MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Ion and electron acceleration in strongly magnetised mildly relativistic shocks

PLASMA
ASTRO

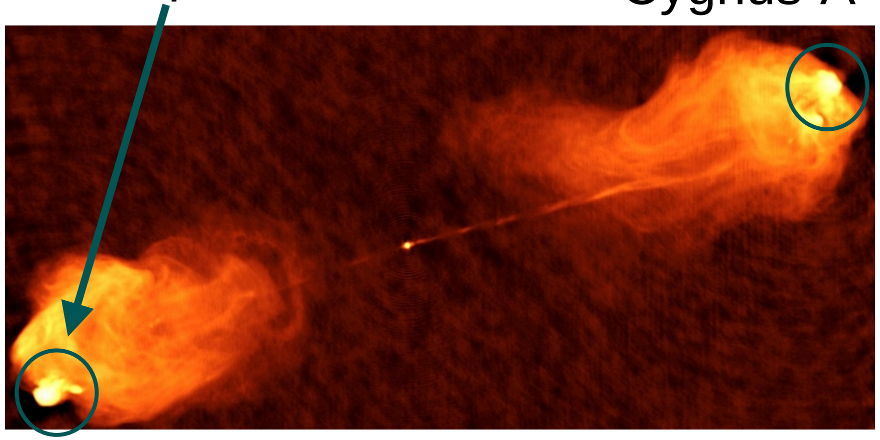
Gabriel Torralba Paz, Jacek Niemiec, Masahiro Hoshino, Takanobu Amano and Shuichi Matsukiyo

Mildly relativistic (MR) shocks in jets

- Strong X-ray or γ-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 $\gamma_{\mathrm{bulk}} \approx 2$–$5$
- Plasma in these jets is expected to be **magnetised**

Hotspots

Cygnus-A



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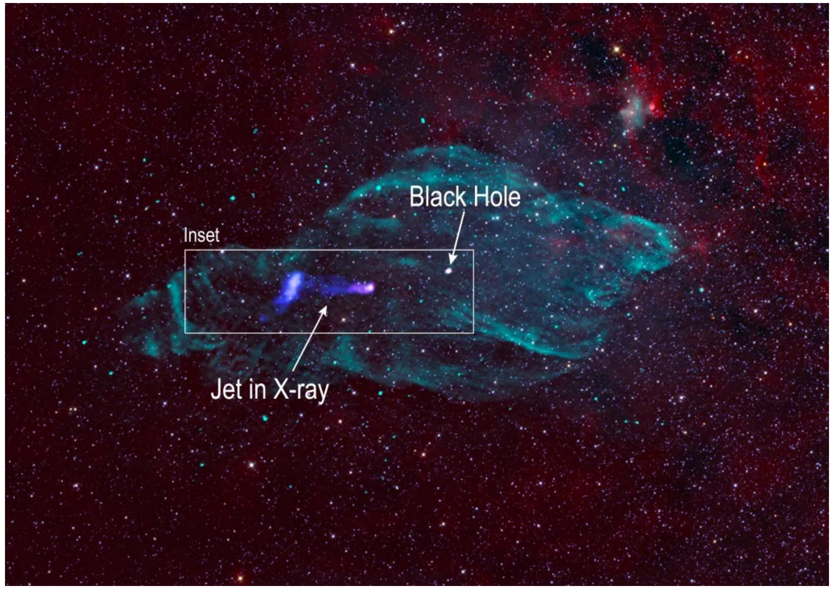
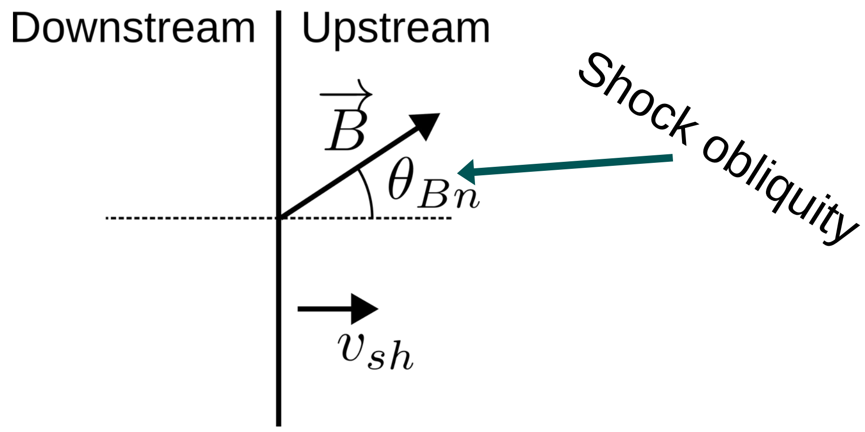
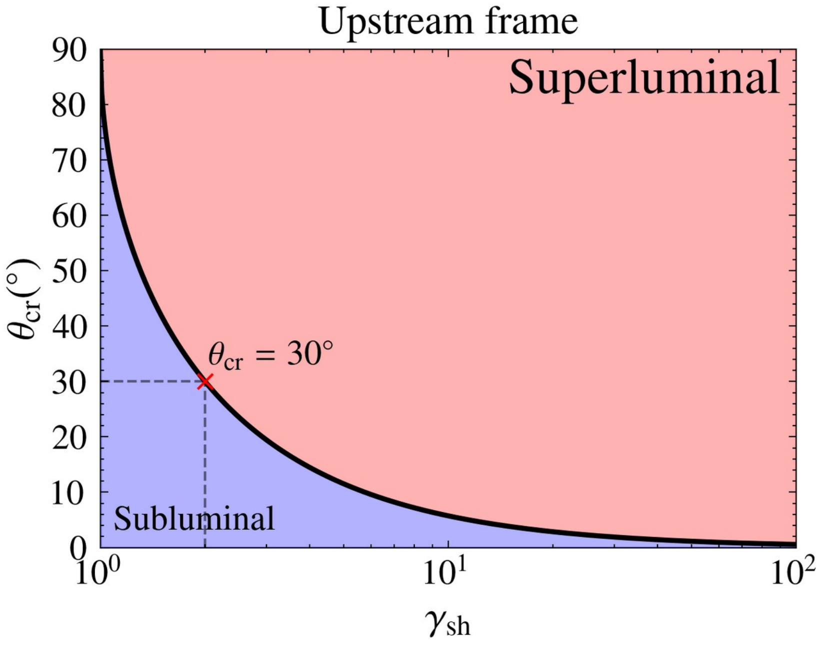


Superluminal and subluminal shocks

- In magnetised shocks, there exists an obliquity angle, $\theta_{\rm cr}$, 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)

