Physical constraints on energy release and heating in solar flares

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Thanks:

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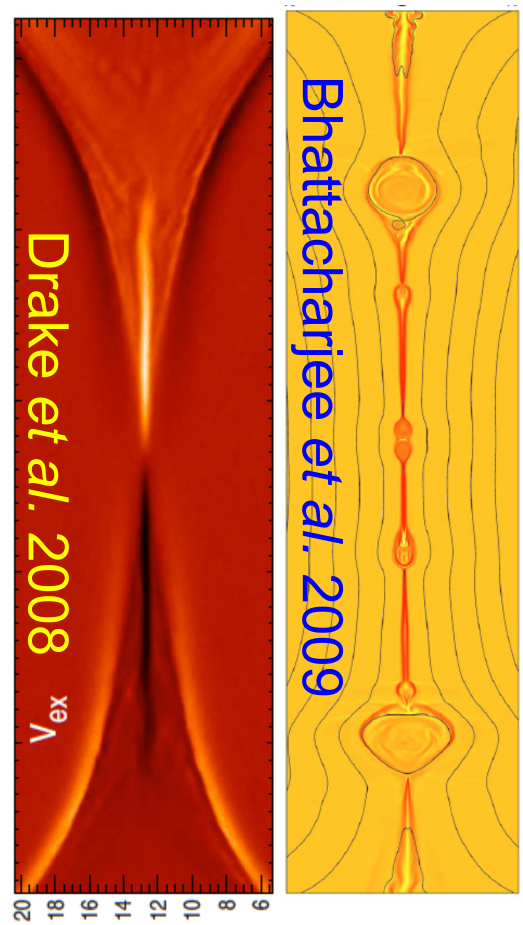
NASA/HSR & NASA/HGI

Resolved: Fast magnetic reconnection occurs on small spatial scales w/in a current sheet

Q: Where is the magnetic energy stored prior to release?

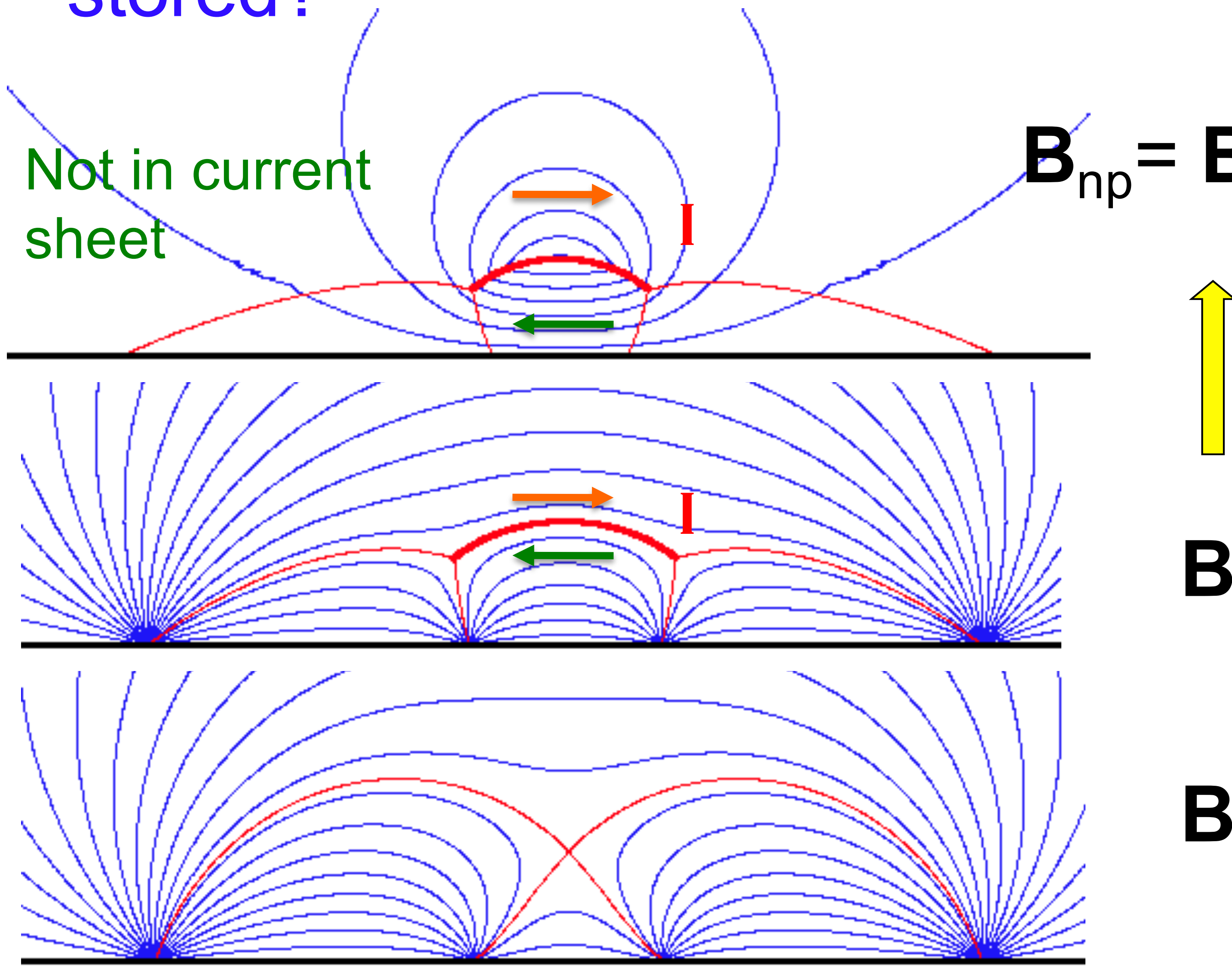
Q: How does reconnection release/convert magnetic energy?

Q: How is plasma density enhanced as much as we observe?



Where is the energy stored?

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



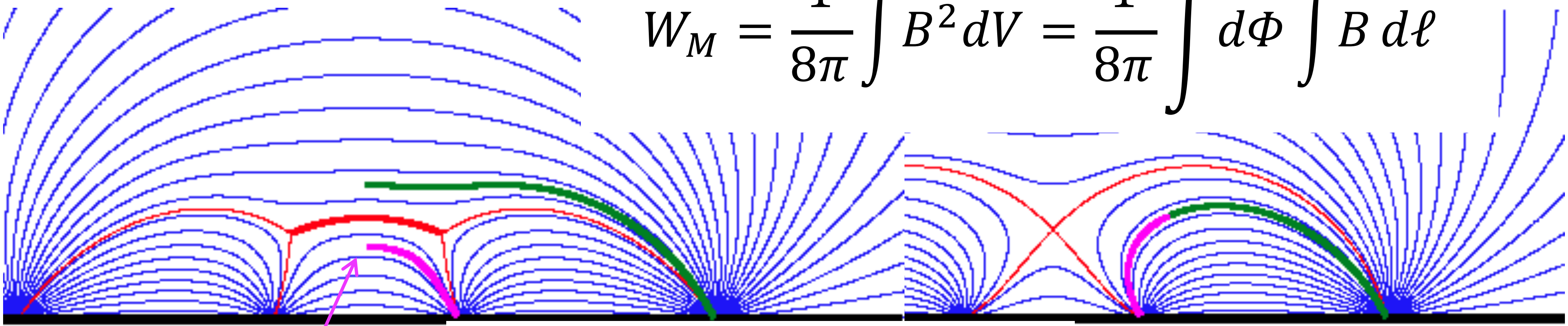
$\mathbf{B}_{np} = \mathbf{B} - \mathbf{B}_0$

