

Particle dynamics and nongyrotropic velocity distribution functions in magnetic reconnection

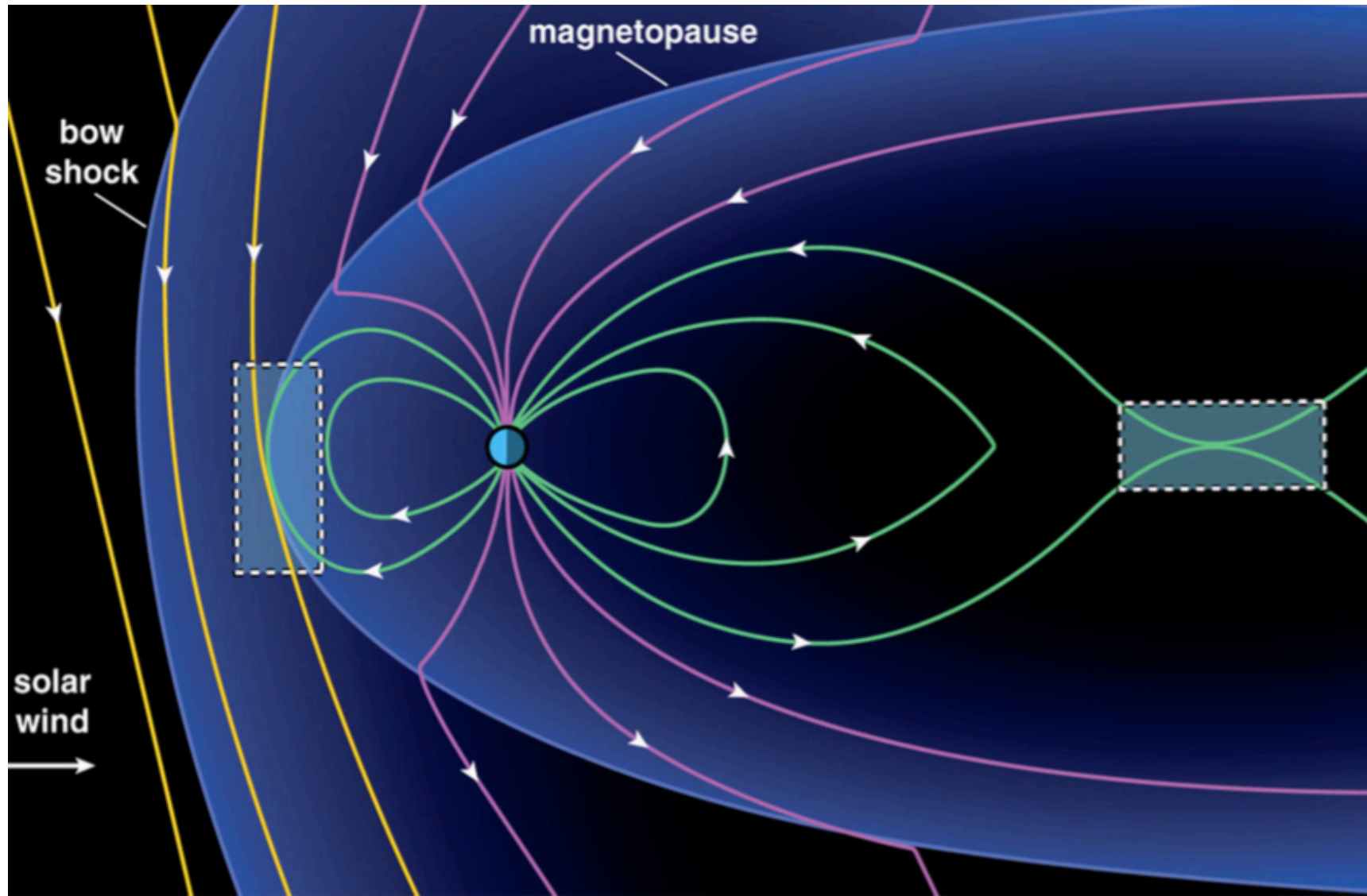
Seiji ZENITANI

Kobe University

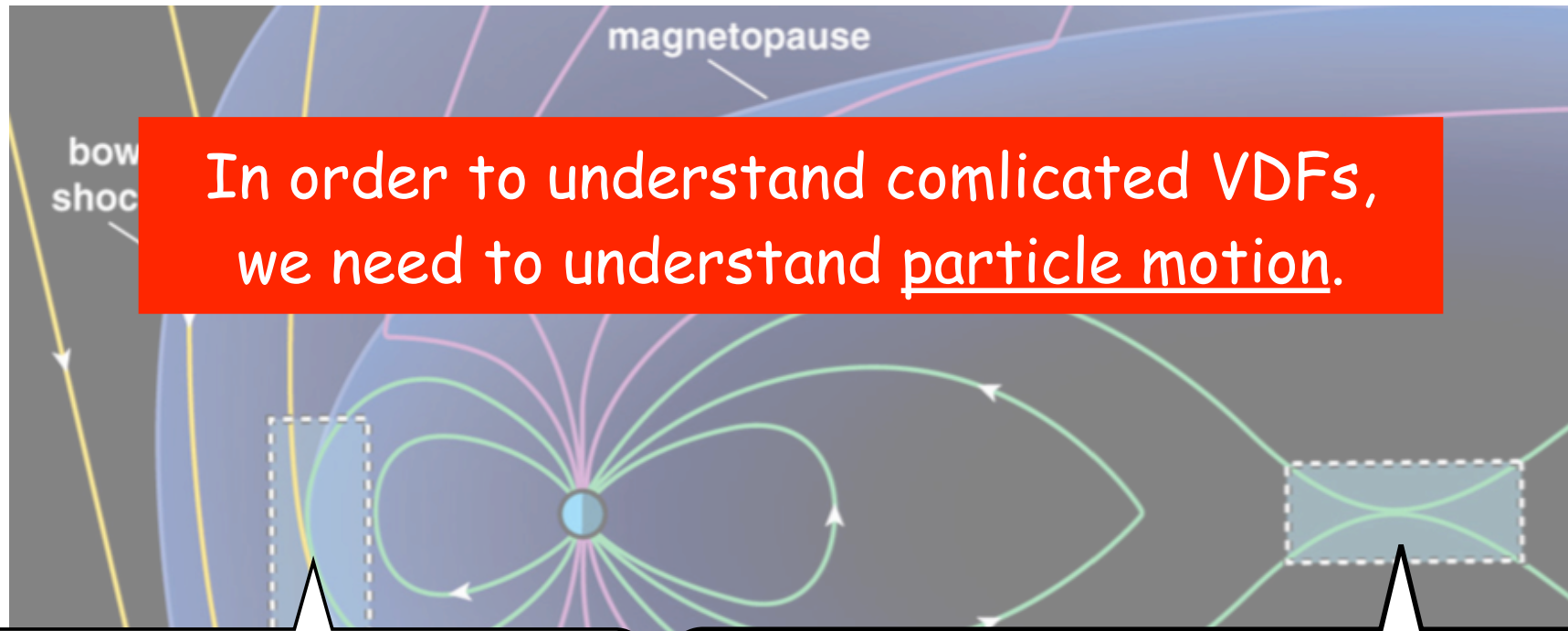
Acknowledgement: T. Nagai, I. Shinohara (JAXA/ISAS)

T. Wada (NAOJ)

Magnetic reconnection in near-Earth space

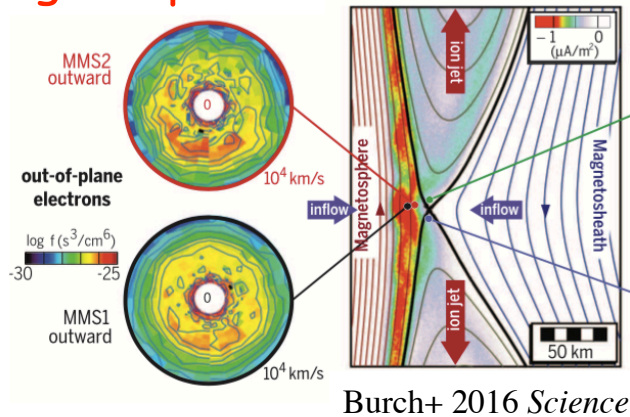


Velocity distribution functions (VDFs)

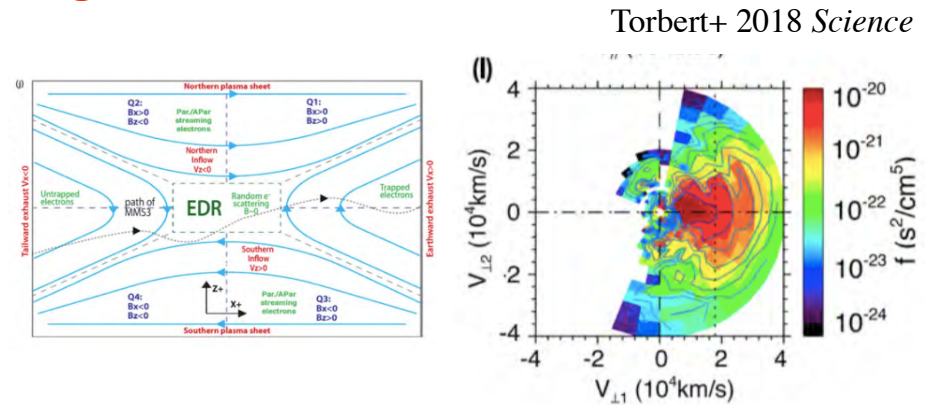


In order to understand complicated VDFs, we need to understand particle motion.

Magnetopause



Magnetotail



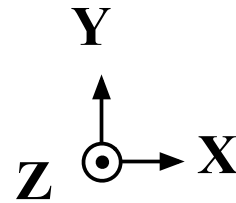
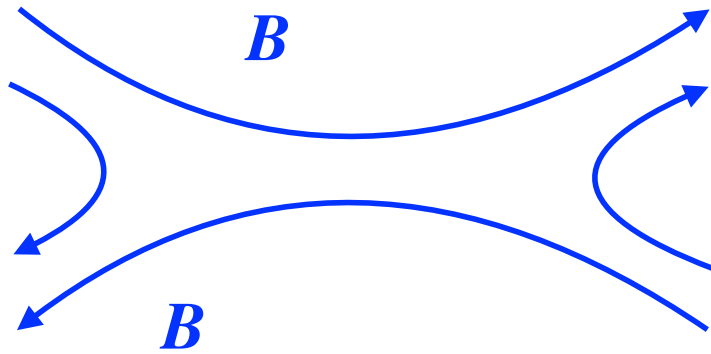
Today's agenda

1. Particle motion in a reconnected geometry
2. Ion motion and VDF in the outflow exhaust
3. Electron motion around the reconnection site

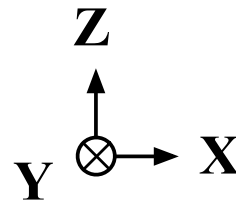
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3. Electron motion around the reconnection site

Notes

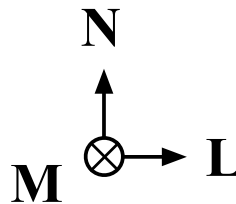
- I employ the GSM-like coordinates
- Signs are sometimes opposite, because figures/equations are taken from my ion/electron papers



- Simulation coordinates



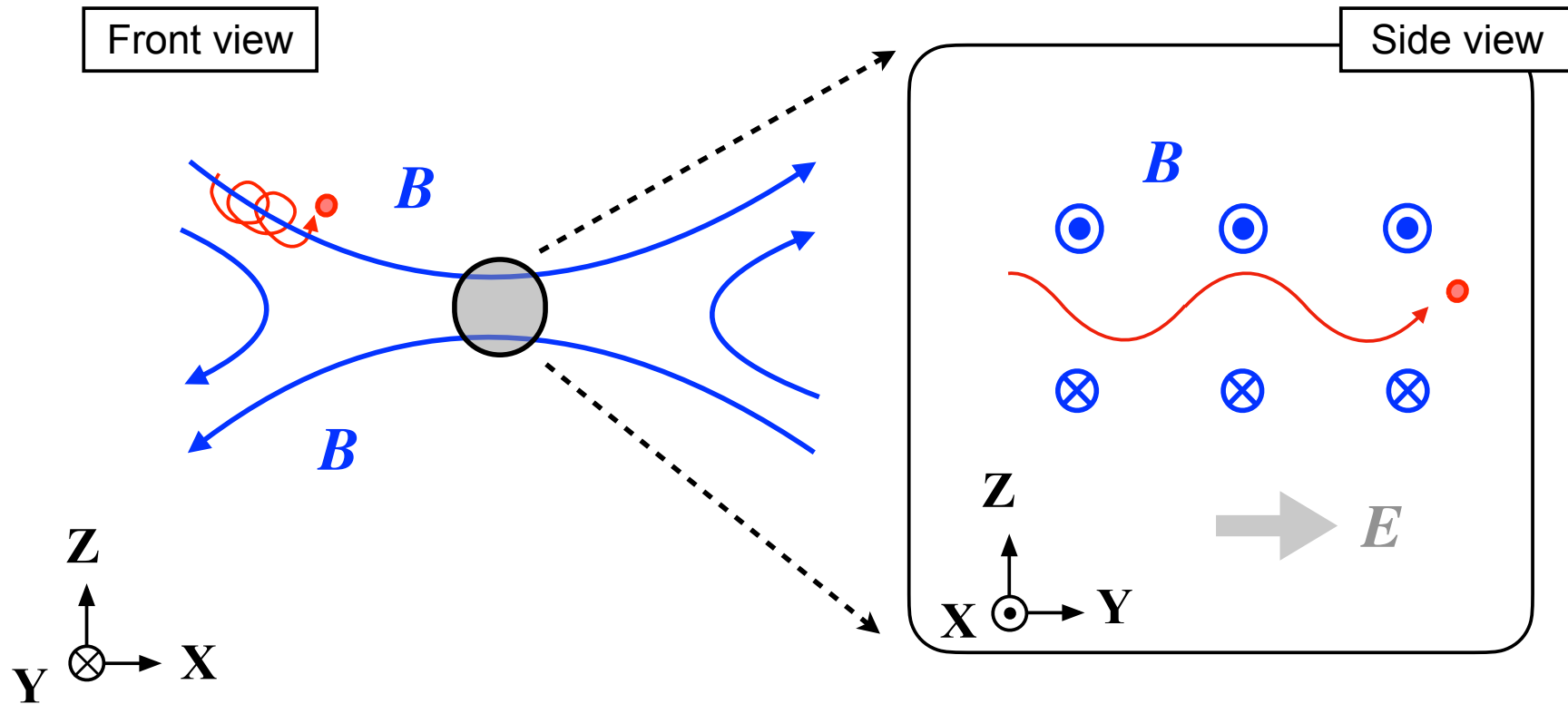
- GSM/GSE-like coordinates
- Magnetotail



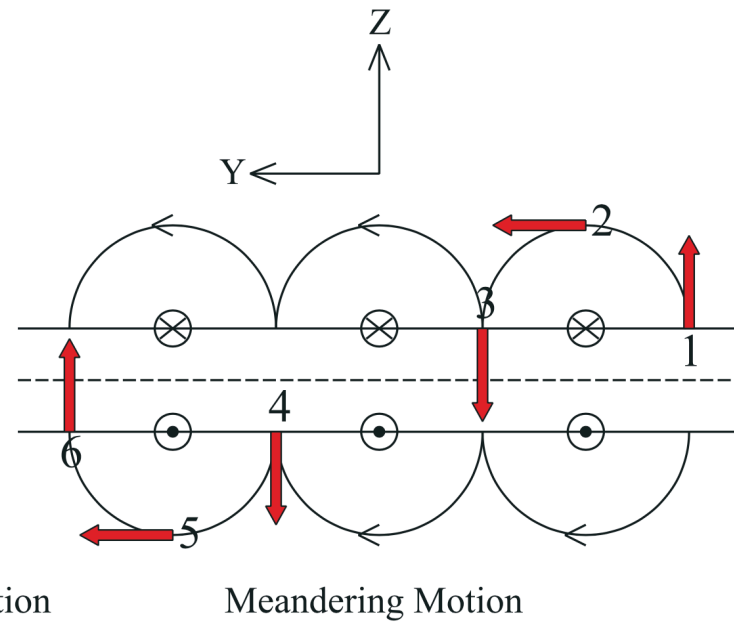
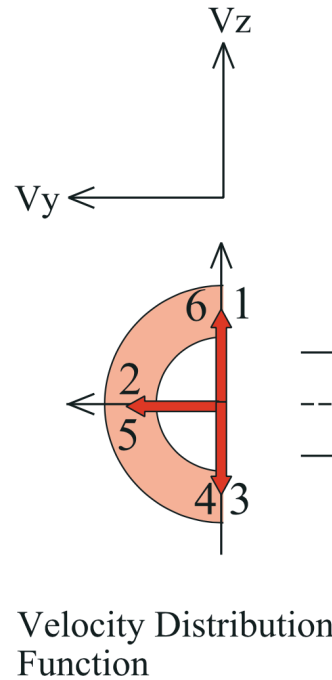
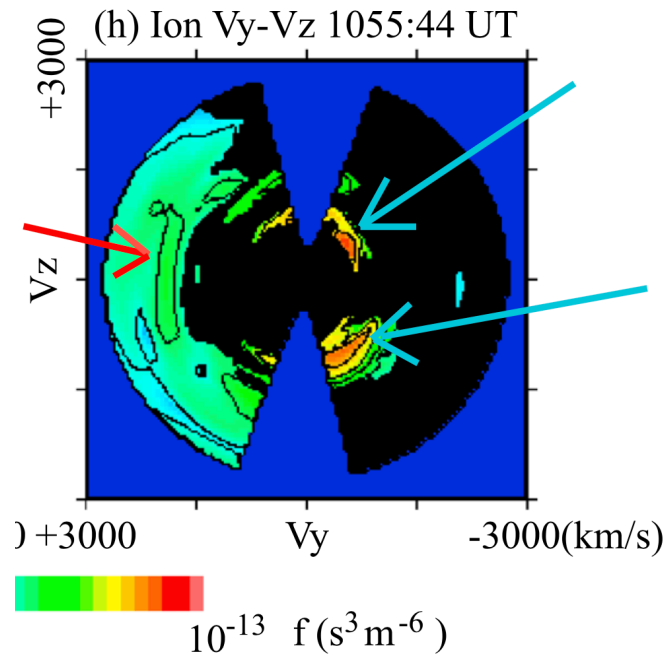
- LMN coordinates
- Magnetopause, foreshock

Meandering motion

- Partial gyration about $+\mathbf{B}_0$
- Partial gyration about $-\mathbf{B}_0$



