MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Ion and electron acceleration in strongly magnetised mildly relativistic shocks

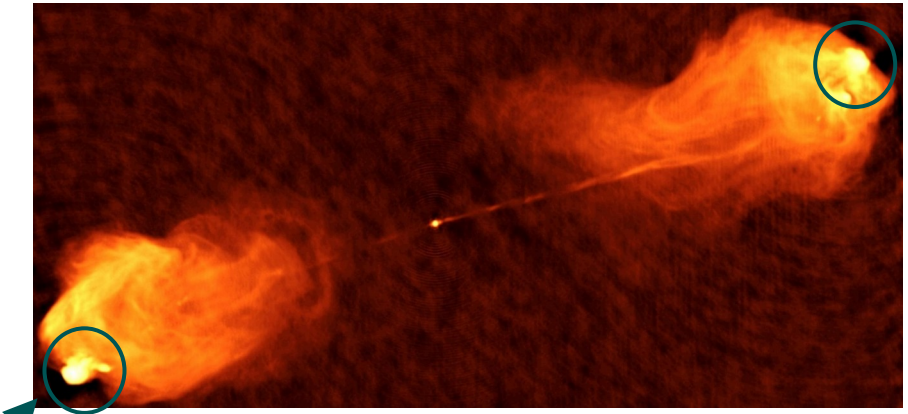
PLASMA ASTRO

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

Mildly relativistic (MR) shocks in jets of AGN

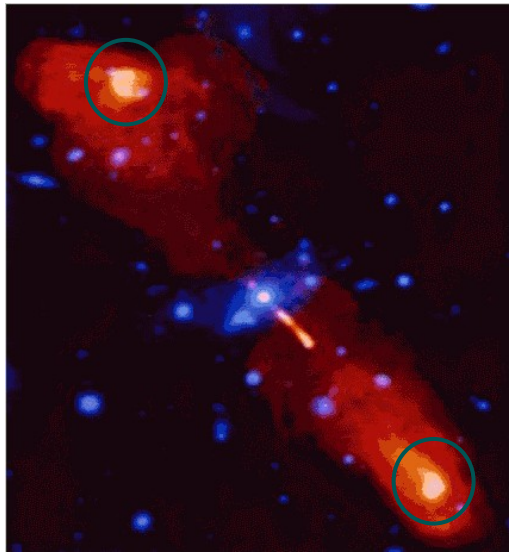
- Strong X-ray and γ-ray emission observed from jets of AGN
  - Indicates particle acceleration
- Particle acceleration commonly associated to **shocks**
  - AGN hotspots may contain mildly relativistic shocks
    - $\gamma_{\mathrm{bulk}} \approx 2\text{–}5$
  - Plasma in these jets is expected to be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

Cygnus-A



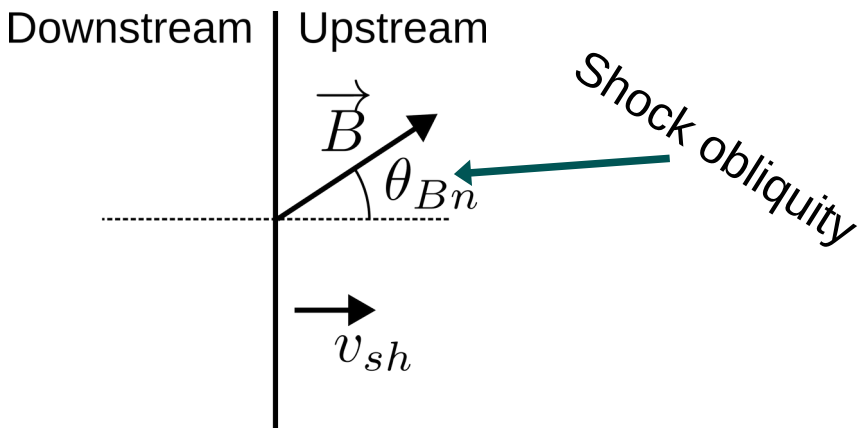
Hotspots

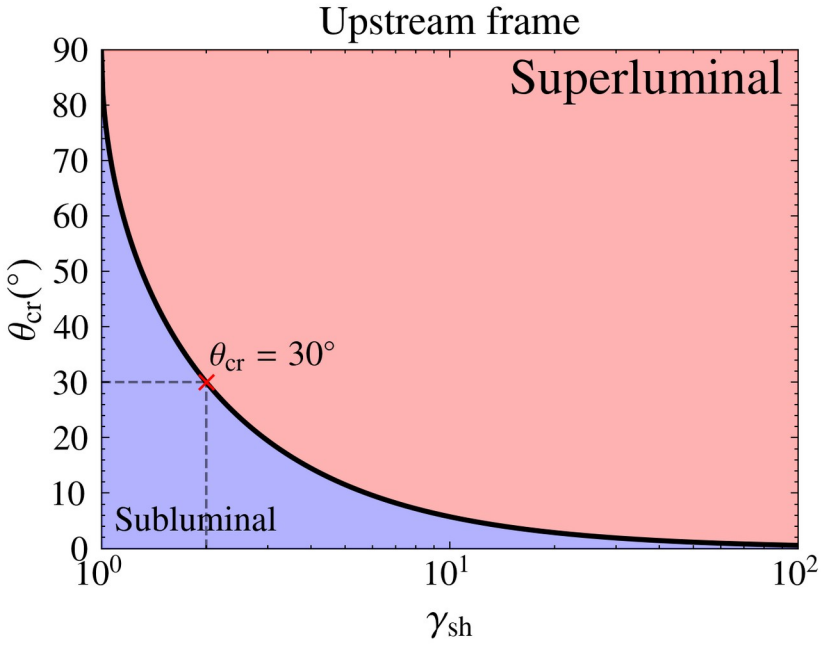
3C 219



Superluminal and subluminal shocks

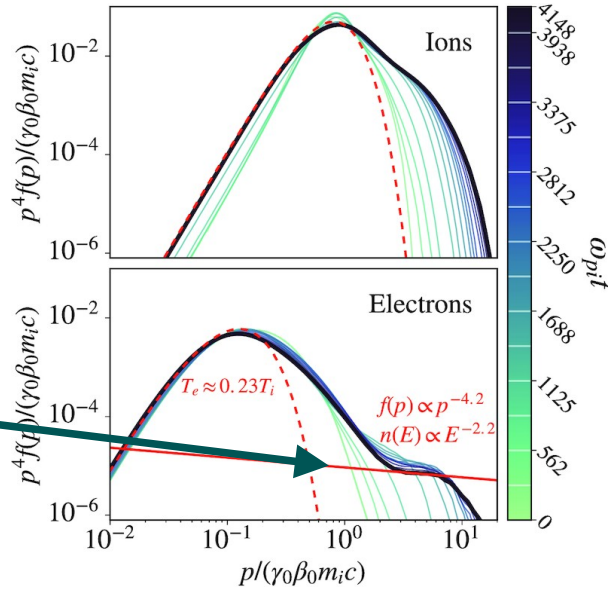
- In magnetised shocks, there exists an obliquity angle, $\theta_{\rm cr}$, defined as:
  - Shock frame: $\tan(\theta_{cr})=c/v_{sh}$
  - Upstream frame: $\cos(\theta_{cr})=v_{sh}/c$
- Depending on the obliquity angle, the shock behaves differently:
  - $\theta_{Bn}<\theta_{cr}$: particles can reflect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



