Particle energization in astrophysical shocks - synergies with heliospheric shock physics

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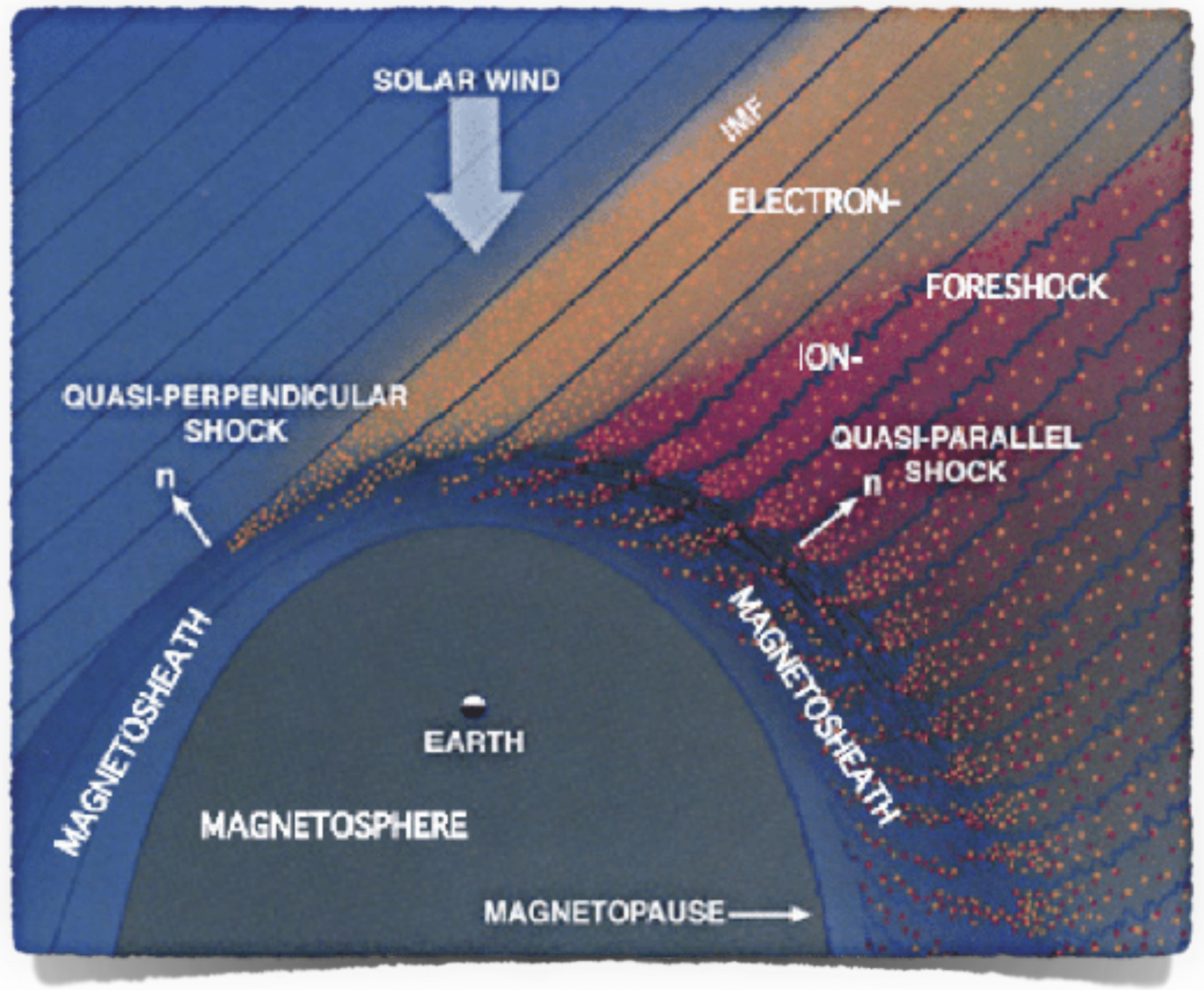
Space and Astrophysical systems that host shocks, magnetic reconnection regions and turbulence

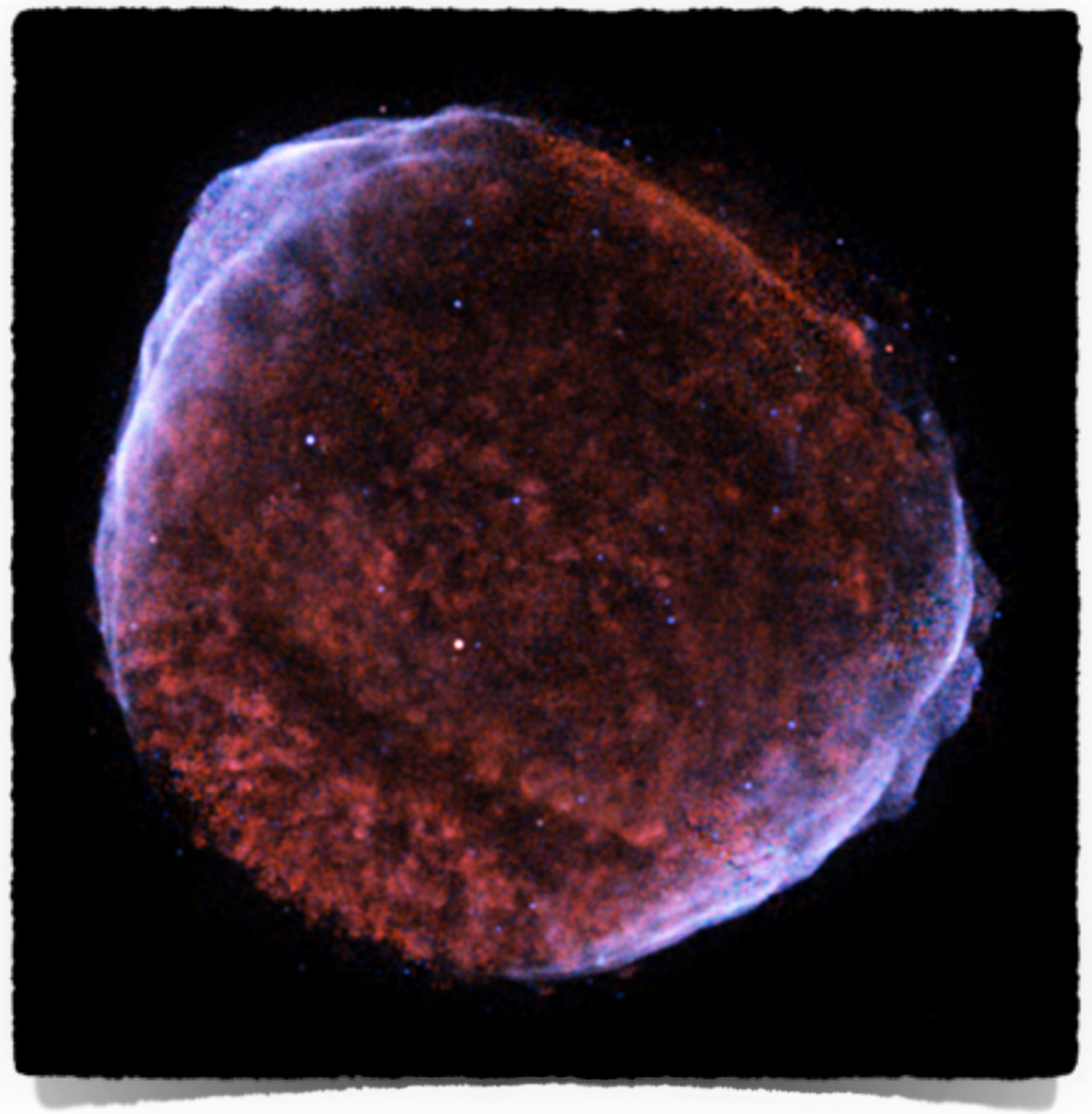
Non-relativistic systems

Shock physics dependent mainly on M_A, β, θ_{Bn}, but also on ω_{pe}/Ω_{ce}; $M_S = M_A\sqrt{2/\gamma\beta}$

Earth's bow shock: M_A=2-10
Saturn's bow shock: M_A=5-150
CME shocks: M_A=2-3 (?)
β~0.01-1



SNR shocks: M_A=10-200 (1000)
β~0.01-1

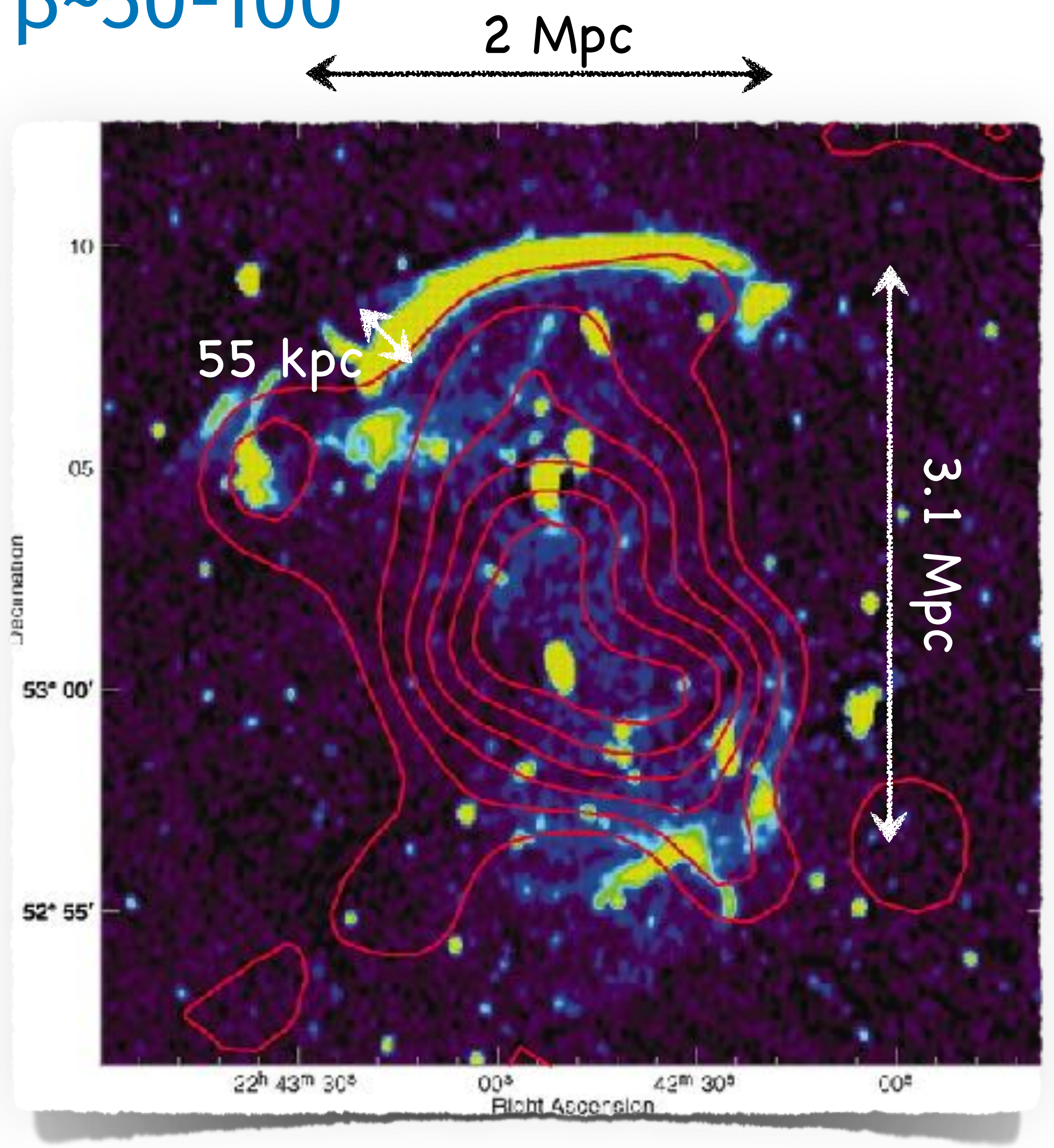


radio - X-ray synchrotron emission: GeV - 100 TeV electrons (power-law)

