Storage, Release, and Conversion of Magnetic Energy by Solar Flare Reconnection

A Story of the Large Scales

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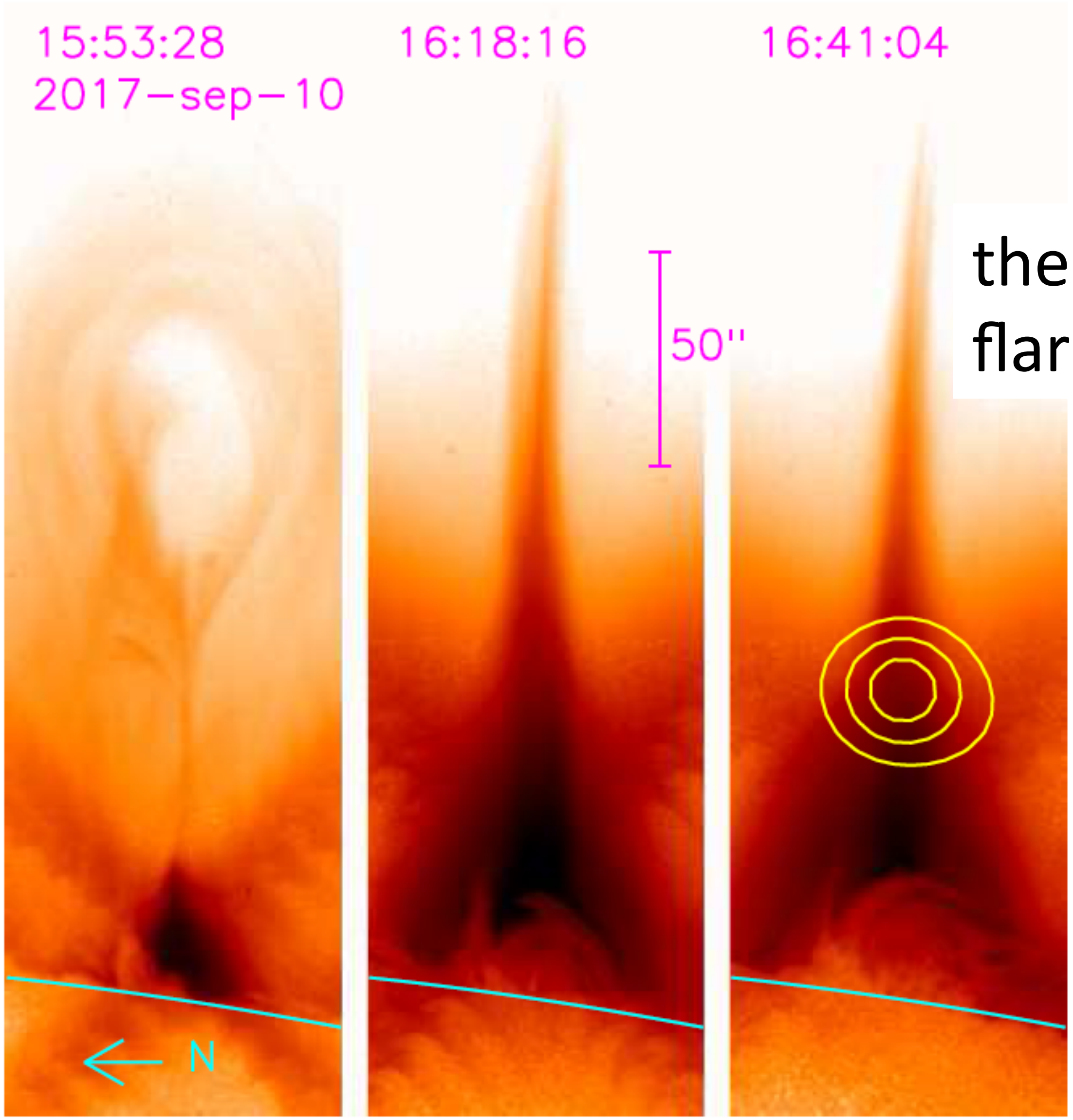
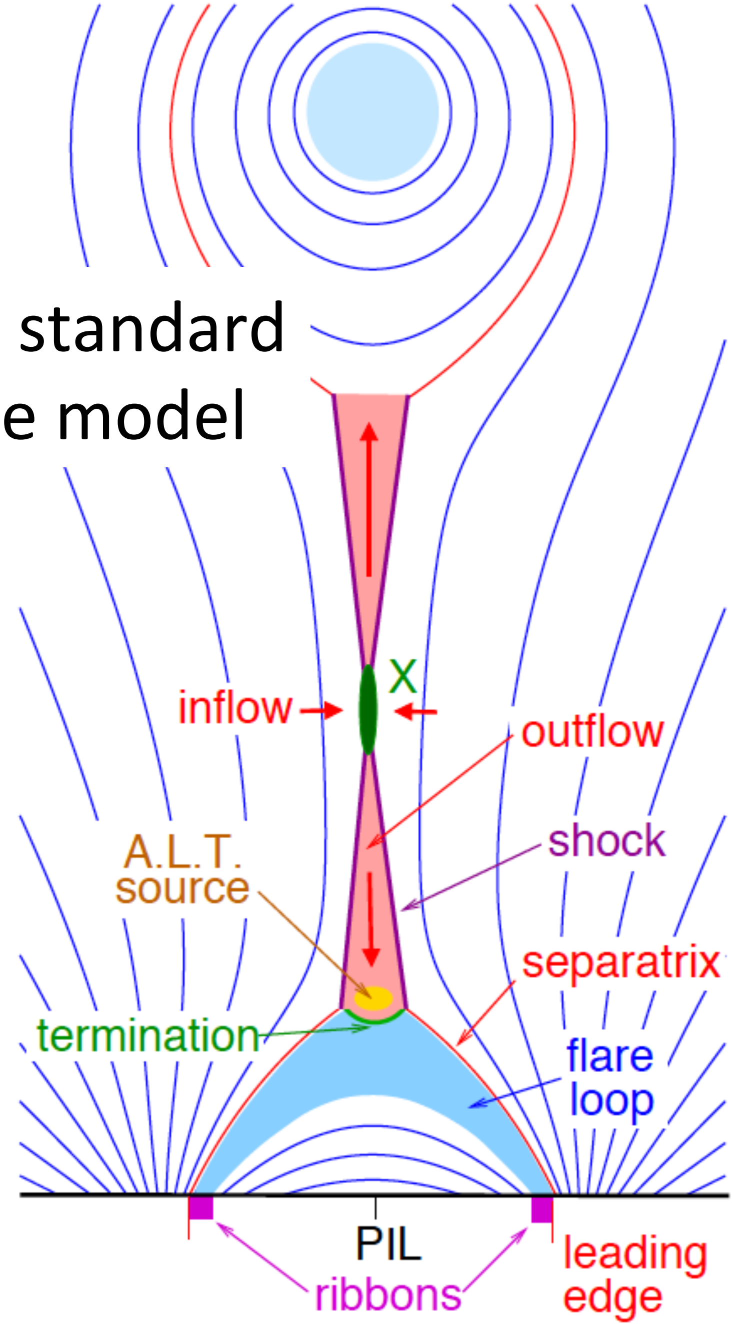


(DWL in Oxford Res. Enc. Phys. 2019)

the standard flare model



Outline

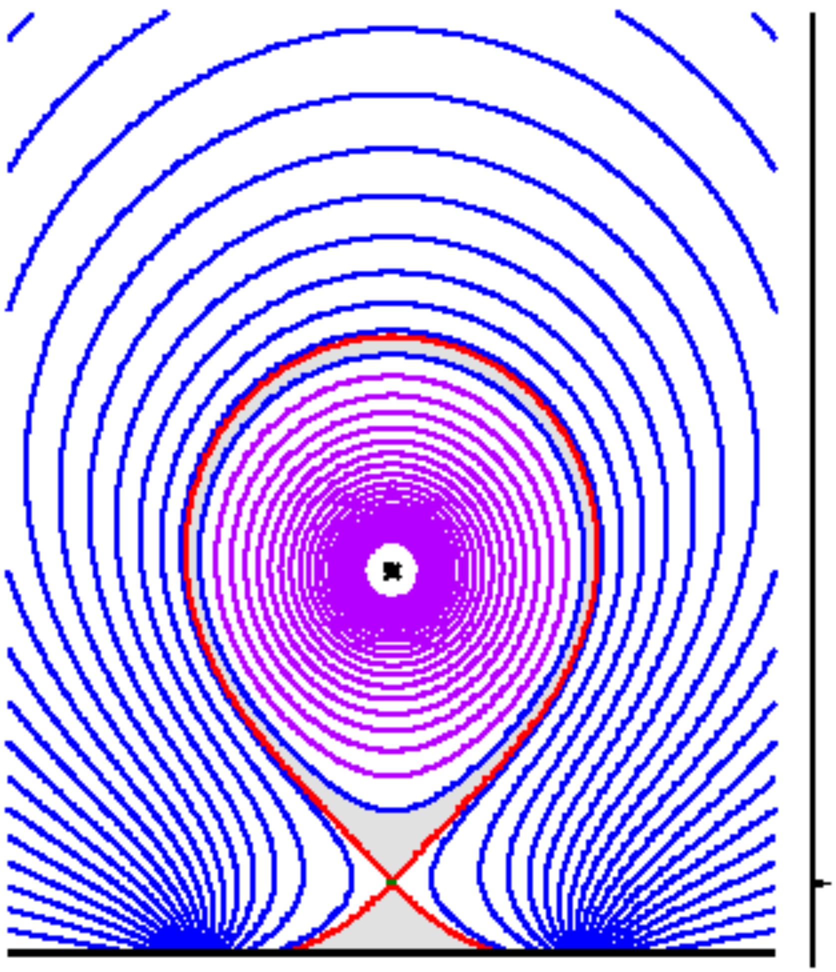
The Large Scale Story of a Solar Flare:

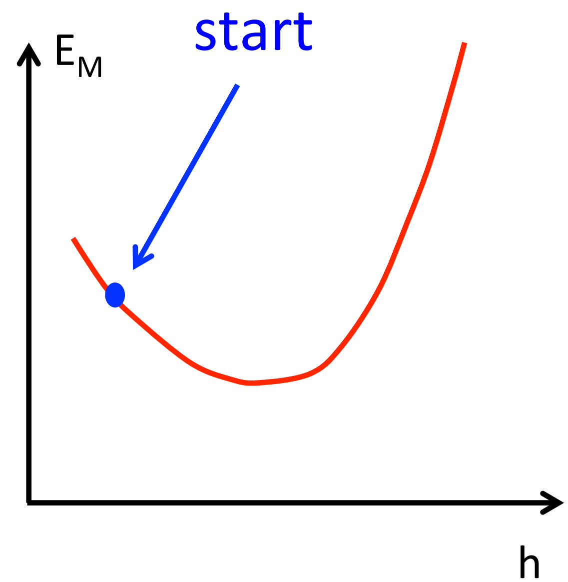
I. Energy Storage & Release
   - ❖ How is energy stored: in current sheet
   - ❖ How is it released: reconnection ➔ field line shortening

