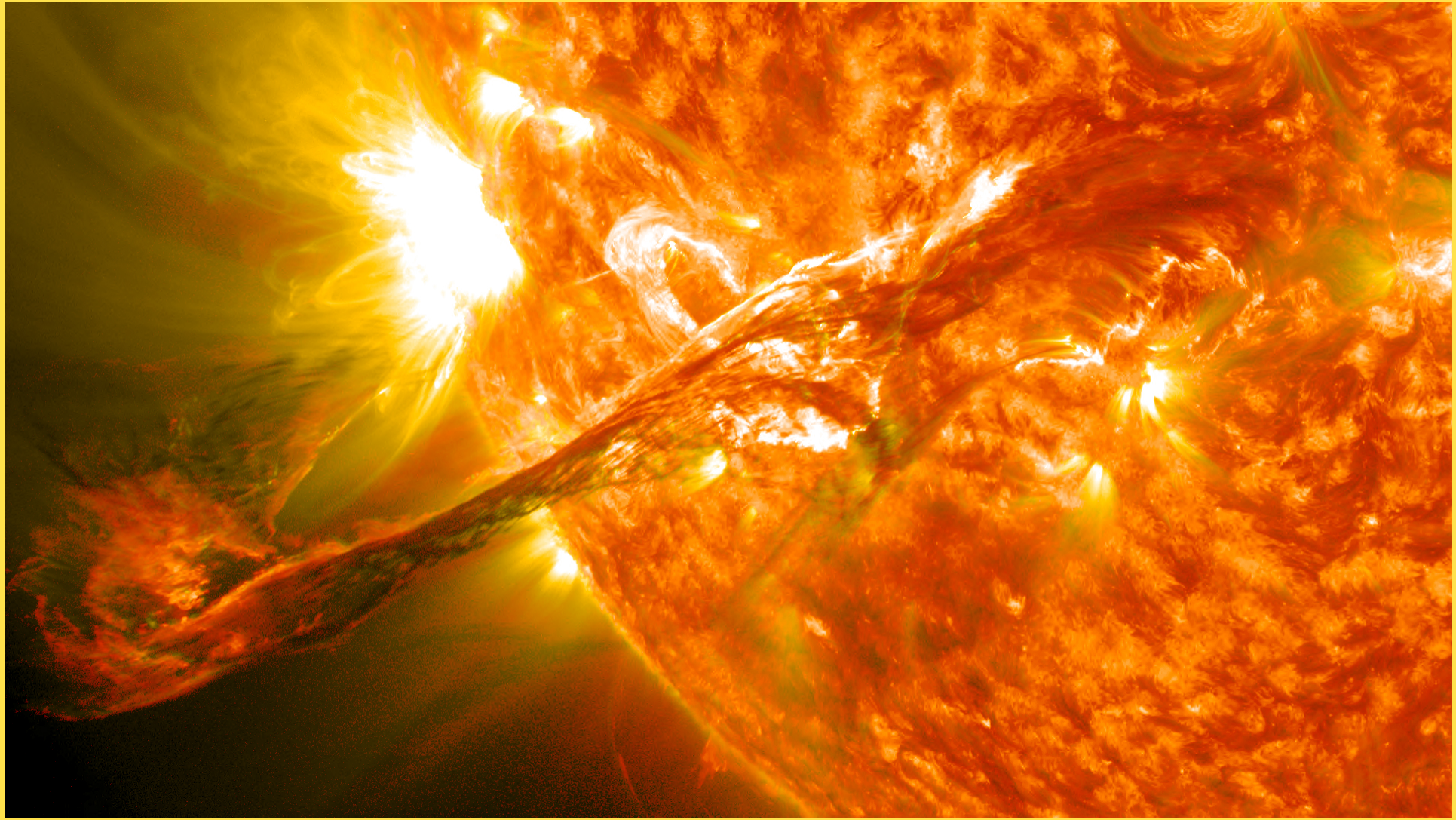
Magnetic Reconnection on the Sun



by Eric Priest (St Andrews)

ESPD Senior Prize Lecture (Sept 10, 2021)

1. INTRODUCTION

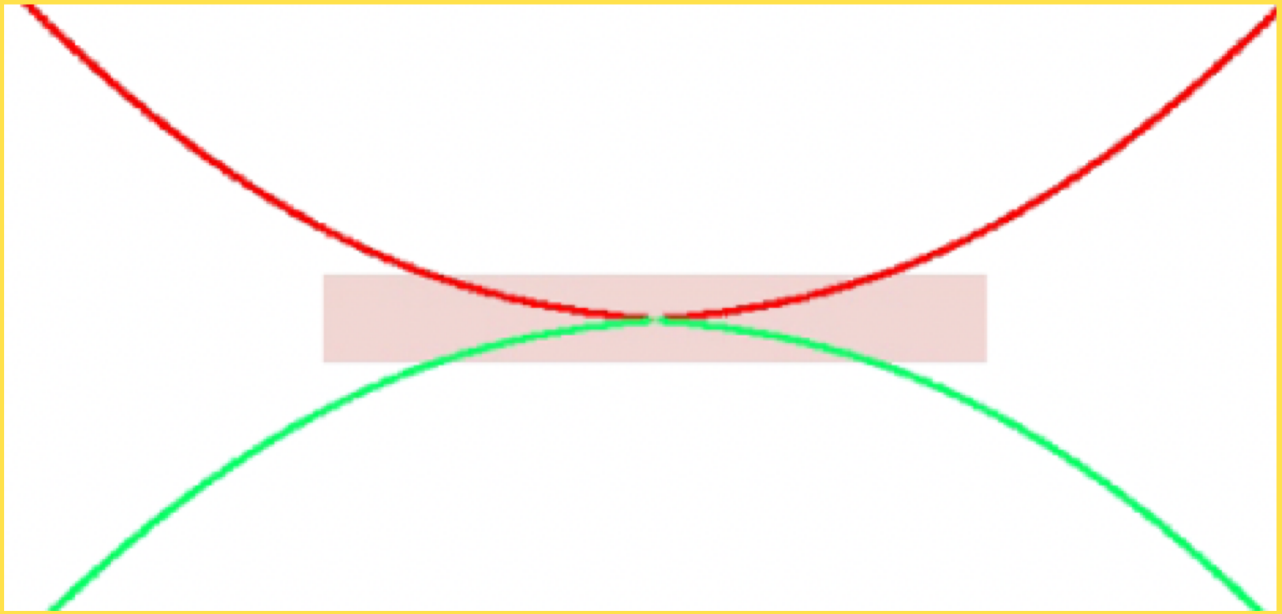
I have been fortunate

- Career researching such an intriguing & beautiful topic – Our Sun.

- Shared journey with such wonderful collaborators:

Jean **Heyvaerts**, Bernie **Roberts**, Alan **Hood**, Peter **Cargill**, Philippa **Browning**, Terry **Forbes**, Pascal **Demoulin**, Clare **Parnell**, Duncan **Mackay**, Slava **Titov**, Gunnar **Hornig**, Dana **Longcope**, David **Pontin**, Fernando **Moreno Insertis**, Pradeep **Chitta**.

Reconnection -fundamental process in plasma



- Changes the topology – paths of particles & heat
- Converts magnetic energy to heat & K.E
- Accelerates fast particles

2.In 2D, reconnection only at an X-Point in j sheet

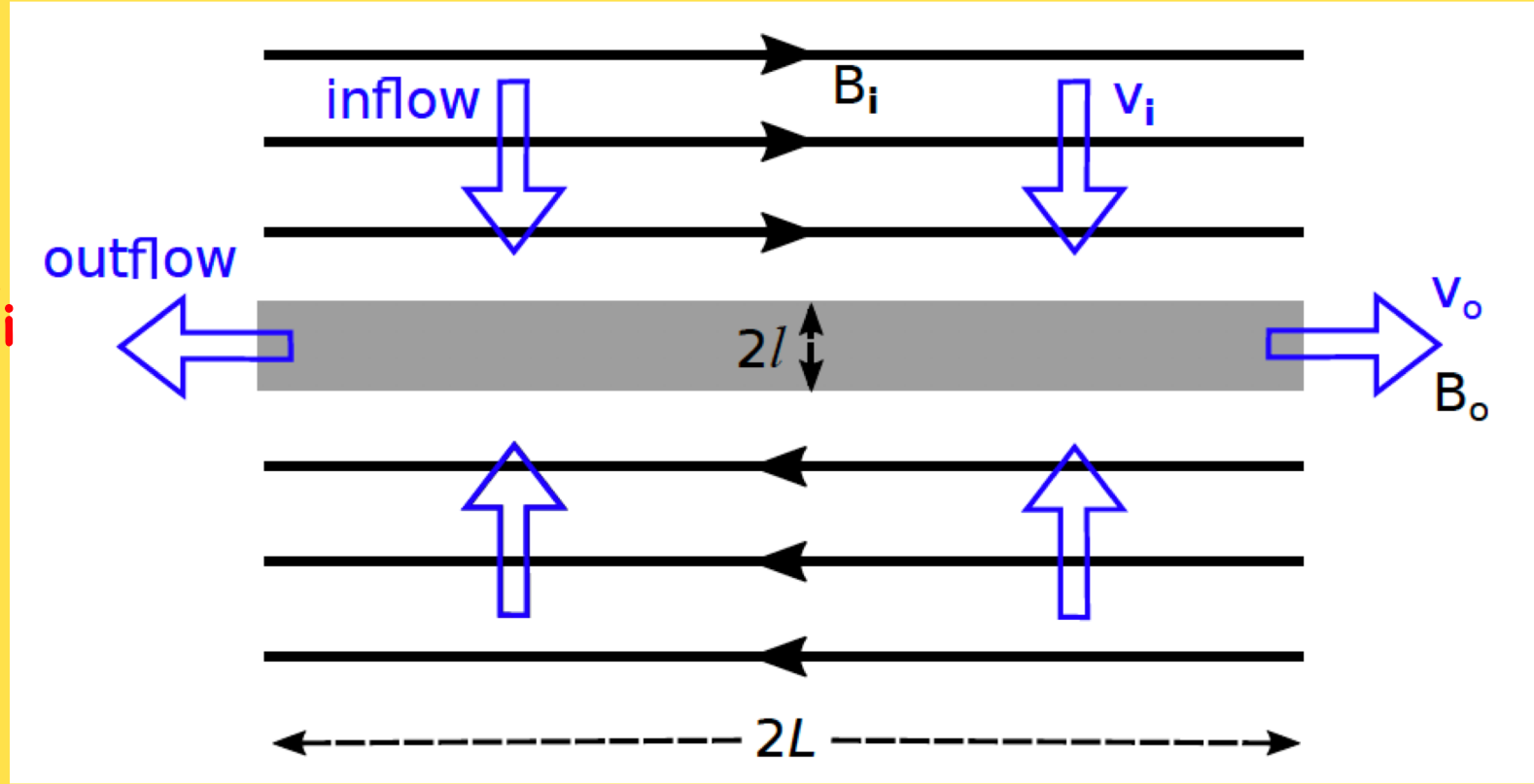
For a simple current sheet of length L,

B carried in at speed v_i

(reconnection rate)

