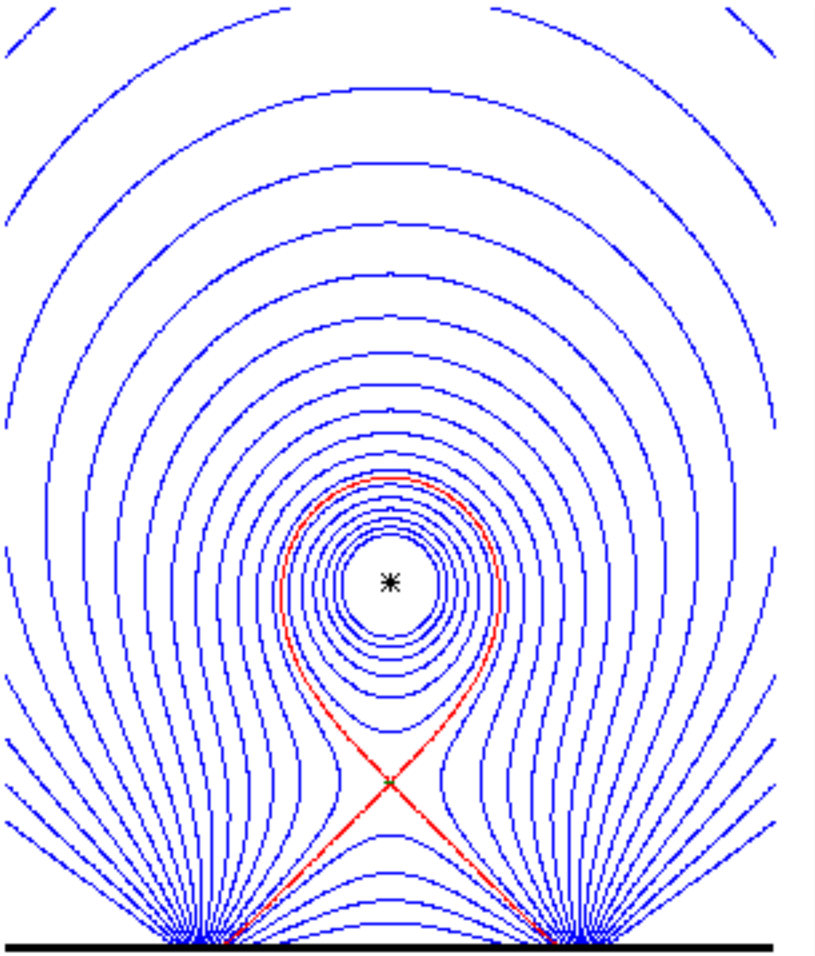
Magnetic Reconnection

Its role in CMEs & flares

Lecture 3

Jan. 25, 2017

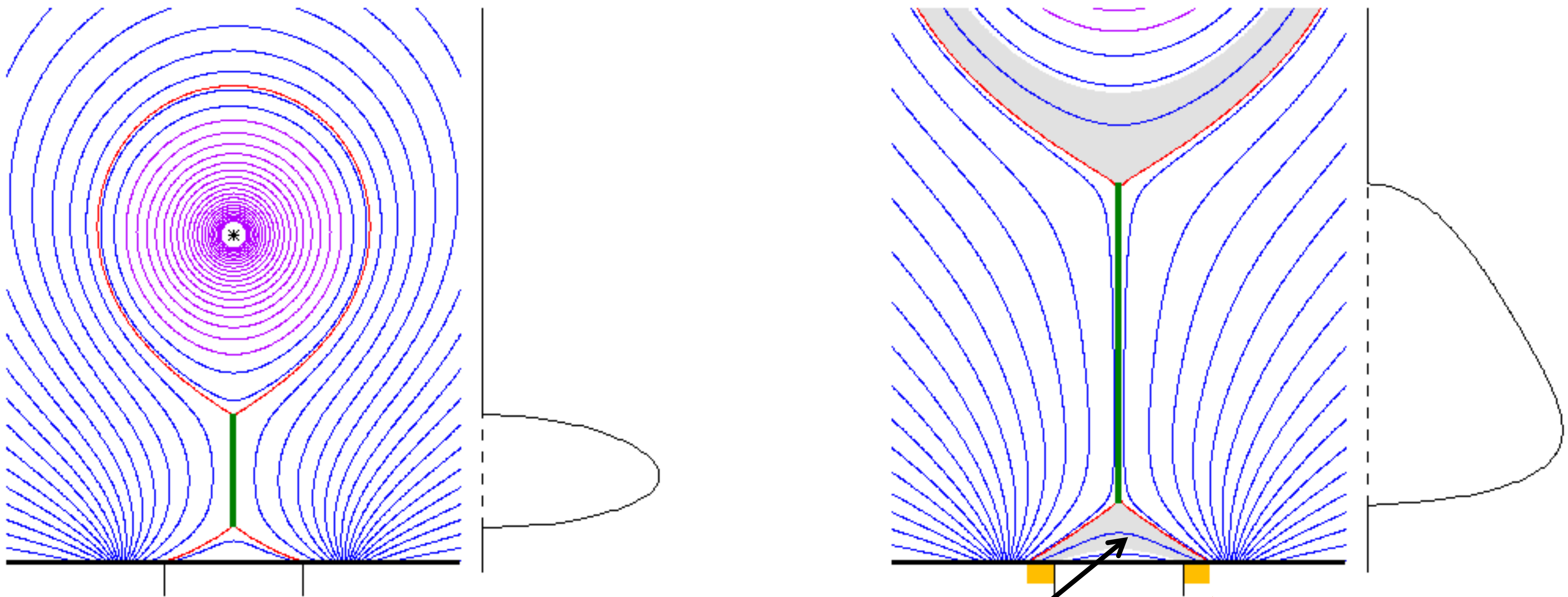


Last time:

- Ideal evolution:
  $\eta=0 \;\rightarrow\; E'=0$
- Can lead to LoE
- LoE produced current sheet (CS)
- Q: can we still demand $E'=0$ @ CS?
- If not, what happens next?

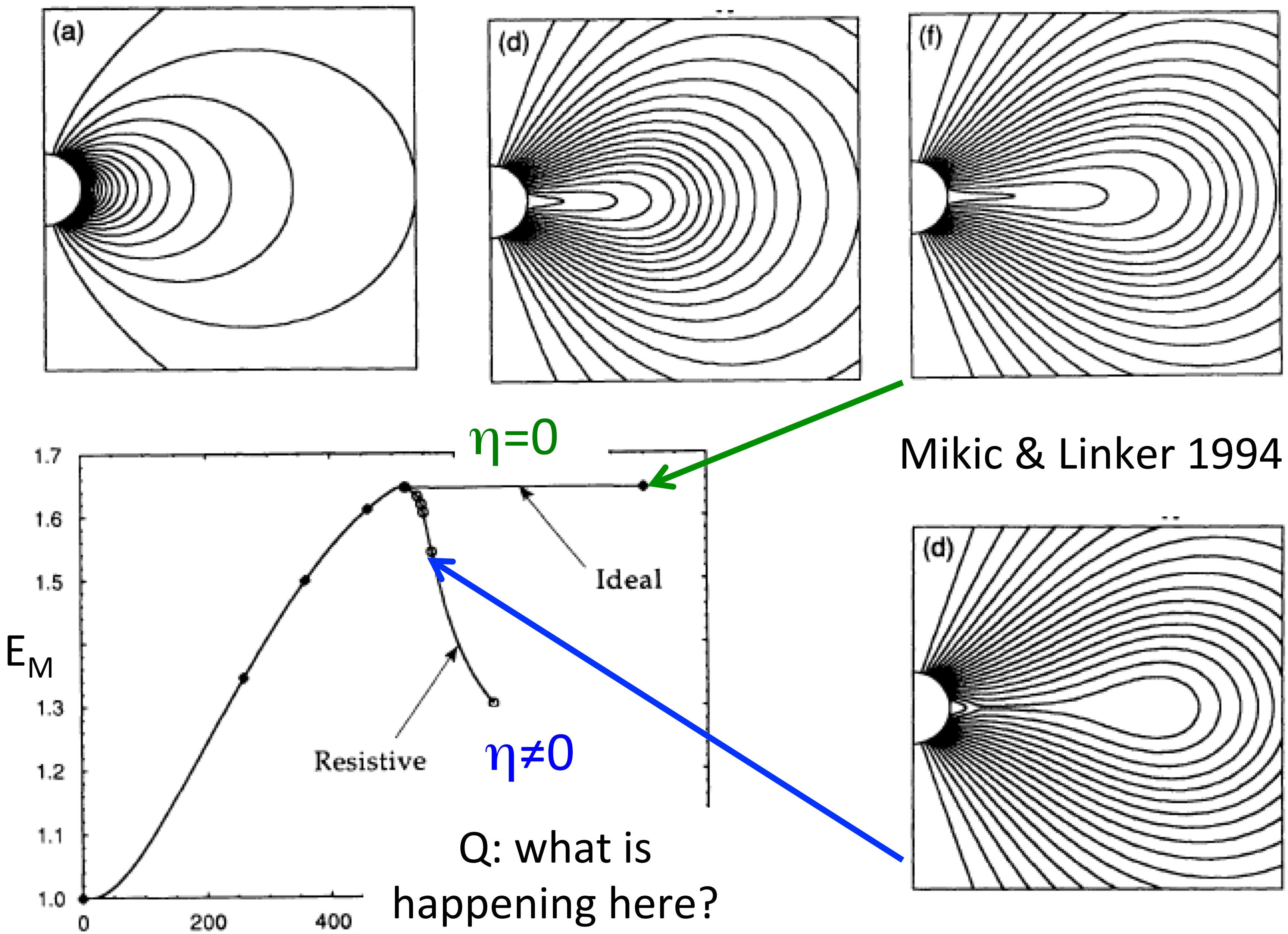
Eruption via reconnection

Assume E’ ≠ 0 @ CS (why? how?) ➔



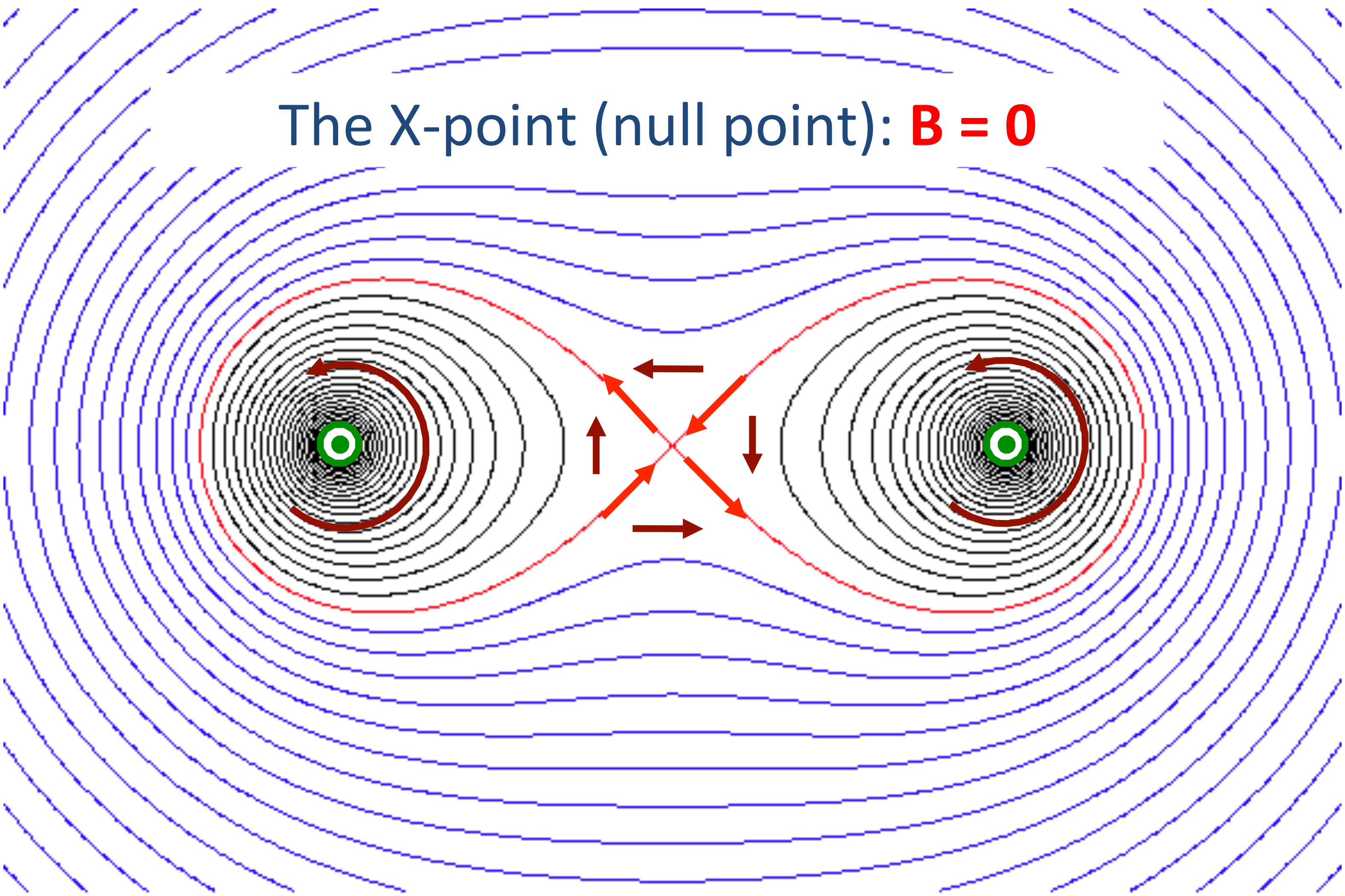
- Φ beneath CS increases
- Downward force decreases

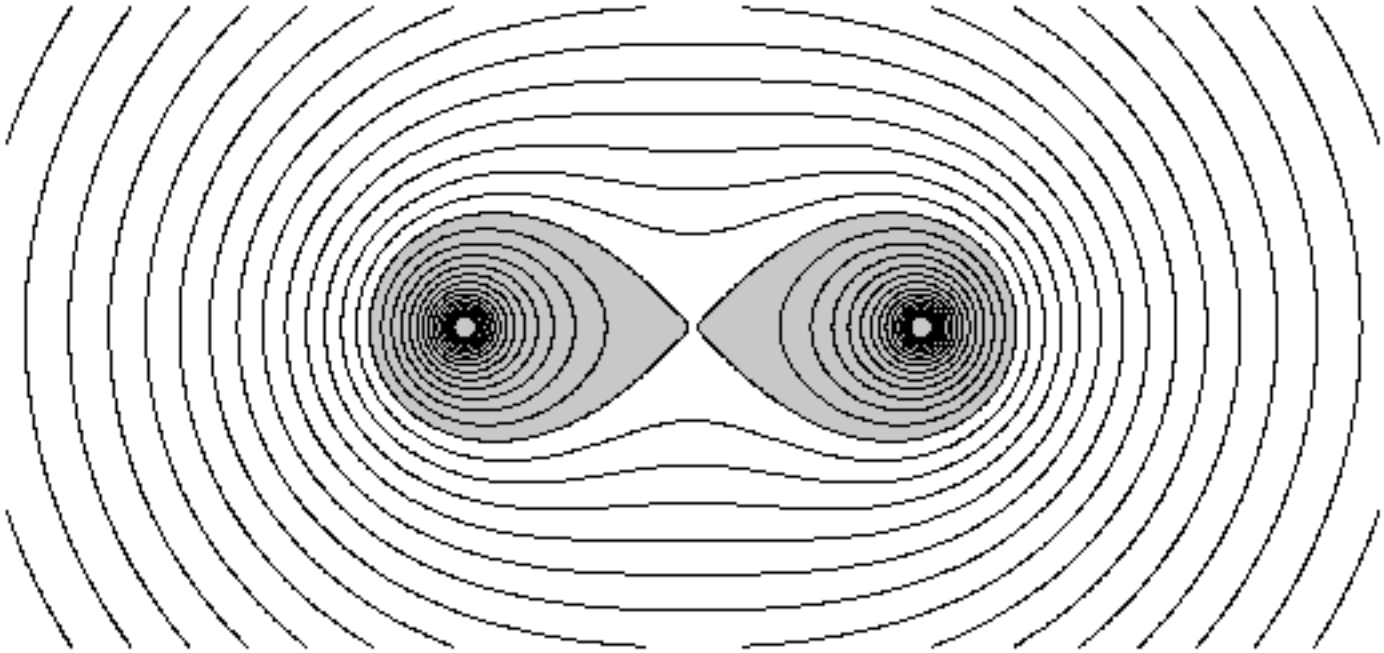
  (reconnection reduces overlying flux)
- Flux rope rises
- Flare signatures produced by E’



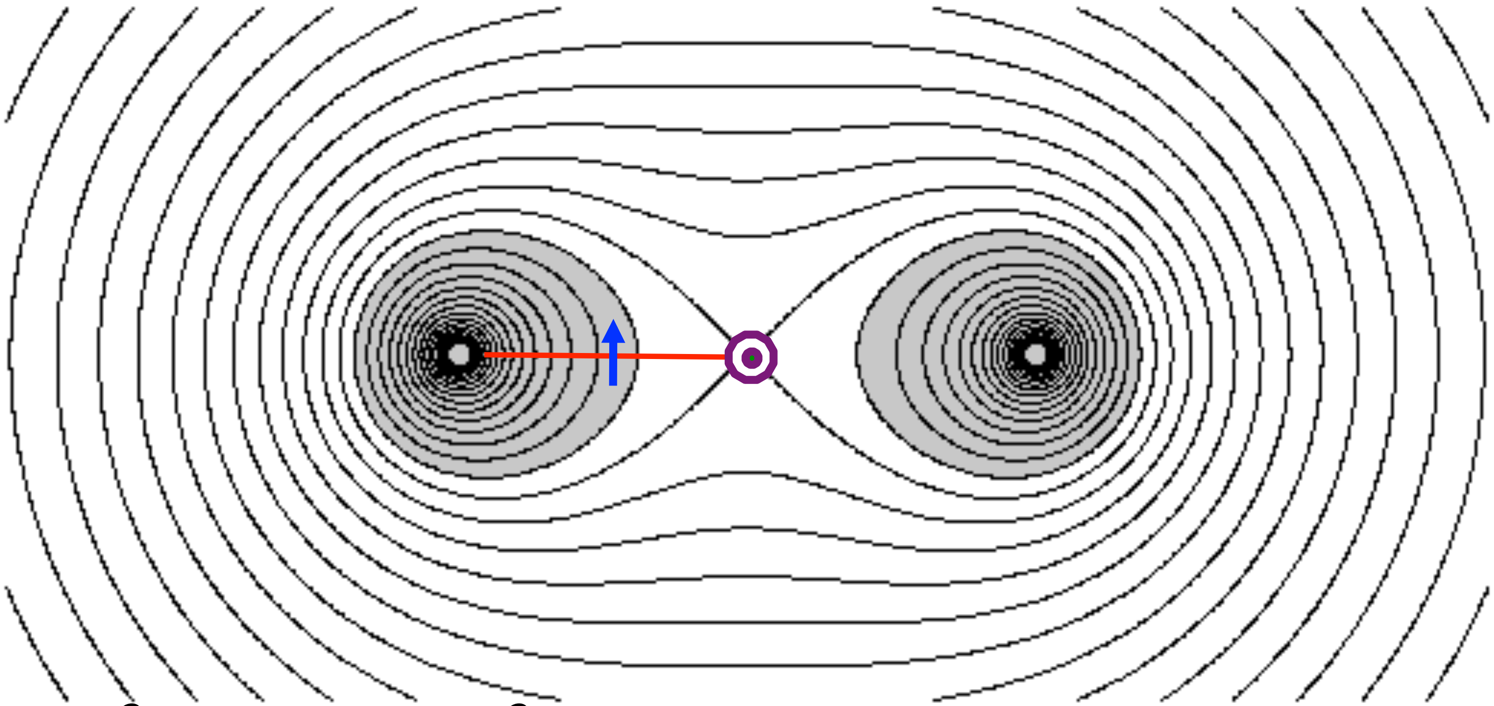
(a)
(d)
(f)
η=0
Mikic & Linker 1994
(d)
1.7
1.6
1.5
1.3
1.2
1.1
1.0
0
200
400
E_M
Ideal
Resistive
η≠0
Q: what is happening here?

Simpler toy: Parallel wires in vacuum



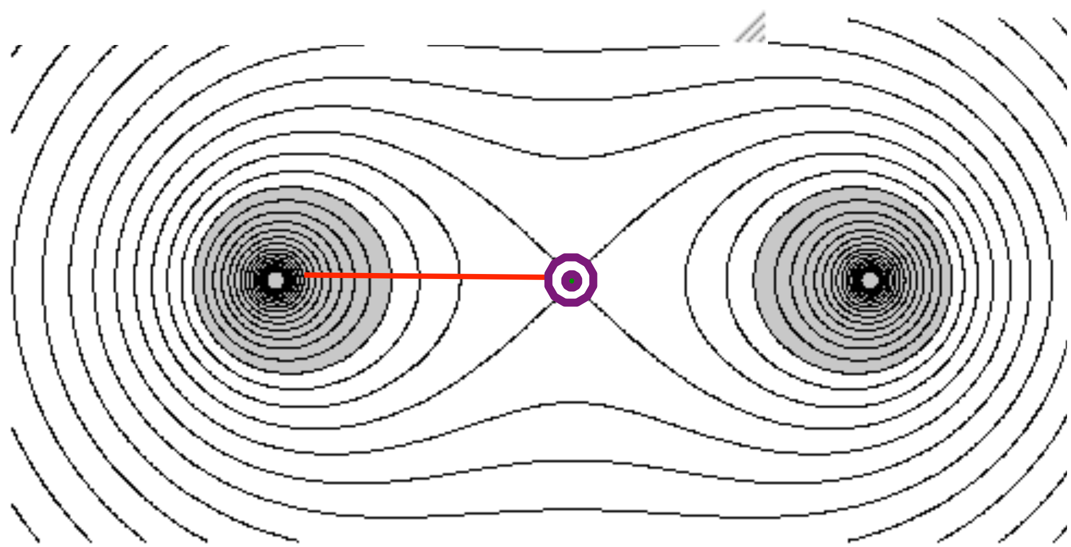


Separate wires **slowly**



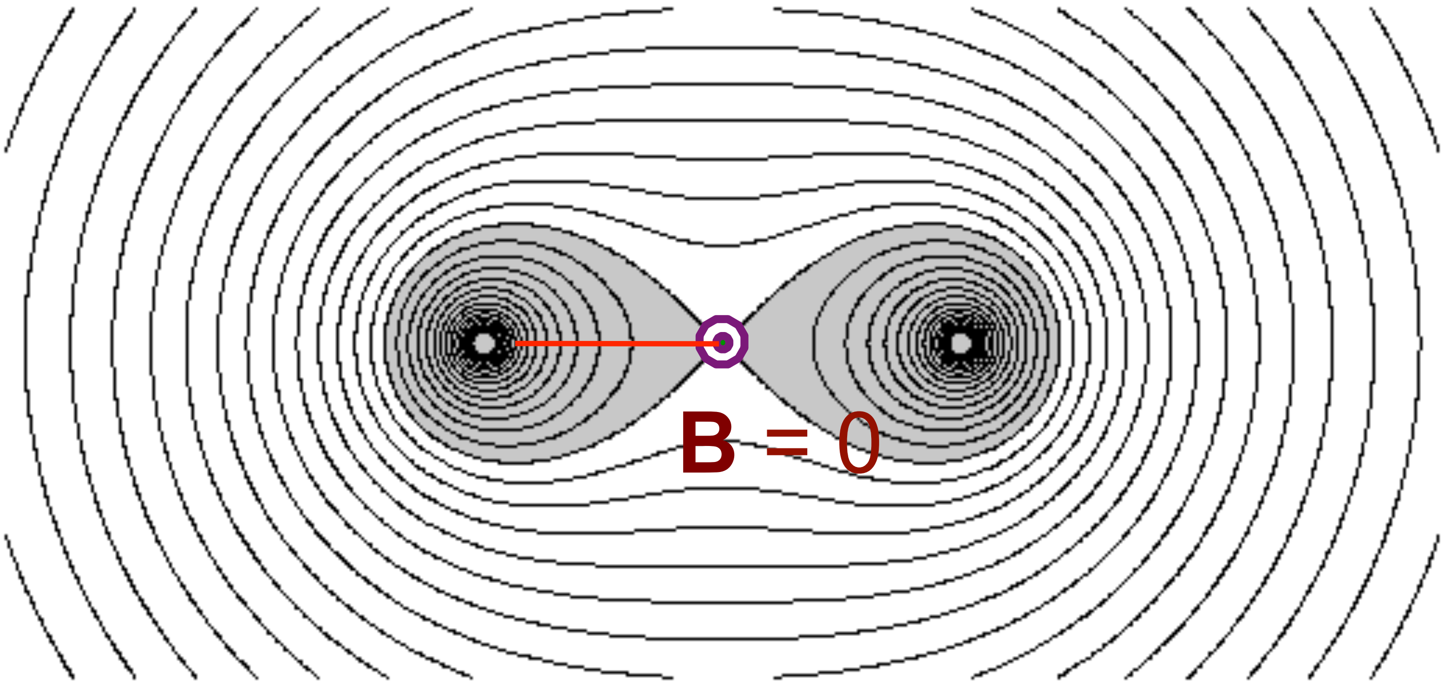
$$\Phi = \int \mathbf{B}\cdot d\mathbf{a} = L_z \underbrace{\int B_y dx}_{\psi}$$

$$\frac{d\Phi}{dt} = -\oint \mathbf{E}\cdot d\mathbf{l} = L_z E_z(0)$$



$E_z = d\psi/dt$

- Good conductor: $\mathbf{E} = 0$
- Good moving conductor: $\mathbf{E} + \mathbf{u} \times \mathbf{B} = 0$