B

$\mathbf{B}_0$

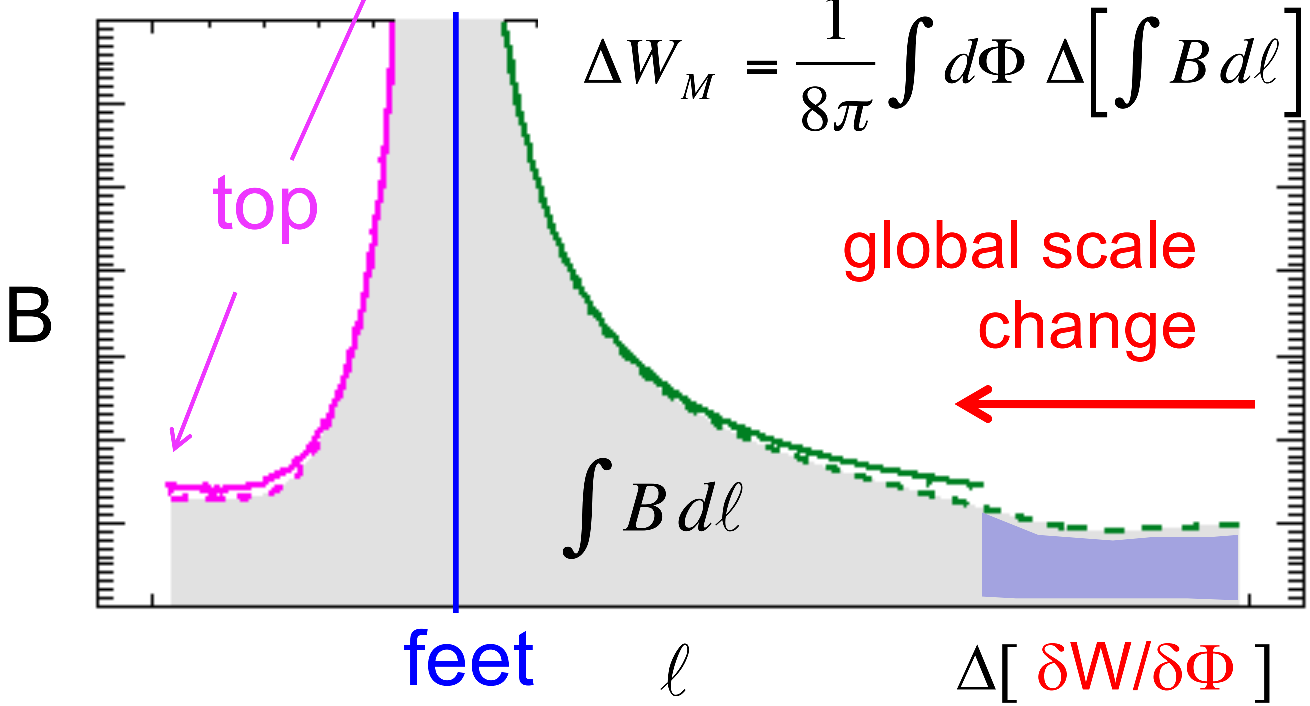
One (idiosyncratic) interpretation:
Energy stored as **Excess Length** of field lines

$$W_M = \frac{1}{8\pi}\int B^2 dV = \frac{1}{8\pi}\int d\Phi \int B\, d\ell$$



$$\Delta W_M = \frac{1}{8\pi}\int d\Phi\, \Delta\left[\int B\, d\ell\right]$$

mostly from shortening field lines



… accompanied by compression

$$\Delta V = \int d\Phi\, \Delta\left[\int \frac{d\ell}{B}\right] < 0$$

How reconnection (i.e. topological change) **enables*** field line shortening (a.k.a. energy release)

$$W_M = \frac{1}{8\pi}\int d\Phi \int B\, d\ell \qquad \Delta W_M \sim \delta\Phi\, B\, w \qquad \Delta W_M \sim \delta\Phi\, B\, \Delta L$$