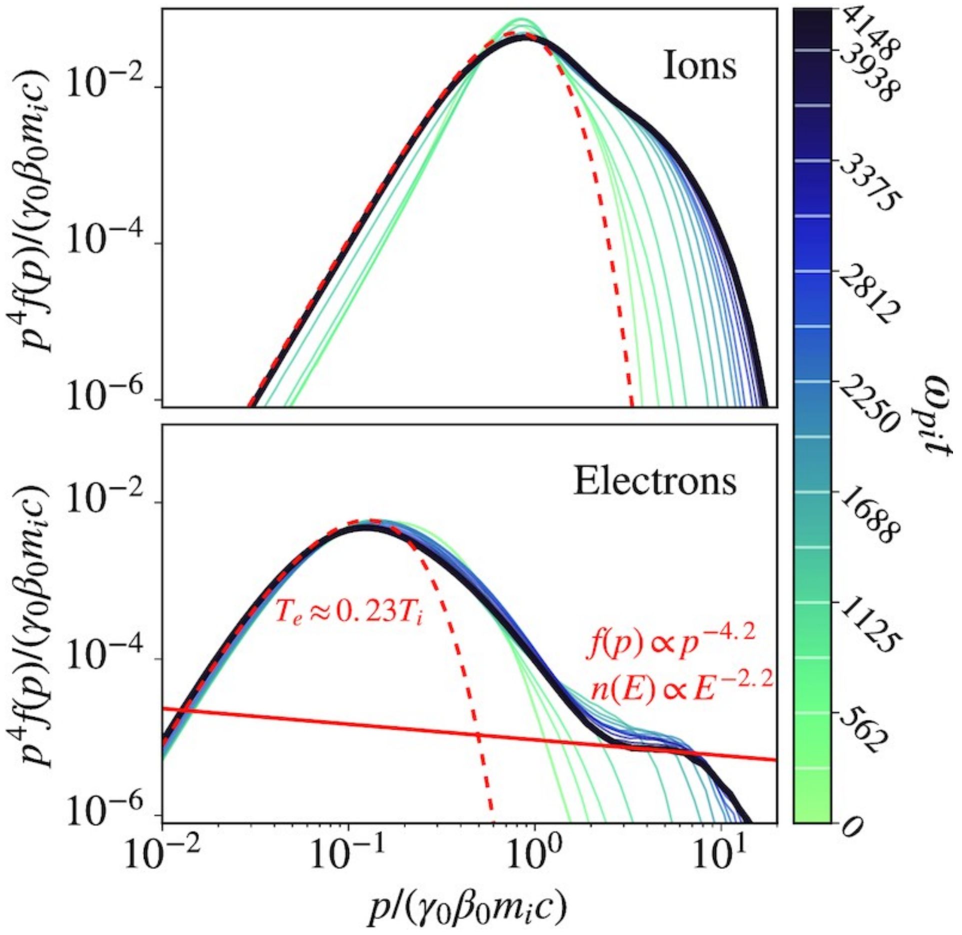




Already studied mechanisms in MR shocks

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

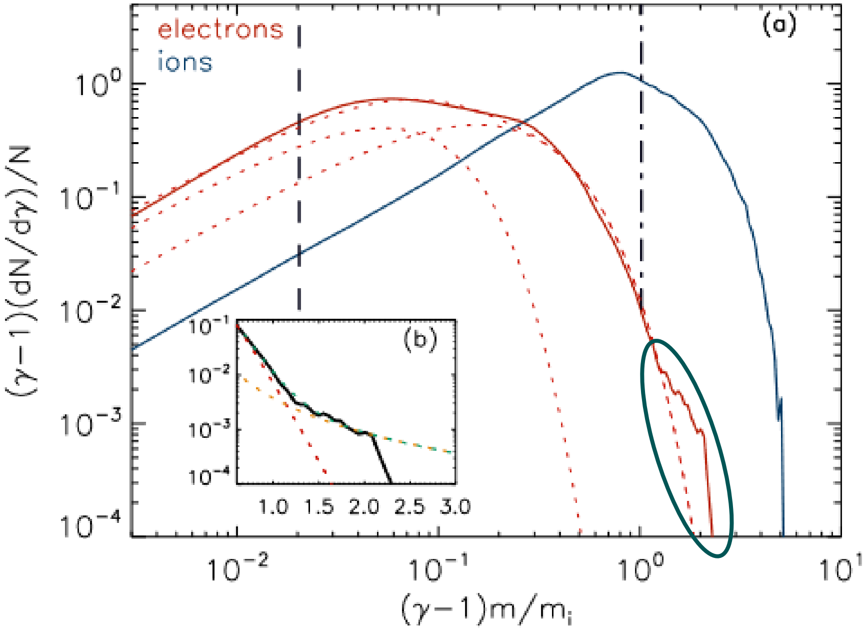


Crumley et al. 2019

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

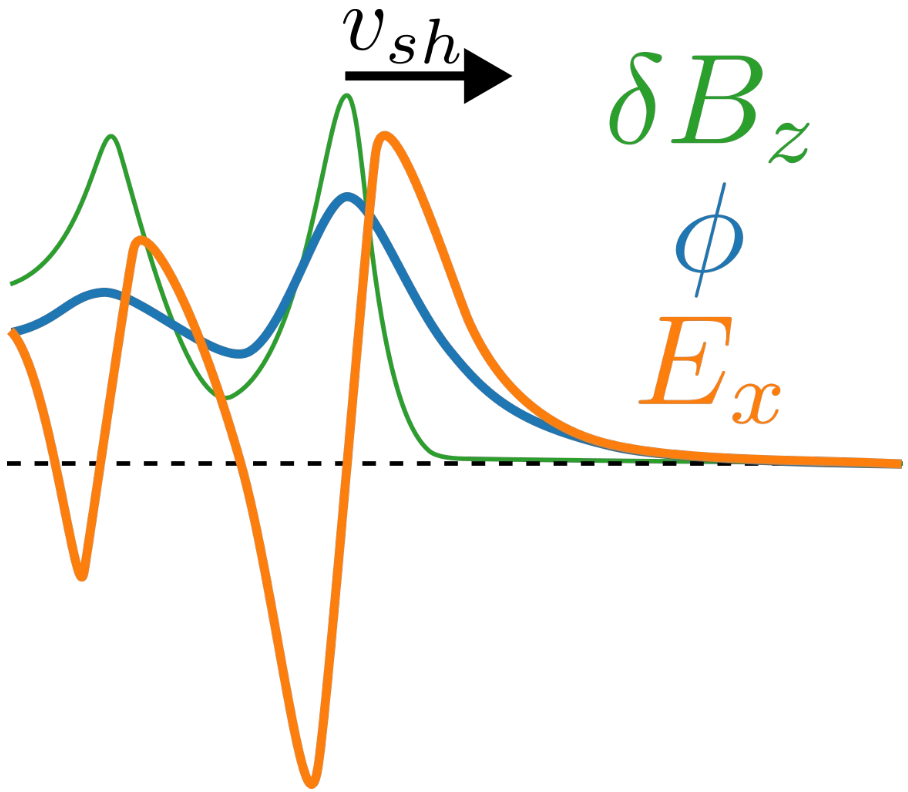


Ligorini et al. 2021

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 **B**)
  - Large-amplitude waves are highly non-stationary!

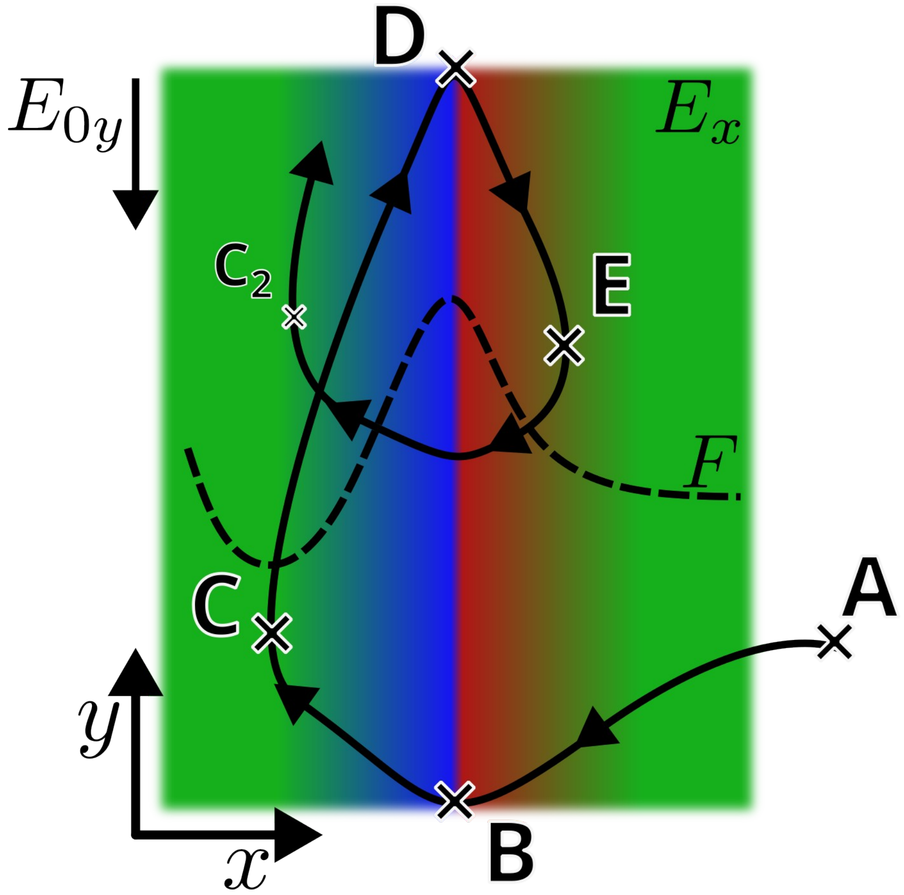
Structure of a large-amplitude magnetosonic shock wave



Trapping and acceleration mechanism

Mechanism cycle

- A: Upstream electron reaches the shock.
- B: Electron attracted by φ
- C: Electron is **reflected** behind the pulse
- C → D: Electron is **greatly accelerated** by motional electric field E_{0y}
- D → 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

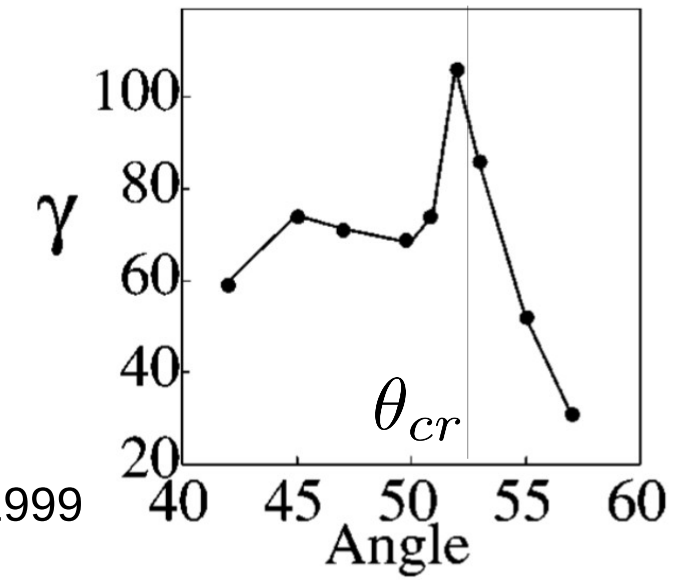
$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} m_e c^2 = -e\mathbf{E}\cdot\mathbf{v} \to \Delta\gamma m_e c^2 = e\Delta\phi - eE_{0y}\int v_y \mathrm{d}t$$

- Most energetic mechanism section is C→D:

$$\Delta E_{CD} = e\left(\phi_D - \phi_C\right) - eE_{0y}\int_C^D v_\parallel \frac{B_y}{B}\,\mathrm{d}t + eE_{0y}\int_C^D \frac{E_x}{E_{0y} + v_\parallel \frac{B_{0x}B}{B_z}}\,\mathrm{d}x$$

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

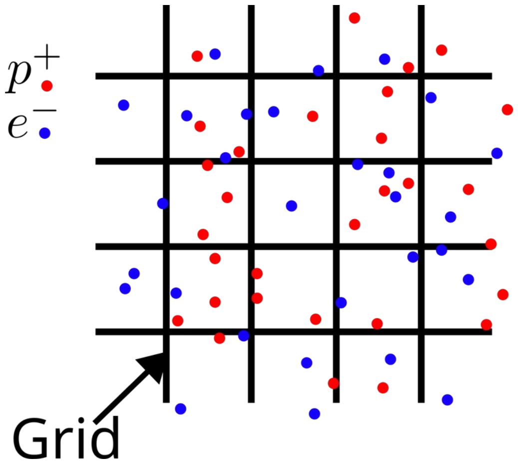
$$\Delta E_{CD} \approx e\phi_D + \frac{-e\phi_D}{1 + \frac{cB_{0x}}{E_{0y}}} = \frac{e\phi_D}{1 - \frac{v_{\mathrm{sh}}}{c}\frac{B_{0z}}{B_{0x}}} = \frac{e\phi_D}{1 - \frac{\tan\theta_{Bn}}{\tan\theta_{cr}}}$$

