UCLA

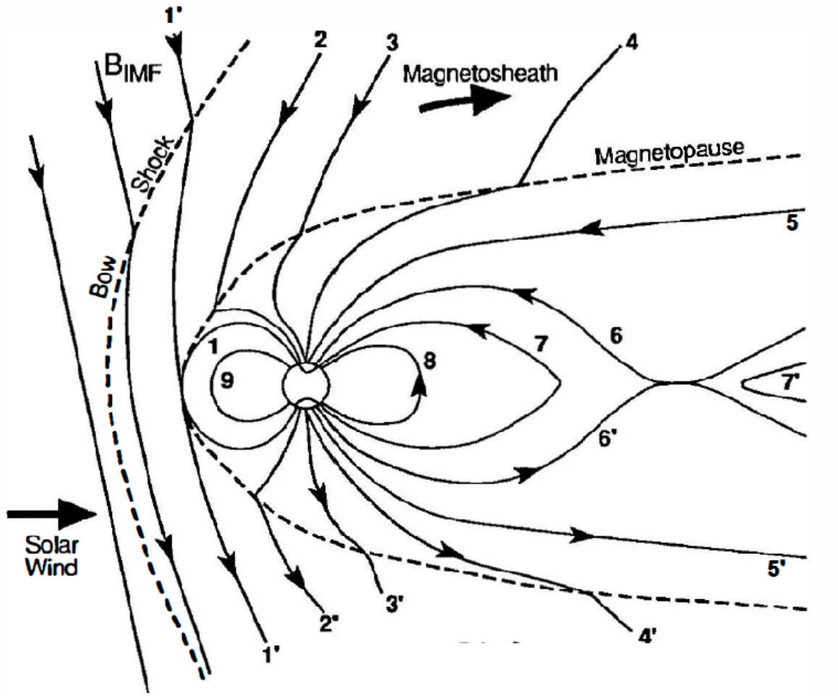
Flux rope interactions in the magnetosphere and beyond

Y. Qi, C. T. Russell, Y.-D. Jia, X. Y. Wang, Y. Lin, S. Lu

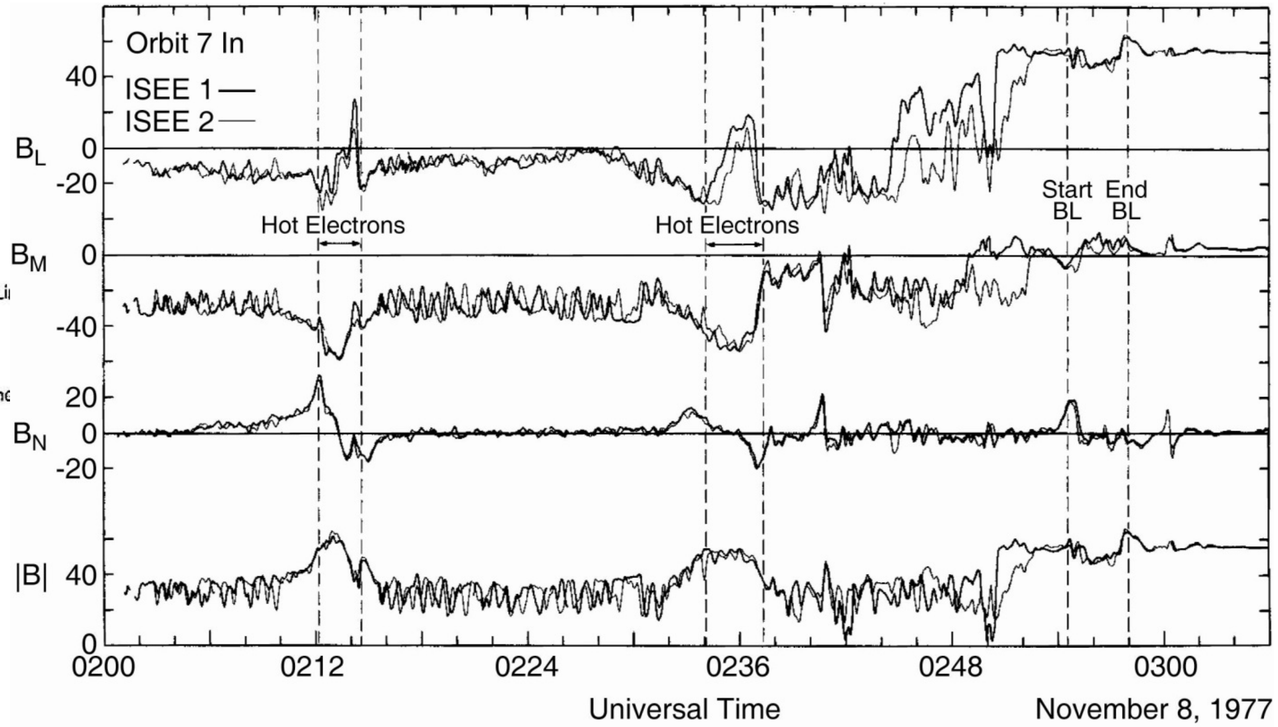
Presented by Yi Qi
April 7th, 2021

Magnetic reconnection at the Earth and Flux Transfer Events (FTEs)

- Dungey cycle: the global convention enabled by magnetic reconnection



Kivelson and Russell , 1995



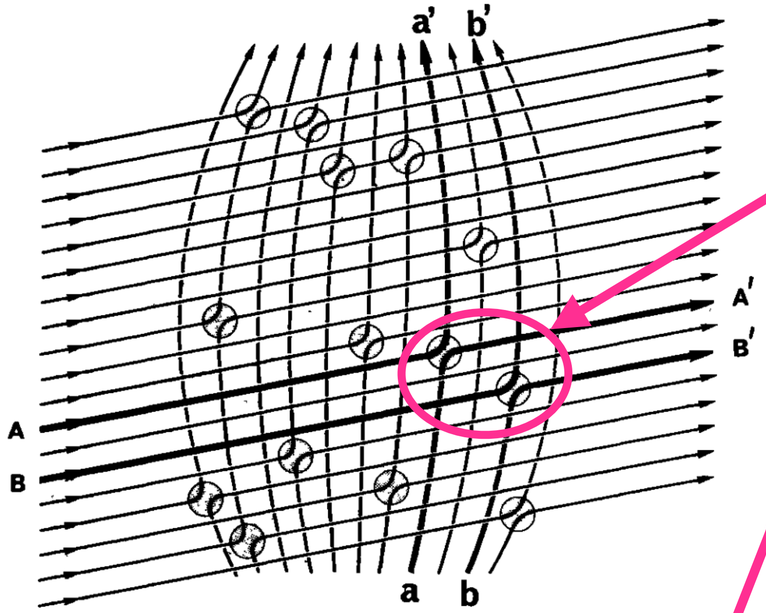
Russell and Elphic, 1978

- The first observation of magnetic flux ropes near the magnetopause by ISEE 1 and 2 spacecraft (Russell and Elphic, 1978)

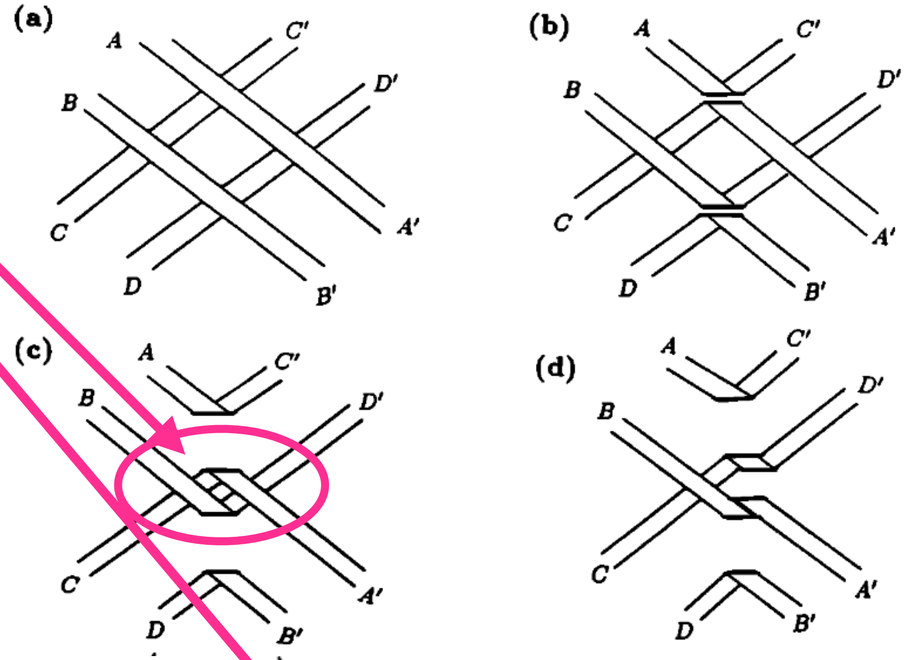
- Since these flux ropes were moving and contained magnetic flux (about 20 MWb here), we called them flux transfer events (FTEs).

