Dissipation in relativistic pair-plasma reconnection: revisited

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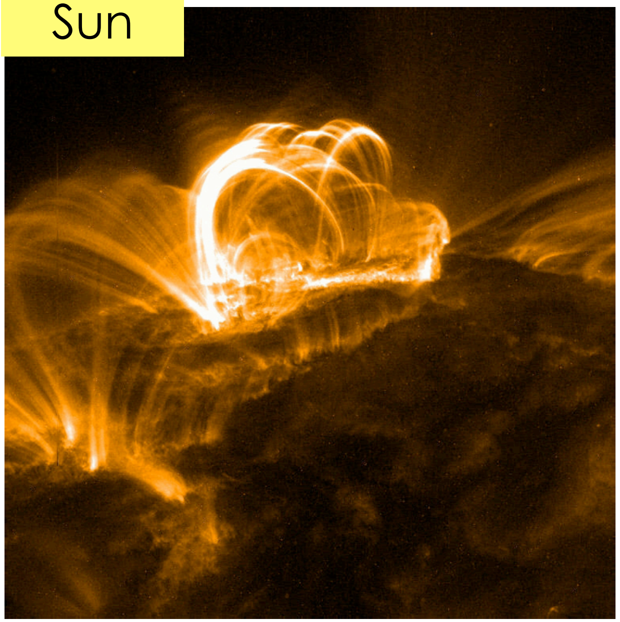
Outline

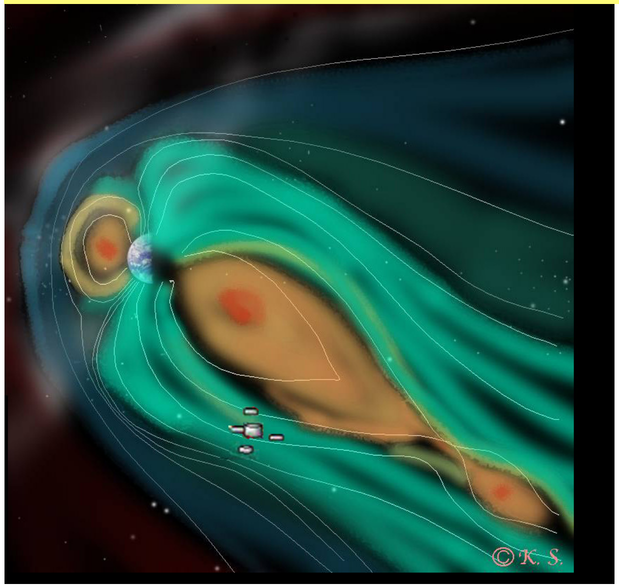
- 1. Dissipation in relativistic pair-plasma reconnection: revisited
  - Ohm's law in a relativistic kinetic plasma
  - Application to 2D PIC simulation of relativistic reconnection
- 2. Electron orbits in nonrelativistic reconnection
  - Fundamental pieces of reconnection system
  - Various electron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

Magnetic reconnection

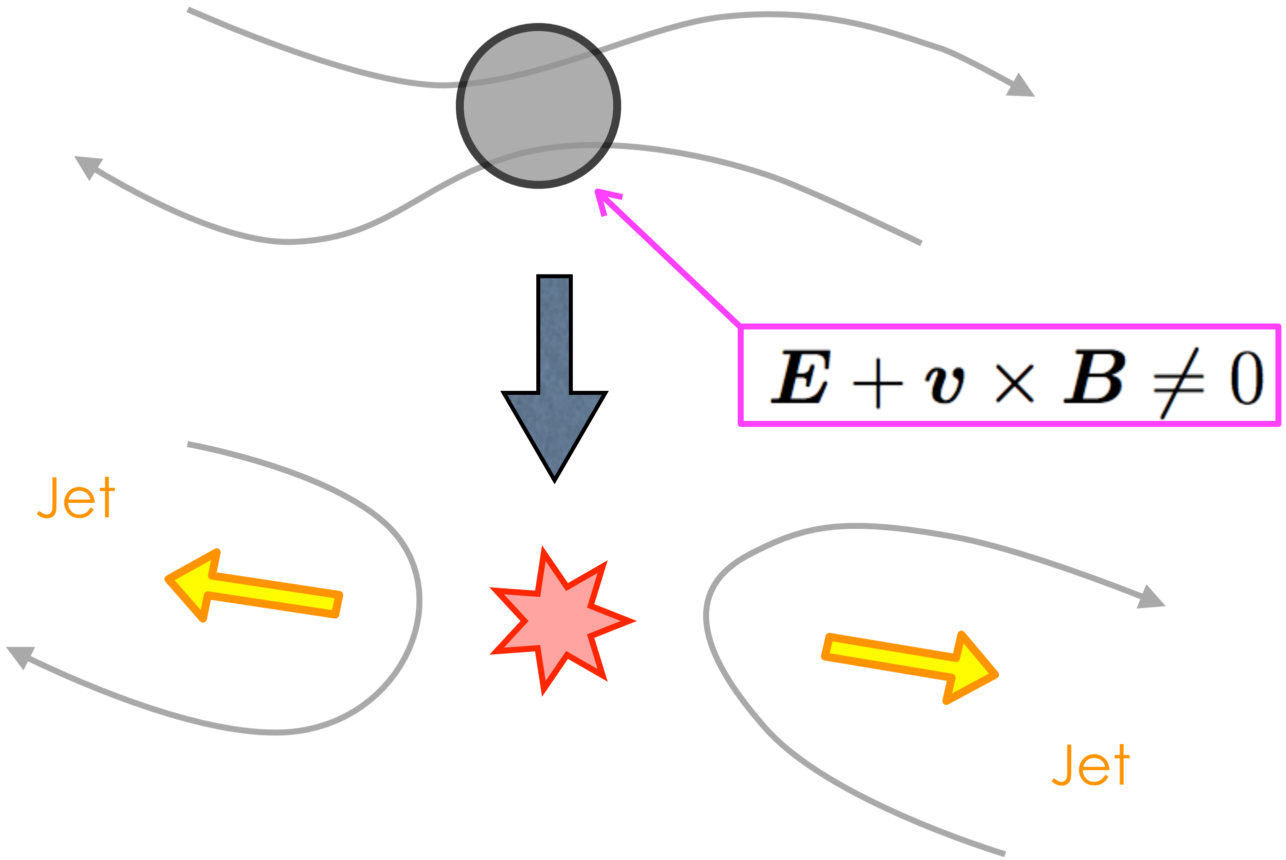
Sun



Earth's Magnetosphere

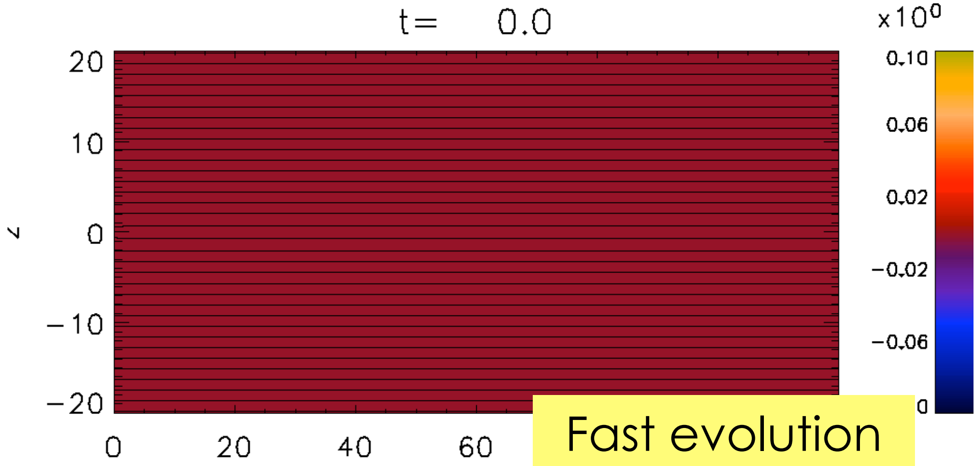


- Ideal MHD condition is violated
- This is necessary to change the topology



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

Localized η

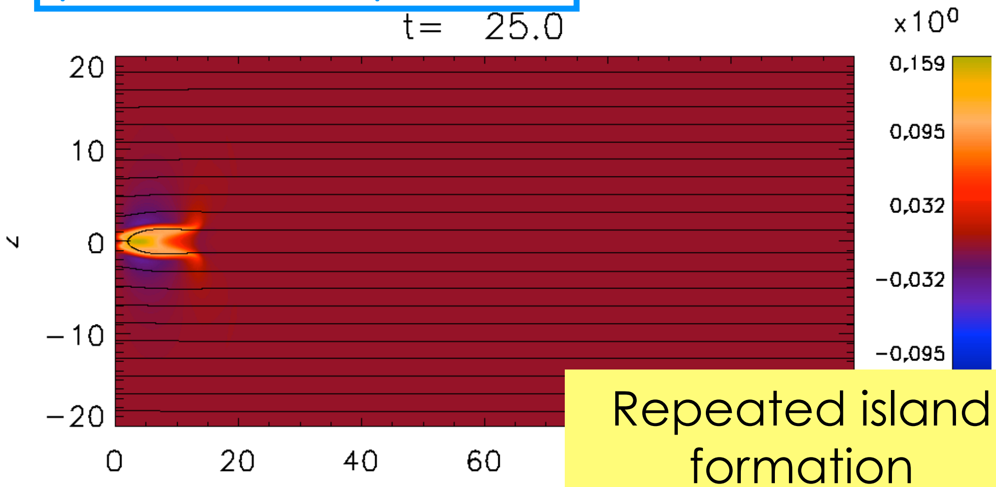


Fast evolution

- Effective resistivity (Resistive/dissipative term)

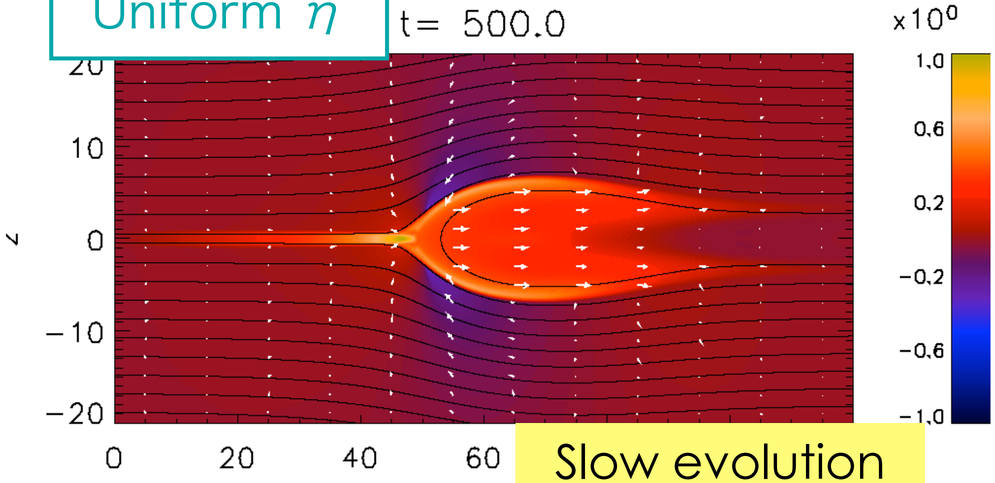
$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta_{\rm eff}\, \boldsymbol{j}$$

parameter dependent



Repeated island formation

Uniform η



Slow evolution

Zenitani+ 2010 ApJ

Ohm's law in a kinetic plasma

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

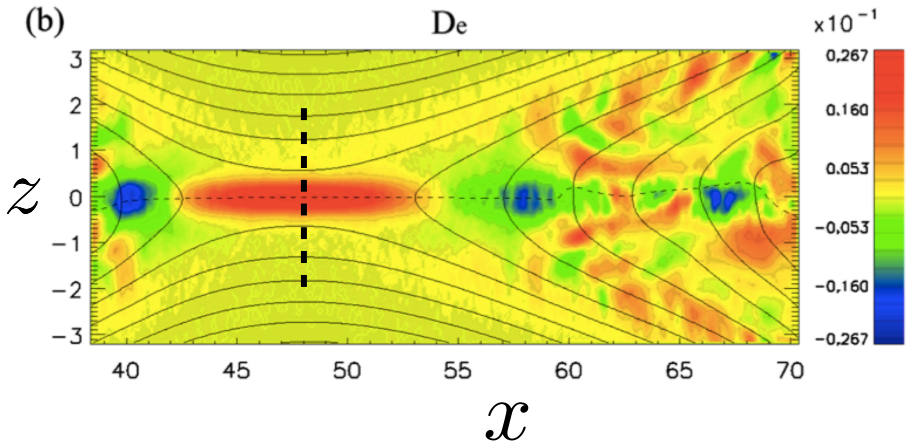
$$\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B} = -\frac{1}{n_e q}\nabla\cdot\overleftrightarrow{P}_e - \frac{m_e}{q}\left(\frac{d\boldsymbol{v}_e}{dt}\right) + \ldots \approx \eta \boldsymbol{j}$$

