Turbulent magnetic reconnection and particle acceleration at nonrelativistic shocks of young supernova remnants

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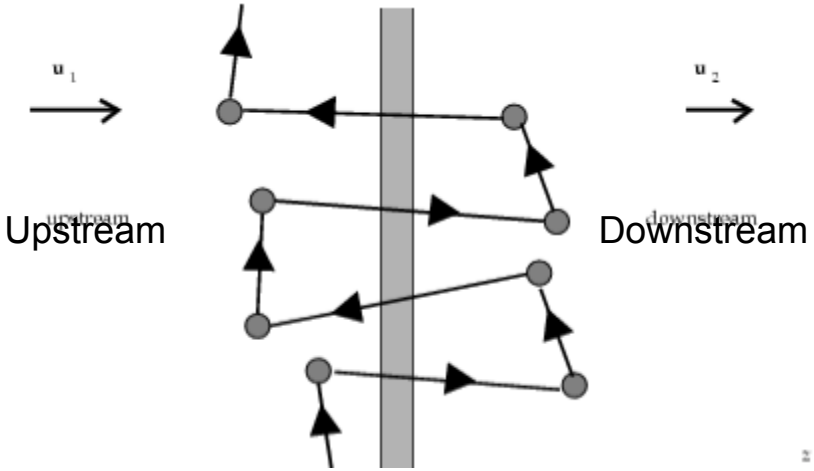
Diffusive Shock Acceleration

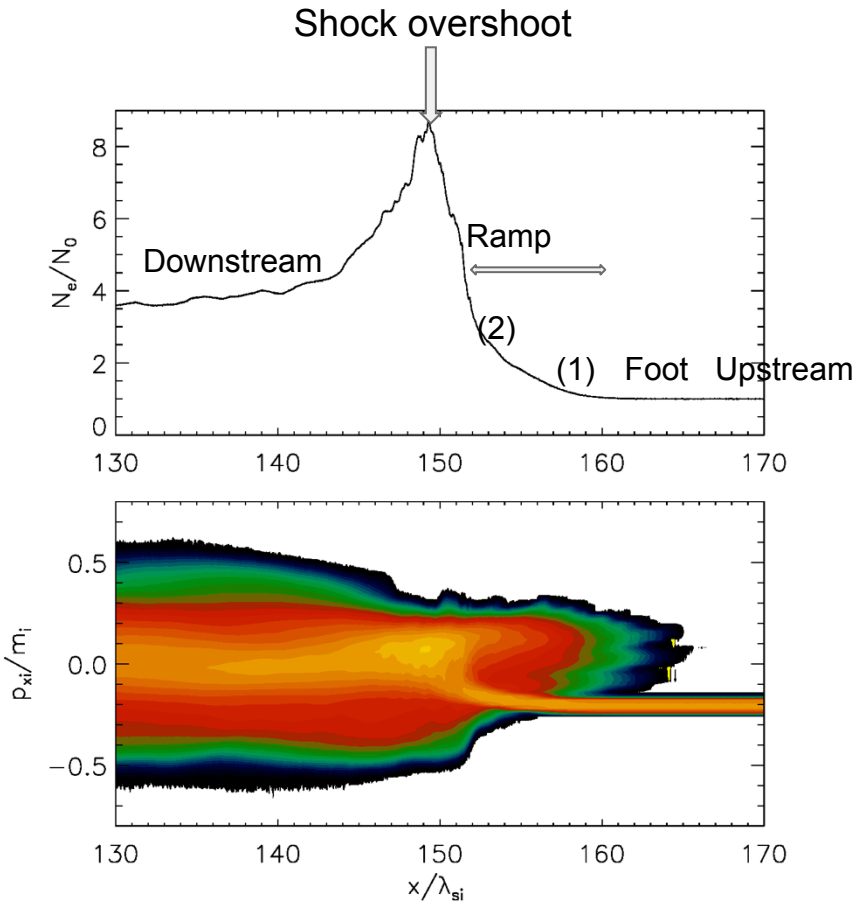
Diffusive Shock Acceleration (DSA) process at young SNR shocks assumed to provide the main part of Galactic cosmic-ray flux. Possibly relevant for mildly-relativistic flows in AGN jets.

Attributes relevant for DSA:

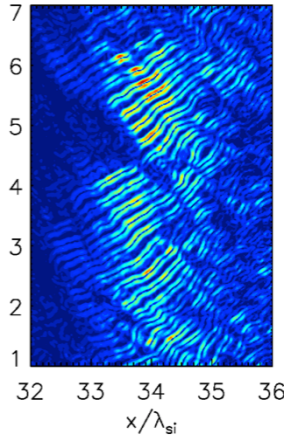
- shock structure: ion driven but electron dynamics important
- EM field amplitudes
- particle pre-acceleration processes: electron injection constitutes the central unresolved issue



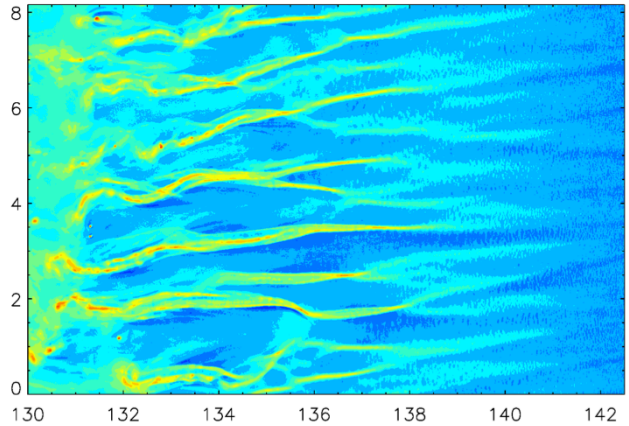
Perpendicular shock structure



(1) Buneman instability (electrostatic waves), interaction of reflected ions and upstream electrons



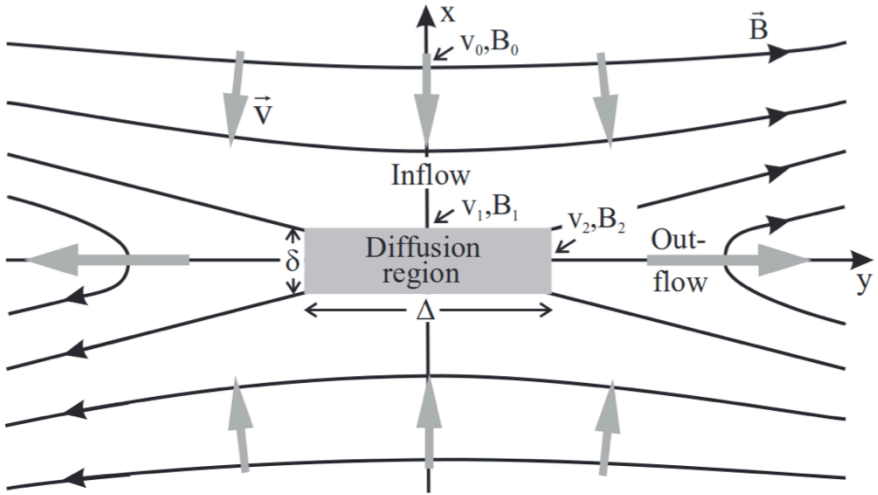
(2) ion-beam-Weibel instability, interaction of reflected and upstream ions

