Plasma particle dynamics in collisionless magnetic reconnection

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60 YEARS

0. Old tales

1. Ion dynamics

2. Electron dynamics

3. Perspectives

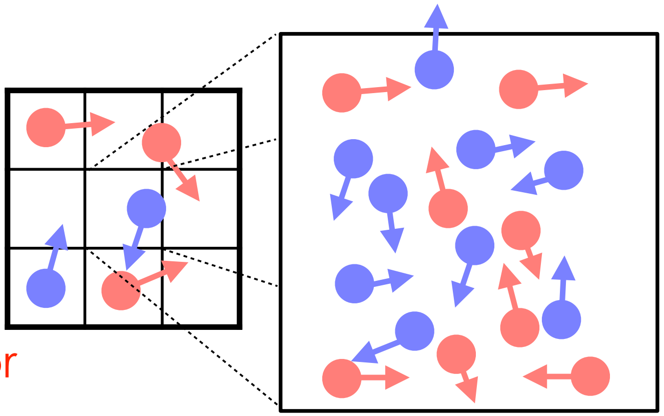
U. Tokyo, STP (Solar Terrestrial Physics) group

"Super Terasawa Physics"

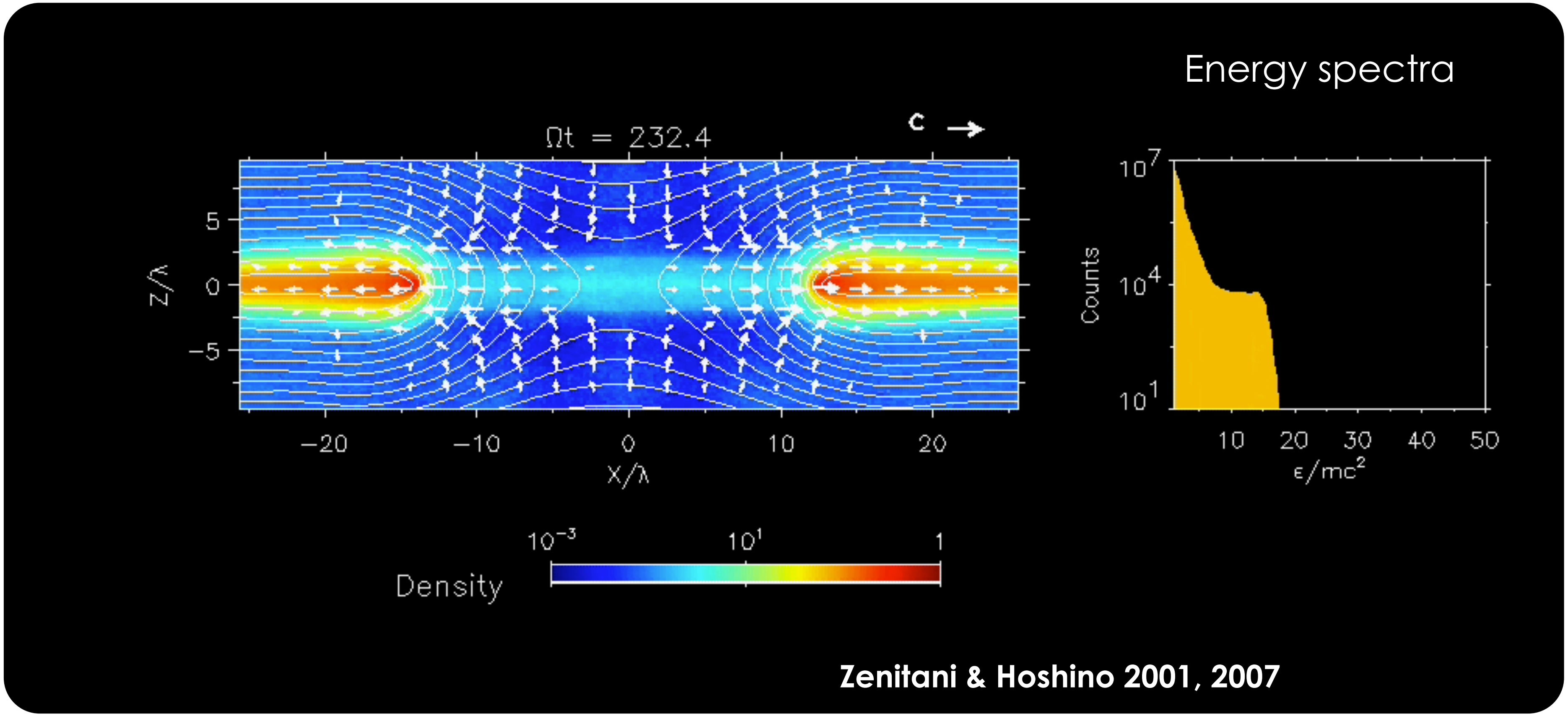
"Masahiro Hoshino Dynamics"

- We initially considered:
  - Relativistic magnetic reconnection (SZ, Ph.D thesis 2006)
  - Reconnection in rotating systems (Hoshino, Shirakawa, 2013-2015)

Relativistic reconnection:
Particle-in-Cell (PIC) simulation



- Relativistic reconnection is a particle accelerator
- SZ & Hoshino 2001-2008 (5 papers; 440 citations)



(シミュレーション研究会スライド)

Selected topics on Relativistic Particle-in-Cell Simulations

S. Zenitani (Kyoto U), T. N. Kato (NAOJ), T. Umeda (Nagoya U)

- 1. Loading
  - Loading velocity distributions by random variables (Sobol 1976, Swisdak 2013, Zenitani 2015)
  - Lorentz transformation for the spatial part (Zenitani 2015)
- 2. Computation
  - EM field (Haber 1974, Vay 2013, Ikeya & Matsumoto 2015)
  - Particle (Vay 2008, Zenitani & Kato 2018b, Zenitani & Umeda 2018c)
- 3. Diagnosis & Interpretation
  - Relativistic fluid decomposition (Zenitani 2018a)

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Poster

- 2. Computation
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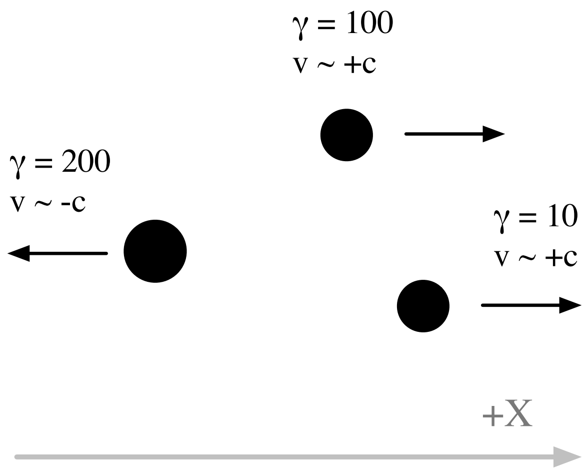
Relativistic fluid mechanics is a nightmare...

Energy flow

Landau frame

$$T^{i0} = T^{0j} = 0$$



Number flow

Eckart frame

$$N^i = 0$$

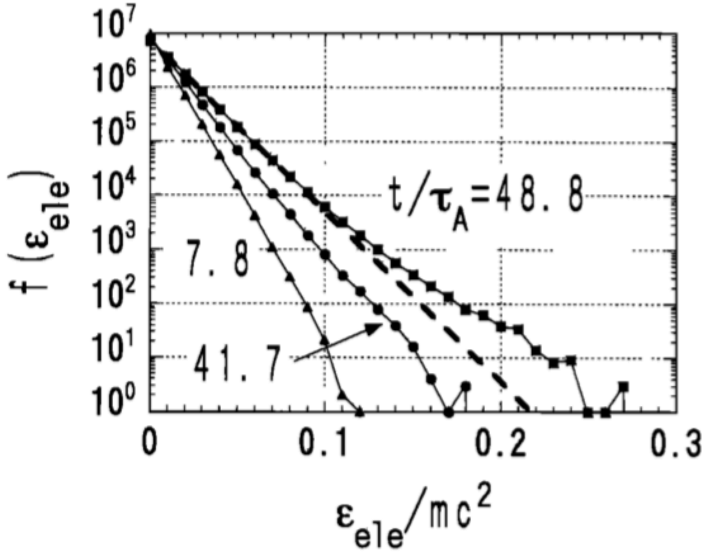
$$T^{\alpha\beta} = \int f(u) u^\alpha u^\beta \frac{d^3u}{\gamma}$$

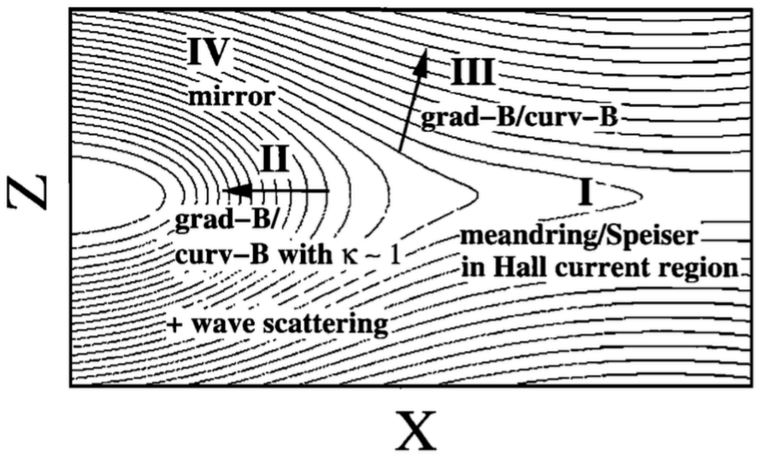
$$T^{\alpha\beta} = \mathcal{E} u^\alpha u^\beta + q^\alpha u^\beta + q^\beta u^\alpha + P^{\alpha\beta}$$

$$\begin{aligned}
\mathcal{E} &\equiv T^{\alpha\beta} u_\alpha u_\beta \\
q^\alpha &\equiv -\Delta^\alpha_\beta T^{\beta\gamma} u_\gamma \\
P^{\alpha\beta} &\equiv \Delta^\alpha_\gamma \Delta^\beta_\delta T^{\gamma\delta} \\
\Delta^{\alpha\beta} &= g^{\alpha\beta} + u^\alpha u^\beta
\end{aligned}$$

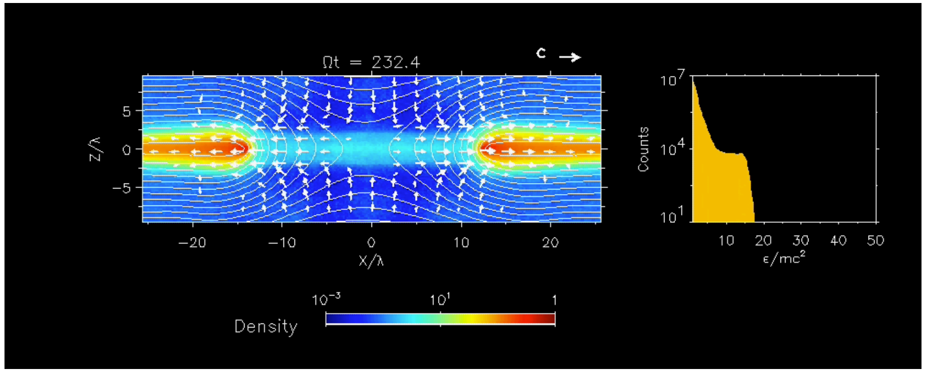
--> Fluid analysis in relativistic reconnection (SZ 2018 PPCF)

Reconnection as a particle accelerator

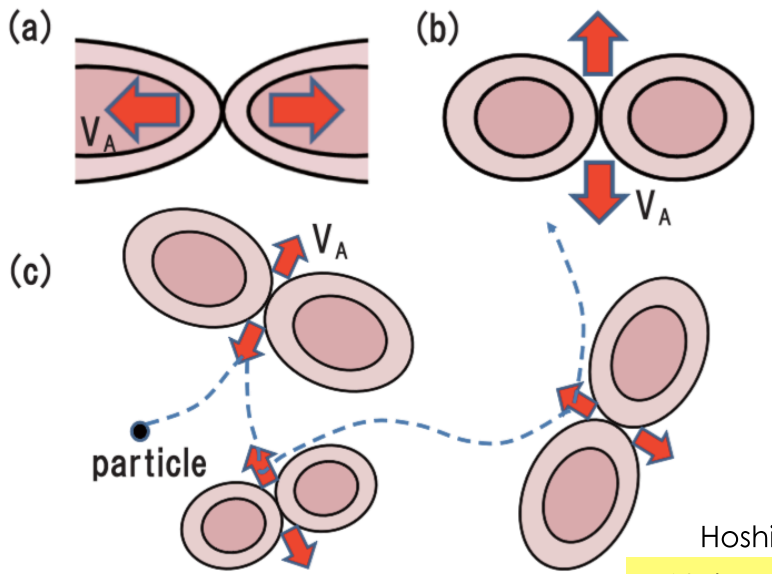




Hoshino+ 2001, 2005 JGR



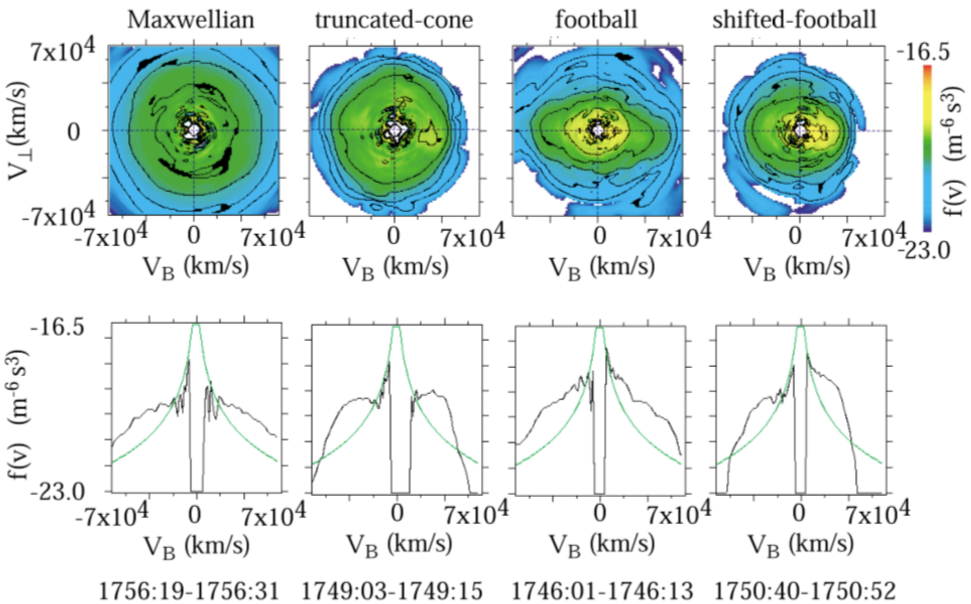
SZ & Hoshino 2001 ApJL

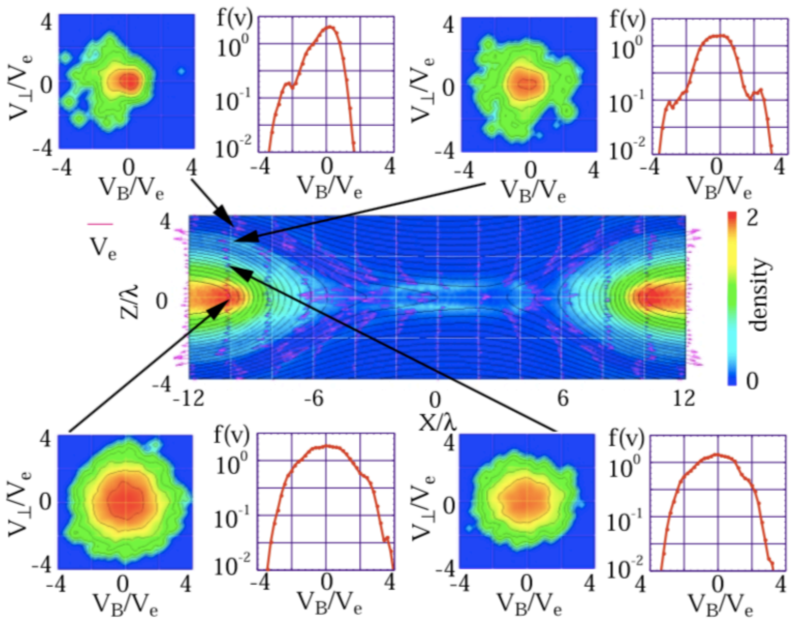


Hoshino 2012 PRL

※ Not confirmed by SZ

Electron dynamics in reconnection





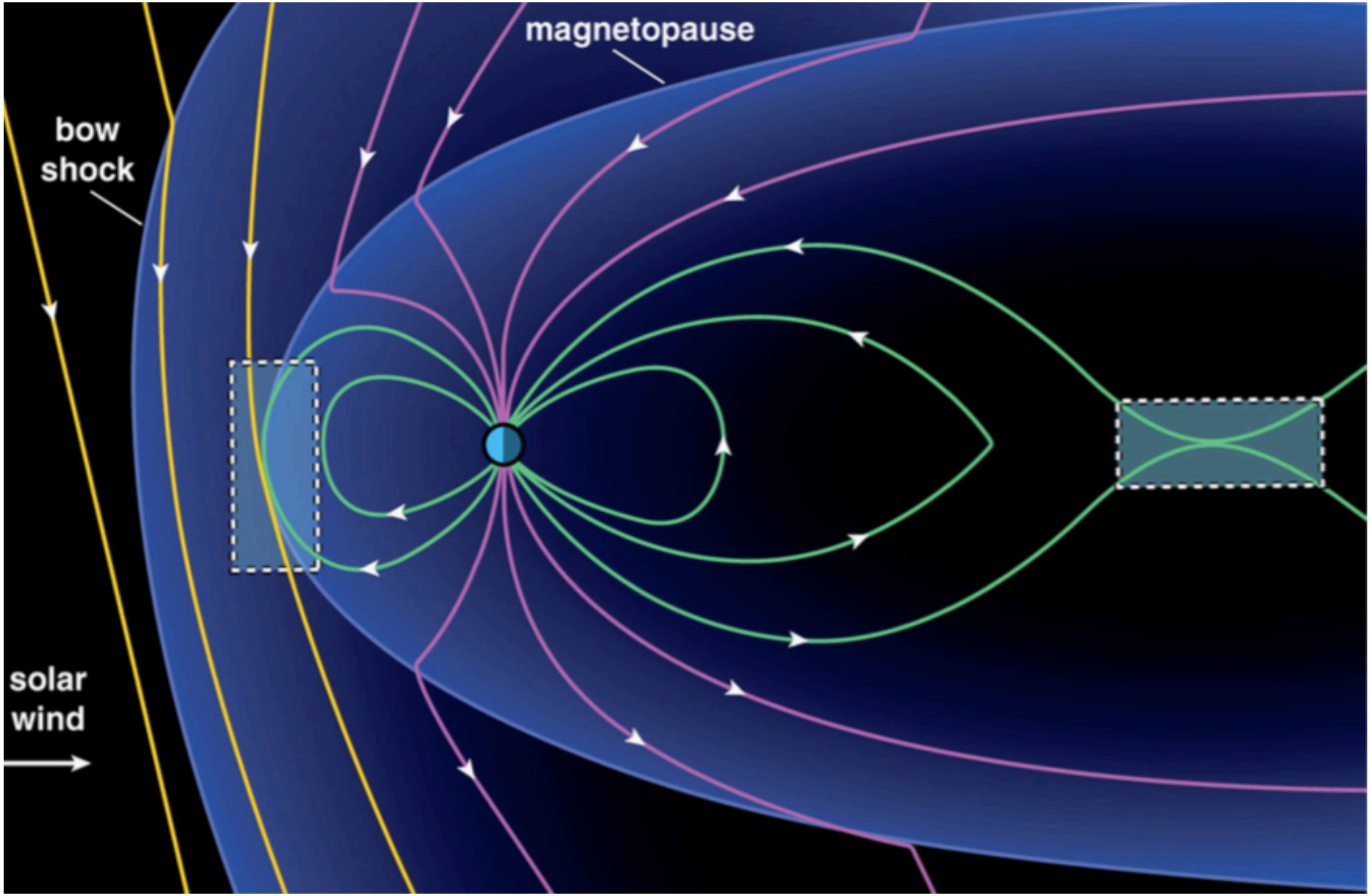
Hoshino+ 2001 EPS

Masahiro-Hoshino Dynamics (MHD) is very different from the standard MHD

Beyond MHD

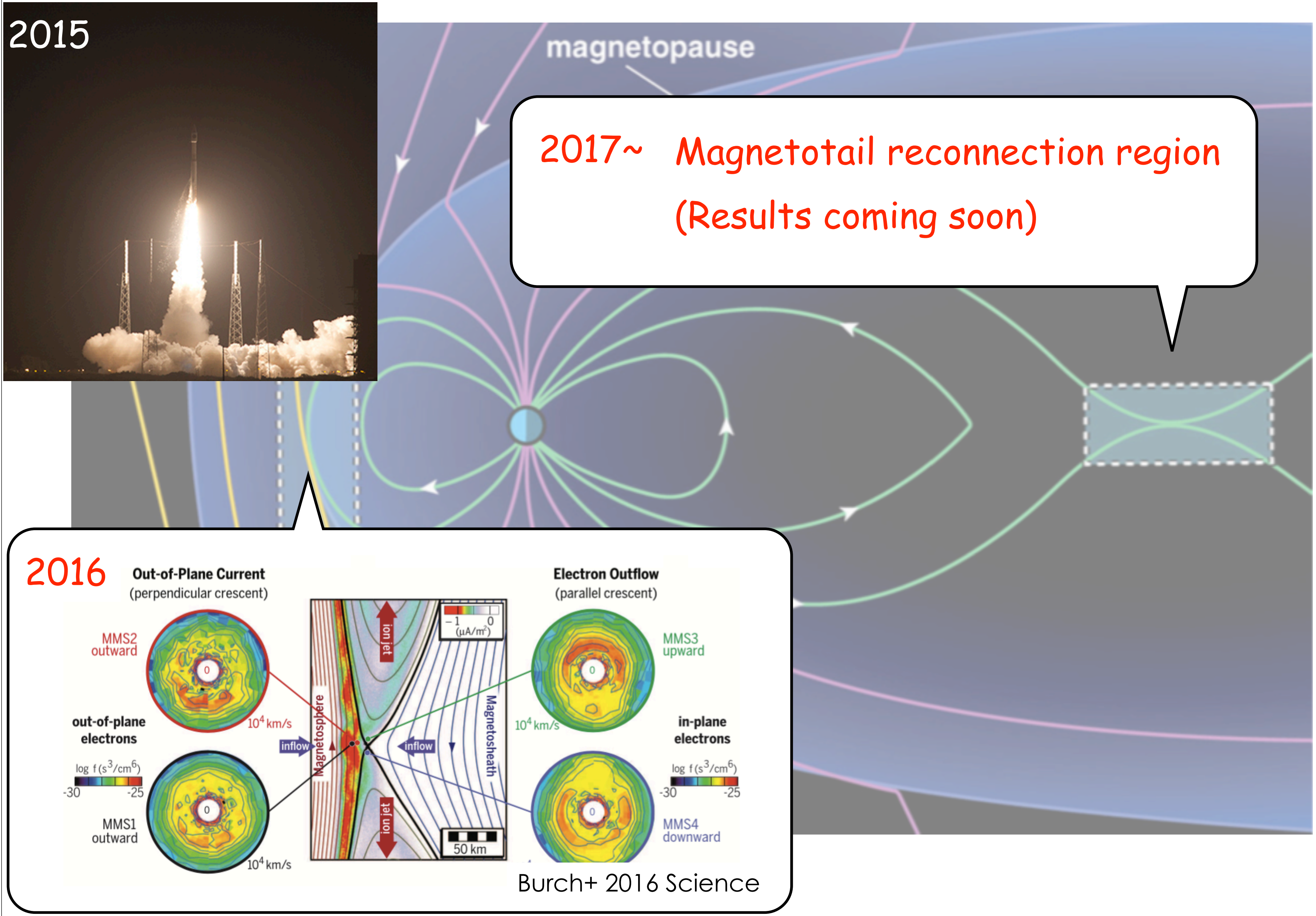
Our recent results (SZ+ 2013,2016)