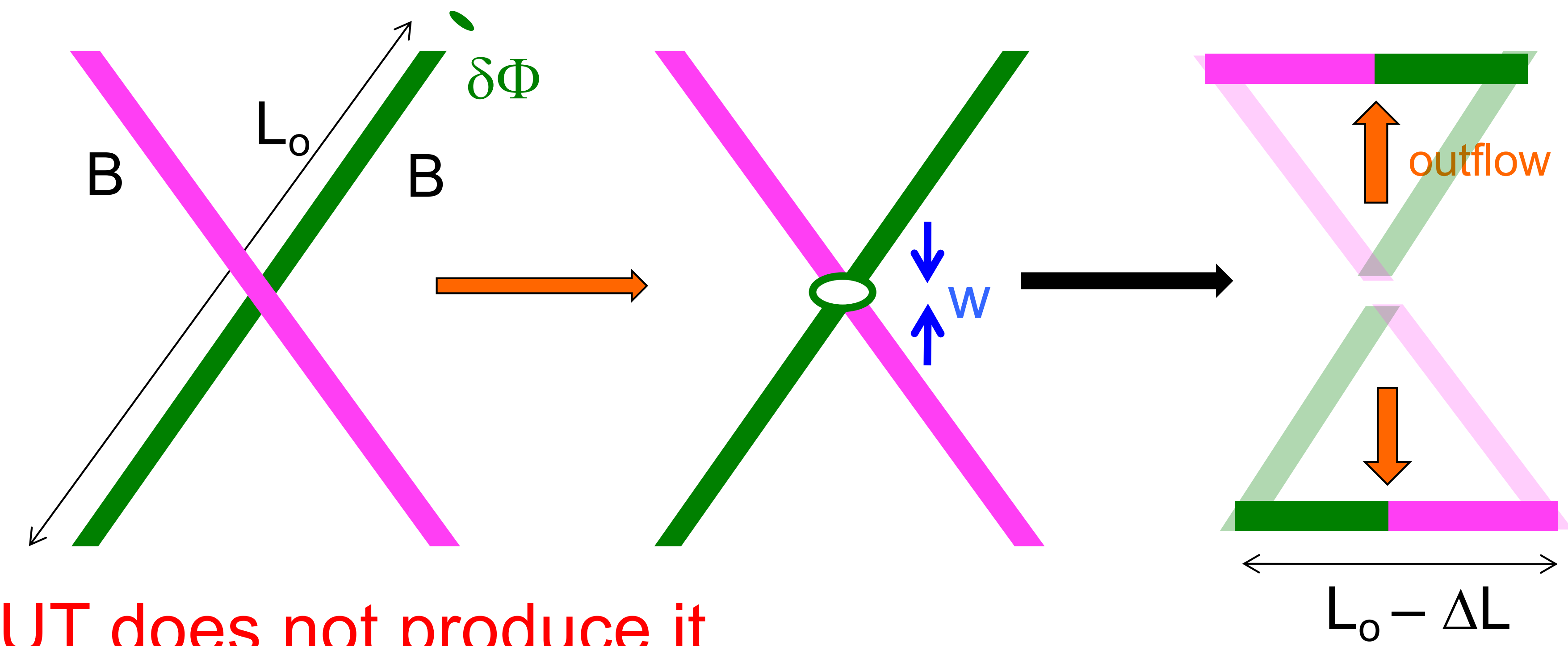
Fate of 2 flux bundles

topology change

Dissipation – accompanied by **E**

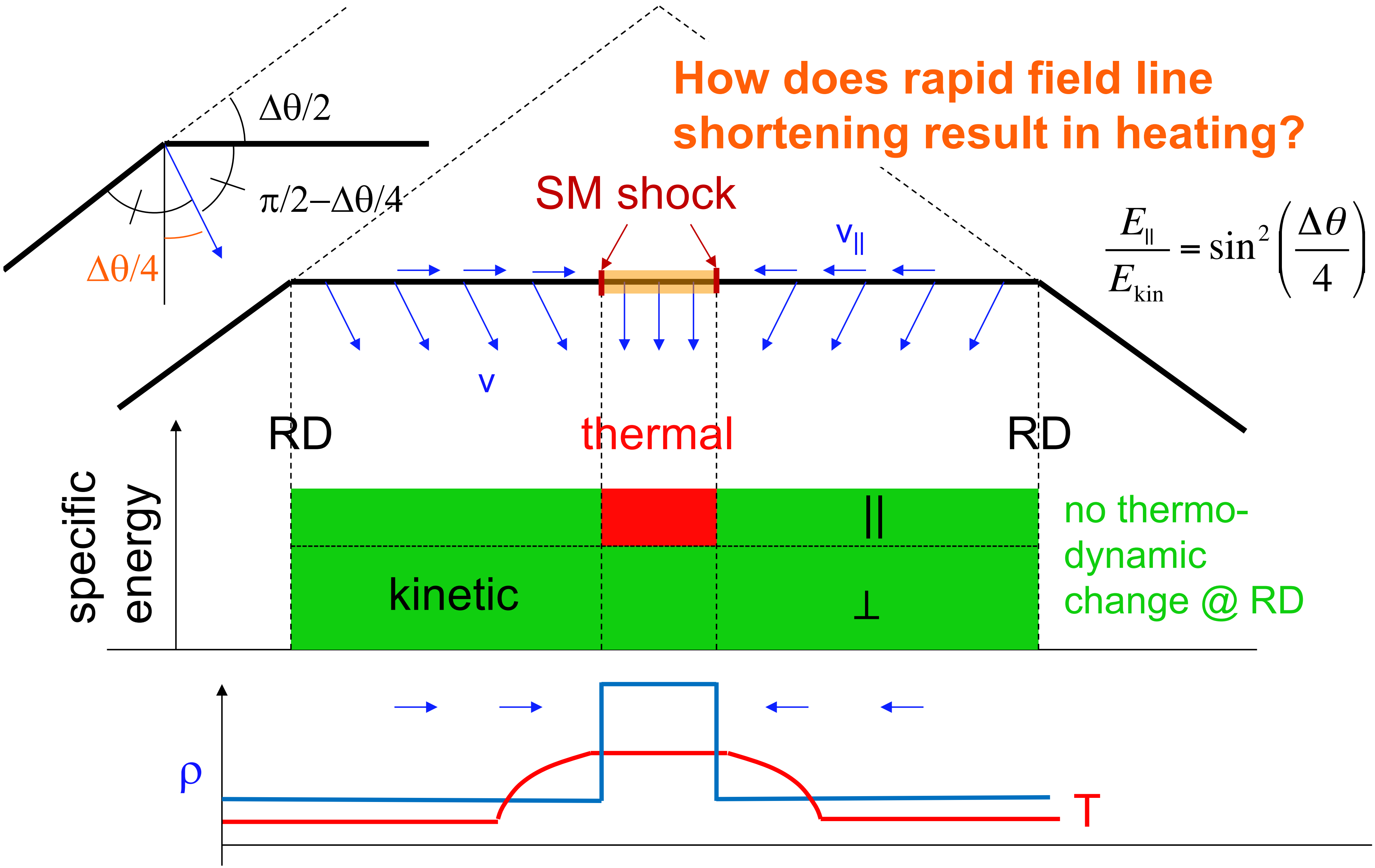
geometry change

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



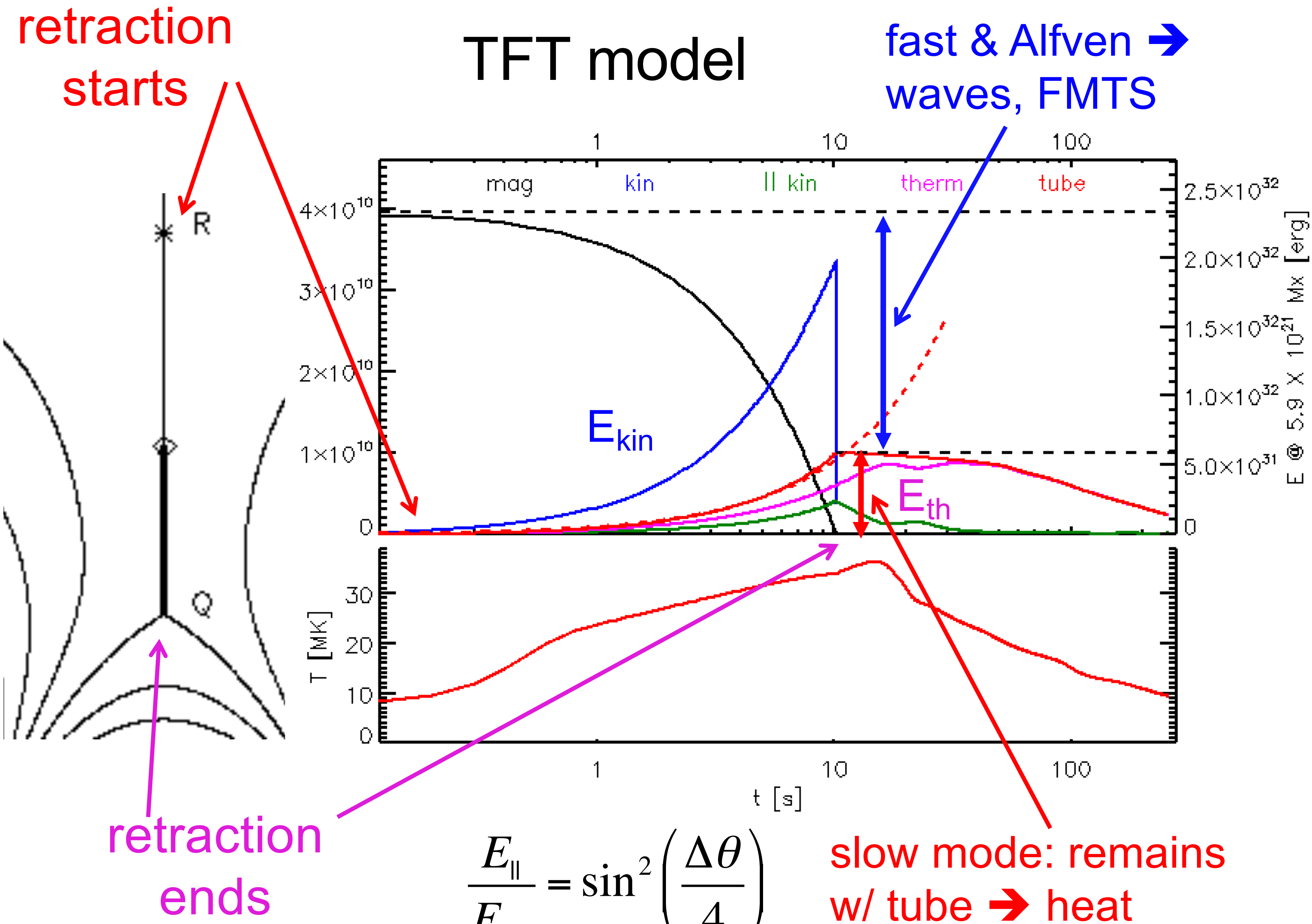
* BUT does not produce it

How does rapid field line shortening result in heating?



A: thermalization @ shocks

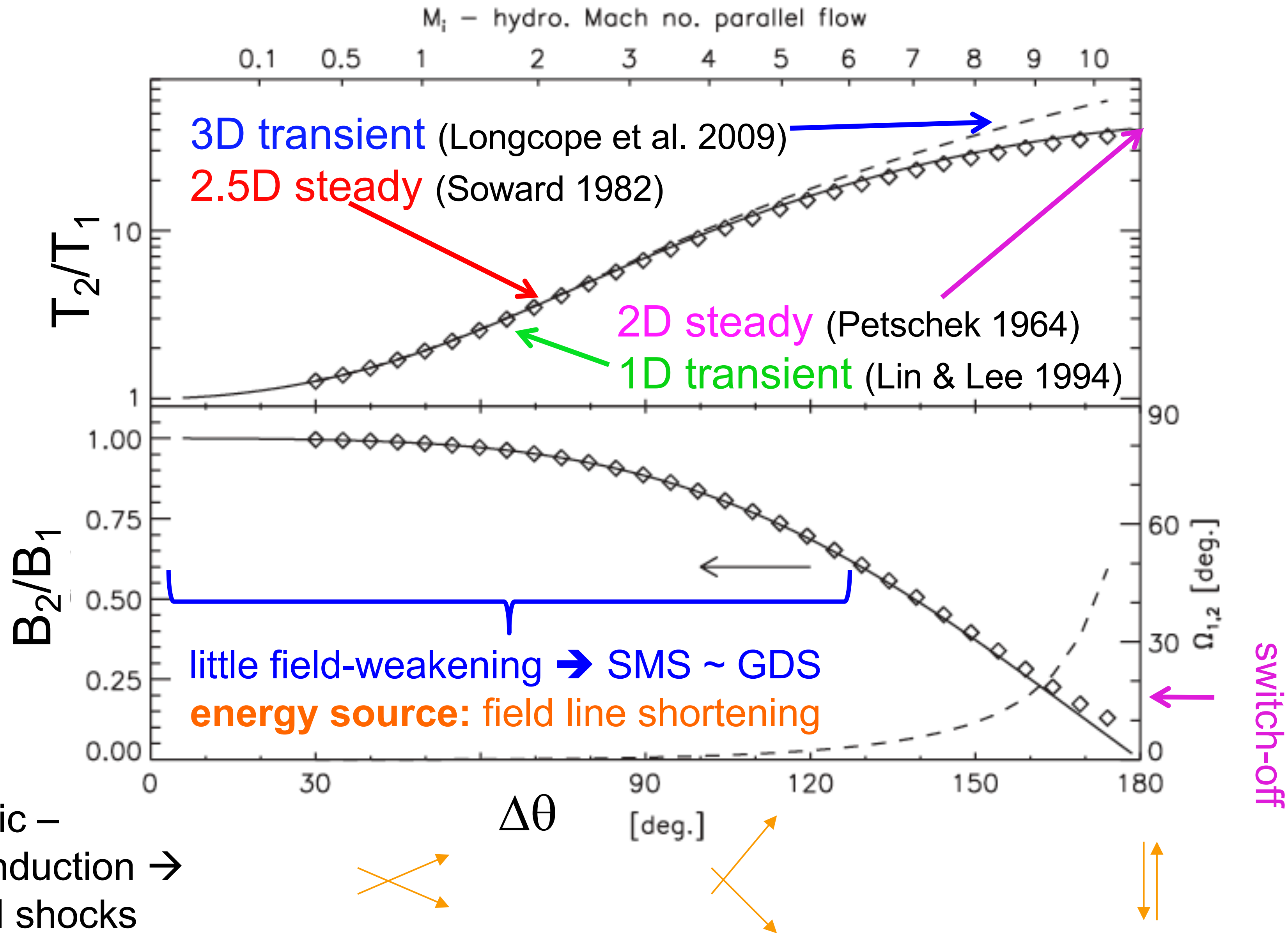
TFT model



$$\frac{E_{\parallel}}{E_{\mathrm{rel}}} = \sin^2\left(\frac{\Delta\theta}{4}\right)$$

