Collisionless magnetic reconnection

Does the dissipation mechanism matter?

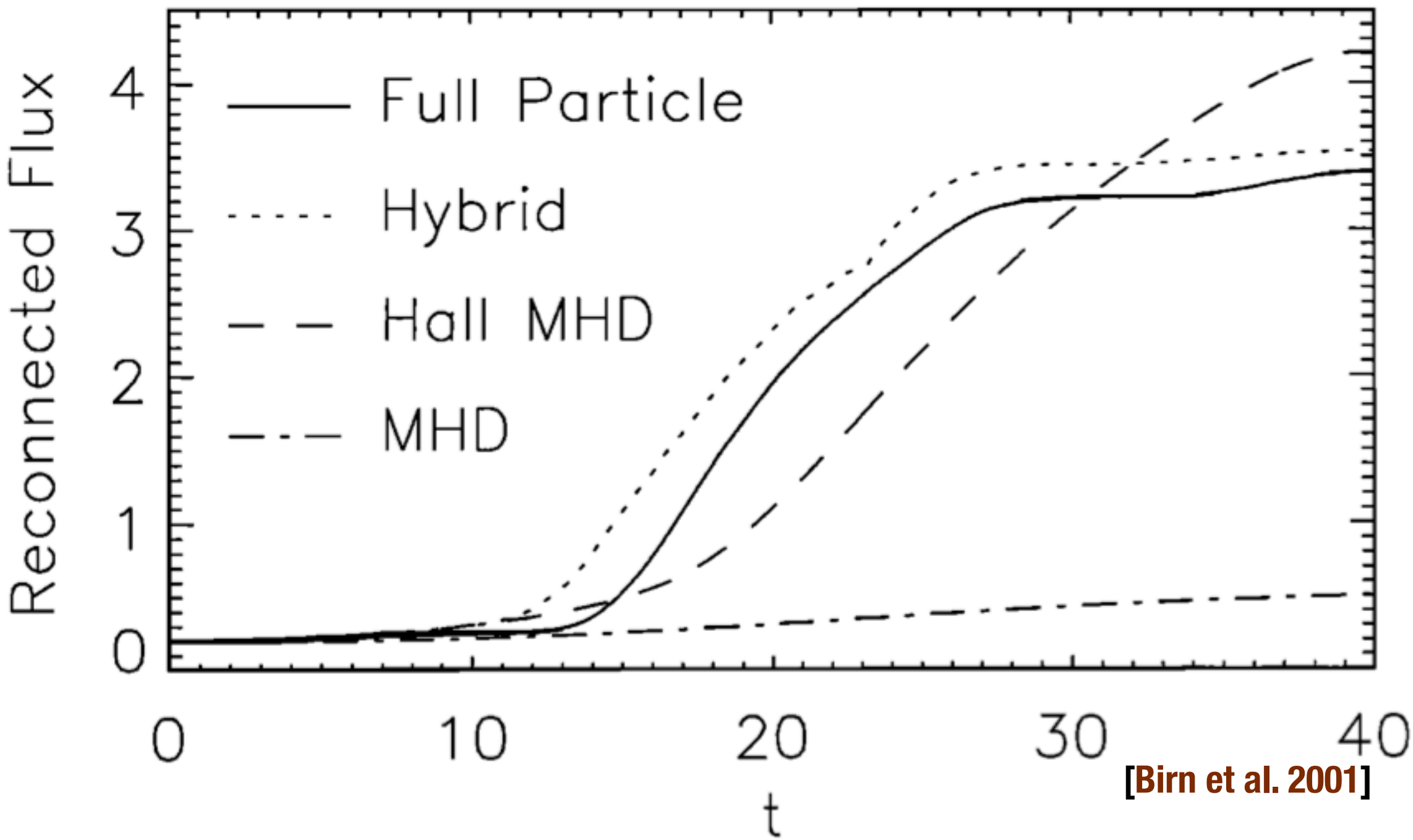
If time : Asymmetric kinetic initial steady state

Nicolas Aunai

Michael Hesse, Masha Kuznetsova, Rebekah Evans, Carrie Black (NASA/GSFC)

Gerard Belmont, Roch Smets (LPP/CNRS/UPMC)

2001 : GEM reconnection challenge



[Birn et al. 2001]

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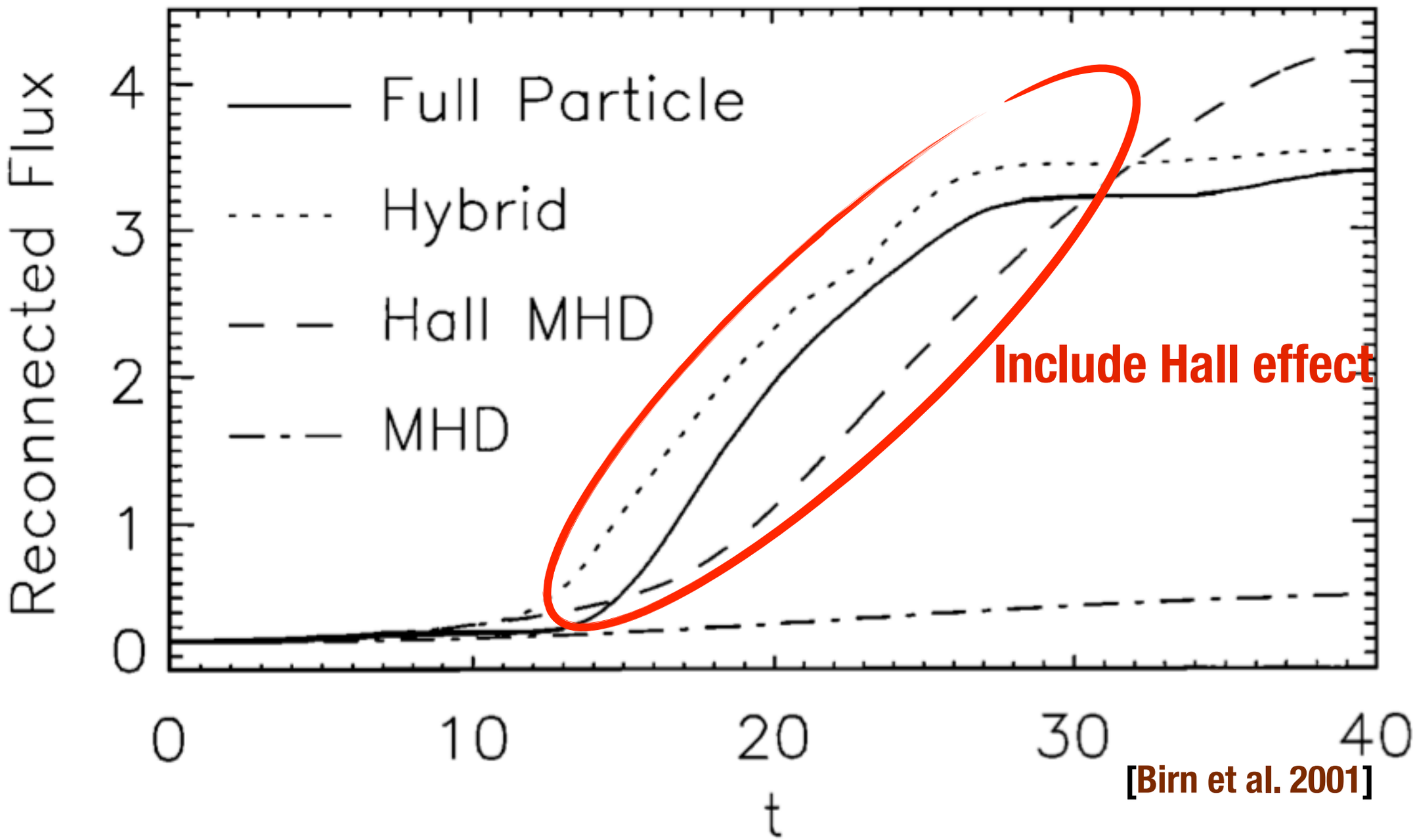

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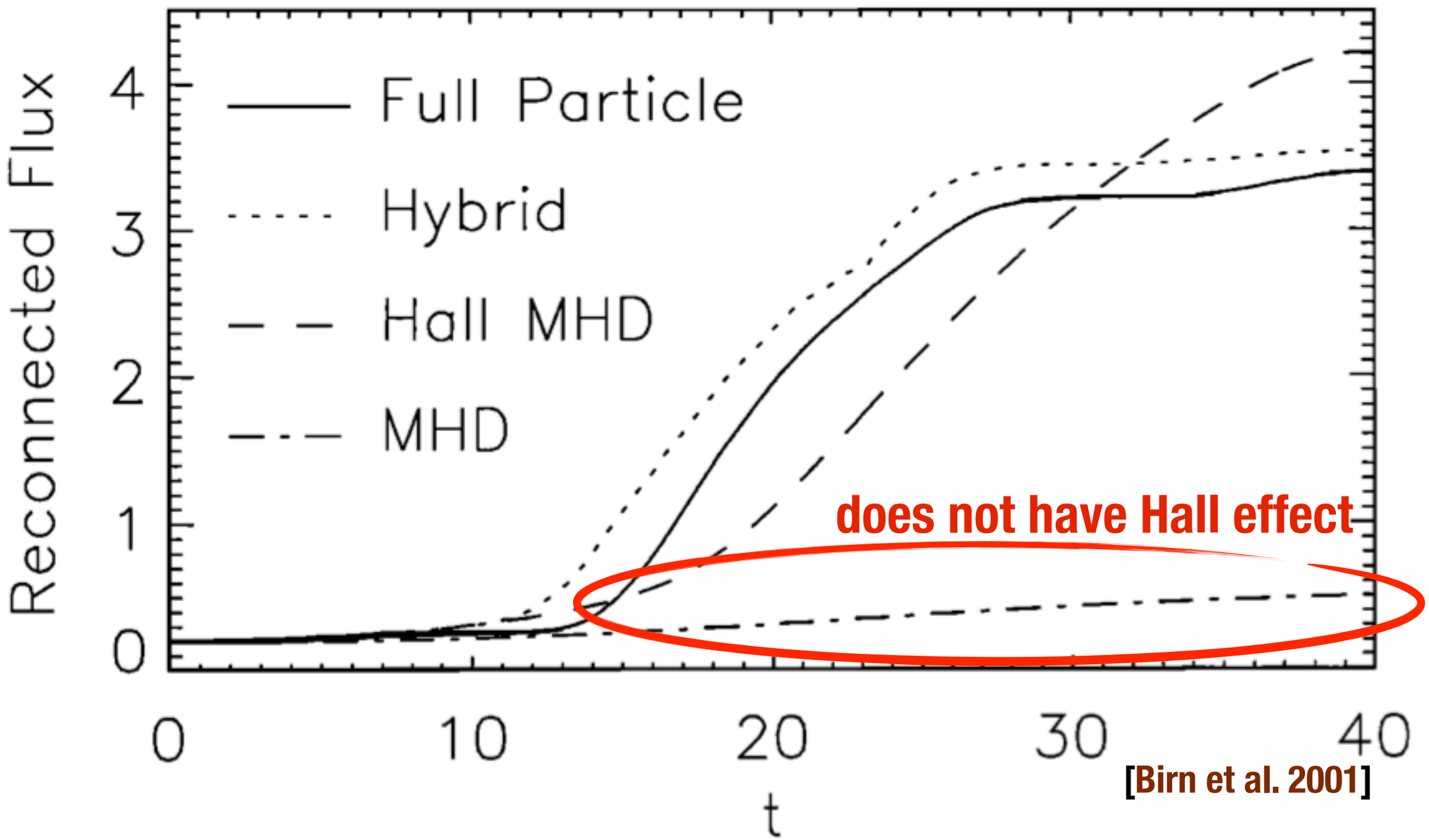

does not have Hall effect

[Birn et al. 2001]

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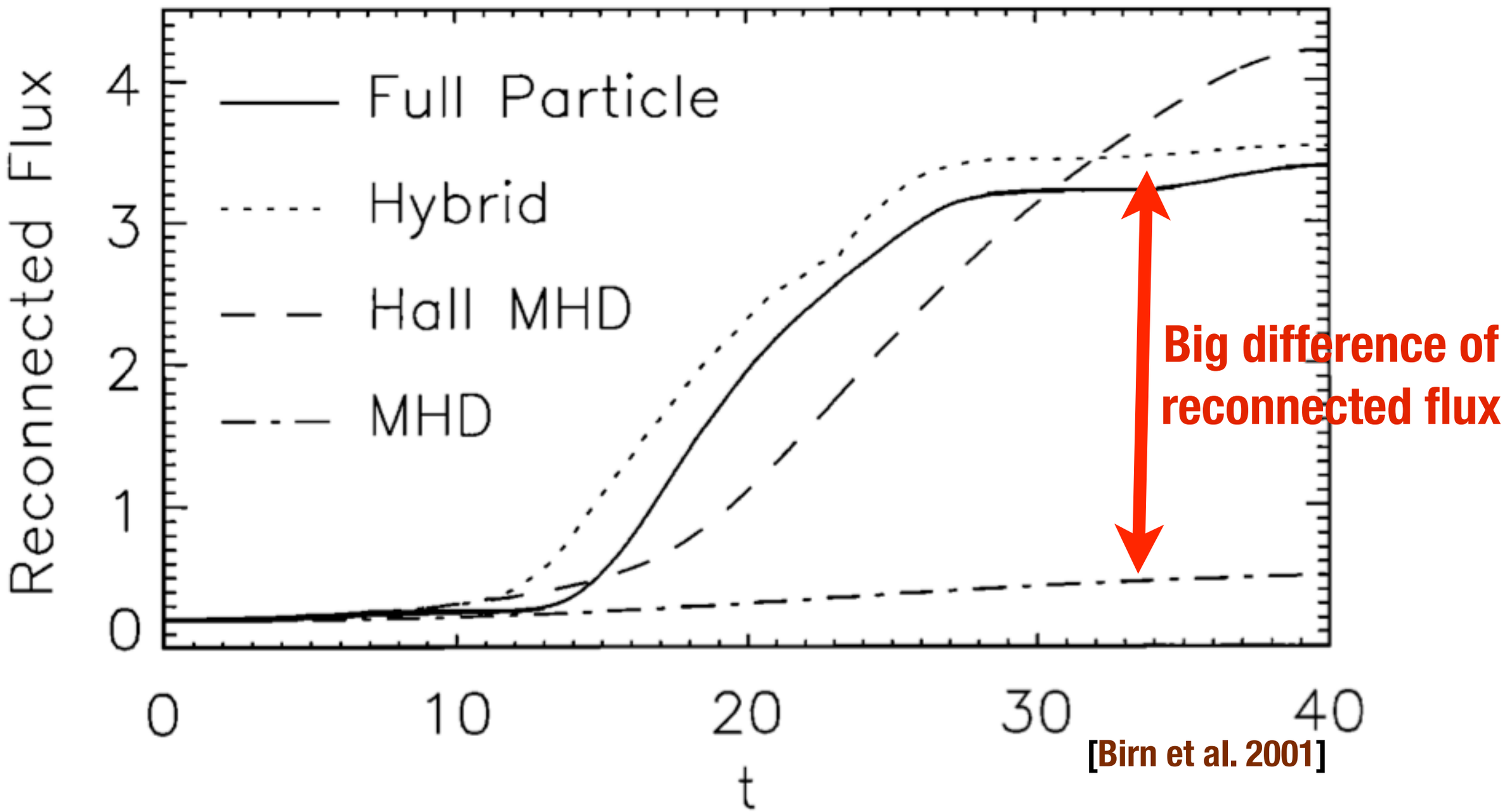

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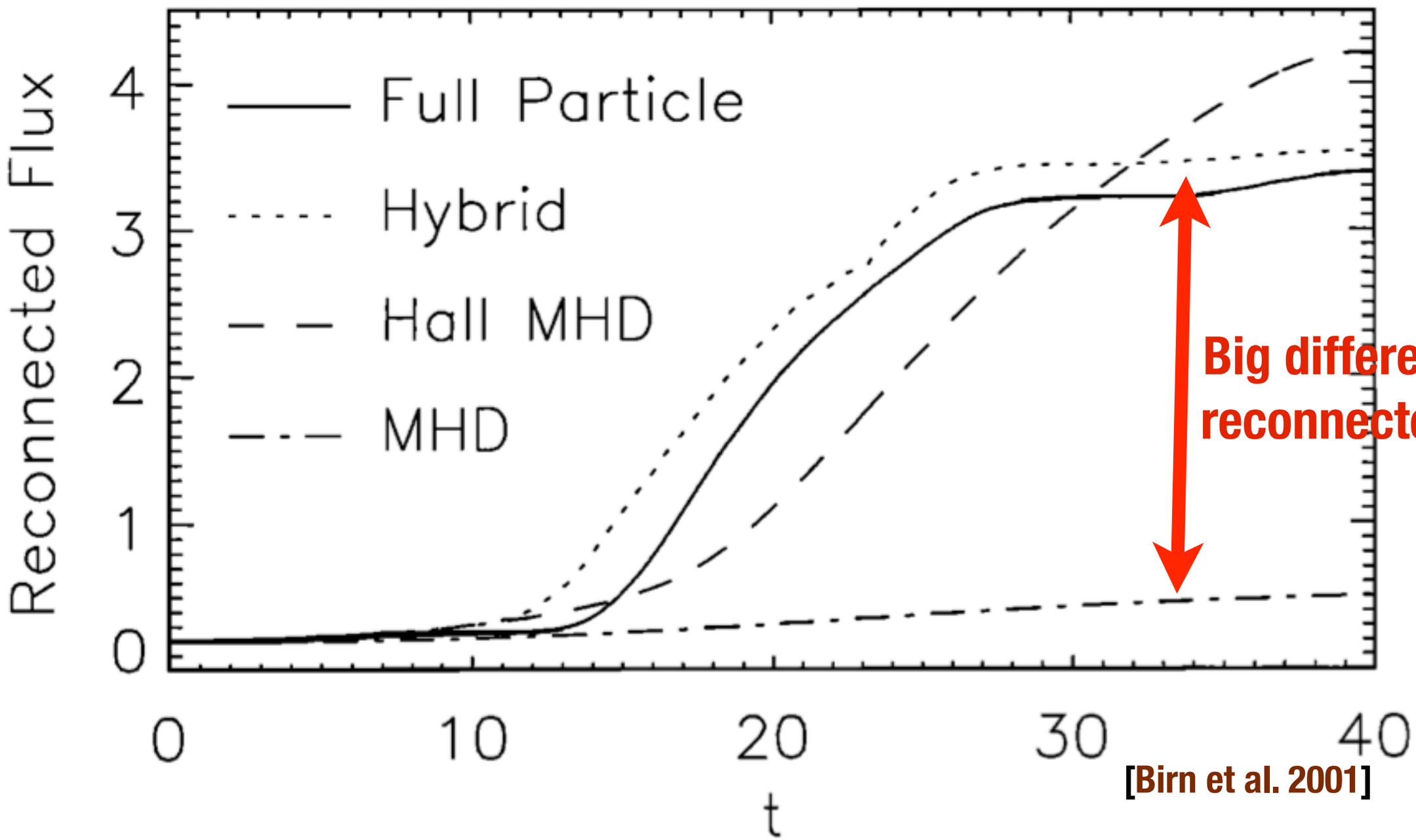
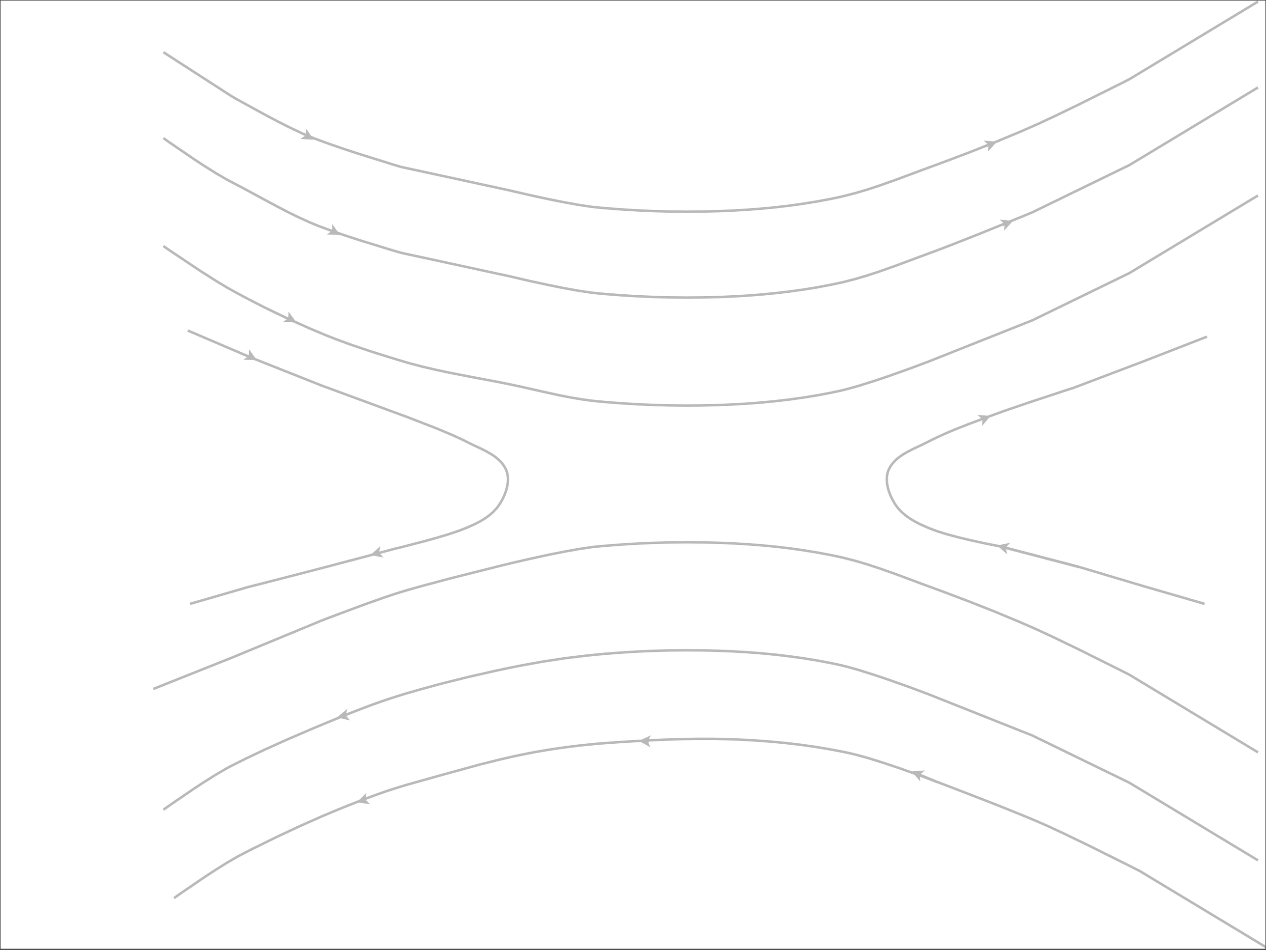


[Birn et al. 2001]

Two major conclusions

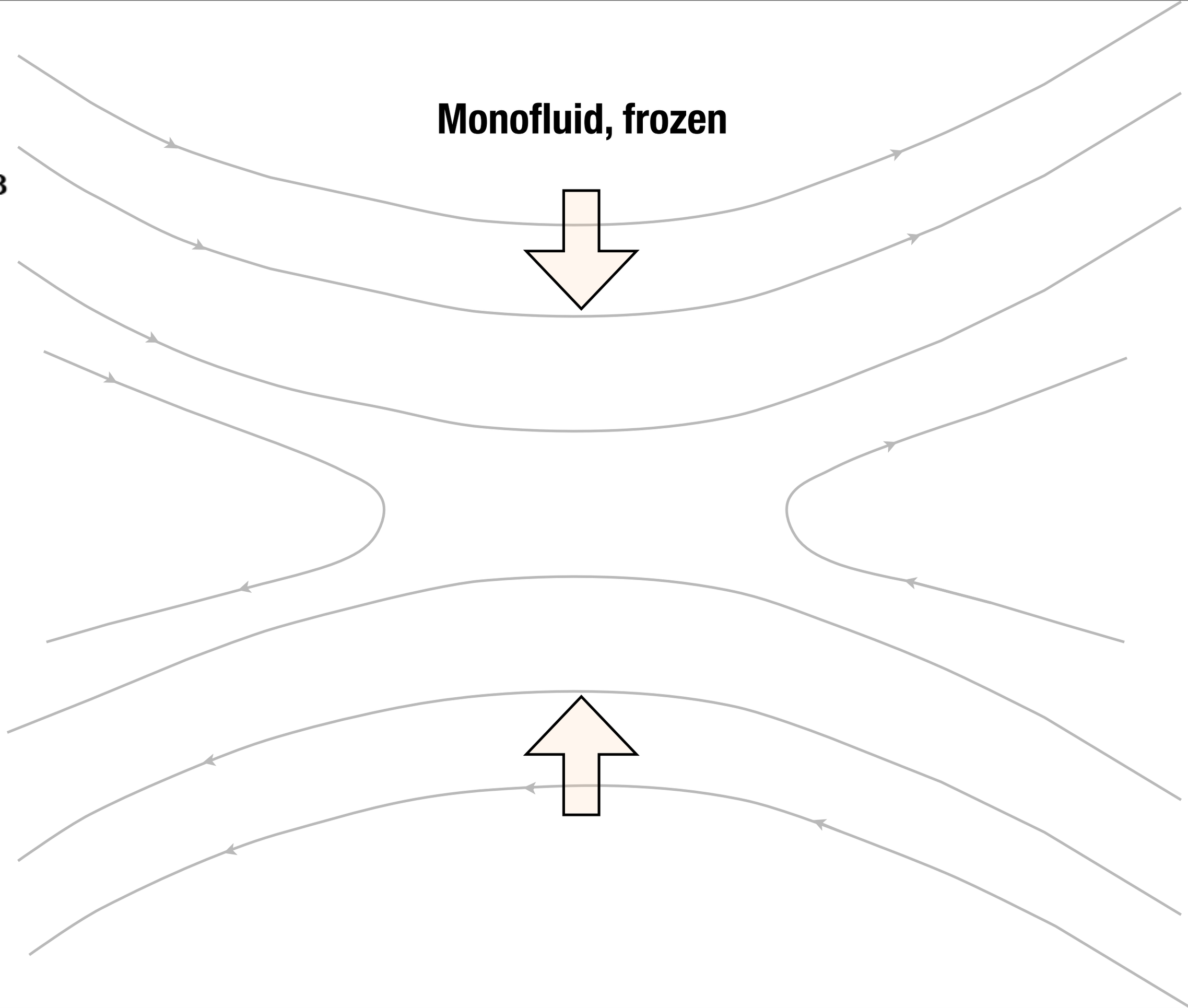
1/ The Hall term is necessary for fast reconnection

2/ The reconnection rate does not depend on the dissipation mechanism



Monofluid, frozen

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B}$$



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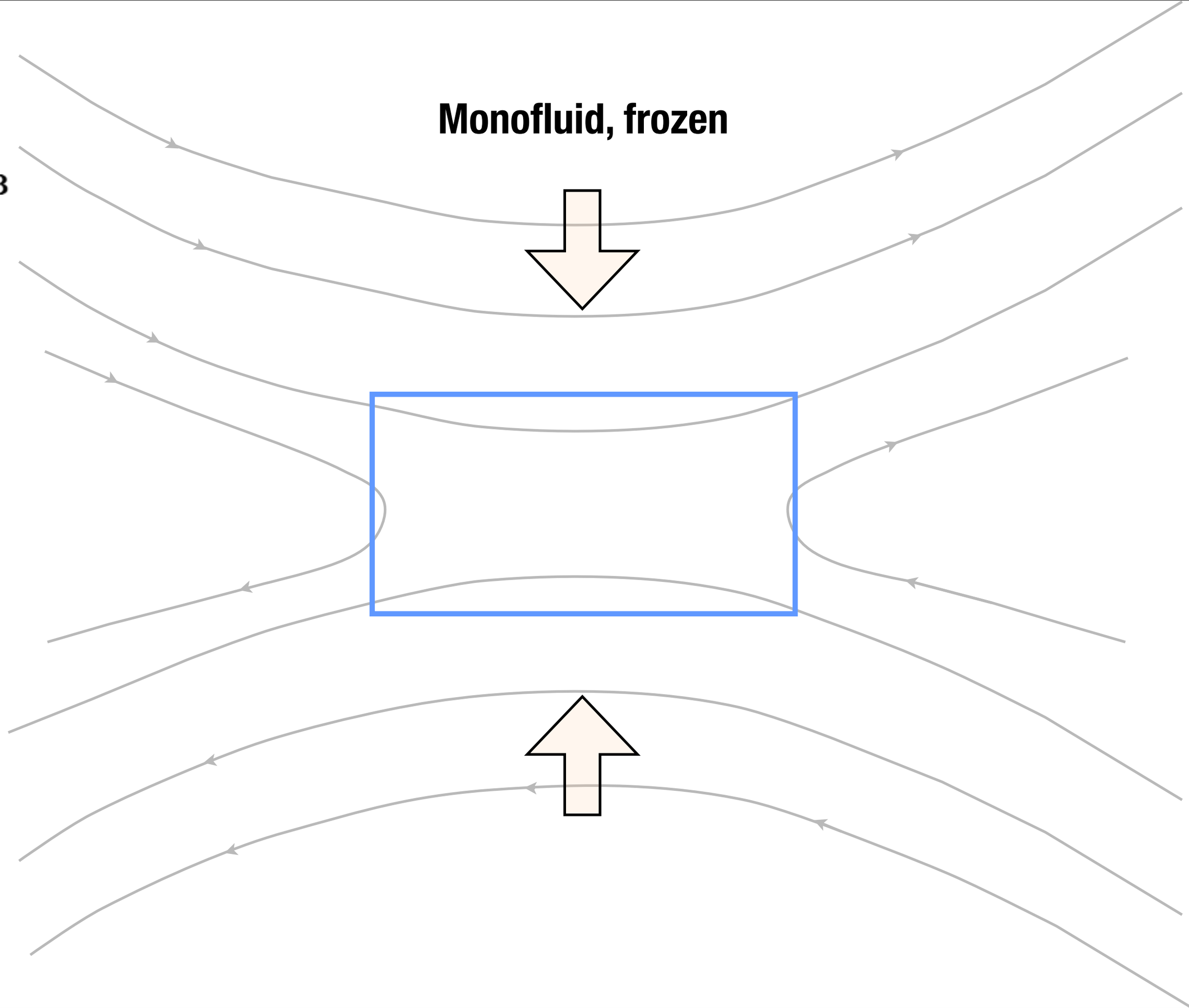

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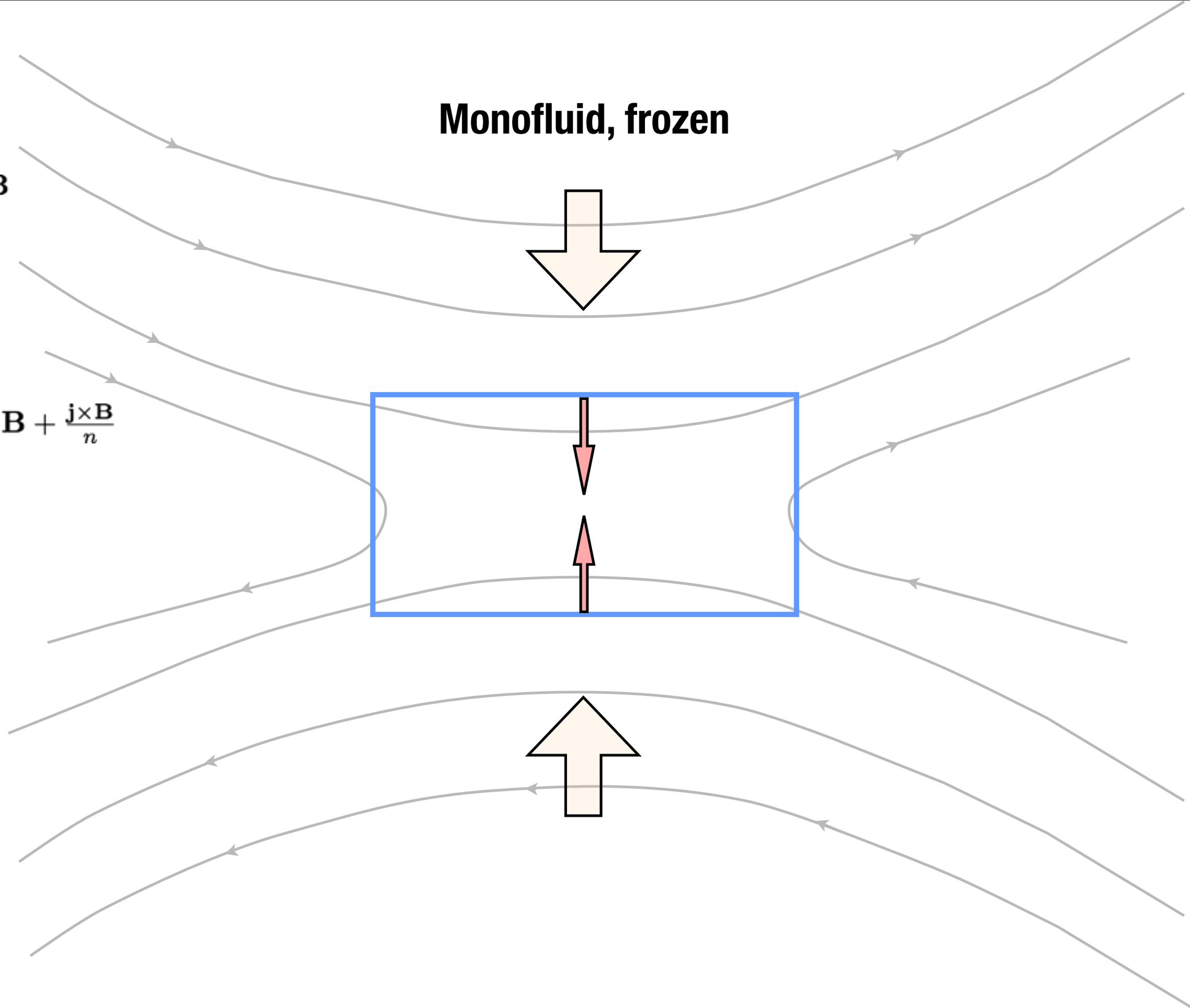

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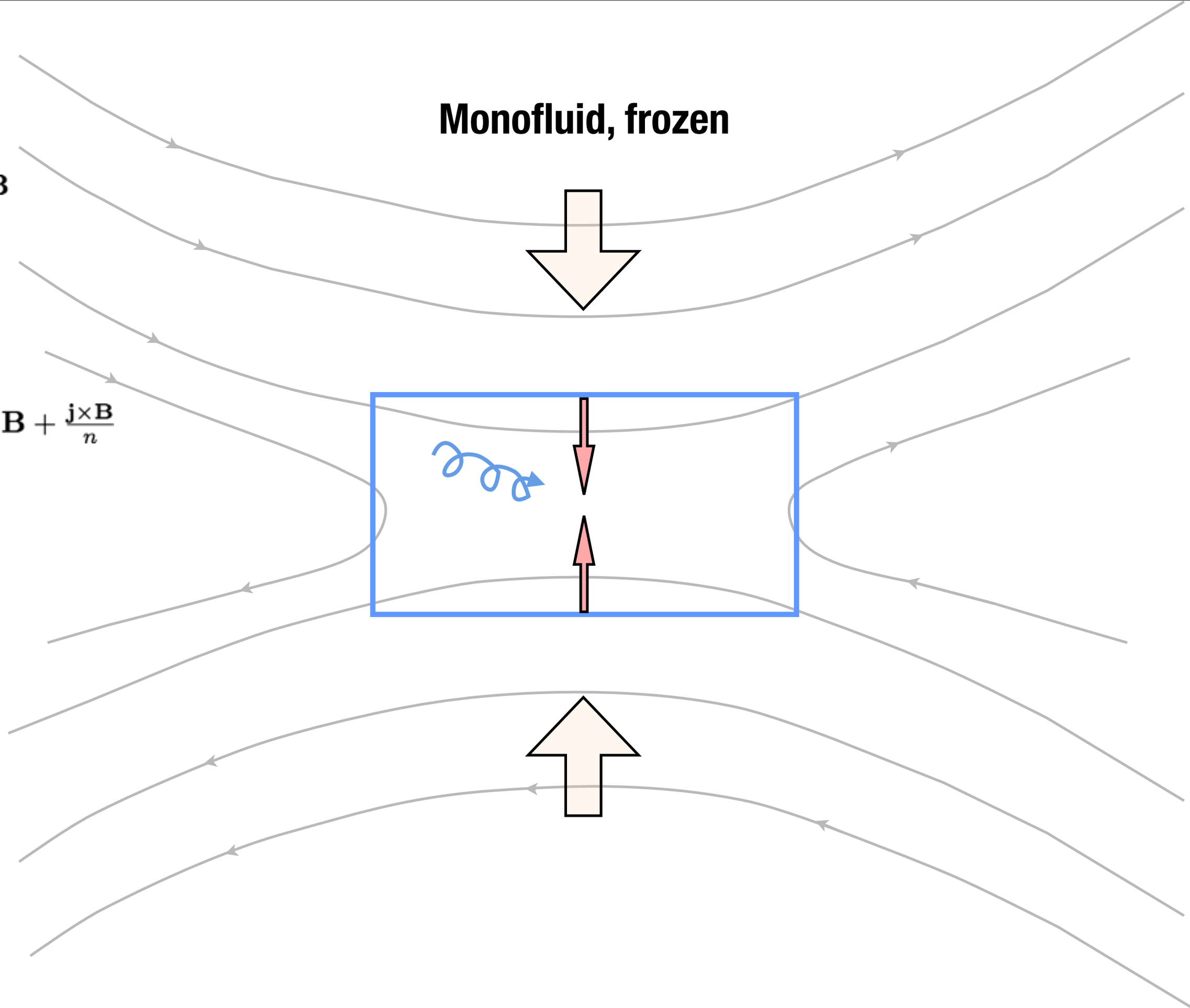