II. Energy Conversion
   - ❖ How is magnetic energy converted to other forms? – one possibility = Petschek model

III. The Solar Flare

Eruption w/o reconnection





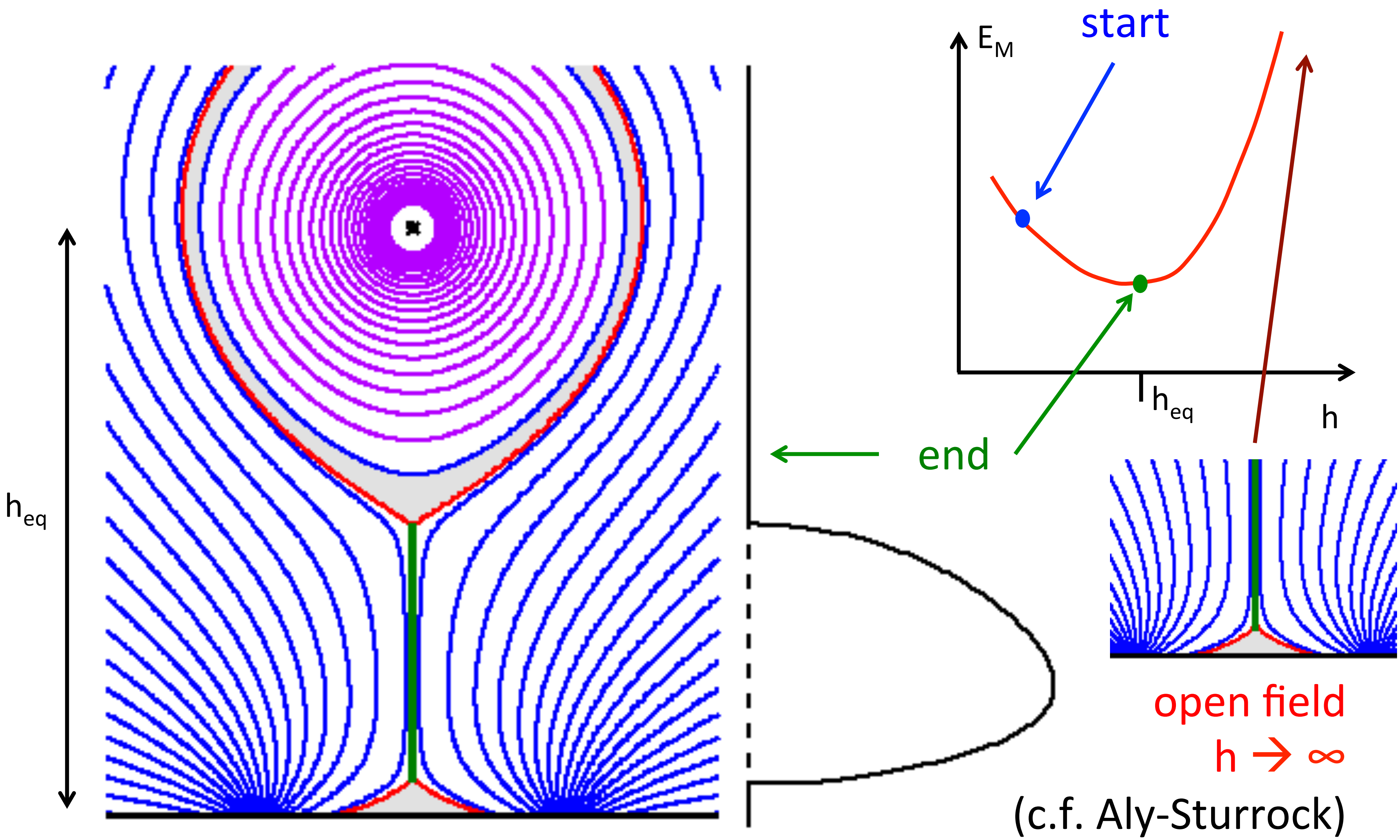
no reconn…

➔ E’ = 0

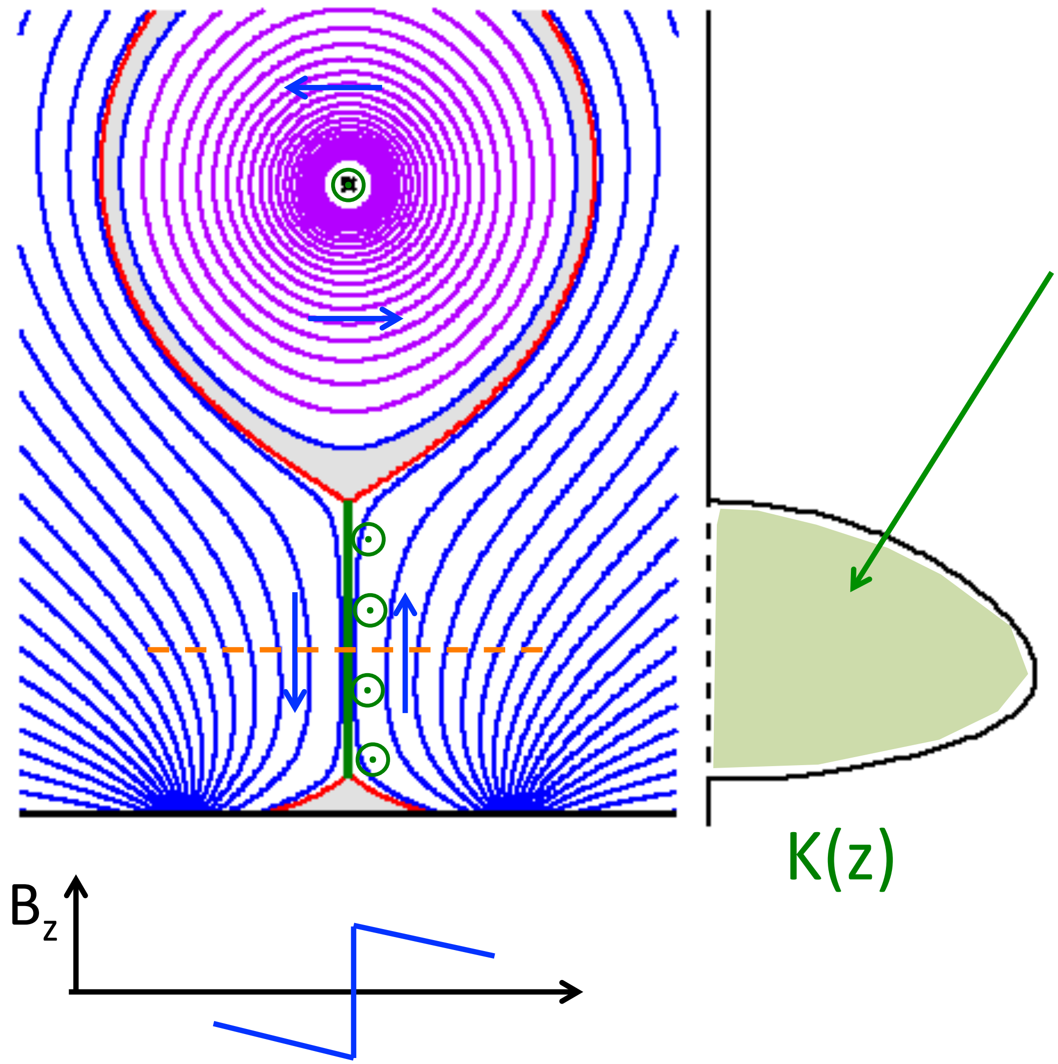
➔ Φ = const

after Lin & Forbes 2000

Eruption w/o reconnection



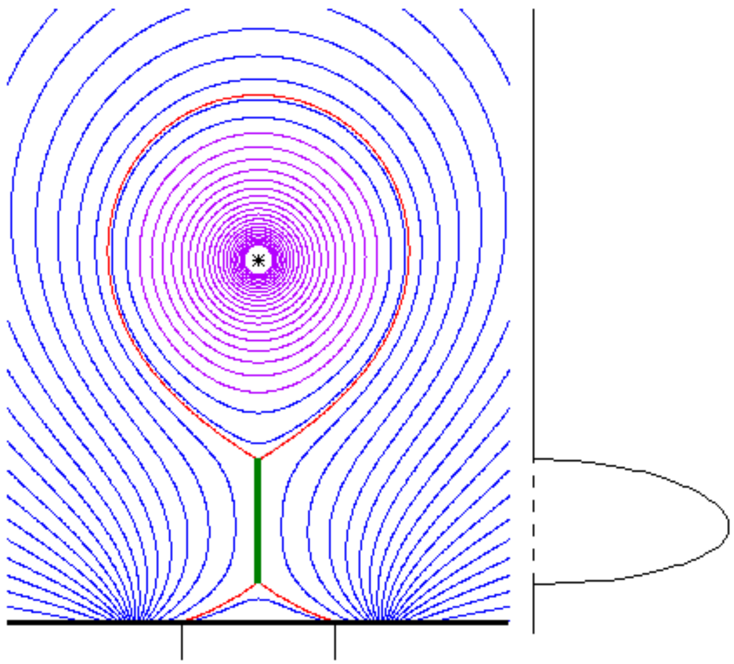
Current sheet

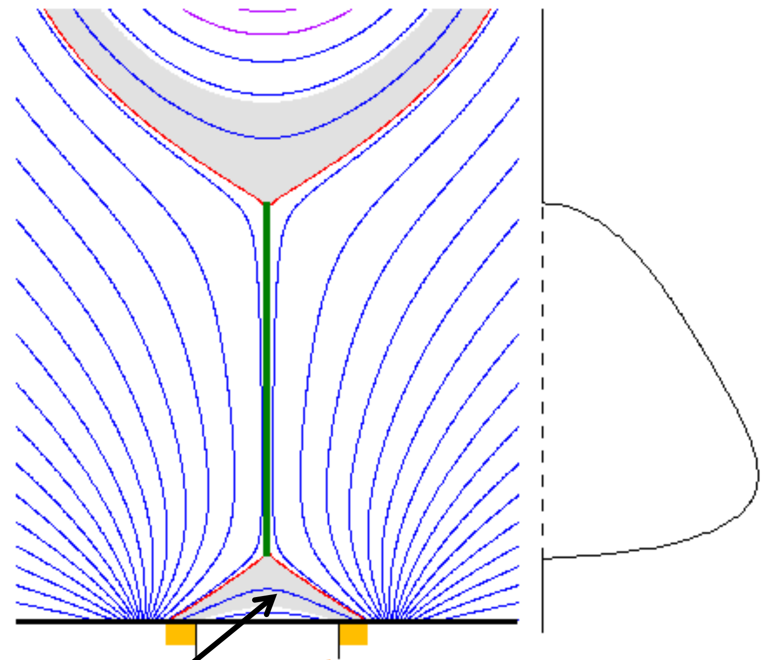


- X-point → CS
- B_z discontinuous
- Current in sheet
- Exerts downward force on line current
- Balances upward force from image: CS is equilibrium
- Equivalent: tension from overlying field holds flux rope down

Eruption via reconnection

Allow E’ ≠ 0 @ CS

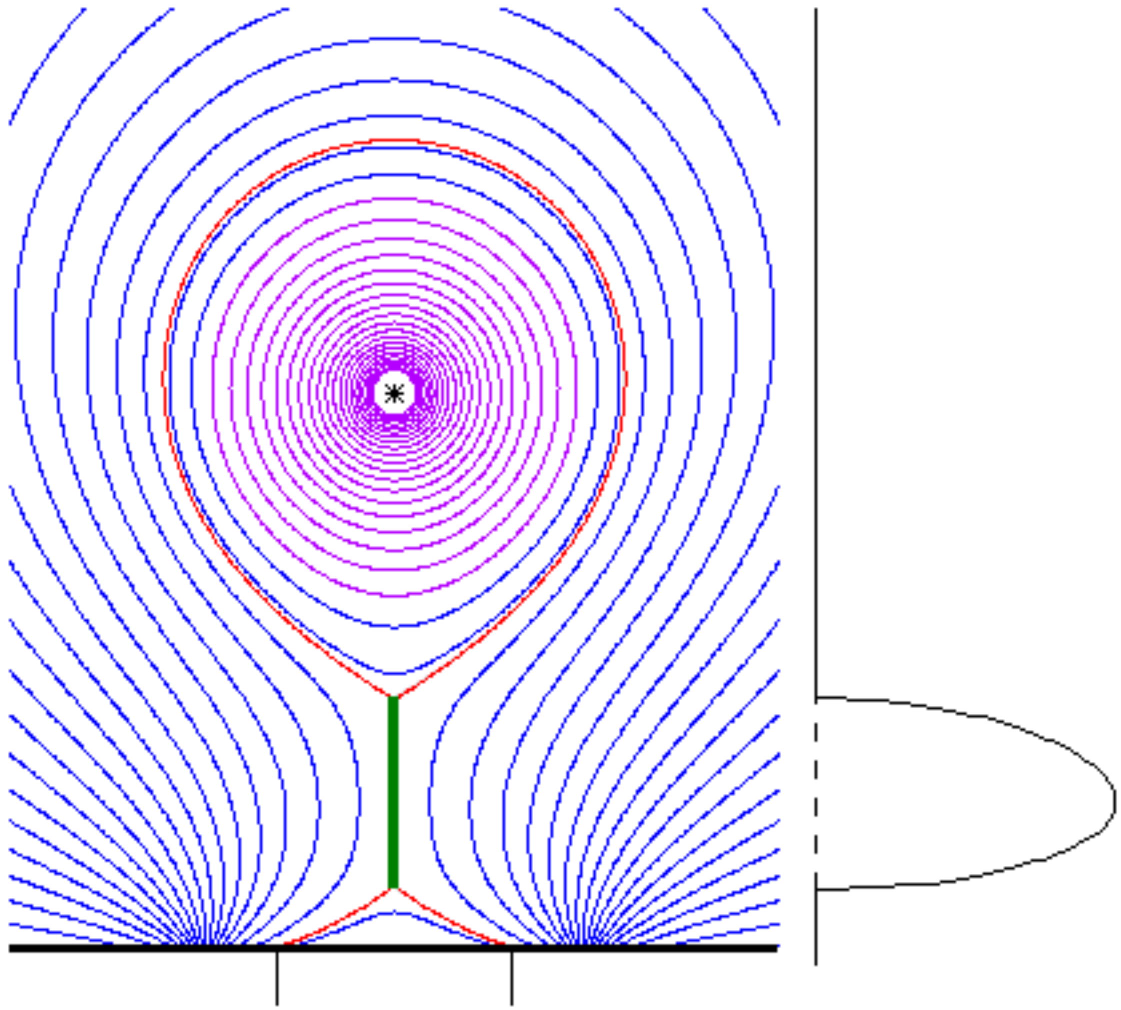




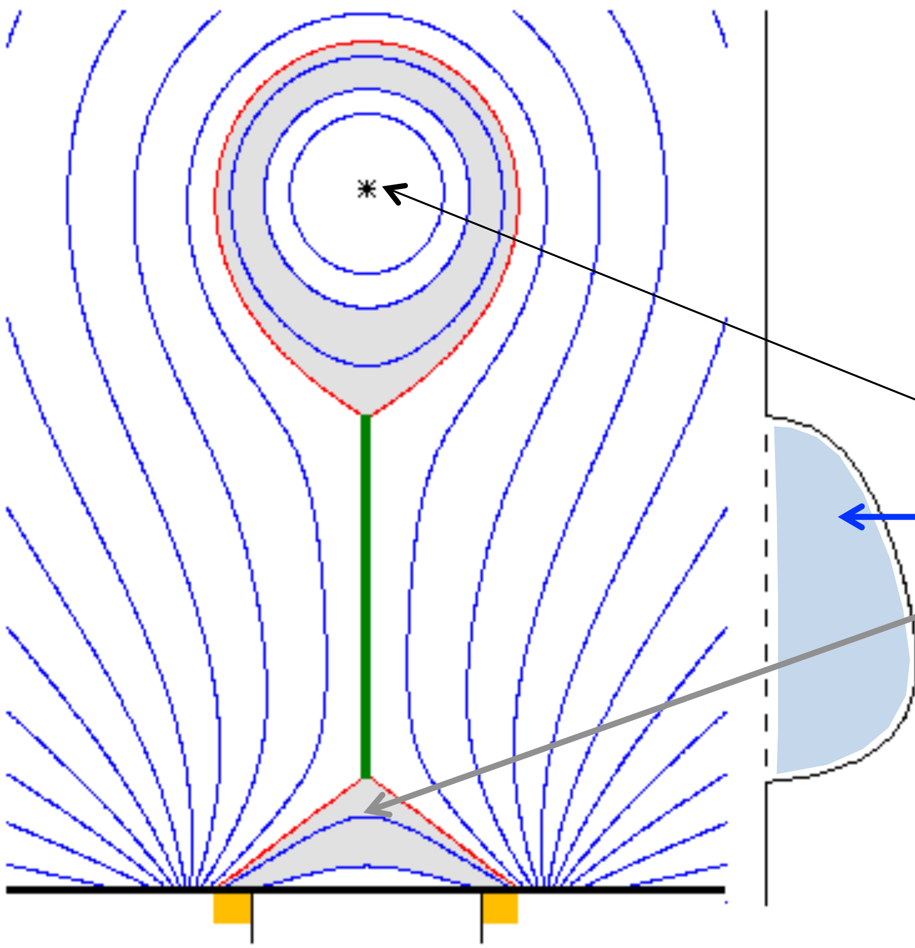
- Φ beneath CS increases
- Downward force decreases