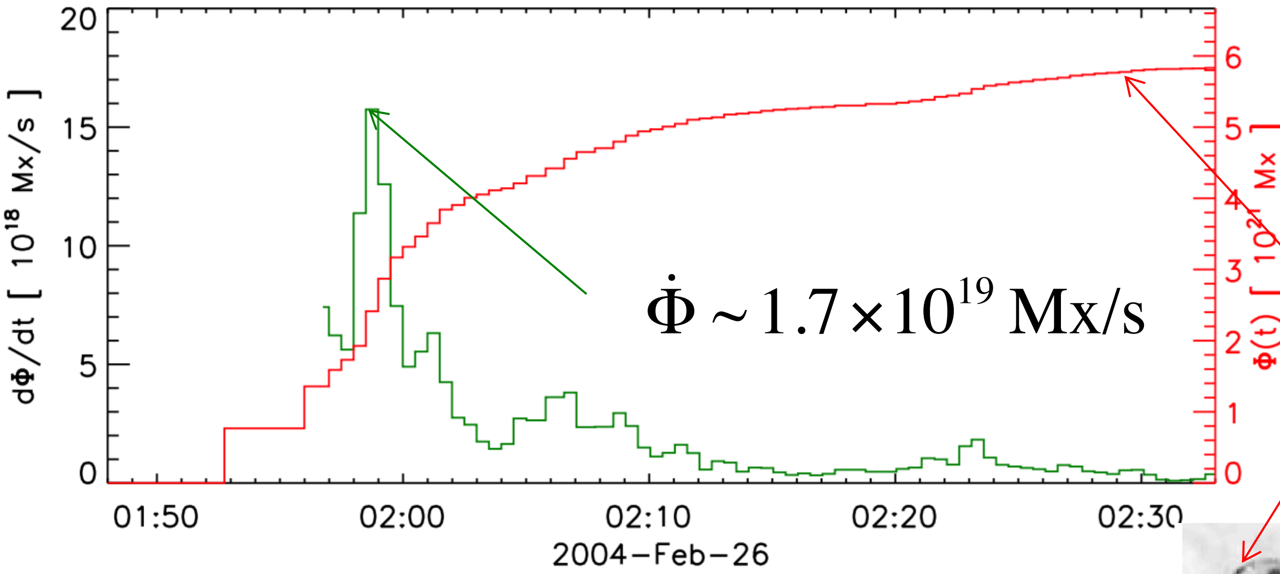
Devil's Advocate: ``This doesn't seem like Petschek reconnection''

Dana: It captures same heating as 2.5D Petschek…
compare using Rankin-Hugoniot relations*