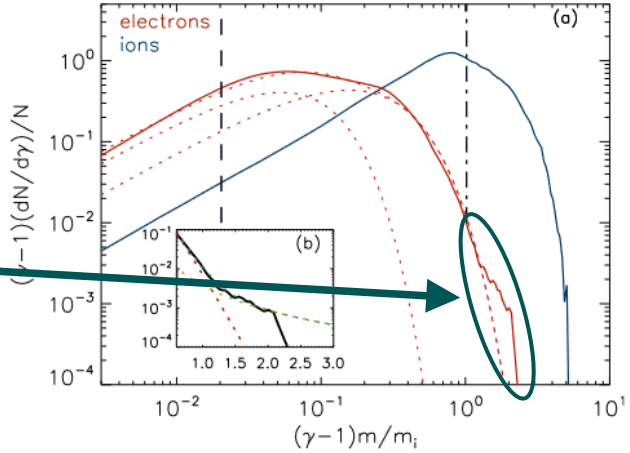


Already studied mechanisms in MR shocks

- 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

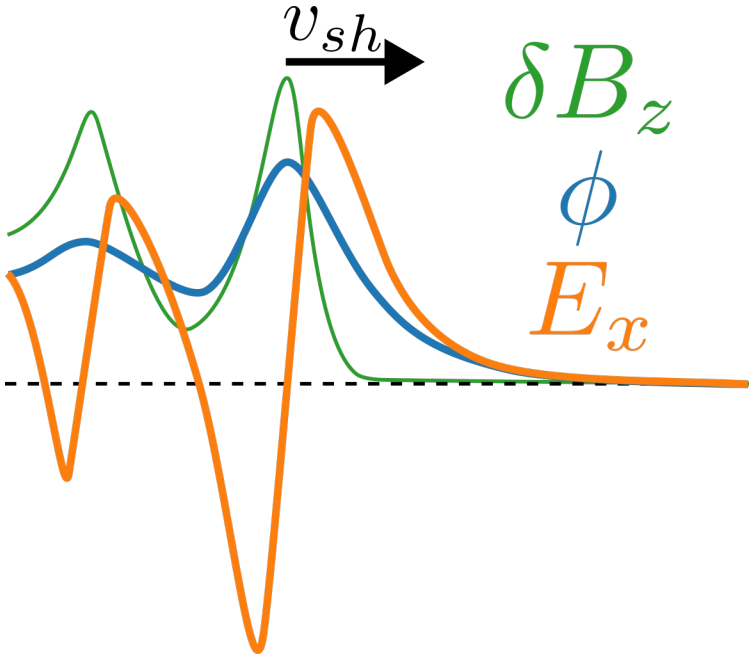


Ligorini et al. 2021

An alternative solution

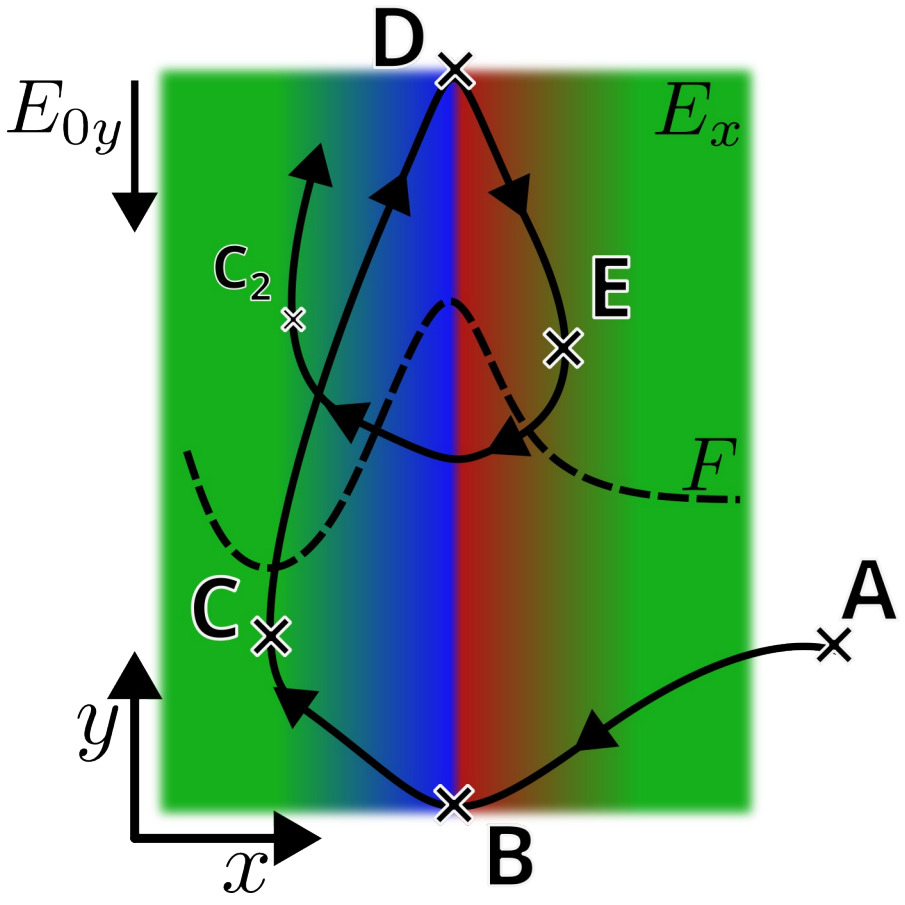
- A **large-amplitude subluminal** magnetosonic shock wave propagating in a magnetised plasma ($\sigma_e \gtrsim 1$) is capable of **reflecting** and **trapping** electrons.
  - Electrons follow magnetic field lines
  - They can be reflected at potential minima **ALONG** magentic field lines
    - Key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