  (reconnection reduces overlying flux)
- Flux rope rises (CME)
- **Solar flare**

Eruption via reconnection



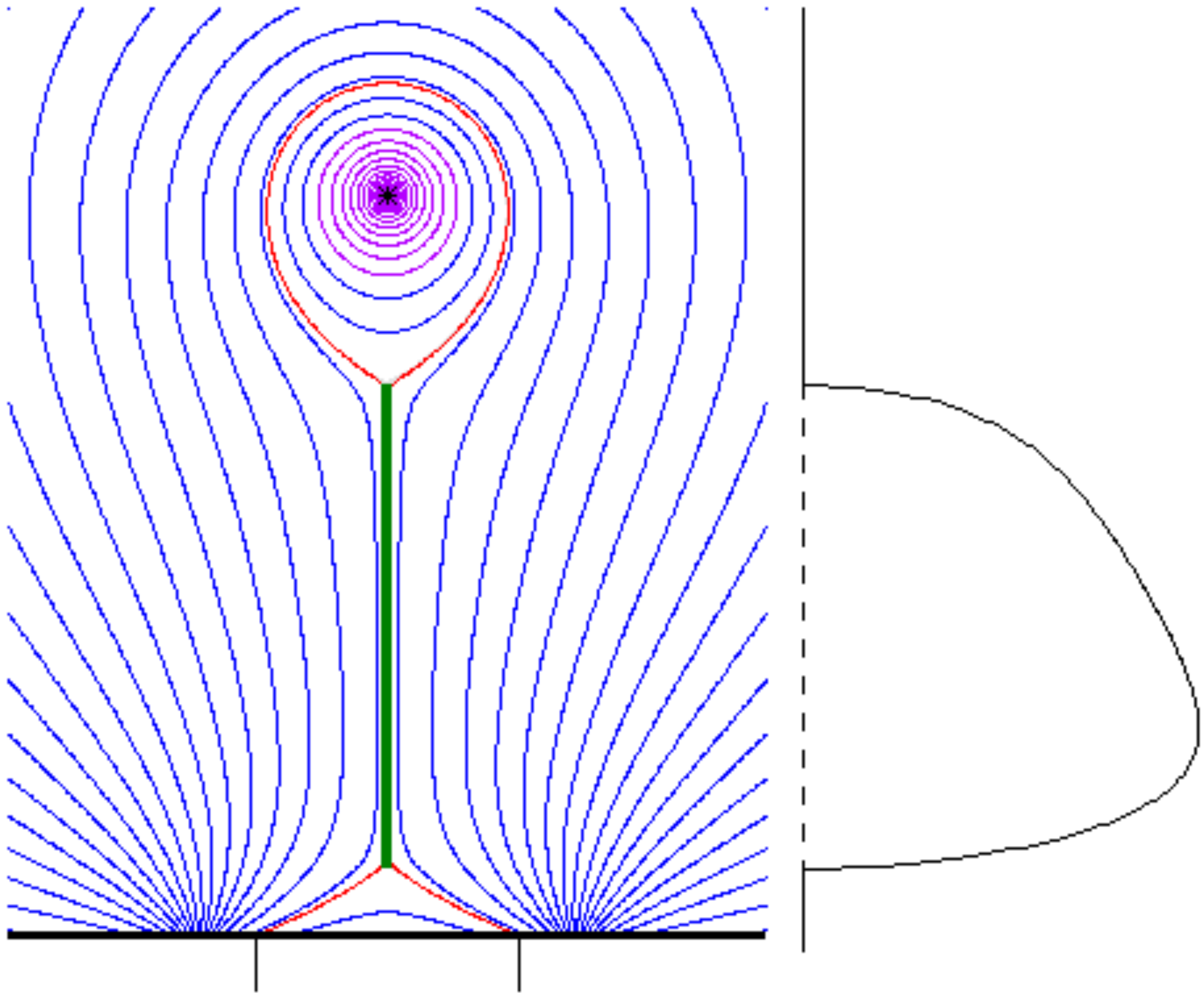
Energy of a flare



Q: How much energy is released by magnetic reconnection?

Experiment:

- Fix flux rope (focus on flare)
- Integrate current $\mathbf{I}$
- Track reconnected flux in arcade $\Phi(t)$

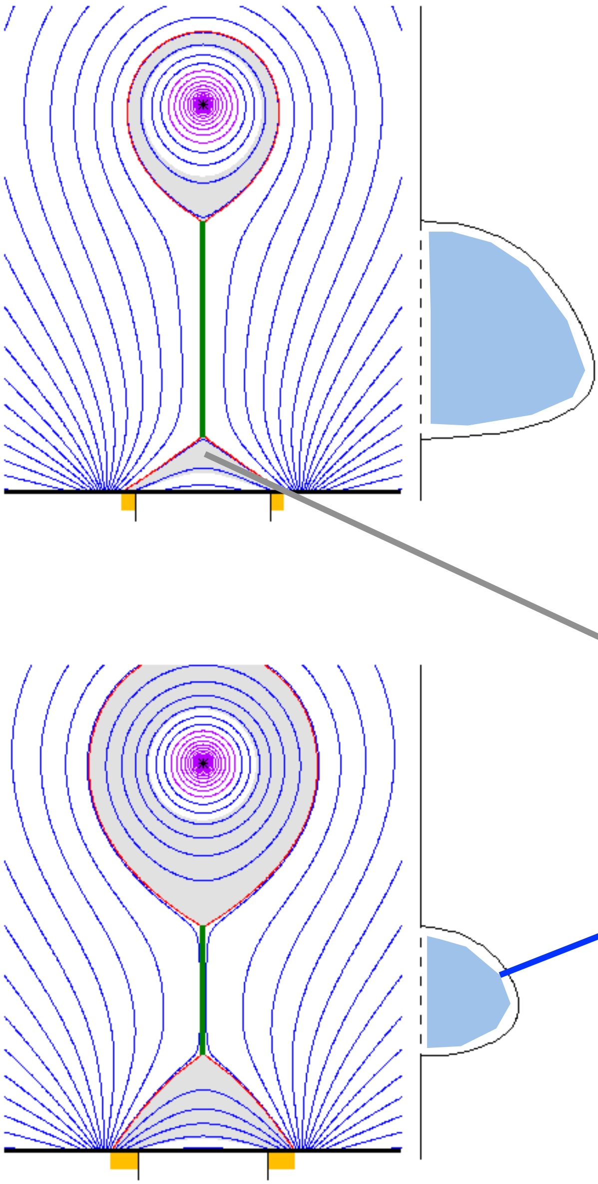


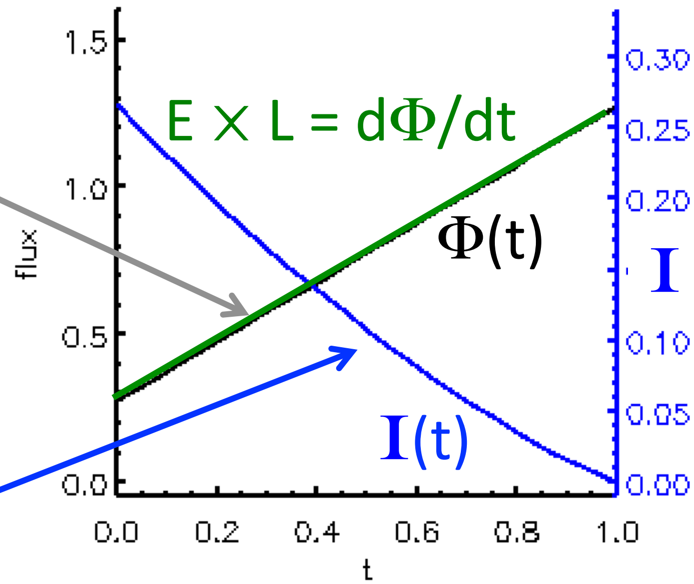
Electrodynamic work done by field

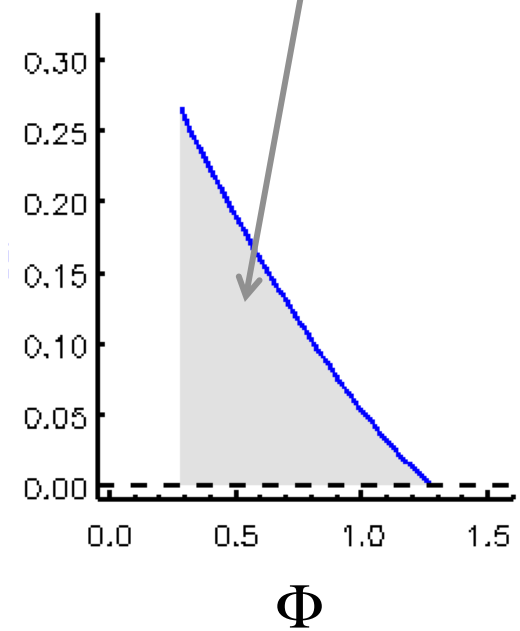
$$W = \int I\, E\, dt = \frac{1}{c}\int I\, \frac{d\Phi}{dt}\, dt = \frac{1}{c}\int I\, d\Phi$$

