Electron particle dynamics in collisionless magnetic reconnection

Seiji ZENITANI

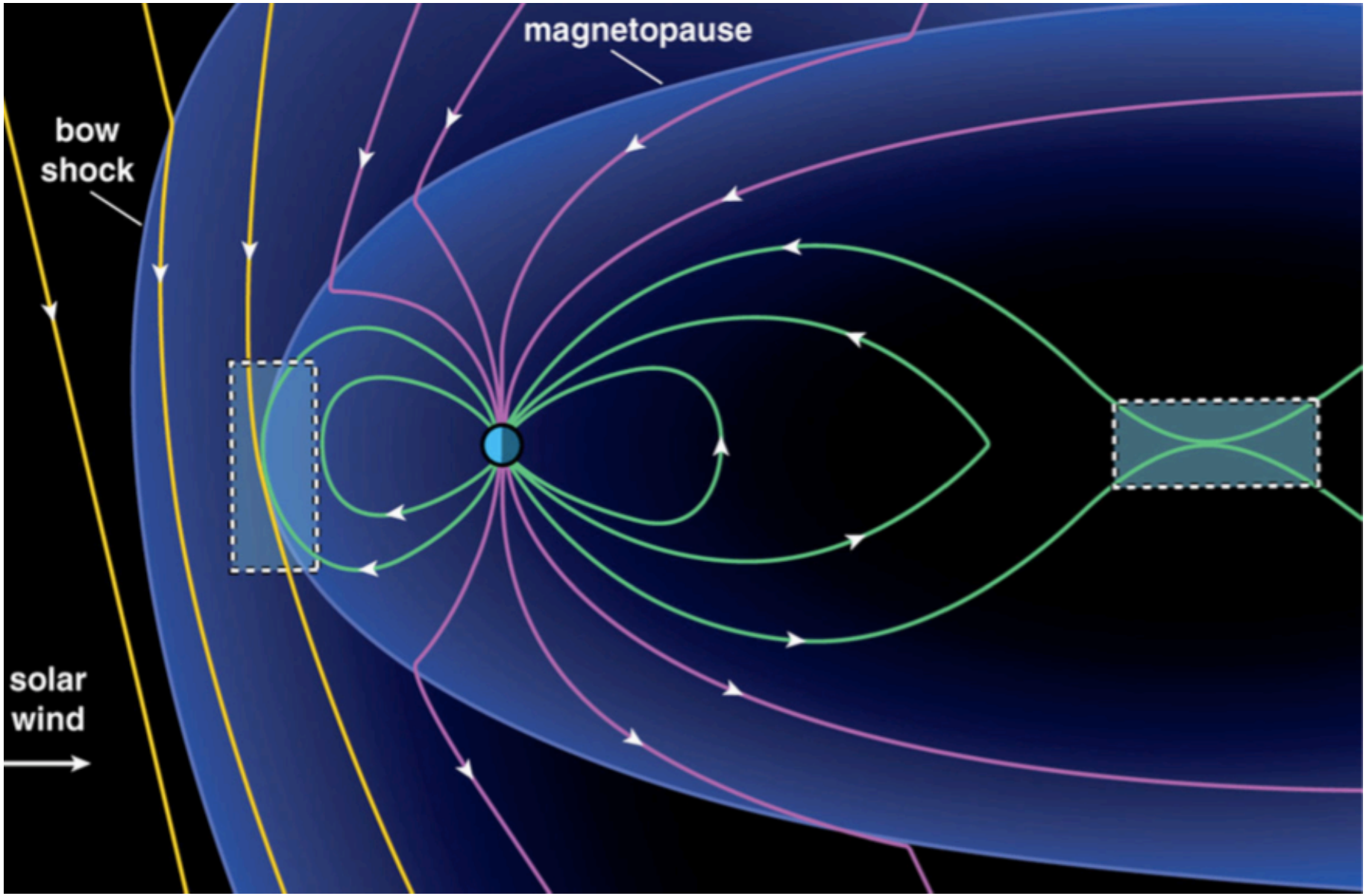
Kyoto University

Outline

- 1. Electron orbits in antiparallel reconnection
- 2. Electron-physics signatures in asymmetric reconnection
- 3. New measure of electron mixing

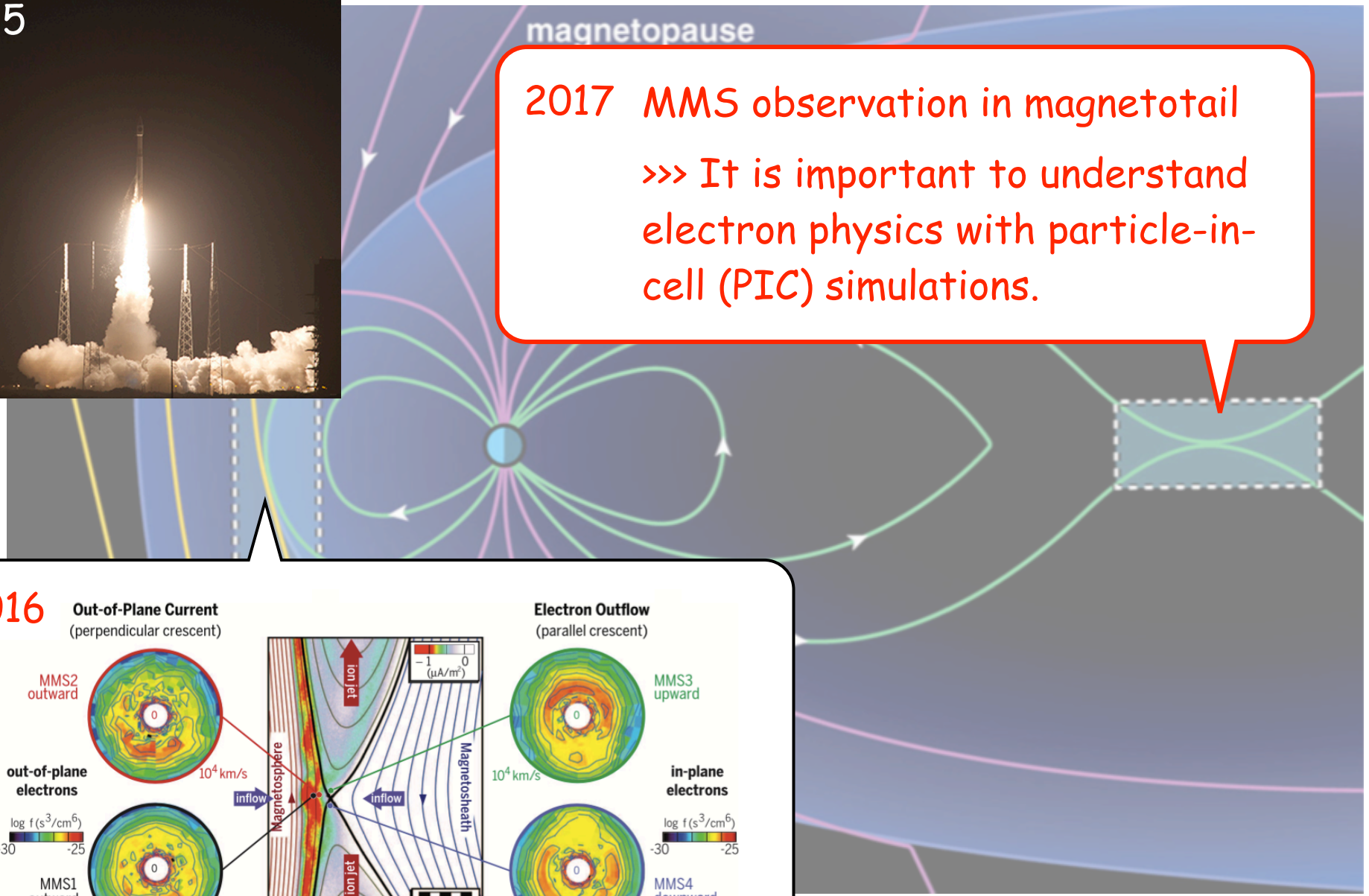
1. Antiparallel reconnection

Magnetic reconnection in near-Earth space



Burch+ 2016 Space Sci. Rev.

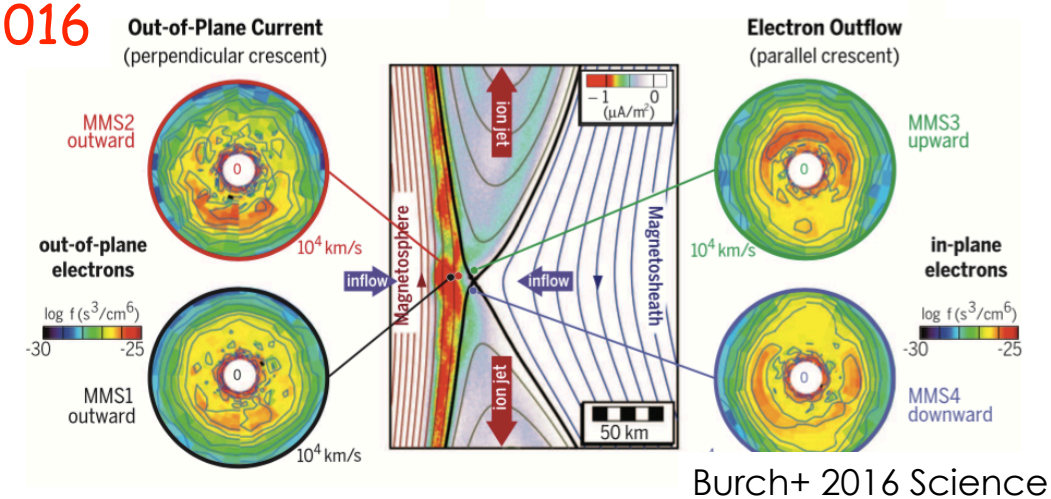
Magnetospheric Multiscale (MMS) mission



2017 MMS observation in magnetotail

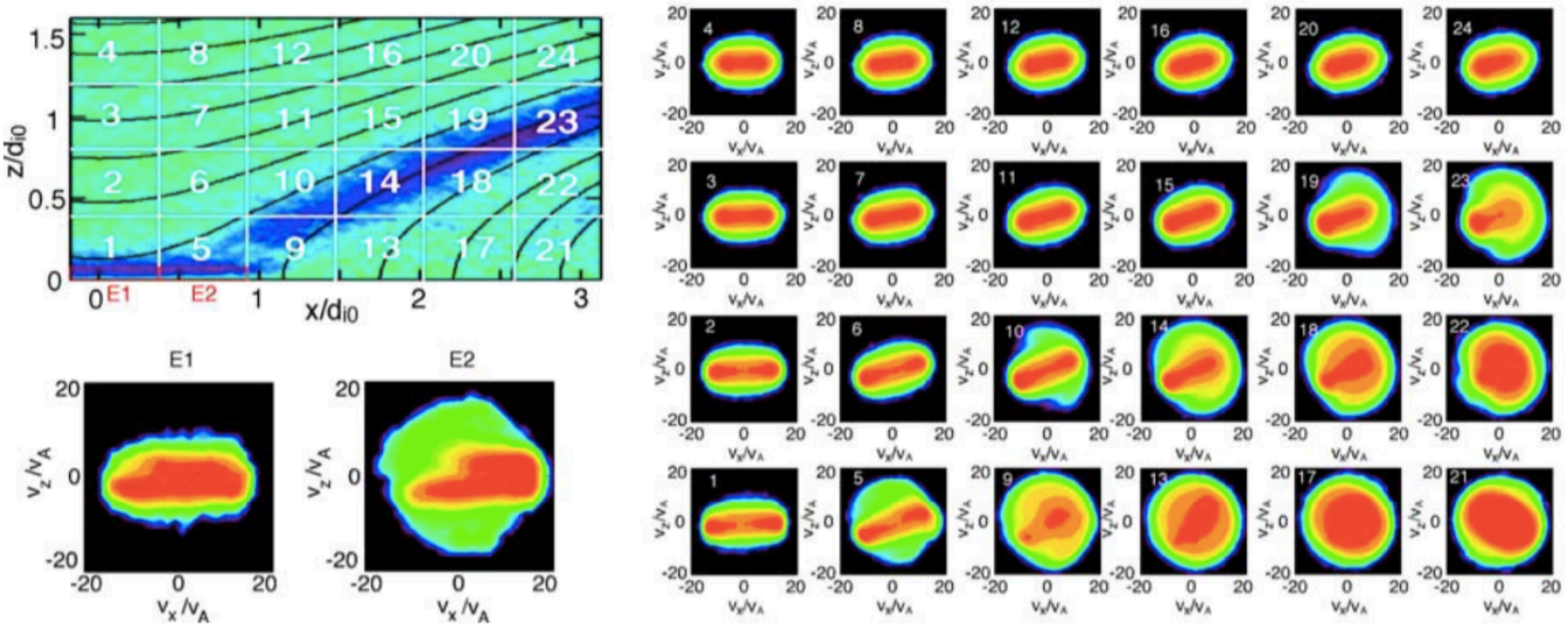
>>> It is important to understand electron physics with particle-in-cell (PIC) simulations.

2016



Burch+ 2016 Science

Electron velocity distribution functions (VDFs) in PIC simulation

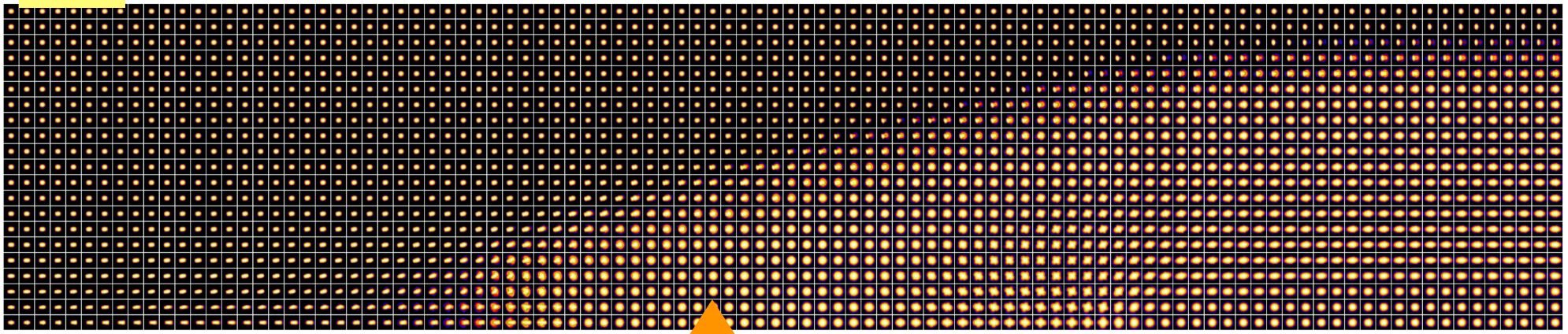


Chen+ 2008 JGR

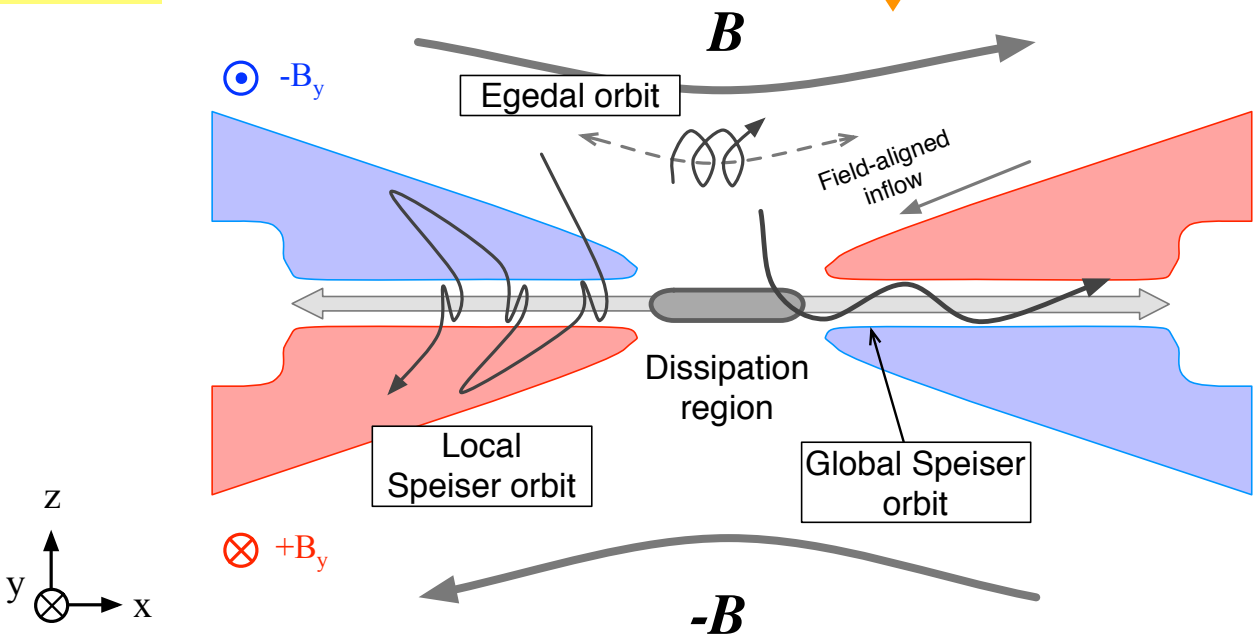
- Many PIC studies on electron-physics signatures in symmetric MRX
  - Hoshino+ 2001, Pritchett 2006, Chen+ 2008, 2009, Ng+ 2011, 2012, Hesse+ 2011, Bessho+ 2014, Shuster+ 2014, 2015, Cheng+ 2015

Electron VDFs vs electron orbits

VDFs



Orbits

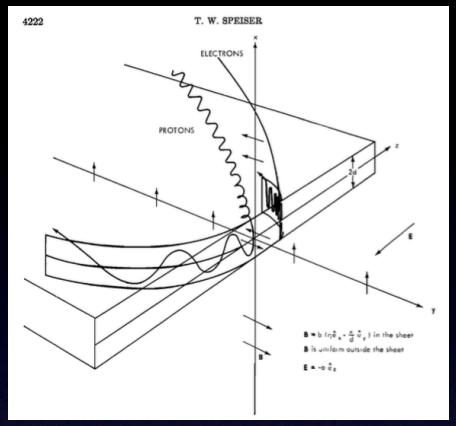


- In addition to VDFs, we have to understand electron orbits, too.

Do we really understand electron orbits?

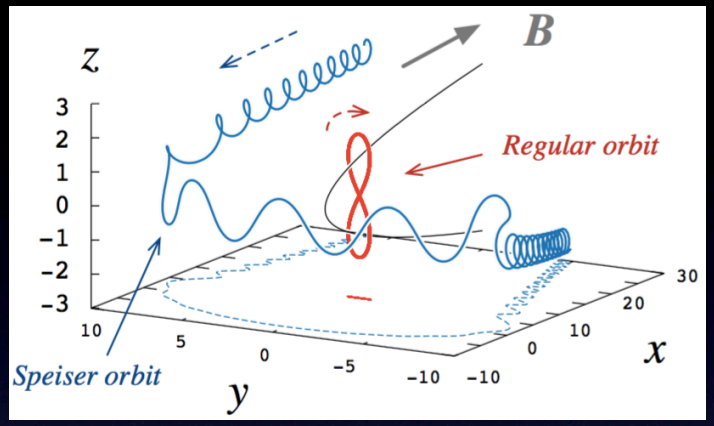
Orbit theories

1965



Speiser 1965

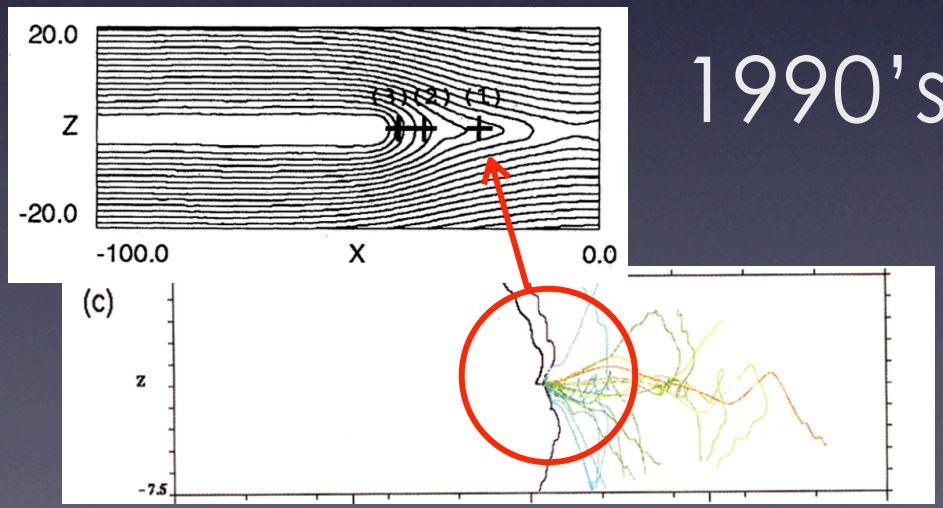
1980's



Chen & Palmadesso 1986, Buchner & Zelenyi 1989

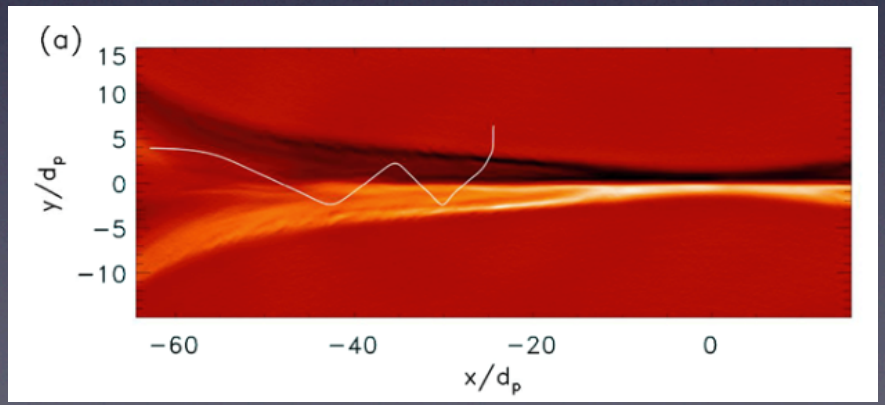
Ion orbits

1990's



Nakamura+ 1998

2000's

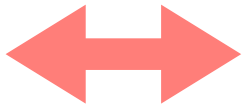


Drake+ 2009

Do we really understand electron orbits?