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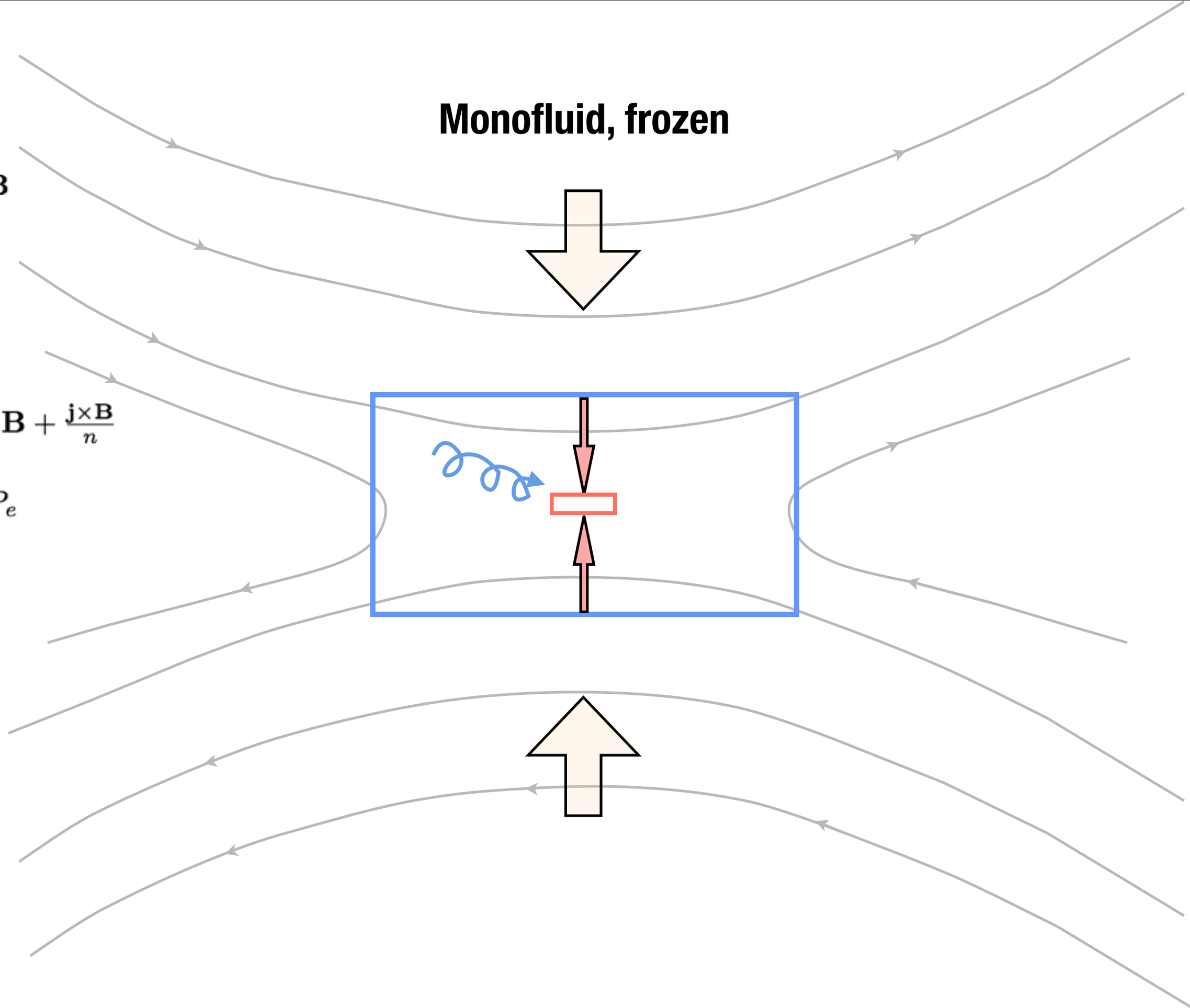

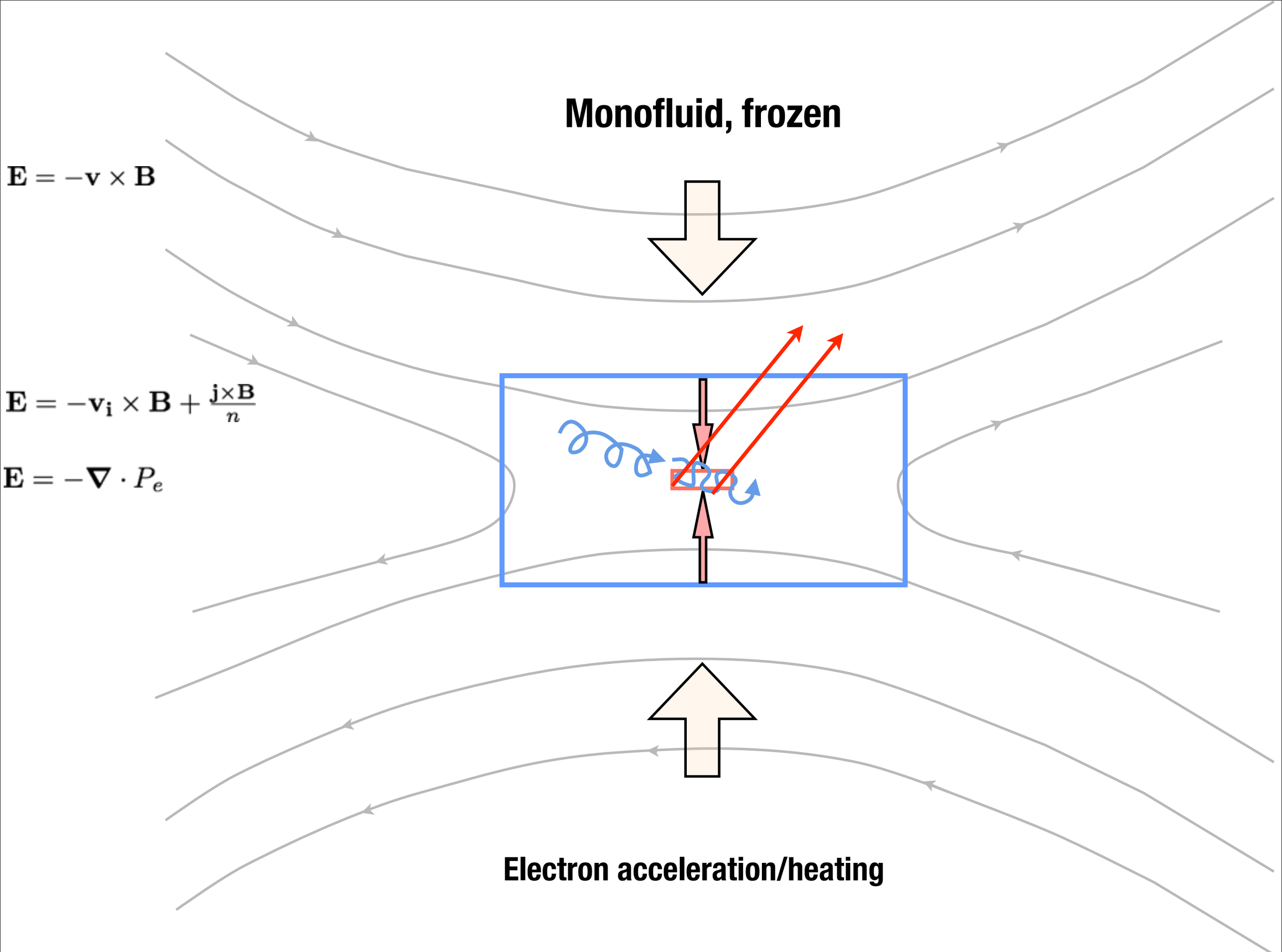
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Electron acceleration/heating

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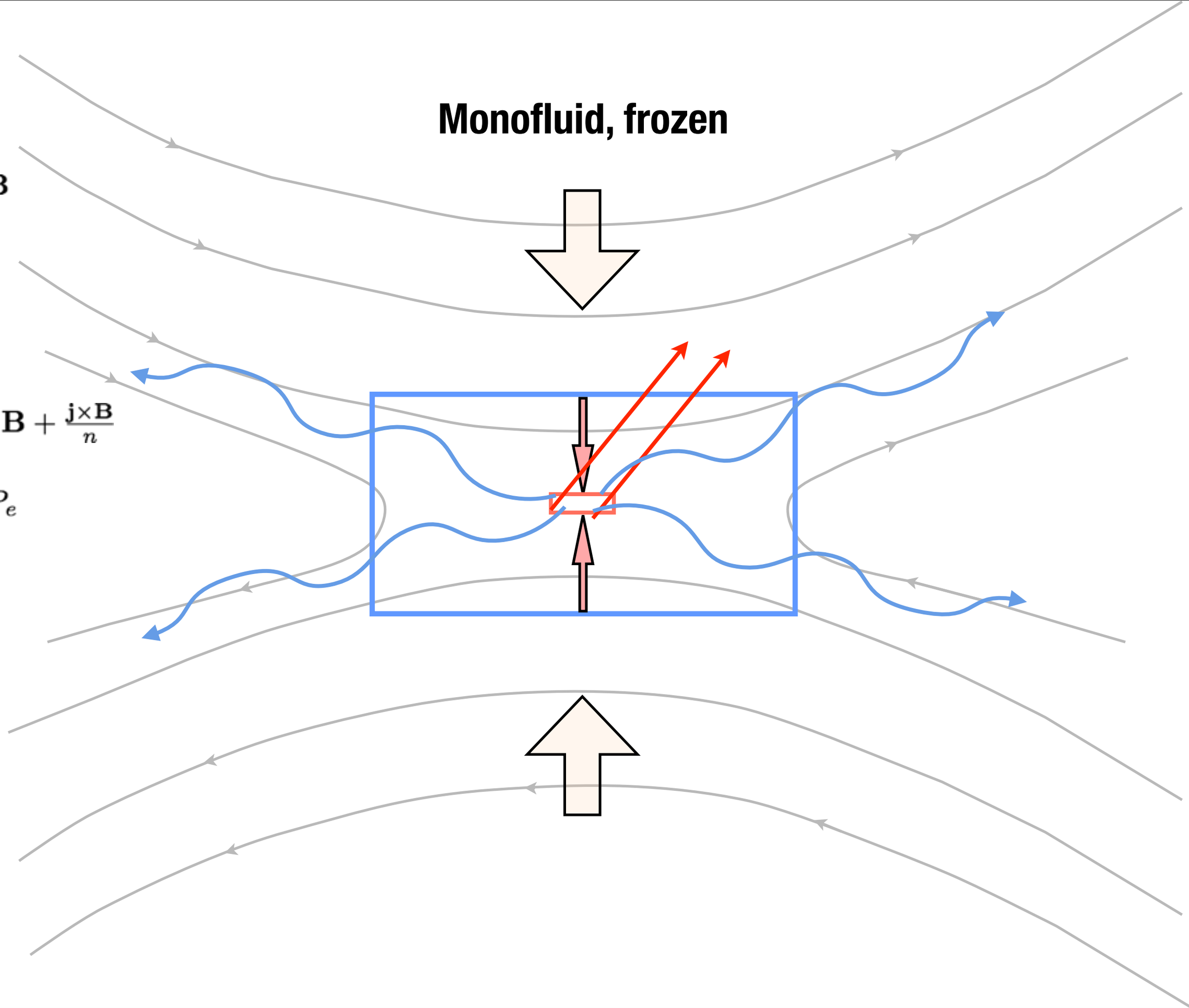

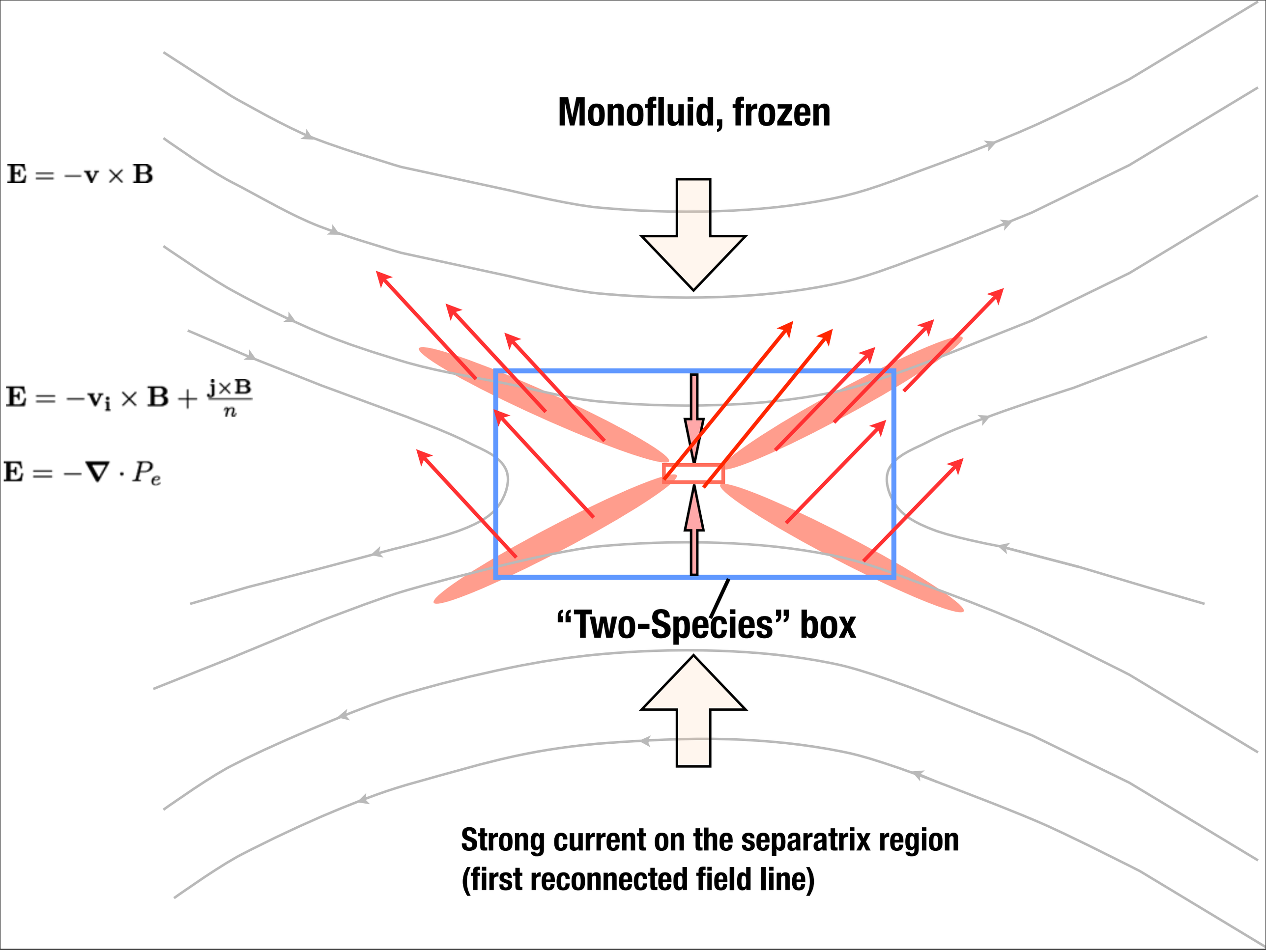
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"Two-Species" box
Strong current on the separatrix region
(first reconnected field line)

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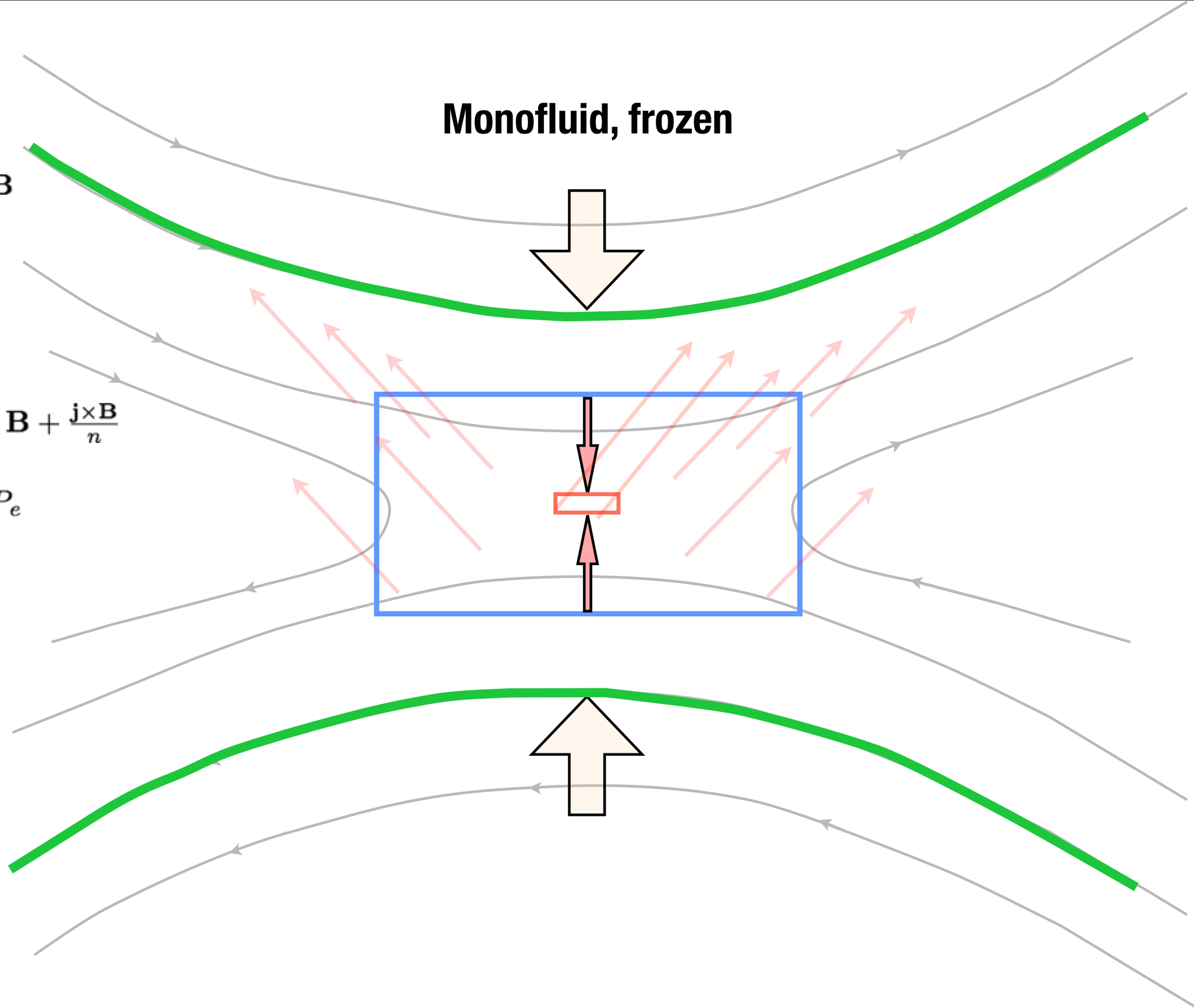

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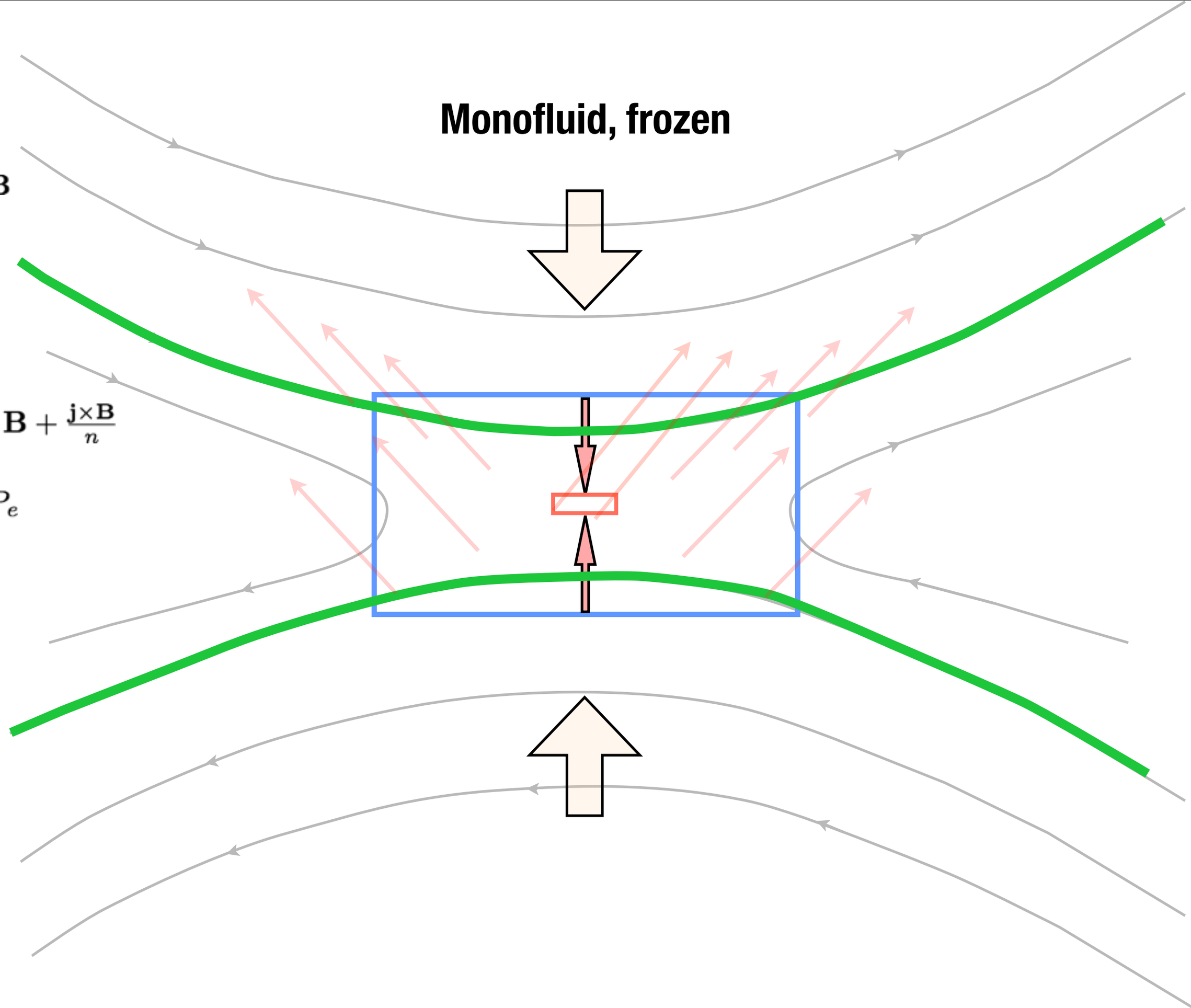

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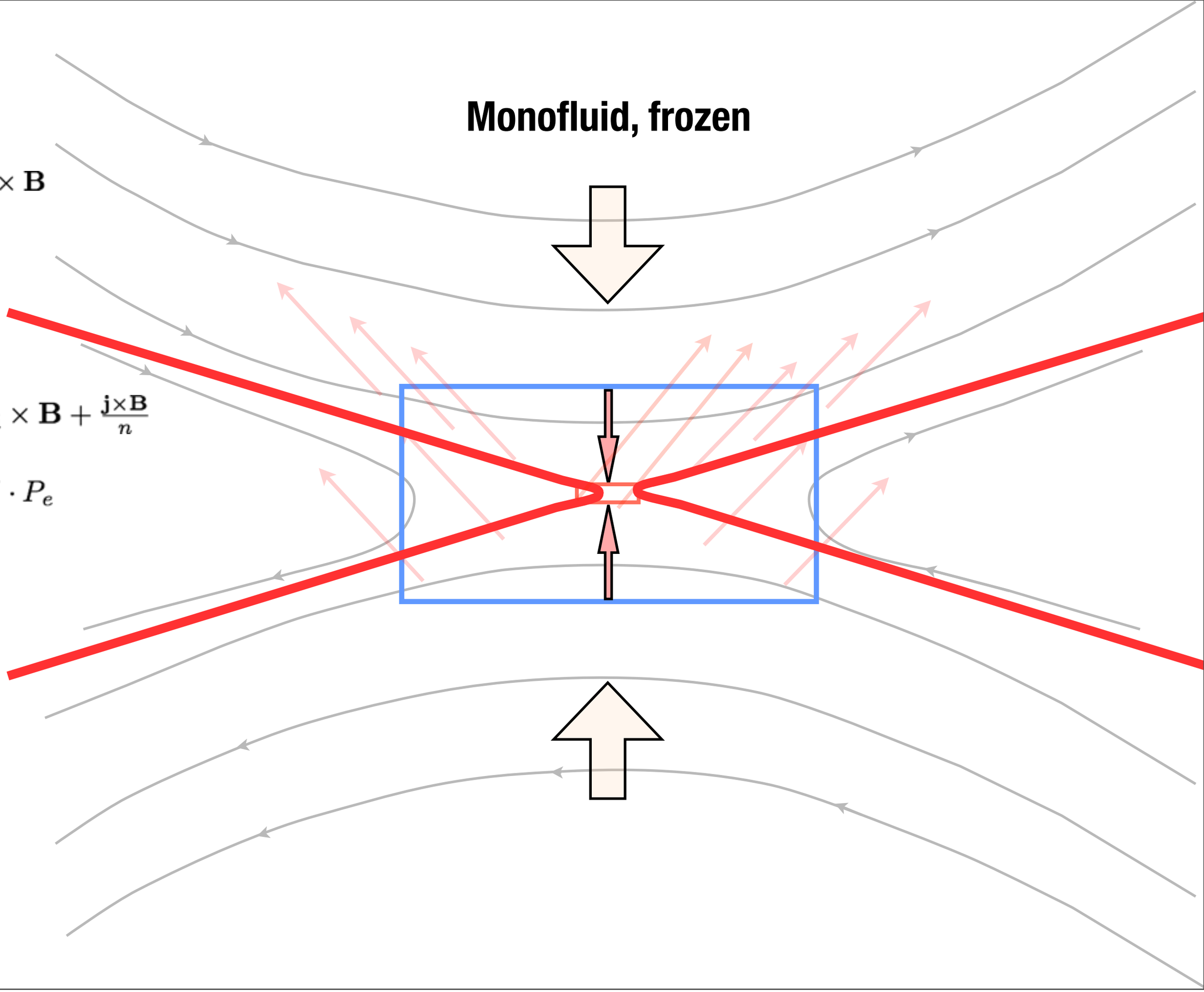