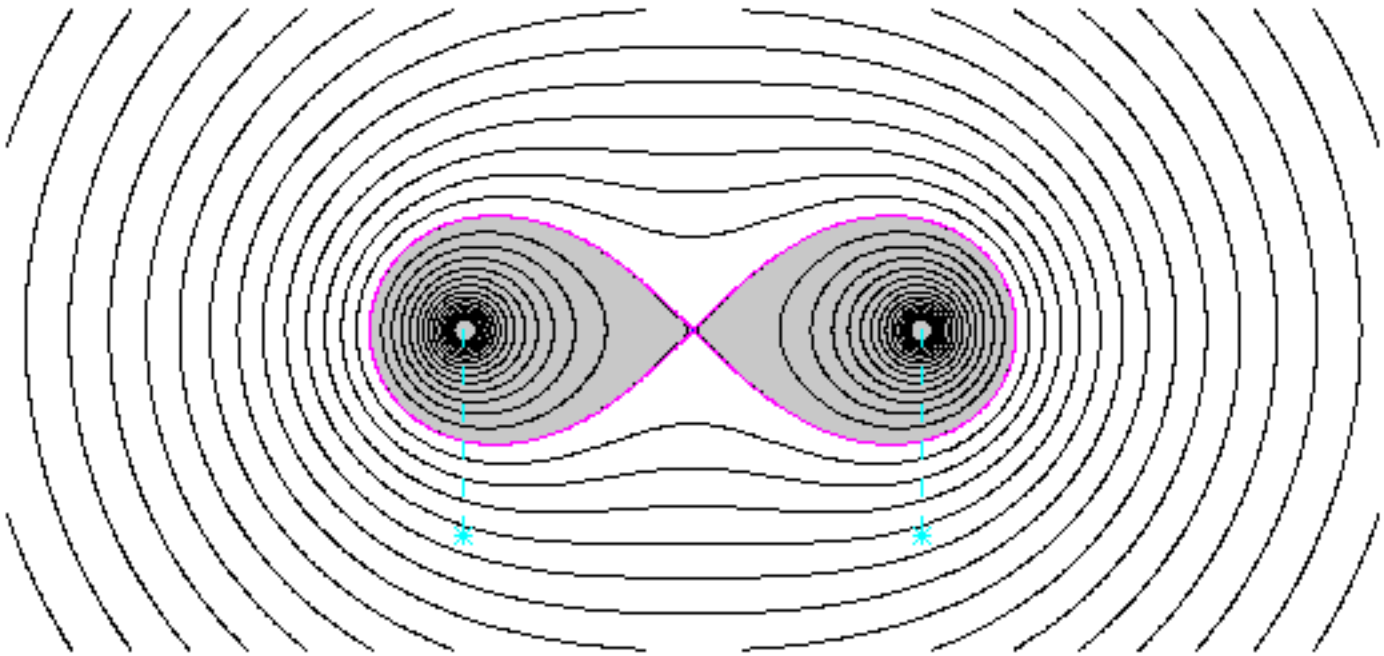


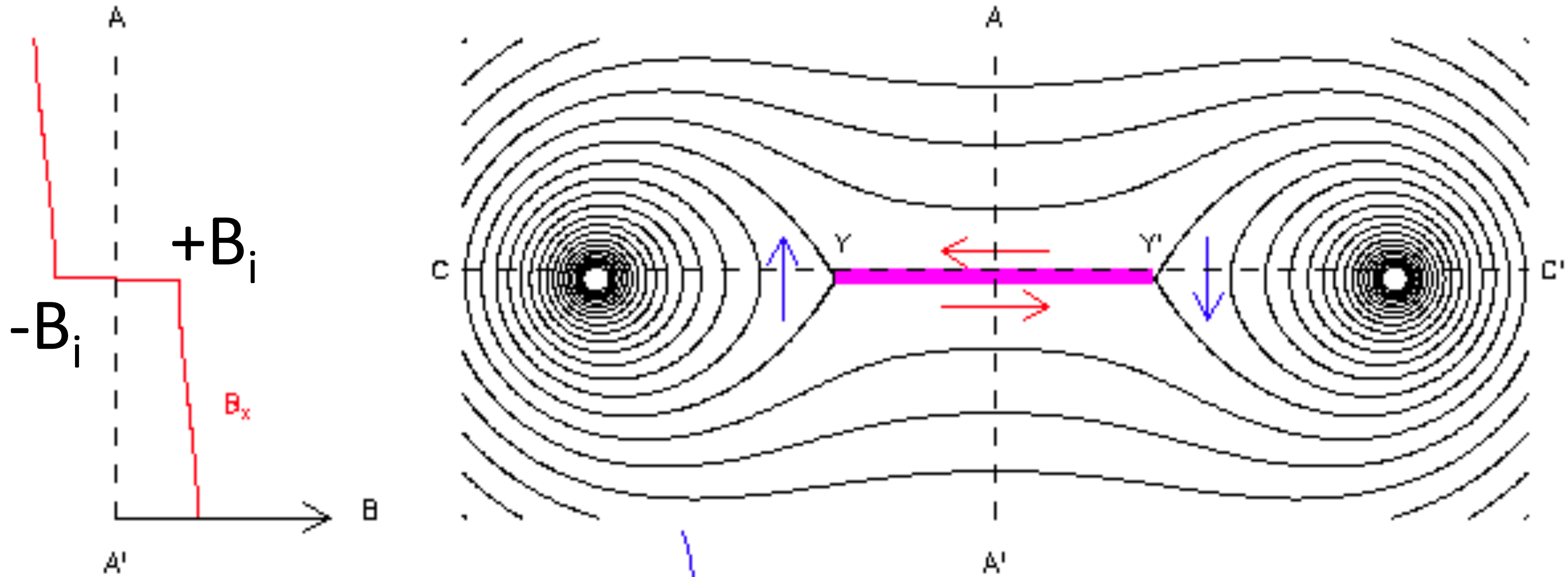
- $E_z + \cancel{(\mathbf{u} \times \mathbf{B})_z} = 0$

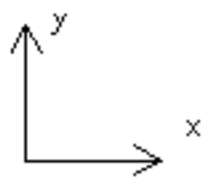
$E_z = d\psi/dt$

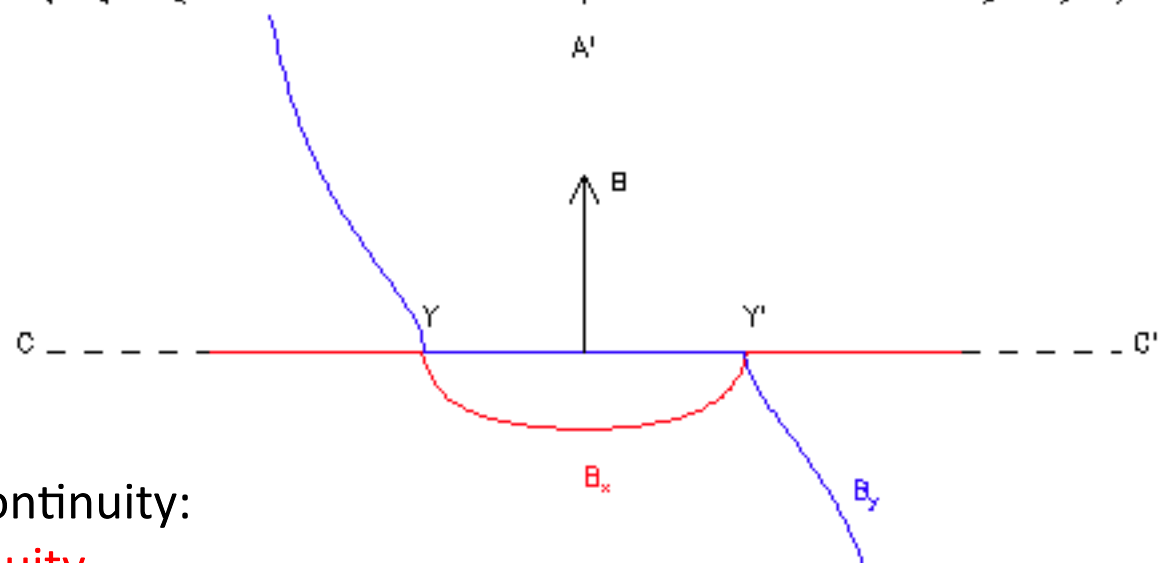
- ψ = const.

- Mag. Energy >> plasma energy (β<<1)
- Move slowly
- Min. magnetic energy









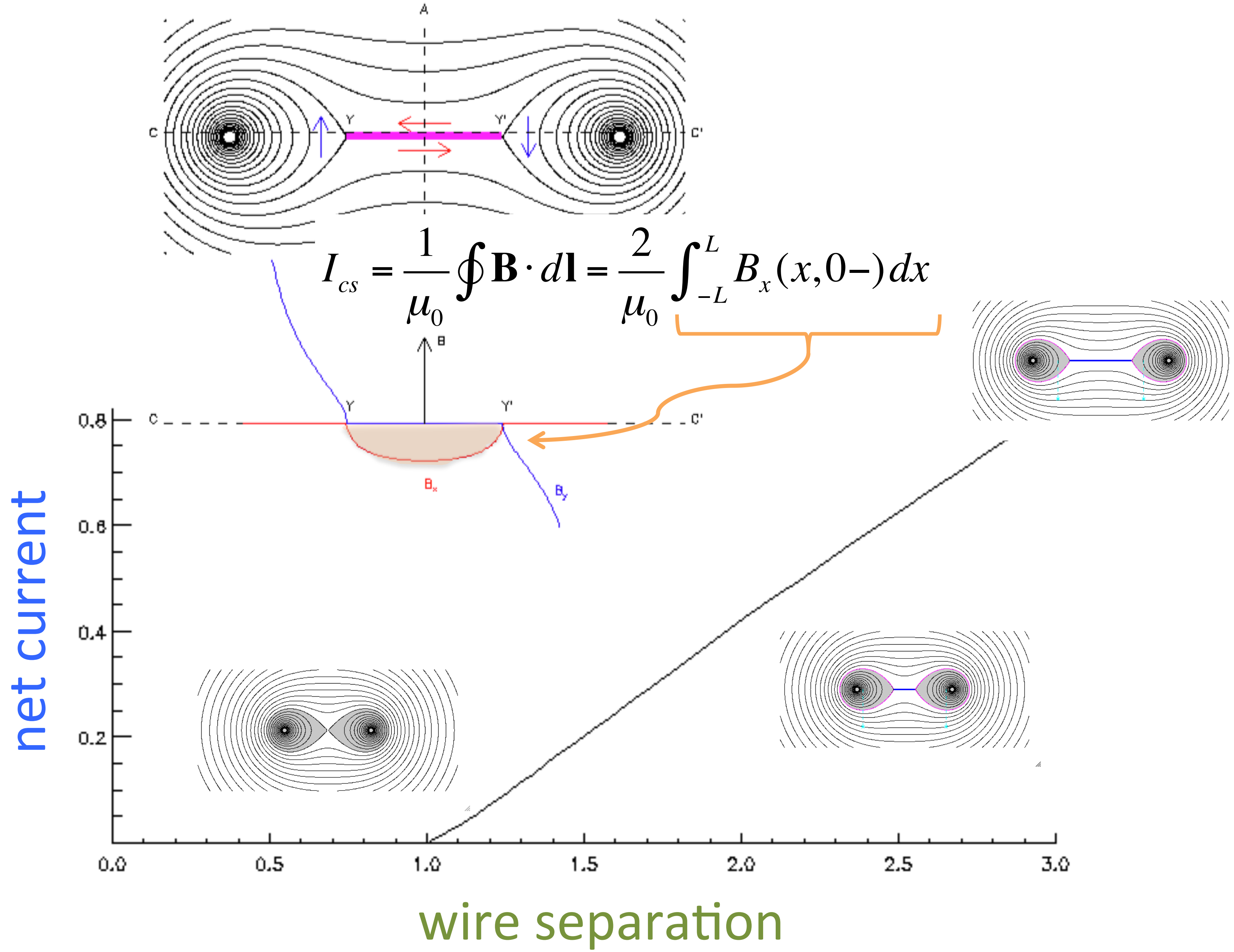
Magnetic field discontinuity:
tangential discontinuity

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B} = 2B_x(x,0-)\,\delta(y)\,\hat{\mathbf{z}}$$

Magnetic equilibrium

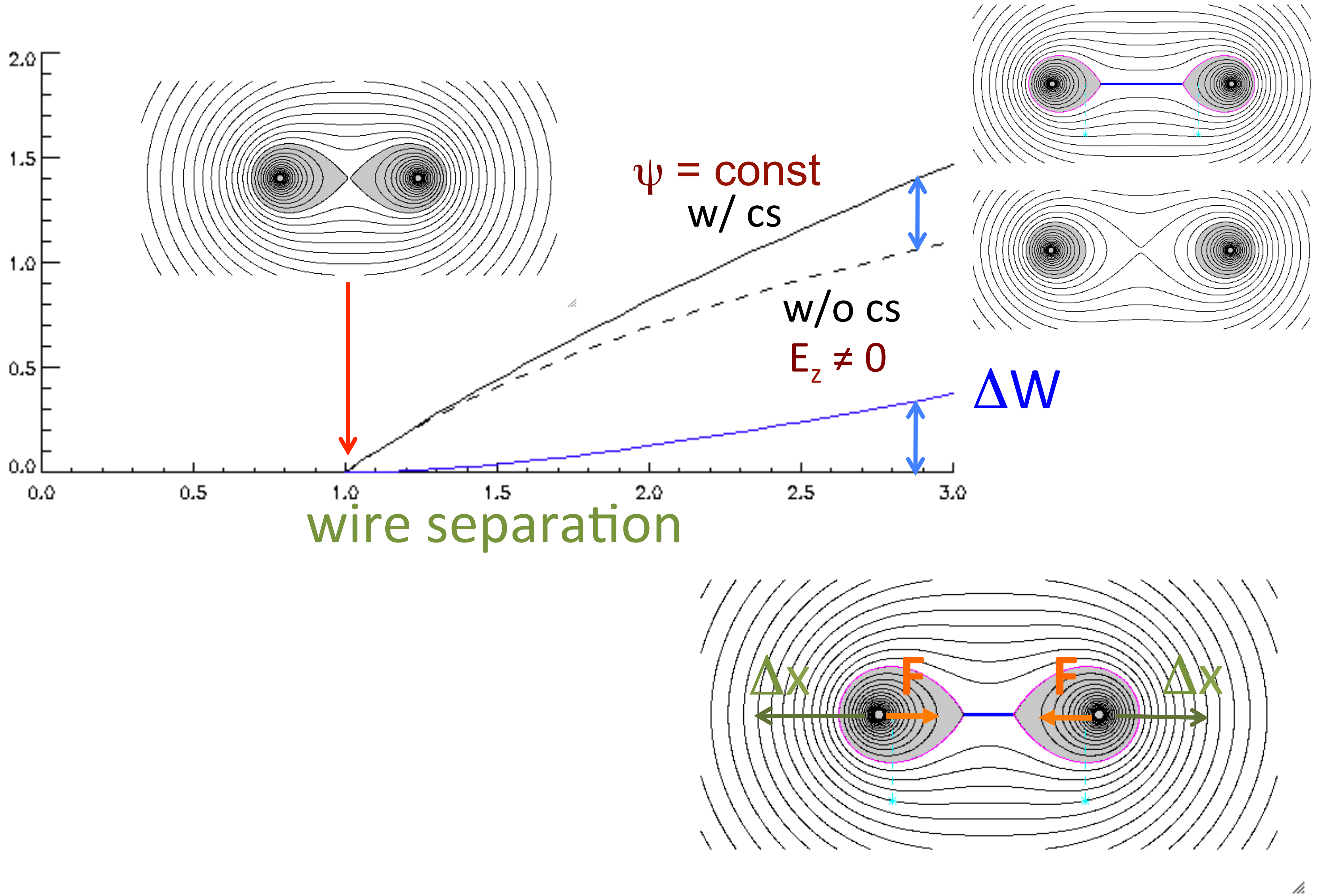
$$\mathbf{J} \times \mathbf{B} \propto \left(\nabla \times \mathbf{B}\right) \times \mathbf{B} = \tfrac{1}{2}\,\hat{\mathbf{y}}\,\frac{\partial}{\partial y}\left|\mathbf{B}\right|^2 = 0$$

Minimum magnetic energy state

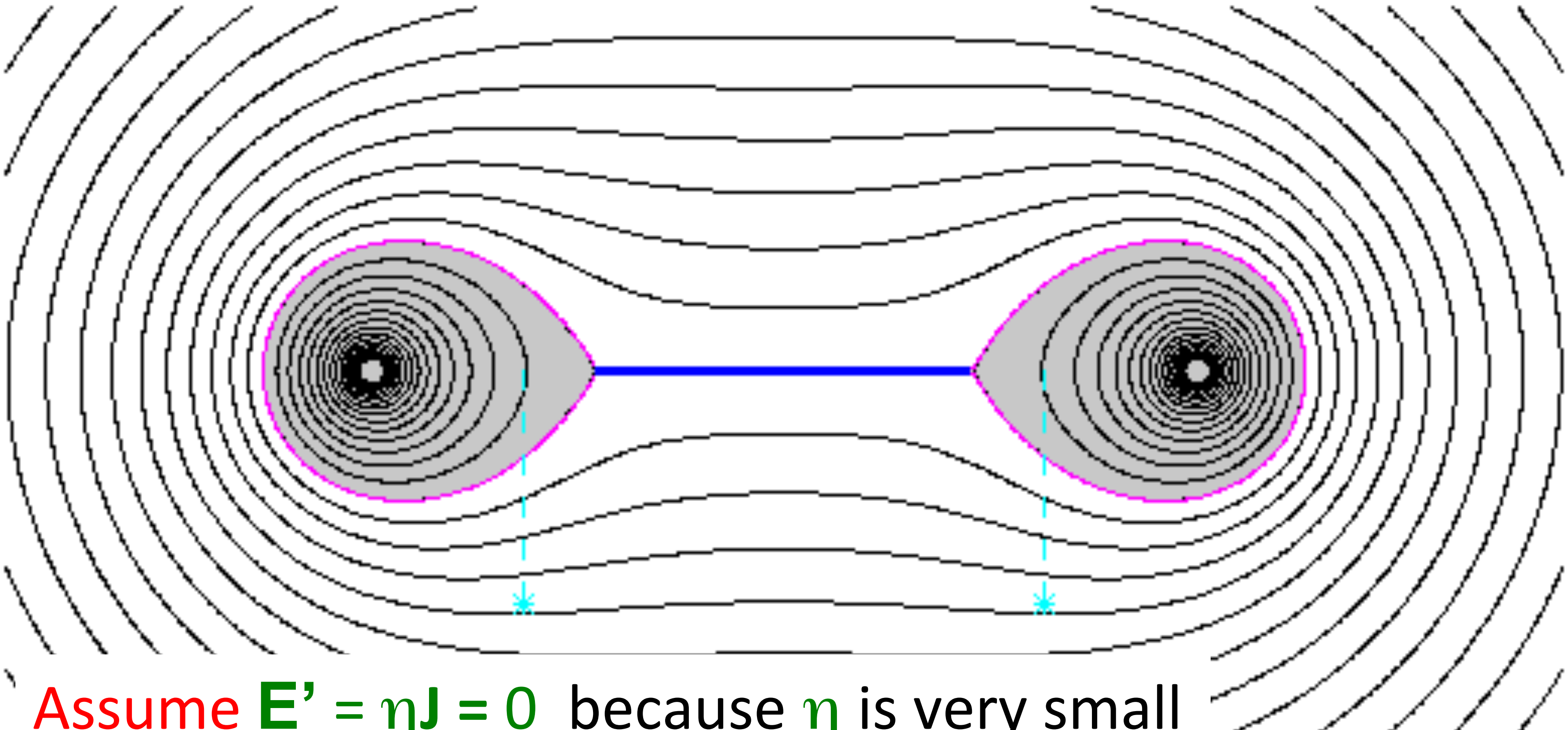


$$I_{cs} = \frac{1}{\mu_0}\oint \mathbf{B}\cdot d\mathbf{l} = \frac{2}{\mu_0}\underbrace{\int_{-L}^{L} B_x(x,0-)\,dx}$$

Work done on wires



The reconnection paradox



Assume **E'** = ηJ = 0 because η is very small

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B} = 2B_x(x,0-)\delta(y)\hat{\mathbf{z}}$$

Assumption
➔ discontinuity

Is **E'** = ηJ = 0 when J → ∞?

Ohm's law

- Q: What makes a conductor "good"? (**E**=0)

  (e.g. copper or gold? a plasma?)

- A: electrons move to eliminate **E**
- Q: What might limit "goodness"? (**E**≠0)
- A: electrons cannot respond effective

$$\mathbf{J} = en_e(\mathbf{v}_i - \mathbf{v}_e)$$

momentum eq. of electron fluid

$$m_e n_e \frac{d\mathbf{v}_e}{dt} = -\nabla\cdot\overleftrightarrow{P}_e - en_e\mathbf{E} - \frac{en_e}{c}\mathbf{v}_e\times\mathbf{B} + \overbrace{m_e n_e \nu_{ei}(\mathbf{v}_i - \mathbf{v}_e)}^{\text{drag}}$$

$$\overbrace{\mathbf{E} + \tfrac{1}{c}\underbrace{\boxed{\mathbf{v}_i}}_{\sim\,\mathbf{u}}\times\mathbf{B}}^{\mathbf{E}'} = -\overbrace{\frac{m_e}{e}\frac{d\mathbf{v}_e}{dt}}^{\text{electron inertia}} - \frac{1}{en_e}\nabla\cdot\overleftrightarrow{P}_e + \overbrace{\frac{1}{en_e c}\mathbf{J}\times\mathbf{B}}^{\text{Hall term}} + \overbrace{\boxed{\frac{m_e\nu_{ei}}{e^2 n_e}}}^{\eta_e}\mathbf{J}$$

$$\eta_e = 4\pi\frac{\nu_{ei}}{\omega_{pe}^2}$$

$$\eta = \nu_{ei}\left(\frac{c}{\omega_{pe}}\right)^2$$

cgs

Generalized Ohm's law

What's really important?

$$\mathbf{E} = -\tfrac{1}{c}\mathbf{u}\times\mathbf{B} - \frac{m_e}{e}\frac{d\mathbf{v}_e}{dt} - \frac{1}{en_e}\nabla\cdot\overleftrightarrow{P}_e + \frac{1}{en_e c}\mathbf{J}\times\mathbf{B} + \eta_e\mathbf{J}$$

$$\underbrace{-\tfrac{1}{c}\mathbf{u}\times\mathbf{B}}_{\text{(i)}} \quad \underbrace{\frac{m_e}{e}\frac{d\mathbf{v}_e}{dt}}_{\text{(ii)}} \quad \underbrace{\frac{1}{en_e}\nabla\cdot\overleftrightarrow{P}_e}_{\text{(iii)}} \quad \underbrace{\frac{1}{en_e c}\mathbf{J}\times\mathbf{B}}_{\text{(iv)}} \quad \underbrace{\eta_e\mathbf{J}}_{\text{(v)}}$$

$$\frac{\text{(i)}}{\text{(v)}} = \frac{uB/c}{\eta_e\left(cB/\ell\right)} = \frac{\ell u}{\eta} \equiv Rm \sim \frac{u}{v_{th,e}}\frac{\ell_{mfp}\ell}{\left(c/\omega_{pe}\right)^2}$$

$$\frac{\text{(i)}}{\text{(ii)}} = \frac{uB/c}{(u/\ell)m_e cB/e^2 n_e\ell} = \frac{\ell^2}{c^2 m_e/e^2 n_e} \sim \left(\frac{\ell}{c/\omega_{pe}}\right)^2$$

$$\frac{\text{(i)}}{\text{(iv)}} = \frac{uB/c}{B^2/en_e\ell} = \frac{u\ell}{Bc/en_e} \sim \left(\frac{u}{v_A}\right)\left(\frac{\ell}{c/\omega_{pi}}\right)$$

$$\frac{\text{(i)}}{\text{(iii)}} = \frac{uB/c}{p_e/en_e\ell} = \frac{u\ell}{k_B Tc/eB} = \left(\frac{u}{c_s}\right)\left(\frac{\ell}{r_{g,i}}\right)$$

Importance of term depends on length scale of solution

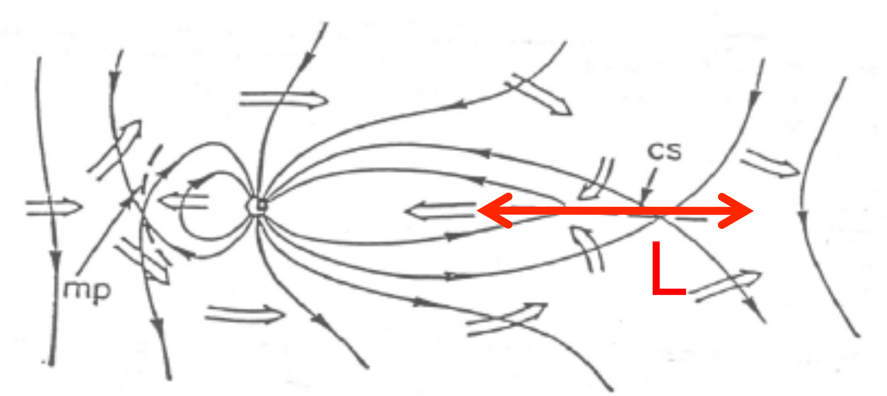
On large scales plasma is very good conductor

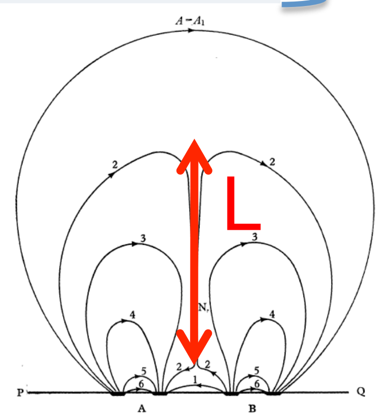
$$\ell >> r_{g,i}\,,\ \frac{c}{\omega_{pi}}$$

How large is "large"?