Flux tube entanglement: interlinking and generating new flux tube pairs through magnetic reconnection

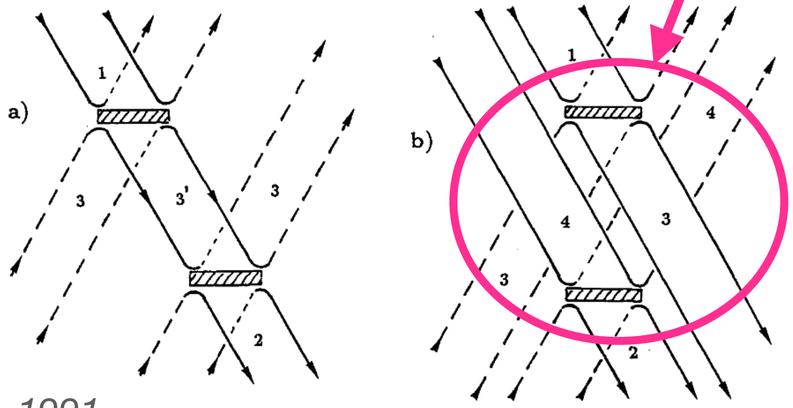
Nishida et al., 1989



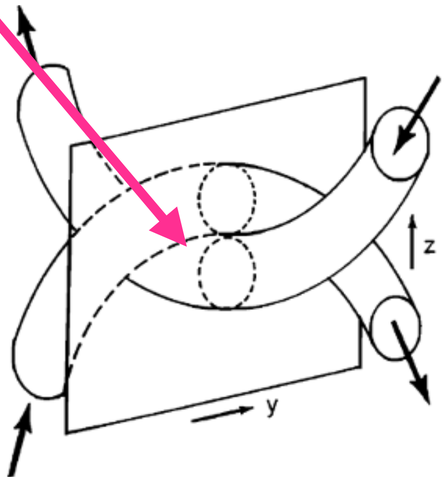
Lee et al., 1993



Entanglement



Otto et al., 1991

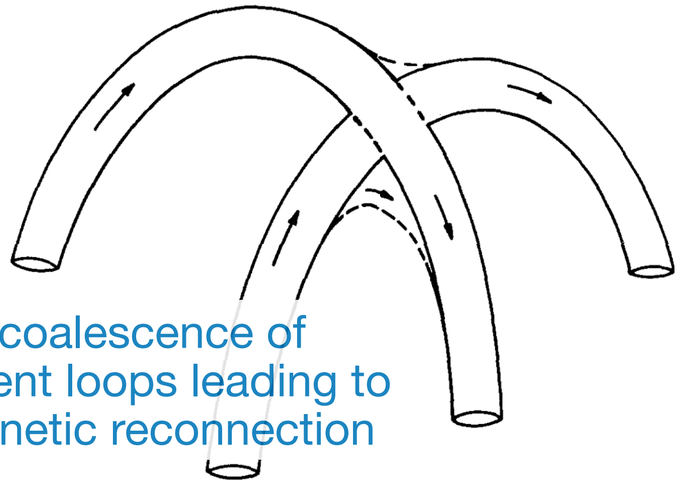


Hesse et al., 1990

Magnetic reconnection in solar corona

- It has been proposed that the **solar flares** were triggered by an observed **interaction of two or more flux tubes** leading to **magnetic reconnection** (Frazier & Stenflo 1972; Kiplinger et al. 1983 ; Hanaoka 1994 ; and Falewicz & Rudawy 1999; Linton et al., 2001)

- The collision and reconnection of flux tubes could be involved in**:**
  - Two ribbon flares (Sturrock et al. 1984 ; Machado et al. 1993 ; Klimchuk 1997)
  - X-ray-bright points (Priest, Parnell, & Martin 1994)
  - Compact flares (Jakimiec et al. 1998)



The coalescence of current loops leading to magnetic reconnection

Fig. 1. Geometrical model of the interaction of two post-flare coronal loop

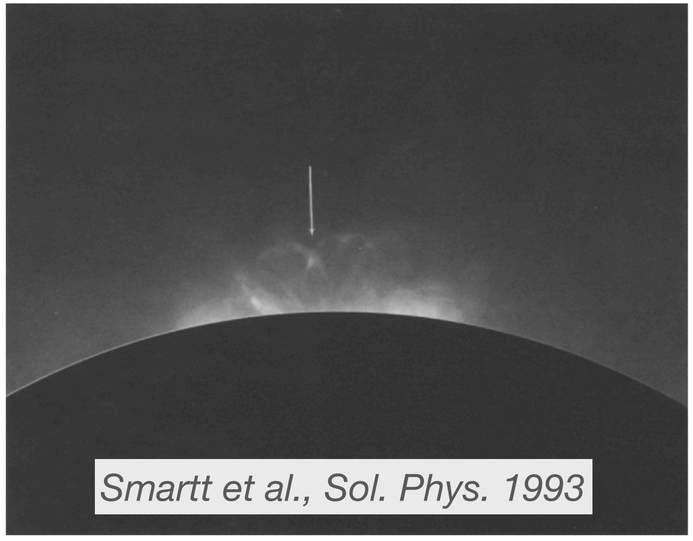
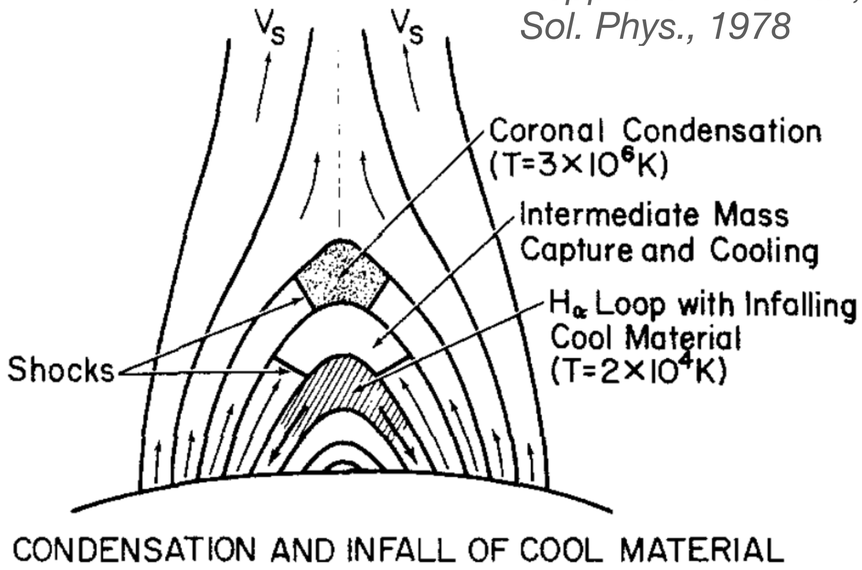


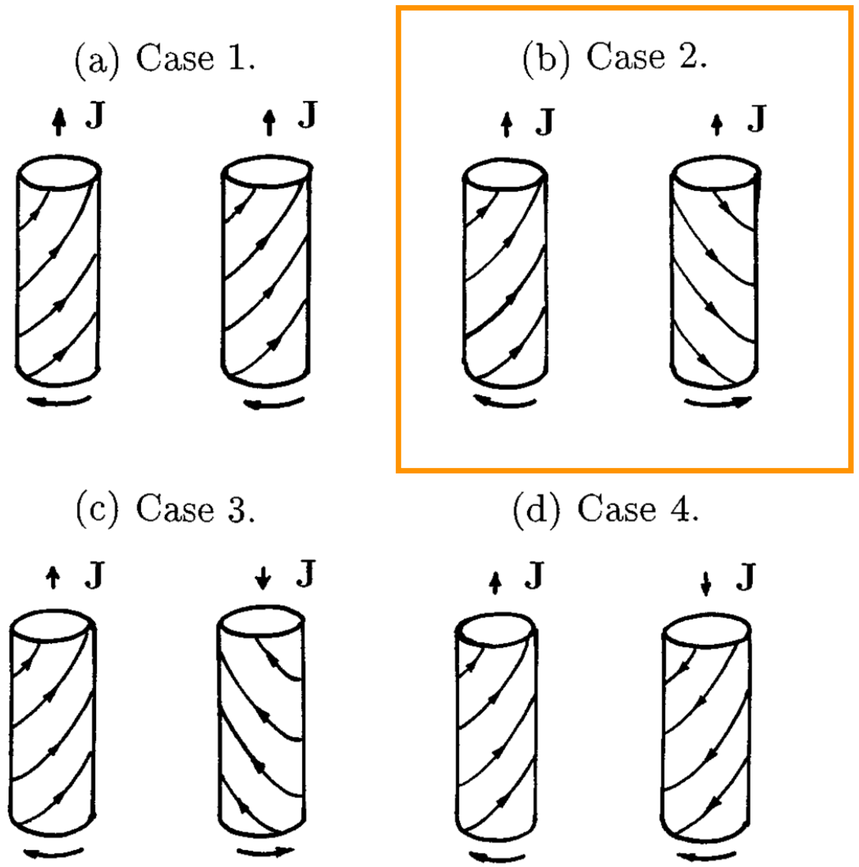
Fig. 2. Post-flare loop system of 28 April, 1990, recorded in the emission of the green coronal line (5303 Å; Fe XIV). The enhancement, indicated by an arrow, is at a height of 6×10^4 km above the limb.

Kopp and Pneuman, Sol. Phys., 1978



Schematic of the entire loop prominence system during the **reconnection** process

Early studies on the flux tube interaction in solar corona 1



Case	1	2	3	4
Current	Attracting	Attracting	Repelling	Repelling
B_z	Parallel	Opposite	Parallel	Opposite
Helicity injection	Yes	Zero or small	Zero or small	Yes
Final state force-free	Yes	No	Yes	No
Reconnection	No	Yes	No	Yes[a]
Magnetic nulls	No	Yes	No	No
Closed field lines	No	Yes	No	Yes

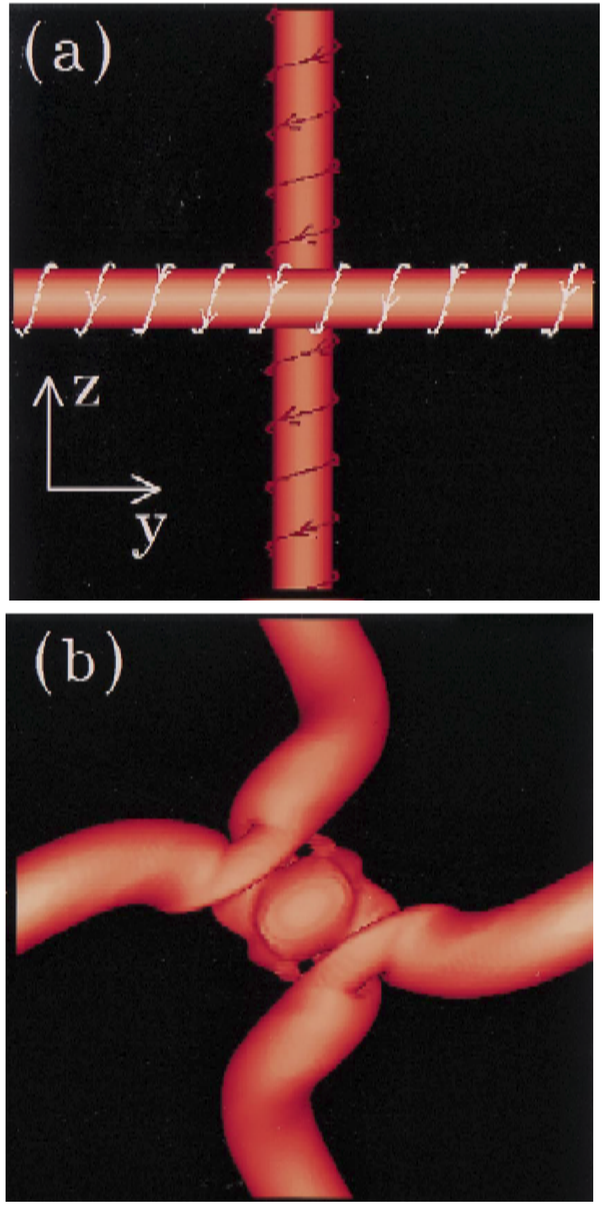
[a]Flux merging in case 4 occurs at the boundary.