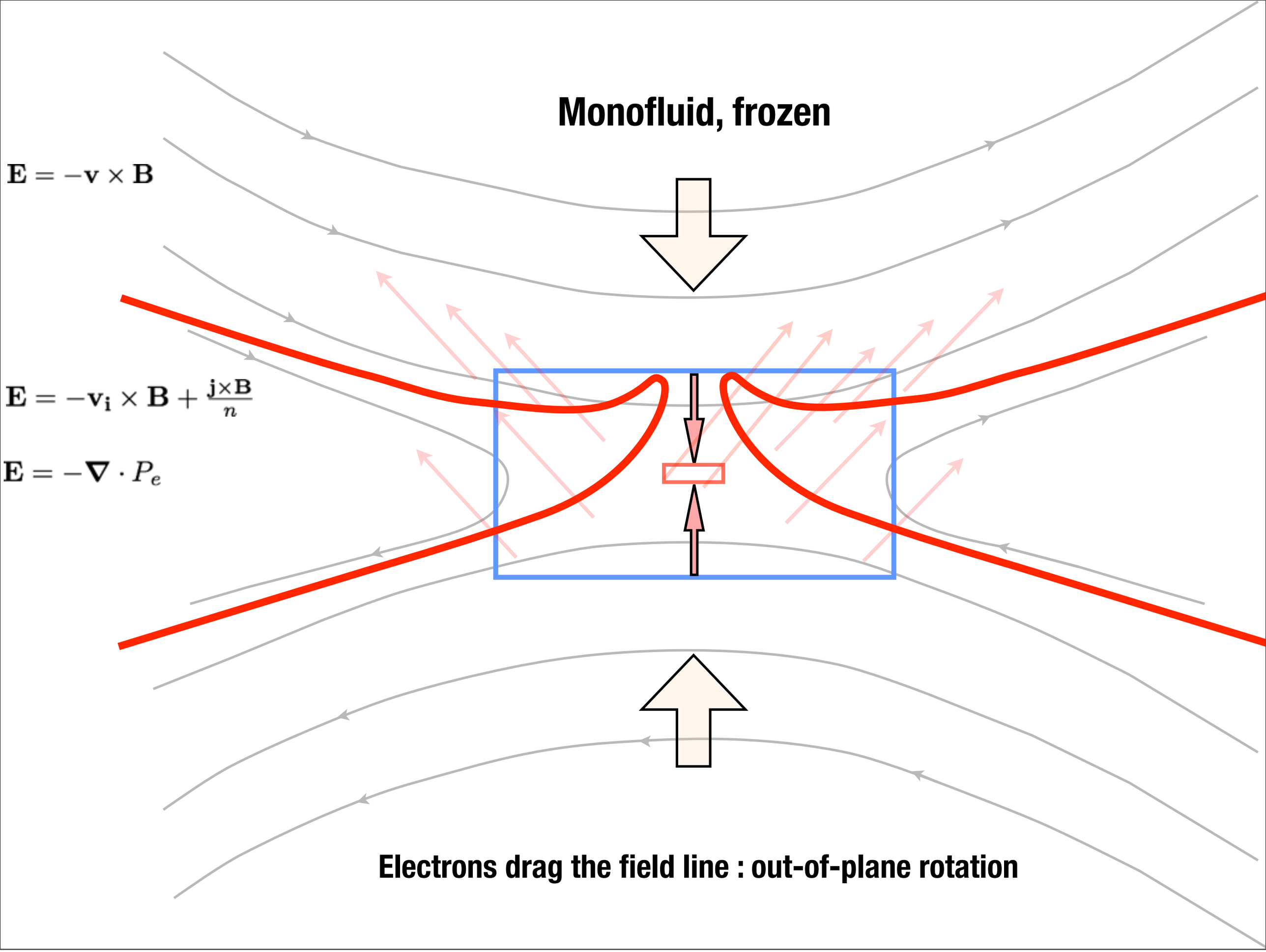
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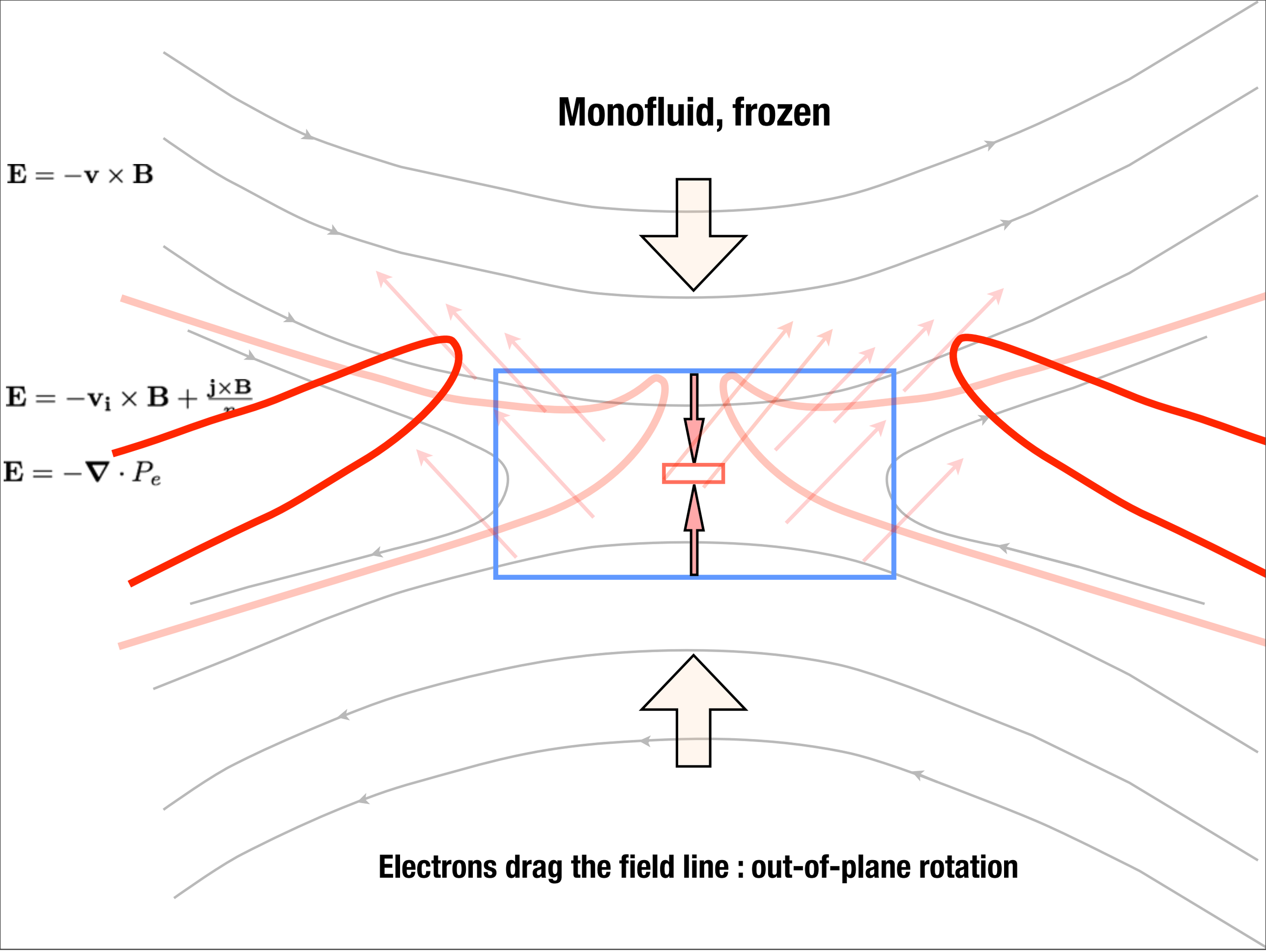
Electrons drag the field line : out-of-plane rotation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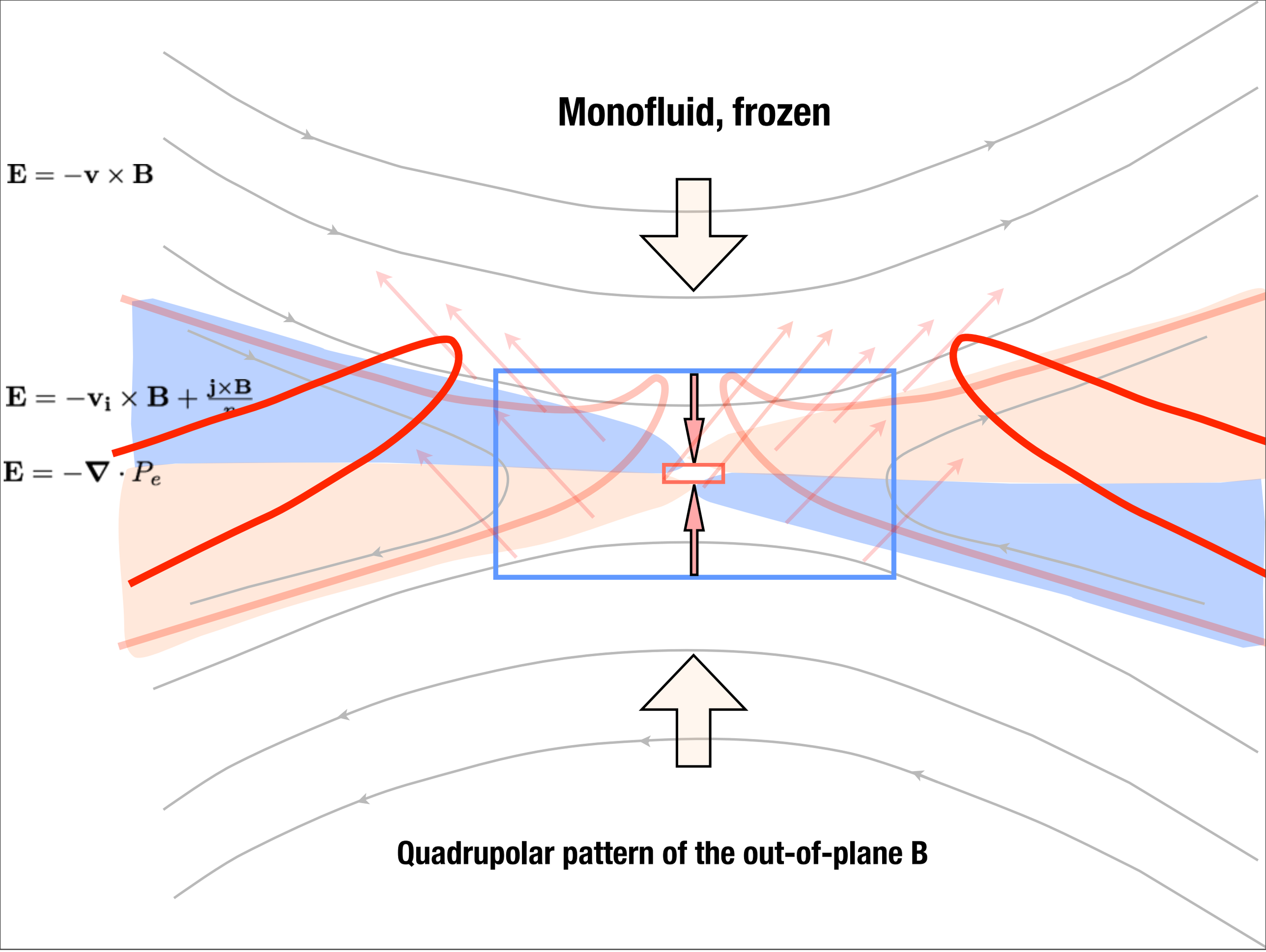
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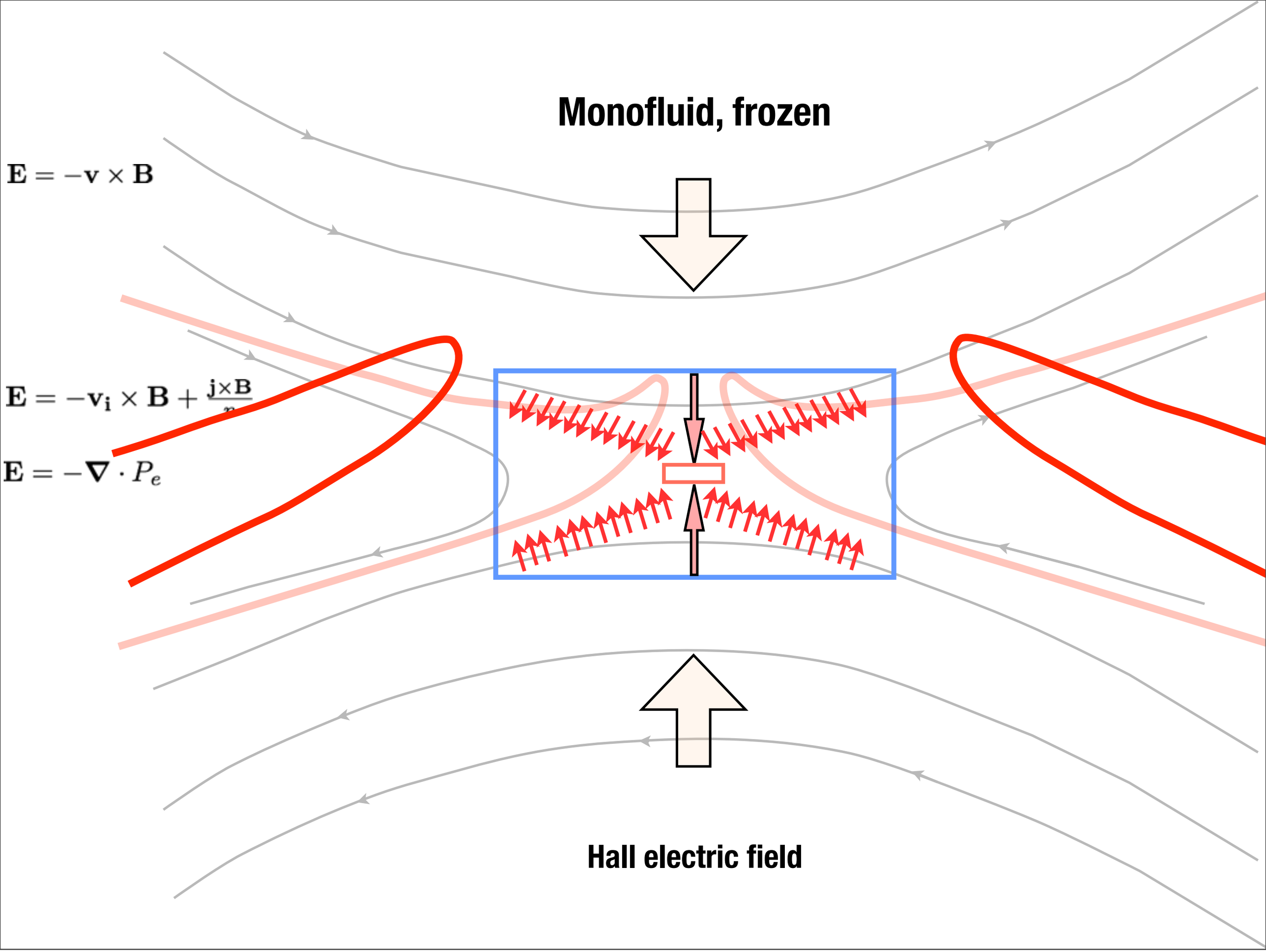
Quadrupolar pattern of the out-of-plane B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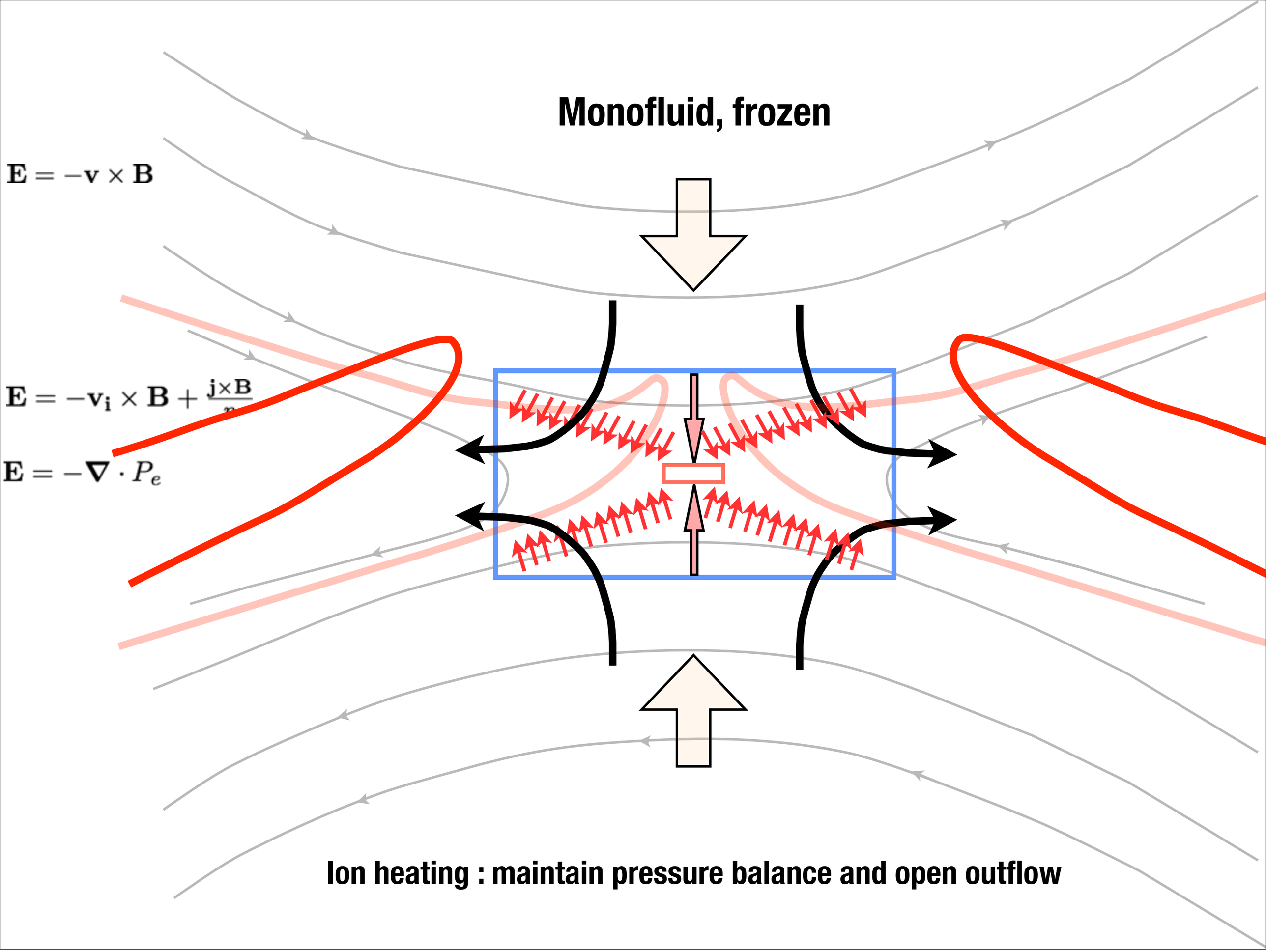
Hall electric field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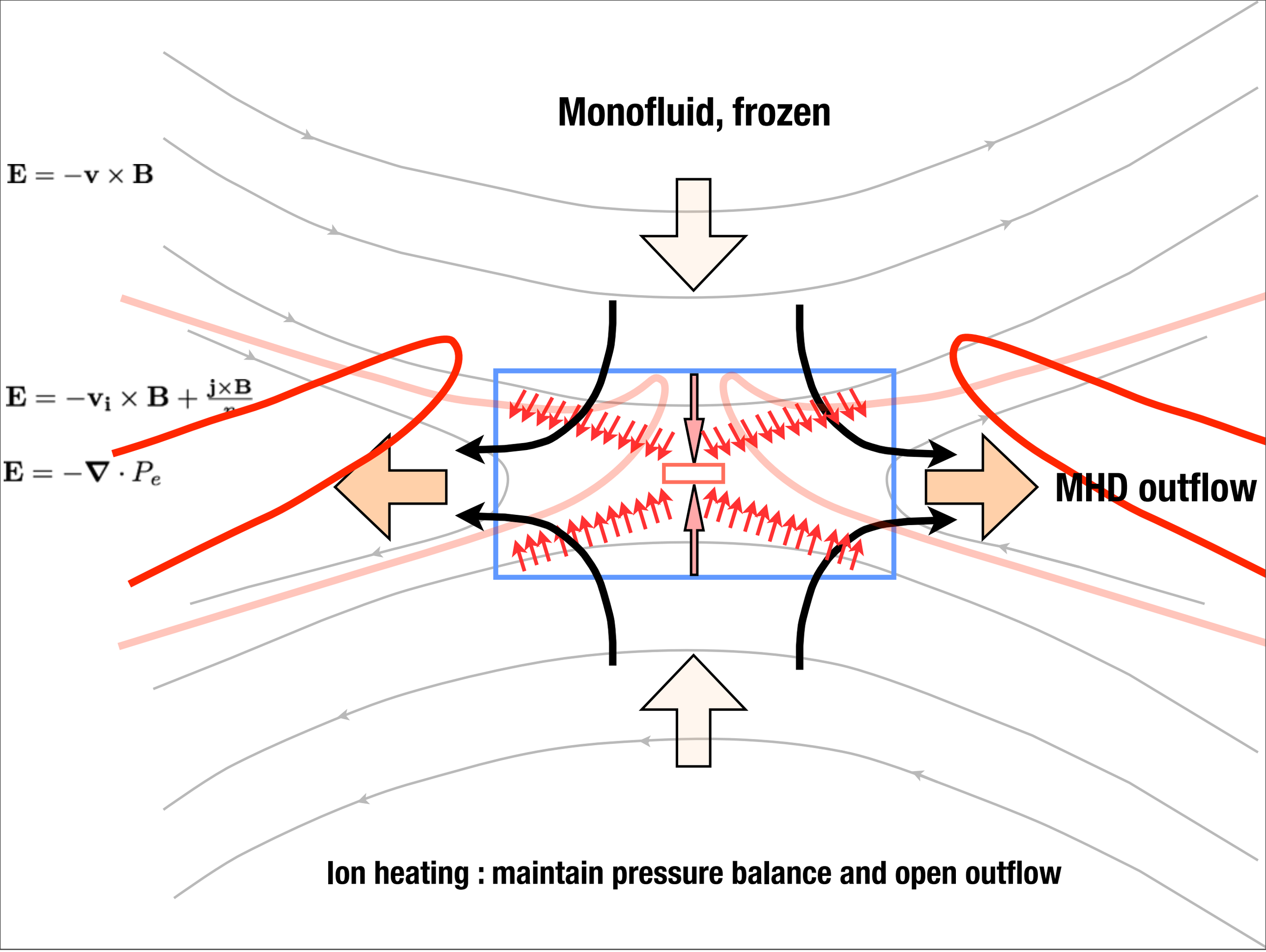
Ion heating : maintain pressure balance and open outflow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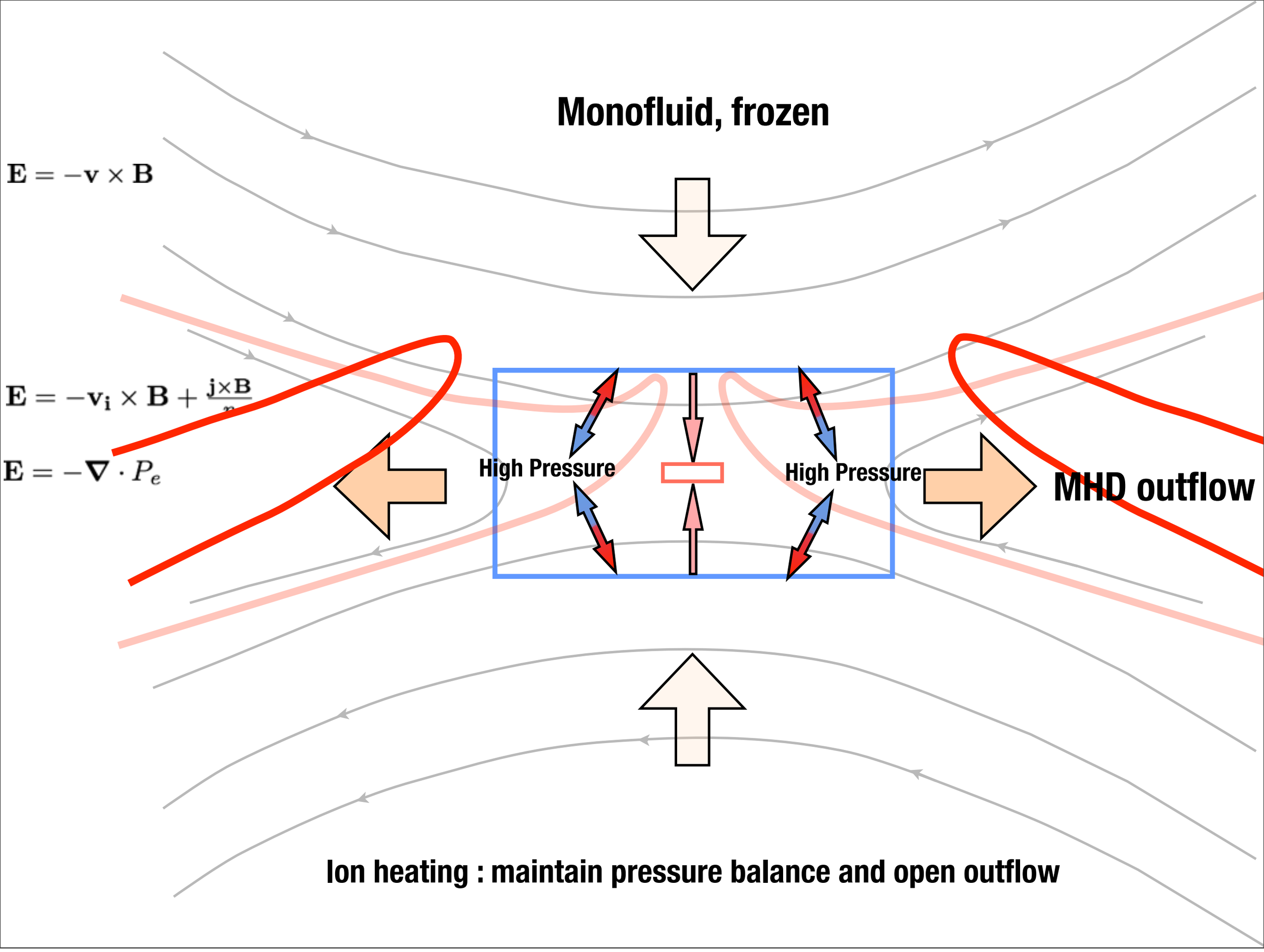
MHD outflow
Ion heating : maintain pressure balance and open outflow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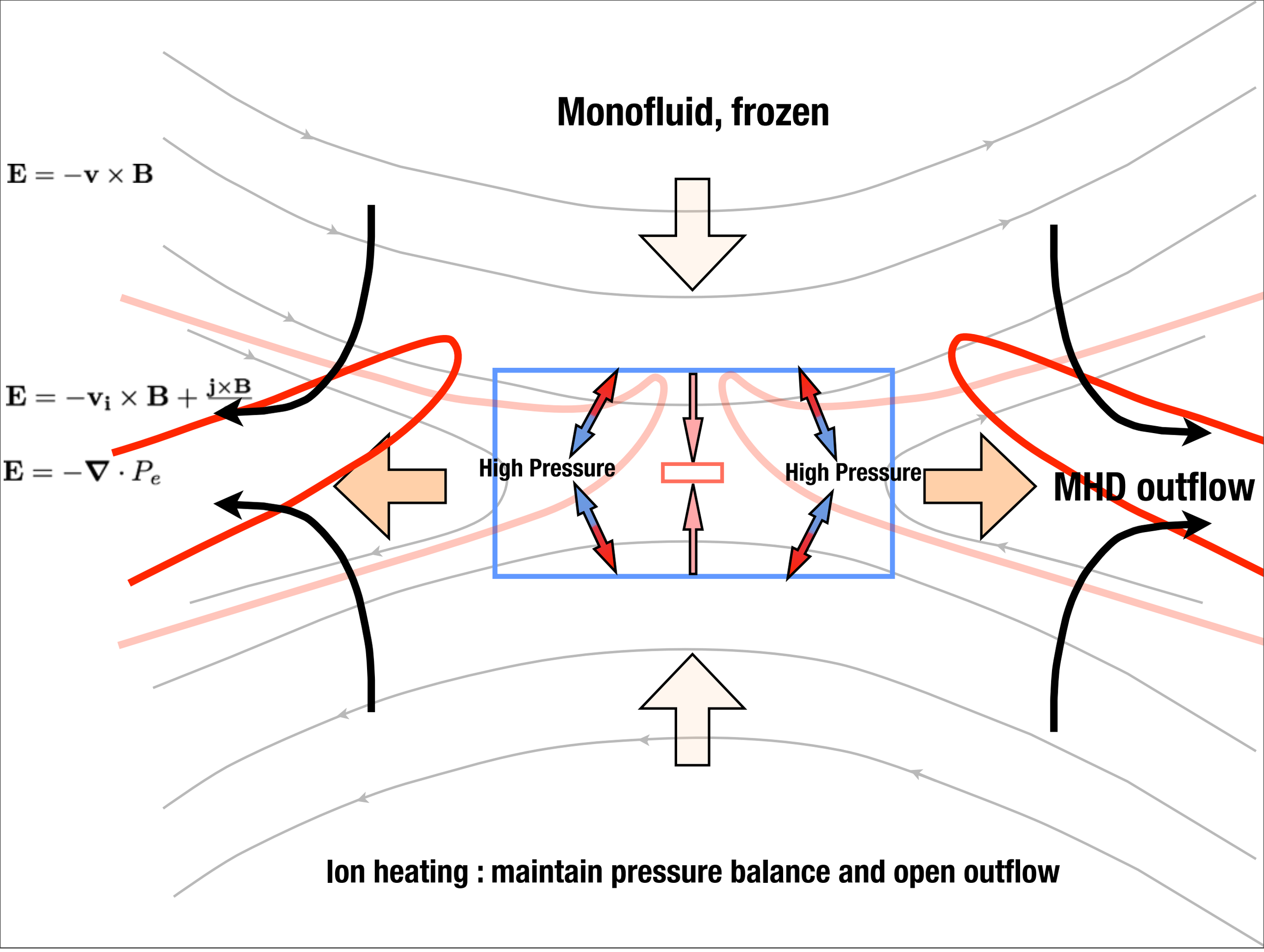
High Pressure
High Pressure
MHD outflow
Ion heating : maintain pressure balance and open outflow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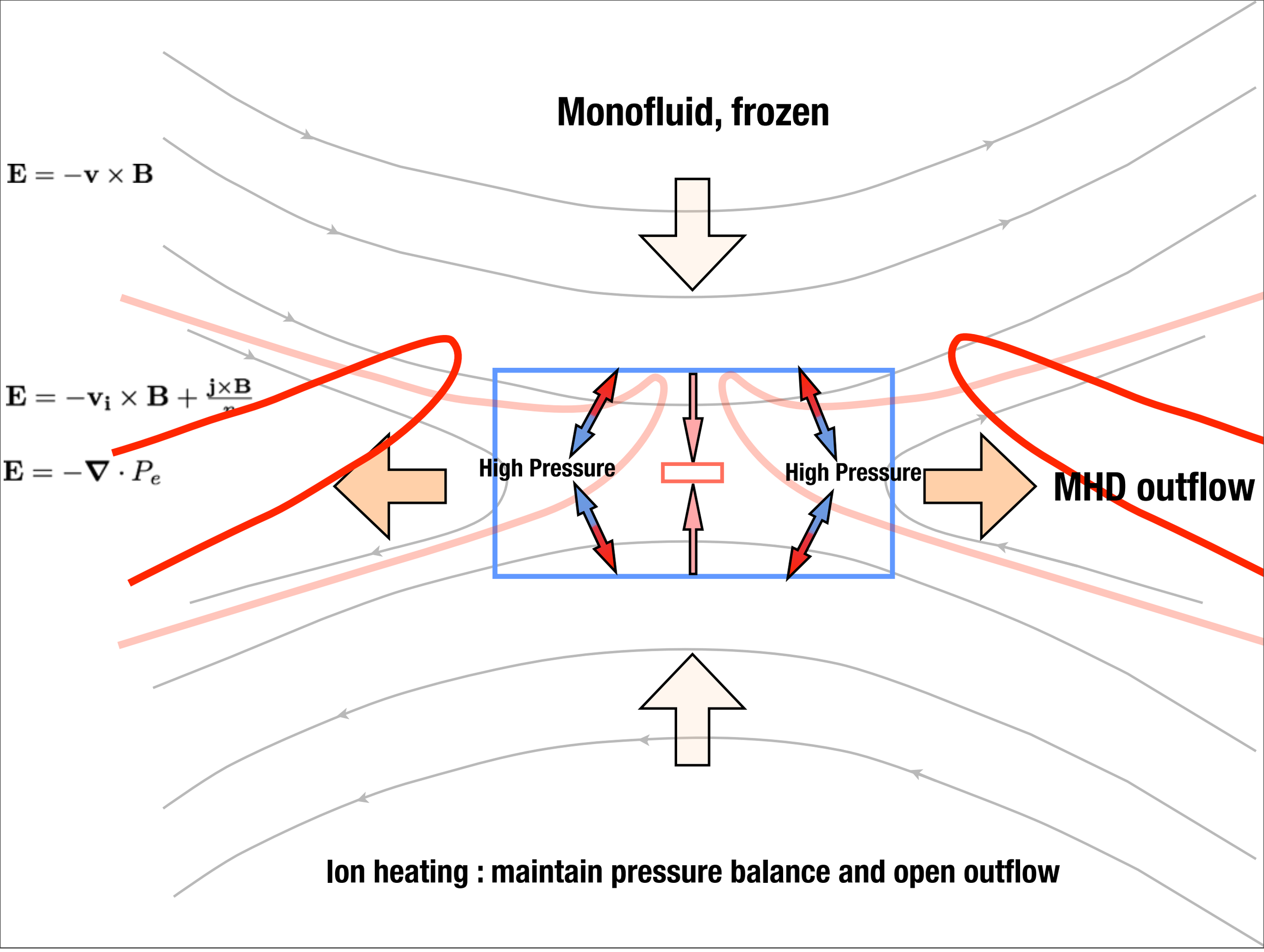
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What physics in the simulations?

Ohm's law

Model

Scales

What physics in the simulations?

Ohm's law **Model** **Scales**

$$\mathbf{E} = -\mathbf{v_i} \times \mathbf{B} + \frac{\mathbf{j} \times \mathbf{B}}{nq} - \frac{\boldsymbol{\nabla} \cdot \mathbf{P_e}}{nq} + \frac{m_e}{e} d_t \mathbf{v}_e$$

What physics in the simulations?

Ohm's law	Model	Scales
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$\cancel{\mathbf{E} = -\mathbf{v_i} \times \mathbf{B}}$	MHD Plasma is frozen in B	

What physics in the simulations?

$$\mathbf{E} = -\mathbf{v_i} \times \mathbf{B} + \frac{\mathbf{j} \times \mathbf{B}}{nq} - \frac{\boldsymbol{\nabla} \cdot \mathbf{P_e}}{nq} + \frac{m_e}{e} d_t \mathbf{v}_e$$

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+ Numerical dissipation

What physics in the simulations?

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+ Numerical dissipation

As long as this is resolved and dominant

What physics in the simulations?

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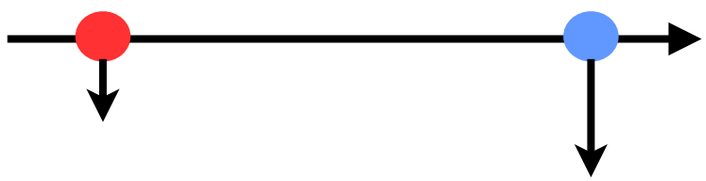
+ Numerical dissipation

As long as this is resolved and dominant

any of these is ok and does not change the rate

Electrons non ideal scales

They can change field line connectivity

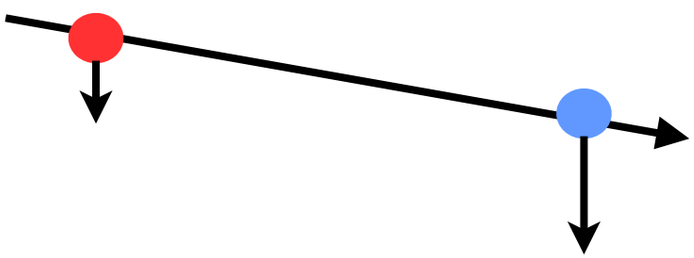


Without it

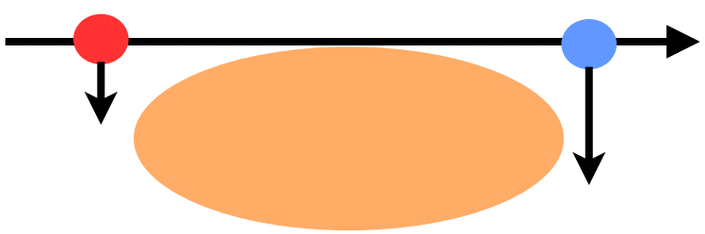
With a non-ideal region

Electrons non ideal scales

They can change field line connectivity



Without it



With a non-ideal region

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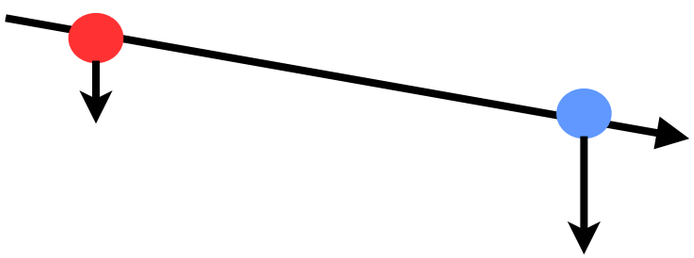
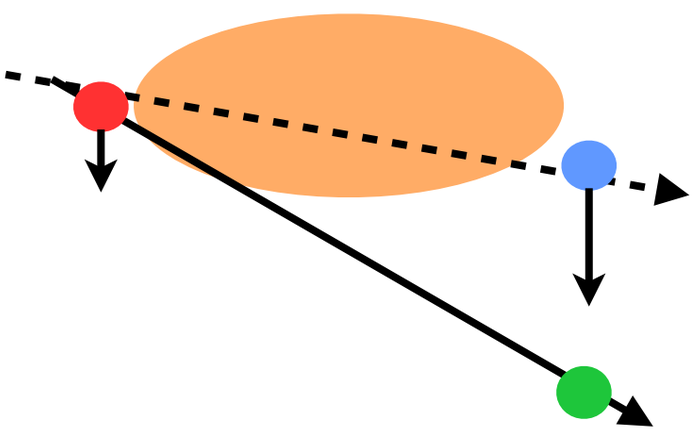


Without it



With a non-ideal region

Newly connected point

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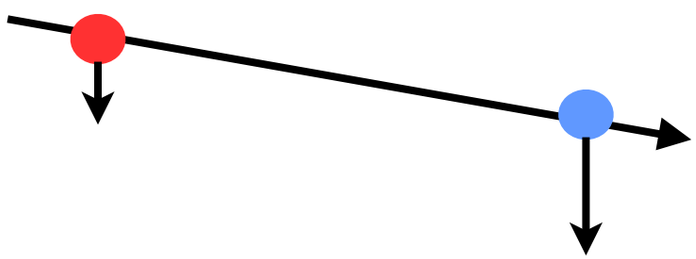
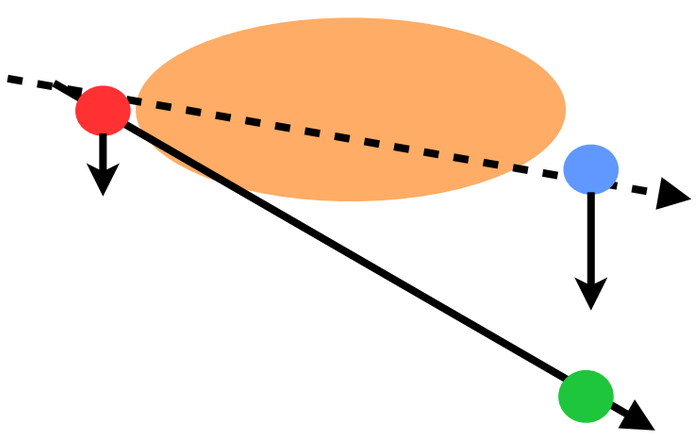


Without it



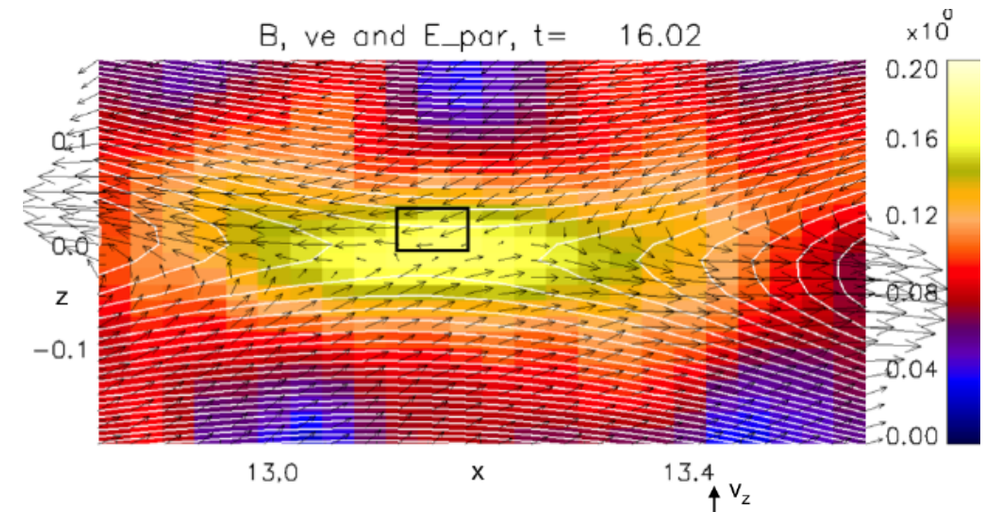
With a non-ideal region

Newly connected point

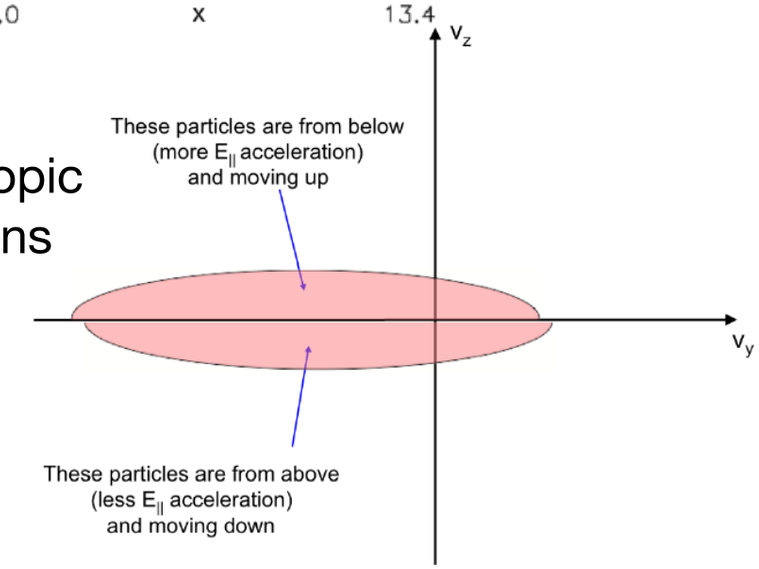
What they are in fully kinetic systems

[Hesse 2011]

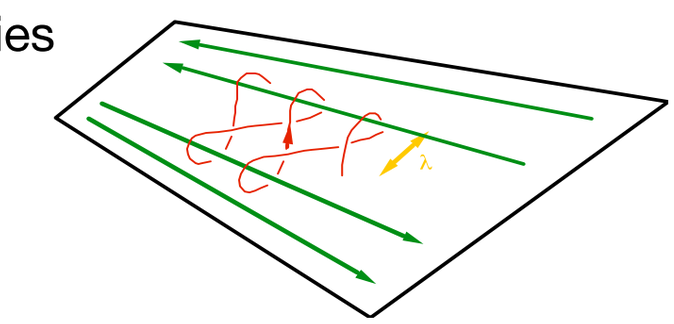
Collisionless mixing of particle with different dynamical origin



Non-gyrotropic distributions

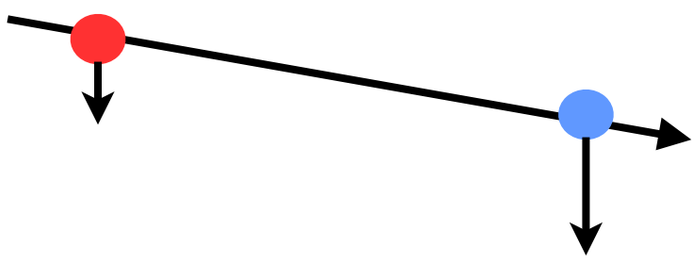


"unmagnetized" trajectories



Electrons non ideal scales

They can change field line connectivity



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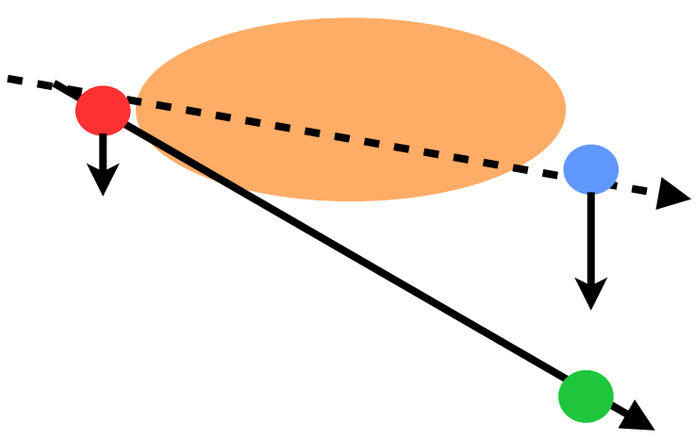

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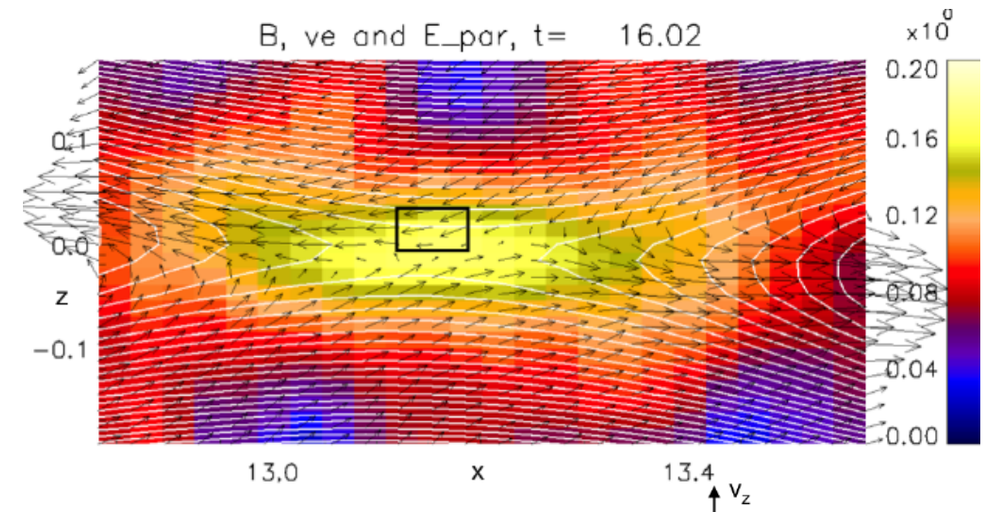

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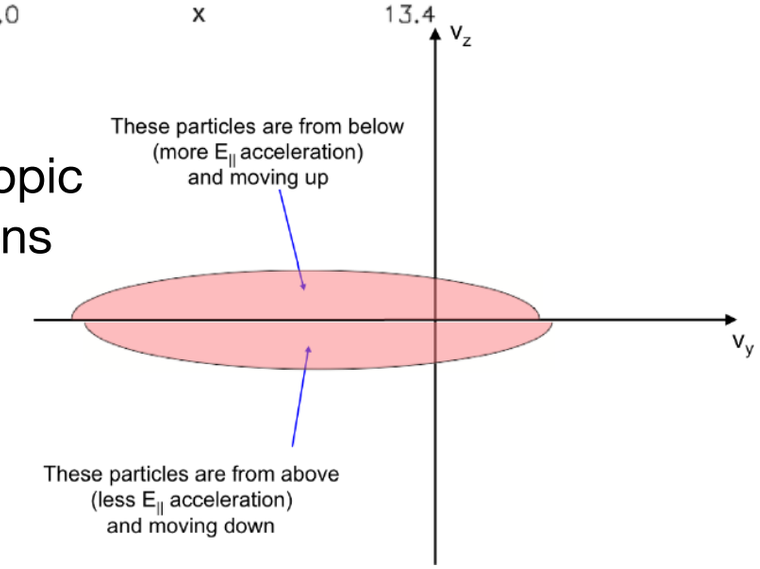

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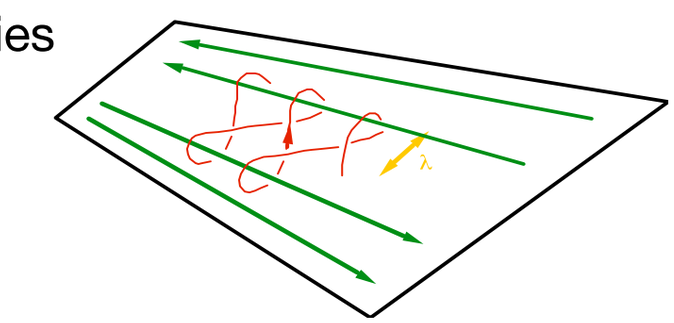

Fundamentally important to understand reconnection but does not affect its global rate

