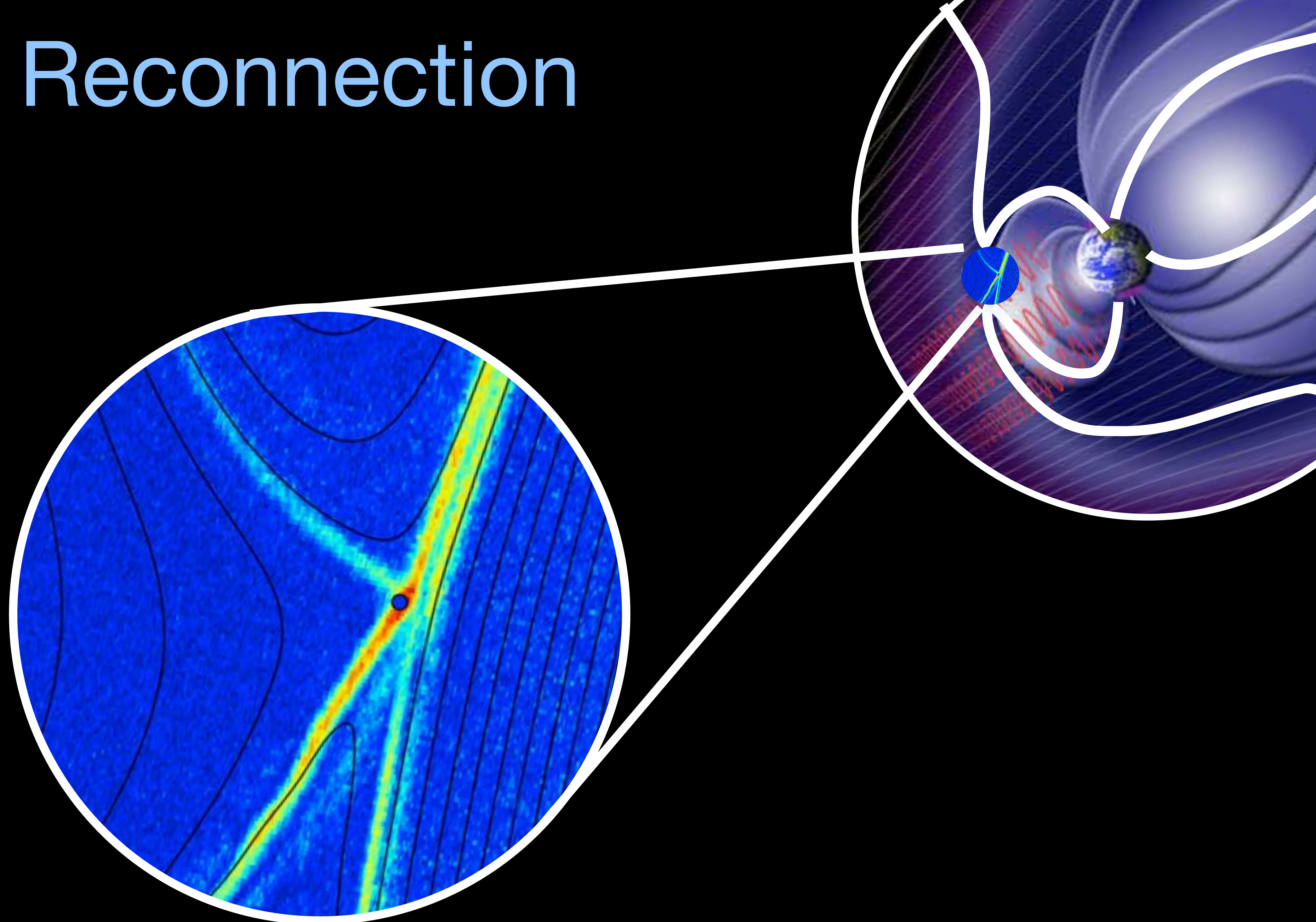
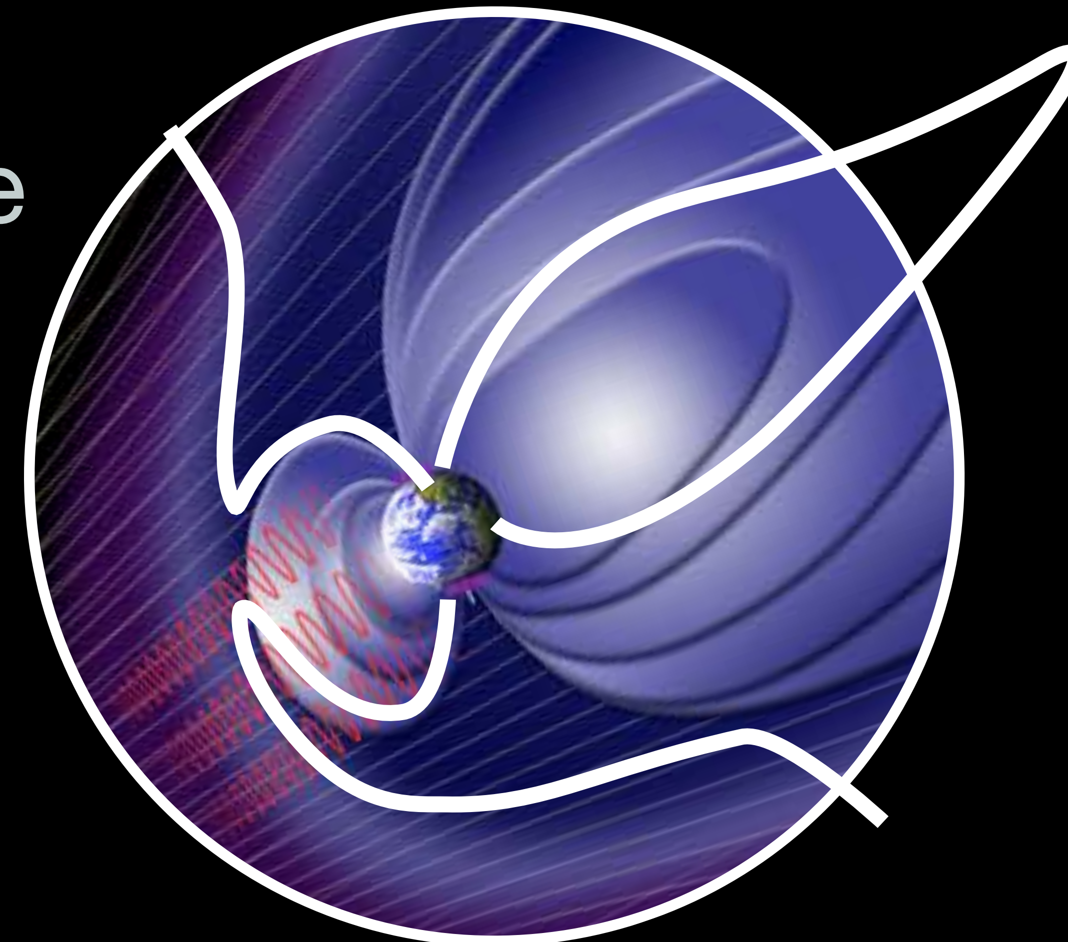
Magnetic Reconnection



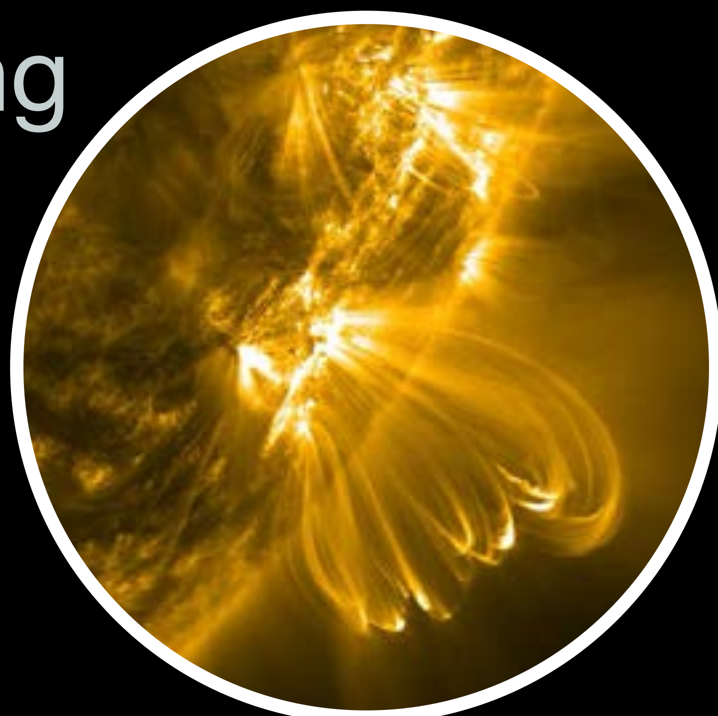
Nicolas Aunai
CNRS - LPP

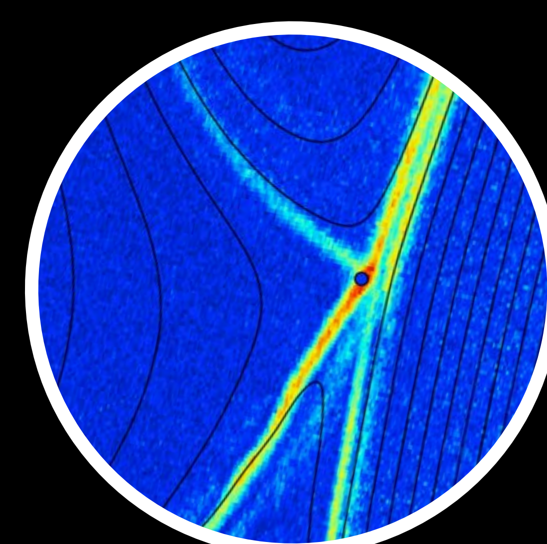
ICTP - College on Plasma Physics - Nov. 2016

MultiScale



Acceleration
Heating





Micro-
physics

Chap. 1 - A bit of history…

When did all this start?

Sunspots, solar eruptions

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

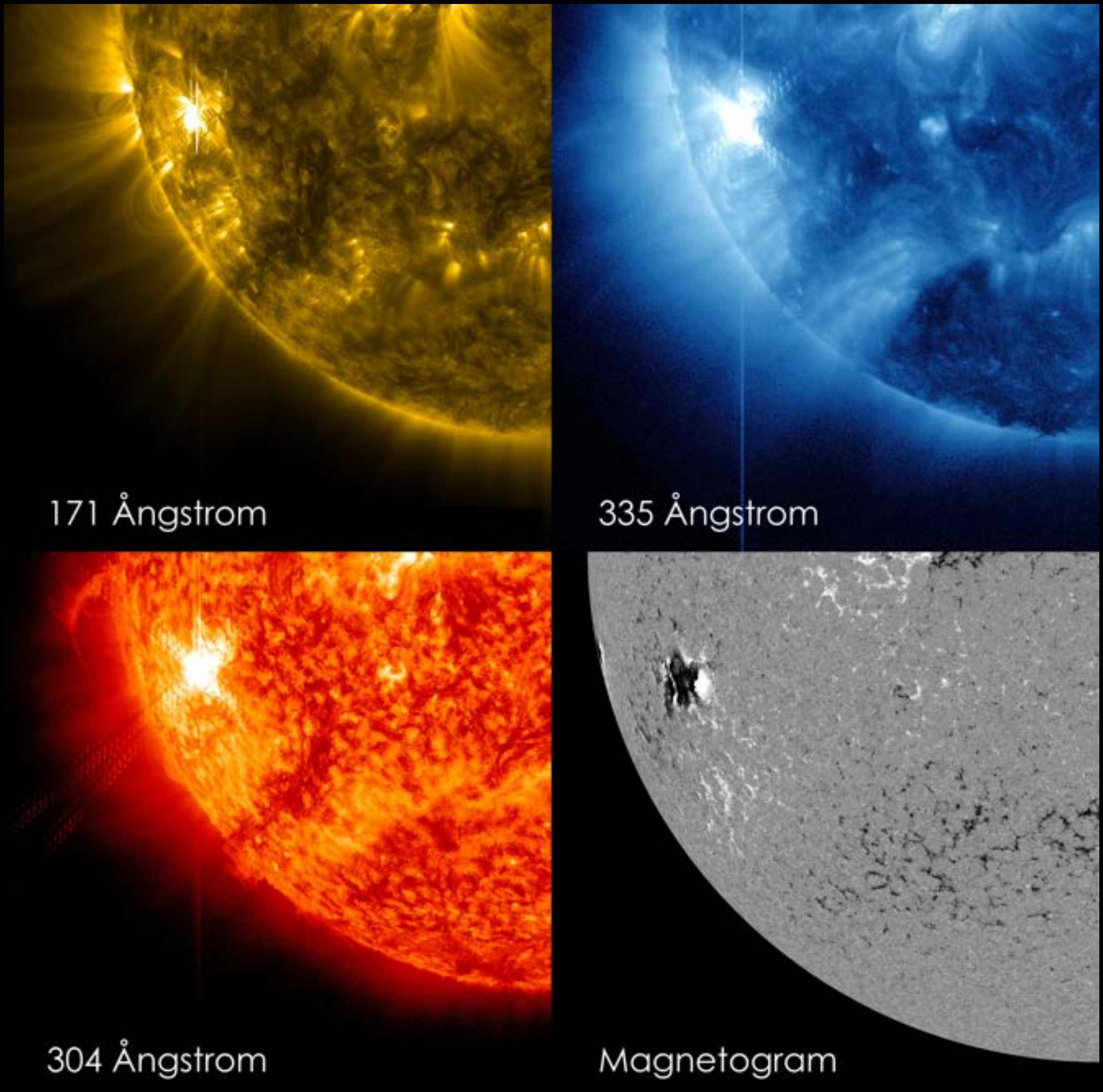
VOLUME 89 JUNE 1939 NUMBER 5

THE RELATIONS BETWEEN ERUPTIONS AND SUNSPOTS

R. G. GIOVANELLI

In this paper a preliminary examination is made of the statistical relationships between sunspots and the solar eruptions that are associated with them. The analysis deals with the probability of an eruption in relation to the size, type, and development of the associated spot group.

« Active regions »



MAGNETIC AND ELECTRIC PHENOMENA IN THE SUN'S ATMOSPHERE ASSOCIATED WITH SUNSPOTS

R. G. Giovanelli

(Received 1946 December 9; received in final form 1947 December 29)

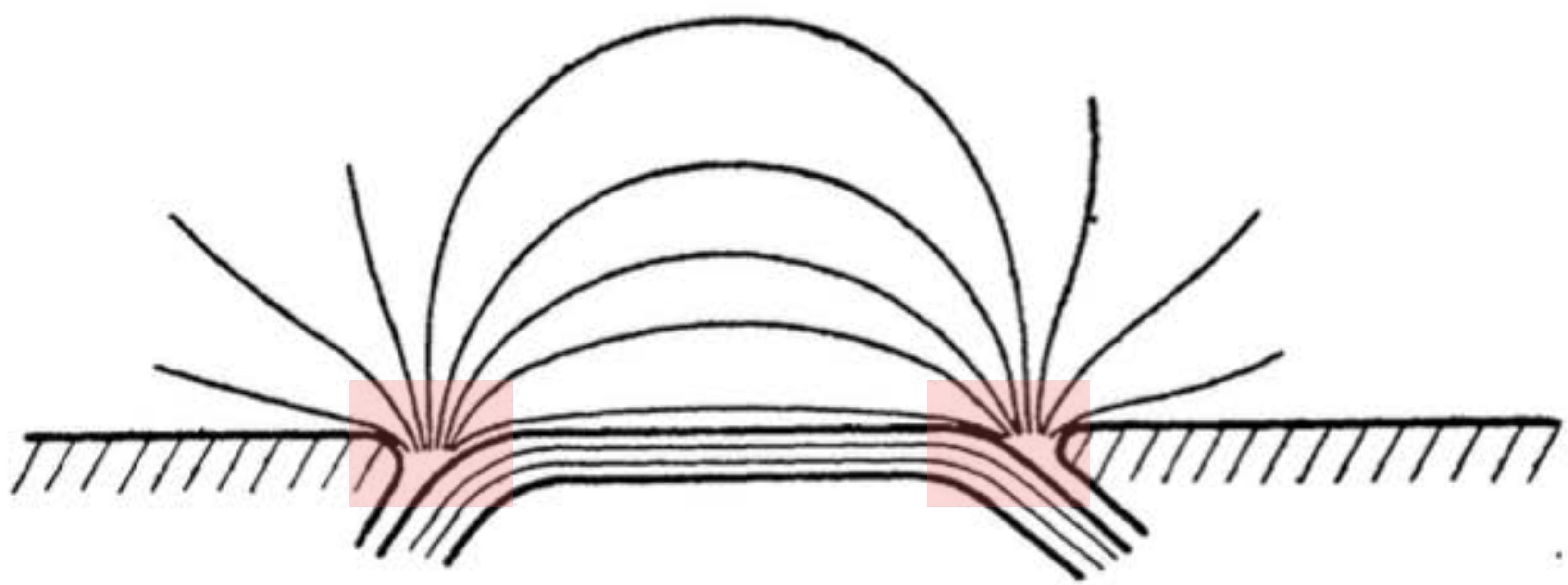
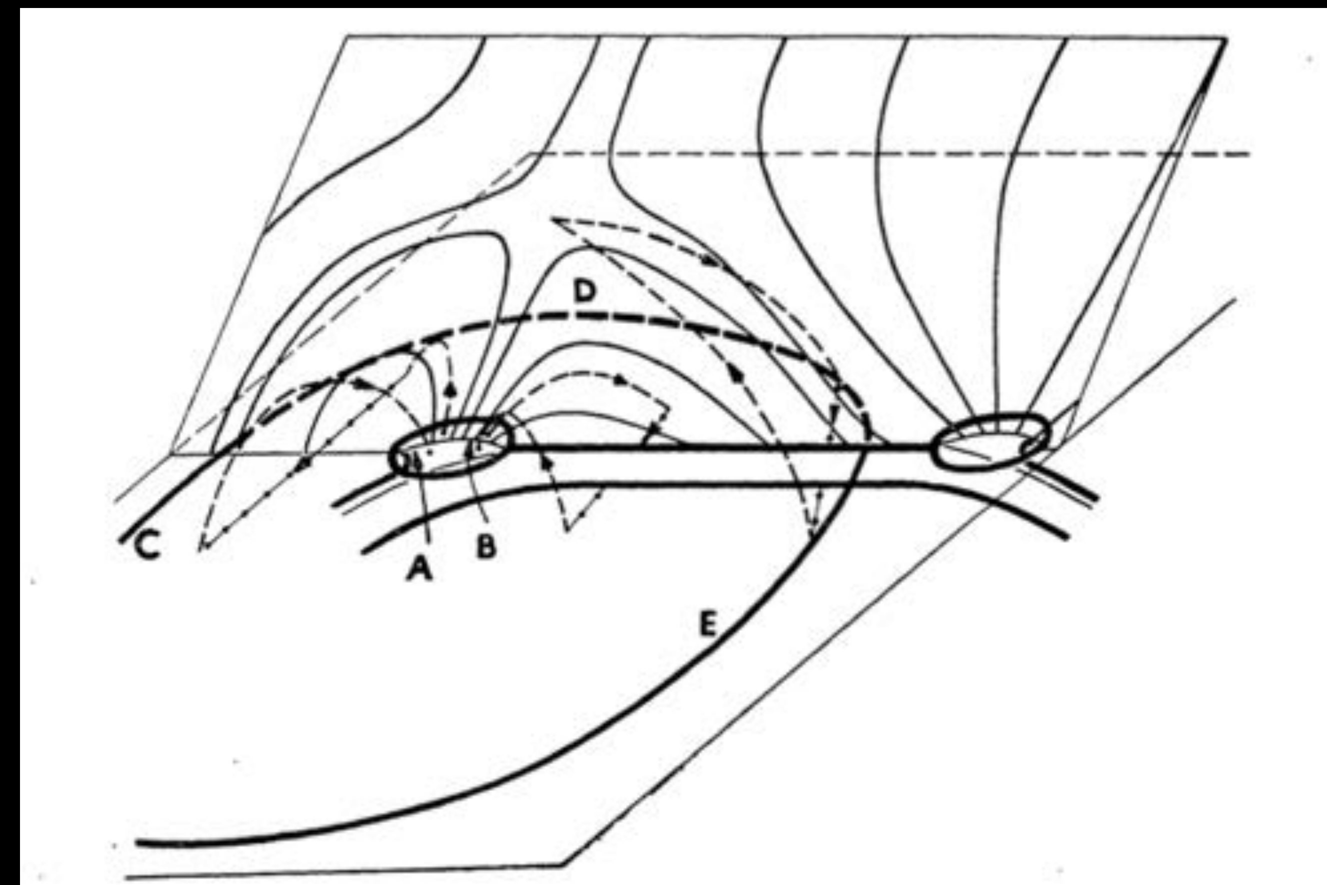


FIG. 3.—*Vertical cross-section through bipolar spot group during growth.*

The magnetic field near a sunspot group during its growth is presumably somewhat as shown above. Part of the original toroidal magnetic field is still below the surface. As lines of force break through, they give rise to an increase in the flux from the sunspots.

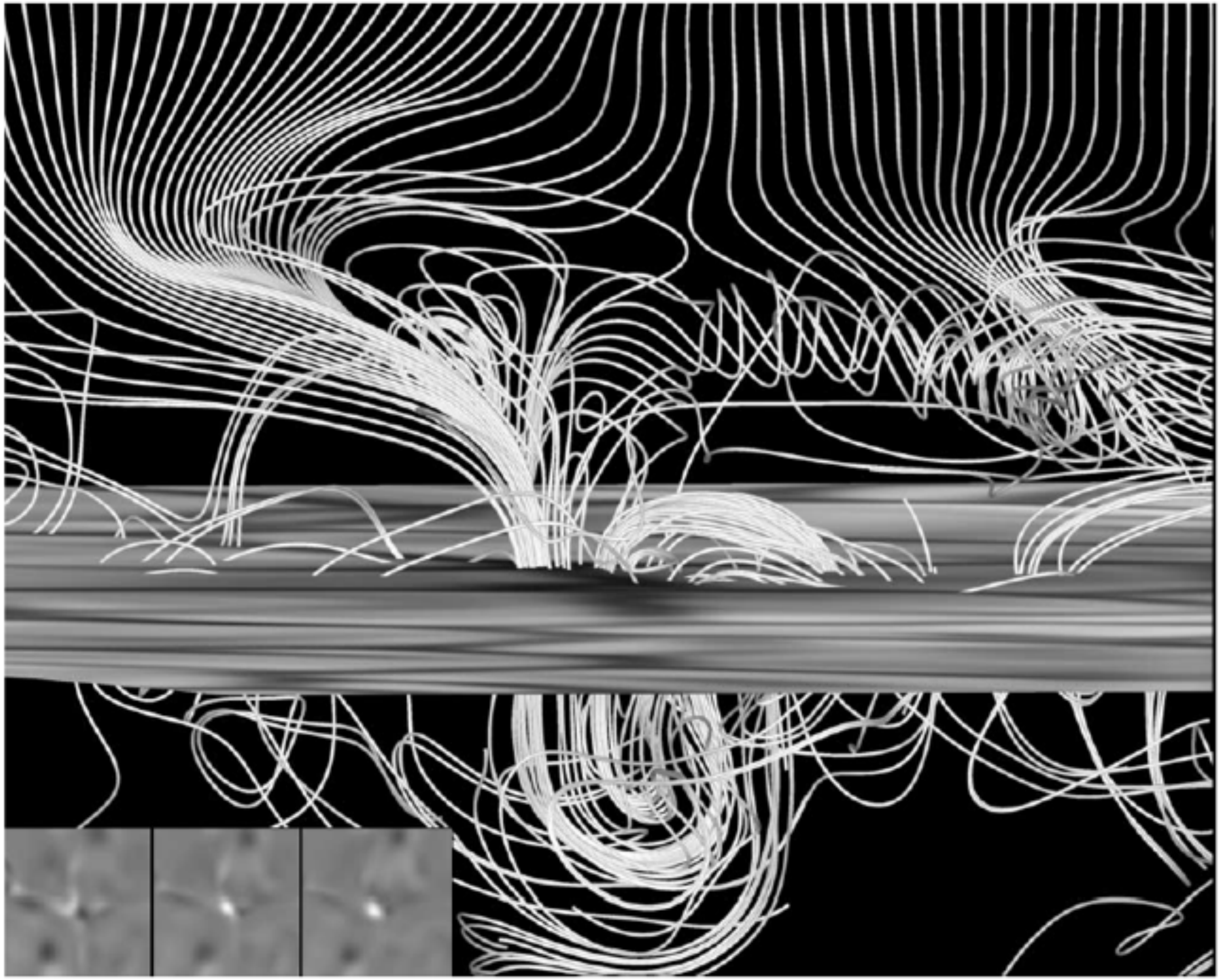
sunspots
neutral points,
electric field,
acceleration



Discussion.—We have discussed the induced electromotive forces caused by the changing magnetic fields of sunspots and have shown that in certain neighbouring regions of the chromosphere and corona whose locations depend in part on the configuration of the total magnetic field near sunspots there will be both electric fields and electric currents. The electric fields may be of the order of 10^5 e.m.u., i.e. 10^{-3} volts per cm. Free electrons under the influence of such fields can readily acquire, owing to their long mean free paths, energy sufficient to cause excitation of hydrogen and other atoms. The localization of these phenomena in the neighbourhood of sunspots suggests a basis of an explanation of solar flares. A quantitative discussion, which will be published shortly, shows that many of the essential phenomena of flares can be so explained. The theory also leads to possible explanations of other observed phenomena, for example a certain type of prominence and the emission of radiation in the one-metre band.

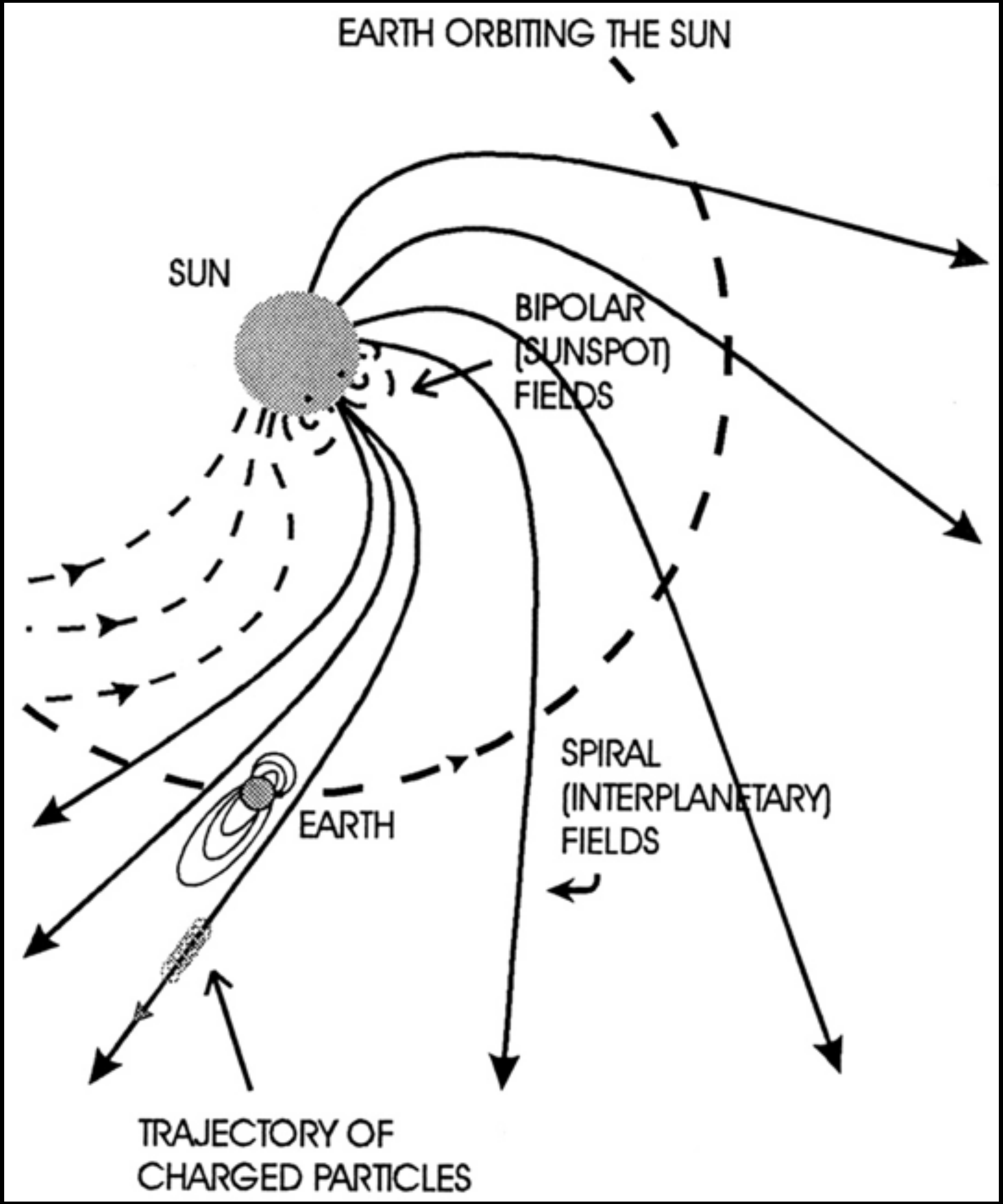
THE MAGNETIC CONNECTION BETWEEN THE CONVECTION ZONE AND CORONA IN THE QUIET SUN

W. P. ABBETT
Space Sciences Laboratory, 7 Gauss Way, University of California, Berkeley, CA 94720-7450; abbett@ssl.berkeley.edu
Received 2007 March 15; accepted 2007 May 11



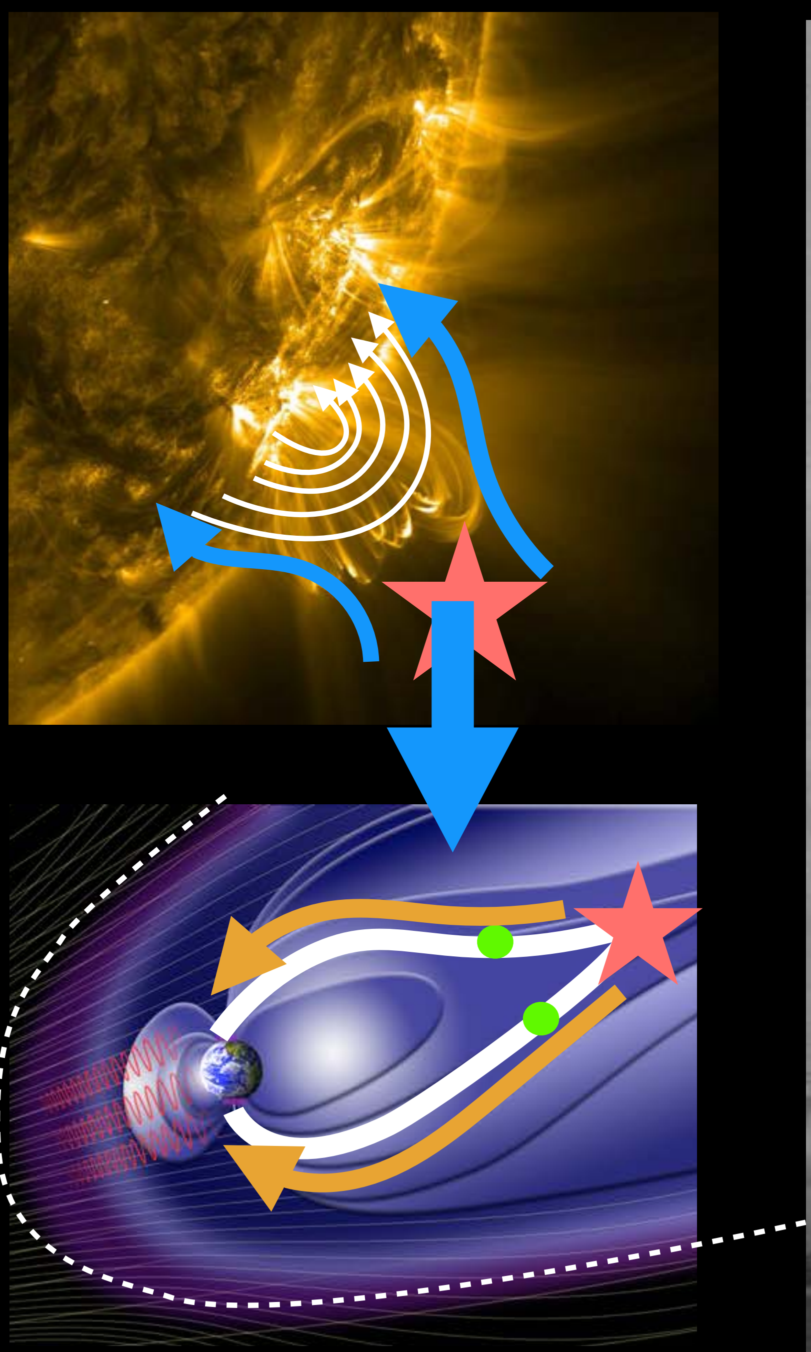
Solar wind

(E. Parker, 1958)



Hoyle and the magnetosphere

(Cowley, A&G 2016)



J. Dungey

Magnetosphere dynamics, Reconnection, Aurorae

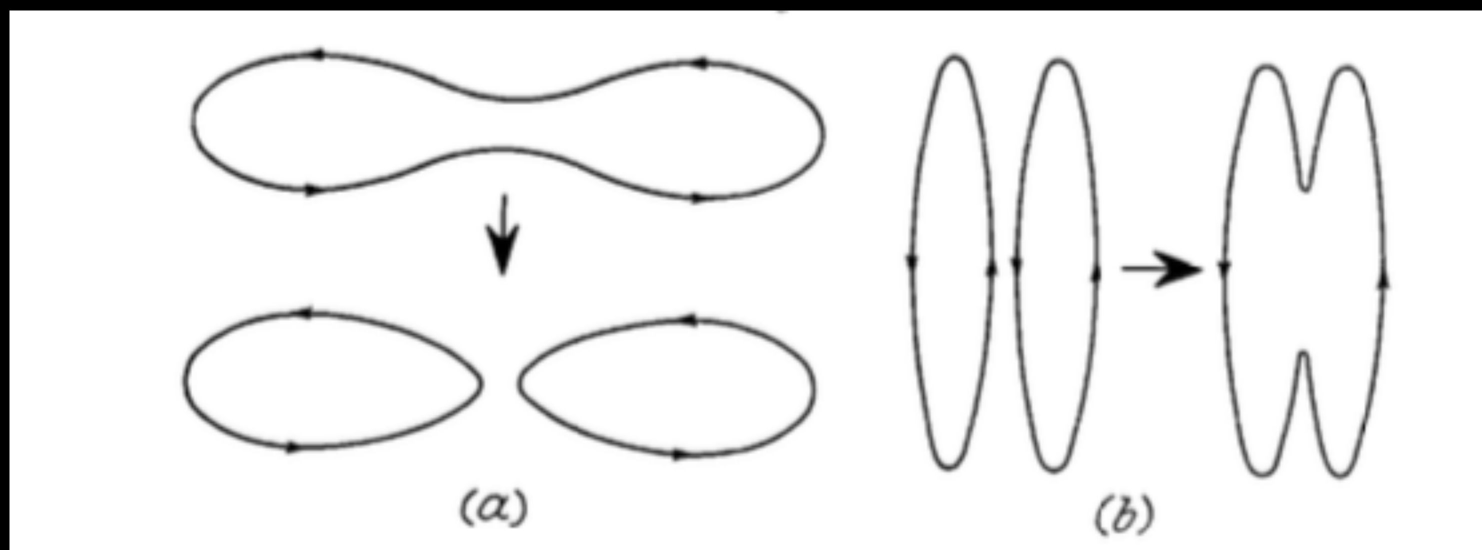
H. Alfvén

Nobel Prize winner in 1970

"for fundamental work and discoveries in magnetohydro-dynamics with fruitful applications in different parts of plasma physics"

J. Dungey

« electrical discharges in Astrophysical systems »



(Dungey, 1953)

examples. In (*a*) two parts of a loop of force are close together with their fields in opposite directions, and the result is that the loop of force breaks into two loops, whose total length is less than that of the original loop. In (*b*) the reverse process occurs, but the length of the final loop is less than the combined length of the original two loops. In both cases field energy is released and field energy from a relatively large region is concentrated on the particles in the neighbourhood of the neutral point.

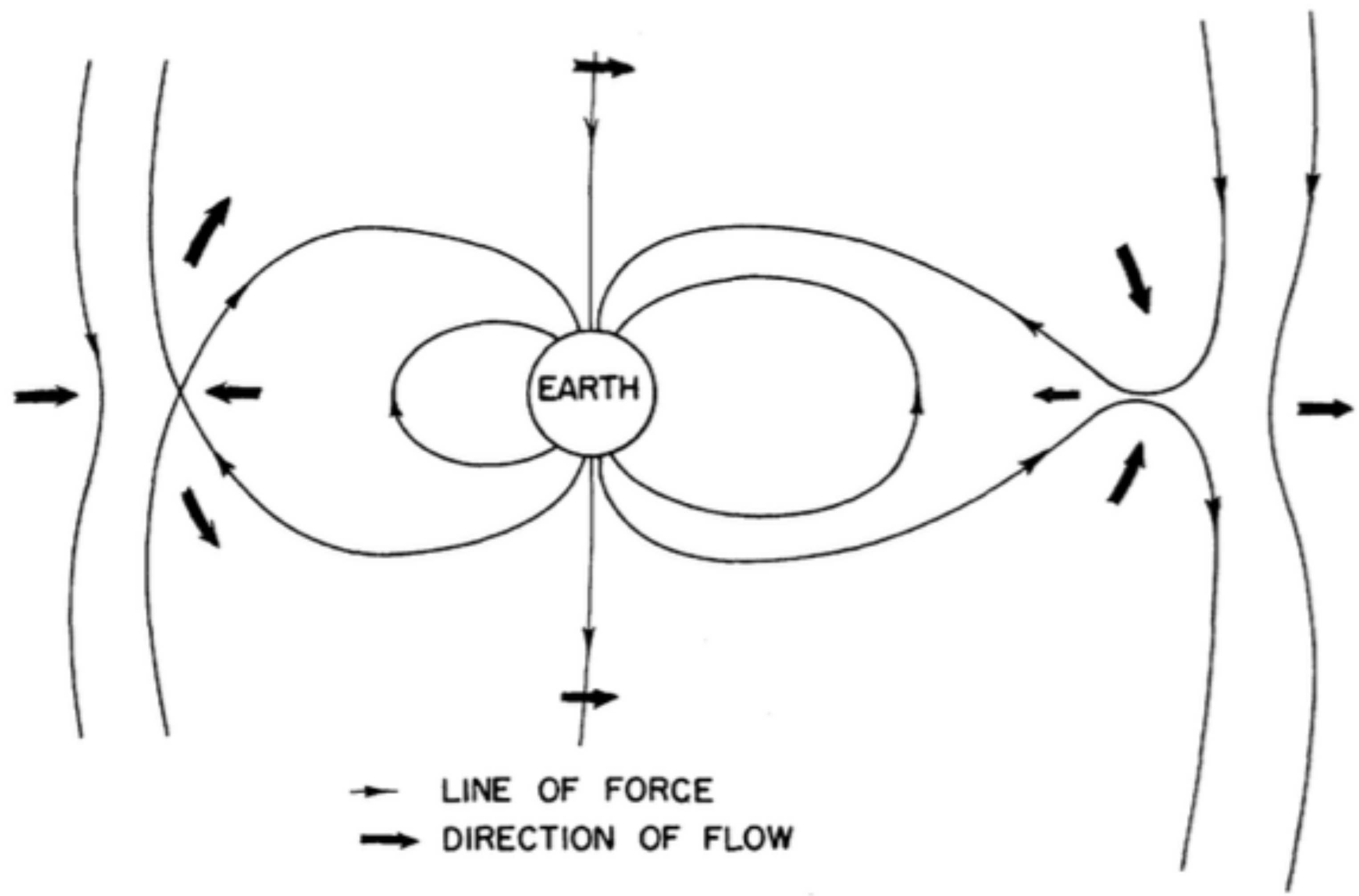
PHYSICAL REVIEW LETTERS

VOLUME 6 JANUARY 15, 1961 NUMBER 2

INTERPLANETARY MAGNETIC FIELD AND THE AURORAL ZONES*

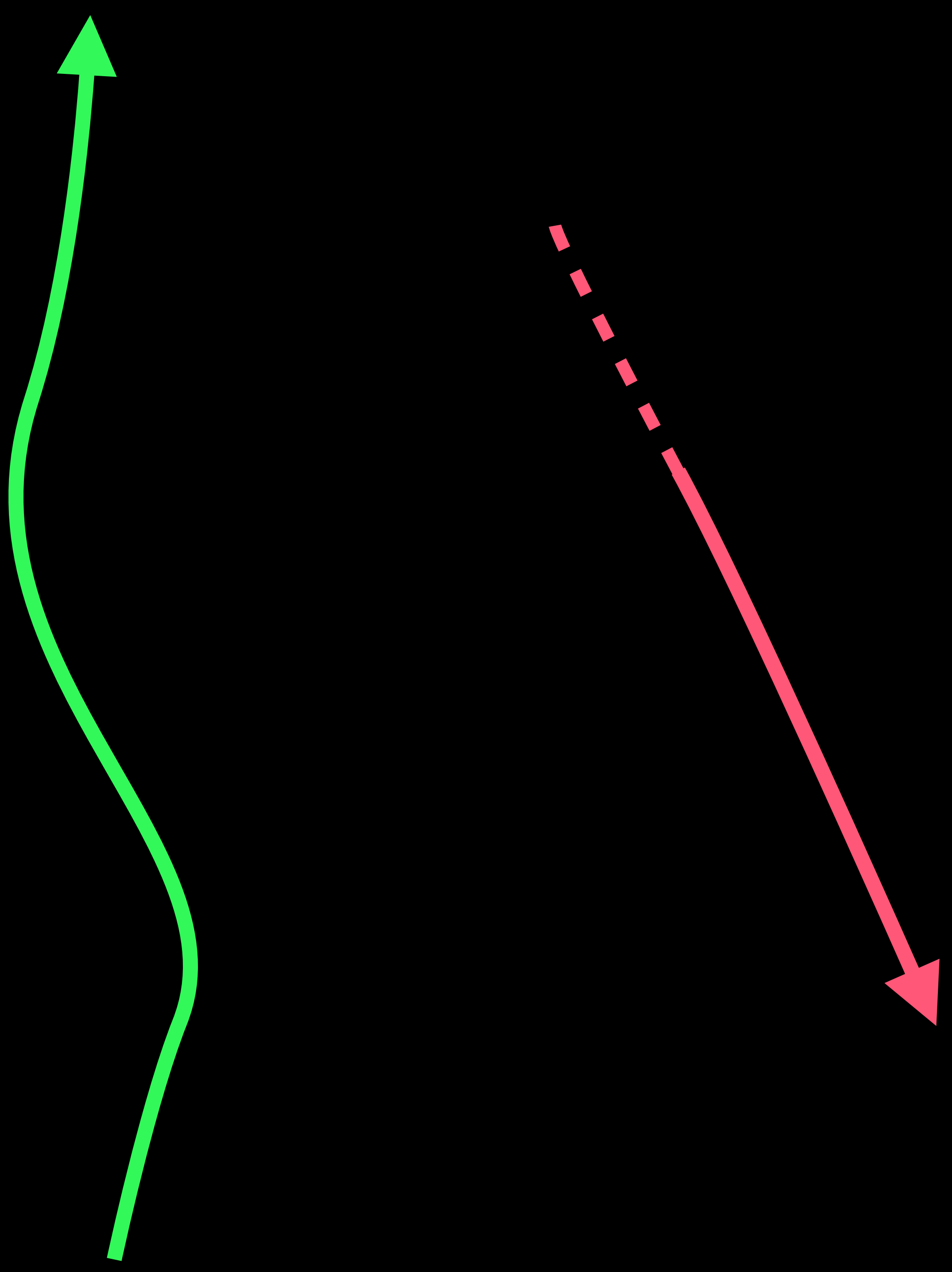
J. W. Dungey†
Ionosphere Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania

(Received November 10, 1960; revised manuscript received December 22, 1960)

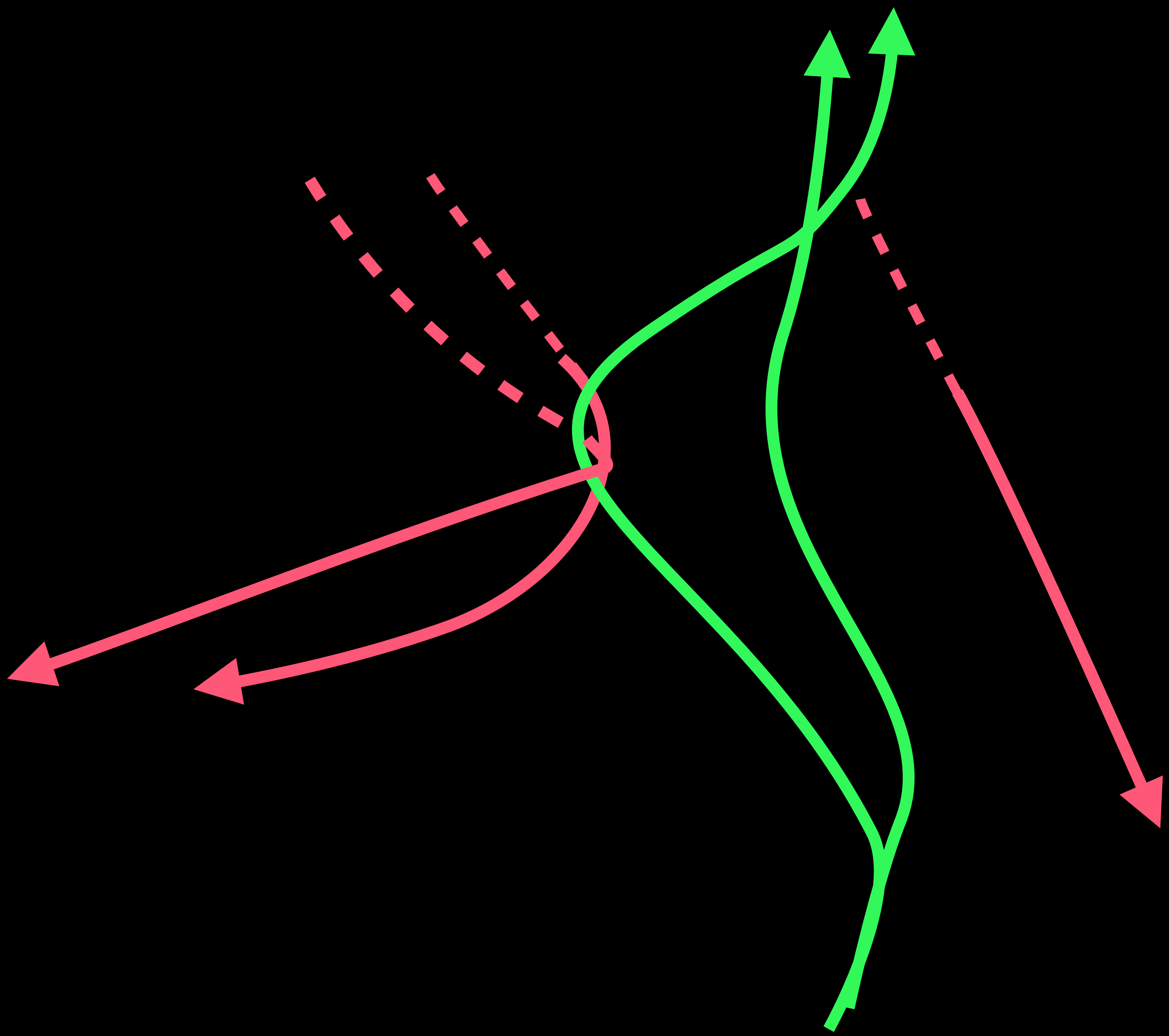


"I think I had been to visit somebody at the Institute d'Astrophysique in Montparnasse in the morning. And then I was sitting on a terrace, preparing my talk [...]. A lot of people find that preparing a talk is stimulating, and I think I had been struggling to see this for a long time, actually. It was only then that I actually saw the idea of the open magnetosphere. [...] [During the evening talk in Meudon, ...] everybody said, you know, it's good, because it's amusing. They didn't believe it but thought it was artistic, or something.

In a collisionless plasma
Magnetic field lines behave like rubber band

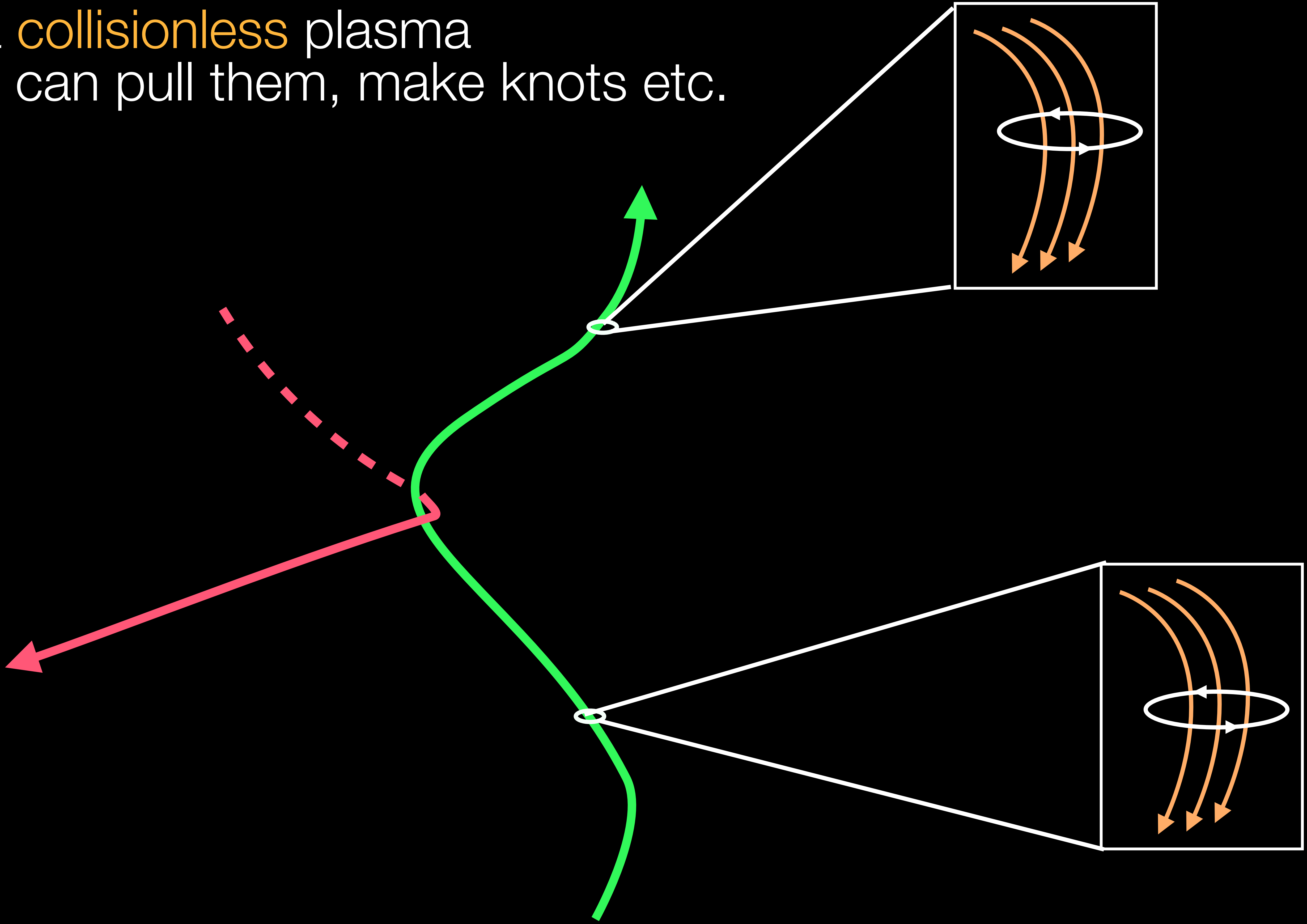


In a collisionless plasma
you can pull them, make knots etc.

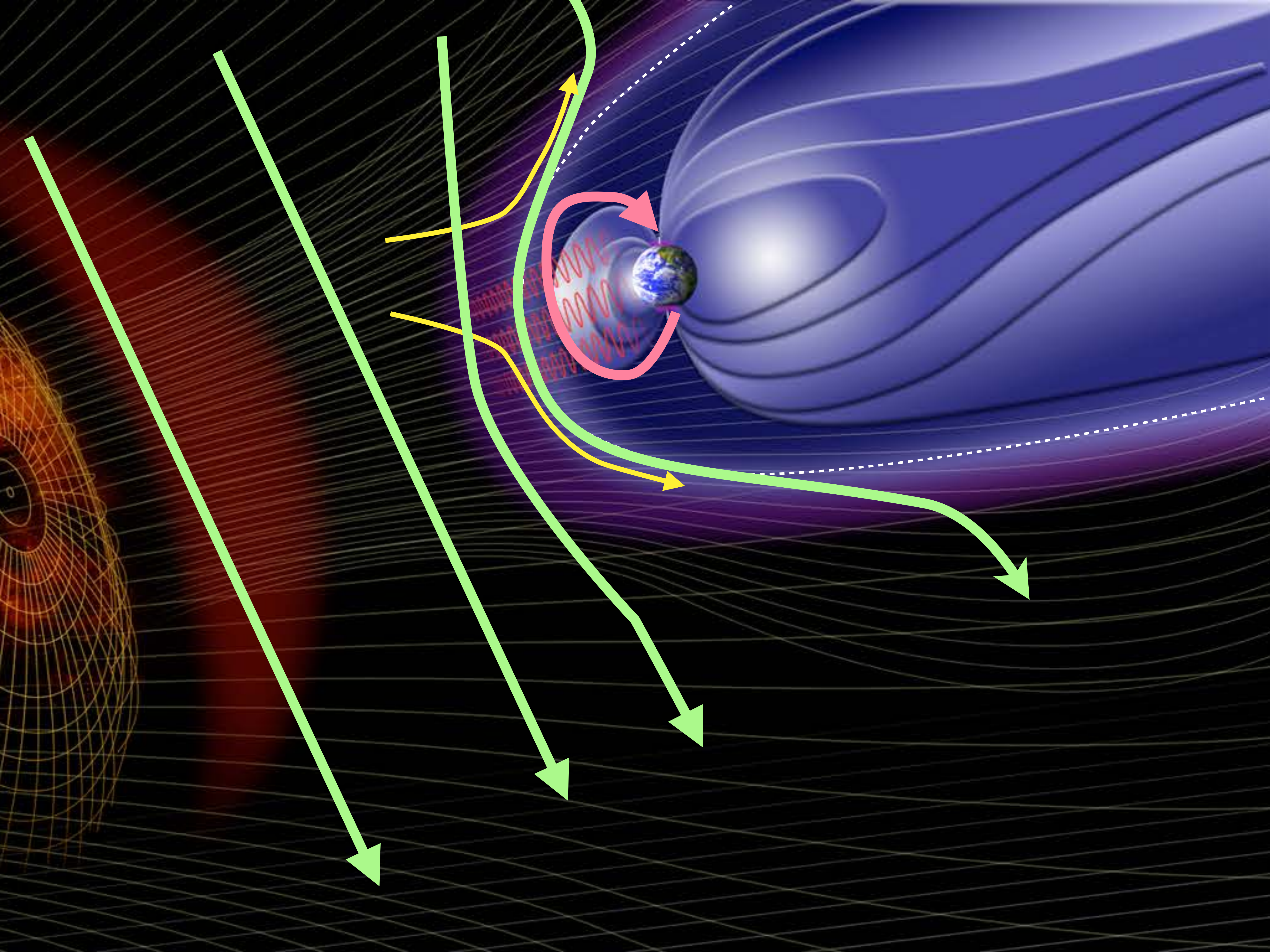


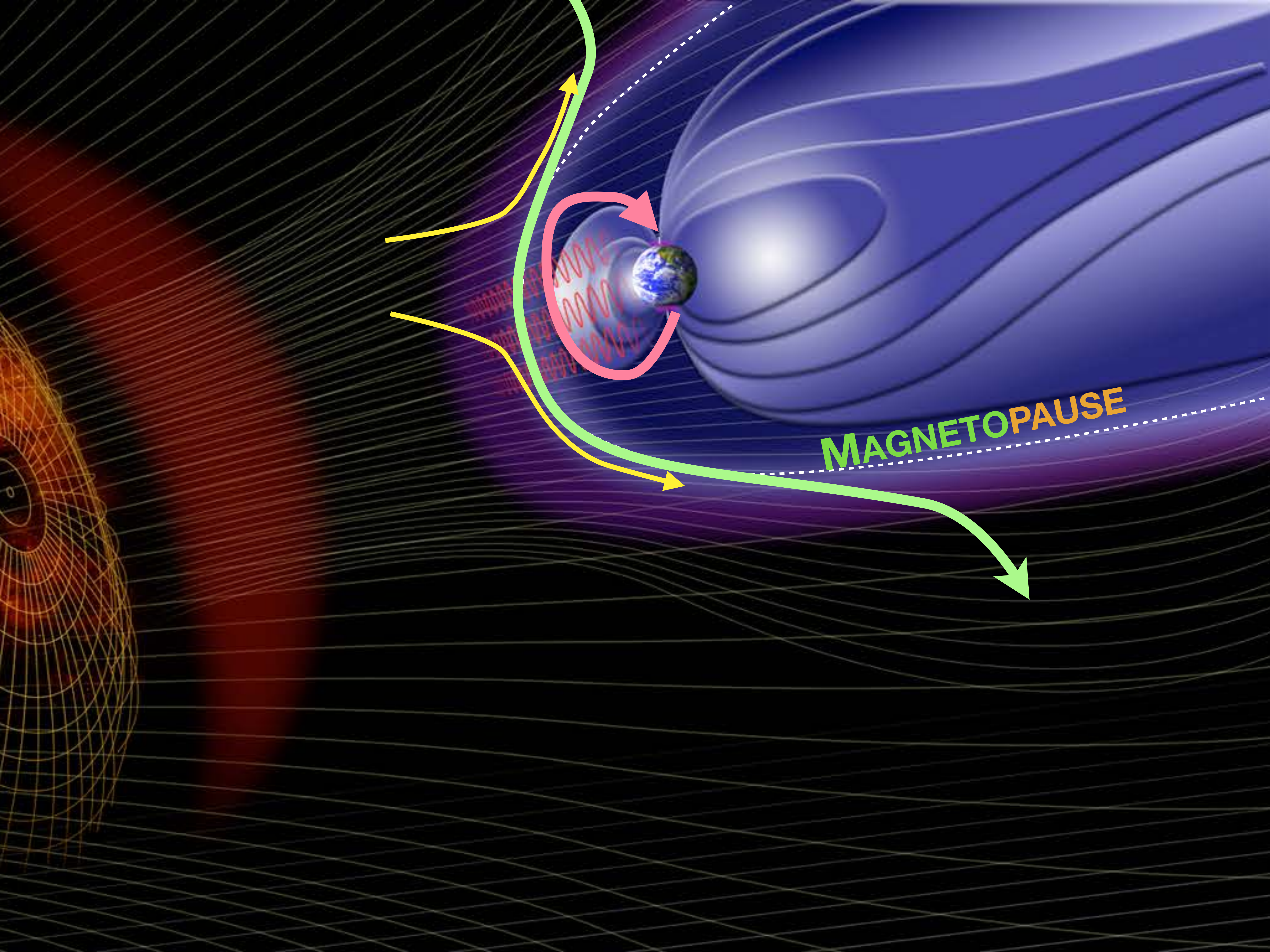
their evolution must conserve the field line connectivity

In a collisionless plasma
you can pull them, make knots etc.

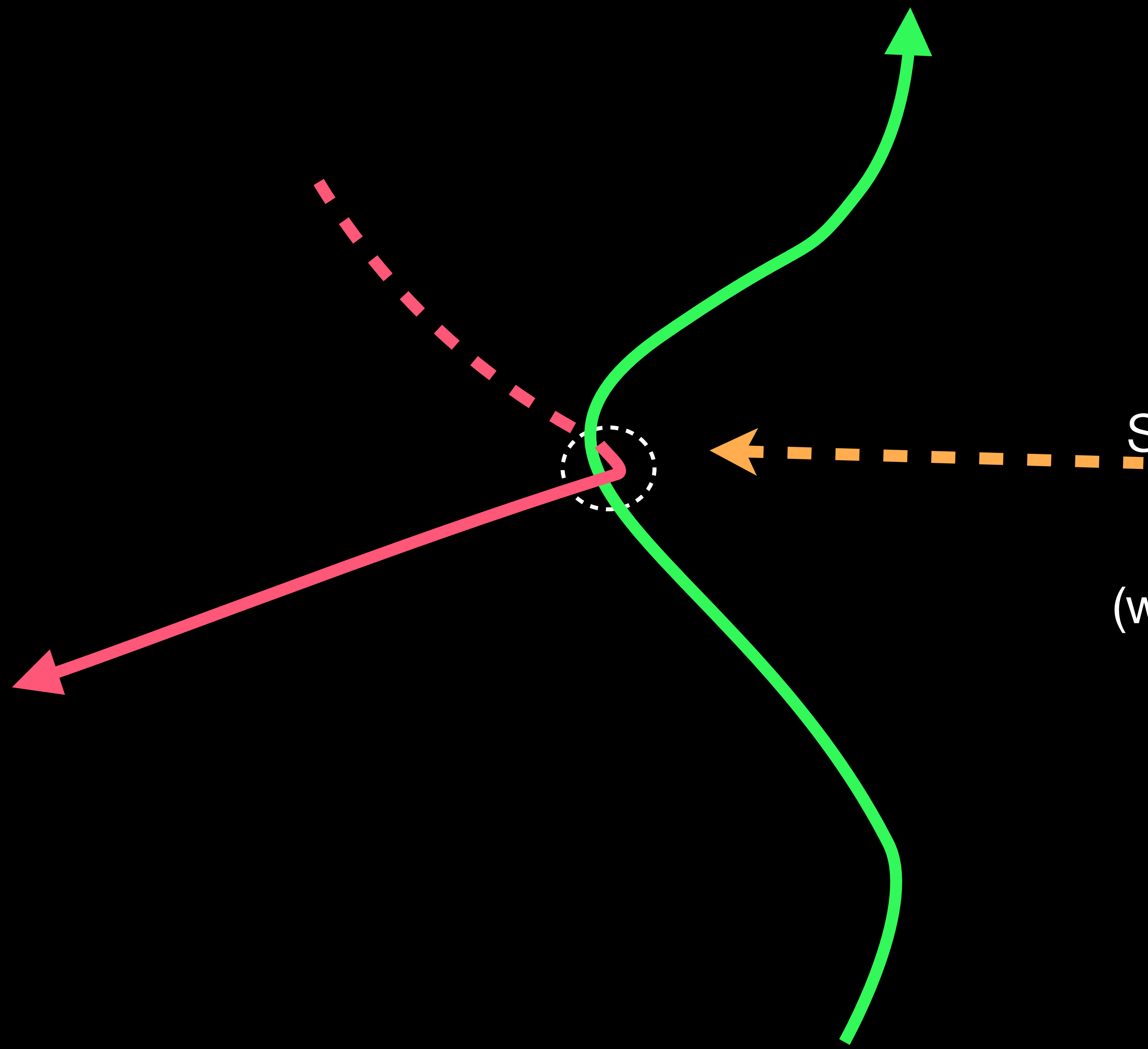


their evolution must conserve the field line connectivity




MAGNETOPAUSE

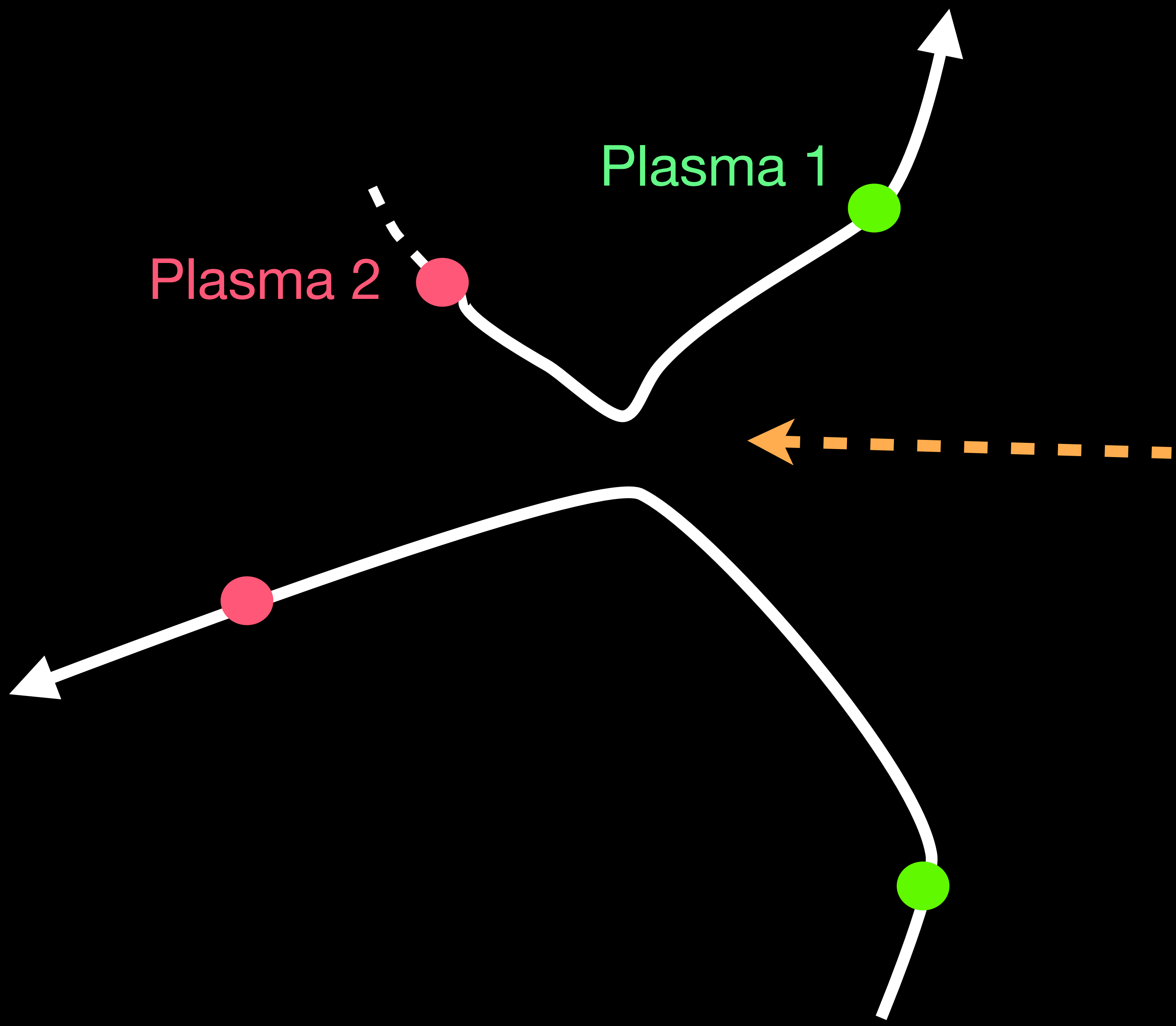
… but if you pull too hard…



strong gradient = non ideal processes

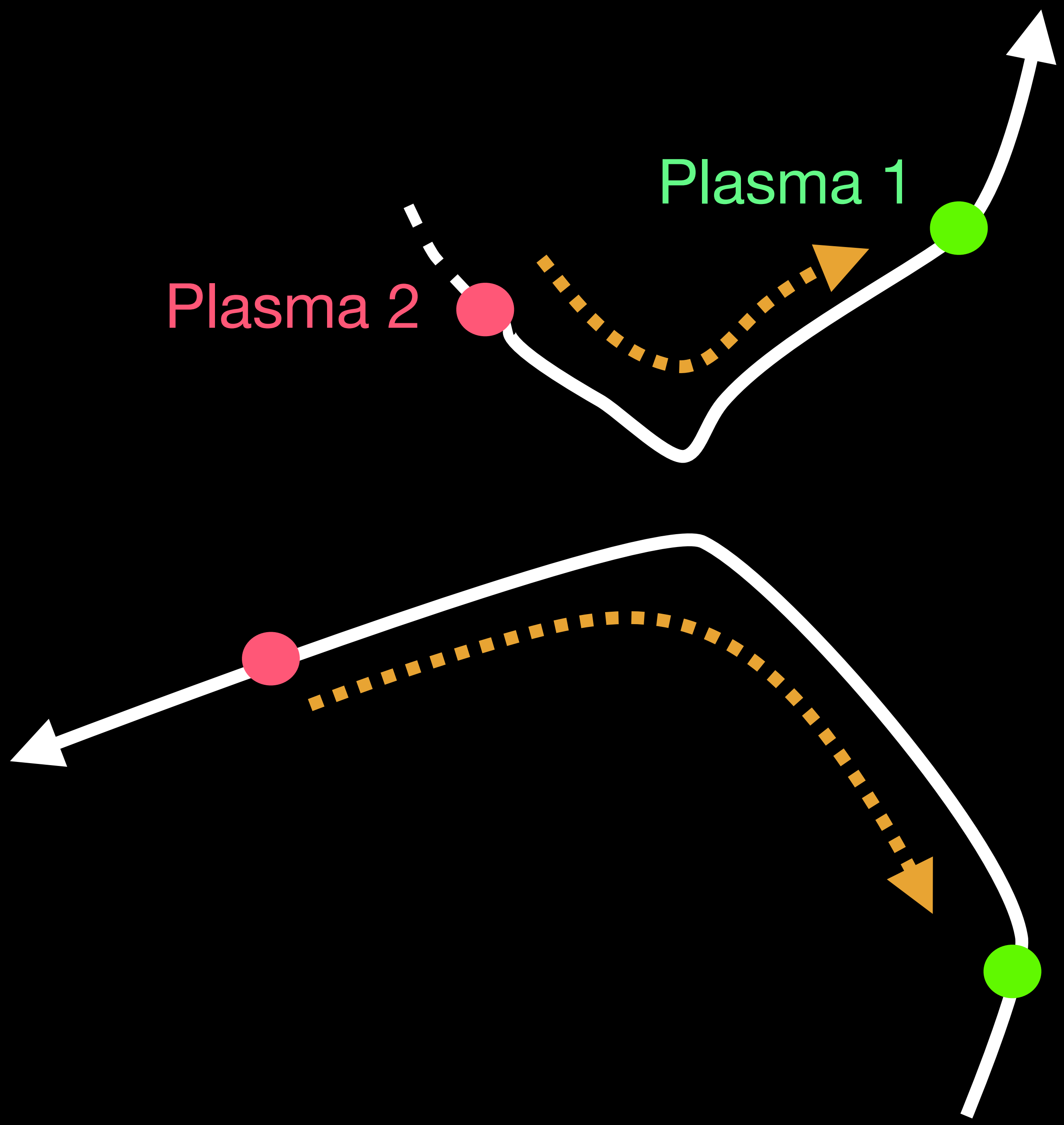
(we'll come back on them later)

… but if you pull too hard…



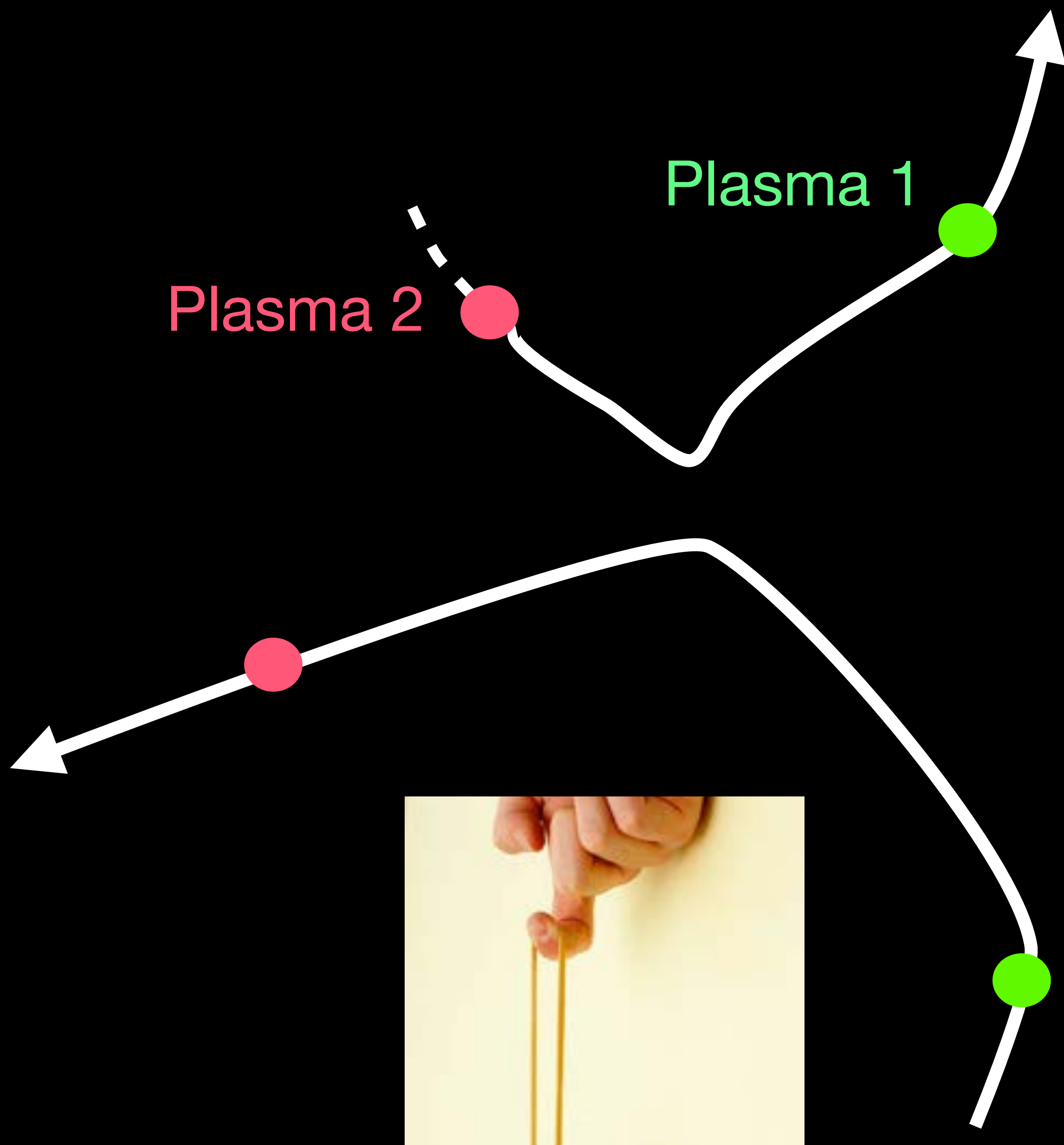
Magnetic
Re-connection

Two important consequences



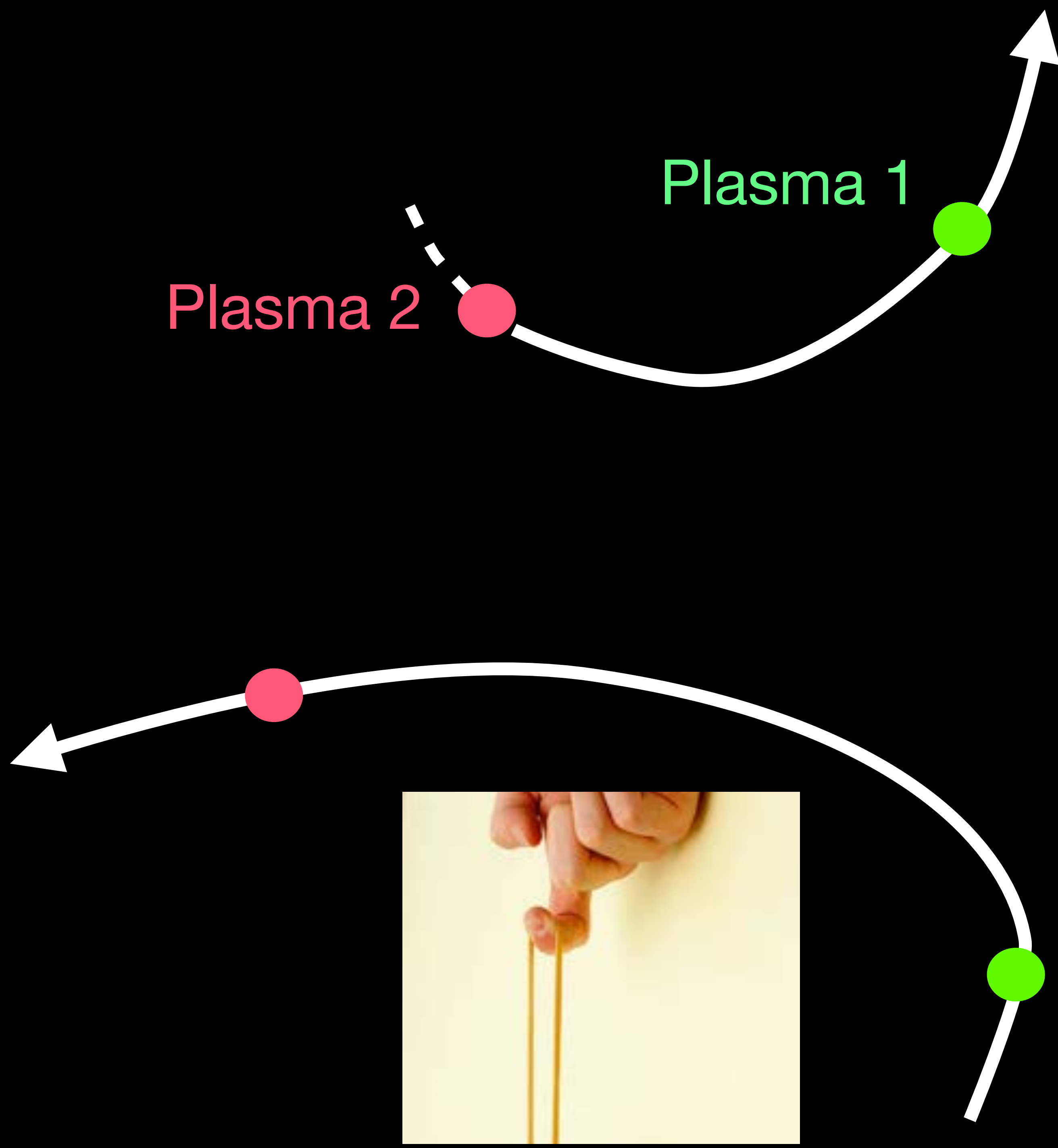
1 plasma transport into previously forbidden regions

Before « breaking » the connectivity, we've accumulated energy



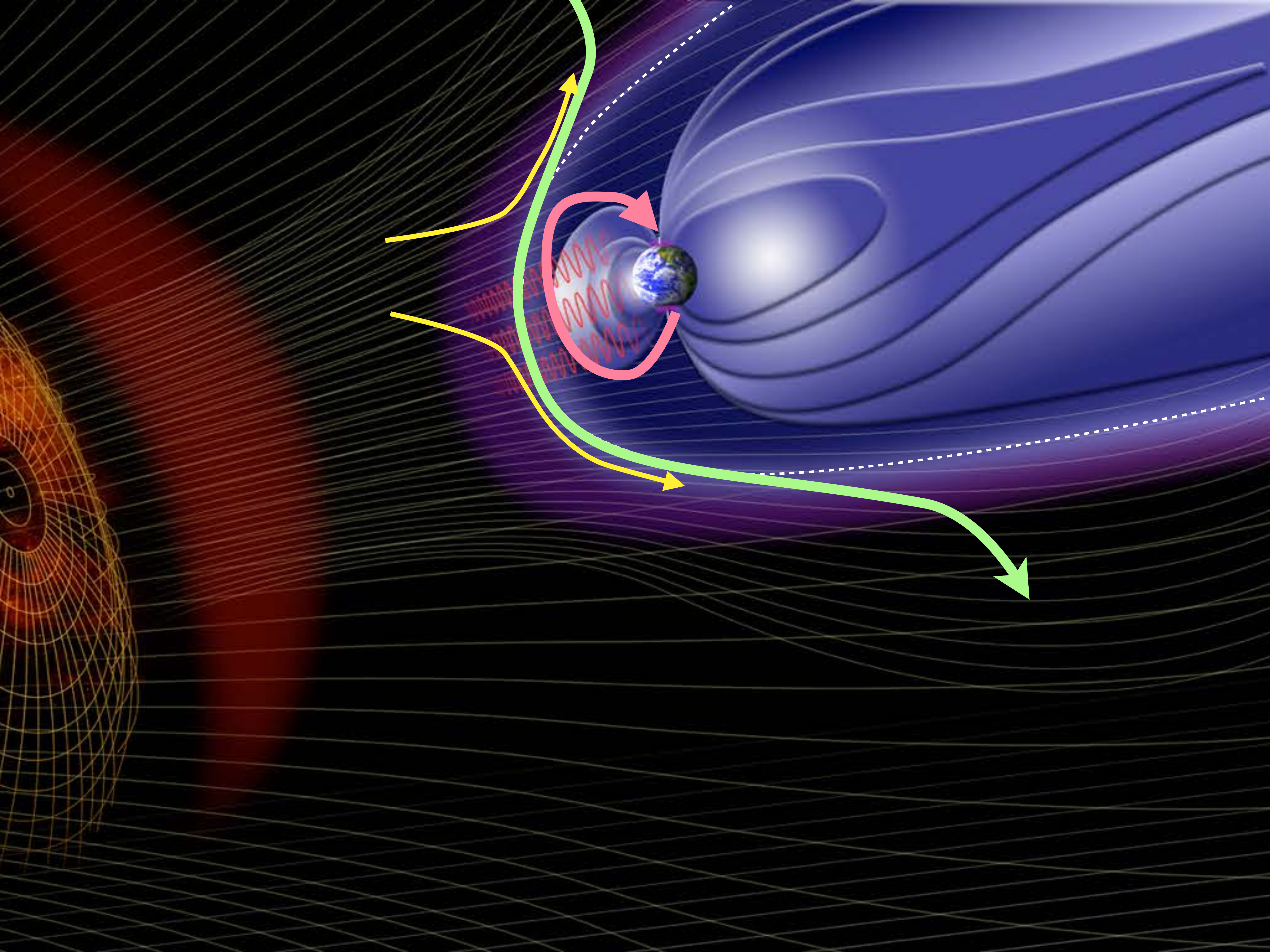
2 release magnetic energy

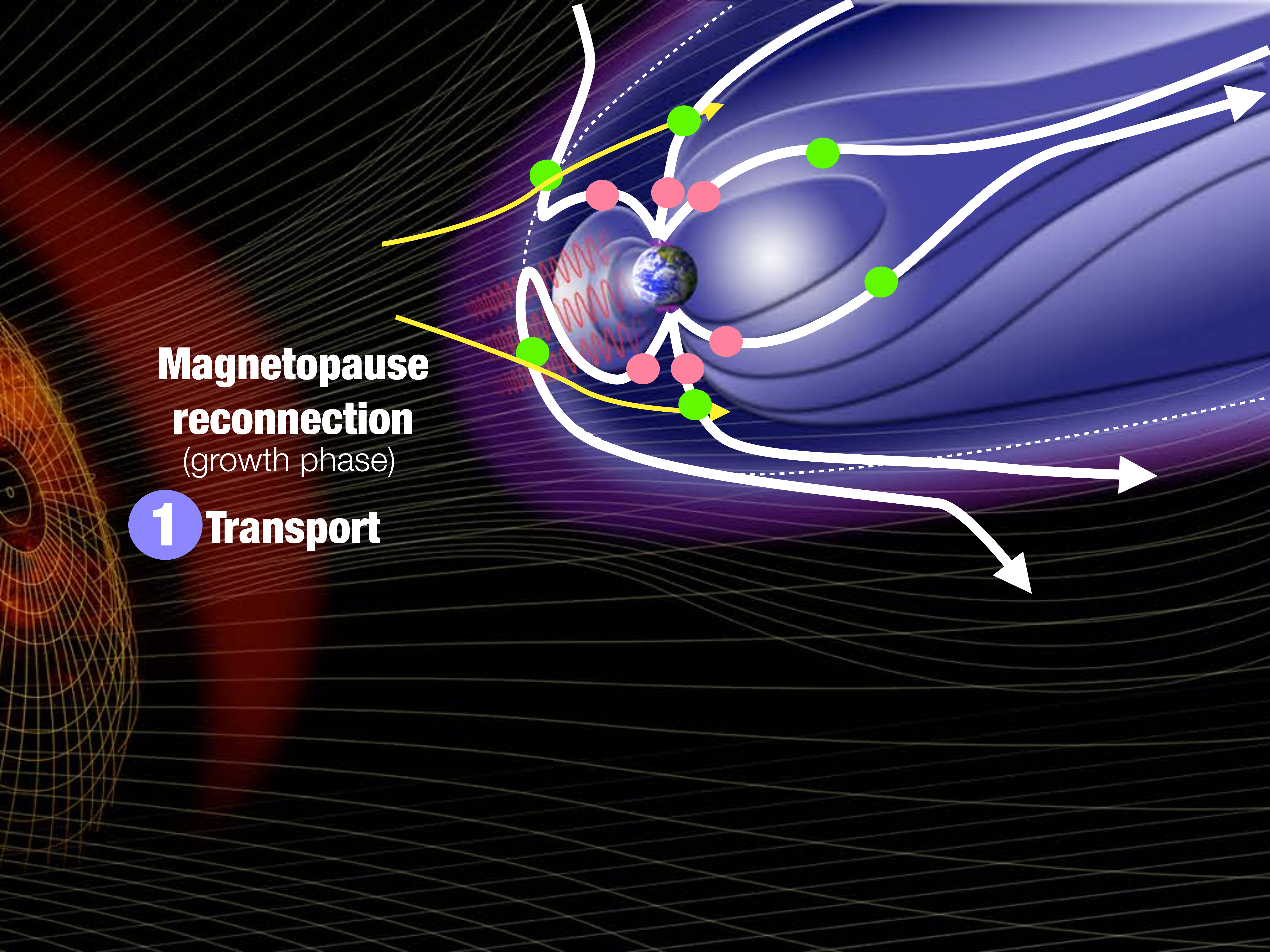
... which is transferred to the plasma!

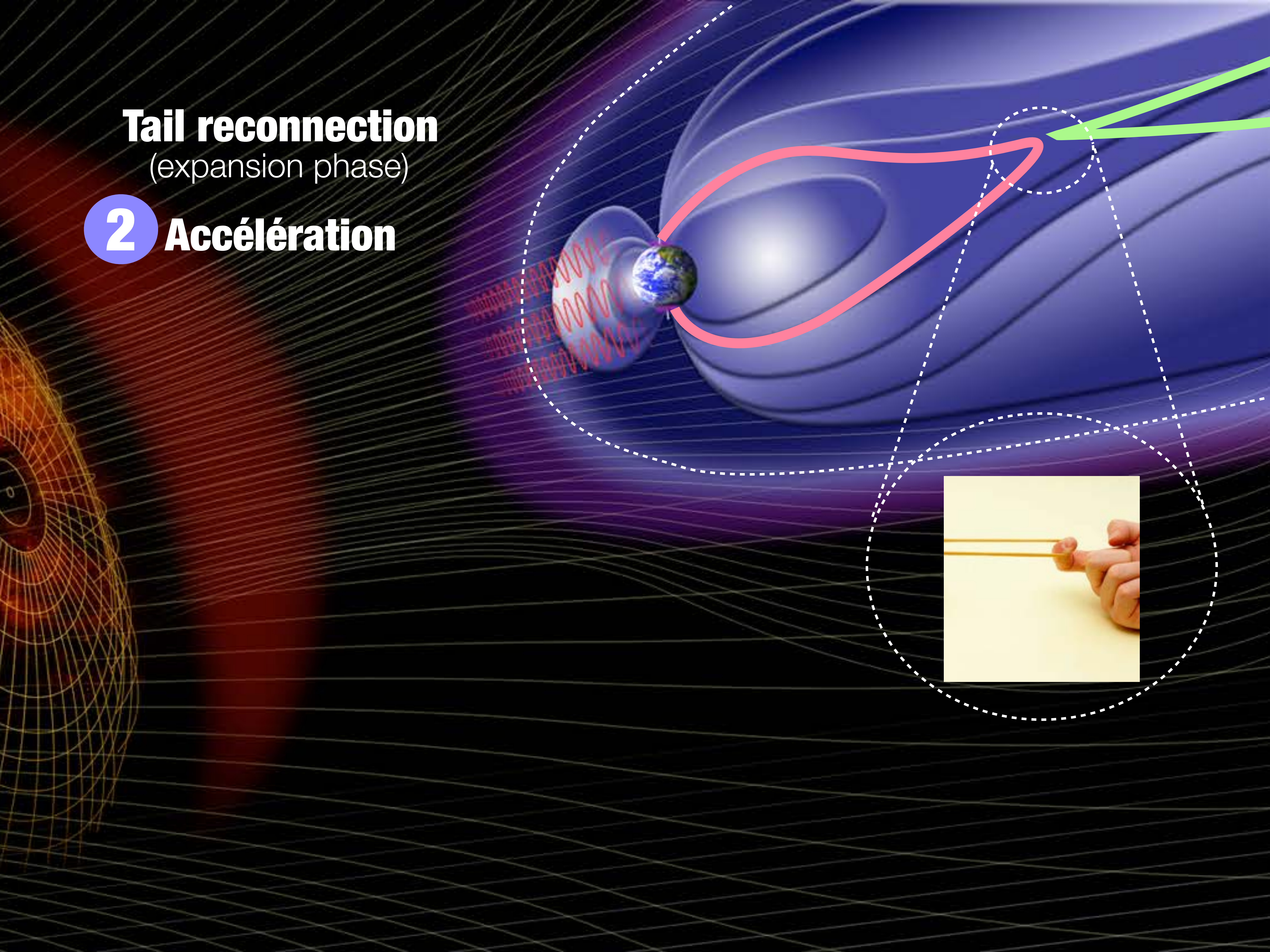


2 release magnetic energy

into plasma heat and kinetic energy

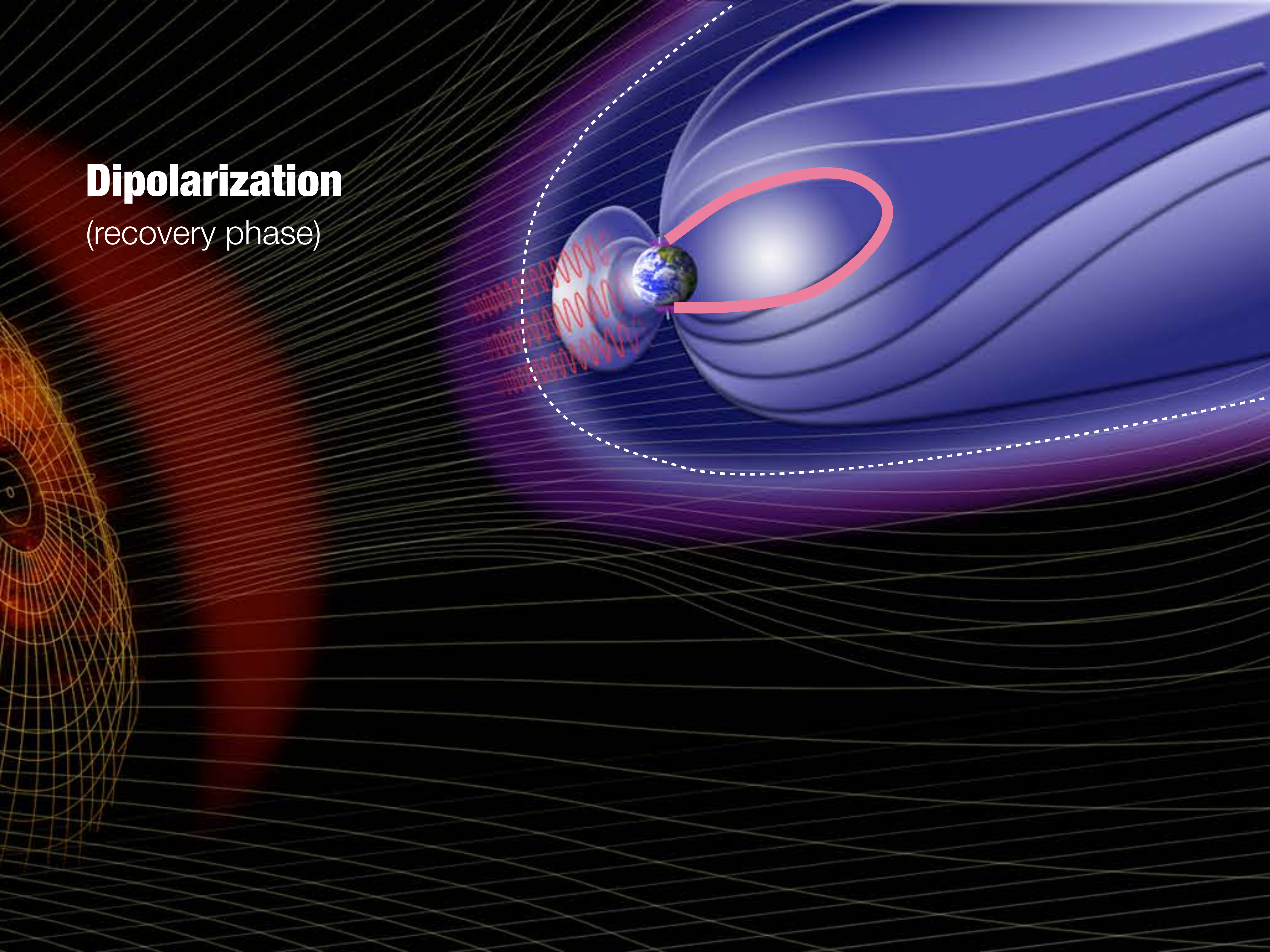



Magnetopause
reconnection
(growth phase)
1 Transport


Tail reconnection
(expansion phase)
2 Accélération

Dipolarization

(recovery phase)



50 yrs later

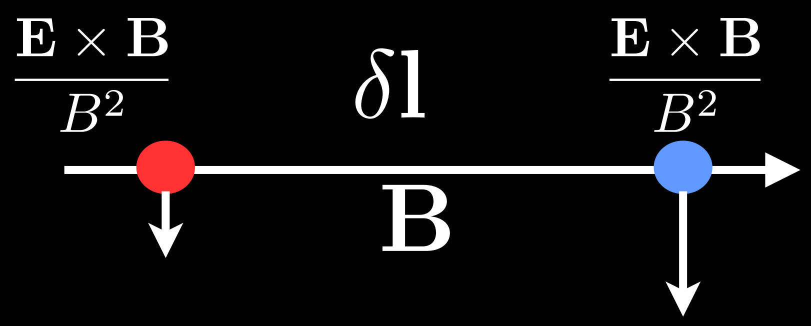
The process of dayside and nightside reconnection just described was first proposed by Dungey (1961). Since then, important details have been filled in, including dependency on external solar wind conditions, time dependency, and near-continuous presence of a distant X-line. ***However, the basic picture of flux transport into and out of the magnetosphere and of the circulation of plasma within the magnetosphere driven by reconnection remains unchanged since it was first introduced.***

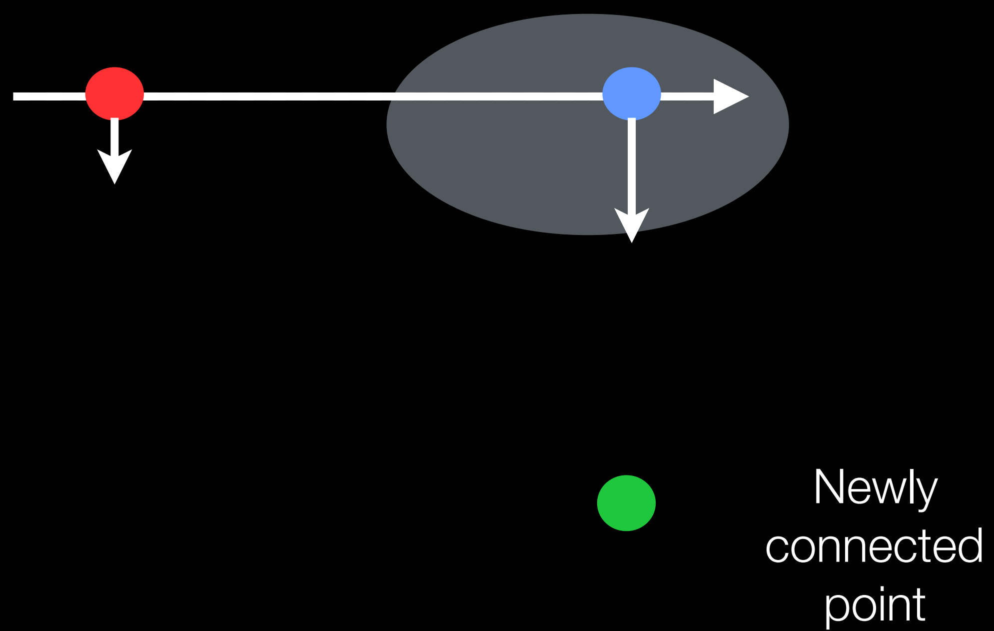
(Fuselier et al. 2011)

Chap. 2 - « reconnecting » field lines?

What does it mean? How does it work?