Ions

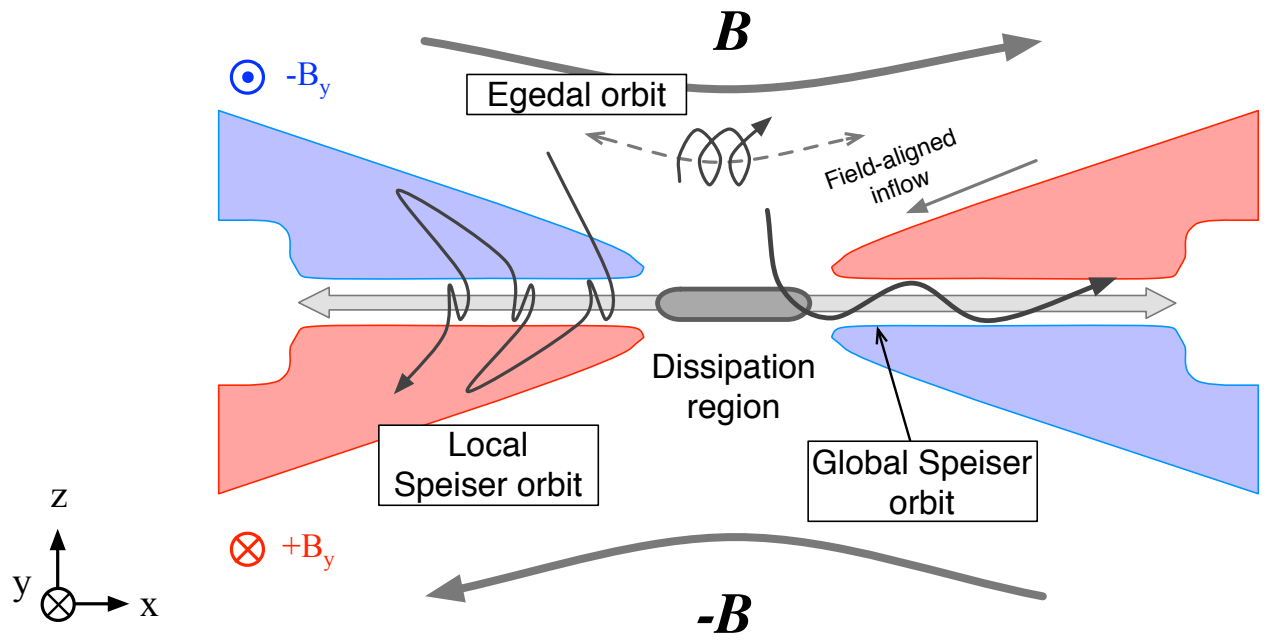
- Gyration
- Large gyroradius



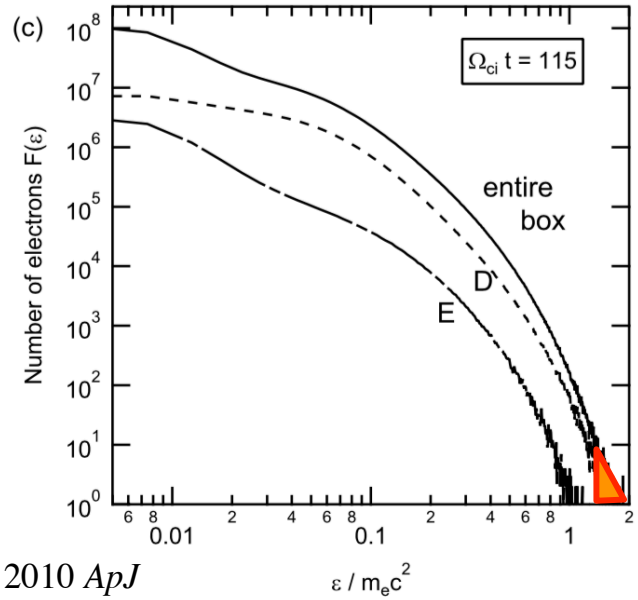
Electrons

- Opposite gyration
- Small gyroradius
- (Response to E field)