Hybrid simulations (without physical dissipation) are fast

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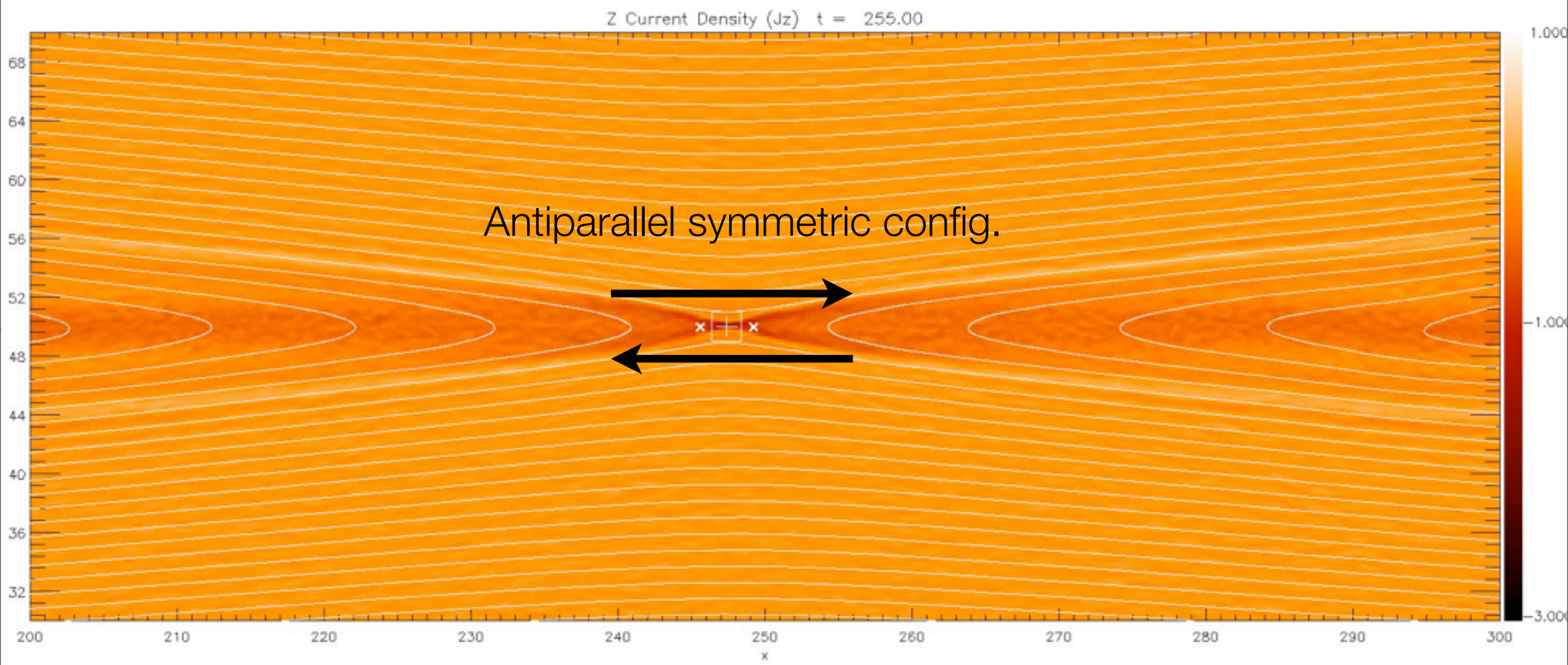

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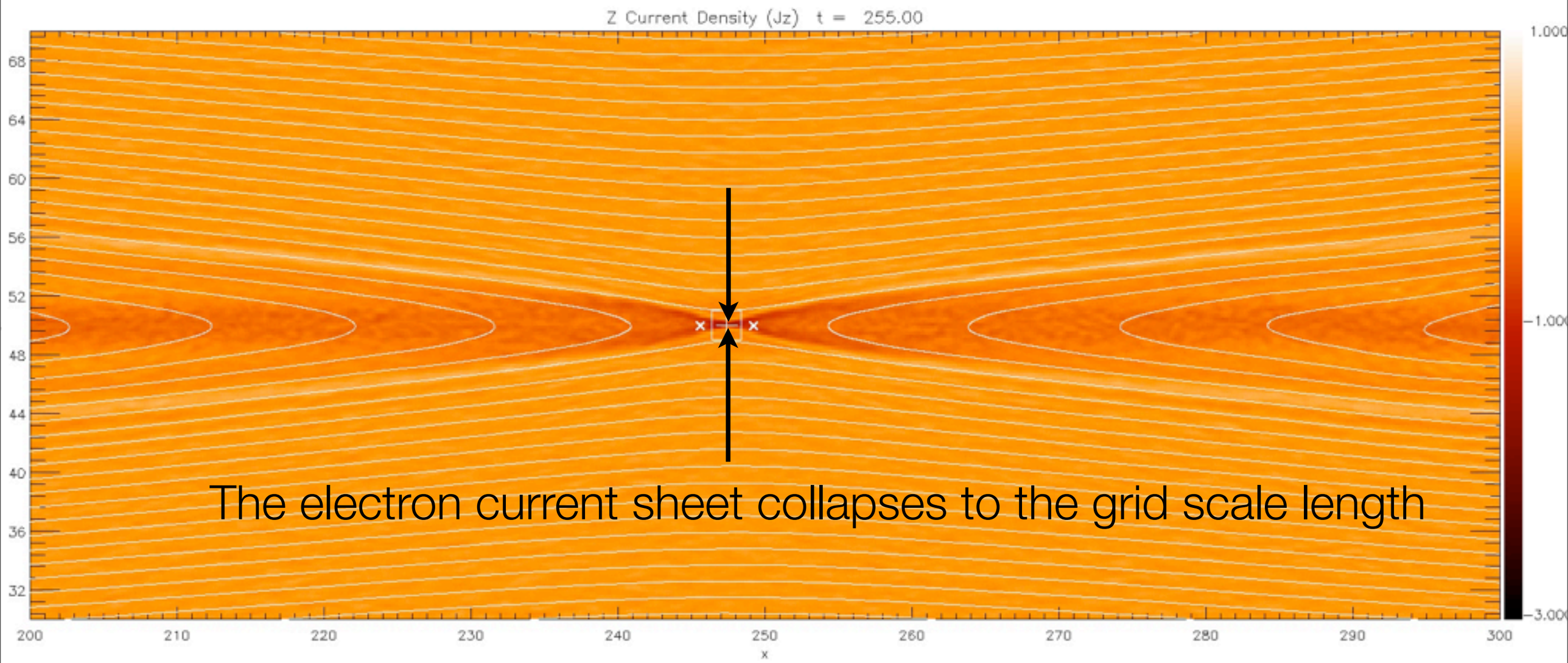

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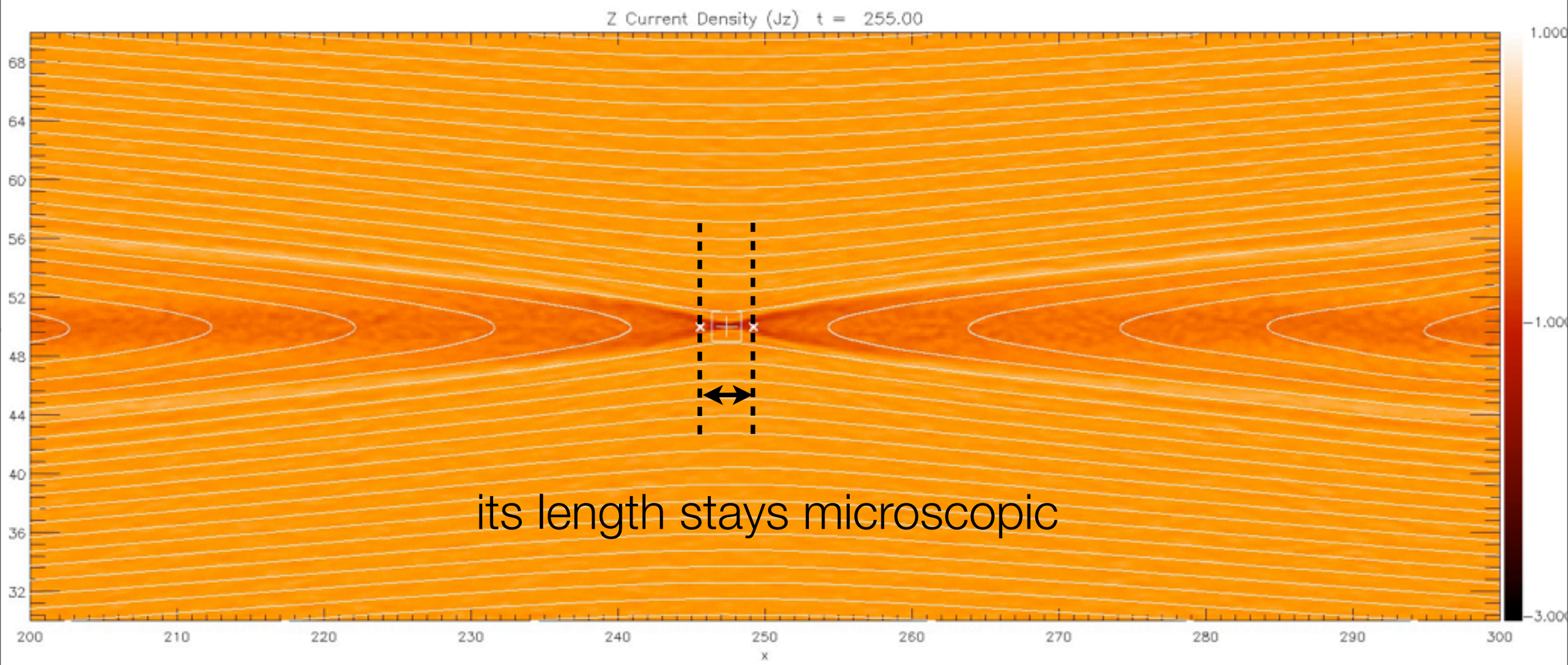

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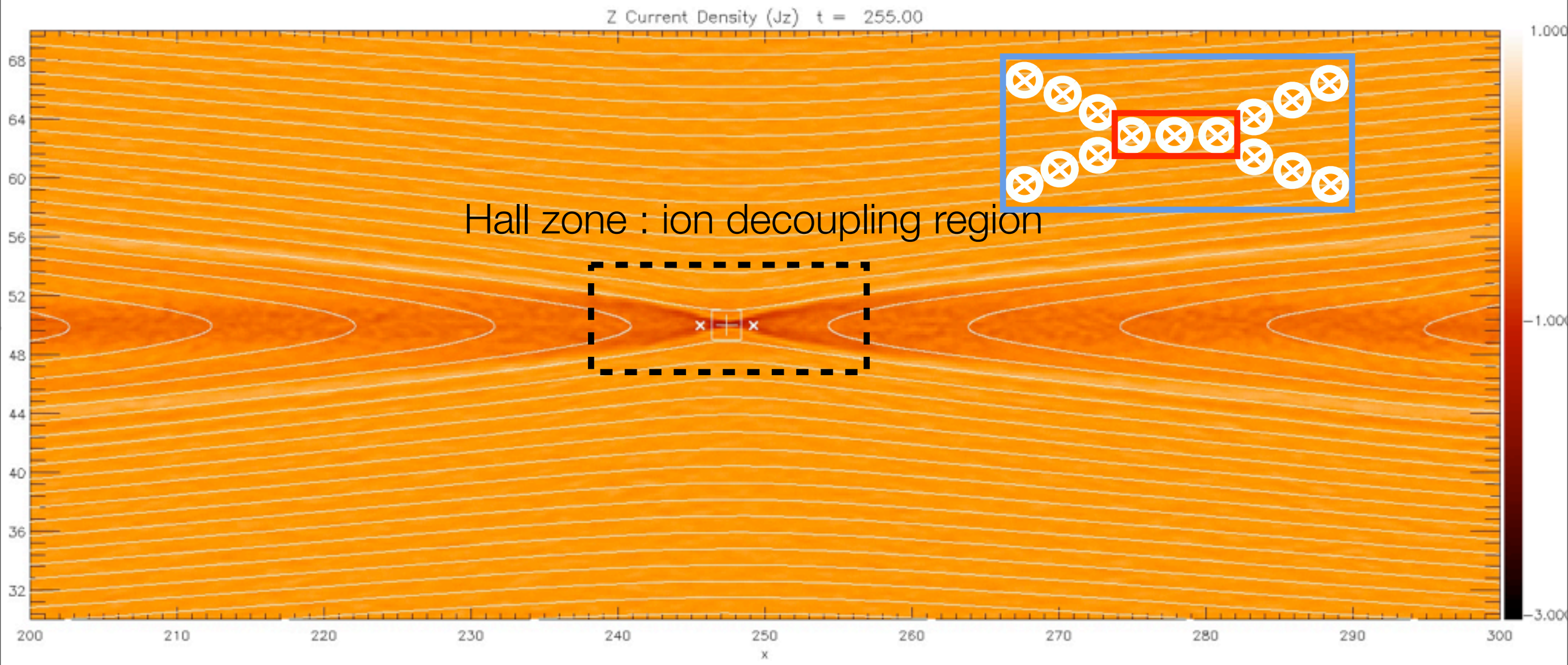

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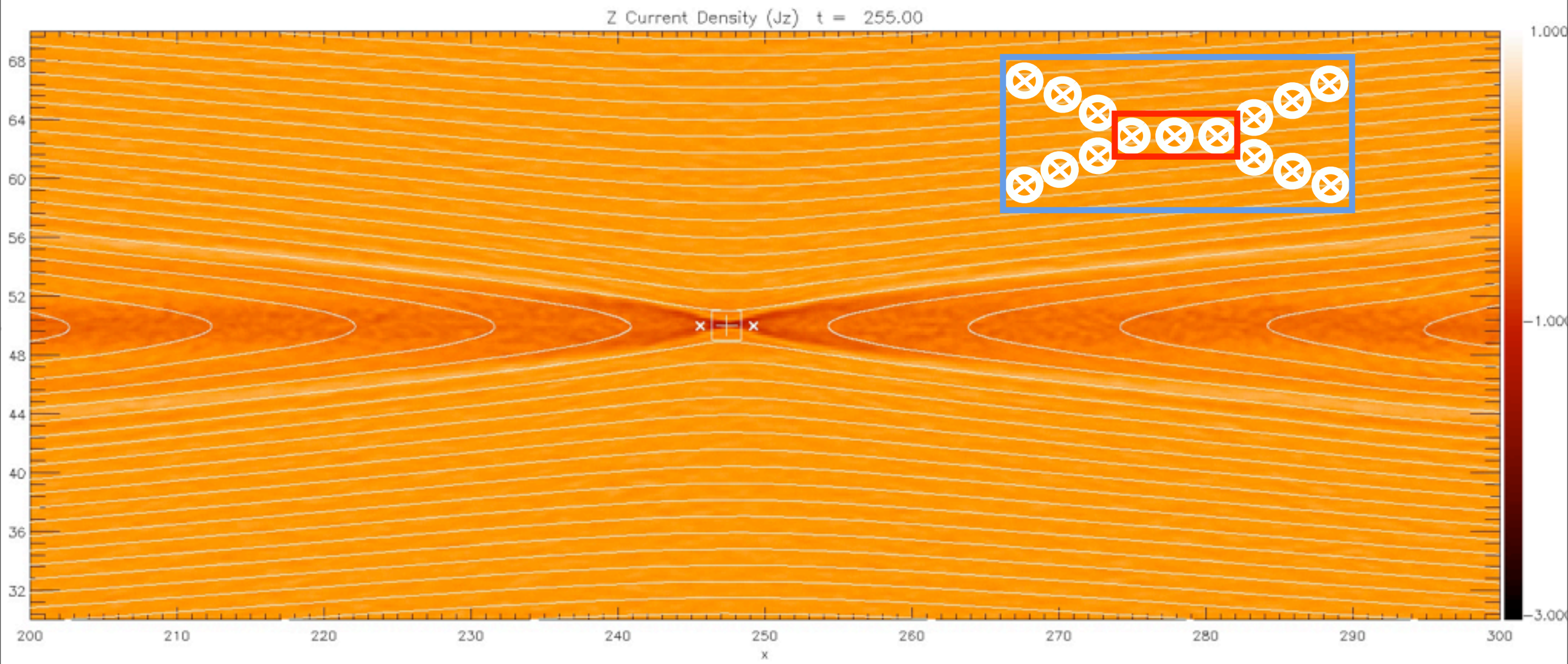

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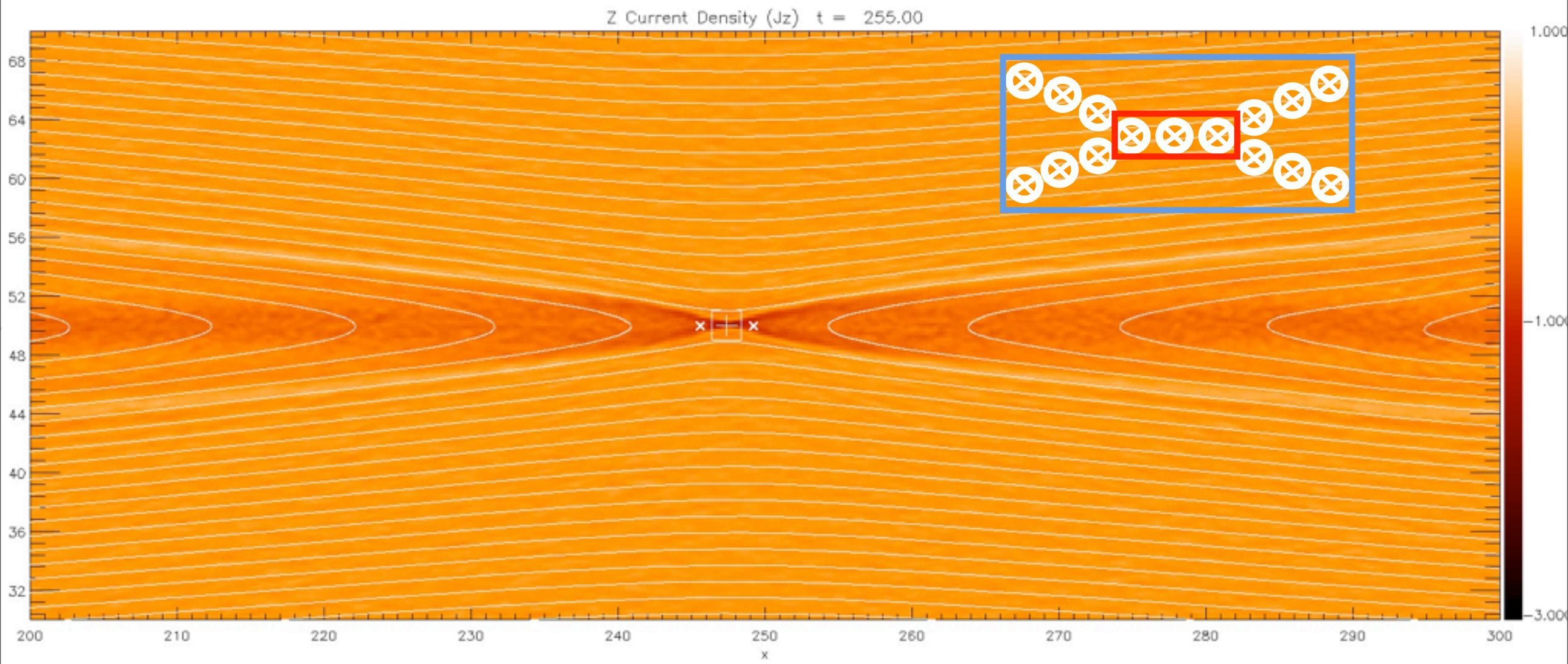
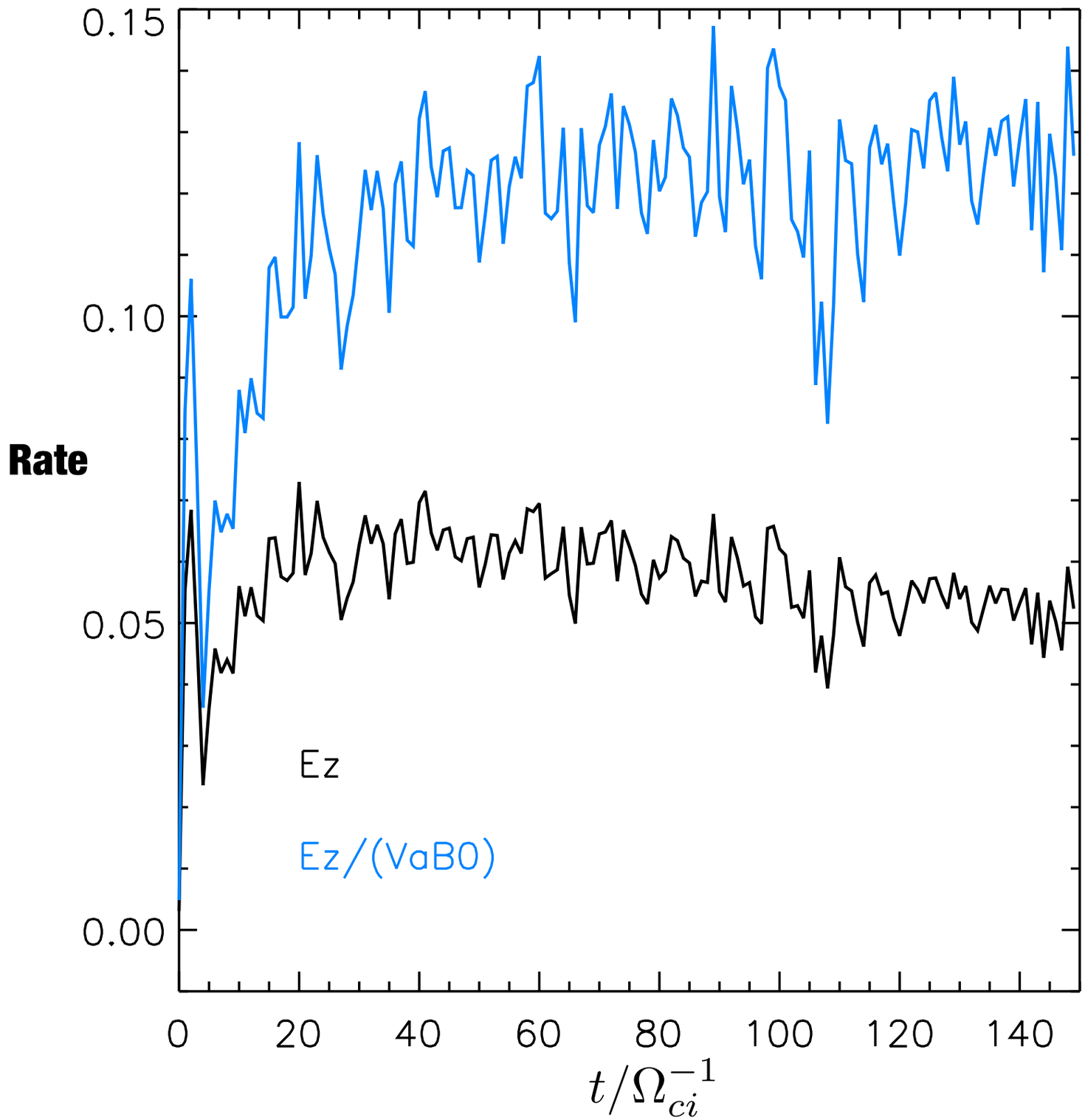


Reconnection appears fast and steady

Although no physical dissipation length scale is resolved

“Numerical dissipation” seems sufficient

Hybrid simulations (without physical dissipation) are fast



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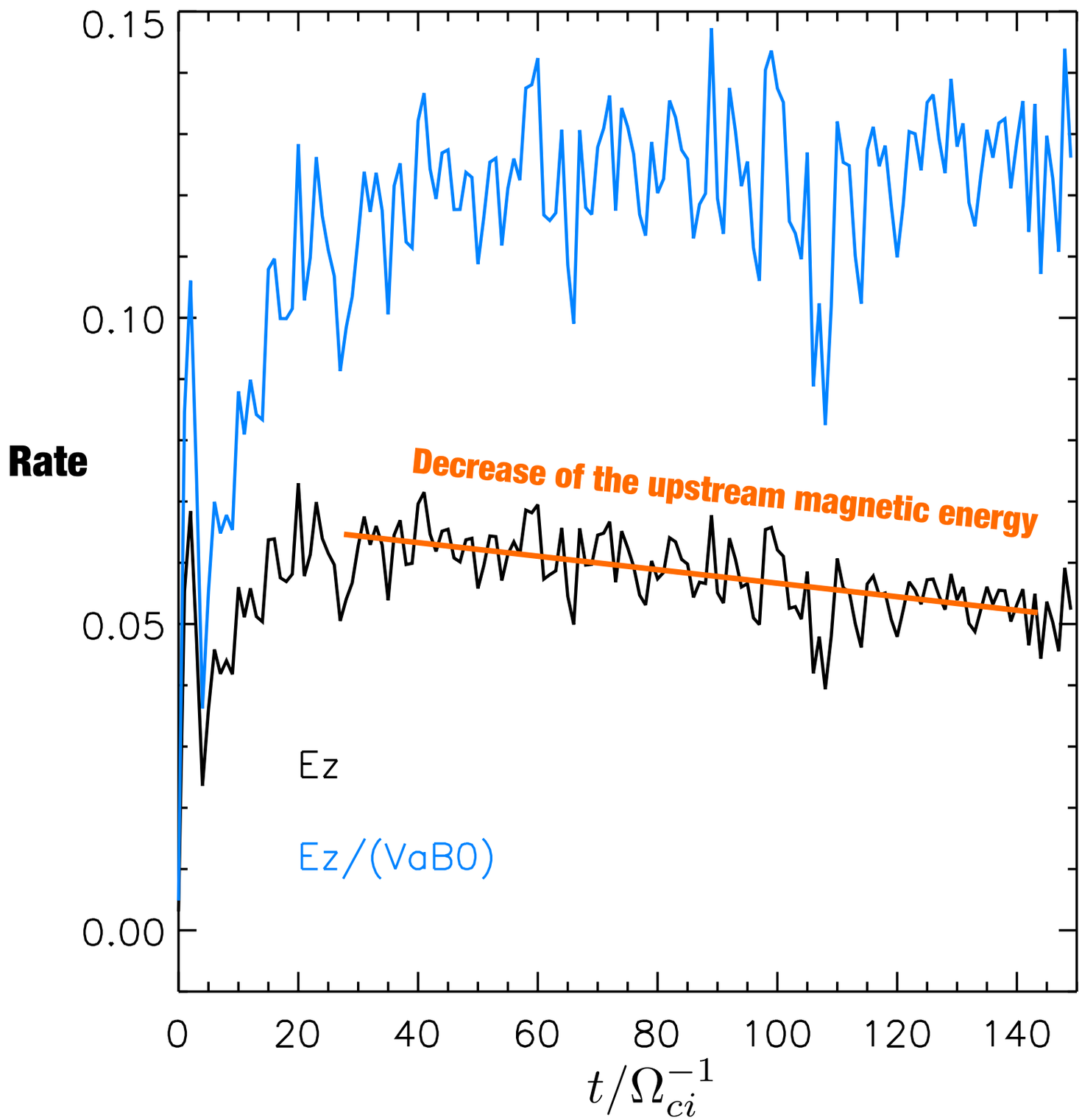

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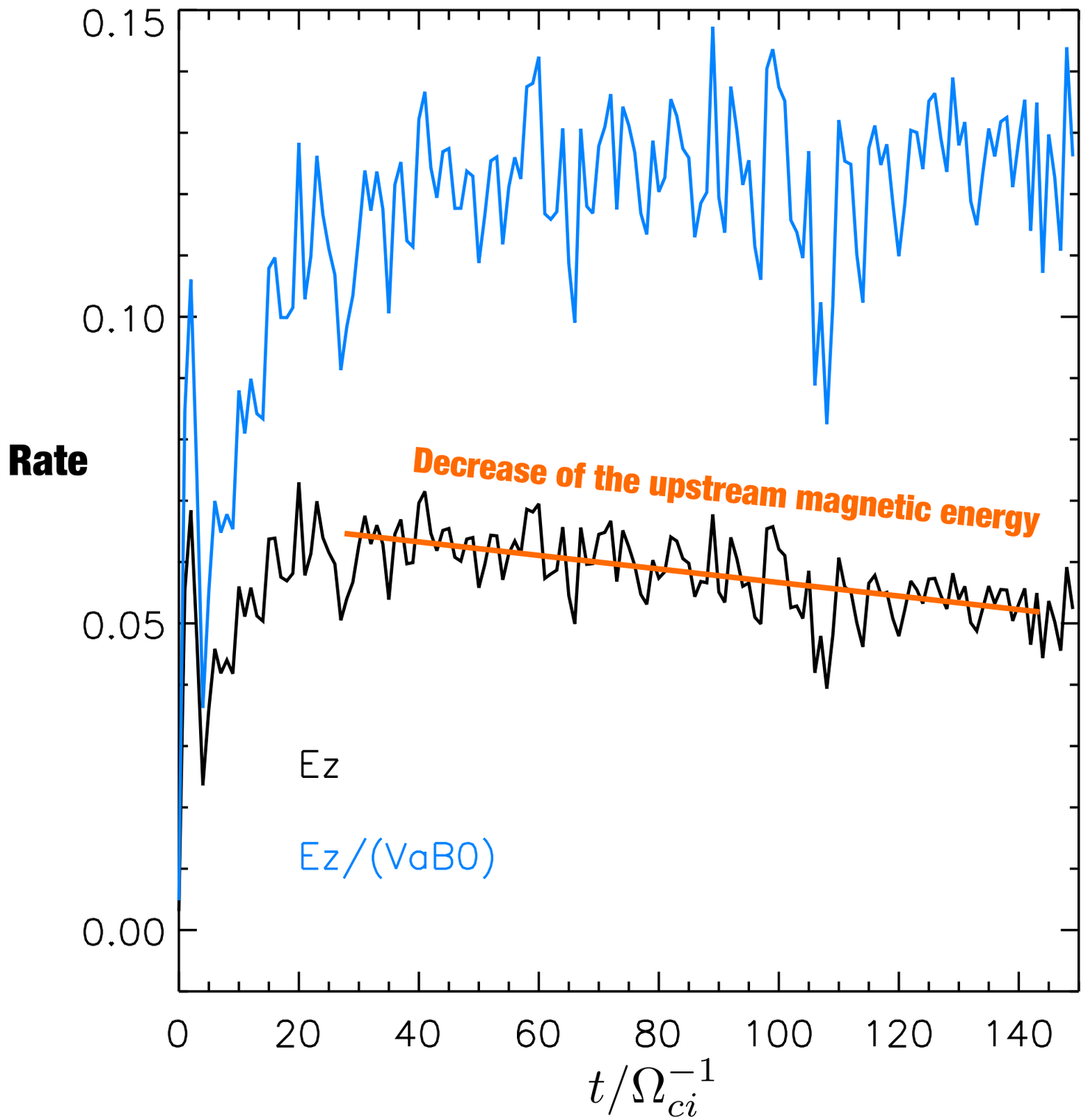
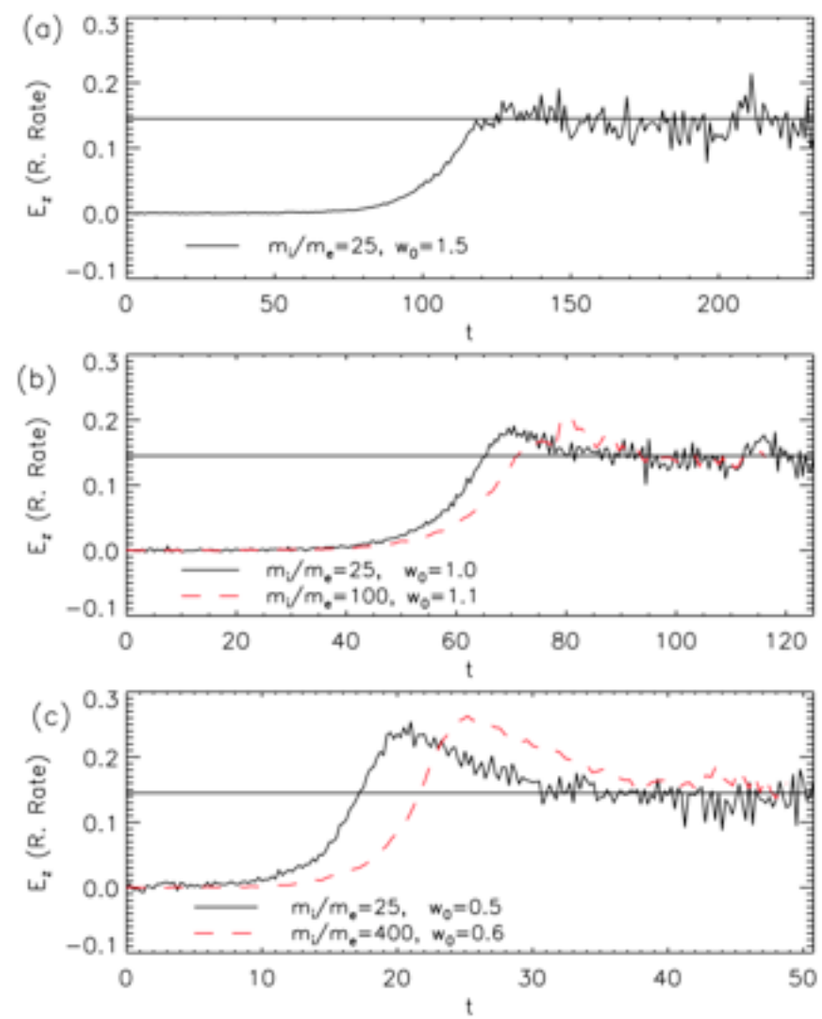
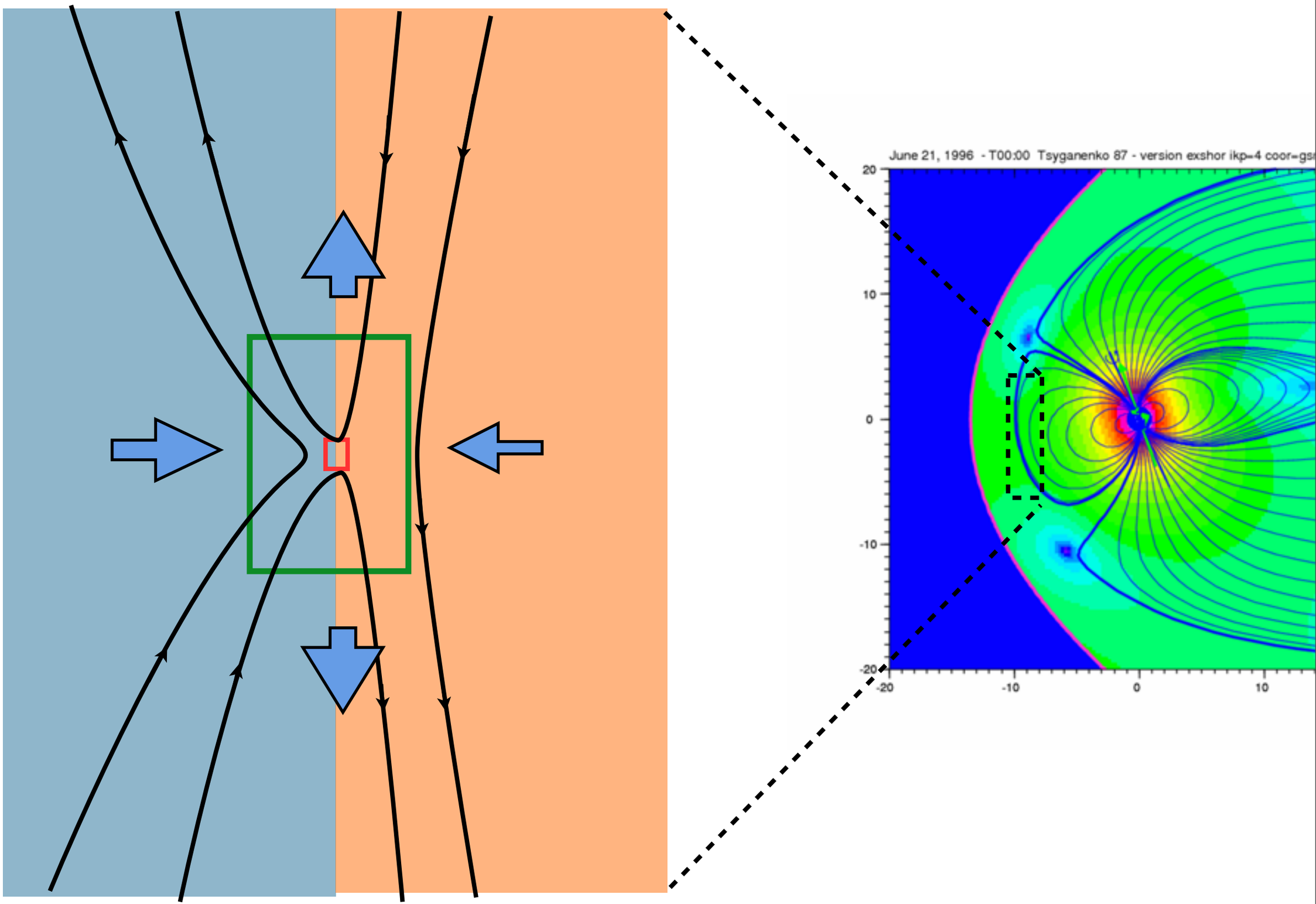


Rate consistent with literature
Reconnection is steady

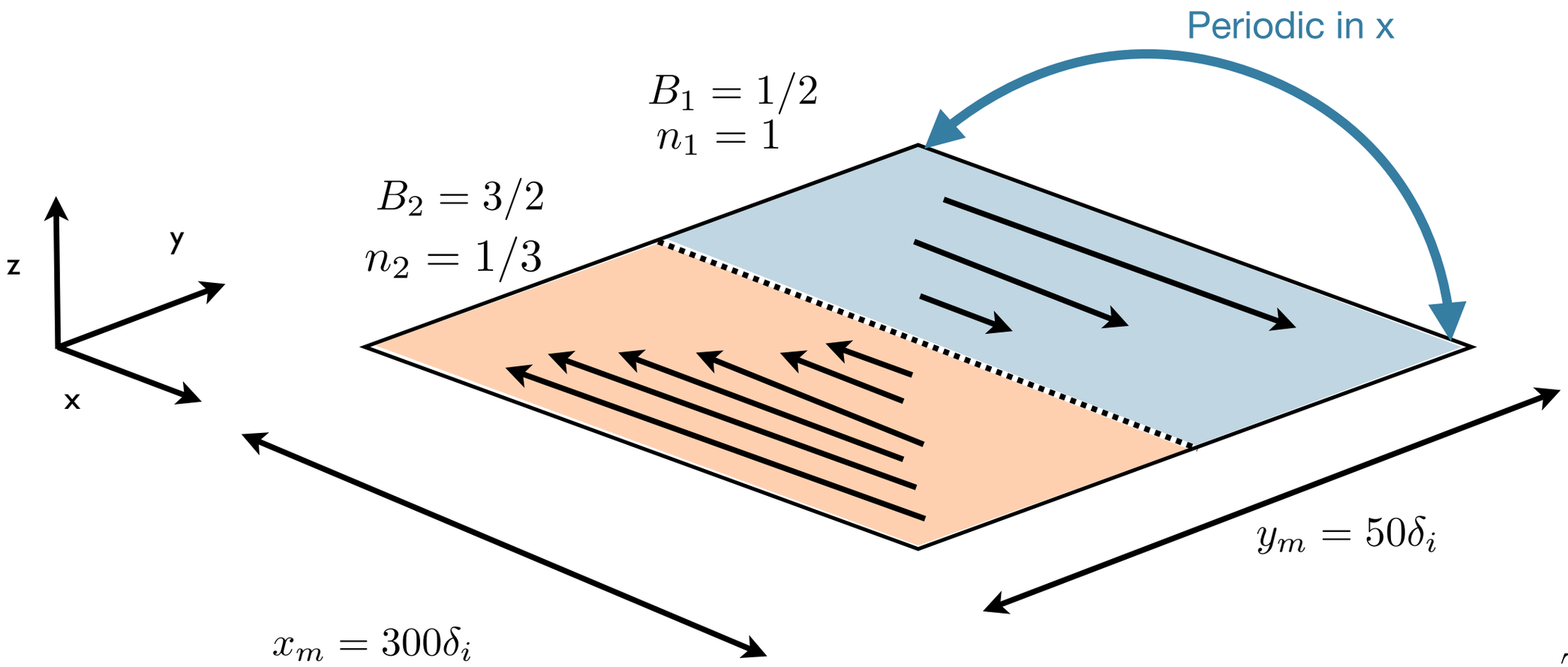


[Shay et al PRL 2007]