- Depending on **the direction of the twist (helicity)** and **the relative signs of the longitudinal magnetic field Bz** , the system falls into four classes

Y -T Lau et al., PoP 1996

Early studies on the flux tube interaction in solar corona 2

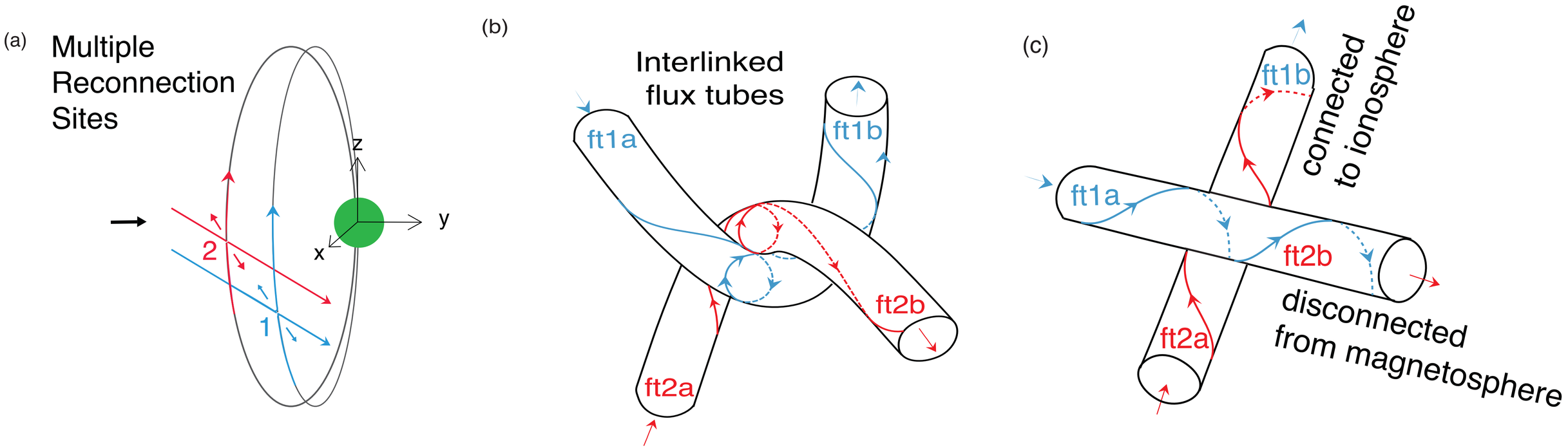
- Linton et al., The Astrophysical Journal, 2001
  - Different **angles** between the colliding flux tubes
  - Co- or counter-**helicity** flux tubes
  - Four classes of interaction:
    - **Bounce** (no appreciable reconnection)
    - **Merge**
    - **Slingshot** (The most efficient reconnection)
    - **Tunnel** (a double reconnection)



Linton et al., 2001

Flux tube entanglement has been seen by MMS at the Earth

- Flux tube entanglement and reconnection at the interface has been observed by the MMS (Kacem et al., 2018; Øieroset et al., 2019; Fargette et al., 2020; Hwang, Dokgo et al., 2020; Kieokaew et al., 2020)



[Russell and Qi, 2020 GRL]

Geophysical Research Letters

Research Letter | Full Access

Temporal Evolution of Flux Tube Entanglement at the Magnetopause as Observed by the MMS Satellites

Y. Qi, C. T. Russell, Ying-Dong Jia, M. Hubbert

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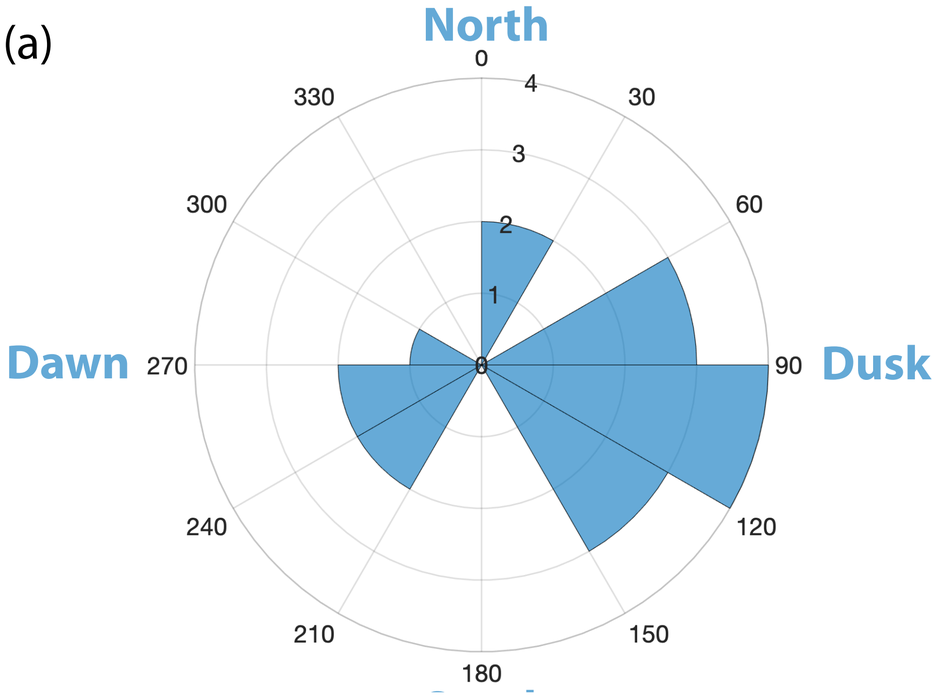
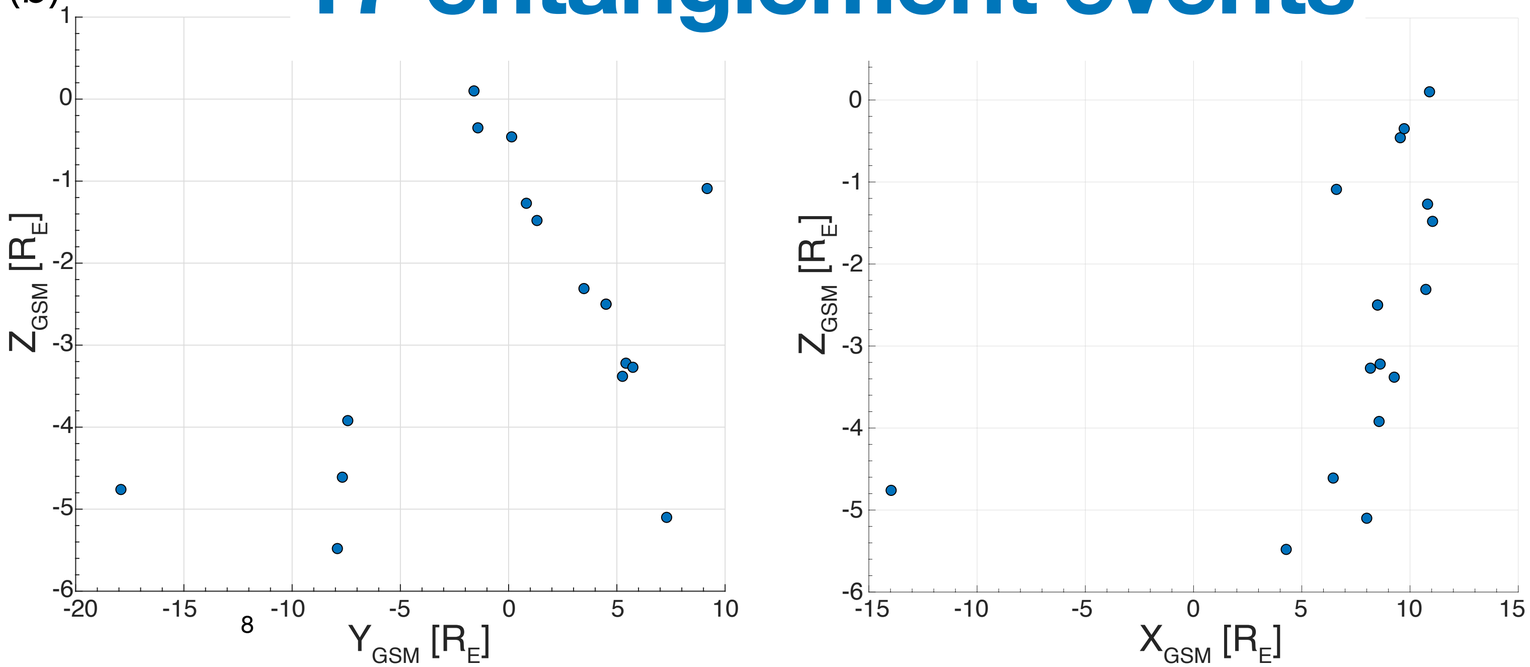
- A significant increase in both magnetic field strength and total pressure (the sum of plasma thermal pressure nkT and magnetic pressure $B2/(2\mu 0)$) ($\Delta Ptot \gtrsim 50\%$)
- A sharp rotation of the magnetic field (i.e., a thin current sheet) around the maximum pressure location (the current duration < 25%)
- A sudden change in the electron pitch-angle distribution across the central current sheet