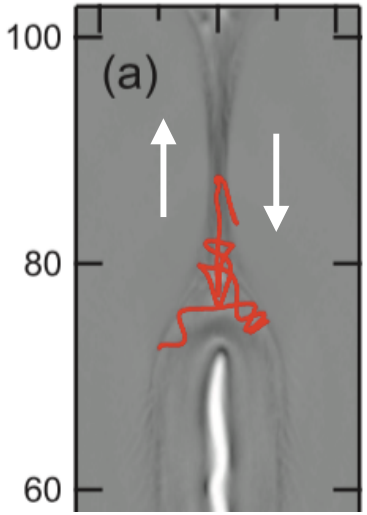
Previous expectation

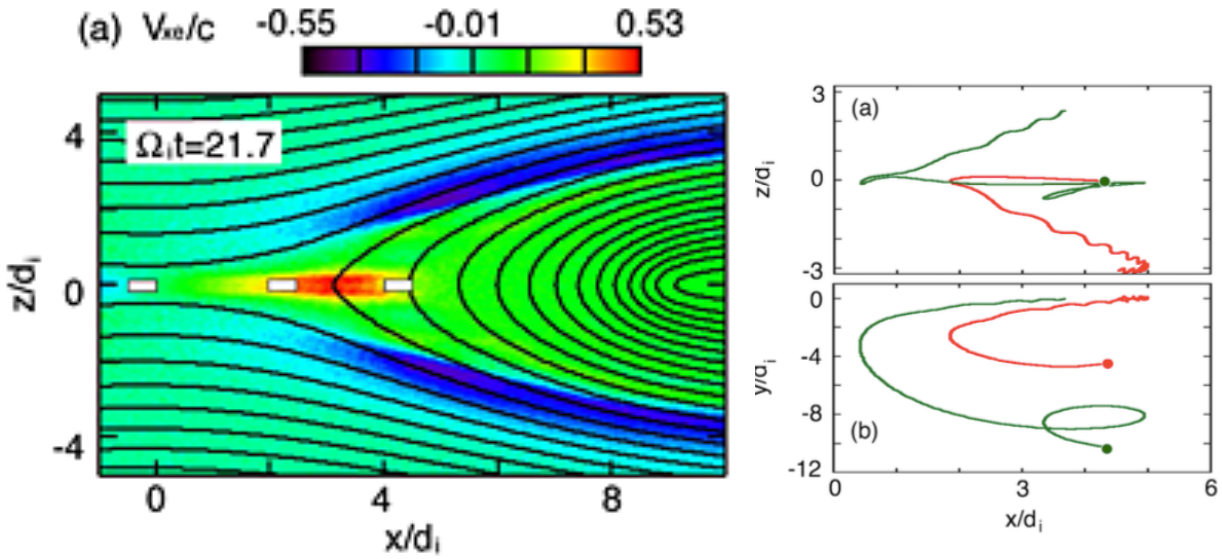


Trajectory analysis in PIC simulations

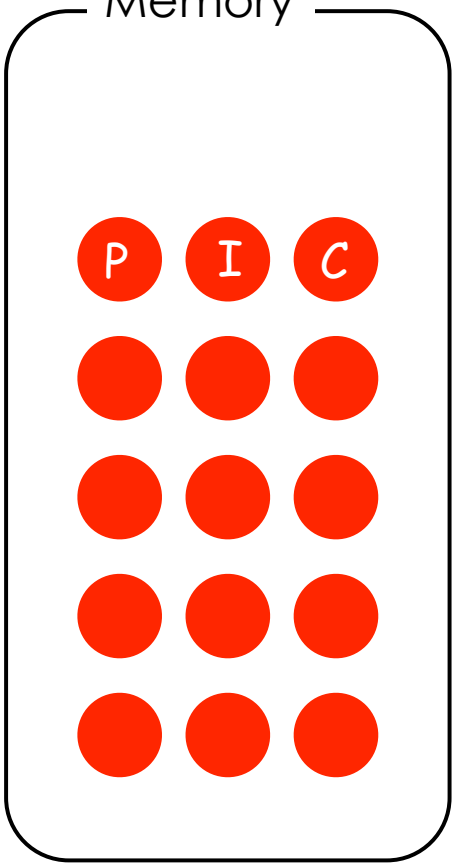


Oka et al. 2010 *ApJ*

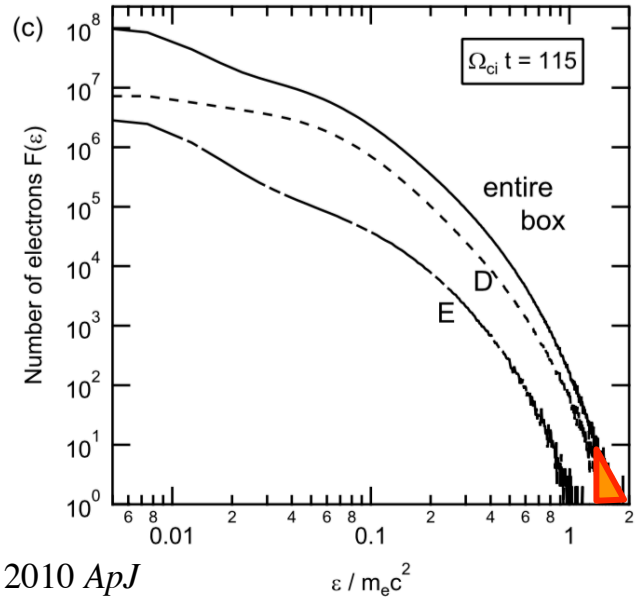




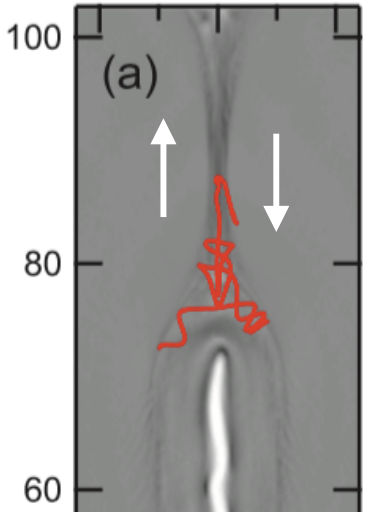
Bessho et al. 2014 *GRL*

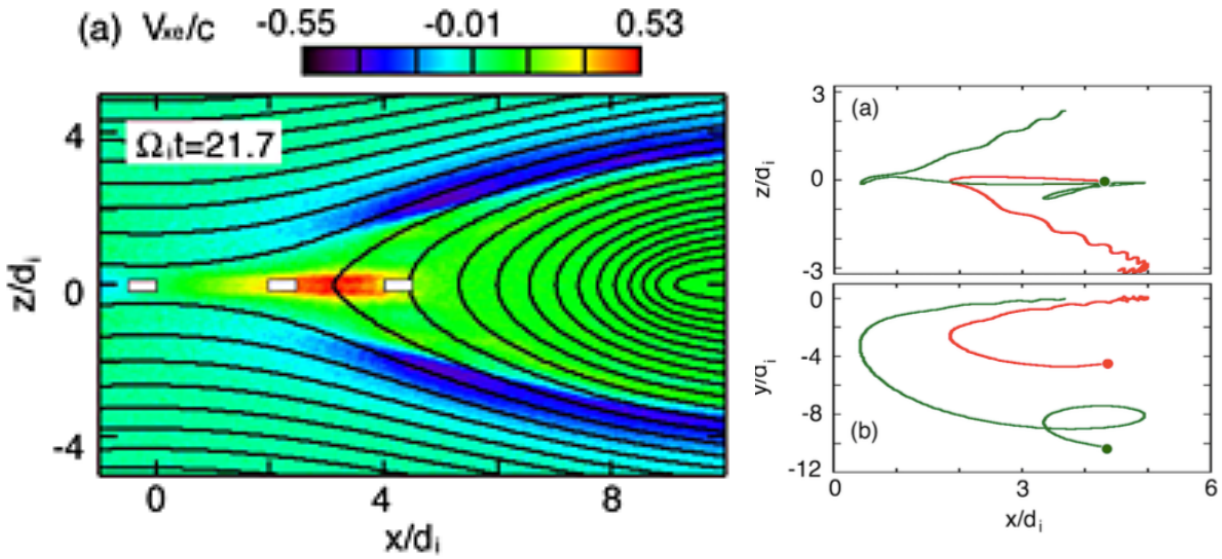


Trajectory analysis in PIC simulations

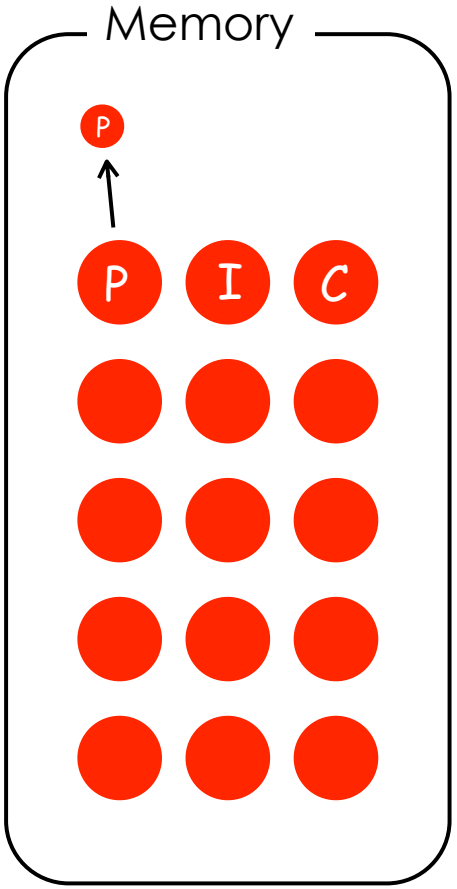


Oka et al. 2010 *ApJ*

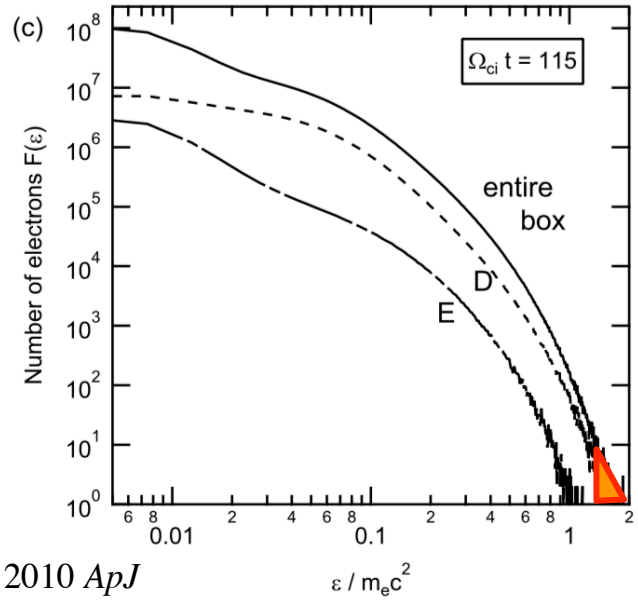




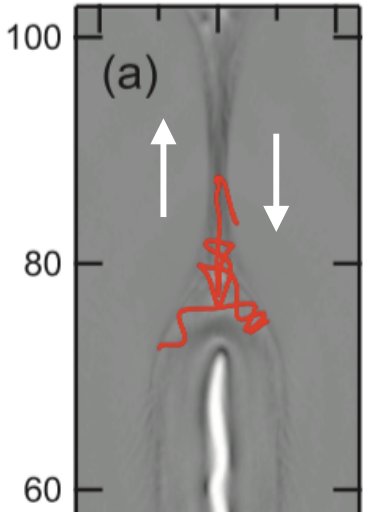
Bessho et al. 2014 *GRL*

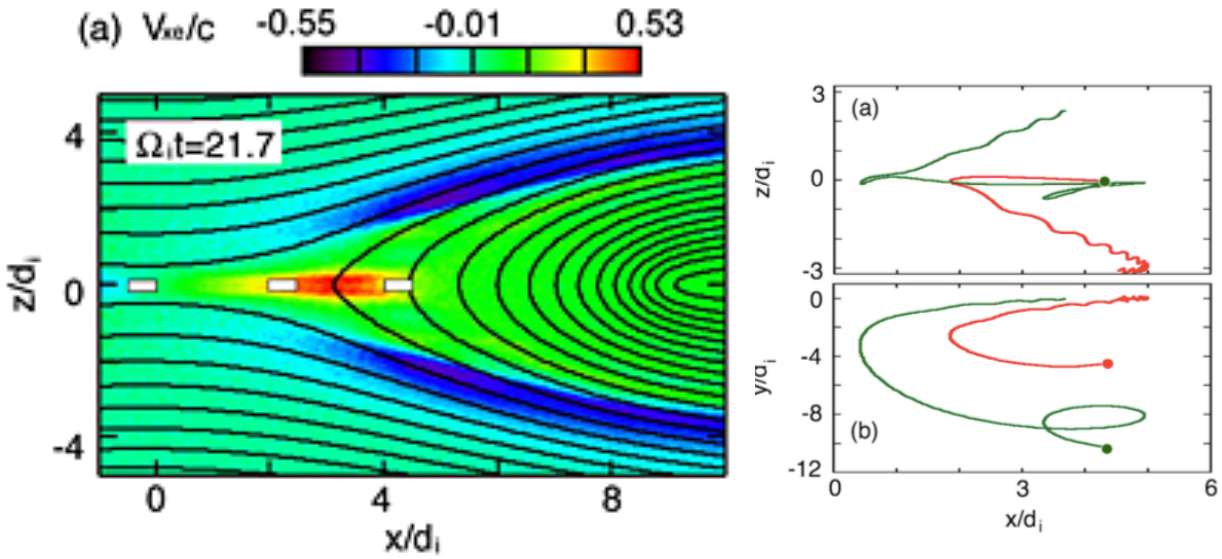


Trajectory analysis in PIC simulations

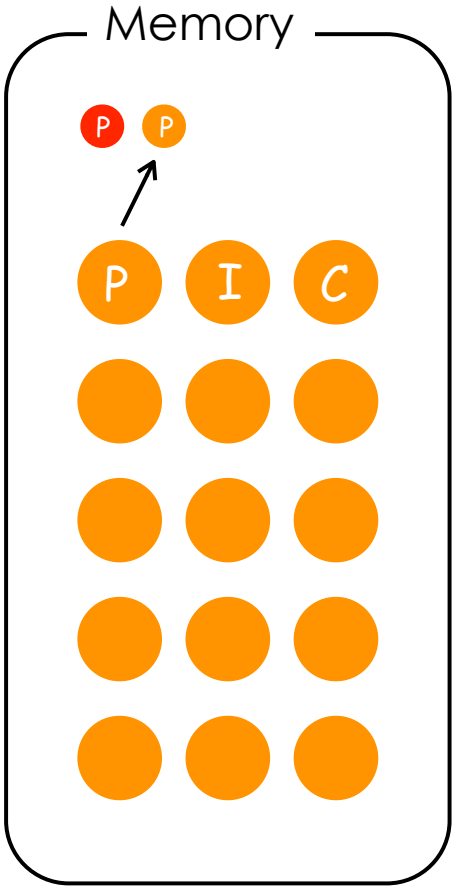


Oka et al. 2010 *ApJ*

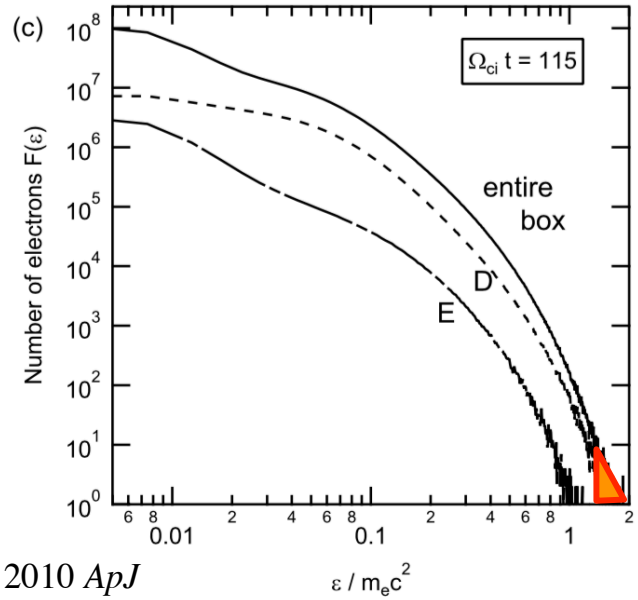




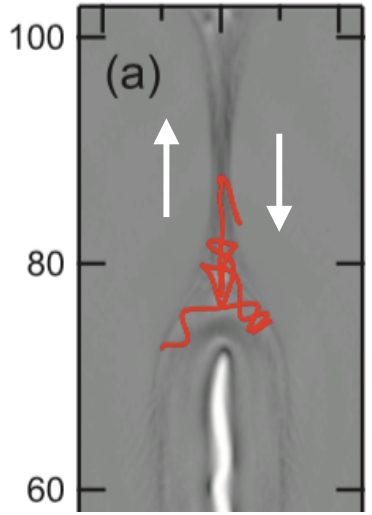
Bessho et al. 2014 *GRL*

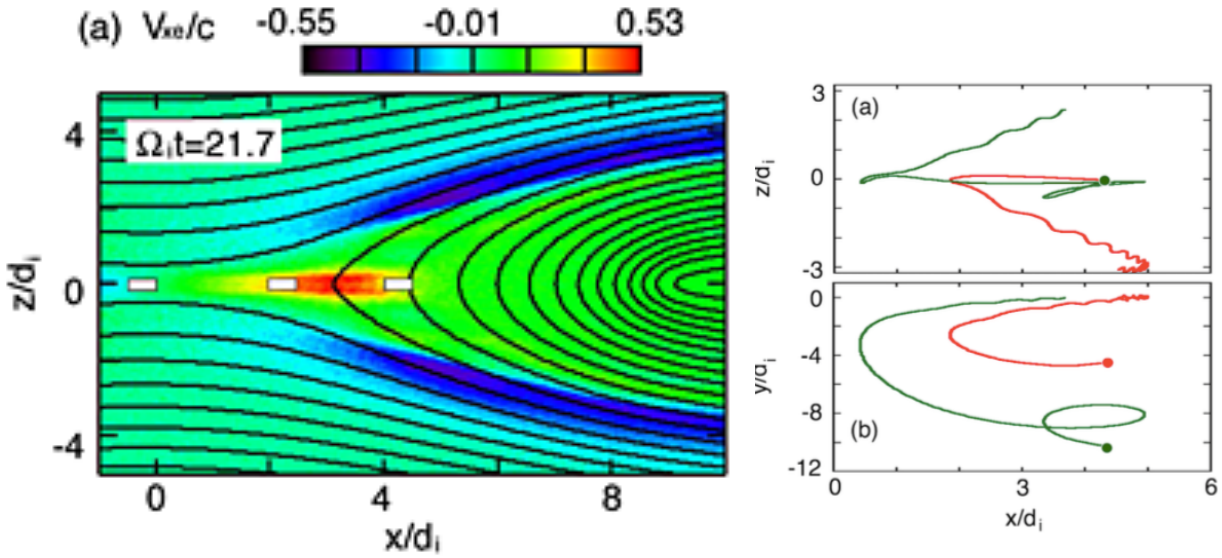


Trajectory analysis in PIC simulations

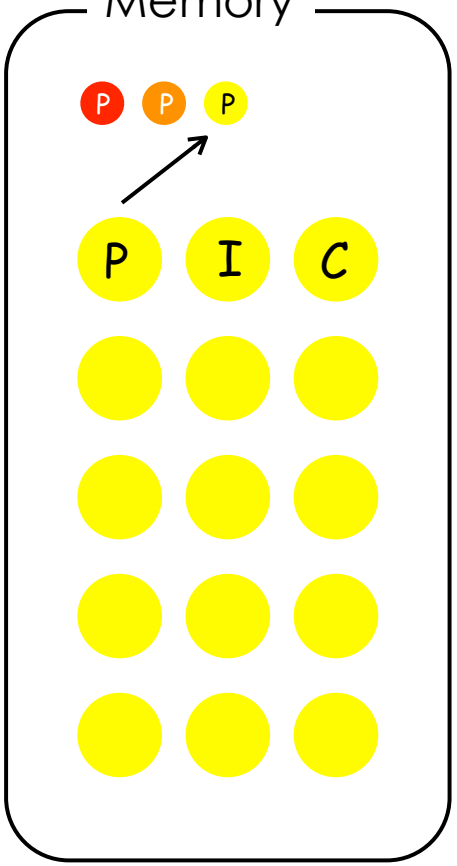


Oka et al. 2010 *ApJ*

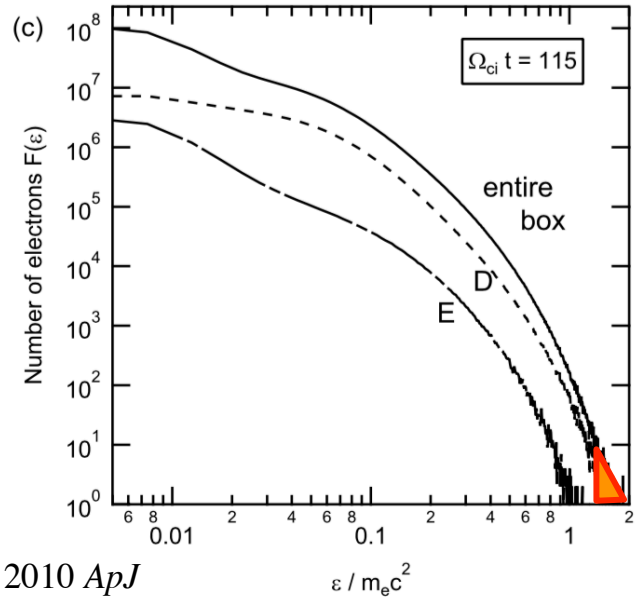




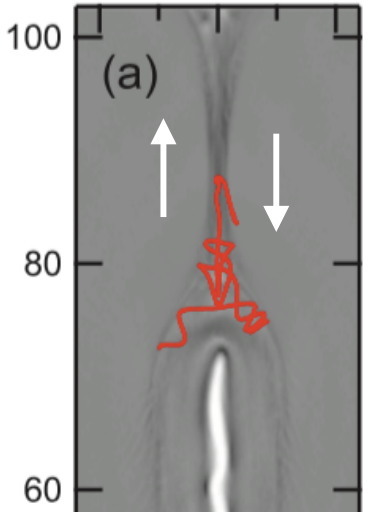
Bessho et al. 2014 *GRL*

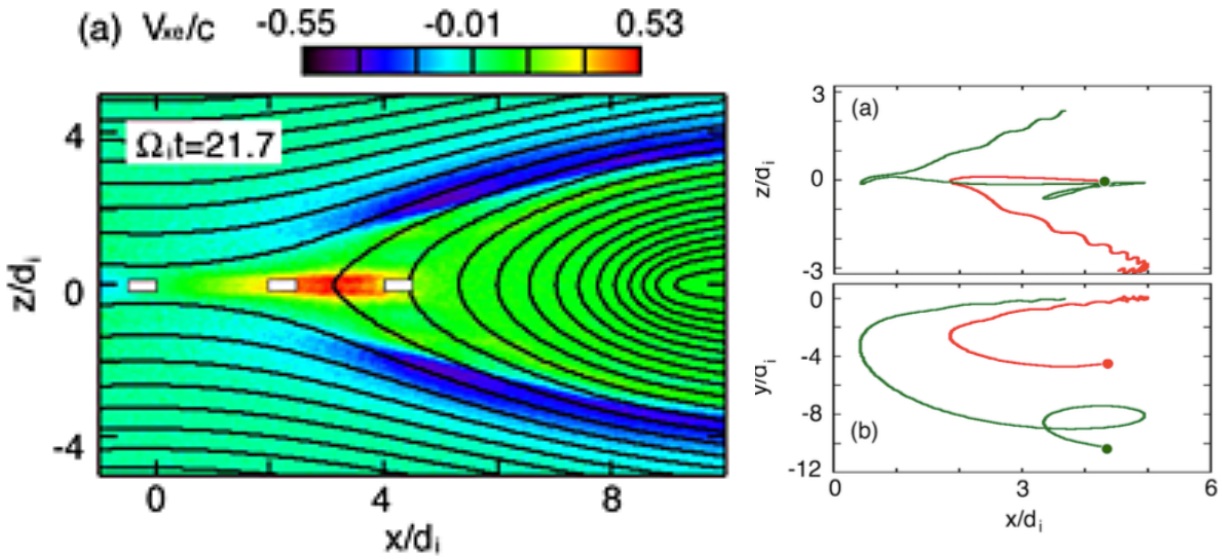


Trajectory analysis in PIC simulations

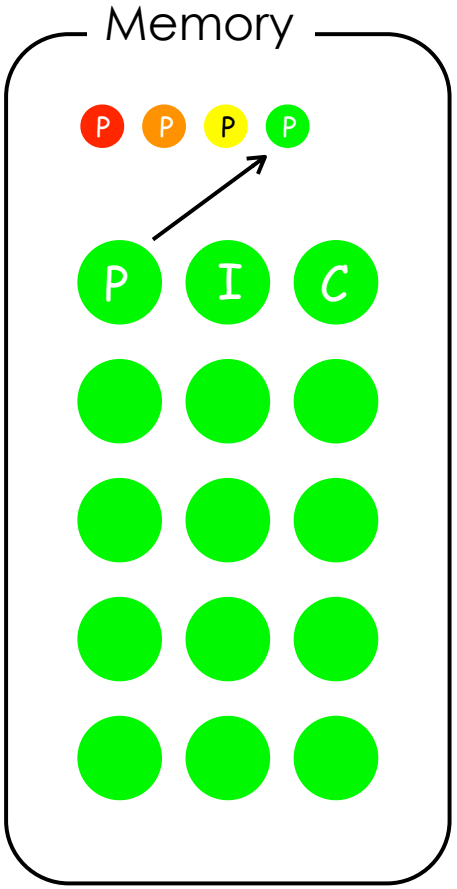


Oka et al. 2010 *ApJ*

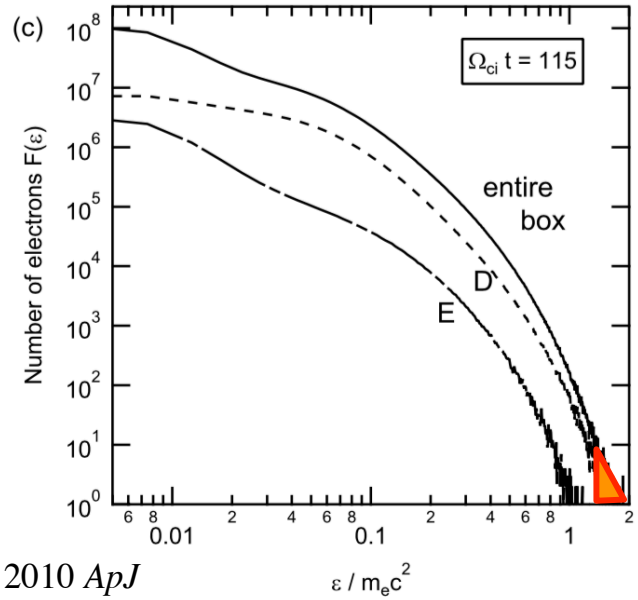




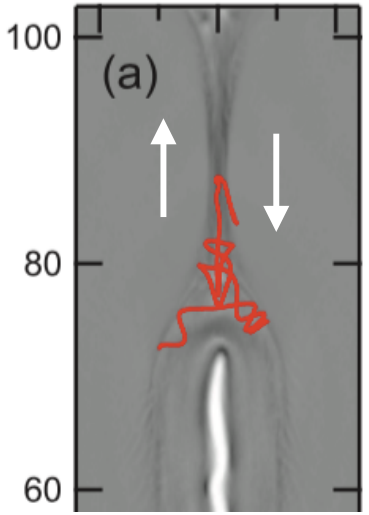
Bessho et al. 2014 *GRL*