X-ray filaments: m.f. amplification (30-250 μG)

DSA

ICM shocks: M_s=2-5
β~50-100



radio synchrotron polarised emission (power-law)

quasi-perpendicular shocks

DSA

Relativistic systems

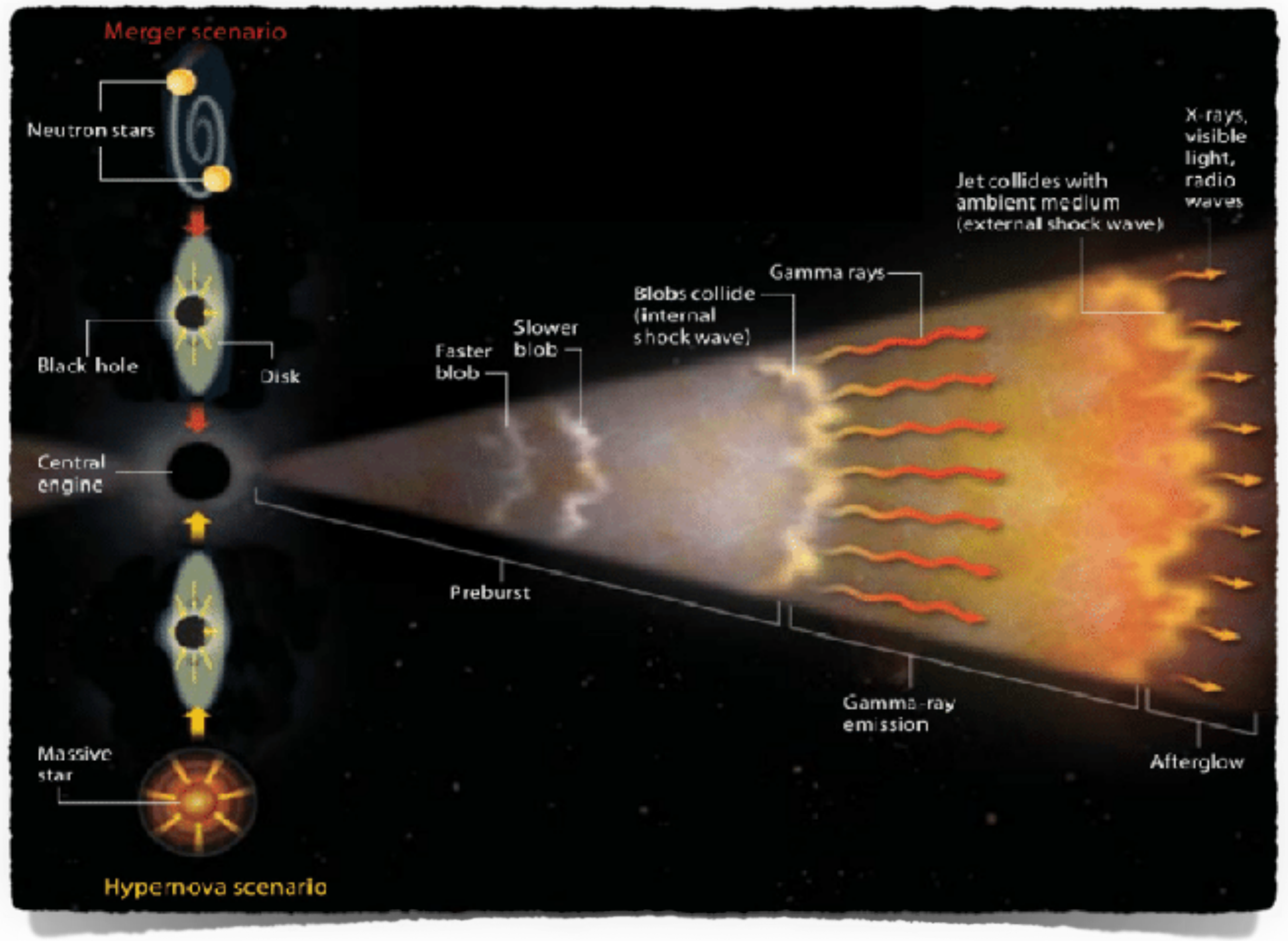
Shocks better defined by the shock Lorentz factor $\gamma_{sh} \gg 1$ and upstream magnetisation

$$\sigma_j = \Omega_{cj}^2/\omega_{pj}^2,\ j = \{e, p\};\quad \sigma^{-1} = \sigma_p^{-1} + \sigma_e^{-1}$$

Gamma-ray Bursts (GRBs):

γ_{sh} ~ 100-1000

σ << 1

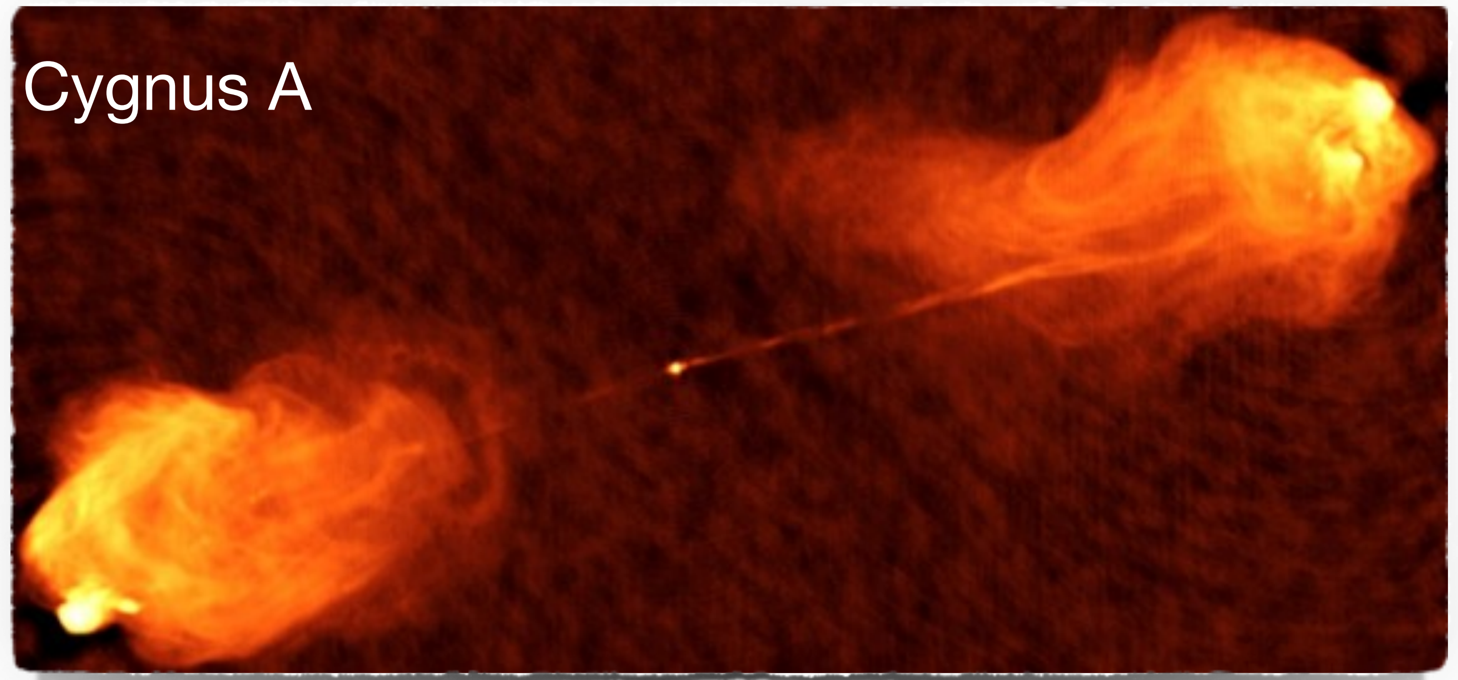


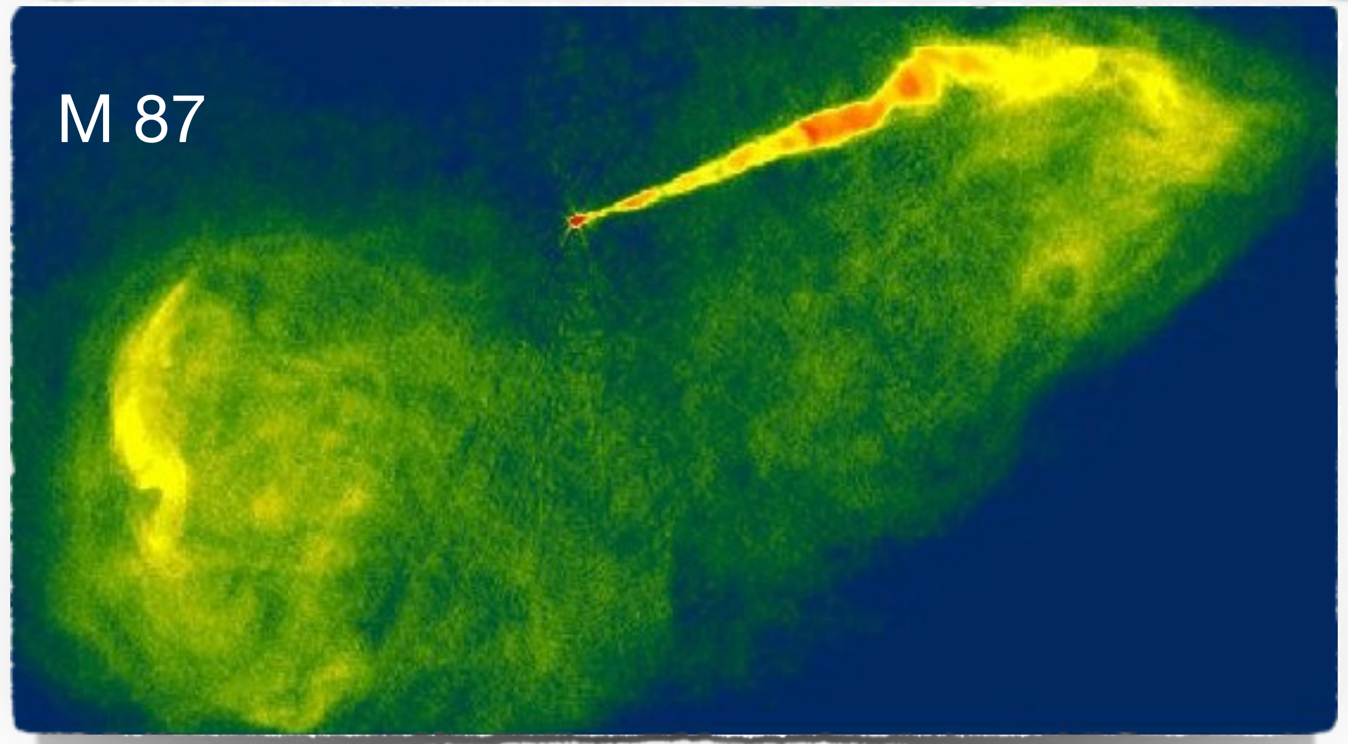
Active Galactic Nuclei (AGN), blazars:

γ_{sh} ~ 10-20

σ ~ 0.1

multiple sites of particle acceleration (shocks, turbulence, shear layers, magnetic reconnection)



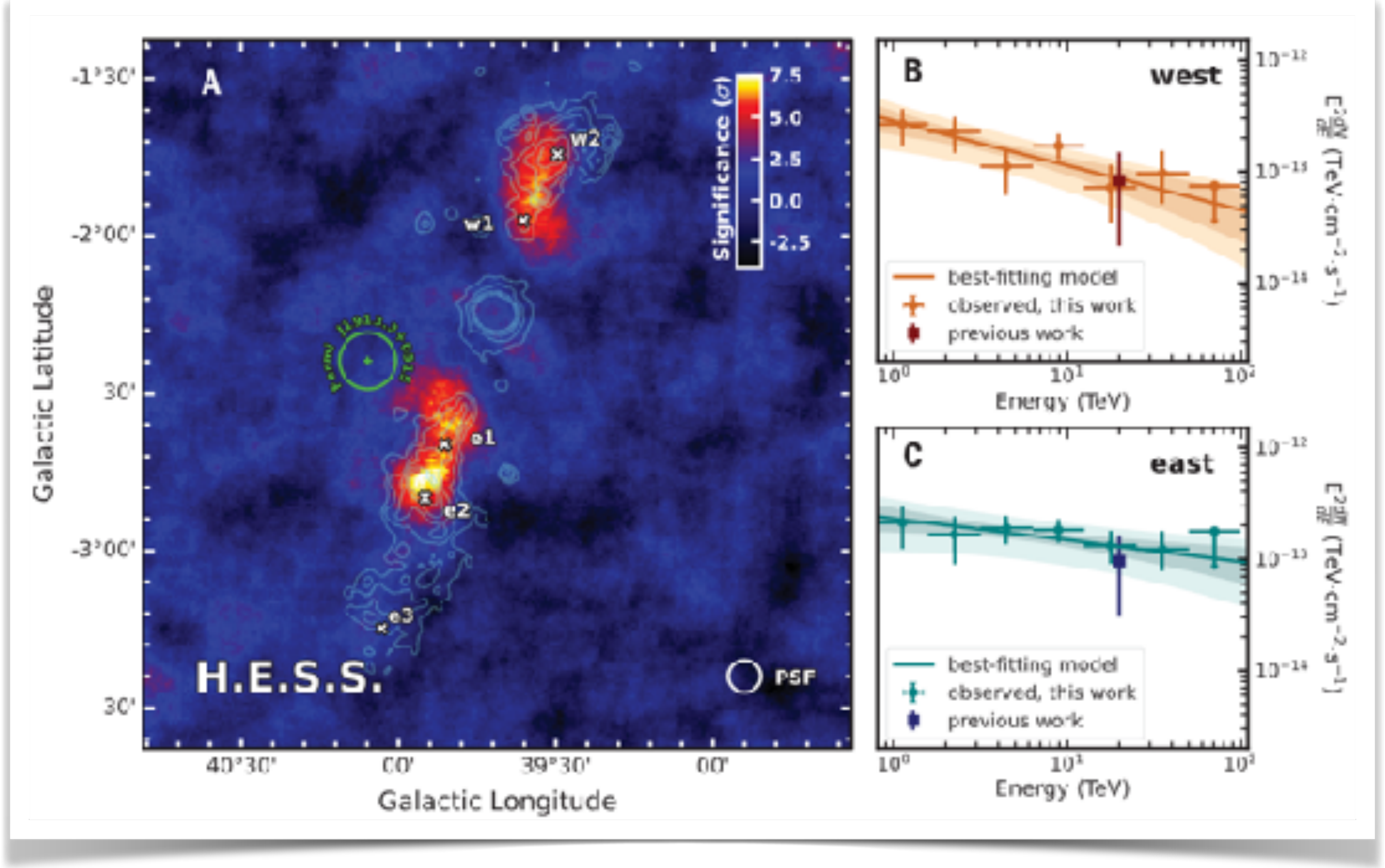


Micro-quasars (black-hole+supergiant binaries):

γ_{sh} ~ 2-10

σ ~ 0.1-1 (?)

collimation shocks



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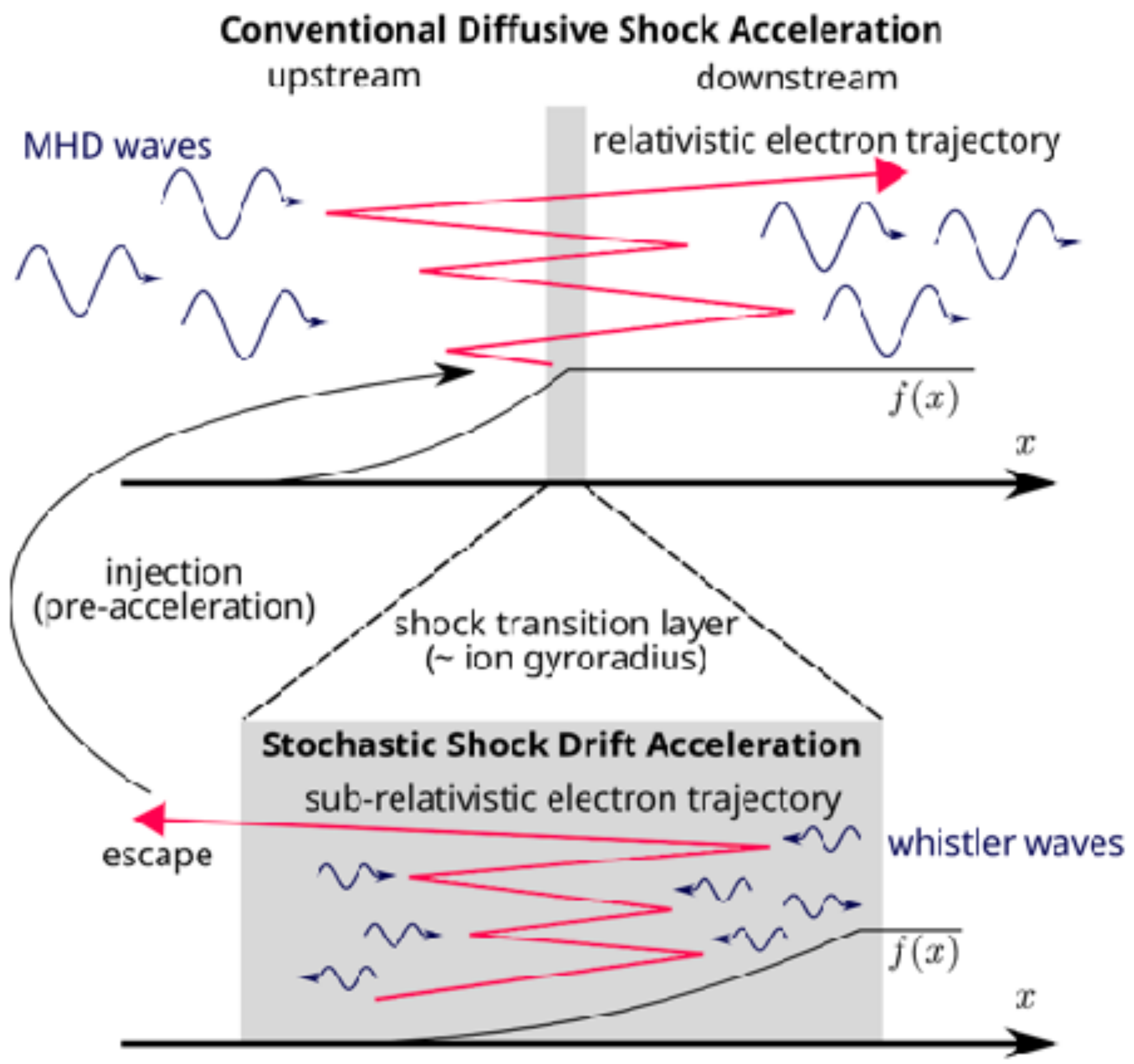
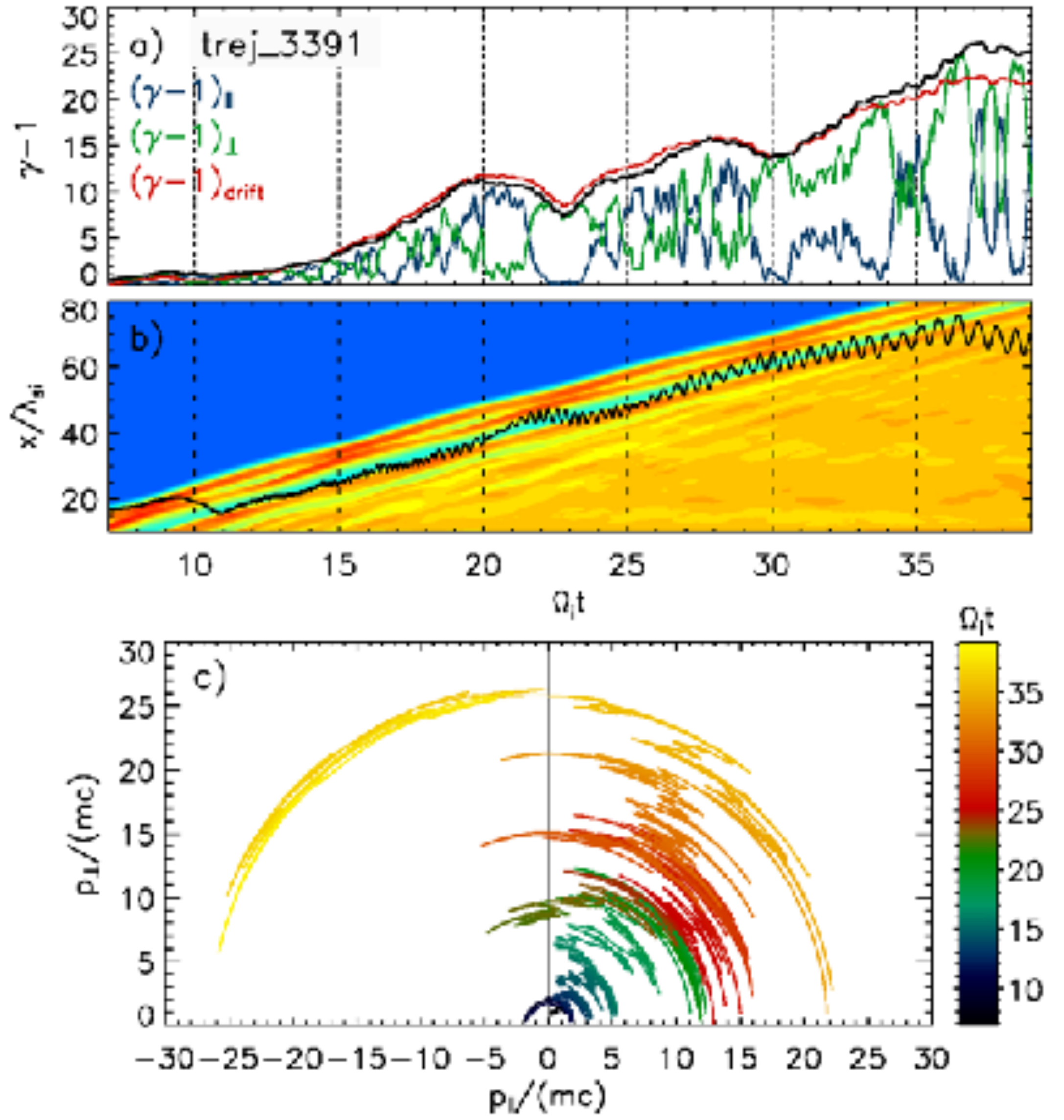
My recent and current research - particle energisation in astrophysical shocks, synergies with heliospheric shocks; PIC simulations