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

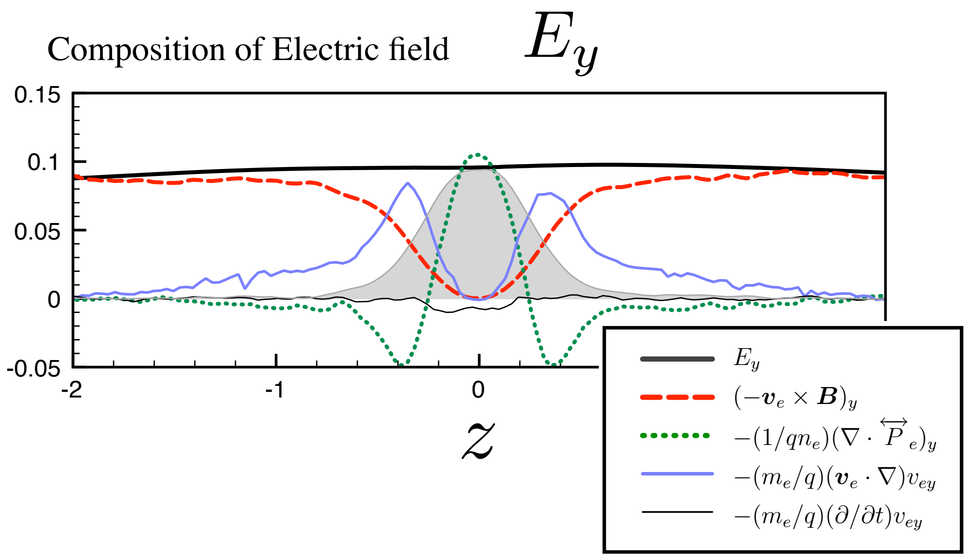
Bulk inertia

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

2D particle-in-cell (PIC) simulation



Zenitani+ 2011 PRL



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

Bulk inertia

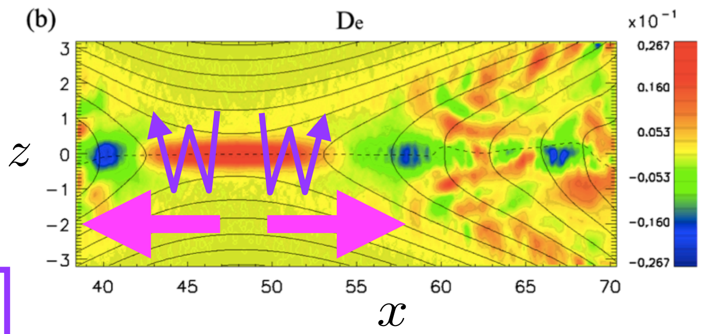
And some more...
- Wave-particle interaction
- Anomalous viscosity

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

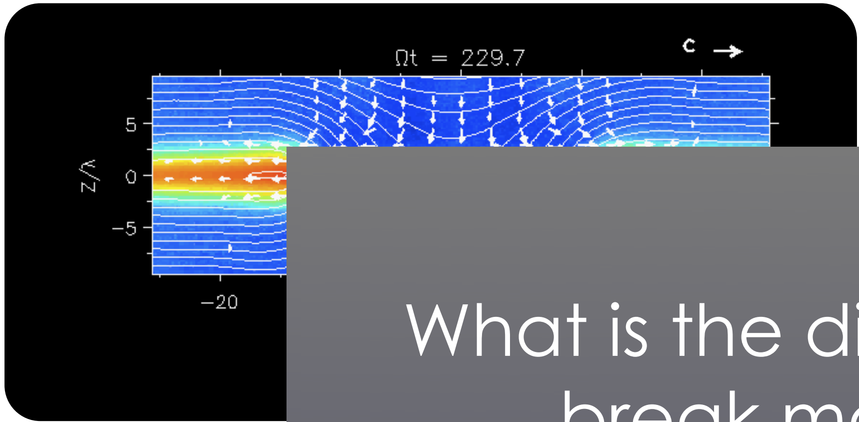
$$E_y \approx -\frac{1}{2en}\left(\frac{\partial v_{ex}}{\partial x}\right) L^2 \Delta(m_e n v_{ey})$$

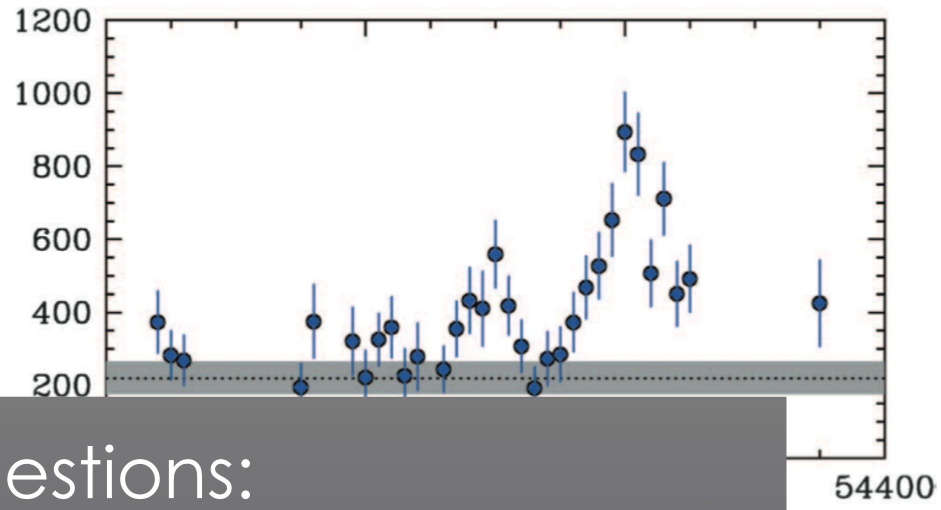
Medium-scale
convection
in the outflow direction

Local momentum
transport (diffusion)
due to particle motion



Relativistic kinetic reconnection





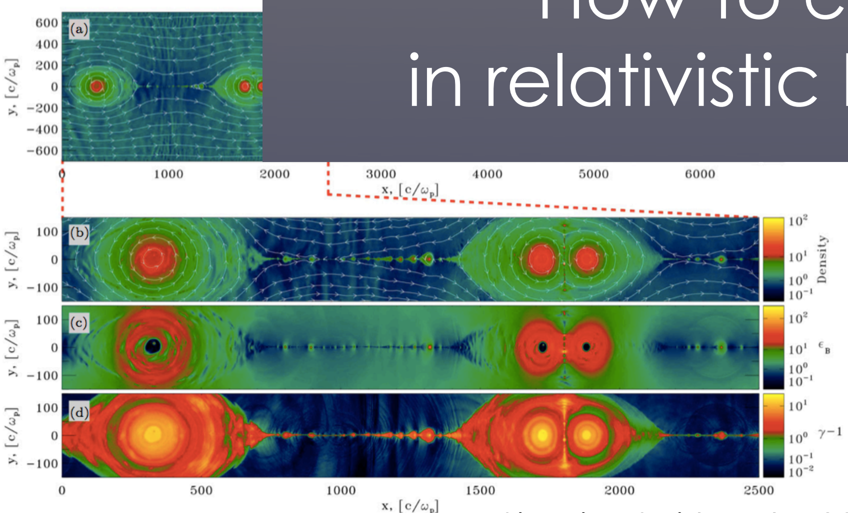
ni 2011

Questions:

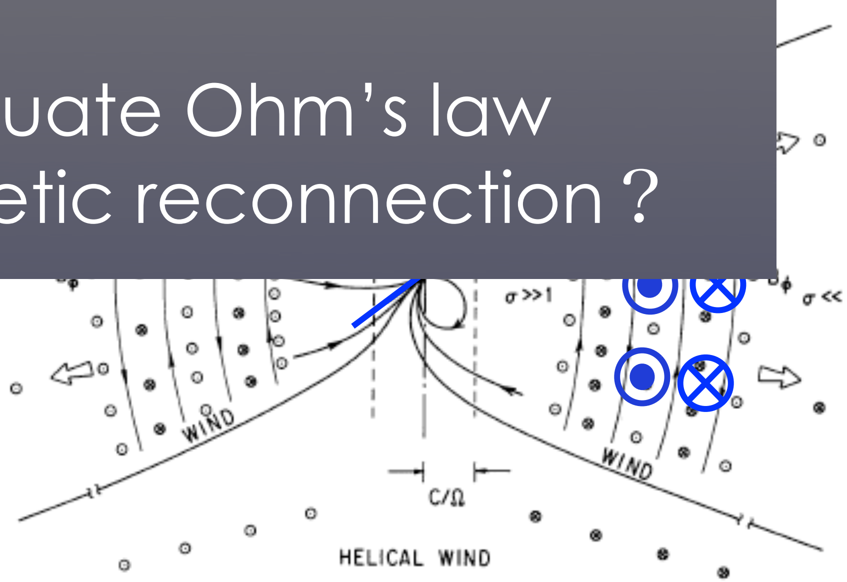
What is the dissipation mechanism to break magnetic field lines ?

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

Kinetic simu



Sironi & Spitkovsky 2014



Pulsar wind

Coroniti 1990

Hesse & Zenitani (2007) analysis

- We started from the Vlasov equation

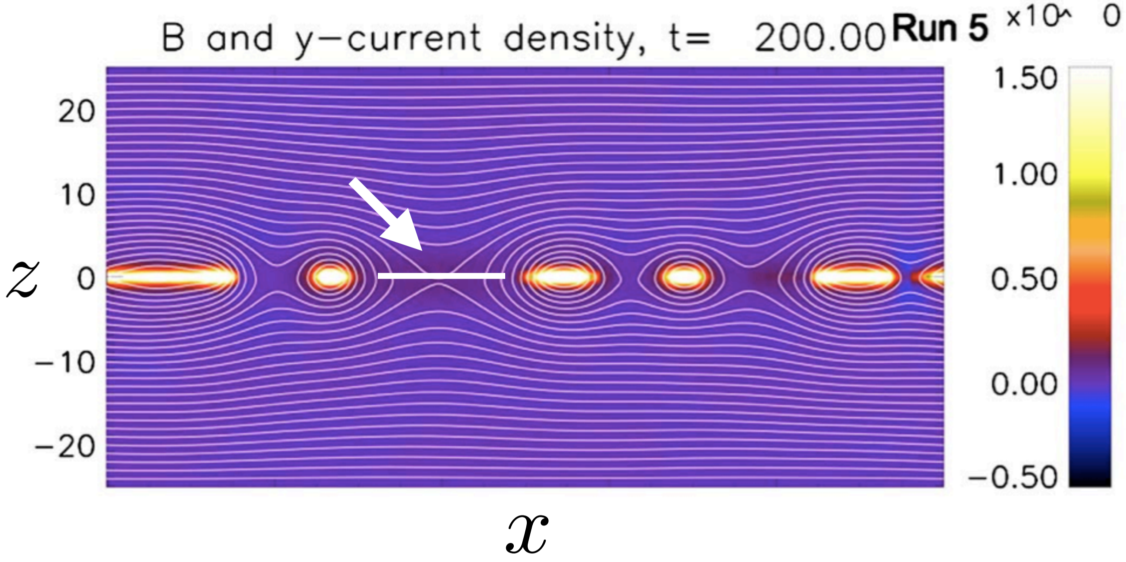
$$\frac{\partial f}{\partial t} + \frac{\vec{u}}{\gamma} \cdot \nabla f + \frac{q}{m}\left(\vec{E} + \frac{\vec{u}}{\gamma} \times \vec{B} \right) \cdot \frac{\partial f}{\partial \vec{u}} = 0$$

Problems...
- Symmetry
- Physical meaning

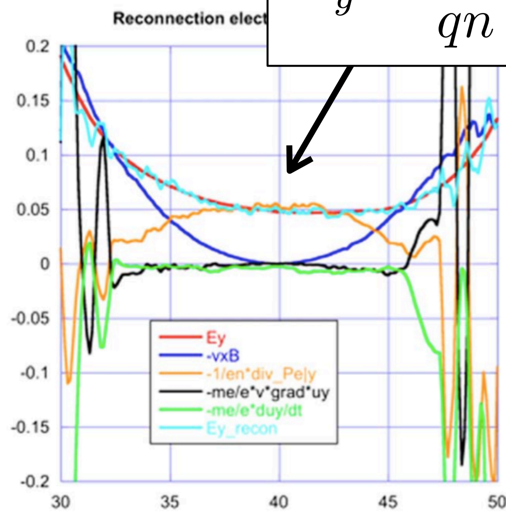
- Ohm's law with Wright=Hadley (1974) pressure tensor

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

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



$$E_y \approx \frac{1}{qn} \nabla \cdot \overleftrightarrow{P}$$



Hesse & Zenitani 2007

Ohm's law in a relativistic kinetic plasma

- Stress-energy tensor

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

- Standard decomposition

w^α : heat flow

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

Heat flow tensor

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

- Energy momentum equation for relativistic plasmas

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

- Relativistic Ohm's law (with ∂_t=0)

Heat flow inertia (new in relativistic regime)

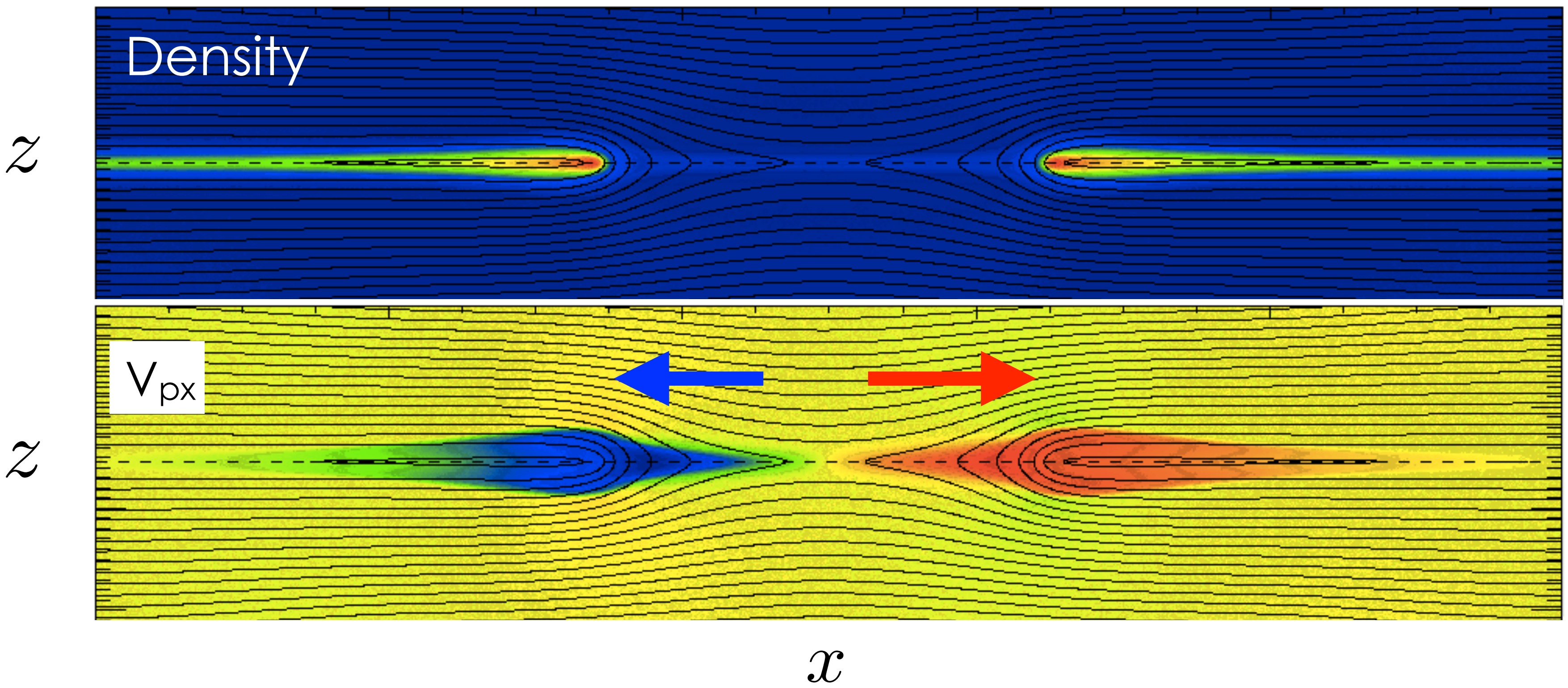
$$\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B} = \frac{1}{\gamma n q} \nabla \cdot \left(w u^i u^j + Q^{ij} + P^{ij} \right)$$