= drop in magnetic energy

– energy release

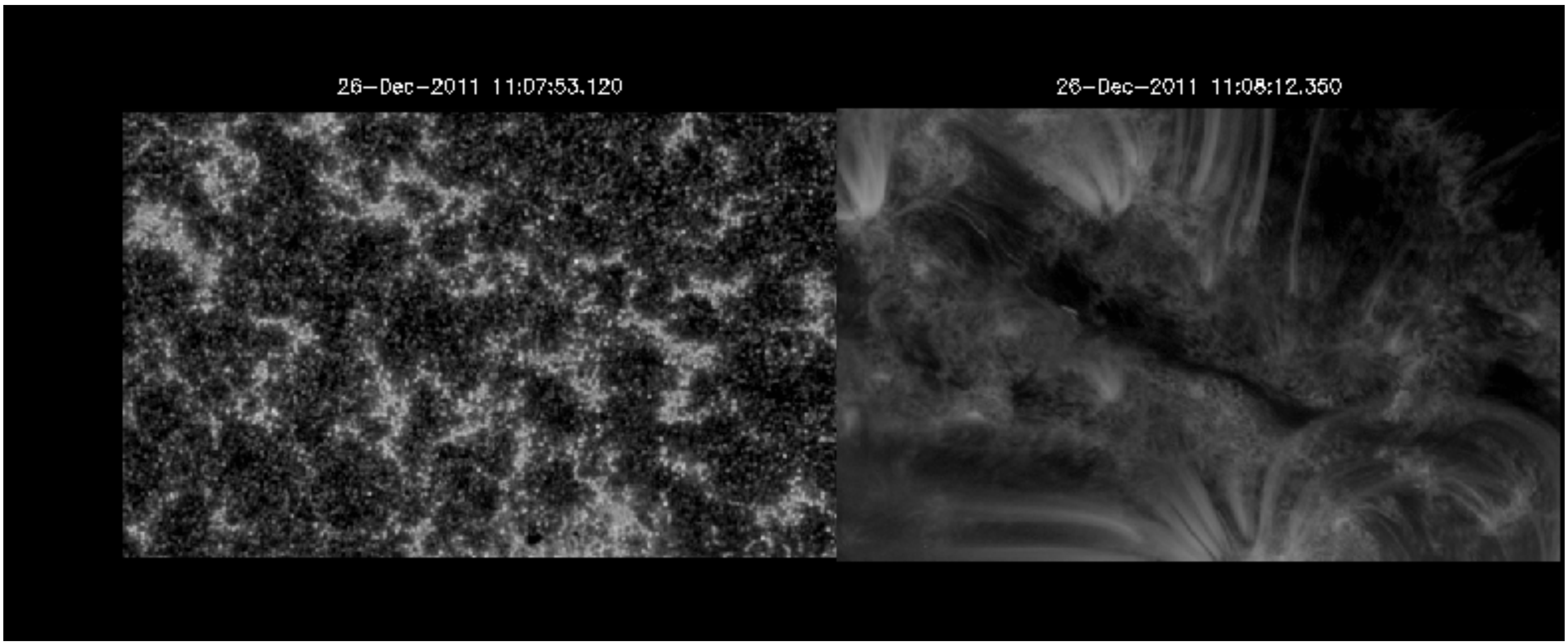




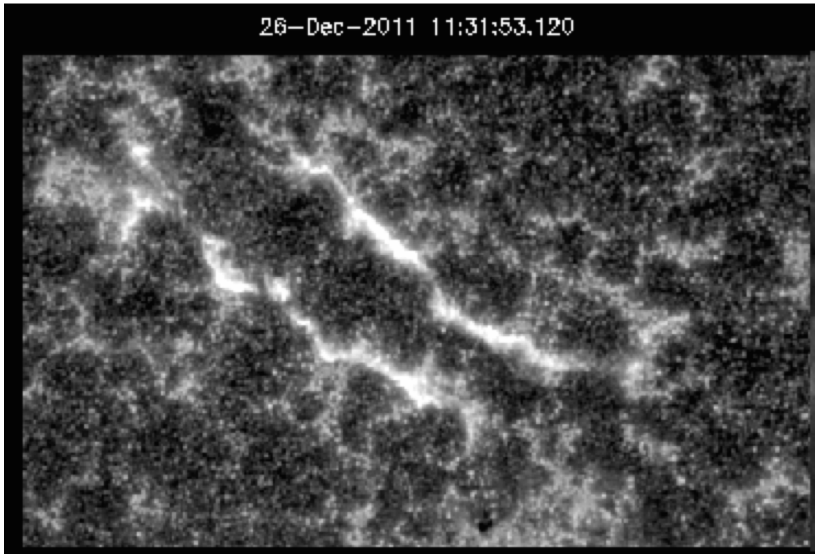


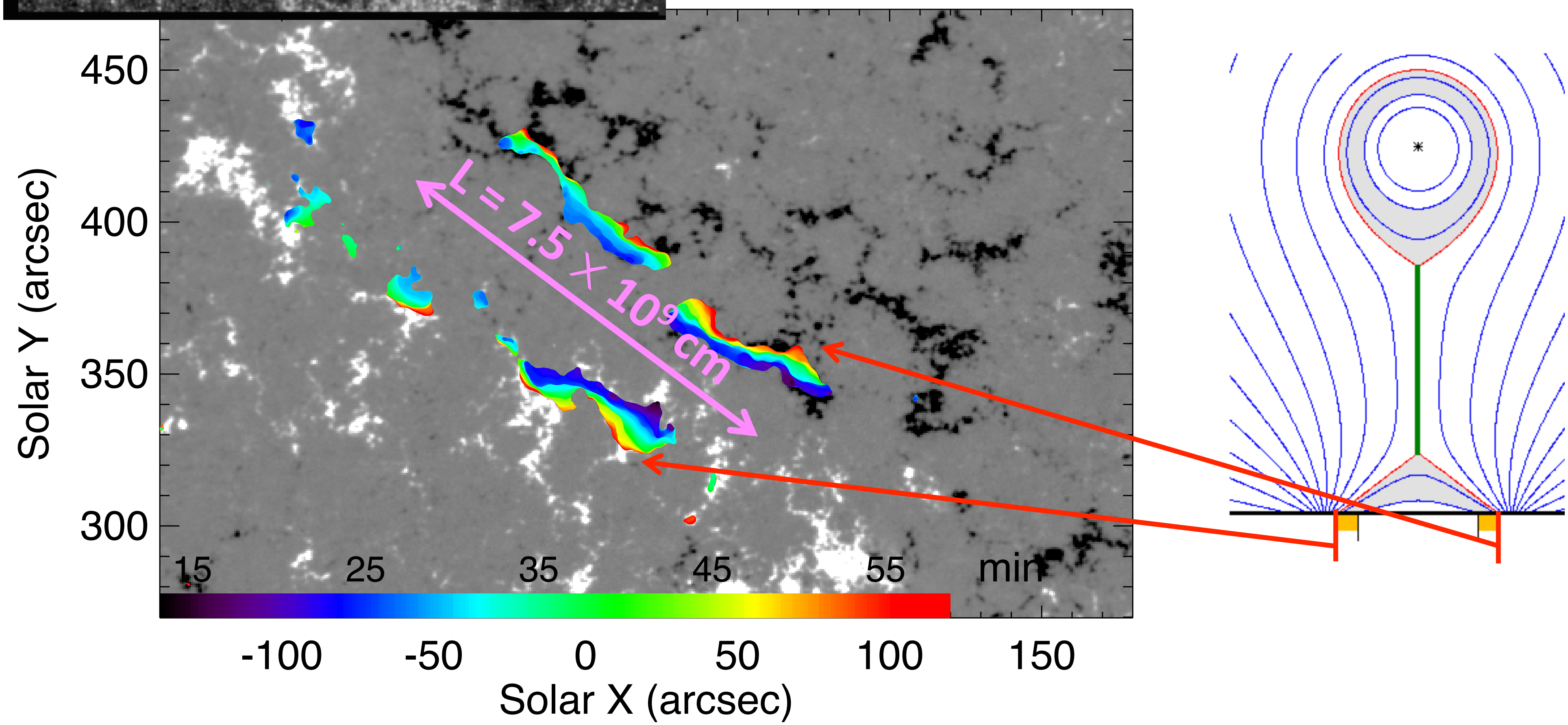
AIA 1600 A:
100,000 K plasma
chromospheric feet

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

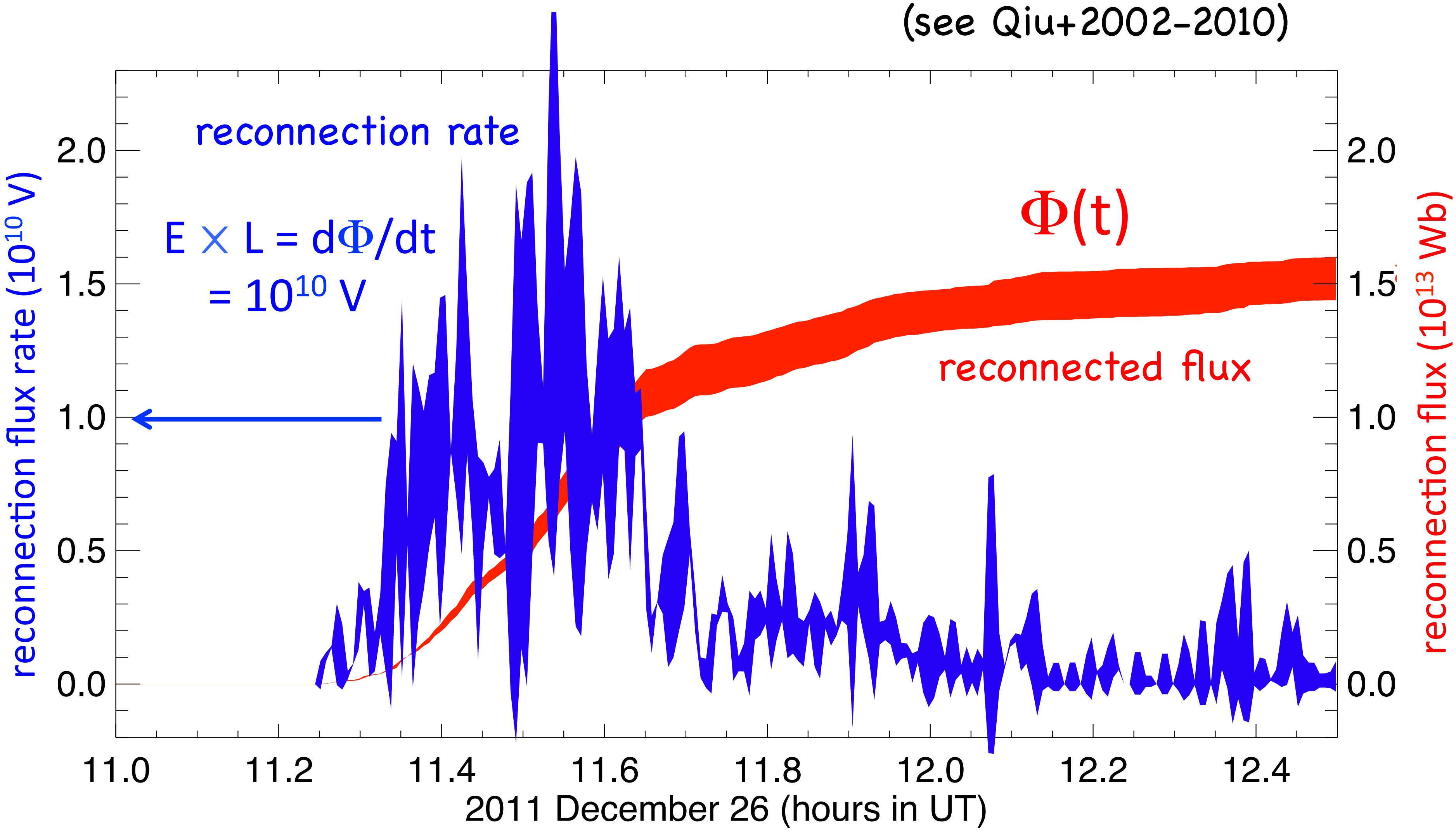


Flux measured from flare ribbons





(see Qiu+2002-2010)

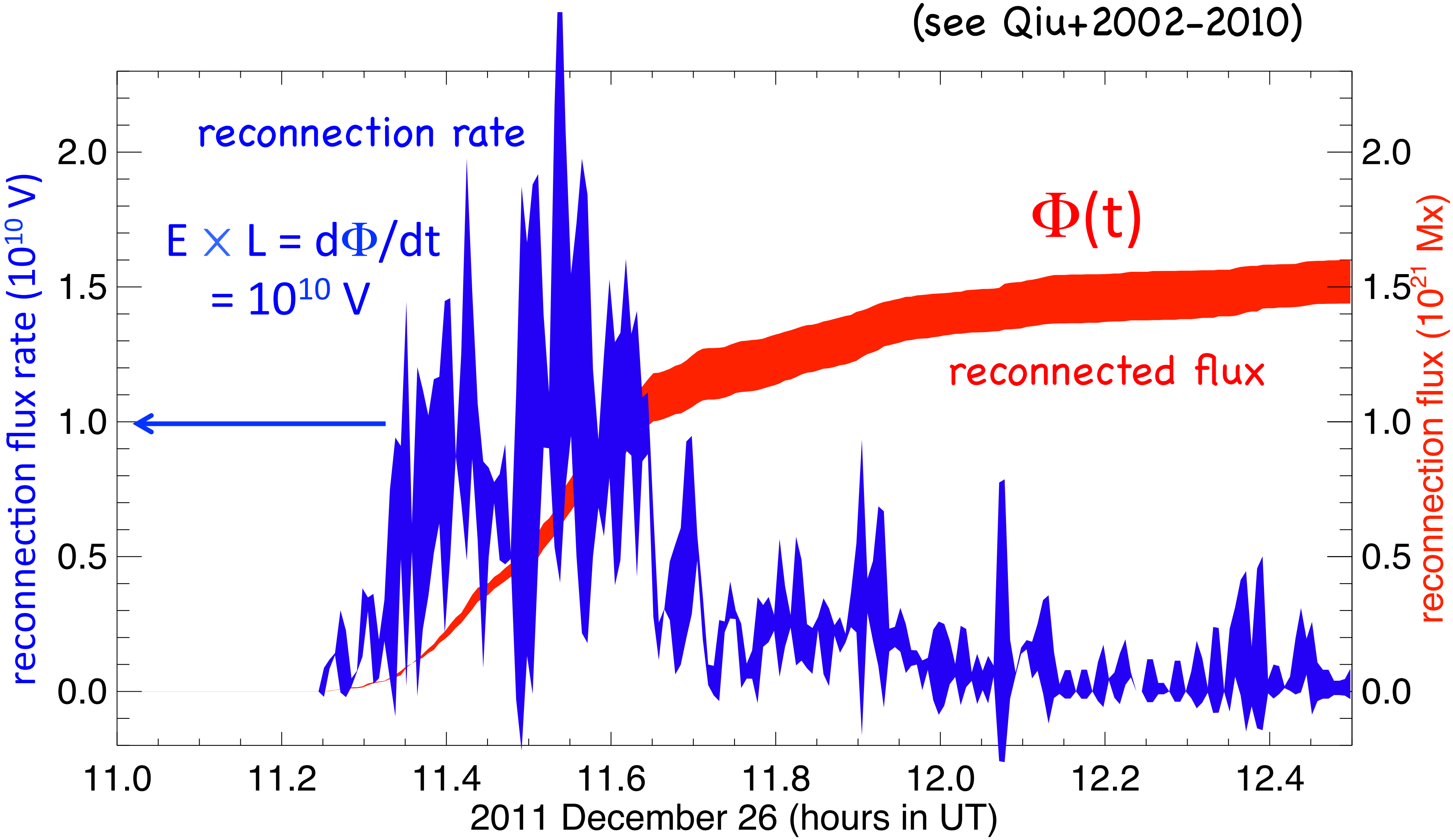


$$I_0 \sim \frac{\Delta\Phi}{\mu_0 L} \sim \frac{1.5\times10^{13}\,\mathrm{Wb}}{4\pi 10^{-7}\cdot 7.5\times10^{7}\,\mathrm{m}} = 1.6\times10^{11}\ \mathrm{A}$$

160 GA

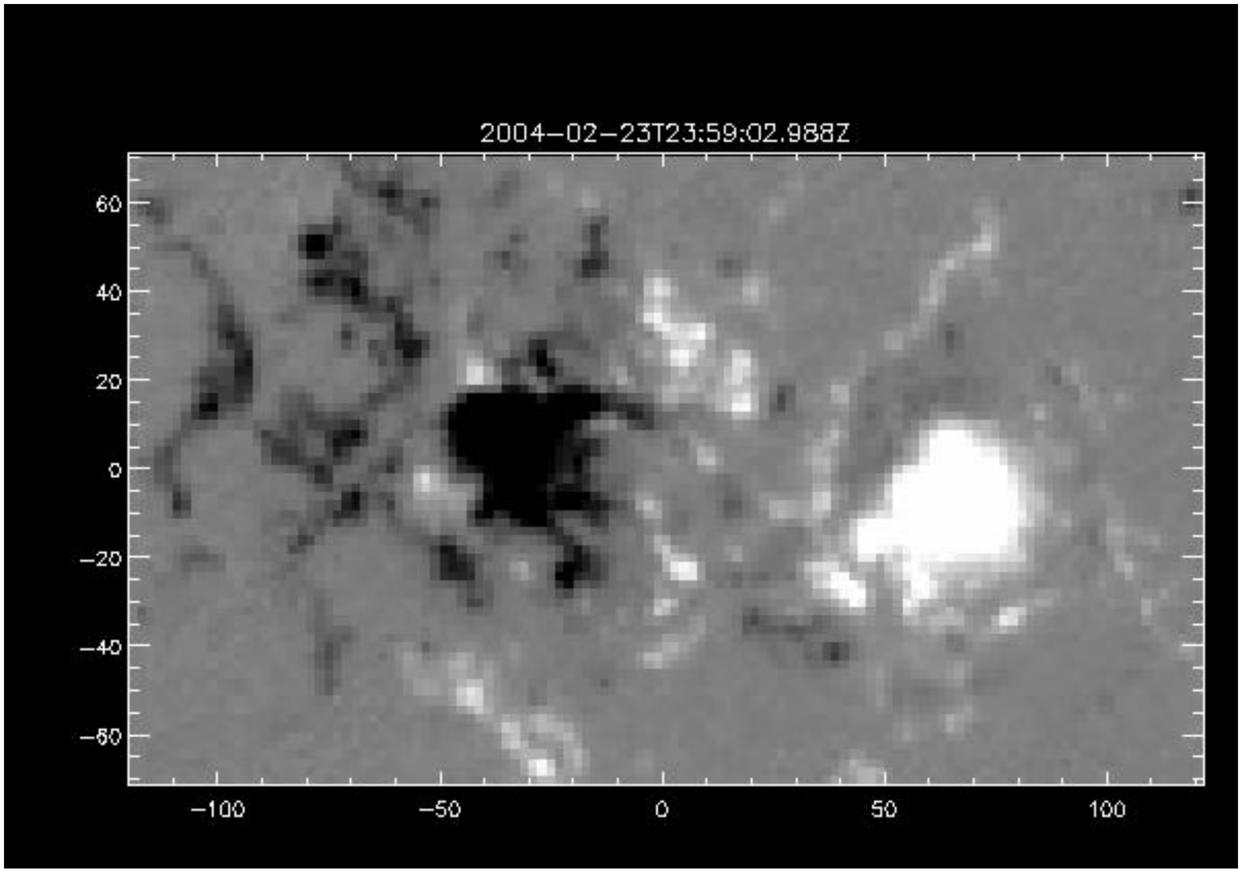
$S \sim 10^{13}$

(see Qiu+2002-2010)