- Electron injection to Diffusive Shock Acceleration (DSA), electron and ion heating, energy partition, magnetic field amplification
  - Shock-surfing Acceleration (SSA) at high M_A (quasi-)perpendicular shocks
  - Stochastic Shock Drift Acceleration (SSDA): wave-particle-interactions-aided SDA process
    - Weibel-instability-mediated high M_A shocks
    - Low Mach number shocks in high beta plasmas
- Non-DSA acceleration mechanisms at relativistic magnetised shocks

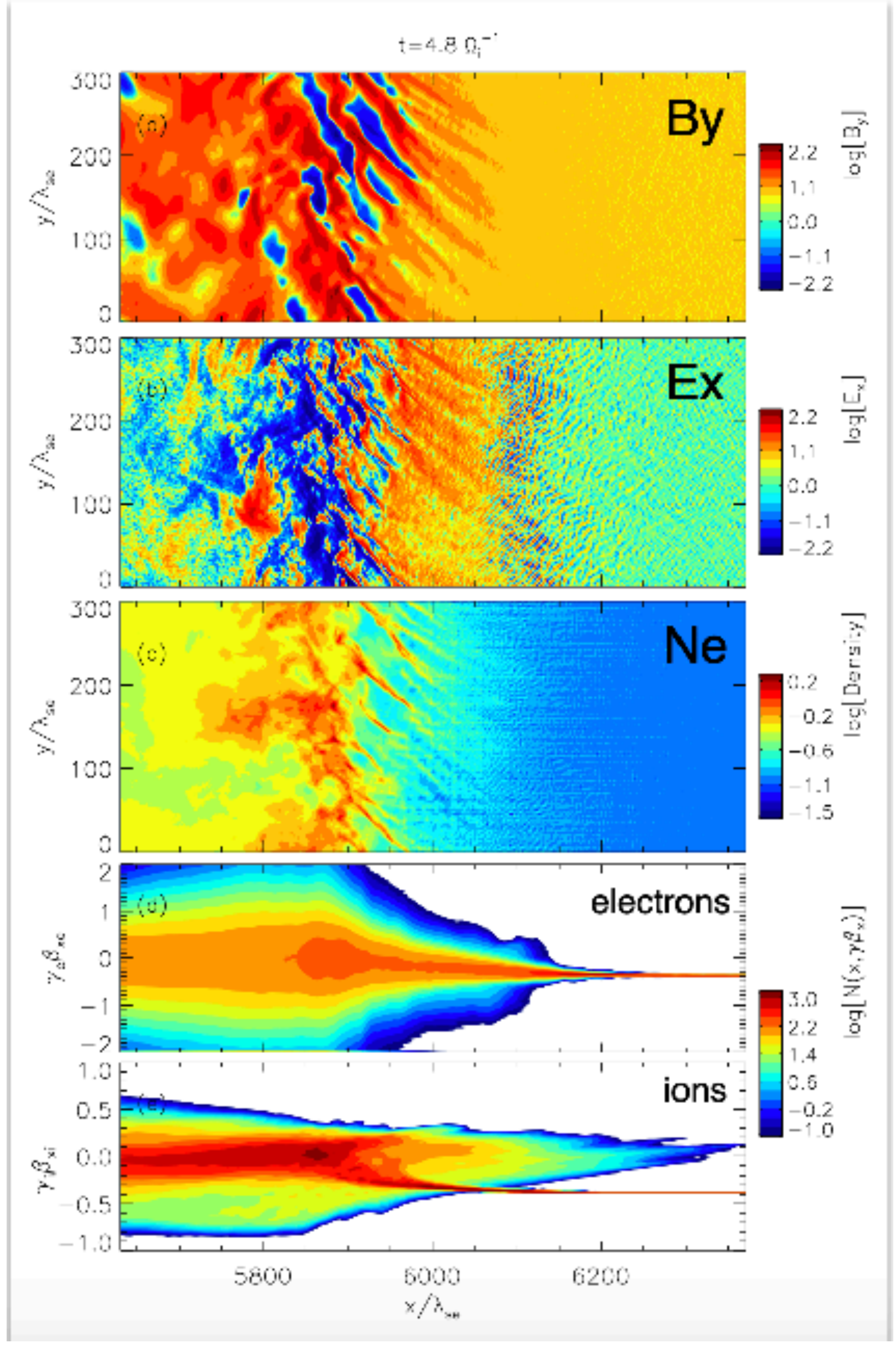


Amano & Hoshino 2020



Kobzar et al. 2021, Kobzar et al. in prep

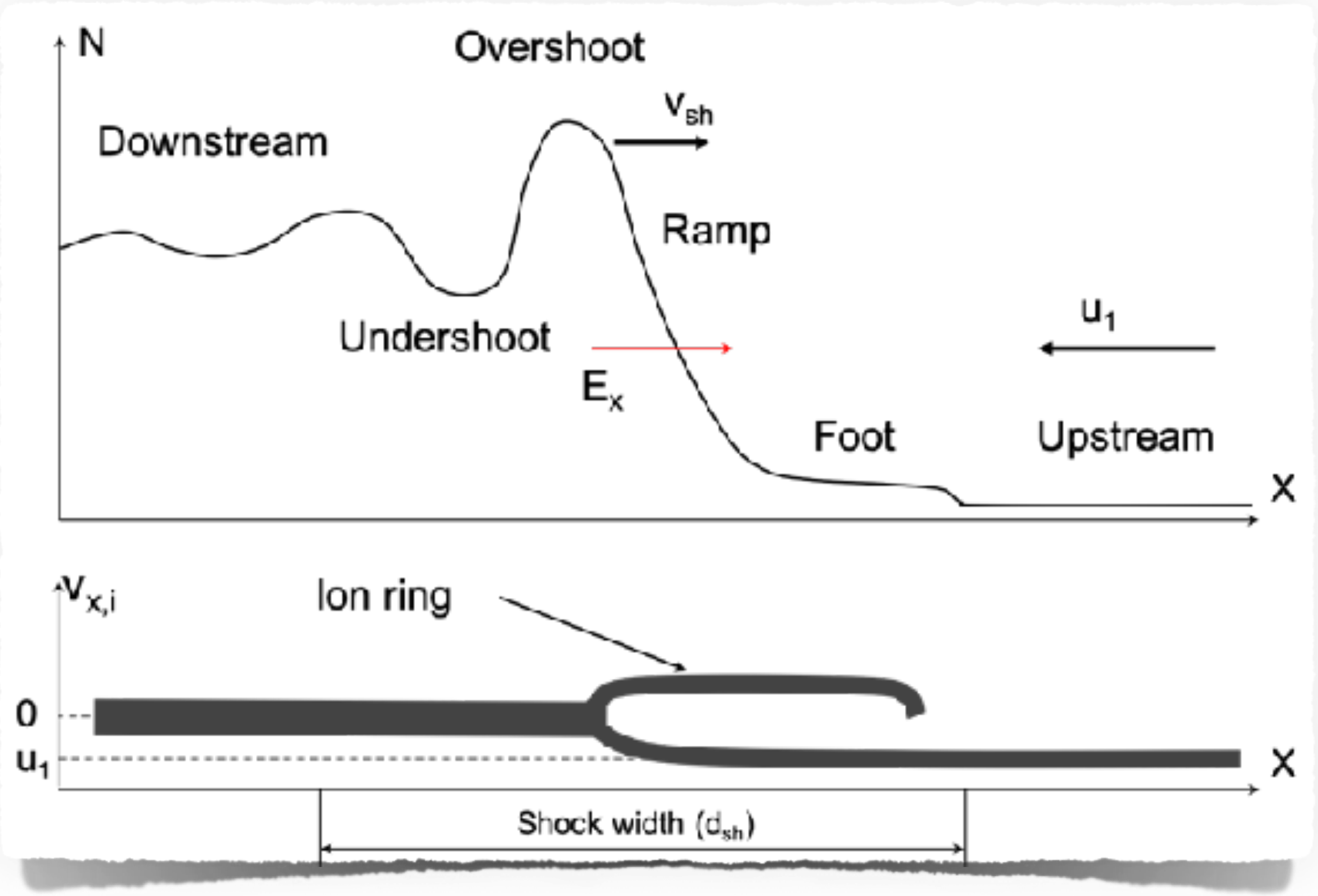
Amano & Hoshino 2007
Matsumoto et al. 2012, 2013, 2015, 2017
Wieland et al. 2016
Bohdan et al. 2017, 2019a, 2019b, 2020

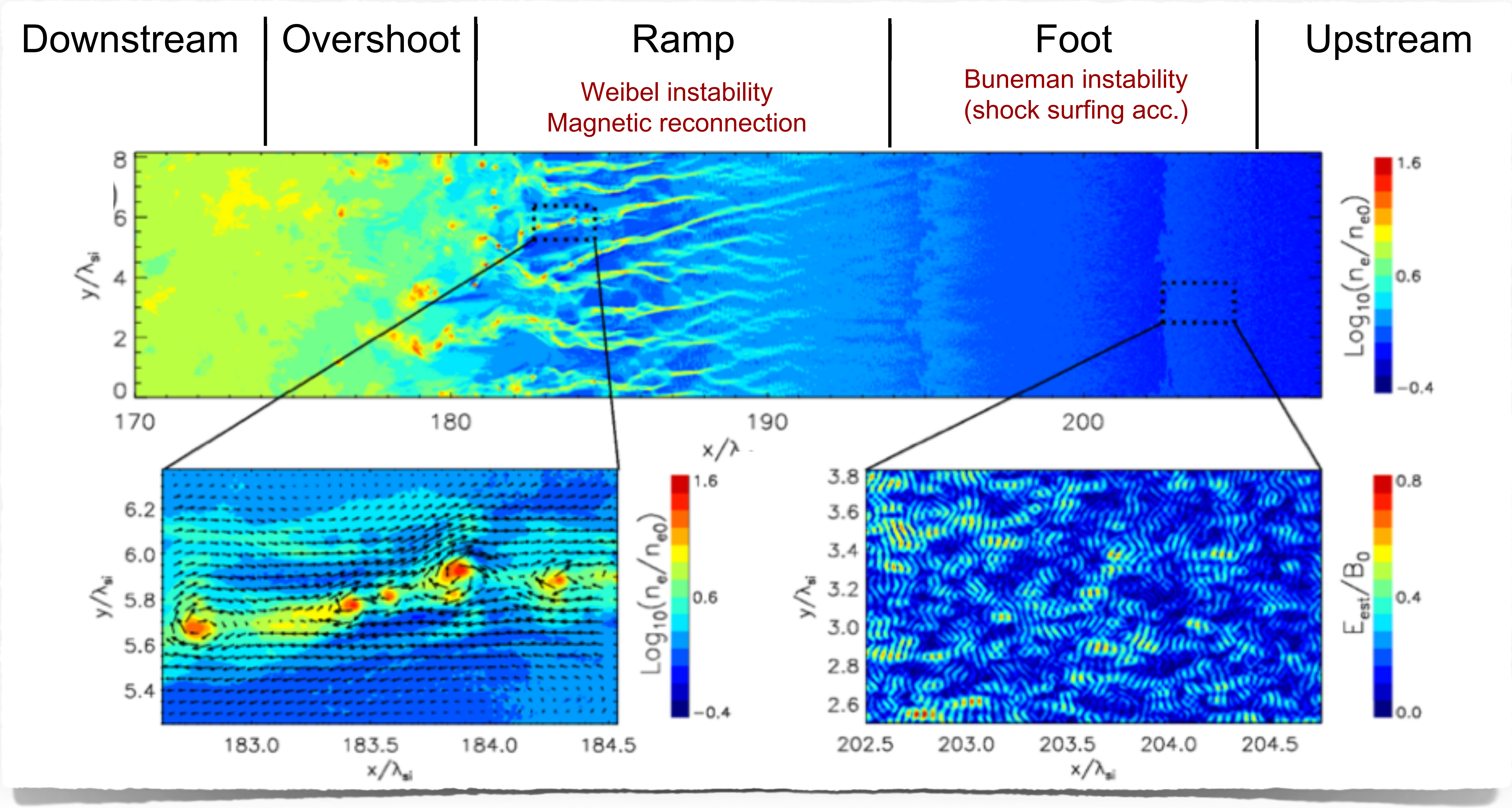


Example topics relevant to the program:

- Relation of WI to AIC-driven rippling modes (general synergies)
- Weibel instability filaments and magnetic reconnection (topic of week 2)
- Mildly relativistic shocks in magnetised plasmas (topic of week 3)

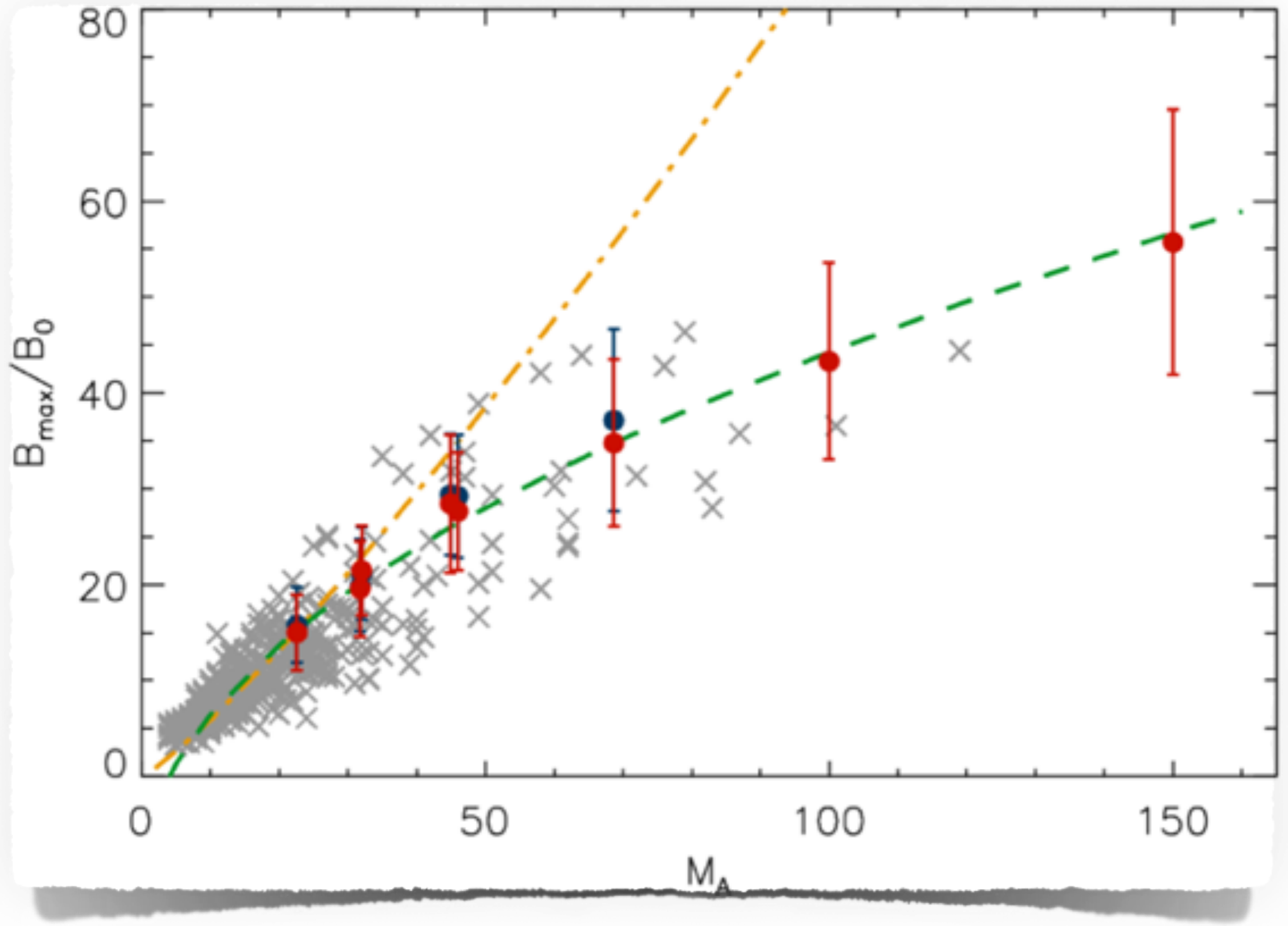
Microstructure of a quasi-perpendicular high Mach number shock



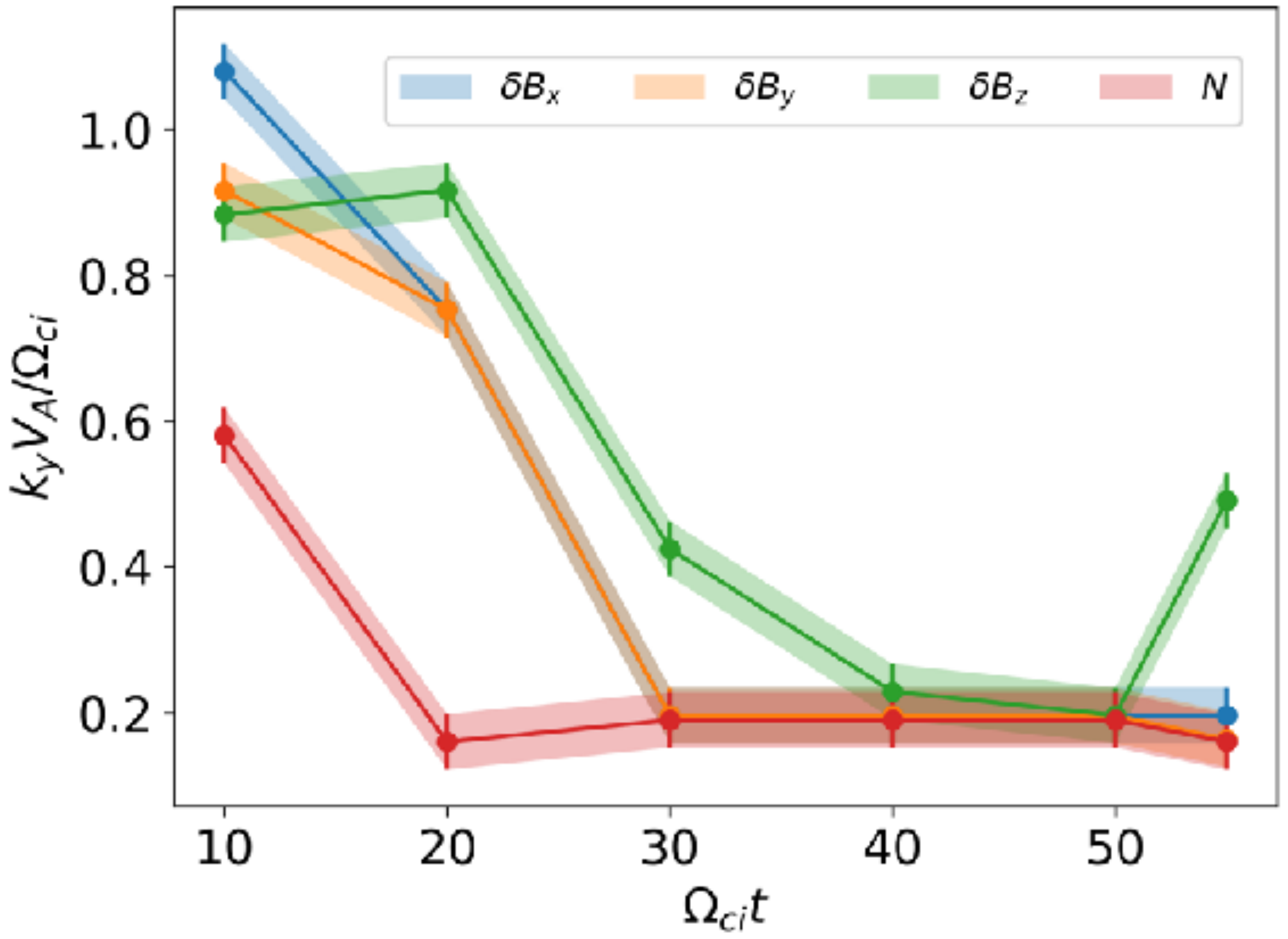


Relation of WI to AIC-driven rippling modes

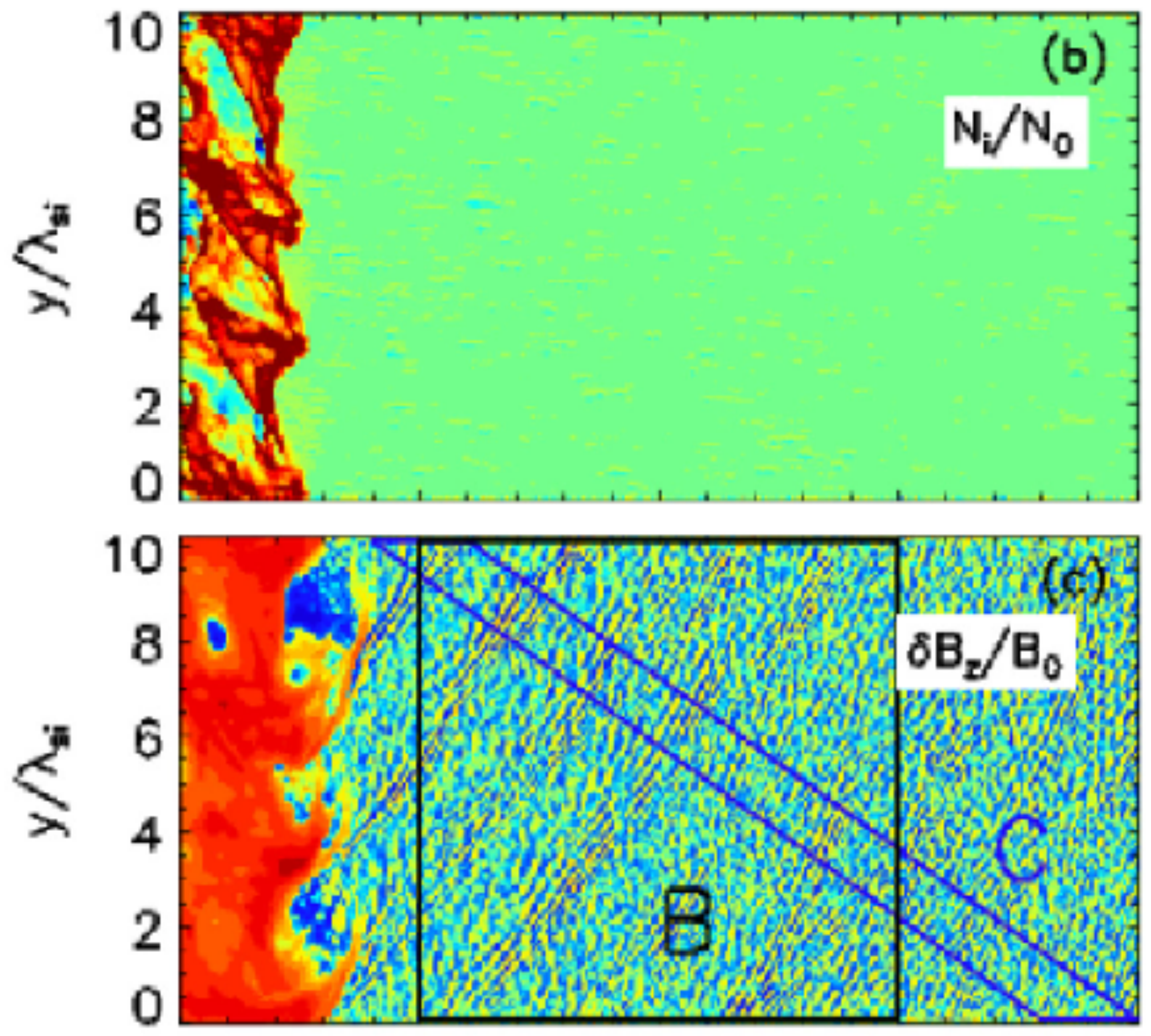
- Weibel instability and Alfven Ion Cyclotron instability sourced by the same effective temperature anisotropy induced by ions reflected from the shock and gyrating in a background upstream field
- Instability regime depends on the growth rate $\gamma_{max}/\Omega_{ci} \lesssim 1 \ (\gg 1)$ (Nishigai & Amano 2021)
- Transition at sonic and Alfvenic Mach numbers ~20-40
- Weibel turbulence might account for magnetic field amplification at SNR shocks and is consistent with in-situ measurements at Saturn's bow shock (Bohdan et al. 2021) - possibly also at specific Earth bow shock conditions (?)
- Understanding the physics of shock rippling relevant to other astrophysical systems (e.g. cluster shocks, blazar internal mildly relativistic shocks)



