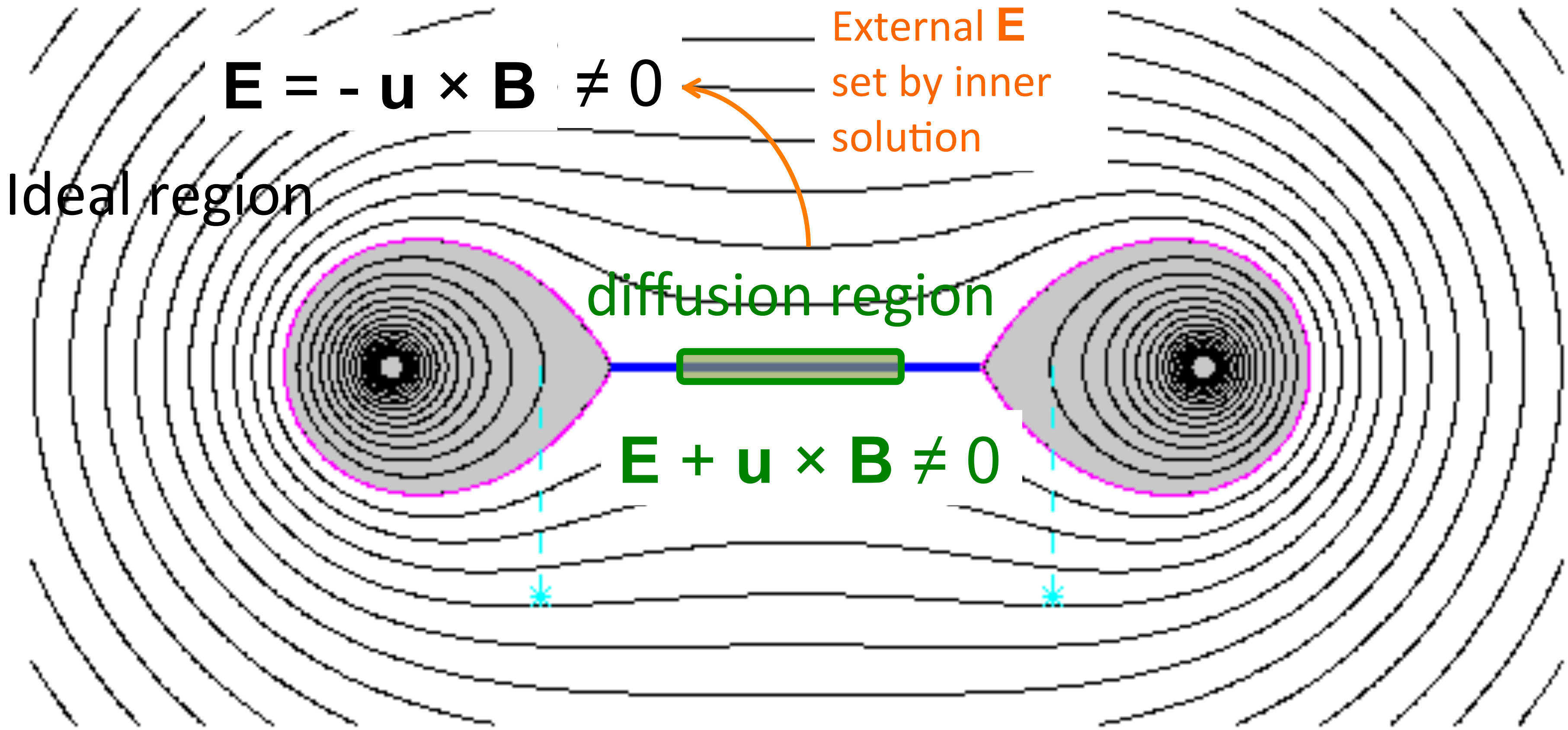
Magnetic Reconnection

Its role in CMEs & flares – part II

Lecture 4

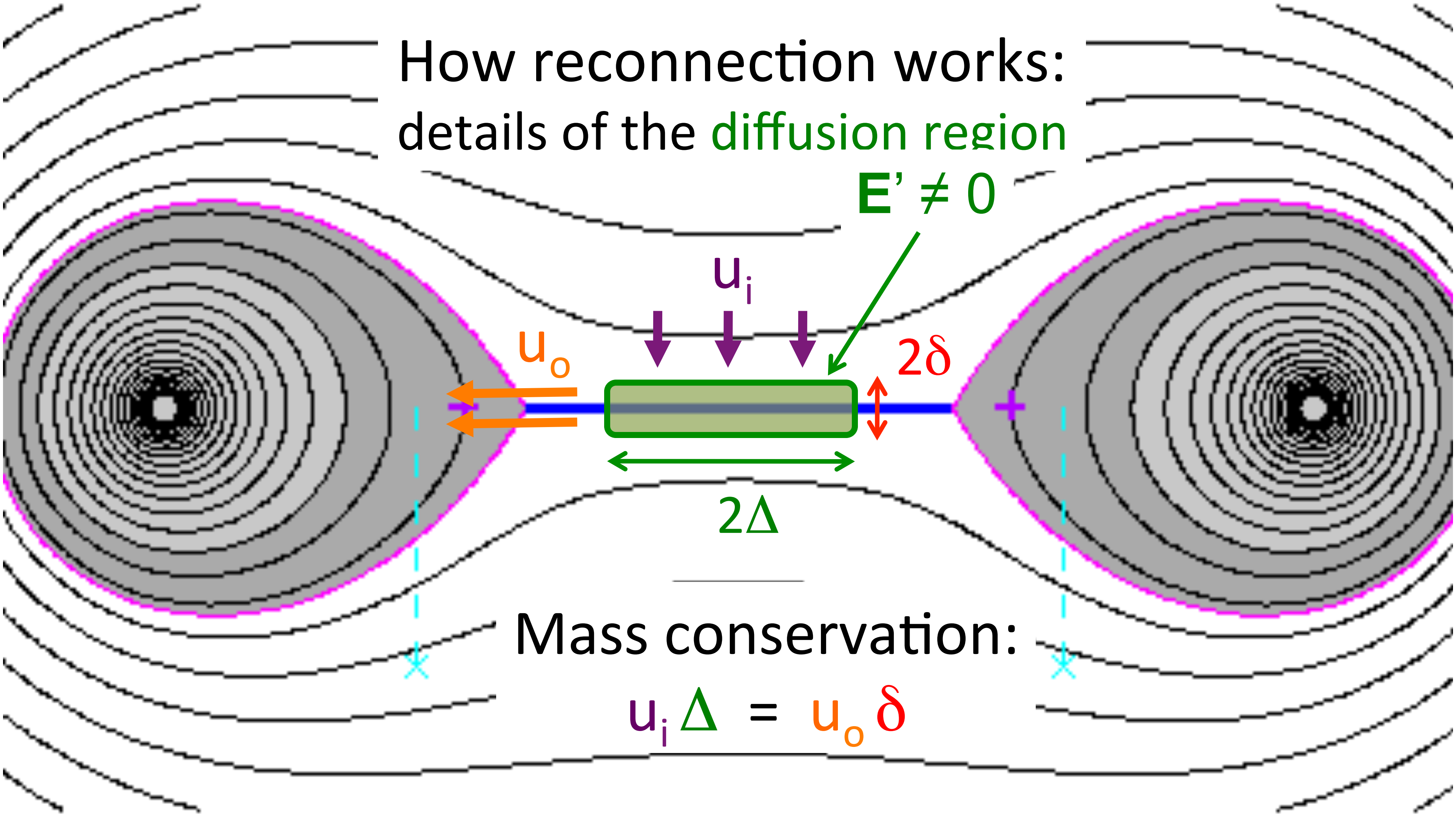
Jan. 30, 2017

Last Time:
Reconnection paradox



How reconnection works:

details of the diffusion region



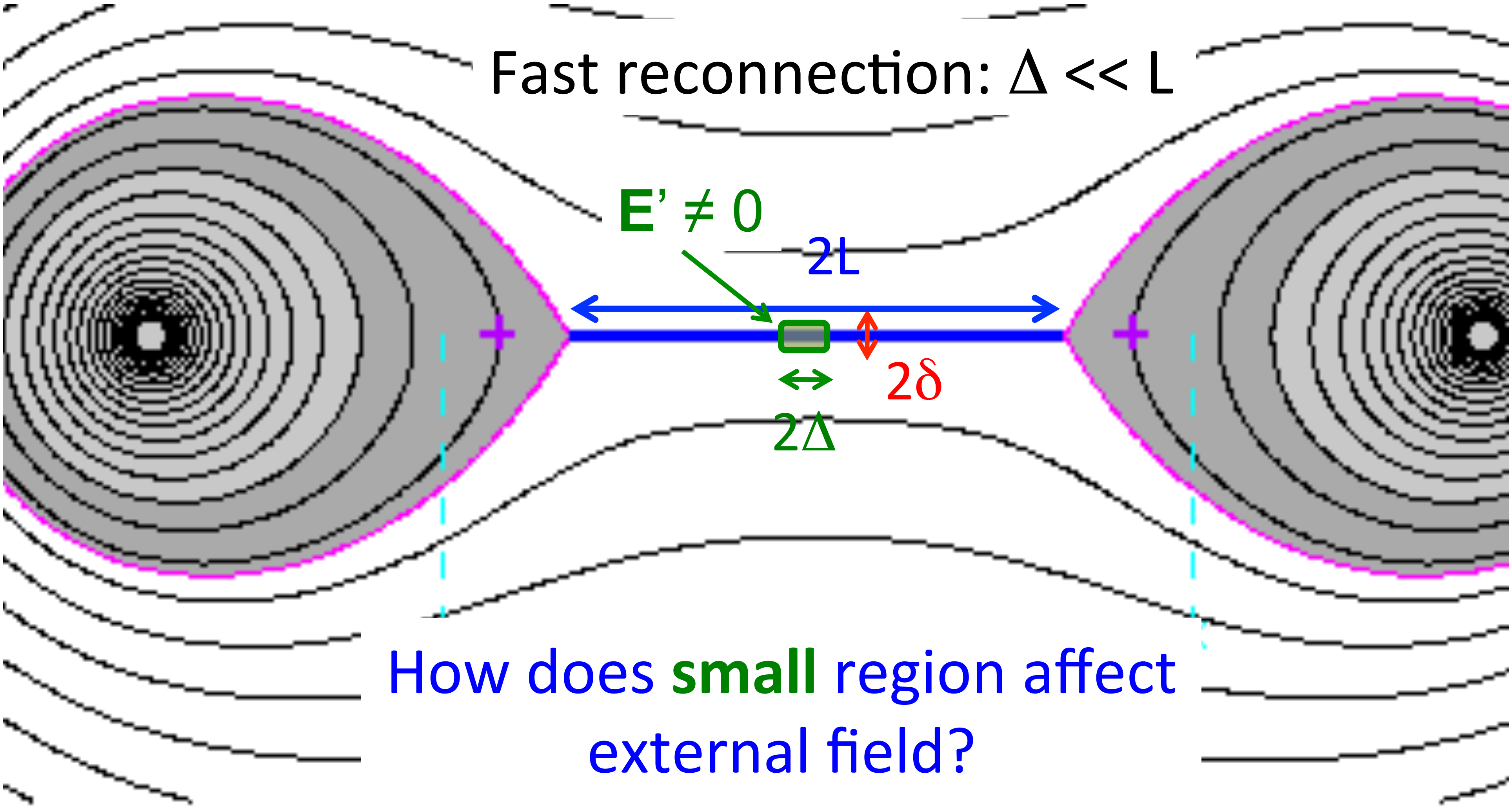
Mass conservation:

$u_i \Delta = u_o \delta$

$$M_{Ai} = \frac{u_i}{v_A} = \frac{\delta}{\Delta}$$

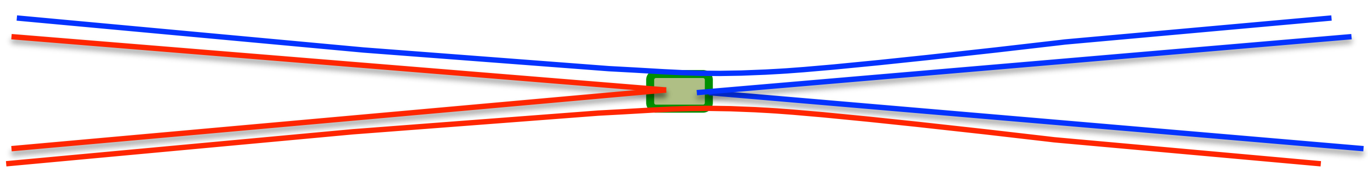
Aspect ratio of diffusion region

Fast reconnection: $\Delta << L$



How does **small** region affect external field?

It creates bent field lines…



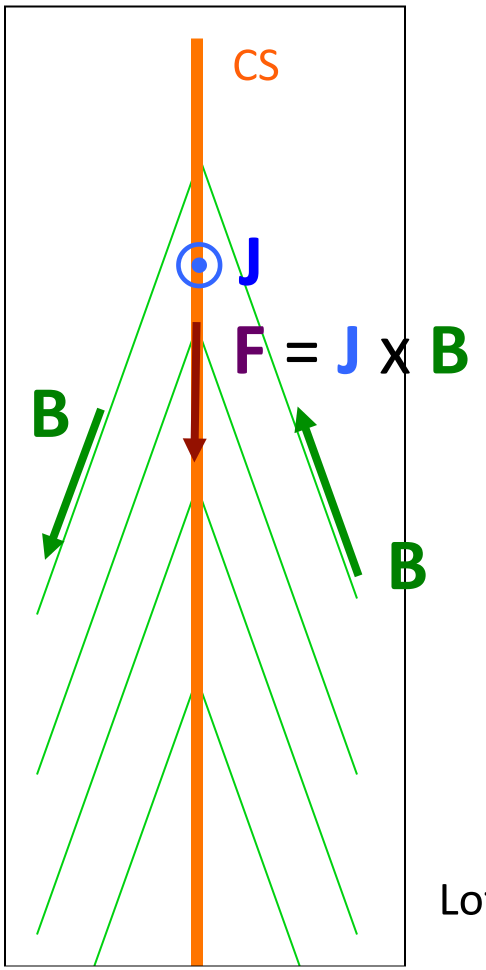
… what next?

