MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Ion and electron acceleration in strongly magnetised mildly relativistic shocks

PLASMA ASTRO

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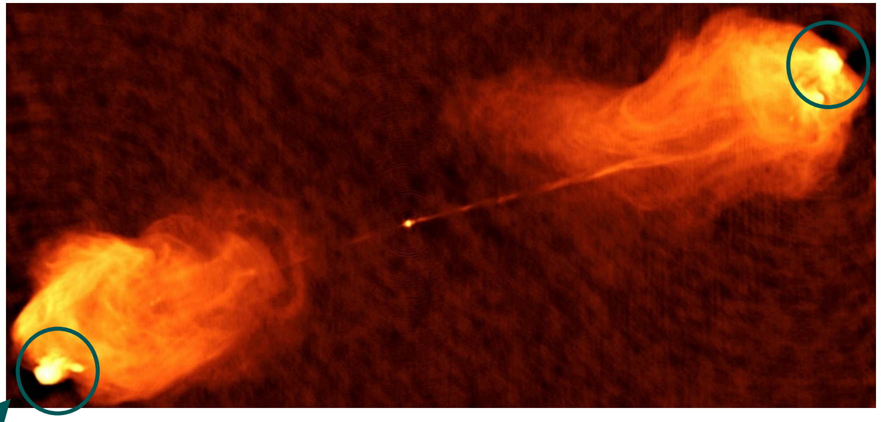
Mildly relativistic (MR) shocks in jets of AGN

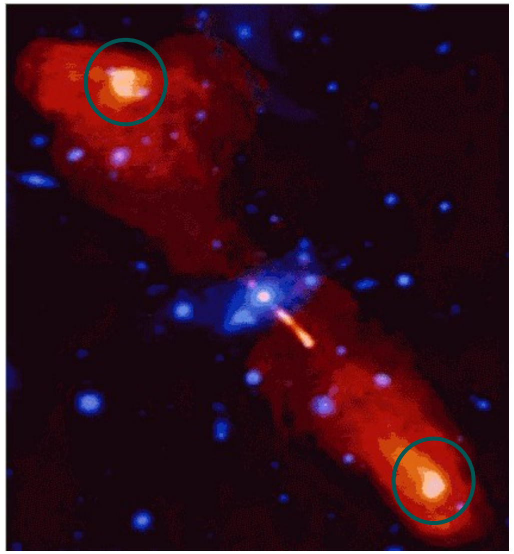
- Strong X-ray and γ-ray emission observed from jets of AGN
  - Indicates particle acceleration
- Particle acceleration commonly associated to **shocks**
  - AGN hotspots may contain mildly relativistic shocks
    - $\gamma_{\text{bulk}} \approx 2\text{–}5$
  - Plasma in these jets is expected to be **magnetised**

Cygnus-A



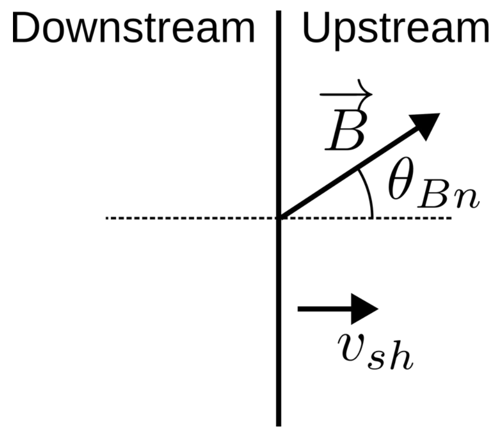
Hotspots

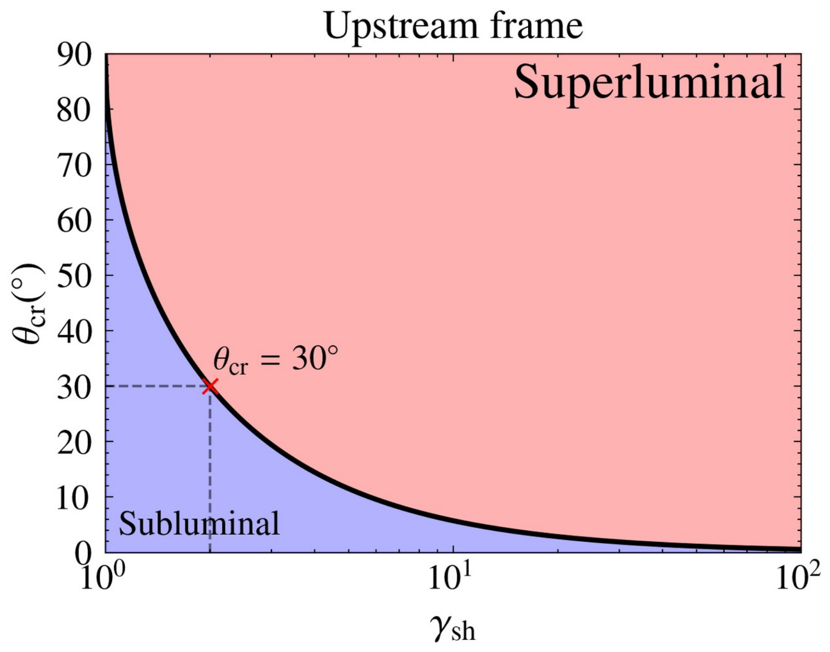
3C 219



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)

