

Dissipation in relativistic pair-plasma reconnection: revisited

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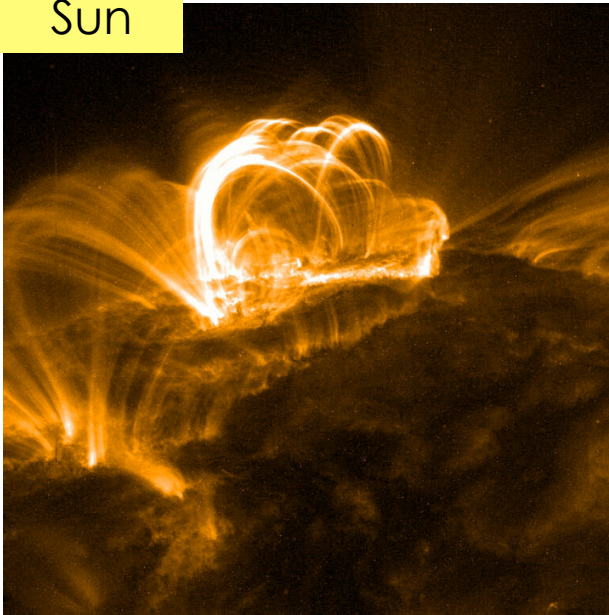
I. Shinohara (JAXA/ISAS), T. Nagai (Tokyo tech), M. Hesse (NASA/GSFC)

Outline

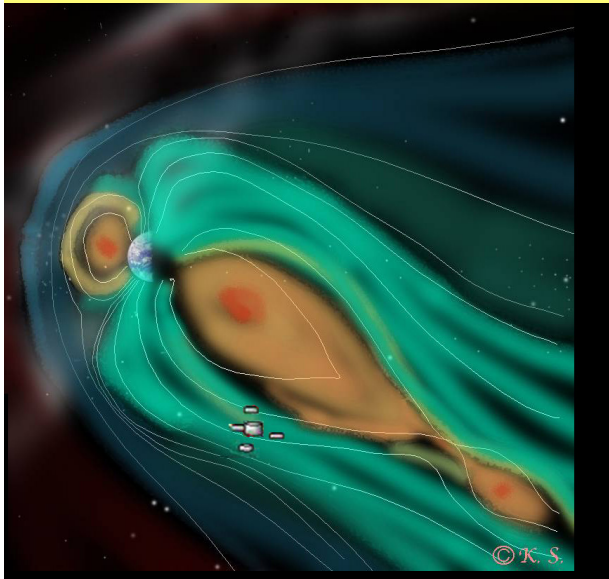
- 1. Dissipation in relativistic pair-plasma reconnection: revisited
 - Ohm's law in a relativistic kinetic plasma
 - Application to 2D PIC simulation of relativistic reconnection
- 2. Electron orbits in nonrelativistic reconnection
 - Fundamental pieces of reconnection system
 - Various electron orbits
 - Implications for particle acceleration
- Appendix: A small tale near Perdue

Magnetic reconnection

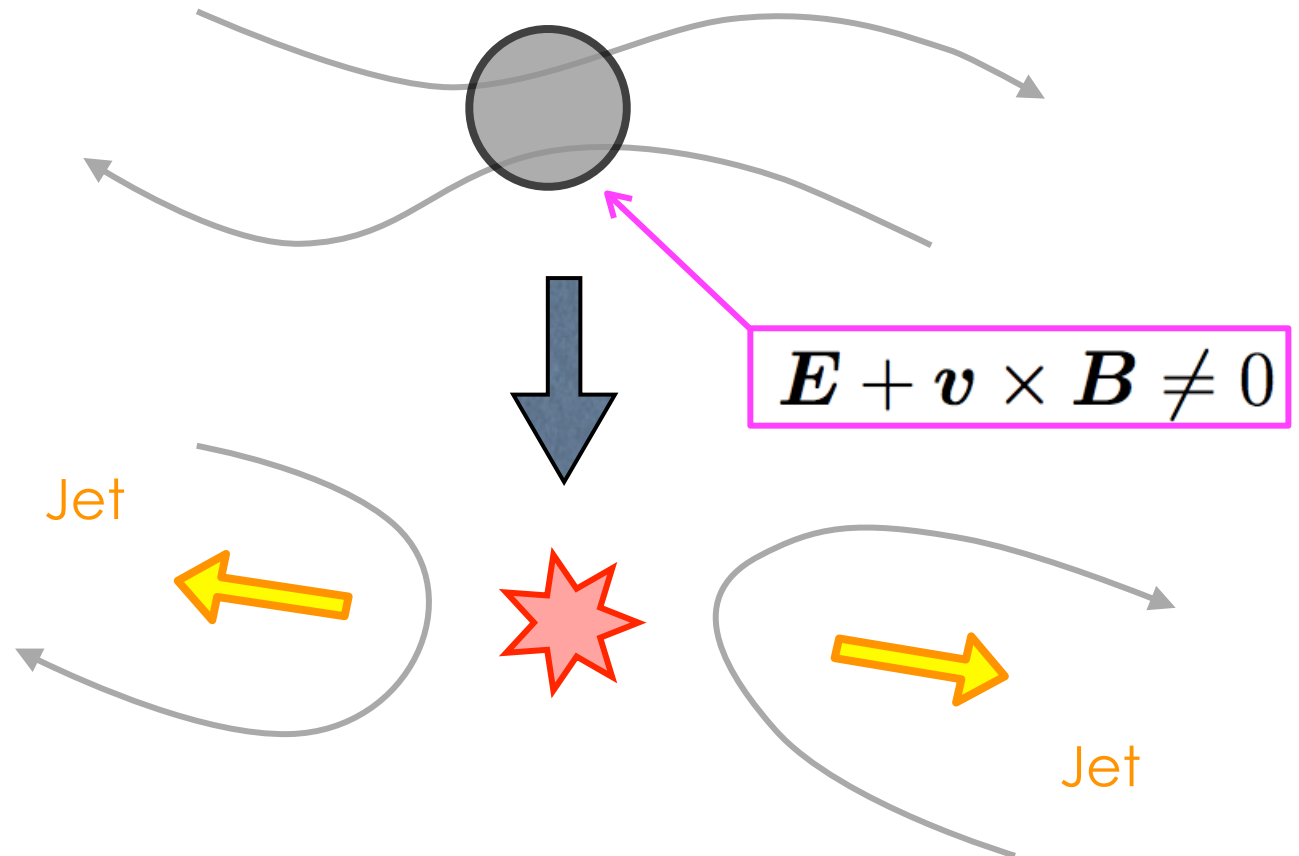
Sun



Earth's Magnetosphere

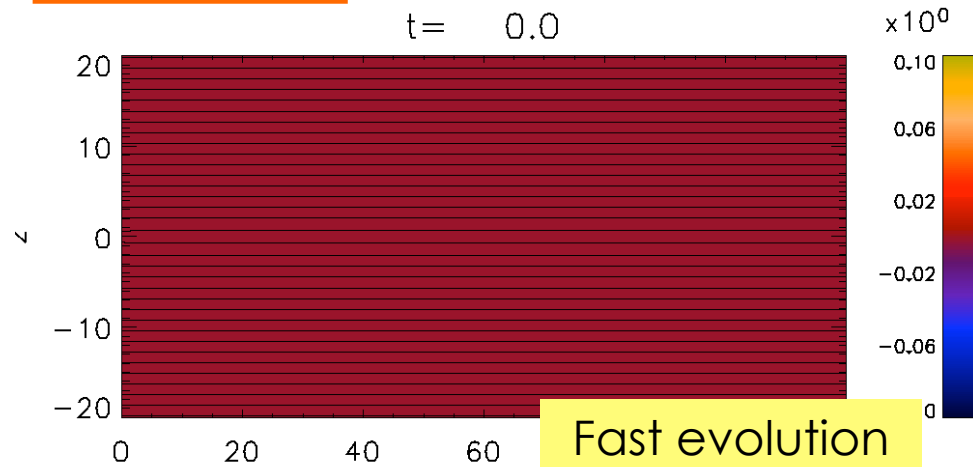


- Ideal MHD condition is violated
- This is necessary to change the topology



Resistive MHD simulations: reconnection is sensitive to η_{eff}

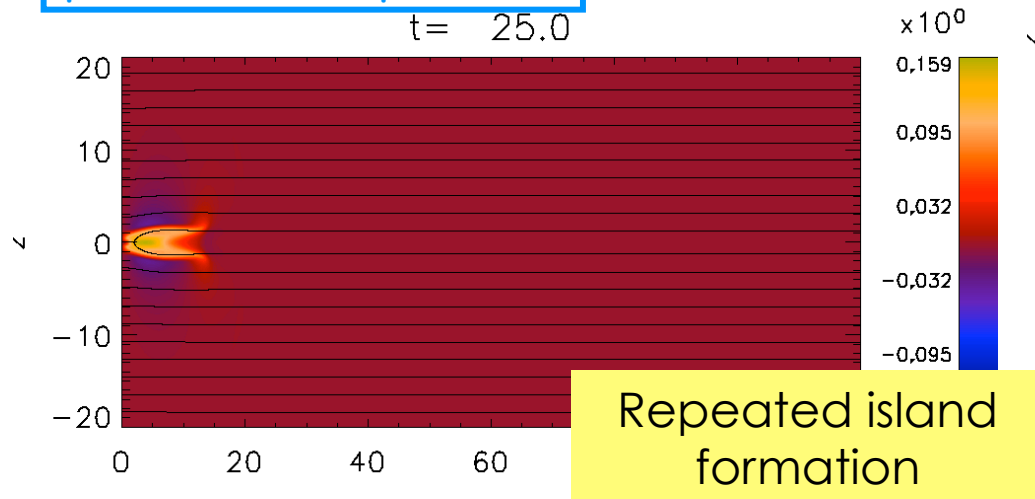
Localized η



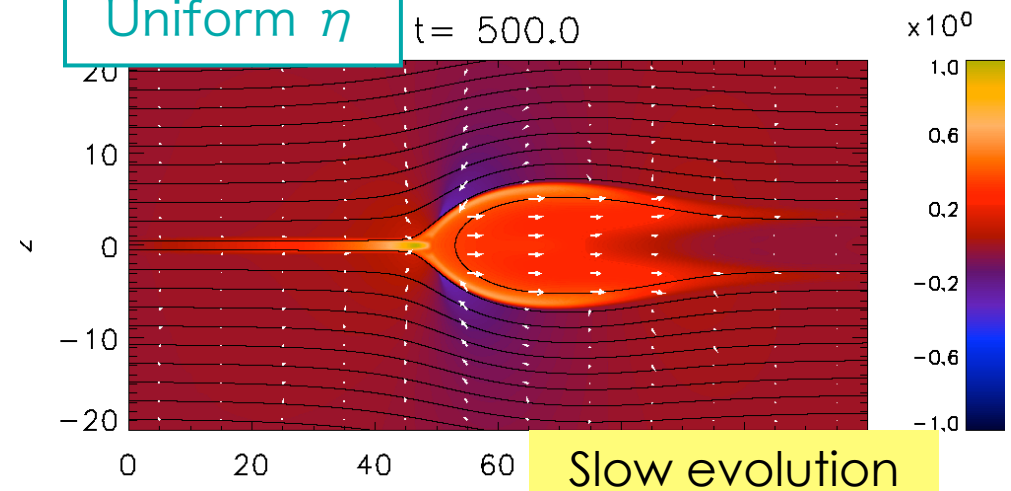
- Effective resistivity
(Resistive/dissipative term)

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta_{\text{eff}} \mathbf{j}$$

parameter dependent



Uniform η



Ohm's law in a kinetic plasma

- Which term (& what physics) violates the ideal condition?

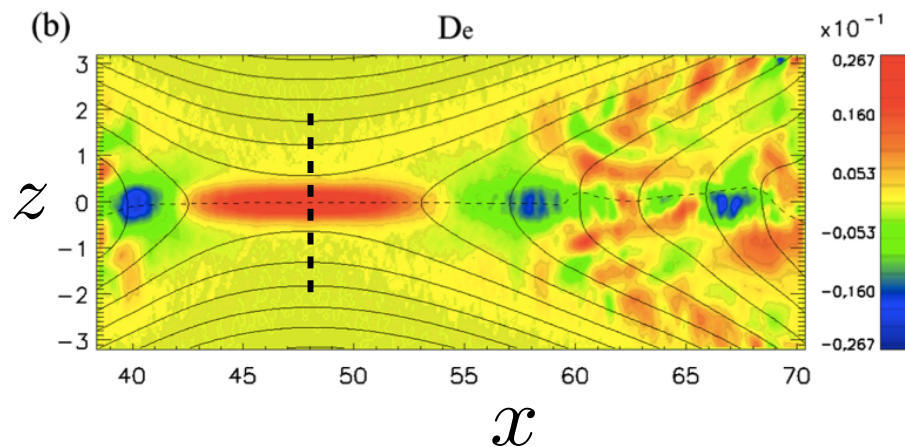
$$\mathbf{E} + \mathbf{v}_e \times \mathbf{B} = -\frac{1}{n_e q} \nabla \cdot \overleftrightarrow{\mathbf{P}}_e - \frac{m_e}{q} \left(\frac{d\mathbf{v}_e}{dt} \right) + \dots \approx \eta \mathbf{j}$$

Thermal inertia
(Local momentum transport)
Hesse+ 1999, 2011

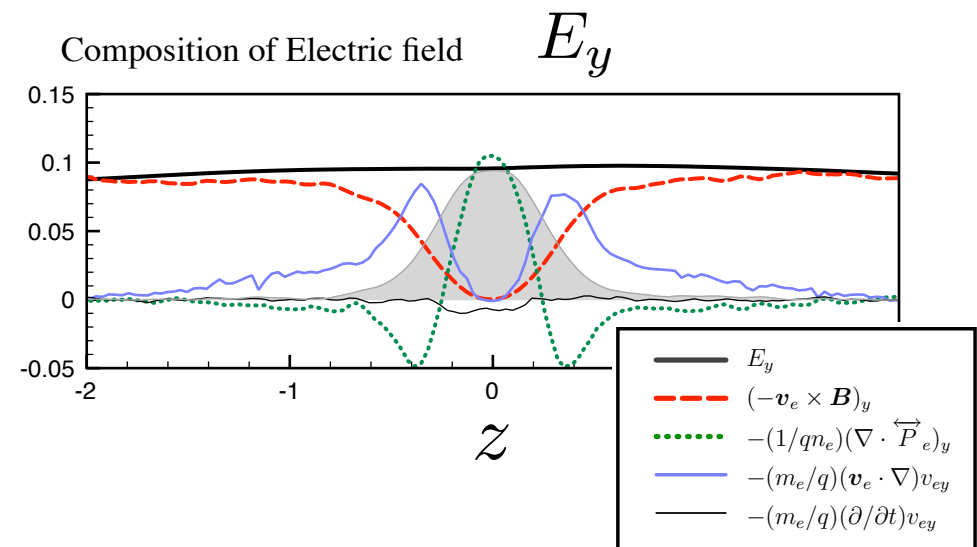
Bulk inertia

And some more...
- Wave-particle interaction
- Anomalous viscosity

2D particle-in-cell (PIC) simulation



Zenitani+ 2011 PRL



Ohm's law in a kinetic plasma

- Which term (& what physics) violates the ideal condition?

$$\mathbf{E} + \mathbf{v}_e \times \mathbf{B} = -\frac{1}{n_e q} \nabla \cdot \overleftrightarrow{\mathbf{P}}_e - \frac{m_e}{q} \left(\frac{d\mathbf{v}_e}{dt} \right) + \dots \approx \eta \mathbf{j}$$

Thermal inertia
(Local momentum transport)
Hesse+ 1999, 2011

Bulk inertia

And some more...

