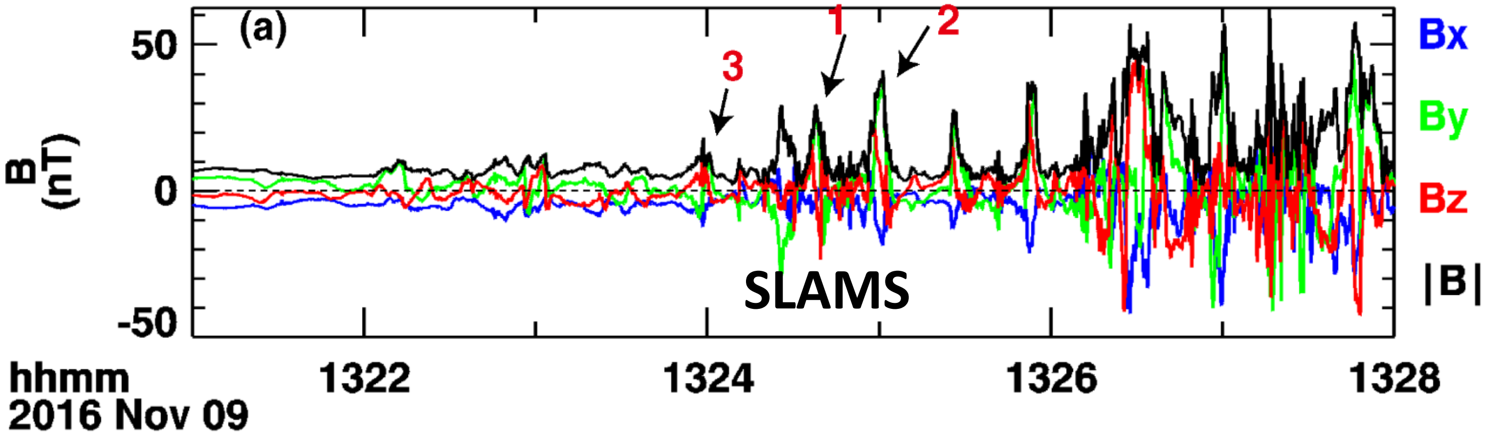
Kinetic instabilities and magnetic reconnection in the Earth's quasi-parallel bow shock

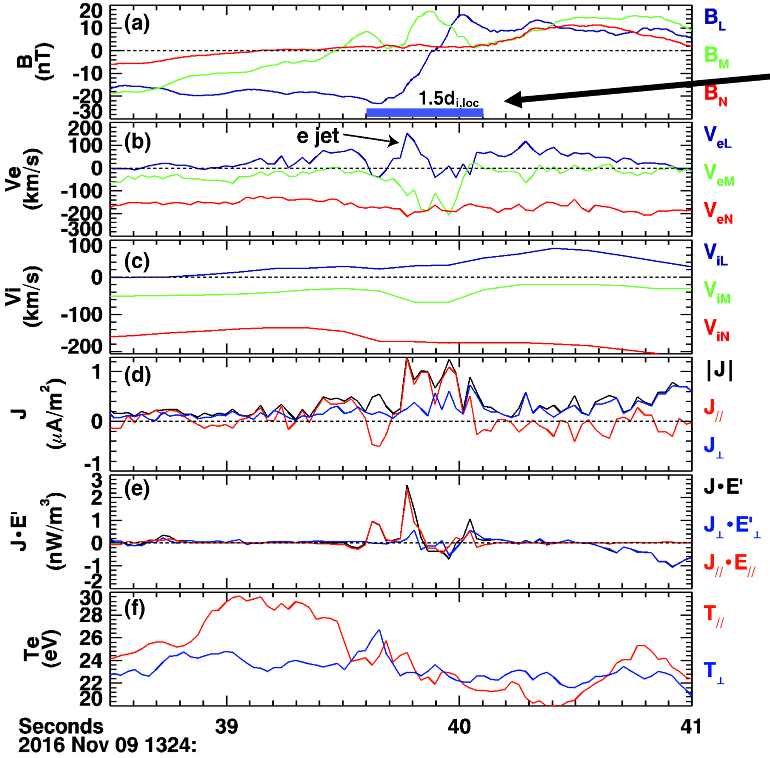
Naoki Bessho[1,2], Li-Jen Chen[2], Shan Wang[1,2], Jonathan Ng[1,2], Michael Hesse[3], and Lynn Wilson III[2]

1. University of Maryland, College Park
2. NASA Goddard Space Flight Center
3. University of Bergen

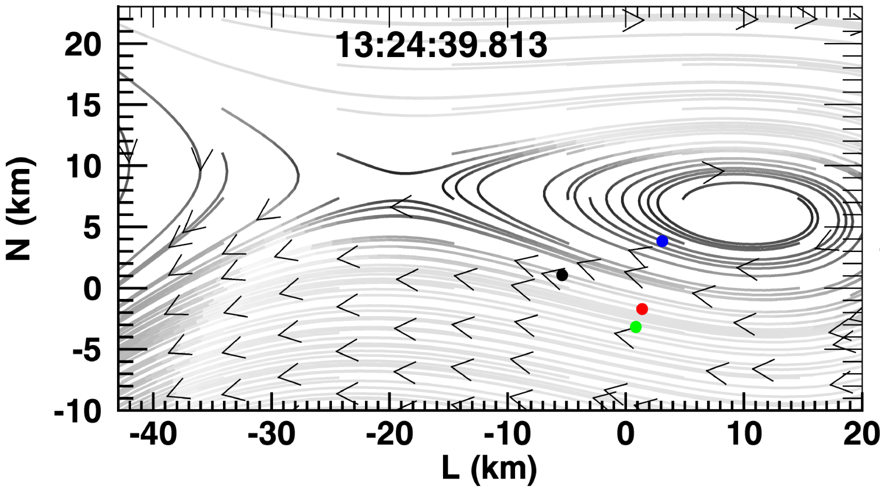
MMS has been observing active reconnecting current sheets in the Earth's bow shock, in magnetosheath (shock downstream) (Yordanova et al. 2016, Vörös et al. 2018, Chasapis et al. 2018, Phan et al. 2018, Wilder et al. 2018) and the foreshock/transition region (Wang et al. 2019, 2020, Gingell et al. 2019, 2020).



[Wang et al., 2020]



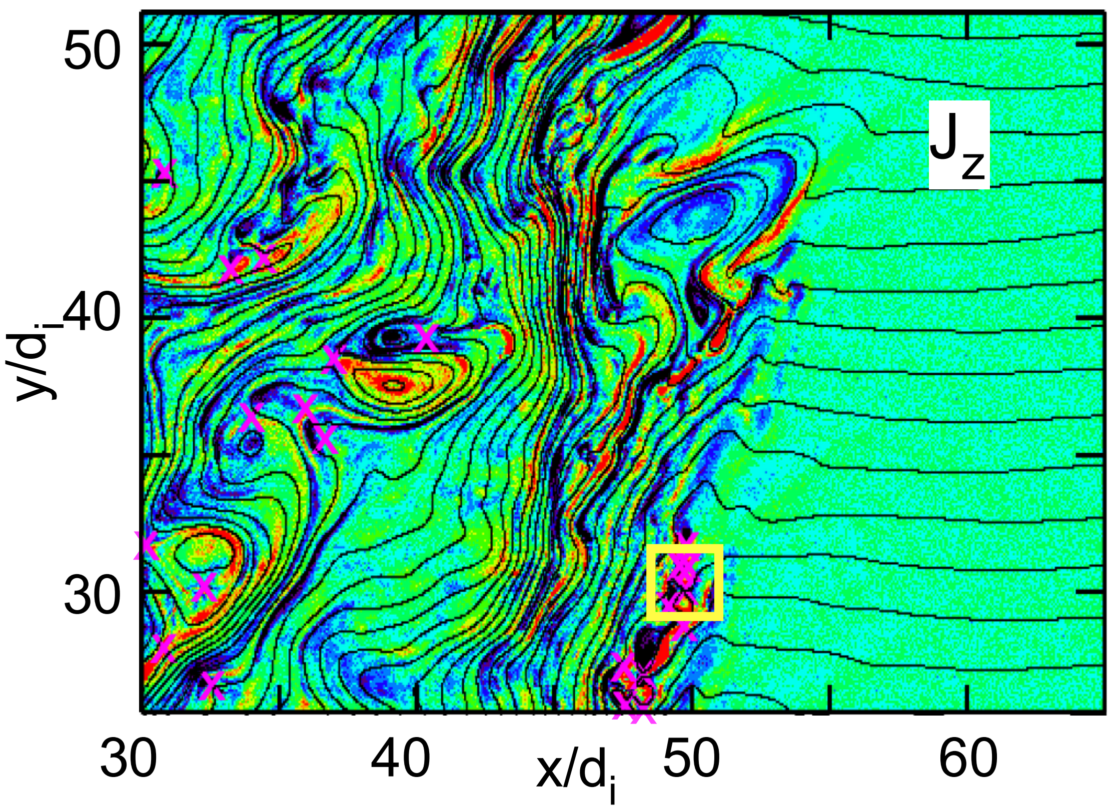
Reconnecting current sheet inside amplified non-resonant mode waves ('SLAMS') with electron outflow jet in the foreshock