$$v_i = \frac{v_{Ai}}{R_{mi}^{1/2}}$$

[Sweet-Parker, 1958]



$$R_{mi} = \frac{L\, v_{Ai}}{\eta},$$

Magnetic Reynolds No

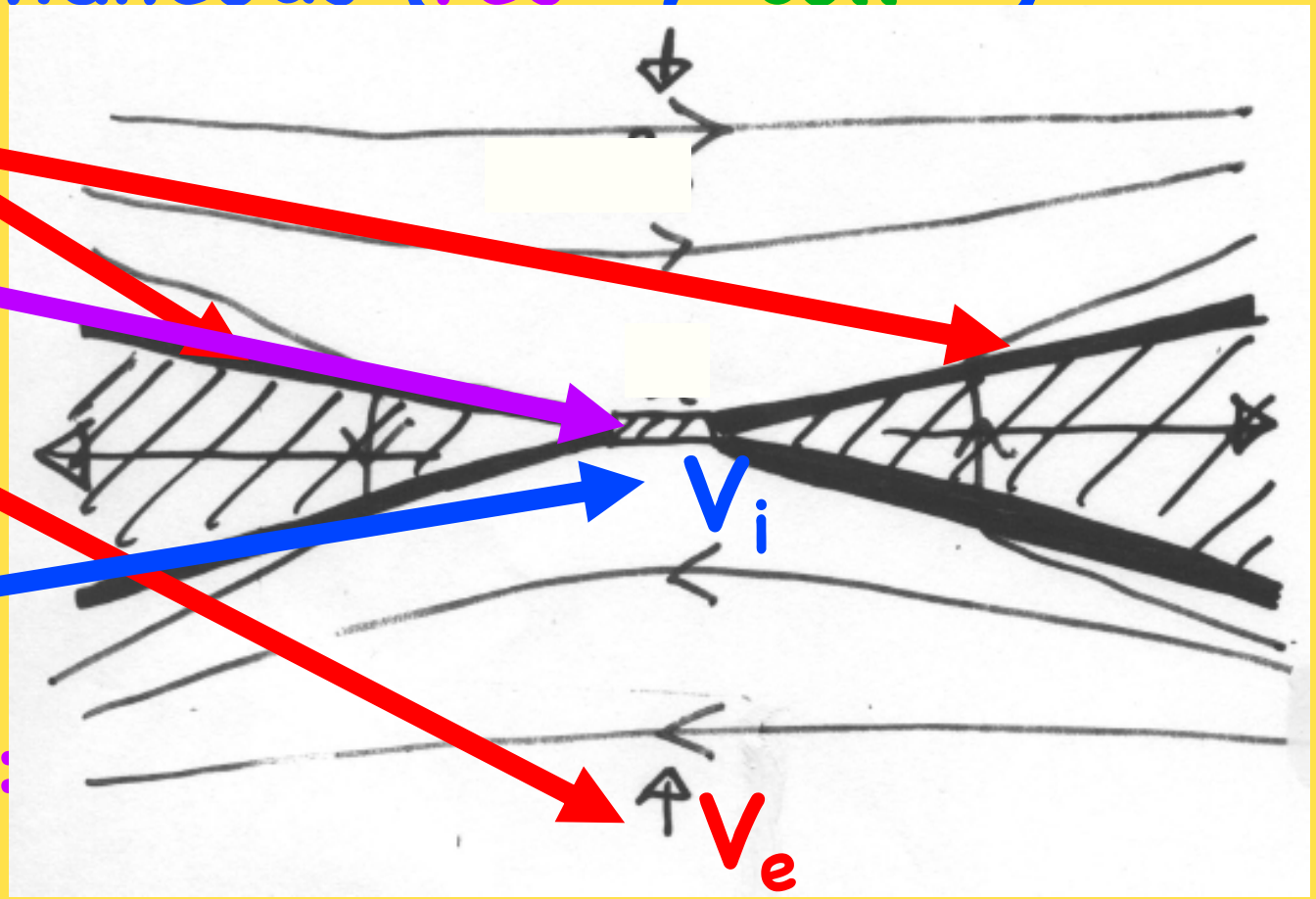
Fast Reconnection (i) Spontaneous (res^{ve} / coll^{less})

Much of energy at slow shocks

from small central current sheet

Reconnection rate is external speed V_e

≠ **speed v_i** at inflow to j sheet



For resistive MHD (Petschek):

$[V_i = V_{Ai} / R_m^{1/2}]$ **and** $V_e = 0.1\ V_{Ae}$

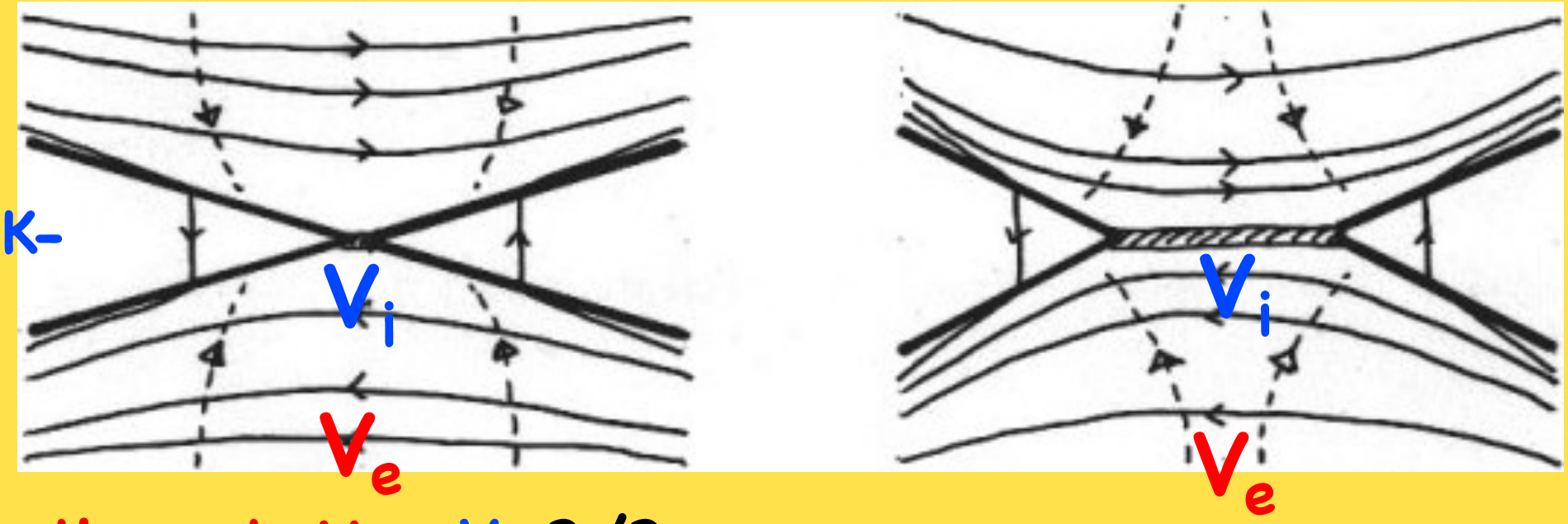
provided η enhanced by j-driven microinstabilities (need show for Sun)

For collisionless plasma $[V_i = 0.01\ V_{ai}]$ **and** $V_e = 0.1\ V_{Ae}$

[Kleva 1995; Birn, 2001] (From local simulations – need global + theory)

Fast Reconnection (ii) Driven - [e.g., coronal heating, ?flare]

PETSCHEK-TYPE



FLUX PILEUP

Reconnection rate $V_e = V_i \; B_i/B_e$

depends on V_i (resistive / collisionless) and B_i/B_e (nature inflow- conv/div)

Reconnection occurs at driving rate V_e - Up to a maximum allowed V_e^*

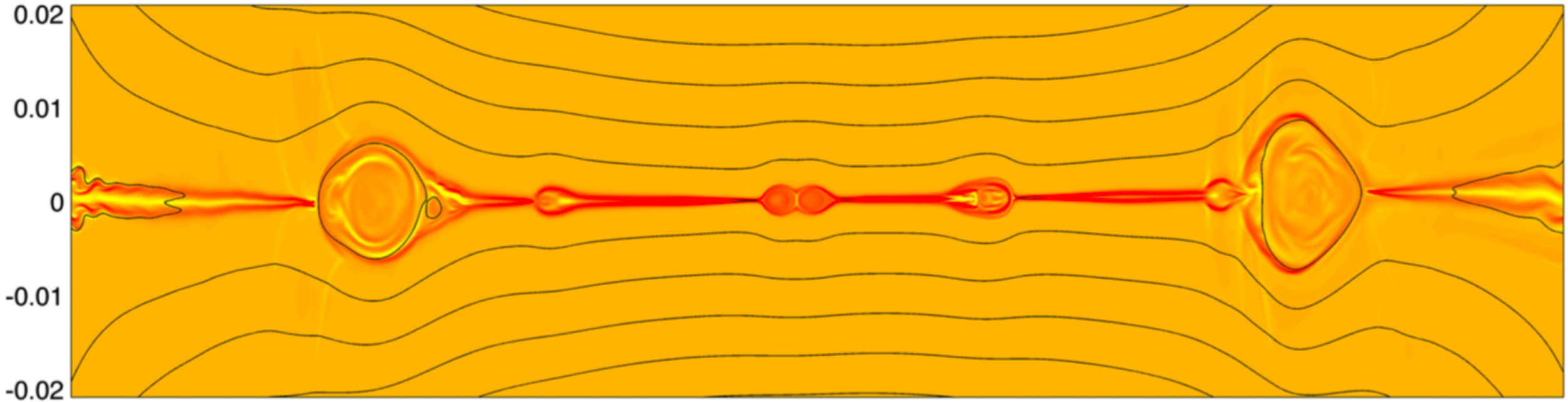
[For Converging flow $V_e^* = 0.1\, V_{Ae}$ (res^{ve}/col^{less})]

