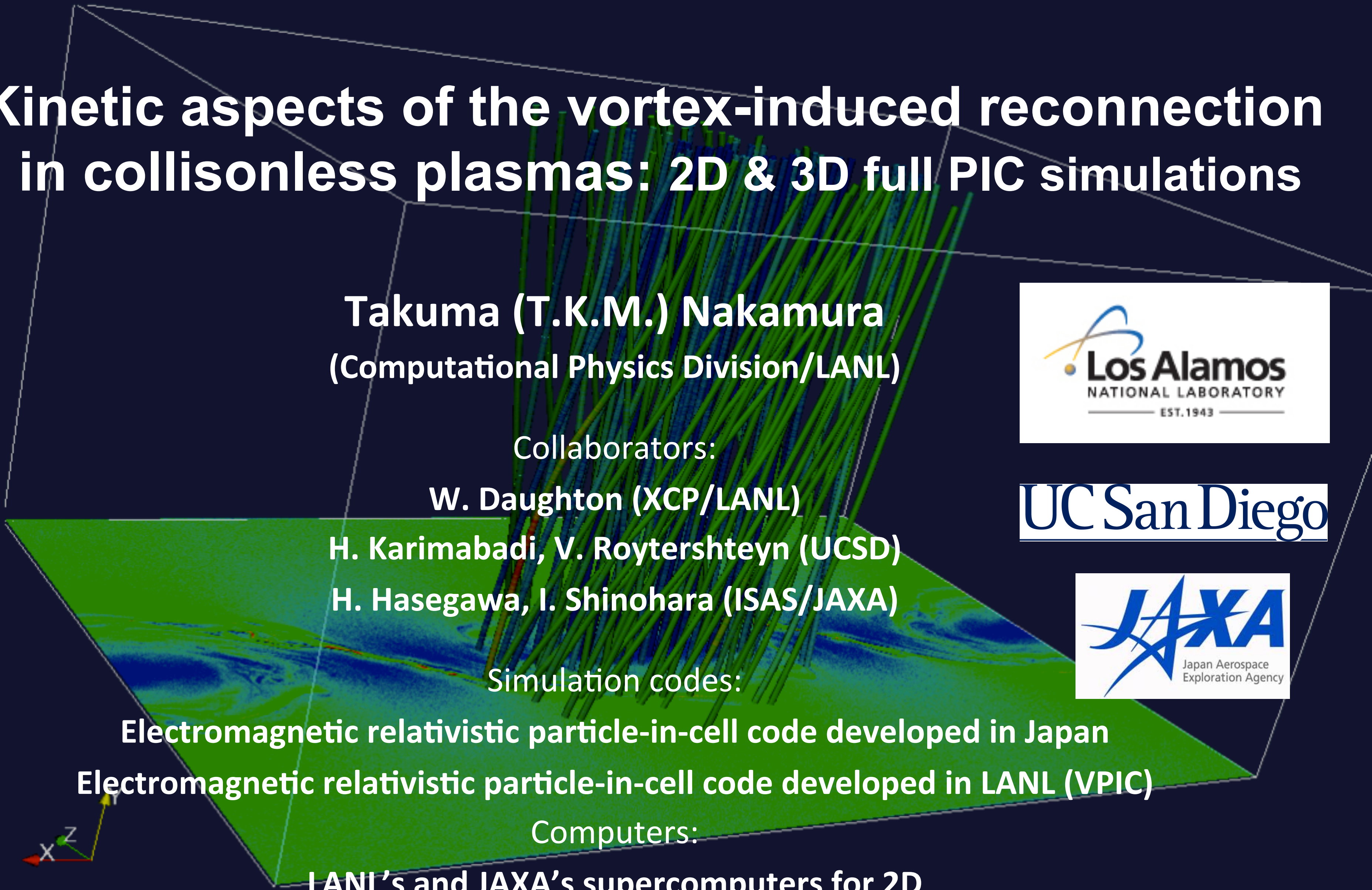
Kinetic aspects of the vortex-induced reconnection in collisonless plasmas: 2D & 3D full PIC simulations



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Simulation codes:

Electromagnetic relativistic particle-in-cell code developed in Japan

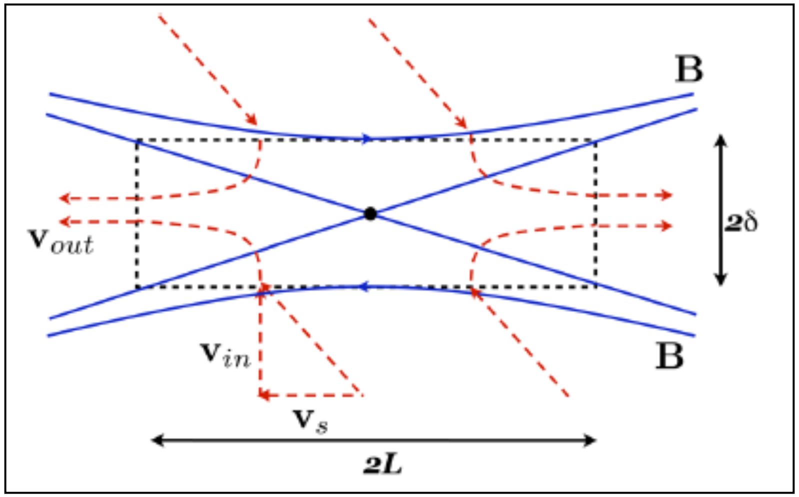
Electromagnetic relativistic particle-in-cell code developed in LANL (VPIC)

Computers:

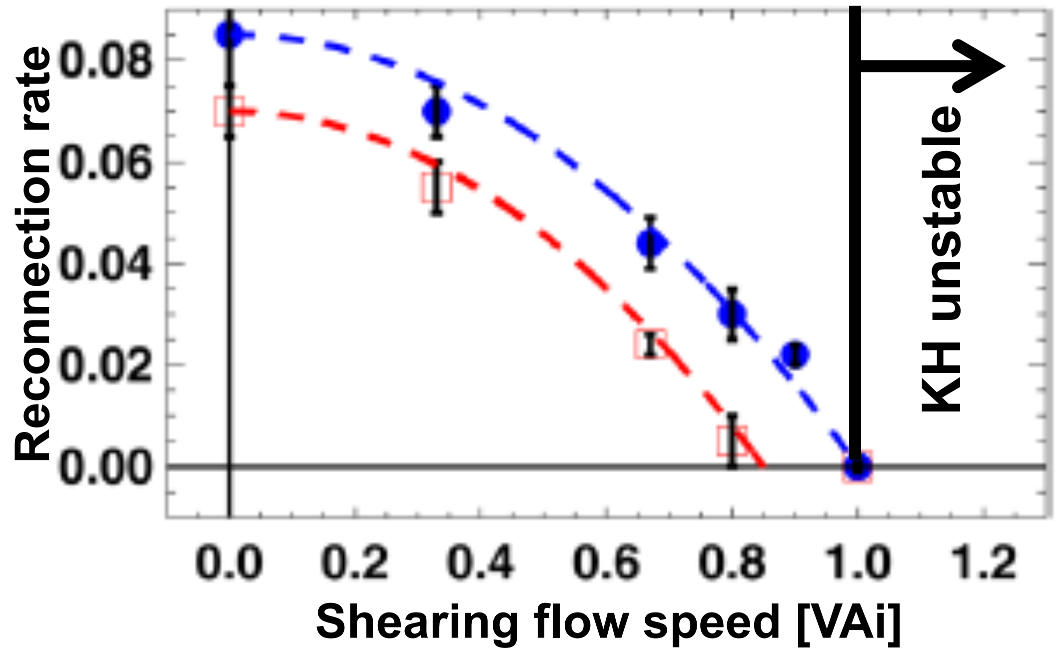
LANL's and JAXA's supercomputers for 2D

Jaguar (Oak Ridge Leadership Computing Facility) for 3D

Reconnection + velocity shear



Reconnection region with velocity shear

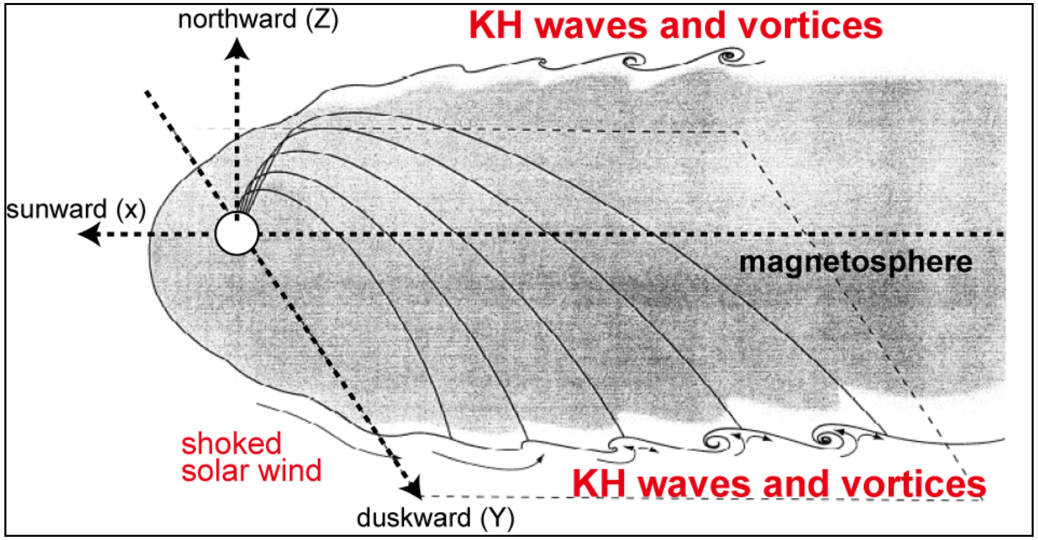


[Cassak & Otto, 2011]

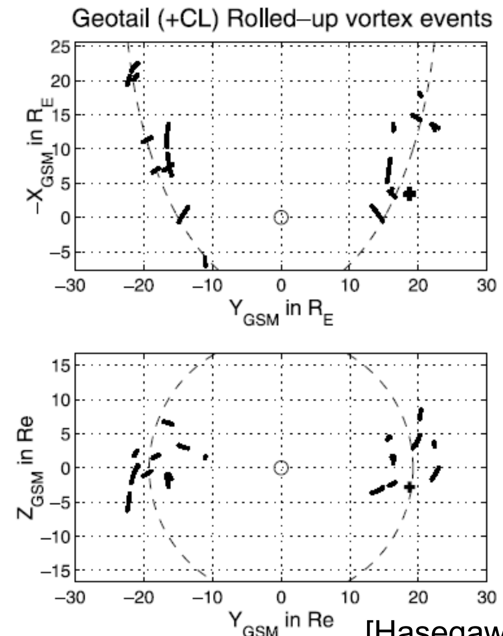
◆Basically, the velocity shear reduces the reconnection rate [e.g., Cassak & Otto, 2011].

◆BUT, super Alfvenic shearing flow produces the Kelvin-Helmholtz instability.
→ **The resulting KH vortex can induce reconnection.**

KH vortex at the Earth's magnetopause



[Fairfield et al., 2000]



[Hasegawa et al. ,2006]

◆At the planetary magnetopause, the velocity shear between solar wind and magnetospheric plasmas increases with down tail distance.

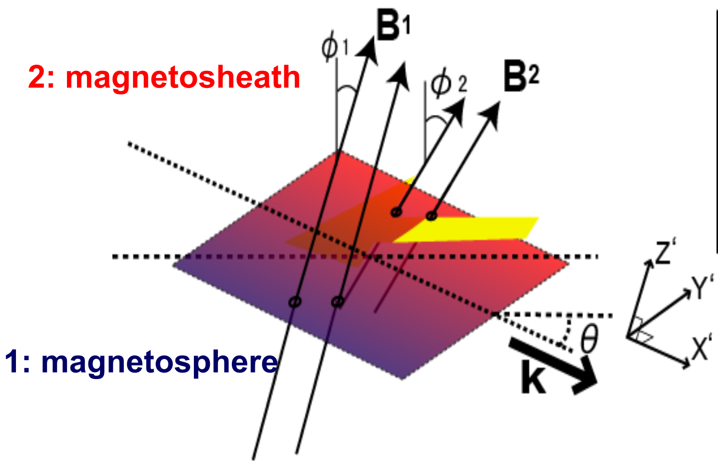
→KH vortices would grow along the tail-flank magnetopause.

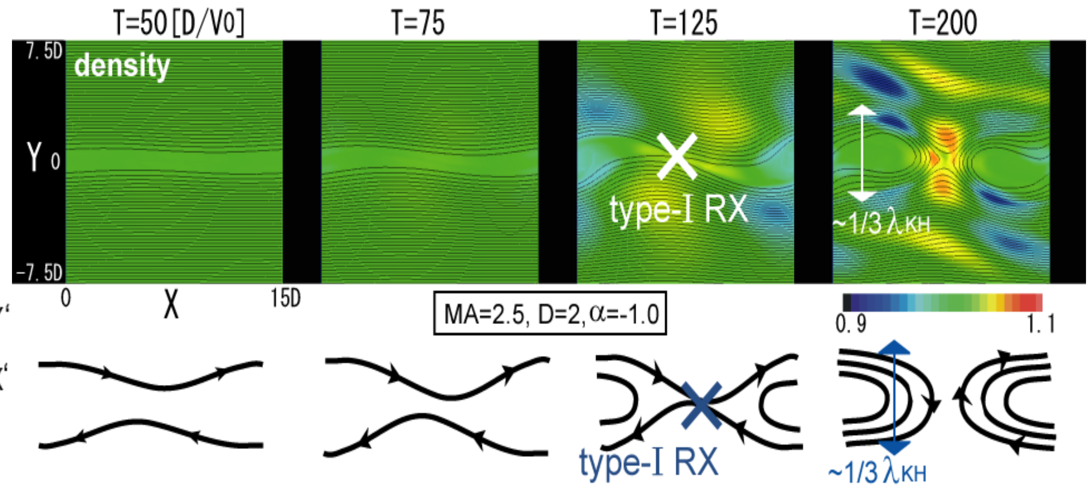
→ Indeed, in-situ observations have confirmed the rolled-up vortices there.

[e.g., Fairfield et al., 2000; Hasegawa et al., 2004, 2006, using Geotail, Cluster, THEMIS].

Q. Can the vortex-induced reconnection also occur there?

VIR at the Earth's magnetopause





The type-I VIR by two-fluid simulation [Nakamura et al., 2008]

A. Yes.

→ Linear analyses suggested that **the vortex-induced reconnection (VIR) commonly appear** at the Earth's magnetopause [Nakamura et al., 2006, 2008].

← This is because the magnetic shear (the current sheet) always exists at the magnetopause.

◆Note that **the VIR can lead to plasma mixing** along reconnected field lines, and would form the part of the tail-flank low-latitude boundary layer (LLBL).

1. 2D symmetric case [Nakamura et al., JGR, 2011]

(Plasmas and fields are symmetric across the boundary)

2. 2D asymmetric case [Nakamura et al., in prep.]