(a)

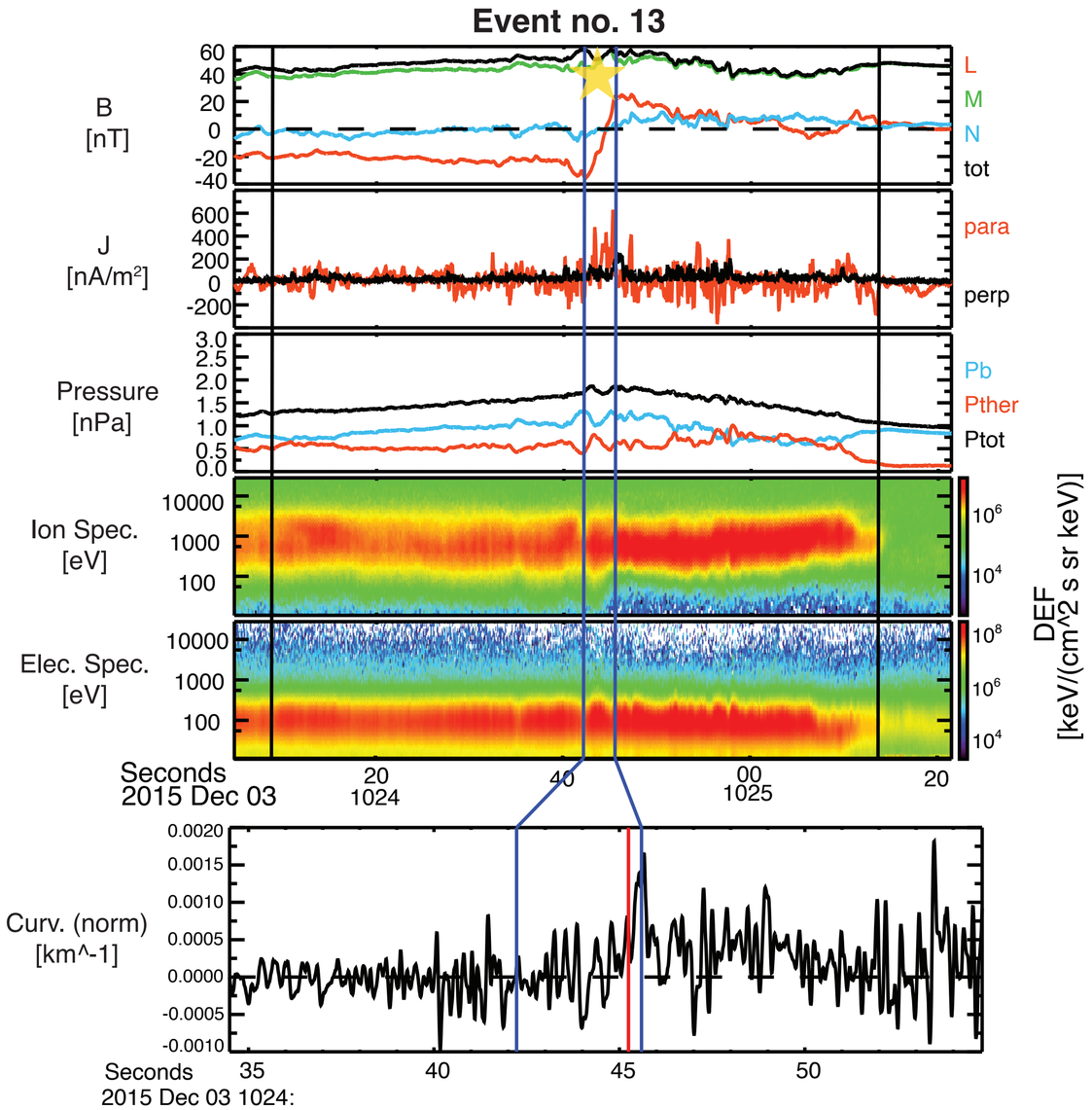


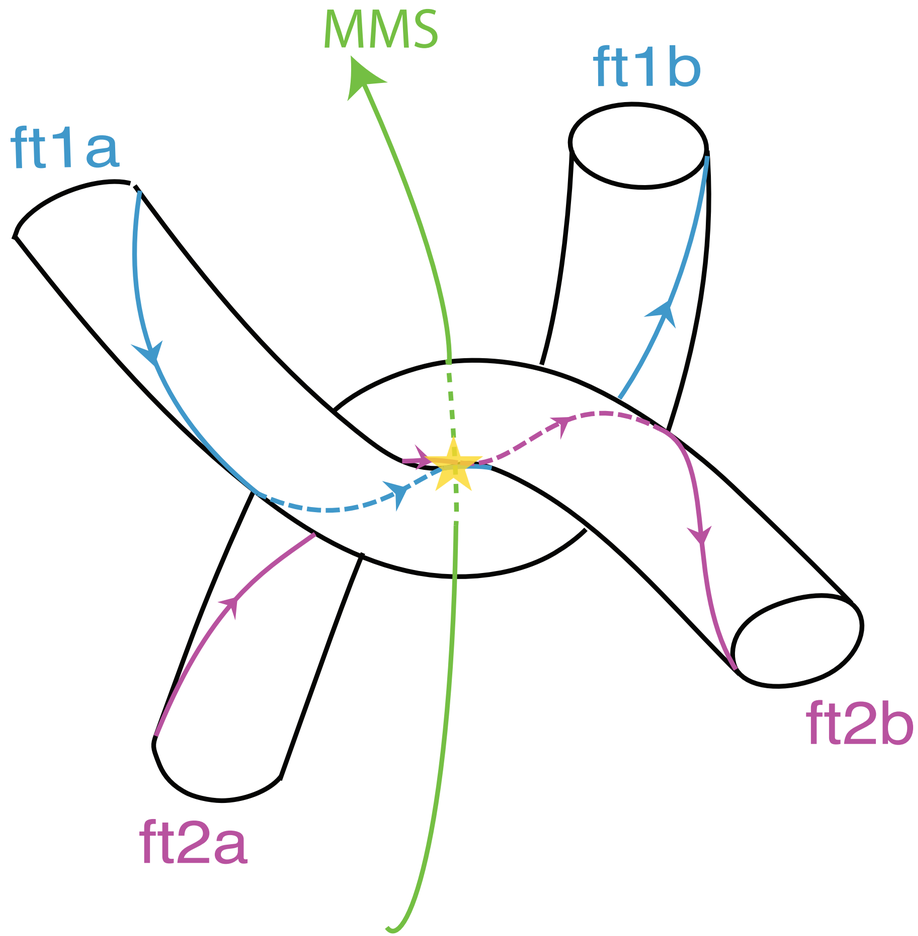
17 entanglement events

(b)