Bulk inertia (including relativistic pressure)

Thermal inertia (Local momentum transport)

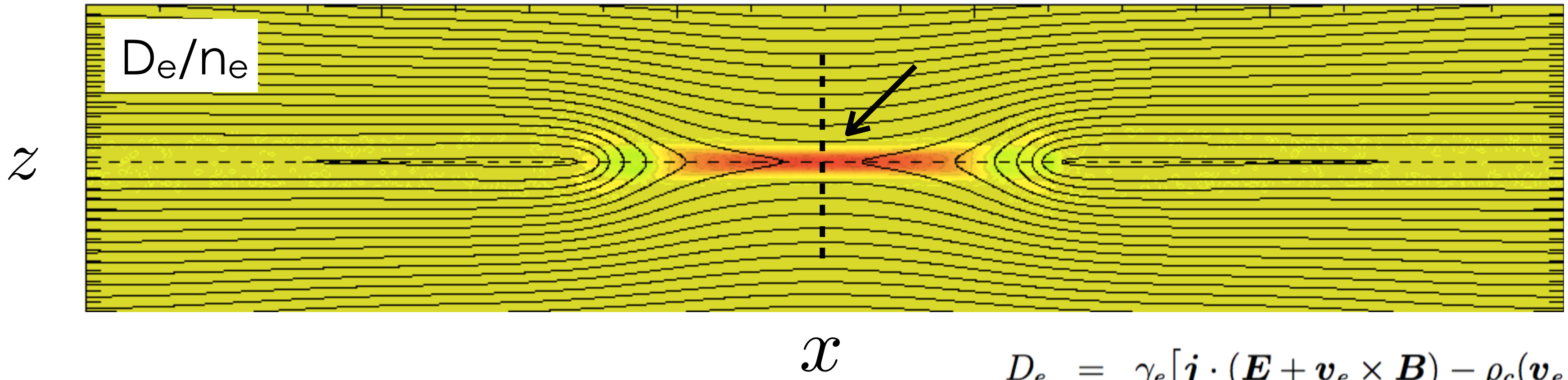
2D Particle-in-Cell simulation

- 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)



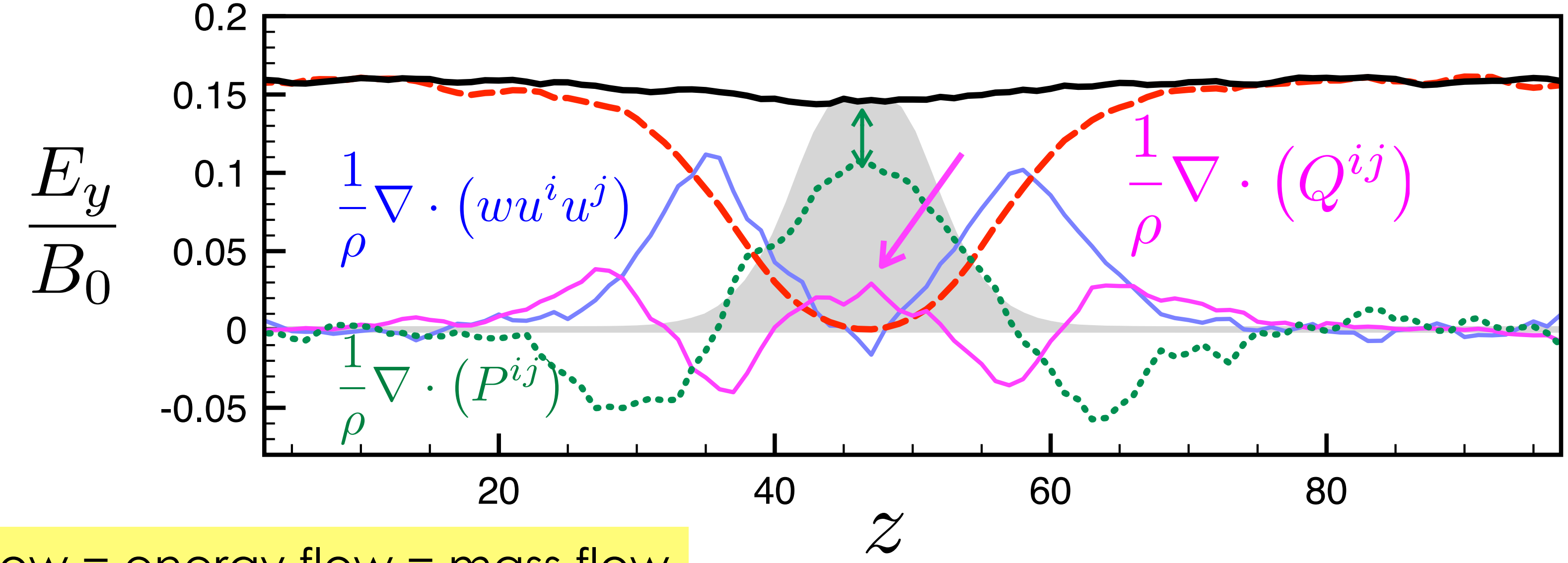
2D Particle-in-Cell simulation

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



$$D_e = \gamma_e[\boldsymbol{j}\cdot(\boldsymbol{E}+\boldsymbol{v}_e\times\boldsymbol{B})-\rho_c(\boldsymbol{v}_e\cdot\boldsymbol{E})]$$