[For Diverging flow $V_e^* = V_{Ae}/R_m^{1/2}$(res^{ve}), $V_e^* = 0.1\, V_{Ae}$ (col^{less}),]

Fast Reconnection (iii) "Impulsive bursty" reconnection [Biskamp 82, Forbes & P 83]

caused by tearing mode when $L > L_{crit} = 100\ l$

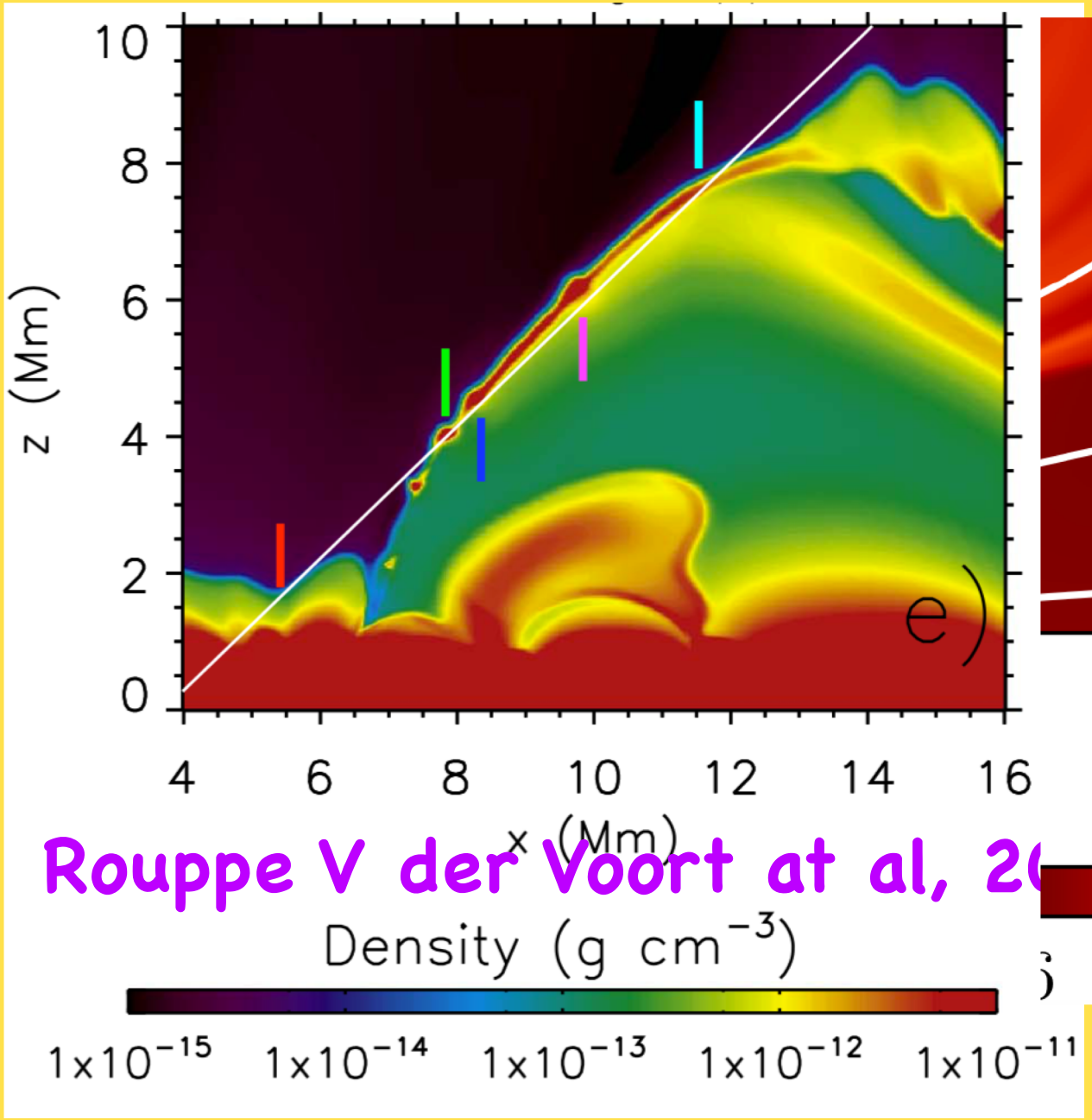
→ recently renewed interest numerical - renamed "plasmoid regime"



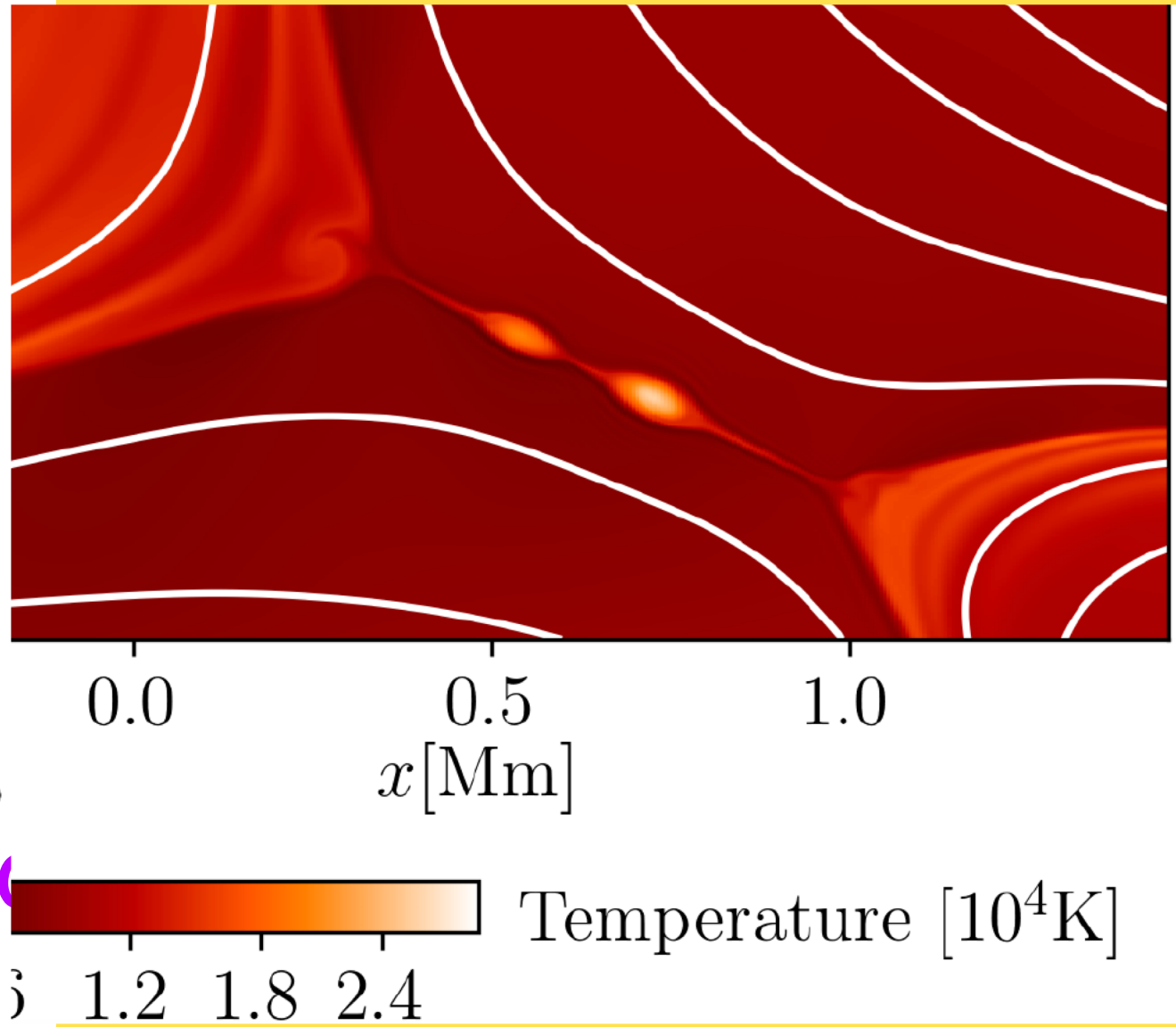
[Bhattacharjee 2009]

-> local reconnection rate $V_i = 0.01\ V_{Ai}$ [Loureiro 2007, Yulei Wang talk]

Impulsive bursty: simulations solar UV bursts in emⁿᵍ/interngflux



Rouppe V der Voort at al, 2(



Peter et al (2019)