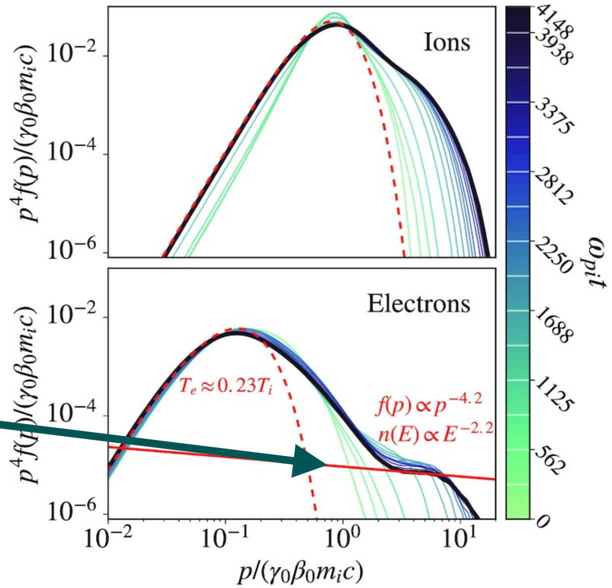




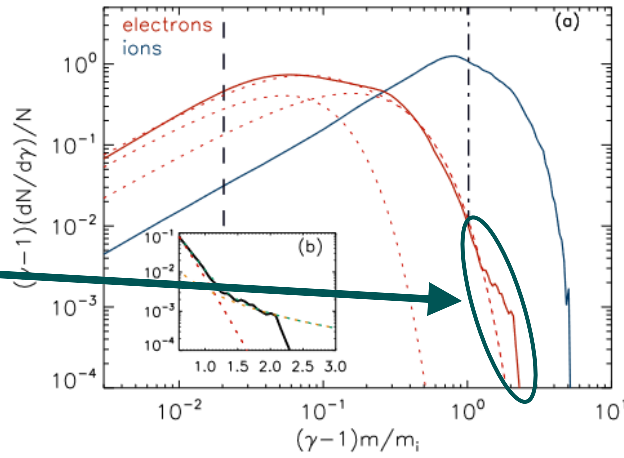
Already studied mechanisms in MR shocks

- Diffusive shock acceleration (DSA): Effective in MR shocks, but only for:
  - Subluminal configurations
  - Unmagnetised or weakly magnetised shocks

- Wakefield acceleration (WFA):
  - Highly efficient in ultra-relativistic shocks
  - Highly **INEFFICIENT** in MR shocks



Crumley et al. 2019

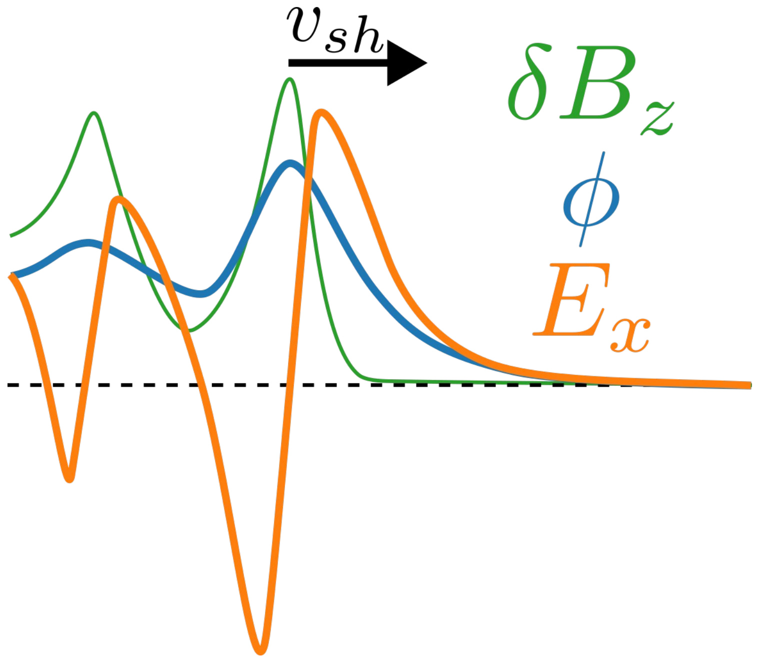


Ligorini et al. 2021

An alternative solution

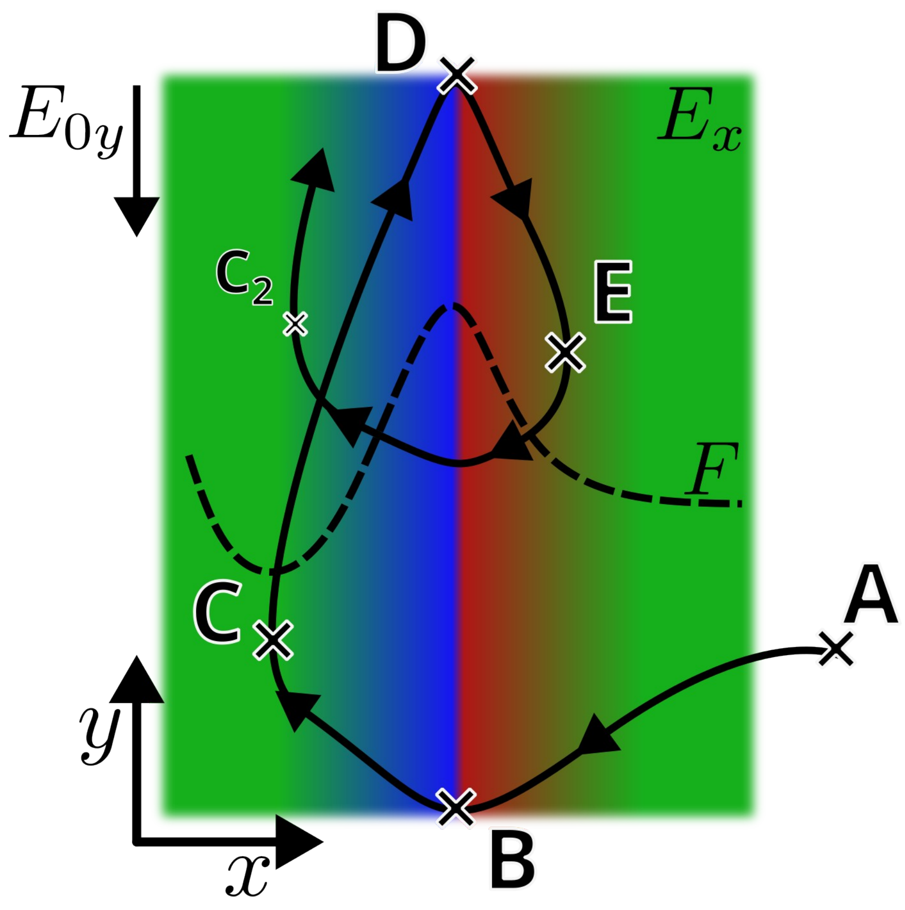
- A **large-amplitude subluminal** magnetosonic shock wave propagating in a magnetised plasma ($\sigma_e \gtrsim 1$) is capable of **reflecting** and **trapping** electrons.
  - Electrons follow magnetic field lines
  - They can be reflected at potential minima **ALONG** magentic field lines
    - Key quantity: pseudo-potential F (electric potential along **B**)

