Relativistic shocks at high magnetisation

[1]GABRIEL TORRALBA PAZ, [2]MASAHIRO HOSHINO, [2]TAKANOBU AMANO, [3]SHUICHI MATSUKIYO AND [1]JACEK NIEMIEC

PARTICLE ASTROPHYSICS IN POLAND 2025

FEBRUARY 22, 2025

Mildly

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UTokyo

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九州大学
KYUSHU UNIVERSITY

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Ultra-relativistic shocks: an overview

Three main sites:

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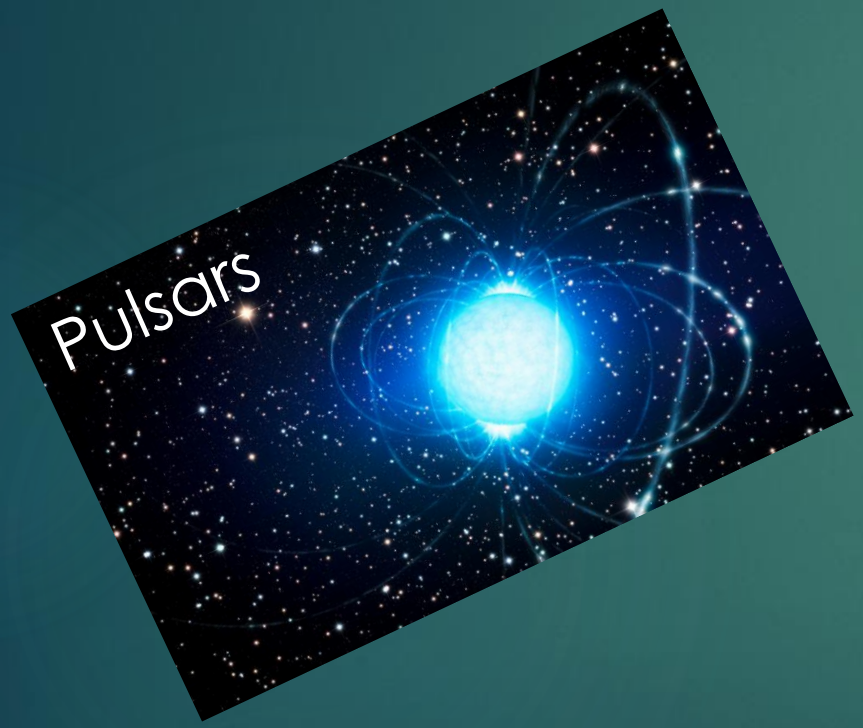

Galactic sources

Ultra-relativistic shocks: an overview

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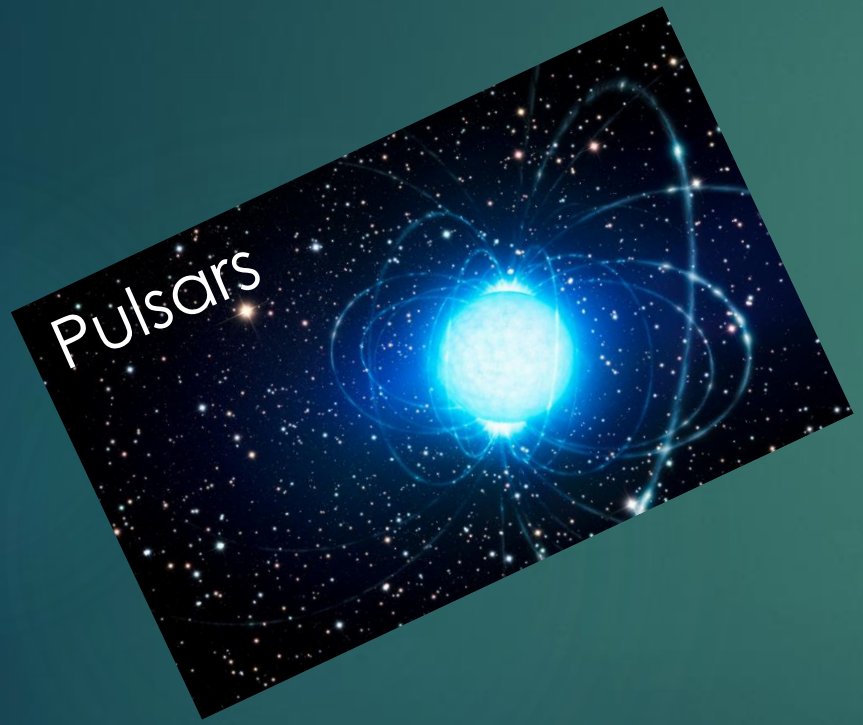

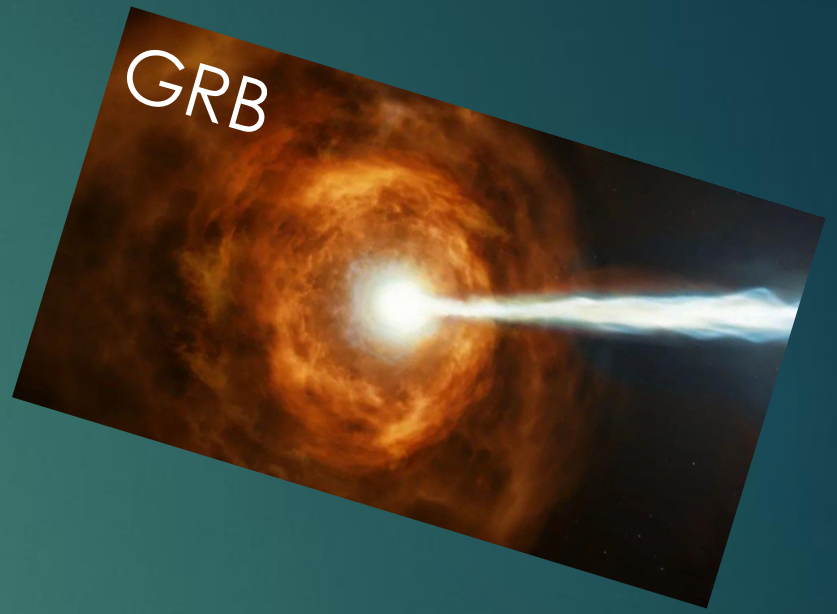

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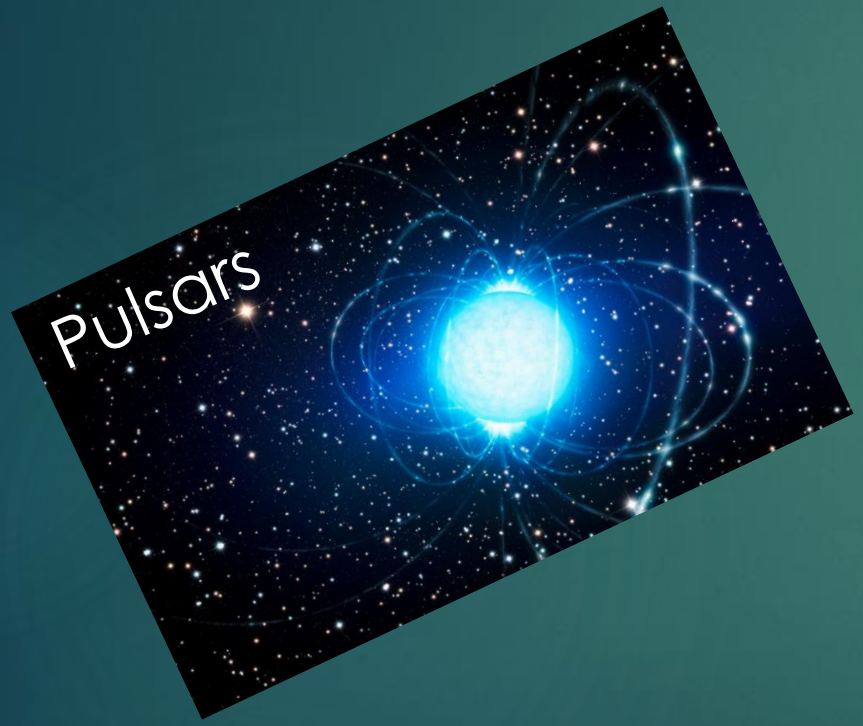

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Extragalactic sources

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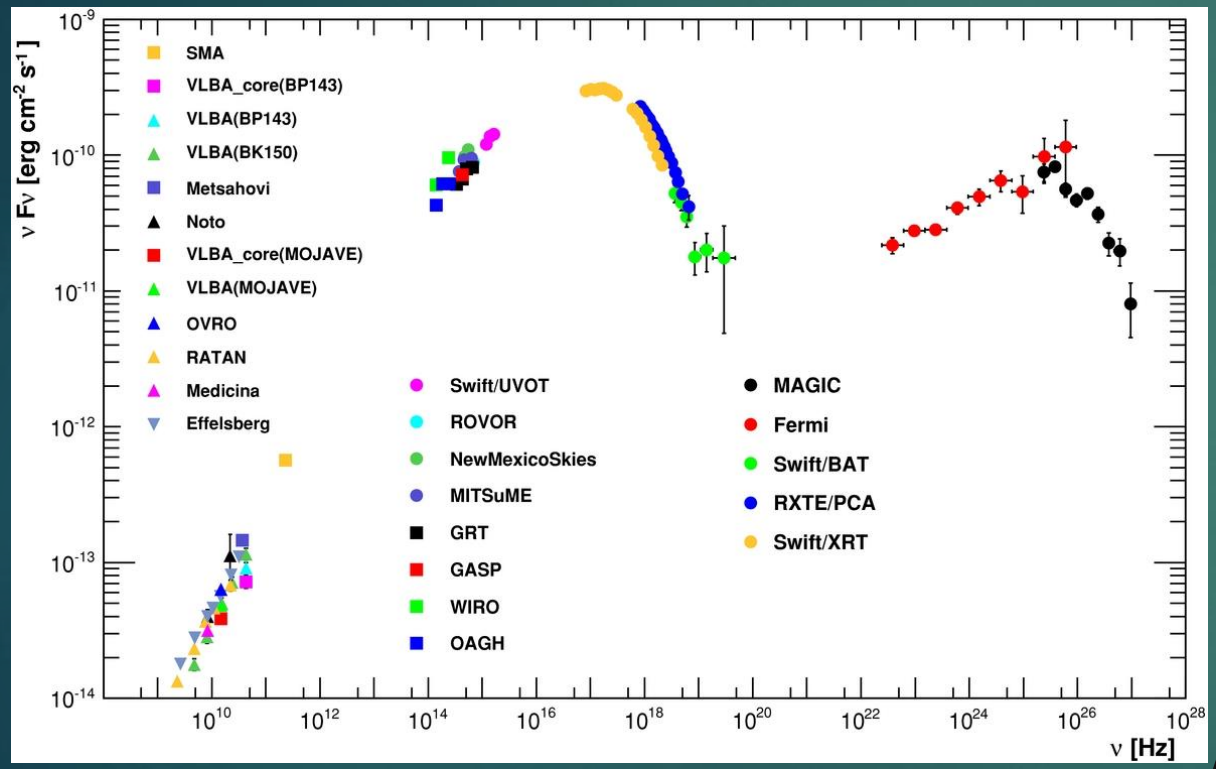

Mrk 421 SED

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Ultra-relativistic shocks: an overview

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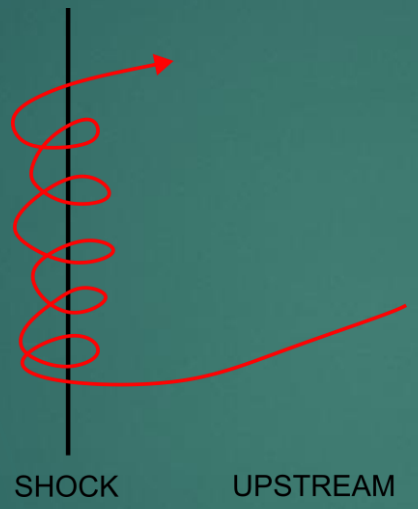

Ultra-relativistic shocks: an overview

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DIFFUSIVE SHOCK ACCELERATION (DSA)

Ultra-relativistic shocks: an overview

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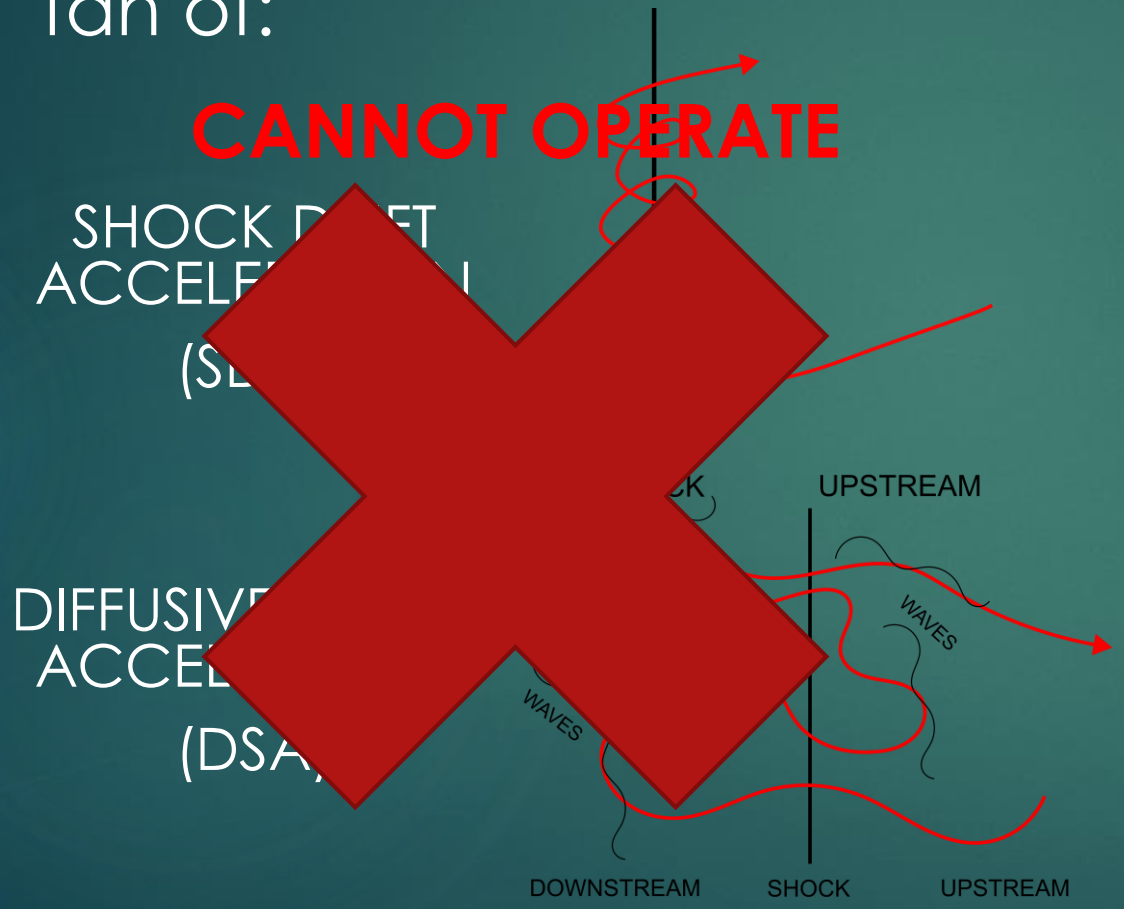

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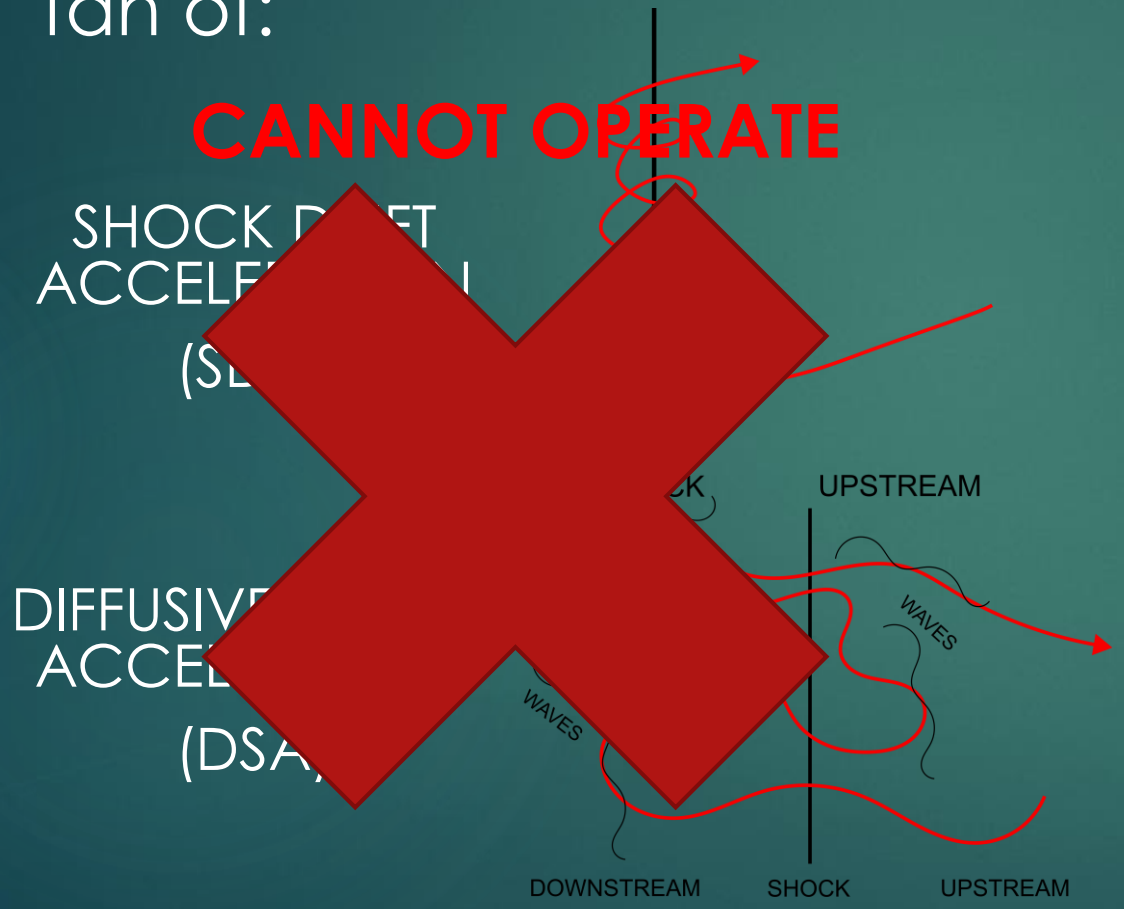

- $\gamma_{sh} \gtrsim 10$

Ultra-relativistic shocks: an overview

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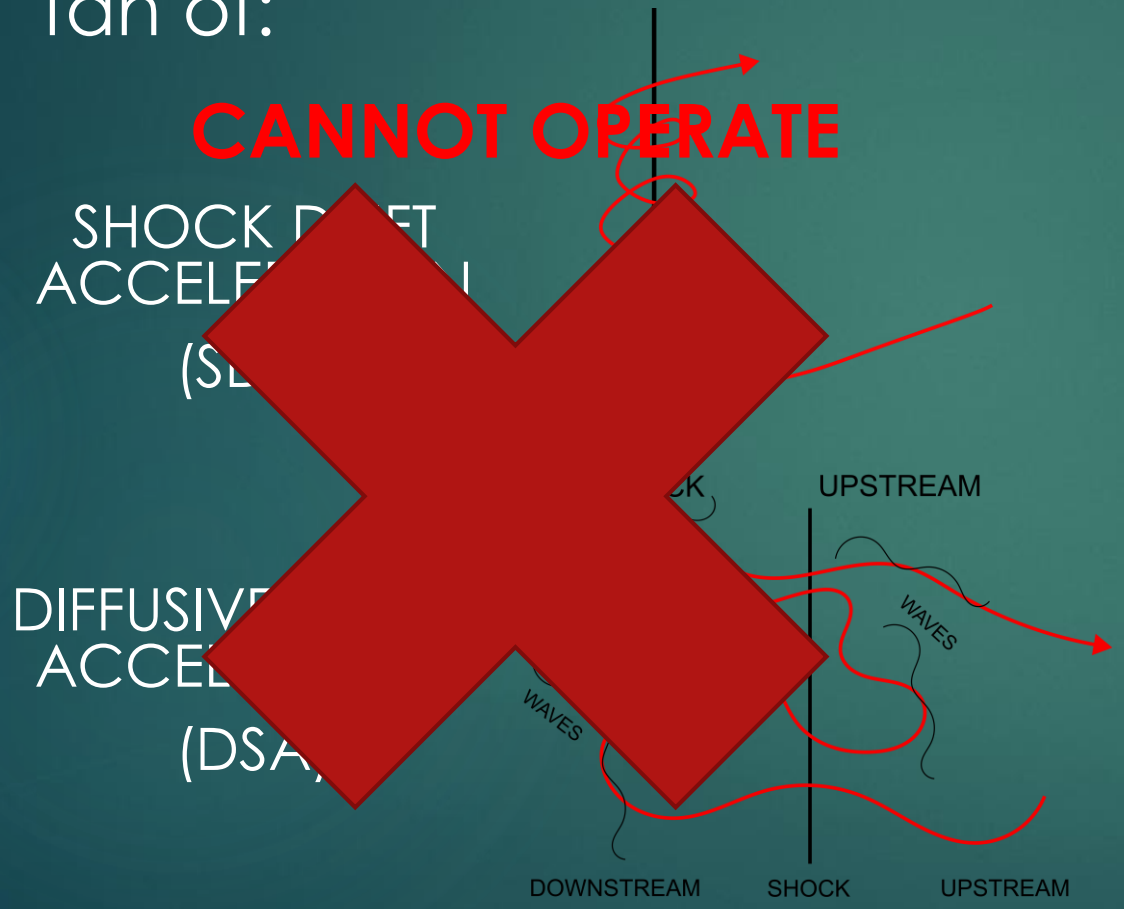

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- Intrinsic superluminal conditions.

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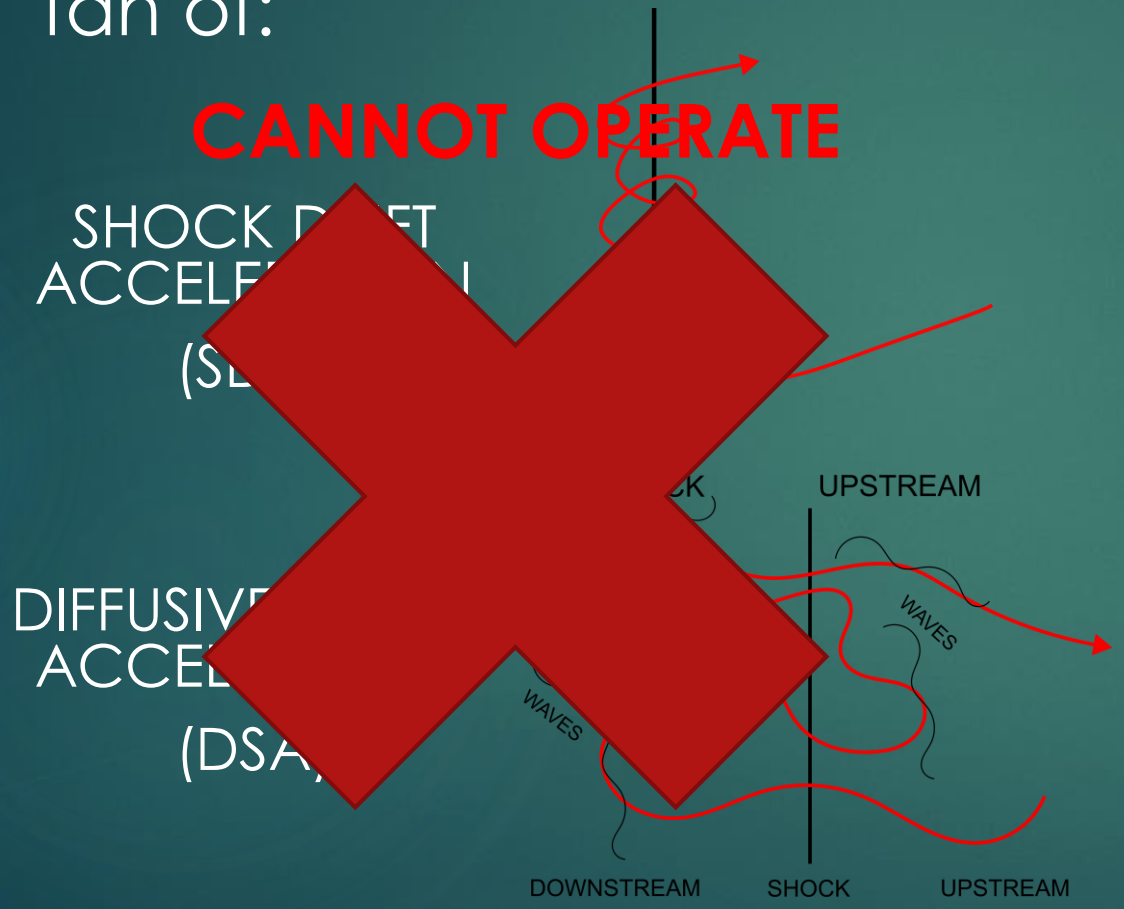

- $\gamma_{sh} \gtrsim 10$
- Intrinsic superluminal conditions.
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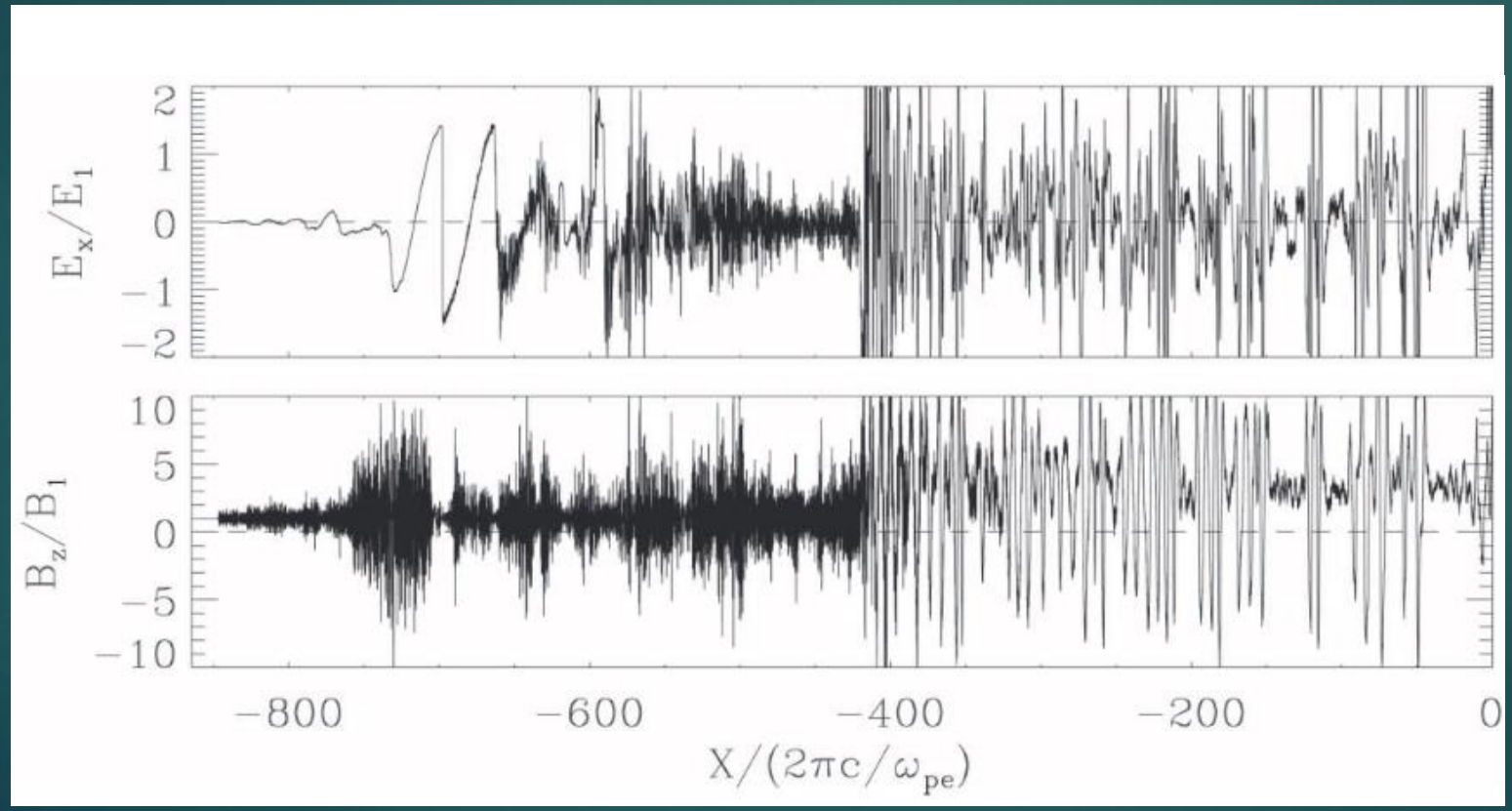
Ultra-relativistic shocks: an overview

- Precursor waves are inherent to quasi-perpendicular relativistic shocks.
  - Origin: Synchrotron Maser Instability (SMI).