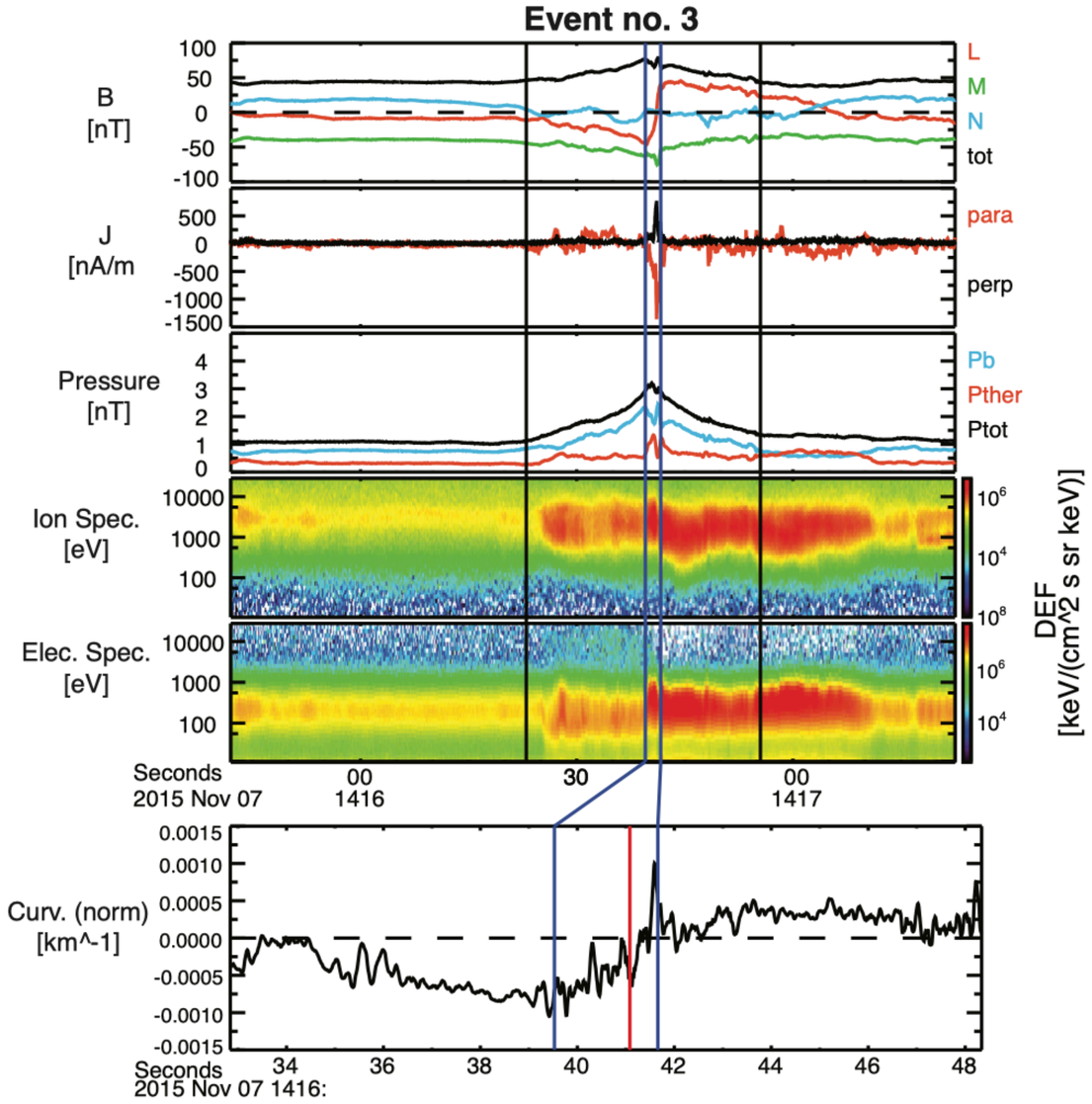


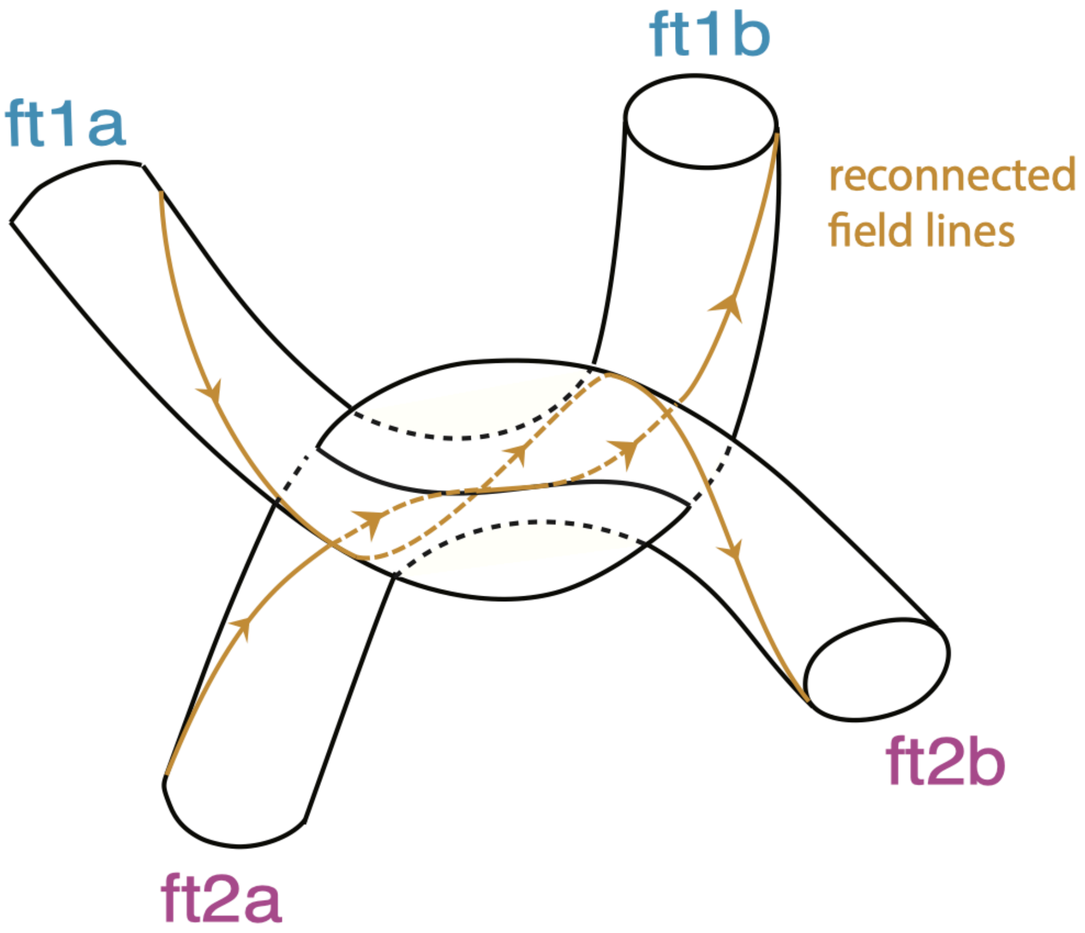
Early Stage


Event no. 13
B [nT]
L
M
N
tot
J [nA/m²]
para
perp
Pressure [nPa]
Pb
Pther
Ptot
Ion Spec. [eV]
Elec. Spec. [eV]
DEF [keV/(cm^2 s sr keV)]
Seconds
2015 Dec 03
1024
1025
Curv. (norm) [km^-1]
Seconds
2015 Dec 03 1024:

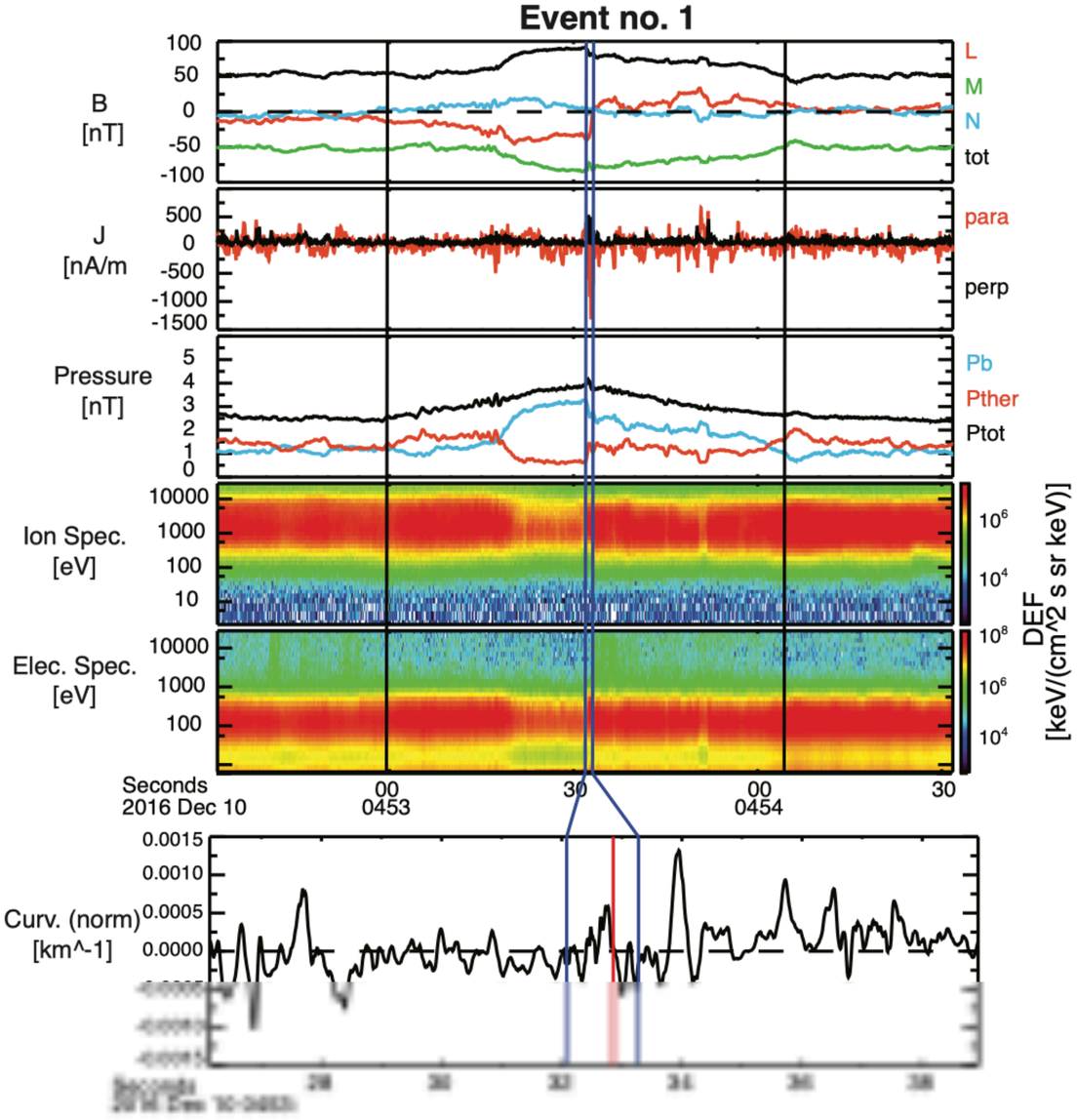

MMS
ft1b
ft1a
ft2b
ft2a

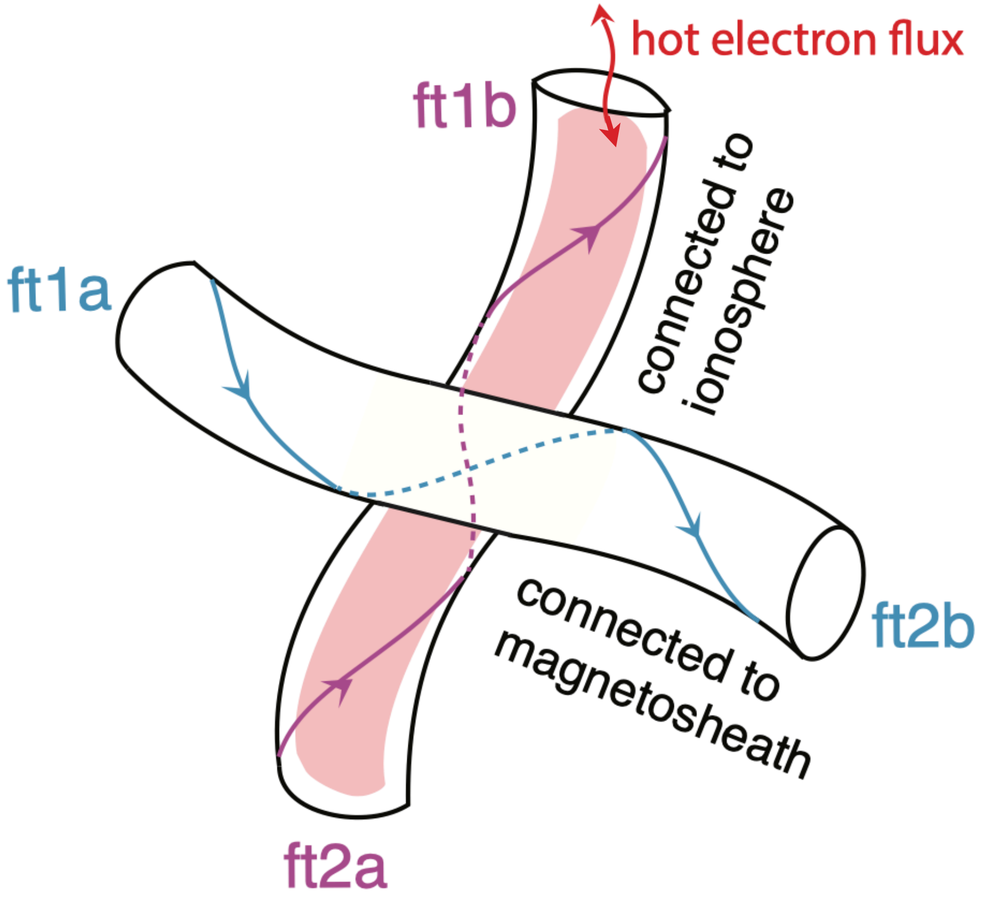
Mid Stage


Event no. 3
B [nT]
L
M
N
tot
J [nA/m
para
perp
Pressure [nT]
Pb
Pther
Ptot
Ion Spec. [eV]
Elec. Spec. [eV]
DEF [keV/(cm^2 s sr keV)]
Seconds
2015 Nov 07
00 1416
30
00 1417
Curv. (norm) [km^-1]
Seconds
2015 Nov 07 1416:


ft1b
ft1a
reconnected field lines
ft2b
ft2a

Late stage


Event no. 1
B [nT]
100
50
0
-50
-100
L
M
N
tot
J [nA/m
500
0
-500
-1000
-1500
para
perp
Pressure [nT]
5
4
3
2
1
0
Pb
Pther
Ptot
Ion Spec. [eV]
10000
1000
100
10
Elec. Spec. [eV]
10000
1000
100
DEF [keV/(cm^2 s sr keV)]
Seconds
2016 Dec 10
00
0453
30
00
0454
30
Curv. (norm) [km^-1]
0.0015
0.0010
0.0005
0.0000


hot electron flux
ft1b
connected to ionosphere
ft1a
ft2b
connected to magnetosheath
ft2a

8 events can be identified as one of the three stages

No.	Date	Time	Duration [sec]	V_cs [km/s]	CS Duration [sec]	CS Ratio [%]	CS Width [km]	Stage
9	2015-12-08	10:27:40	26	222.7	3.50	5.20	202.66	Early
13	2015-12-03	10:24:00	53	73.1	6.36	5.04	246.35	Early
6	2015-11-21	01:56:50	99	72	3.65	3.58	259.92	Mid
3	2015-11-07	14:16:42	33	90.1	6.46	6.36	191.91	Mid
11	2015-11-06	13:24:00	58	113.8	5.12	6.44	337.99	Mid
1	2016-12-10	04:53:32	65	54.5	1.85	1.83	65.40	Late
8	2016-12-28	04:59:18	34	130.2	2.32	2.49	102.86	Late
14	2016-01-18	01:23:00	65	67.7	1.29	3.50	56.87	Late

JGR Space Physics

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Temporal Evolution of Flux Rope/Tube Entanglement in 3-D Hall MHD Simulations

Ying-Dong Jia ✉, Yi Qi, San Lu, C. T. Russell

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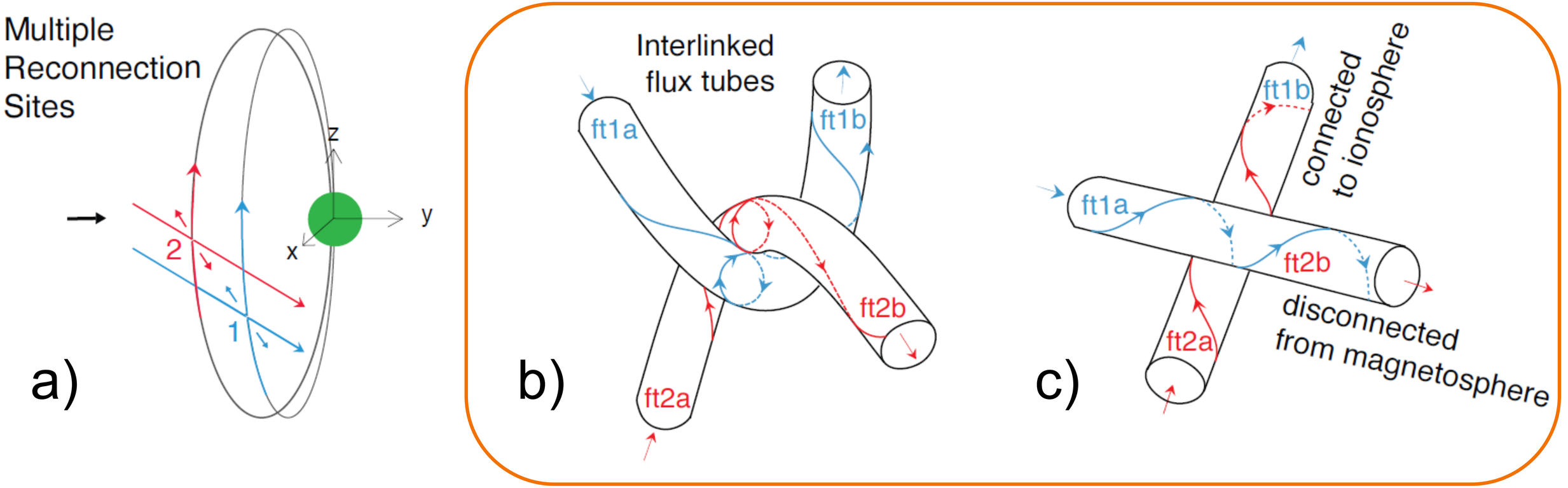
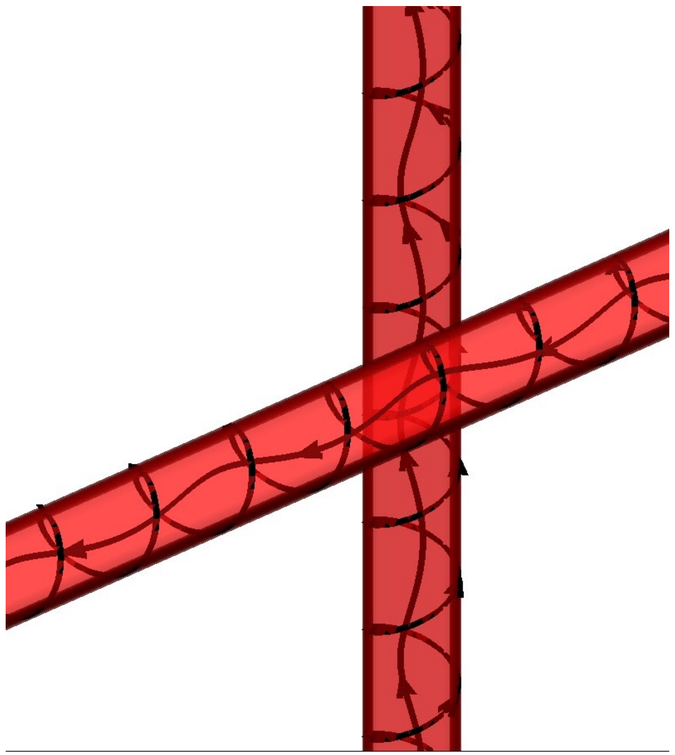
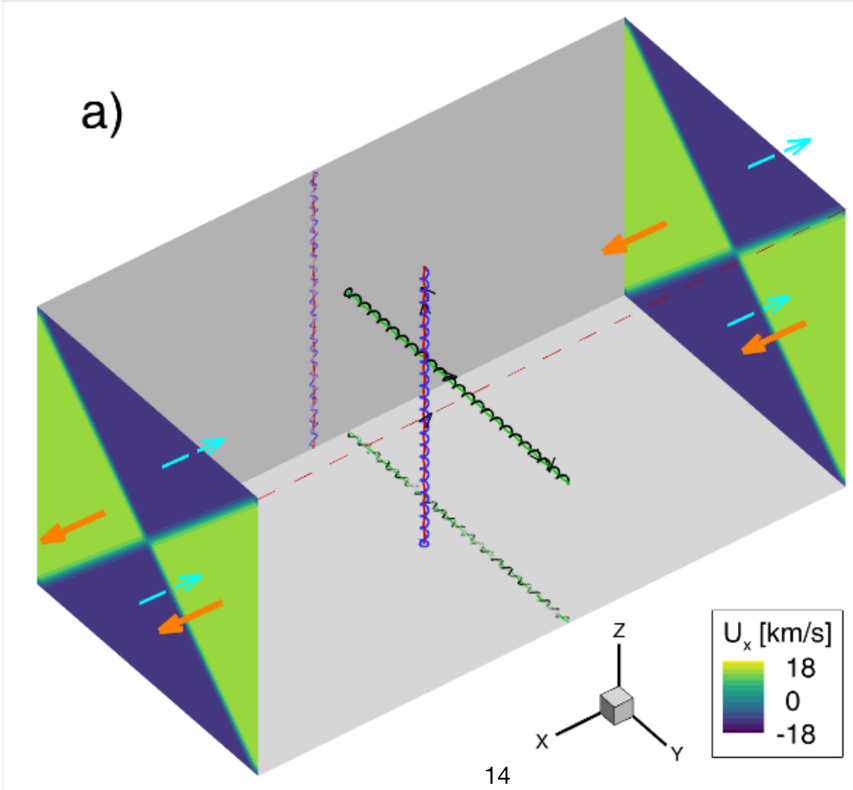