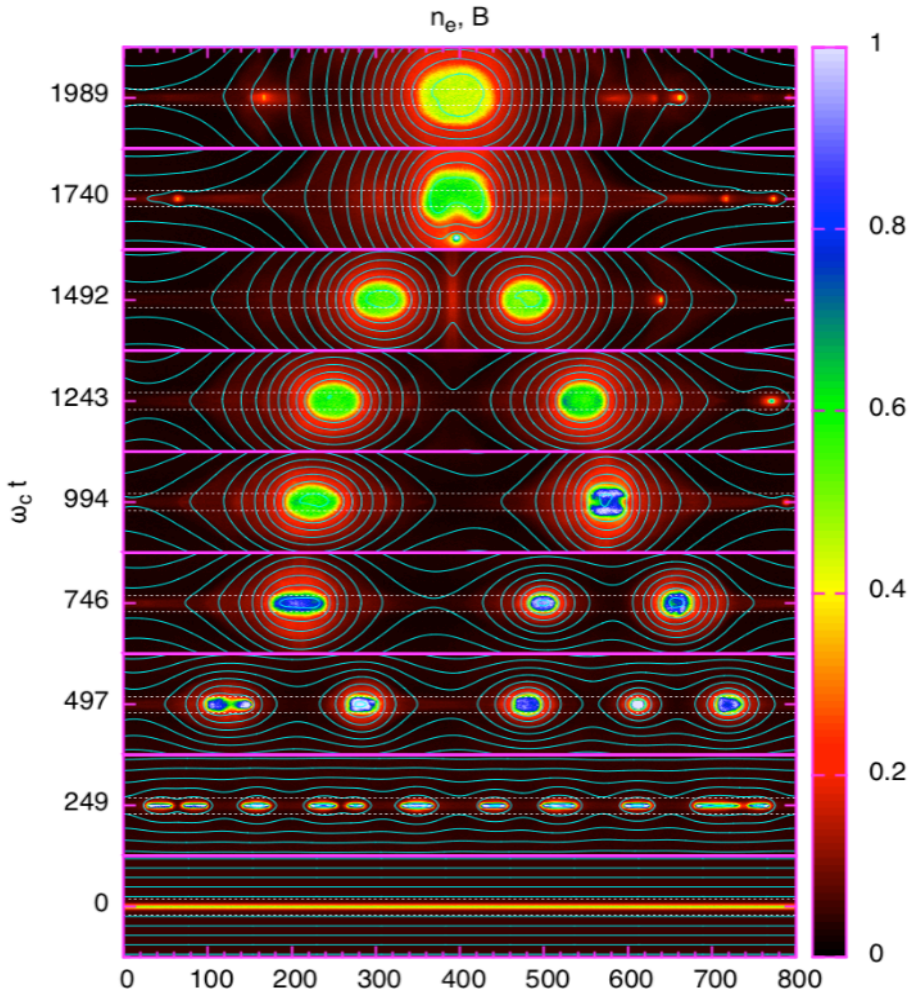


Magnetic reconnection

Ubiquitous plasma process which refers to the breaking and reconnecting of oppositely directed magnetic field lines in a plasma.

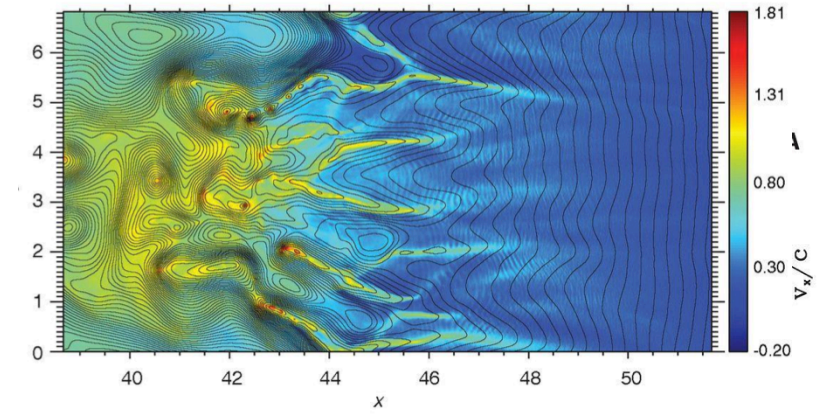
Magnetic energy is converted to kinetic energy, thermal energy and particle acceleration.

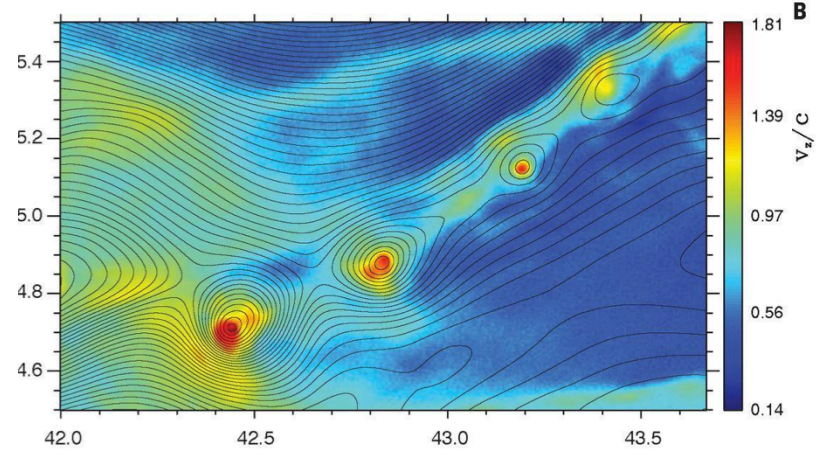


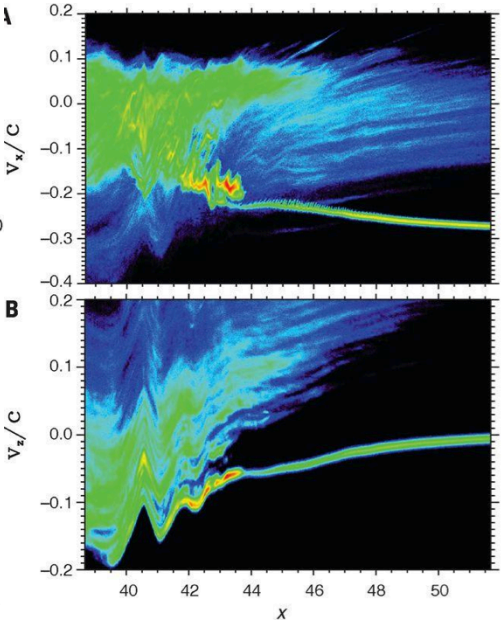


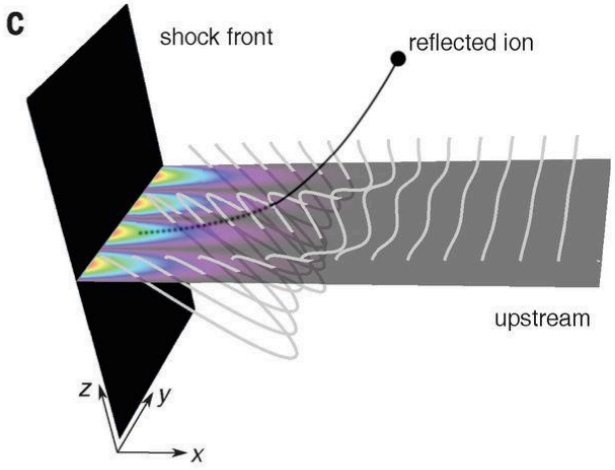
Nalewajko et al. 2015

Spontaneous turbulent reconnection in the foot region at perpendicular high Mach numbers shocks (Matsumoto et al. 2015)