		Earth's magnetotail	Solar corona
External scale	L	10^8 m	10^8 m
Collisionless skin depth	c/ω_{pe}	10^4 m	0.1 m
ion skin depth	c/ω_{pi}	10^6 m	10 m
Ion gyro-radius	$r_{g,i}$	10^5 m	0.1 m

All small :
E+**u**×**B**=0





Classical Resistivity

Rutherford scattering:

Scattering cross section

$$\eta_e = \frac{m_e \nu_{ei}}{e^2 n_e} \sim \frac{m_e}{e^2} v_{th,e} \sigma_{ei}$$

$$\sigma_{ei} \sim \left(\frac{e^2}{\varepsilon_0 m_e v_{th,e}^2} \right)^2$$

$$\boxed{\eta_e \sim \frac{e^2}{\varepsilon_0^2 m_e v_{th,e}^3} \sim \frac{e^2 \sqrt{m_e}}{\varepsilon_0^2 \left(k_b T_e\right)^{3/2}}}$$

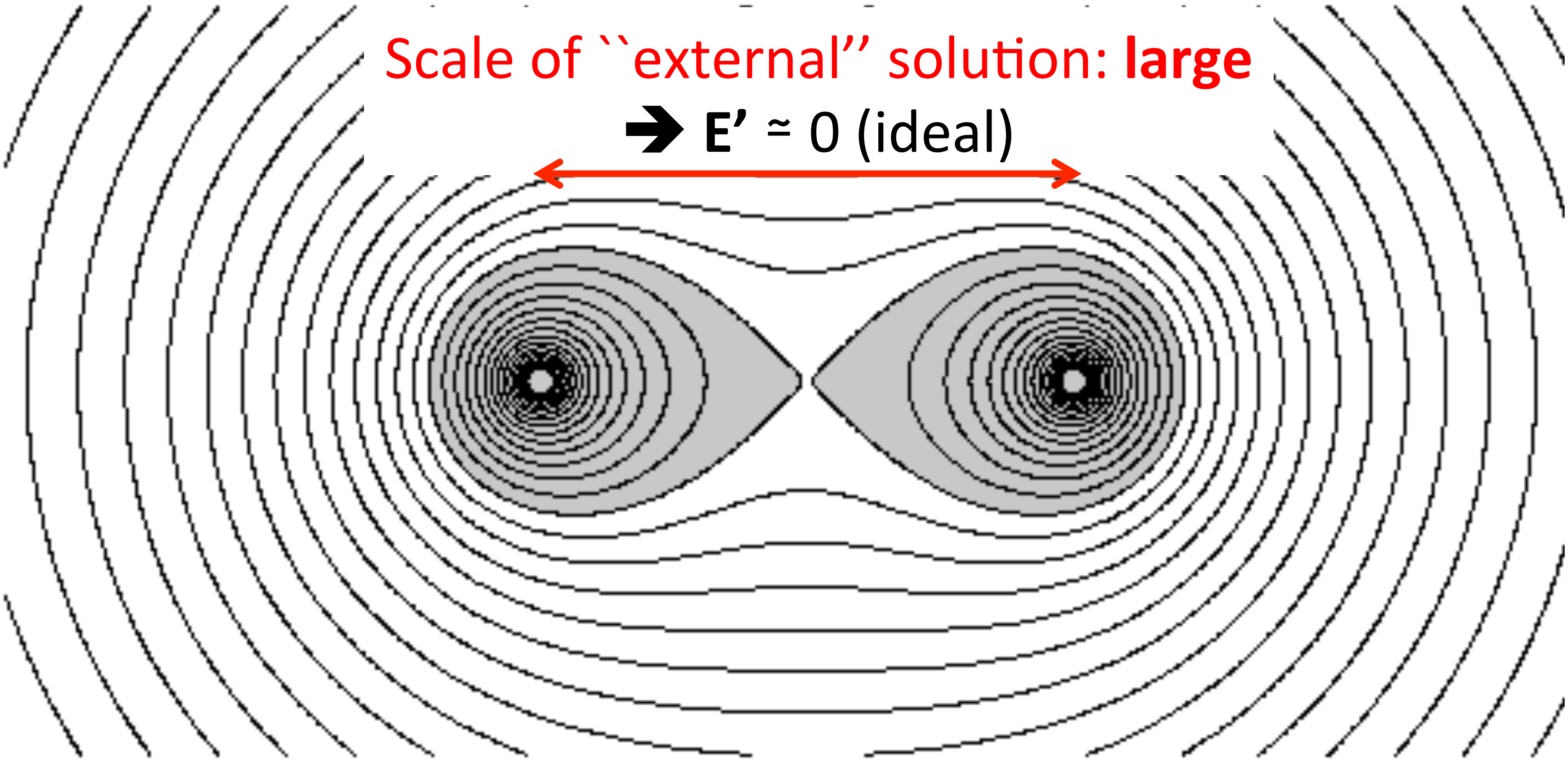
hotter plasma → lower resistivity

Lundquist number:

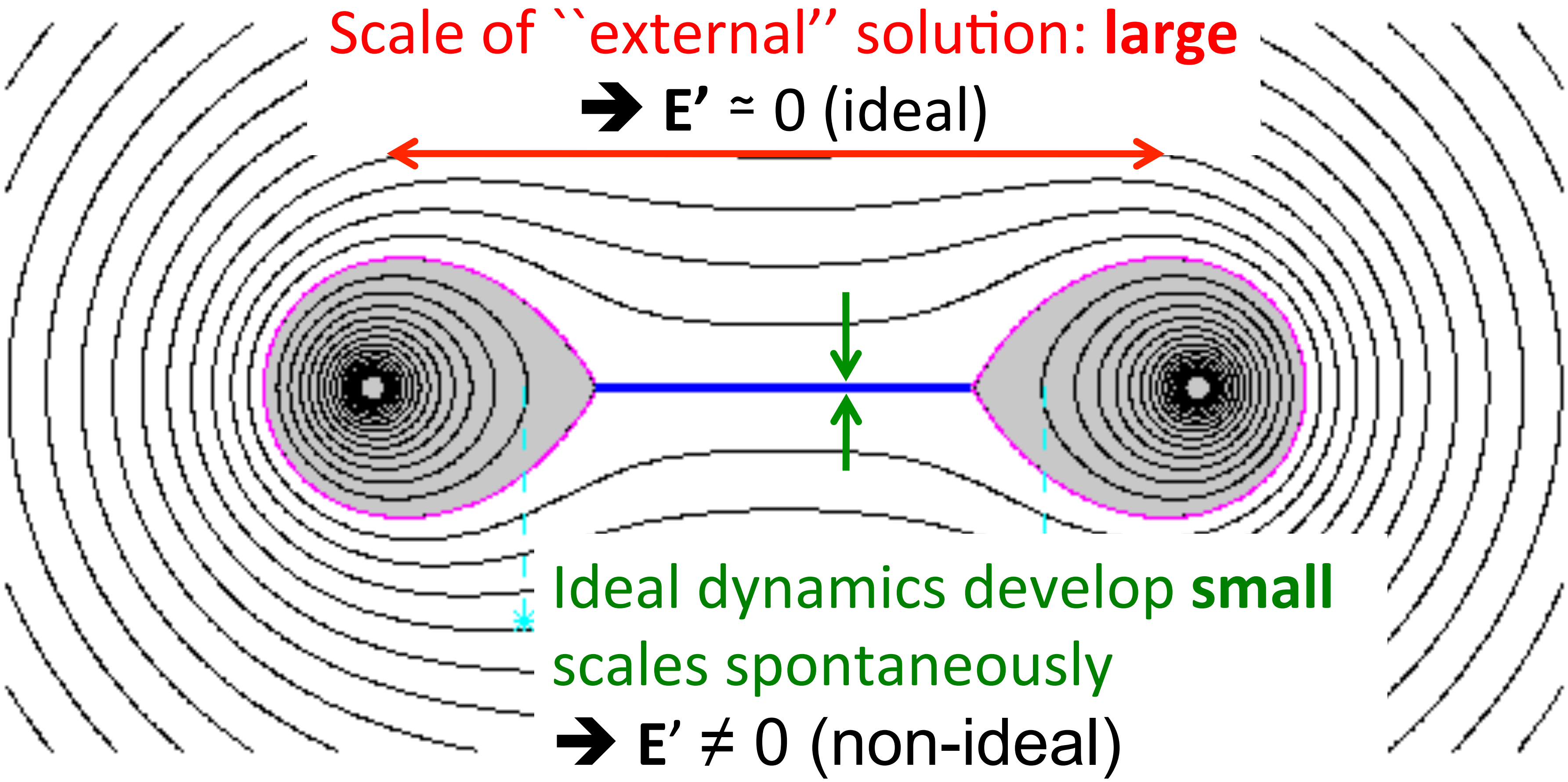
$$S = \frac{\mu_0 L v_A}{\eta_e} \sim \frac{\left(k_b T_e\right)^{3/2}}{e^2 c^4 \sqrt{\mu_0 m_e m_i n_i}} \frac{LB}{\mu_0} \sim \frac{\left|I_{cs}\right|}{I_{sp}}$$

$$I_{sp} = \frac{e^2 c^4 \sqrt{\mu_0 m_e m_i n_i}}{\left(k_b T_e\right)^{3/2}} = 2.3 \times 10^{-3}\,\mathrm{A} \left(\frac{n_i}{10^9\,\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{T_e}{10^6\,\mathrm{K}} \right)^{-3/2}$$

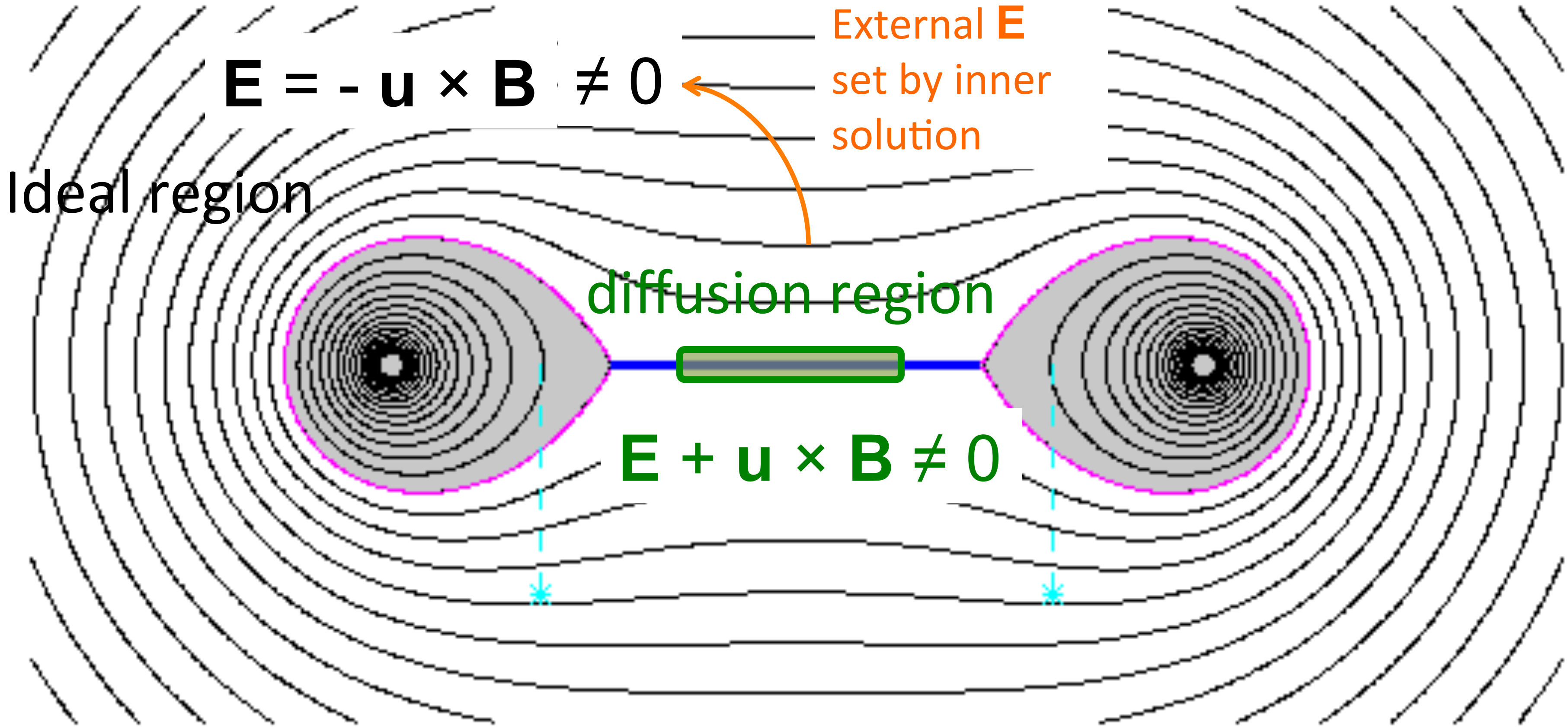
Reconnection paradox



Reconnection paradox

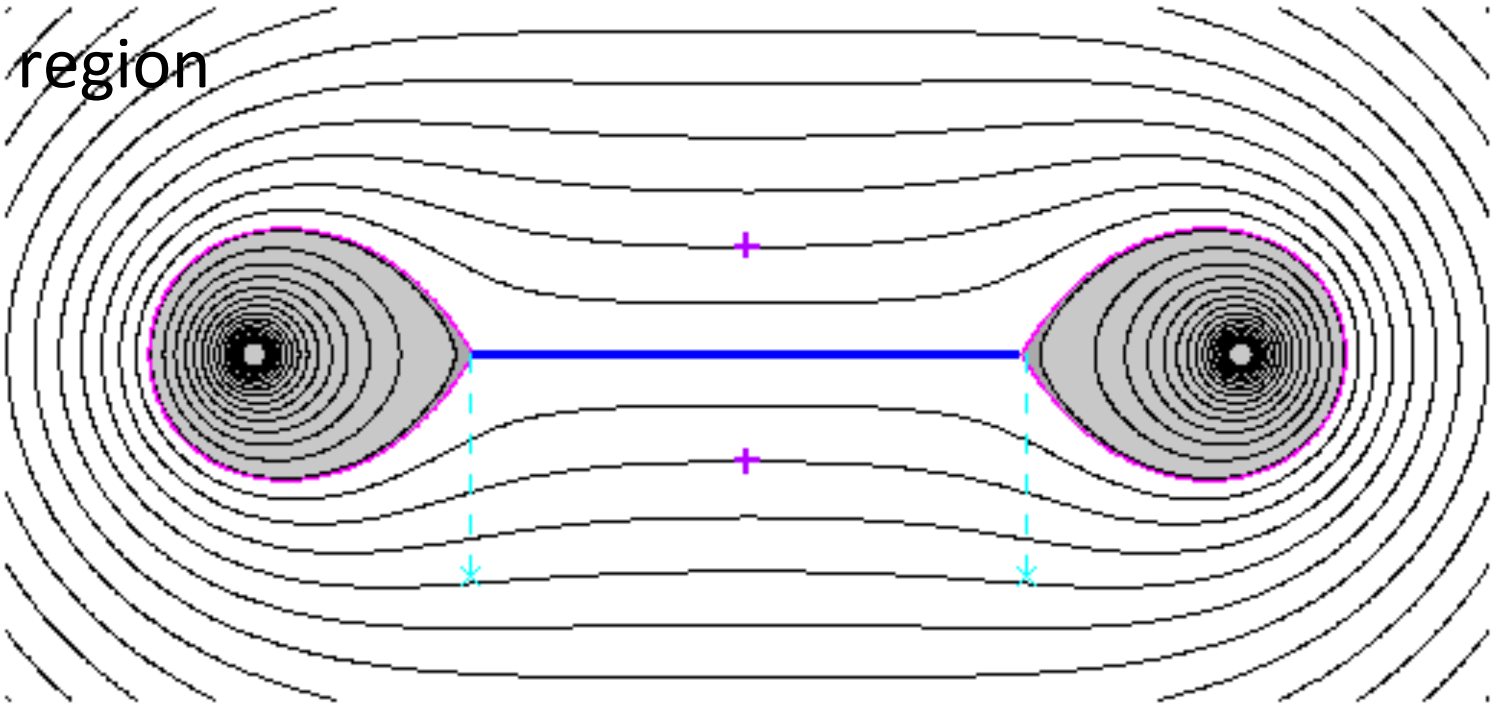


Reconnection paradox

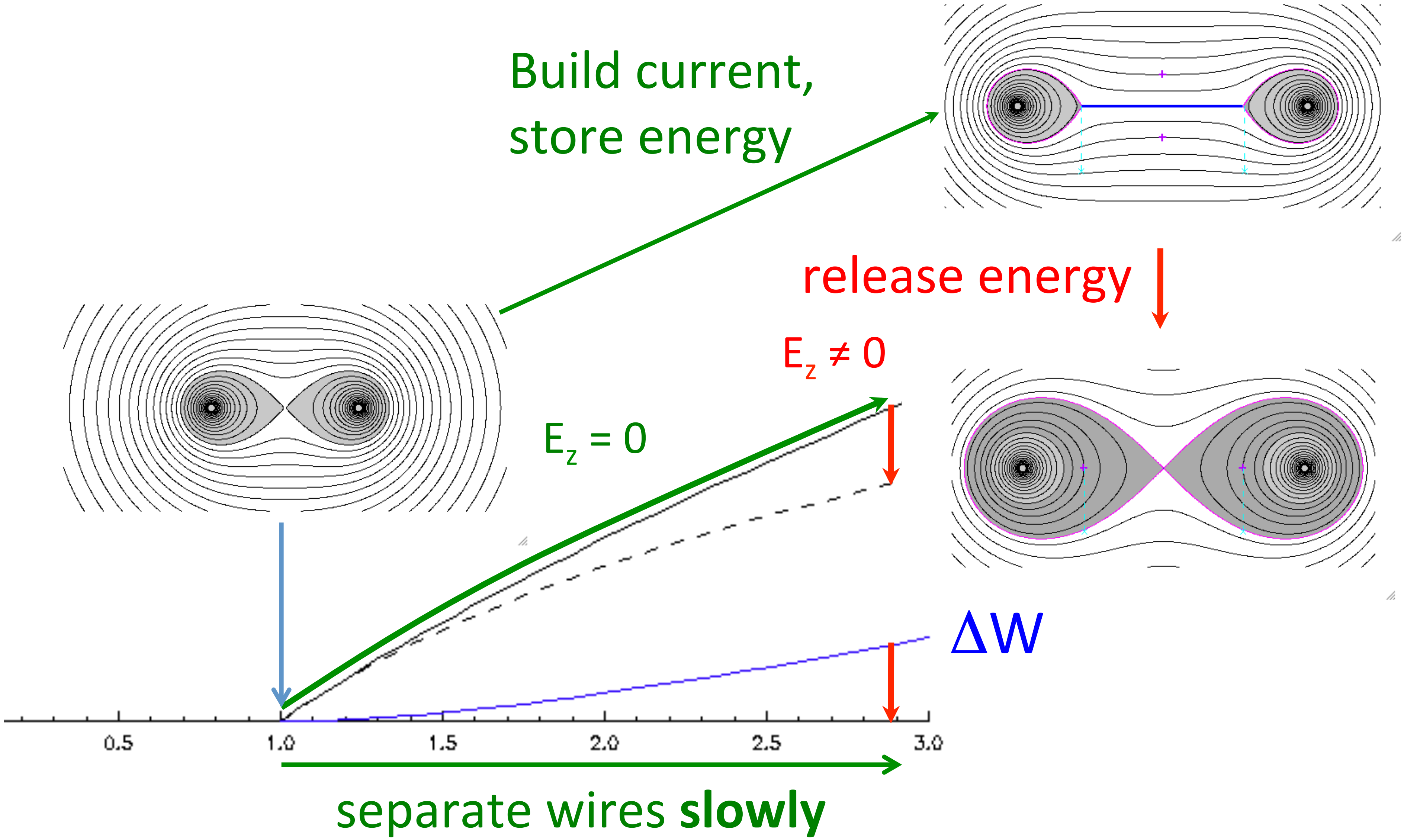


$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} \neq 0$$

Ideal region



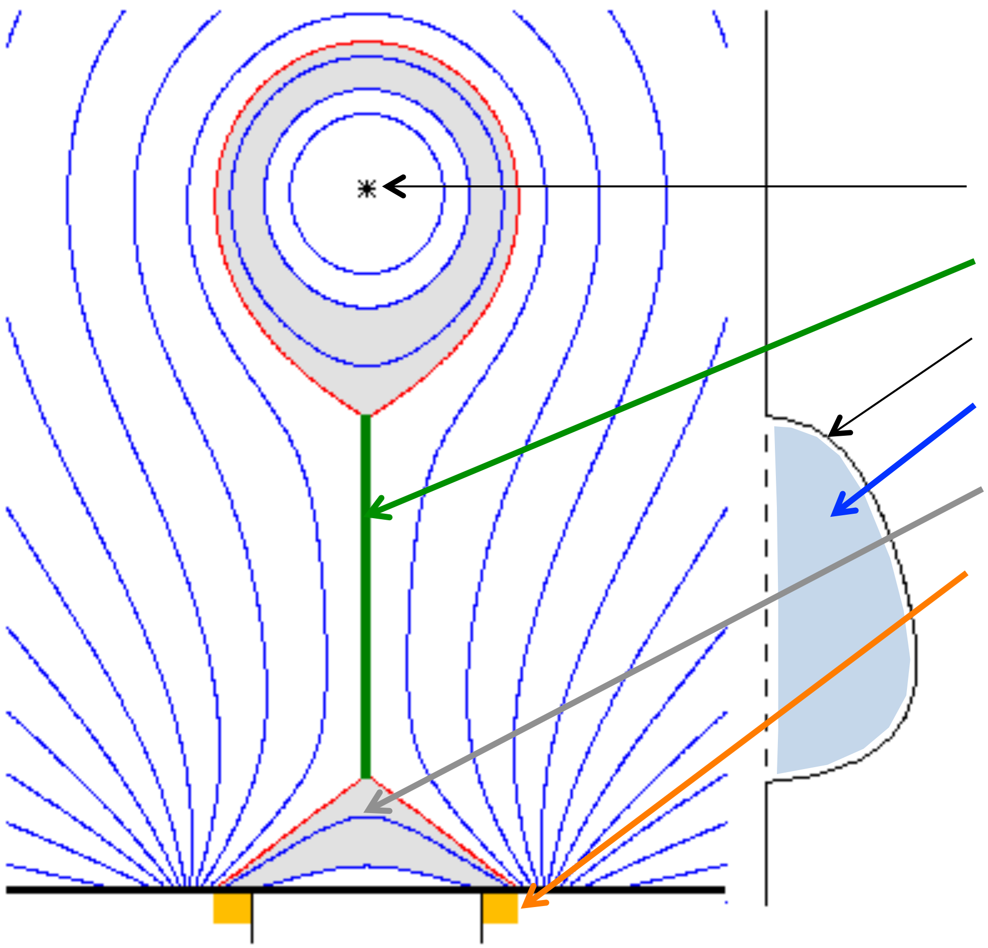
Work done on wires



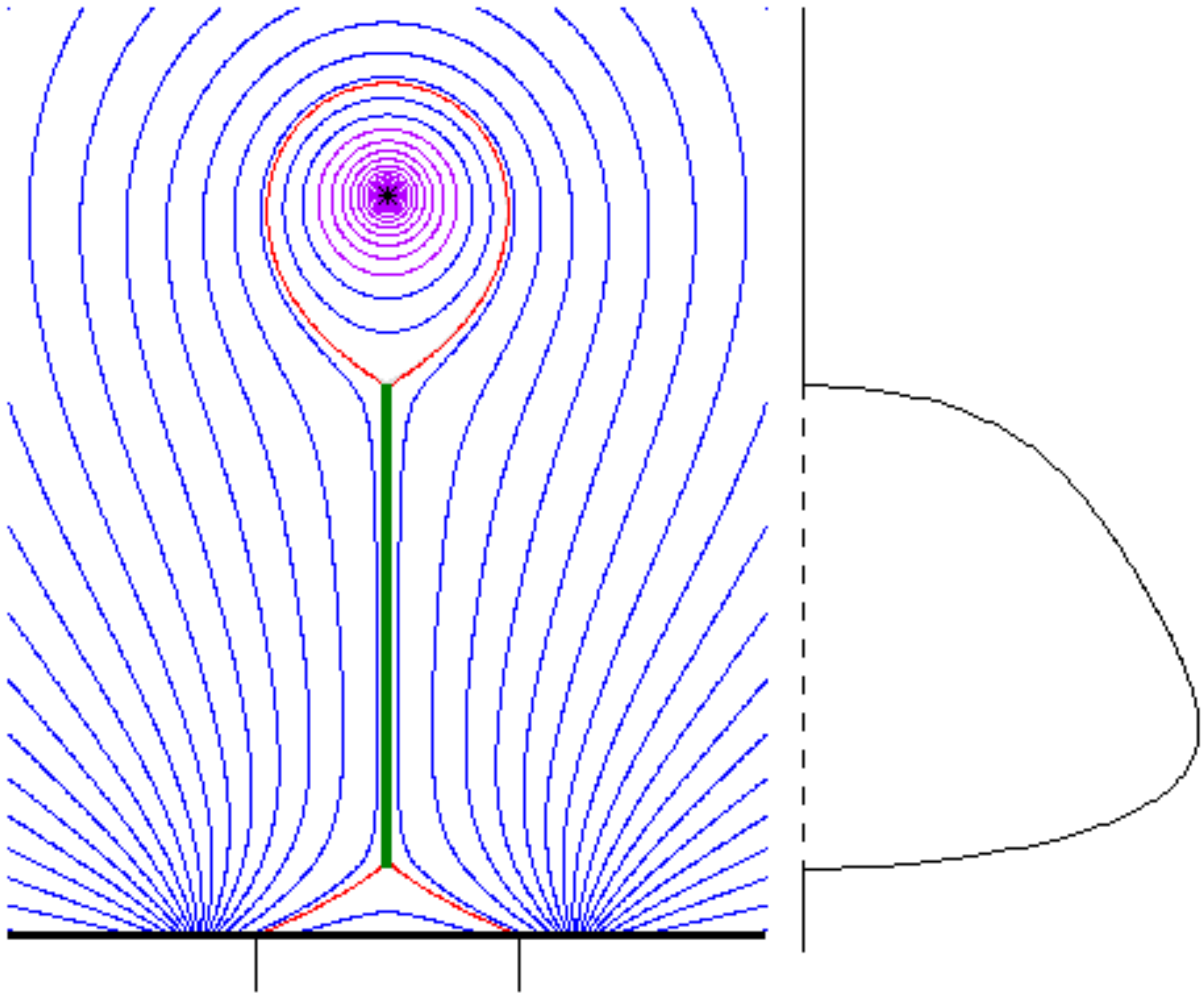
$$\Delta W = \int I_{cs} E\, dt = -\int I_{cs} \frac{d\psi}{dt} dt = -\int I_{cs} d\psi$$

Spontaneous & irreversible

Reconnection in a flare



- Based on Lin & Forbes 2000
- Fix flux rope (focus on flare)
- CS beneath
- Current density **K**(z)
- Integrates to current **I**
- reconnected flux in arcade
- Maps to chromospheric ribbons