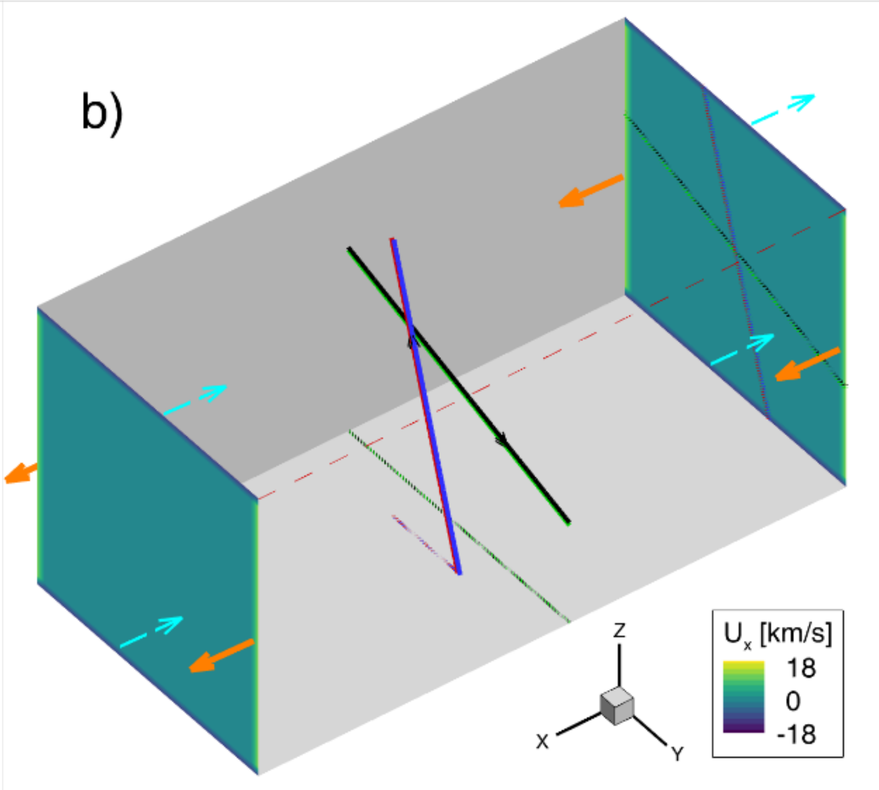
Questions to be answered

? Can flux ropes/flux tubes reconnect?

? Is the process driven by the ambient plasma or by magnetic tension force from the far end of the ropes?