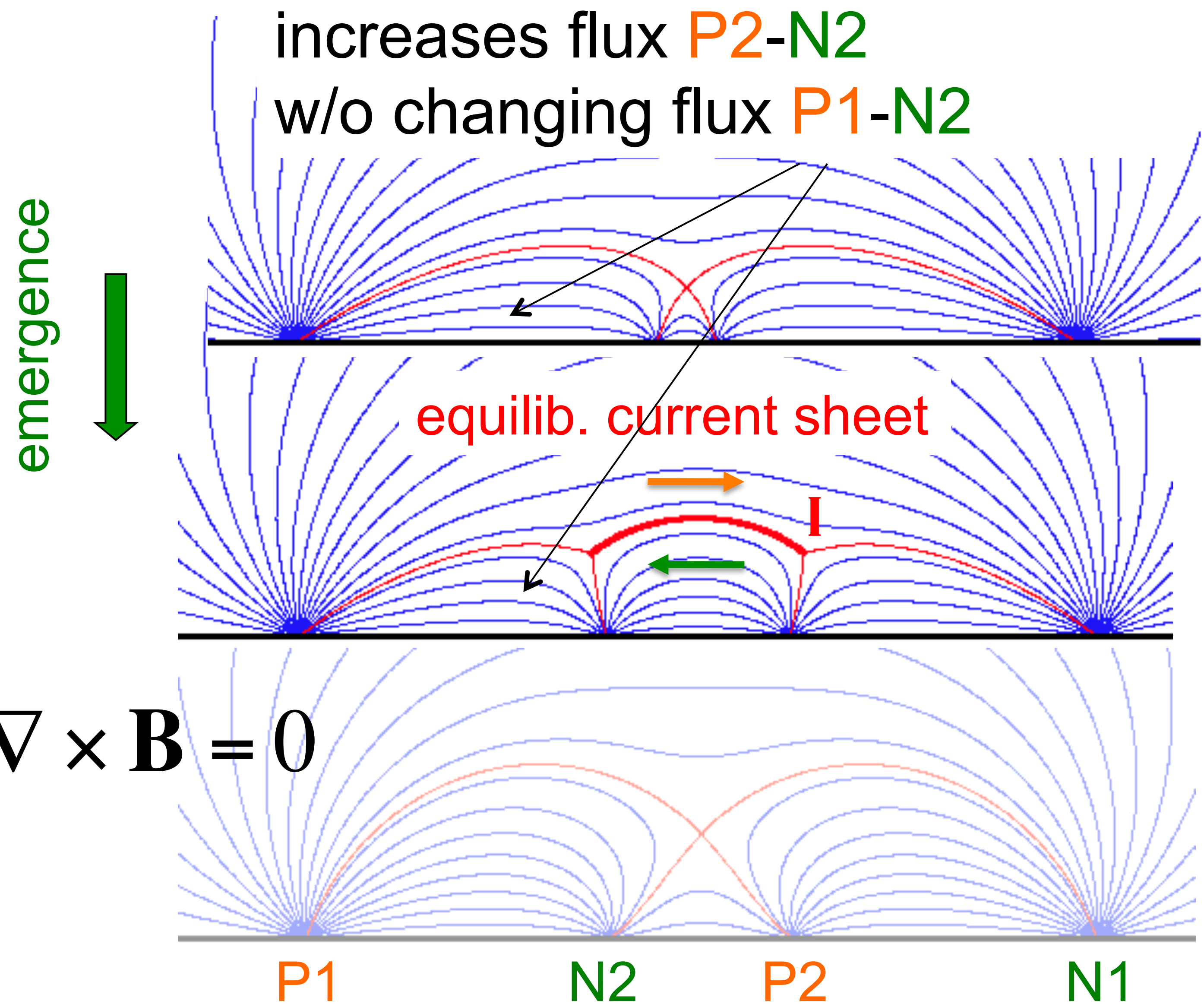


$$W = \int I\, d\Phi \sim \tfrac{1}{2} I_0 \Delta\Phi \sim \frac{(\Delta\Phi)^2}{8\pi L} = \frac{(1.5\times 10^{21})^2}{8\pi\cdot 7.5\times 10^{9}} = 1.2 \times 10^{31}\ \mathrm{erg}$$

Scenario II: Flux Emergence



How does this store energy?

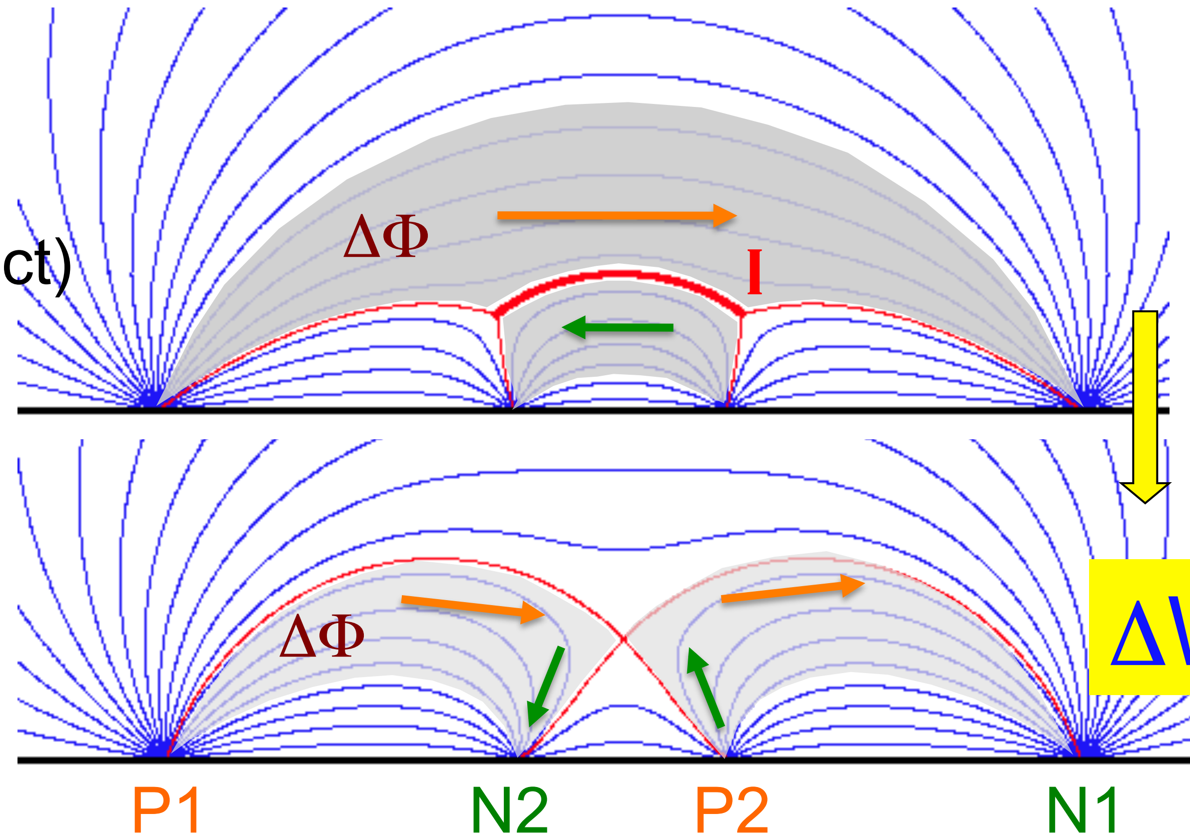


$$\nabla \times \mathbf{B} = 0$$

cf. Heyvarts, Priest & Rust 1977

Energy release: breaking topological constraint on P1-N2 flux: **access** to **lower energy state.**

Transfer (reconnect) flux $\Delta\Phi$ through current sheet I



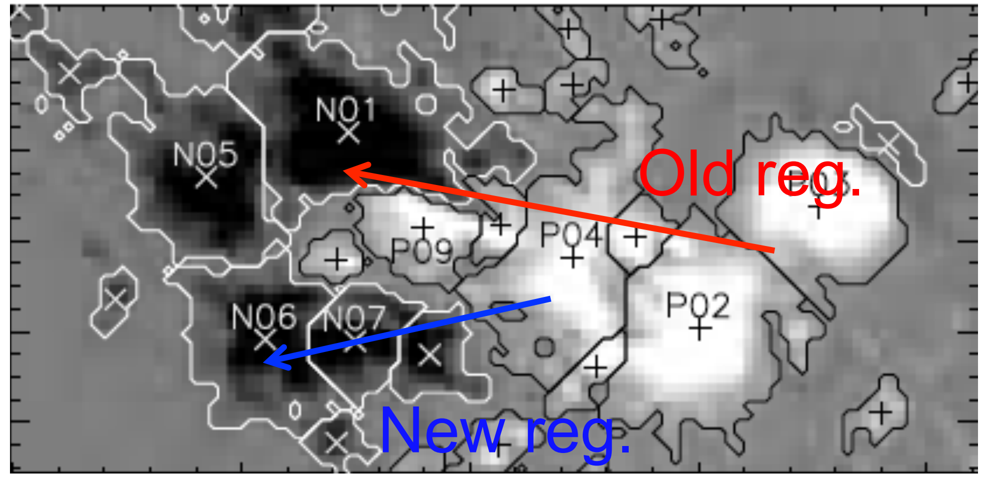
Energy difference

$\Delta W_M \sim I\ \Delta\Phi$

3d version

$$\boxed{\Delta W_M \sim (\Delta\Phi)^2 / 8\pi L \\ \sim 5 \times 10^{31} \text{ ergs}}$$