Magnetic reconnection in near-Earth space

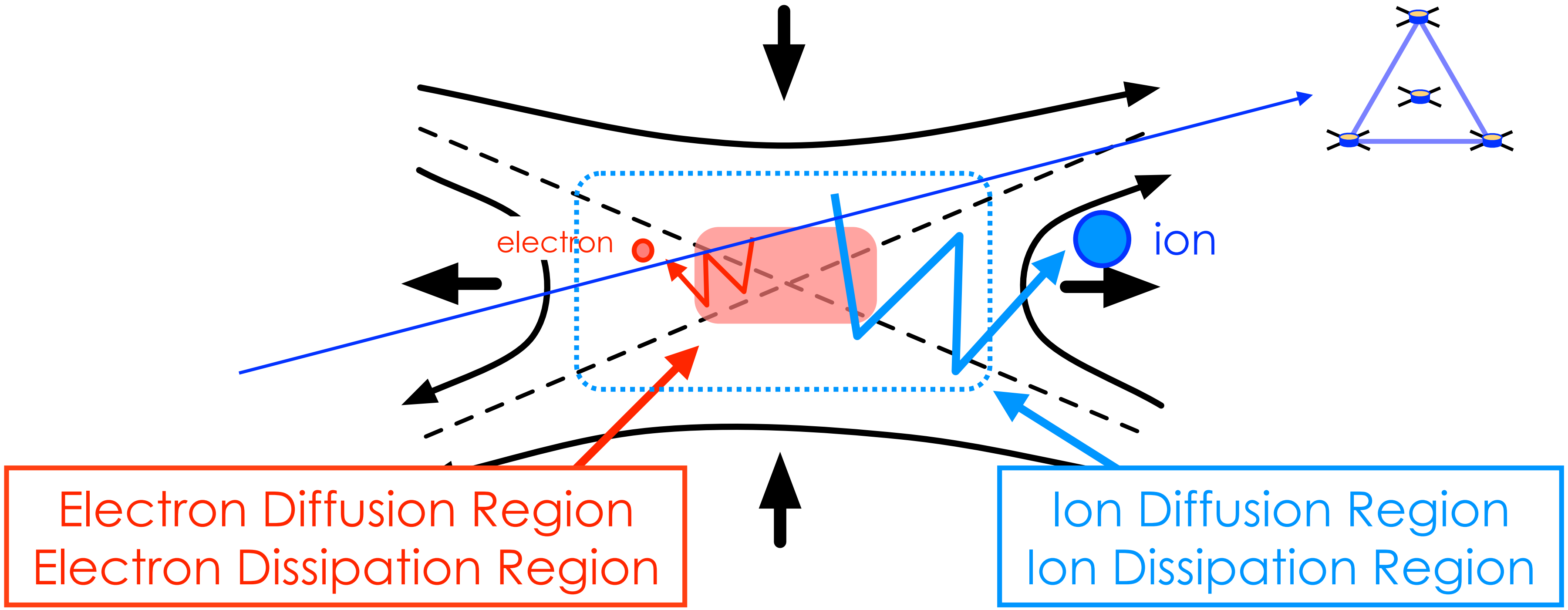


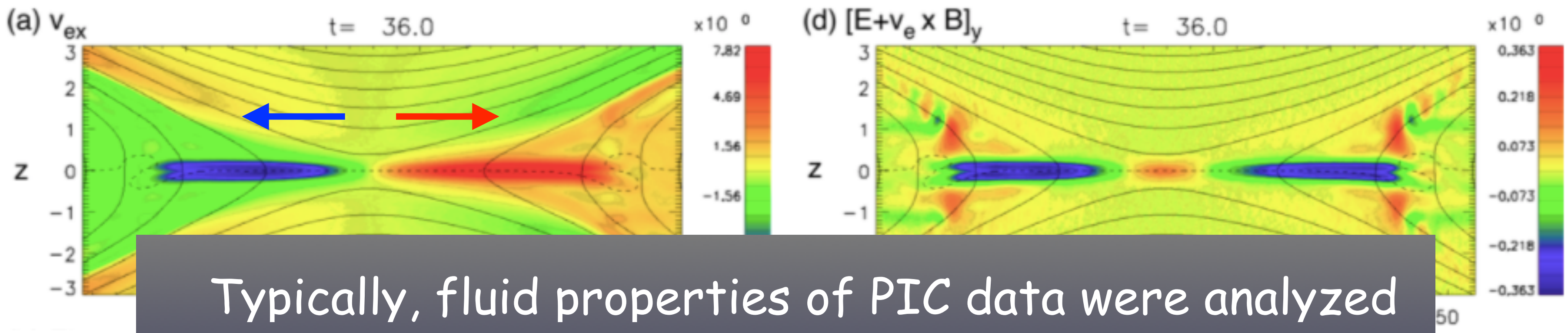
Burch+ 2016 Space Sci. Rev.

Magnetospheric Multiscale (MMS) mission

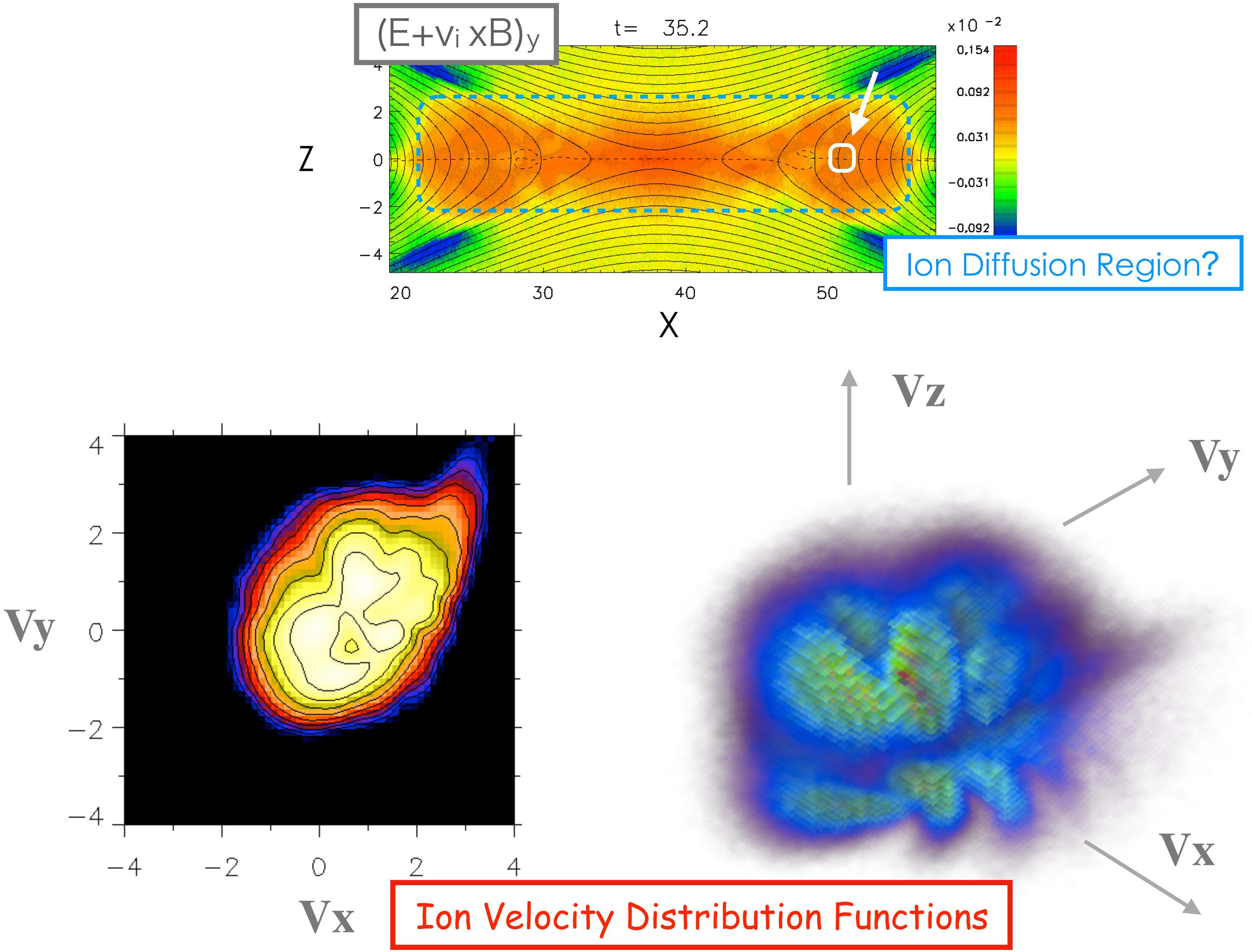


Central engine of magnetic reconnection



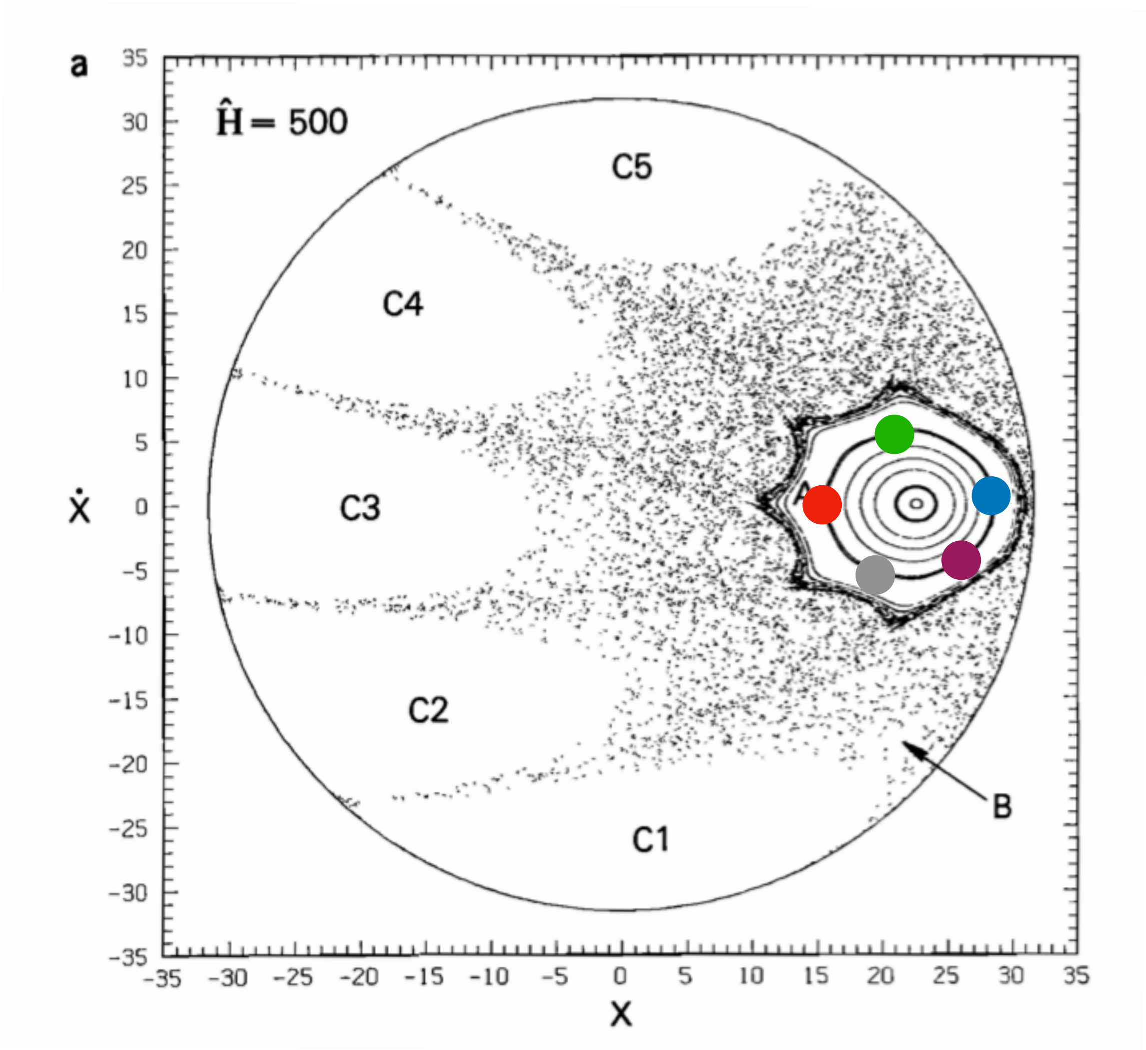


Typically, fluid properties of PIC data were analyzed



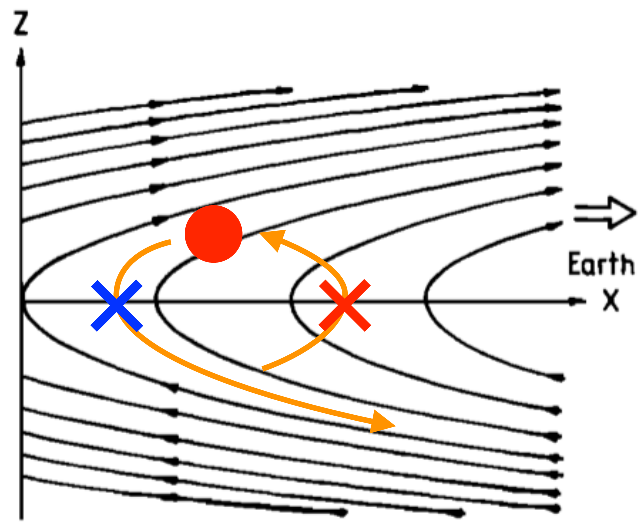
(E+vi xB)y
t= 35.2
x10 -2
0.154
0.092
0.031
-0.031
-0.092
Z
X
Ion Diffusion Region?
Vz
Vy
Vx
Vy
Vx
Ion Velocity Distribution Functions

Nonlinear particle dynamics

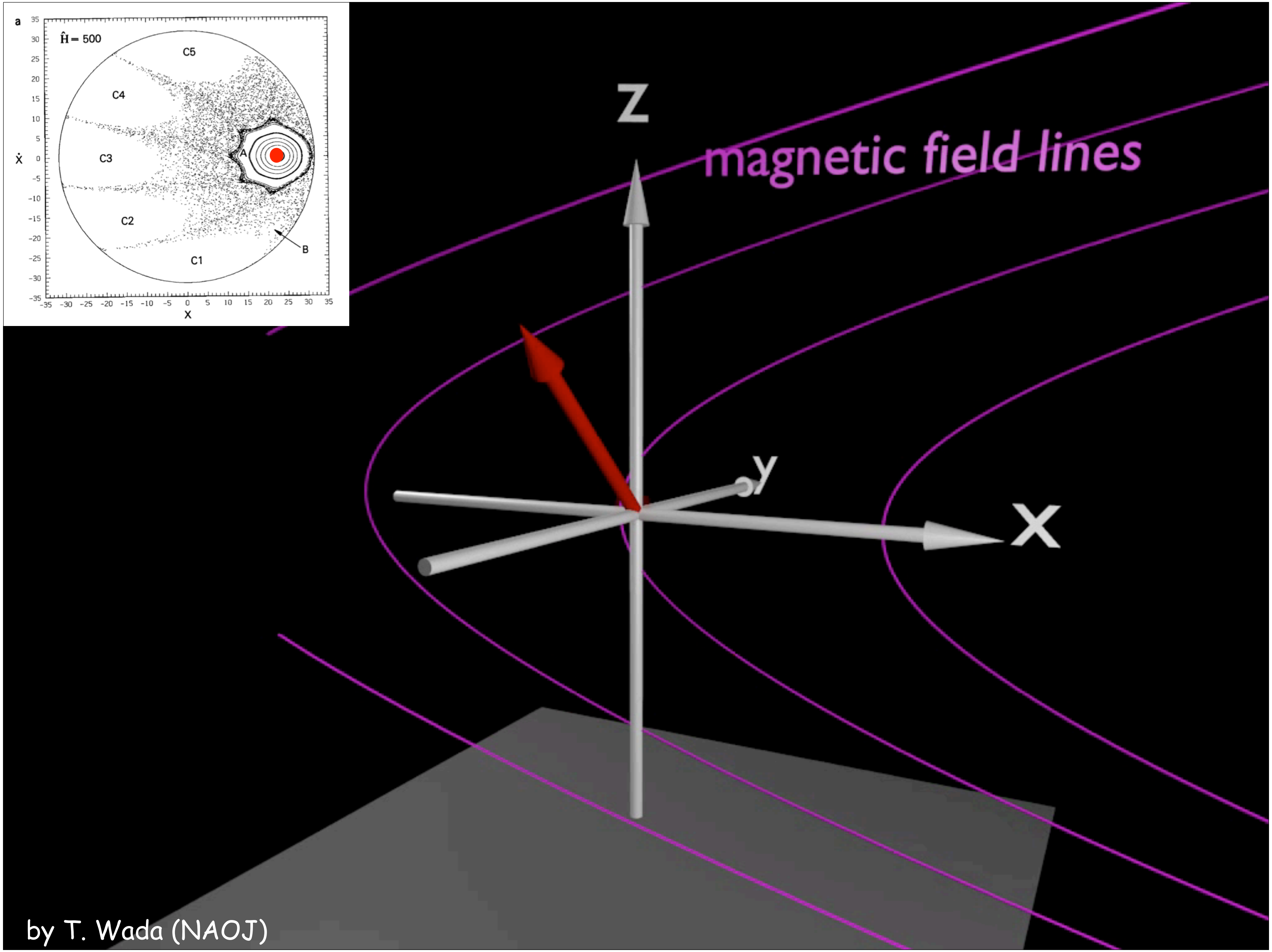


Chen & Palmadesso 1986

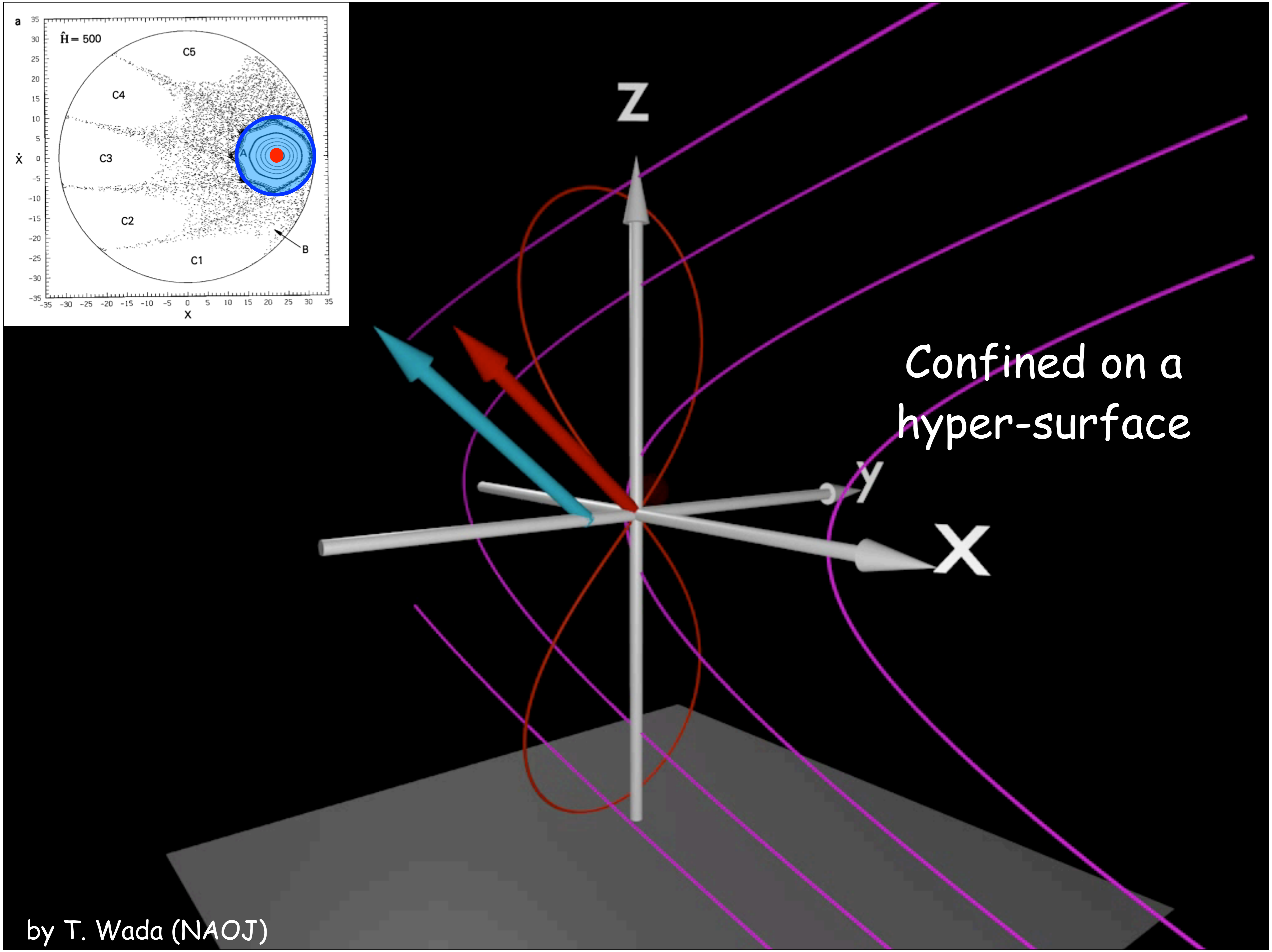
- Poincaré map
- One way to categorize particle orbits