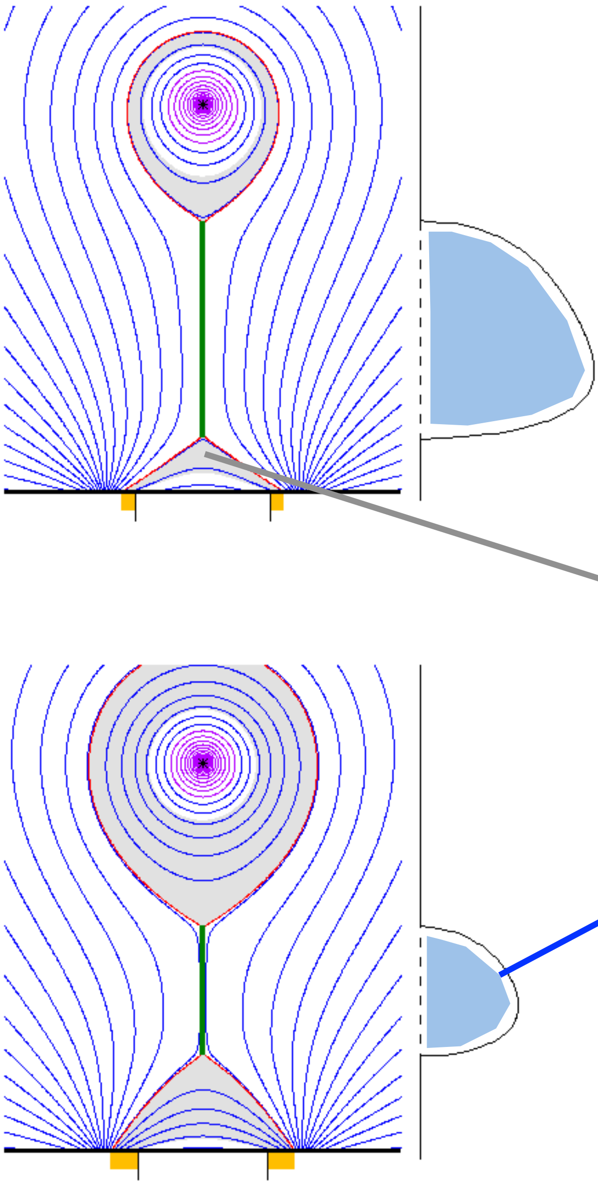


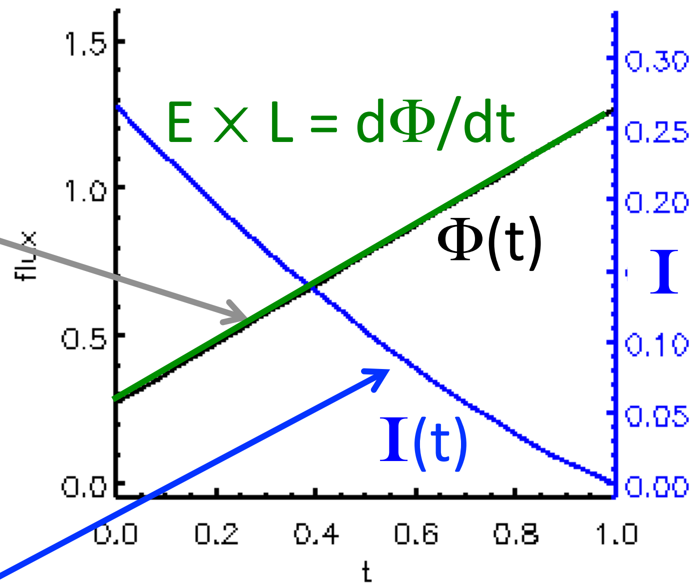
Electrodynamic work done

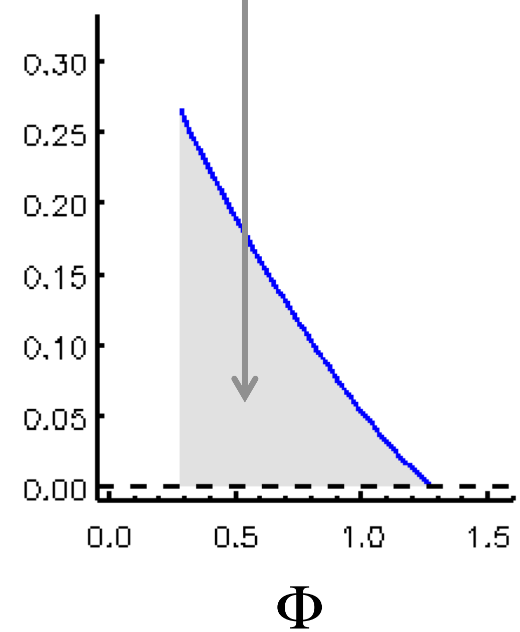
$$W = \int I \, d\Phi$$

= drop in magnetic energy

– energy release

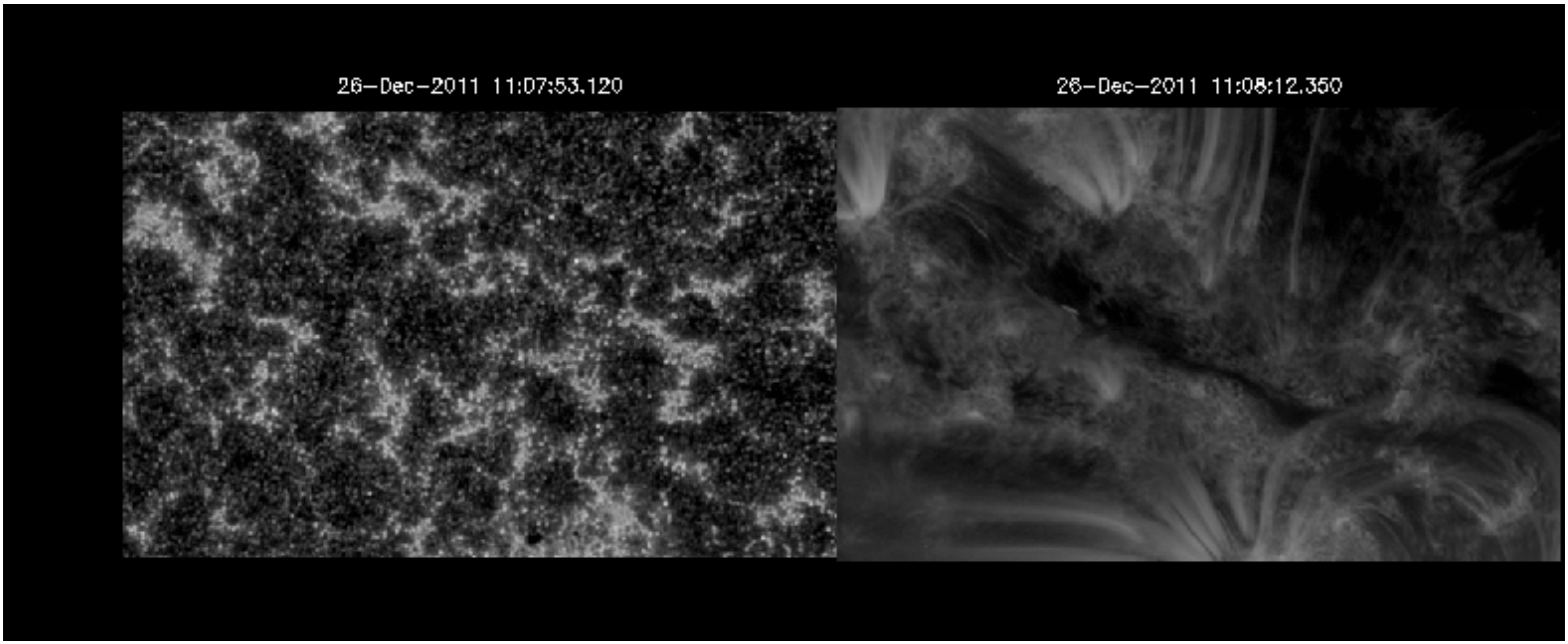




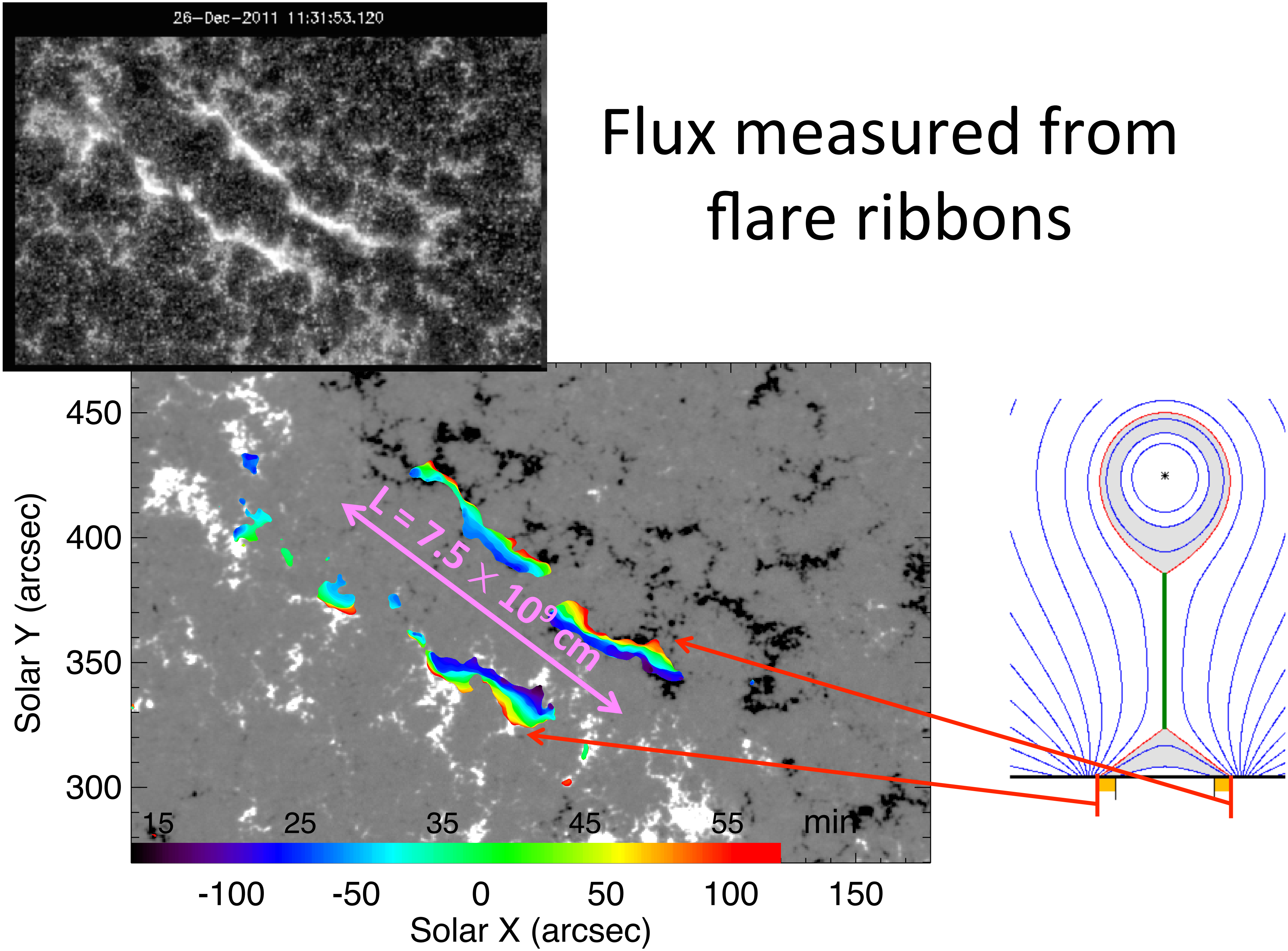


AIA 1600 A:
100,000 K plasma
chromospheric feet

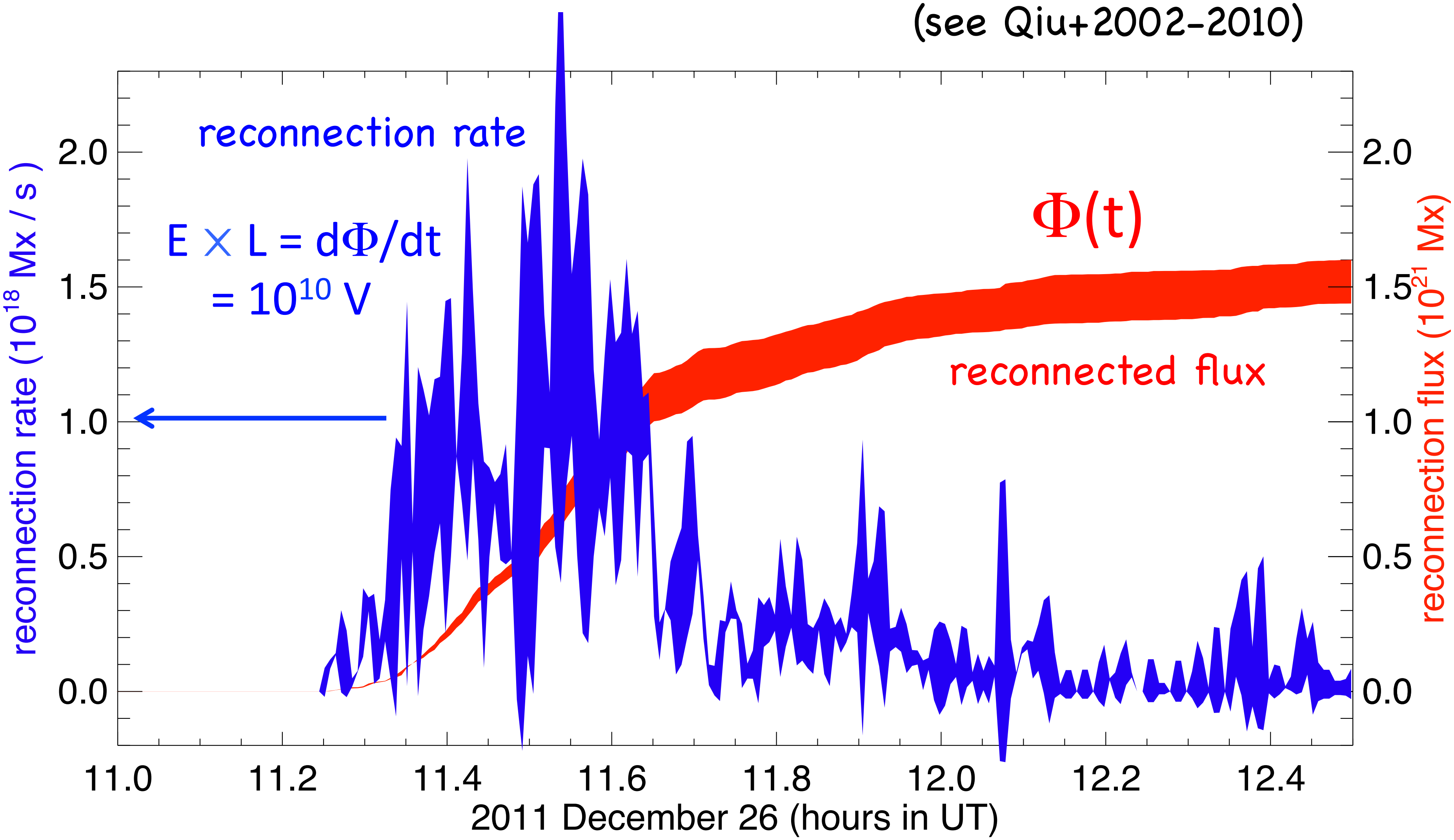
AIA 171 A:
1,00,000 K plasma
coronal loops



Flux measured from flare ribbons



(see Qiu+2002-2010)

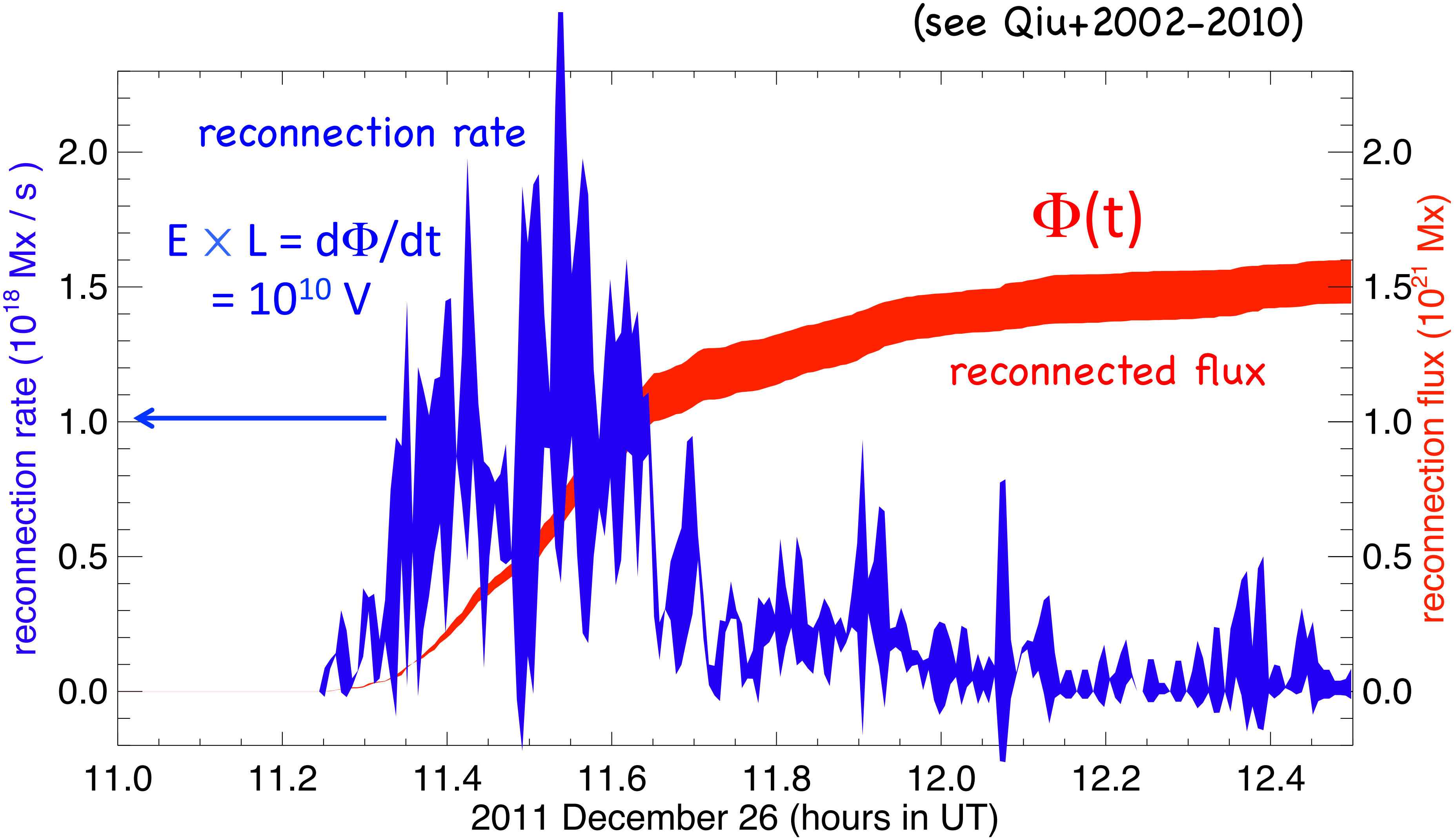


$$I_0 \sim \frac{\Delta\Phi}{\mu_0 L} \sim \frac{1.5\times10^{13}\,\mathrm{Wb}}{4\pi10^{-7}\cdot 7.5\times10^{7}\,\mathrm{m}} = 1.6 \times 10^{11}\ \mathrm{A}$$

160 GA

$S \sim 10^{13}$

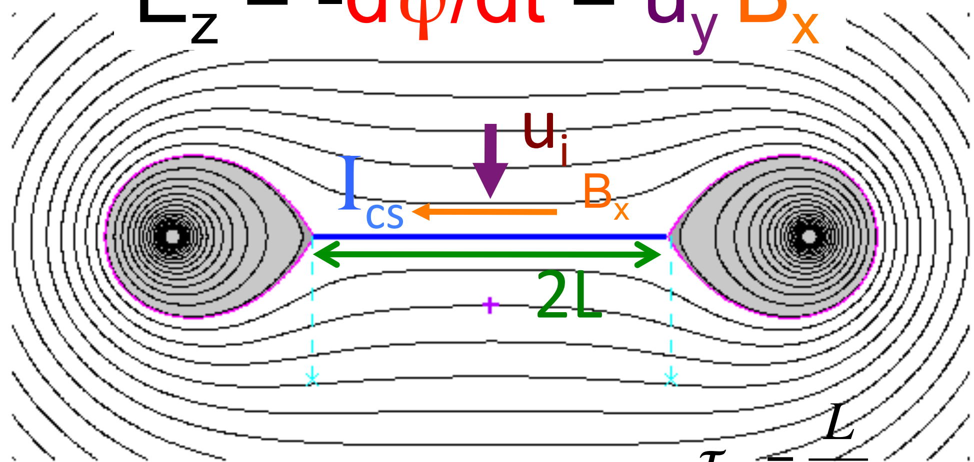
(see Qiu+2002-2010)



$$W = \int I \, d\Phi \sim \tfrac{1}{2} I_0 \Delta\Phi \sim \frac{(\Delta\Phi)^2}{8\pi L} = \frac{(1.5\times10^{21})^2}{8\pi\cdot7.5\times10^9} = 1.2 \times 10^{31}\ \text{erg}$$

Total
reconnection
time

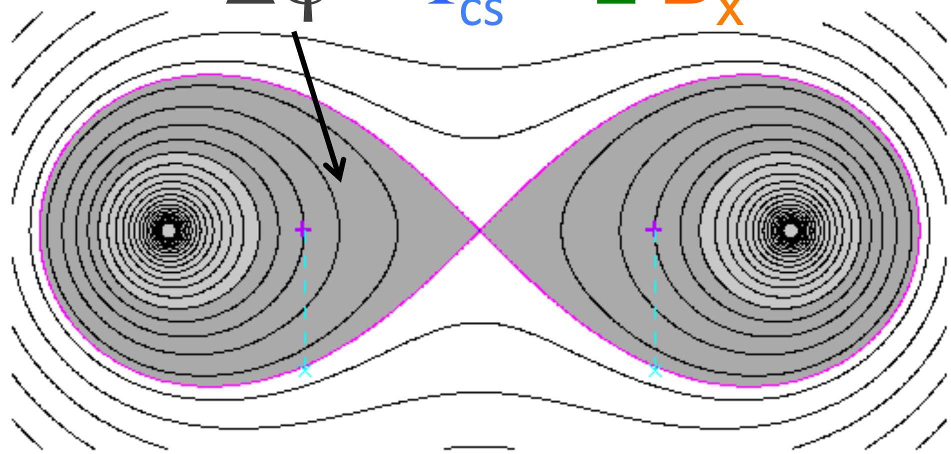
$$E_z = -d\psi/dt = u_y B_x$$



$$\tau_A = \frac{L}{v_A}$$

$$\tau_{\mathrm{rx}} = \frac{\Delta\psi}{d\psi / dt} = \frac{L\,B_x}{u_y B_x}$$

$$\Delta\psi \sim I_{cs} \sim L\,B_x$$



$$\tau_{\mathrm{rx}} = \frac{L}{u_i} = \frac{v_A}{u_i}\,\tau_A = \frac{\tau_A}{M_{Ai}}$$

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

$M_{Ai} << 1$: Slow reconnection

$M_{Ai} \sim 1$: Fast reconnection

Energy
release rate

$$E_M = \int^{\psi} I_{cs}\, d\psi'$$

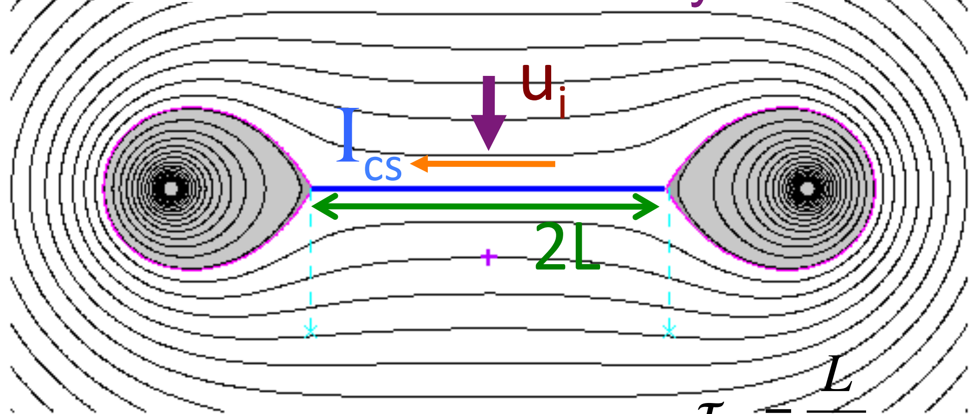
$$\frac{dE_M}{dt} = \frac{d\psi}{dt} I_{cs} \sim u_y B_x^2 L$$

Poynting flux outside CS:

$$\mathbf{S} = \tfrac{1}{4\pi}\mathbf{B}\times(\mathbf{u}\times\mathbf{B}) = \tfrac{1}{4\pi}B_x^2 u_y \hat{\mathbf{y}}$$

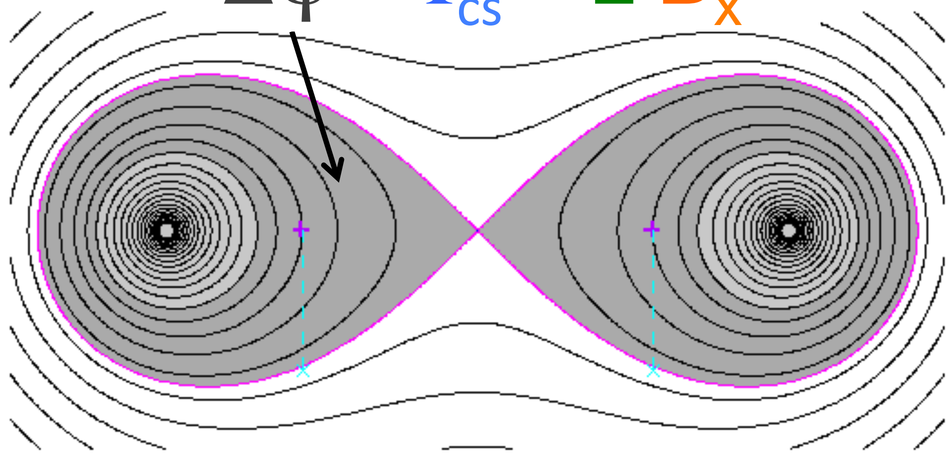
➔ Released energy is carried into CS via Poynting flux

$E_z = -d\psi/dt = u_y B_x$



$\tau_A = \frac{L}{v_A}$

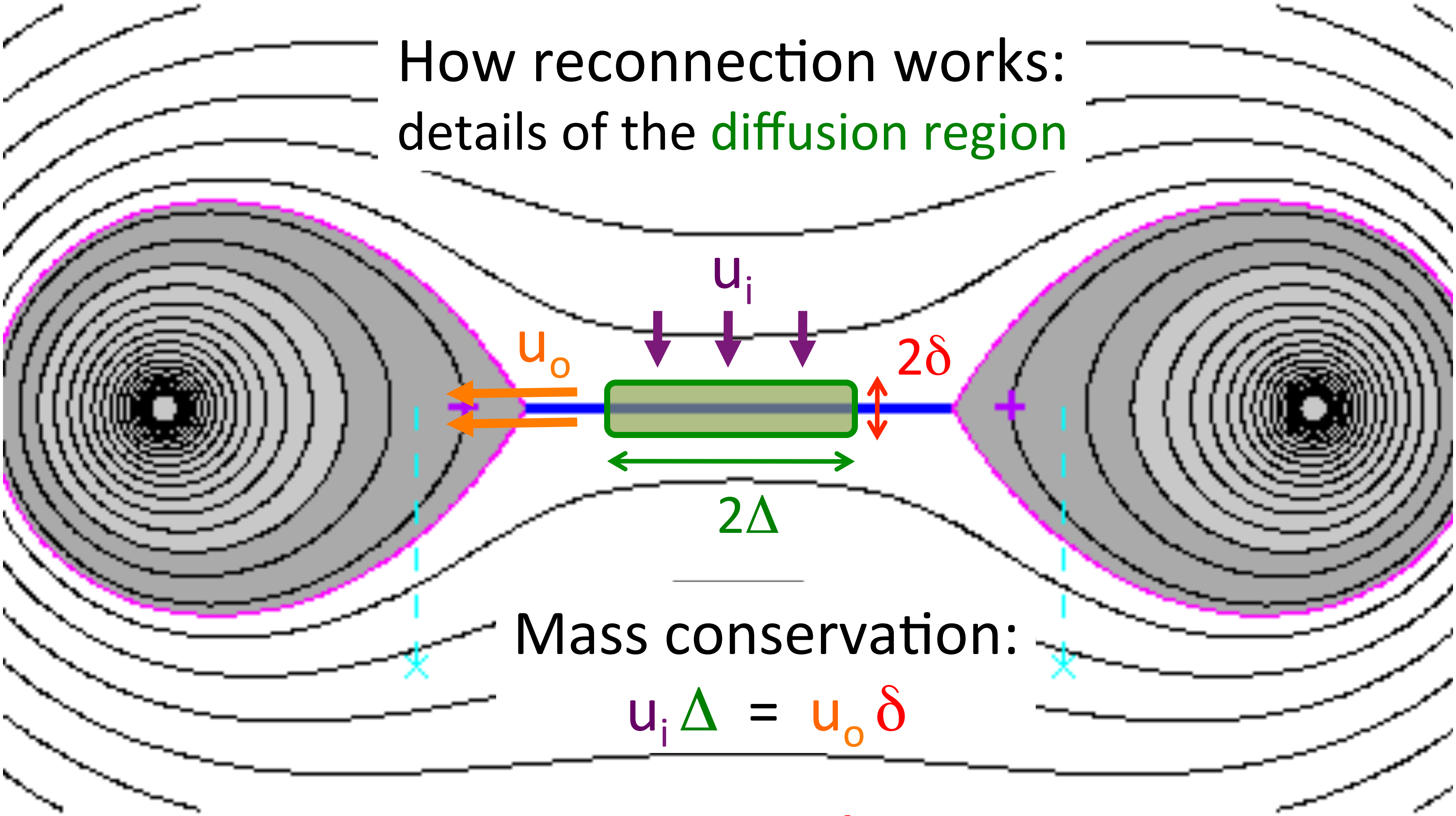
$\Delta\psi \sim I_{cs} \sim L\ B_x$



What happens to energy inside CS?