Response to bend

Lin & Lee 1994

Riemann problem for 1D current sheet (CS)

t=0



Riemann problem:

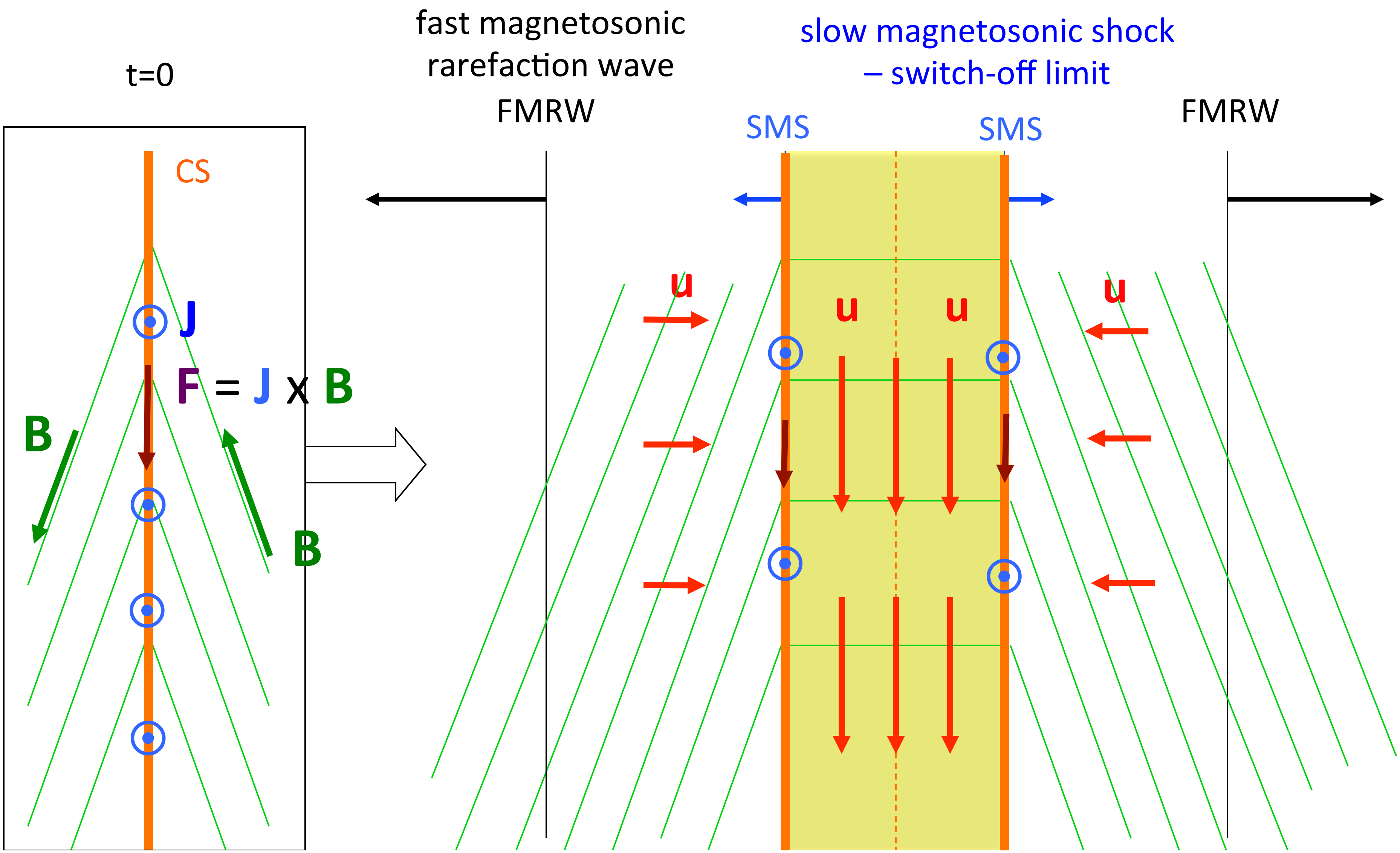
- initialize w/ 2 uniform regions separated by discontinuity (CS)
- Find subsequent time-evolution
- **Solution:** discontinuity decomposes into traveling **shocks** and rarefaction waves

Lots & lots of bent field lines

Response to bend

Lin & Lee 1994

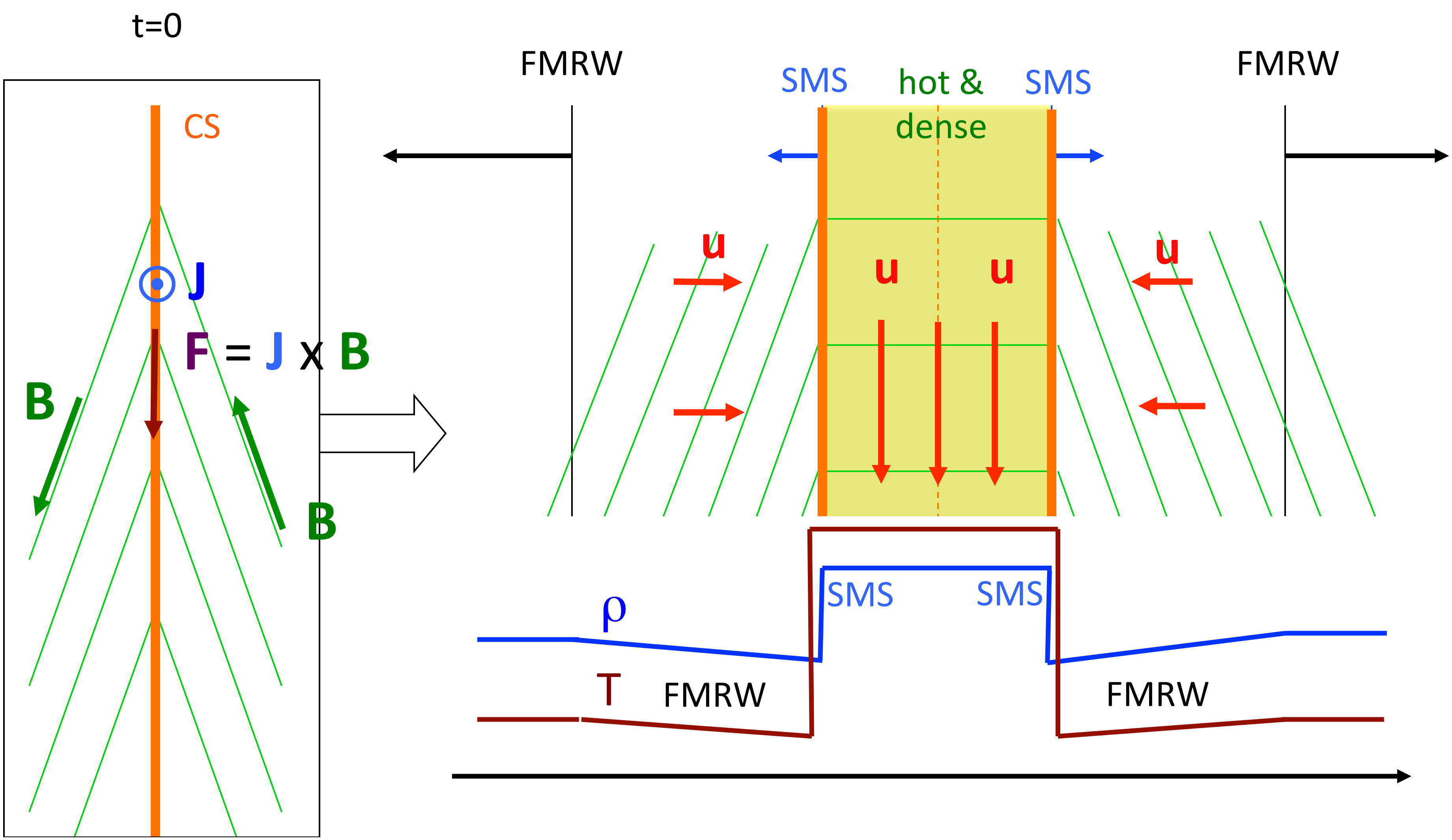
Riemann problem for 1D current sheet (CS)



Response to bend

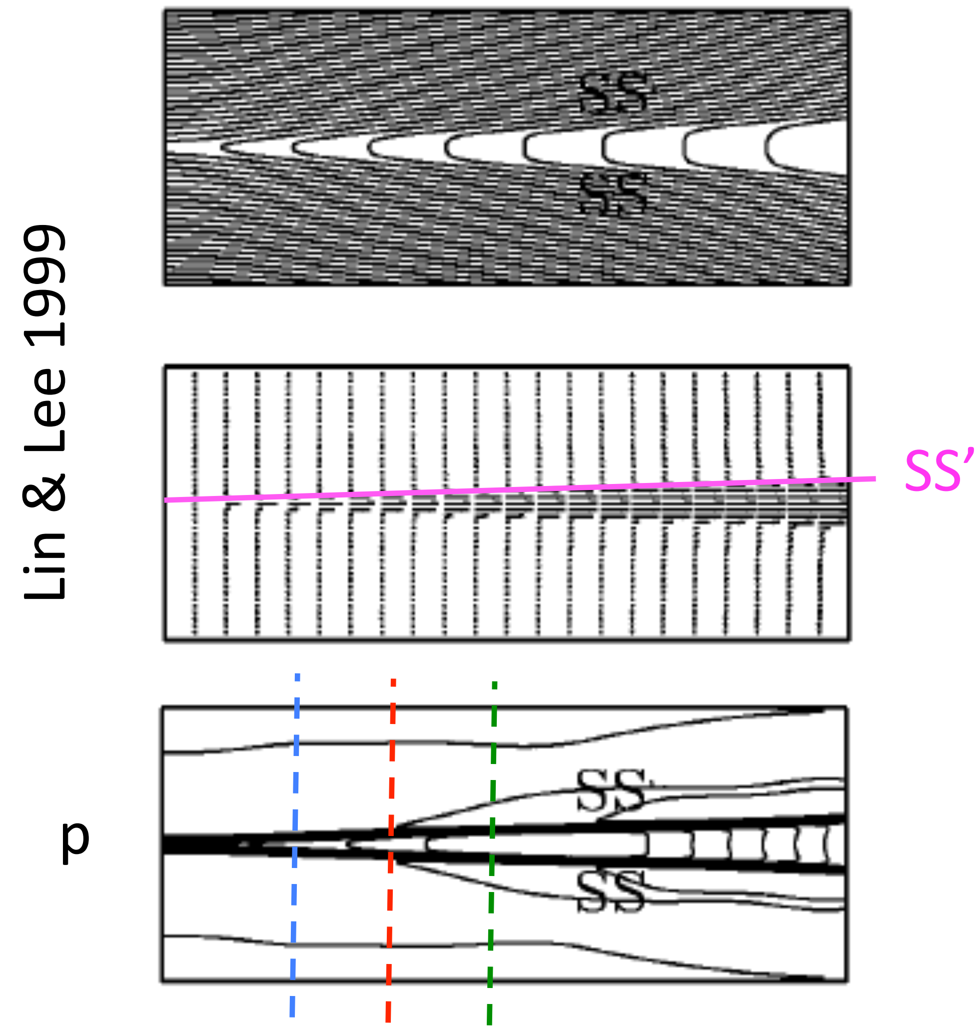
Lin & Lee 1994

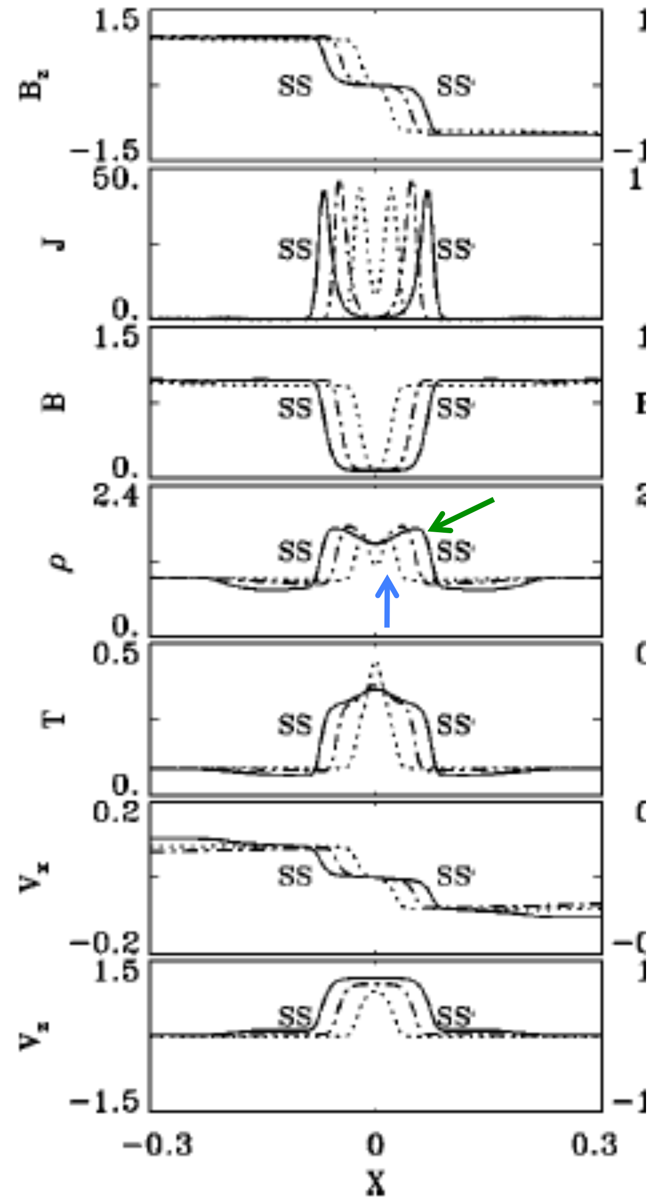
Riemann problem for 1D current sheet (CS)



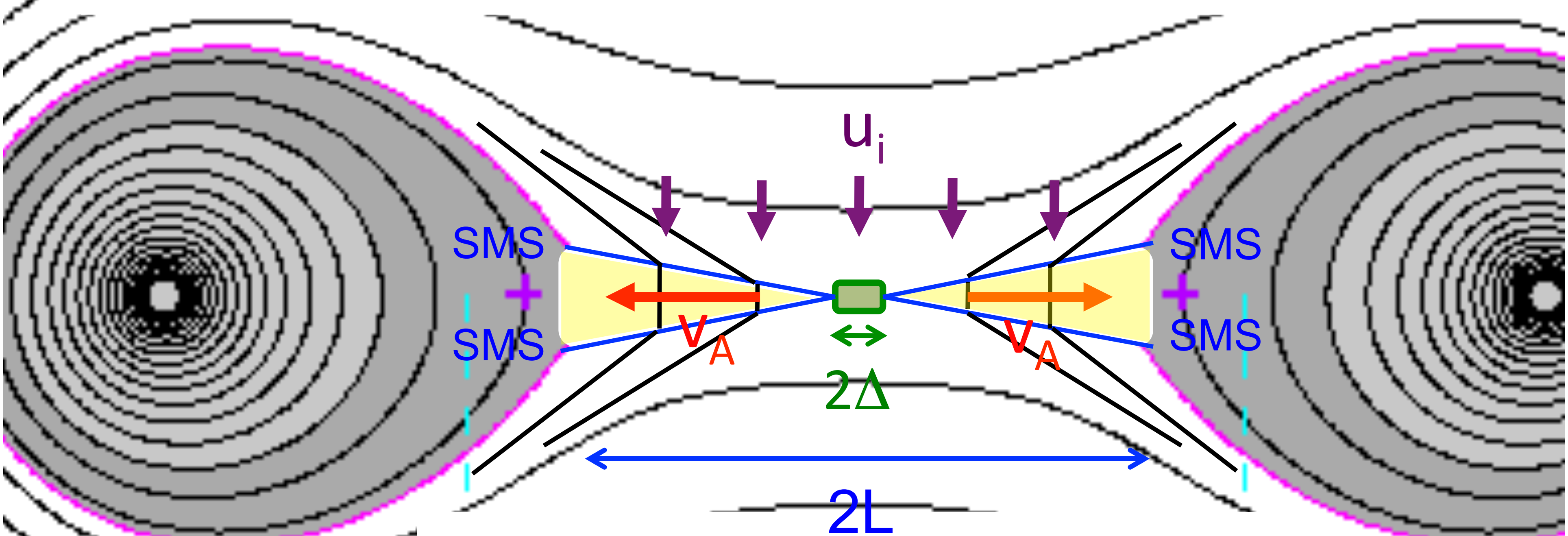
How it works in 2d

Lin & Lee 1999





Petschek reconnection

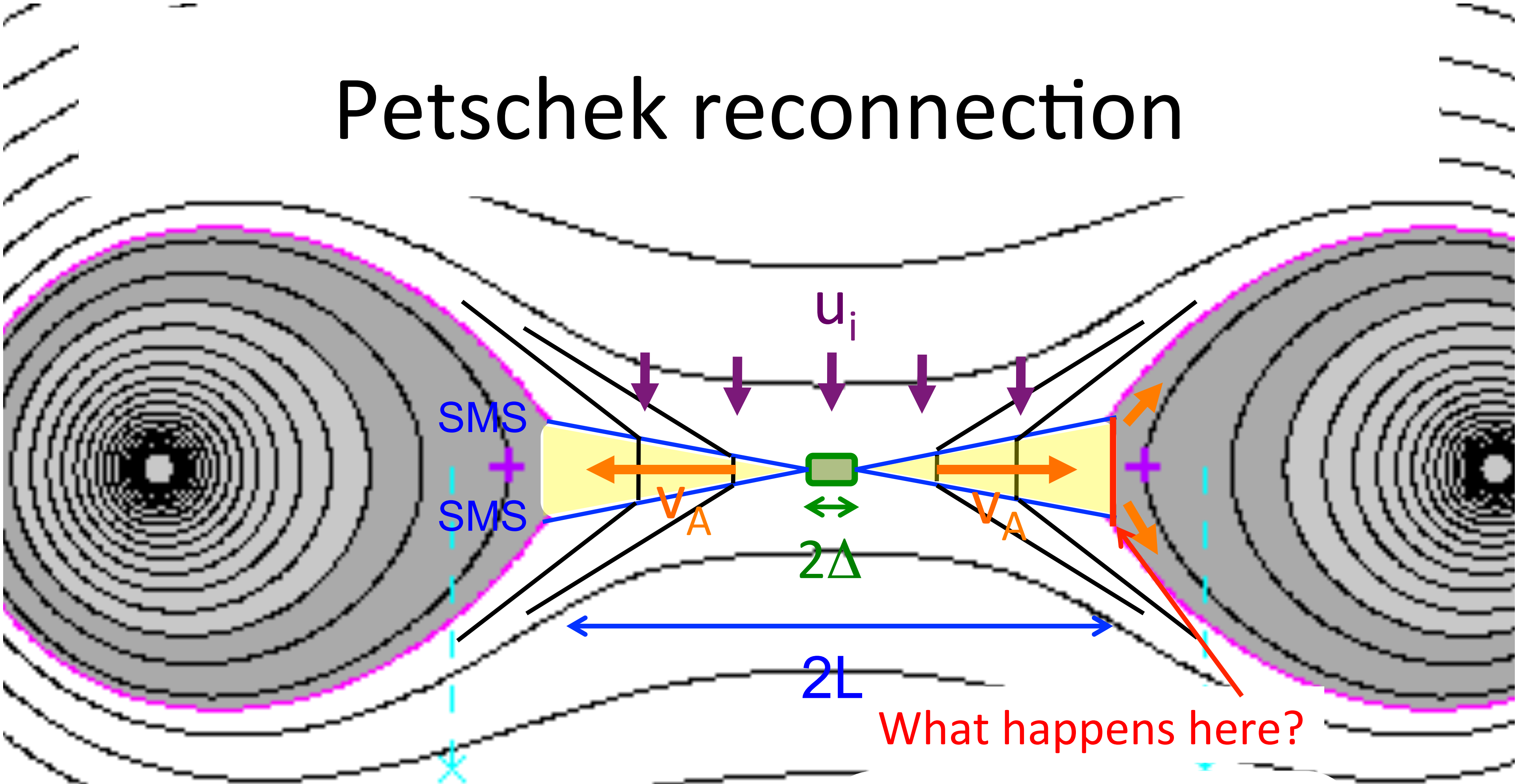


External solution requires current - current appears in SMSs

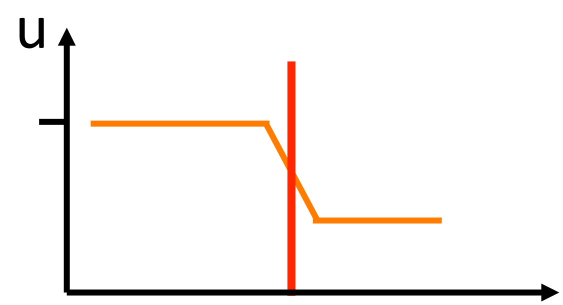
$$\frac{P_\eta}{\dot{E}_M} \sim \frac{\Delta}{L} << 1$$