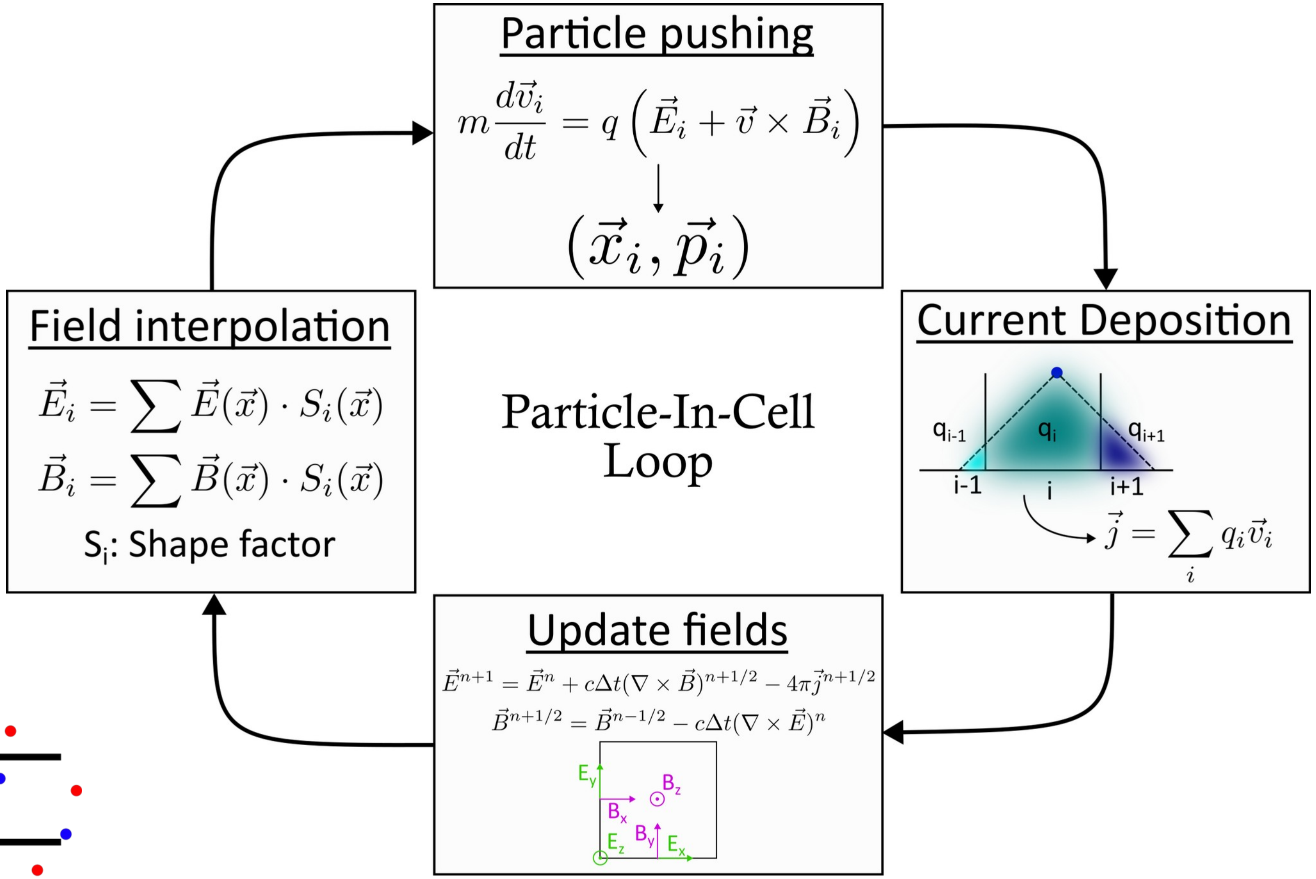


Bessho & Ohsawa, 1999

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

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

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

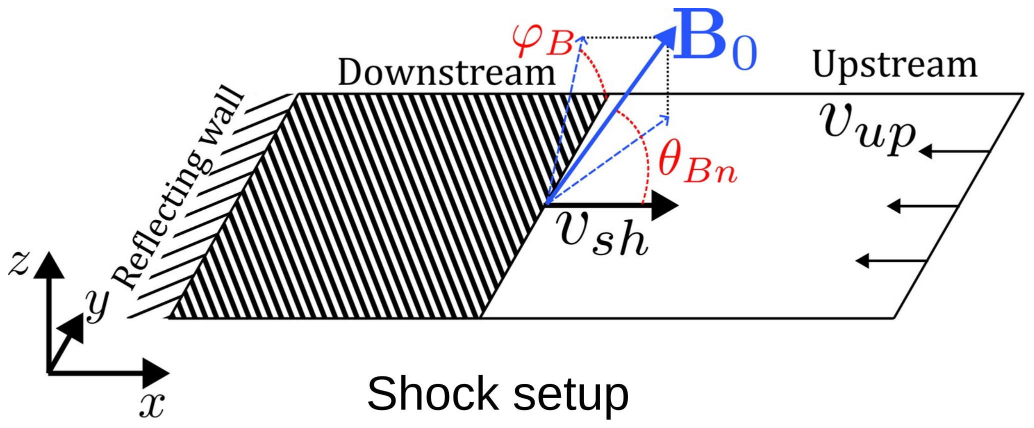
$$\phi_B = 90^\circ (\text{out-of-plane } \mathbf{B})$$

$$m_i/m_e = 100$$

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

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

Sim.	Type of shock	θ_{Bn}	$\gamma_{sh,up}$	$M_{A,up}$
$\theta30$	Oblique subluminal	30°	3.7	1.077
$\theta40$	Oblique superluminal	40°	4.2	1.106
$\theta10$	Quasi-parallel	10°	3.1	1.035