(considering **density jump** across the boundary)

3. 3D symmetric case [On-going]

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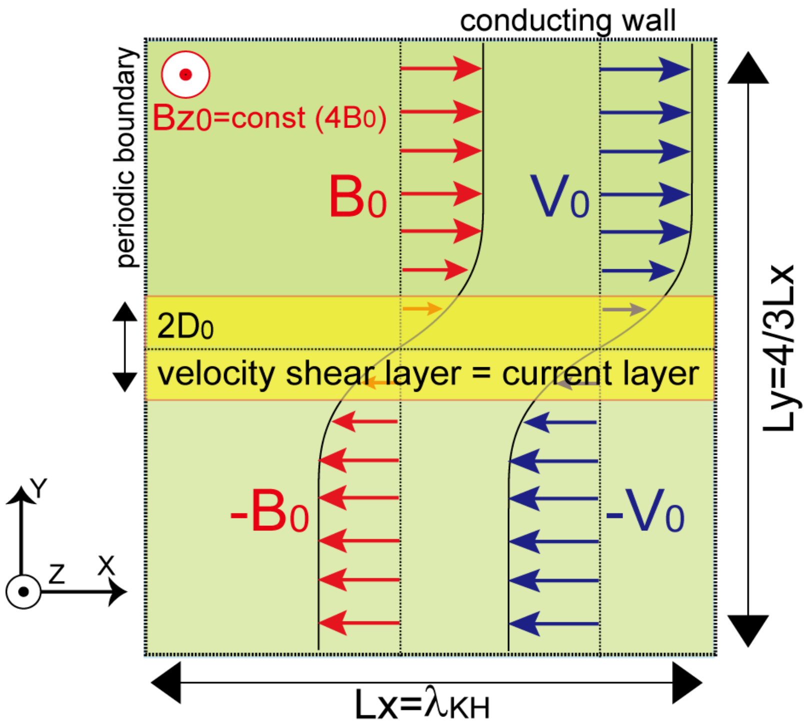
Symmetric case [Nakamura et al., JGR, 2011]

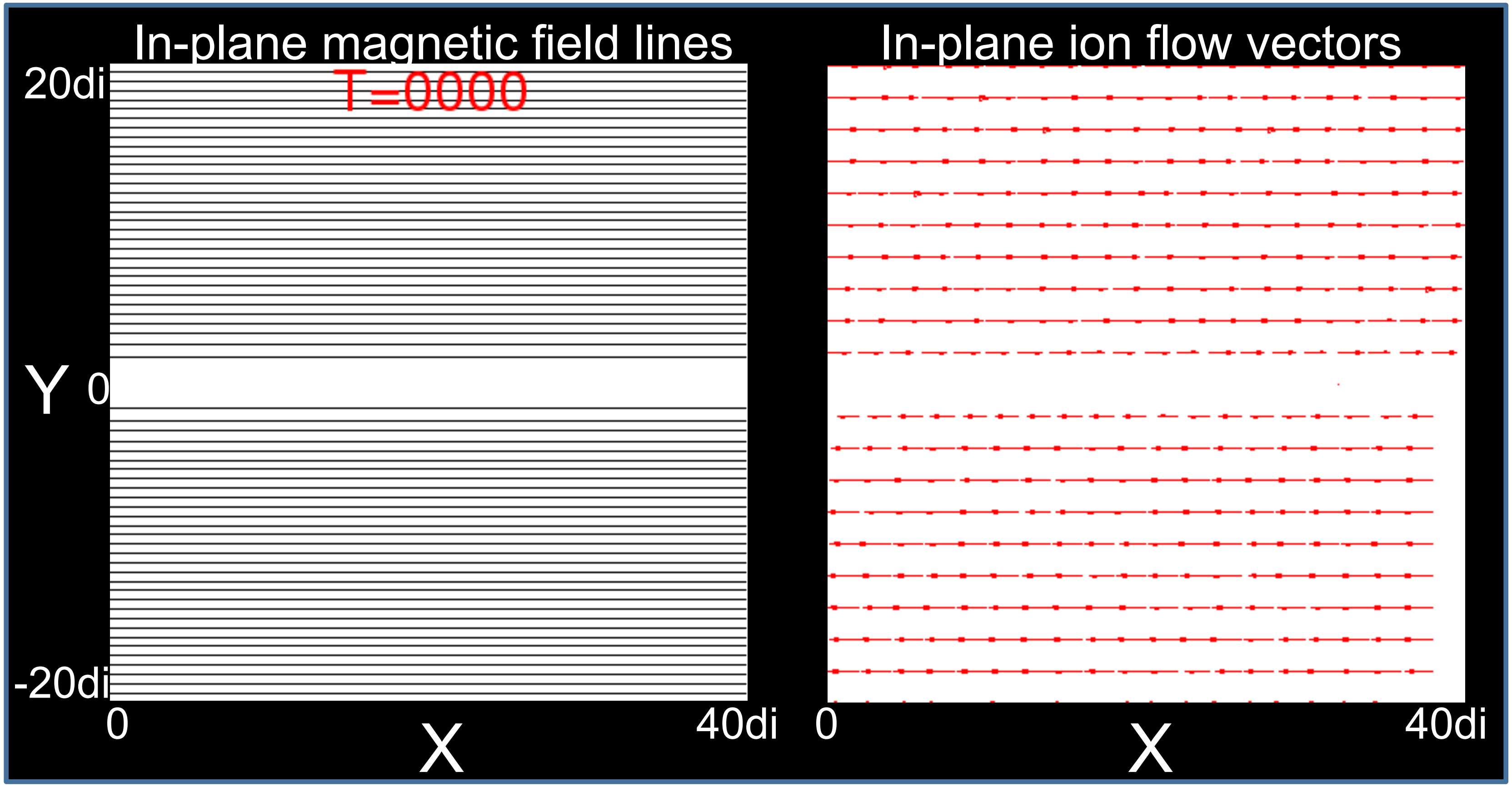
Method：2.5-dimensional full kinetic PIC simulation developed in Japan [Hoshino, 1987]

-Initial parameters-

- $N_0 = N_{i0}$ (uniform)
- $B_{z0} = 4 * B_0$ (uniform)
- $B_{x0} = B_0 * \tanh(Y/D_0)$ （current sheet）
- $V_{x0} = V_0 * \tanh(Y/D_0)$ （velocity shear layer）
- $D_0 = 2.0$ [di] (MHD-scale boundary layer)
- $M_A = V_0/V_{A0} = 4.375$ (strong KHI)
  (KHI can grow when $M_A > 2$ [Miura & Pritchett, 1982])
- $L_x = \lambda_{KH} = 20D_0$
  (~fastest growing KH mode [Miura & Pritchett, 1982])
- Other parameters:
  - $T_{i\_CS}/T_{e\_CS} = 1/8$, $T_{i\_bg}/T_{e\_bg} = 1$
  - $M_i/M_e = 25, 100$
  - $\omega_{pe}/\Omega_e = 2.0$
  - 100 particles/grid