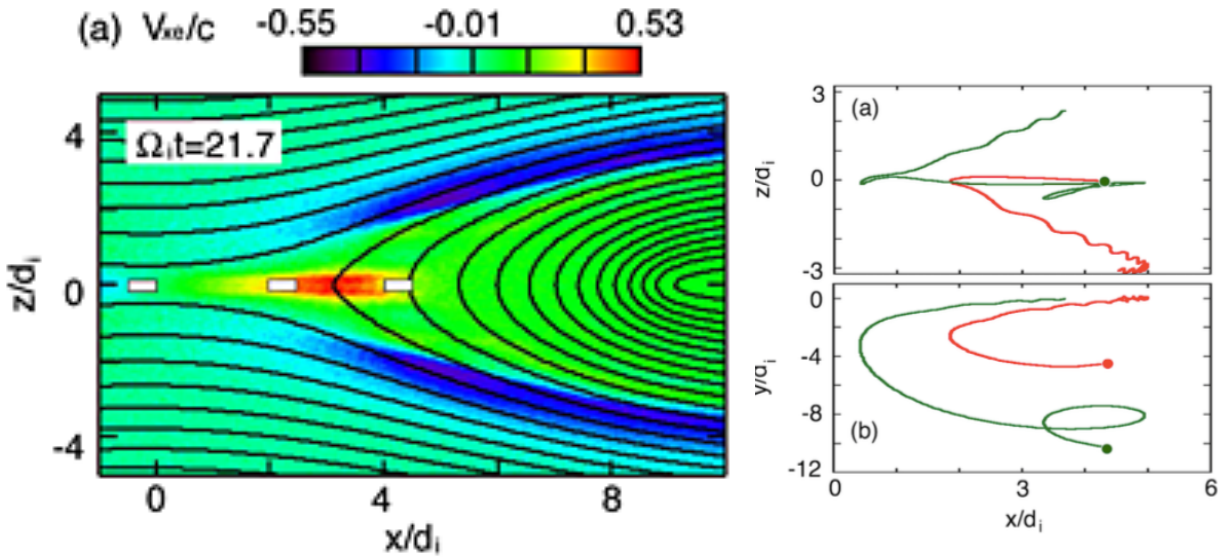


Trajectory analysis in PIC simulations

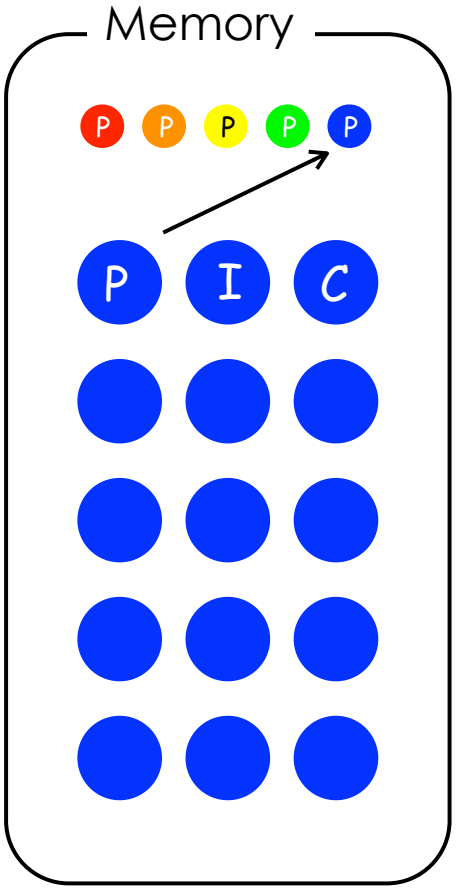


Oka et al. 2010 *ApJ*

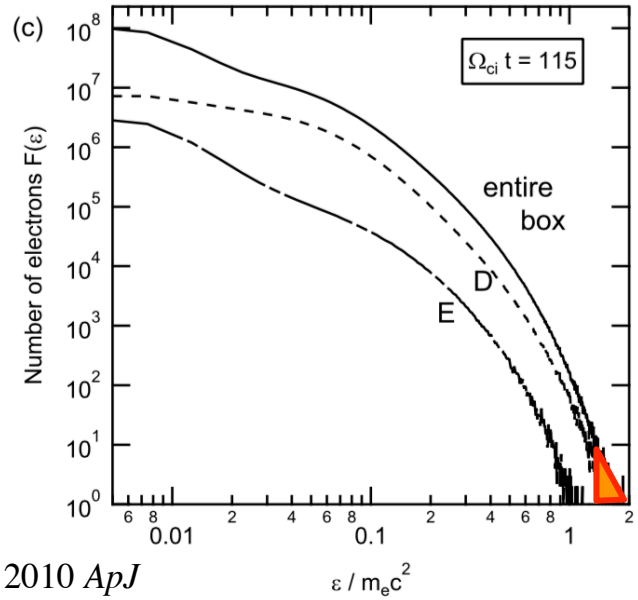




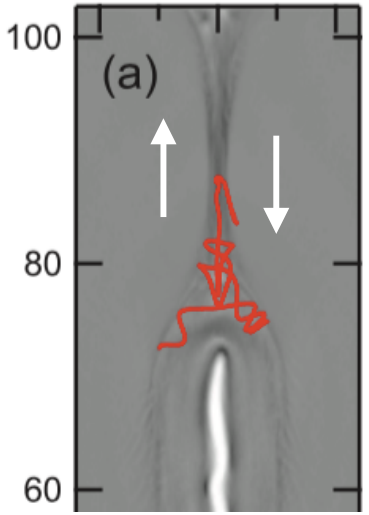
Bessho et al. 2014 *GRL*



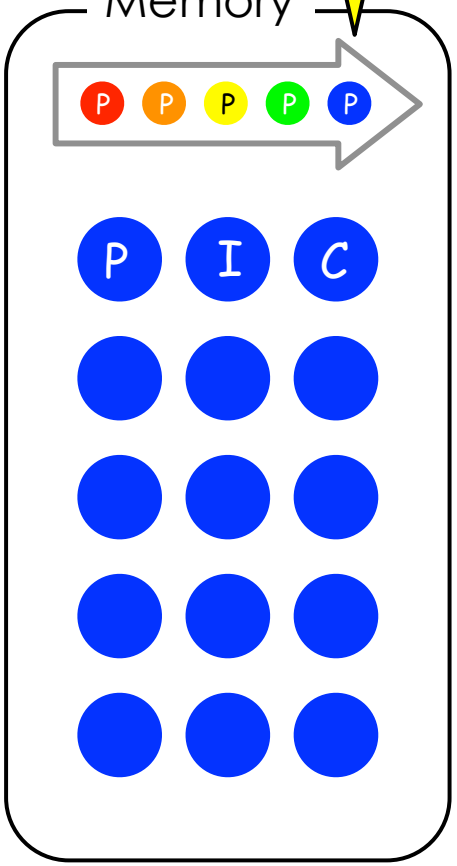
Trajectory analysis in PIC simulations

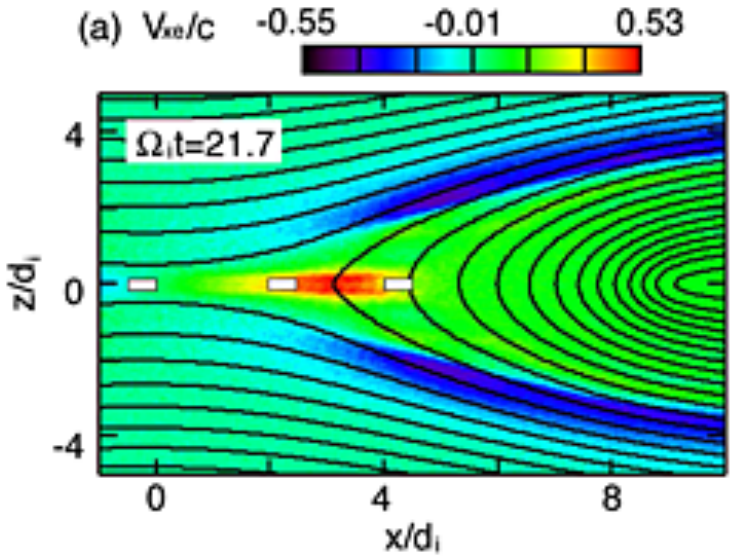


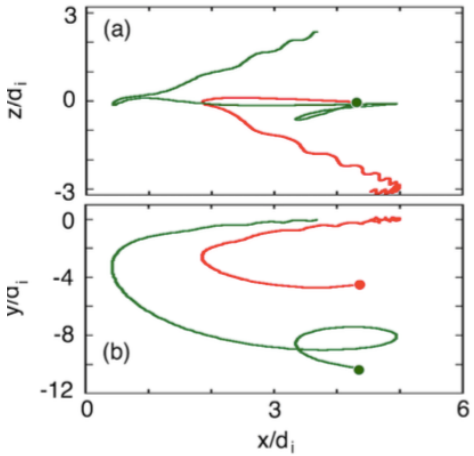
Oka et al. 2010 *ApJ*



The number of self-consistent trajectories is limited

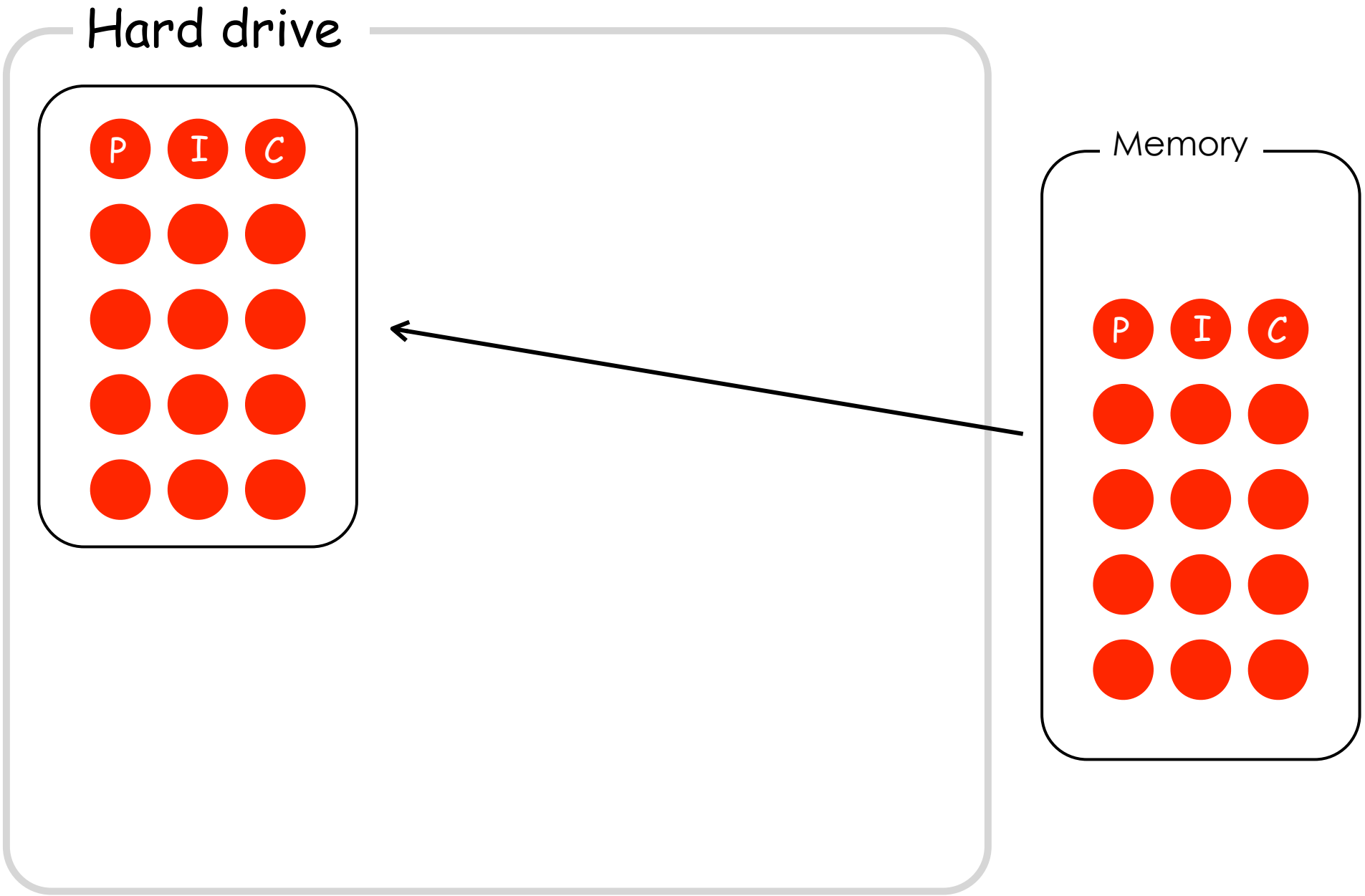




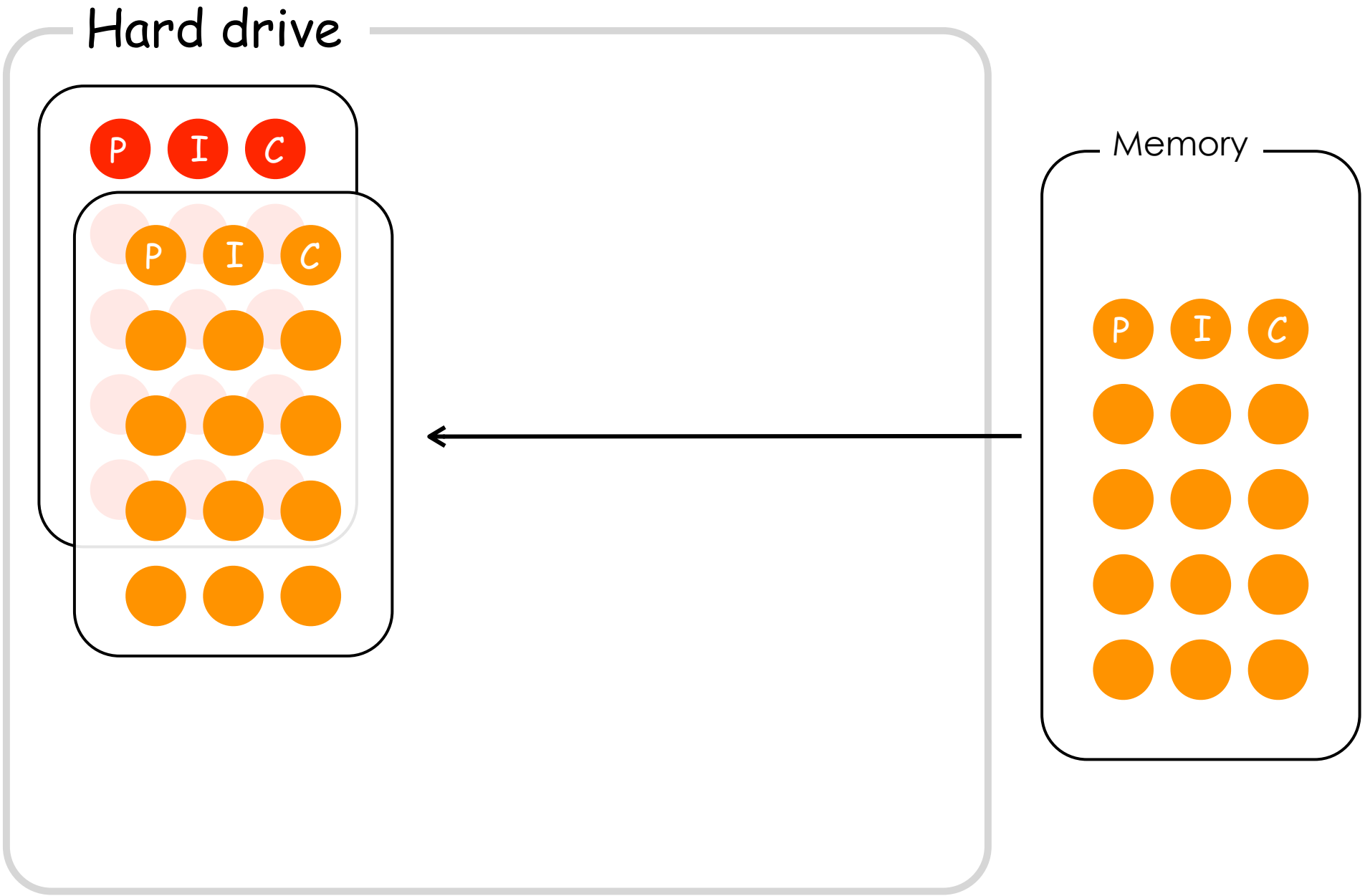


Bessho et al. 2014 *GRL*

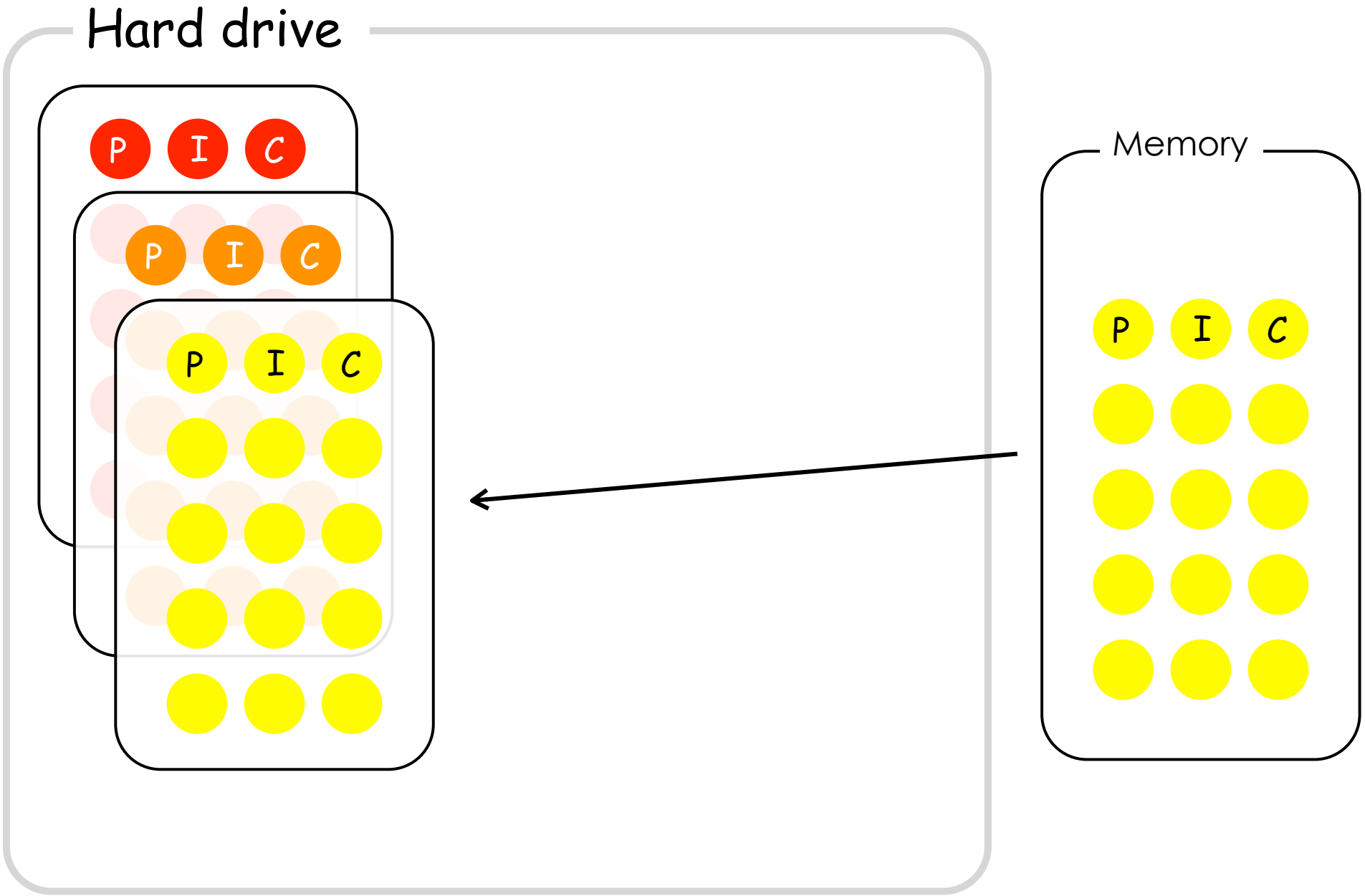
Our simple solution



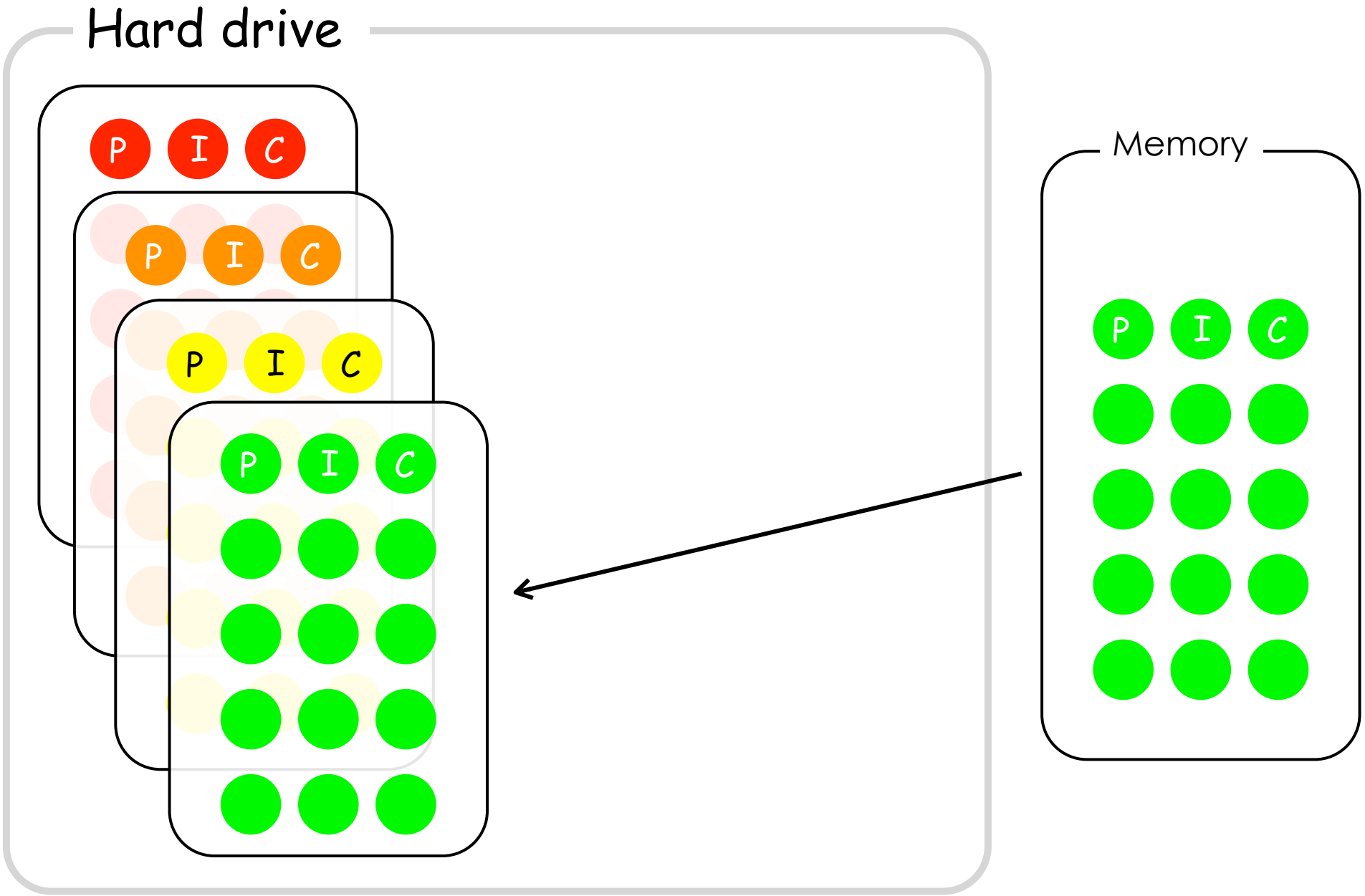
Our simple solution



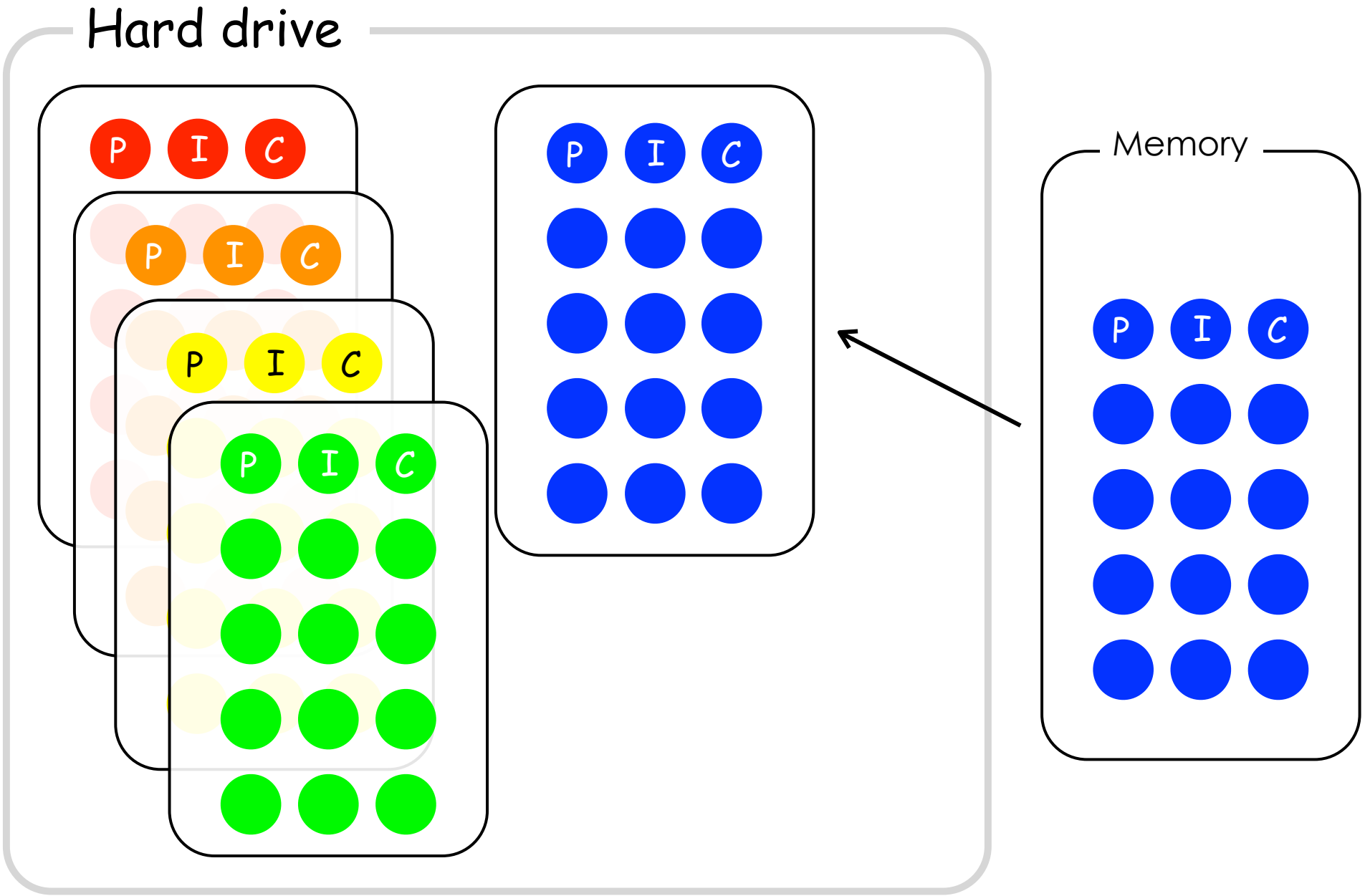
Our simple solution



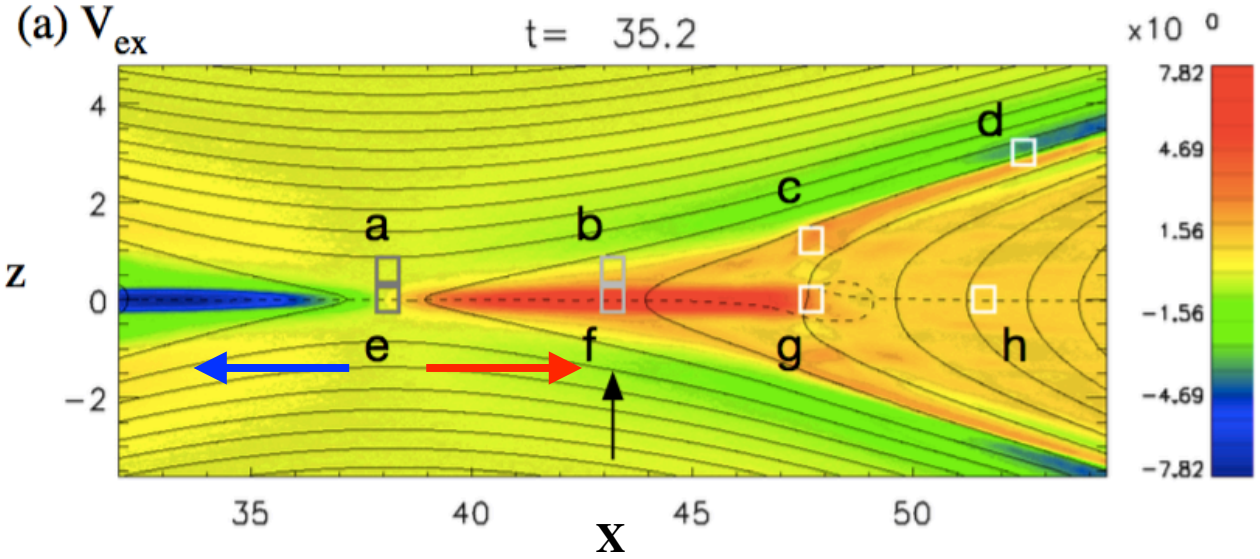
Our simple solution



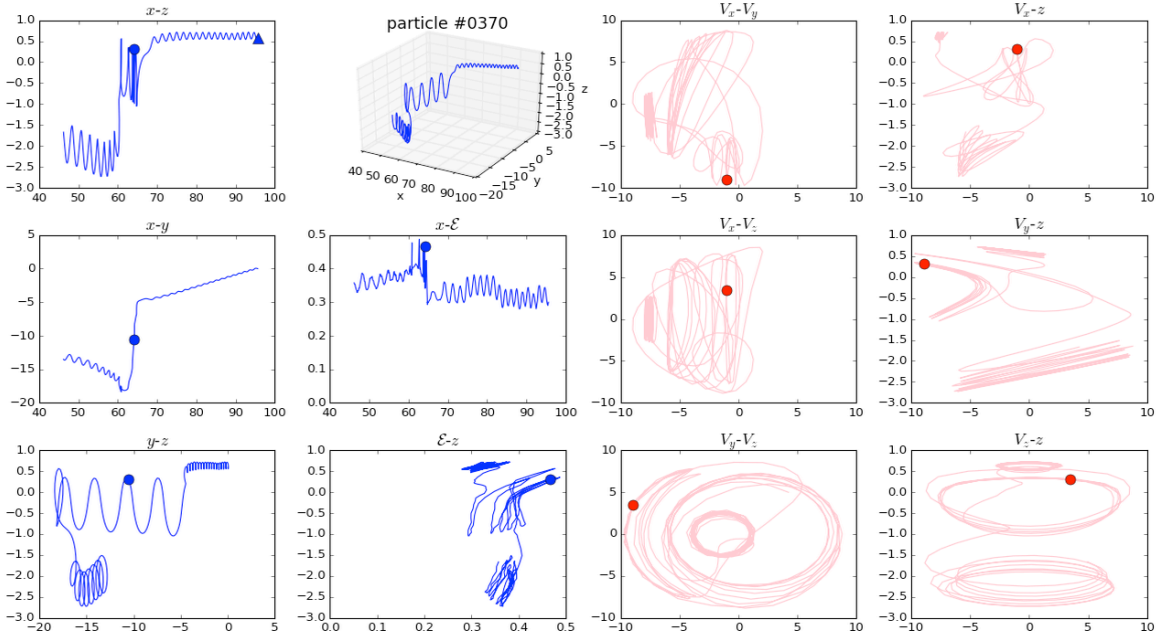
Our simple solution



PIC simulation & full Lagrange analysis



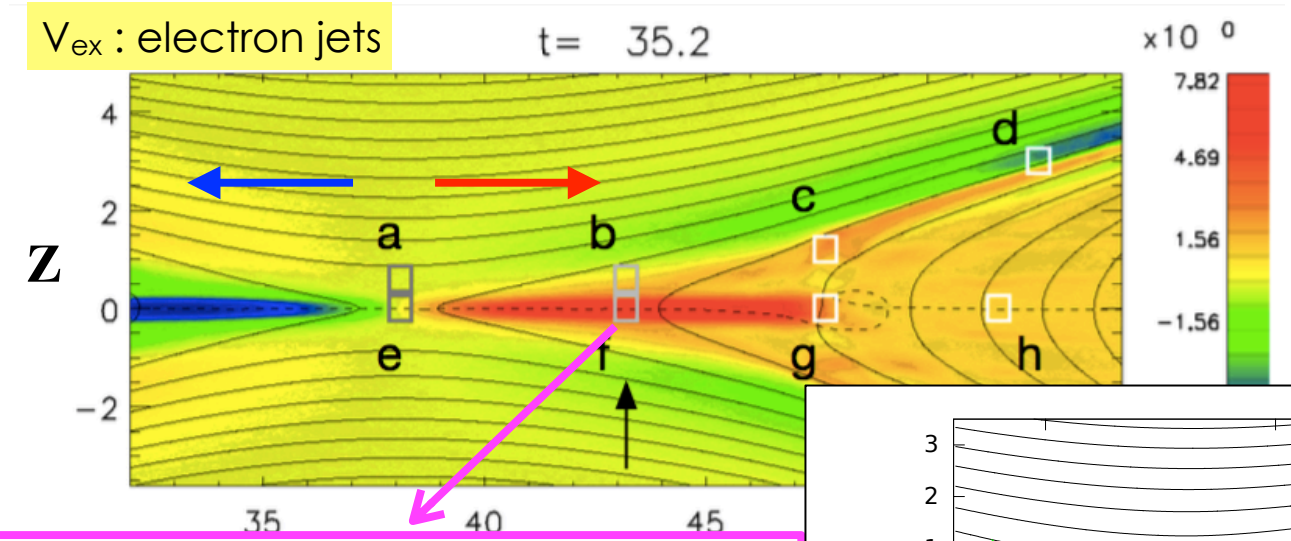
- 2.5D
- m_i/m_e=100
- 76.8 x 38.4 [d_i]
- Harris sheet
- n_{bg}/n_{cs} = 0.2
- 2 x 10^9 particles



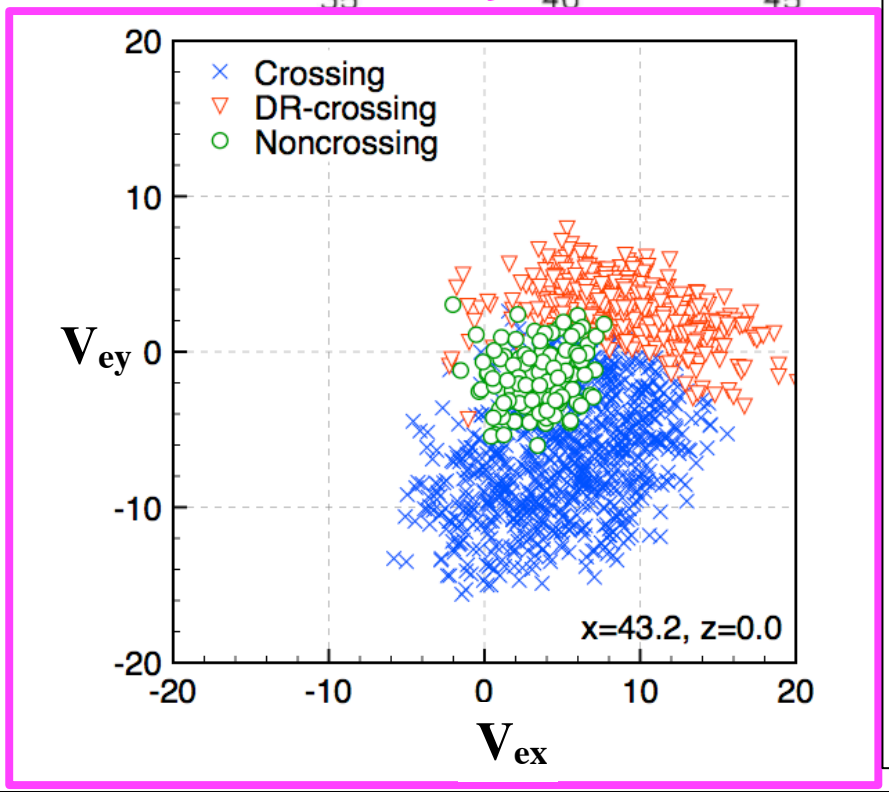
- **20,000,000 electron orbits from 1250 snapshot data**

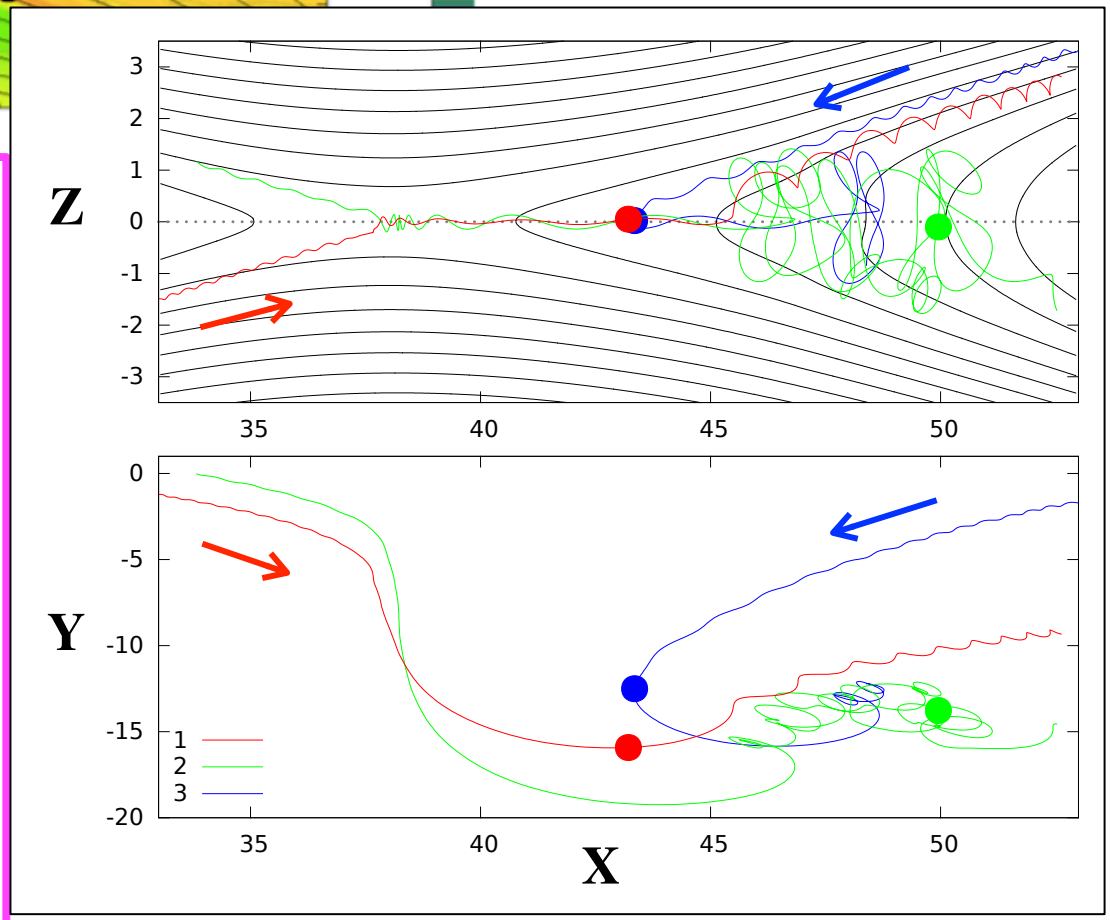
- 3,000 orbits are inspected with DES (dual-eyeball spectrometers; a.k.a. naked eyes)