* unrealistic – therm. conduction → isothermal shocks

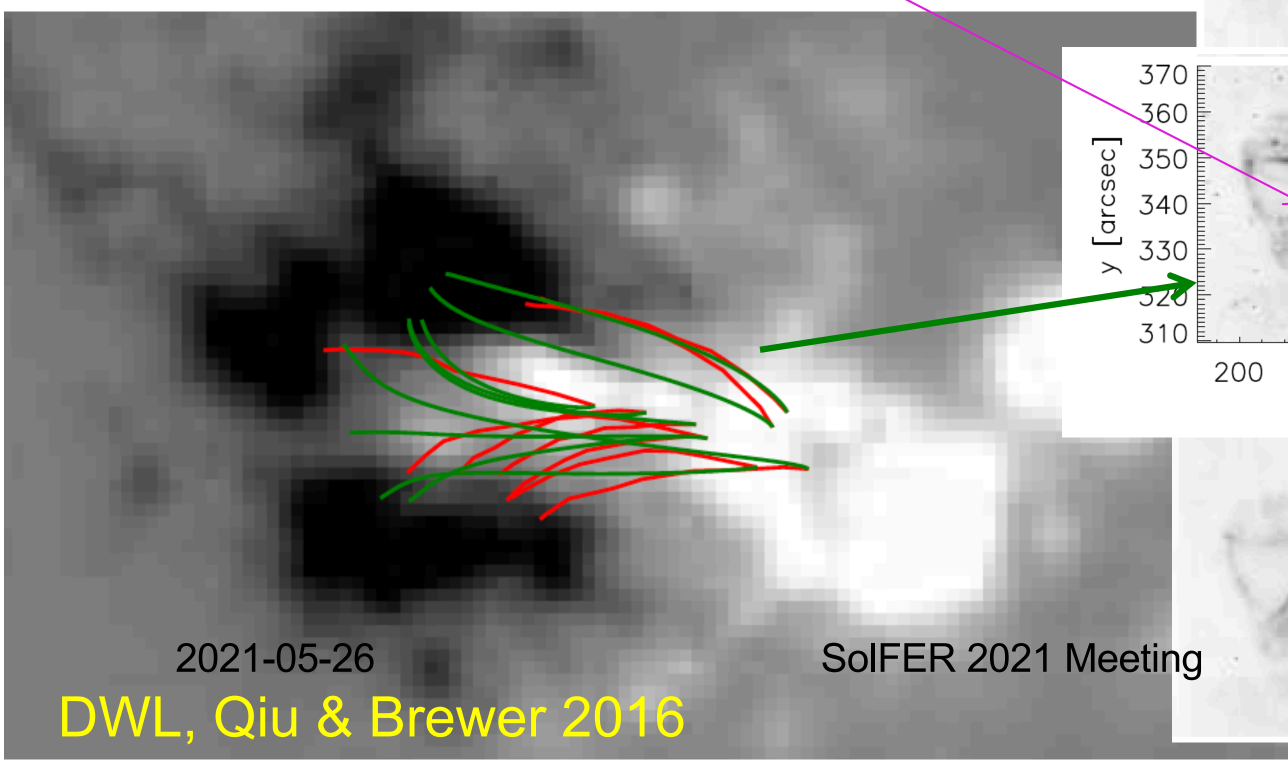
Example I: 2004-Feb-26

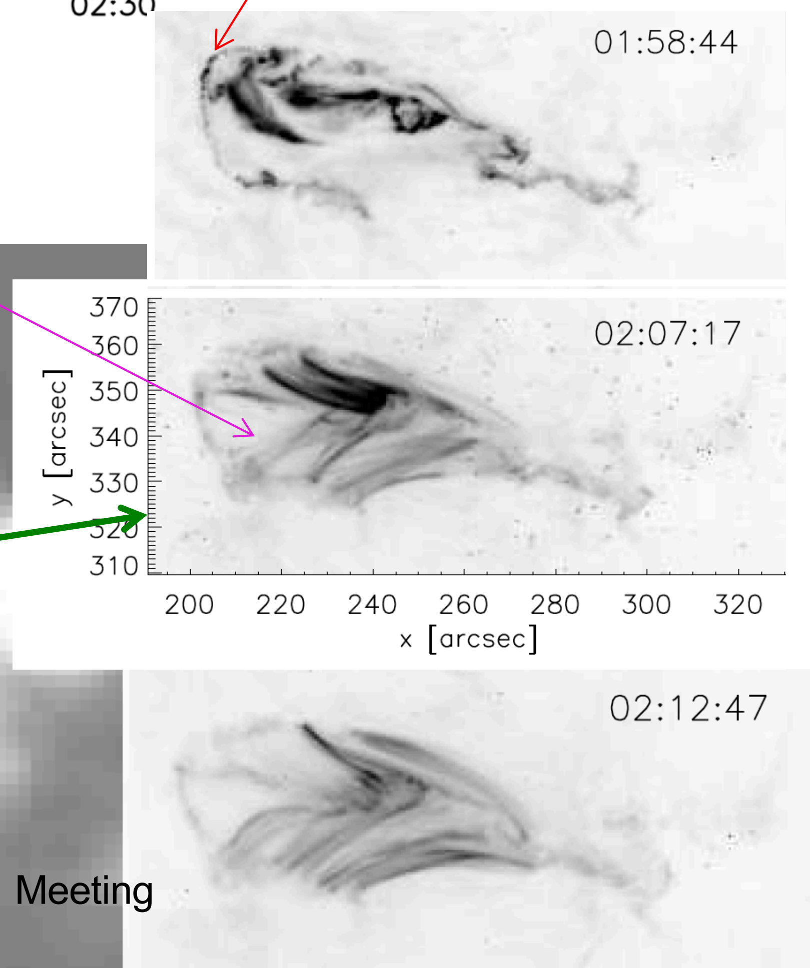


Ribbons – sweep flux

$\Delta\Phi \sim 6 \times 10^{21}$ Mx

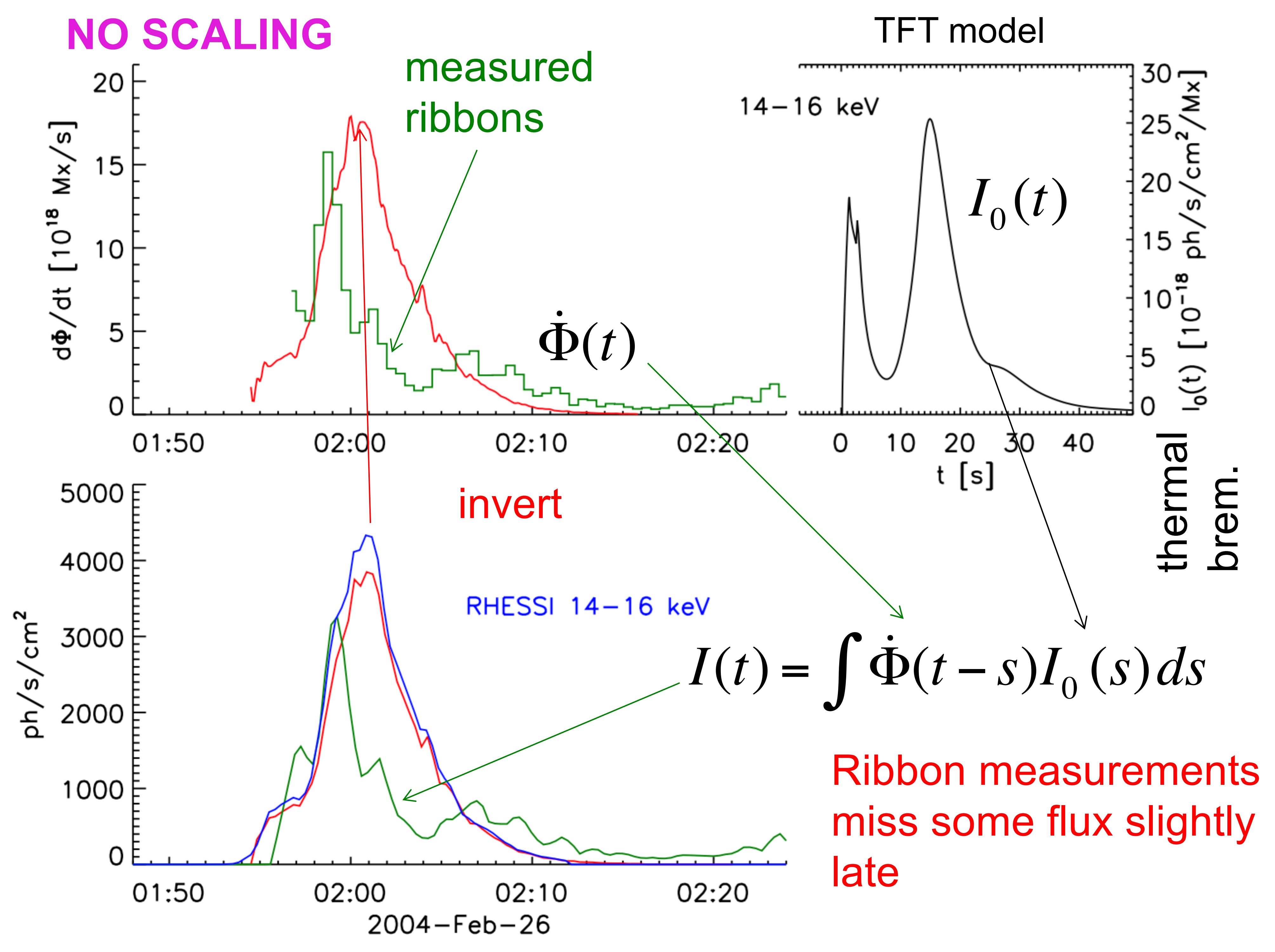
140 Loops: $\delta\Phi = 10^{19}$ Mx



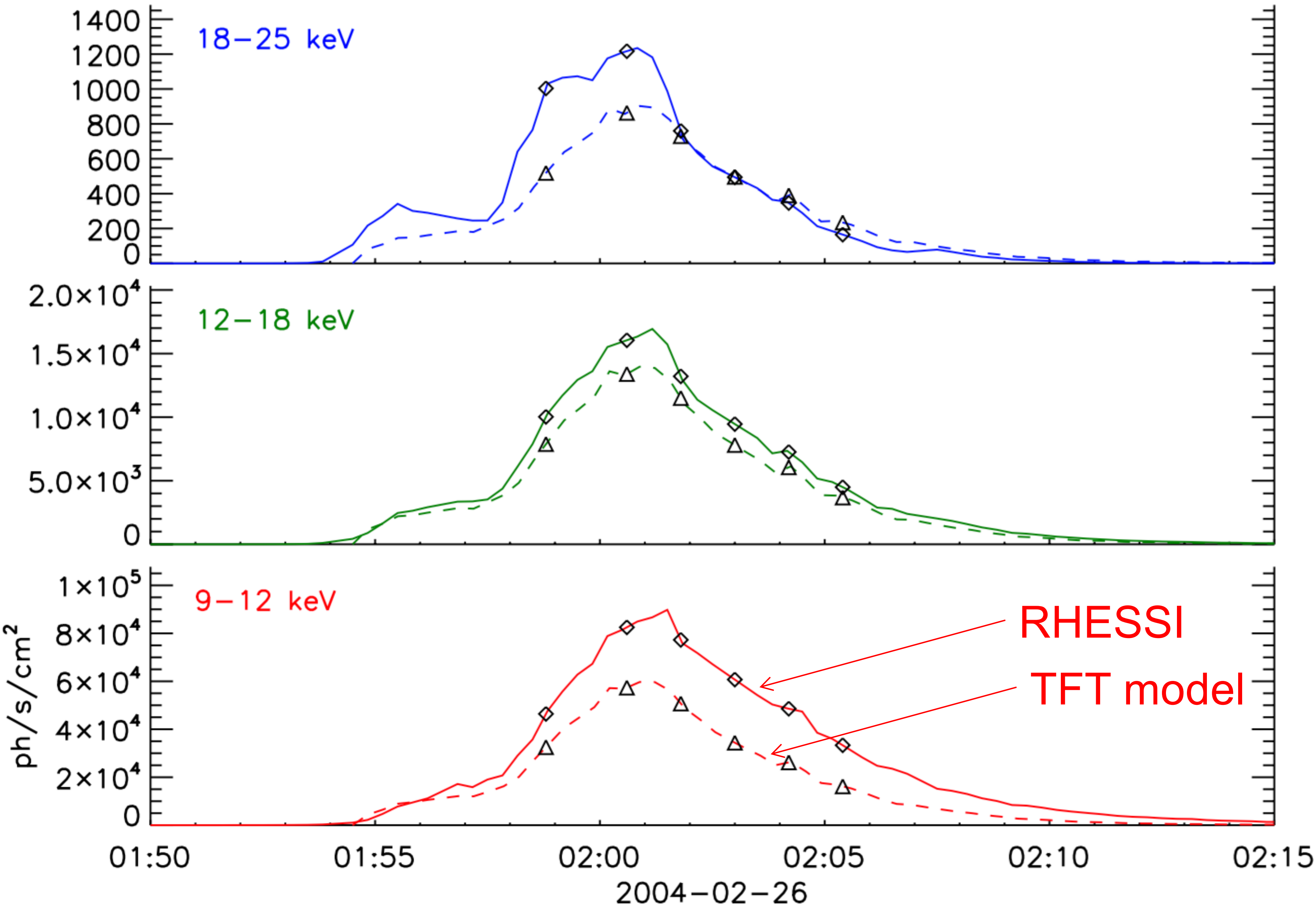


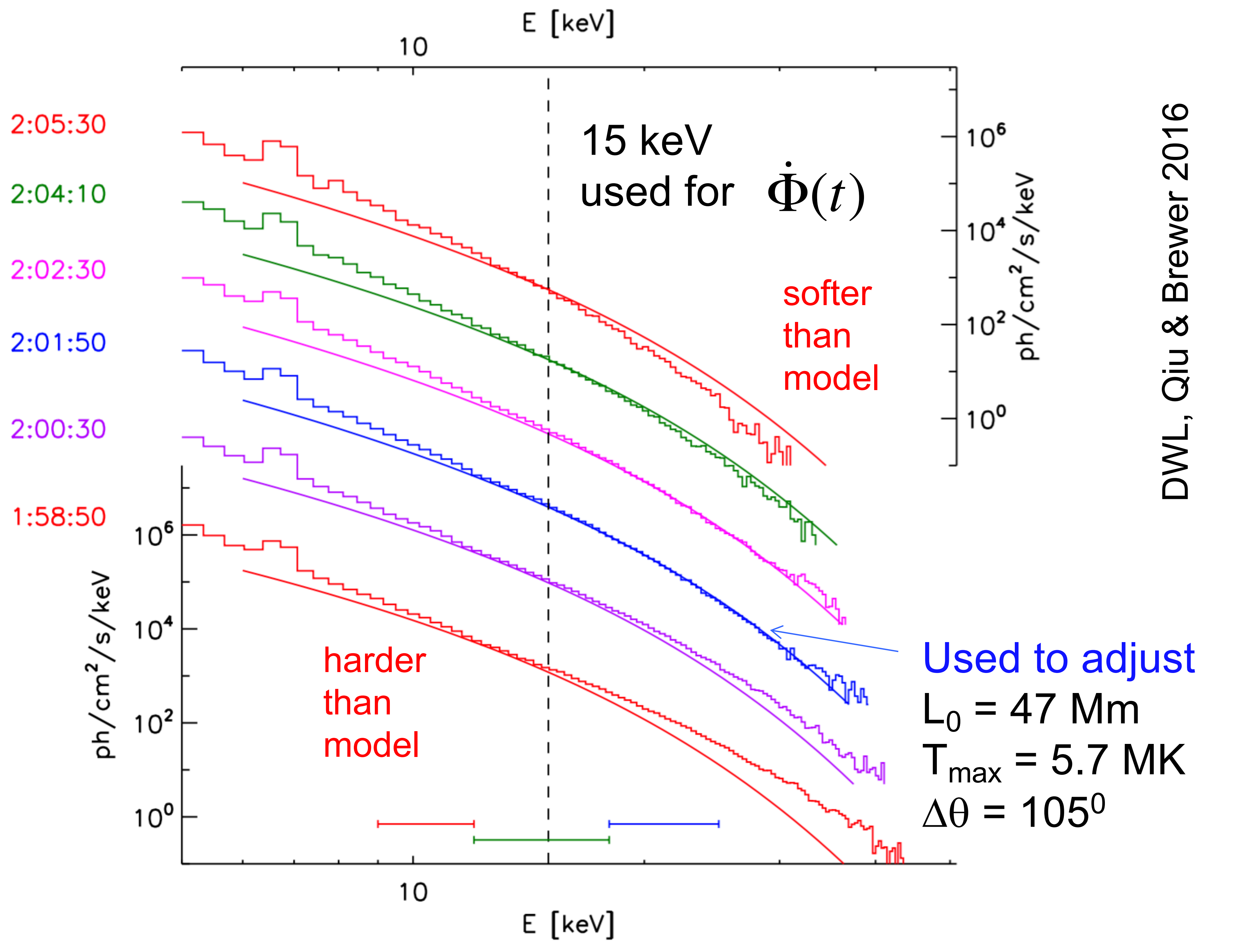
TRACE 171

DWL, Qiu & Brewer 2016



NO SCALING
measured ribbons
TFT model
14–16 keV
$I_0(t)$
$\dot{\Phi}(t)$
dΦ/dt [10^18 Mx/s]
01:50
02:00
02:10
02:20
I₀(t) [10^-18 ph/s/cm²/Mx]
t [s]
thermal brem.
invert
RHESSI 14–16 keV
ph/s/cm²
2004–Feb–26
$I(t) = \int \dot{\Phi}(t-s) I_0(s)\, ds$
Ribbon measurements miss some flux slightly late