Structure of a large-amplitude magnetosonic shock wave



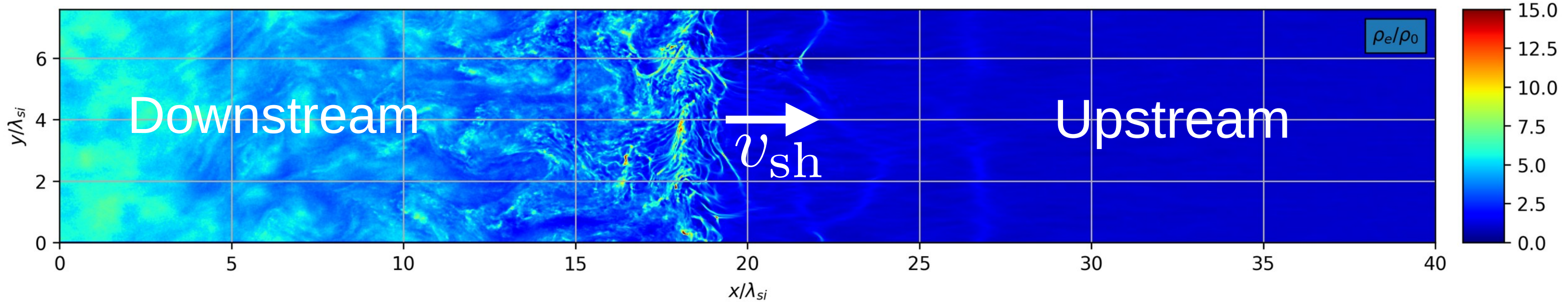
Trapping and acceleration mechanism

- 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!)



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 electromagnetic field (defined on a grid)
  - Computationally expensive! We simulate in **2.5D**
    - 2 spatial dimensions
    - 3-dimensional vector-like quantities (**B**, **E**, **j**)



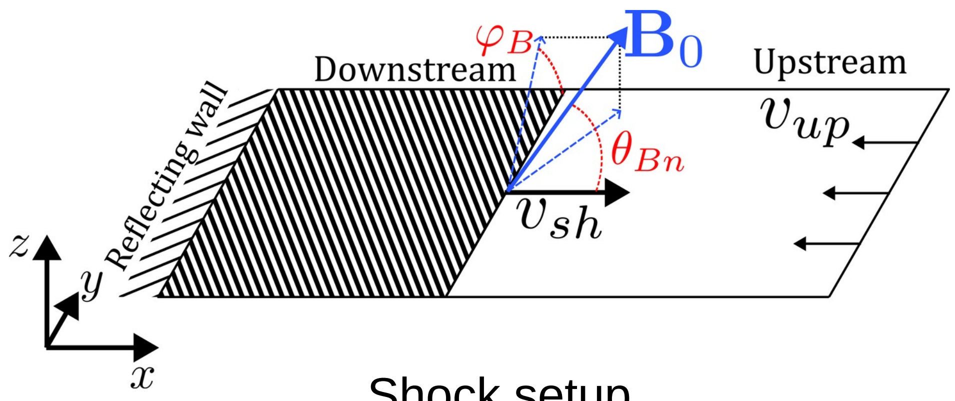
Typical PIC simulation plot: electron density ρ_e

Simulation setup

- $\gamma_0 = \sqrt{5} \approx 2.24$
- $\sigma^{-1} = \sigma_i^{-1} + \sigma_e^{-1} = 1.0$
  - $\sigma_i \approx 1,\ \sigma_e \approx 100 \quad \sigma_j = \frac{\Omega_j^2}{\omega_{pj}^2}$
- $M_s \to \infty,\ M_A \gtrsim 1$
- Reflecting wall setup

$$\lambda_{se} = 40\Delta(\text{high resolution})$$
$$\phi_B = 90^\circ(\text{out-of-plane } \mathbf{B})$$
$$m_i/m_e = 100$$

