ST15-08-D2-PM2-P-017

Kinetic aspects of the ion current layer in a reconnection outflow exhaust

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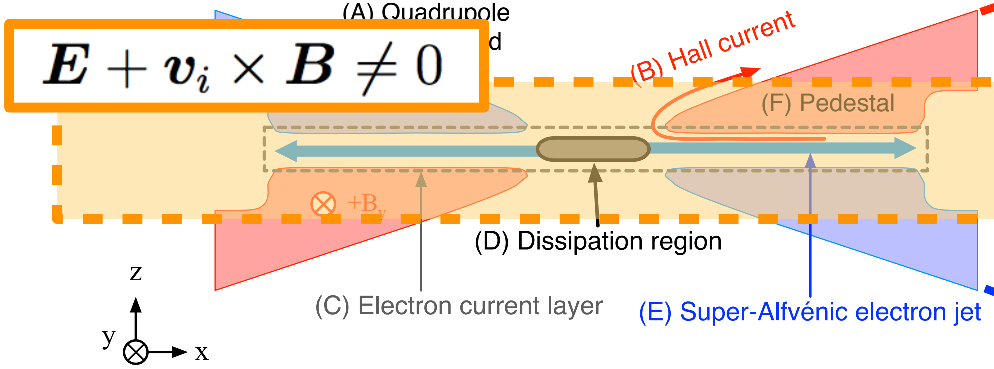
S. Zenitani, I. Shinohara, T. Nagai, and T. Wada, *Physics of Plasmas* **20**, 092120 (2013).

Ion-scale structure of reconnection

Inflow Alfvén speed, $c_{A,in}$

$\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B} \neq 0$



Zenitani et al. 2011 PoP

$v_{i,x} < c_{A,in}$

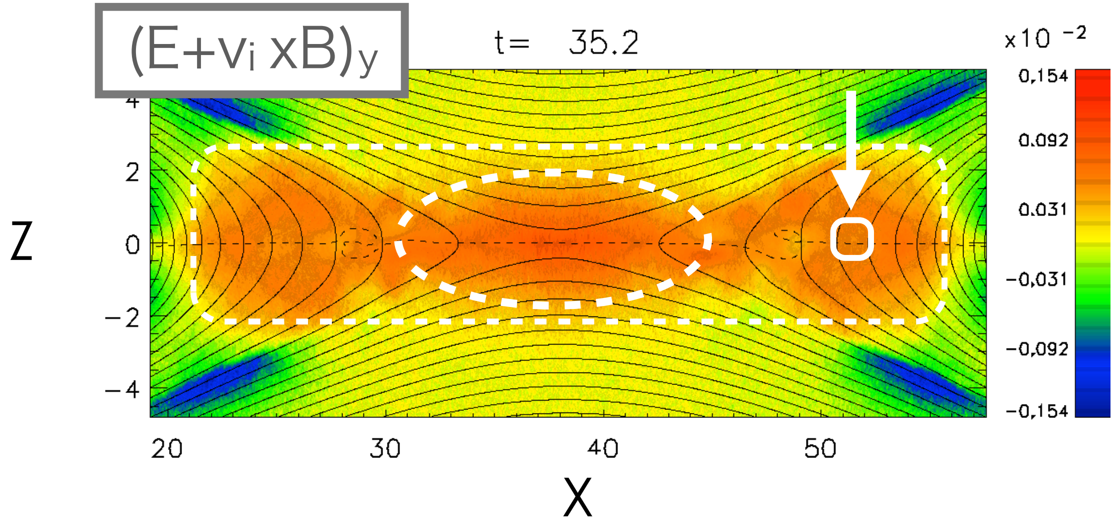
Hybrid
Nakamura et al. 1998 JGR
Lottermoser et al. 1998 JGR
Arzner & Scholer 2001 JGR
Higashimori & Hoshino 2012 JGR

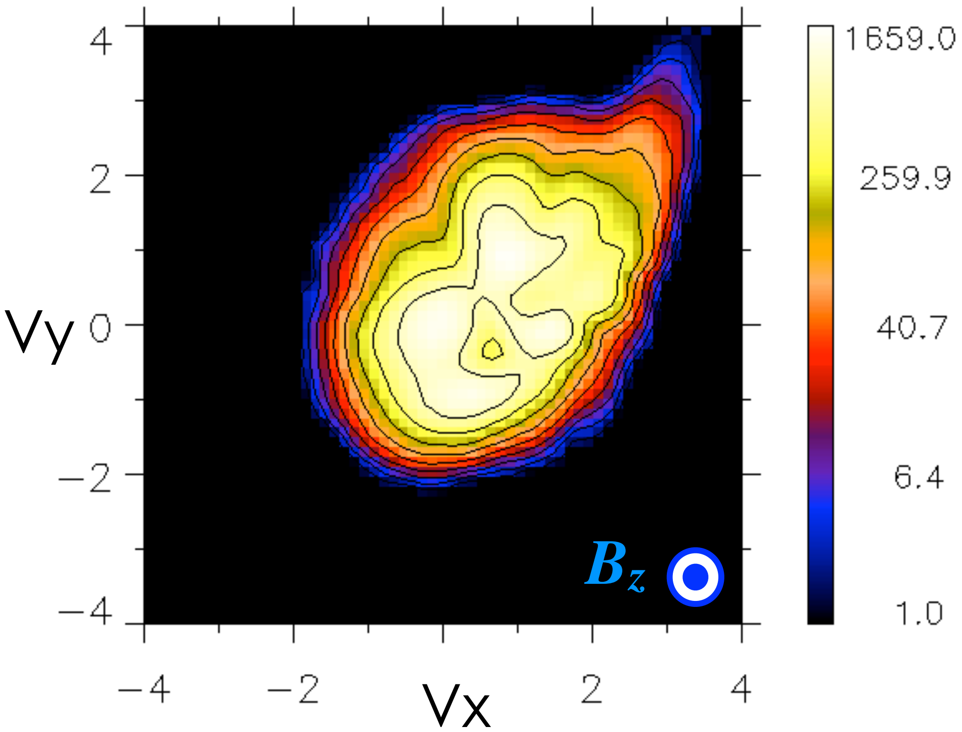
Kinetic
Drake et al. 2009 JGR
Liu et al. 2011--2012 PoP

30-40% of inflow Alfvén speed
Karimabadi et al. 2007 GRL
Wu et al. 2011 PoP

- Q1. Why is the ion ideal condition violated?
- Q2. Why is the ion flow sub-Alfvénic?

Ion velocity distribution function

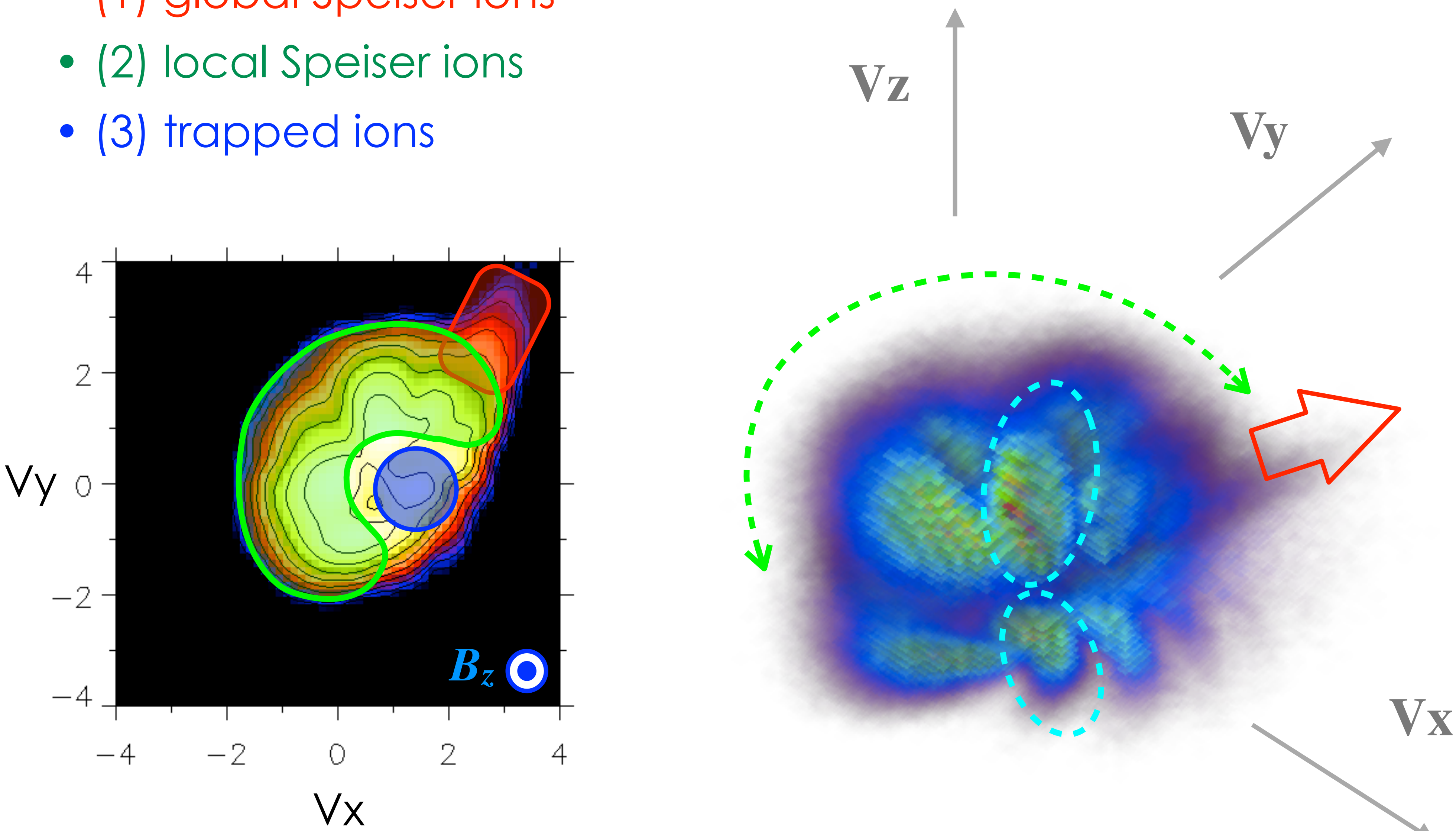




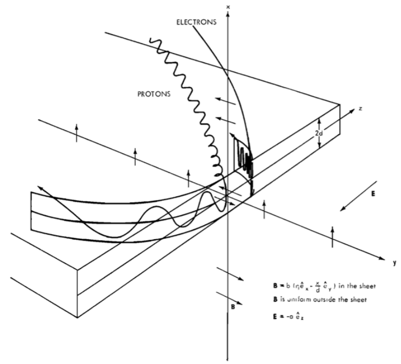
- Non-ideal, but outside the ion diffusion region
- Non-Maxwellian