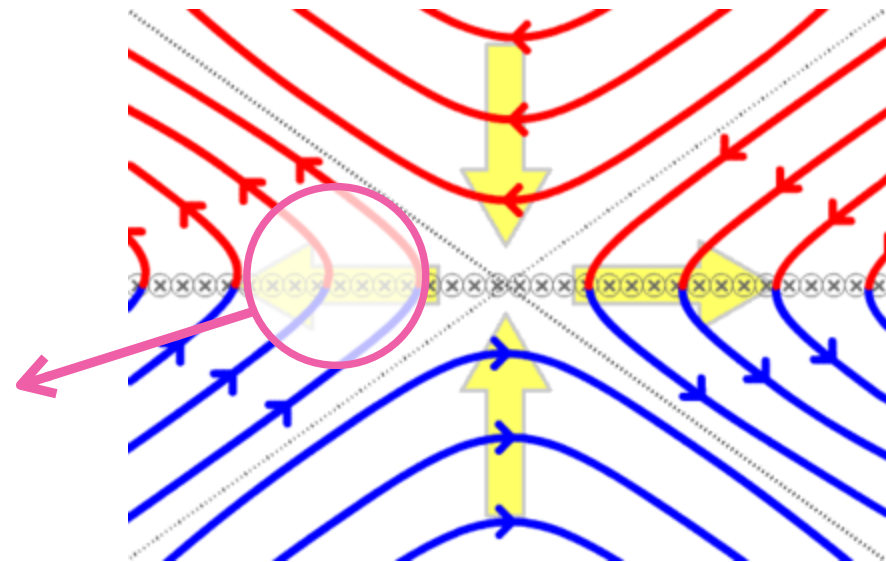
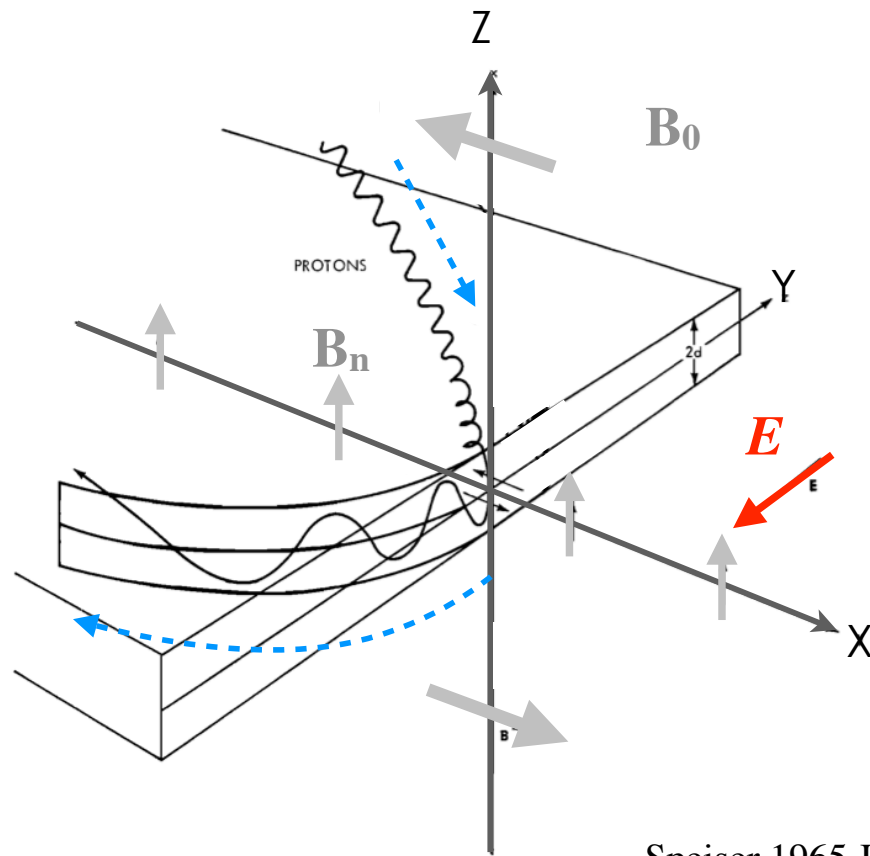
Meandering ions



- Meandering ions are confirmed in Geotail observations of magnetotail reconnection

Speiser motion

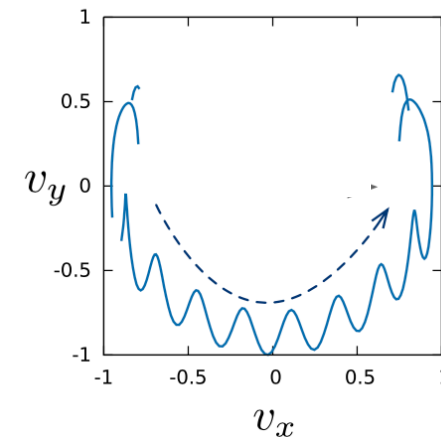
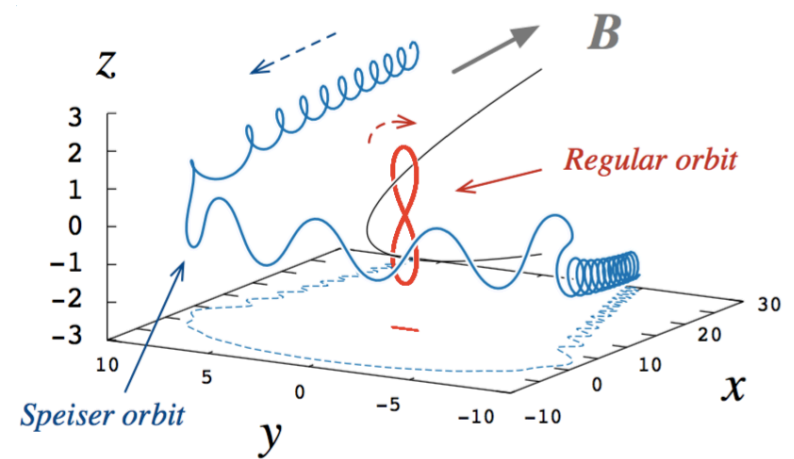
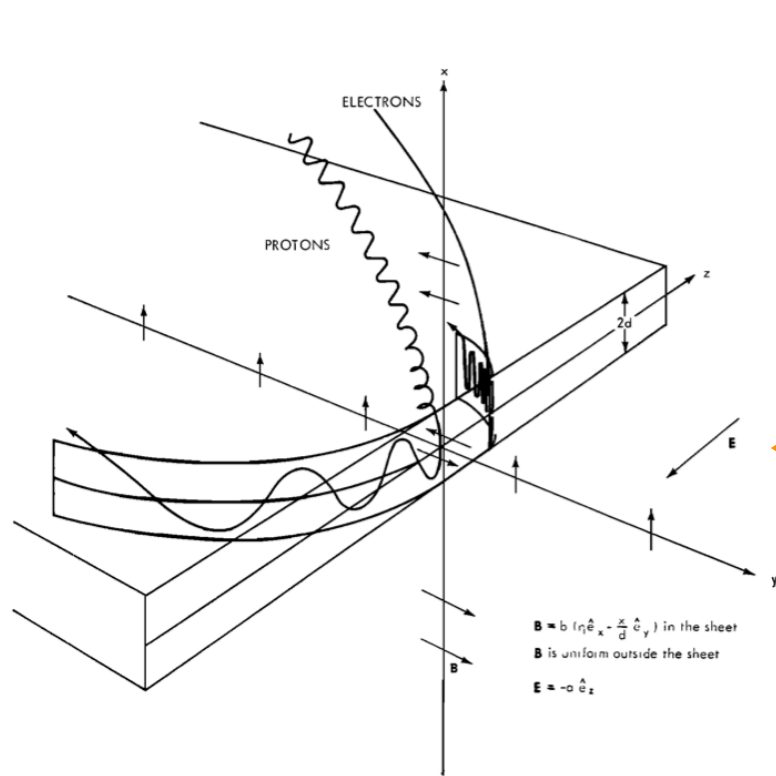
- Meandering motion + slow gyration about \mathbf{B}_n



Speiser 1965 JGR

Speiser motion in a moving frame

- Consider a moving frame, in which E is transformed away
- In the velocity space, particle goes through a half ring during the meandering phase.



Particle motion in a parabolic field

- Model field

$$\mathbf{B} = B_0(z/L)\mathbf{e}_x + B_n\mathbf{e}_z, \quad \mathbf{E} = 0,$$

- Equation of motion

$$m_e(d\mathbf{v}_e/dt) = -e(\mathbf{v}_e \times \mathbf{B})$$

- can be simplified into:

$$\begin{cases} \ddot{x} = -\Omega_n \dot{y} \\ \ddot{y} = -\omega_b^2 (\dot{z}/|v_e|)z + \Omega_n \dot{x} \\ \ddot{z} = \omega_b^2 (\dot{y}/|v_e|)z, \end{cases}$$

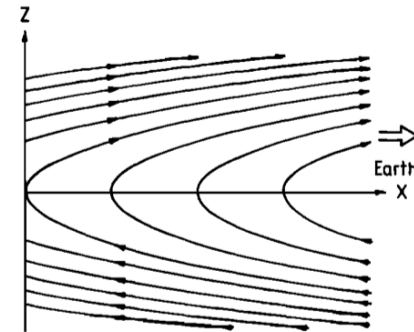
where

$$\Omega_n = eB_n/m_e$$

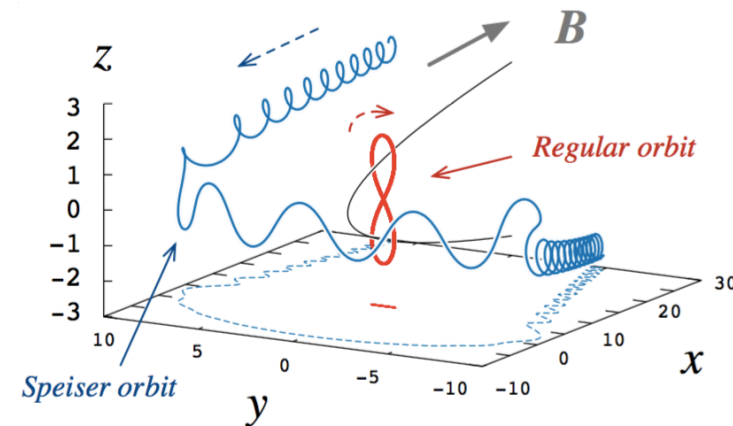
$$\omega_b = \sqrt{eB_0|v_e|/m_eL}$$

Turning frequency by $B_z (B_n)$

Meandering frequency



Buchner & Zelenyi
1989 JGR

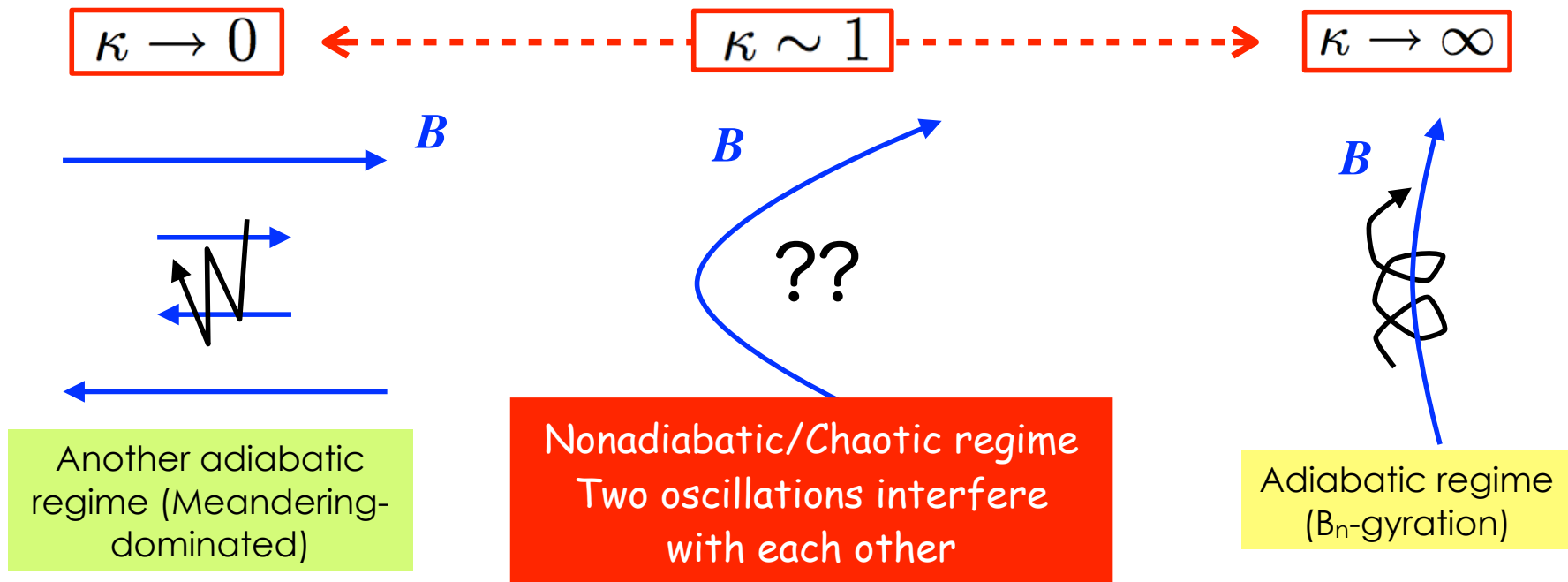


Curvature parameter

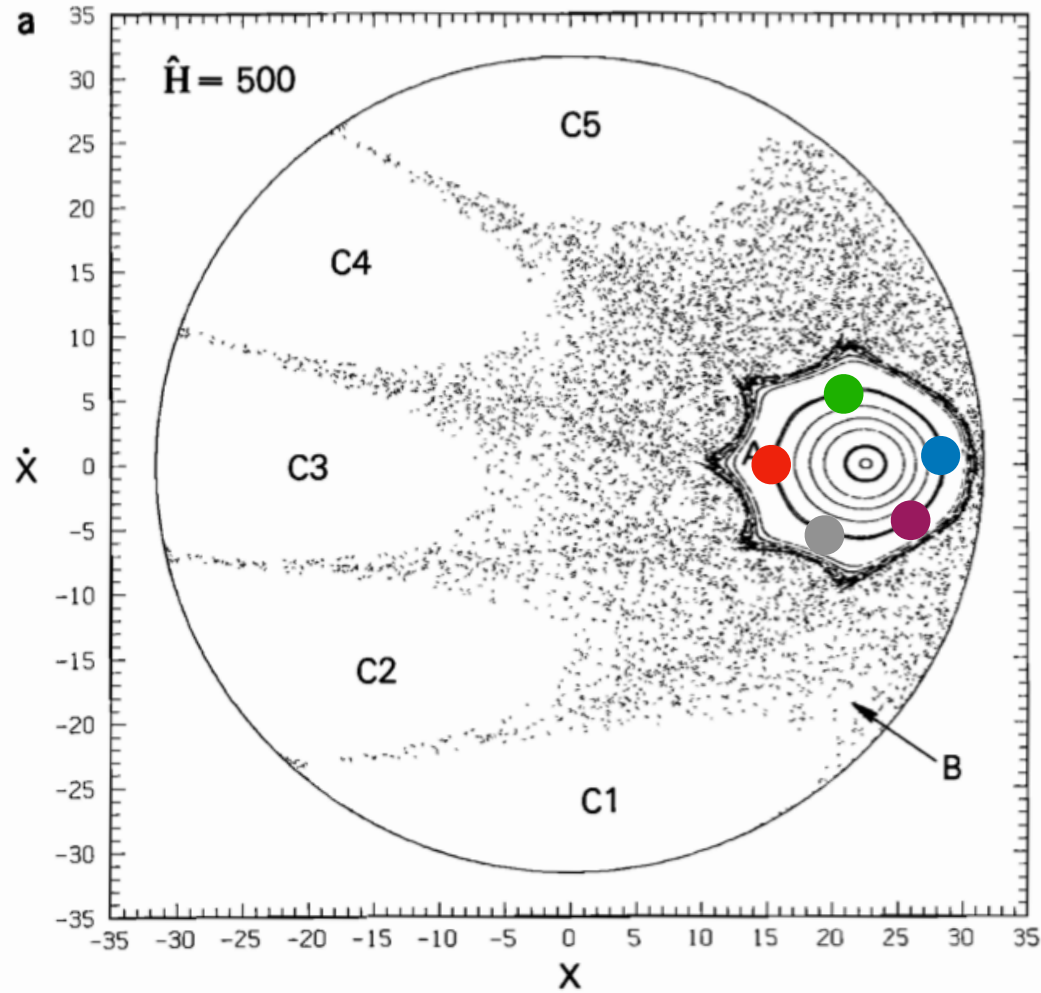
- Ratio of the two frequencies
- Ratio of the magnetic curvature radius to the maximum Larmor radius

$$\kappa \equiv \frac{\Omega_n}{\omega_b} = \sqrt{\frac{R_{c,\min}}{r_{L,\max}}}$$

Buchner & Zelenyi 1989 JGR

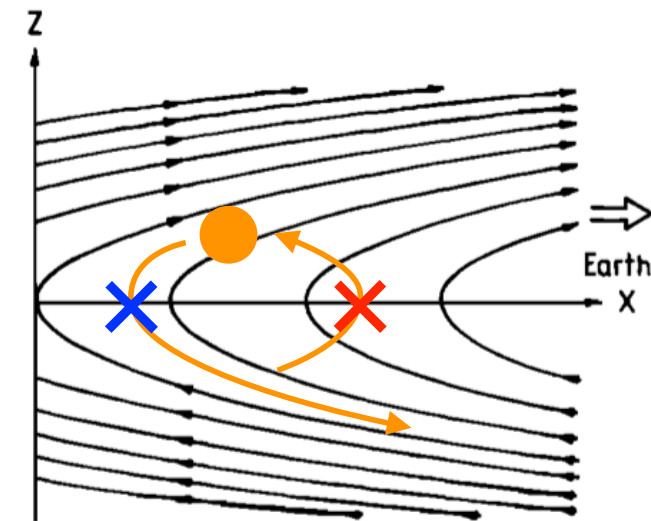


Poincaré map

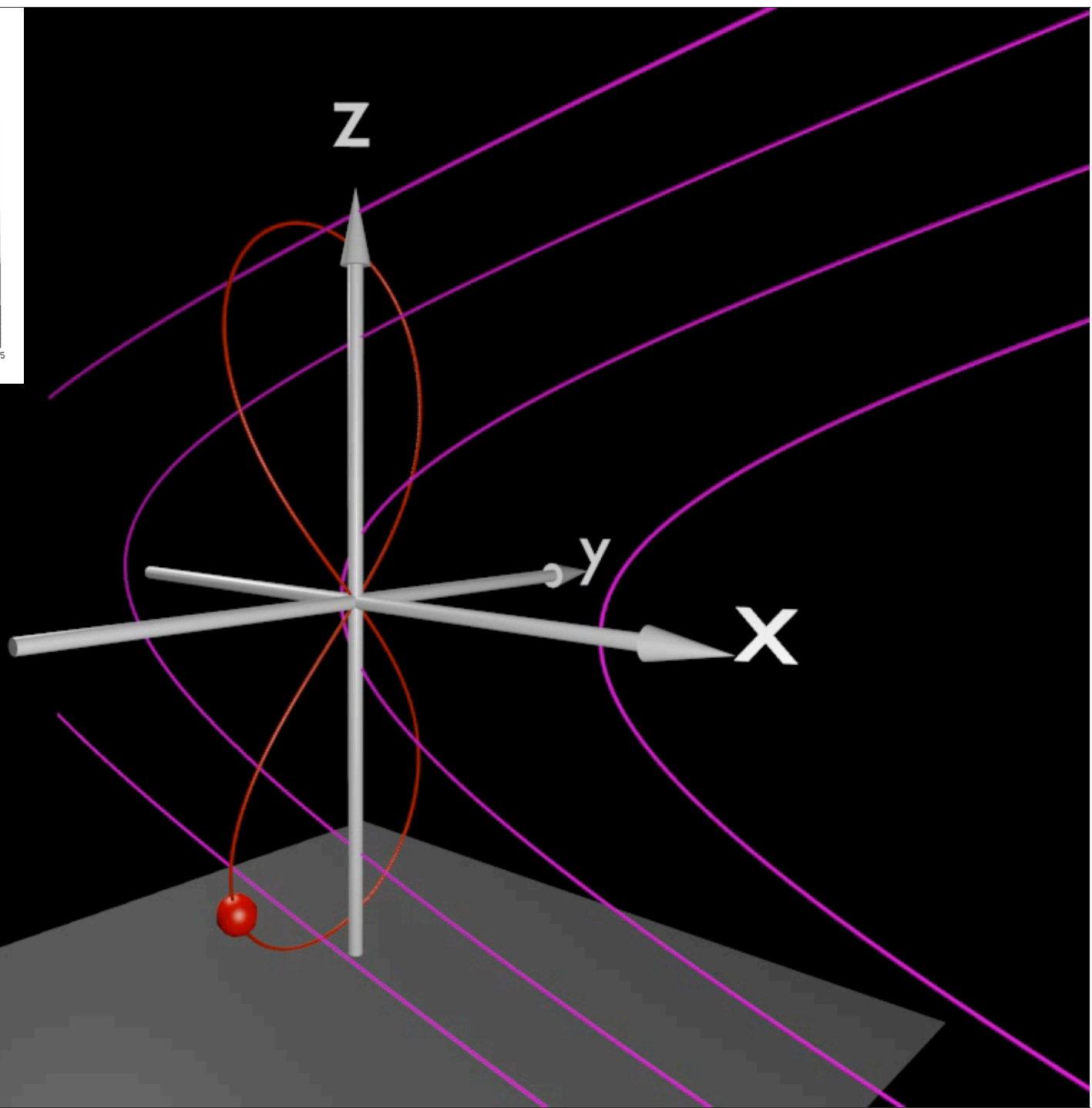
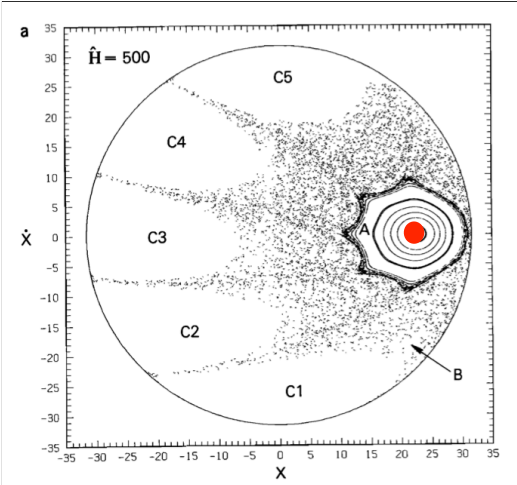