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

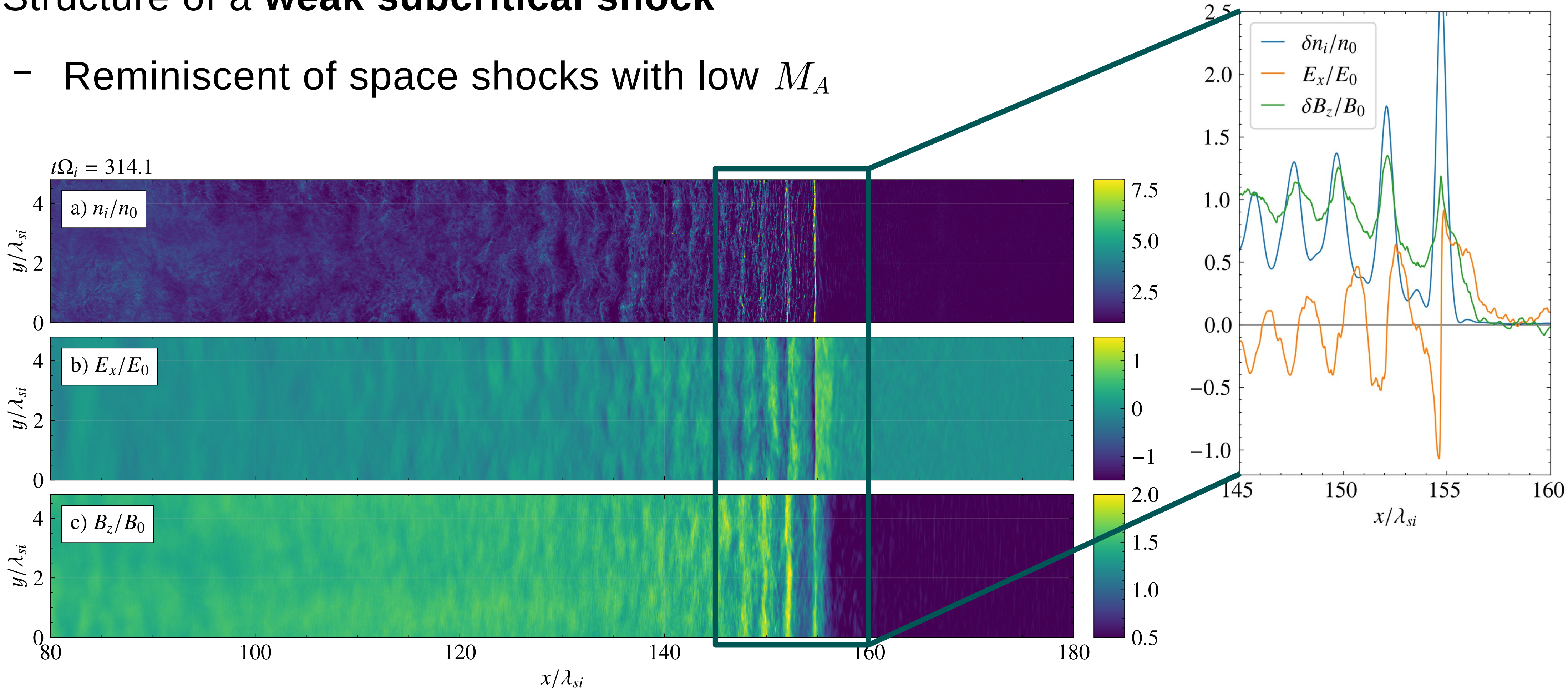


Shock setup

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

Structure

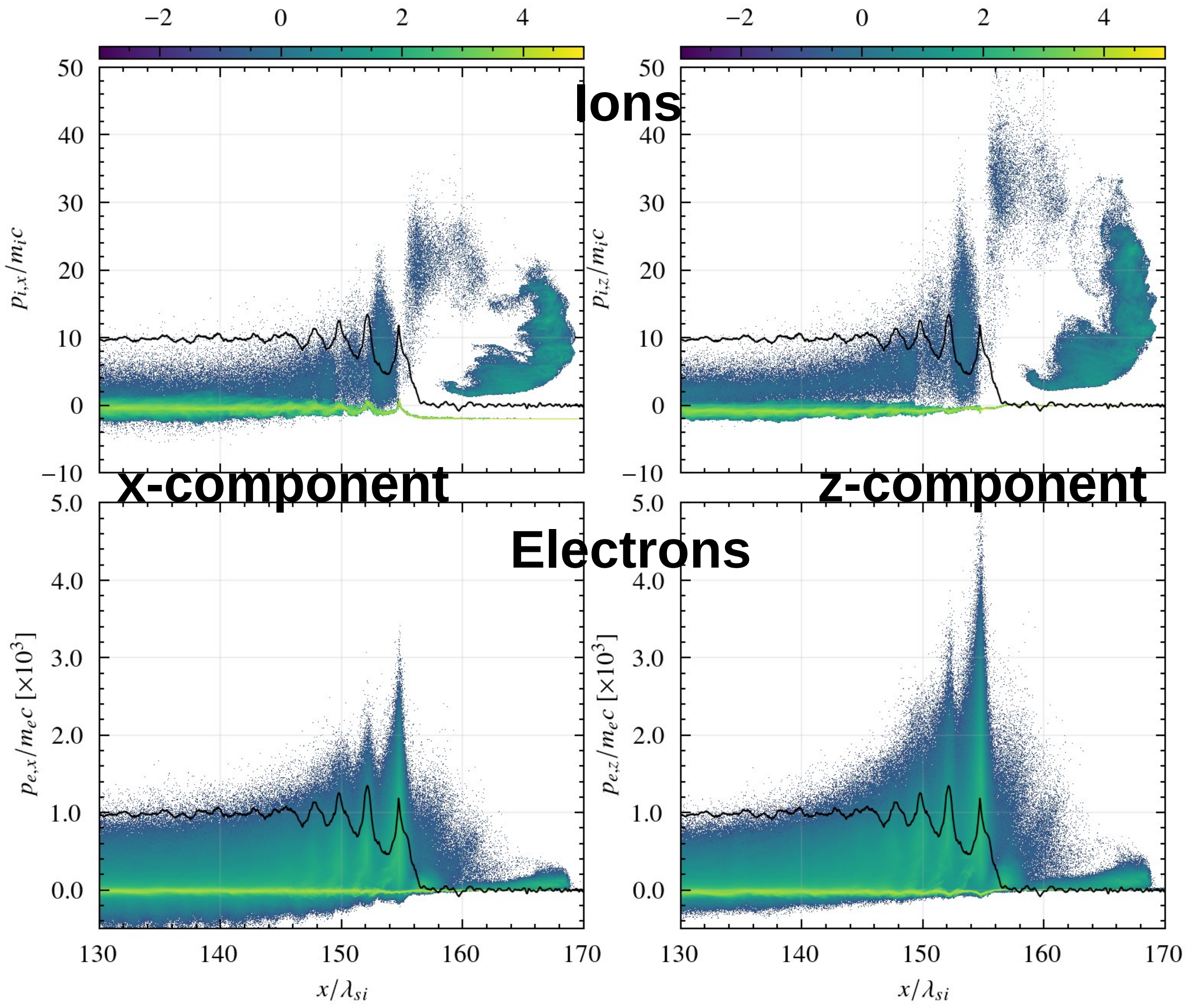
- Structure of a **weak subcritical shock**
  - Reminiscent of space shocks with low M_A



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

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**

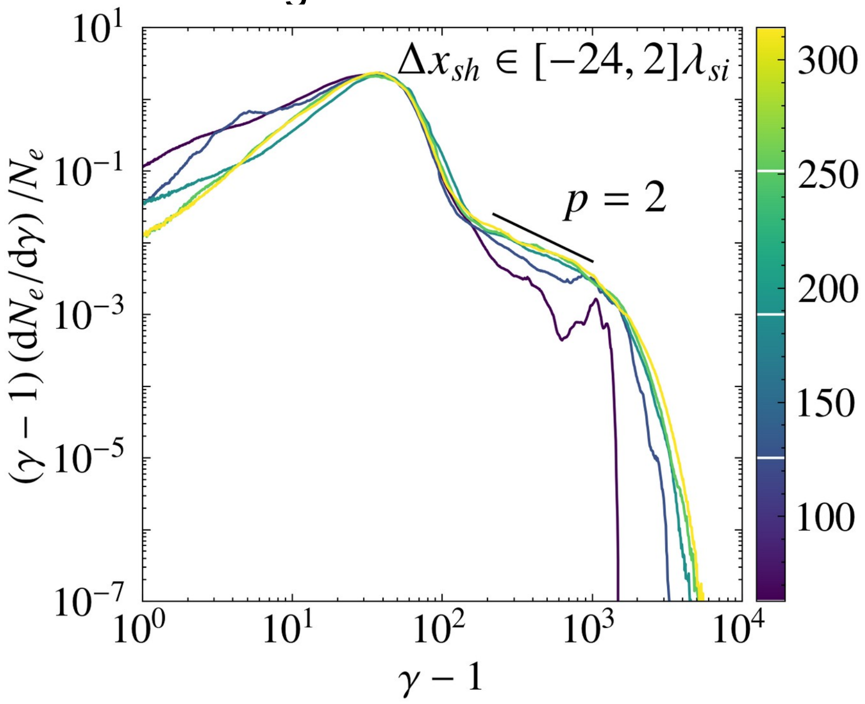


Oblique subluminal shock ($\theta_{Bn}=30^\circ$)

