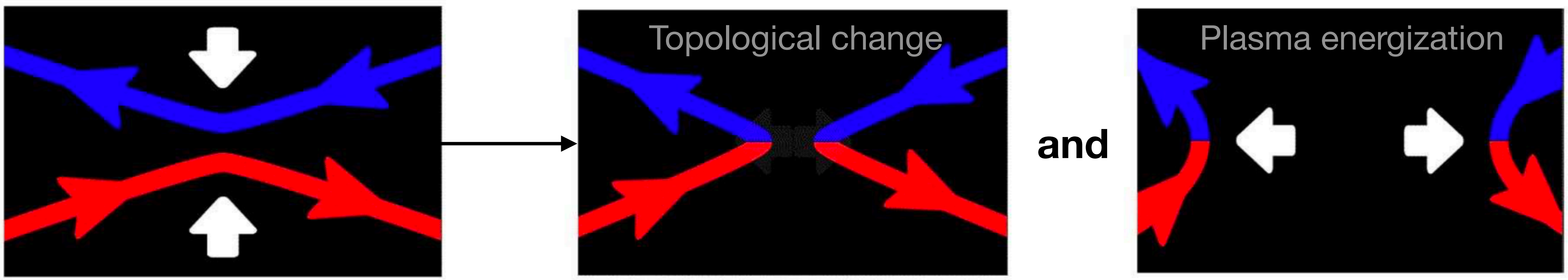
Magnetic Reconnection

What does that mean for MHD description of plasmas

What is Magnetic Reconnection?

Magnetic reconnection is the **breaking** and **rejoining** of magnetic field lines in a highly conducting plasma

- Means topological change in the magnetic field happens (why topology is so important for magnetic fields?)



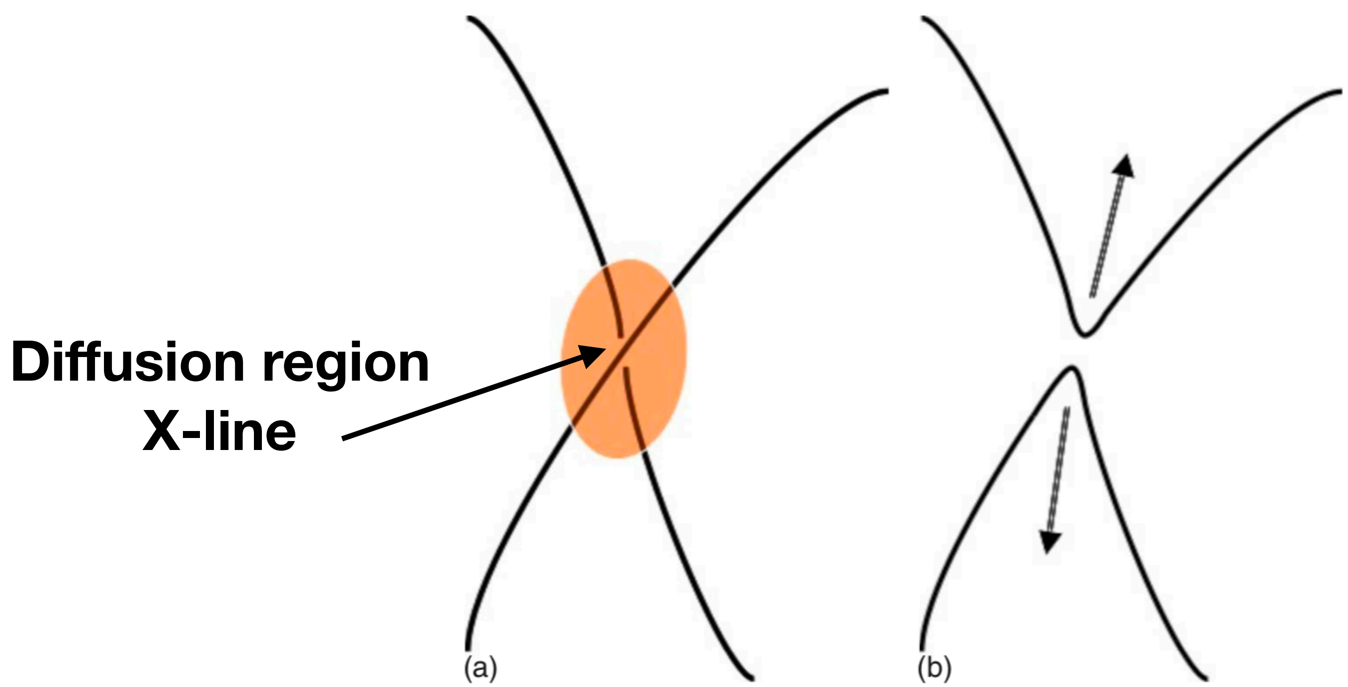
Reconnection **converts** magnetic **energy** into kinetic energy, thermal energy, and particle acceleration energy

- Reconnection was proposed to explain fast energy release in solar flares (Giovanelli 1946), and was later applied to Earth's magnetosphere (Dungey 1961)

Physical processes often associated with reconnection include: Plasma resistivity, viscosity, thermal conduction, Hall, particle drift, kinetic effect (electron scale), particle acceleration, waves, shocks, instabilities, turbulence, radiation - basically everything

Ingredients of Magnetic Reconnection

- Occurs in regions of very strong magnetic shear (opposite B field directions)
  - Direction of B field changes significantly within a short time and distance
- Release of magnetic energy into kinetic and thermal energy
  - Usually the process is explosive (MHD like)
  - Although the energy released on small scales but with global consequences (non-MHD)
- Changes in magnetic topology (important but that's not the key!)
  - The region where the field line changes topology is called the diffusion region (x-line)

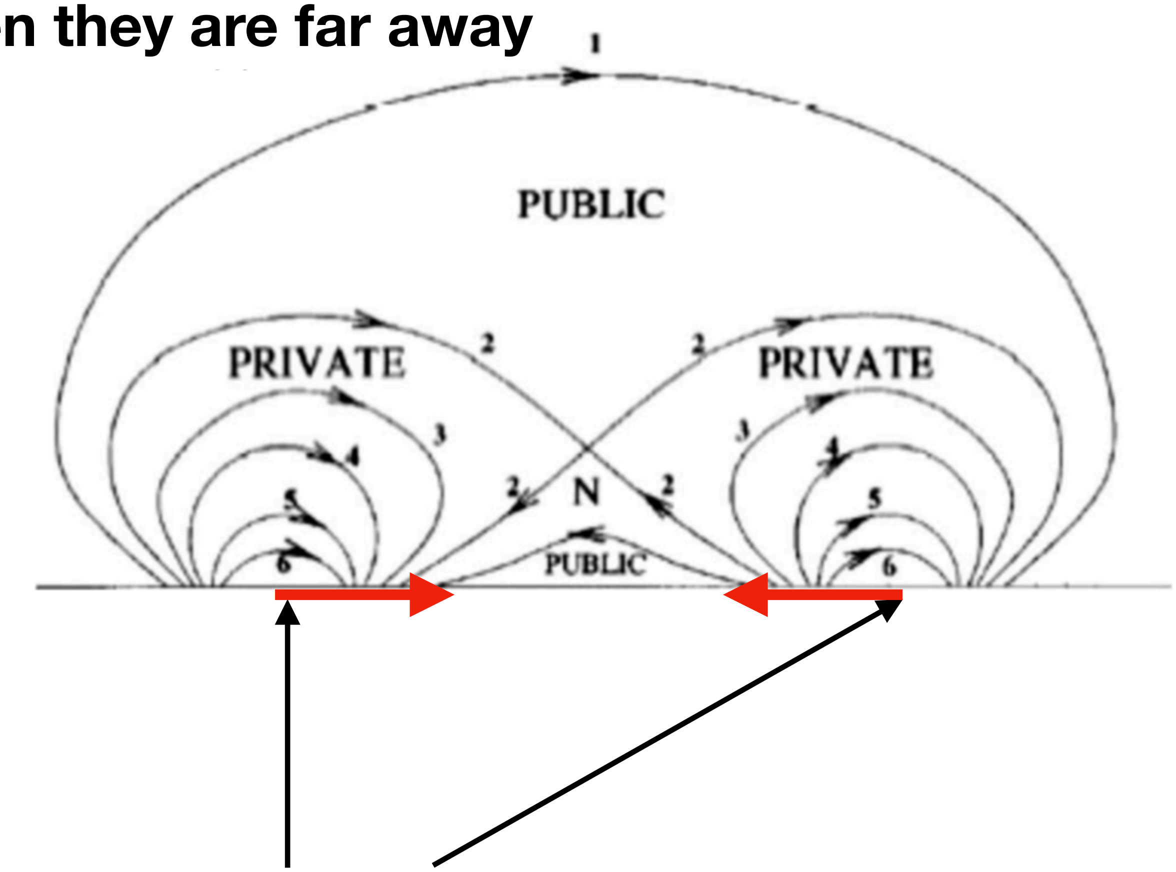


- Generates Alfvénic jets (exhaust flow), particle acceleration and heating
- Operates on a fast time scale, occurs after a slow build-up phase

First thoughts about Magnetic Reconnection

Evolution of field lines when a pair of sunspots move toward each. From Kulsrud, 1998.

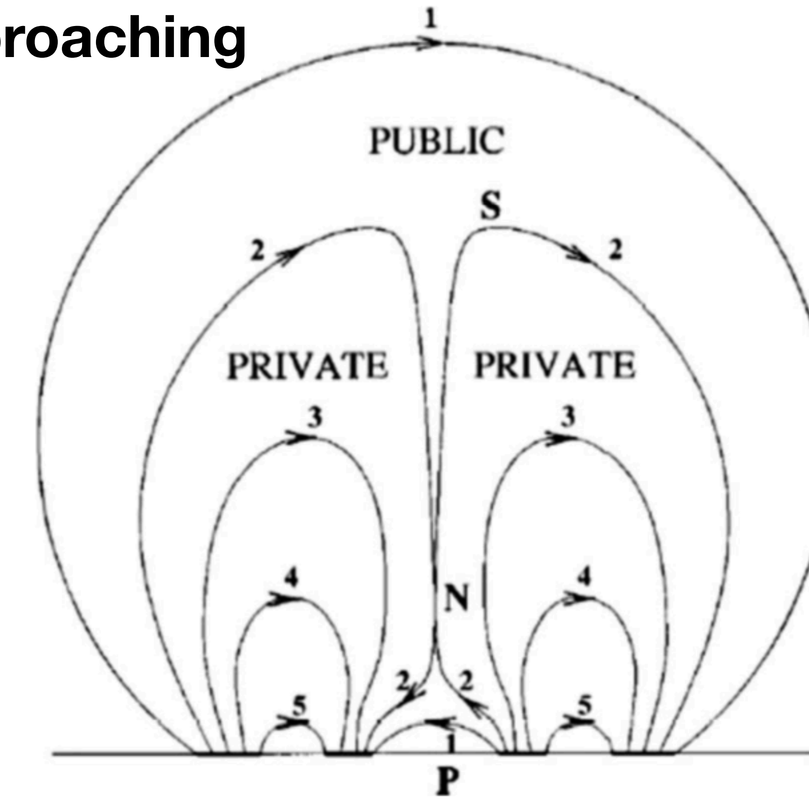
When they are far away



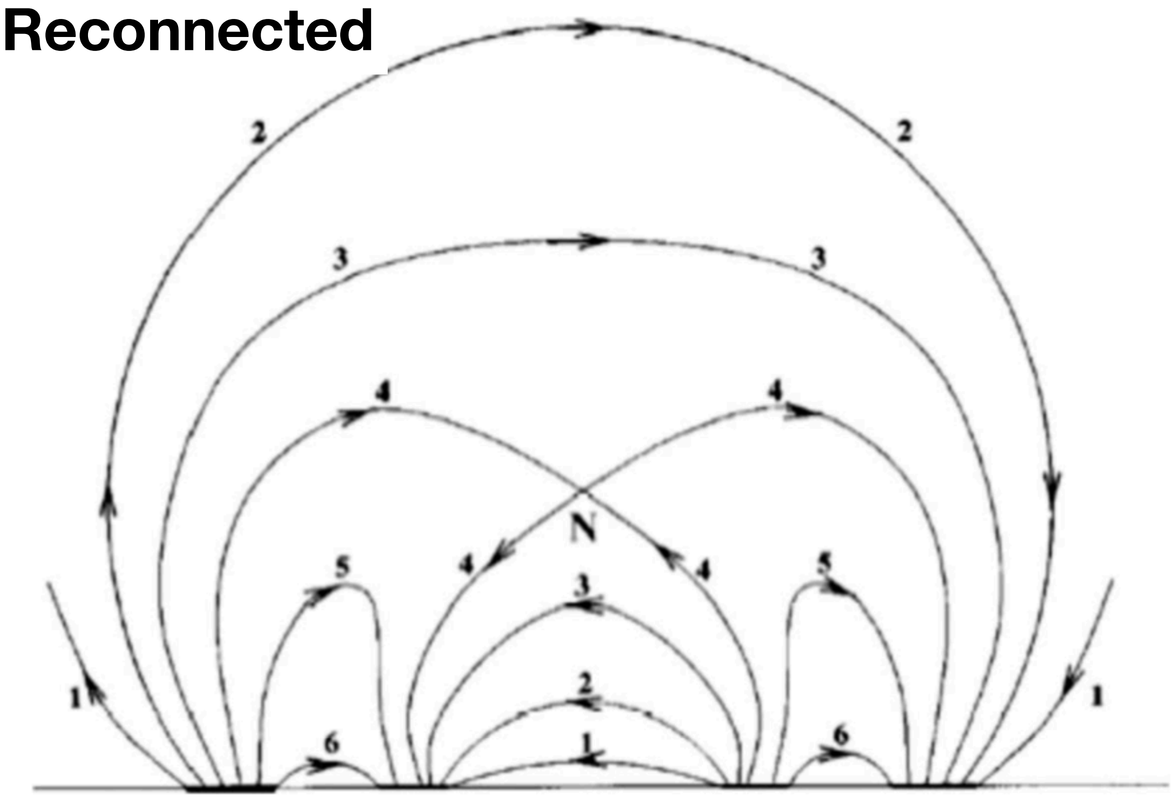
Two sun spots
Moving towards each other

So at the N-point (Null), magnetic topology (connectivity changes and “private” field lines become “public” field lines connecting the two sunspots - reconnection