Ion velocity distribution function

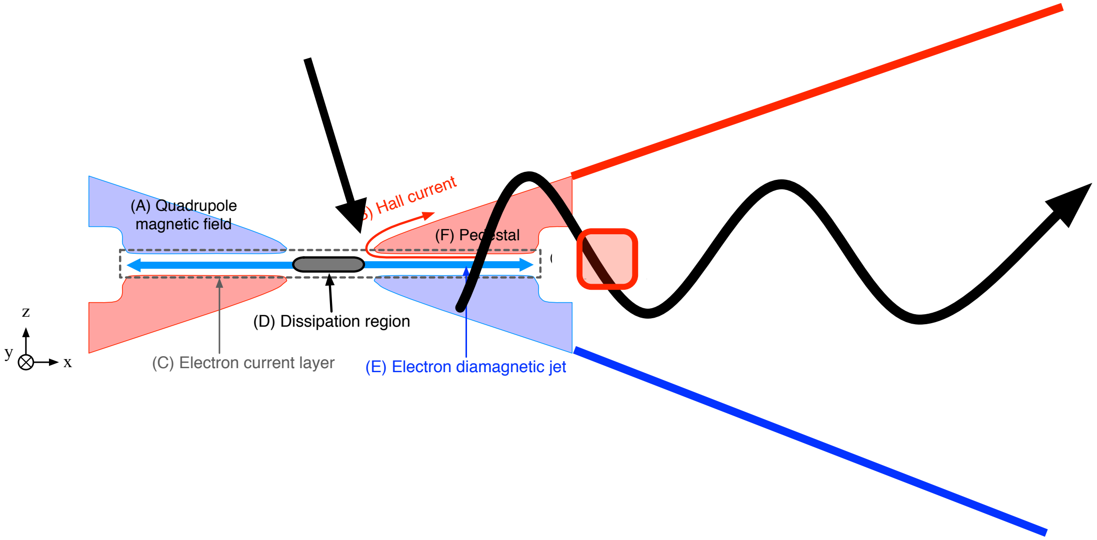
- (1) global Speiser ions
- (2) local Speiser ions
- (3) trapped ions

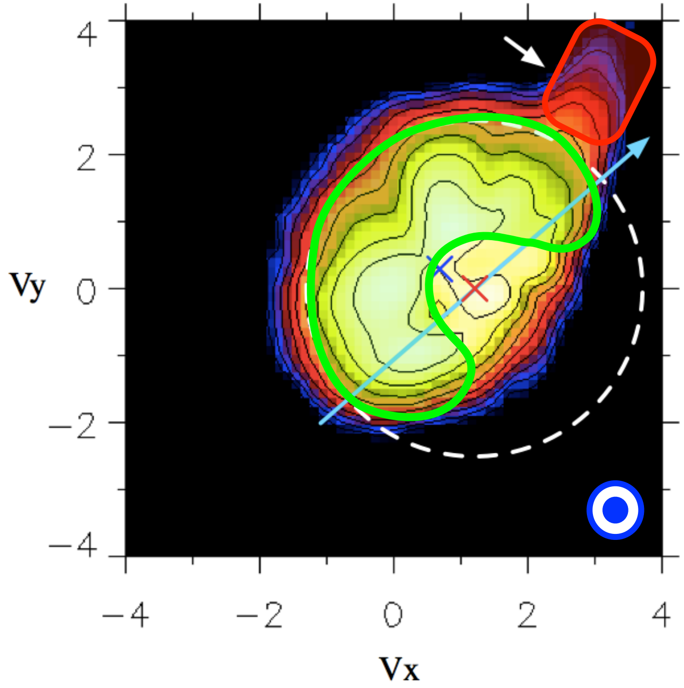


Two Speiser orbits

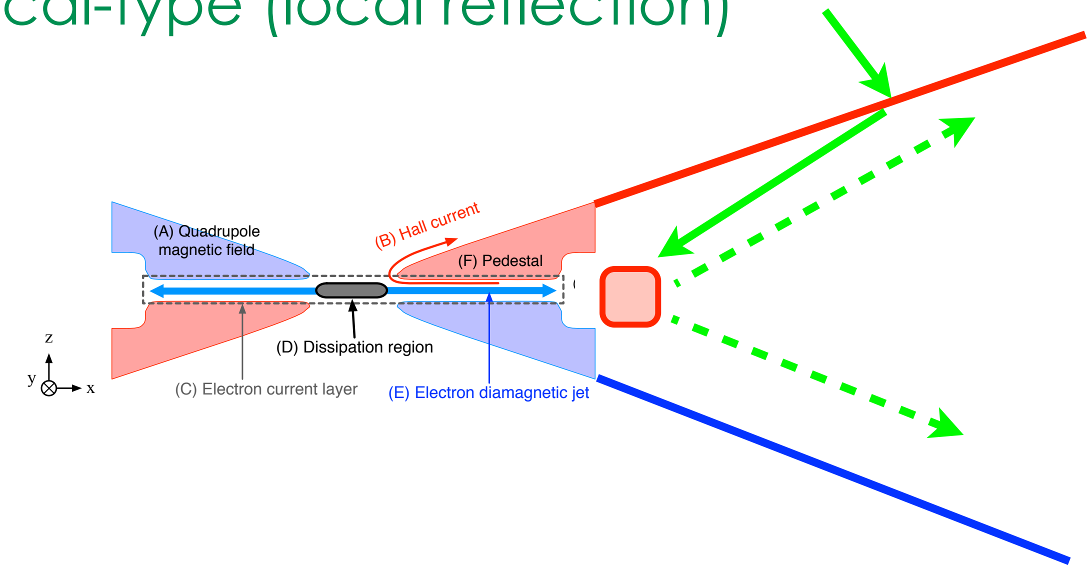


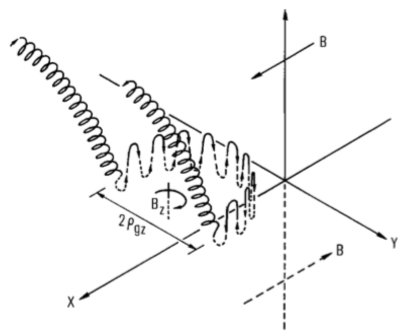
- Global-type (classical one)



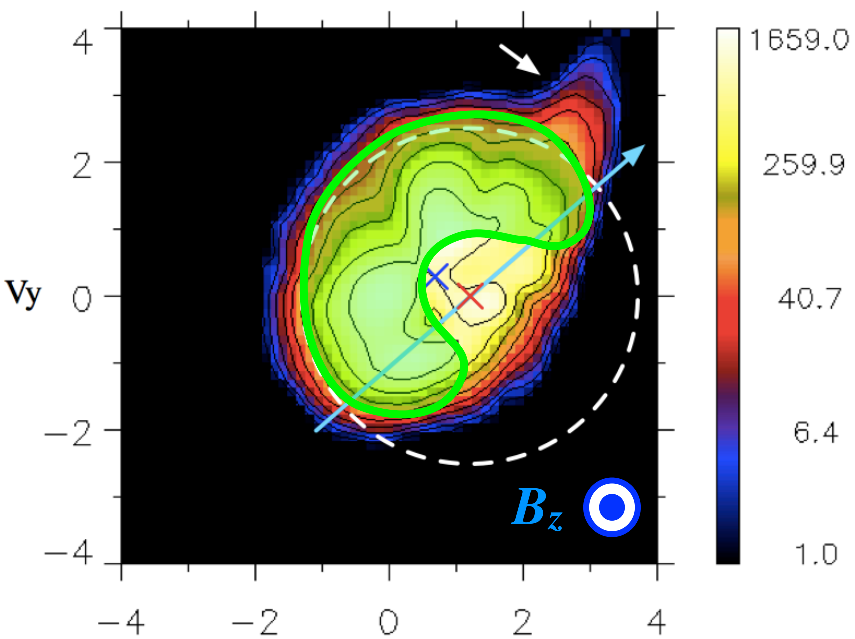


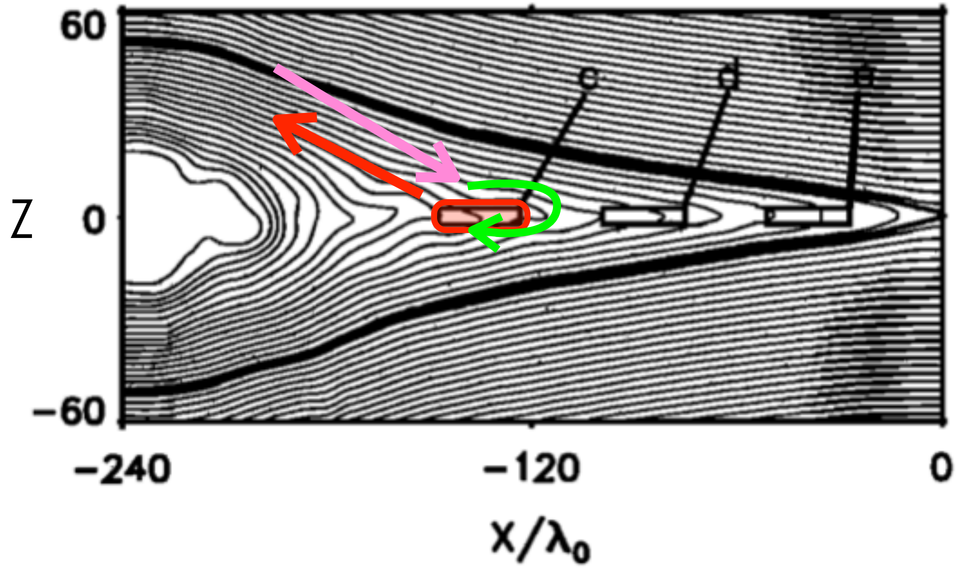
- Local-type (local reflection)