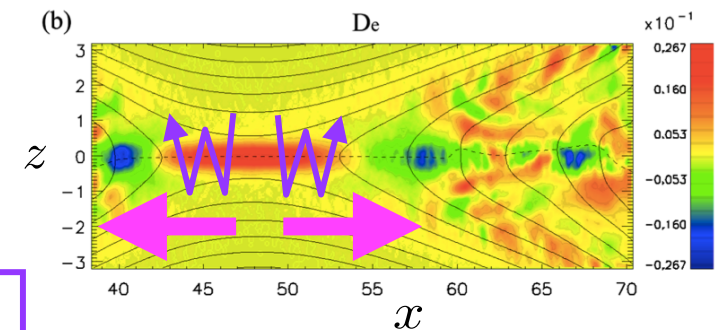
- Wave-particle interaction
- Anomalous viscosity

- Thermal inertia for 2D, symmetric case (reviewed by Hesse+ 2011)

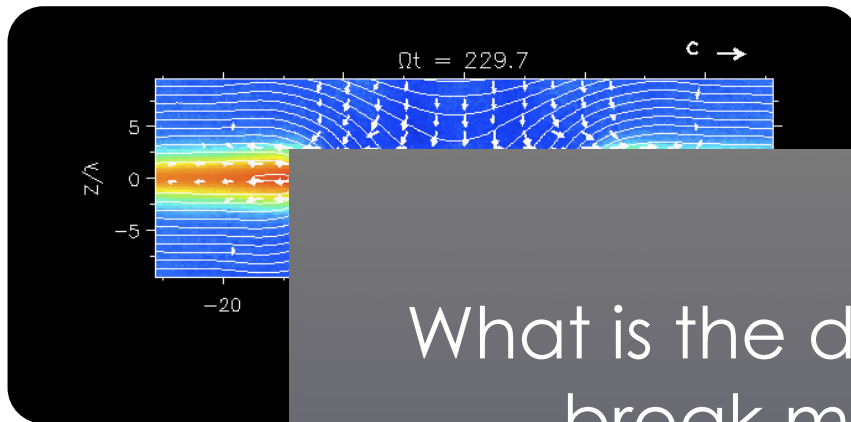
$$E_y \approx -\frac{1}{2en} \left(\frac{\partial v_{ex}}{\partial x} \right) L^2 \Delta (m_e n v_{ey})$$

Medium-scale
convection
in the outflow direction

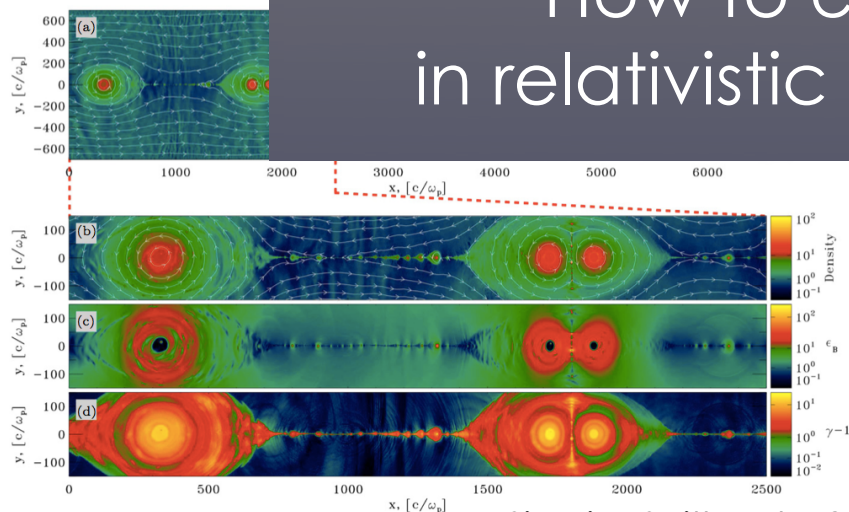
Local momentum
transport (diffusion)
due to particle motion



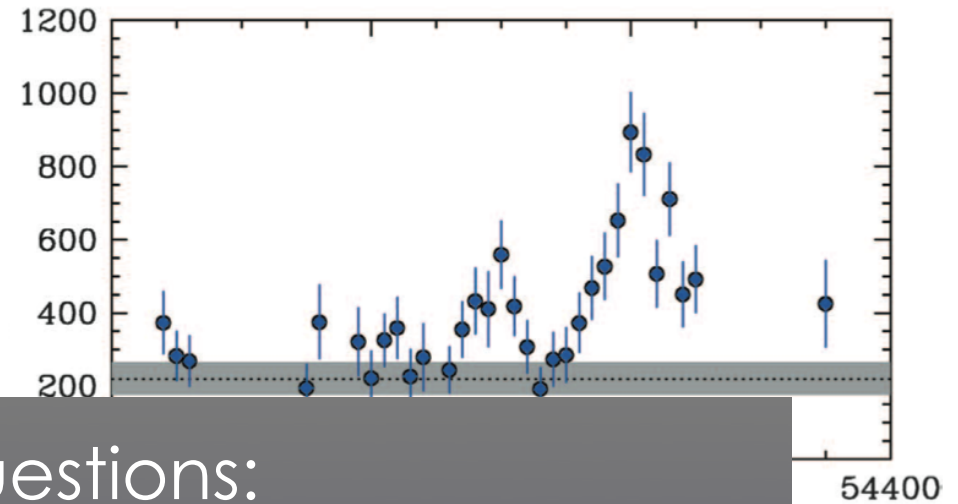
Relativistic kinetic reconnection



Kinetic simulation



Sironi & Spitkovsky 2014

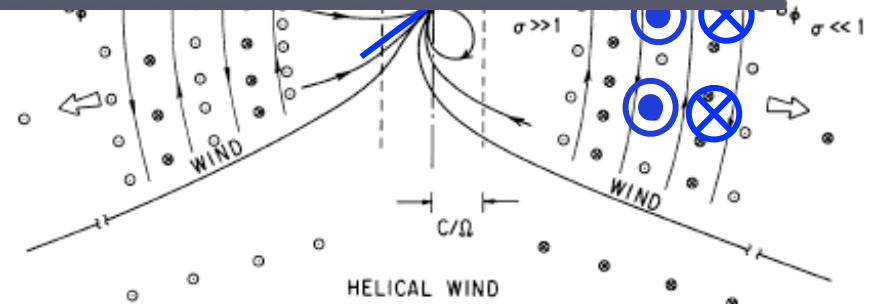


ni 2011

Questions:

What is the dissipation mechanism to break magnetic field lines ?

How to evaluate Ohm's law in relativistic kinetic reconnection ?



Pulsar wind

Coroniti 1990

Hesse & Zenitani (2007) analysis

- We started from the Vlasov equation

$$\frac{\partial f}{\partial t} + \frac{\vec{u}}{\gamma} \cdot \nabla f + \frac{q}{m} \left(\vec{E} + \frac{\vec{u}}{\gamma} \times \vec{B} \right) \cdot \frac{\partial f}{\partial \vec{u}} = 0$$

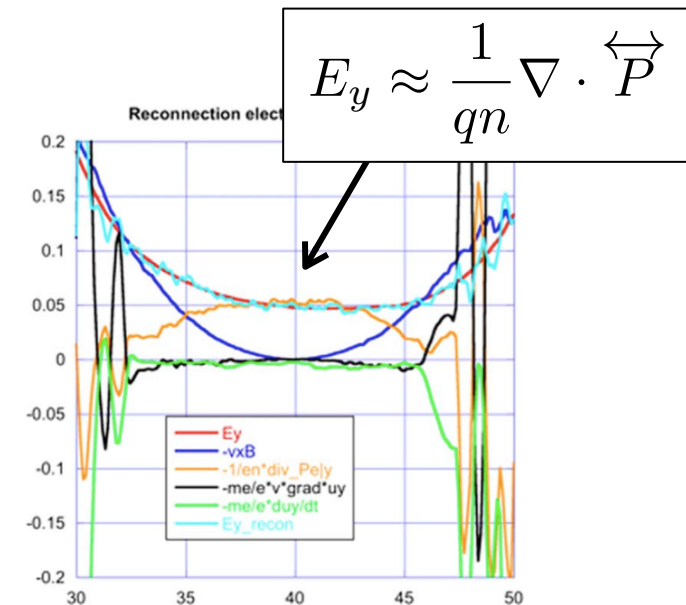
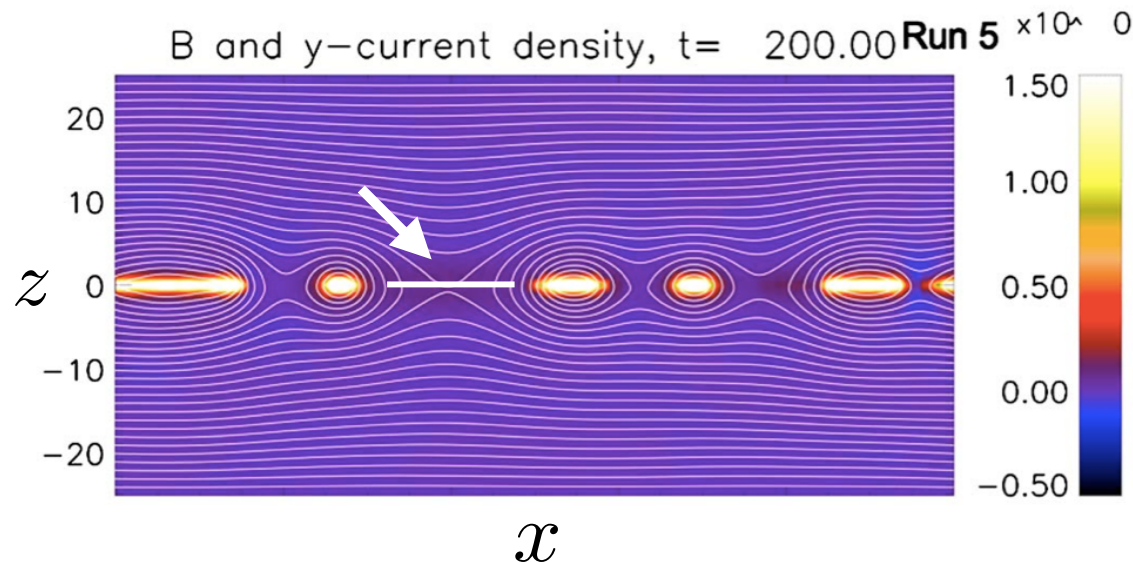
Problems...