Approaching

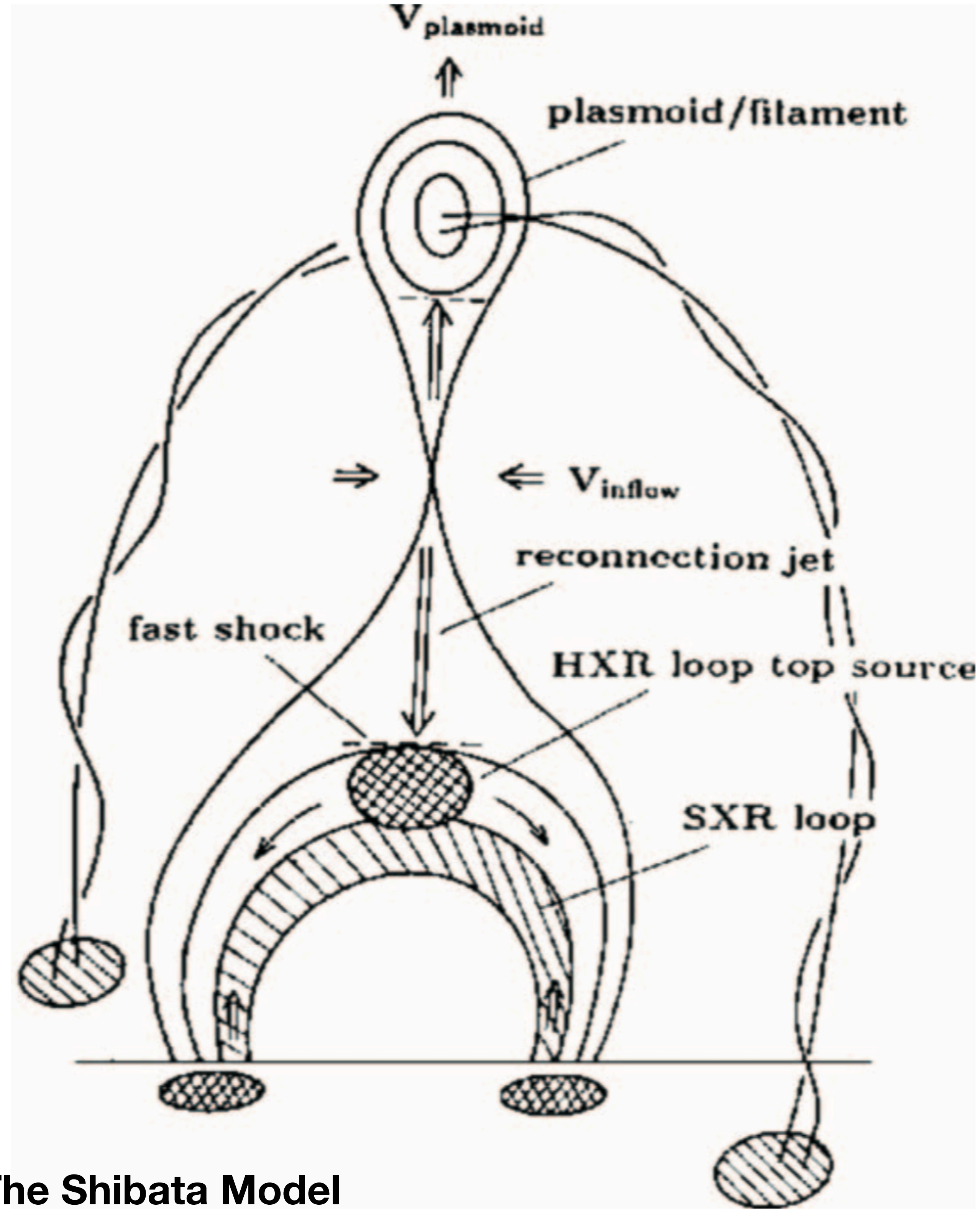


Reconnected



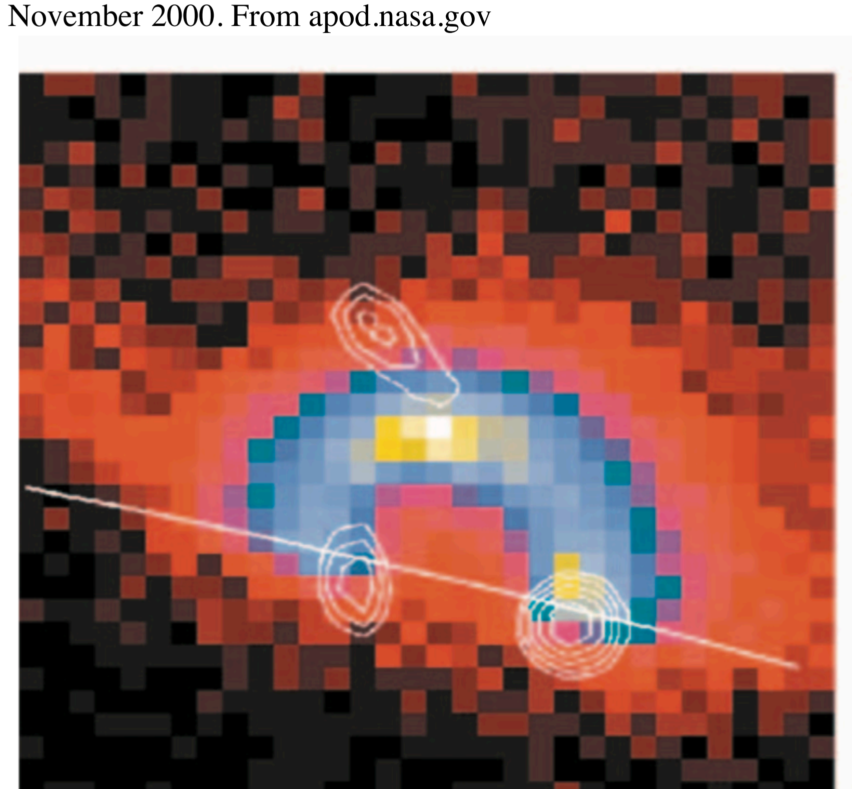
Examples of Magnetic Reconnection

Solar flare



The Shibata Model

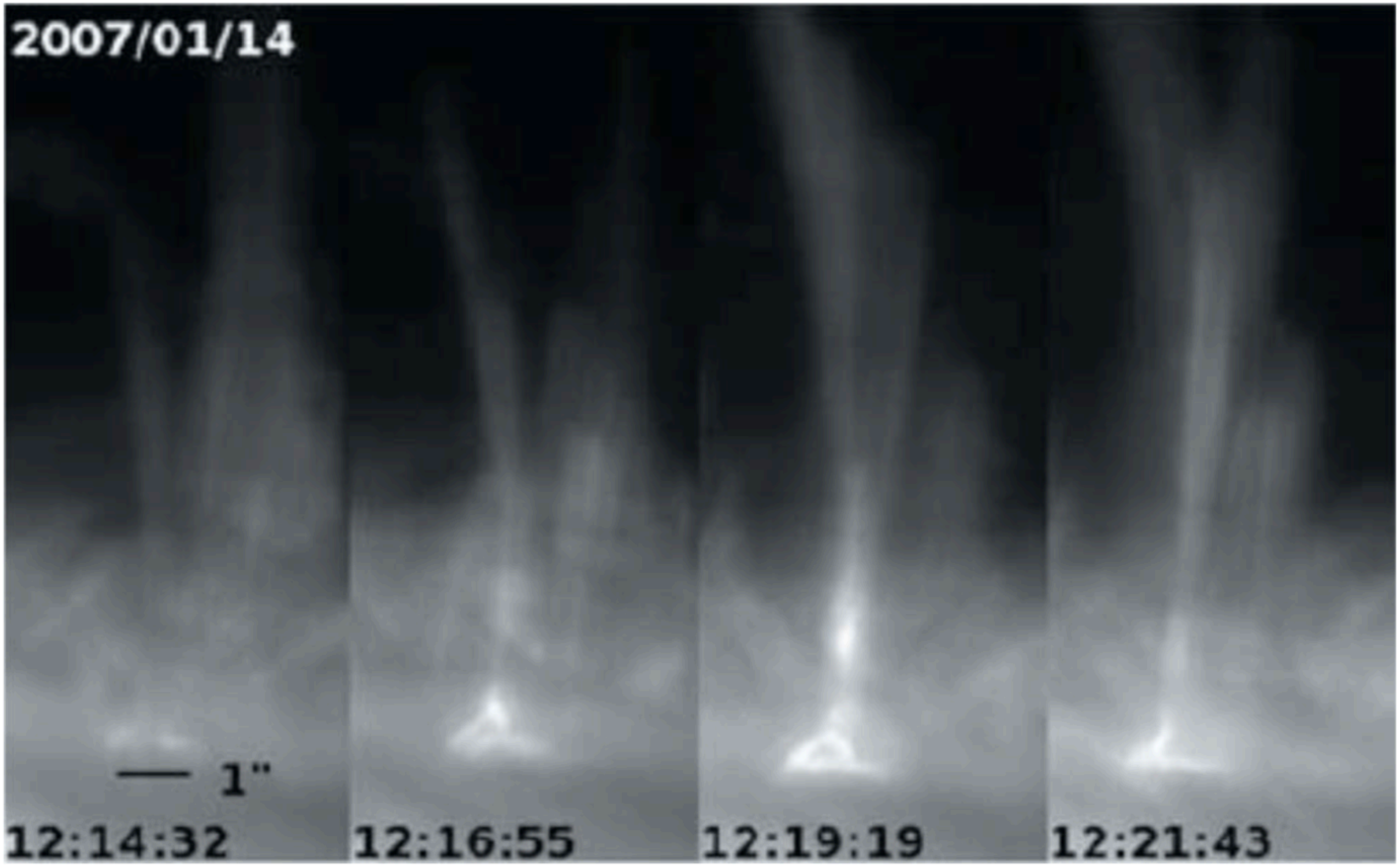
Color Solar flare image at 171 Å from TRACE satellite on 9 November 2000. From apod.nasa.gov



Hard-x-ray image from the top of an arcade adapted from Masuda *et al.*, 1994

Examples of Magnetic Reconnection

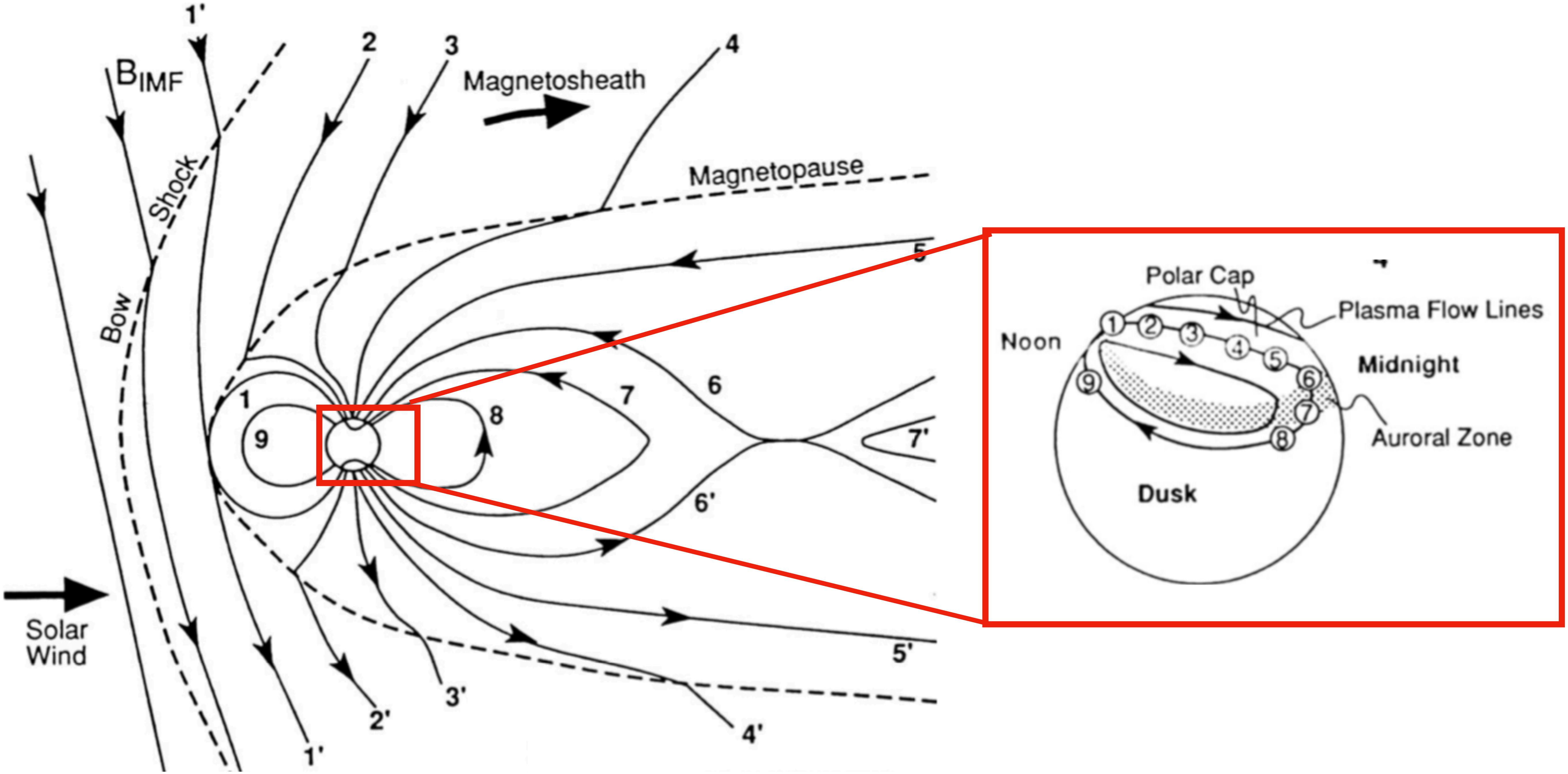
Solar flare signatures of reconnection



Time evolution of typical Ca jets observed in Ca II H broadband filter of Hinode-SOT. Times are shown in UT. From Shibata *et al*., 2007.

Examples of Magnetic Reconnection

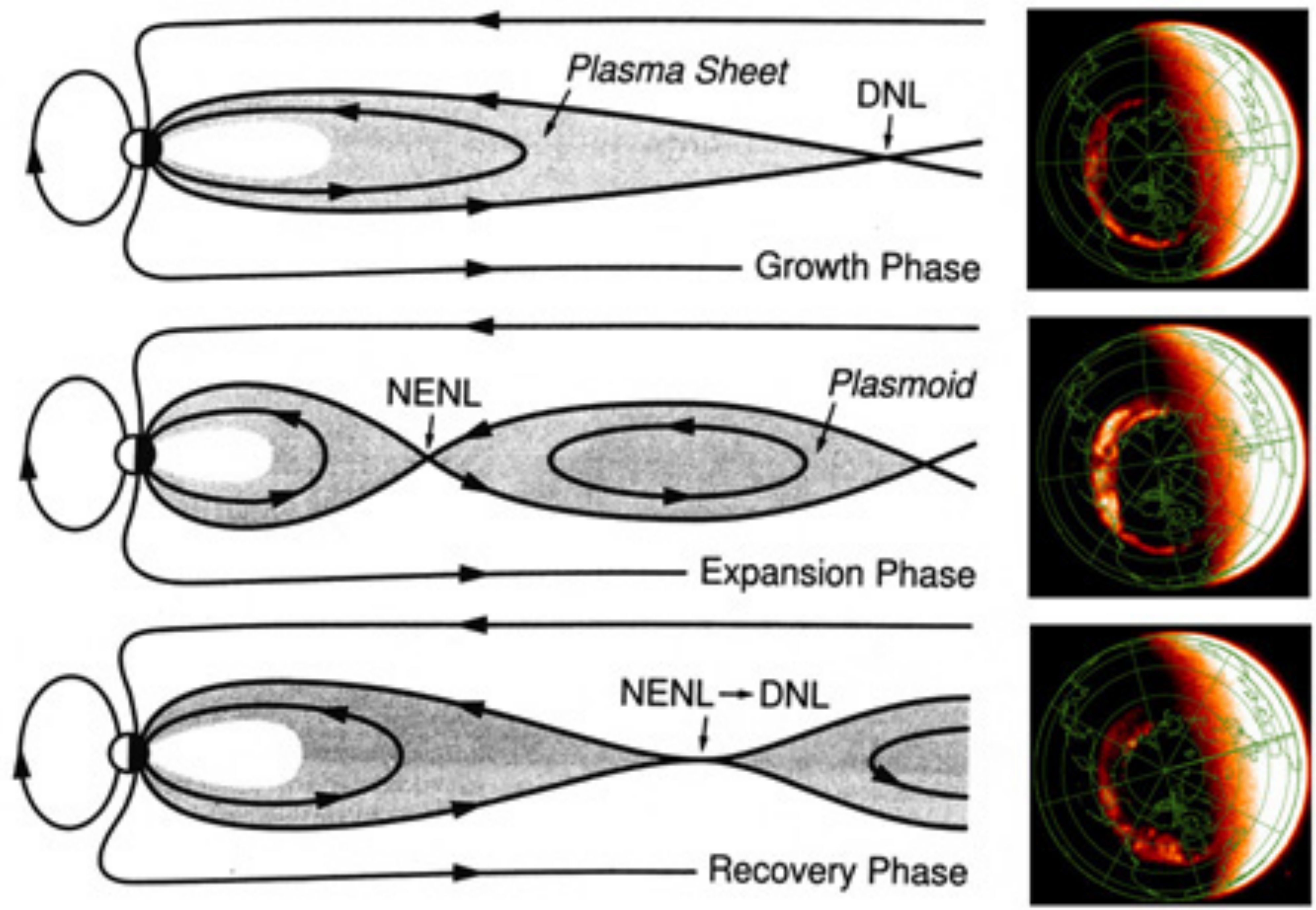
Dungey Cycle (Magnetosphere)



The topology of the Earth's magnetosphere is determined by magnetic reconnection (otherwise it's a dipole)