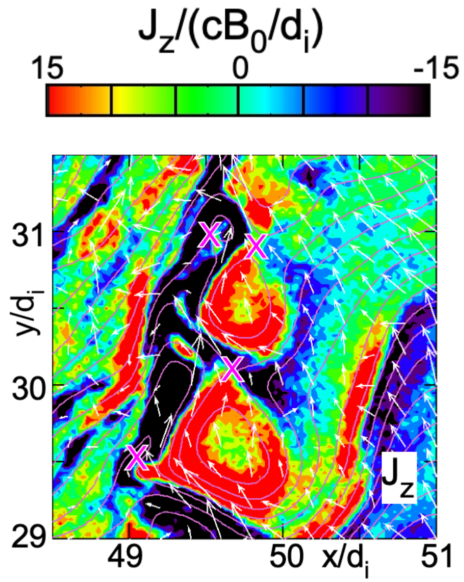


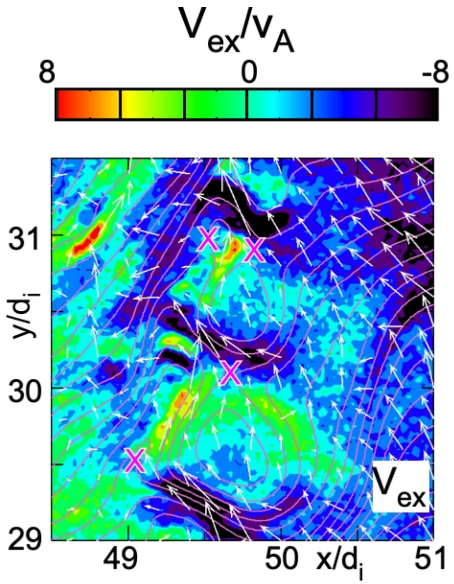
Reconstructed X-line magnetic field topology

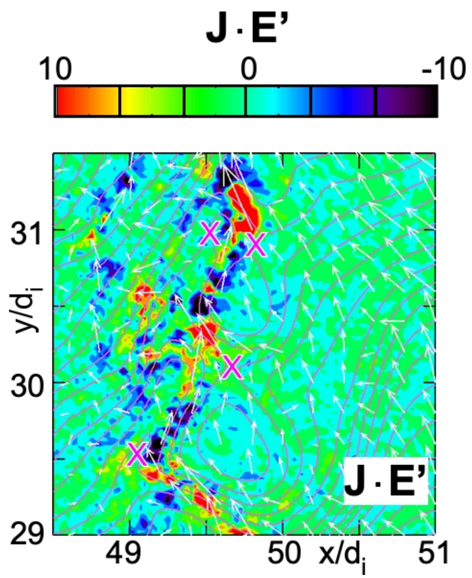
2D PIC simulation of a quasi-parallel shock (θ=25 degrees, M_A=11.4)

Bessho et al. 2020, POP









Reconnecting current sheets in the box

Electron-scale current sheets $J_z<0$

Strong electron jets $V_{ex} <0$

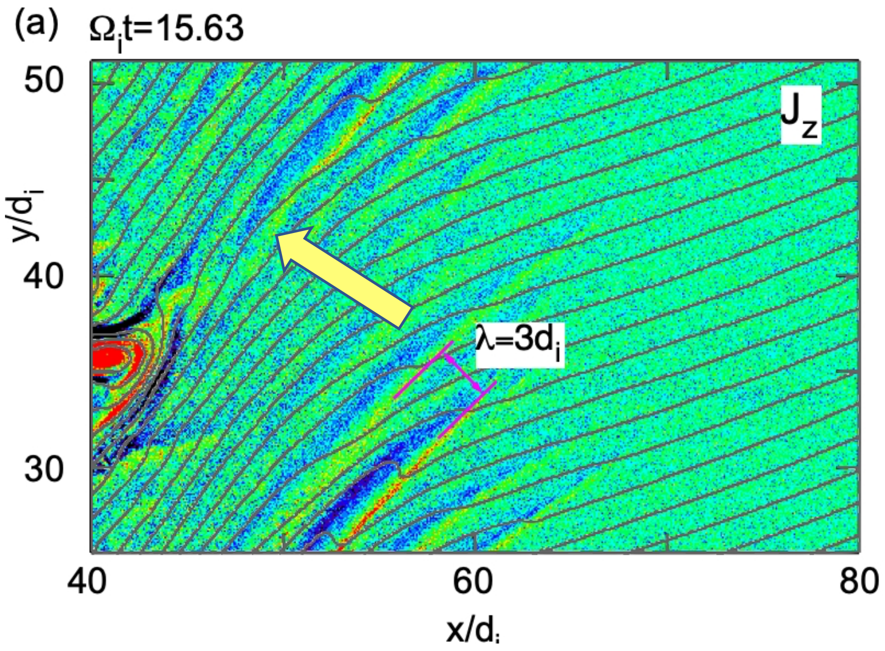
Electron-only reconnection

Energy dissipation rate

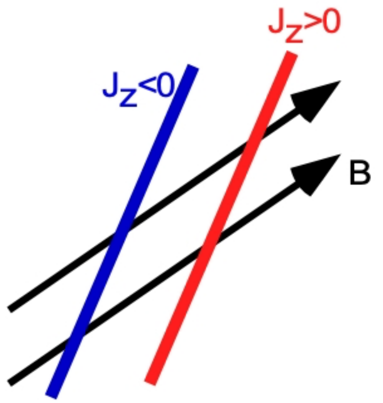
$J \cdot E' \sim 30\ cB_0^2/d_i$

in the outflow region

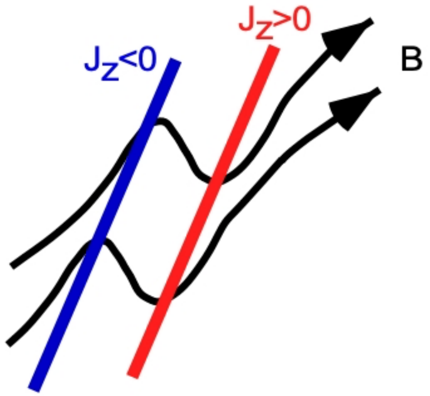
Long-wavelength (LW) mode and short-wavelength (SW) mode