$I/c \sim \Delta\Phi/L \sim 4 \times 10^{11}$ A



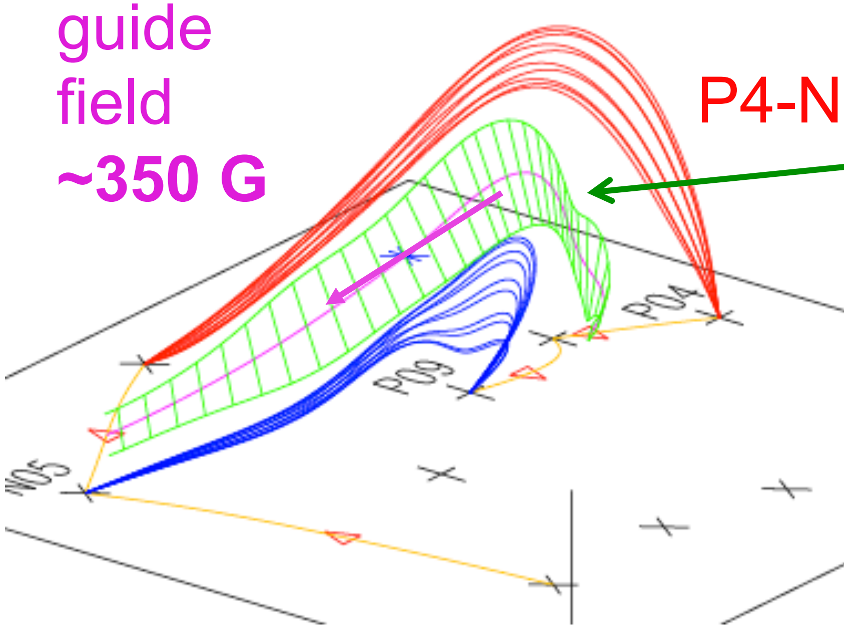
L ~ 50 Mm

$$\boxed{\Delta\Phi \sim 3 \times 10^{21} \text{ Mx}}$$

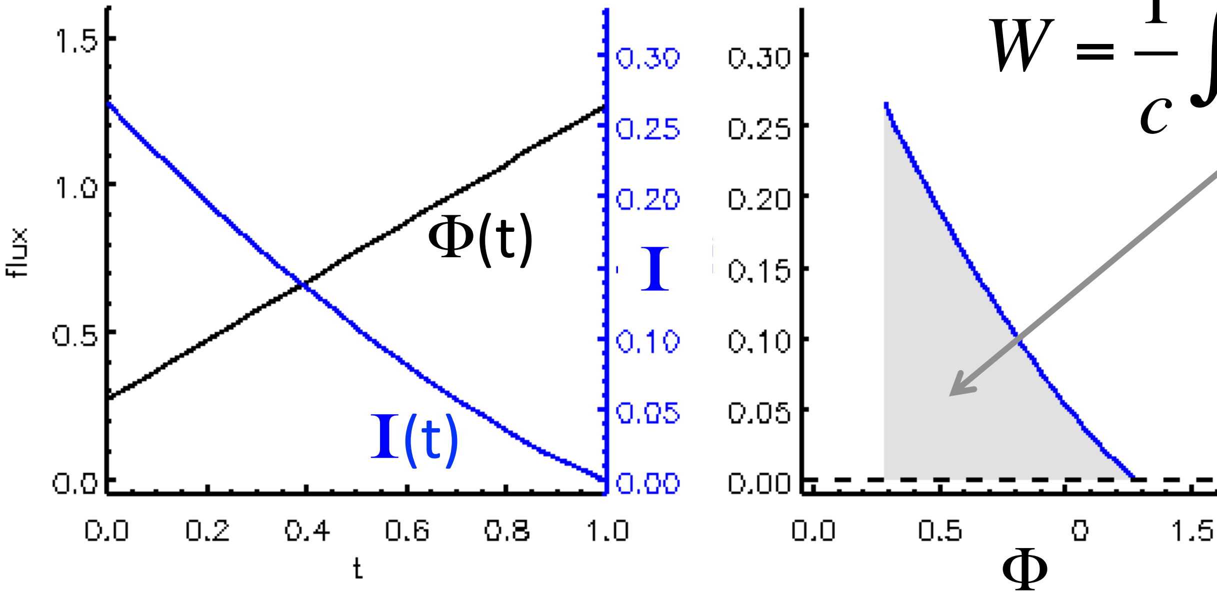
DL, Des Jardins *et al.* 2010

guide field **~350 G**

P4-N1



3d Model: current sheet forms along separator: stores energy



$$W = \frac{1}{c}\int I\, d\Phi$$

W = work done by EM field

as reconnection transfers flux

— NOT (nec.) Joule dissipation —

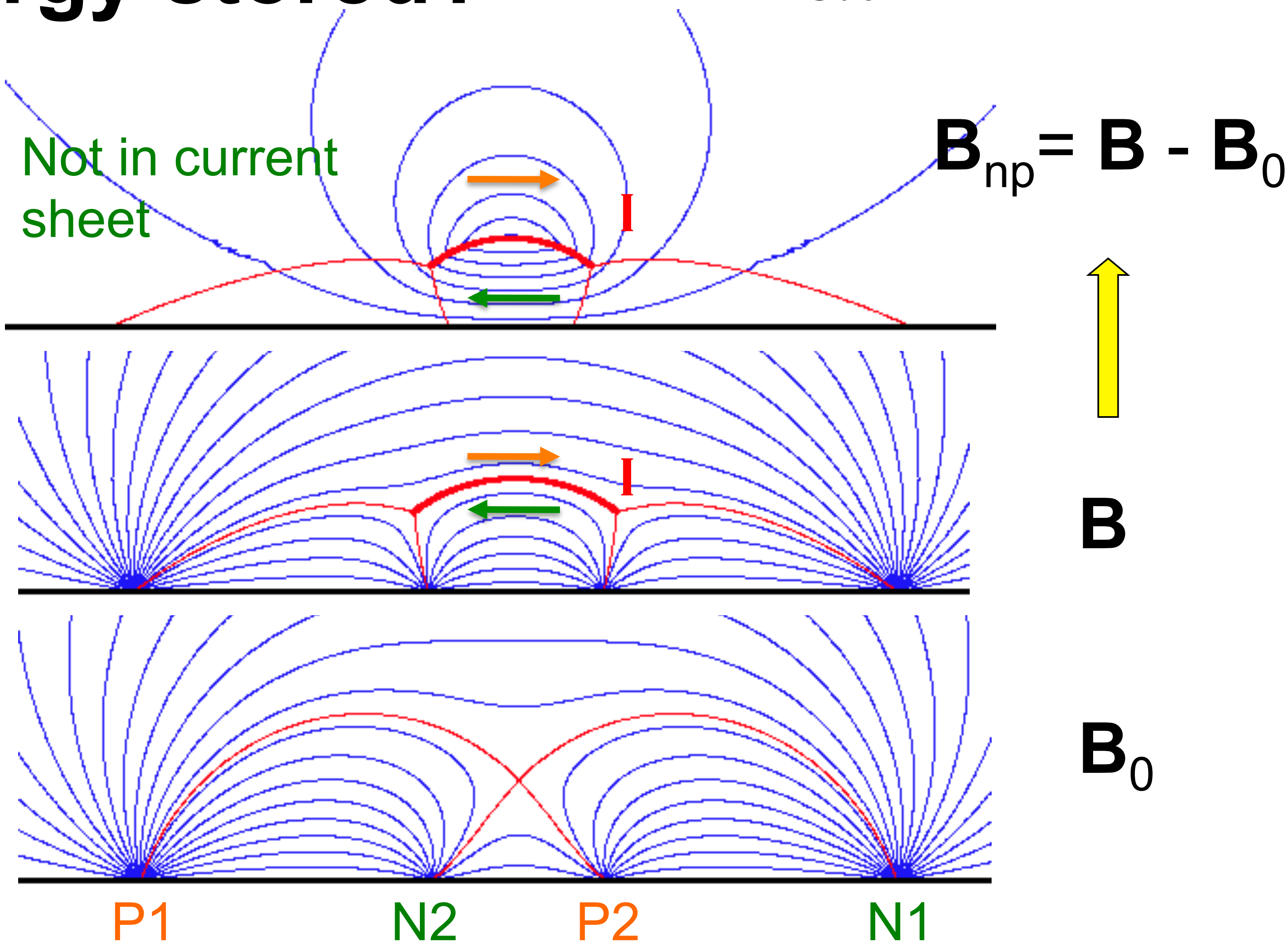
W = magnetic energy lost (released)

Q: Where does energy go?

Q: How is it converted?

Where is the energy stored?

$$\Delta W_M = \frac{1}{8\pi}\int \left|\mathbf{B}-\mathbf{B}_0\right|^2 d^3x$$

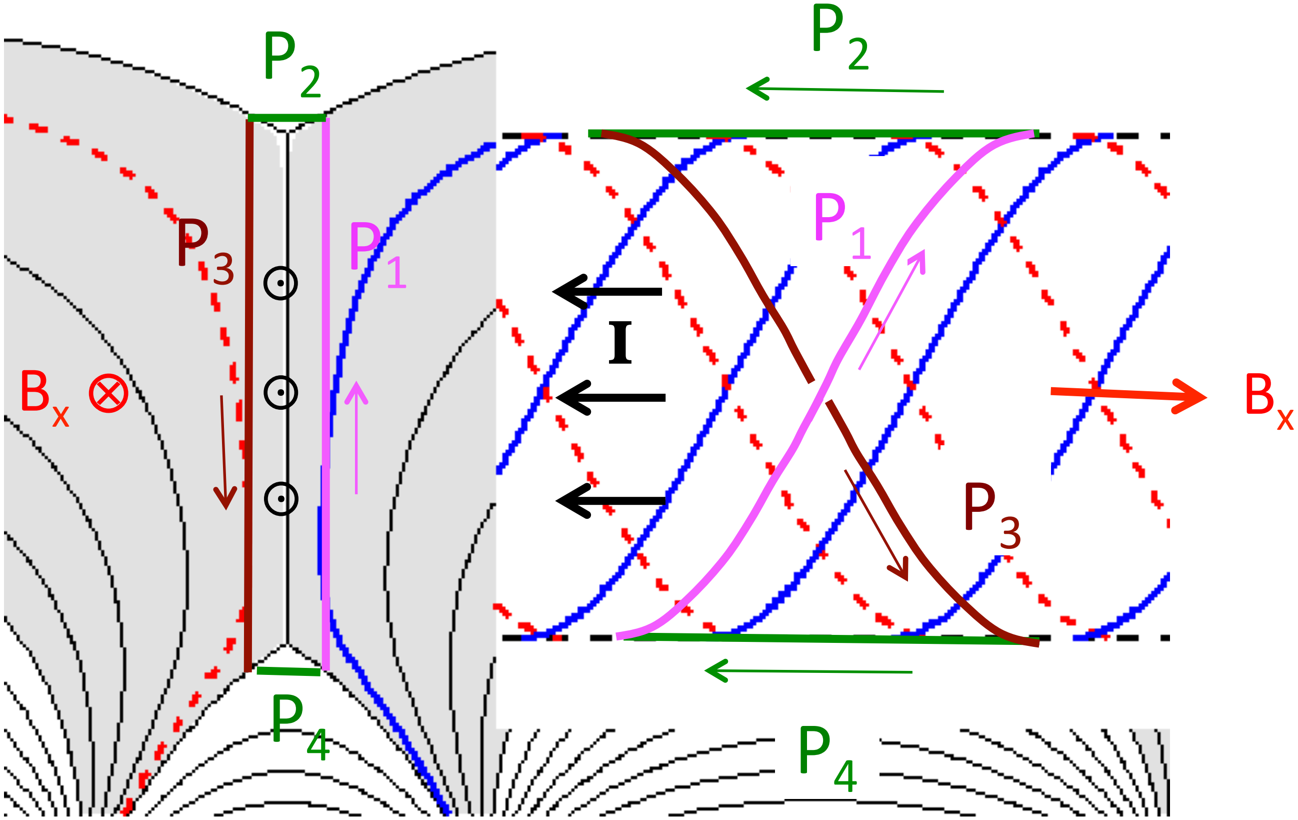


How is it stored/ released

$$W = \int \frac{I}{c}\, d\Phi$$

reconnect element $\delta\Phi$:

$$\delta W = \frac{I}{c}\delta\Phi = \frac{\delta\Phi}{4\pi}\oint \mathbf{B}\cdot d\mathbf{l} = \frac{\delta\Phi}{4\pi}\left(\int_{P_1+P_3} \mathbf{B}\cdot d\mathbf{l} + \int_{P_2+P_4} \mathbf{B}\cdot d\mathbf{l}\right)$$



Guidoni & DWL 2011

break & splice legs 1 & 3

reverse legs 2 & 4

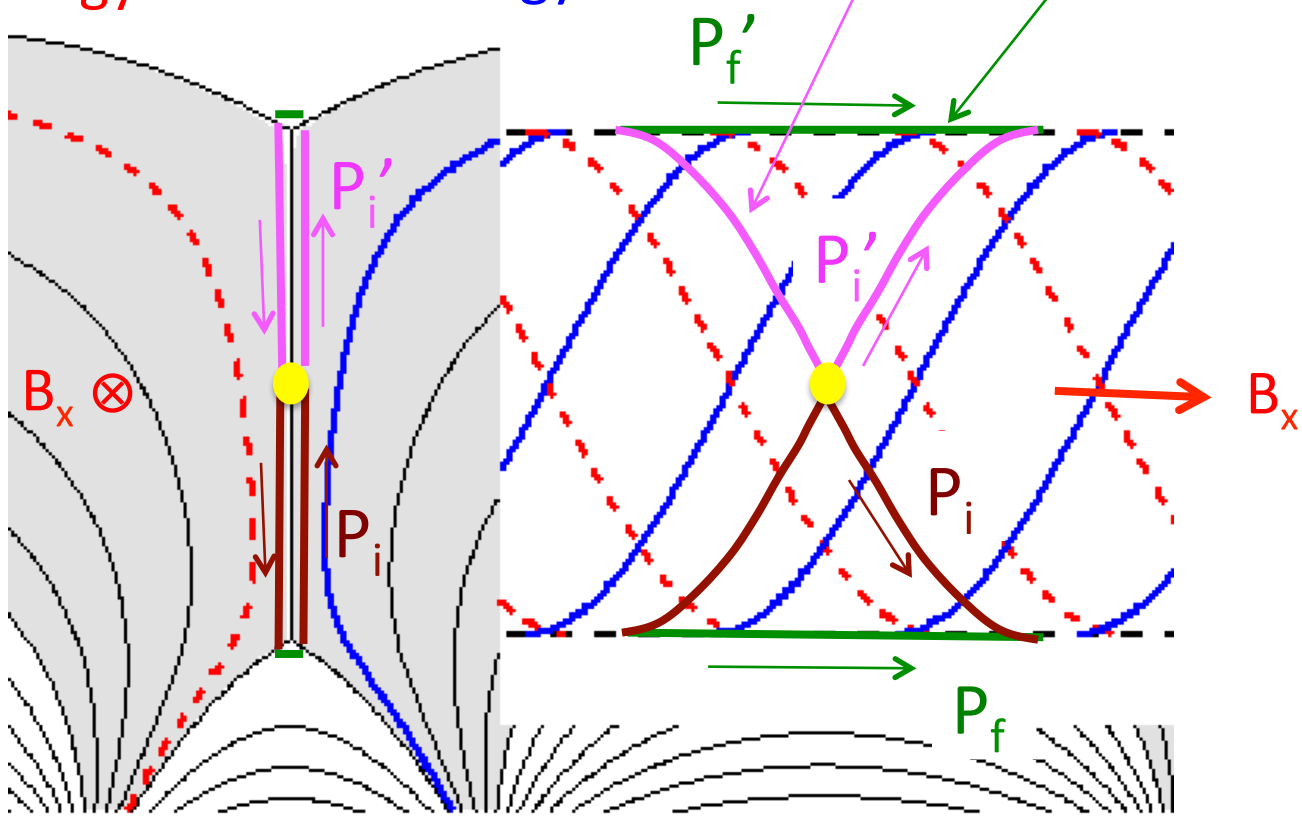
field line after reconnection

field line after retraction

$$\frac{\delta W}{\delta \Phi} = \boxed{\frac{1}{4\pi}\int_{P_i+P_i'} \mathbf{B}\cdot d\mathbf{l}} - \boxed{\frac{1}{4\pi}\int_{P_f+P_f'} \mathbf{B}\cdot d\mathbf{l}}$$