Examples of Magnetic Reconnection

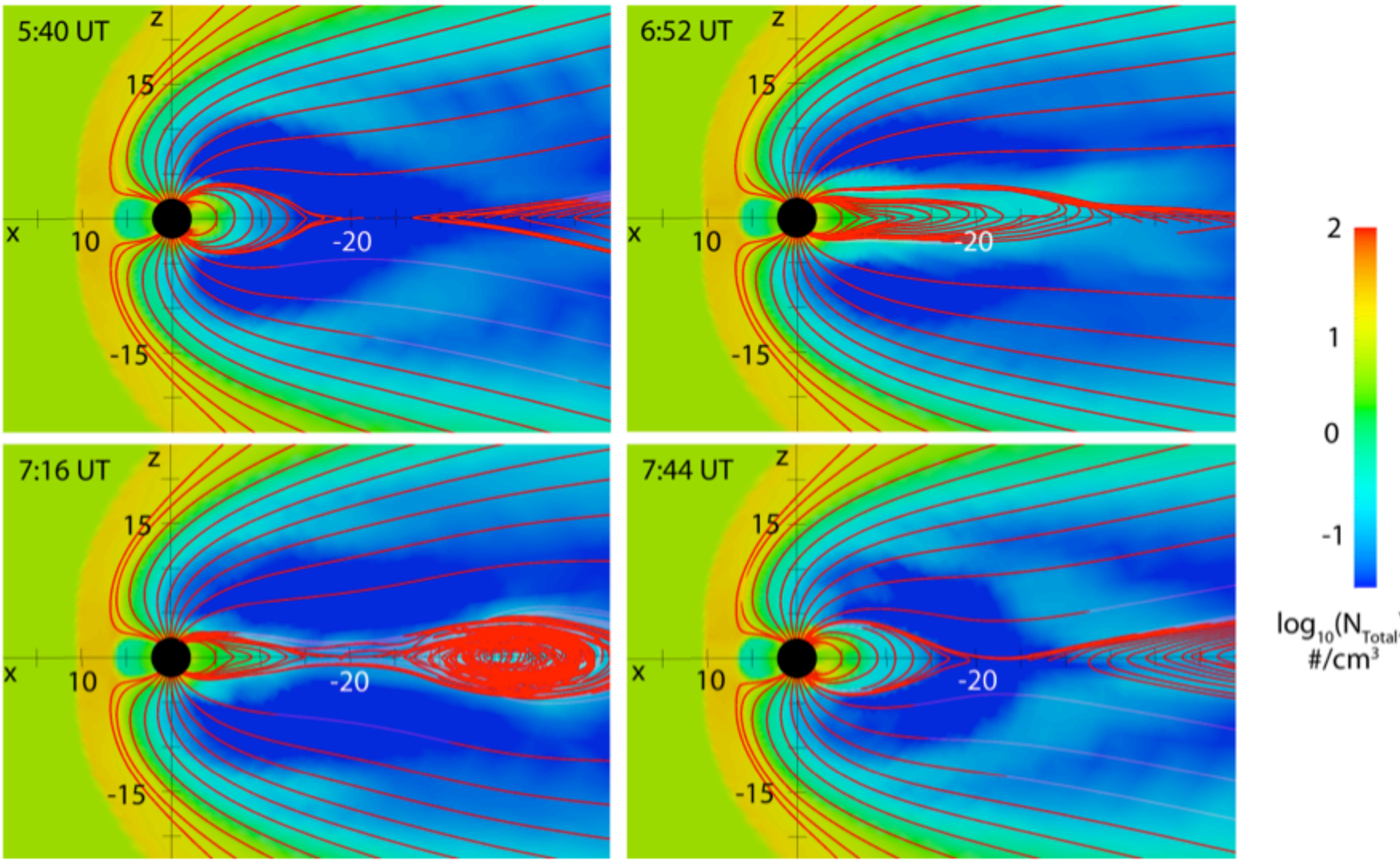
Isolated substorms (Magnetosphere)



Magnetotail reconnection is often associated with energization - aurora

Examples of Magnetic Reconnection

Sawtooth Oscillations (Magnetosphere)

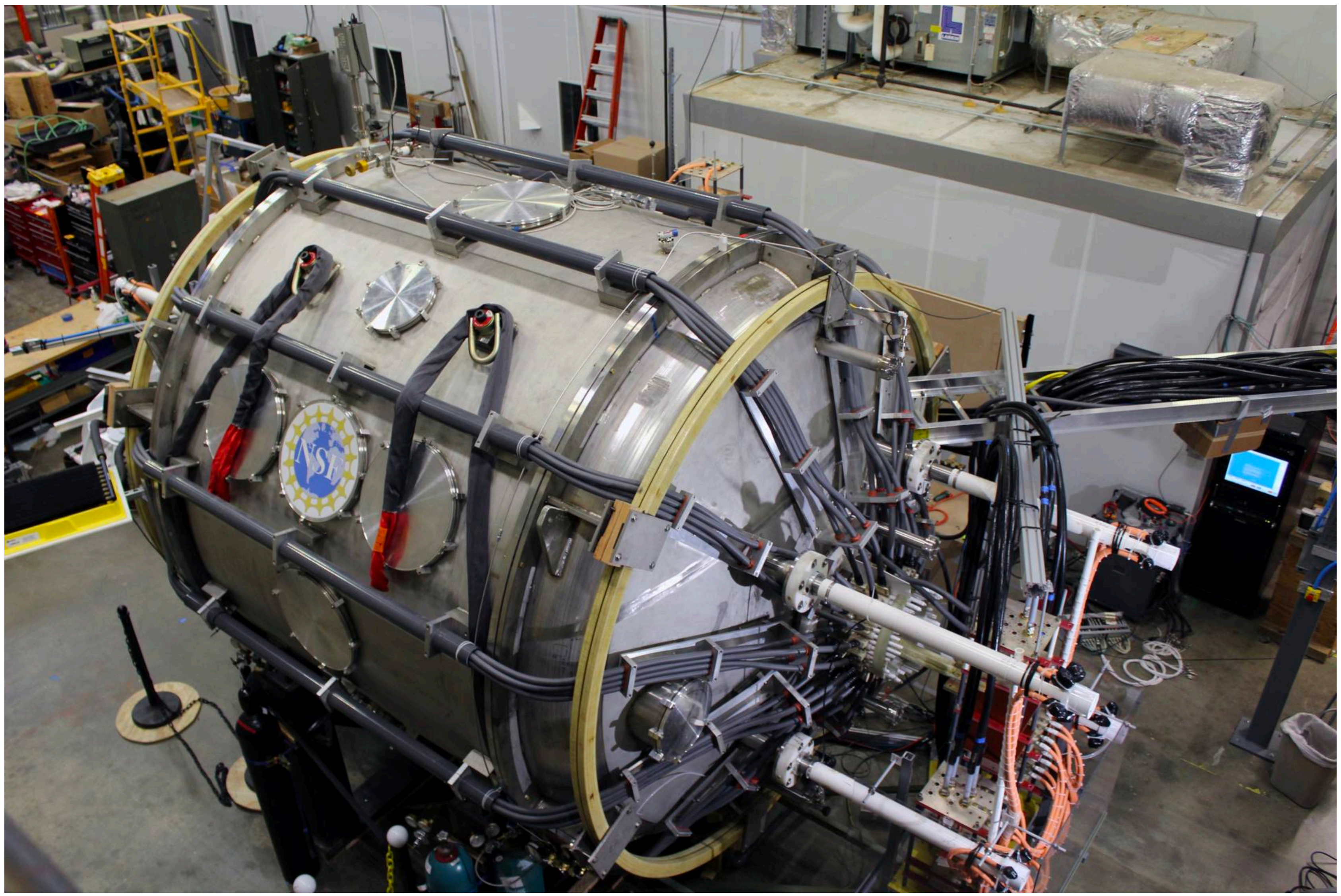


Brambles et al. [2011]

Examples of Magnetic Reconnection

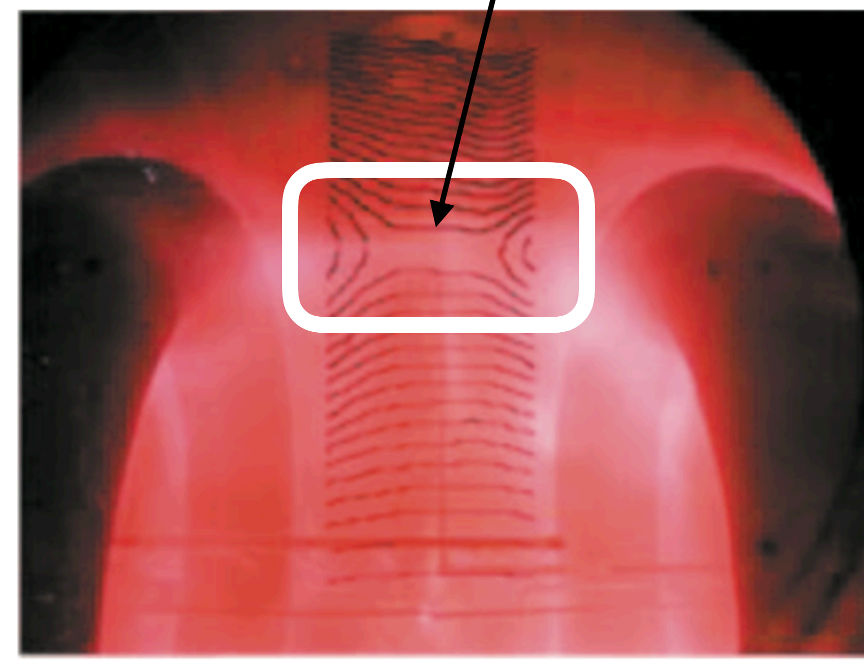
Laboratory Plasma

MRX @Princeton Plasma Physics Laboratory (PPPL)



http://mrx.pppl.gov/.

Reconnection

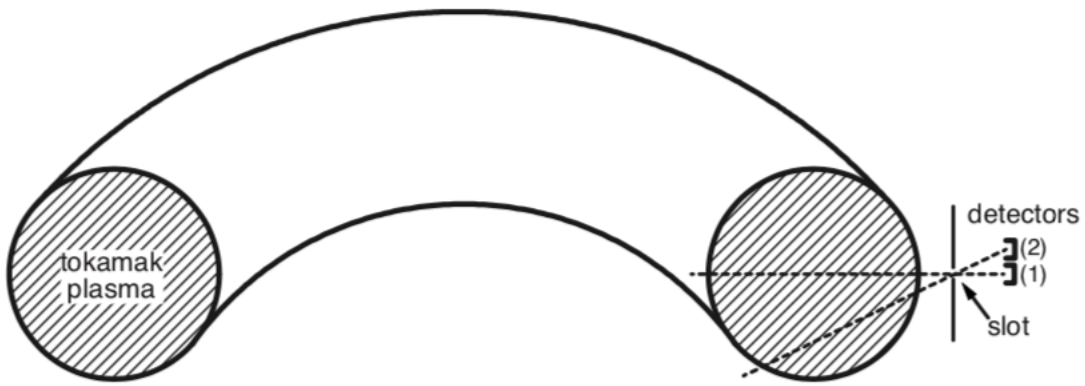


Photograph time integrated of controlled driven reconnection discharges in hydrogen in the MRX, superimposed with flux contours calculated from measurements by magnetic probes. Oppositely directed field lines are seen to meet and reconnect in the recon- nection region. From Yamada, 1999b.

Examples of Magnetic Reconnection

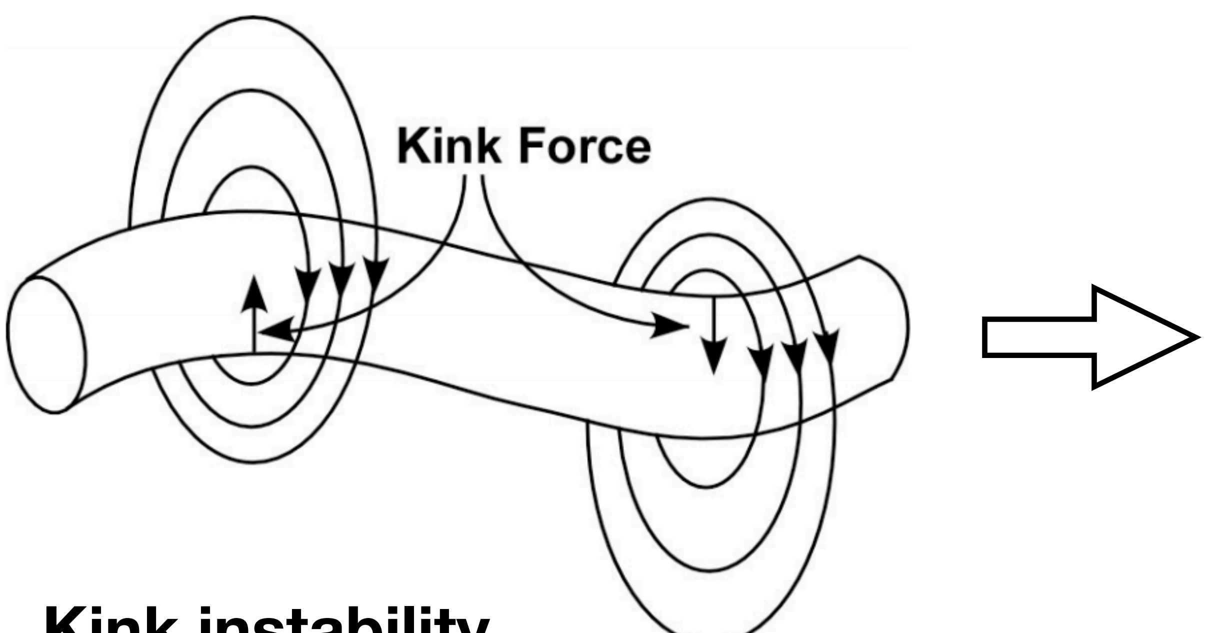
Sawtooth reconnection in Tokamaks

Confined hot plasma

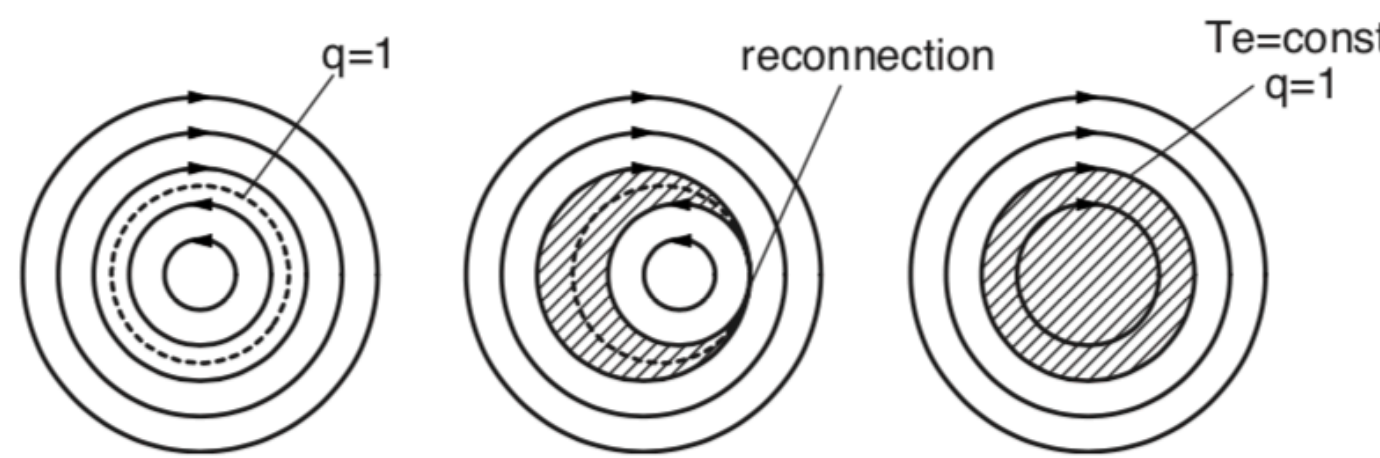


Sawtooth changes in Te

This phenomenon is a consequence of plasma instability (MHD physics) and magnetic reconnection (not entirely MHD physics):



Kink instability



Open Questions in Magnetic Reconnection

- What sets the reconnection rate? - how fast do topology and energy change
- Why there is often a sudden onset to fast reconnection? - explosive
- What is the interplay between microphysics and global dynamics? - scales of physics
- How are particles accelerated and heated?
- What are the roles of turbulence, instabilities and asymmetry?
- How does magnetic reconnection occur in 3D configuration space?
- How does reconnection behave in extreme astrophysical environments?
    - Neutron star atmospheres
    - Supernovae
    - Black hole accretion
    - Stellar chromospheres
    - Protoplanetary disks

Magnetic Reconnection in MHD

- Release of magnetic energy into kinetic and thermal energy
  - Usually the process is explosive (MHD like)

Let's take a look at the energy equations in MHD

Kinetic energy $$\frac{\partial}{\partial t}(\frac{1}{2}\rho u^2) + \nabla \cdot (\frac{1}{2}\rho u^2 \mathbf{u}) + \mathbf{u} \cdot \nabla p - \mathbf{u} \cdot \mathbf{J} \times \mathbf{B} = 0$$

Internal energy $$\frac{\partial}{\partial t}\rho e + \nabla \cdot \rho e \mathbf{u} + p \nabla \cdot \mathbf{u} = 0$$

Magnetic energy $$\frac{\partial}{\partial t}(\frac{1}{2}B^2) + \nabla \cdot \left[B^2 \mathbf{u} - \mathbf{u} \cdot \mathbf{B}\mathbf{B}\right] + \mathbf{u} \cdot \mathbf{J} \times \mathbf{B} = 0$$

So magnetic energy can only be converted to kinetic energy through motion (not thermal energy). Then the first thing to try is to include resistivity $\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J}$

Kinetic energy $$\frac{\partial}{\partial t}(\frac{1}{2}\rho u^2) + \nabla \cdot (\frac{1}{2}\rho u^2 \mathbf{u}) + \mathbf{u} \cdot \nabla p - \mathbf{u} \cdot \mathbf{J} \times \mathbf{B} = 0$$

Internal energy $$\frac{\partial}{\partial t}\rho e + \nabla \cdot \rho e \mathbf{u} + p \nabla \cdot \mathbf{u} - \eta J^2 = 0$$

Magnetic energy $$\frac{\partial}{\partial t}(\frac{1}{2}B^2) + \nabla \cdot \left[B^2 \mathbf{u} - \mathbf{u} \cdot \mathbf{B}\mathbf{B}\right] + \mathbf{u} \cdot \mathbf{J} \times \mathbf{B} + \eta J^2 = 0$$

Magnetic Reconnection in MHD

The idea of magnetic reconnection first originated in the attempts to understand the heating of the solar corona and the origin of the enormous energy observed in solar flares.