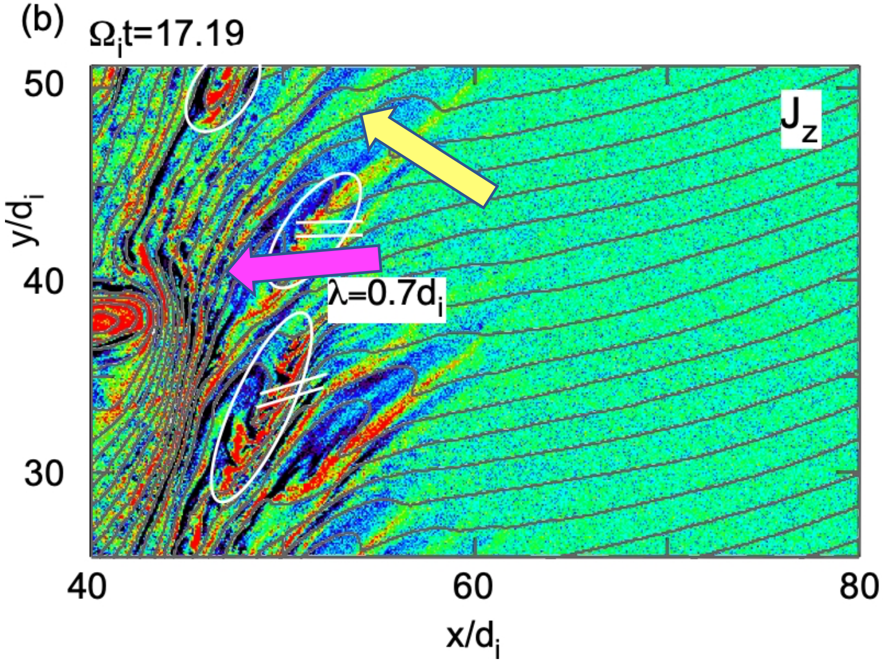


In the early stage, long-wavelength (LW) modes (λ ~ 3d_i) are generated, propagating downstream.

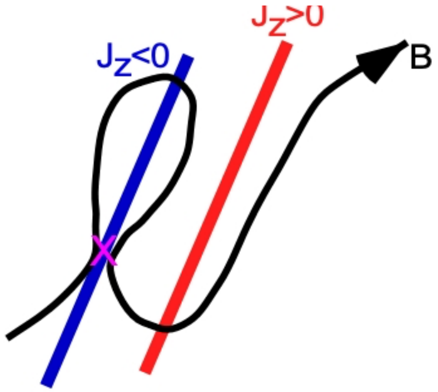


Magnetic field lines are bent due to these generated waves.



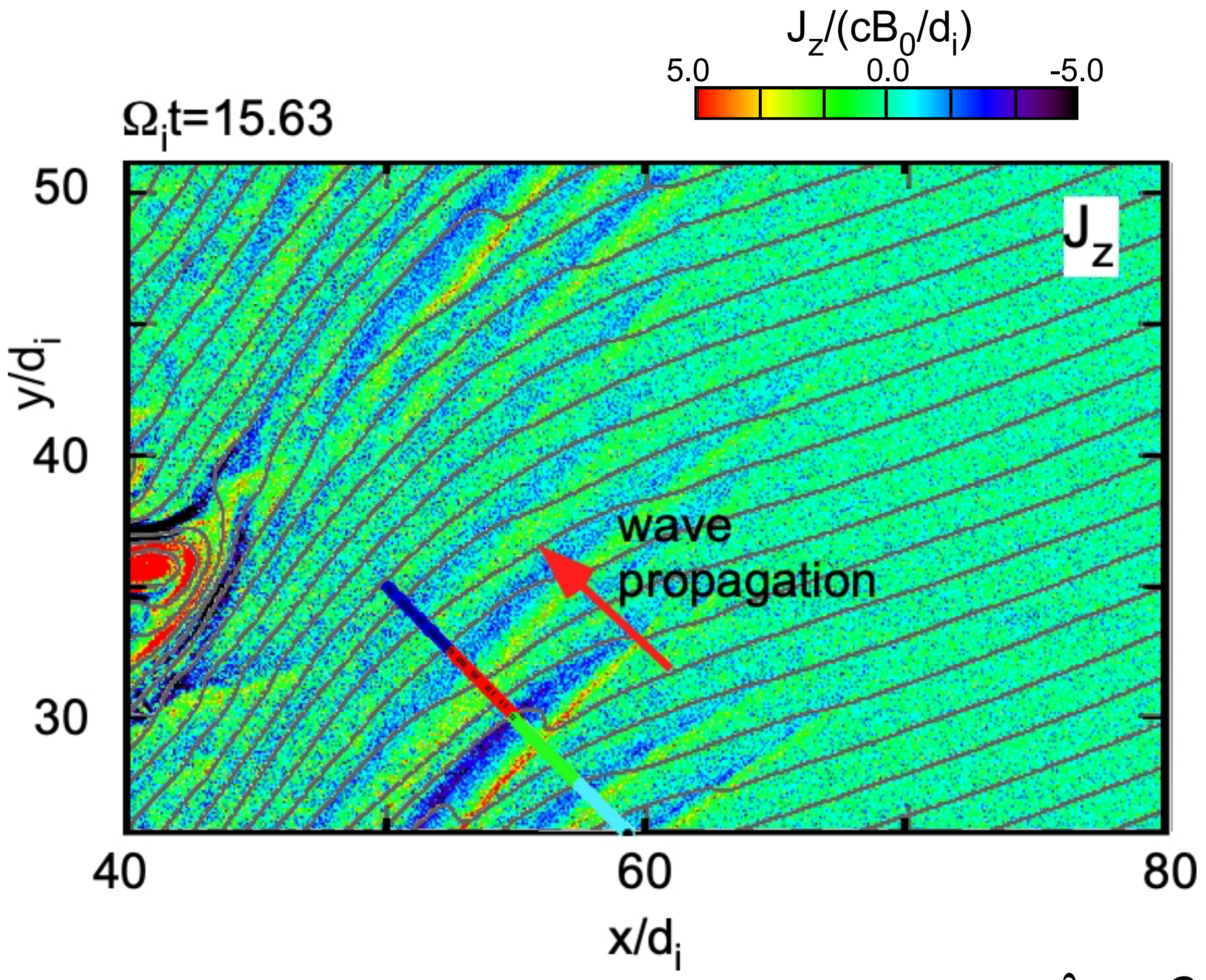


Later, short-wavelength (SW) modes (λ ~ 0.7d_i) are generated, along the wave planes of the LW modes.

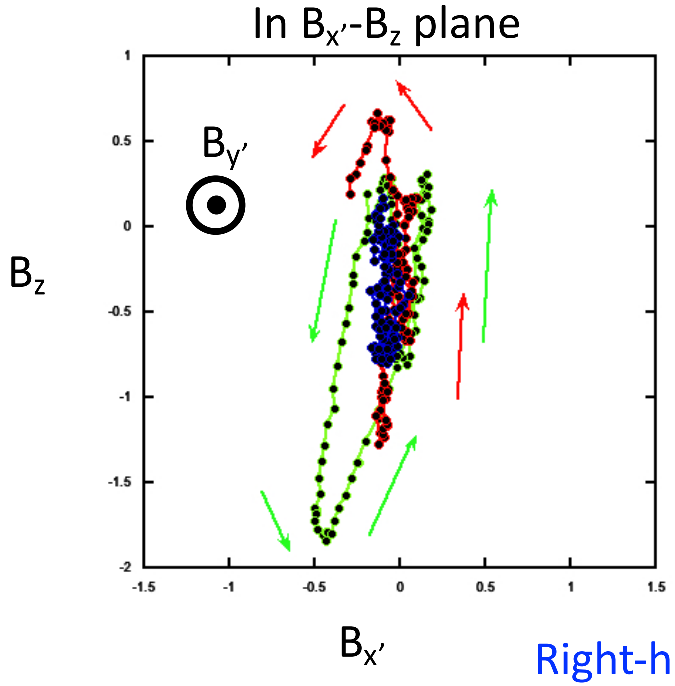


Reconnection occurs where two oppositely-directed field lines come into contact.

