Excitation of MHD Waves By Plasmoid Ejections in Solar Corona Reconnection

Liping Yang[1,2], Lei Zhang[1], Jiansen He[2], Hardi Peter[3], Chuanyi Tu[2], Linghua Wang[2], Shaohua Zhang[4], and Xueshang Feng[1]

1 SIGMA Weather Group, State Key Laboratory for Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, 100190 Beijing, China
2 School of Earth and Space Sciences, Peking University, 100871 Beijing, China
3 Max-Planck-Institut fur Aeronomie, Max-Planck-Strasse, D-37191 Katlenburg-Lindau, Germany
4 Center of Spacecraft Assembly Integration and Test, China Academy of Space Technology, Beijing 100094, China

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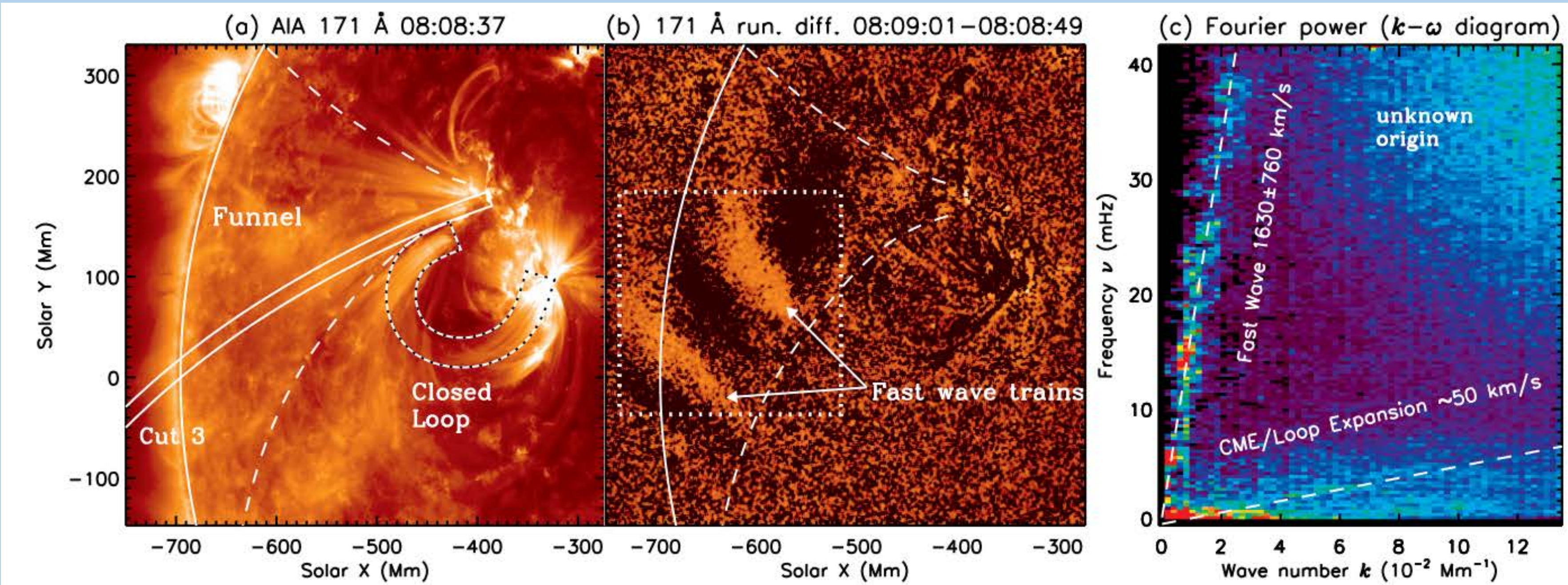
Observations of fast-mode waves

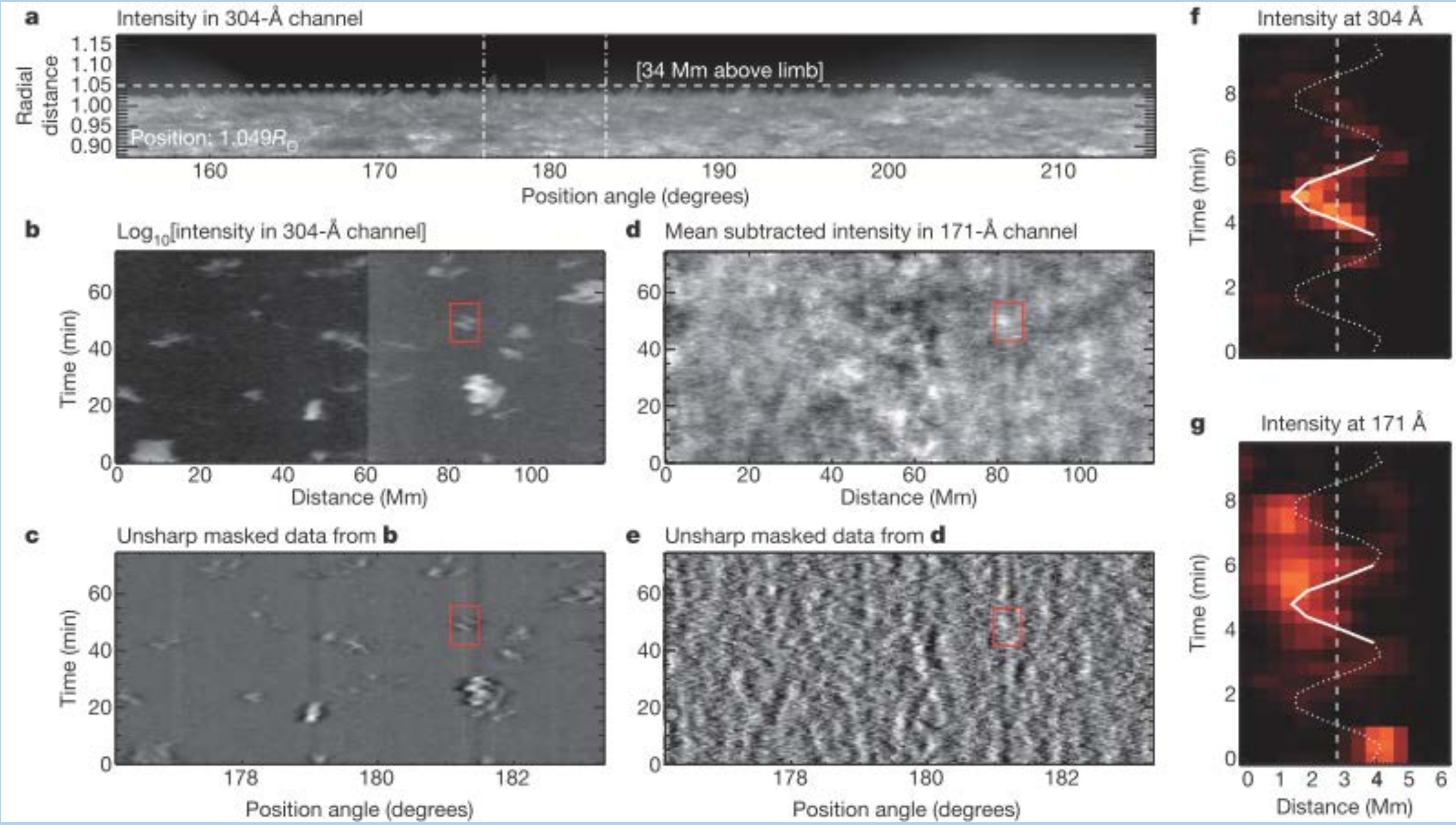


Ofman et al., 2011

FMWs are detected by SDO/AIA in the corona, with speeds of 1000 – 2000 km/s.

Fourier analysis reveals a broad frequency distribution, with the strongest peak coinciding with quasi-periodic pulsations of the flare emission (Liu et al., 2010; Ofman et al., 2011; Shen & Liu 2012; Yuan et al. 2013, etc.).

Observations of Alfven waves

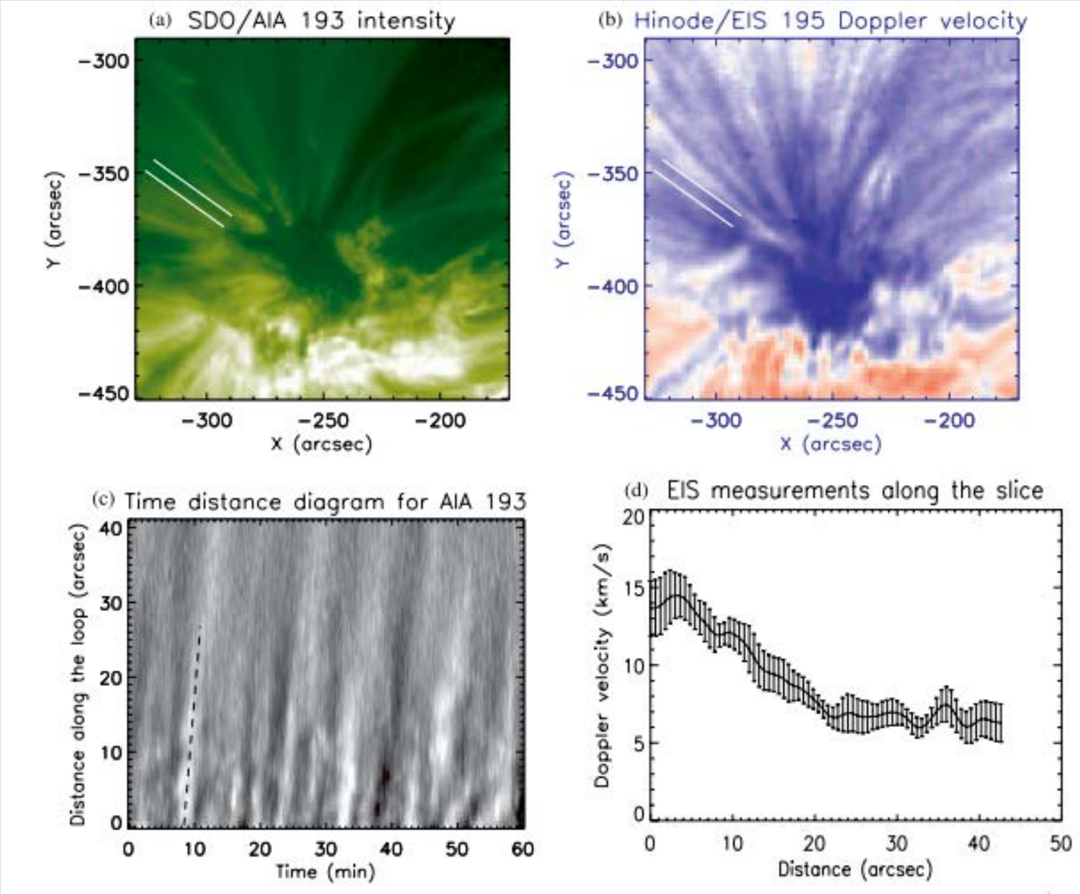


McIntosh et al., 2011

Observations from Hinode/SOT, SDO/AIA , COMP/Fe xiii, and etc, reveal Alfven waves permeate the chromosphere, transition region, and corona.