Asymmetric reconnection is more general



Asymmetric setup



$B_{z0} = 1$

$\Delta x = 0.15$

$\Delta y = 0.15$

$T = cst = 3/2$

$$\mathbf{E} = -\mathbf{v_i} \times \mathbf{B} + \frac{\mathbf{j} \times \mathbf{B}}{nq} - \frac{\boldsymbol{\nabla} P_e}{nq} + \eta \mathbf{j}$$

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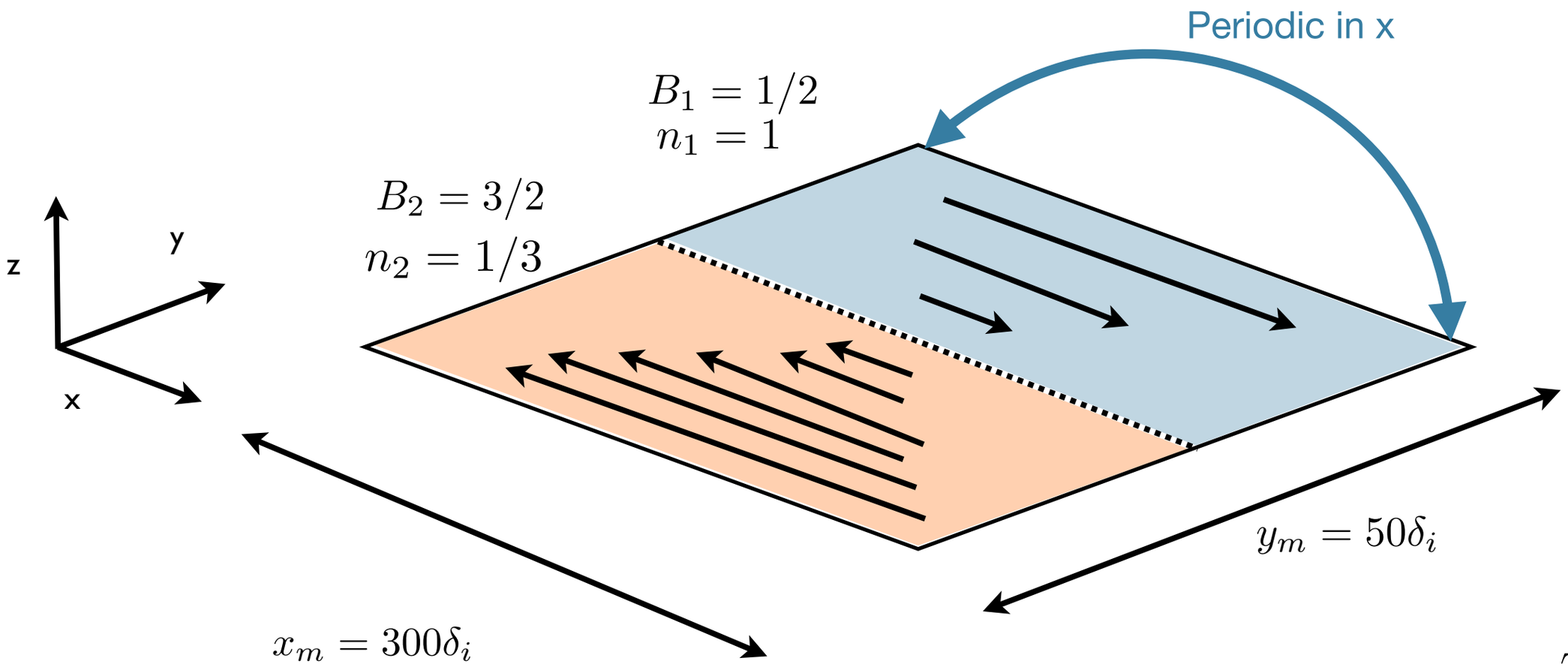

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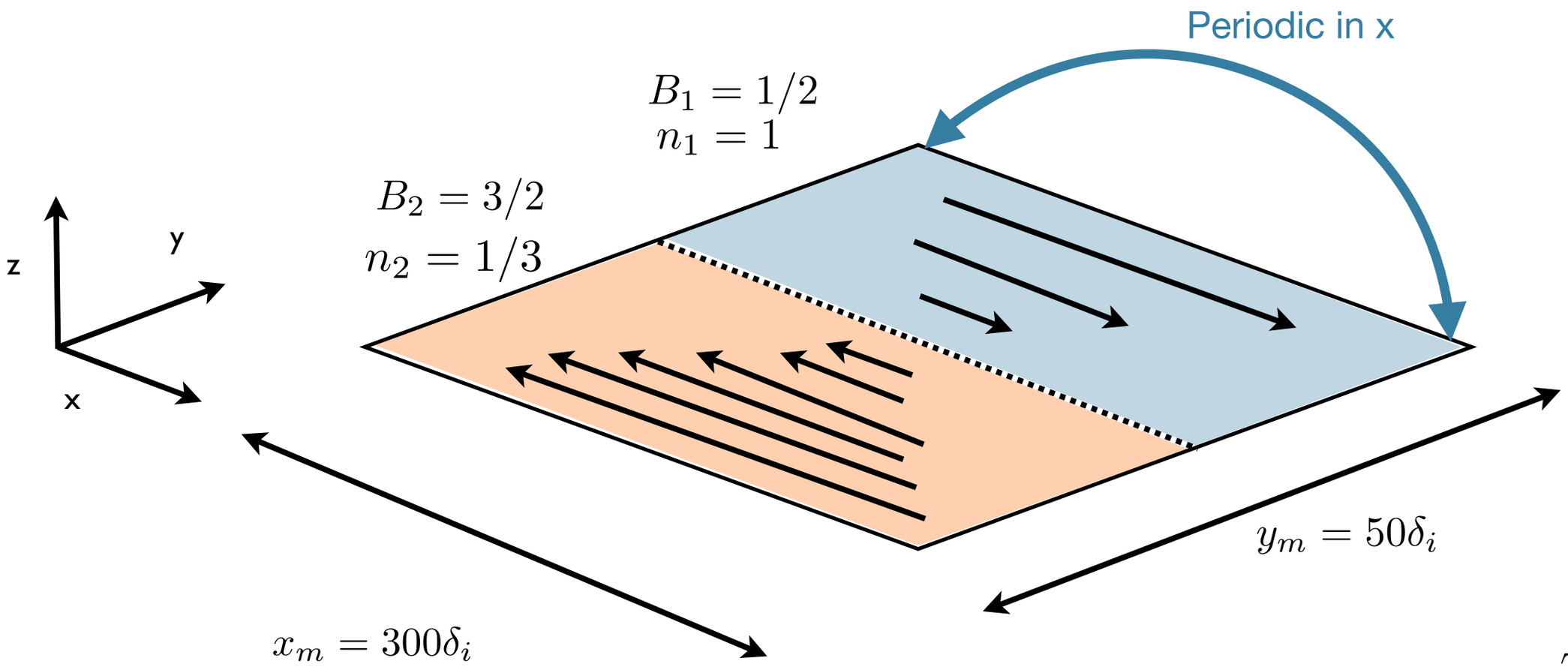
Isotherm closure for the electron fluid

Asymmetric setup



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Isotherm closure for the electron fluid

small dissipation for numerical stability

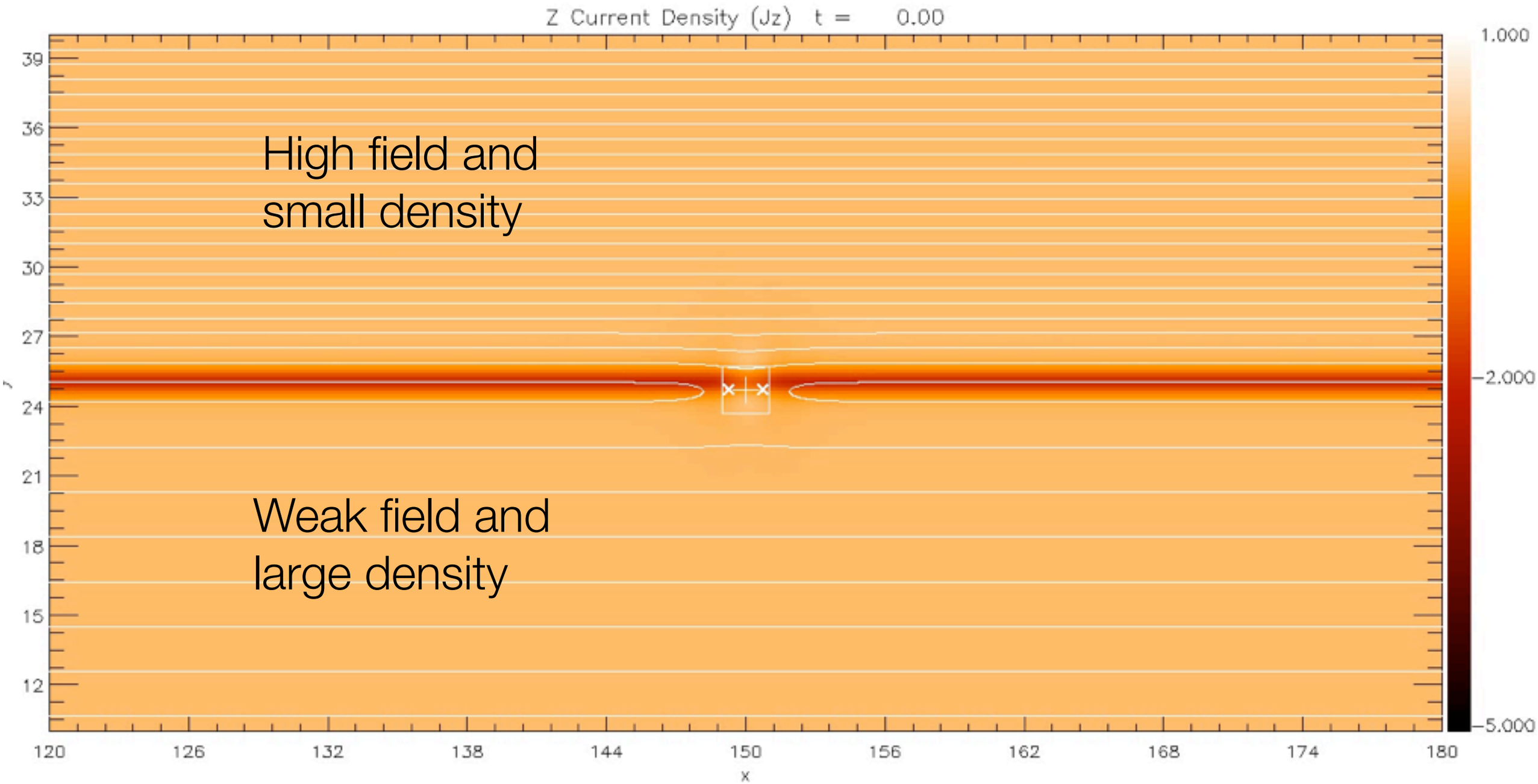
$$S = \frac{\mu_0 \delta_i V_A}{\eta} = 10^3$$

$$dx/2 \Longrightarrow 2J_z$$

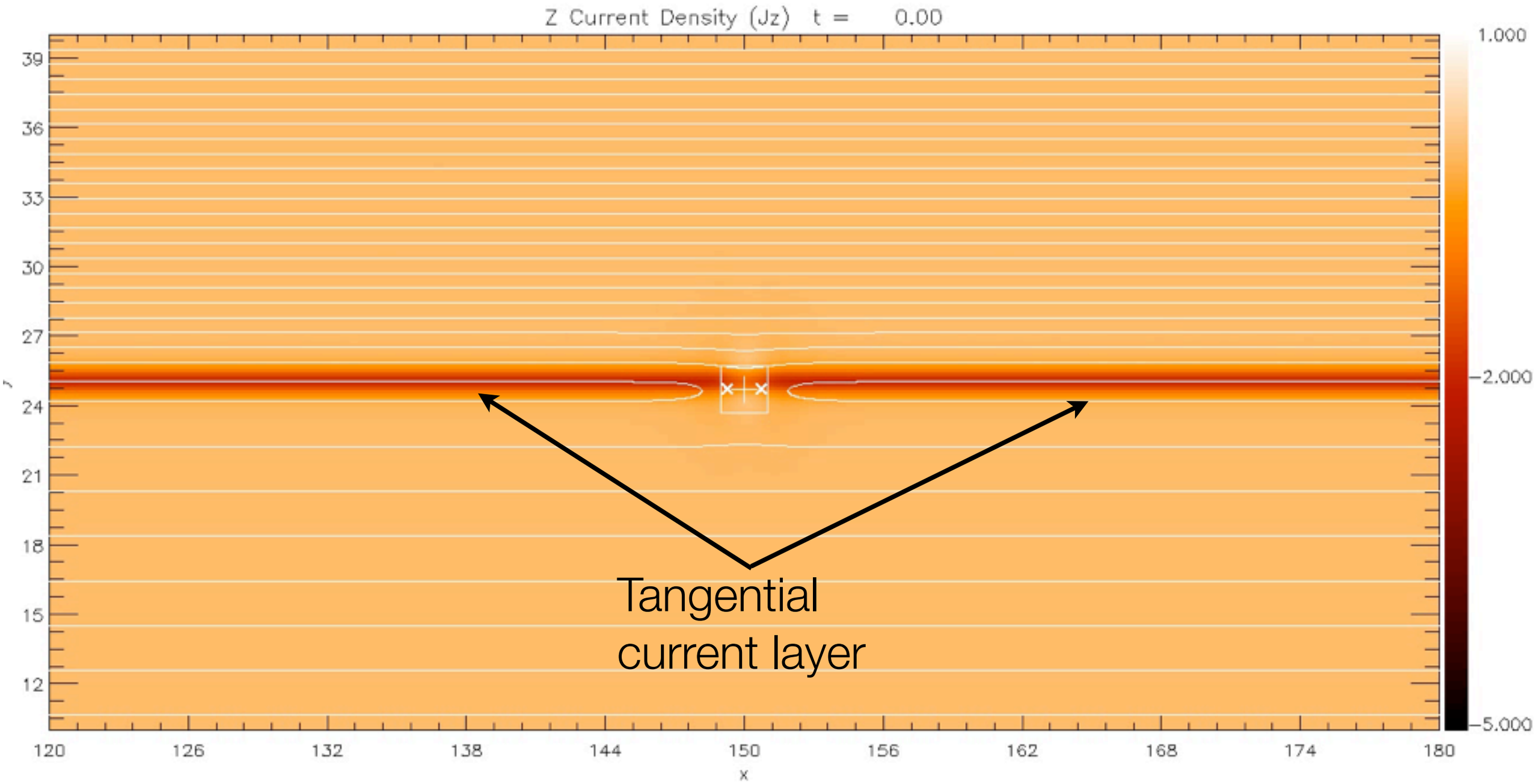
Reconnection of field lines is done my numerical dissipation

Result :

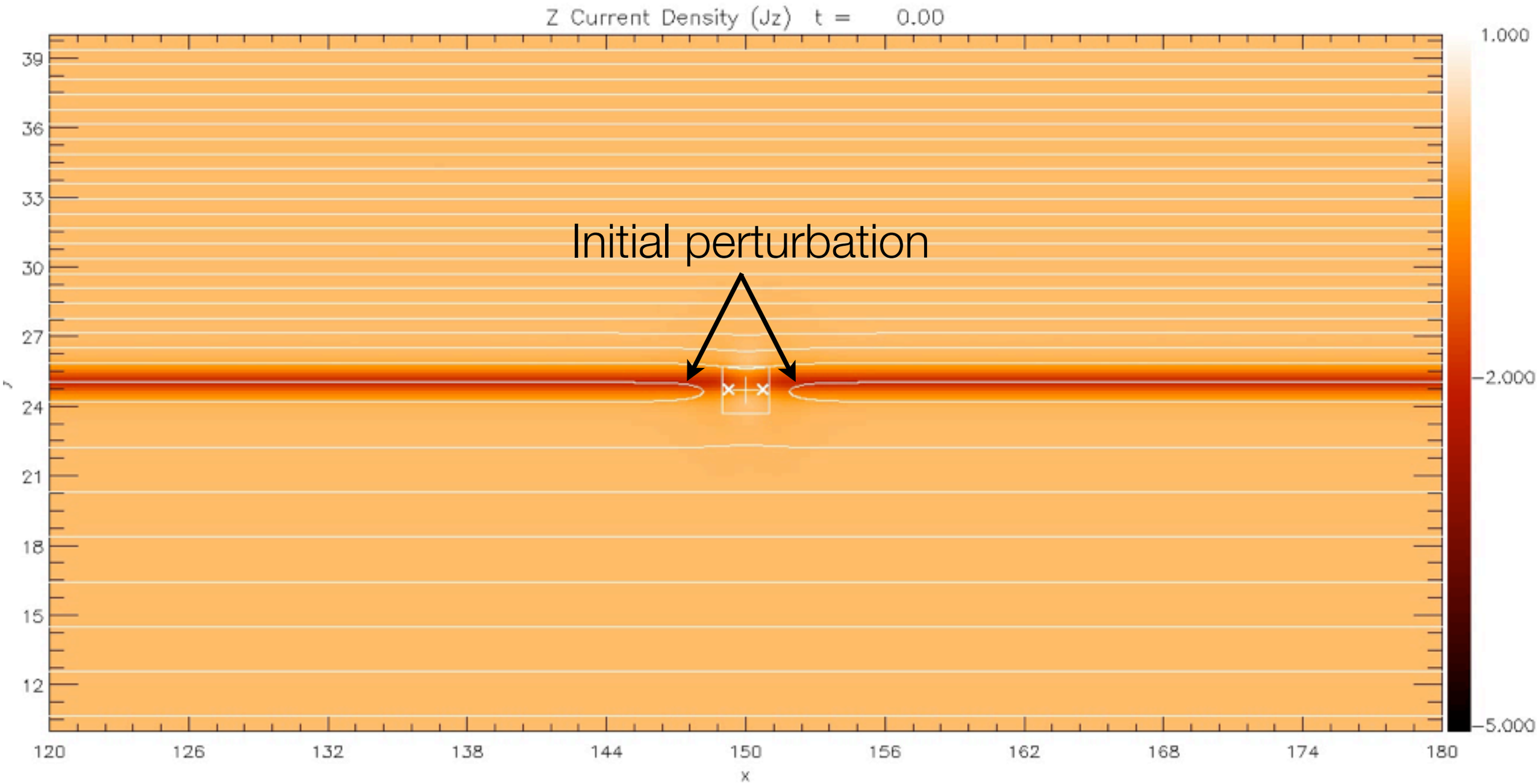
Result :


Z Current Density (Jz) t = 0.00
High field and
small density
Weak field and
large density
39
36
33
30
27
24
21
18
15
12
120
126
132
138
144
150
156
162
168
174
180
x
1.000
-2.000
-5.000

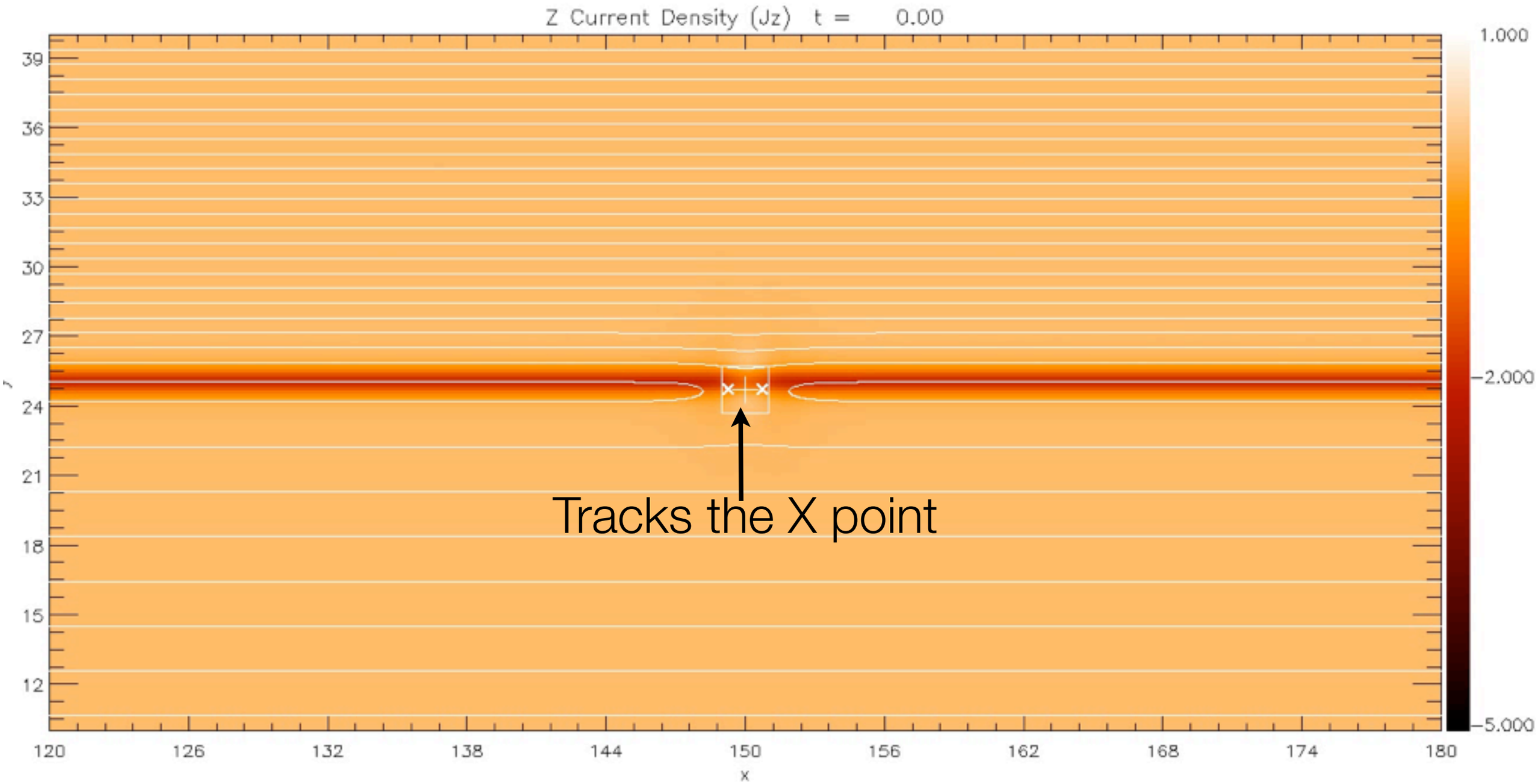
Result :


Z Current Density (Jz) t = 0.00
1.000
-2.000
-5.000
39
36
33
30
27
24
21
18
15
12
120
126
132
138
144
150
156
162
168
174
180
x
Tangential
current layer

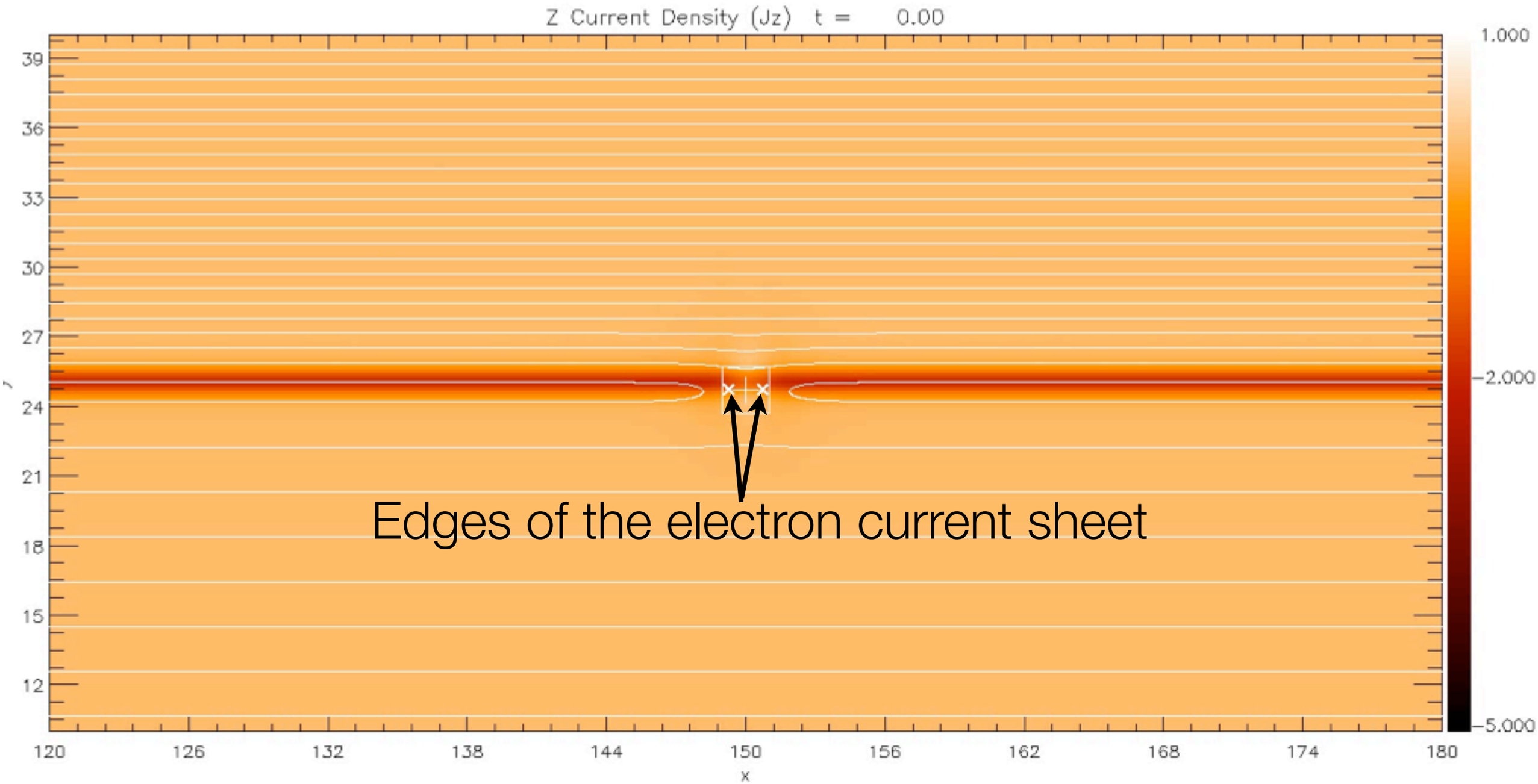
Result :


Z Current Density (Jz) t = 0.00
Initial perturbation
1.000
-2.000
-5.000
39
36
33
30
27
24
21
18
15
12
120
126
132
138
144
150
156
162
168
174
180
x

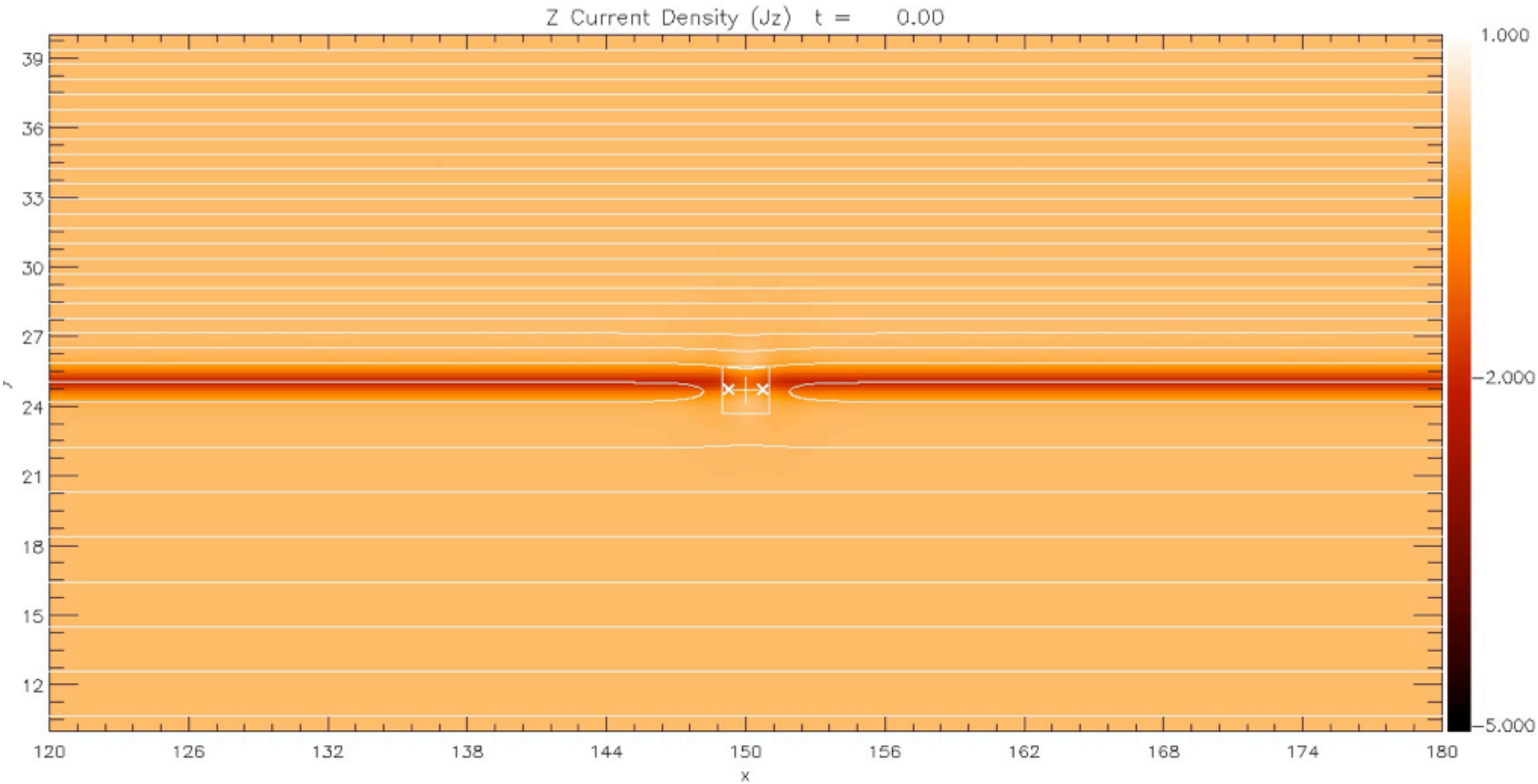
Result :


Z Current Density (Jz) t = 0.00
1.000
-2.000
-5.000
39
36
33
30
27
24
21
18
15
12
120
126
132
138
144
150
156
162
168
174
180
x
Tracks the X point

Result :


Z Current Density (Jz) t = 0.00
39
36
33
30
27
24
21
18
15
12
y
120
126
132
138
144
150
156
162
168
174
180
x
1.000
-2.000
-5.000
Edges of the electron current sheet

Result :


Z Current Density (Jz) t = 0.00
39
36
33
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24
21
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12
y
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132
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x
1.000
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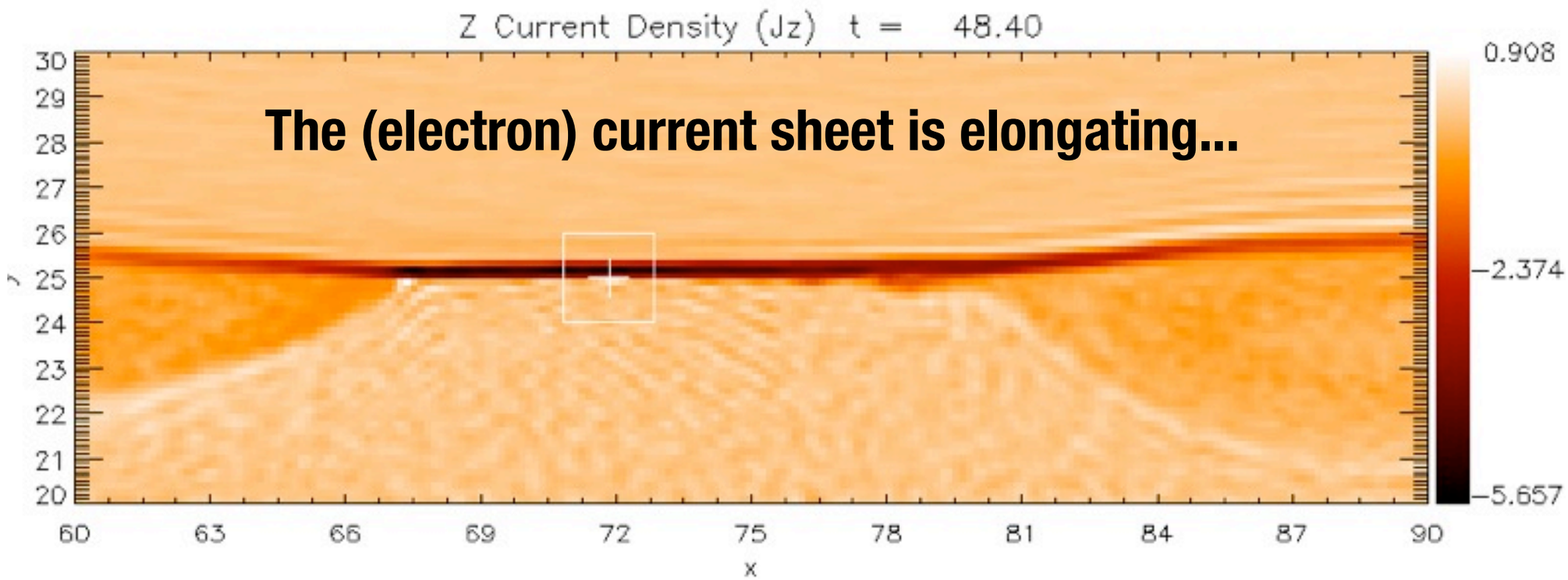
What did we see ?