Chen & Palmadesso 1986

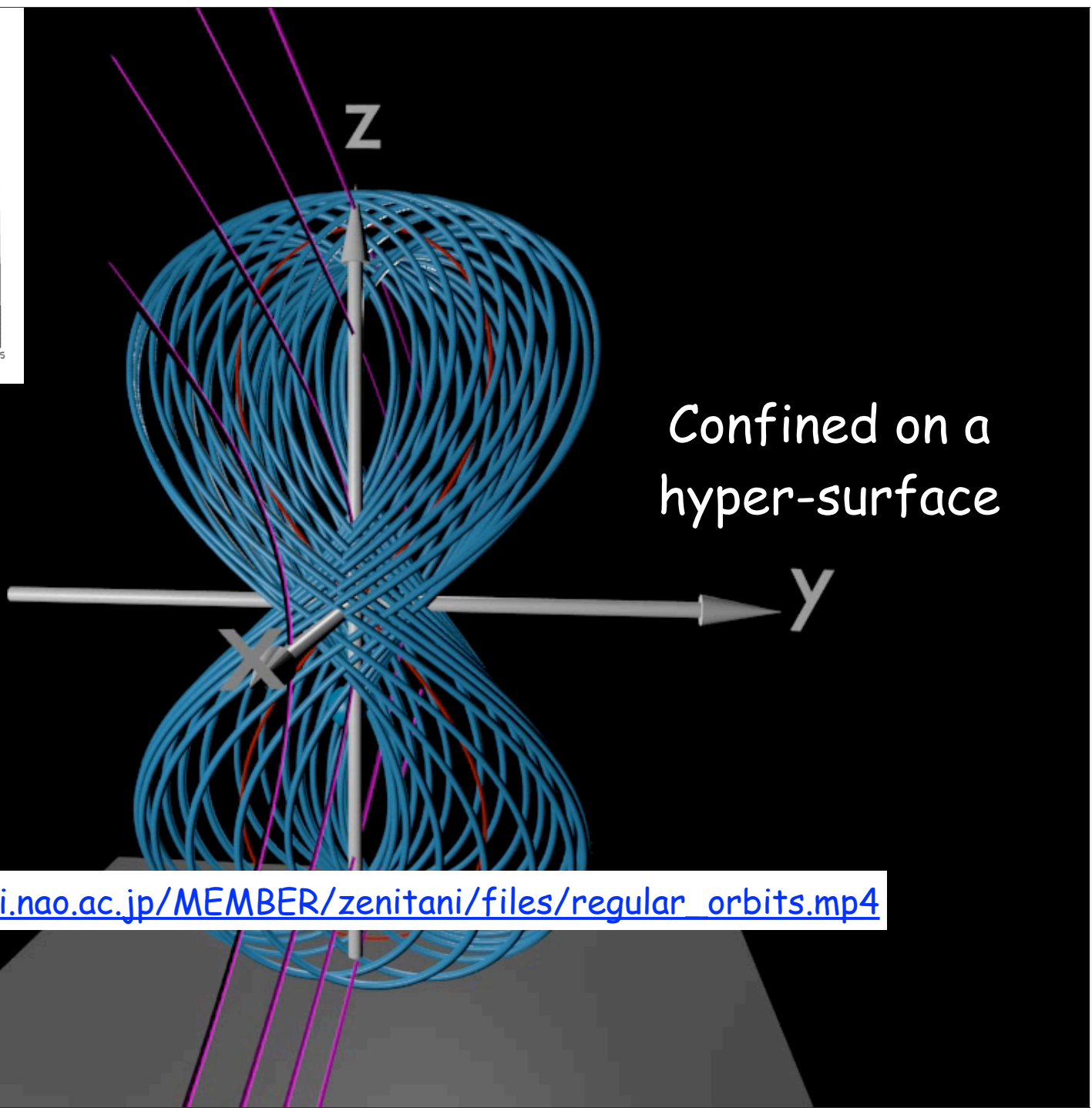
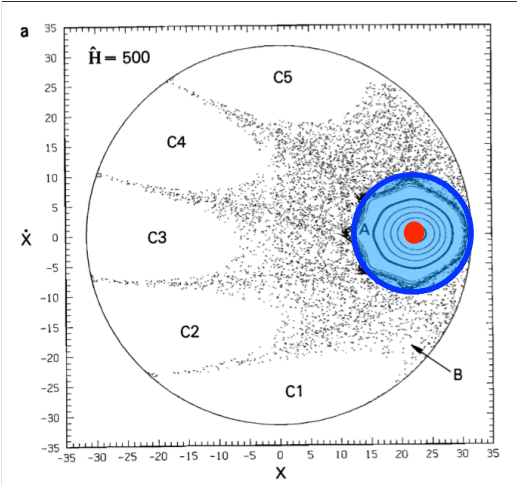
- One way to categorize particle orbits



Buchner & Zelenyi 1989



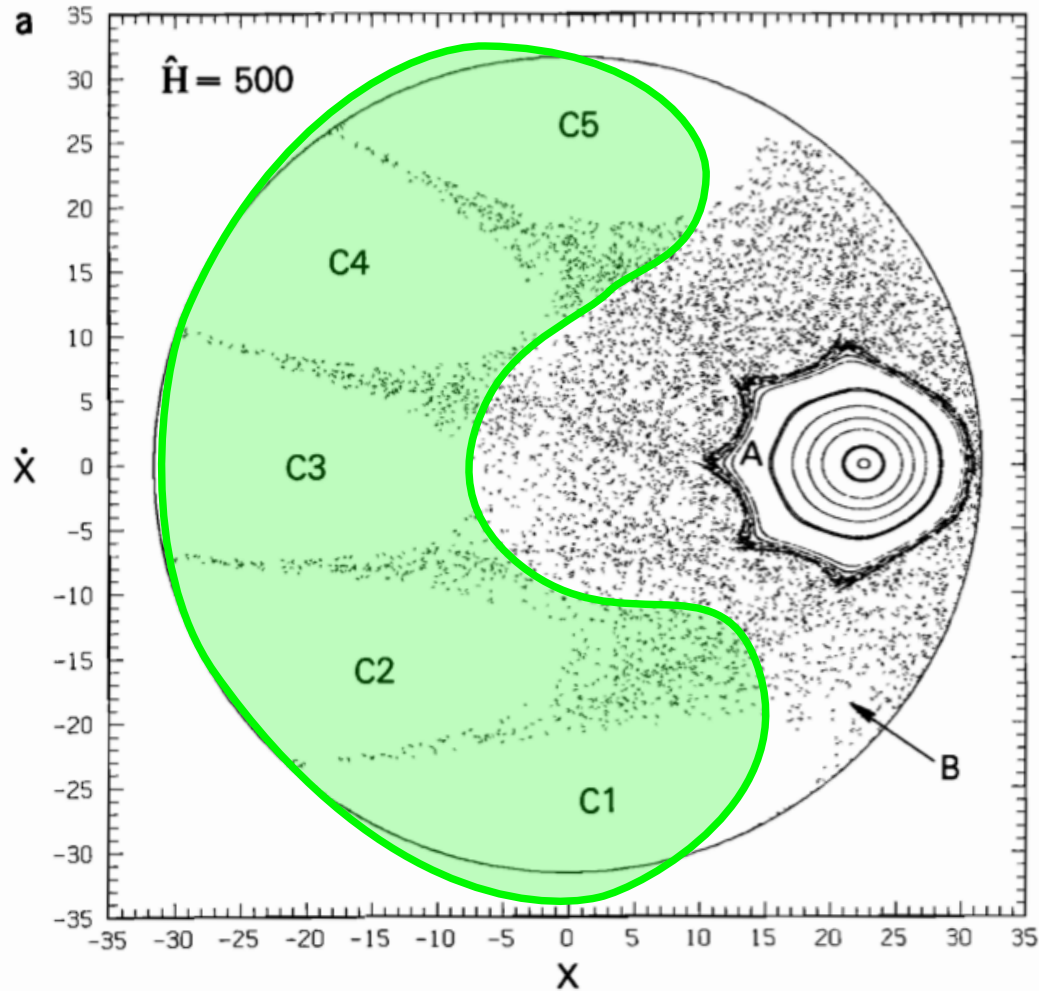
by T. Wada (NAOJ)



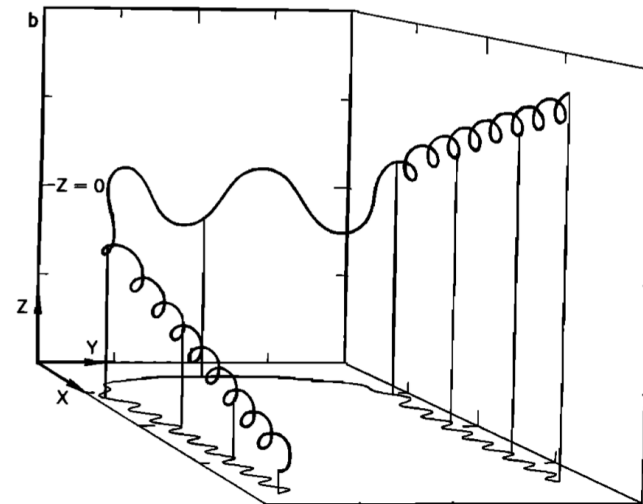
https://sci.nao.ac.jp/MEMBER/zenitani/files/regular_orbits.mp4

by T. Wada (NAOJ)

Speiser motion in Poincaré map

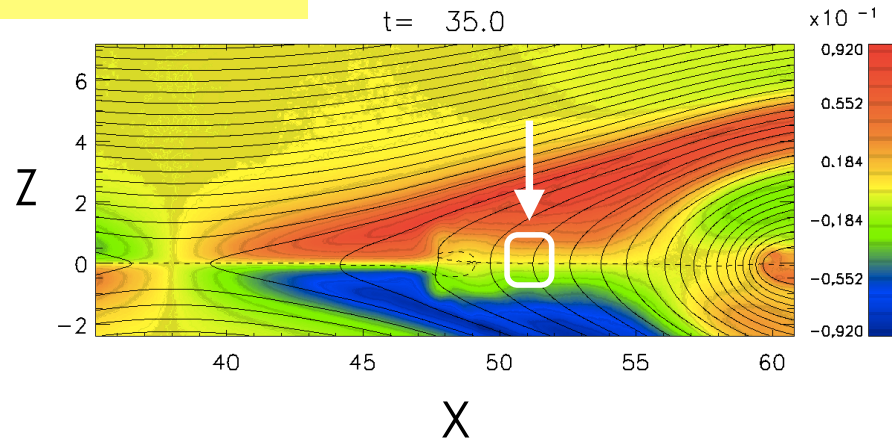


- Empty regions correspond to Speiser motion
- The particle goes far away

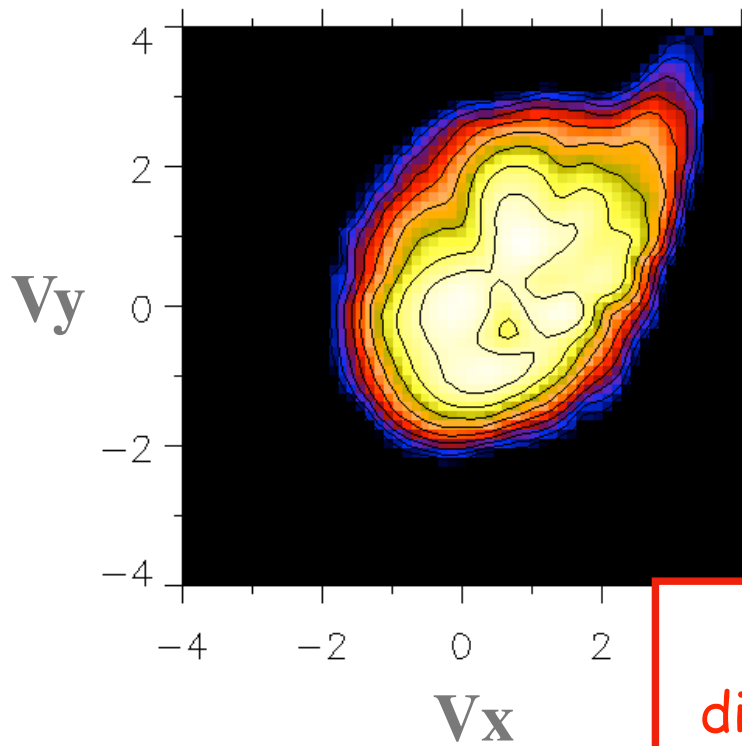


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3. Electron motion around the reconnection site