- Symmetry
- Physical meaning

- Ohm's law with Wright=Hadley (1974) pressure tensor

$$\vec{E} + \langle \vec{v} \rangle \times \vec{B} = \frac{1}{qn} \nabla \cdot \mathbf{P} + \frac{m}{q} \left(\frac{\partial}{\partial t} \langle \vec{u} \rangle + \langle \vec{v} \rangle \cdot \nabla \langle \vec{u} \rangle \right) \quad \mathbf{P} = \int d^3u \frac{\vec{u} \vec{u}}{\gamma} f - n \langle \vec{v} \rangle \langle \vec{u} \rangle$$

- Thermal inertia** sustains reconnection, similarly as nonrelativistic reconnection



Ohm's law in a relativistic kinetic plasma

- Stress-energy tensor

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

- Standard decomposition

$$W^{\alpha\beta} = w u^\alpha u^\beta + w^\alpha u^\beta + w^\beta u^\alpha + w^{\alpha\beta}$$

w^α : heat flow

$$Q^{\alpha\beta} \equiv w^\alpha u^\beta + w^\beta u^\alpha$$

Heat flow tensor

- Energy momentum equation for relativistic plasmas

$$\partial_\beta W^{\alpha\beta} = -\frac{1}{c} F^{\alpha\beta} j_\beta$$

- Relativistic Ohm's law (with $\partial_t=0$)

$$\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} = \frac{1}{\gamma n q} \nabla \cdot (w u^i u^j + Q^{ij} + P^{ij})$$

Bulk inertia
(including relativistic pressure)

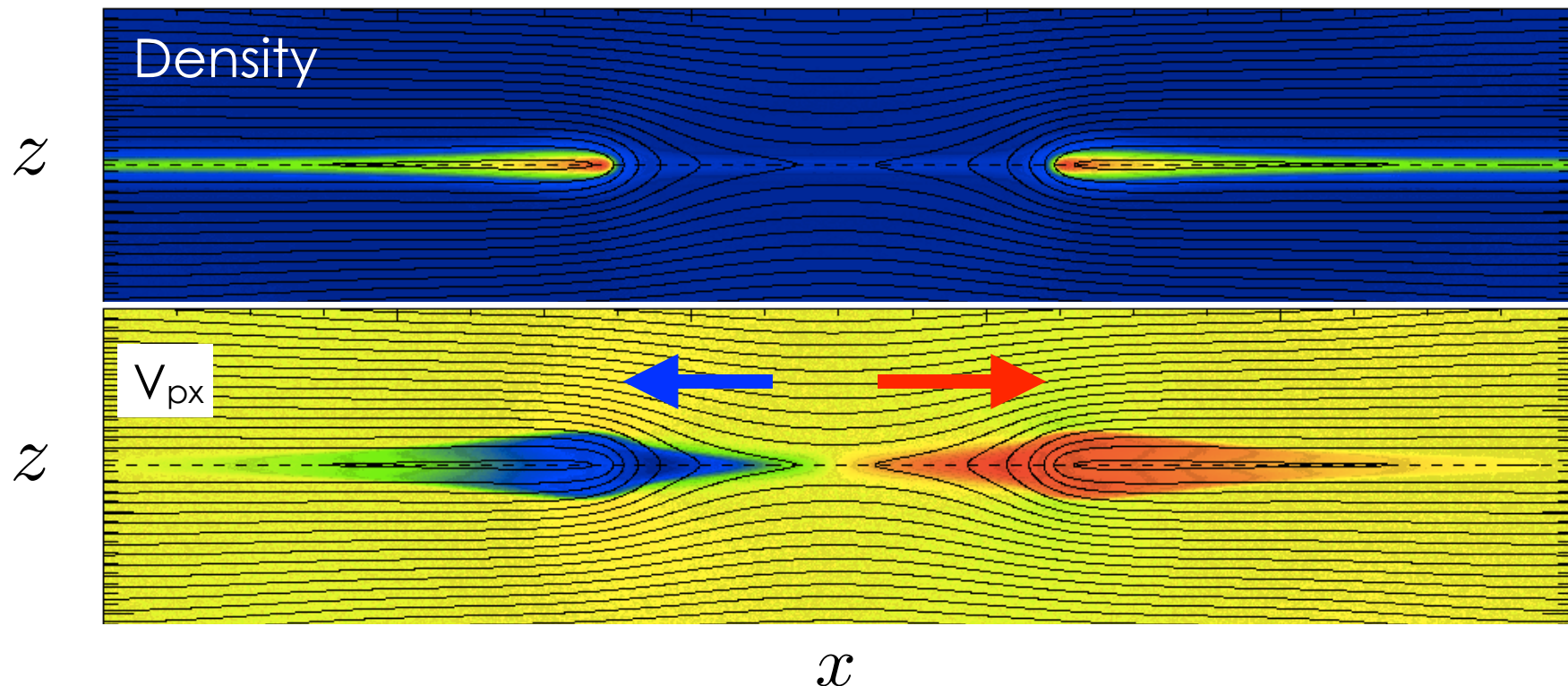
Thermal inertia
(Local momentum transport)

Heat flow inertia
(new in relativistic regime)



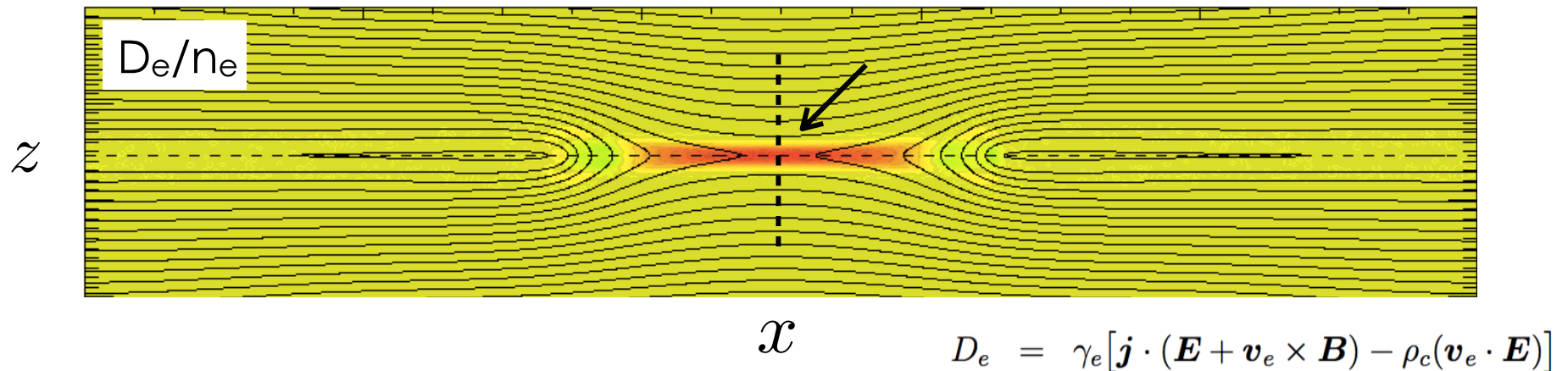
2D Particle-in-Cell simulation

- Relativistic electron-positron plasma
- $T/mc^2=1$, $n_{bg}/n_0=0.1$, $v_{drift}/c=0.3$
- $10^{9.5}$ particles: **10^4** pairs in a cell ($\Leftrightarrow 10^2$ in typical works)

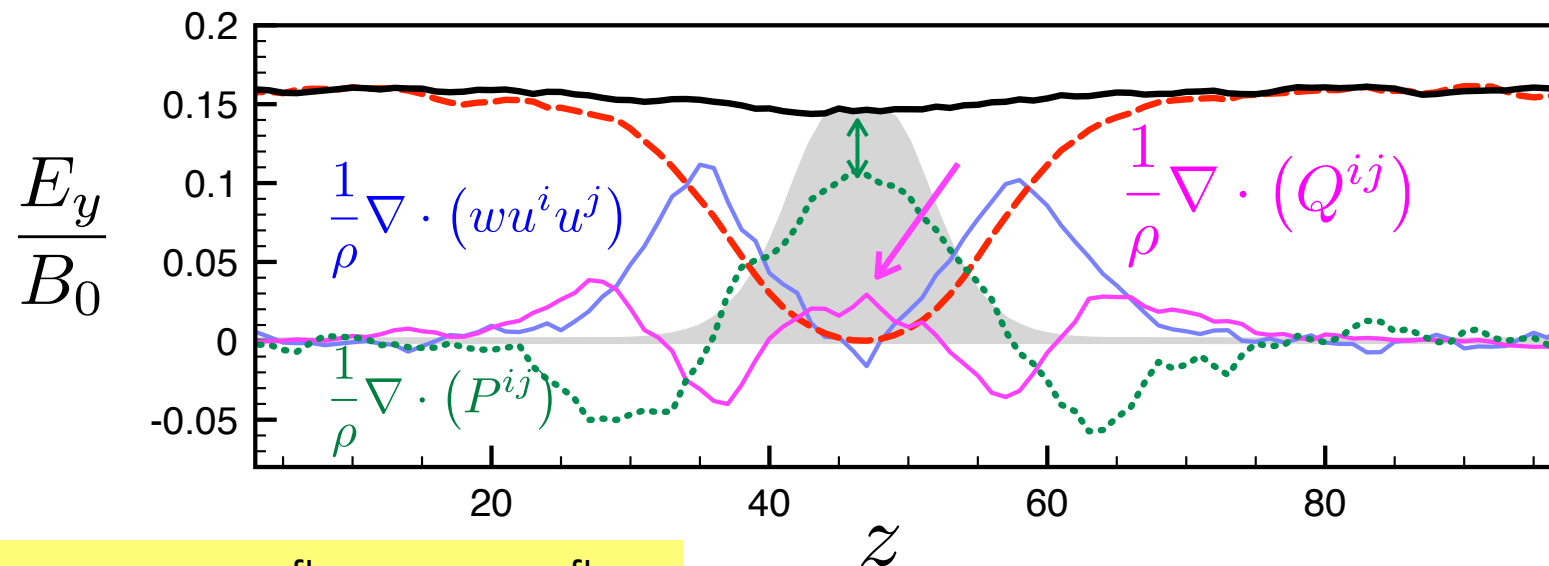


2D Particle-in-Cell simulation

- Energy dissipation per plasma density ($\sim \mathbf{j} \cdot \mathbf{E} / n \sim \eta_{\text{eff}} j^2 / n$)



- Ohm's law: heat flow term appears

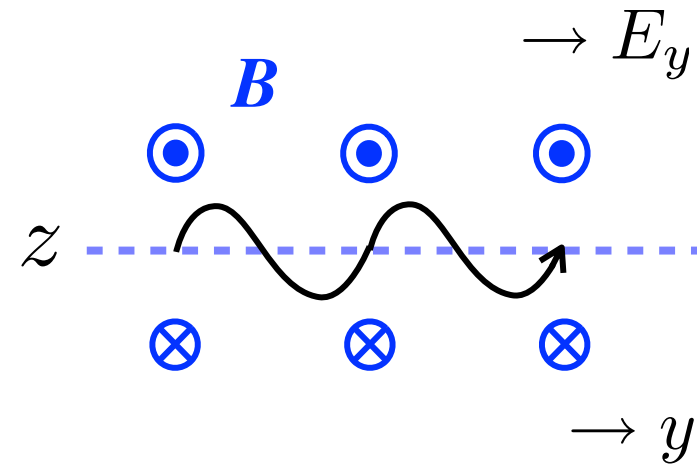
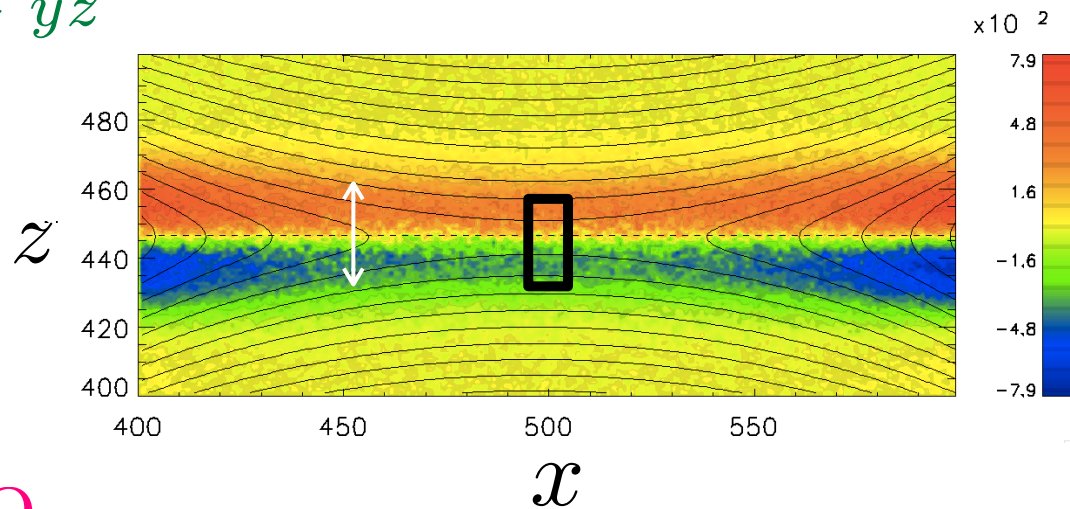


Heat flow = energy flow = mass flow

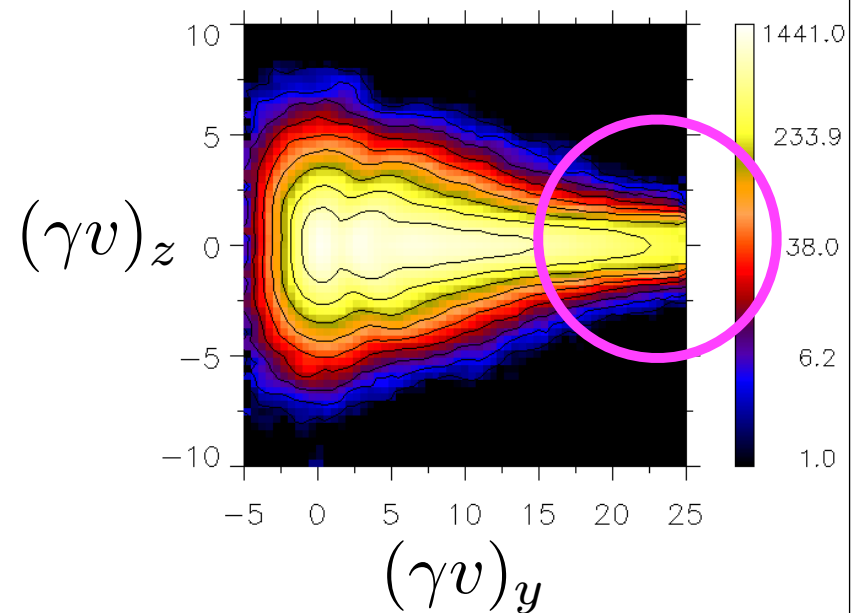
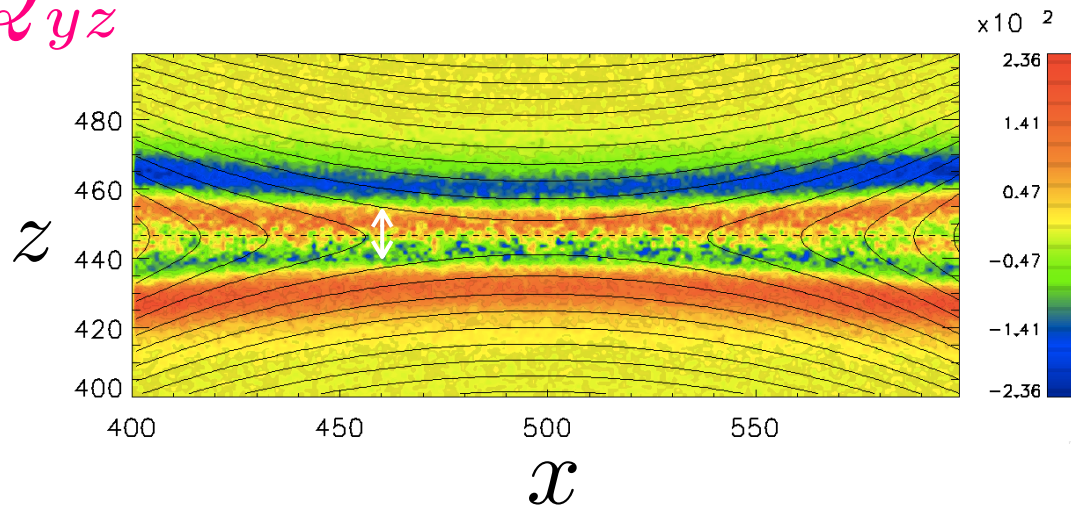
Momentum transport