Structure of a large-amplitude magnetosonic shock wave



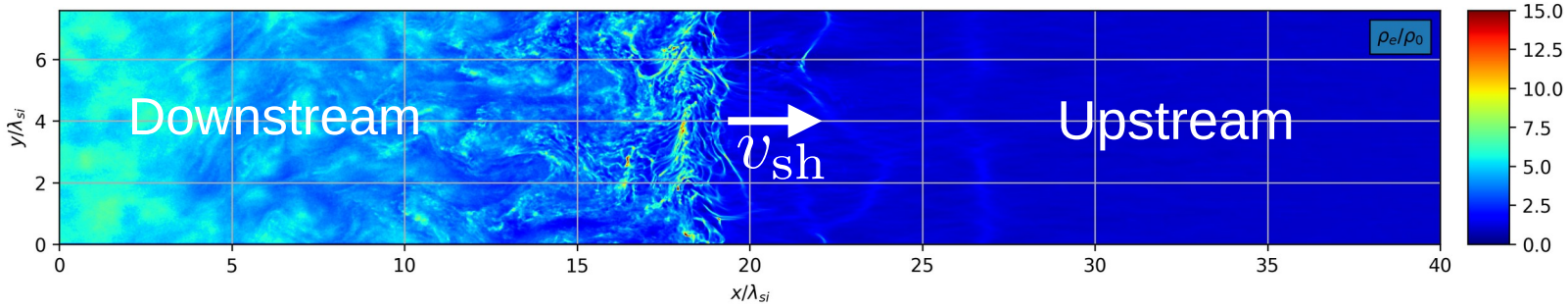
Trapping and acceleration mechanism

- 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 to study small (electron) scales.
  - 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**)



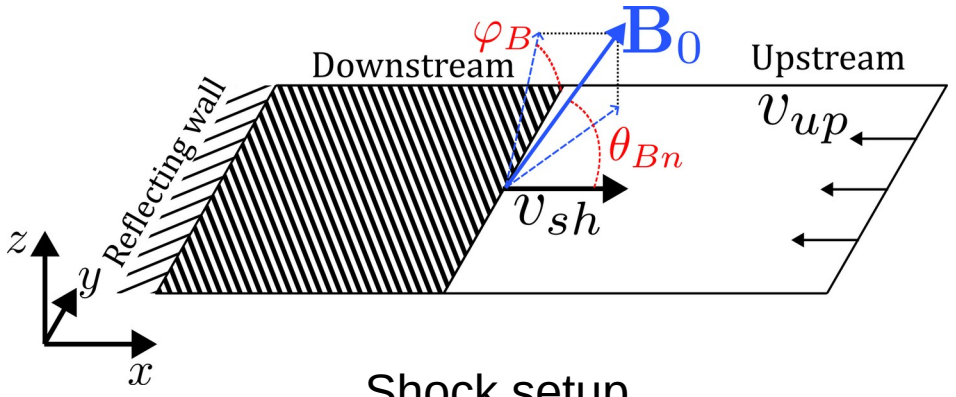
Typical PIC simulation plot: electron density ρ_e

Simulation setup

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

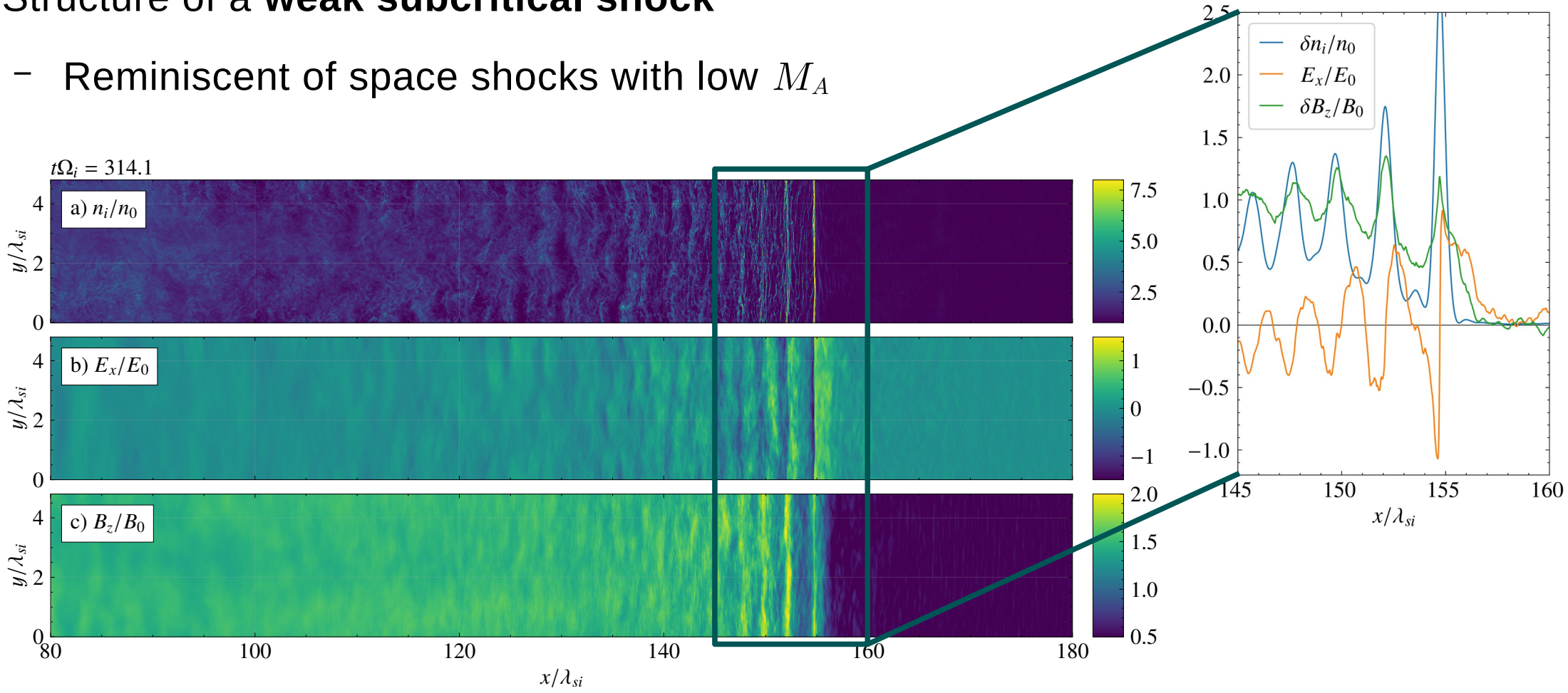


Shock setup

Oblique subluminal shock (θ_{Bn}=30°)