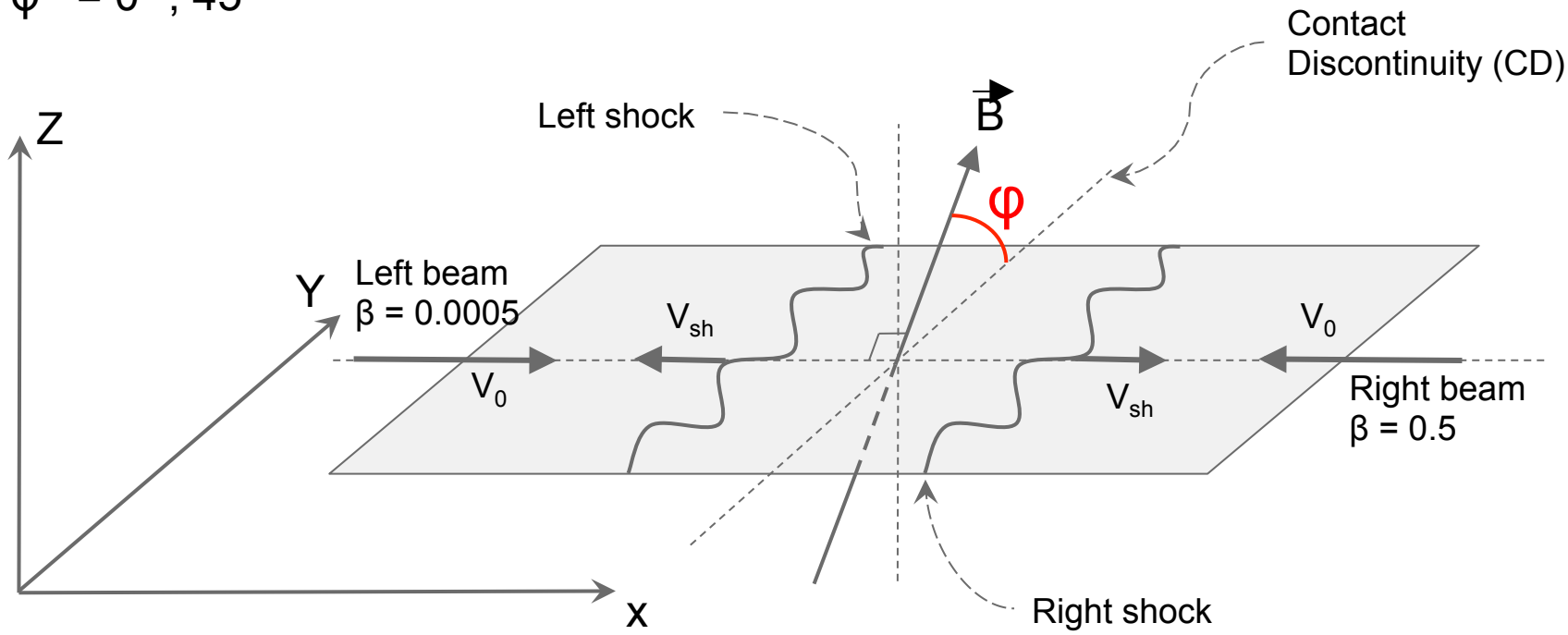


Simulation setup

Particle-in-cell 2D3V simulations

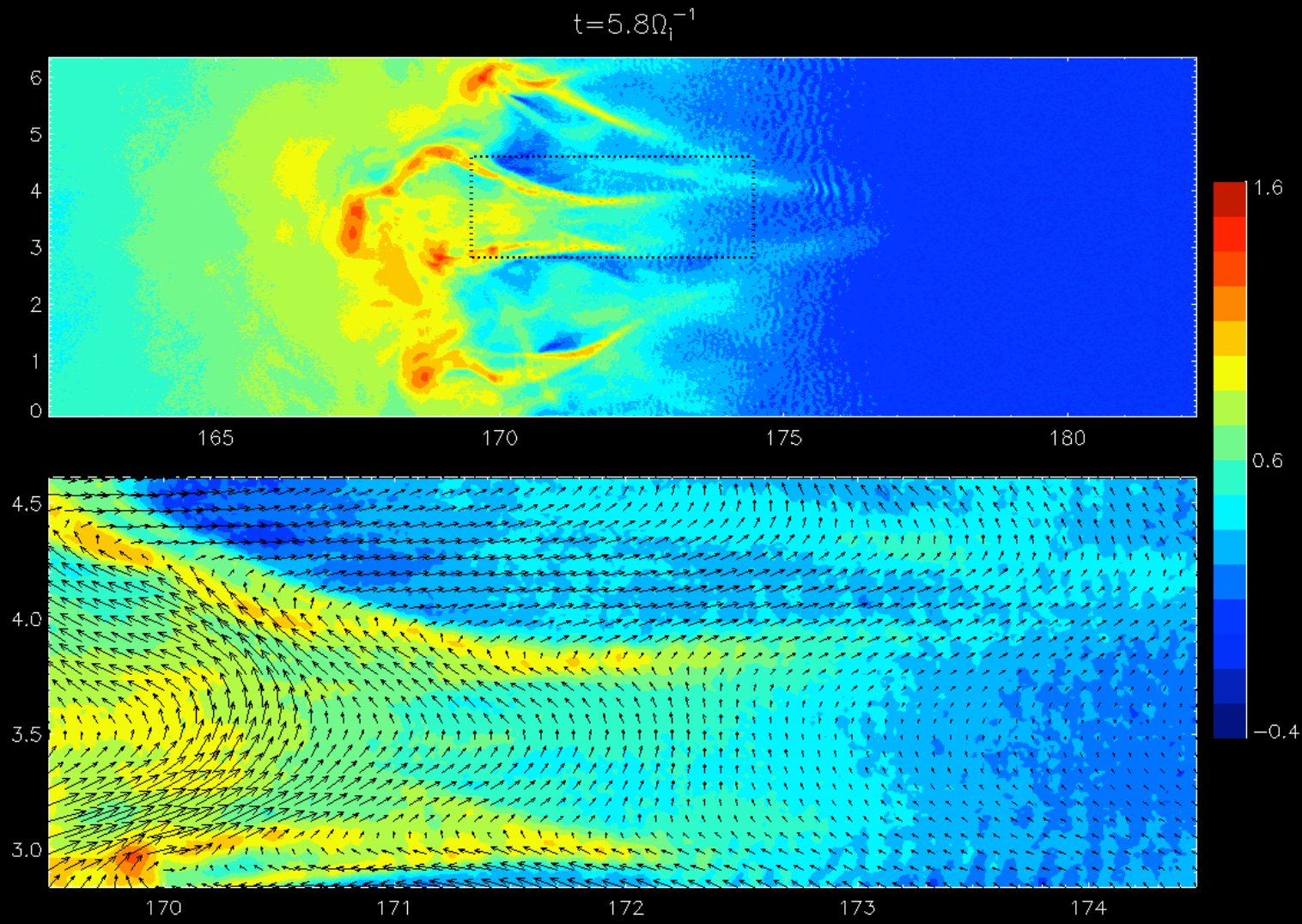
$V_0 = 0.2c$

$\varphi = 0^o ; 45^o$



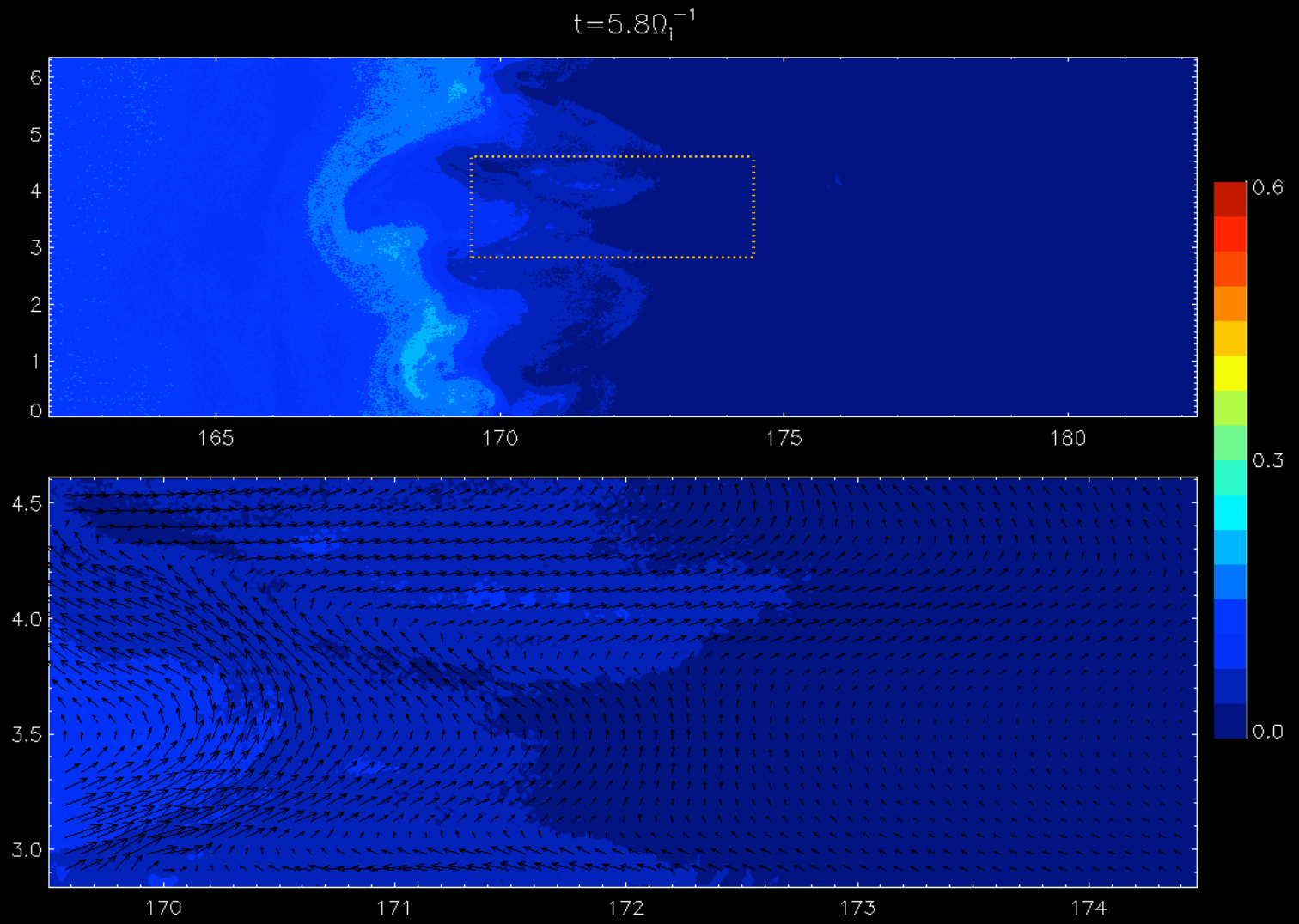
Matsumoto et al. 2015 parameters	Our parameters
$\varphi = 0^o$	$\varphi = 0^o$, 45^o
$m_i/m_e=225$	$m_i/m_e=$ 50, 100, 200, 400