Electron Speiser VDFs in PIC simulation

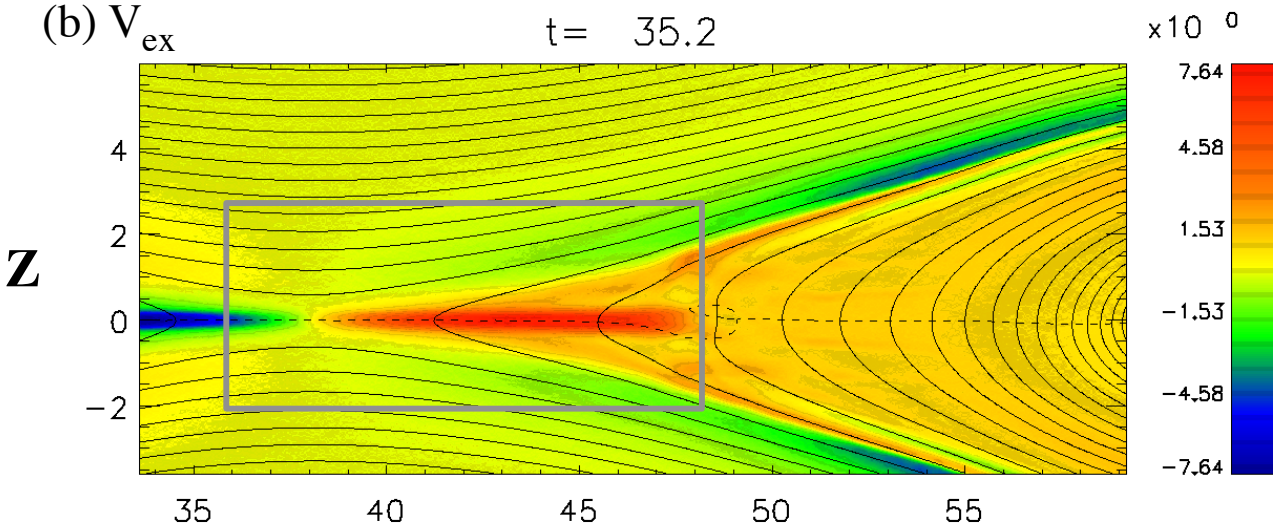


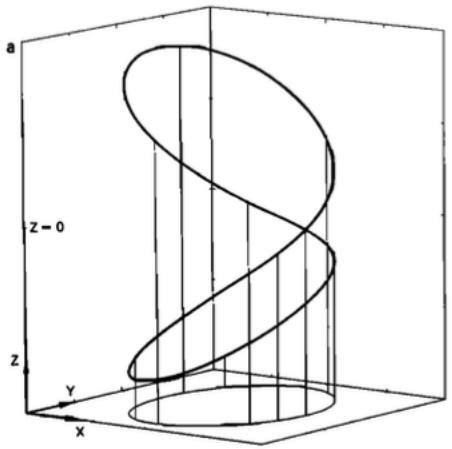
"Global Speiser"
via X-line region
"Local Speiser"
of reflection type



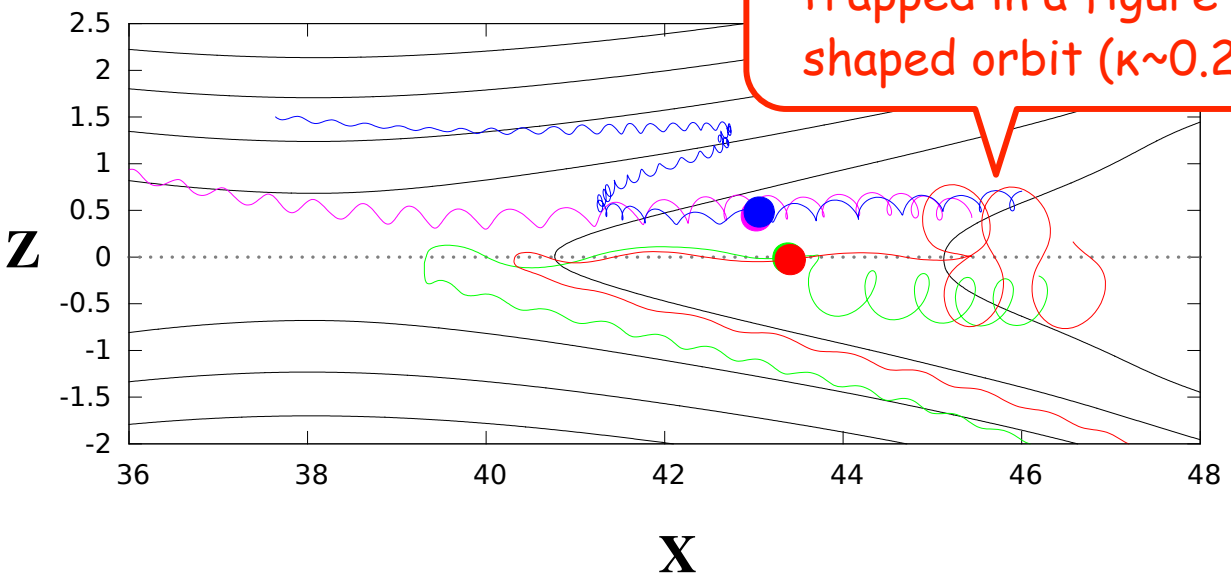


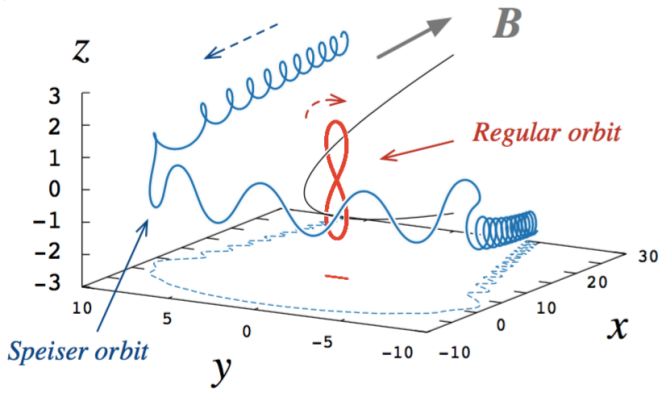
Electron regular orbits





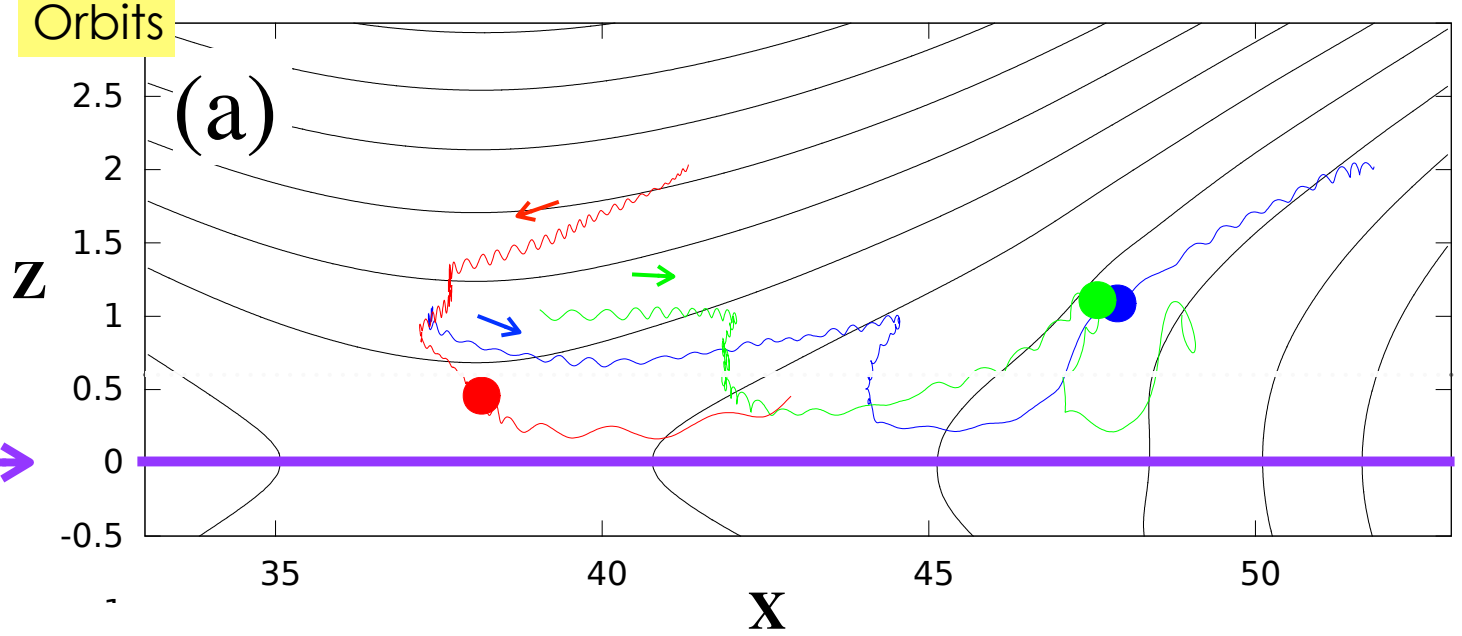
Chen & Palmadesso 1986 *JGR*
Zenitani+ 2013 *PoP*