Hoshino, 2008

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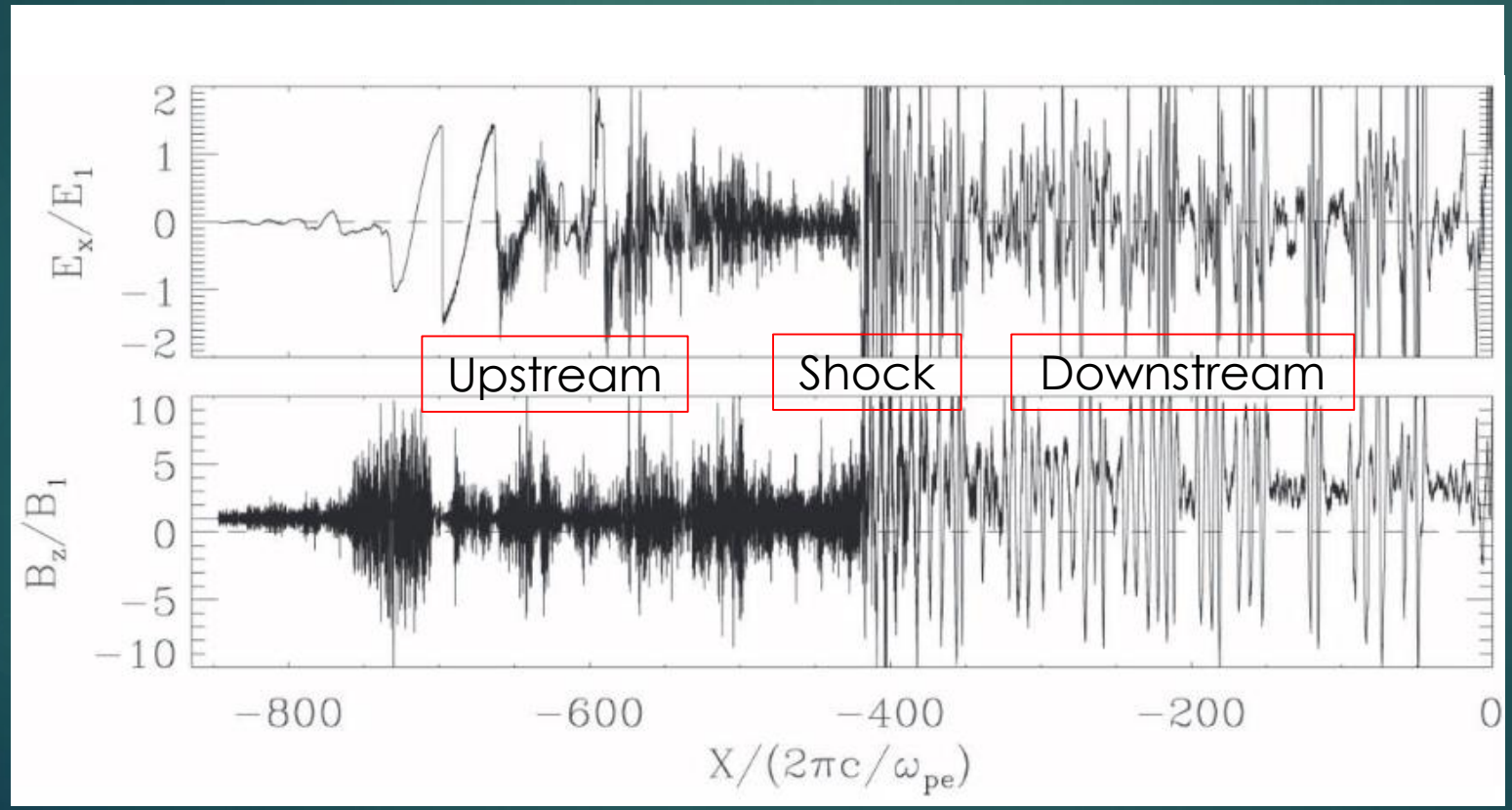

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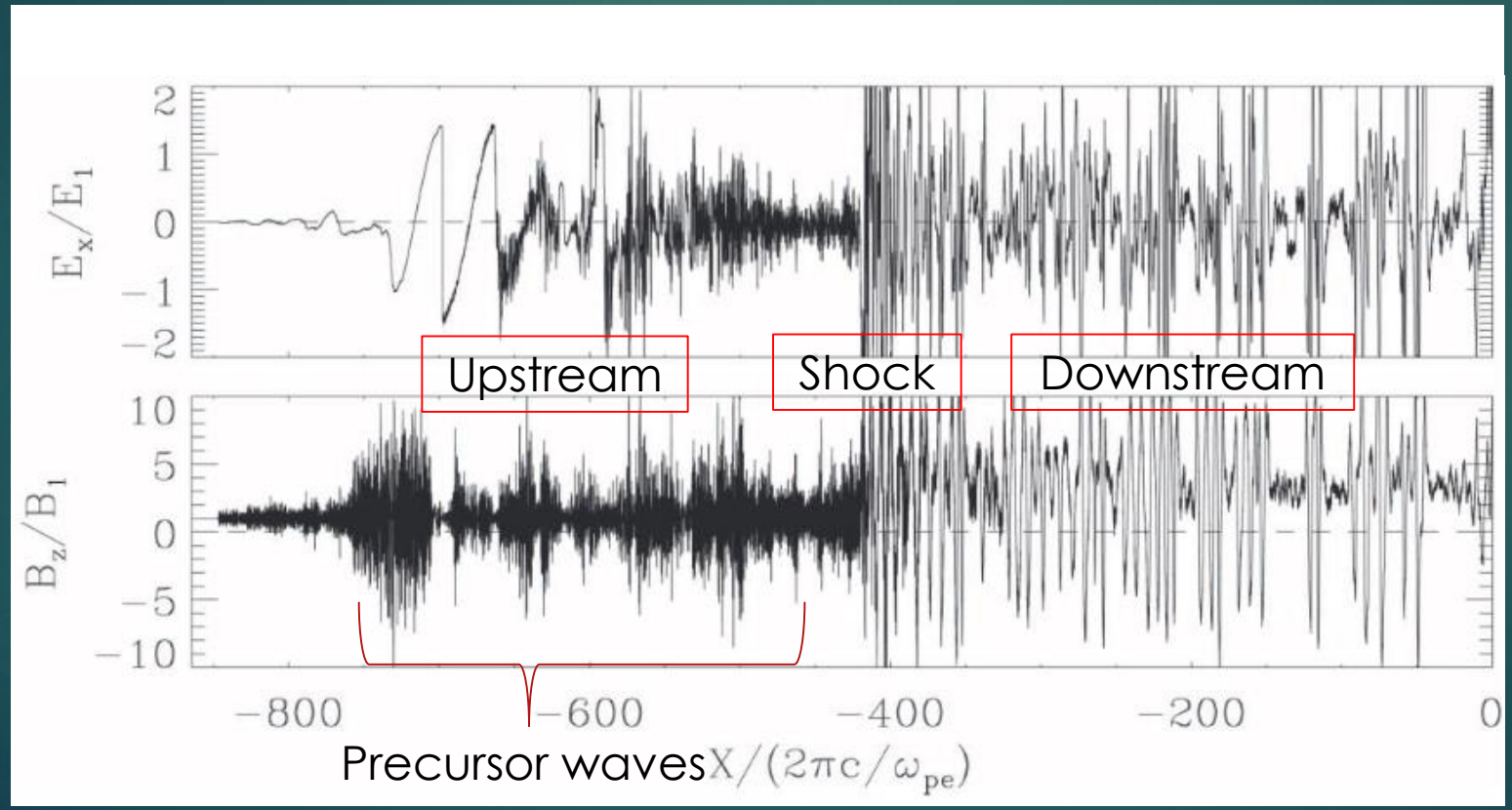

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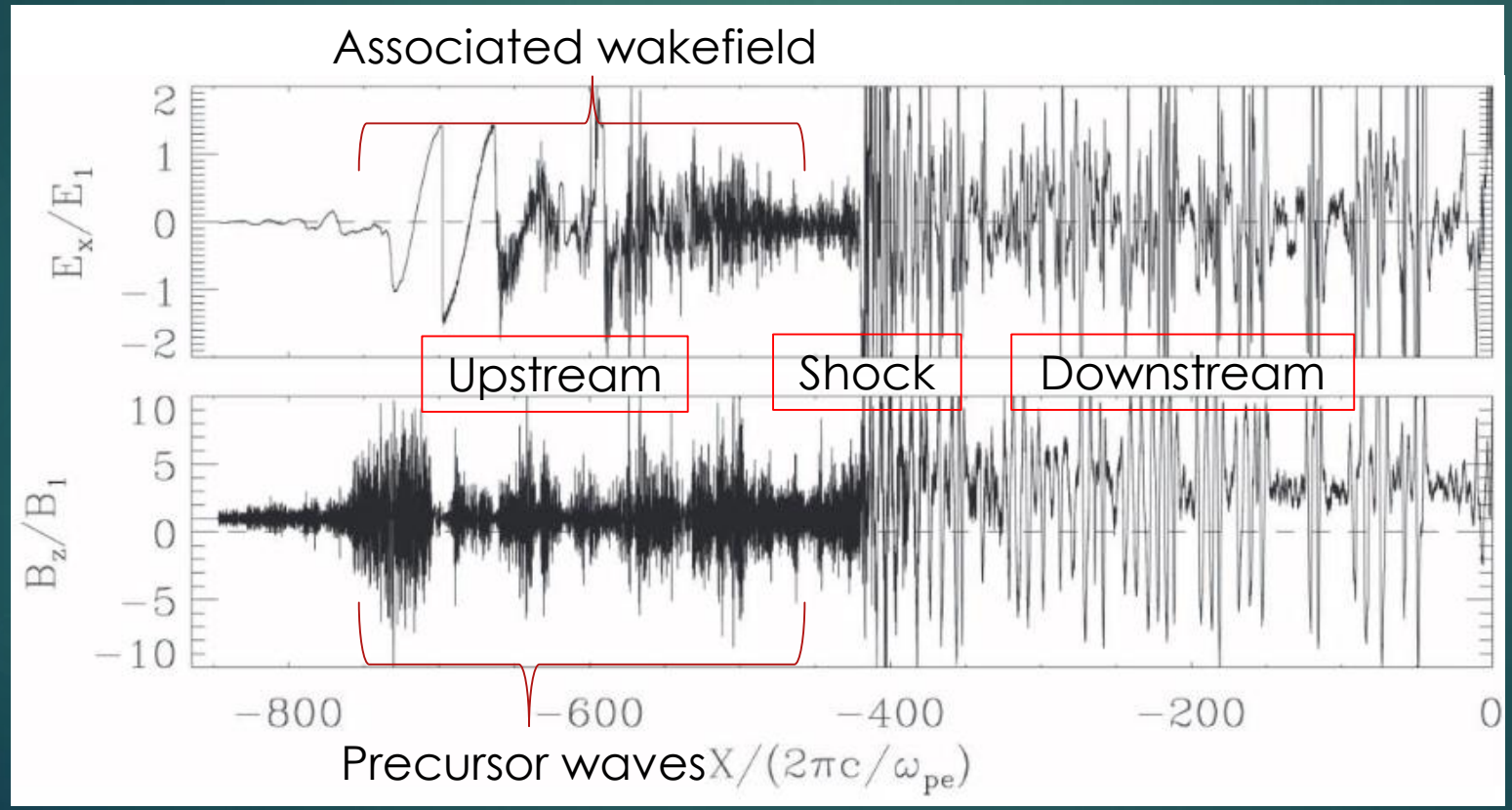

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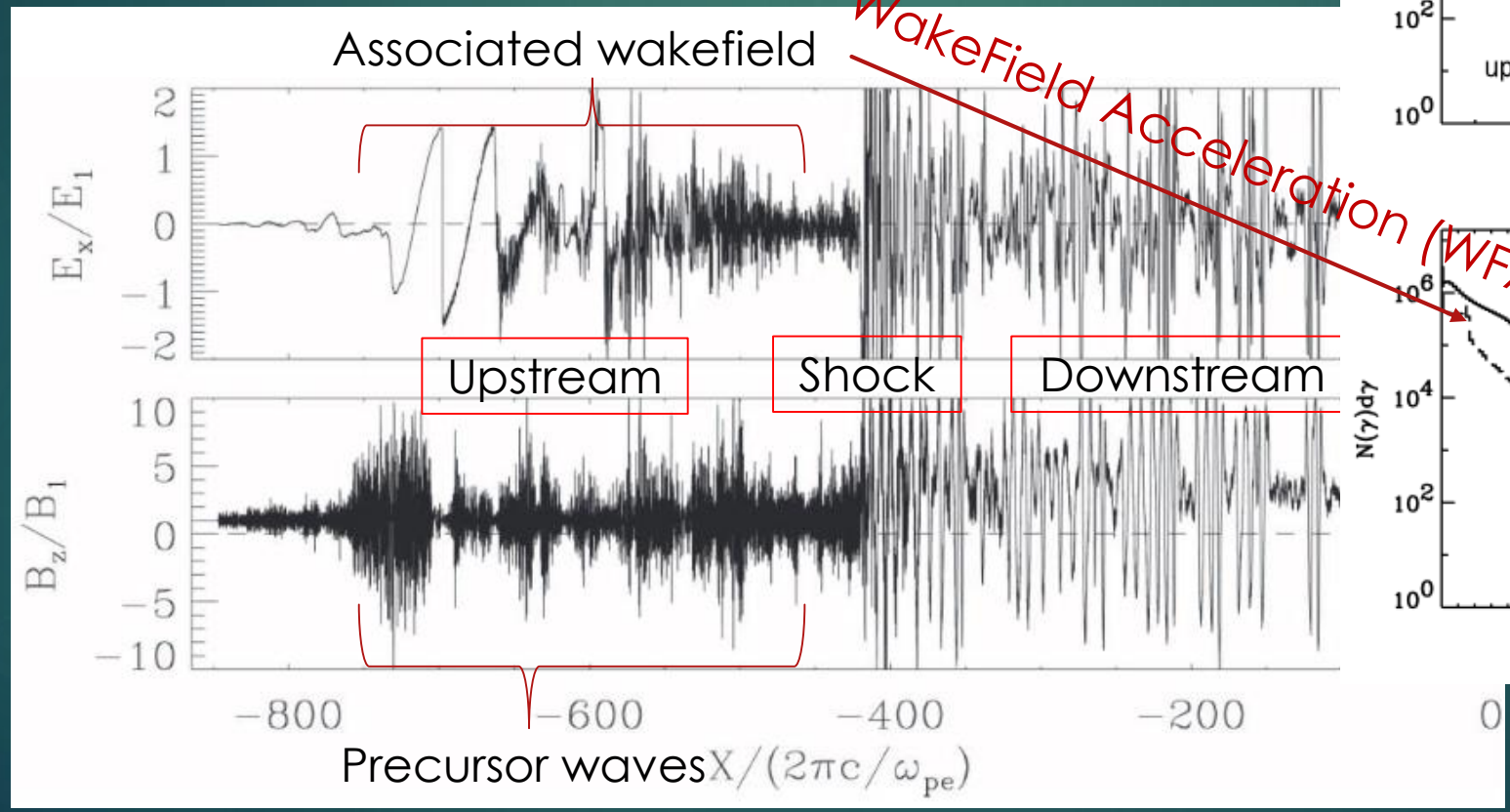

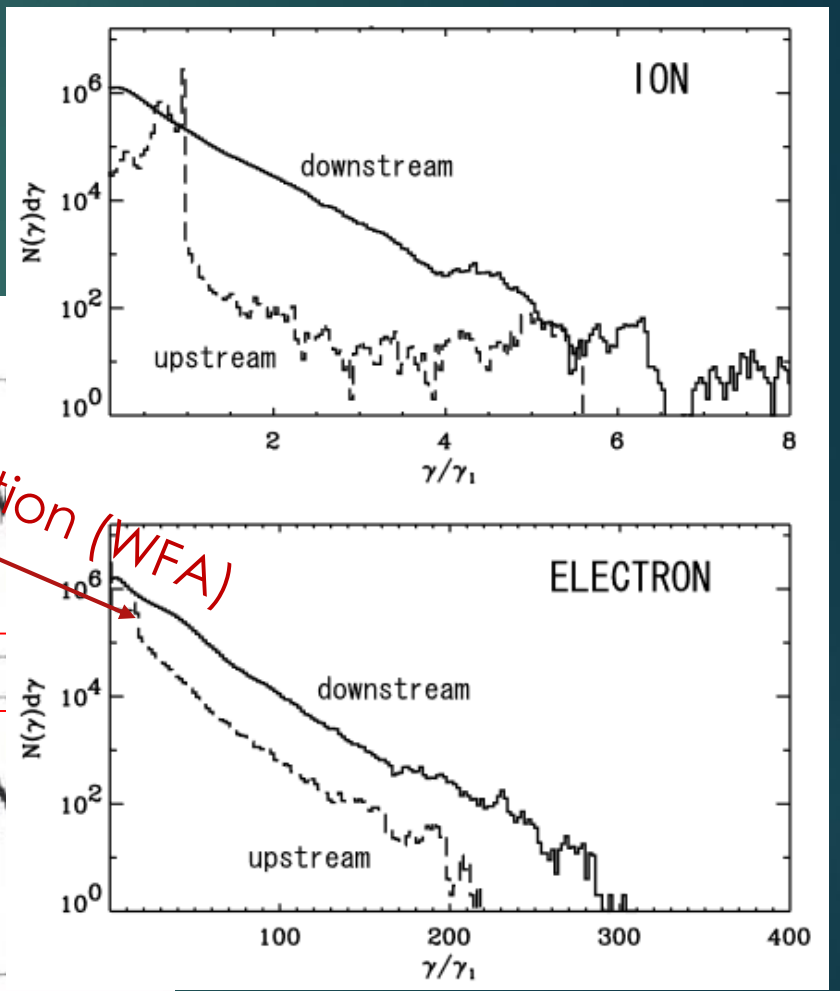

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Ultra-relativistic vs. Non-relativistic vs. ???

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- WFA in relativistic shocks?

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  - You need rel. particles for SMI to be excited.

Ultra-relativistic vs. Non-relativistic vs. ???

- WFA in relativistic shocks? ✓
- WFA in non-rel. shocks? ✗
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- But…

  What about mildly relativistic shocks?

Mildly relativistic shock sites

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Where can we find these?

Mildly relativistic shock sites

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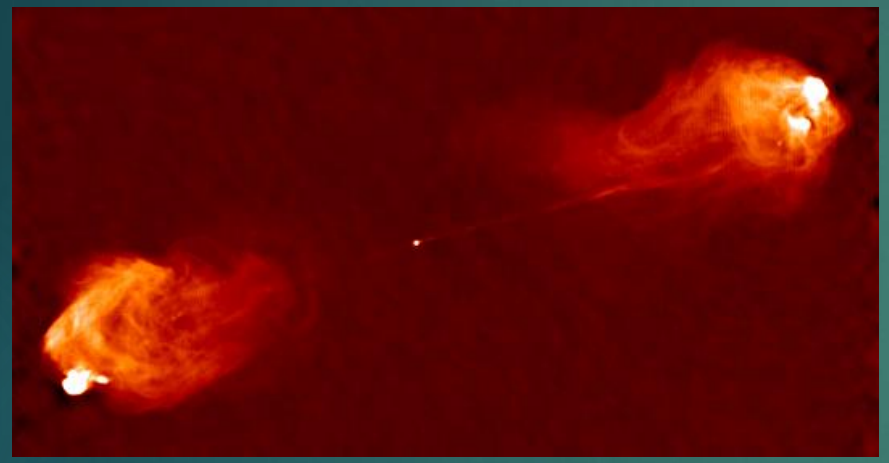

- AGN jets / AGN hot spots

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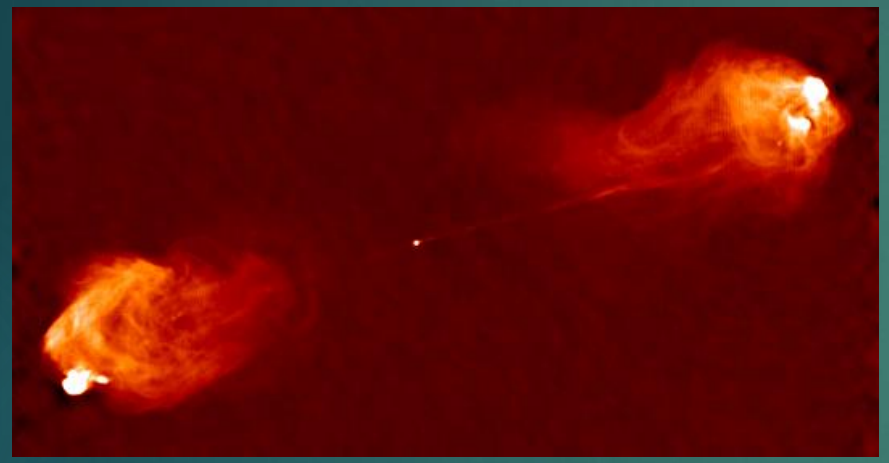

- AGN jets / AGN hot spots
  - $\gamma_{bulk} \sim a\ few$

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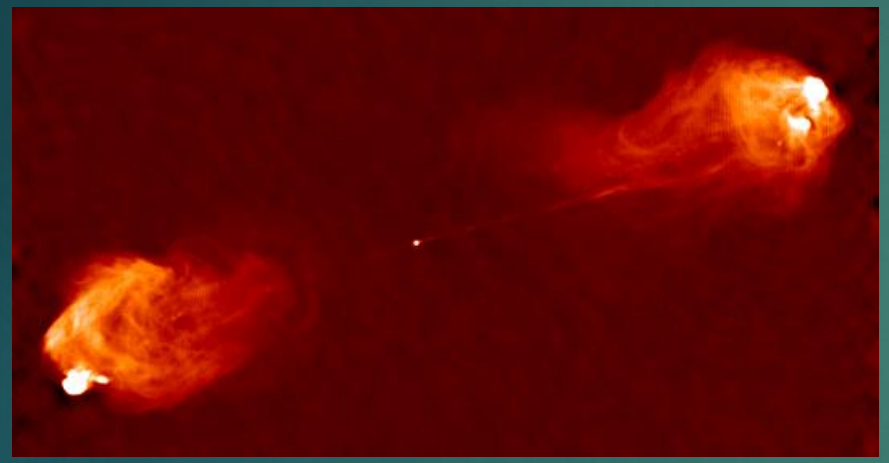

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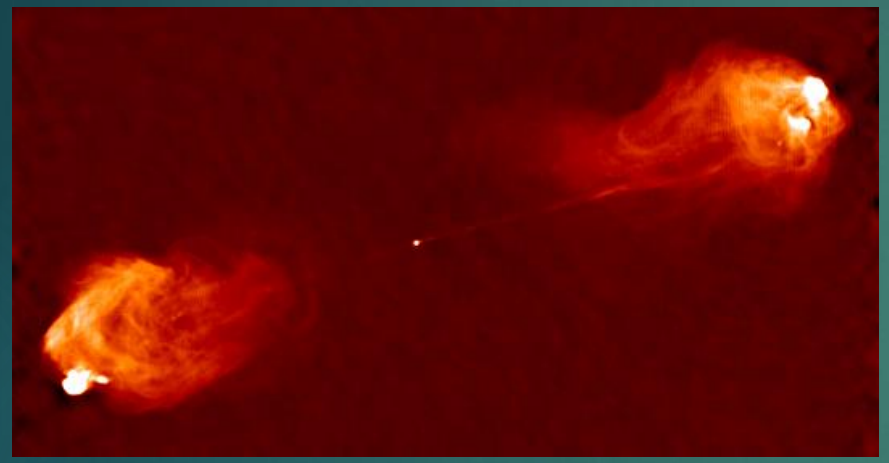