Local condition for reconnection





$$\frac{d}{dt}\left(\delta\mathbf{l}\times\mathbf{B}\right)=0$$

$$\Longleftrightarrow$$

$$\left(\boldsymbol{\nabla}\times\mathbf{E}_{\|}\right)\times\mathbf{B}=0$$

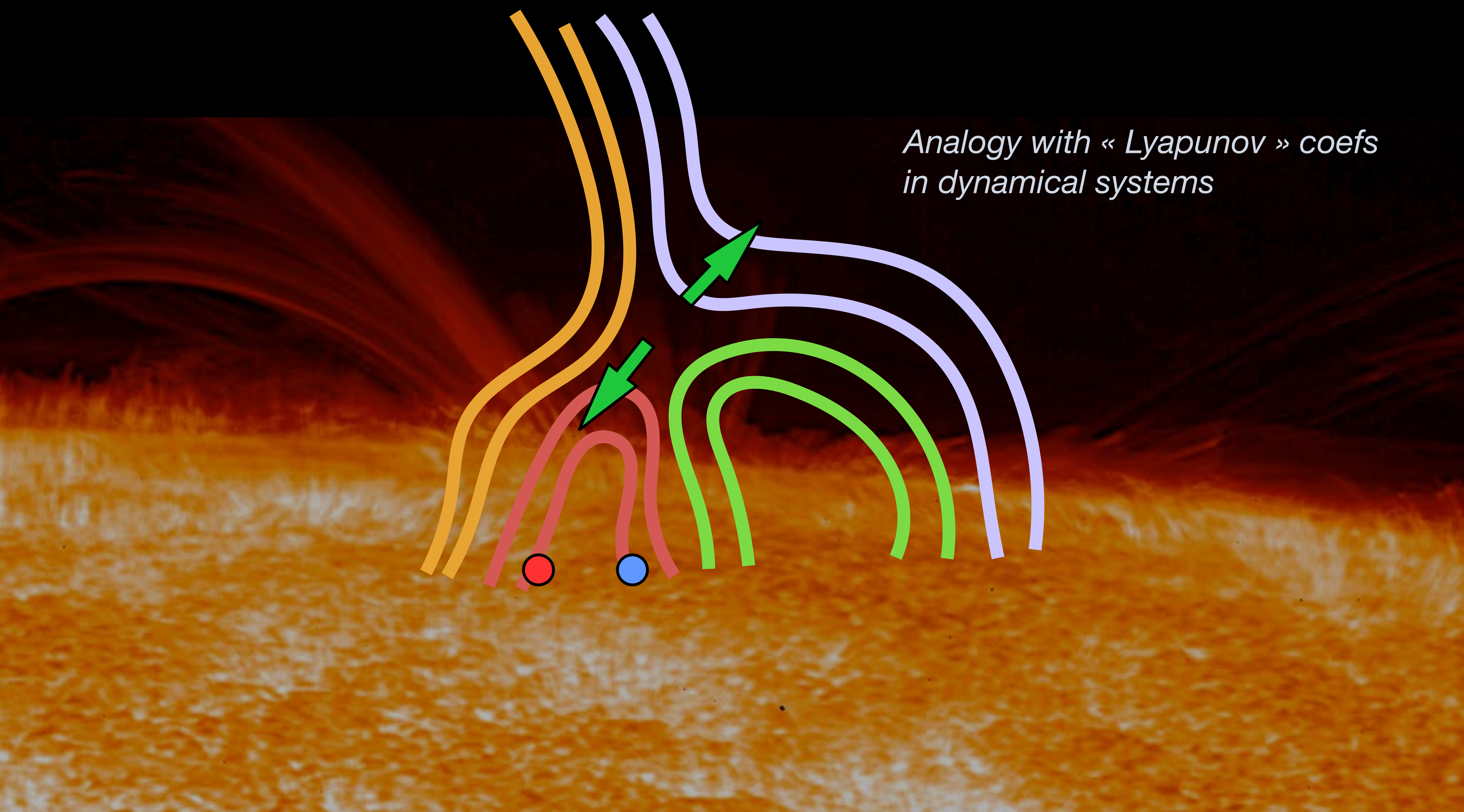
$$\frac{d}{dt}\left(\delta\mathbf{l}\times\mathbf{B}\right)\neq 0$$

$$\Longleftrightarrow$$

$$\left(\boldsymbol{\nabla}\times\mathbf{E}_{\|}\right)\times\mathbf{B}\neq 0$$

Gobal condition for reconnection

To be interesting reconnection should globally change the connectivity of plasma. Reconnection occurs in regions having large gradients of connetivity (concept of Quasi-Separatrix-Layers)



Gobal condition for reconnection

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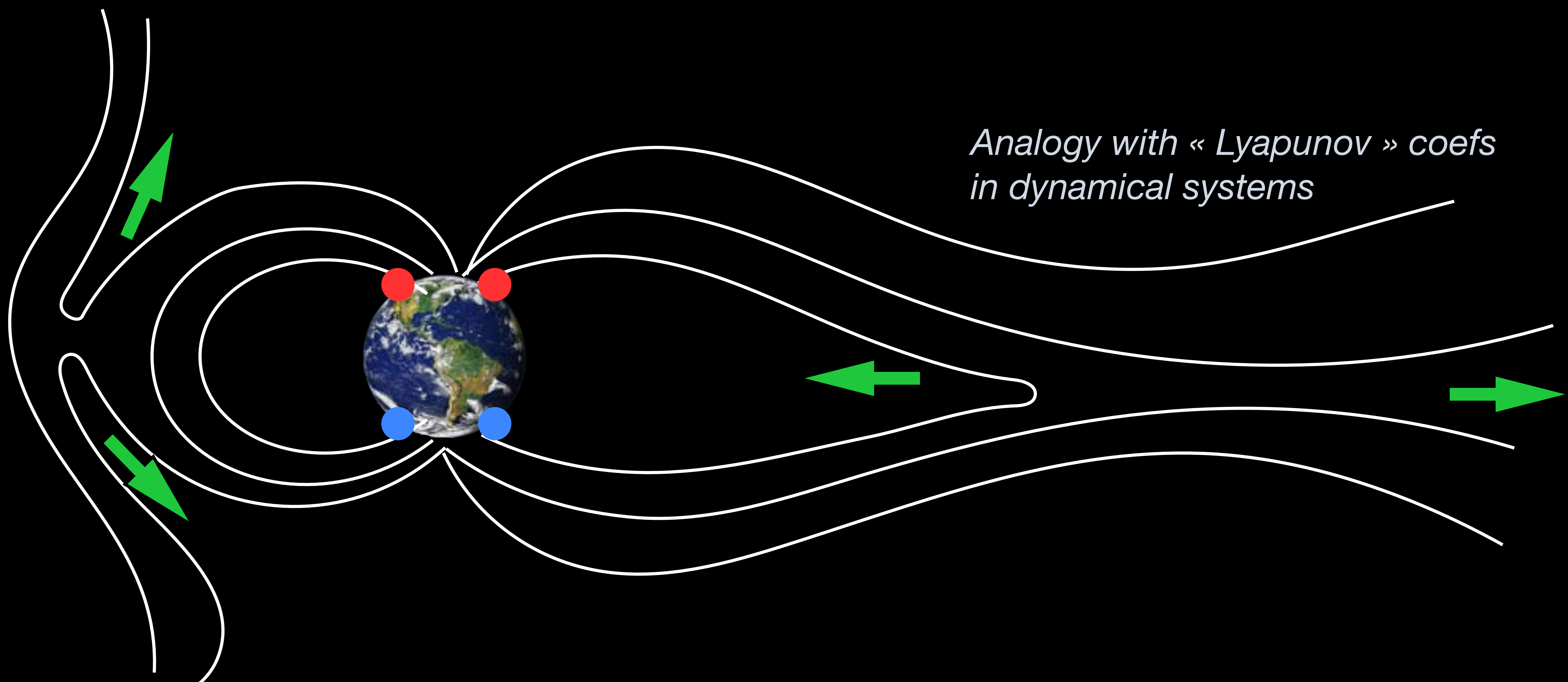
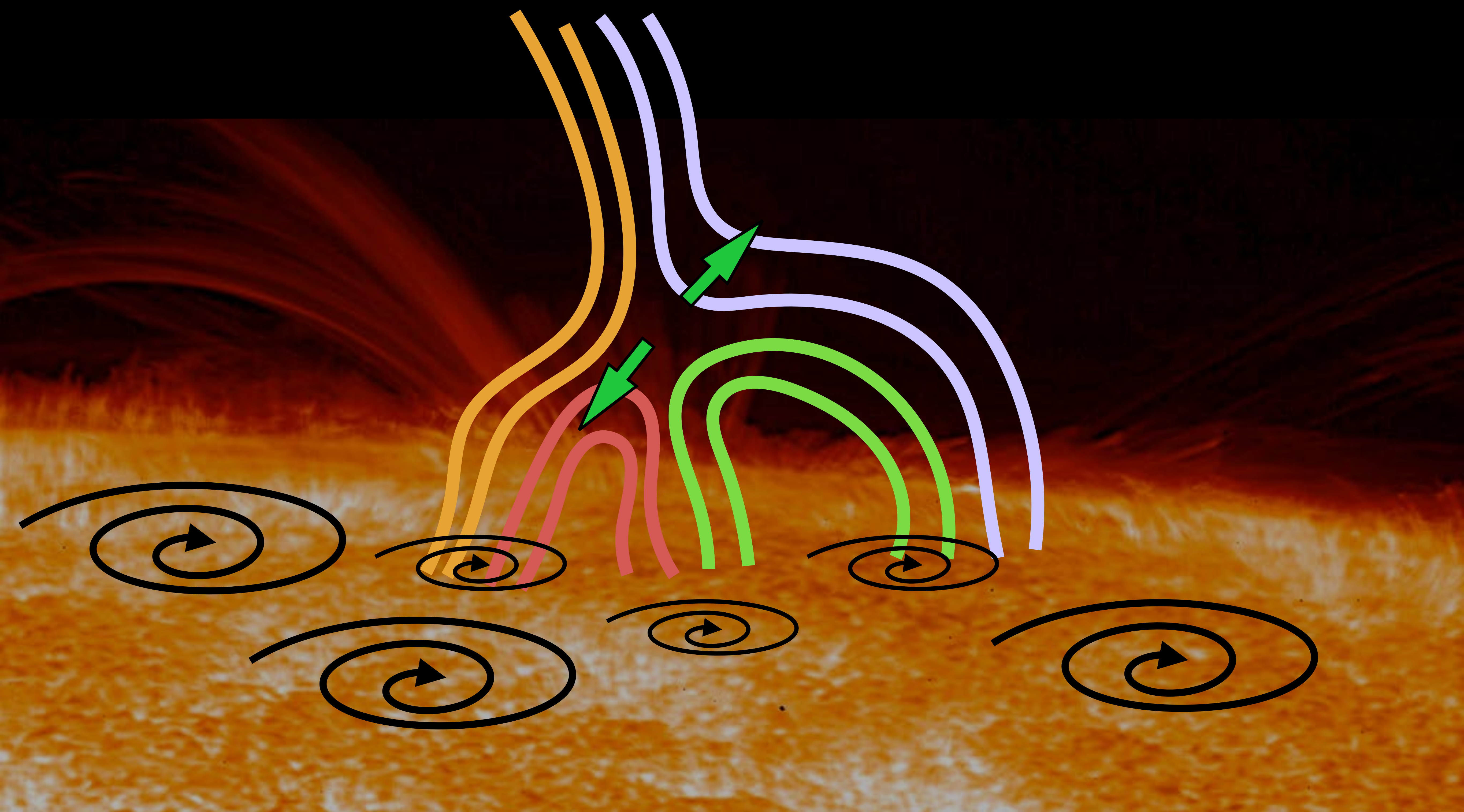


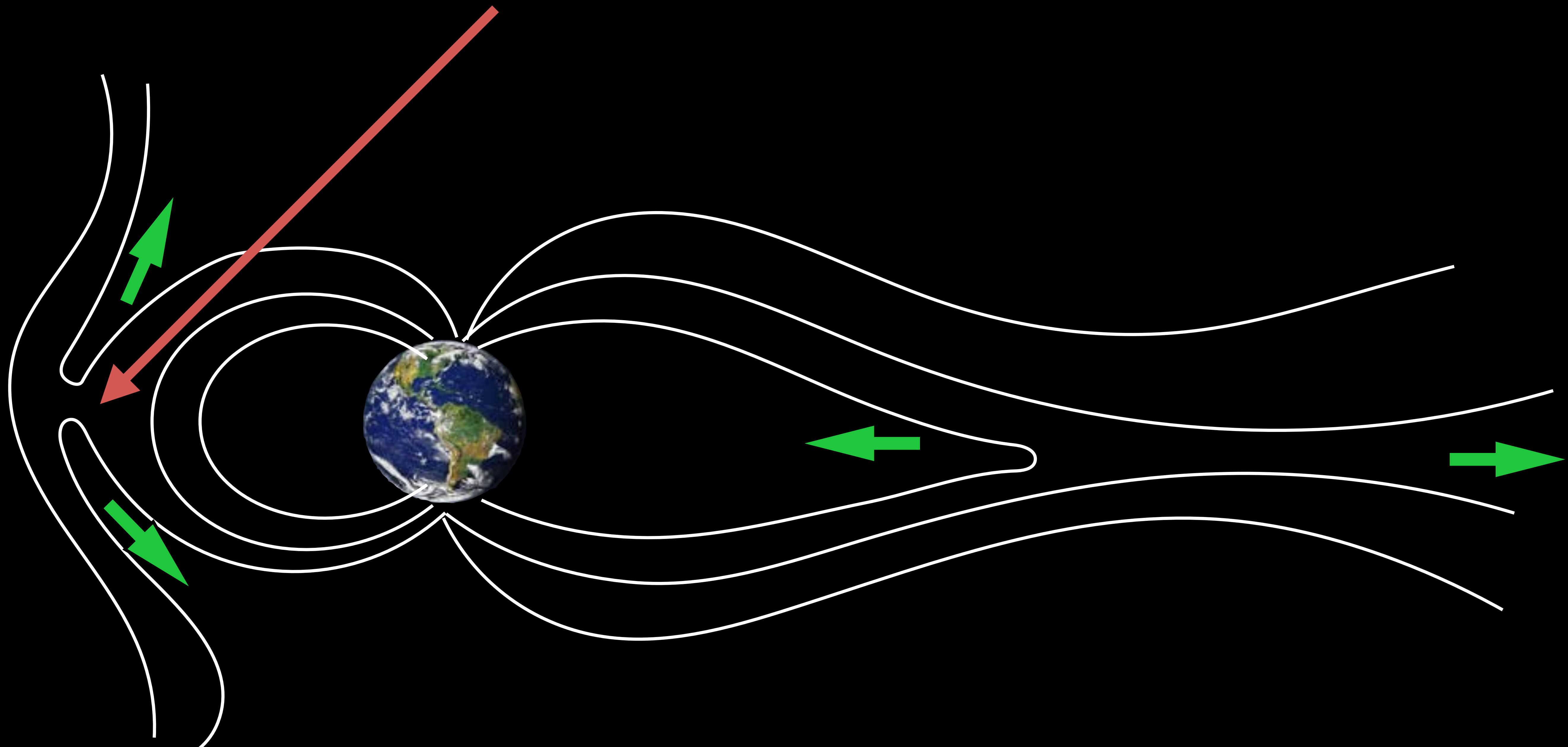
Energy transfer

Photospheric motions, current sheet build-up in high connectivity gradient regions, store energy for some time… onset?



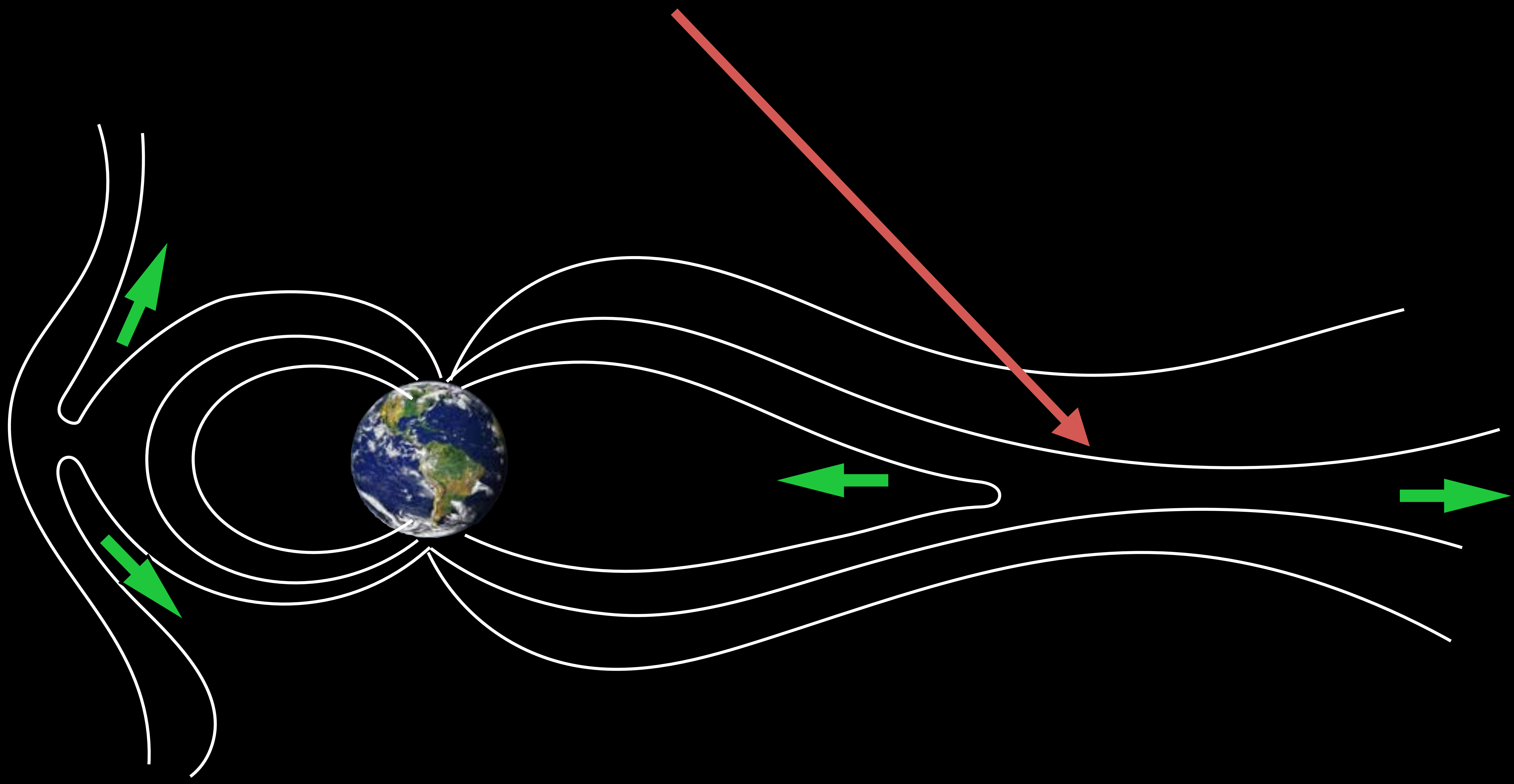
Energy transfer

Solar wind piles-up in the magnetosheath, magnetopause current increases, current sheet thins… onset?

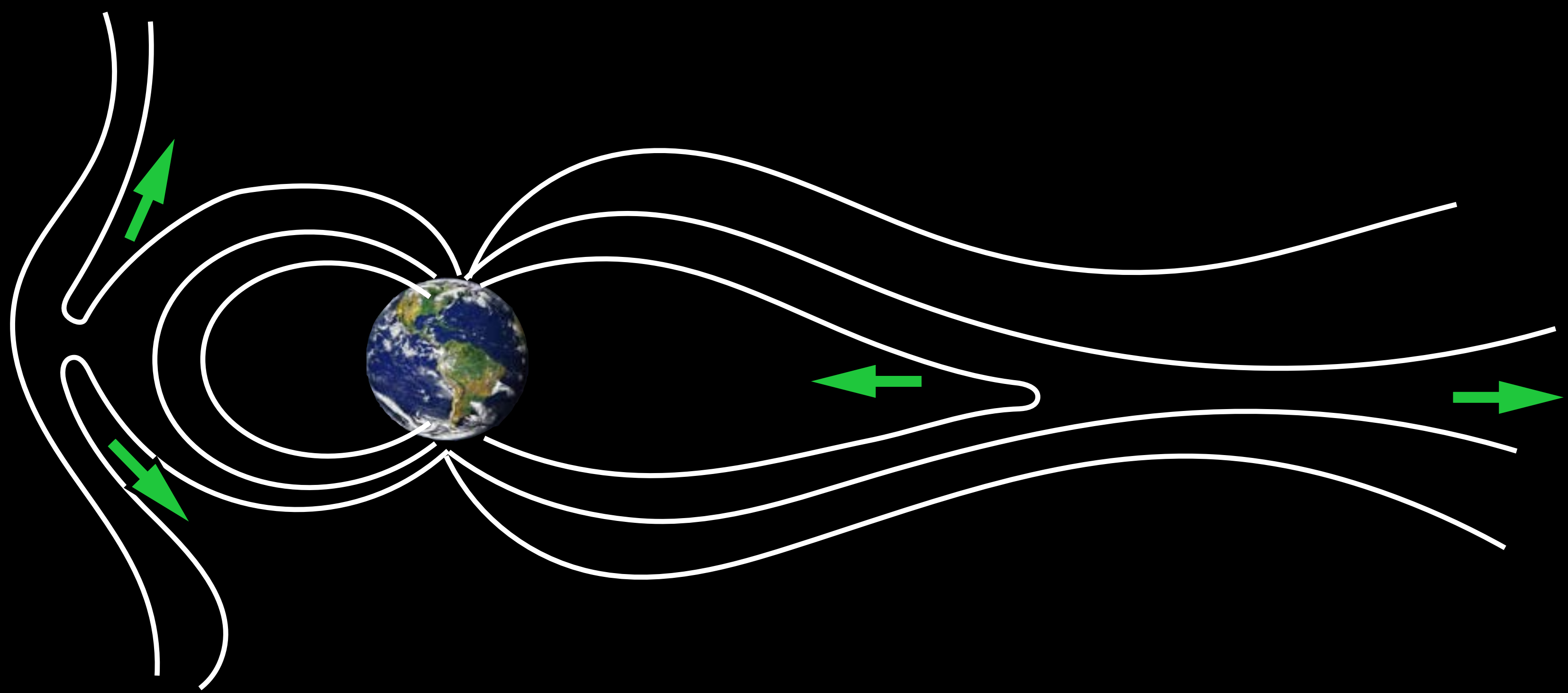


Energy transfer

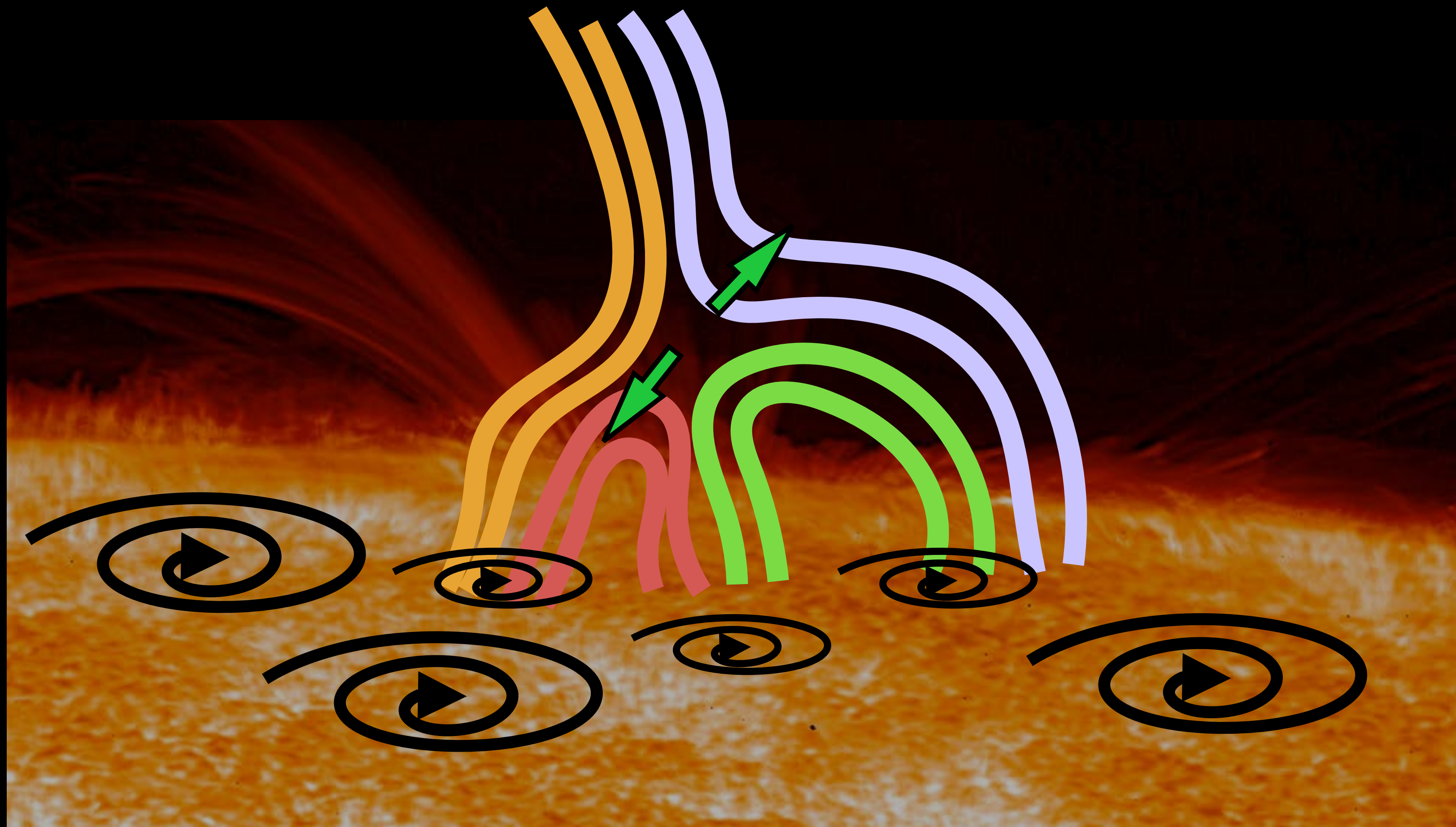
magnetic flux accumulates, current sheet thins… onset?



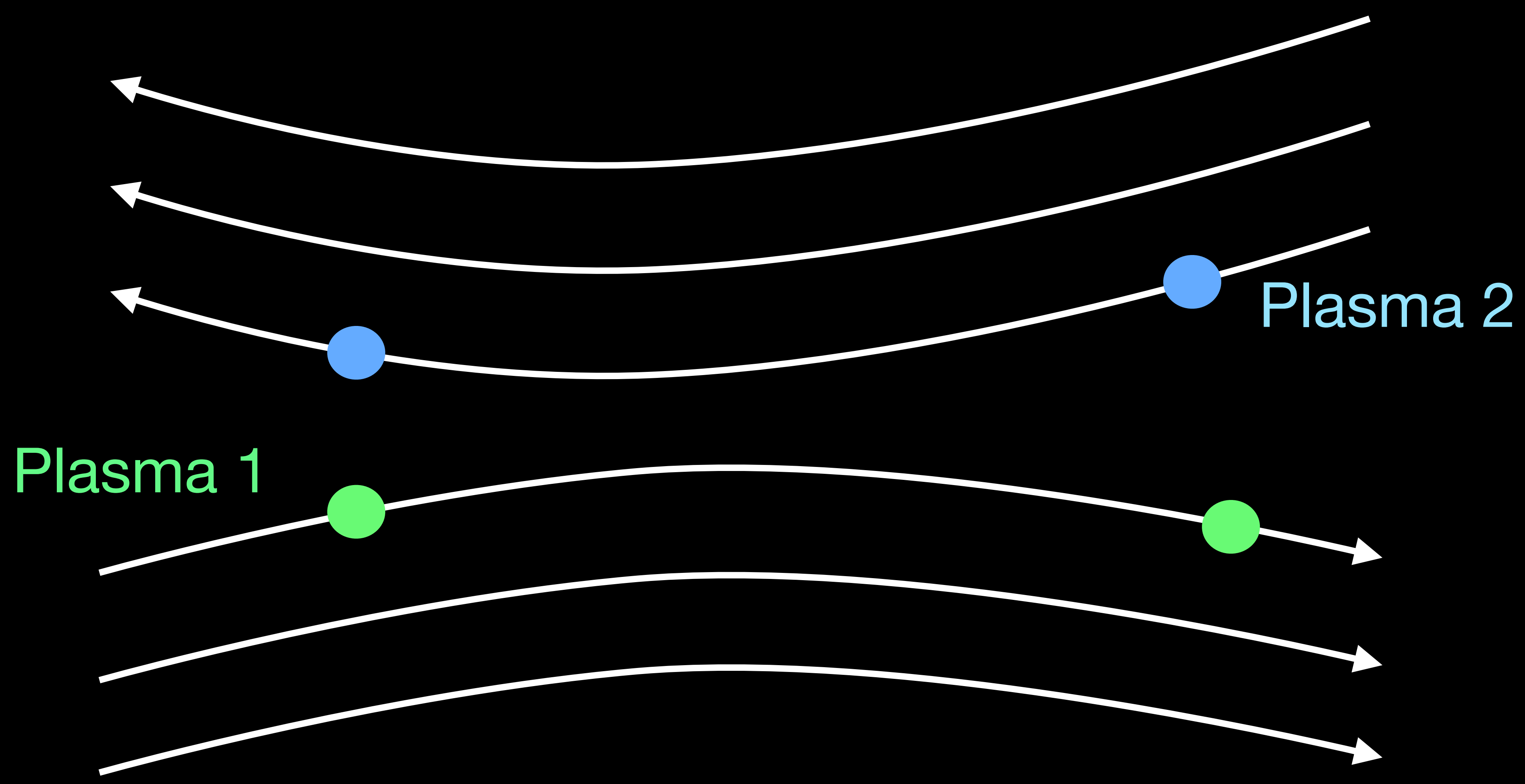
Energy transfer



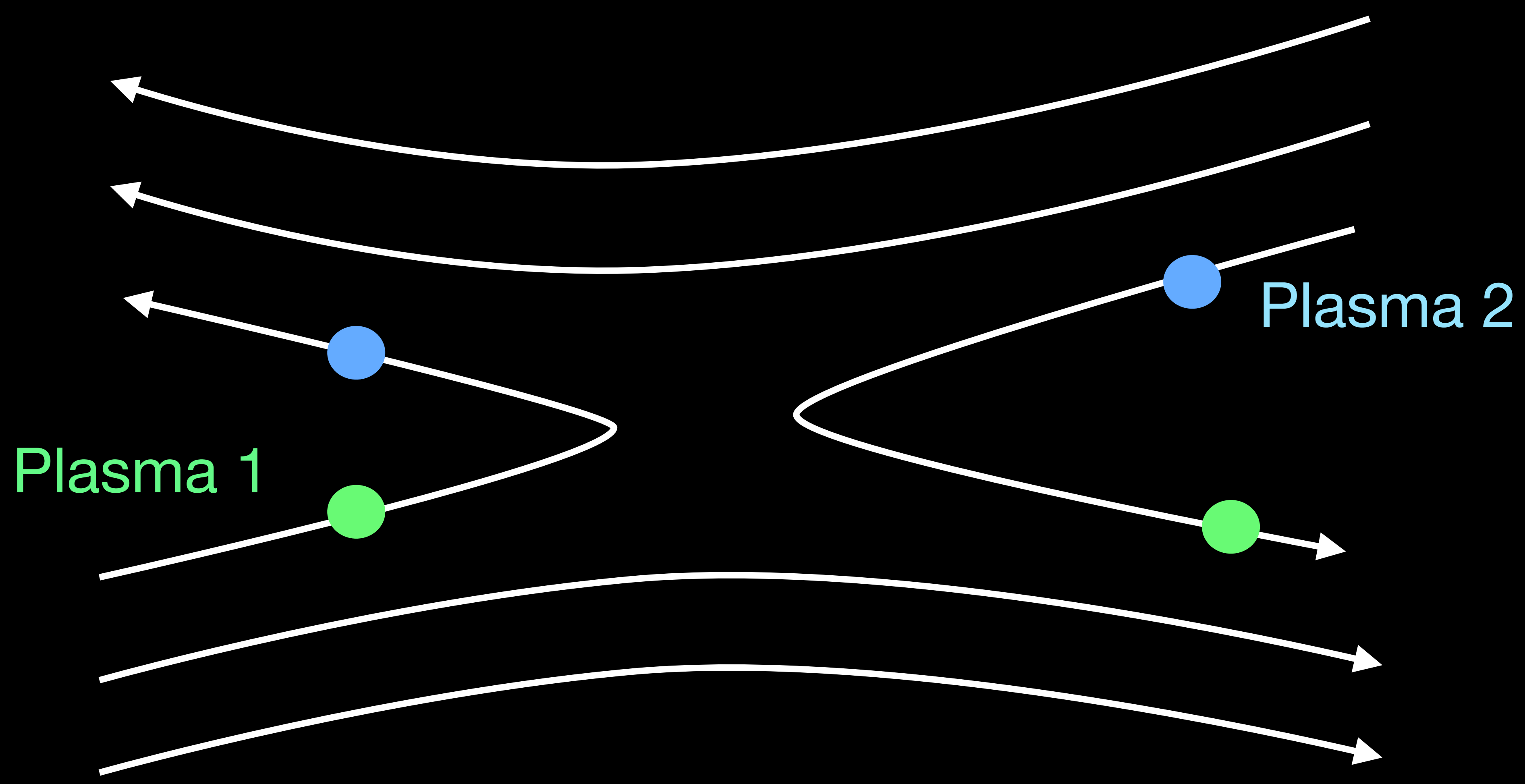
Very often energy is slowly stored in the system and suddenly released



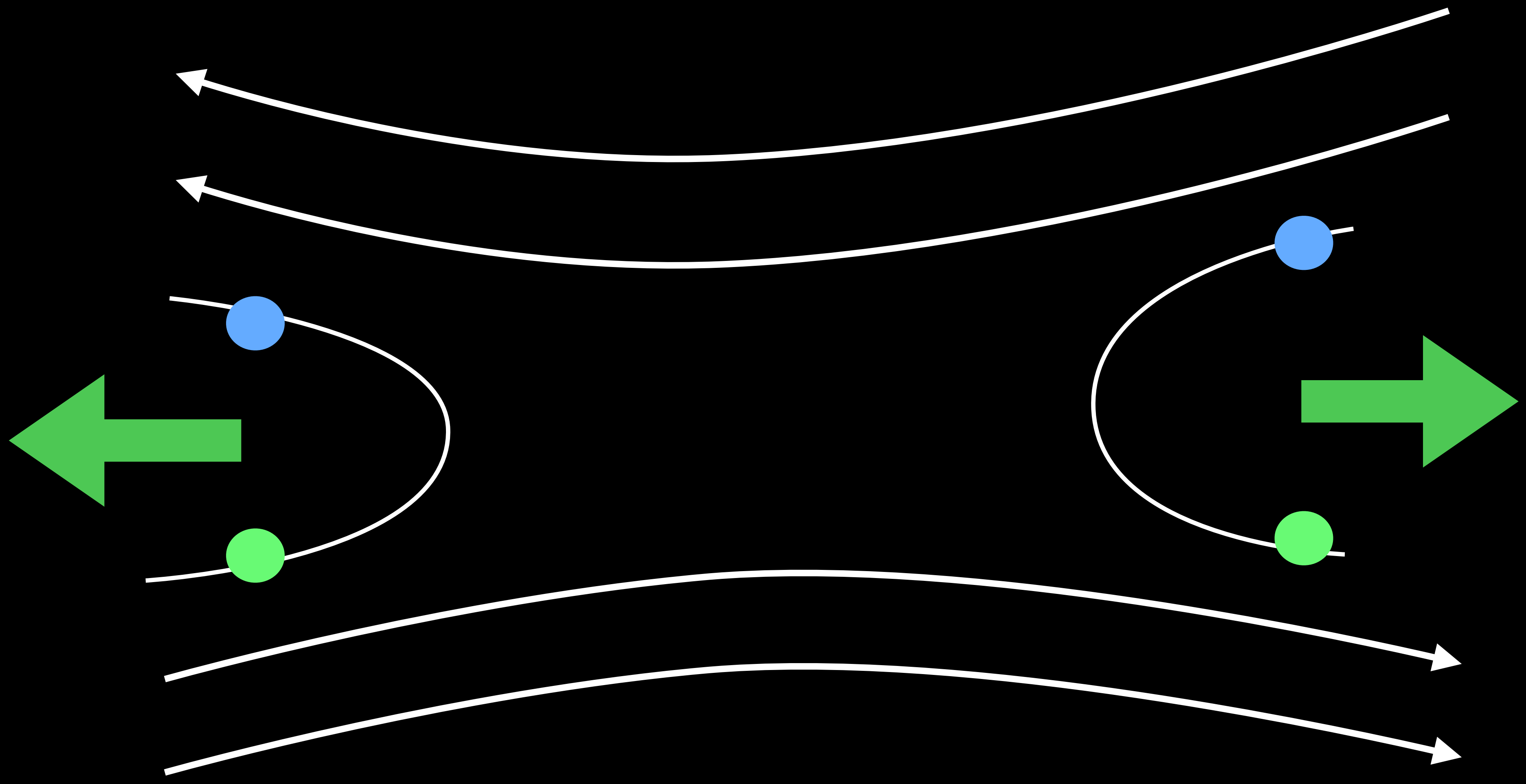
How does it work?
Two magnetized plasmas in « contact »



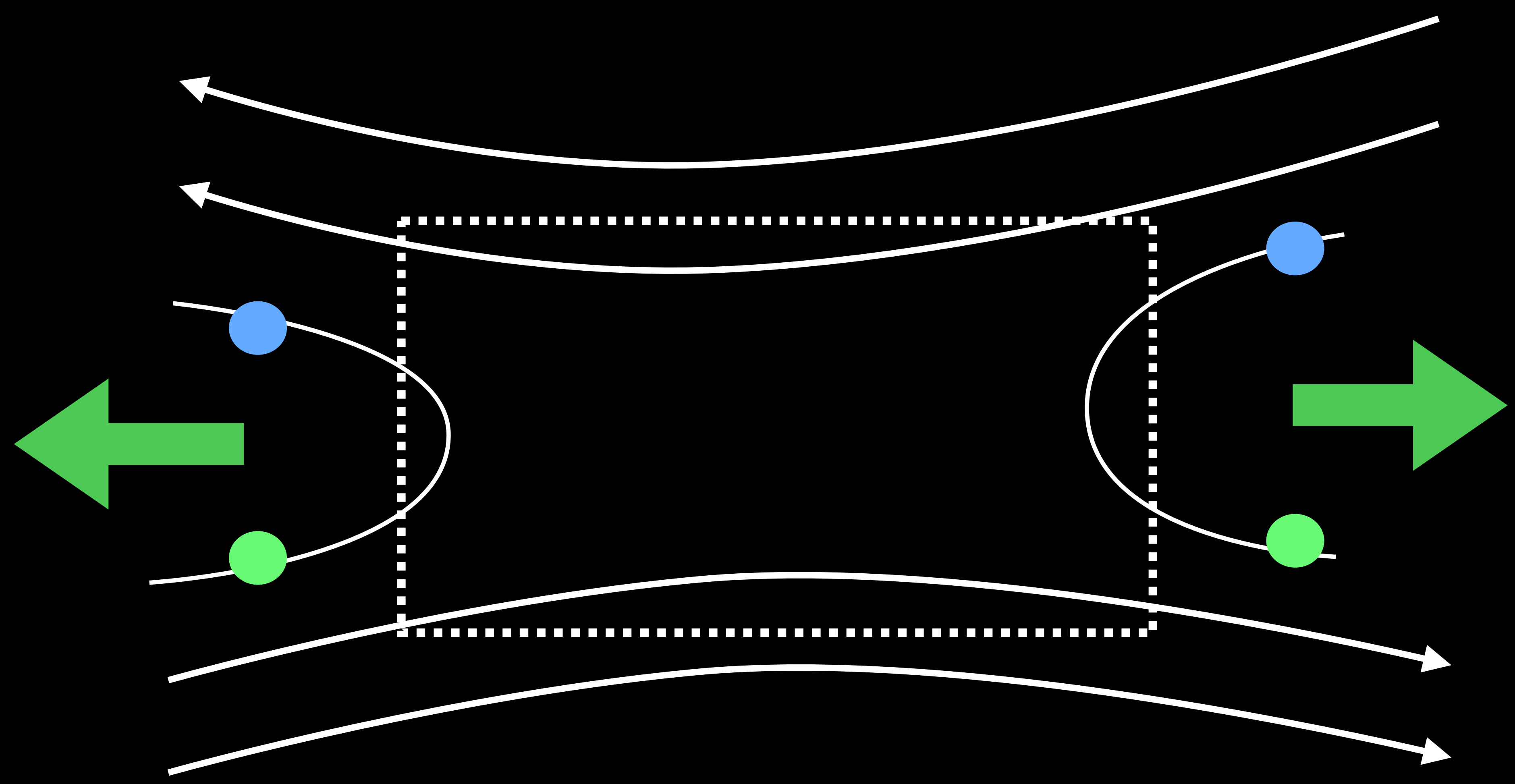
CAN BE RECONNECTED



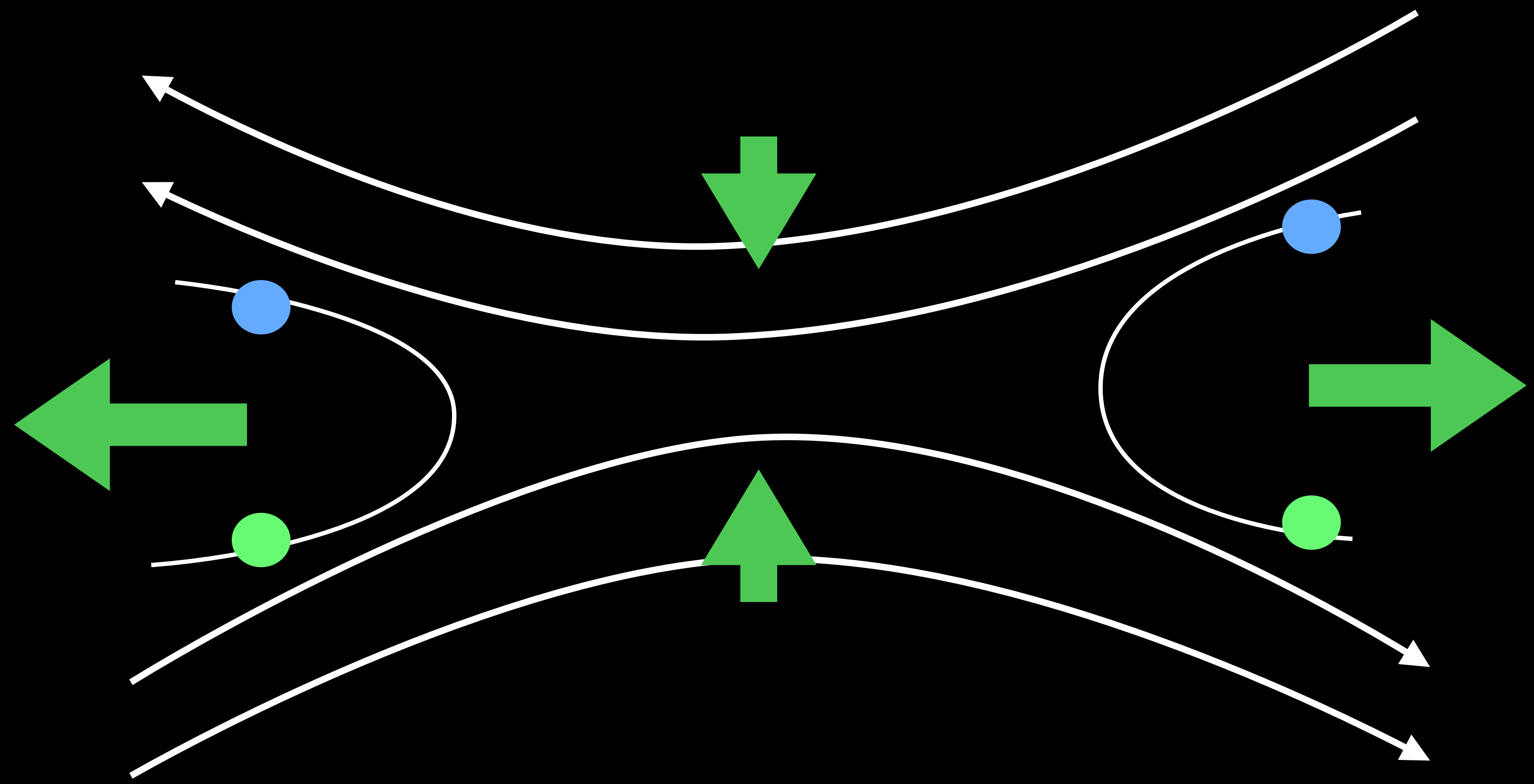
EJECTED FROM THE RECONNECTION SITE



EJECTED FROM THE RECONNECTION SITE

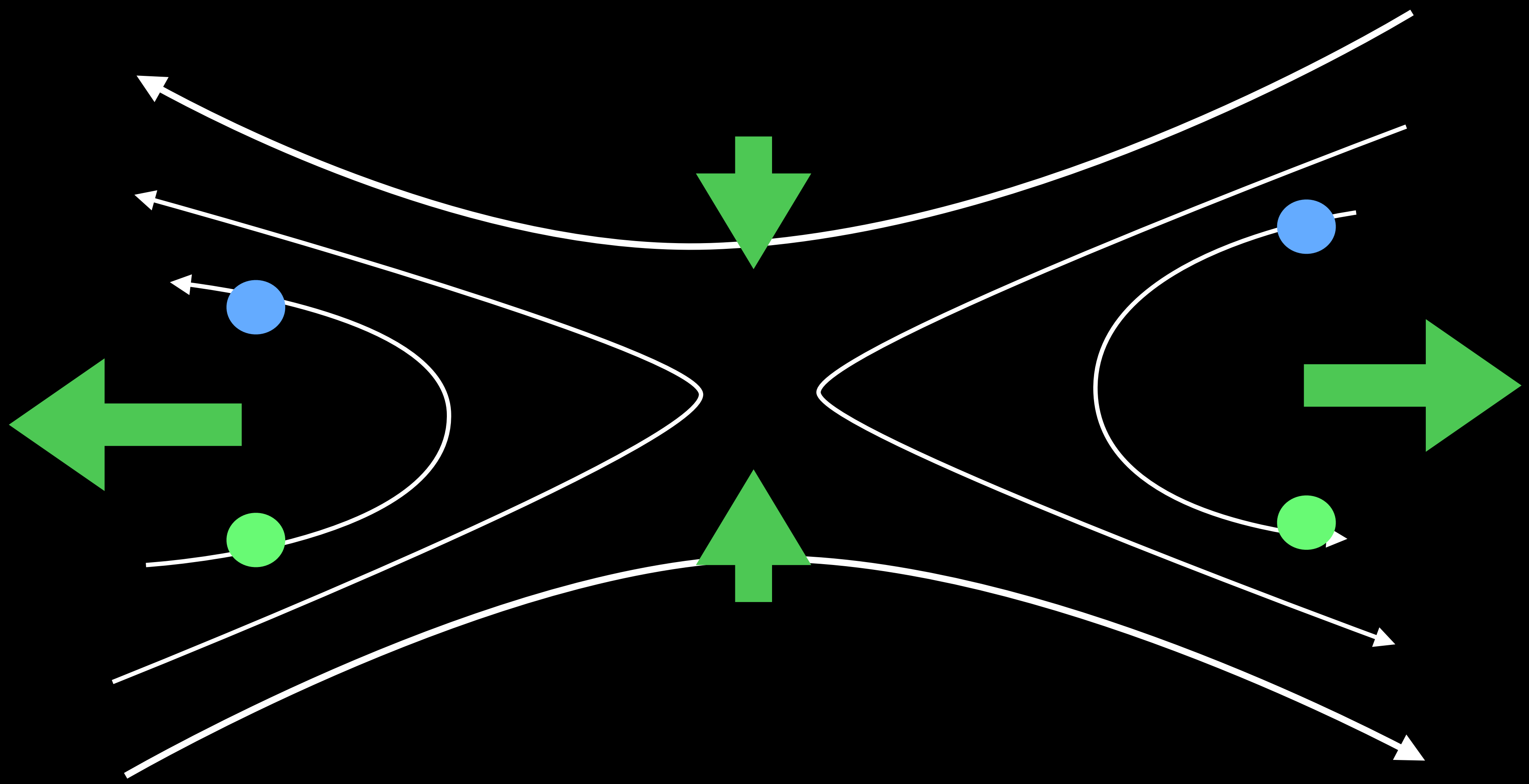


THIS DRIVES THE PULLING OF UPSTREAM FLUX AND PLASMA



WHICH IS RECONNECTED AND EJECTED

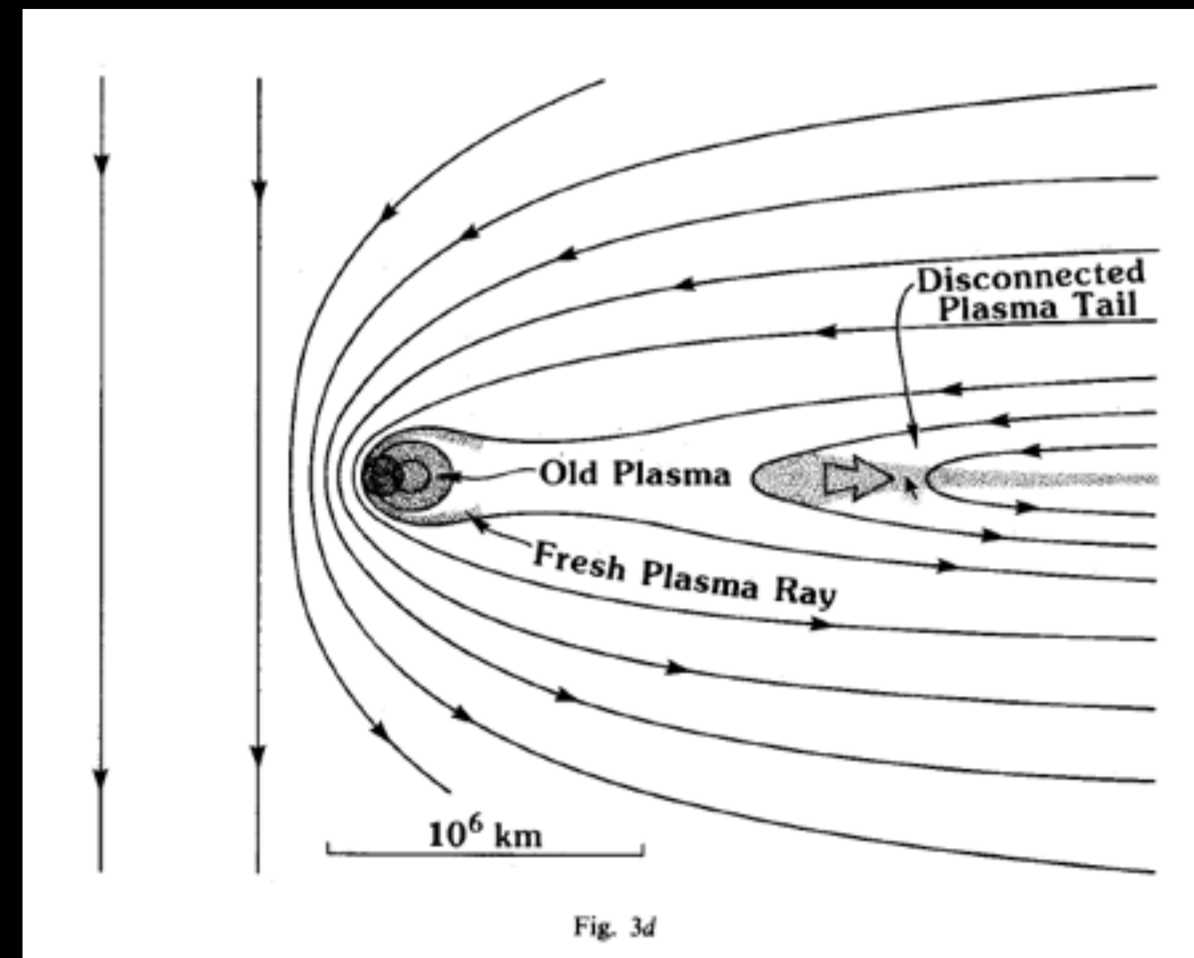
ETC. ETC. AND THE PROCESS IS SELF MAINTAINED



HOW MUCH FLUX DOES IT RECONNECT PER TIME UNIT?

« Seeing reconnection »


Comet Encke seen from Stereo

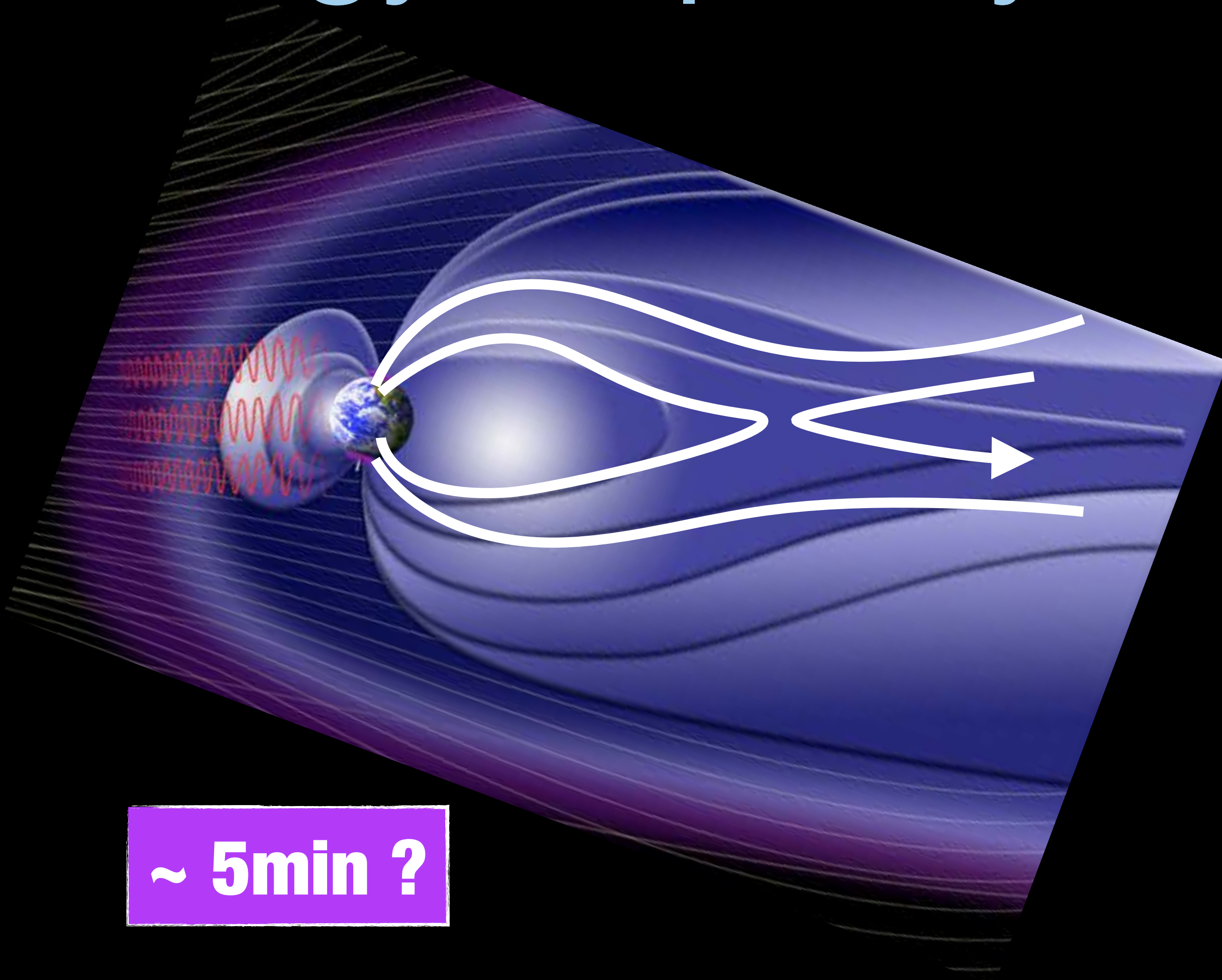


(Russel et al. JGR 1986)

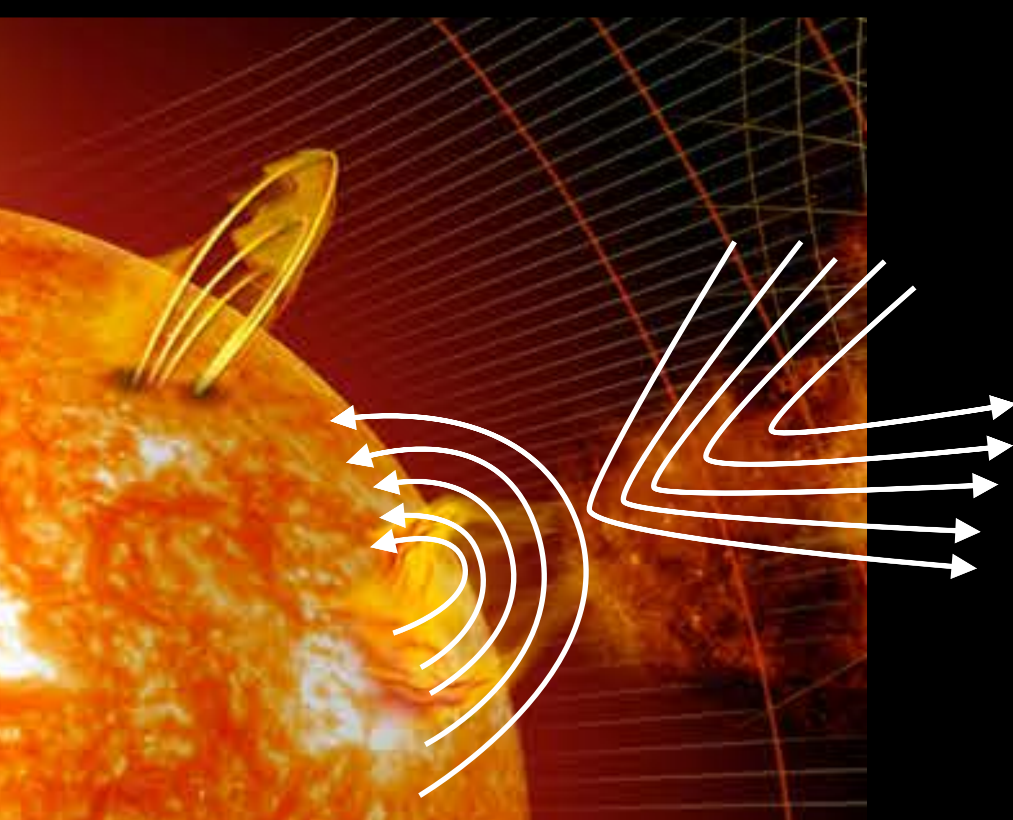
Chap. 3 - The Rate problem

How can reconnection be fast enough?

Energy is quickly released..



~ 5min ?



1950's

1960's

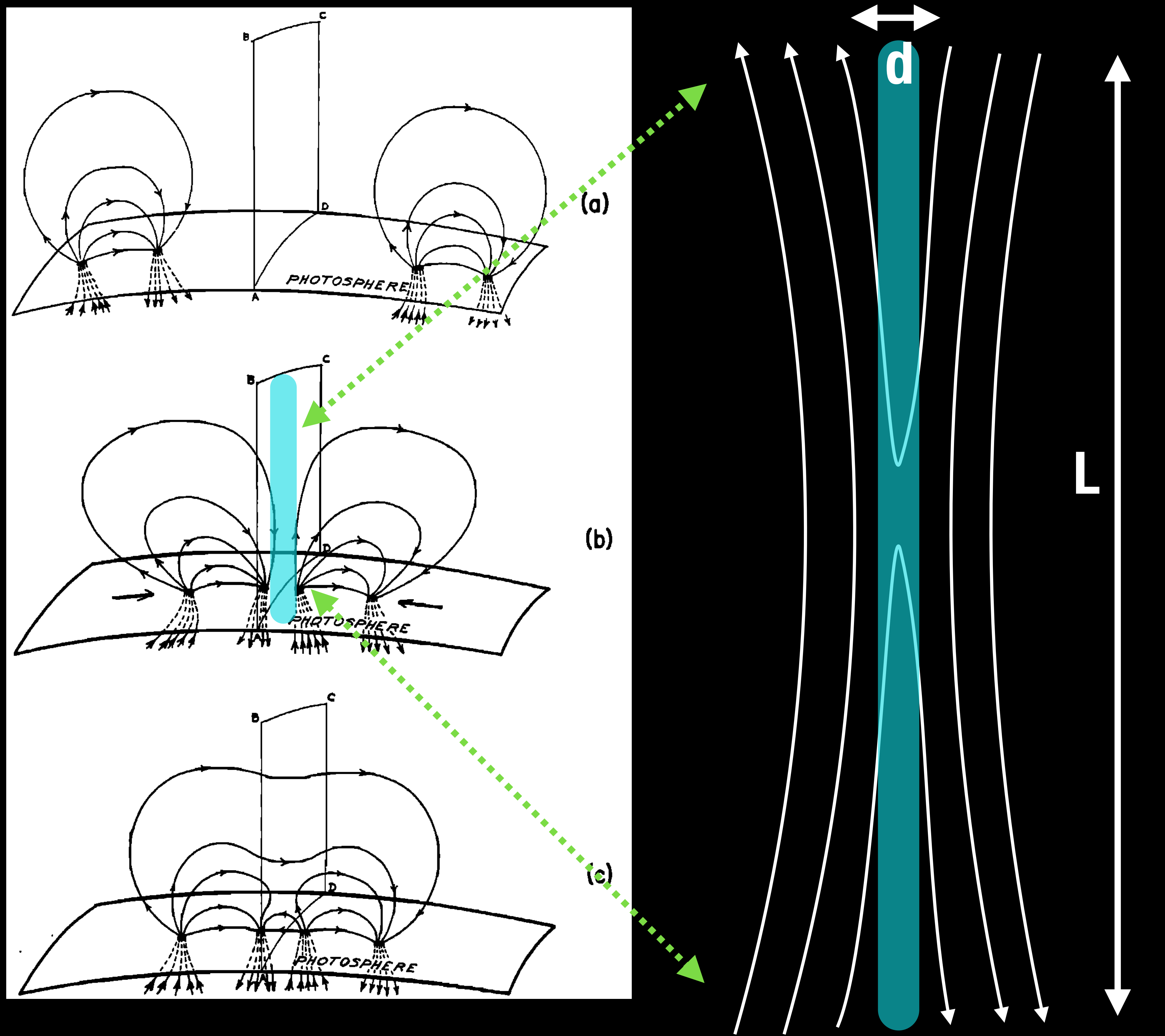
P. Sweet

E. Parker

H. Petschek

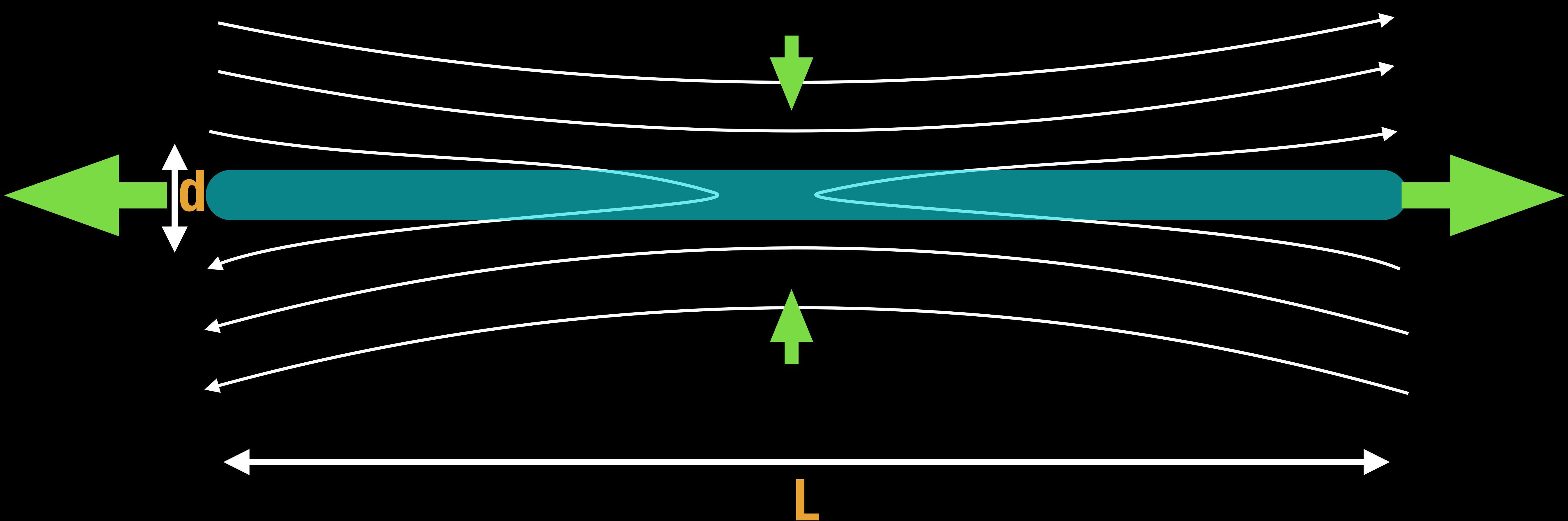
Sweet-Parker Reconnection Model

1950's



Sweet-Parker Reconnection Model

1950's



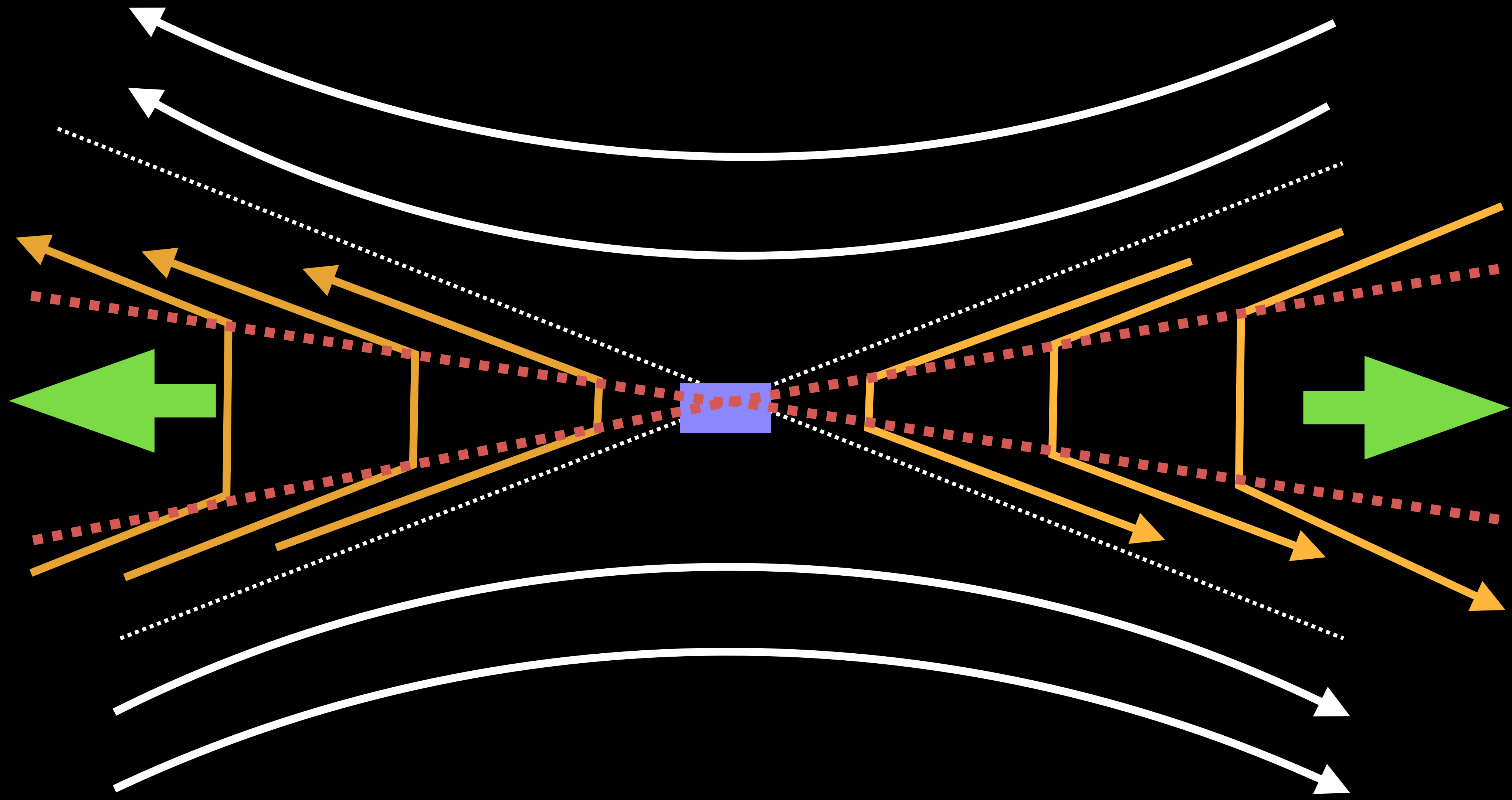
D : IS THE DIFFUSION SCALE LENGTH : VERY SMALL IN WEAKLY COLLISIONAL PLASMAS

L : IS COMPARABLE TO THE CHARACTERISTIC SIZE OF THE RECONNECTING SYSTEM : HUGE IN ASTROPHYSICS

$$v_{in} \sim \frac{d}{L} V_A$$

Petschek Reconnection Model

1960's



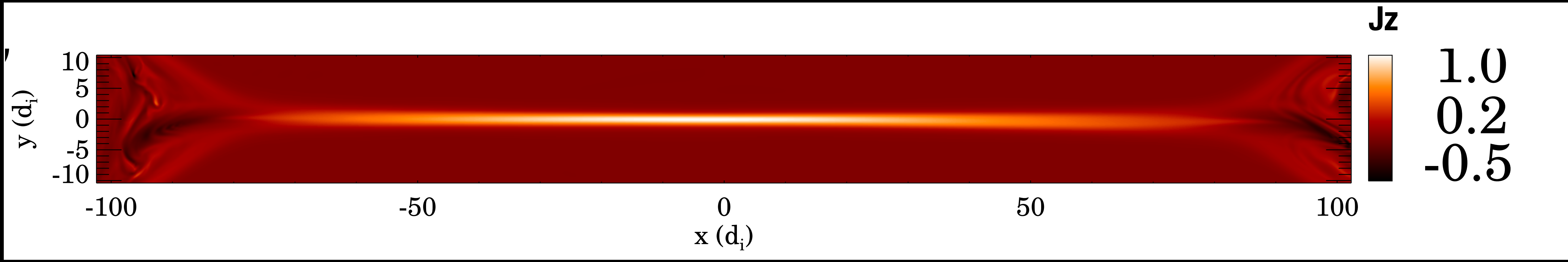
Dissipation region is (chosen to be) localized in both directions

No bottleneck, FAST RECONNECTION

The plasma is accelerated through shocks (switch-off slow shocks)

Problem : can't justify the local enhancement of resistivity

Resistive MHD simulation



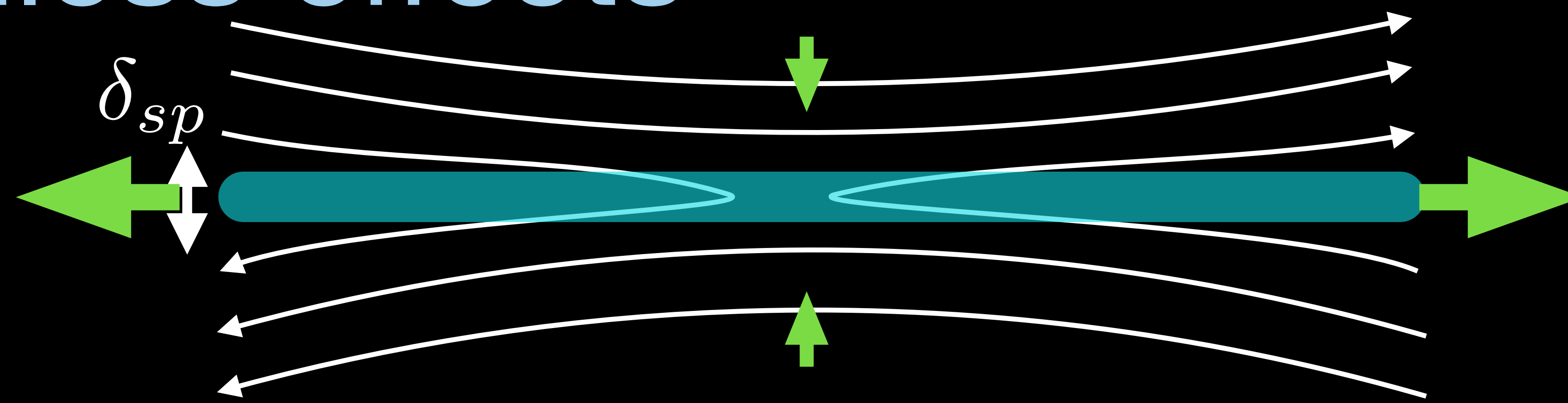
(Cassak et al. 2006)

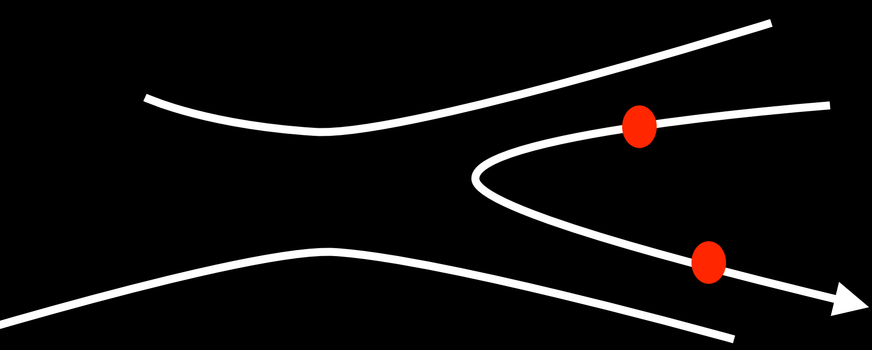
Macroscopic (system size) current sheet with a resistive width

SWEET-PARKER MECHANISM

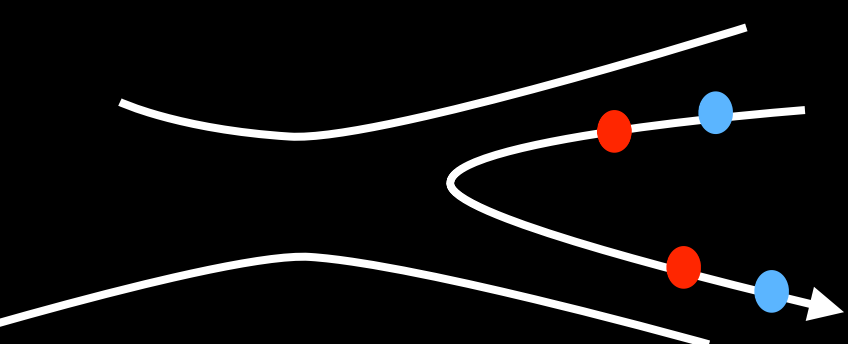
Unless you strongly enhance the resistivity locally : create the black box

Collisionless effects

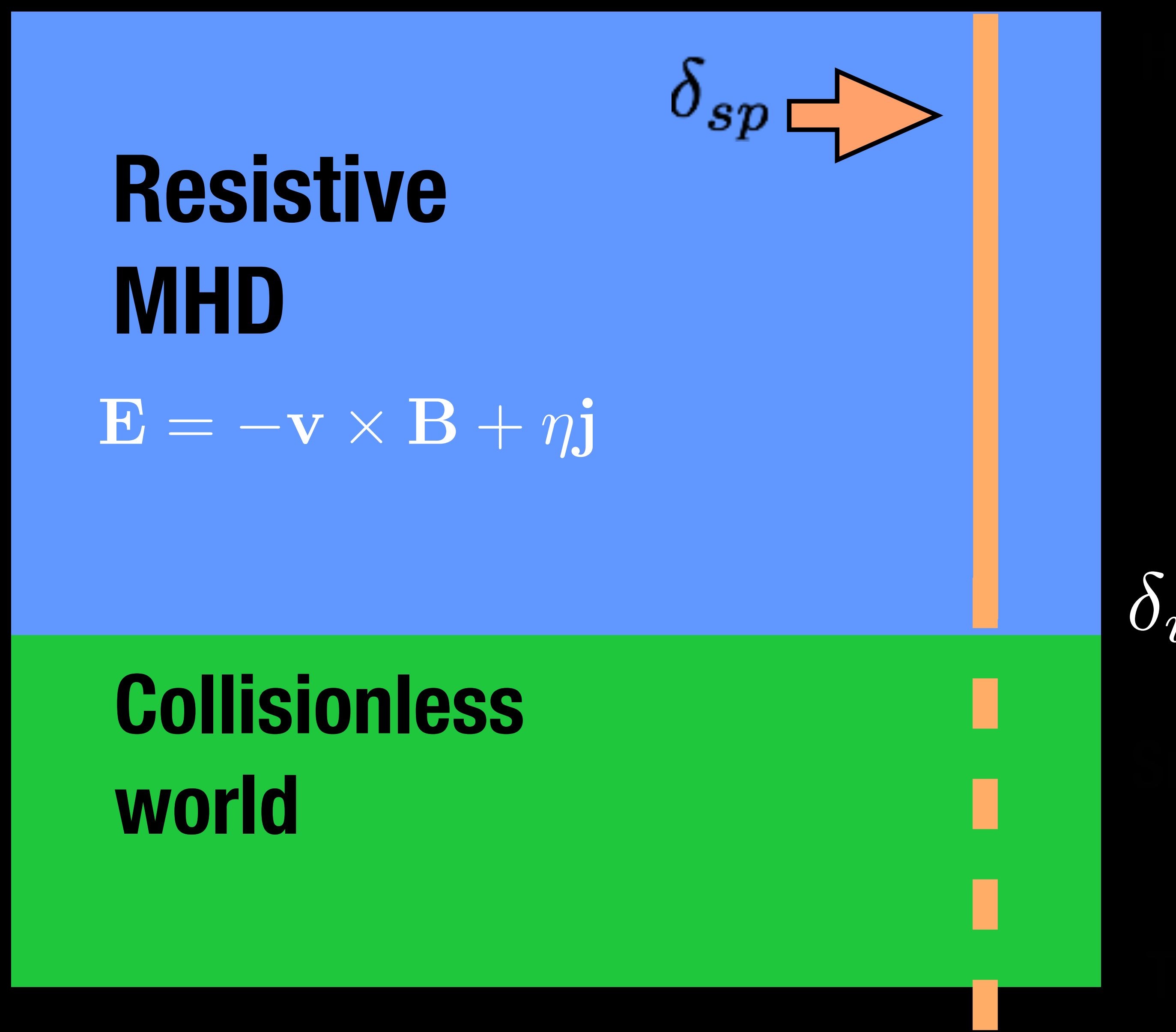




SINGLE FLUID FROZEN IN THE MAGNETIC FIELD

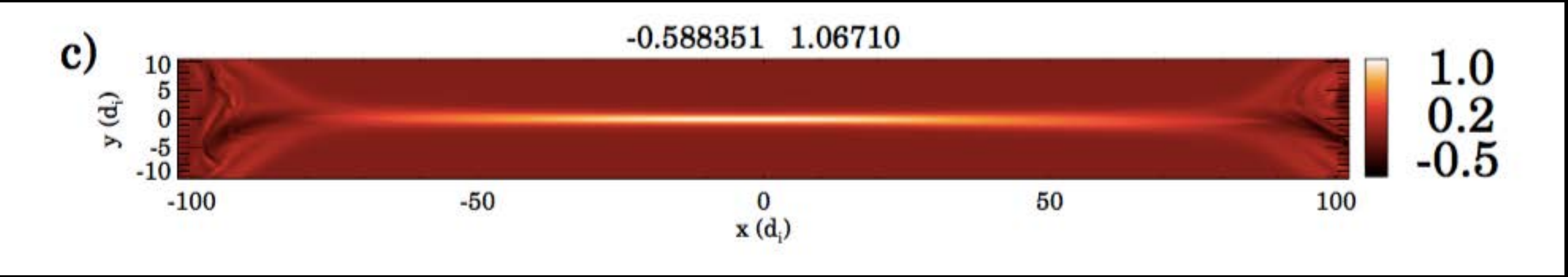


ONLY ELECTRONS ARE ASSUMED TO BE FROZEN IN B. ION INERTIA ALLOW THEM TO DETACH AT SMALL SCALES

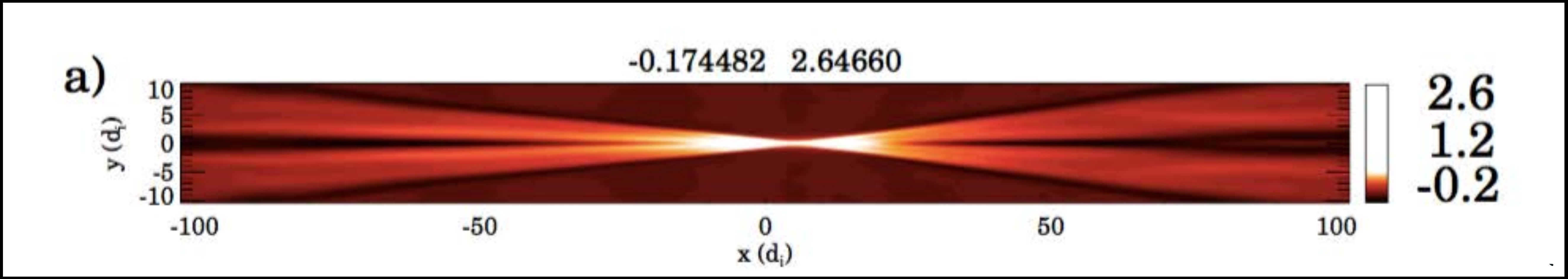


$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + k\delta_i \frac{\mathbf{j} \times \mathbf{B}}{ne} - k\beta_e \delta_i \frac{\nabla P_e}{ne}$$

Hall MHD leads to fast reconnection



$$\delta_{SP} < \delta_i$$

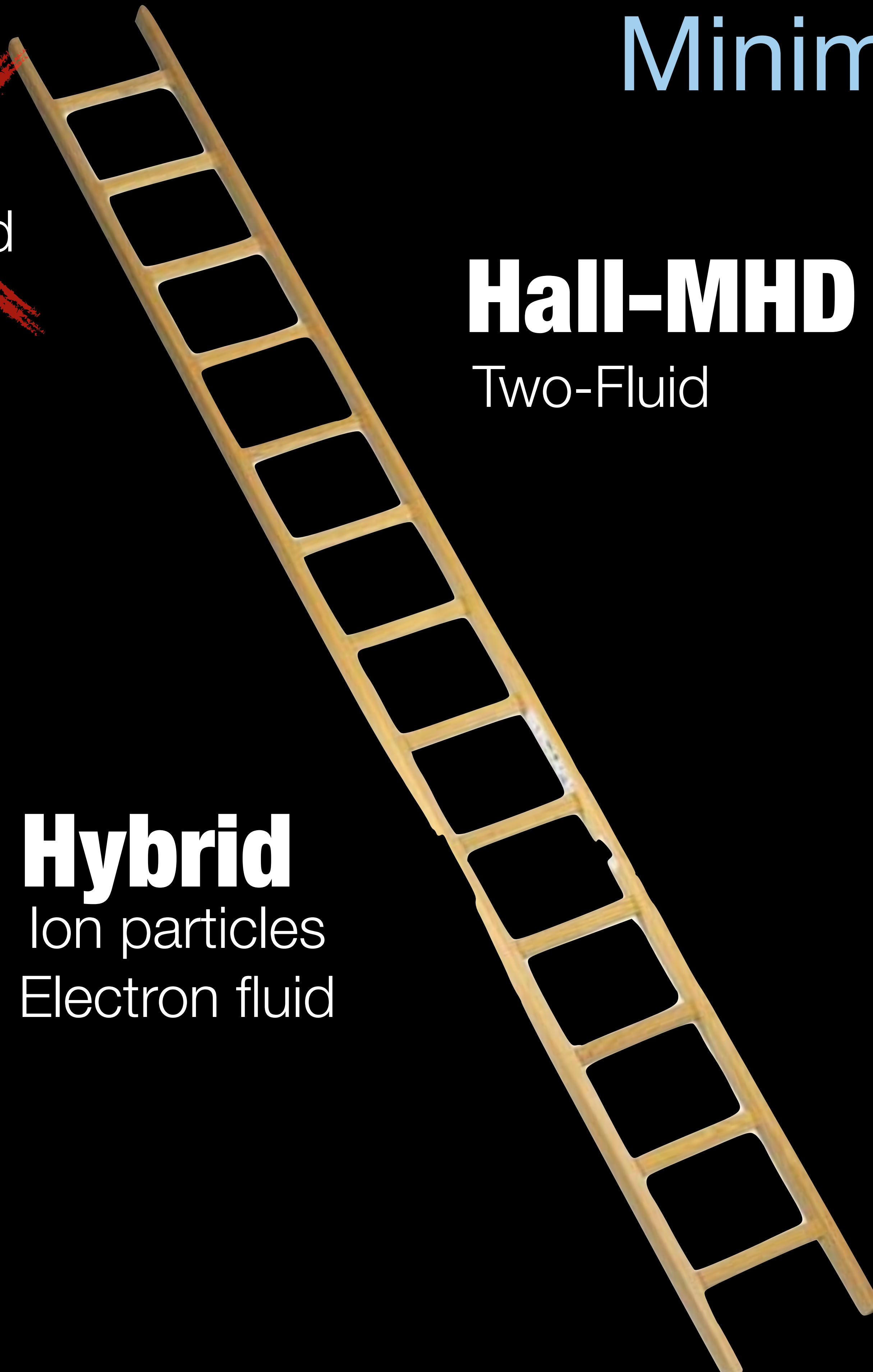


(Cassak et al. 2006)

Minimum model?