Structure

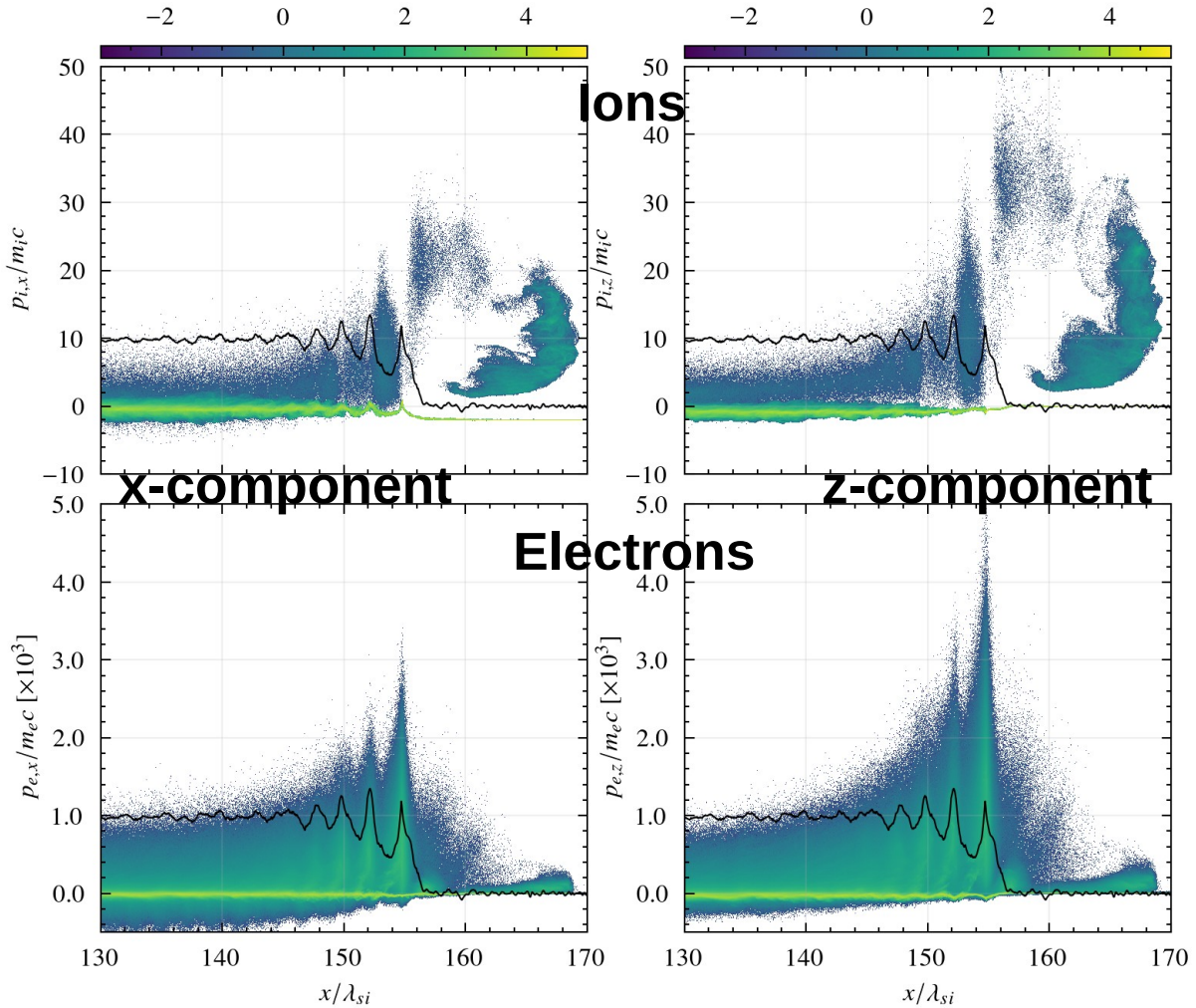
- Structure of a **weak subcritical shock**
  - Reminiscent of space shocks with low M_A



Oblique subluminal shock (θ_{Bn}=30°)

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**

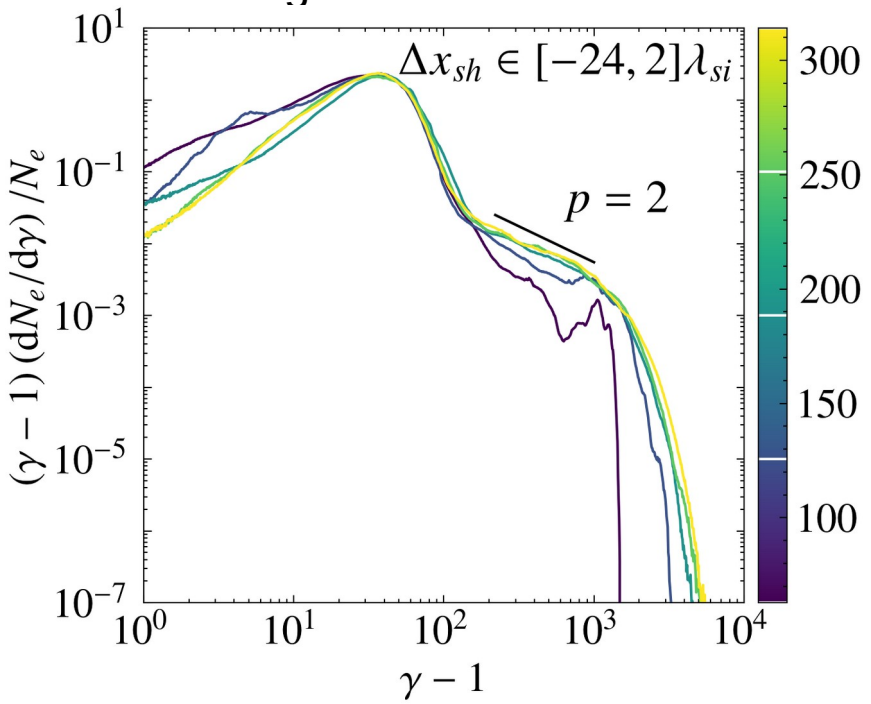


Oblique subluminal shock ($\theta_{Bn}=30^\circ$)