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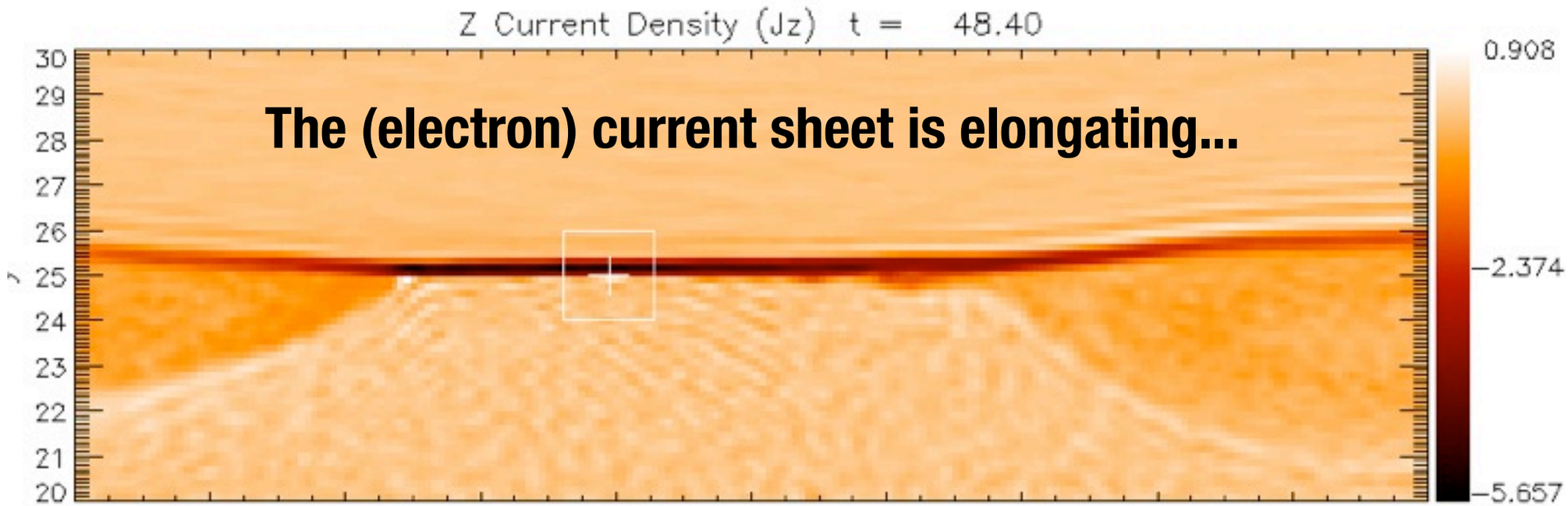
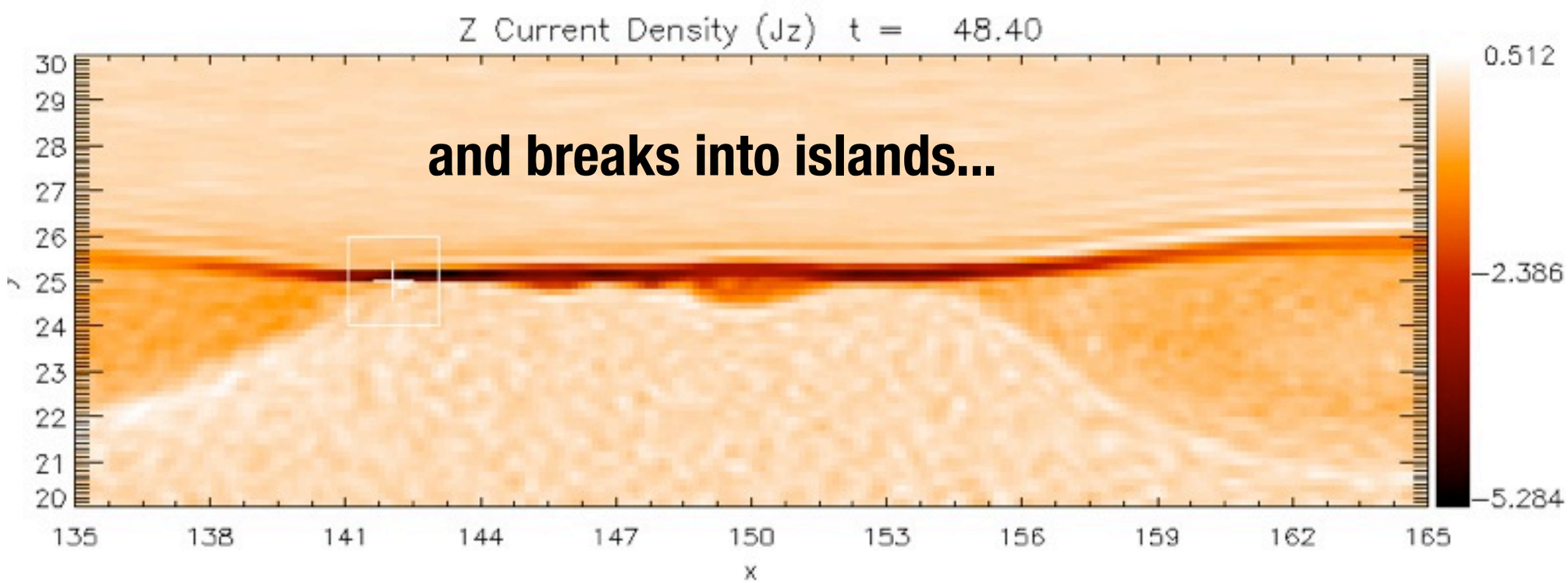
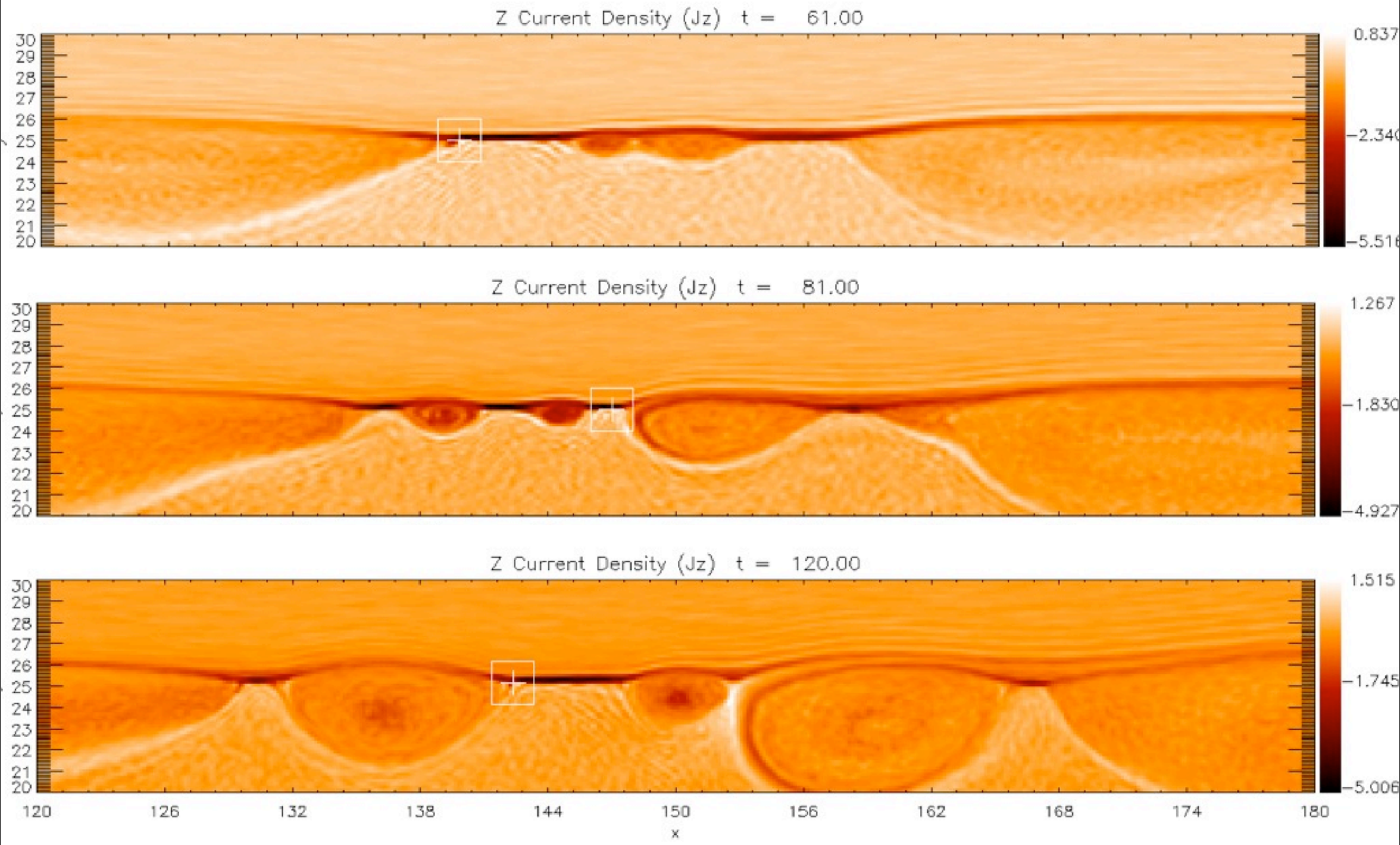
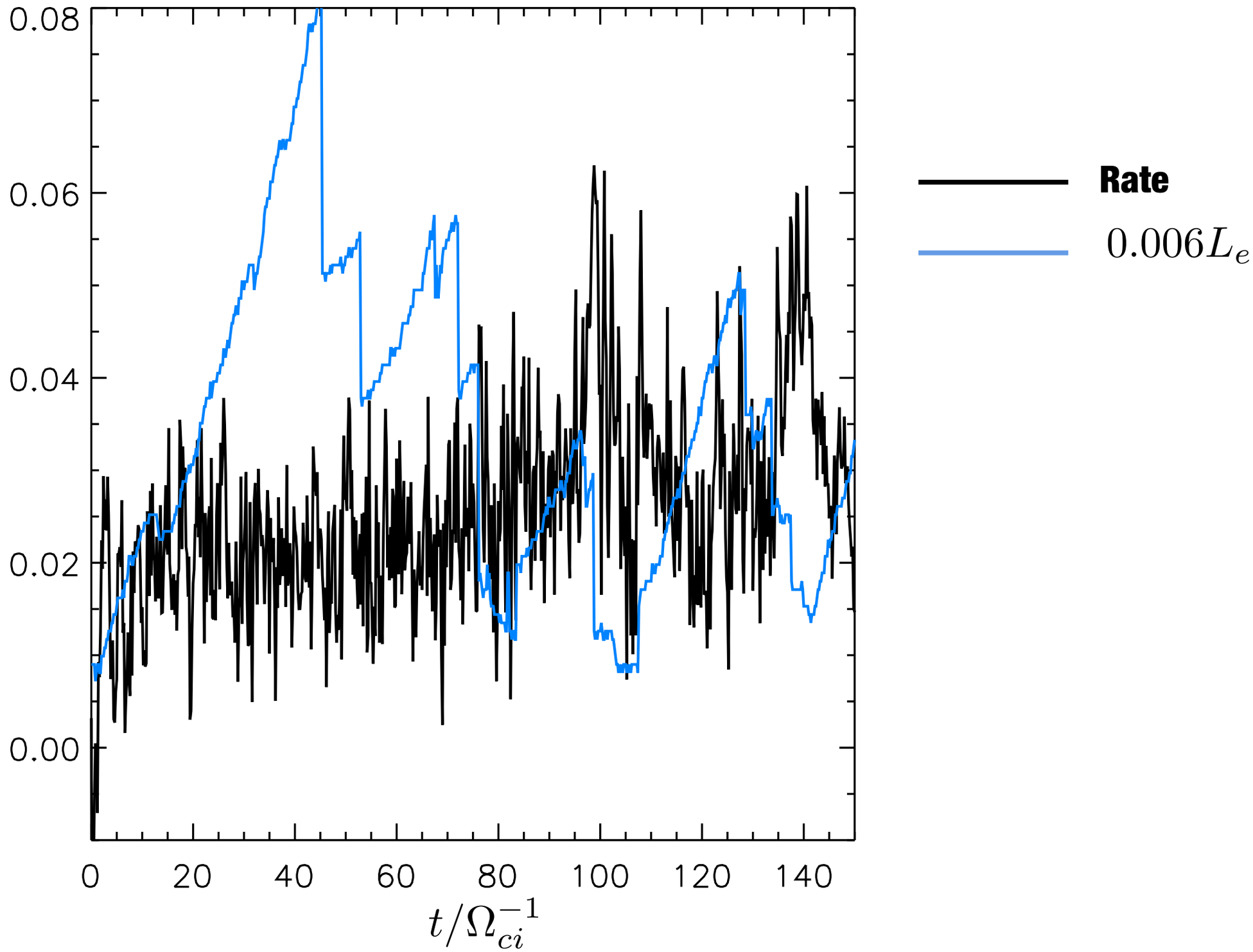




Elongation/breaking oscillations



The reconnection rate is modulated by the formation of islands



Why is it elongating?

Two possibilities :

δ_i (~1) is not sufficiently resolved ($dy = 0.15\delta_i$)

Numerical diffusion leads to a “numerical Sweet-Parker-like regime”

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δ_i (~1) is not sufficiently resolved ($dy = 0.15\delta_i$)

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OR

The Hall effect is sufficiently resolved but the dissipation is too weak.

Why is it elongating?

Two possibilities :

δ_i (~1) is not sufficiently resolved ($dy = 0.15\delta_i$)

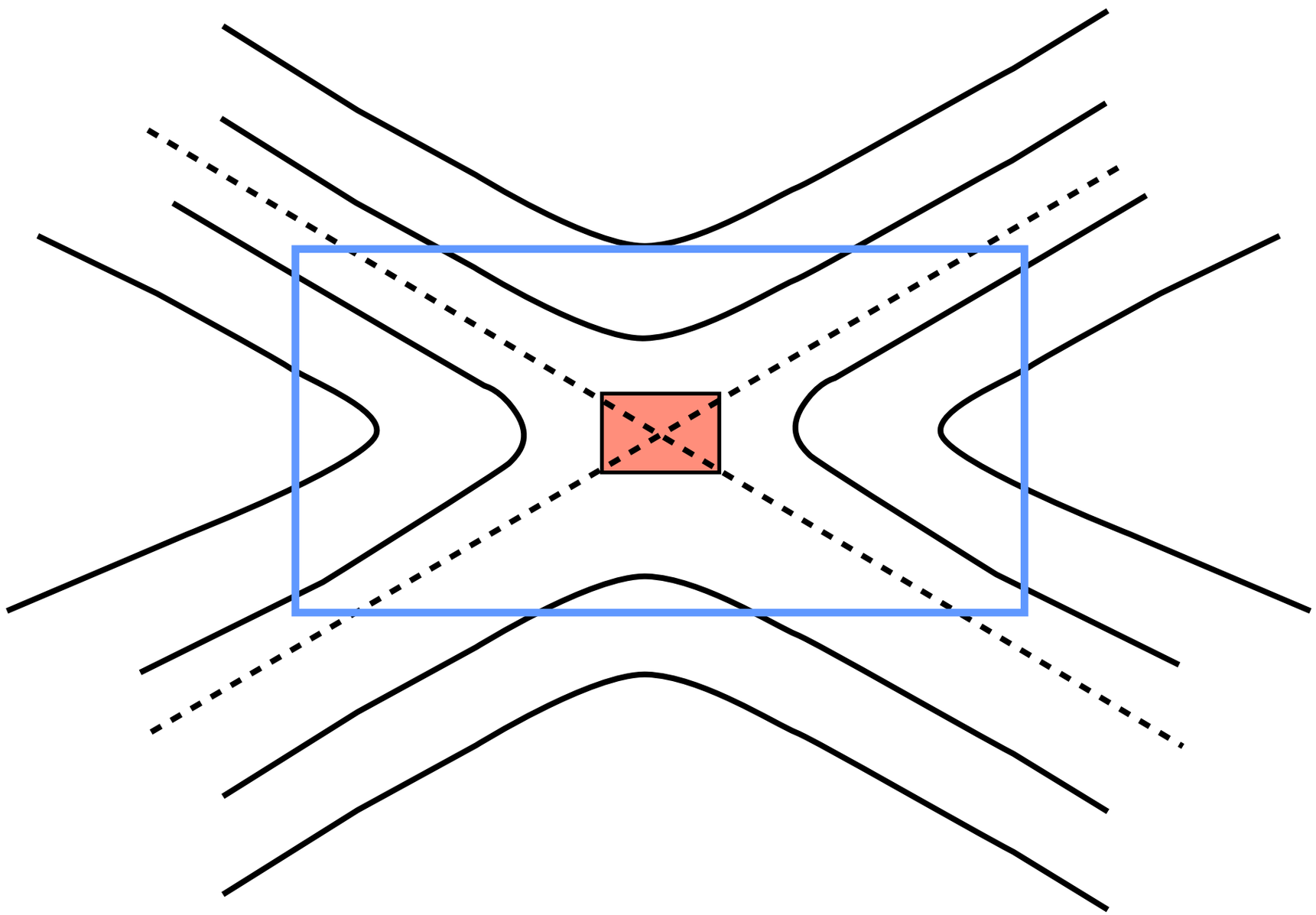
Numerical diffusion leads to a “numerical Sweet-Parker-like regime”

OR

The Hall effect is sufficiently resolved but the dissipation is too weak.

Somehow contradicts the paradigm that says that dissipation does not matter, **unless it dominates over the Hall effect**

If the dissipation is too weak, the field lines can't reconnect before the hot downstream plasma has moved away



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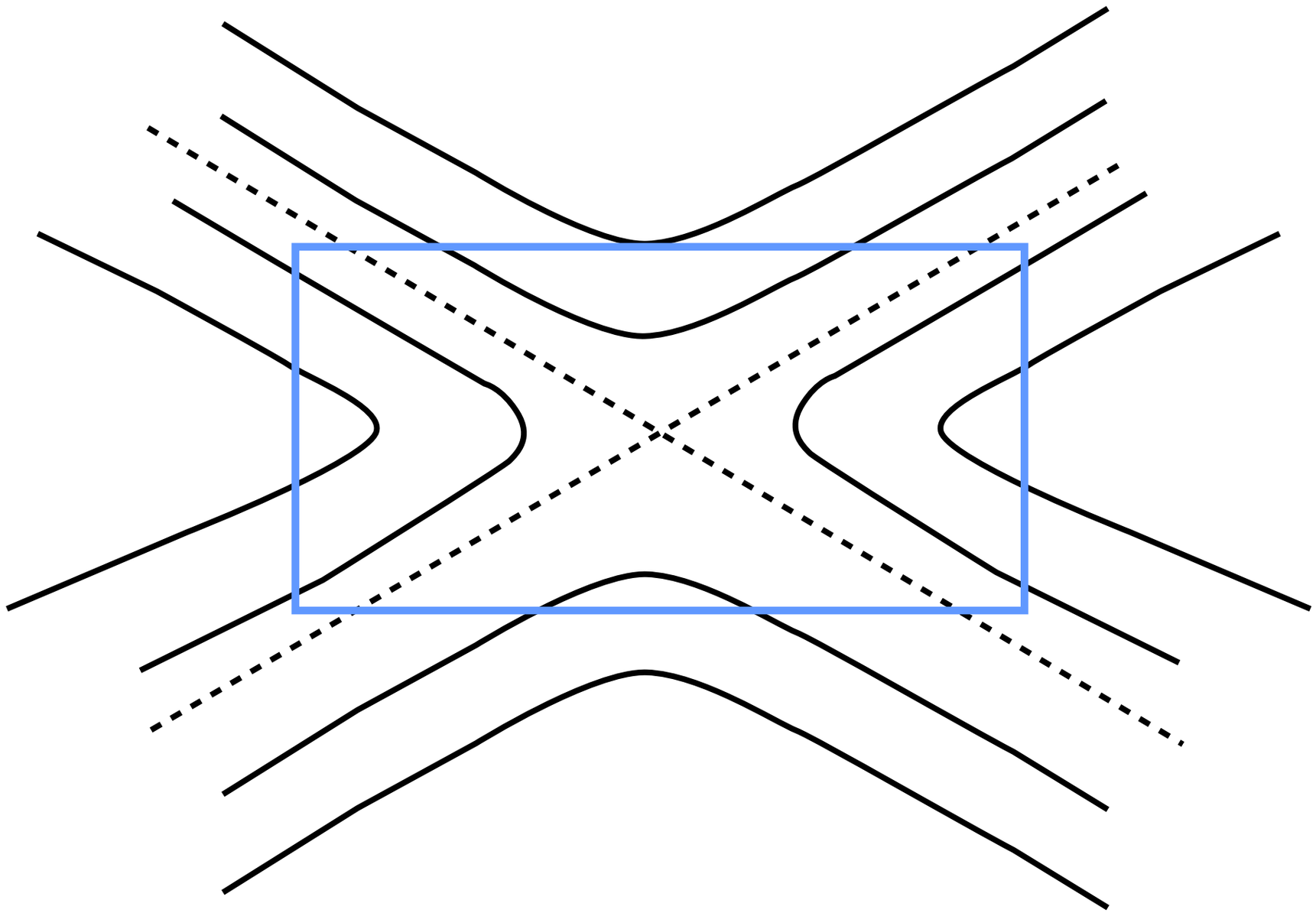

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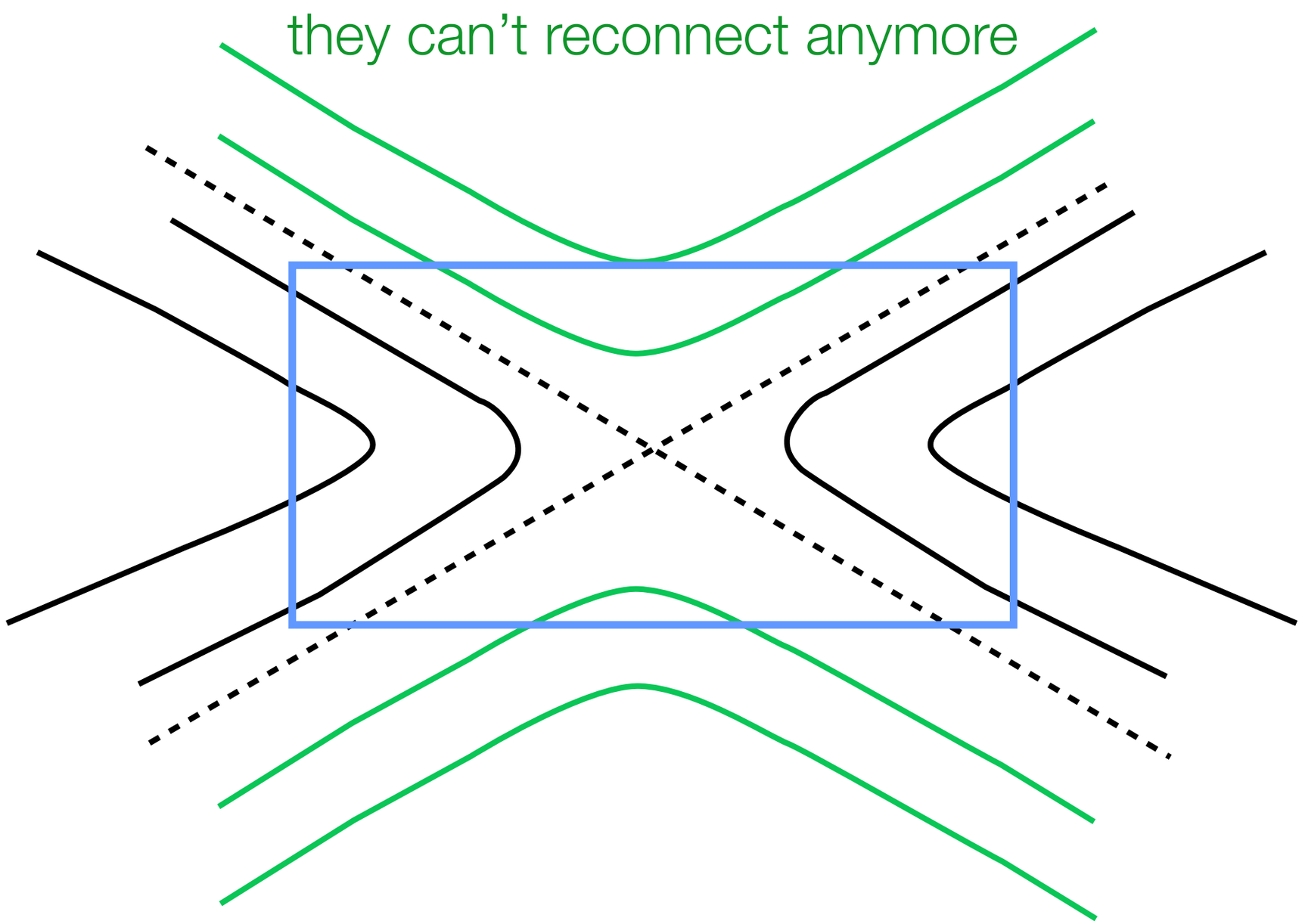

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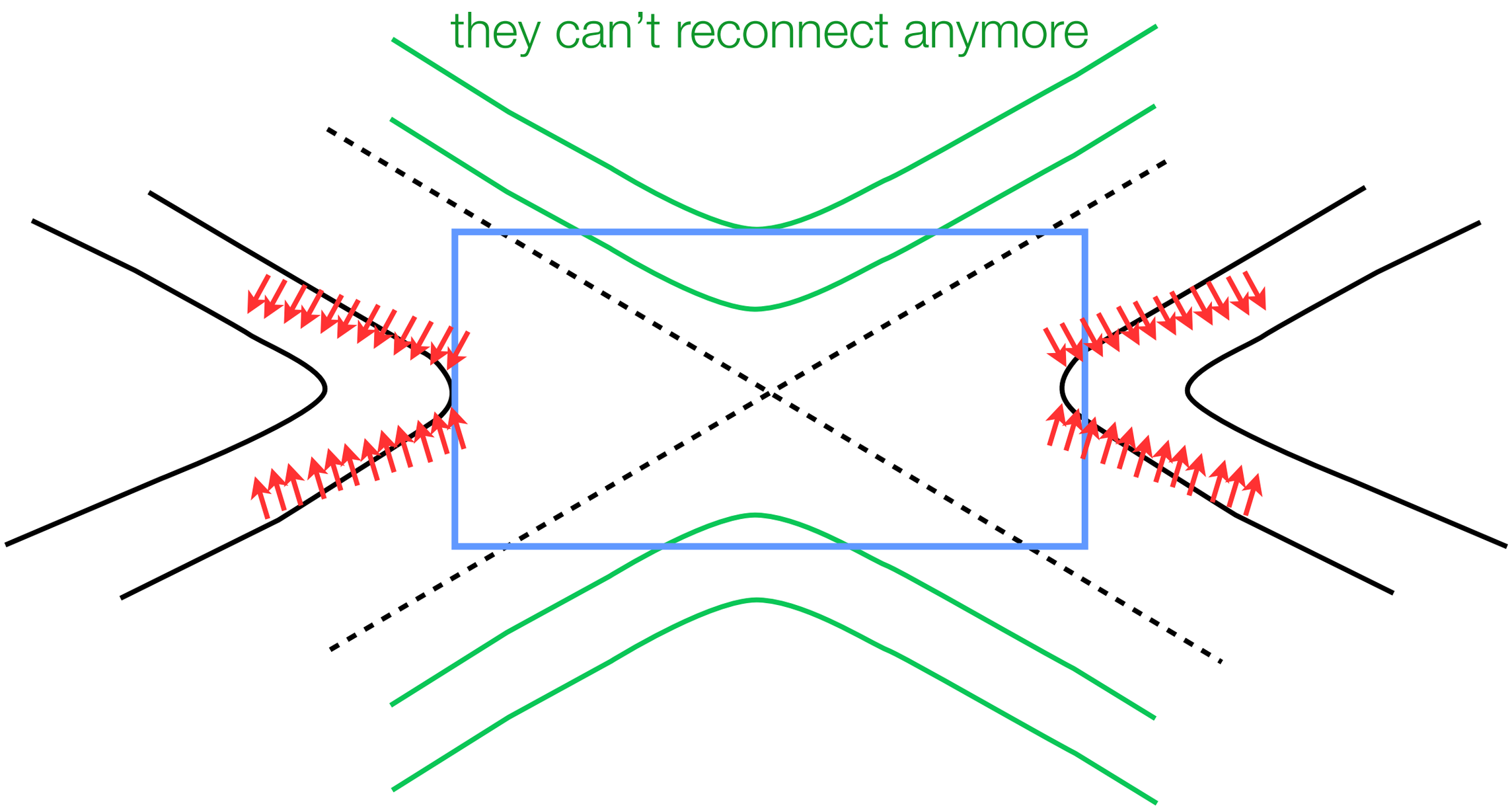

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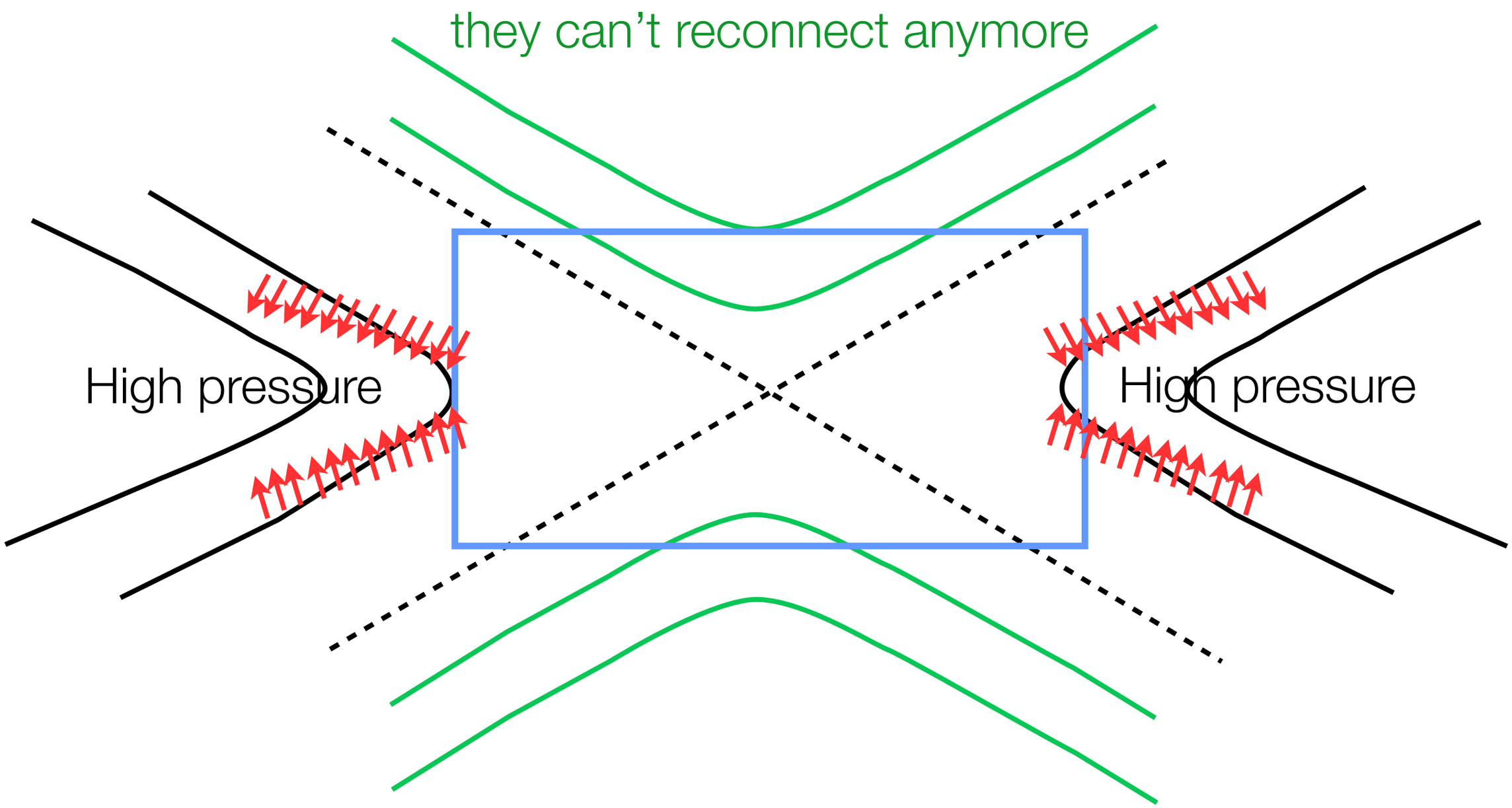

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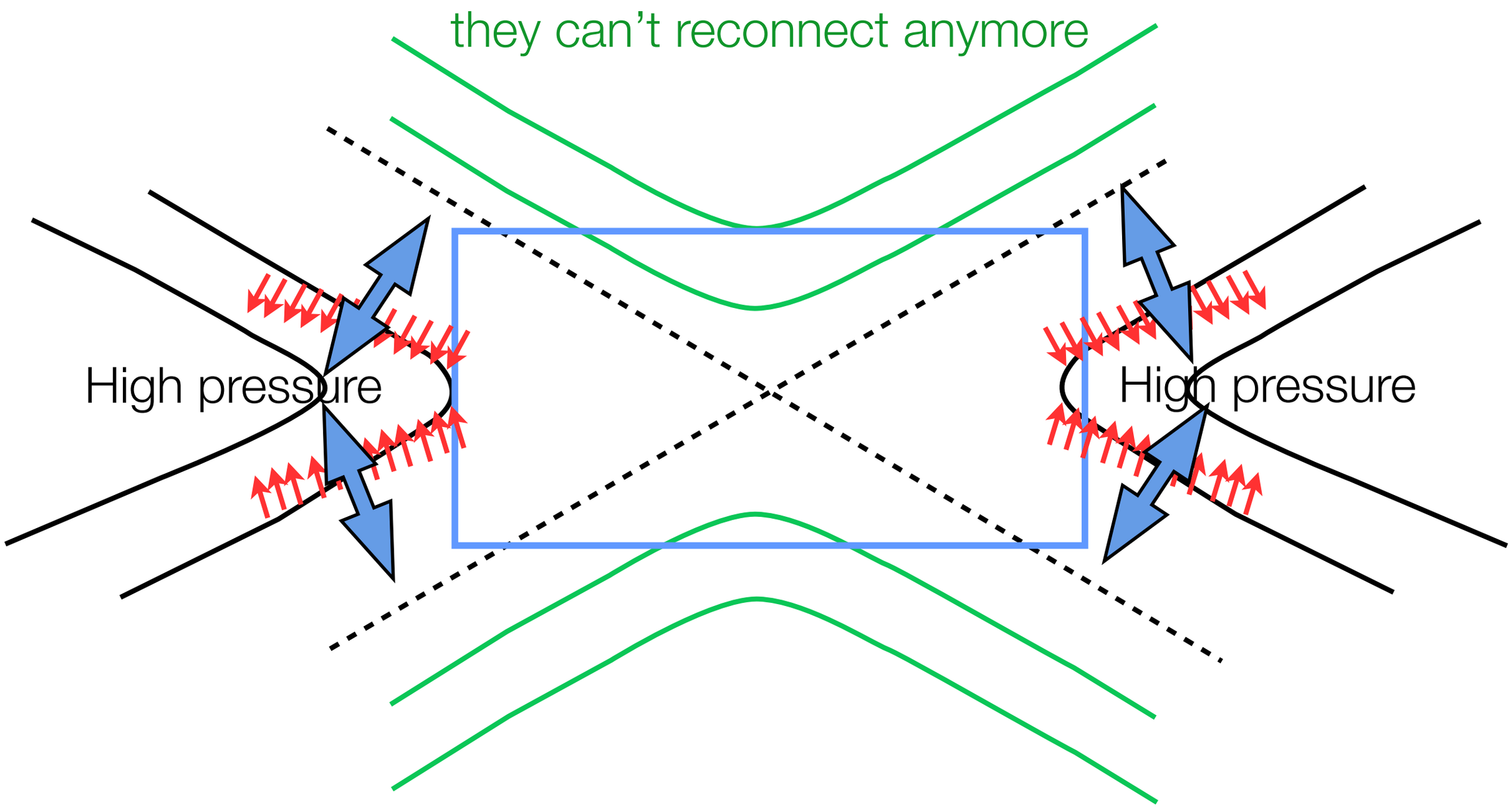

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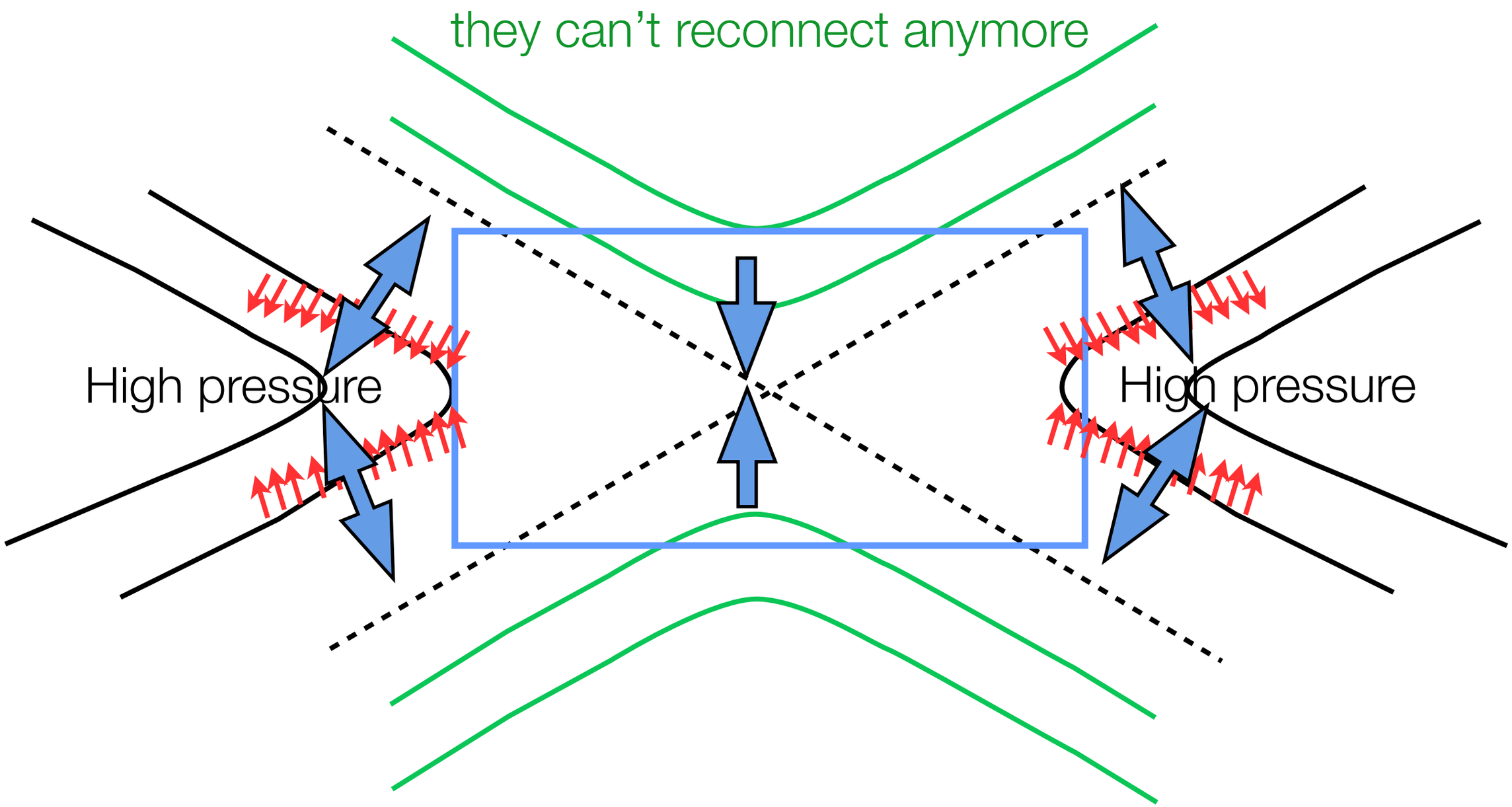