How reconnection works:

details of the diffusion region



Mass conservation:

$$u_i \Delta = u_o \delta$$

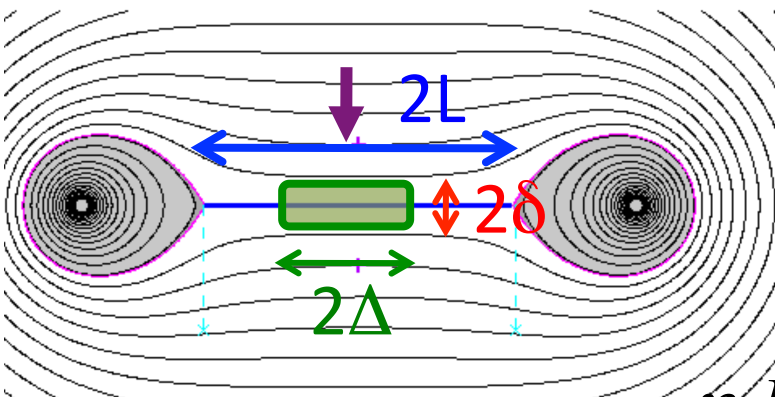
$$M_{Ai} = \frac{u_i}{v_A} = \cancelto{\sim 1}{\frac{u_o}{v_A}} \frac{\delta}{\Delta} \approx \frac{\delta}{\Delta}$$

Aspect ratio of diffusion region

Classic Ohm's law

$$\mathbf{E}+\mathbf{u}\times\mathbf{B}=-m_e\cancel{\frac{d\mathbf{v}_e}{dt}}-\cancel{\frac{1}{en_e}\nabla\cdot\vec{P}_e}+\cancel{\frac{1}{en_e}\mathbf{J}\times\mathbf{B}}+\eta_e\mathbf{J}$$

Ideal region $E_z \approx u_i B_i$



diffusion region $E_z \approx \eta_e J_z \sim \dfrac{\eta_e B_i}{\mu_0 \delta}$

$$u_i \sim \frac{\eta_e}{\mu_0 \delta}$$

advection balances diffusion

$$Rm=\frac{u_i \mu_0 \delta}{\eta_e}\sim 1$$

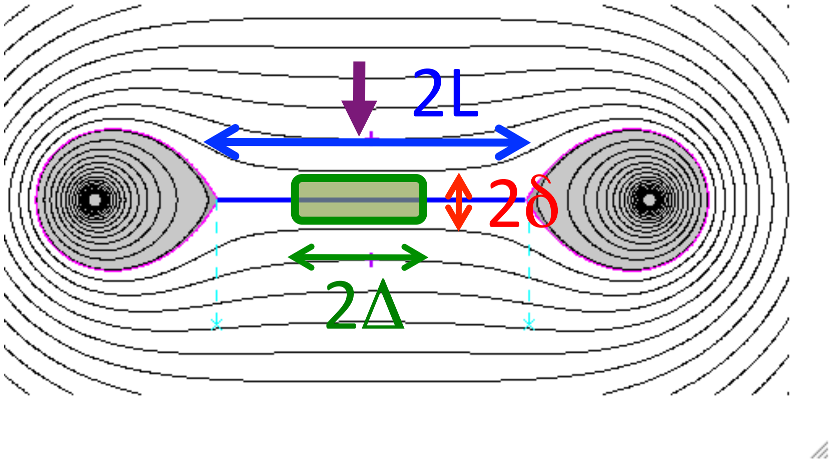
$$M_{Ai}=\frac{u_i}{v_A}=\frac{\eta_e}{v_A \mu_0 \delta}=\frac{\eta_e}{\mu_0 L v_A}\frac{L}{\delta}=S^{-1}\frac{L}{\delta}$$

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

from mass conservation

$$M_{Ai}=S^{-1/2}\sqrt{\frac{L}{\Delta}} \quad \& \quad \delta=S^{-1/2}\sqrt{L\Delta}$$

Rate of Ohmic dissipation



$$P_\eta = \mu_0 \int_{DR} \eta_e J^2 da \sim \mu_0 \eta_e \left(\frac{B_i}{\mu_0 \delta} \right)^2 \Delta\delta$$

$$P_\eta \sim S^{-1} v_A B_i^2 L \frac{\Delta}{\delta}$$

diffusion region $\quad J_z \sim \frac{B_i}{\mu_0 \delta}$

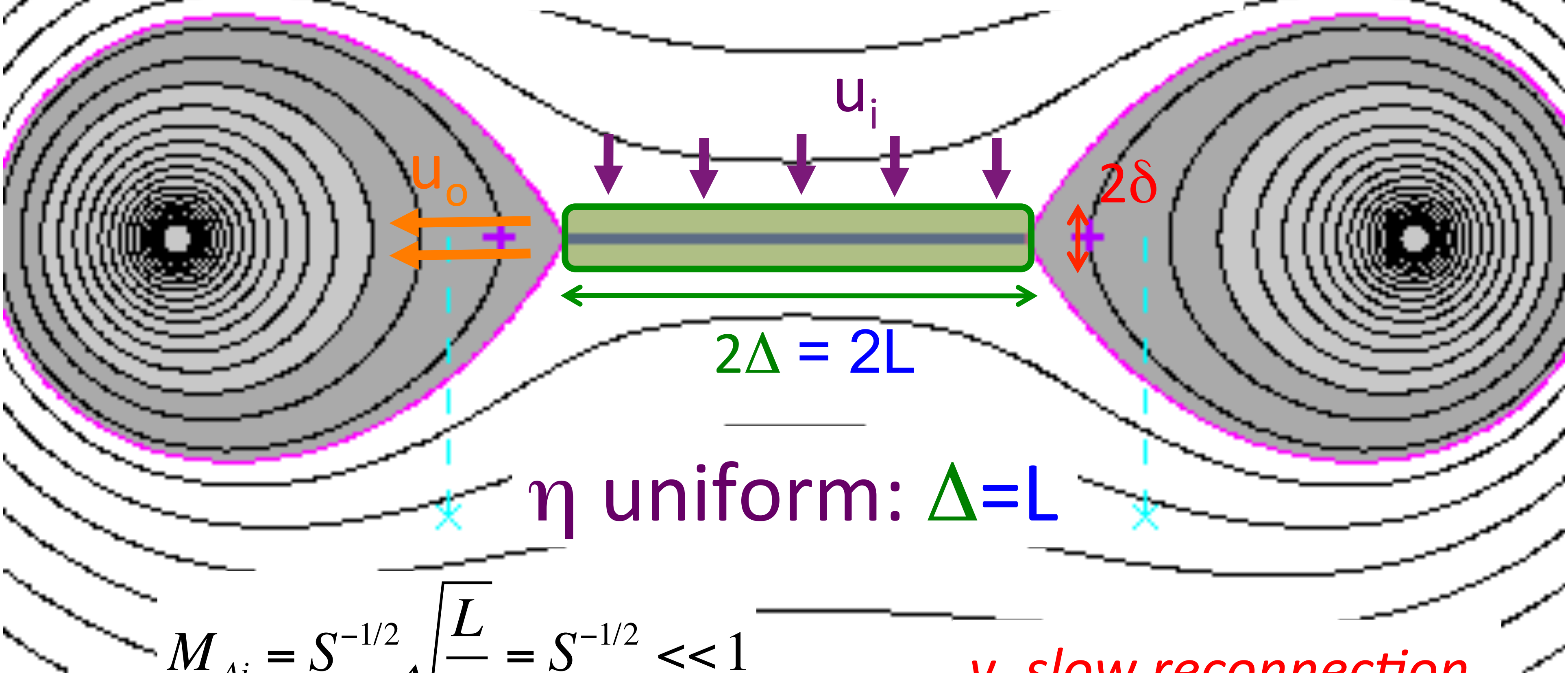
$$M_{Ai} = \frac{u_i}{v_A} = \frac{\delta}{\Delta} \sim S^{-1/2} \sqrt{\frac{L}{\Delta}}$$

Compare to energy release rate:

$$\dot{E}_M \sim u_i B_i^2 L$$

$$\boxed{\frac{P_\eta}{\dot{E}_M} \sim S^{-1} \frac{v_A}{u_i} \frac{\Delta}{\delta} \sim \frac{\Delta}{L}}$$

Special case: Sweet-Parker



η uniform: $\Delta = L$

$$M_{Ai} = S^{-1/2}\sqrt{\frac{L}{\Delta}} = S^{-1/2} << 1$$

v. slow reconnection

$$\frac{L}{\delta} = S^{1/2}\sqrt{\frac{L}{\Delta}} = S^{1/2} >> 1$$

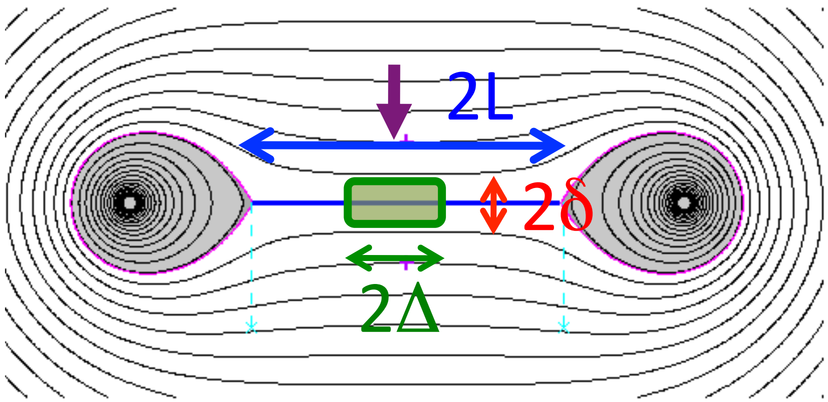
v. great aspect ratio

$$P_\eta \sim \dot{E}_M$$

Released energy is Ohmically dissipated

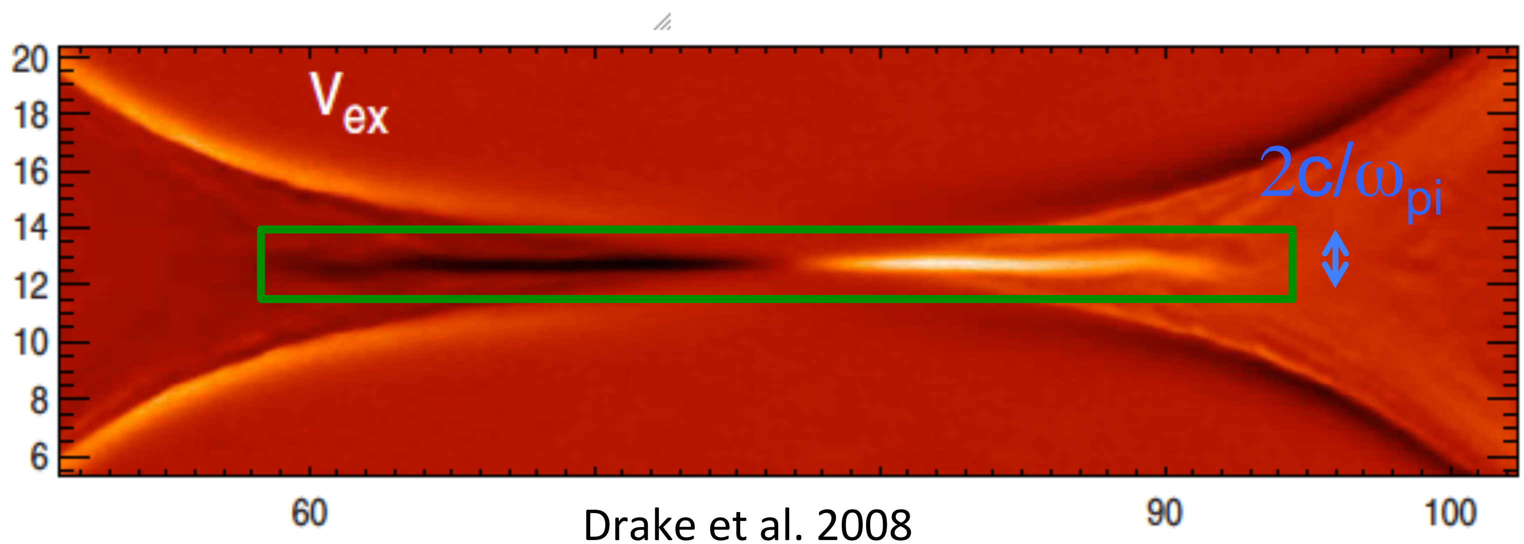
Collisionless reconnection

$$\mathbf{E}+\mathbf{u}\times\mathbf{B} = -m_e \frac{d\mathbf{v}_e}{dt} - \frac{1}{en_e}\cancel{\nabla\cdot\vec{P}_e} + \frac{1}{en_e}\mathbf{J}\times\mathbf{B} + \cancel{\eta_e \mathbf{J}}$$



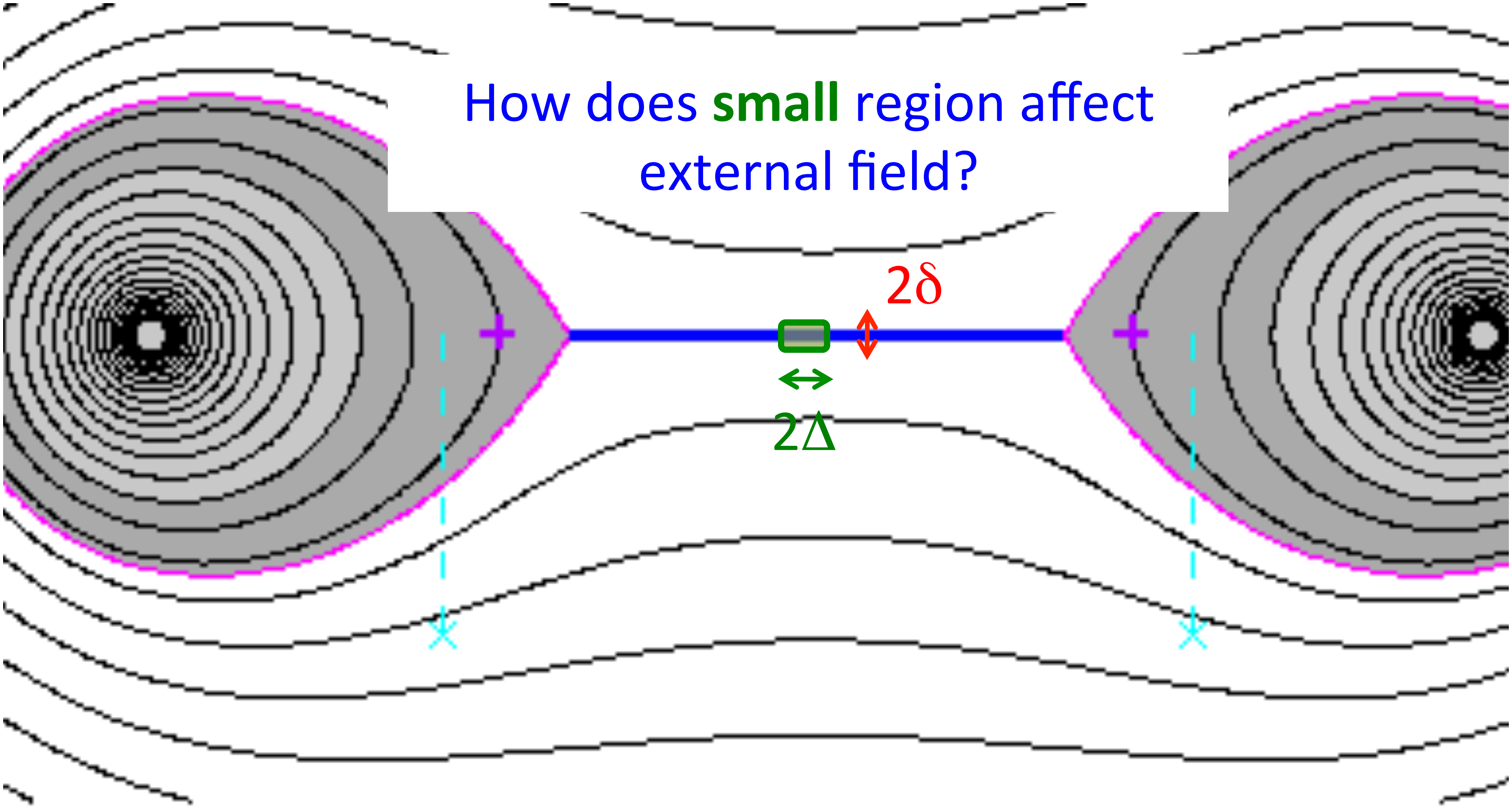
$\Delta \sim \delta \sim c/\omega_{pi}$ from Hall term

$$M_{Ai} = \frac{\delta}{\Delta} \sim 1$$ from mass conservation

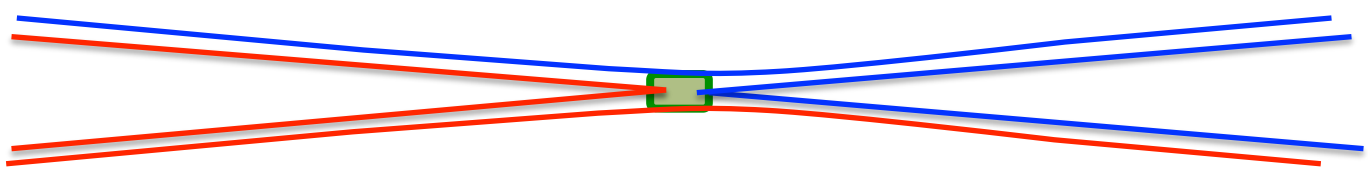


Drake et al. 2008

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



It creates bent field lines...



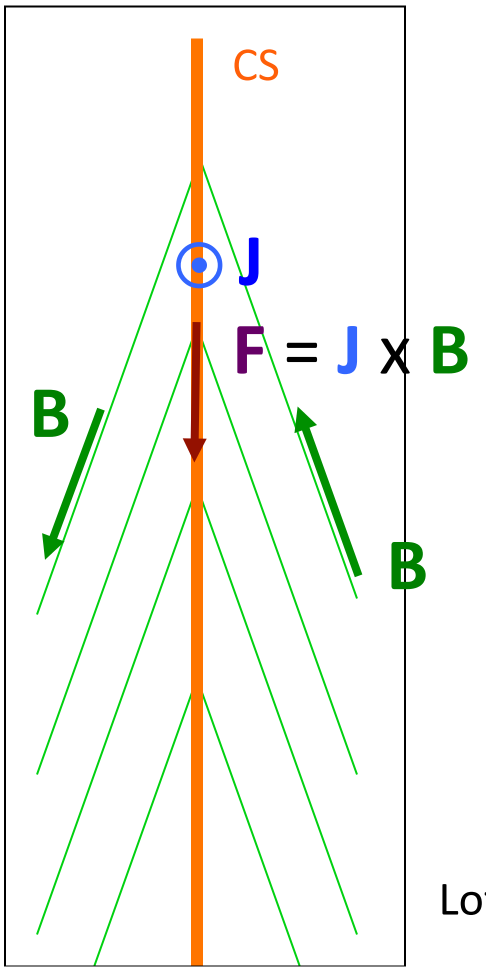
... what next?

Response to bend

Lin & Lee 1994

Riemann problem for 1D current sheet (CS)

t=0



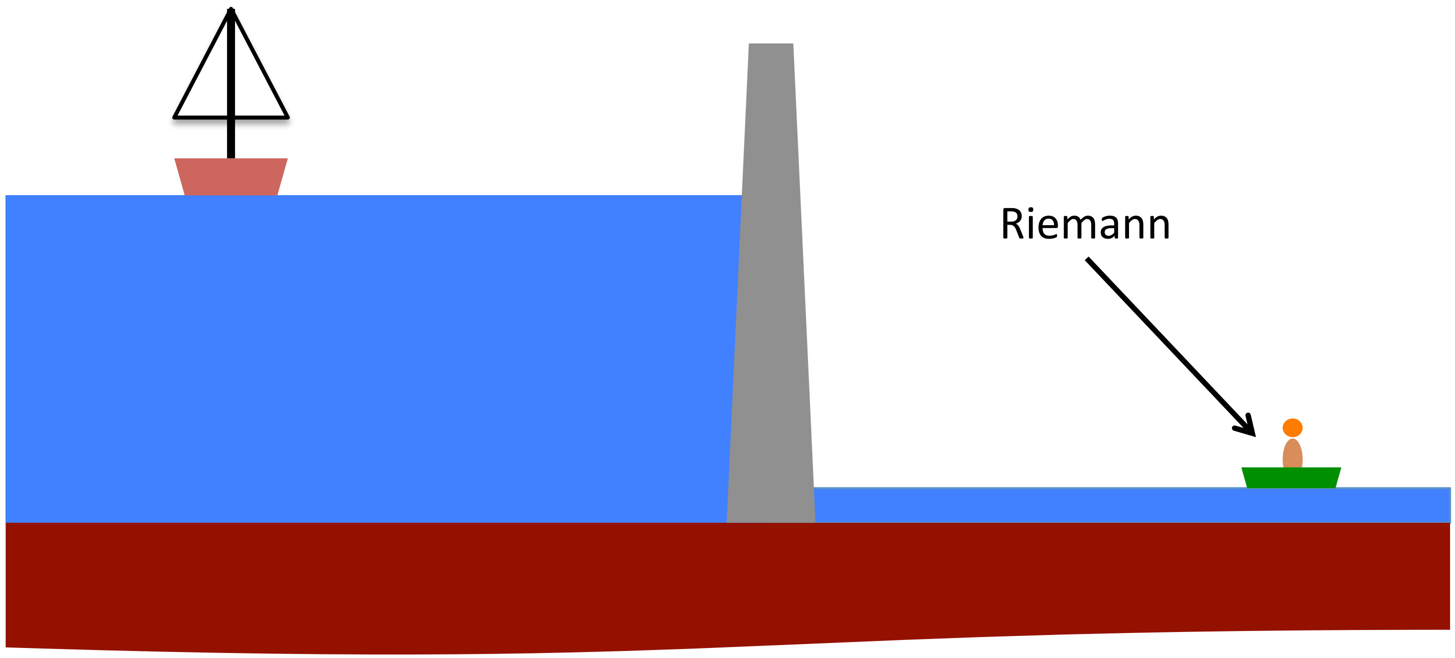
Lots & lots of bent field lines

Riemann problem:

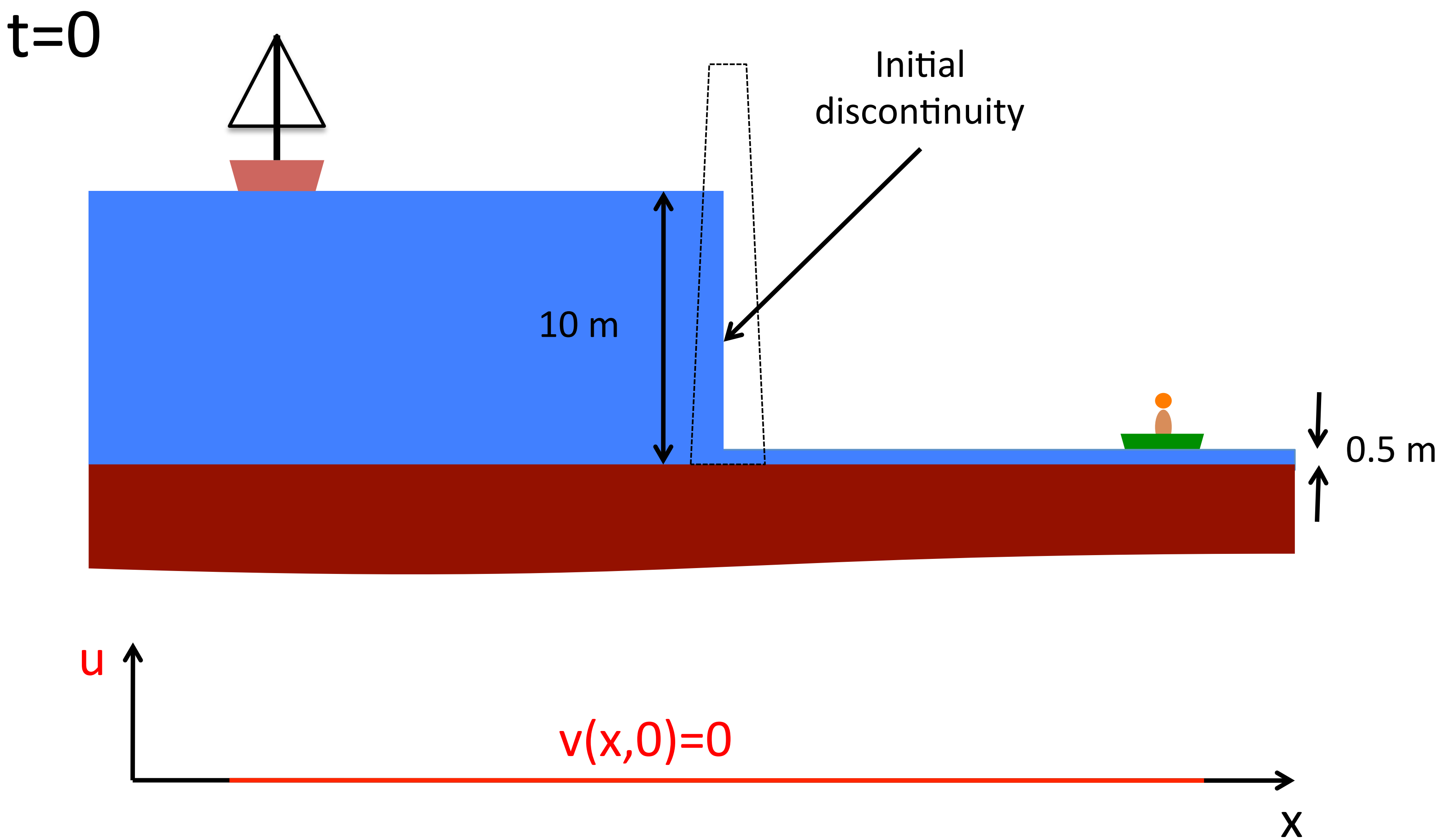
- initialize w/ 2 uniform regions separated by discontinuity (CS)
- Find subsequent time-evolution
- **Solution:** discontinuity decomposes into traveling **shocks** and rarefaction waves

Riemann’s Problem:

what happens when the dam breaks?

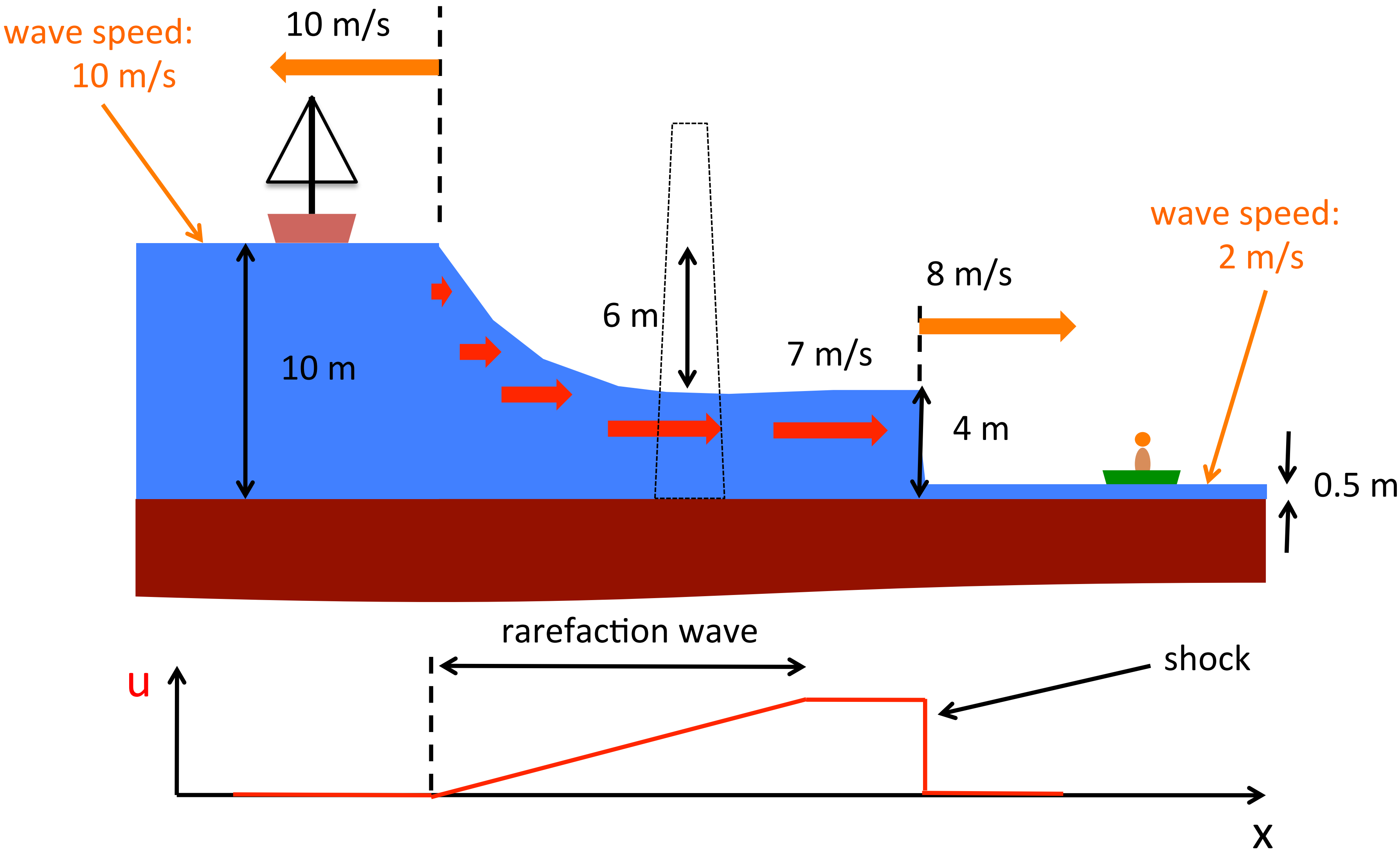


Riemann's Problem:
what happens when the dam breaks?