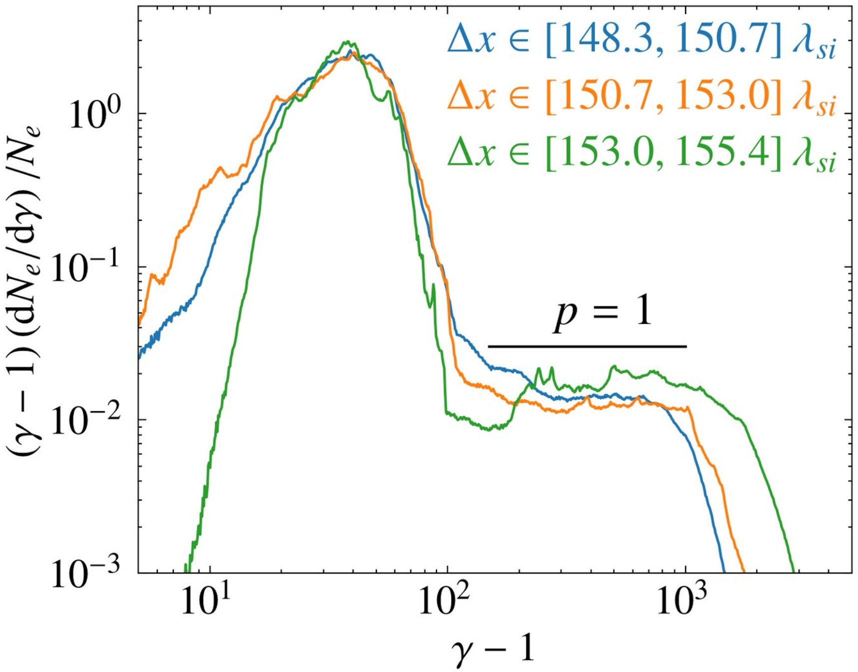
Electron energy spectra

- High-energy power-law-like tail with index $p=2$
  - Number of high-energy electrons **increases over time**
- Individual pulses show an index of $p=1$

Electron spectra
along the shock transition



Electron spectra
for individual consecutive pulses

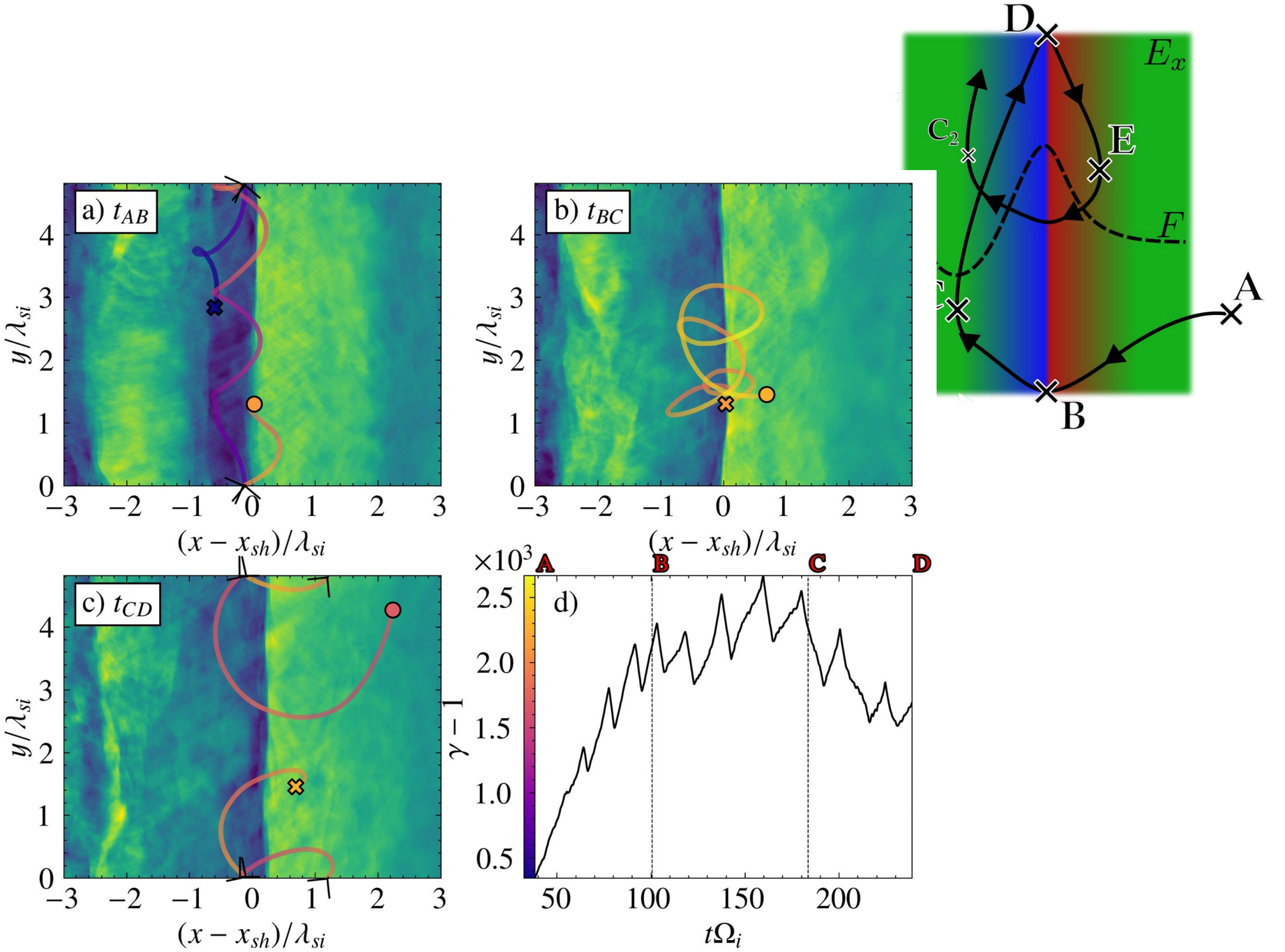


Oblique subluminal shock ($\theta_{Bn}=30^{\circ}$)