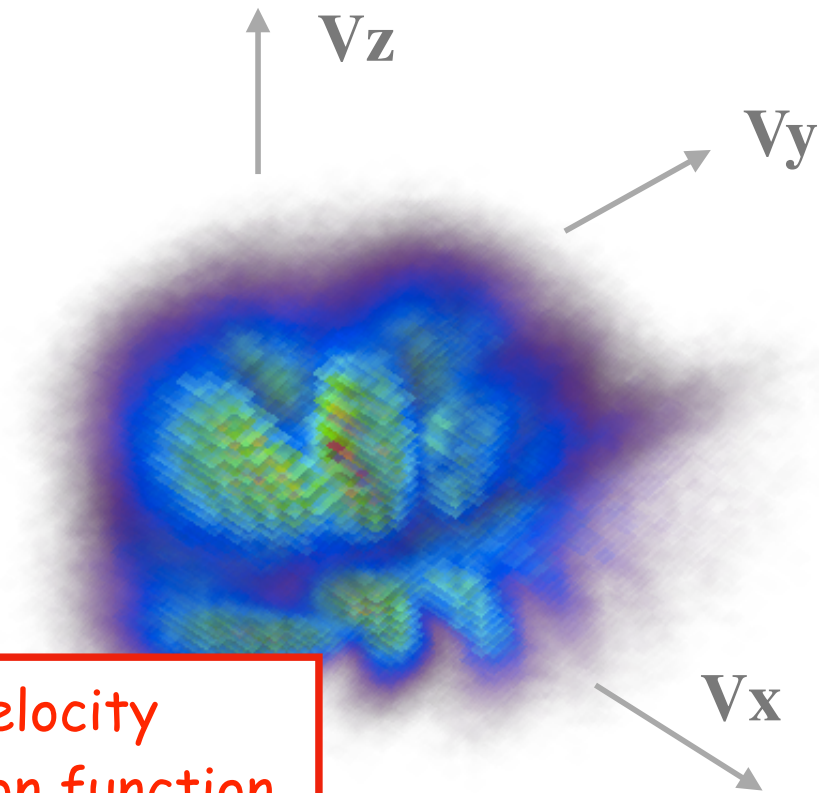
2-D PIC simulation



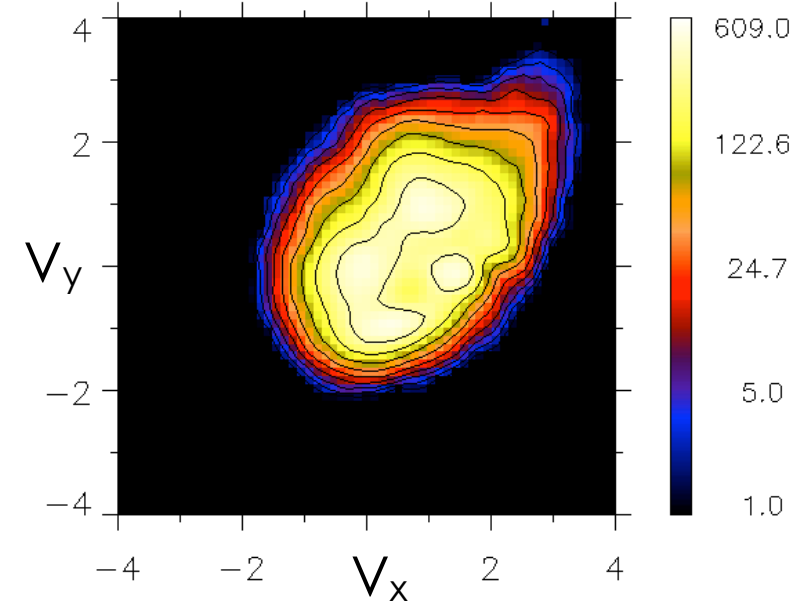
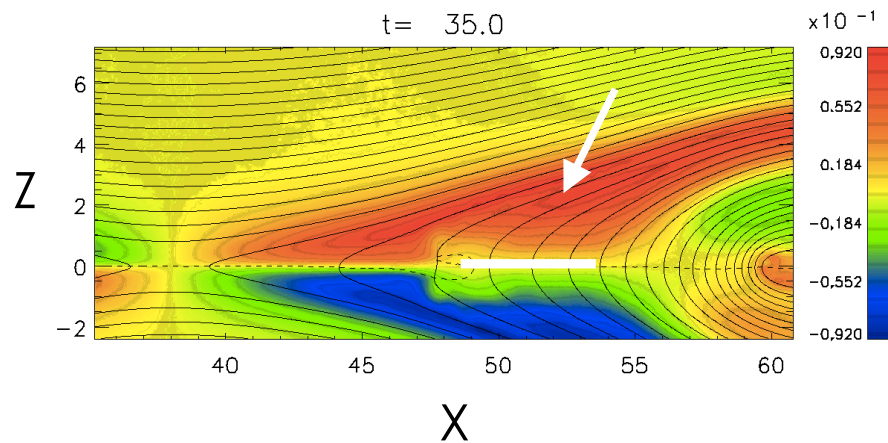
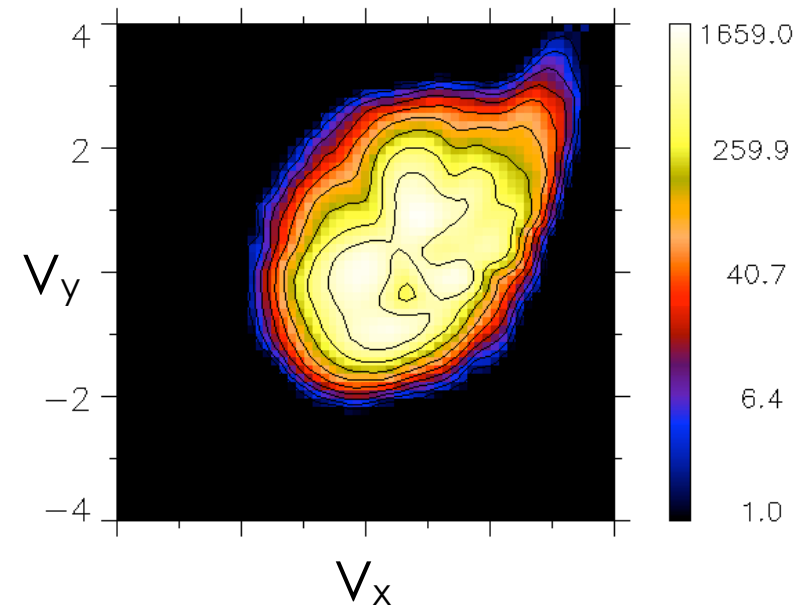
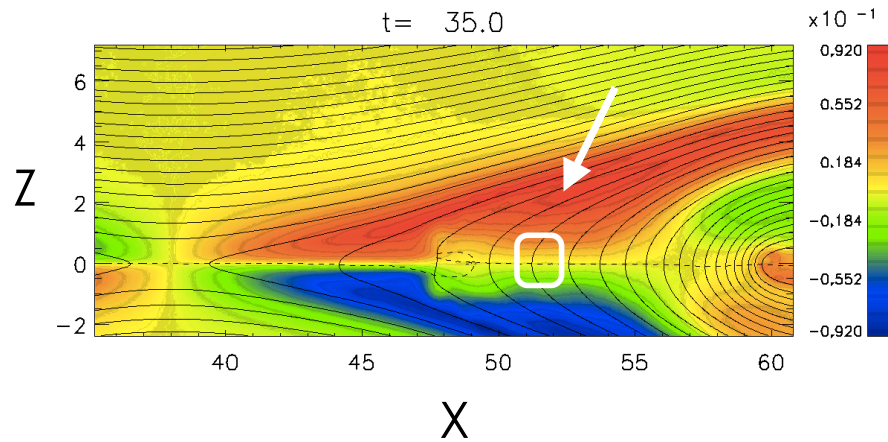
- 2.5D
- $m_i/m_e=100$
- $76.8 \times 38.4 [d_i]$
- Harris sheet
- $n_{bg}/n_{cs} = 0.2$
- 2×10^9 particles



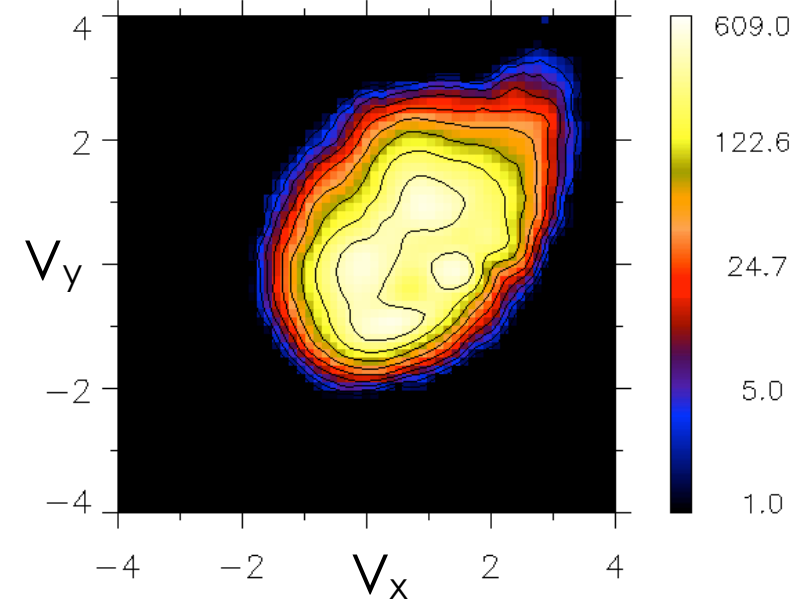
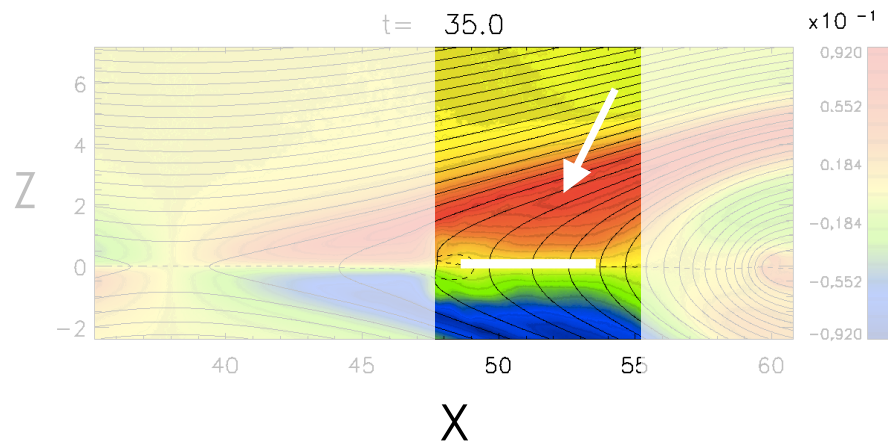
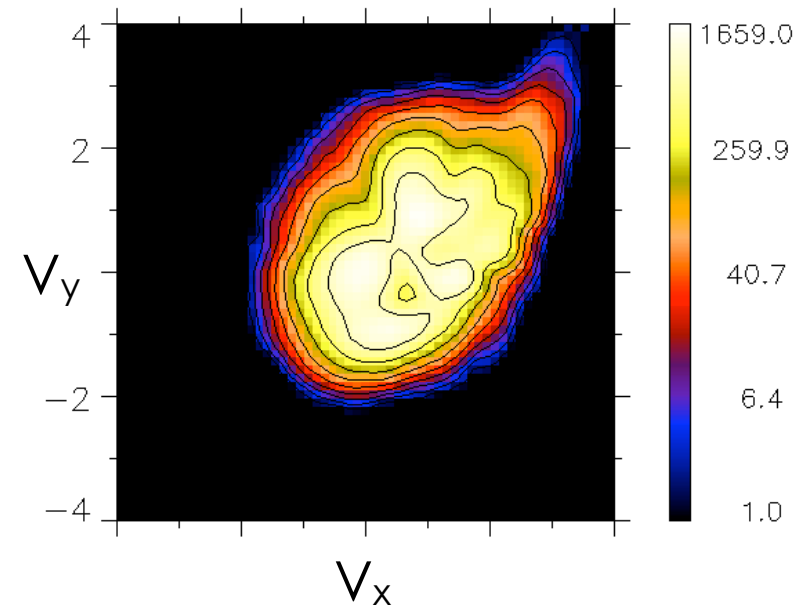
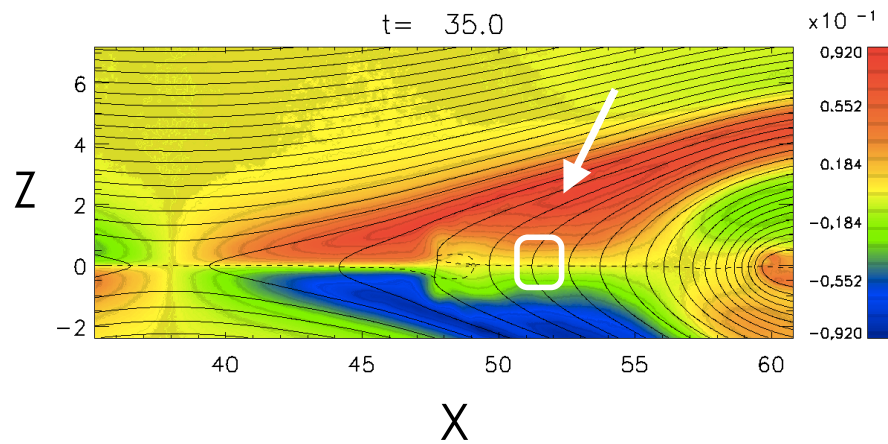
Ion velocity distribution function



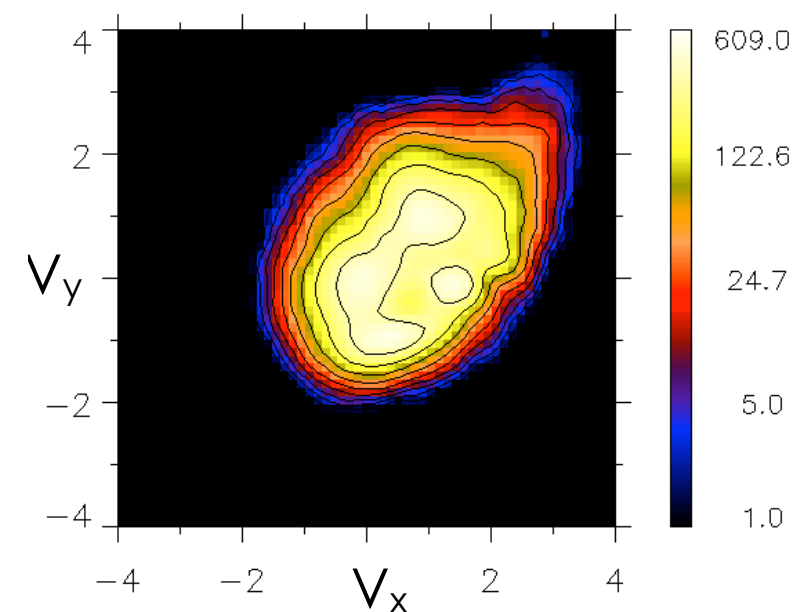
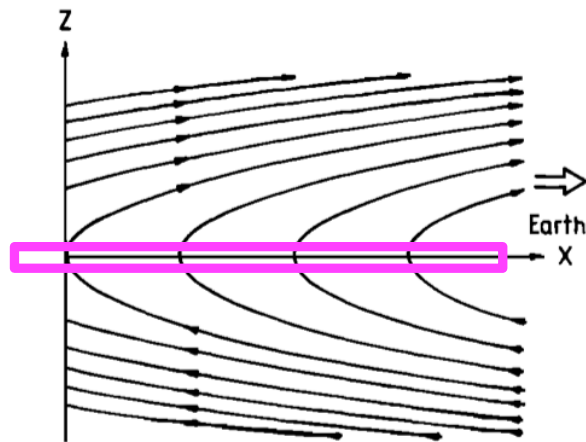
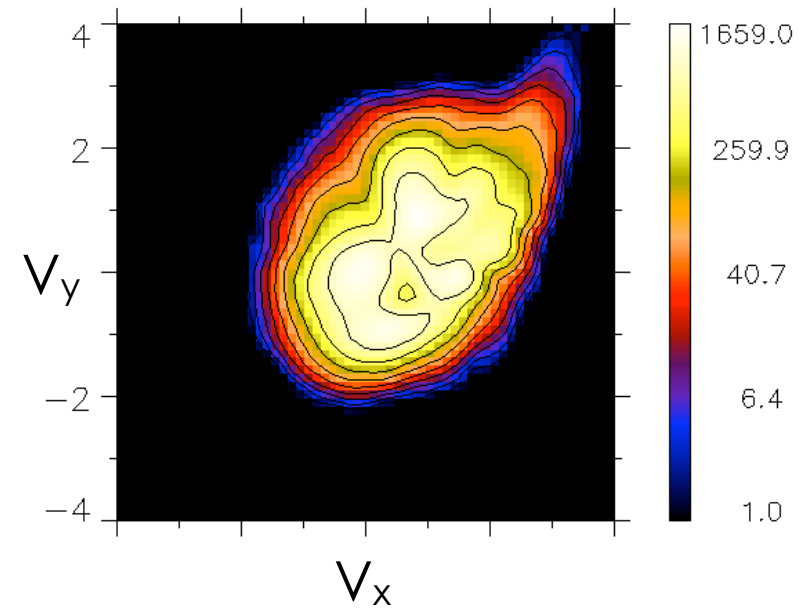
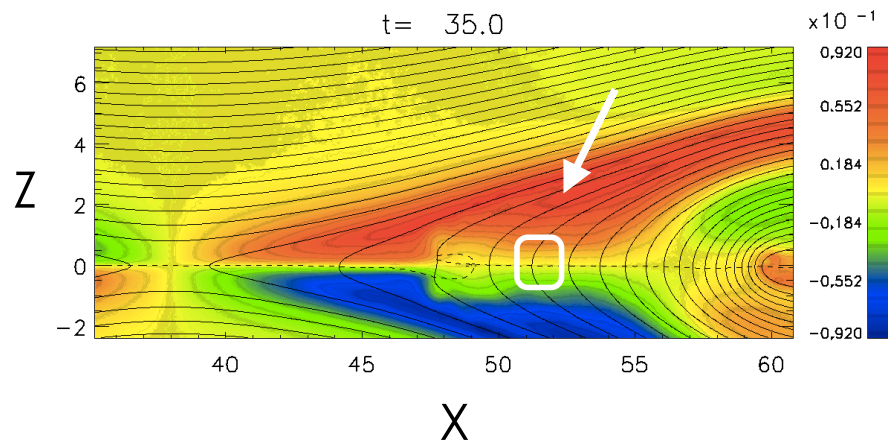
Ion velocity distribution function (VDF)



Ion velocity distribution function (VDF)

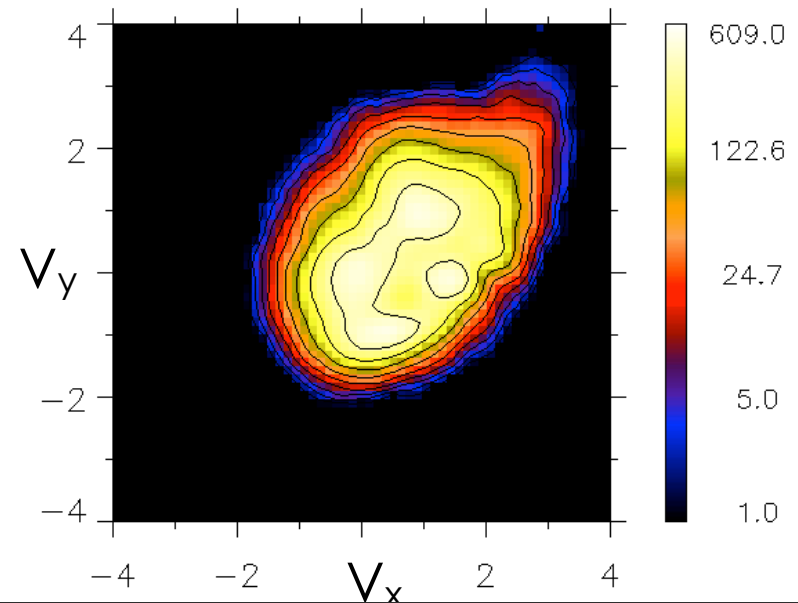
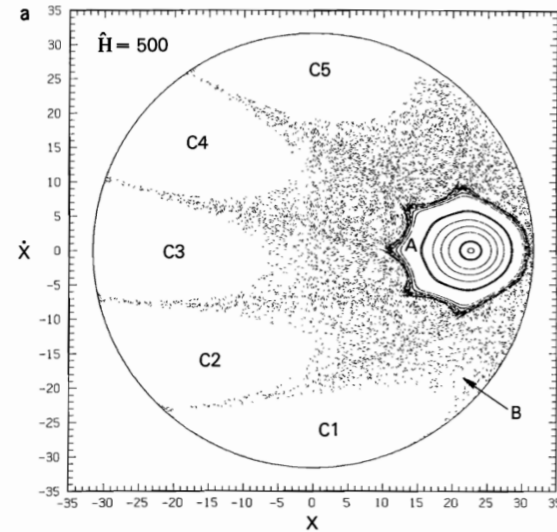
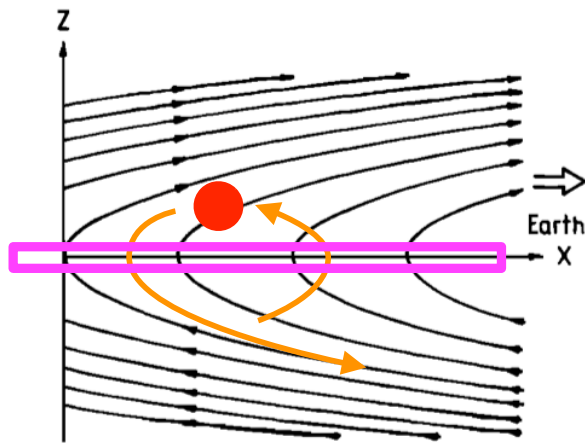
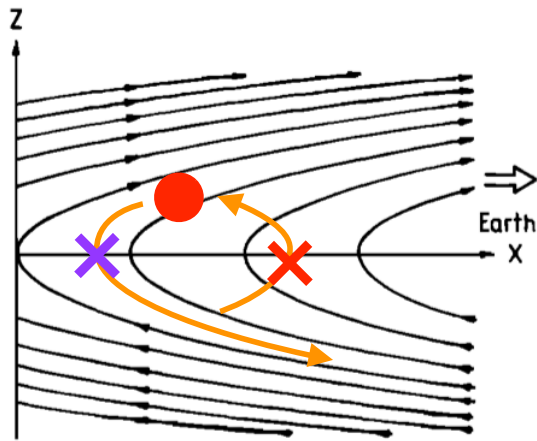


Ion velocity distribution function (VDF)