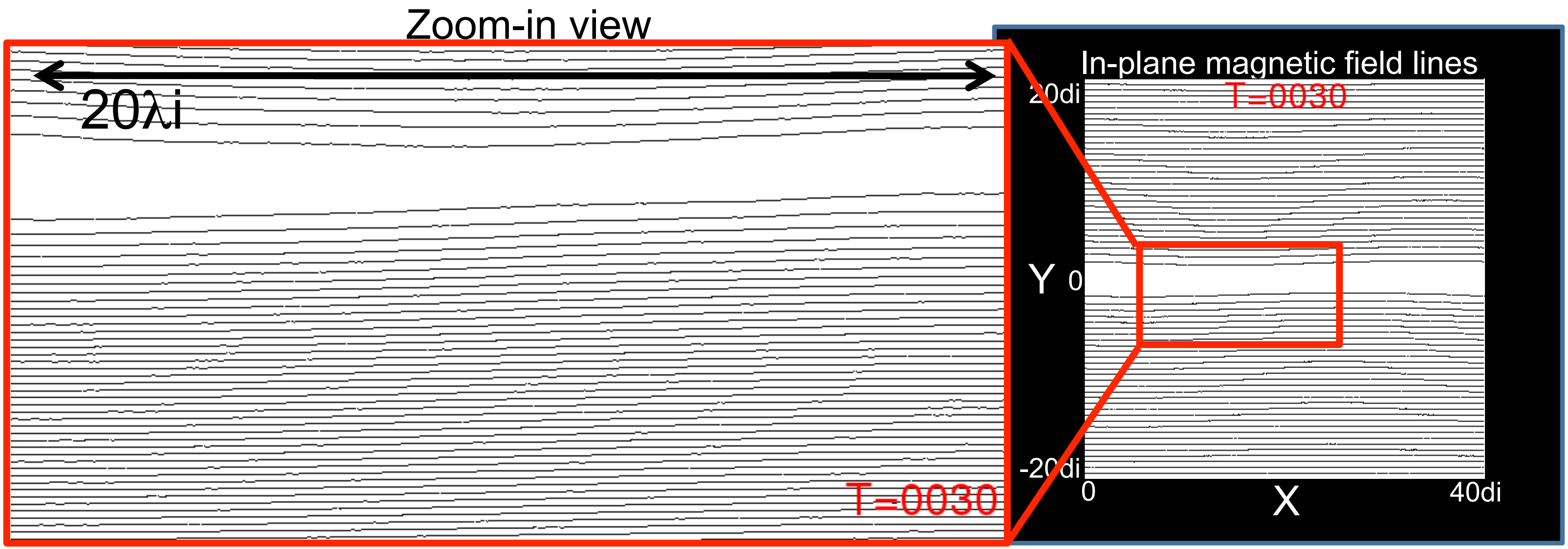


Overview of symmetric case [Nakamura et al., 2011]



- ◆(T<50) The KHI grows and locally compresses the current sheet.
- ◆(T~50) Multiple reconnection occurs at the compressed thin current sheet.
- ◆(T~80) Finally, the KH vortex is highly rolled-up as a large magnetic island.

Multiple island formation [Nakamura et al., 2011]



(T=30-50)

◆The strong vortex flow produces a thin and long current sheet.

(T=60-80)

◆Multiple magnetic islands are formed and move toward the main body of the vortex.

(T~80)

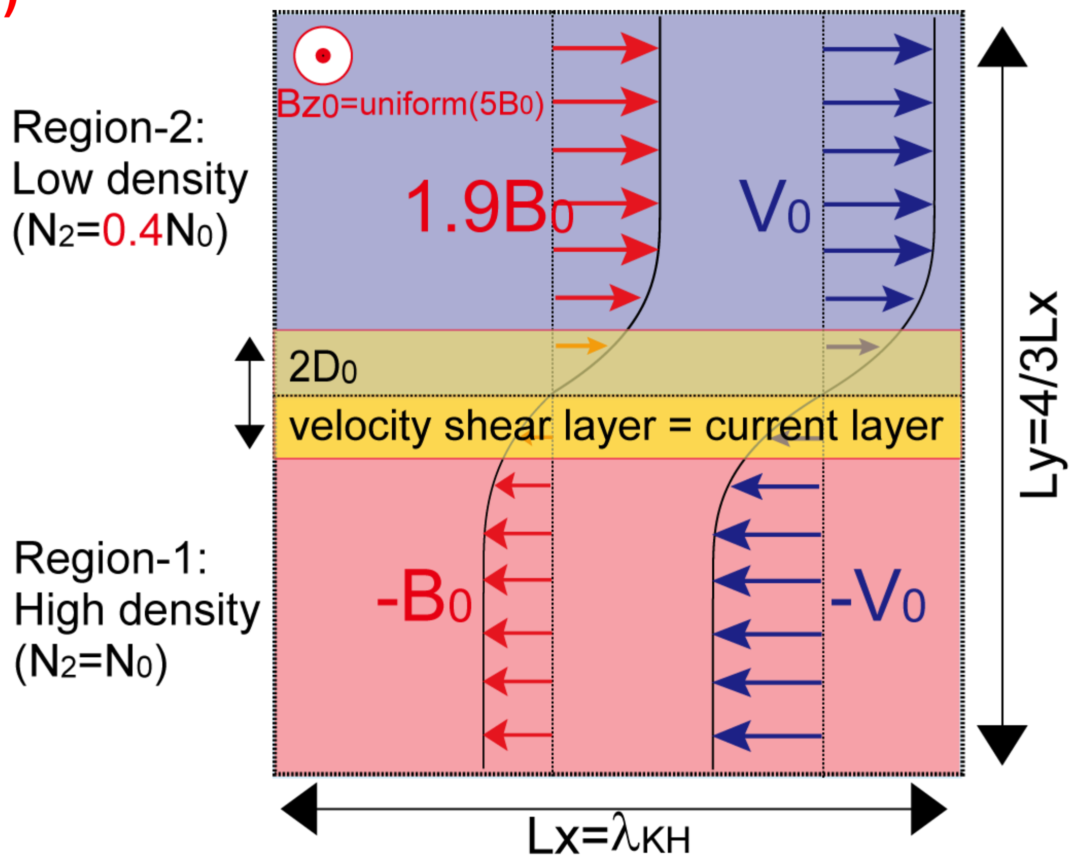
◆Multiple magnetic islands are incorporated in turn into the vortex body via the re-reconnection.

Asymmetric case [Nakamura et al., in prep.]

Method : 2.5-dimensional full kinetic PIC simulation developed in LANL (VPIC) [Bowers., 2008,2009]

-Initial parameters-

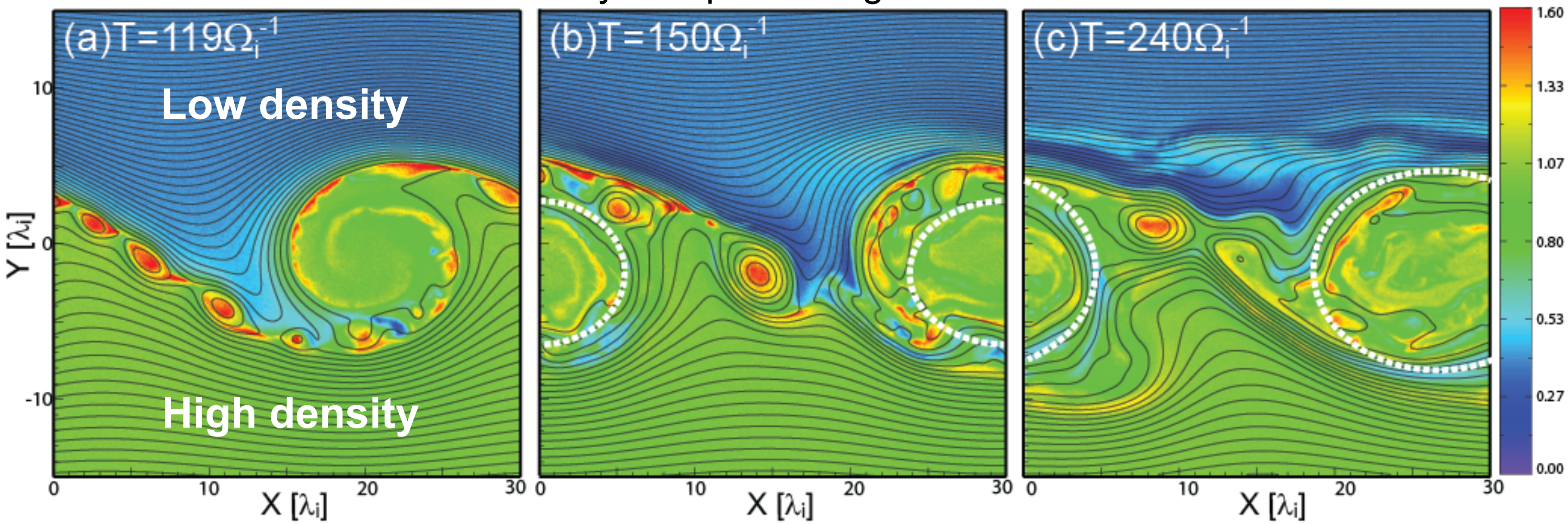
- **$N_1 : N_2 = 1 : 0.4$ (density jump)**
- $Bx_1 : Bx_2 = 1 : 1.875$
- $Bz_0 = 5 * B_0$ (uniform)
- $Vx_0 = V_0 * \tanh(Y/D_0)$
- $D_0 = 2.0$ [di] (MHD-scale)
- $MA = V_0/V_{Ax1} = 7.0$ (strong KHI)
- $Lx = \lambda_{KH} = 15D_0$
- Other parameters:
  - $Ti/Te = 2.5$
  - $Mi/Me = 25,100$
  - $\omega_{pe}/\Omega_e = 1.25$
  - 100 particles/grid