- Strong particle acceleration gives rise to Q_{yz}
- Scale high: Q is more confined than P

P_{yz}

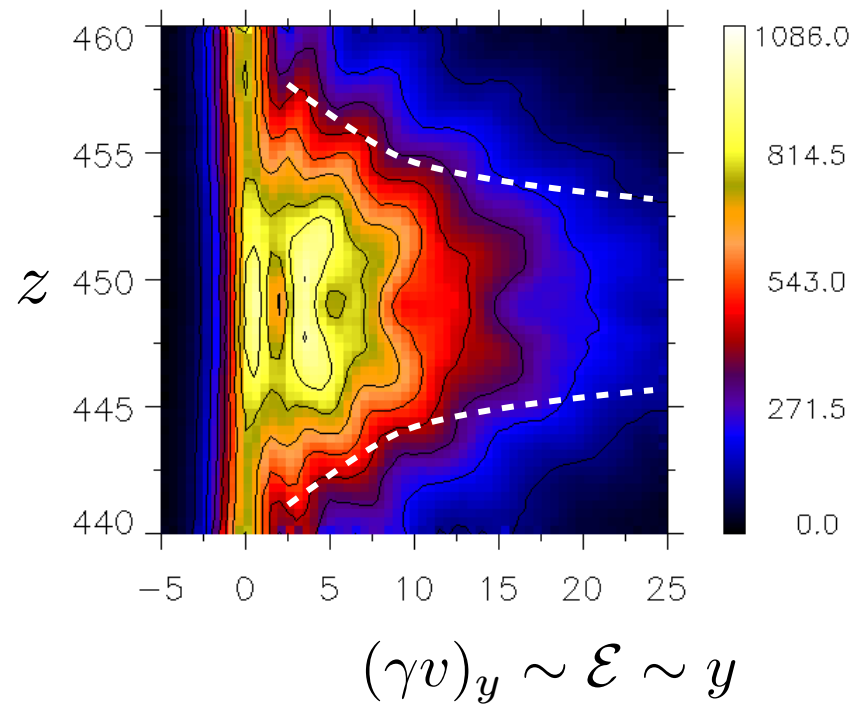


Q_{yz}

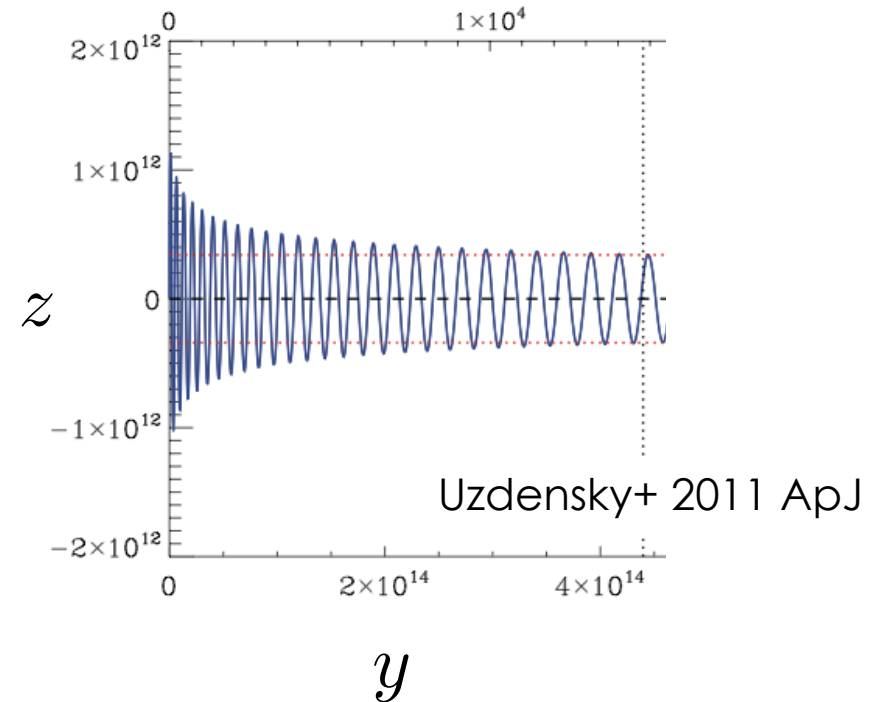


Speiser motion - relativistic focusing

Phase-space diagram



Test particle tranjectory



- Envelope shrinks as particles are accelerated

$$z_{max} \sim \mathcal{E}^{-1/3} \quad (\text{Uzdensky+ 2011})$$

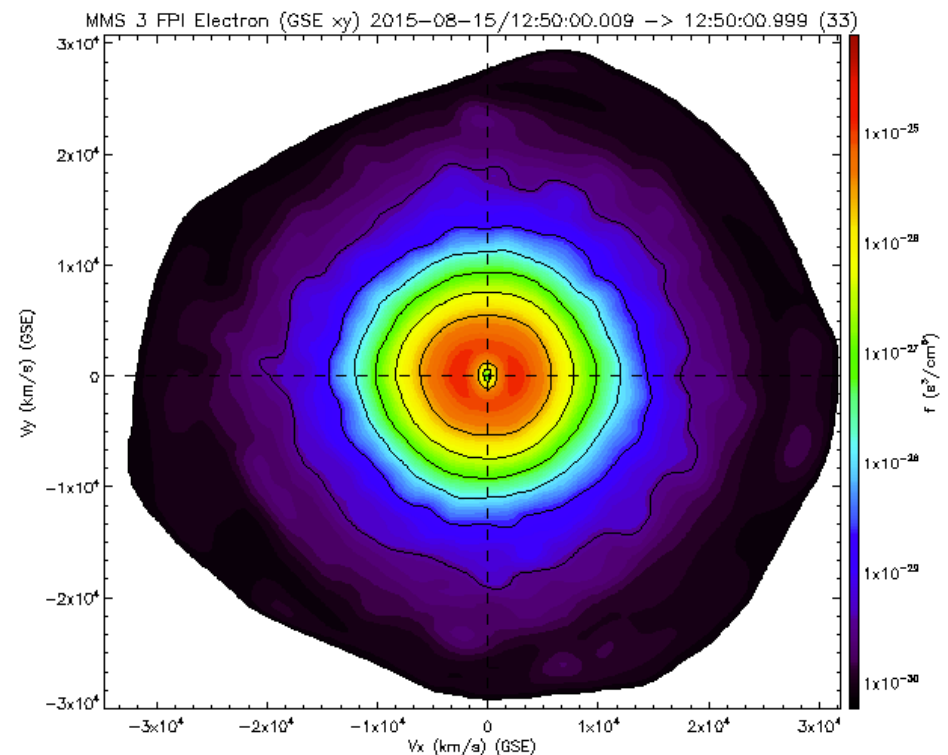
- Less pronounced in the nonrelativistic regime

$$z_{max} \sim t^{-1/4} \sim \mathcal{E}^{-1/8} \quad (\text{Speiser 1965 JGR, modified})$$

2. Electron orbits in nonrelativistic reconnection

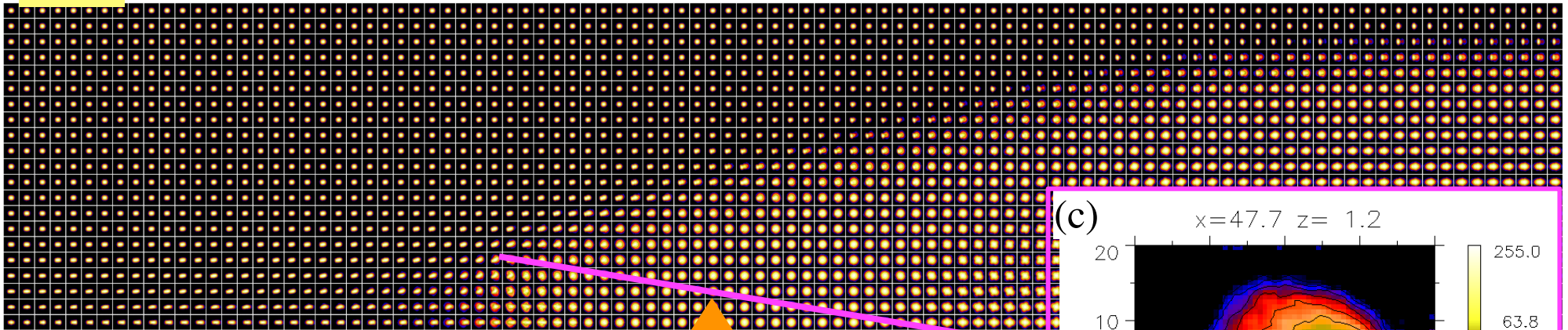
Magnetospheric MultiScale (MMS) mission

- MMS observes near-Earth reconnection sites: the magnetopause in 2015-2016 and the magnetotail in 2017.
- MMS is the first mission to observe **electron Velocity Distribution Function (VDF)** at unprecedented resolution.

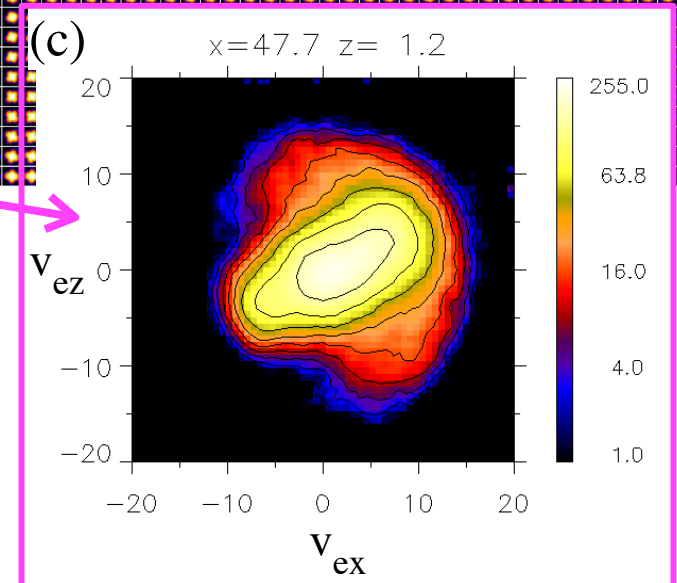
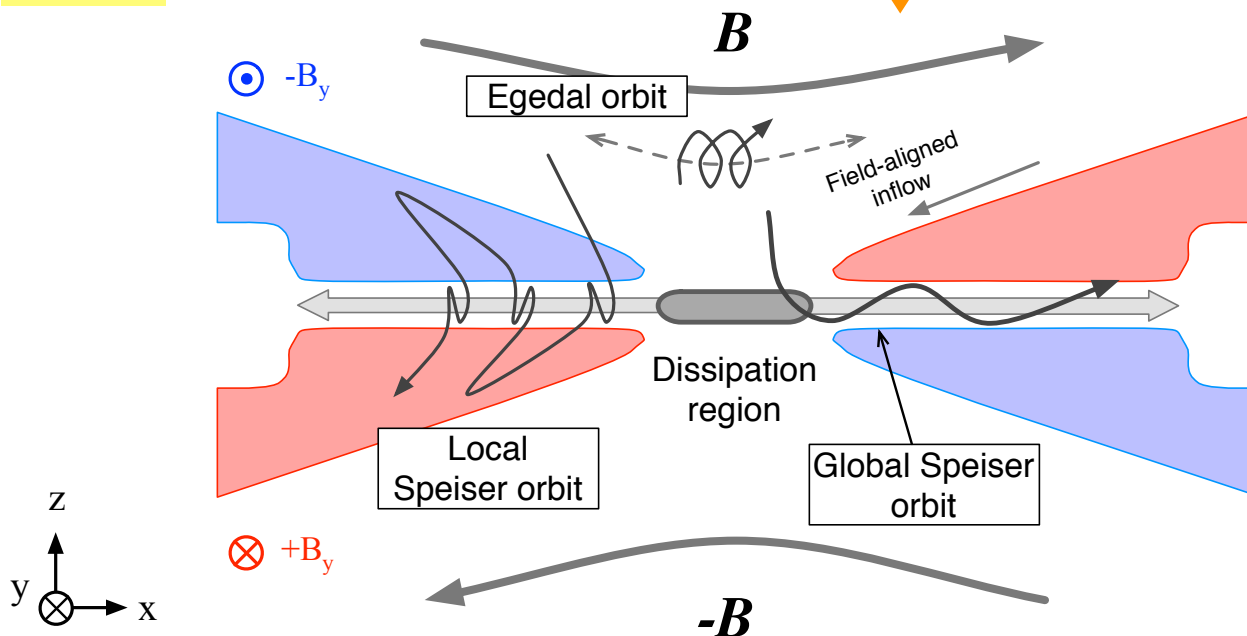