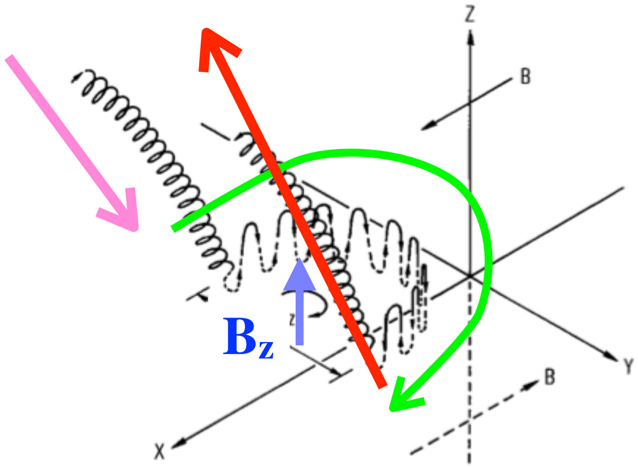




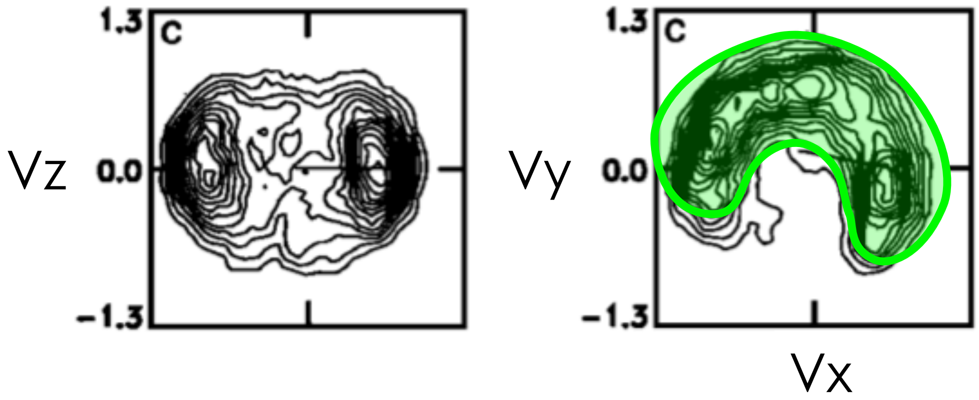
(Local-type) Speiser orbit







Lyons & Speiser 1985 JGR
Speiser 1965 JGR



Lottermoser et al. 1998 JGR
Nakamura et al. 1998 JGR

Orbit theory in a parabolic field

Curvature radius of ***B***

$$\kappa = \sqrt{\frac{R_{\min}}{\rho_{\max}}}$$

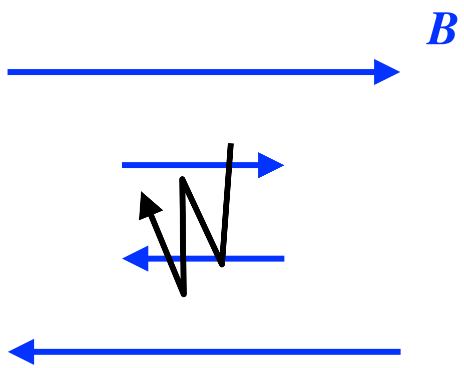
~ Larmor radius

Nonlinear system

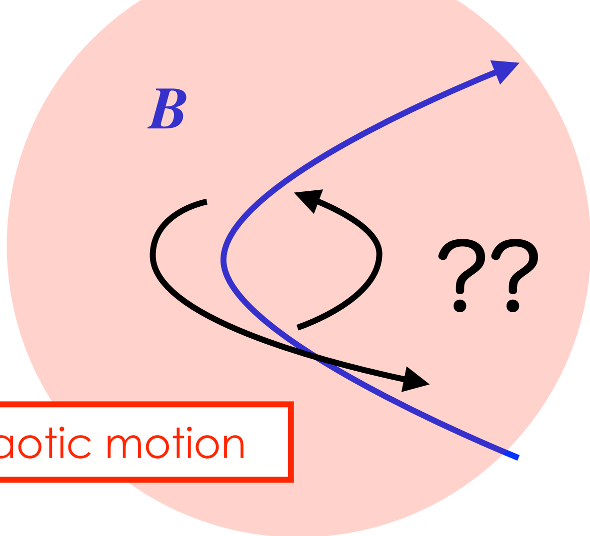
$$\ddot{x} = \kappa \dot{y}$$
$$\ddot{y} = z\dot{z} - \kappa \dot{x}$$
$$\ddot{z} = -z\dot{y}$$

Büchner & Zelenyi 1986, 1989

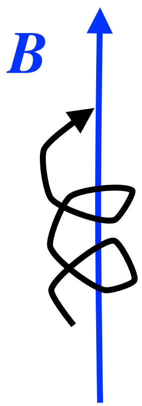
$\kappa \to 0$ | $\kappa \sim 1$ | $\kappa \to \infty$



Bounce motion
(I-adiabatic)

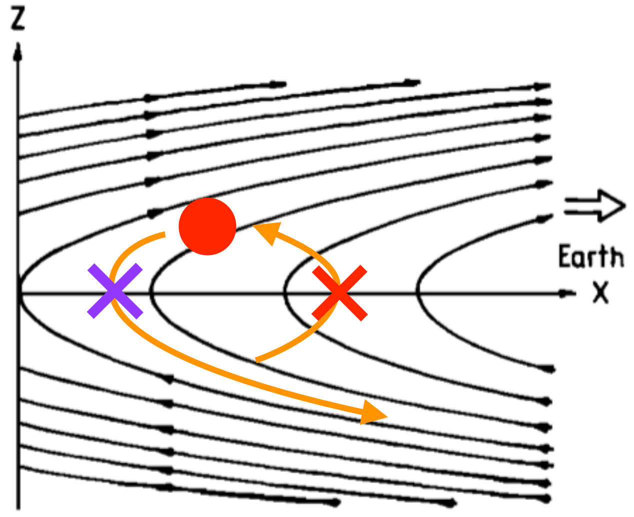


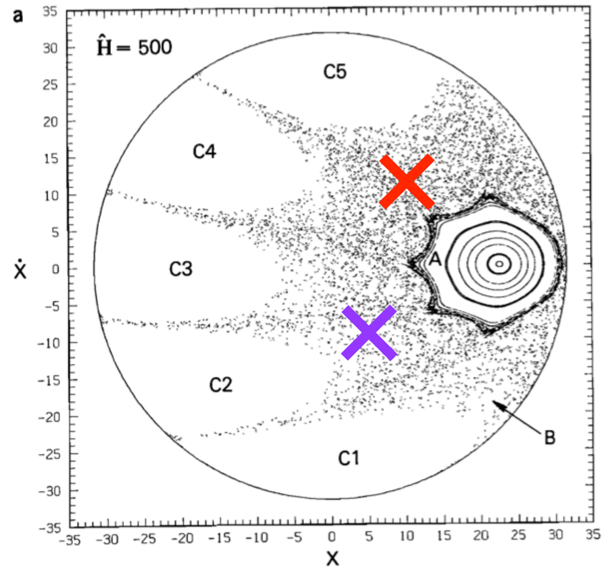
Chaotic motion



Gyro motion
(μ-adiabatic)

Orbit theory in a parabolic field





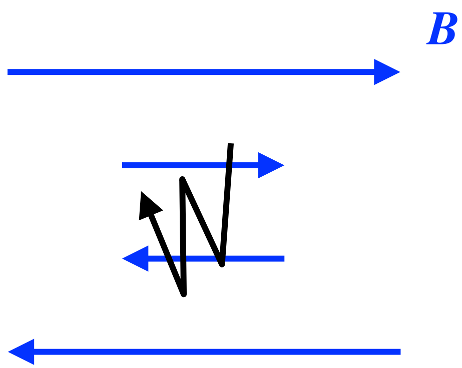
$\kappa \sim 1$

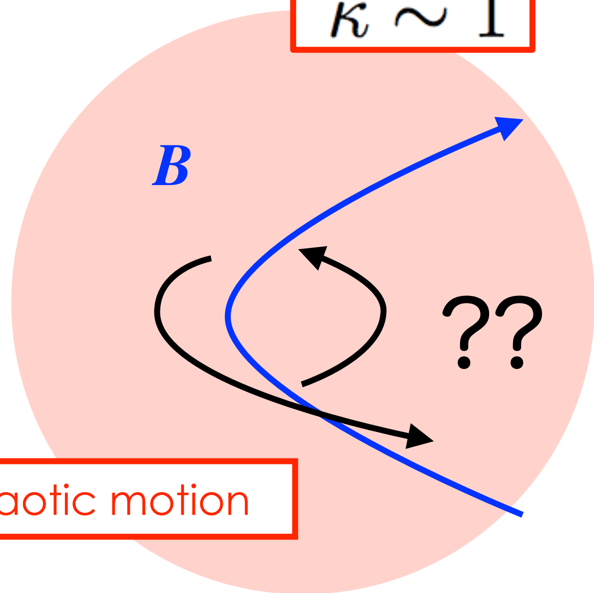
Chen & Palmadesso 1986

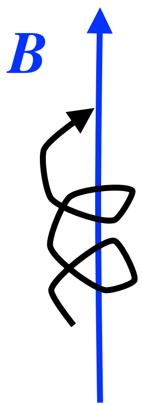
$\kappa \to 0$

$\kappa \sim 1$

$\kappa \to \infty$





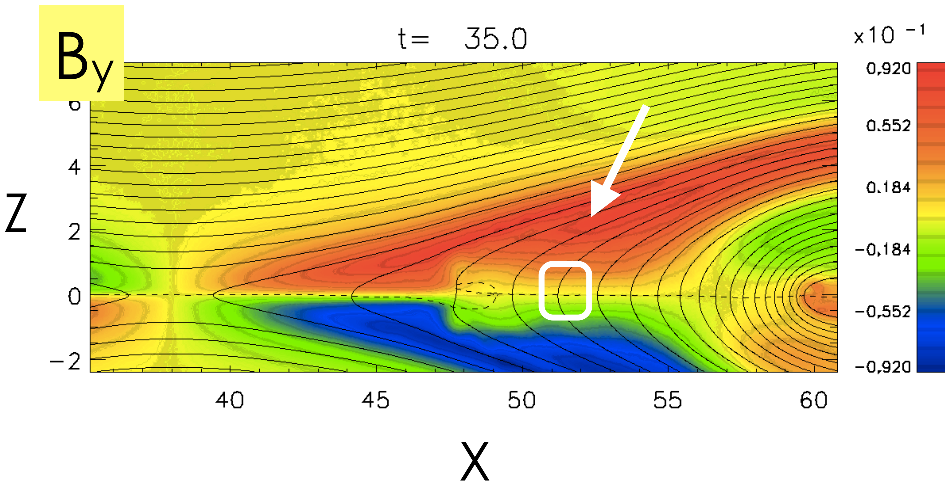


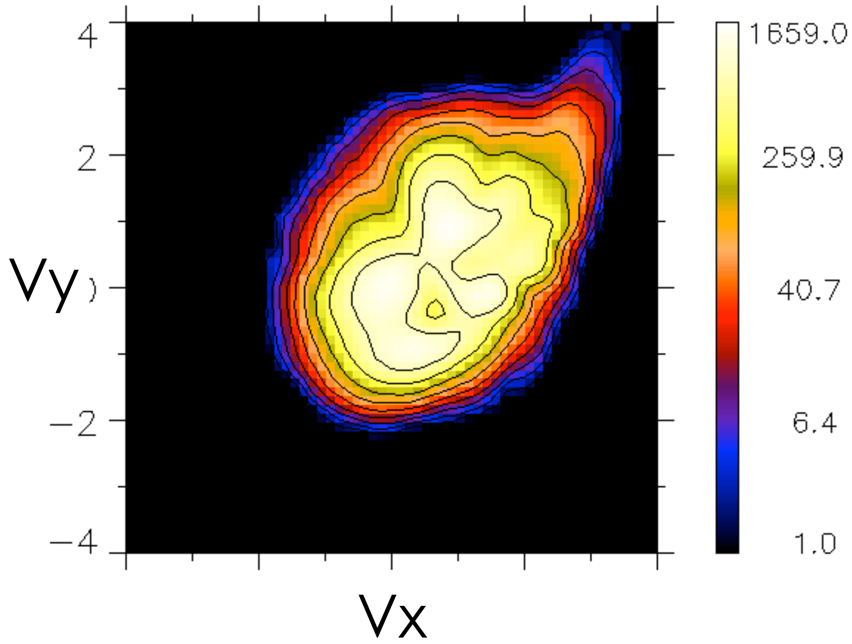
Bounce motion (I-adiabatic)