Overview of asymmetric case

$V_0 = 7.0 V_{iA1}$, $D_0 = 2.0 \lambda_i$, $N_1 : N_2 = 1 : 0.4$

Ion density & in-plane magnetic field lines

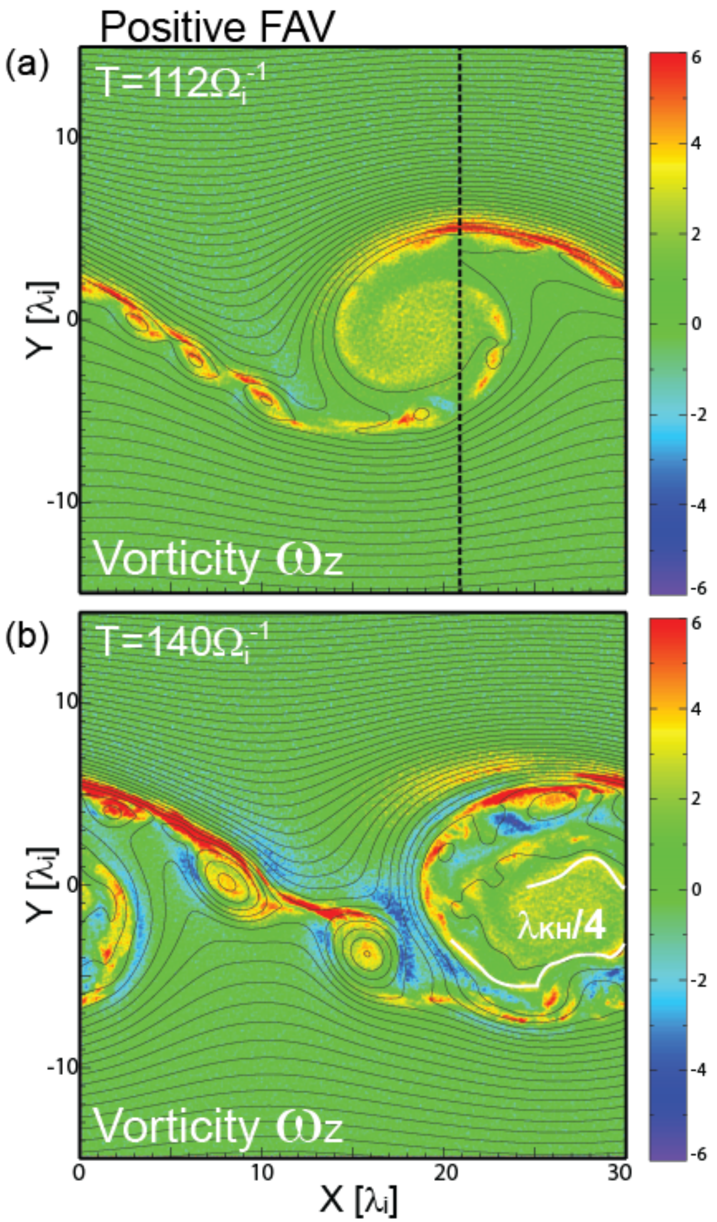


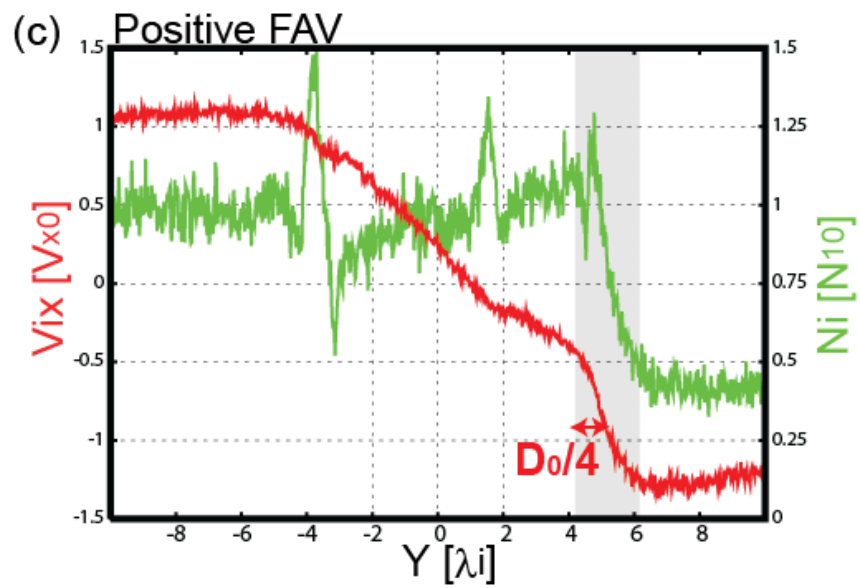
◆(T~119) Multiple islands are formed in the compressed current sheet.

◆(T~150) **Secondary KH waves** grow within the parent vortex.

◆(T~240) **Turbulence** is produced within the vortex.

Unstable secondary shear layer





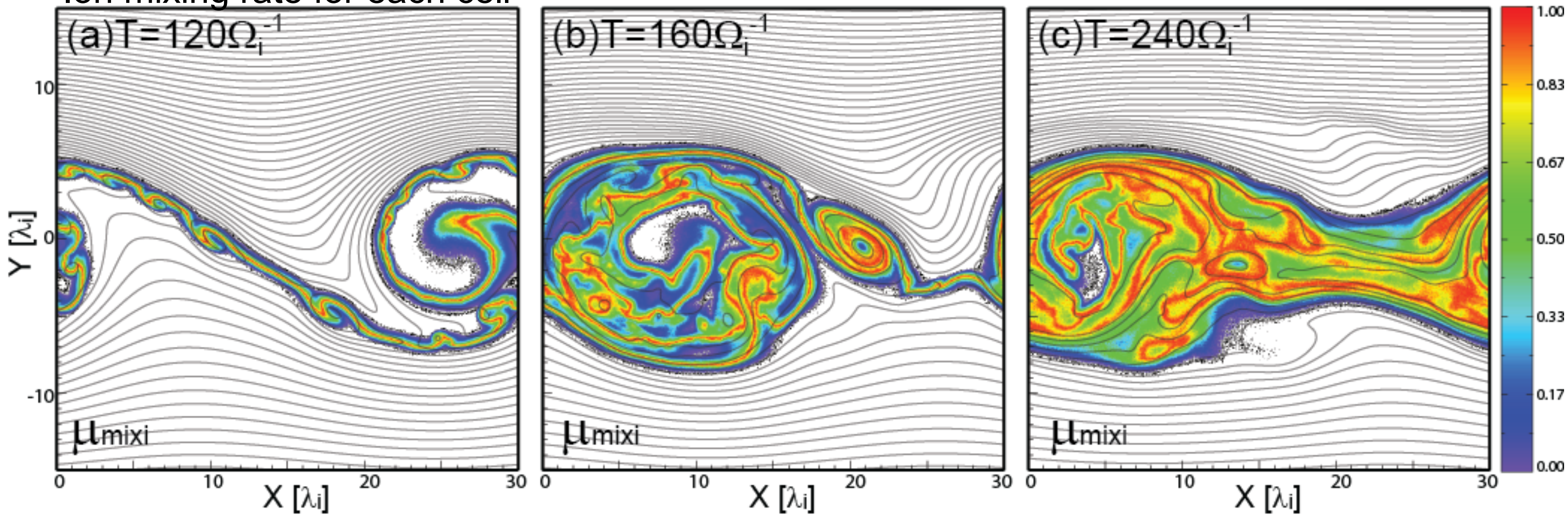
◆The density jump leads to the formation of the secondary velocity shear layer.