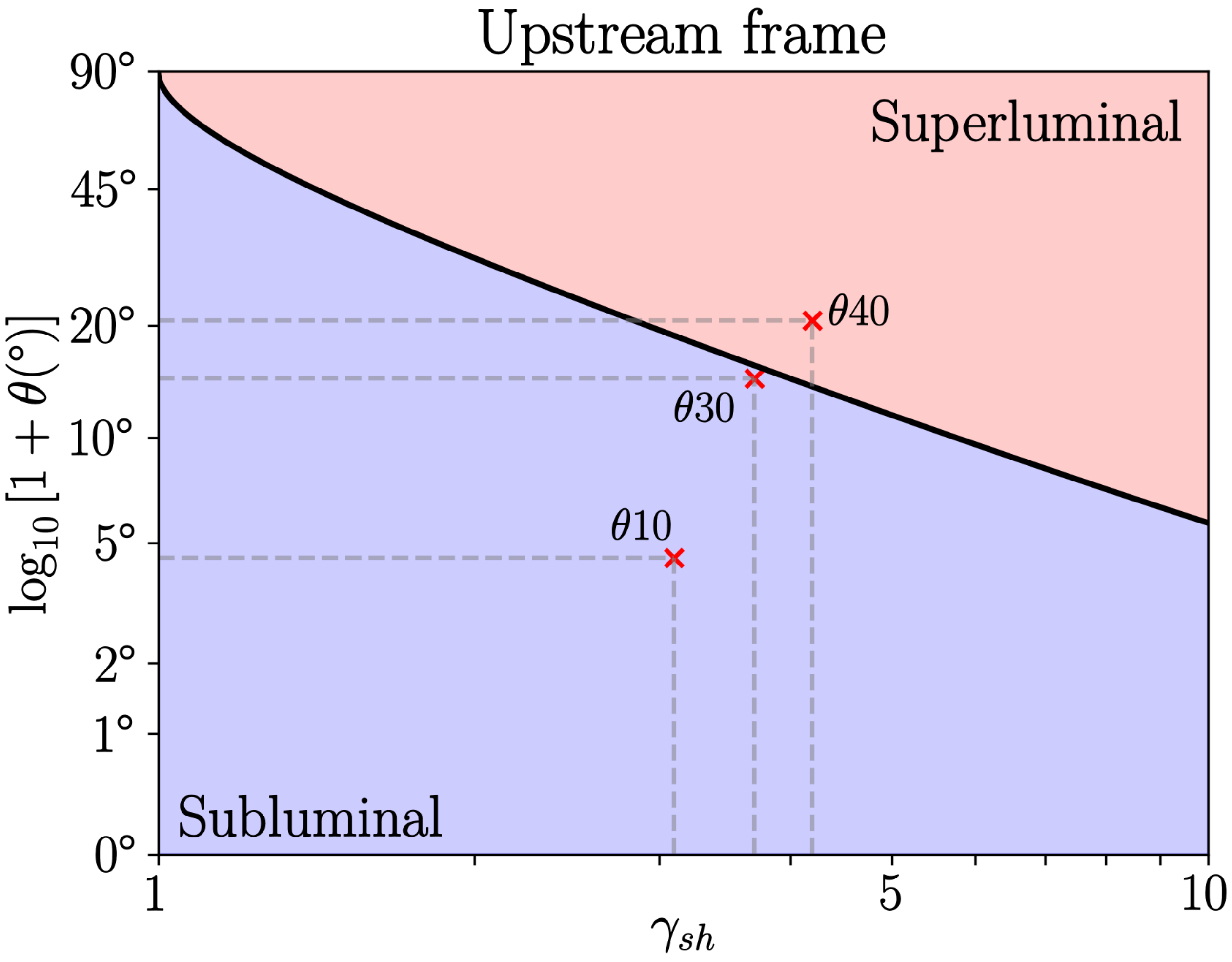


Shock setup

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

Simulation setup

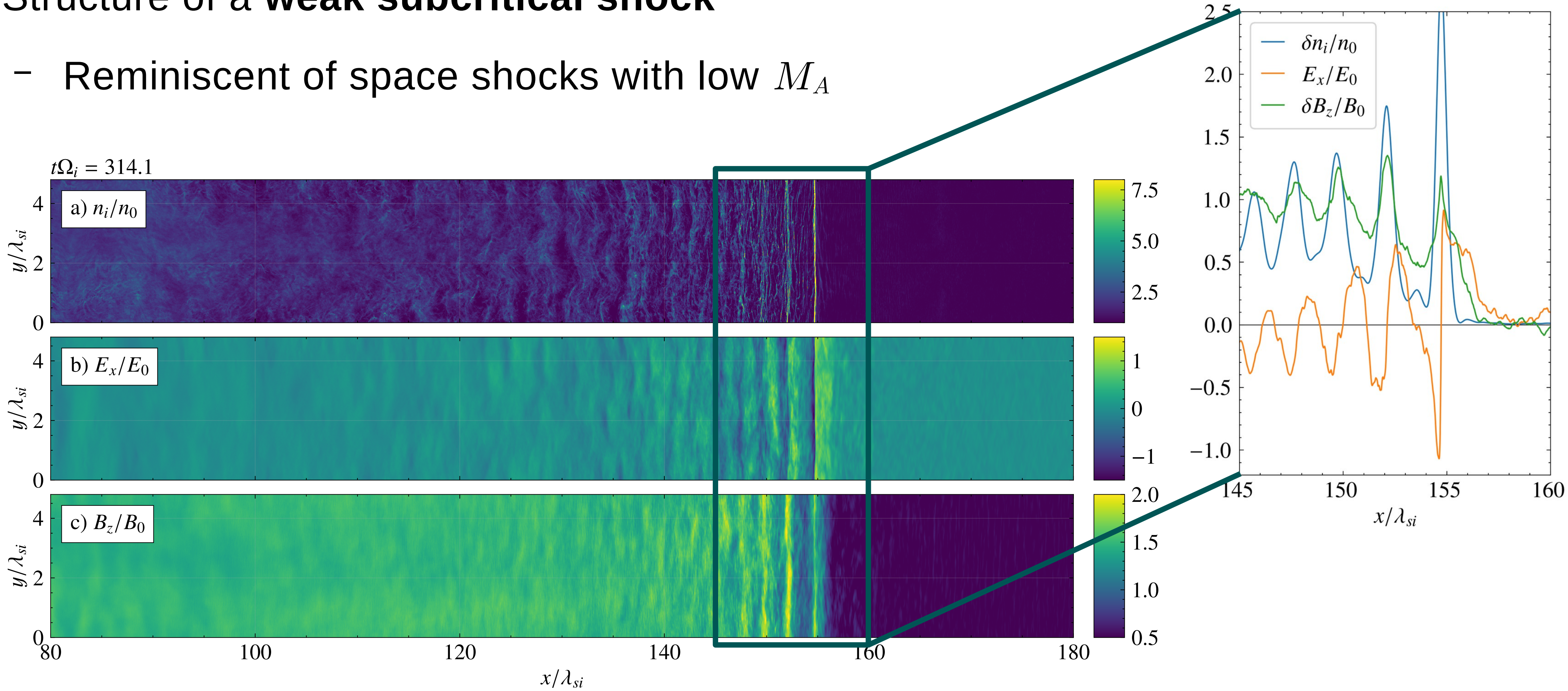
Setup location in θ vs. γ space



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

Structure

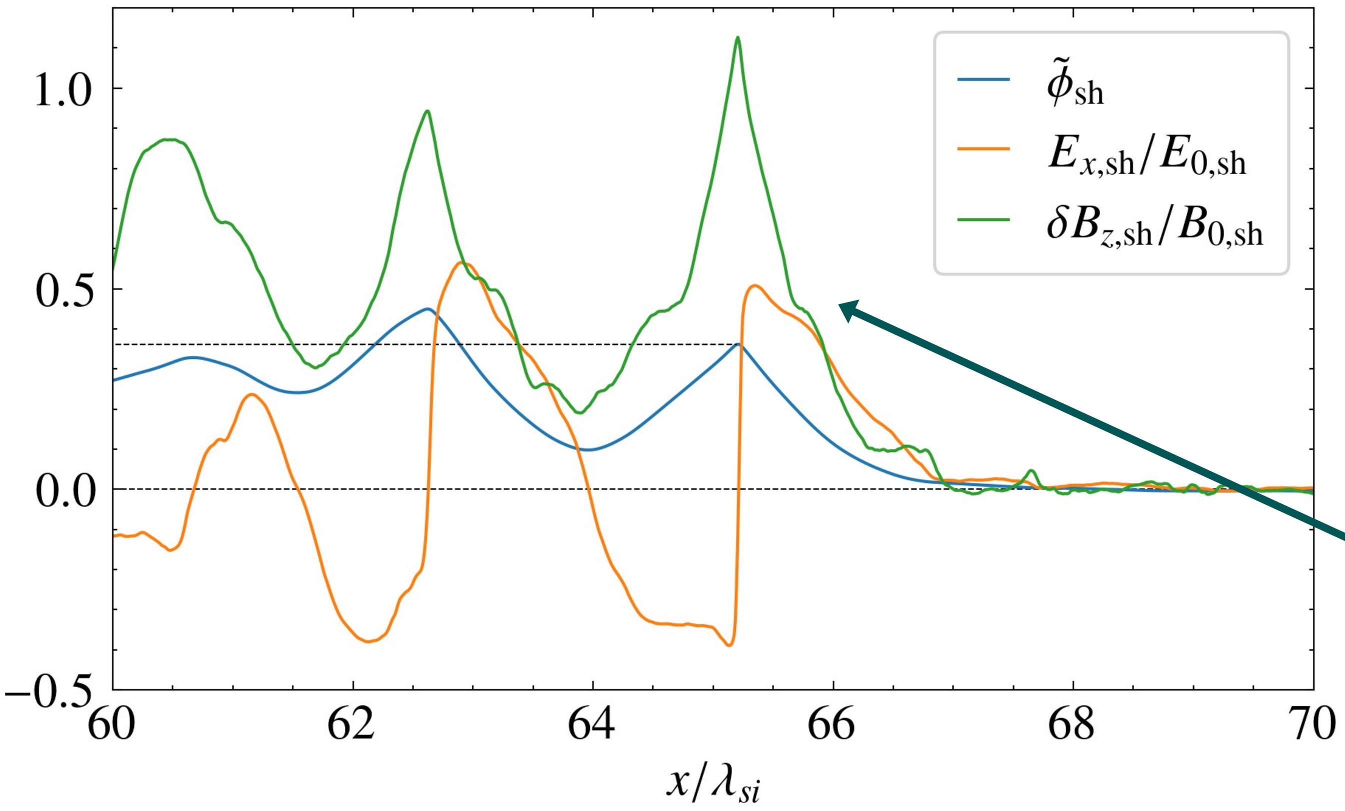
- Structure of a **weak subcritical shock**
  - Reminiscent of space shocks with low M_A

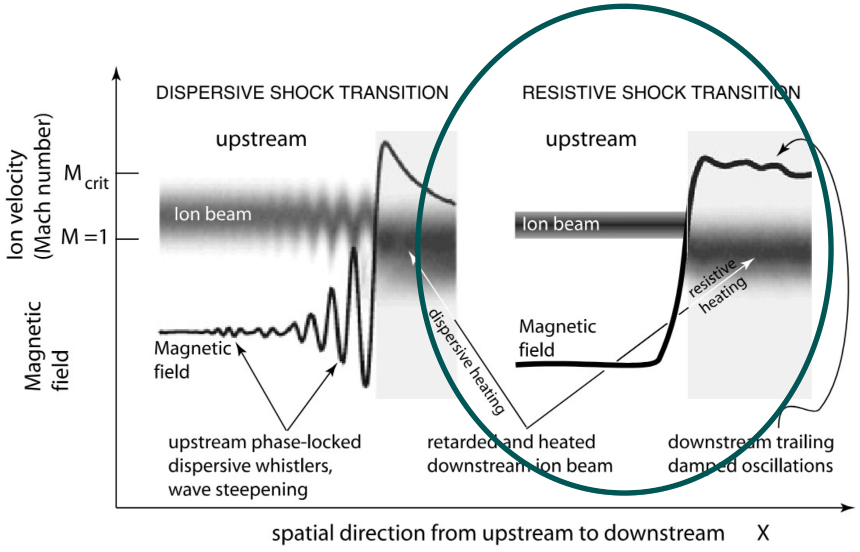


Oblique subluminal shock ($\theta_{Bn}=30^{\circ}$)

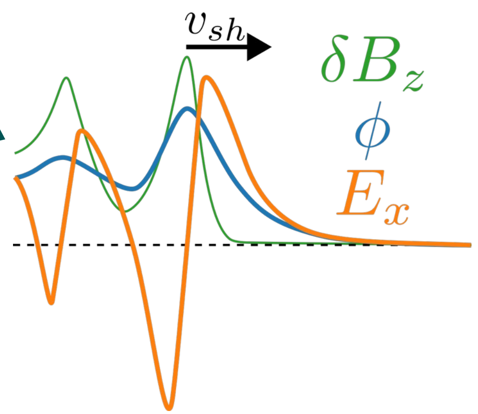
Shock potential

- Shock potential = **E**x**B** electron drift + electron motion parallel to **B** + ion current contribution
- Resistive processes regulate the shock steepening





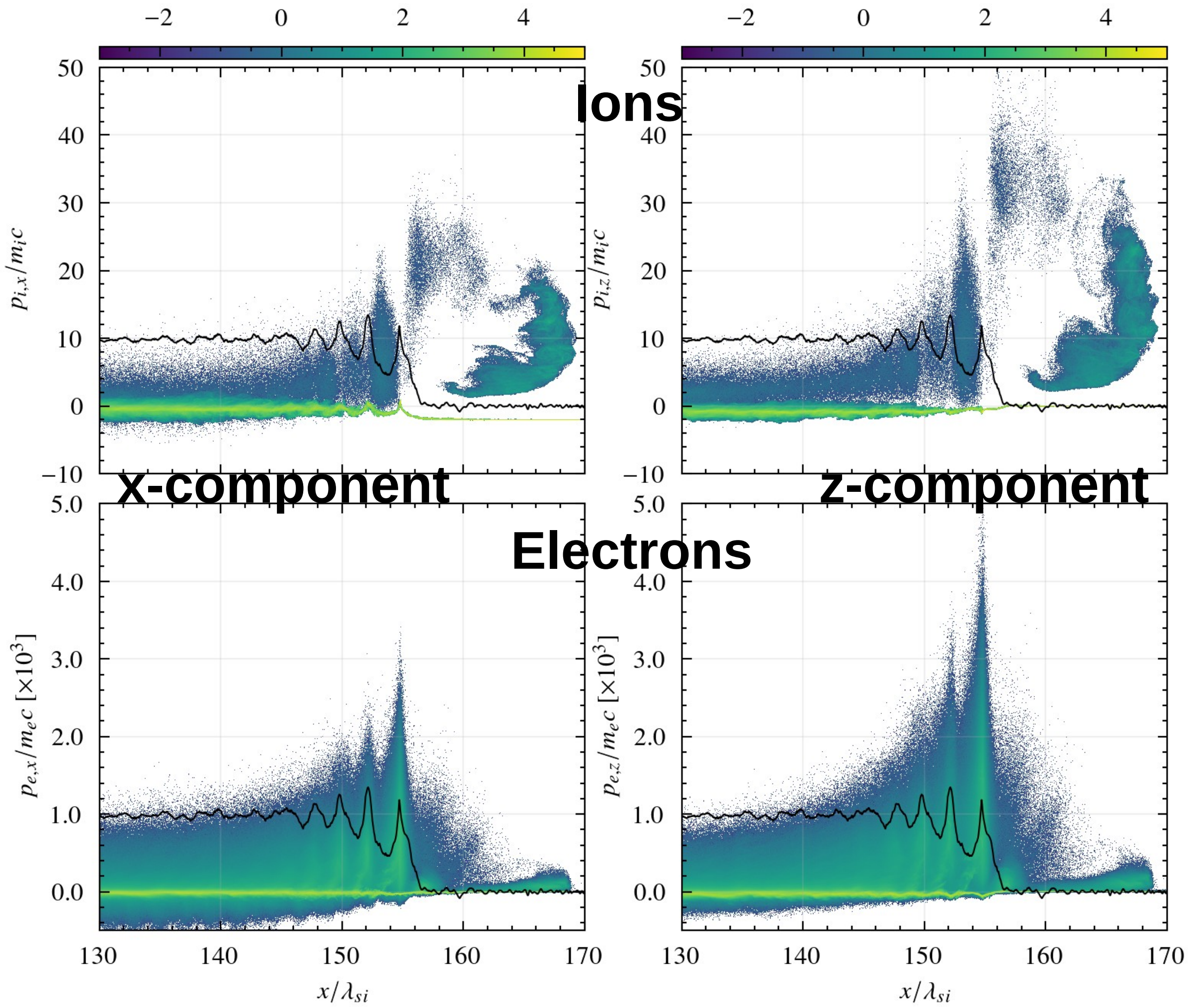
Balogh and Treumann, 2013



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**

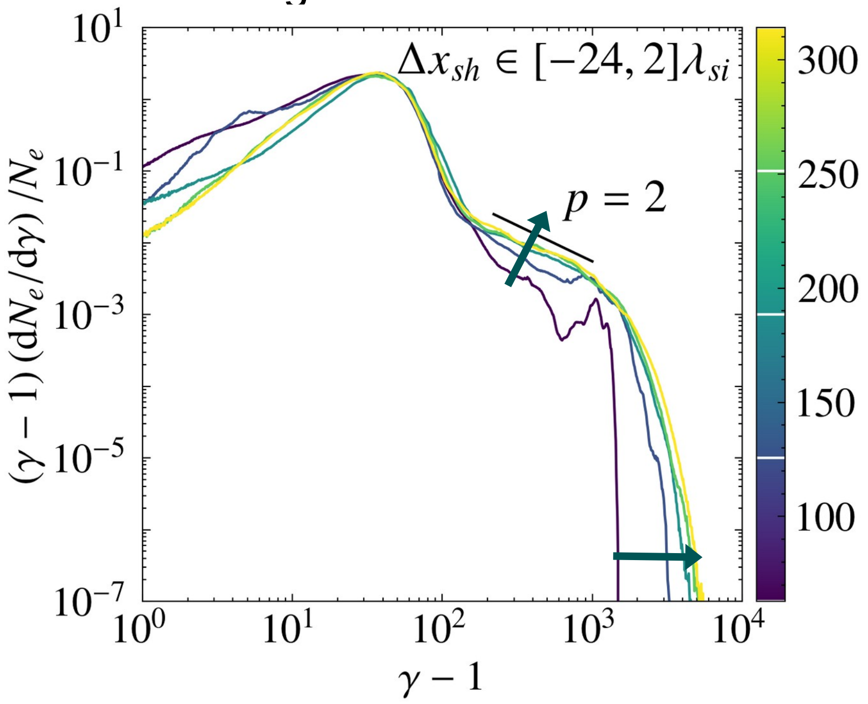


Oblique subluminal shock ($\theta_{Bn}=30^\circ$)