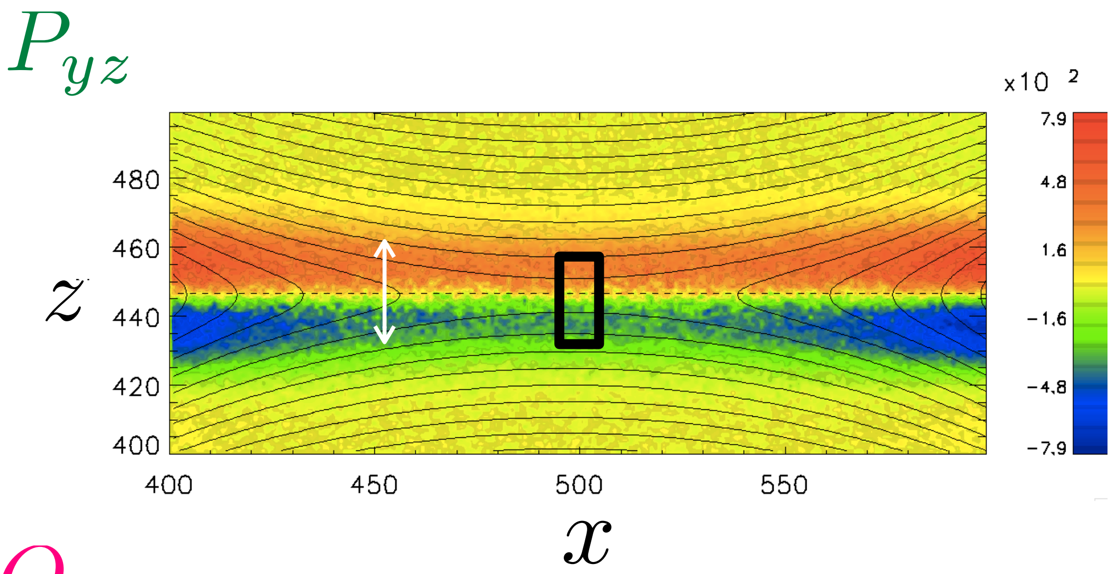
- Ohm's law: **heat flow term** appears

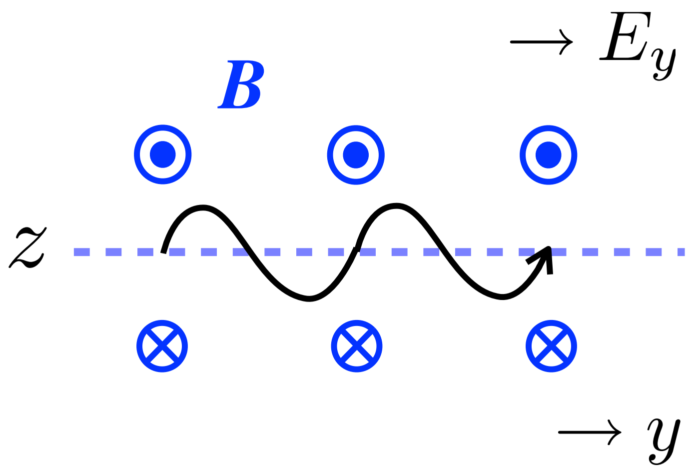


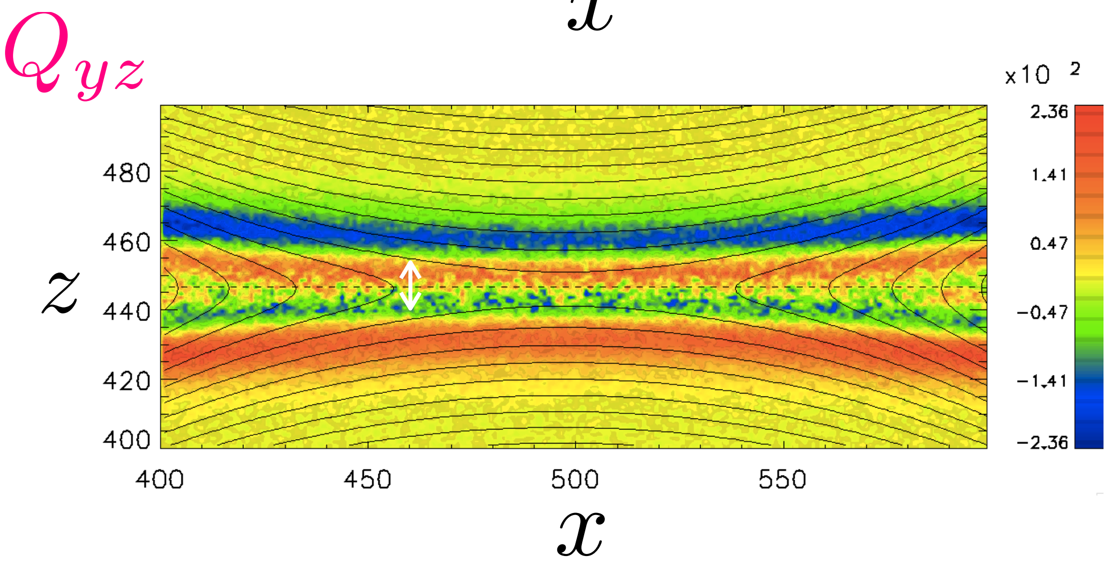
Heat flow = energy flow = mass flow

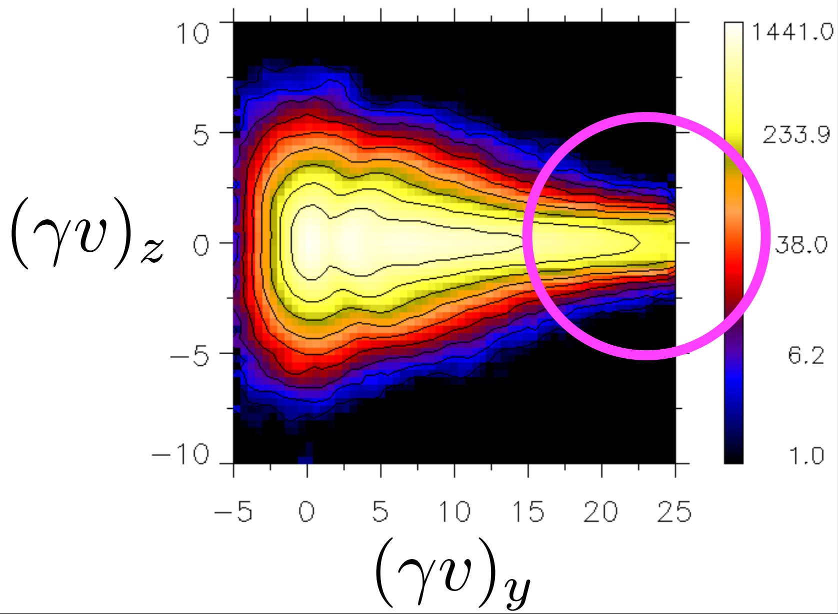
Momentum transport

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



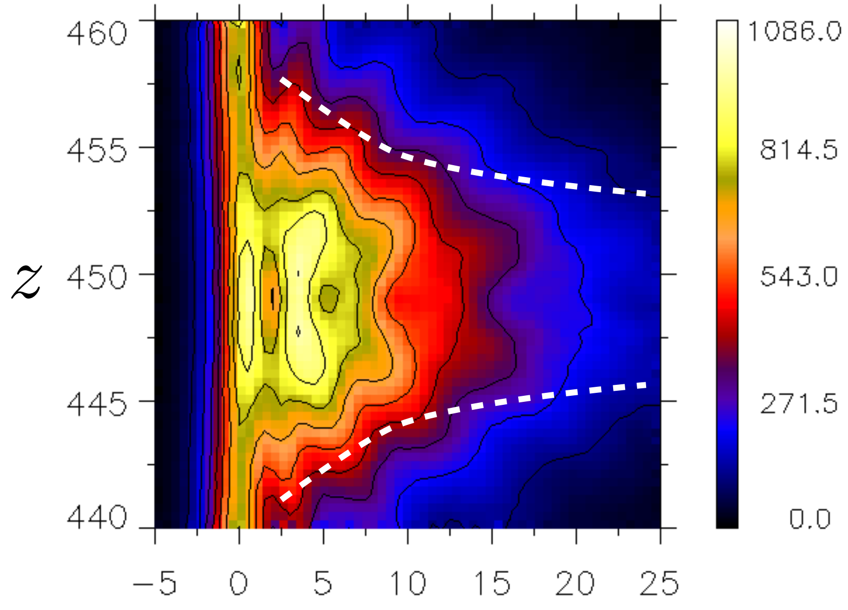






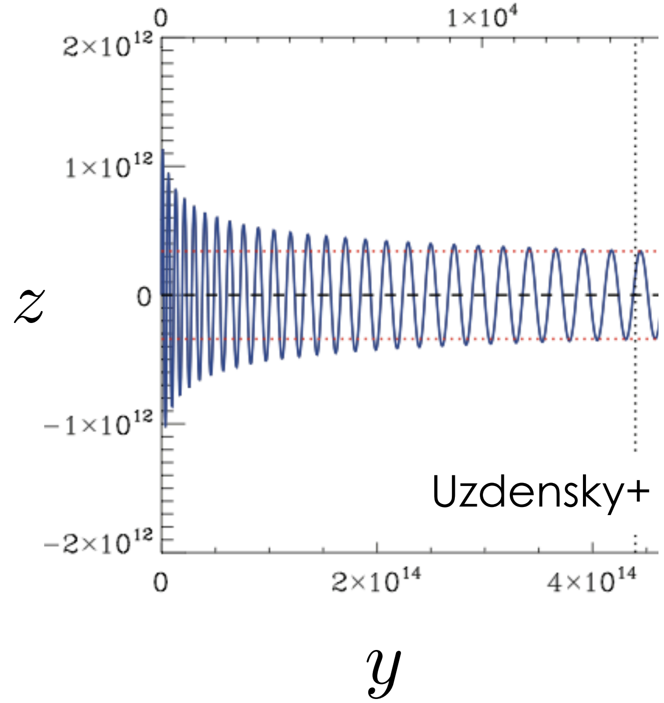
Speiser motion - relativistic focusing

Phase-space diagram



$(\gamma v)_y \sim \mathcal{E} \sim y$

Test particle tranejctory



- Envelope shrinks as particles are accelerated

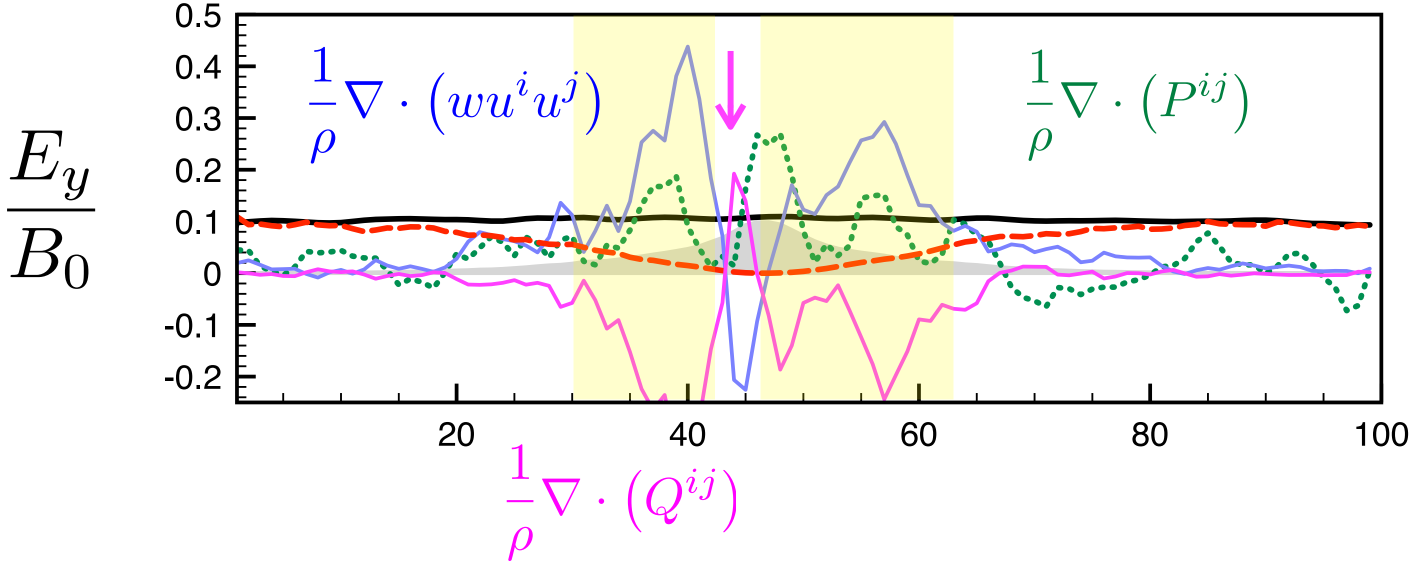