Electron VDFs vs electron orbits

VDFs



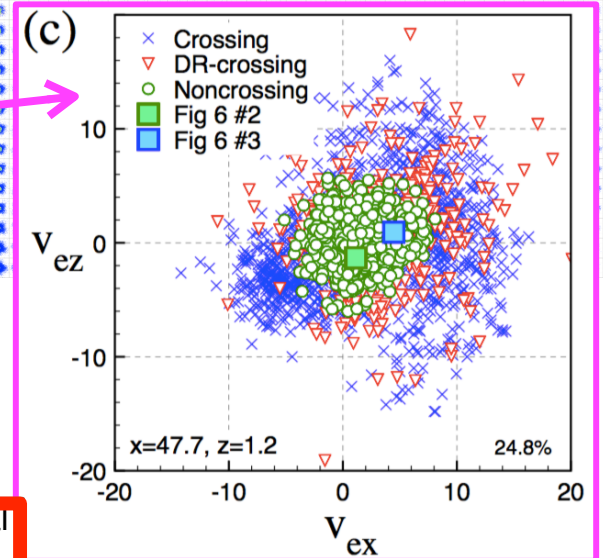
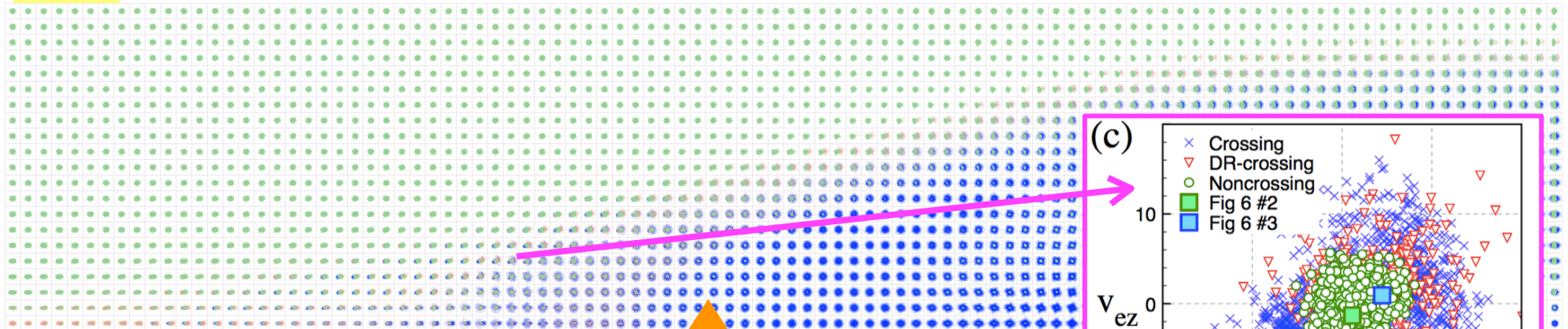
Orbits



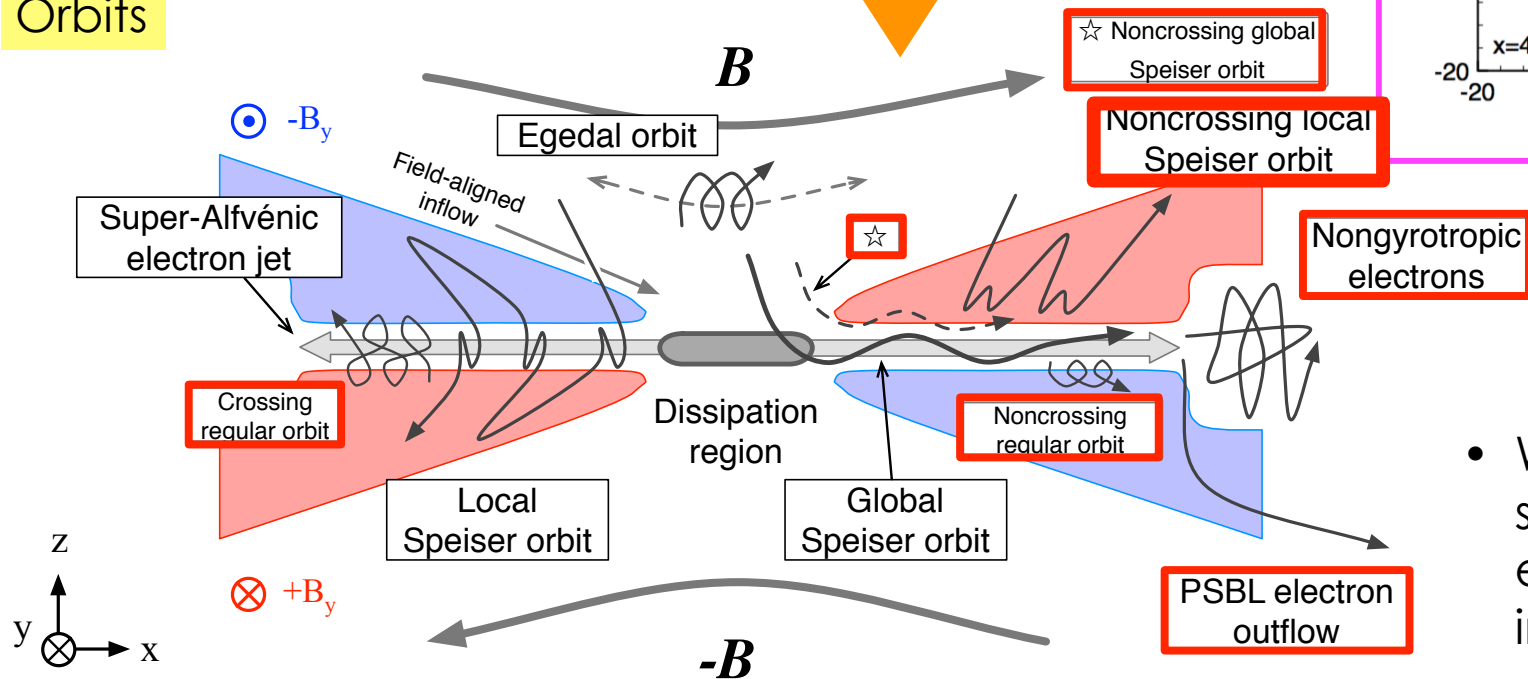
- We analyze 2×10^7 self-consistent electron orbits in our PIC simulation

Electron VDFs vs electron orbits

VDFs



Orbits



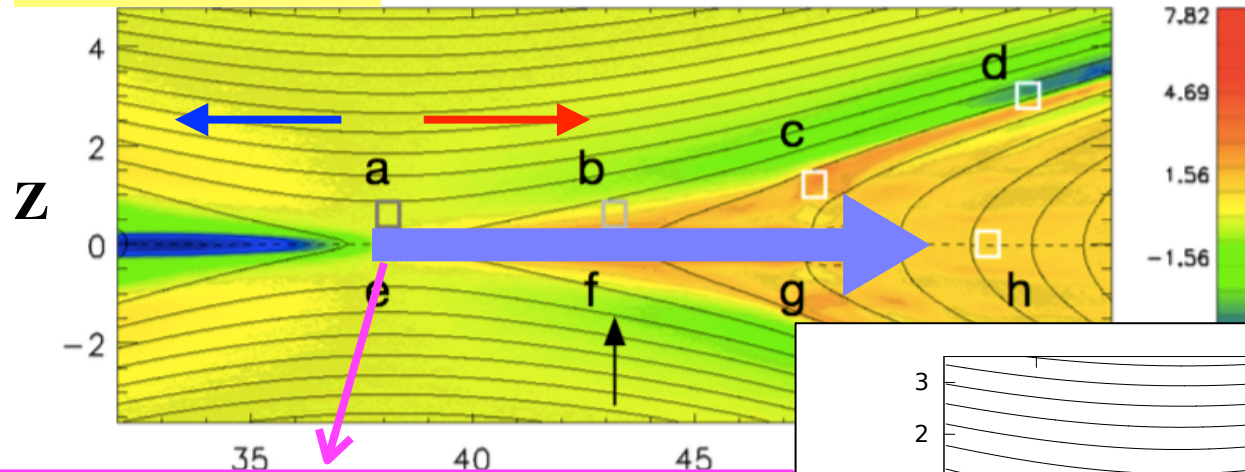
- We analyze 2×10^7 self-consistent electron orbits in our PIC simulation

Electron Speiser VDFs in PIC simulation

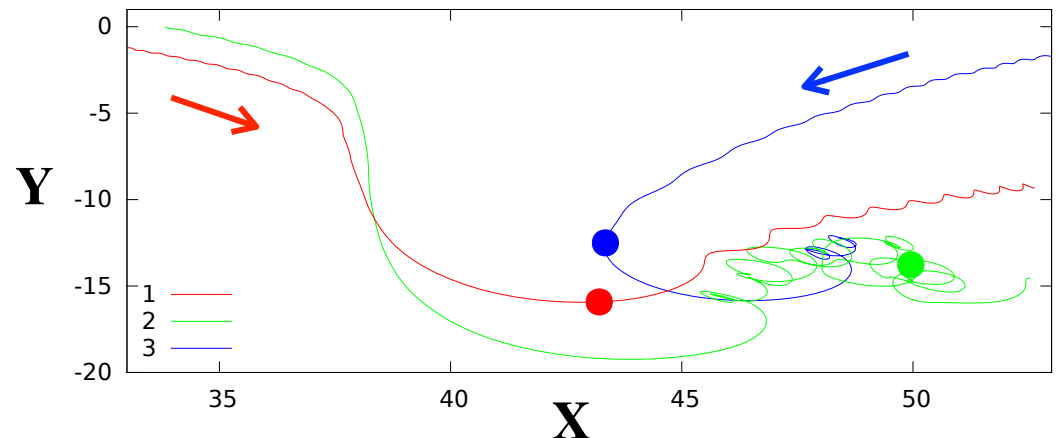
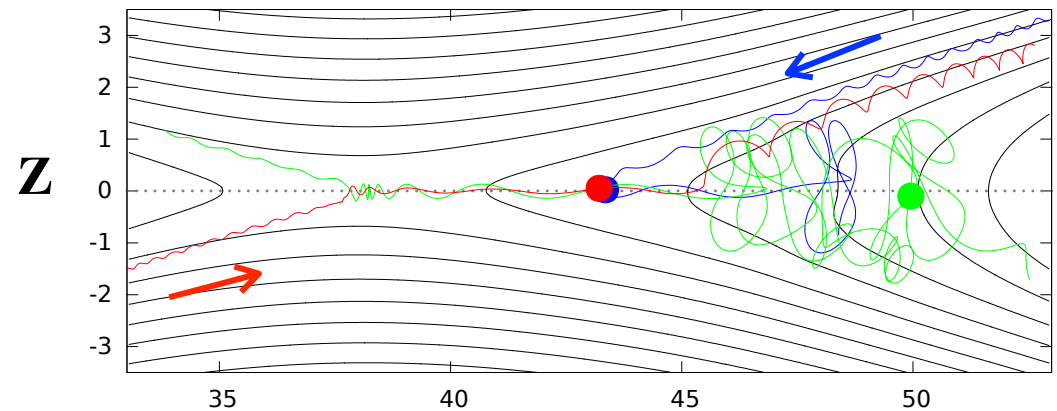
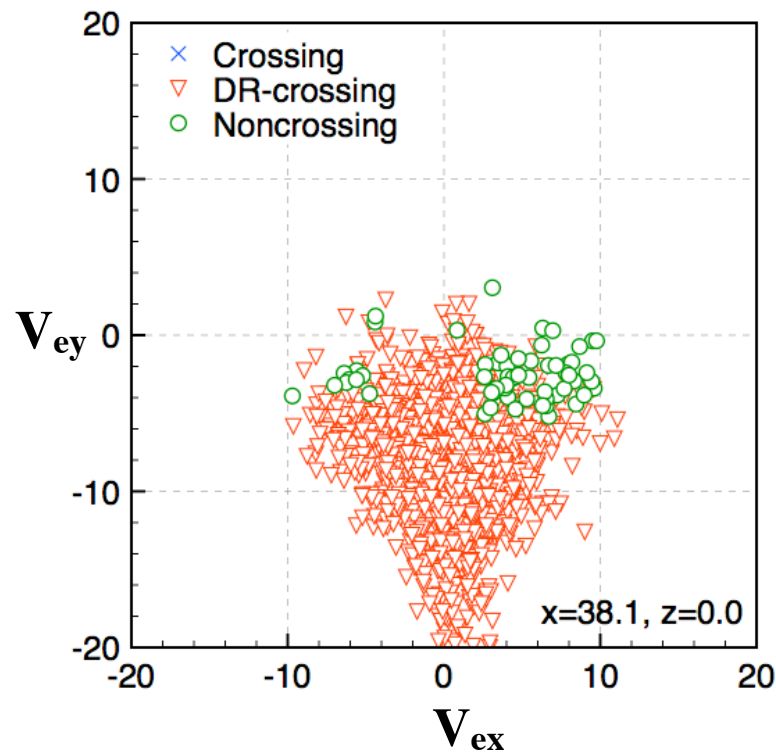
V_{ex} : electron jets