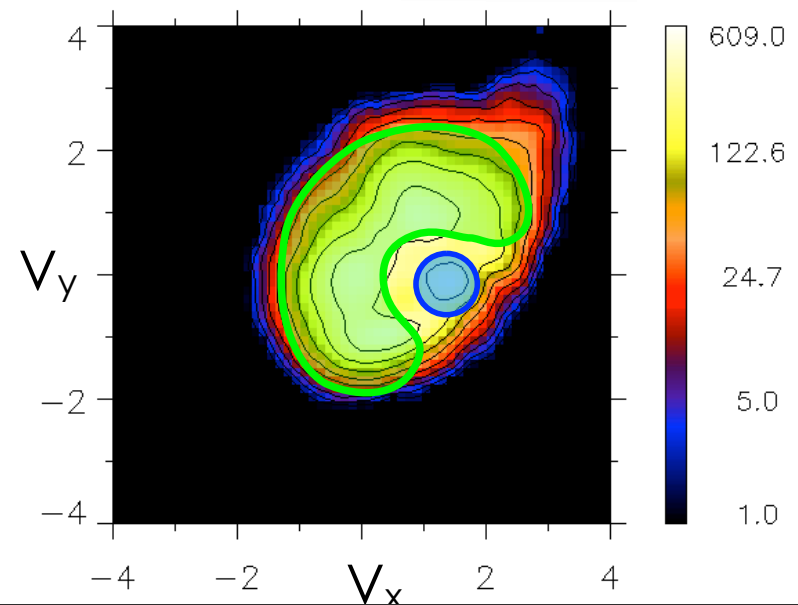
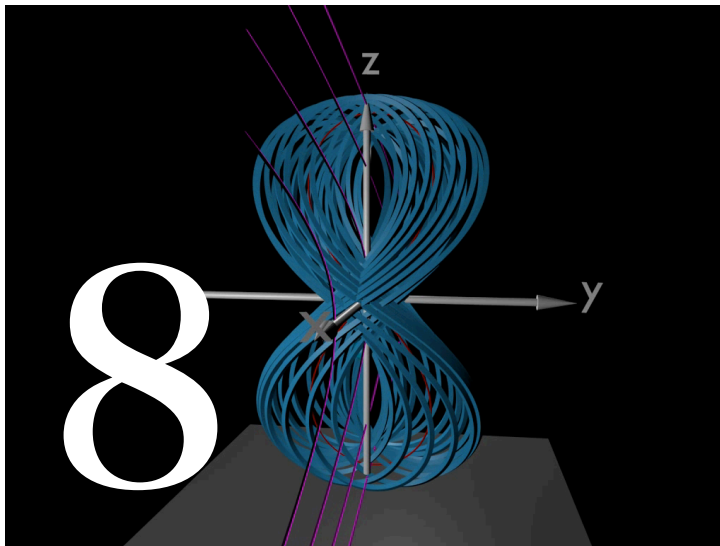
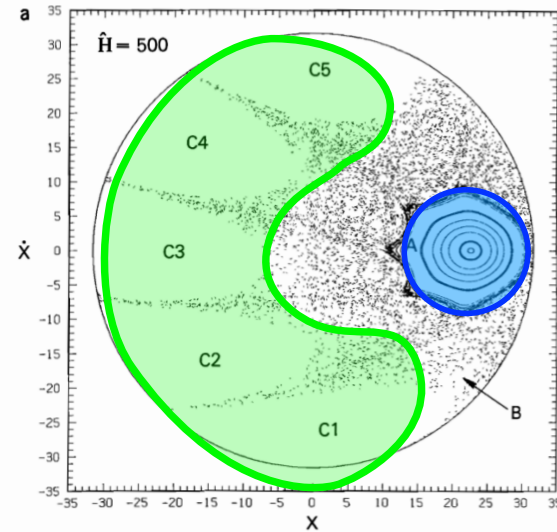
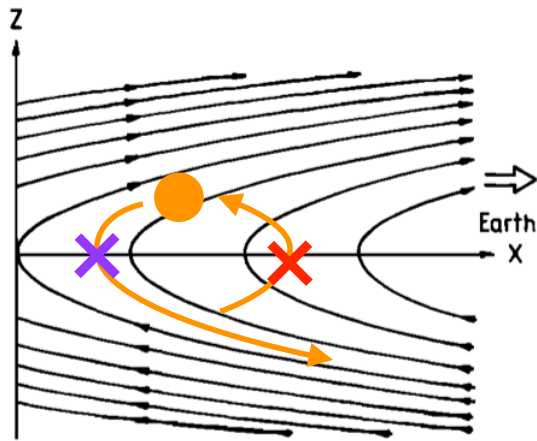
Poincaré map vs 2-D VDF

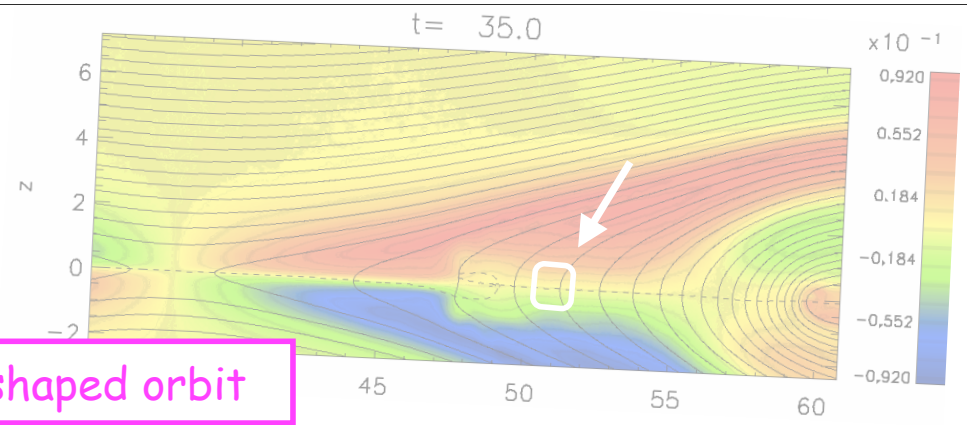
Mapping of two parameters from 5 (x, y, V_x, V_y, V_z)
Similar systems — two degrees of freedom



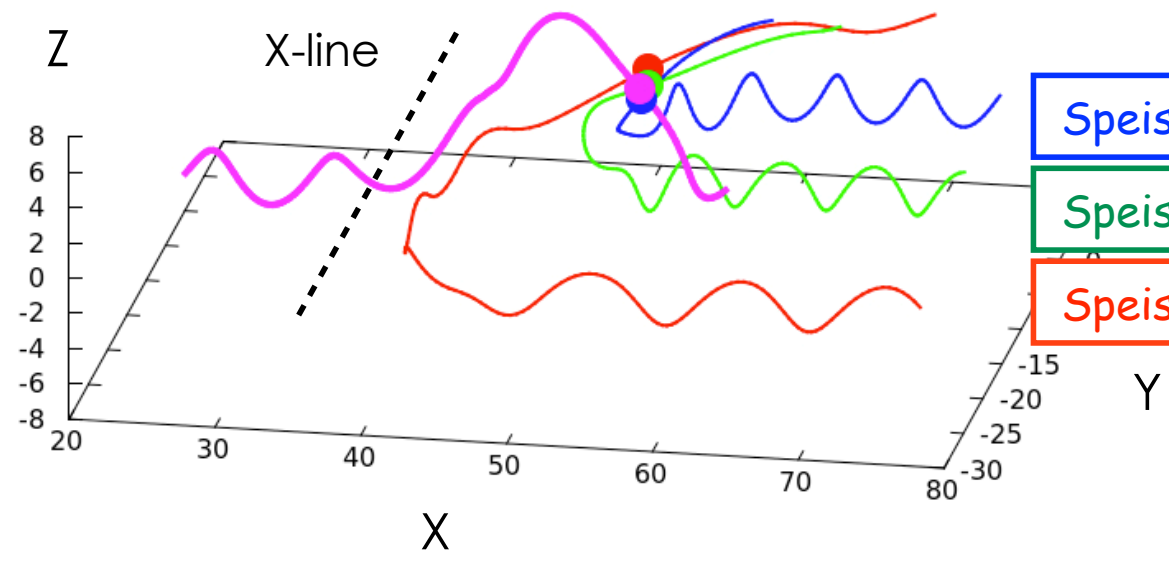
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Similar systems — two degrees of freedom





8-shaped orbit

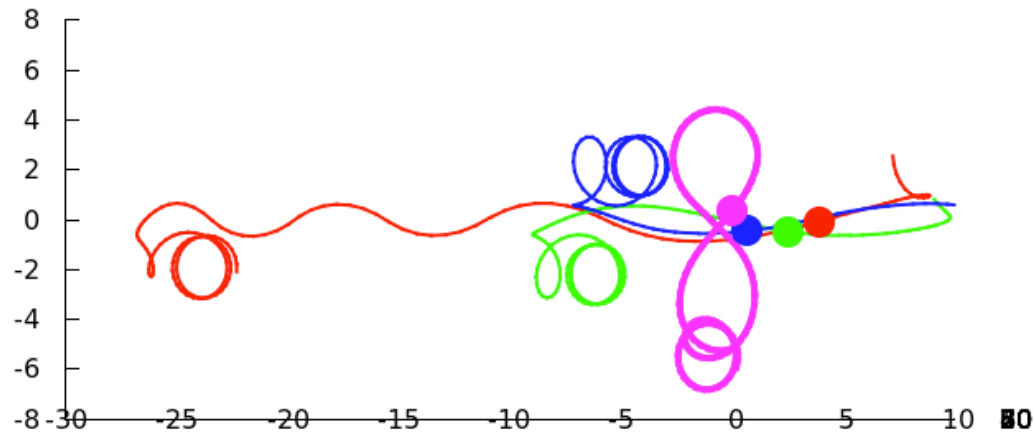


Speiser orbit (known)

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Ion orbits in PIC simulation

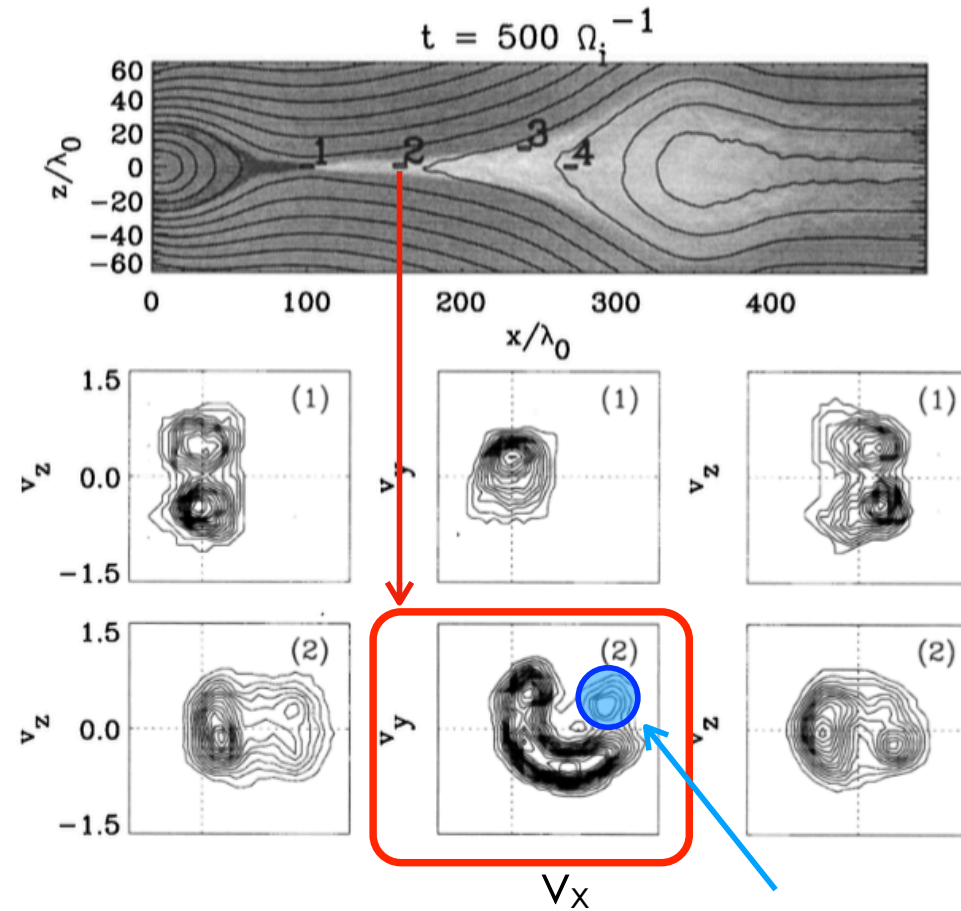
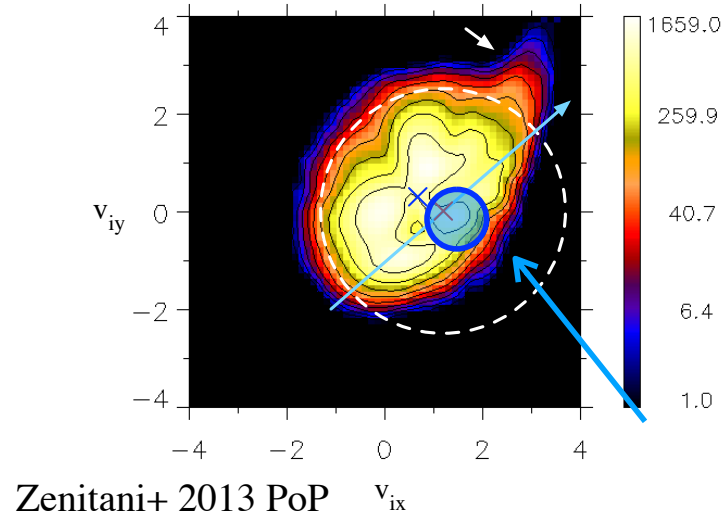


8-shaped orbit in a rotated,
moving (outflow) frame

We have discovered figure-8-shaped ion orbits in reconnection

Signatures of 8-shaped-orbit ions

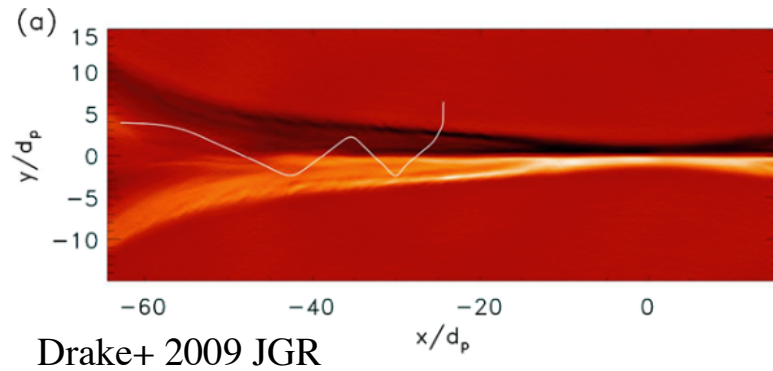
- Occasionally found in the near-exhaust



Arzner & Scholer 2001 JGR

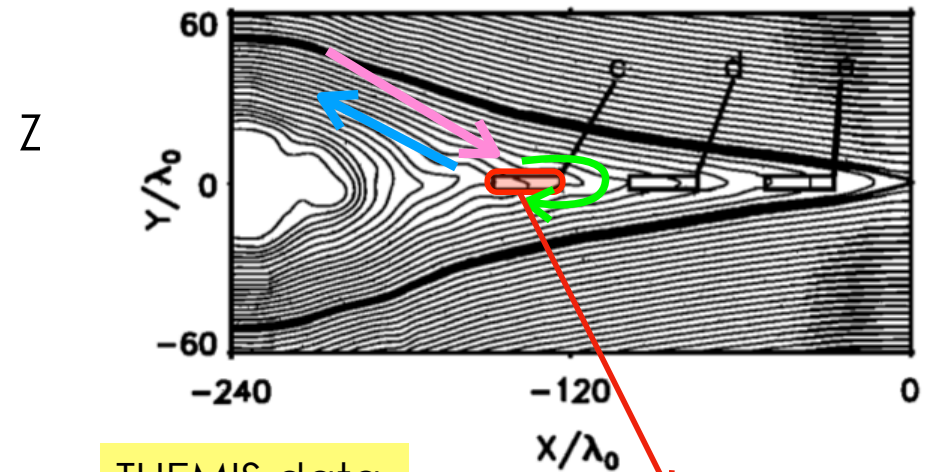
Signatures of Speiser motion

- A half ring corresponds to Speiser motion in the outflow frame

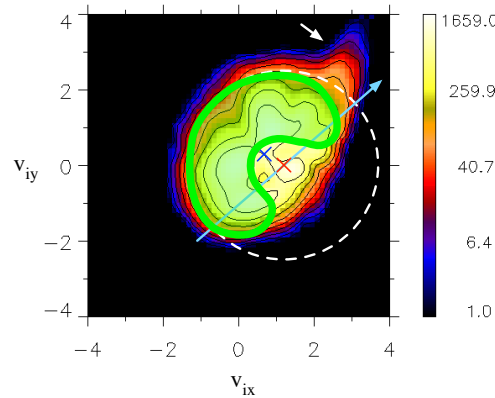


PIC simulations

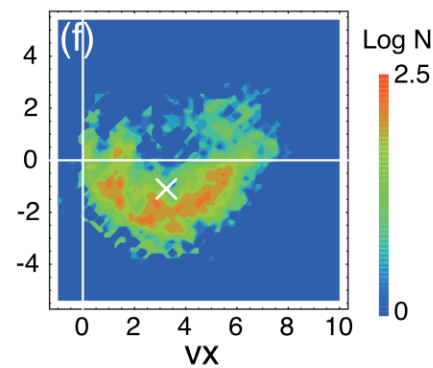
Hybrid simulation



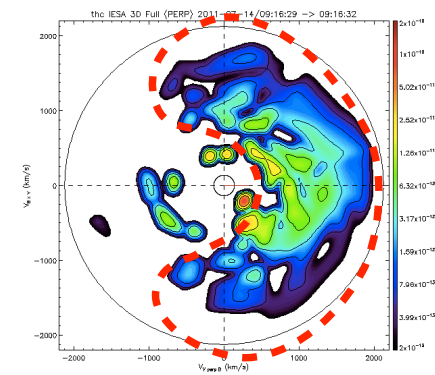
THEMIS data



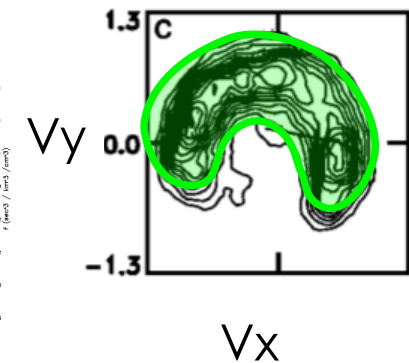
Zenitani+ 2013 PoP



Fujimoto+ 2016 PoP



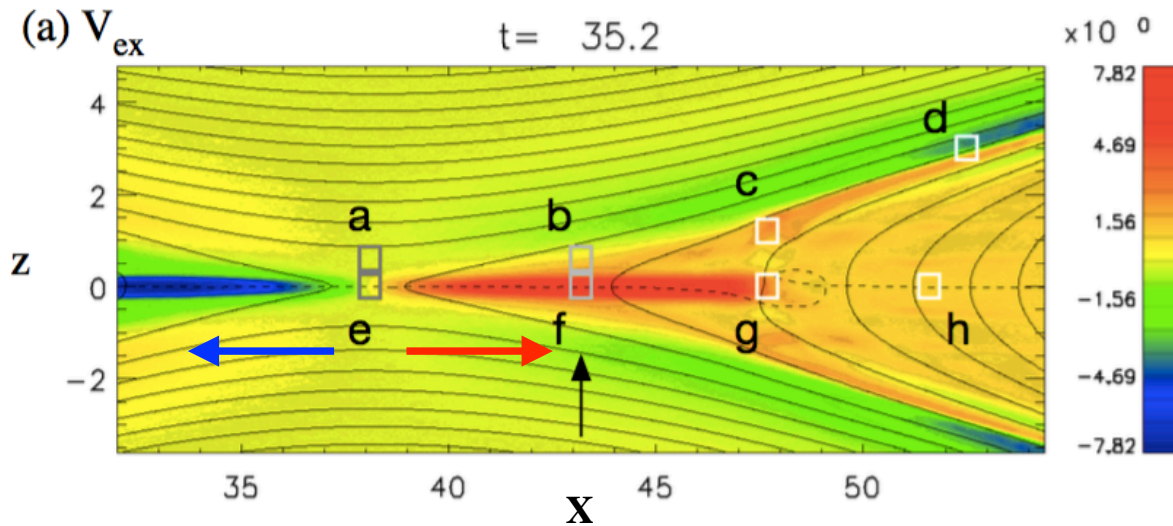
Hietala+ 2015 GRL



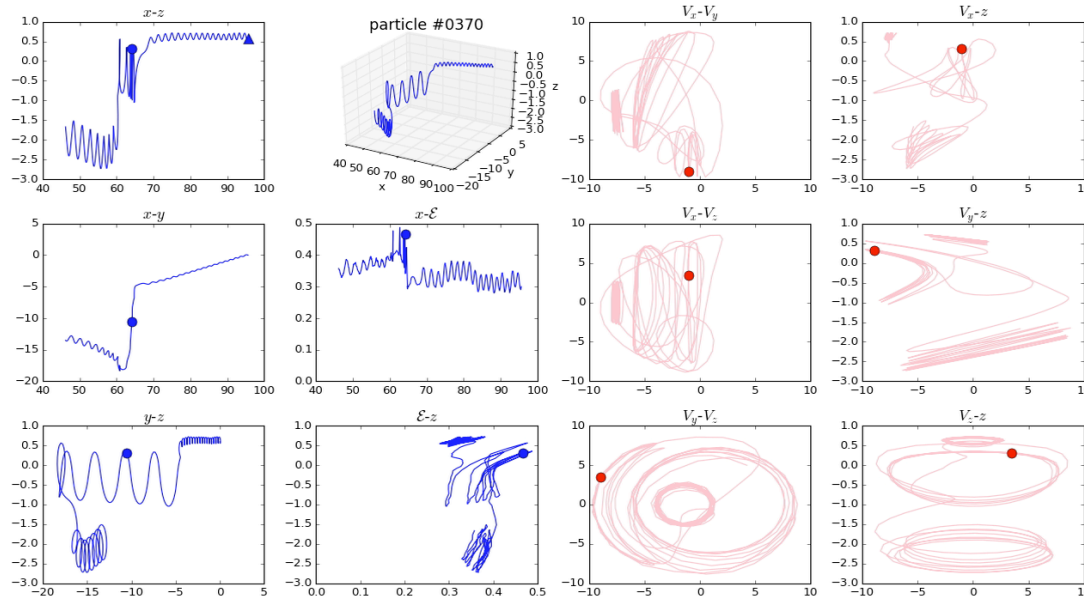
Lottermoser+ 1998 JGR

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Electron orbits in PIC simulation