LW mode



Hodogram analysis

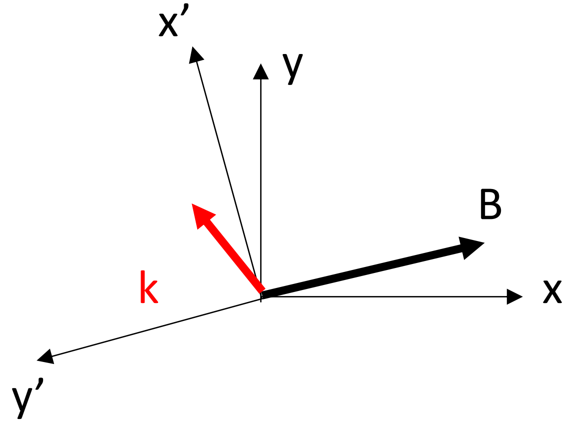


Right-handed

$\lambda \sim$ 2-3 d_i

$\omega \sim 13\Omega_i$

$V_{ph} \sim 6 V_A$

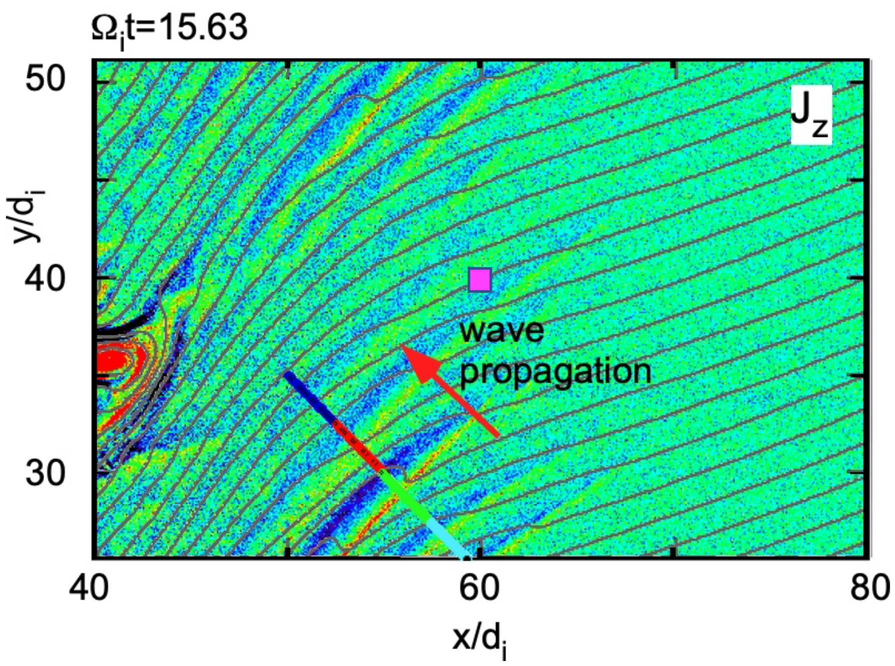


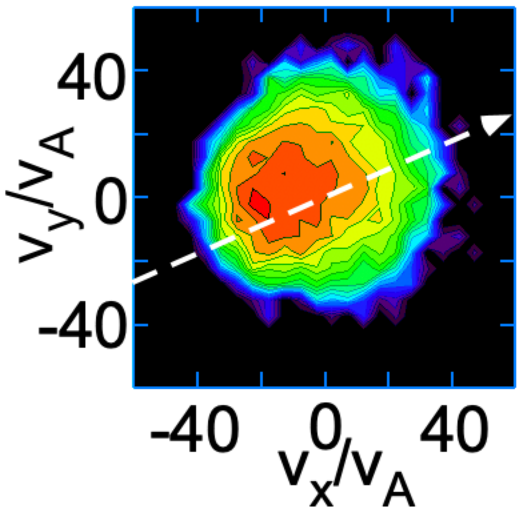
LW modes are right-handed waves in the simulation frame (~ shock frame)

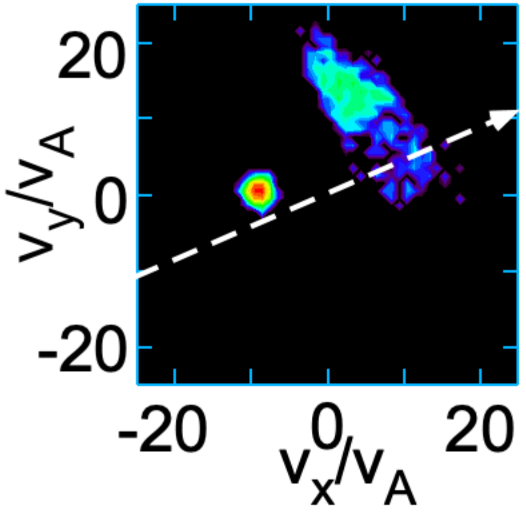
VDF position

Electron
Single peak

Ion
Two components
Reflected ions move in the positive x

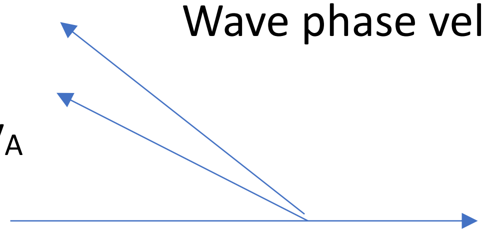






Wave phase velocity ~ 5.6 v_A

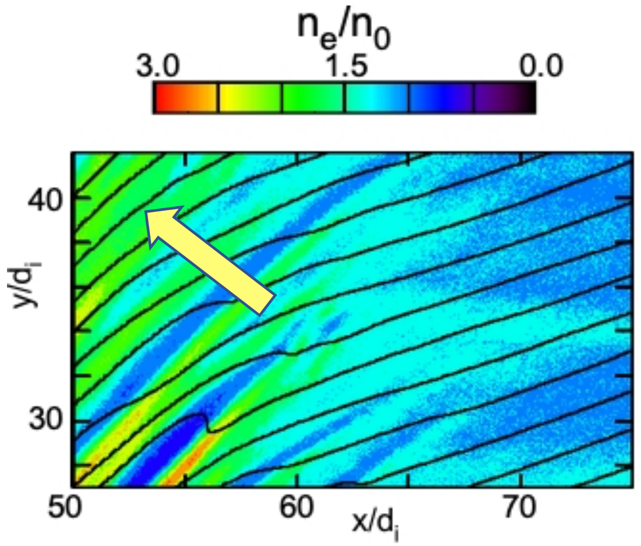
Ion fluid velocity ~ 5.2 v_A
(in $50d_i < x < 55d_i$)

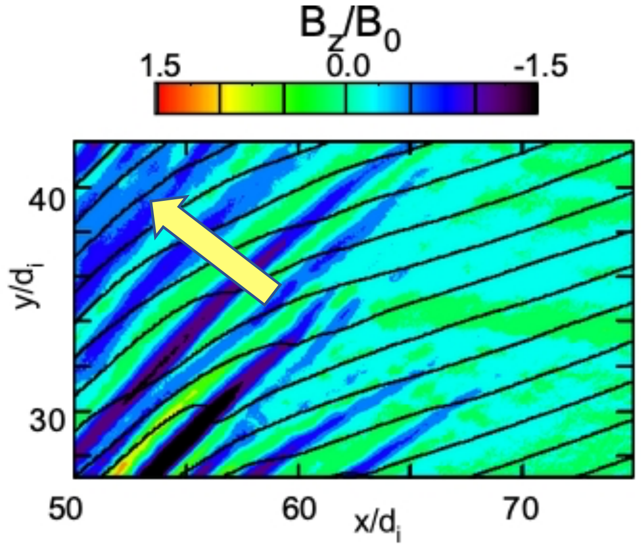


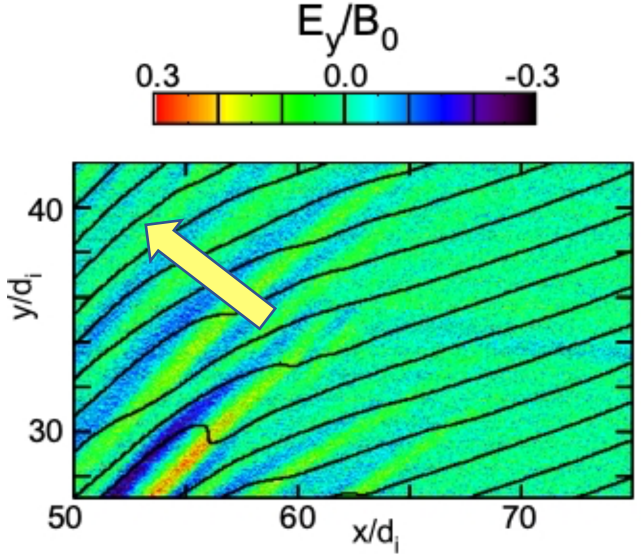
Waves are propagating in the negative x direction
in the plasma rest frame.
Polarization in the plasma rest frame --- right-handed