energy before

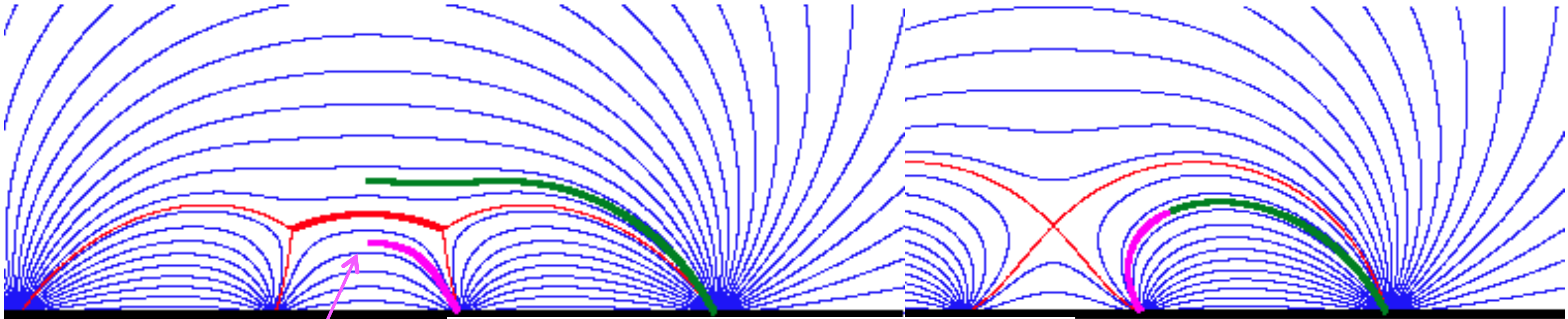
energy after

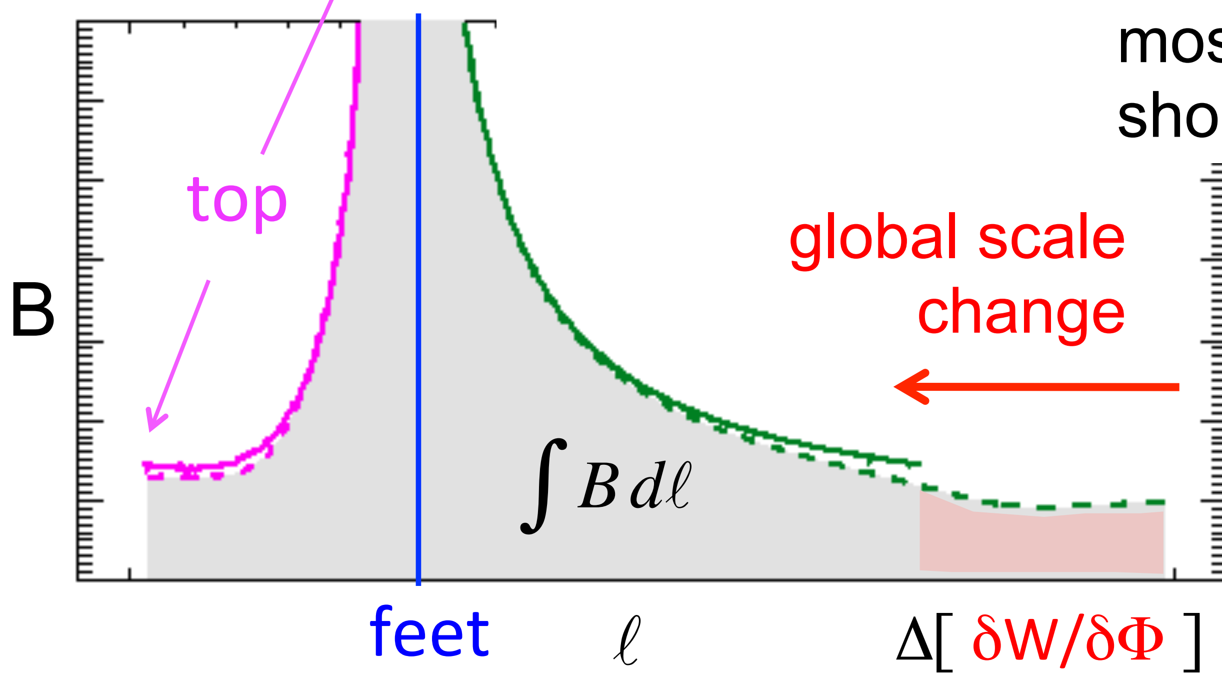


Guidoni & DWL 2011

Energy released per reconnected flux $\delta\Phi$

$$\frac{\delta W}{\delta \Phi} = \Delta\left[\frac{1}{4\pi}\int \mathbf{B}\cdot d\mathbf{l}\right]$$





mostly from shortening field lines

… accompanied by compression

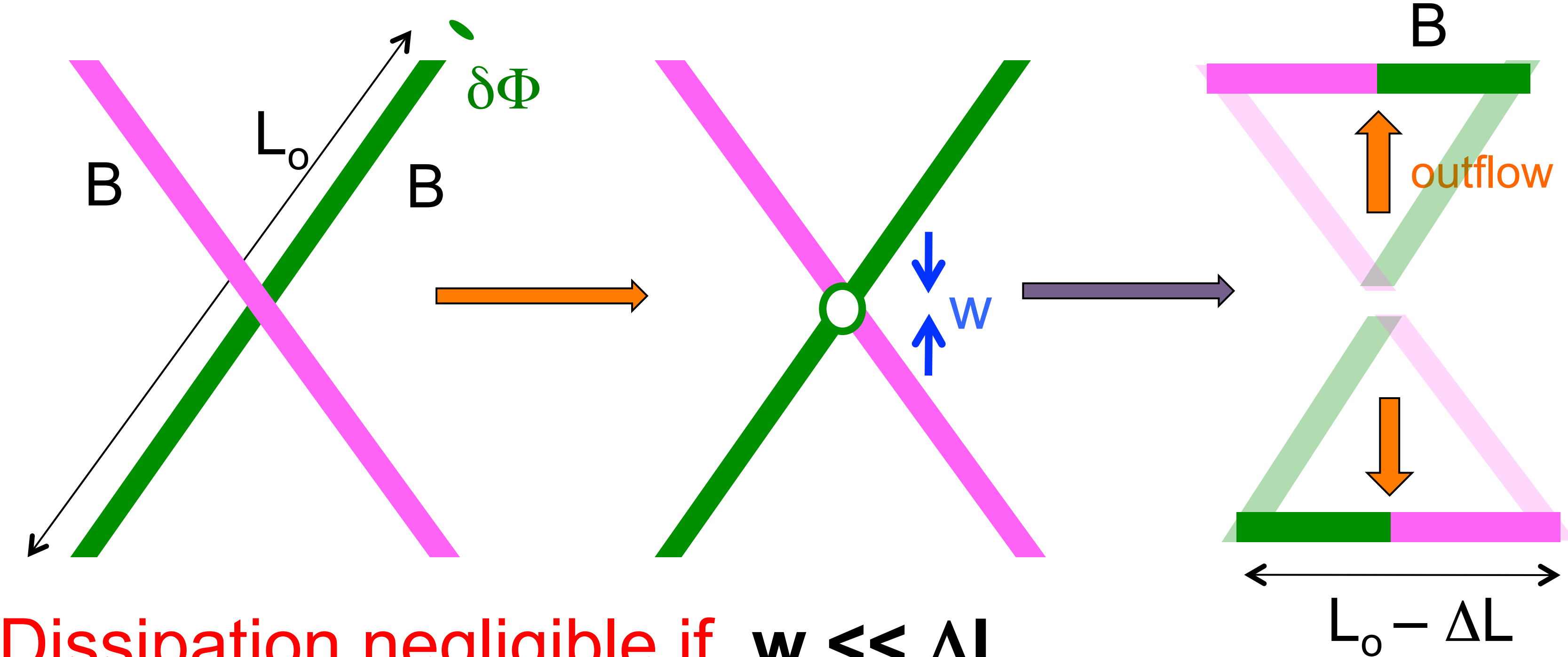
$$\delta V = \delta\Phi \int \frac{d\ell}{B}$$

$$W_M \sim \delta\Phi \int B\, d\ell \qquad \Delta W_M \sim \delta\Phi\, B\, w \qquad \Delta W_M \sim \delta\Phi\, B\, \Delta L$$

Fate of 2 flux bundles

topology change
Dissipation – accompanied by **E**

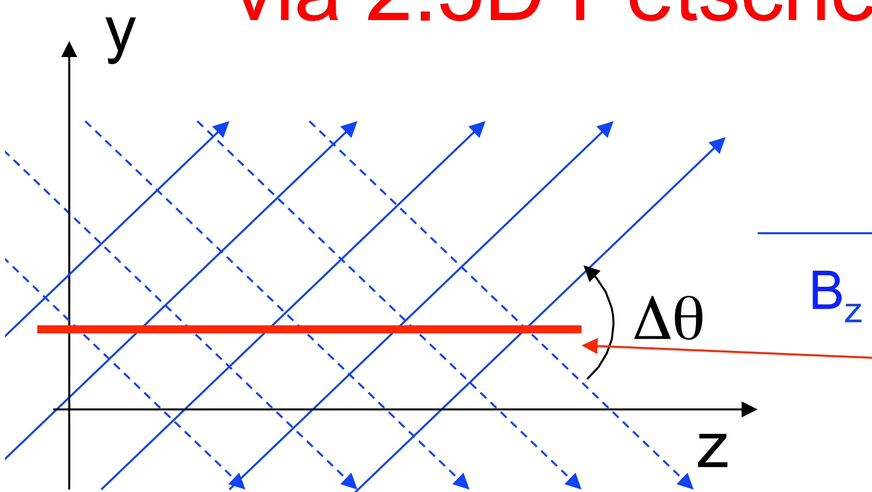
geometry change
Retraction – no need for **E – IDEAL**



- Dissipation negligible if **w << ΔL**
- Energy **release**: **ideal** & on global scale

Energy conversion
via 2.5D Petschek

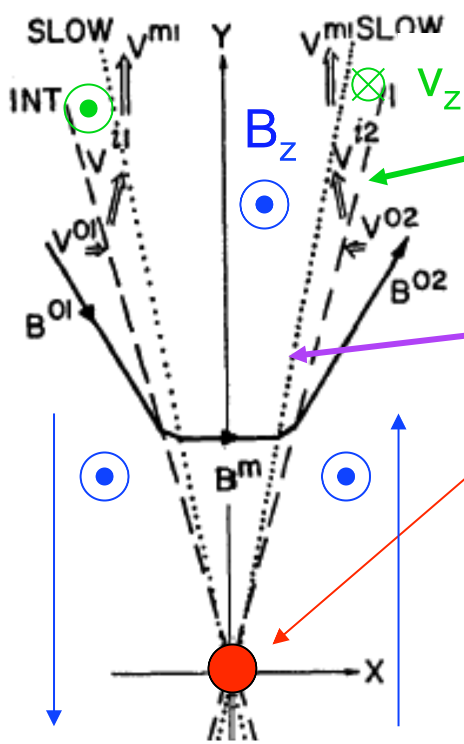
Petschek & Thorne 1967
Soward 1982
Skender *et al.* 2003



- CS between field @ Δθ
  (include "guide field" B_z)
- steady model
- Recon'n @ **X-point*** on CS
  (localized E_z imposed)

➔ **2 shocks** (co-planarity):

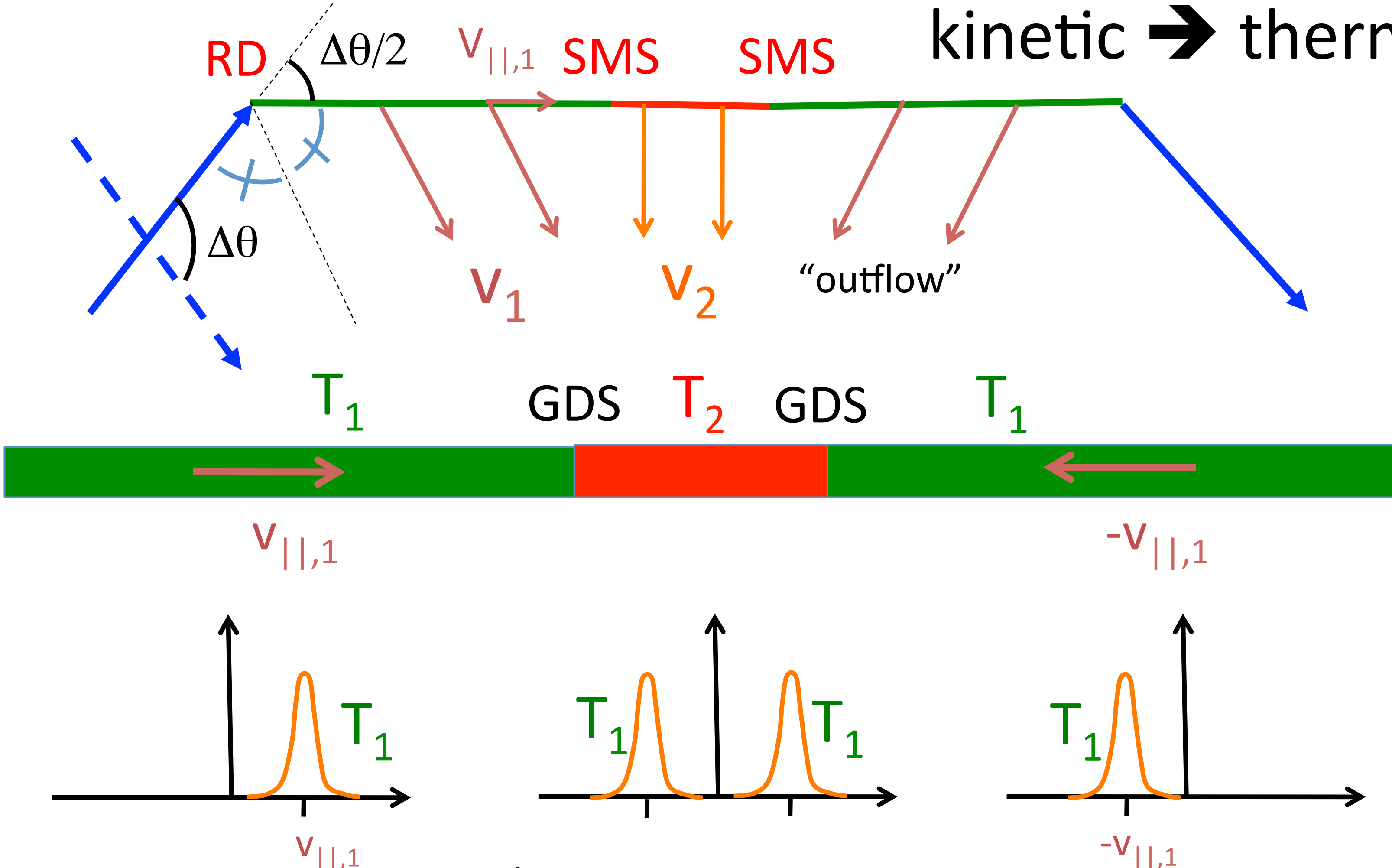
- **Rotational disont. (RD)**
  - |**B**| unchanged
  - ↑ KE in bulk flow & v_z
- **Slow Shock (SMS)**
  - |**B**| reduced slightly
  - v_z ➔ 0 (∴ KE ↓)
  - ↑ thermal energy