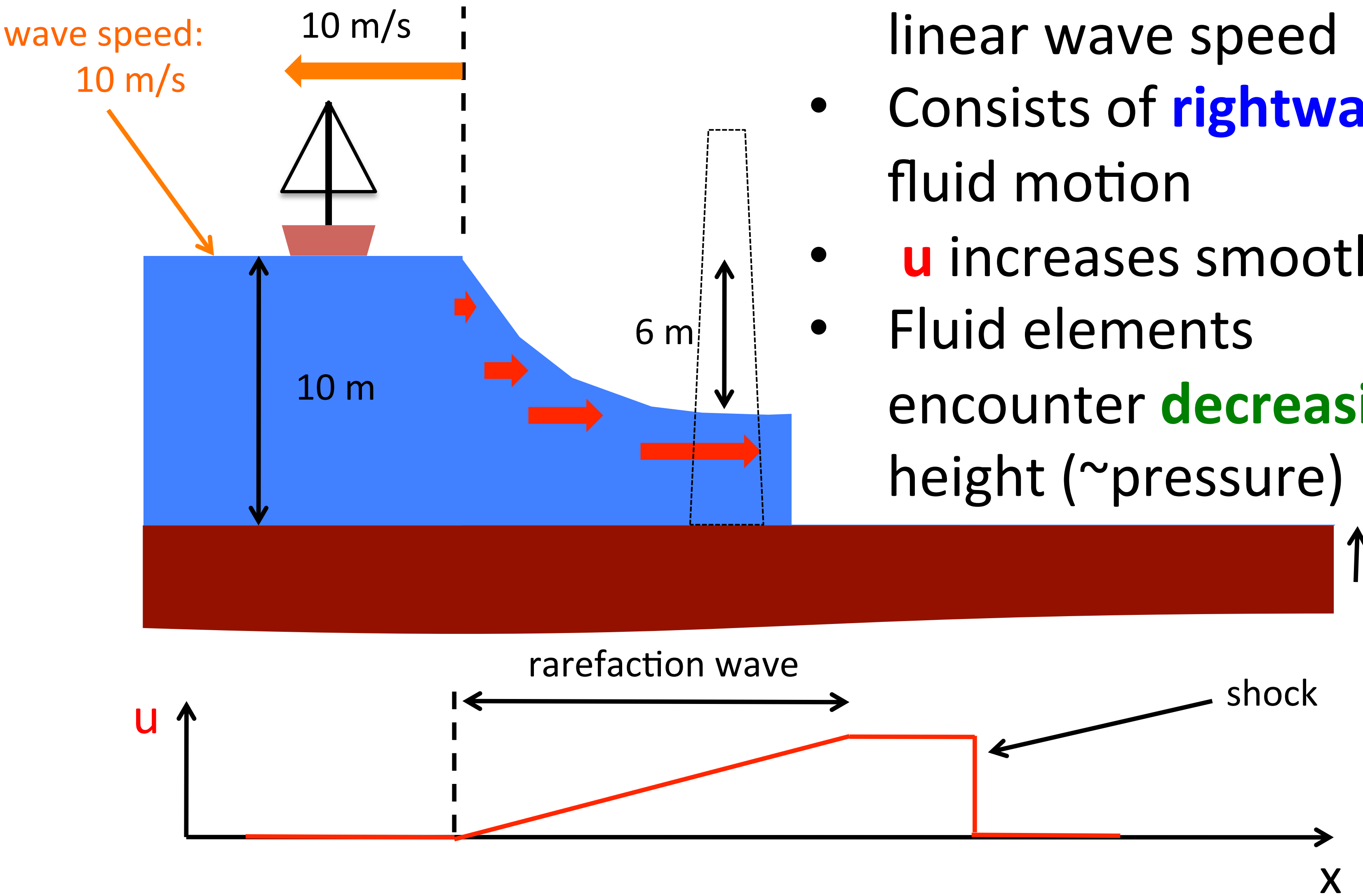
Riemann’s Problem:

what happens when the dam breaks?



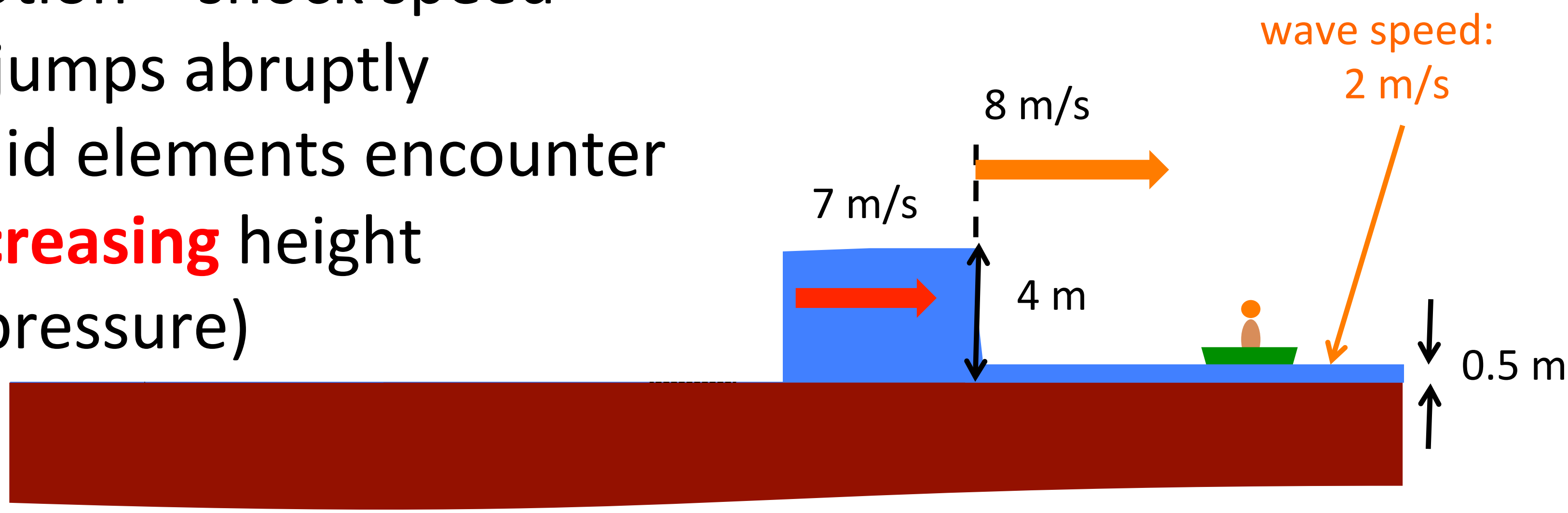
The rarefaction wave:

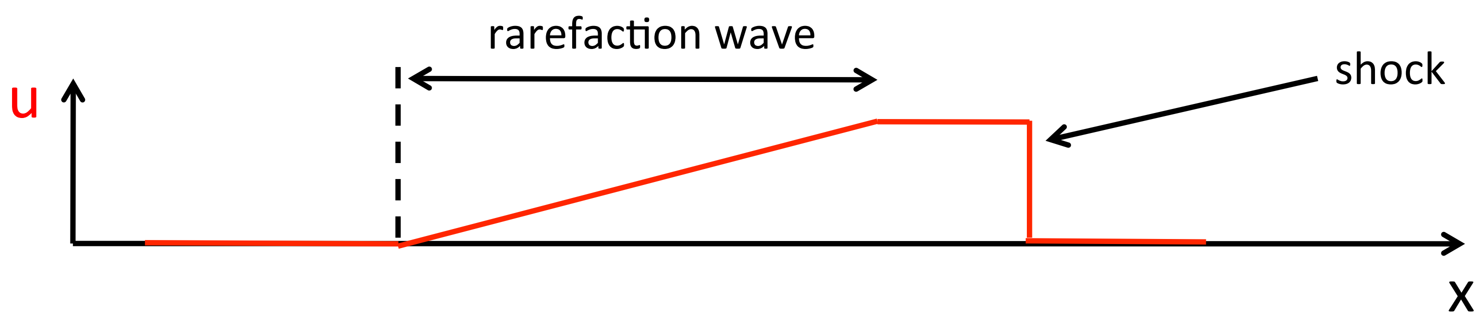
- Expands **leftward** @ linear wave speed
- Consists of **rightward** fluid motion
- **u** increases smoothly
- Fluid elements encounter **decreasing** height (~pressure)



The shock:

- Propagates **rightward** **faster** than linear wave speed
- Initiates **rightward** fluid motion < shock speed
- **u** jumps abruptly
- Fluid elements encounter **increasing** height (~pressure)





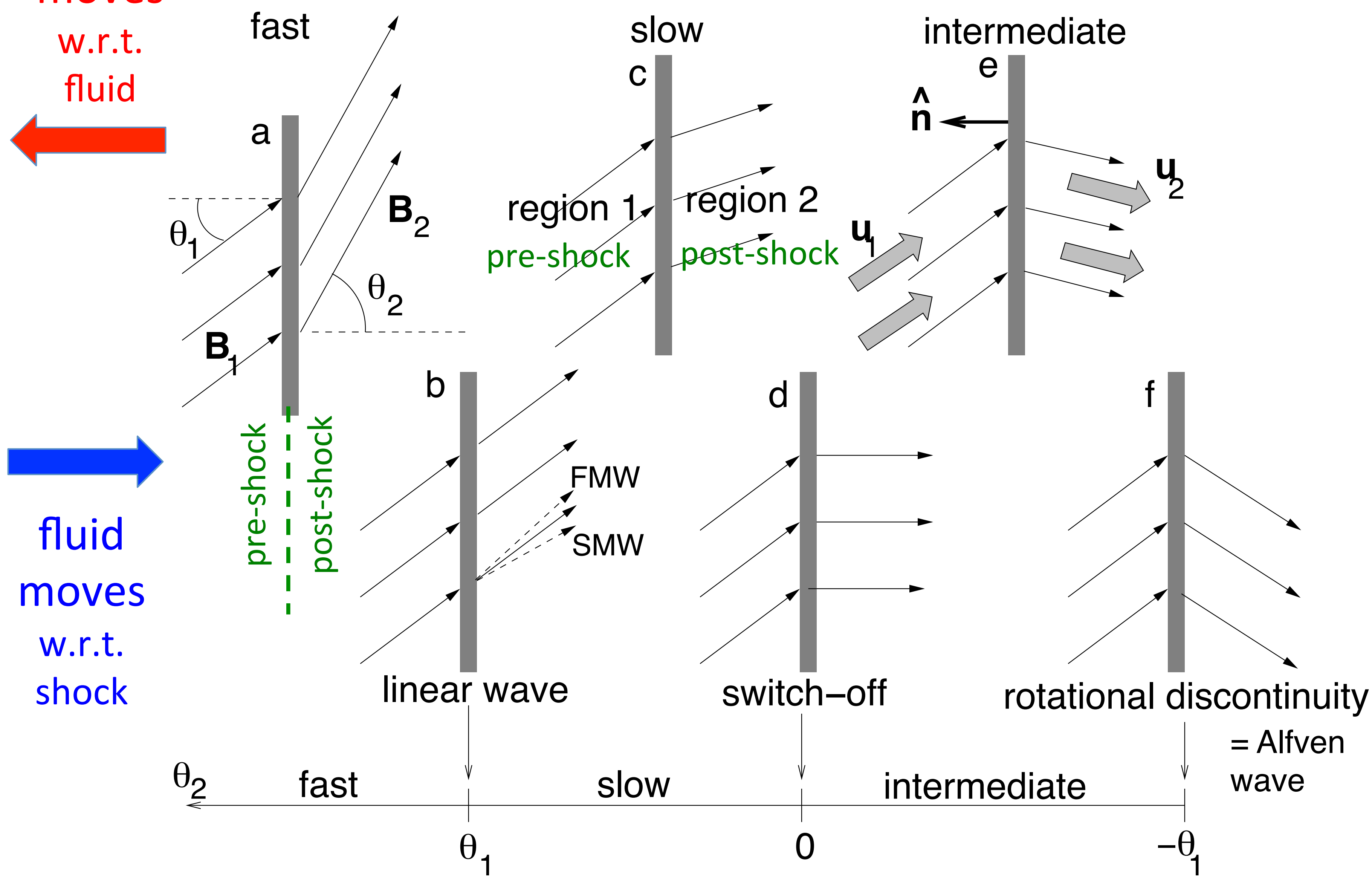
MHD shocks

- Abrupt **jump** in fluid properties: ρ, $\mathbf{u}$, p & $\mathbf{B}$
- Fluid elements always **encounter** increasing ρ, p
- Weak (infinitesimal) jump $\Longrightarrow$ linear wave
    - MHD has 3 waves: Fast, Slow & Alfven
    - → 3 shocks: Fast, Slow & Intermediate
    - Each changes* $\mathbf{u}$, p & $\mathbf{B}$ differently
- Finite jumps (nonlinear) always propagate† faster than corresponding linear wave speed
- Standing shock: flow **into** shock is supersonic. shock slows it to be subsonic

* satisfy conservation laws → Rankin-Hugoniot relations

† propagating into fluid @ rest. Standing shock comes from change of reference frame

MHD shocks

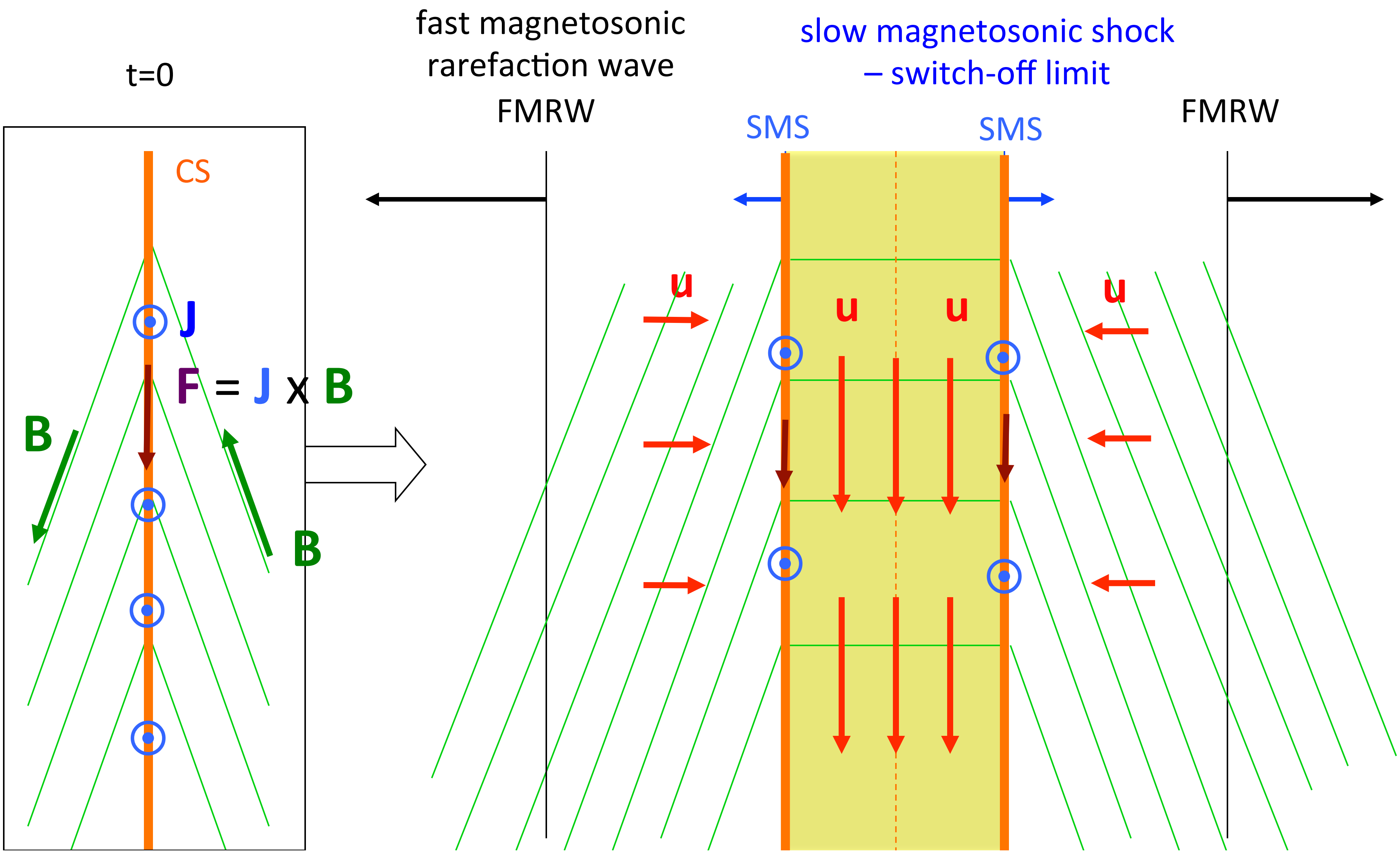


shock
moves
w.r.t.
fluid
fluid
moves
w.r.t.
shock
fast
a
θ_1
$\mathbf{B}_1$
$\mathbf{B}_2$
θ_2
pre-shock
post-shock
slow
c
region 1
region 2
pre-shock
post-shock
intermediate
e
$\hat{\mathbf{n}}$
$\mathbf{u}_1$
$\mathbf{u}_2$
b
FMW
SMW
linear wave
d
switch–off
f
rotational discontinuity
= Alfven
wave
θ_2
fast
slow
intermediate
θ_1
0
$-\theta_1$

Response to bend

Lin & Lee 1994

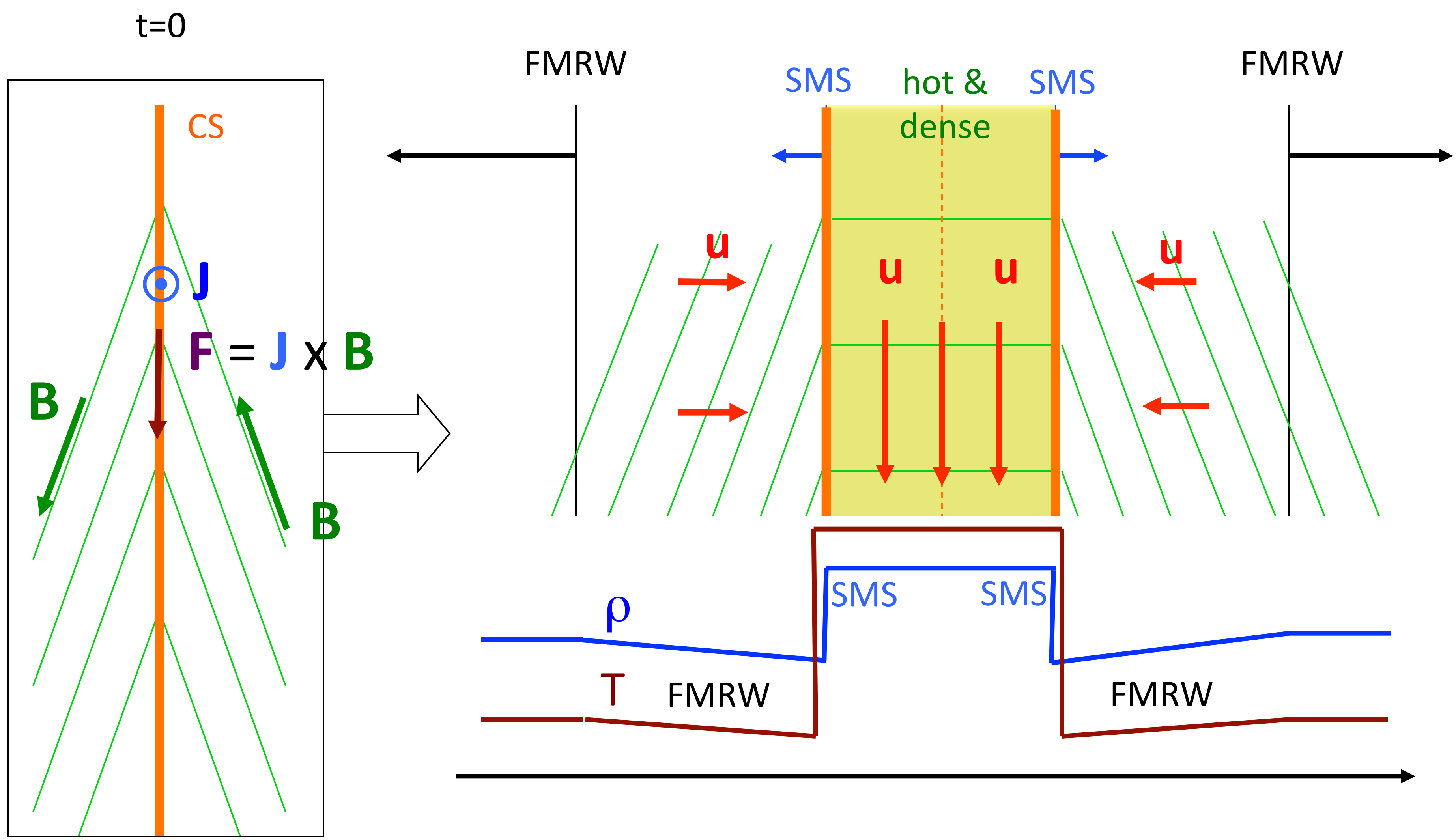
Riemann problem for 1D current sheet (CS)



Response to bend

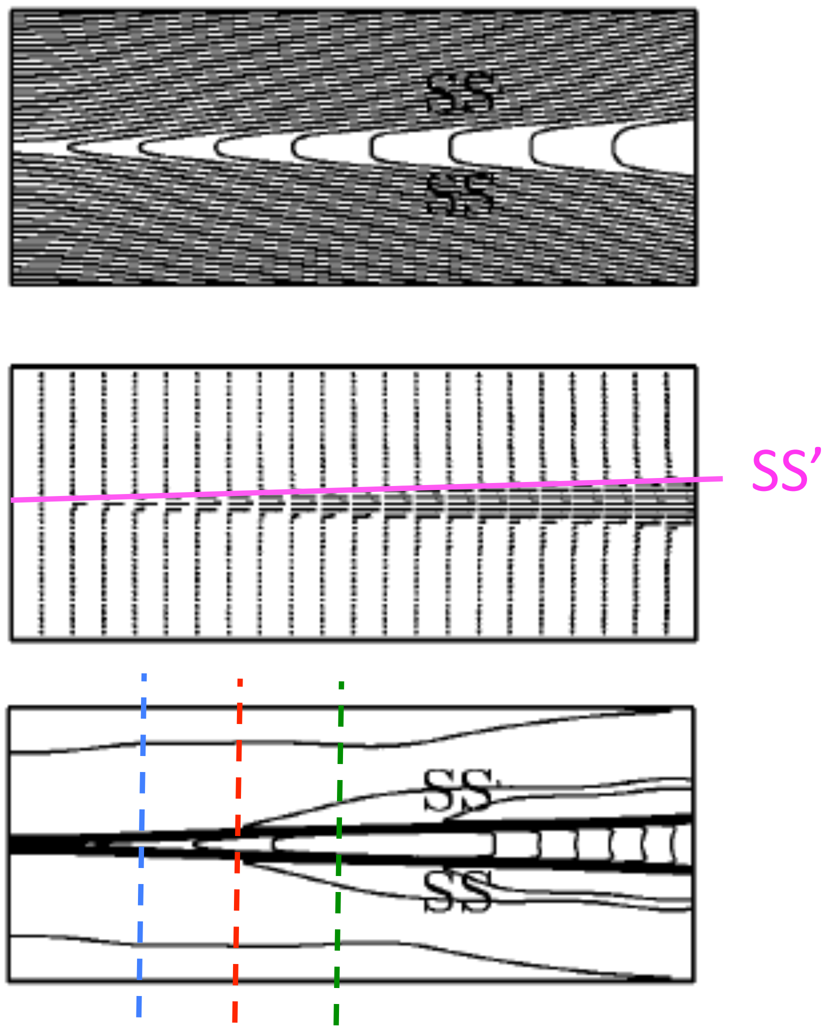
Lin & Lee 1994

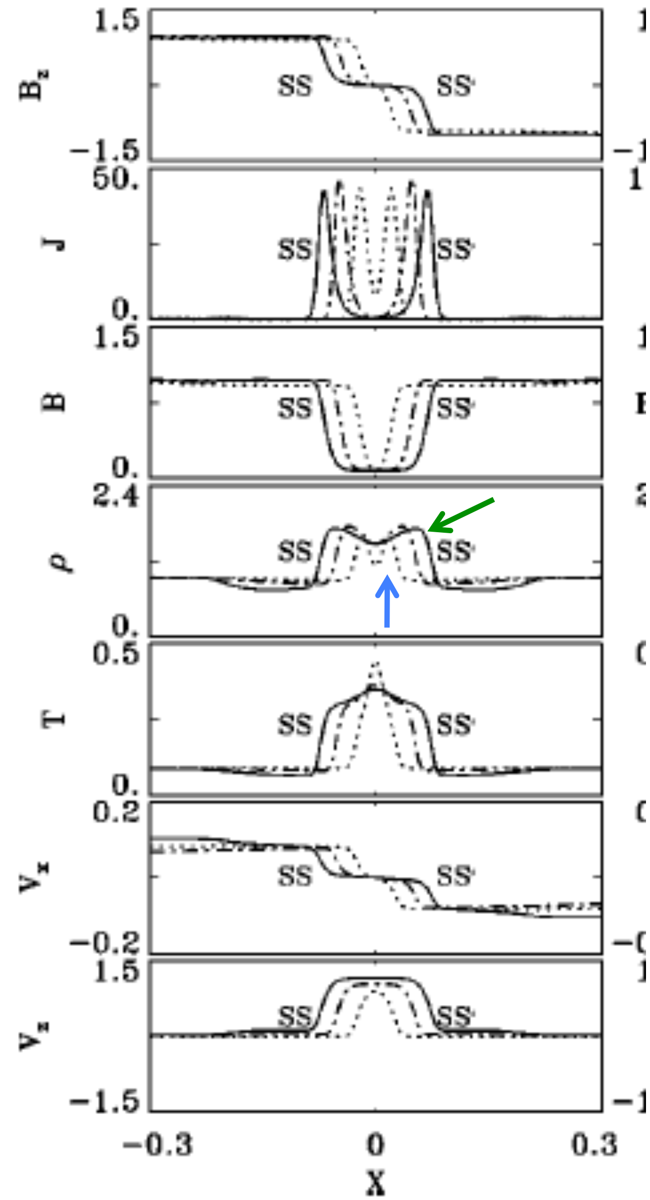
Riemann problem for 1D current sheet (CS)