3. 3D reconnection – very different from 2D

(i) Structure of Null Point

In 2D,

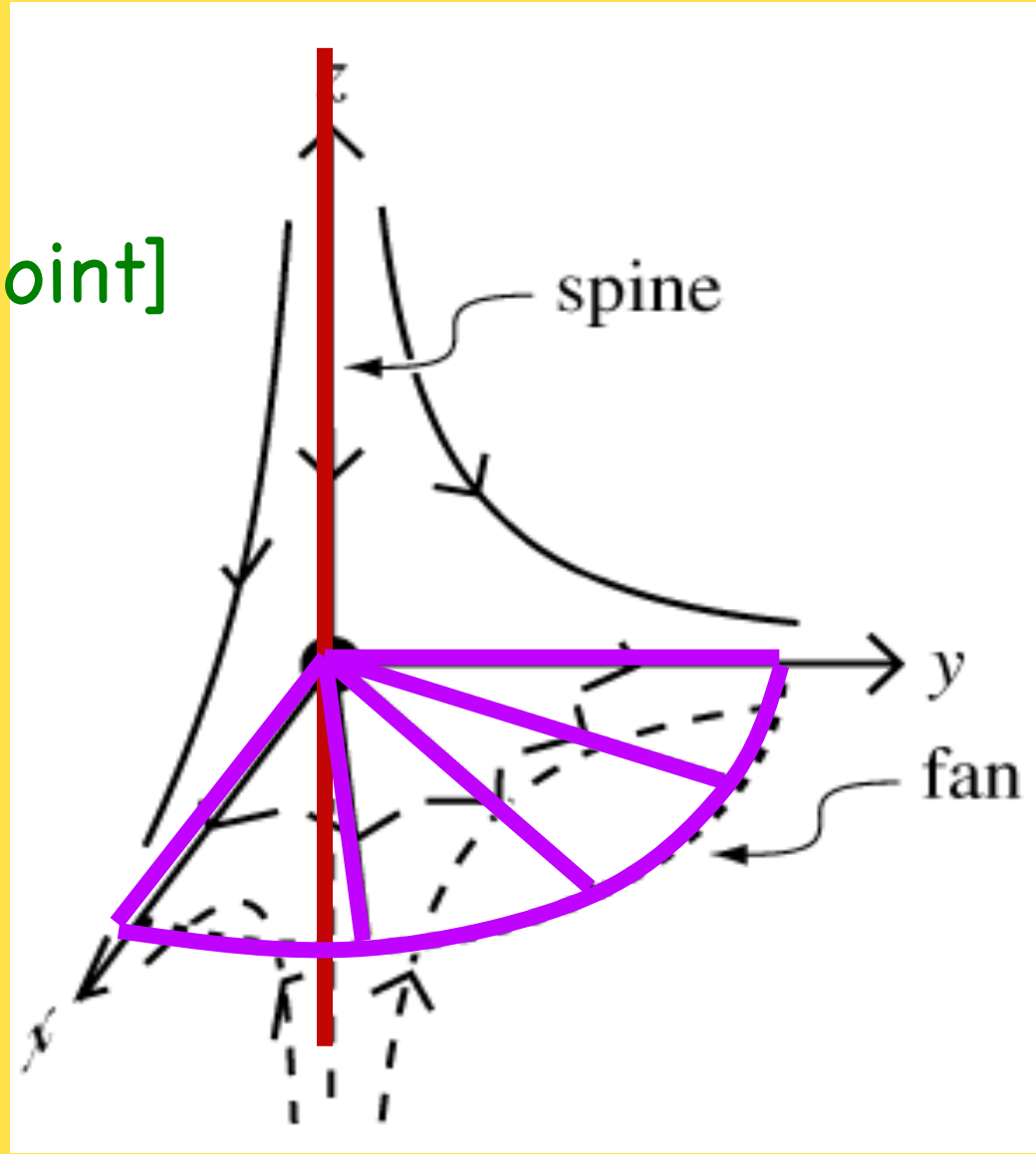
a null forms an X-point [or an O-point]

In 3D,

2 families of field lines
link to null point:

Spine Field Line

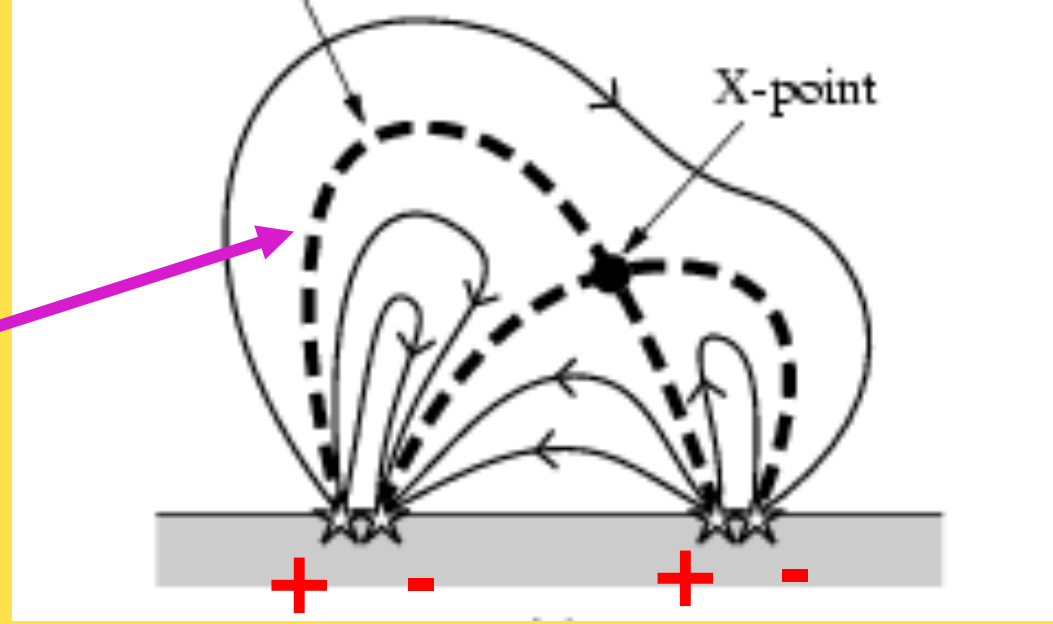
Fan Surface



(ii) Magnetic Topology

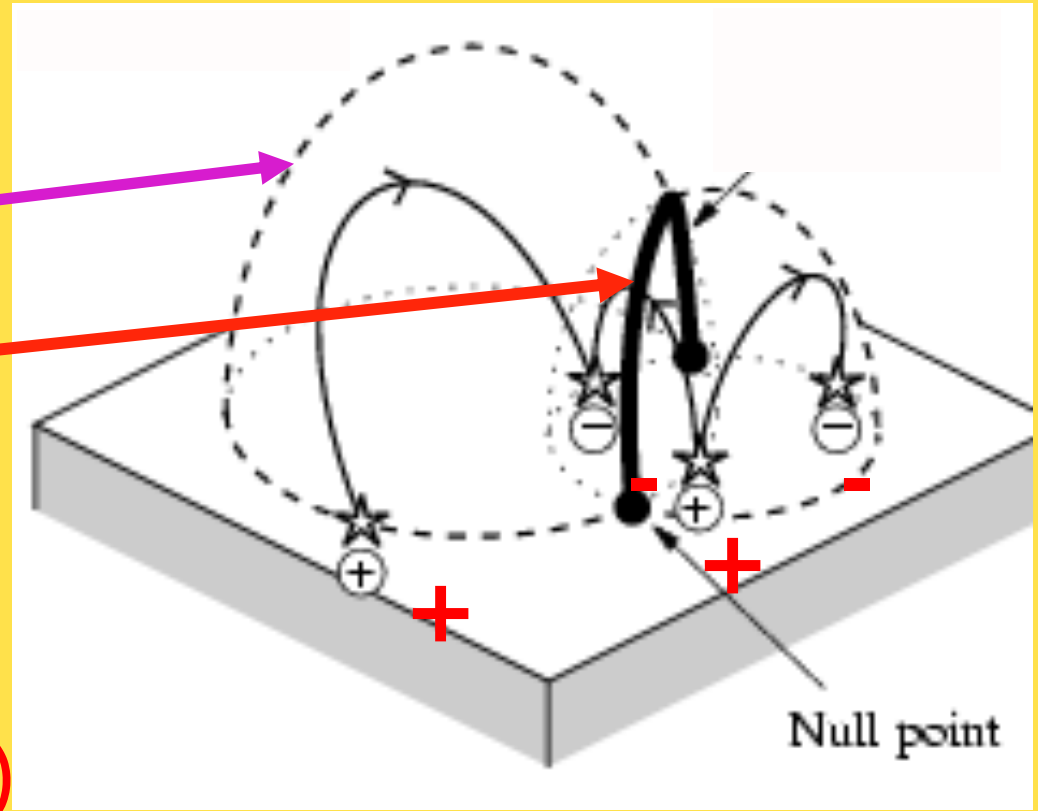
4 spots + - + -:

In 2D: B lines from X-pt form "separatrix" curves



In 3D: B lines from fans of 2 null pts form separatrix surfaces

-- intersect in **separator**



If move sources below photo,

separatrices -> QSLs

separator -> quasi-separator (hyperbolic flux tube)

(iii) Types of Reconnection

In 2D: Reconnection at X-point

In 3D: several locations where j strong:

- 1. near a null point [Pontin, Masson]
- 2. at a separator [Parnell, Longope]

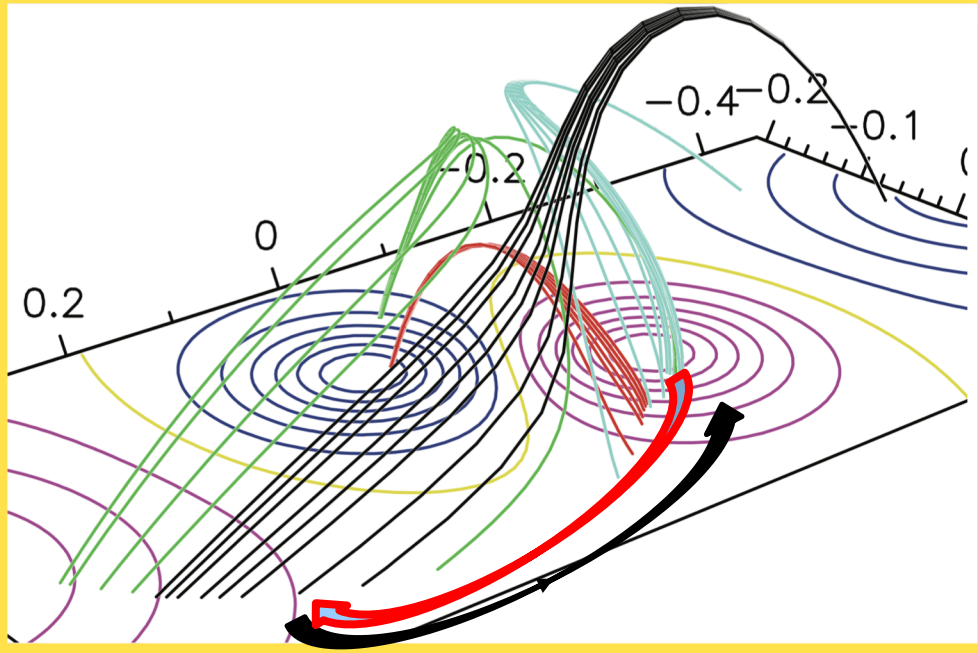
- discontinuity in mapping of B-line footpoints
- as cross separatrix