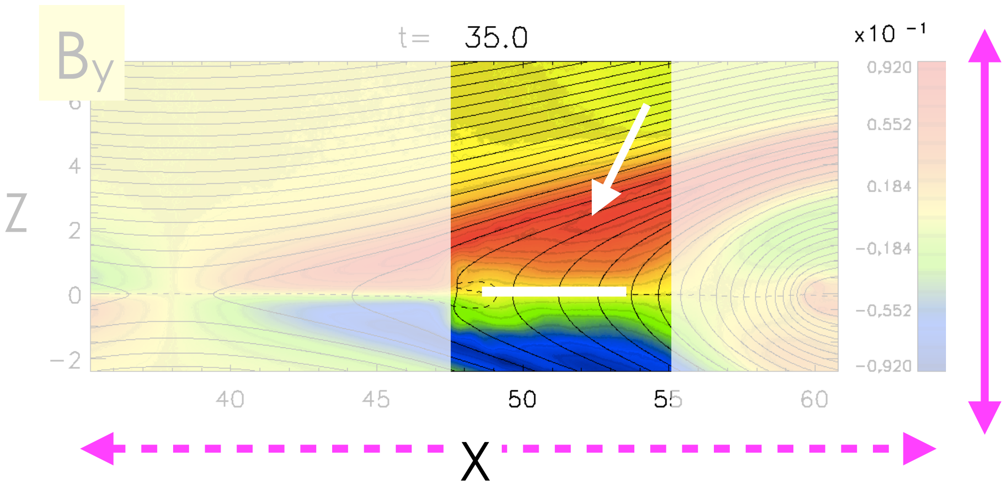
Chaotic motion

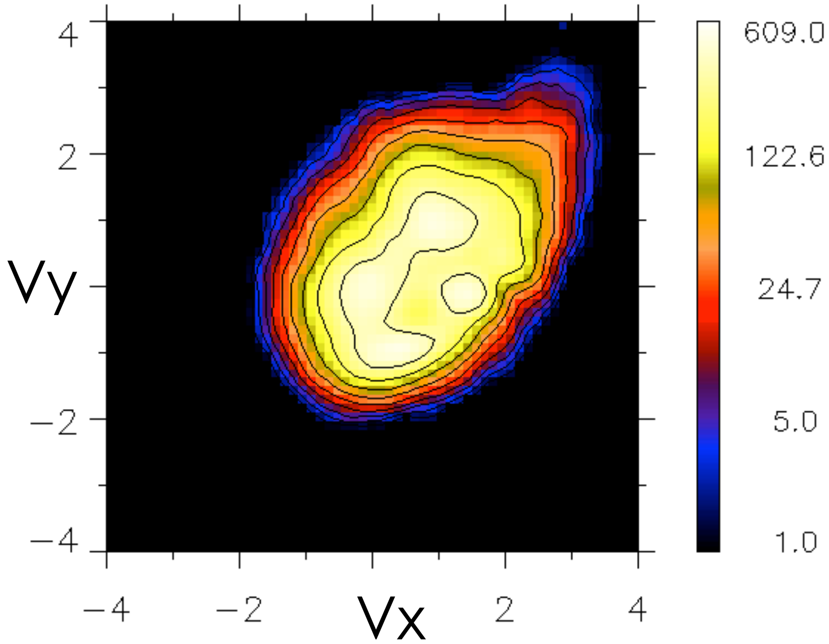
Gyro motion (μ-adiabatic)

Ion distribution function



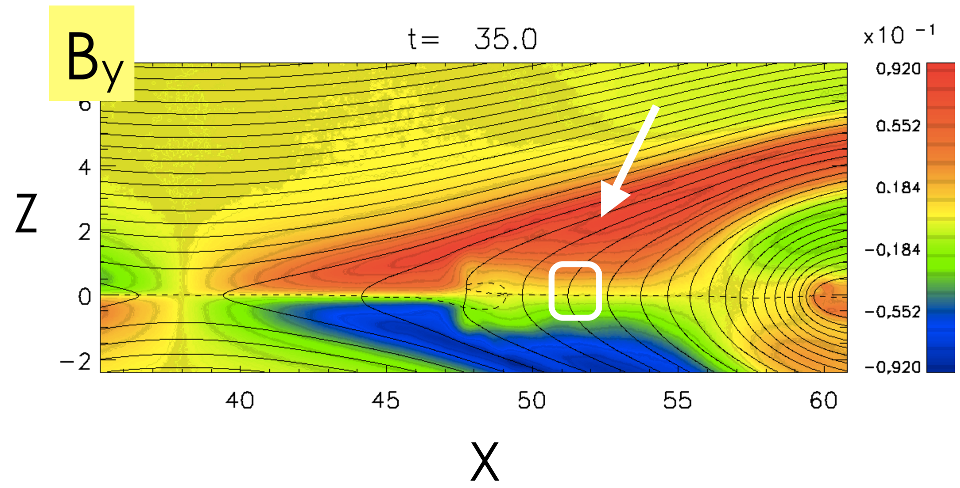


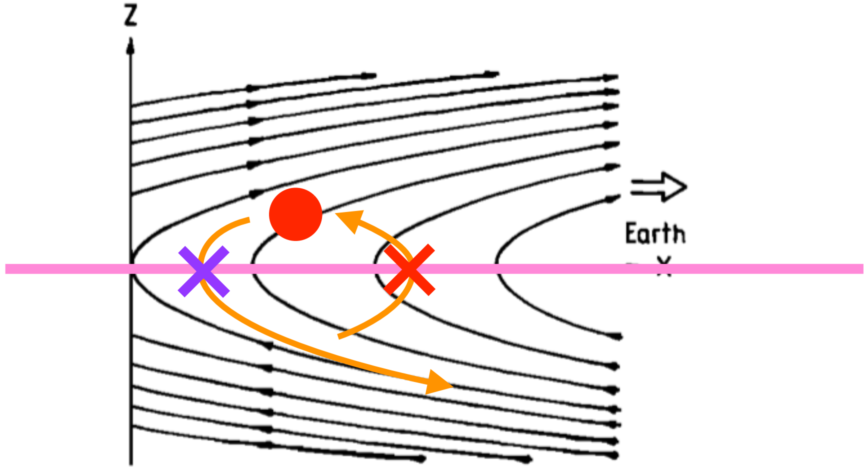


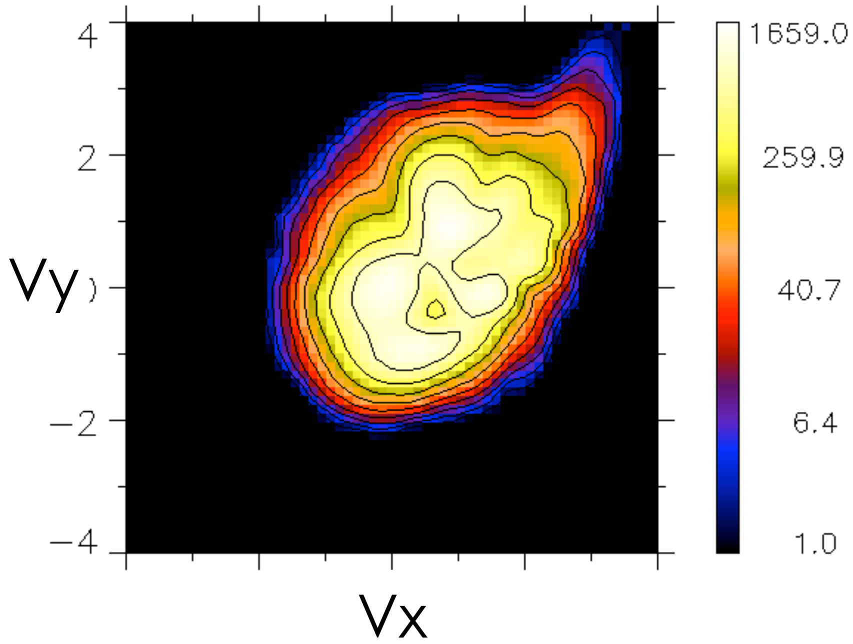


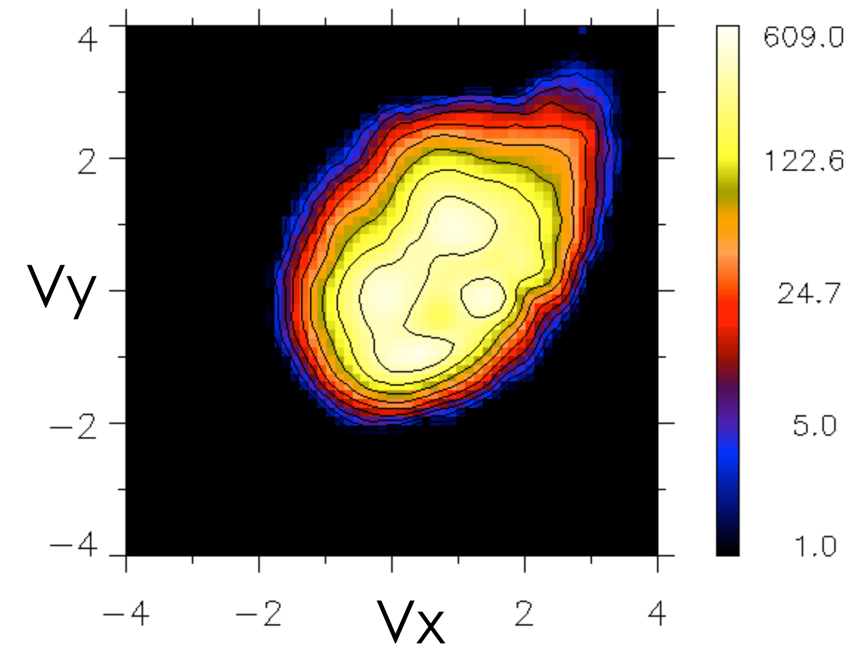
$$\left(\frac{\partial}{\partial x}\right) \ll \left(\frac{\partial}{\partial z}\right)$$