◆The VIR releases in-plane magnetic field within the vortex.

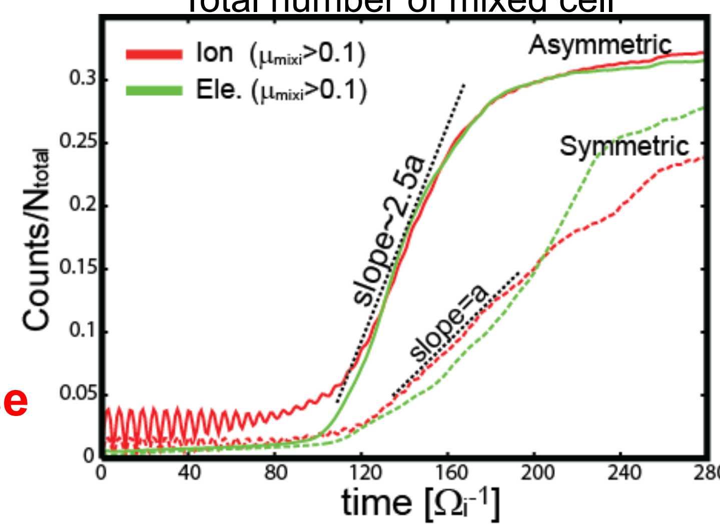
◆The 2ndary shear layer is always unstable for the 2ndary KHI within the vortex.

Plasma mixing in asymmetric case

Ion mixing rate for each cell



Total number of mixed cell

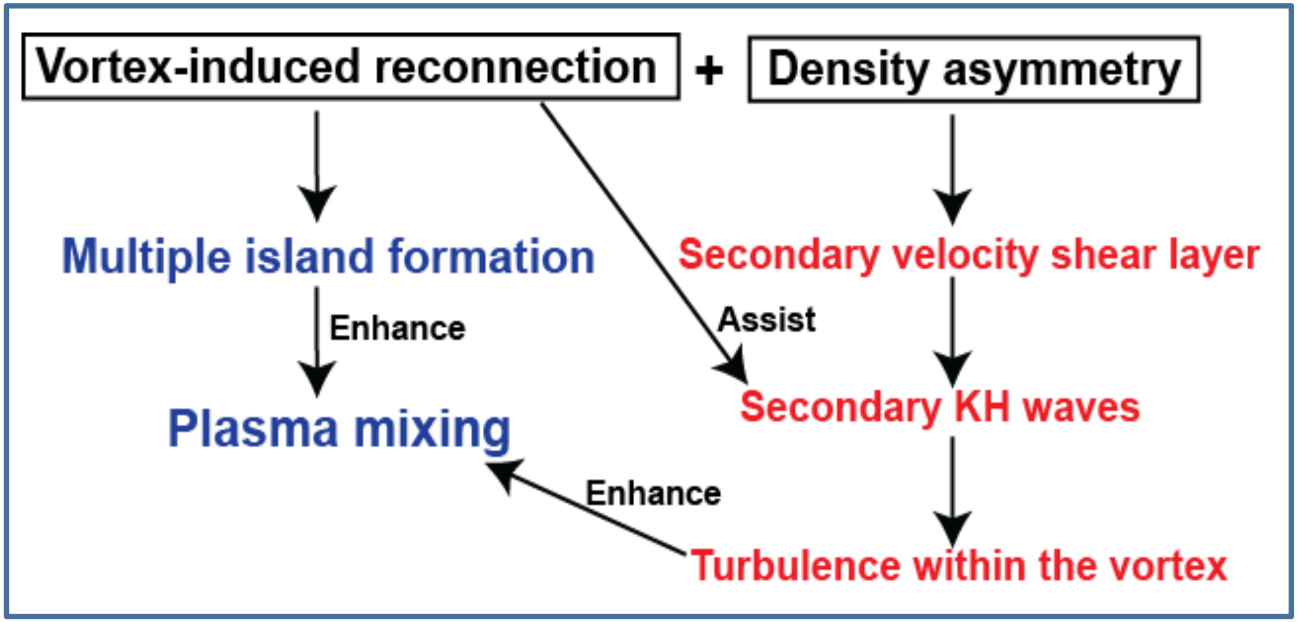


◆(T<120) The vortex-induced reconnection (VIR) starts causing plasma mixing as well as the symmetric case.

◆(T>120) Plasma mixing is further enhanced by **2ndary KH waves** and resulting **turbulence** unlike the symmetric case.

◆**Consequently, plasma mixing in asymmetric case progresses more quickly than symmetric case.**

Summary (2D)



- The **VIR** process accompanies the **multiple island formation** in the compressed current sheet.
  → The multiple island formation leads to the **efficient plasma mixing** within the vortex.
- The **density jump** across the shear layer leads to the formation of the **secondary shear layer**.
- The VIR can release the in-plane magnetic field within the vortex, and hence **the secondary KH instability** is always unstable within the vortex.
- Resulting secondary KH waves eventually cause **turbulence within the vortex**.
  → The turbulence formation **enhances the plasma mixing** within the vortex.

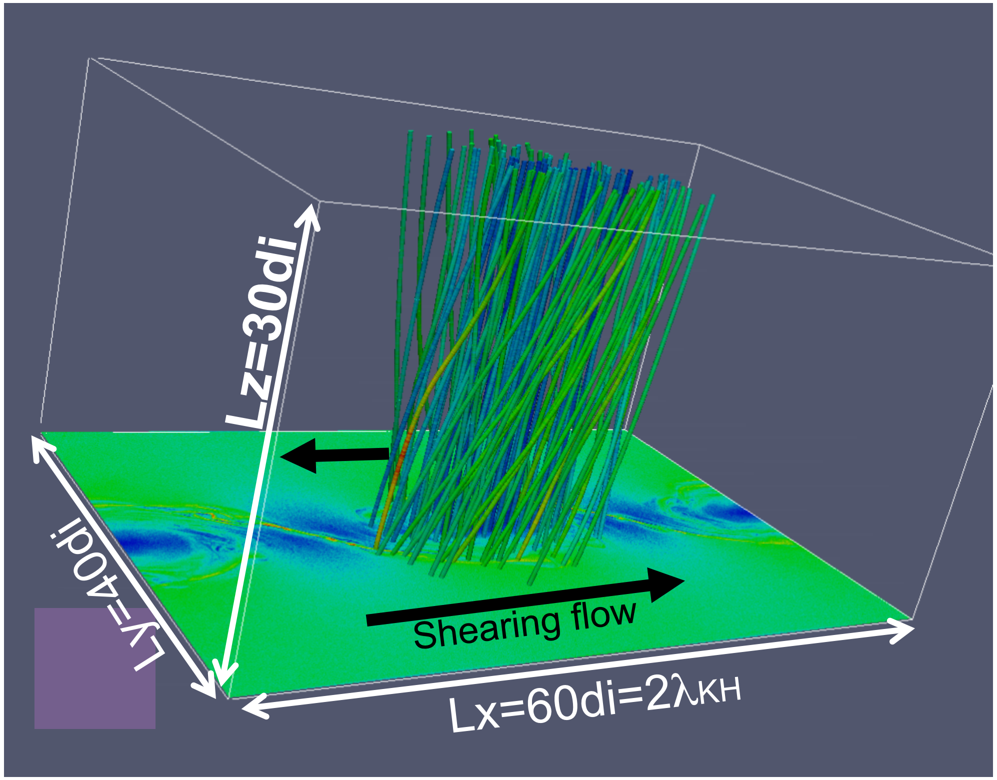
2D v.s. 3D (symmetric case)