~~MHD~~

~~Single Fluid~~



Hall-MHD

Two-Fluid

Hybrid

Ion particles

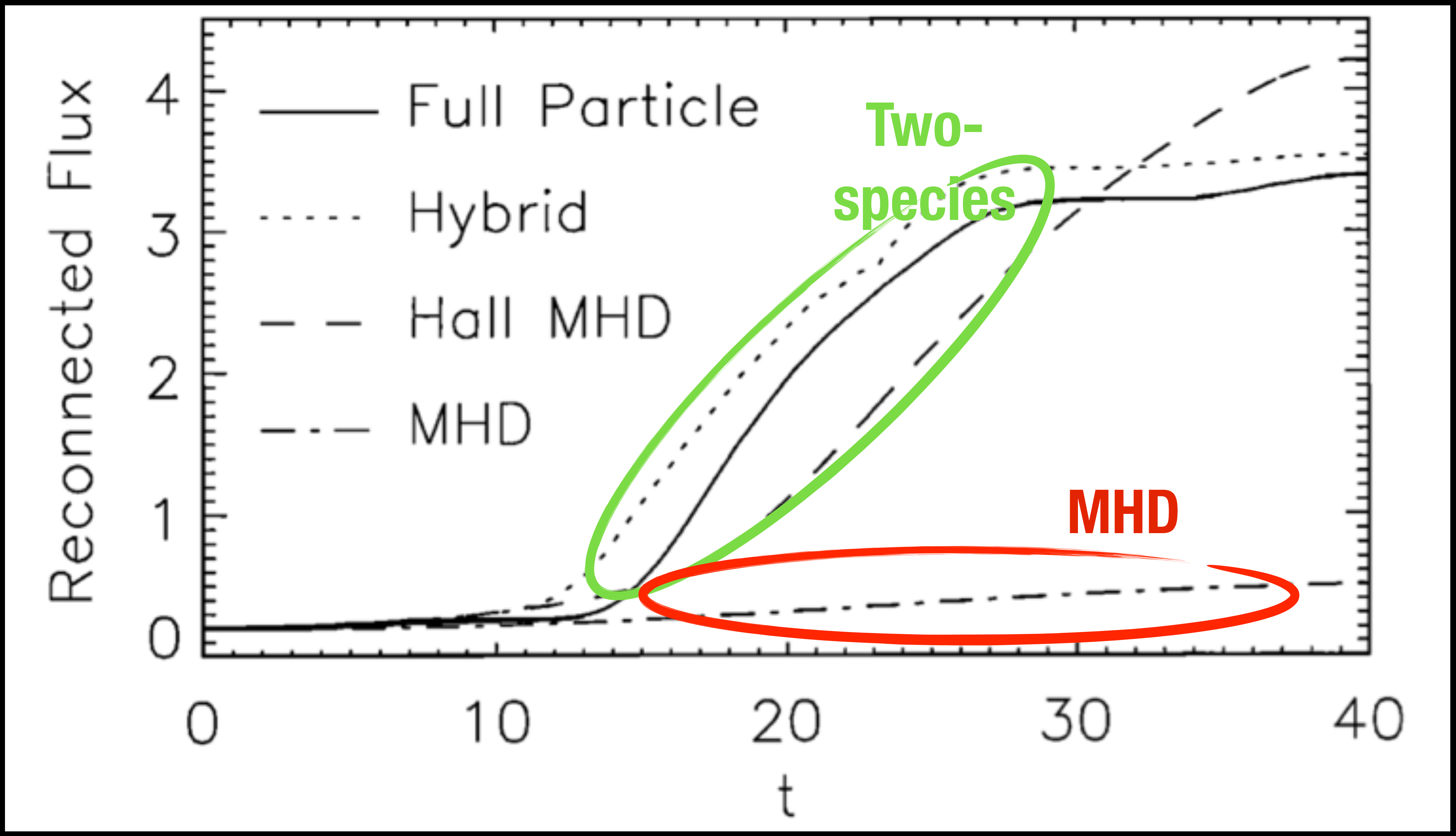
Electron fluid

Full-PIC

Ion particles

Electron particles

« Standard » collisionless reconnection model



$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{1}{ne}\left(\mathbf{j} \times \mathbf{B} - \boldsymbol{\nabla} \cdot \mathbf{P}_e\right)$$

Fully kinetic codes

Lagrangian Vlasov $$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

$$m_i \frac{d\mathbf{v}_{pi}}{dt} = e\left(\mathbf{v}_{pi} \times +\mathbf{B} + \mathbf{E}\right)$$

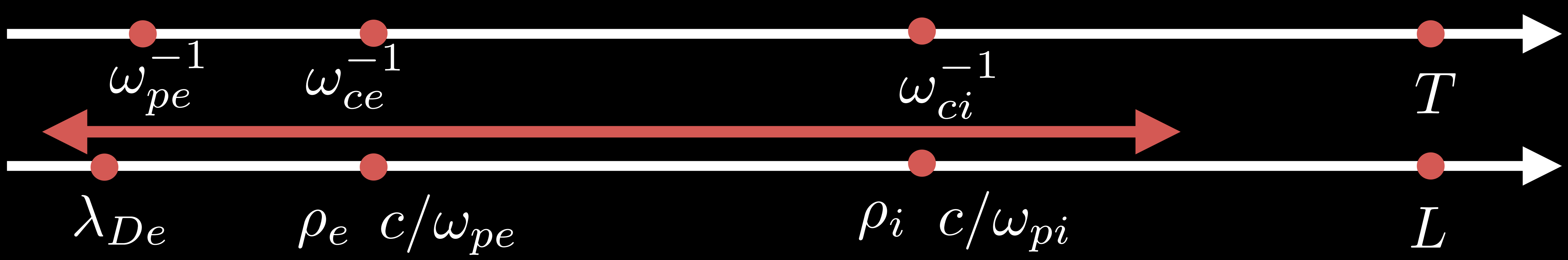
Move macroparticles

Interpolate moments on grid

Solve fields on grid

$$\frac{\partial \mathbf{E}}{\partial t} = c^2 \left(\boldsymbol{\nabla} \times \mathbf{B} - \mu_0 \mathbf{j}\right) \qquad \frac{\partial \mathbf{B}}{\partial t} = -\boldsymbol{\nabla} \times \mathbf{E}$$

Interpolate fields on macroparticles



HYBRID CODES

Lagrangian Vlasov for **IONS**

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

$$m_i \frac{d\mathbf{v}_{pi}}{dt} = e\left(\mathbf{v}_{pi} \times +\mathbf{B} + \mathbf{E}\right)$$

Move ion macroparticles

Interpolate moments on grid

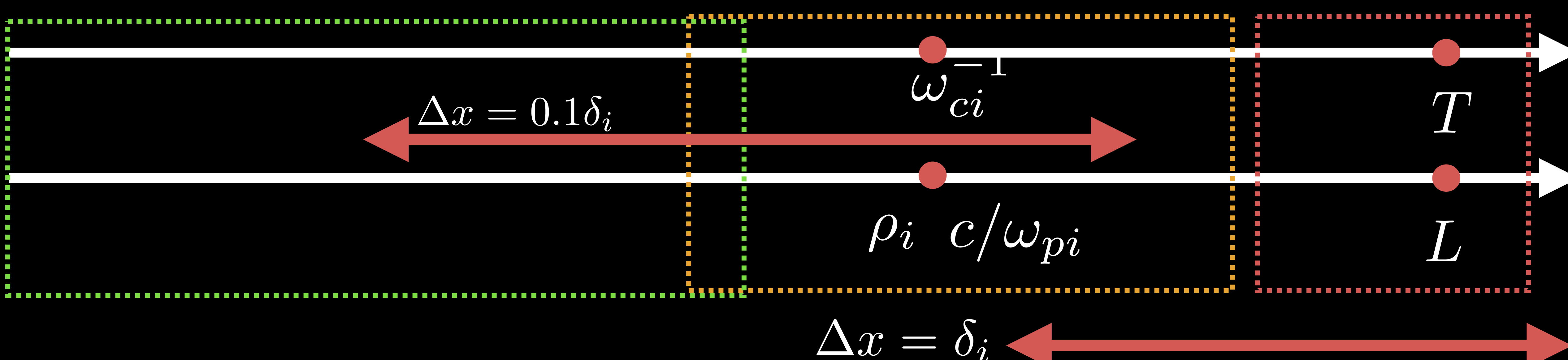
Interpolate fields on ion macroparticles

Solve fields on grid

$$\frac{\partial \mathbf{B}}{\partial t} = -\boldsymbol{\nabla} \times \mathbf{E}$$

$$\boldsymbol{\nabla} \times \mathbf{B} = \mu_0 \mathbf{j}$$

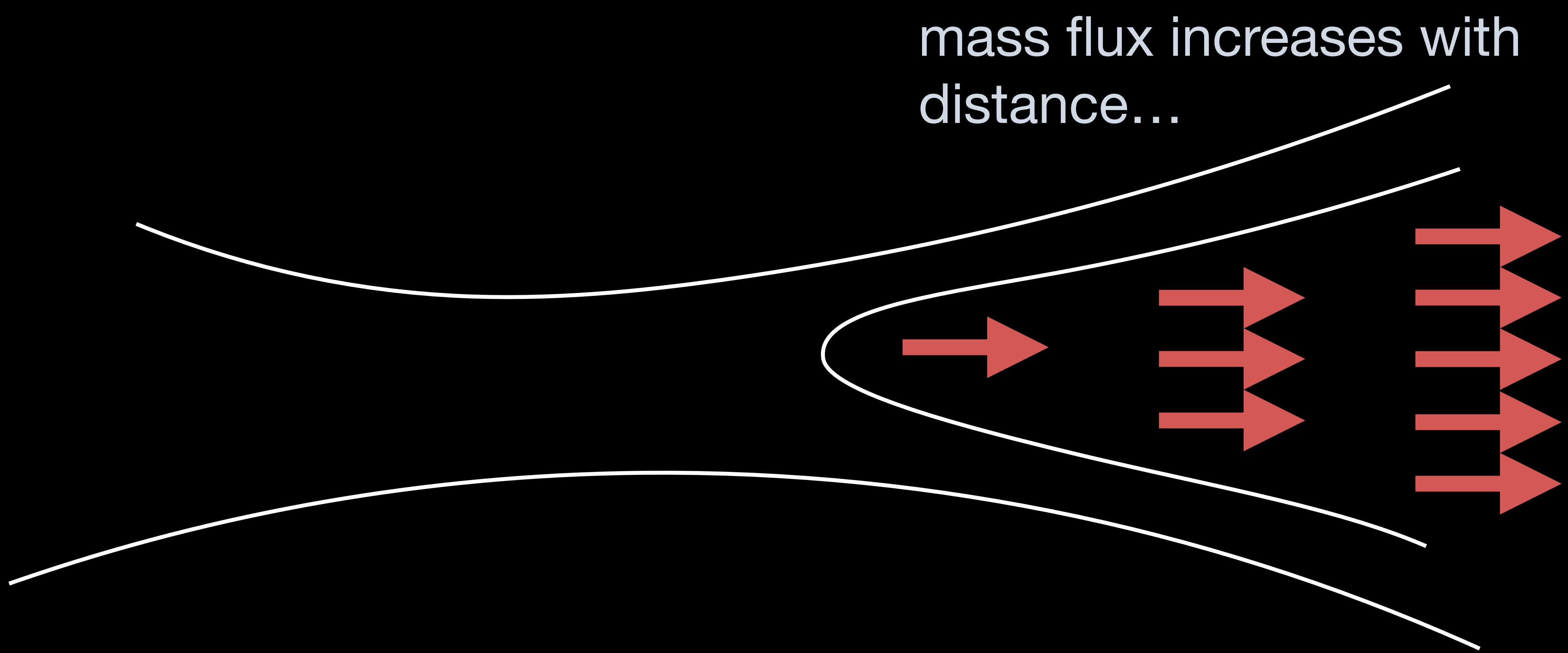
$$\mathbf{E} = \boxed{-\mathbf{v}_i \times \mathbf{B}} + \boxed{\frac{1}{ne}\left(\mathbf{j} \times \mathbf{B} - \boldsymbol{\nabla} \cdot \mathbf{P}_e\right)}\boxed{+\,\mathbf{D}}$$



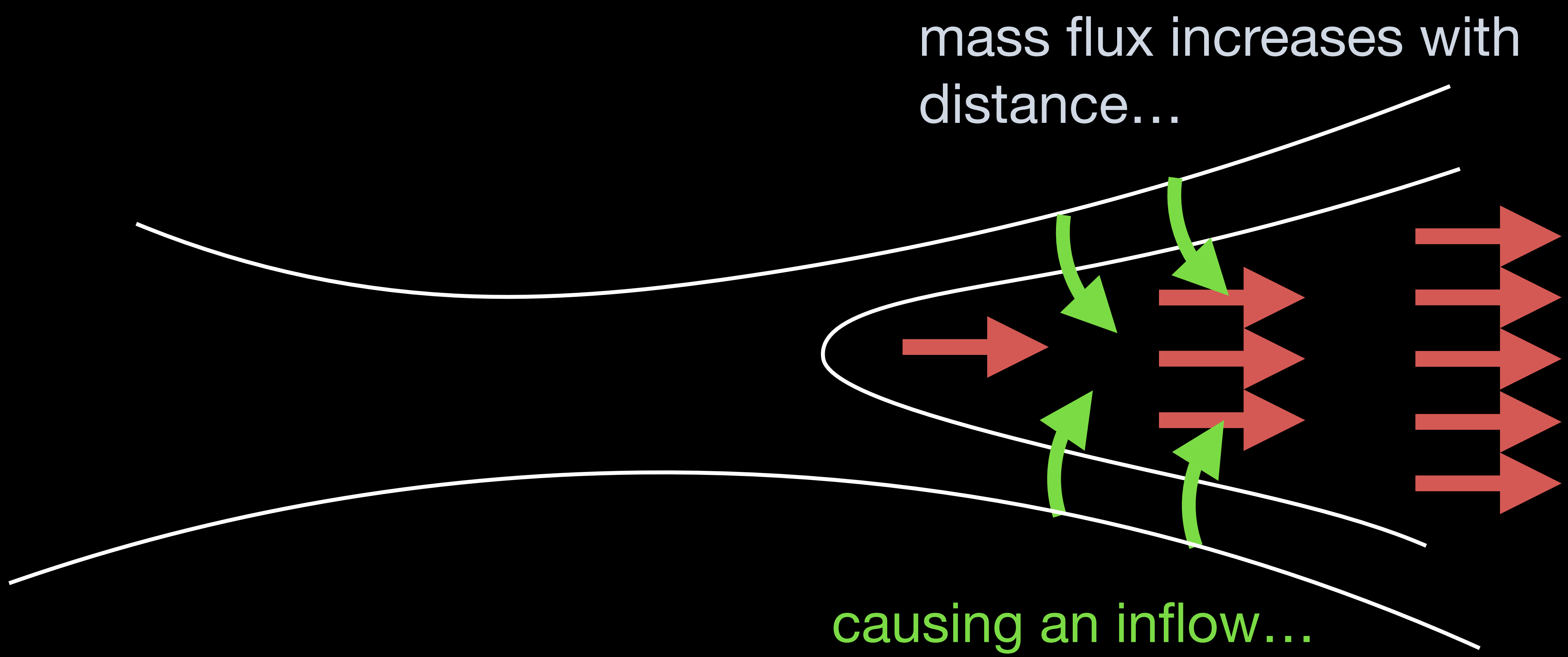
Chap. 4 - collisionless reconnection

Ion and electron collisionless dynamics

Imagine we have an open outflow with no
« dispersive velocity »



Imagine we have an open outflow with no « dispersive velocity »



Imagine we have an open outflow with no
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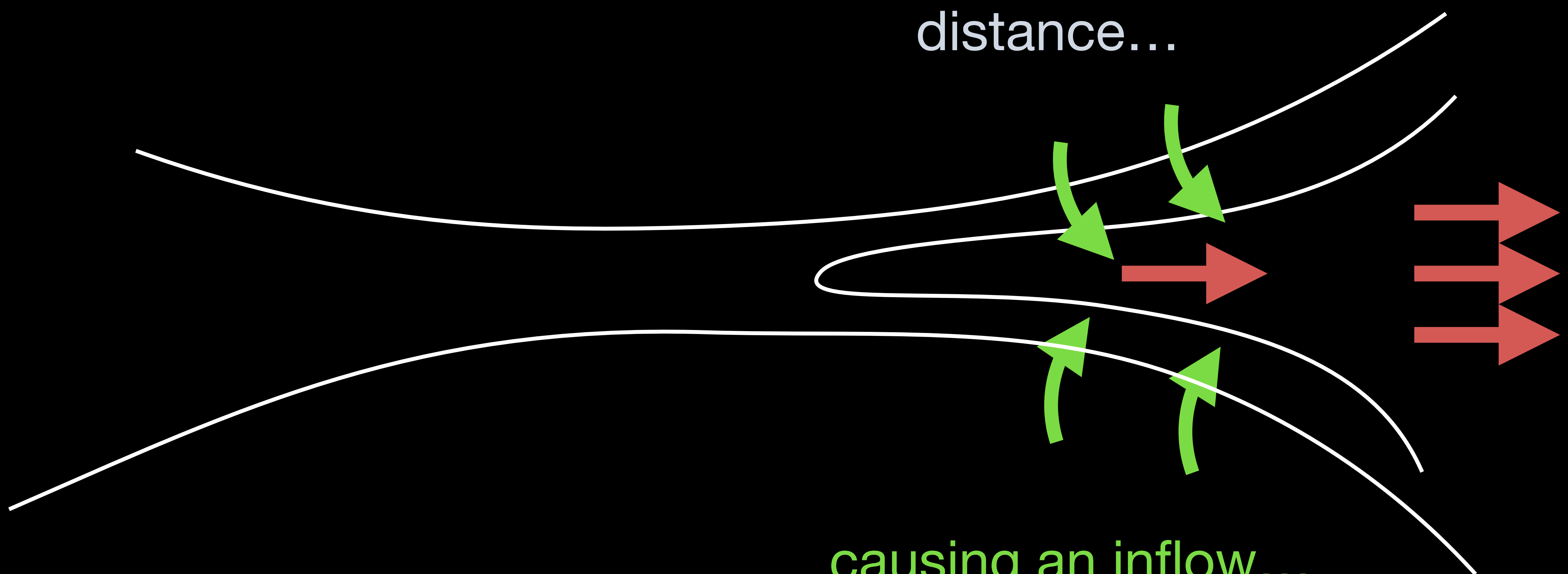
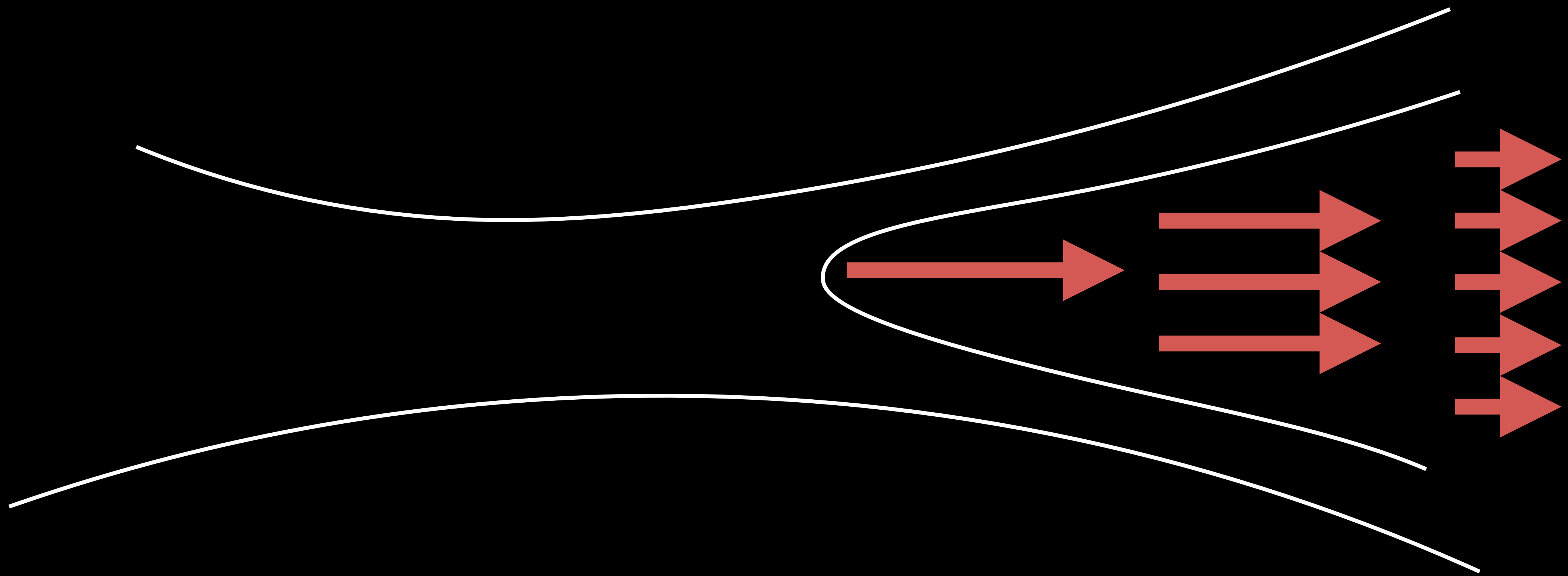


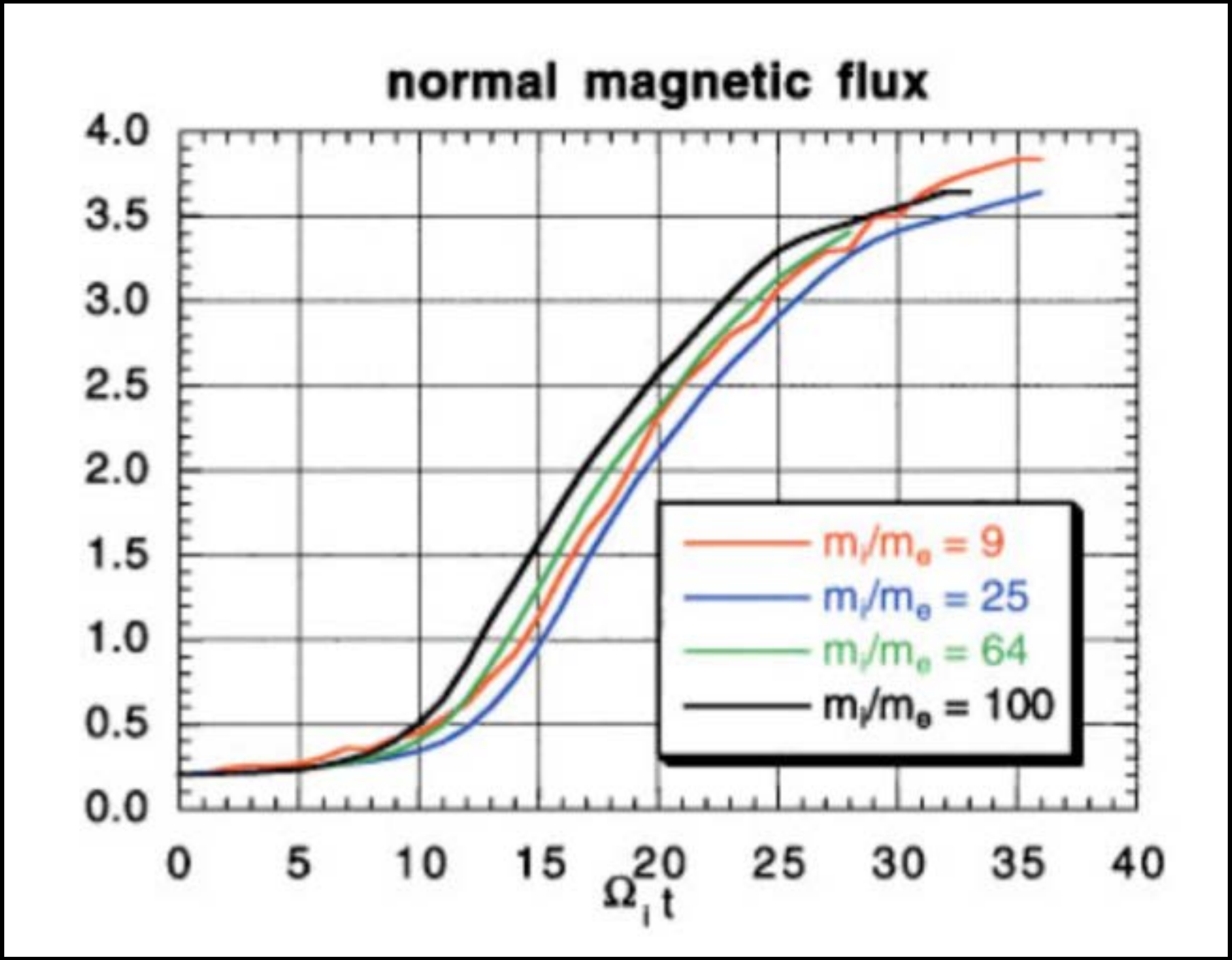
Sweet-Parker solution

Imagine we have an open outflow **with** « dispersive velocity »



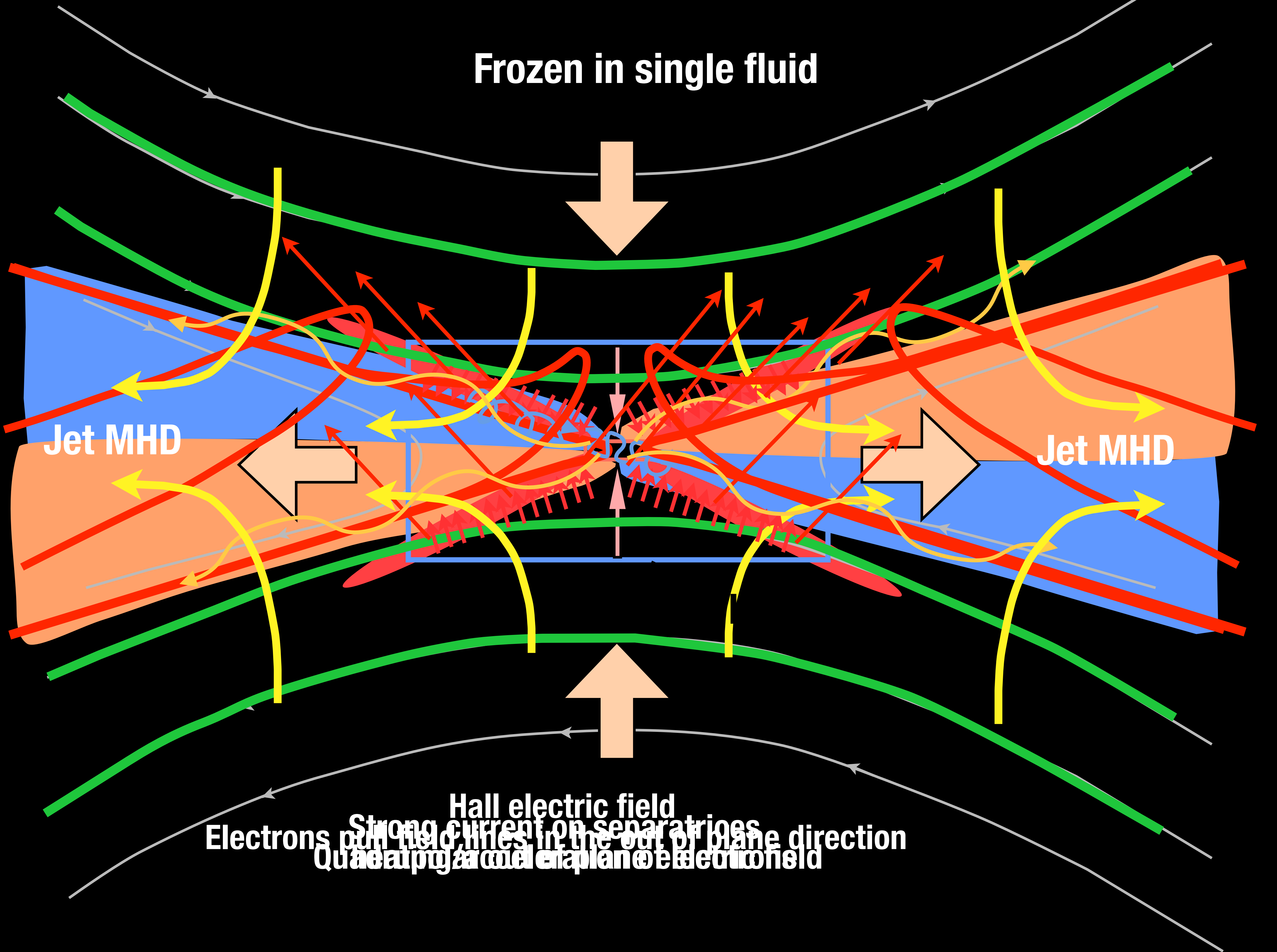
velocity decreases with increasing distance/scale

independent of electron mass?



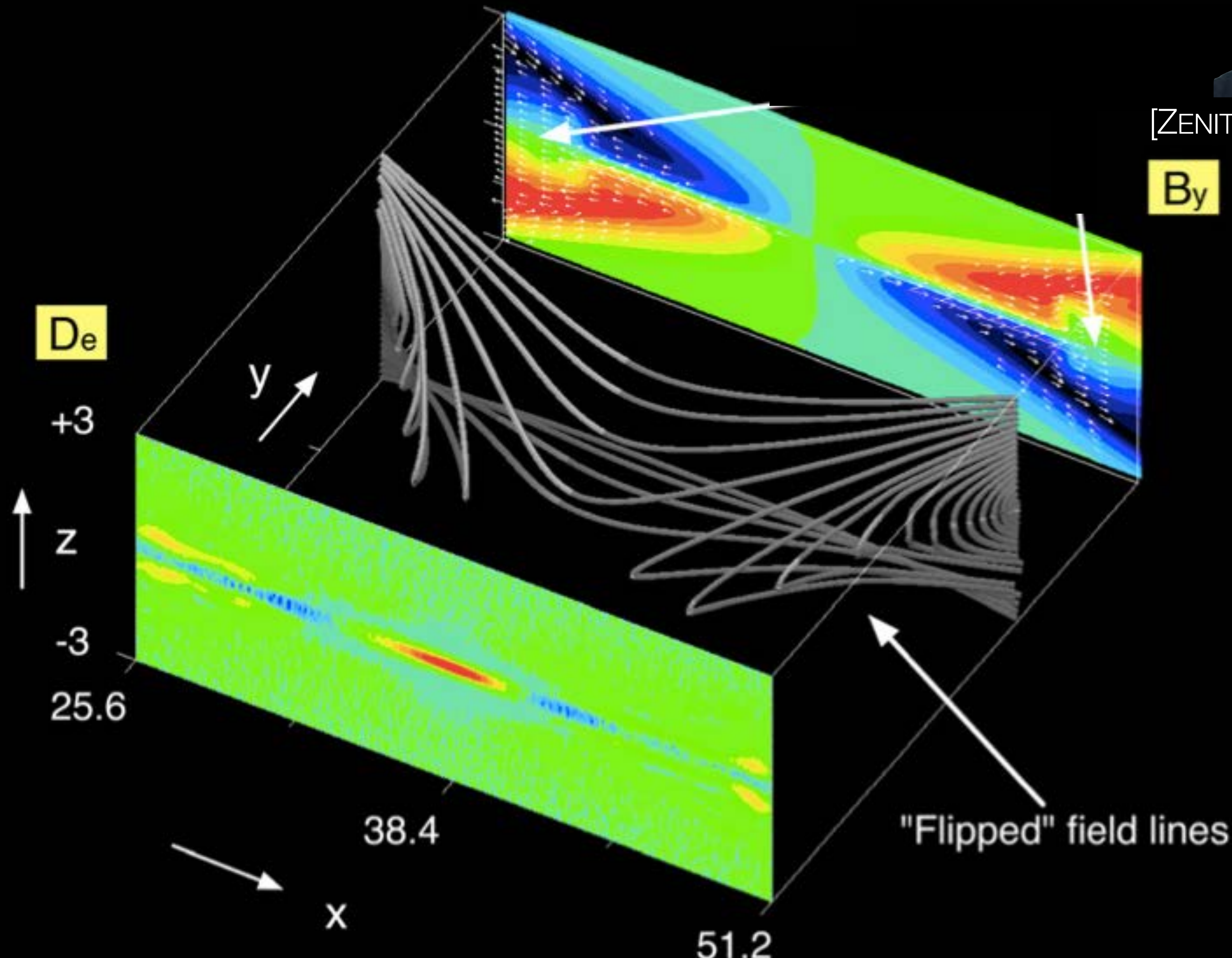
(Hesse et al. 1999)

Collisionless reconnection model

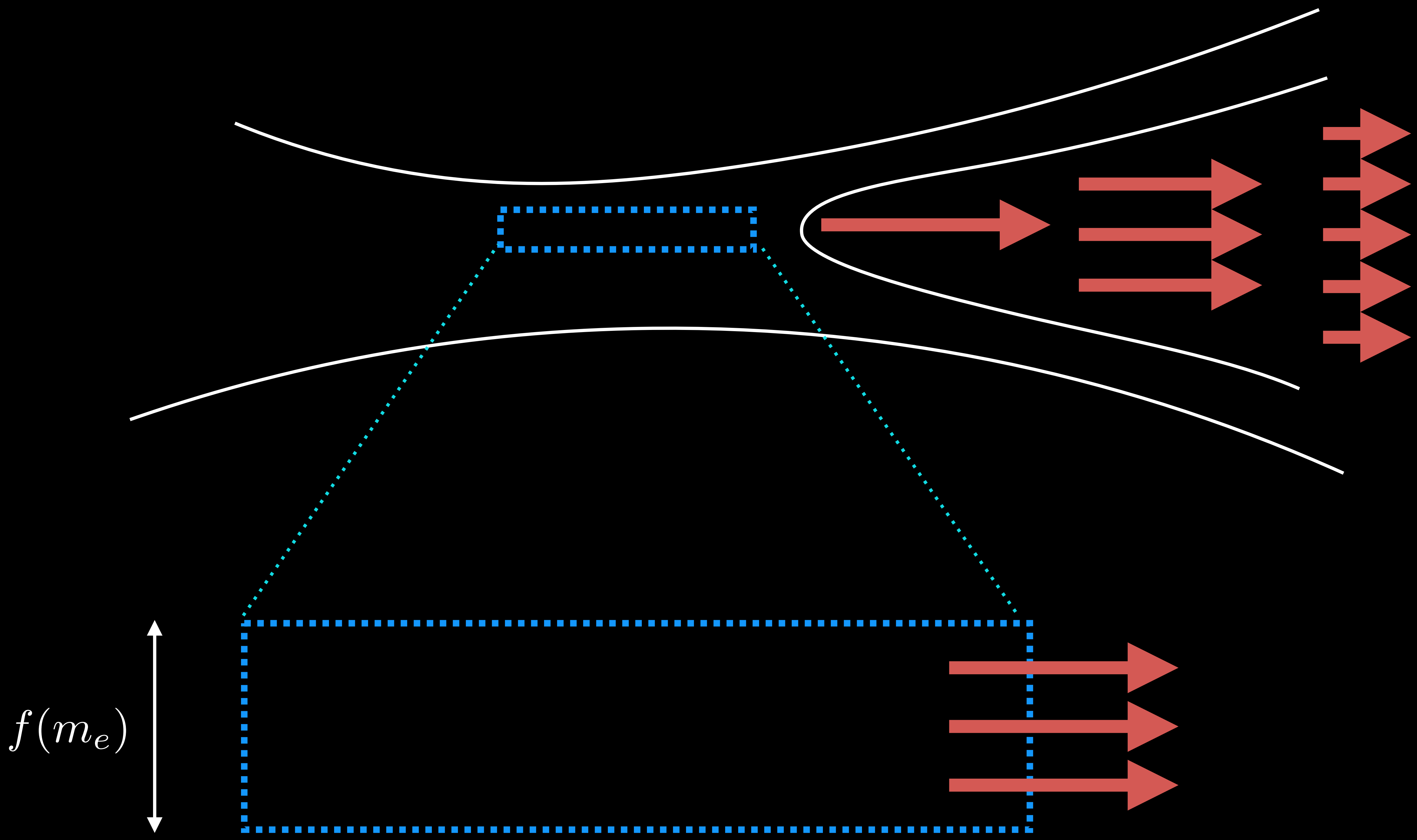


QUADRUPOLAR PATTERN :
SMOCKING GUN OF COLLISIONLESS EFFECTS

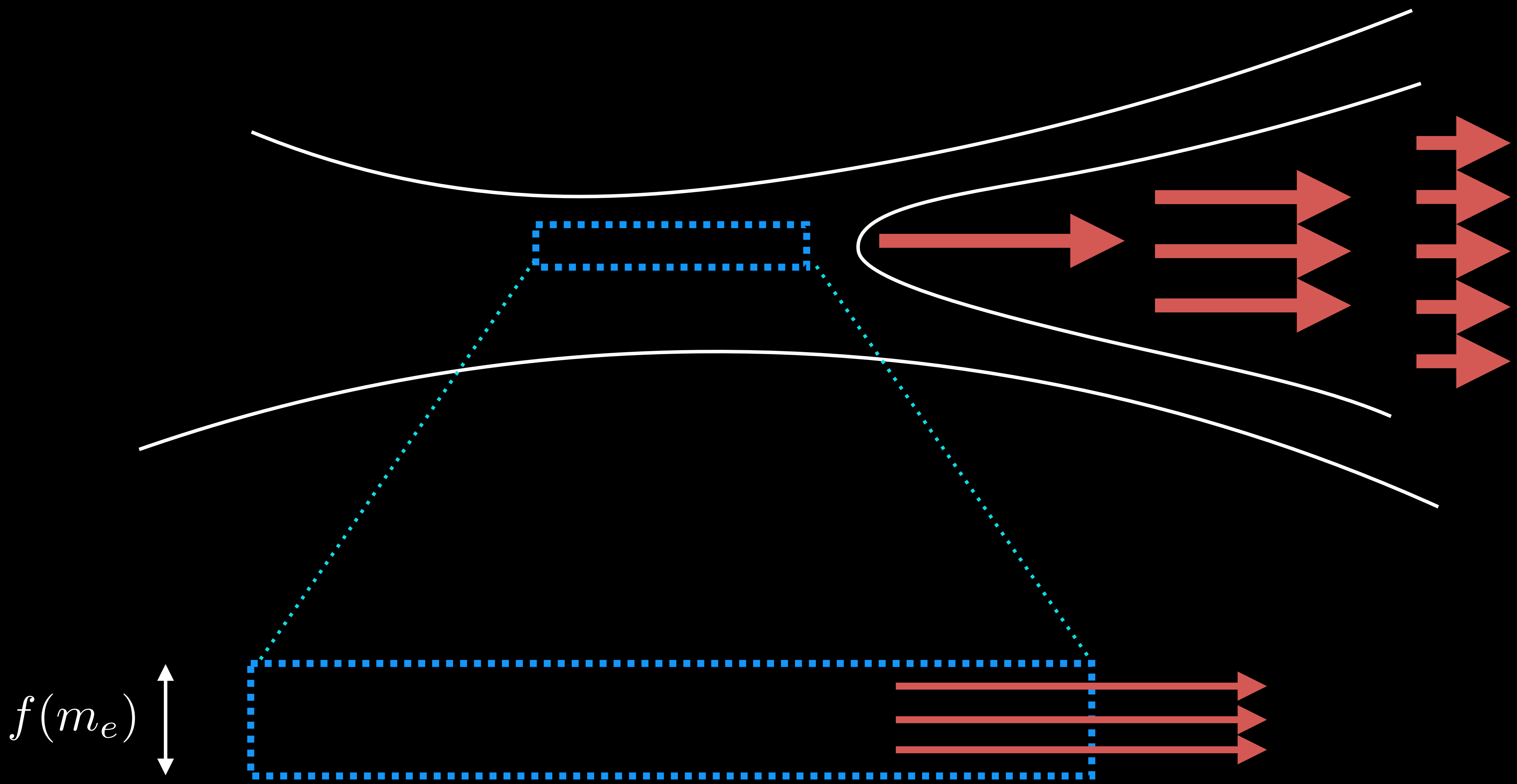
[ZENITANI ET AL 2011]



Independent of the electron mass?



Independent of the electron mass?



Independent of the electron mass?

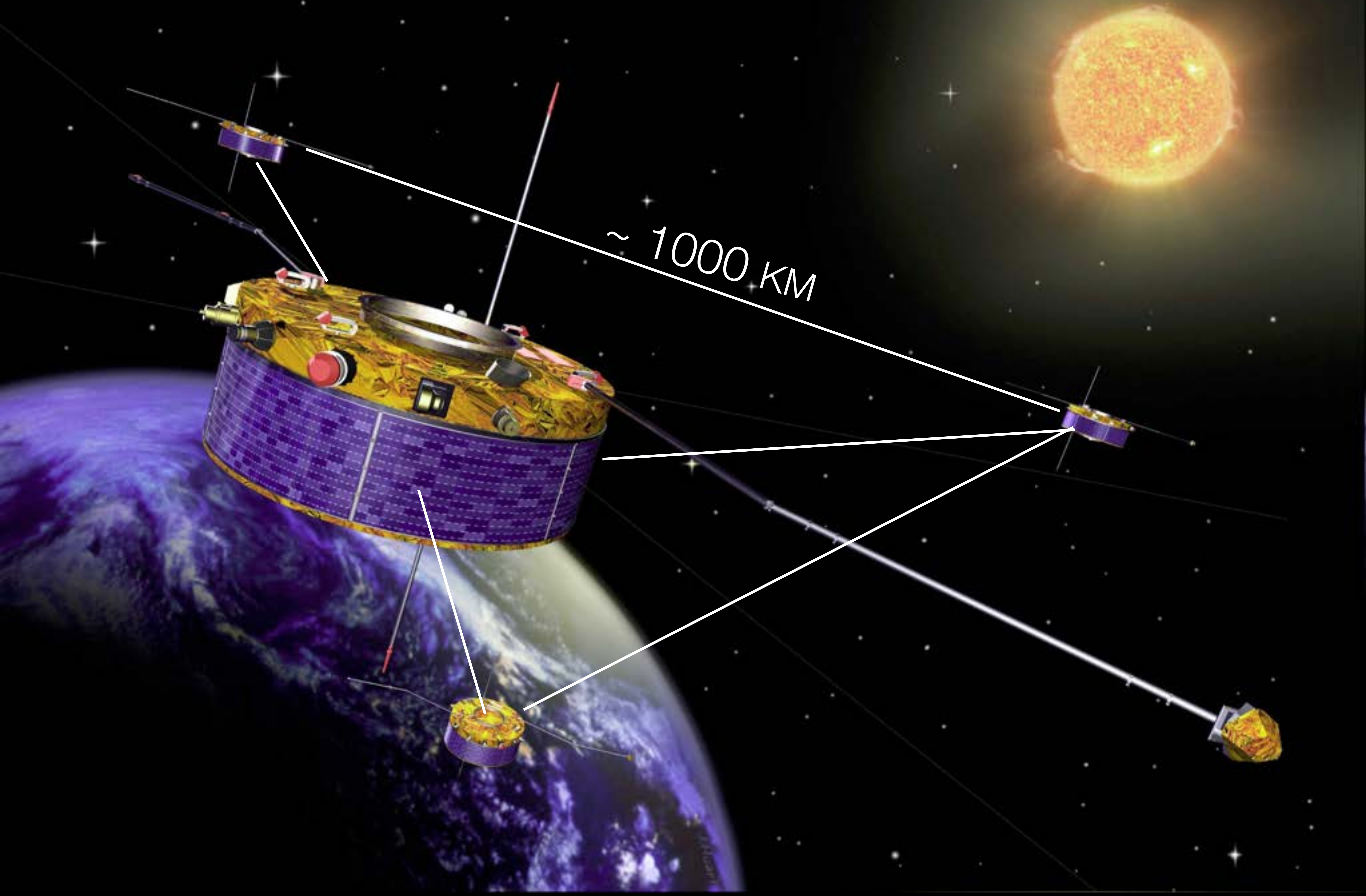
« whistler » dispersion $v_{out} \sim k$

$$F \sim v_{out}\delta \sim k/k = cst \qquad f(m_e) \sim \delta_e \qquad v_{out} \sim V_{Ae}$$

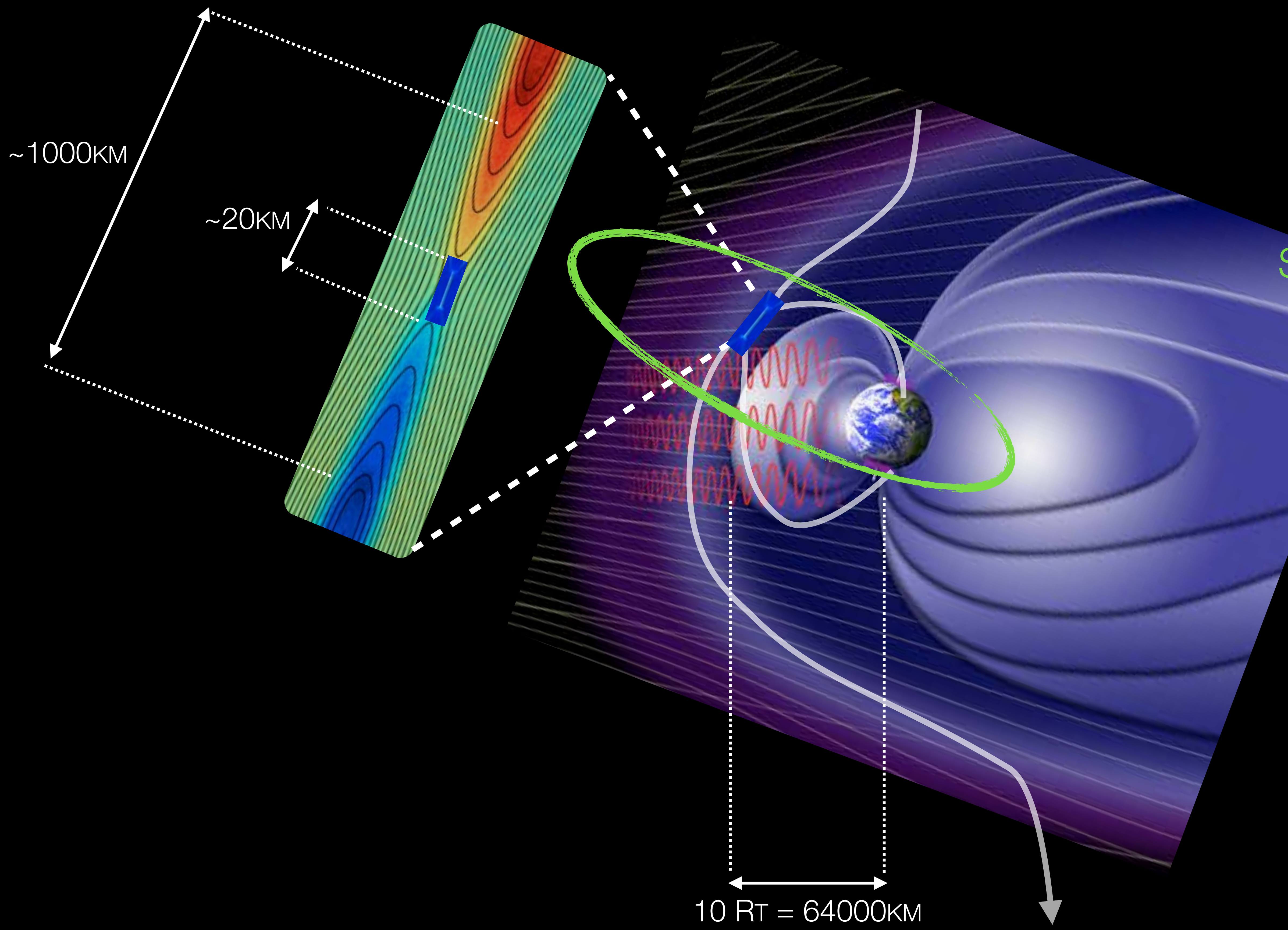
ESA/CLUSTER MISSION

2002

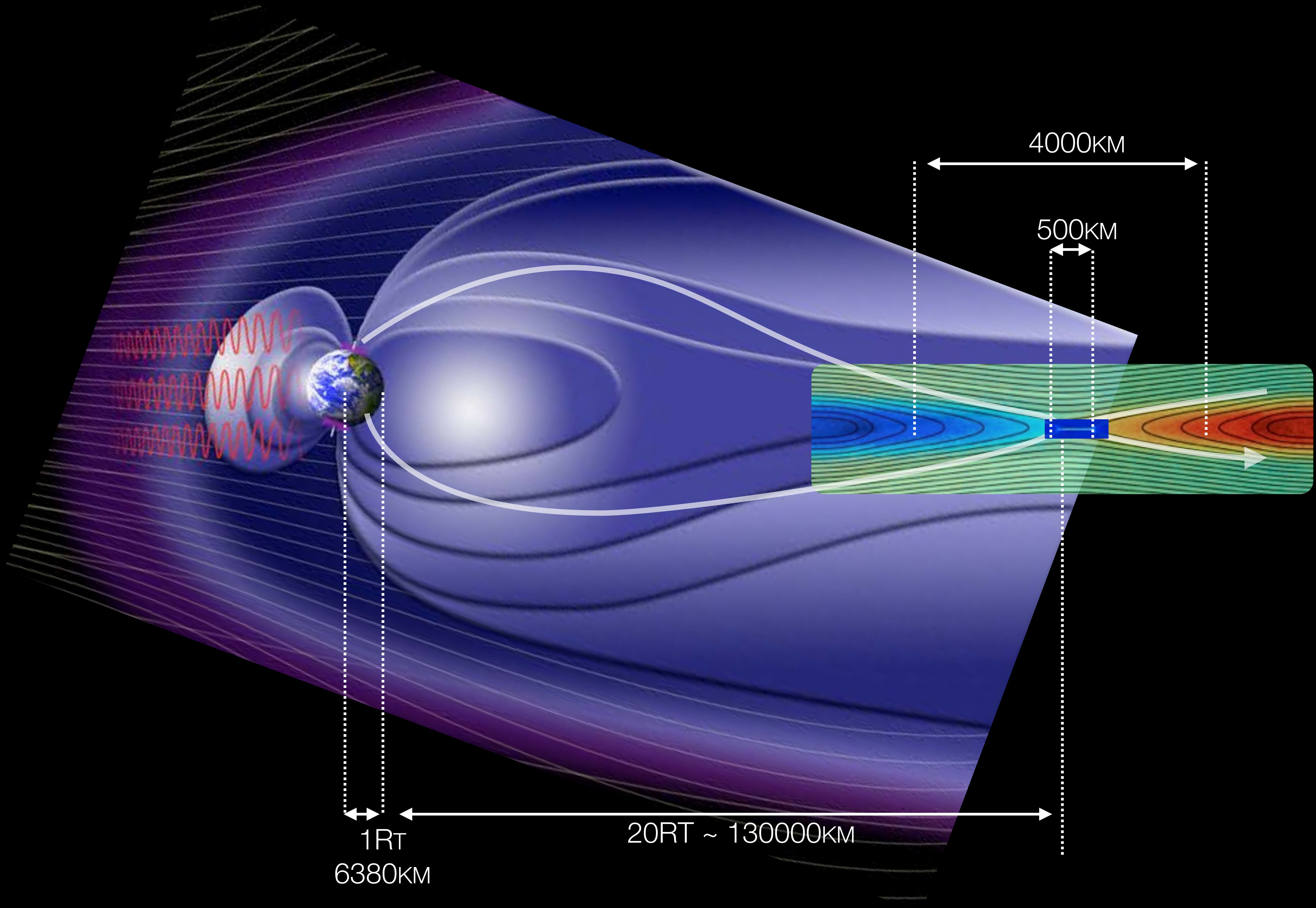
FIRST FORMATION OF SPACECRAFT FOR 3D MEASUREMENTS



A SENSE OF SCALES INVOLVED IN THE PROCESS

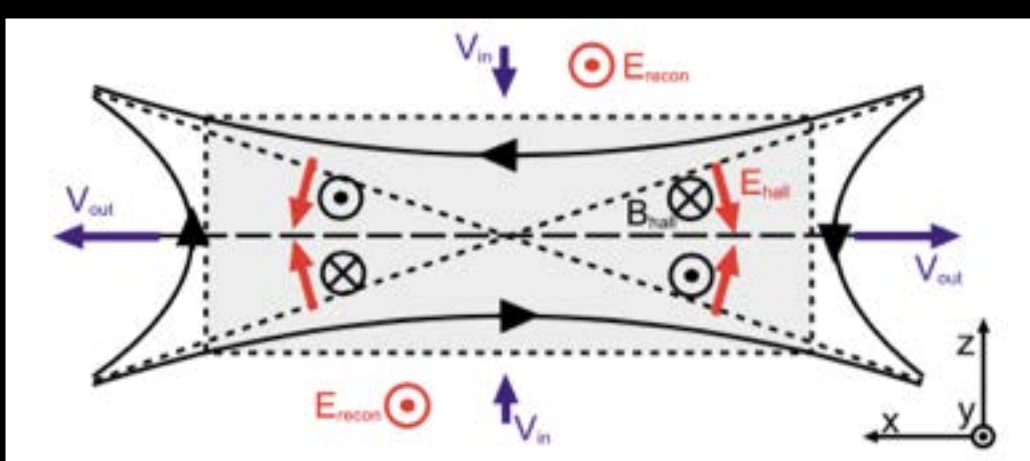


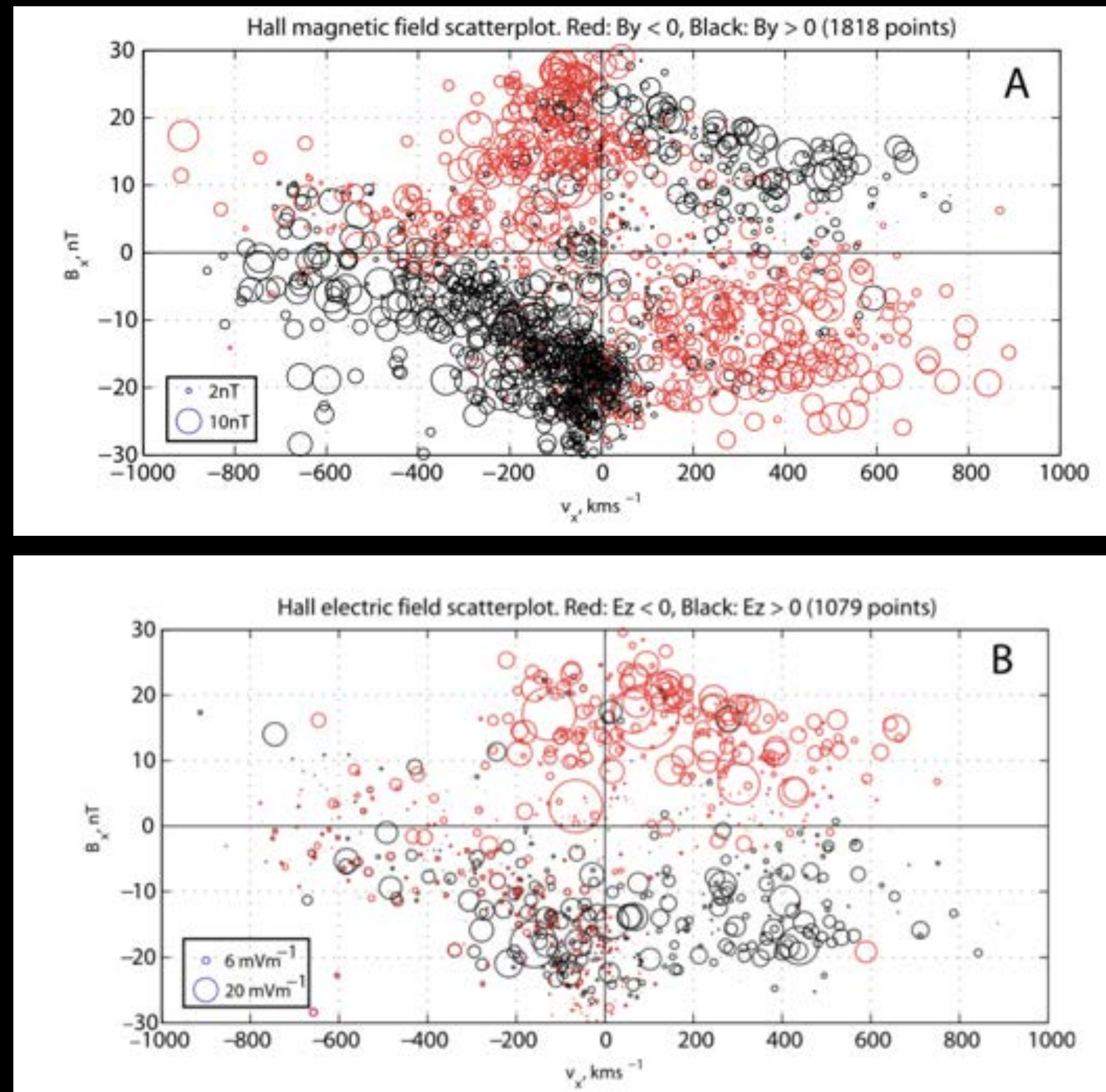
A SENSE OF SCALES INVOLVED IN THE PROCESS



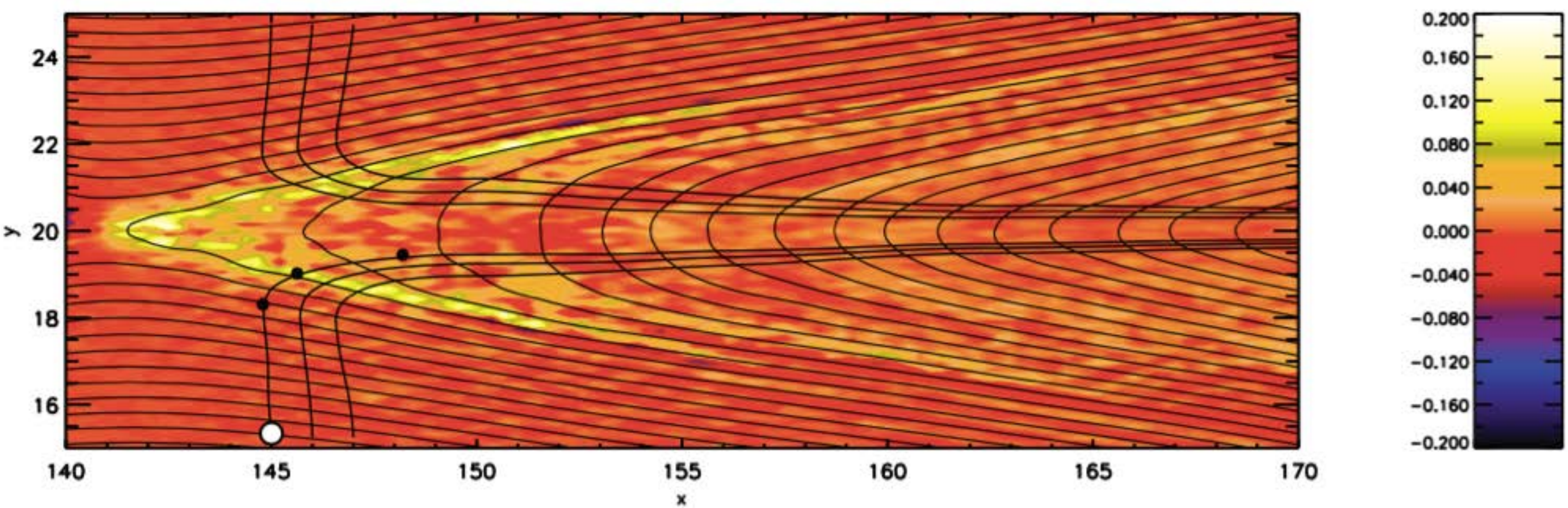
AVERAGE PROPERTIES OF MAGNETOTAIL RECONNECTION

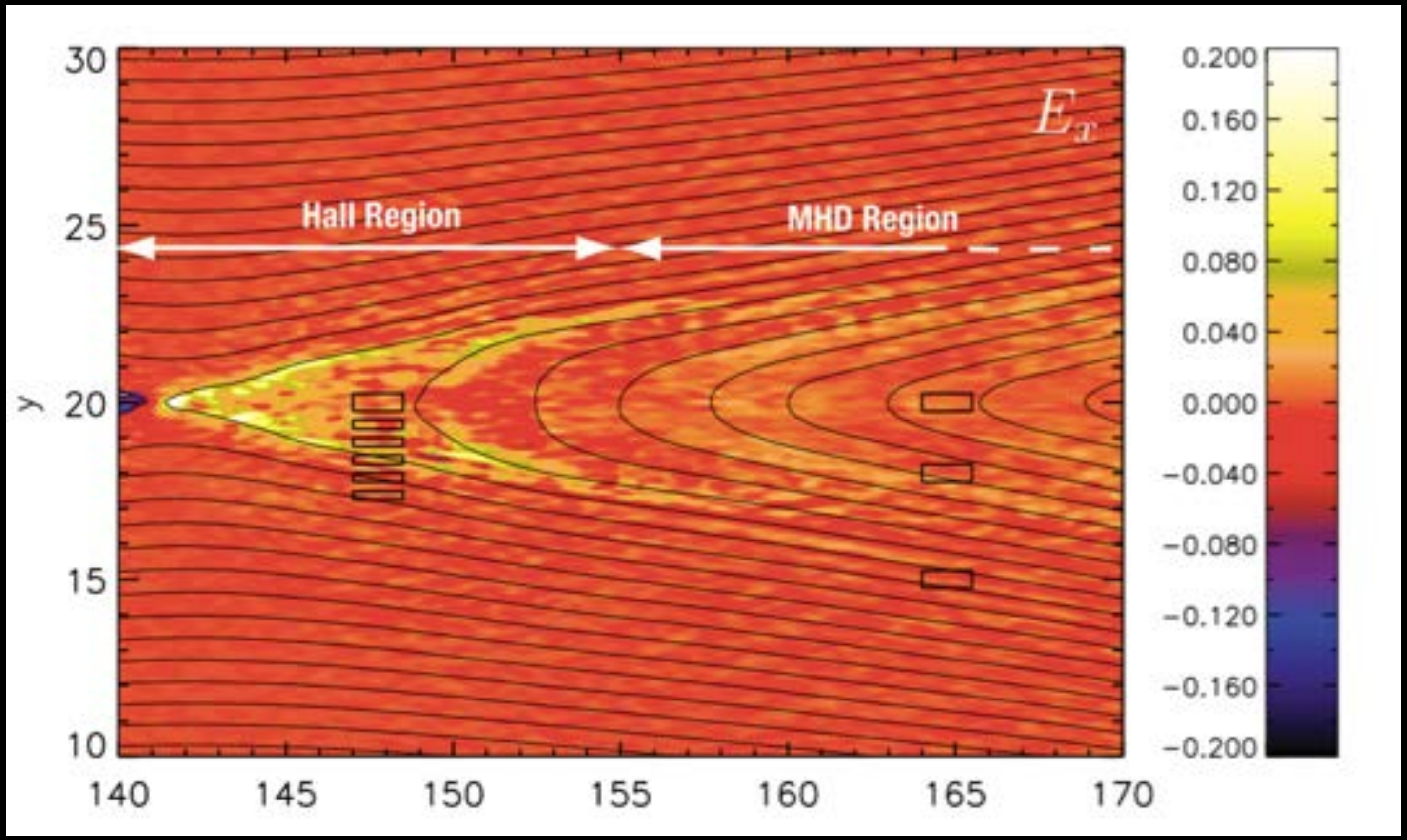
(Eastwood et al. 2010)

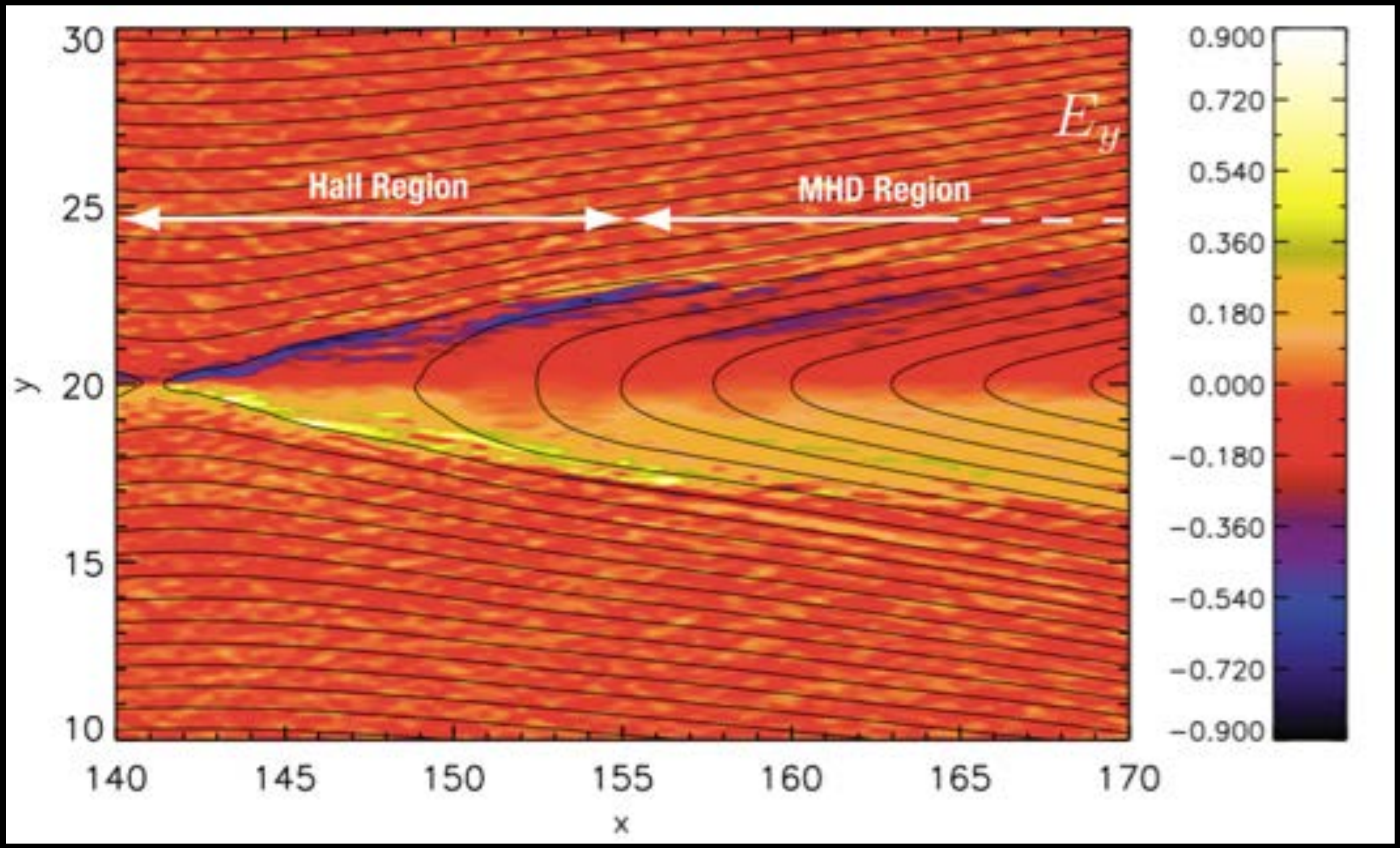




How is the plasma accelerated?



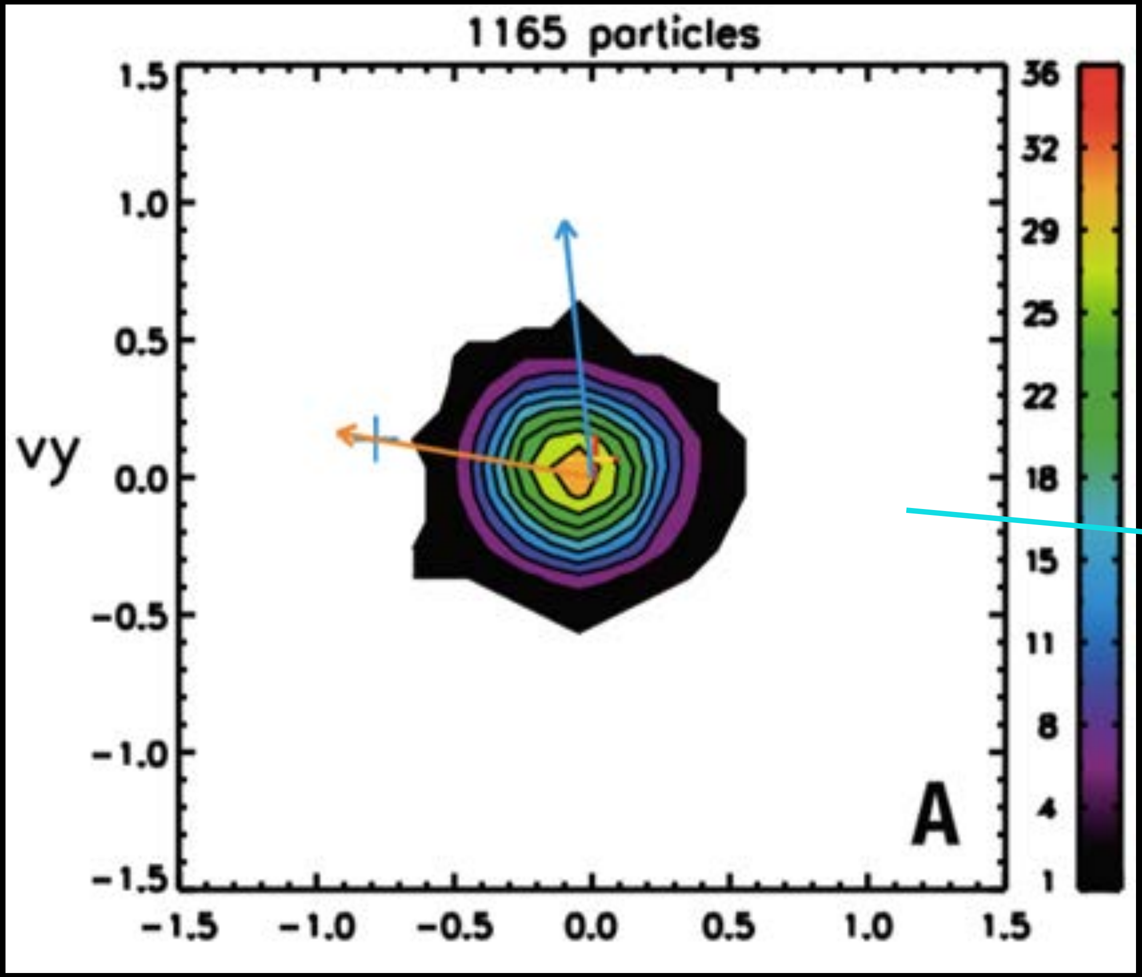


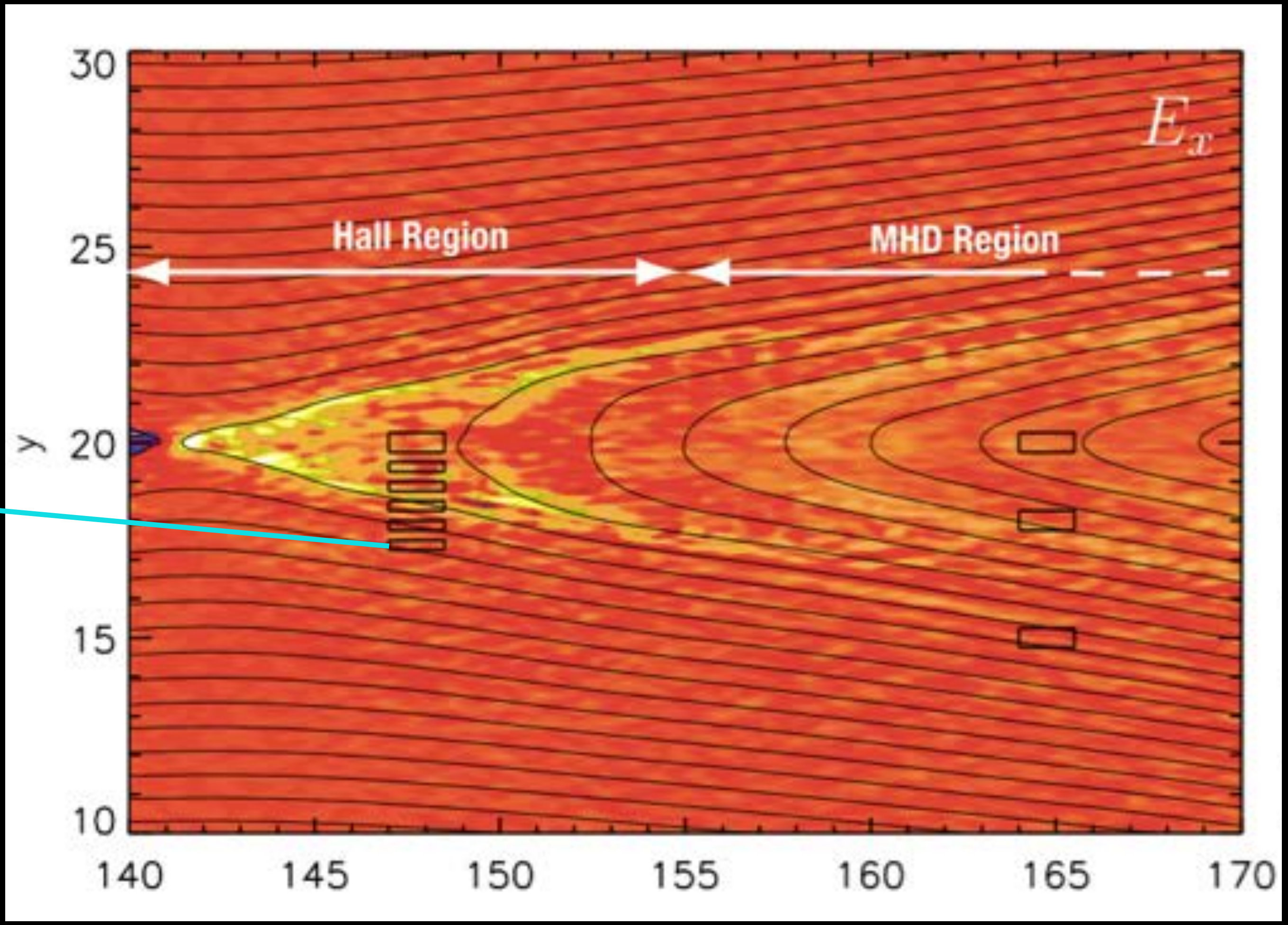


(*Aunai et al. 2011*)

ION DISTRIBUTION FUNCTIONS

Upstream isotropic distribution

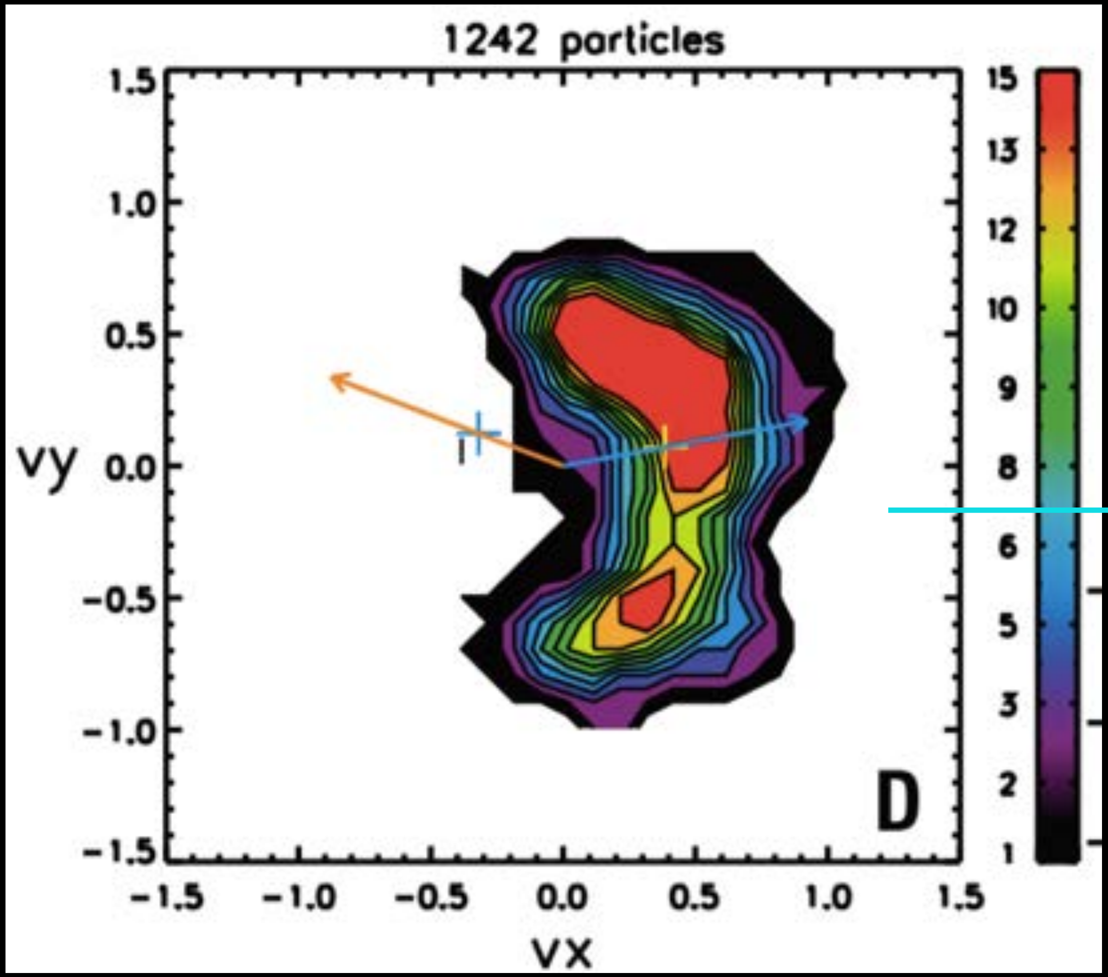


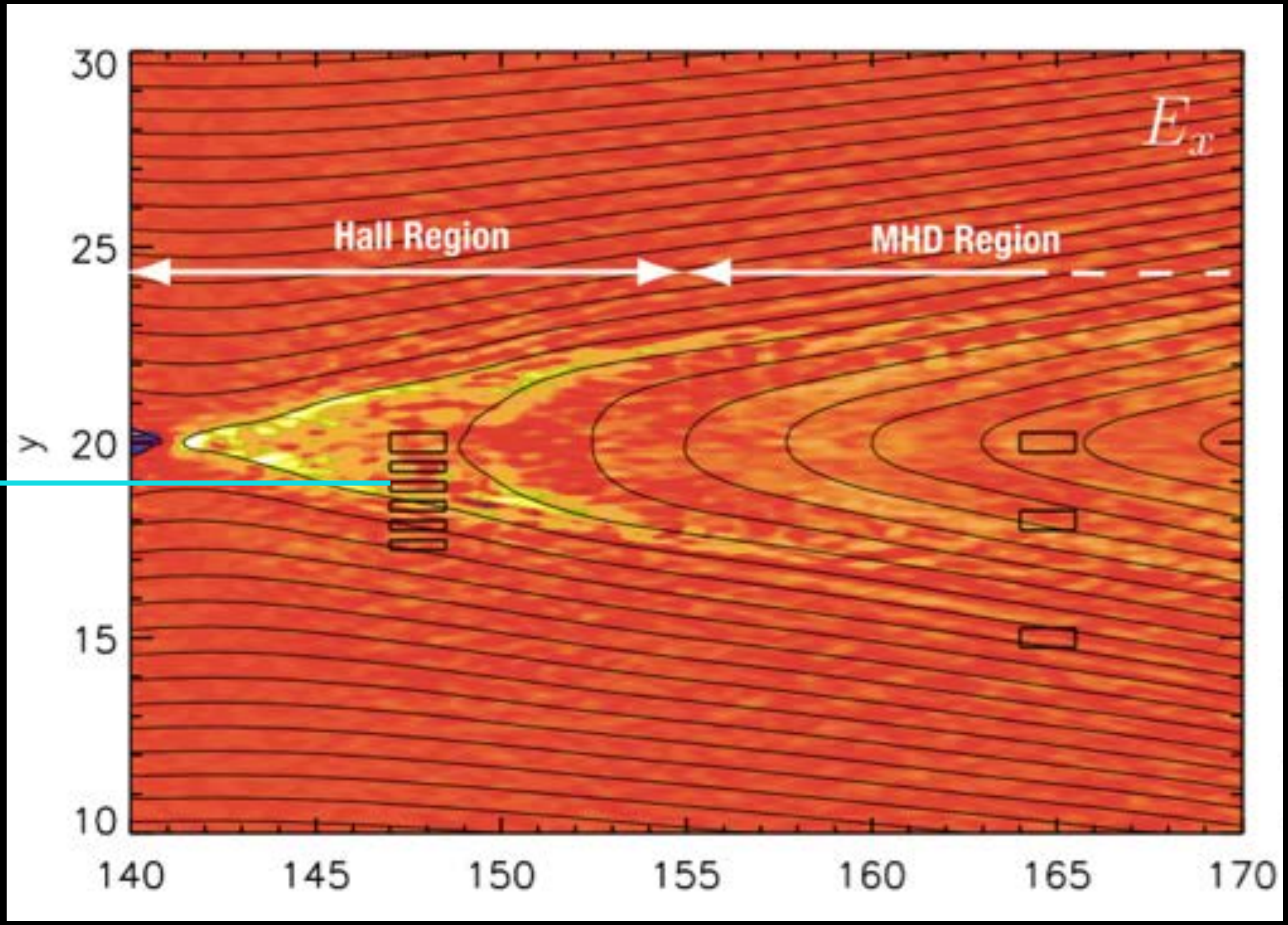


$$P_{xy} = 0$$

ION DISTRIBUTION FUNCTIONS

Exhaust distribution

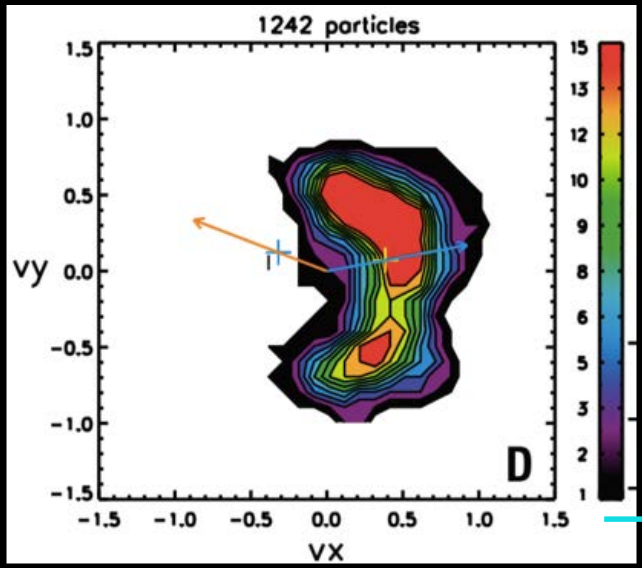




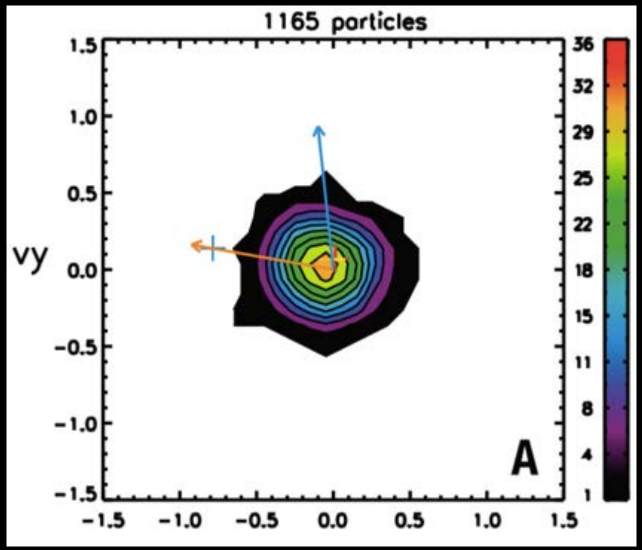
$$P_{xy} > 0$$

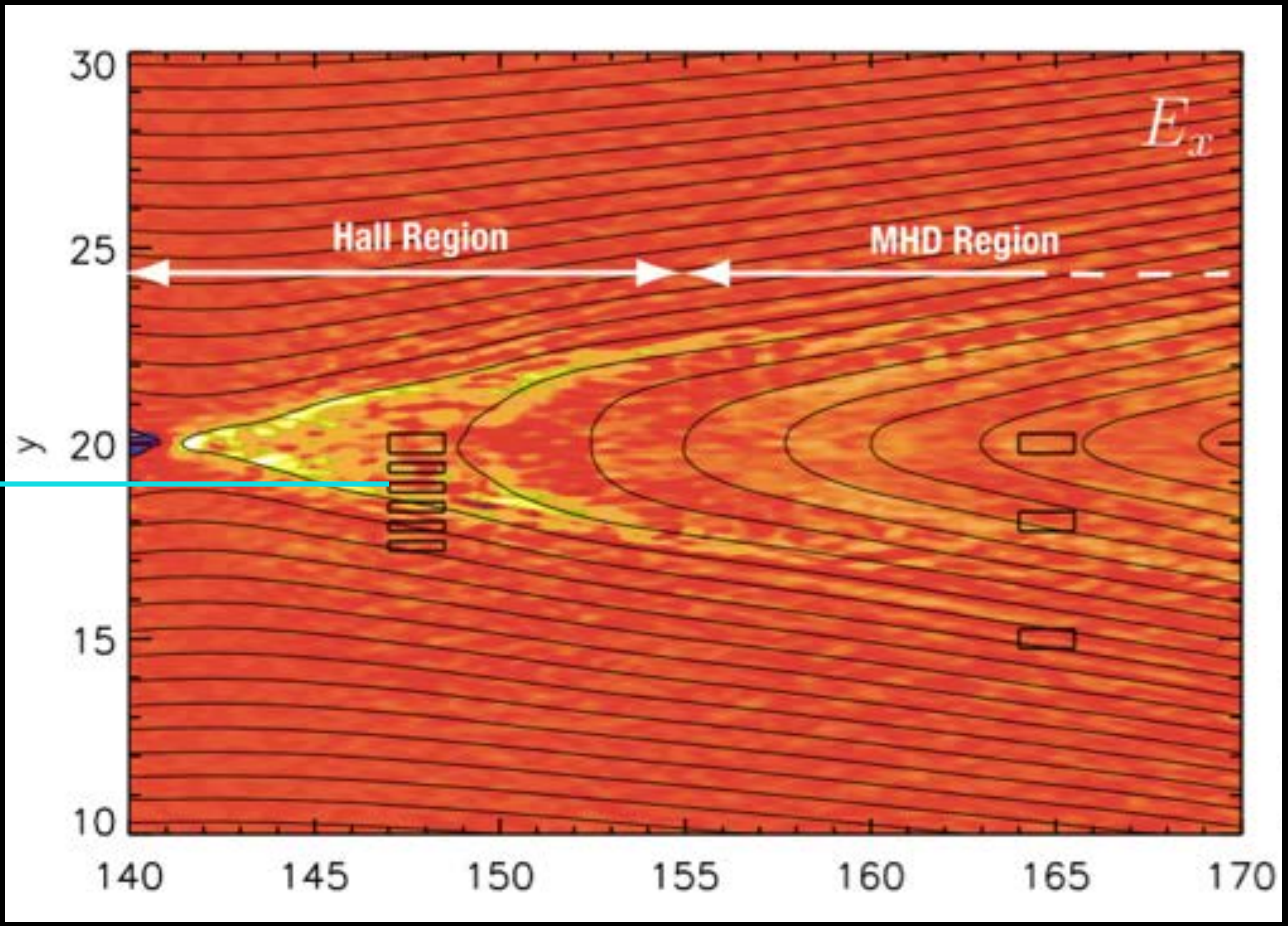
Ion distribution functions

Exhaust distribution

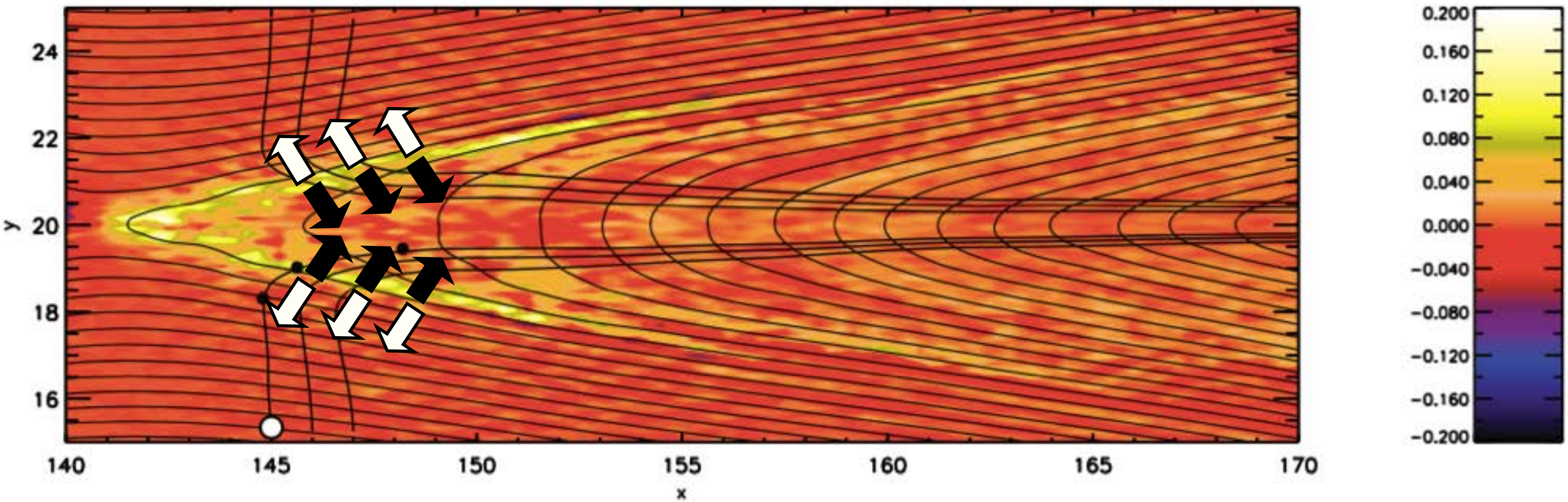


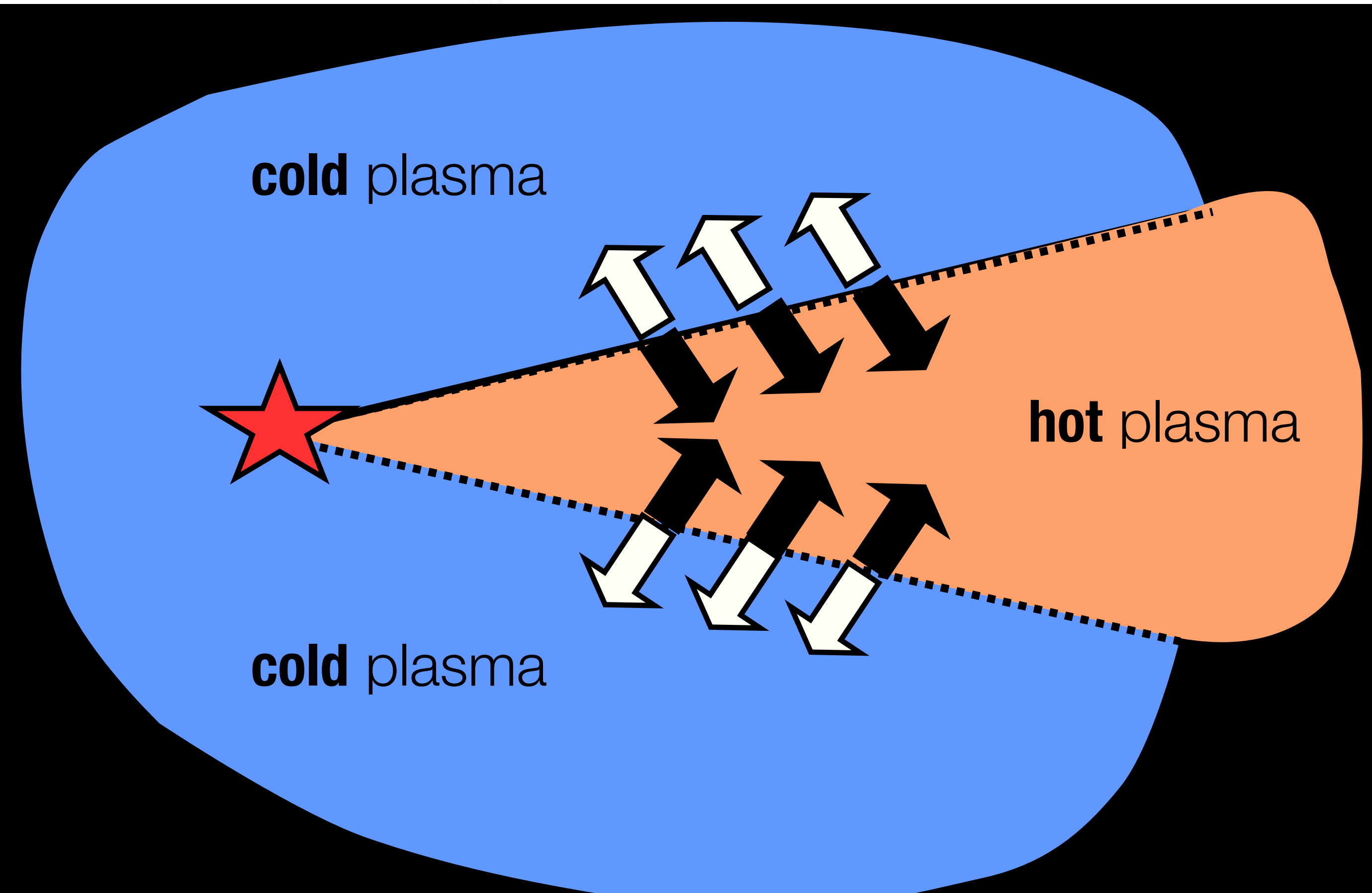
$$\frac{\partial P_{xy}}{\partial y} > 0$$





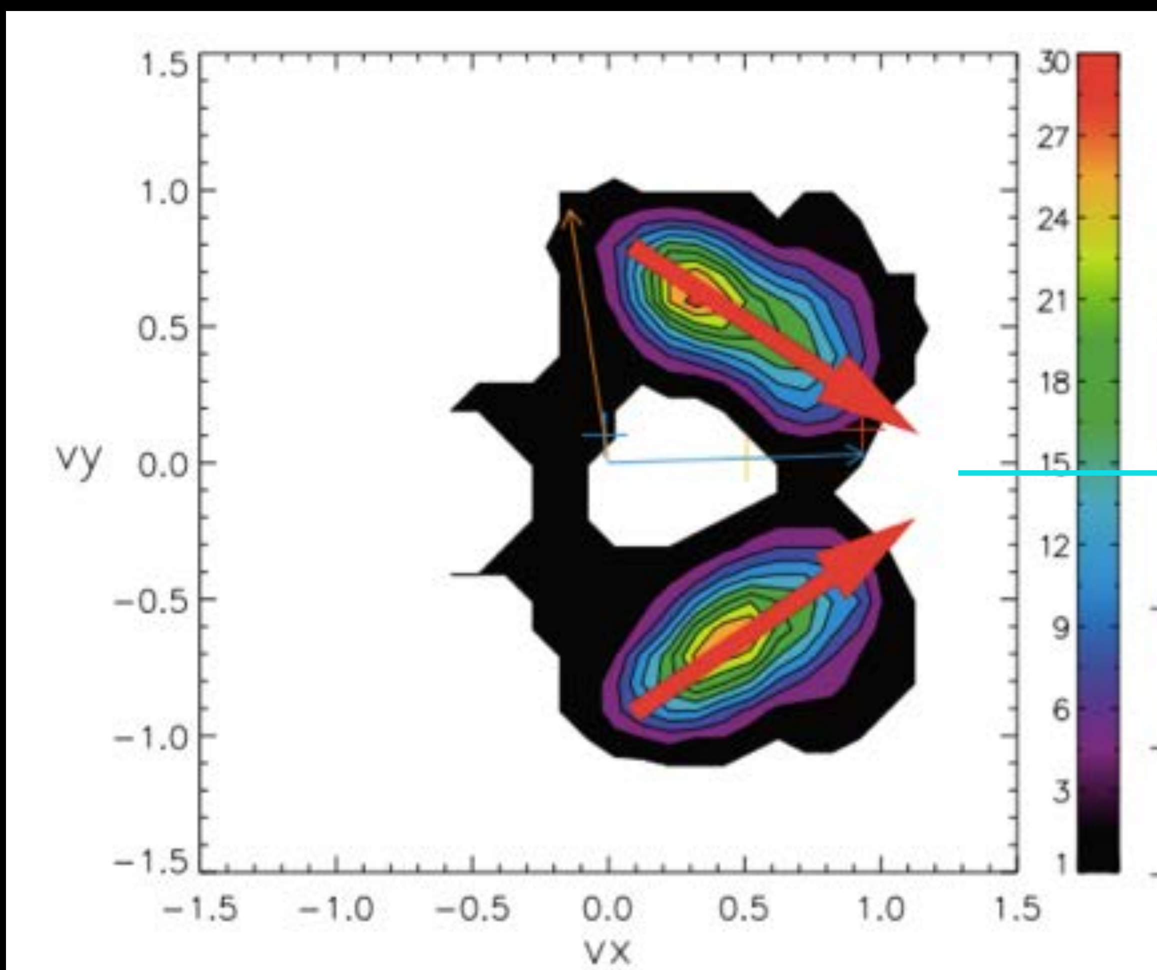
FLUID FORCES

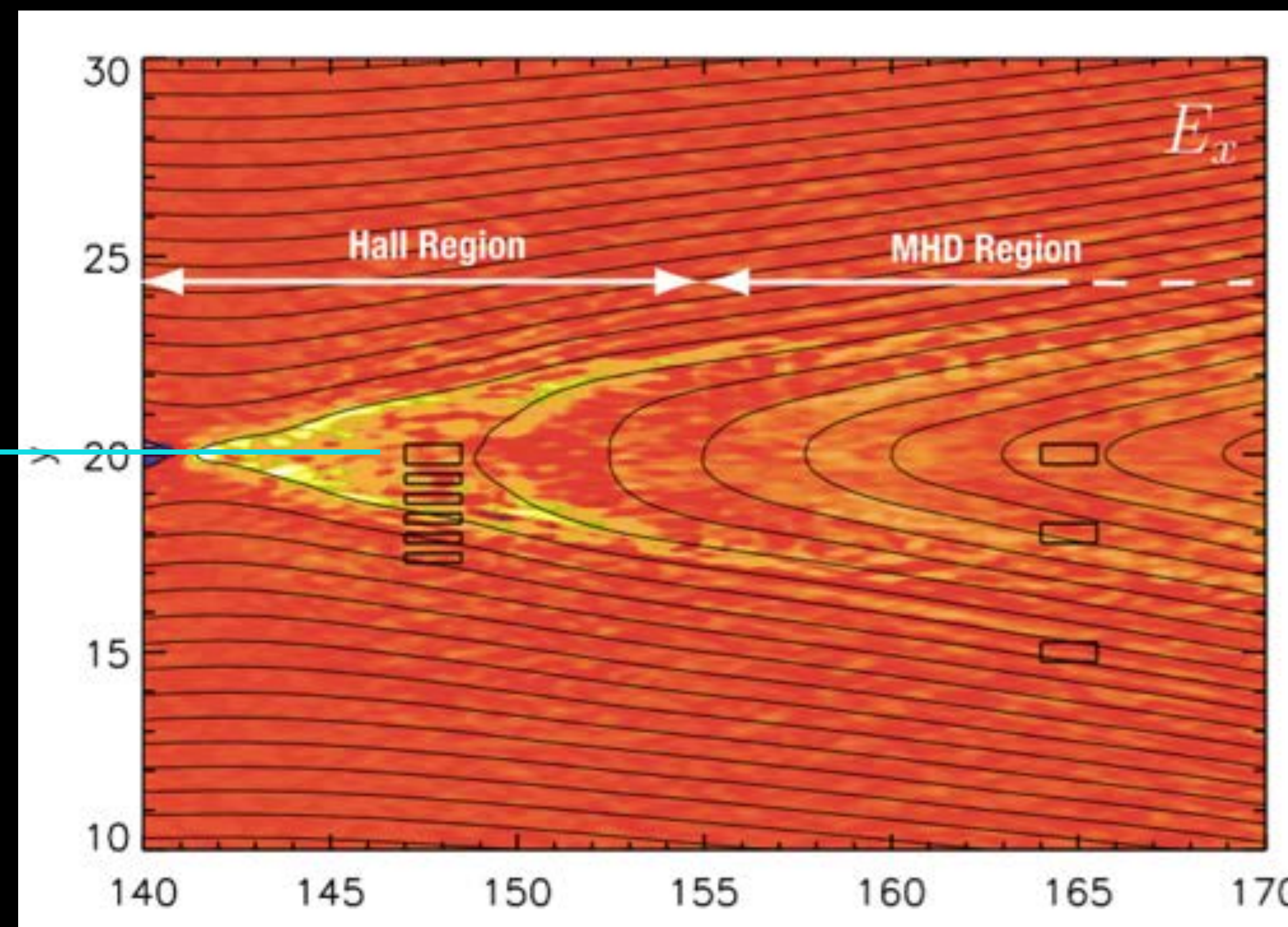




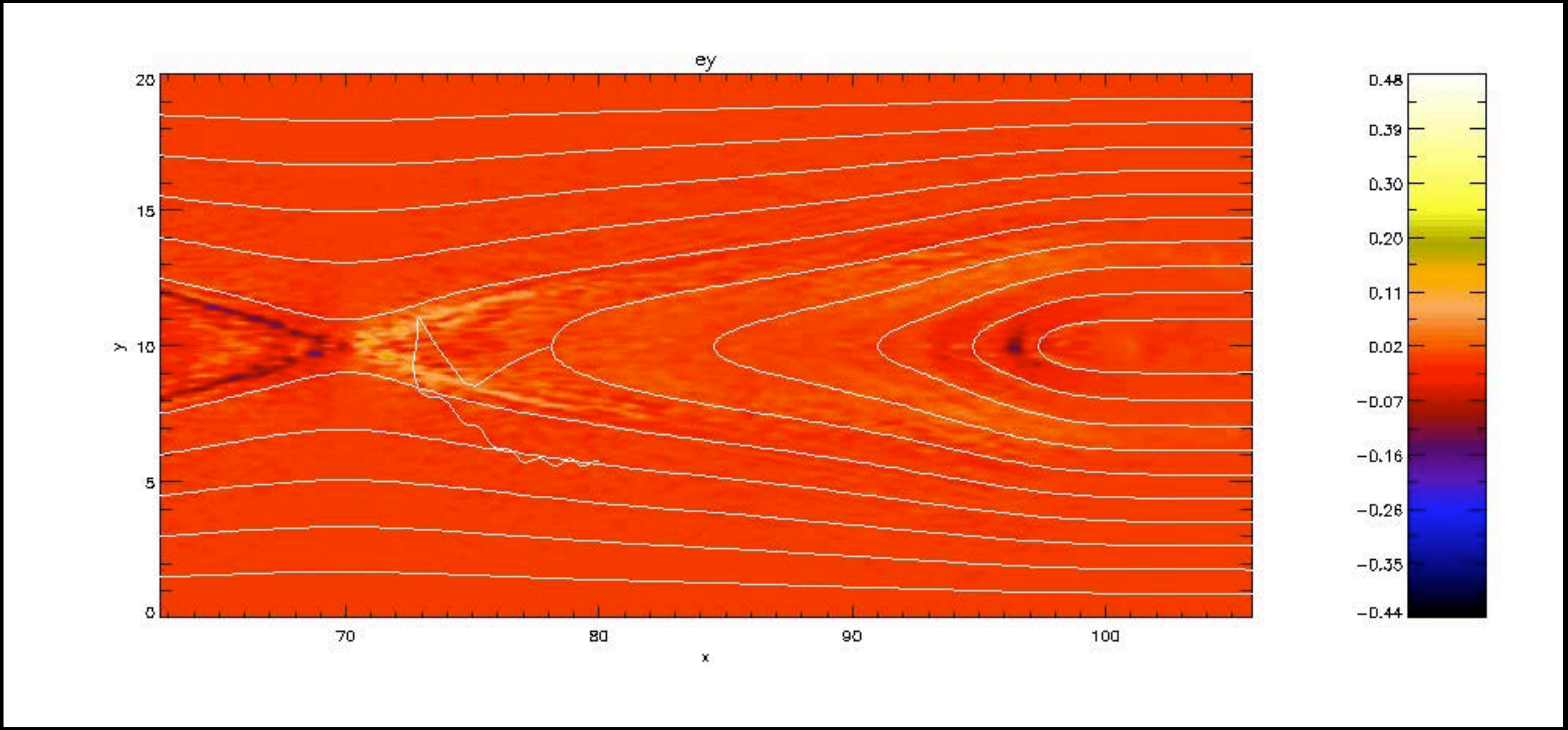
ION DISTRIBUTION FUNCTIONS

midplane distribution

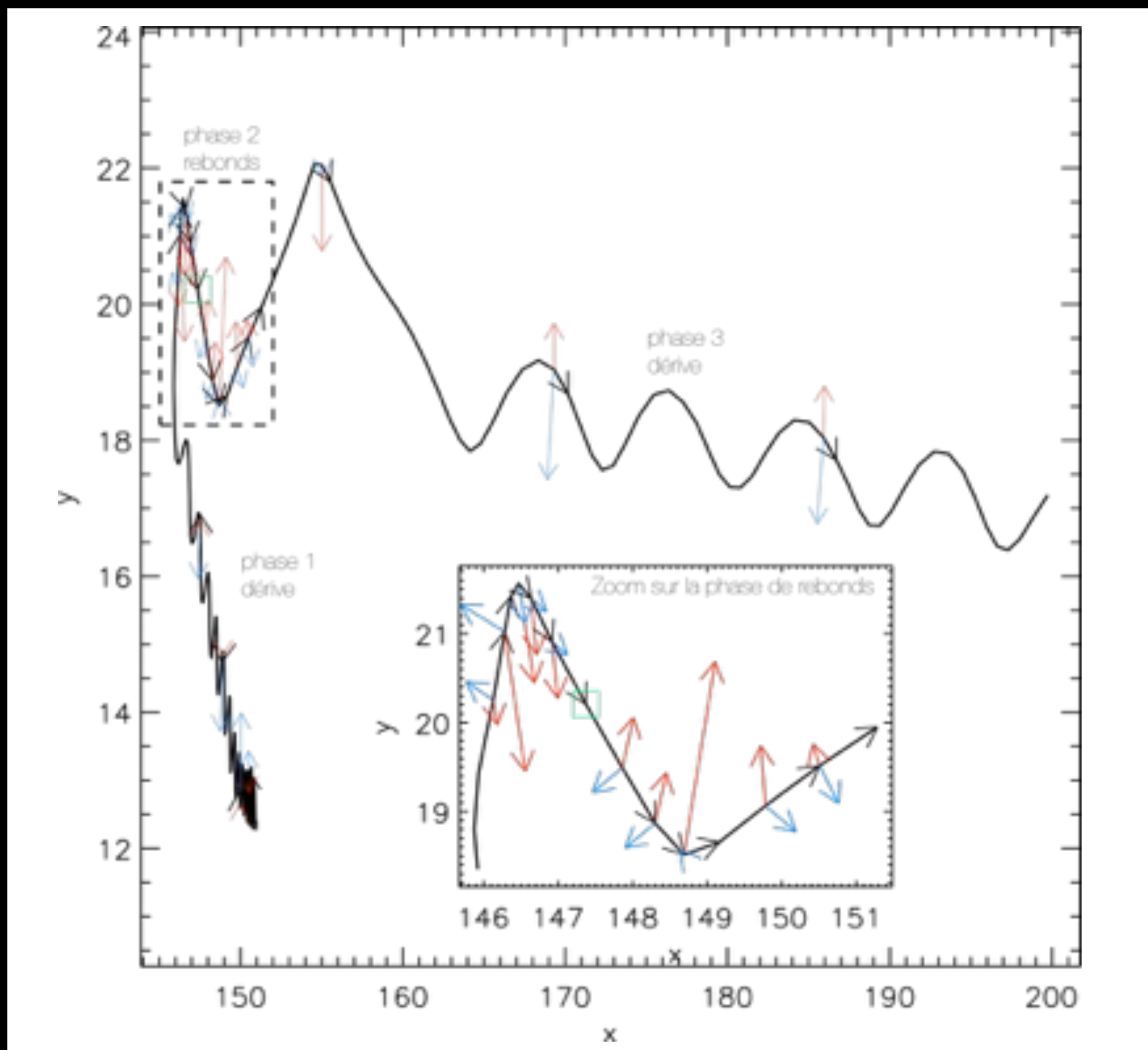




INDIVIDUAL ION DYNAMICS

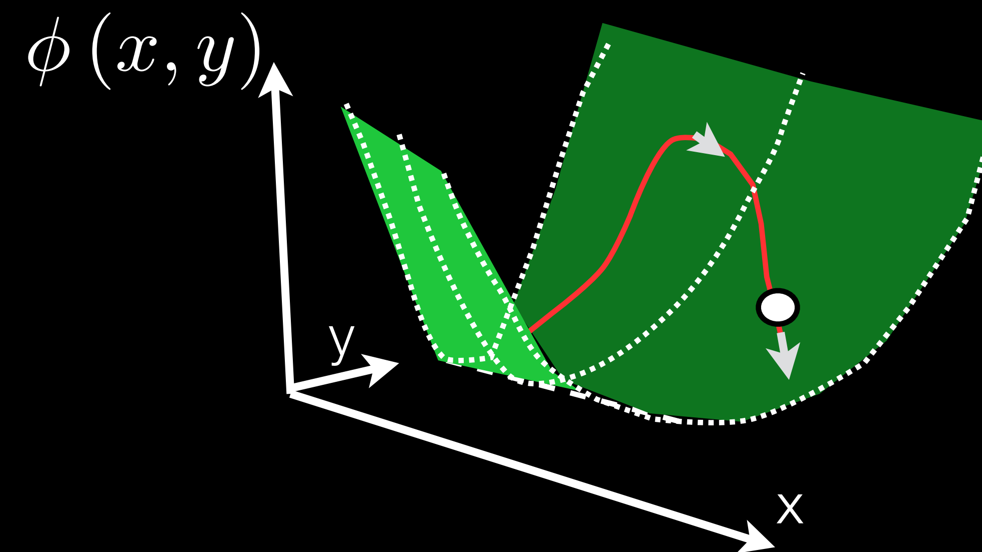


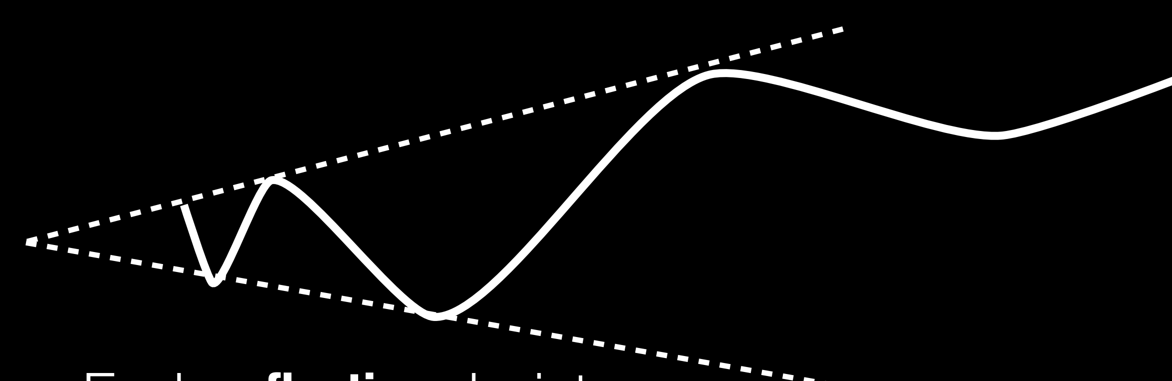
Individual ion dynamics



Particle dynamics

Particle bounce motion in a diverging potential well

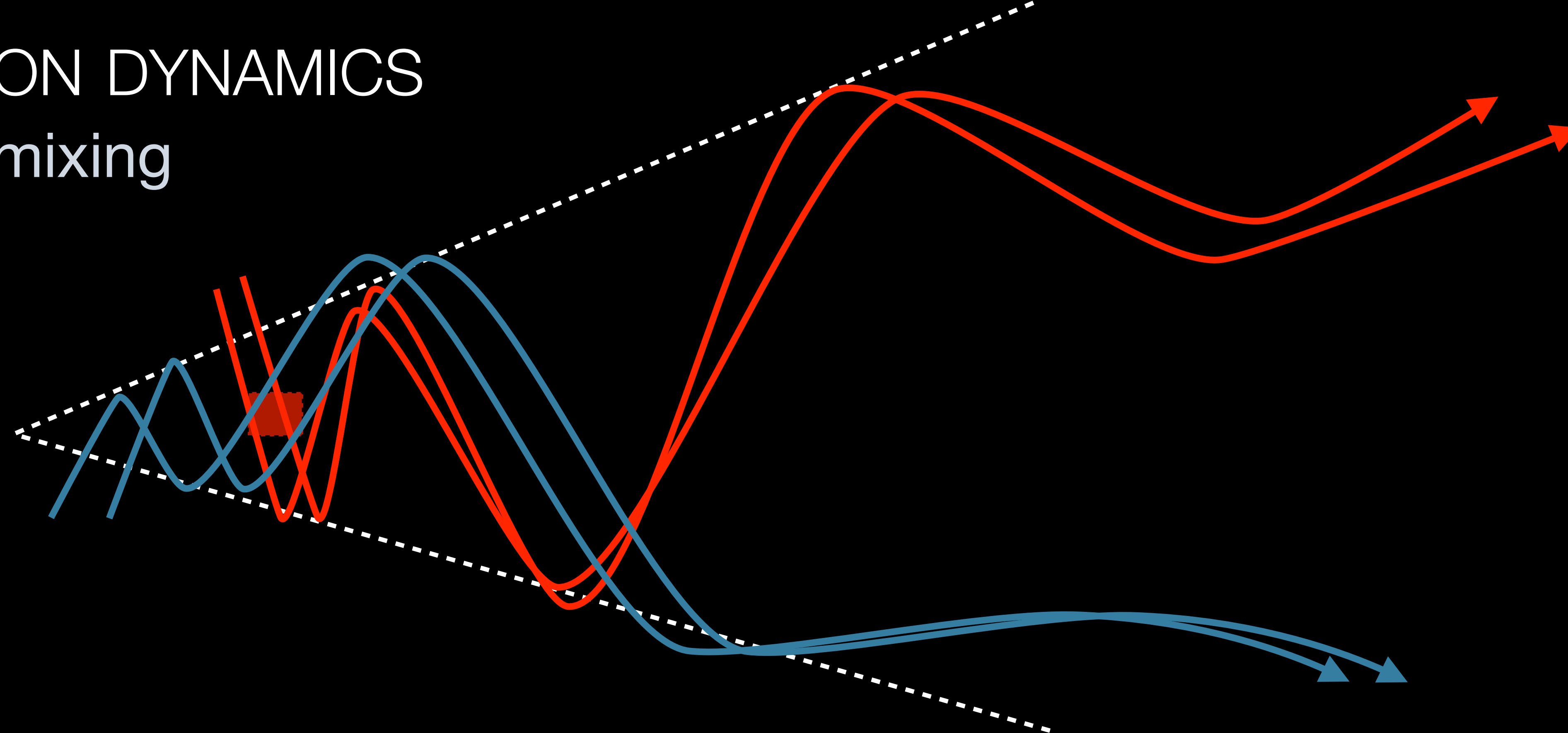


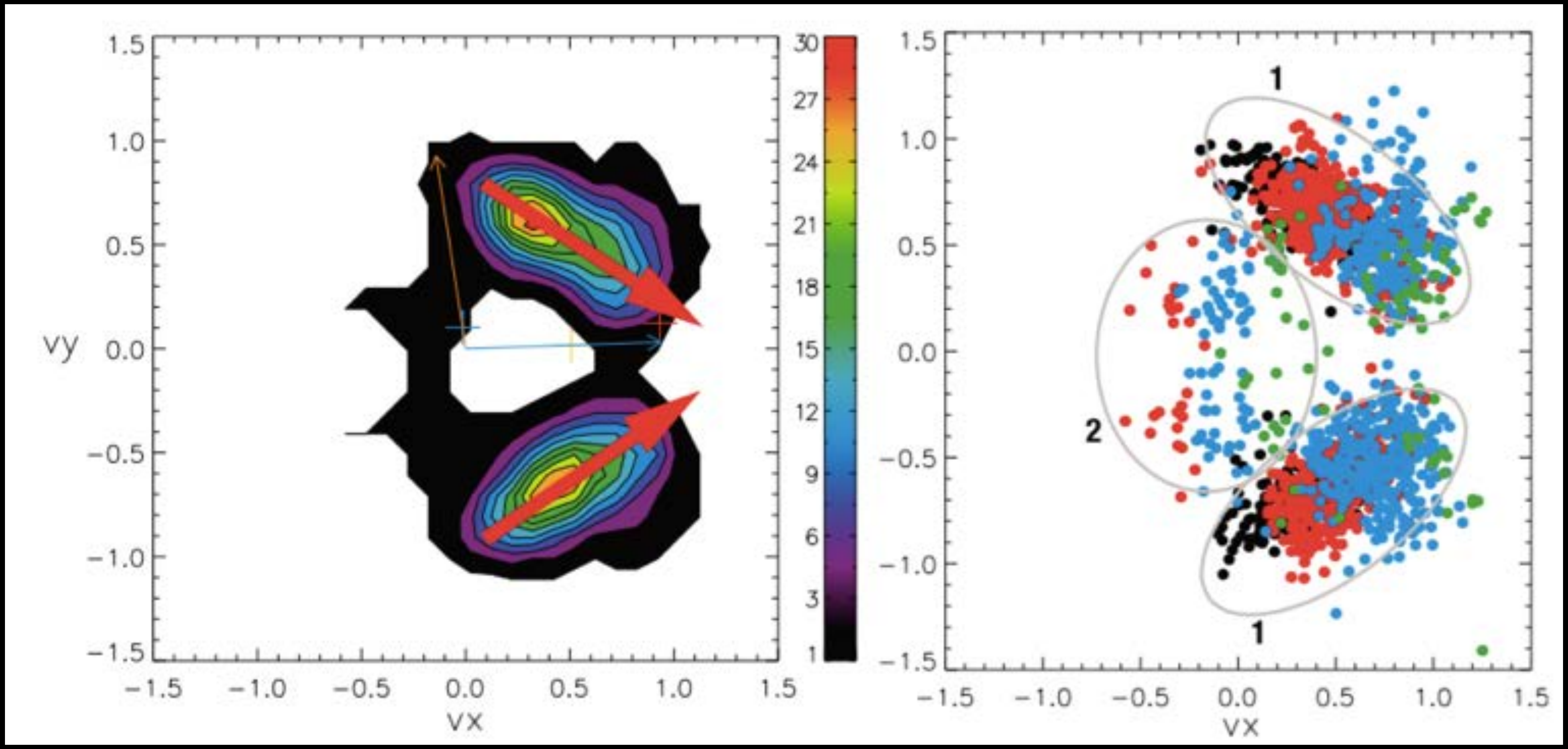


Each **reflection** deviates **irreversibly** the particle toward the downstream direction