Buchner & Zelenyi 1989

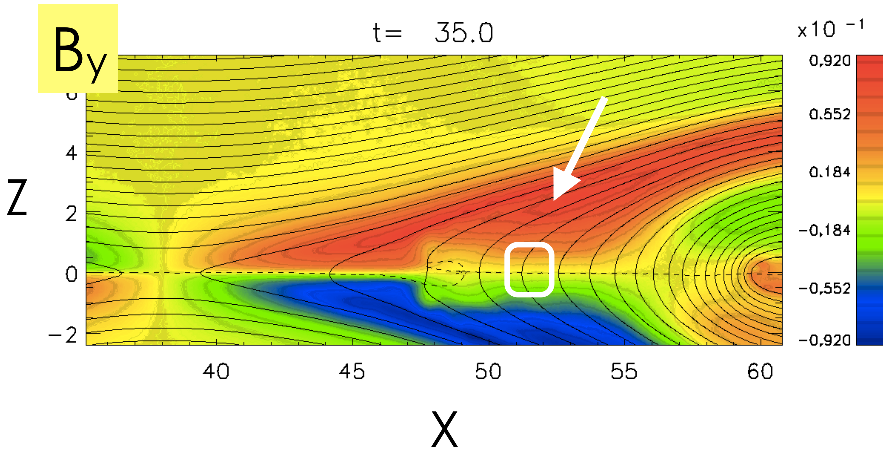


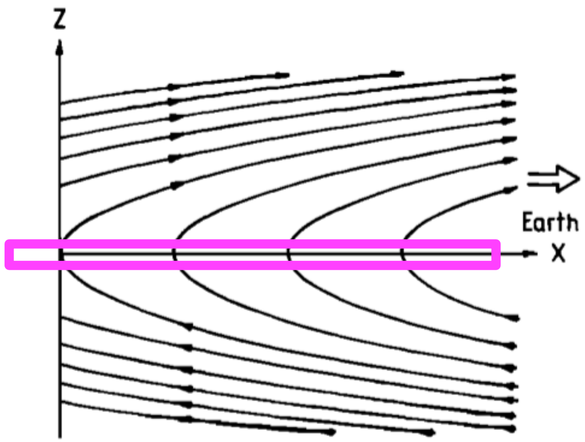
a
Ĥ = 500
C5
C4
C3
C2
C1
A
B
ẋ
x
z
magnetic field lines
y
x
by T. Wada (NAOJ)

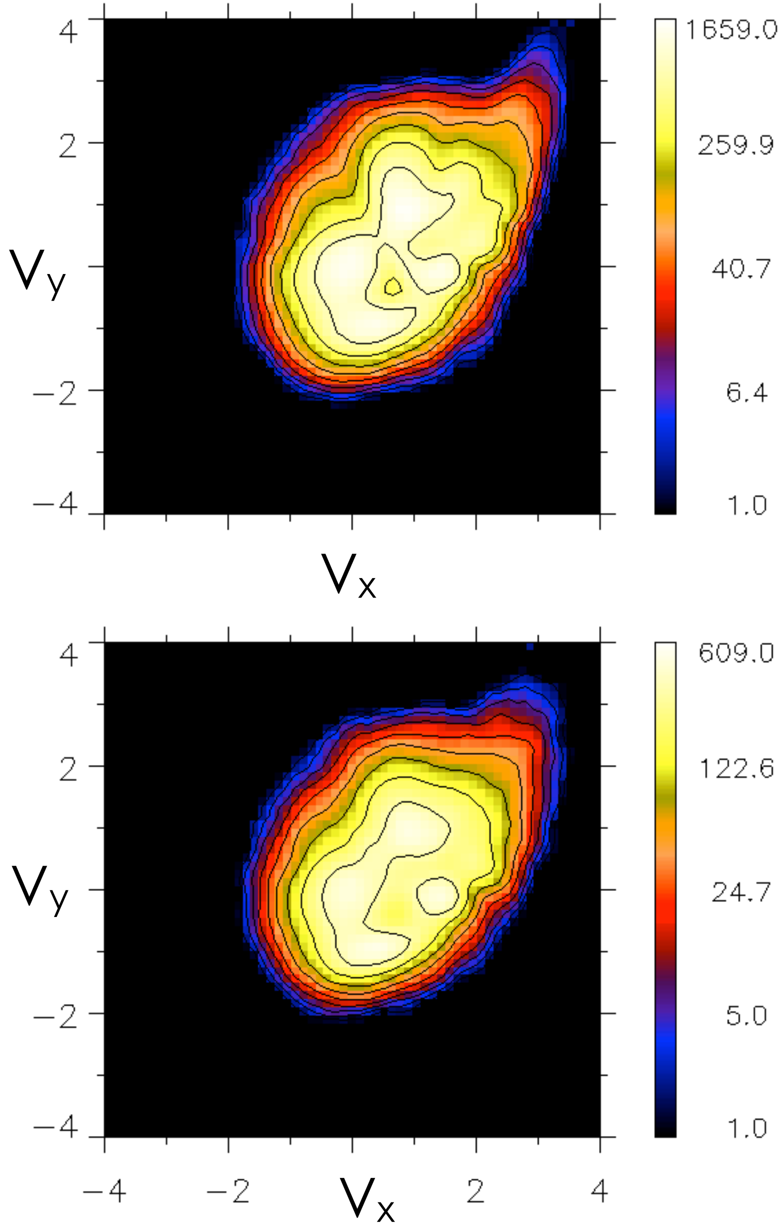


Ĥ = 500
C5
C4
C3
C2
C1
A
B
Z
y
X
Confined on a
hyper-surface
by T. Wada (NAOJ)

Ion velocity distribution function (VDF)

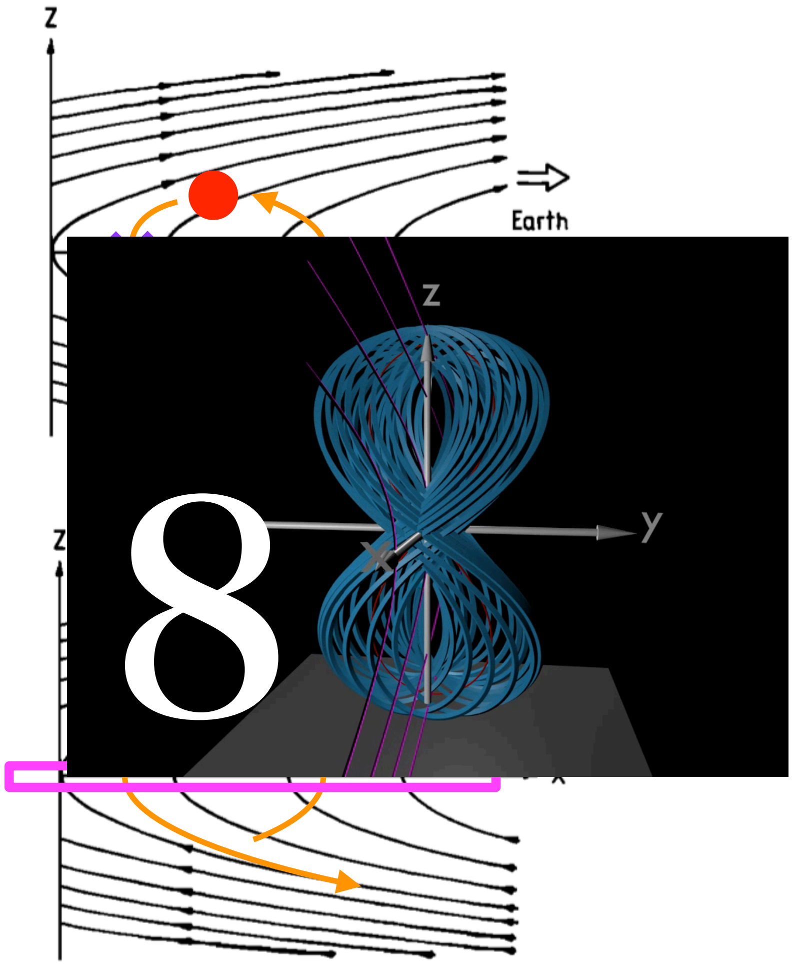


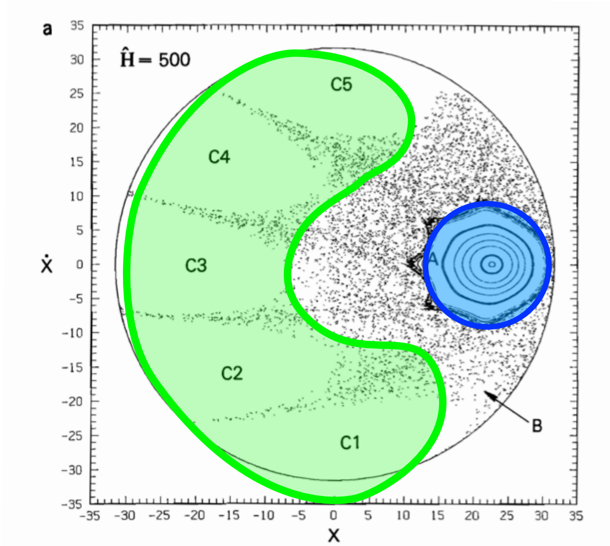


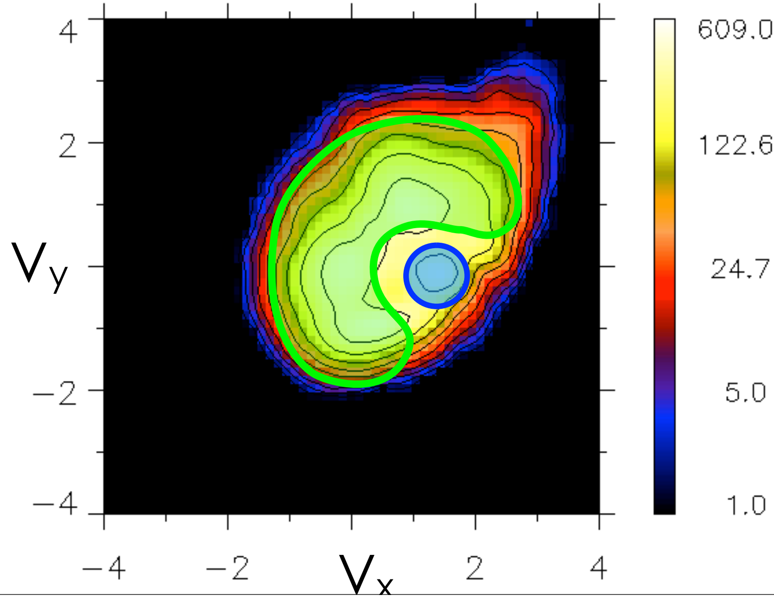


VDF & Poincaré map

Two choices from 5 free parameters (x, y, V_x, V_y, V_z)

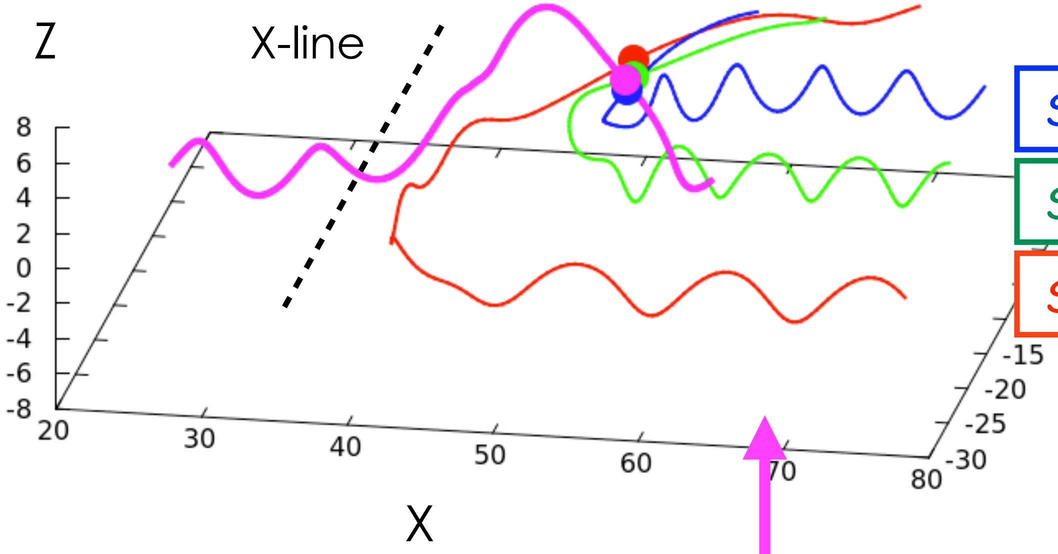






Ion orbits in PIC simulation

8-shaped orbit



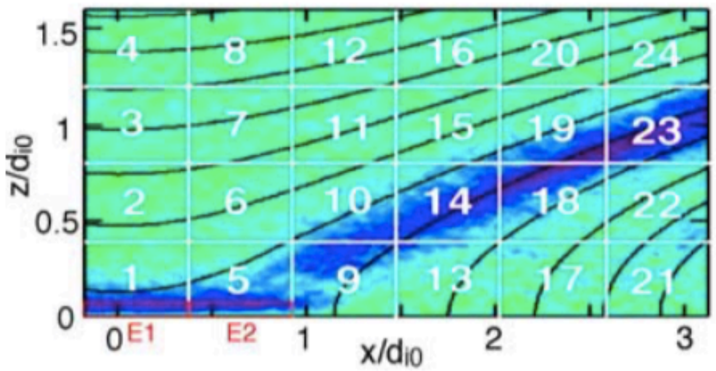
Speiser orbit (known)

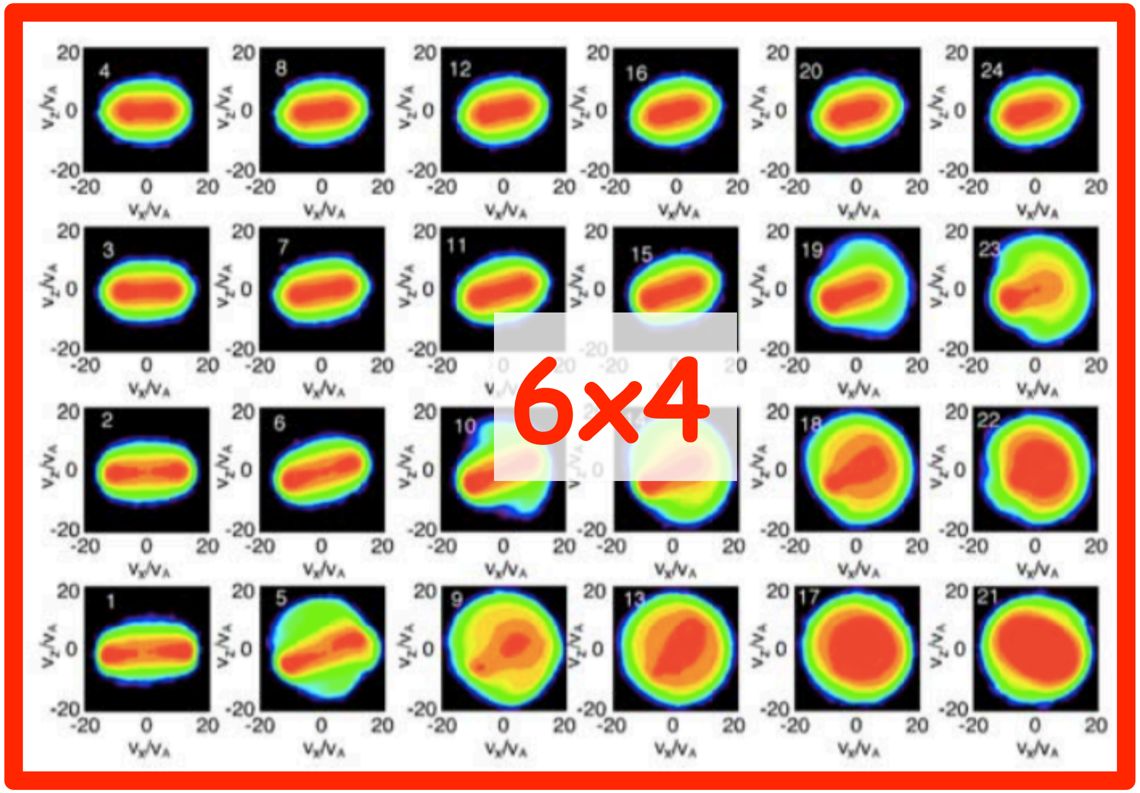
Speiser orbit (known)

Speiser orbit (known)

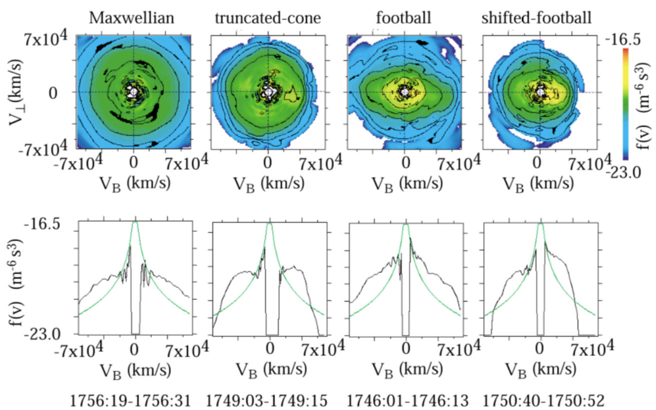
First demonstration of
8-shaped orbit in PIC simulation