~ 2D run ~

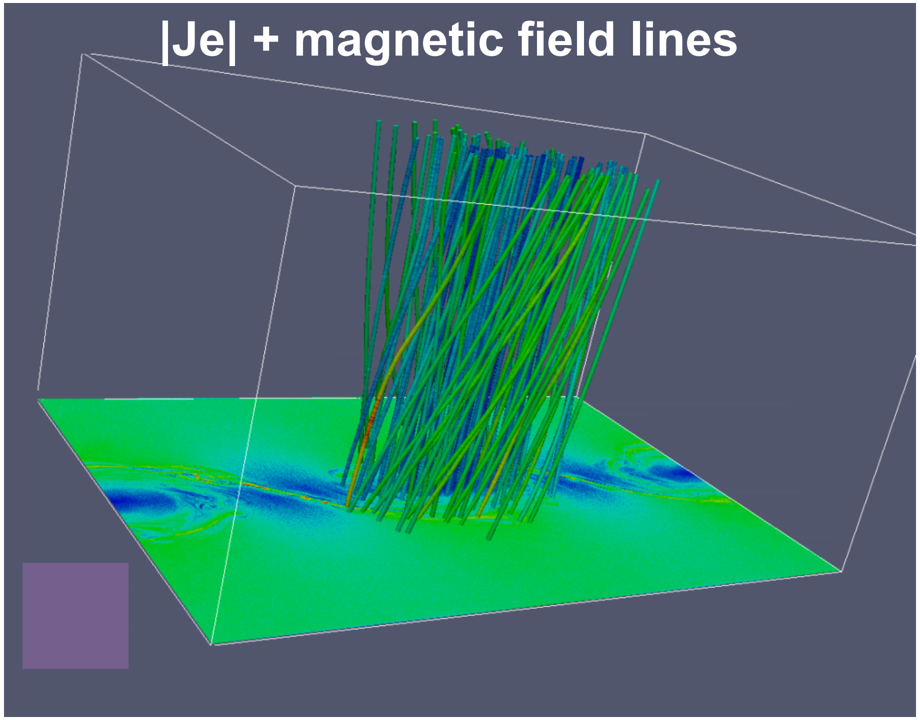
- L_x x L_y = 2048 x 1368 = 60di x 40di (Mi/Me = 25)
- 7.3 x 10^8 particles (260 particles/cell)

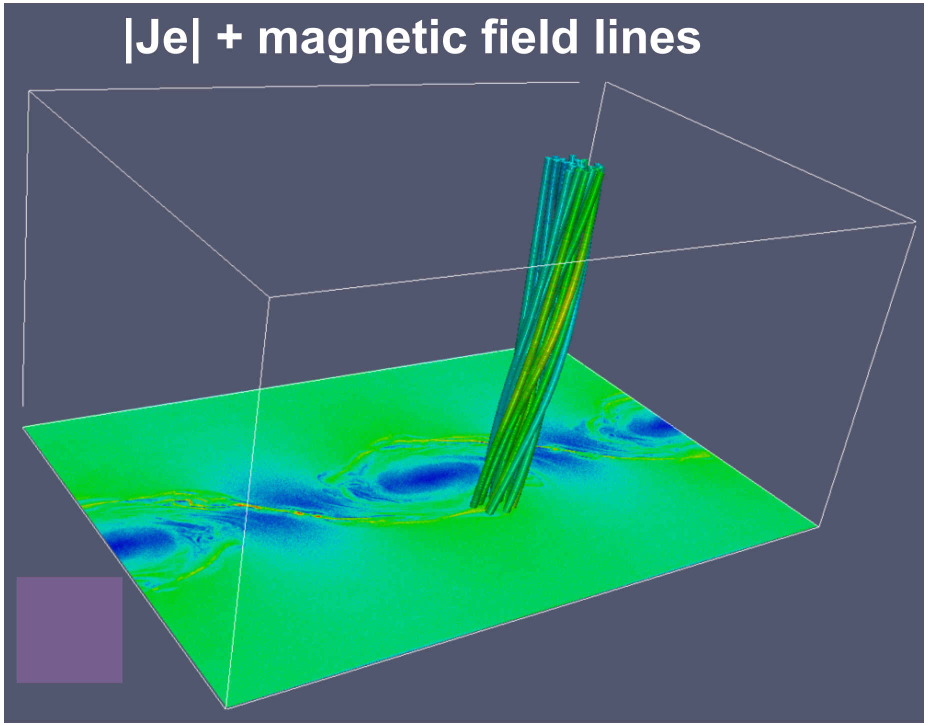
~ 3D run ~

- L_x x L_y **x L_z** = 2048 x 1368 **x 1024** = 60di x 40di **x 30di** (Mi/Me = 25)
- 7.5 x 10^{11} particles (260 particles/cell)



2D v.s. 3D (symmetric case)