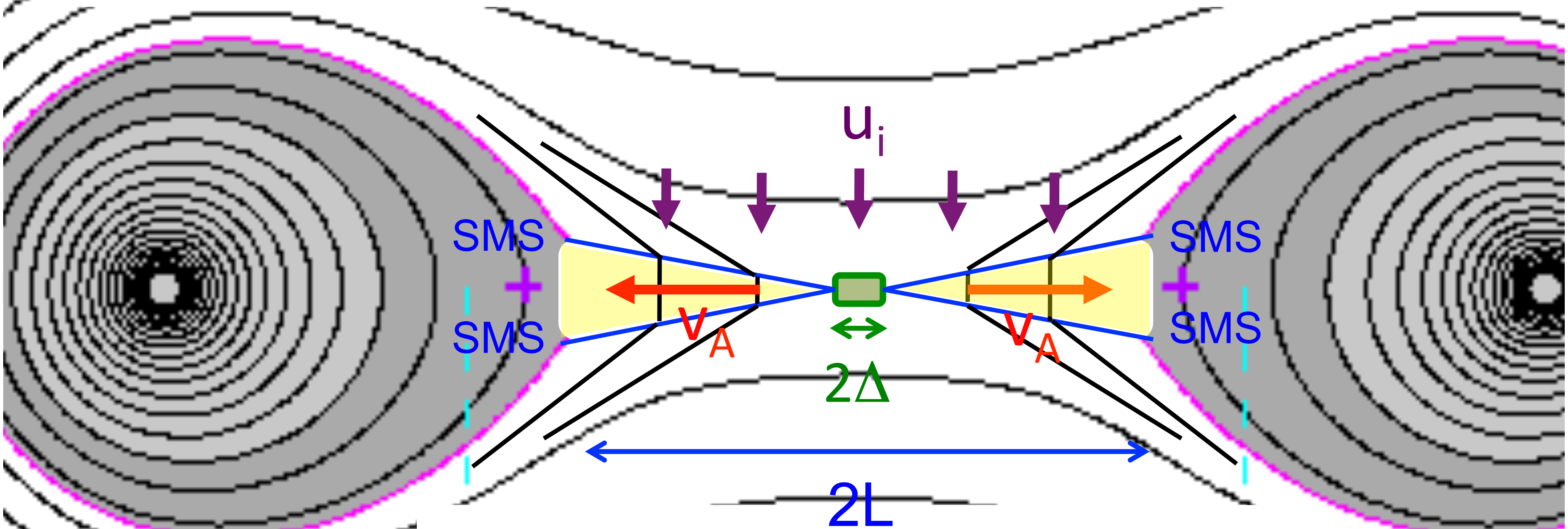
How it works in 2d

Lin & Lee 1999





Petschek reconnection

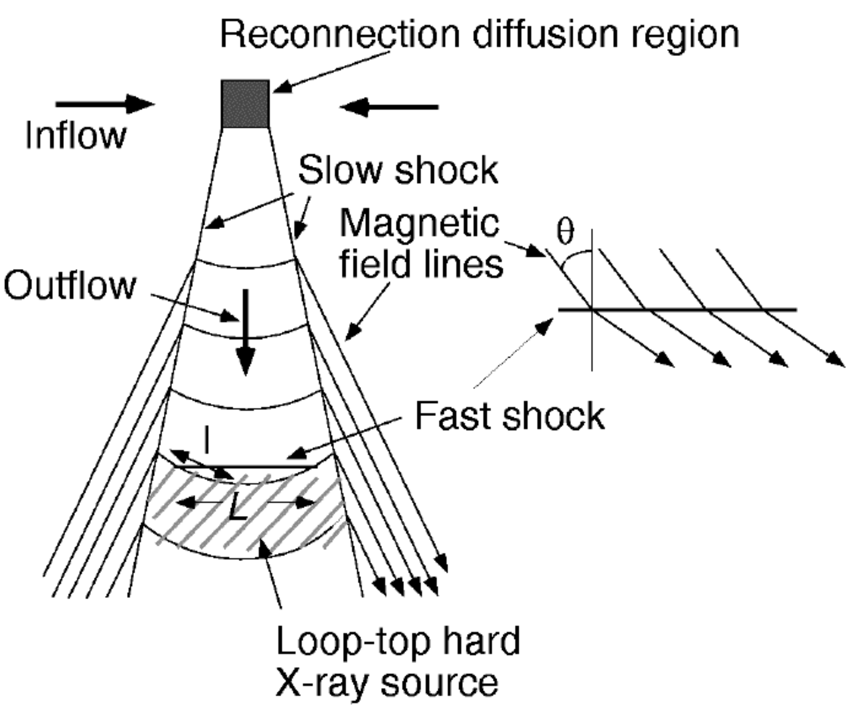


External solution requires current -
current appears in SMSs

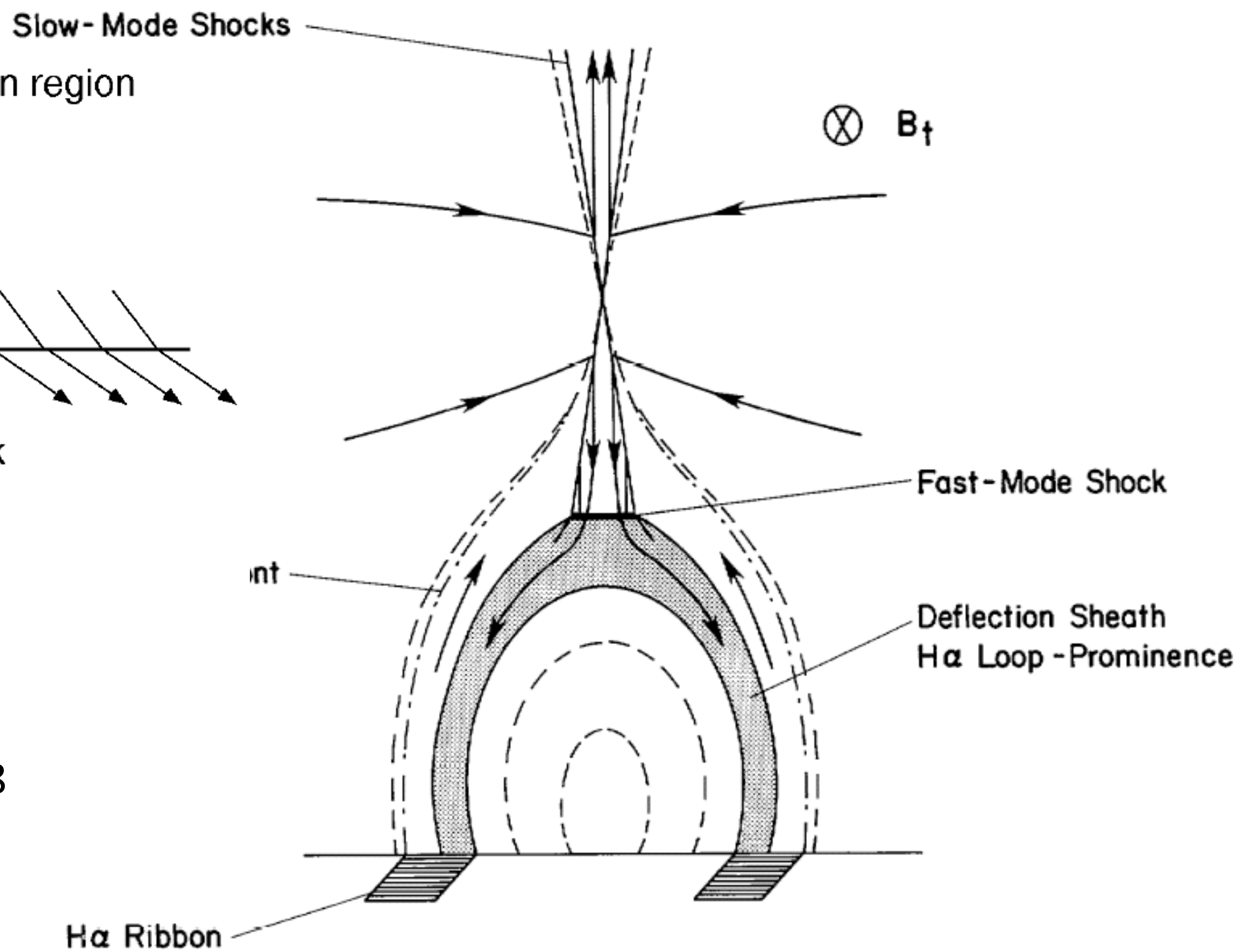
$$\frac{P_\eta}{\dot{E}_M} \sim \frac{\Delta}{L} << 1$$

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

How it works in a flare



Tsuneta and Naito 1998



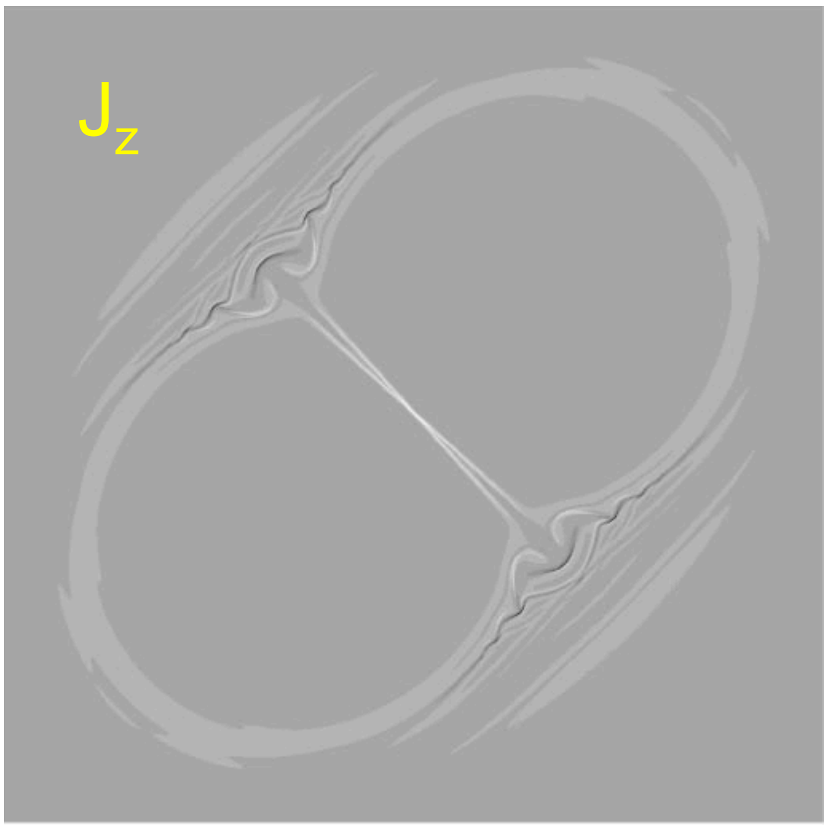
Forbes, T.G., and Malherbe 1986

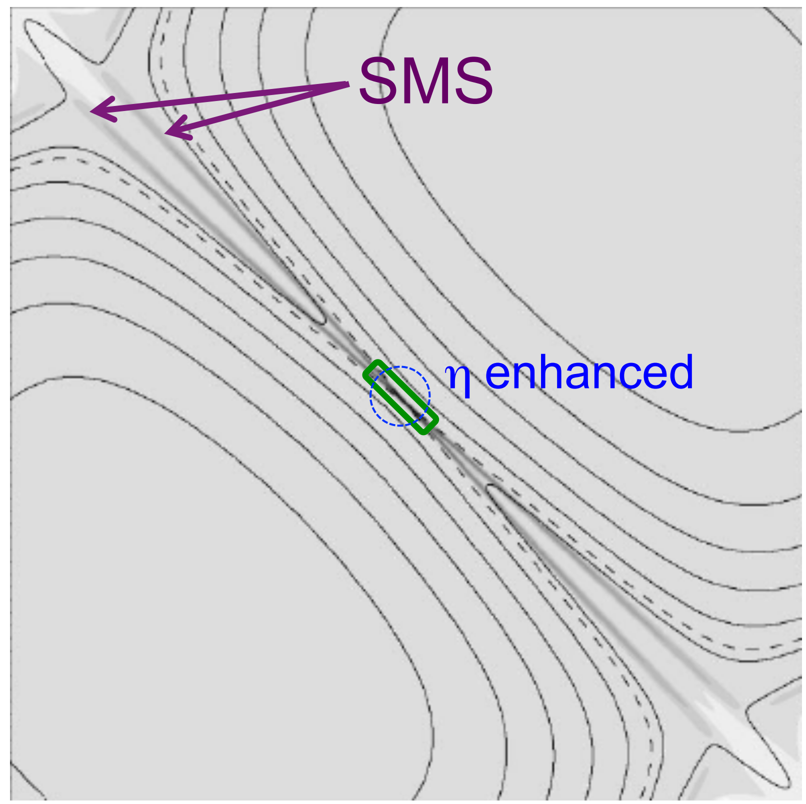
Q: Will resistivity always result in slow (Sweet-Parker) reconnection?

A: Yes, if η is uniform in space…

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

Biskamp & Scwartz 2001

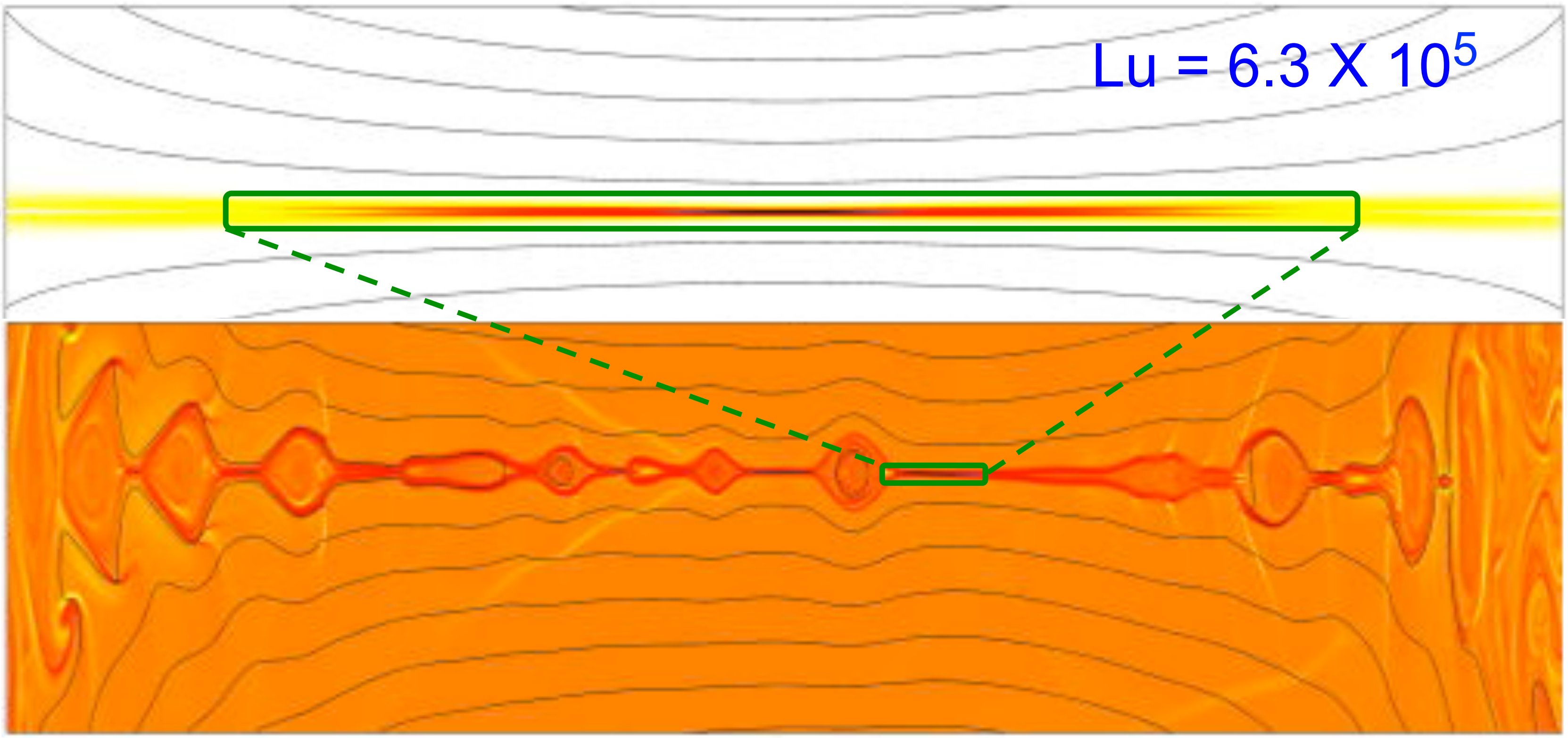




*as by micro-instability

Q: Is slowly reconnecting sheet stable?

A: No. Subject to resistive instability: tearing mode



Bhattacharjee *et al.* 2009 (vertical scale is expanded)

- Solution becomes time-dependant
- Smaller diffusion region(s) develop w/ larger $\delta/\Delta \sim M_{Ai}$

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 $\underbrace{\text{close encounters}}_{\text{= collisions}}$ 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

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

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

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

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

$\Delta << L$

Energy budget

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

Work done by changing **B**:

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

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

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

Mag. $\longrightarrow$ internal

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

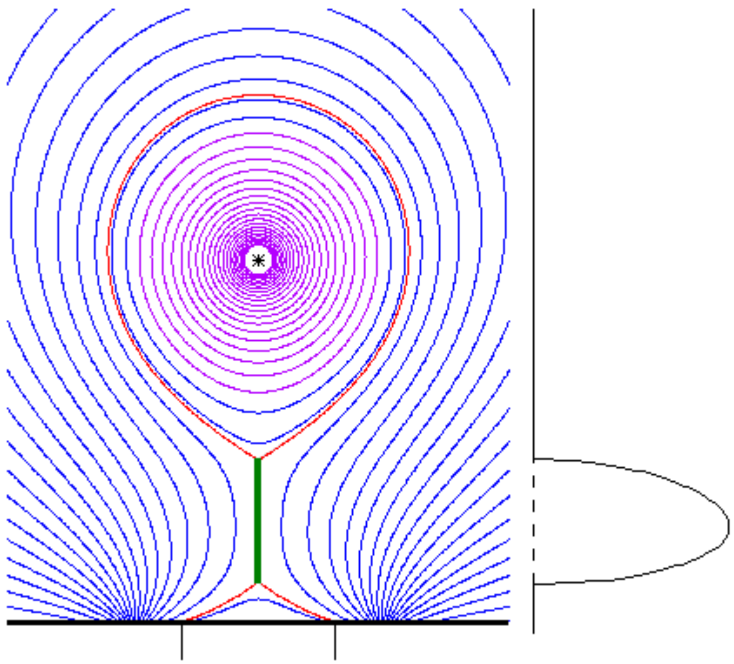
- η from particle-particle collisions – classical resistivity – **YES** – see 2nd law of thermo
- η from wave-particle interaction – anomalous resistivity – **???** – non-Maxellian dist'n

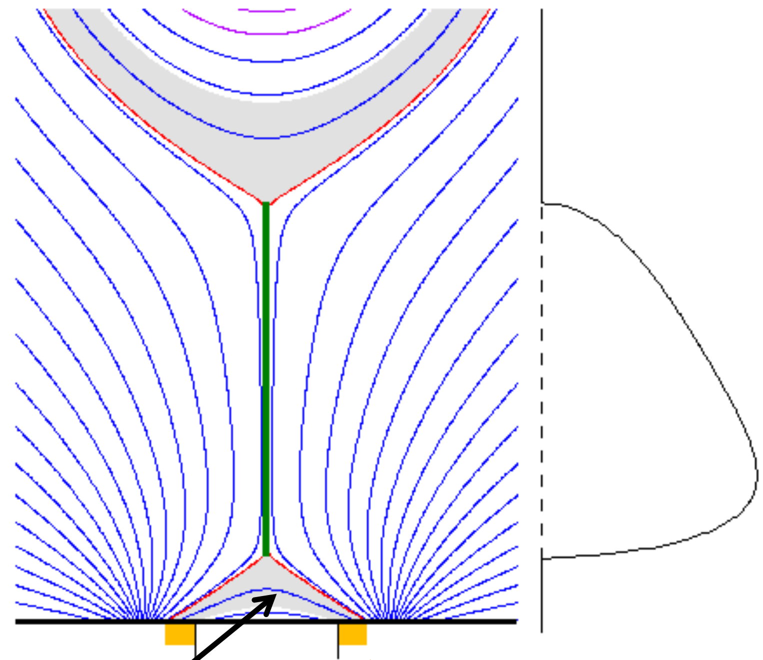
Evolution via reconnection

- 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

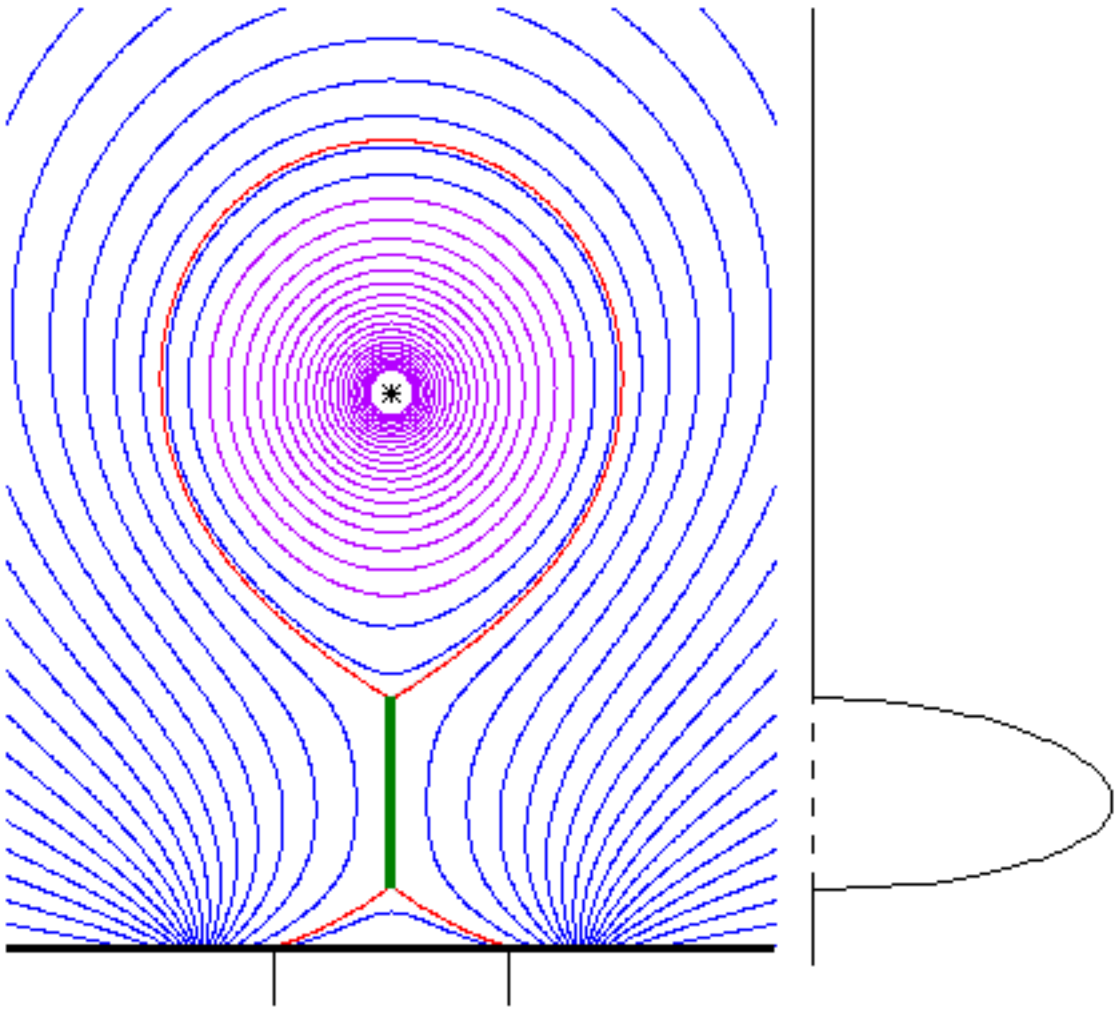
Assume E’ ≠ 0 @ CS (more later) ➔

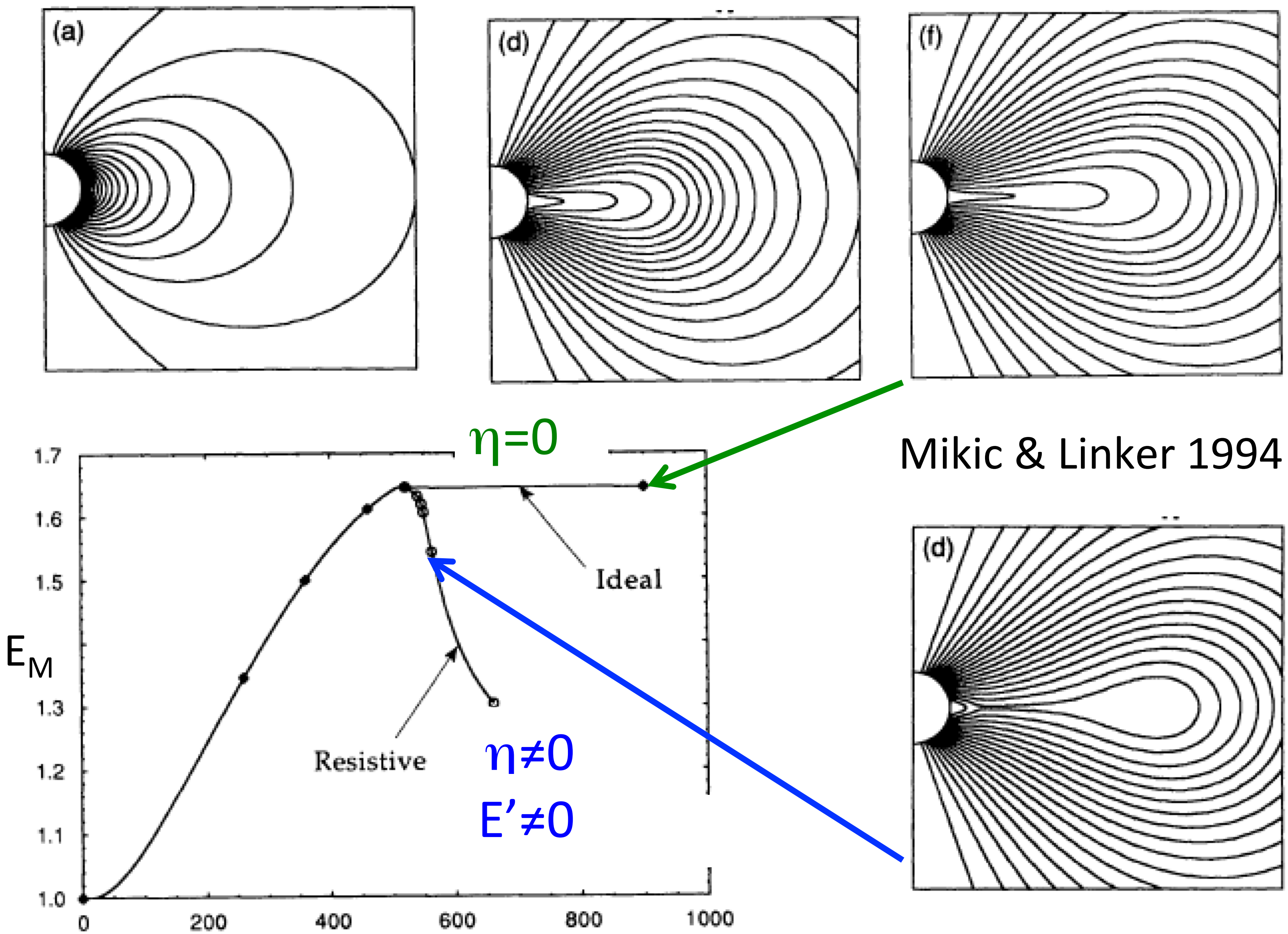




- Φ beneath CS increases
- Downward force decreases
  (reconnection reduces overlying flux)
- Flux rope rises
- Flare signatures produced by E’