The velocity amplitude of Alfven waves is estimated to be in the range of about 10 to 25 km/s , periods range from about 50 to 500 s, and phase speed is the order of 1000 km/s (De Pontieu et al. 2007; Tomczyk et al. 2007; He et al. 2009; McIntosh et al. 2011, etc.).

Observations of slow-mode waves



Wang et al., 2013

Slow-mode waves are observed as quasi-periodic propagating disturbances found in the corona, and usually propagate at a temperature-dependent speed, which is close to the sound speed in the corona, and their periods cover a wide range of about 3–30 min (DeForest & Gurman 1998; De Pontieu et al. 2005, Wang et al. 2013, etc.).

Motivations

- Tigers of MHD waves in the solar atmospheres:
  - photospheric or chromospheric longitutinal or transverse oscillations (De Pontieu et al. 2004, Liu et al. 2011, Shen & Liu 2012, etc.)
  - magnetic reconnections (Axford & McKenzie 1992; Tu et al. 2005, etc.)

- Object: investigate MHD waves excited by magnetic reconnections
  - interchange flare is simulated with high magnetic Reynolds number.

Yang et al., 2015, ApJ, 800, 111.

Numerical MHD model

- Equations: resistive MHD equations with gravity.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + \mathbf{I}(p + \frac{1}{2}\mathbf{B}^2) - \mathbf{B}\mathbf{B} \right] = \rho \mathbf{g}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\mathbf{u}(e + p + \frac{1}{2}\mathbf{B}^2) - (\mathbf{u} \cdot \mathbf{B})\mathbf{B} \right] = \rho \mathbf{u} \cdot \mathbf{g} + \nabla \cdot (\mathbf{B} \times \eta \mathbf{j})$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = \eta \nabla^2 \mathbf{B}$$

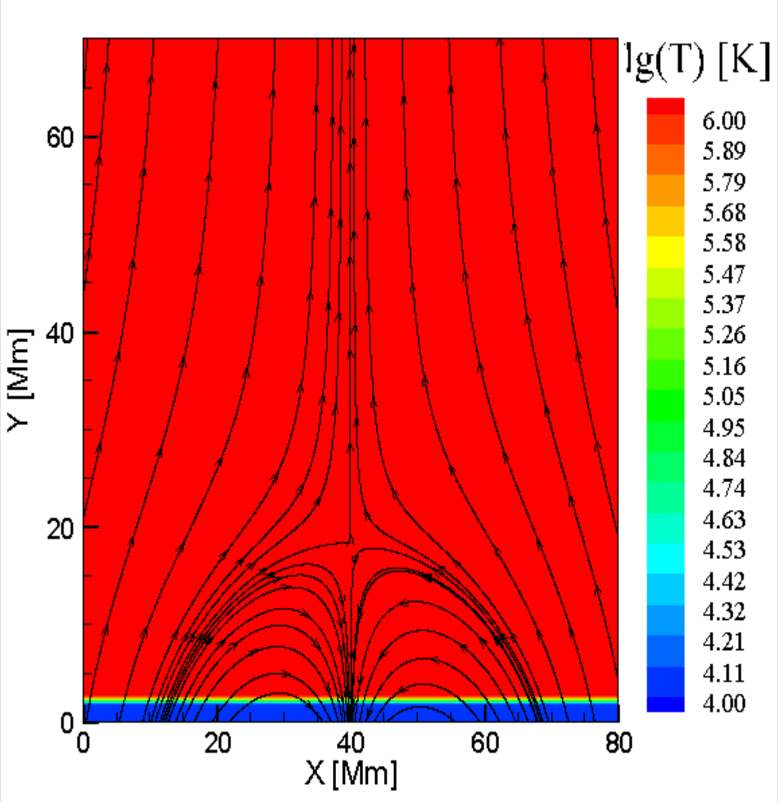
Magnetic Reynolds number: 10^5

- Scheme: Splitting-based finite volume (Feng et al. 2011, Yang et al. 2013a,b)
  - fluid part solved by Godunov-type central method
  - magnetic part handled by CT approach
  - a second-order accurate linear ansatz reconstruction
  - HLL approximate Riemann solvers for numerical fluxes
  - 2-order TVD Runge–Kutta time stepping for time integration
- Grids: rectangle adaptive mesh refinement (AMR), grid sizes of 12.5 km (min, concentrating on the reconnection region), 100 km (max)

Numerical MHD model

- Initial conditions:
  - Plasma: hydrostatic equilibrium ranging from solar chromospheric (10^4 K) to solar corona (10^6 K)
  - Magnetic field: potential field with uniform background field and line dipoles
- Boundary conditions:
  - Right&Left boundary is open
  - Upper boundary is free
  - Bottom boundary is line-tied with footpoint shearing flow set as

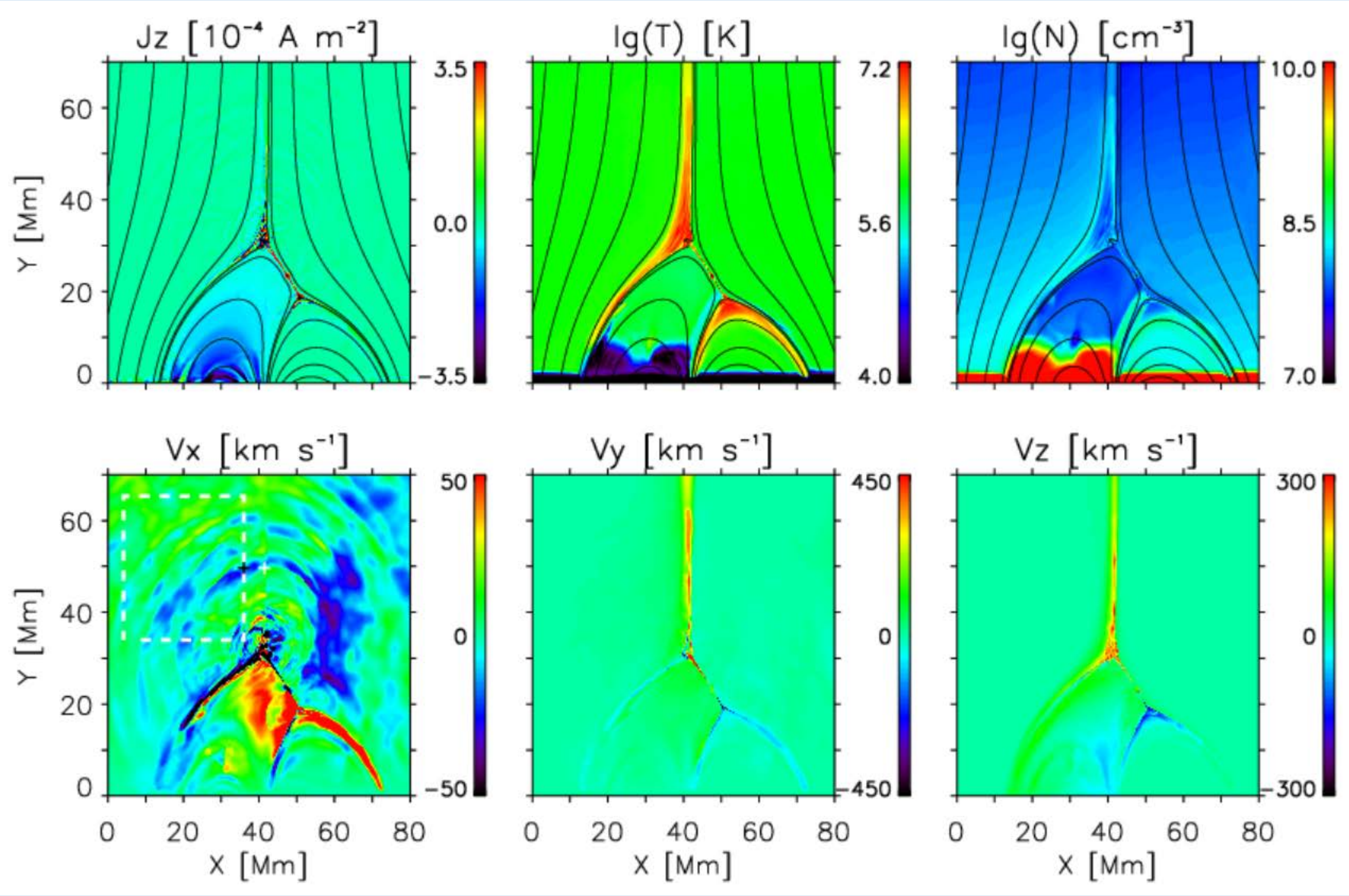
$$V_z = \begin{cases} 0, & |(x - x_0)| \geqslant d \\ 1.5 \sin(\pi(x - x_0)/d)((x - x_0)^2 - d^2)^2, & |(x - x_0)| \leqslant d, \end{cases}$$



Reconnection site at solar corona with temperature (10^6 K)