Ion distribution function







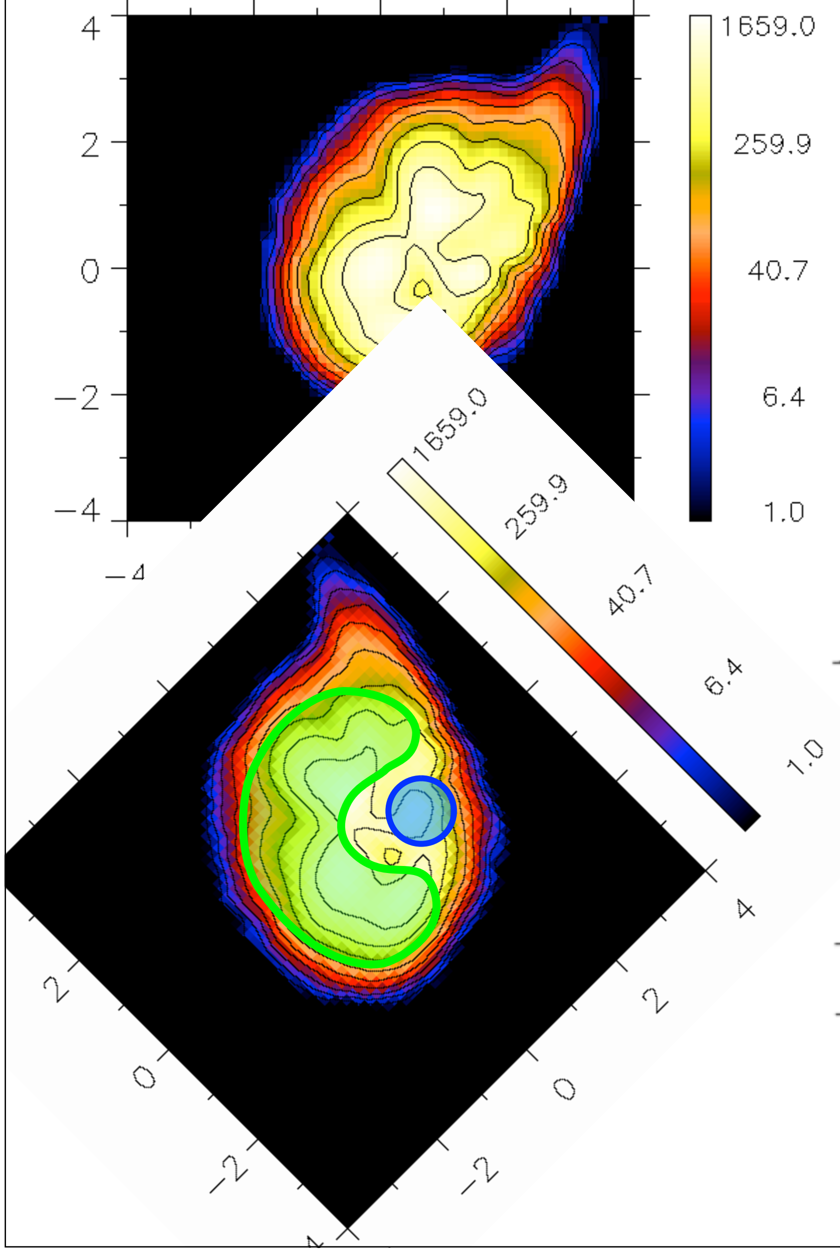


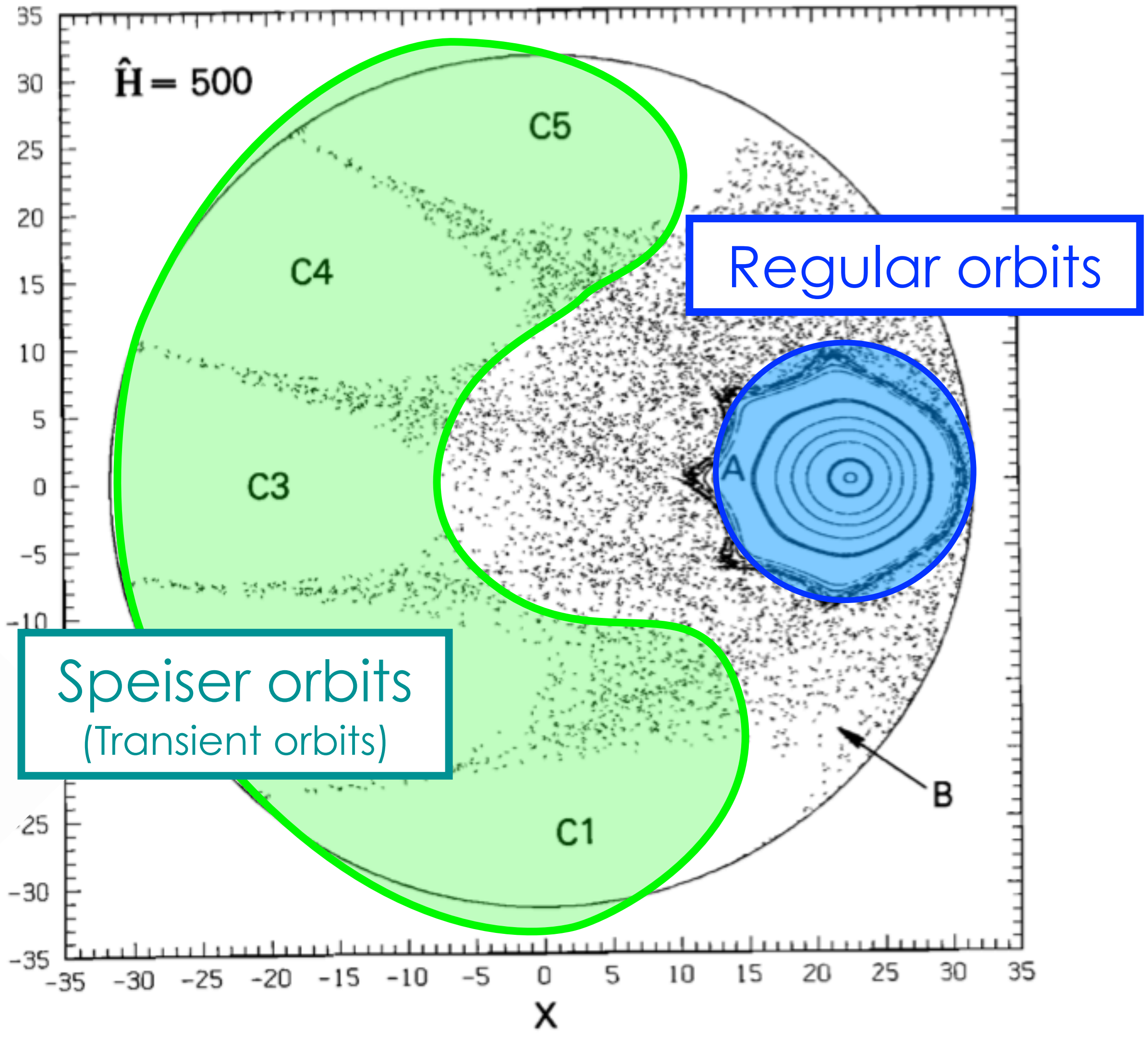
Two of 5 variables (x, y, **V_x**, **V_y**, V_z) at z=0

with a factor of $1/v_z$

Distribution function ⇔ Poincaré map

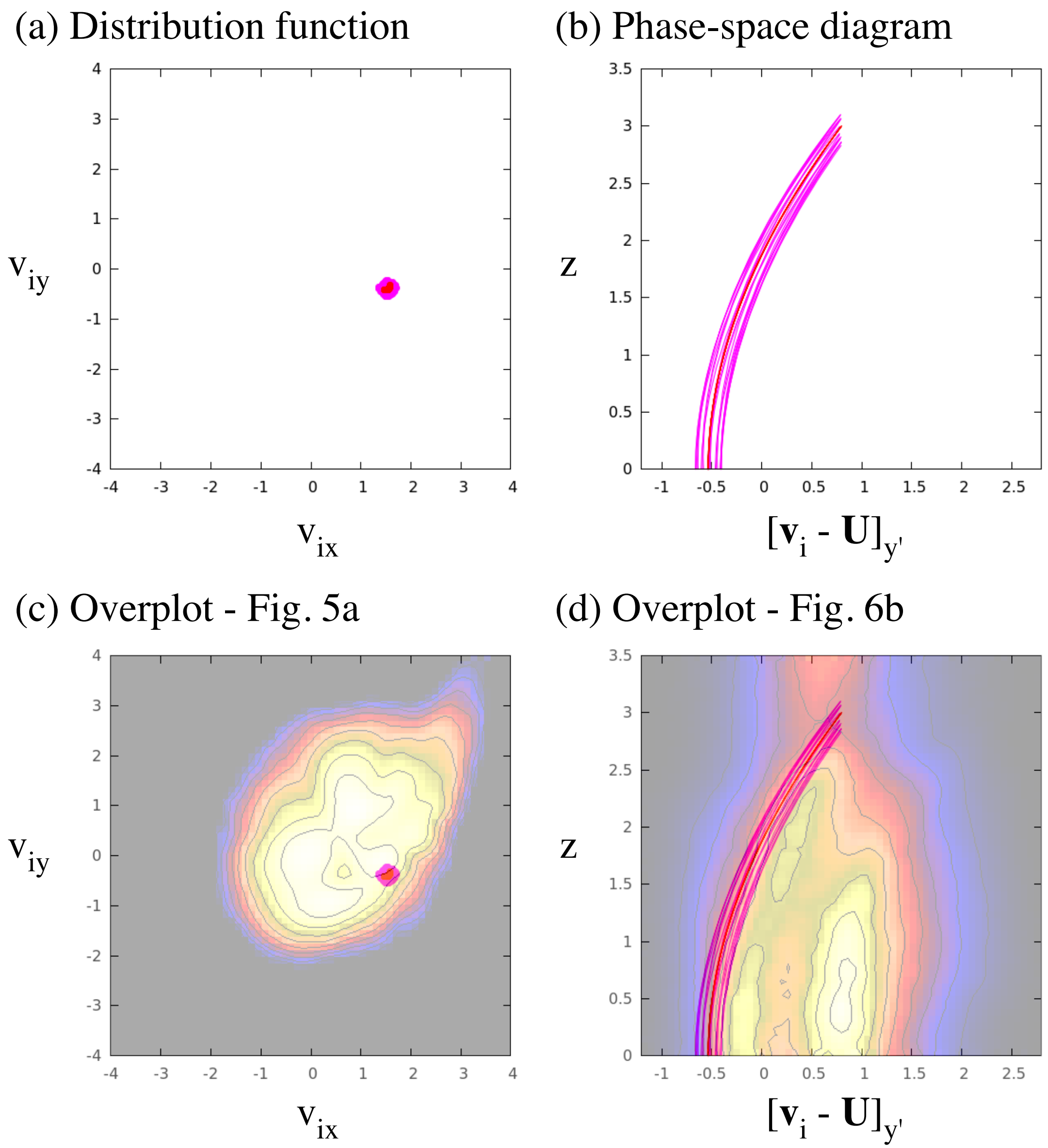
- $(x, \dot{x}) \Leftrightarrow (-\dot{y}, \dot{x})$