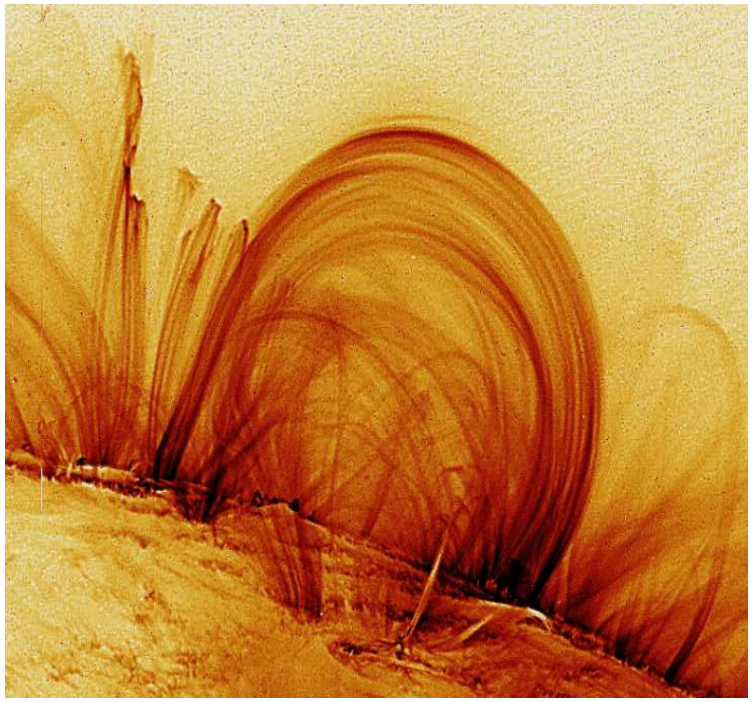
So the **resistivity** term converts magnetic energy to thermal energy (heating). Are we done?

Not really! If all the reconnection is through resistivity, then the time scale is estimated as

$$\tau \sim R_m \cdot V_A$$

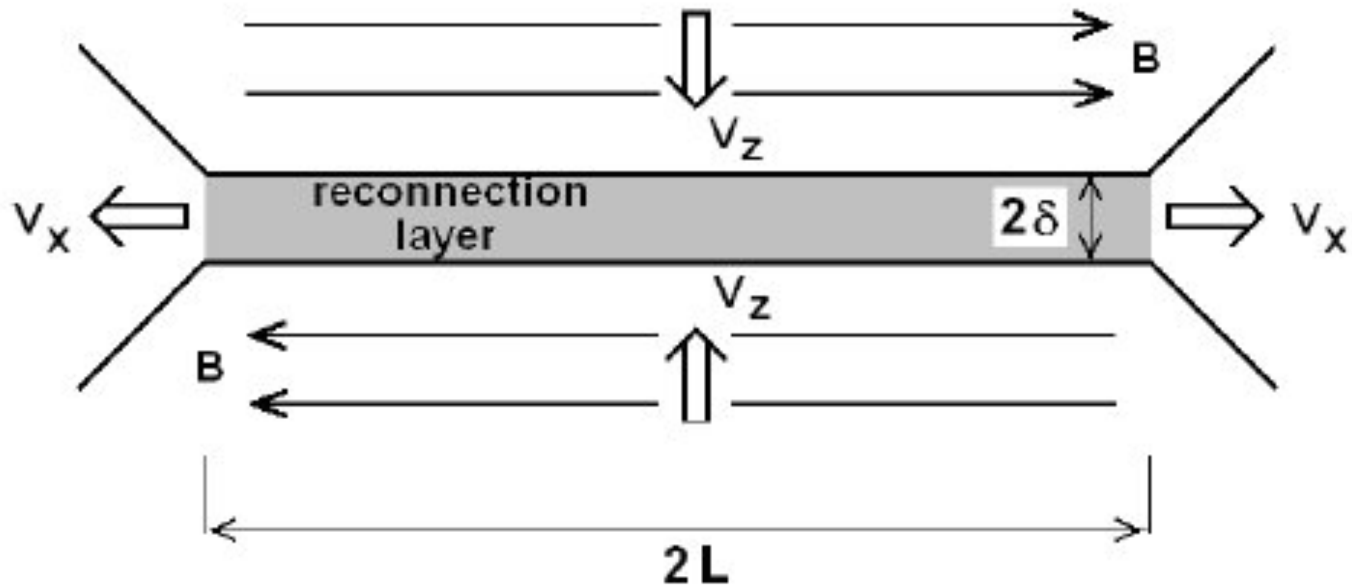
In collisionless plasmas tau is typically huge, which means the energy conversion between magnetic field and plasma is very slow - not observed

In the solar corona, the resistive decay time is usually 10^8 second (several years), much slower than the observed solar flare time scale (minutes to hours)



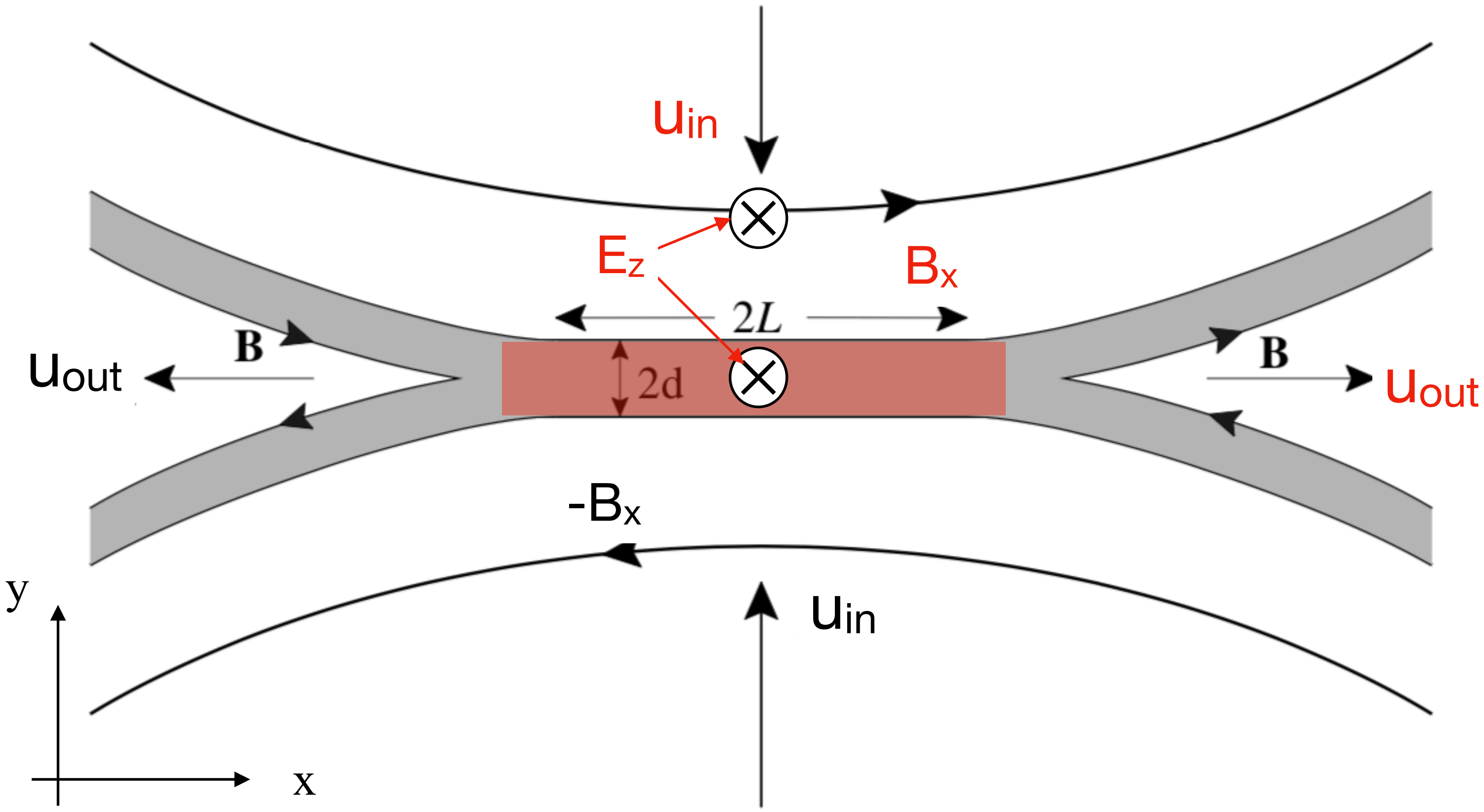
Resistivity is unlikely the answer!

The Sweet-Parker Model



- The Sweet-Parker model provides the simplest description of resistive reconnection
- Assumptions of the Sweet-Parker model
  - Steady-state
    - Uniform or out-of-plane electric field
    - Balance stuff going into the current sheet with stuff leaving it
  - Elongated current sheet
    - Neglect kinetic energy of inflow
    - Neglect magnetic energy of outflow
  - No resistivity outside the current sheet
  - No 3D effects

The Scales of the Sweet-Parker Model



Ohm's law: $\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J}$

- Outside the diffusion layer:

$$E_z + u_{in} B_x = 0$$

- Inside the diffusion layer:

$$E_z = \eta J_z$$

- Connect the two electric fields using Faraday's law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}} = 0$$

Which means the electric field outside and inside the diffusion layer must equal: $\boxed{u_{in} B_x = \eta J_z}$

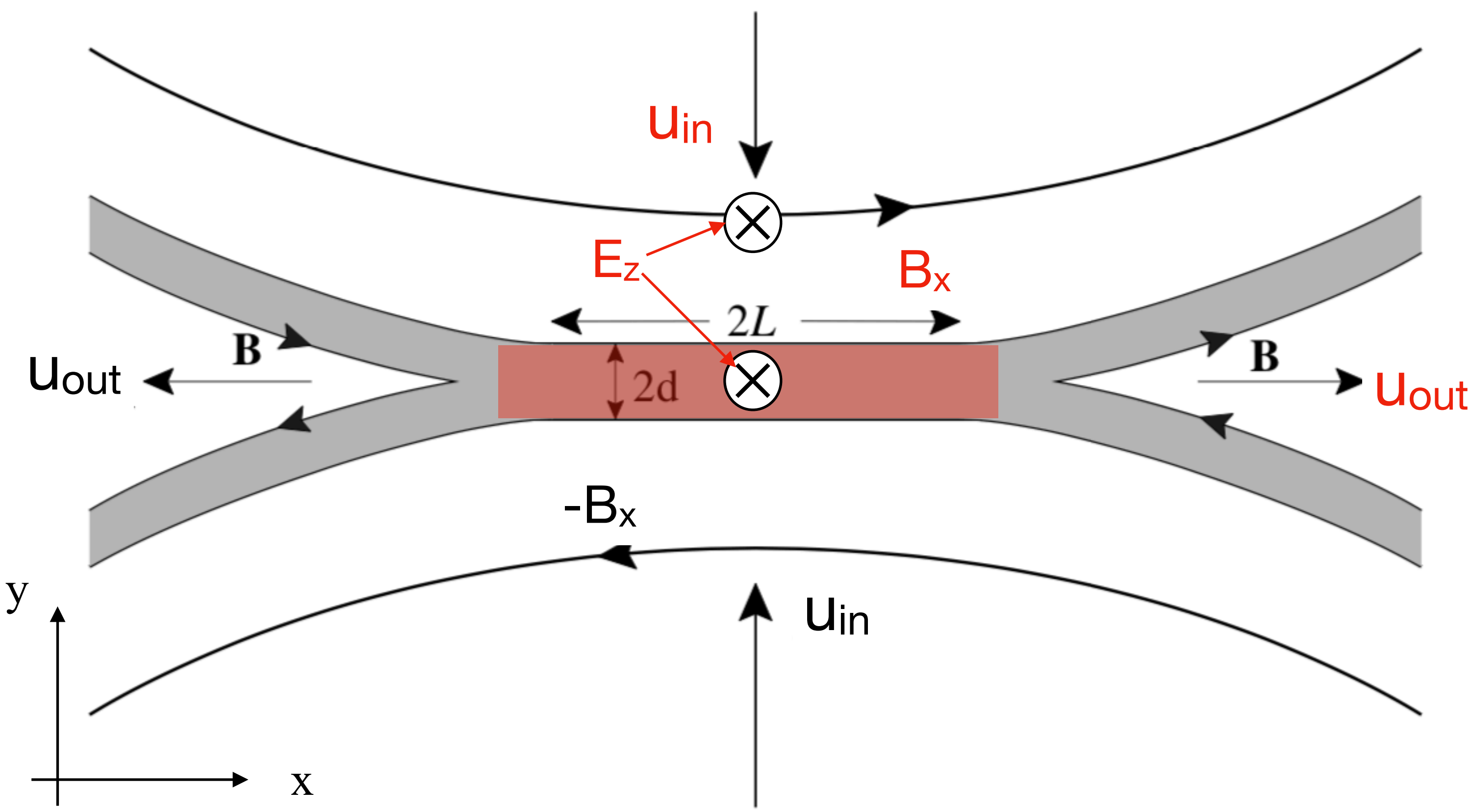
Energy conservation (all inflow magnetic energy converts to kinetic energy):

$$\frac{1}{2} B_{in}^2 = \frac{1}{2} \rho u_{out}^2 \longrightarrow \boxed{u_{out} = V_A \equiv \frac{B_x}{\sqrt{\rho}}}$$

Ampere's law:

$$\int \mathbf{B} \cdot d\mathbf{l} = I \xrightarrow{\text{Integrate around resistive layer}} B_x(4L) \approx J_z \cdot (2L) \cdot (2\delta) \longrightarrow \boxed{B_x = J_z \delta}$$

The Scales of the Sweet-Parker Model



If we combine the results from Ohm's law and Ampere's law, we find the inflow:

$$\boxed{u_{in} = \frac{E_z}{B_x} = \frac{\eta J_z}{J_z \delta} = \frac{\eta}{\delta}}$$

Interesting interpretation of the above:

$$\frac{u_{in}\delta}{\eta} \equiv R_m = 1$$

This equation means that the inflow speed and the width of the diffusion layer adjust themselves such that the magnetic Reynold's number is 1 - convection balances diffusion