Saturn's bow shock data and PIC simulations of WI turbulence (Bohdan et al. 2021)

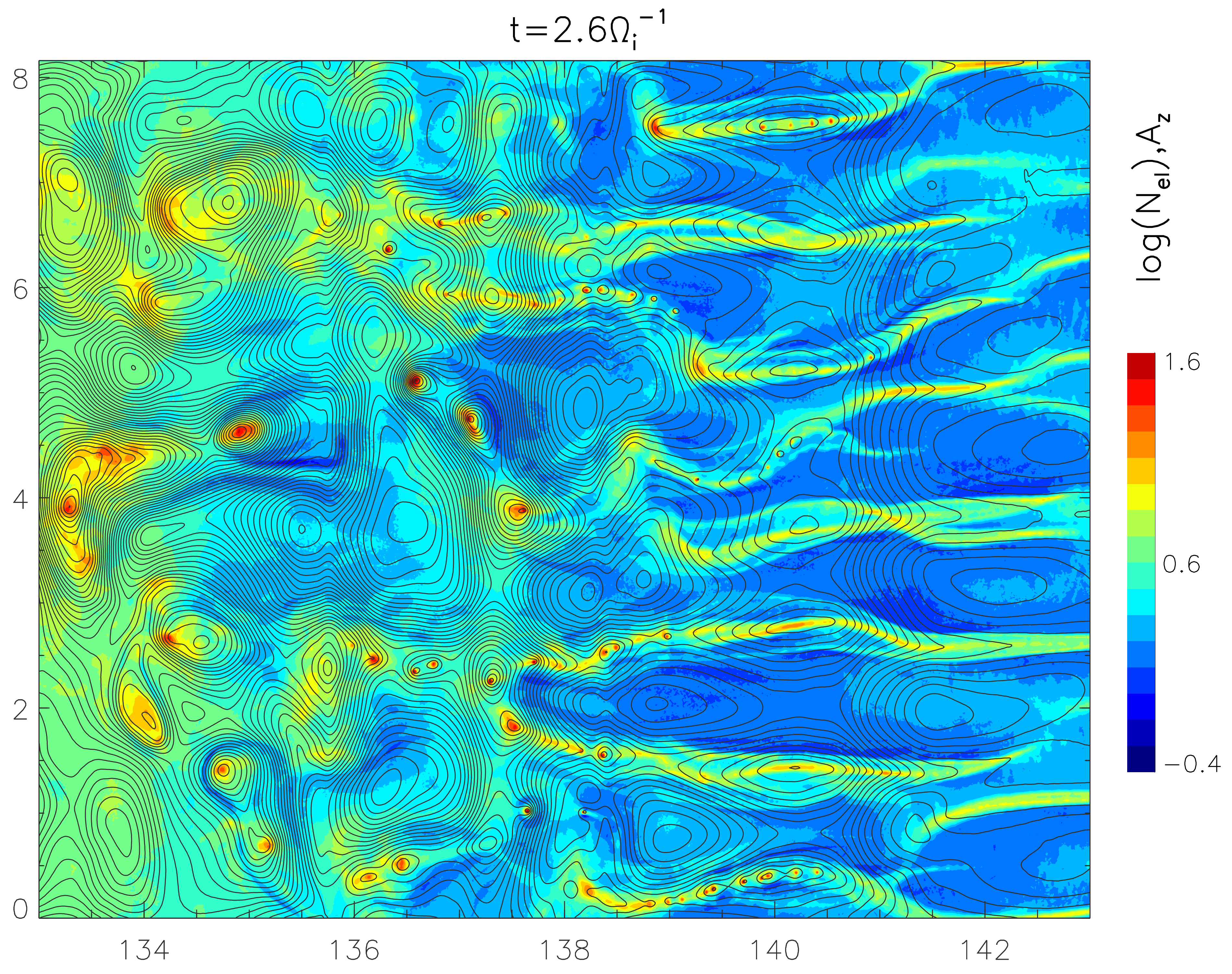


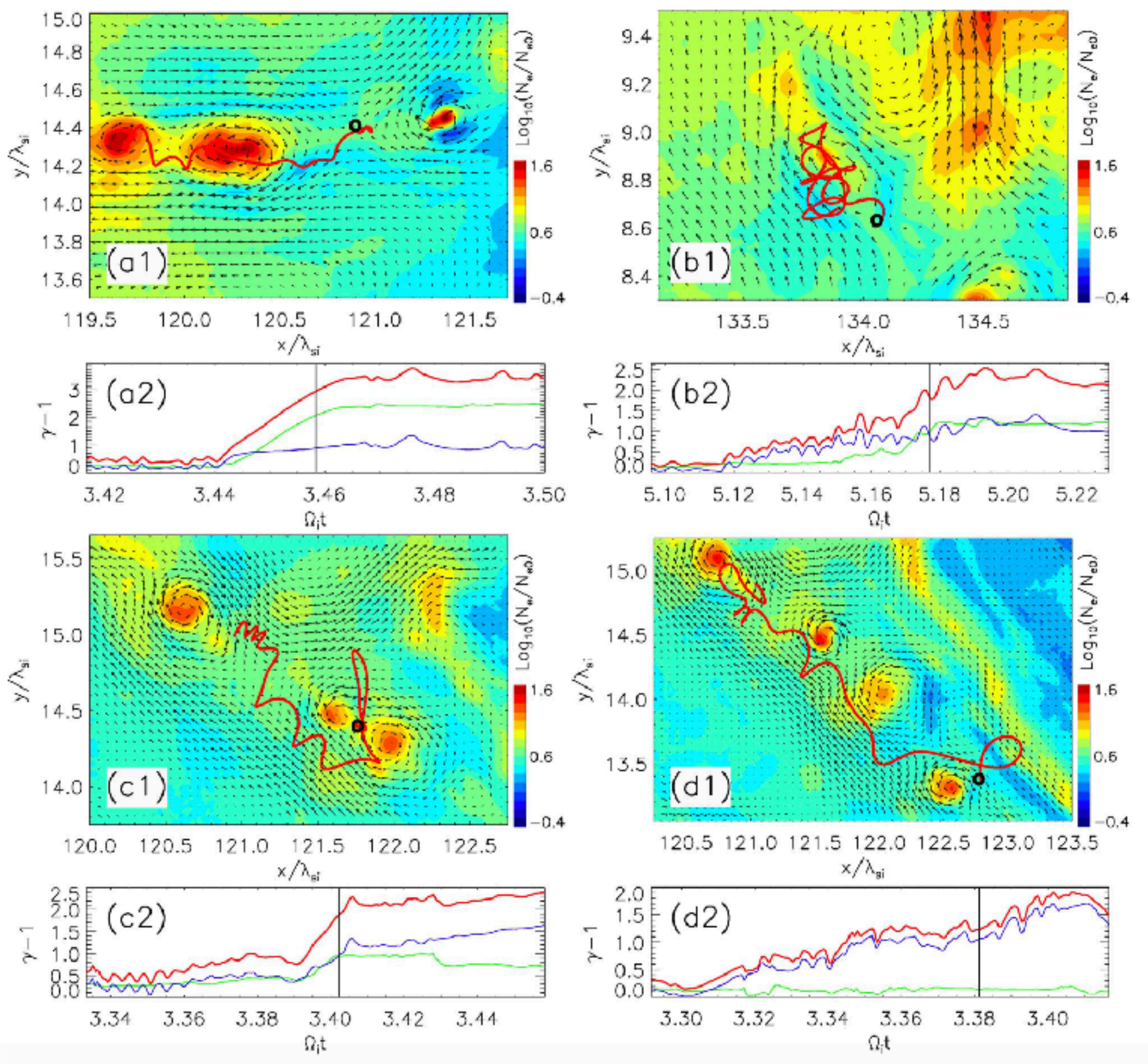
Boula et al. 2024 (2D hybrid); β=20



Ripples at a mildly relativistic shock amplify SMI-induced EM emission and ES wakefields (Ligorini et al. 2020, 2021)