$M_A=41.7$	$M_A=$ 22.6 - 68.7
$L_y=6.8\ \lambda_{si}$	$L_y=$ (6.1 - 24) λ_{si}

Magnetic reconnection in the foot region, in-plane magnetic field configuration



Legend:
Color map - electron density,
Black arrows - magnetic field in x-y plane

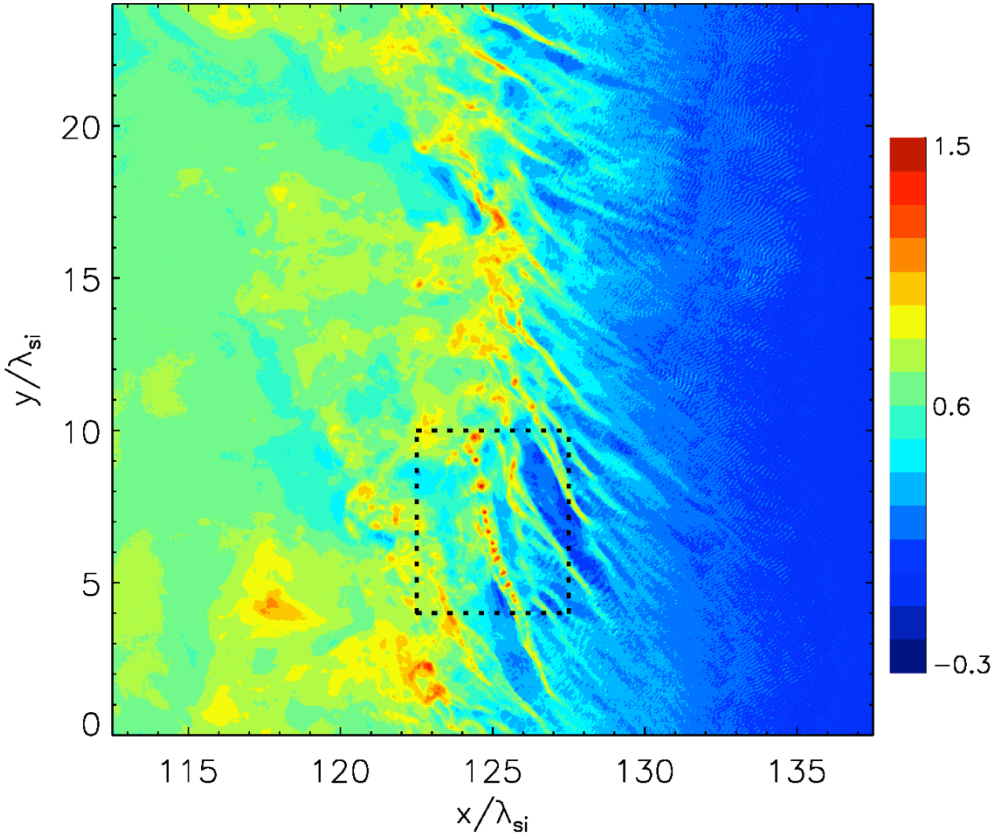
Magnetic reconnection in the foot region, in-plane magnetic field configuration