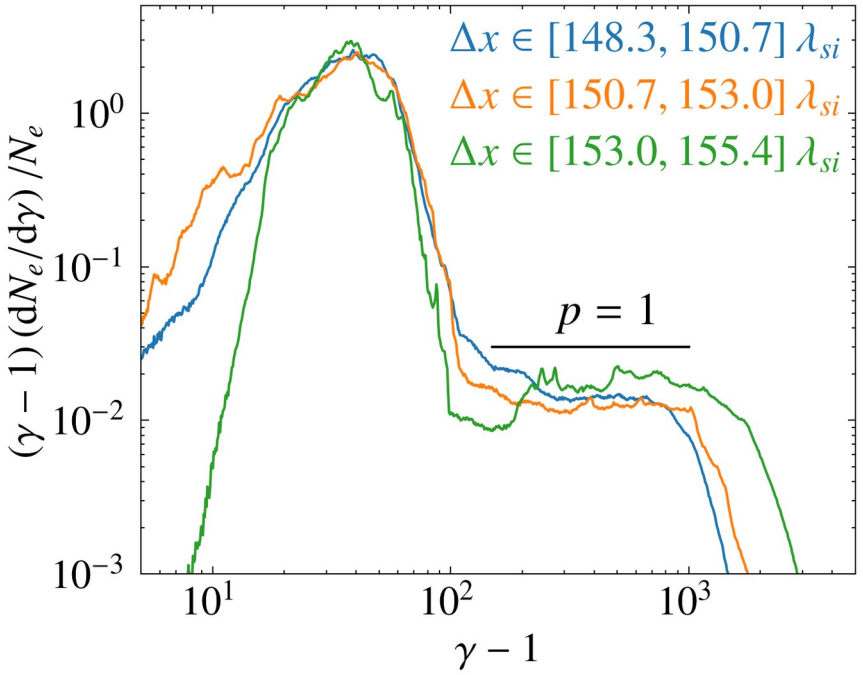
Electron energy spectra

- 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

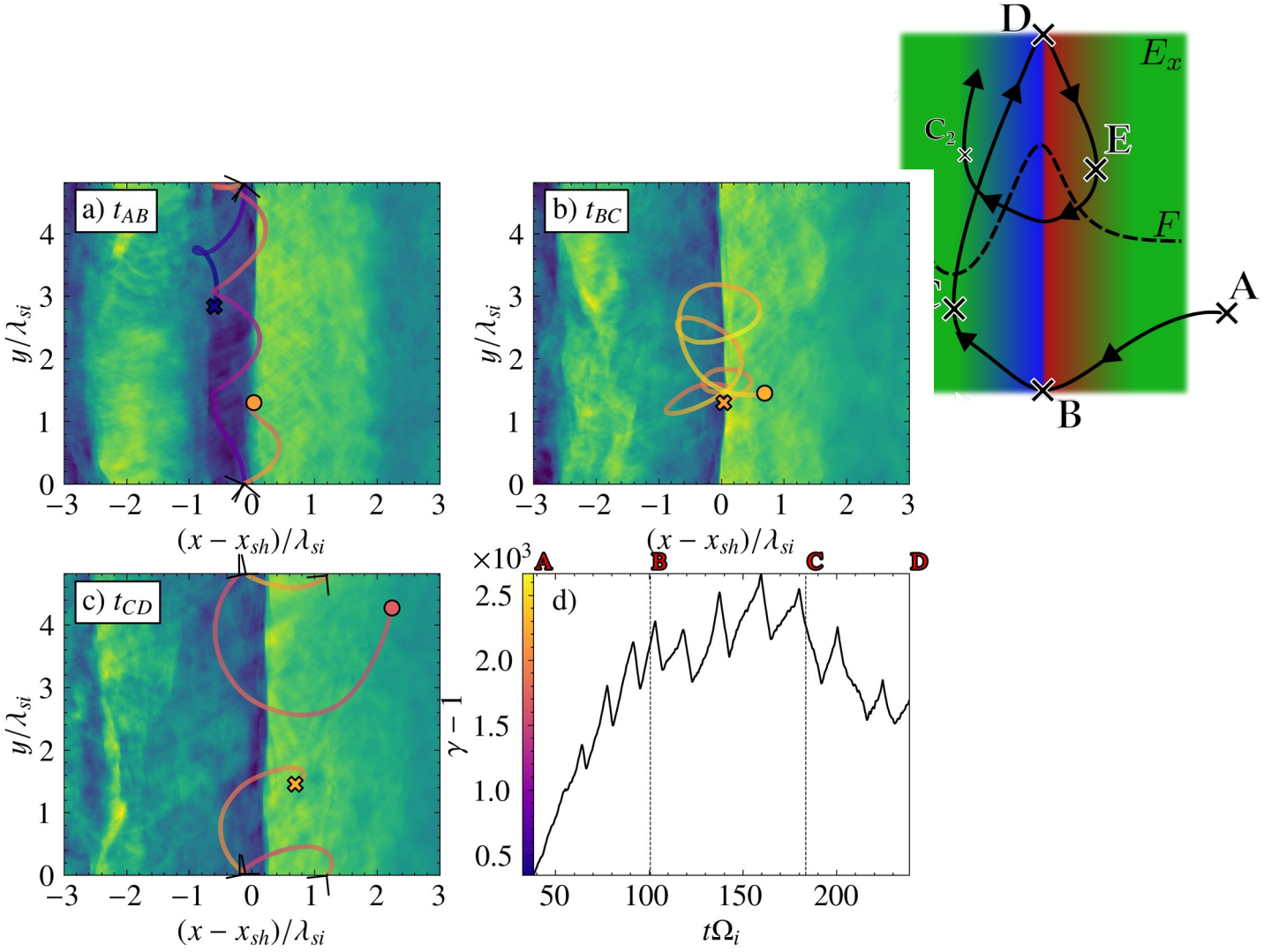


Oblique subluminal shock (θ_{Bn}=30°)