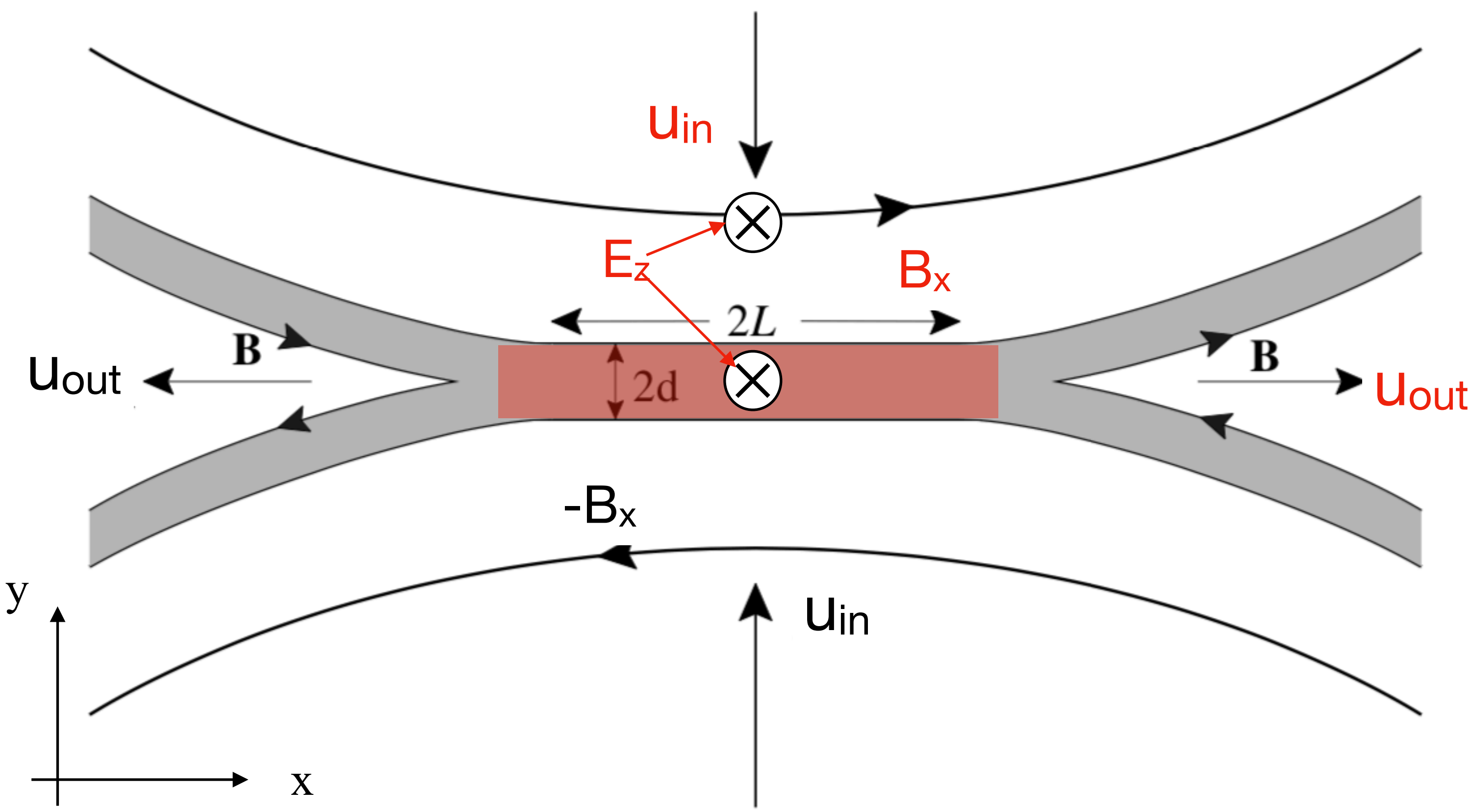
Now we can find the ***reconnection rate*** - which is basically the electric field **Ez** inside the diffusion layer - why?

Let's take a look at the unit of the electric field:

$$E \sim \frac{B}{u} \longrightarrow \frac{\mathrm{Wb/m^2}}{\mathrm{m/s}} = \frac{\mathrm{Wb}}{\mathrm{m \cdot s}} \longrightarrow$$ Flux per unit length per second

That's exactly the time rate of creating magnetic flux per unit length!

The Scales of the Sweet-Parker Model



If we combine the results from Ohm's law and Ampere's law, we find the inflow:

$$\boxed{u_{in} = \frac{E_z}{B_x} = \frac{\eta J_z}{J_z \delta} = \frac{\eta}{\delta}}$$

Recall the outflow speed

$$\boxed{u_{out} = V_A \equiv \frac{B_x}{\sqrt{\rho}}}$$

Another way of defining the reconnection rate is the ratio of inflow and outflow speed.

Consider the **conservation of mass**: $u_{in} L = u_{out} \delta$

Normalized reconnection rate

We have

$$u_{in}^2 = \left(u_{out}\frac{\delta}{L}\right)\left(\frac{\eta}{\delta}\right) \xrightarrow{u_{out} = V_A} u_{in}^2 = u_{out}^2 \frac{\eta}{V_A L} \longrightarrow \frac{u_{in}}{u_{out}} = \sqrt{\frac{1}{V_A L/\eta}} = \frac{1}{\sqrt{S}}$$

S is called the Lundquist number (recall Lecture 6) - magnetic acceleration versus diffusion

- S is defined even without external flow
- S is typically the largest Reynolds number in the problem (sub-Alfvénic)

$$S = \frac{LV_A}{\eta} = \frac{\tau_{res}}{\tau_{Alf}}$$

Is Sweet-Parker Model Good enough?

The answer is in the Maxwell's equations

If we consider the case with no flow - two semi-infinite slabs of magneto fluid with oppositely directed magnetic field are just lying together:

Faraday's law becomes:

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\cancel{\mathbf{u} \times \mathbf{B}})}_{\text{Convective} \to 0} + \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{Diffusive}} \longrightarrow \frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} \xrightarrow{\text{Diffusion Rate}} \sim \frac{1}{S}$$

So the Sweet-Parker reconnection rate is much greater than the diffusive rate: $\frac{1}{\sqrt{S}} > \frac{1}{S}$

Are we done? Not really!

Theories needs to be validated by experiments/observations - we know the Lundquist numbers *S* in most space plasmas:

- Solar corona. : 10^{12} - 10^{14}
- Earth's msphere: 10^{15} - 10^{16}
- Tokamak device: 10^{6} - 10^{8}

$\xrightarrow{\text{Sweet-Parker}}$

Solar flare: ~ months

substorms: ~ days

$\xrightarrow{\text{Compare with observations}}$ **TOO SLOW!**

The Sweet-Parker model cannot be used to explain most reconnection processes

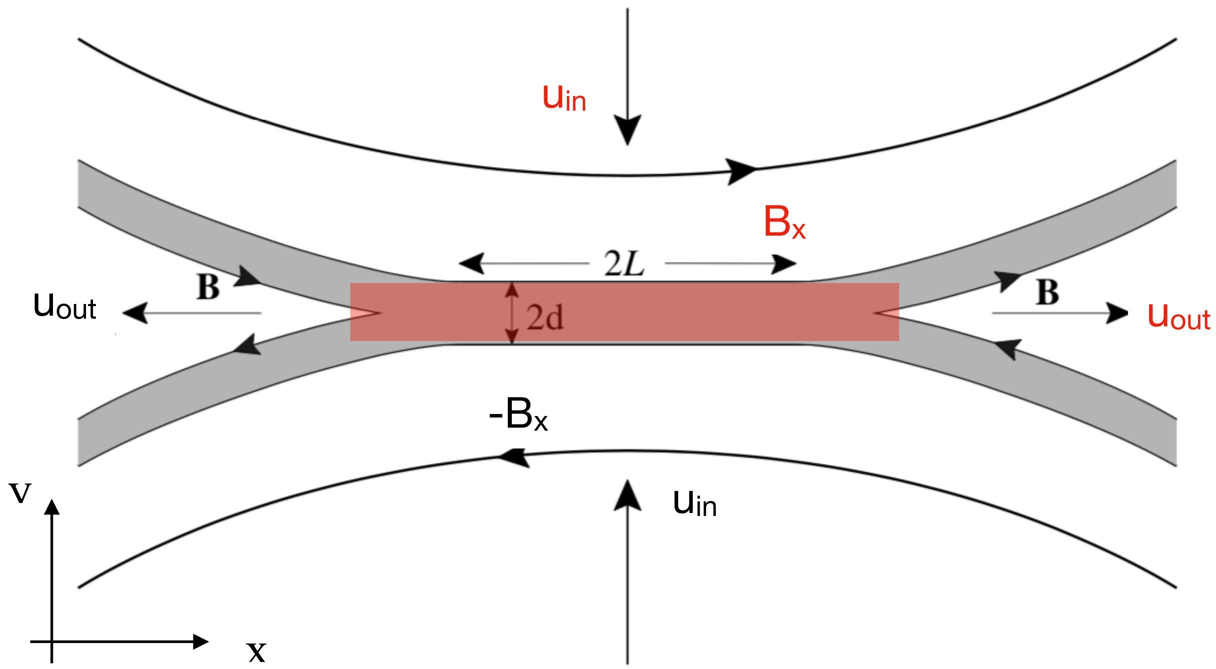
Issues with the Sweet-Parker Model

- For **large Lundquist number plasmas**, the normalized reconnection rate predicted by the Sweet-Parker model is way too slow (~1/S)
- Many of the underlying assumptions used in the Sweet-Parker model are not justified
- Elongated current sheets are unstable to the plasmoid instabilities above a critical Lundquist number of $S > 10^4$.
- The Sweet-Parker model does not describe most geophysical and astrophysical reconnection processes observed
- Cannot explain reconnection that is fast in the limit of collisionless plasma (S-> infinity)
- Fast reconnection through **anomalous resistivity**? (black magic…)
  - Other mechanisms generating higher, localized, effective resistivity? e.g., kinetic instabilities, wave-particle interactions, micro-turbulence
  - Current driven instabilities? Ad-hoc
  - But mechanisms not identified

None of the above are likely MHD physics!

The Fast Reconnection Model: Petschek

Recall the **conservation of mass** across a diffusion layer: $u_{in}L = u_{out}\delta$

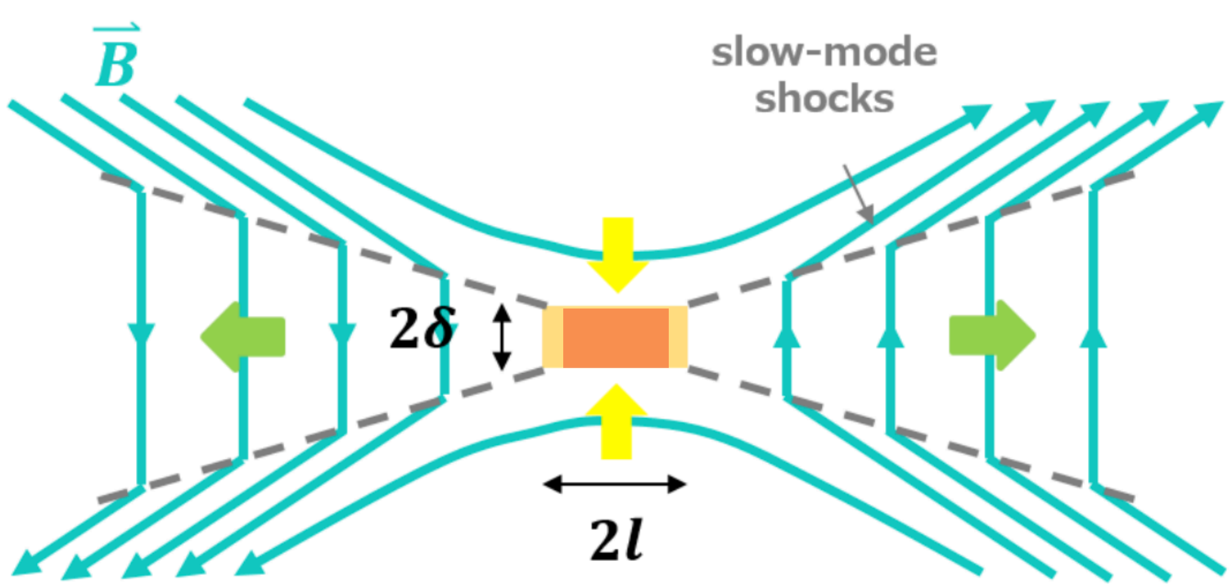


So the outflow speed is in general regulated by the aspect ratio of the diffusion layer:

$$u_{out} = \frac{\delta}{L} u_{in} \xrightarrow[\text{Elongated C.S.}]{\text{Sweet-Parker}} \frac{u_{out}}{u_{in}} = \frac{\delta}{L} \ll 1$$ **Very slow reconn.**

Thus one way to increase the reconnection rate is to have a much shorter length L: $\frac{\delta}{L} \sim \mathcal{O}(1)$

This is the so-called Petscheck (fast reconnection) Model:



Petschek [1964] argues that if the diffusion region width goes like:

$$\delta \sim L \propto \eta$$

With two pairs of slow-mode shock created by the reconnection separating the inflow and outflow region, the reconnection rate is then:

$$\frac{u_{in}}{u_{out}} \sim \frac{1}{\log S}$$ **FAST Reconnection!**

Issues with the Petschek Model

For space plasmas, the Petschek model predicts that the normalized reconnection rate is approximately:

$$\frac{u_{in}}{u_{out}} \sim \frac{1}{\log S} \sim 0.1$$

This is basically what's observed in heliophysics

Are we done? Not really!

Rule of thumb - even though model agrees with data, doesn't guarantee (physically) correct

Problems in the Petschek Model:

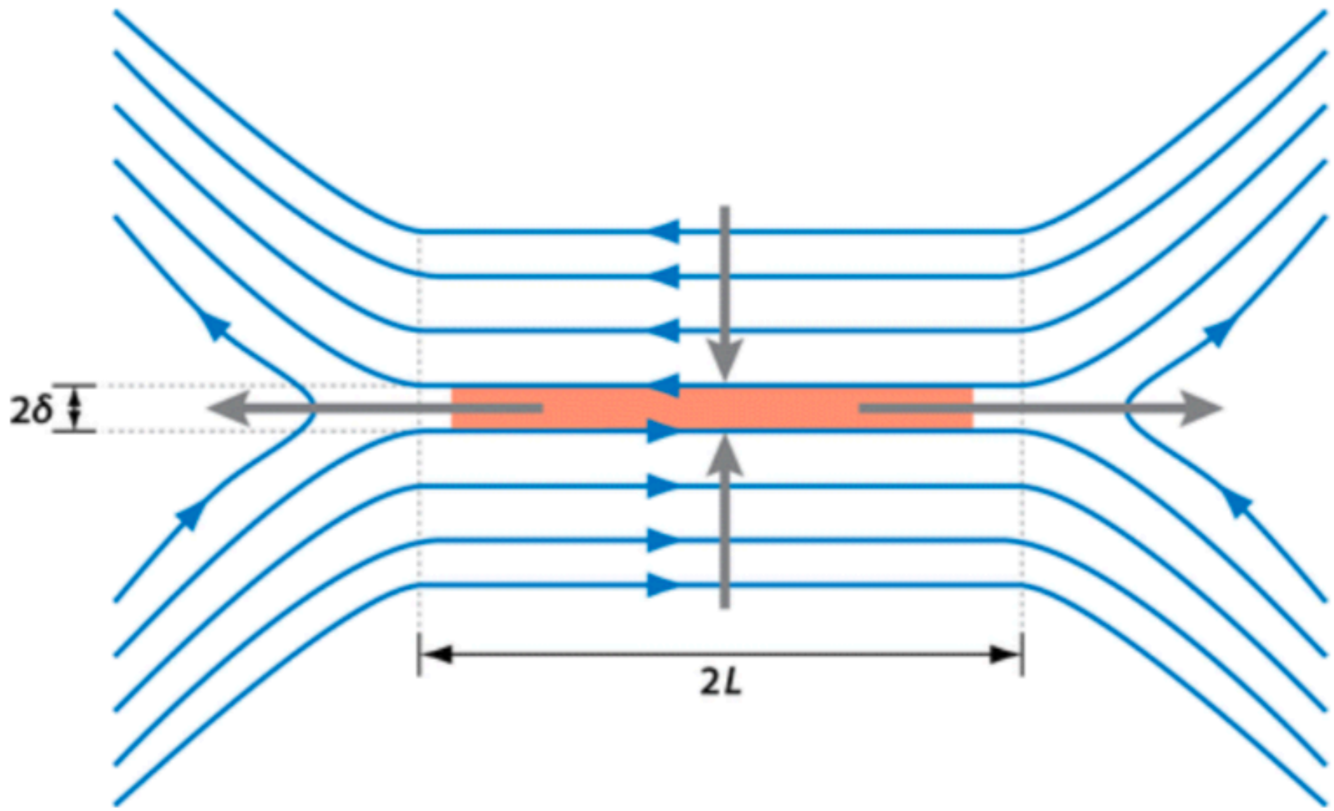
- No mechanism specified for the physics of collisionless resistivity
- Need to specify a localized dissipation (e.g., anomalous resistivity) to get the fast Petschek reconnection in resistive MHD - other collisionless effects
- BUT, these effects occur only on short temporal and spatial scales where MHD assumption of plasma breaks down

Therefore the original Petschek model was not regarded as a viable mechanism for fast reconnection