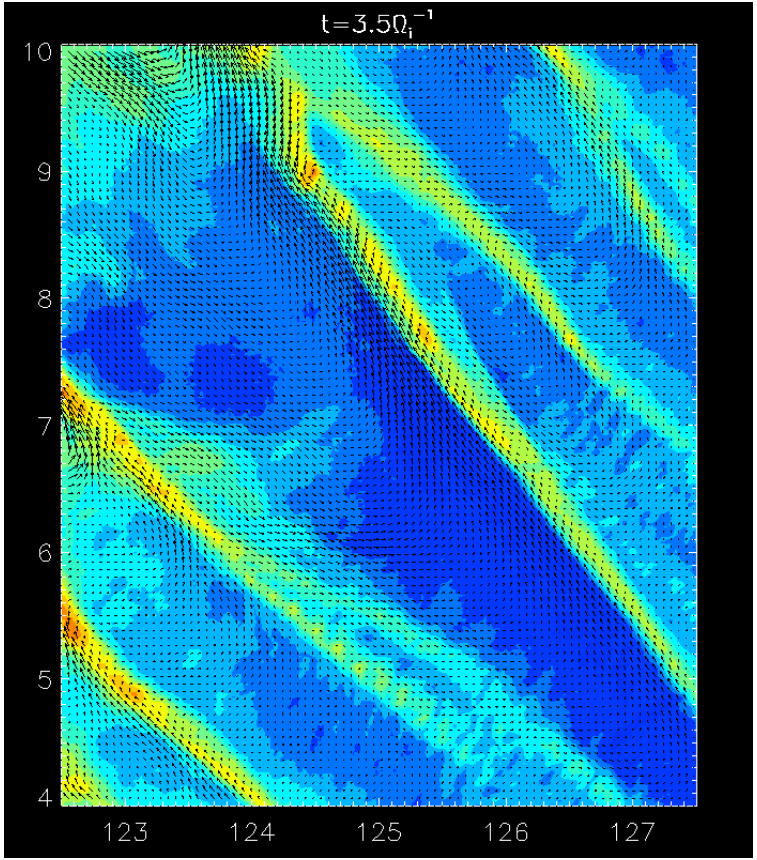


Legend:
Color map - (ɣ-1) of electrons,
Black arrows - magnetic field in x-y plane

Magnetic reconnection
45º magnetic field configuration

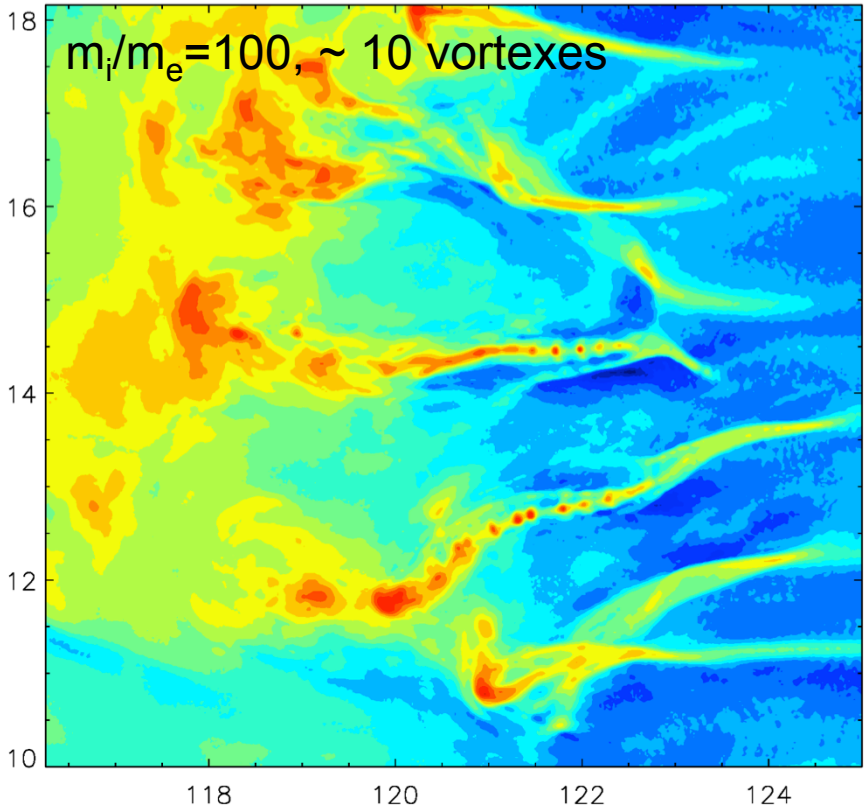
Legend:
Color map - electron density,
Black arrows - magnetic field in x-y plane