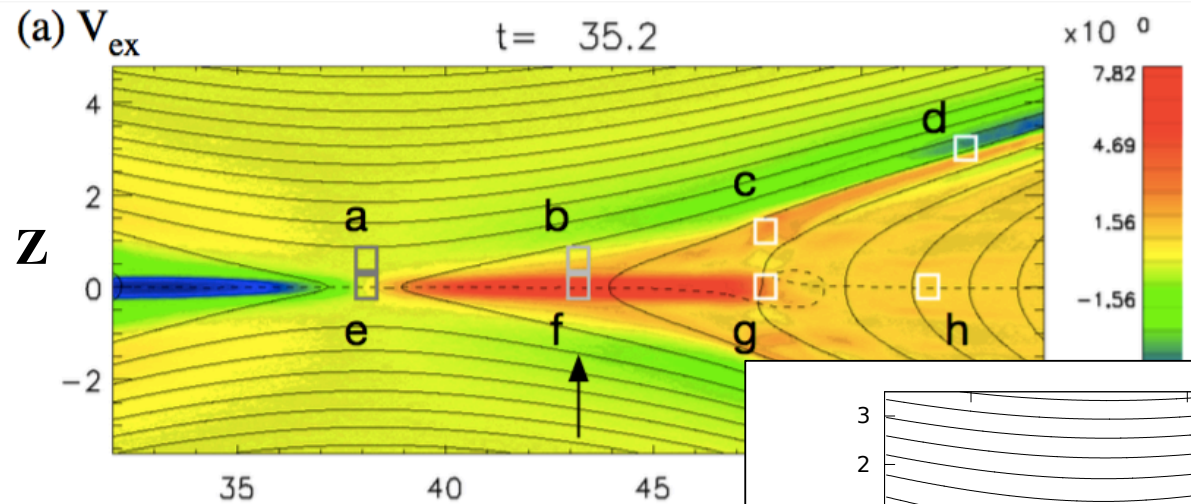


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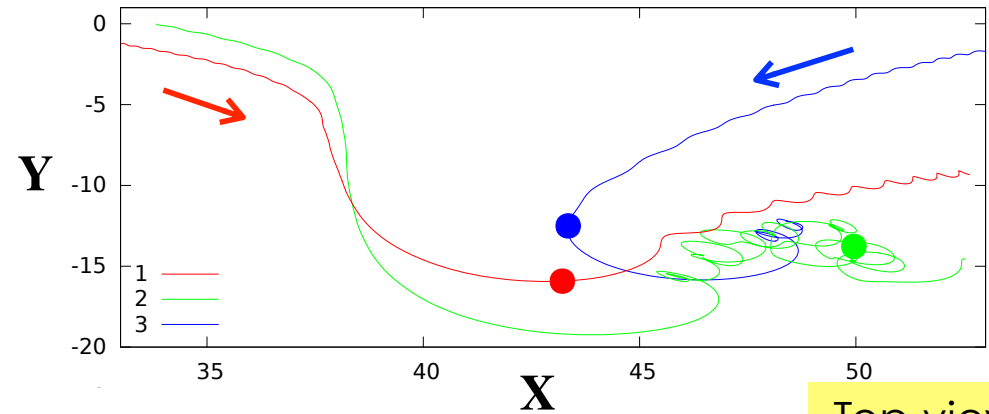
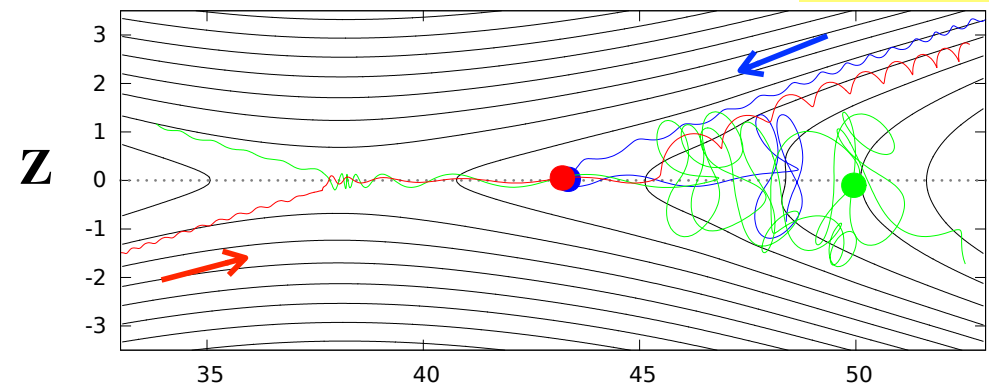
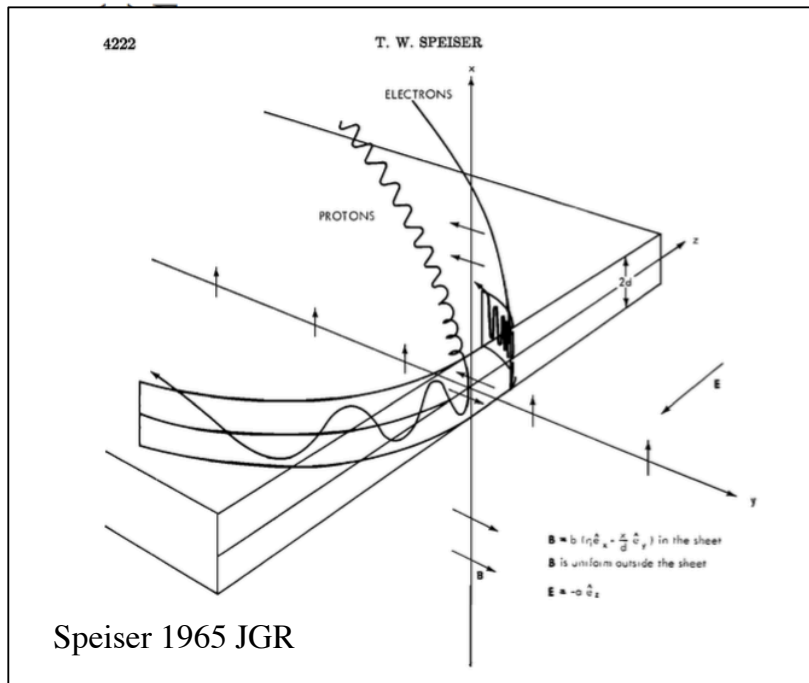
- **20,000,000 electron orbits from 1250 snapshot data**
- 3,000 orbits are inspected with human eyes

Electron Speiser orbits



Speiser orbit
via X-line region
Another Speiser orbit
of reflection type

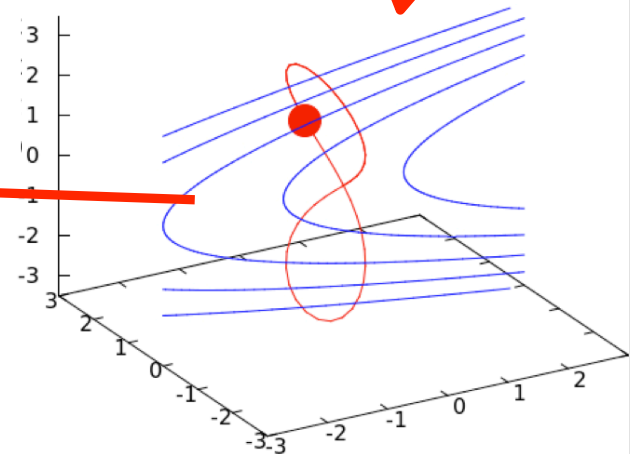
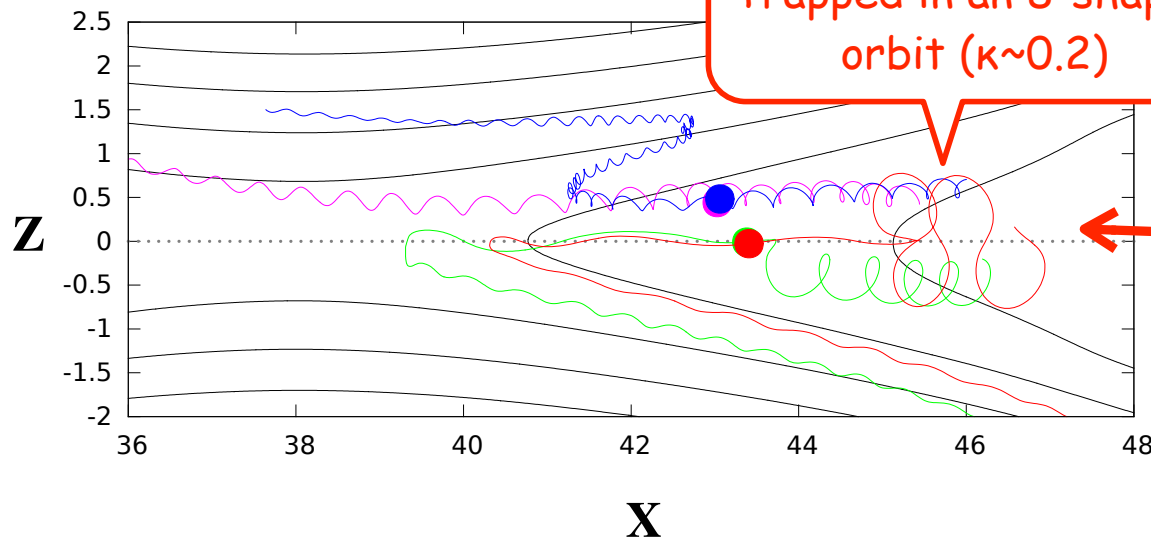
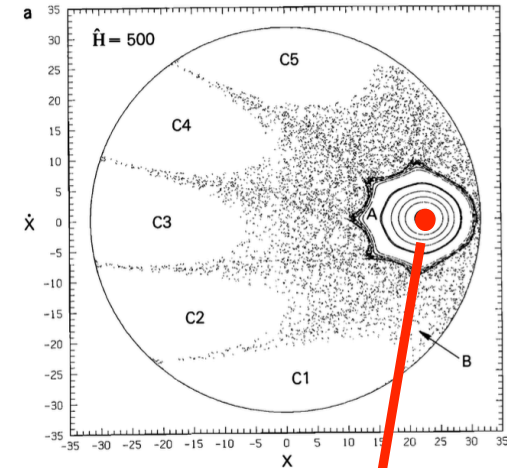
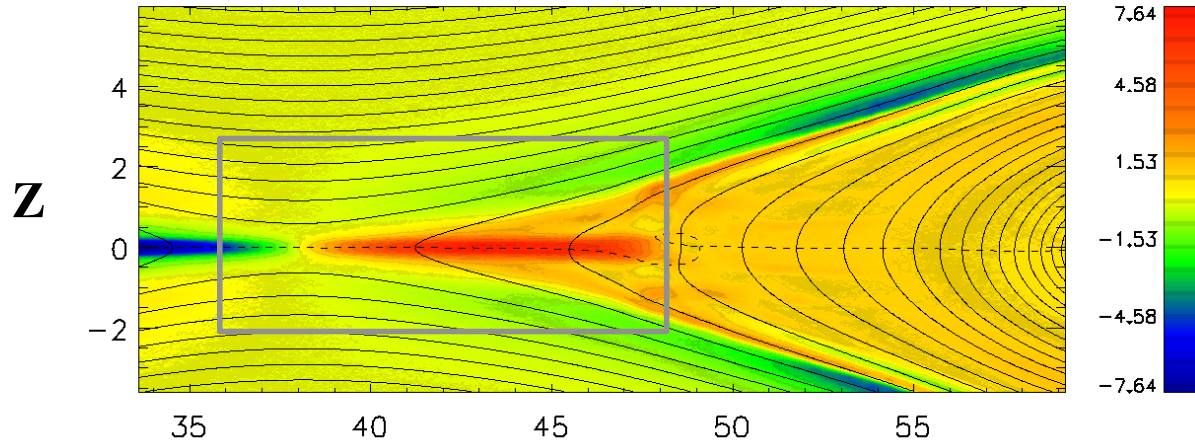
Front view