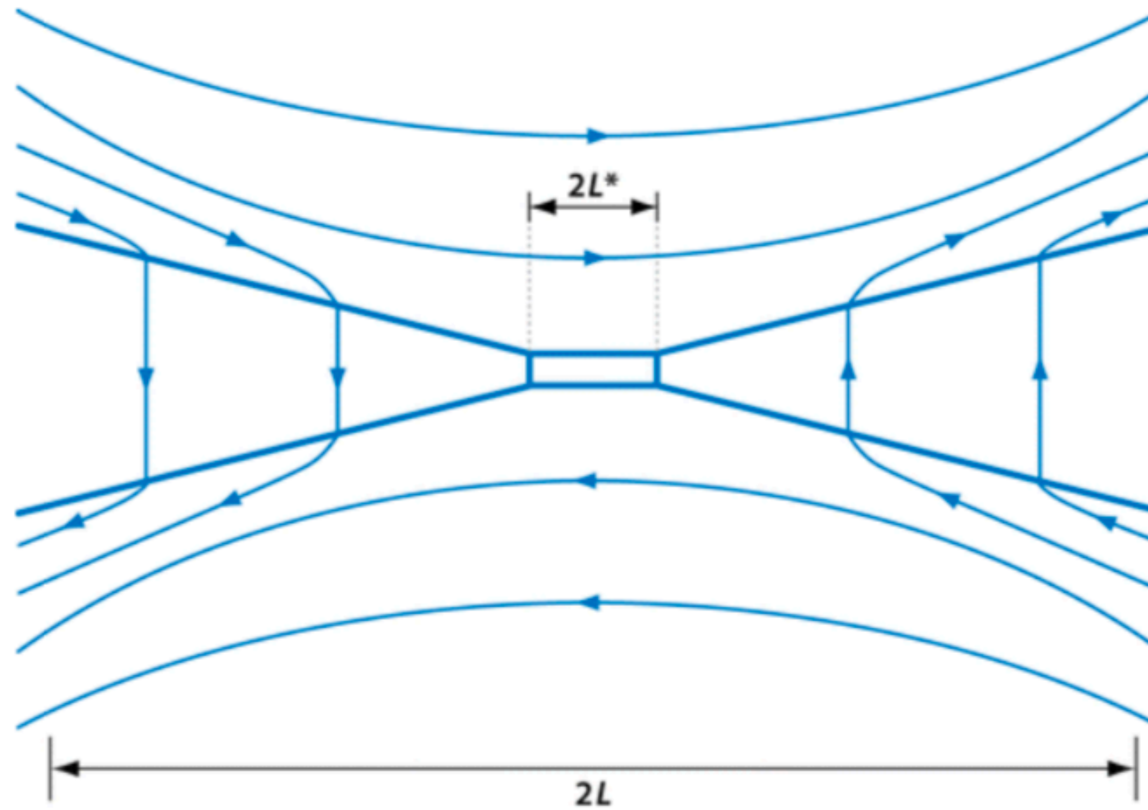
But the key insight is that reconnection is sped up when $\frac{\delta}{L} \sim \mathcal{O}(1)$!

Compare the Classic Pictures of Reconnection

Sweet-Parker



Petschek



Zweibel & Yamada (2009)

How to break the frozen-in condition in MHD?

Recall the generalized Ohm's law:

Electron momentum: $$\frac{\partial n_e m_e \mathbf{u_e}}{\partial t} + \nabla \cdot n_e m_e \mathbf{u_e}\mathbf{u_e} + \nabla p_e + e n_e(\mathbf{E} + \mathbf{u_e} \times \mathbf{B}) = \mathbf{A}_e$$

Ion momentum: $$\frac{\partial n_i m_i \mathbf{u_i}}{\partial t} + \nabla \cdot n_i m_i \mathbf{u_i}\mathbf{u_i} + \nabla p_i - e n_i(\mathbf{E} + \mathbf{u_i} \times \mathbf{B}) = -\mathbf{A}_e$$

Combine: $$(\text{electron momentum}) + (\text{ion momentum}) \times \frac{m_e}{m_i}$$

$$m_e \frac{\partial}{\partial t}(n_i \mathbf{u}_i - n_e \mathbf{u}_e) + m_e \nabla \cdot (n_i \mathbf{u}_i \mathbf{u}_i - n_e \mathbf{u}_e \mathbf{u}_e)$$

$$= \nabla\left(p_e - \frac{m_e}{m_i} p_i\right) + e\left[\left(n_e + \frac{m_e}{m_i}\right)\mathbf{E} + \left(n_e \mathbf{u}_e + \frac{m_e}{m_i} n_i \mathbf{u}_i\right) \times \mathbf{B}\right] - \left(\mathbf{A}_e + \frac{m_e}{m_i}\mathbf{A}_e\right)$$

$$\xrightarrow[\substack{n_e e \mathbf{u}_e - n_i e \mathbf{u}_i = -\mathbf{J} \\ \mathbf{A}_e = n m_e \nu_{ei}(\mathbf{u}_i - \mathbf{u}_e)}]{m_e/m_i \approx 0 \quad n_e = n_i = n} \quad \frac{m_e}{e}\frac{\partial \mathbf{J}}{\partial t} + m_e \nabla \cdot (n \mathbf{u}_i \mathbf{u}_i - n \mathbf{u}_e \mathbf{u}_e) = \nabla p_e + ne(\mathbf{E} + \mathbf{u}_e \times \mathbf{B}) - \underbrace{n m_e \nu_{ei}(\mathbf{u}_i - \mathbf{u}_e)}_{\sim ne\eta\mathbf{J}}$$

From the multi-fluid Hall MHD equations we know that $\mathbf{u}_e \approx \mathbf{u} - \frac{\mathbf{J}}{ne} \quad \mathbf{u}_i \approx \mathbf{u} + O(\frac{m_e}{m_i})$

Then $$\frac{m_e}{ne}\nabla \cdot (n \mathbf{u}_i \mathbf{u}_i - n \mathbf{u}_e \mathbf{u}_e) = \frac{m_e}{ne^2}\nabla \cdot \left(\mathbf{u}\mathbf{J} + \mathbf{J}\mathbf{u} - \frac{\mathbf{J}\mathbf{J}}{ne}\right)$$

Generalized Ohm's law

$$\boxed{\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\mathbf{J} \times \mathbf{B} - \frac{1}{ne}\nabla p_e + \frac{m_e}{ne^2}\nabla \cdot \left(\mathbf{u}\mathbf{J} + \mathbf{J}\mathbf{u} - \frac{\mathbf{J}\mathbf{J}}{ne}\right)}$$

How to break the frozen-in condition in MHD?

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\mathbf{J} \times \mathbf{B} - \frac{1}{ne}\nabla p_e + \frac{m_e}{ne^2}\nabla \cdot \left(\mathbf{uJ} + \mathbf{Ju} - \frac{\mathbf{JJ}}{ne}\right)$$

Convective

MHD scale

Resistive

Collision scale

Hall

Ion gyro scale

Ambipolar

Electron thermal scale

Electron inertia

Electron intertial scale

The frozen-in condition (E+uxB = 0) may be broken by

- The classic/anomalous resistivity term
- The divergence of the electron pressure term
- The electron inertia term

Again: the Hall term is NOT a resistivity

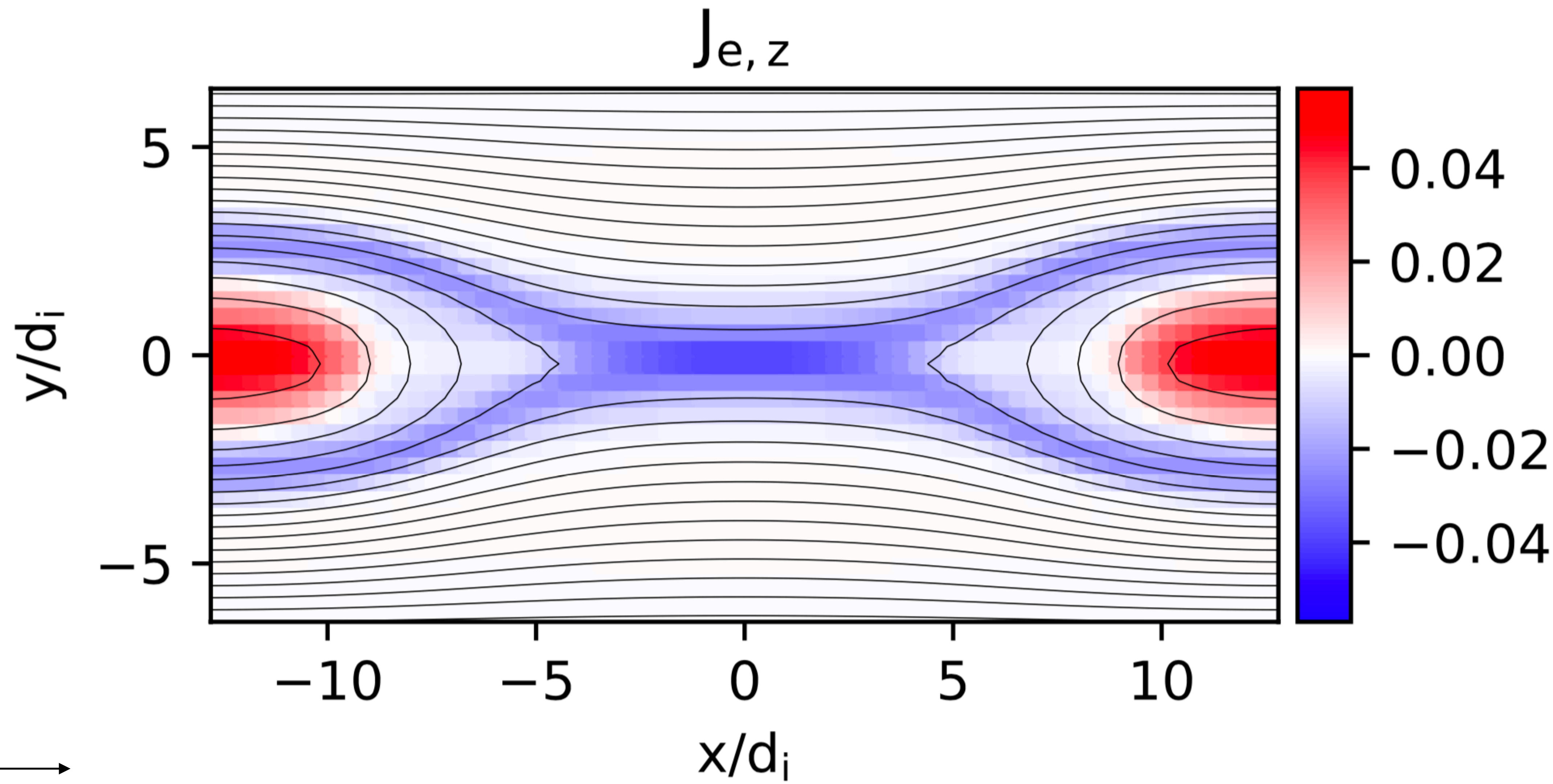
HOWEVER, the Hall term doesn't break the frozen-in condition but can restructure the reconnection region (collisionless reconnection) - Why?

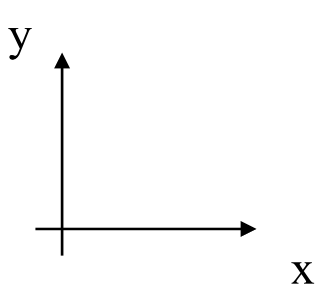
$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \frac{1}{ne}\mathbf{J} \times \mathbf{B} \xrightarrow{\mathbf{J}/ne = \mathbf{v_d}} \mathbf{E} + (\mathbf{u} - \mathbf{u}_d) \times \mathbf{B} = 0$$

Still forze-in

All these additional terms in the generalized Ohm's law introduce new physics into the system over short spatial and temporal scales - e.g., ion inertial length, electron gyro scale

The GEM Reconnection Challenge





Initial conditions:

$$B_x(y) = B_0 \tanh(y/\lambda)$$

$$n(y) = n_0 \mathrm{sech}^2(y/\lambda) + n_\infty$$

$$p(y) + B^2(y) = \mathrm{const}$$

Equilibrium state

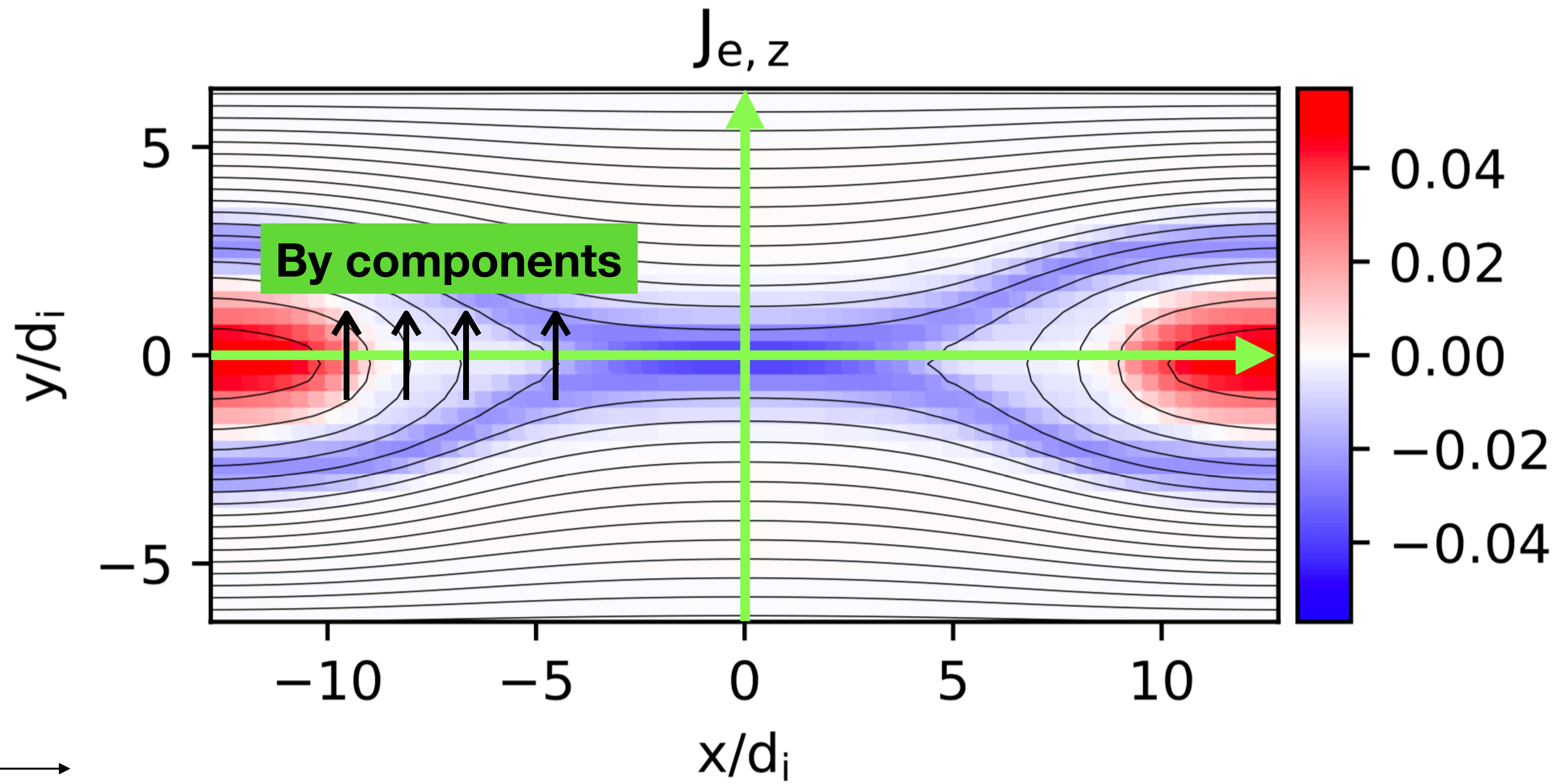
$$\mathbf{B}_1 = \hat{\mathbf{y}} \times \nabla \psi$$

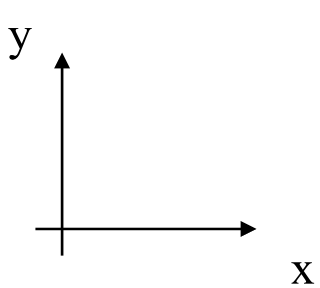
$$\psi(x, y) = \psi_0 \cos(2\pi x/L_x)\cos(\pi y/L_y)$$