Electron tracing

Representative high-electron

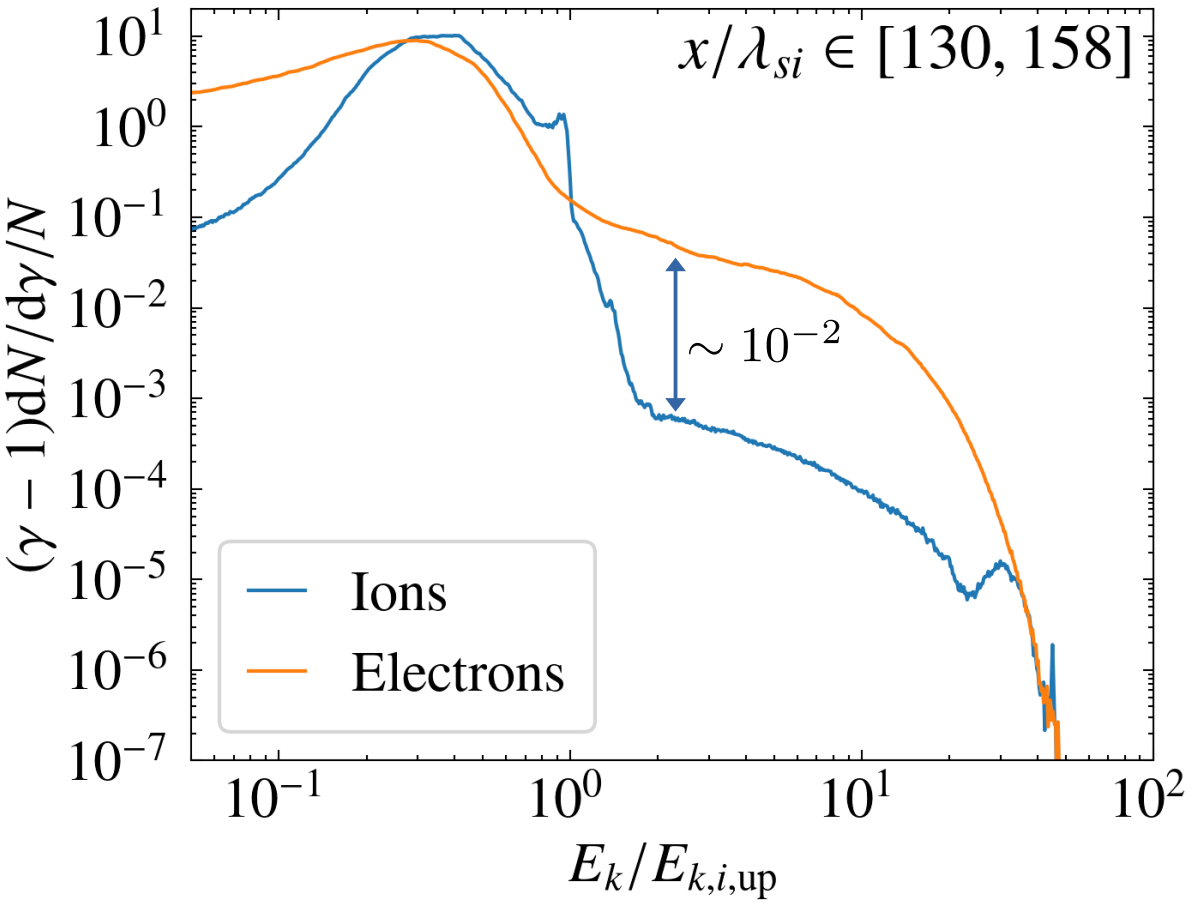
- t_{AB}: the electron is **trapped** and gains energy by the **motional electric field**
- t_{BC}: the electron scatters off magnetic field fluctuations and suddenly changes direction
- t_{CD}: the electron loses energy as it moves in the opposite direction, but remains trapped



Oblique subluminal shock (θ_{Bn}=30°)

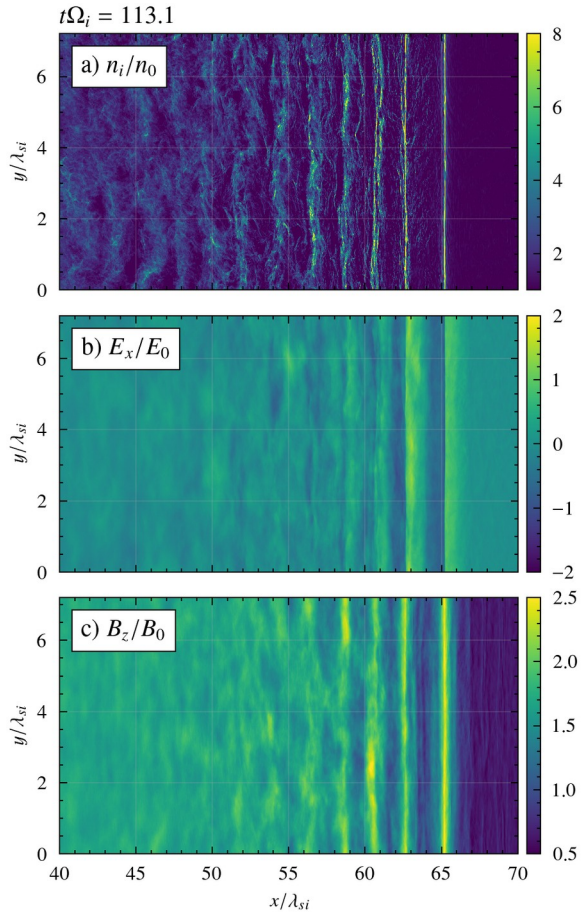
Ion spectra

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

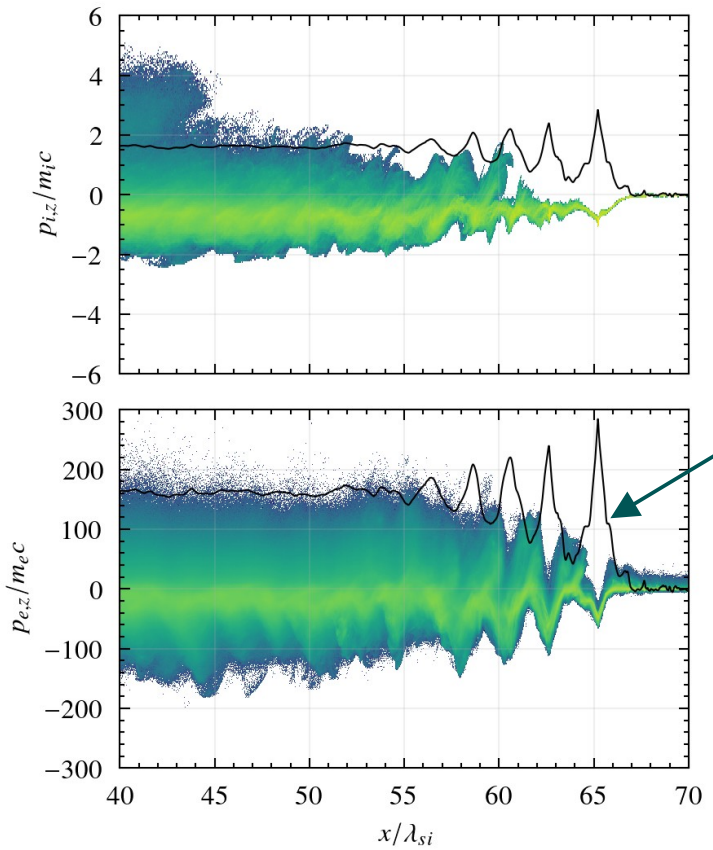


Oblique superluminal shock (θ_{Bn}=40°)