Released energy is converted to heat & KE by SMSs - very little is Ohmically dispated

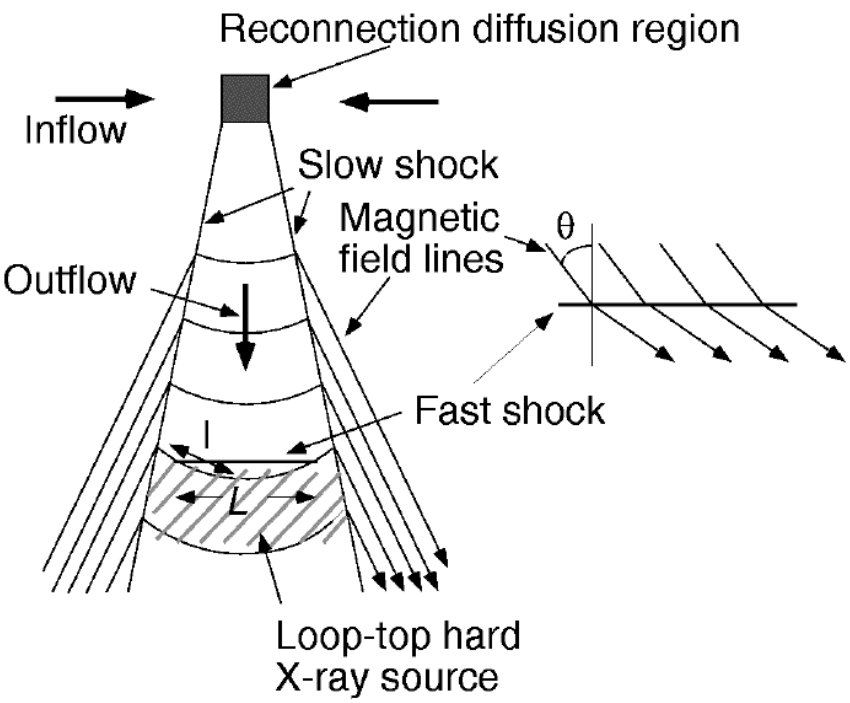
Petschek reconnection



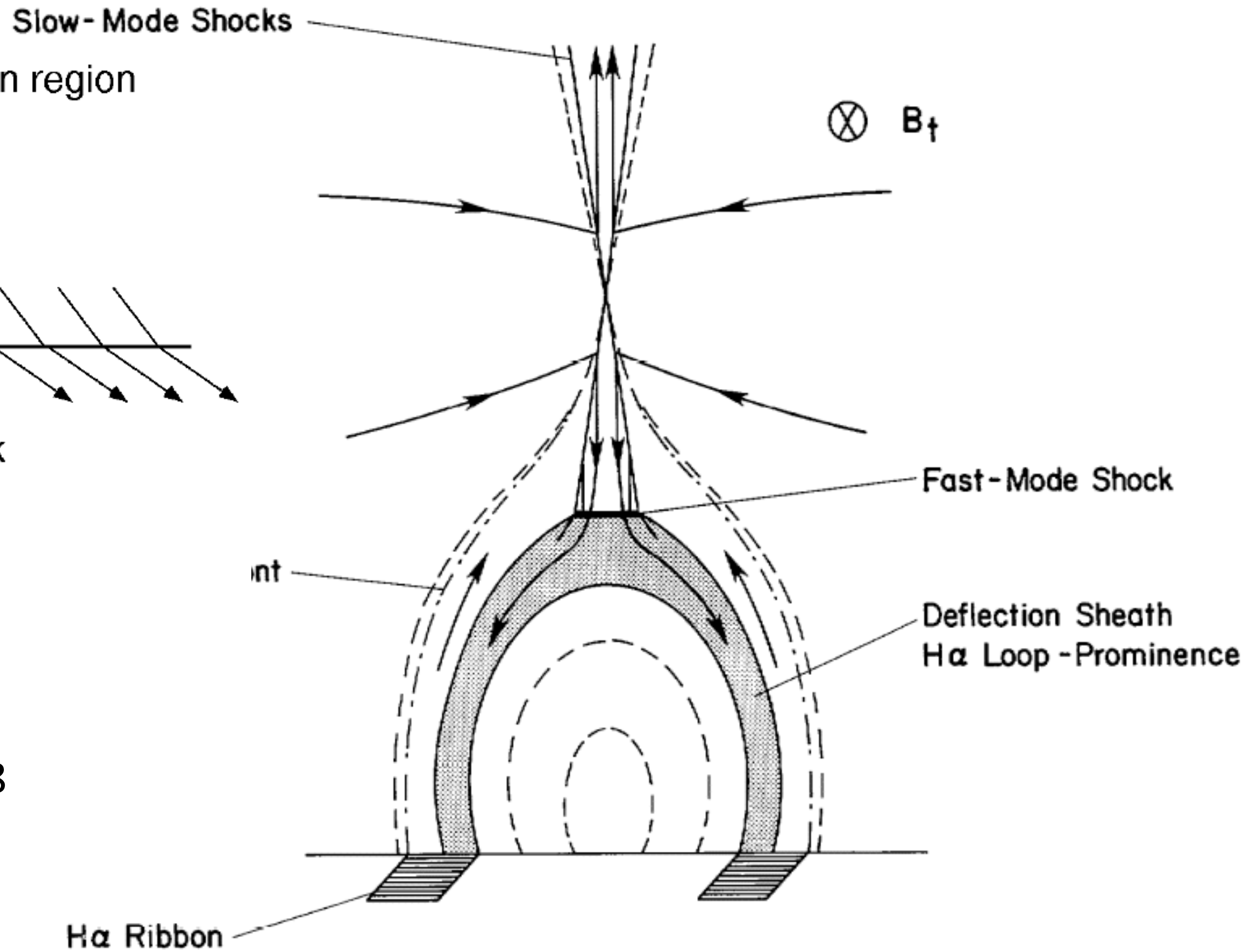
1. FMS if the local FMS speed is below outflow speed:
   Fast Mode Termination Shock
2. Otherwise: a smooth region of flow deceleration



How it works in a flare



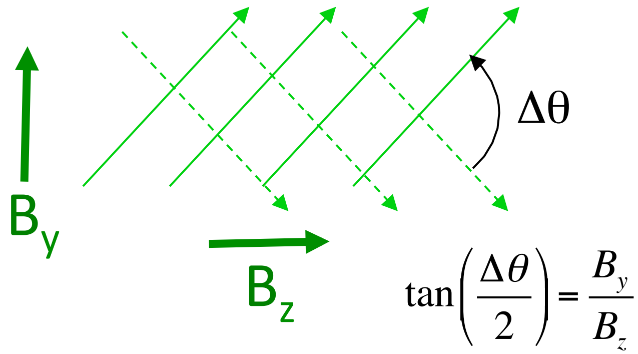
Tsuneta and Naito 1998

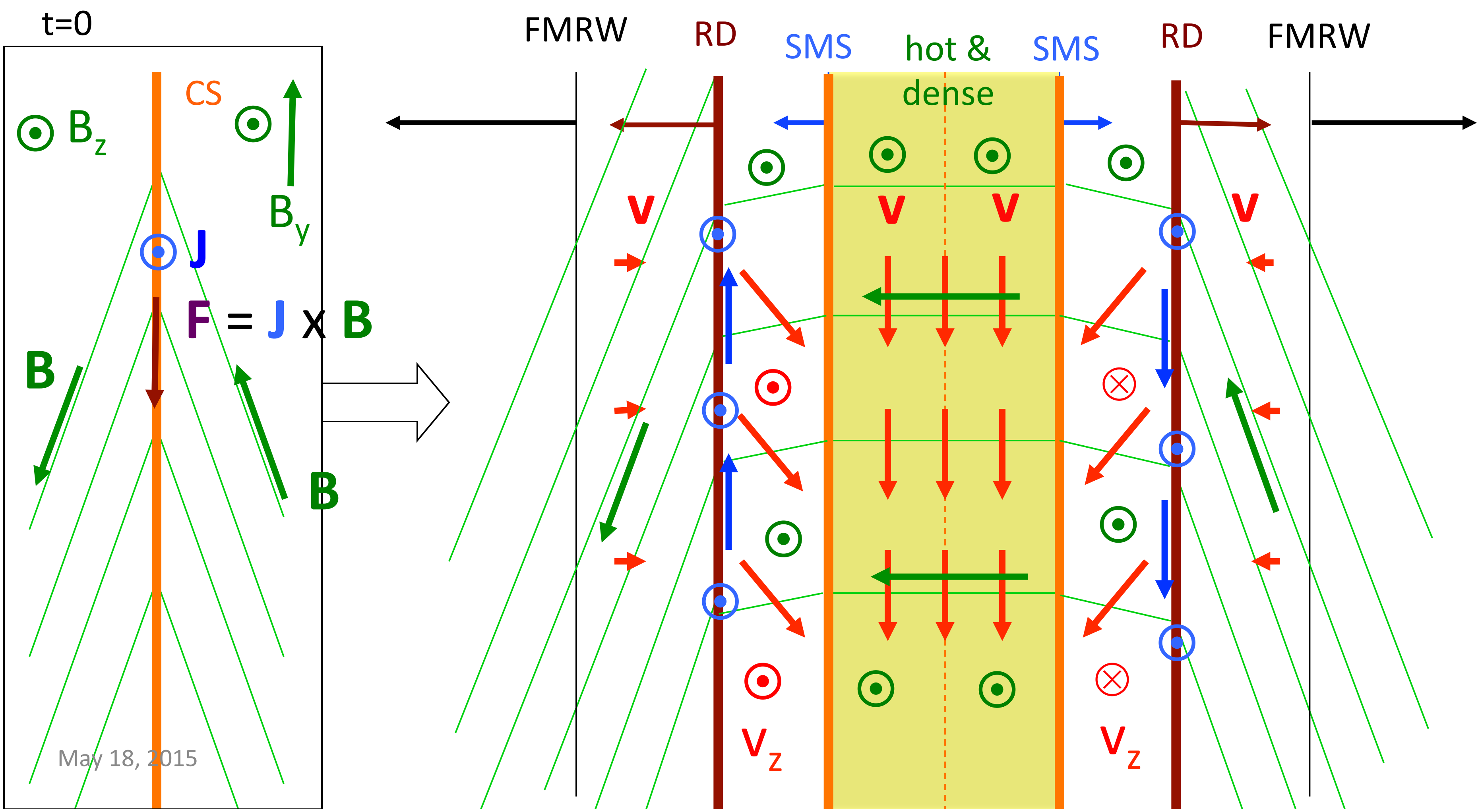


Forbes, T.G., and Malherbe 1986

Riemann problem in 2.5d

Lin & Lee
1994



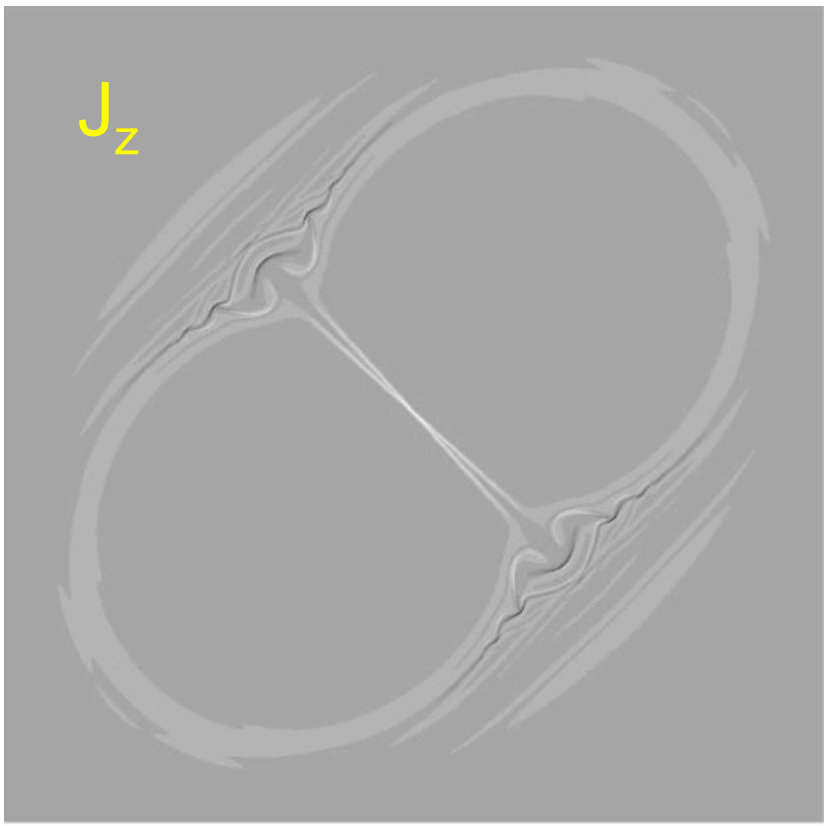


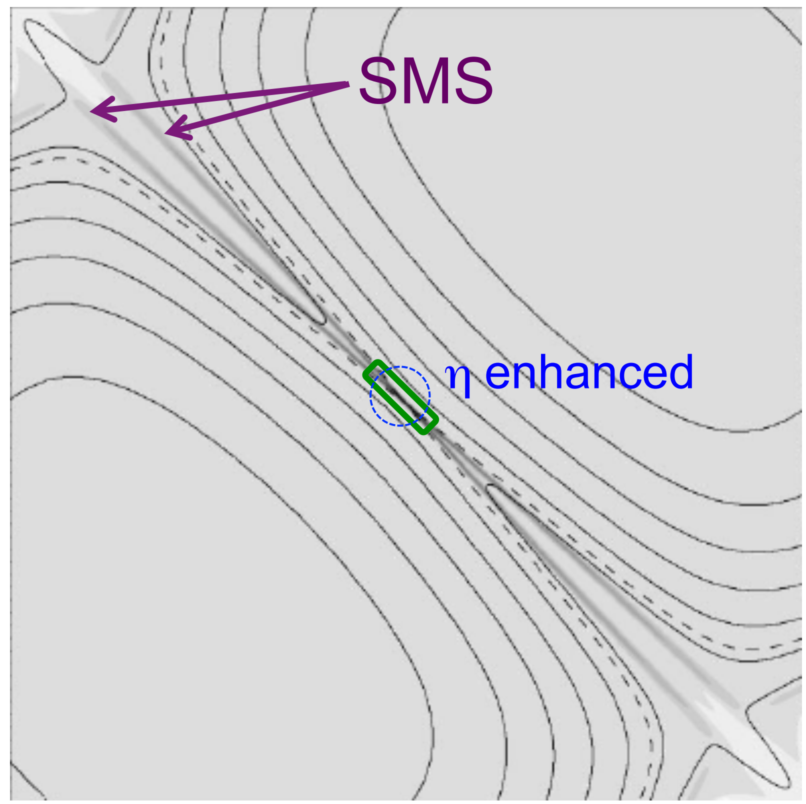
Q: Will resistivity always result in slow (Sweet-Parker) reconnection?