Perturbation

So the GEM reconnection is driven rather than spontaneous

The GEM Reconnection Challenge



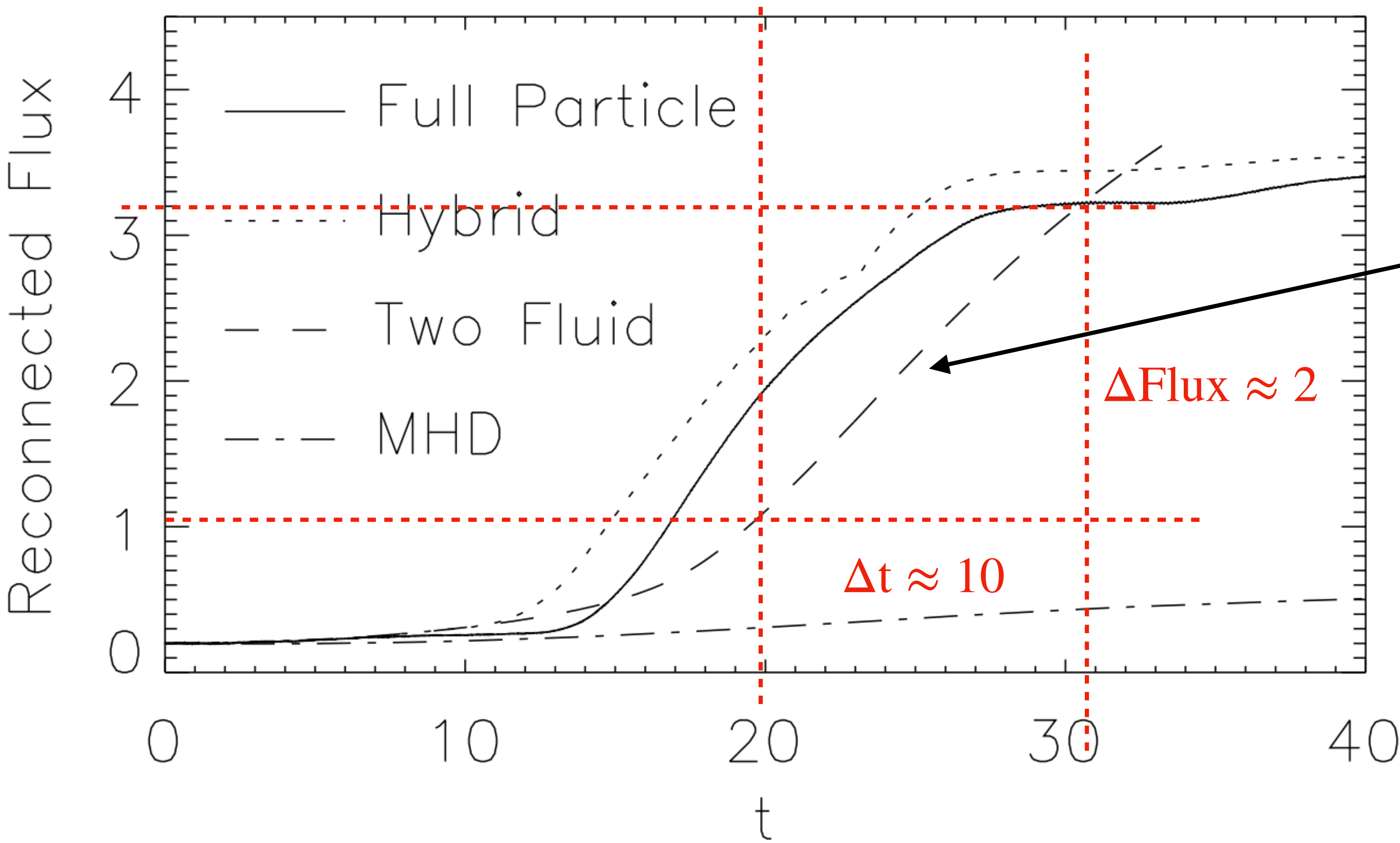


To estimate the reconnection rate in the simulations we use the Faraday's law:

$$\frac{d}{dt}\int \mathbf{B}\cdot d\mathbf{S} = \oint \mathbf{E}\cdot d\mathbf{l} \xrightarrow{\text{2-D geometry}} \underbrace{\frac{d}{dt}\int B_y \cdot dx}_{\text{Rate of creating magnetic flux}} = \phi_{reconn}$$

Reconnection Potential

The GEM Reconnection Challenge



The slope is basically the reconnection rate

$$\frac{d}{dt}\int B_y \cdot dx = \phi_{reconn}$$

The reconnection rate is approximately 0.2

Conclusions from the GEM reconnection challenge

- When uniform resistive is used - get Sweet-Parker (slow) reconnection
- The Hall term determines the fast reconnection rate, not the dissipation
- The reconnection rate is insensitive to the dissipation mechanism, and is much larger than the resistive MHD reconnection rate

Limitations of the GEM reconnection challenge

- 2-D physics
- Does not adapt to solar reconnection where energy is important

But, Hall Physics isn't Everything!

- In resistive Hall MHD, elongated current sheets becomes unstable easily, more like X-points

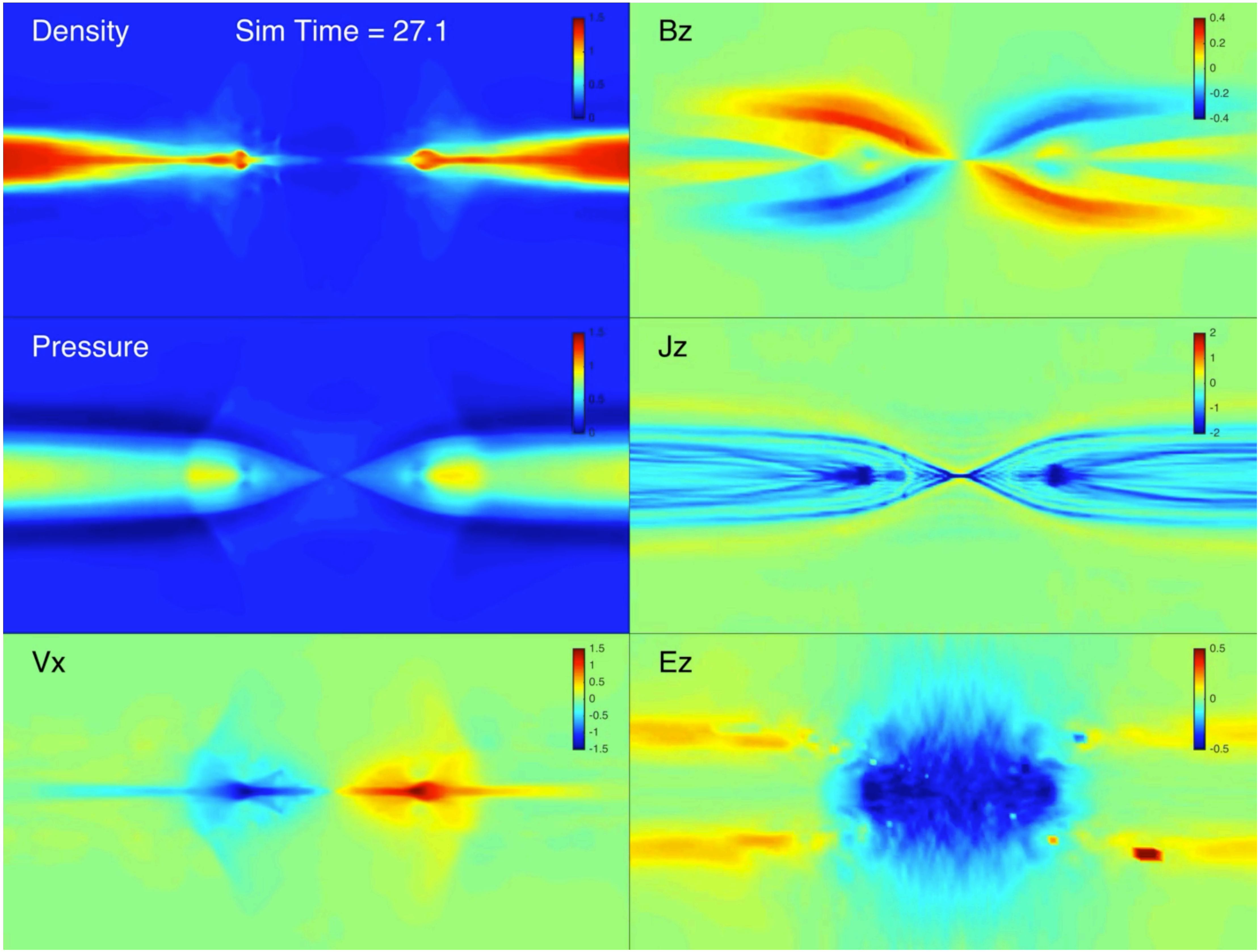
- The $\dfrac{\nabla \cdot \mathbf{P}_e}{ne}$ term is best studied using particle simulations (PIC, particle-in-cell)

- PIC simulations of magnetic reconnection in a positron-electron plasma still show fast reconnection - there's no Hall term!

- 3-D configuration is important for magnetic reconnection in general

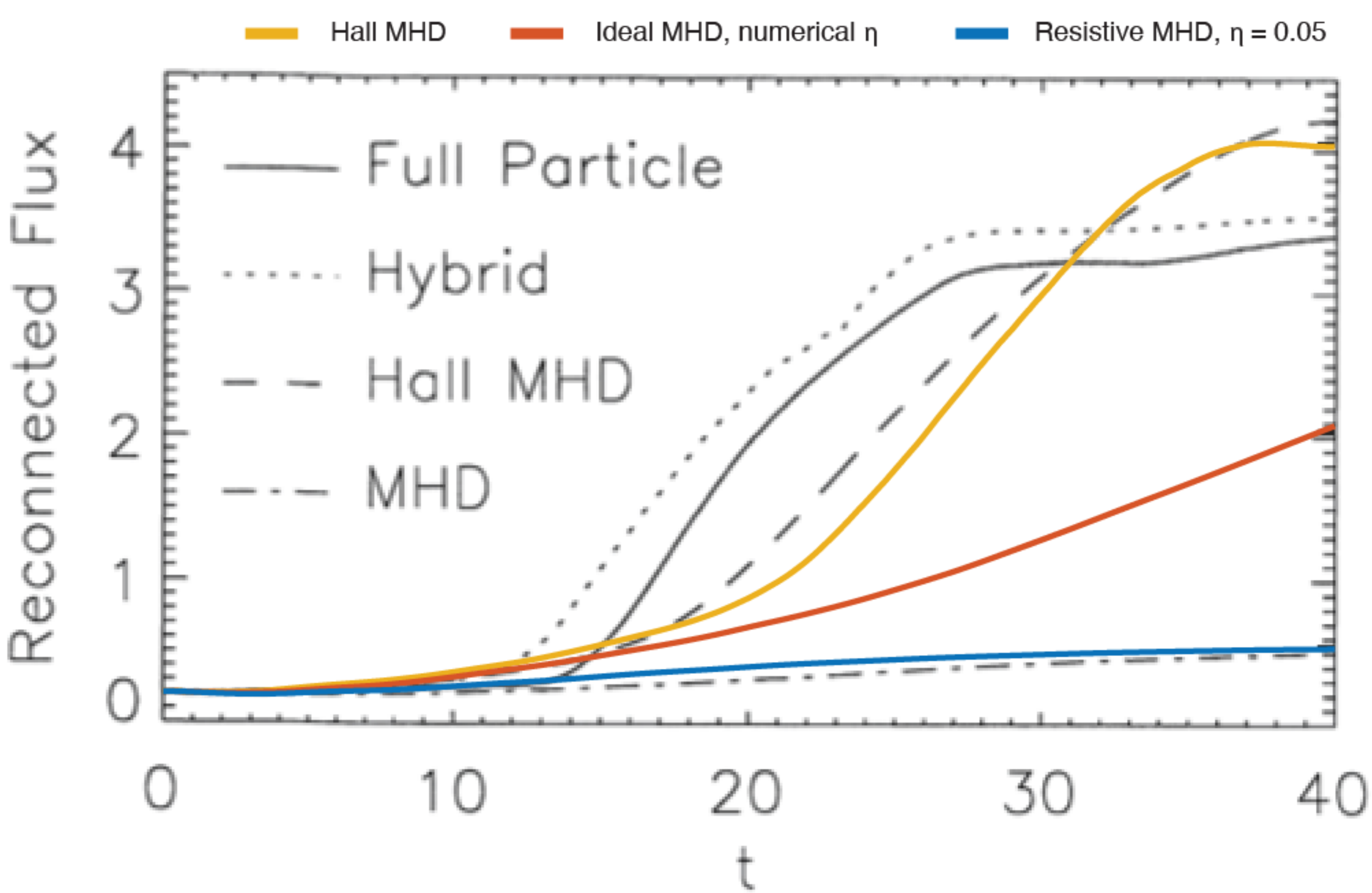
- Collisionless reconnection is fundamentally different from Sweet-Parker and Petschek reconnection models - electron-ion decouple at small scales

The GEM Reconnection using Hall MHD



The GEM Reconnection using MHD

GAMERA simulations



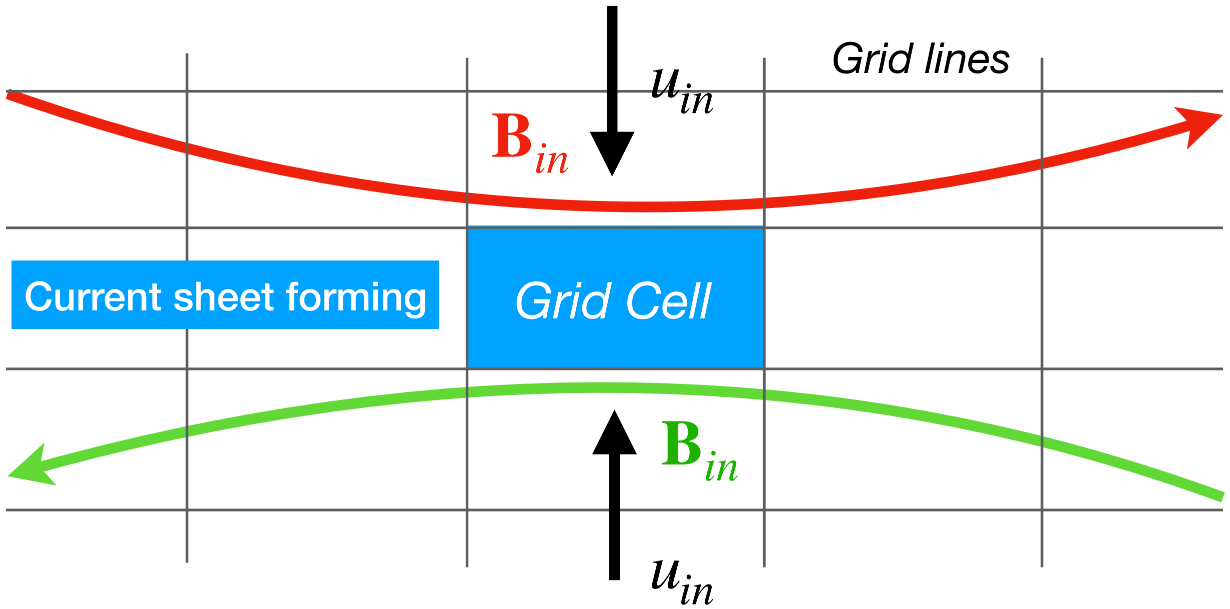
Conclusions from the GAMREA-GEM reconnection challenge

- Resistive GAMERA simulations (eta = 0.05) shows slow reconnection
- Hall GAMERA simulations gives fast reconnection (~0.2)
- The vanilla simulation (“ideal” MHD) gives also fast reconnection rate (0.1)

Some thing wrong here?