Electron VDFs in PIC simulation



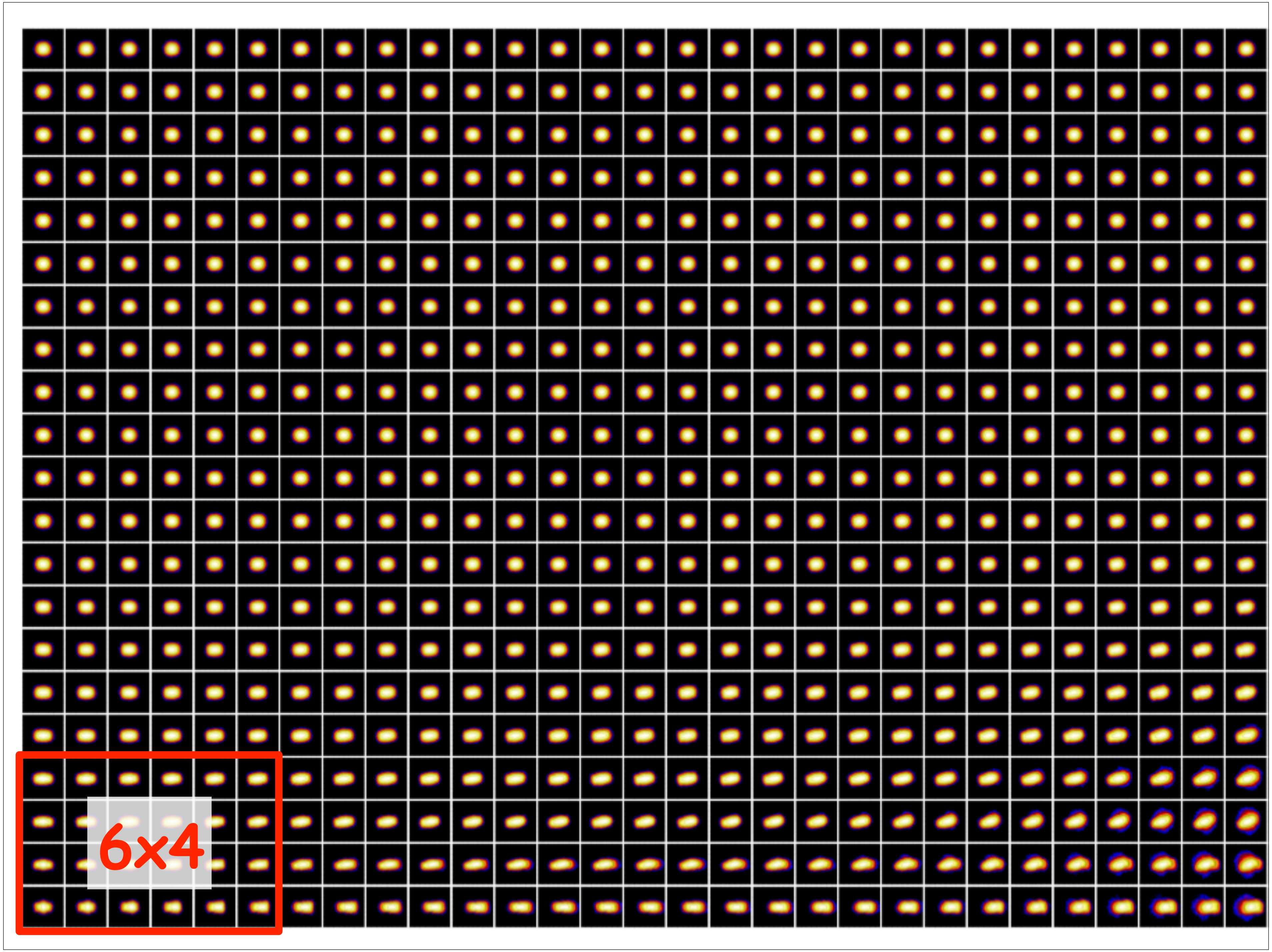


Chen+ 2008 JGR



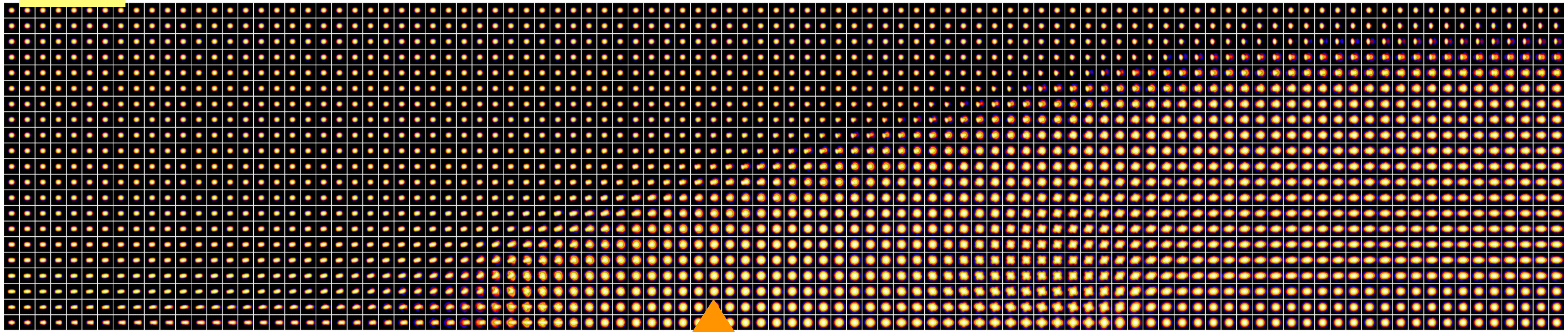
Hoshino+ 2001 EPS

- Many PIC studies on electron VDFs
  - Hoshino+ 2001, Pritchett 2006, Chen+ 2008, 2009, Ng+ 2011, 2012, Bessho+ 2014, Shuster+ 2014, 2015, Cheng+ 2015

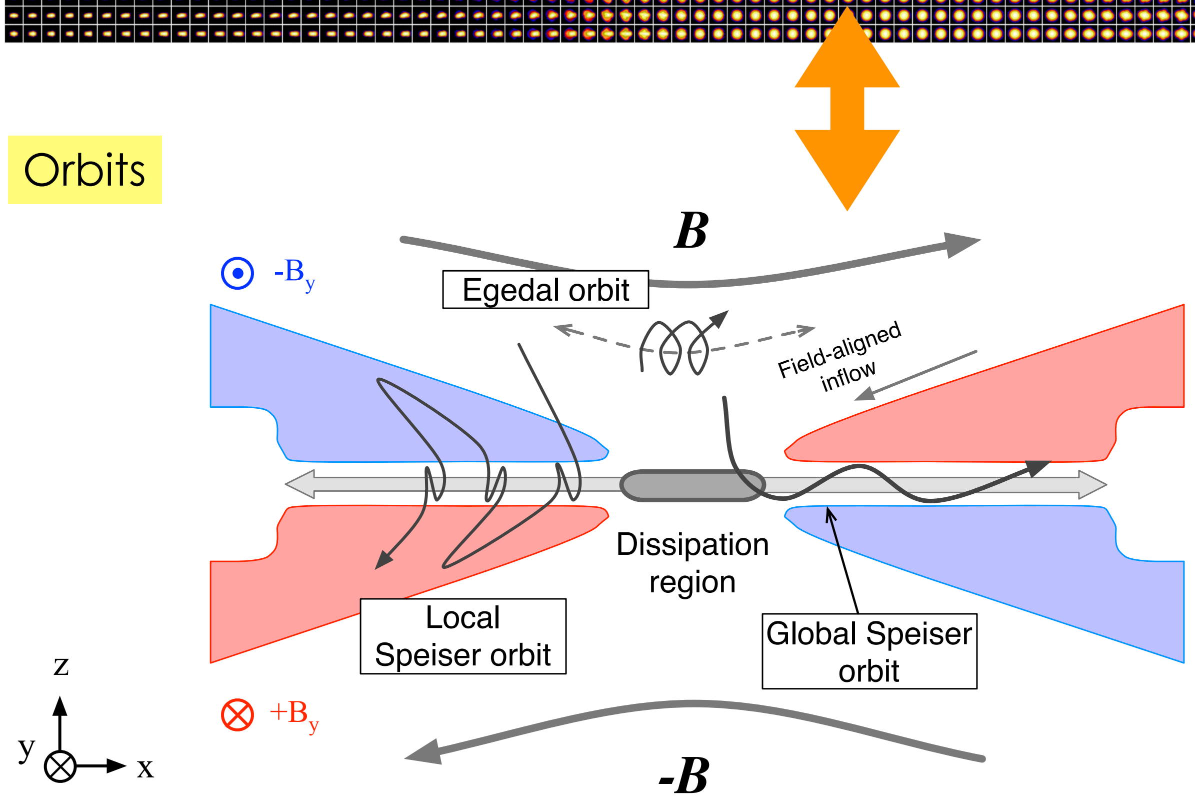

6x4

Electron VDFs vs electron orbits

VDFs



Orbits



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

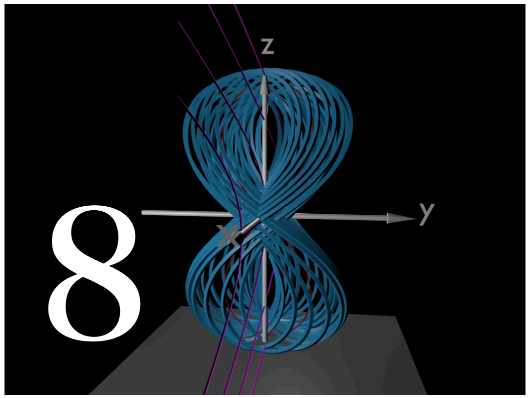
Do we really understand electron orbits?

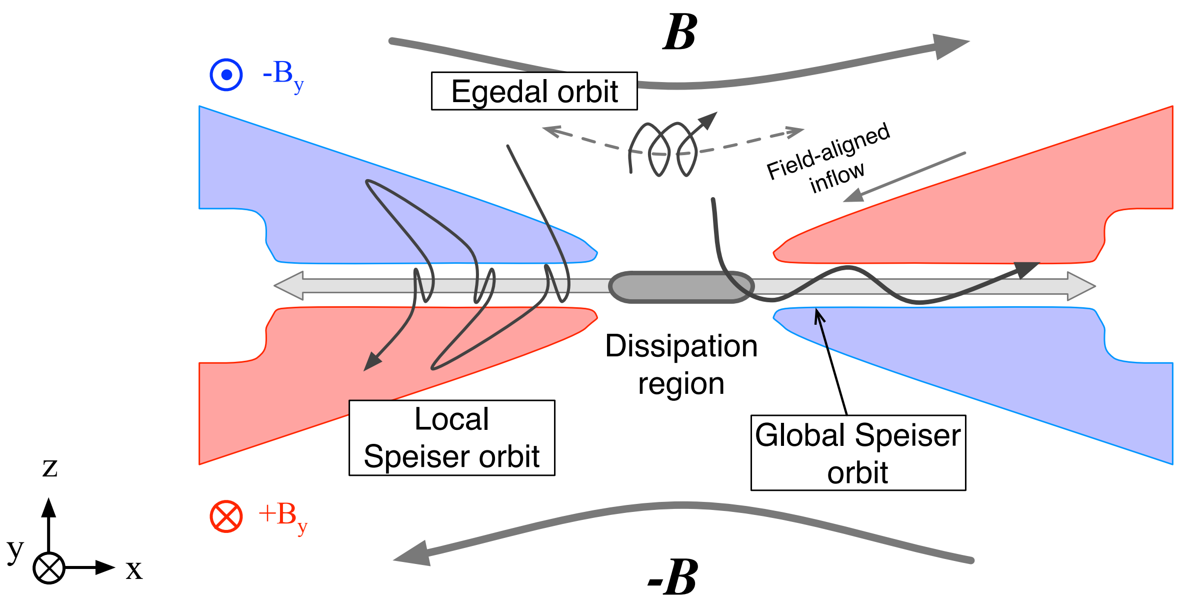
Do we really understand electron orbits?

Ions
- Gyration
- Large gyroradius

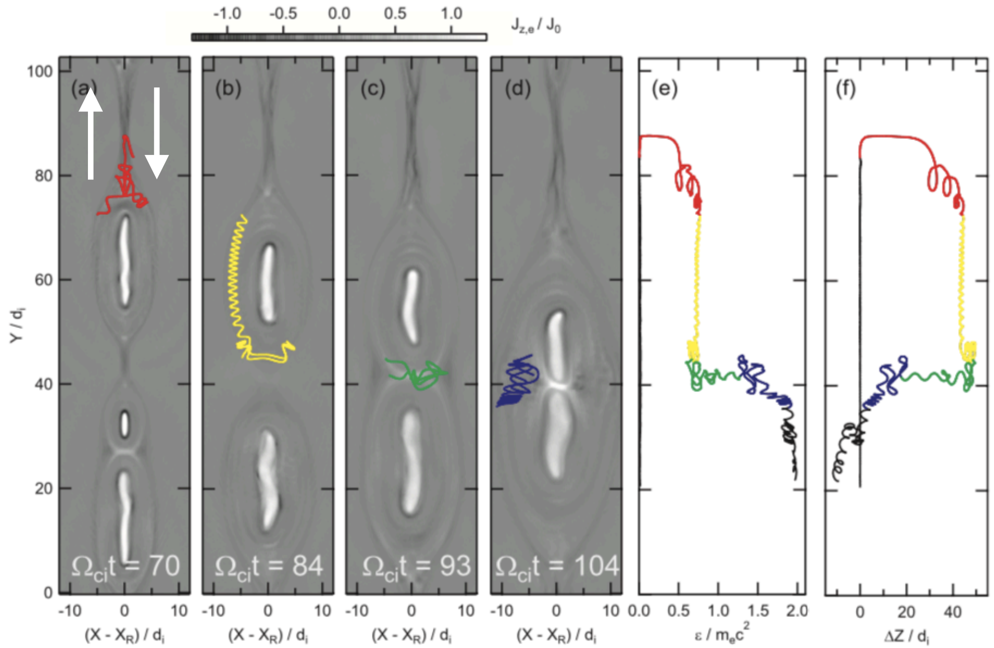
Electrons
- Opposite gyration
- Small gyroradius
- (Response to E field)