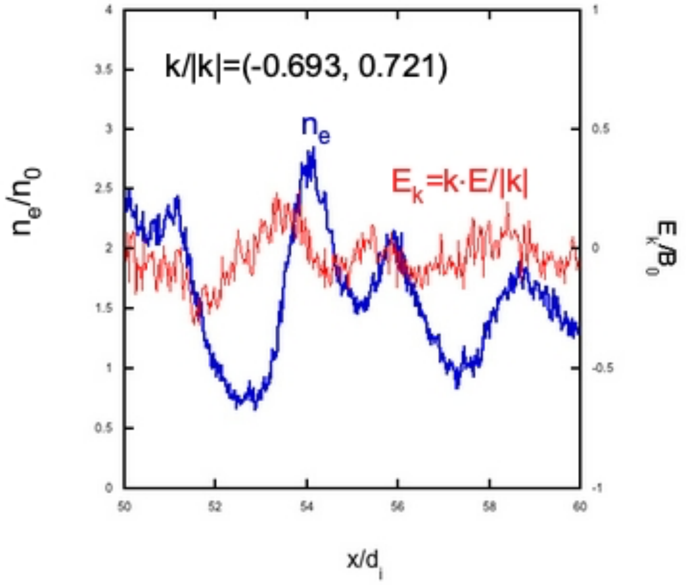
Non-resonant ion-ion beam instability
consistent with MMS observations
(Chen et al. submitted)

LW wave that leads to the secondary instability (SW wave)

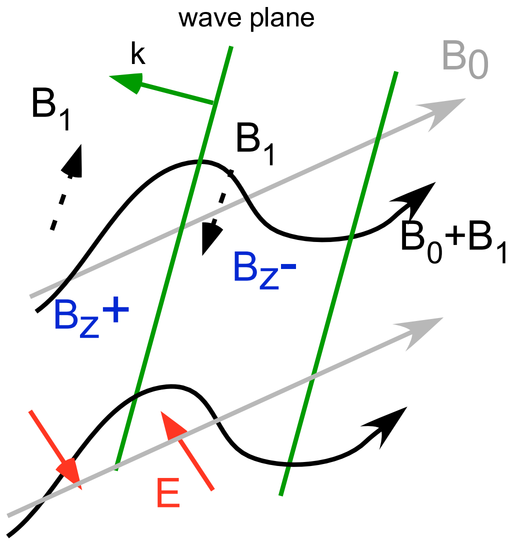


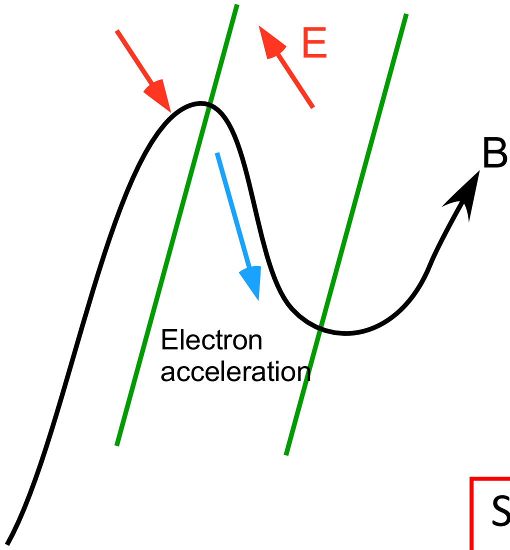






Electrostatic fluctuations are induced

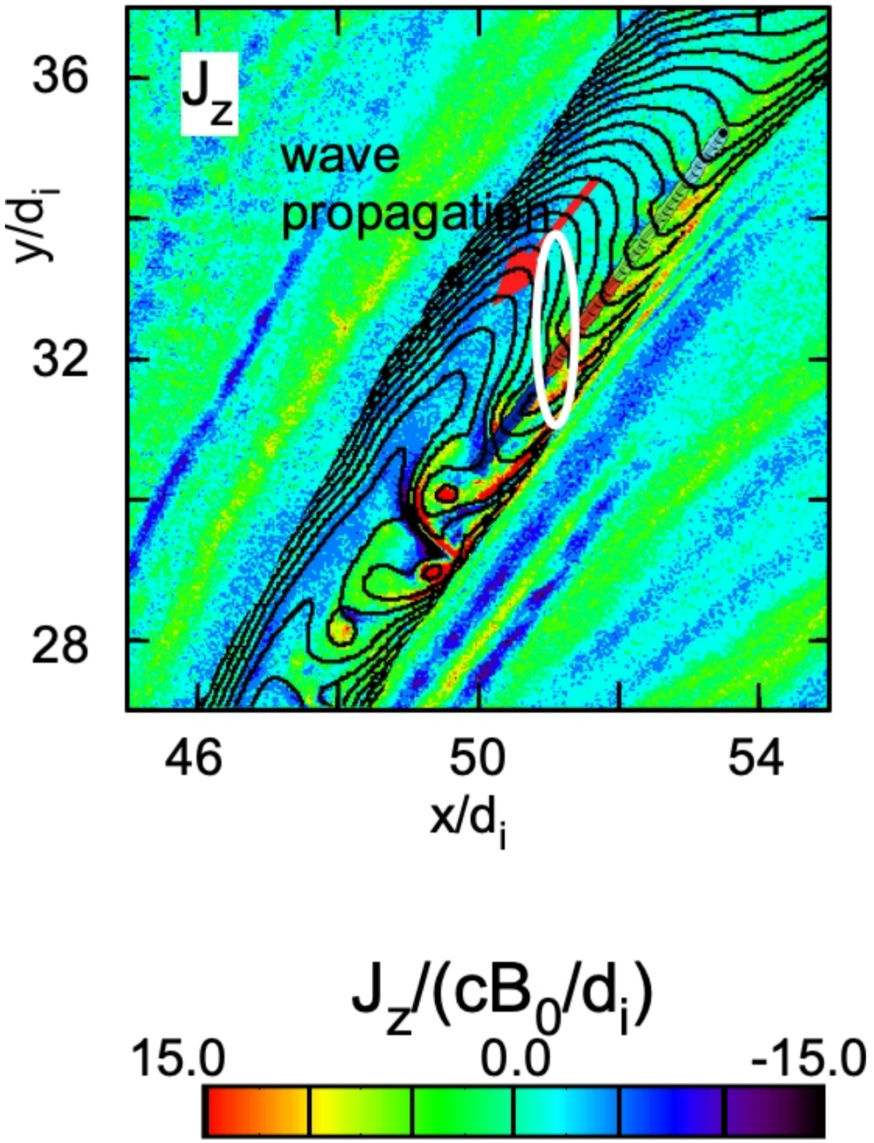




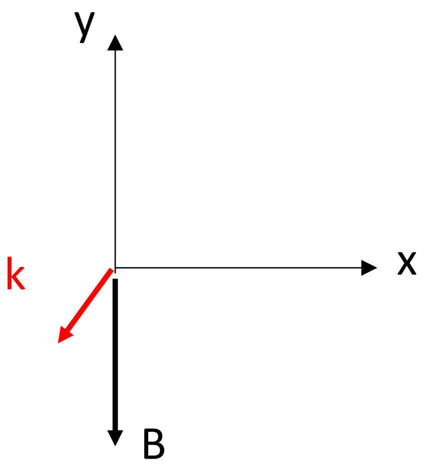
Parallel acceleration due to the LW mode