A: Yes, if η is uniform in space…

But not, when $\eta(\mathbf{x})$ is locally enhanced*

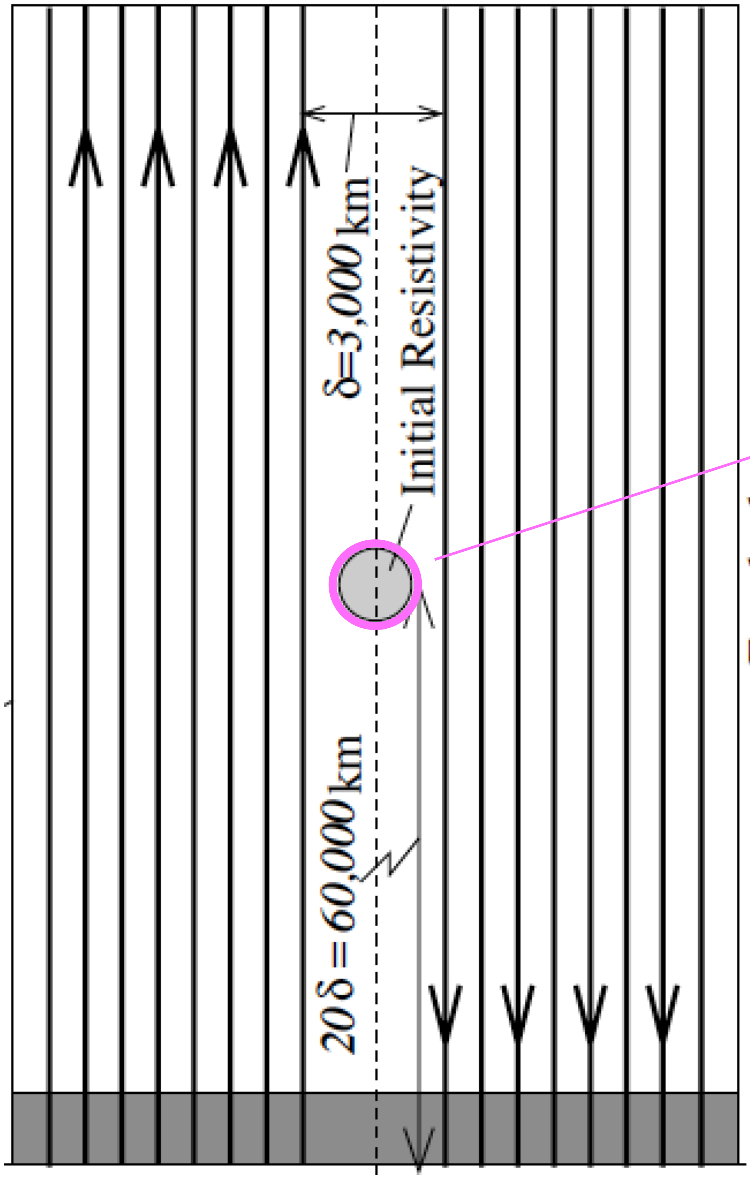
Biskamp & Scwartz 2001

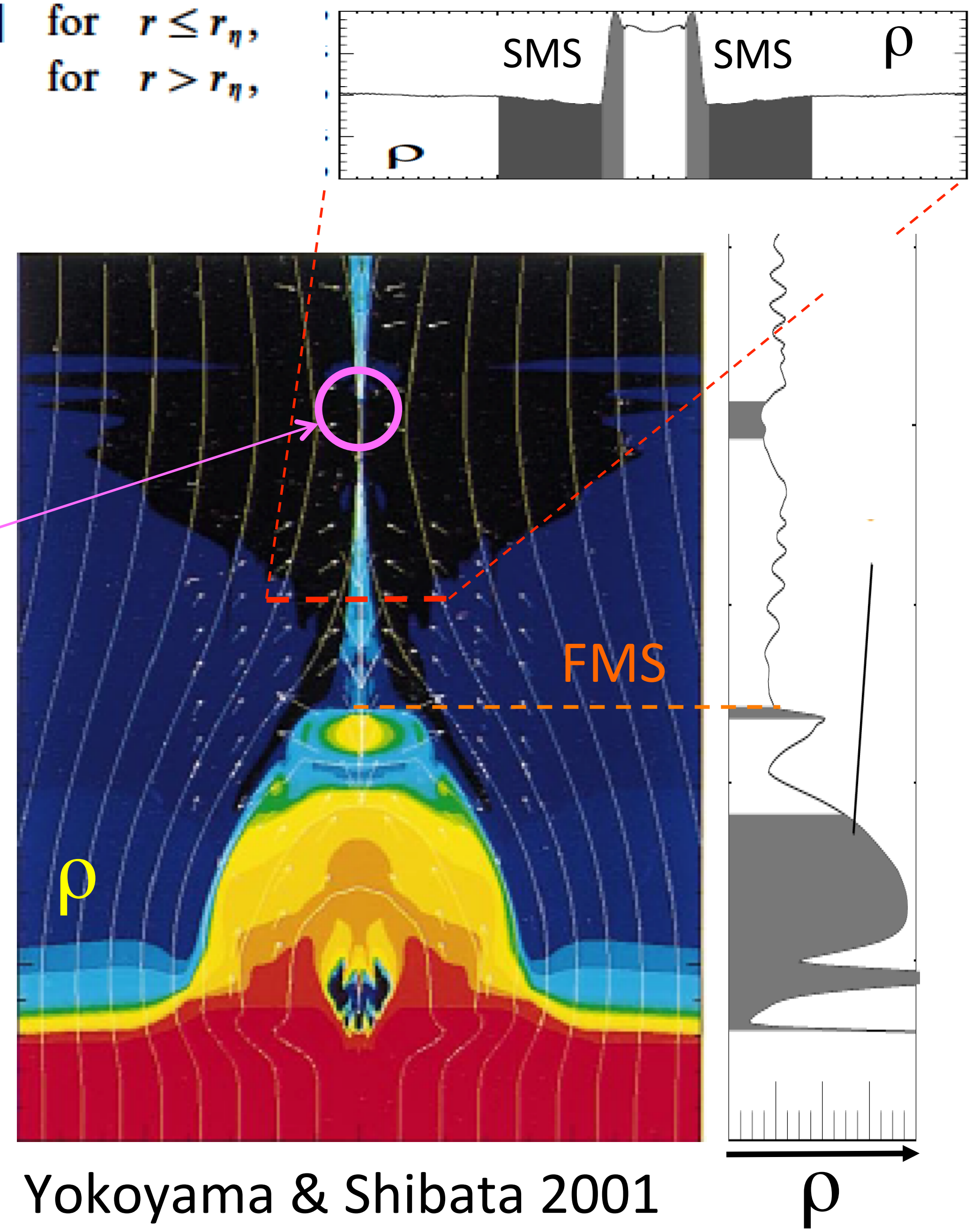




*as by micro-instability

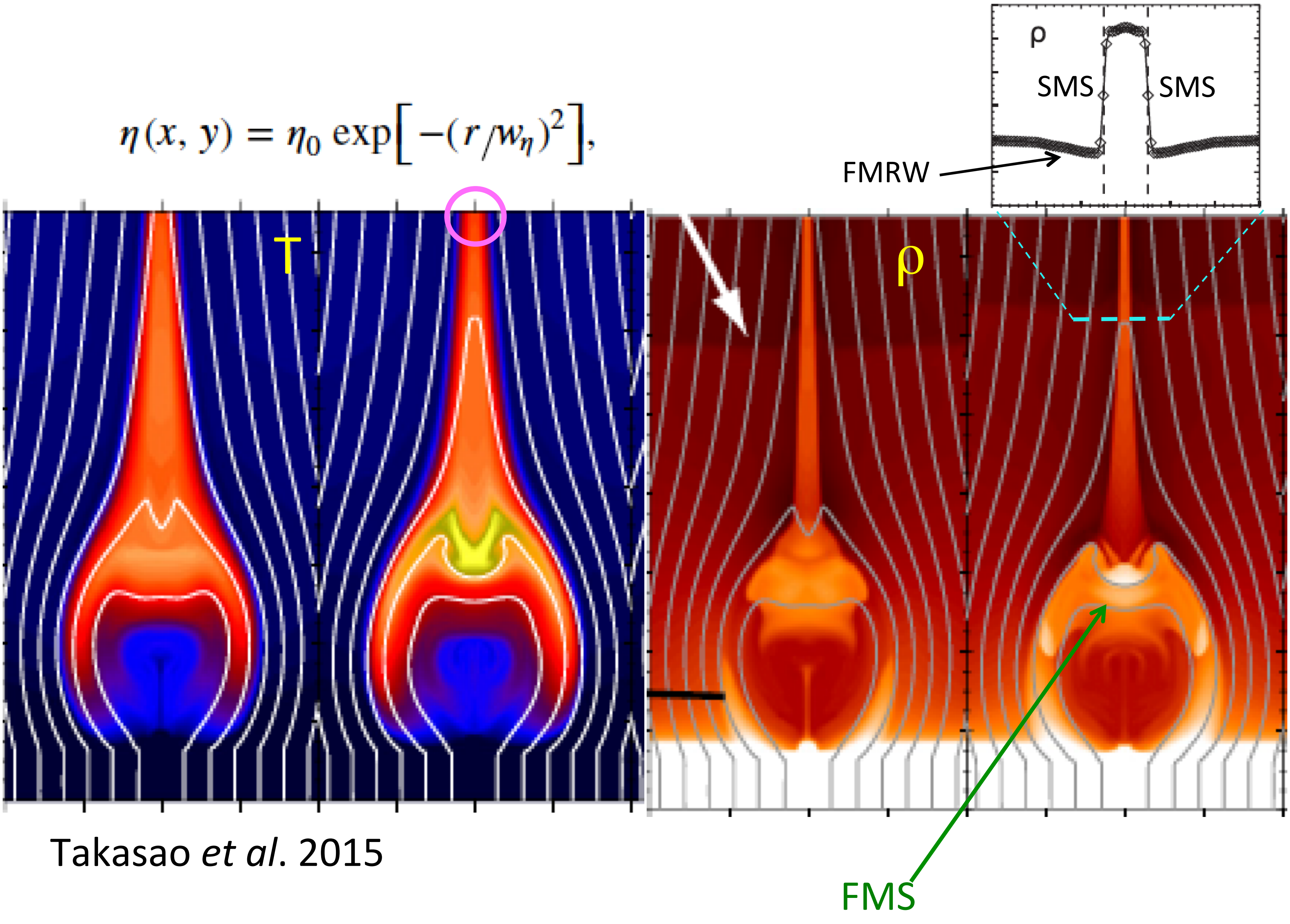
$$\eta(x, z, t \le t_\eta) = \begin{cases} \eta_{i0}[2(r/r_\eta)^3 - 3(r/r_\eta)^2 + 1] & \text{for} \quad r \le r_\eta , \\ 0 & \text{for} \quad r > r_\eta , \end{cases}$$





Yokoyama & Shibata 2001

$$\eta(x, y) = \eta_0 \exp\left[-(r/w_\eta)^2\right],$$



Takasao *et al*. 2015

Anomalous resistivity

Electron momentum eq. → generalized Ohm's law

$$m_e \frac{d\mathbf{v}_e}{dt} = -e(\mathbf{E} + \tfrac{1}{c}\mathbf{u}\times\mathbf{B}) - \frac{1}{n_e}\nabla\cdot\overleftrightarrow{P}_e + \frac{1}{n_e c}\mathbf{J}\times\mathbf{B} + \underbrace{m_e \nu_{ei}(\mathbf{v}_i - \mathbf{v}_e)}_{\text{drag from ions}}$$

Q: What is this "drag" force?

A: An **average** force from random **E** fields originating from the ions.

$$= \frac{m_e \nu_{ei}}{e n_e}\mathbf{J} = e\eta_e \mathbf{J}$$

"Classical" drag: **E** is experienced during close encounters with individual ions

= collisions – cross section $\sigma_{ei} \sim \dfrac{e^4}{m_e^2 v_{th,e}^4}$

$$\nu_{ei} = n_e v_{th,e}\sigma_{ei} \qquad \Rightarrow \eta_e \sim \eta_{sp} \sim v_{th,e}^{-3} \sim T^{-3/2}$$

Anomalous resistivity

Electron momentum eq. → generalized Ohm's law

$$m_e \frac{d\mathbf{v}_e}{dt} = -e(\mathbf{E} + \tfrac{1}{c}\mathbf{u}\times\mathbf{B}) - \frac{1}{n_e}\nabla\cdot\overset{\leftrightarrow}{P}_e + \frac{1}{n_e c}\mathbf{J}\times\mathbf{B} + \underbrace{m_e \nu_{ei}(\mathbf{v}_i - \mathbf{v}_e)}_{\text{drag from ions}}$$

drag from ions

$$= \frac{m_e \nu_{ei}}{e n_e}\mathbf{J} = e\eta_e \mathbf{J}$$

Other source of random electric field: **plasma instability**

Expect $\nu_{ei} \sim \gamma$ growth rate

If instability draws energy from relative e/i motion then

$\gamma \sim |\mathbf{v}_i - \mathbf{v}_e|^\alpha$ when $|\mathbf{v}_i - \mathbf{v}_e| > v_{cr}$

$$\eta_e = \begin{cases} \eta_{sp}, & |J| < J_{cr} = e n_e v_{cr} \\ \eta_{sp} + C(|J|/J_{cr} - 1)^\alpha, & |J| > J_{cr} \end{cases}$$

can lead to

$\eta_e >> \eta_{sp}$

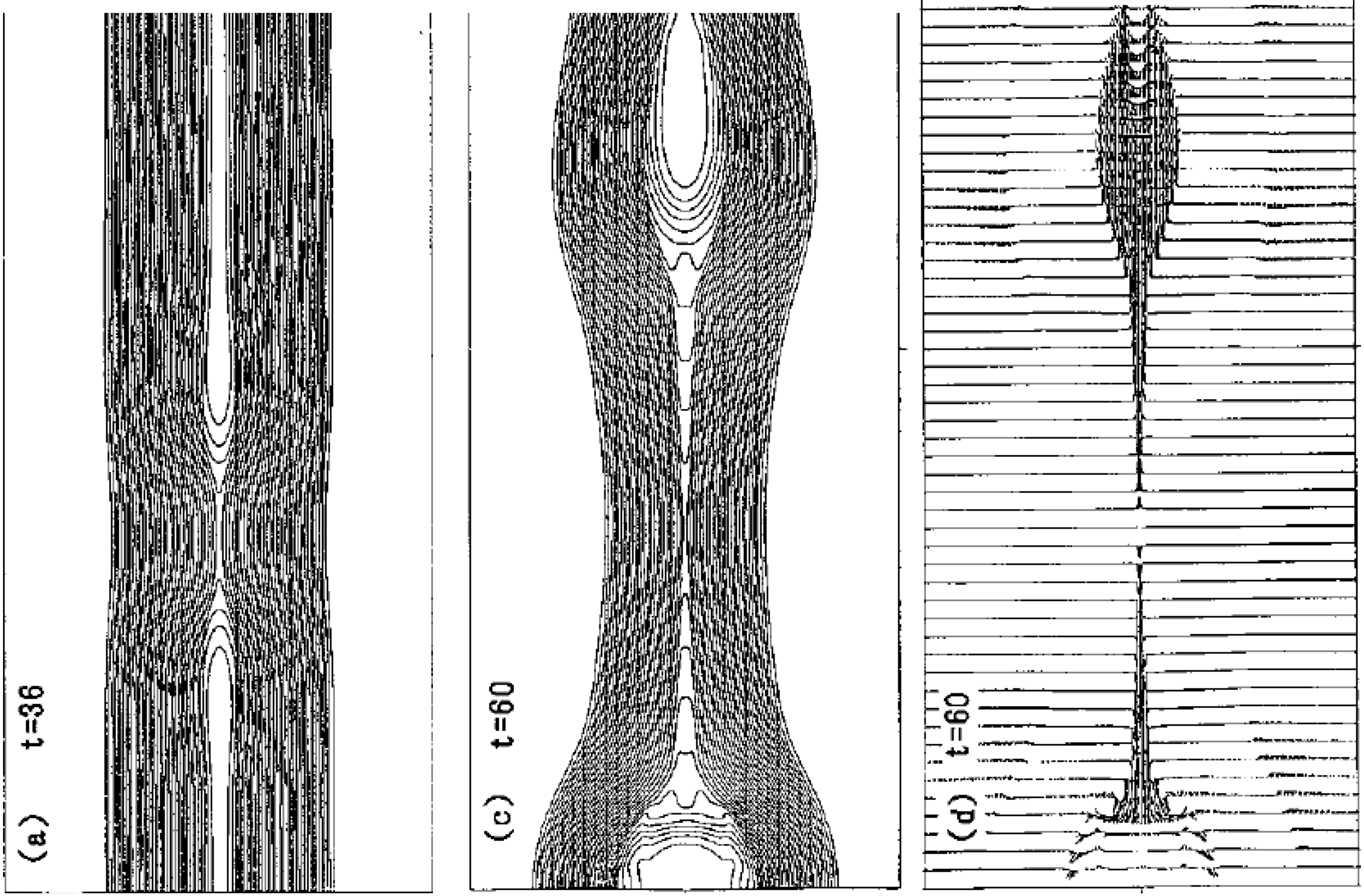
and

$\Delta << L$

$$\eta(\mathbf{r},t) = k_R[\,|\mathbf{V_D}(\mathbf{r},t)| - V_C] \quad \text{for } |\mathbf{V_D}| > V_C\,,$$
$$= 0 \quad \text{for } |\mathbf{V_D}| < V_C\,,$$

$$\mathbf{v}_D = \mathbf{v}_i - \mathbf{v}_e \propto \frac{\mathbf{J}}{\rho}$$

Ugai 1996



Energy budget

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J}$$

Work done by changing **B**:

$$\mathbf{J} \cdot \mathbf{E} = -\tfrac{1}{c}\mathbf{J} \cdot (\mathbf{u} \times \mathbf{B}) + \eta_e |\mathbf{J}|^2$$

work by Lorentz force

$$= \mathbf{u} \cdot (\tfrac{1}{c}\mathbf{J} \times \mathbf{B}) = \mathbf{u} \cdot \mathbf{F}_L$$

Mag. $\longleftrightarrow$ Kin.