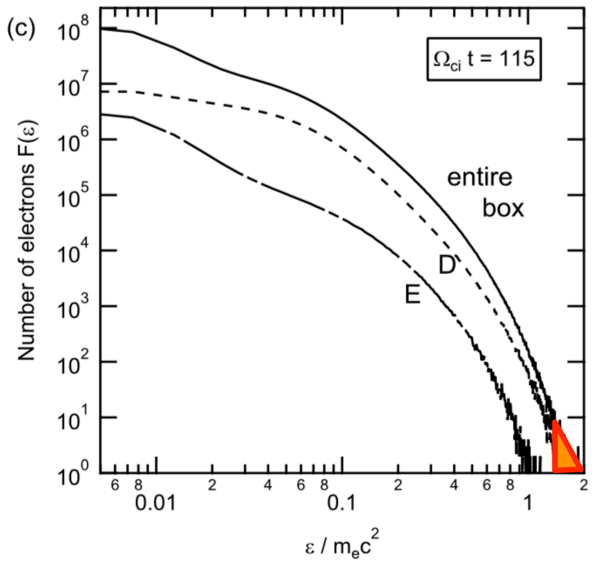
Previous expectation

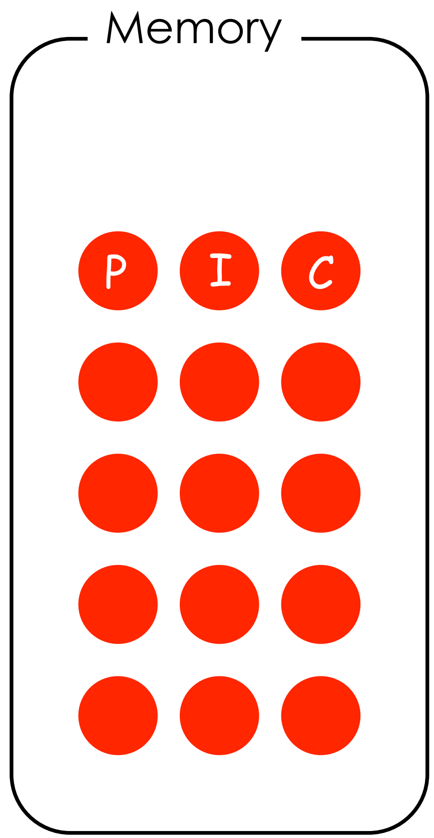




Trajectory analysis in PIC simulations

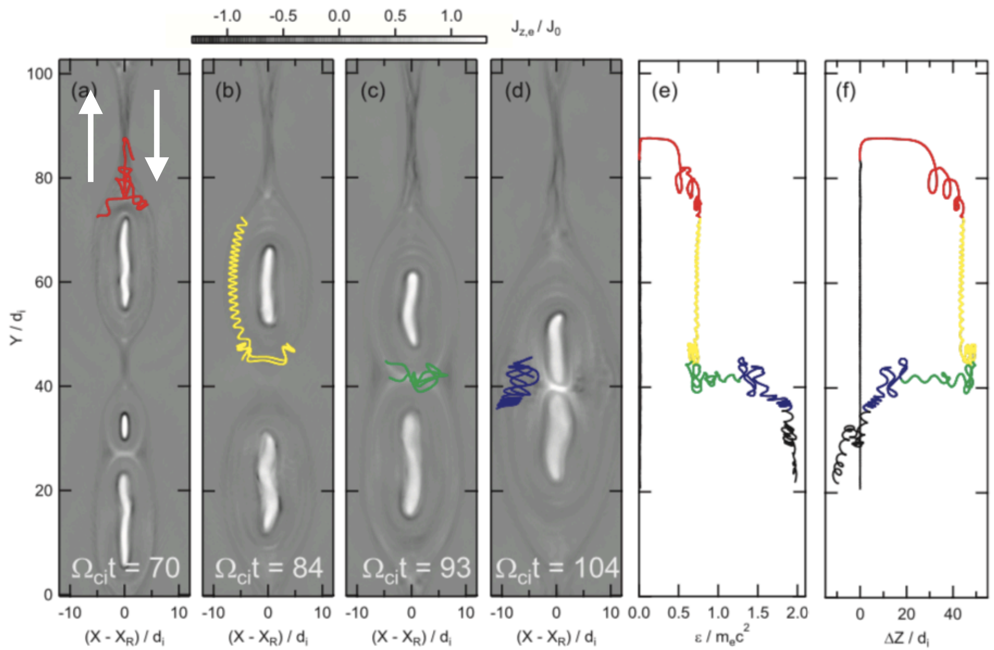


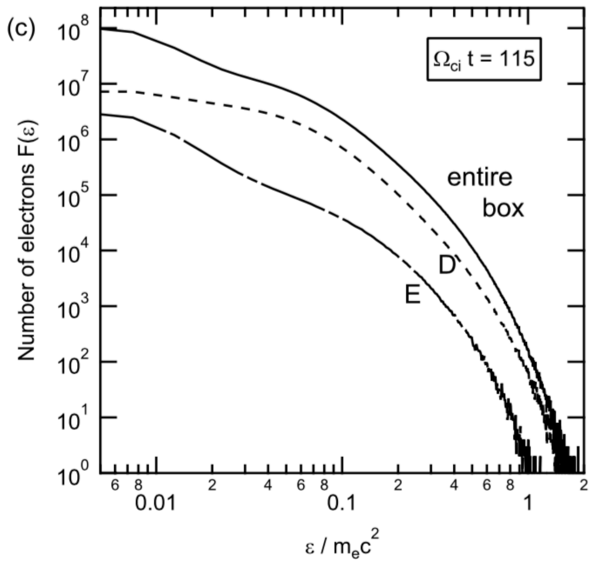


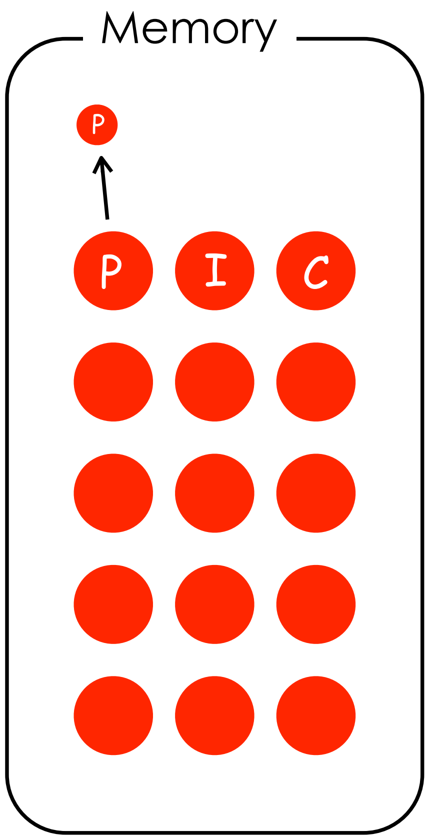


Oka et al. 2010 *ApJ*

Trajectory analysis in PIC simulations







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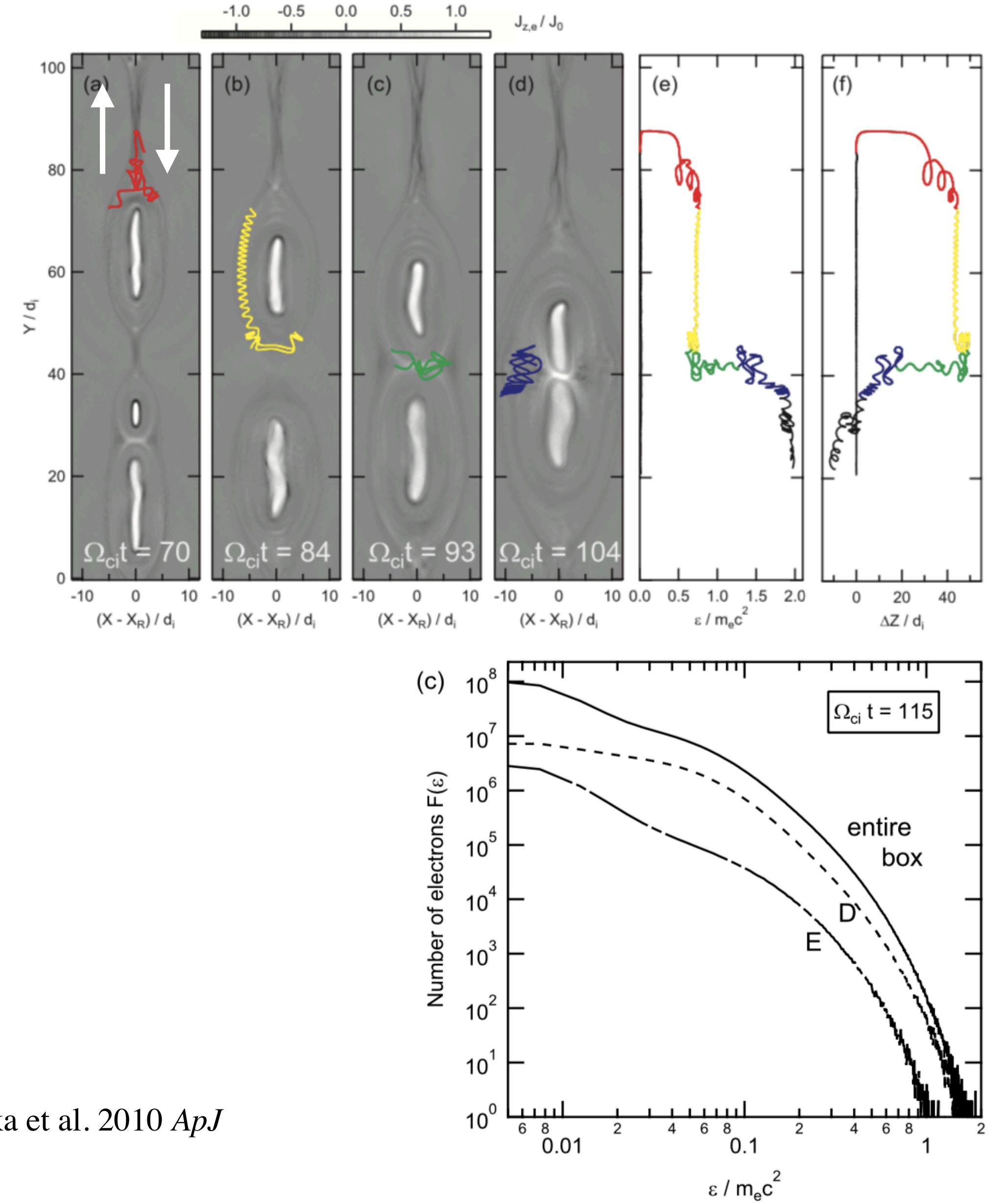
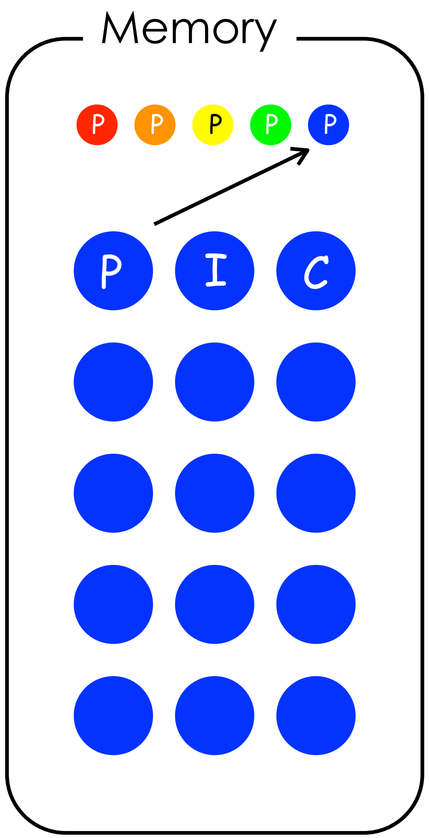
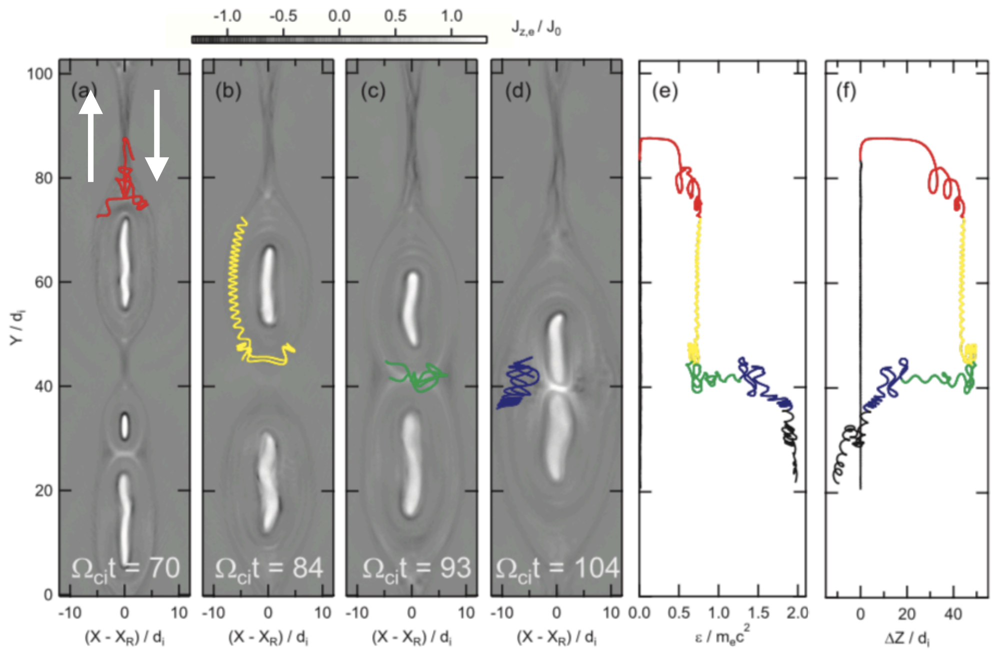
Trajectory analysis in PIC simulations

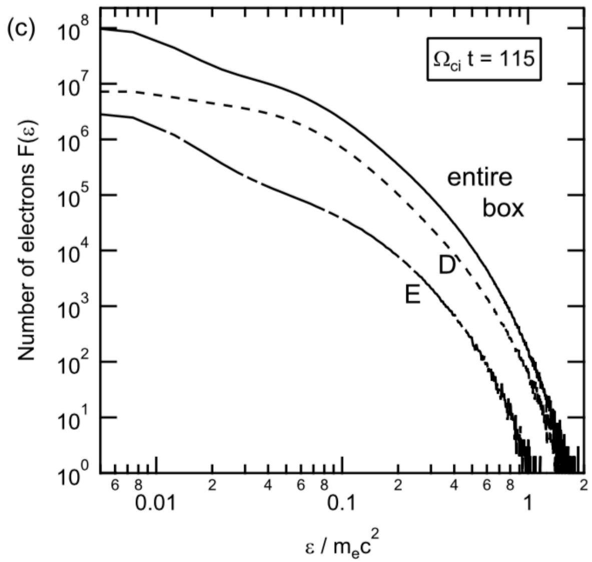




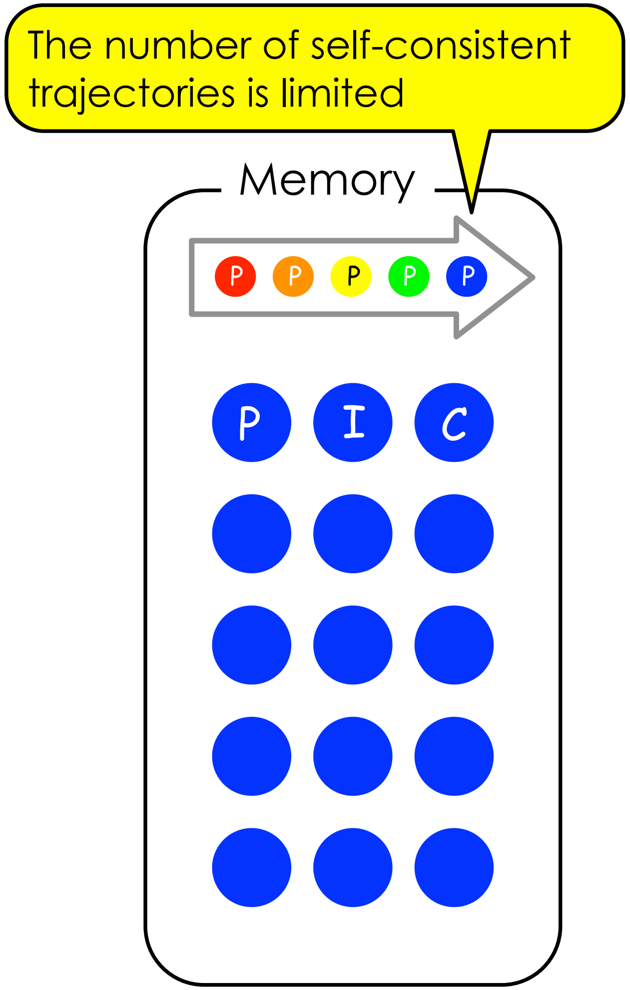
Oka et al. 2010 *ApJ*

Trajectory analysis in PIC simulations

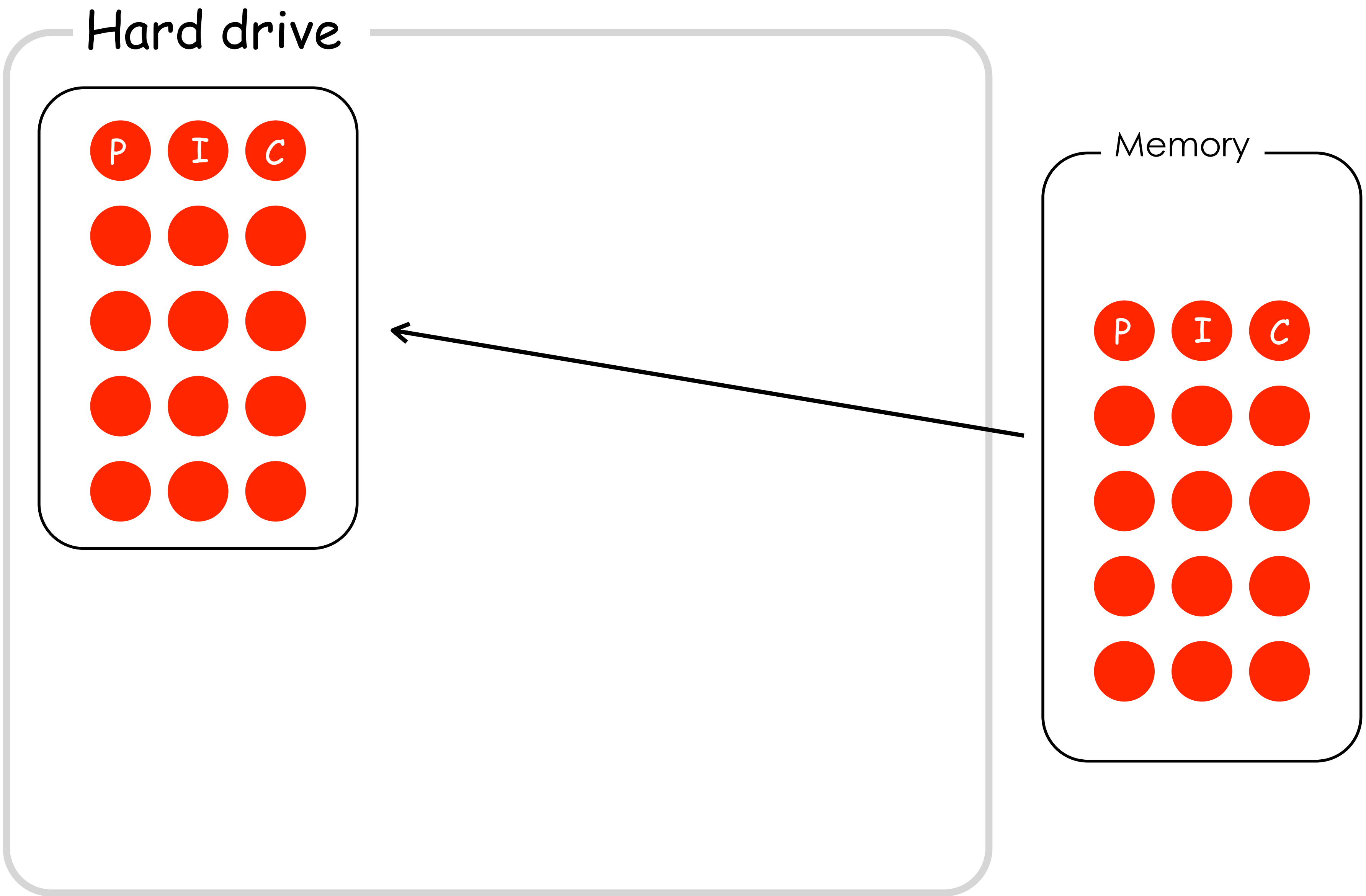




Oka et al. 2010 *ApJ*



Our simple solution



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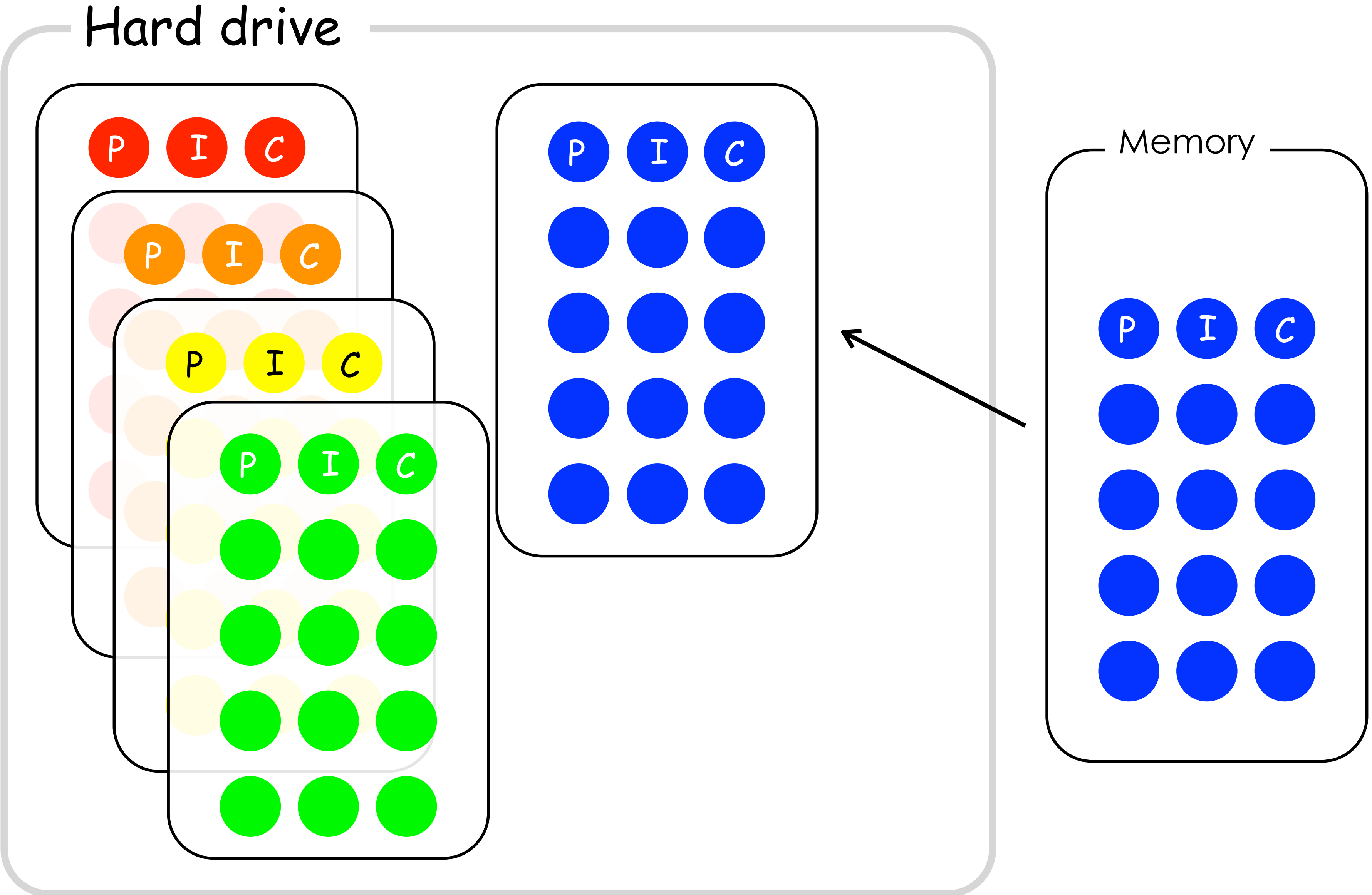
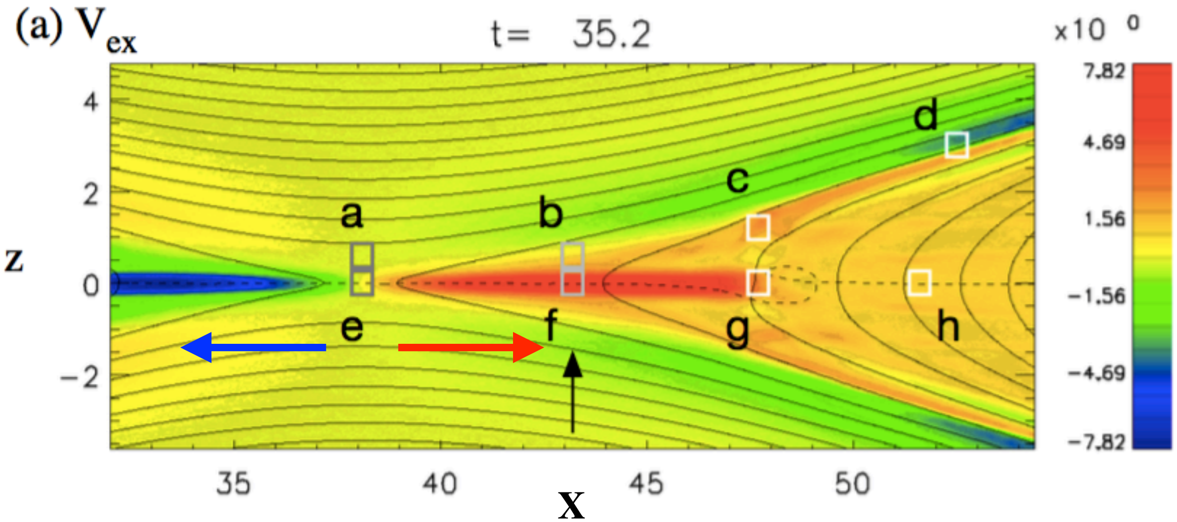
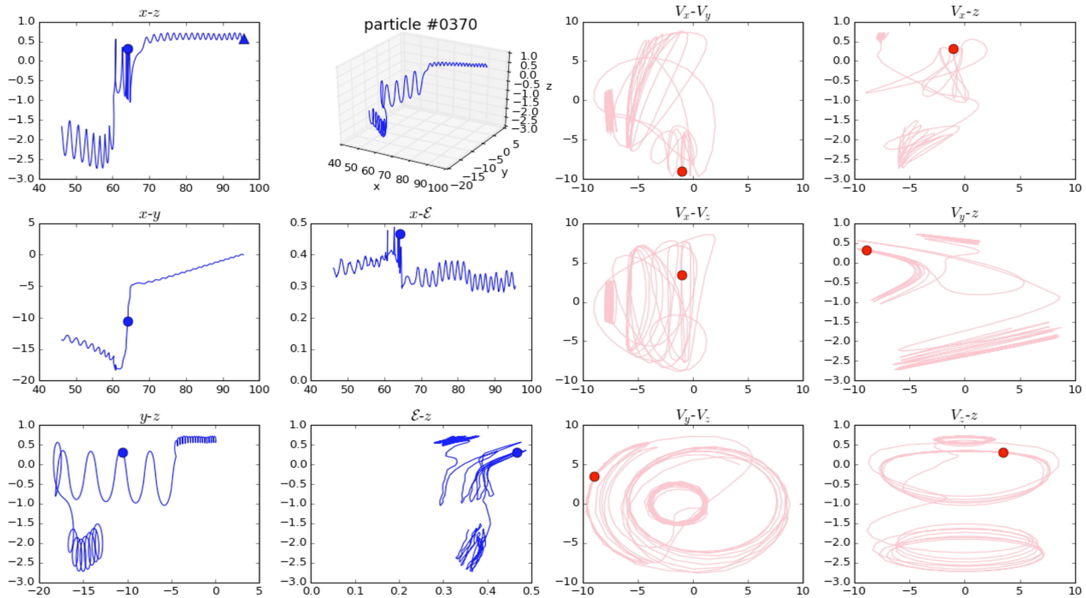


PIC simulation & full Lagrange analysis

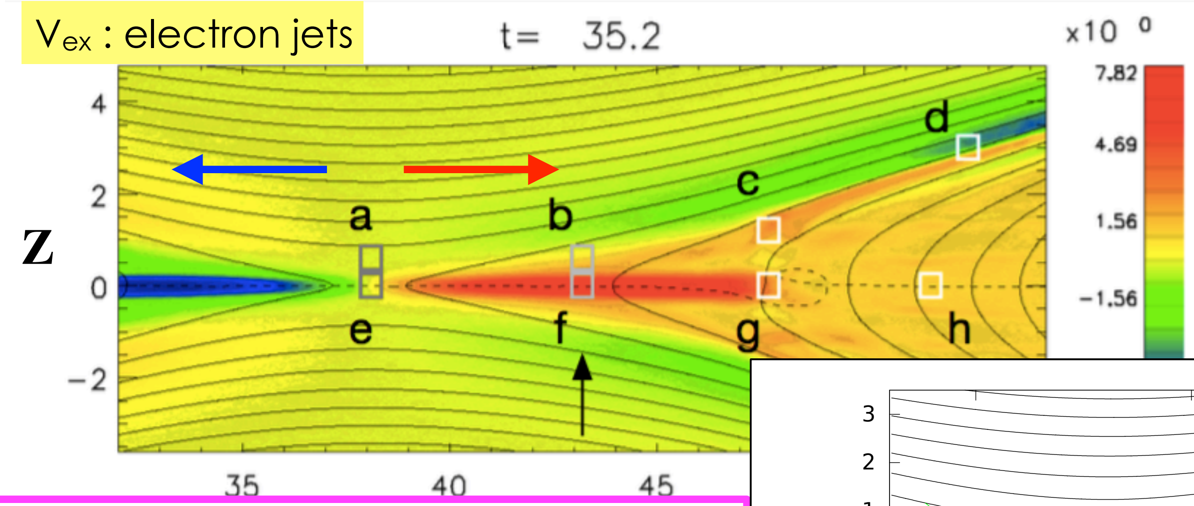


- 2.5D
- m_i/m_e=100
- 76.8 x 38.4 [d_i]
- Harris sheet
- n_{bg}/n_{cs} = 0.2
- 2 x 10^9 particles

