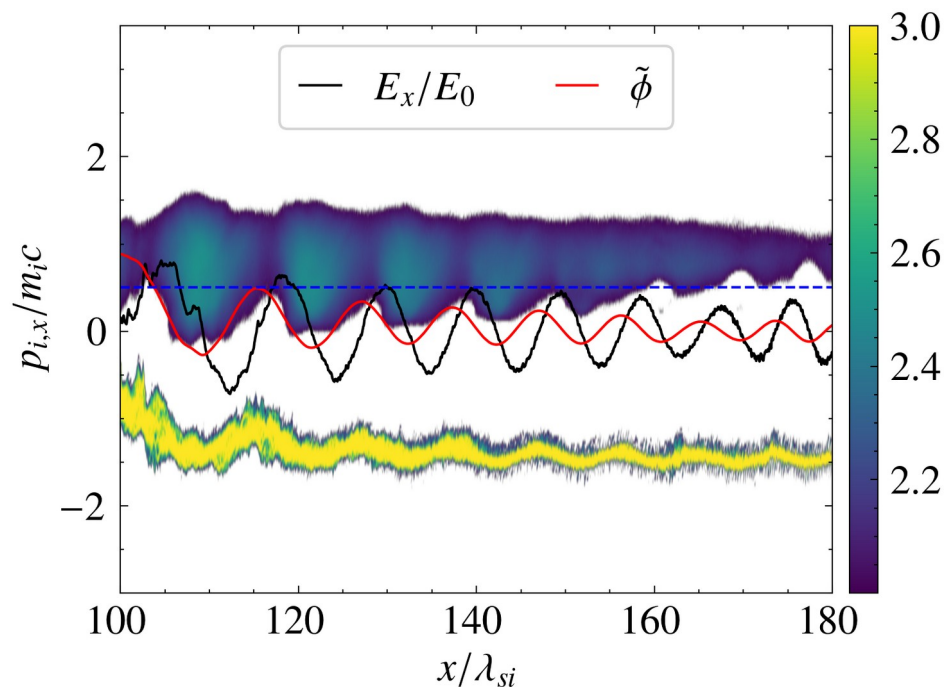
See also Sakai, et al. 2005 and Nariyuki et al. 2008



# Quasi-parallel shock ( $\theta_{Bn}=10^\circ$ )

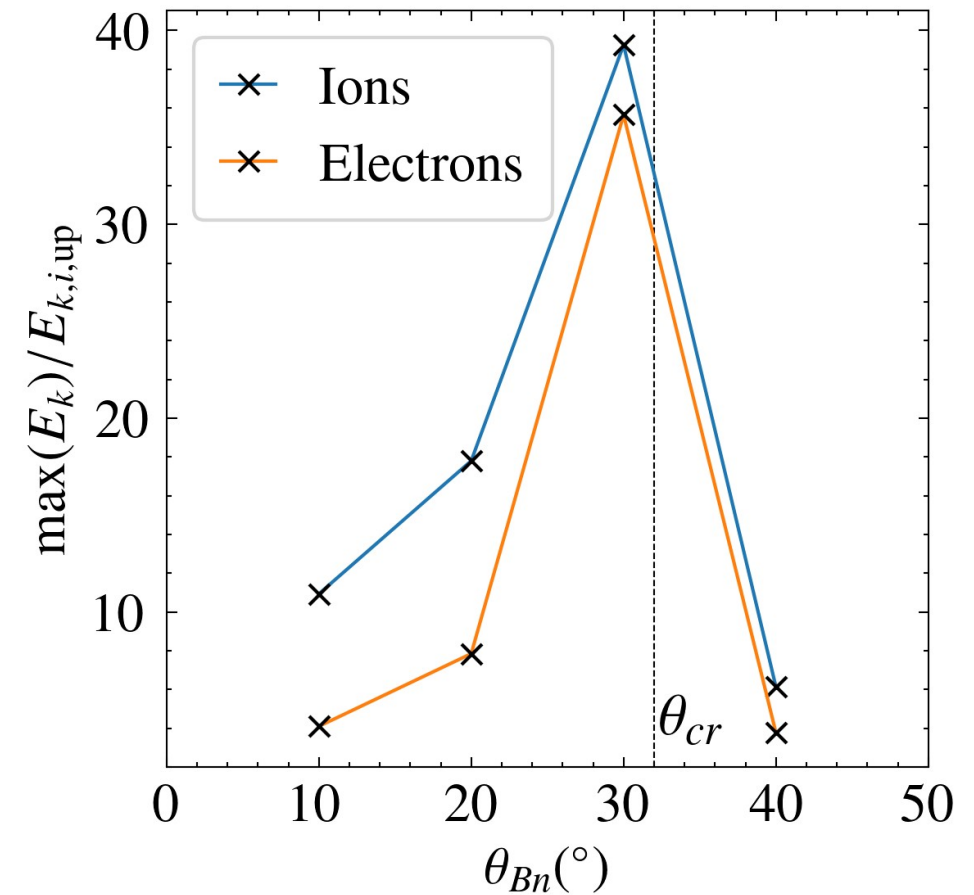
## Particle heating and energy spectra

- No strong particle acceleration
  - More efficient ion than electron heating
- Dominant ion heating mechanism: ion trapping



# Efficiency of the trapping mechanism

- $\max(E_k)$  increases as  $\theta_{Bn}$  gets closer to the critical angle (subluminal regime)
- Past the critical angle, the maximum energy decreases drastically (superluminal regime).
- The trend well agrees with the theoretical expectation



# Summary



- The shock structure in all simulations is reminiscent of weak subcritical shocks
  - The shock obliquity determines the structure
- The trapping mechanism provides a non-thermal power-law spectral component of index  $p=1$  (the entire shock transition shows  $p=2$ )
  - The maximum energy is sensitive to the shock obliquity:
    - Subluminal: efficient acceleration as  $\theta_{Bn}$  gets close to the critical angle
    - Superluminal: efficiency drops drastically
- While the simulation is 2D, the underlying physics is expected to persist with the same efficiencies in 3D (supported by additional simulations with in-plane magnetic field)

# Thank you

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