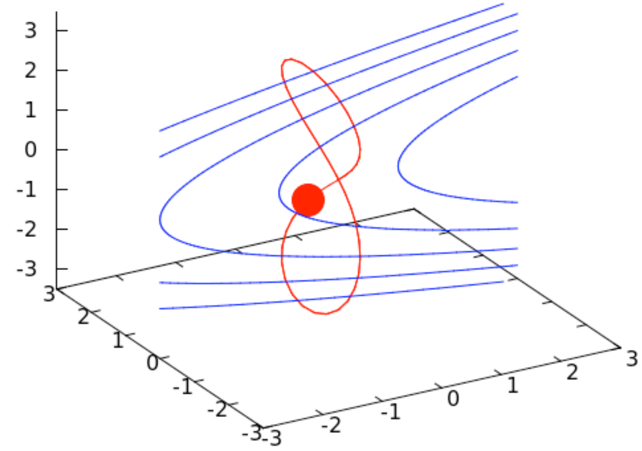


Chen & Palmadesso 1986 JGR

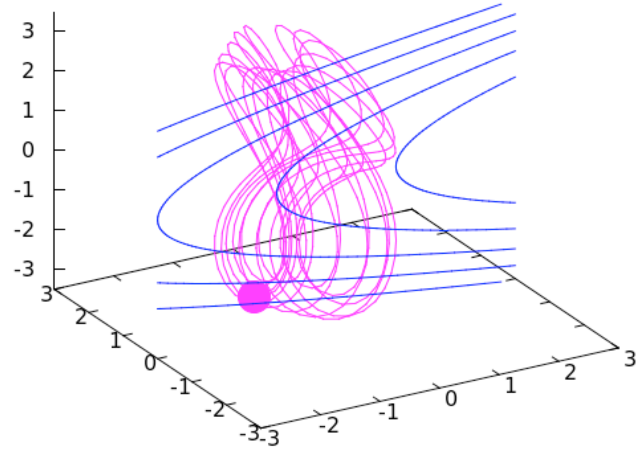
Regular orbits



- Stationary orbit

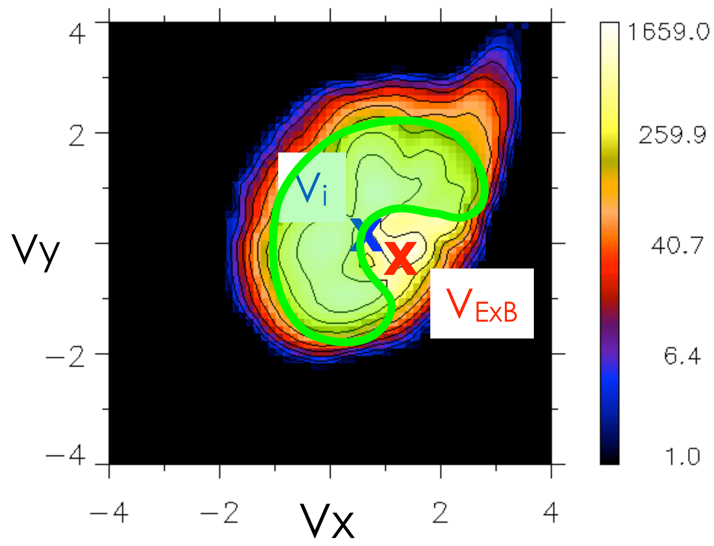


- + Weak perturbation



See also http://th.nao.ac.jp/MEMBER/zenitani/files/regular_orbits.mp4

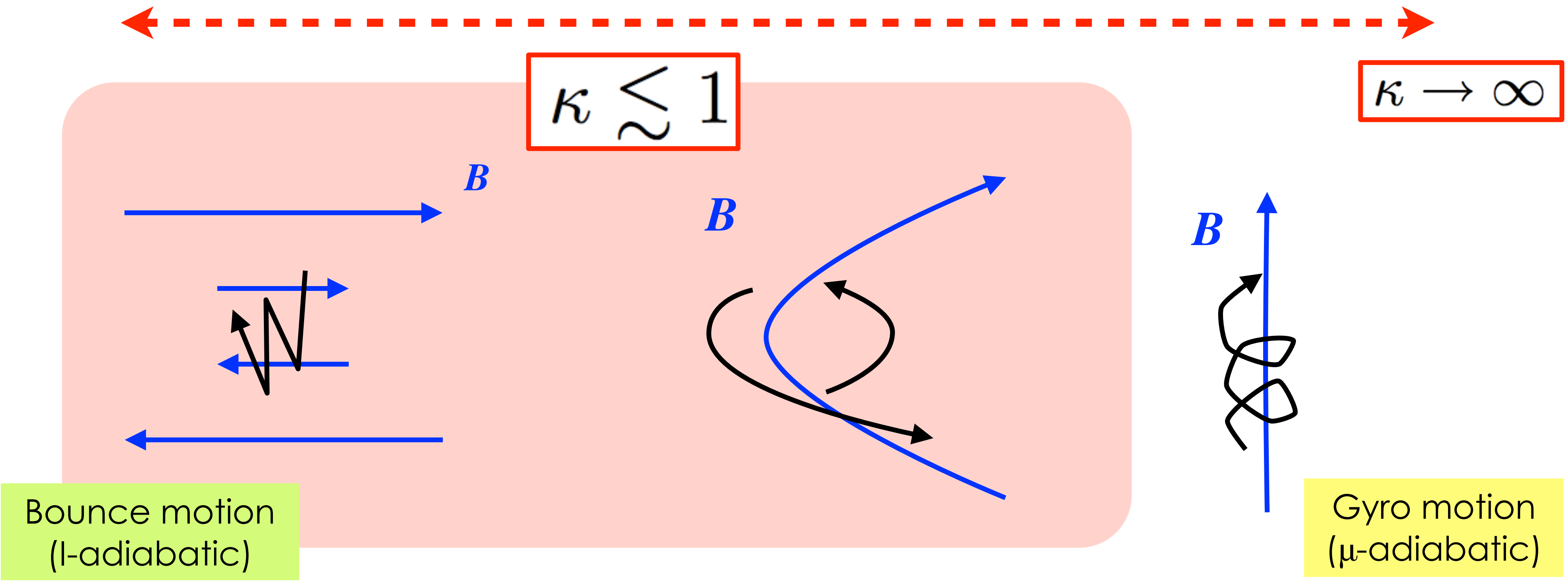
Nongyrotropic regime!!



- Since particles no longer gyrate, we do not expect the idealness in the $\kappa \lesssim 1$ regime.

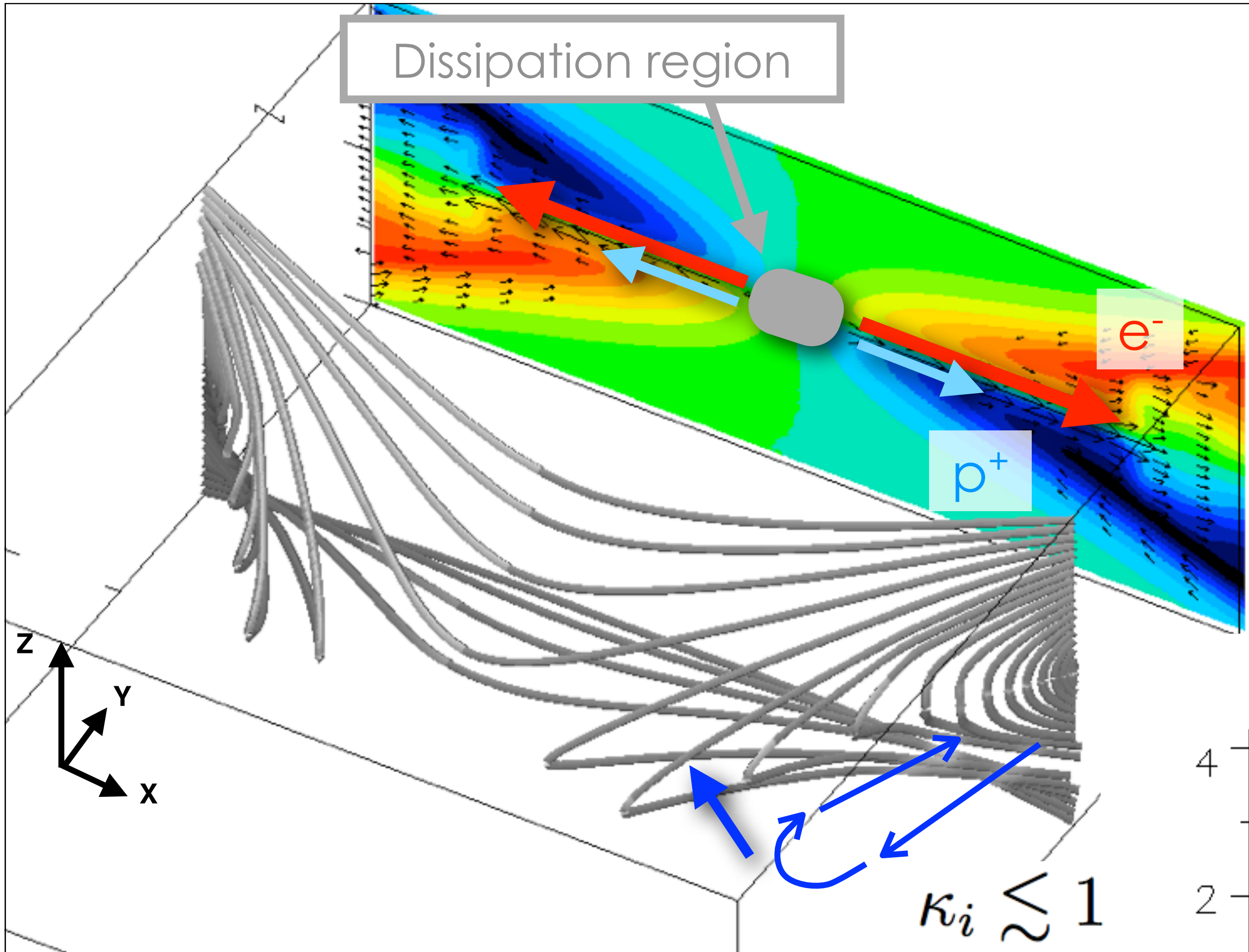
$$\boldsymbol{v_i} \neq \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