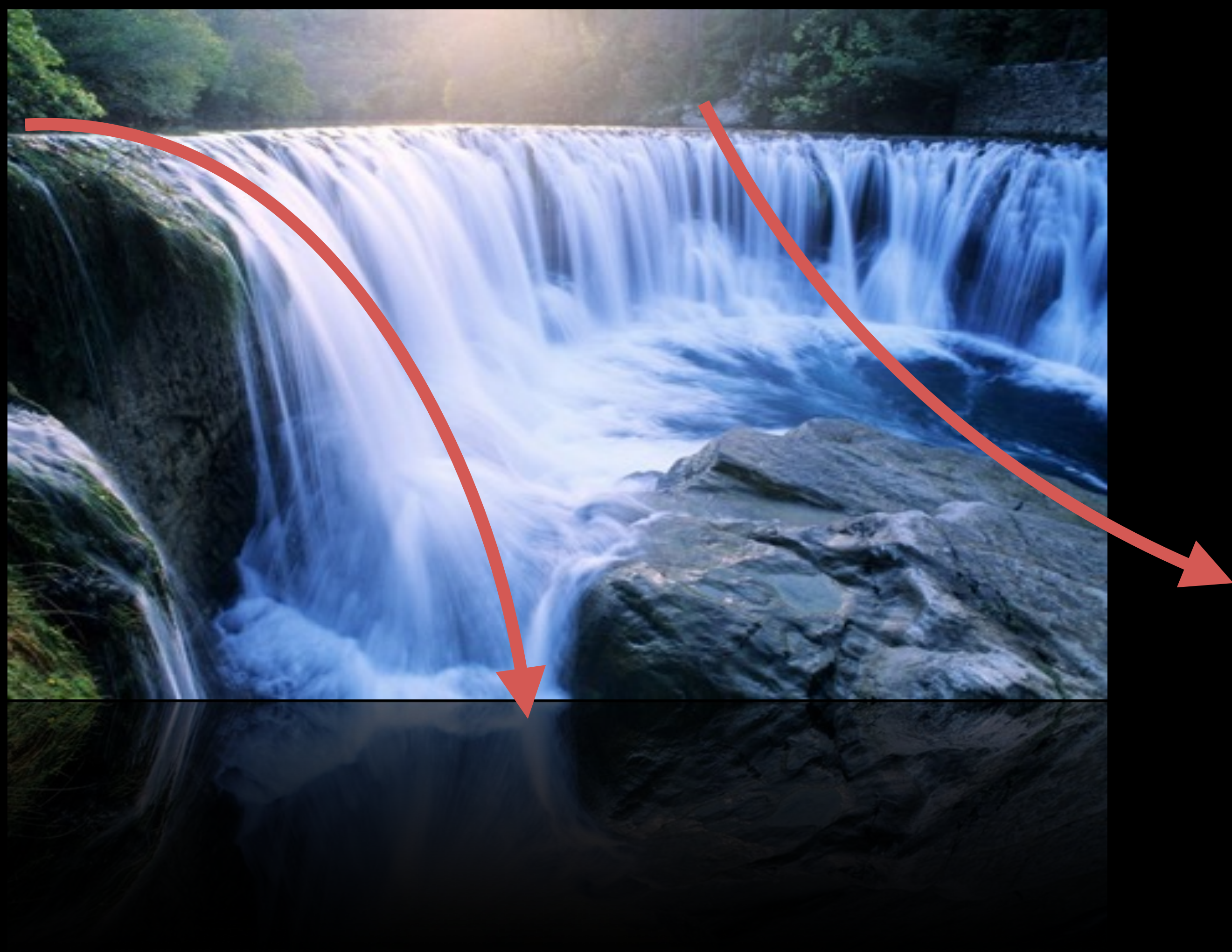
INDIVIDUAL ION DYNAMICS

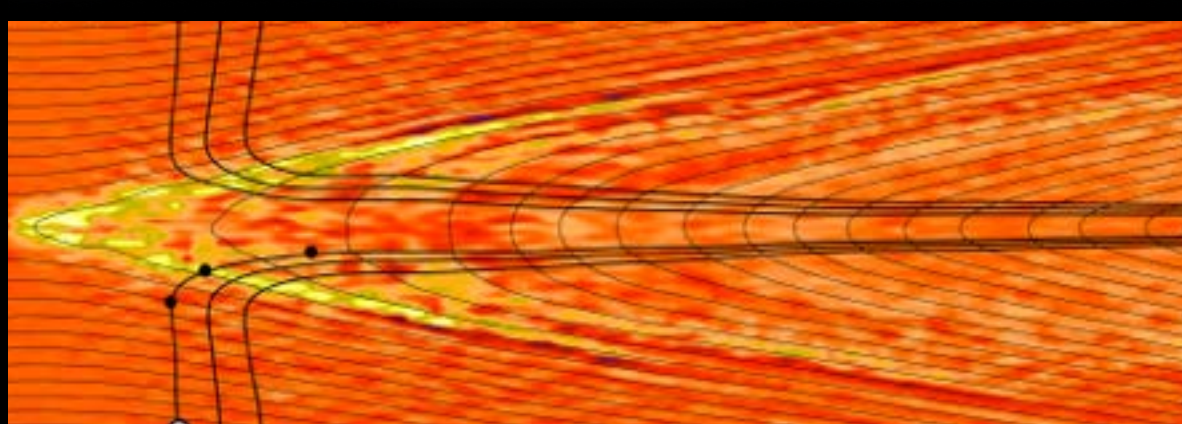
Collisionless mixing





kinetic/fluid « duality »





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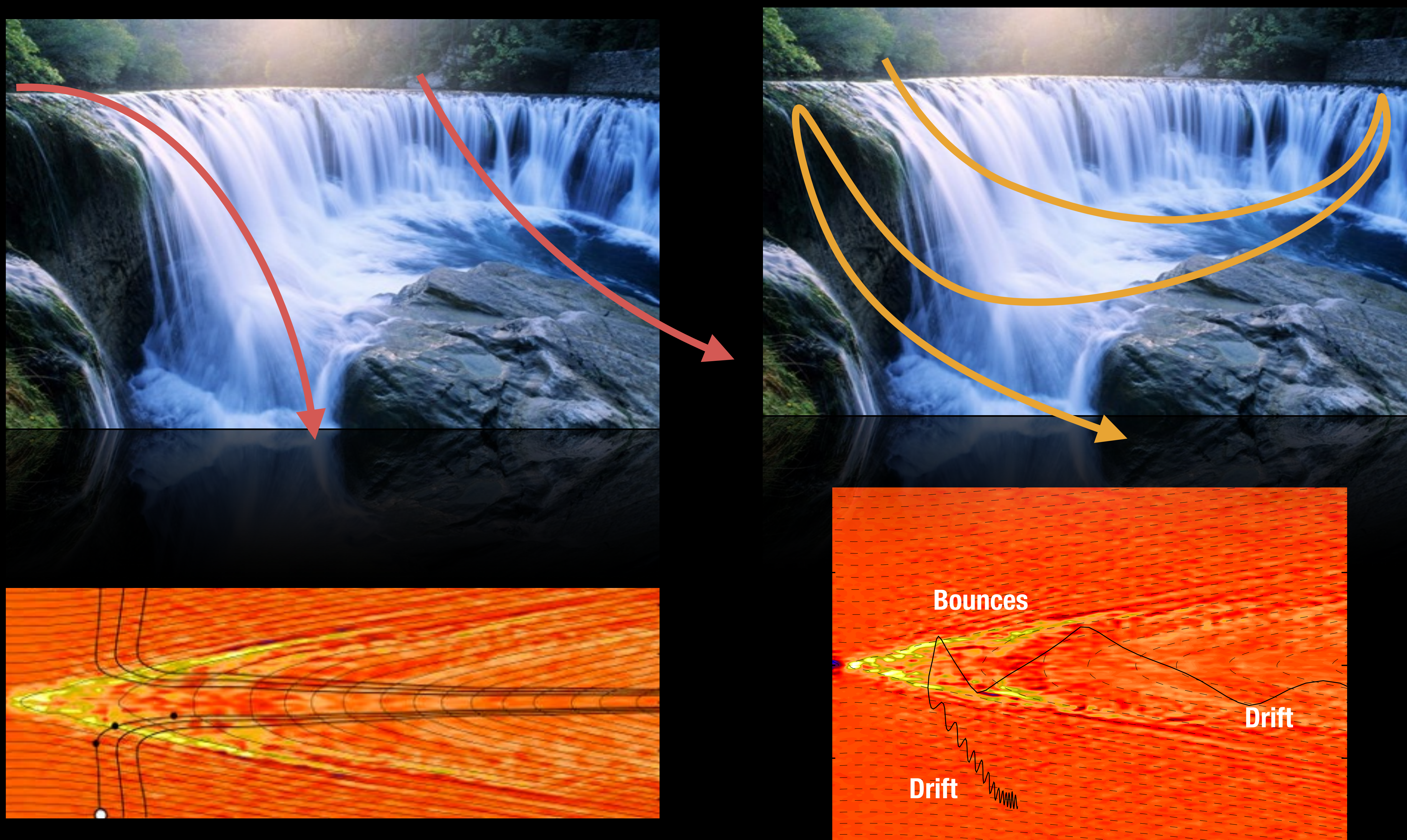
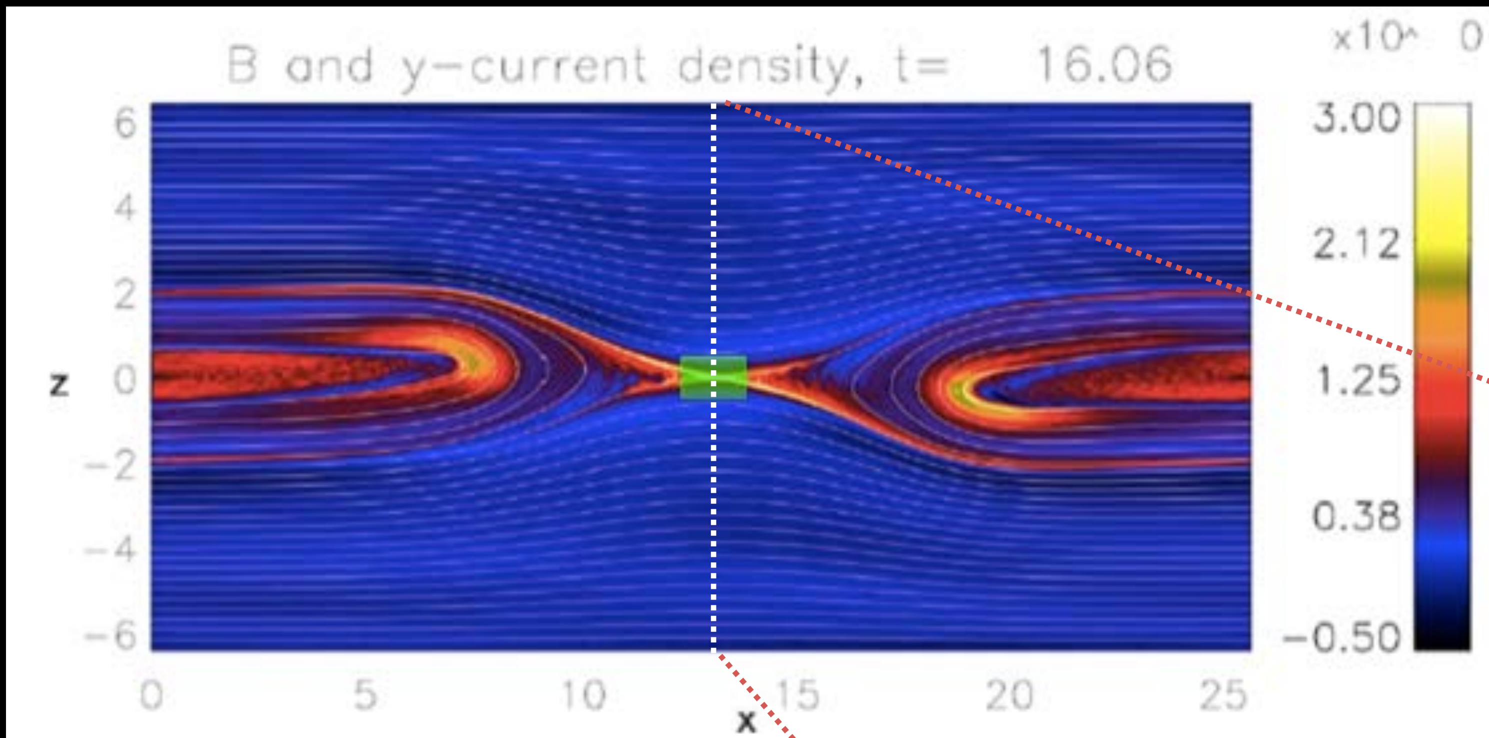
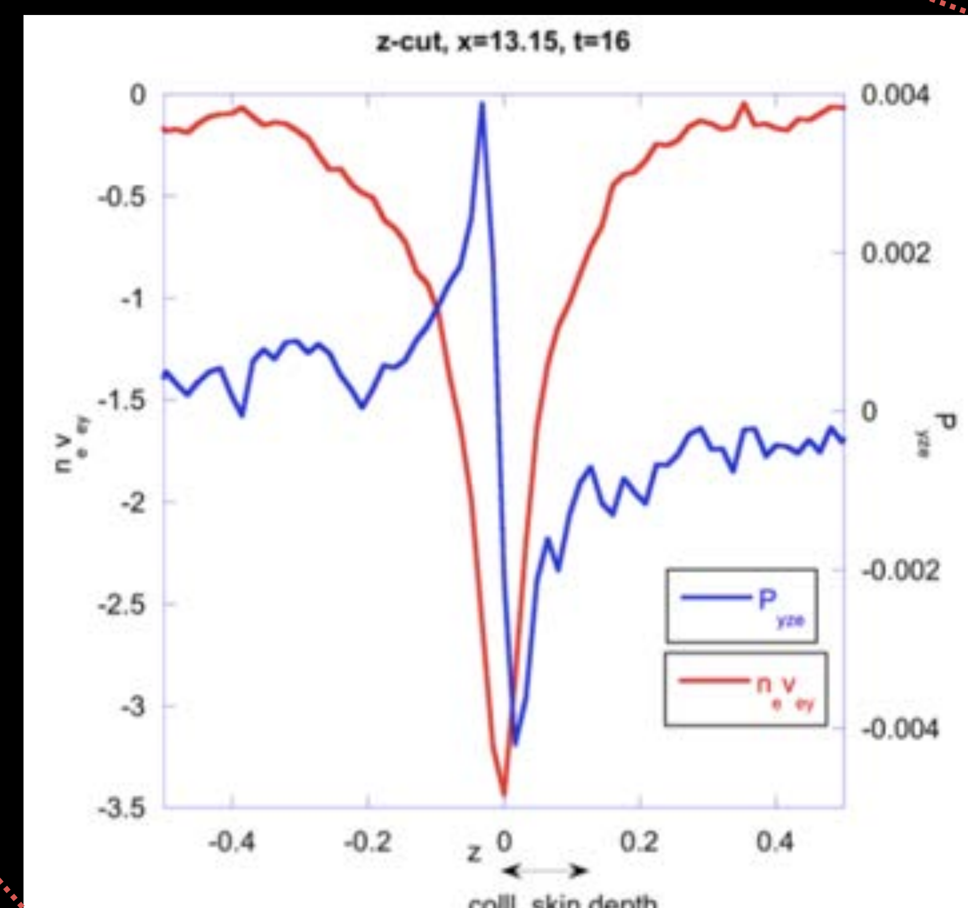


What really happens at the X line?



(Hesse et al. 2011)

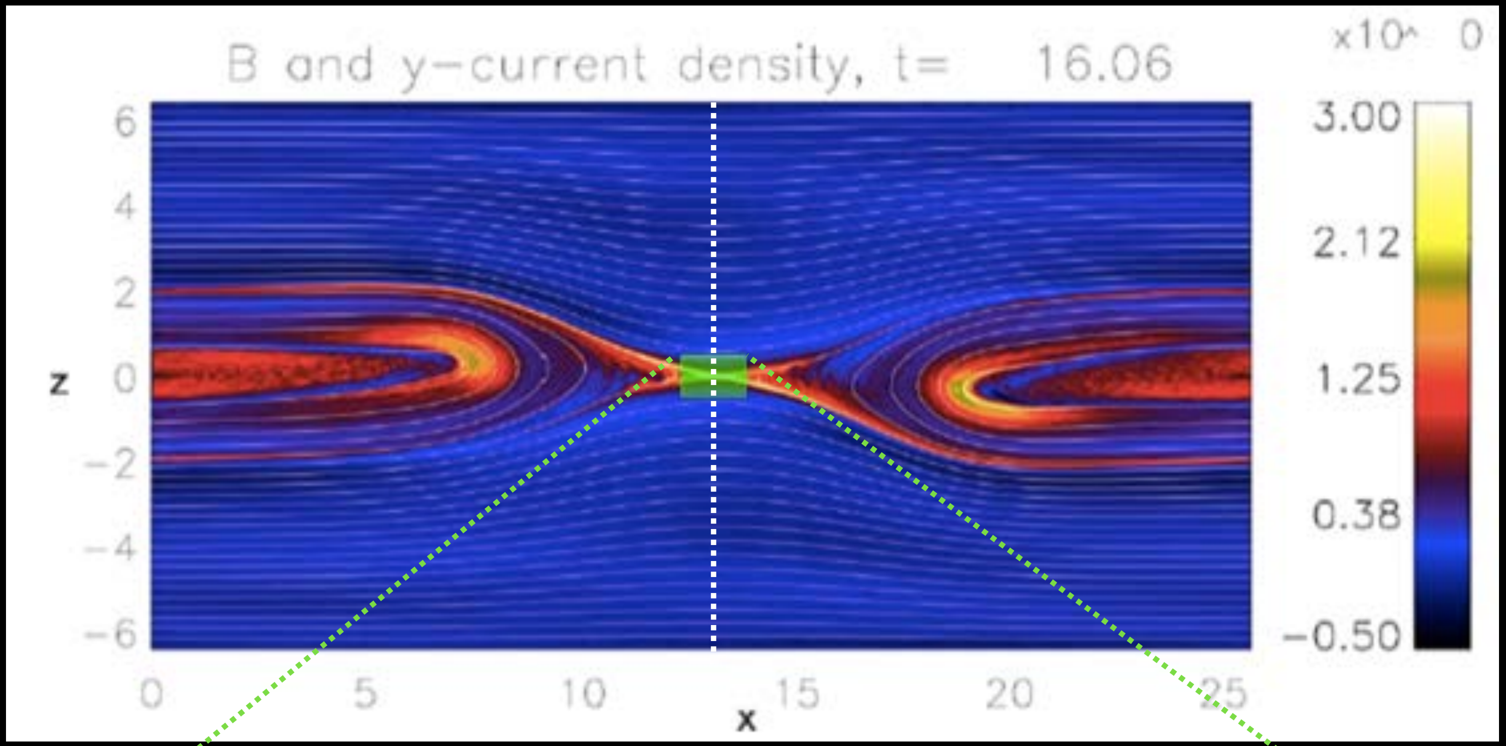


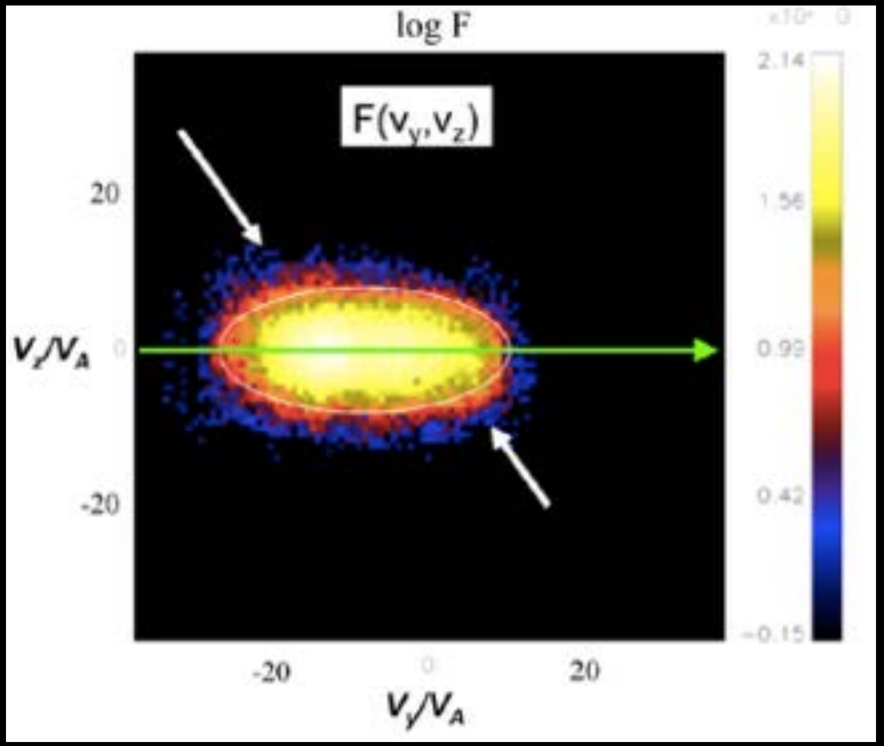
Current sheet collapses at the **electron** skin depth or Larmor radius

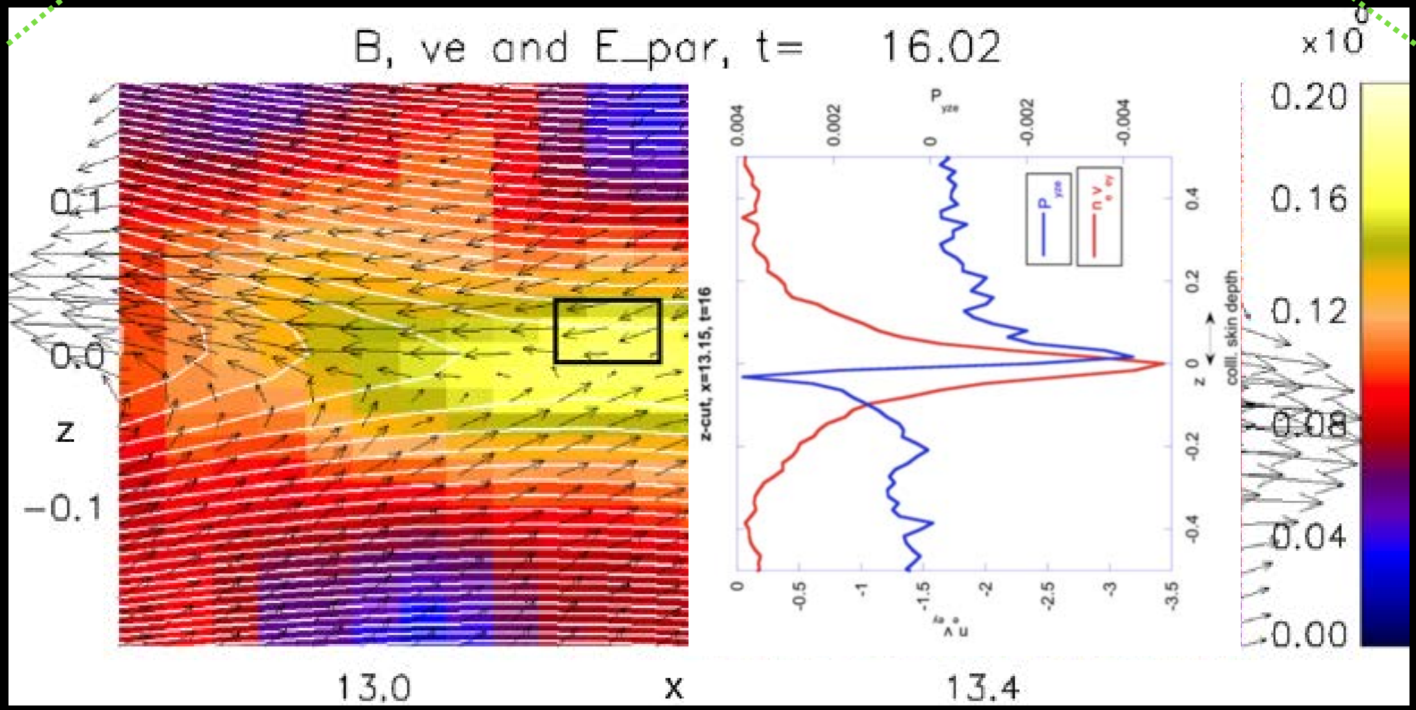
$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{1}{ne}\left(\mathbf{j} \times \mathbf{B} - \boxed{\nabla \cdot \mathbf{P}_e}\right)$$

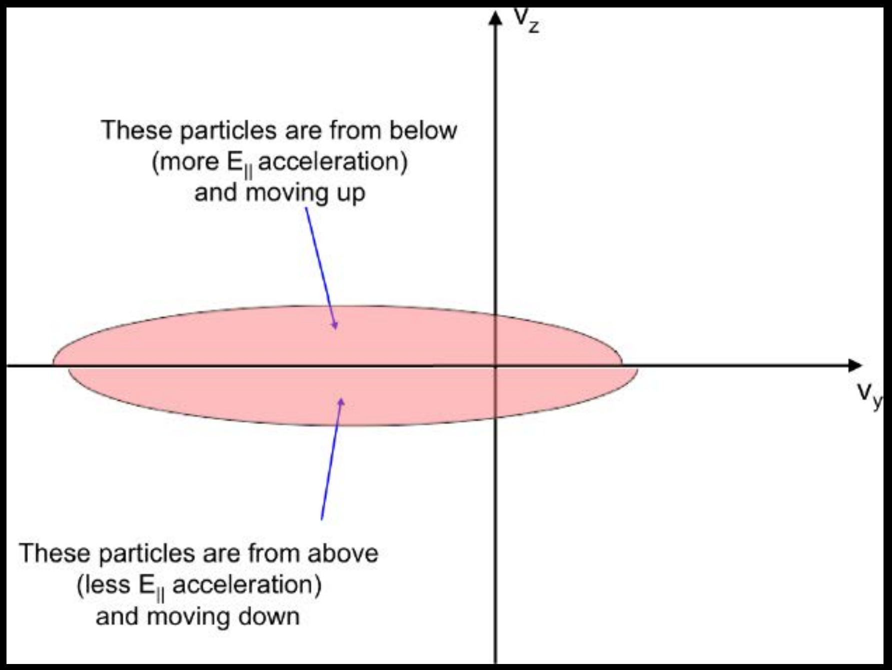
WHAT REALLY HAPPENS AT THE X LINE?

Mixing of low energy incoming e- with energized outgoing e-









WHAT REALLY HAPPENS AT THE X LINE?

The role of the reconnection electric field is to maintain the current density associated to the field reversal at the electron scale that would otherwise decay with a diffusion law

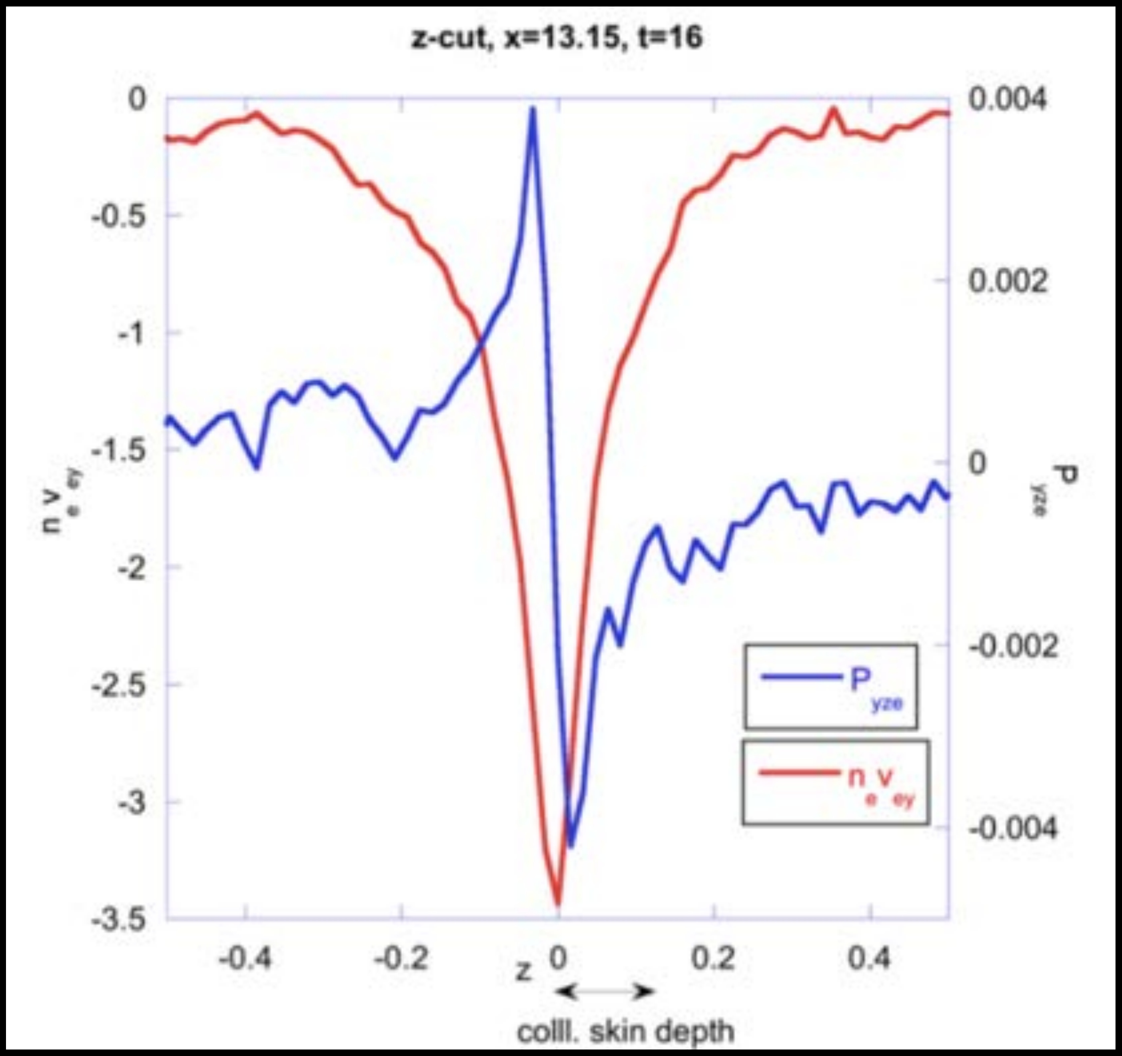
$$\frac{\partial}{\partial t}\left(-en_e v_{yz}\right) \approx -\frac{-e^2 n_e}{m_e} E_y + \kappa \nabla^2 \left(-en_e v_{ye}\right) \approx 0$$

$$E_y \approx \frac{1}{en_e} \kappa \nabla^2 \left(-en_e v_{ye}\right)$$

(....quite a lot of calculation...)

$$E \approx \underbrace{\frac{1}{2en} r_L^2 \frac{\partial v_x}{\partial x}}_{\kappa} \nabla^2 \left(mnv_y\right)$$ With guide field

$$E \approx \frac{1}{e} \frac{\partial v_{ex}}{\partial x} \sqrt{2m_e T_e}$$ Antiparallel



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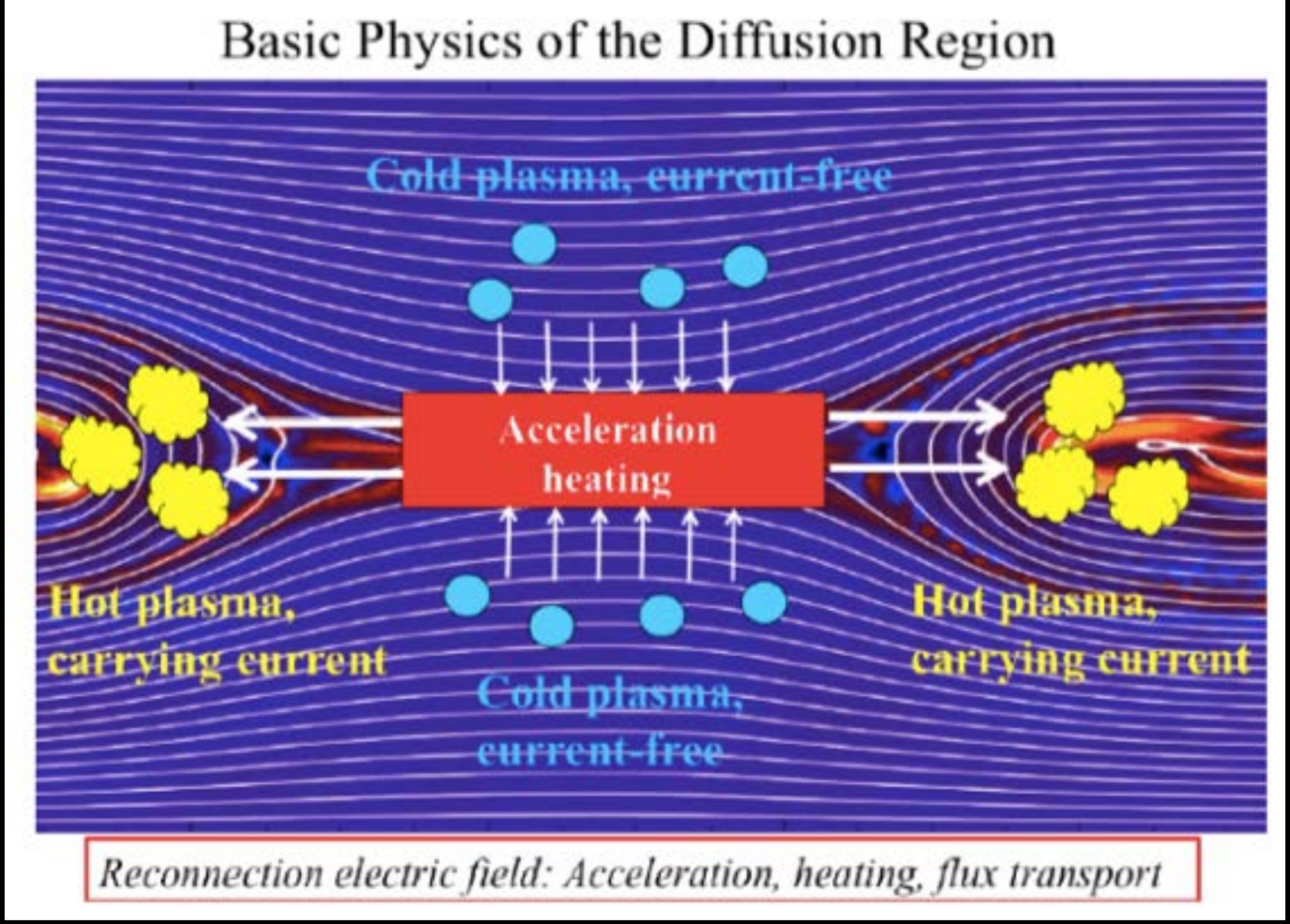
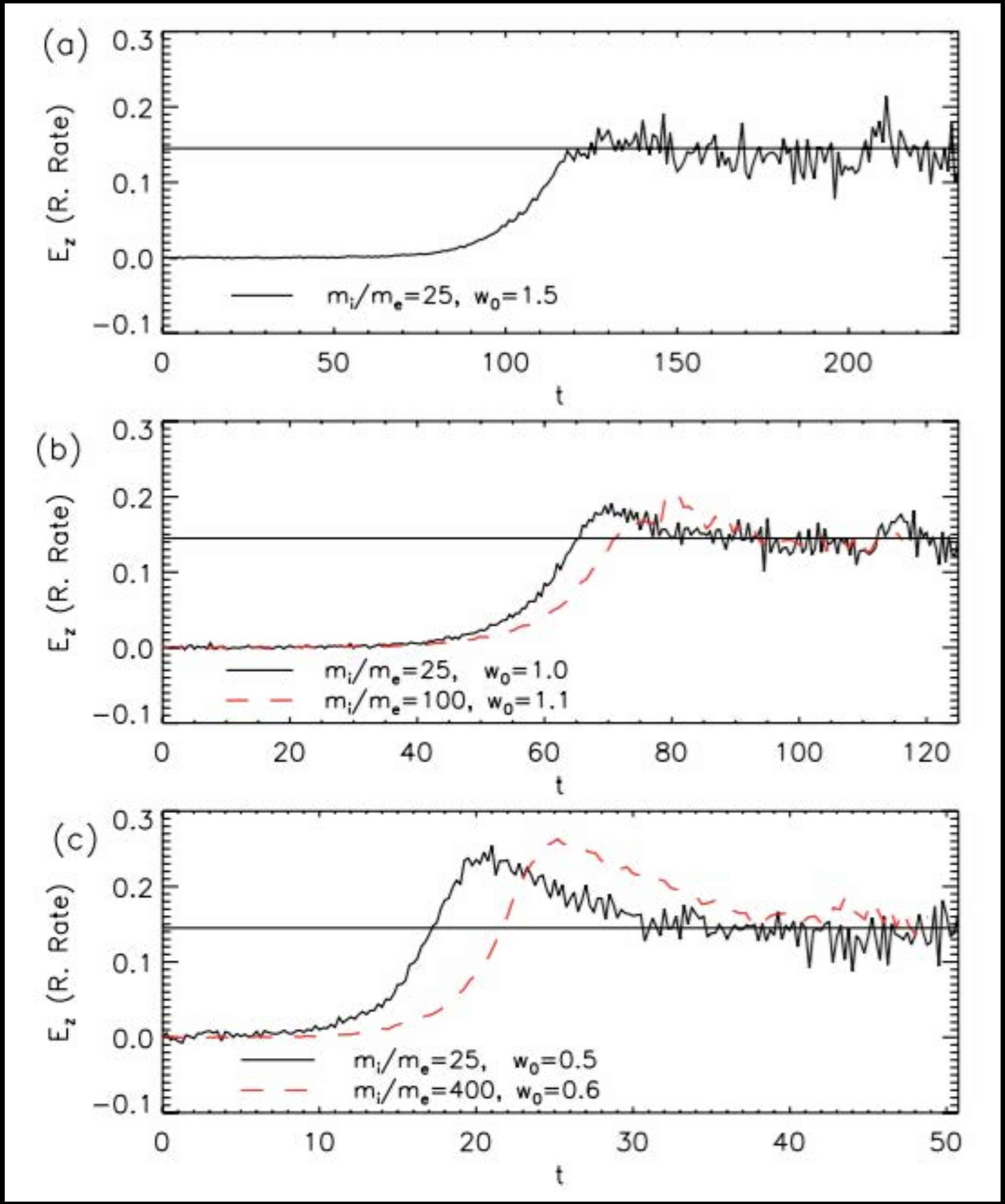


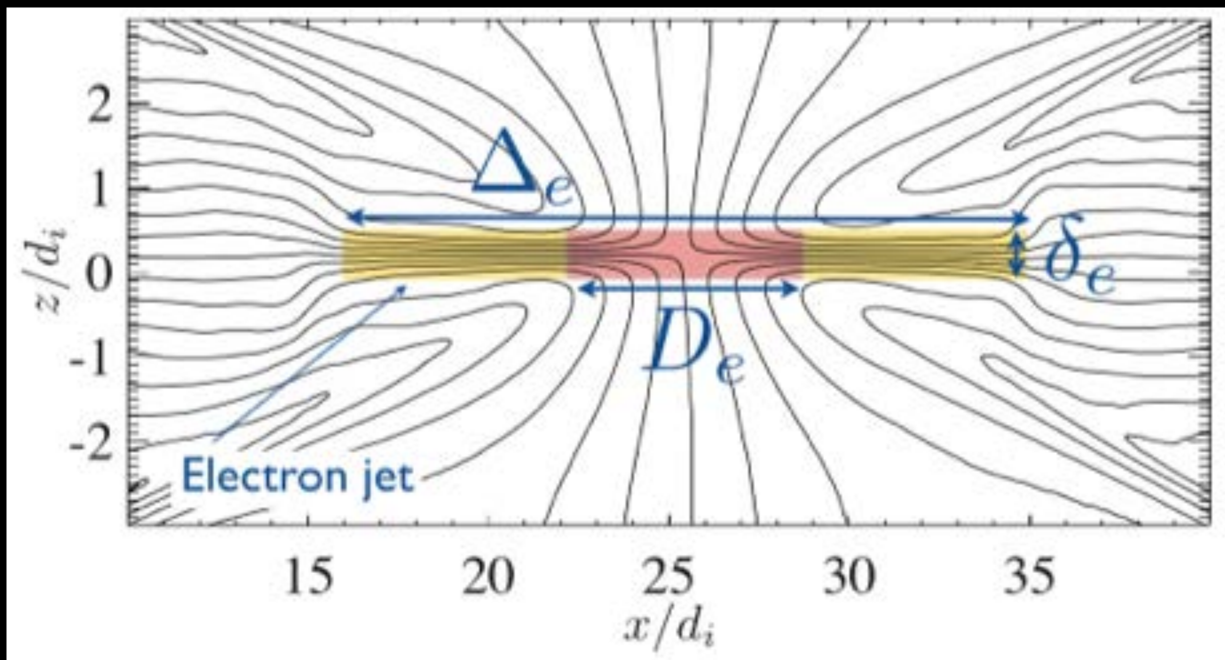
QUASI-STEADY RECONNECTION, NORMALIZED RATE ~0.1

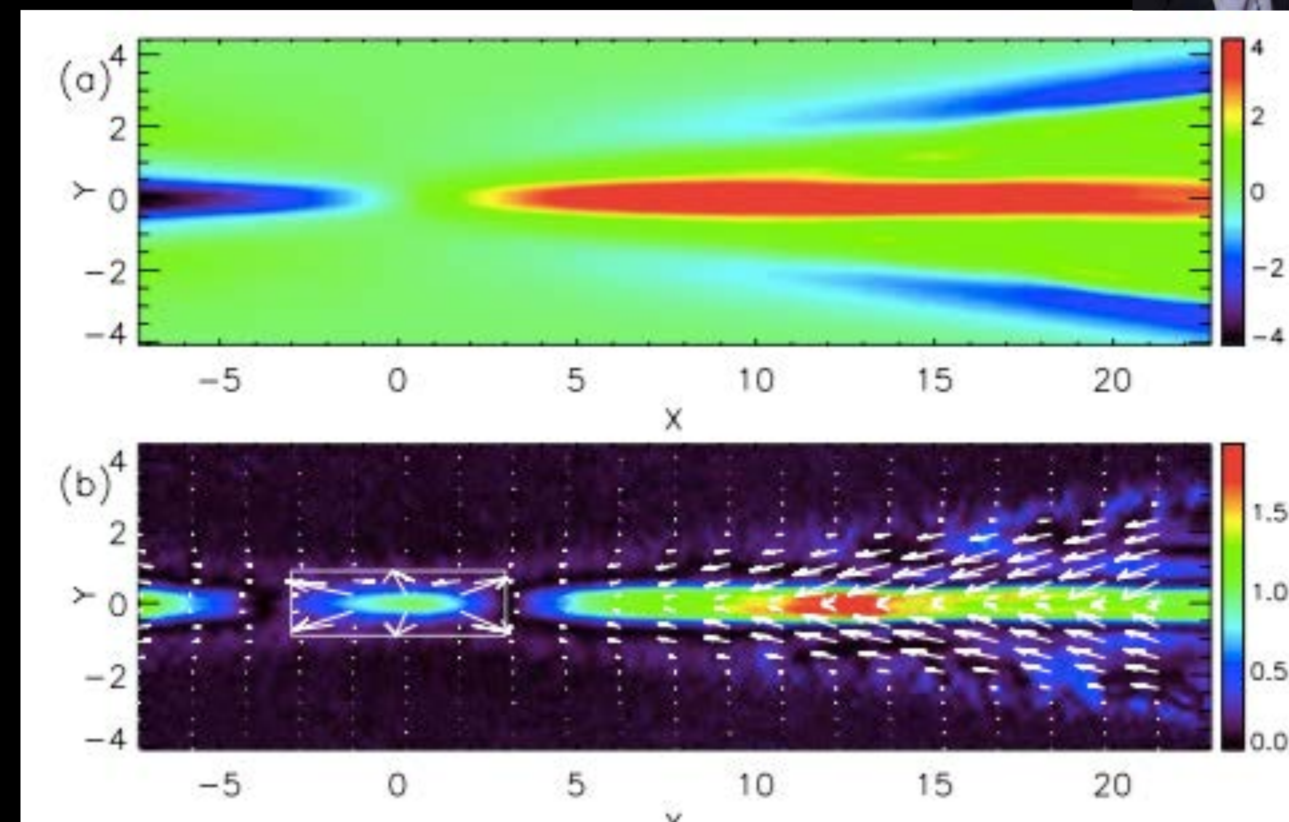
(Shay et al. 2007)



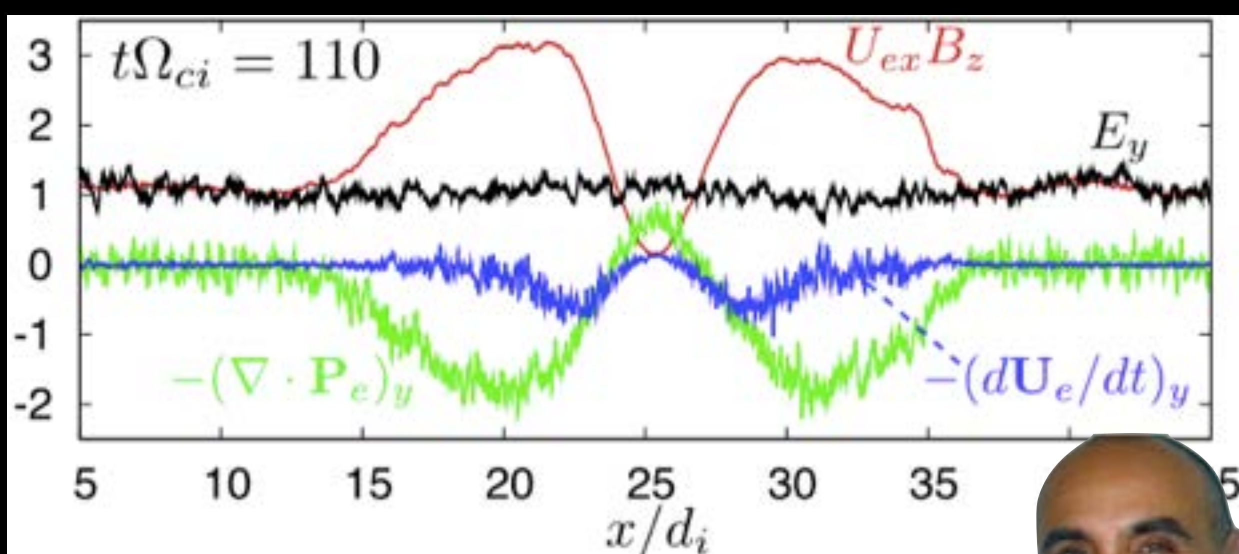
ELECTRON BOTTLENECK?

Outer part of the electron current layer… elongates—> secondary tearing—>shortens etc.





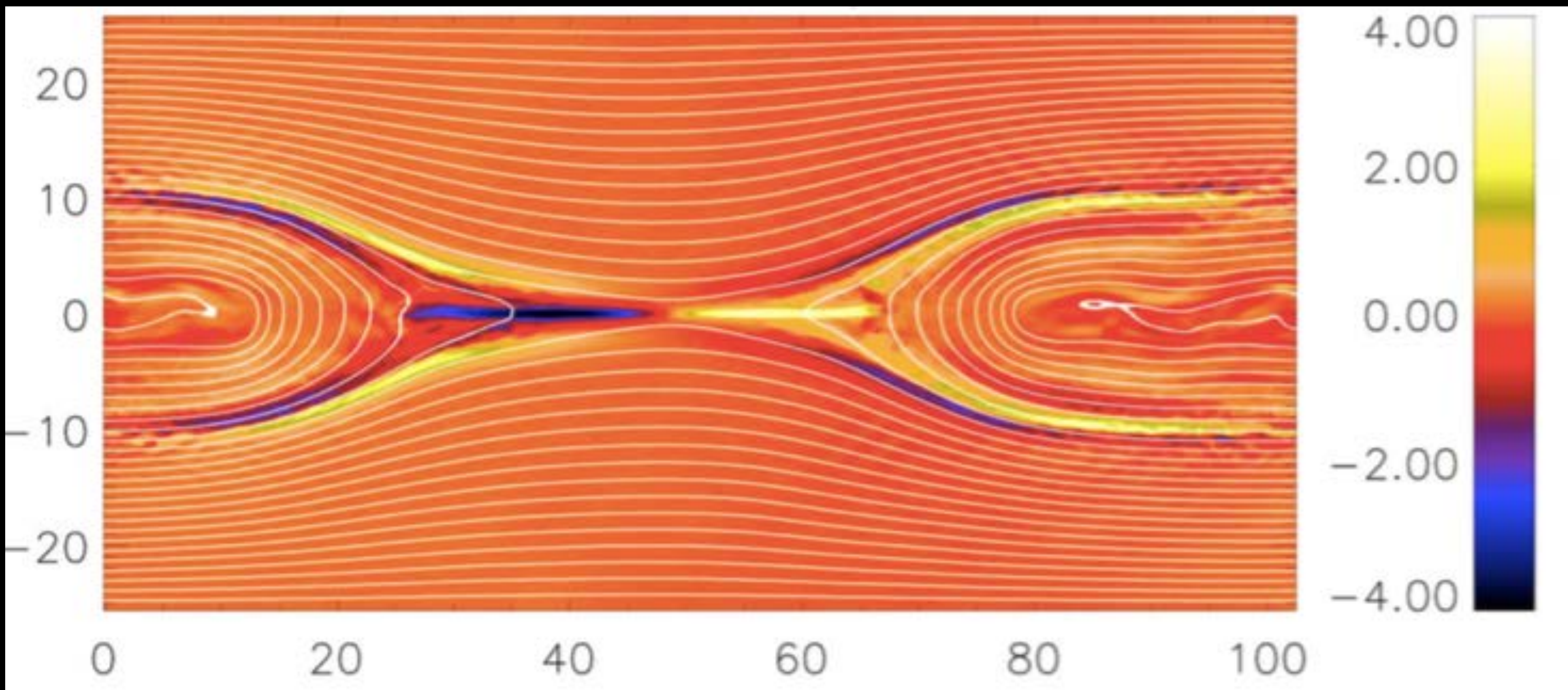
(Shay et al. 2007)



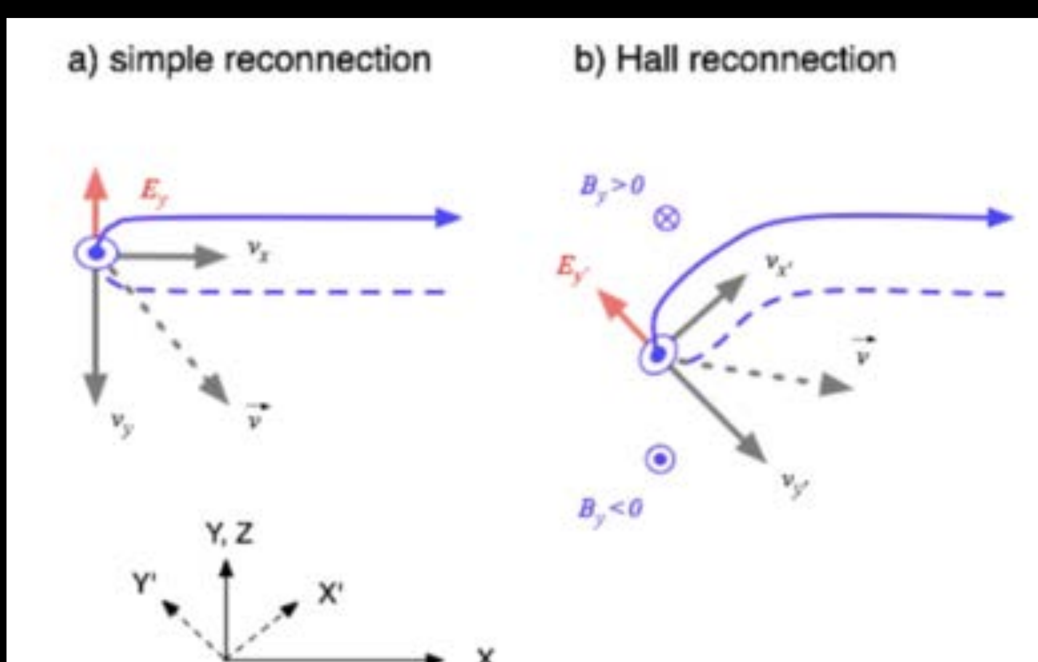
(Karimabadi et al. 2007)

How long is the DIFFUSION region?

ELECTRONS JETS: CURRENT SUPPORTING THE REVERSAL OF THE OUT-OF-PLANE B



(Hesse et al. 2008)



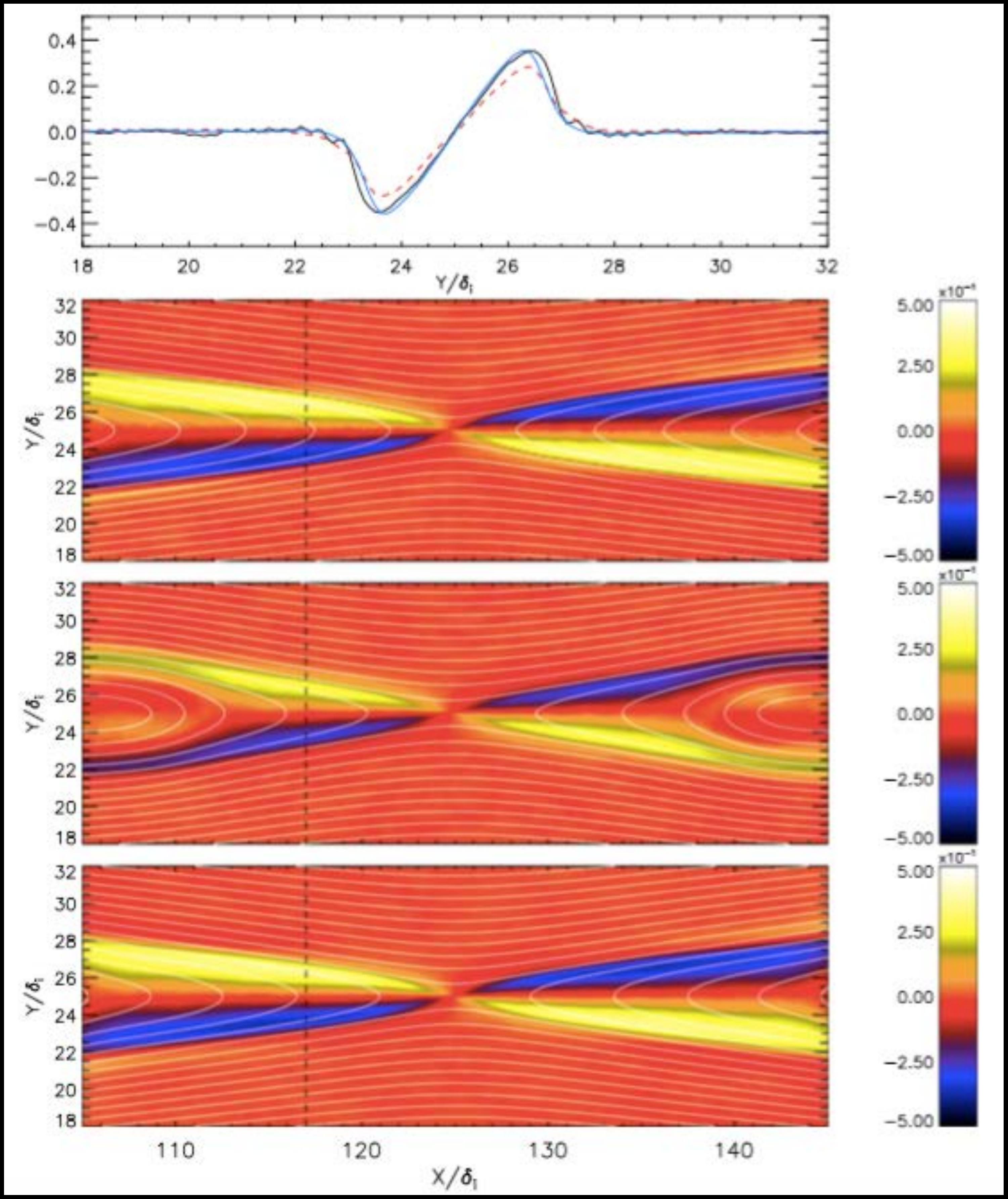
The outflow jet, […], appears to be a regular structure, which is readily explained by effects not commonly associated with dissipation, such as diamagnetic and ExB drifts. It is in this sense that we use the term "nondissipative."

HYBRID CODE MISS THIS PHYSICS: EFFECT OF DISSIPATIVE TERMS

no dissipative term

$\eta \mathbf{j}$

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



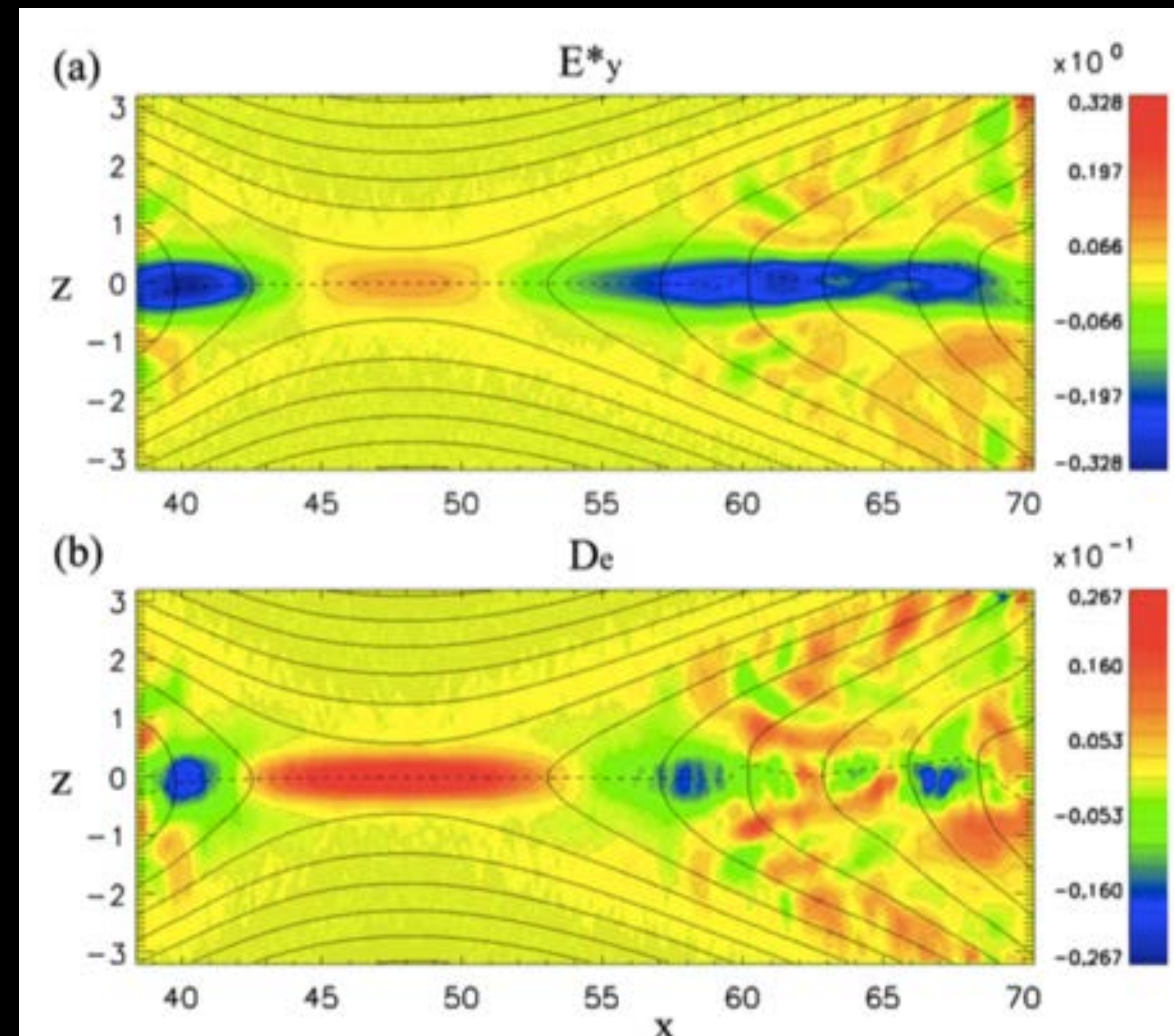
(Aunai et al. 2013)

NON-IDEAL VS « DISSIPATIVE »

Choosing the frame of electron bulk motion (the number density's flow), we obtain the *electron-frame dissipation measure*,

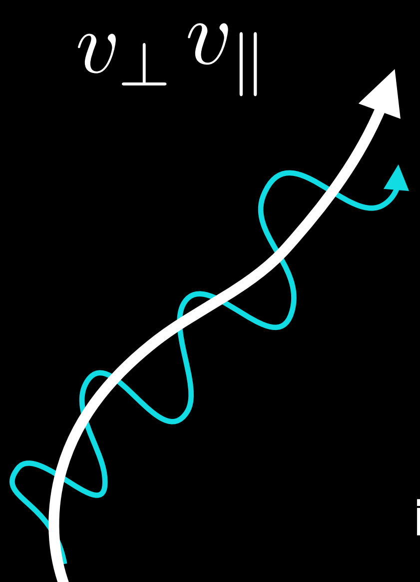
$$D_e = \gamma_e[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c(\boldsymbol{v}_e \cdot \boldsymbol{E})]. \qquad (7)$$

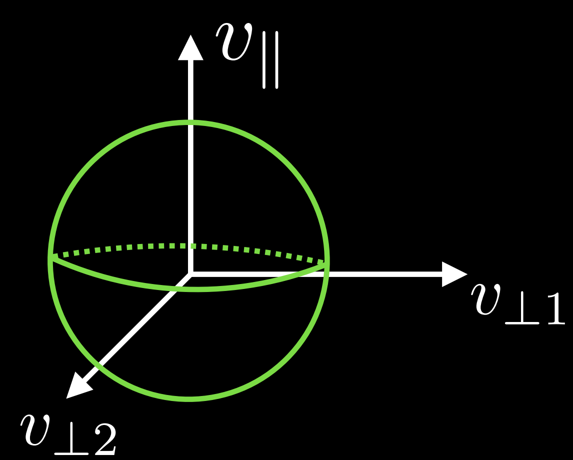
In the nonrelativistic limit, one can simplify Eq. (7) by setting $\gamma_e \to 1$. One can confirm this by multiplying $\boldsymbol{j}' = qn_i\boldsymbol{v}_i' = (\boldsymbol{j} - \rho_c\boldsymbol{v}_e)$ and $\boldsymbol{E}' = \boldsymbol{E}^* = (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})$.



(Zenitani et al. 2011)

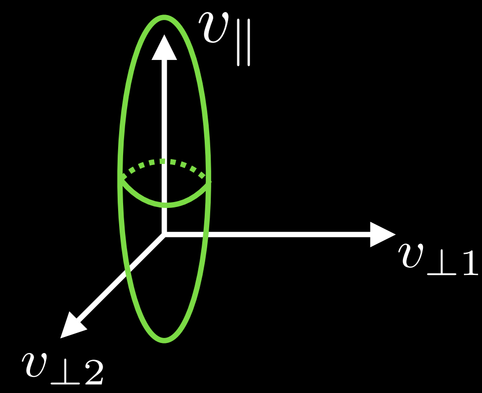
Concept of gyrotropy





isotropic distribution

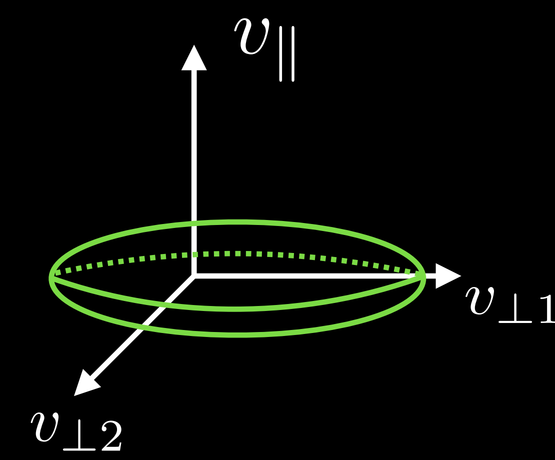
$$\begin{pmatrix} P & 0 & 0 \\ 0 & P & 0 \\ 0 & 0 & P \end{pmatrix}$$



anisotropic distribution

$$T_{||} > T_\perp$$

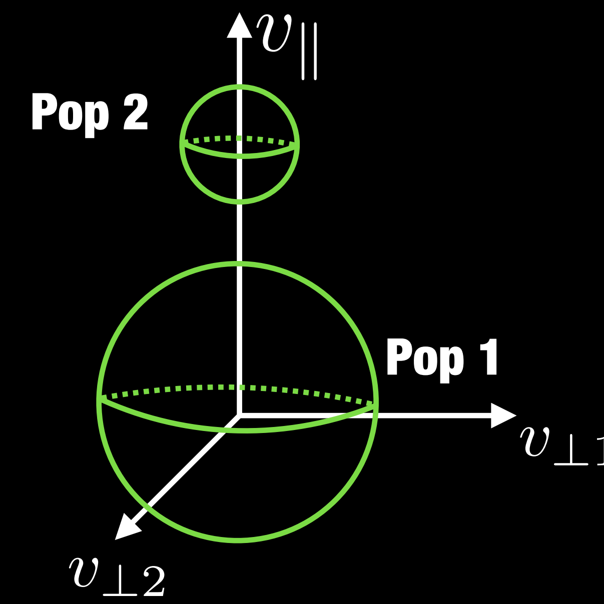
$$\begin{pmatrix} P_{||} & 0 & 0 \\ 0 & P_\perp & 0 \\ 0 & 0 & P_\perp \end{pmatrix}$$



anisotropic distribution

$$T_{||} < T_\perp$$

$$\begin{pmatrix} P_{||} & 0 & 0 \\ 0 & P_\perp & 0 \\ 0 & 0 & P_\perp \end{pmatrix}$$



complicated anisotropic

$$T_{||} > T_\perp$$

$$\begin{pmatrix} P_{||} & 0 & 0 \\ 0 & P_\perp & 0 \\ 0 & 0 & P_\perp \end{pmatrix}$$

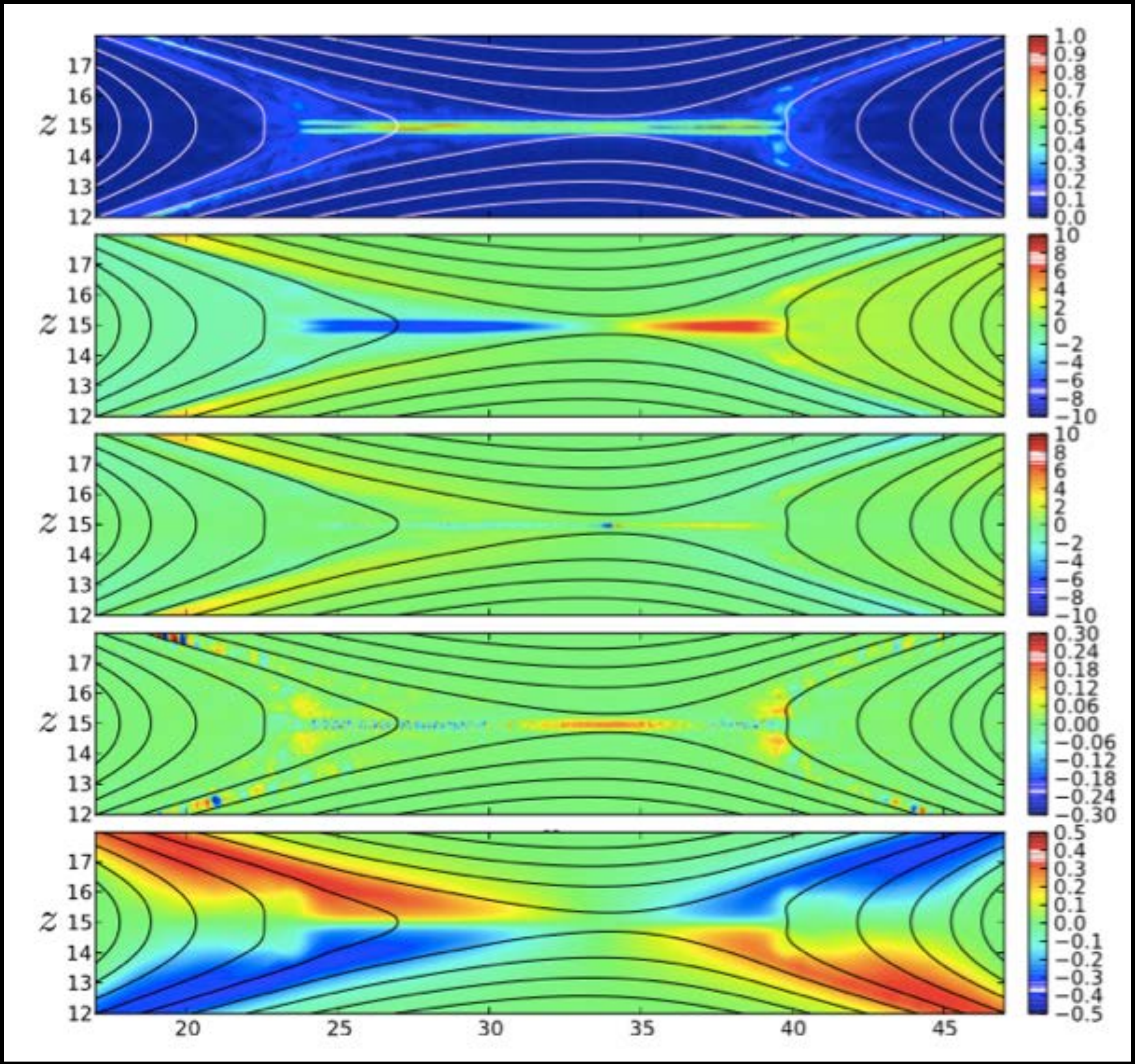
Generally true as long as $\lambda \gg \rho_L$ **and** $\omega \ll \omega_c$

NON-GYROTROPY IN THE CONTEXT OF MAGNETIC RECONNECTION

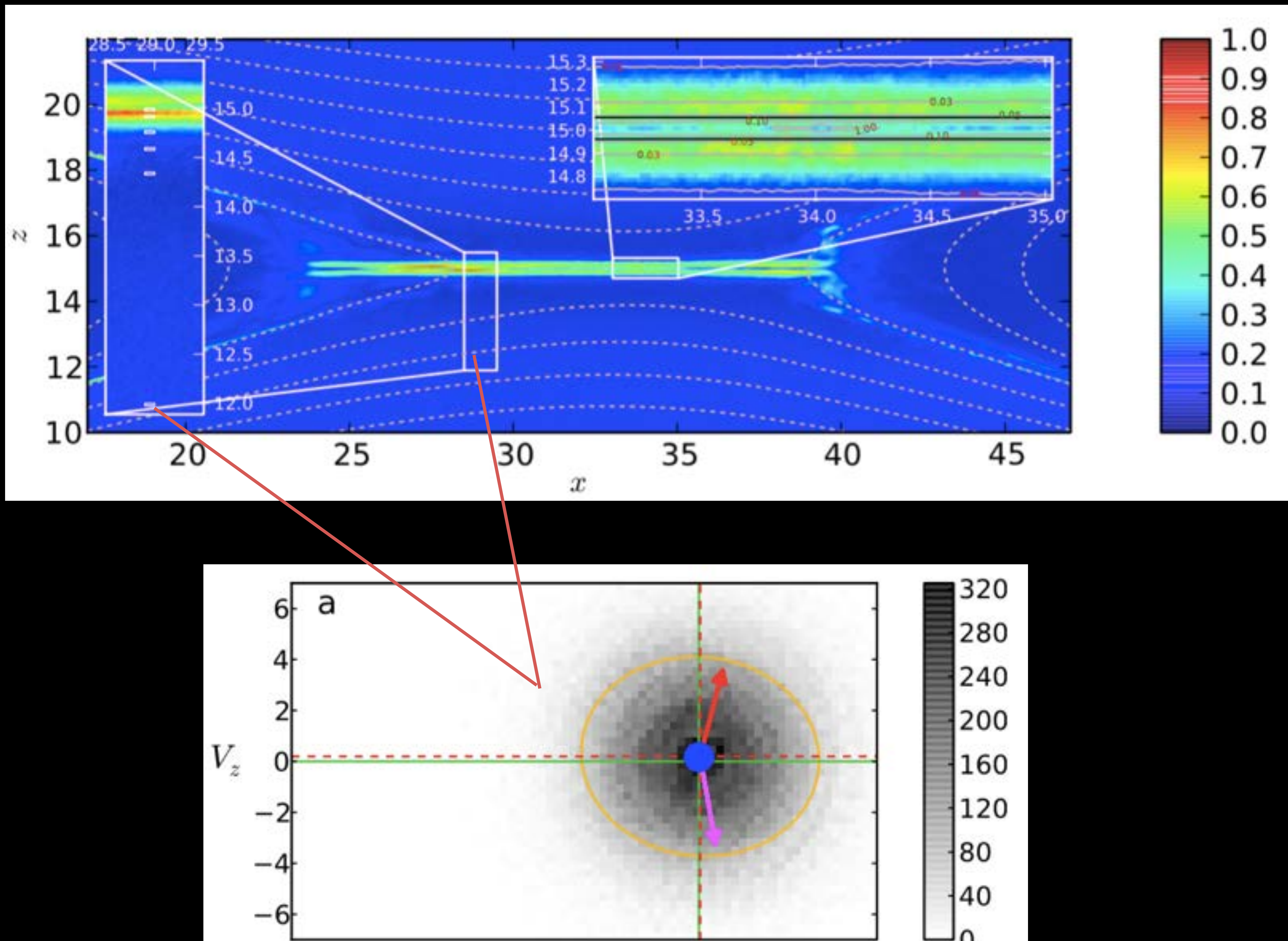
non-gyrotropic electron jet

electron jet

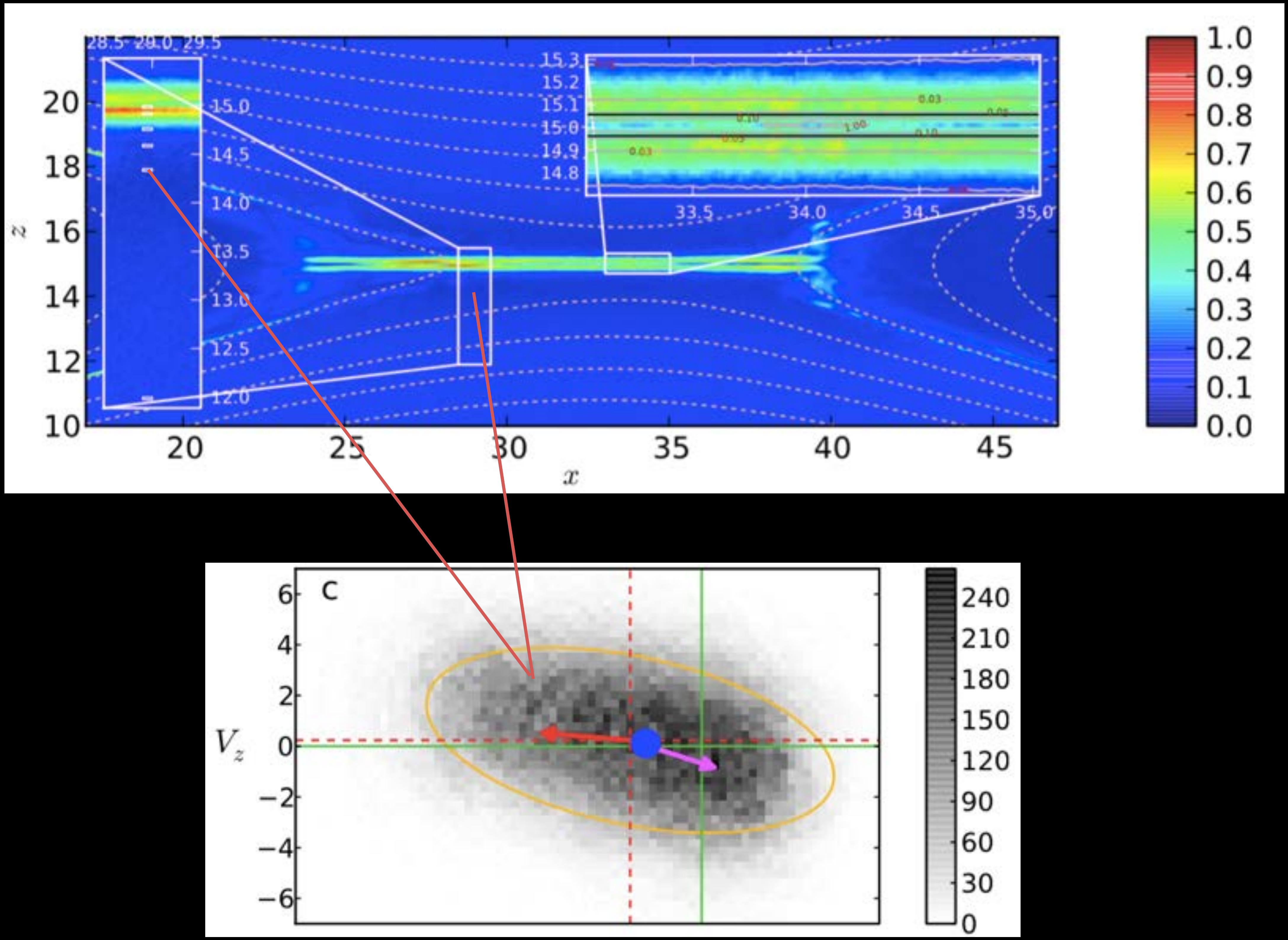
« dissipation »



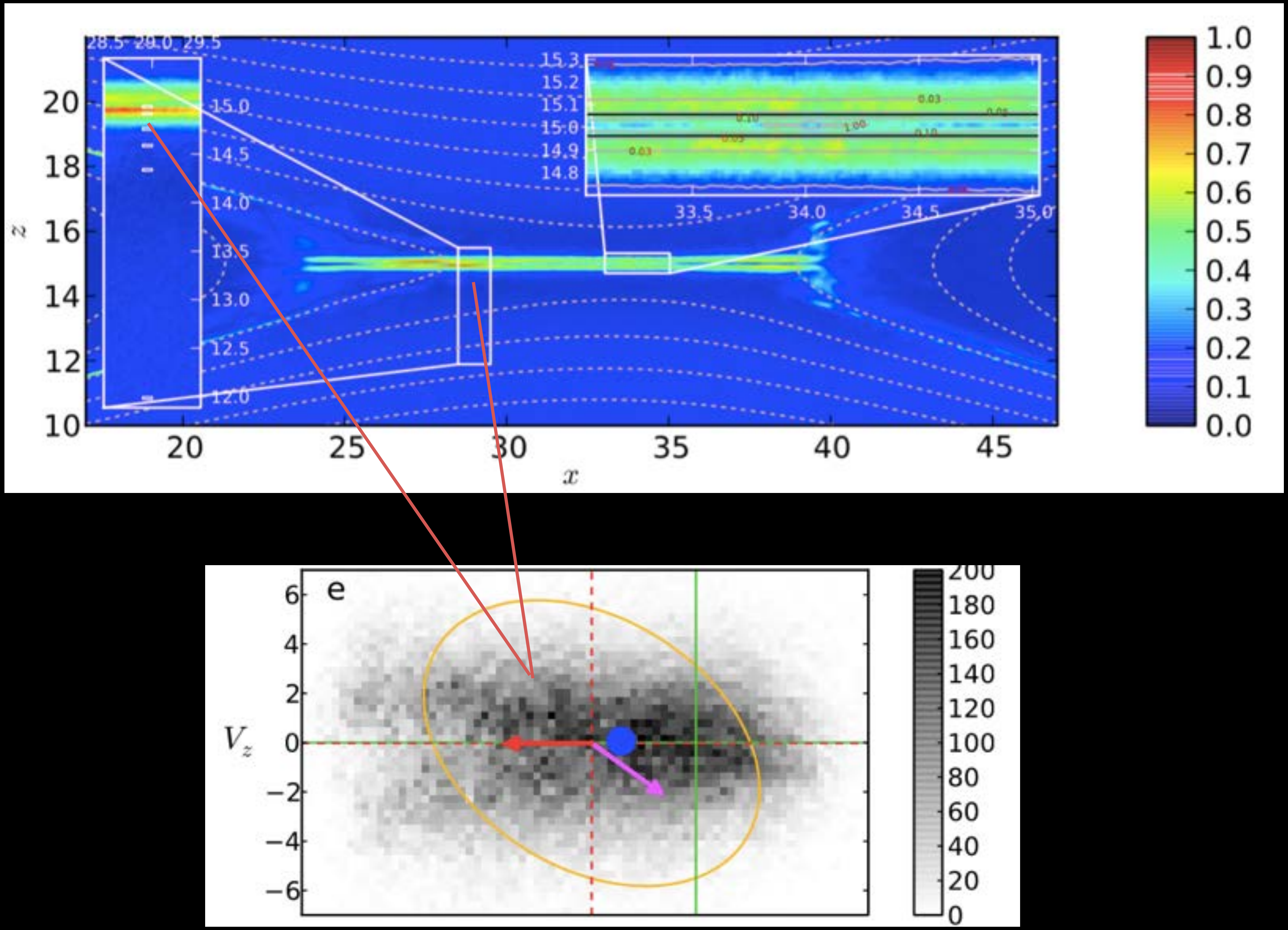
(Aunai et al. 2013)



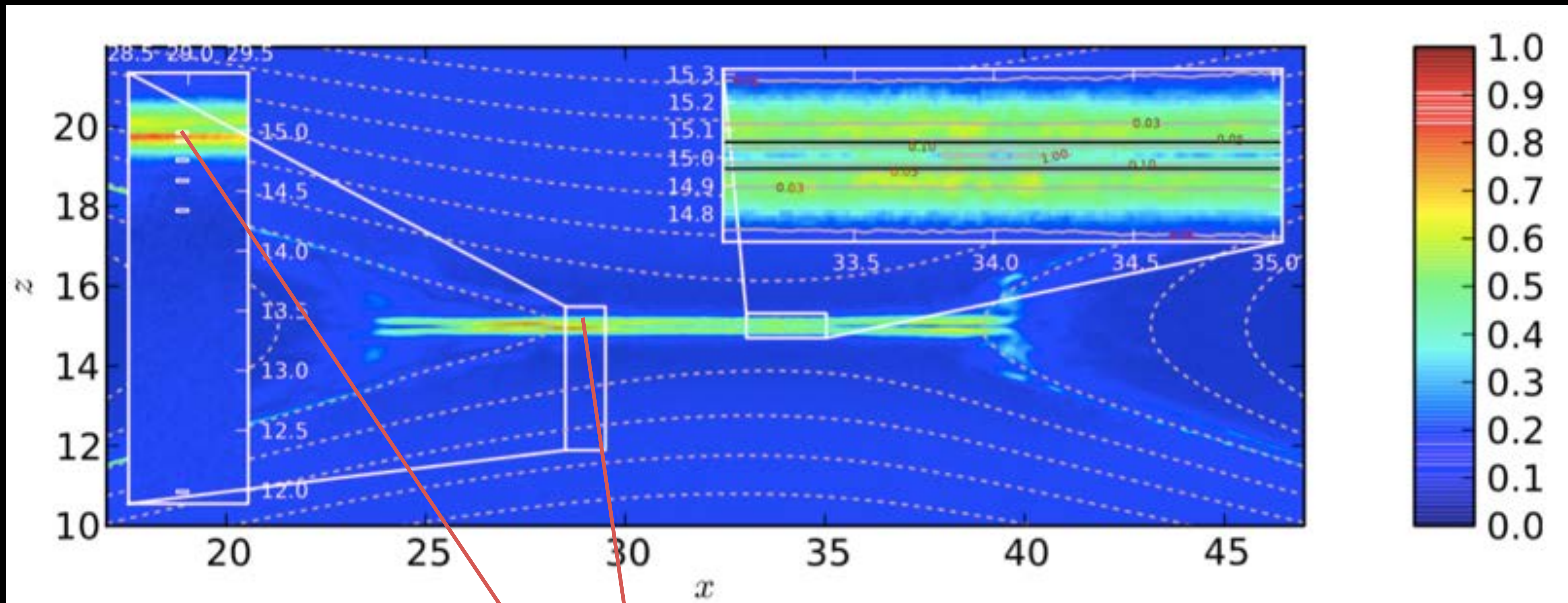
isotropic inflow

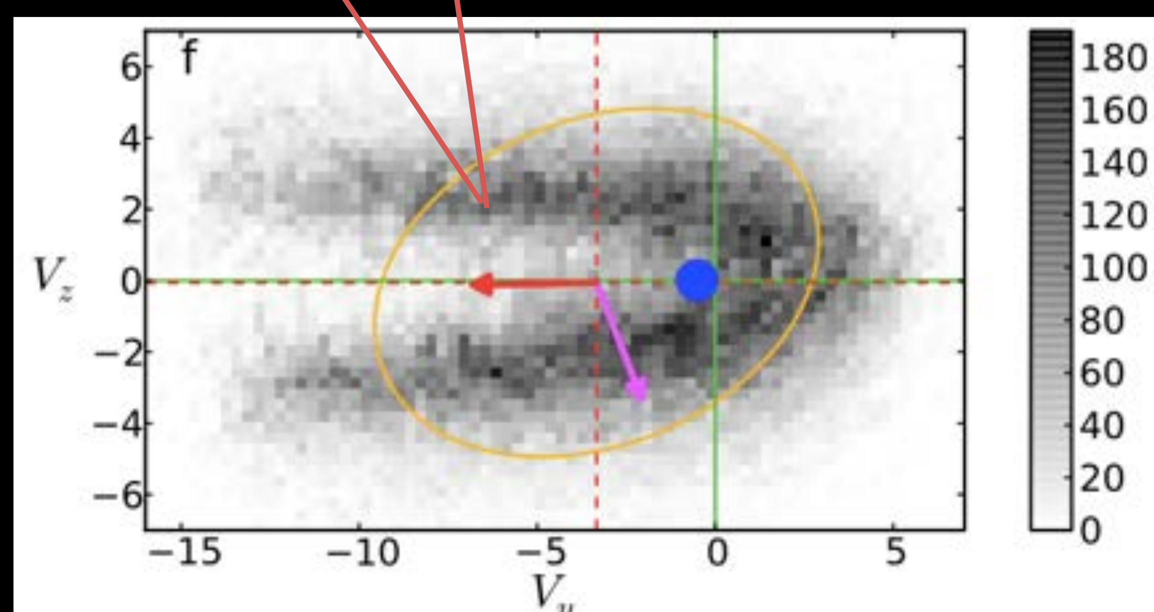


Anisotropic outflow



nongyrotropic outflow





Electrons nongyrotropy maps regions of non-adiabatic dynamics

irreversibility?

dissipation?