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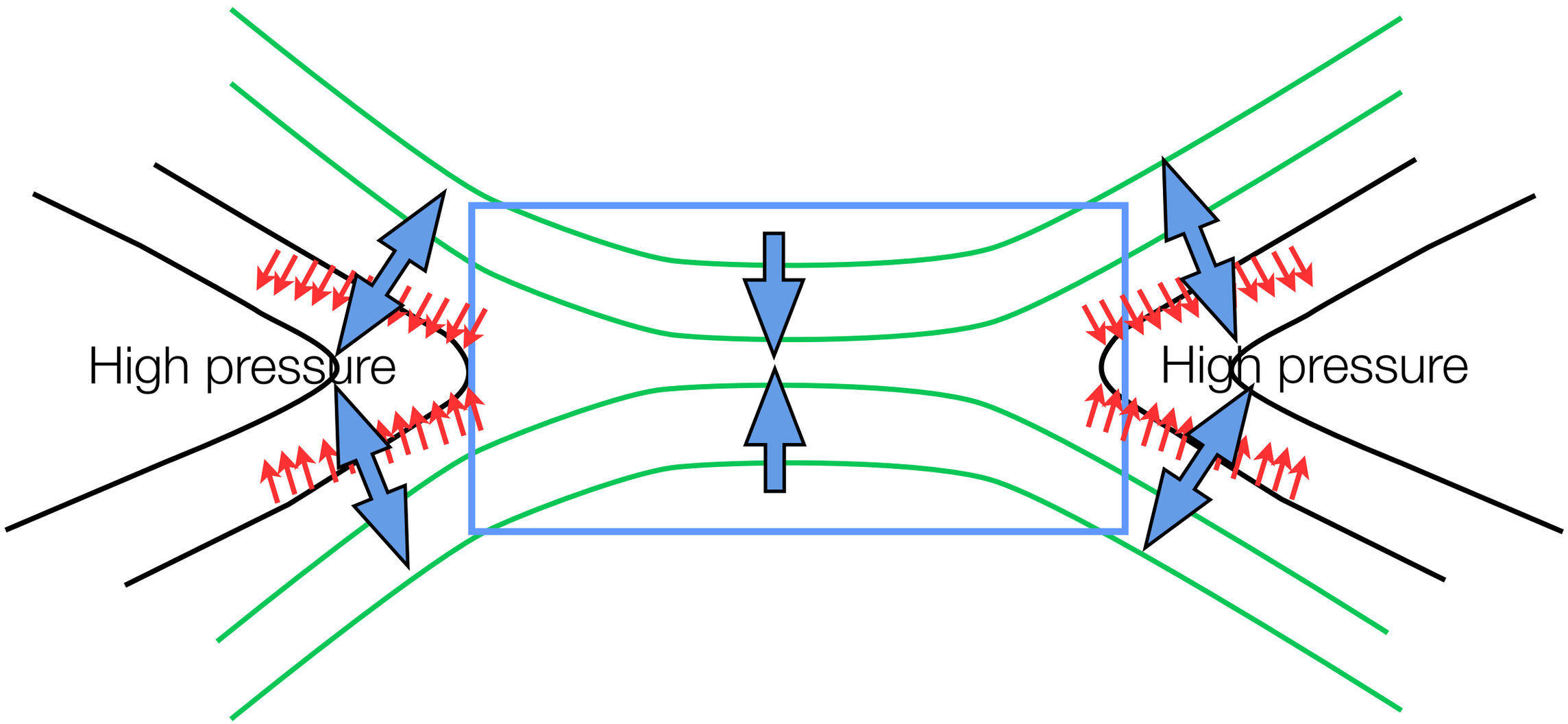
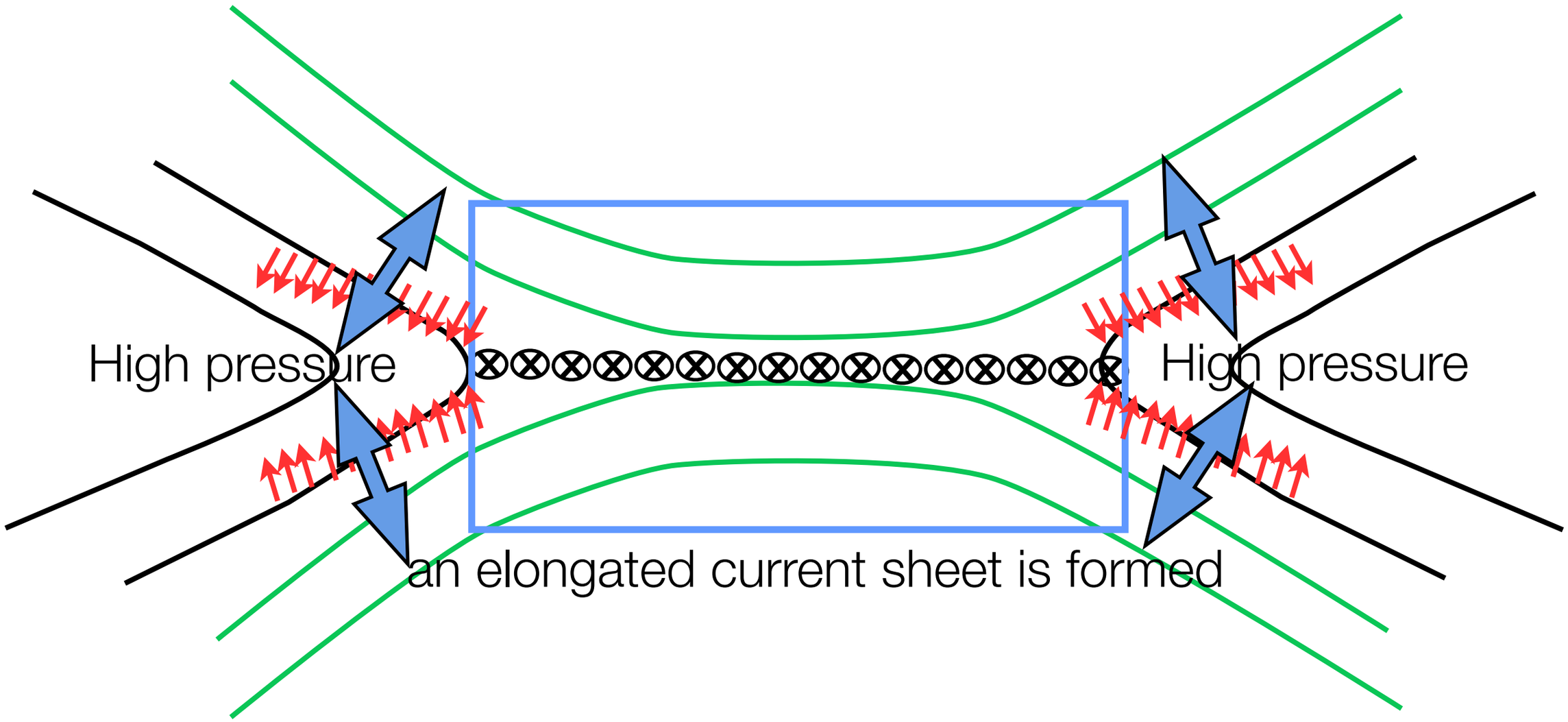
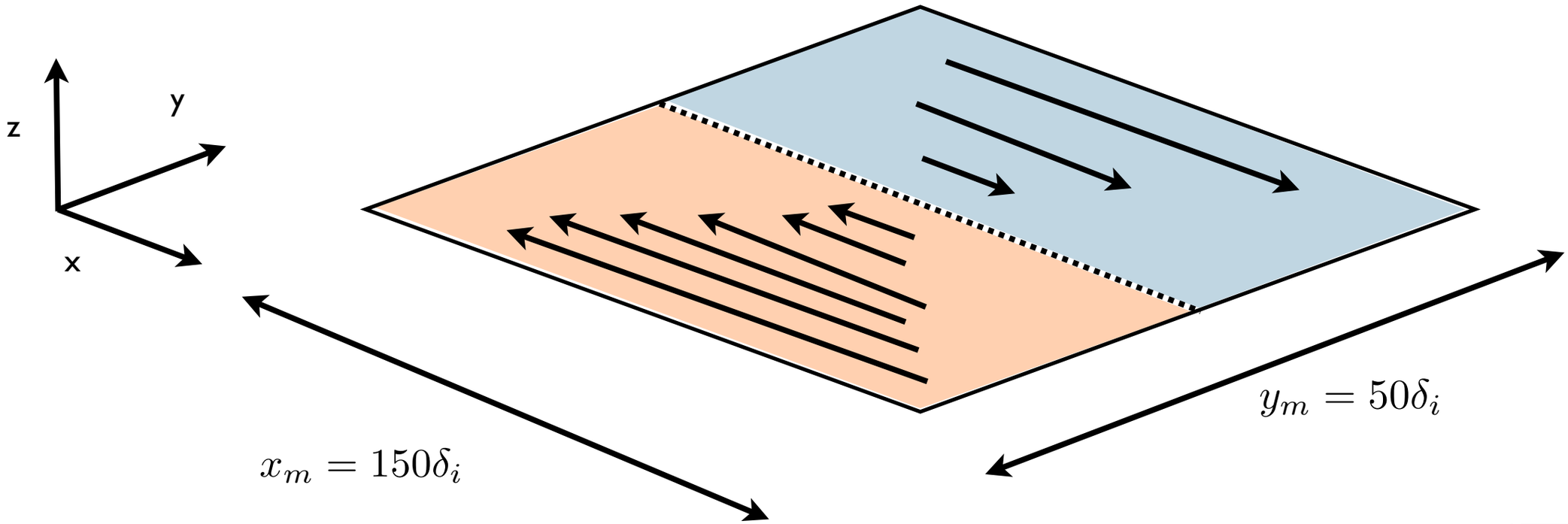


If the dissipation is too weak, the field lines can't reconnect before the hot downstream plasma has moved away



New simulation : increase the resistivity

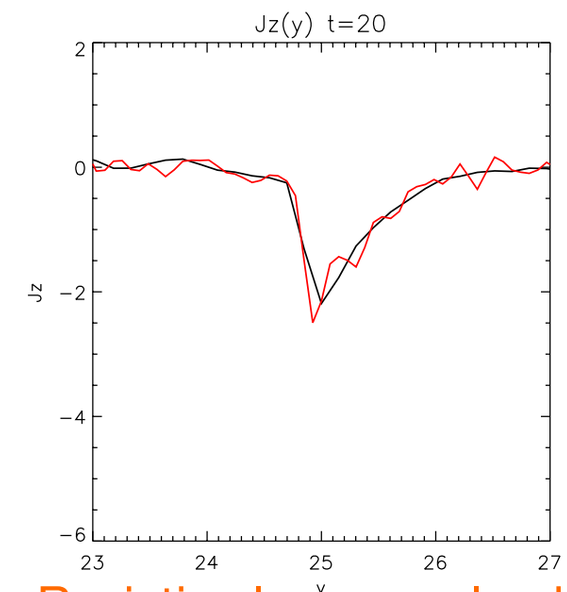


$$\mathbf{E} = -\mathbf{v_i} \times \mathbf{B} + \frac{\mathbf{j} \times \mathbf{B}}{nq} - \frac{\nabla P_e}{nq} + \eta \mathbf{j}$$

$$S = \frac{\mu_0 \delta_i V_A}{\eta} = \frac{1}{7} 10^3$$

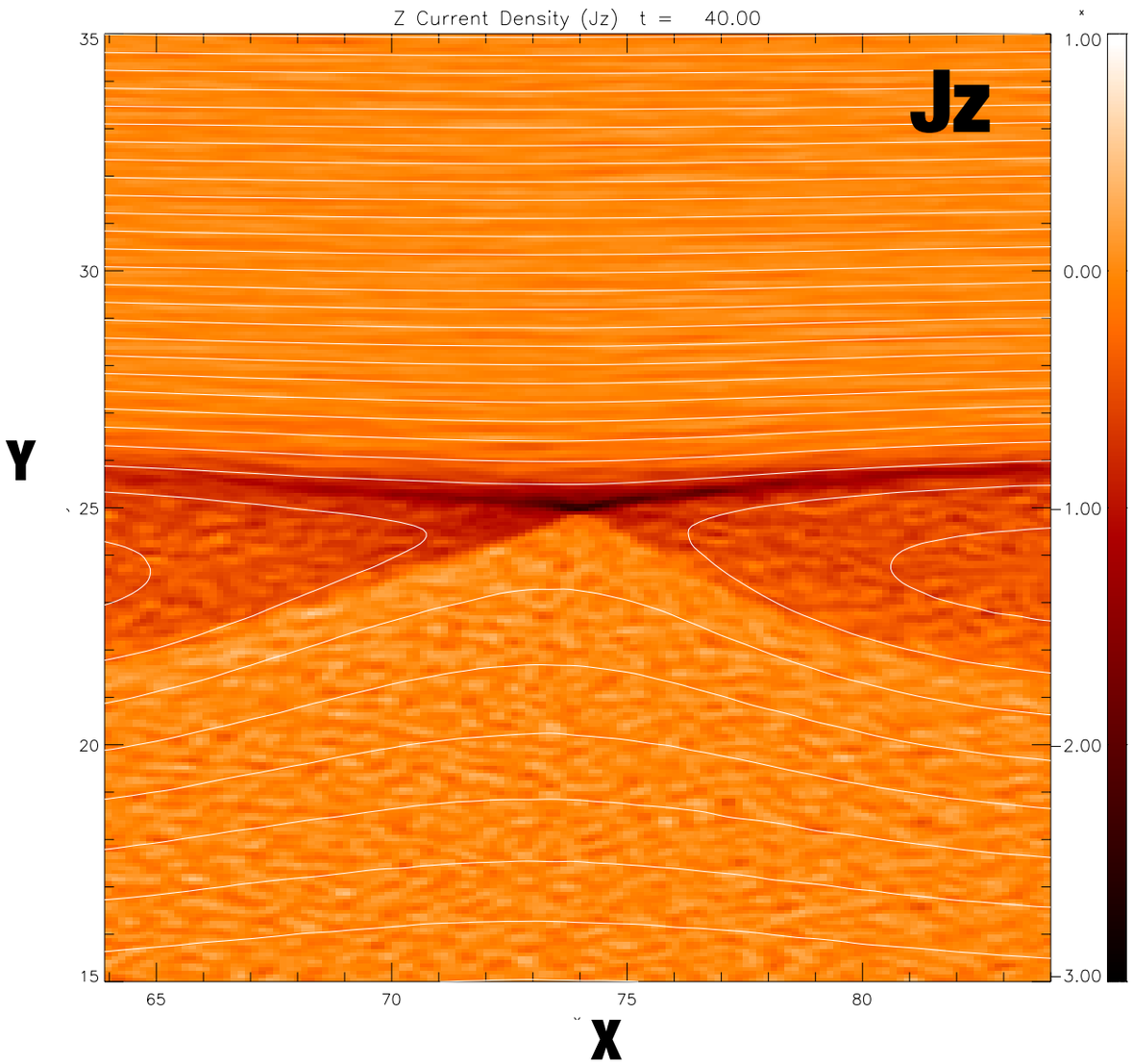
$$dy = 0.15\delta_i$$

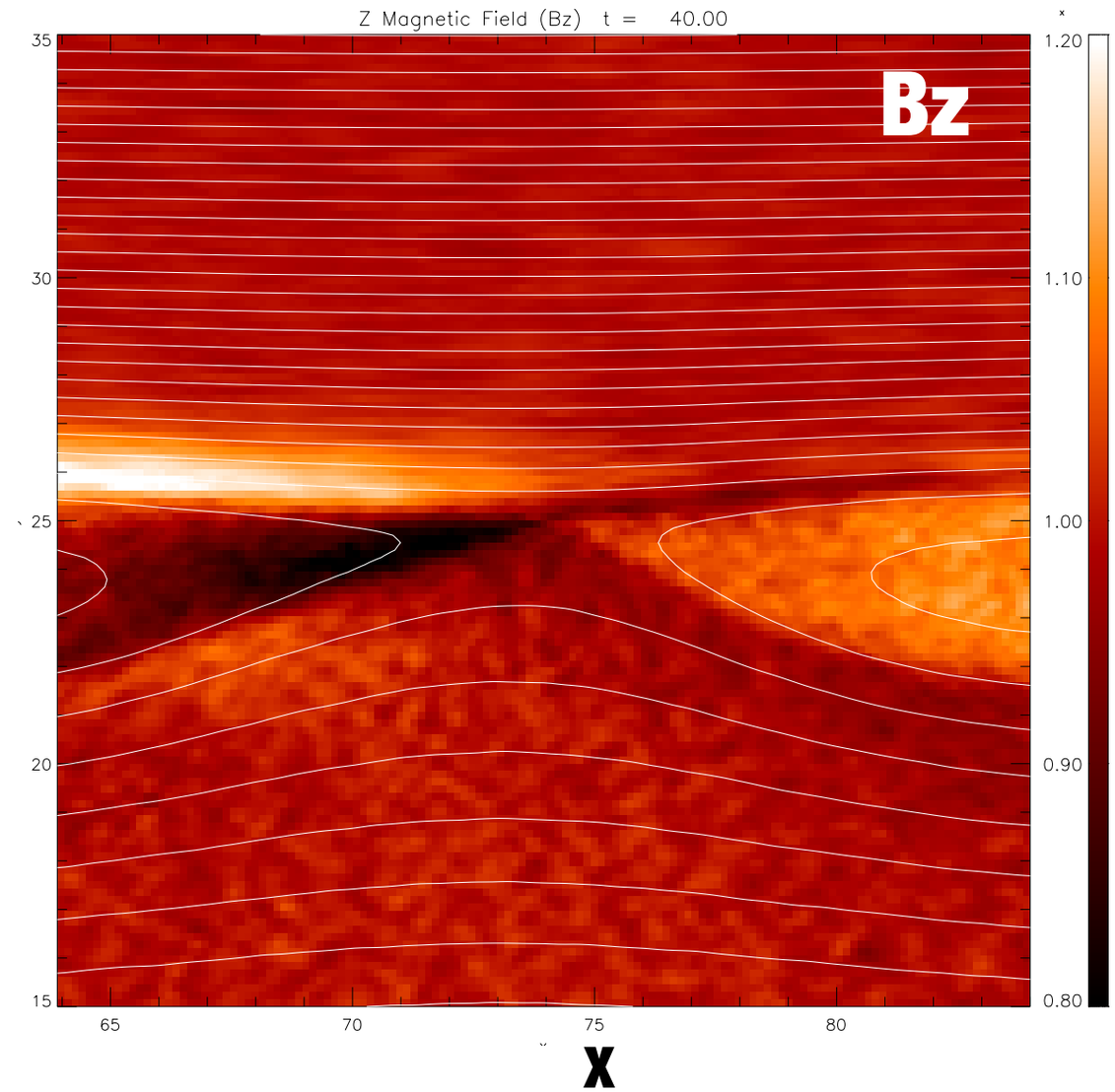
$$dy = 0.076\delta_i$$



Resistive layer resolved

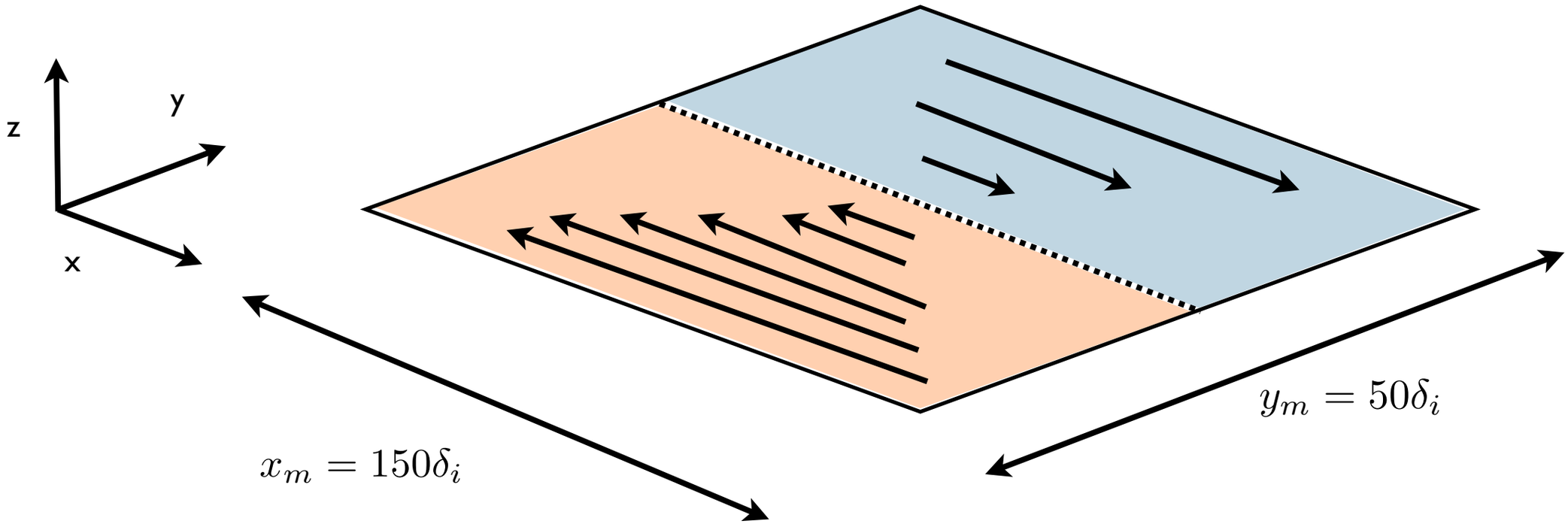
Result :





No more elongation of the electron current sheet
The process is steady and the exhaust open
The out-of-plane B indicates that Hall physics is occuring

New simulation : Change the dissipation mechanism

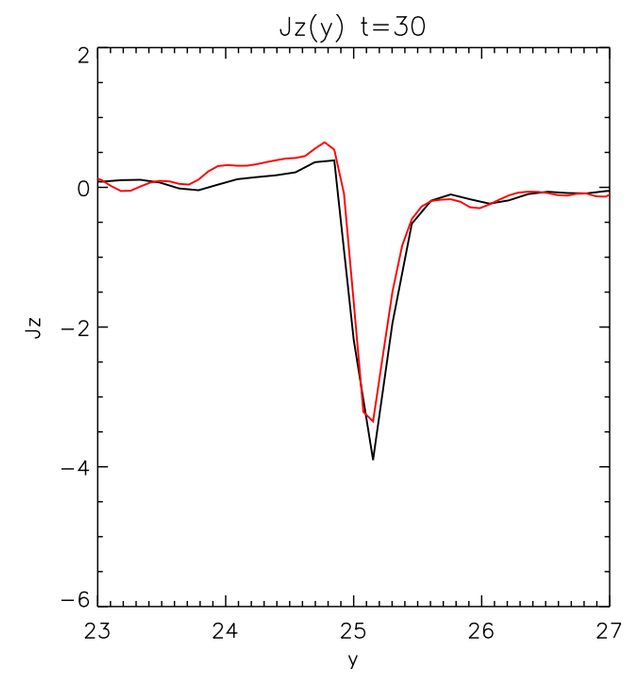


$$\mathbf{E} = -\mathbf{v_i} \times \mathbf{B} + \frac{\mathbf{j} \times \mathbf{B}}{nq} - \frac{\boldsymbol{\nabla} P_e}{nq} - \nu \boldsymbol{\nabla}^2 \mathbf{j}$$

$$E \approx \frac{1}{2en} \rho_L^2 \frac{\partial v_x}{\partial x} \nabla^2 (m n v_z)$$

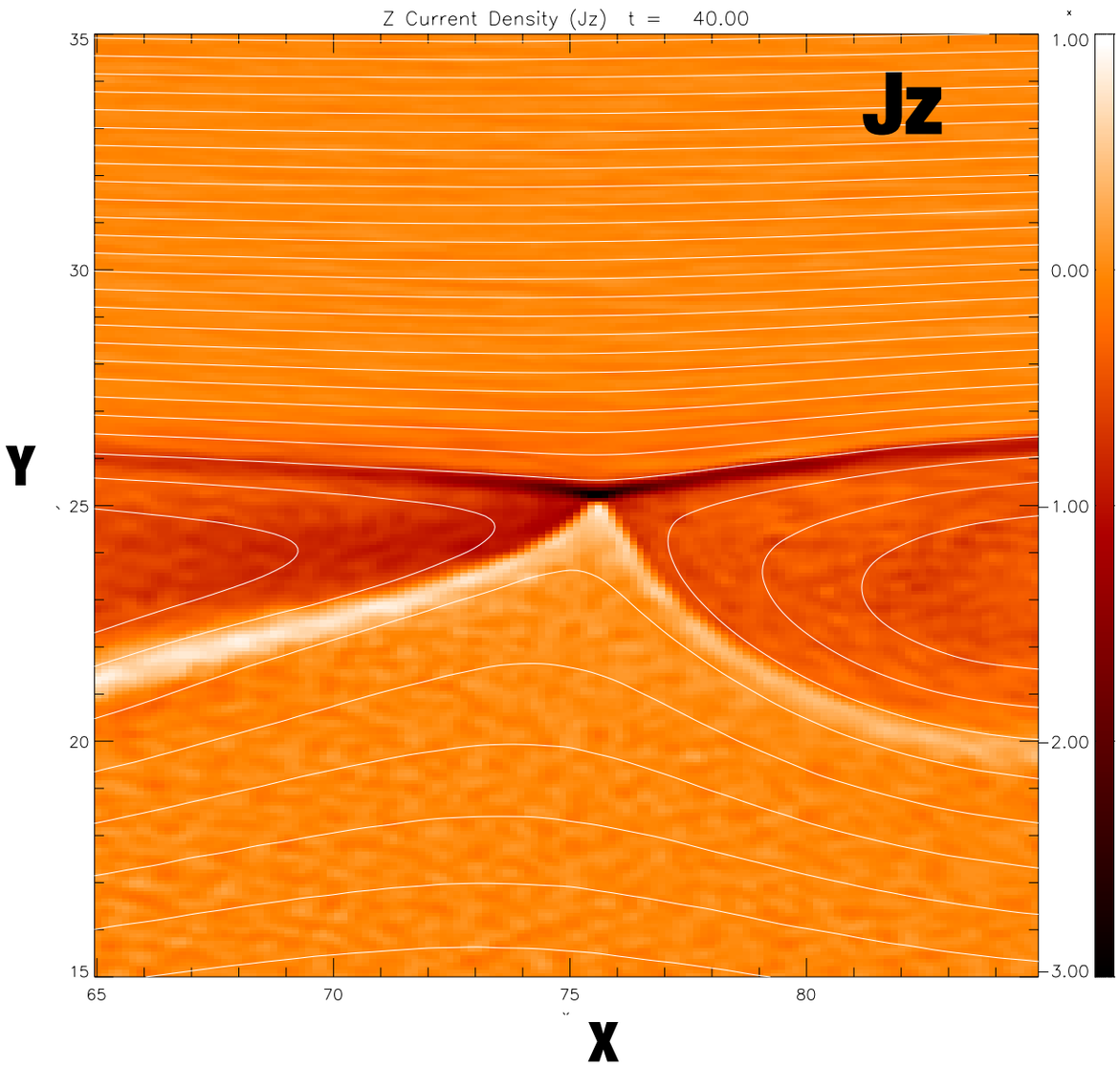
[Hesse 2011]

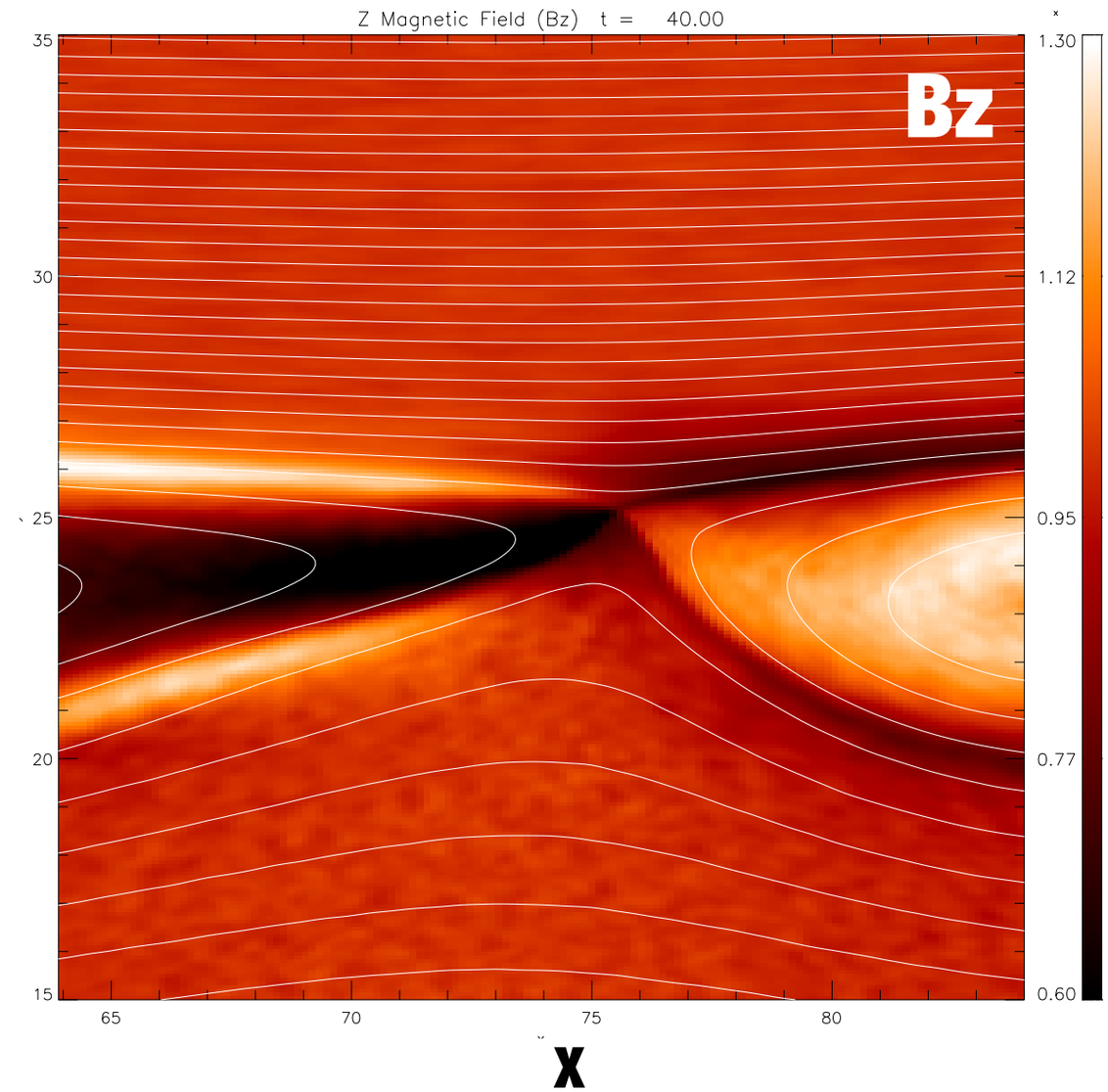
$$\nu = 2.5 \cdot 10^4$$
$$dy = 0.15\delta_i$$
$$dy = 0.076\delta_i$$



The layer is resolved

Result :





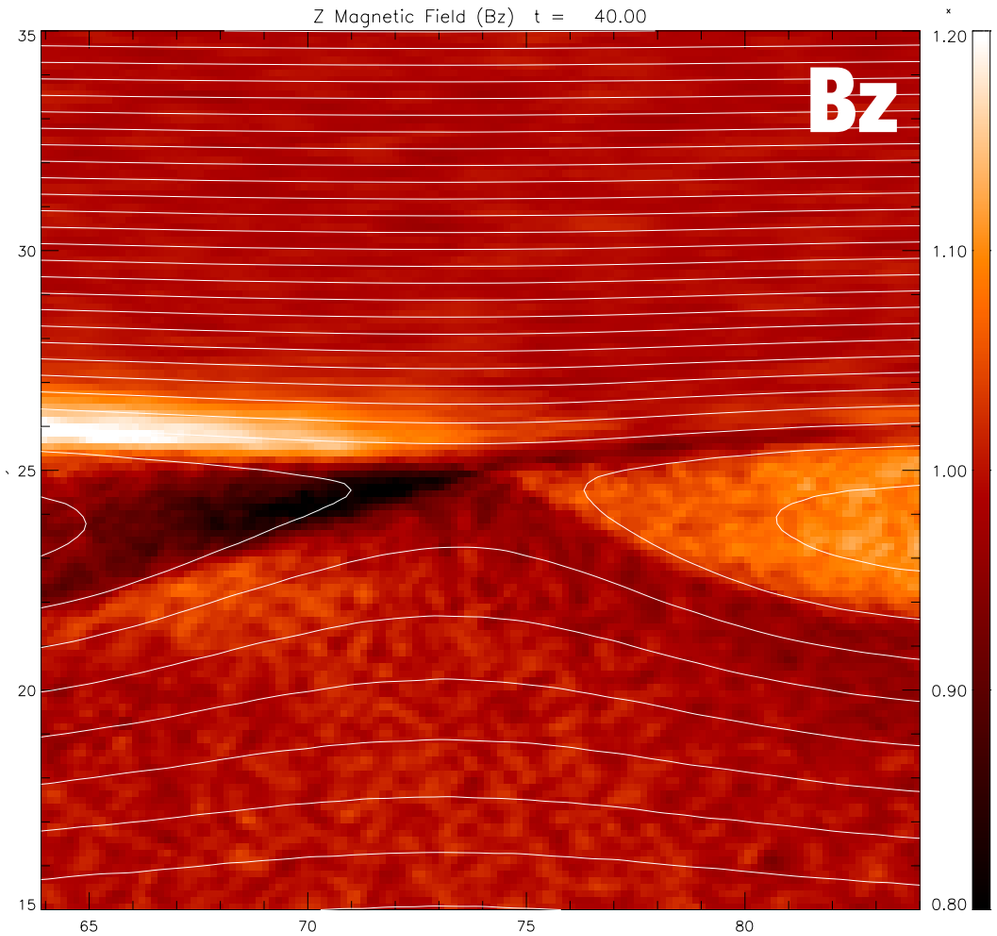
Still no elongation of the current sheet