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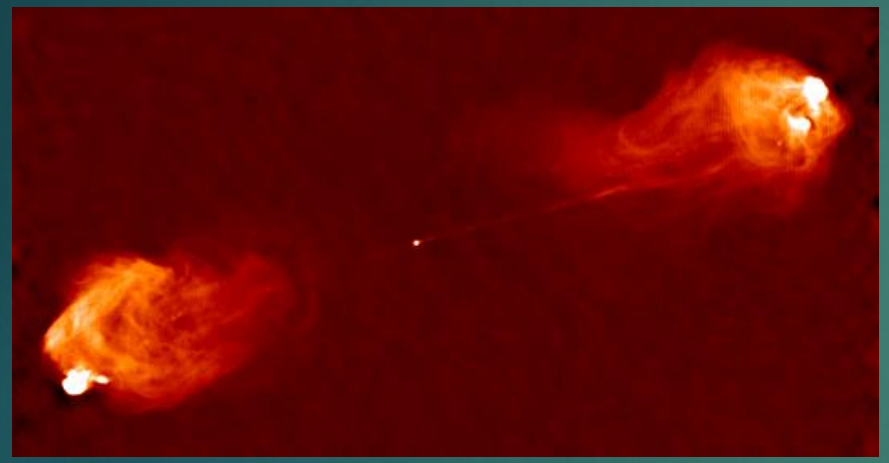

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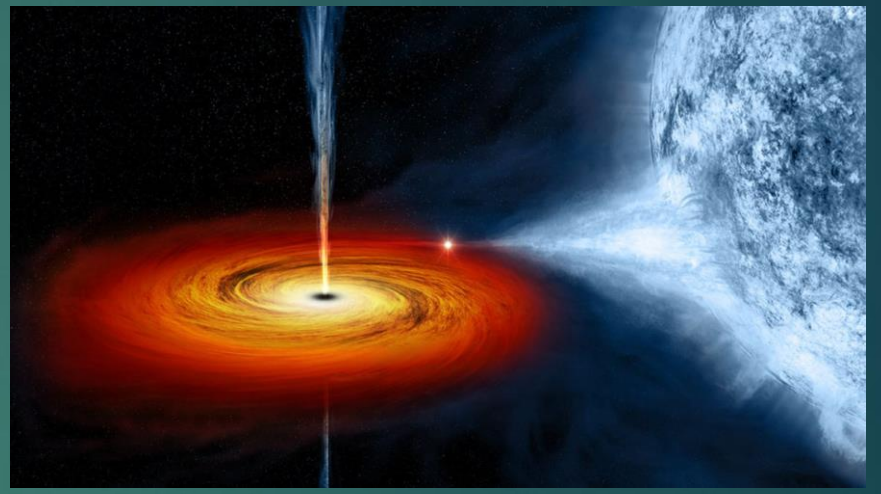

- X-ray binaries / Microquasars

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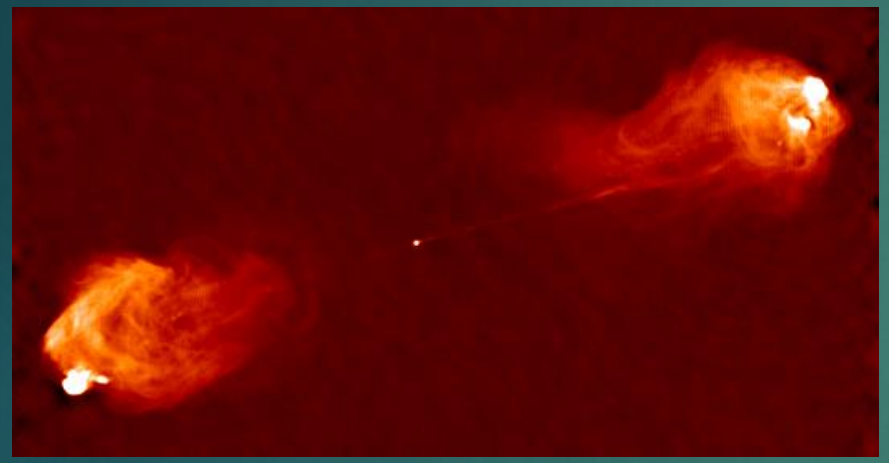

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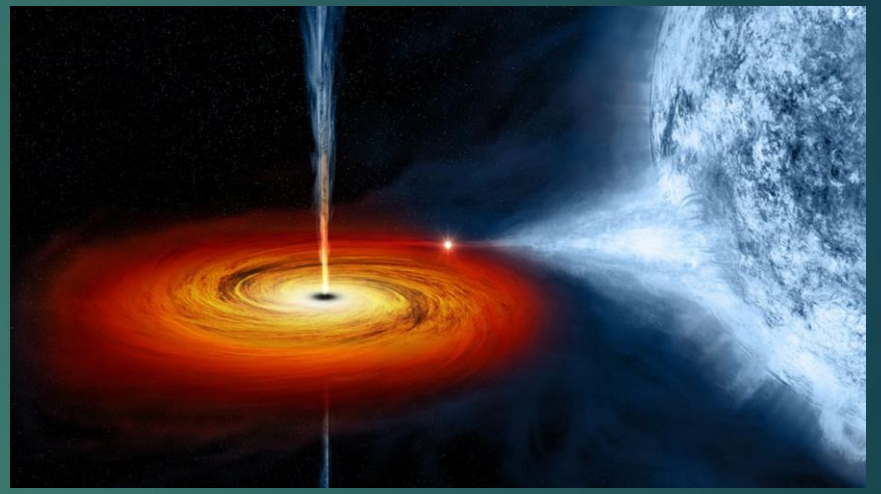

- X-ray binaries / Microquasars
  - Jets (mildly rel. locations)

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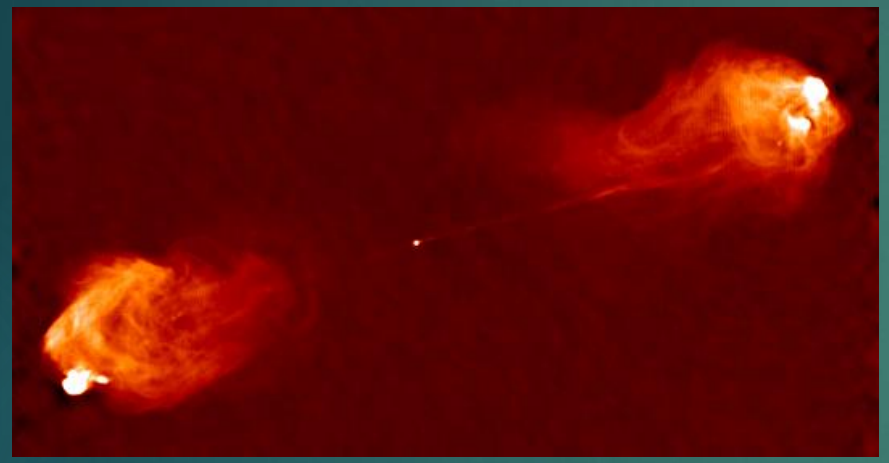

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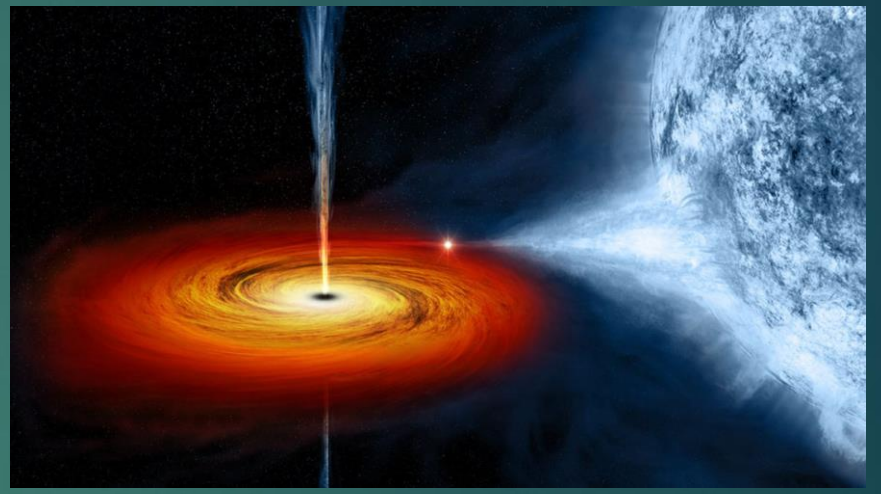

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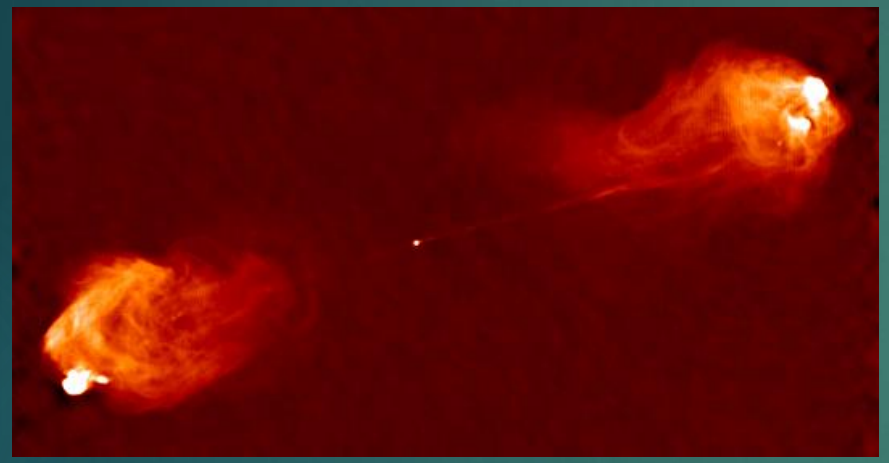

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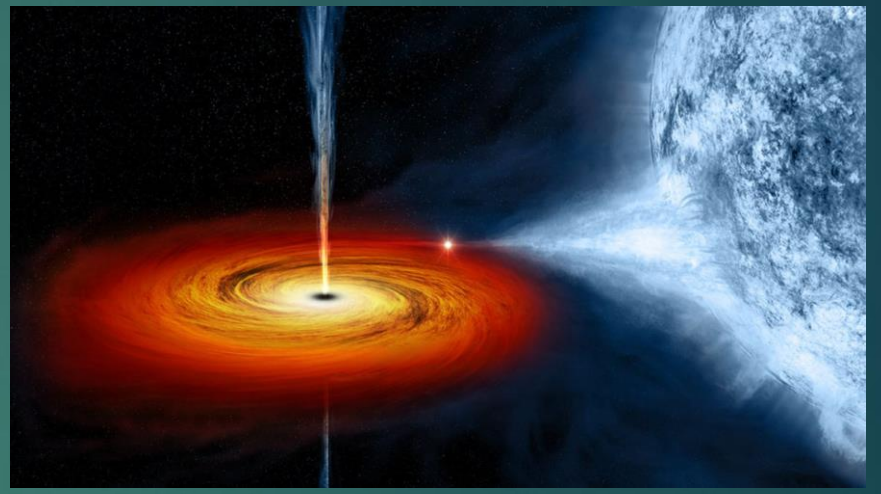

- X-ray binaries / Microquasars
  - Jets (mildly rel. locations)
  - Quite strong B field
  - Classic example: SS 433

WFA in mildly relativistic shocks

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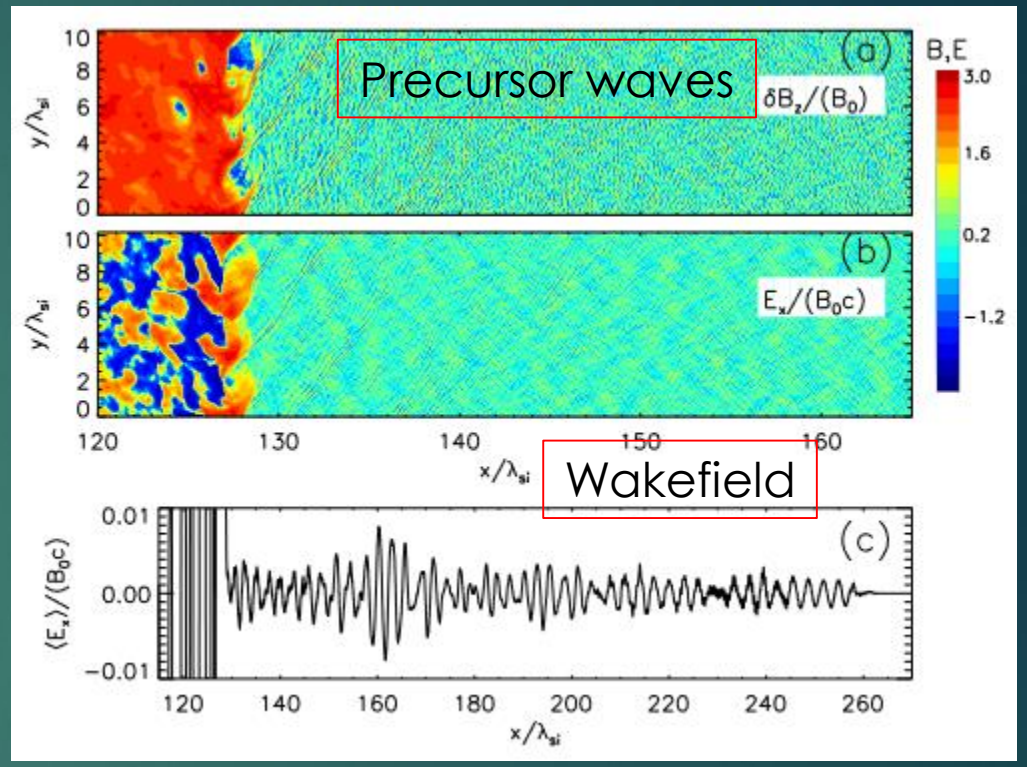

PIC simulation of a strictly perpendicular mildly relativistic shock. Taken from Ligorini, A., et al. 2021.

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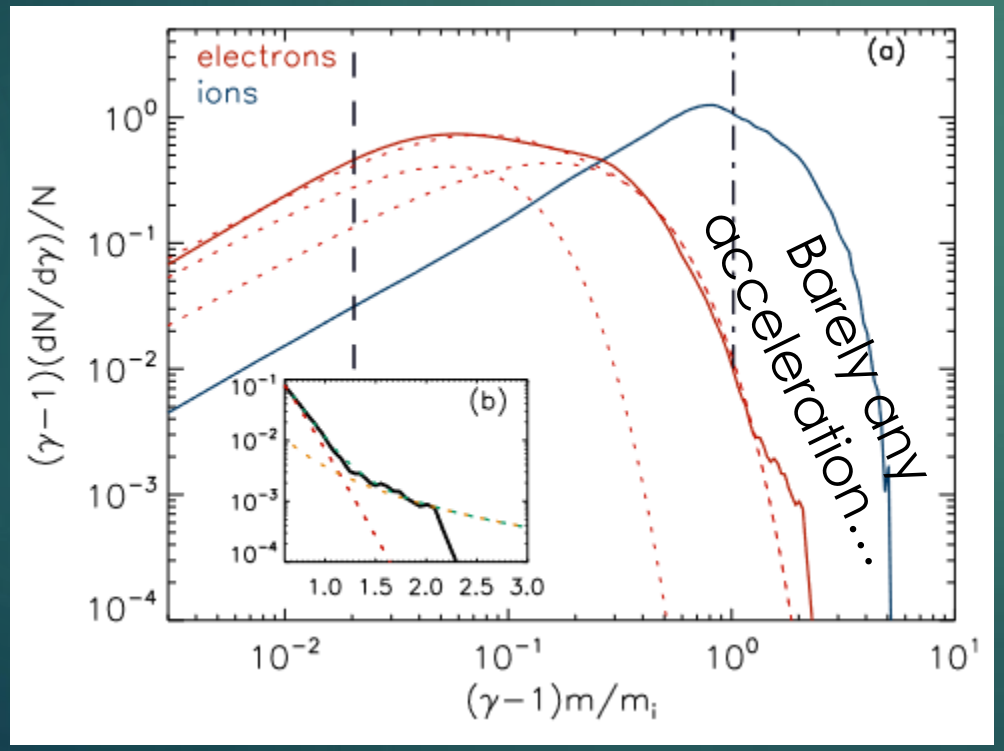

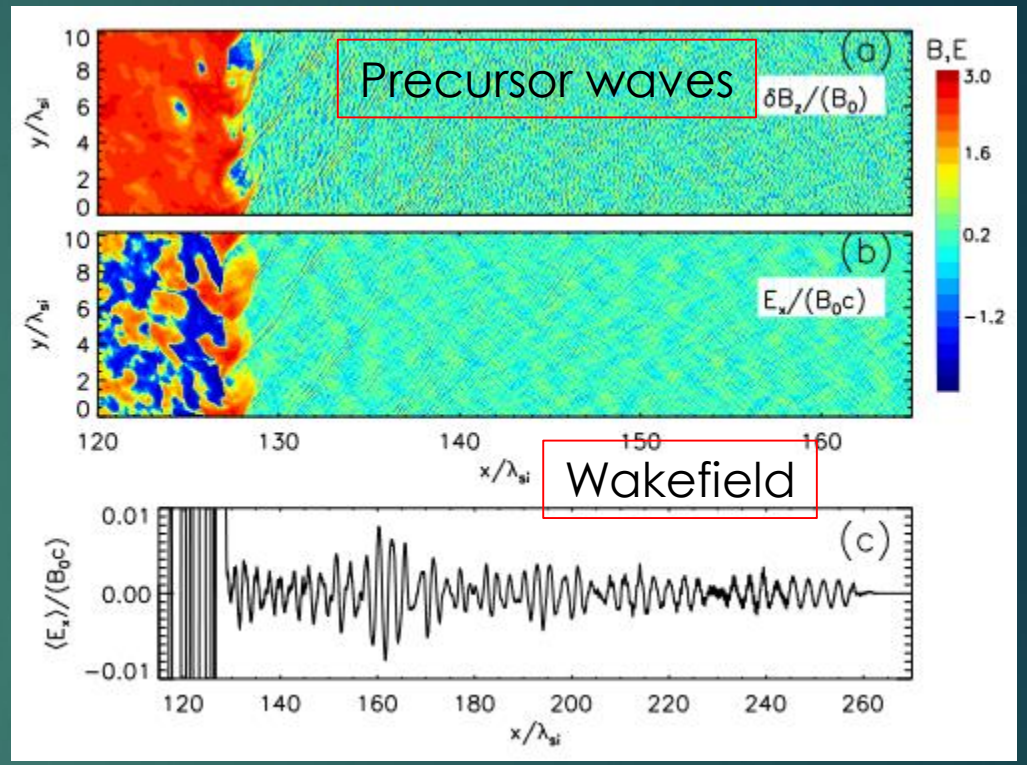

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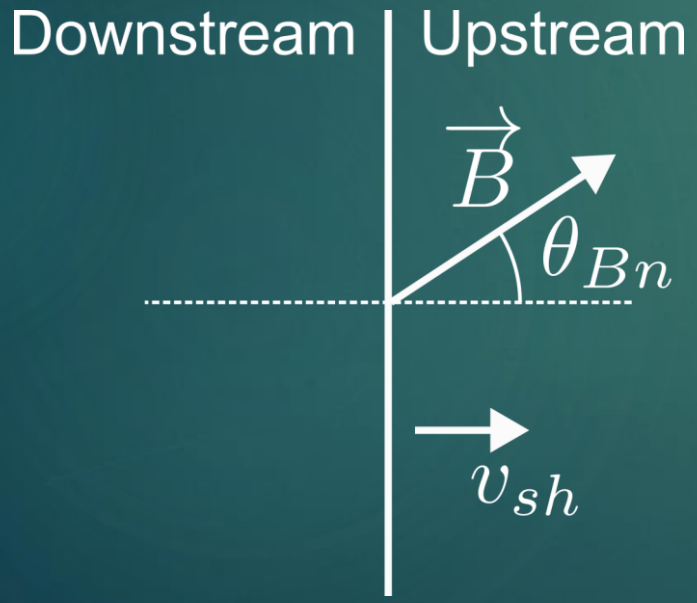

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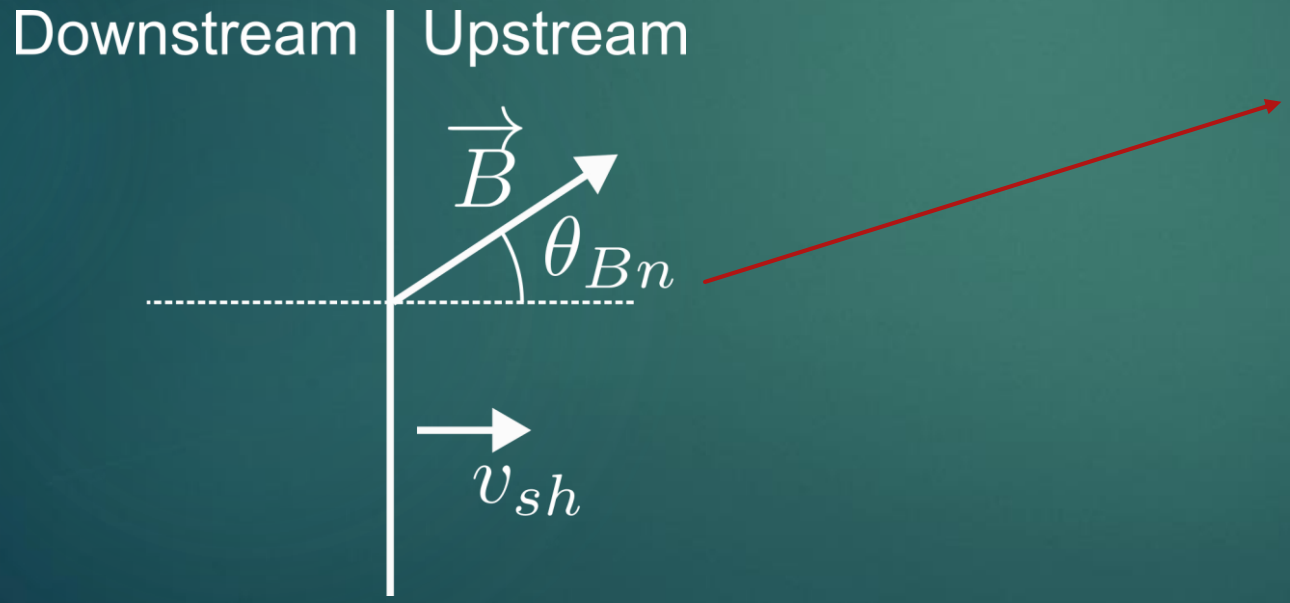
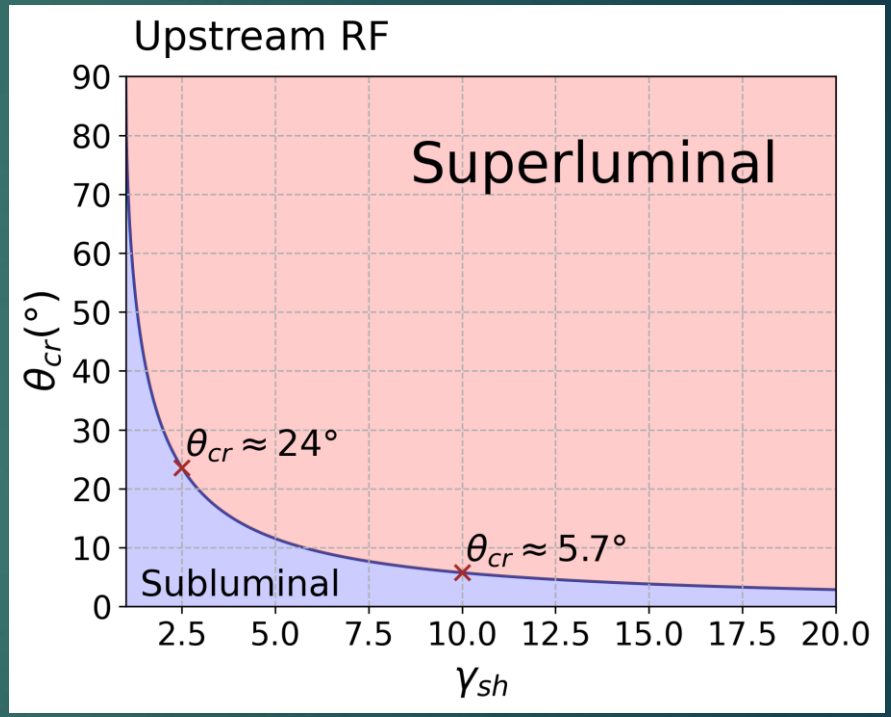


$$v_{sh} = c \cos \theta_{cr}$$



Critical angle vs. Shock Lorentz factor with two examples.

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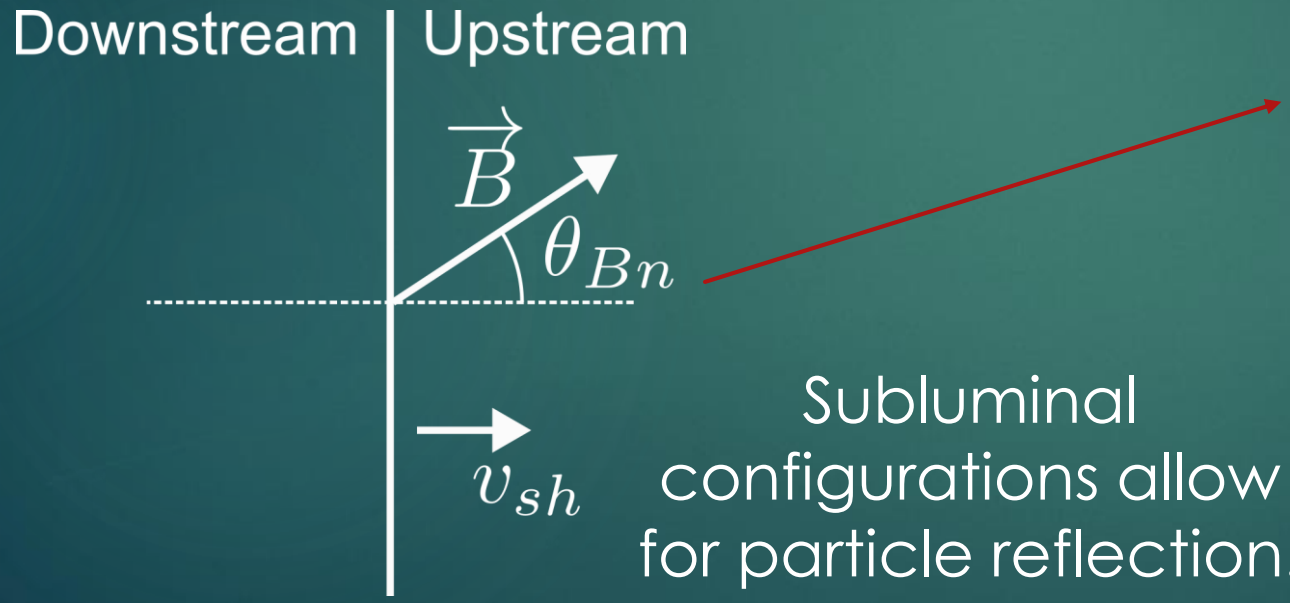

Subluminal configurations allow for particle reflection!