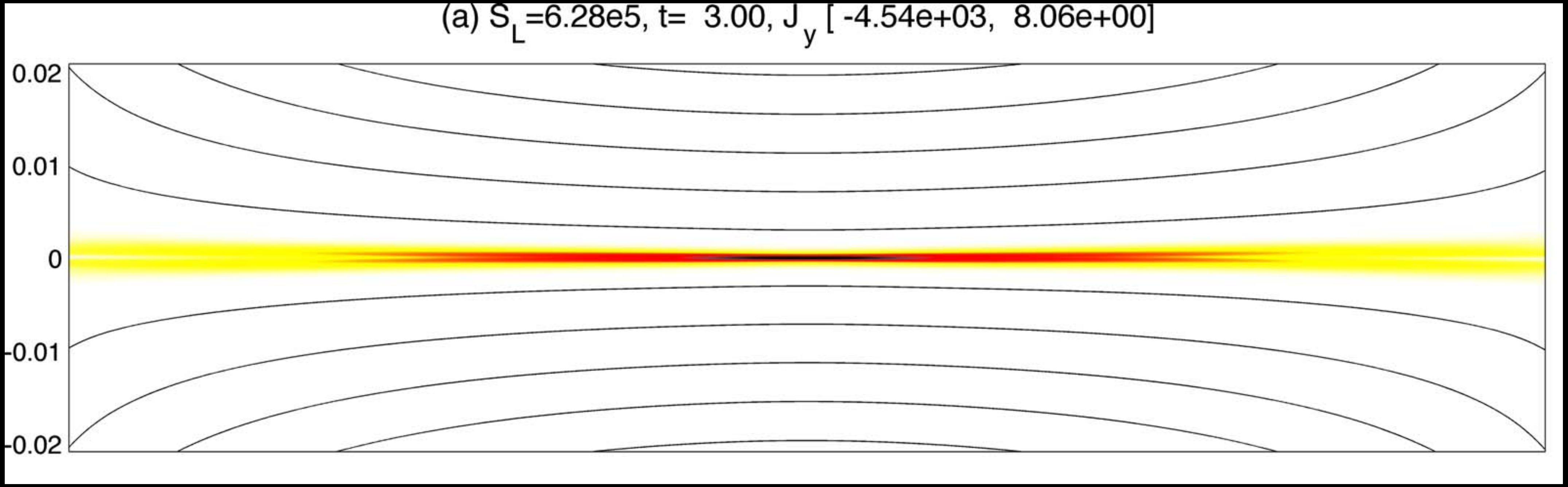
nongyrotropic outflow

Chap. 5 - Plasmoids

Unsteady reconnection

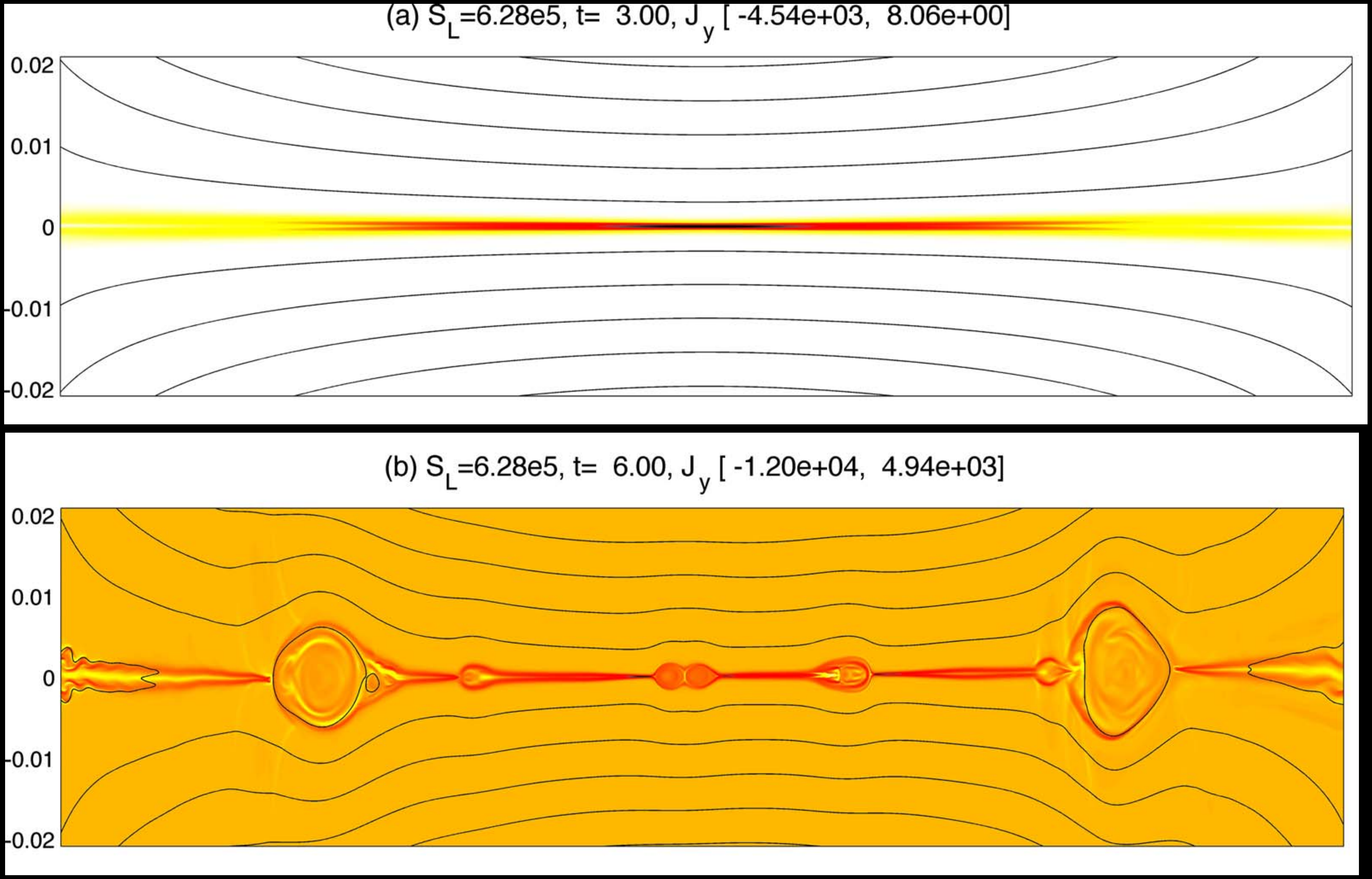
PLASMOIDS IN MHD FOR HIGH LUNDQUIST NUMBERS

(bhattacharjee et al. 2013)



PLASMOIDS IN MHD FOR HIGH LUNDQUIST NUMBERS

(bhattacharjee et al. 2013)

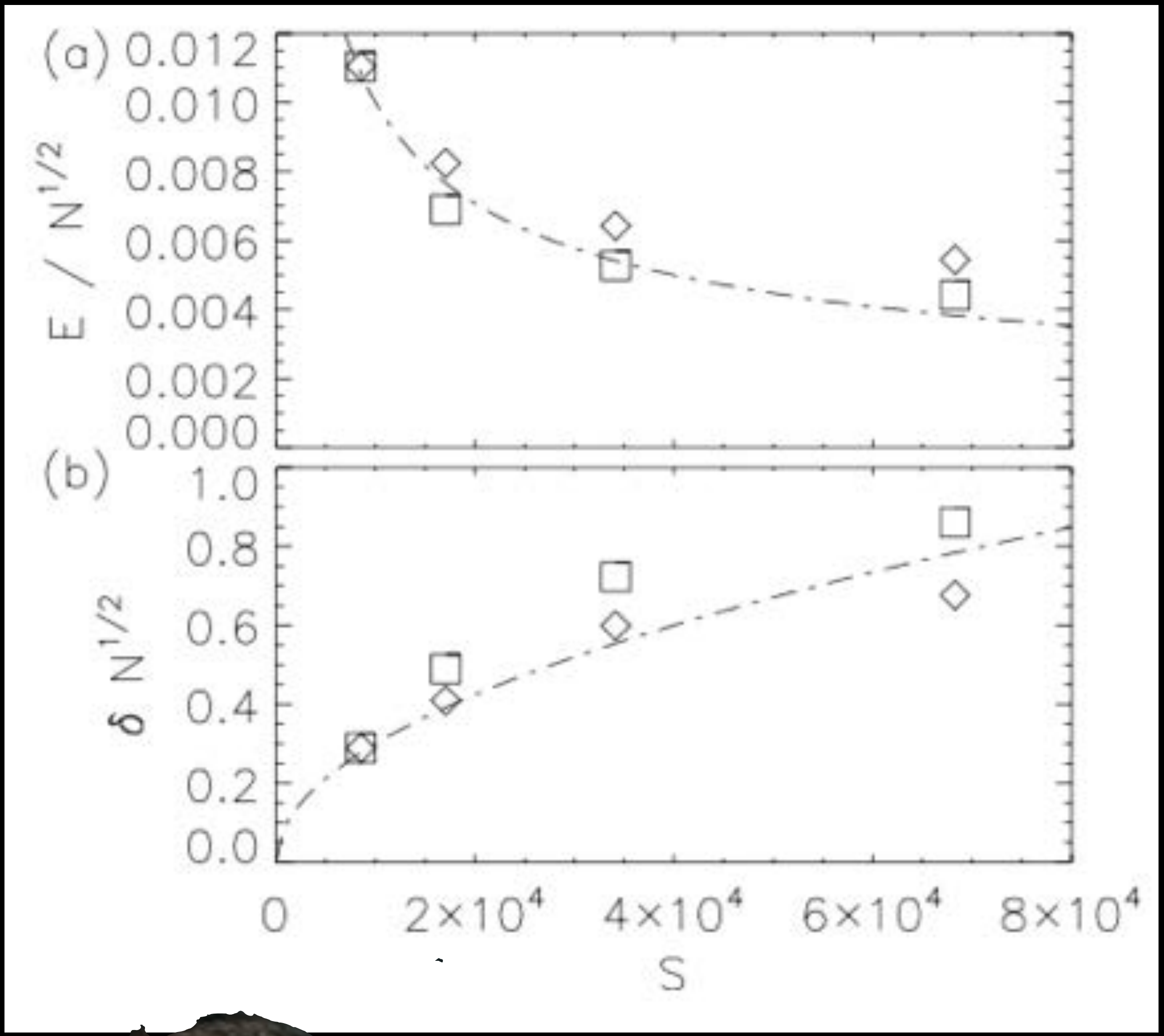


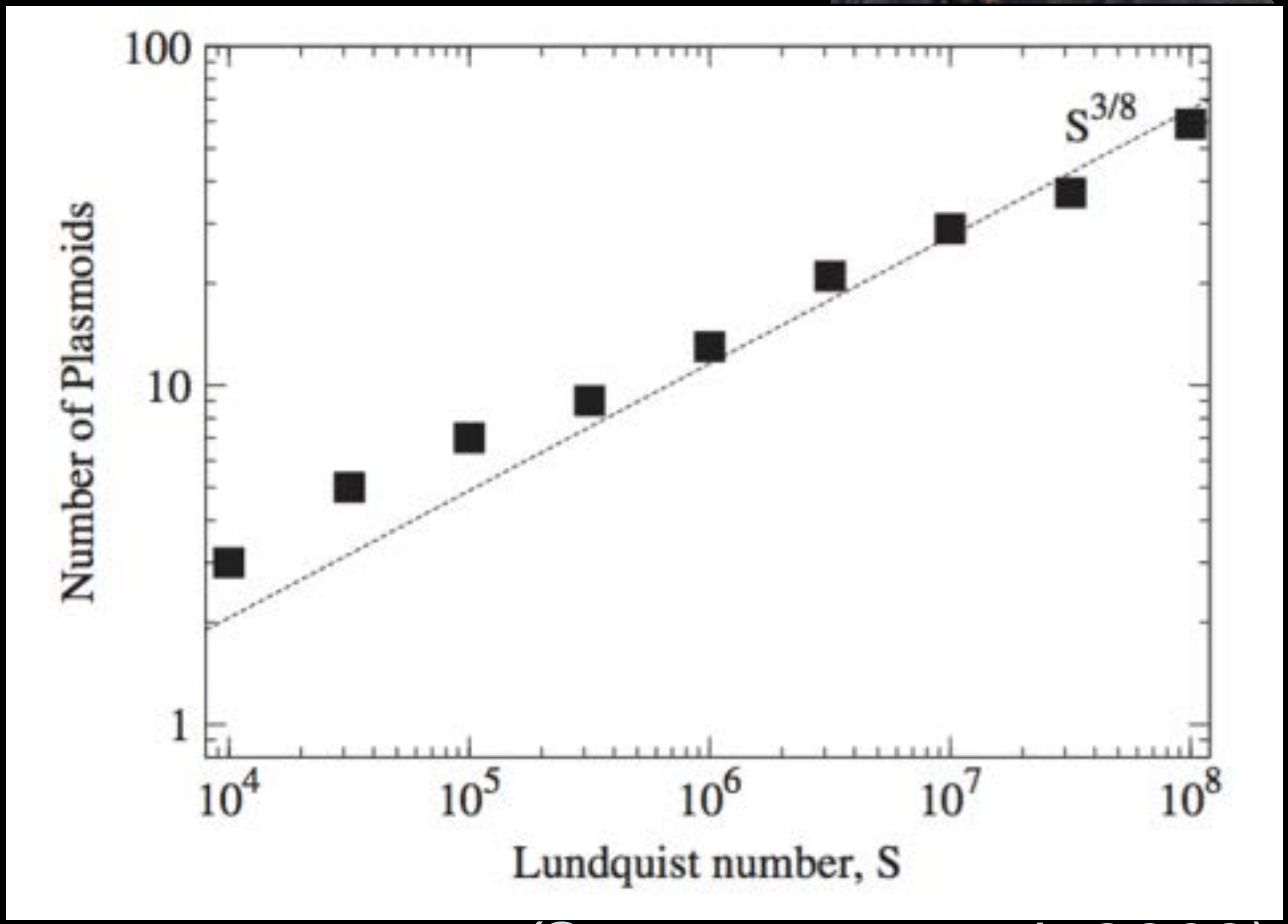
There are plasmoids.. ok and so, what? $\longrightarrow$ $E \sim E_{SP}\sqrt{N}$

$$\delta \sim \frac{\delta_{SP}}{\sqrt{N}}$$

SCALING WITH PLASMOIDS

$$E \sim E_{SP}\sqrt{N}$$





(Cassak et al. 2009)

(Samtaney et al. 2009)

$$E \sim S^{-(1-3/8)/2} \sim S^{-5/16}$$

faster than SP but still slow reconnection

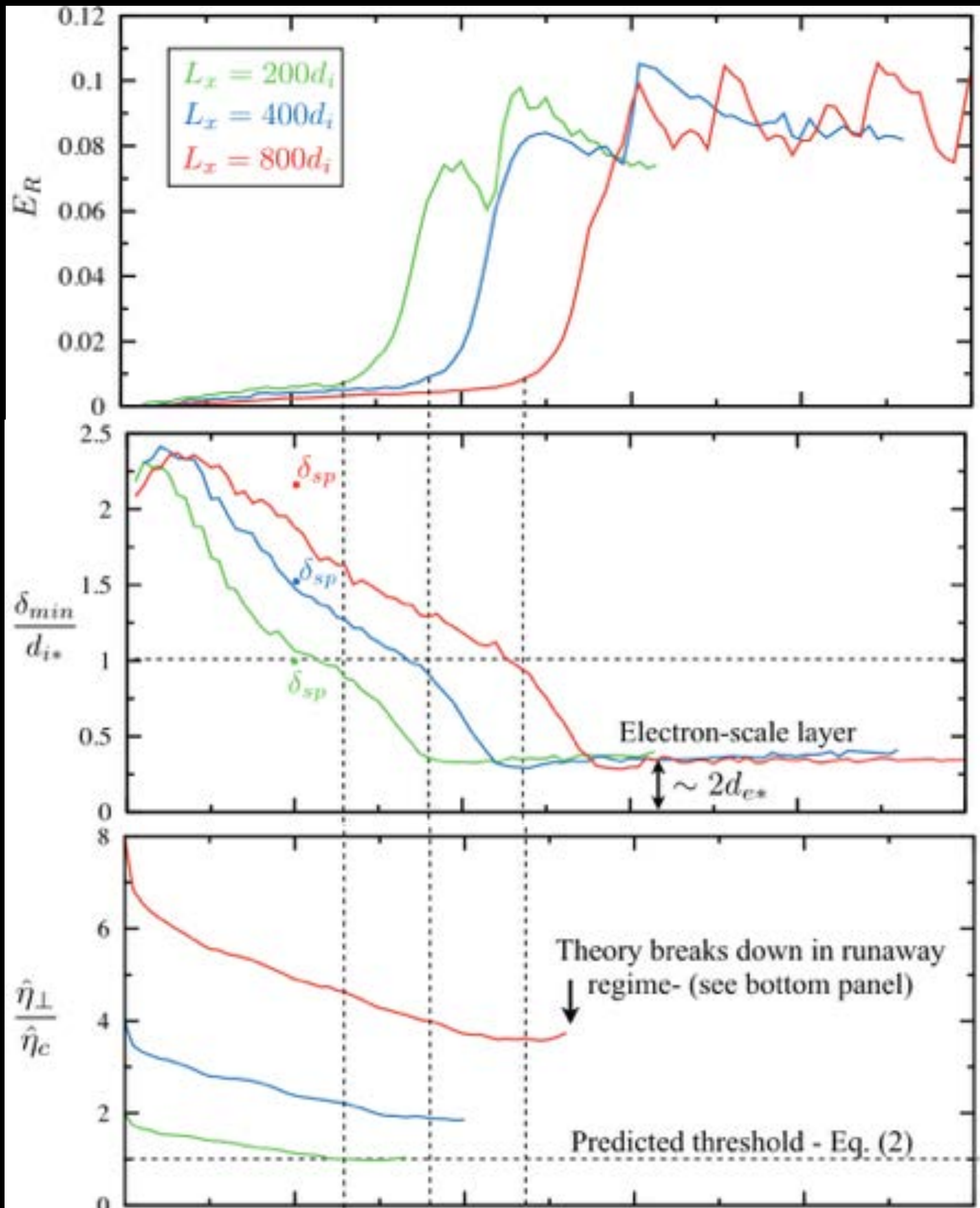
Assume that N_p plasmoids form within the original SP layer and that the new layers between the islands also follow the same SP scaling but with a reduced length:

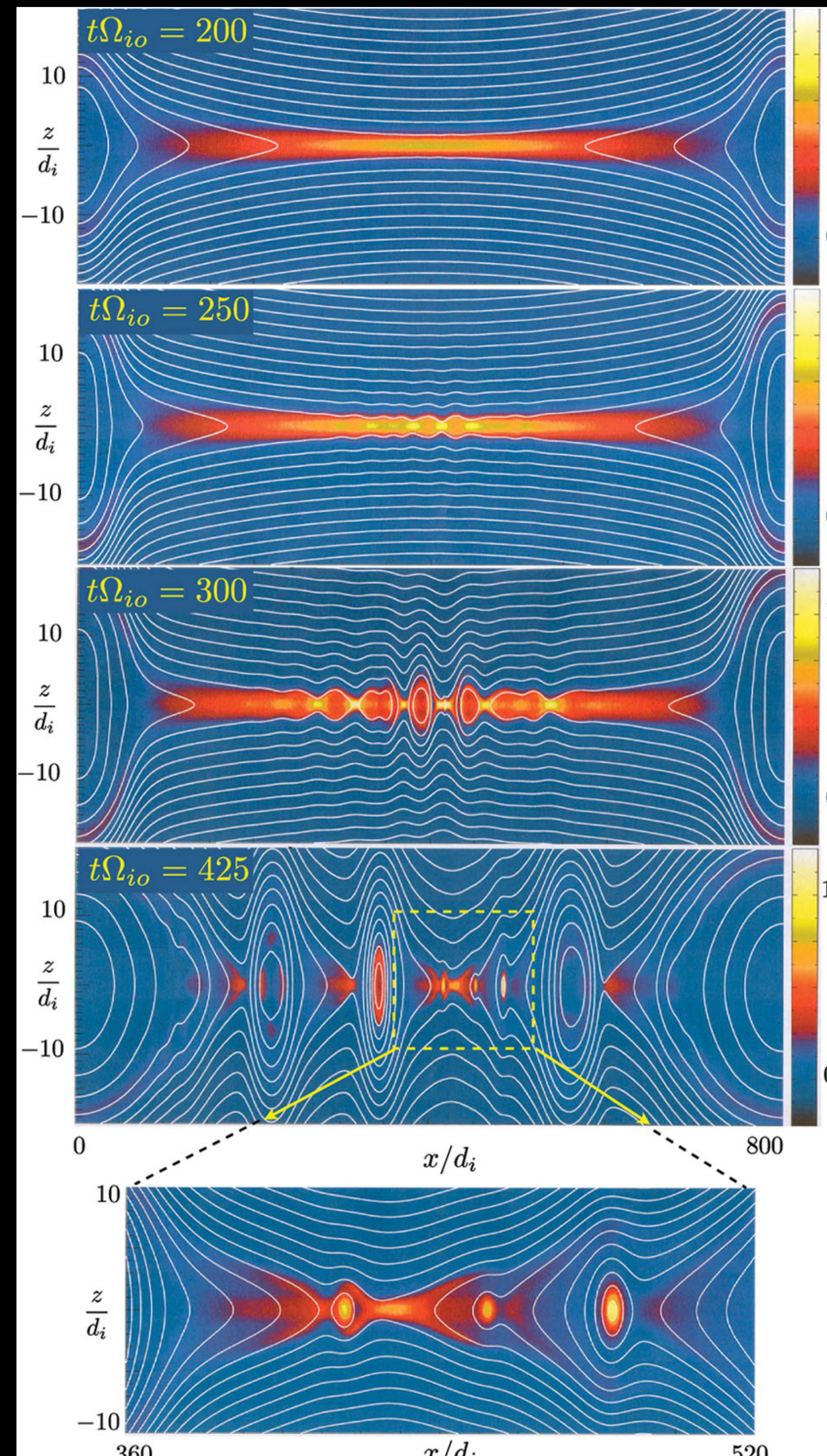
$L \sim L_{sp}/N_p$ The thickness becomes $\delta \sim \delta_{sp}/\sqrt{N_p}$

Imagine we have $N_p >> 1$ at some point we'll have $\delta \to< \delta_i$

TRANSITION TO FAST RECONNECTION!

PIC WITH COLLISIONS *(Daughton et al. 2009)*





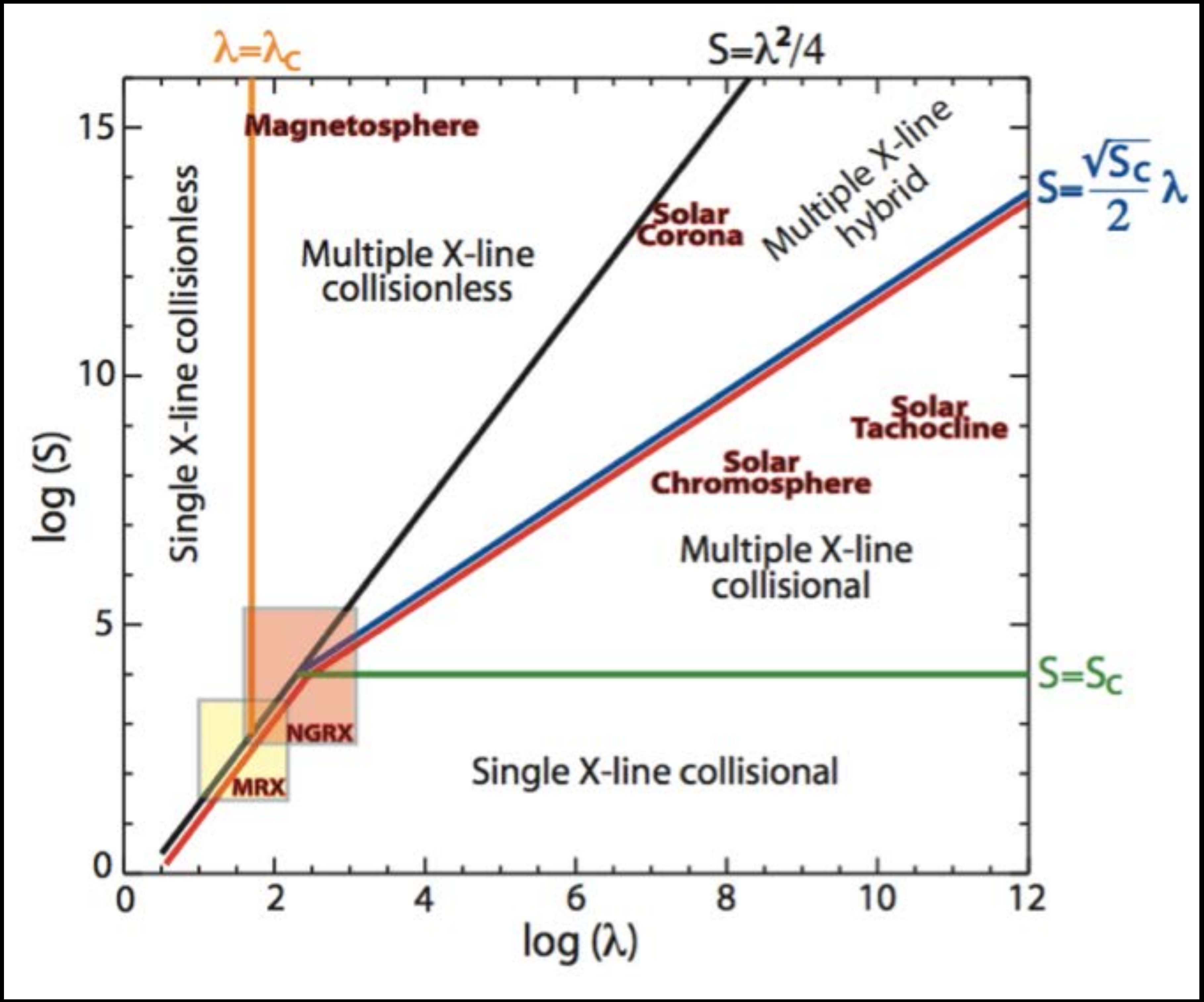
$$\eta_\perp = \eta_{\perp 0}\left(\frac{T_0}{T_e}\right)^{3/2}$$

$$\eta_\perp < \frac{\delta_i}{L_{sp}} \equiv \eta_c$$

« PHASE DIAGRAM » FOR RECONNECTION
(Ji & Daughton. 2011)

non-collisional

Highly collisional



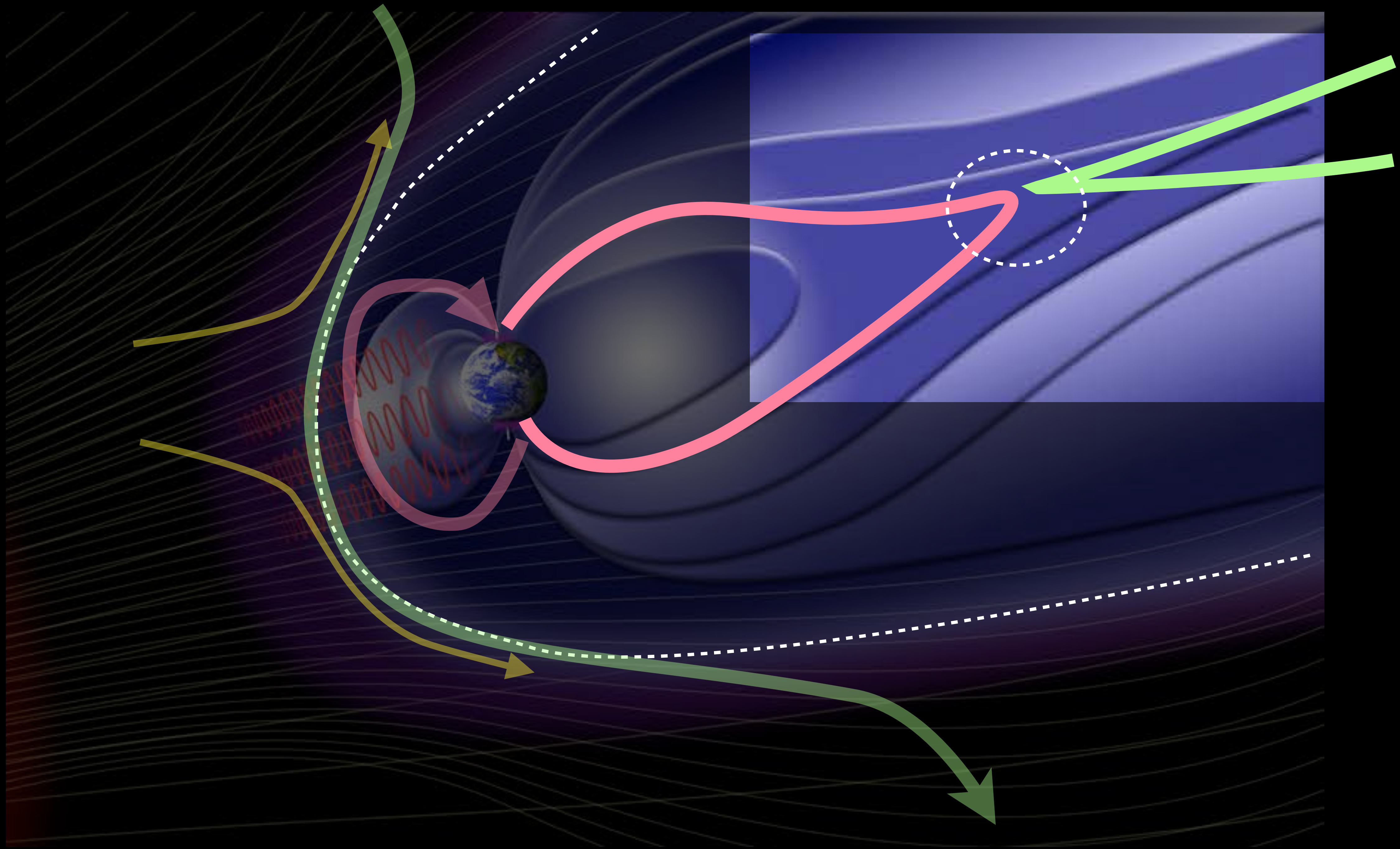
Small systems

Big systems

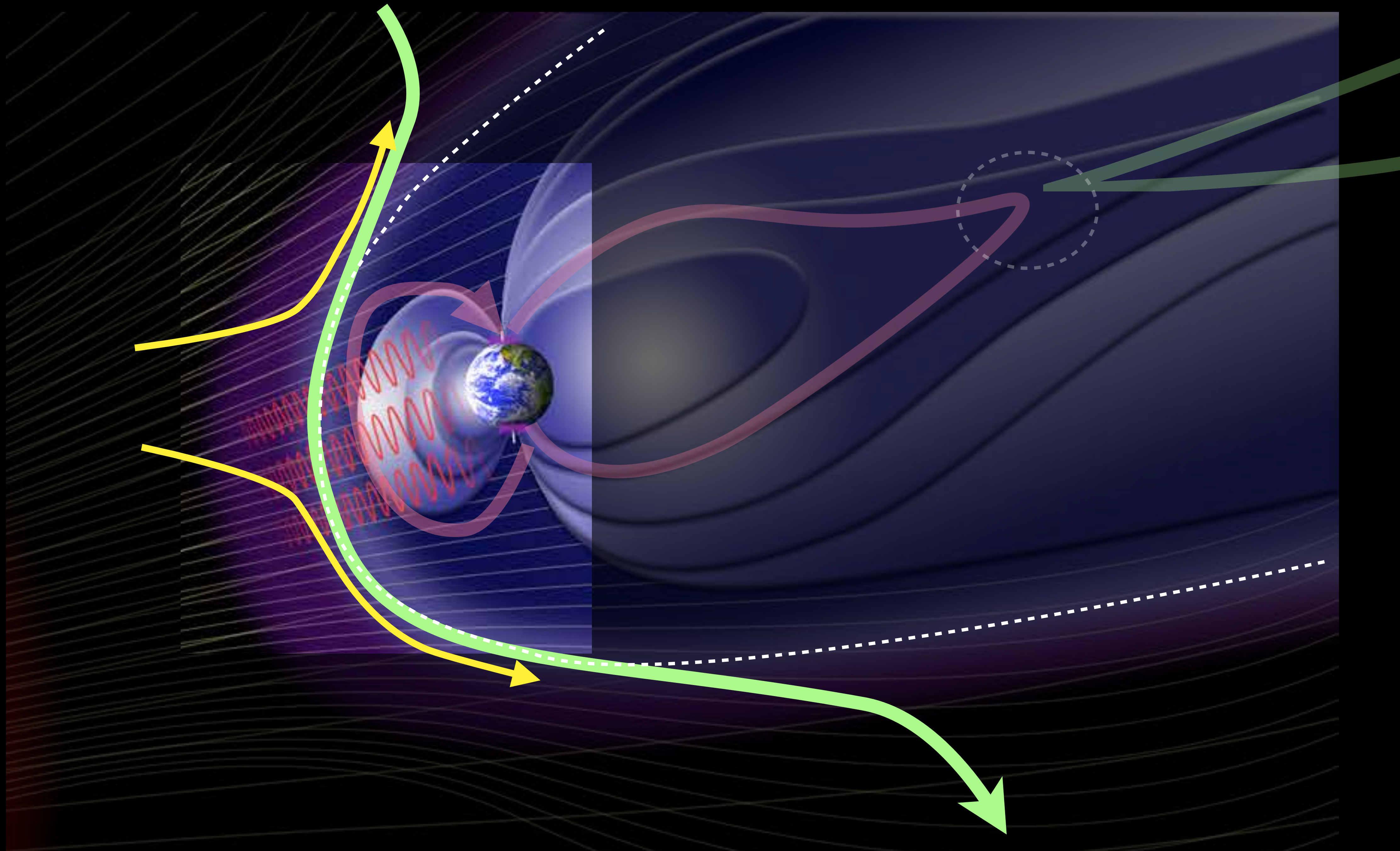
Chap. 6 -asymmetric reconnection

all we've seen so far was the simple case…

« SYMMETRIC » CURRENT SHEET

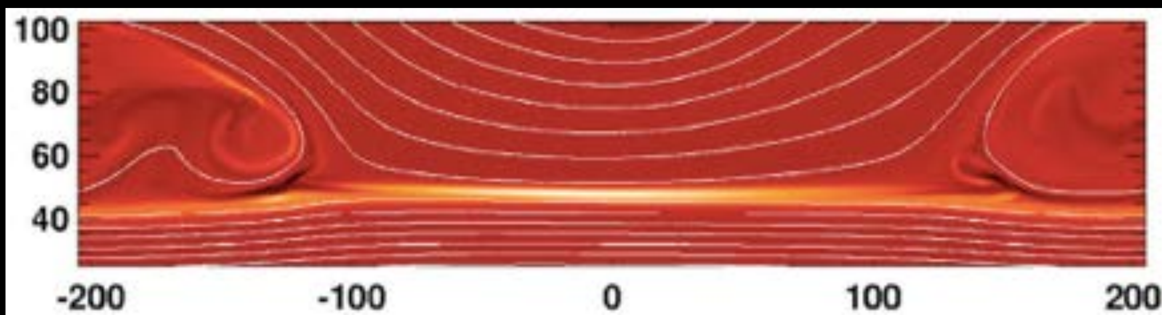


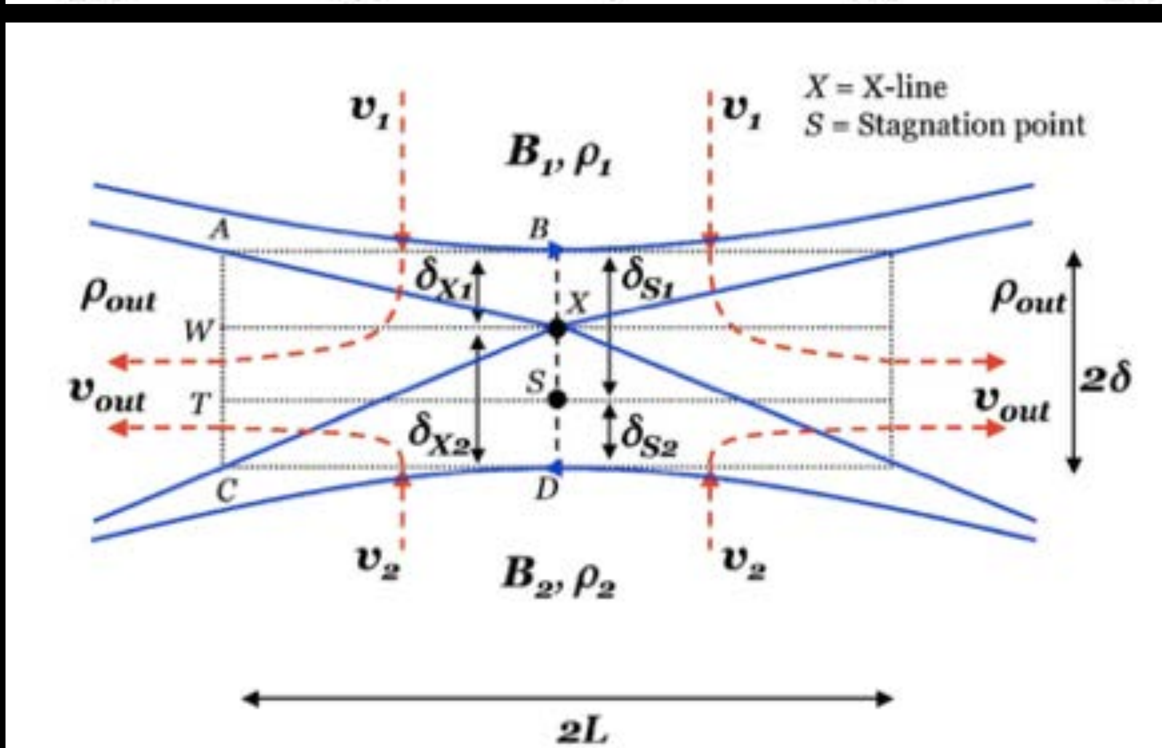
« ASYMMETRIC » CURRENT SHEET

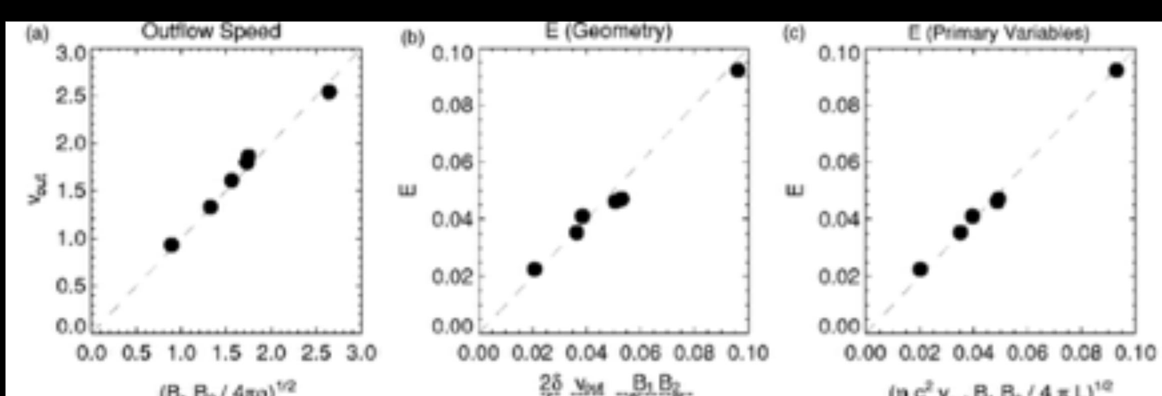


SWEET-PARKER ANALYSIS OF ASYMMETRIC MAGNETIC RECONNECTION

(Cassak & Shay 2007)





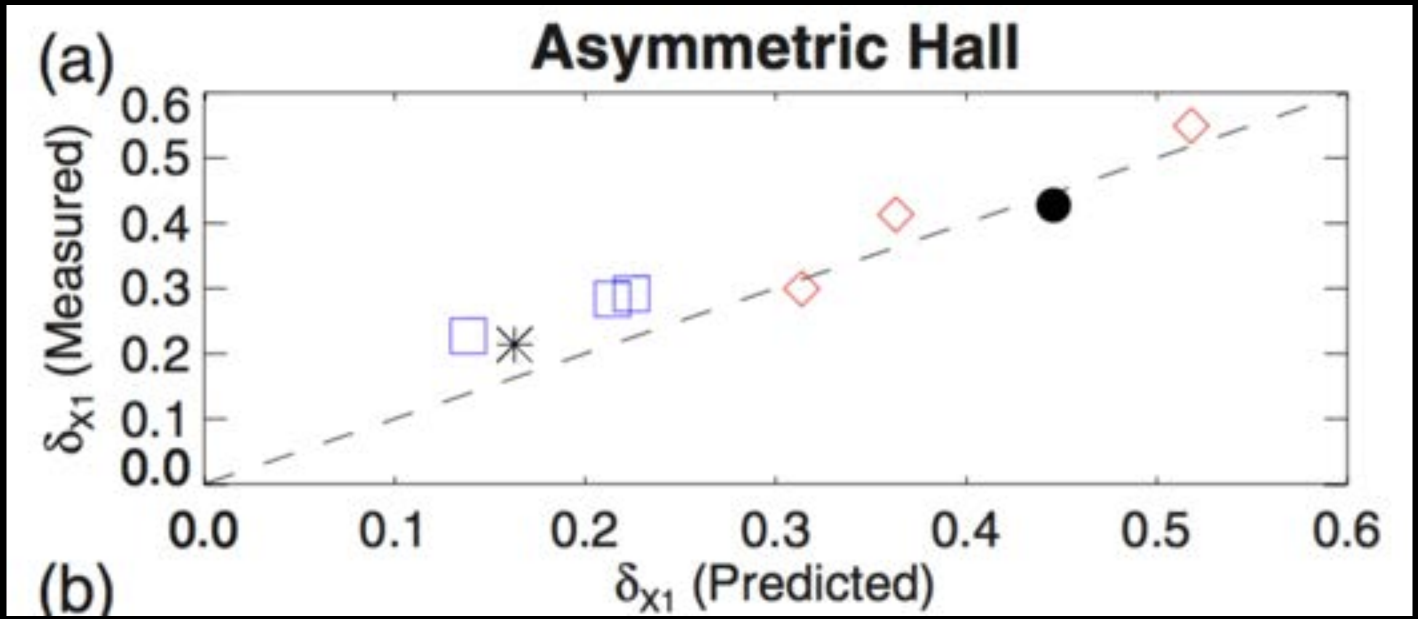


$$v_{\rm out}^2 \sim \frac{B_1 B_2}{4\pi\rho_{\rm out}}.$$

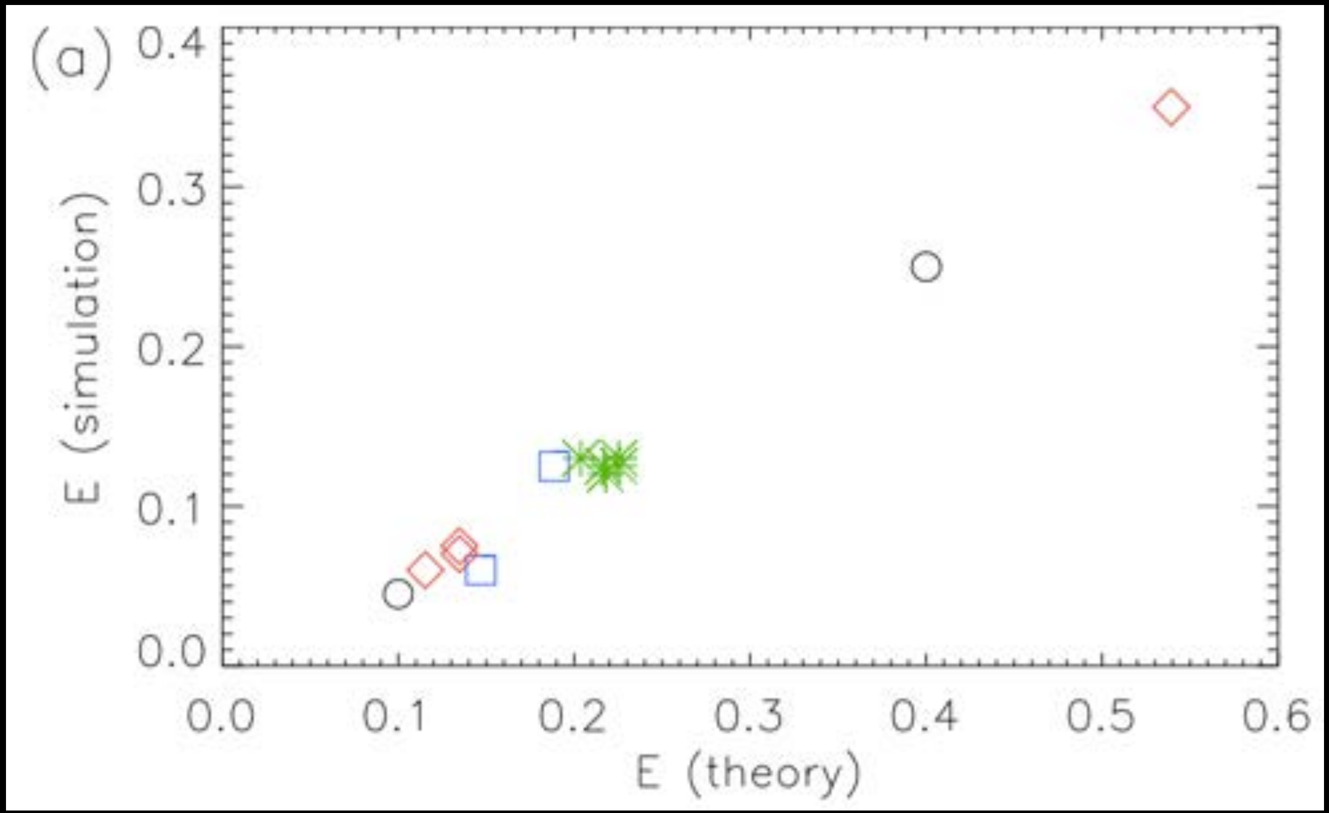
$$\rho_{\rm out} \sim \frac{\rho_1 B_2 + \rho_2 B_1}{B_1 + B_2}.$$

$$E \sim \left(\frac{B_1 B_2}{B_1 + B_2}\right)\frac{v_{\rm out}}{c}\frac{2\delta}{L}.$$

SCALING LAWS IN HALL MHD AND PIC



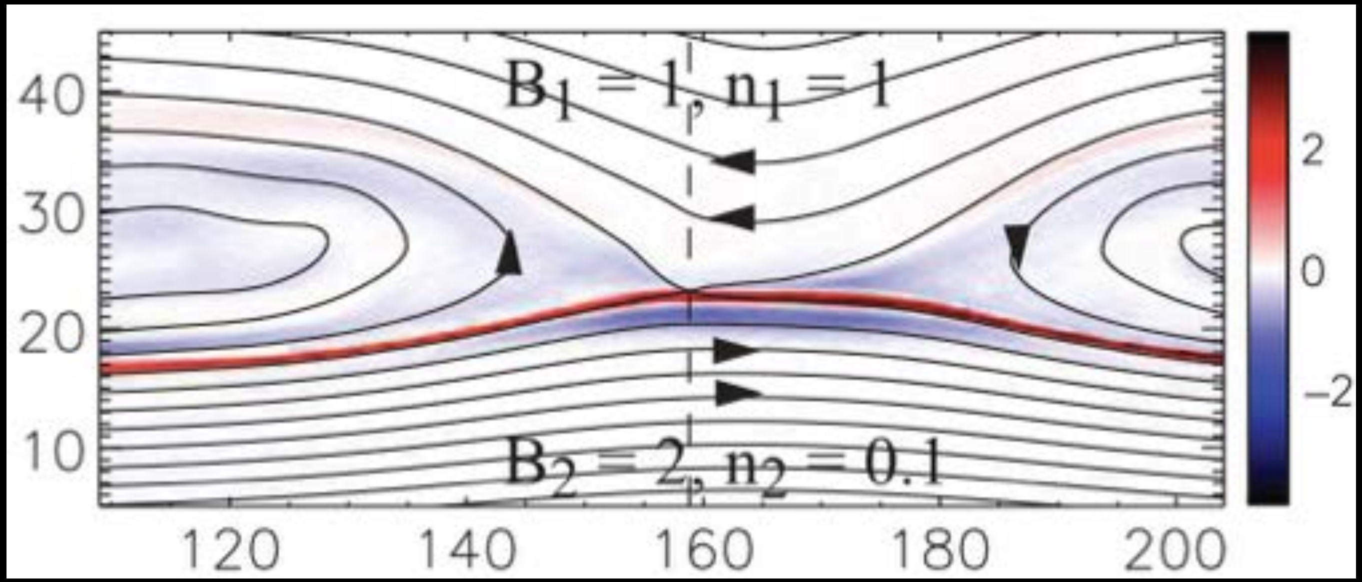
(Cassak & Shay 2009)



(Malakit et al 2010)

SIGNATURES OF ASYMMETRIC RECONNECTION

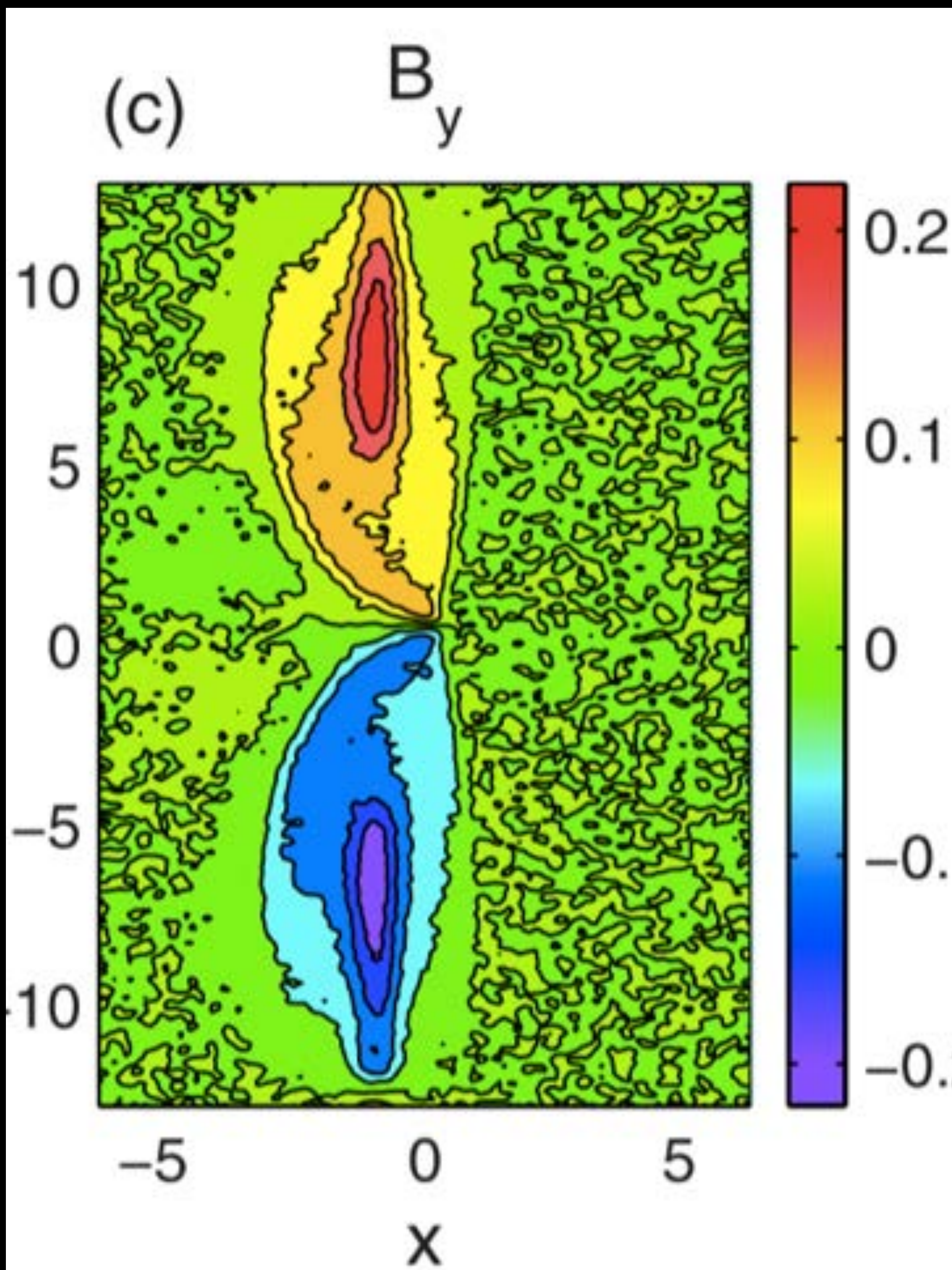
(Malakit et al. 2010)

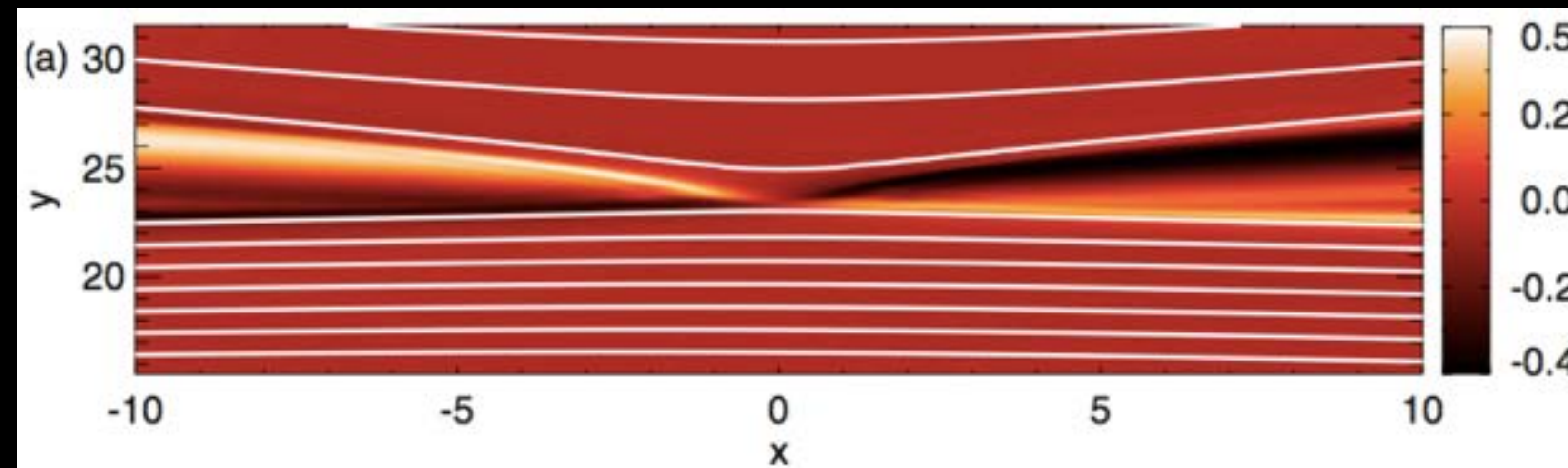


strong deformation of field lines on weak magnetic field side

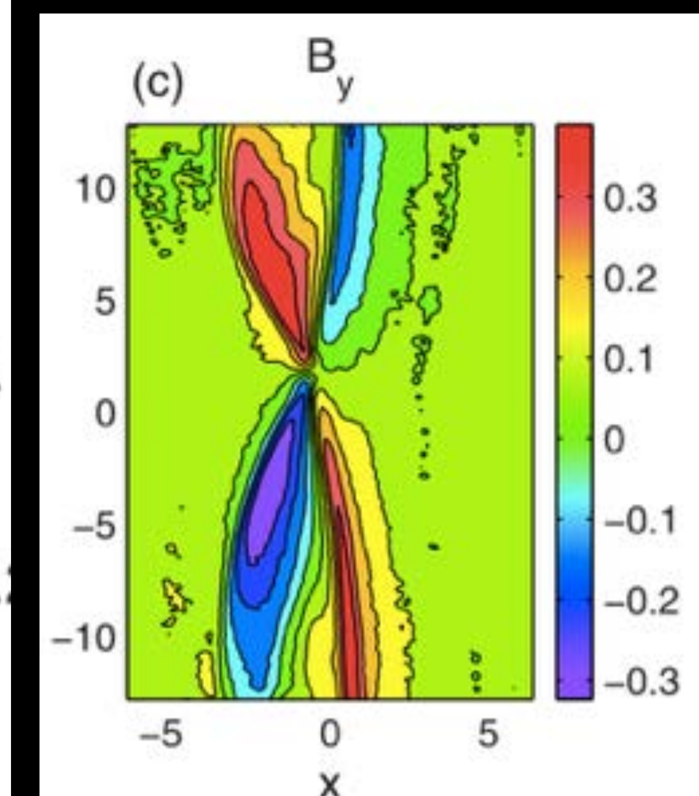
Signatures of asymmetric reconnection

out-of-plane B becomes monopolar





(Cassak & Shay 2009)

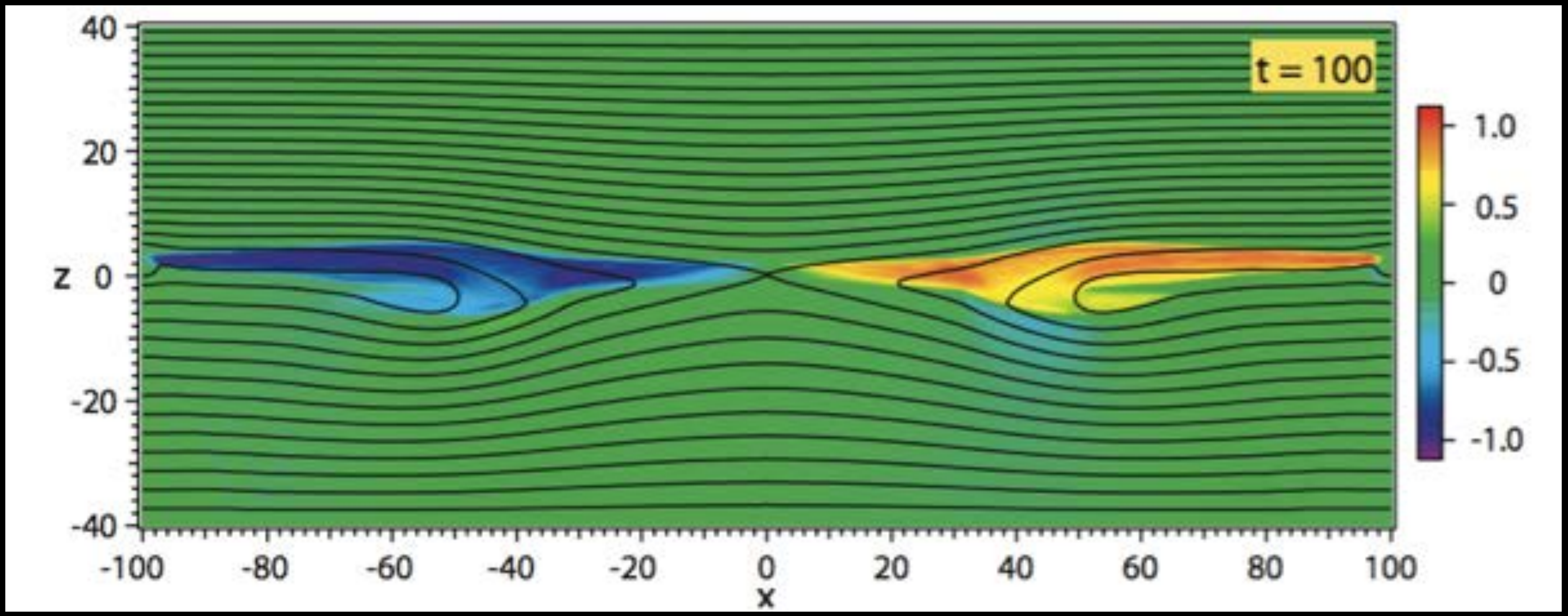


Weaker on the strong field / small density side

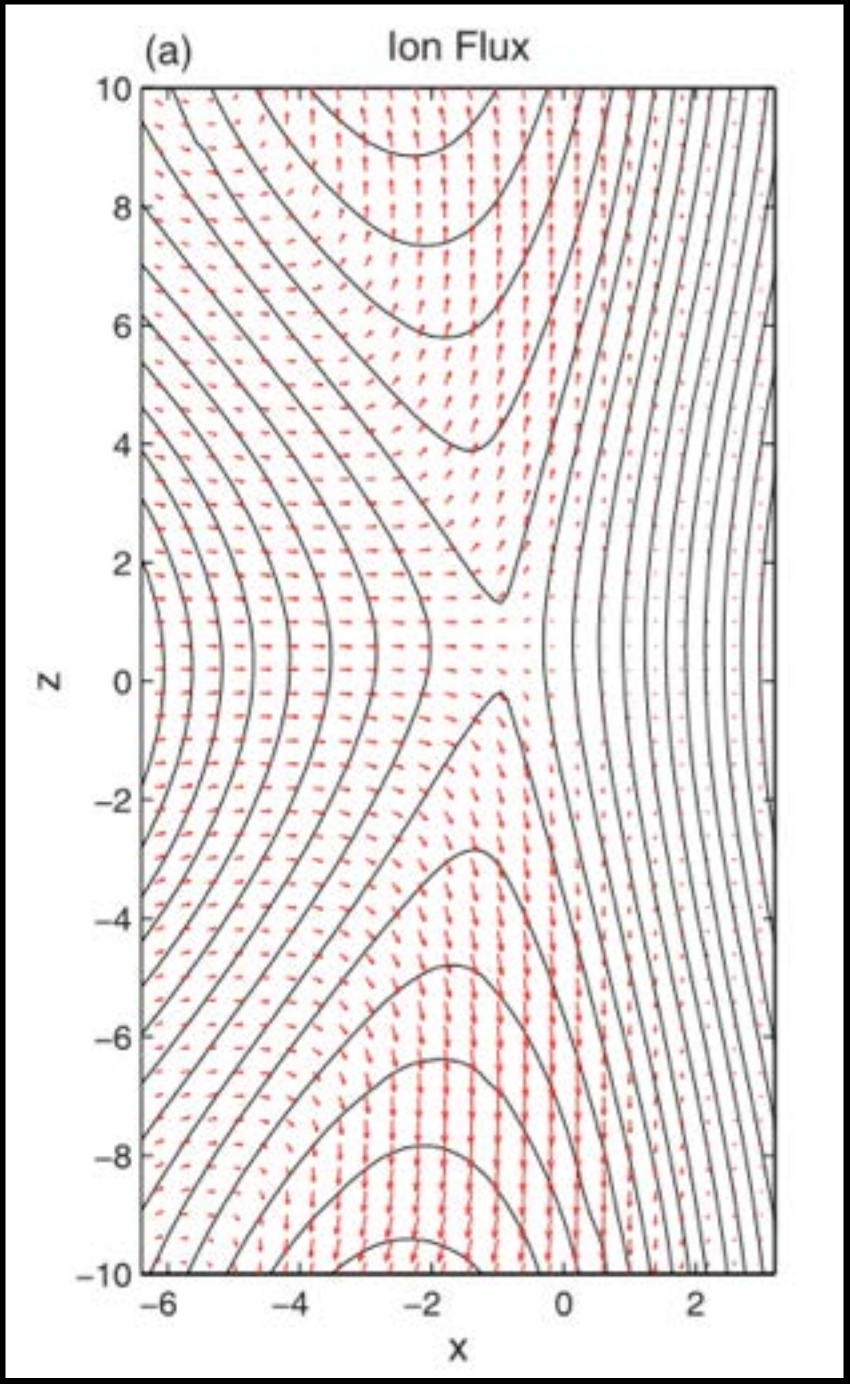
(Pritchett 2008)

SIGNATURES OF ASYMMETRIC RECONNECTION

outflow shifted on the high Alfvén speed side



(Birn et al. 2008)

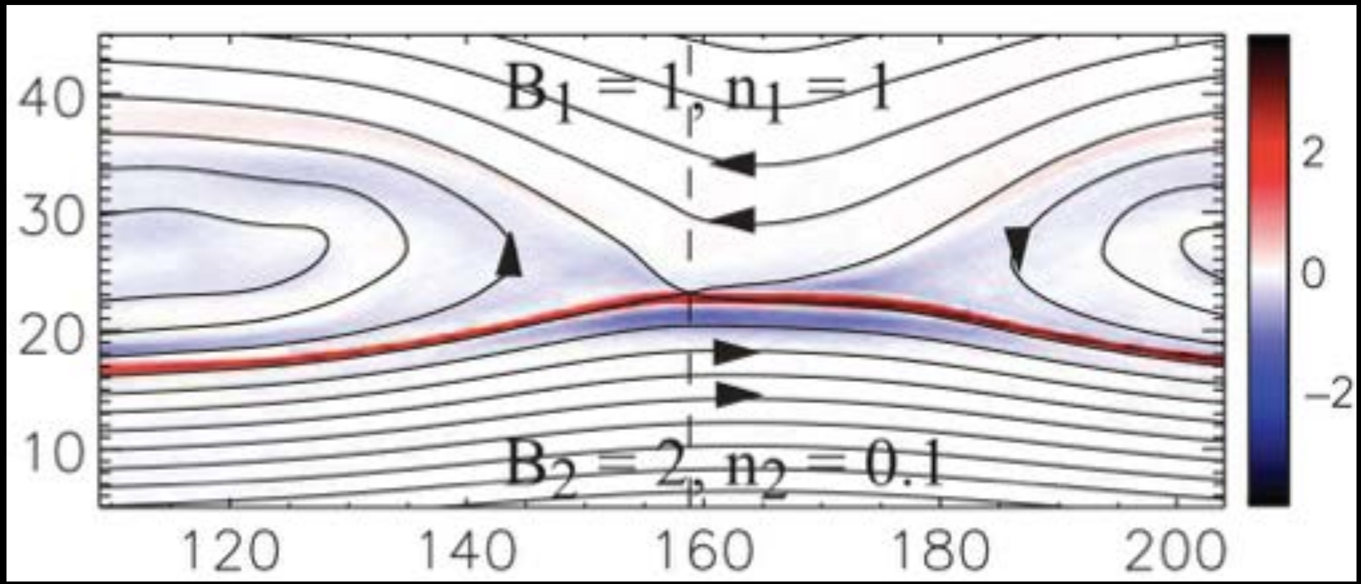


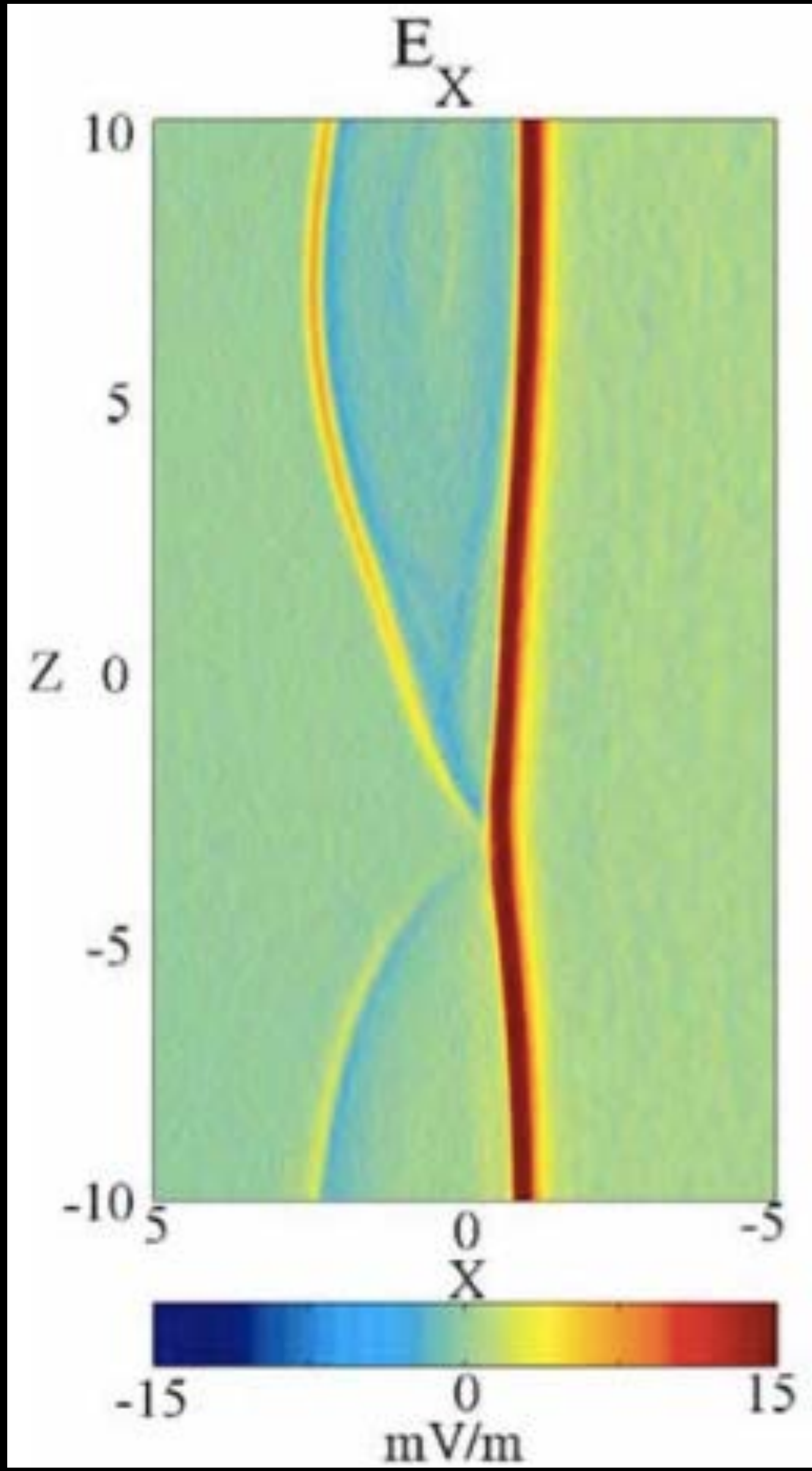
(Pritchett 2008)

SIGNATURES OF ASYMMETRIC RECONNECTION

strong normal electric field on strong field side

(Malakit et al. 2010)

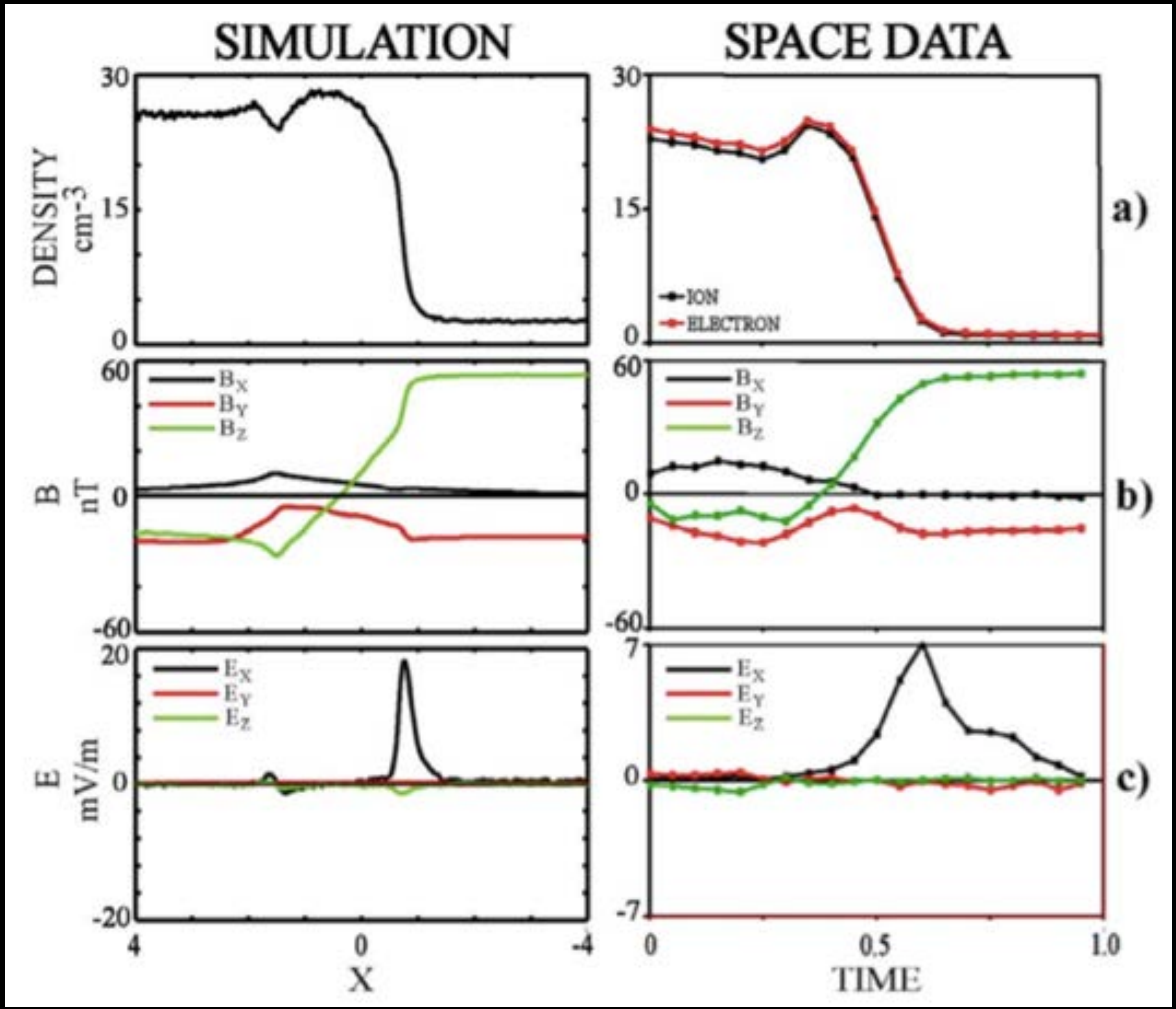




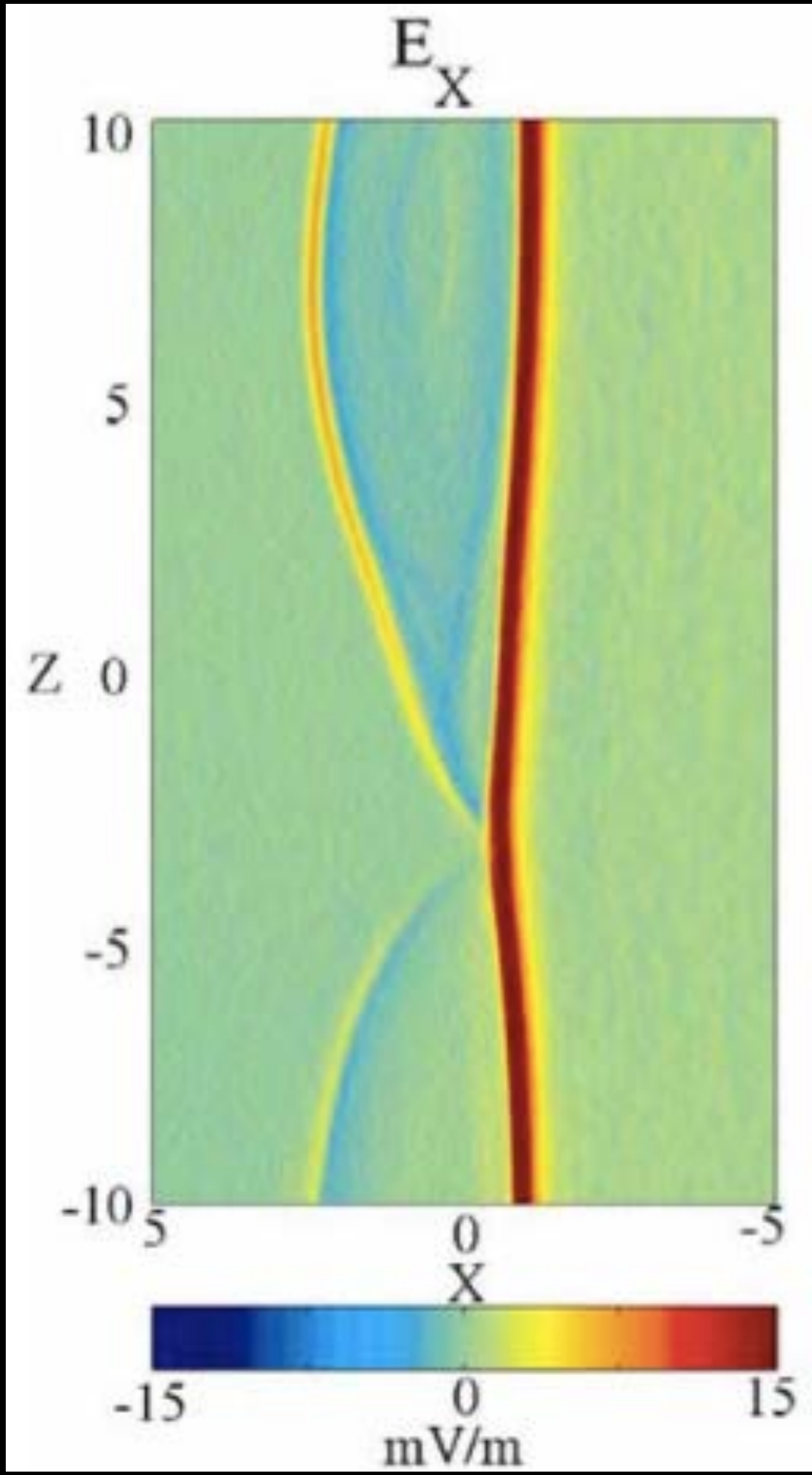
(Mozer et al. 2008)

Signatures of asymmetric reconnection

strong normal electric field on strong field side



(Mozer et al. 2008)



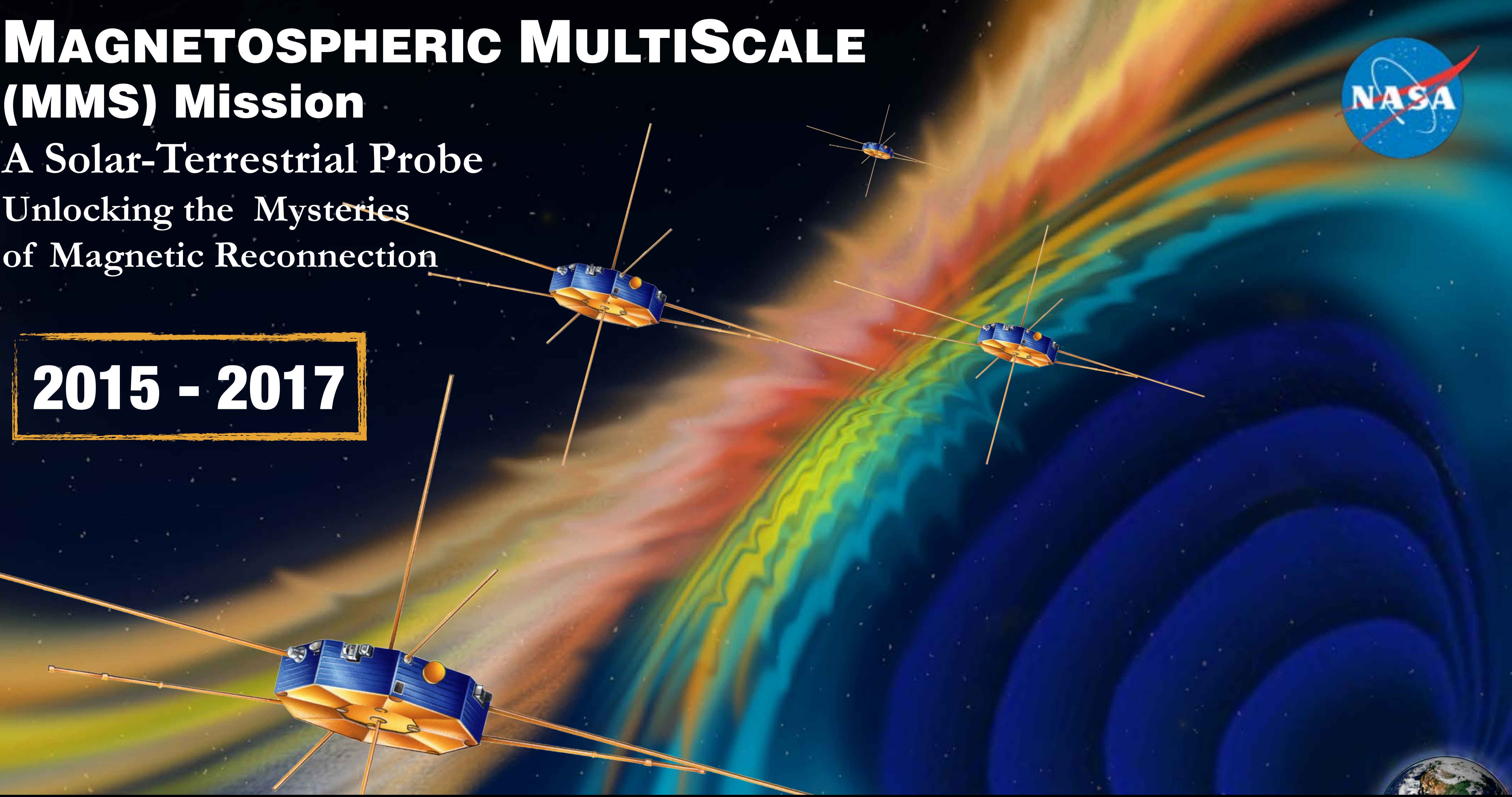
(Mozer et al. 2008)

Magnetospheric MultiScale (MMS) Mission

A Solar-Terrestrial Probe

Unlocking the Mysteries of Magnetic Reconnection

2015 - 2017



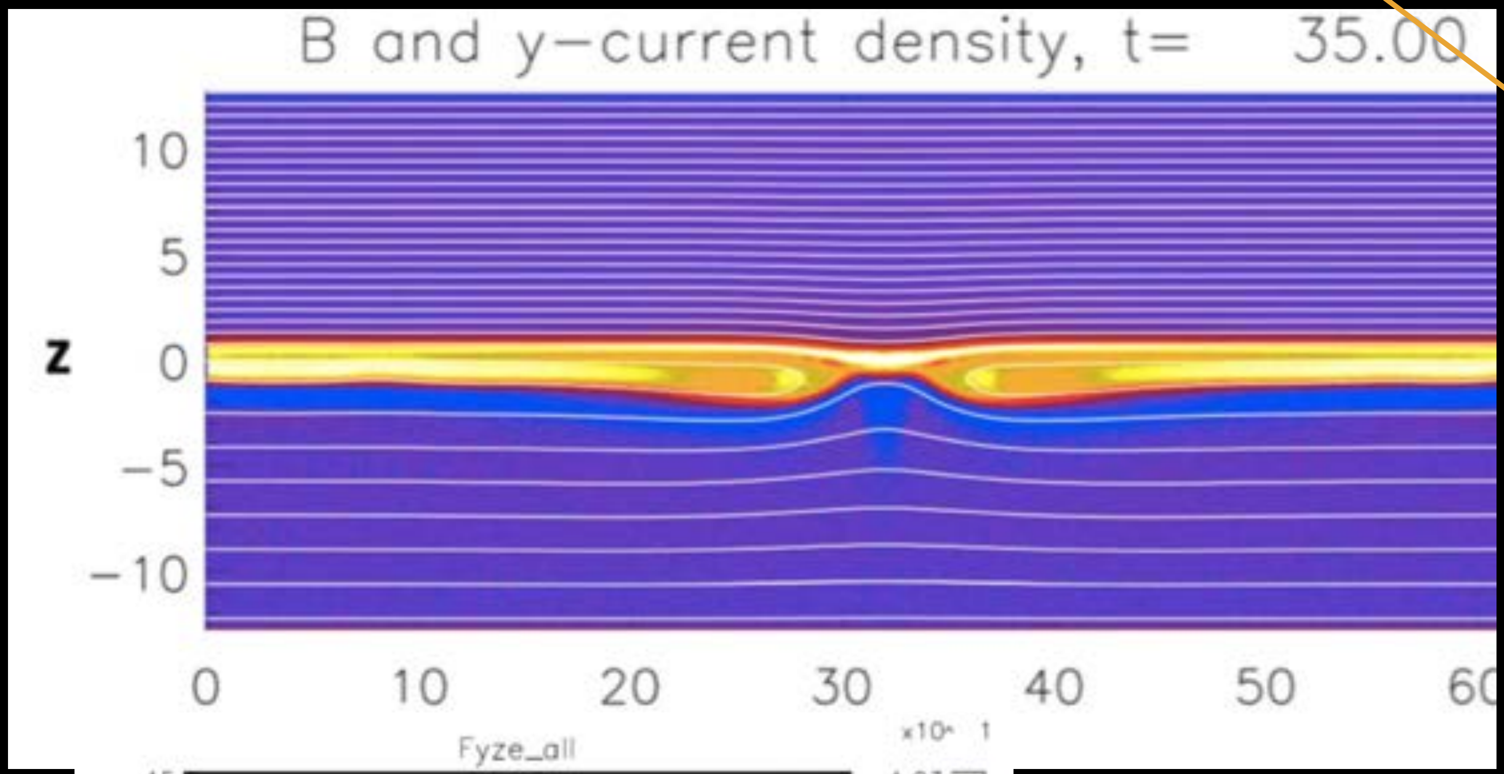
Main objective : Reconnection at electron scale

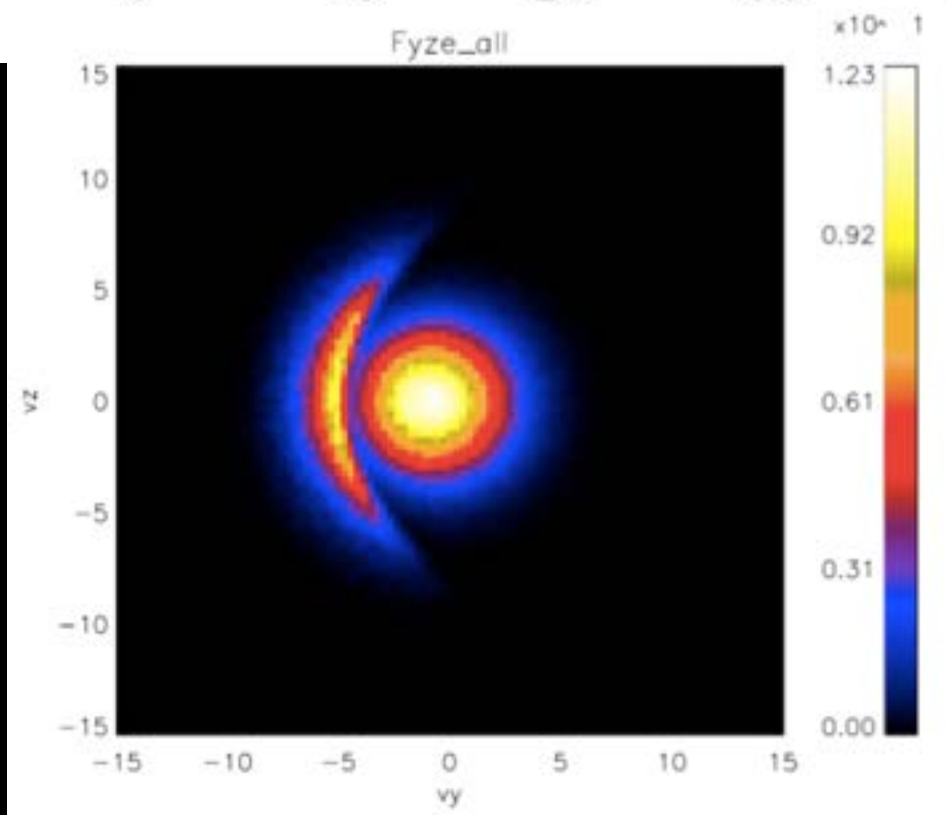
Electron distributions: 30ms, ions: 150ms
(cluster: 4s)

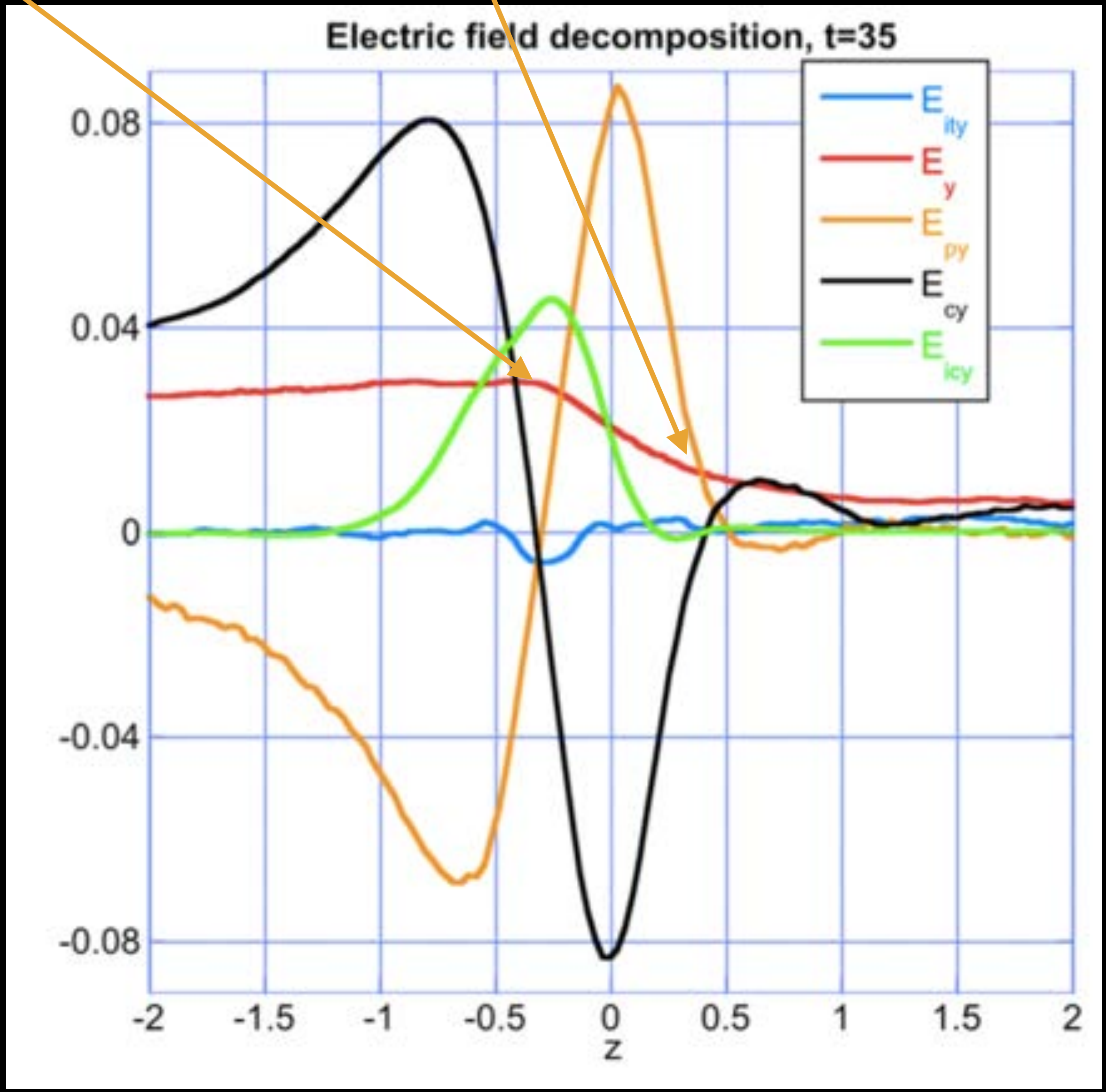
WHAT REALLY HAPPENS AT THE X LINE?

The pressure tensor is not the main contributor to the reconnection electric field at the X line!

It is at the flow stagnation point!