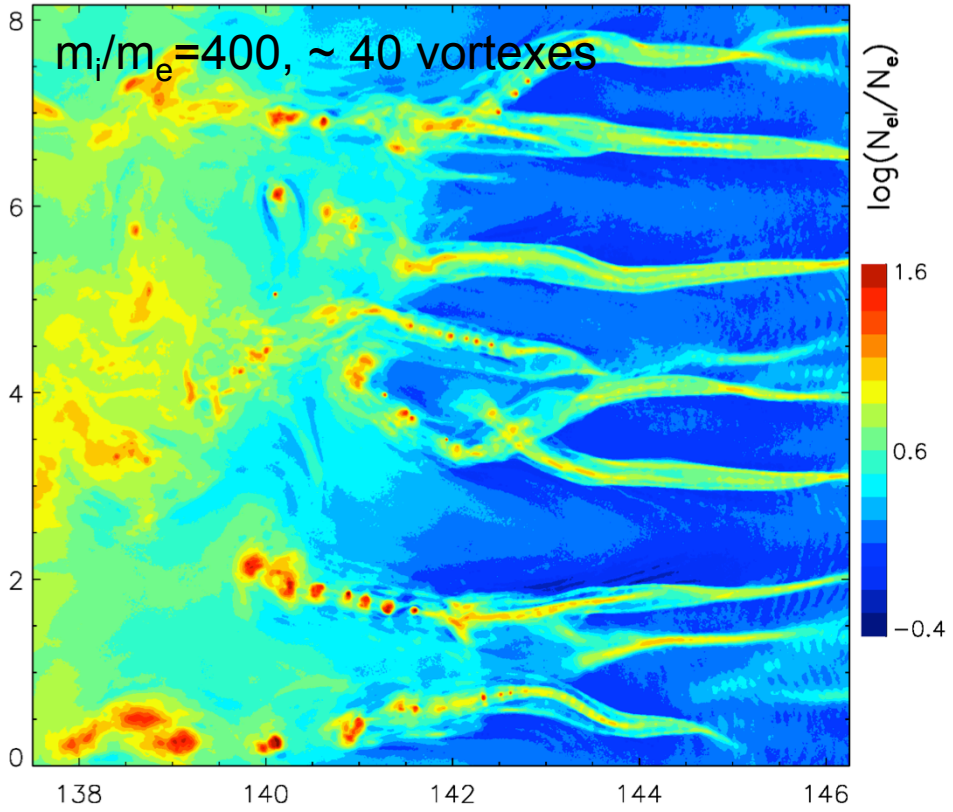




Magnetic vortex statistics

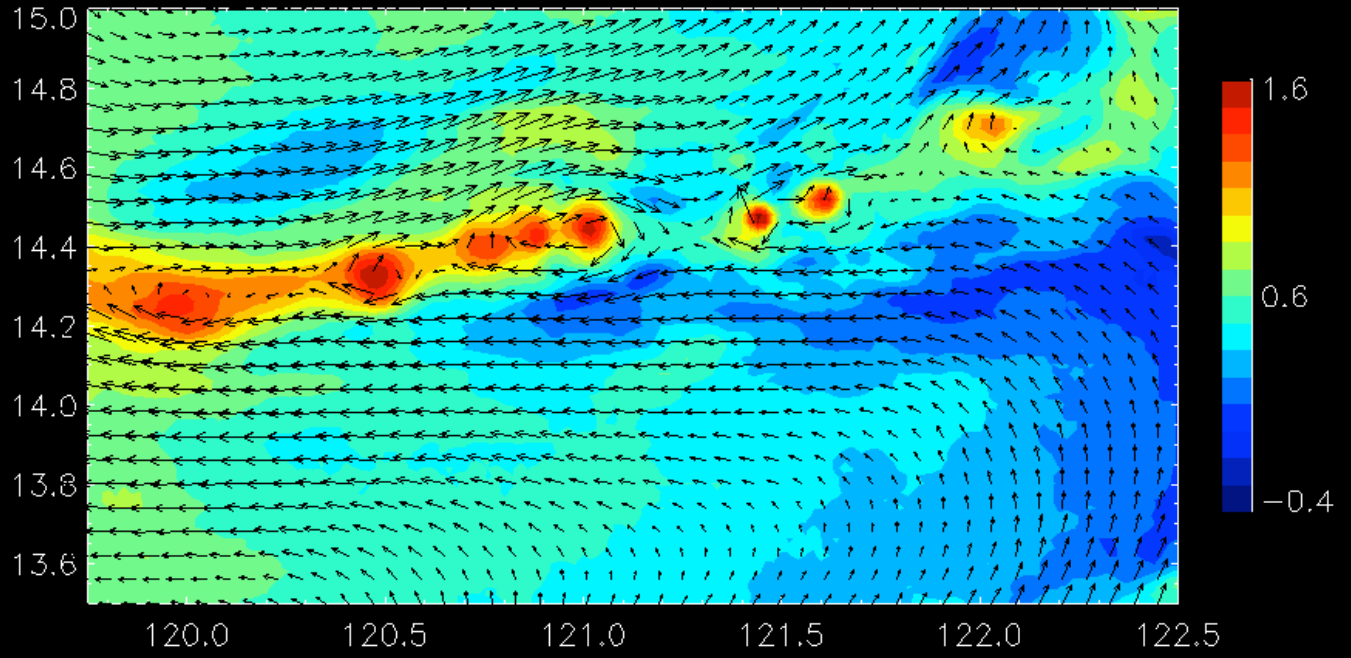
increase with mass ratio
larger for higher plasma beta
larger for 45^{o} configuration

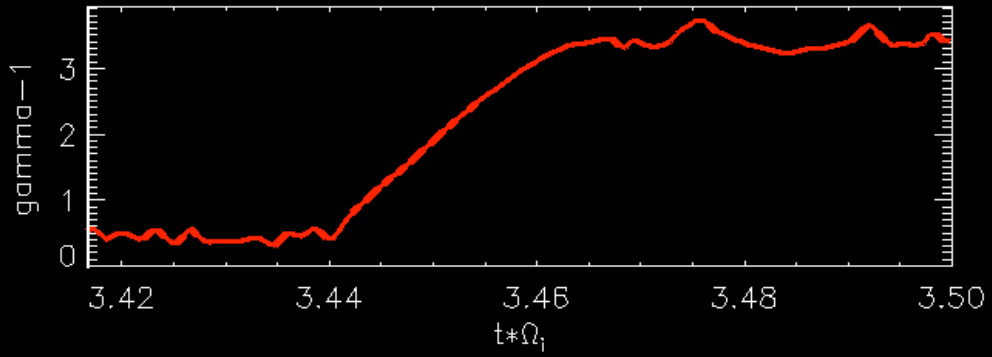




Particle acceleration

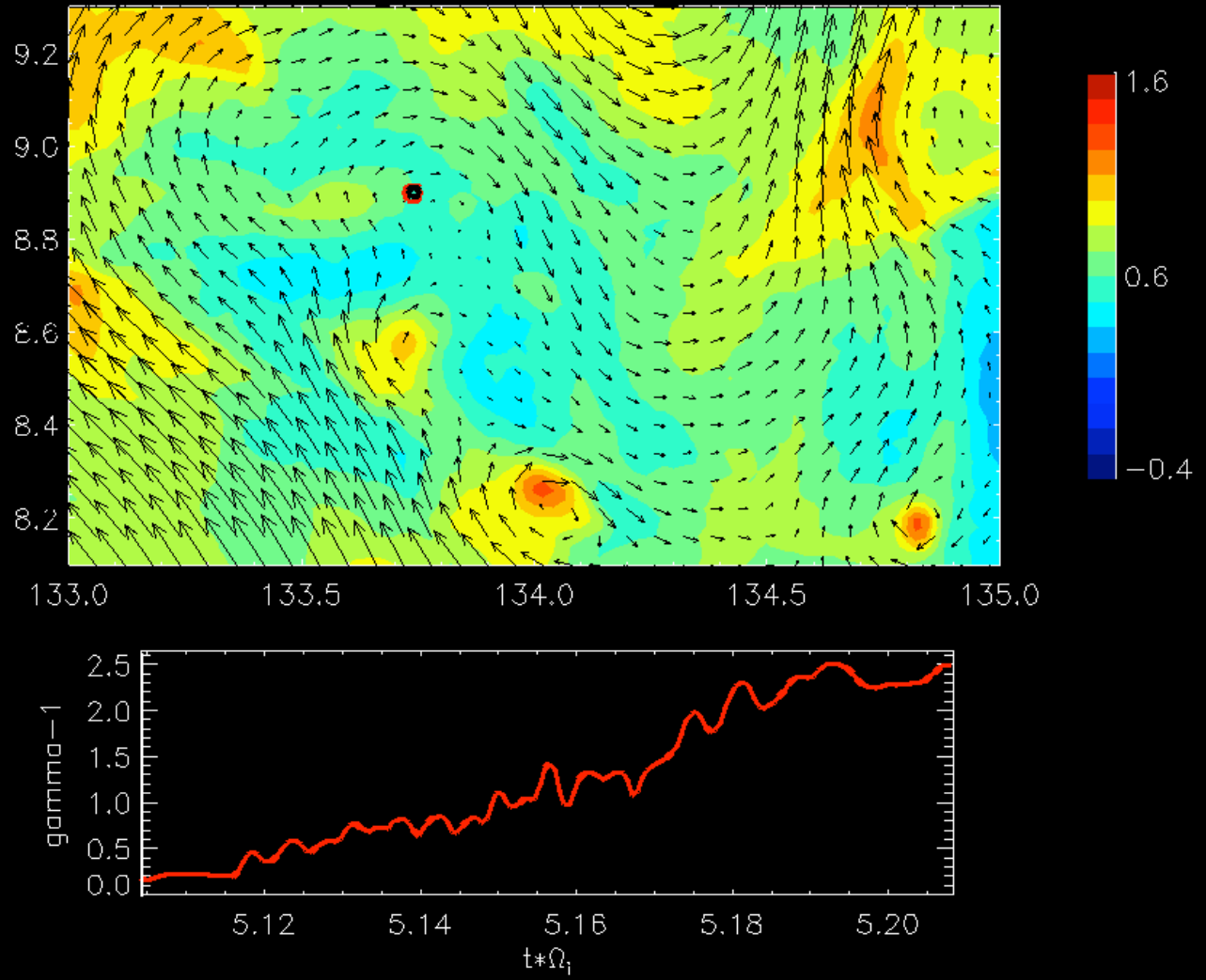
Trajectory of electron accelerated by E_z in x-point region