18−25 keV
12−18 keV
9−12 keV
RHESSI
TFT model
ph/s/cm^2
1400
1200
1000
800
600
400
200
0
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
0
1×10^5
8×10^4
6×10^4
4×10^4
2×10^4
0
01:50
01:55
02:00
02:05
02:10
02:15
2004−02−26



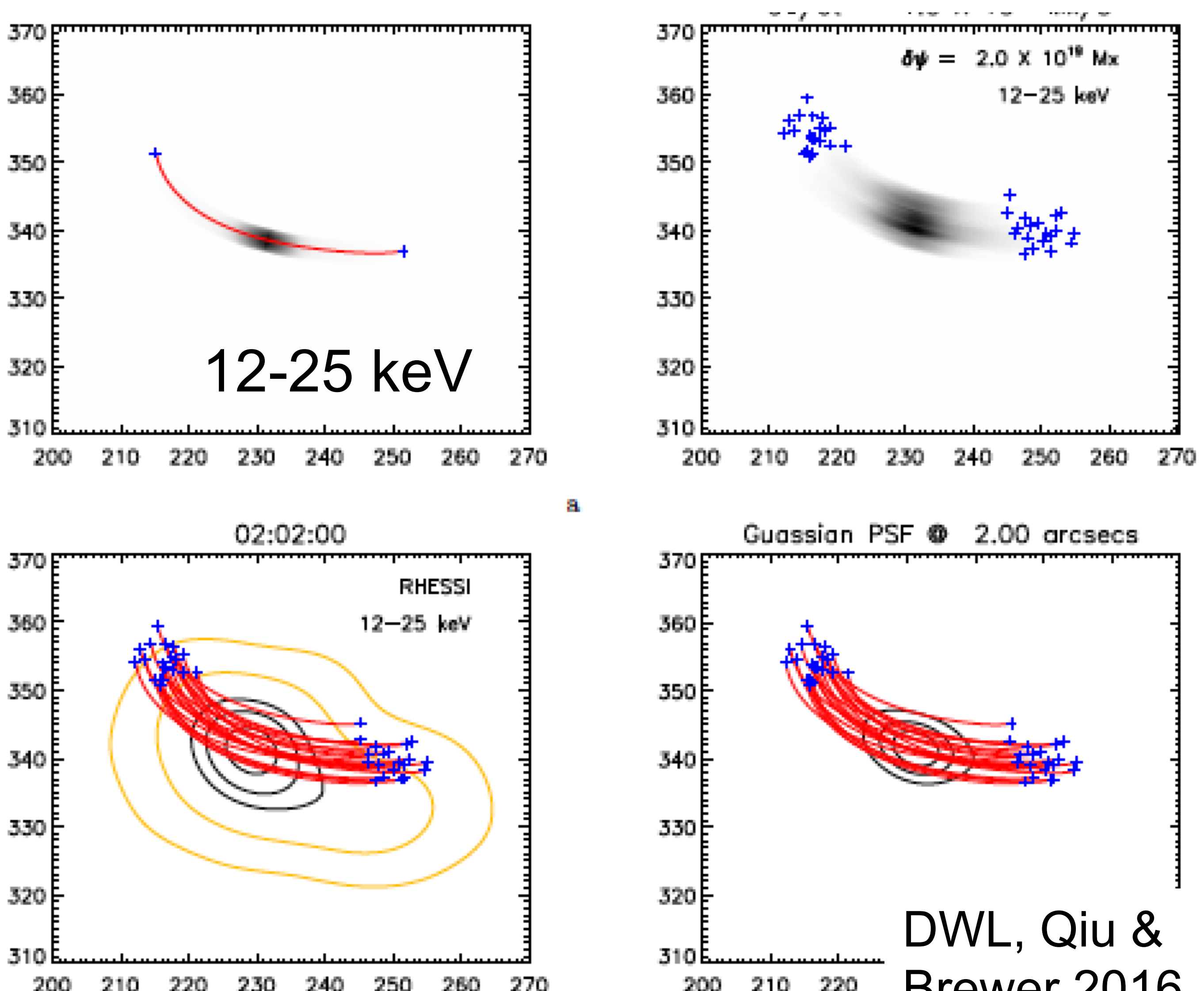
E [keV]
10
2:05:30
2:04:10
2:02:30
2:01:50
2:00:30
1:58:50
15 keV
used for $\dot{\Phi}(t)$
softer
than
model
harder
than
model
10^6
10^4
10^2
10^0
$ph/cm^2/s/keV$
Used to adjust
L_0 = 47 Mm
T_{max} = 5.7 MK
$\Delta\theta = 105^0$
DWL, Qiu & Brewer 2016

What a slow-mode shock looks like…

$\delta\Phi = 2 \times 10^{19}$ Mx

$\dot{\Phi} = 10^{19}$ Mx/s

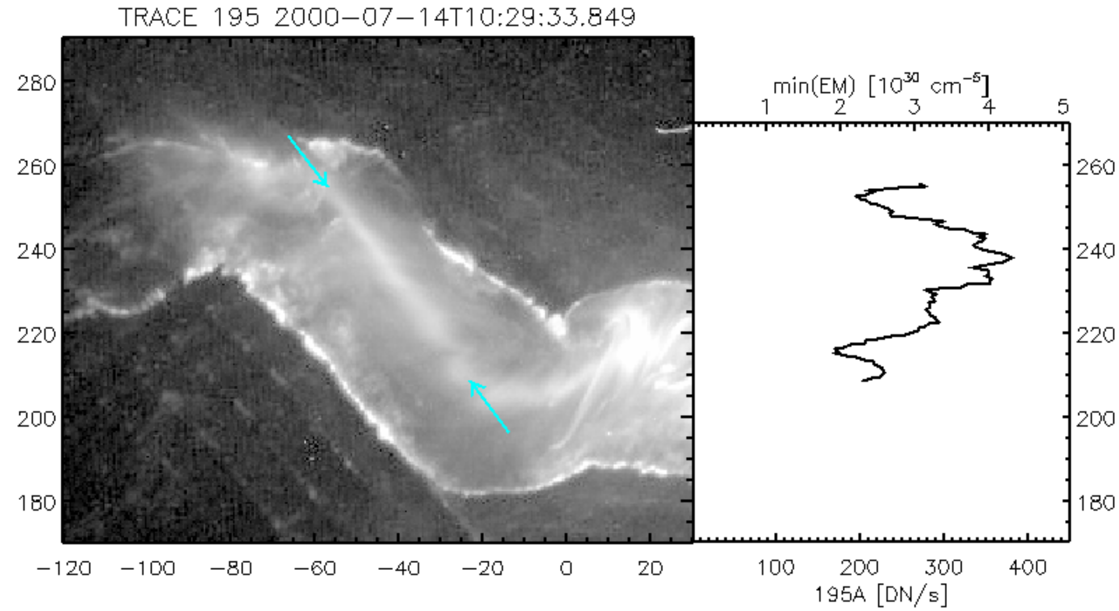
hot dense plug from SMS – persists @ base of CS