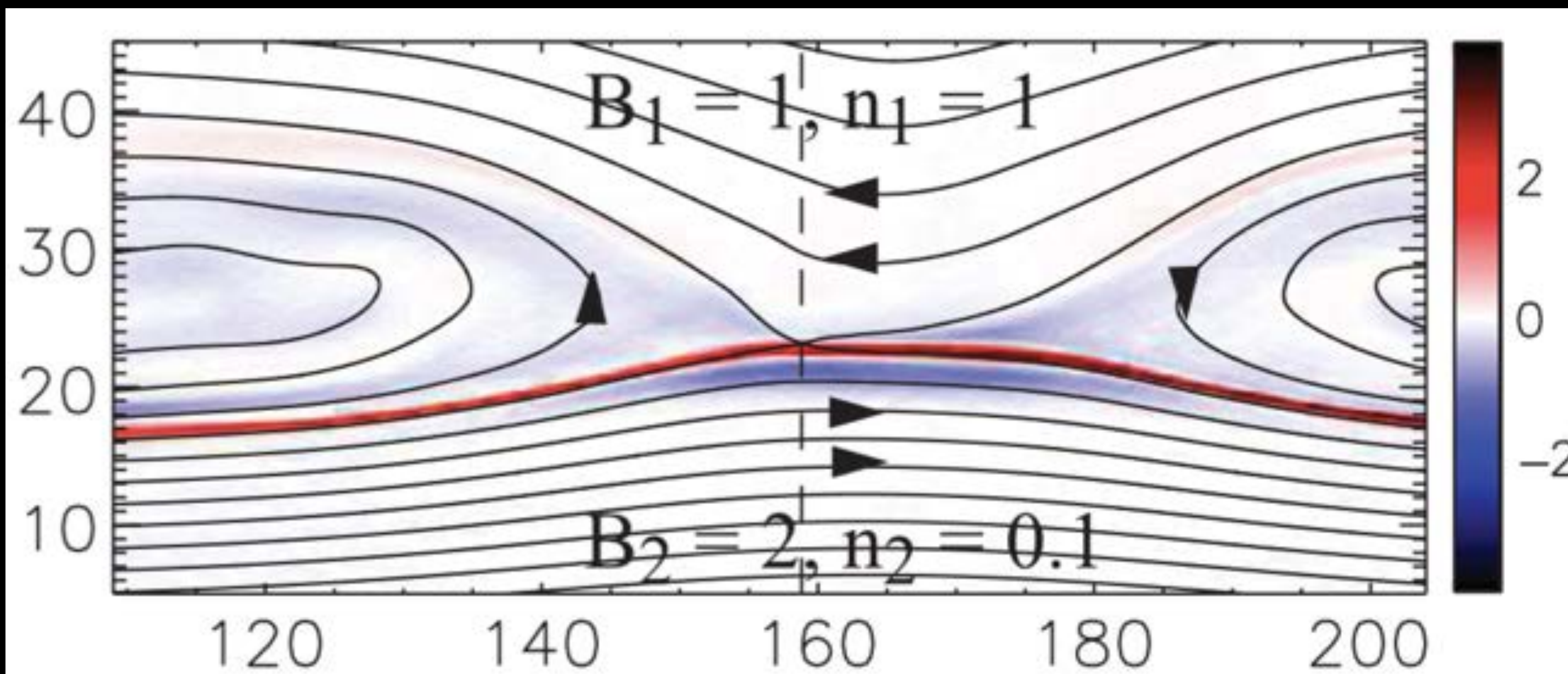


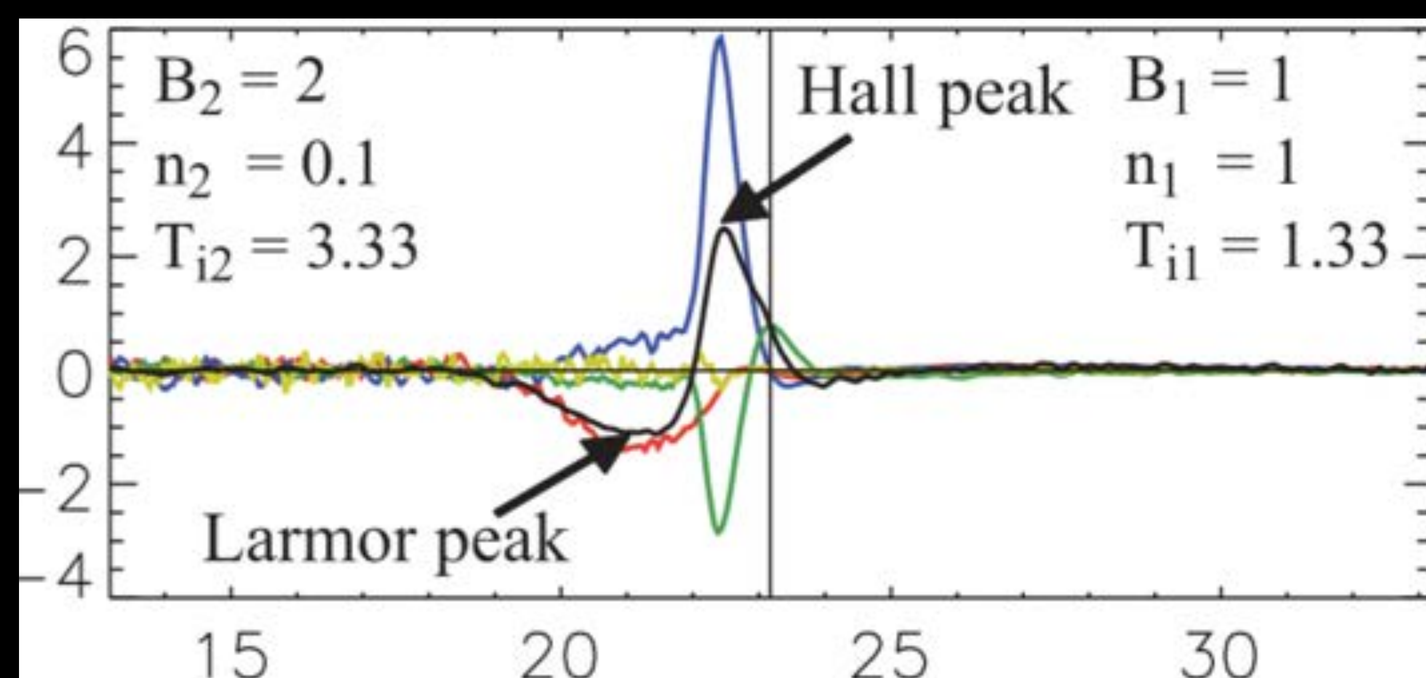
$$\mathbf{E} = -\mathbf{v}_i \times \mathbf{B} + \frac{1}{ne}(\mathbf{j} \times \mathbf{B} - \boldsymbol{\nabla} \cdot \mathbf{P}_e) + \mathbf{D}$$

SIGNATURES OF ASYMMETRIC RECONNECTION

'Larmor electric field'

(Malakit et al. 2010)

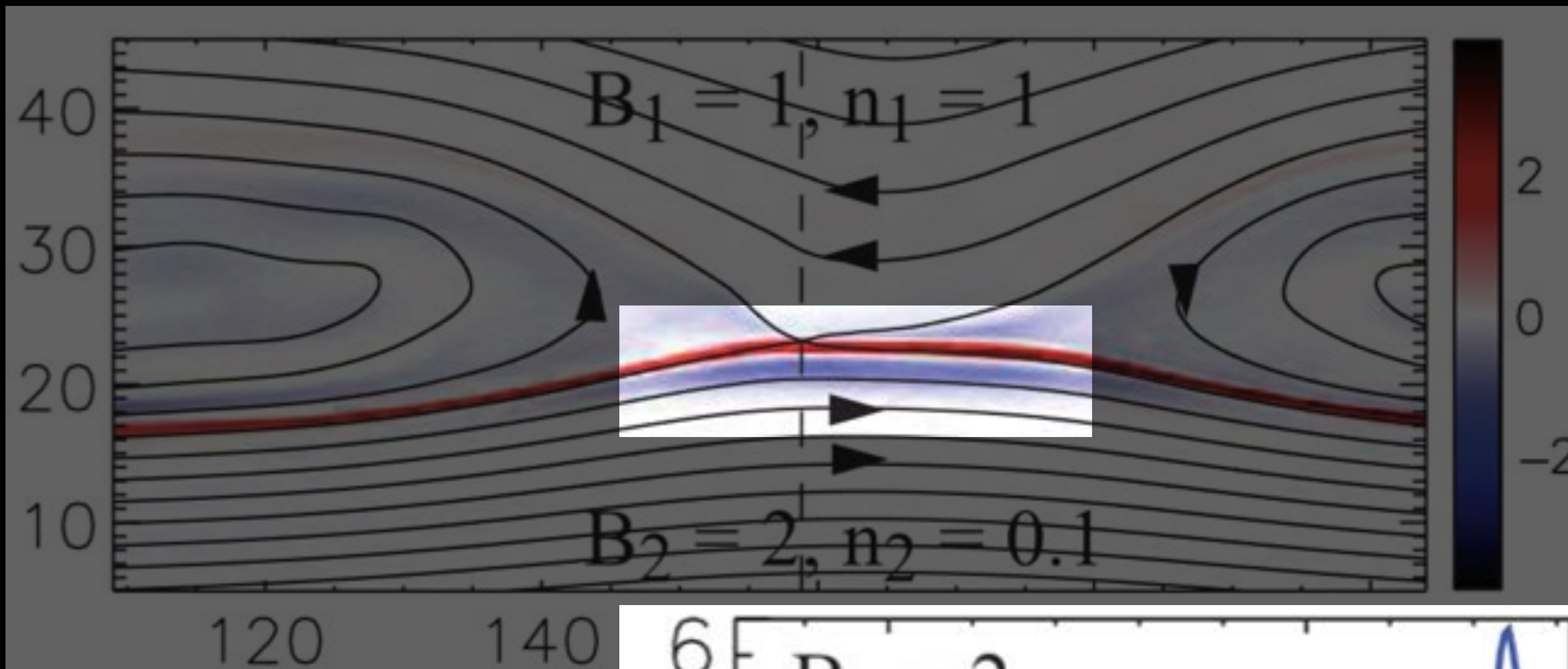


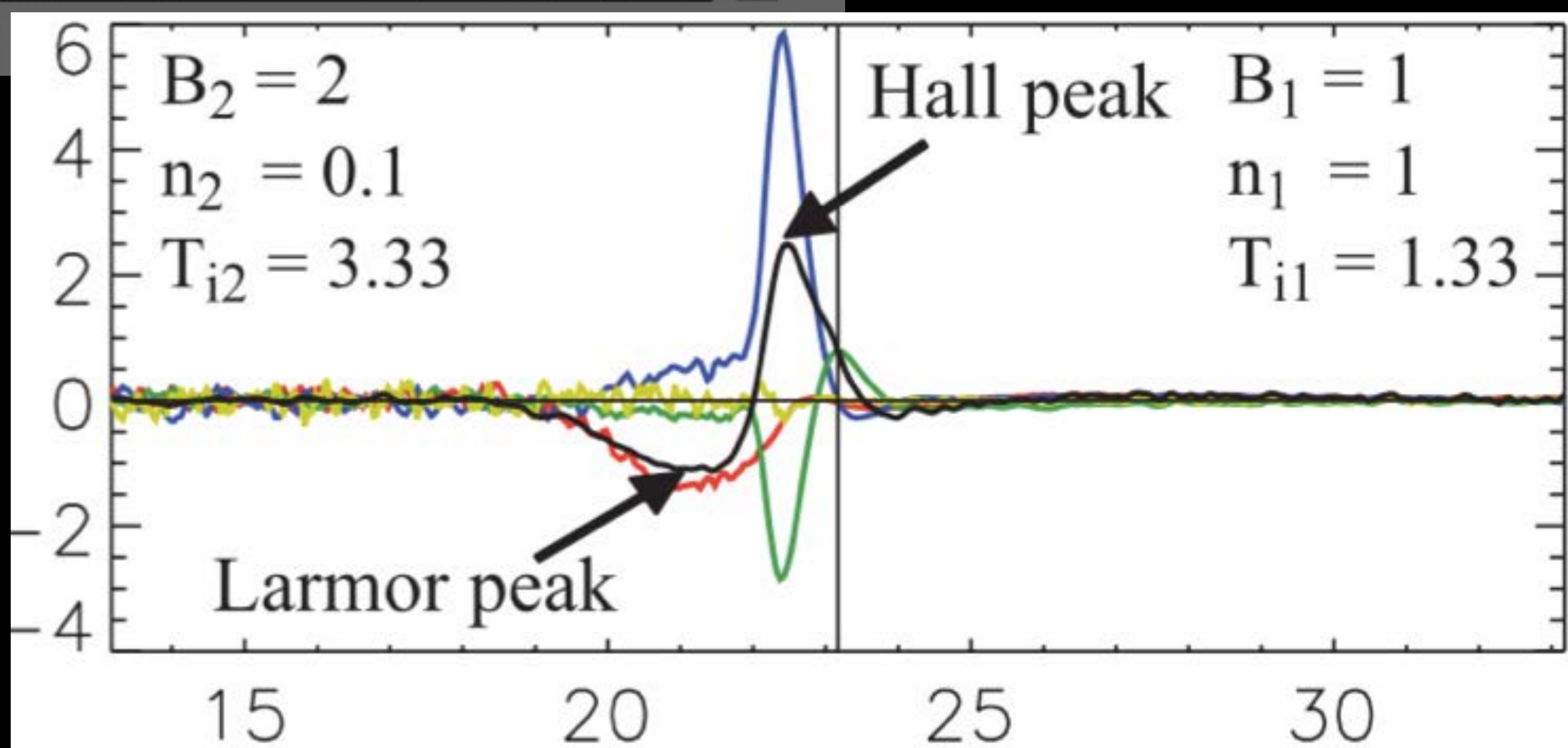


SIGNATURES OF ASYMMETRIC RECONNECTION

'Larmor electric field'

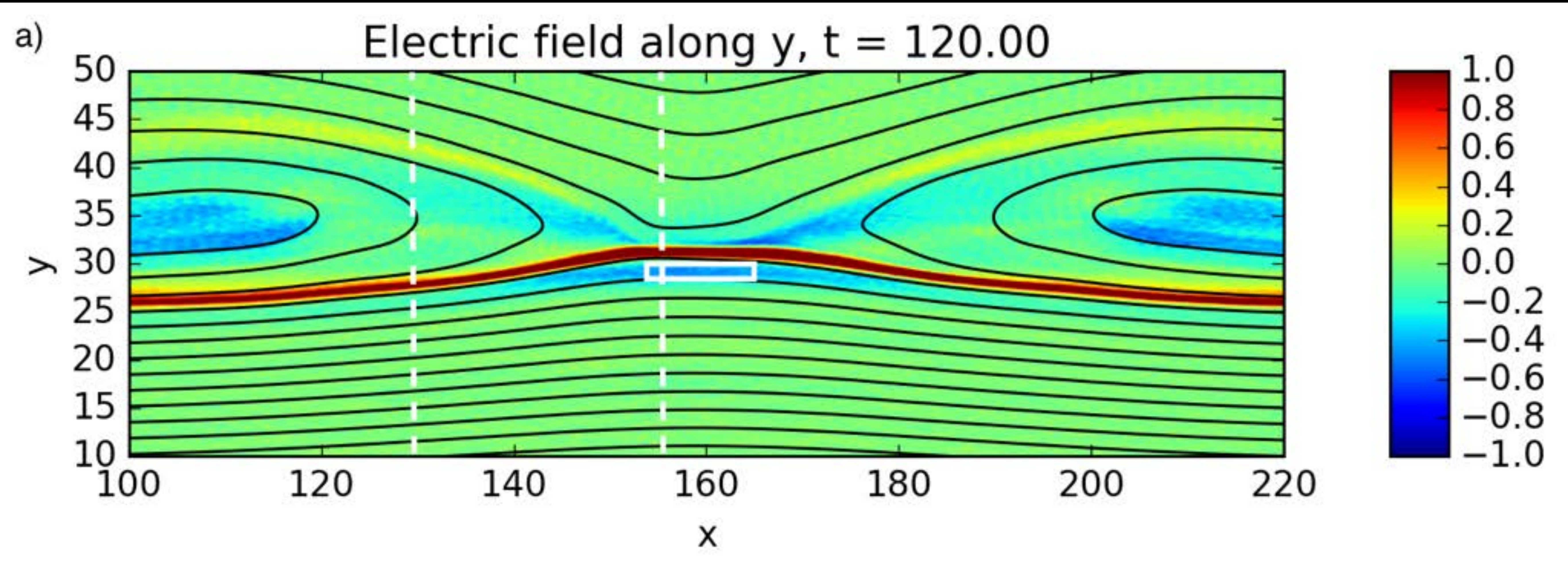
(Malakit et al. 2010)





Signatures of asymmetric reconnection

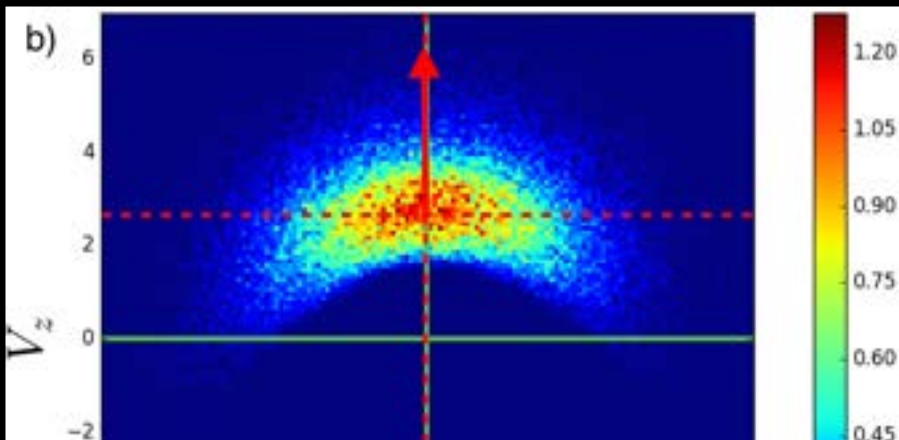
'Larmor electric field'

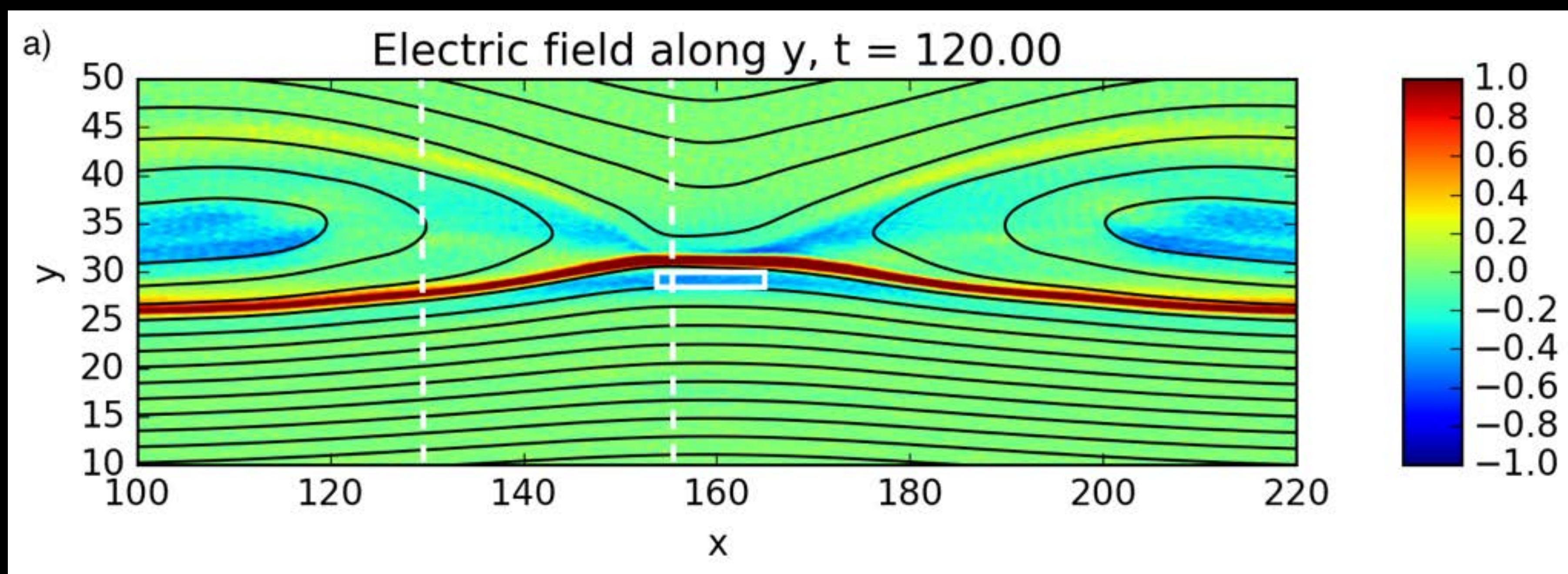


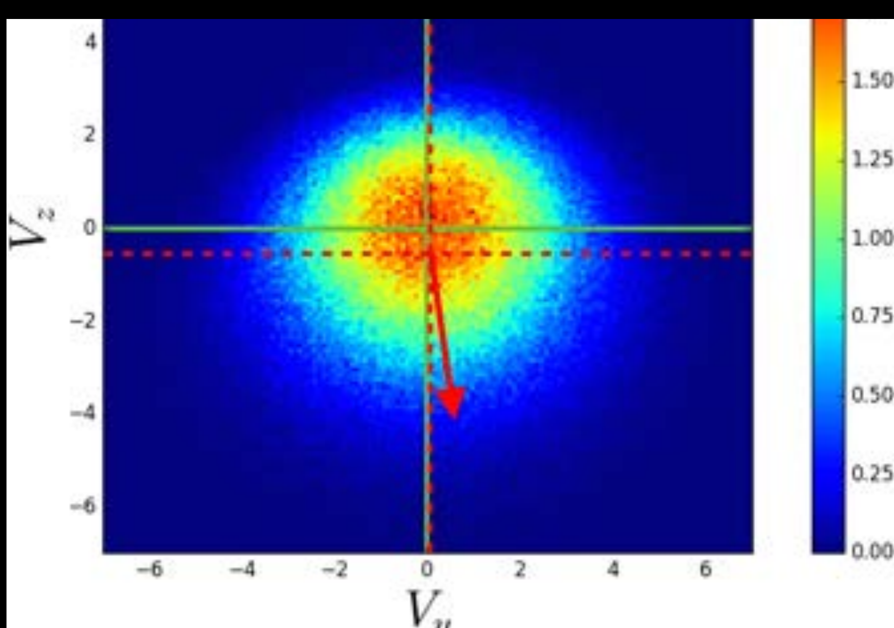
(Dargent et al. in prep)

Signatures of asymmetric reconnection

'Larmor electric field'



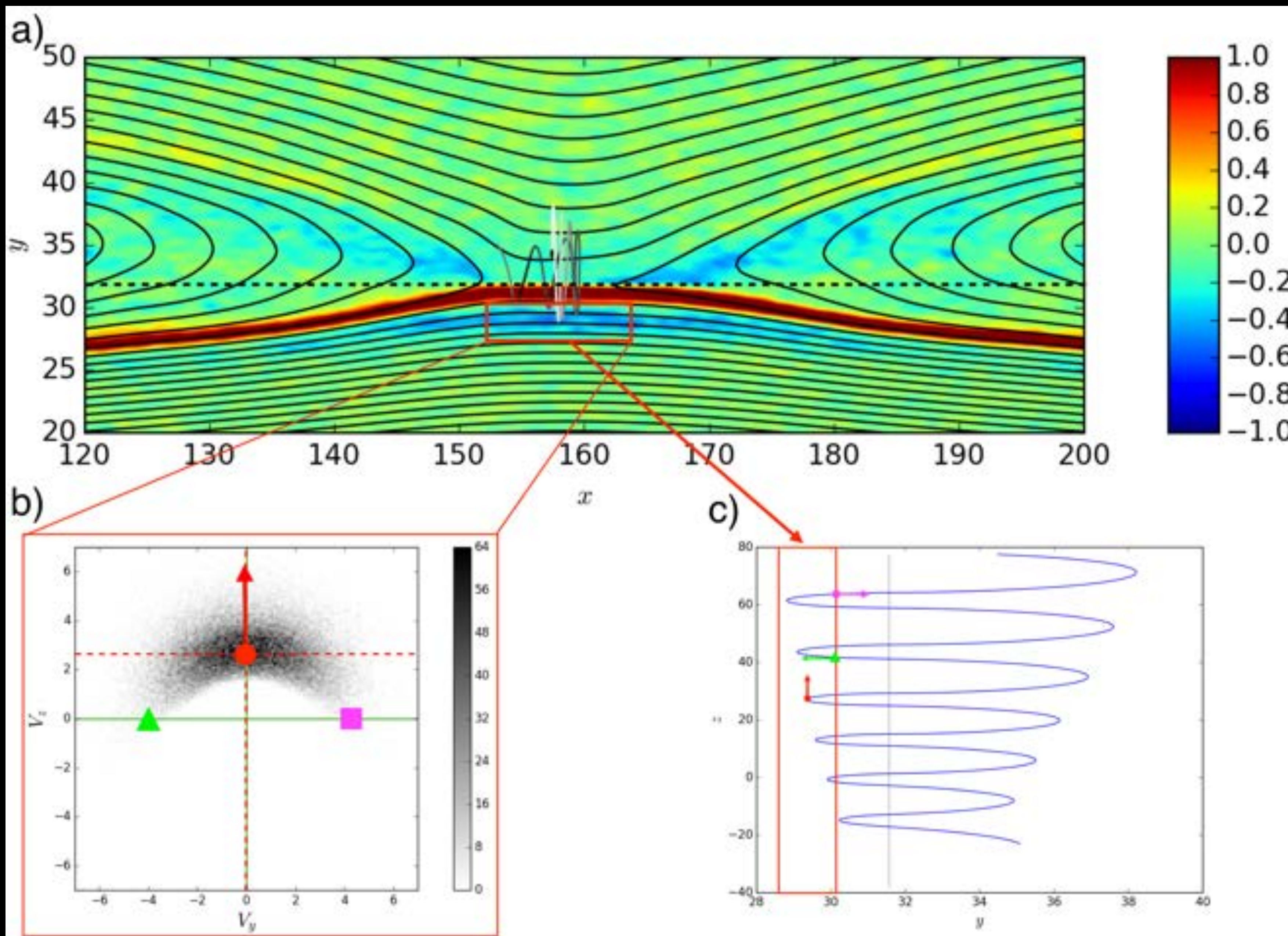




(Dargent et al. in prep)

Signatures of asymmetric reconnection

'Larmor electric field'

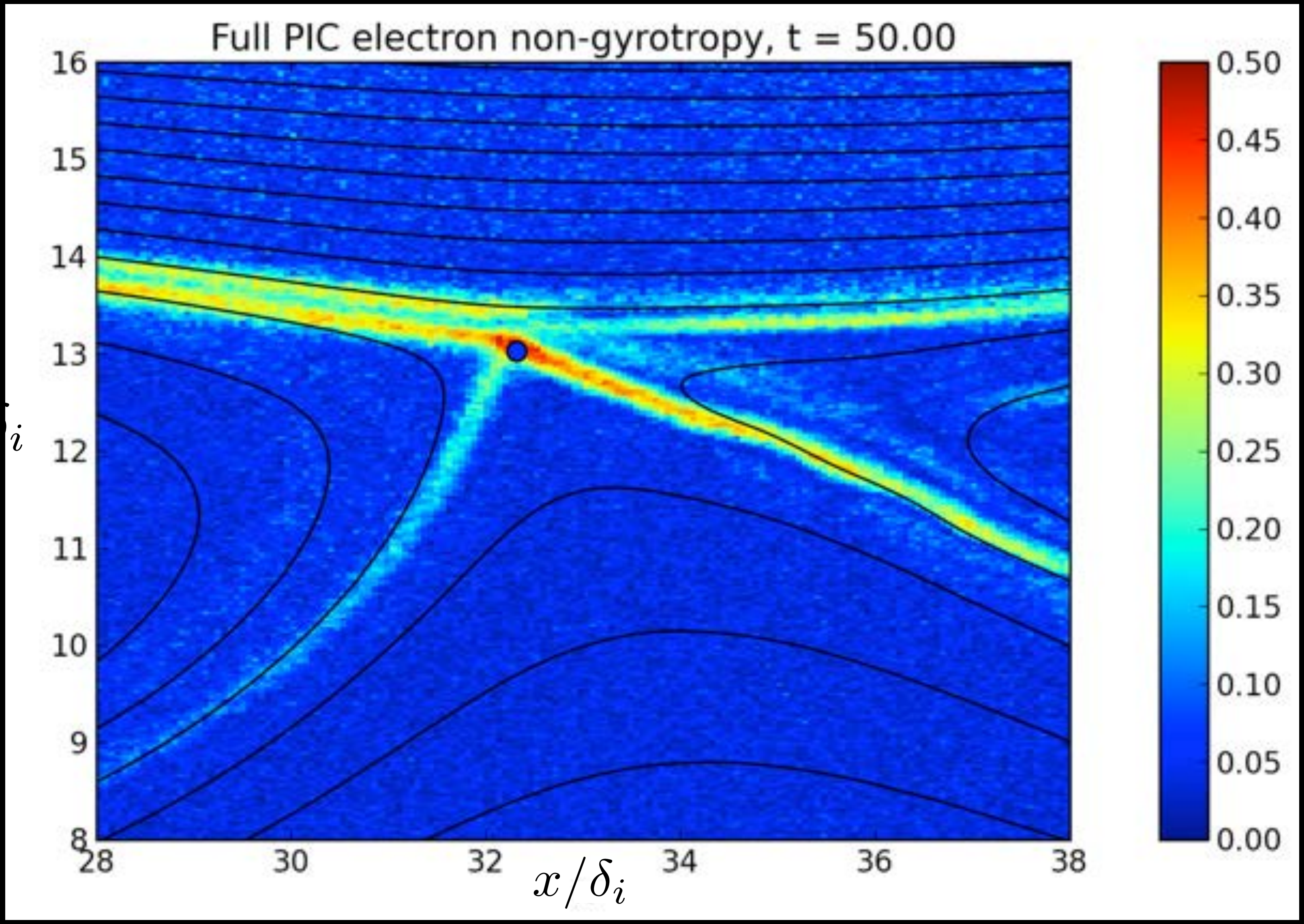


(Dargent et al. in prep)

Degree of non-gyrotropy

(N. Aunai et al. 2013)

Highlight regions where electrons
« do not behave as a fluid »



$$\mathbf{P} = \mathbf{G} + \mathbf{N}$$

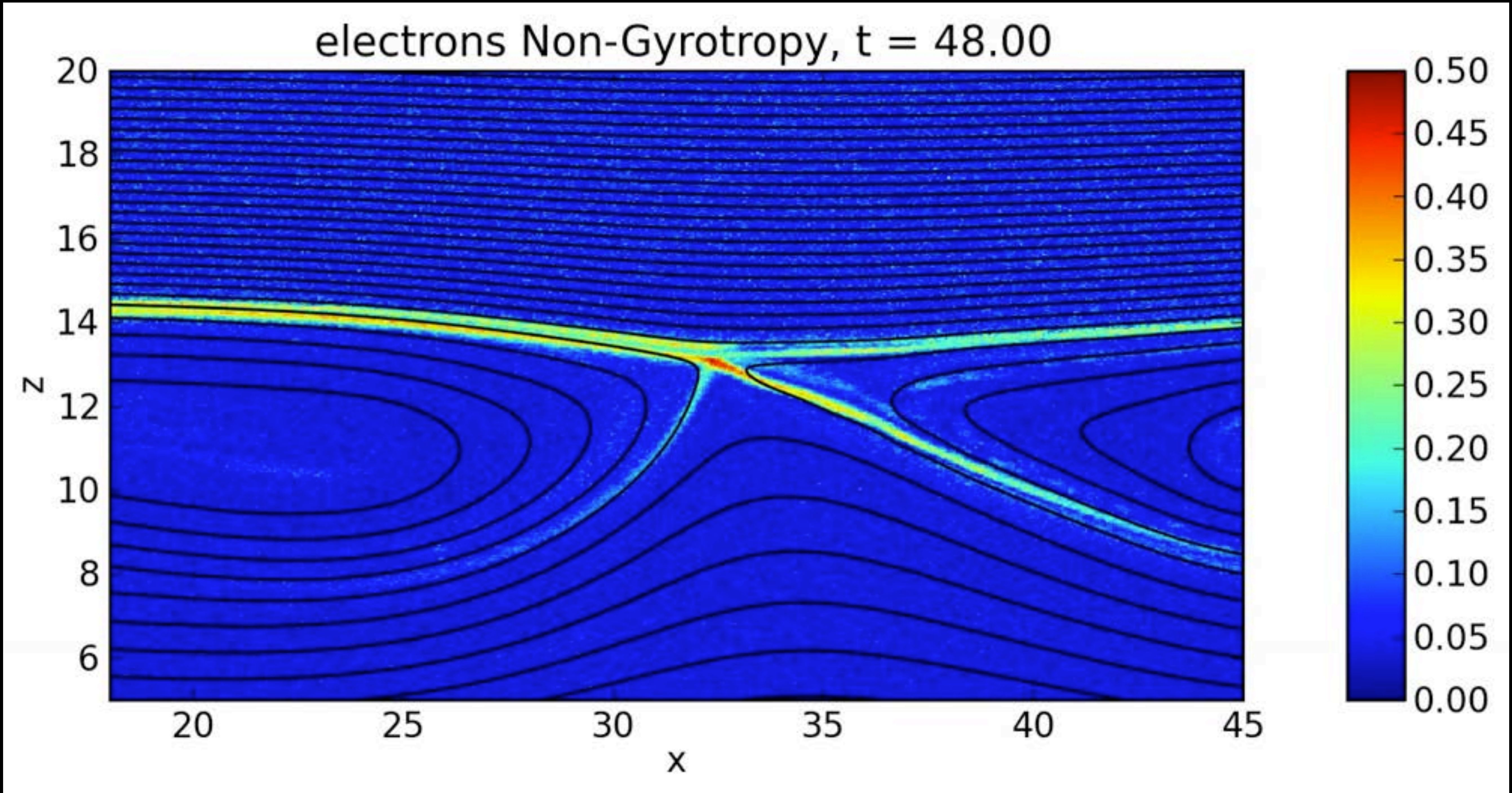
$$\mathbf{G} = P_\perp \mathbf{I} + \left(P_\parallel - P\perp\right)\mathbf{bb}$$

$$D_{ng} = \frac{\sqrt{\sum_i \lambda_i^2}}{U} = 2\frac{\sqrt{\sum_{i,j} N_{ij}^2}}{Tr\left(\mathbf{P}\right)}$$

- Fully capture the nongyrotropy of a distribution function
- valid for any species (electrons in this case)

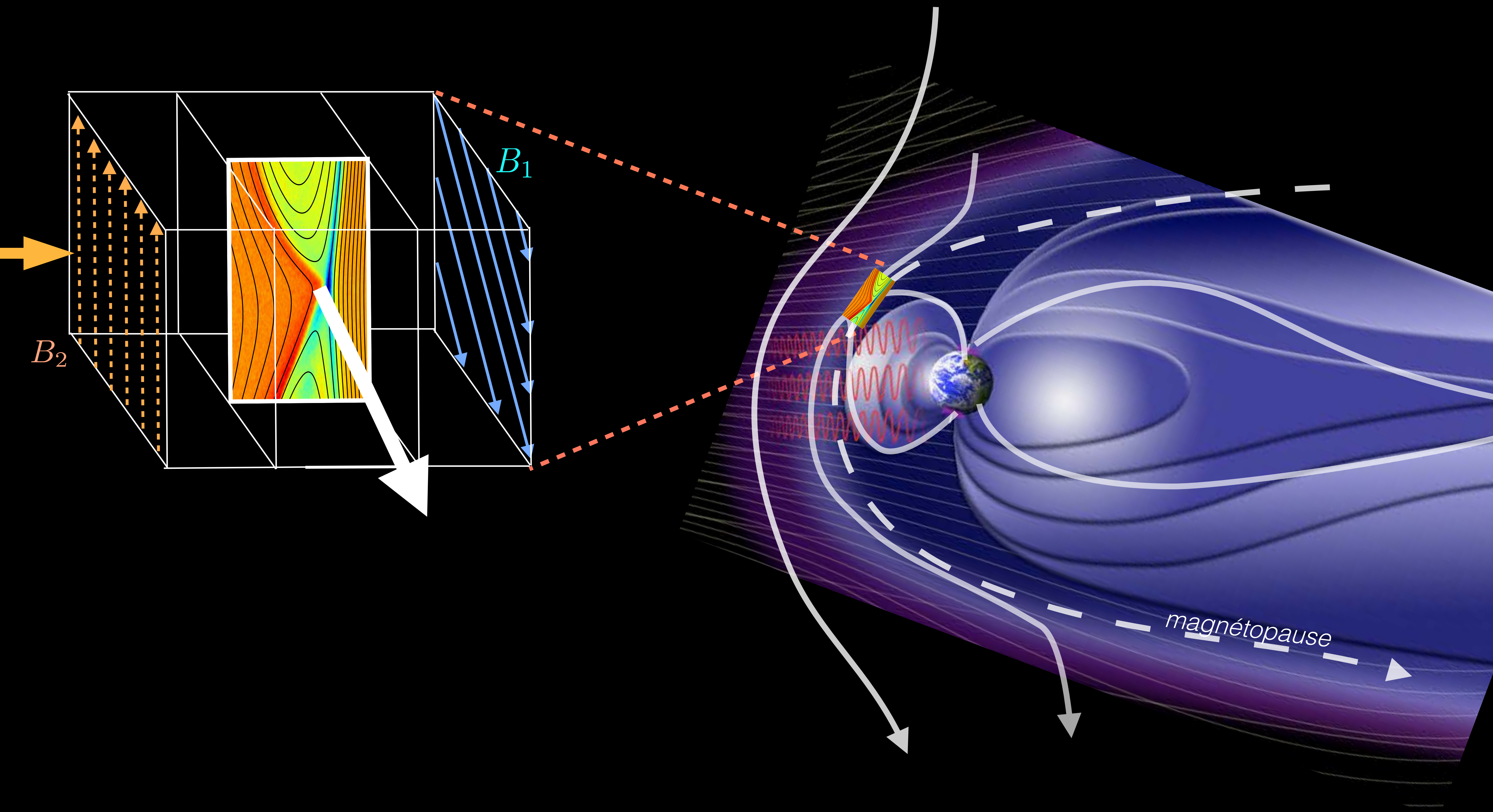
Degree of non-gyrotropy

Highlight regions where electrons « do not behave as a fluid »

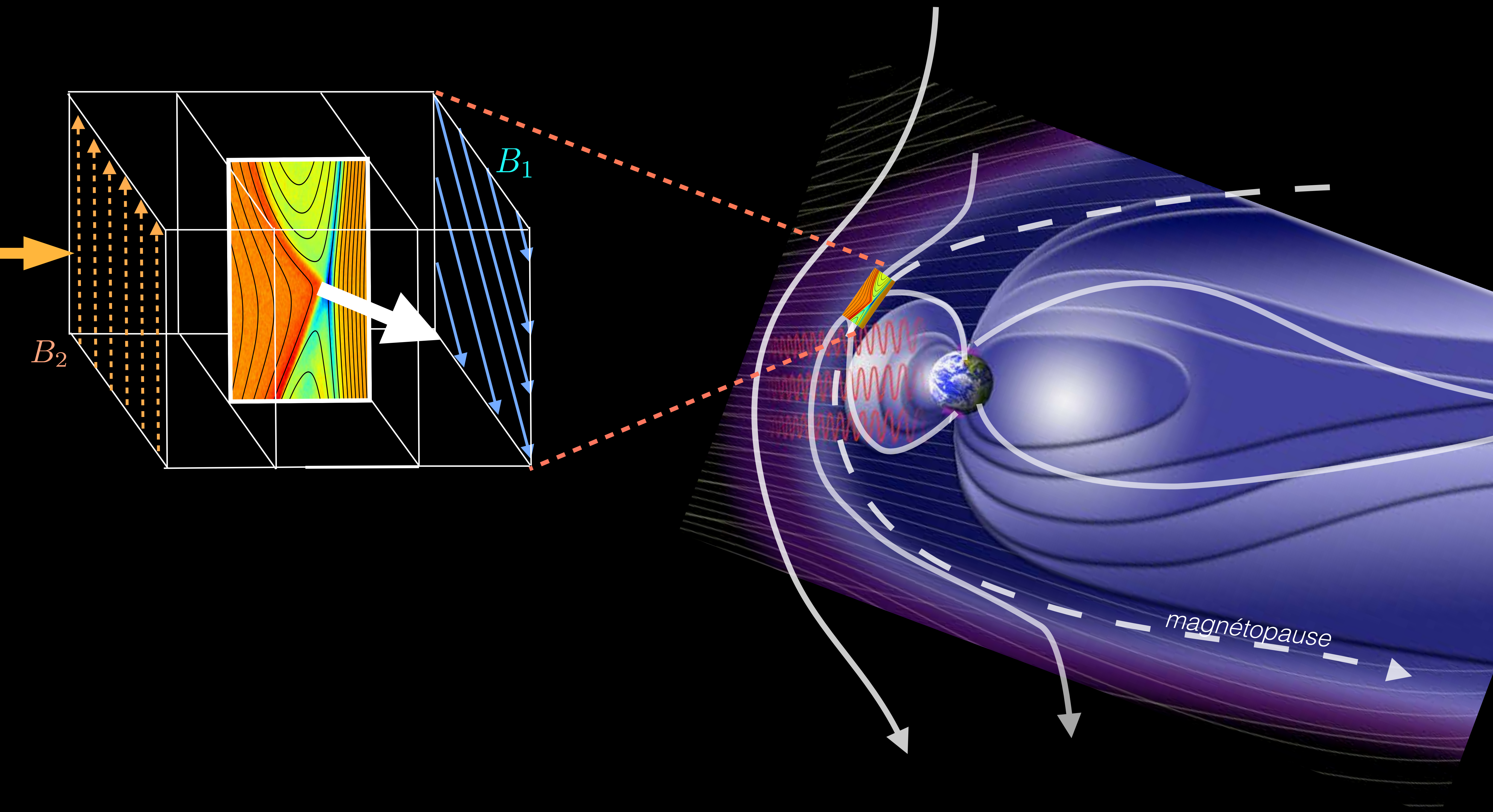


Chap. 7 - MultiScale Reconnection

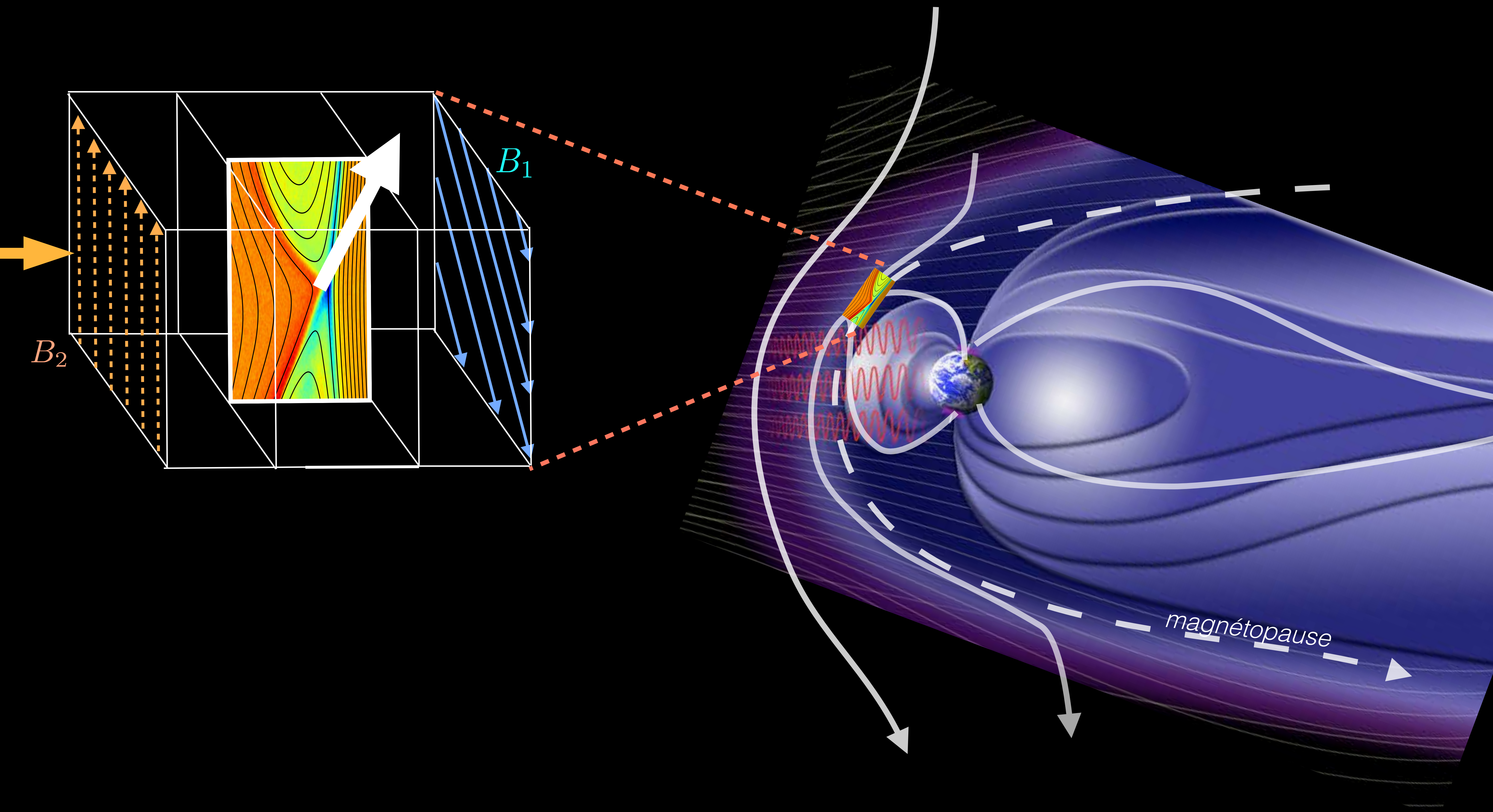
WHAT IS THE LOCAL ORIENTATION OF THE X LINE?



What is the local orientation of the X line?

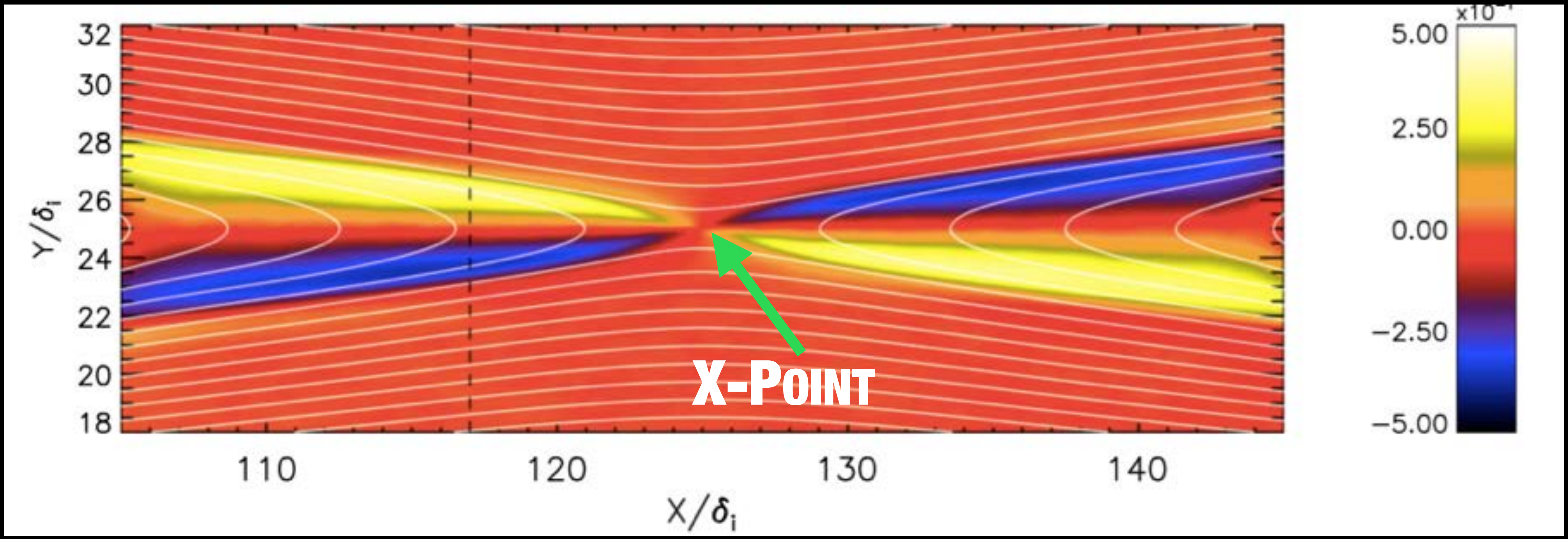


WHAT IS THE LOCAL ORIENTATION OF THE X LINE?



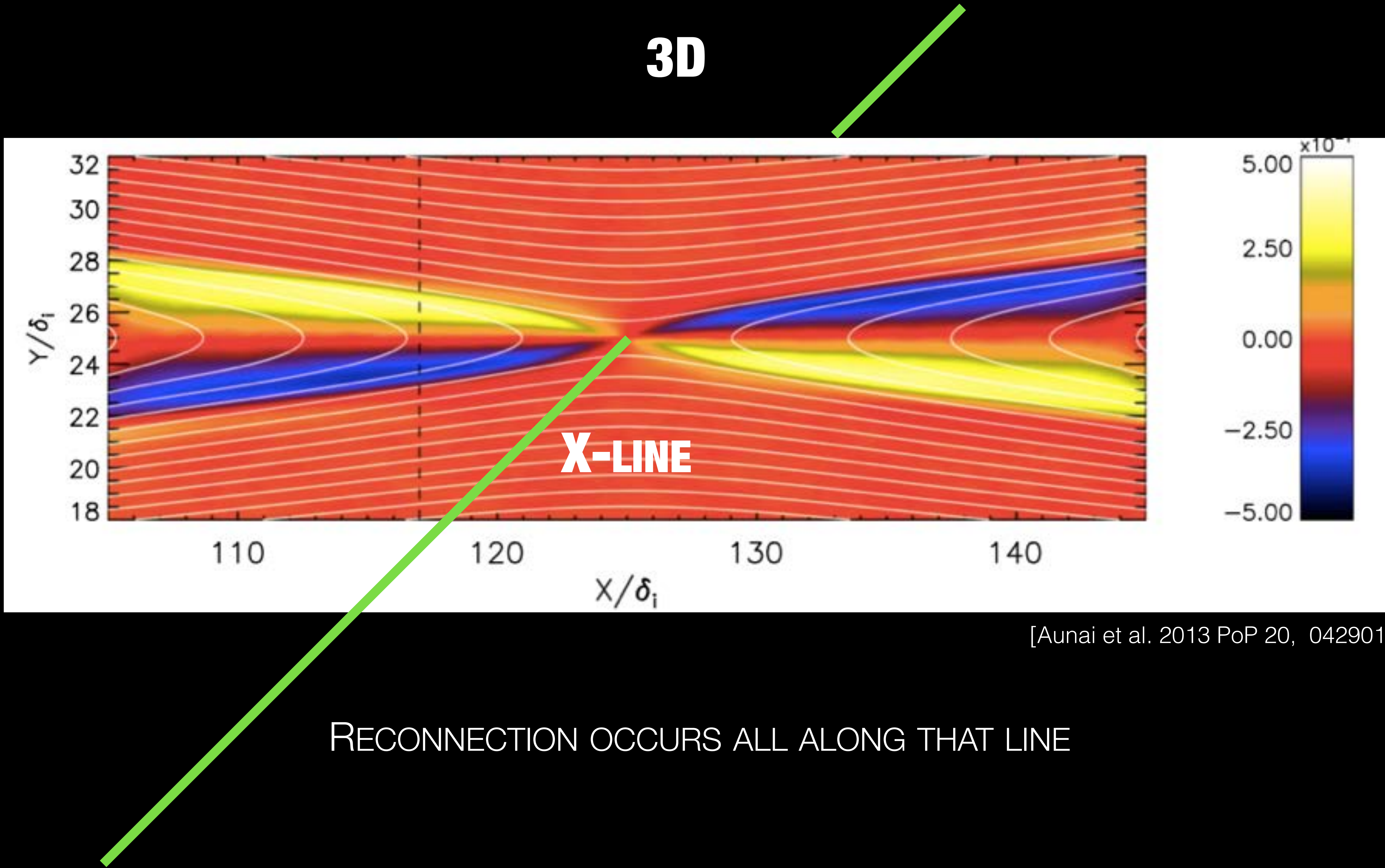
What is an X-line? Local viewpoint

2D



[Aunai et al. 2013 PoP 20, 042901]

WHAT IS AN X-LINE? Local viewpoint

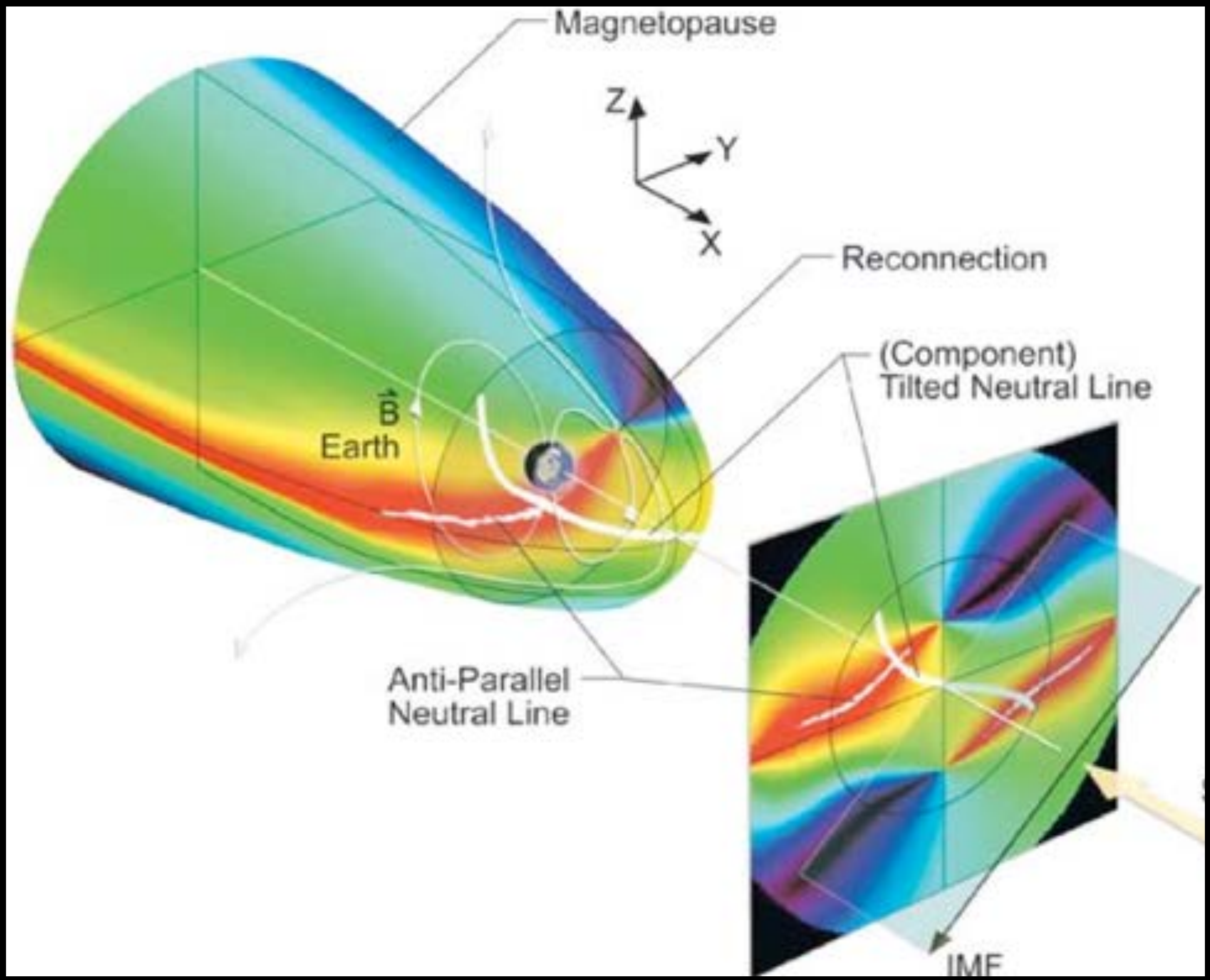


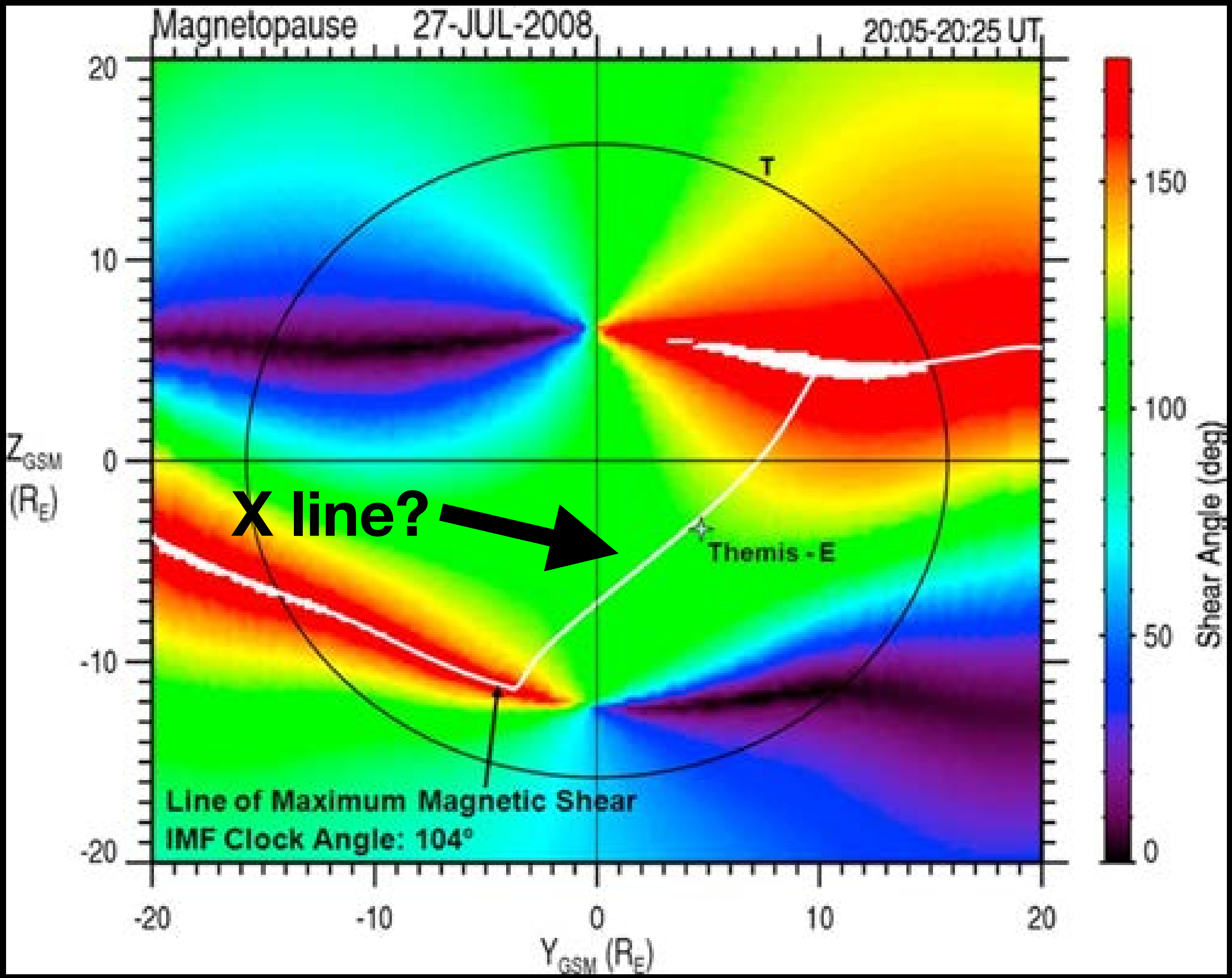
[Aunai et al. 2013 PoP 20, 042901]

RECONNECTION OCCURS ALL ALONG THAT LINE

What is an X-line? Global viewpoint

[Trattner et al. 2012]





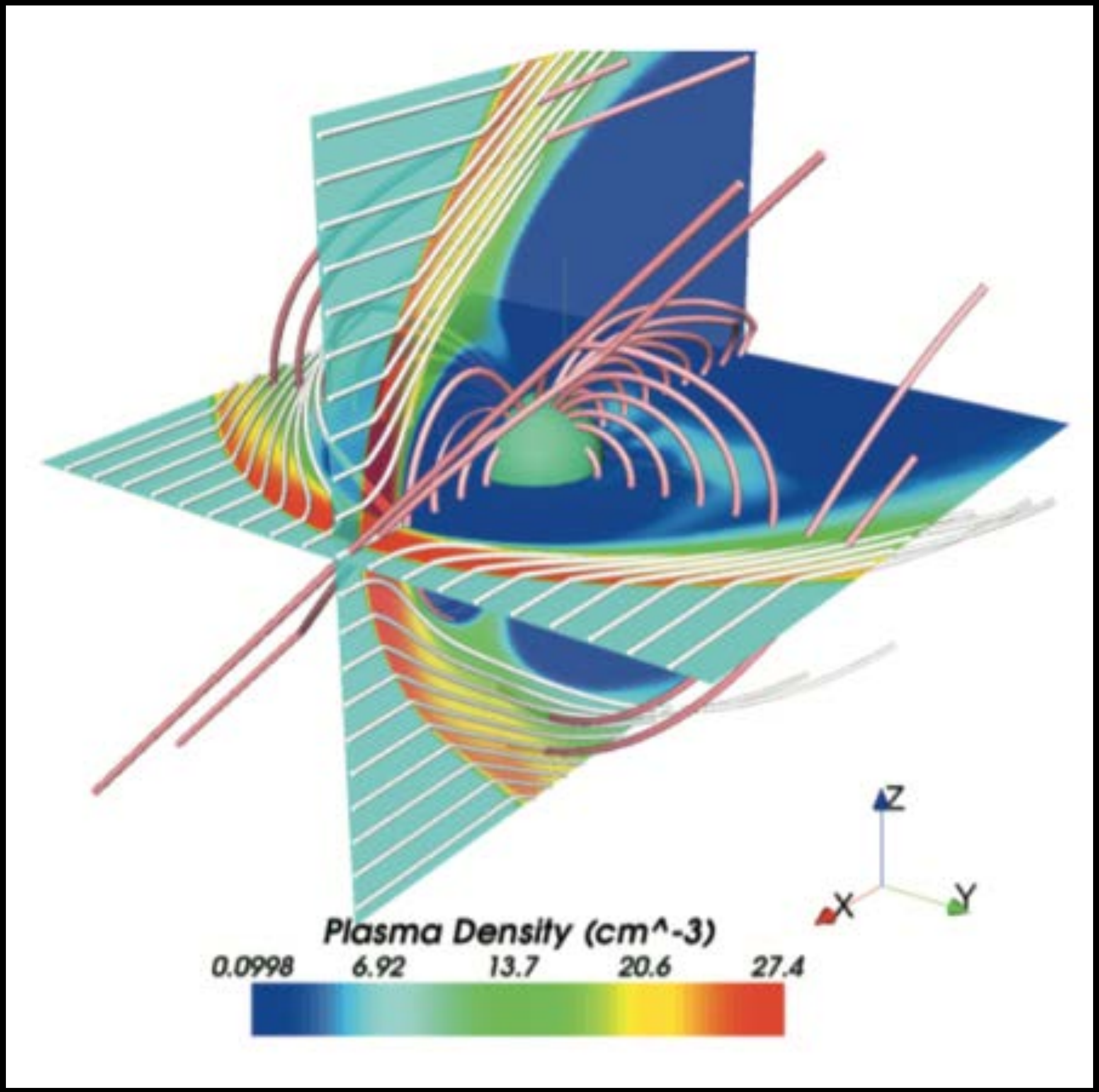
Viewed from the sun, color=shear angle

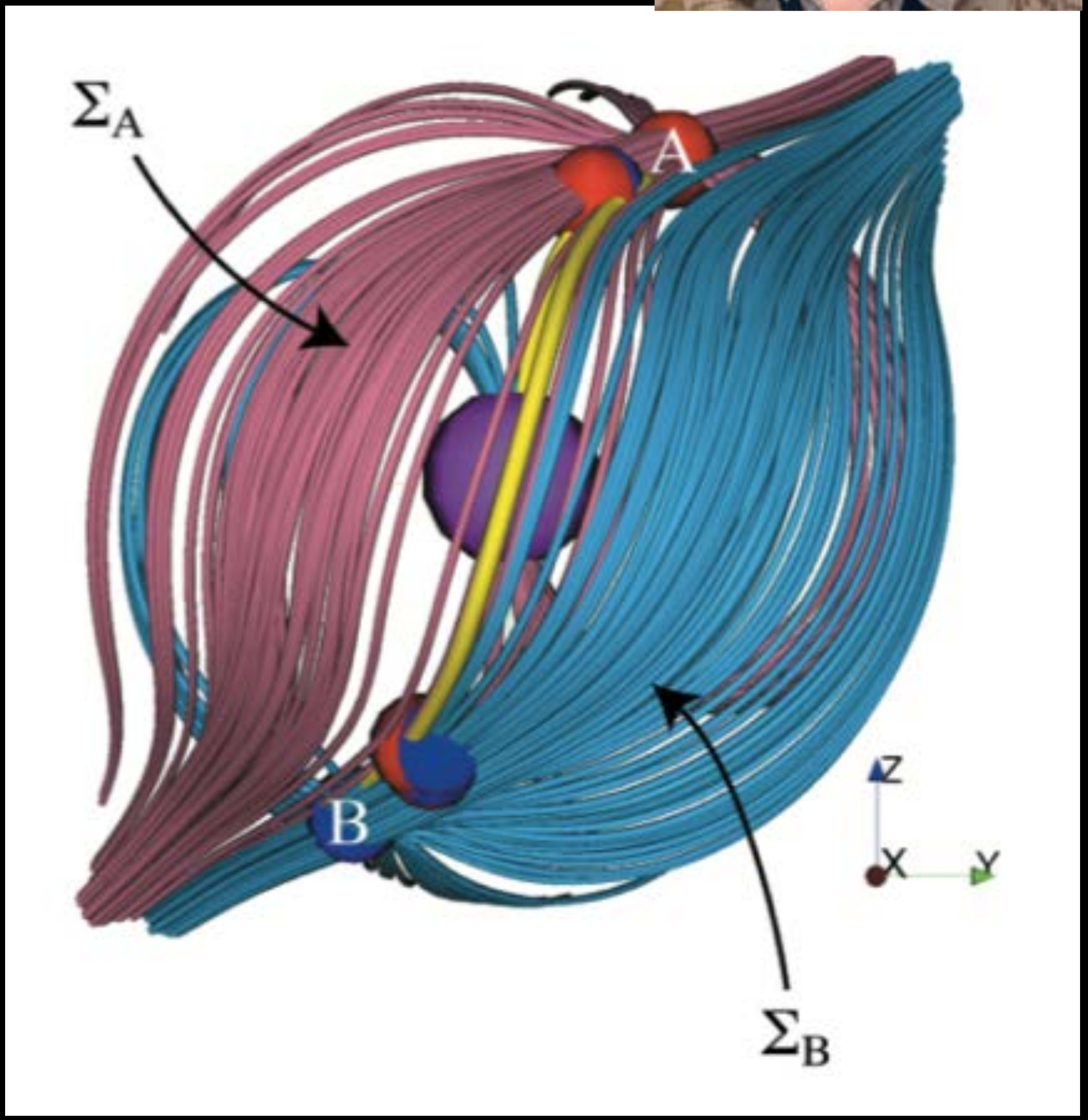
- Where does it start ? and why ?
- How does it spread?
- How does it evolve?

- How does it affect transport?
- How does it couples to solar wind?
- etc.

WHAT IS AN X-LINE? Global viewpoint

(Dorelli et al. 2007)

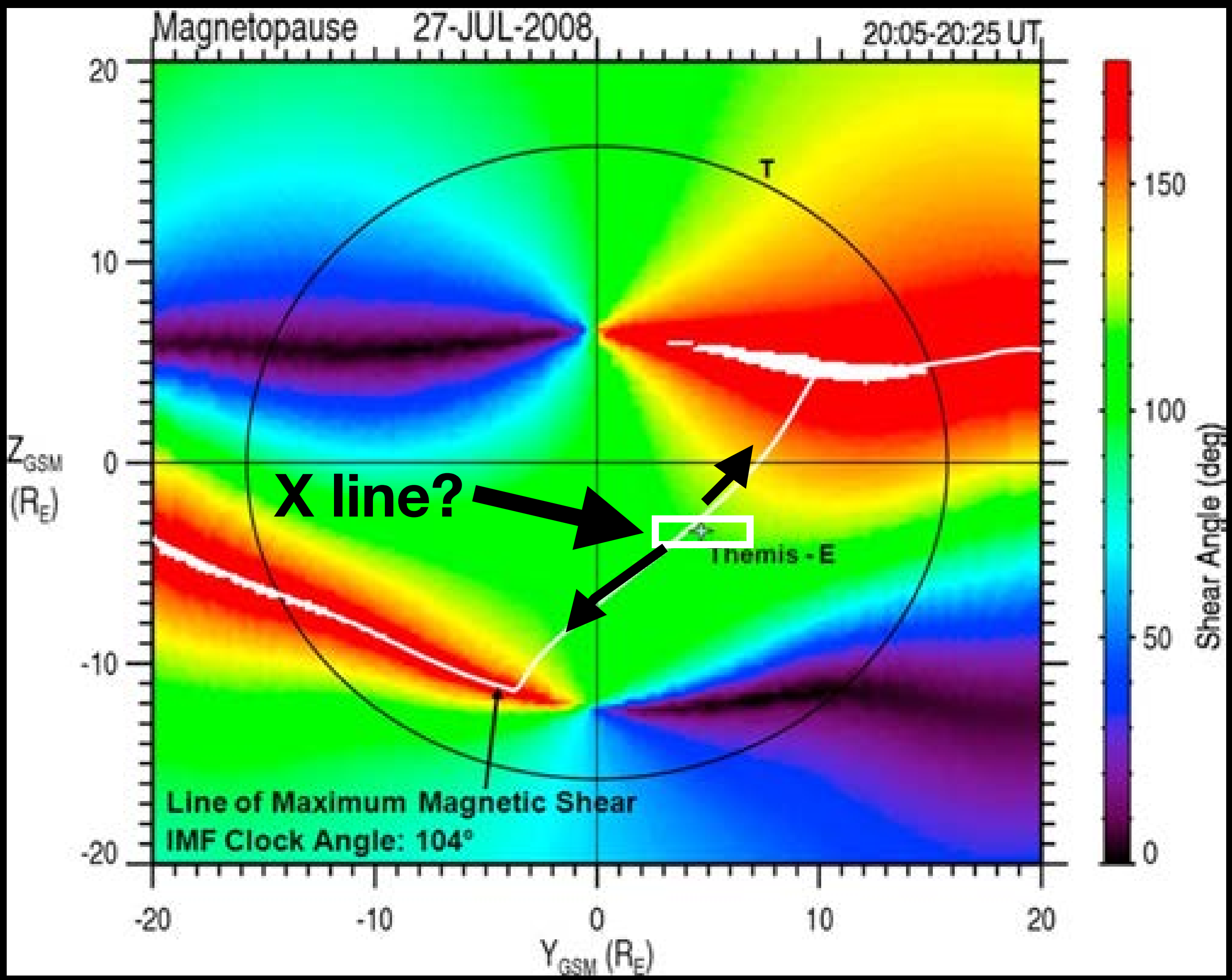


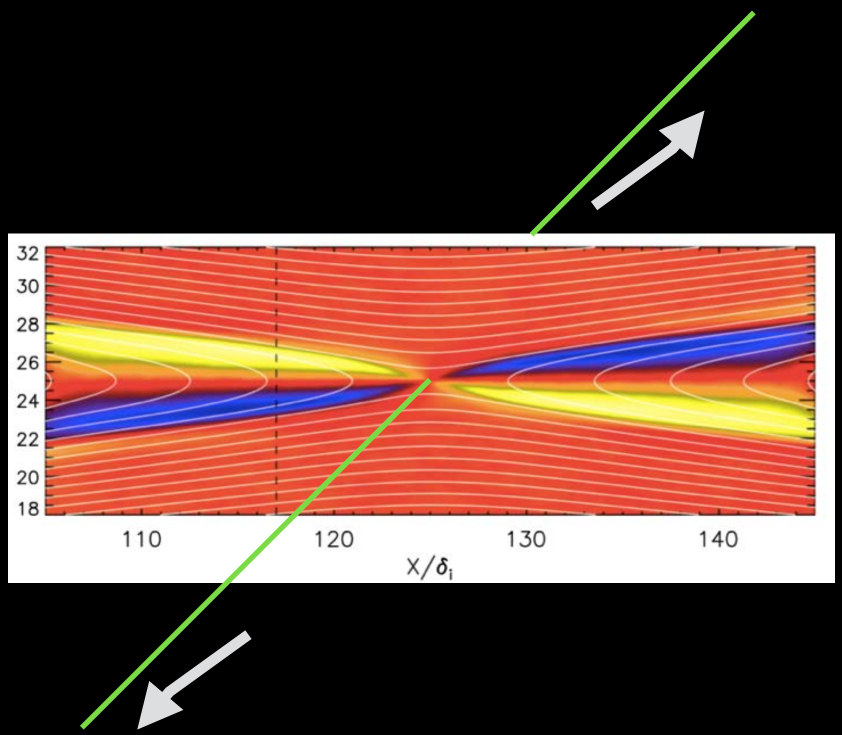


Reconnection occurs at the global magnetic separator

WHAT IS AN X-LINE? Global viewpoint

[Trattner et al. 2012]





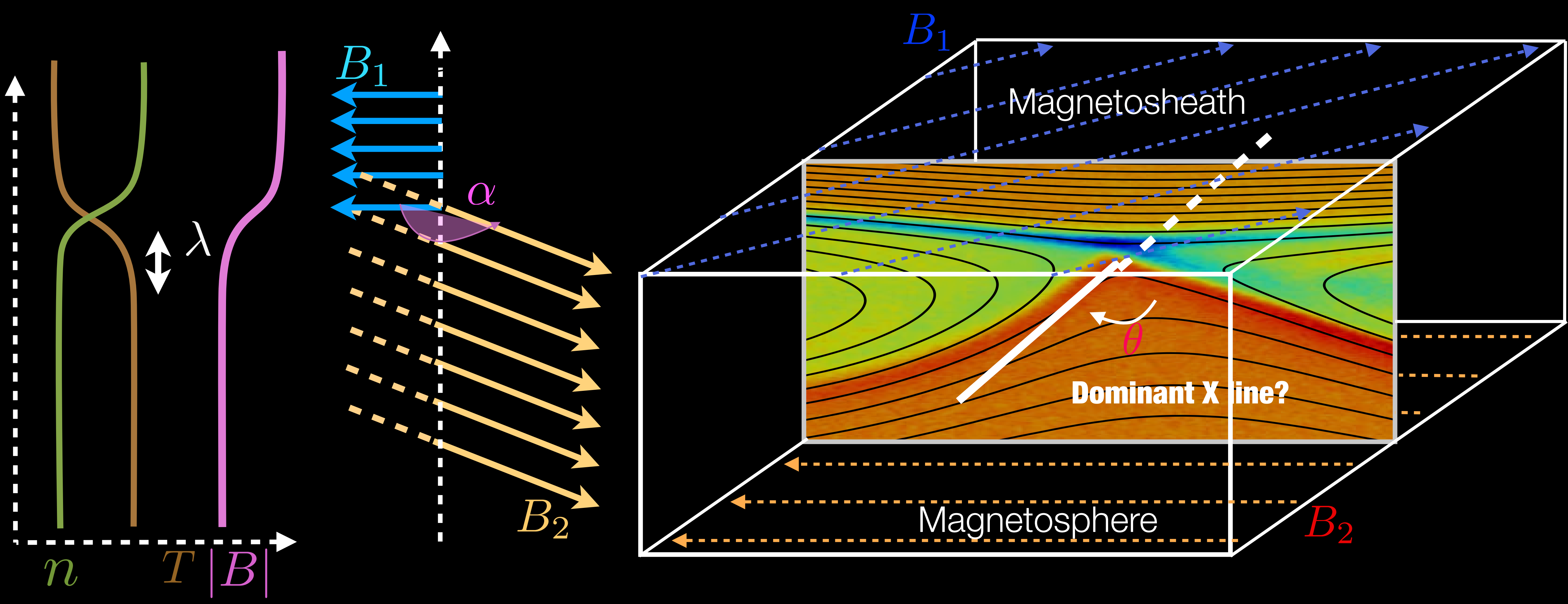
Global model : need large scale variations to now the direction to follow

Small scale : reconnnection self-consistently orient itself **as a function of upstream parameters only**

Local orientation = follow global X line?

LOCAL PHYSICS How does the X line orient itself as a function of **upstream** parameters only?

Asymmetric current sheet
2D or 3D local simulations of
magnetic reconnection



DIAMAGNETIC SUPPRESSION

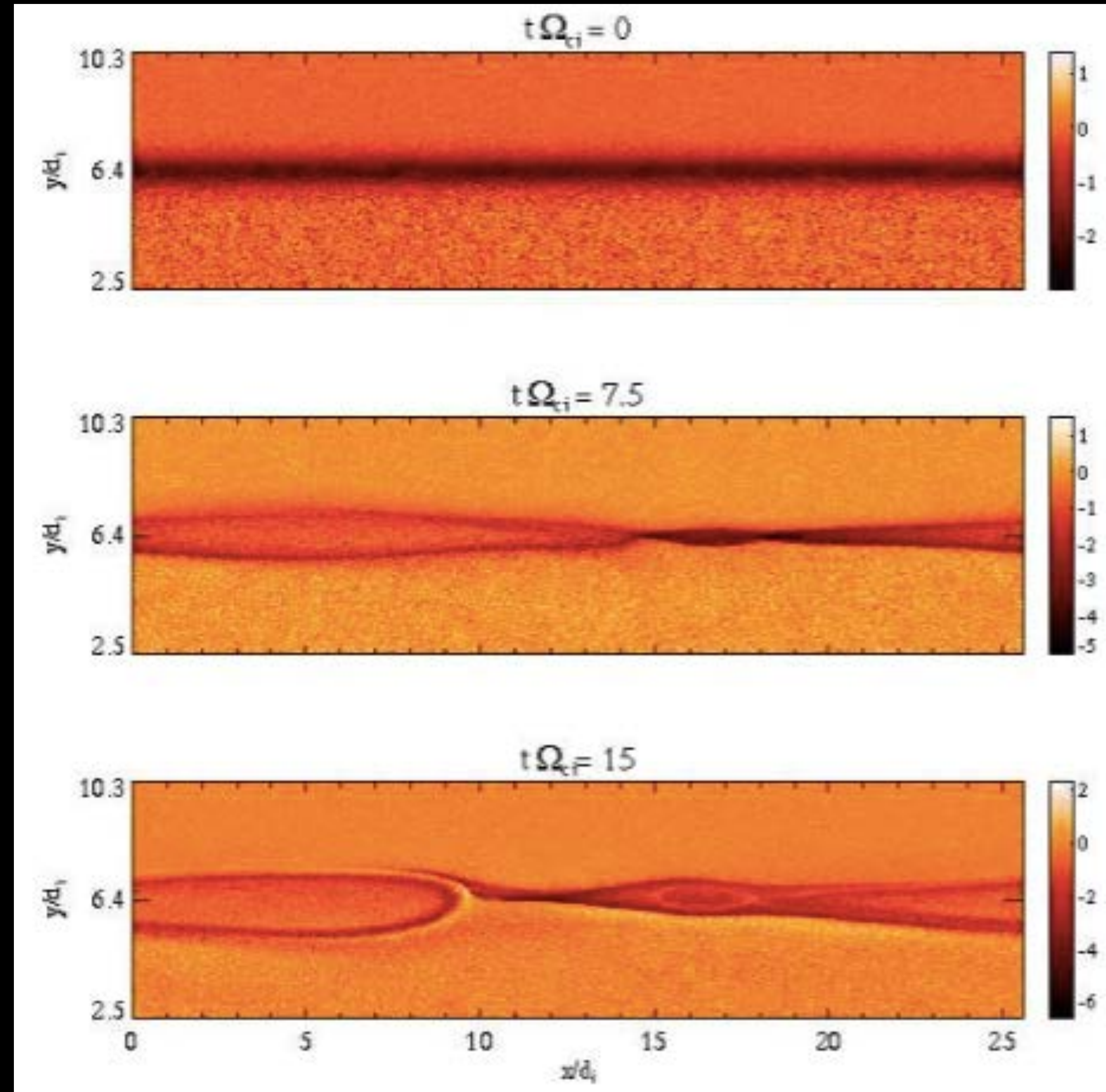
Diamagnetic drift of the X-line

$$V = -\frac{\nabla P \times \mathbf{B}}{qnB^2}$$

Suppress reconnection if

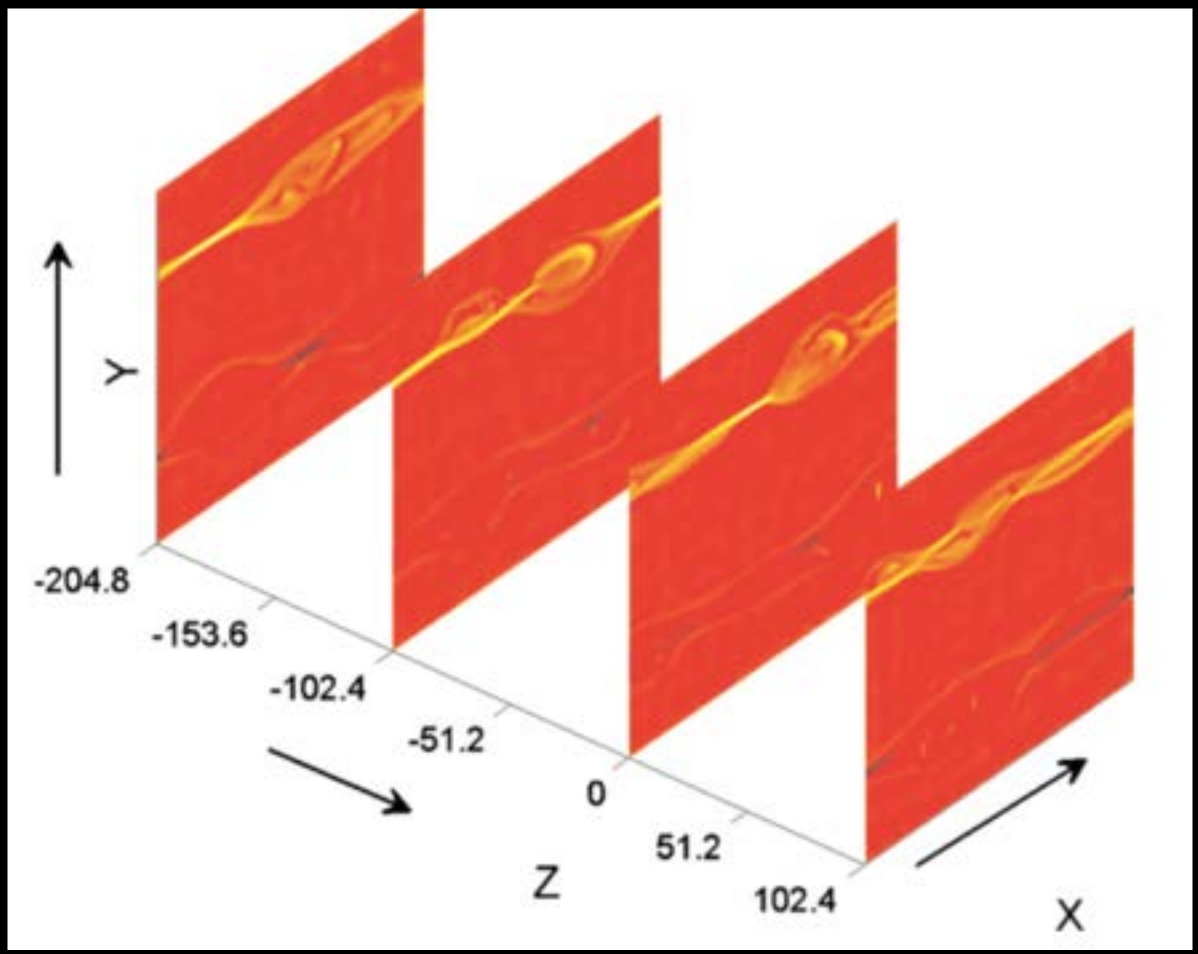
$$V > V_A$$

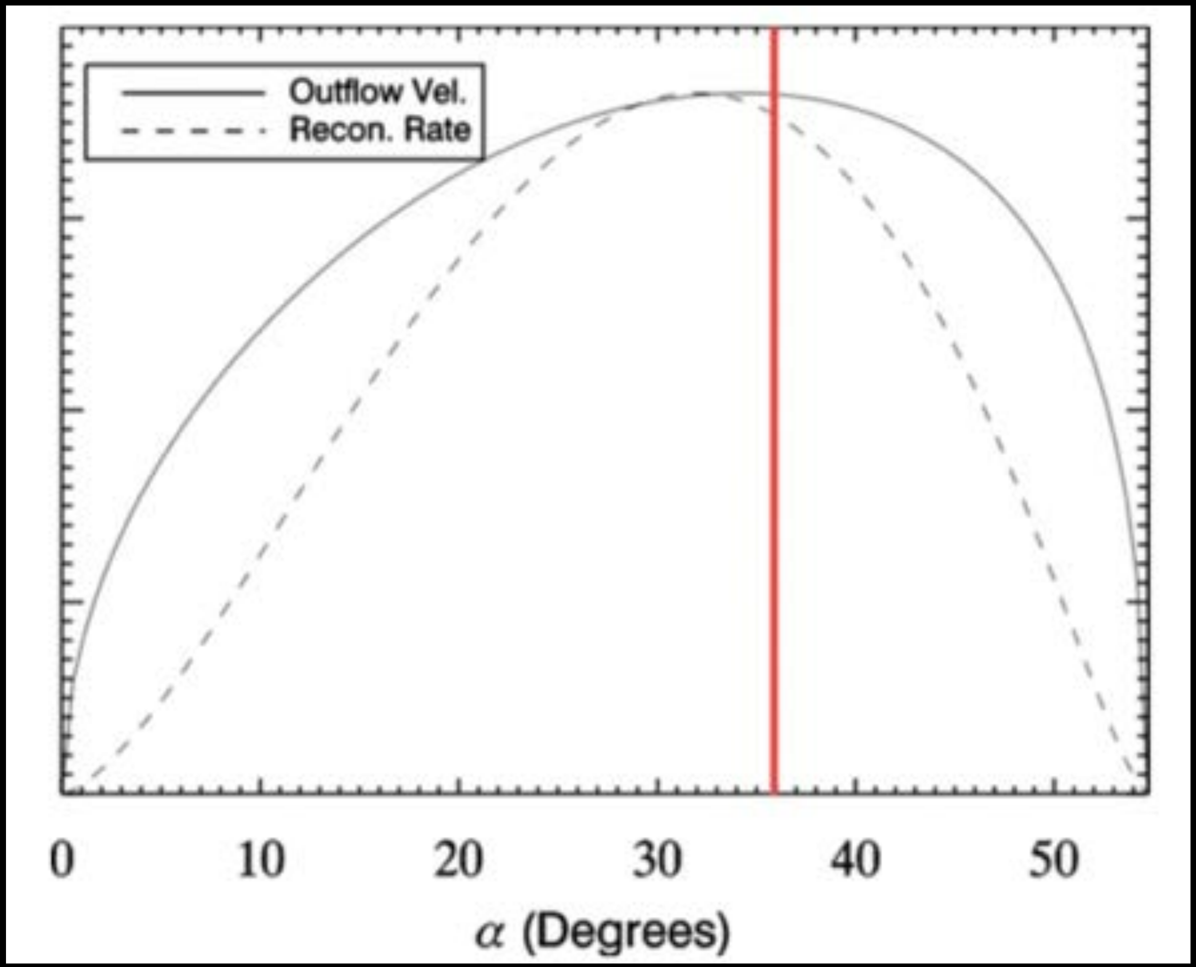
reconnection plane should *minimize* this effect



(Swisdak et al. 2007)

ORIENTATION IN 3D MHD *(Schreier et al. 2010)*



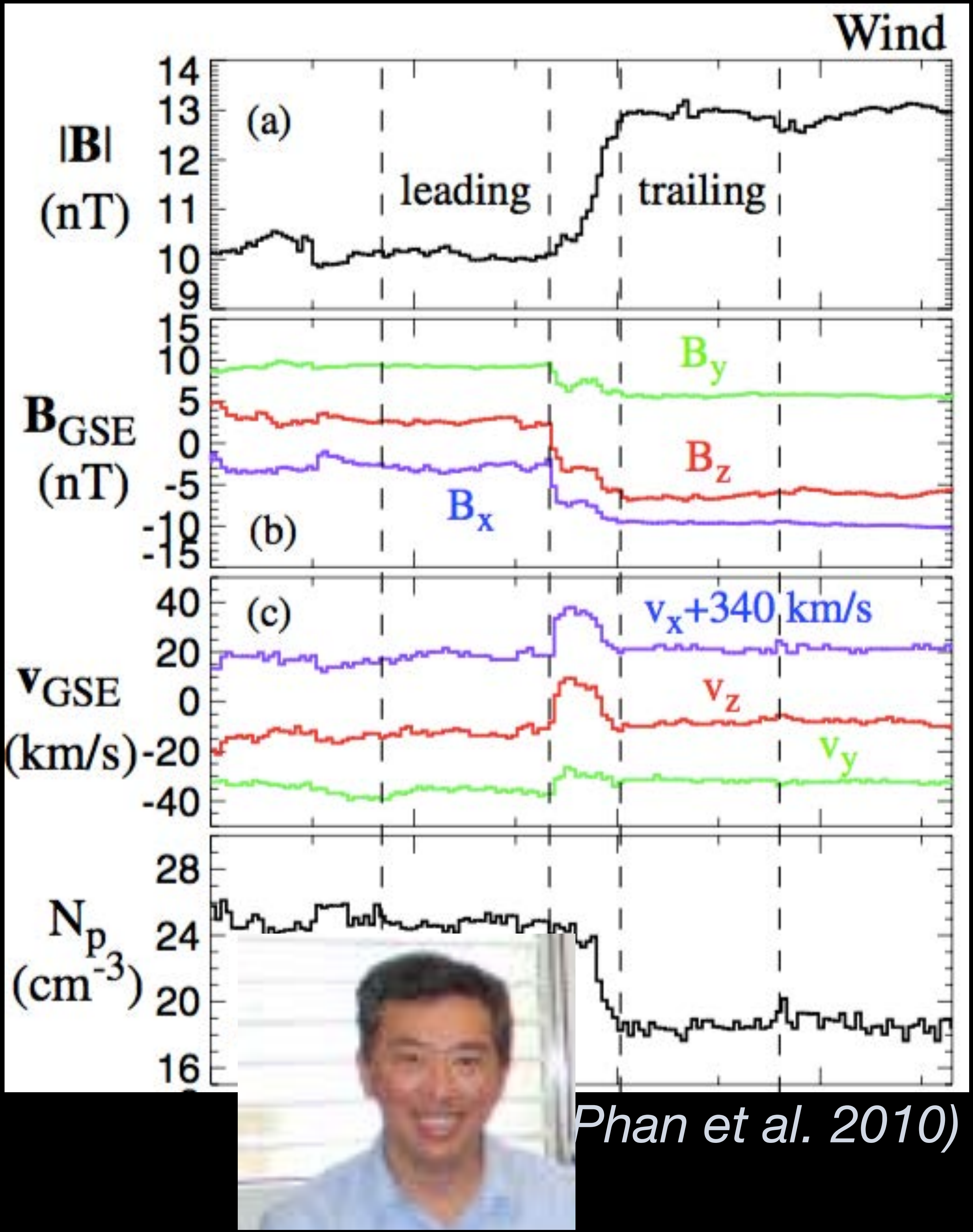


« The » X line seems to be oriented along the direction maximizing the outflow velocity

$$V_{out}^2 = (B_1 + B_2)\,\frac{B_1 B_2}{B_2\rho_1 + B_1\rho_2}$$

(Swisdak et al. 2007)

LMN COORDINATES



Phan et al. 2010)

Eigenvectors of

$$M^B_{\mu\nu} \equiv \langle B_\mu B_\nu \rangle - \langle B_\mu \rangle \langle B_\nu \rangle$$

Are directions in which the magnetic field has

- the largest variation (L)
- the smallest variation (N)
- the intermediate variation (M)

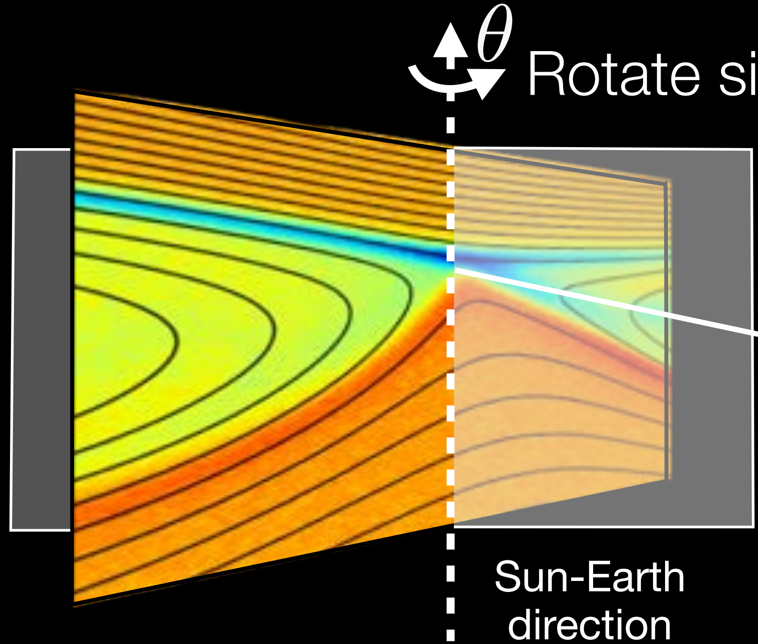
direction N is for 1D transitions: the normal direction

L and M are tangential

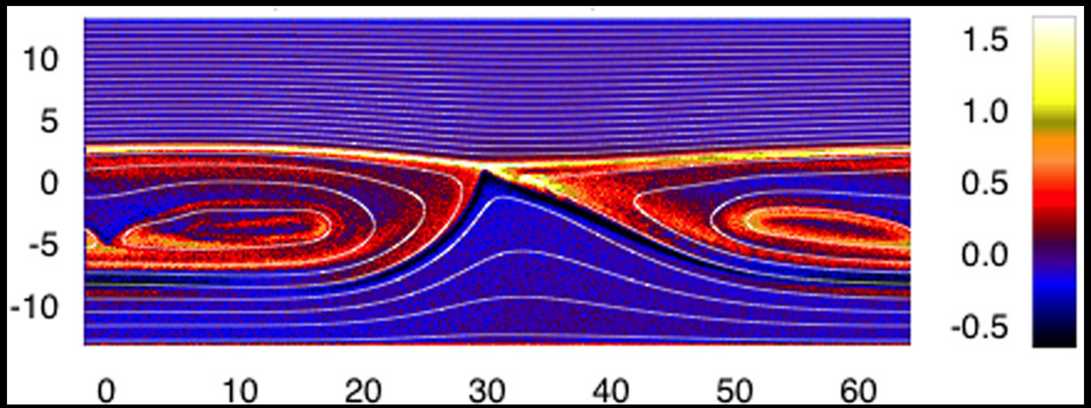
L : often associated with the reconnecting component

M: associated with the X line direction!

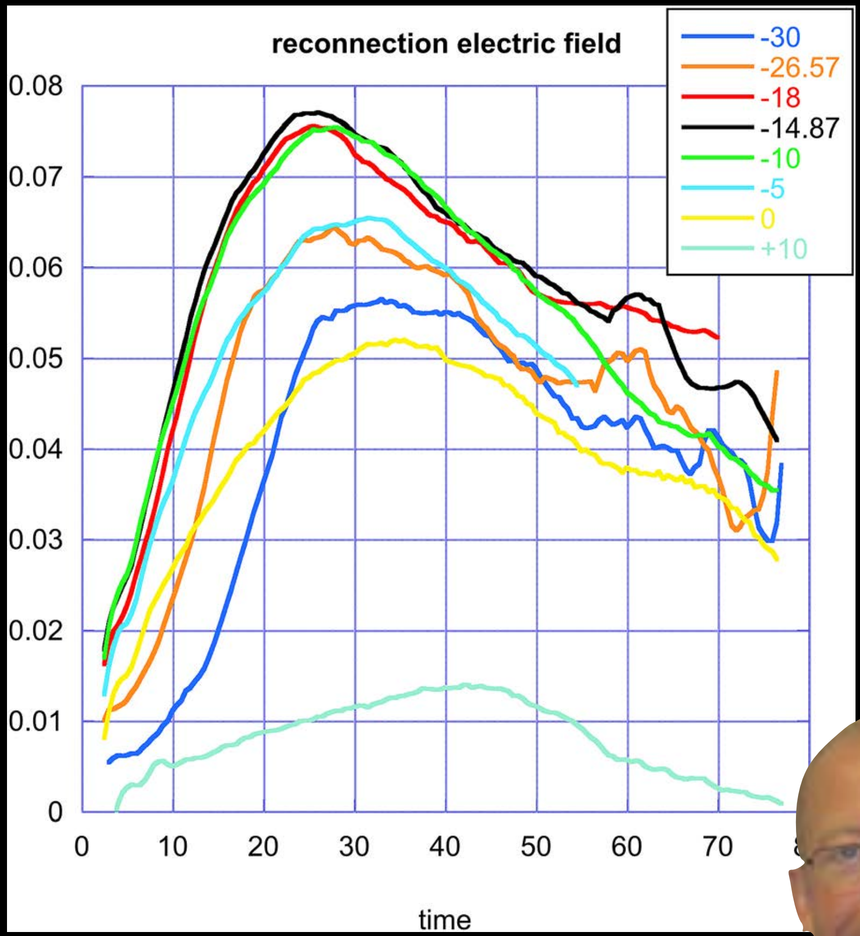
LOCAL PHYSICS 2D study rotating the simulation plane *(Hesse et al. 2013)*



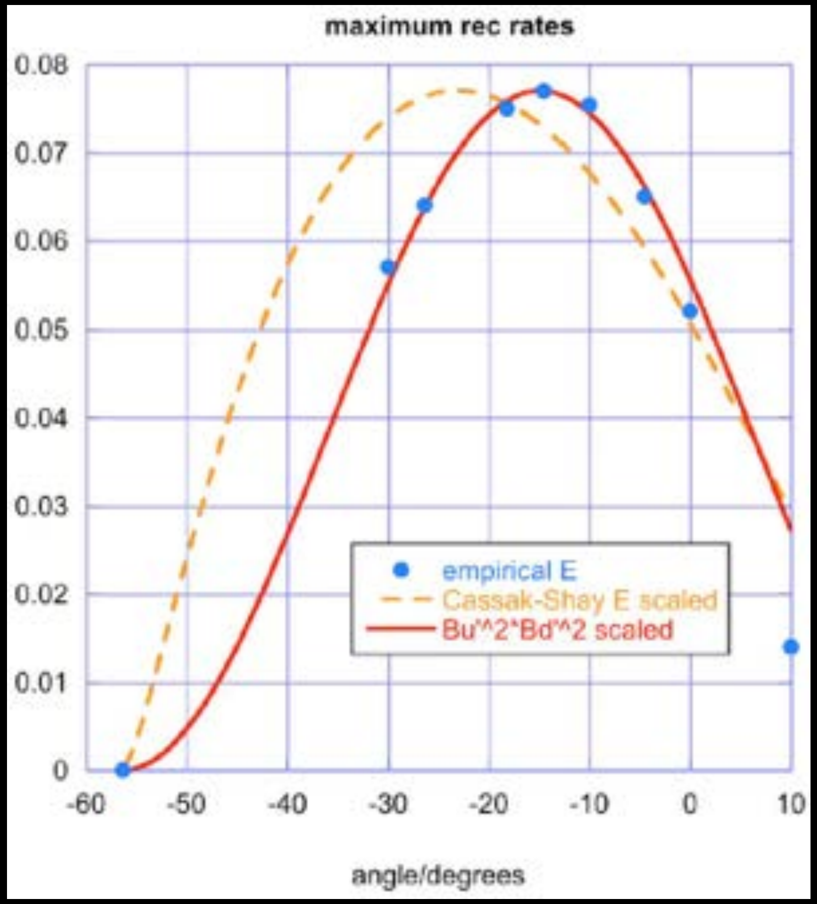
do simulation



Plot rate VS time



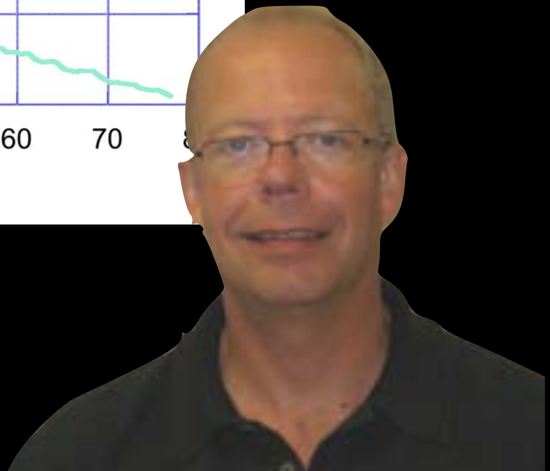
max(Rate)
vs angle



$$max(B_{1x}(\theta)^2 \, B_{2x}(\theta)^2)$$

X line along bisector

3D effects?