More flux seems to have been reconnected

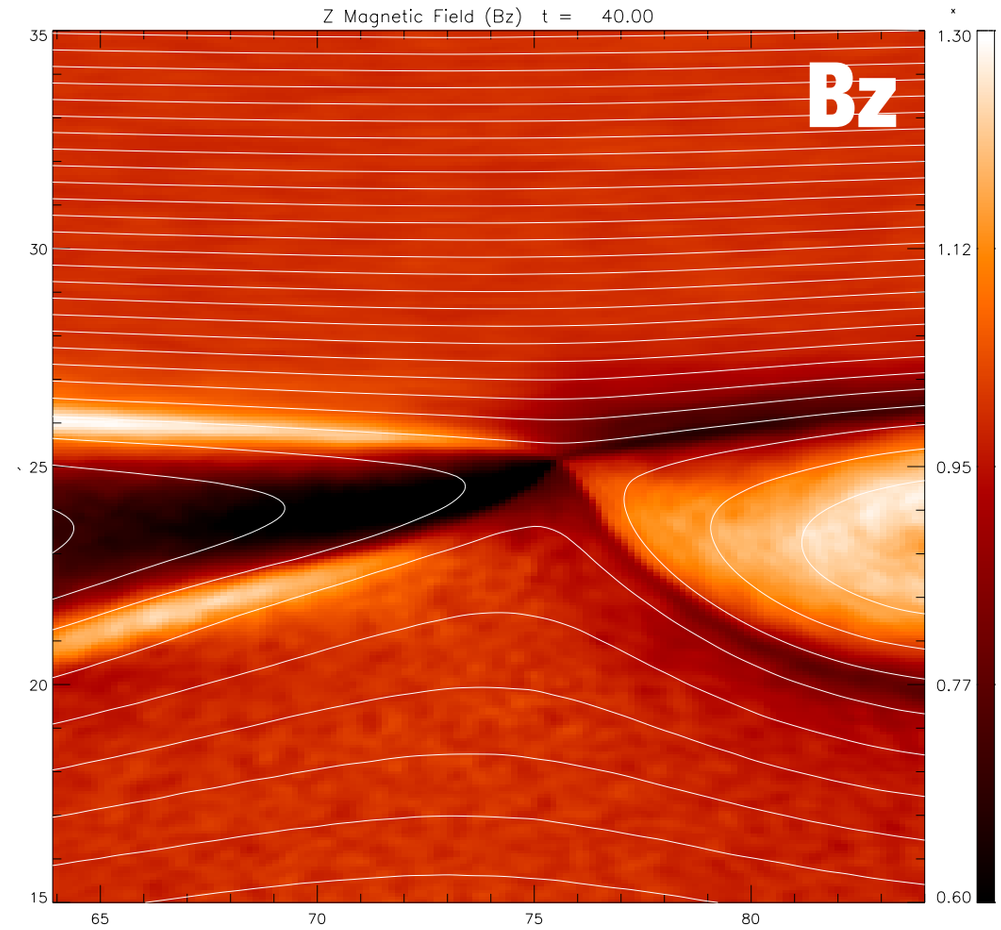
Stronger out-of-plane B

Comparison with full PIC

$\eta \mathbf{j}$



$\nu \nabla^2 \mathbf{j}$



Comparison with full PIC

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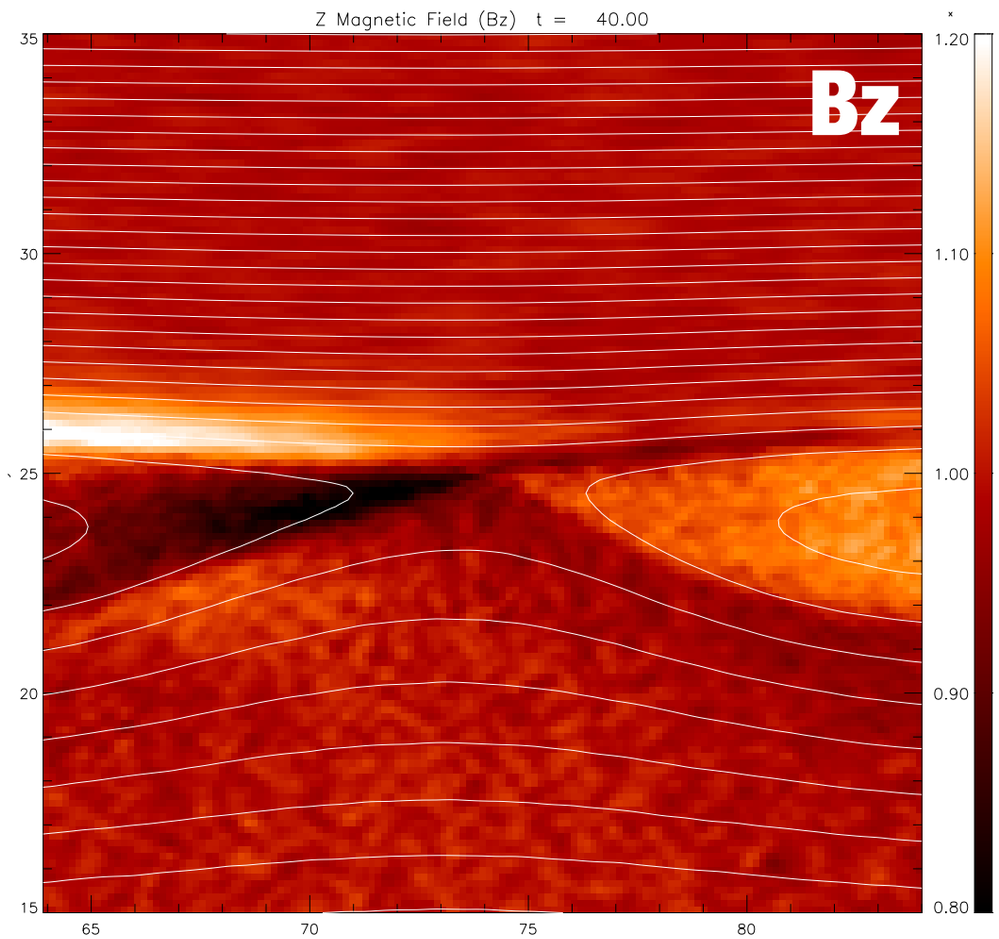
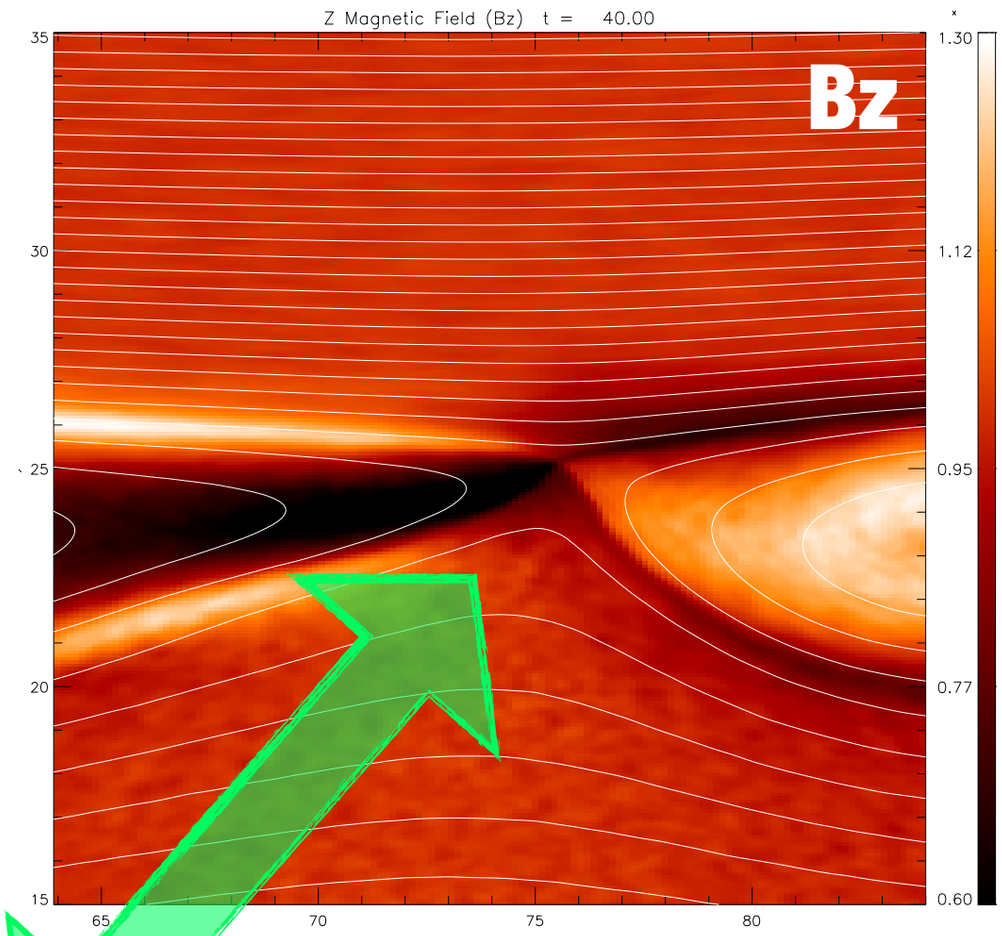
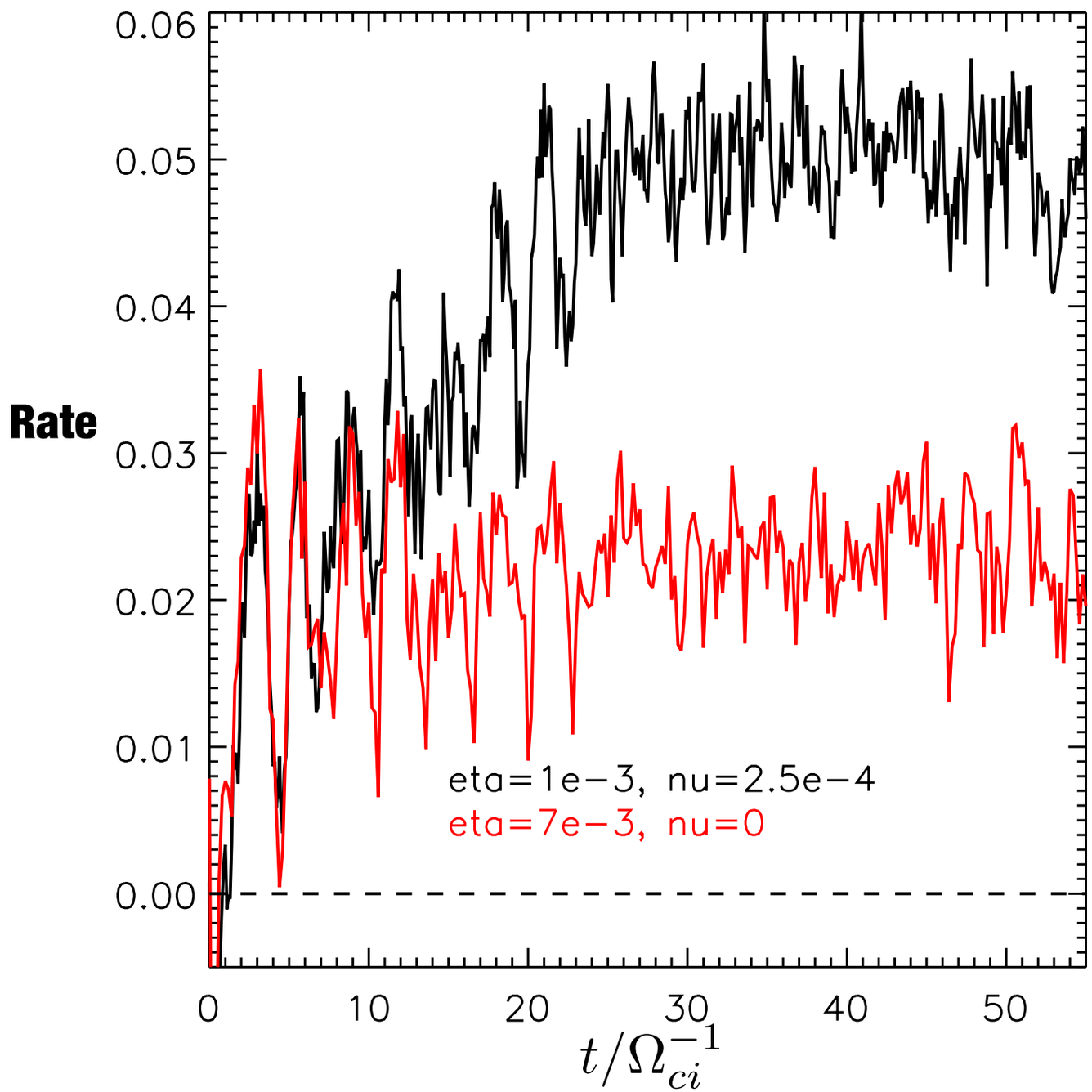


$\nu \nabla^2 \mathbf{j}$



Full PIC

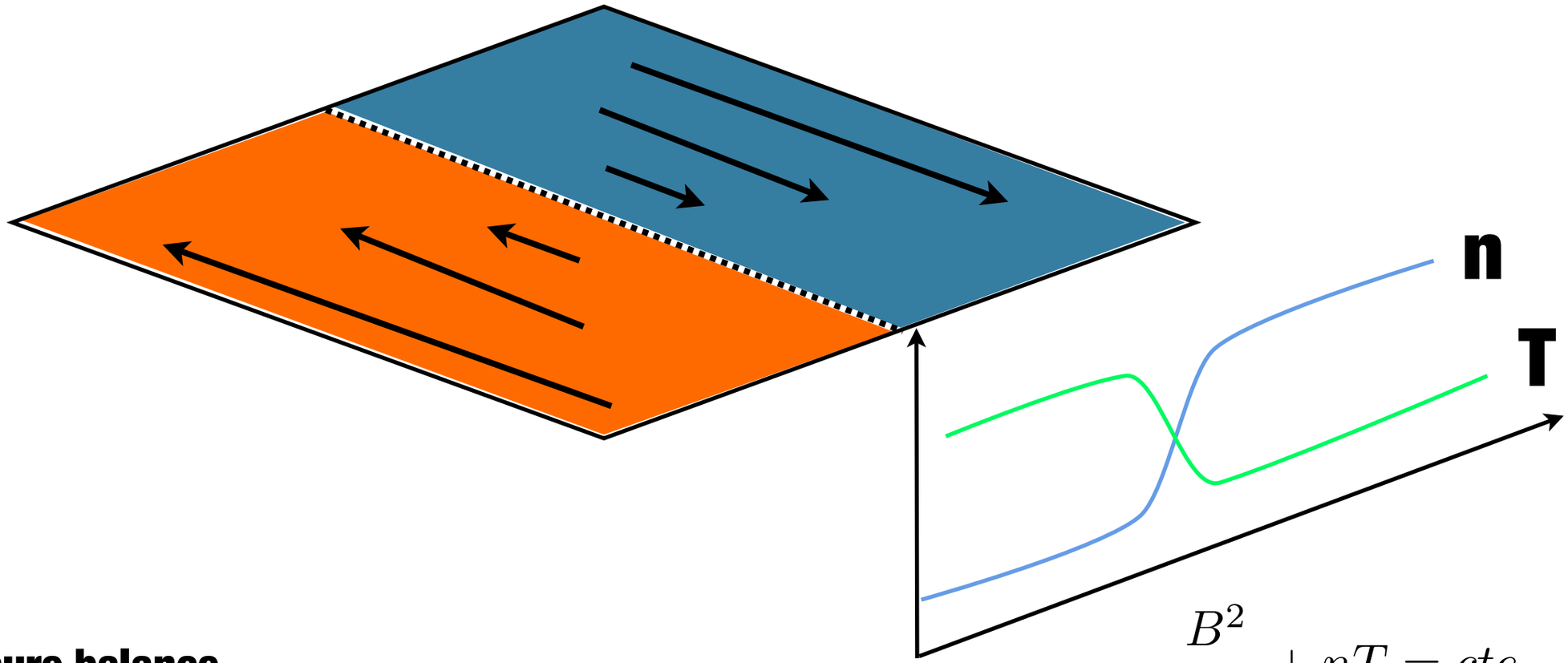
Reconnection rate for the resistive and hyperresistive runs



How does the rate change with ν and η ?

How asymmetric systems are initialized ?

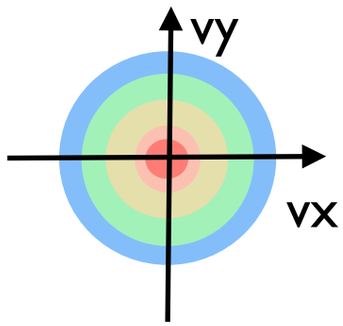
Initial condition model



$$\frac{B^2}{2\mu_0} + nT = cte$$

Fluid pressure balance

Maxwellian distribution



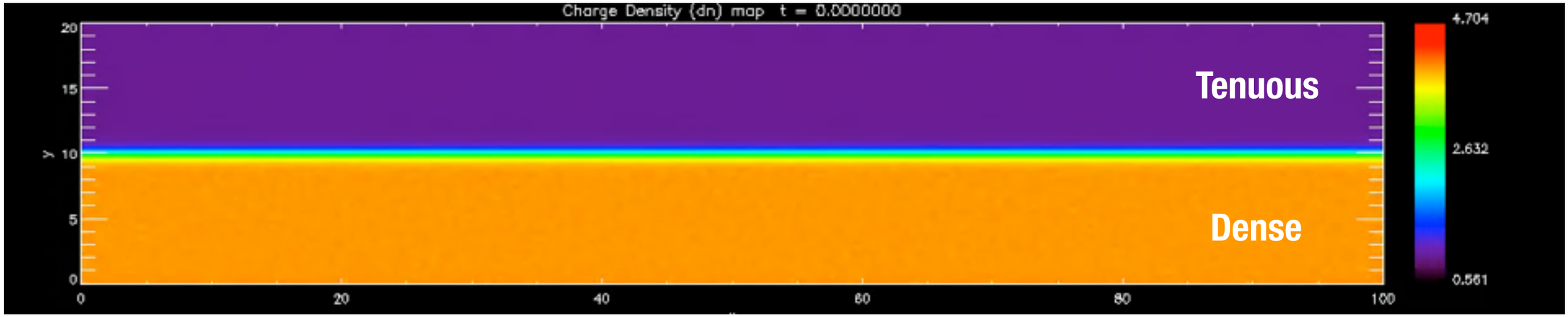
Initial condition model

Not a steady state

Overall pressure balance is preserved (the current sheet stays in the center of the domain)

Ion kinetic perturbation due to their gyration around B lines : affects neighboring distributions

Initial condition model



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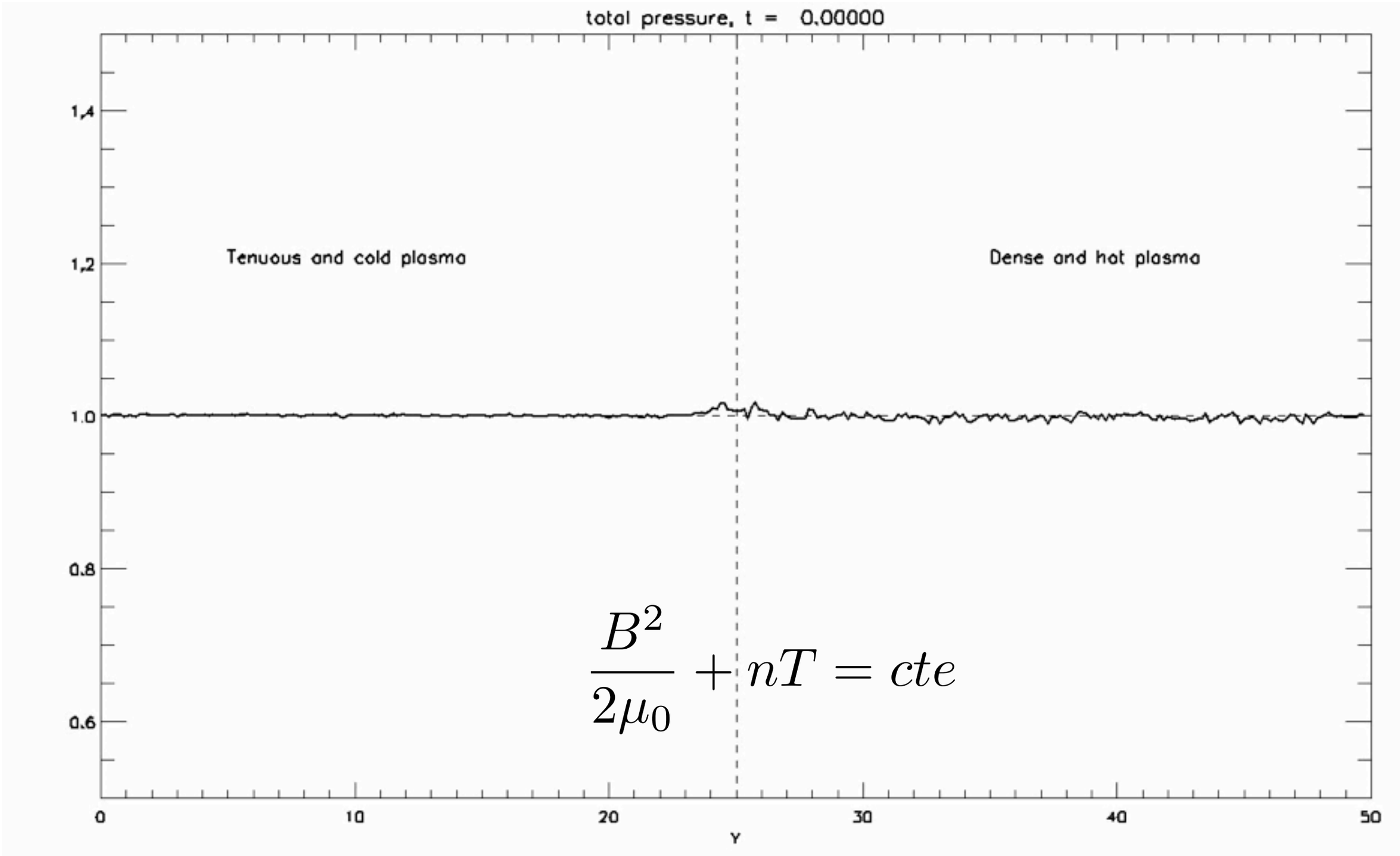
Unsteady initial condition

$$\frac{B^2}{2\mu_0} + nT = cte$$

Unsteady initial condition



$$\frac{B^2}{2\mu_0} + nT = cte$$

Kinetic equilibrium for asymmetric configurations

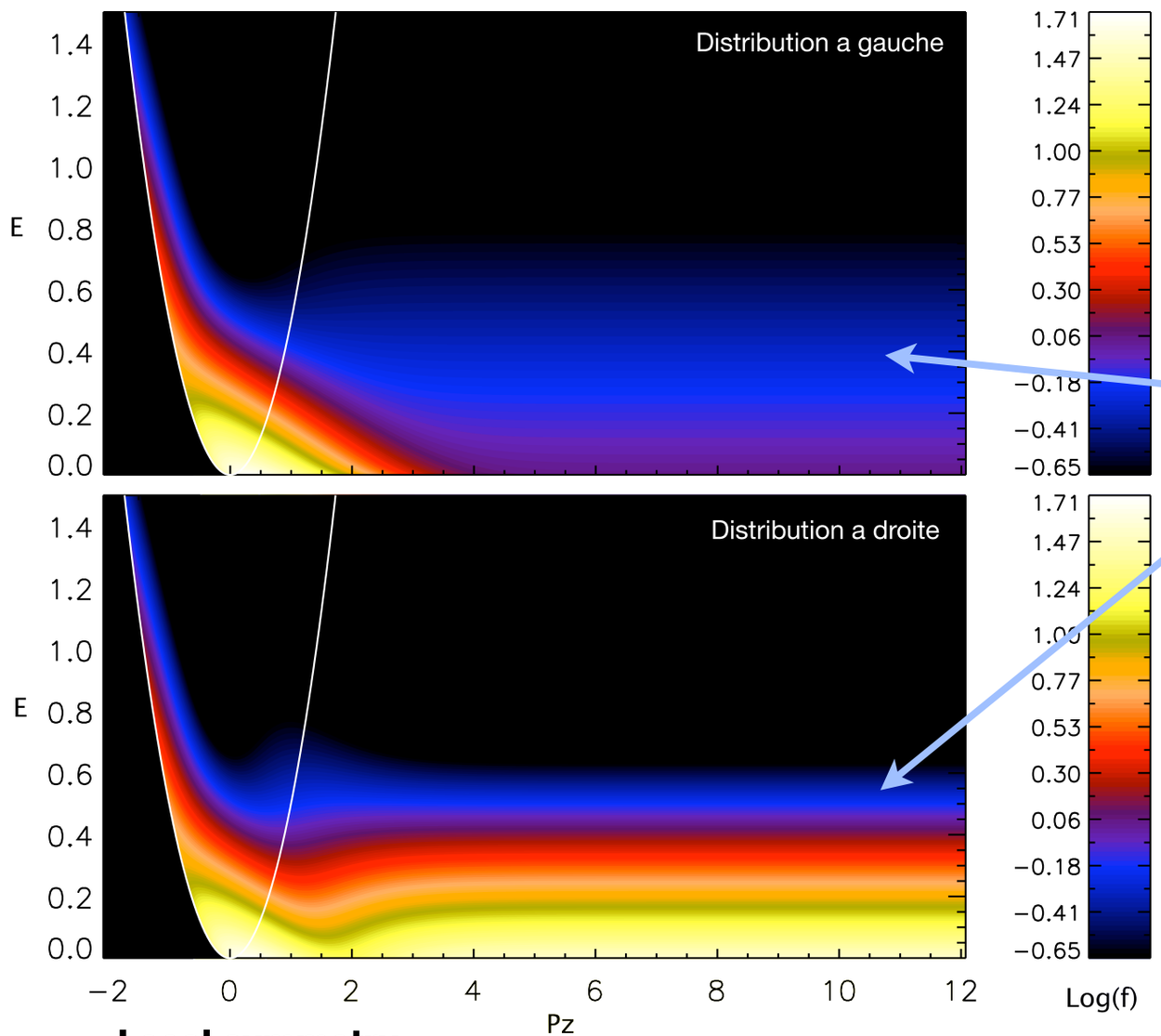
Choose B profile, asymptotic n1, n2, T1, T2 [Belmont et al PoP 2012, Aunai et al. 2012 almost submitted]

For simplicity here : assume E=0, Te=0 (all the current carried by ions)

$$B_x(y) = tanh(y)$$

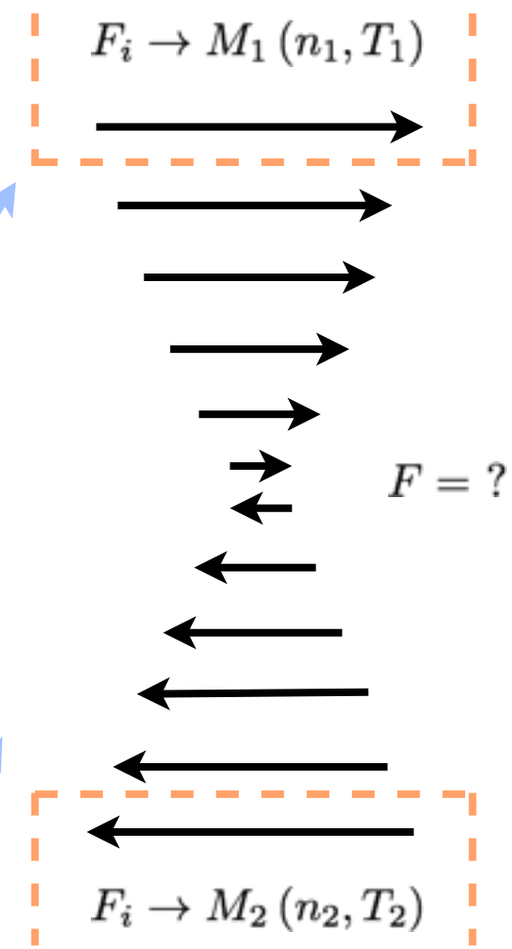
Shared central population

One different distribution on each side !

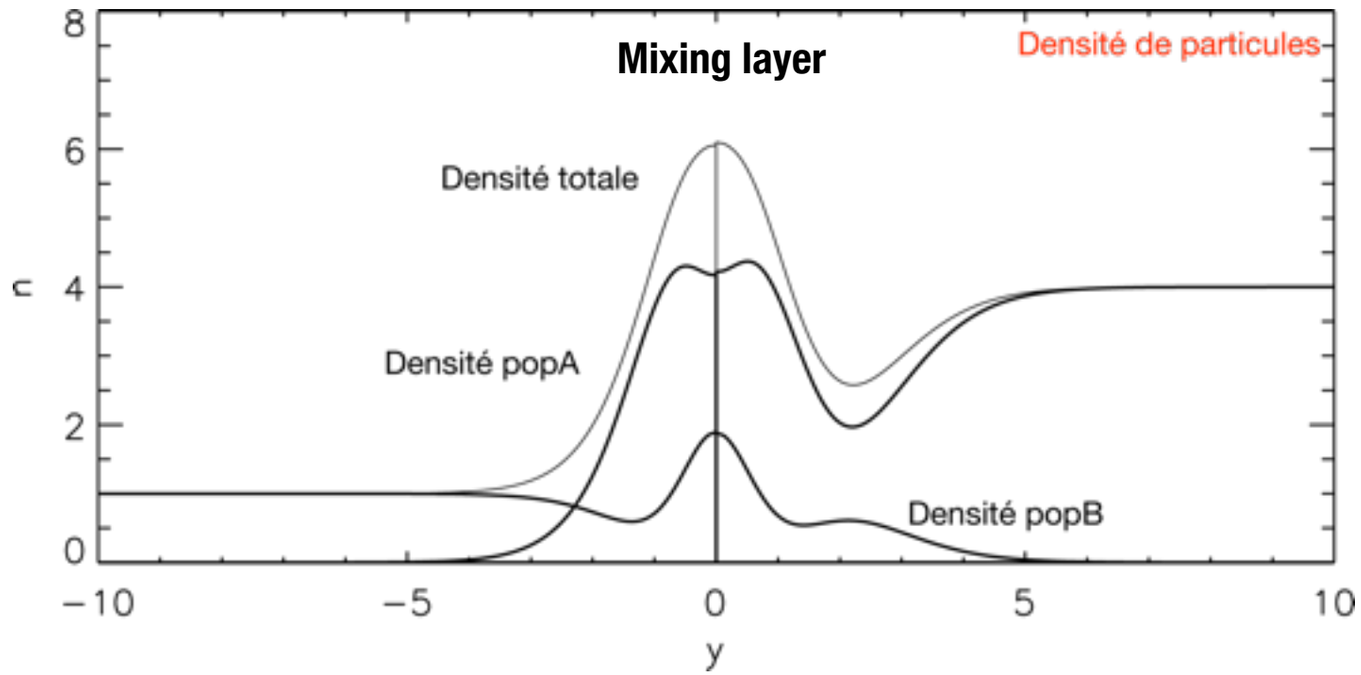


Local symmetry inevitable

Maxwellian boundaries

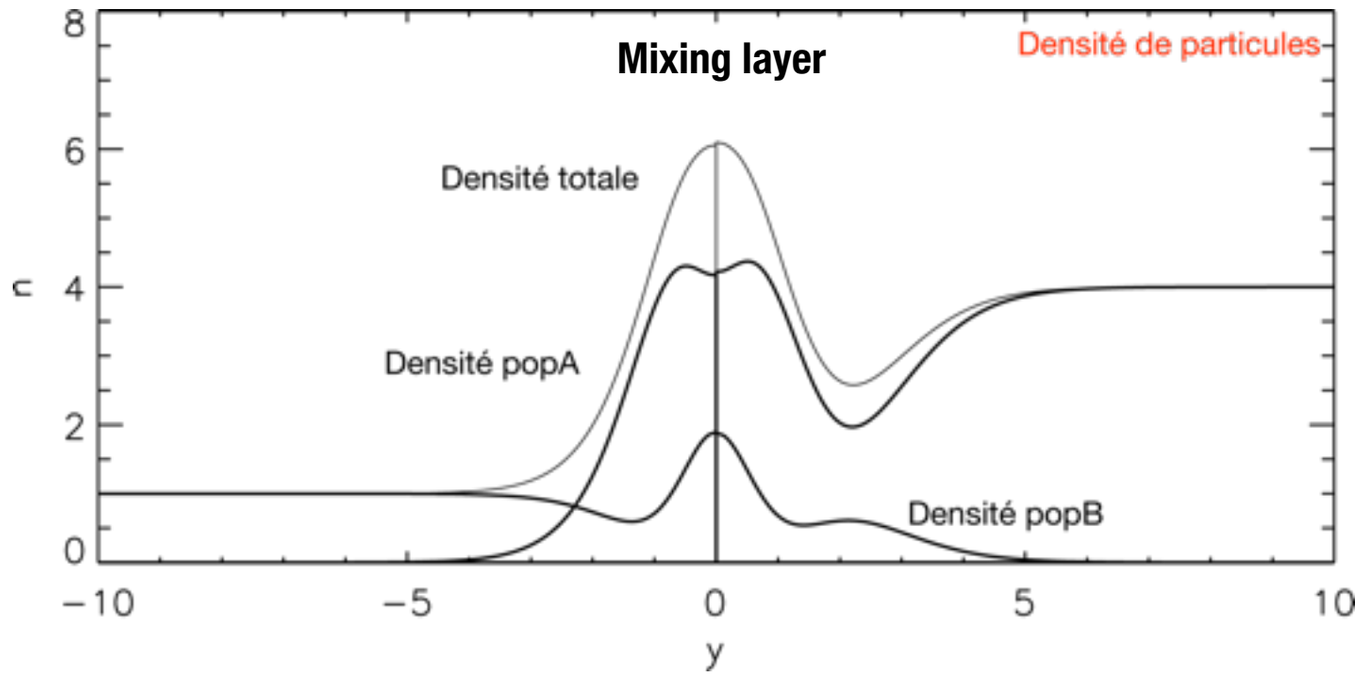


A solution :

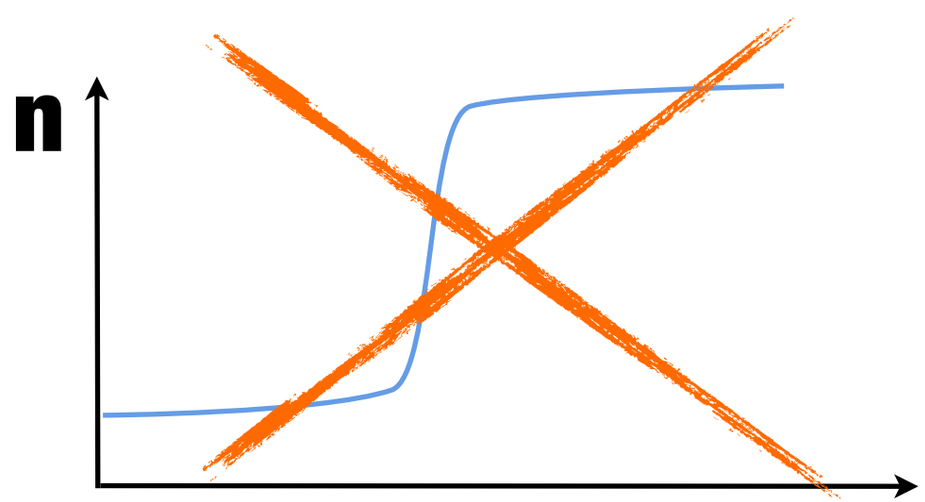


Moments are not simply monotonic

A solution :



Moments are not simply monotonic

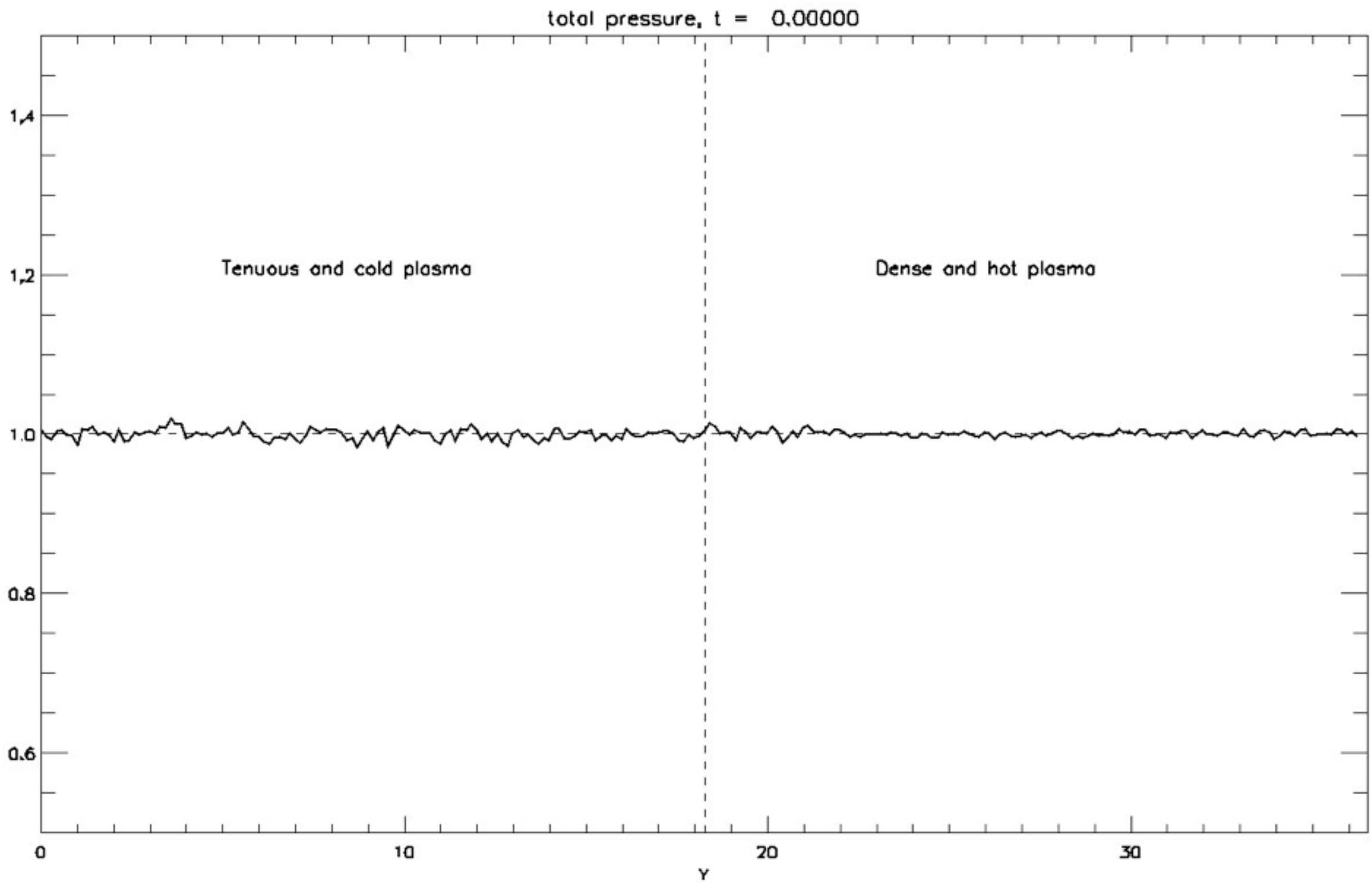


Initialization with the moments of the kinetic solution

But still with local Maxwellian distributions with n, V, full P

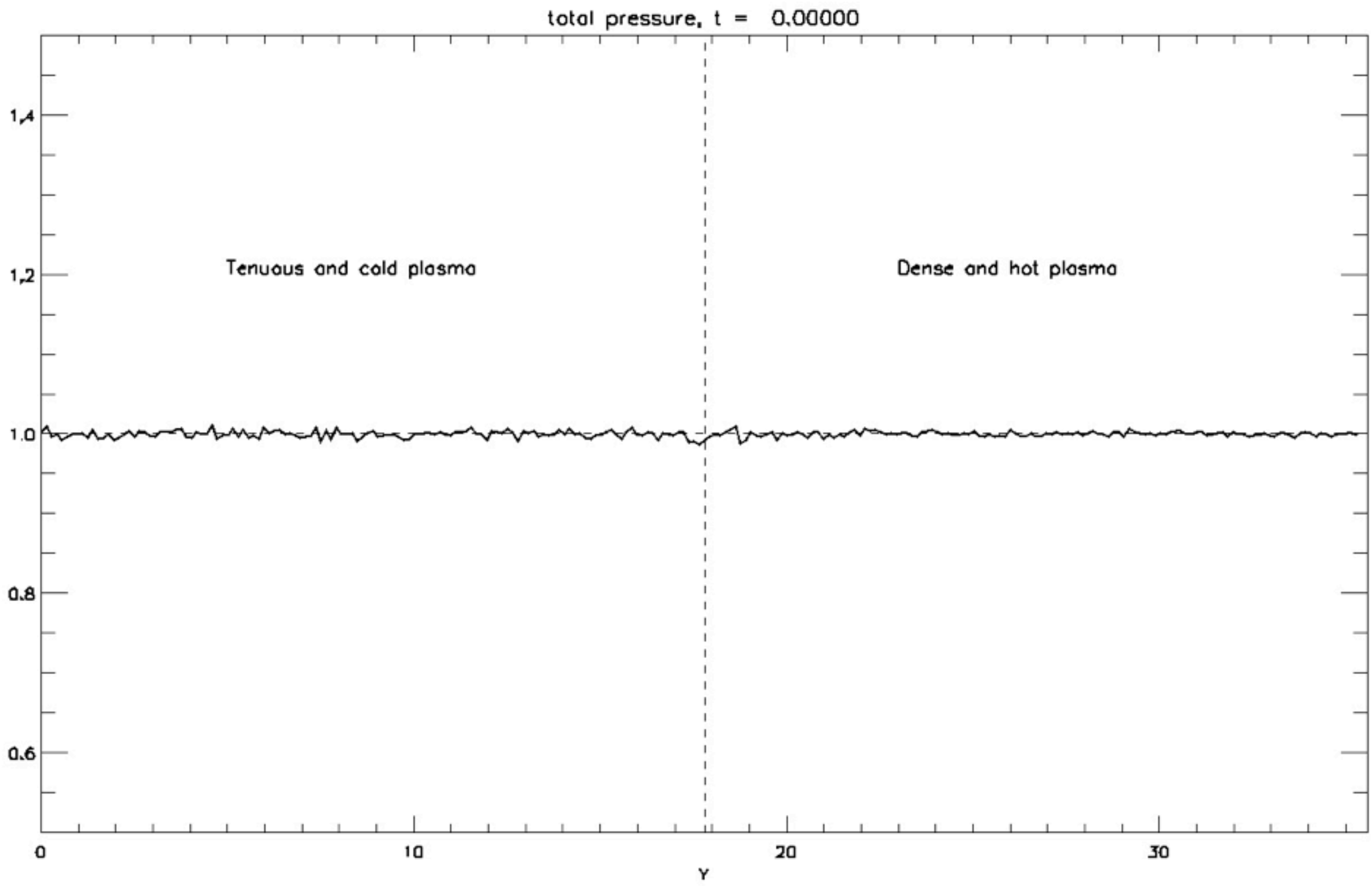
Initialization with the moments of the kinetic solution

But still with local Maxwellian distributions with n, V, full P



Initialization with the full distribution

Initialization with the full distribution



Summary

Hybrid simulations of symmetric reconnection are fast without physical dissipation

The dissipation term seems to play a more important role in asymmetric systems

Very few theories of asymmetric kinetic equilibria: never used as an initial condition for kinetic simulations

Most (all?) previous theories give uncontrollable B profiles

New theoretical method to build ion scale steady states in asymmetric configuration

Theory validated by kinetic simulation : simulations of current sheets in asymmetric config. can be initialized with a true steady state

Next

- How does the rate depend on the resistivity ?
- On the electron viscosity ?
- How do hybrid models compare to full PIC ?
- What is the fluid expression of the electron kinetic dissipation in asymmetric systems ?

Generalize the kinetic equilibrium theory to B rotation, normal E, finite Te.

Test its behavior within a fully kinetic system

Does phenomena like M. reconnection depend on the initial state?