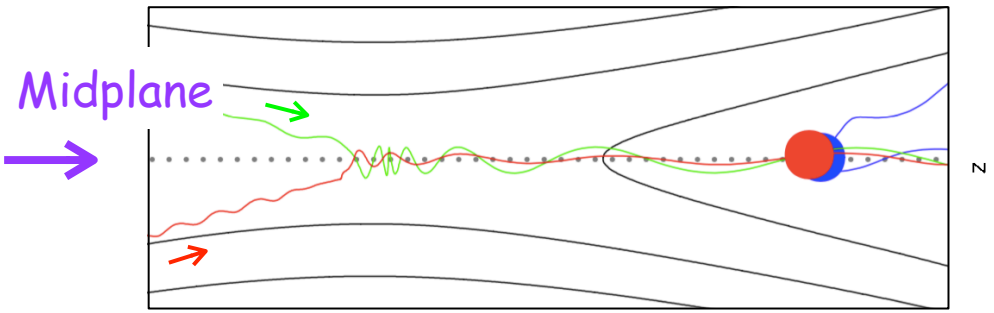
Noncrossing electrons

Orbits

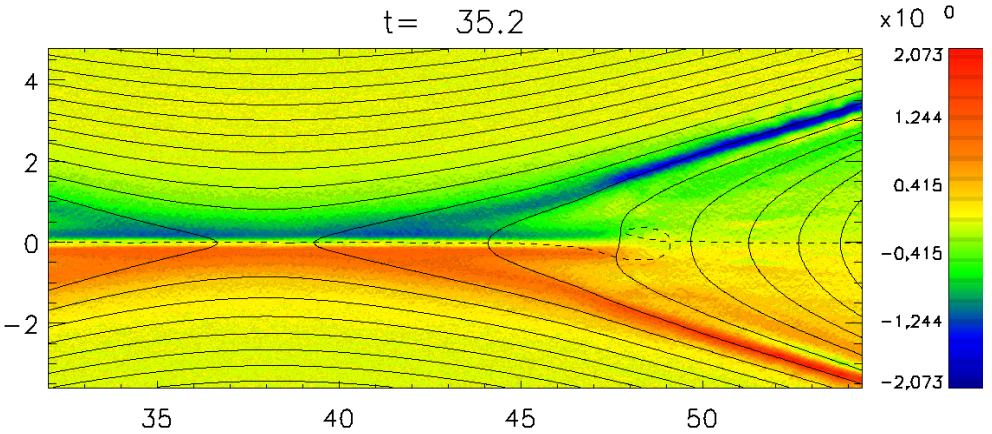


Midplane →

Traditional orbits

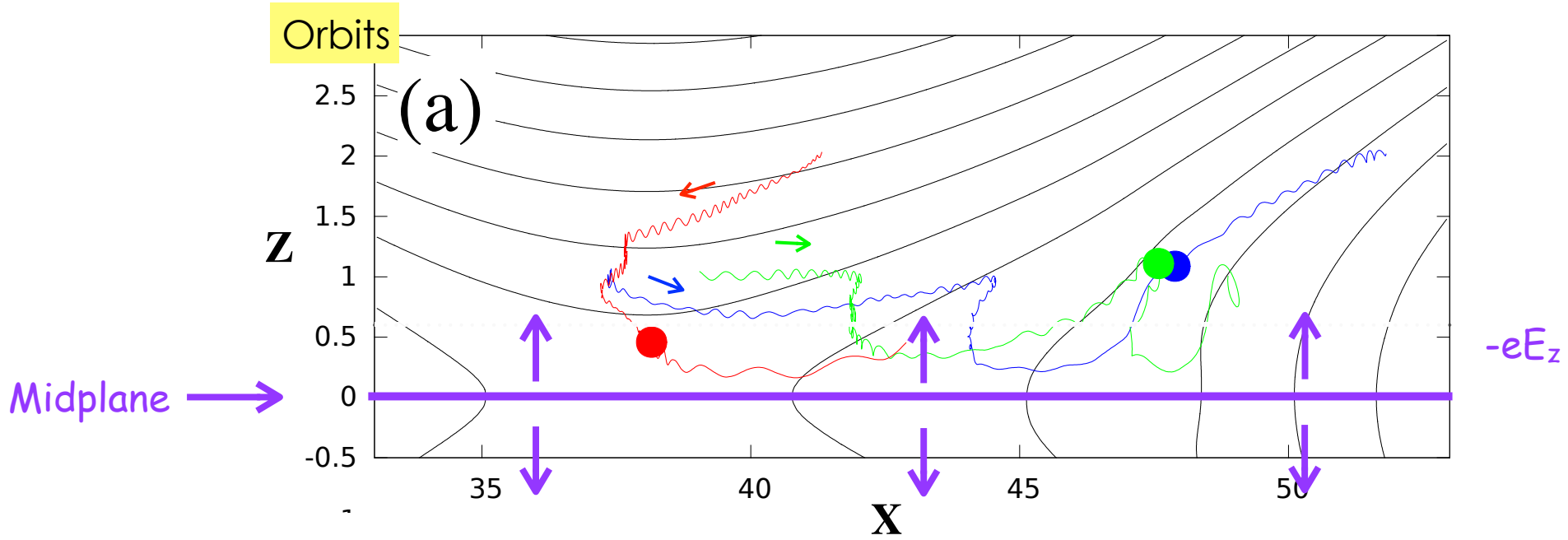


Electrostatic field E_z

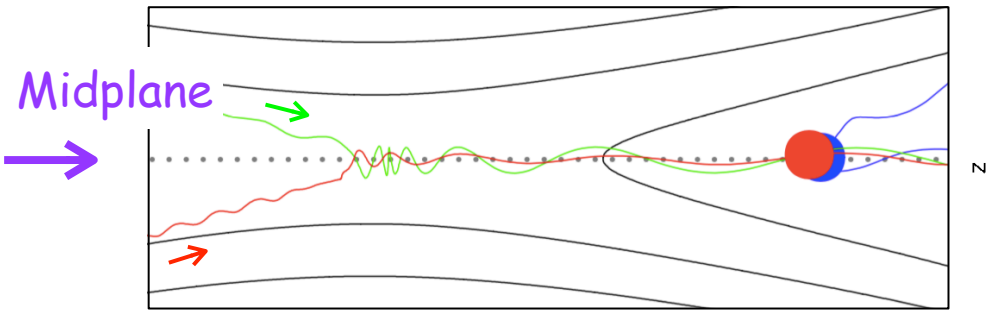


Noncrossing electrons

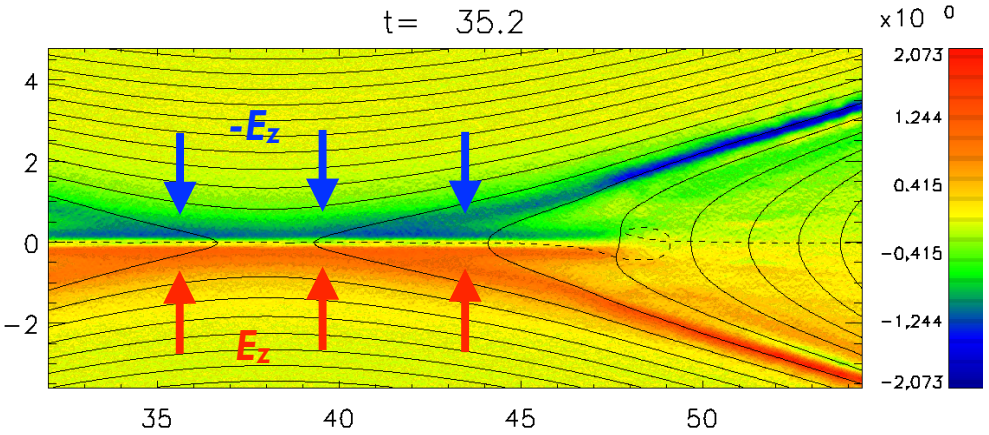
Orbits



Traditional orbits

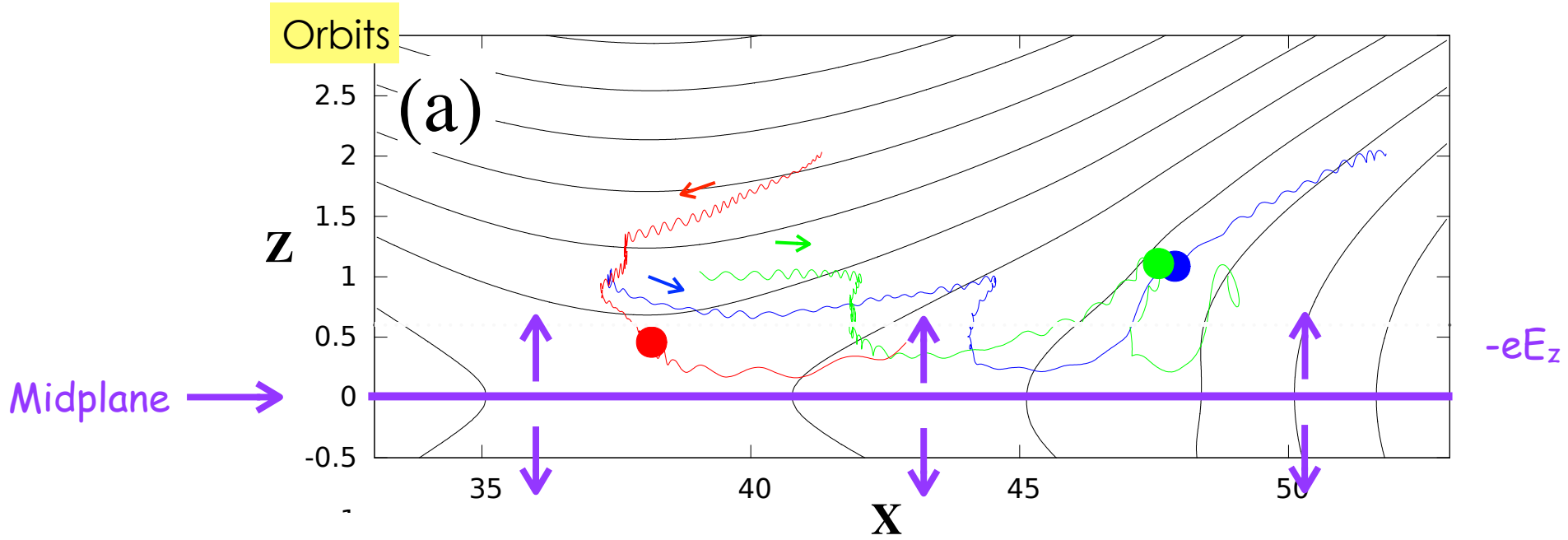


Electrostatic field E_z

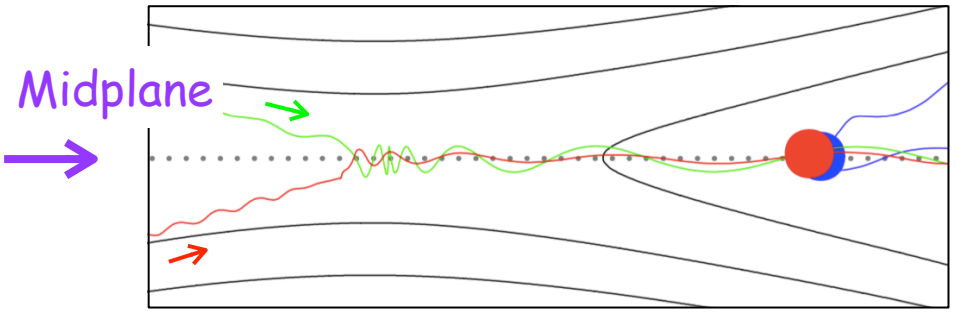


Noncrossing electrons

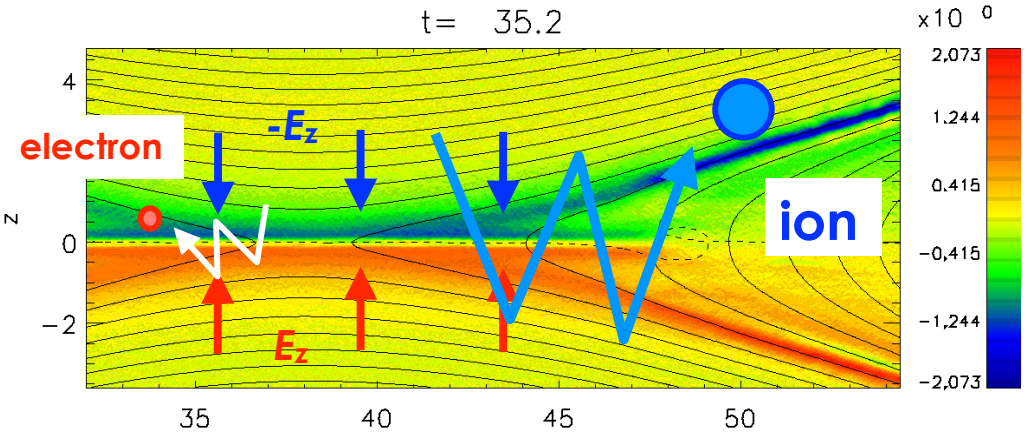
Orbits



Traditional orbits

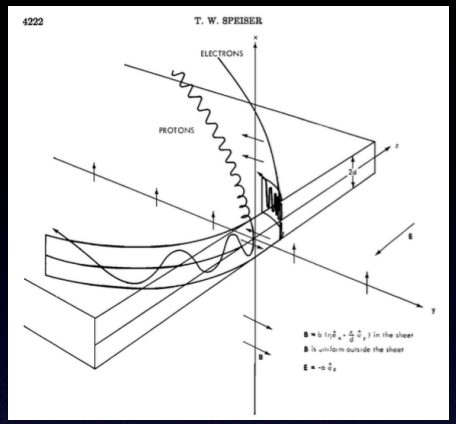


Electrostatic field E_z



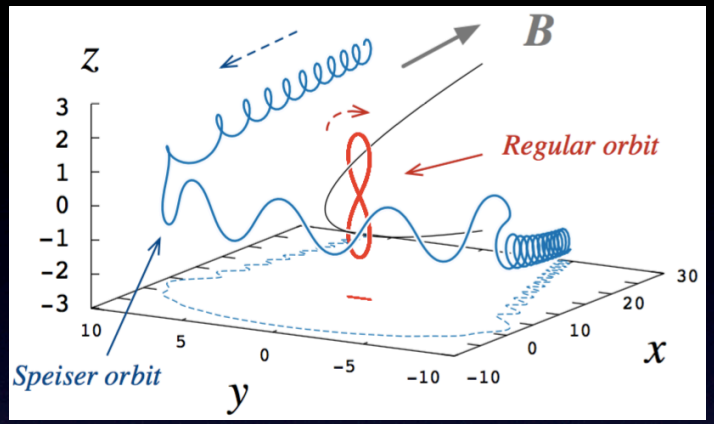
Orbit theories

1965



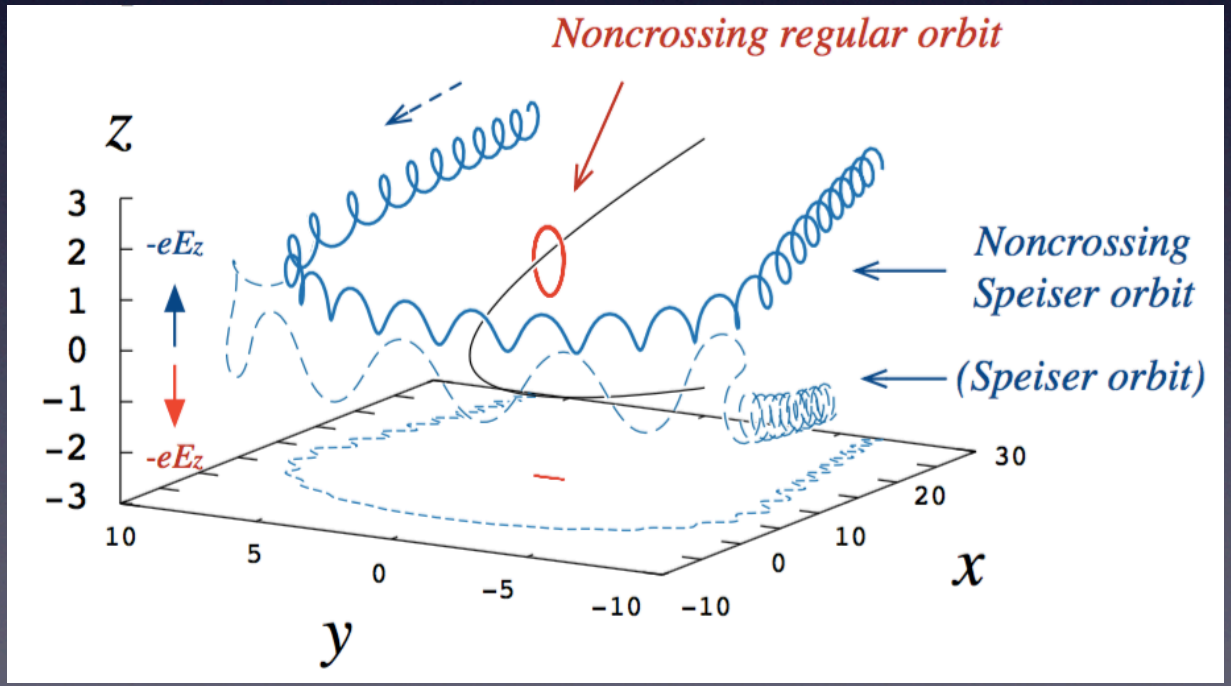
Speiser 1965

1980's



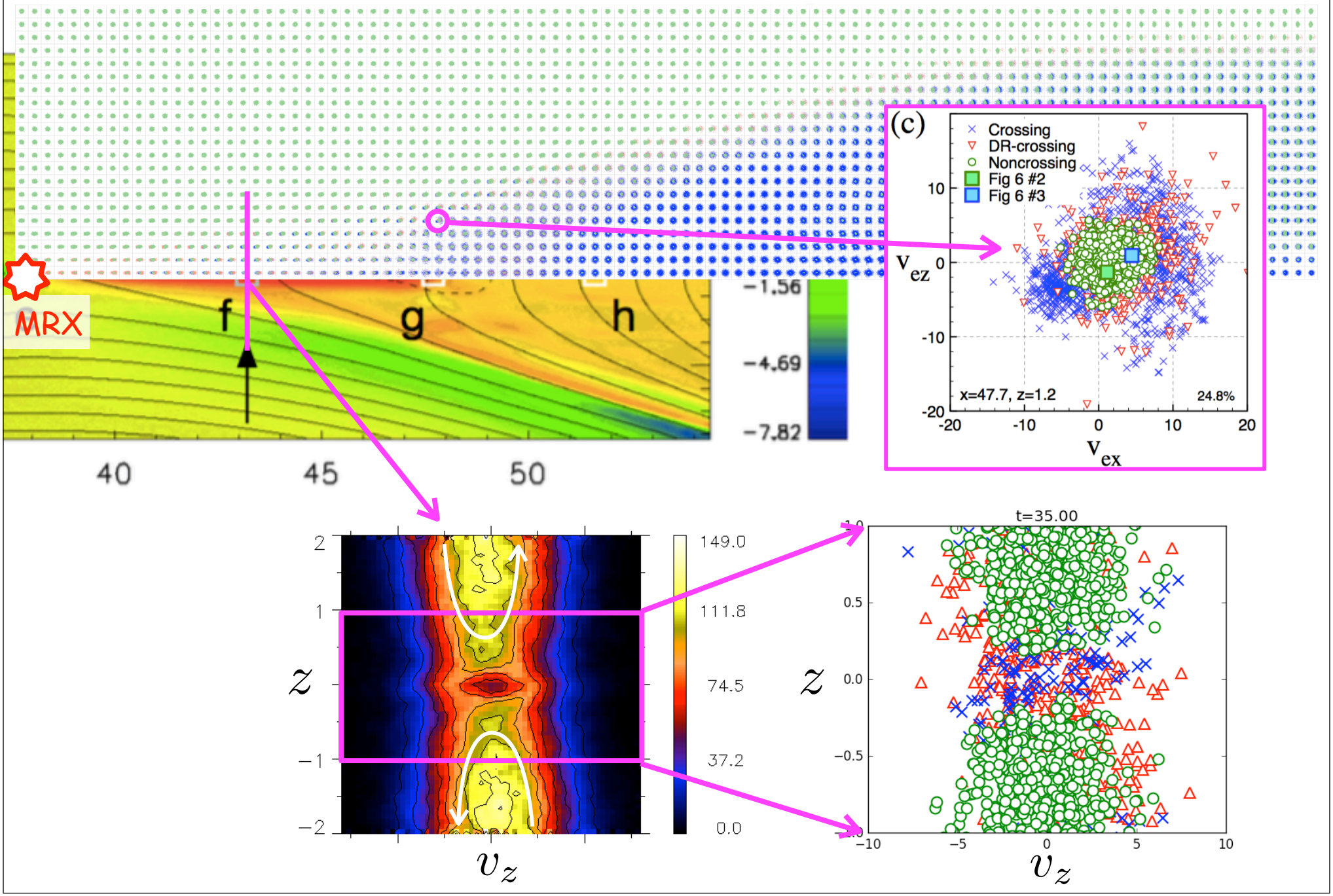
Chen & Palmadesso 1986, Buchner & Zelenyi 1989

2016



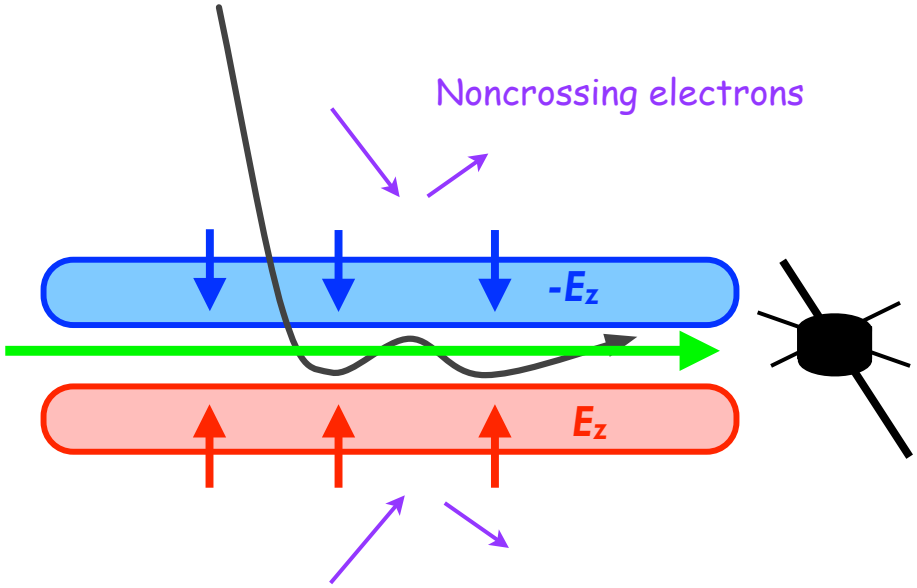
Zenitani & Nagai 2016

Noncrossing electrons: majority in number

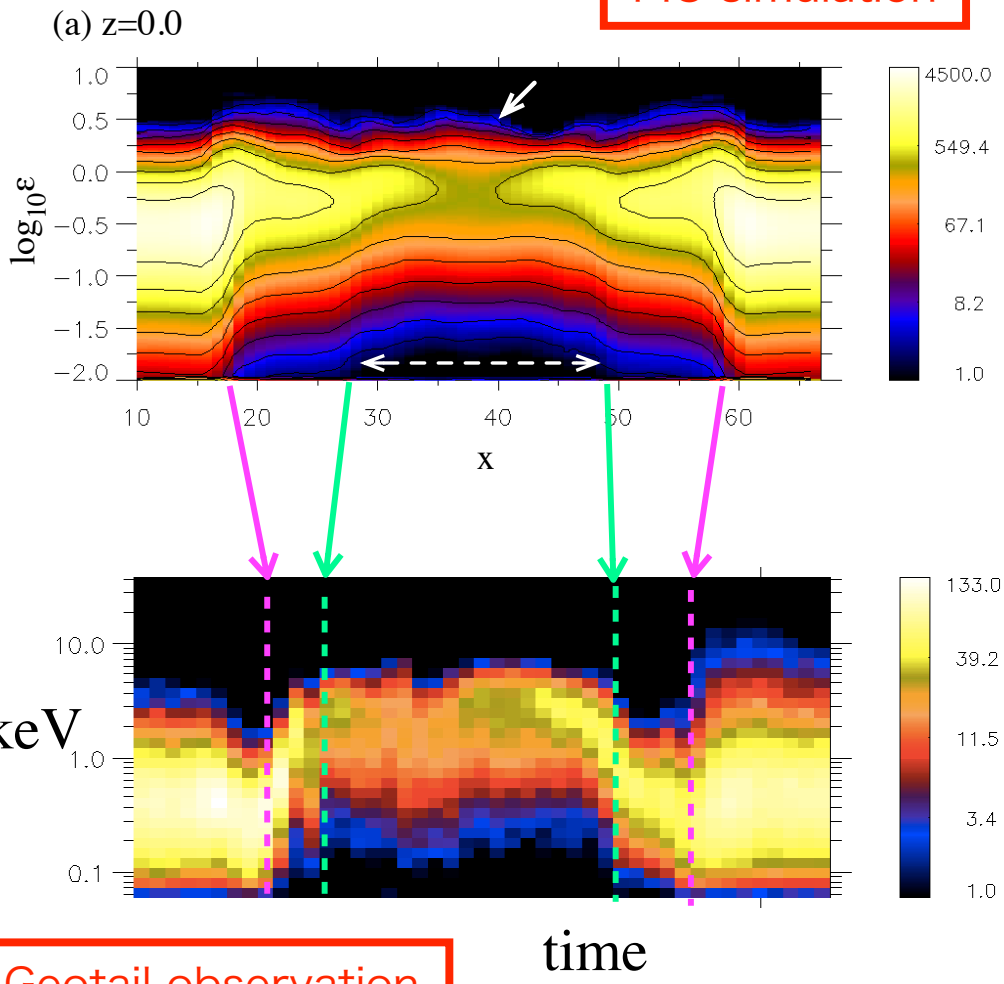


Observational signatures: ET diagram

- Midplane (super-Alfvénic e jet)
  - Speiser-accelerated electrons
  - Low-energy noncrossing electrons are absent



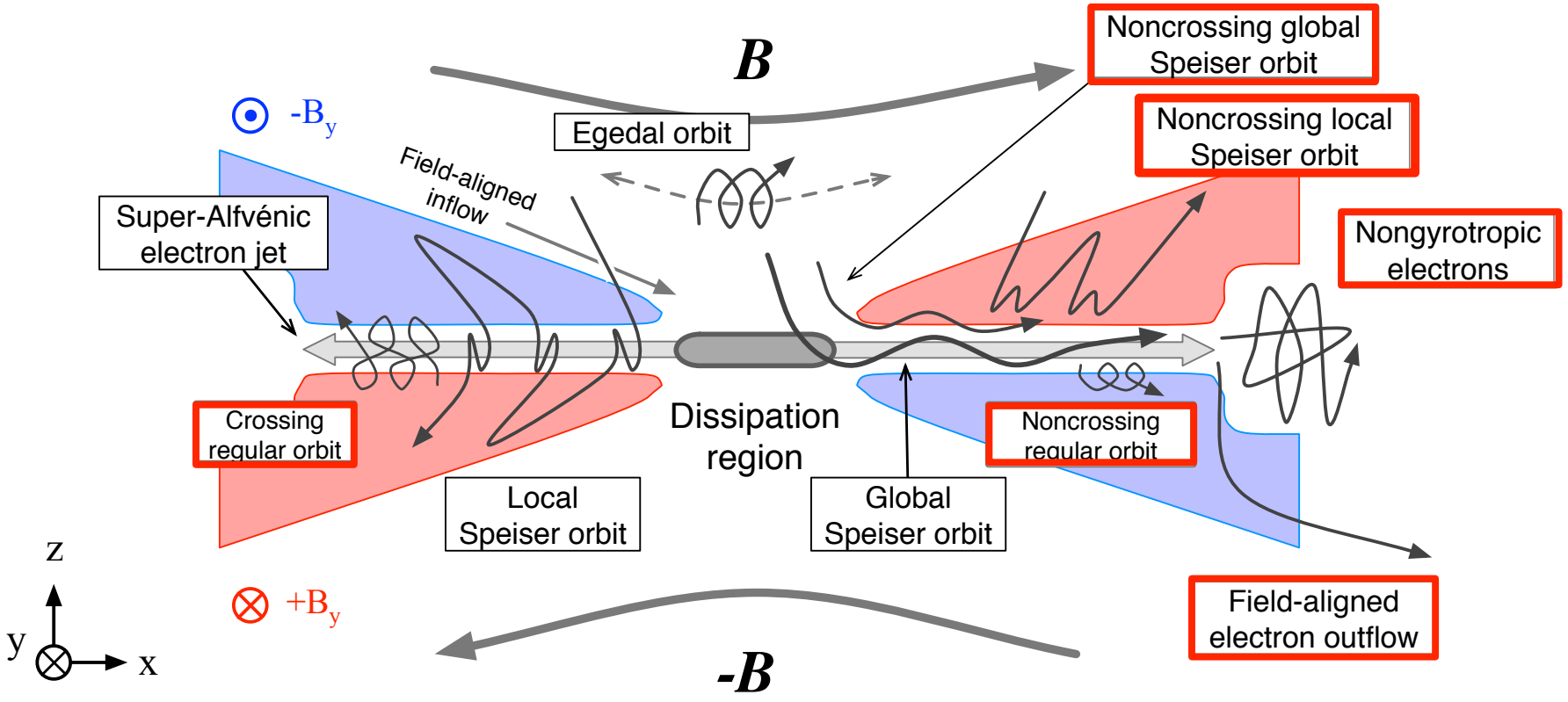
PIC simulation



Geotail observation

2007-05-05 (Nagai+ 2013 *JGR*)

State-of-art picture of electron orbits



Zenitani & Nagai 2016 *PoP*

- Many new orbits are found
- Noncrossing electrons are **MAJORITY** in number density
- This will lead to the revision of theoretical models

2. Asymmetric reconnection

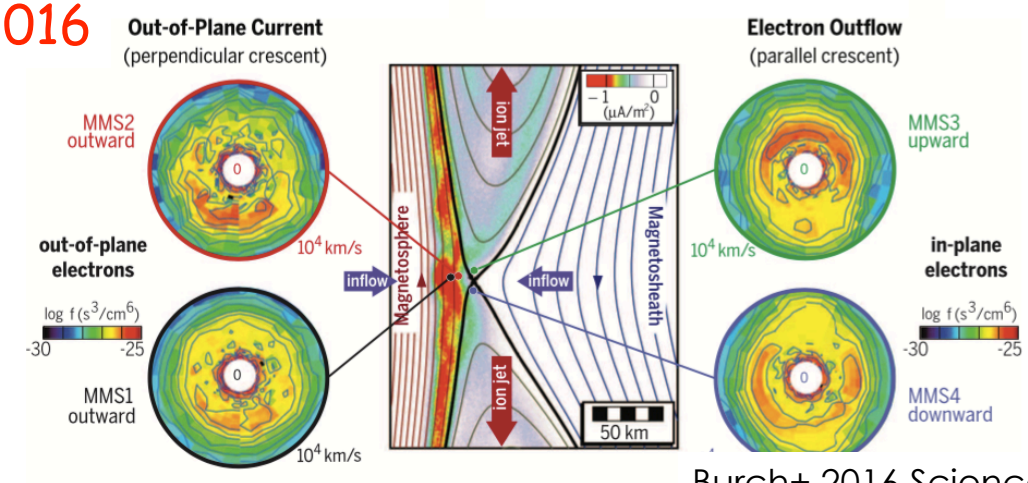
Asymmetric reconnection at the magnetopause

magnetopause

2017 MMS observation in magnetotail

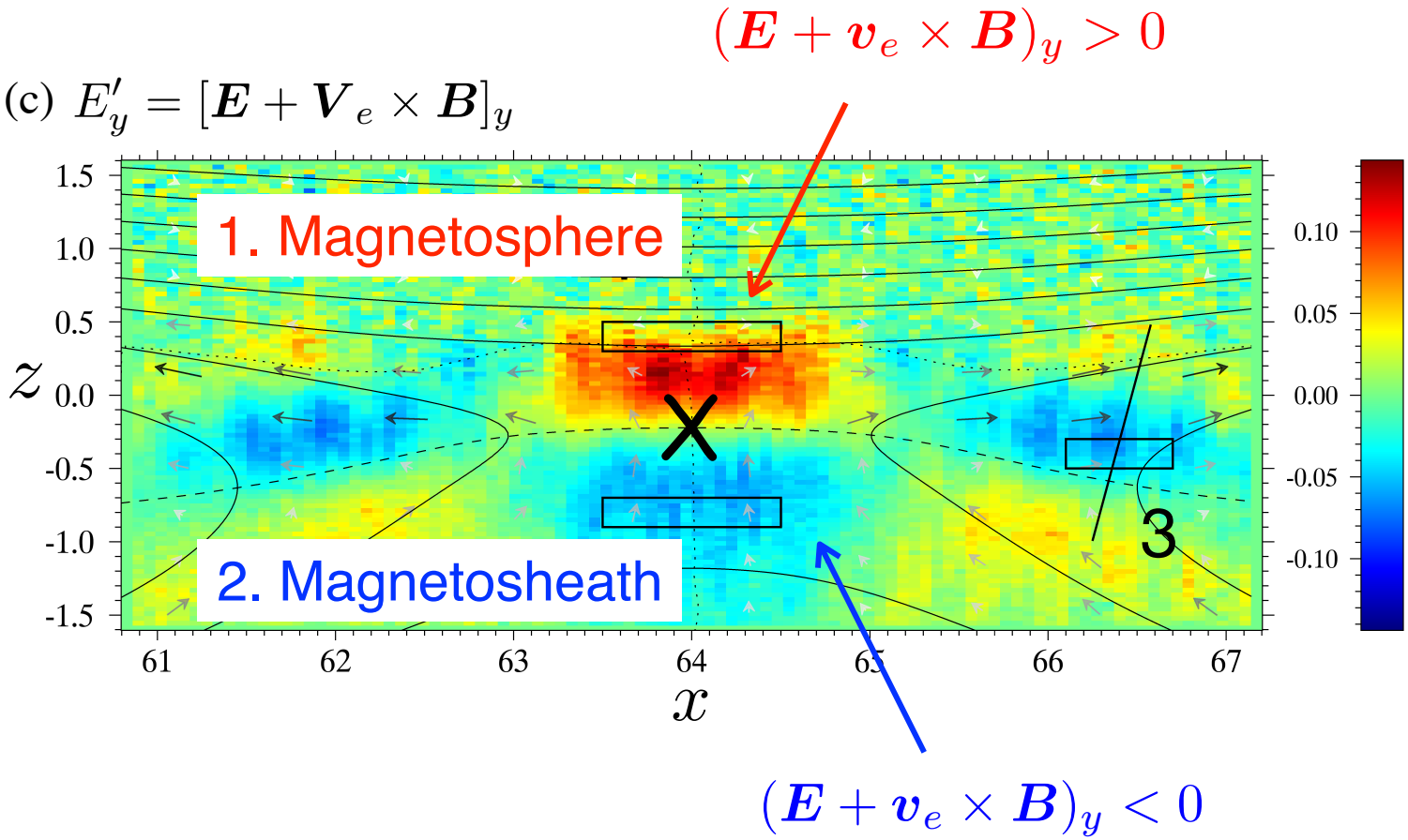
>>> It is important to understand electron physics with particle-in-cell (PIC) simulations.

2016



Burch+ 2016 Science

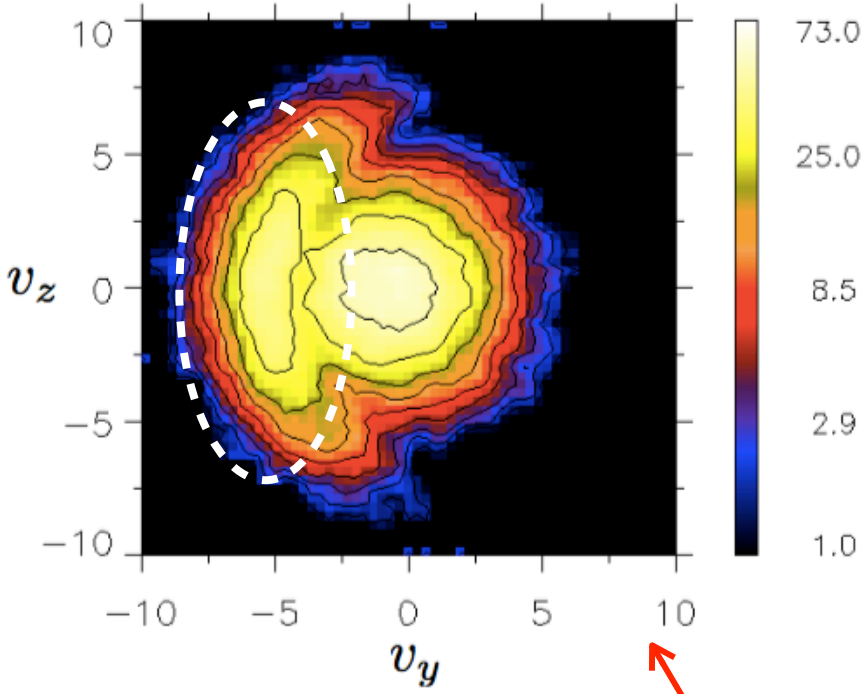
Electron-physics signatures near the X line



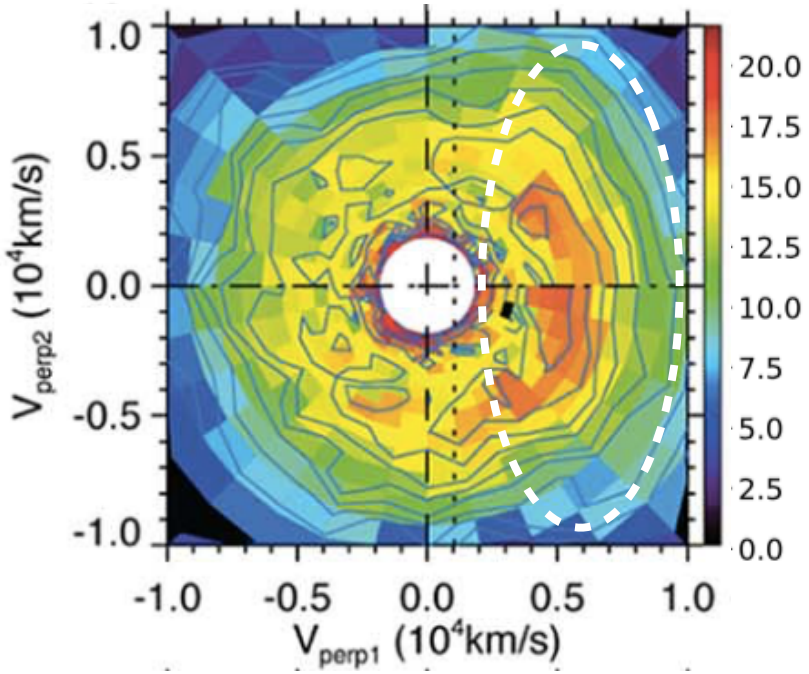
Same as in Pritchett 2008, Hesse+ 2013 PoP, 2014 GRL