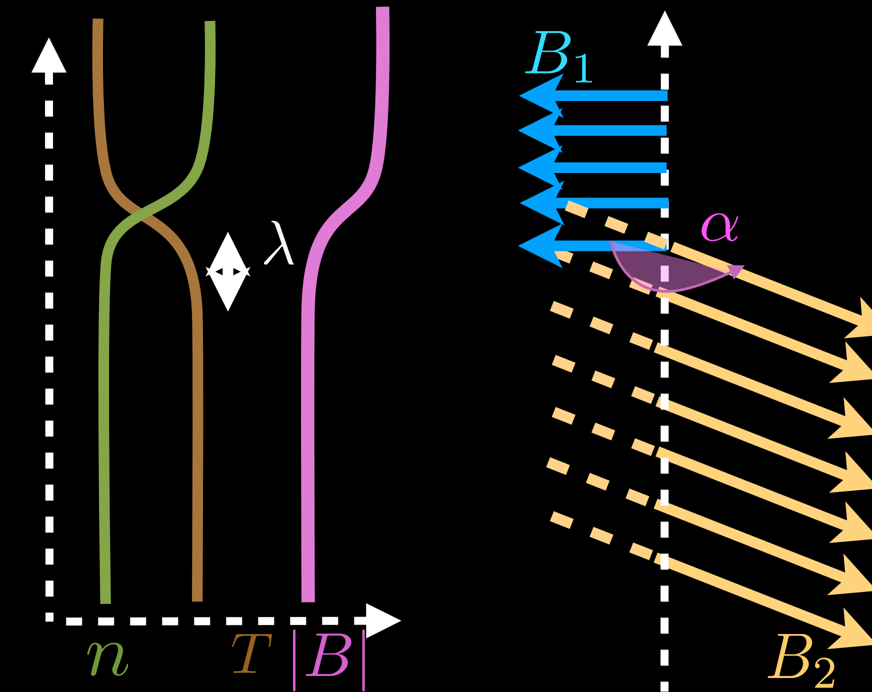


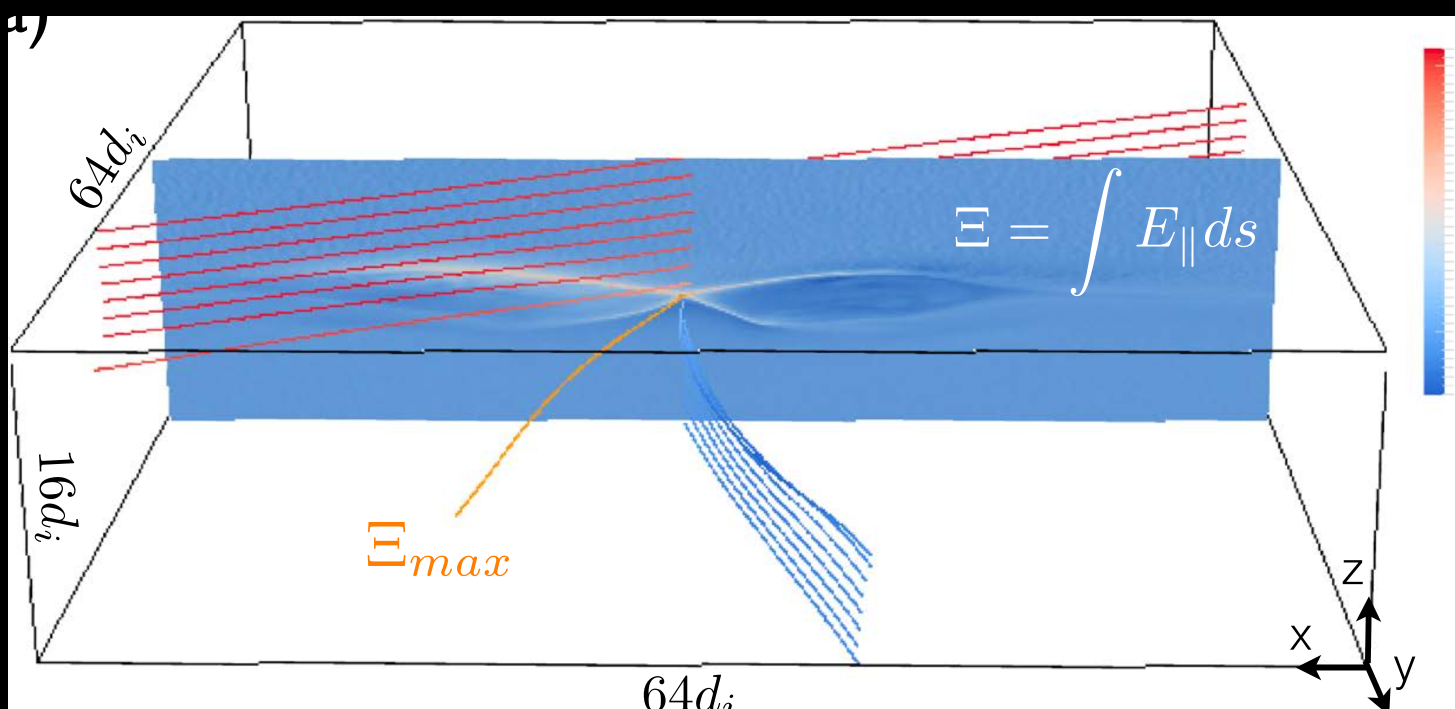
LOCAL PHYSICS

What is the orientation in 3D full PIC? *[Liu et al. 2013]*

Same initial asymmetry as
[Hesse et al. 2013]

Influence of 3D effects?
Initial 3D perturbation





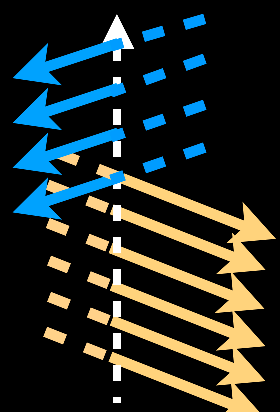
Still leads to X line along the bisector

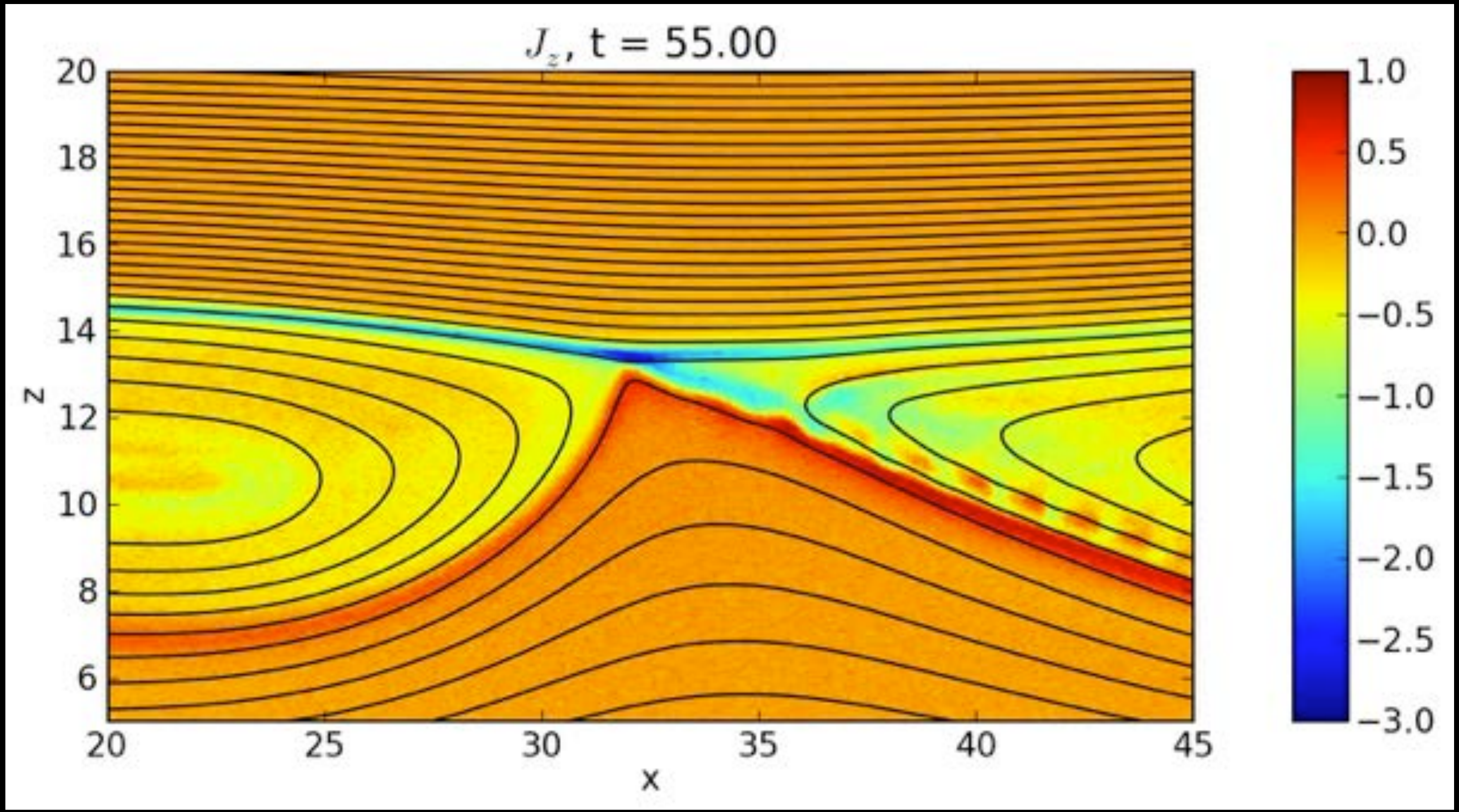
consequence of small domains?

still valid for different B profiles and shears?

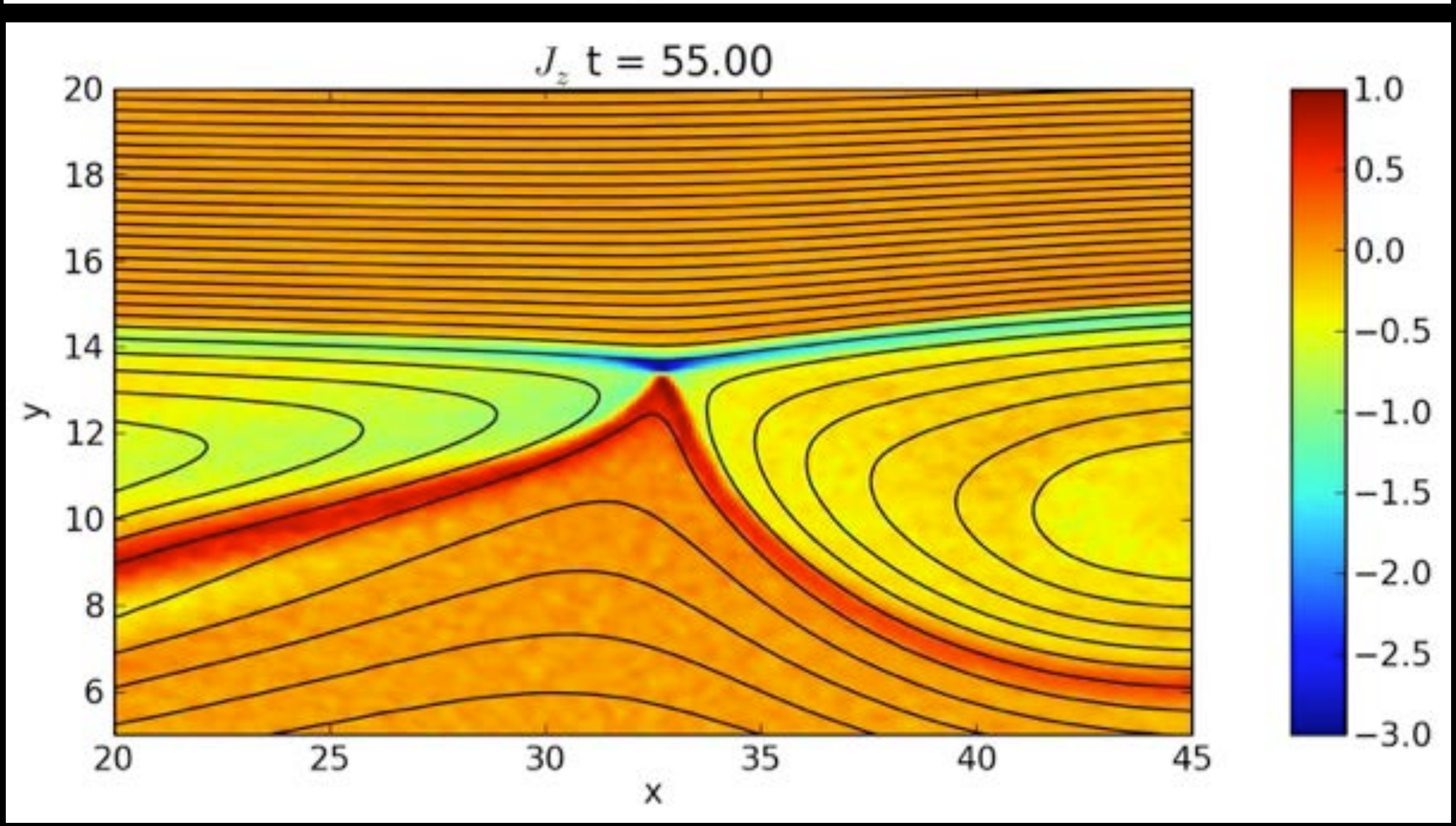
Fluid electrons VS particle electrons models

Full PIC





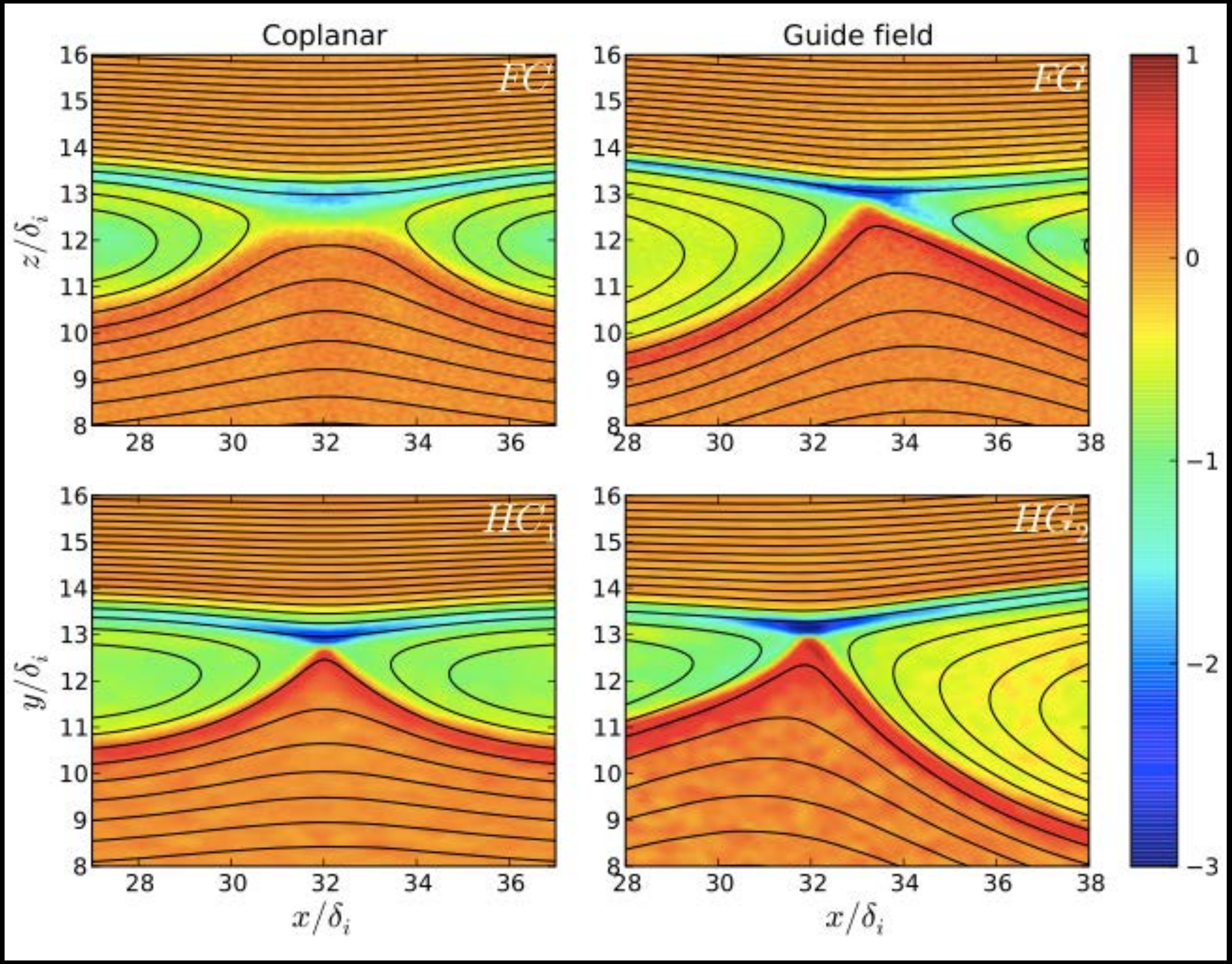
Hyper-resistive Hybrid



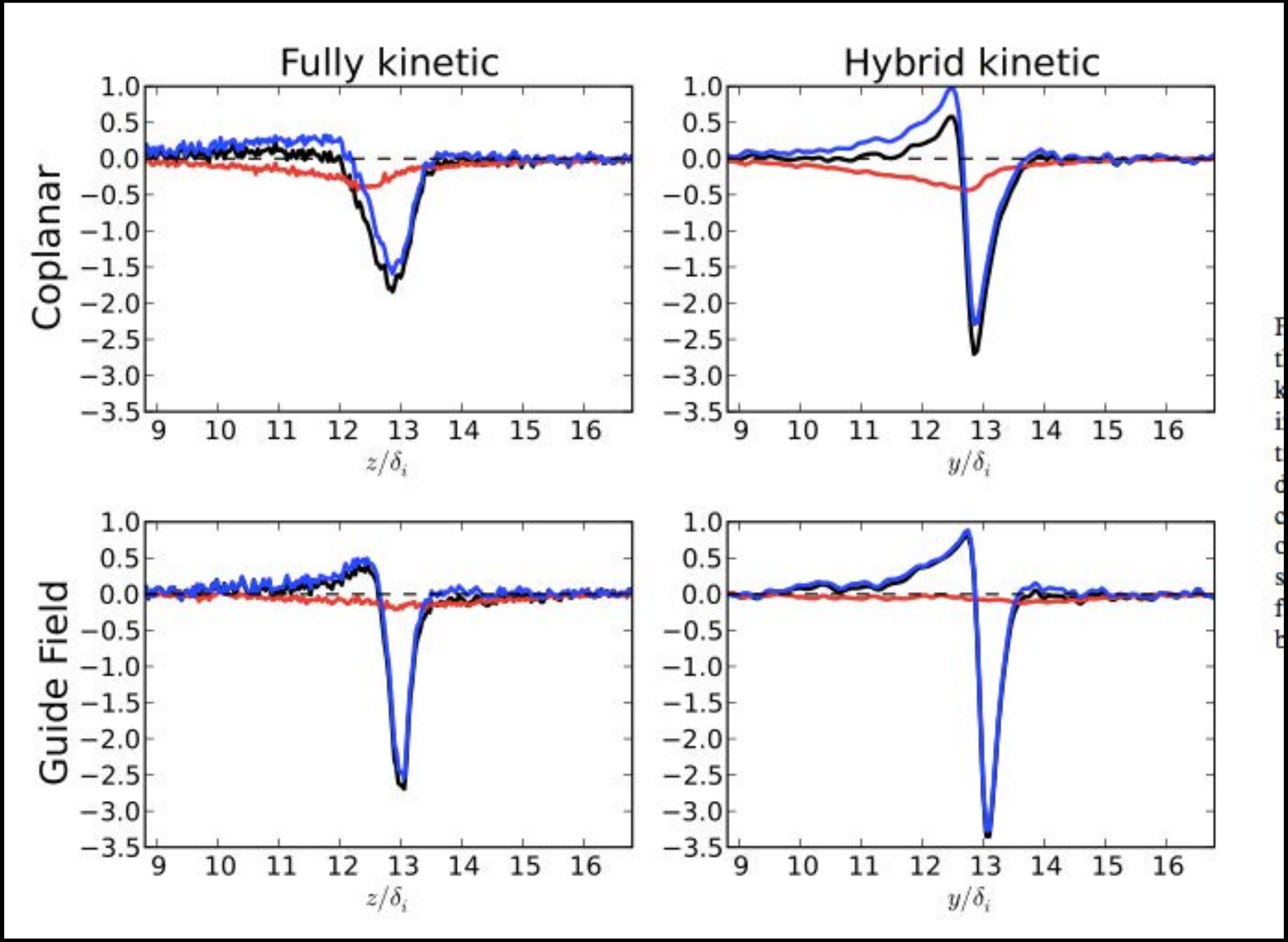
out-of-plane current density

Full PIC

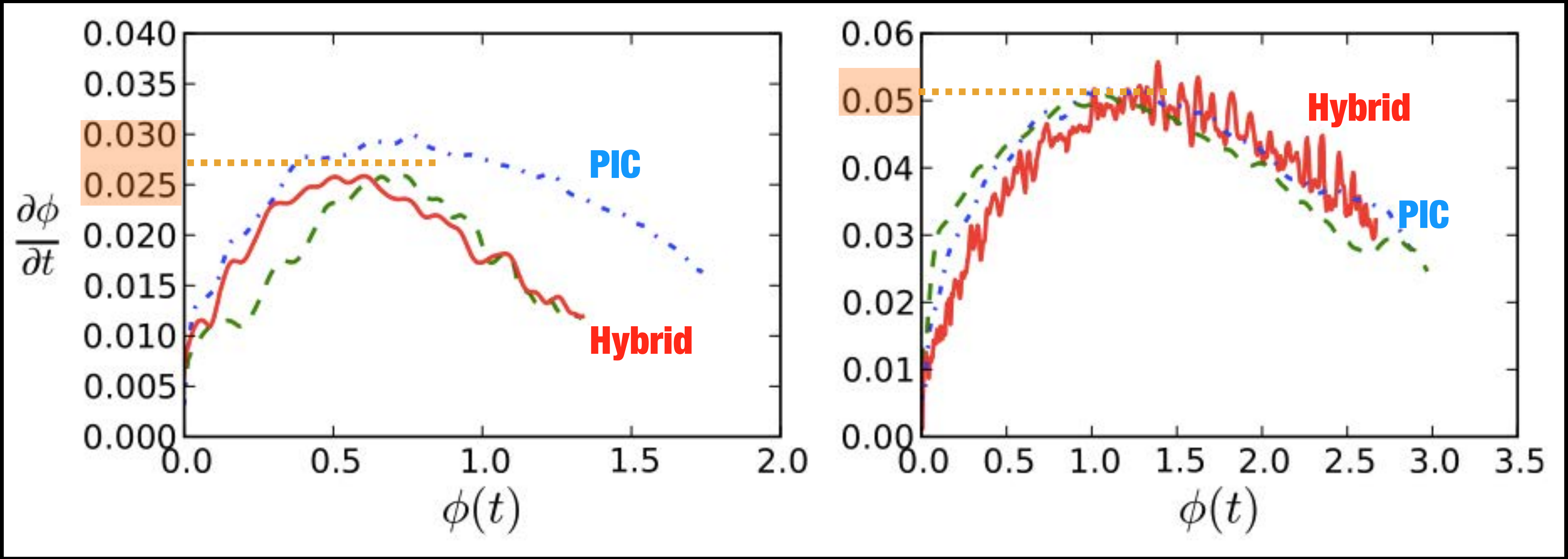
Hybrid



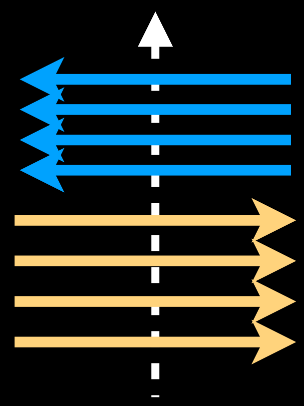
Ion, electron and total current through the X line

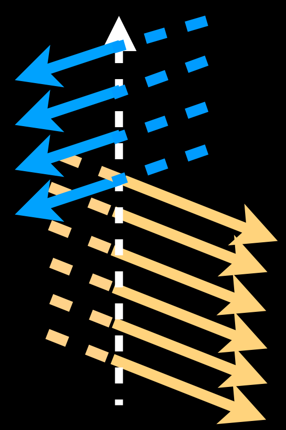


Hybrid vs PIC reconnection rate



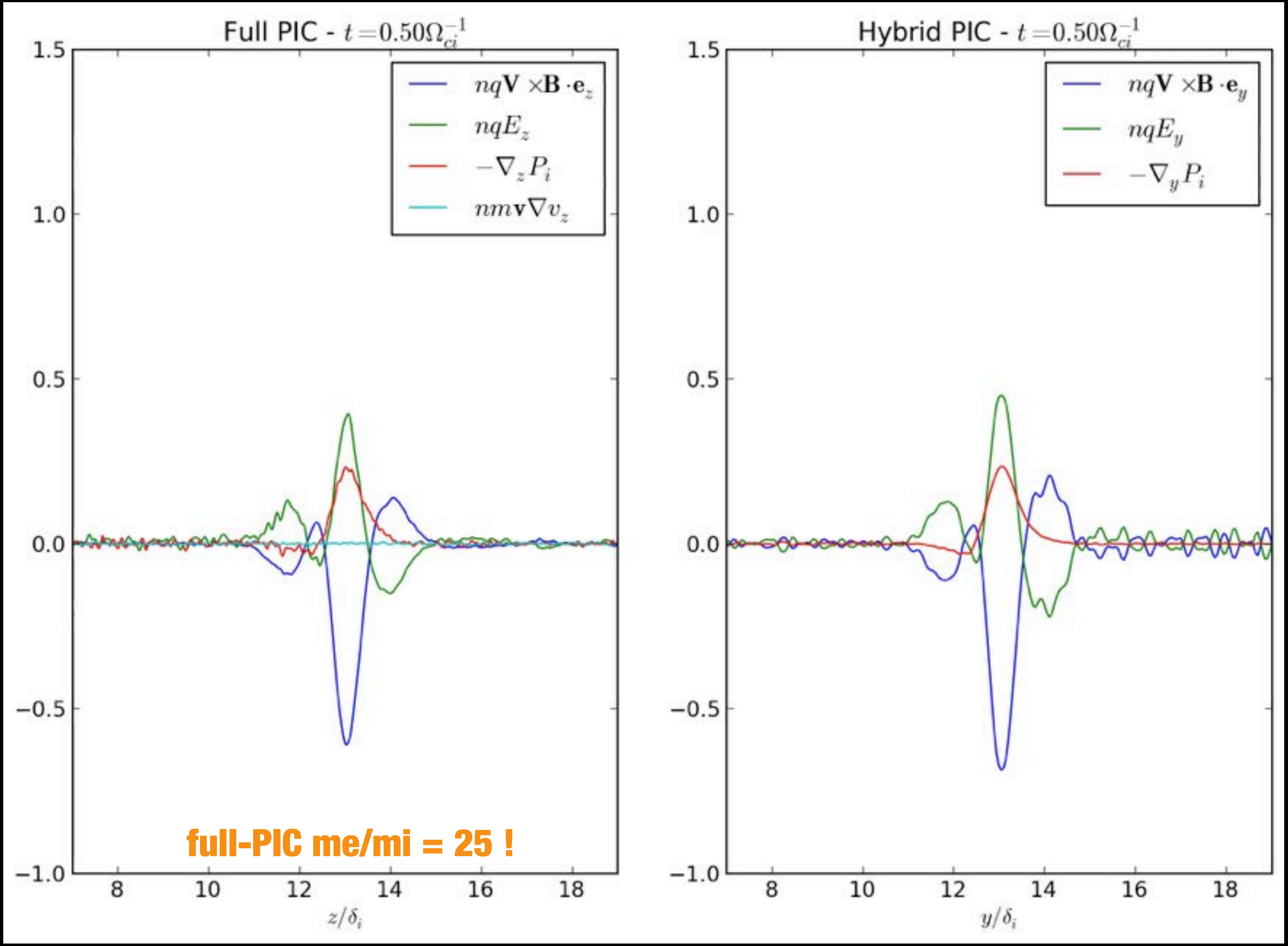
[Aunai et al 2013a]



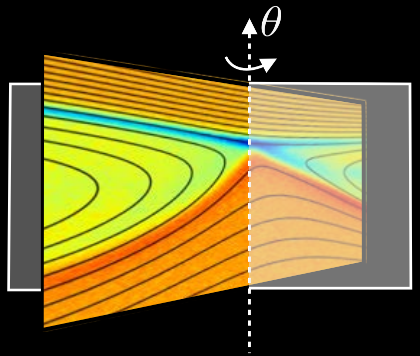


Coplanar is slow because the in-plane field on one side is too weak and ions are unmagnetized over a huge area in the inflow

Fluid initialization : full-PIC vs Hybrid-PIC



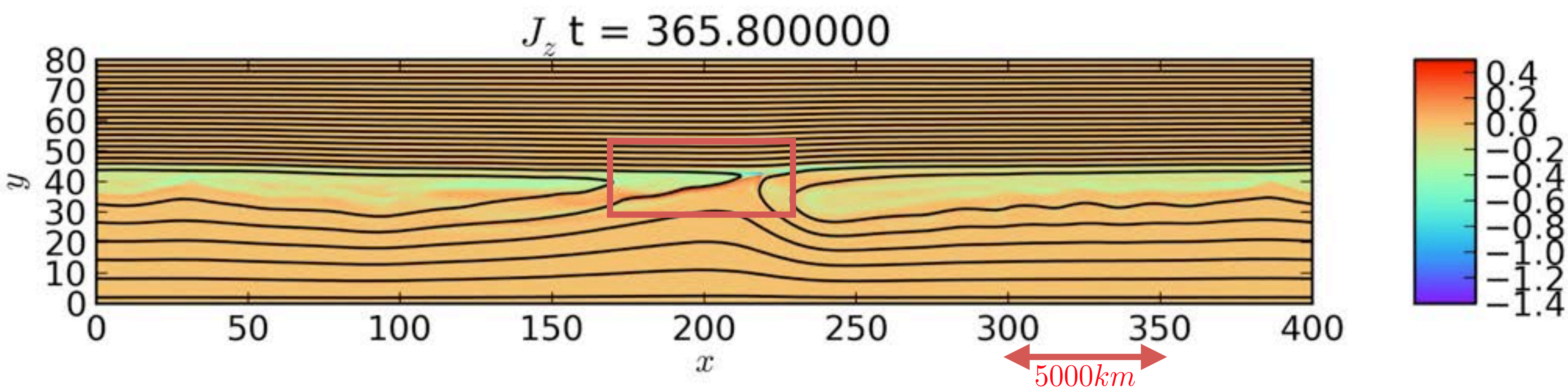
X LINE ORIENTATION Hybrid runs varying shear angles and asymmetry



simulation
plane
rotation

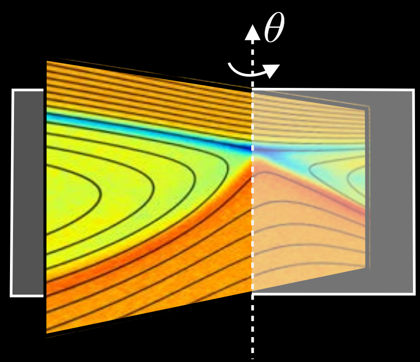
B shears, 90° and 130°
different asymmetry

[Aunai et al. 2016]



X LINE ORIENTATION

Hybrid runs varying shear angles and asymmetry

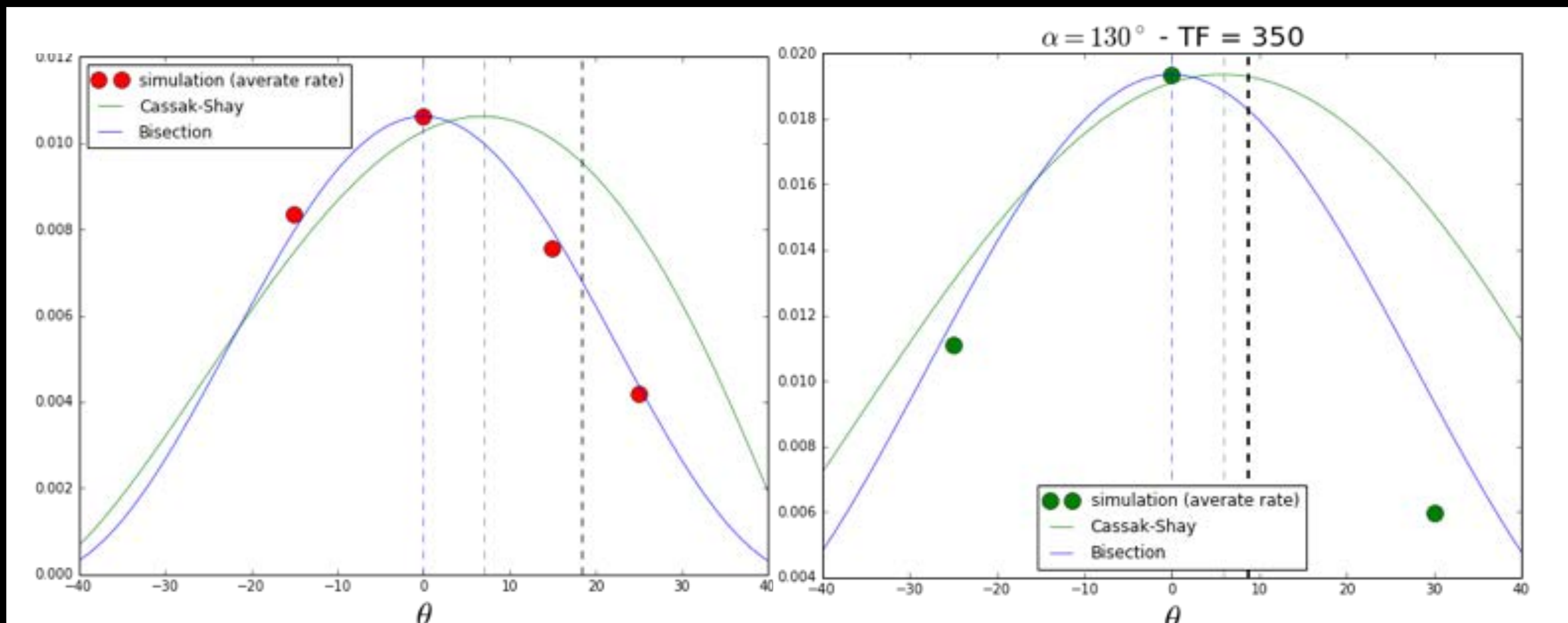


simulation plane rotation

B shears, 90° and 130°
different asymmetry

B shear 90°

B shear 130°

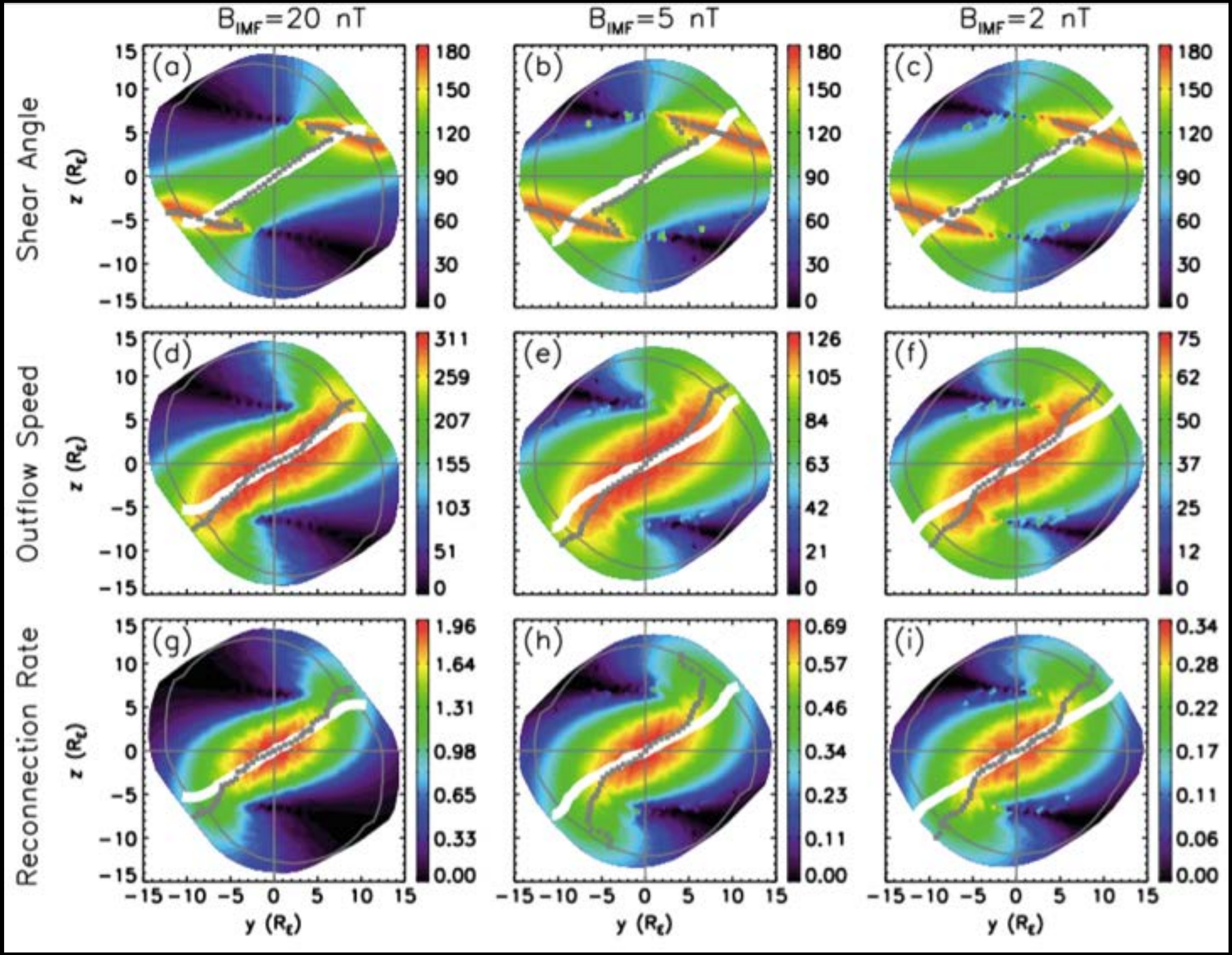


Reconnection rate as a function of the plane orientation

Bisecting upstream fields lead to faster rates

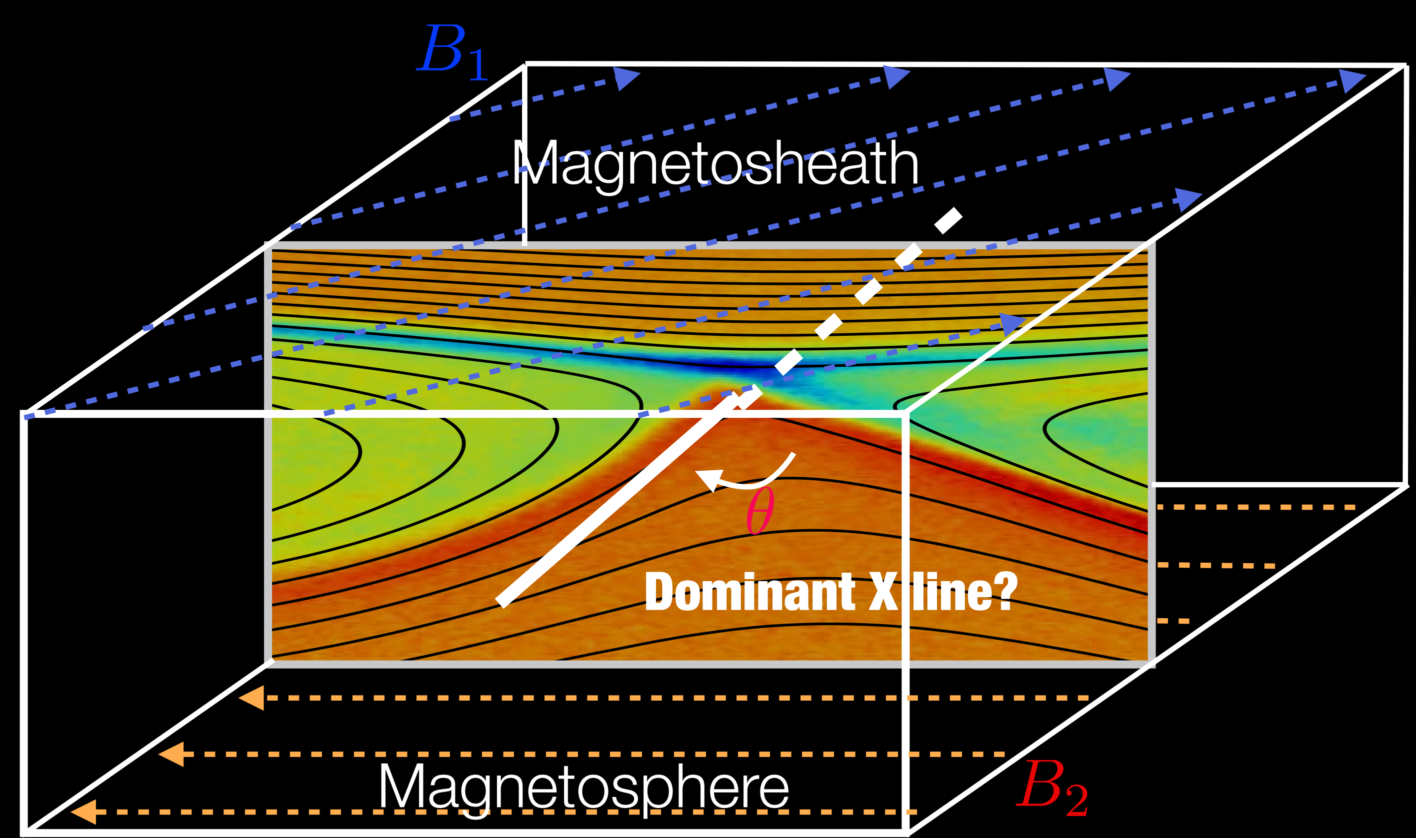
GLOBAL MHD

show very similar patterns for all predictions

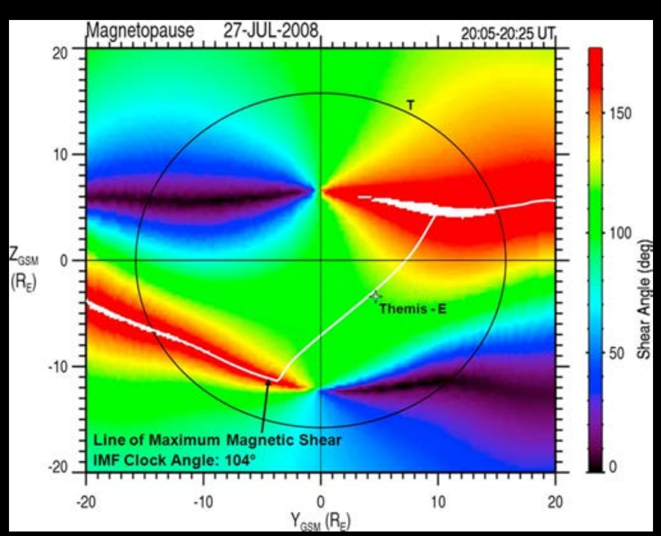


(Komar et al. 2015)

X-LINE ORIENTATION

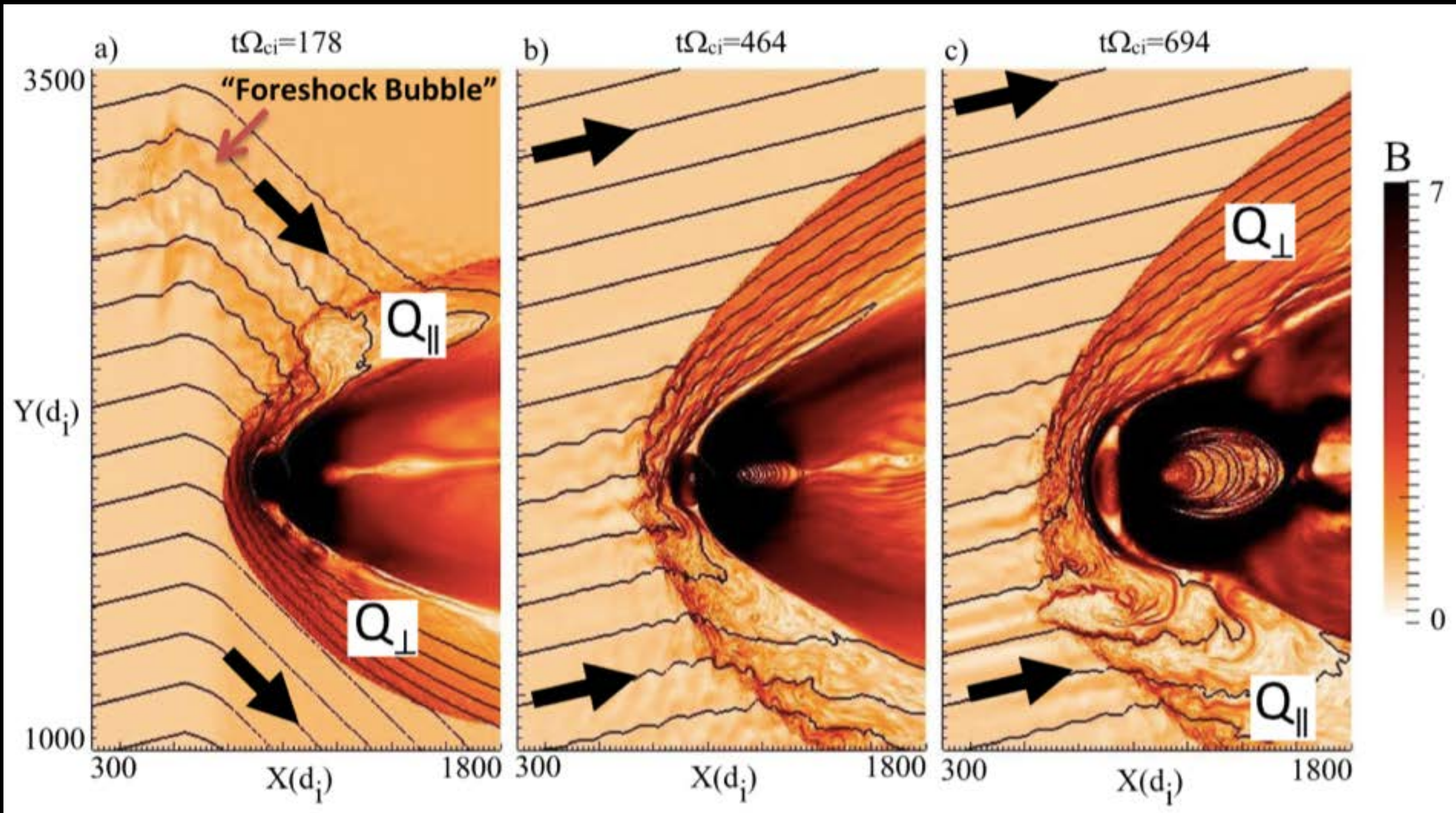


- Reconnection seems to orient itself along the bisector of upstream fields
- This seems to occur in 2D and 3D
- In linear tearing and nonlinear phase
- For different upstream (plasma and B) values
- For different shear angles



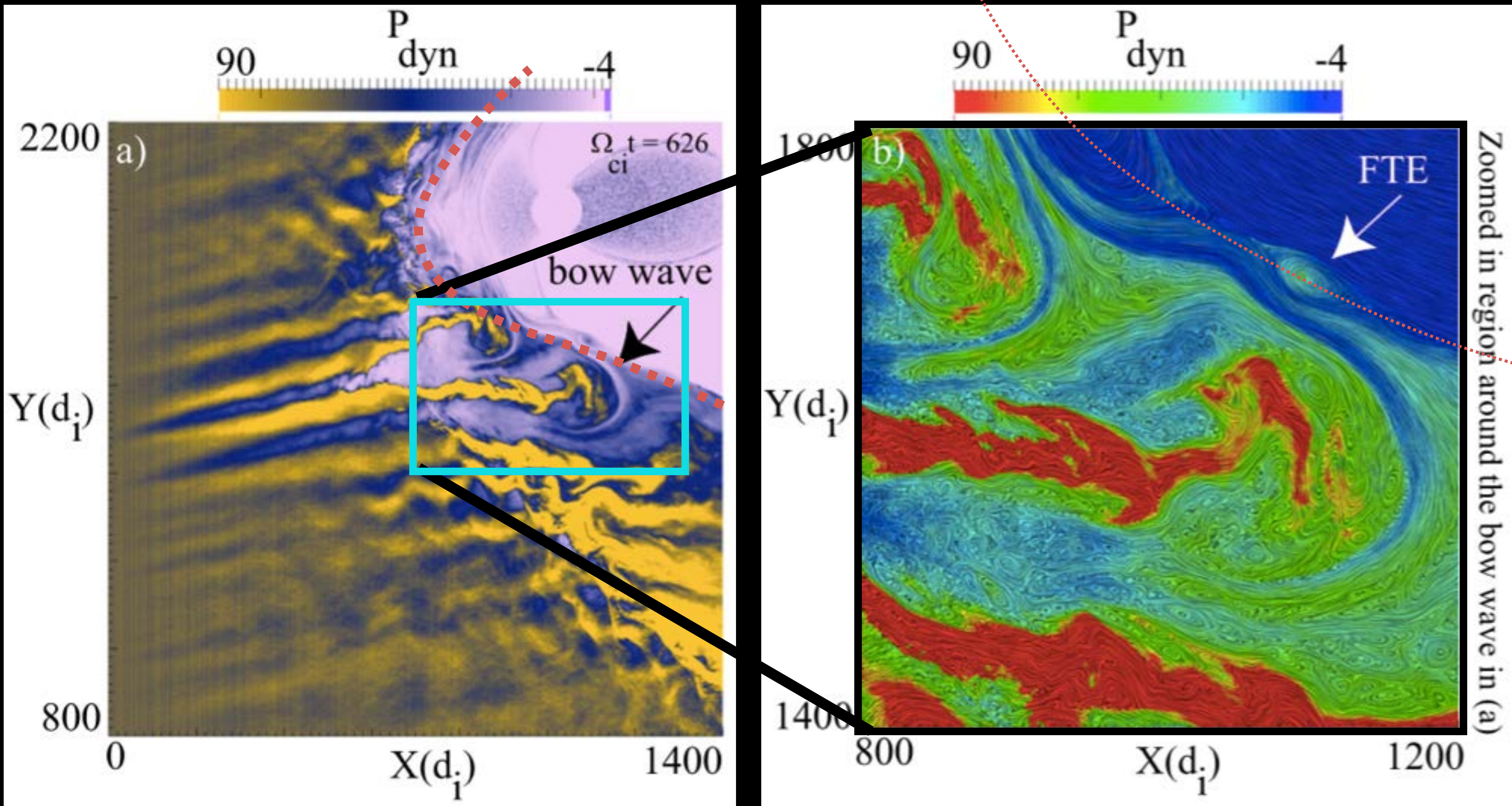
- Need to include geometry (3D)
- Need to study X line propagation
- Where does it start?

shock & reconnection



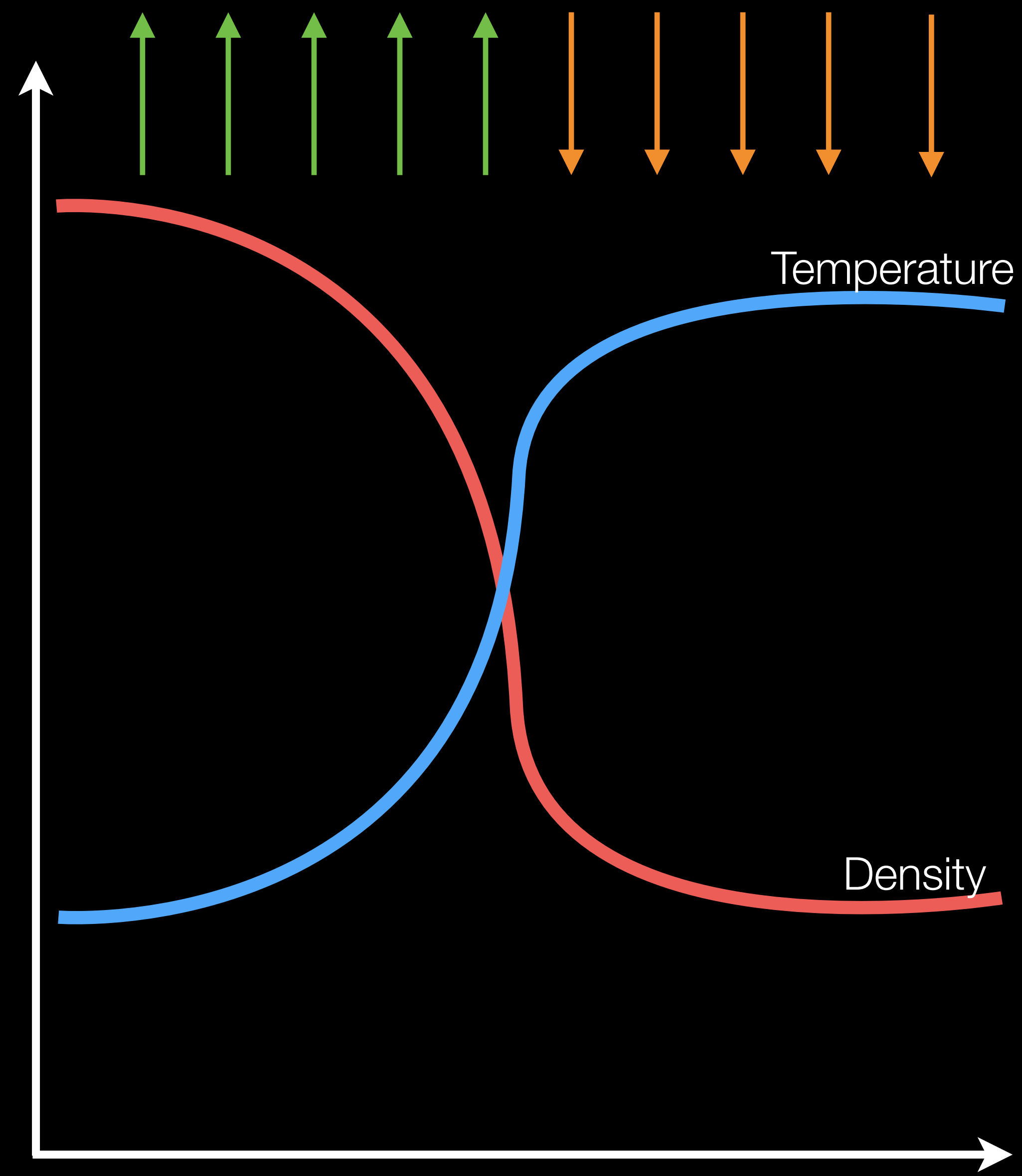
(Karimabadi et al. 2014)

shock & reconnection



(Karimabadi et al. 2014)

Tangential asymmetric equilibrium

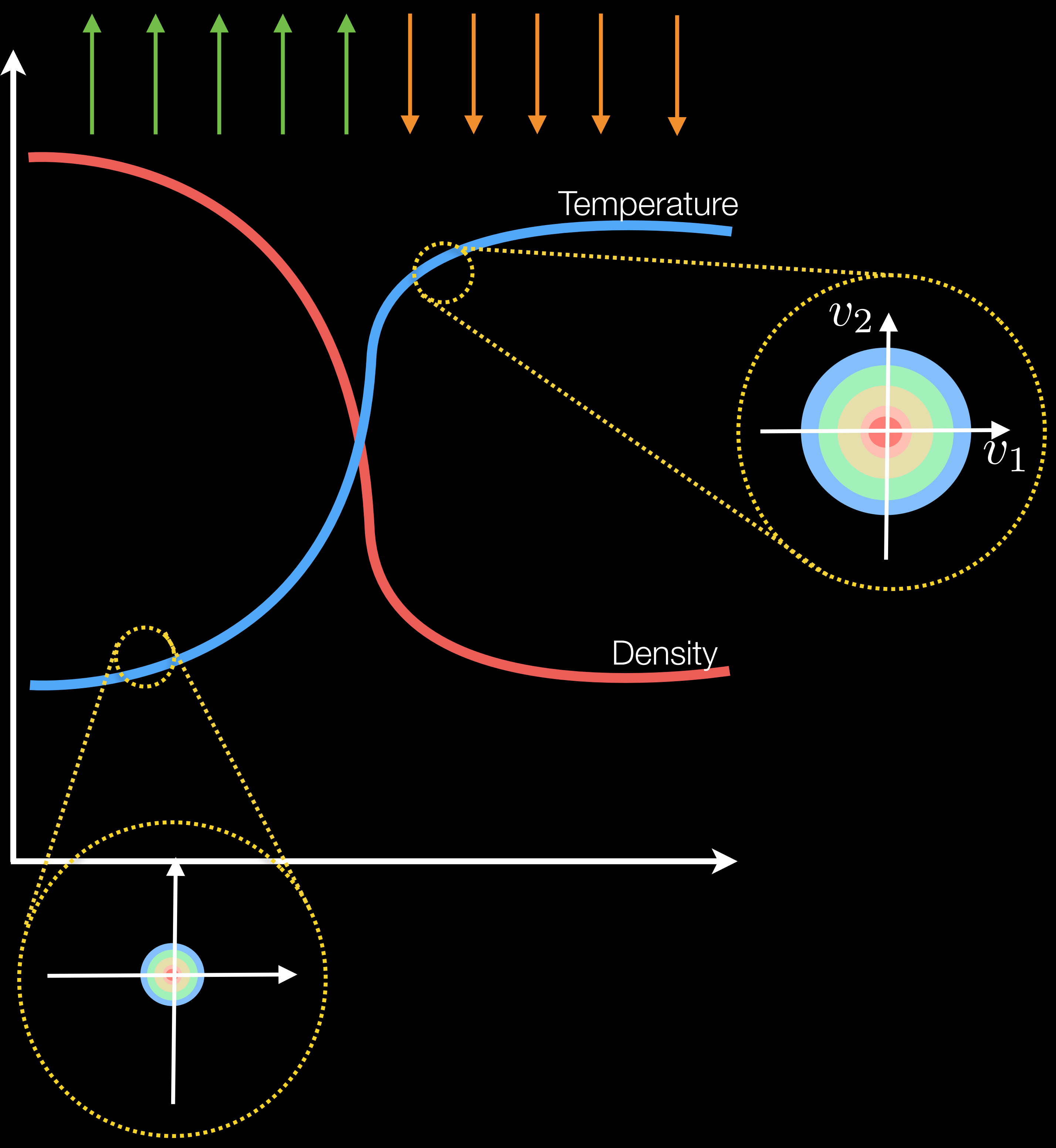


Forget the plasma is collisionless :

Find density, temperature and magnetic profiles satisfying the pressure balance condition

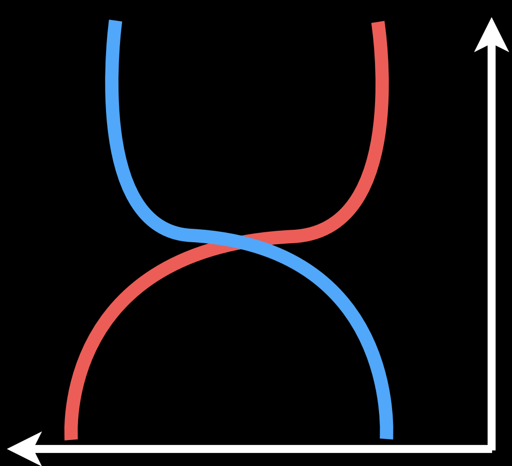
$$\partial_n \left(nkT + \frac{B^2}{2\mu_0} \right) = 0$$

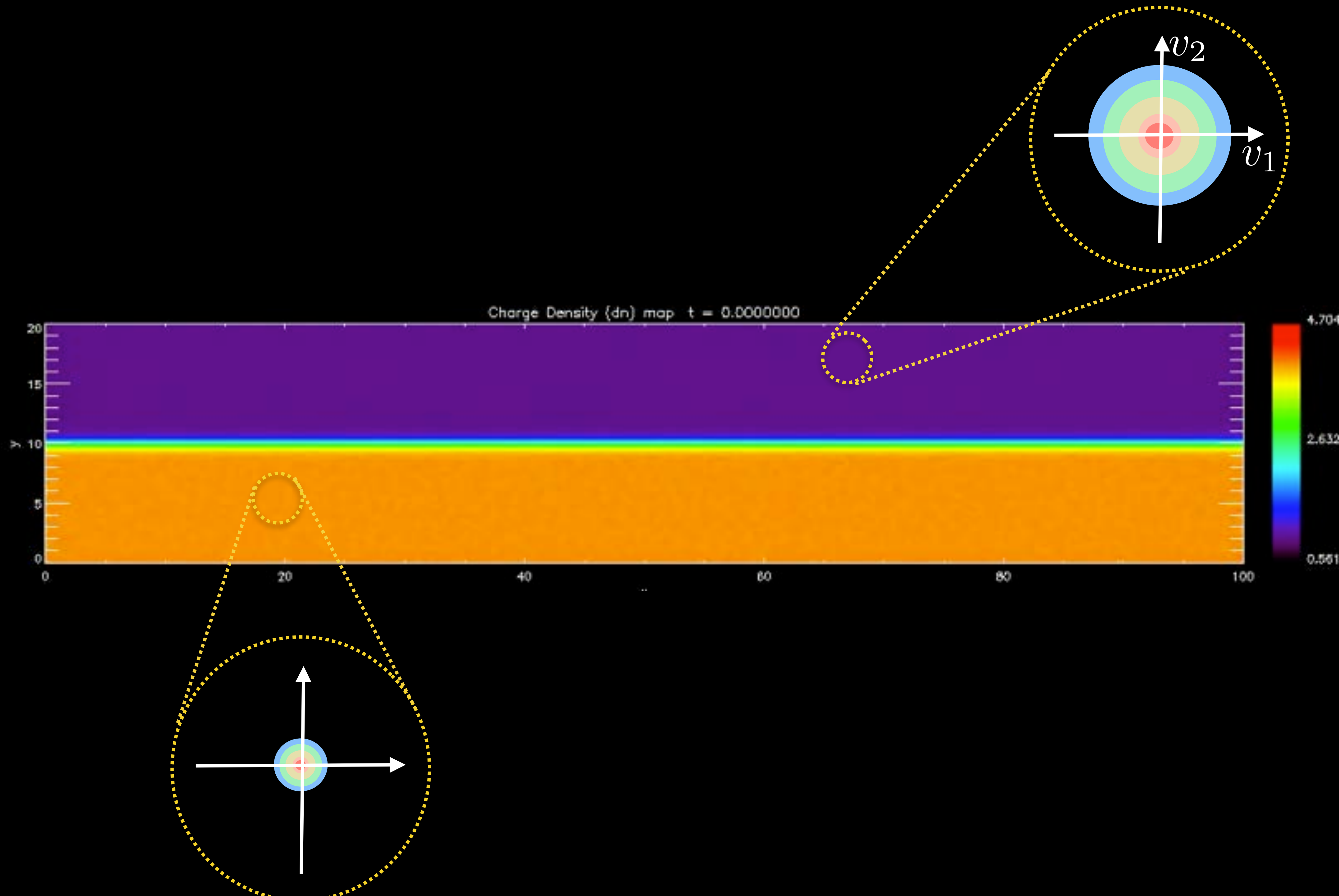
Tangential asymmetric equilibrium



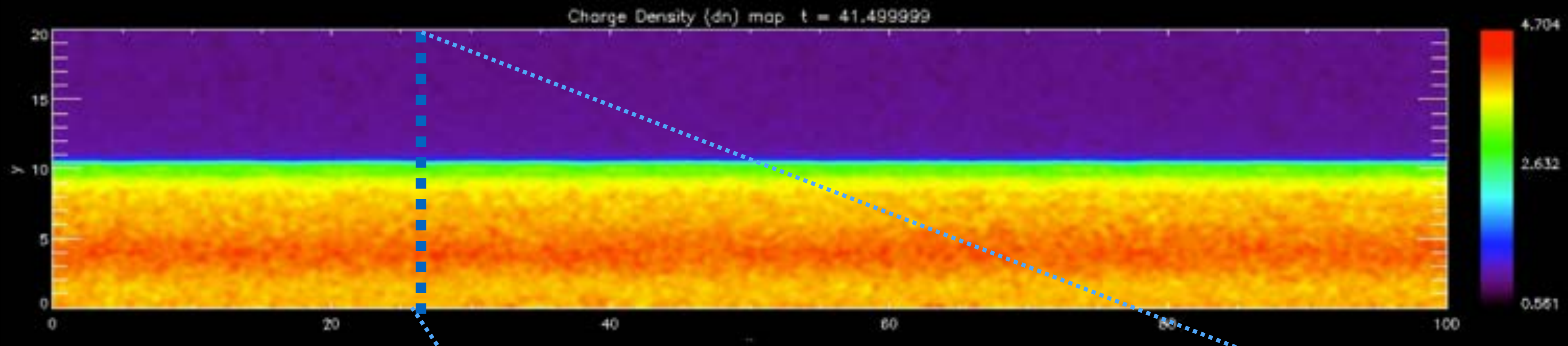
Assume the plasma is represented by locally Maxwellian distributions with appropriate moments n,v,T

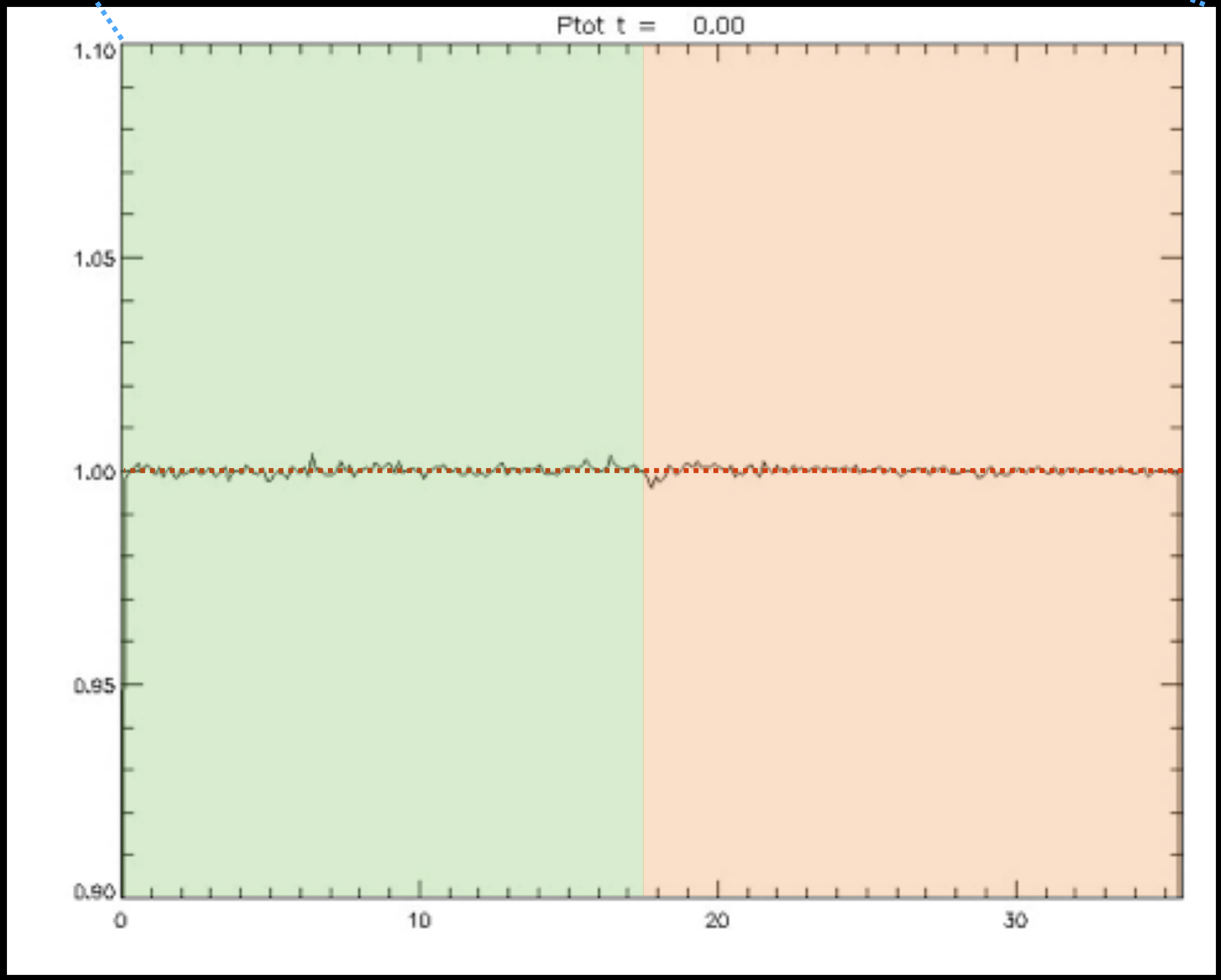
Tangential asymmetric equilibrium





Tangential asymmetric equilibrium





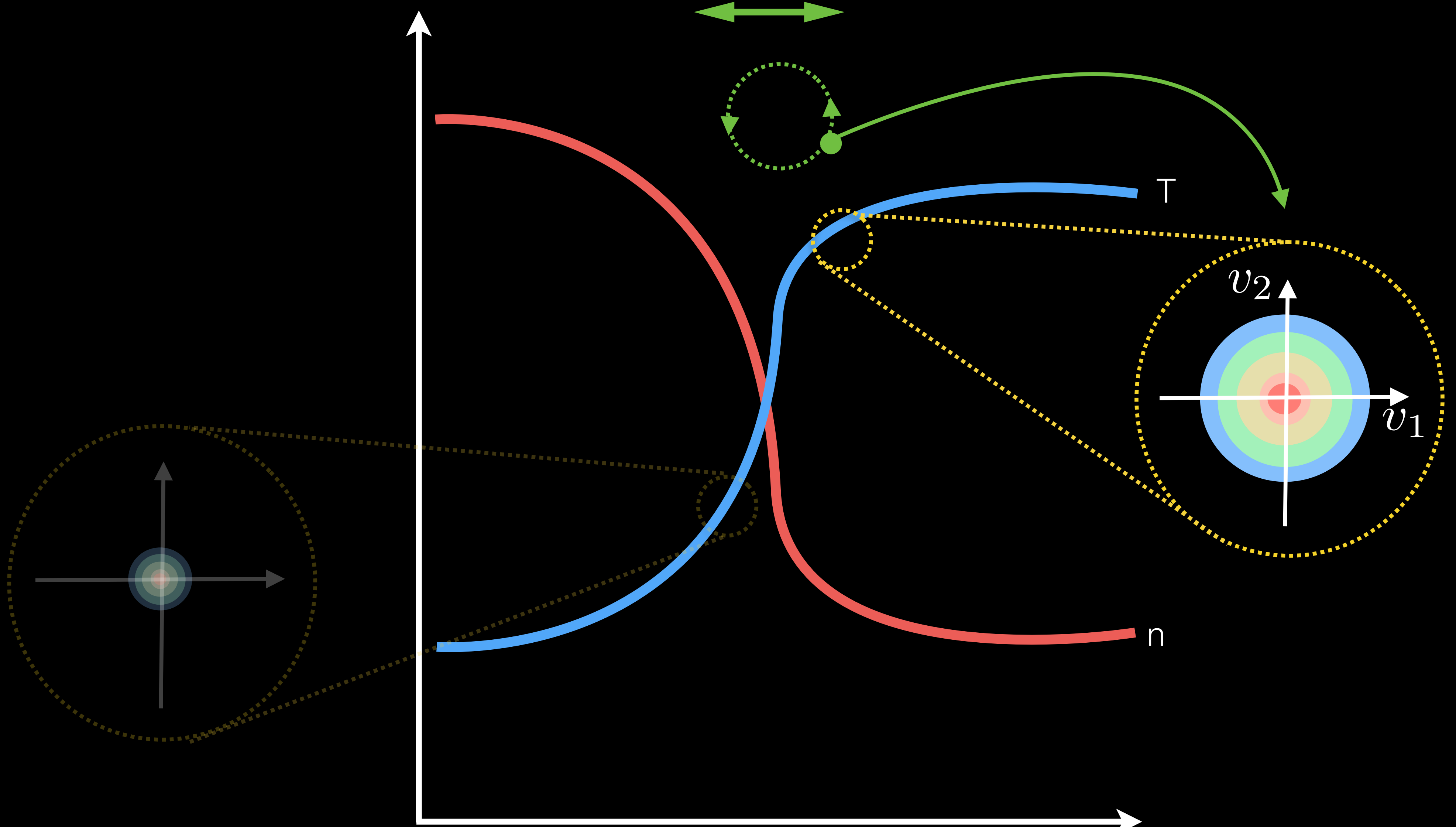
Not a steady state

Perturbation grows and propagate as a magnetosonic wave

$$nkT + \frac{B^2}{2\mu_0}$$

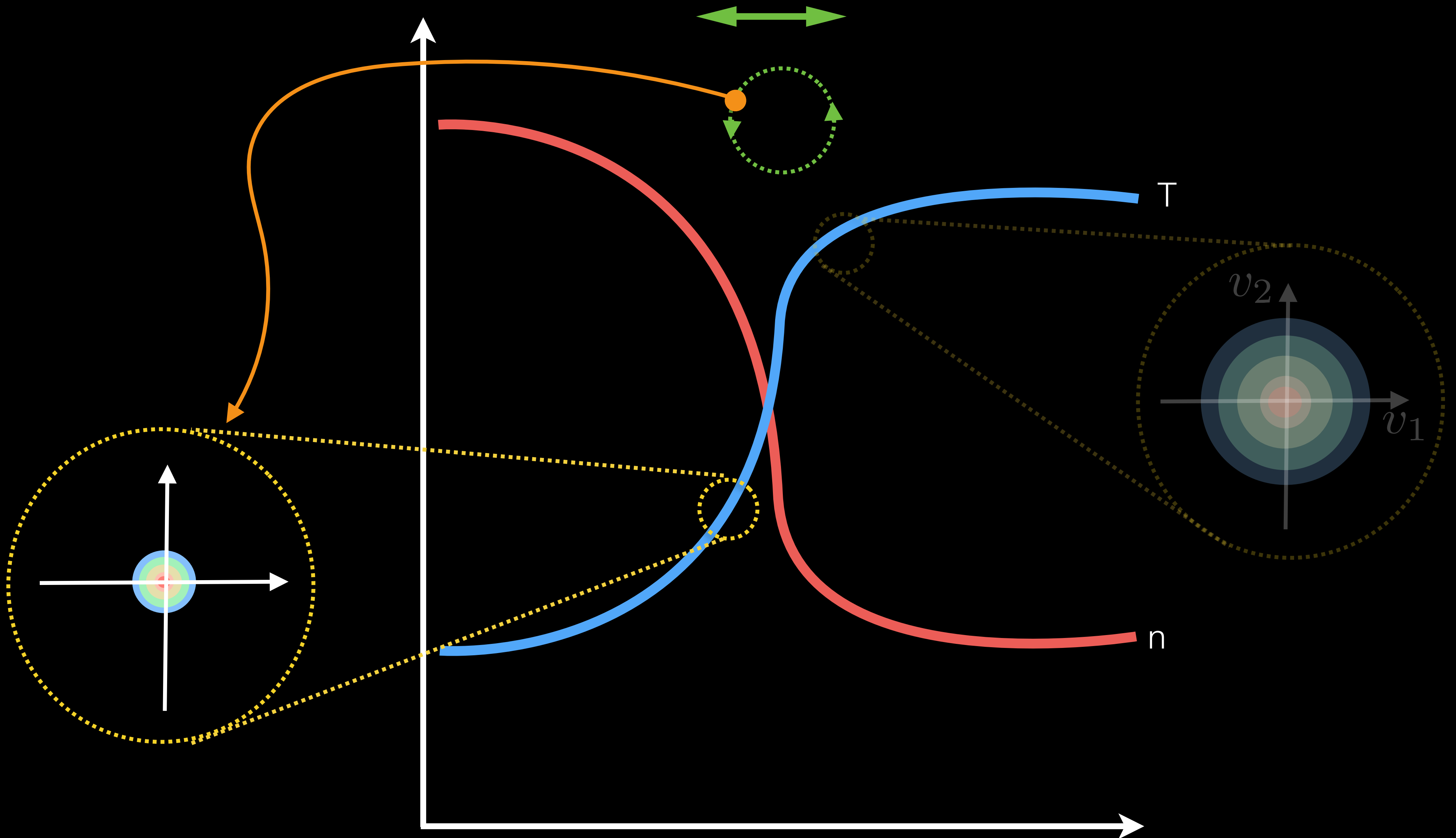
Where is the wave from?

t=0
This particle belongs to the RHS distribution

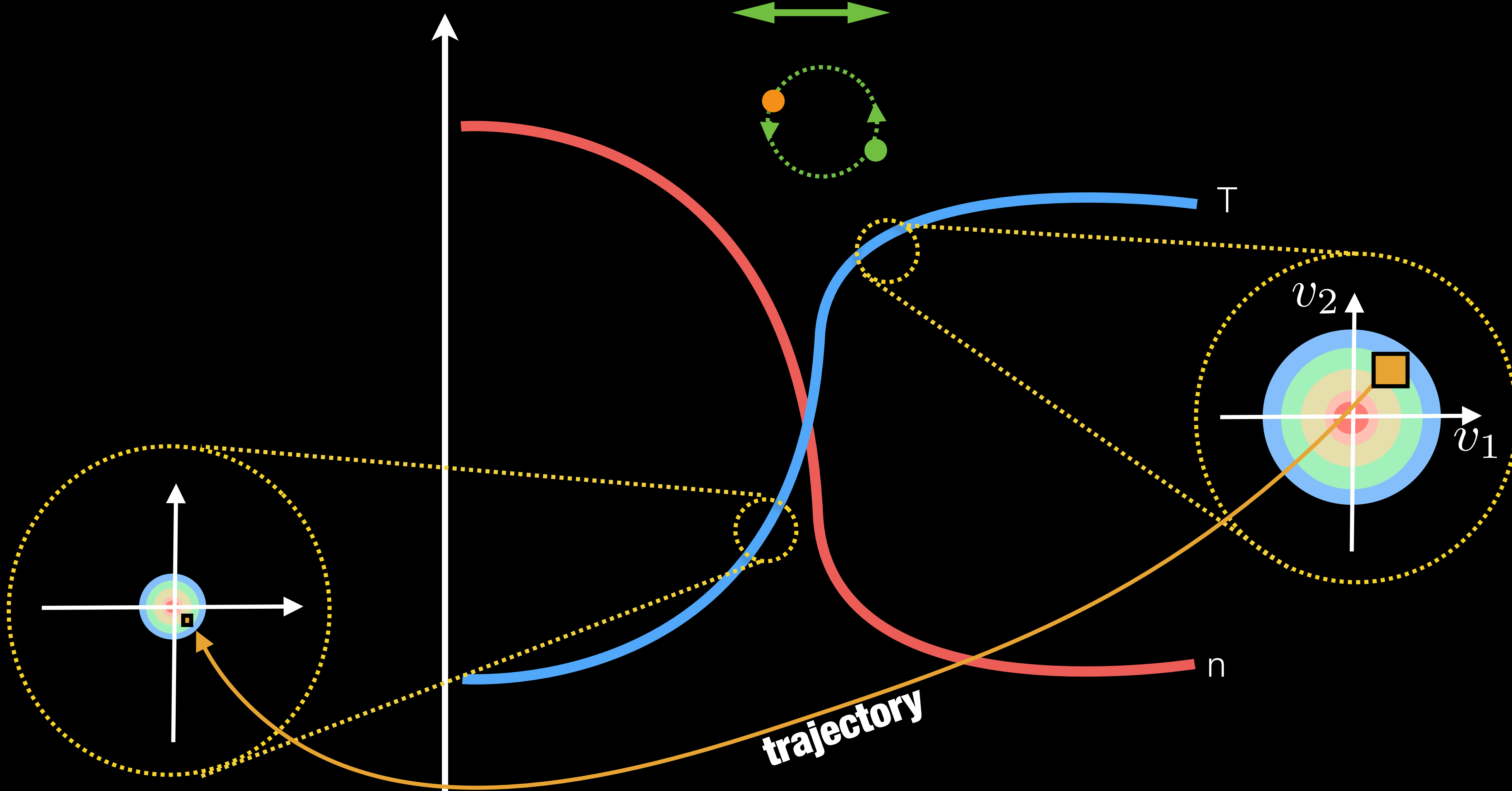


Where is the wave from?

t = dt
The particle now belongs
contributes to the LHS population



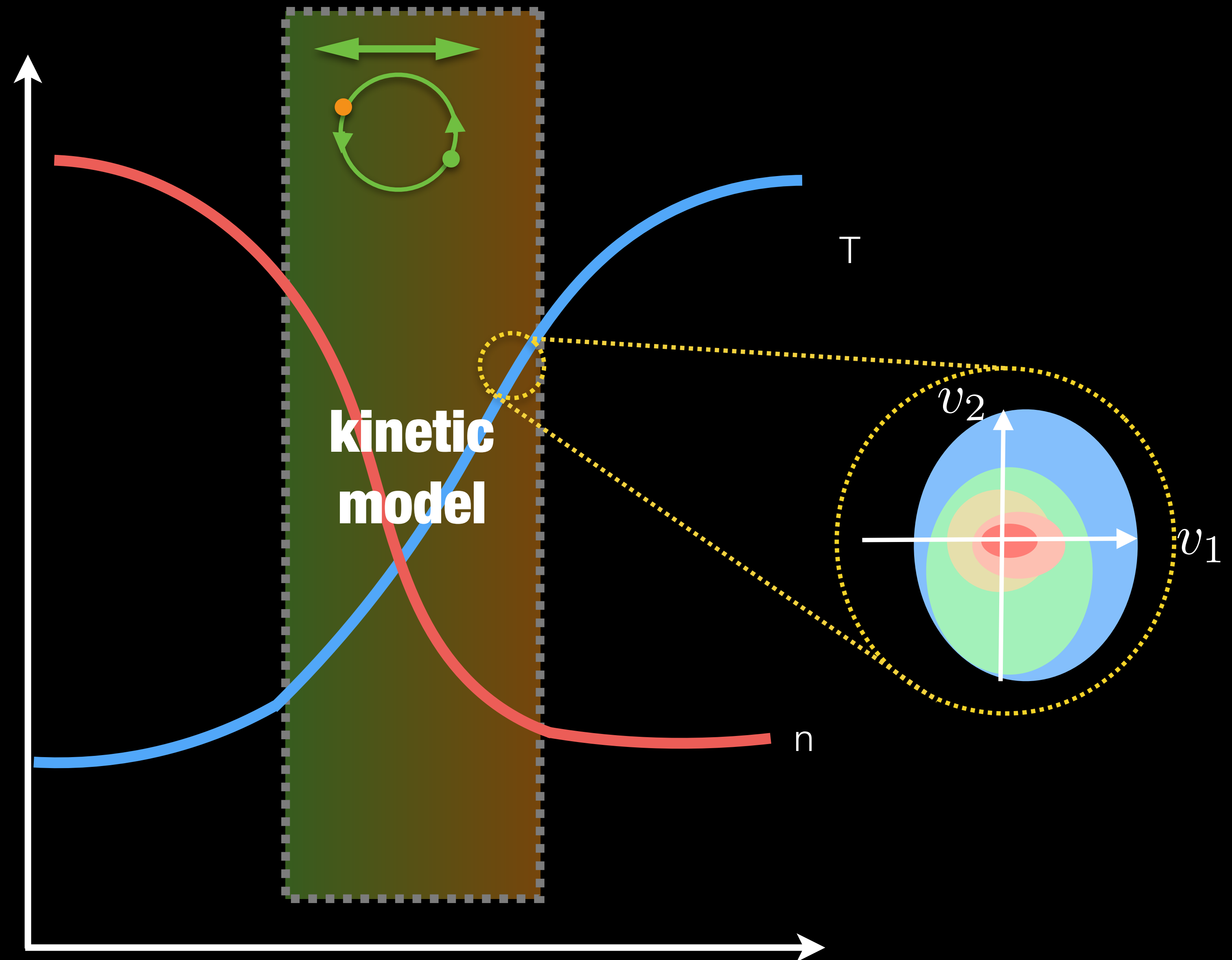
Where is the wave from?



$$\frac{\partial f}{\partial t} \neq 0$$

ANY local distribution will be perturbed by such Finite Larmor Radius effects in high gradient regions

We need a kinetic model

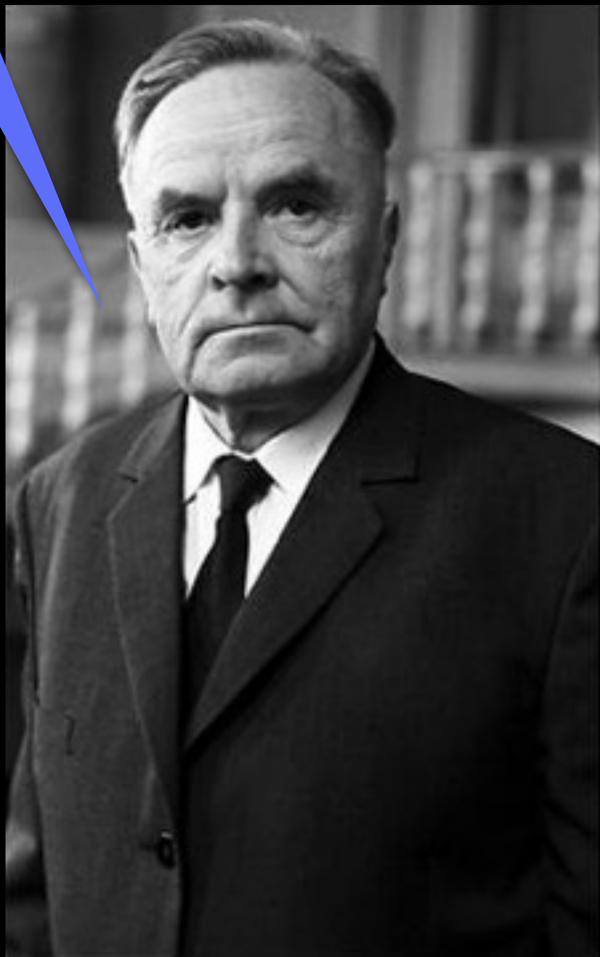


Find a kinetic equilibrium

$$\frac{dF(\mathbf{r},\mathbf{v},t)}{dt} = 0$$

K_i **constants of motion**

$$F\left(K_i\right) \longrightarrow \frac{\partial F}{\partial t} = 0$$



Find a kinetic equilibrium

1- choose reasonable form of distribution

2- inject its moments in maxwell's equations

$$\rho = \sum_s q_s \int F_s\left(\mathbf{v_s}, y\right) d\mathbf{v}$$

$$\mathbf{j} = \sum_s q_s \int \mathbf{v}_s F_s\left(\mathbf{v_s}, y\right) d\mathbf{v}$$

$$\nabla \cdot \mathbf{E} = \rho/\epsilon_0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

$$\partial_t \mathbf{E} = c^2\left(\nabla \times \mathbf{B} - \mu_0 \mathbf{j}\right)$$

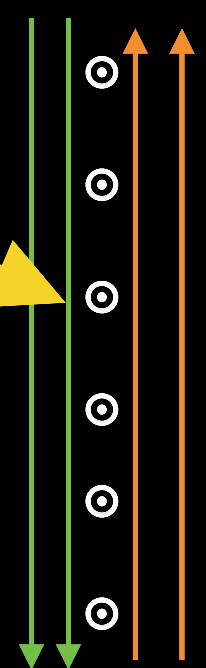
$$\frac{dF(\mathbf{r}, \mathbf{v}, t)}{dt} = 0$$

K_i constants of motion

$$F\left(K_i\right) \rightarrow \frac{\partial F}{\partial t} = 0$$

Non-trivial relationship

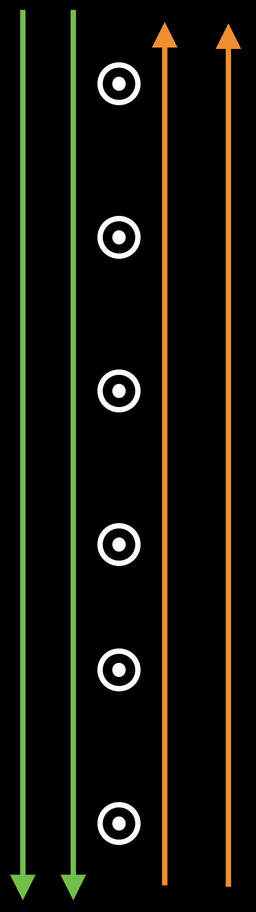
?? F(K) ??



Different approach : prescribe the fields you want !

Quick overview - see G. Belmont's talk tomorrow for more details

$$B(y) = \tanh(y)$$



and assume E=0
(because it's easier)

We assume a fraction of the current and pressure is supported by the electrons.

We search for a steady ion distribution within this context

We need multi-valued distribution functions!

Quick overview - see G. Belmont's talk tomorrow for more details

As we move along 'y' new particles appear in the distribution...

A particle located at the position y

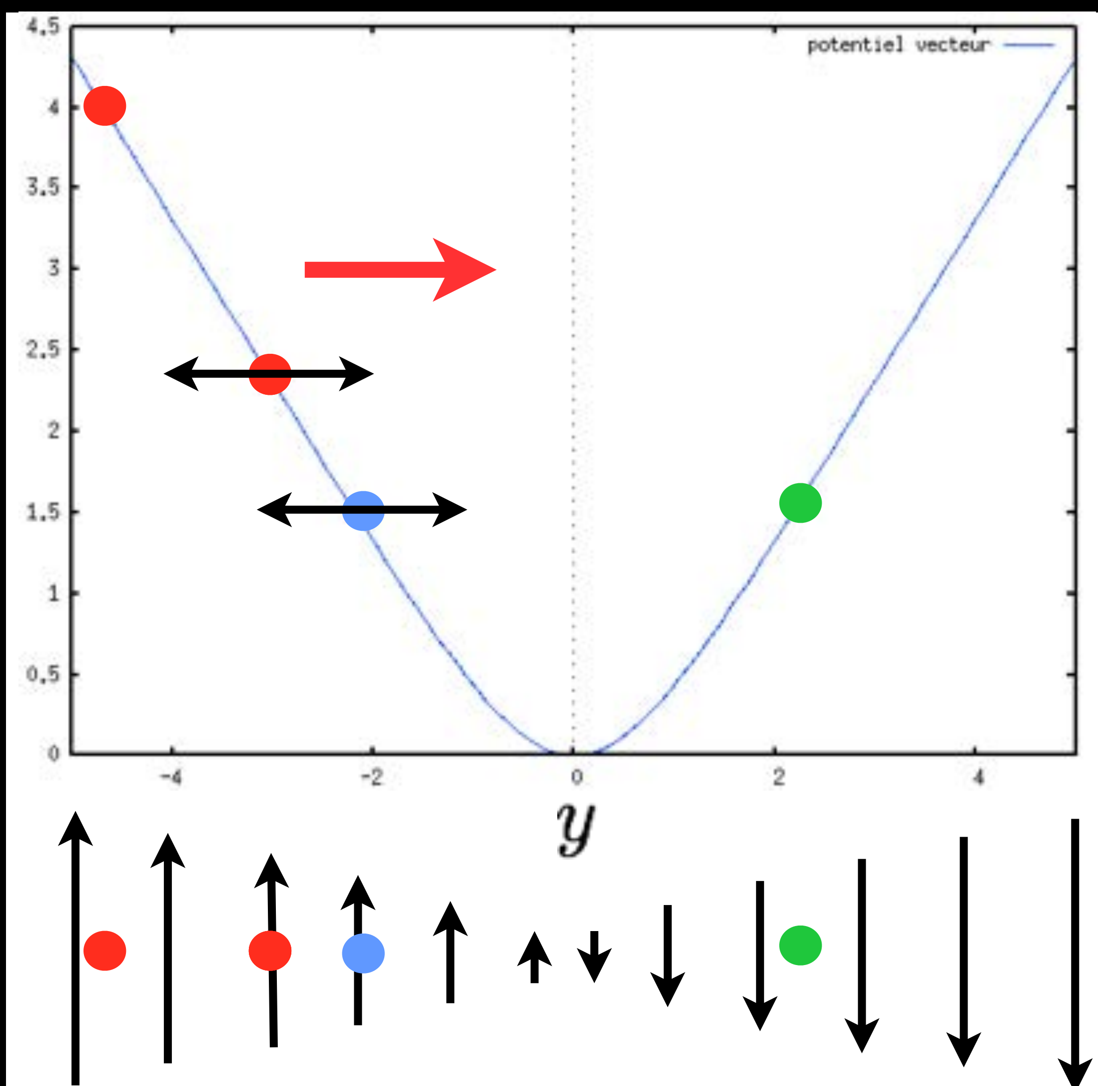
Monotonic variation of y...

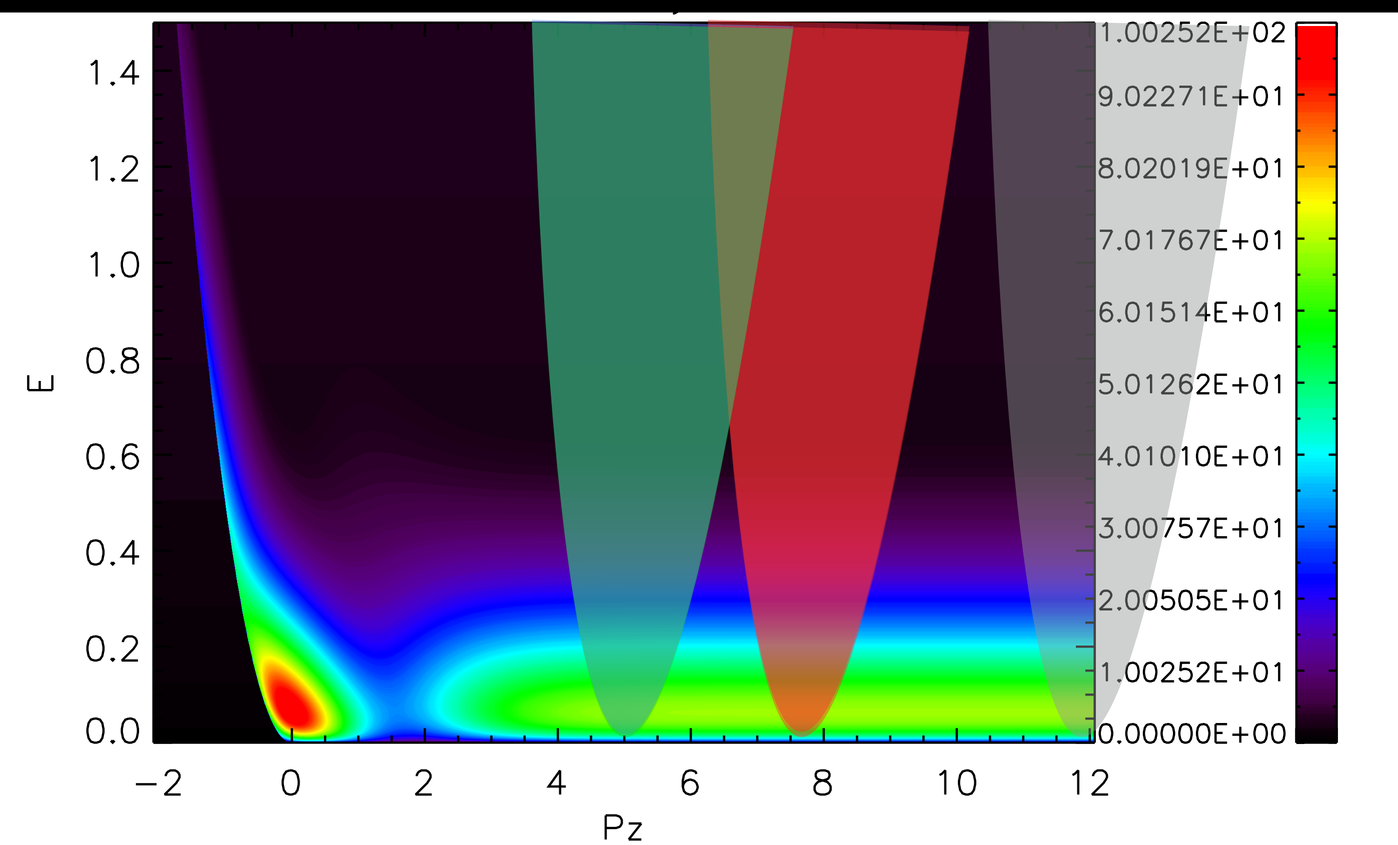
...they left behind as we move further...

Is inside the parabola $E \geq \frac{(P_z - A_z(y))^2}{2m}$ in (E,P)

is a U-turn in (E,P) !

... and thus have **no reason to be the same** after the U-turn (on the other side)





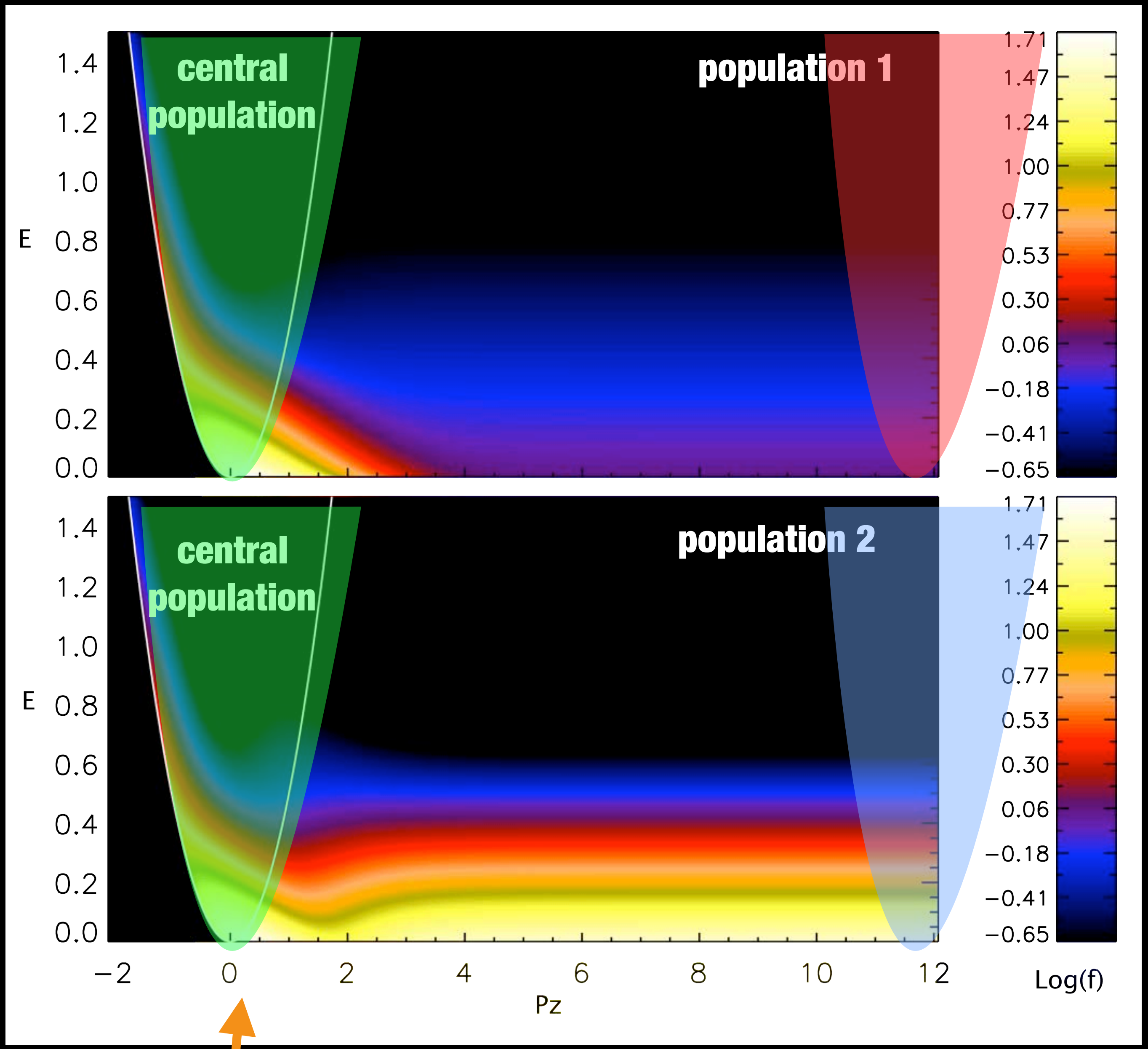
Symmetric solution if unique F explains why all previous solutions are symmetric (e.g. famous Harris sheet)

Particles on one side DO NOT ACCESS the distribution on the OTHER SIDE !