$t = 35.2$

$\times 10^0$

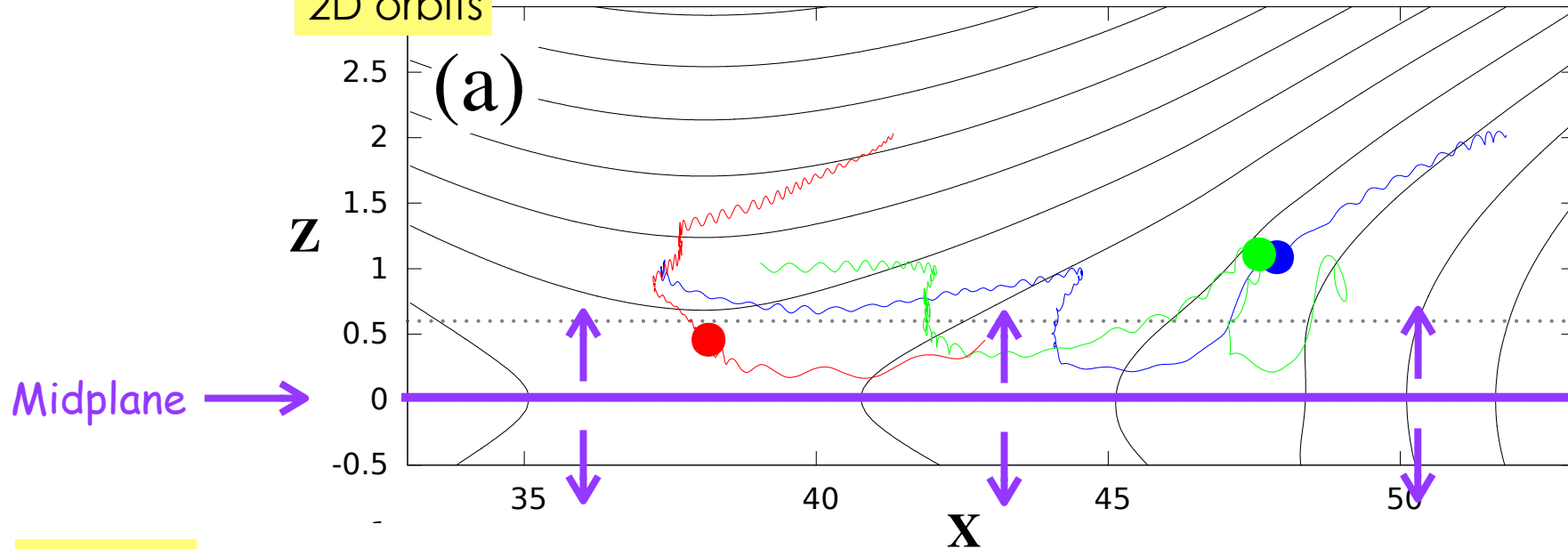


"Global Speiser"
via X-line region
"Local Speiser"
of reflection type

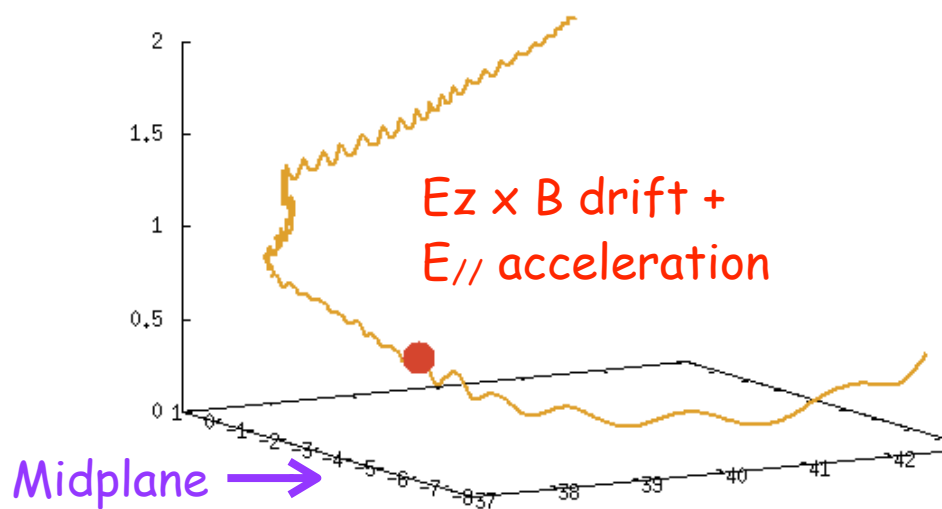


Noncrossing Speiser-like orbits

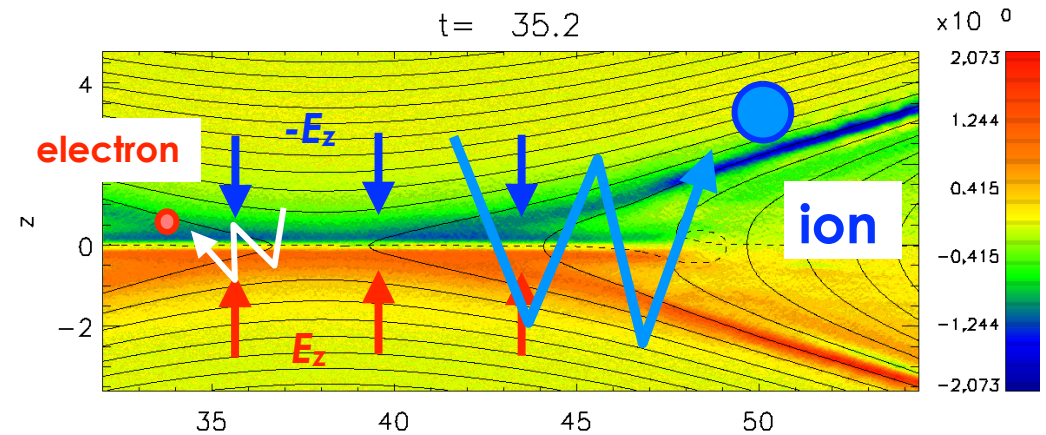
2D orbits



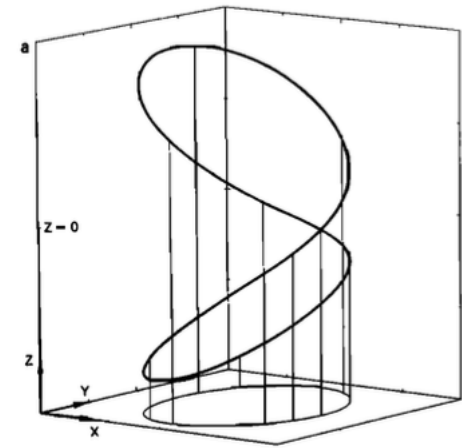
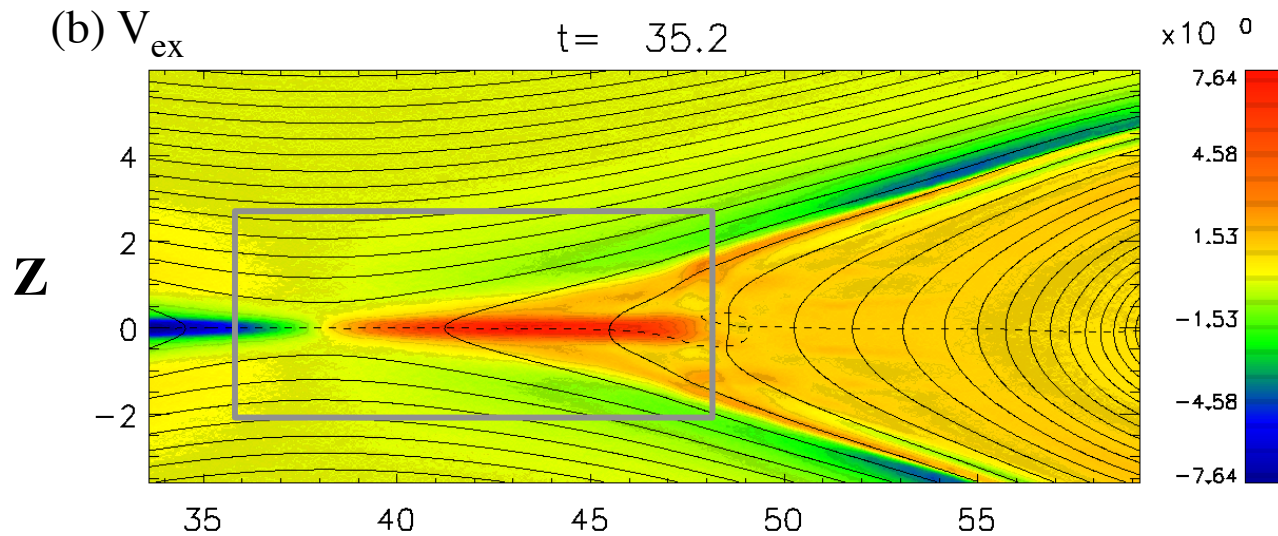
3D orbit



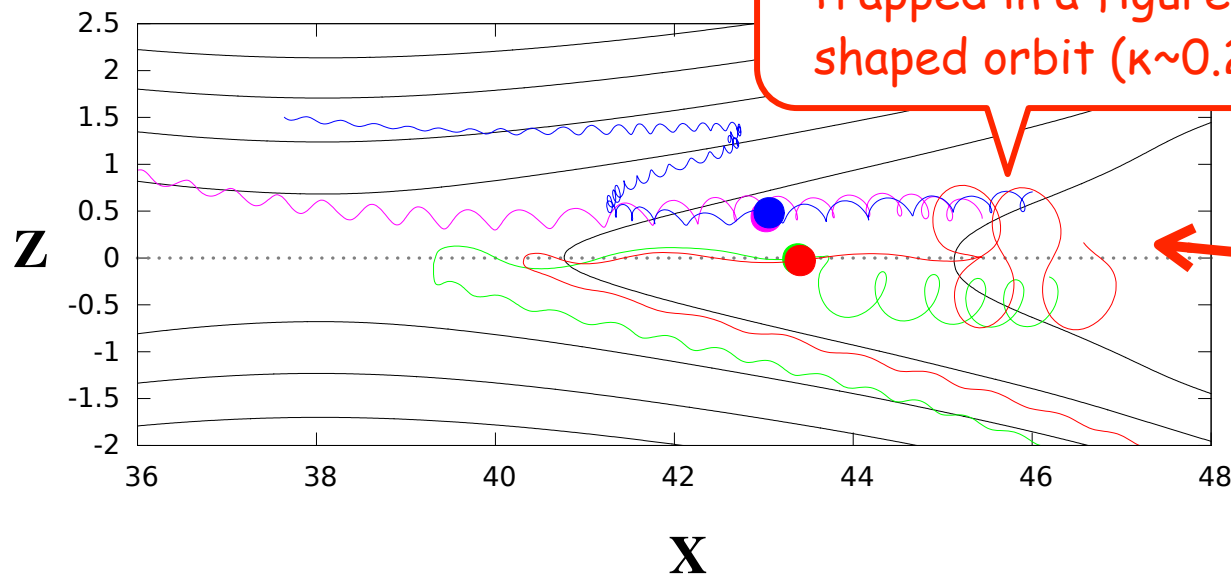
Electrostatic field E_z



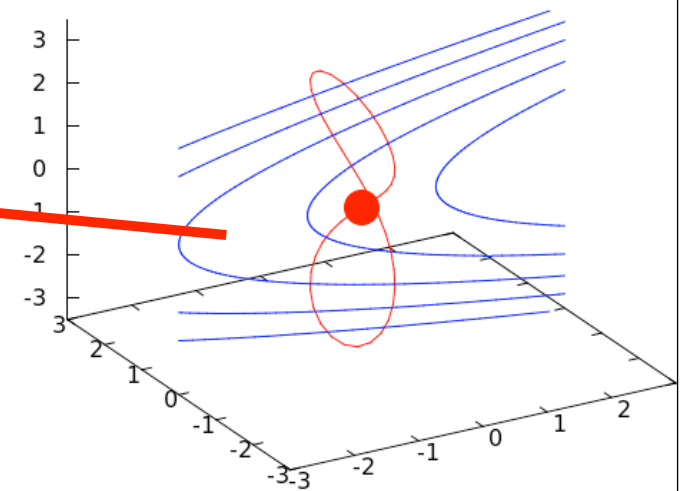
Electron regular orbits



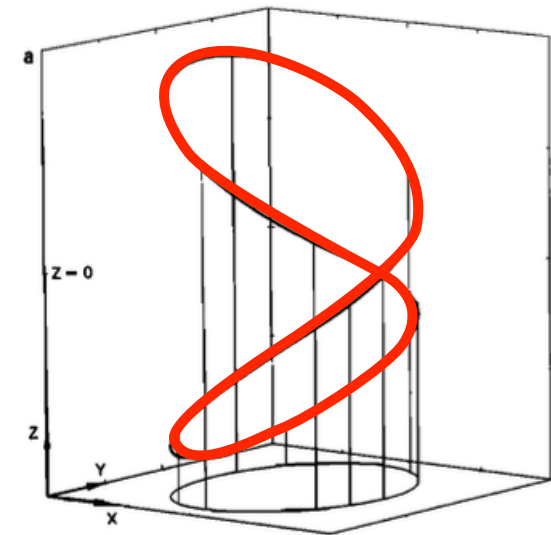
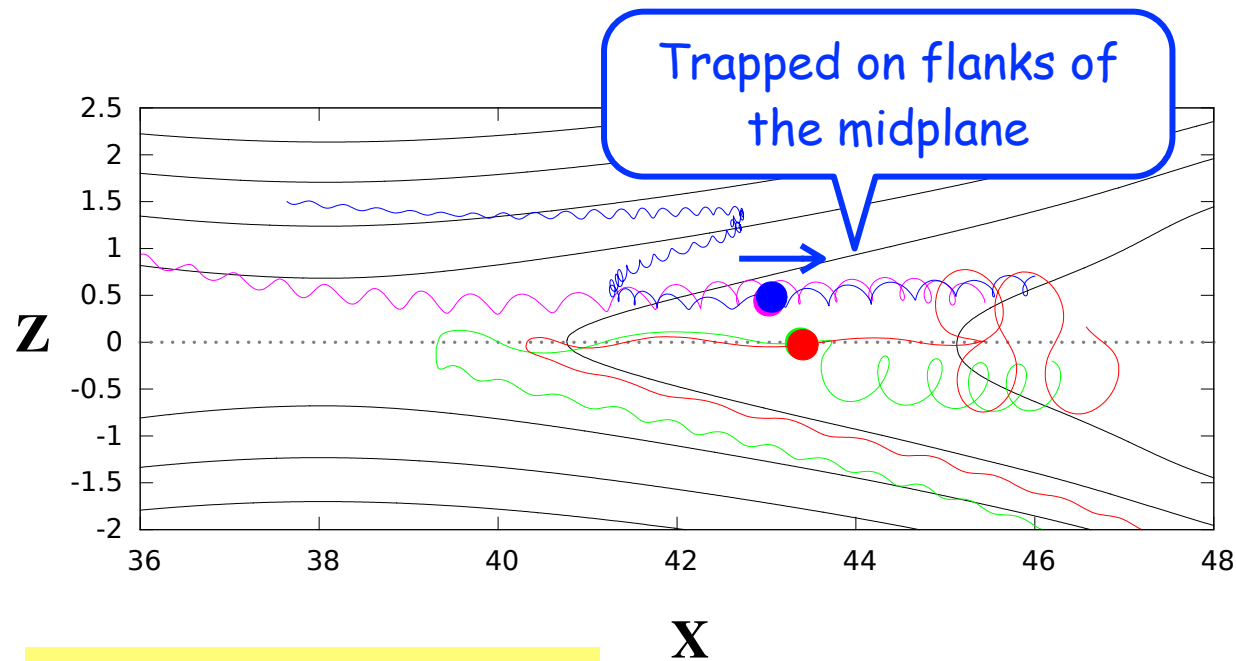
Chen & Palmadesso 1986 *JGR*