  $z_{max} \sim \mathcal{E}^{-1/3}$ (Uzdensky+ 2011)

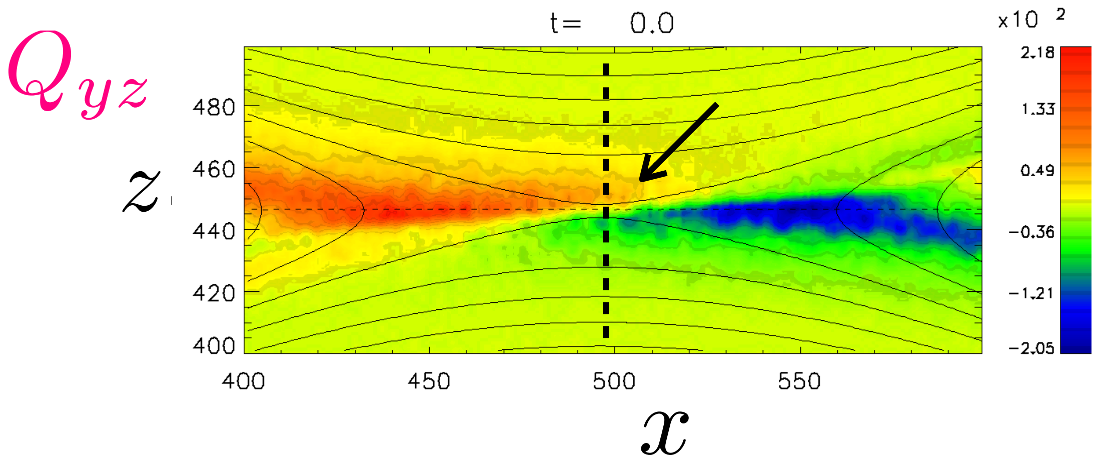
- Less pronounced in the nonrelativistic regime

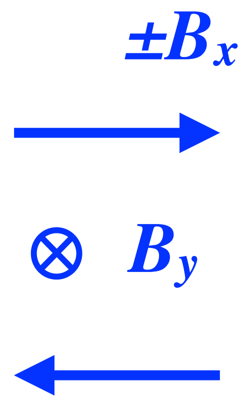
  $z_{max} \sim t^{-1/4} \sim \mathcal{E}^{-1/8}$ (Speiser 1965 JGR, modified)

Guide-field reconnection

- The **heat flow inertia** may sustain the reconnection electric field
- The **heat flow term** cancels the **bulk inertial term** in the inflow sides



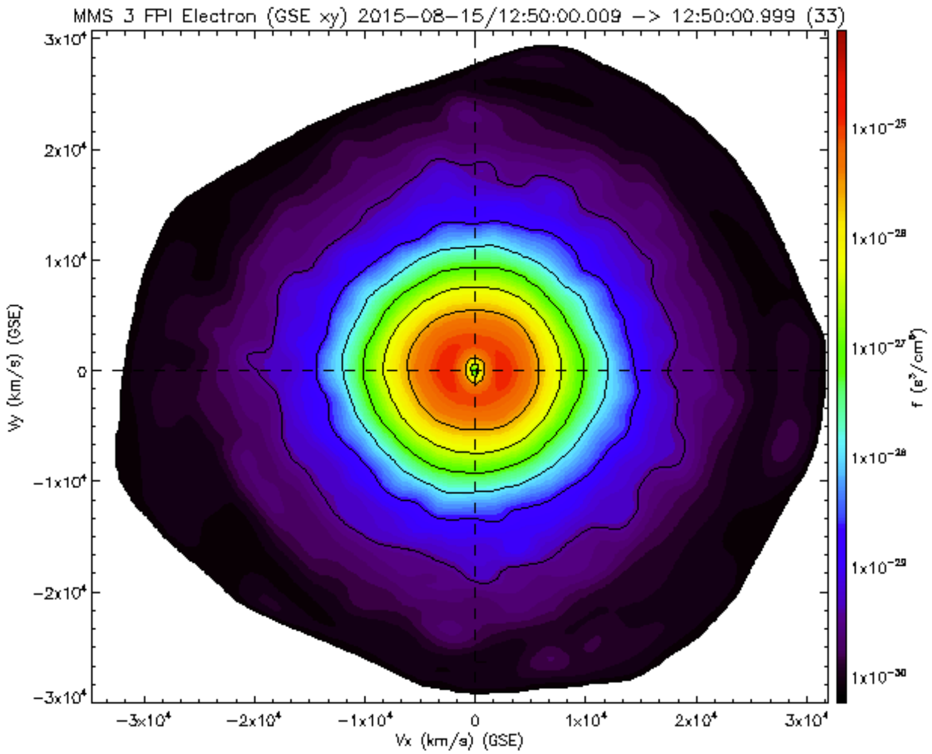




2. Electron orbits in nonrelativistic reconnection

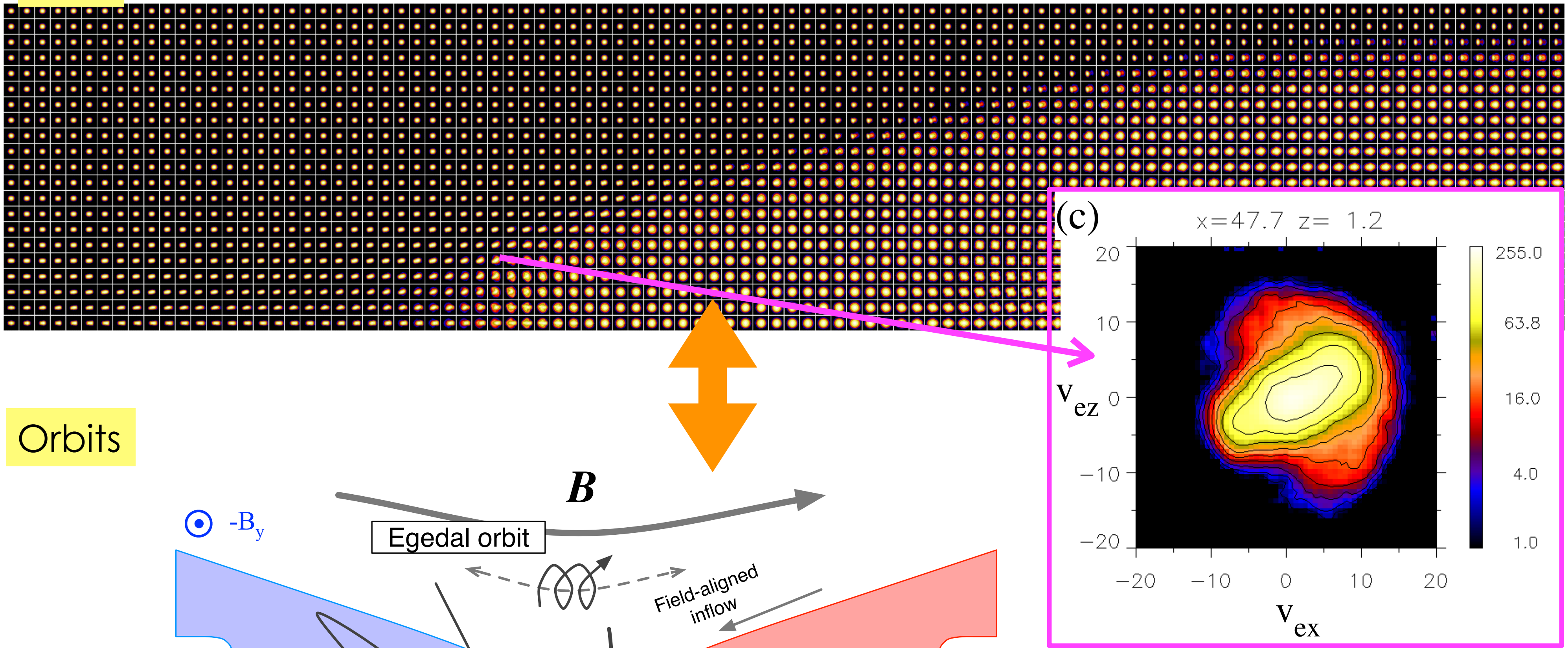
Magnetospheric MultiScale (MMS) mission

- 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.