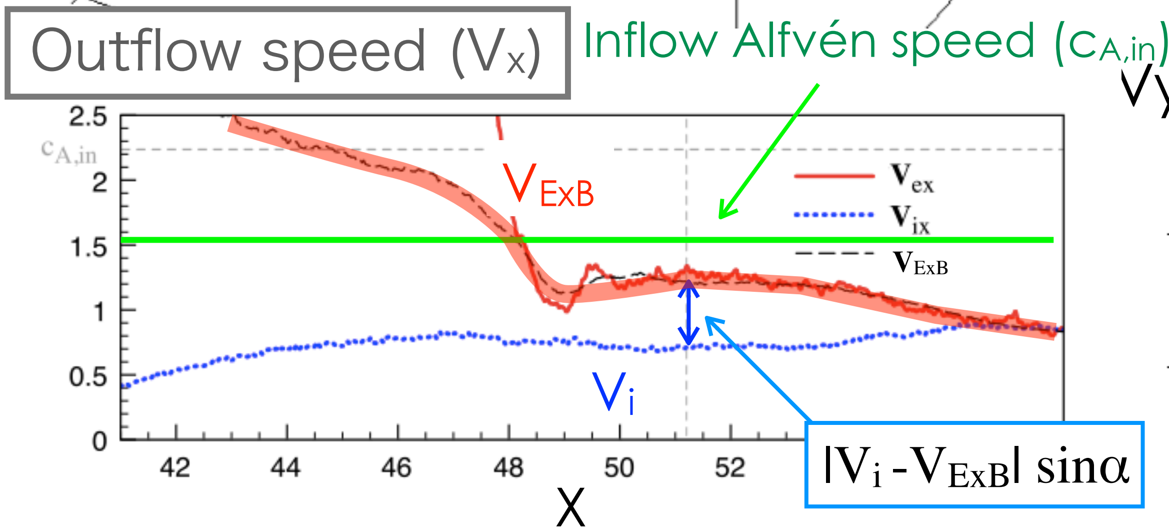
$$\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B} \neq 0$$