Ohmic dissipation

$$\frac{\partial}{\partial t}\left(\tfrac{3}{2}p\right) = \cdots + \eta |\mathbf{J}|^2$$

Mag. $\longrightarrow$ internal

Q: does dissipated energy End up as **heat** (i.e. increased T in Maxwellian)?

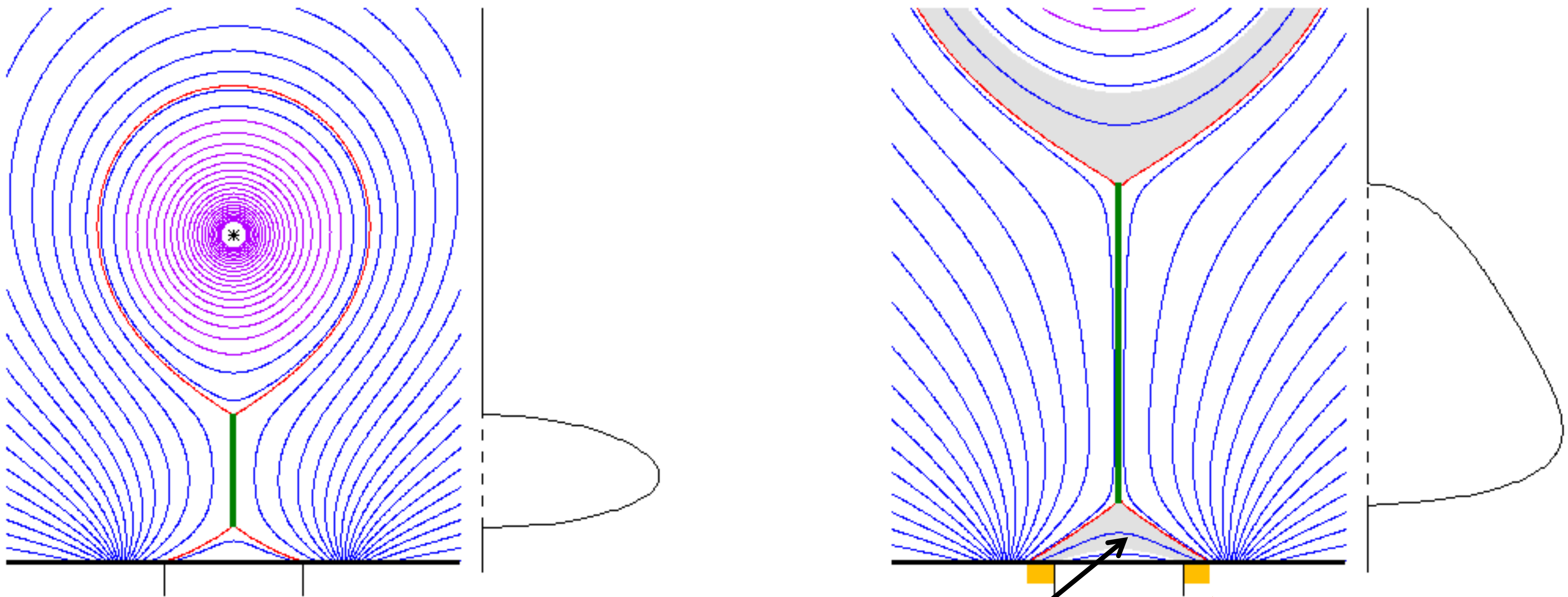
- η from particle-particle collisions – classical resistivity – **YES** – see 2nd law of thermo
- η from wave-particle interaction – anomalous resistivity – **???** – non-Maxellian dist'n

Evolution via reconnection

- Reconnection @ CS will change topology
  - Transfer flux across CS
  - Dissipate energy at site of CS
- Can facilitate eruption (overcome obstacle presented by Aly-Sturrock)
- Evolution can lead to LoE –
  - Rapid ideal energy release
  - Development of more intense CS
  - Still more reconnection

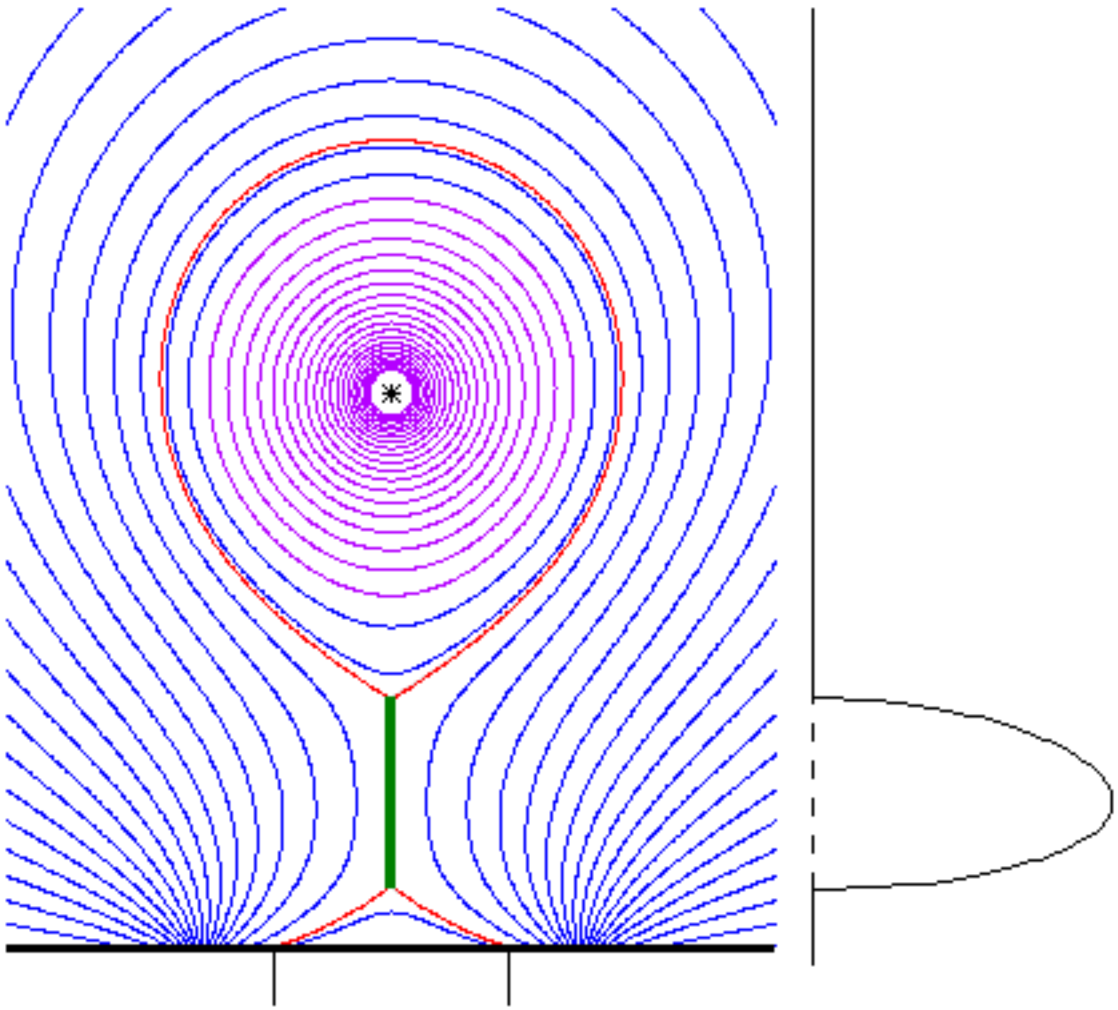
Eruption via reconnection

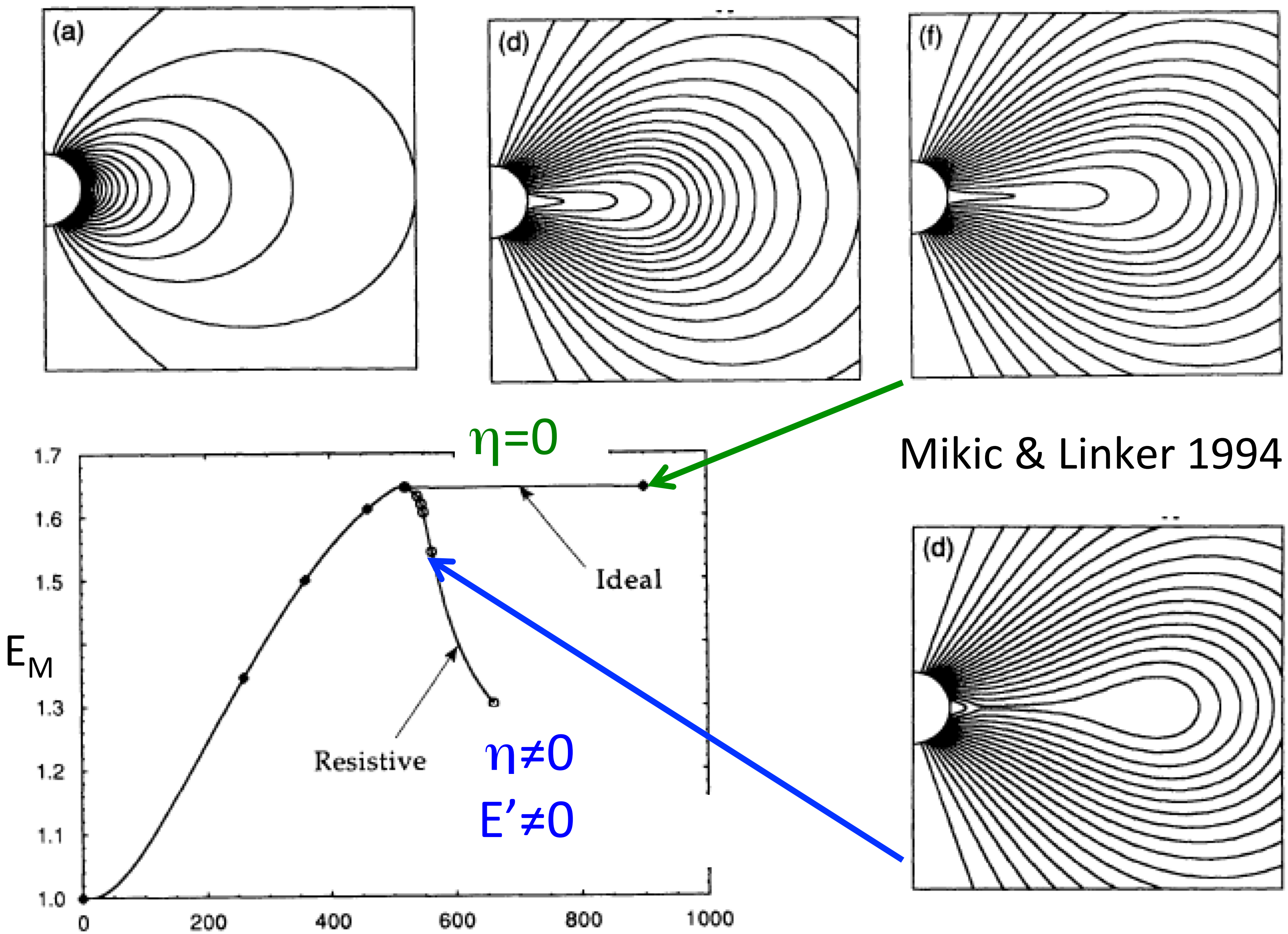
Assume E’ ≠ 0 @ CS (more later) ➔



- Φ beneath CS increases
- Downward force decreases
  (reconnection reduces overlying flux)
- Flux rope rises
- Flare signatures produced by E’