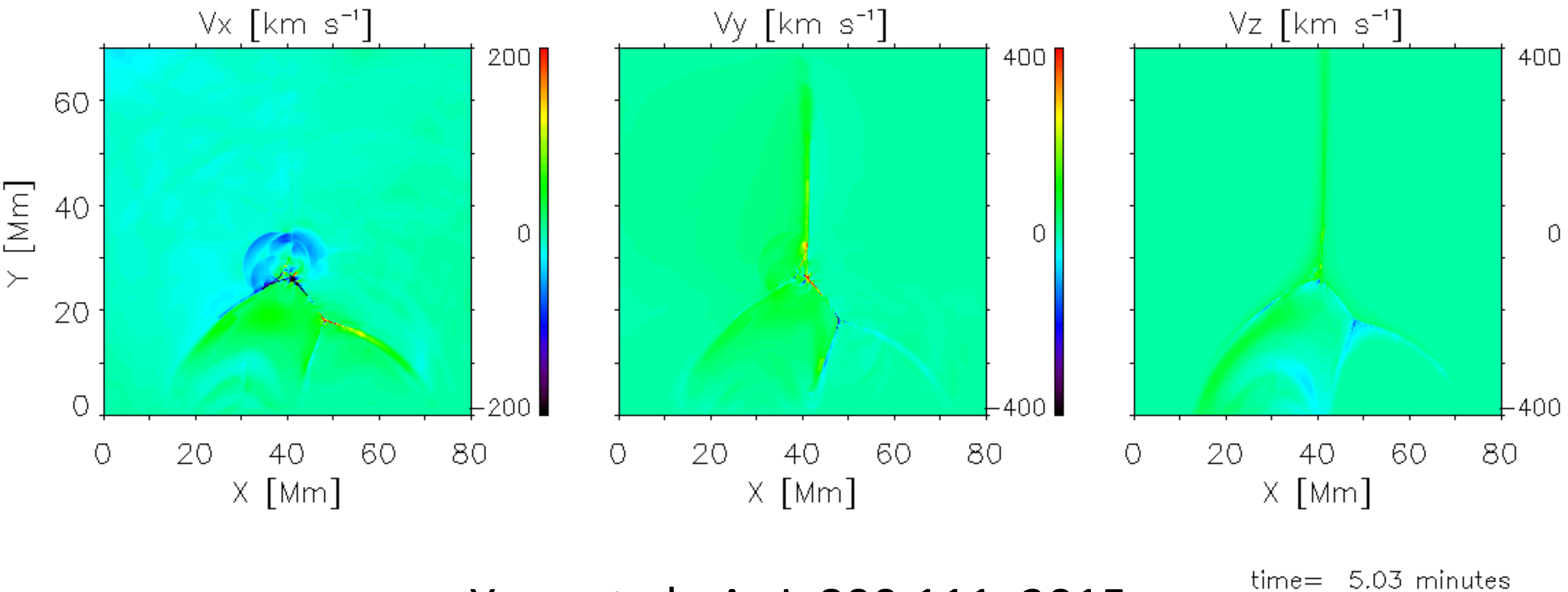
Yang et al., 2015, ApJ, 800, 111.

2.5D Simulation of Reconnection



Yang et al., 2015, ApJ, 800, 111.

Waves Launched from the Reconnection Site



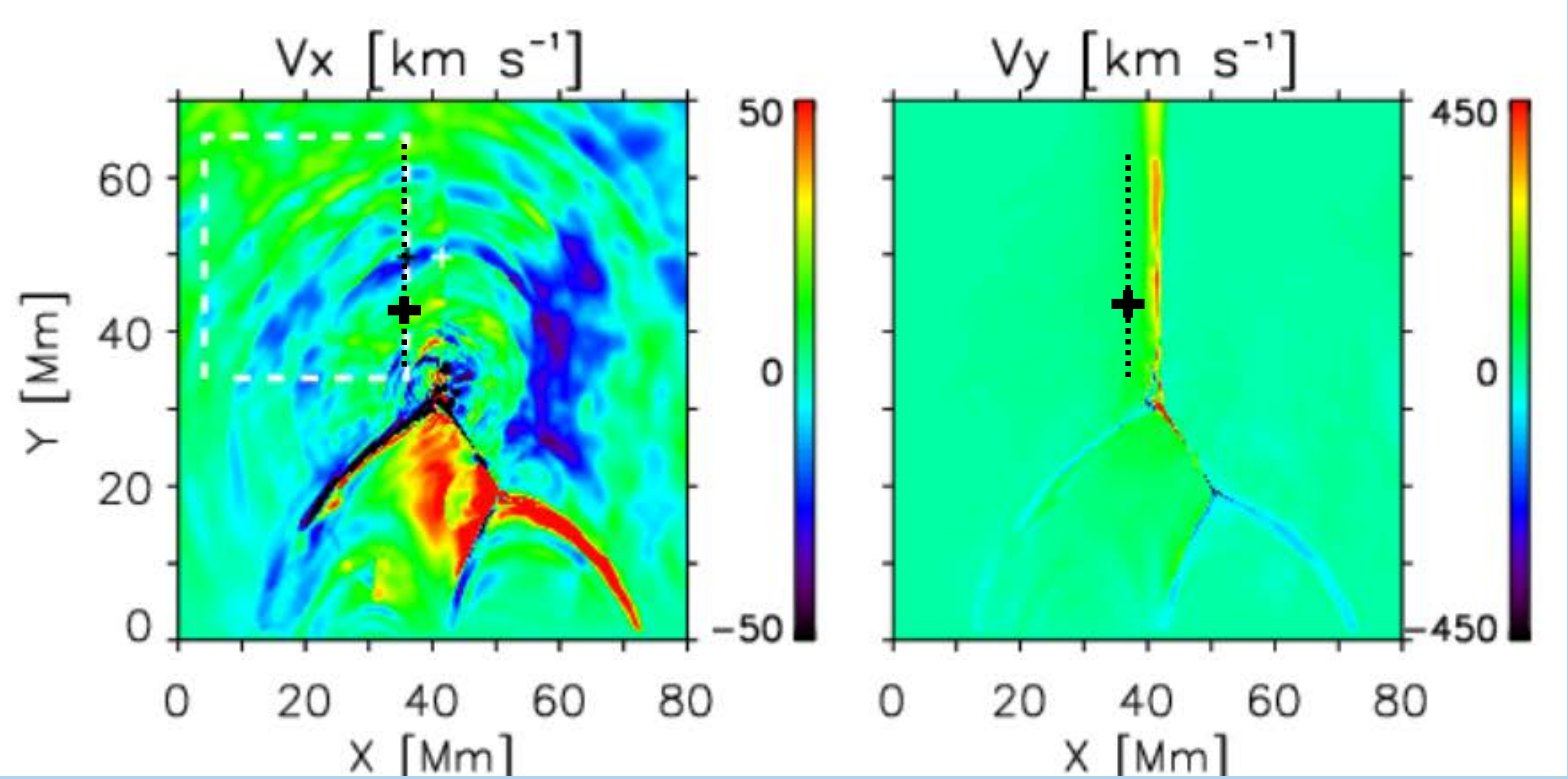
Yang et al., ApJ, 800:111, 2015

Vx movie: multiple arc-shaped perturbations

Vy movie: perturbations parallel to magnetic fields

Vz movie: perturbations perpendicular to magnetic fields

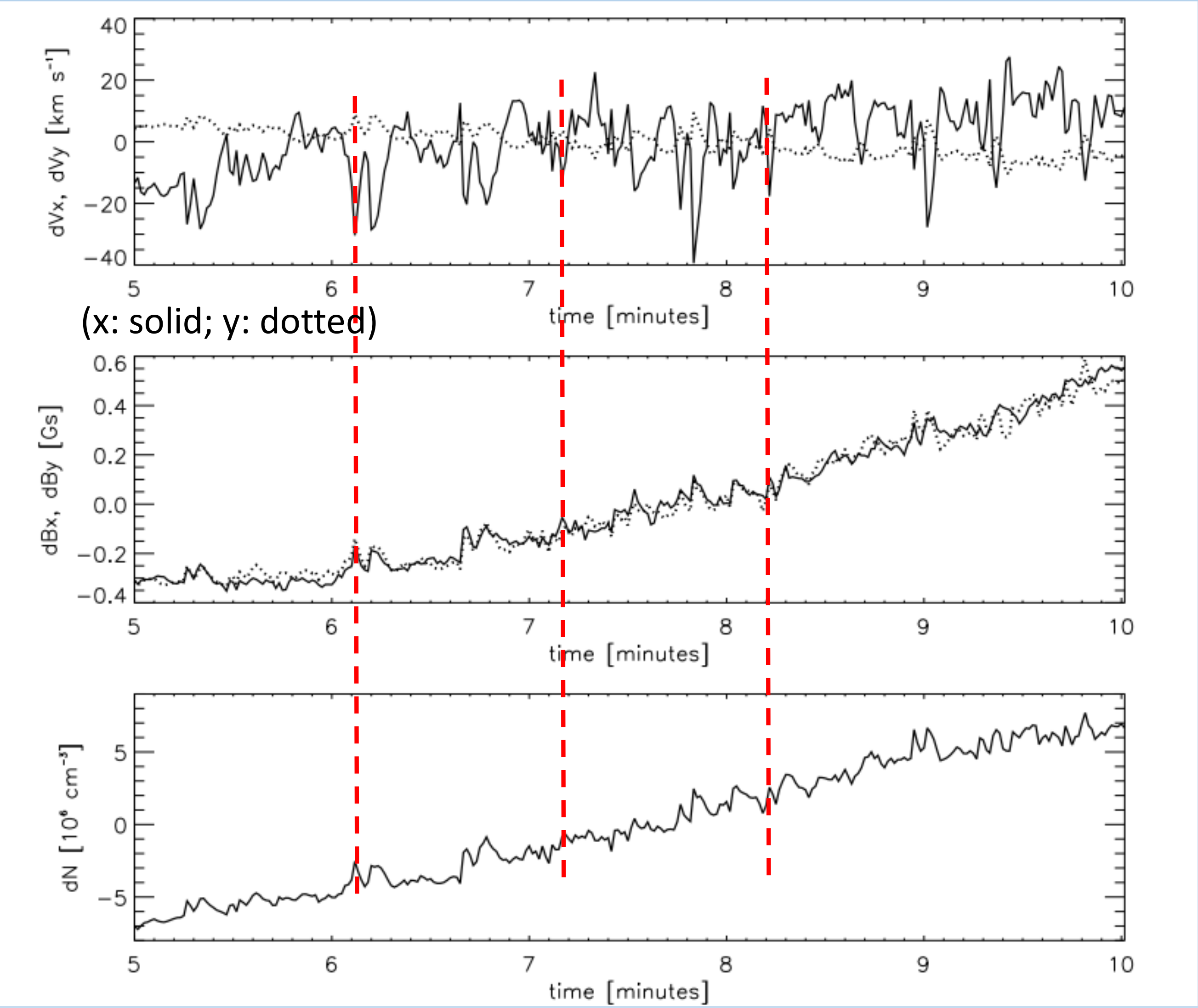
Identify Waves Launched from the Reconnection Site