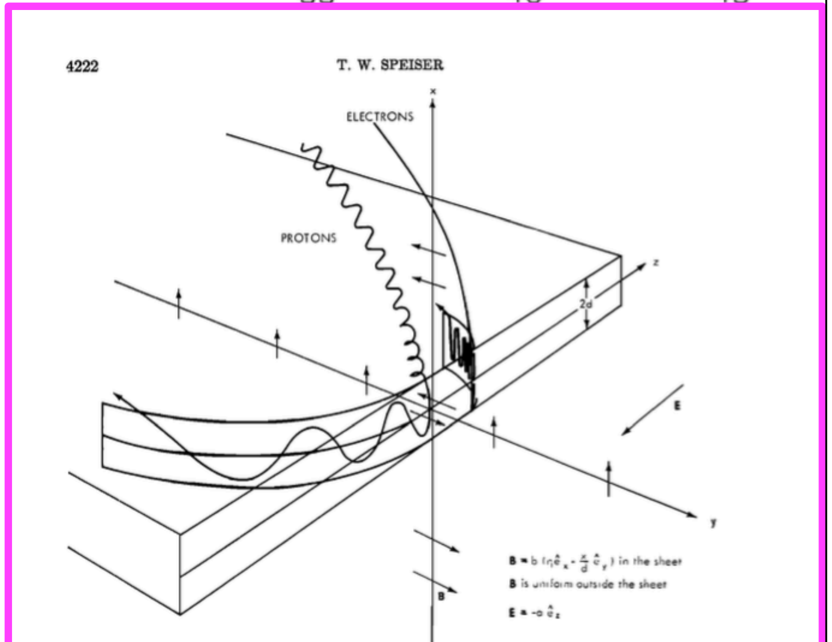


- **20,000,000 electron orbits from 1250 snapshot data**
- 3,000 orbits are inspected with eyes

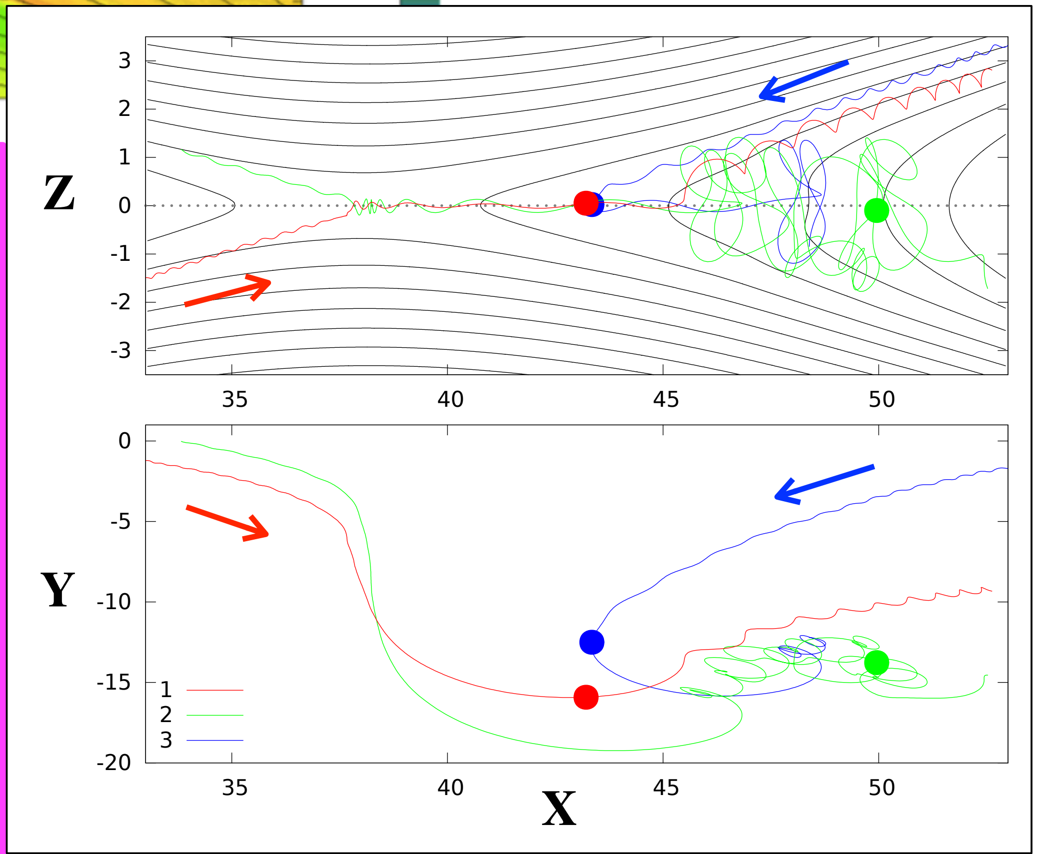
Electron Speiser VDFs in PIC simulation



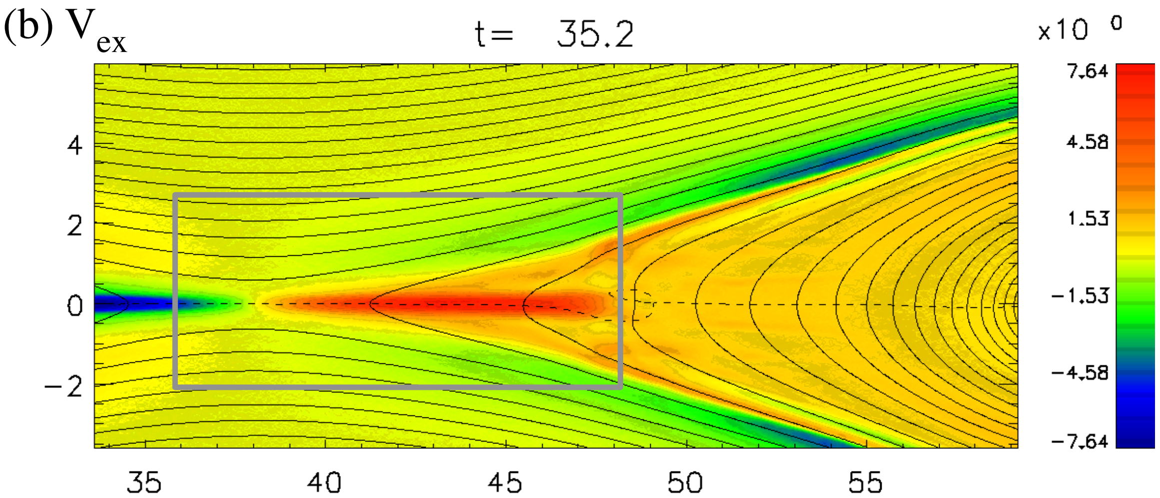
"Global Speiser"
via X-line region
"Local Speiser"
of reflection type

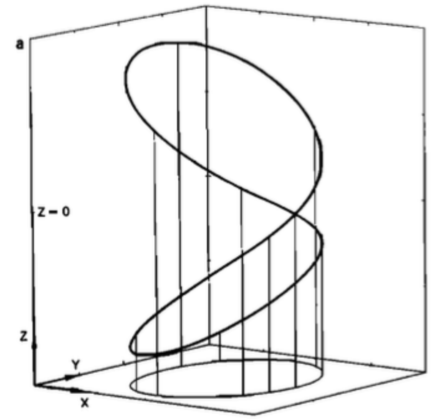


Speiser 1965 JGR

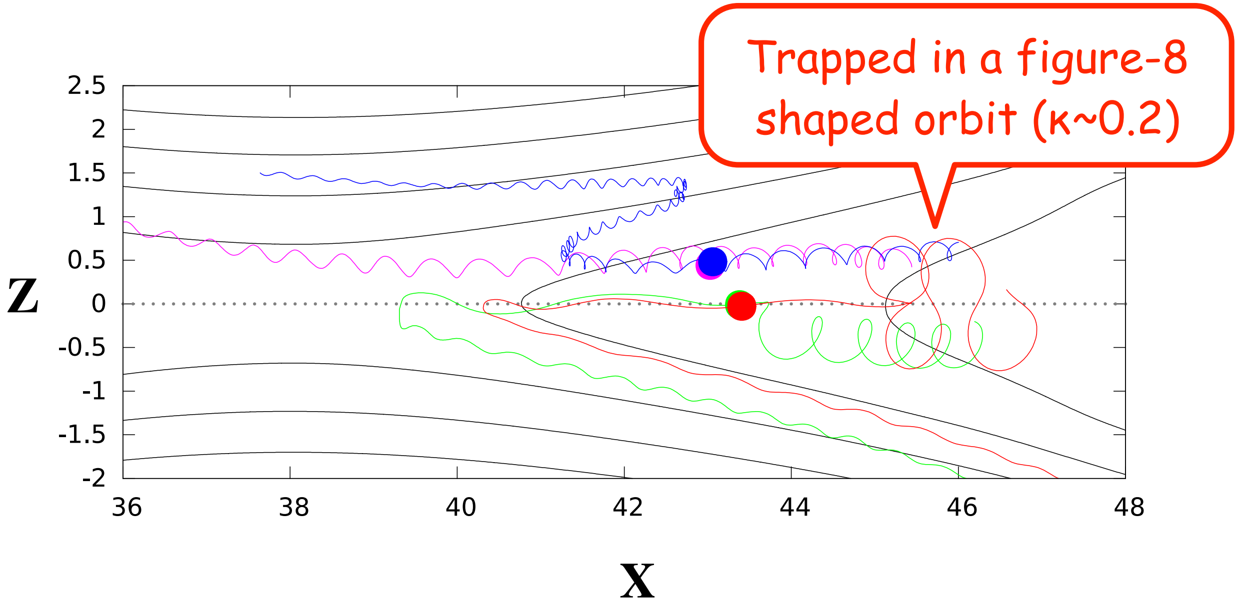


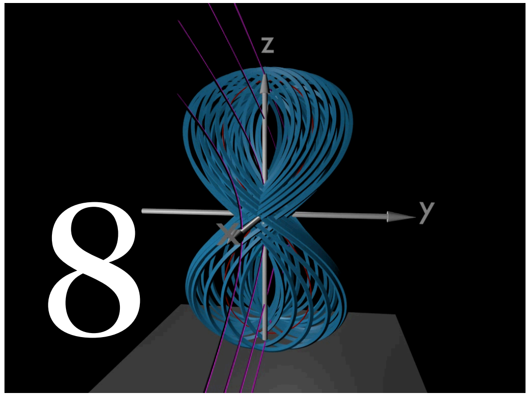
Electron regular orbits





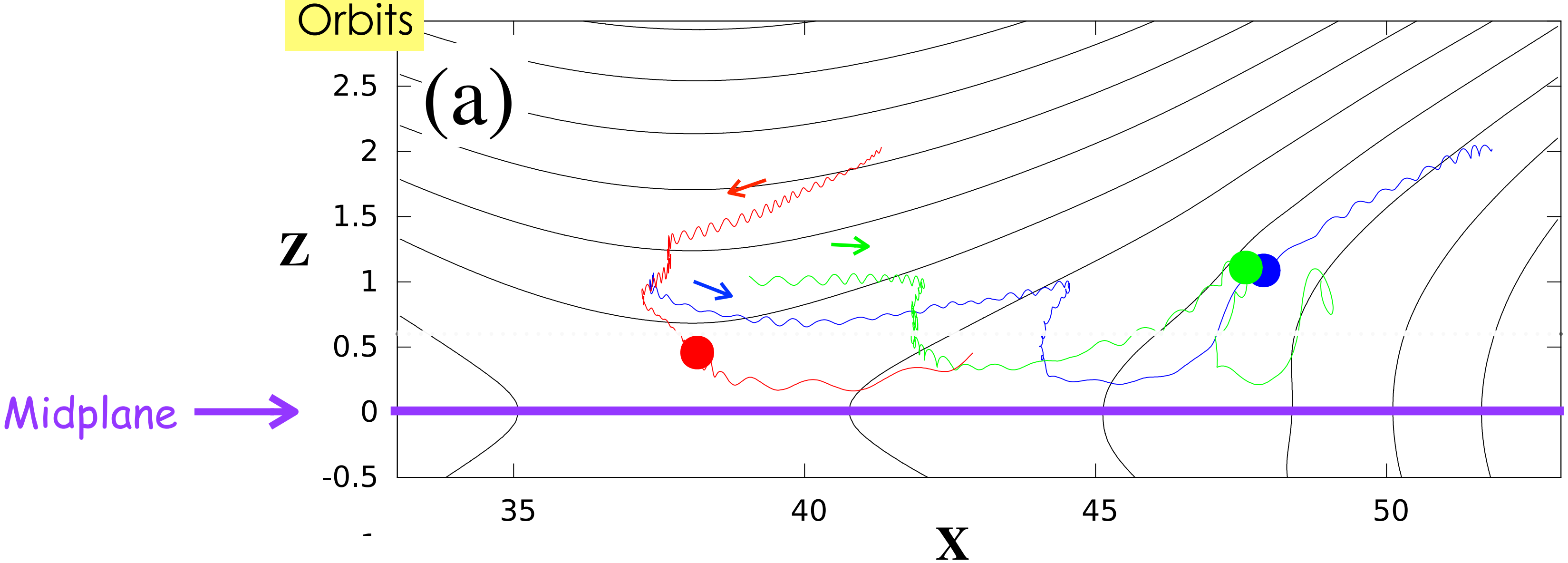
Chen & Palmadesso 1986 *JGR*
Zenitani+ 2013 *PoP*