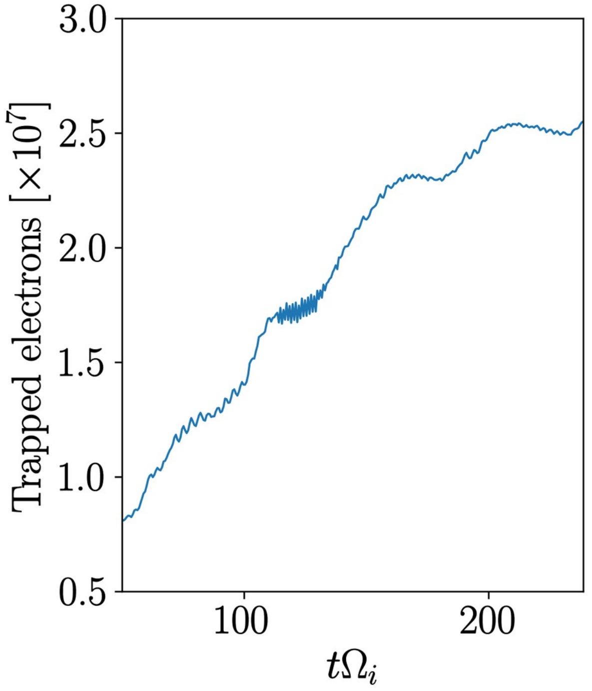
Electron energy spectra

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

Electron spectra along the shock transition



Number of trapped electrons

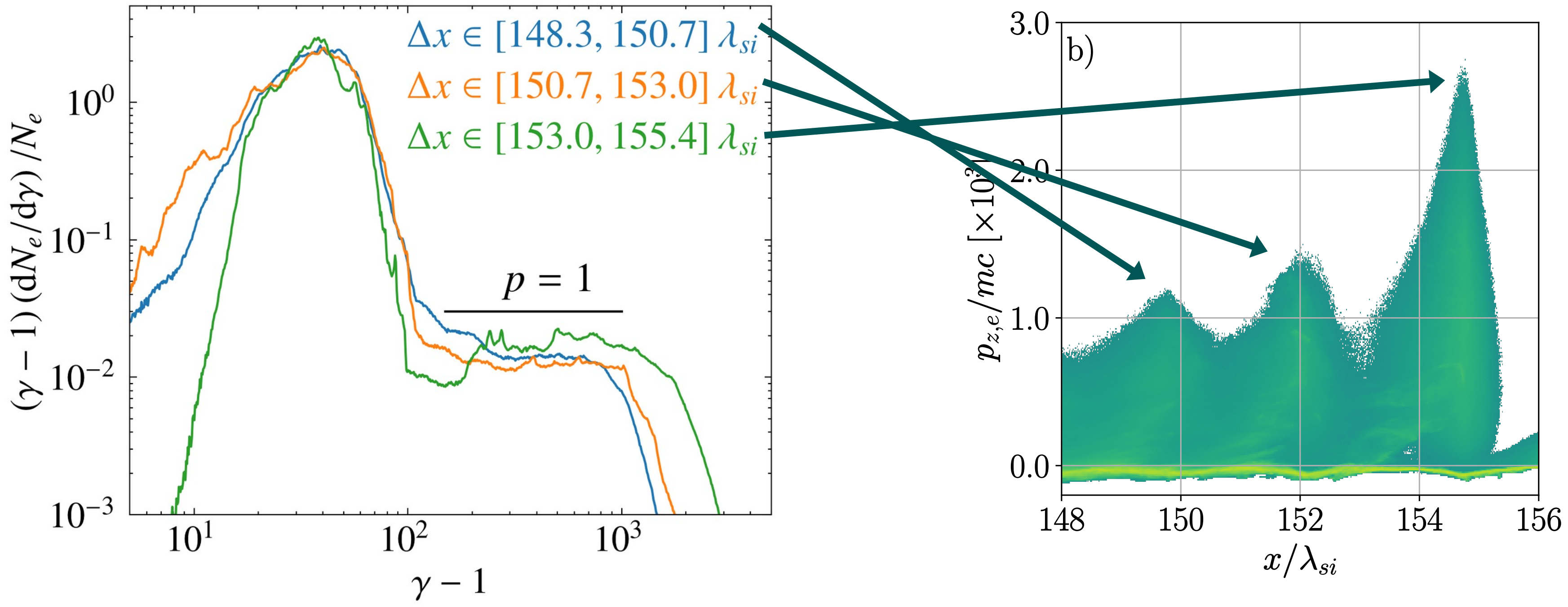


Oblique subluminal shock (θ_{Bn}=30°)

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

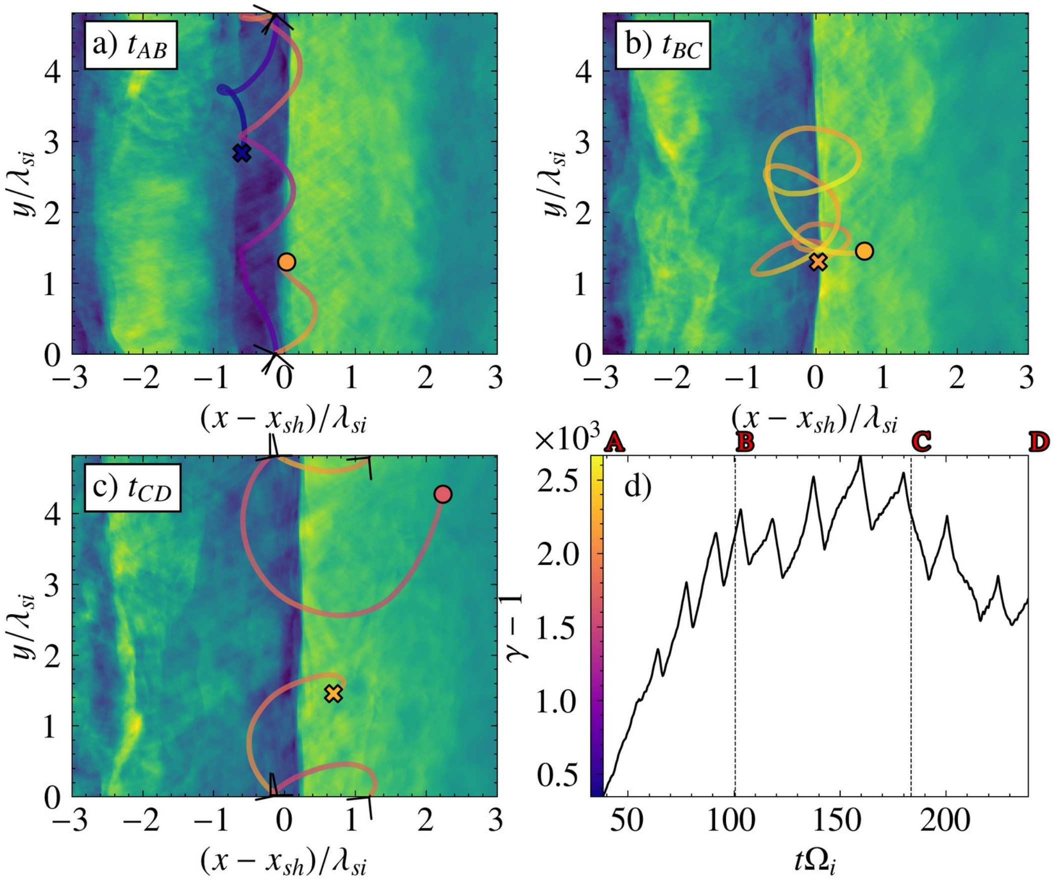


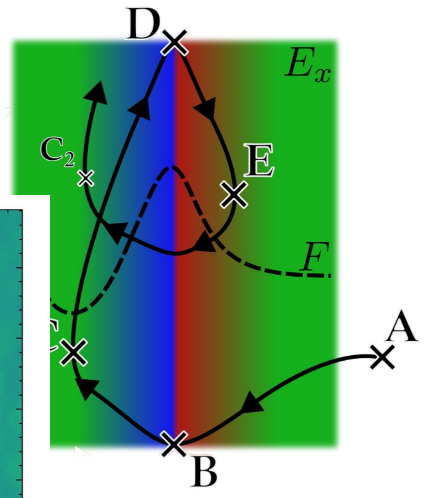
Oblique subluminal shock ($\theta_{Bn}=30^{\circ}$)

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

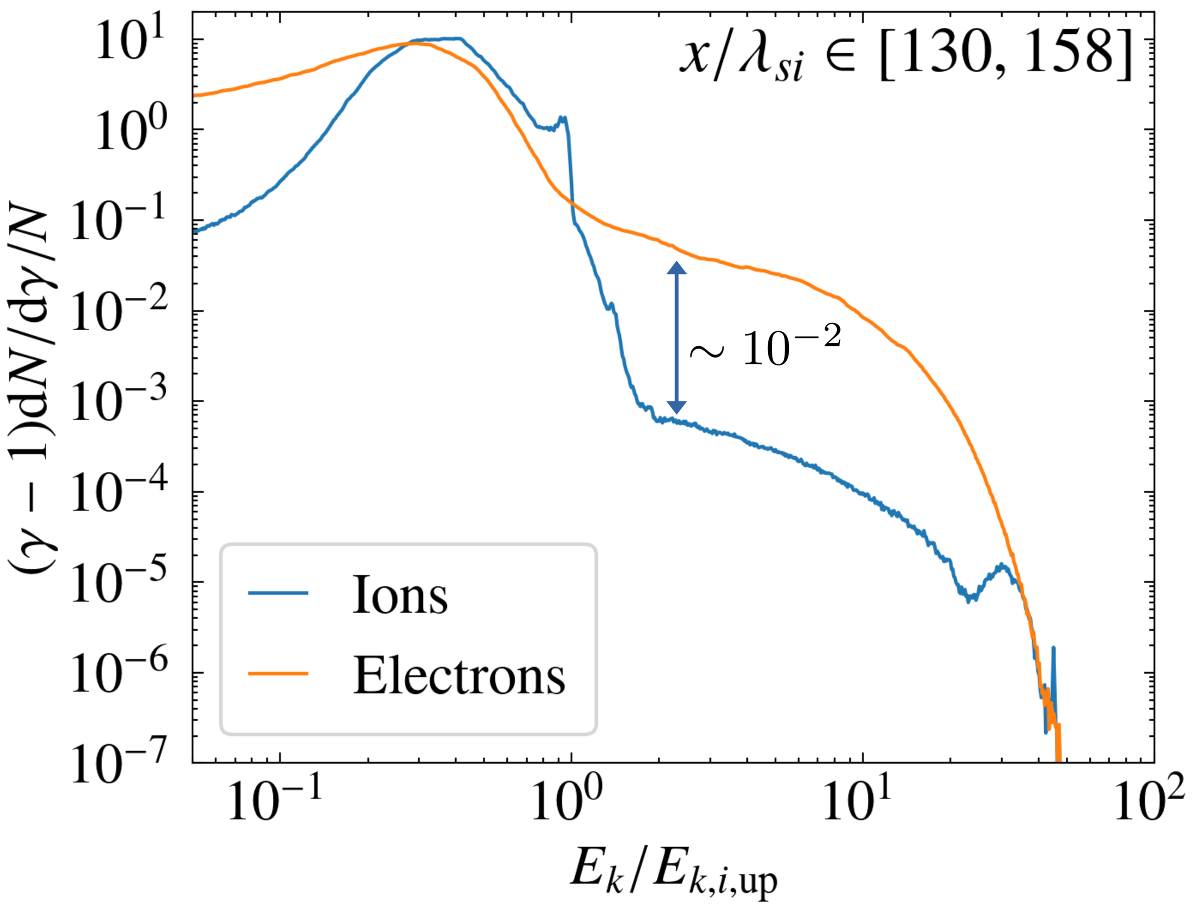




Oblique subluminal shock ($\theta_{Bn}=30^{\circ}$)