Black Cross: get temporal evolutions of the perturbed quantities and see their correlations

Dot black line: get time–distance plots of the perturbed quantities and see their propagations

Fast-mode Waves Launched from the Reconnection Site

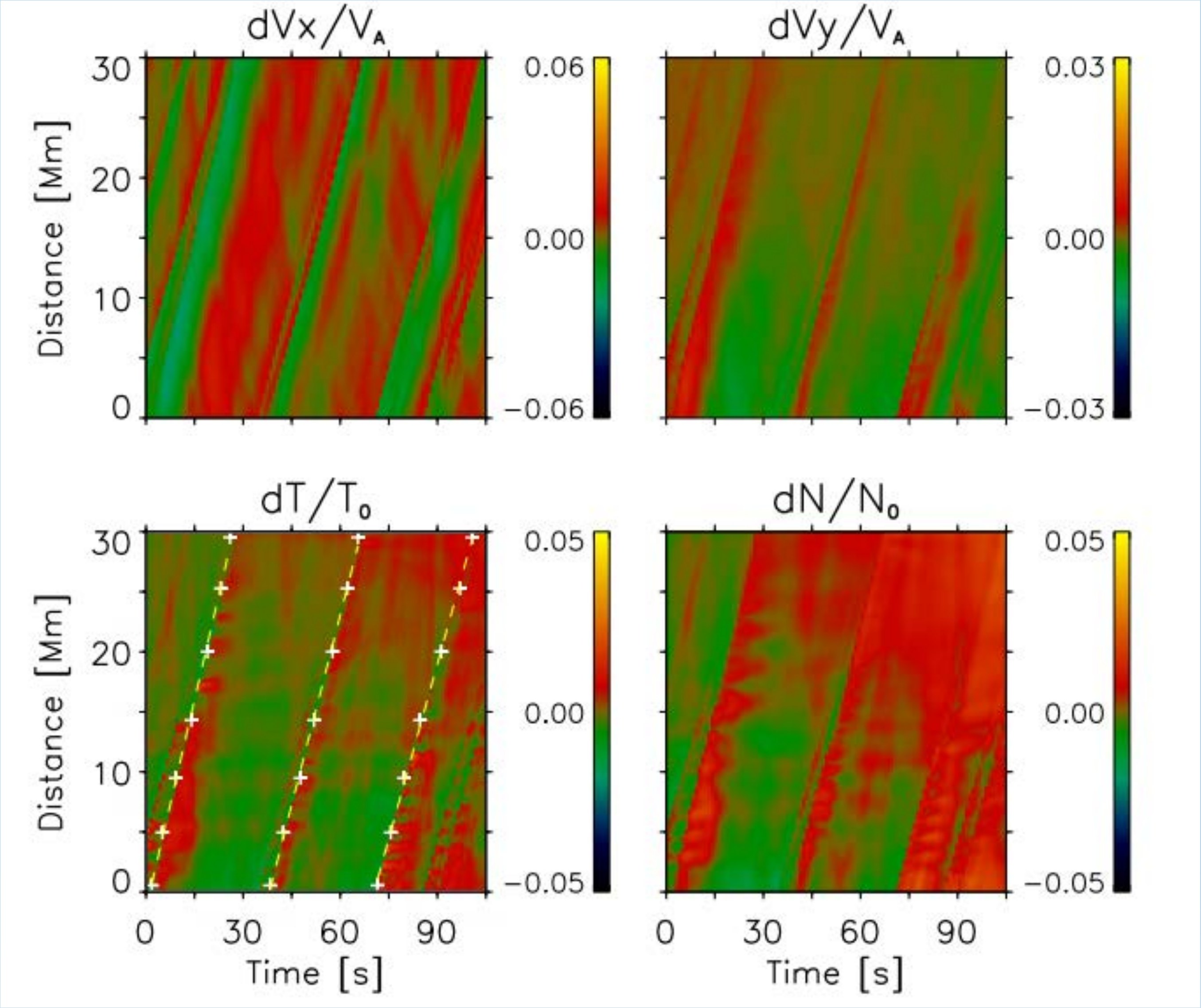


1. dBx ~ — dVx
2. dBy ~ —dVx
3. dB ~ dN

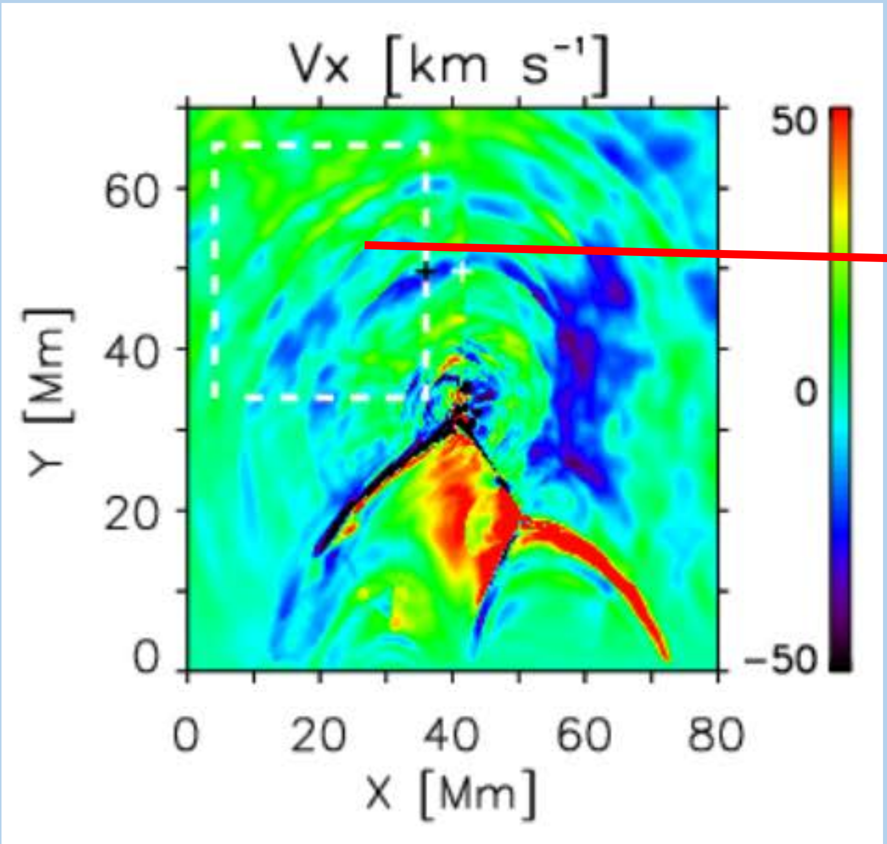
Arc-shaped Perturbations satisfy the polarity relations of fast-mode wave.

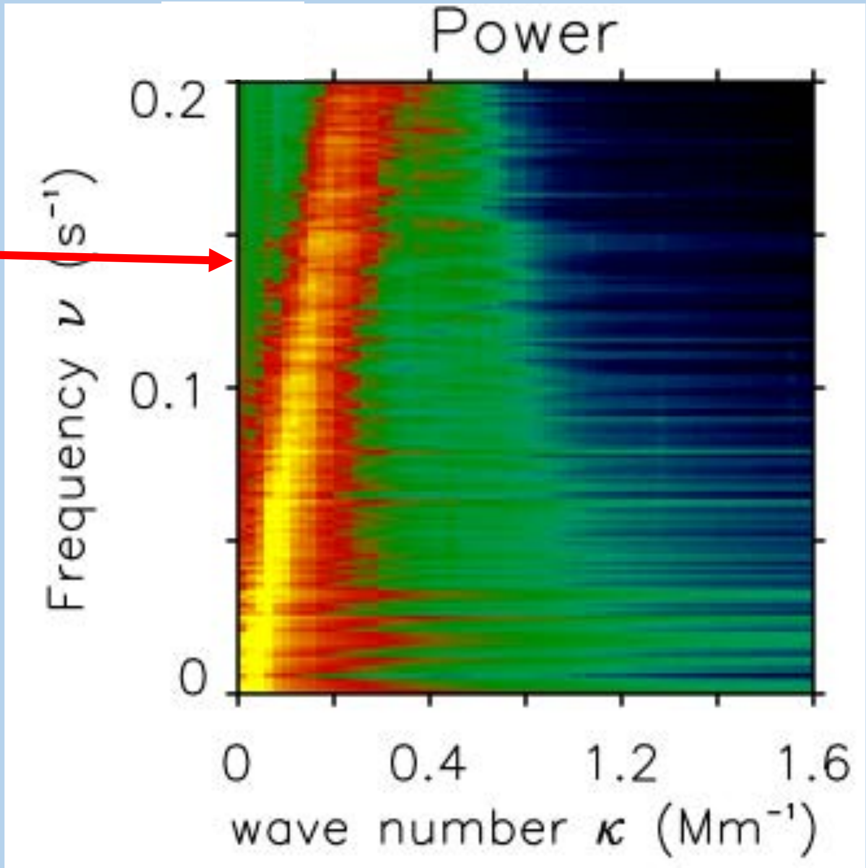
Fast-mode Waves Launched from the Reconnection Site

Propagation speed: ~ 1000 km/s, consistent with the phase speed of the fast-mode wave, thus verifying that these arc-shaped perturbations are fast-mode waves.