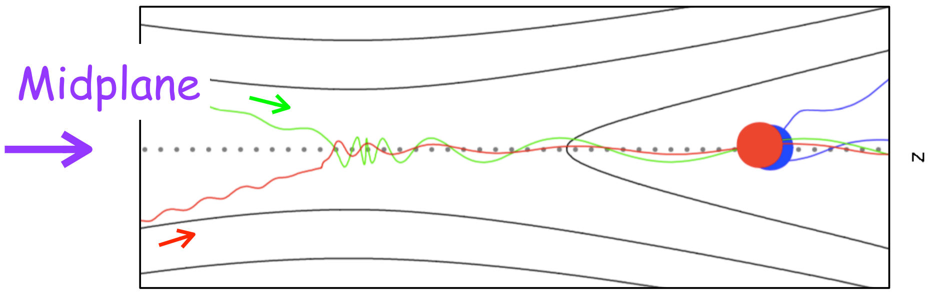


Noncrossing electrons

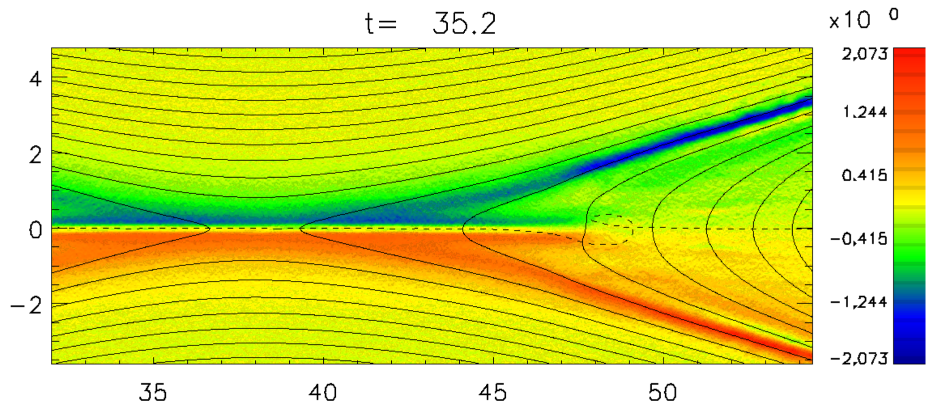
Orbits



Traditional orbits

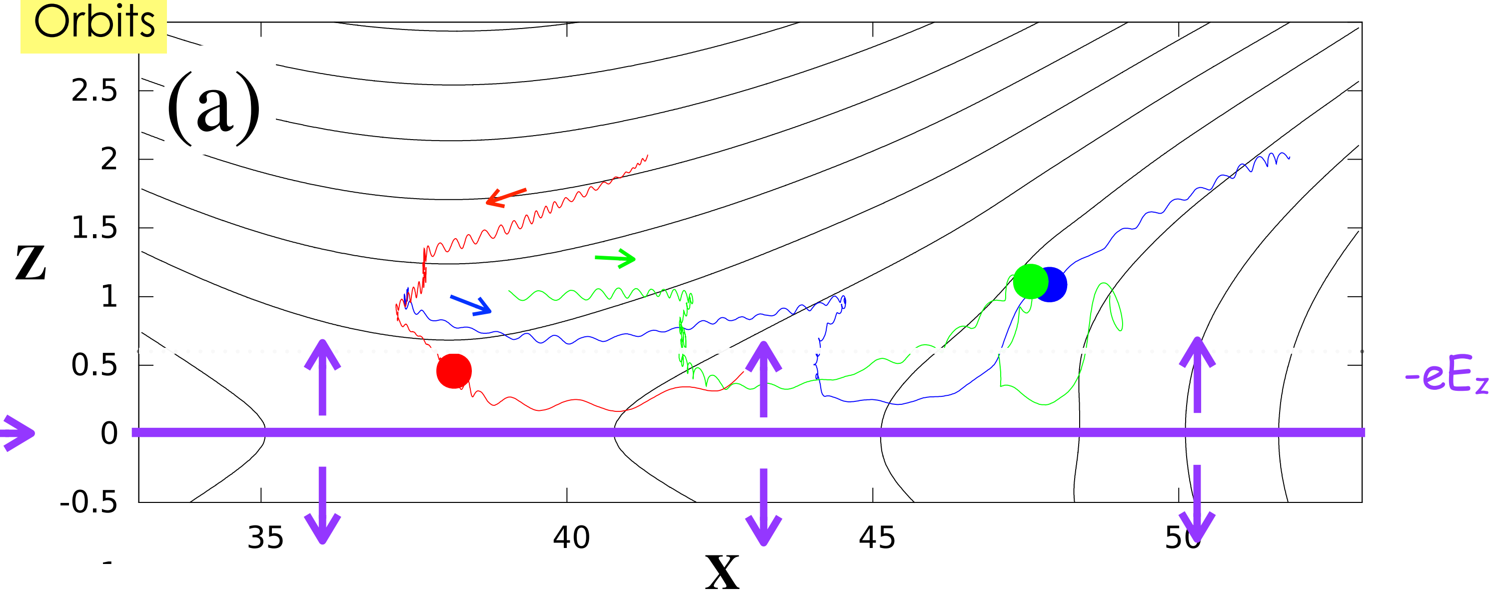


Electrostatic field E_z

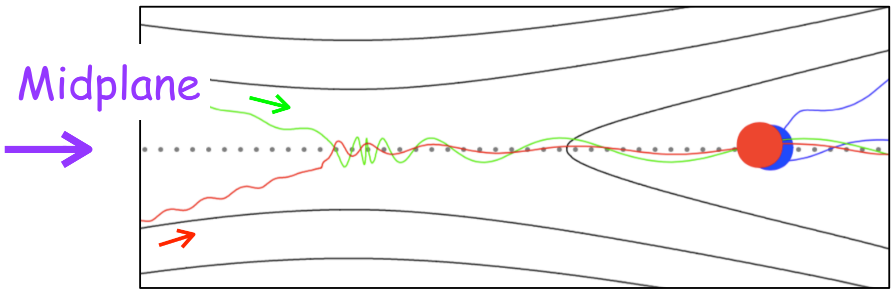


Noncrossing electrons

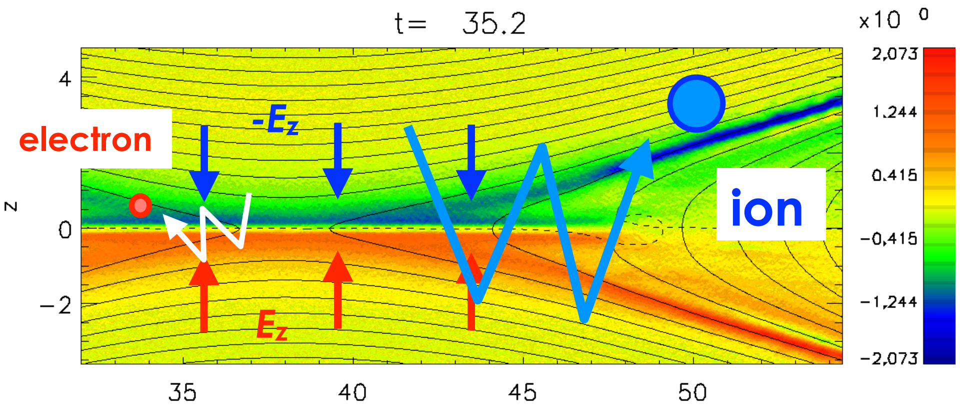
Orbits



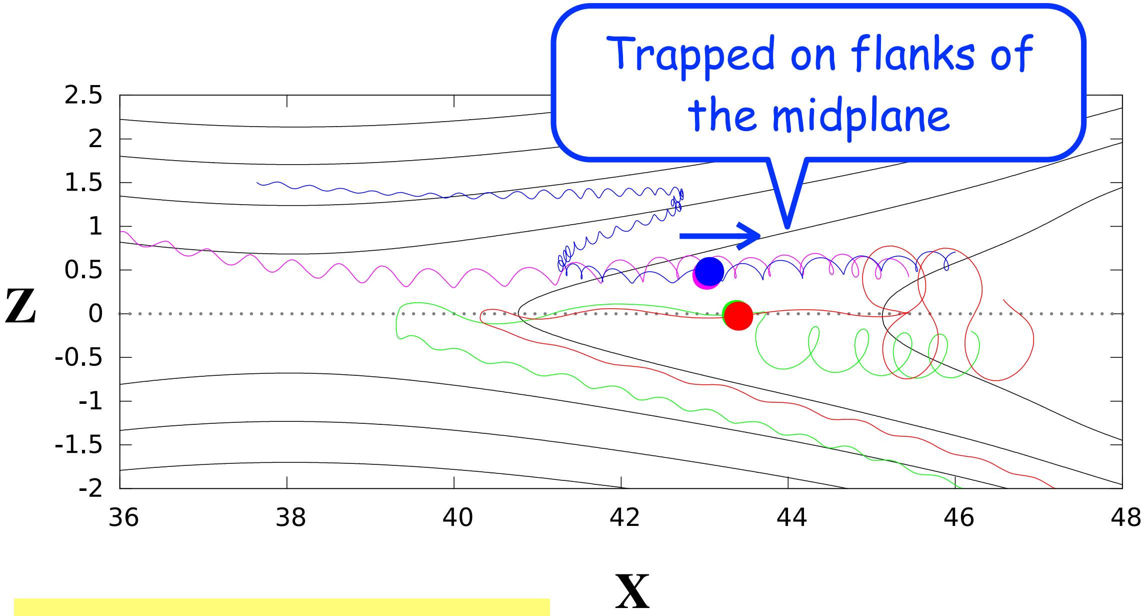
Traditional orbits



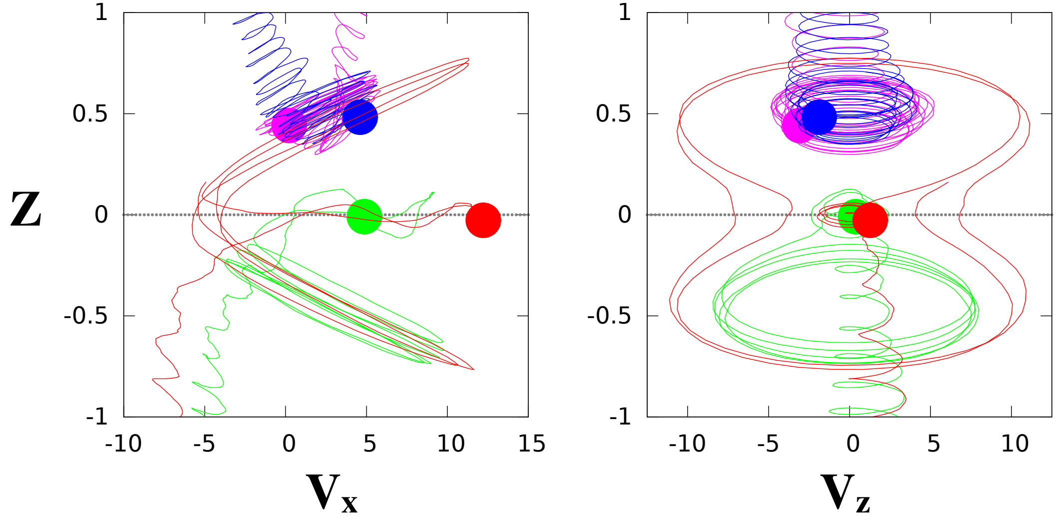
Electrostatic field E_z

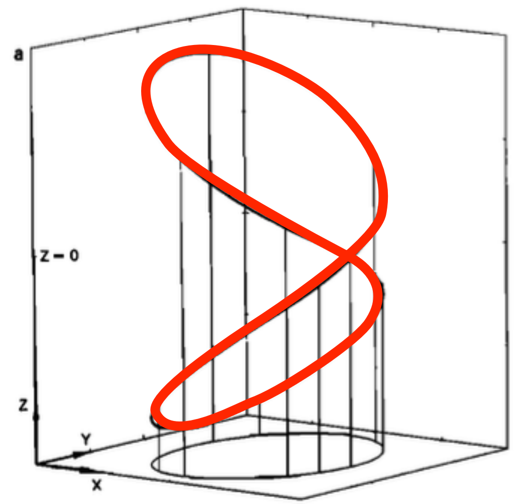


Noncrossing regular orbits



Phase-space diagrams

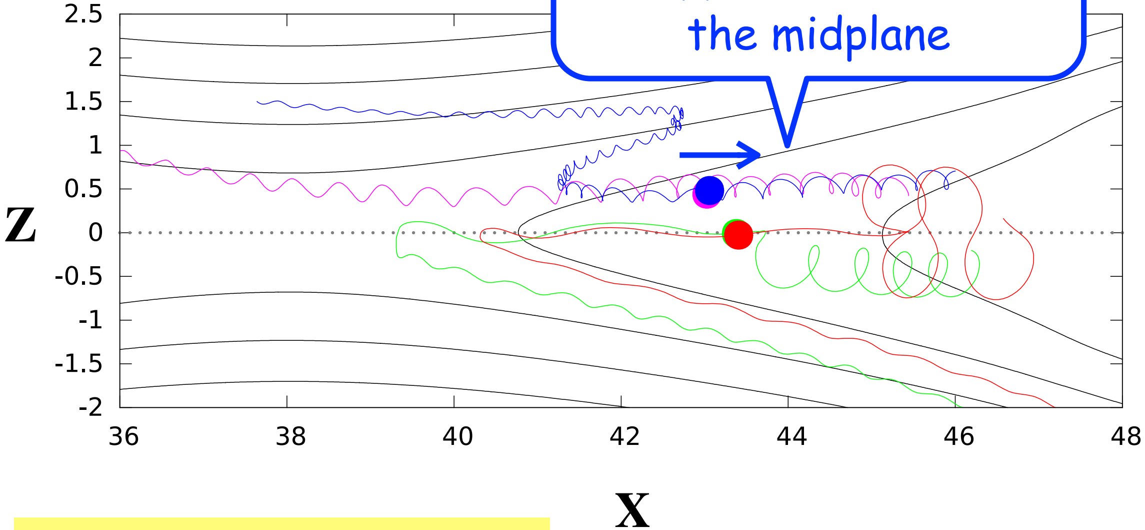


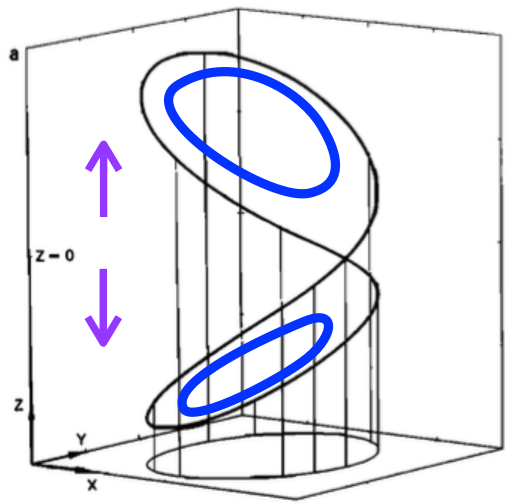


Chen & Palmadesso 1986 *JGR*

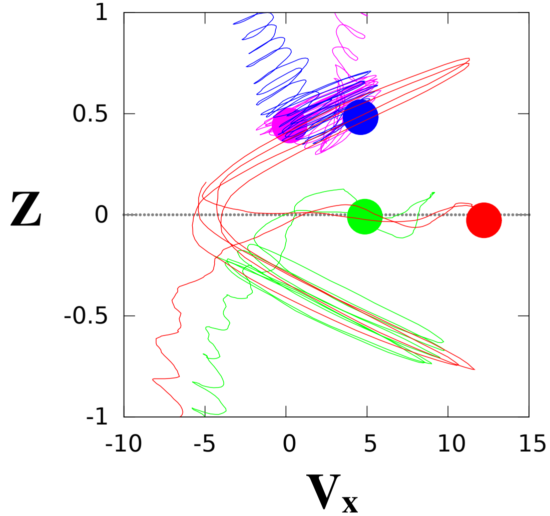
Noncrossing regular orbits

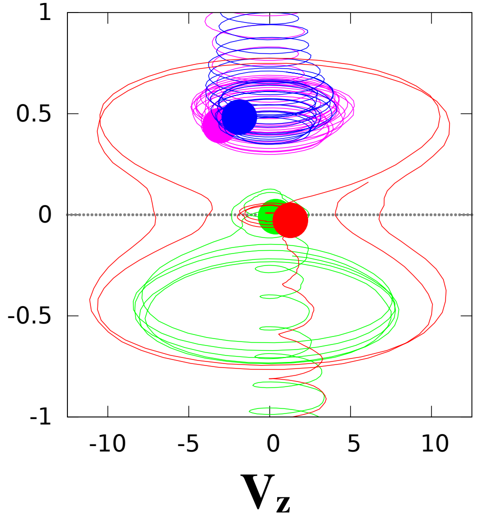
Trapped on flanks of the midplane





Phase-space diagrams



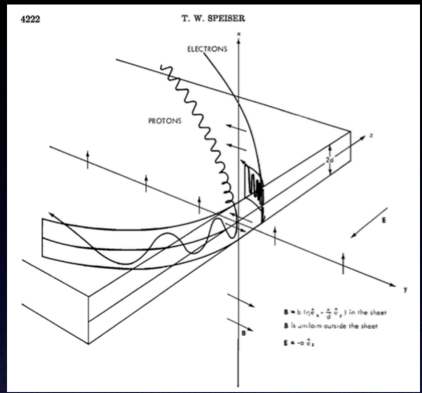


Chen & Palmadesso 1986 *JGR*

Detached from the midplane, due to E_z

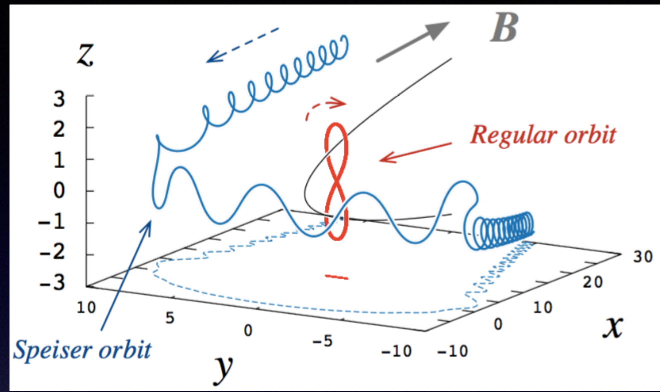
Orbit theories

1965



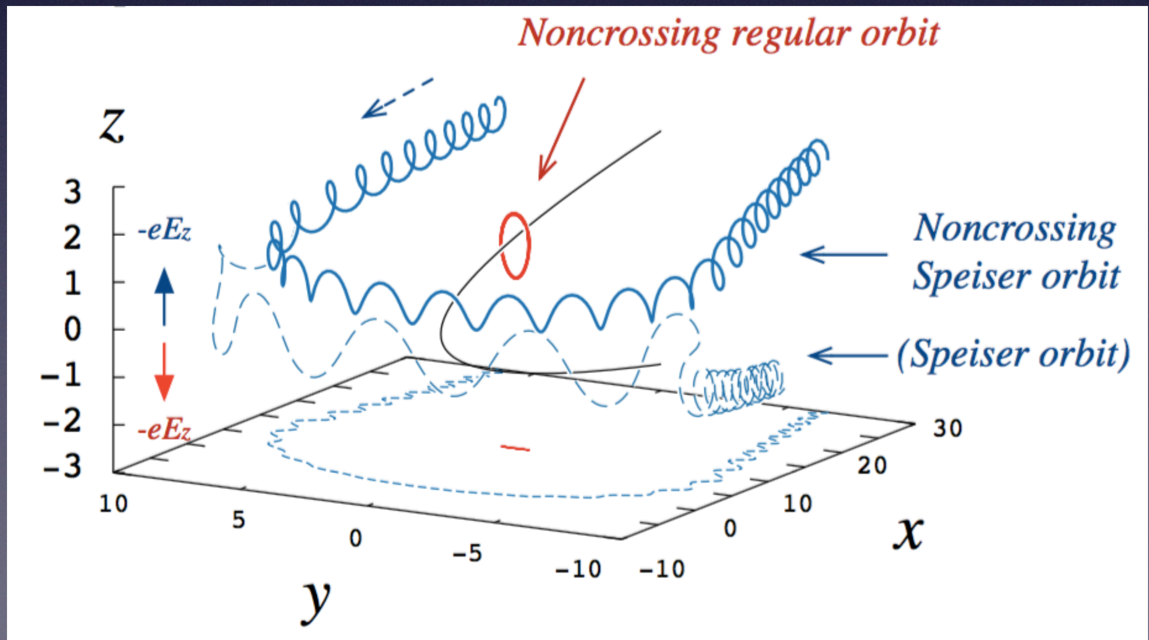
Speiser 1965

1980's



Chen & Palmadesso 1986, Buchner & Zelenyi 1989

2016

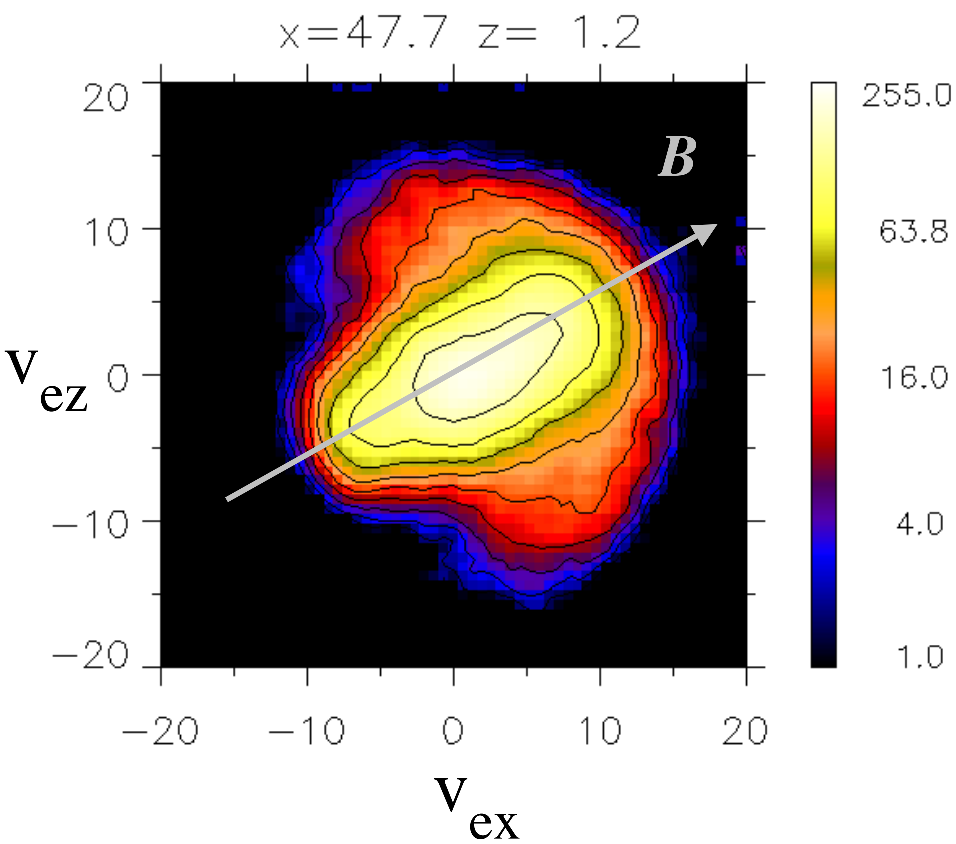


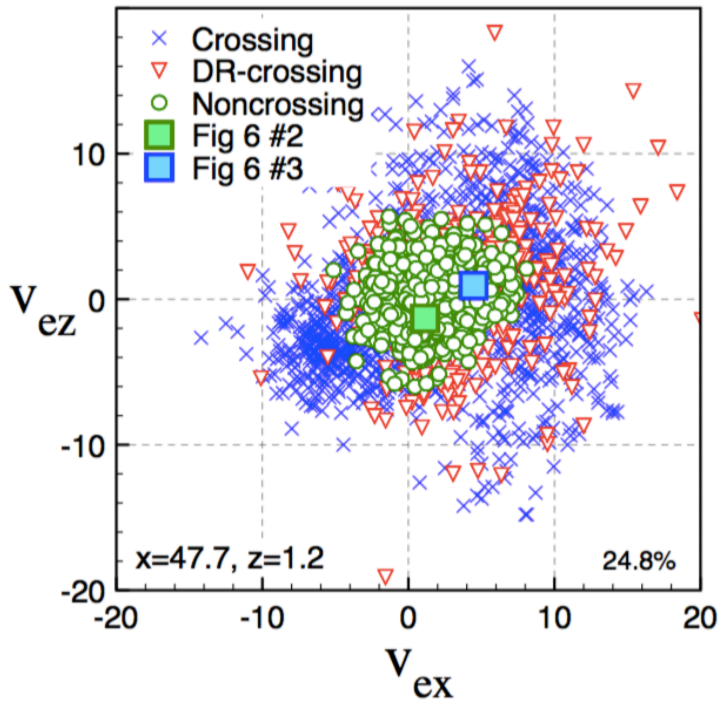
A related theory came out recently: Tsai+ 2017