Electron tracing

Representative high-electron

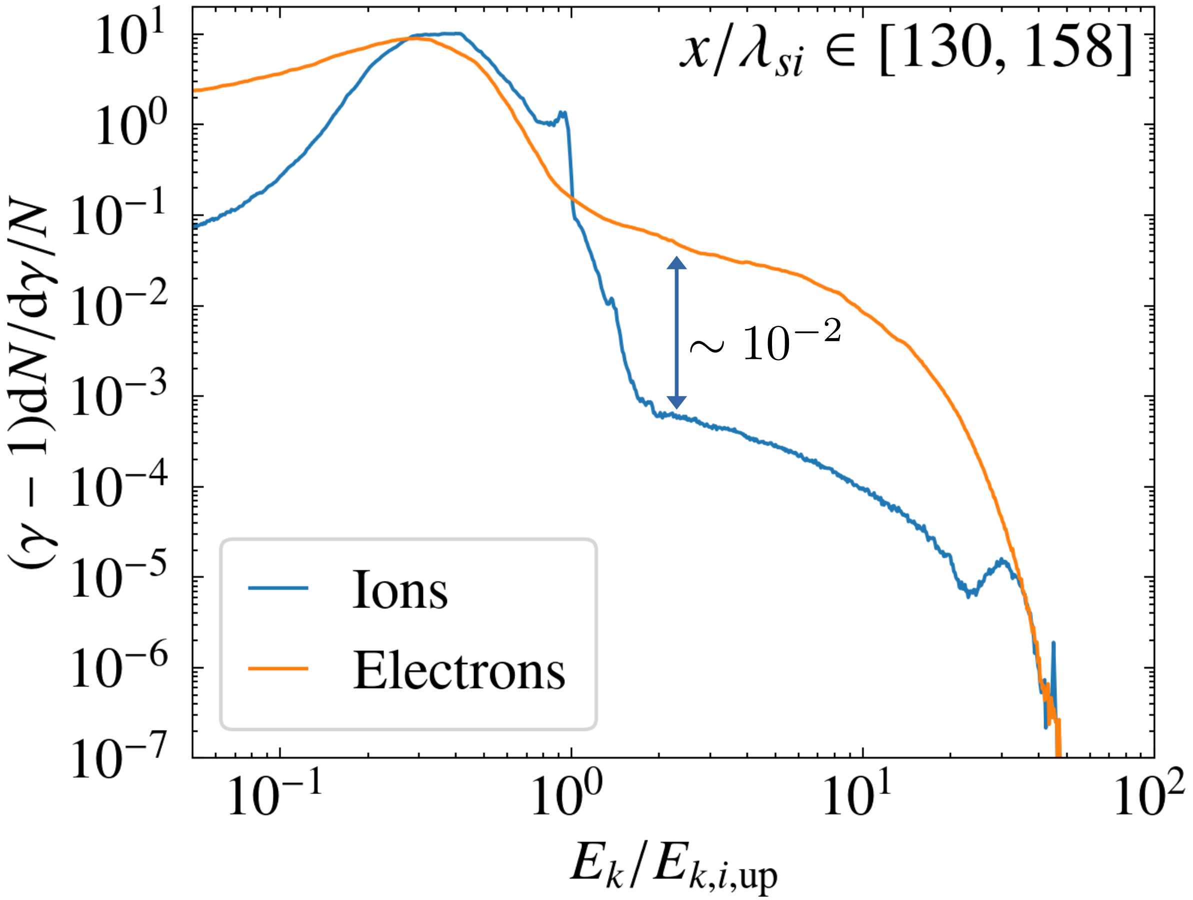
- t_{AB}: the electron is **trapped** and gains energy by the **motional electric field**
- t_{BC}: the electron scatters off magnetic field fluctuations and suddenly changes direction
- t_{CD}: the electron loses energy as it moves in the opposite direction, but remains trapped



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

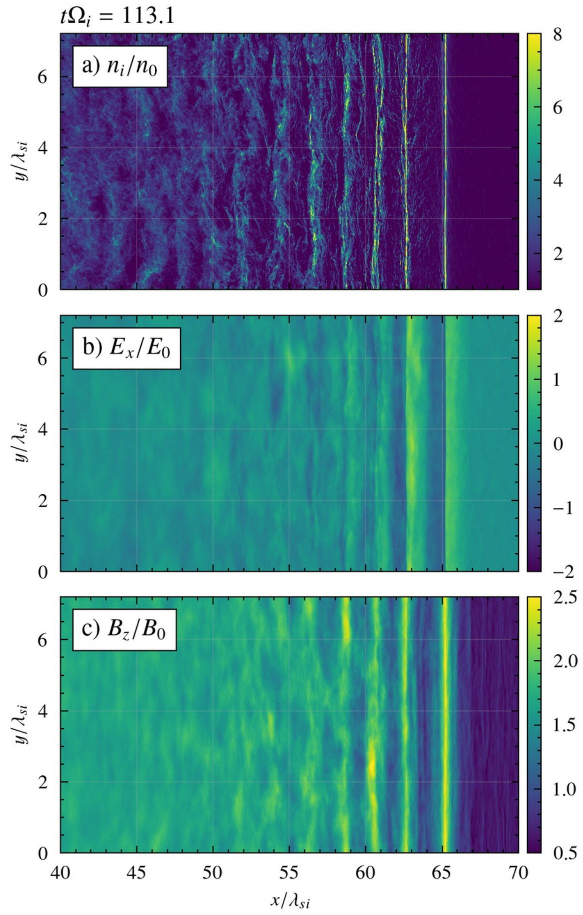
Ion spectra

- 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
    - $r_{g,i} \sim \delta x_{\rm sh}$
  - Potential troughs are shallower than peaks

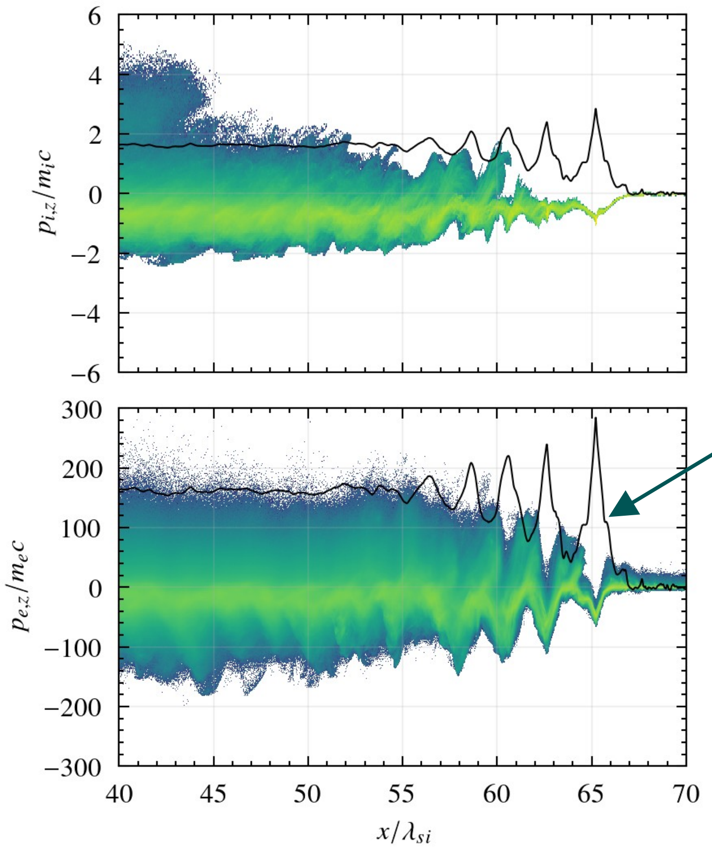


Oblique superluminal shock ($\theta_{Bn}=40^{\circ}$)