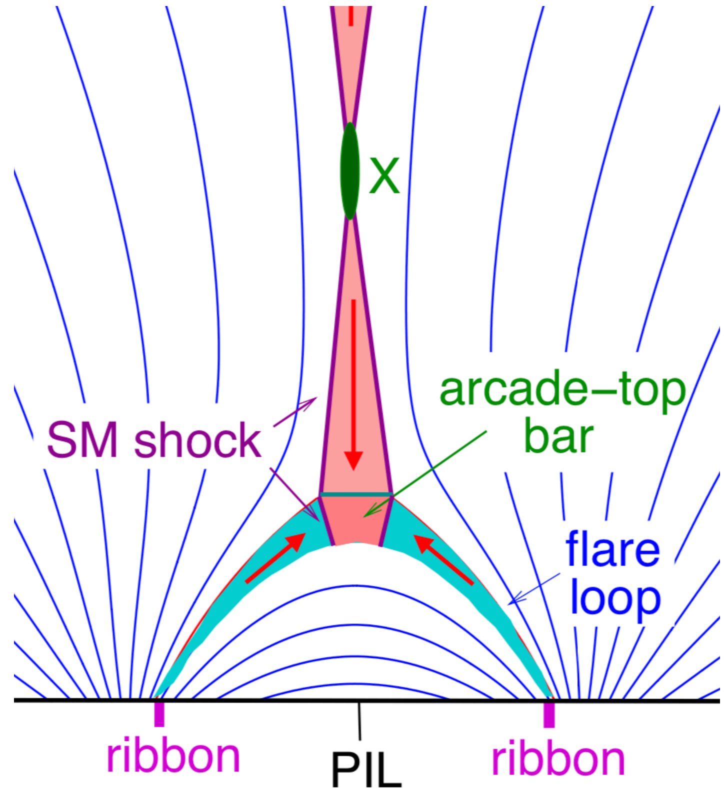


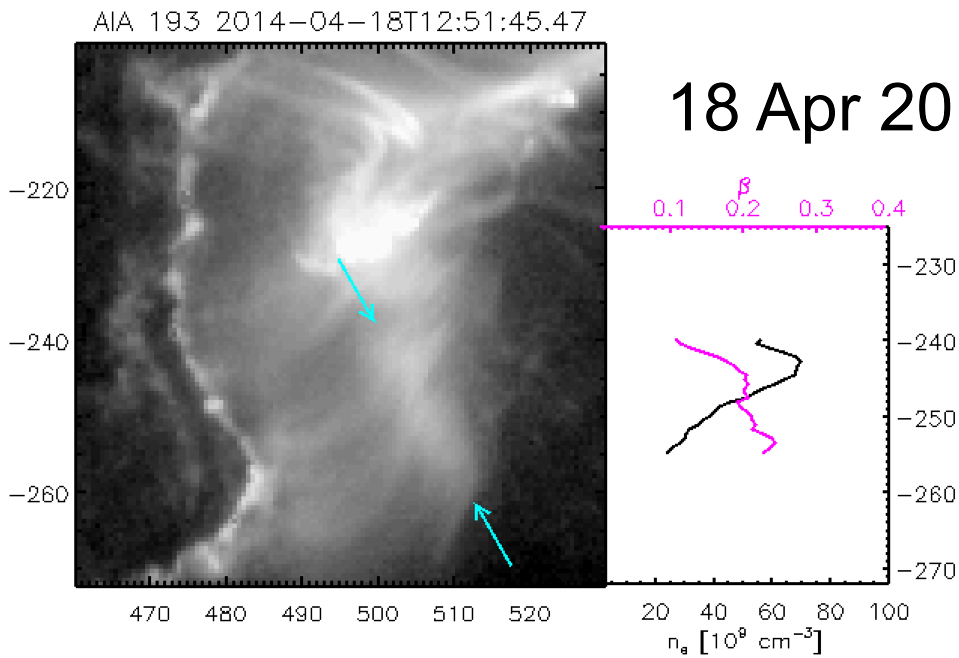
RHESSI 12-25 keV

DWL, Qiu & Brewer 2016

2021-05-26





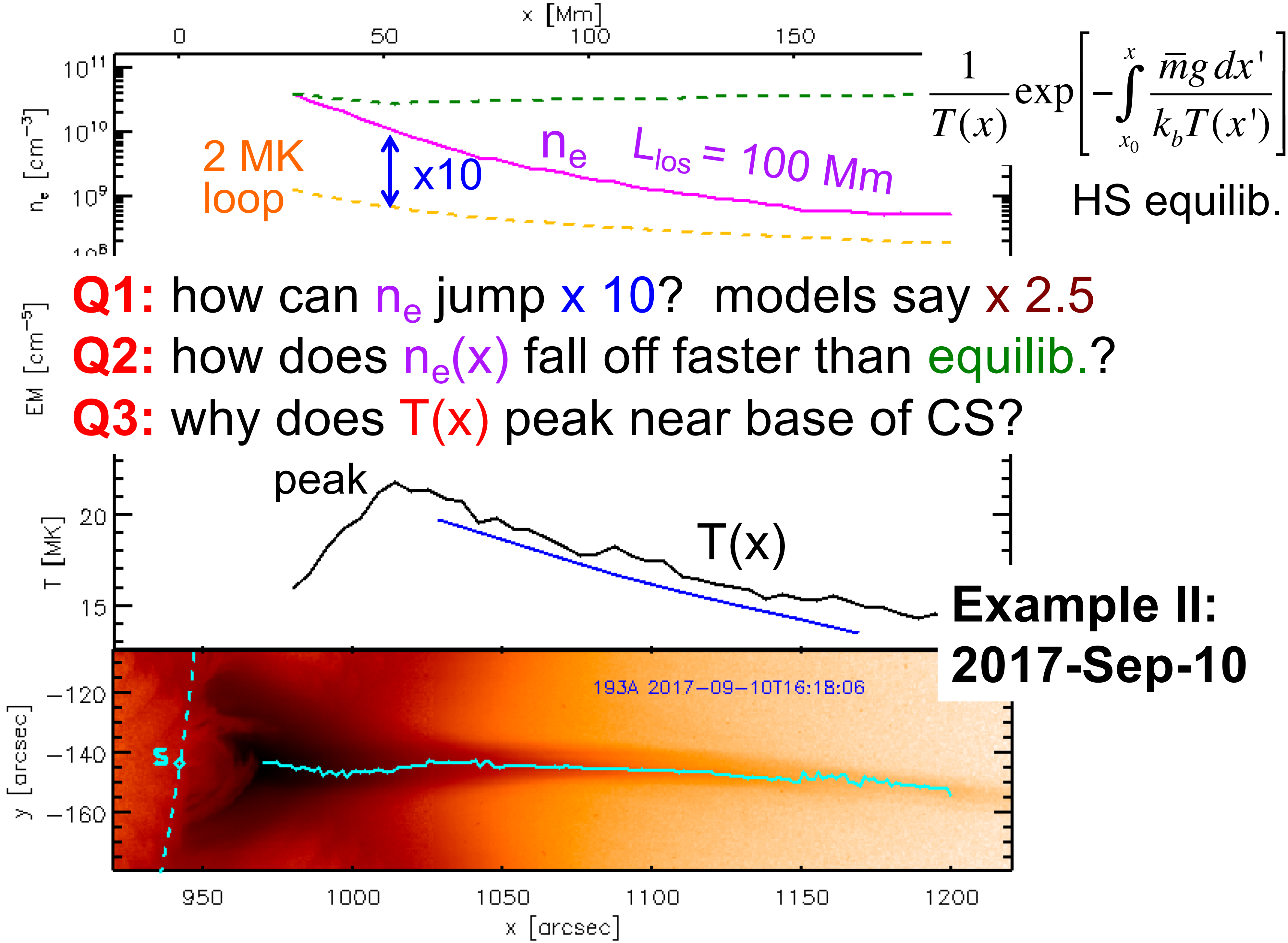


18 Apr 2014

Observing slow shocks –

~15 MK bar along top of arcade = bottom of plasma sheet

Example II: 2017-Sep-10

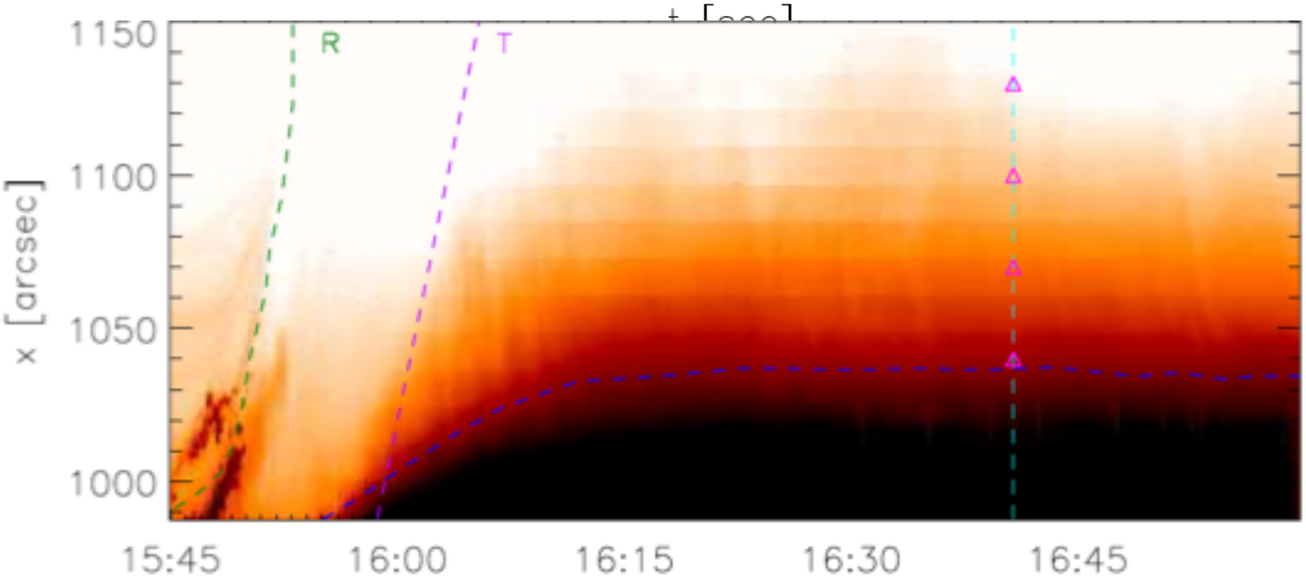


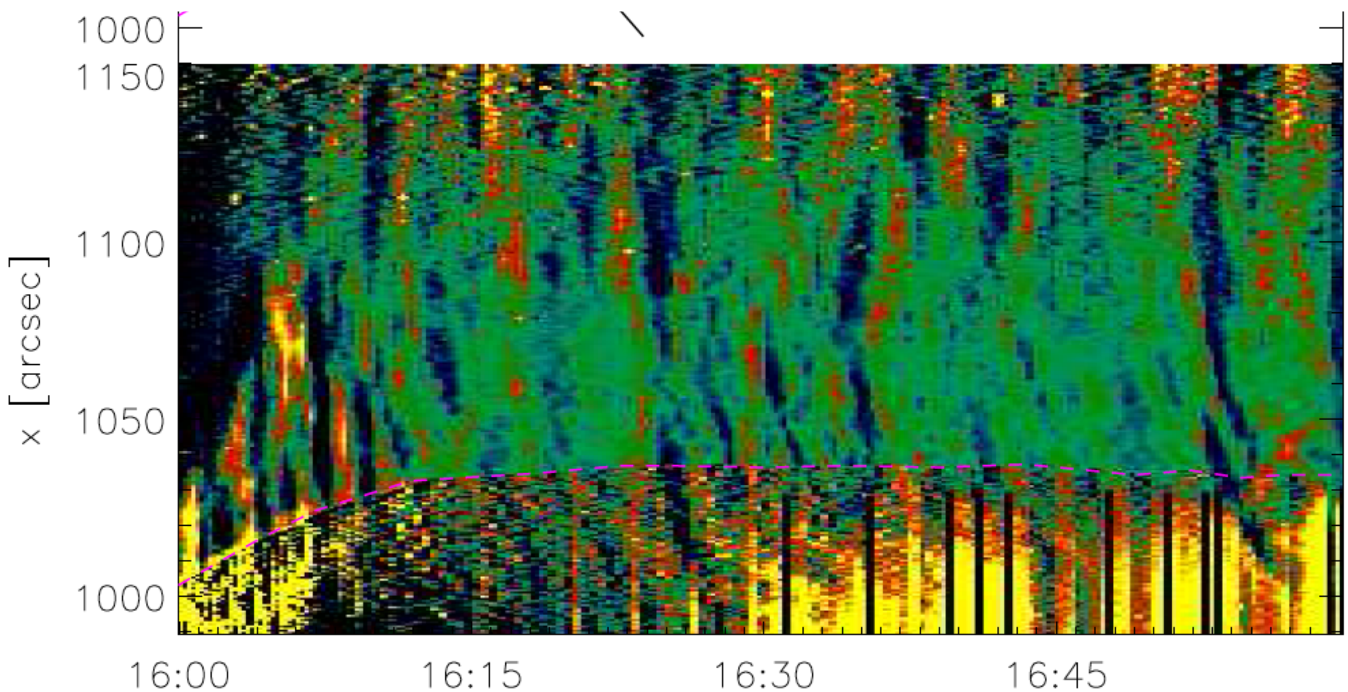
Q1: how can n_e jump x 10? models say x 2.5

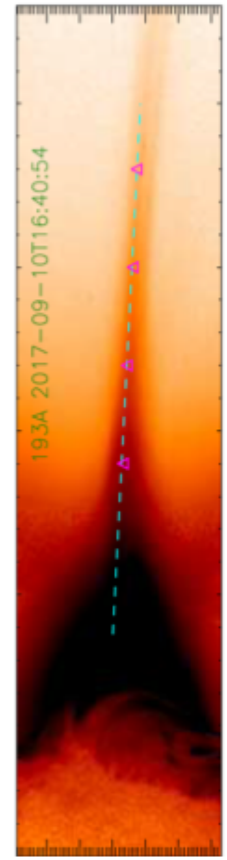
Q2: how does $n_e(x)$ fall off faster than equilib.?

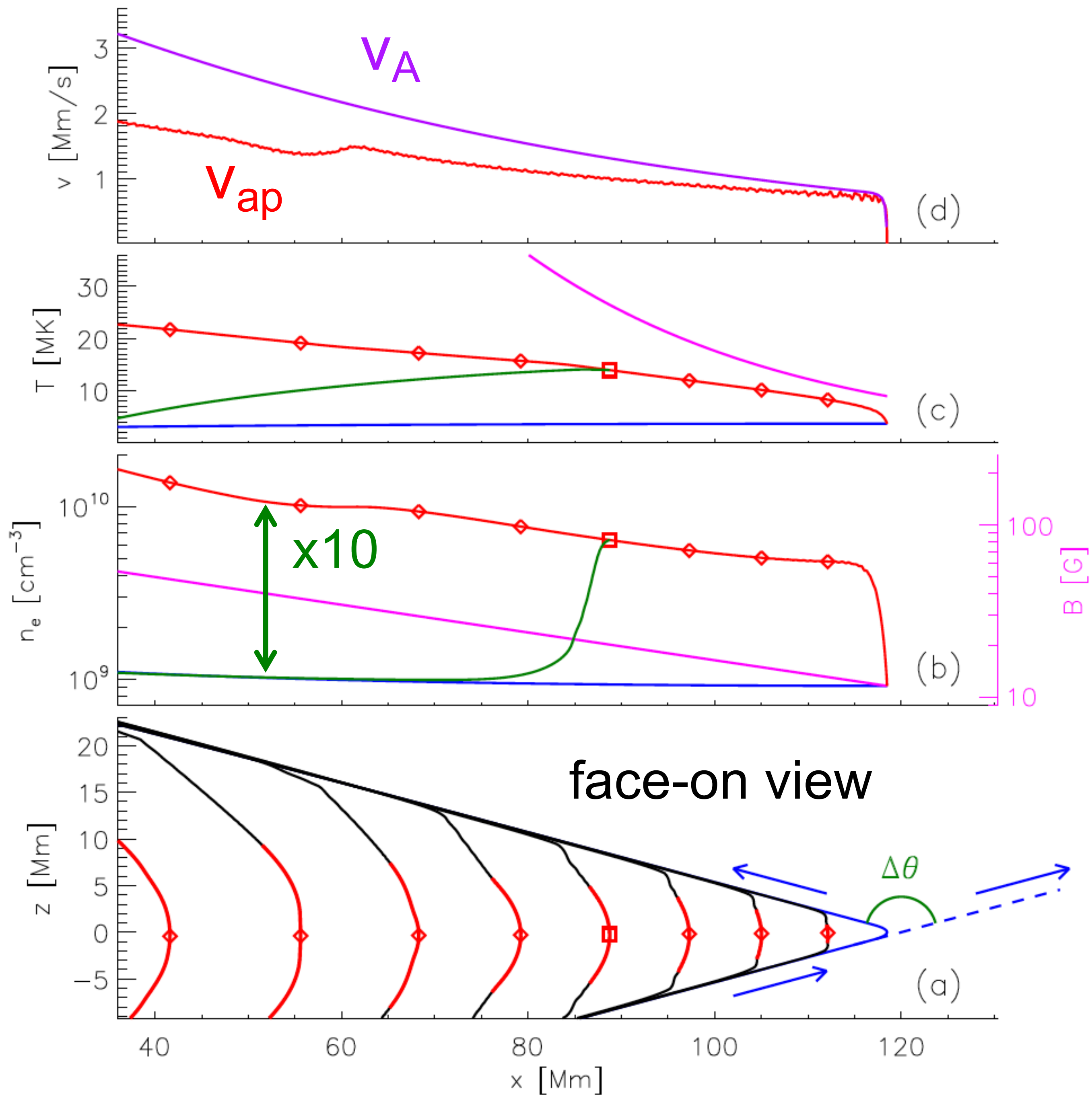
Q3: why does T(x) peak near base of CS?

SADs or SADLs ?









T(x) increases downward

retraction through a sheet w/ varying B(x)

Points to consider

- Energy (**mag**) stored **by current sheet** (not **@** CS)
- Energy released by shortening field lines

  … **following** reconnection
- Shortening via Lorentz Force (tension):

  mag → **kin** (ions)
- Global rate ≠ local **E** field
- Fraction of energy remains w/ loop – **flare**
- Release must be accompanied by compression/density enhancement – important feature of observations