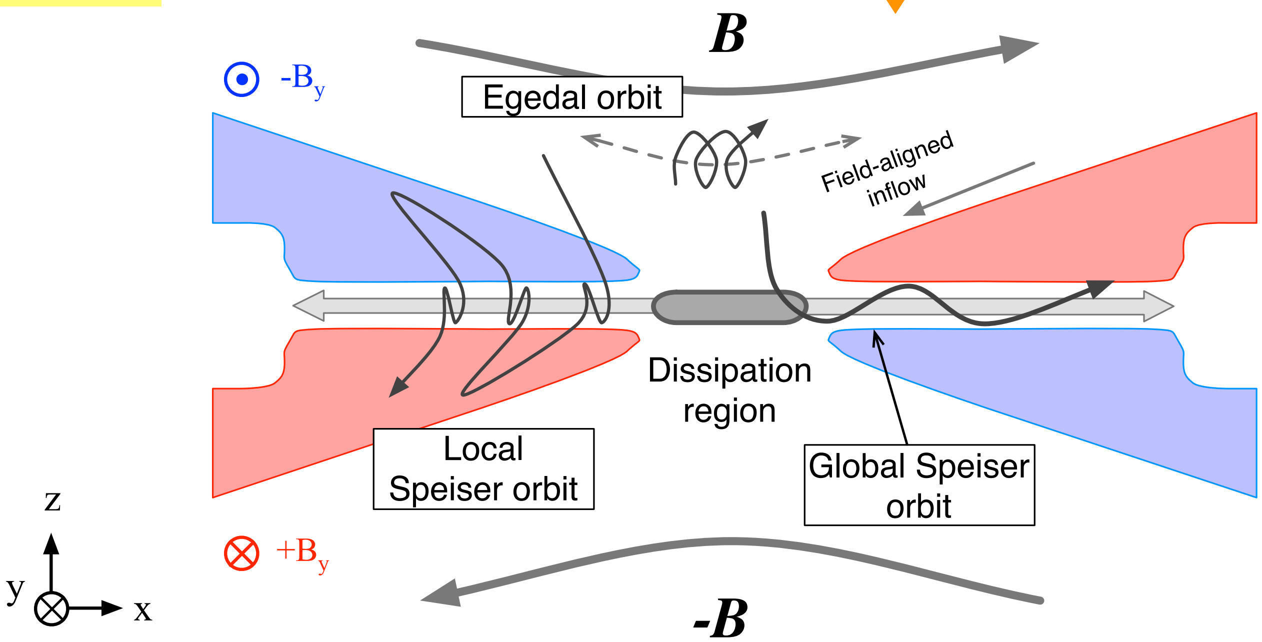


Electron VDFs vs electron orbits

VDFs



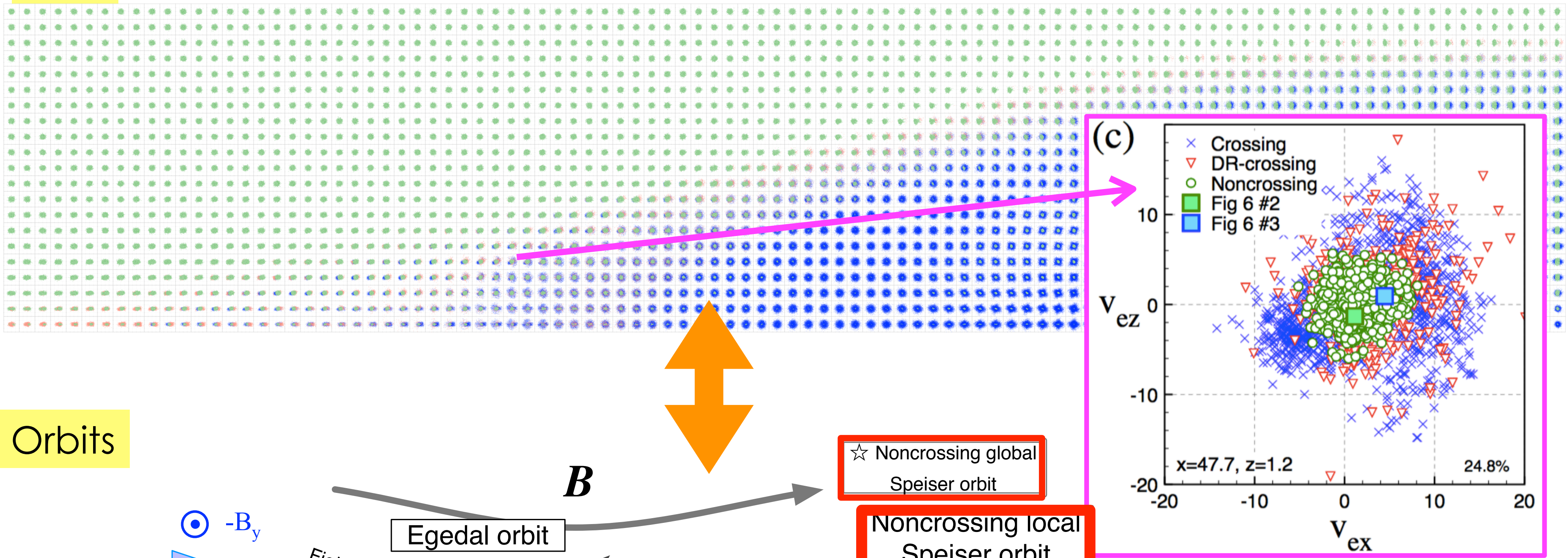
Orbits



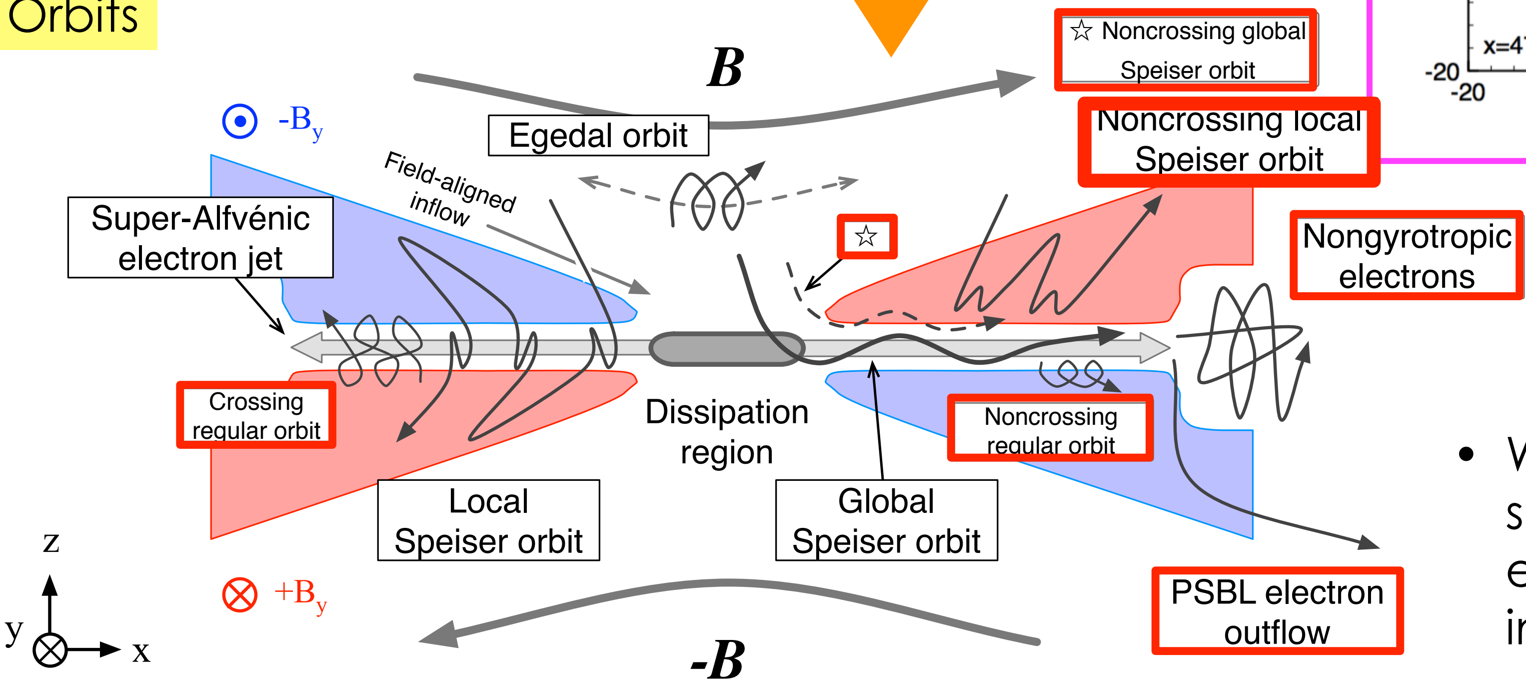
- We analyze 2 x 10^7 self-consistent electron orbits in our PIC simulation

Electron VDFs vs electron orbits

VDFs



Orbits



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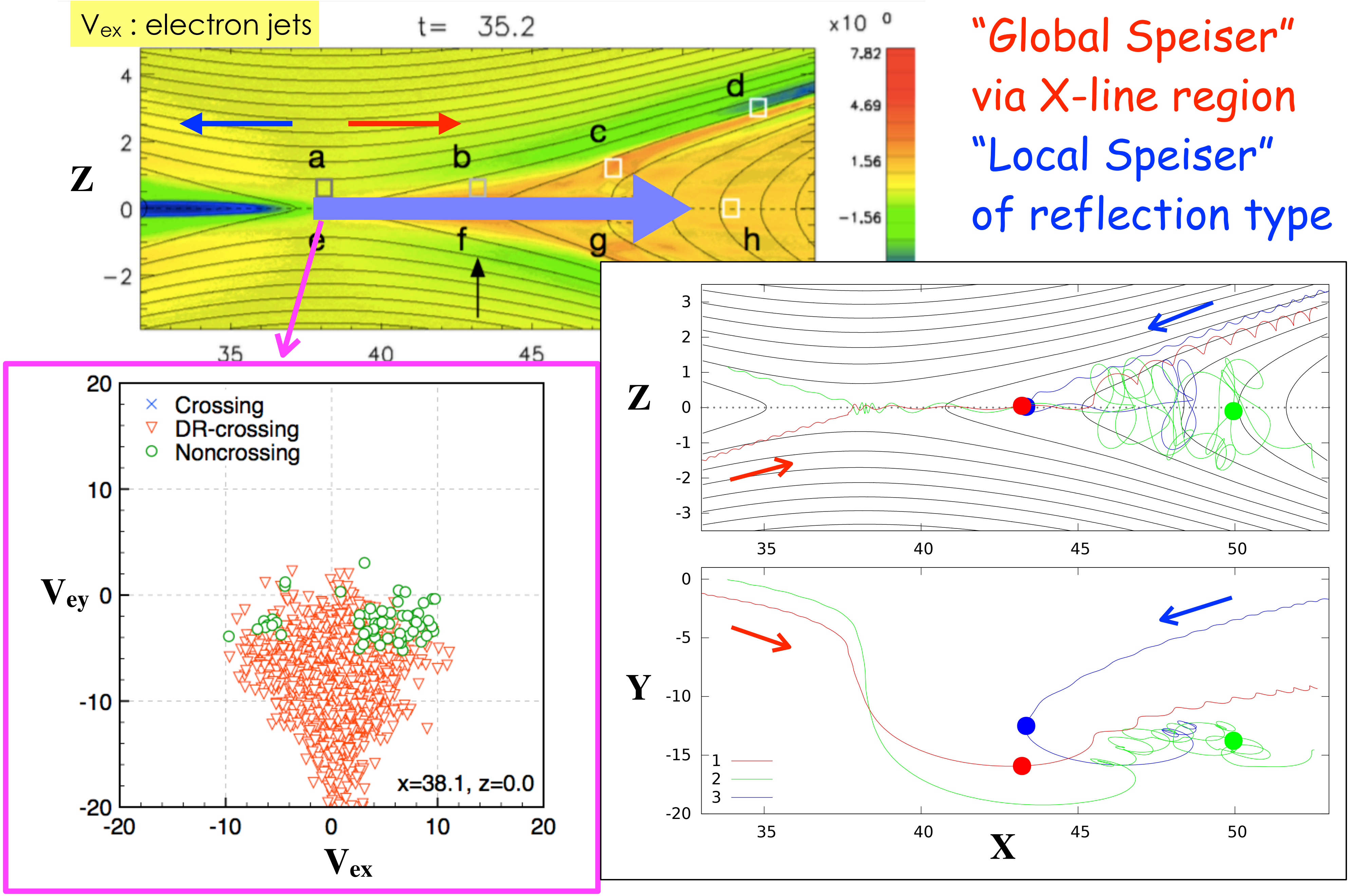
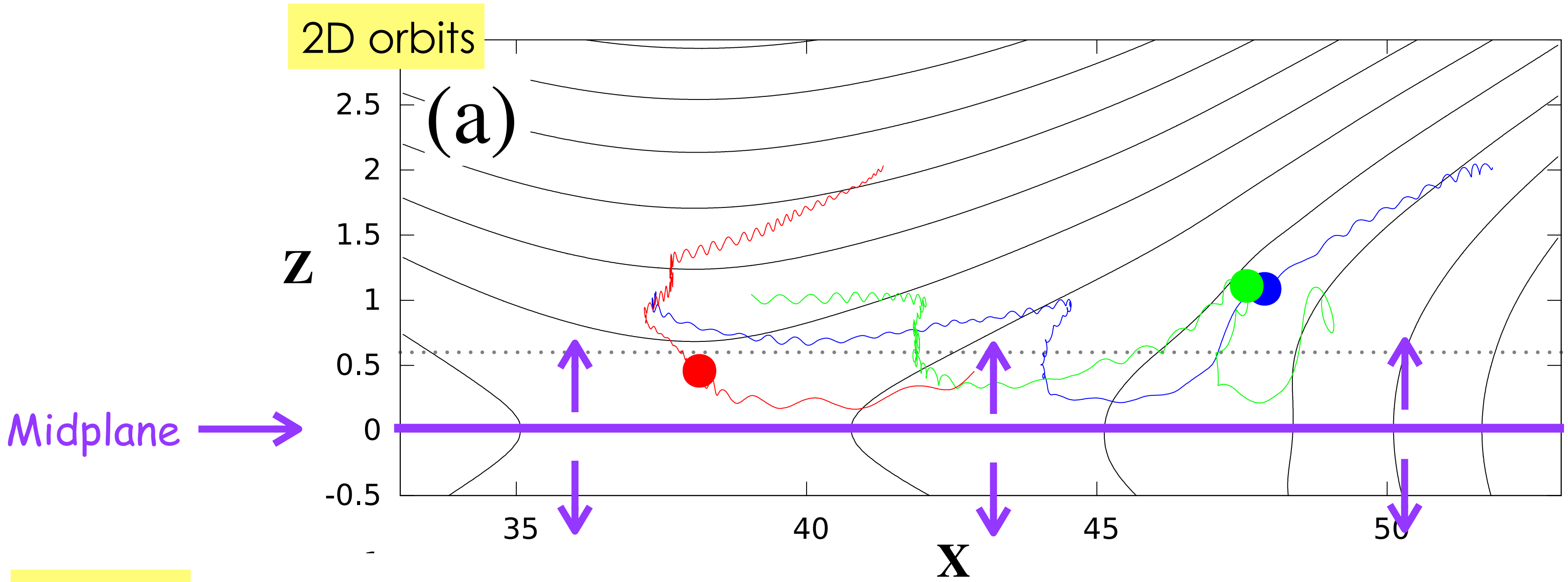
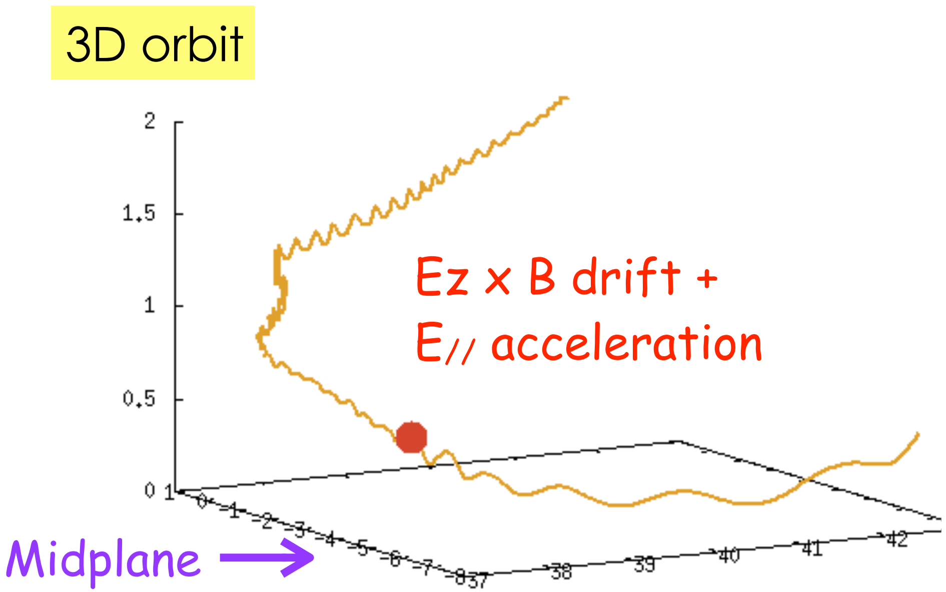
Electron Speiser VDFs in PIC simulation