Sphere-side: Crescent-shaped VDF

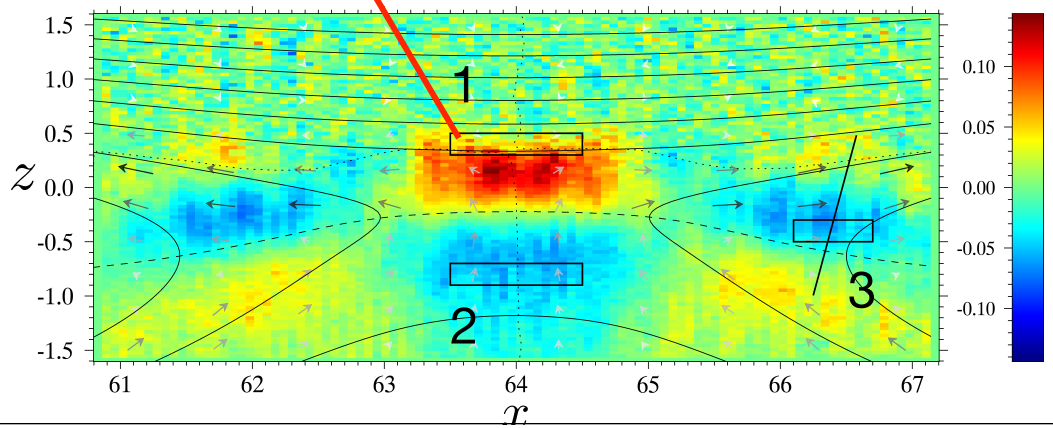
Electron velocity distribution function



MMS observation (Burch+ 2016 Science)



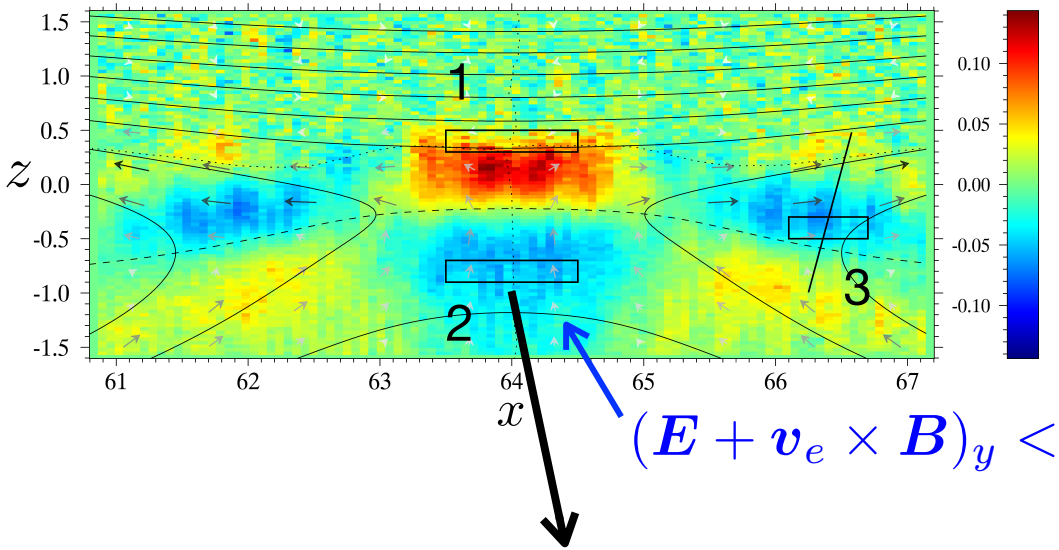
(c) E'_y



See also
Hesse+ 2014 *GRL*
Bessho+ 2016 *GRL*
Shay+ 2016 *GRL*

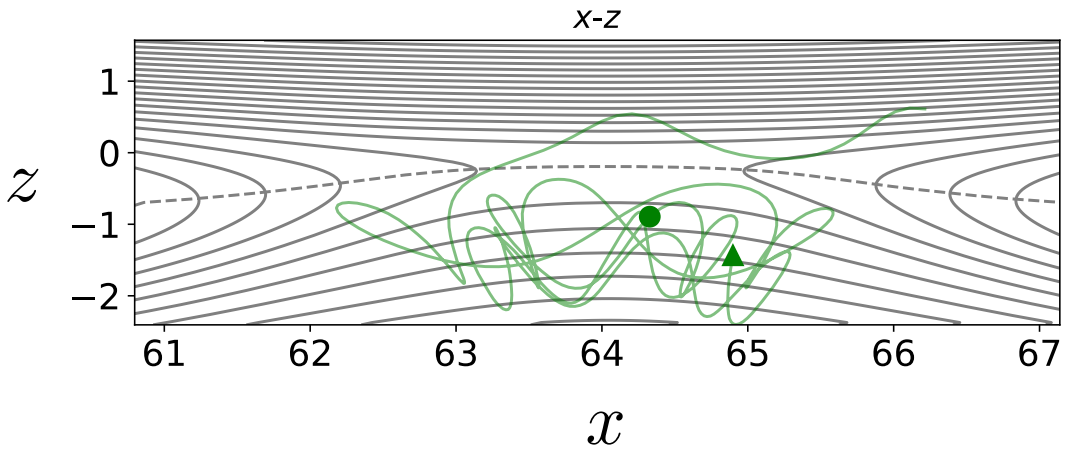
Sheath-side: Nonadiabatic electrons

(c) $E'_y = [\boldsymbol{E} + \boldsymbol{V}_e \times \boldsymbol{B}]_y$



$(\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})_y < 0$

Typical orbit through Region 2

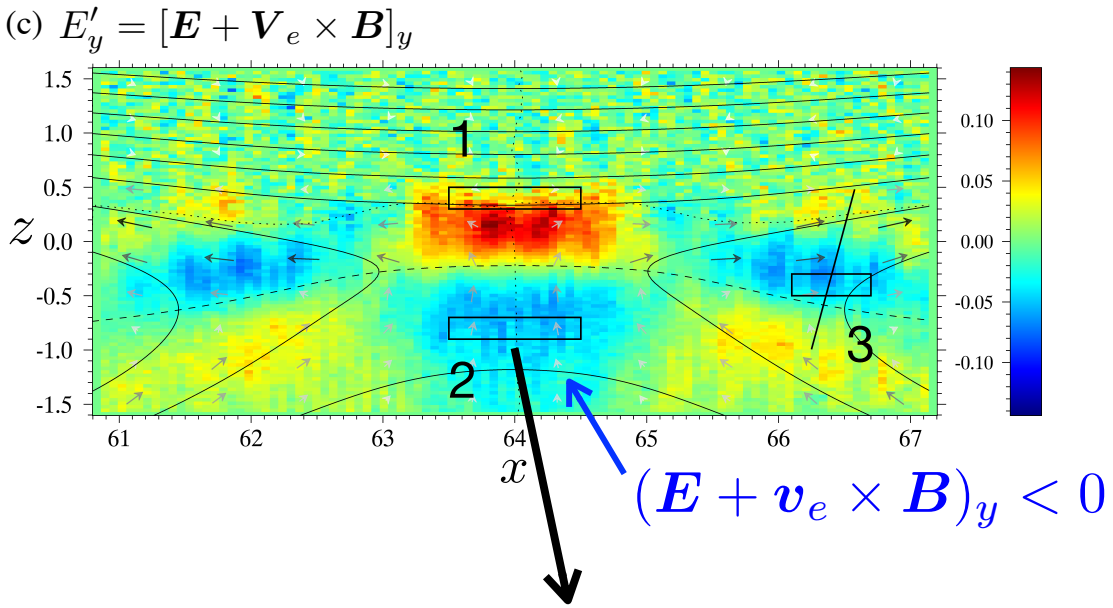


- Chaotic orbit
- No longer a gyration + ExB drift

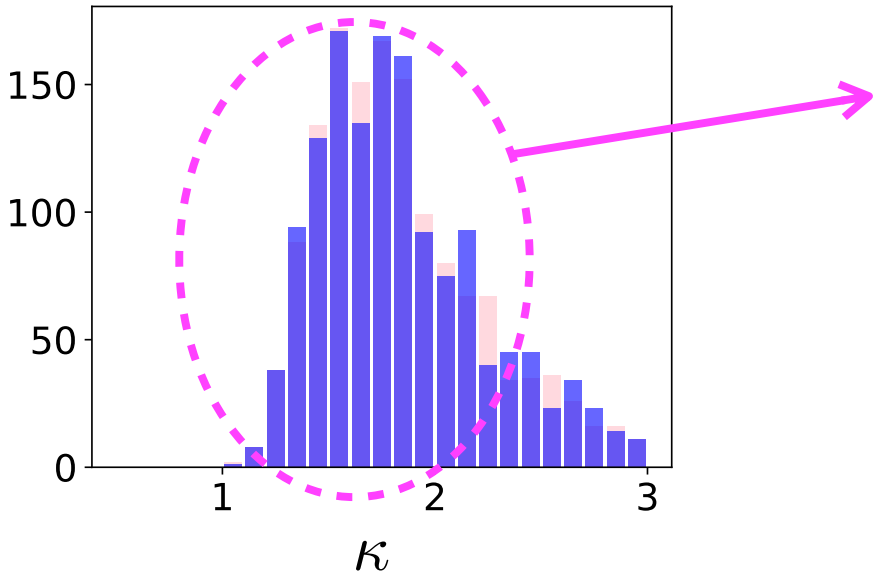
$$\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B} \neq 0$$

Zenitani+ 2017 *JGR*

Sheath-side: Nonadiabatic electrons



Curvature parameters in Region 2



- Curvature parameter
  (Buchner & Zelenyi 1989 *JGR*)

$$\kappa \equiv \sqrt{\frac{R_c}{\rho}}$$

Magnetic curvature radius

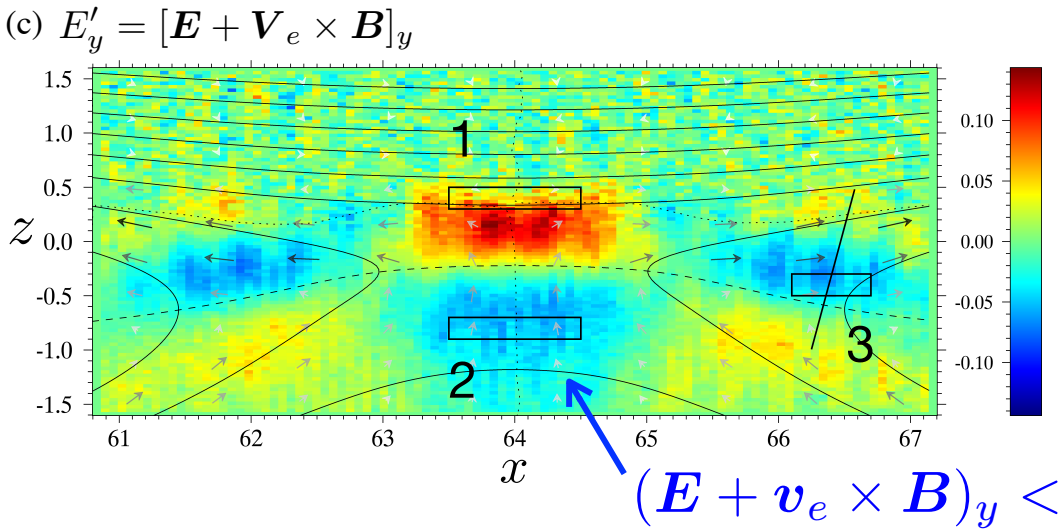
Electron Larmor radius

Weakly nonadiabatic (1<k<2.5)

- $\varrho \sim R_C$
- Chaotic motion
- No longer a gyration + ExB drift

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

Sheath-side: Nonadiabatic electrons

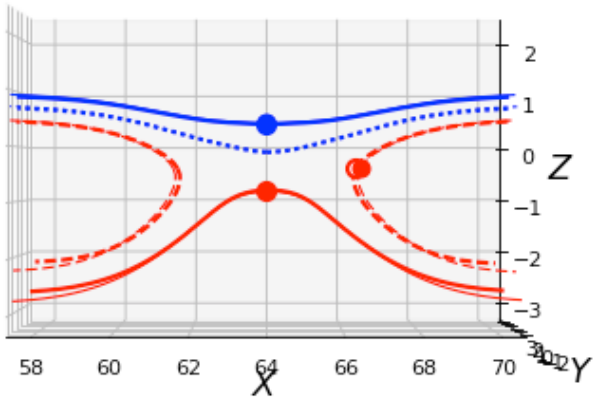


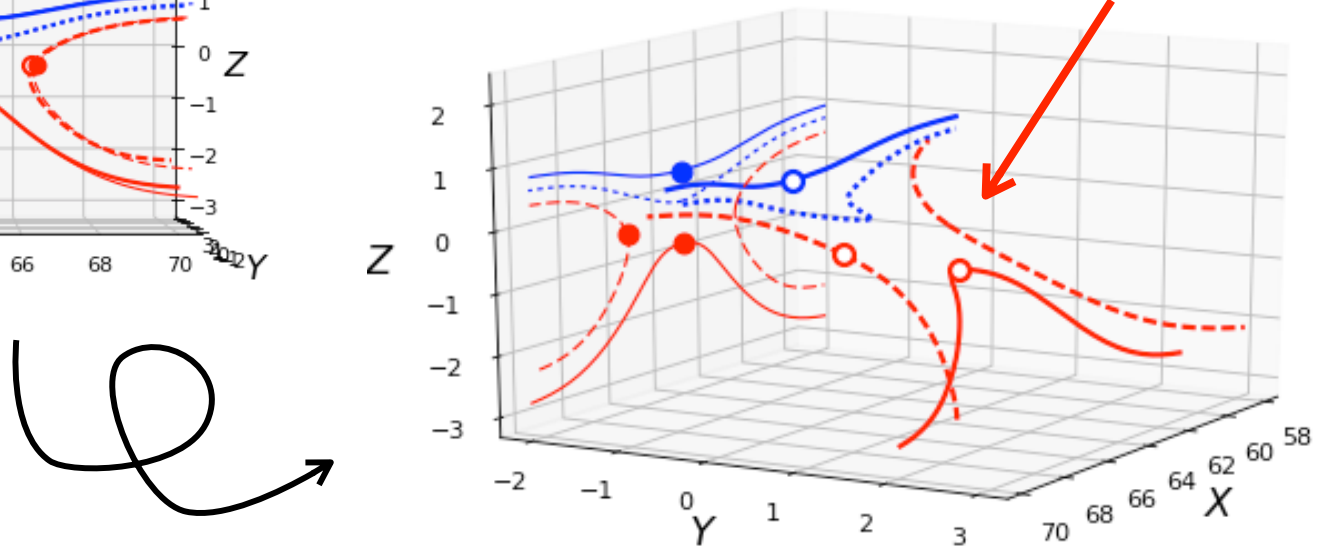
- Curvature parameter
  (Buchner & Zelenyi 1989 *JGR*)

$$\kappa \equiv \sqrt{\frac{R_c}{\rho}}$$

Magnetic curvature radius

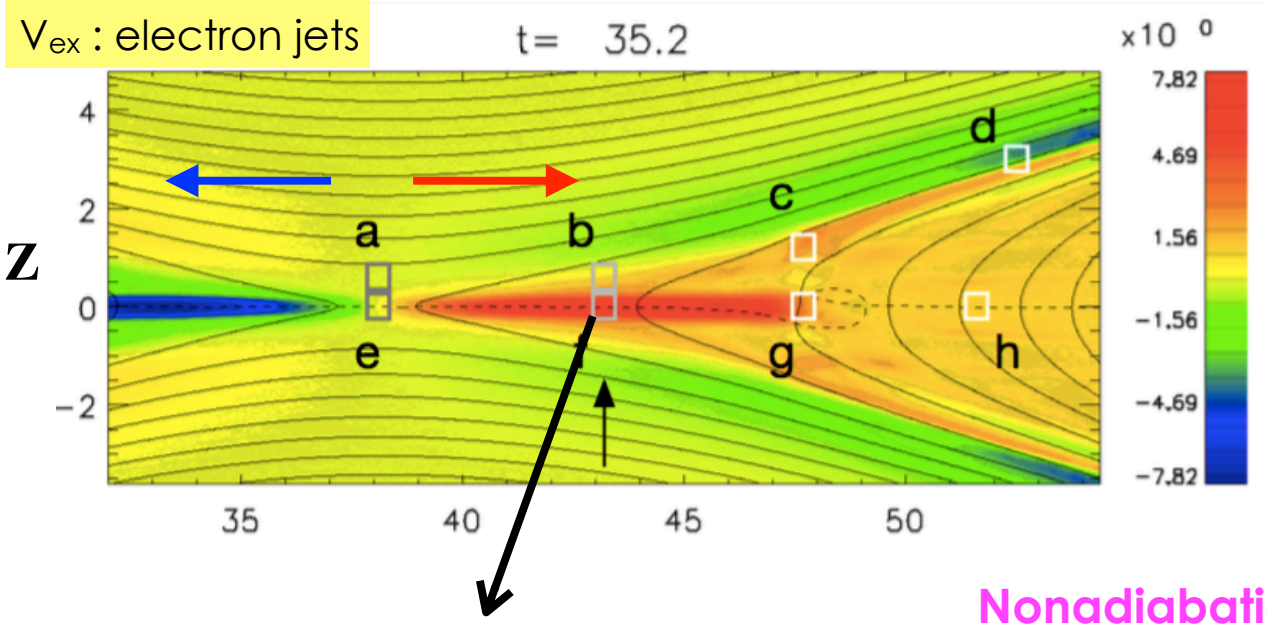
Electron Larmor radius

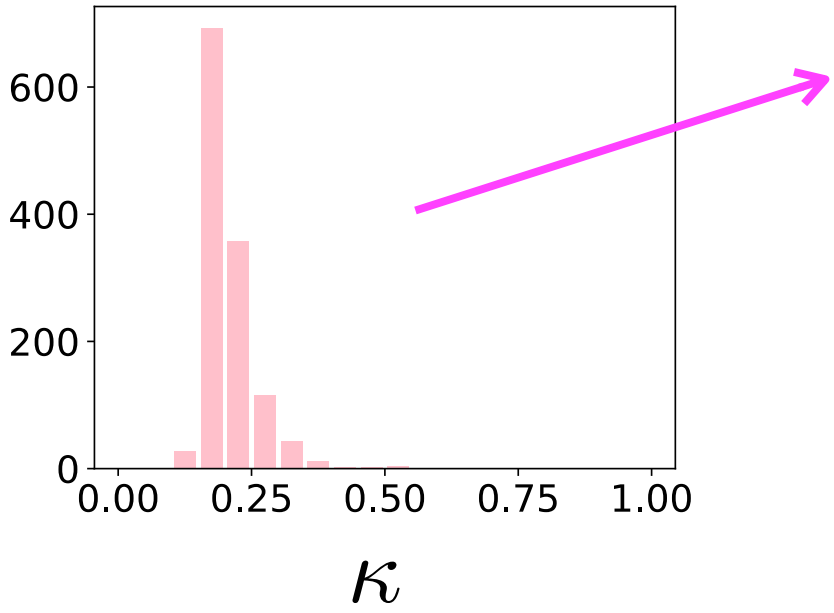




Electron jet in symmetric reconnection

V_{ex} : electron jets





Nonadiabatic (k << 1)

- Speiser motion
- No longer a gyration + ExB drift

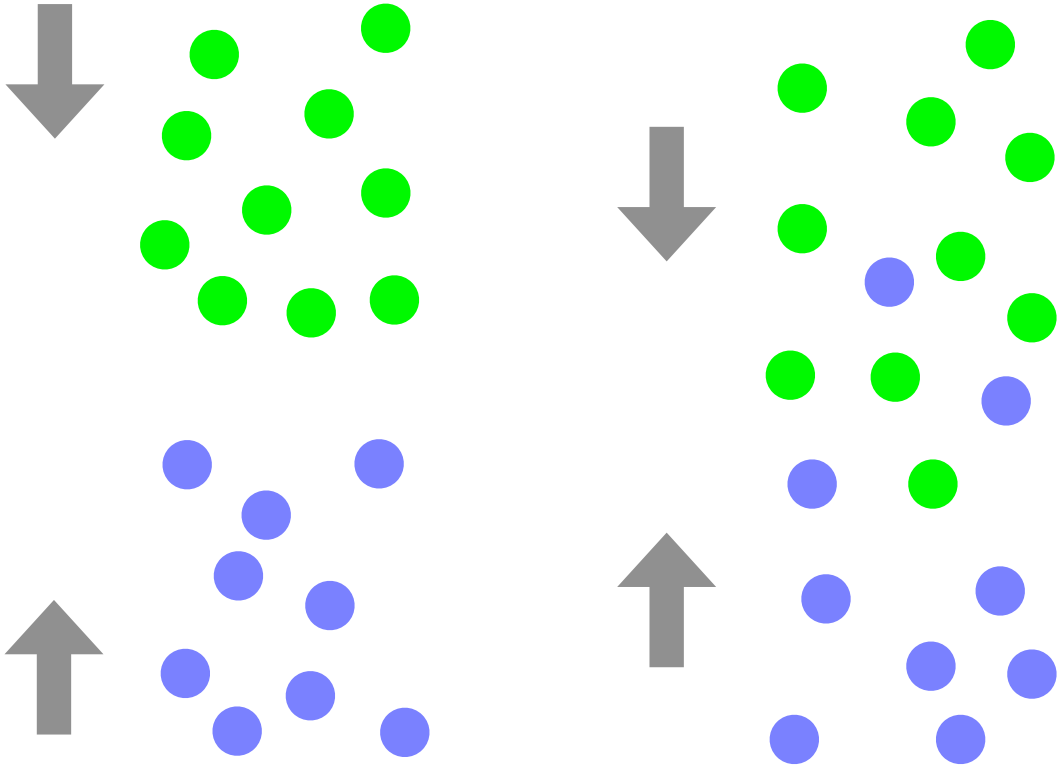
$$\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B} \neq 0$$

- Non-idealness (Shay+ 2007 *PRL*, Karimabadi+ 2007 *GRL*)
- ⇒ Electron-physics signatures can be better organized by adiabaticity (Le+ 2013 *PRL*)

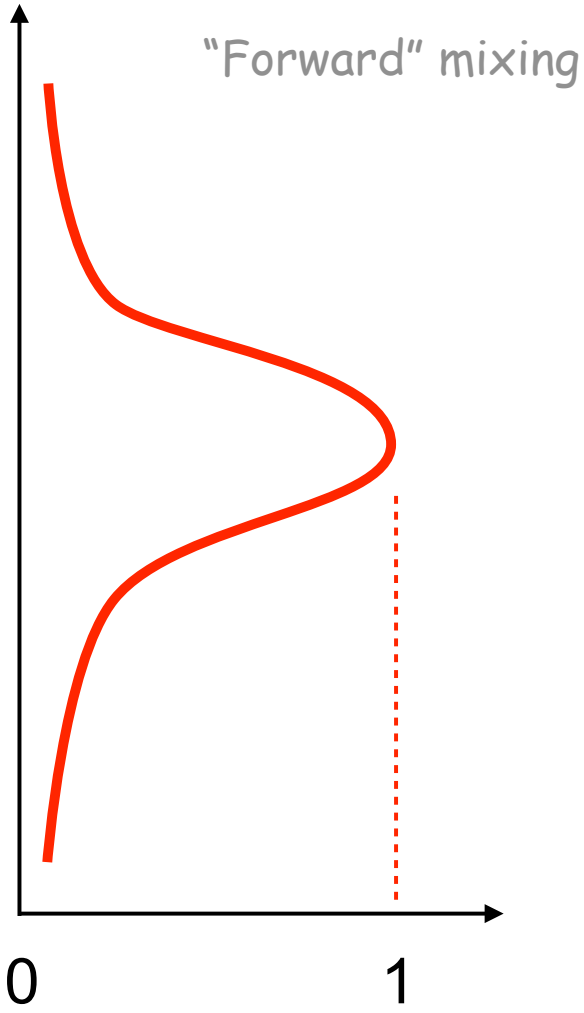
3. Electron mixing

Quantifying electron mixing (1/3)