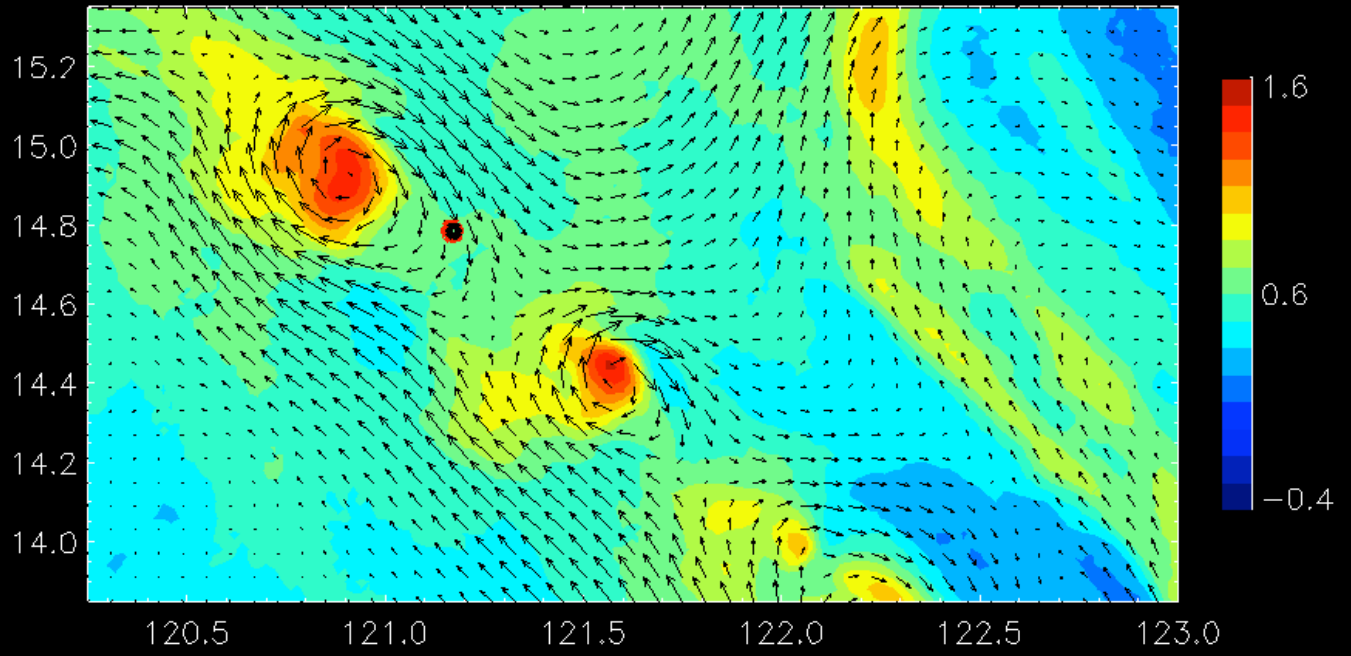
Legend:
Top panel: Color map - electron density, Black arrows - magnetic field in x-y plane, red line - trajectory of electron, black circle - position of electron;
Bottom panel: (ɣ-1) of electron, white line - time step for top panel.

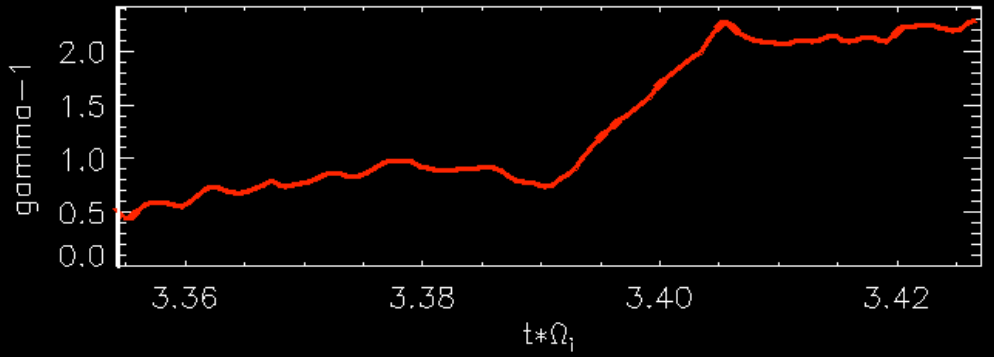
Trajectory of electron captured by magnetic vortex



Legend:
Top panel: Color map - electron density, Black arrows - magnetic field in x-y plane, red line - trajectory of electron, black circle - position of electron;
Bottom panel: (ɣ-1) of electron, white line - time step for top panel.

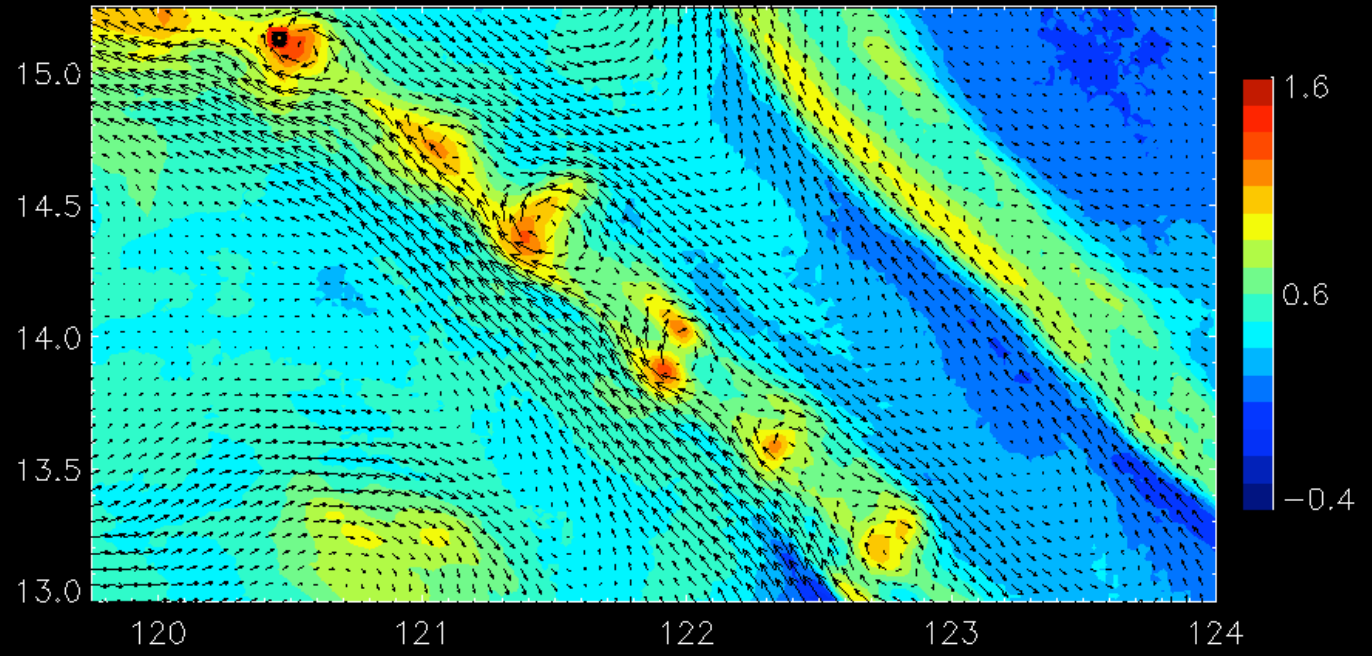
Trajectory of electron accelerated via bouncing between colliding islands