Secondary instability to excite the SW mode

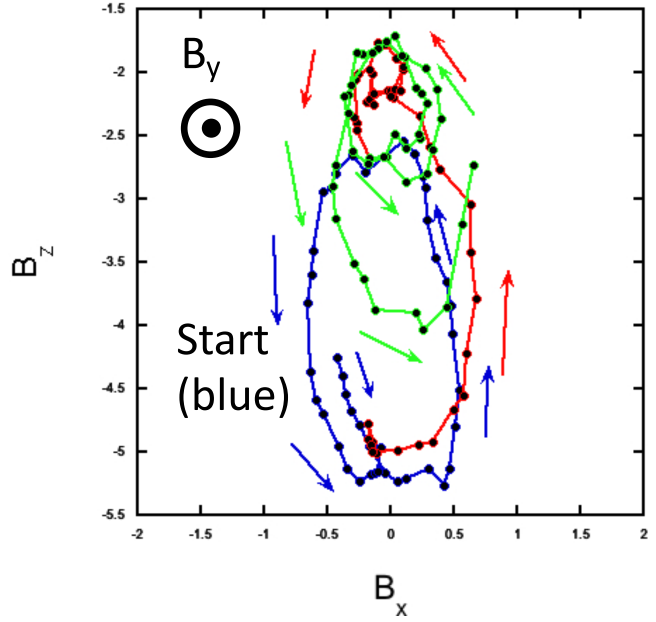
SW mode



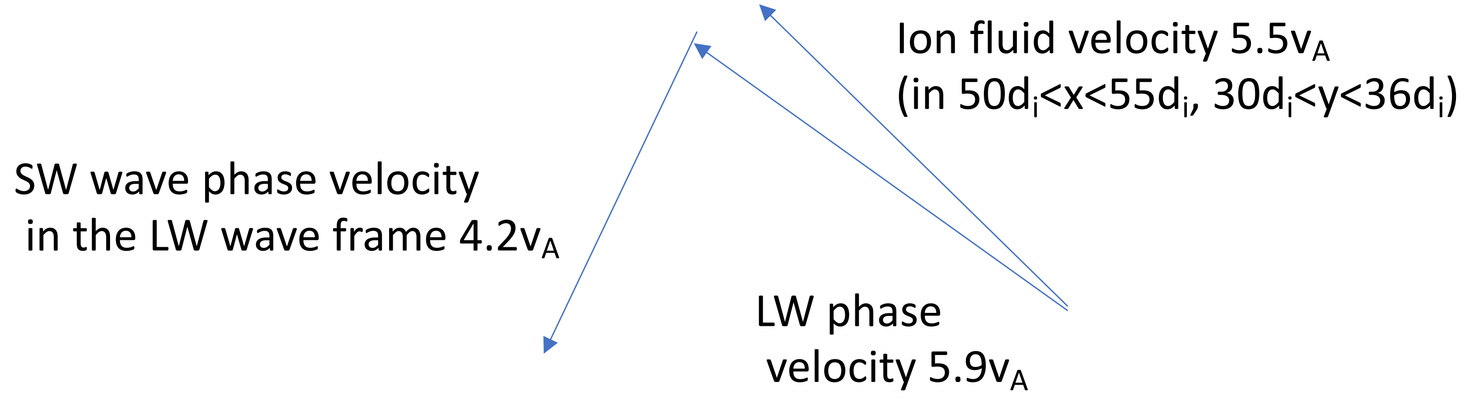
Hodogram analysis



In B_x-B_z plane



Right-handed

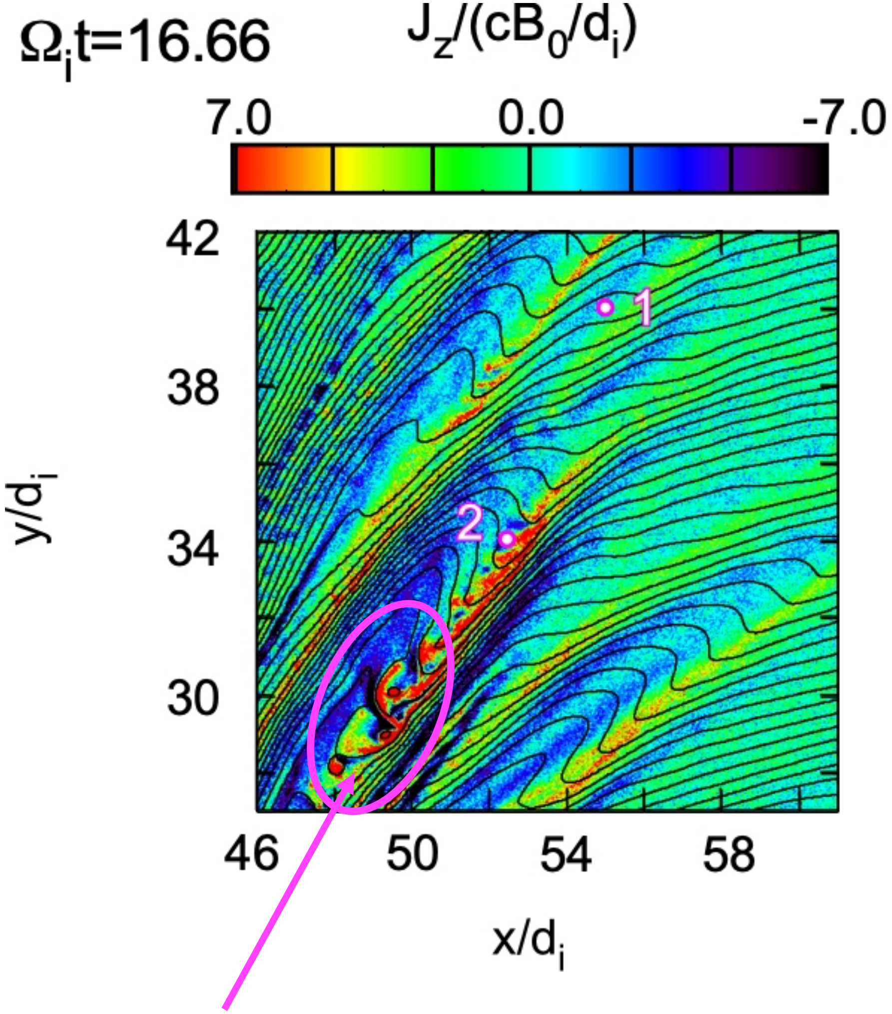


SW wave is propagating in the negative y direction in the plasma rest frame

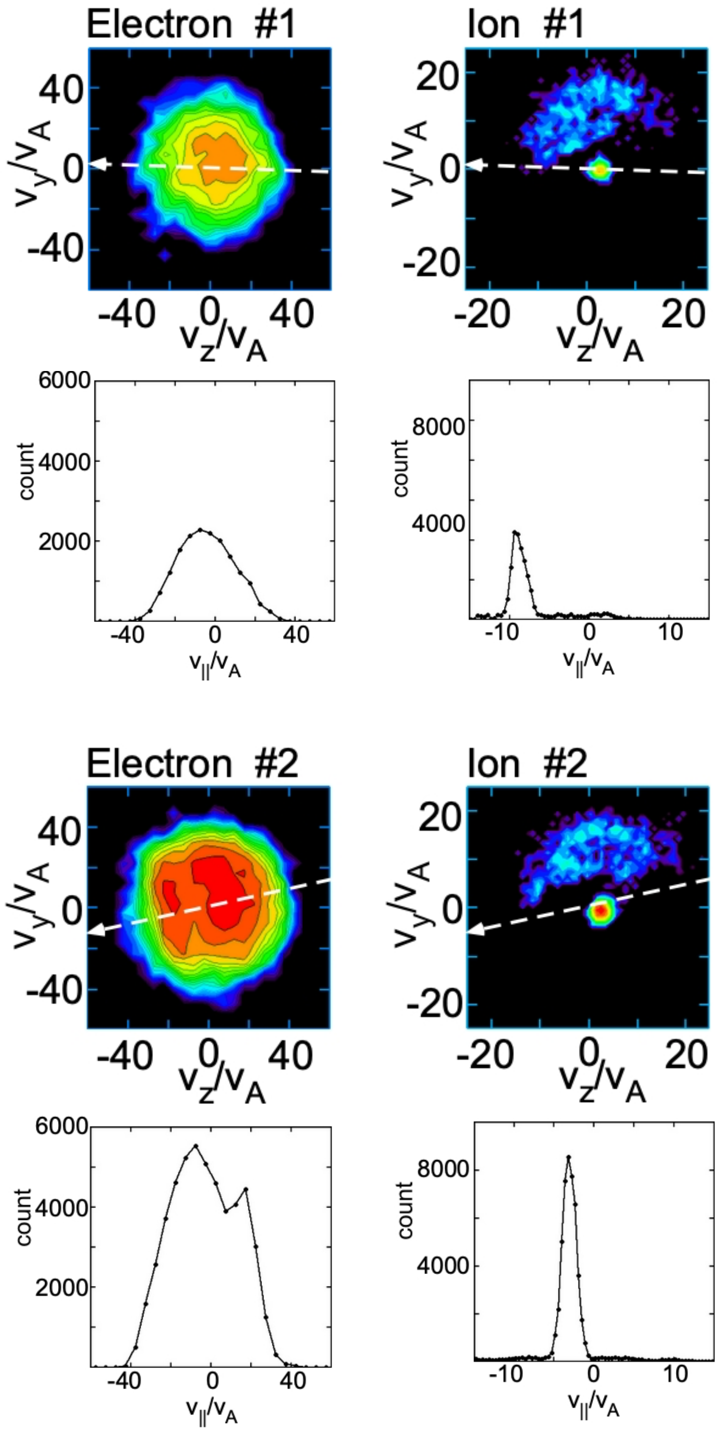
$\lambda < 1d_i$ $\omega \sim 25$-$40\ \Omega_i$ in the plasma rest frame (note $m_i/m_e=200$, $\Omega_e=200\Omega_i$)