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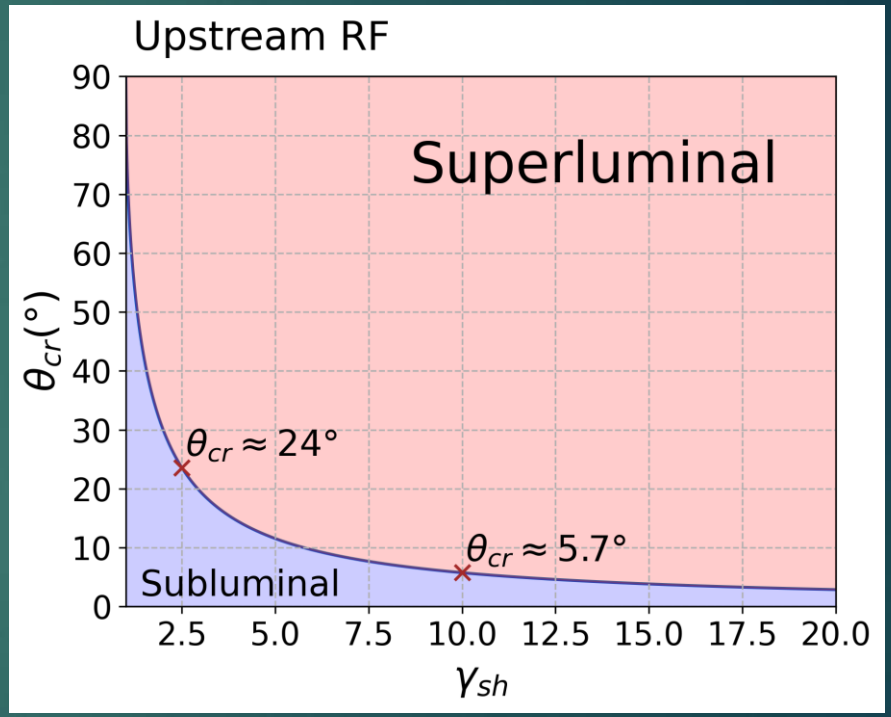

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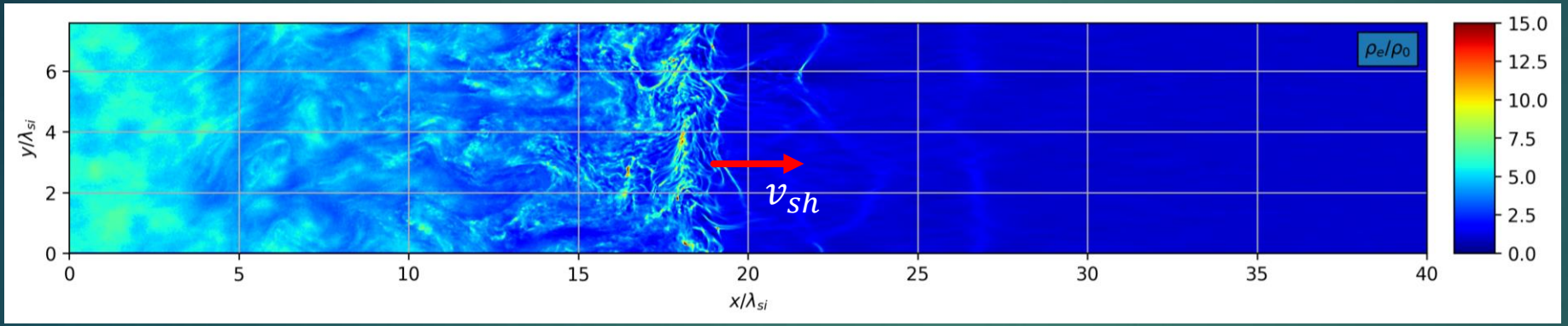

Typical PIC simulation plot: electron density ρ_e.

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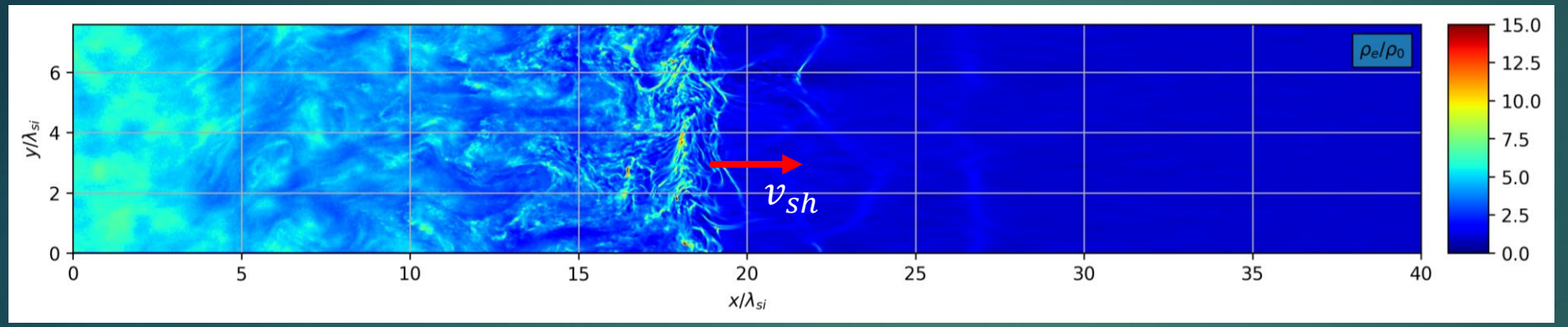

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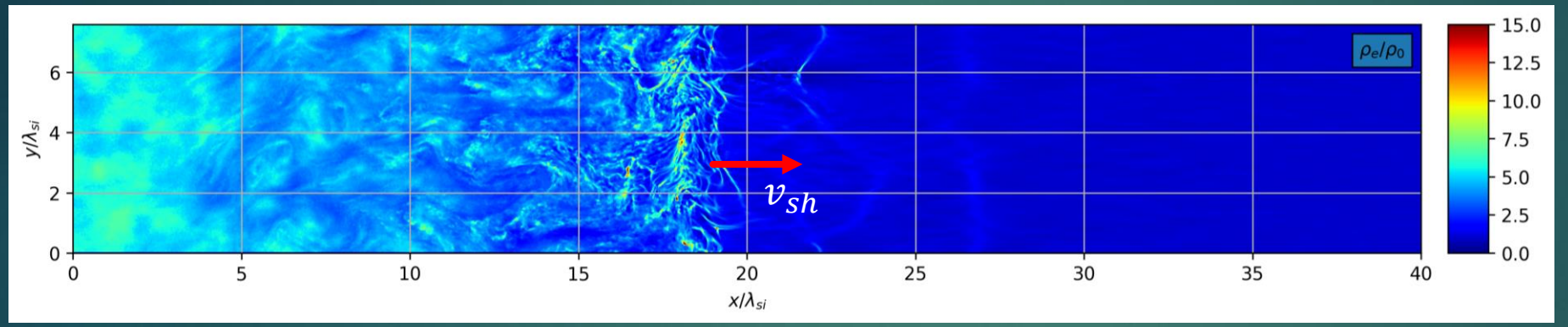

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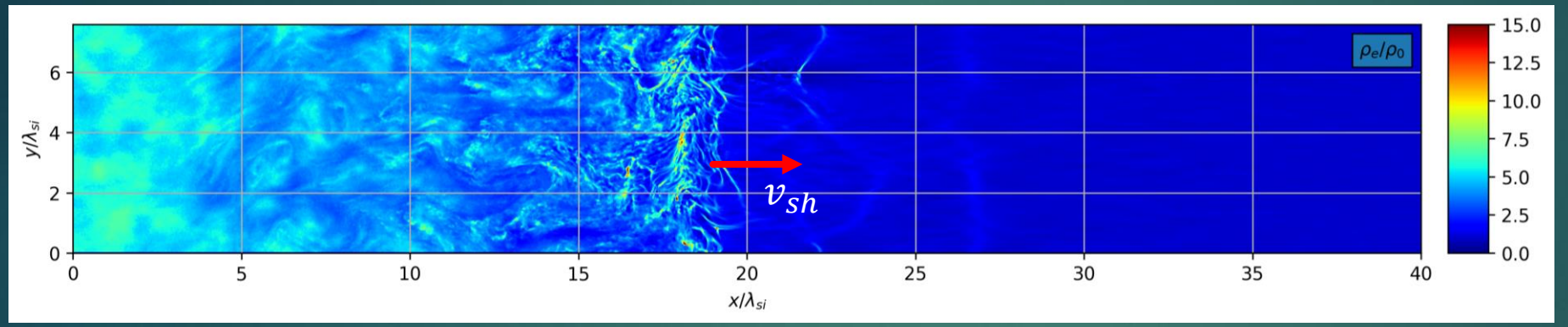

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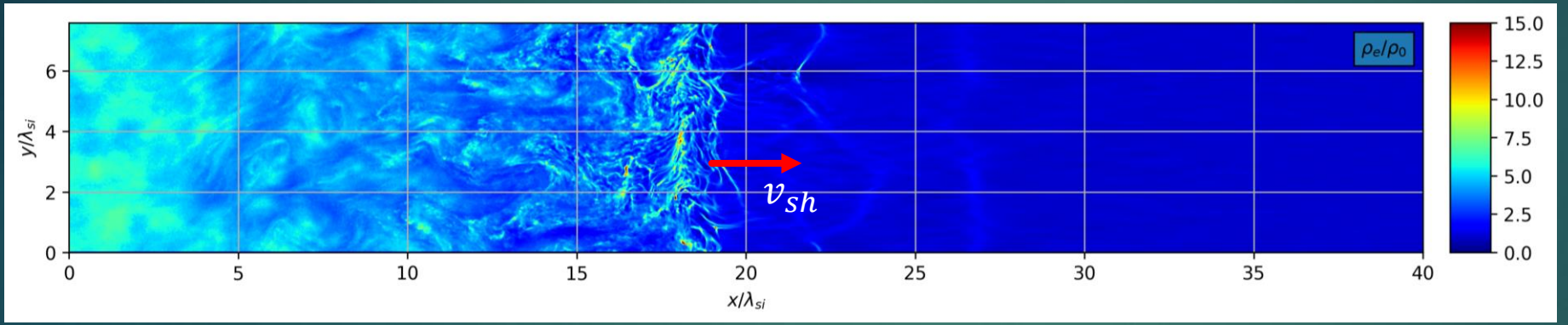

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  - Self-consistent electromagnetic field.
  - Fully solve eqs. motion and Maxwell equations.

Subluminal mildly relativistic shocks

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- Mildly relativistic[1] strongly magnetised[2] oblique[3] shocks:

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$$\sigma = \frac{\Omega_c^2}{\omega_p^2} = \frac{B^2}{\mu_0 \gamma n m c^2}$$

Subluminal mildly relativistic shocks

- Mildly relativistic[1] strongly magnetised[2] oblique[3] shocks:

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2. Magnetisation $\sigma = 1$

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3. Obliquity $\theta_{Bn} = 10°, 30°$

Subluminal mildly relativistic shocks

- Mildly relativistic[1] strongly magnetised[2] oblique[3] shocks:

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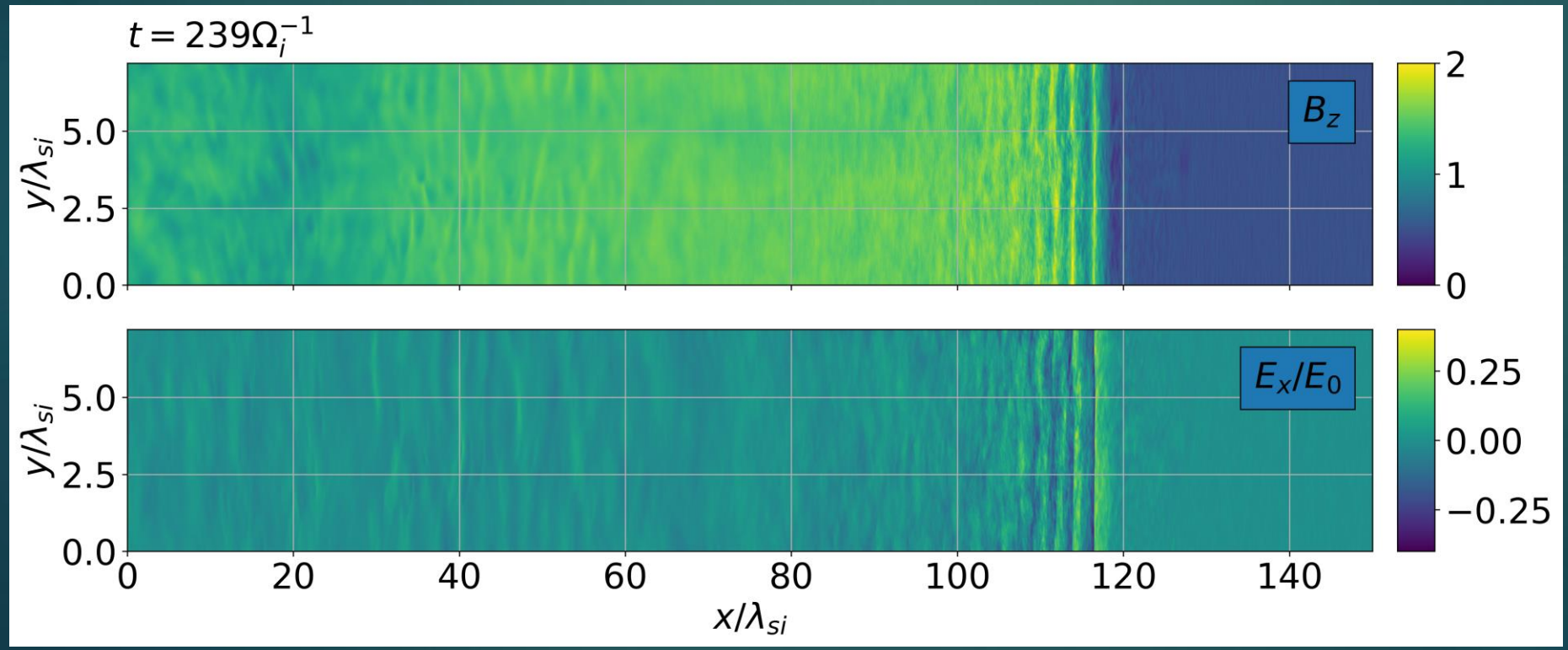
2. Magnetisation $\sigma = 1$

$$\sigma = \frac{\Omega_c^2}{\omega_p^2} = \frac{B^2}{\mu_0 \gamma n m c^2}$$

3. Obliquity $\theta_{Bn} = 10°, 30°$

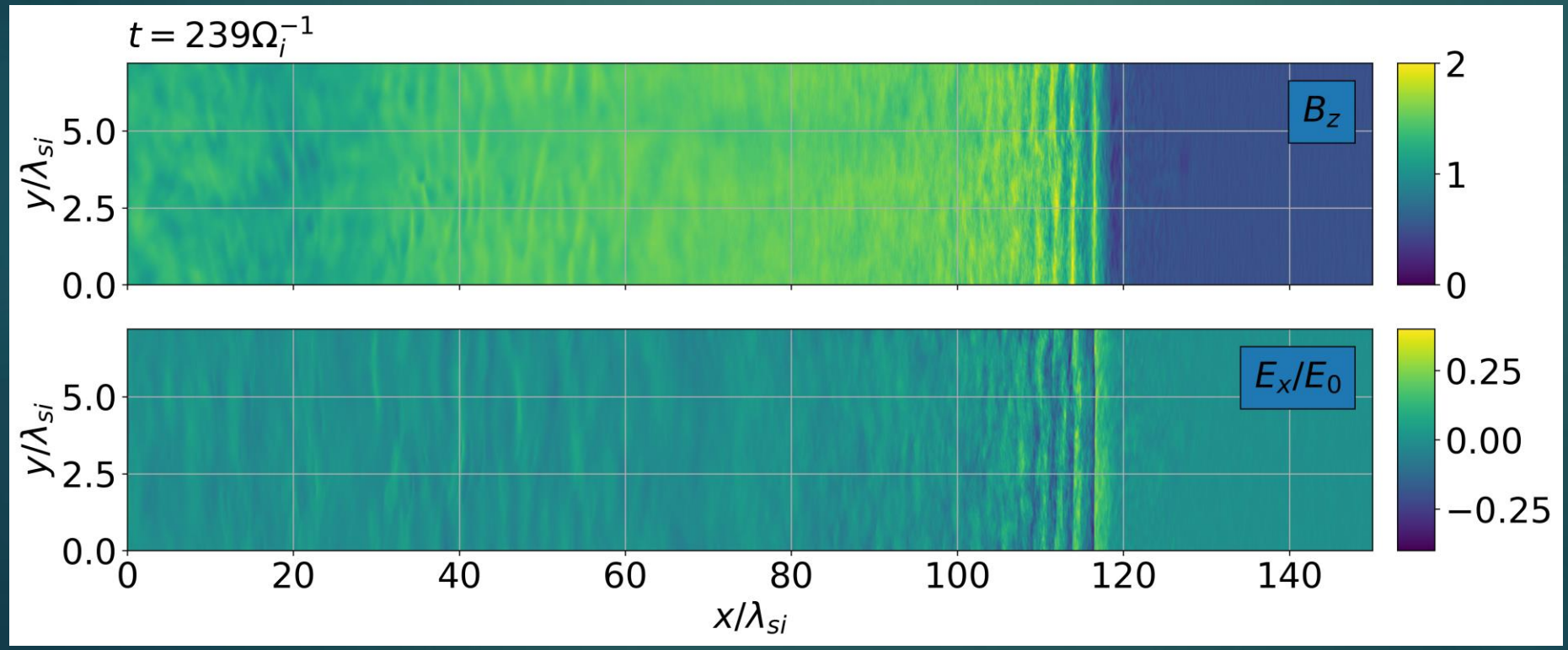
- This "middle ground" of mildly rel. shocks looks promising!

Shock structure at θ=30°



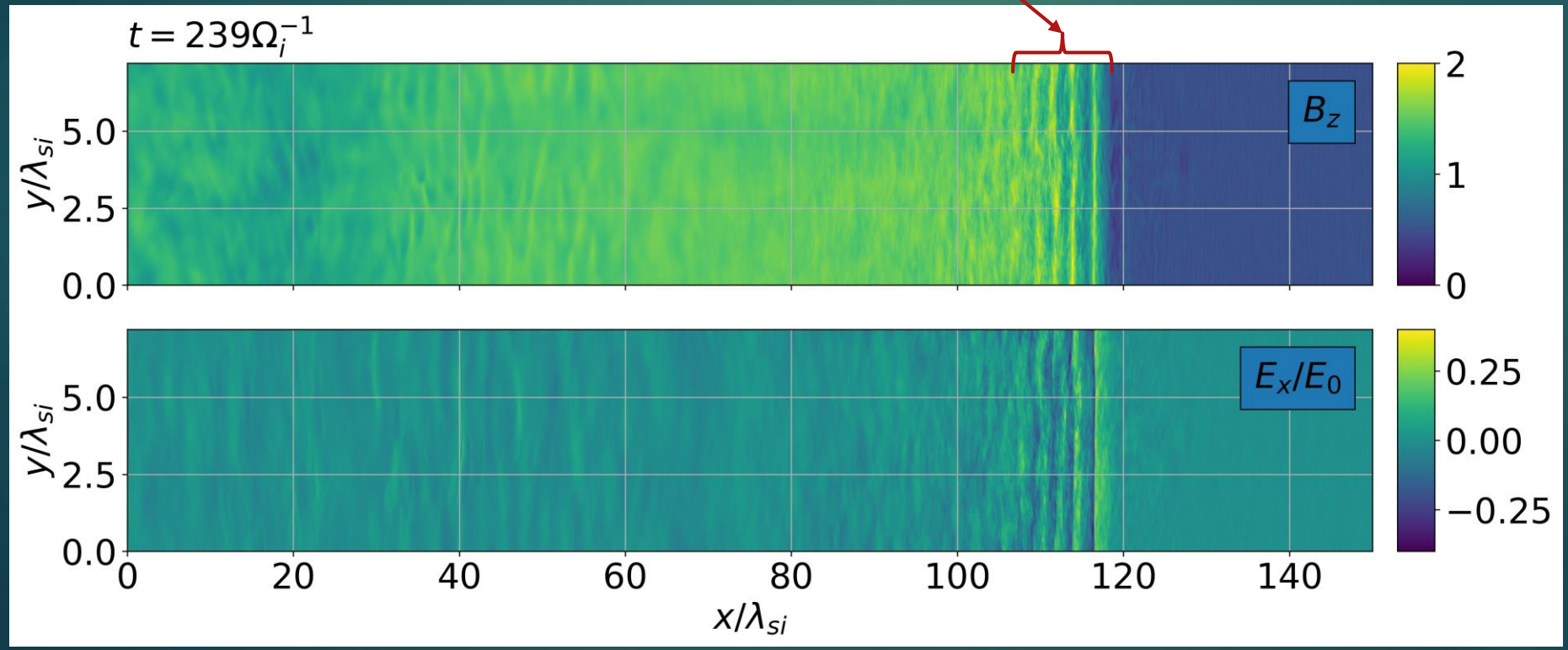
Shock structure at θ=30°

- Atypical shock



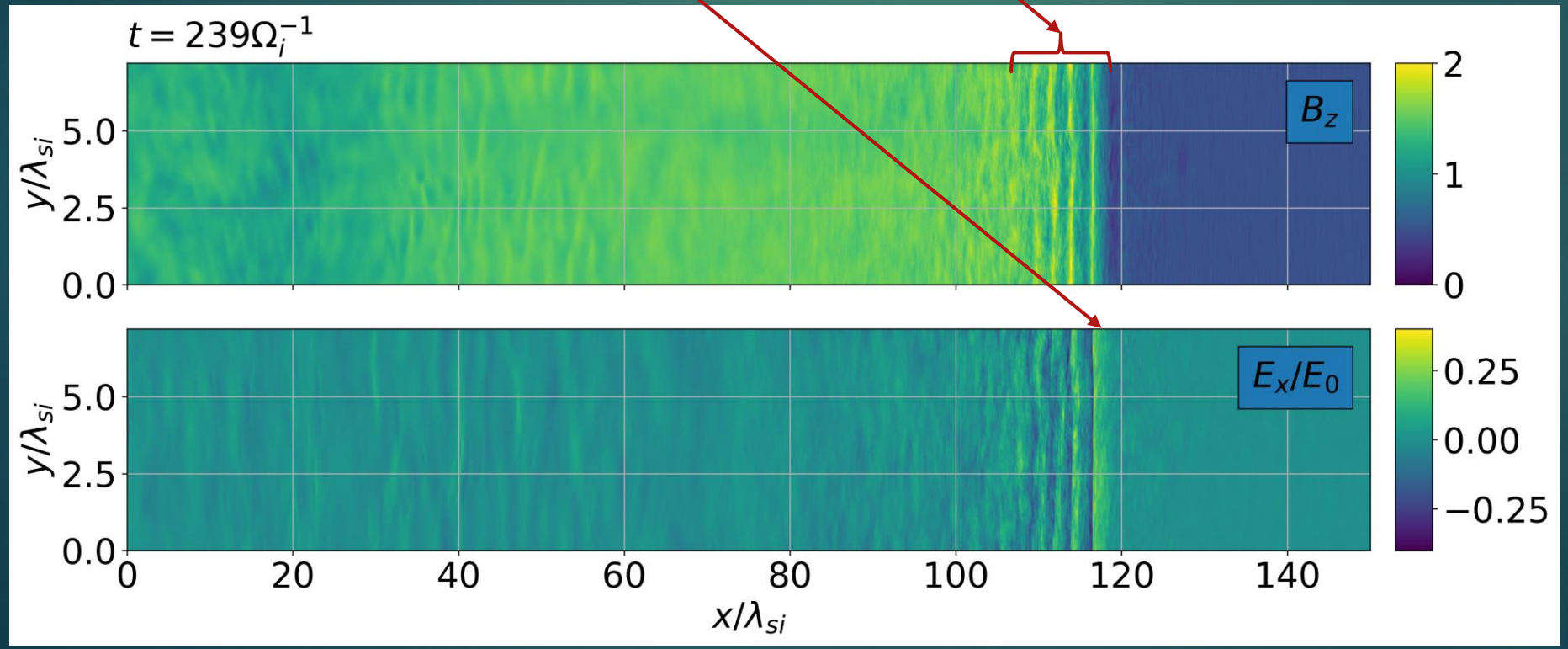
Shock structure at θ=30°

- Atypical shock
  - Series of magnetosonic waves.



Shock structure at θ=30°

- Atypical shock
  - Series of magnetosonic waves.
  - Strong E_x gradient.