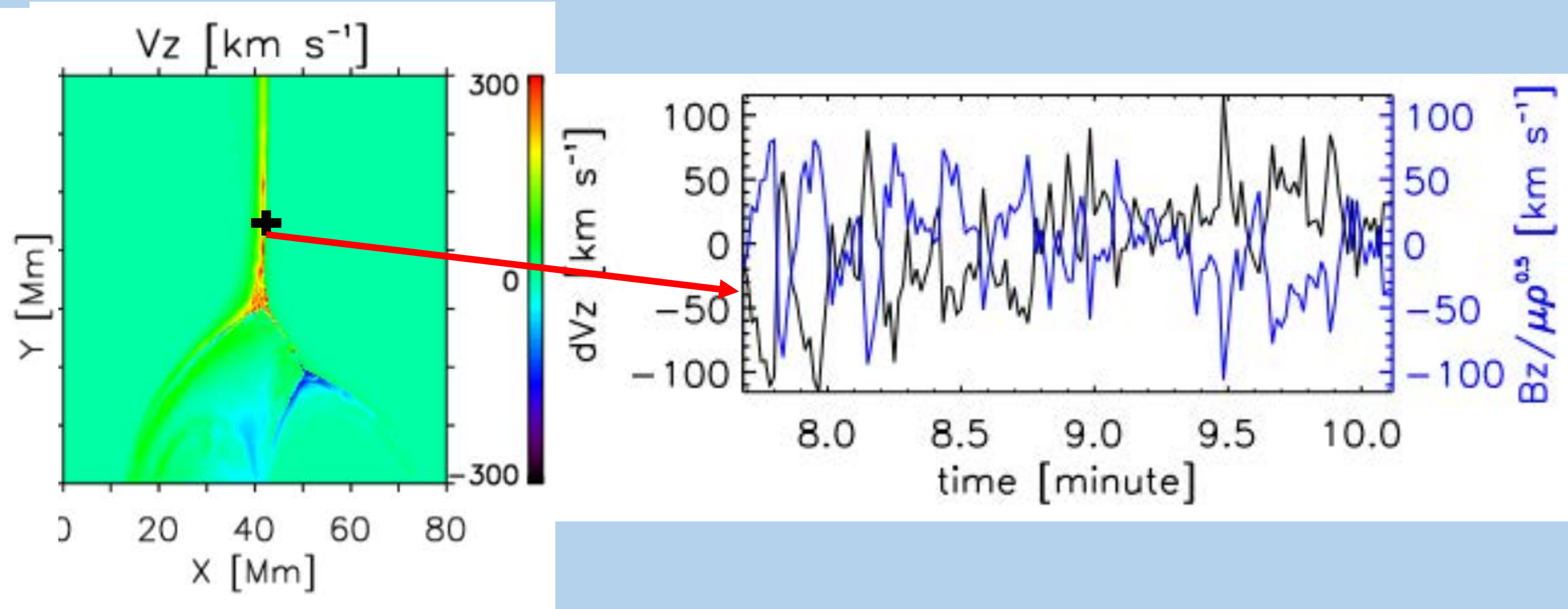
Fast-mode Waves Launched from the Reconnection Site





Period behavior of the excited fast-mode waves:
broad frequency distribution with a linear steep ridge describing its dispersion.

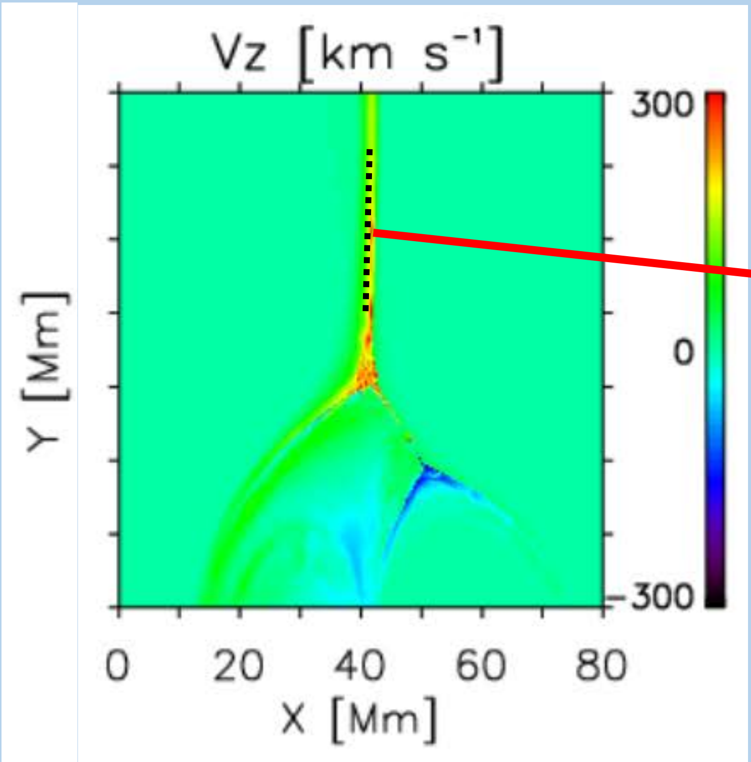
Alfven Waves Launched from the Reconnection Site

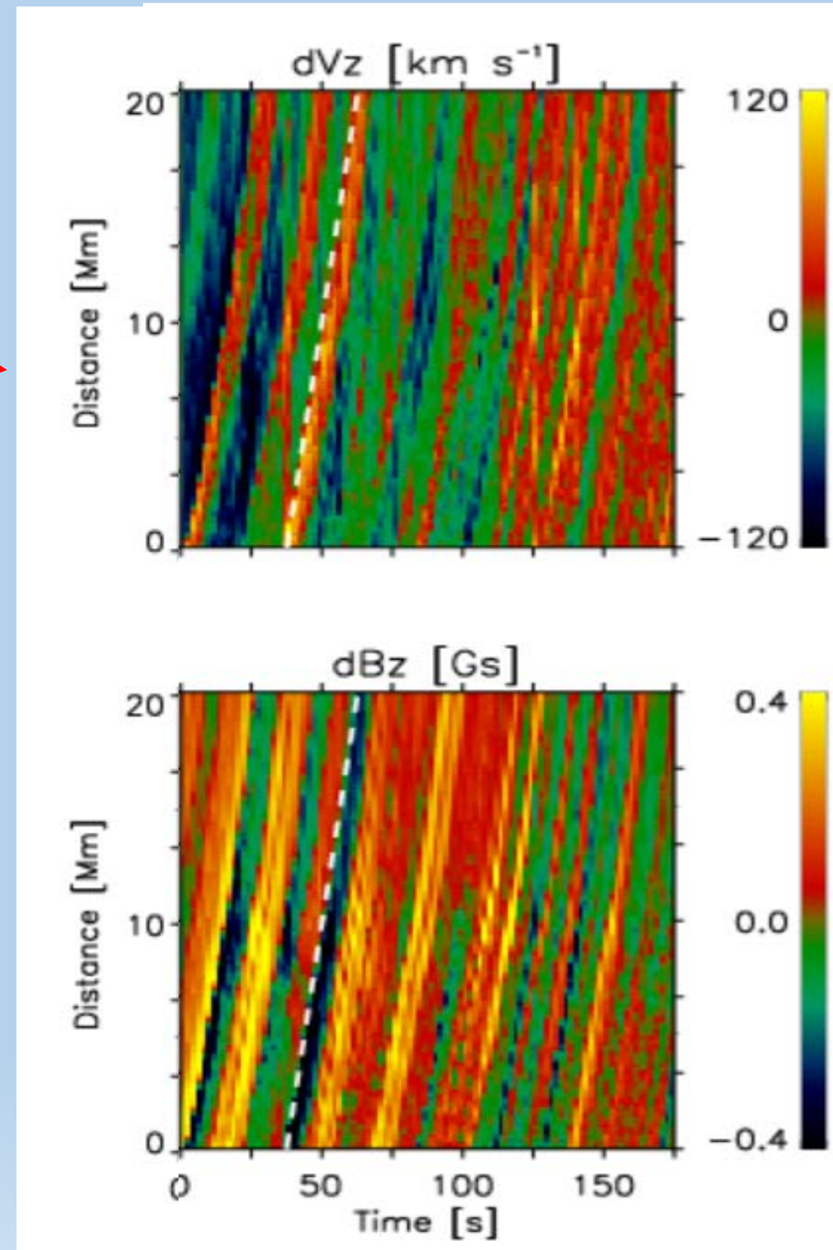


Perturbations of Vz satisfy the polarity relations of up-propagating alfven wave: $\frac{\delta B_{\perp}}{\delta V_{\perp}} \approx \frac{B_0}{V_A}$