Whistler wave due to electron beams

Electron and ion distribution functions in LW and SW modes



Small-scale reconnection



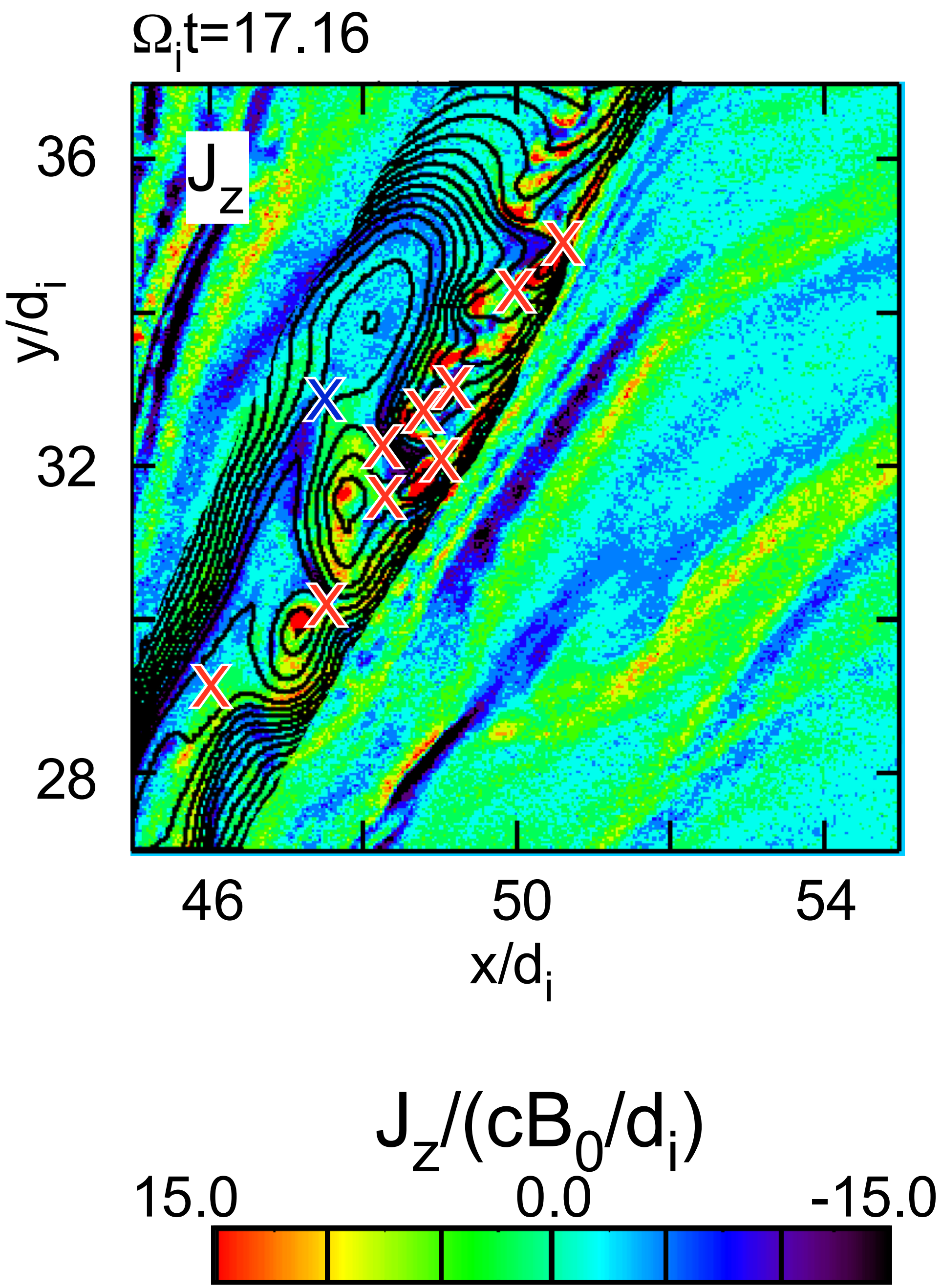
Region #1
LW modes ~ 2-3d_i, right-handed
Two ion beams (cold inflow, hot reflected)
Single-peaked electron

Non-resonant ion mode

Region #2
SW modes < 1d_i, right-handed
Two ion beams (cold inflow, hot reflected)
Multiple electron beams (two-peaked)