- 3. at quasi-separator

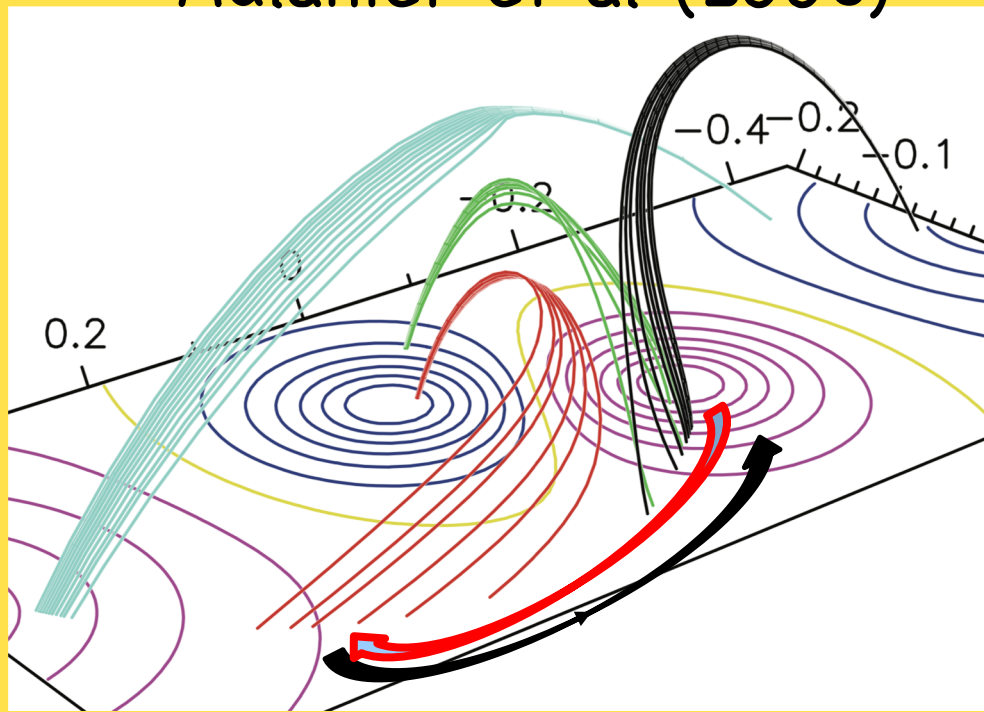
- finite jump in mapping as cross QSL
[Demoulin, Titov, Aulanier]

In each of 3 cases, Q (squashing degree)>>1
+ **field lines flip or slip**
[magnetic helicity conservation]

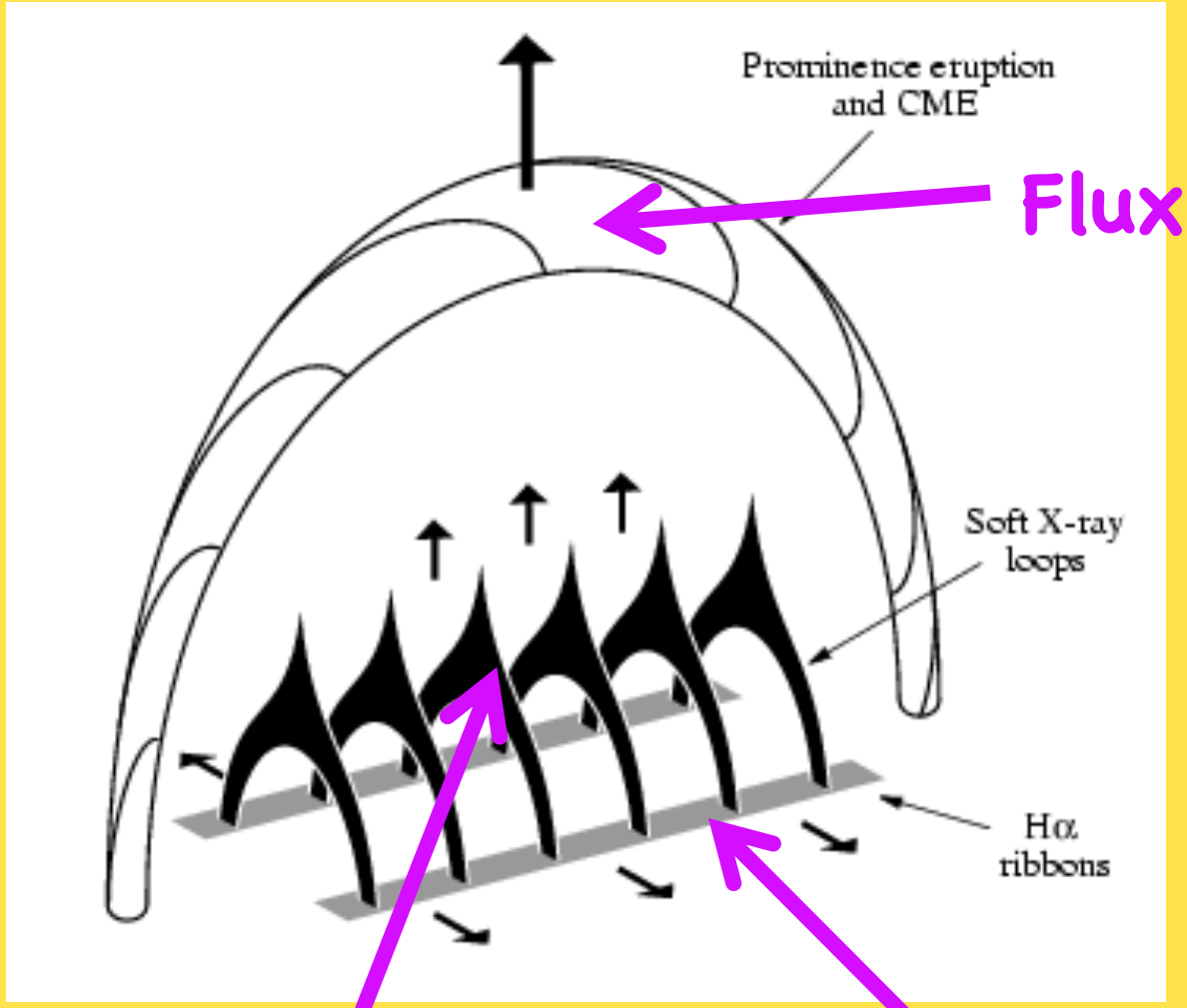
[Pariat06, Aulanier07, Janvier13, Dudik14]



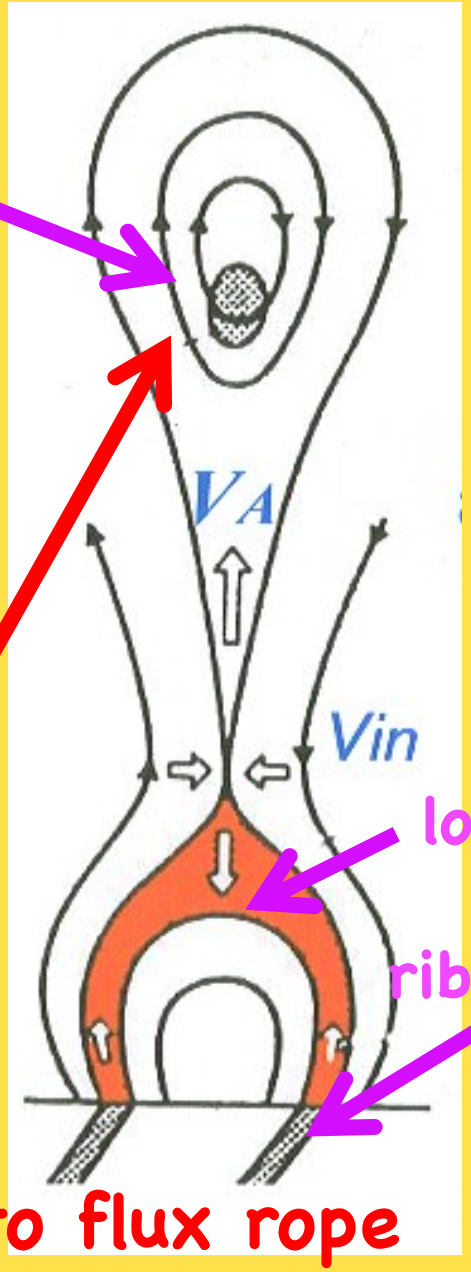
Aulanier et al (2006)



4. Solar Flares–2D Reconⁿ explains many aspects



Flux rope



loops
&
ribbons

In 2D vertical section

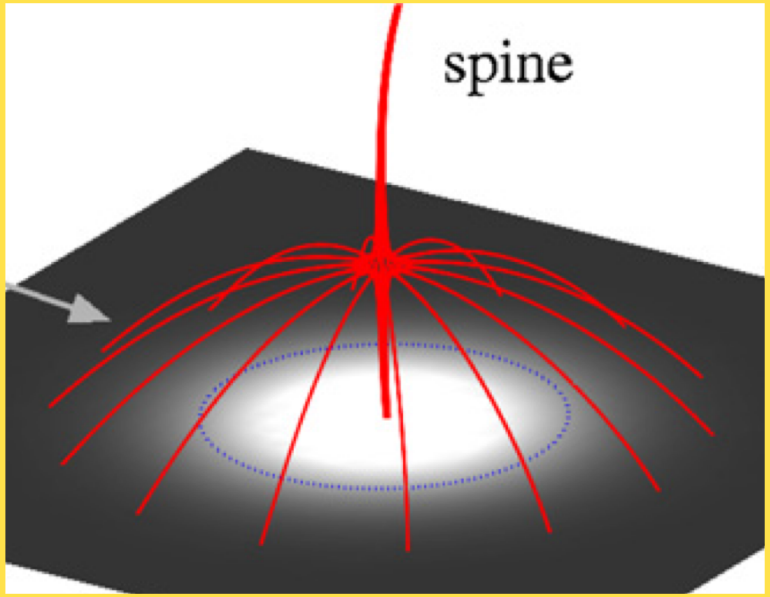
Creation + rise of hot flare loops
+ separation of chromospheric ribbons