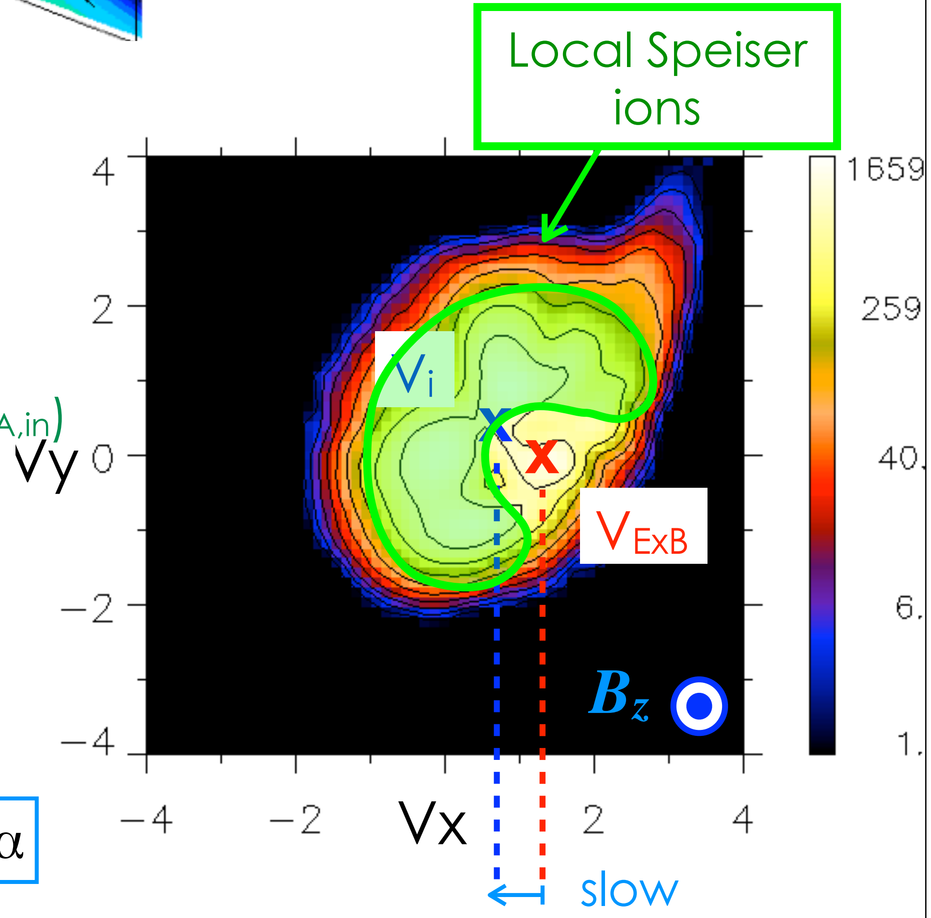


Sub-Alfvénic ion flow

= Ensemble of the swing-by motion of local Speiser ions

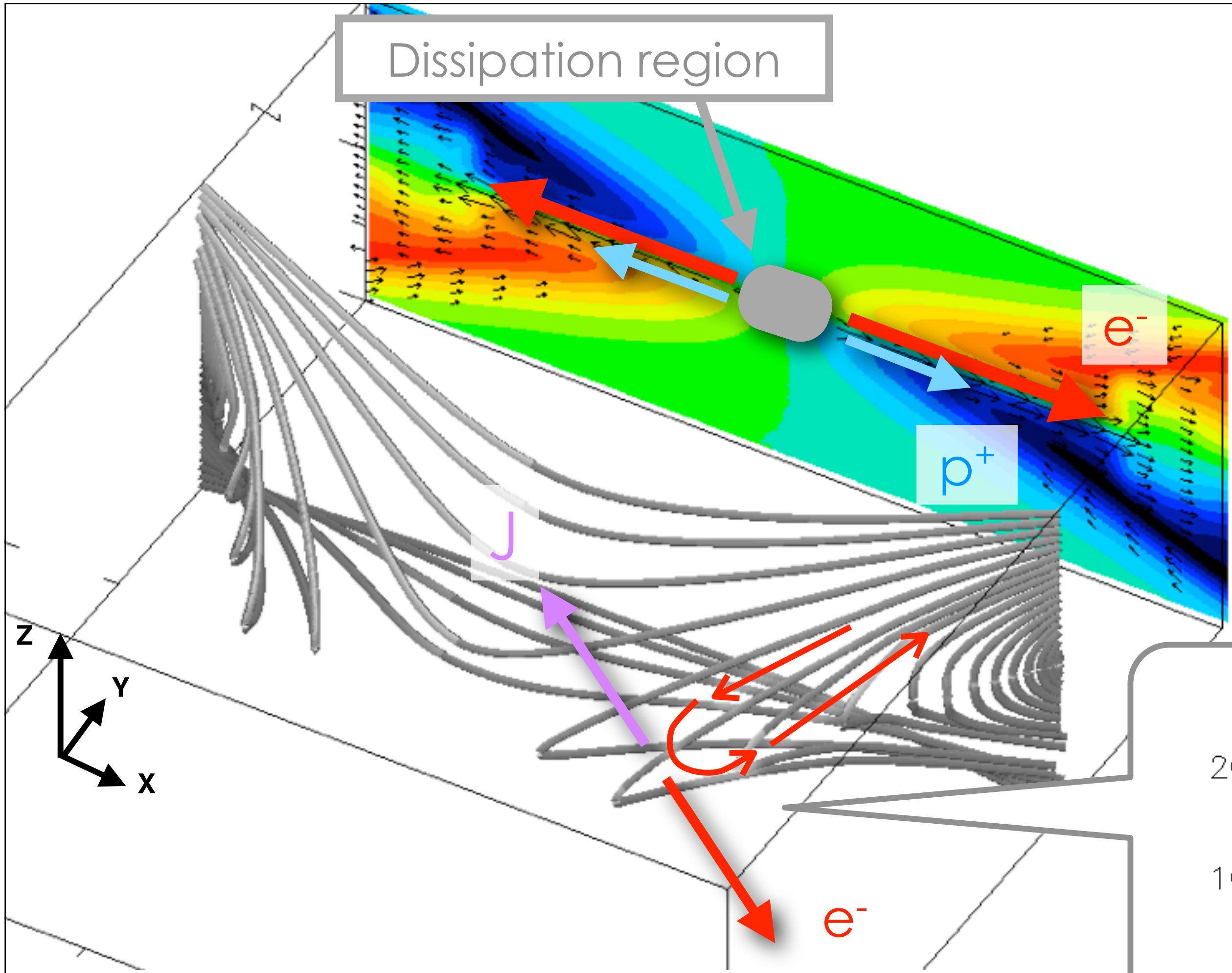


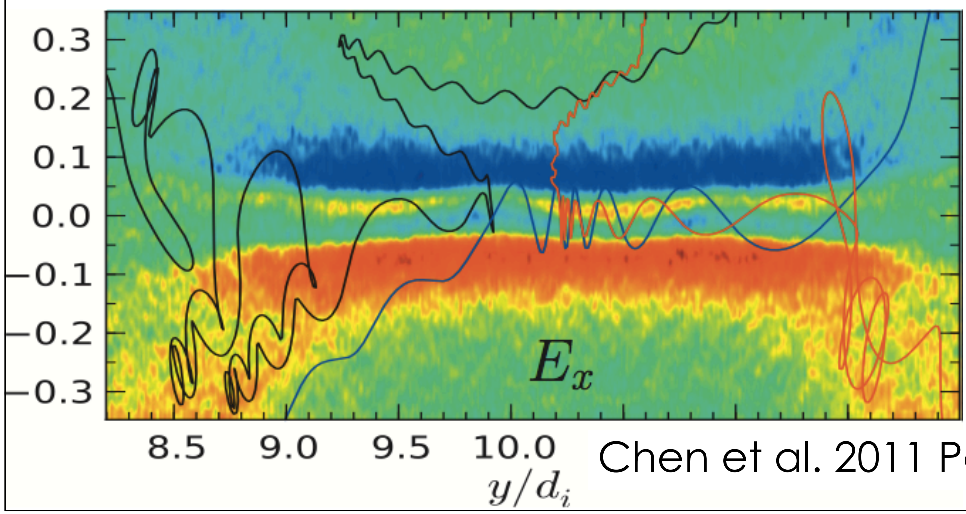




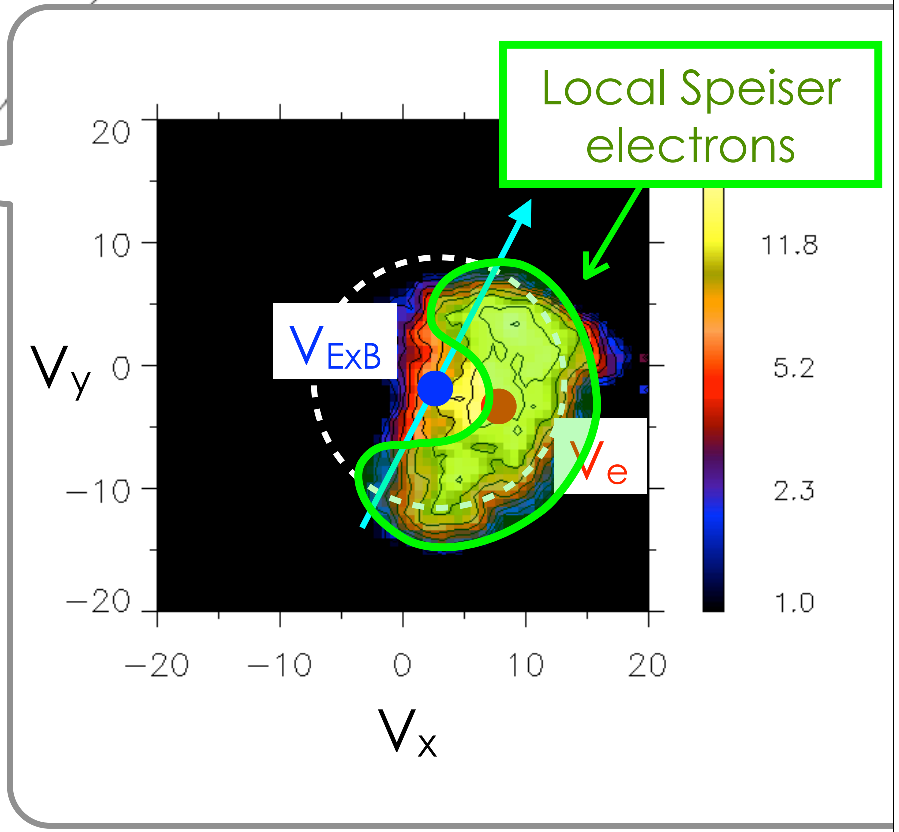
Super-Alfvénic electron jet

= Ensemble of the swing-by motion of local Speiser electrons



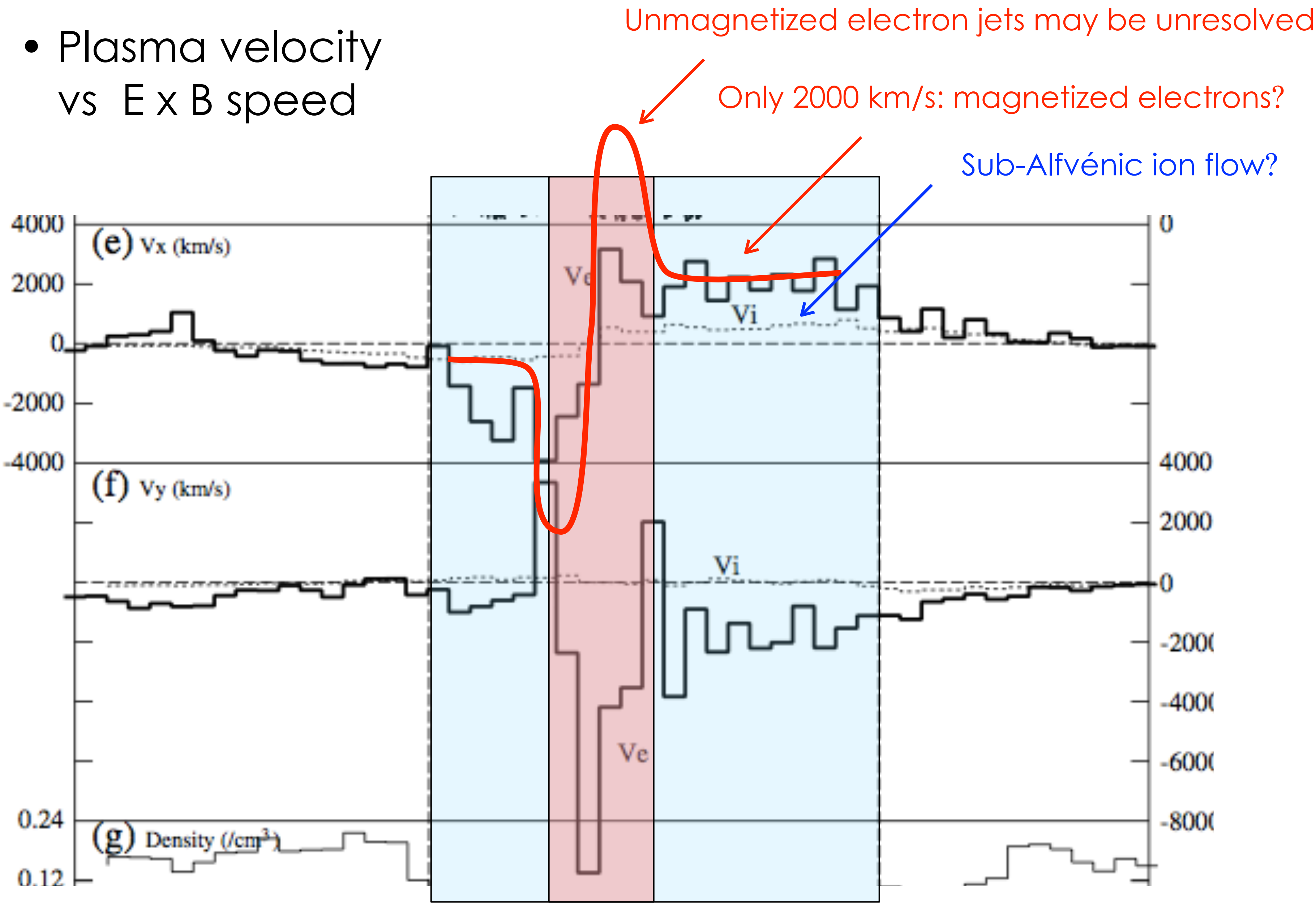


Chen et al. 2011 PoP



Geotail 2007-05-05 event

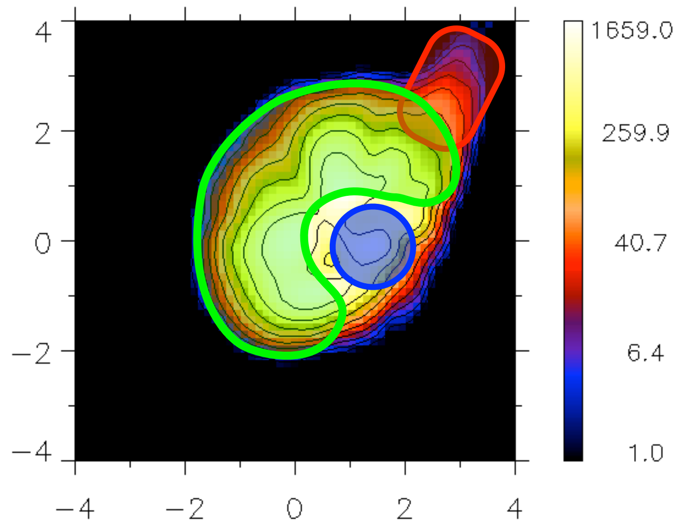
- Plasma velocity vs E x B speed



Nagai, SZ et al. 2013b JGR

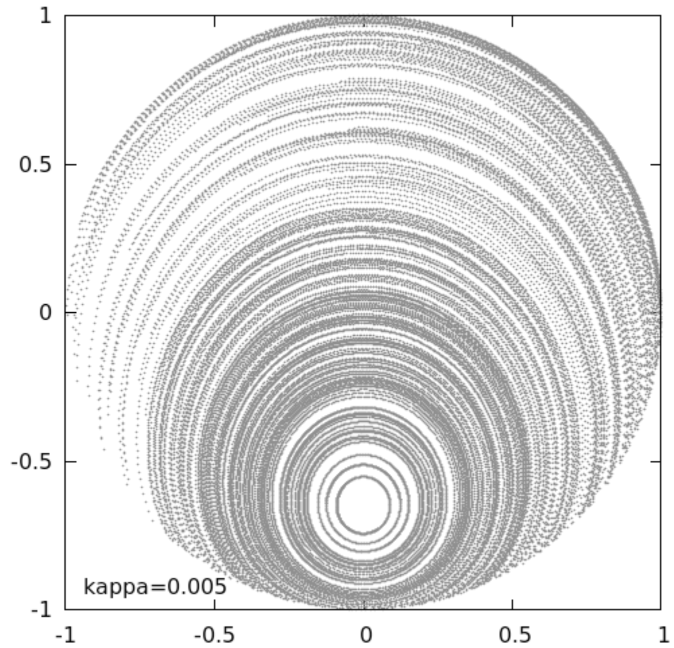
Summary

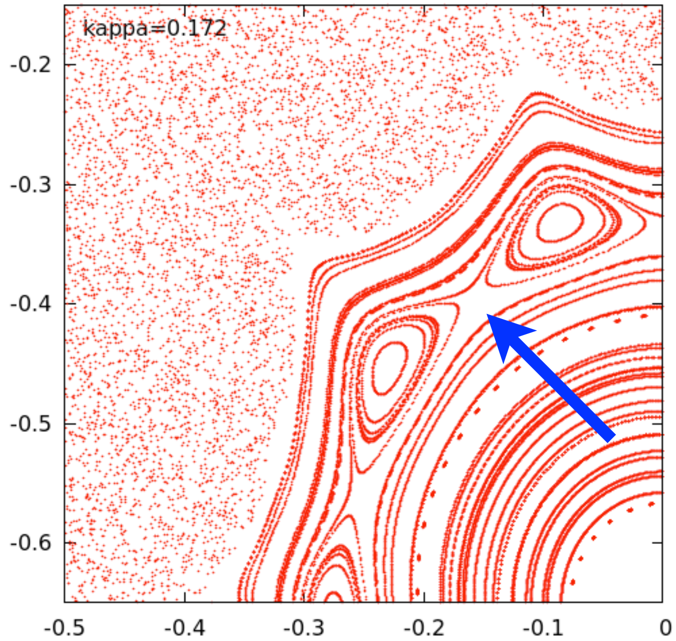
- We have examined an ion velocity distribution function in the reconnection outflow:
  - (1) Global Speiser ions
  - (2) Local Speiser ions
  - (3) Trapped ions
    - Regular orbits in the chaos theory
    - First demonstration in PIC simulation



- Plasma ideal condition
  - Easily violated in the $\varkappa<1$ regime
  - Particles no longer gyrate
- Local-Speiser motion explains
  - Sub-Alfvénic ion flow
  - Super-Alfvénic electron jet
- Better understanding of the outflow region from the viewpoint of particle motion

Chaos in reconnection





Reconnection in chaos

Magnetic reconnection is
a fascinating multi-scale process!