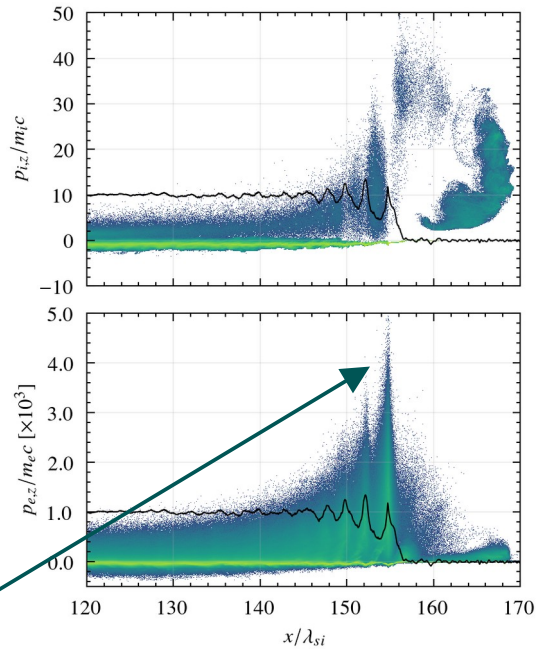
- Similar structure, **inefficient** acceleration
  - Superluminal conditions prevent electrons from being trapped



Superluminal



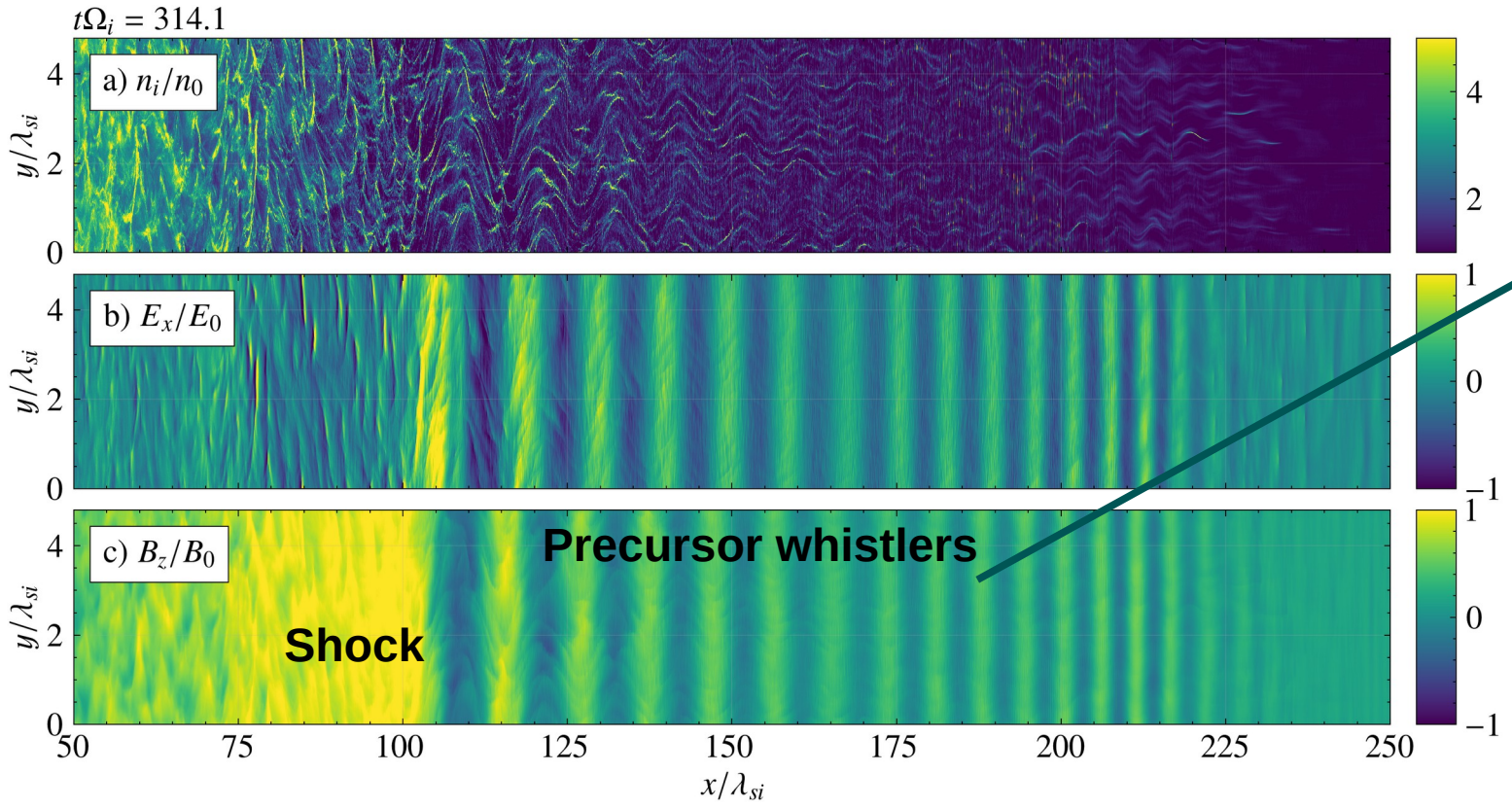
Subluminal



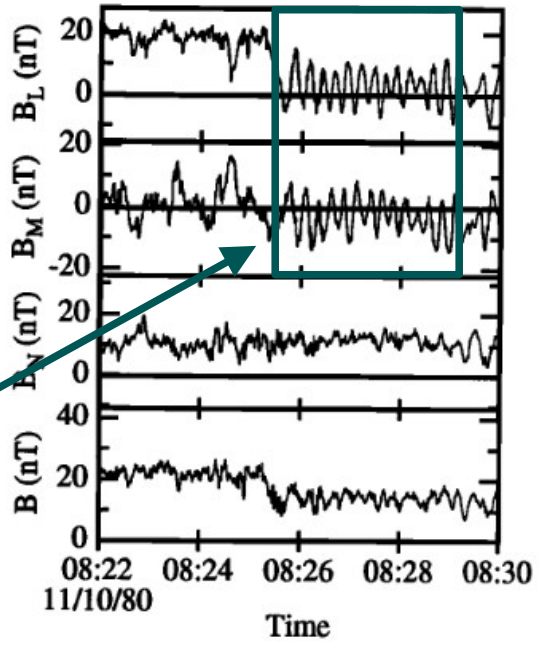
Quasi-parallel shock ($\theta_{Bn}=10^\circ$)