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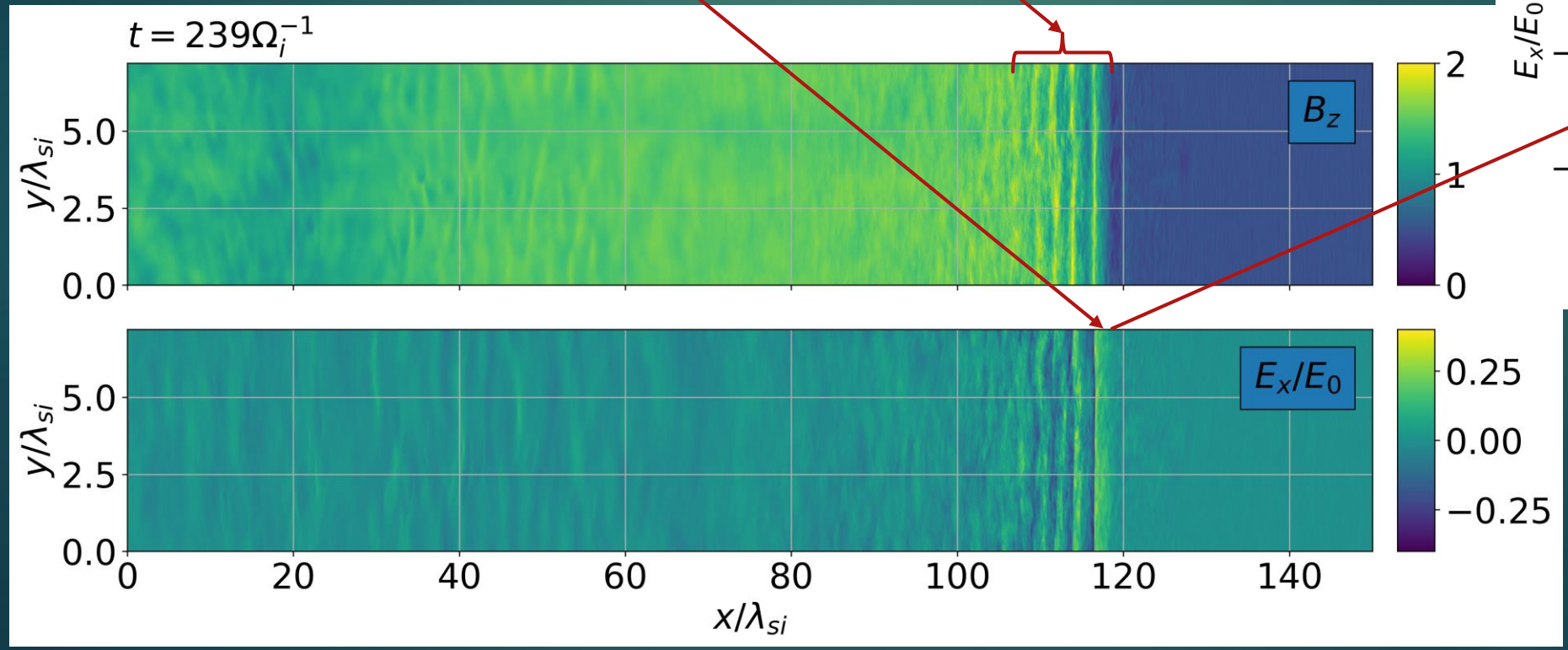
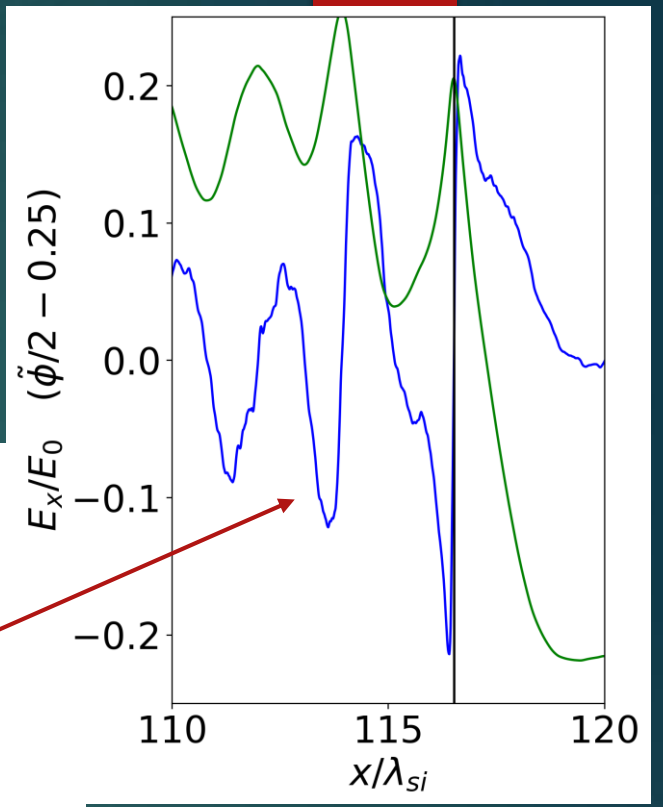
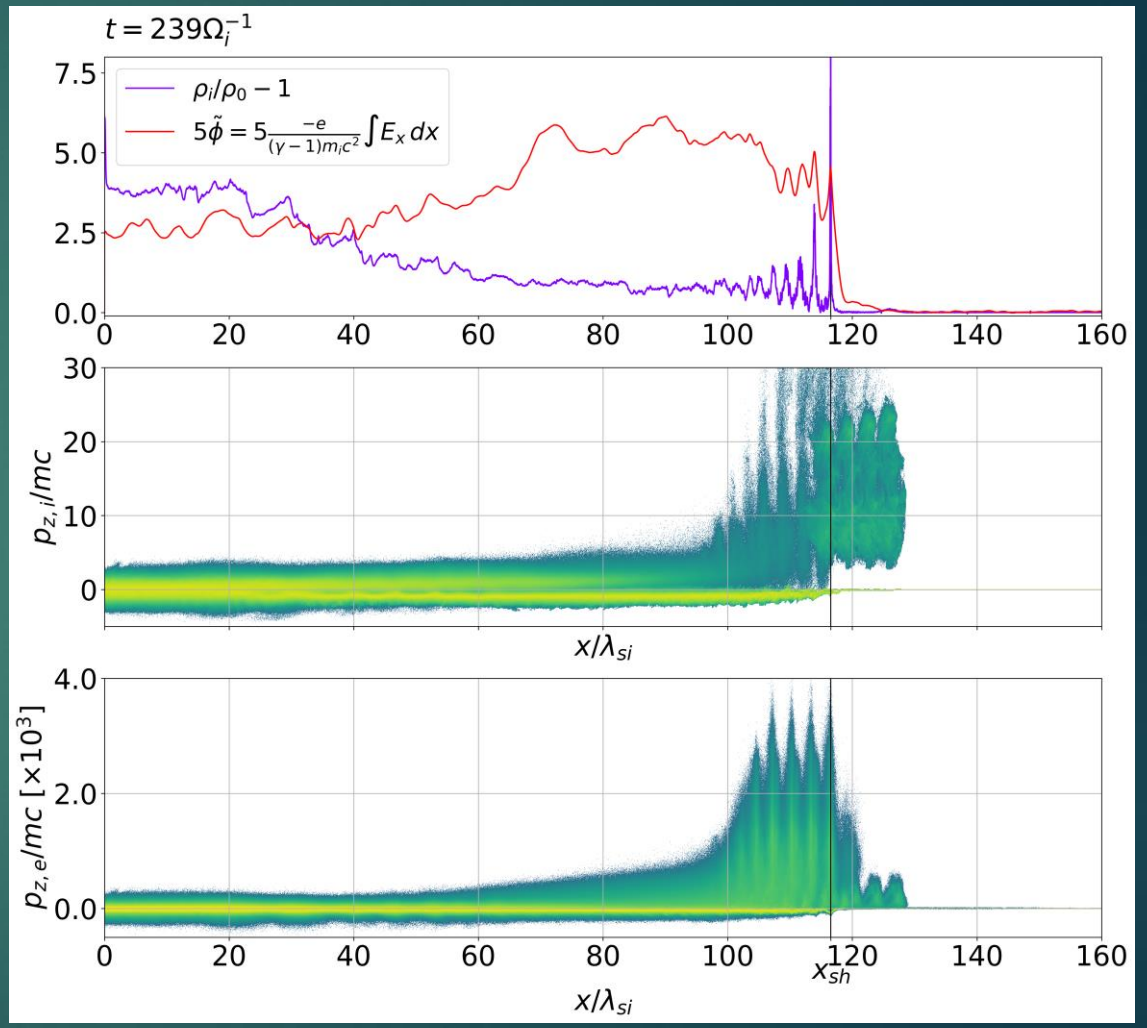




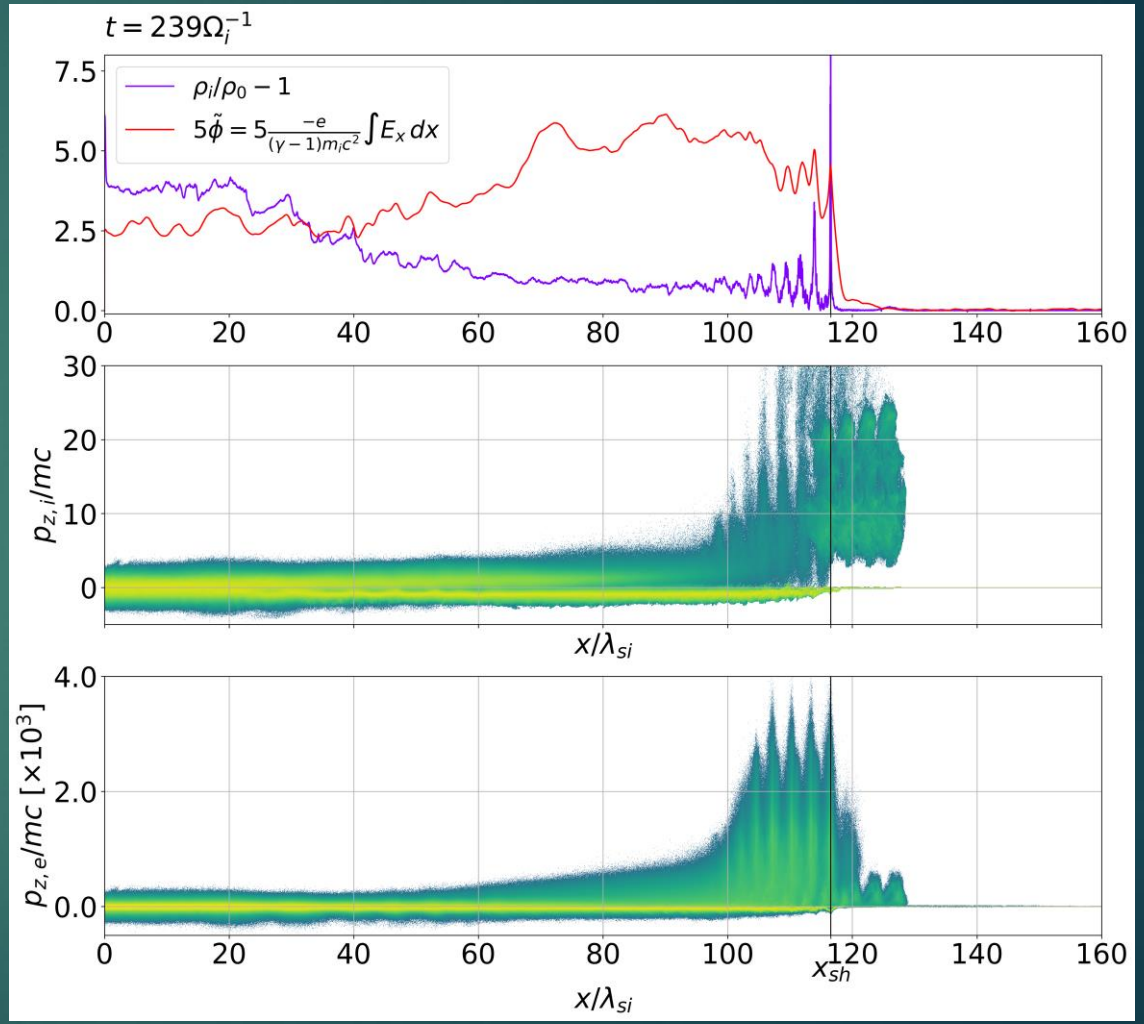
Phase space and acceleration



Electrostatic potential and normalised momentum in z-direction (ions and electrons)

Phase space and acceleration

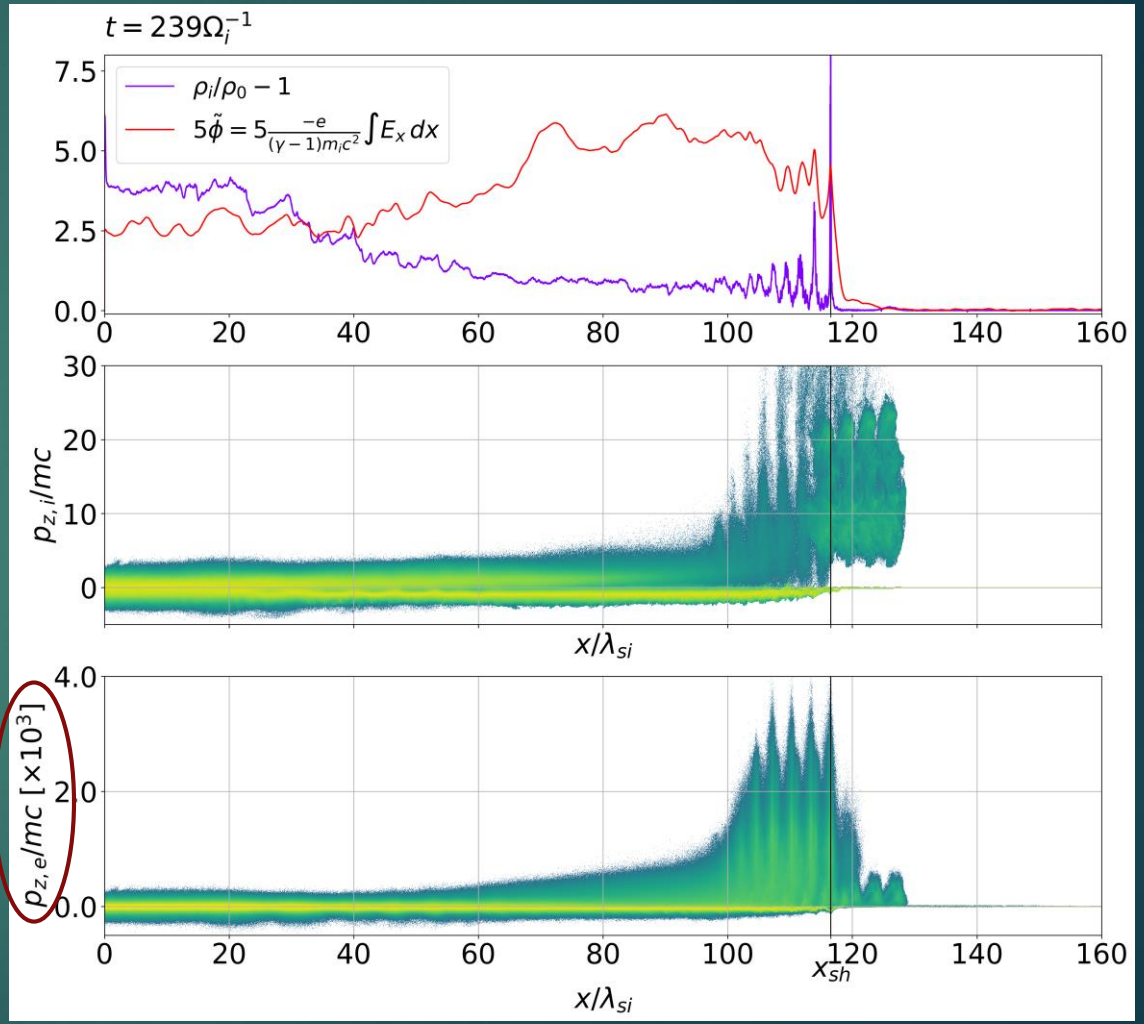
- Strong ion and electron acceleration.



Electrostatic potential and normalised momentum in z-direction (ions and electrons)

Phase space and acceleration

- Strong ion and electron acceleration.
  - Note the units!



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- Strong ion and electron acceleration.
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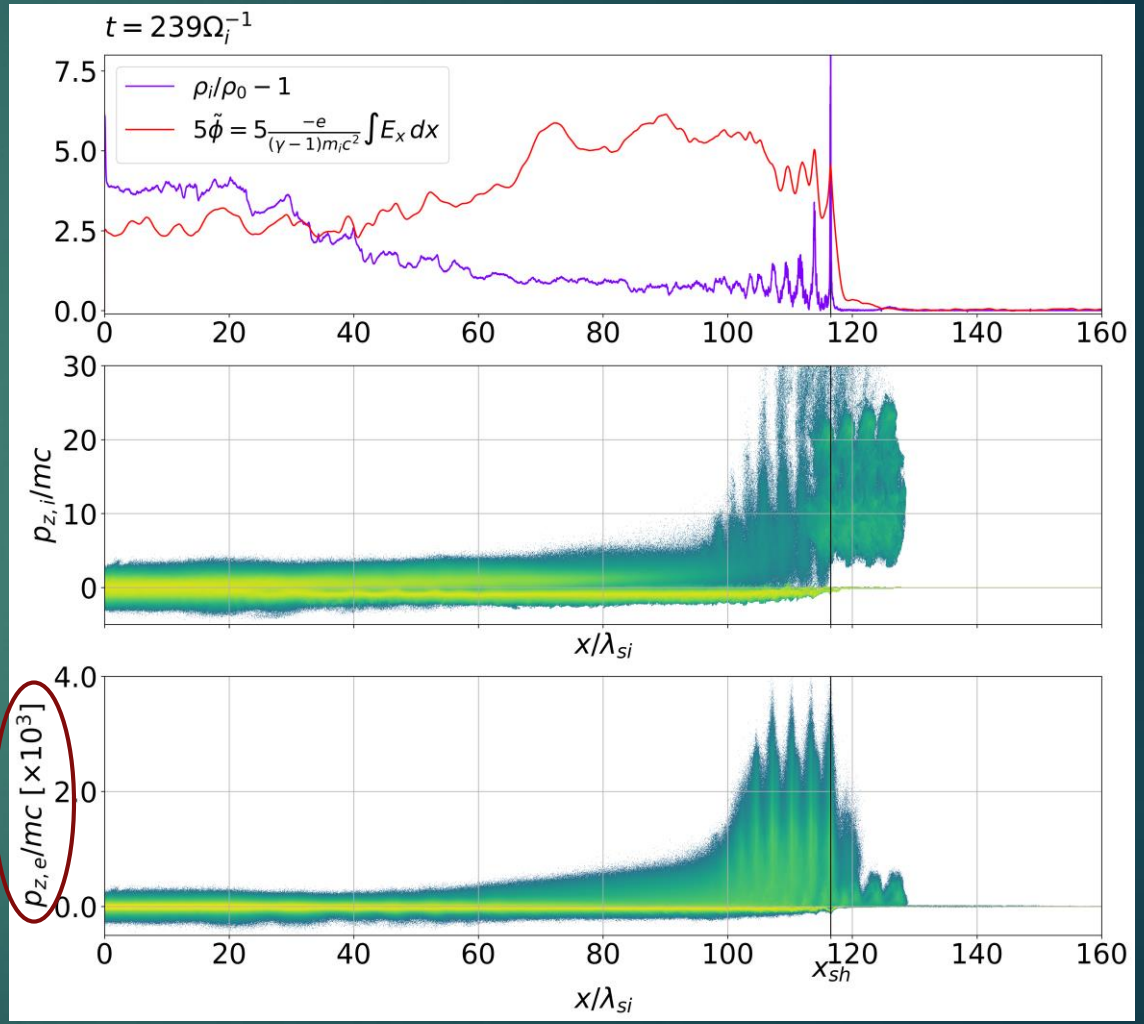
- Clearly, there must be a relation with ϕ.



Electrostatic potential and normalised momentum in z-direction (ions and electrons)

Phase space and acceleration

- Strong ion and electron acceleration.
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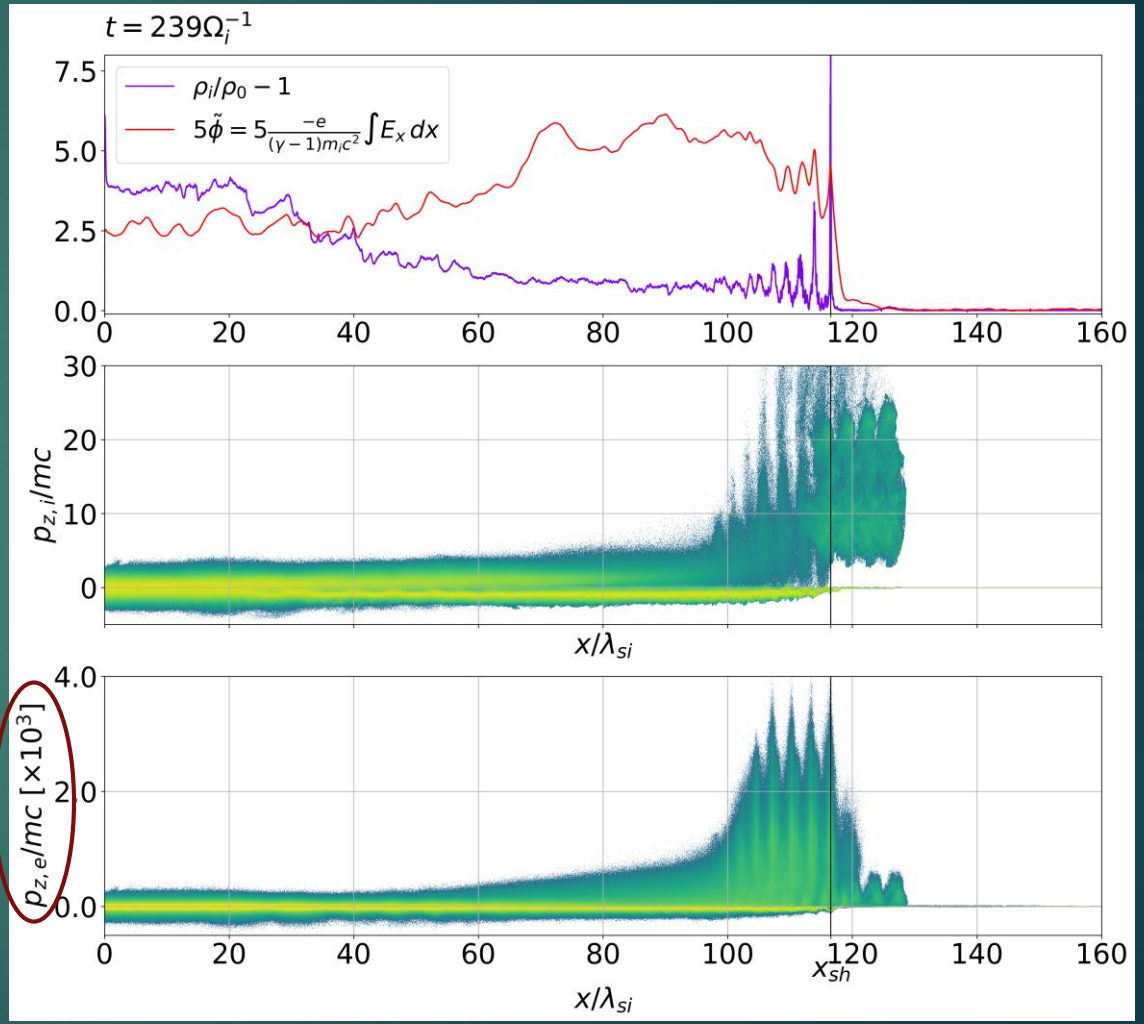
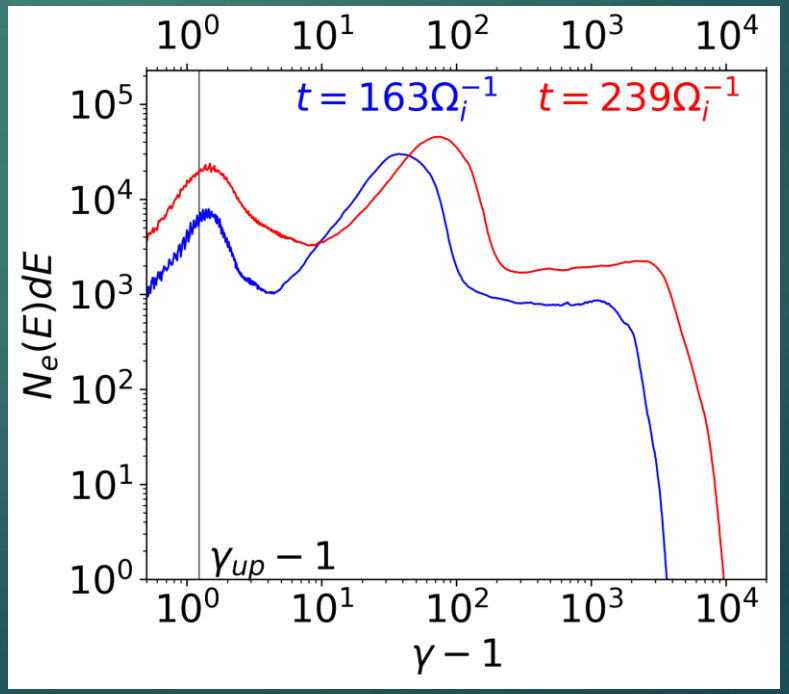
- Clearly, there must be a relation with ϕ.
- Acceleration parallel to **B**.
  - p_x and p_z.