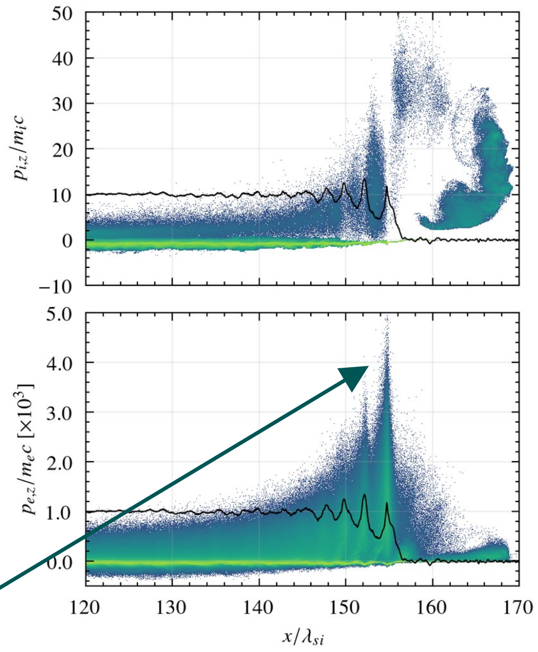
- Similar structure, **inefficient** acceleration
  - Superluminal conditions prevent electrons from being trapped



Superluminal



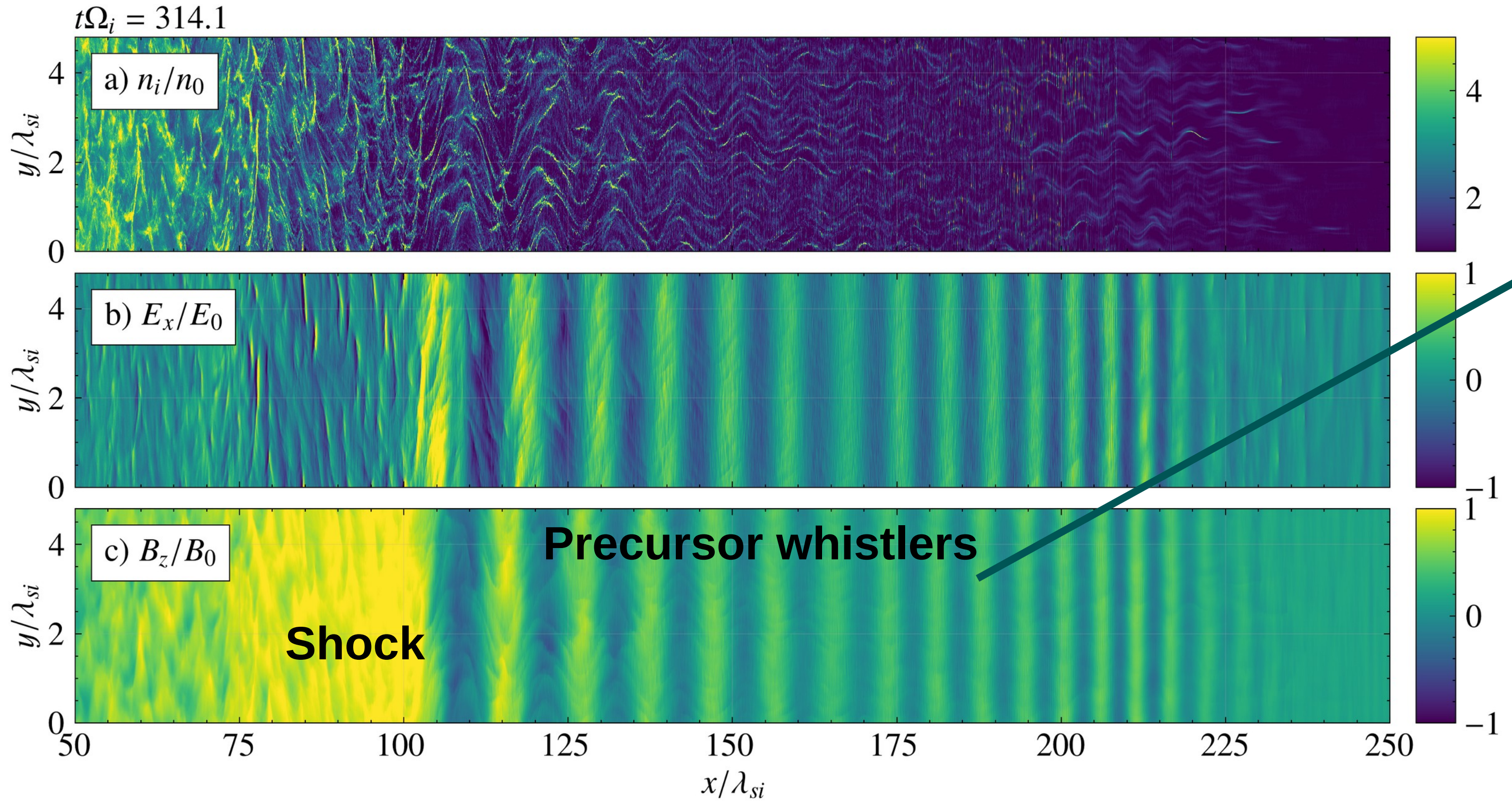
Subluminal



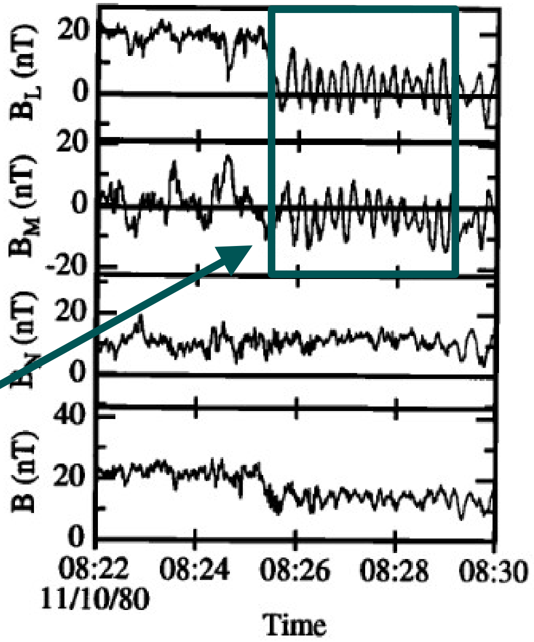
Quasi-parallel shock ($\theta_{Bn}\!=\!10^\circ$)