Eruption via reconnection

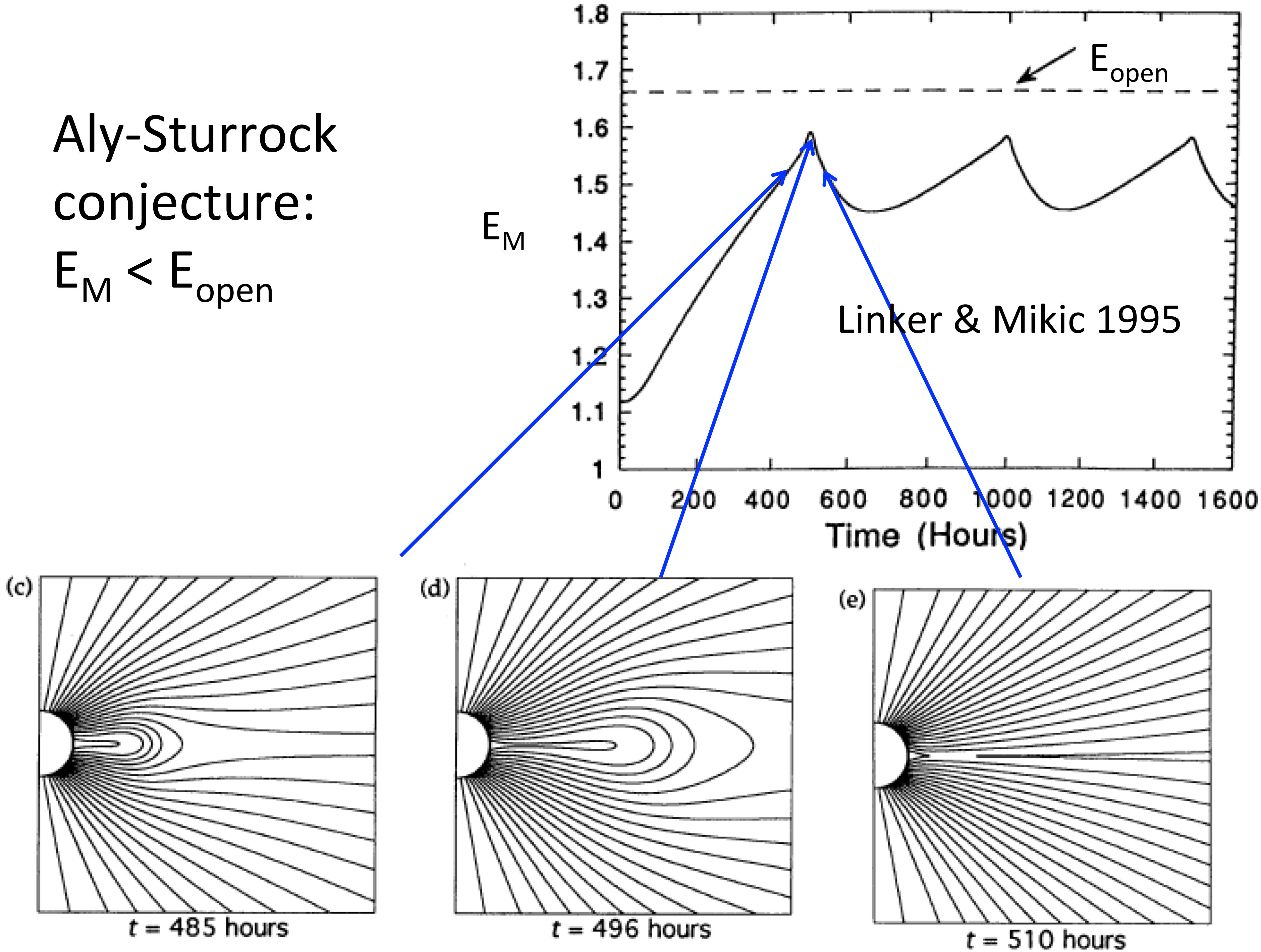




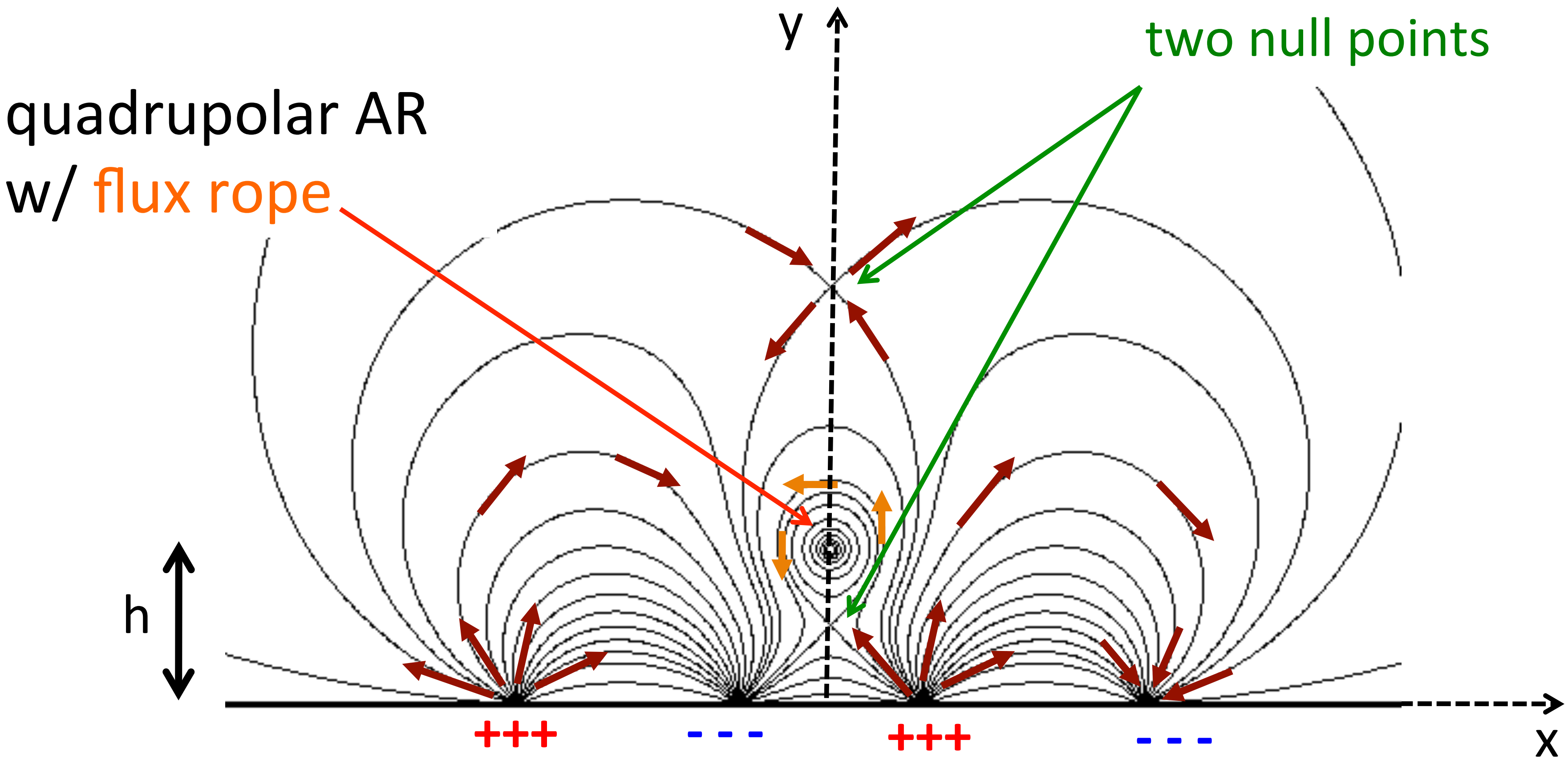
(a)
(d)
(f)
(d)
η=0
Mikic & Linker 1994
1.7
1.6
1.5
1.3
1.2
1.1
1.0
0
200
400
600
800
1000
E_M
Ideal
Resistive
η≠0
E'≠0

Aly-Sturrock conjecture:

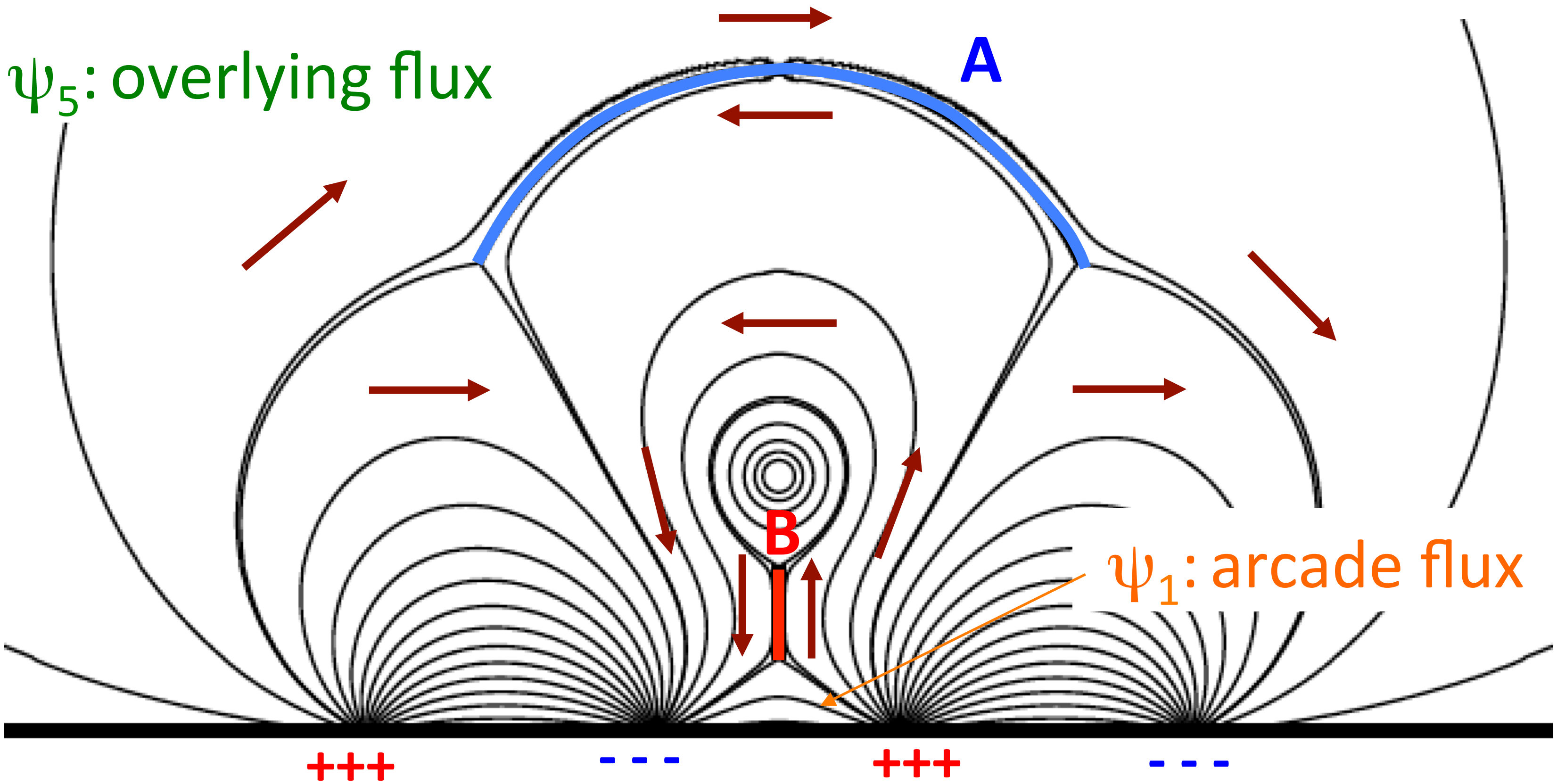
$E_M < E_{open}$



Slightly more complex toy model*



*from Longcope & Forbes 2014



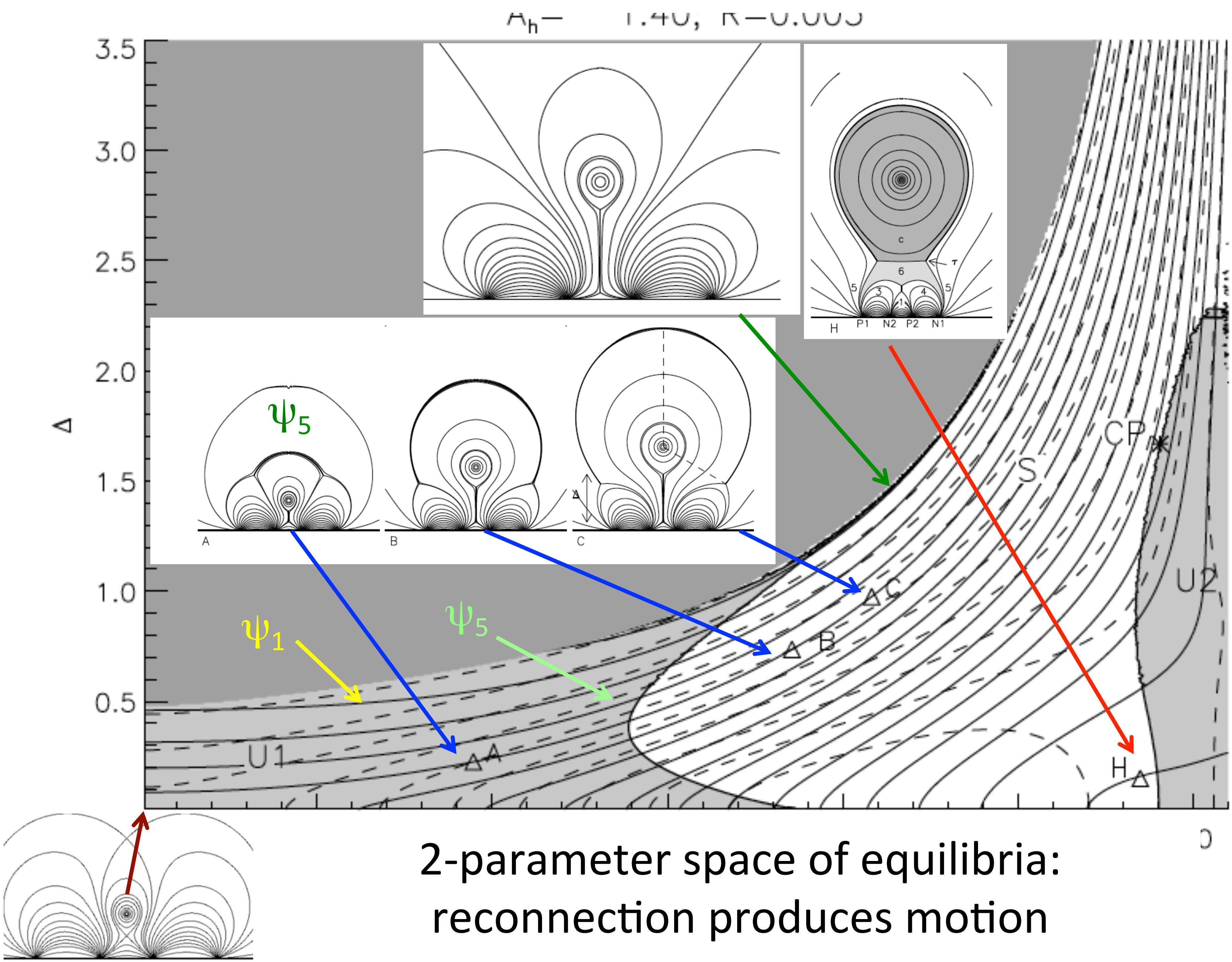
2 null points ➔ 2 CSs

2 CSs ➔ 2 sites for reconnection:

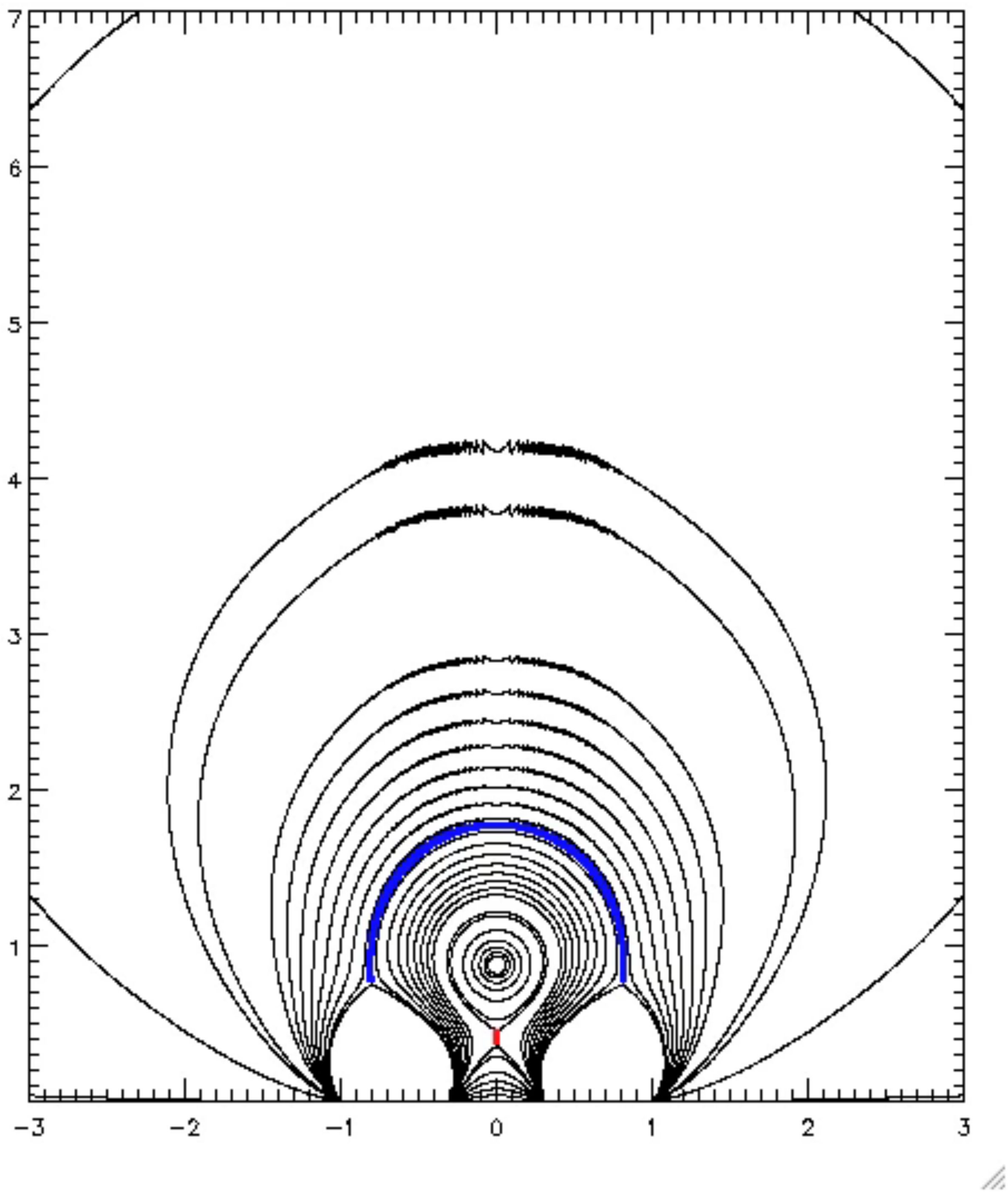
A: breakout reconnection: decreases ψ_5

B: tether-cutting reconnection: increases ψ_1

Reconnection changes equilibrium



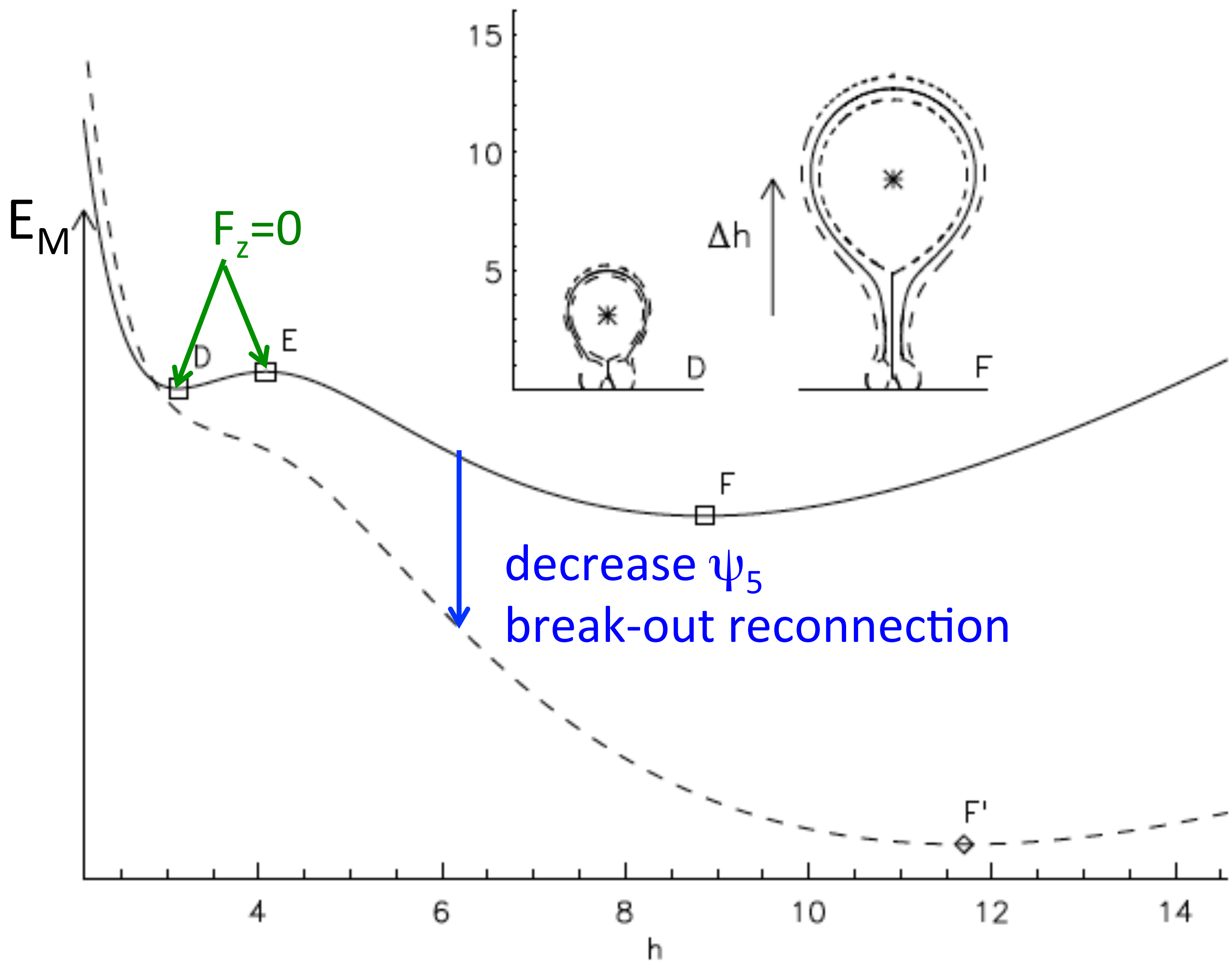
2-parameter space of equilibria: reconnection produces motion



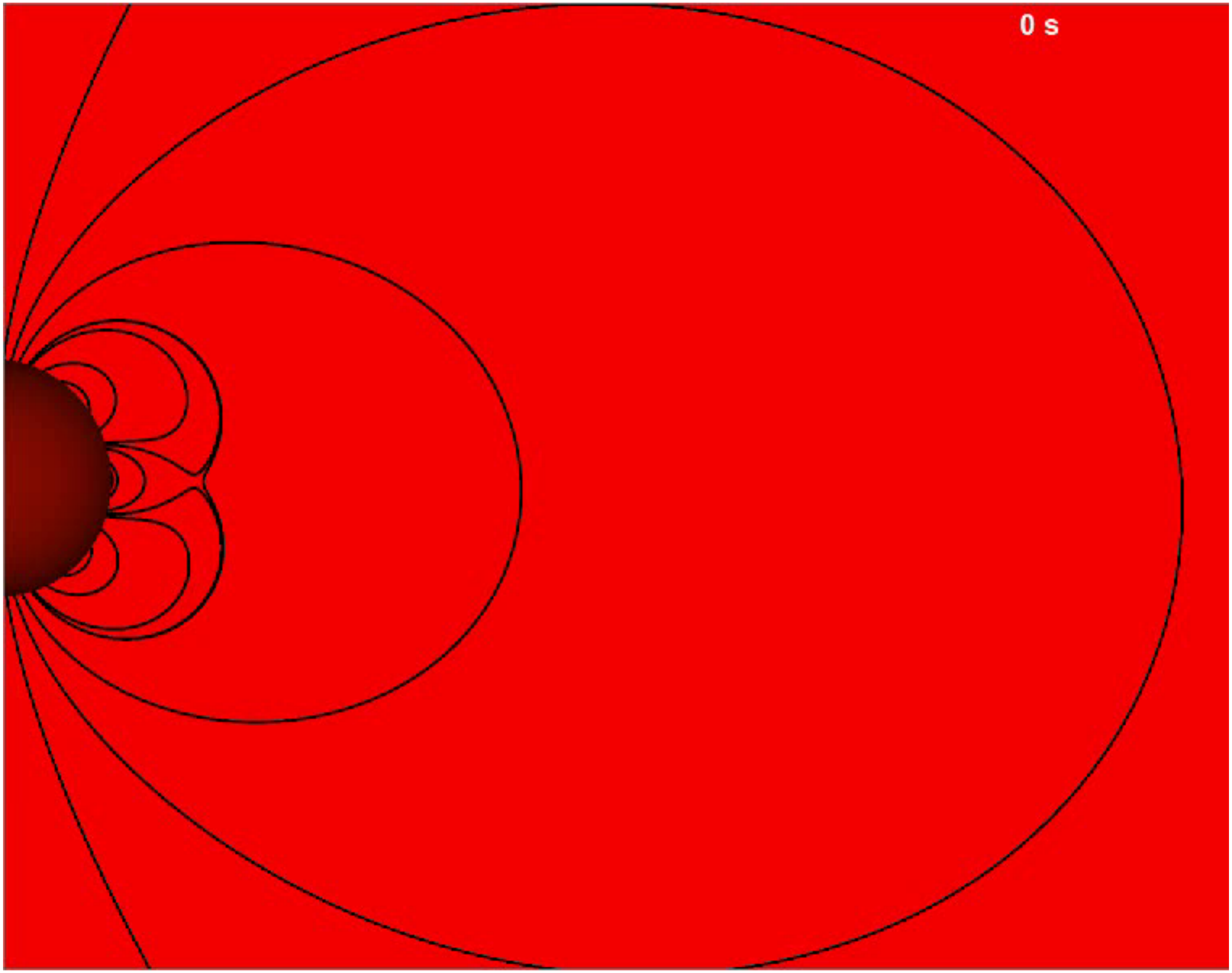
Slow evolution via breakout reconnection:

- Decreases overlying flux ψ_5
- Leaves unchanged arcade flux ψ_1

Loss of equilibrium through reconnection

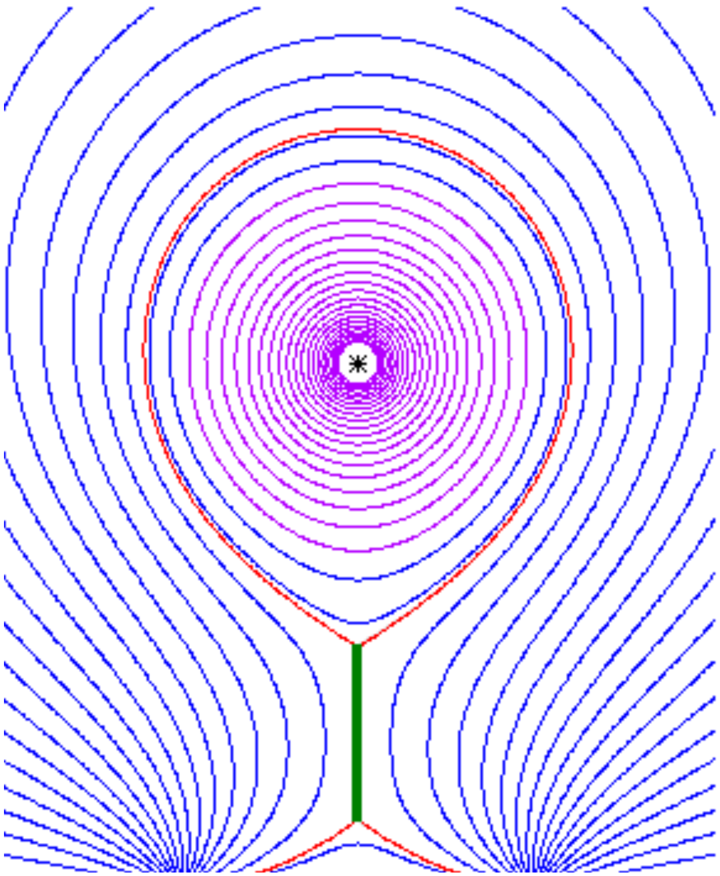


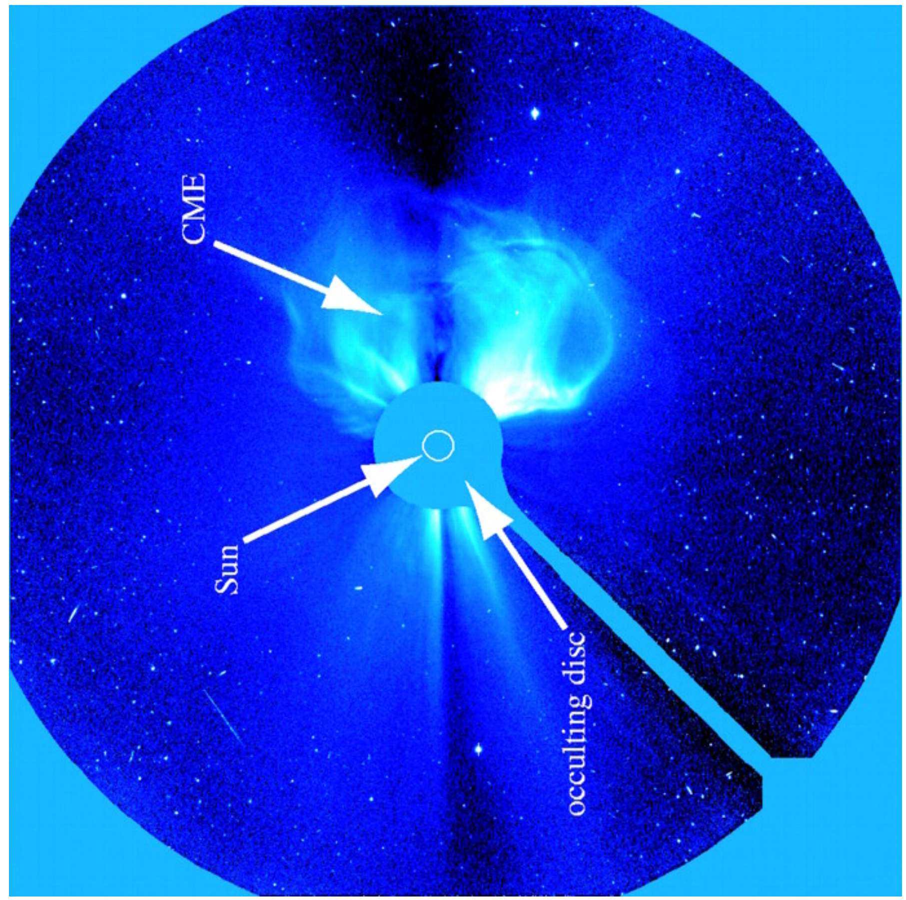
Numerical solution from Karpen et al. 2012



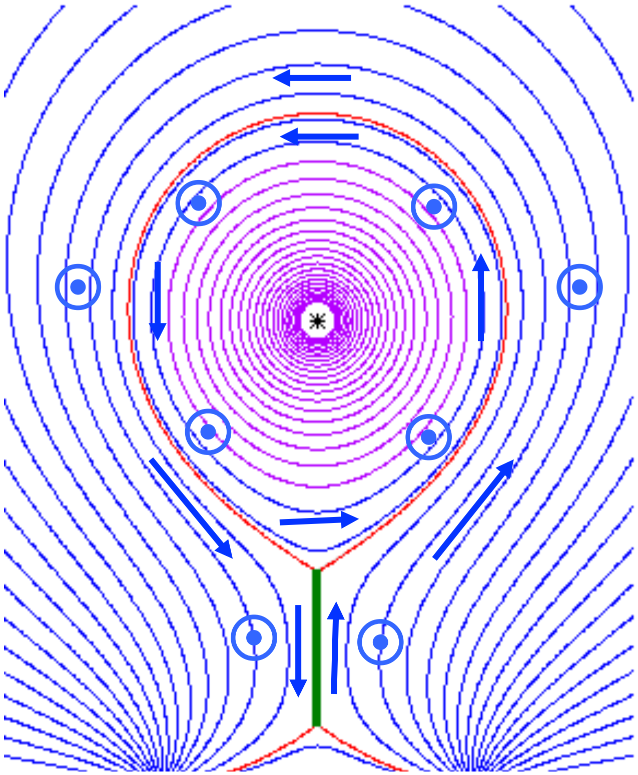
Flux ropes

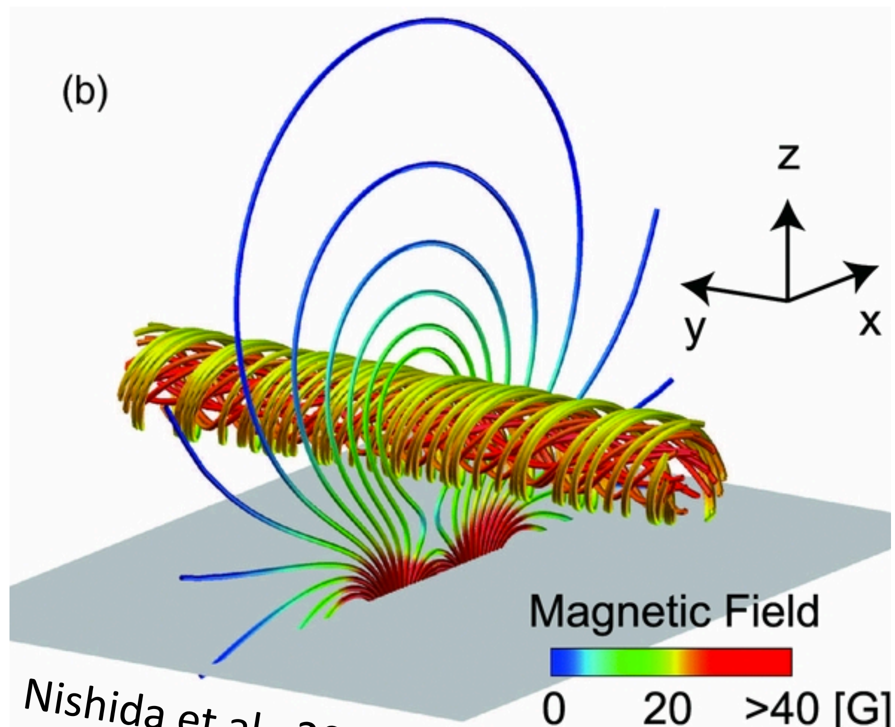
Reconnection: produced flux rope which erupts