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 ($\theta_{Bn}=30^{\circ}$)

Maximum particle energy

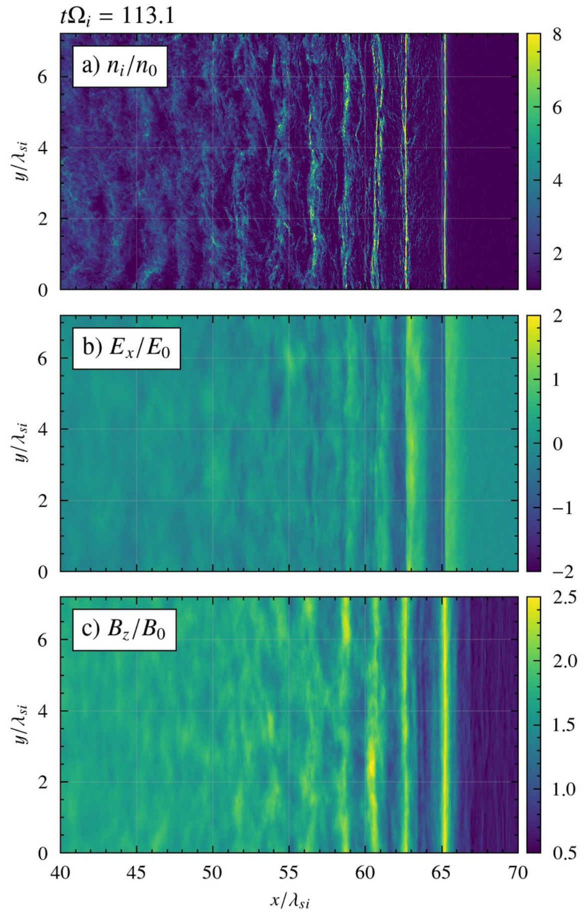
- Maximum electron energy scales with mass ratio
  - For a given σ_i , the electric potential ϕ scales linearly with the ion mass
  - Confirmed by a simulation with higher-mass ratio $(m_i/m_e=400\ )$
- Upper limit given by the confinement region i.e. shock width:
  - $\Delta\, x_{\rm sh} \sim r_{g,i}$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

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

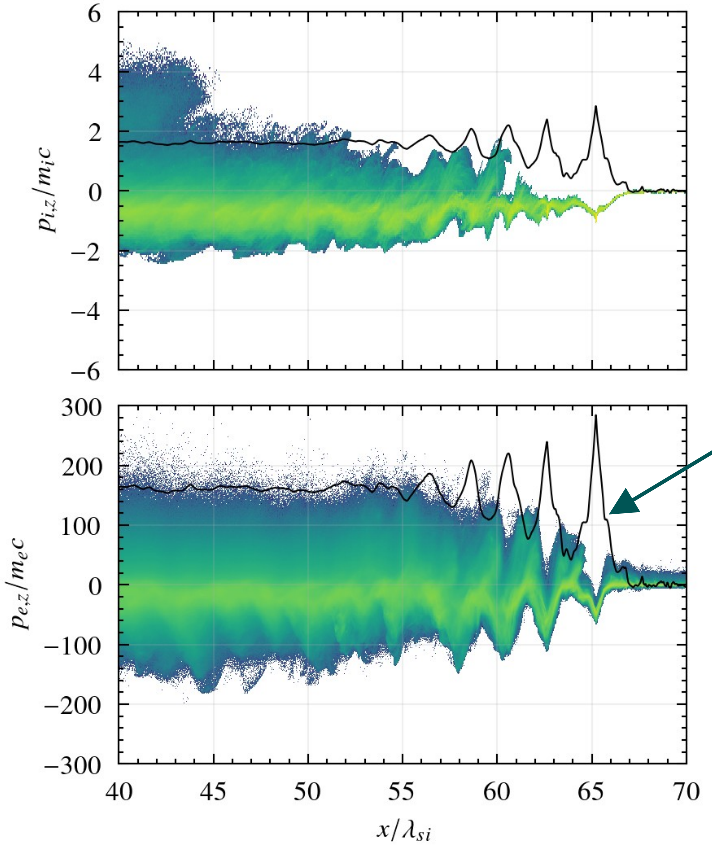
- Ions easily escape sine their gyroradii is already of the order of the shock width

Oblique superluminal shock (θ_{Bn}=40°)

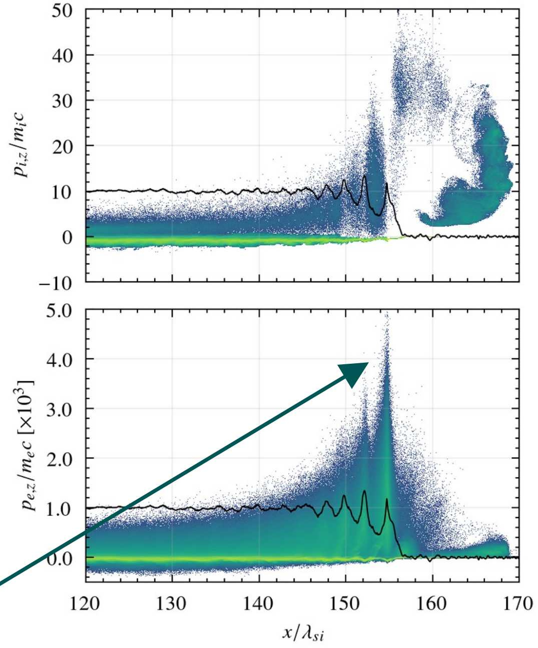
- Similar structure, **inefficient** acceleration
  - Superluminal conditions prevent electrons from being trapped



Superluminal



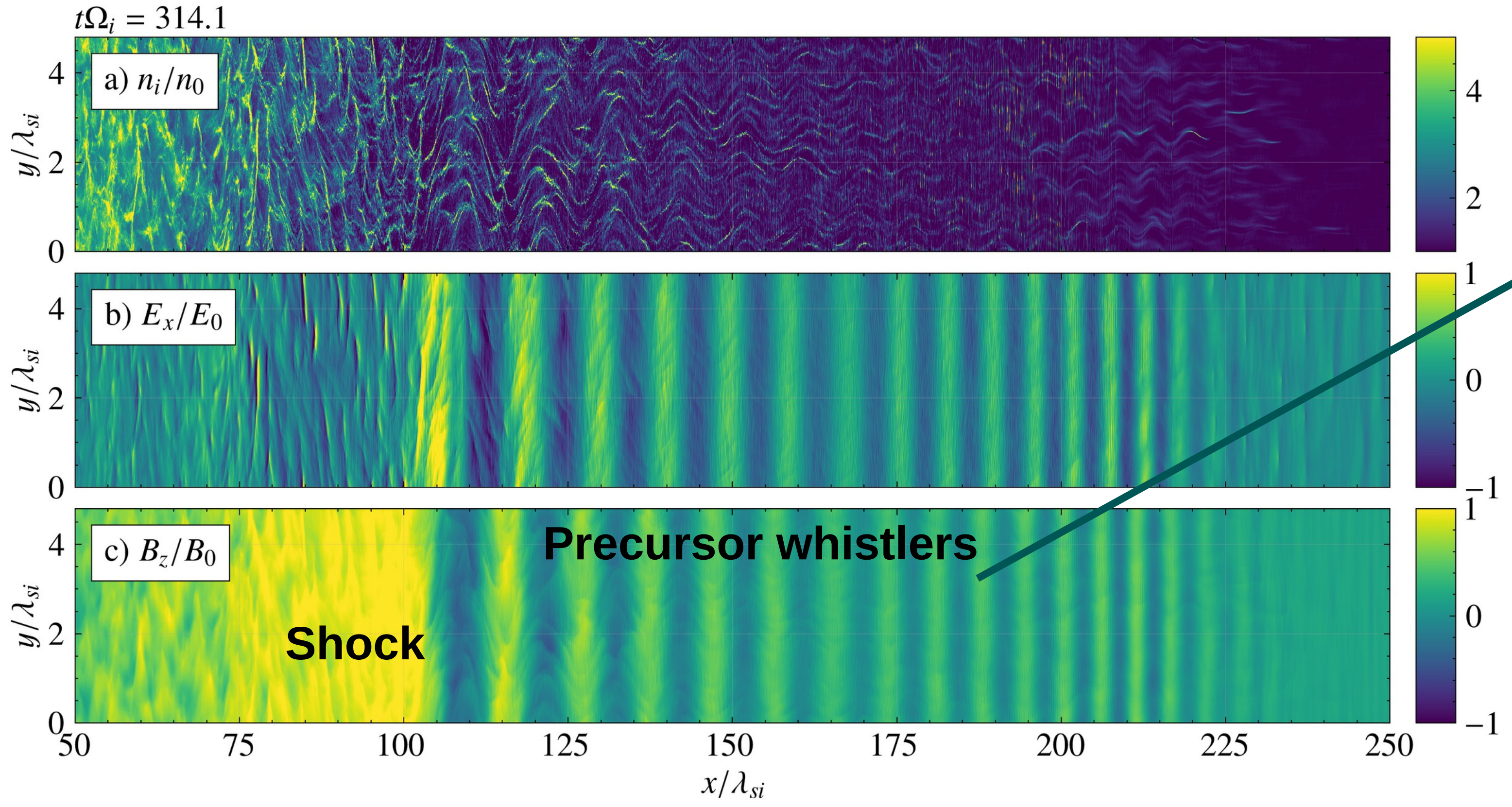
Subluminal



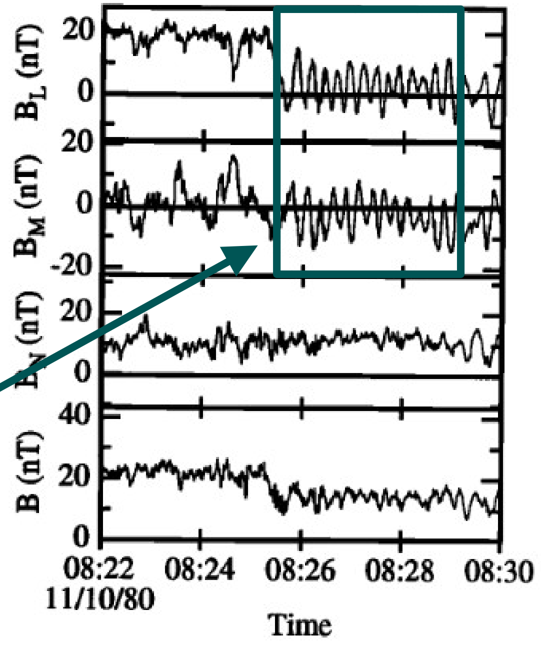
Quasi-parallel shock ($\theta_{Bn} = 10^\circ$)