Structure

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



Farris et al. 1994

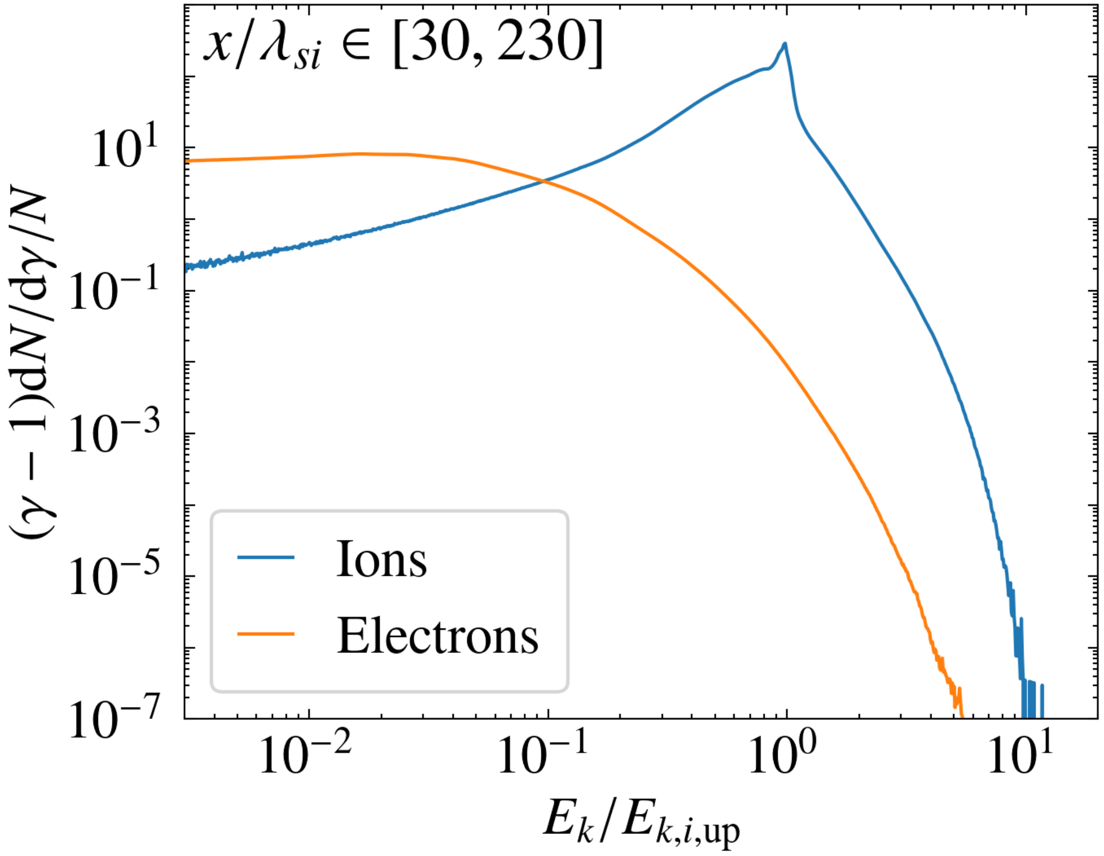


ISEE 1 measurements
November, 1980

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

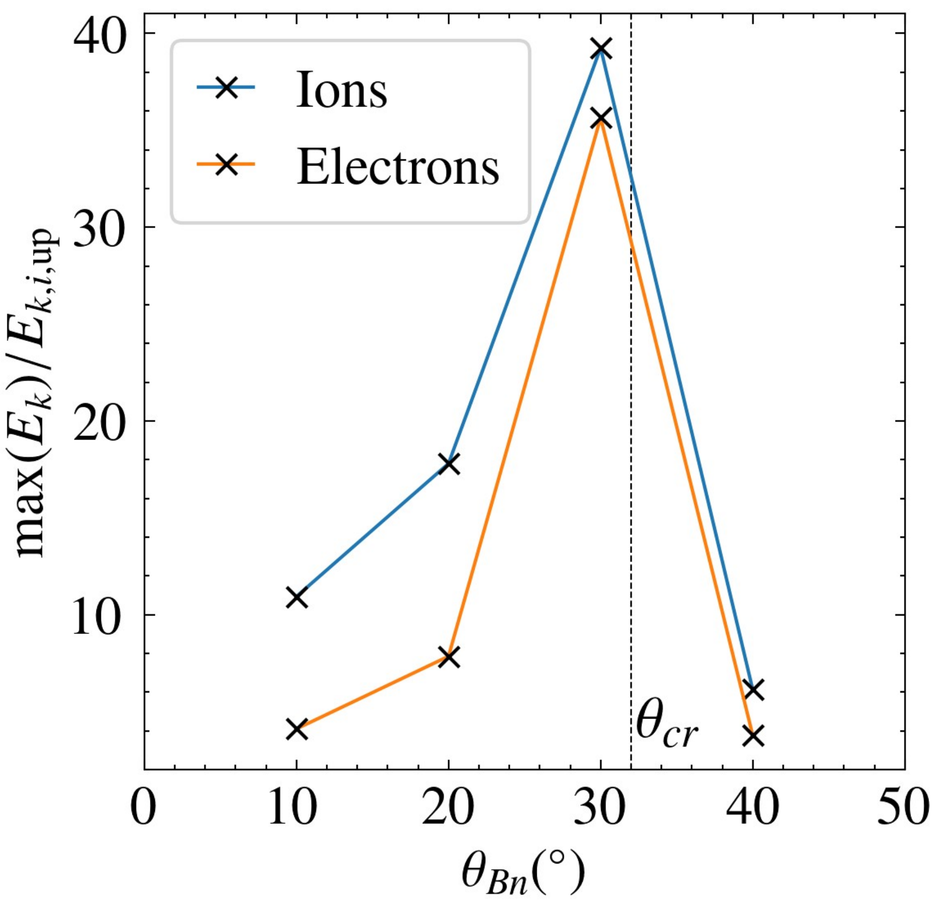
Heating and energy spectra

- The interaction of whistlers + upstream plasma gives rise to several plasma instabilities
  - They contribute to particle energisation
- Mainly particle heating, little acceleration.
  - More efficient ion than electron heating
  - Kinetic energy ratio in
    - Precursor whistler region: $\langle E_{k,e}\rangle / \langle E_{k,i}\rangle \approx 0.1$
    - Downstream region: $\langle E_{k,e}\rangle / \langle E_{k,i}\rangle \approx 0.2$



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 trapping mechanism provides a non-thermal power-law spectral component of index $p=1$
  - The maximum energy varies with respect to the critical angle
    - 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 runs with an in-plane configuration of **B**

Thank you

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