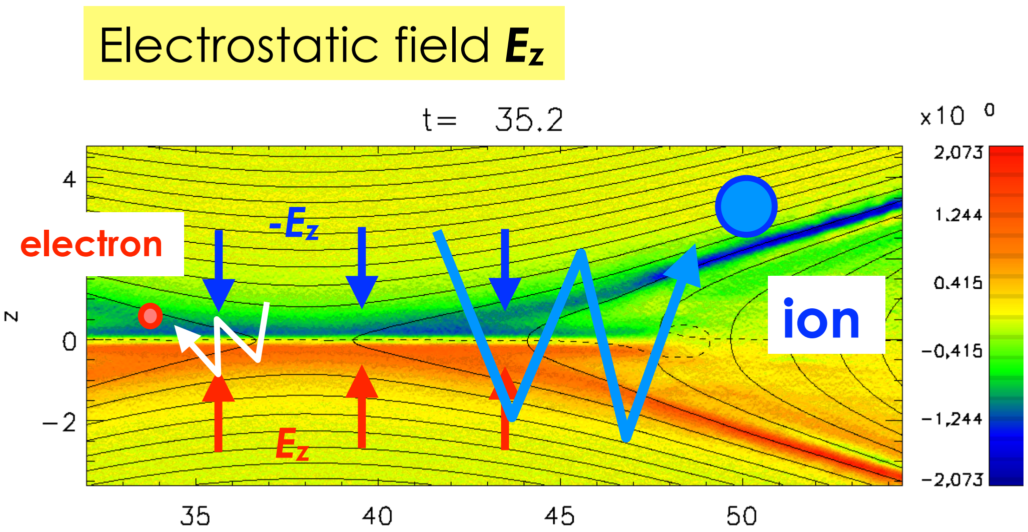


"Global Speiser"
via X-line region
"Local Speiser"
of reflection type

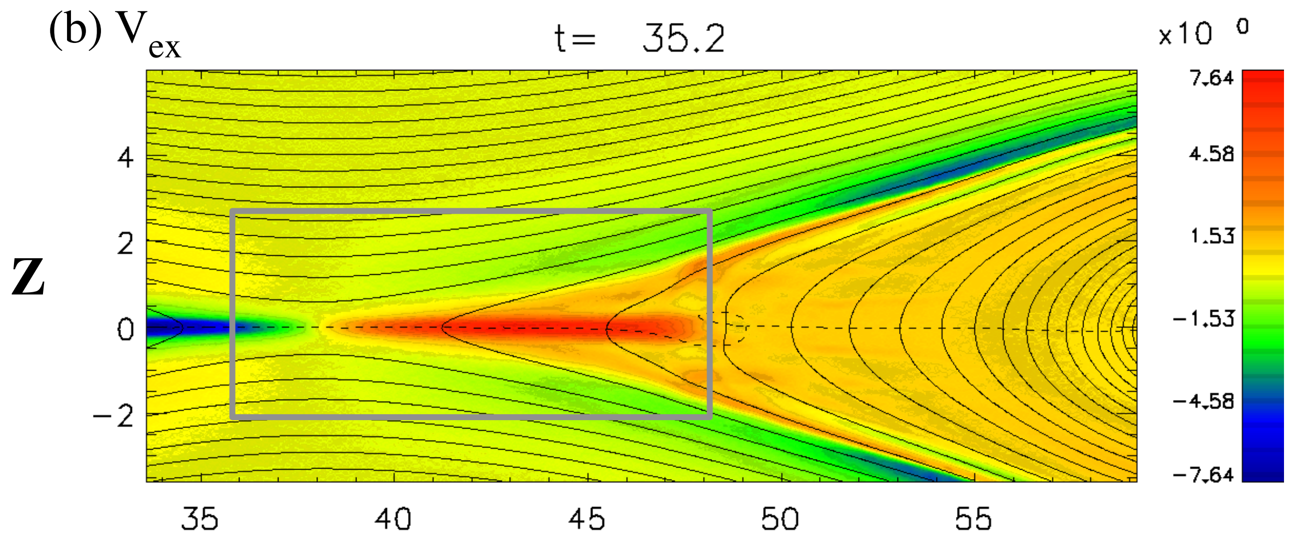
Noncrossing Speiser-like orbits

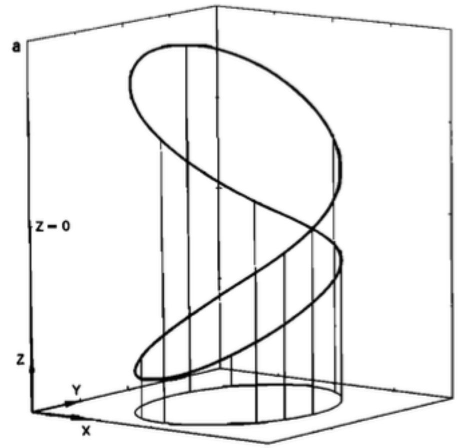




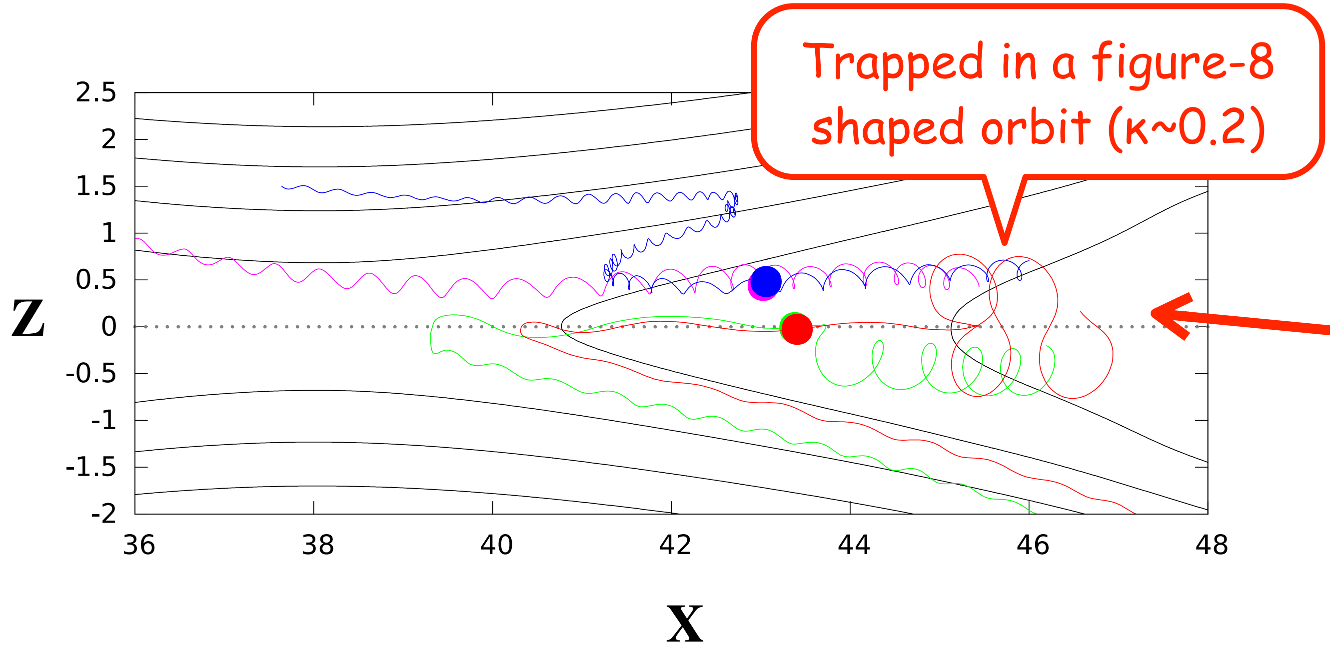


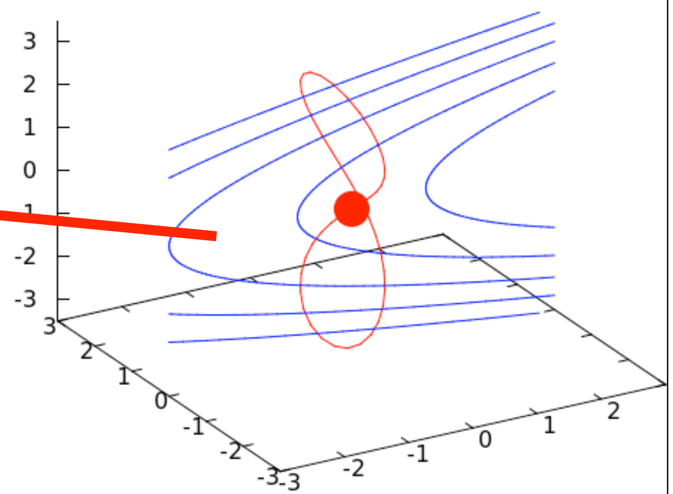
Electron regular orbits





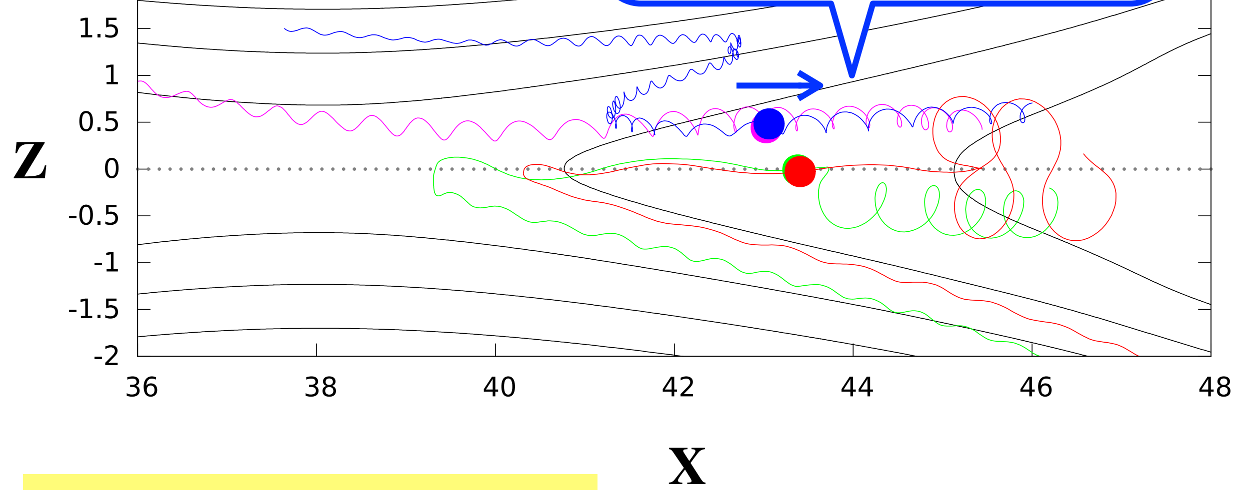
Chen & Palmadesso 1986 *JGR*



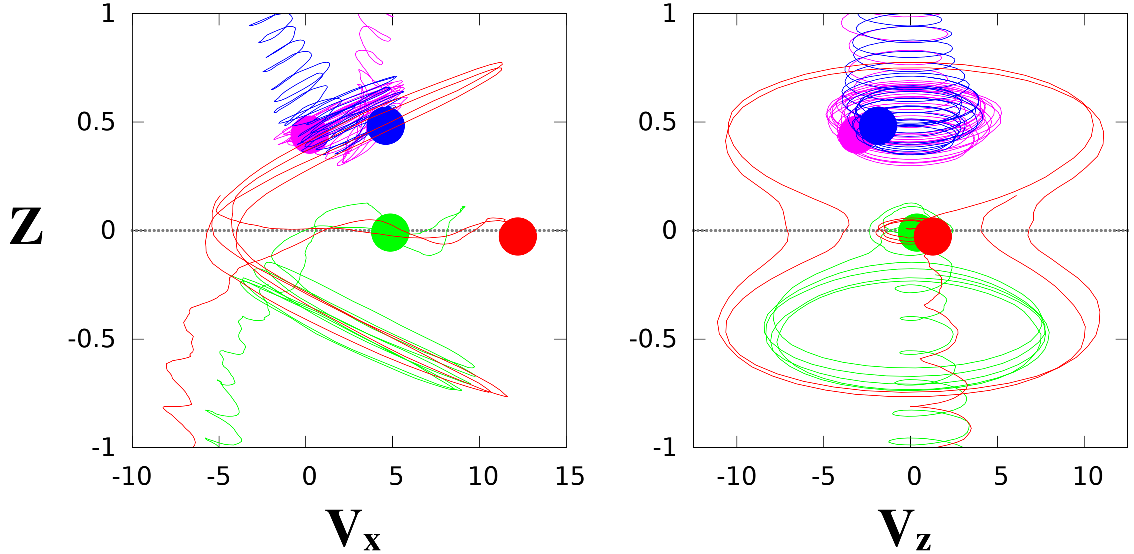


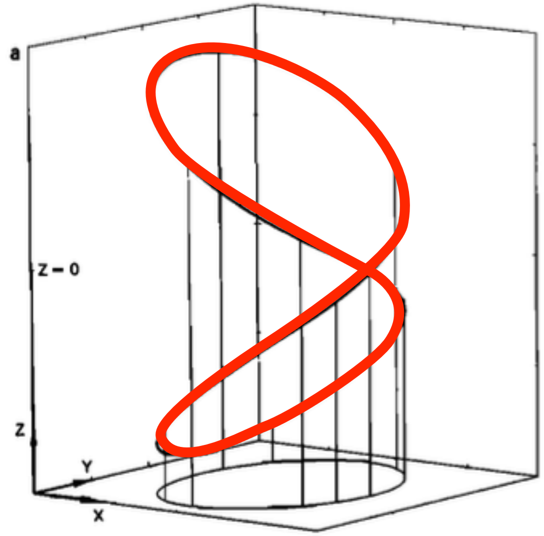
Noncrossing regular orbits

Trapped on flanks of the midplane



Phase-space diagrams





Chen & Palmadesso 1986 *JGR*

Noncrossing regular orbits

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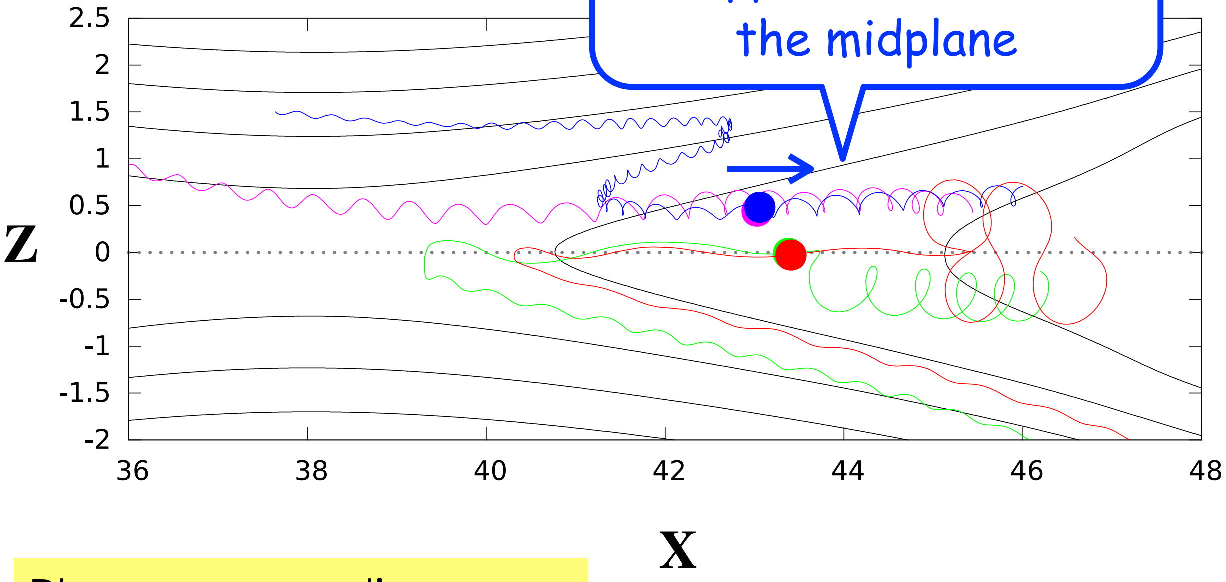

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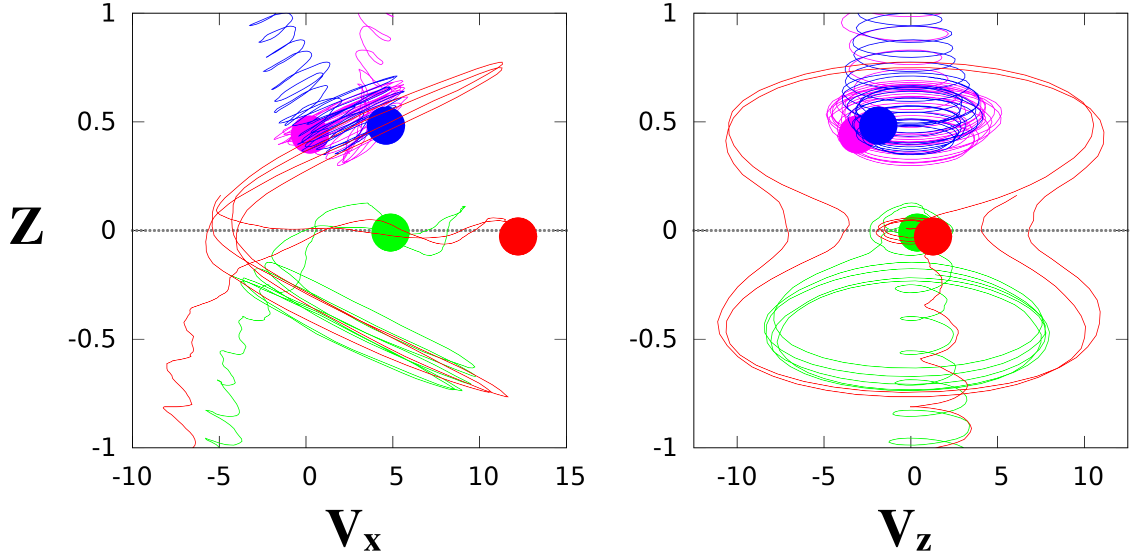
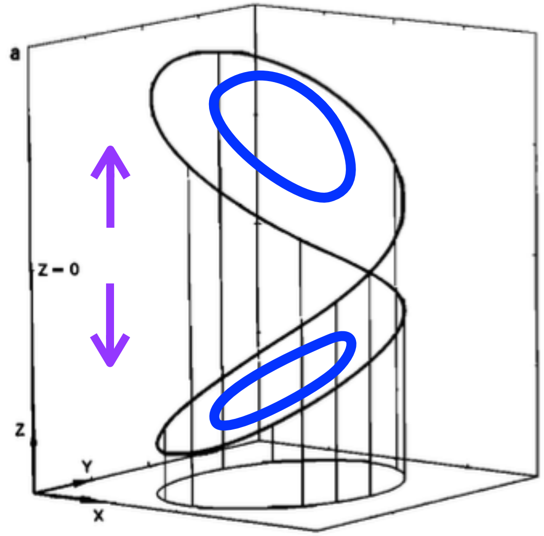