Structure

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



Farris et al. 1994

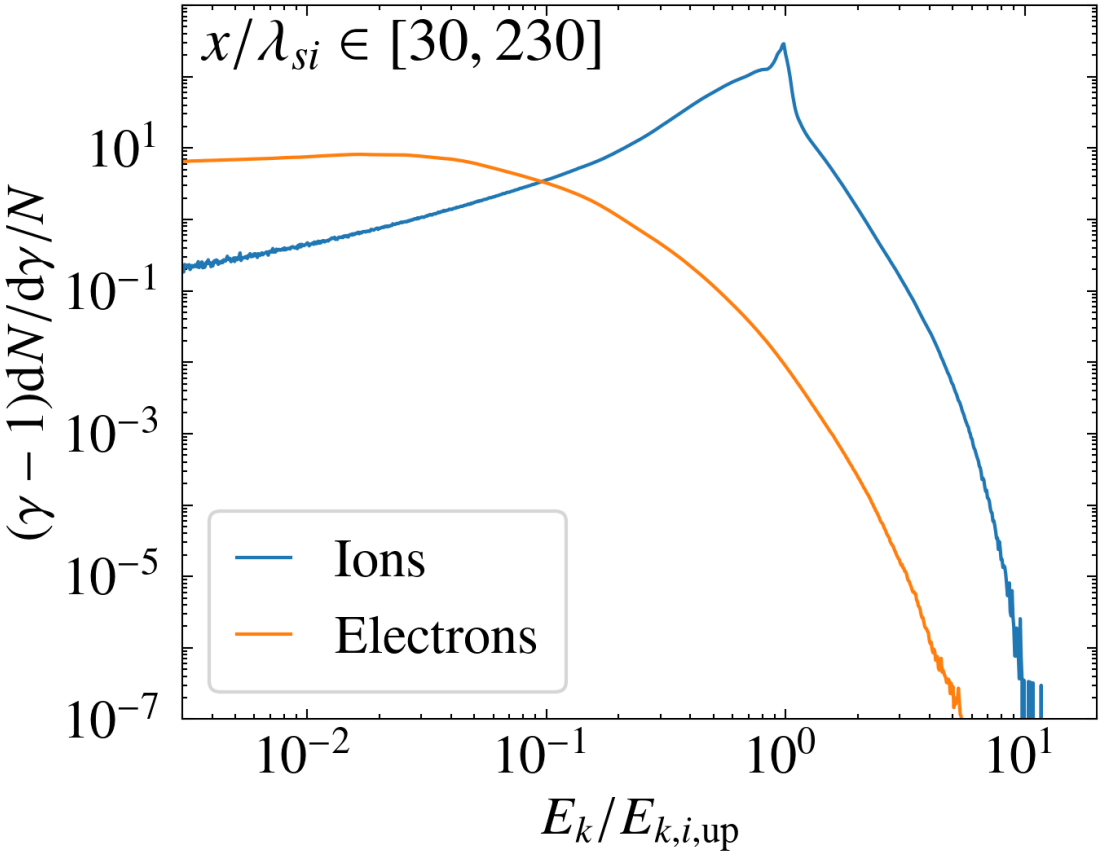


ISEE 1 measurements
November, 1980

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

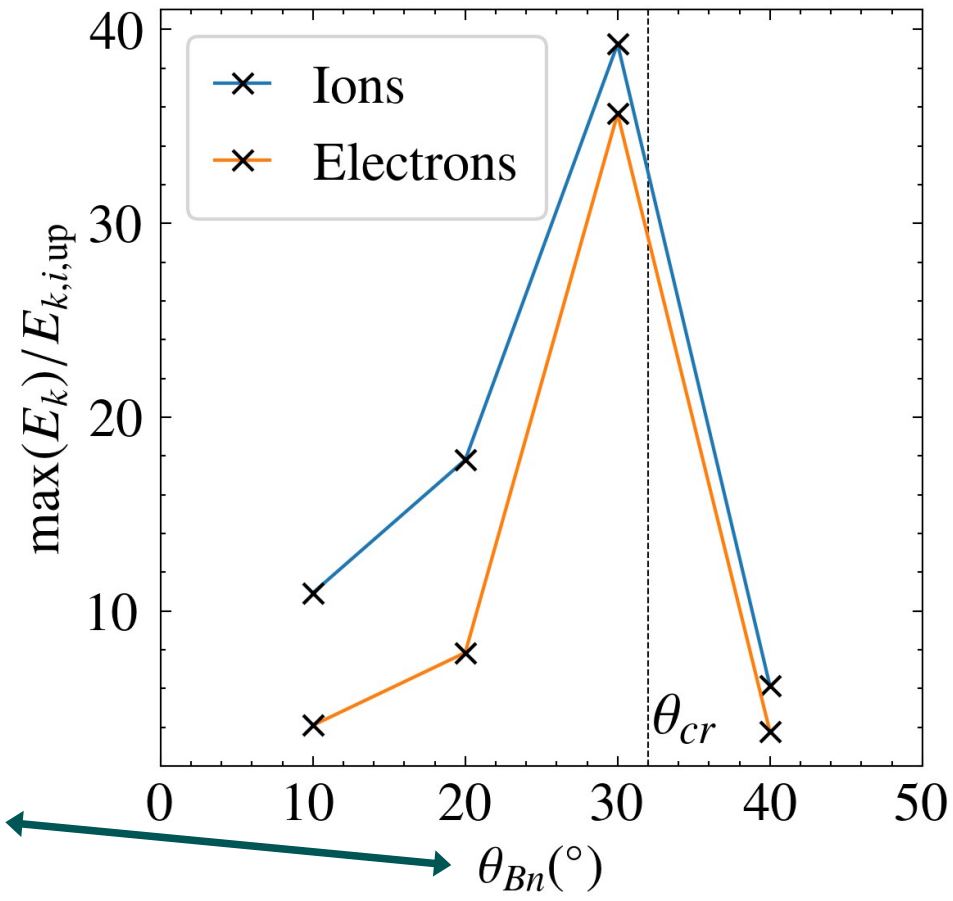
Heating and energy spectra

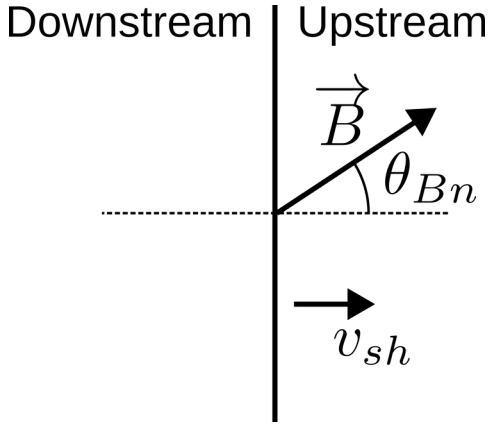
- The interaction of whistlers + upstream plasma gives rise to several plasma instabilities
  - They contribute to particle energisation
- Mainly particle heating, little acceleration.
  - More efficient ion than electron heating
  - Kinetic energy ratio in
    - Precursor whistler region:
      $$\langle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

- We study, for the first time, highly magnetised mildly relativistic shocks that are likely to occur in AGN hotspots
- 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