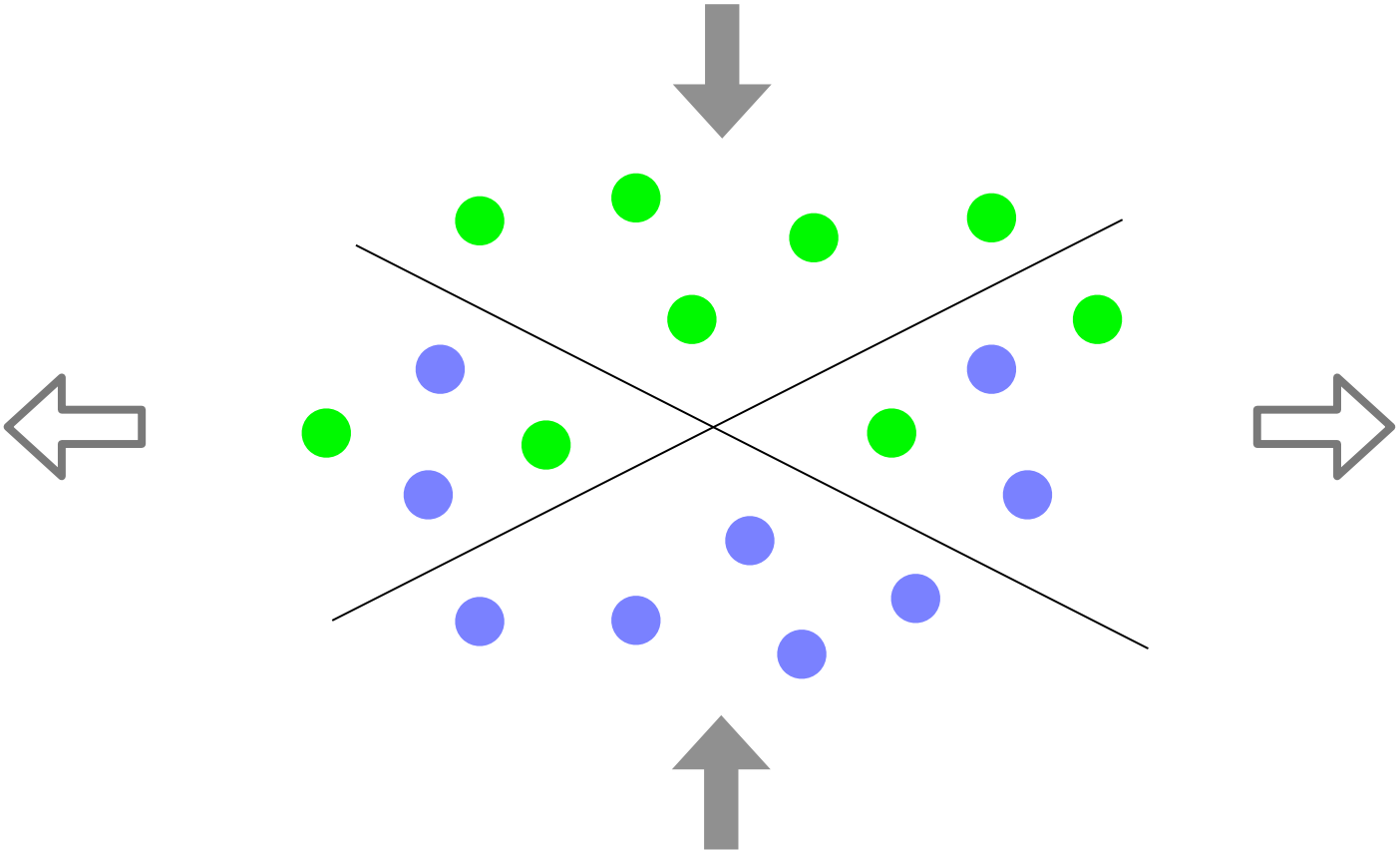
$+\Delta t$



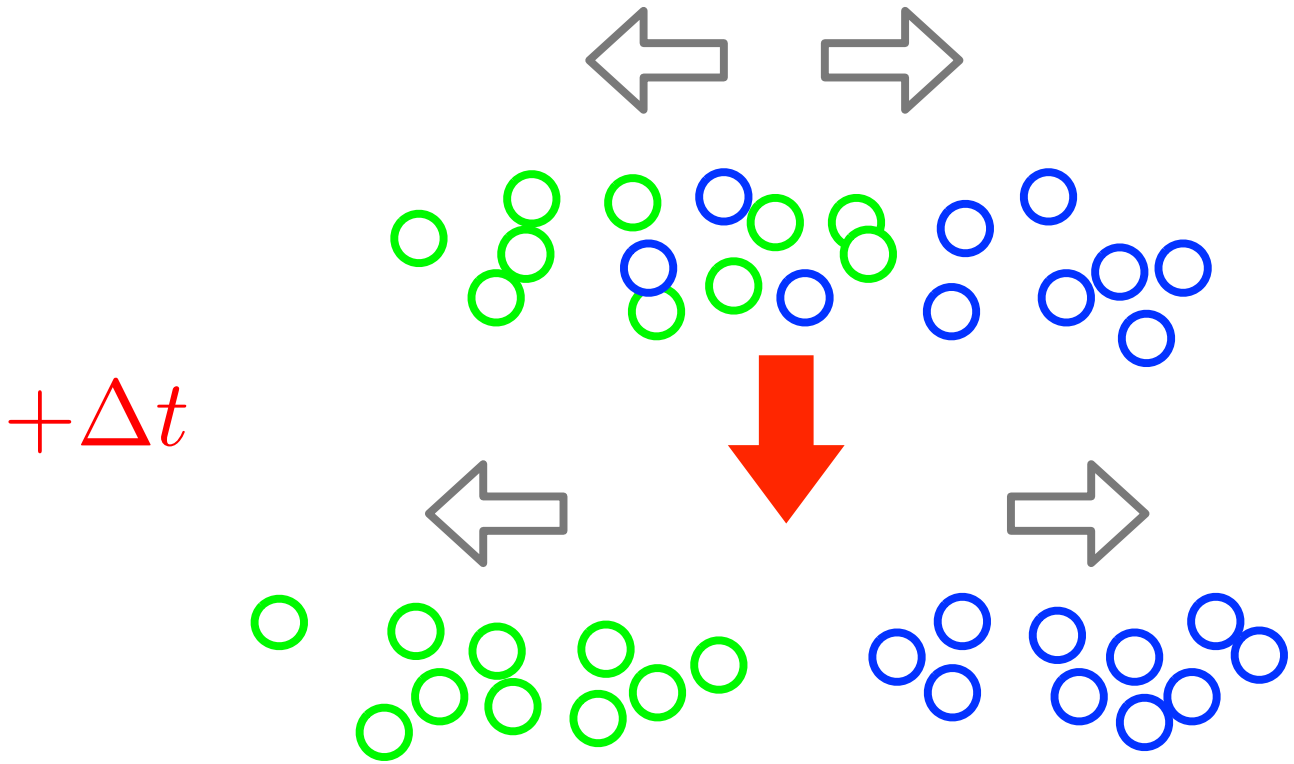
$\mathcal{M}_f(t_0, \Delta t)$



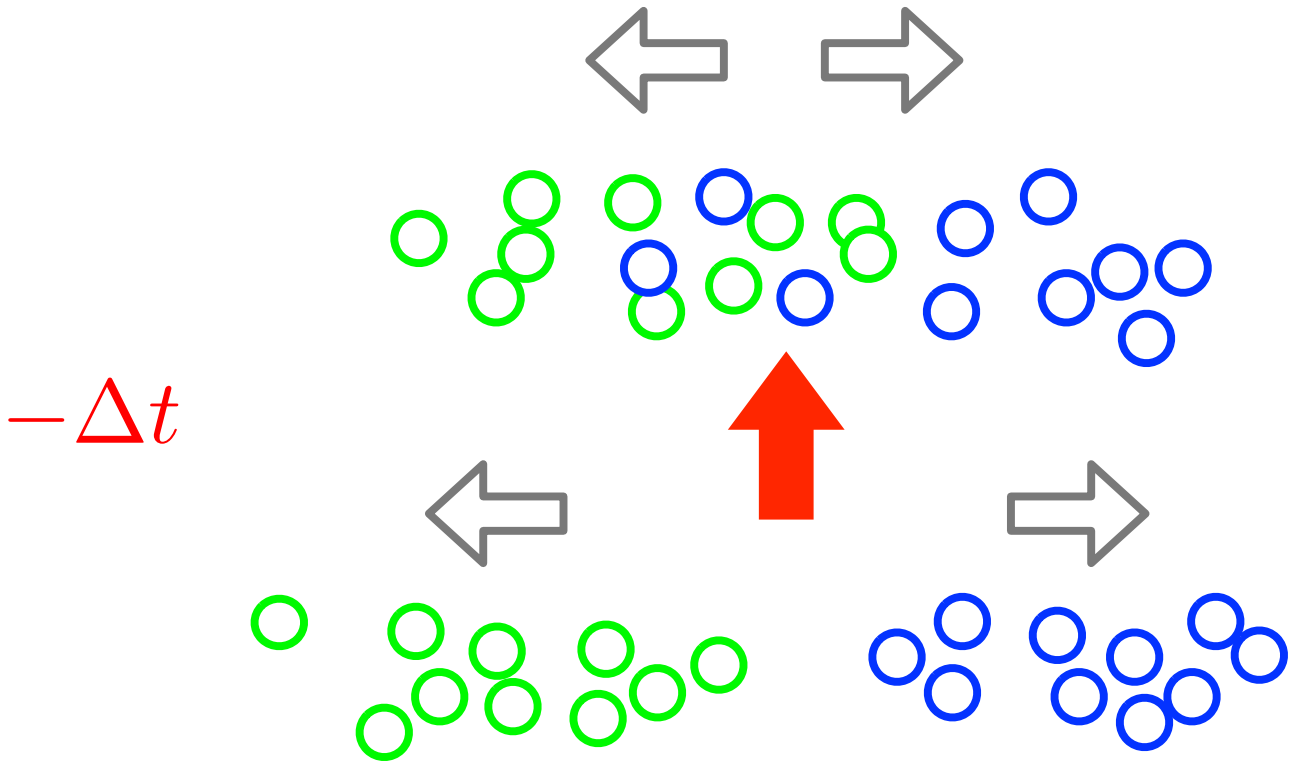
Quantifying electron mixing (2/3)

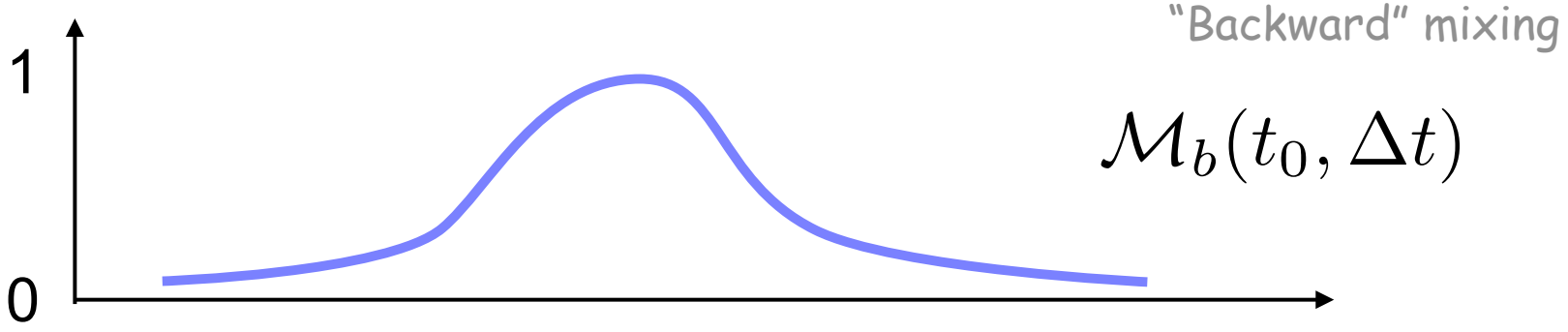


Quantifying electron mixing (3/3)



Quantifying electron mixing (3/3)





Finite-time mixing fraction (FTMF)

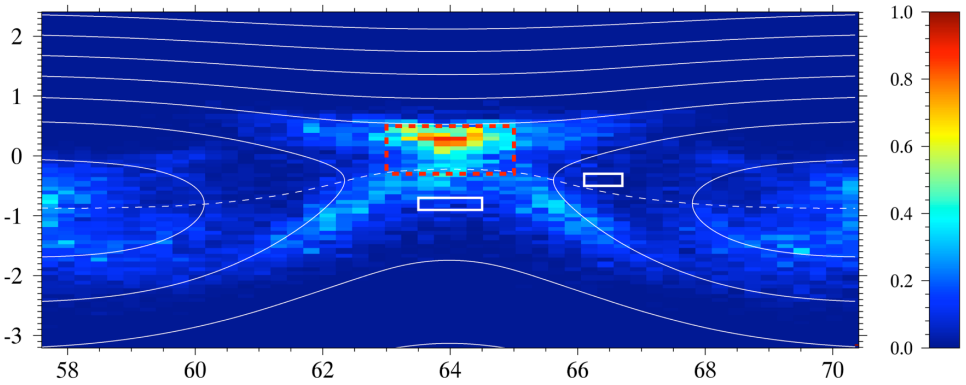
$$\mathcal{M}_R(t_0, \Delta t) \equiv \mathcal{M}_{\rm f}(t_0, \Delta t) \times \mathcal{M}_{\rm b}(t_0, \Delta t)$$

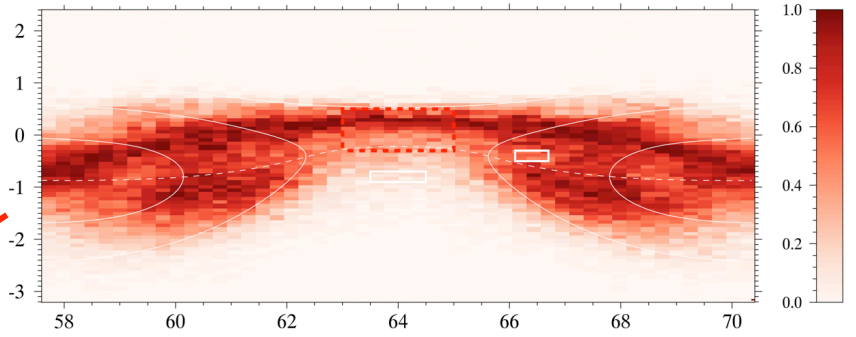
t_0 : time of interest

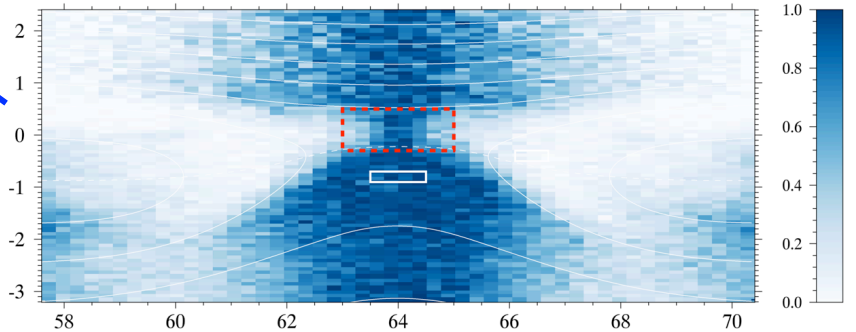
Δt : an electron-scale time interval

$\mathcal{M}_{\rm f}(t_0, \Delta t)$

$\mathcal{M}_R(t_0, \Delta t)$







$\mathcal{M}_{\rm b}(t_0, \Delta t)$

Mixing measure

Zenitani+ 2017 JGR

vs

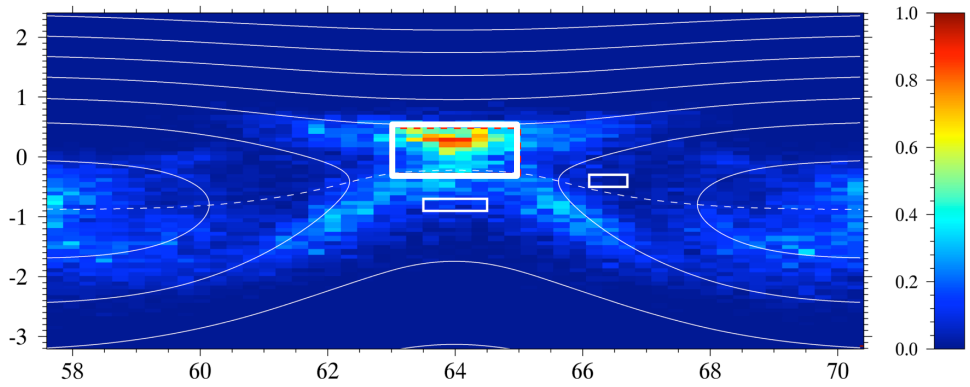
Energy dissipation

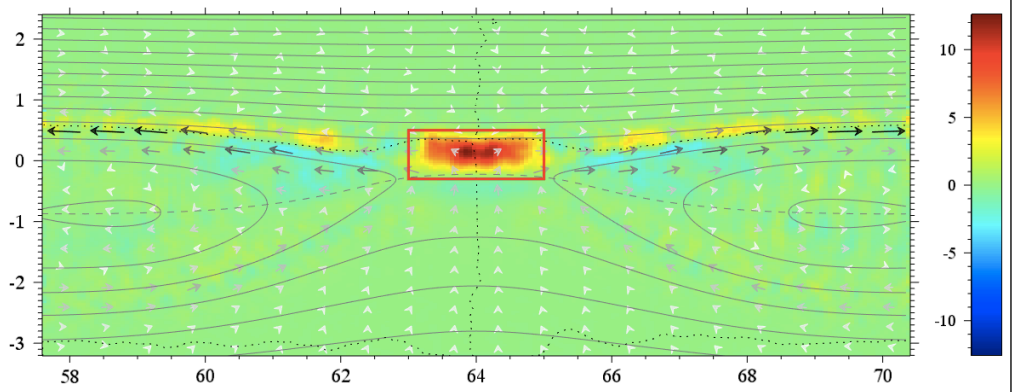
Zenitani+ 2011 PRL

$$\mathcal{M}_R(t_0, \Delta t)$$

$$\mathcal{D}_e \simeq \boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})$$

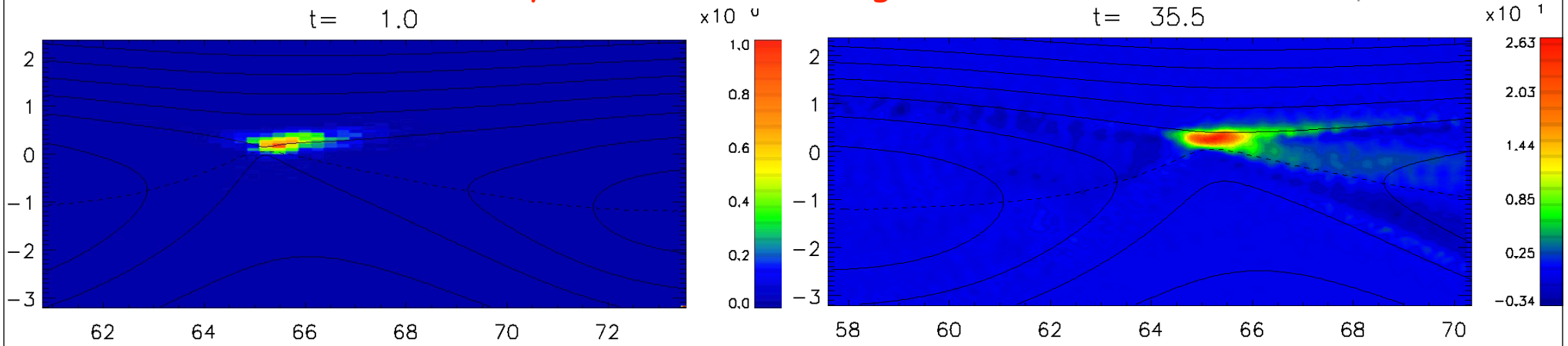
Asymmetric RX





Asymmetric RX with a guide-field

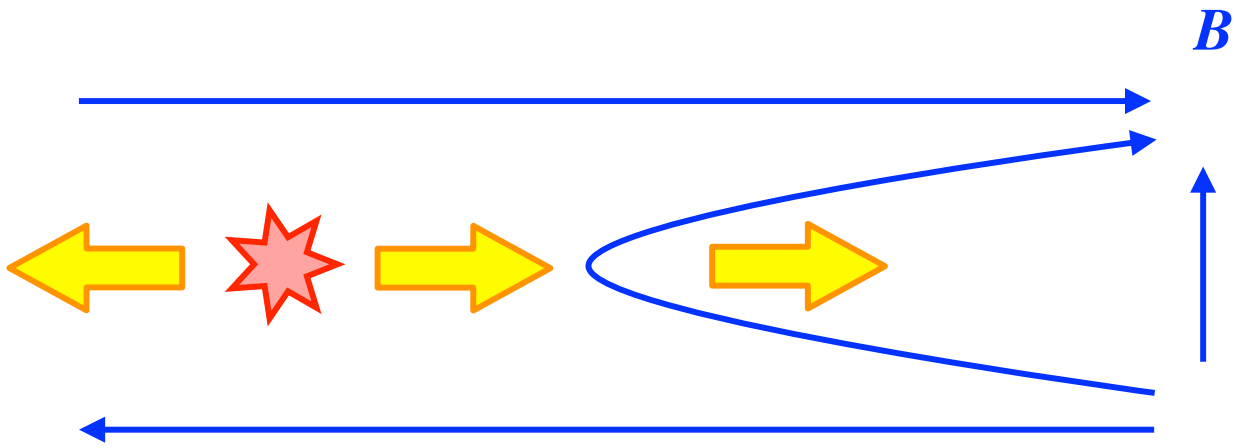
⊗ B_y



Summary

- 1. Antiparallel reconnection
  - Many new electron orbits are found
  - Noncrossing electrons due to electrostatic field
  - Noncrossing electrons are majority in number density
- 2. Asymmetric reconnection
  - Nonadiabatic electrons, due to steep curvature in 3D
- ⇒ Electron orbits & signatures: more research needed
- 3. Electron mixing
  - We have introduced *finite-time mixing fraction* (FTMF)
  - FTMF marks the energy-dissipation region
- References
  - Zenitani & Nagai, *Phys. Plasmas* **23**, 102102 (2016)
  - Zenitani, Hasegawa, & Nagai, *J. Geophys. Res.* **122**, 7396 (2017)

Particle motion in a curved B-field



Curvature parameter

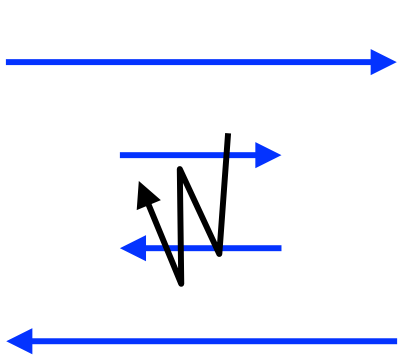
Curvature radius of ***B***

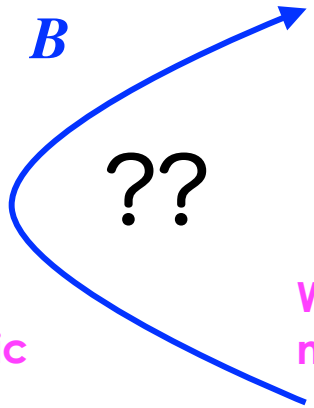
$$\kappa = \sqrt{\frac{R_{\min}}{\rho_{\max}}}$$

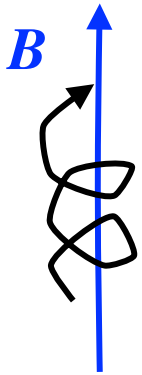
~ Larmor radius

Buchner & Zelenyi 1989 *JGR*

$\kappa \to 0$ ⟵ $\kappa \sim 1$ ⟶ $\kappa \to \infty$







Meandering motion (I-adiabatic)

Nonadiabatic

$\kappa \lesssim 1$

Weakly nonadiabatic

$1 \lesssim \kappa \lesssim 2.5$

Gyromotion (adiabatic)