Yang et al., 2016

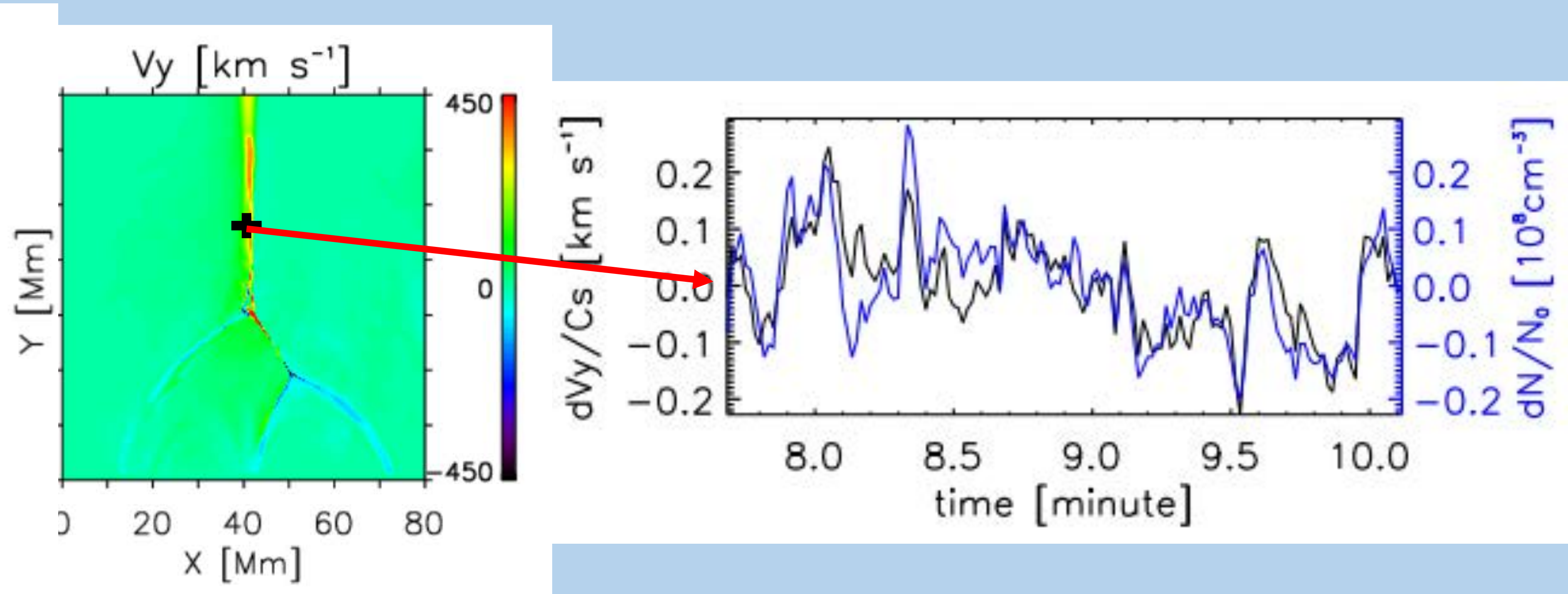
Alfven Waves Launched from the Reconnection Site





The average propagating speed of perturbations of Vz:
800 km/s, consistent with the Alfven speed there, thus verifying that they are Alfven waves.

Slow-mode Waves Launched from the Reconnection Site

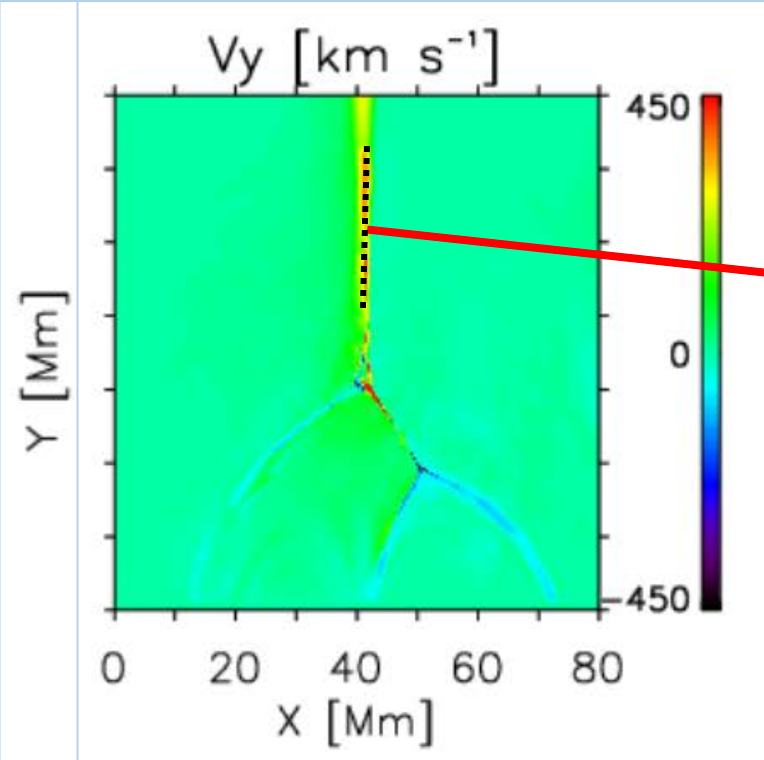


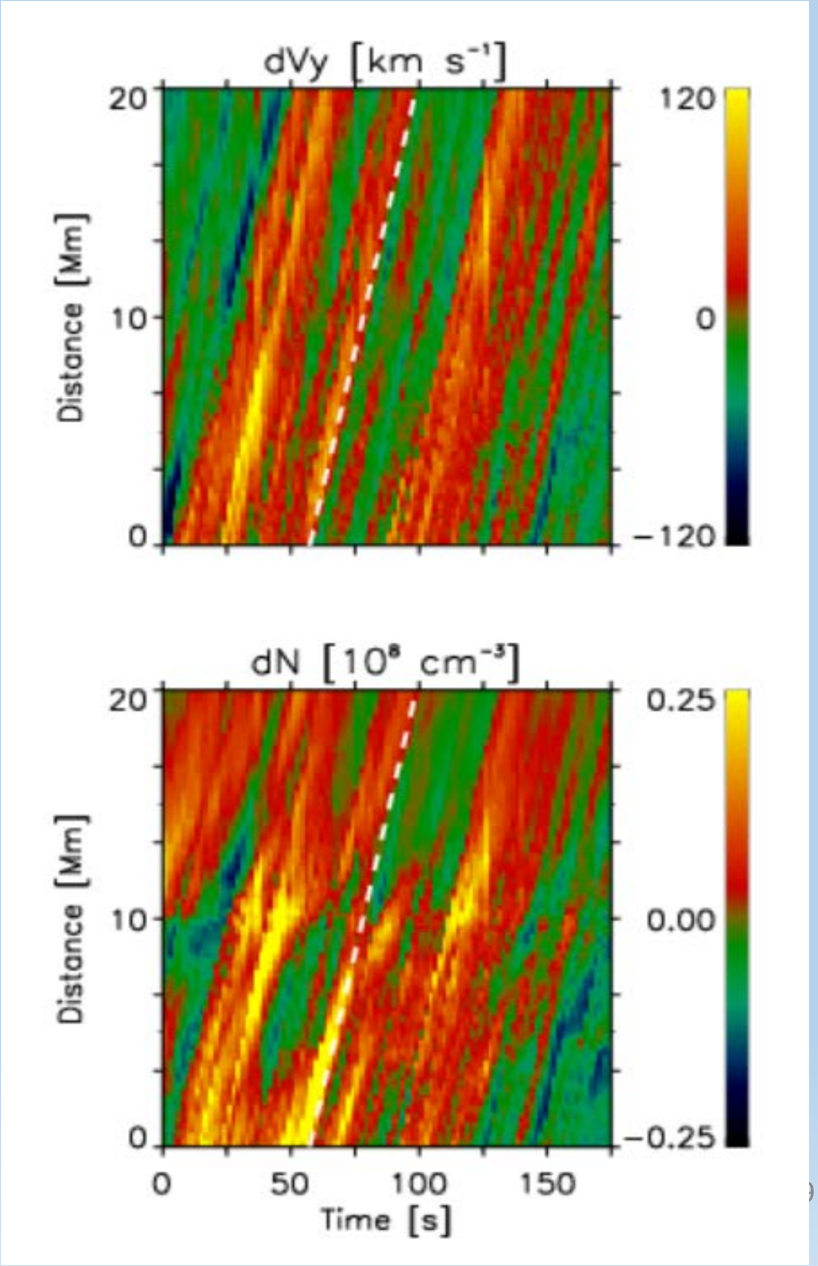
Perturbations of Vy satisfying the polarity relations of parallel-propagating slow-mode wave:

$$\frac{\delta\tilde{\rho}}{\delta\tilde{v}_{\|}} \approx \frac{\rho_0}{c_s}.$$

Yang et al., 2016

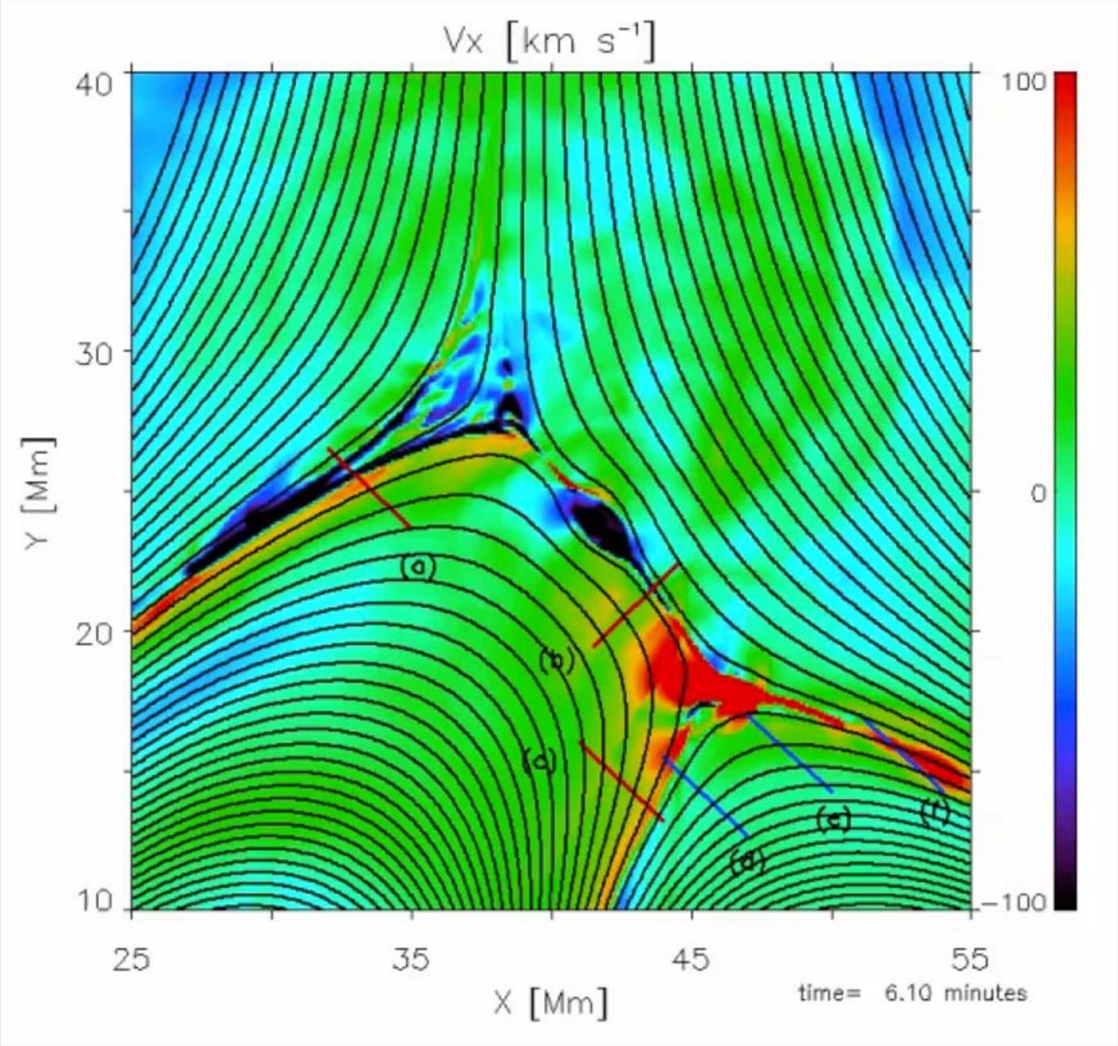
Slow-mode Waves Launched from the Reconnection Site