Top view

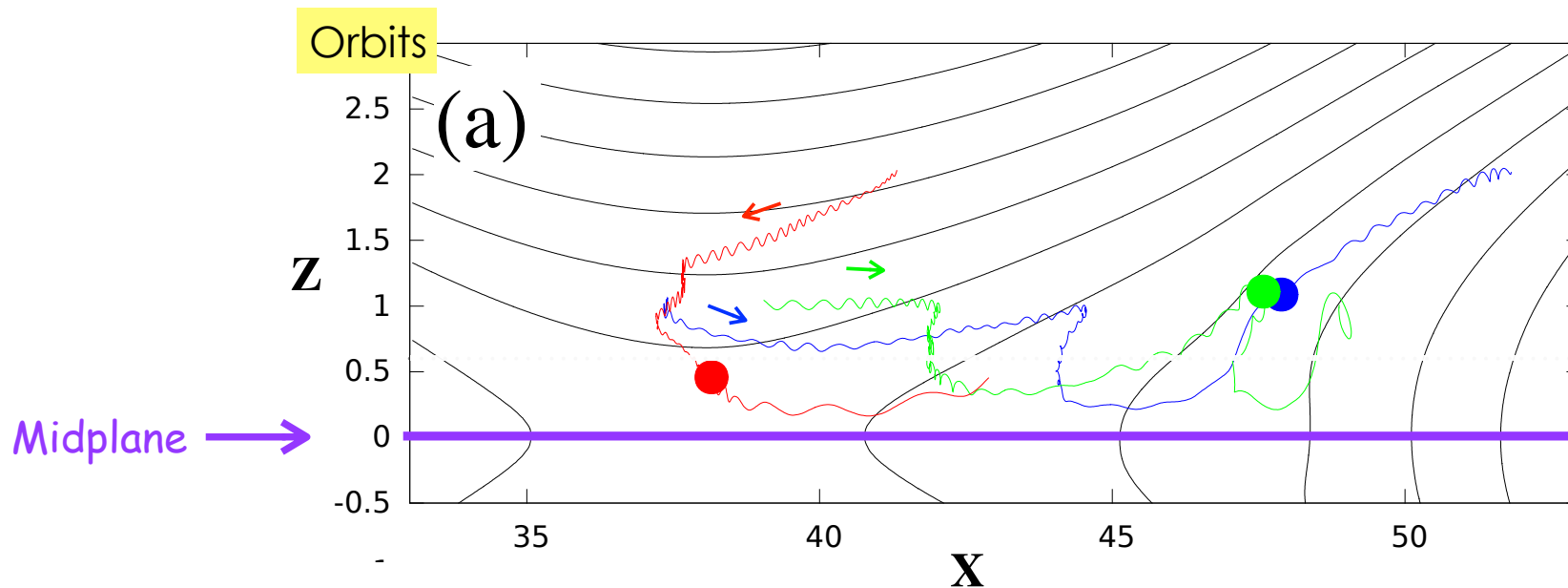
Electron 8-shaped orbit

(b) V_{ex} $t = 35.2$ $\times 10^0$

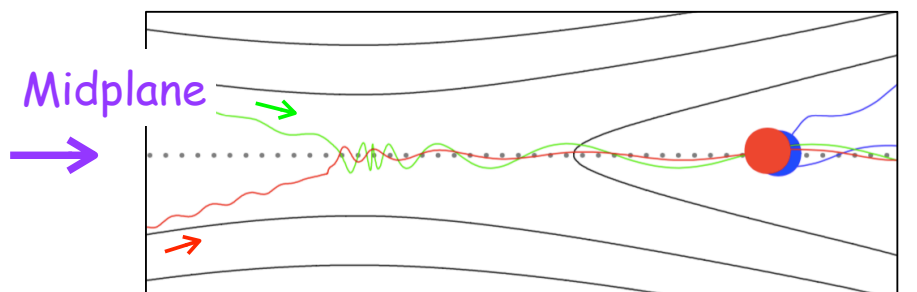


Chen & Palmadesso 1986 JGR

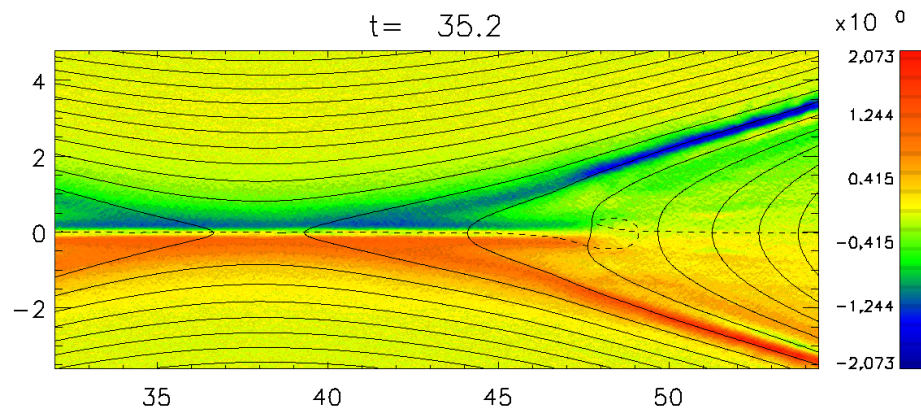
Surprise: Noncrossing electrons



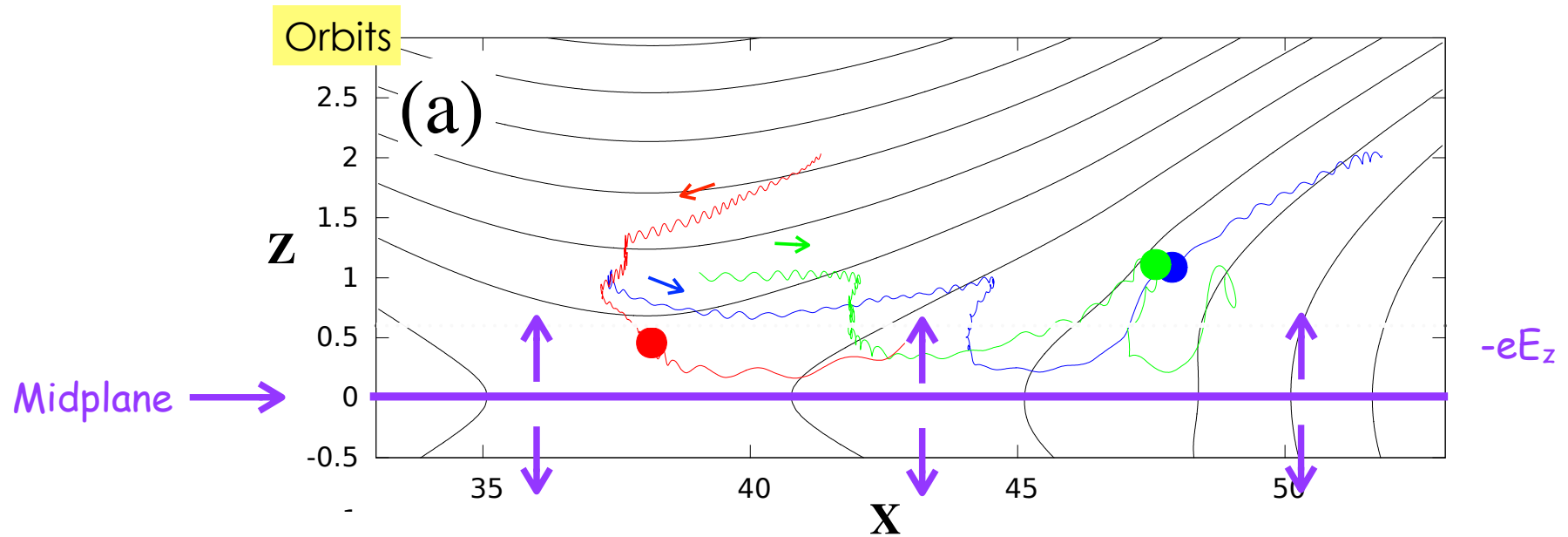
Traditional Speiser orbits



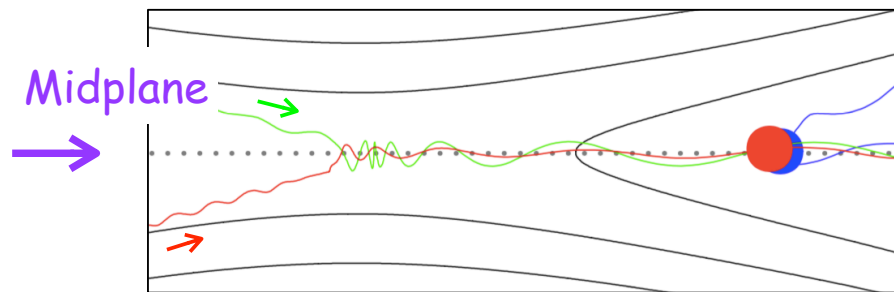
Electrostatic field E_z



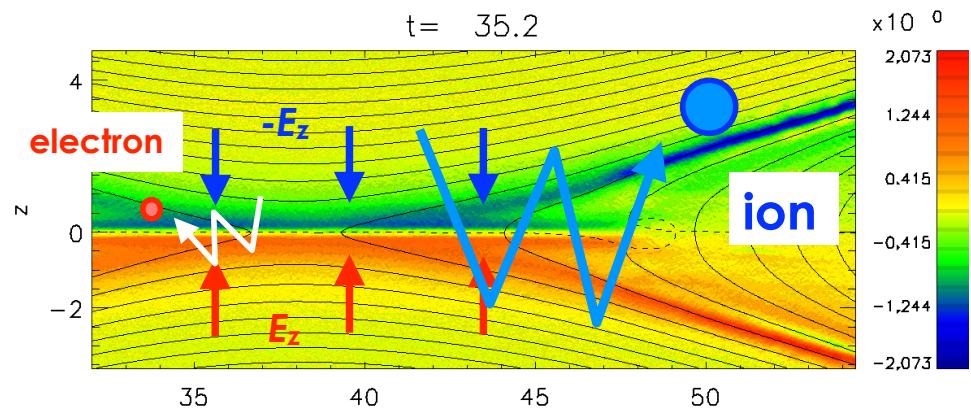
Surprise: Noncrossing electrons



Traditional Speiser orbits

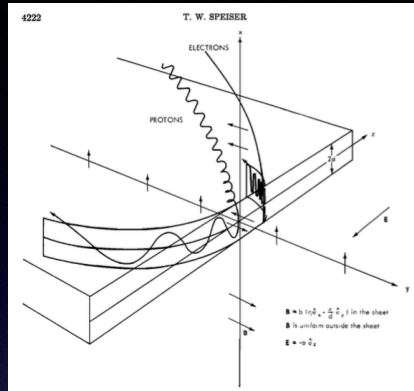


Electrostatic field E_z



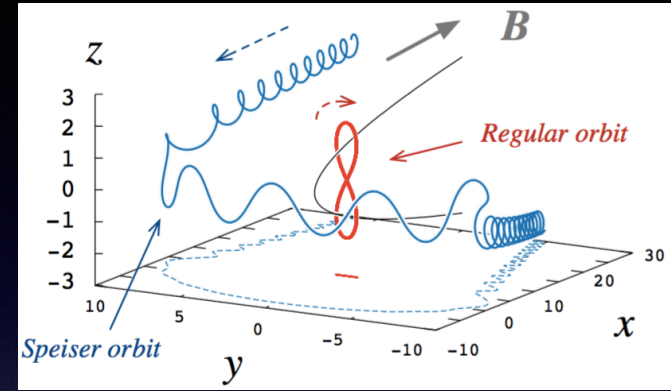
Orbit theories

1965



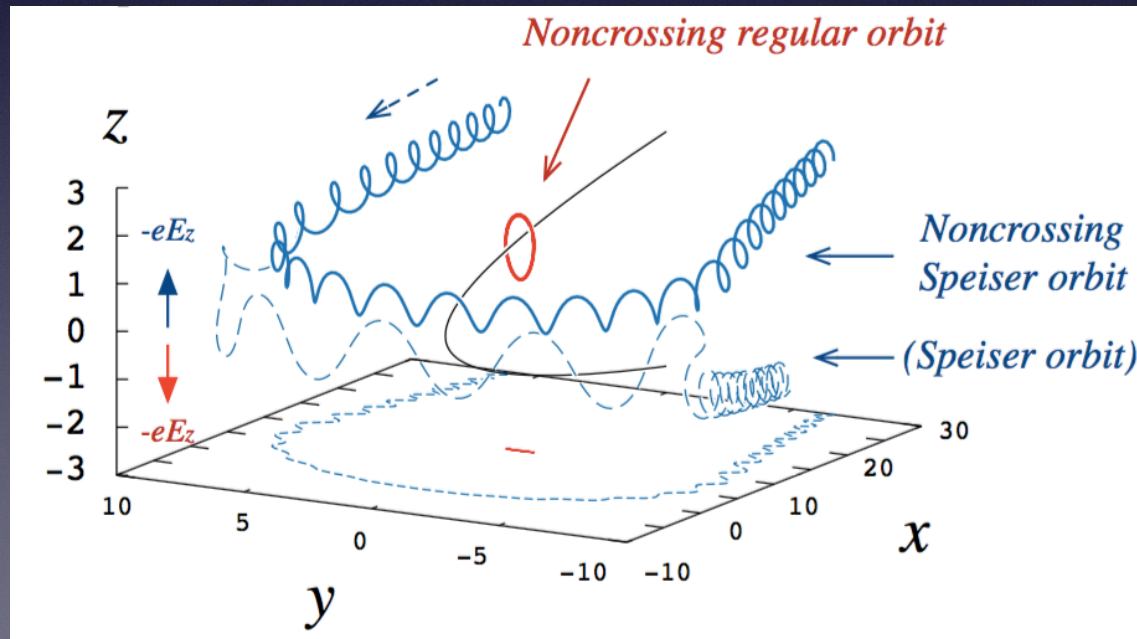
Speiser 1965

1980's



Chen & Palmadesso 1986, Buchner & Zelenyi 1989

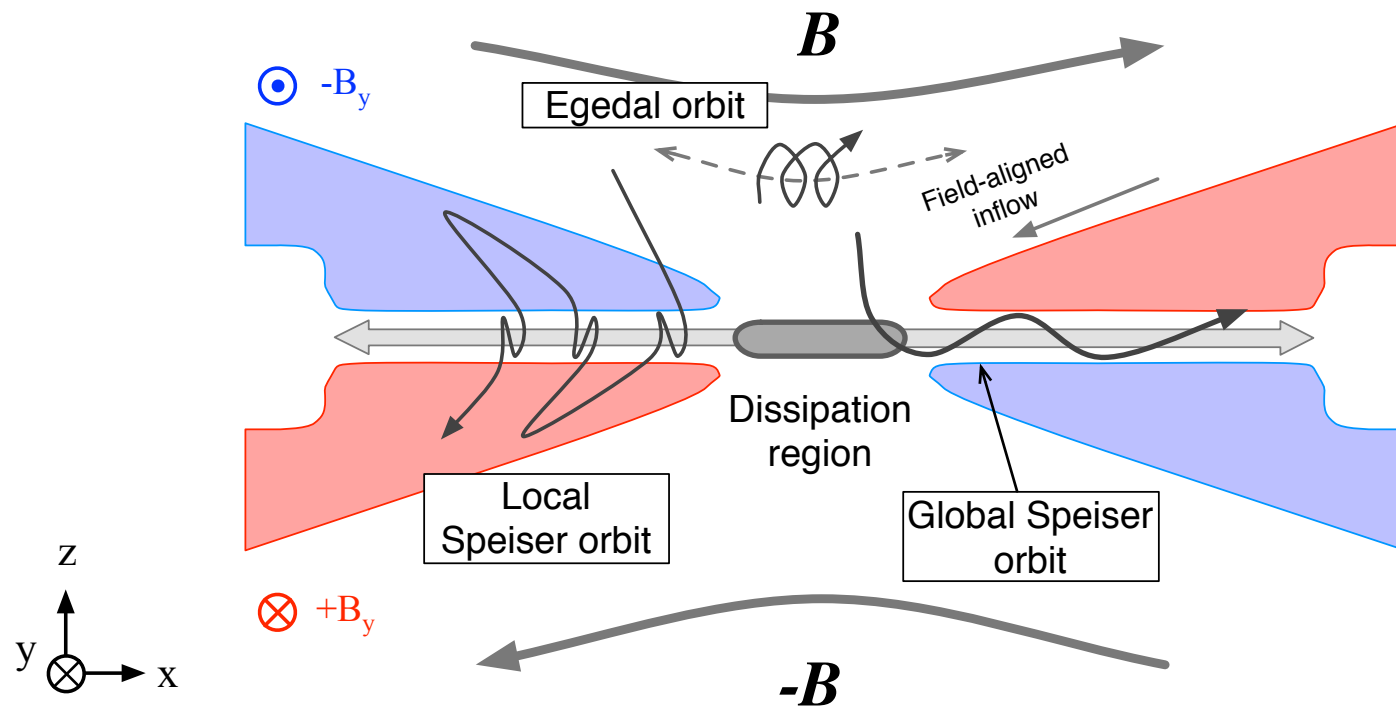
2016



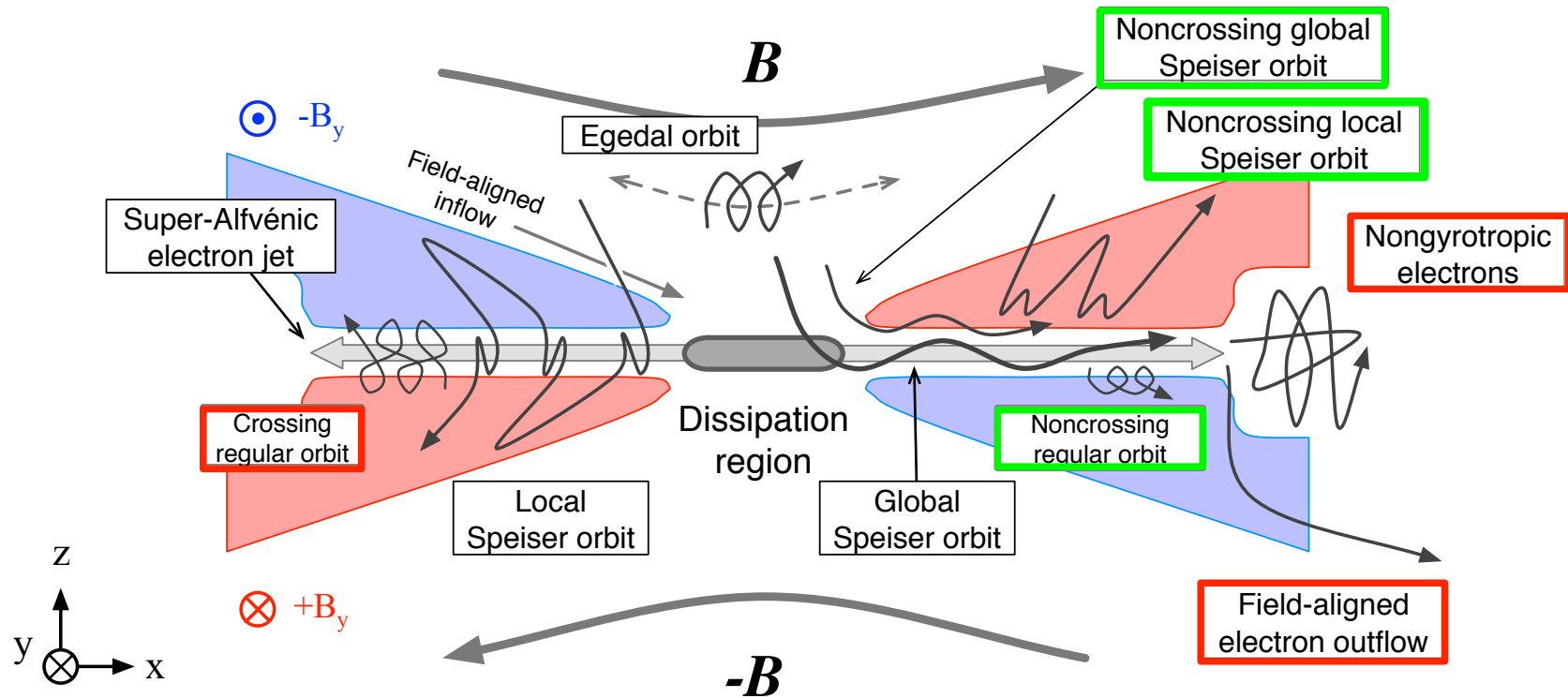
A related theory came out recently:
Tsai+ 2017

Zenitani & Nagai 2016

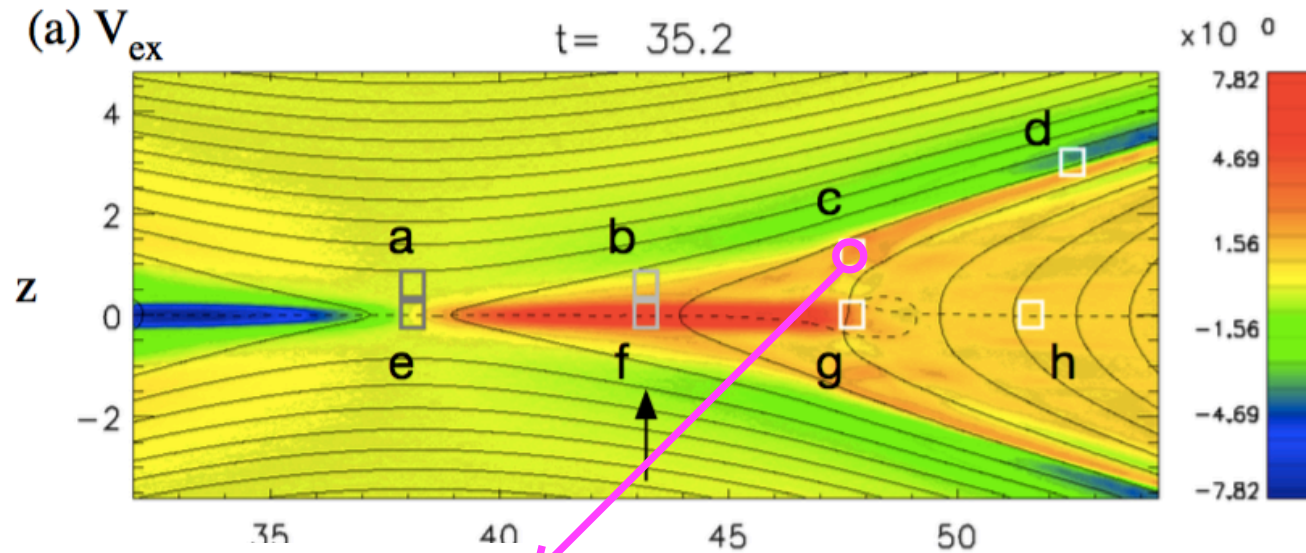
Previous picture of electron orbits



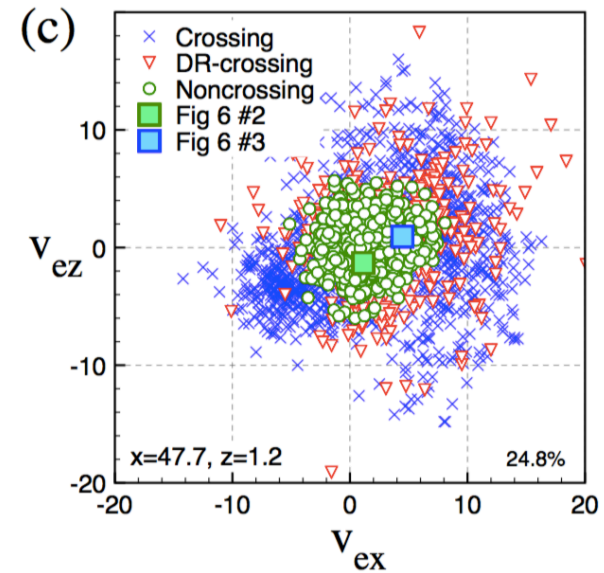
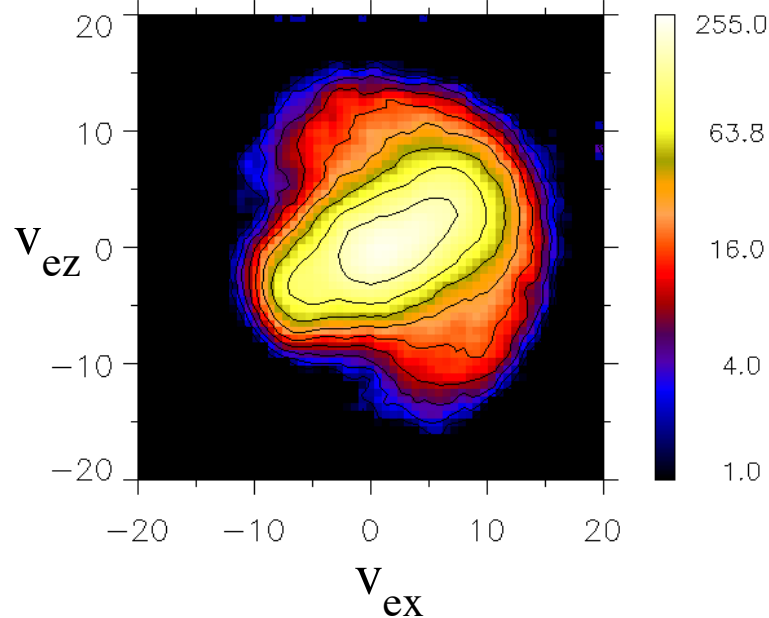
New picture of electron orbits