(assuming no particles with infinite energy)

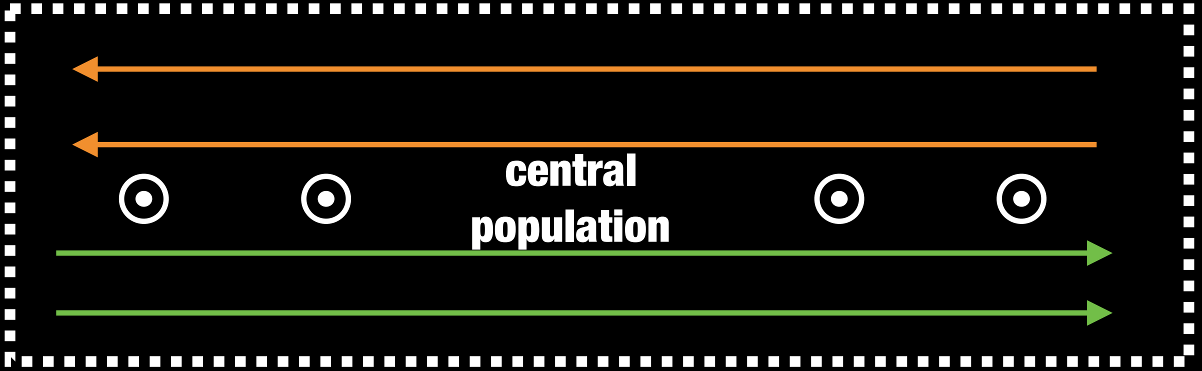
We need multi-valued distribution functions!

Quick overview - see G. Belmont's talk tomorrow for more details



Local parity of the solution

$$F_1 \rightarrow M_1(n_1, T_1)$$

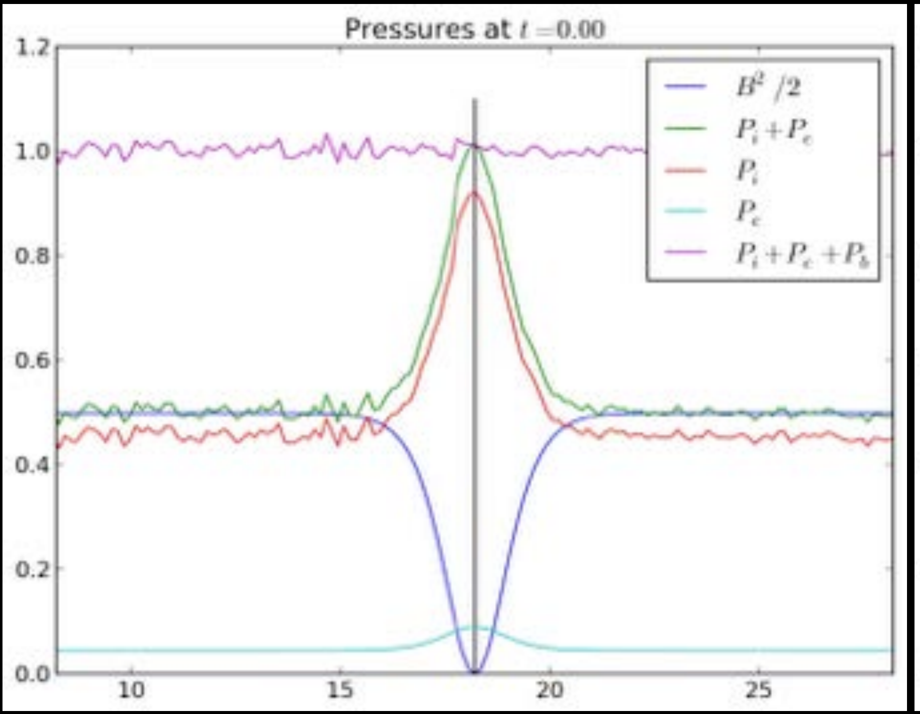


$$F_2 \rightarrow M_2(n_2, T_2)$$

Test the theory

Run A

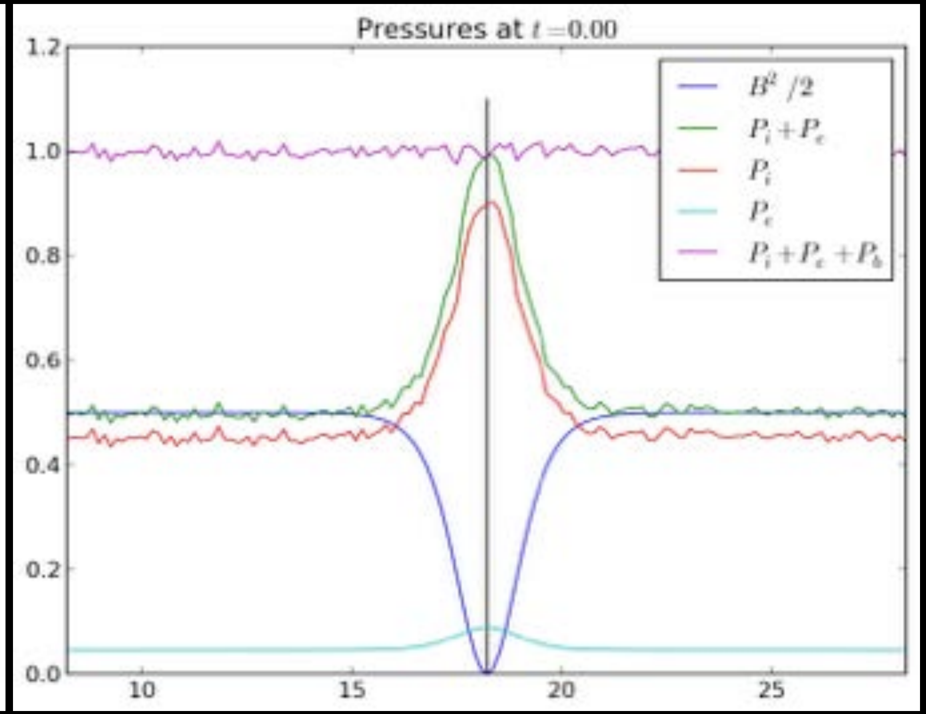
Pressure balance
locally Maxwellian



Very unsteady (we knew already)

Run B

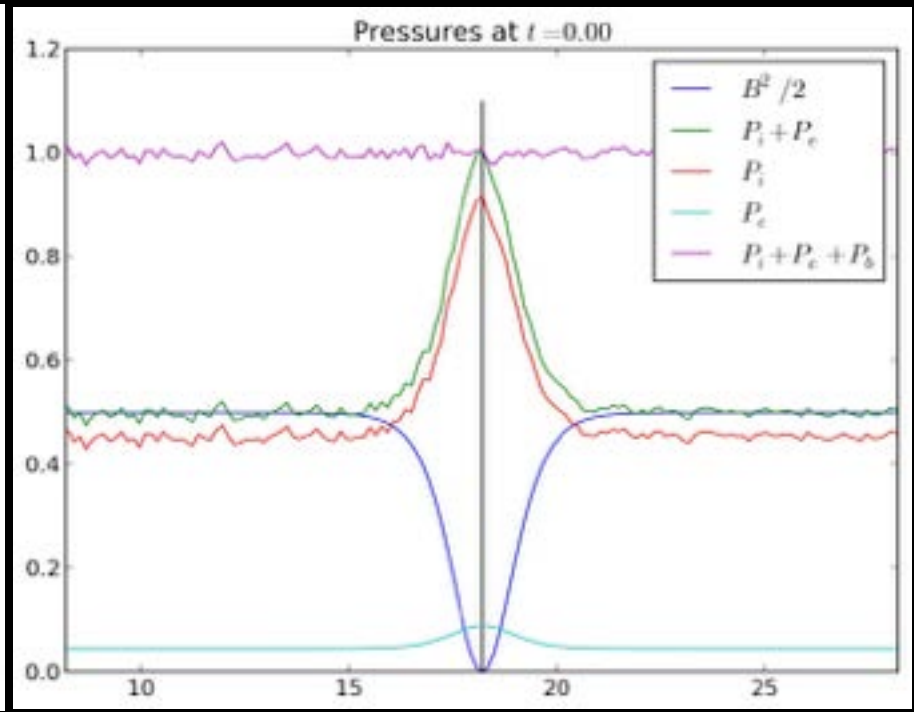
Kinetic equilibrium



Steady state (we hoped !)

Run C

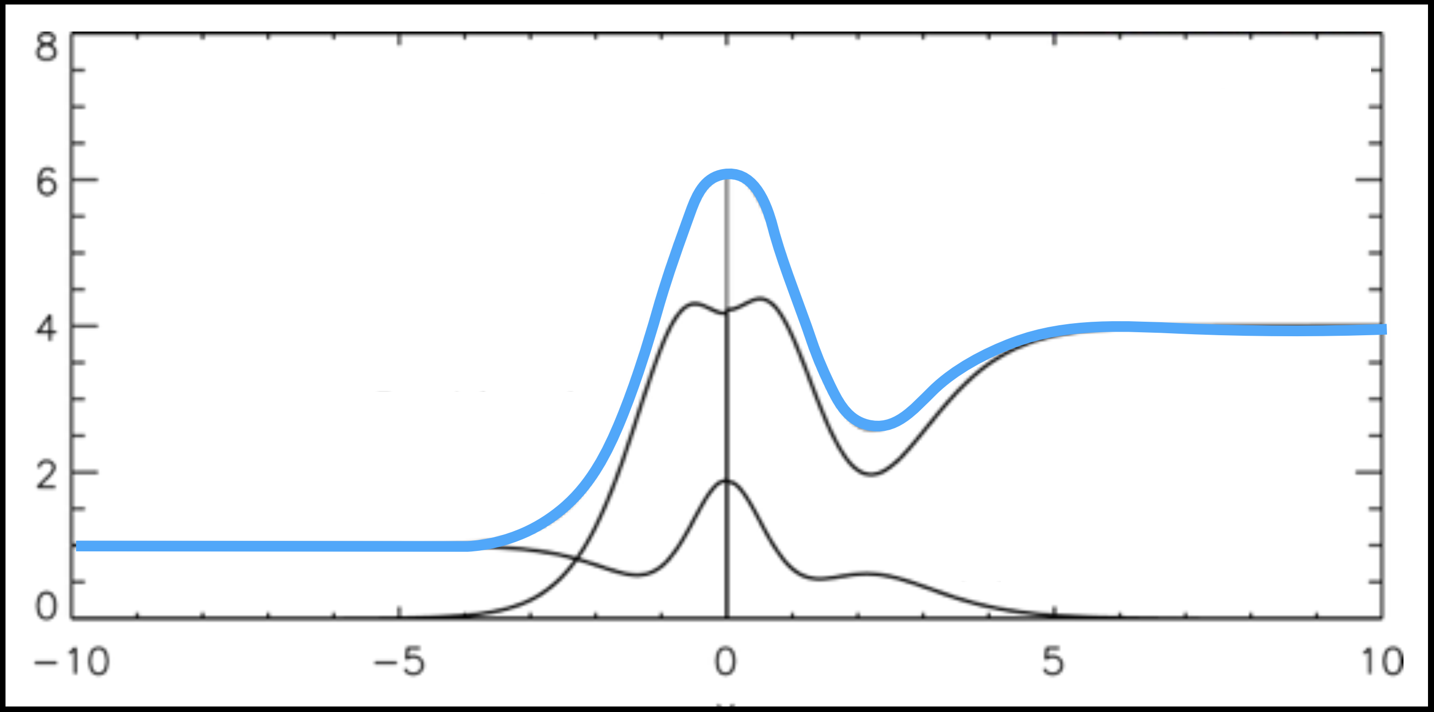
3 moments from the kinetic eq.
+ Locally Maxwellian



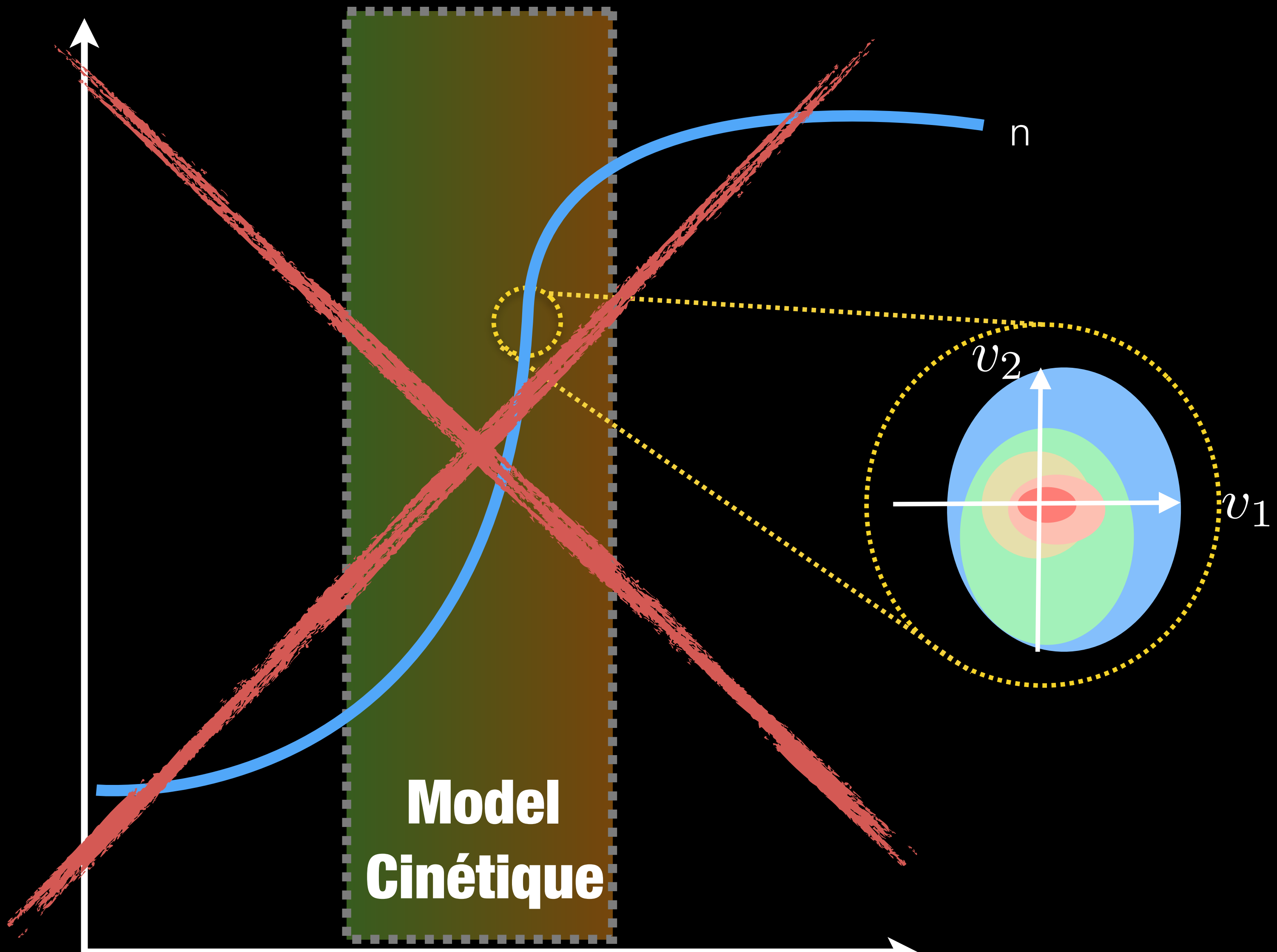
Less unsteady than with arbitrary moments

One needs to know the full F

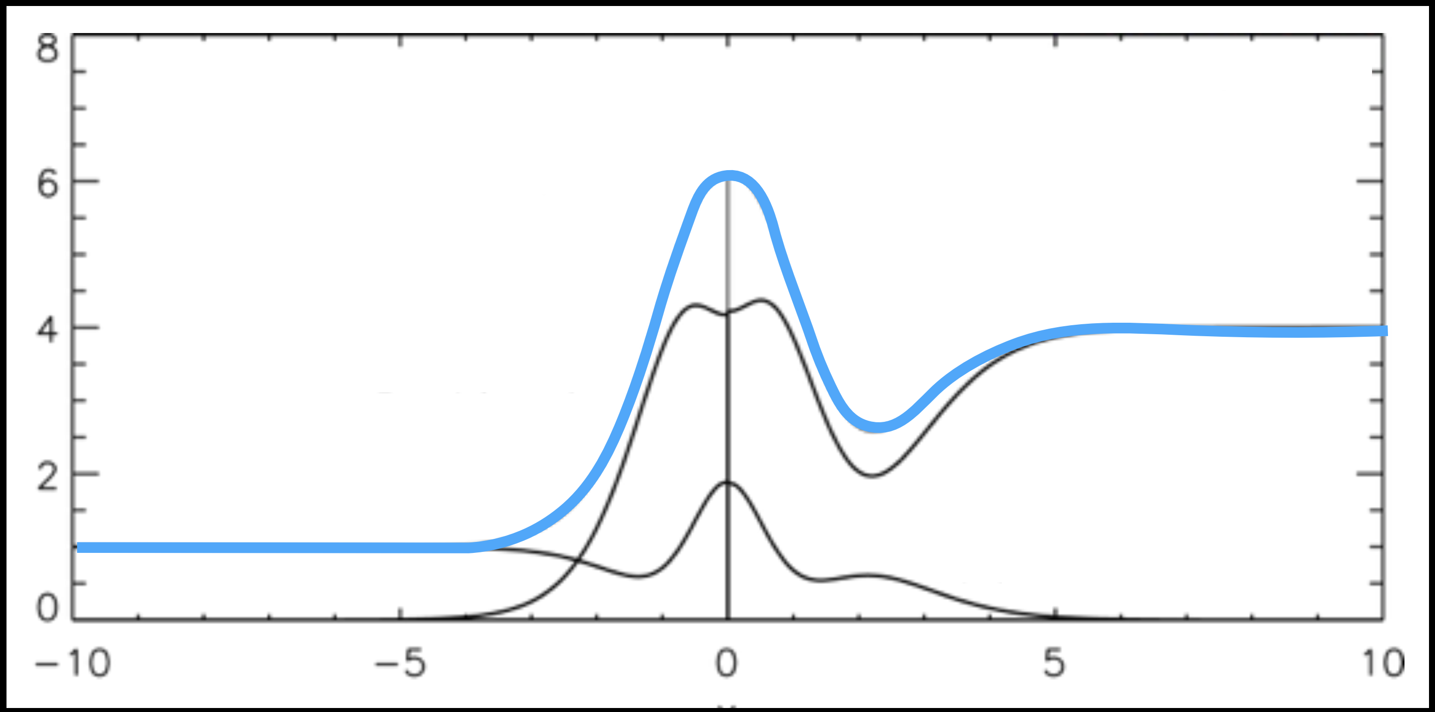
solution density profile



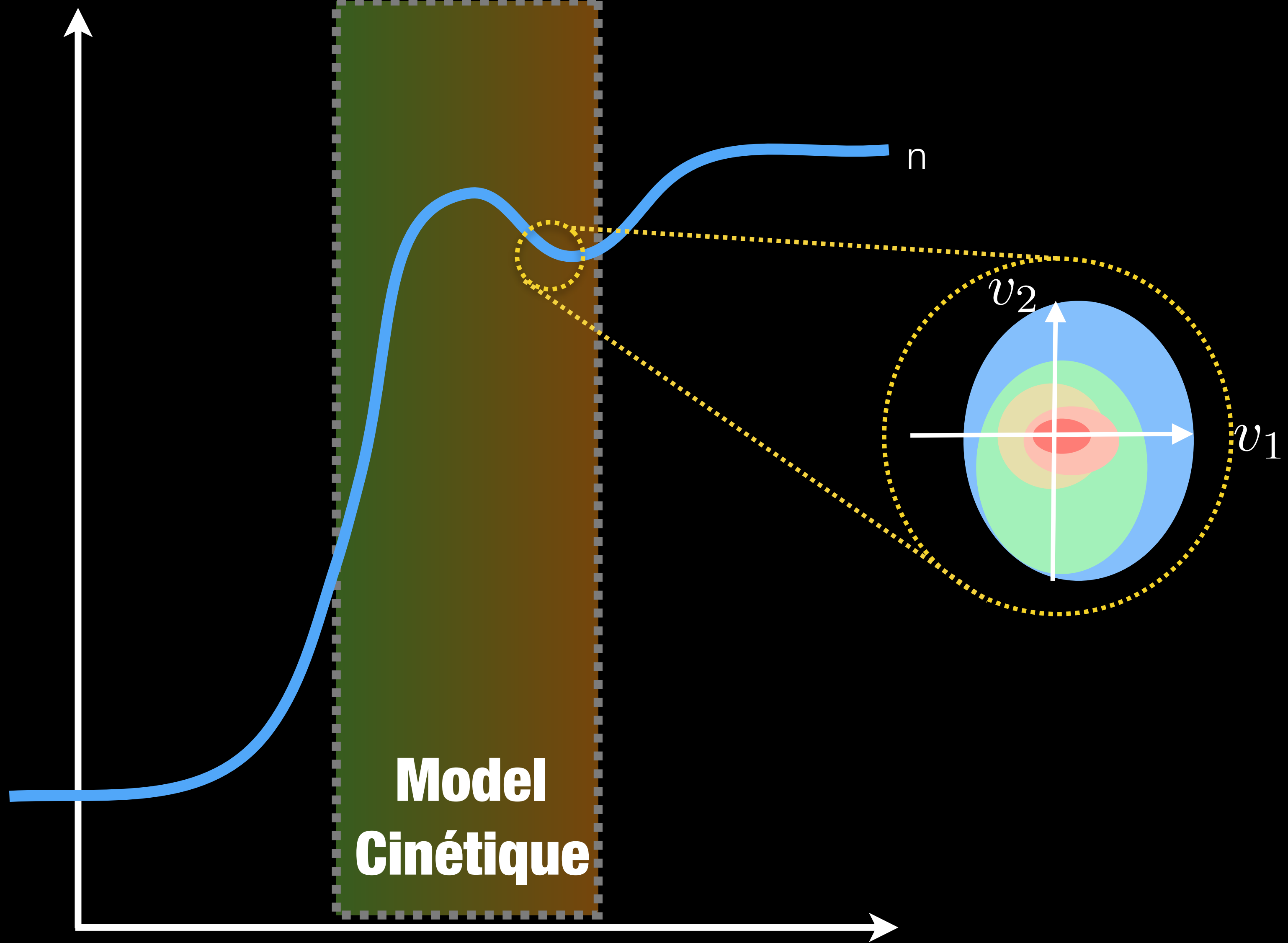
Total density



solution density profile



Total density



Role of the electrons? Test with full PIC code

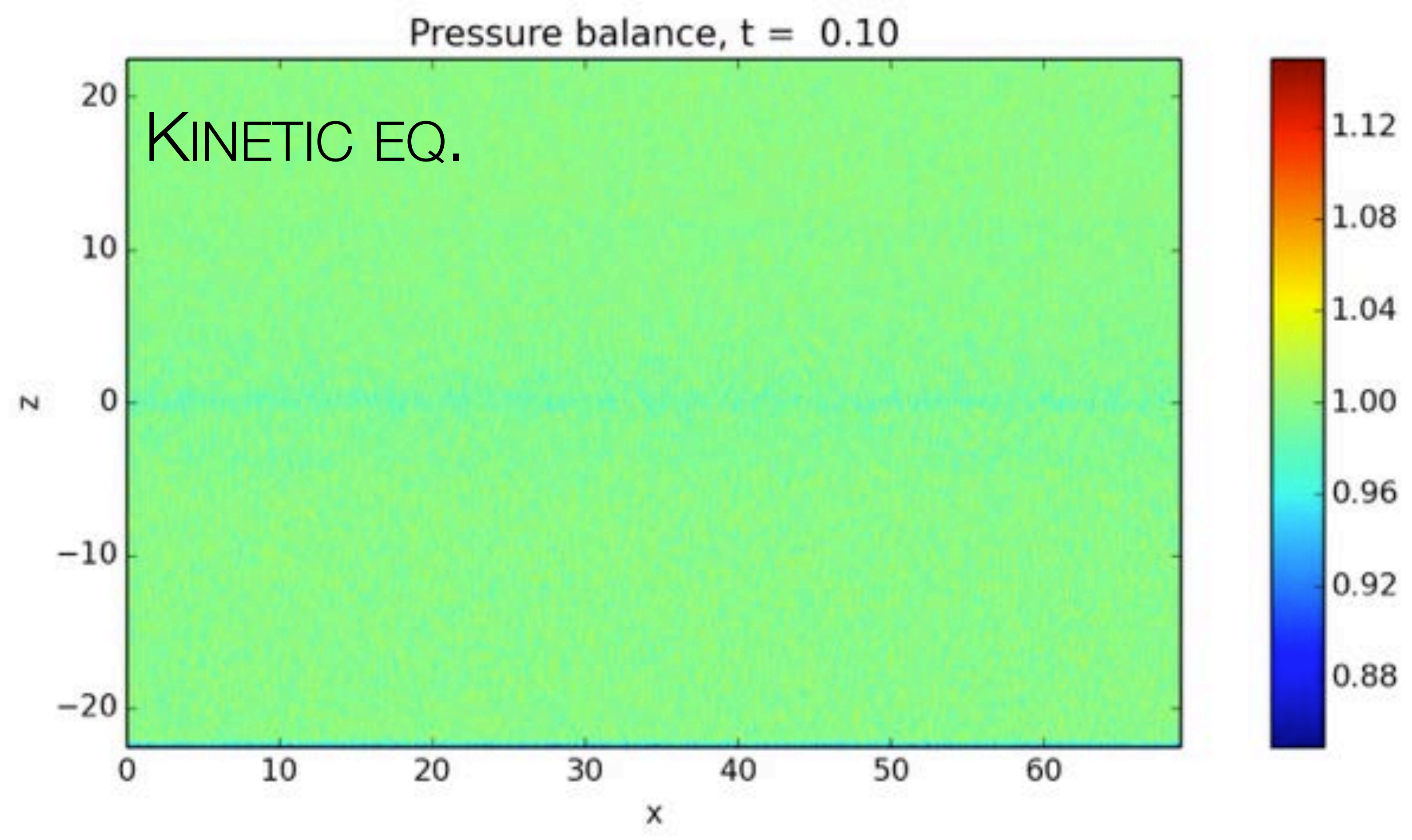
[Dargent et al. 2016]

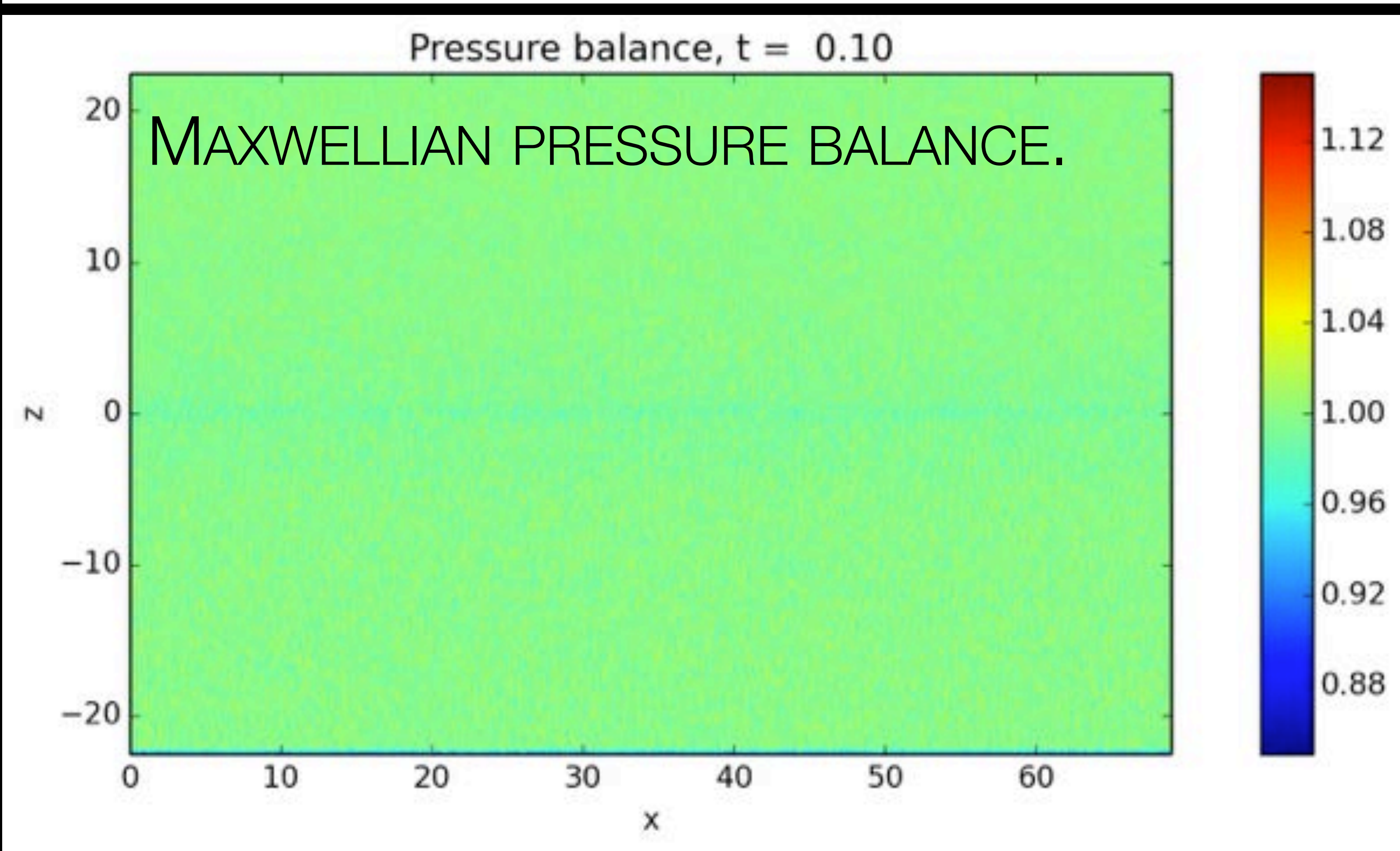
Kinetic solution for the ions

Assume isotropic maxwellian electrons

Electrons **do not** perturb the pressure balance

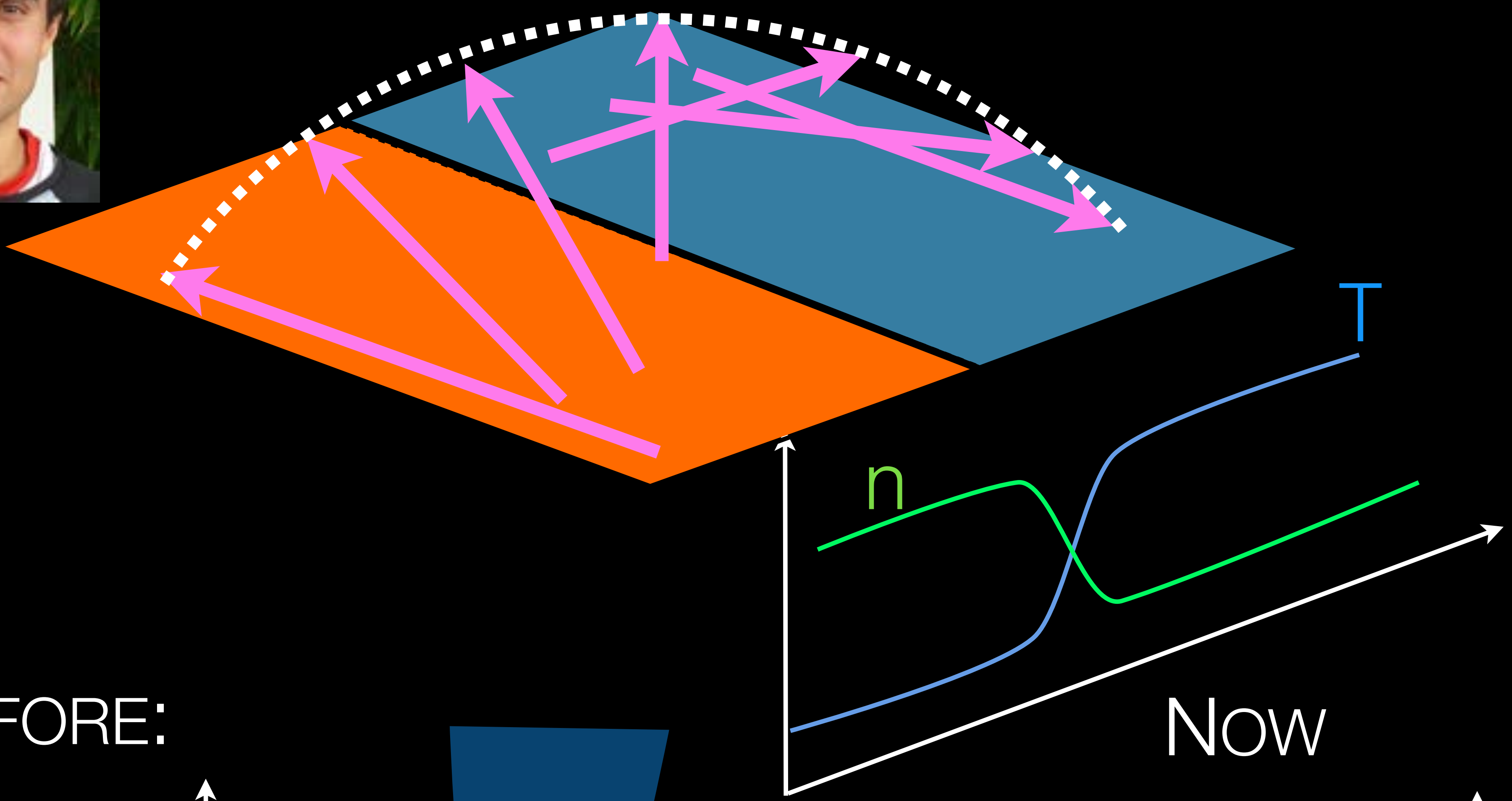
Deviations from the initial condition remain within the electron bounce width

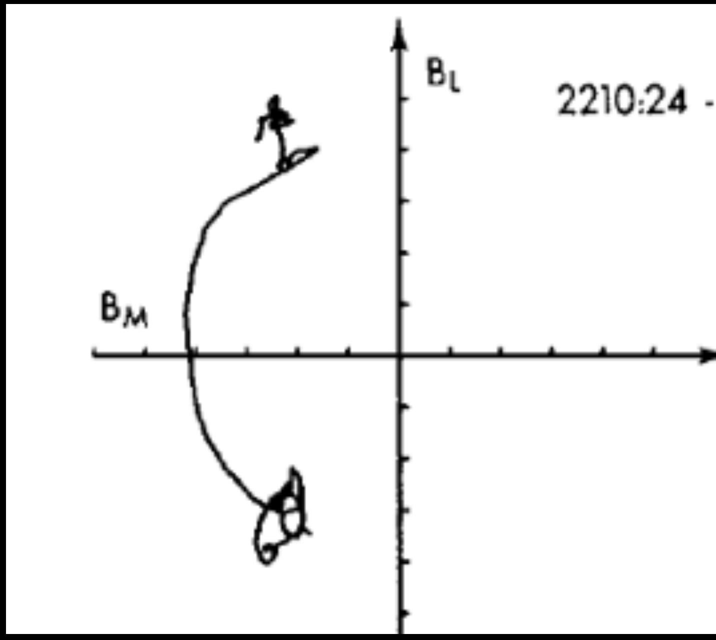




Generalizing to more realistic magnetopause-like layers

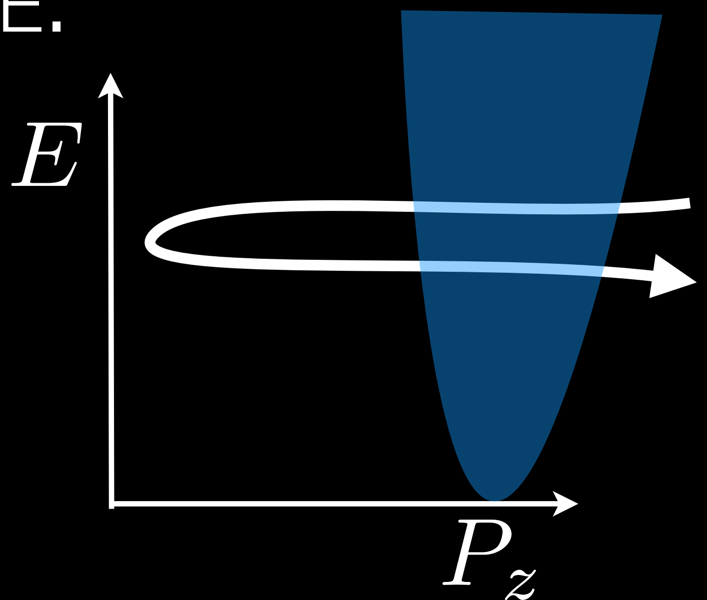
[Dorville et al. in 2016]



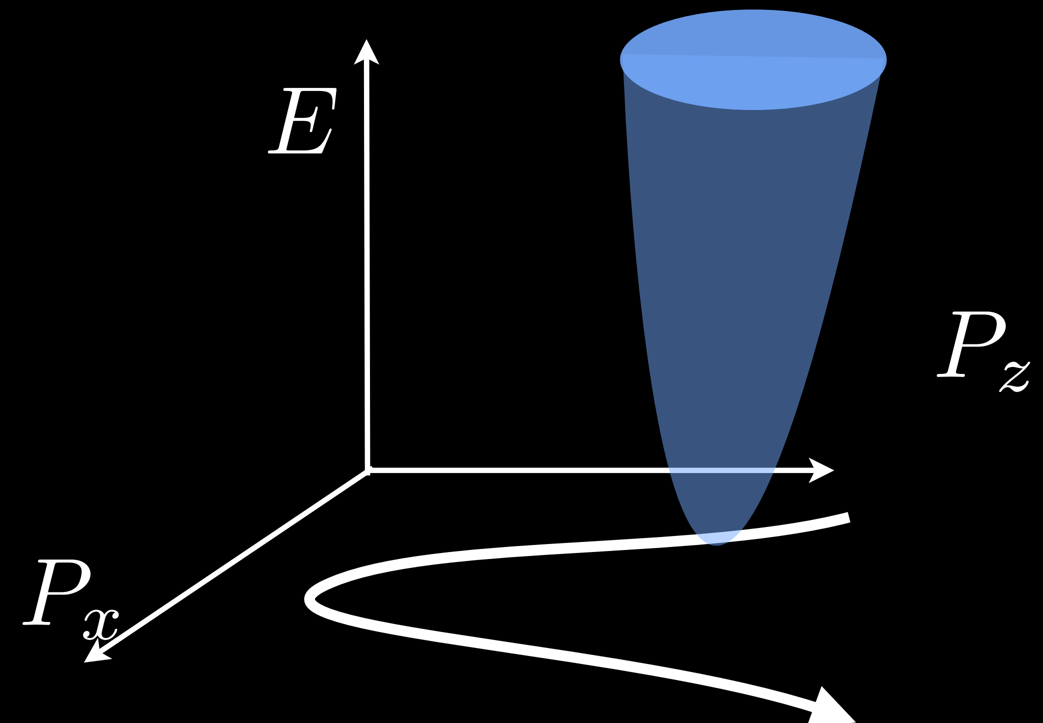


[Berchem et al. 82]

Before:



Now



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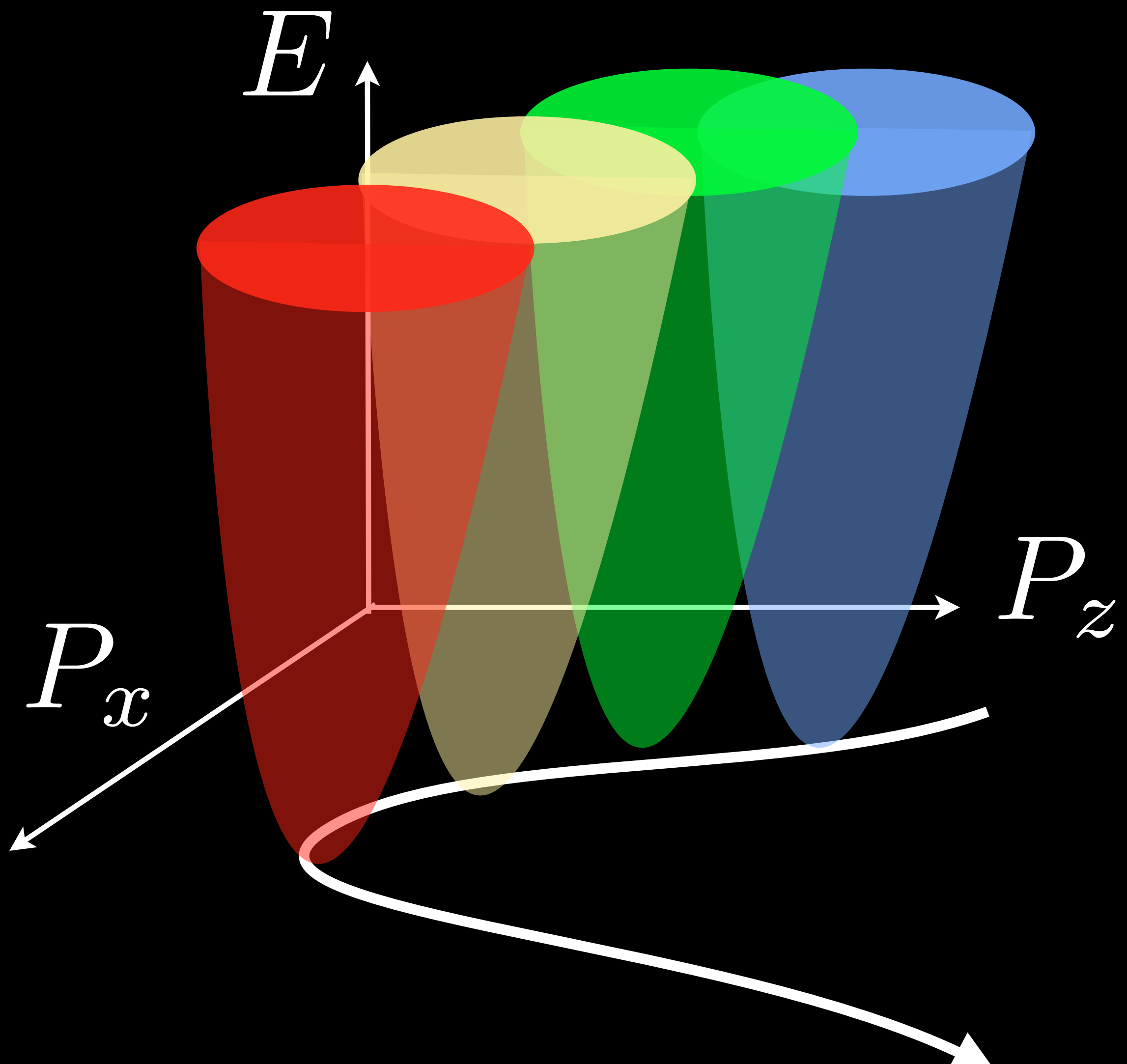

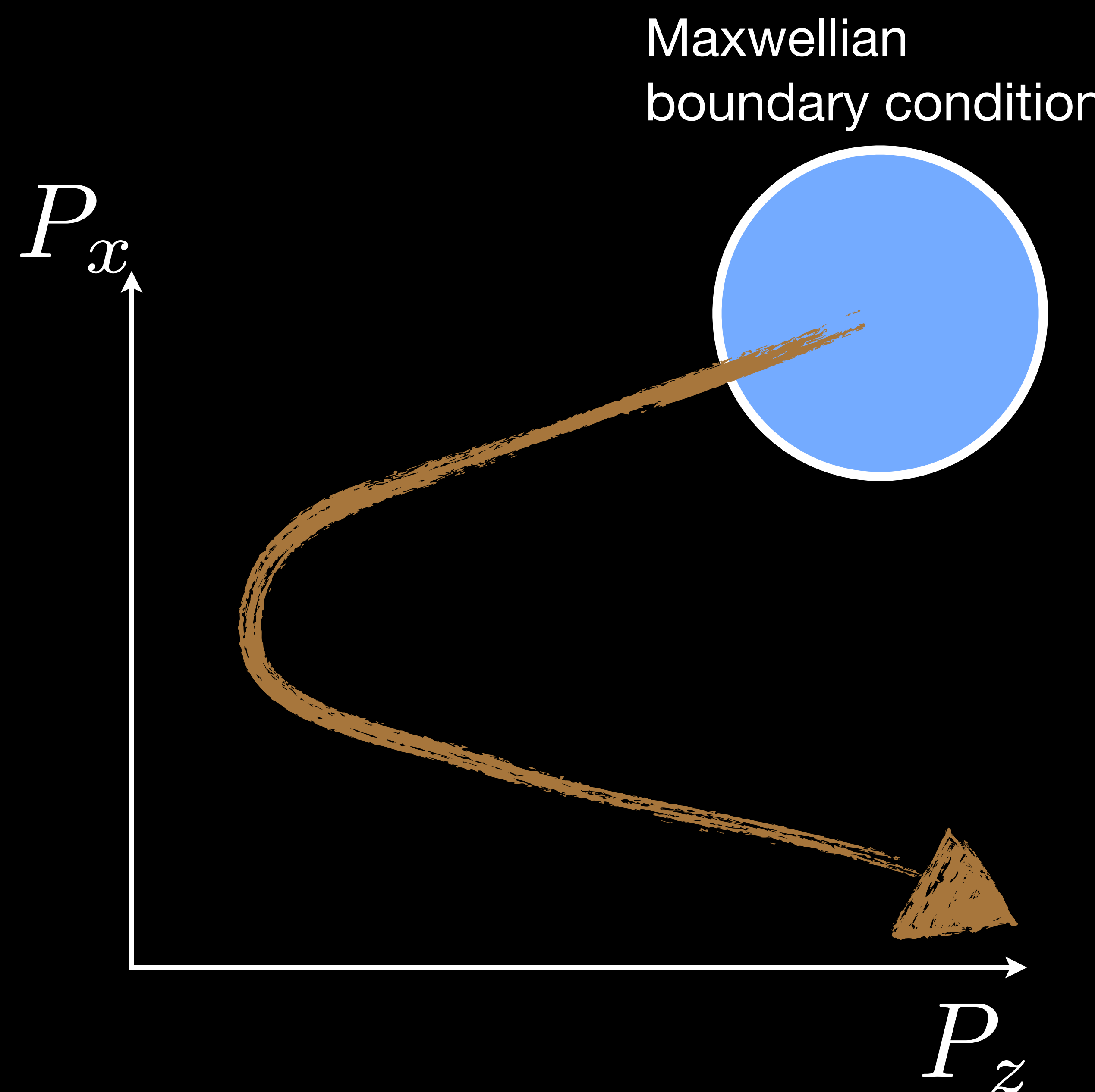

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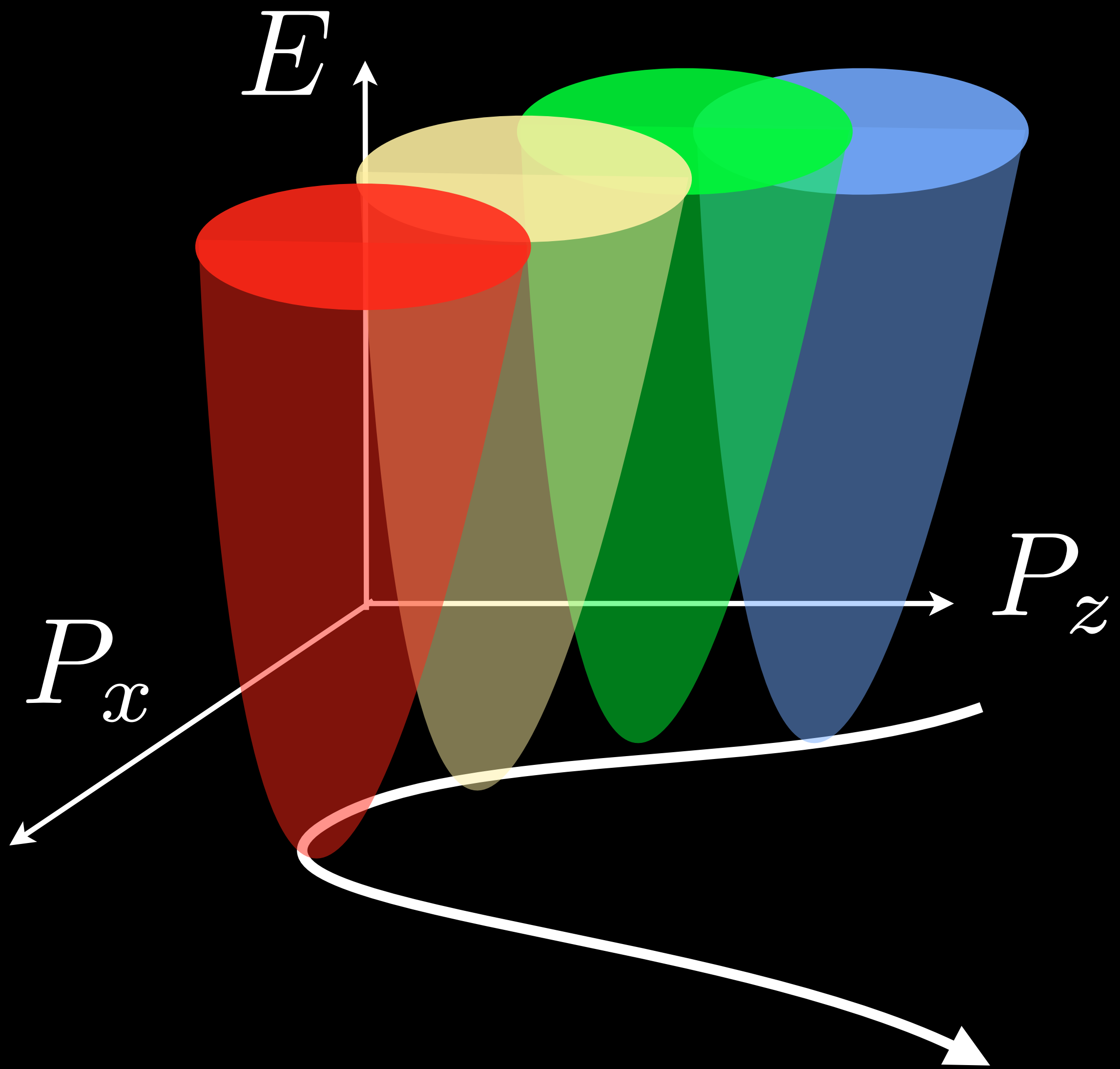
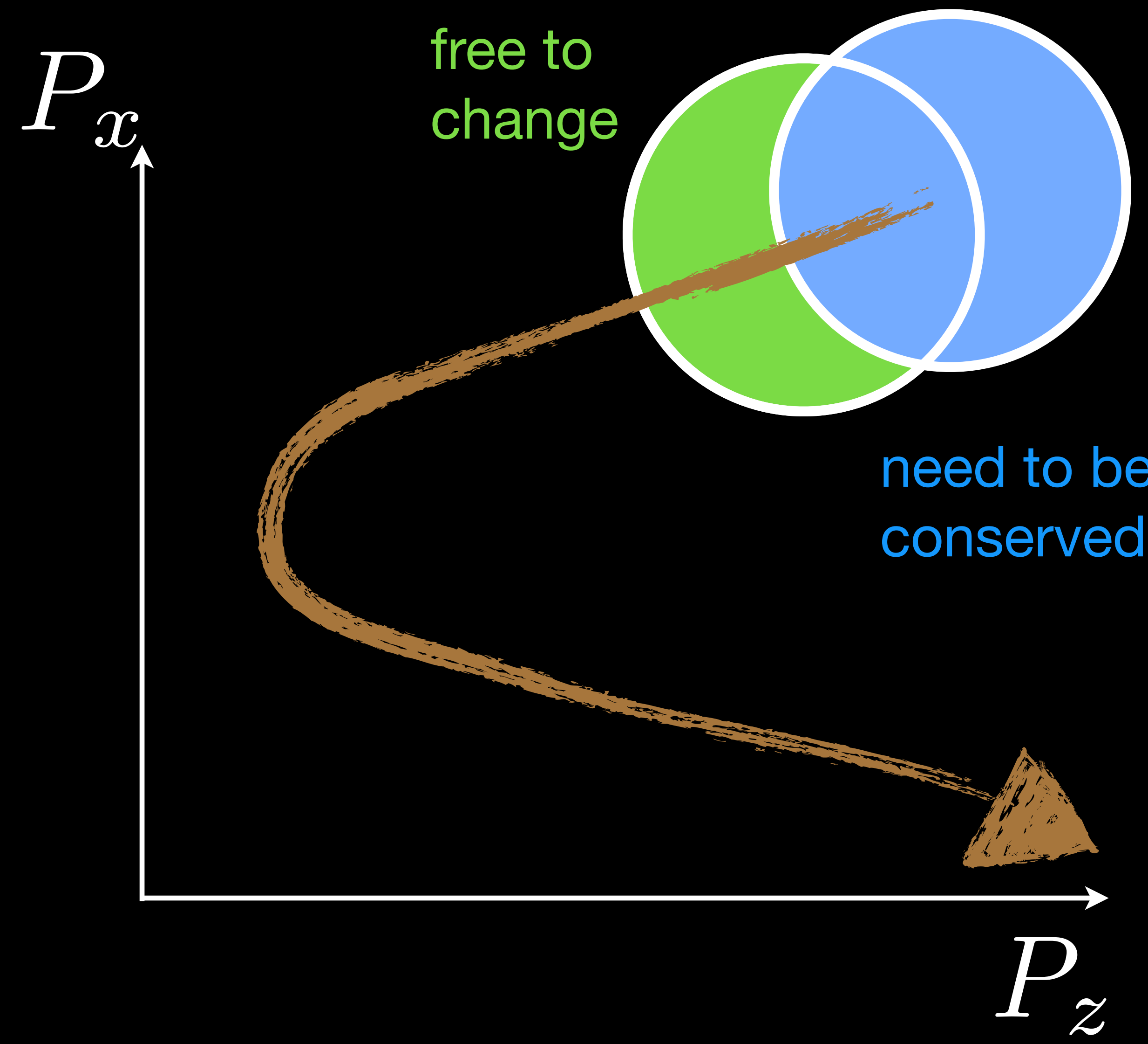
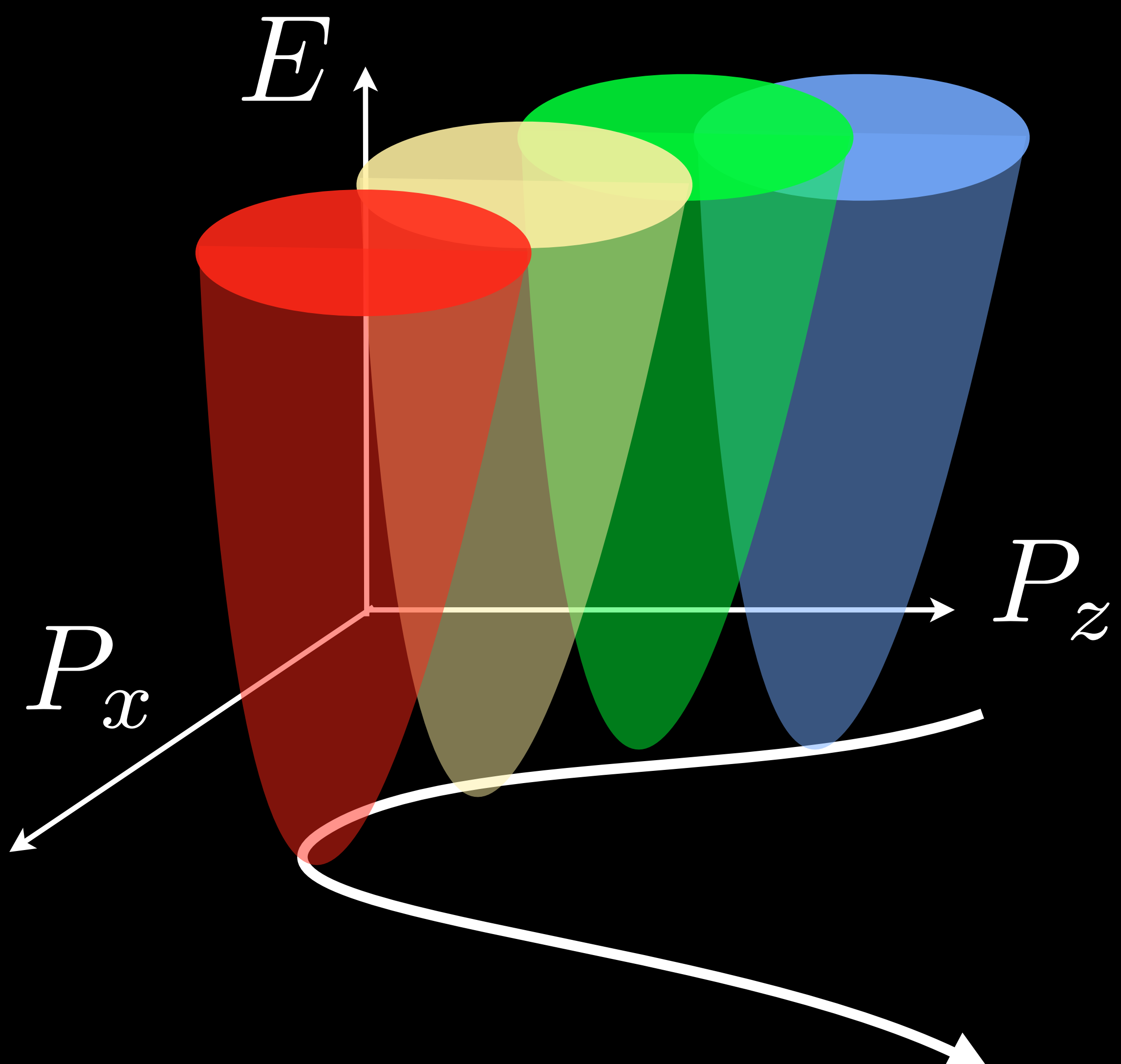
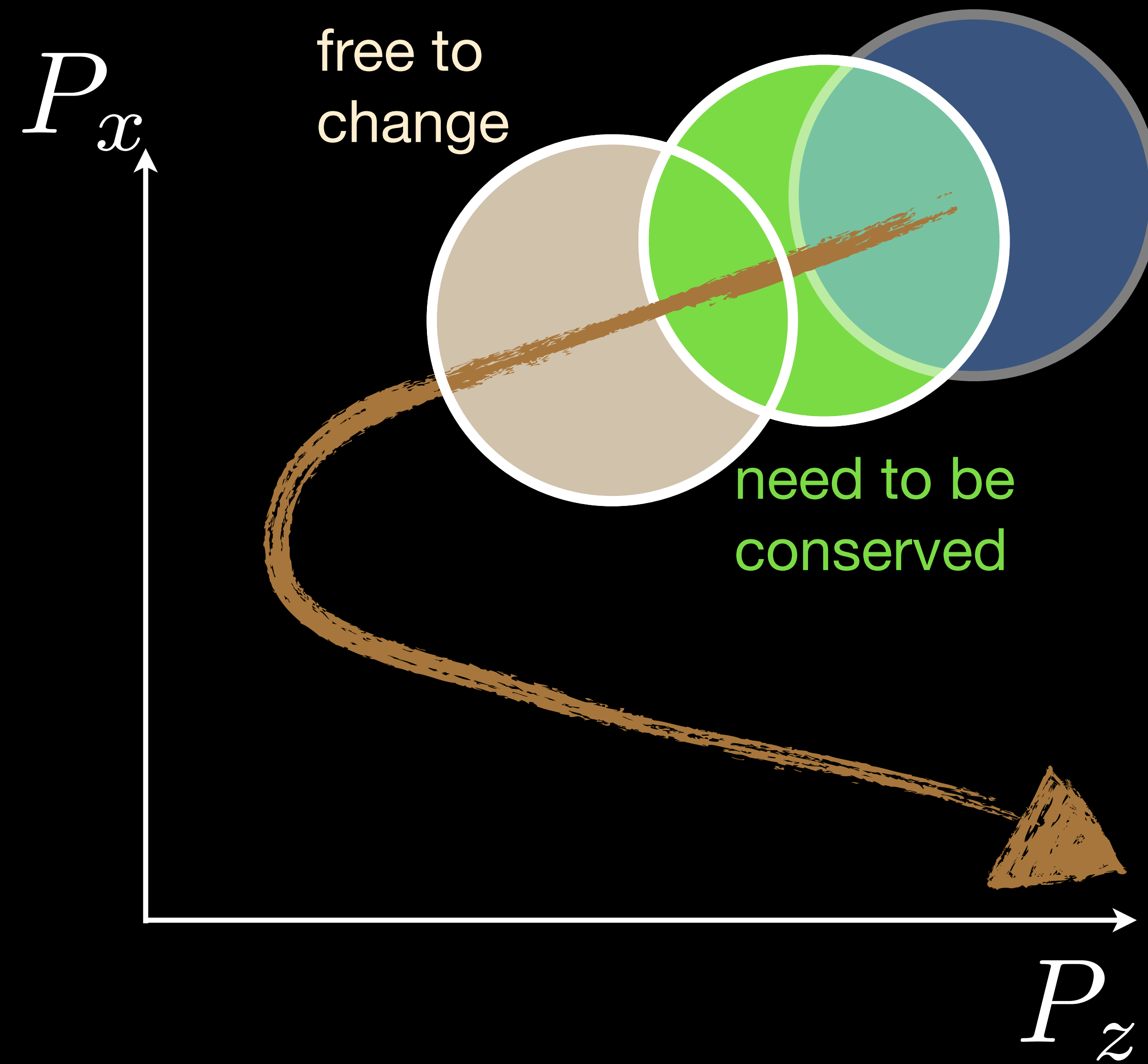




Fill the part that is free to change so that Ampere's equation (J) and pressure balance (P) are satisfied

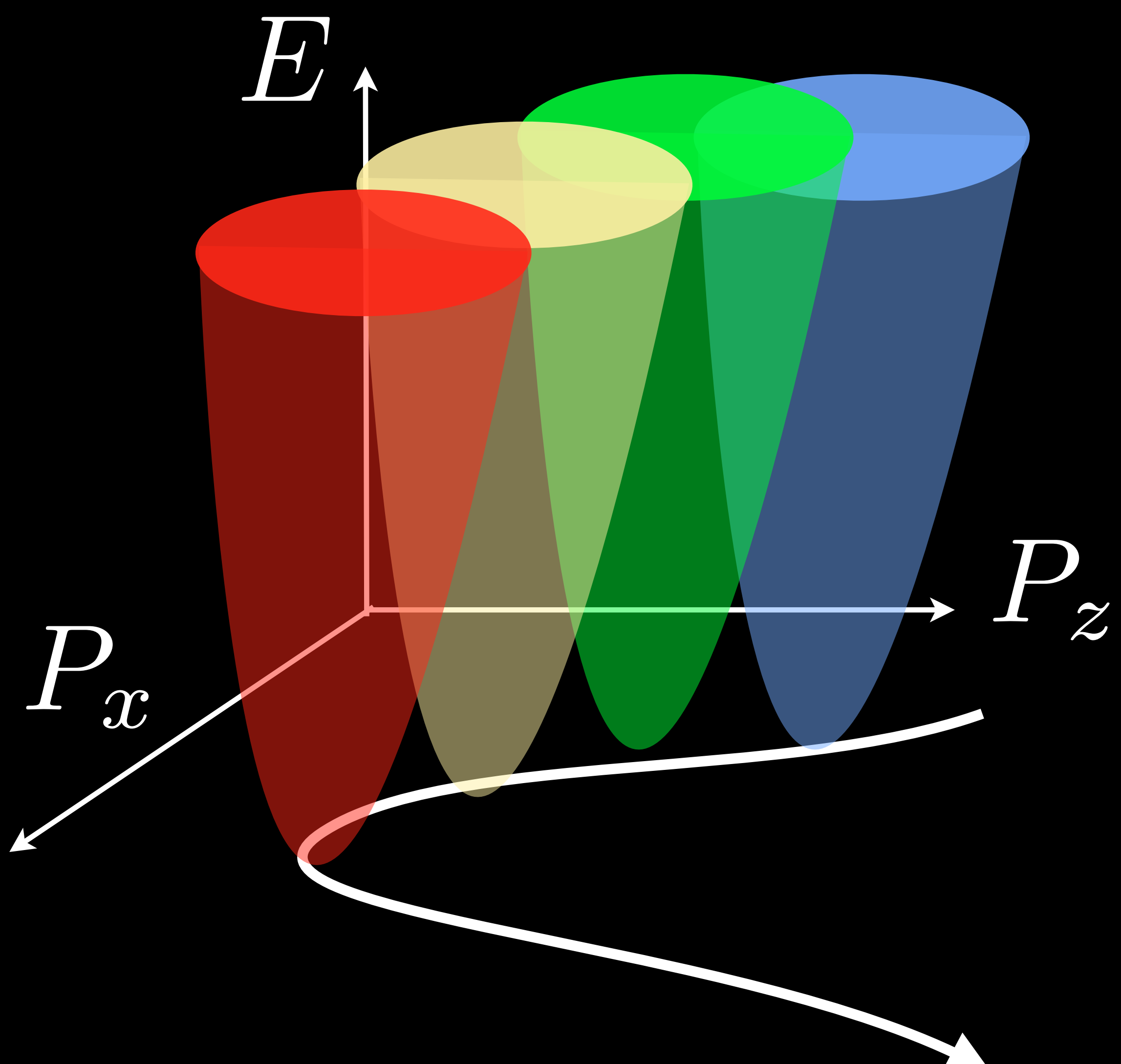
Generalizing to more realistic magnetopause-like layers

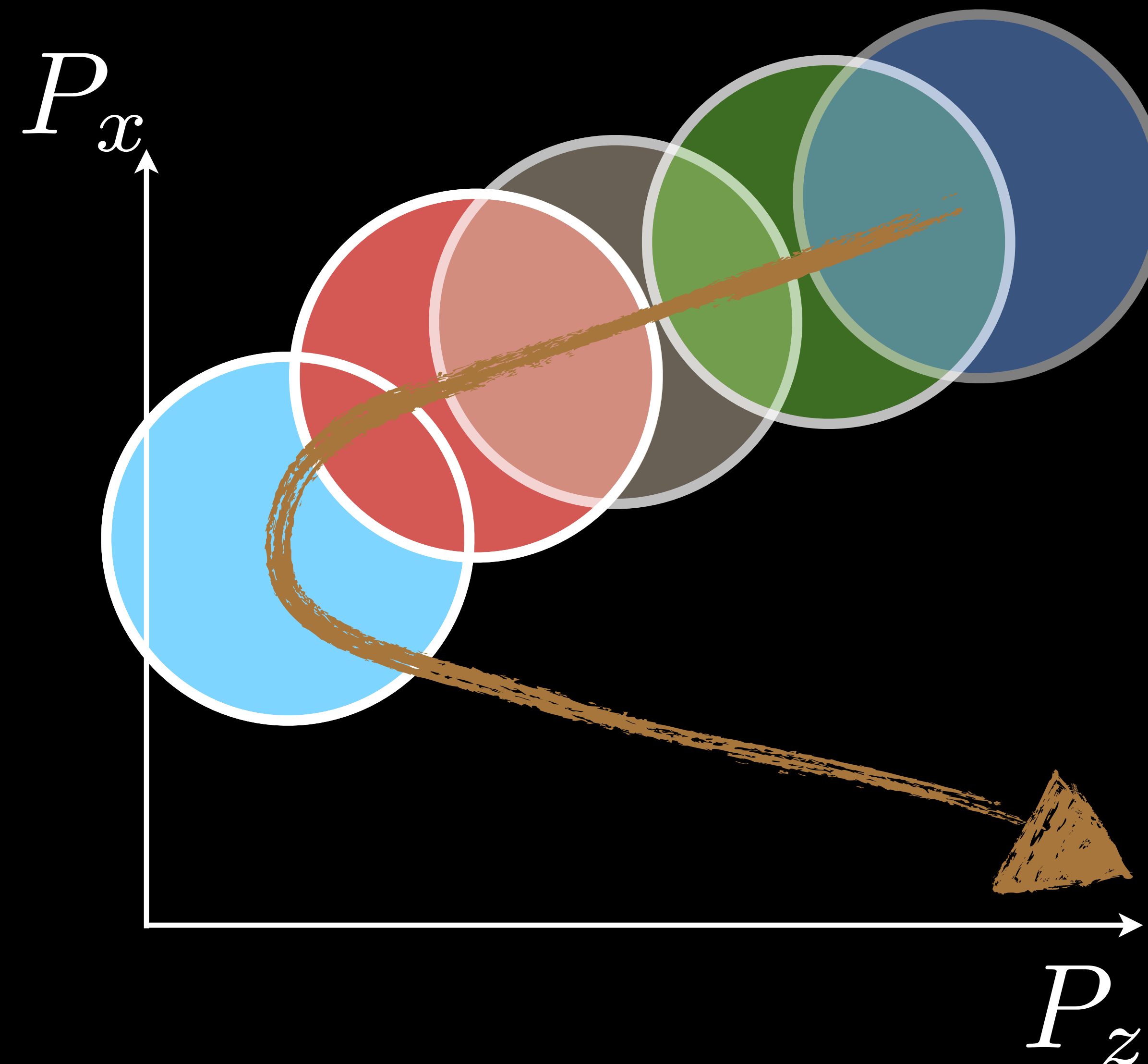




Fill the part that is free to change so that Ampere's equation (J) and pressure balance (P) are satisfied

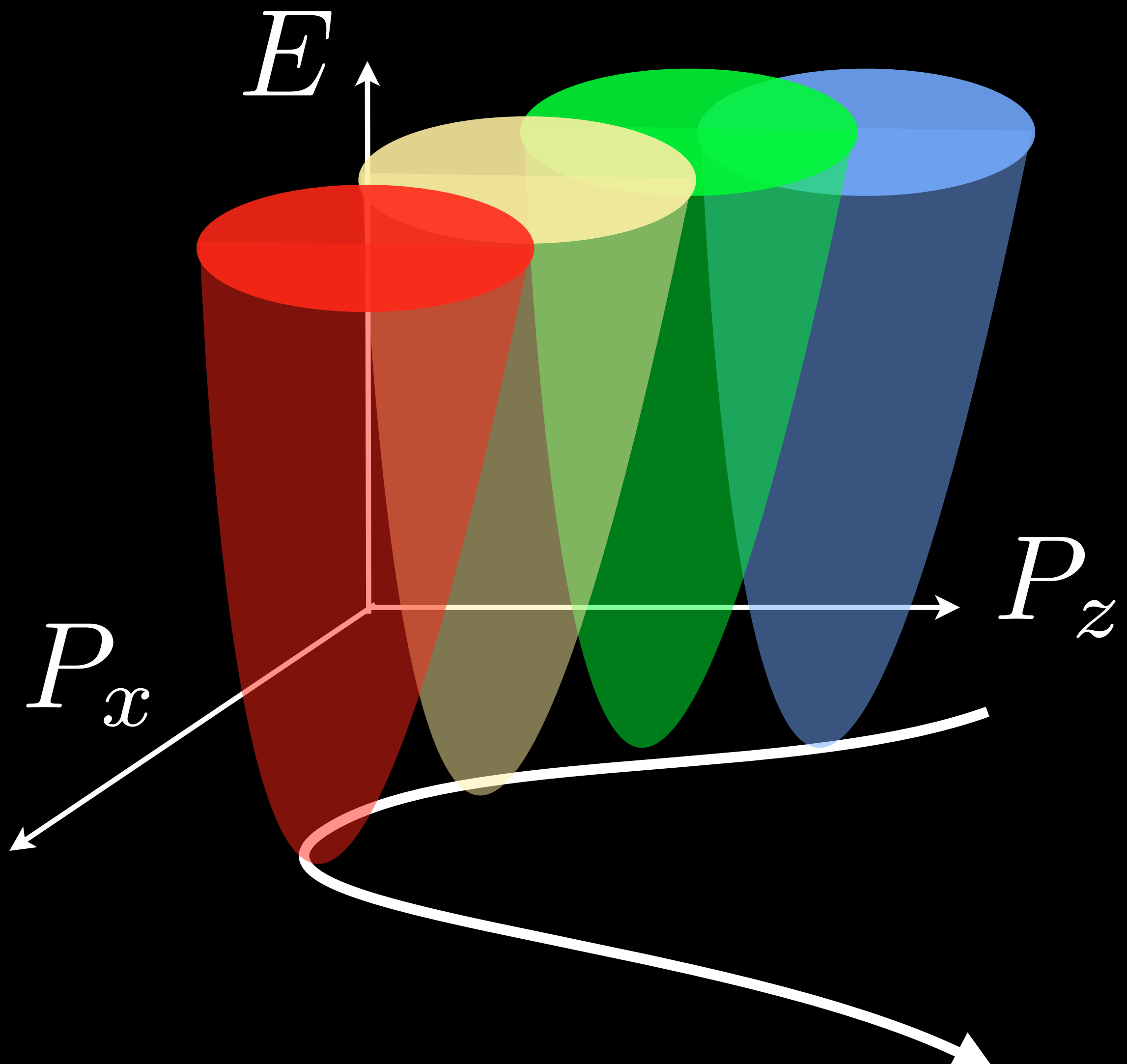
GENERALIZING TO MORE REALISTIC MAGNETOPAUSE-LIKE LAYERS

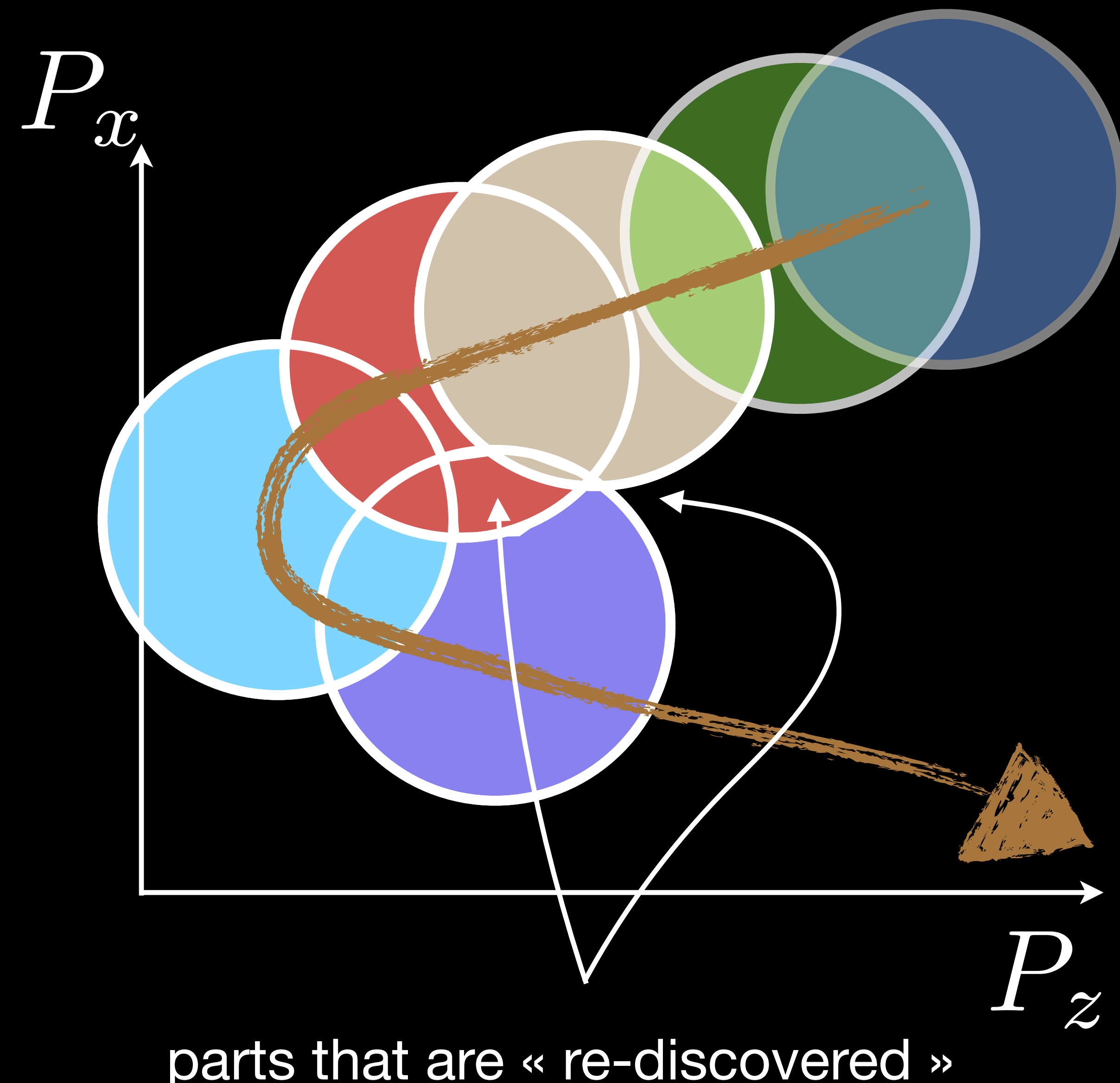




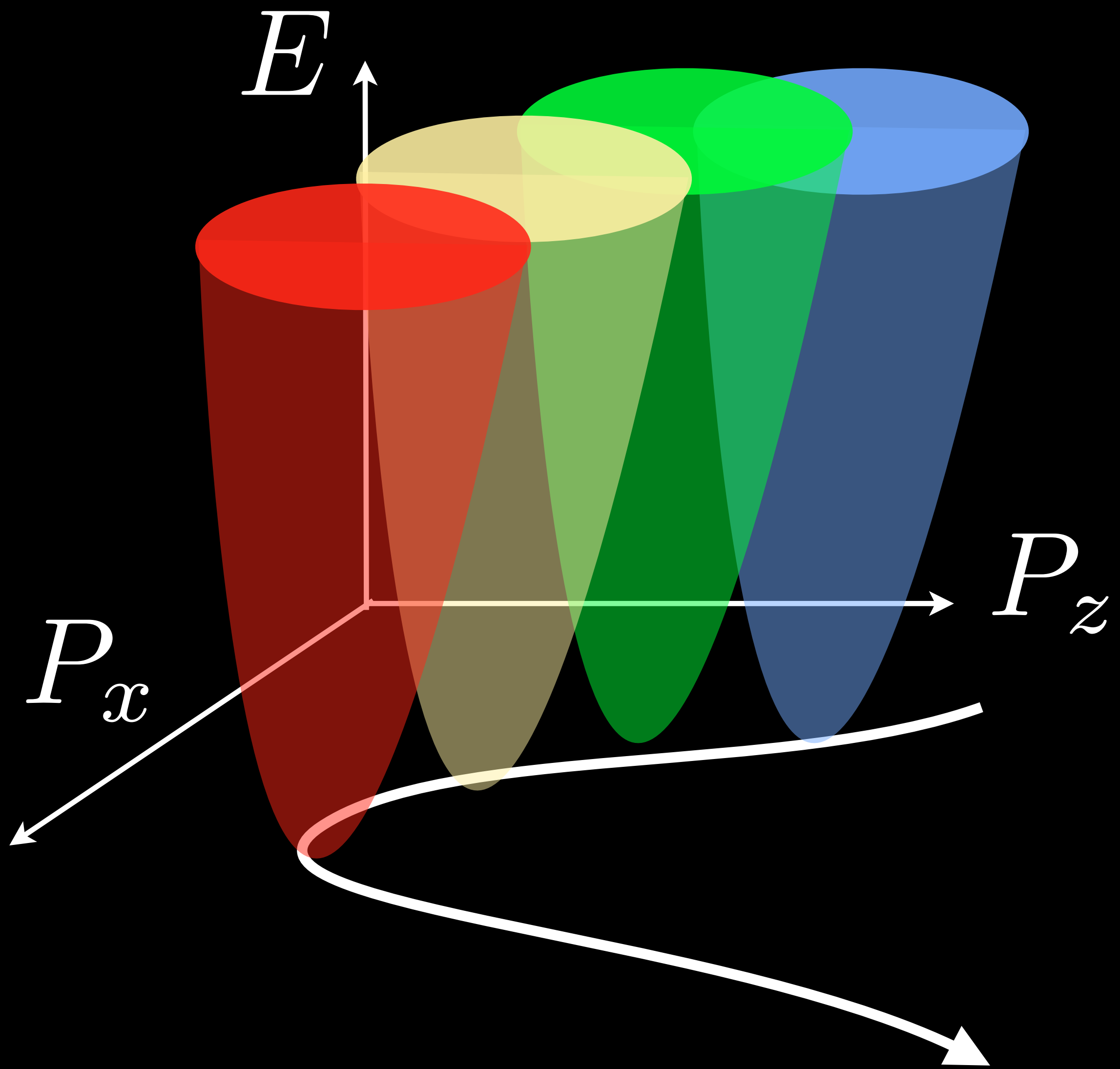
follow the path imposed by the vector potential

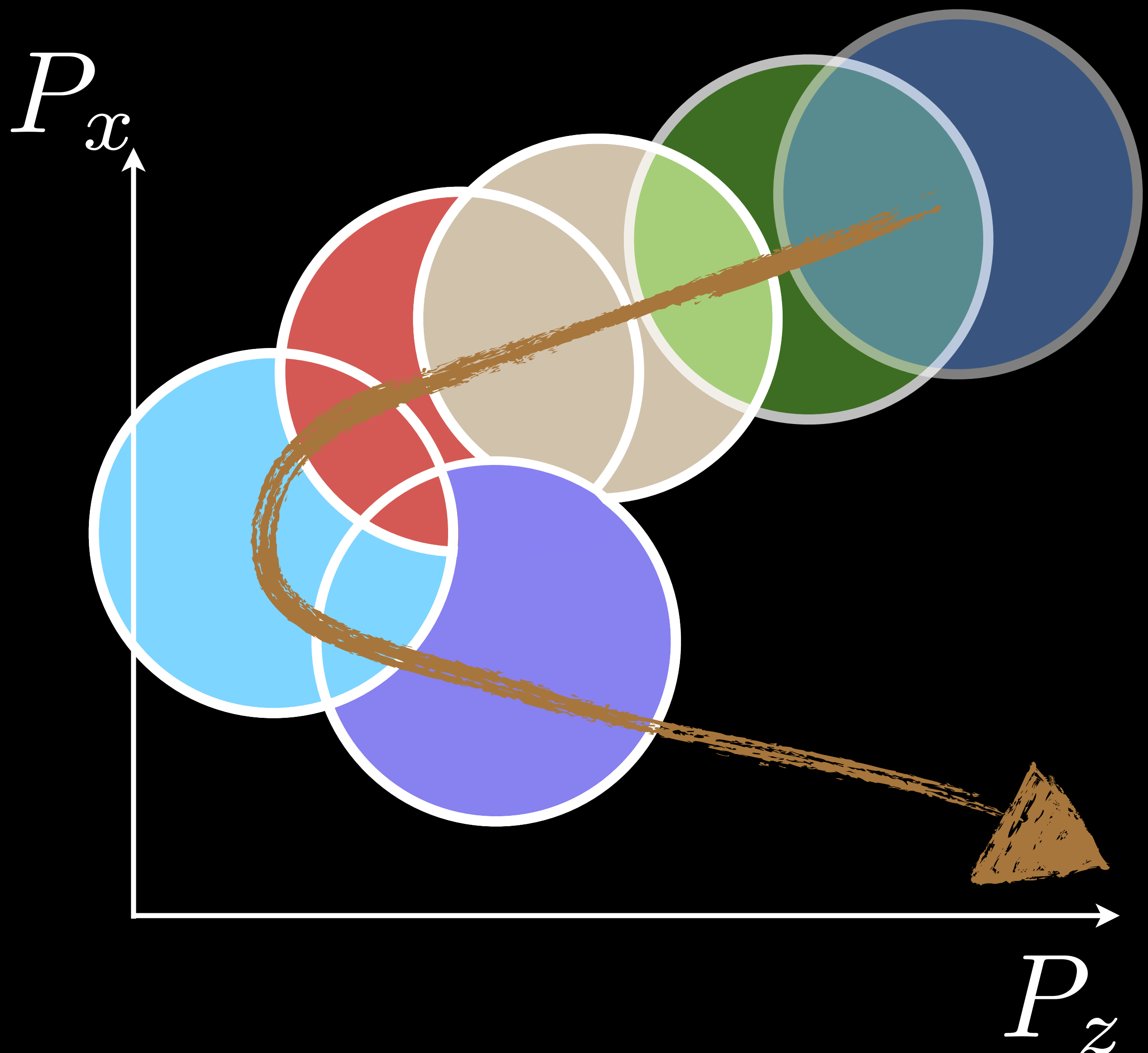
Generalizing to more realistic magnetopause-like layers





Generalizing to more realistic magnetopause-like layers

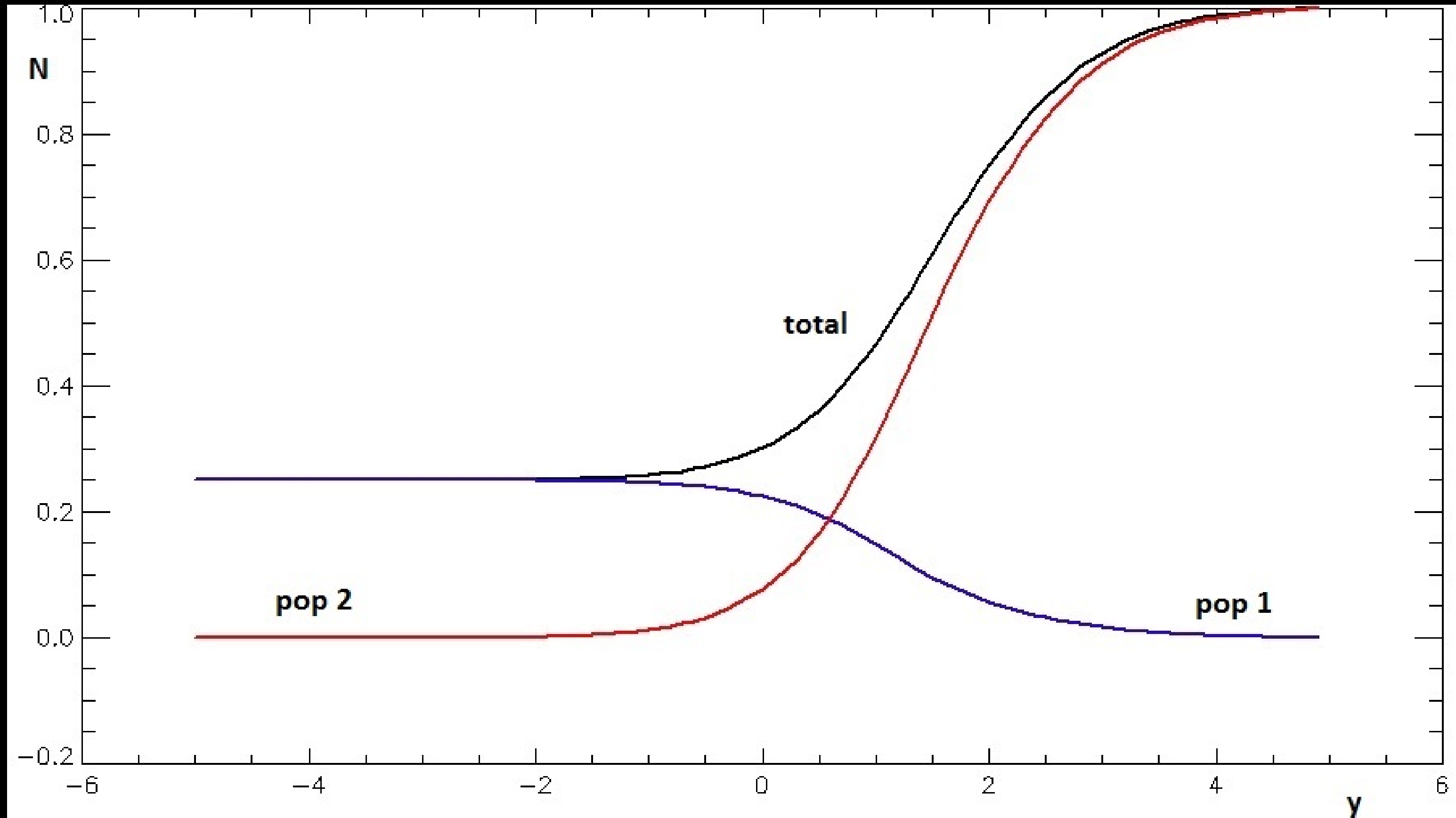




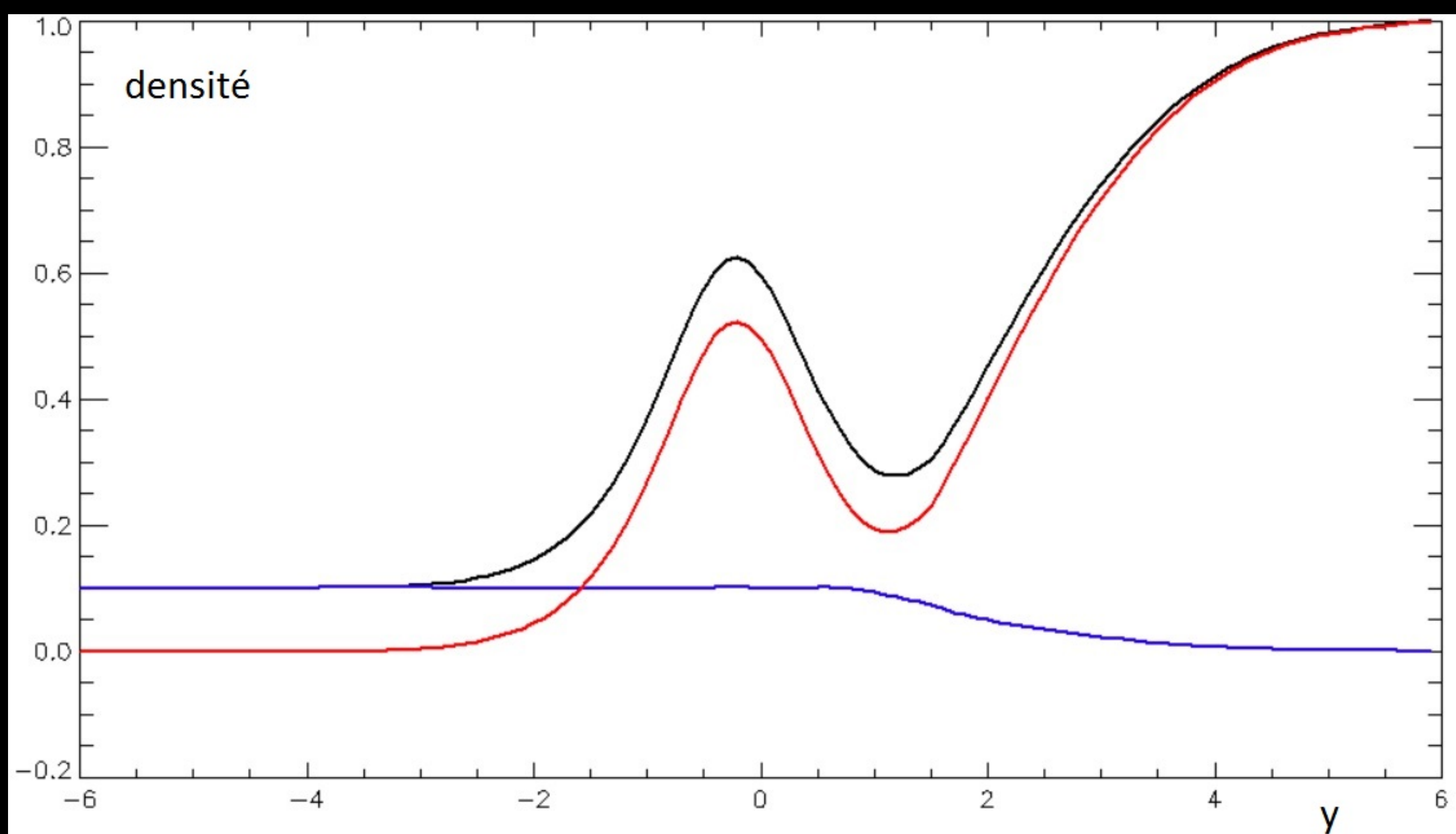
parts that are « re-discovered »

== new populations
== free to change

THEORETICAL STEADY DENSITY PROFILES



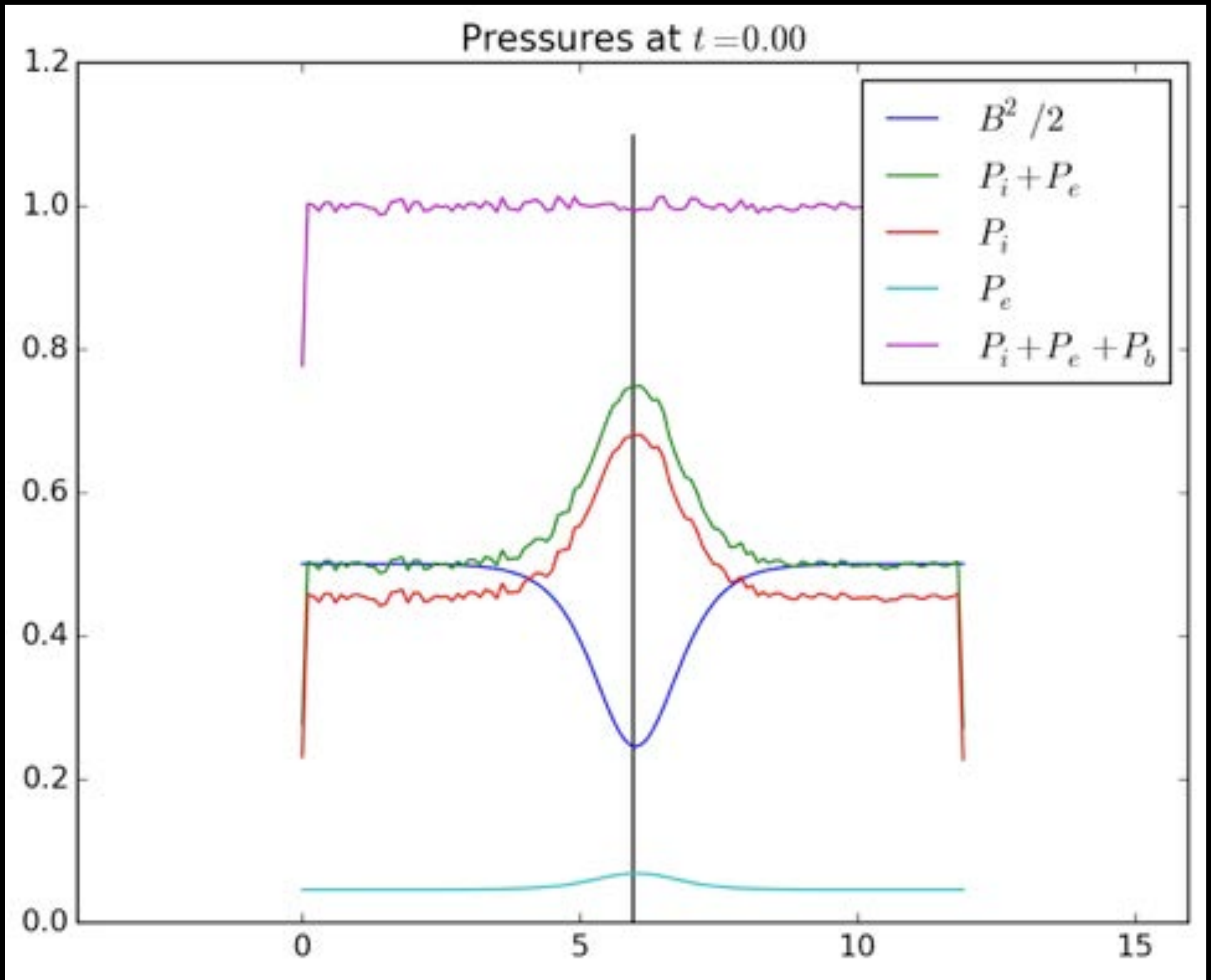
Density profiles for a force free case



Density profiles for an elliptic hodogram

Test with Hybrid simulations

kinetic equilibrium



n,V,P from kinetic solution
+ Maxwellian distributions