Electrostatic potential and normalised momentum in z-direction (ions and electrons)

Electron acceleration



Electron acceleration

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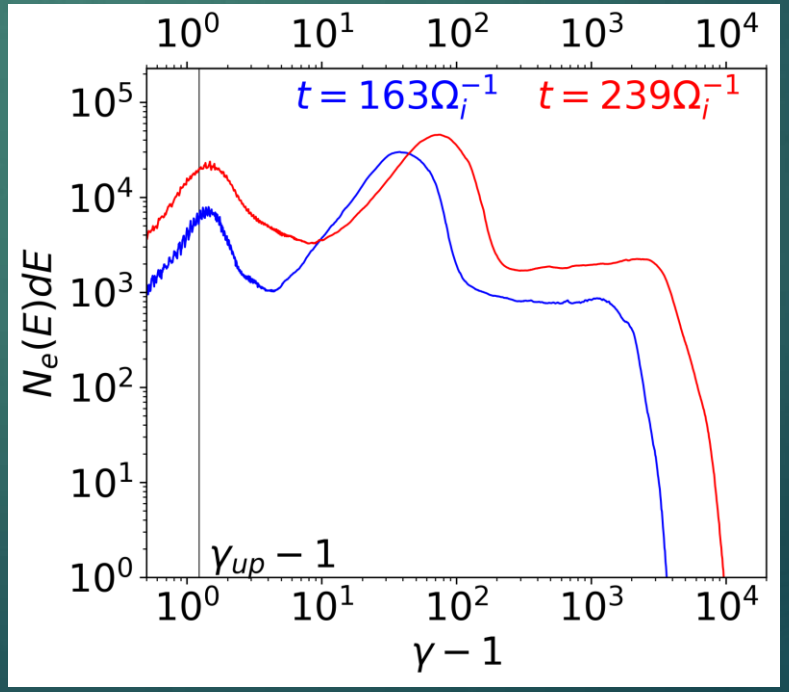
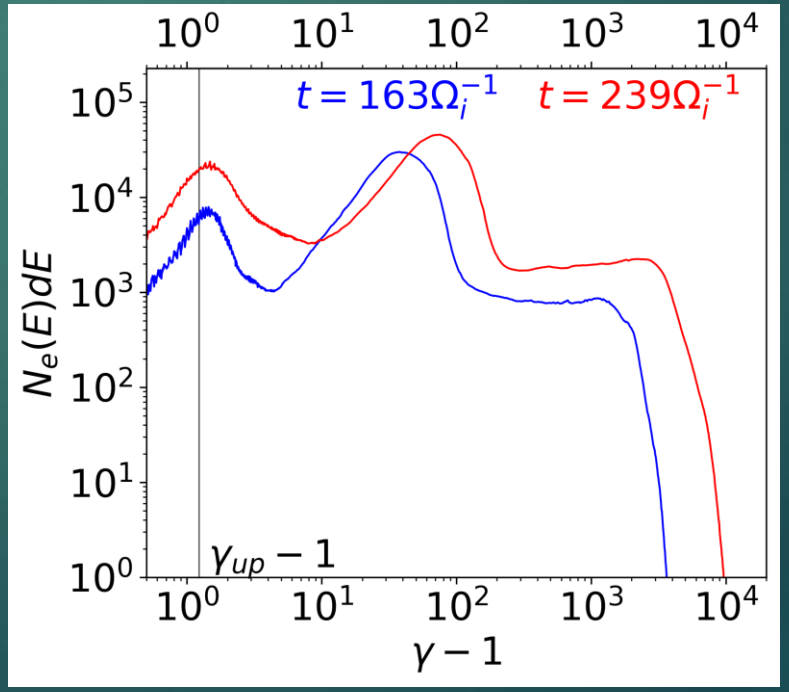


Electron acceleration

- Following Bessho and Ohsawa 1999, 2002:
  - Strong magnetosonic wave + Oblique magnetic field



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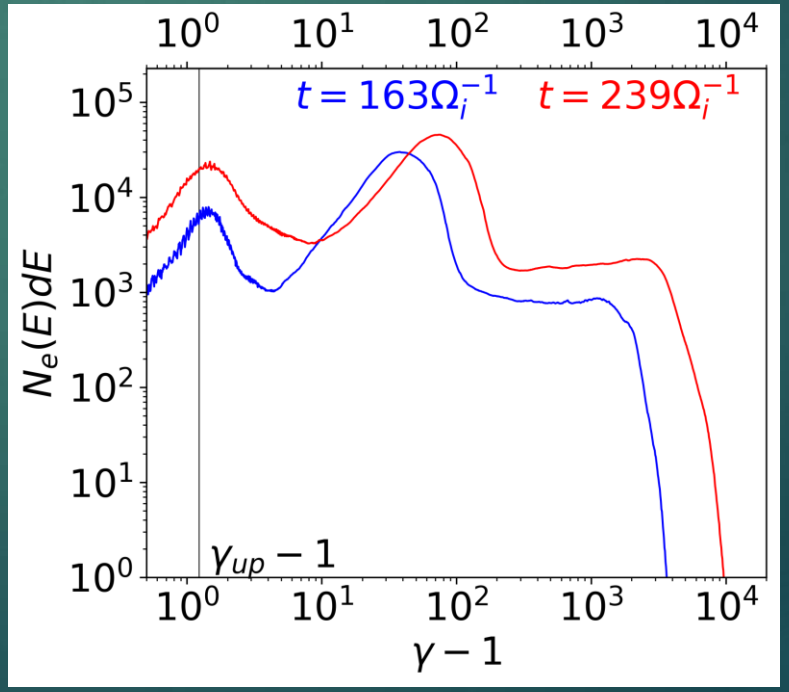

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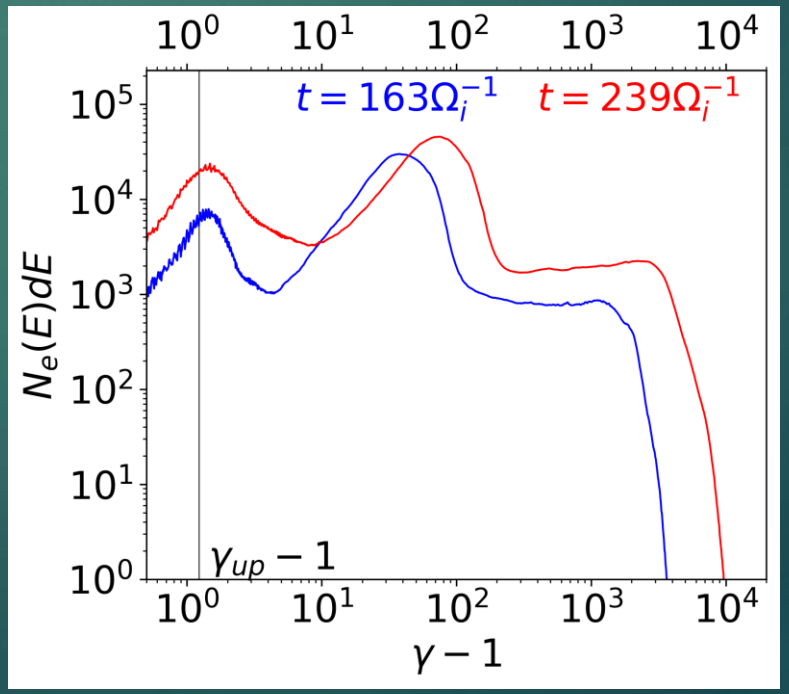
  - Electron trapping and acceleration!



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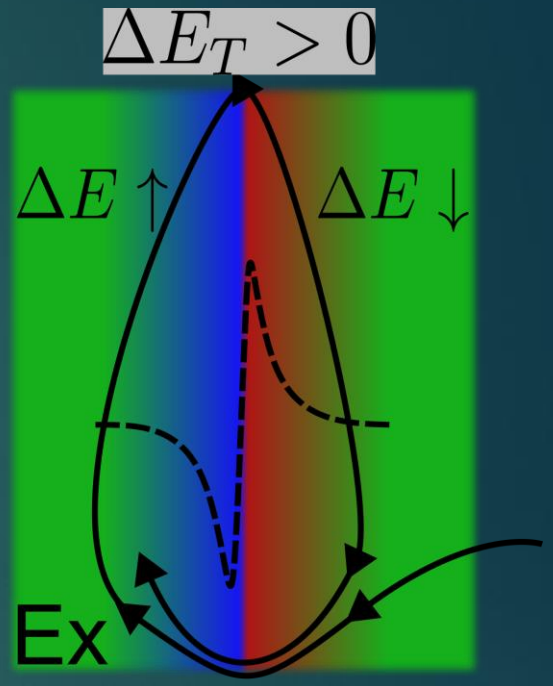

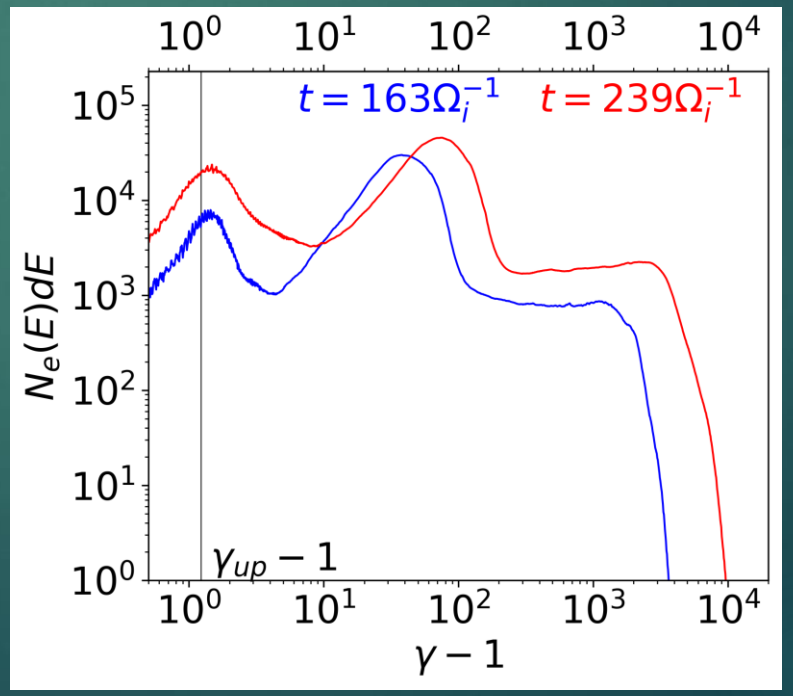

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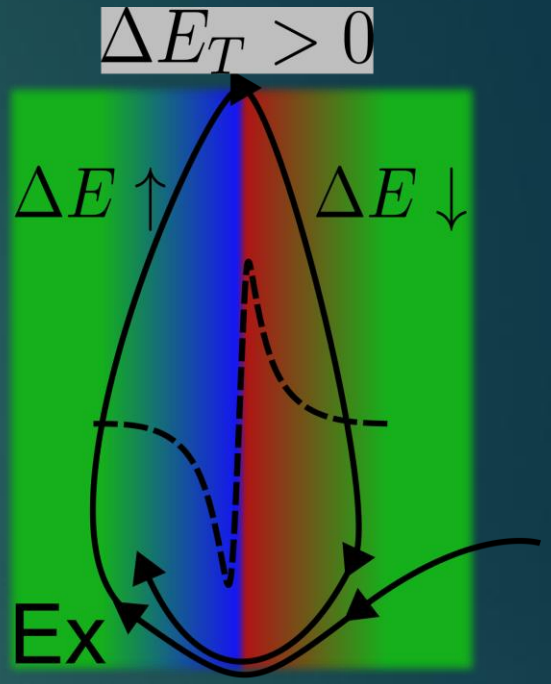
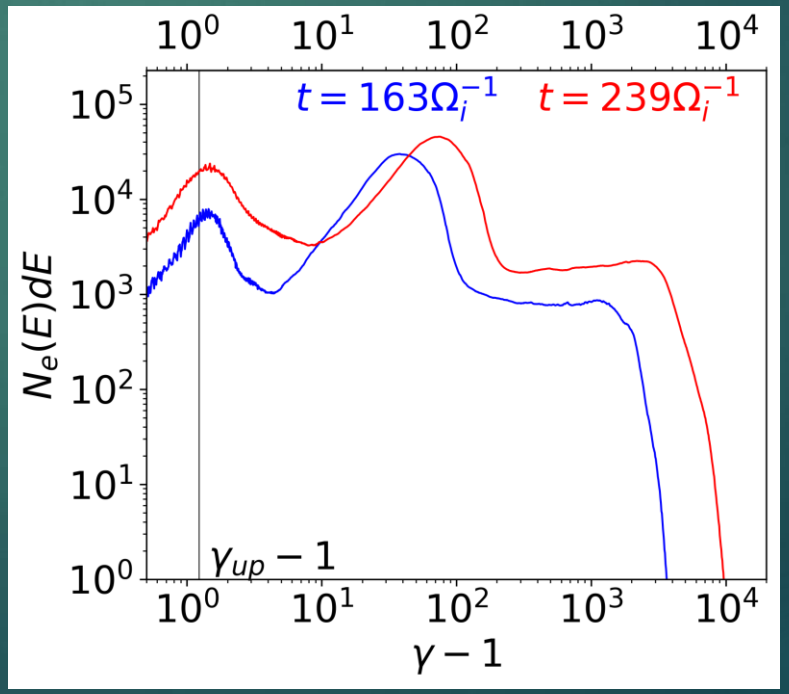
1. Electrons get trapped in the large electrostatic potential.
2. Acceleration over many cycles.





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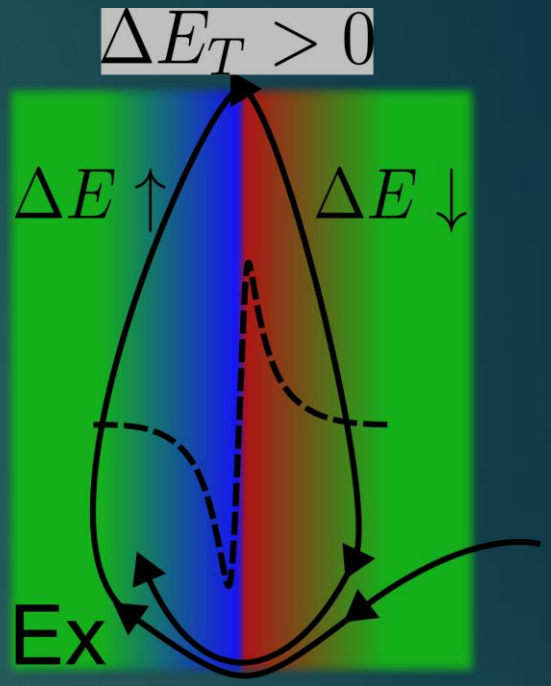
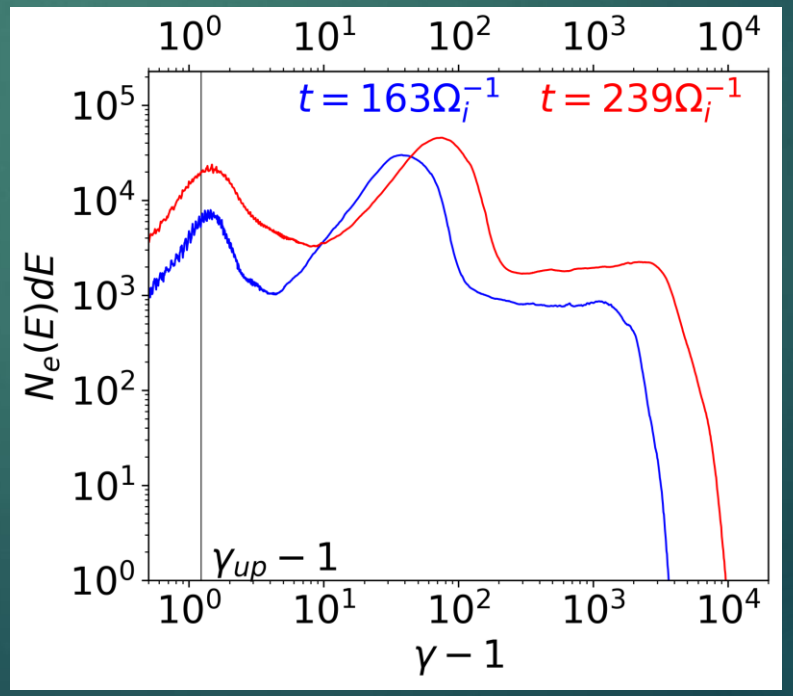
3. Net energy increases!





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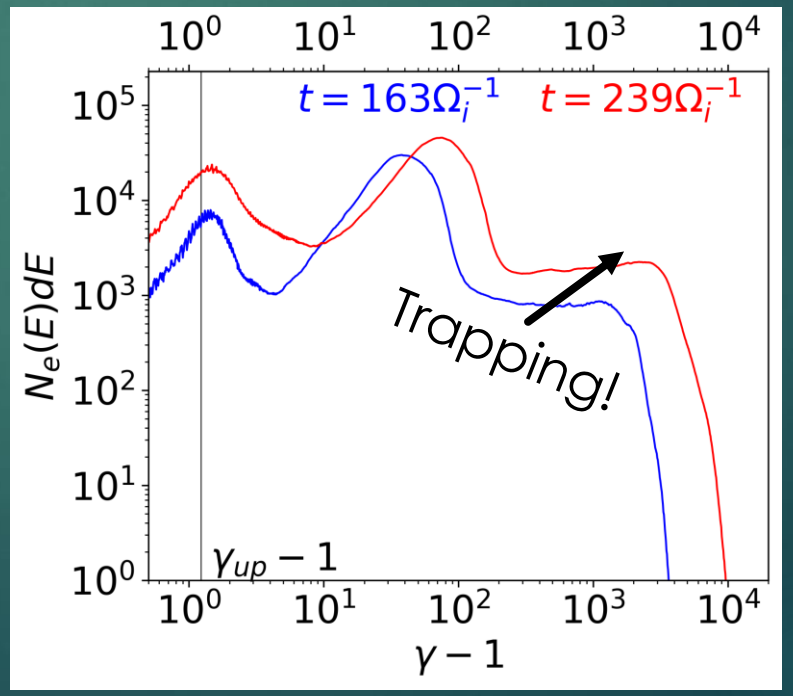

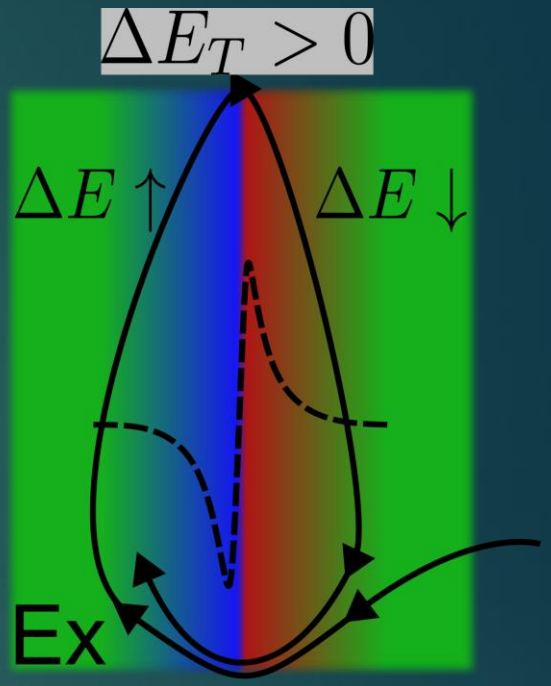

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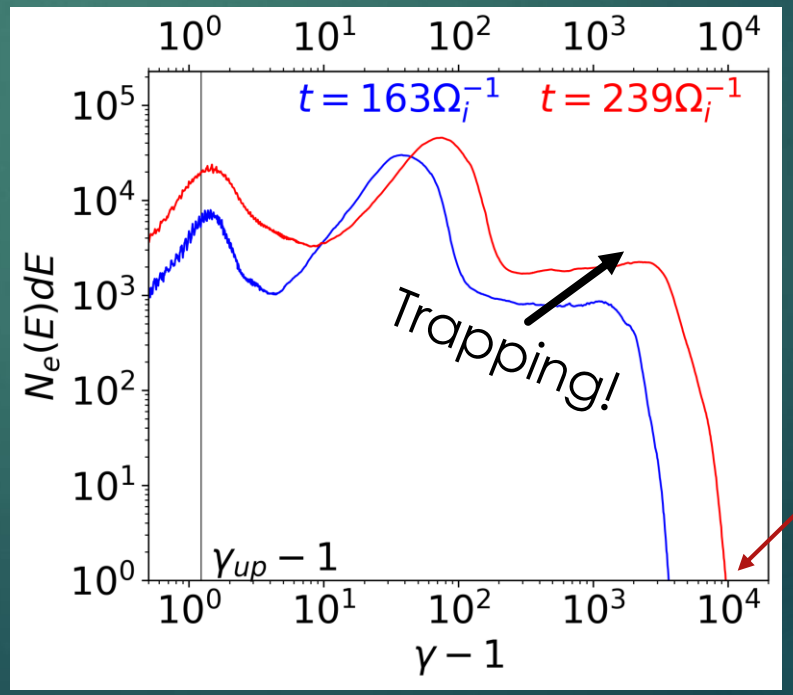
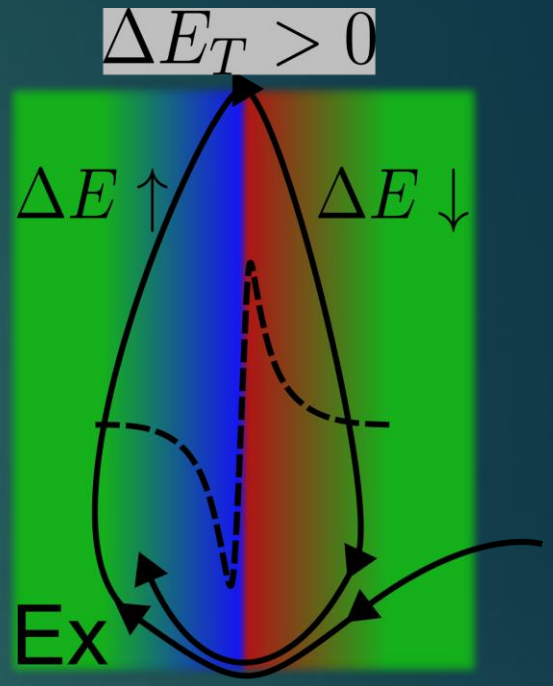
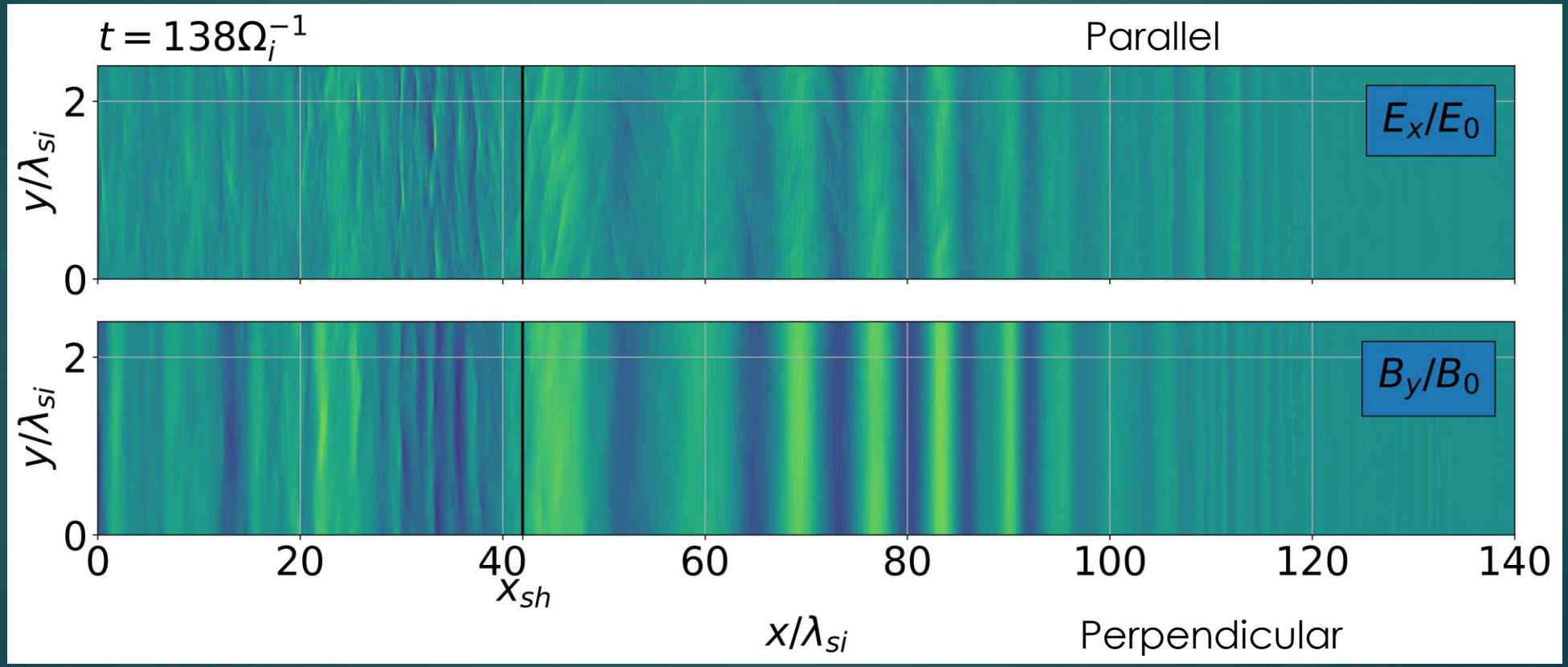




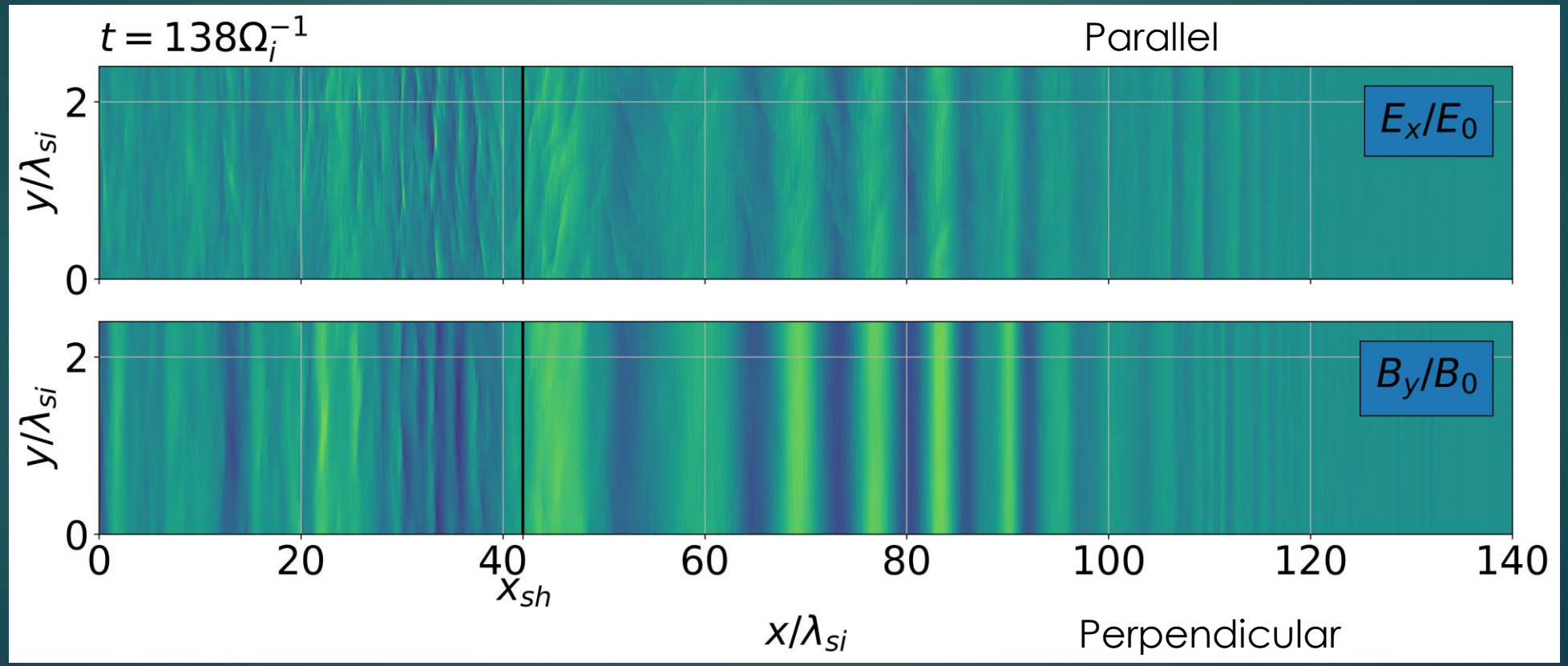
$\gamma_{max} \approx 10{,}000$

Shock structure at θ=10°



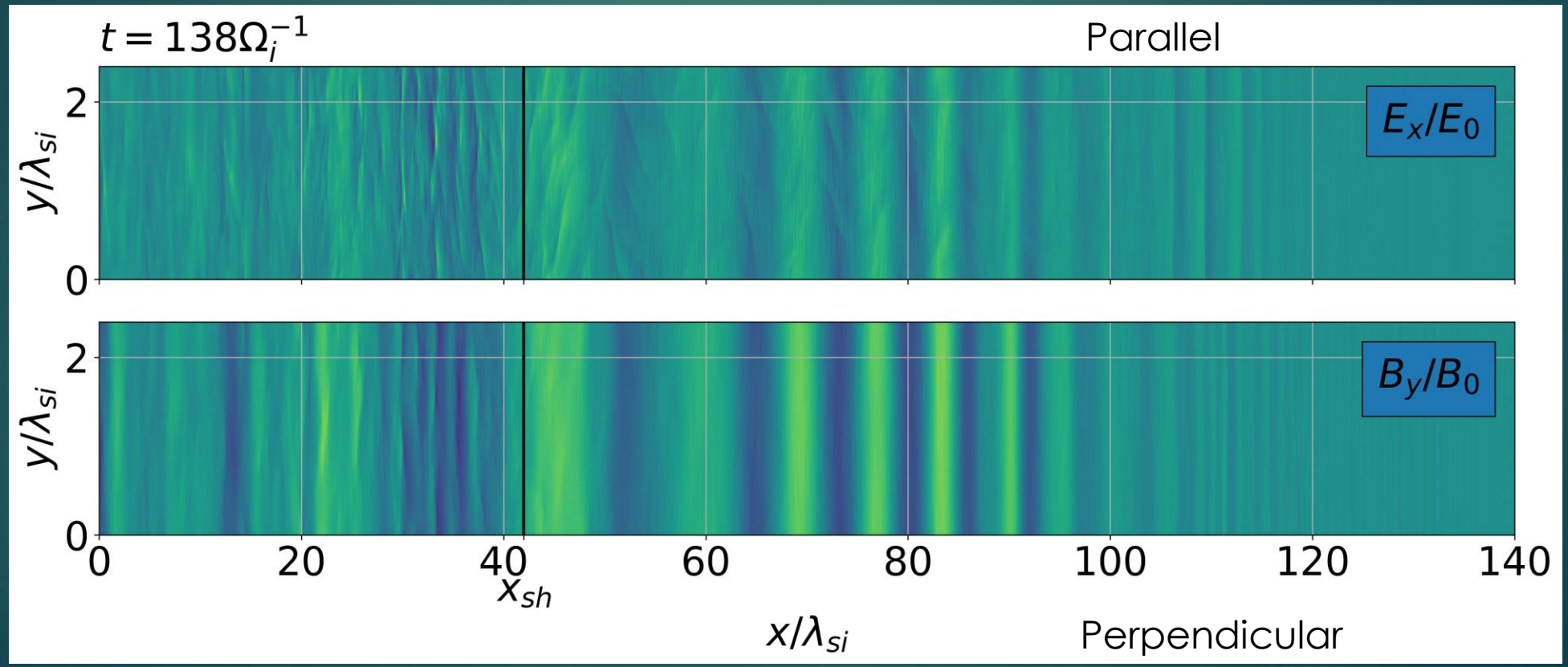
Shock structure at Θ=10°

- Blurred shock at $x \approx 42\lambda_{si}$.