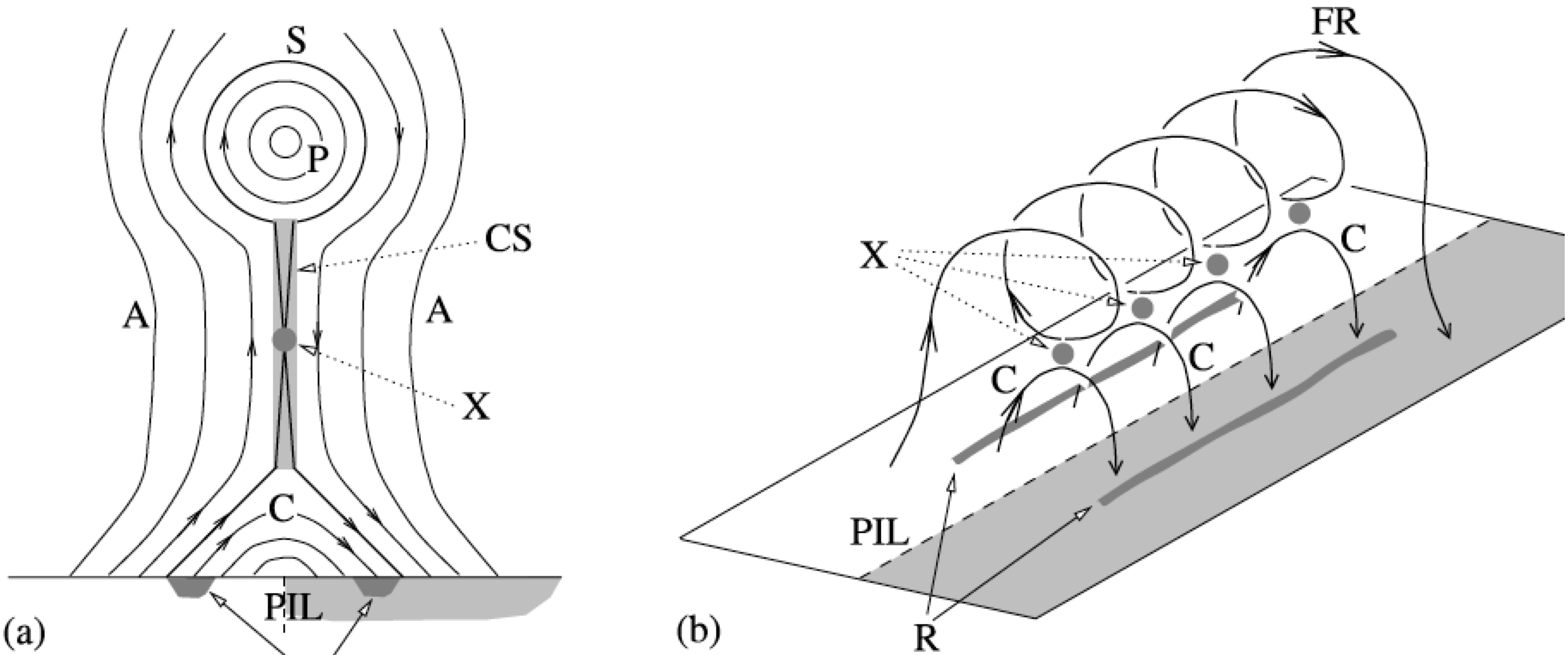
Twisted flux ropes





Nishida et al. 2013

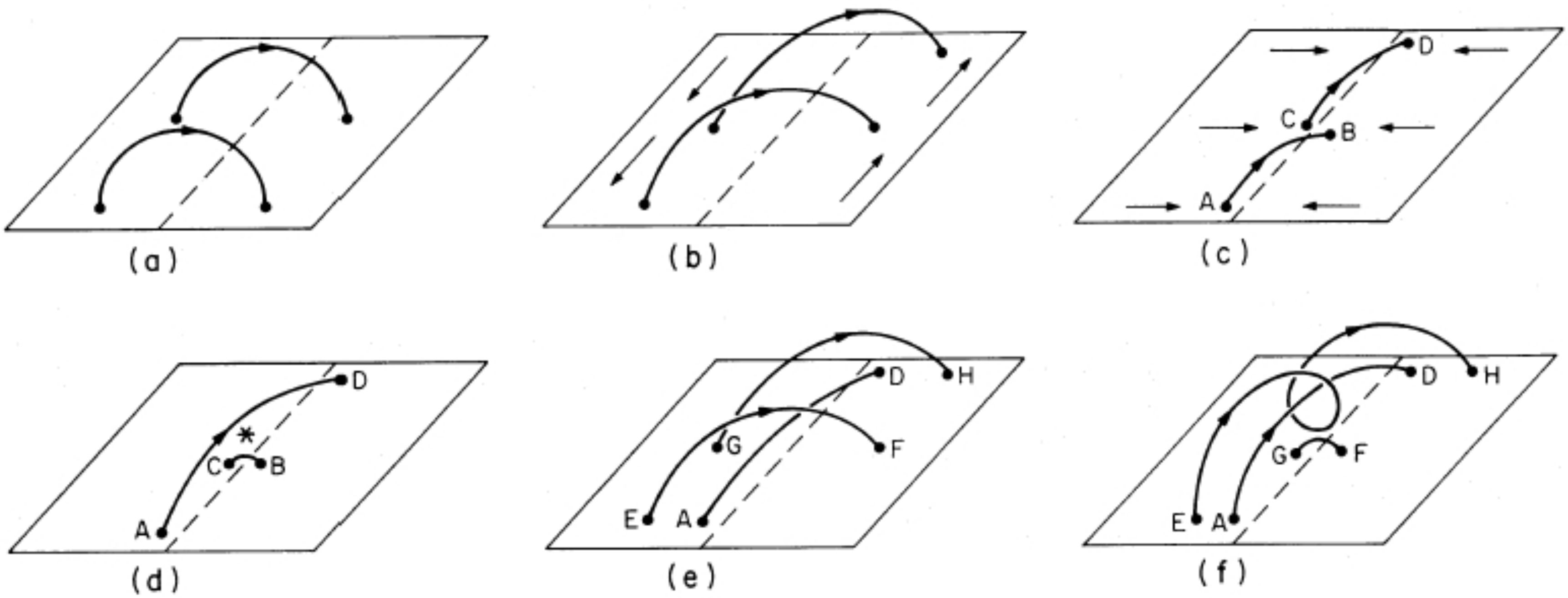
2.5d Reconnection: produces twisted flux rope



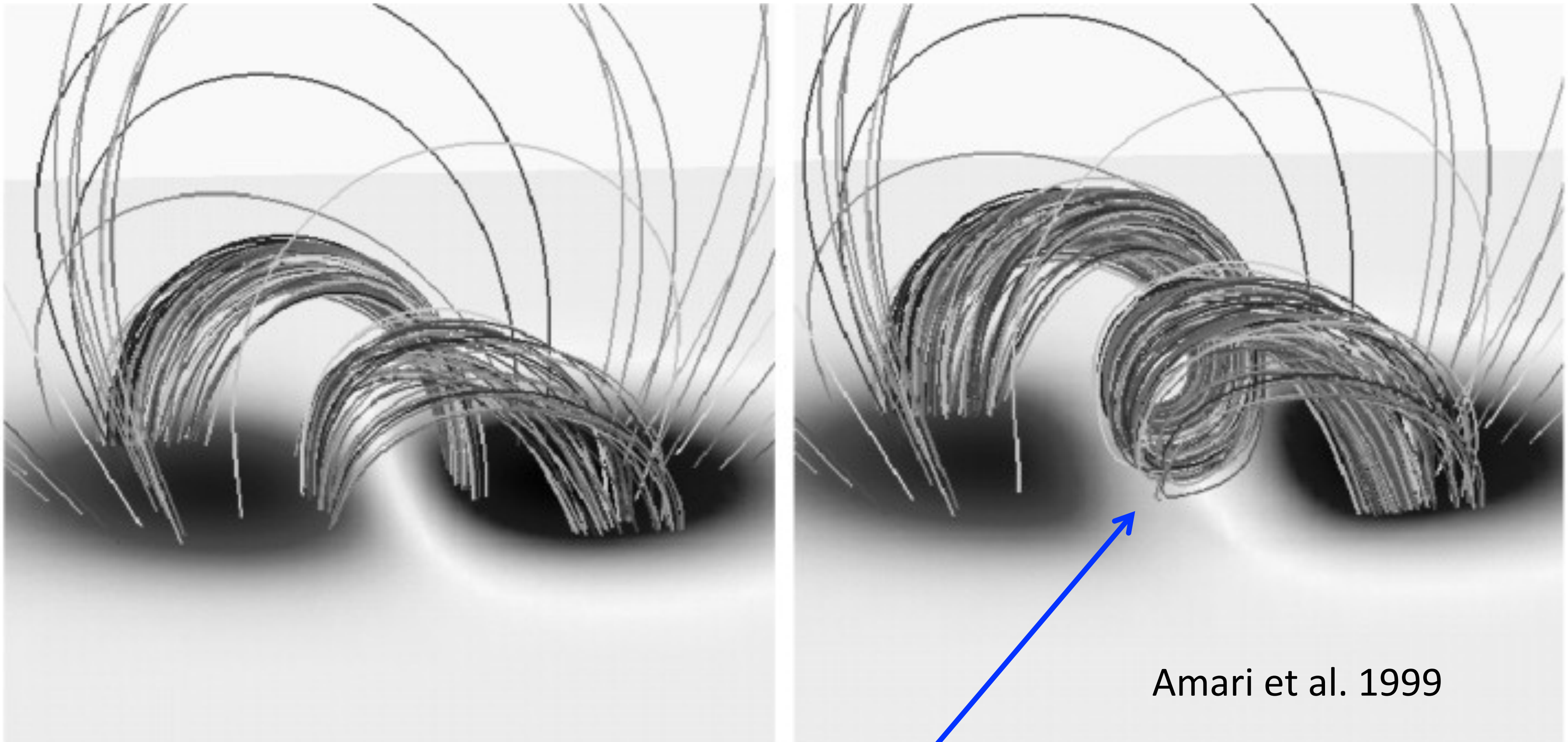
Longcope & Beveridge 2007

AND 3d reconnection

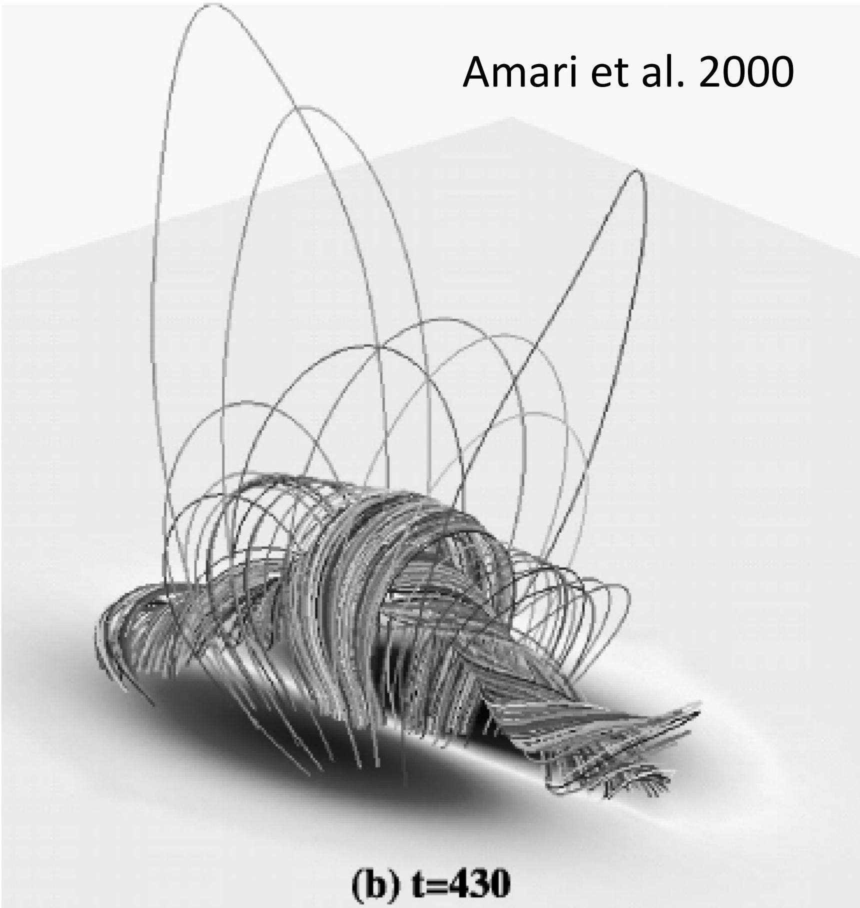
Reconnection can create twisted flux rope before eruption

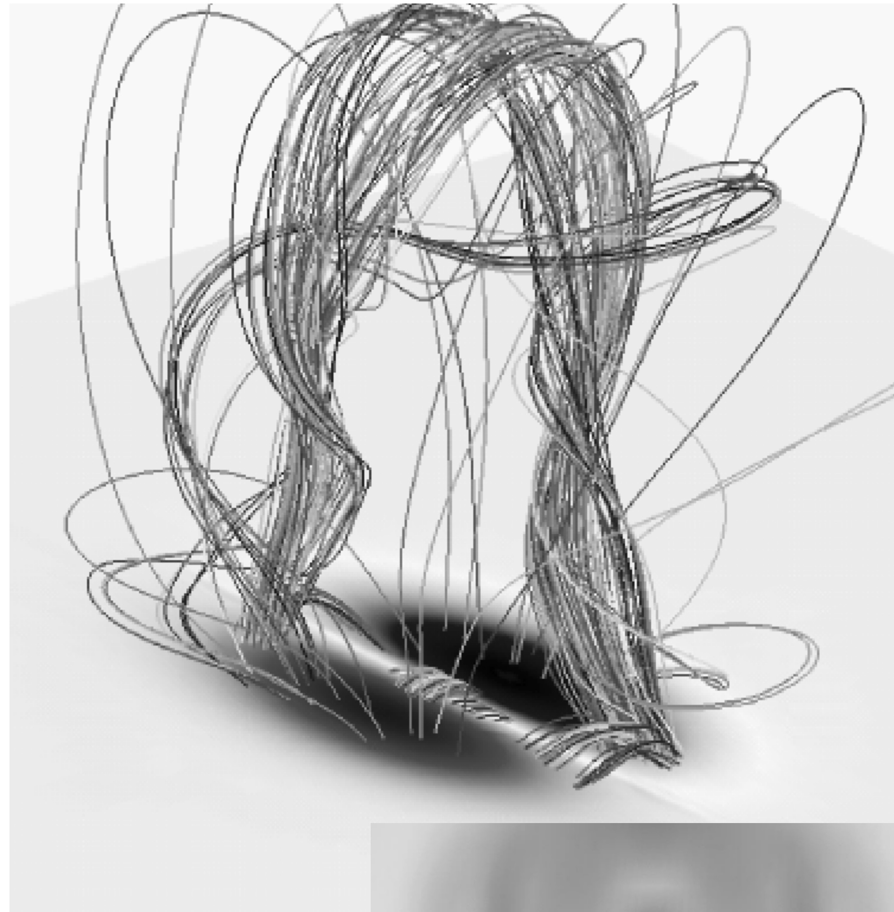


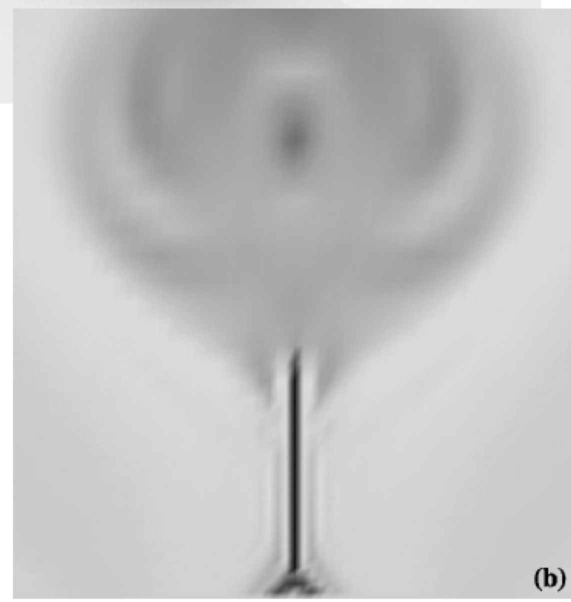
Van Ballegooijen & Martens 1989



Reconnection w/
subduction:


Amari et al. 2000
(b) t=430




(b)

Summary

- Large scales → ideal evolution (E'=0)
- Can develop CSs → small scales → E'≠0 in CS
- Non-ideal evolution: reconnection
  - Releases magnetic energy
  - Converts to heat, KE, …?
  - Can lead to LoE → more CSs & more reconnection
- Reconnection can produce twisted flux ropes which erupt