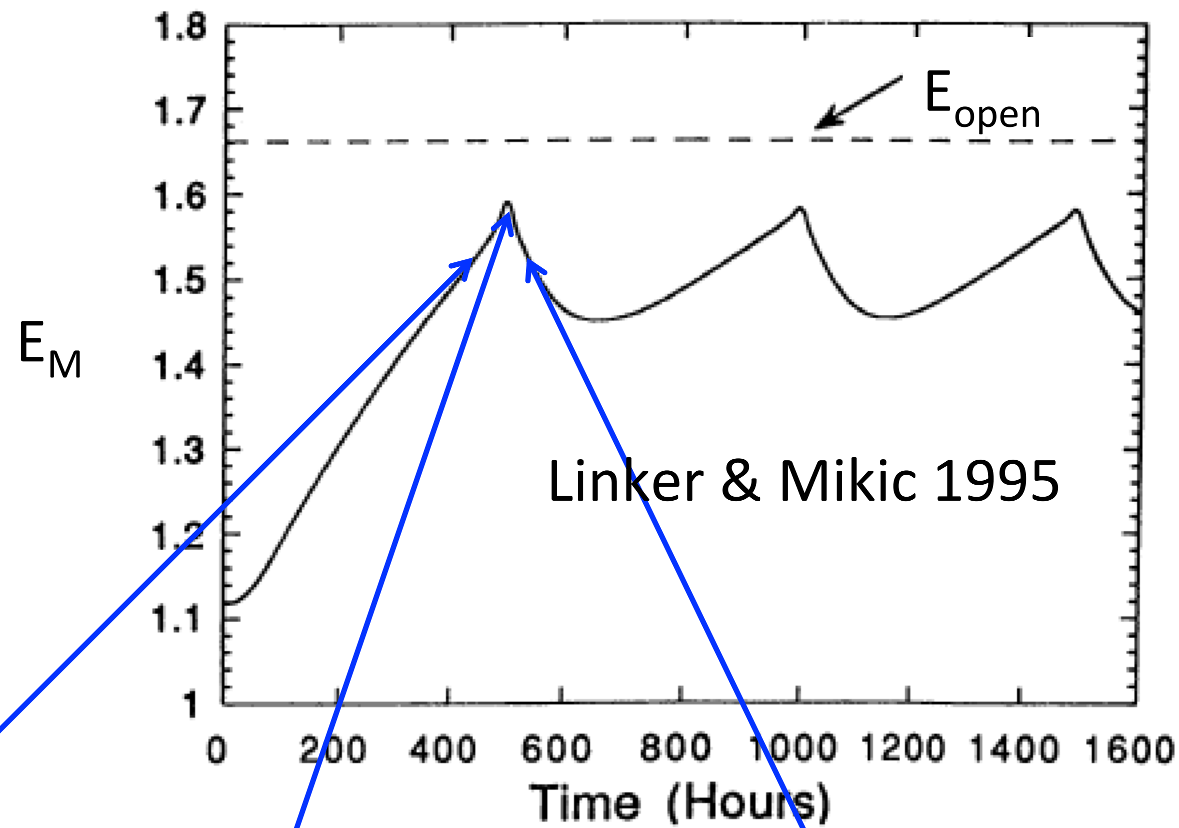
Eruption via reconnection

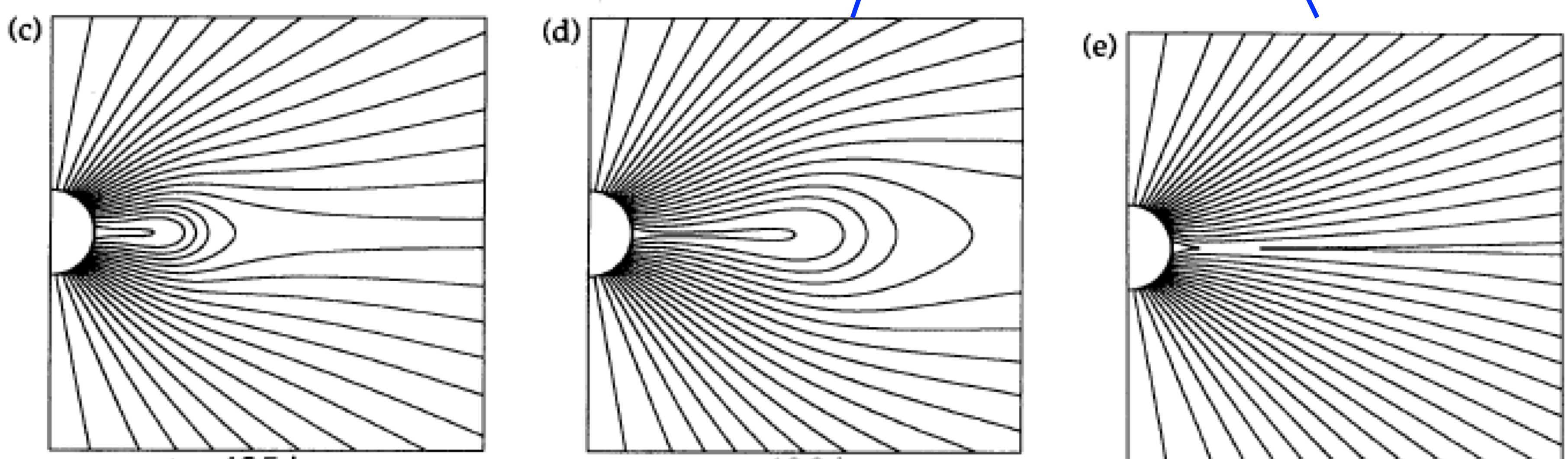




(a)
(d)
(f)
η=0
Mikic & Linker 1994
(d)
1.7
1.6
1.5
E_M
1.3
1.2
1.1
1.0
0
200
400
600
800
1000
Ideal
Resistive
η≠0
E'≠0

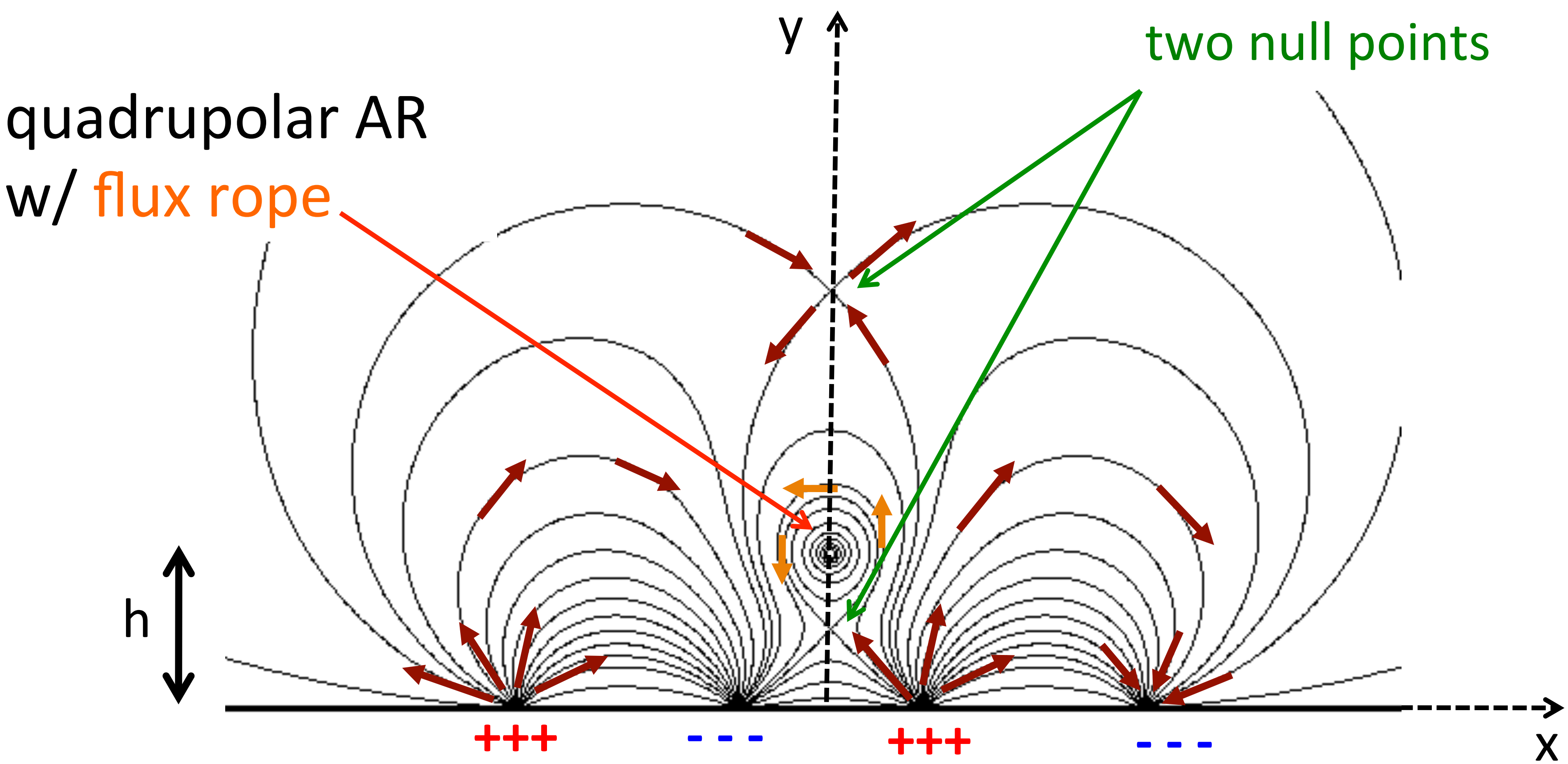
Aly-Sturrock conjecture:
$E_M < E_{open}$



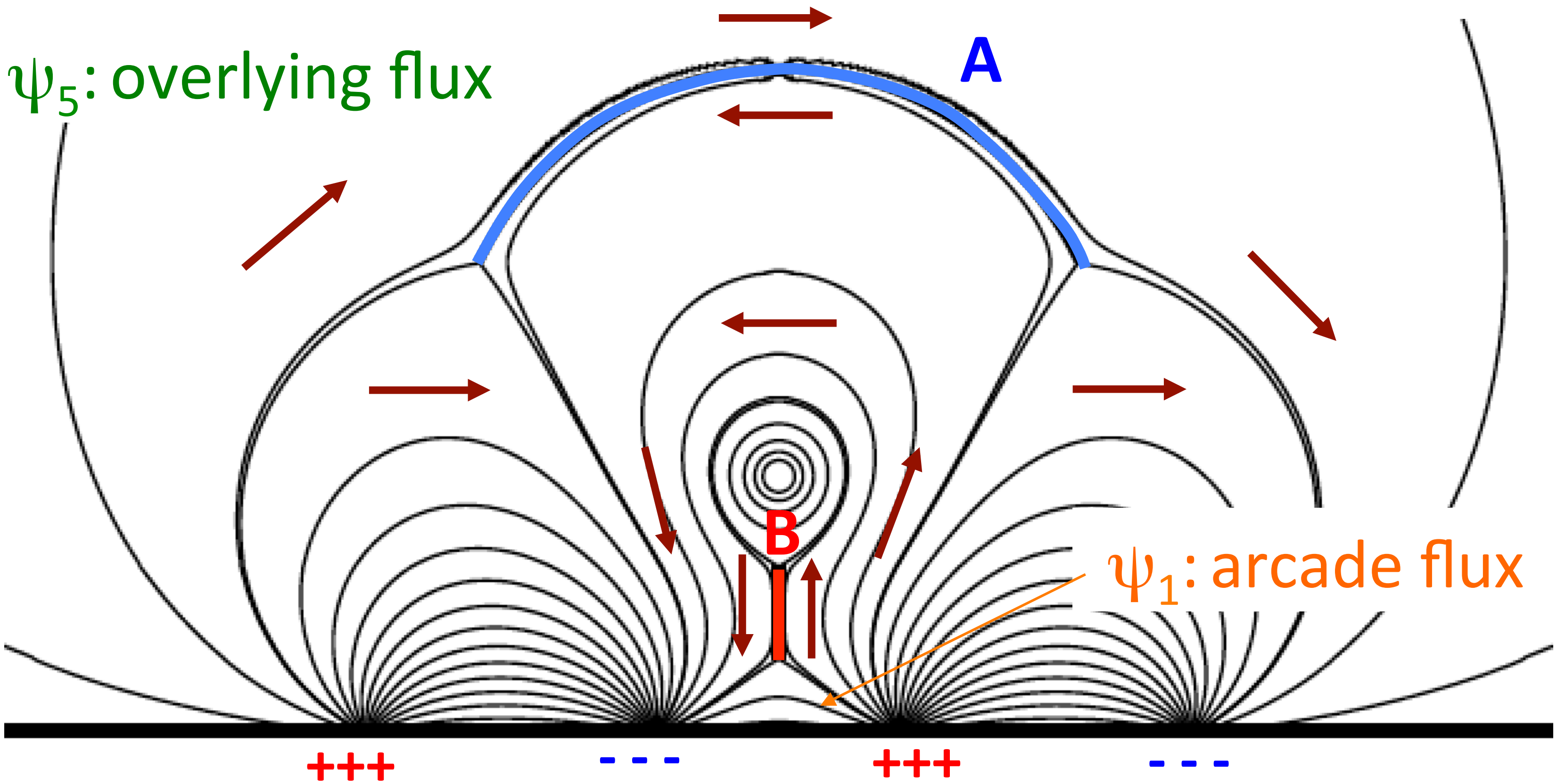


t = 485 hours
t = 496 hours
t = 510 hours

Slightly more complex toy model*



*from Longcope & Forbes 2014



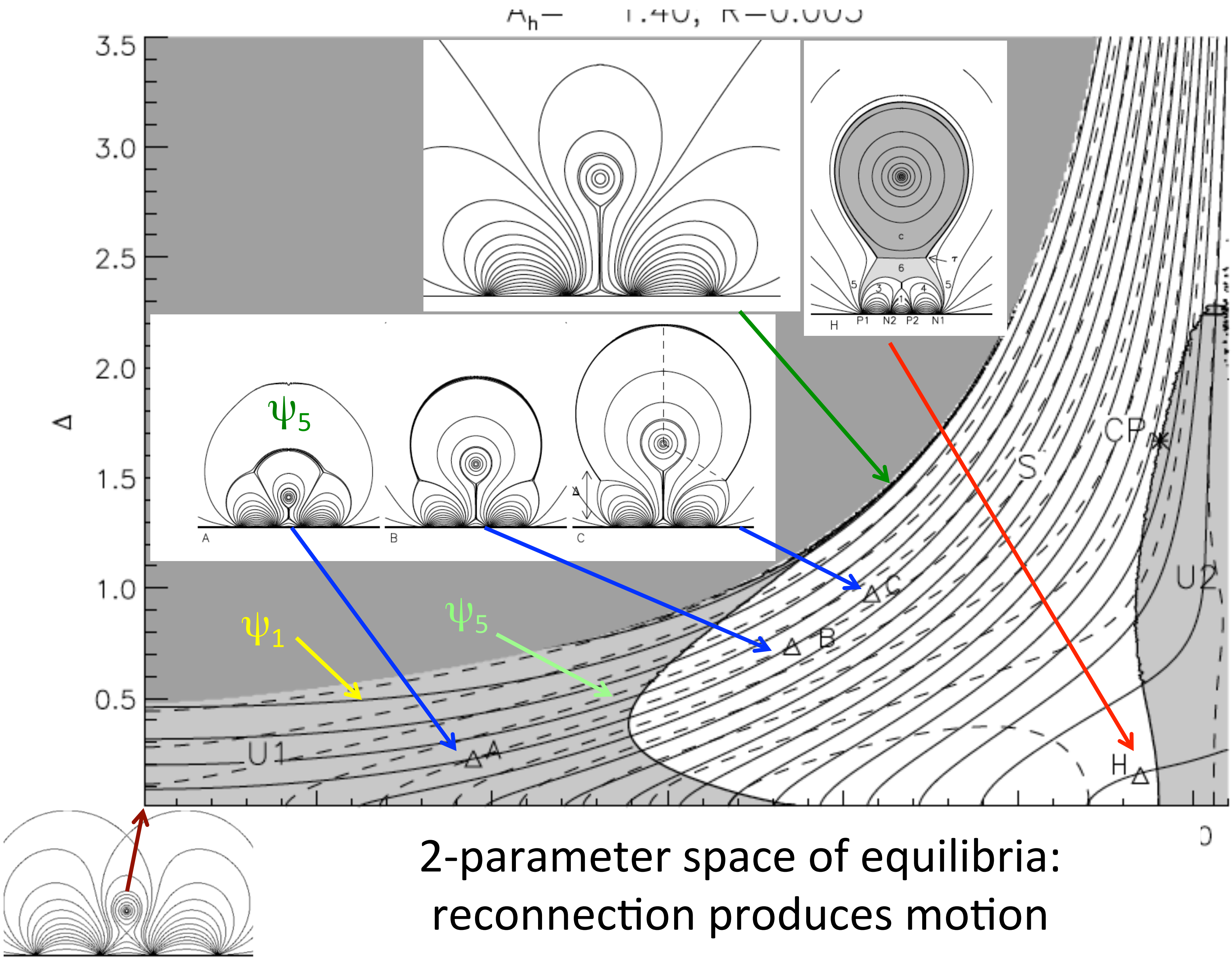
2 null points ➔ 2 CSs

2 CSs ➔ 2 sites for reconnection:

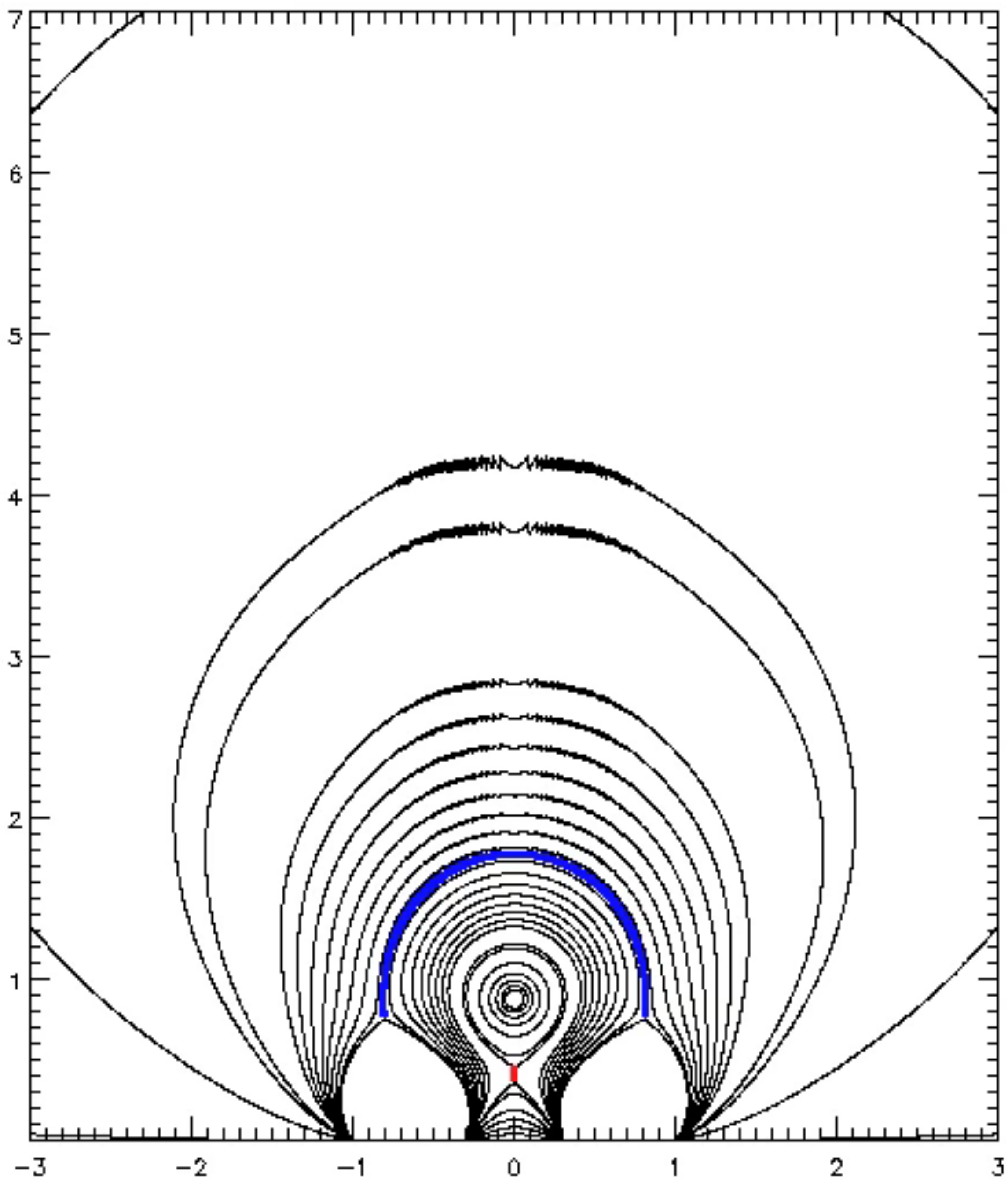
A: breakout reconnection: decreases ψ_5

B: tether-cutting reconnection: increases ψ_1

Reconnection changes equilibrium



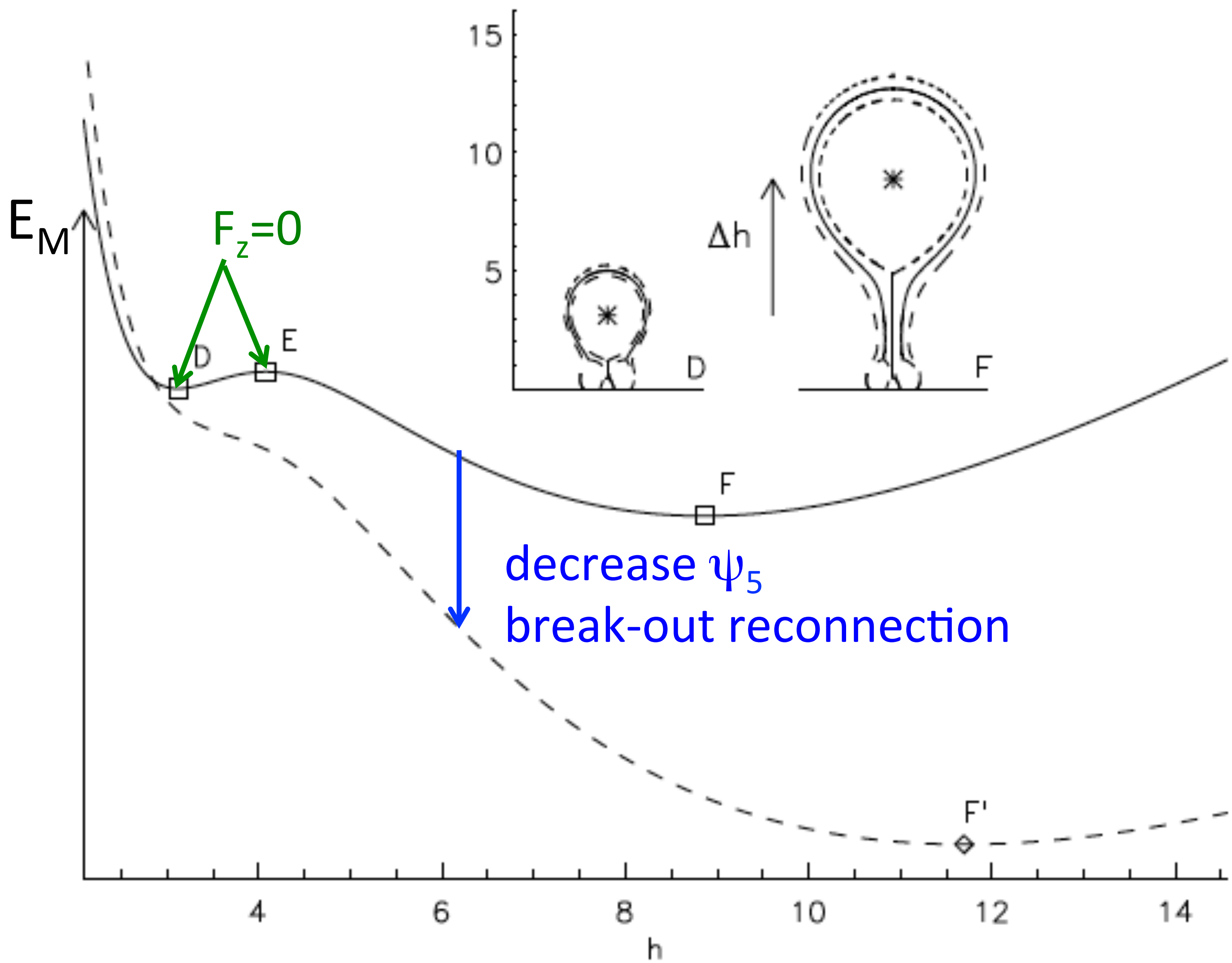
2-parameter space of equilibria:
reconnection produces motion



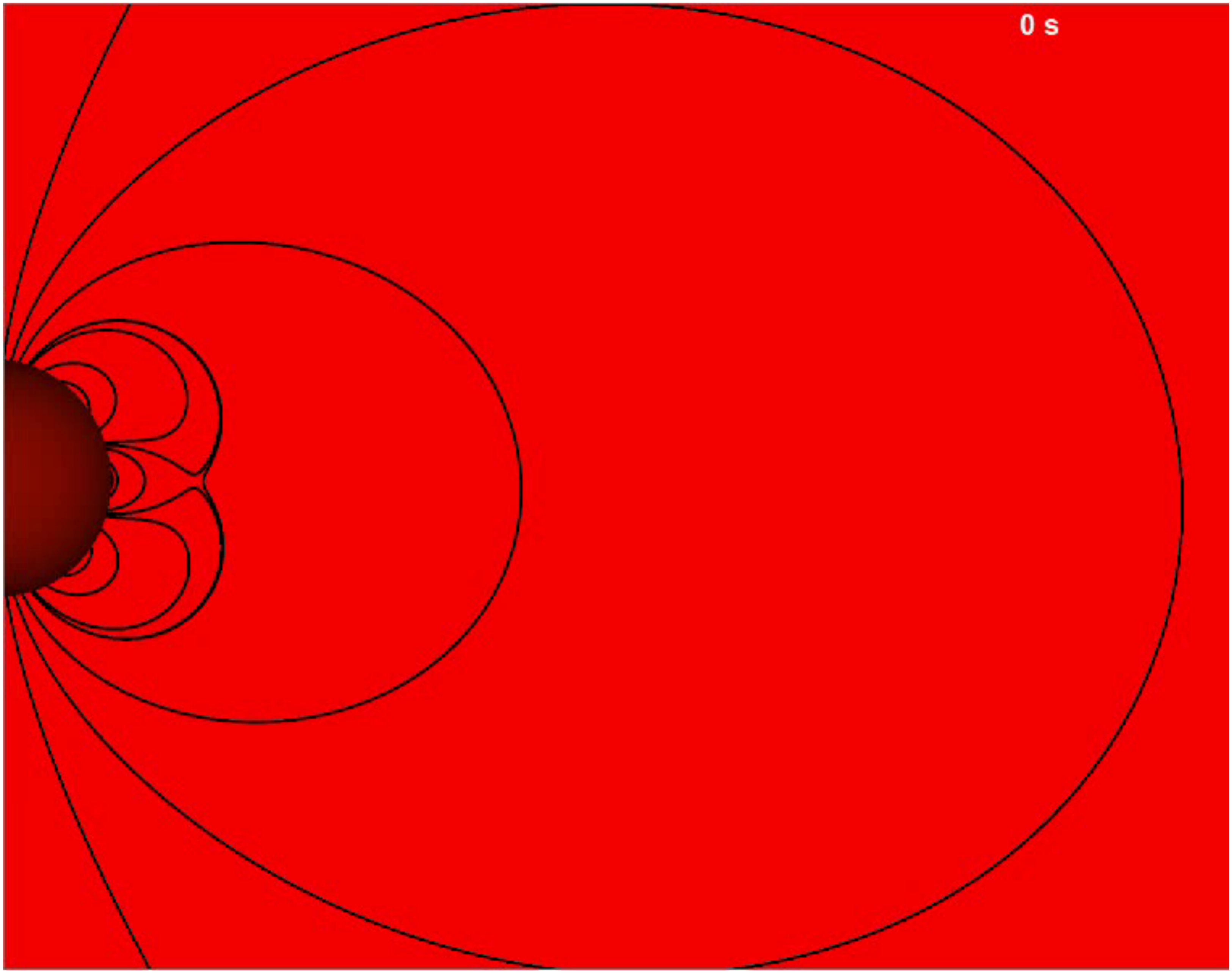
Slow evolution via breakout reconnection:

- Decreases overlying flux ψ_5
- Leaves unchanged arcade flux ψ_1

Loss of equilibrium through reconnection



Numerical solution from Karpen et al. 2012



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