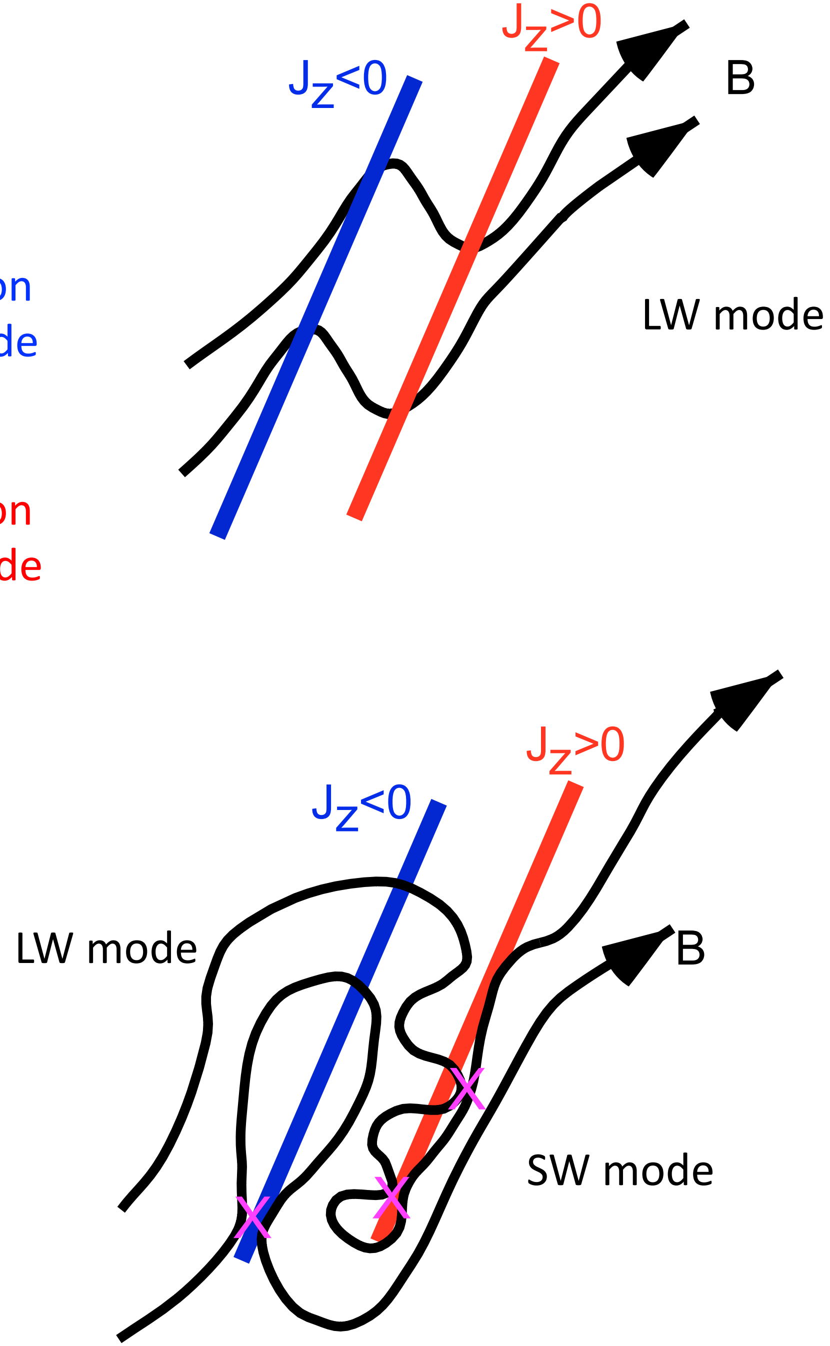
Whistler by parallel beams or MTSI?

How reconnection X-lines are formed by the two types of waves



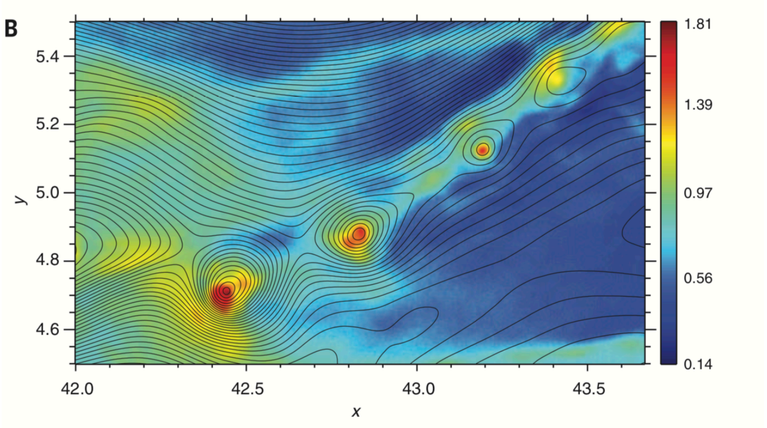
X: Reconnection due to LW mode

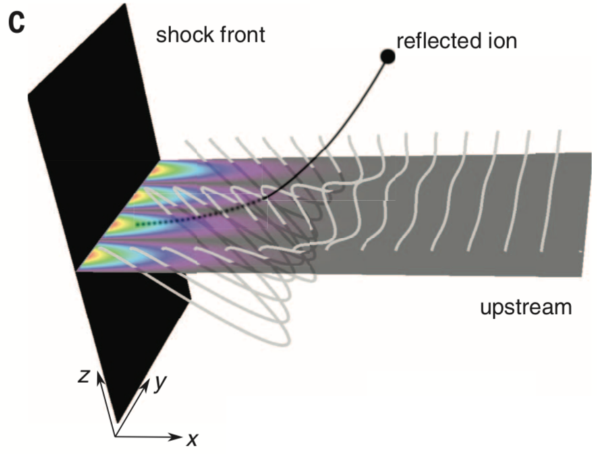
X: Reconnection due to SW mode



Astrophysical shocks (supernova remnants etc.)

M_A ~ 40 or larger (Matsumoto et al. 2015)
Perpendicular shock

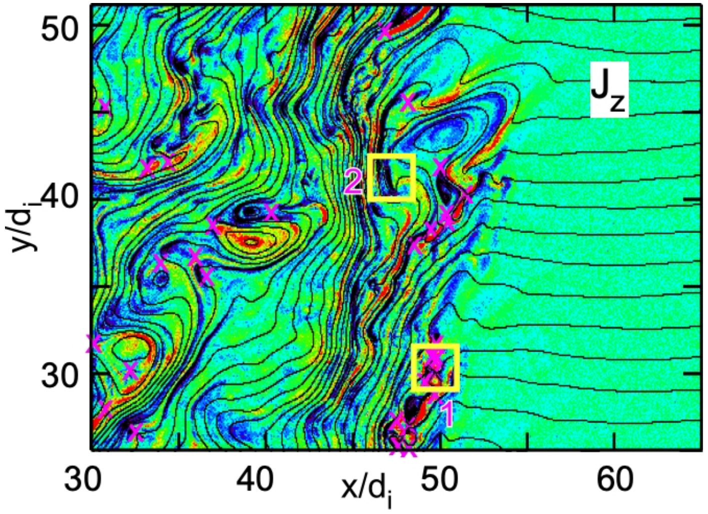


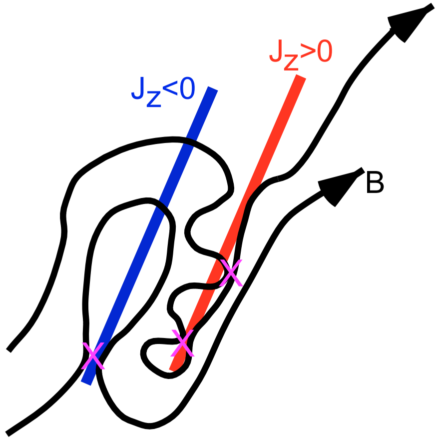


Reconnection is due to Weibel instability

In the Earth's bow shock

M_A ~ 10 or larger (our results)
Quasi-parallel shock





Reconnection is due to non-resonant ion instability and whistler waves/MTSI (?)

Summary

Magnetic reconnection in a quasi-parallel shock (θ=25 degrees, M_A~11.4) has been studied by means of 2D full PIC simulation.

In the shock transition and downstream regions, winding magnetic field lines are generated due to kinetic waves.

Long-wavelength (LW) waves (λ~ 3d_i) and short-wavelength (SW) waves (λ< 1d_i) are excited in the shock transition region.

Long-wavelength waves are due to a non-resonant ion-ion beam instability.

Short-wavelength waves (whistler waves) are excited due to multiple electron and ion beams. Electron beams are due to the electrostatic field in LW waves.

These two types of waves cause bending of magnetic field lines, and reconnection can occur.