Trapped in a figure-8 shaped orbit ($\kappa \sim 0.2$)

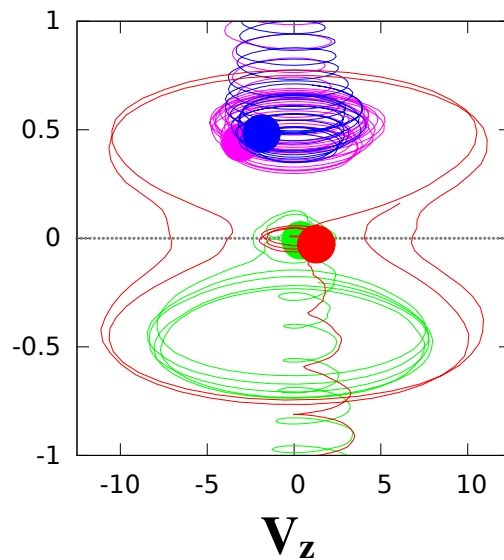
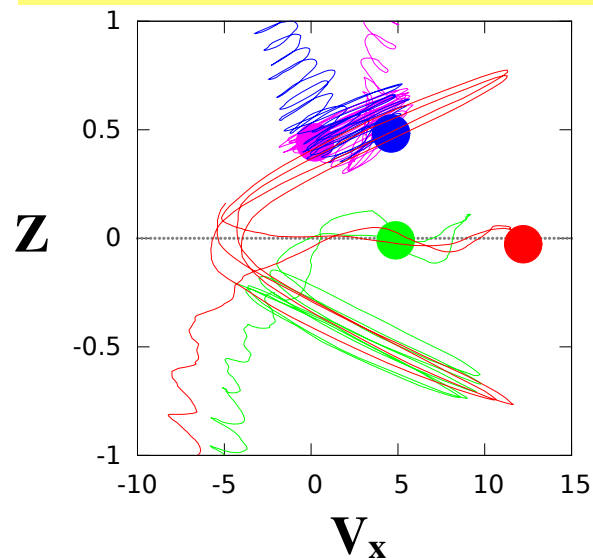


Noncrossing regular orbits

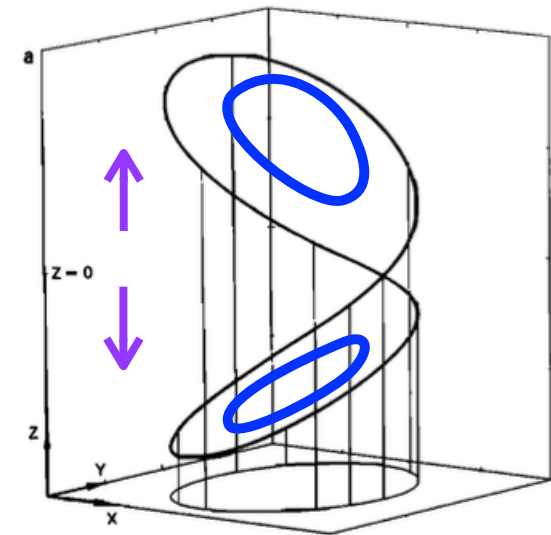
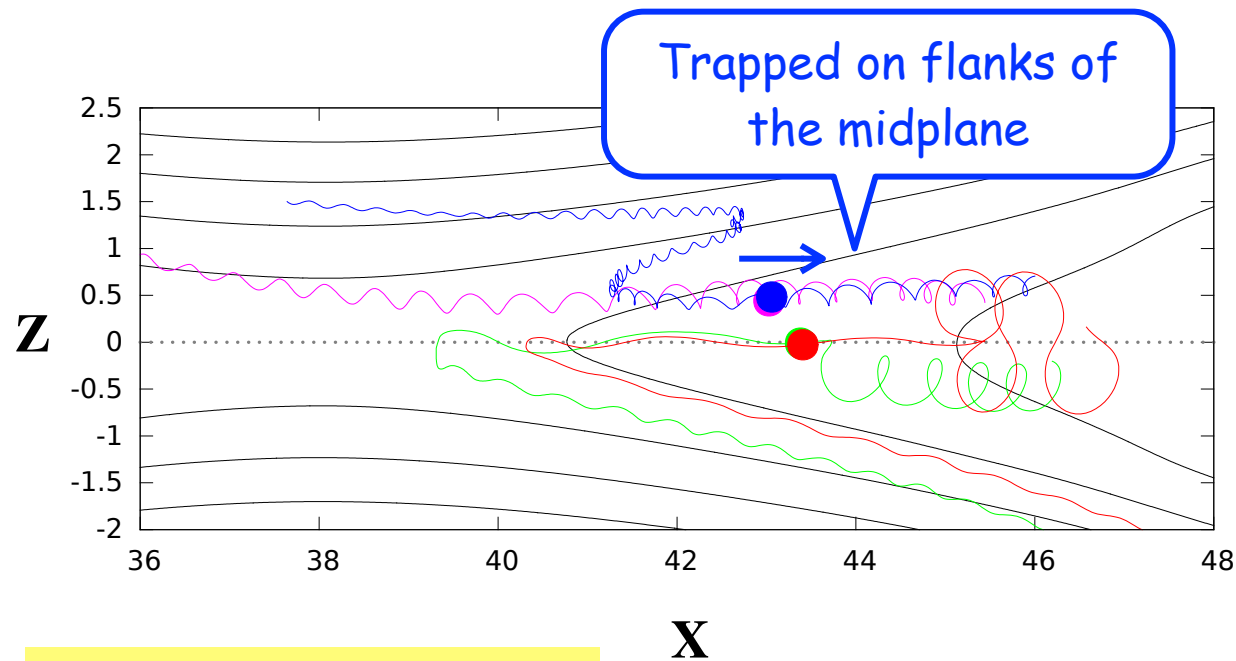


Chen & Palmadesso 1986 *JGR*

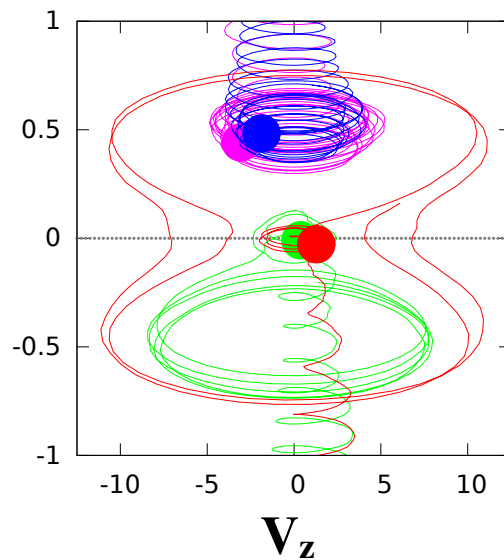
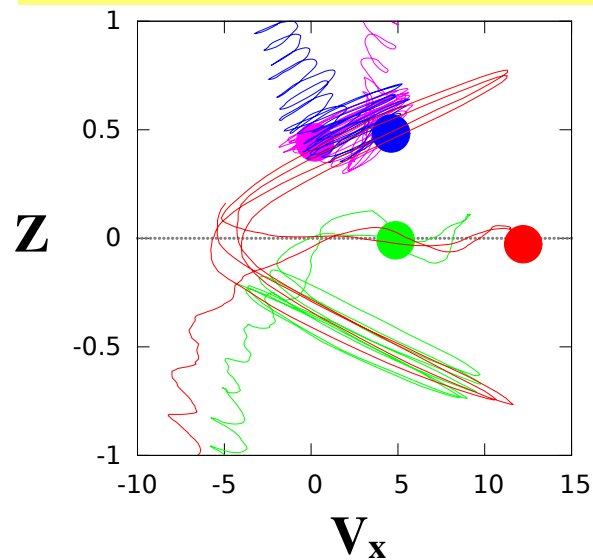
Phase-space diagrams



Noncrossing regular orbits



Phase-space diagrams

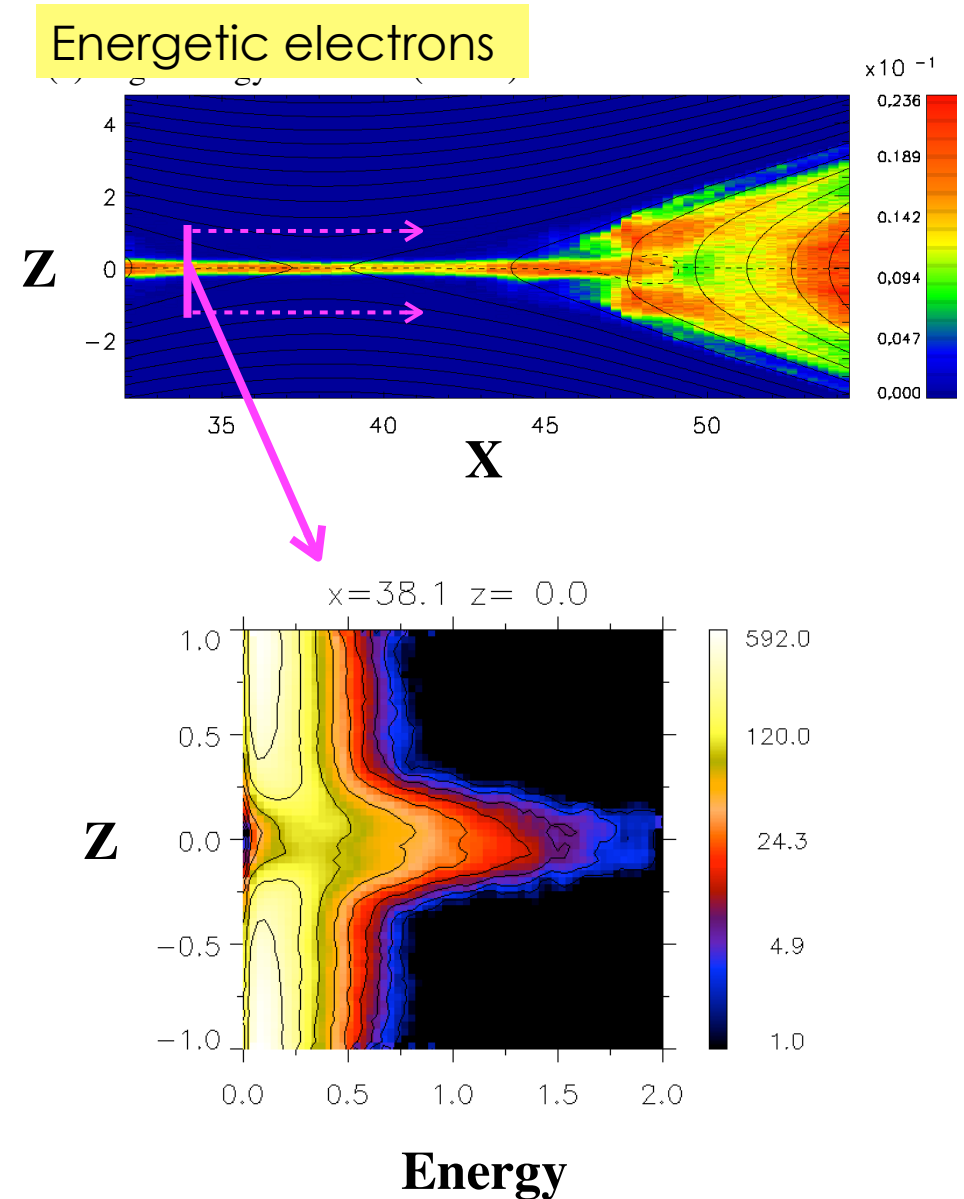
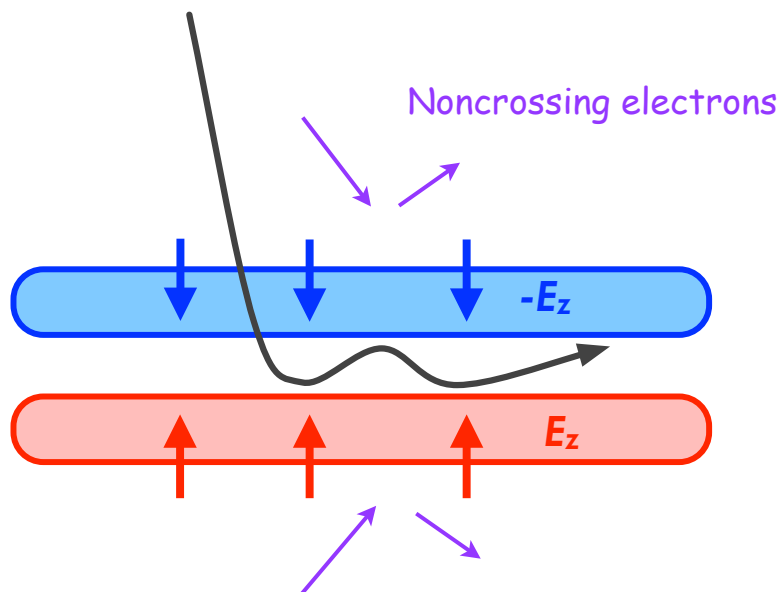