Weibel instability filaments and magnetic reconnection

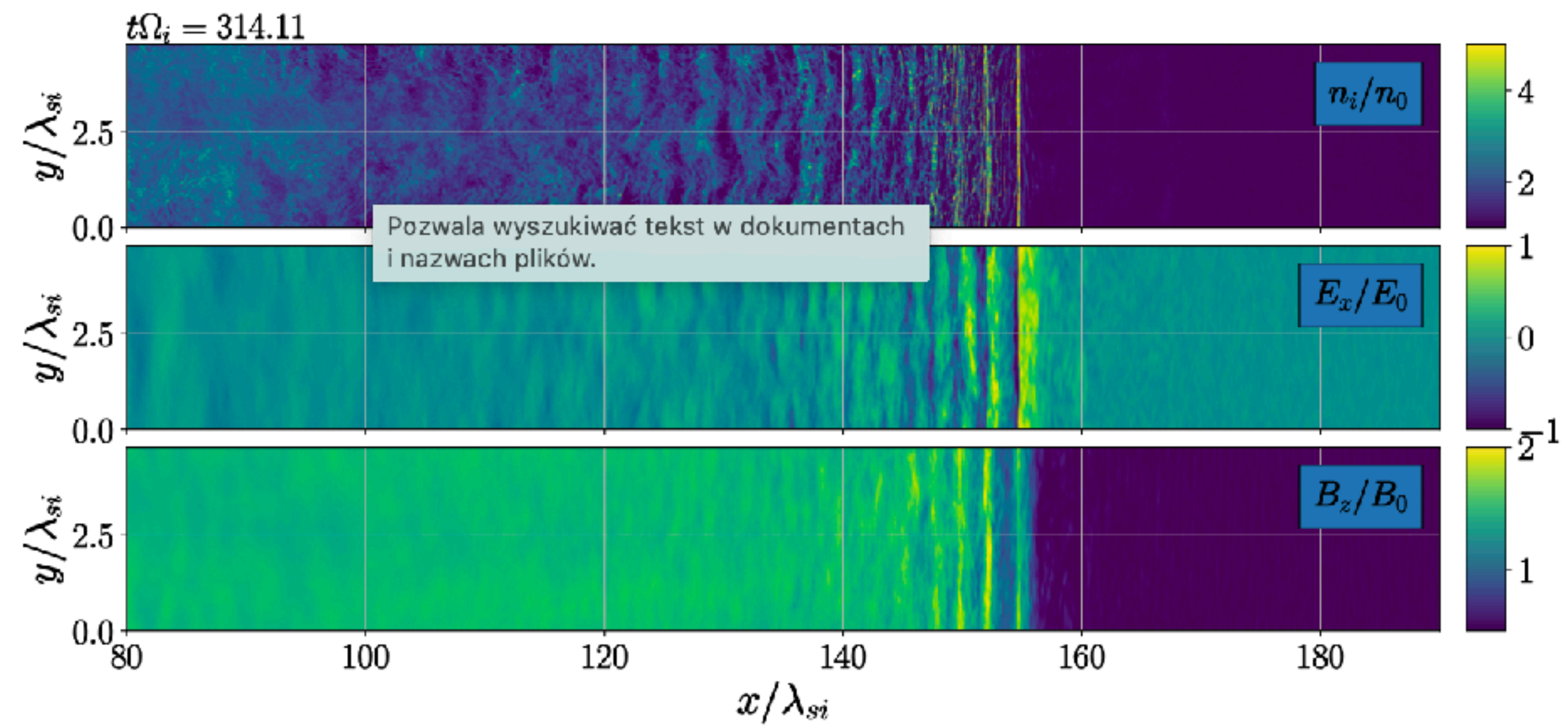


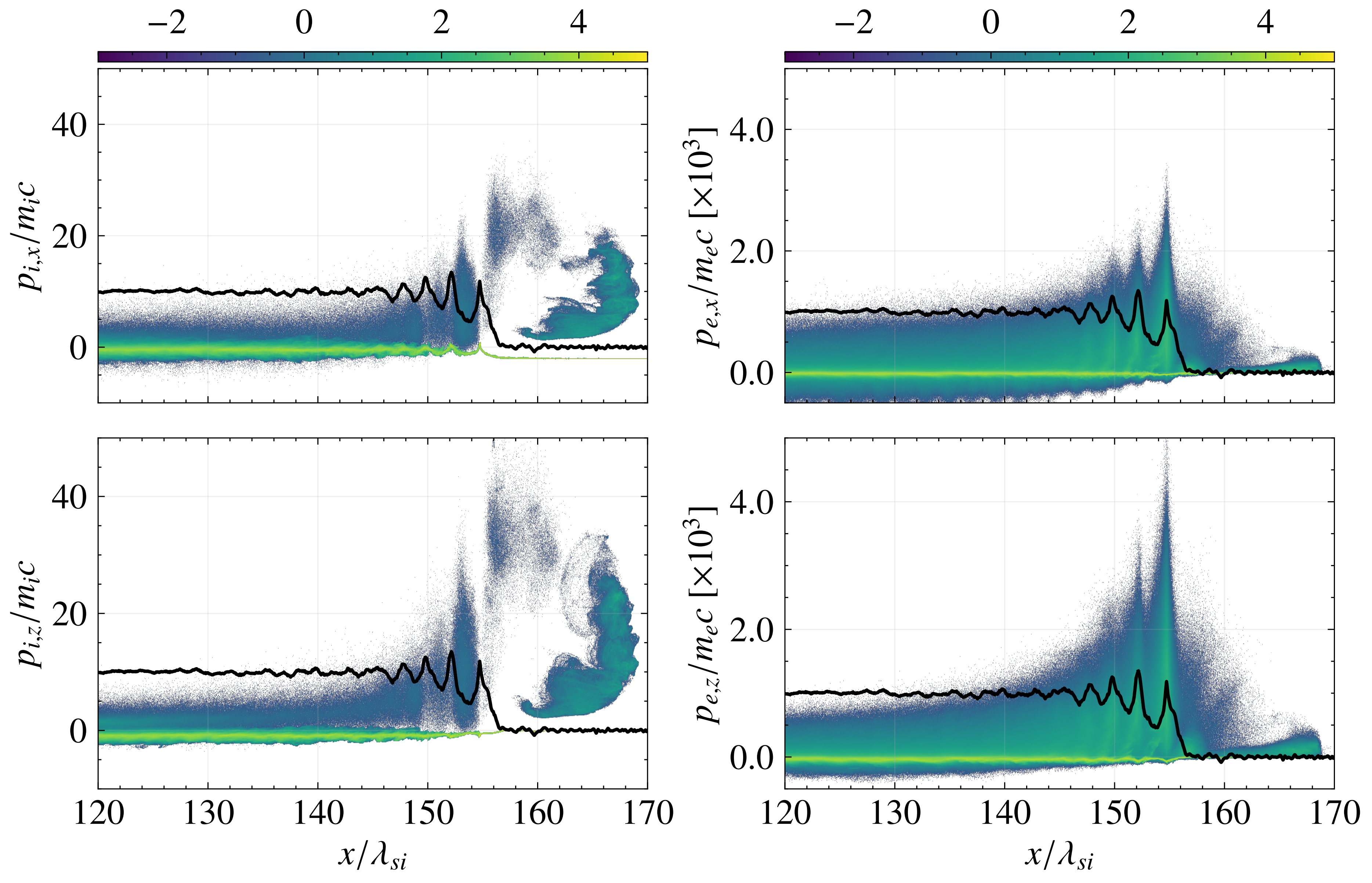


- turbulent magnetic reconnection takes place in current sheets within filamentary shock transition and downstream. As a result, magnetic islands are formed along current sheets.
- the process is intermittent, effectiveness vary with the phase of cyclic shock reformation
- additional source of electron energization (Matsumoto et al. 2015, Bohdan et al. 2020)

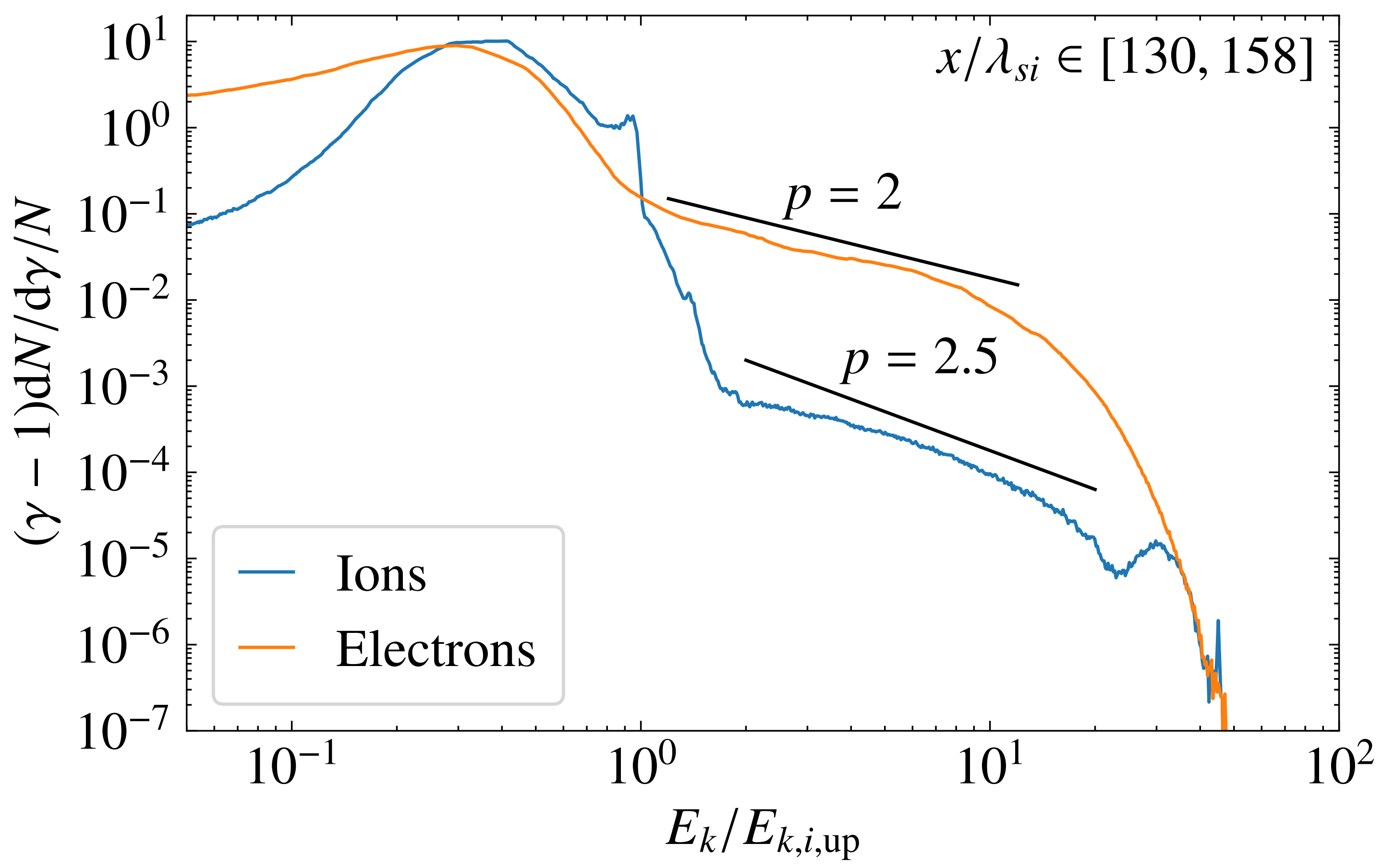
Stochastic collisions with magnetic structures, acceleration in a magnetic island, an X-point, or during magnetic island coalescence...