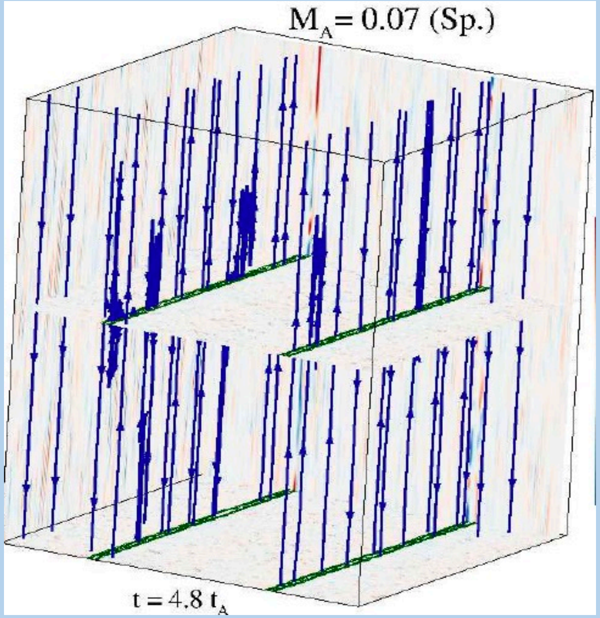
The average propagating speed of perturbations of Vy:
430 km/s, consistent with the sonic speed there, thus verifying that they are slow-mode waves.

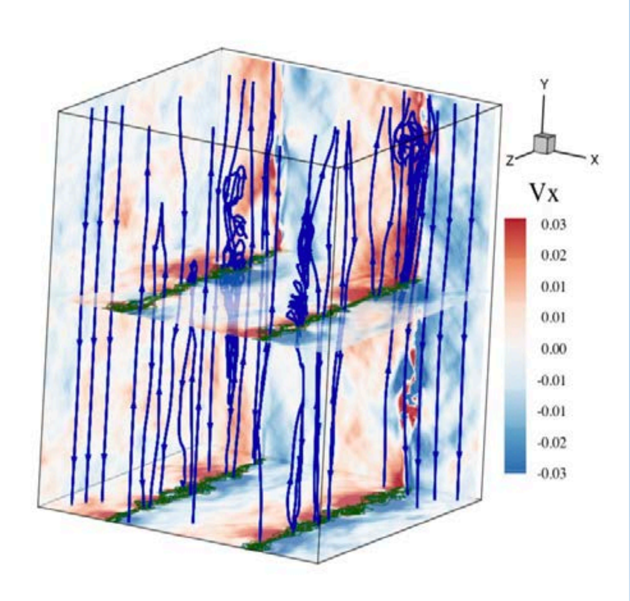
Waves Excitation by Plasmoid Ejections



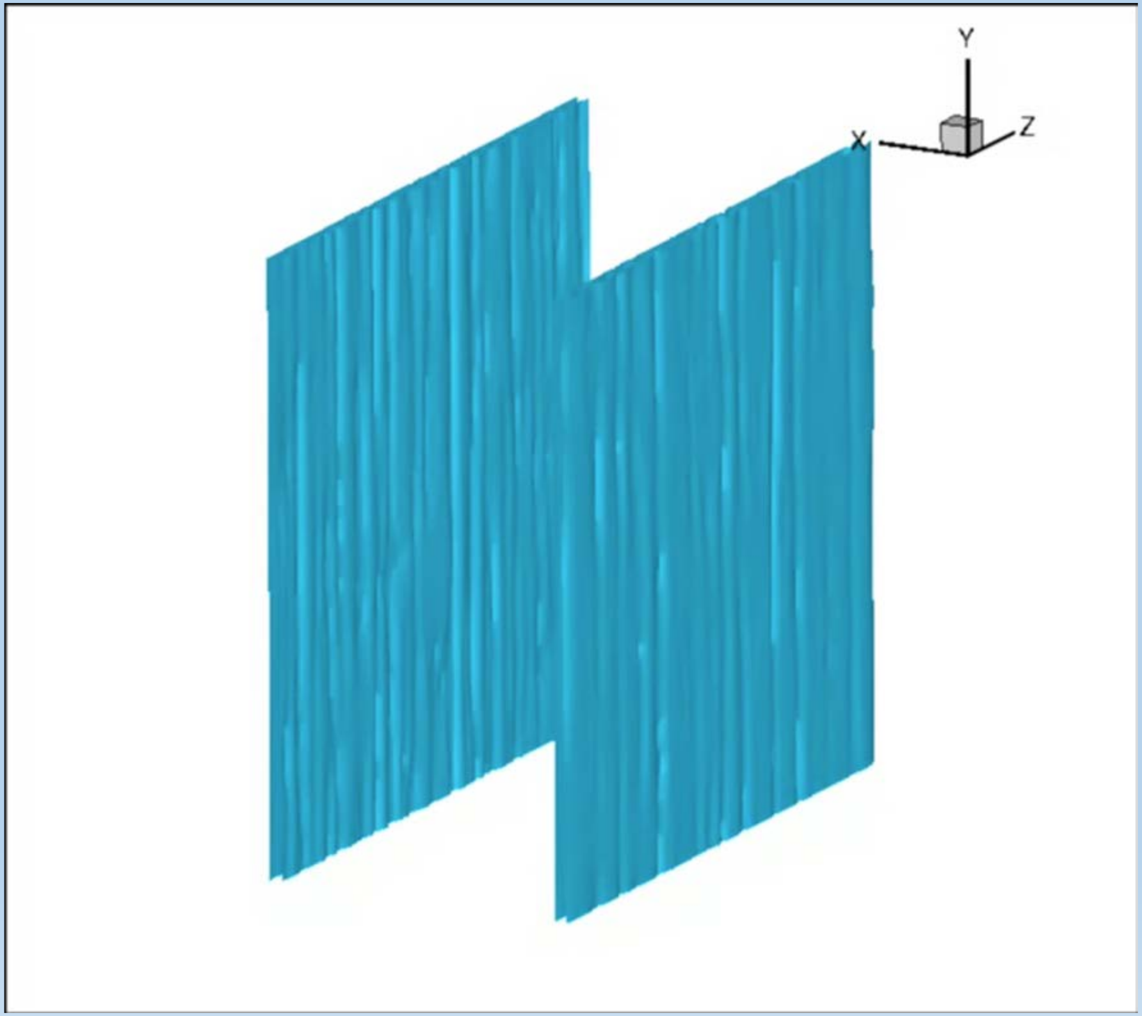
Wave excitation: Ejected plasmoids → collisions with magnetic fields in the outflow region