Reconnection adds magnetic flux/helicity (twist) to flux rope

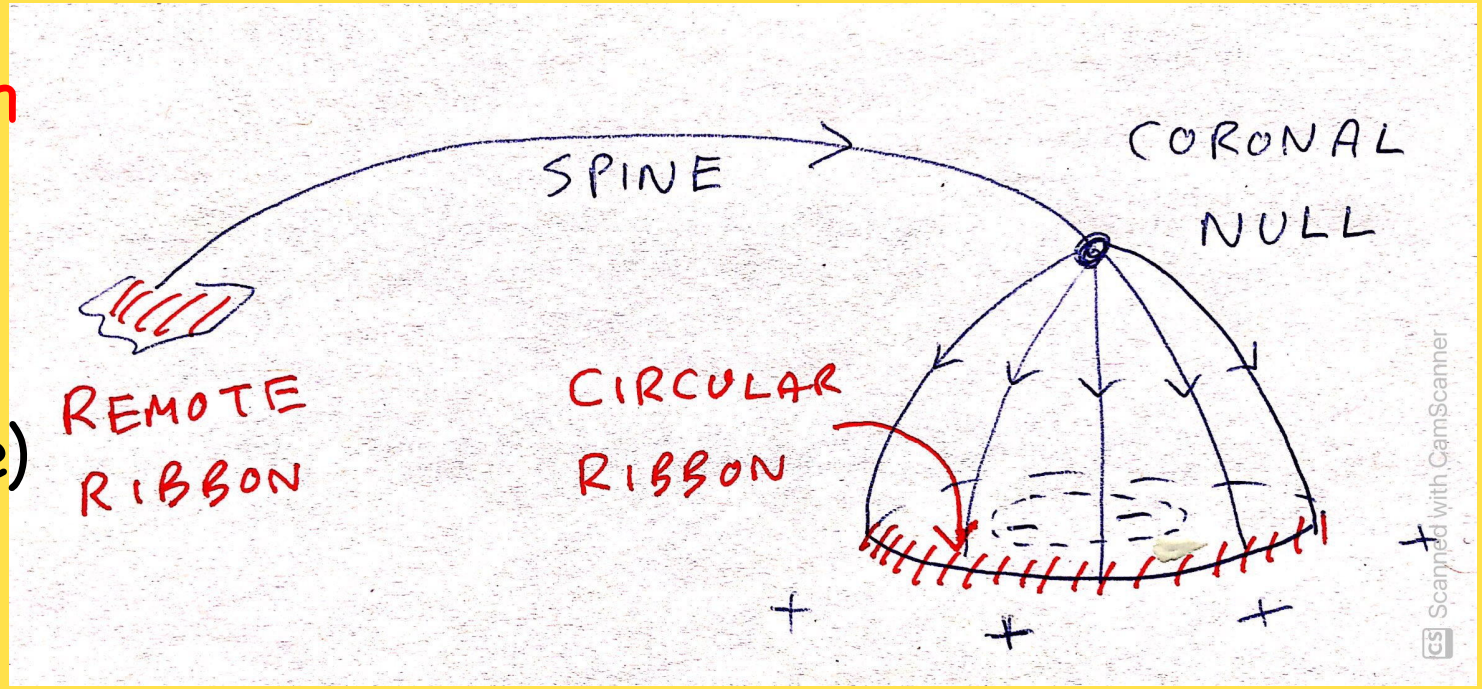
Many Extra Effects from 3D

- Some flares at **coronal null point**

[Demoulin94, Aulanier01, Masson 09,
Pontin 13, Hou 19, Yang 20]

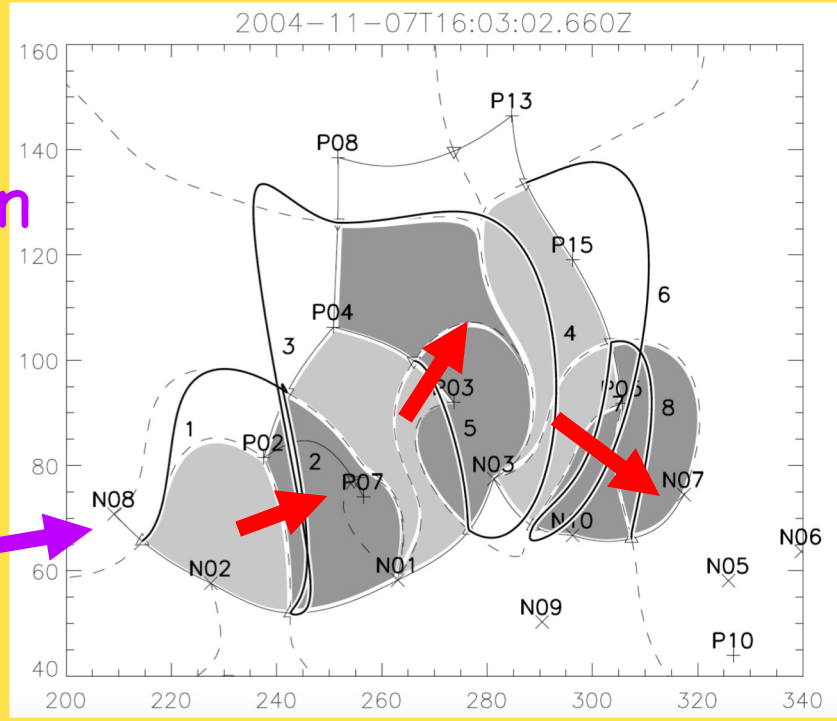


where spine-fan reconnection
forms circular ribbon
(where fan reaches surface)
+ remote ribbon
(where spine reaches surface)



[Other 3D Effects]

Ex. 32 separators [Topological skeleton for active region Longcope07]

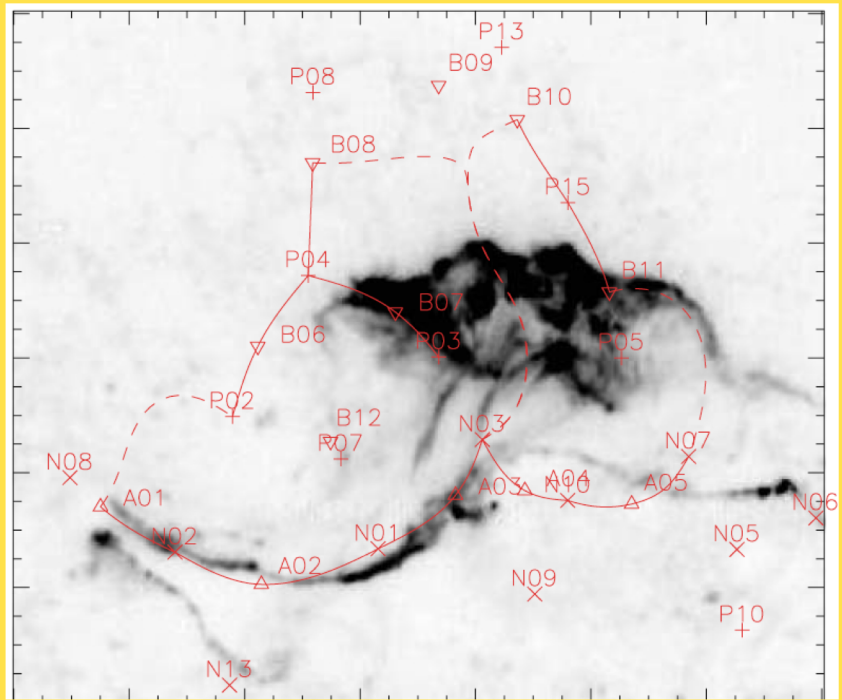


- Some flares at **separators**

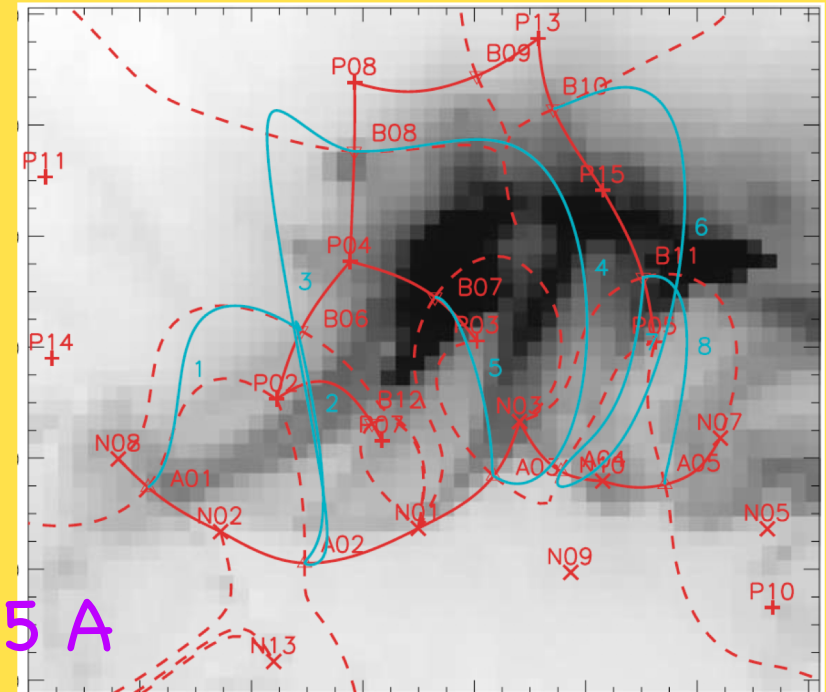
[Demoulin93, vanDriel94, Longcope, 96, 07, Parnell 10]