Structure

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



Farris et al. 1994

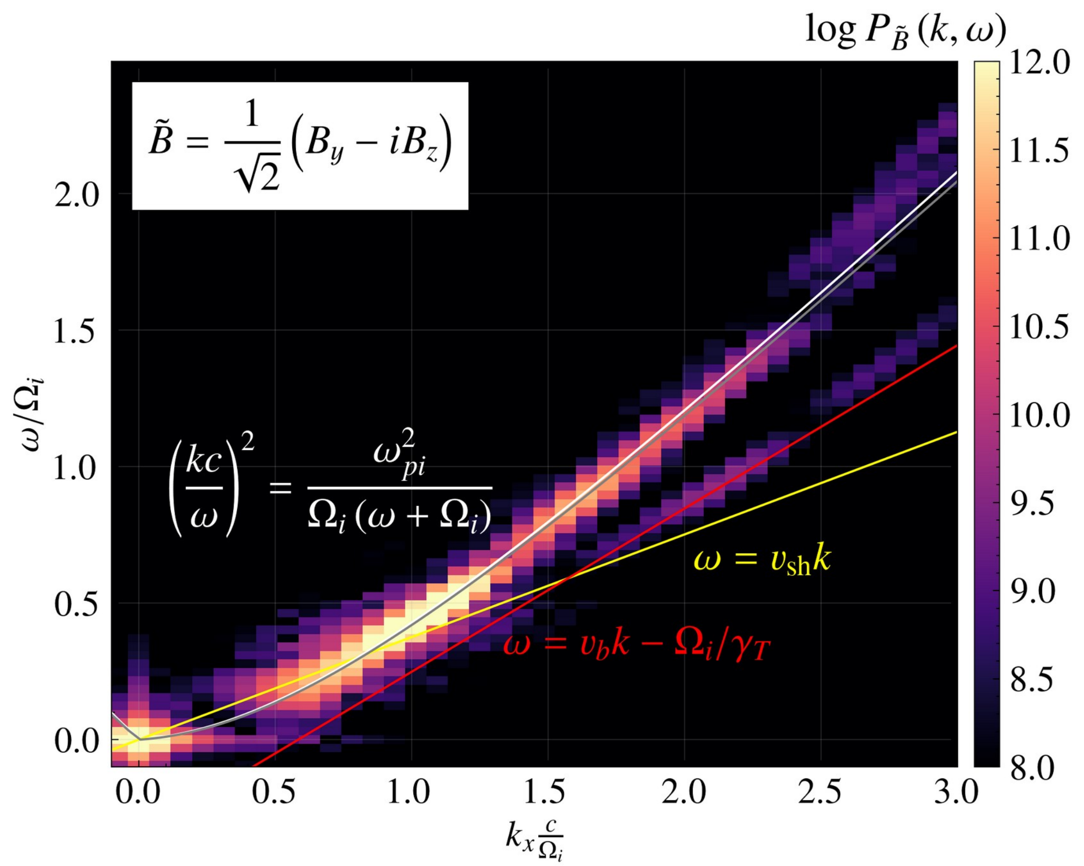


ISEE 1 measurements
November, 1980

Quasi-parallel shock (θ_{Bn}=10°)

Precursor wave train

- The waves in front of the shock are whistler waves. Confirmed by:
  - $M_{A,\mathrm{up}} < M_{w,\mathrm{up}}$
  - 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)

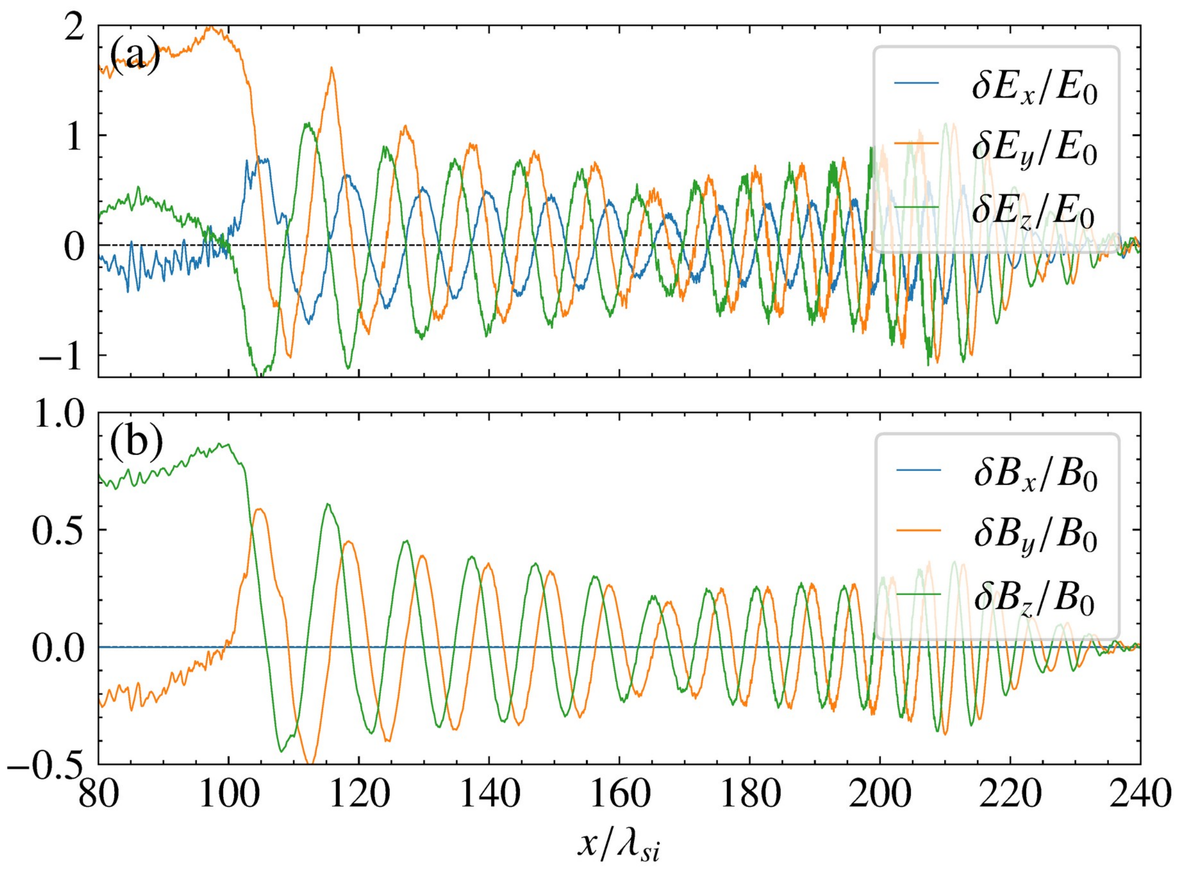


Power spectrum in simulation frame

Quasi-parallel shock (θ_{Bn}=10°)

Structure

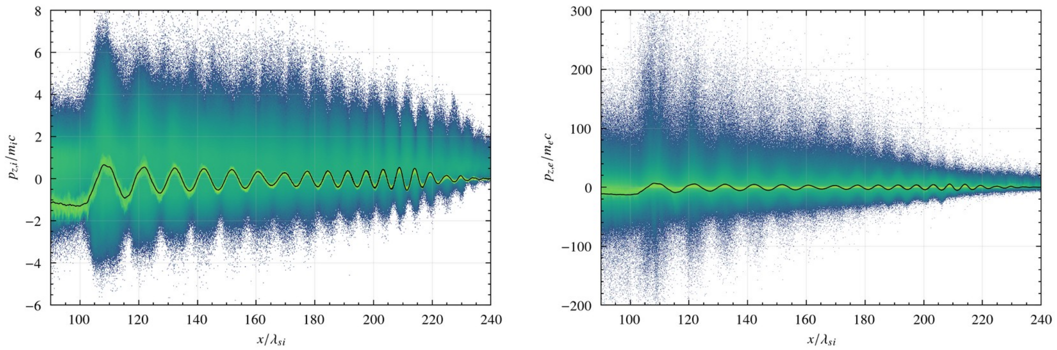
- Whistlers propagate along the shock normal
  - But magnetic field obliquity is finite!
  - Not circularly, but rather elliptically polarised
- As a consequence of quasi-parallel propagation, E_x wave appears
  - Similar amplitude as transverse electric field
  - Same k and ω

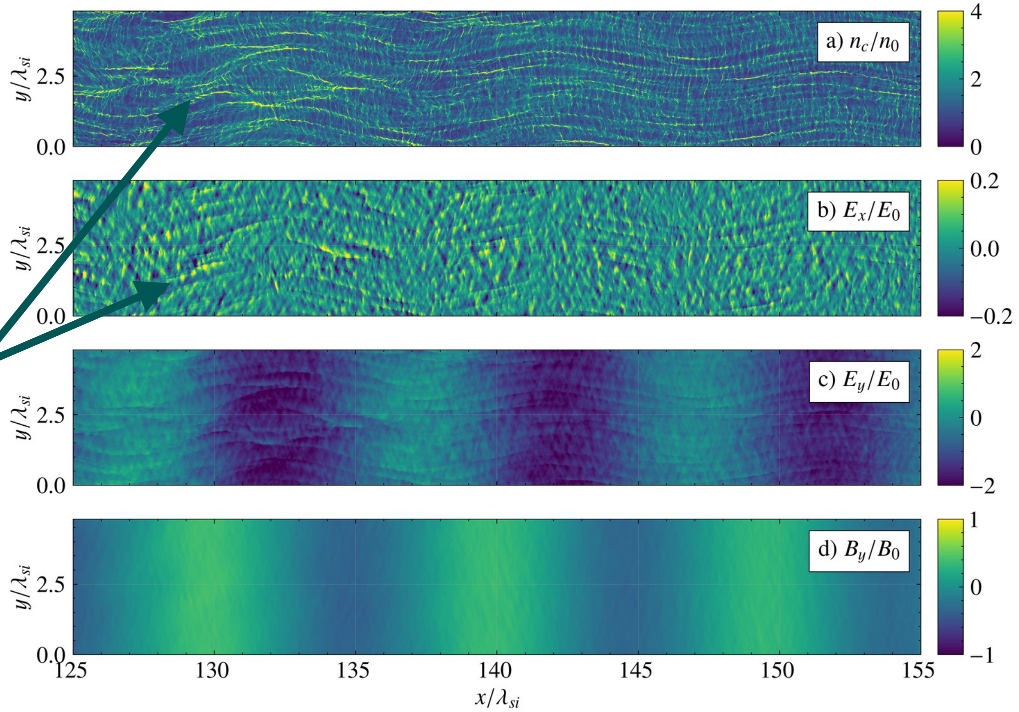


Quasi-parallel shock ($\theta_{Bn}=10^{\circ}$)

Non-linear dynamics: MTSI

- Particles perform a quiver motion in the precursor whistler region.
  - Perpendicular velocity given by the Walén relation (Hollweg et al. 1993):
    - $v_{j,\perp} = -v_{\mathrm{ph}} \dfrac{\Omega_j}{\omega \pm \Omega_j} \dfrac{\delta B_\perp}{B_0}$
- 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