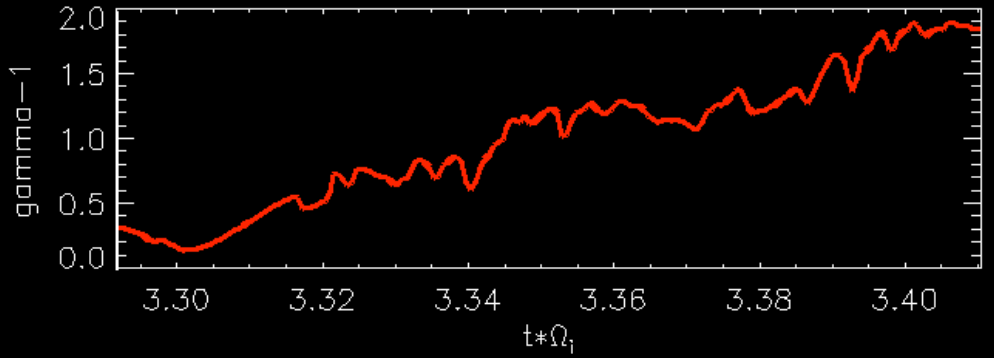




Legend:
Top panel: Color map - electron density, Black arrows - magnetic field in x-y plane, red line - trajectory of electron, black circle - position of electron;
Bottom panel: (ɣ-1) of electron, white line - time step for top panel.

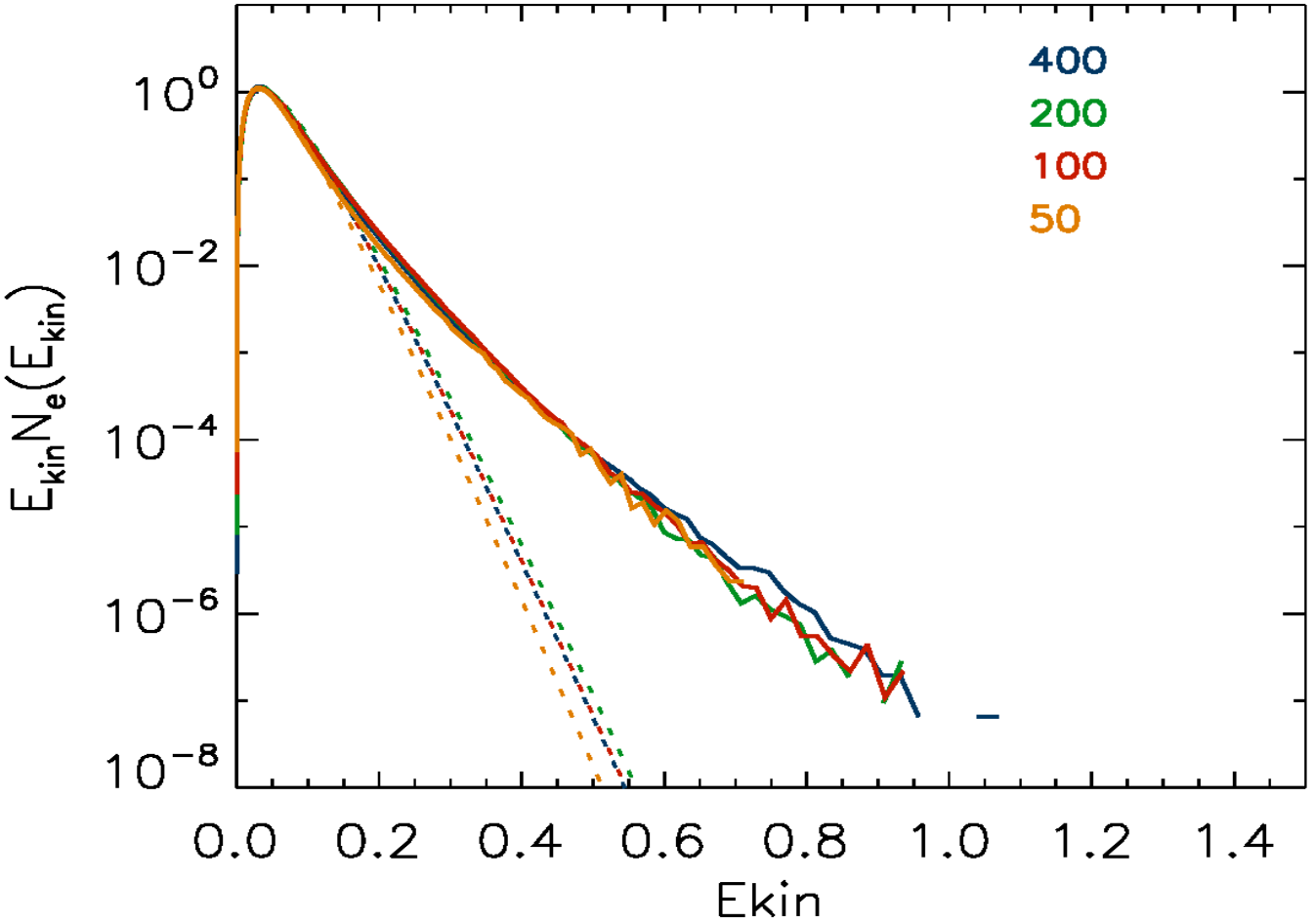
Trajectory of electron accelerated via stochastic interaction with magnetic islands





Legend:
Top panel: Color map - electron density, Black arrows - magnetic field in x-y plane, red line - trajectory of electron, black circle - position of electron;
Bottom panel: (ɣ-1) of electron, white line - time step for top panel.

Downstream spectra after rescaling



Conclusions

1. Magnetic reconnection observed for 45^{o} and in-plane (0^{o}) magnetic field configurations. Particles can be accelerated in the reconnection structures.

2. Efficiency of magnetic reconnection formation linearly depends on ion-to-electron mass ratio.

3. At the same time particle downstream spectra do not change with ion-to-electron mass ratio, suggesting that the role of electron acceleration in the magnetic reconnection structures is subdominant compared to the stochastic acceleration in the turbulent shock precursor.

4. Independence on the ion-to-electron mass ratio makes realistic 3D shock modeling feasible.