Shock structure at Θ=10°

- Blurred shock at $x \approx 42\lambda_{si}$.
- Strong wave activity upstream of the shock.



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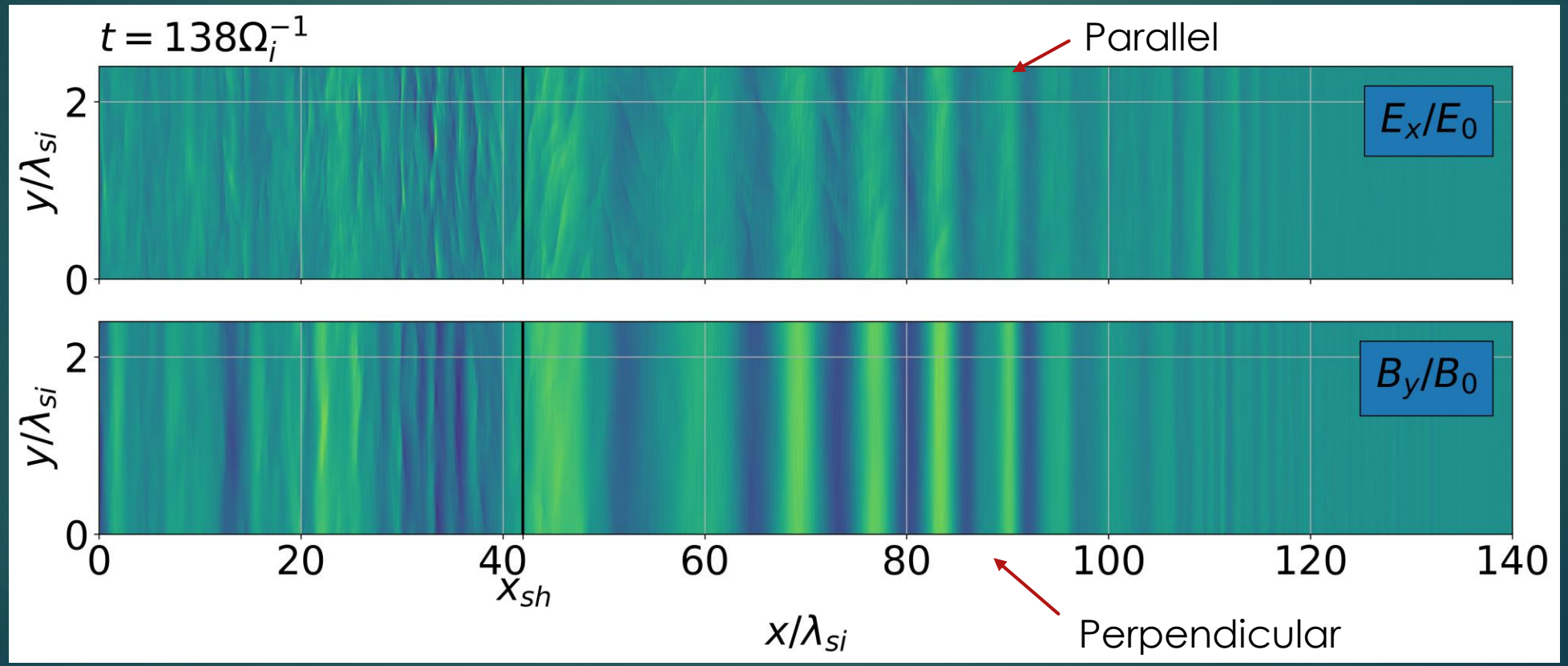

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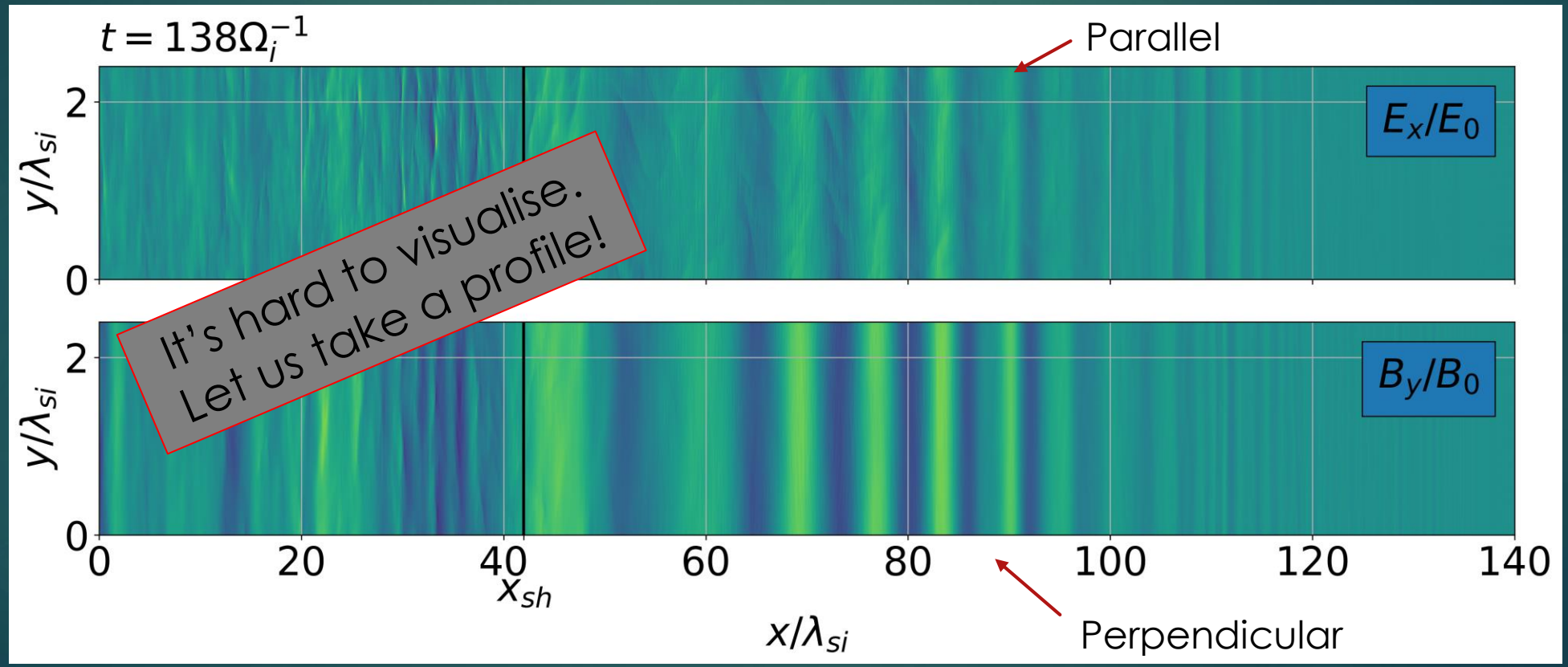
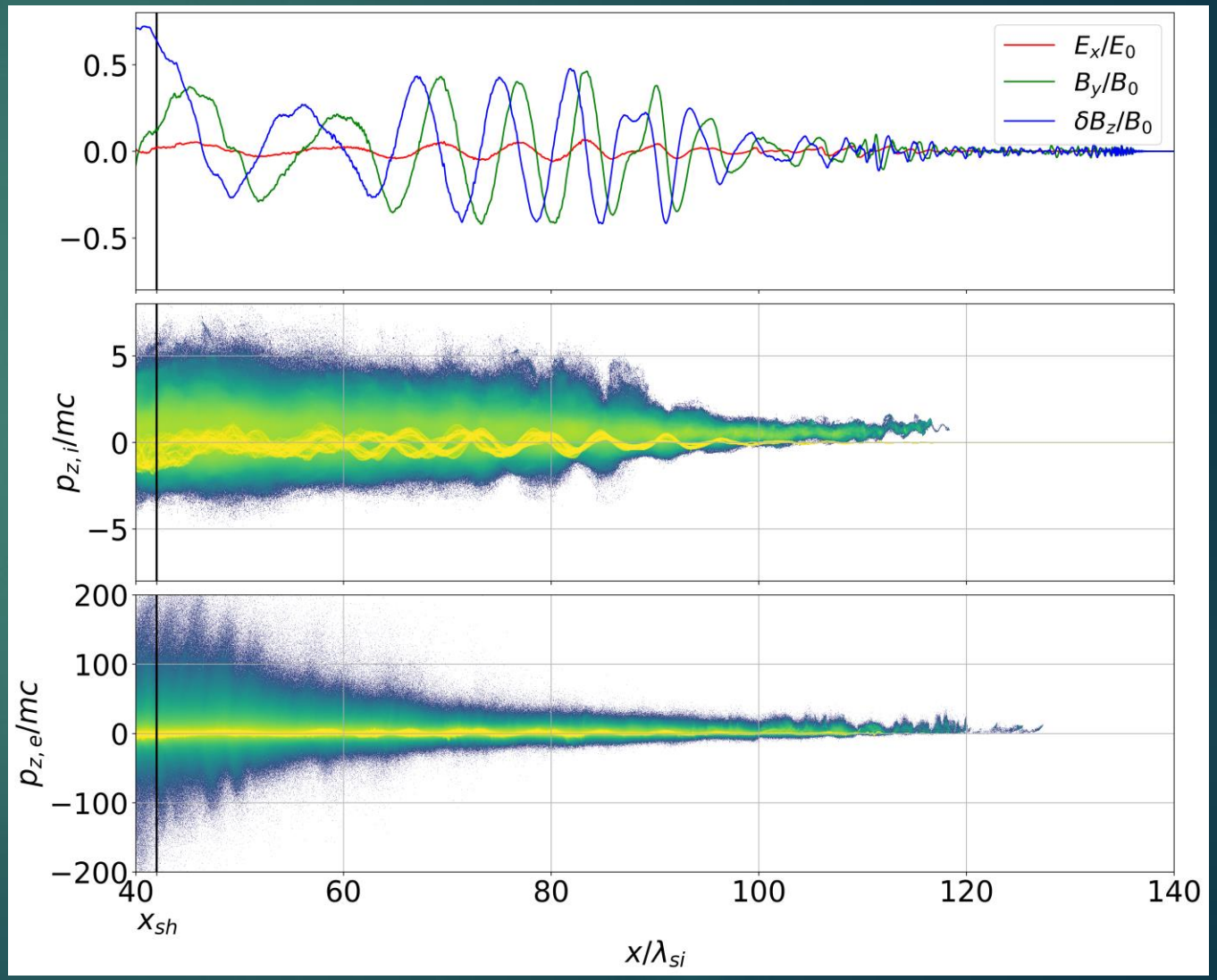
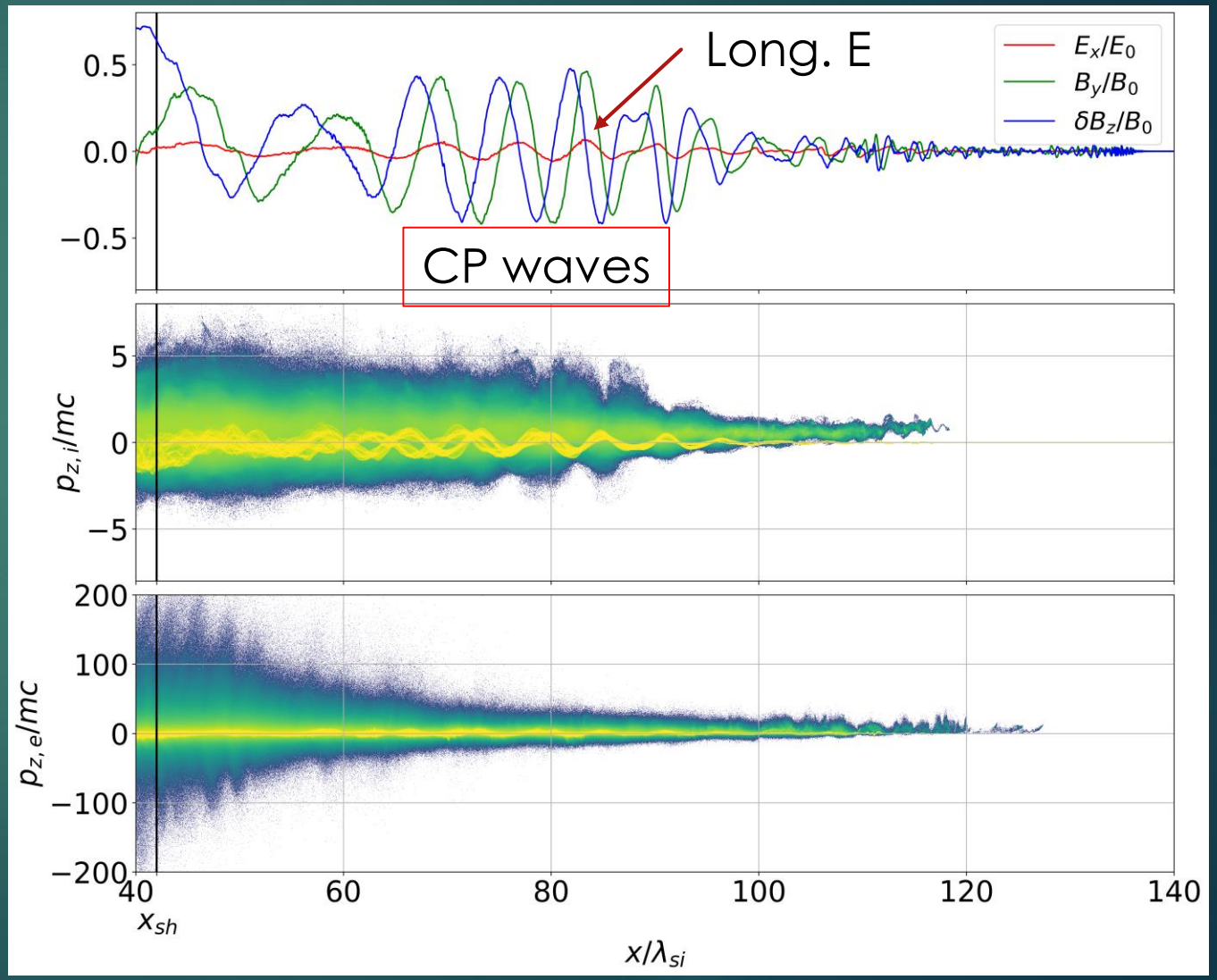


Upstream wave activity



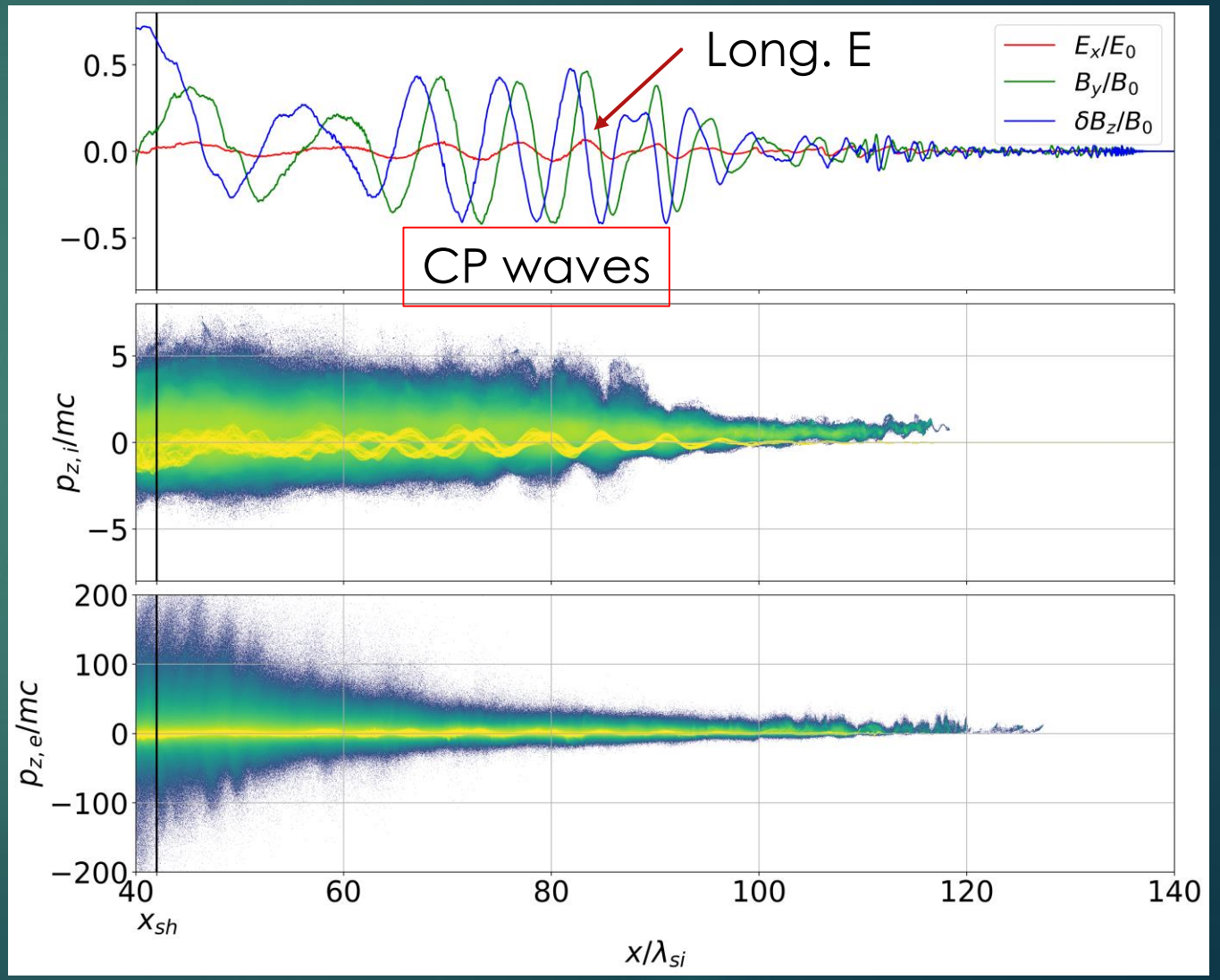
Upstream wave activity

- Right-hand polarised waves + Longitudinal E



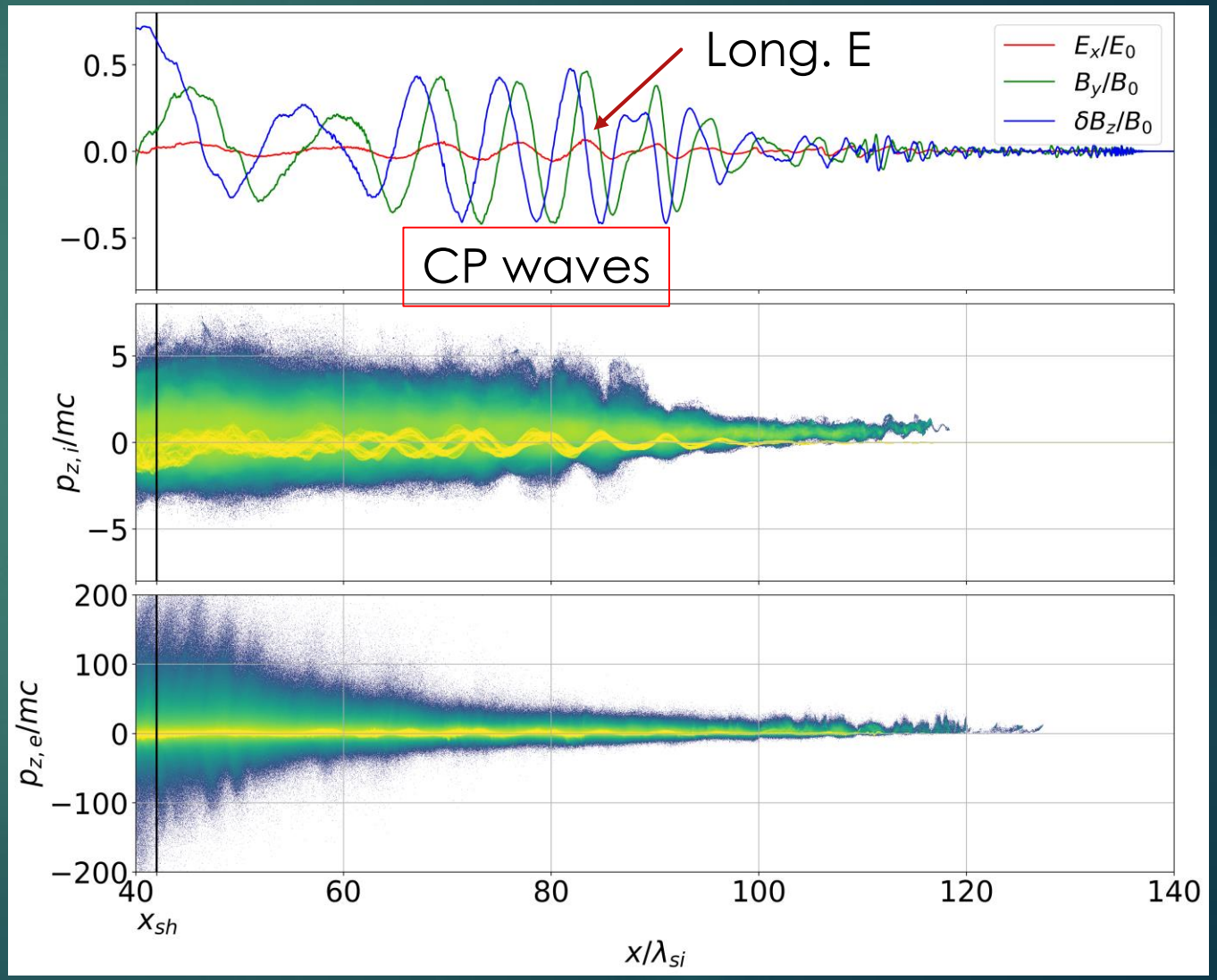
Upstream wave activity

- Right-hand polarised waves + Longitudinal E
- Strong heating + acceleration
  - It coincides with the waves!