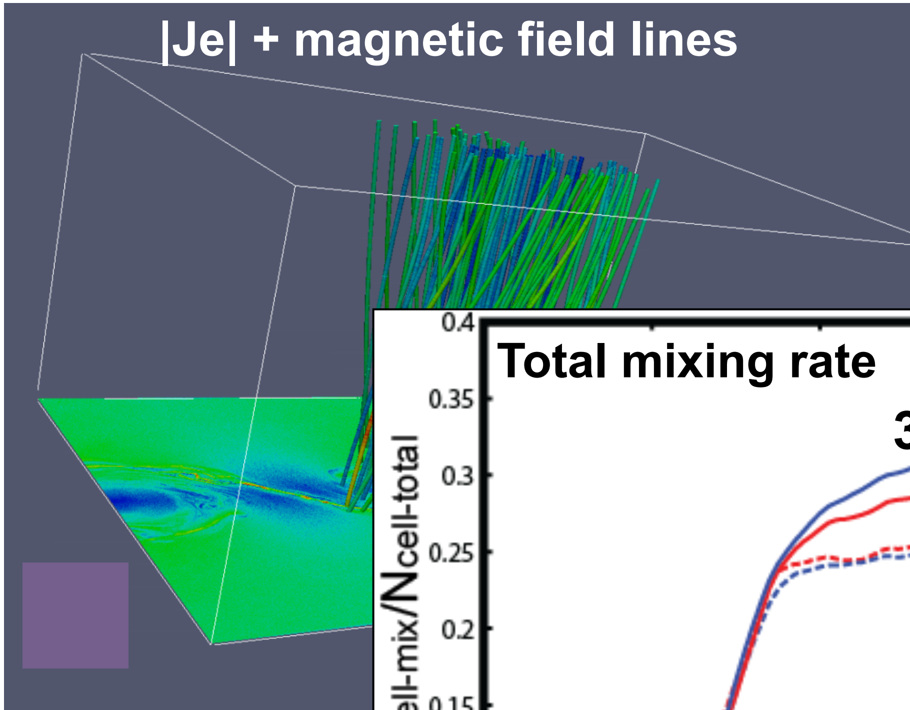


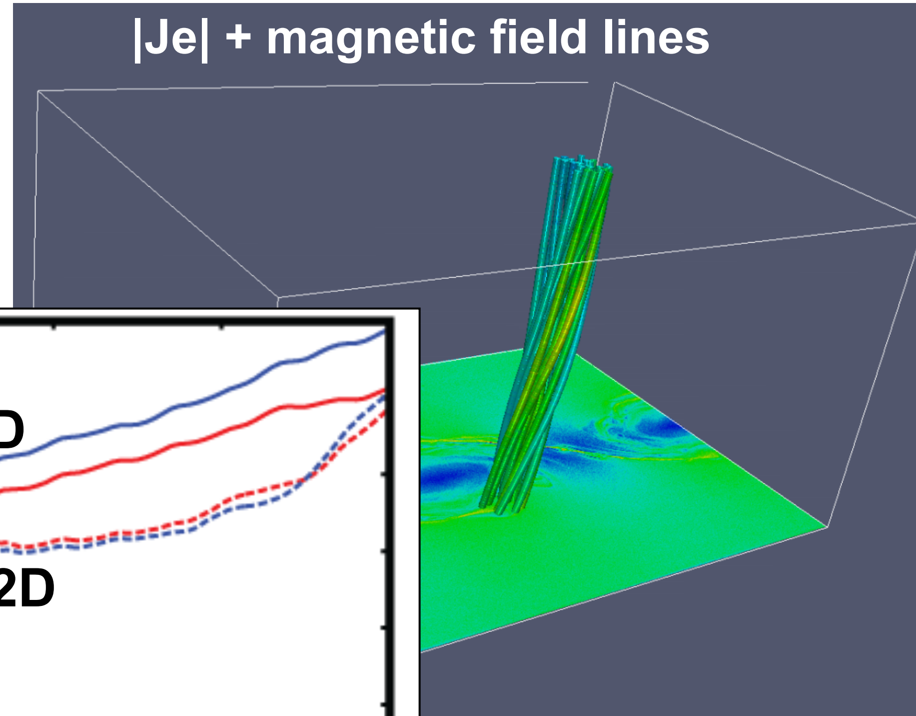


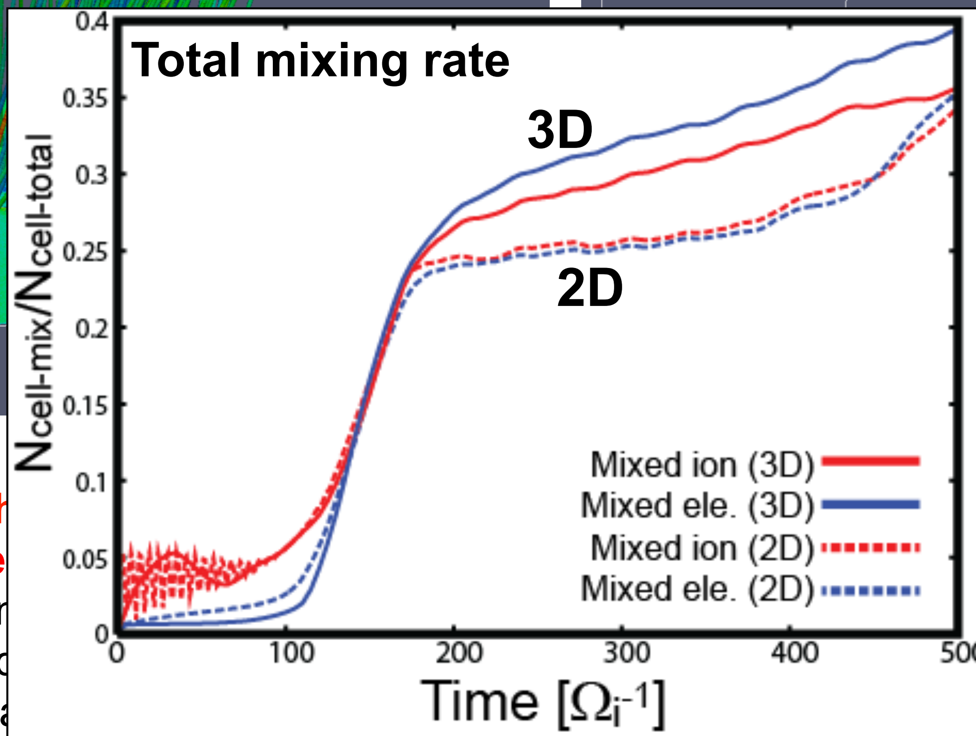
◆**3D magnetic shear** exists along the edge of the vortex.
→ **3D reconnection** occurs and produces flux ropes there.
→ 3D reconnection disturbs the vortex structure and causes turbulence.
→ Inside and outside of the vortex are connected by 3D reconnection (flux ropes).
→ Plasmas inside the vortex can be transported outside the vortex.
→ Mixed area broadens even outside the vortex.

◆**Consequently, plasma mixing in 3D progresses more quickly than 2D.**

2D v.s. 3D (symmetric case)







◆**3D magnetic sh**

→ **3D reconne**

→ 3D reconn ... ulence.

→ Inside and ... ction (flux ropes).

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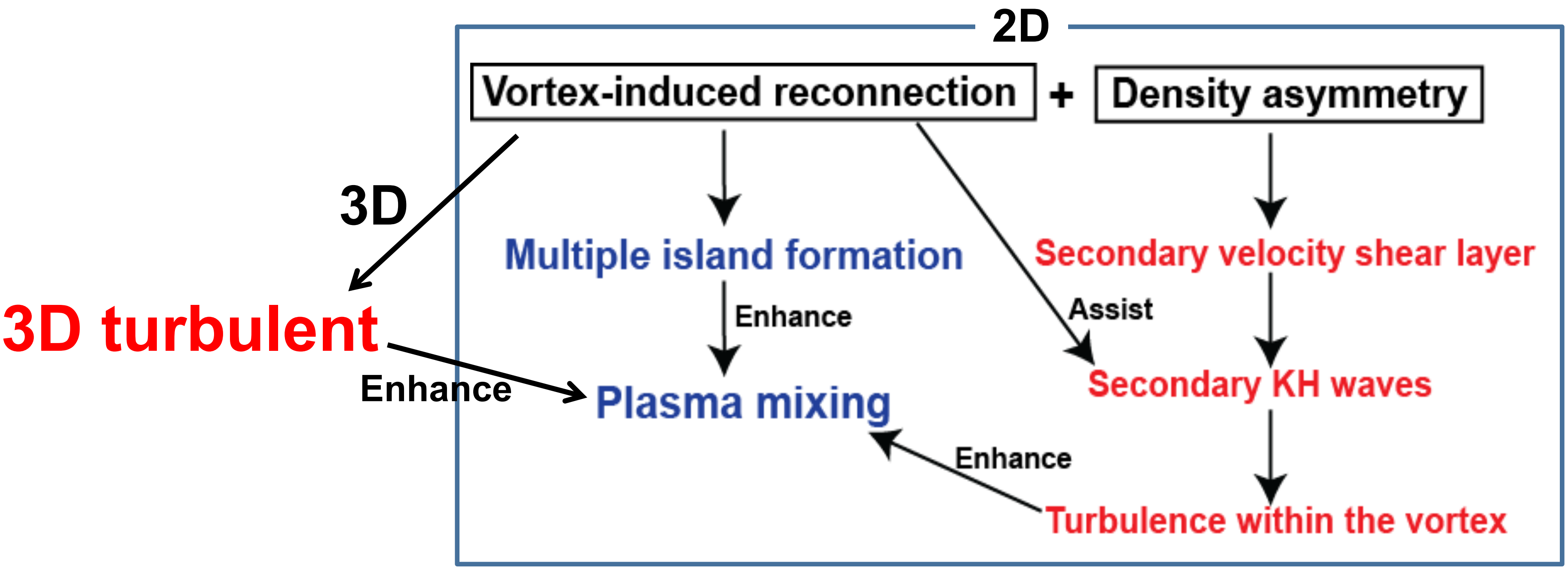
◆**Consequently, plasma mixing in 3D progresses more quickly than 2D.**

Summary



- In 3D, the vortex layer becomes turbulent even in the simple symmetric case.
- 3D turbulence enhances the plasma mixing.

→ The KH vortex in collisionless space plasmas would generally cause turbulence and efficient plasma mixing.