- Explains how flare spreads thro' complex region

across separators from one domain to another



1600 A



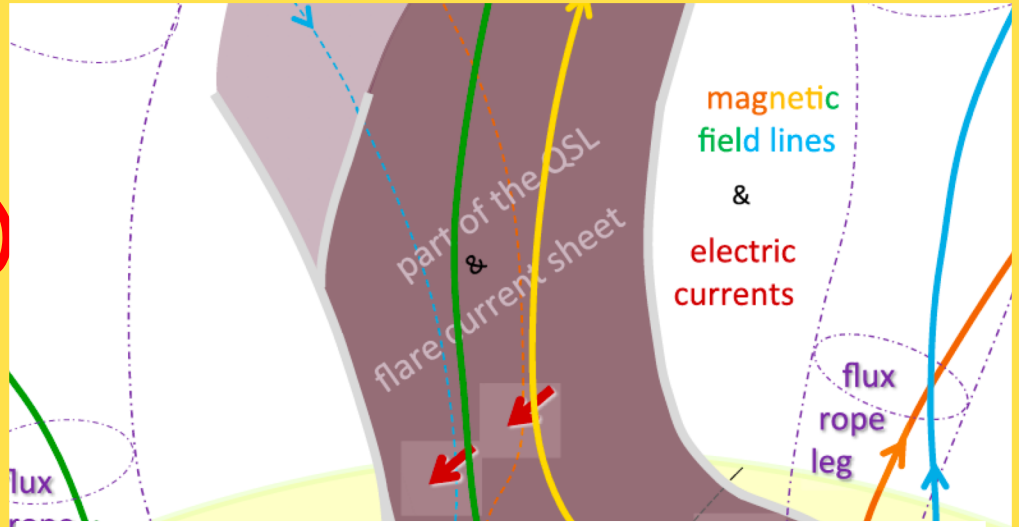
195 A

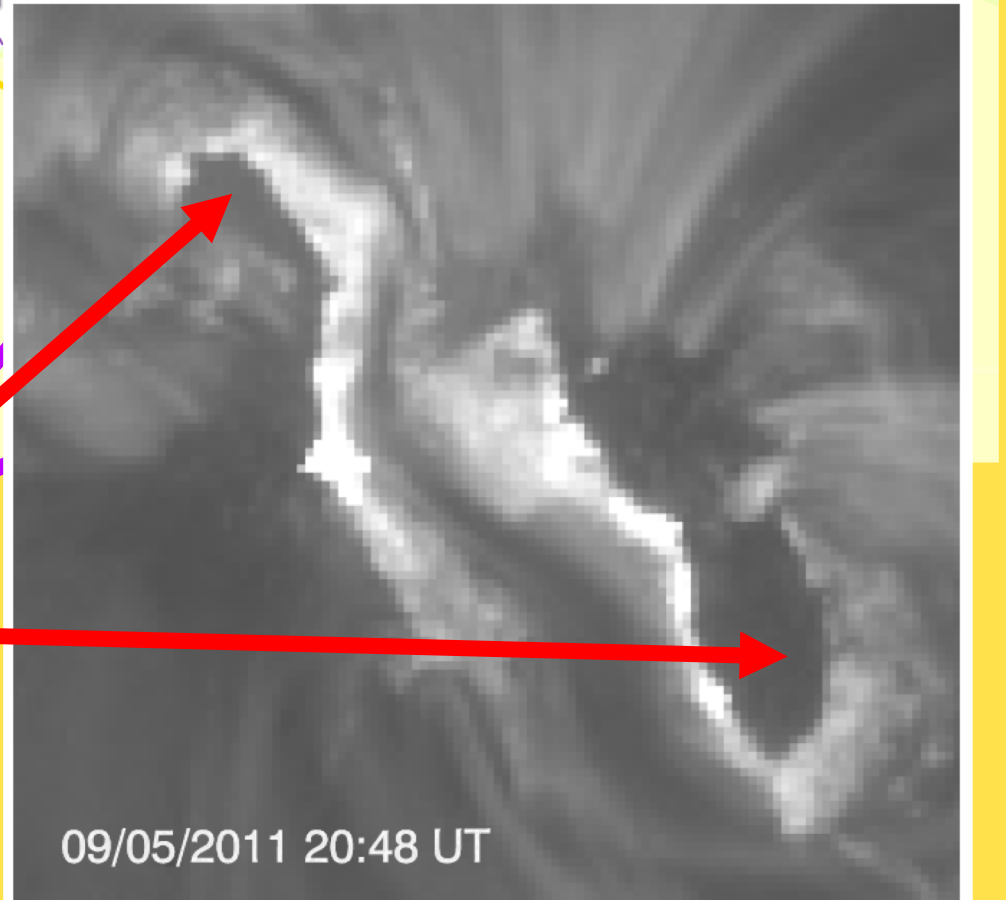
❖ Some flares at **quasi-separator,**
ribbons at feet of **quasi-separatrices (QSLs)**

– v similar to separator ∵ key is j buildup
[Mandrini97, Demoulin97, Aulanier06,
Pariat06, Titov07]

❖ "Standard 3D flare model"
[Aulanier 12, Janvier14]
QSL's (or separatrices) wrap around
flux rope to give a sigmoid –
feet have J-shapes w. hook-shaped ends,
which match the flare ribbons,

[Demoulin96, 97, Mandrini06,
Savcheva12, Janvier13, Kliem13]





Other 3D Effects

- Patchy reconn^{n} -> superarcade downflows
  [Mckenzie99, Longcope18, Awasthi21]

- In impulsive phase, bright knots form [Fletcher04].

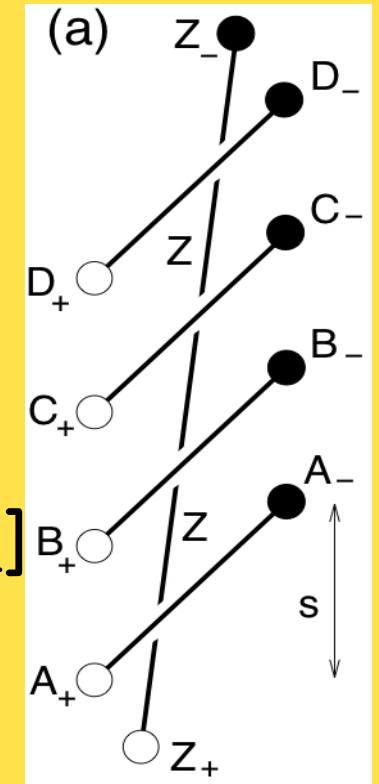
How spread along PIL to form flare ribbons while loop → arcade ?

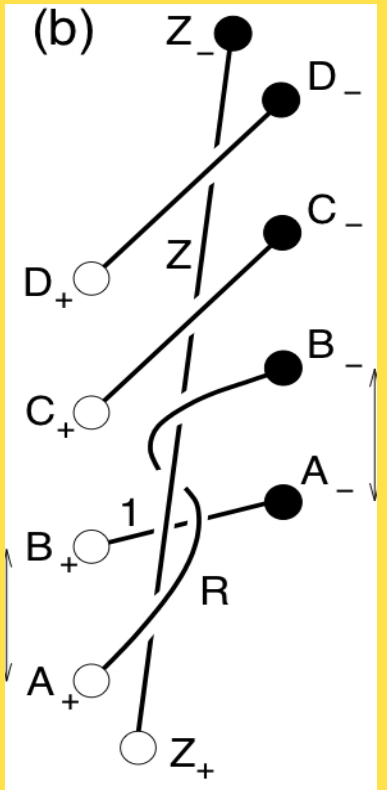
Zipper reconn^{n} spreads reconnection from on loop to another [P+Longcope18]

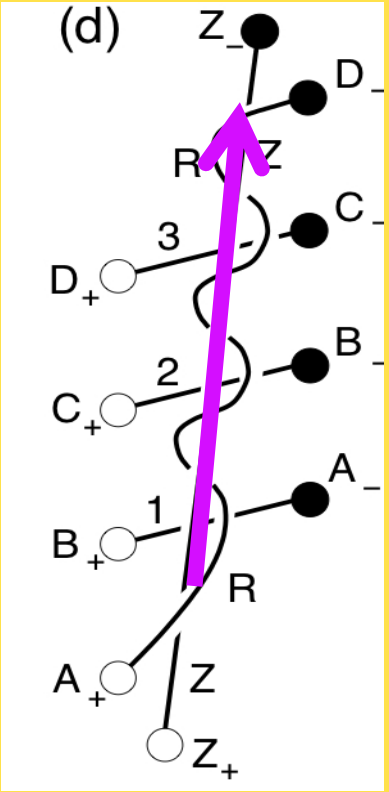
[A_+ A_- reconnects with B_+B_- (conserving mag^{c} hel^{y}) -> C_+C_- -> D_+D_-]

+ creates high-twist core + ribbons


[Mckenzie09]