Upstream wave activity

- Right-hand polarised waves + Longitudinal E
- Strong heating + acceleration
  - It coincides with the waves!
- But there are other kind of waves



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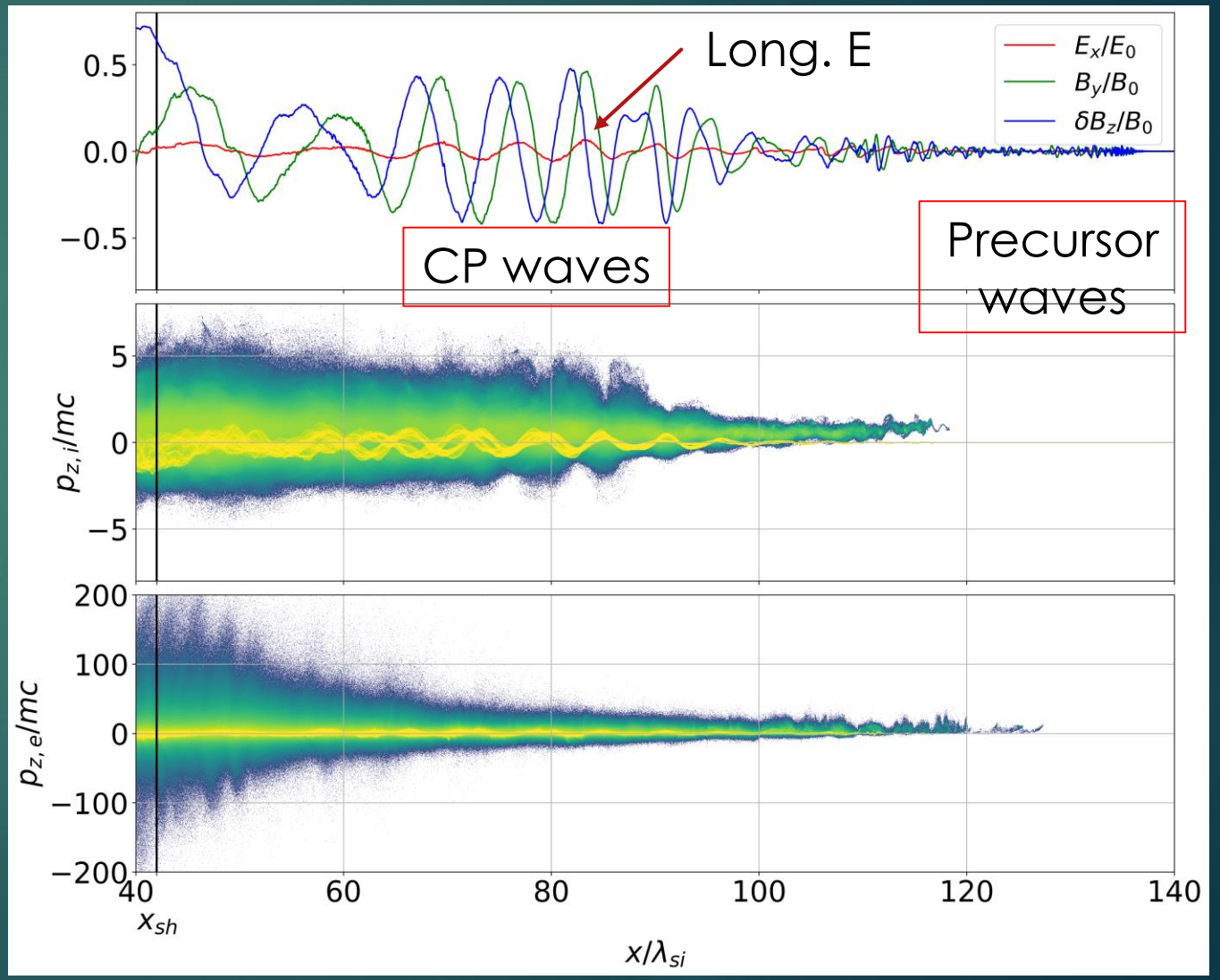
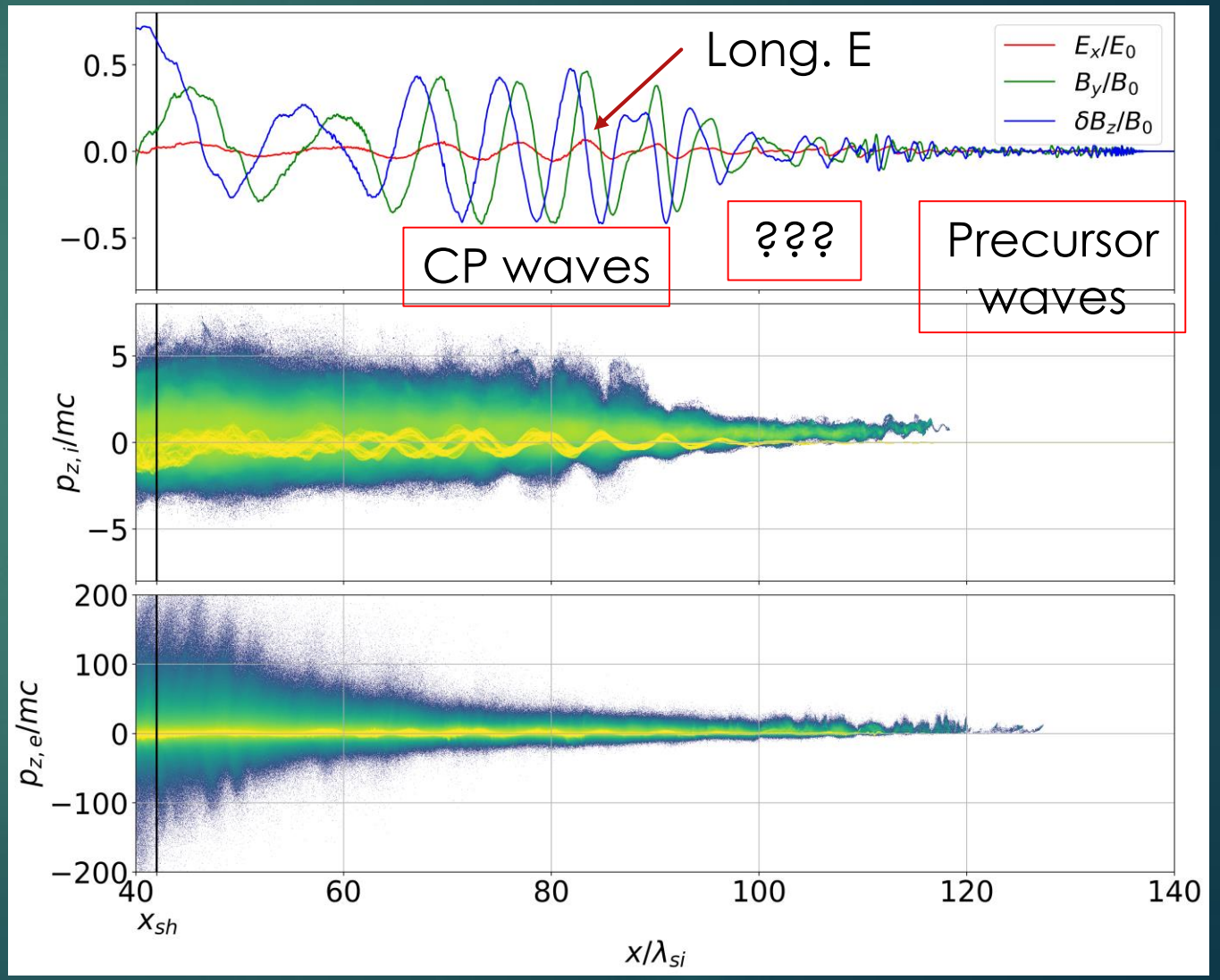
- But there are other kind of waves
  - Precursor waves

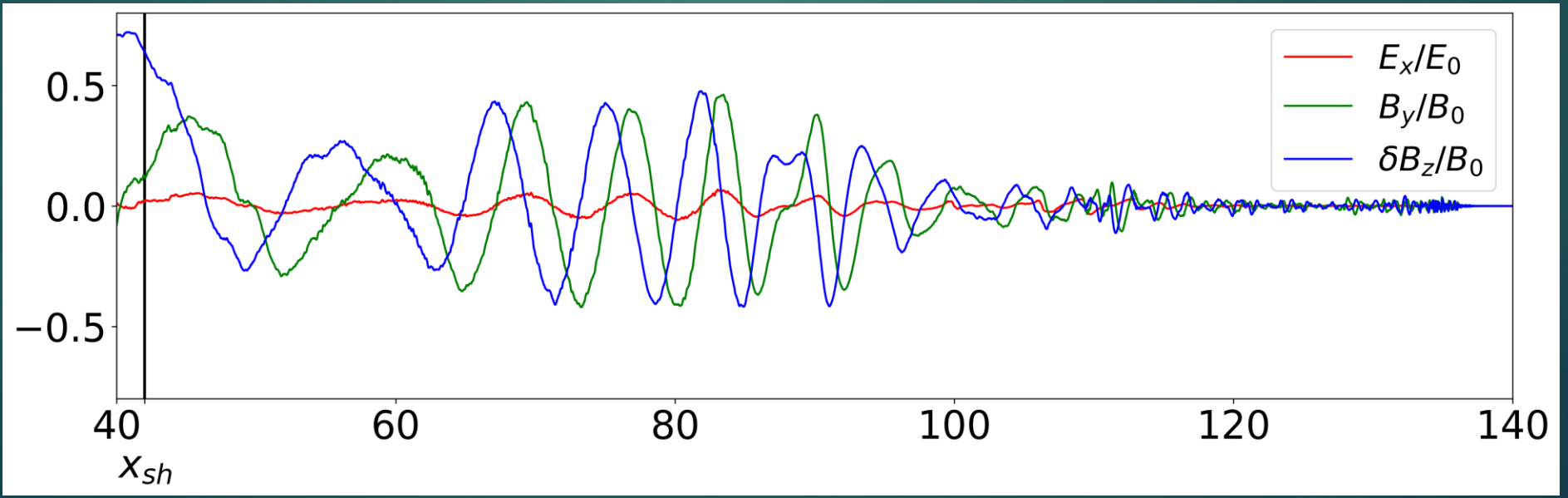


Upstream wave activity

- Right-hand polarised waves + Longitudinal E
- Strong heating + acceleration
  - It coincides with the waves!
- But there are other kind of waves
  - Precursor waves
  - And?

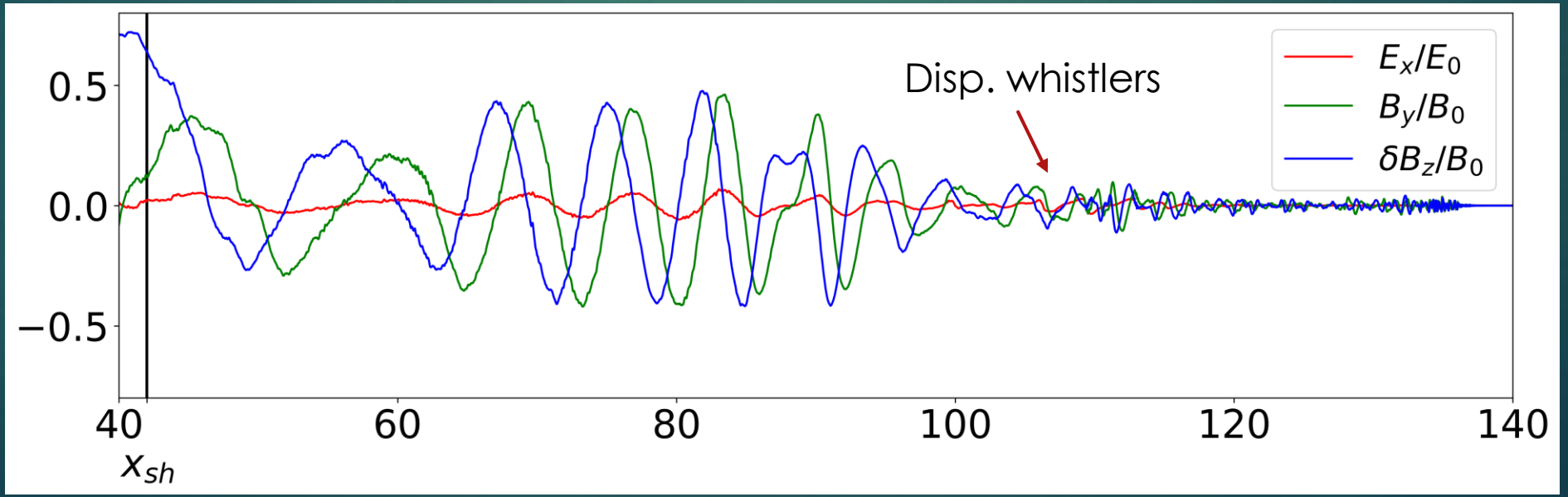


So many waves!



So many waves!

- Very low Mach number ($M_A < M_{cr}$): Dispersive whistlers



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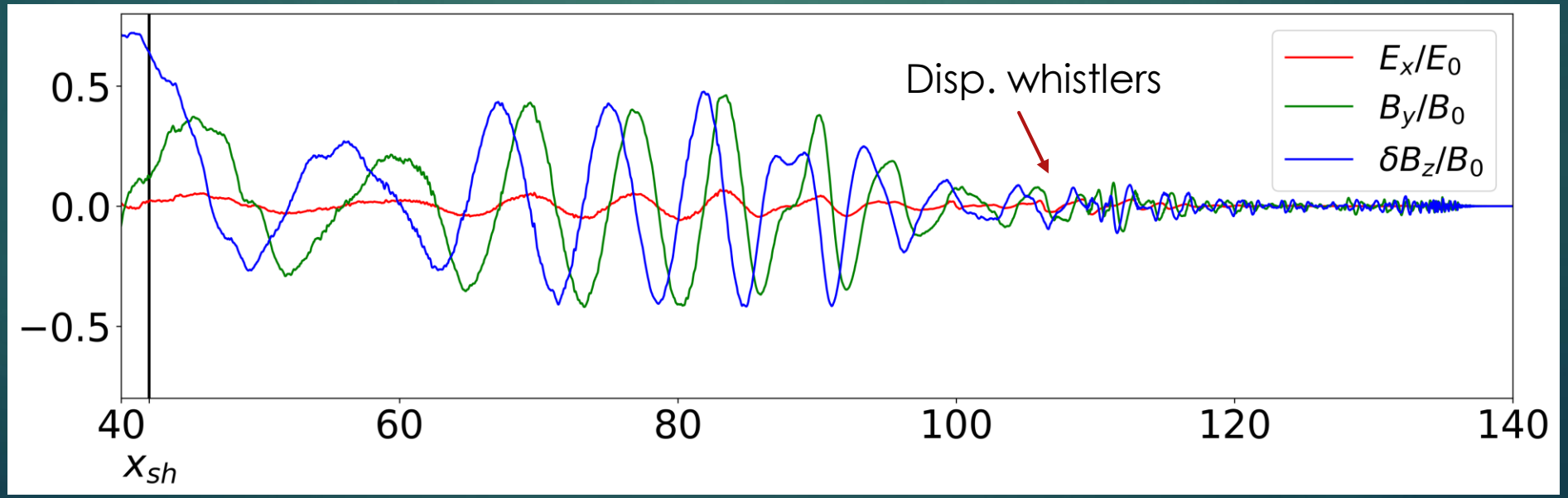
- Large amplitude waves? Two possibilities:



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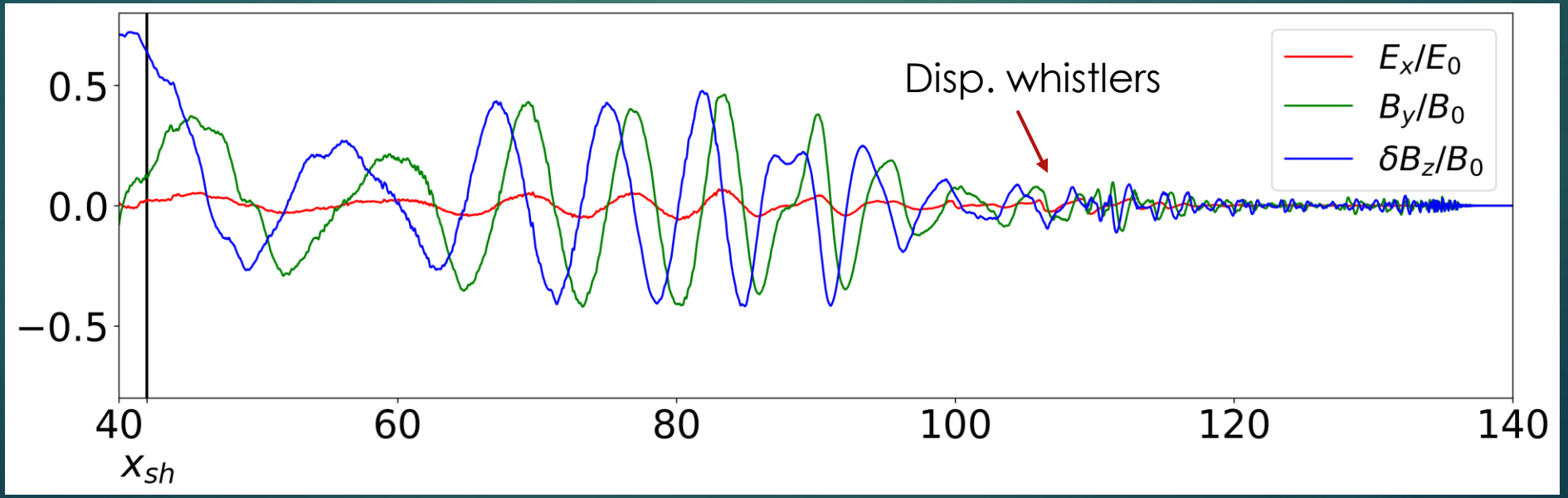

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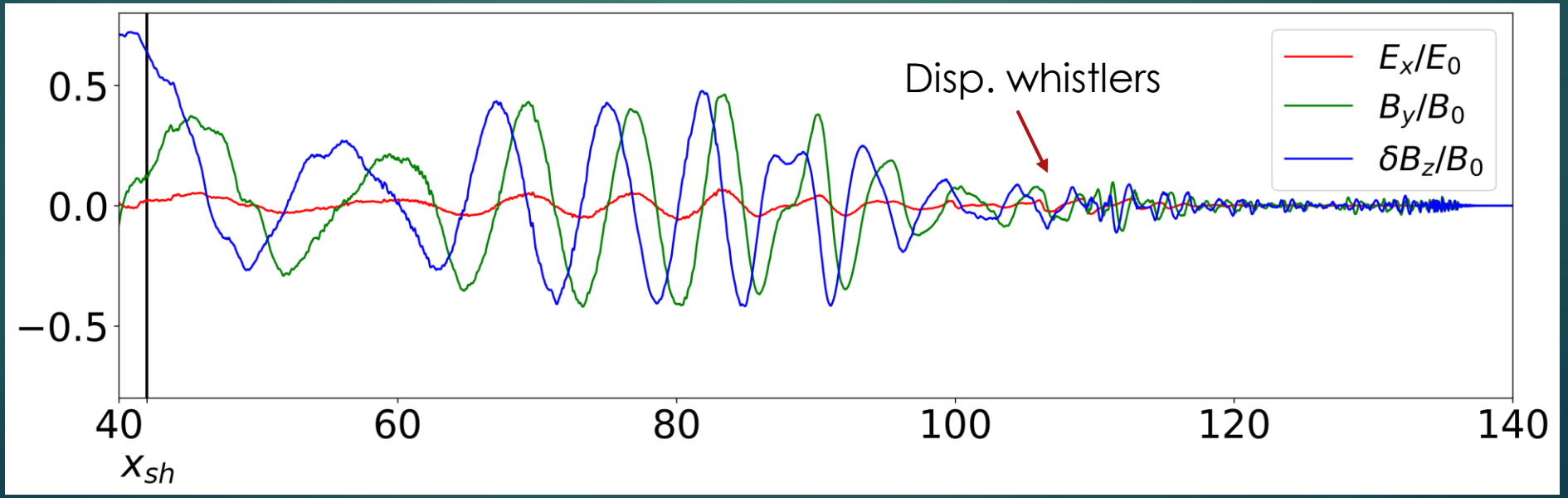

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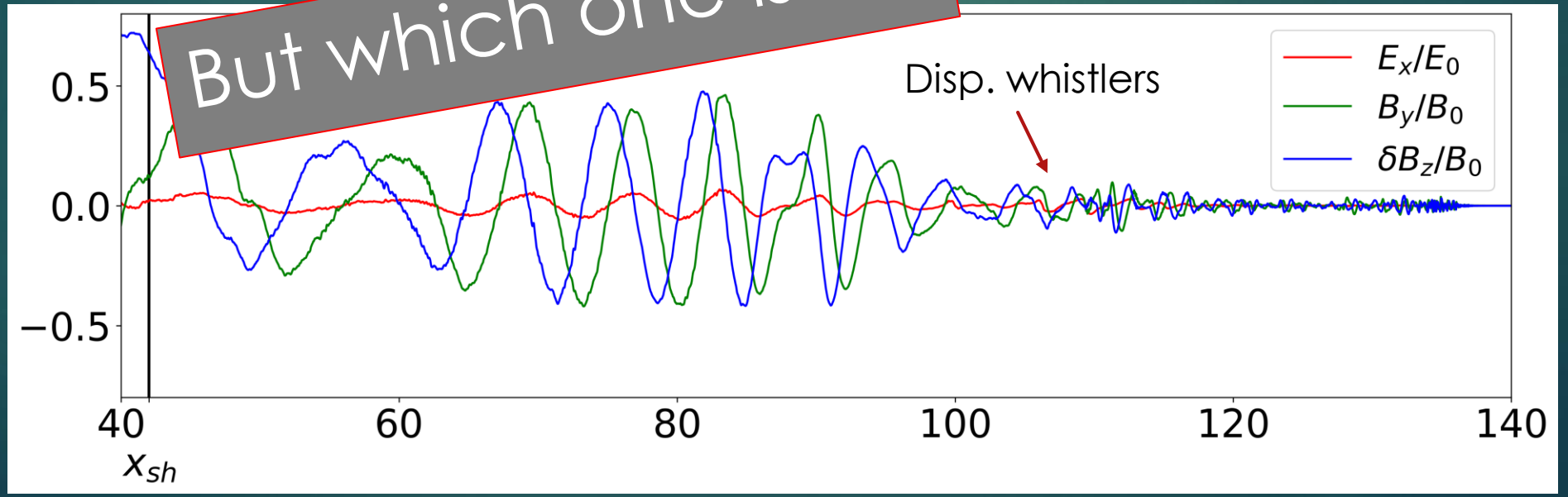

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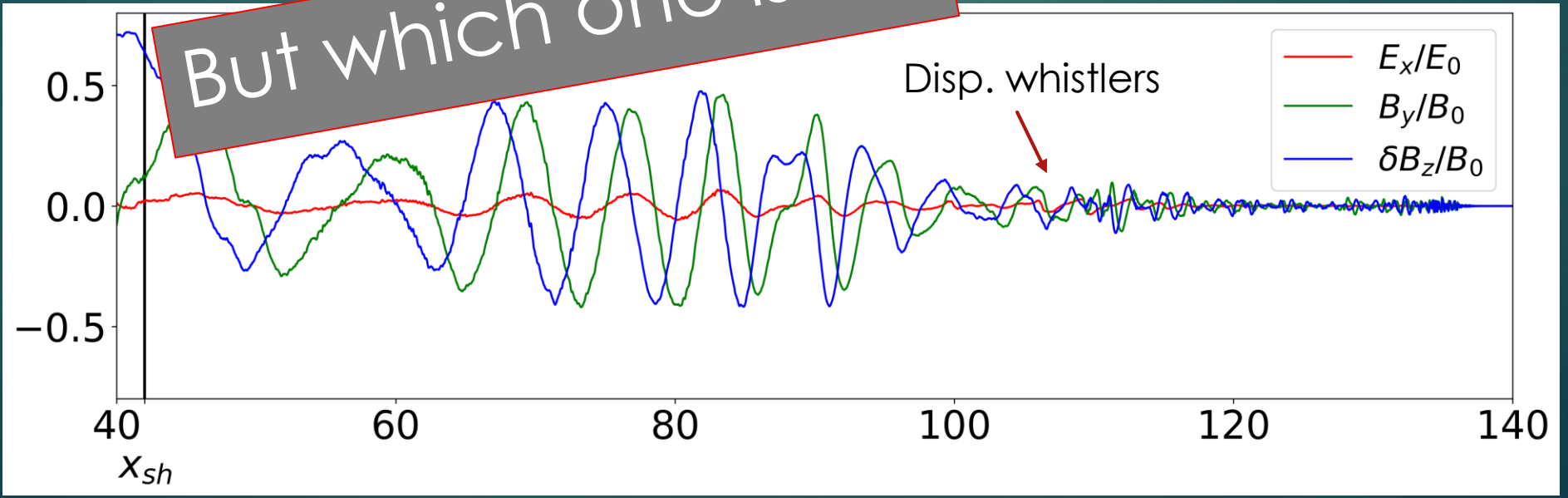

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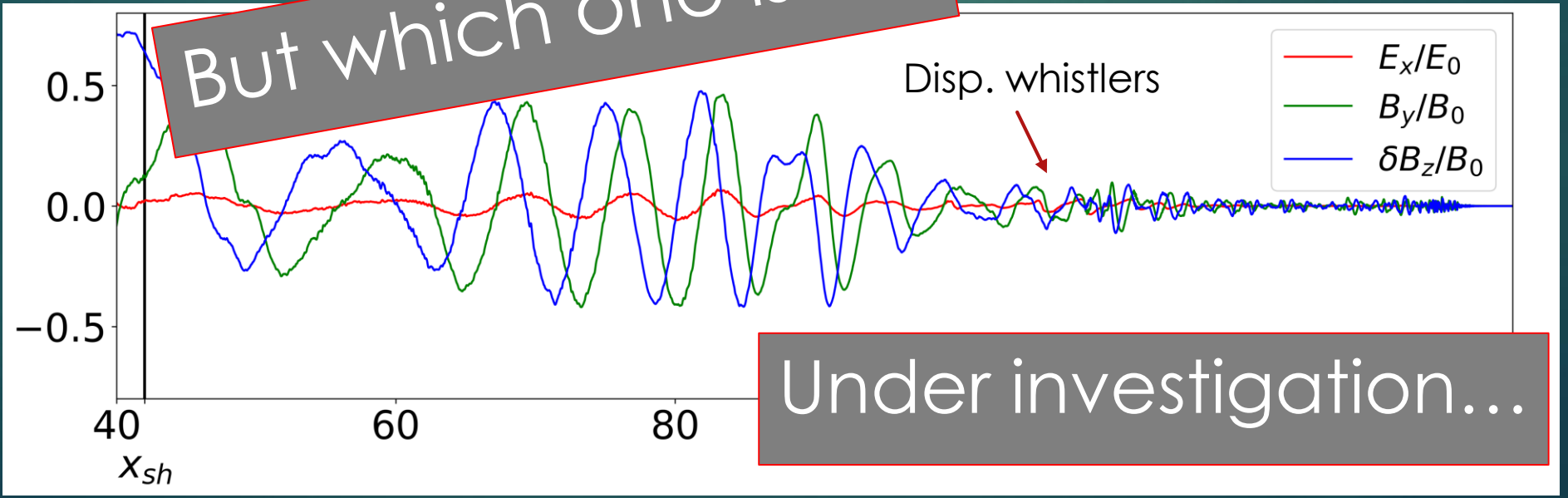

Under investigation…

Summary

- Mildly relativistic shocks enable particle acceleration mechanisms different than that at ultra-rel. shocks at subluminal configurations.
- Oblique shocks accelerate electrons and ions to very high energies.
- Quasi-parallel shocks generate strong waves that mediate strong particle heating and acceleration.