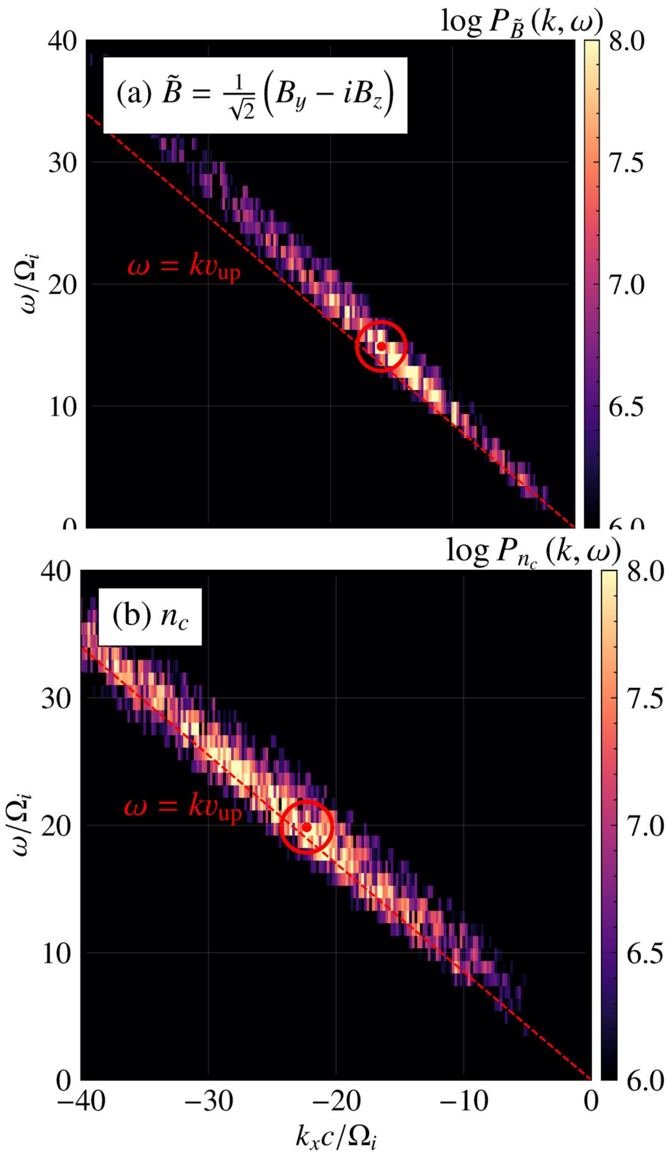




Quasi-parallel shock ($\theta_{Bn} = 10^\circ$)

Non-linear dynamics: PDI

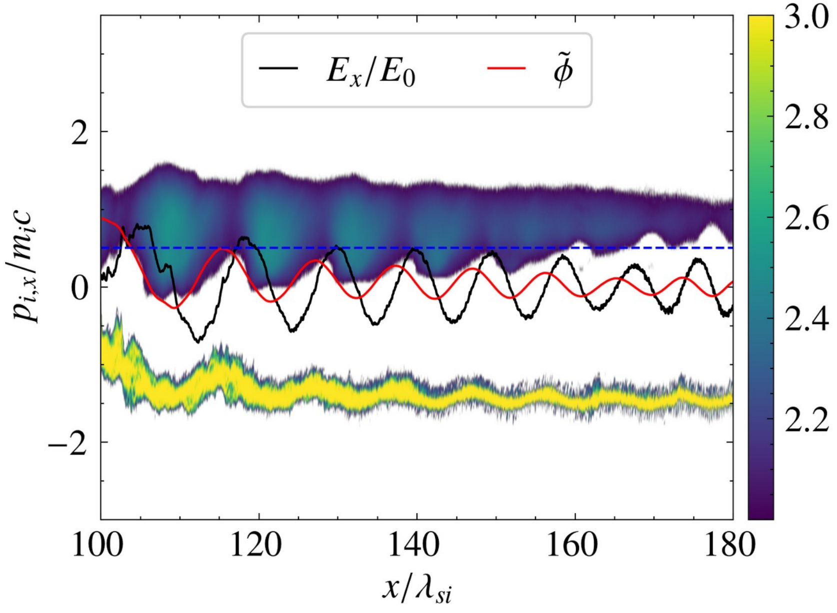
- A large-amplitude circularly polarised wave is unstable to the parametric decay instability (PDI)
- Two daughter waves are generated:
  - Ion-acoustic wave (k_1)
  - Backward-propagating whistler-like wave (k_2)
  - $k_0 = k_1 + k_2$
- Both have significantly higher ω or k
- In the upstream frame, $\omega_1 \approx 0$ (cold plasma, ion acoustic waves do not propagate)
- Electrons interact with PDI-driven waves. Ions do not

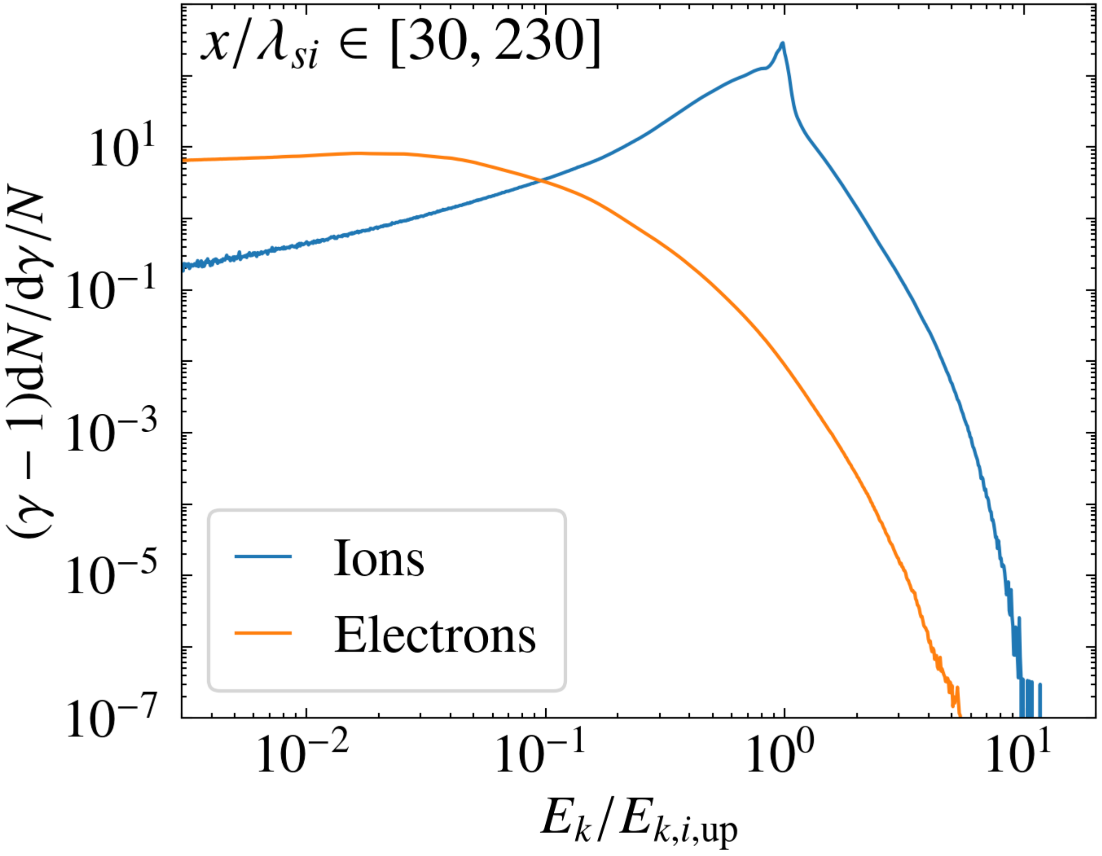


Quasi-parallel shock ($\theta_{Bn}=10^{\circ}$)

Particle heating and energy spectra

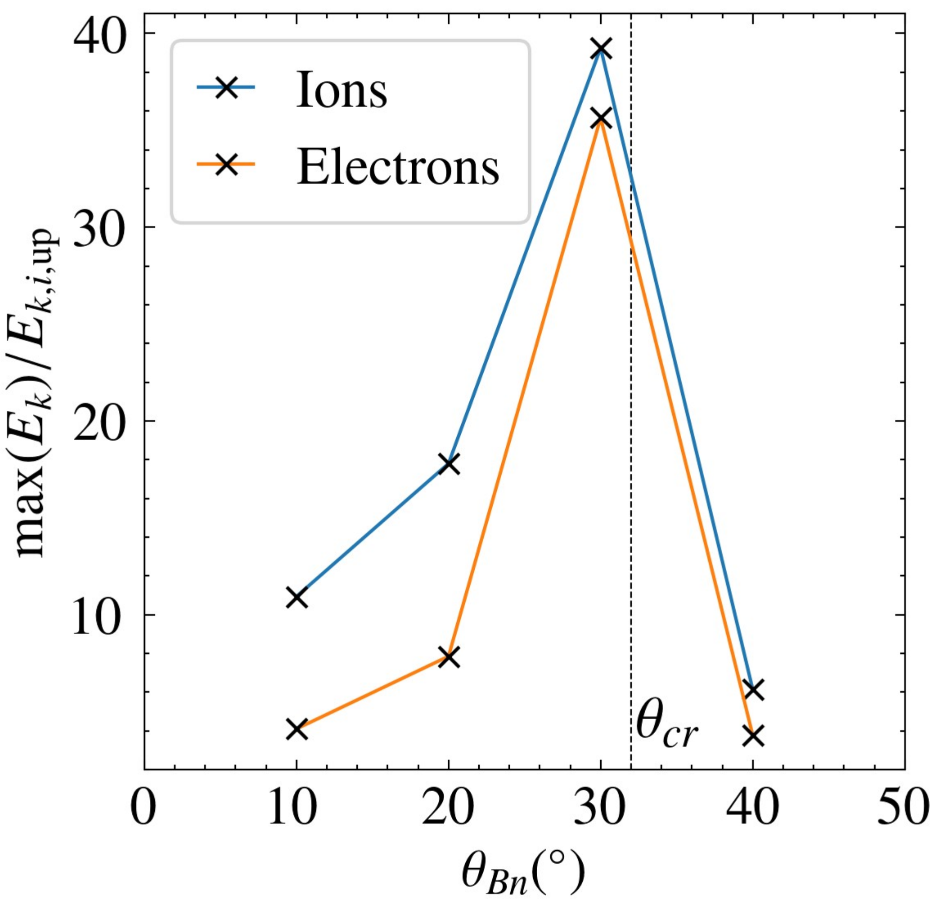
- Instabilities only contribute to particle heating
  - More efficient ion than electron heating
- Dominant ion heating mechanism: ion trapping





Efficiency of the trapping mechanism

- $\max(E_k)$ increases as θ_{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 θ_{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

Dr. Gabriel Torralba Paz

Max Planck Institute for Plasma Physics
Tokamak Theory division
Plasma Astrophysics group
E-mail: gabriel.torralba-paz@ipp.mpg.de