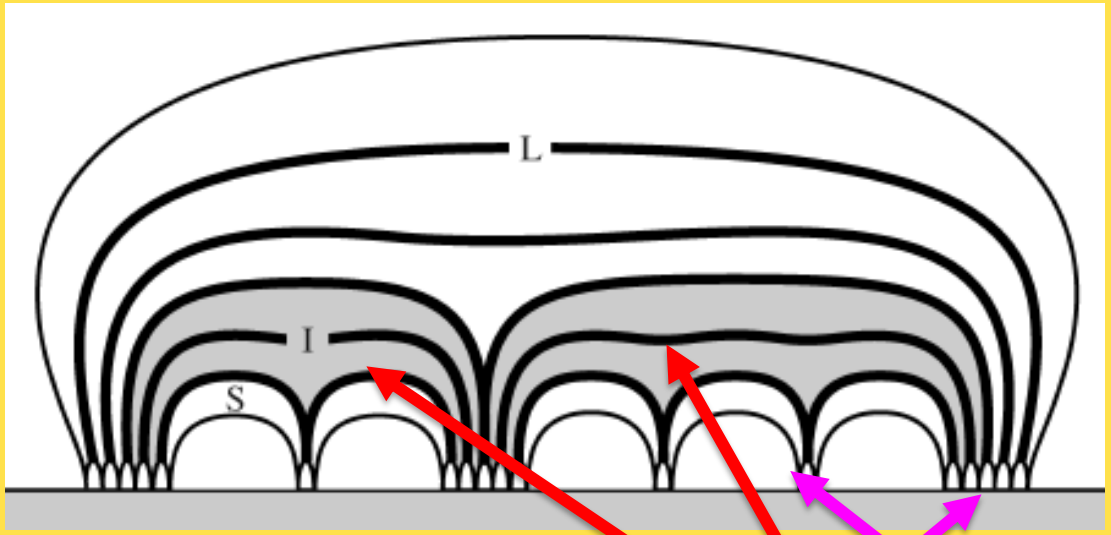


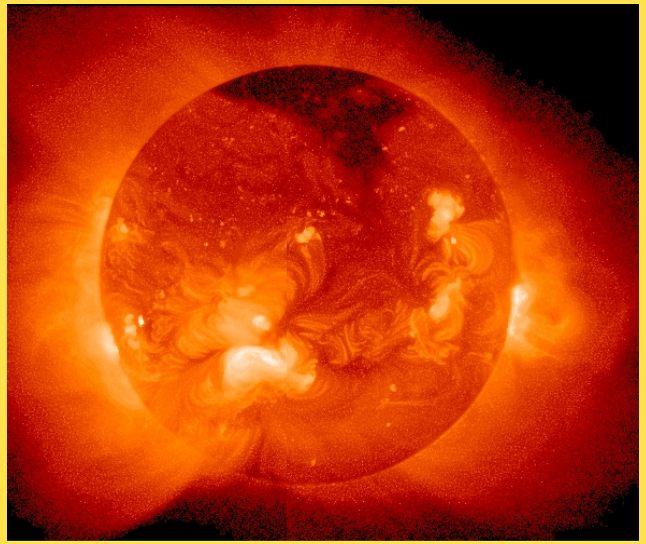




5. Coronal Heating

Coronal Tectonics Model





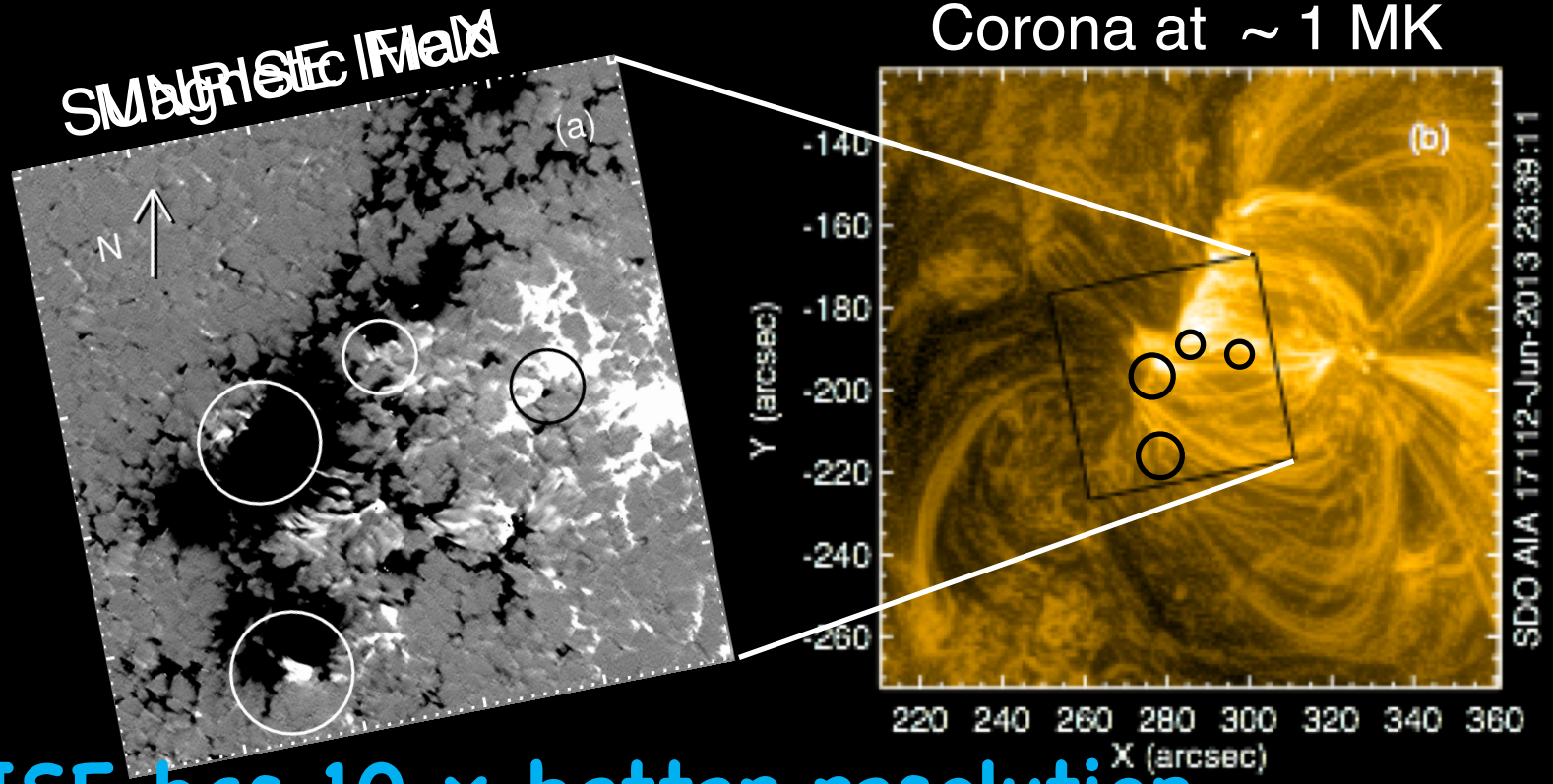
[Priest, Heyvaerts, Title]

- B comes through solar surface in many **sources:**
- flux from each source separated by separatrix surfaces & QSLs
- motions of sources → **j sheets** at these surfaces
- → dissipate by **reconnection** as **"nanoflares"** [Parker]

[see also Danilovic, Dadashi, Milanovic, Joshi, Antolin talks]

Chitta, Peter et al: (2017) region of newly emerging flux

With SUNRISE balloon mission (Solanki et al)



SUNRISE has 10 x better resolution

→ Reconnection at feet

Mixed polarities cancel at photosphere

When mixed polarities cancel & field at coronal loops brighten,

repeats coronal & chromospheric loops

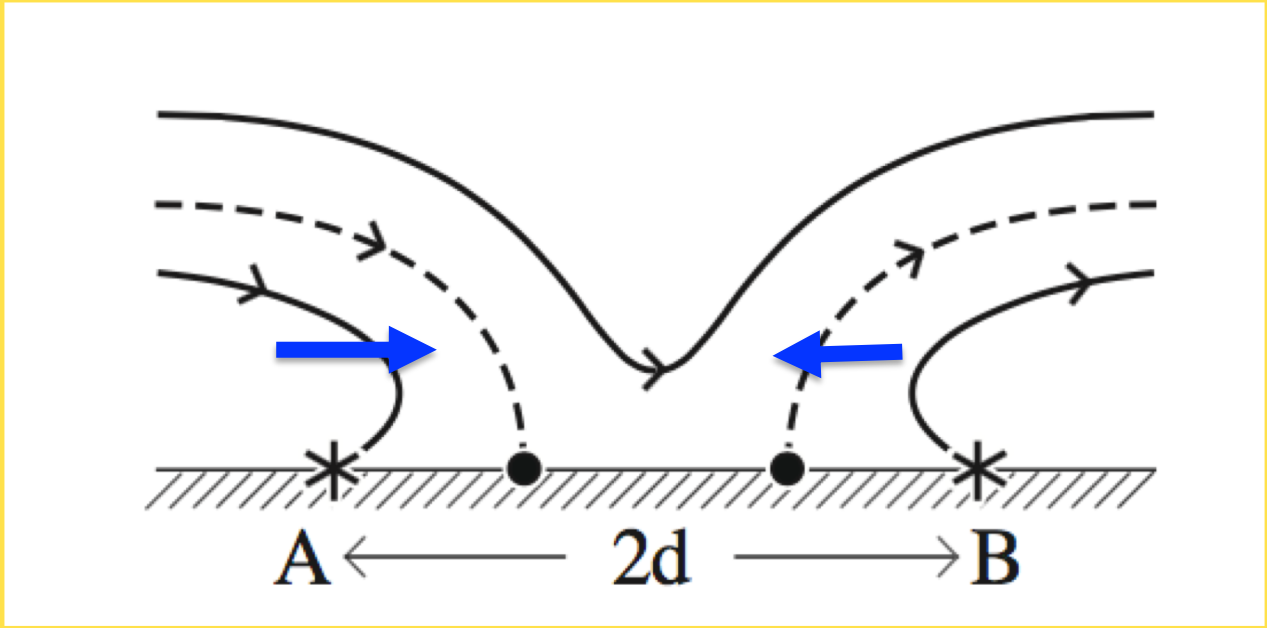
SPECTACULAR DISCOVERY

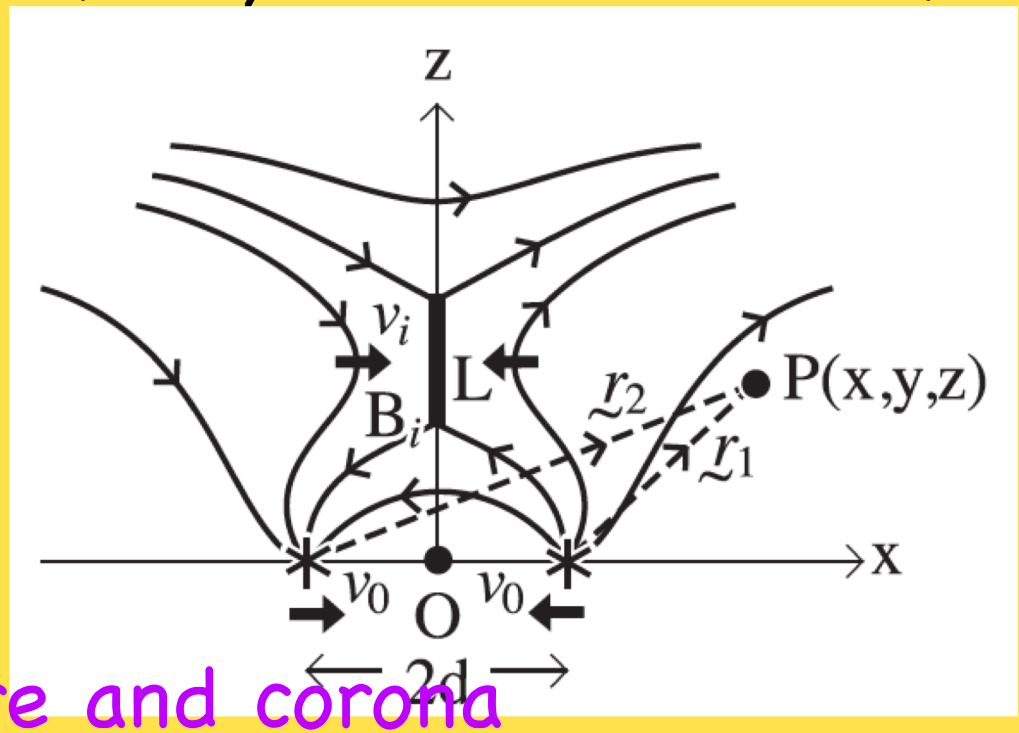
So flux cancellation is much more common than thought.

Important for Ellerman bombs [Rouppe16; Hansteen17], UV bursts [Peter14], for Chromospheric & Coronal Heating

"Cancellation Nanoflare Model": [Priest,Chitta,Syntelis, 2018; Syntelis 21]

when 2 flux sources approach one another, they drive reconnection,





Heating is sufficient for chromosphere and corona

[Chitta18, Chitta20, Peter19, Syntelis19]

CONCLUSION

Reconnection offers many intriguing questions whose answers -> deeper understanding - theoretical, computational, observational

[For more details, see reviews by
Ting Li, Priest & Guo (2021) Proc Roy Soc 477,
Pontin & Priest (2021) Liv Rev Solar Phys]

So let's continue to enjoy challenge & beauty of our amazing Sun