Mildly relativistic subluminal shocks in magnetised plasmas: $\gamma_{sh,up} \simeq 3.7, \sigma = 1$



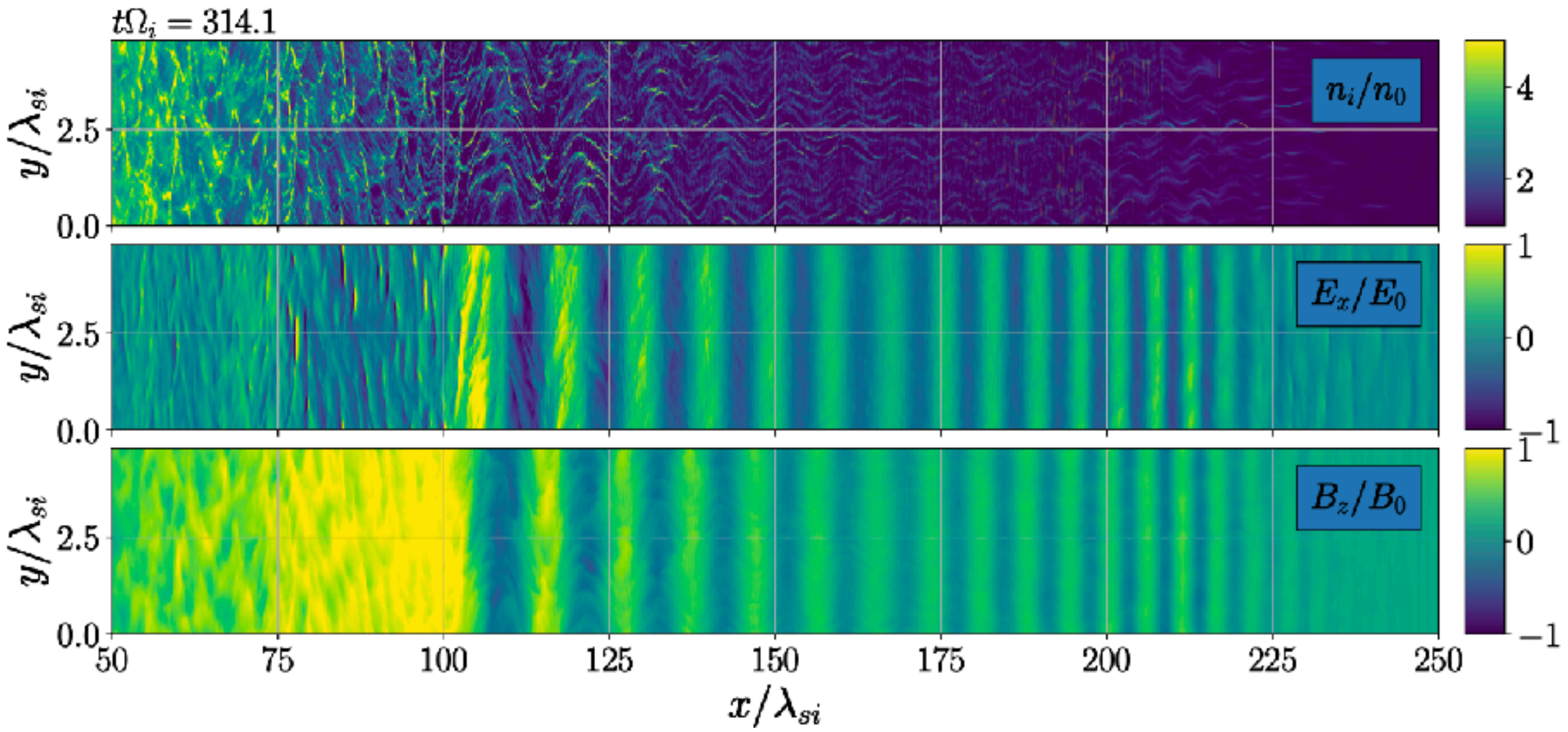


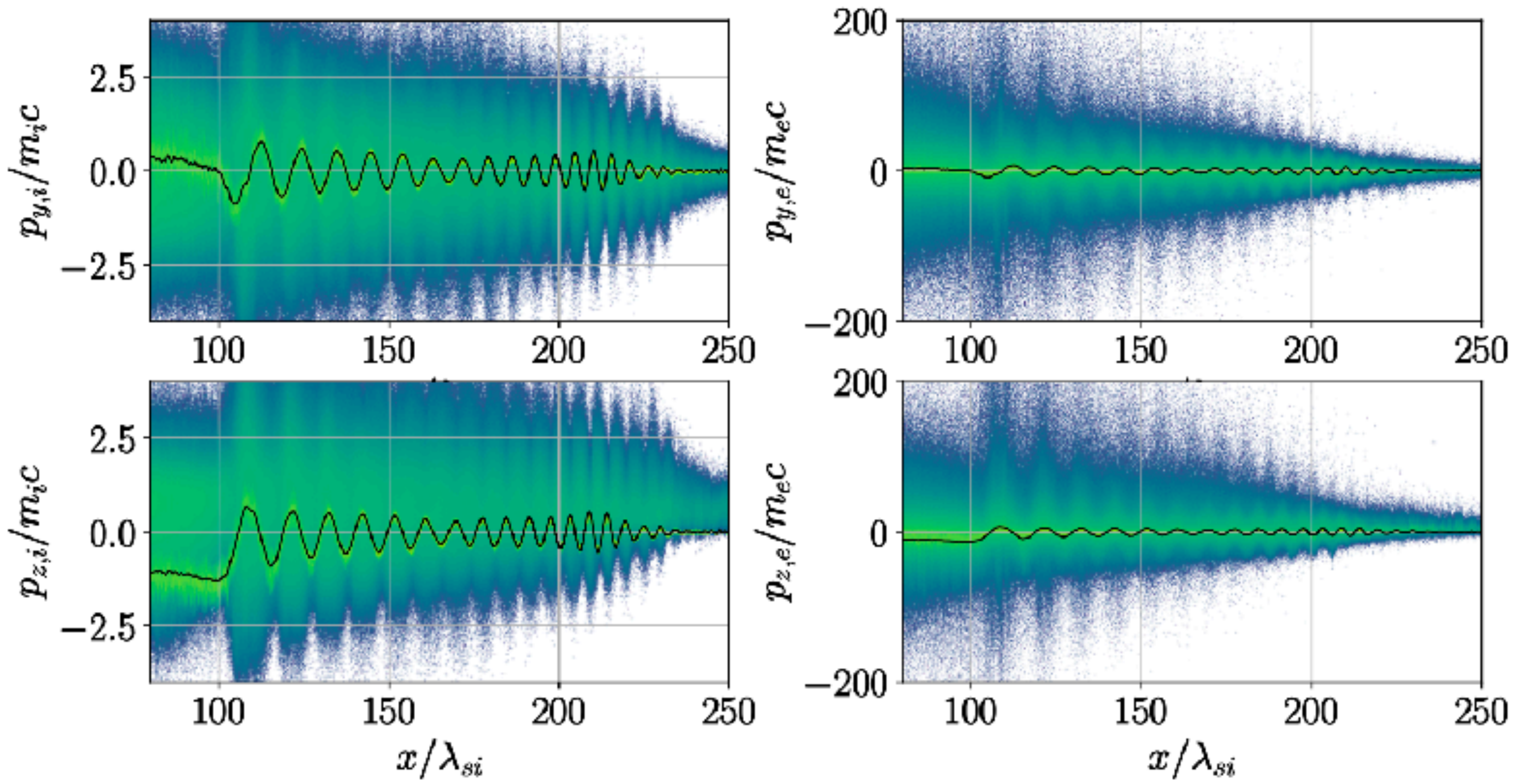
- Oblique ($\theta_{Bn} \simeq 30^o$) strongly magnetized shocks develop large-amplitude magnetosonic wave trains whose structure is reminiscent of weak non-relativistic subcritical space shocks ($M_{A,up} \gtrsim 1.1$).
- The shocks are intrinsically non-stationary and exhibit significant transverse non-uniformities.
- This enables particle reflection and trapping within magnetosonic pulses (Bessho & Ohsawa 1999,...), that leads to efficient heating and acceleration of both electrons and ions in subluminal configurations close to the threshold angle ($\theta_{th} \simeq 32.1^o$).



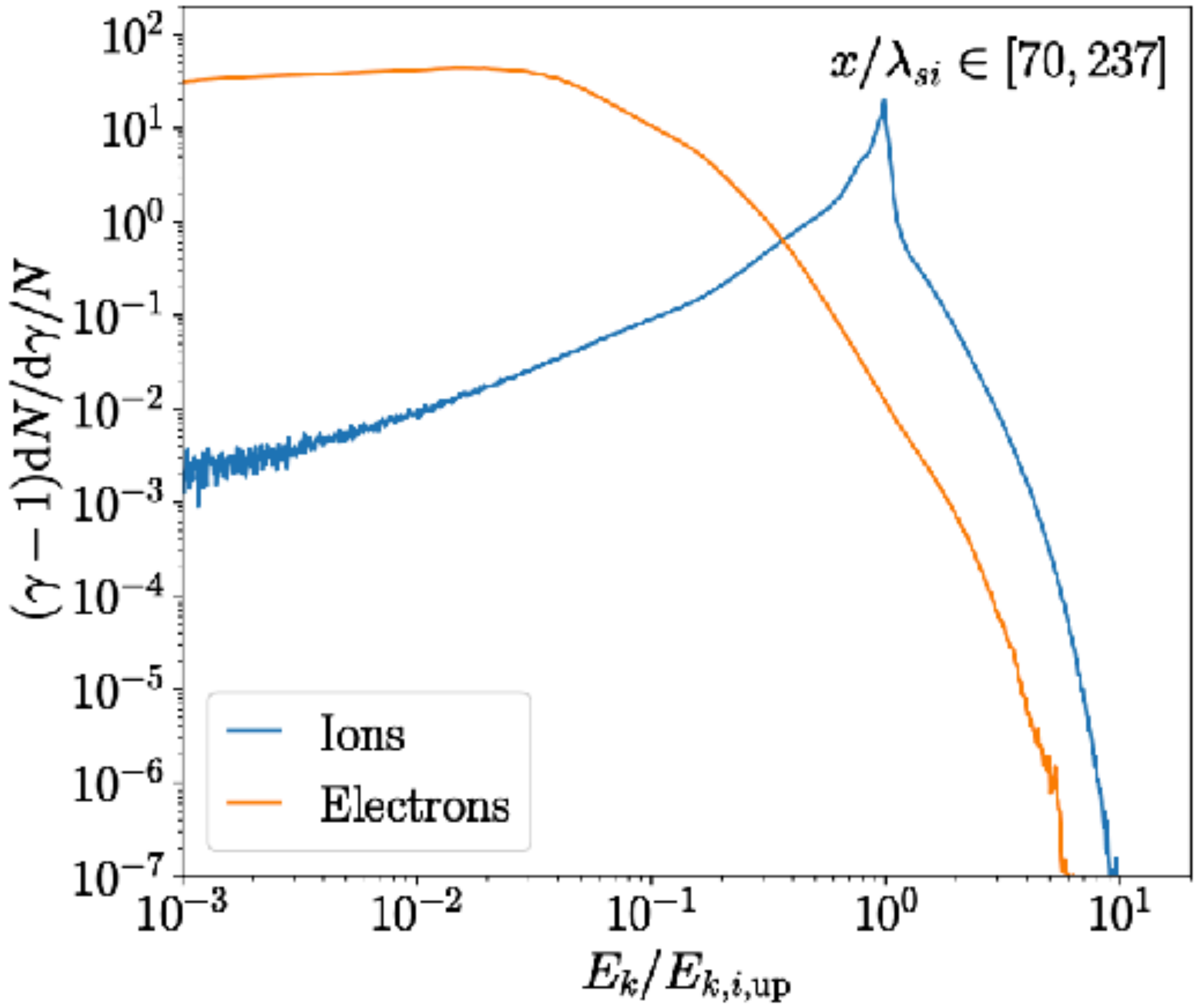
Torralba Paz, PhD Thesis 2026; Torralba Paz et al. in prep.

Mildly relativistic subluminal shocks in magnetised plasmas: $\gamma_{sh,up} \simeq 3.1, \sigma = 1$





- Large-amplitude dispersive whistlers at mildly relativistic magnetised quasi-parallel, $\theta_{Bn} = 10^o$, low Mach number shock, $M_A \simeq 1.04 < M_w \simeq 1.09$.
- Particle interactions with these precursor whistlers and additional wave modes associated with their nonlinear dynamics (e.g. MTSI-driven modes, PDI) leads to strong heating of both species.



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