The odd thing here is numerical resistivity

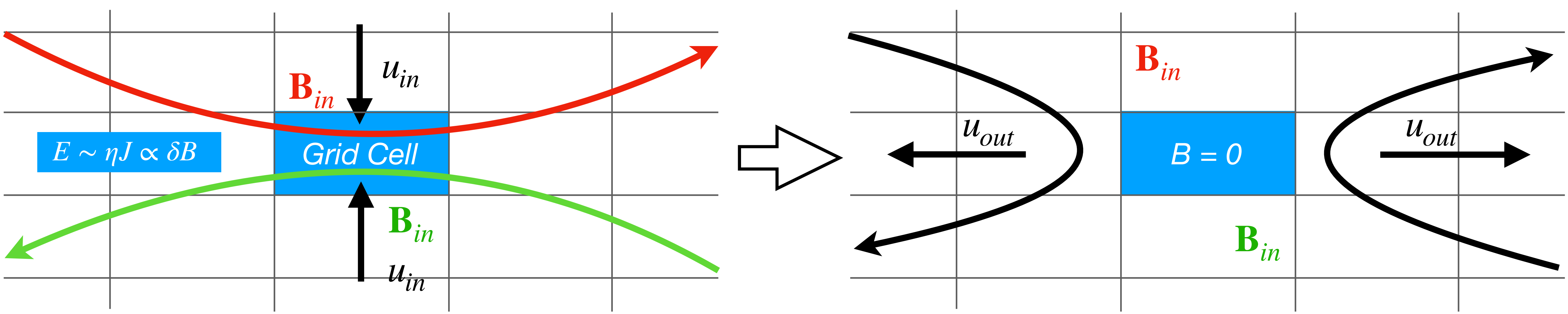
This is how reconnection works in global magnetosphere models (Gamera)



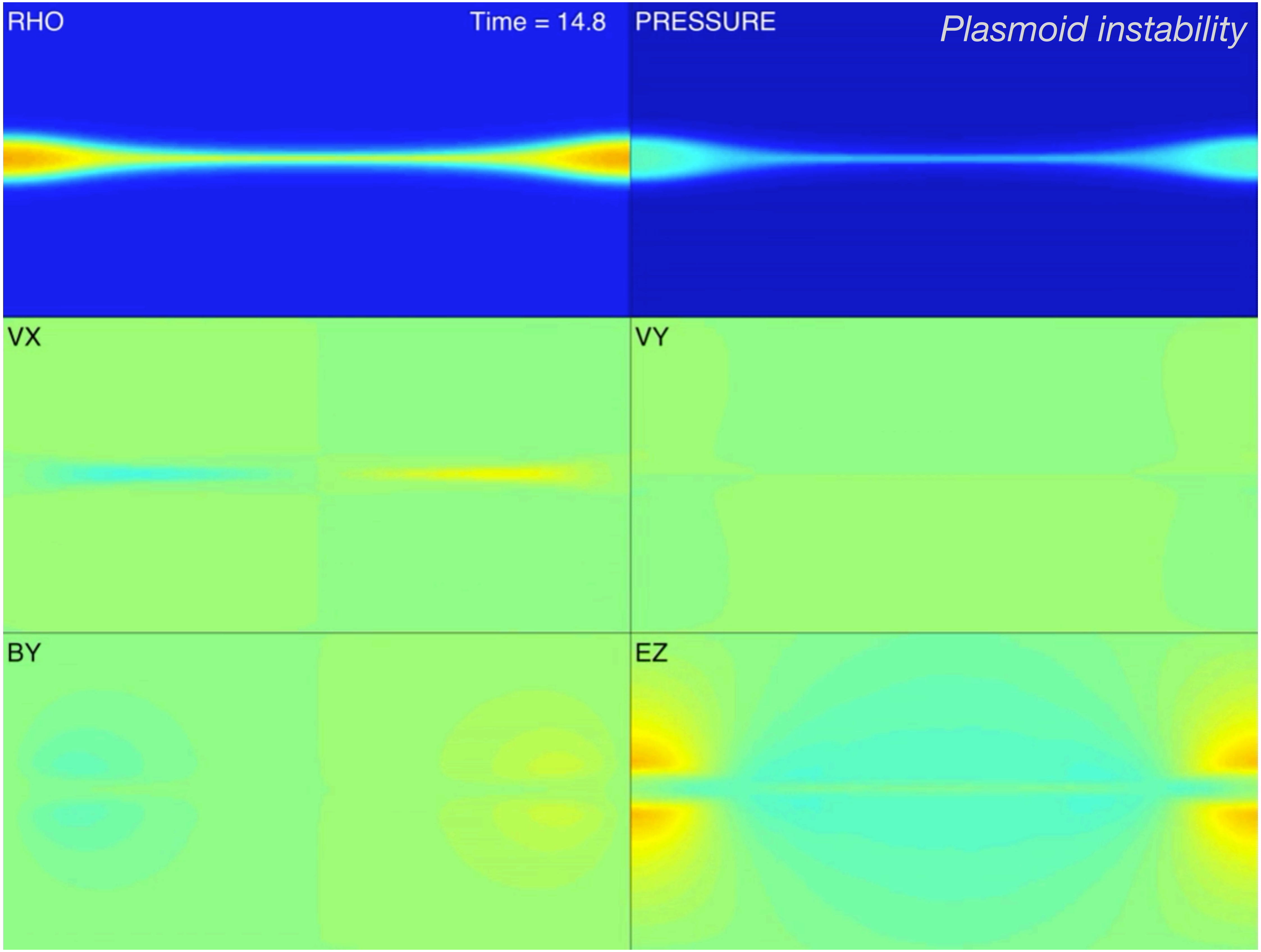
The process of numerical resistivity:

1. Opposite directed magnetic flux tubes approaching a single grid cell (magnetic shear approaching grid scale)
2. Only one solution is allowed in the “diffusion cell”
3. Numerical resistivity from the MHD solver is enabled to annihilate the magnetic field entering the cell - numerical reconnection

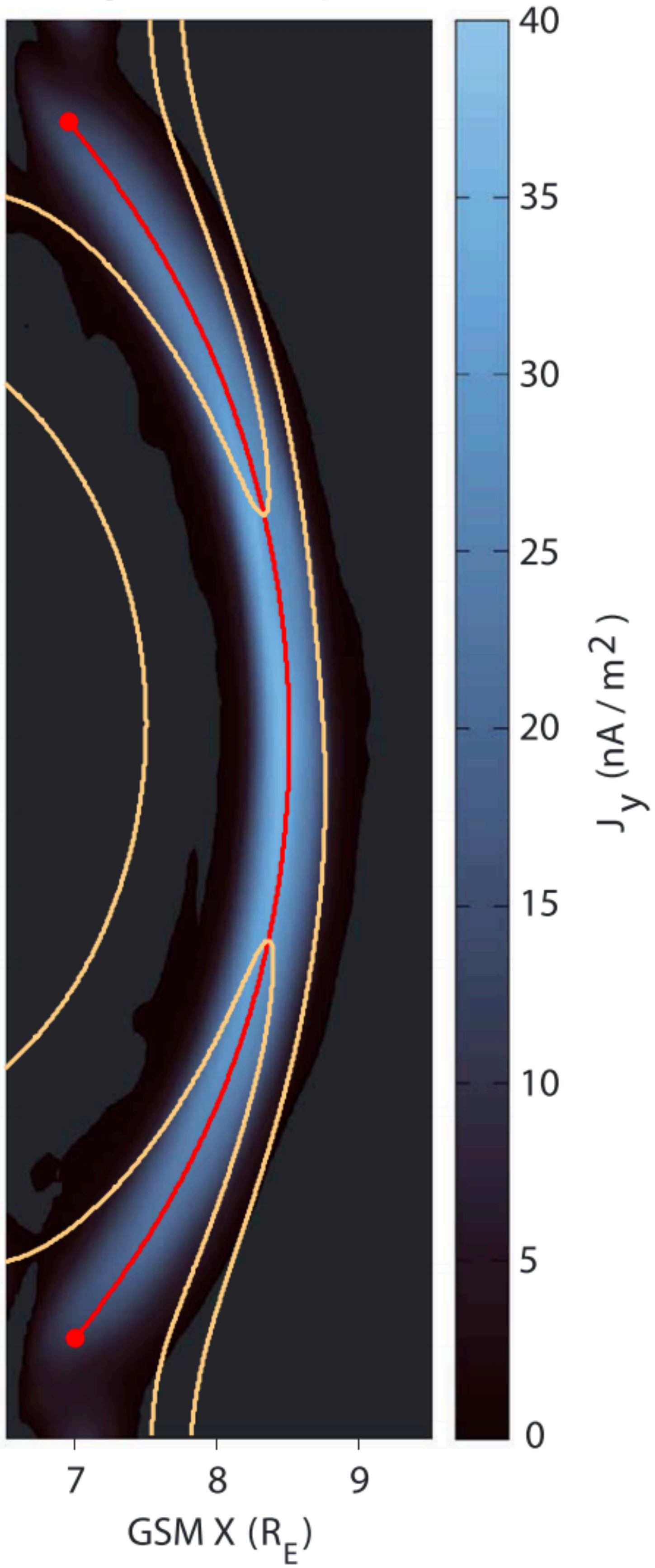
The rate of numerical reconnection is determined by the inflow conditions, through **conservation of mass, energy and flux**



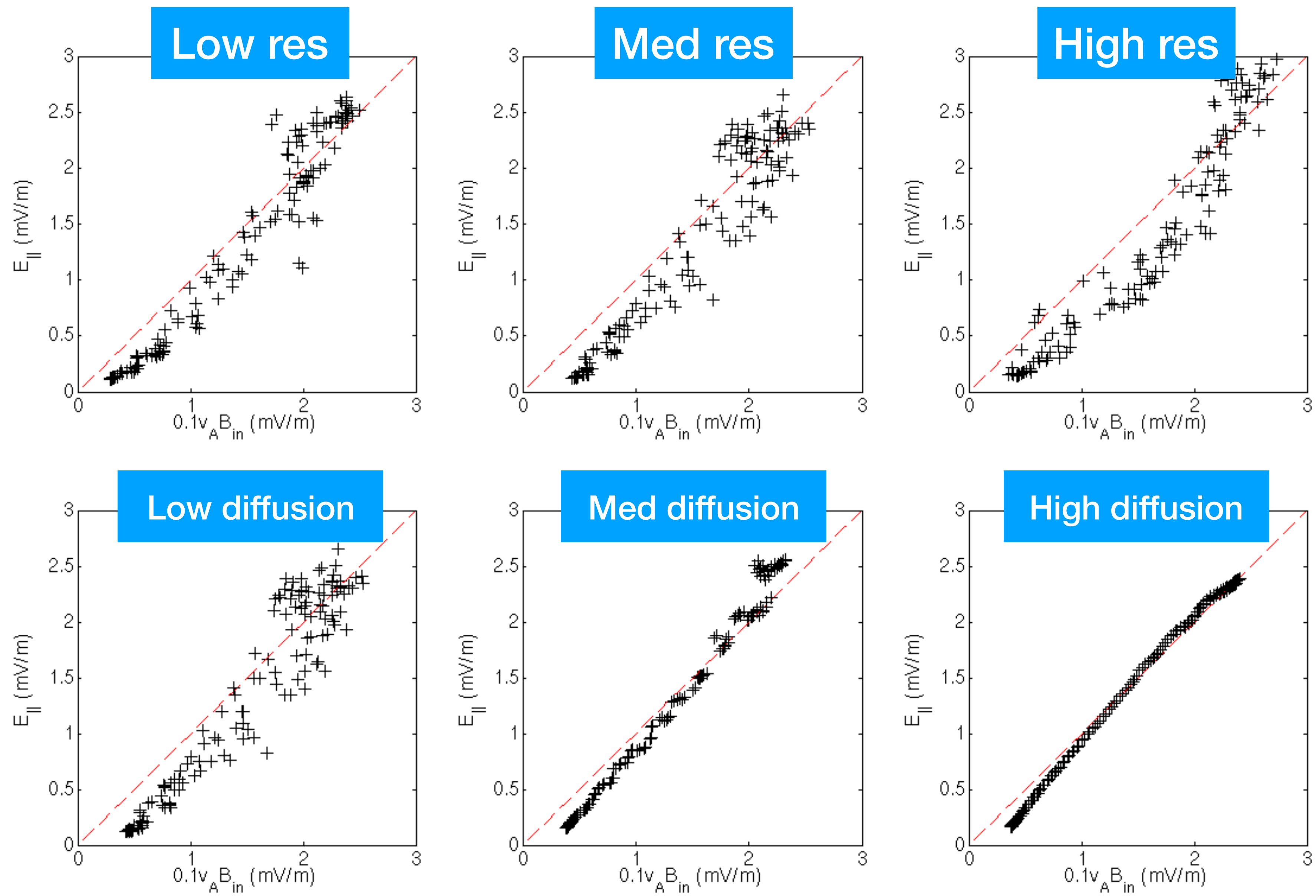
The GEM Reconnection w/ numerical reconn



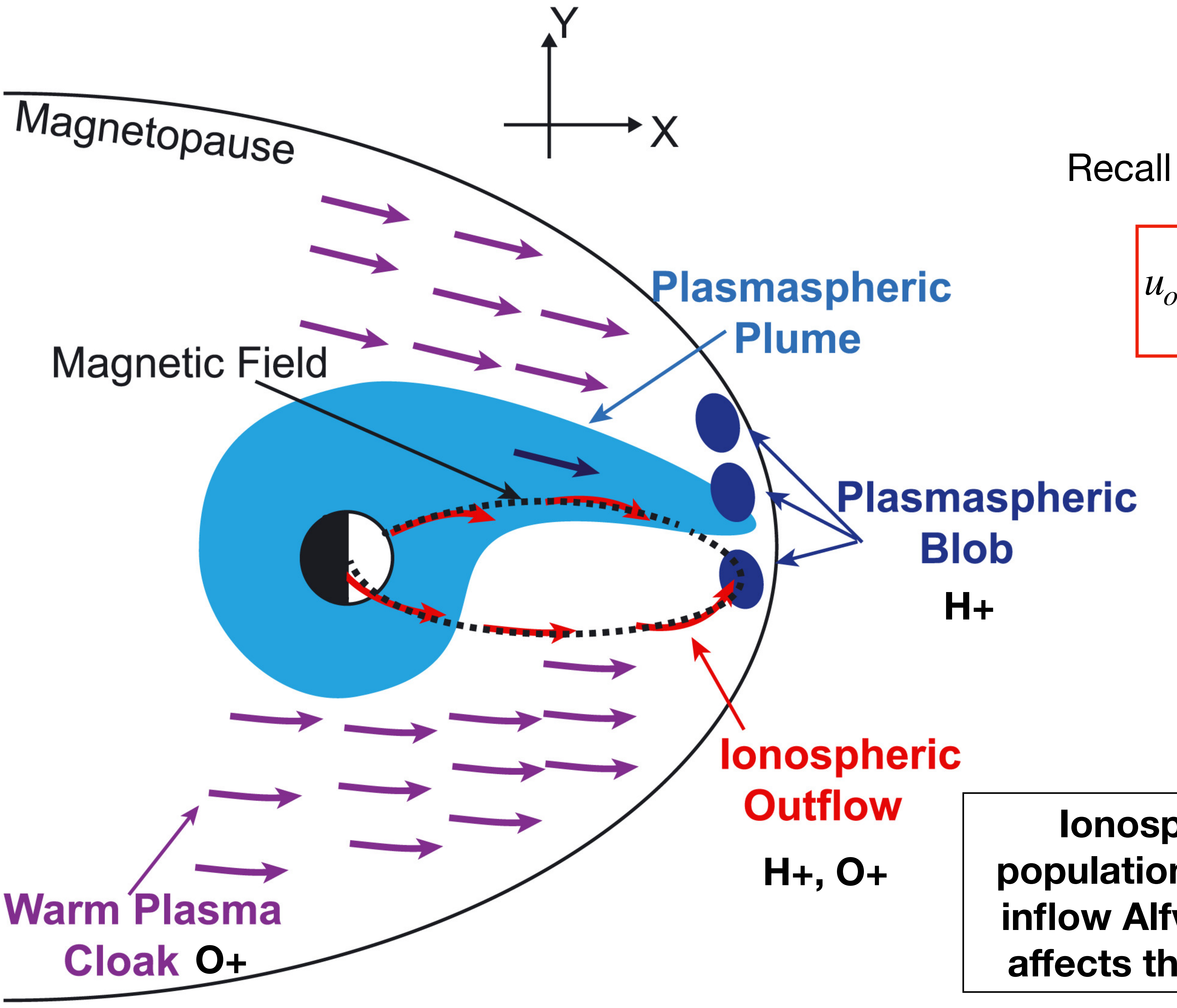
The Rate of Numerical MHD Reconnection



- The rate of numerical reconnection is insensitive to grid size. (numerical diffusion as well)
- When inflow is zero, the numerical reconnection rate is zero - need good numerics to achieve this
  - The numerical algorithm should be good enough to make sure that the numerical resistivity is negligible outside the current sheet (Gamera can do that)



Applications in Magnetospheric Physics



Recall the outflow speed

$$\boxed{u_{out} = V_A \equiv \frac{B_x}{\sqrt{\rho}}}$$

Ionospheric plasma populations may alter then inflow Alfvén speed which affects the outflow speed

Summary of MHD reconnection

- Magnetic reconnection is a fundamental process in space plasma physics, astrophysics and laboratory plasmas
- The **Sweet-Parker** model describes the scaling of steady-state resistivity reconnection at modest Lundquist numbers
- The **Petschek** model describes the scaling of steady-state, fast reconnection with slow shocks forming at the boundary separating the inflow and outflow
- The magnetic reconnection in a global MHD simulation operates through **numerical resistivity**, which is driven by the inflow conditions only.
- The scaling of numerical reconnection in a global magnetosphere simulation follows a Petschek-like model.
- The **Plasmoid instability** facilitates fast reconnection even in resistive (or even numerical resistivity) MHD for high Lundquist number plasma