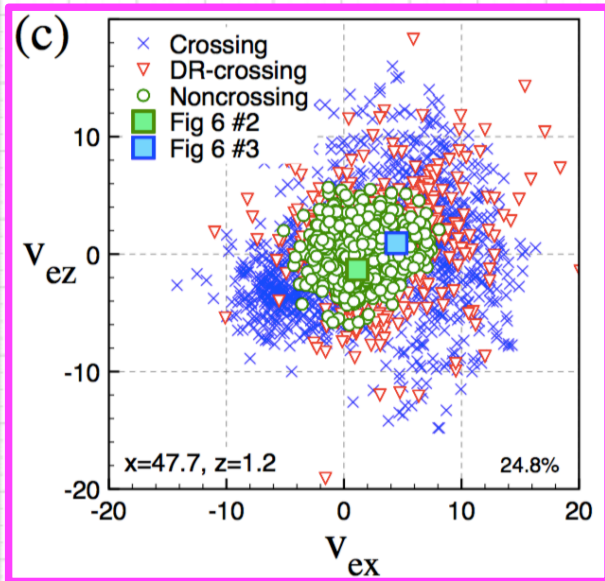
Noncrossing electrons in VDF

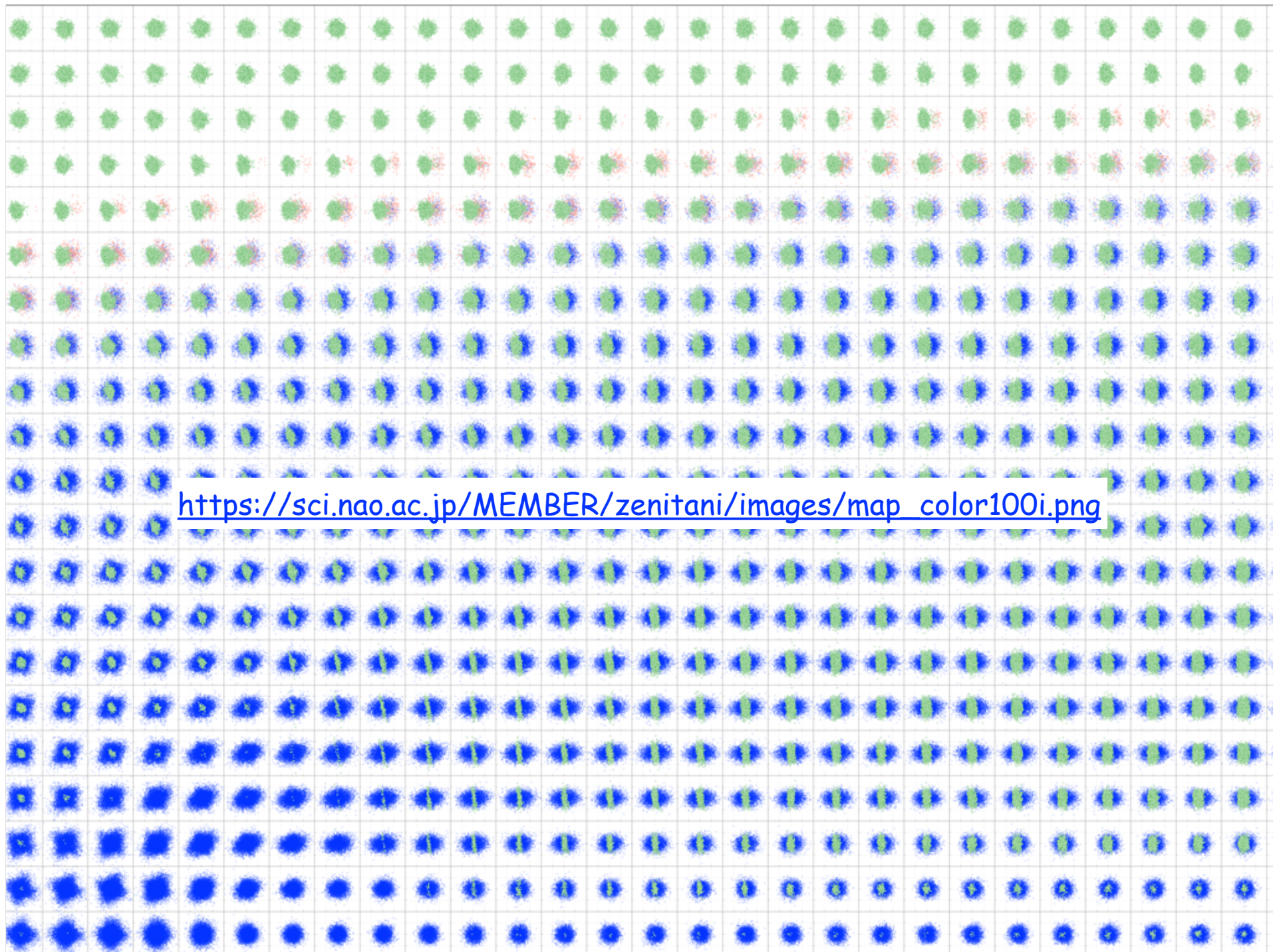


(c) $x=47.7$ $z=1.2$



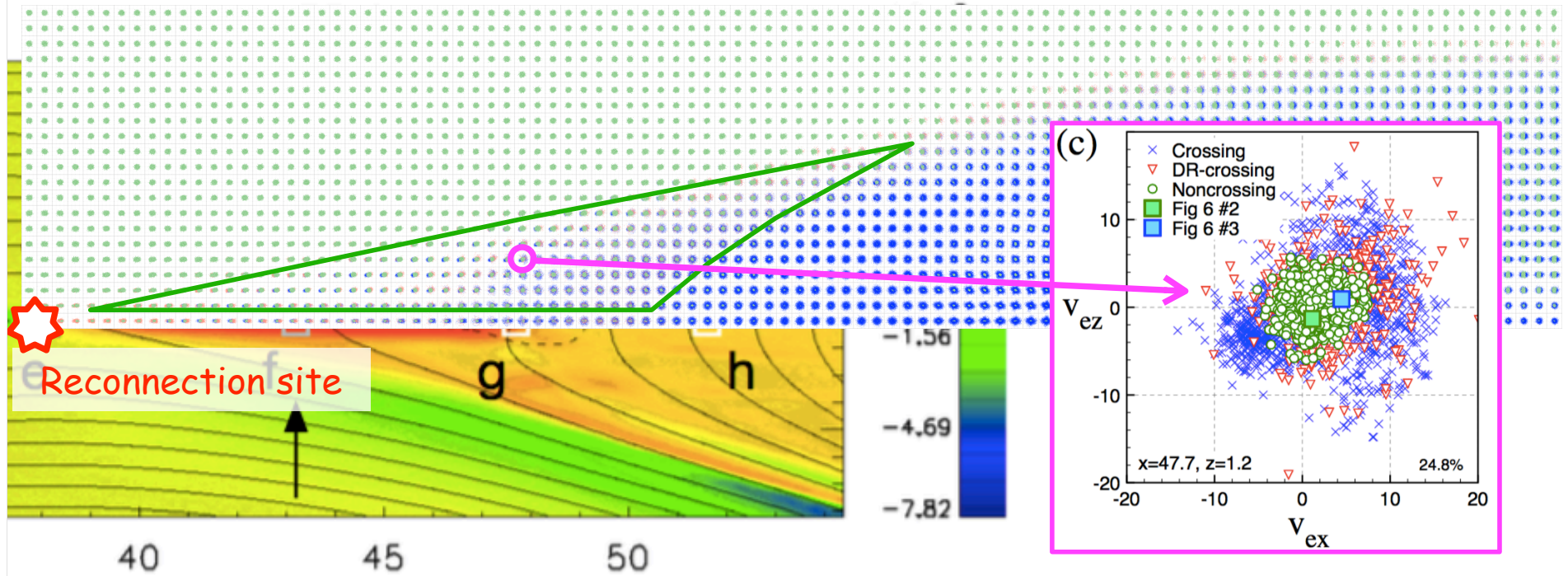
Spatial distribution of VDFs





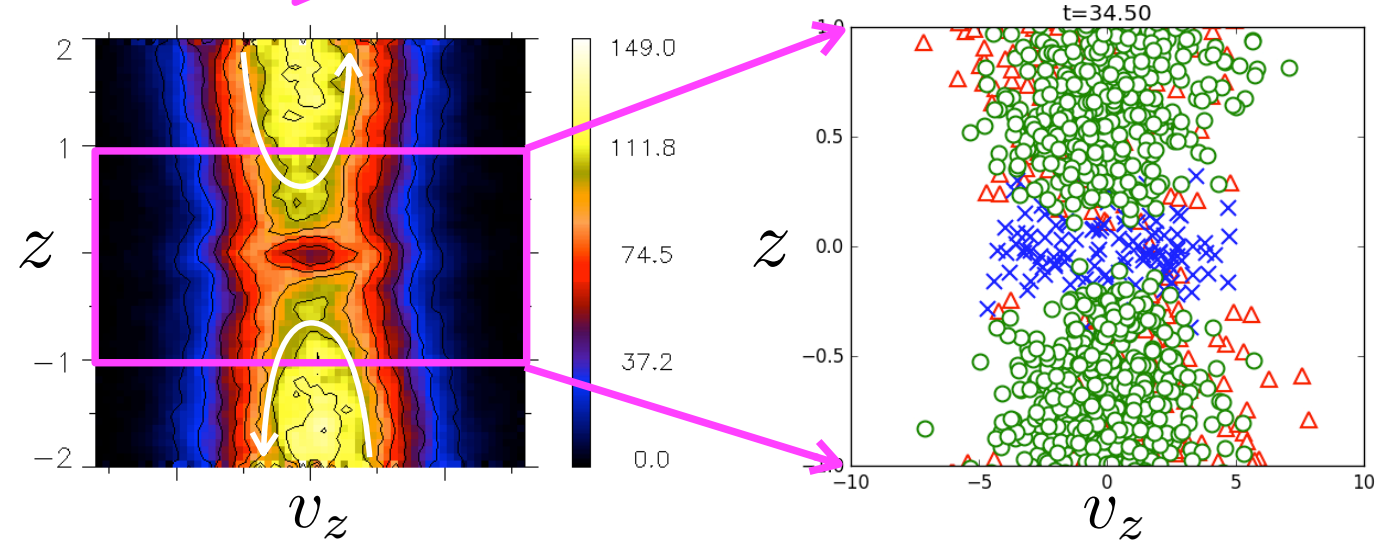
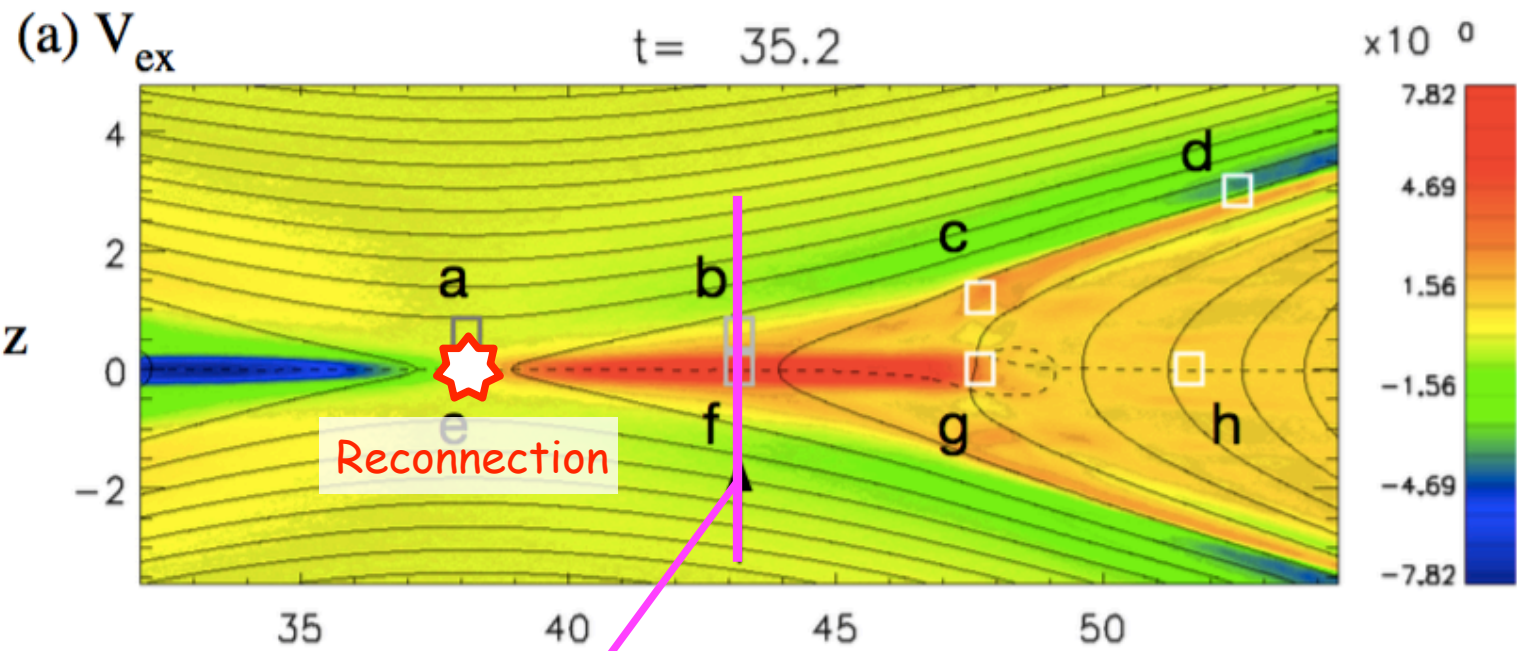
https://sci.nao.ac.jp/MEMBER/zenitani/images/map_color100i.png

Spatial distribution of Noncrossing electrons



- Noncrossing electrons occupy a large area (surrounding the electron jets inside the ion diffusion region)
- They are **majority** in number

Noncrossing electrons: Majority in number



Summary

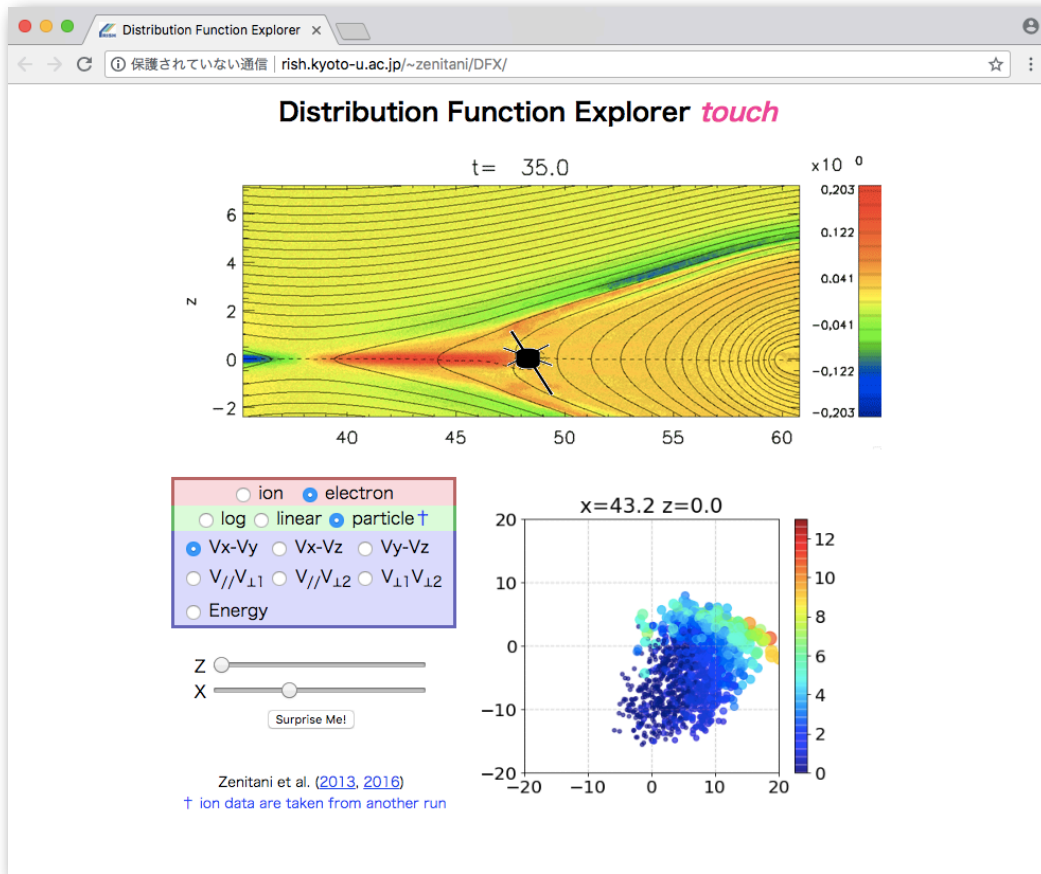
- 1. Particle motion in a reconnected geometry
 - Meandering orbit
 - Speiser orbit
 - Figure-8-shaped orbit
- 2. Ion motion and VDF in the outflow exhaust
 - Ion 8-shaped orbits
- 3. Electron motion around the reconnection site
 - Electron 8-shaped orbits
 - Noncrossing electrons -- They are majority
- References:
 - [1] Zenitani, Shinohara, Nagai, & Wada, *Phys. Plasmas* **20**, 092120 (2013)
 - [2] Zenitani & Nagai, *Phys. Plasmas* **23**, 102102 (2016)
 - [3] Zenitani, *J. Plasma Fusion Res.*, **97**, 47 (2021) [Tutorial article in Japanese]
http://www.jspf.or.jp/Journal/PDF_JSPF/jspf2021_02/jspf2021_02-47.pdf

More research needed!

- 1. Orbit theory
 - Influence of E_z
- 2. Ion 8-shaped orbit
 - Spatial distribution and the reason
 - Signatures of the Ion Diffusion Region (IDR)?
- 3. Noncrossing electrons
 - Signatures in VDFs
 - Influence to electron mixing
 - Two-fluid theory needs to be updated to three-fluid theory?
- Transition to the guide-field cases
- Influence of the 3-D structure
- ...

Thank you for your attention

Online VDF viewer



Touch our data on
your devices



<http://rish.kyoto-u.ac.jp/~zenitani/DFX/>