Chen & Palmadesso 1986 *JGR*

Detached from
the midplane,
due to E_z

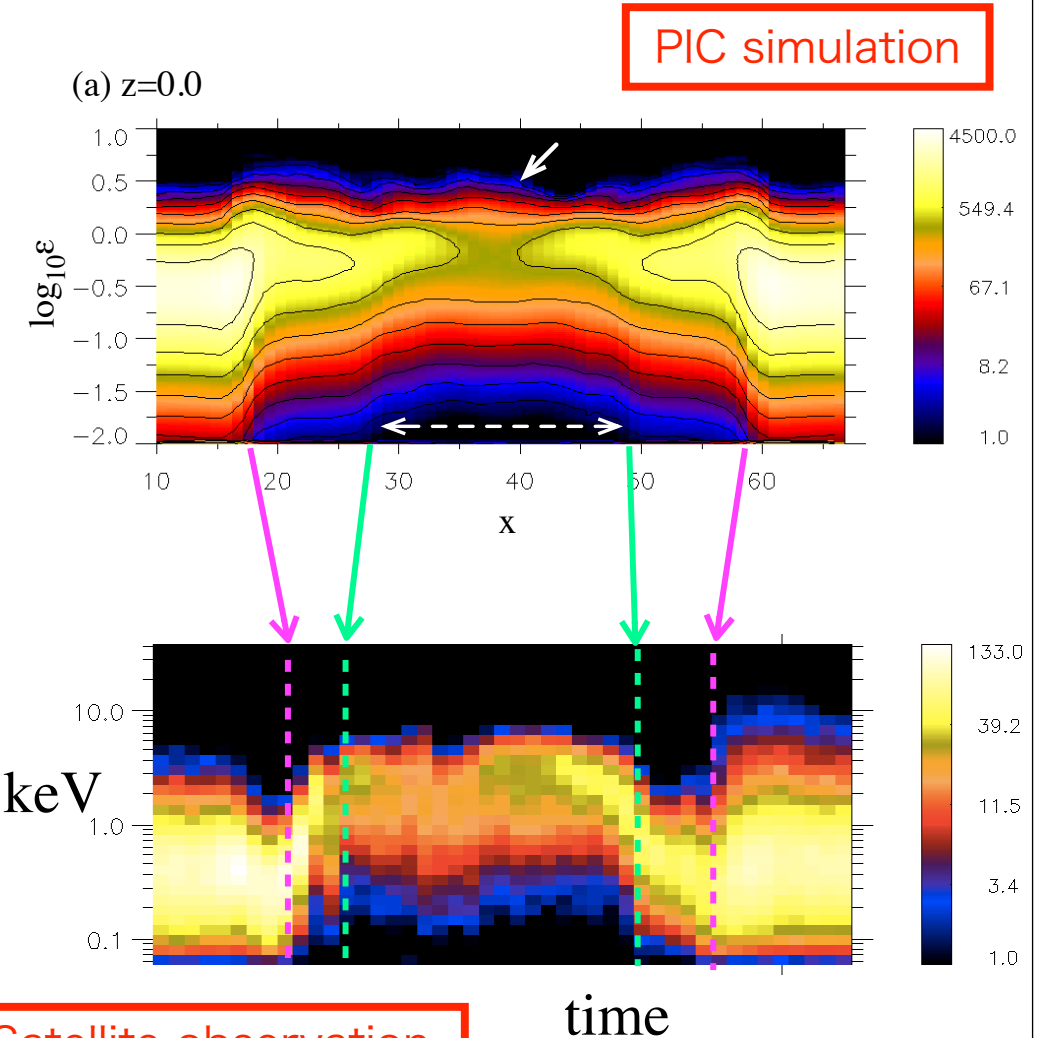
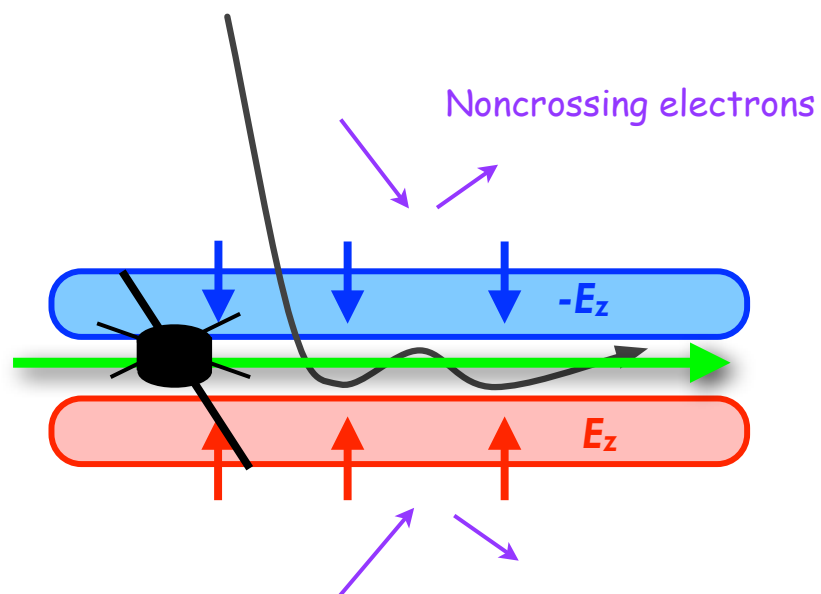
Energetic electrons

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



Observational signatures: ET diagram

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

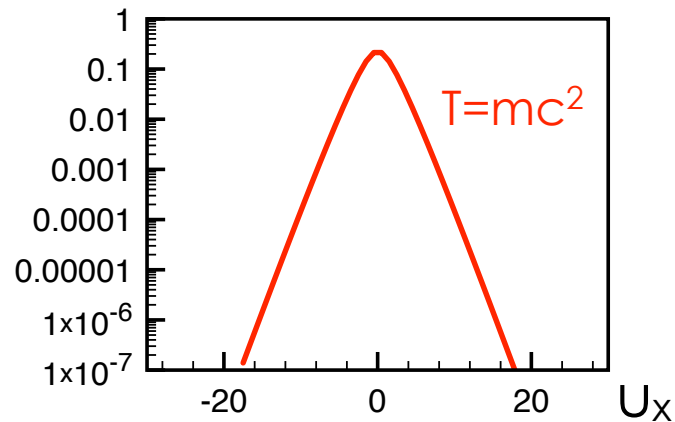


Satellite observation
(Geotail; old one)

Appendix: A small tale near Perdue

Relativistic Maxwell distributions

- Jüttner=Synge distribution



$$f(\mathbf{u})d^3u \propto \exp\left(-\frac{\gamma mc^2}{T}\right)d^3u$$

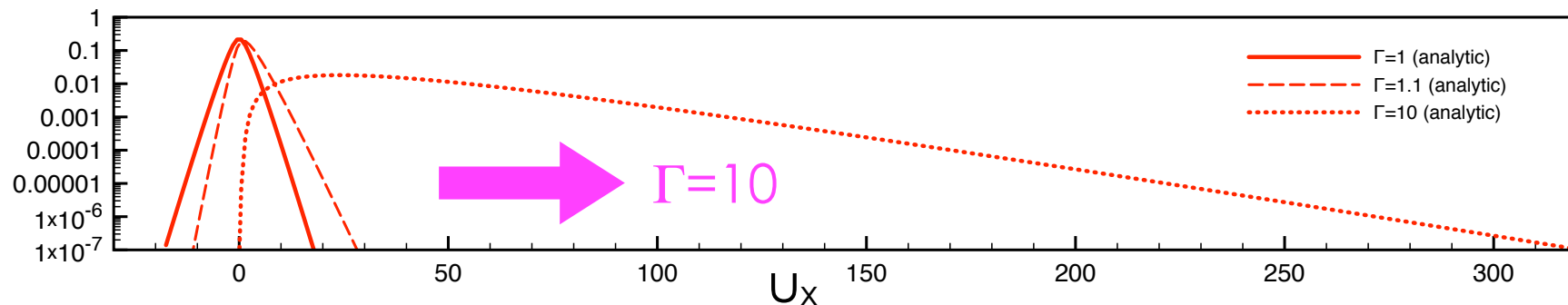
$$\propto \exp\left(-\frac{mc^2\sqrt{1+(u/c)^2}}{T}\right)d^3u$$

$$\mathbf{u} = \gamma \mathbf{v} \quad \gamma = [1 - (\mathbf{v}/c)^2]^{-1/2}$$

- Shifted Maxwell distribution

– Swisdak (2013), Melzani+ (2014) etc.

$$\propto \exp\left(-\frac{\Gamma(\gamma' - \beta u'_x)}{T}\right)d^3u'$$



Modified Sobol algorithm

[Sobol 1976, Pozdnyakov+ 1983, Zenitani 2015]

repeat

generate X_1, X_2, X_3, X_4 , uniform on $(0, 1]$

$u \leftarrow -T \ln X_1 X_2 X_3$

$\eta \leftarrow -T \ln X_1 X_2 X_3 X_4$

until $\eta^2 - u^2 > 1$.

generate X_5, X_6, X_7 , uniform on $[0, 1]$

$u_x \leftarrow u (2X_5 - 1)$

$u_y \leftarrow 2u \sqrt{X_5(1 - X_5)} \cos(2\pi X_6)$

$u_z \leftarrow 2u \sqrt{X_5(1 - X_5)} \sin(2\pi X_6)$

if $(-\beta v_x > X_7)$, $u_x \leftarrow -u_x$

$u_x \leftarrow \Gamma(u_x + \beta \sqrt{1 + u^2})$

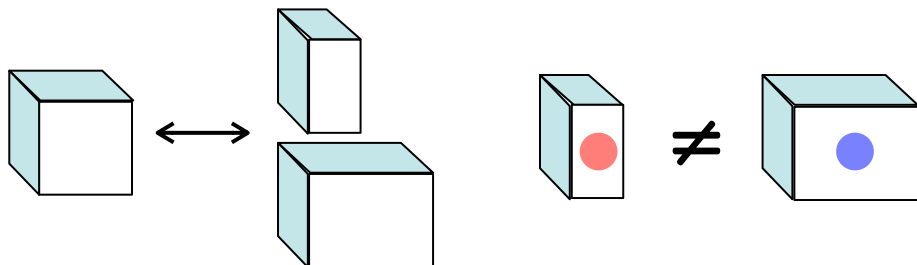
return u_x, u_y, u_z

- **Sobol method**

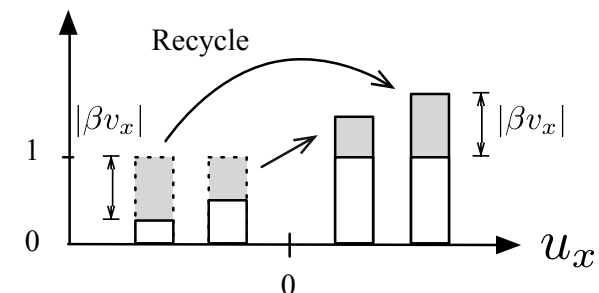
- Stationary Maxwellian
- Reject some particles from 3rd-order Gamma distribution

- **SZ's addition**

- Adjust particle density for Volume transform
- Without this, we will see a big error (33%) in the energy flow



Acceptance factor



Quest for the original reference

British Library

Berkeley

? MIT

Princeton

Perdue

U Illinois Urbana-Champaign

И.М.Соболь

О МОДЕЛИРОВАНИИ НЕКОТОРЫХ РАСПРЕДЕЛЕНИЙ,
СХОДНЫХ С ГАММА-РАСПРЕДЕЛЕНИЕМ

Рассмотрим два нестандартных приема для моделирования случайных величин с плотностями вида

$$p(x) = B_n x^n e^{-b\sqrt{1+x^2}} \quad (1)$$

и

Sobol, I. M., "On Simulation of Certain Distributions Similar to Gamma Distribution", in *Monte Carlo Methods in Computational Mathematics and Mathematical Physics* (1976)

Эти

где при

вистских электронов и частоты фотонов; они использовались в работе [1].

Summary (1/2)

- Relativistic Ohm's law

- Kinetic equations have been re-formulated
- A new dissipation term: **heat flow inertia** is introduced
- Anti-parallel reconnection
 - **Heat flow inertia** partially replaces **thermal inertia** at the X-line
 - Heat-flow region is focused to the midplane, due to the relativistic Speiser motion
- Guide-field reconnection
 - **Heat flow inertia** may replace **thermal inertia** at the X-line
 - It cancels the bulk inertial term in the inflow regions

- Electron orbits in nonrelativistic reconnection

- Speiser orbits - energetic particles
- Regular orbits - trapped in a figure-8 shaped orbit

Summary (2/2)

- Electron orbits in nonrelativistic reconnection (con'd)
 - Noncrossing electrons
 - A new family of particle orbits
 - Modified by the polarization electric field E_z
 - Preferable acceleration for energetic Speiser electrons
 - Consistent with Spacecraft data
- Appendix
 - Sobol algorithm and volume transform algorithm
- References:
 - Hesse & Zenitani, *Phys. Plasmas* **14**, 112102 (2007) (Ohm's law; old results)
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