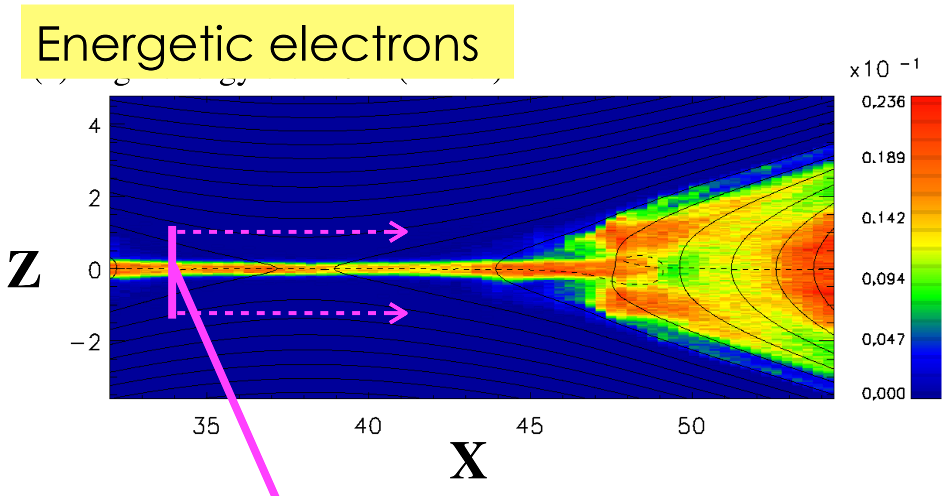


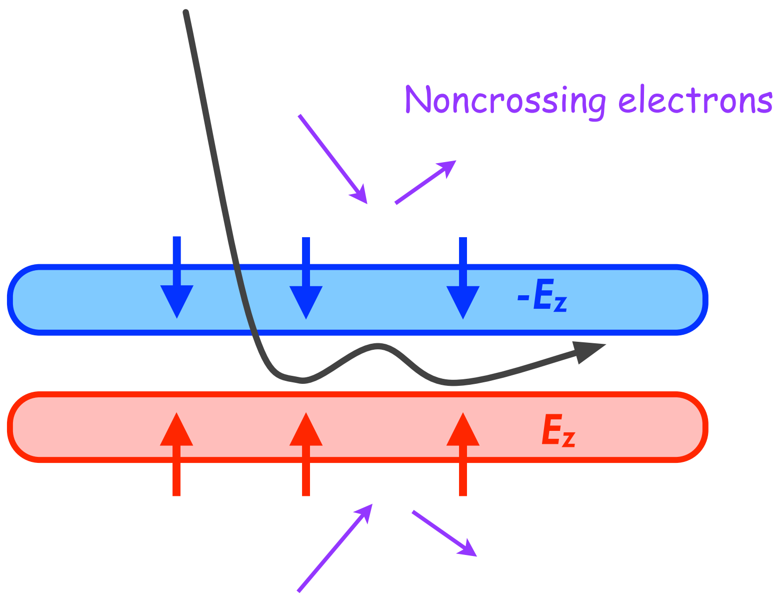
Chen & Palmadesso 1986 *JGR*

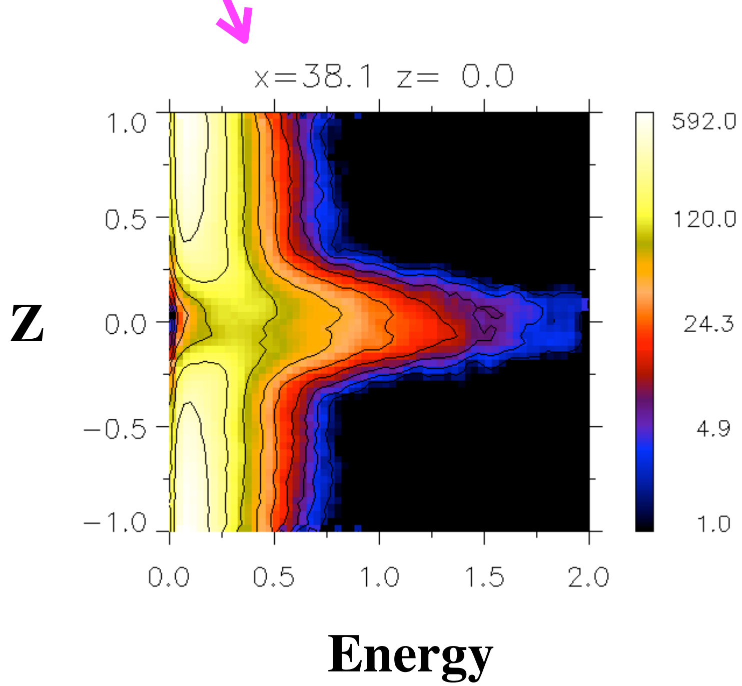
Detached from the midplane, due to E_z

Energetic electrons

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



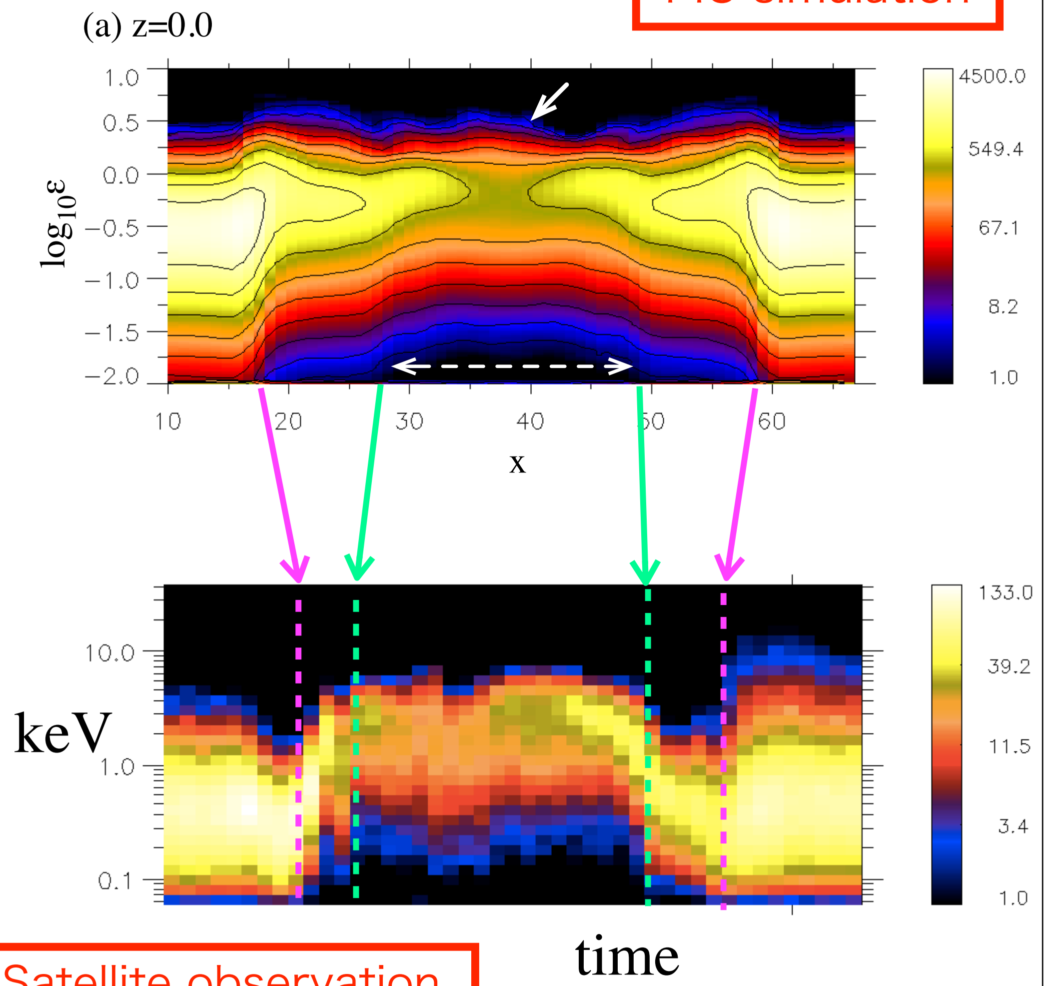


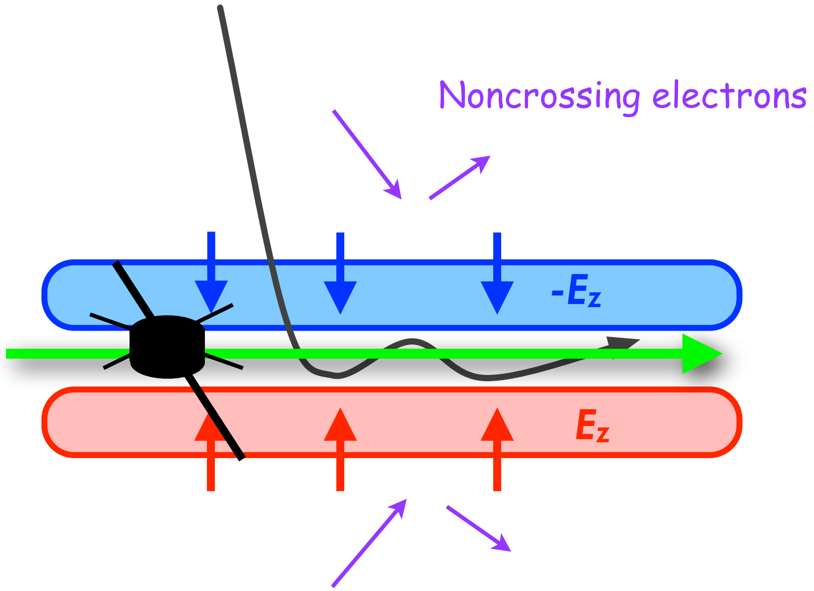


Observational signatures: ET diagram

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

PIC simulation





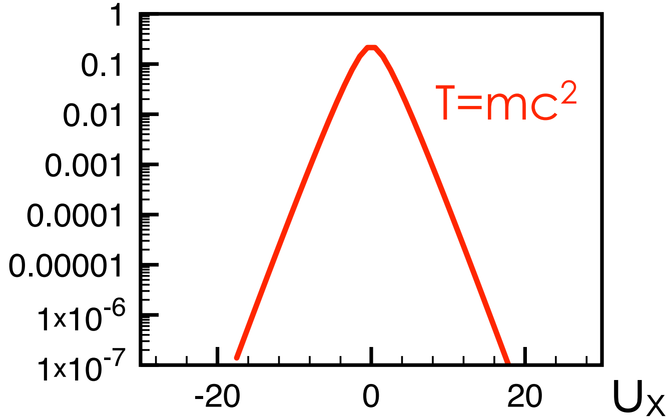
Satellite observation
(Geotail; old one)

2007-05-05 (Nagai+ 2013 JGR)

Appendix: A small tale near Purdue

Relativistic Maxwell distributions

- Jüttner=Synge distribution



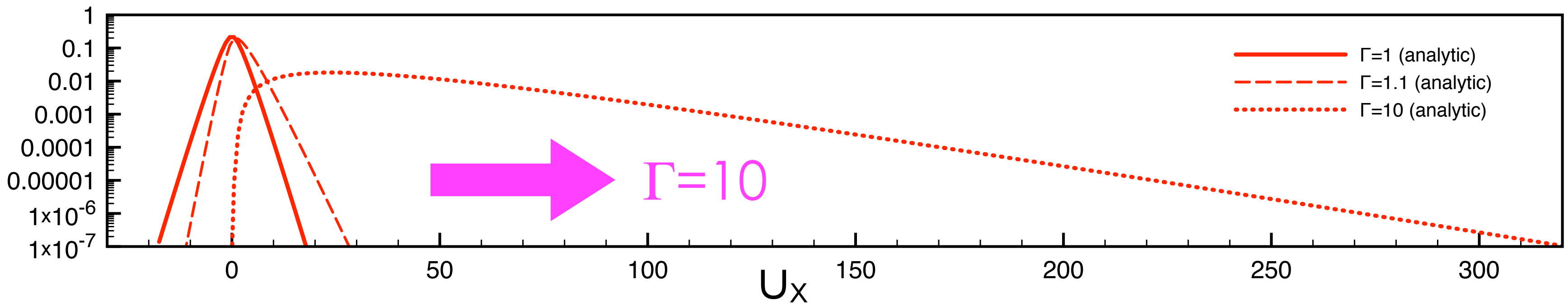
$$f(\boldsymbol{u})d^3u \propto \exp\left(-\frac{\gamma mc^2}{T}\right)d^3u$$

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

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

- 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 $[0, 1]$

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

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

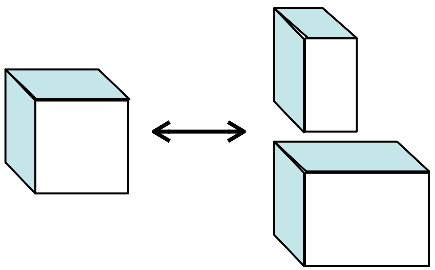
$u_z \leftarrow 2u\sqrt{X_5(1 - X_5)}\sin(2\pi X_6)$

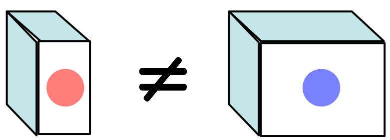
if $(-\beta v_x > X_7)$, $u_x \leftarrow -u_x$

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

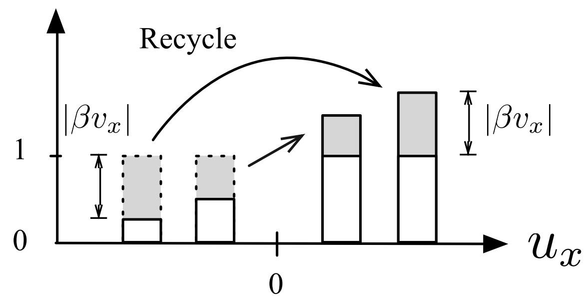
return u_x, u_y, u_z

- 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

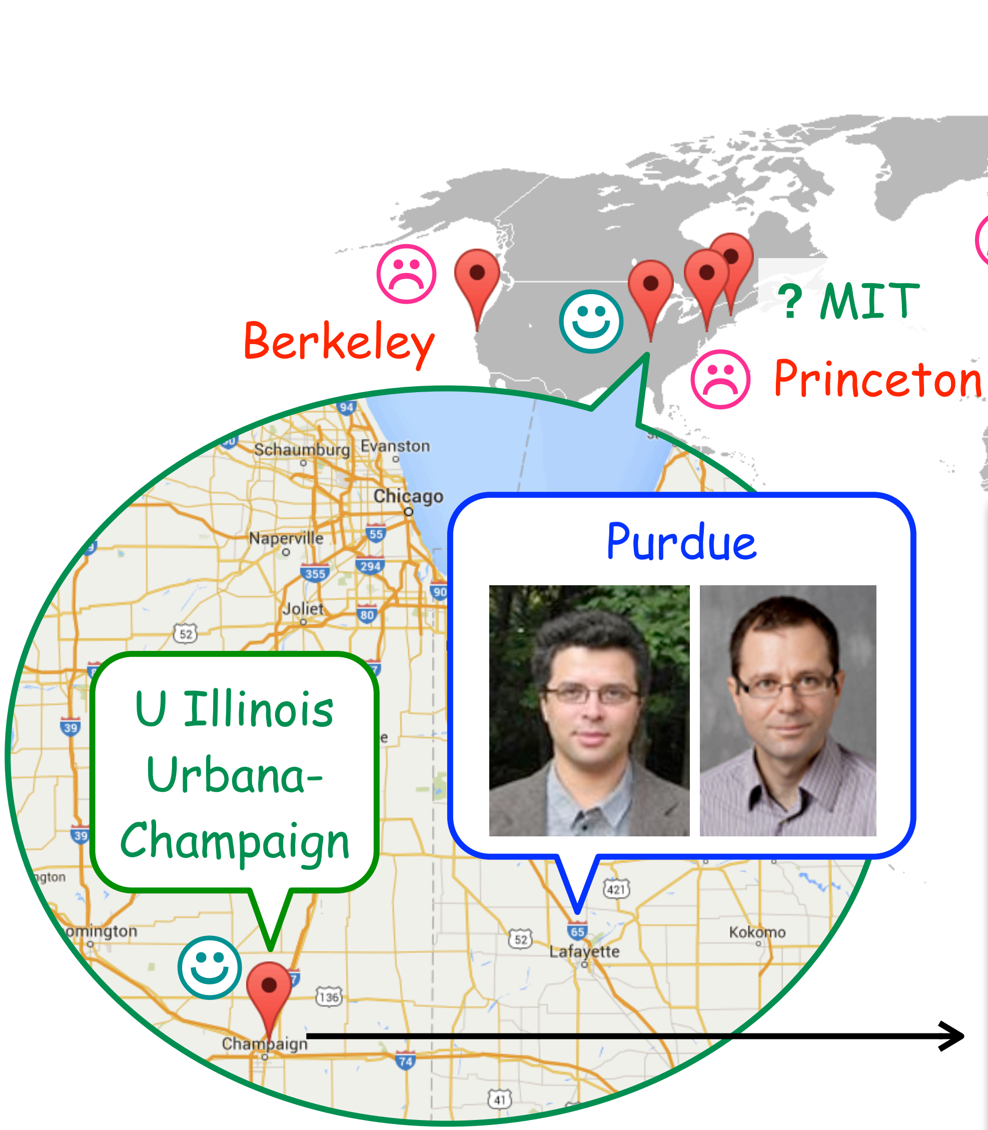


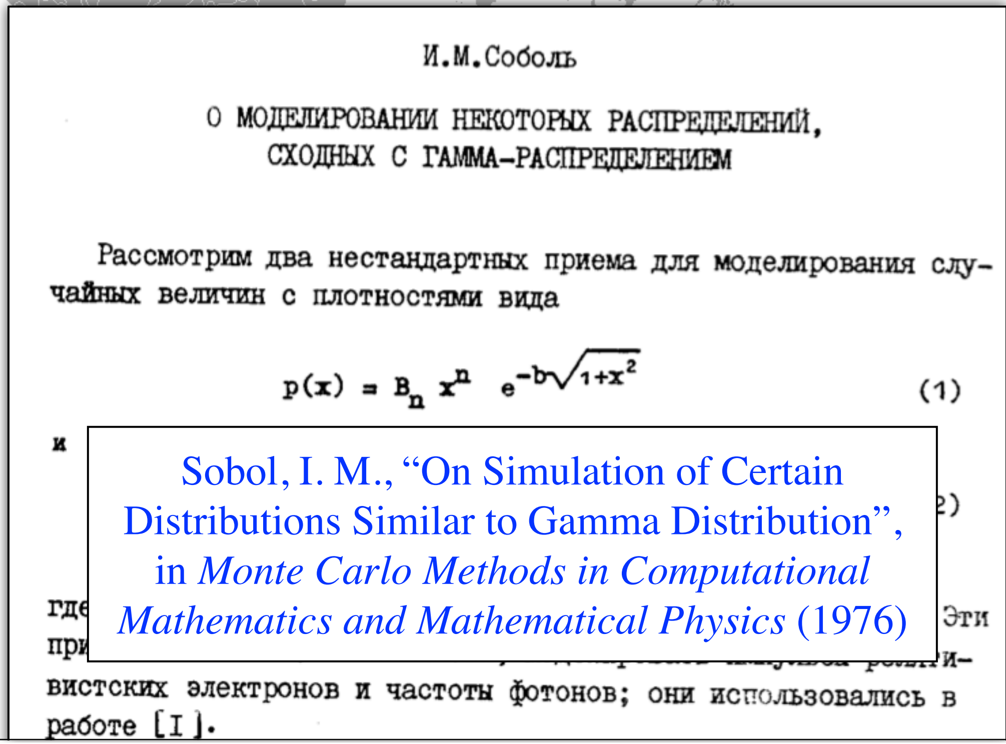


Acceptance factor



Quest for the original reference





И.М.Соболь

О МОДЕЛИРОВАНИИ НЕКОТОРЫХ РАСПРЕДЕЛЕНИЙ,
СХОДНЫХ С ГАММА-РАСПРЕДЕЛЕНИЕМ

Рассмотрим два нестандартных приема для моделирования случайных величин с плотностями вида

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

и

2)

где ... Эти
при... и-
вистских электронов и частоты фотонов; они использовались в
работе [I].

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

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)
  - Zenitani, in prep. (2016b) (Ohm's law; new results)
  - Zenitani, Shinohara, & Nagai, in prep. (2016a) (Electron orbits)
  - Zenitani, *Phys. Plasmas* **22**, 042116 (2015b) (Sobol algorithm)