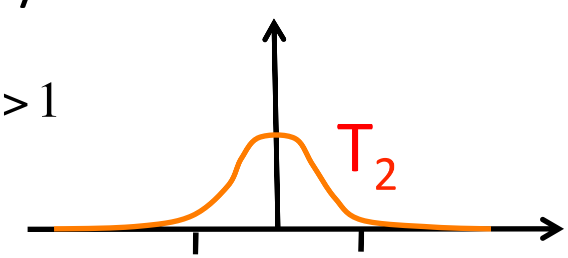
Petschek & Thorne 1967

* line ⊥ to 2d plane

kinetic ➔ thermal



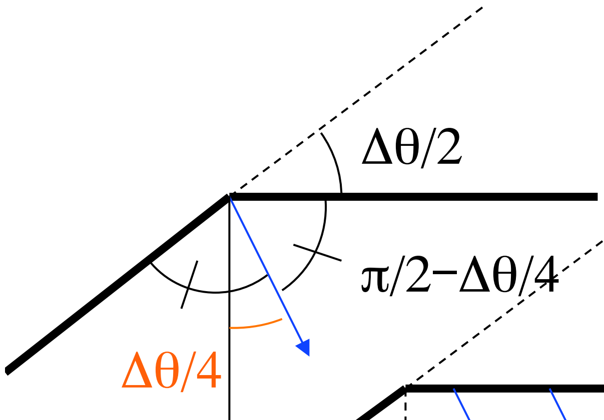
w/ collisions – i.e. shocks



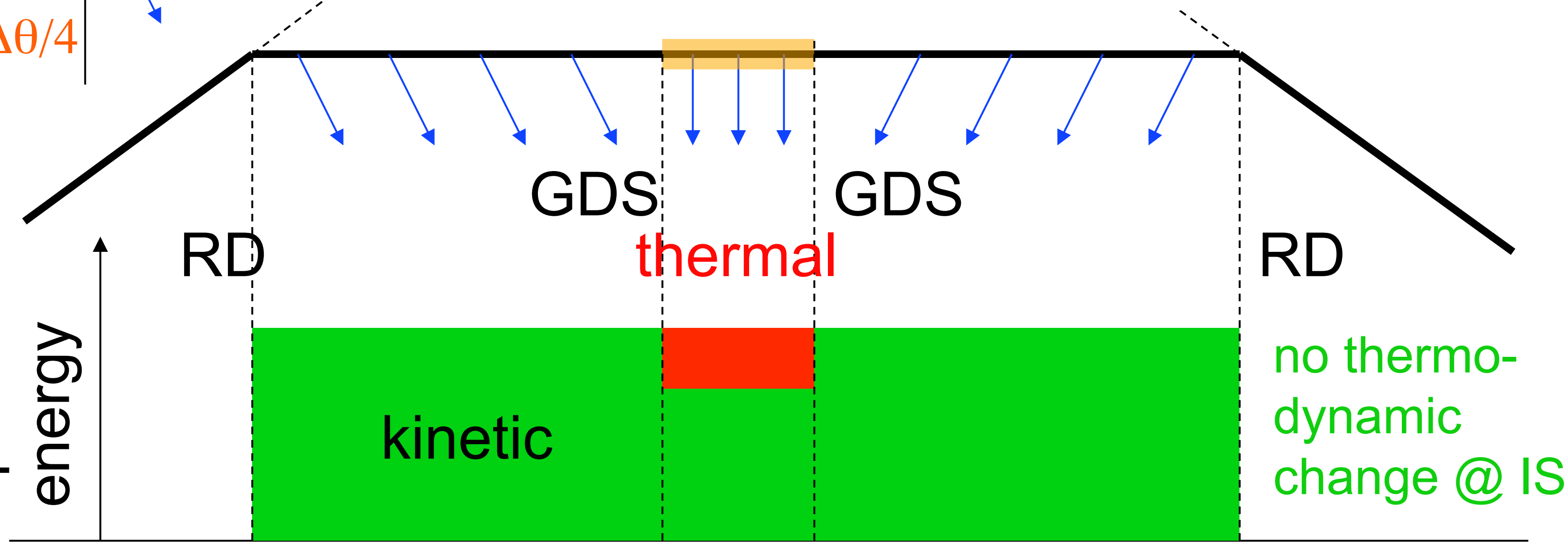
$$\frac{v_{\|,1}}{v_{th,i}} \sim \beta_0^{-1/2} \sin^2(\Delta\theta/4) >> 1$$

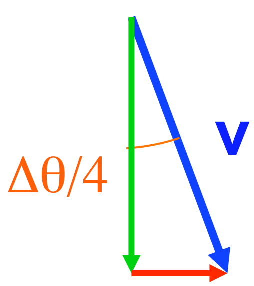
(DWL, Guidoni & Linton 2009)

Energetics



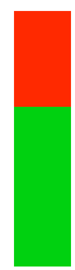
Q: what is the ratio, thermal to kinetic energy?





... post-shock region:
ratio of heights

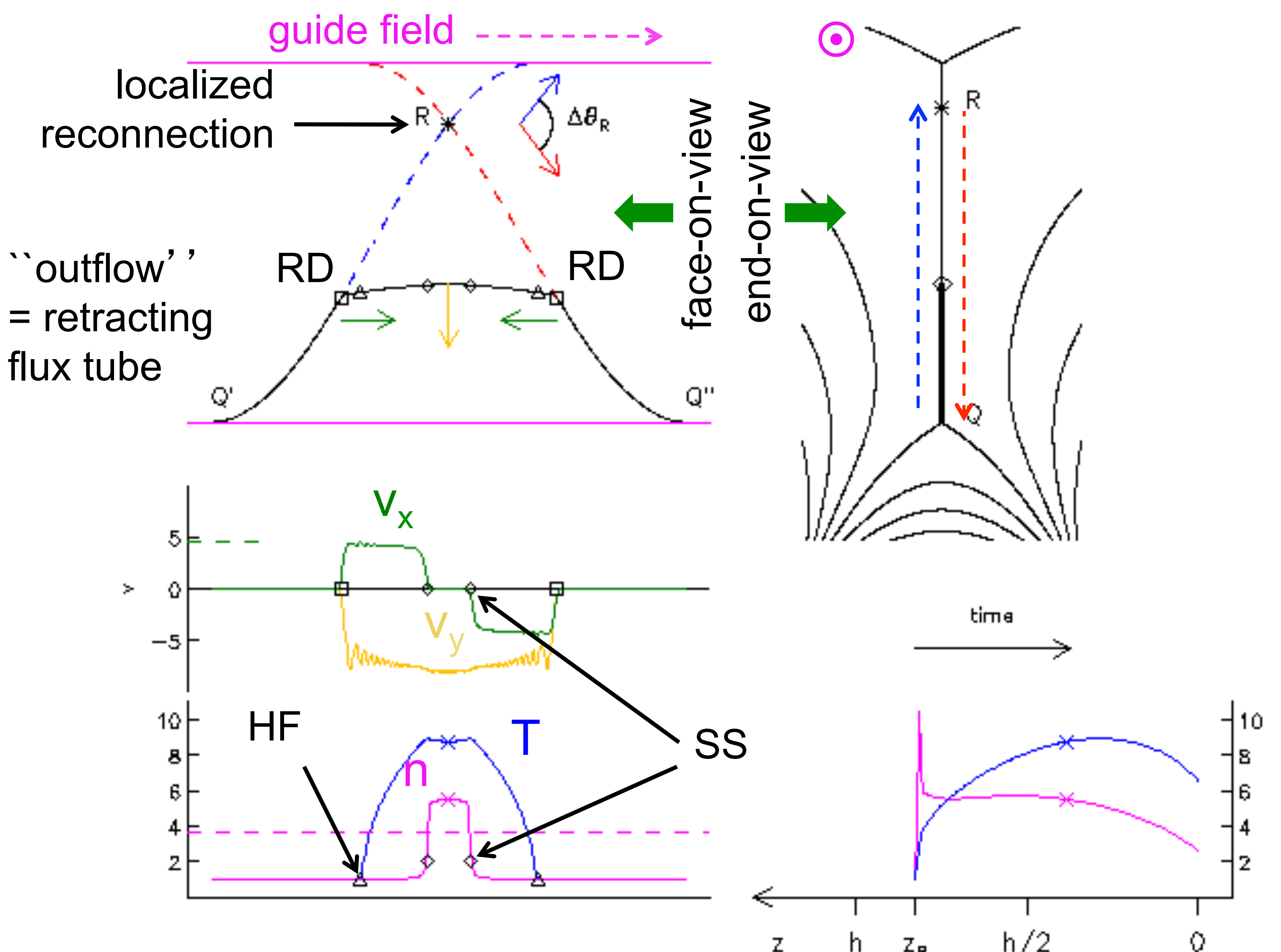
$$\sim \tan^2\left(\frac{\Delta\theta}{4}\right)$$



... all released energy:
ratio of areas

$$\boxed{\sim \beta^{1/2}\tan^2\left(\frac{\Delta\theta}{4}\right)}$$

Dynamics following flare reconnection



Guidoni & DL 2010, 2011

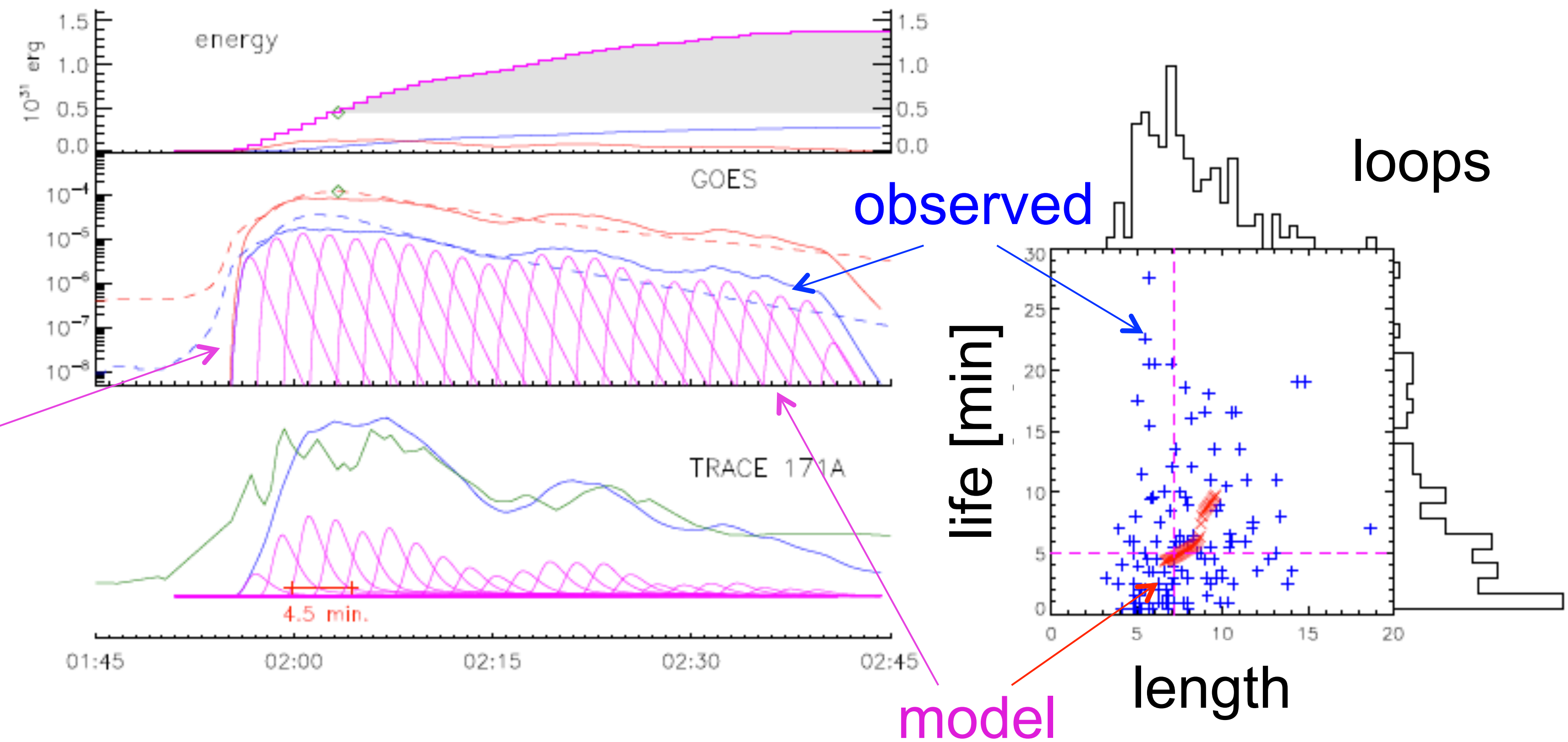
Reconnection rate: distinguish

local rate = E (w/in 1 patch – fast)

mean rate (patch creation rate – not so fast)

energy released over ~ 45 min.~ $10^4\ \tau_A$

1 loop (from 1 patch) lasts 2 - 10 min.



The Big Picture

- Magnetic energy is stored **BY** current sheet – but not **AT** current sheet (CS)
- Released by magnetic reconnection – changes topology of field lines across CS
- Release occurs during retraction of field lines **after** topological change (reconnection)
- Energy decreases primarily due to shortening of field lines through retraction
- Shortening accompanied by plasma compression (shocks?)