3D Simulation of Reconnection

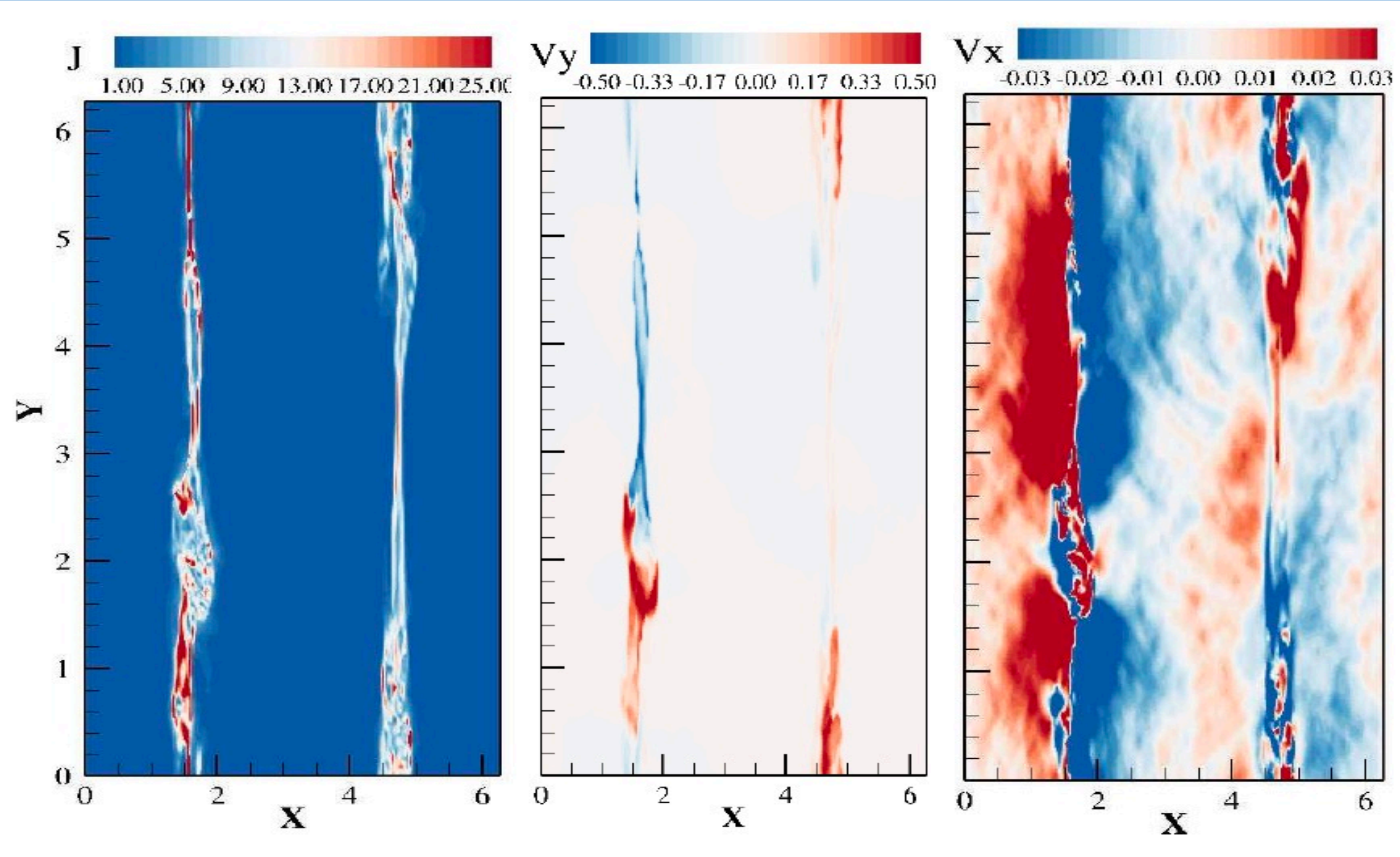




Evolution of current density

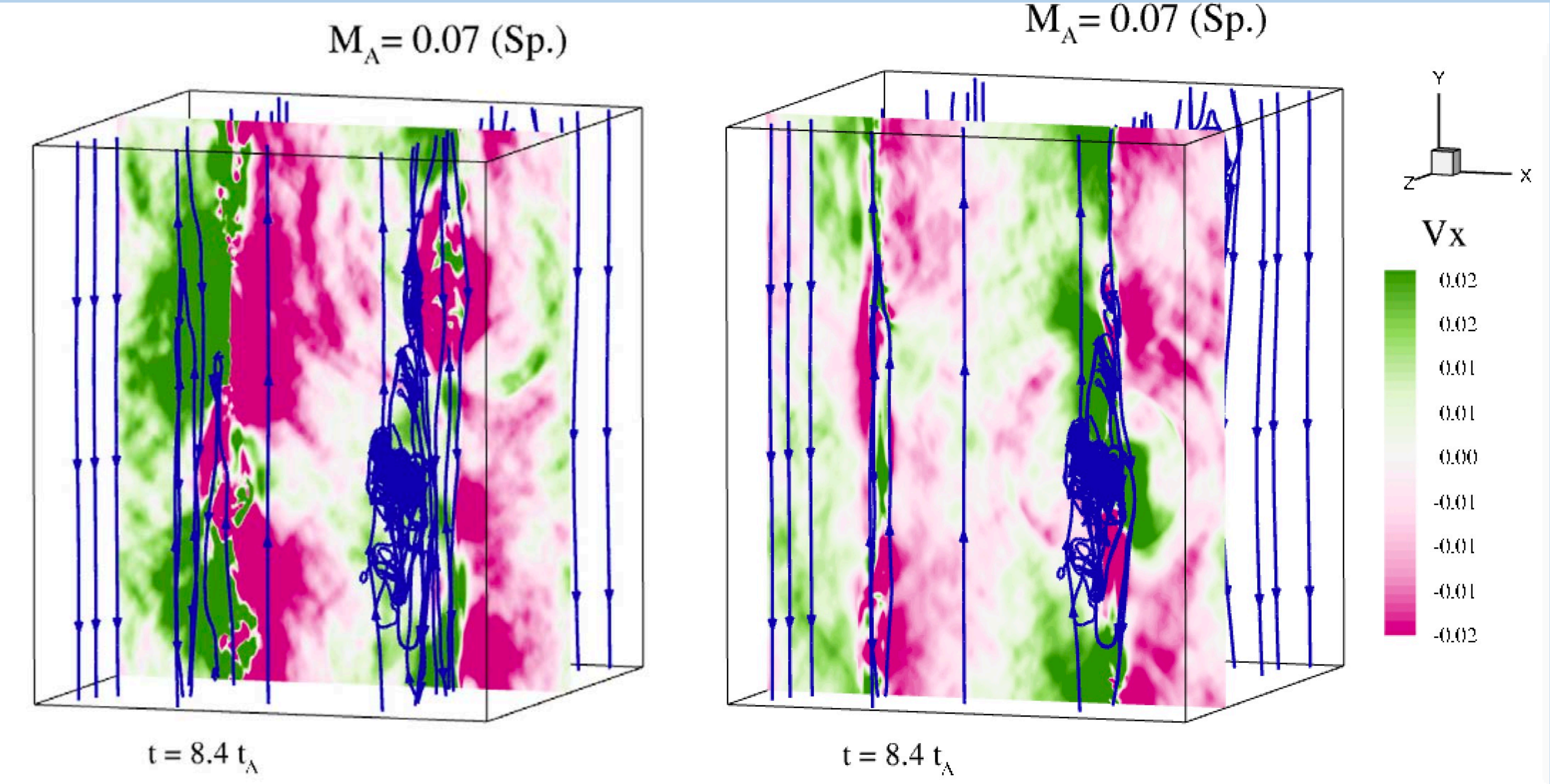


3D Simulation of Reconnection



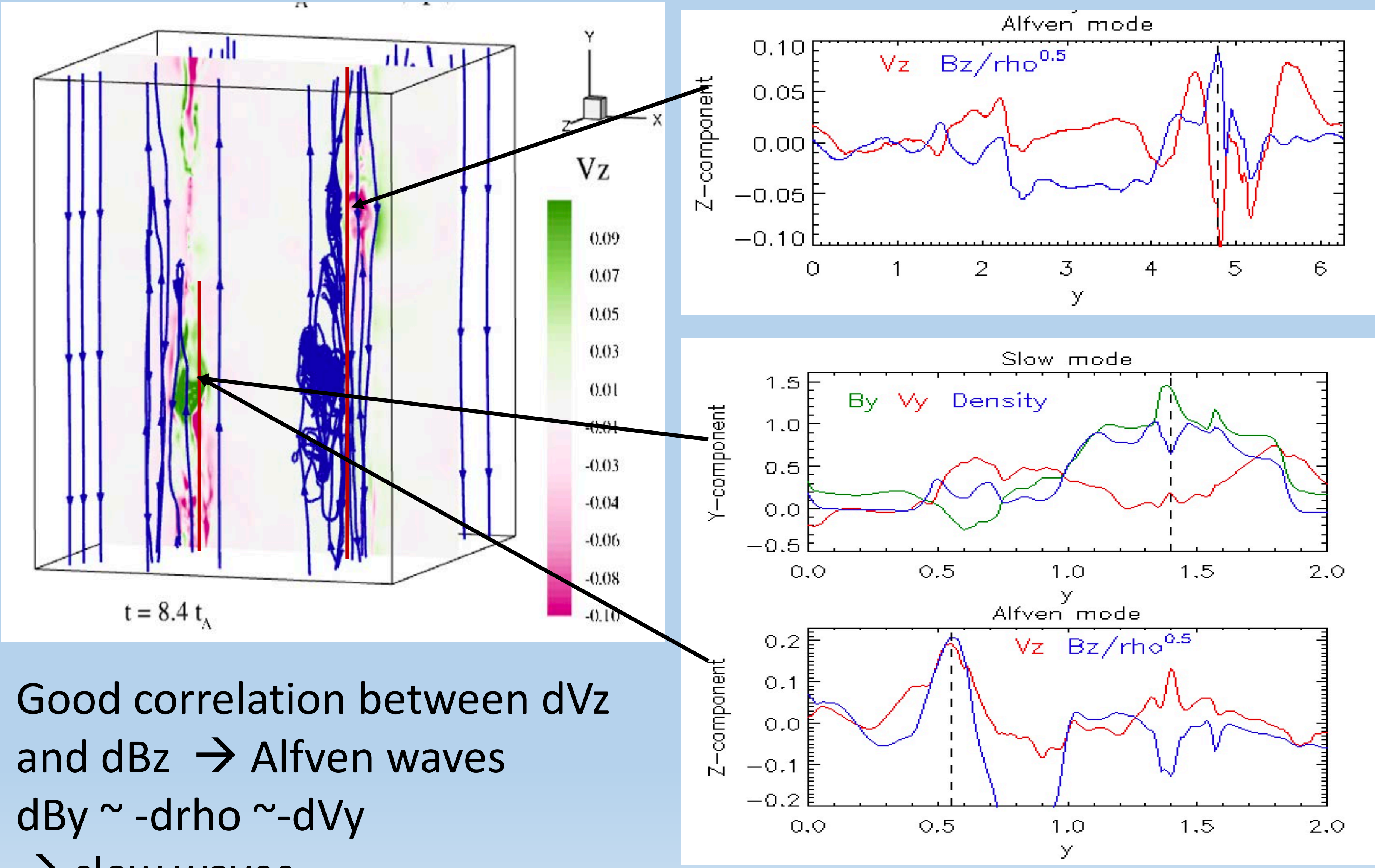
Reconnection signatures: outfow, inflow, broken field lines…..

Wave signatures in 3D Reconnection



Vx： multiple arc-shaped perturbations → fast waves

Wave signatures in 3D Reconnection



Good correlation between dVz and dBz → Alfven waves

dBy ~ -drho ~-dVy

→ slow waves

Summary

- the interchange reconnection in the solar corona was numerically investigated with high magnetic Reynolds number.
- No only outflow but also MHD waves are driven by reconnection.
- The perturbations seen in the distributions of the velocity components Vx, Vy, and Vz satisfy the polarity and dispersion relations of fast-mode, Alfven, and slow-mode waves, respectively, verifying that they are corresponding waves, with features similar to observations.
- The plasmoids hit the field lines in the outflow region, and simultaneously excite the fast-mode, Alfven, and slow-mode waves.

Thanks for your attention!