Zenitani & Nagai 2016

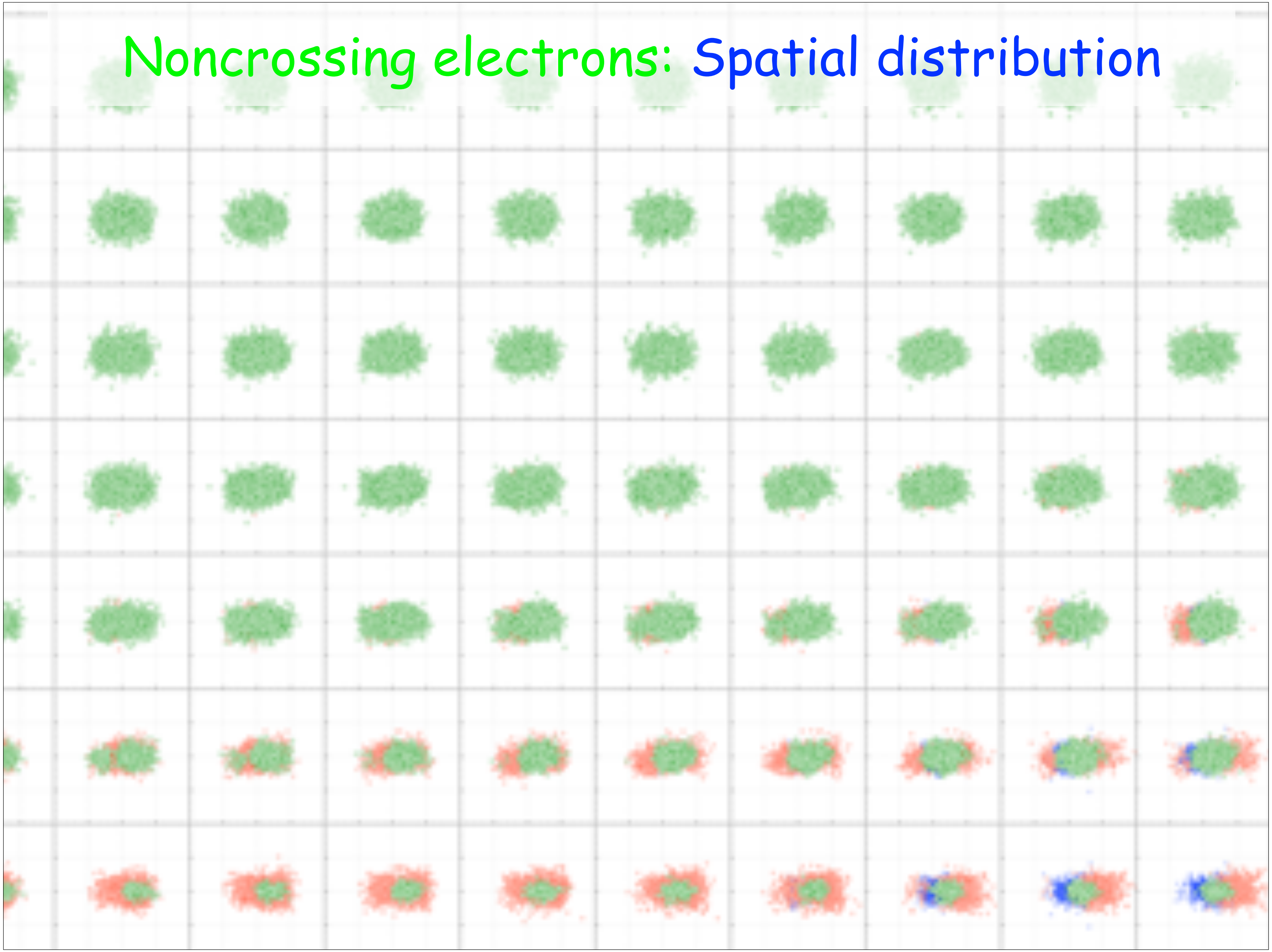
Noncrossing electrons in the VDF

- Cold core is occupied by **noncrossing electrons in green**

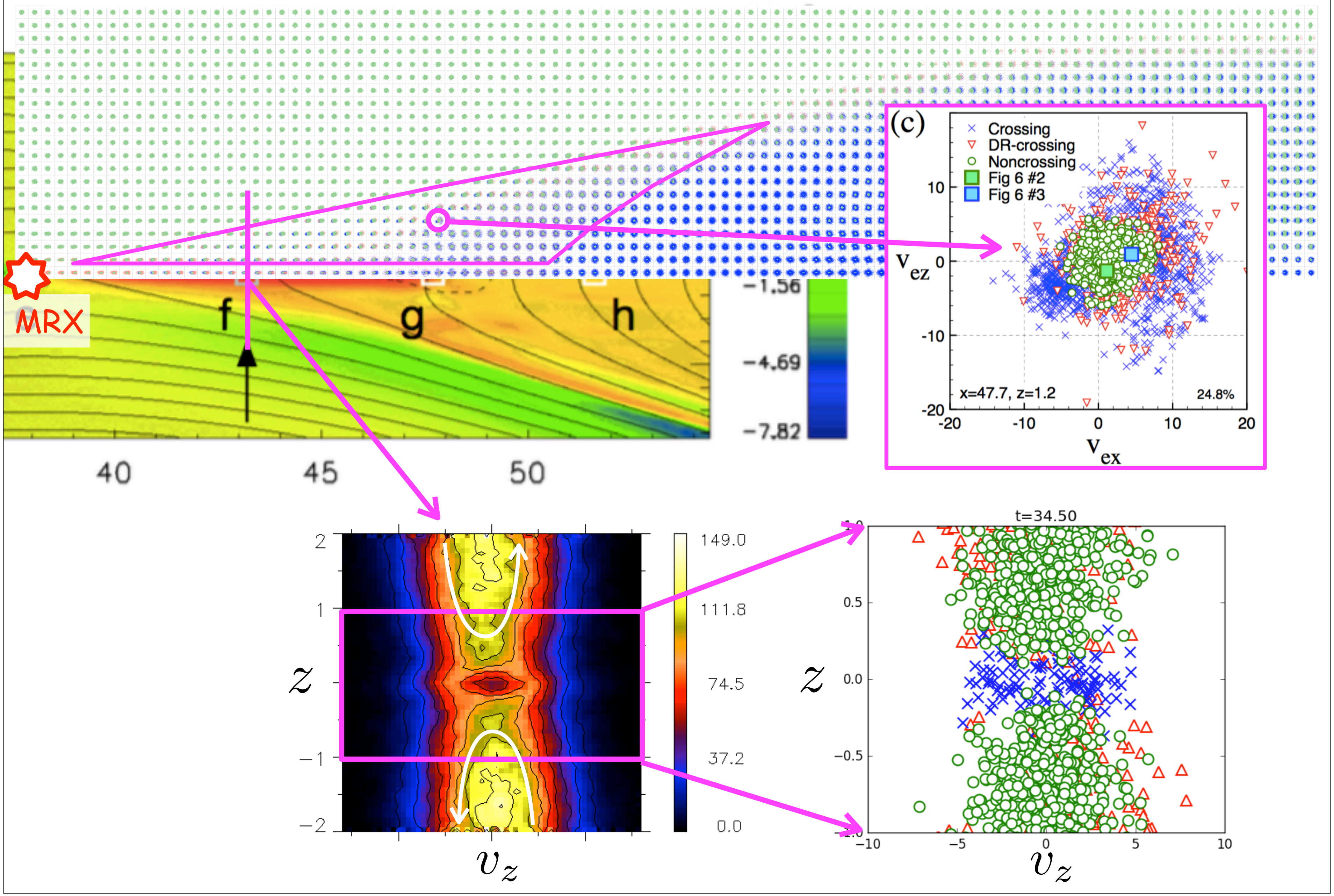




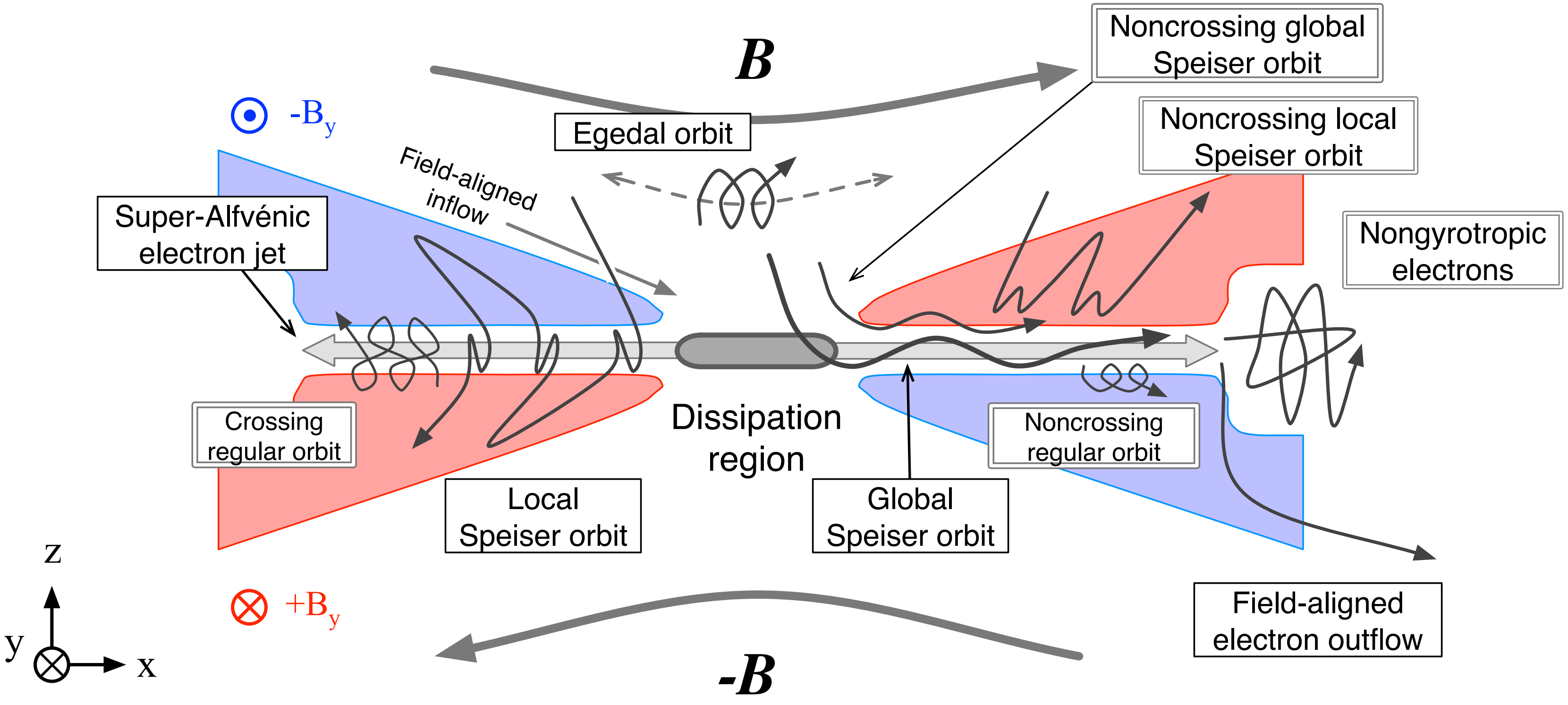
Noncrossing electrons: Spatial distribution



Noncrossing electrons: majority in number



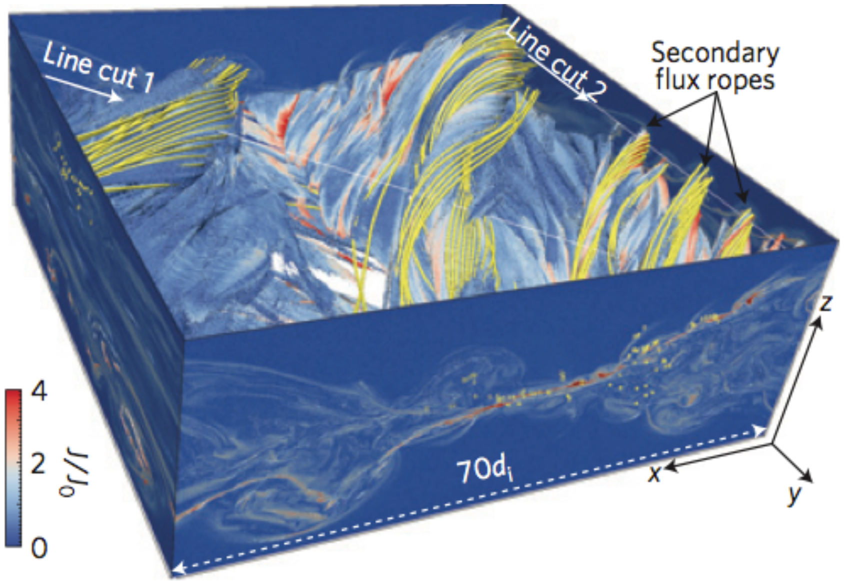
State-of-art picture of electron orbits



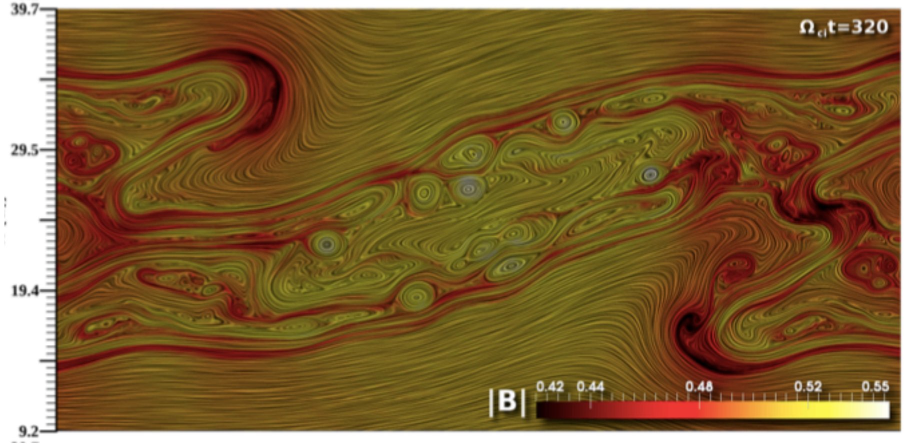
Zenitani & Nagai, *Physics of Plasmas* **23**, 102102 (2016)

PIC シミュレーション研究の課題

- 2010年代　大規模PICシミュレーションで複雑かつ乱流的描像が見えてきた
- 2015年〜　MMS衛星が電子運動論スケールのプラズマ観測を開始
- 流体量解析＋粒子加速研究に行き詰まり感 → さらに進んだ解析で突破
  - 乱流、分布関数、軌道（Zenitani & Nagai 2016）
  - 粒子データを活かした解析



Daughton et al. 2011 *Nature Phys.*



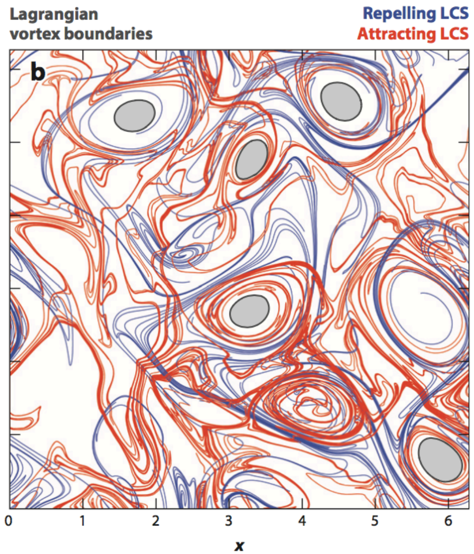
Karimabadi et al. 2013 *Phys. Plasmas*

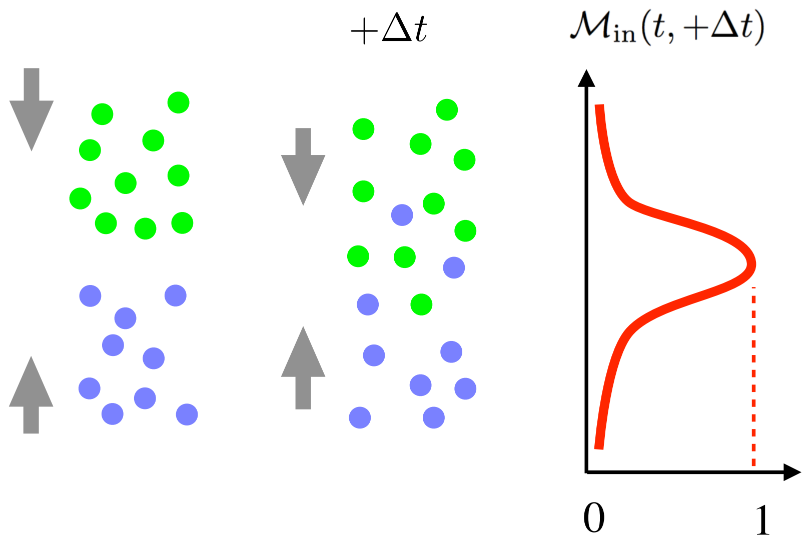
粒子データの活用：プラズマ混合度

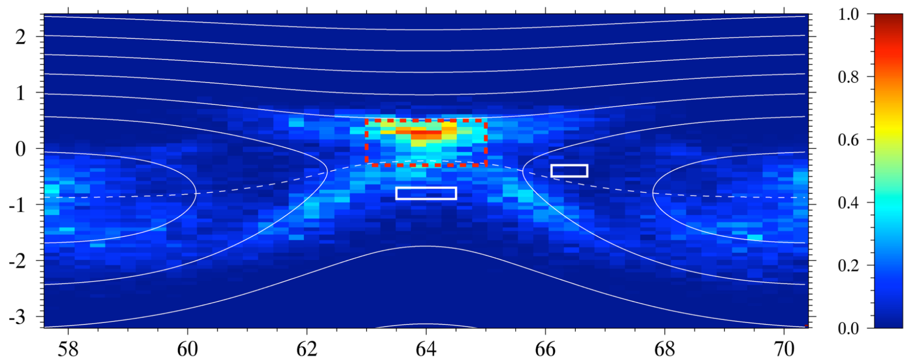
Lagrangian
Coherent
Structure

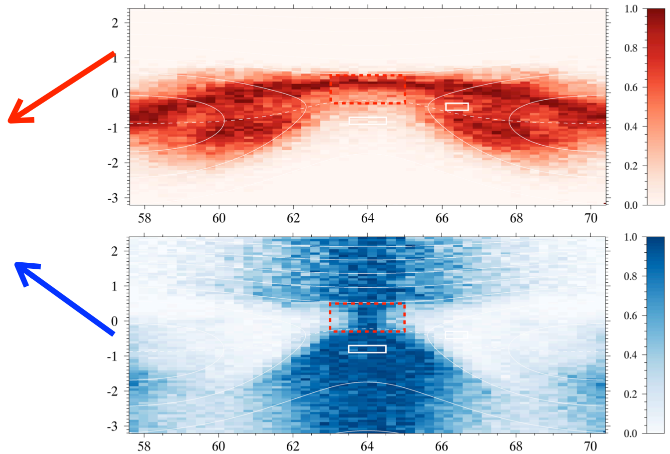
Attracting boundary

Repelling boundary







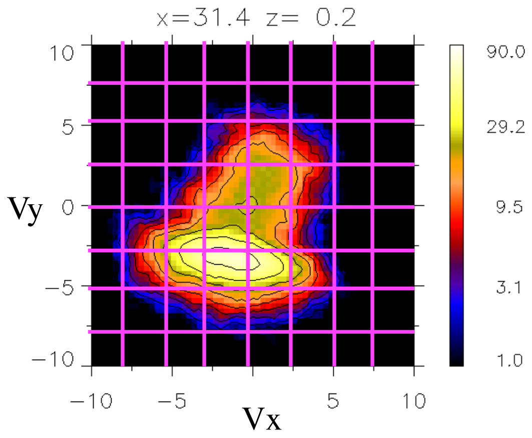


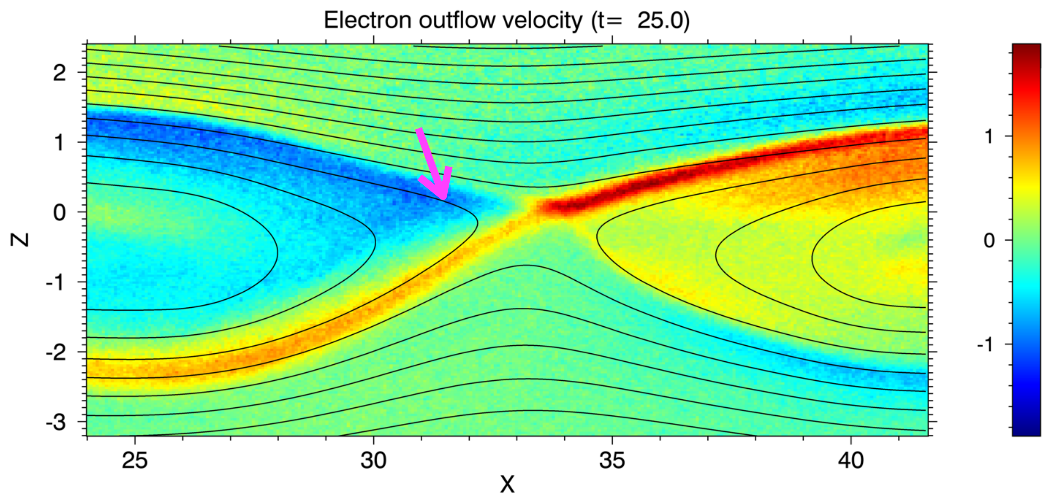
電子混合度

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

Zenitani et al. 2017 JGR

粒子データの活用：エントロピー

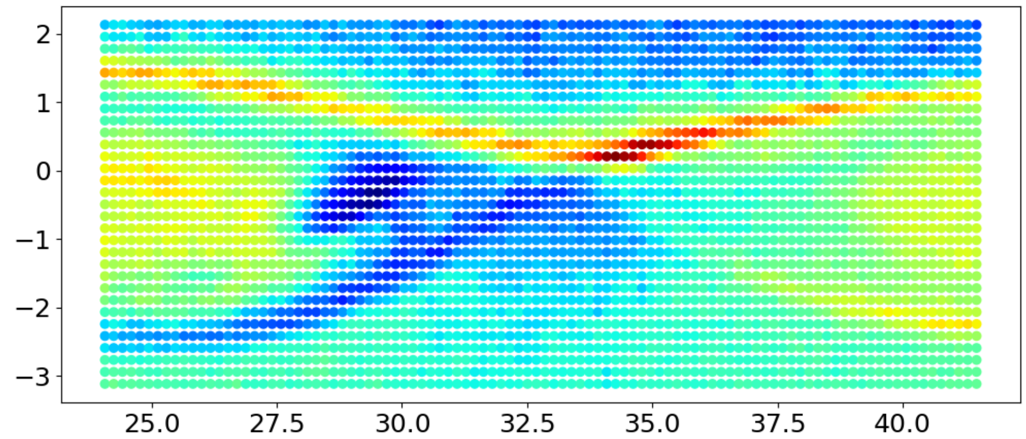




(Shannon) エントロピー

$$-\sum_i p_i \log p_i$$

- p_i：３次元速度空間内の確率密度
- H関数（-f log f）も評価可能
  →現象の不可逆性を議論するヒント

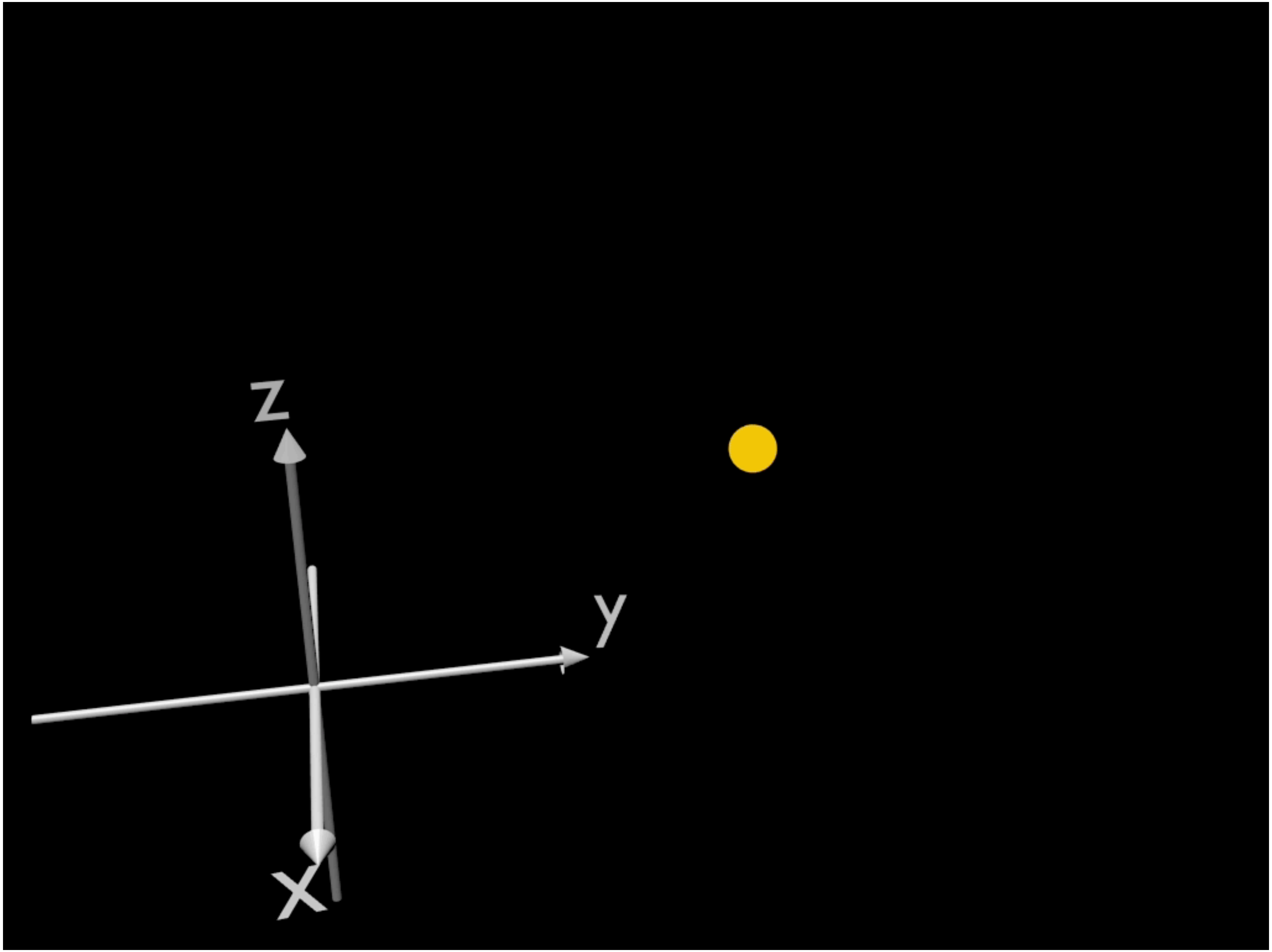


Zenitani et al. 2018d in prep.

Summary

- 0. M.H.D.
  - Particle acceleration and electron dynamics
- 1. Ion dynamics
  - Poincaré-map analysis has revealed figure-8 shaped orbits
- 2. Electron dynamics
  - Full-Lagrange analysis has revealed many new electron orbits
  - Noncrossing electrons: majority in number density
- 3. Future direction
  - Better usage of PIC data: Orbits, particle mixing, and entropy…
- References

  - Zenitani, Shinohara, Nagai, & Wada, *Phys. Plasmas* **20**, 092120 (2013)
  - Zenitani & Nagai, *Phys. Plasmas* **23**, 102102 (2016)


z
y
x

Thank you for your attention!