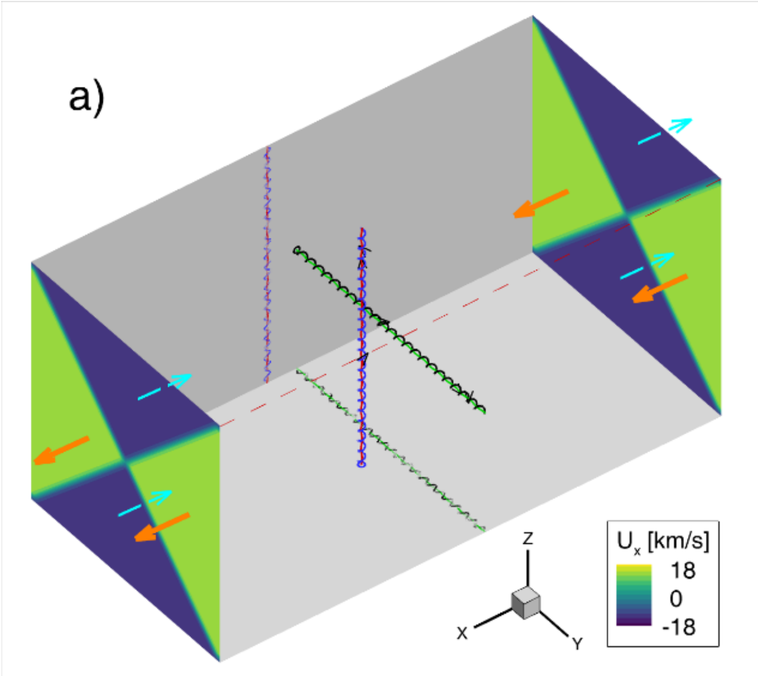


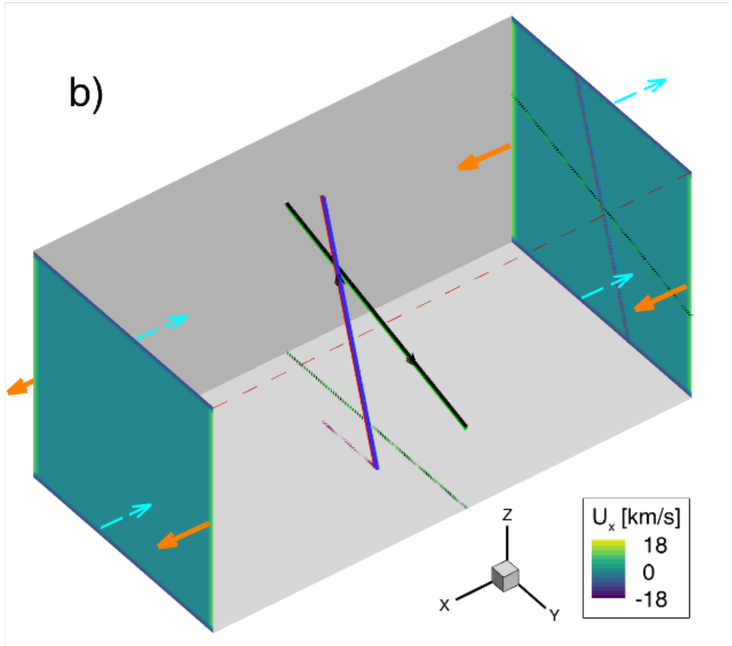




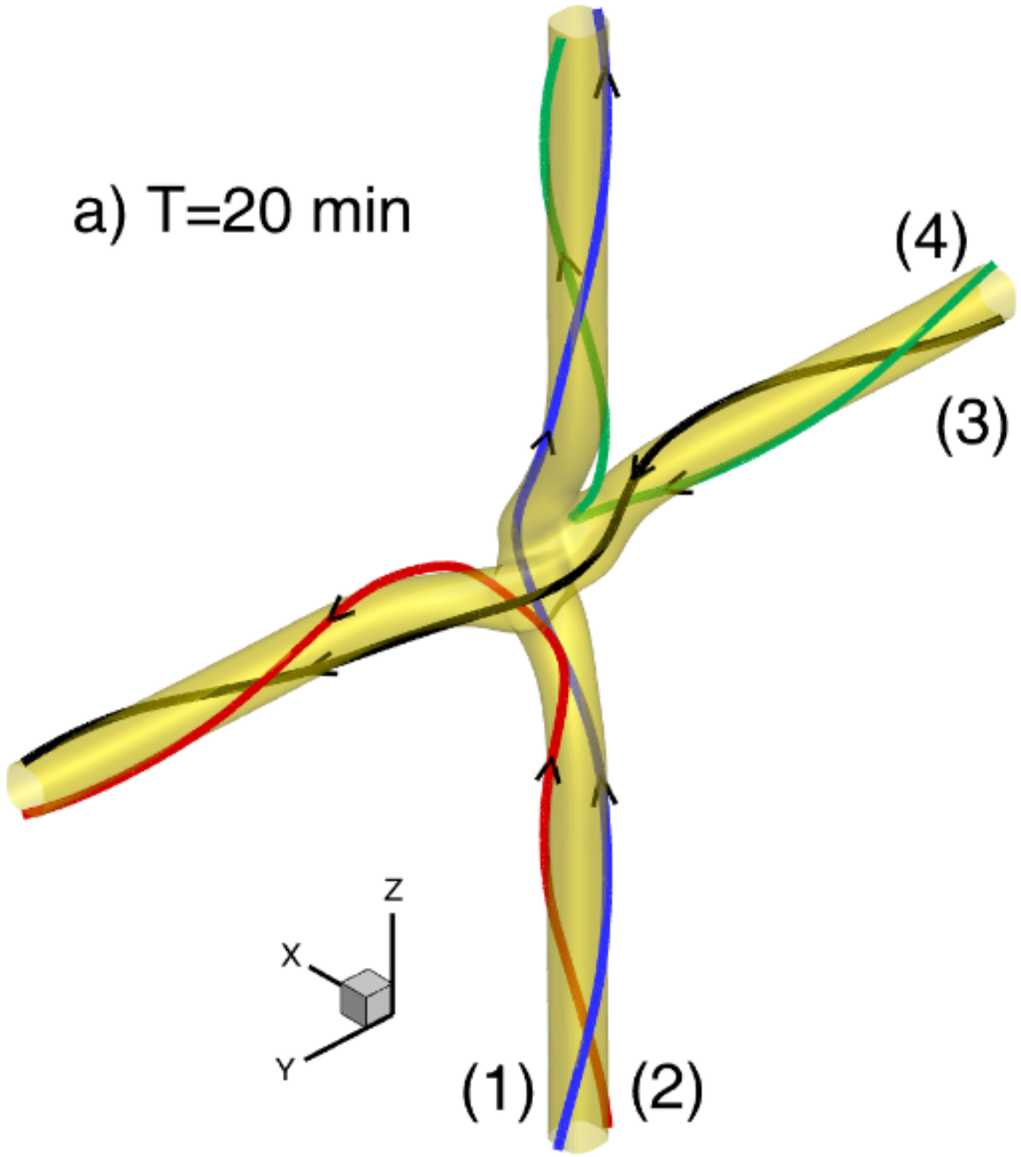
4 different cases

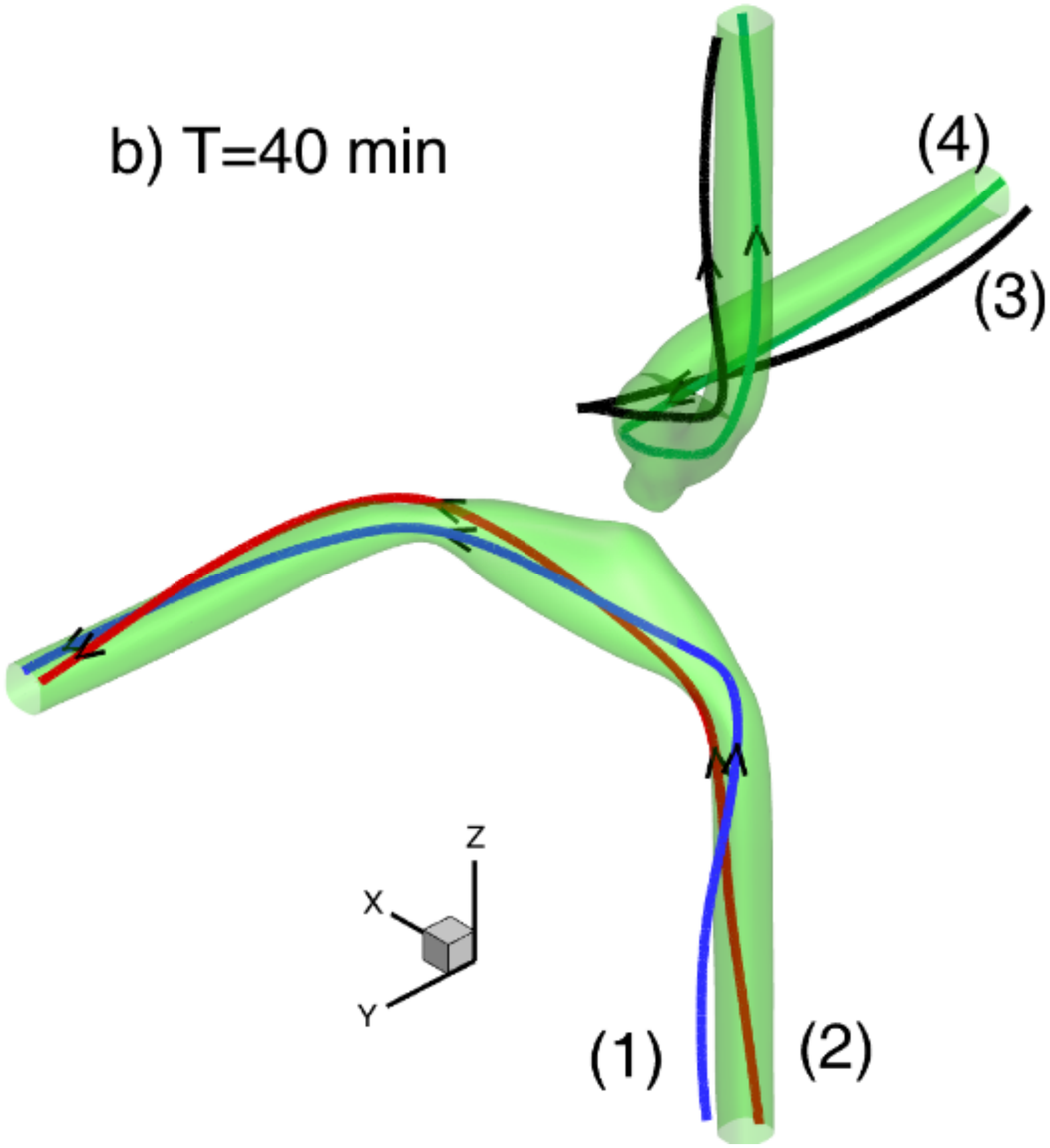
	BC case A Dynamic pressure	BC case B Tension force
IC type 1: Flux rope	Case A1	Case B1
IC type 2: Bφ = 0 Flux tube	Case A2	Case B2



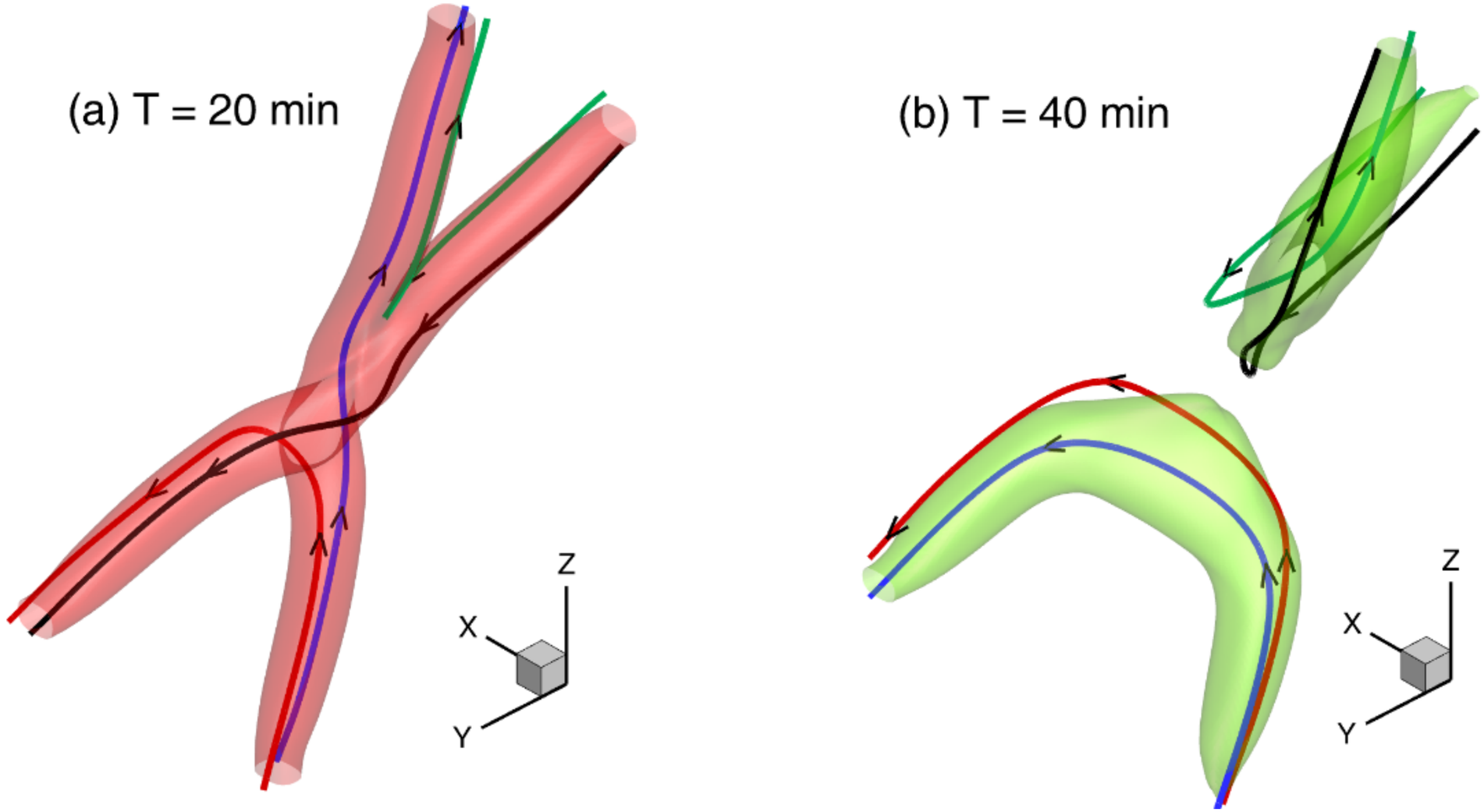


Entangled flux ropes: reconnection occurs successfully





Entangled flux tubes: reconnection still occurs

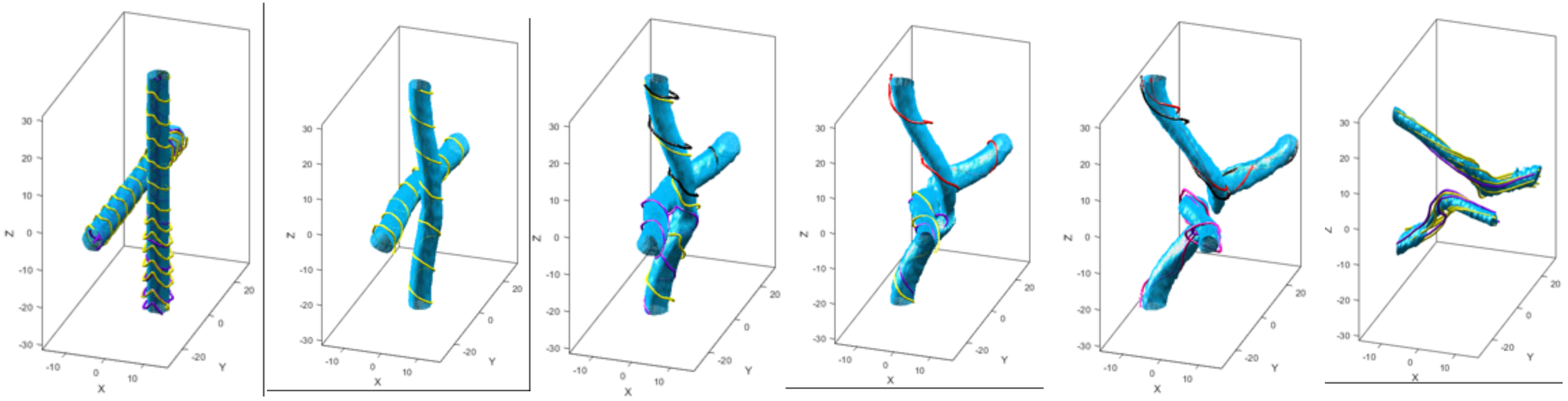


Hybrid simulation went through similar processes

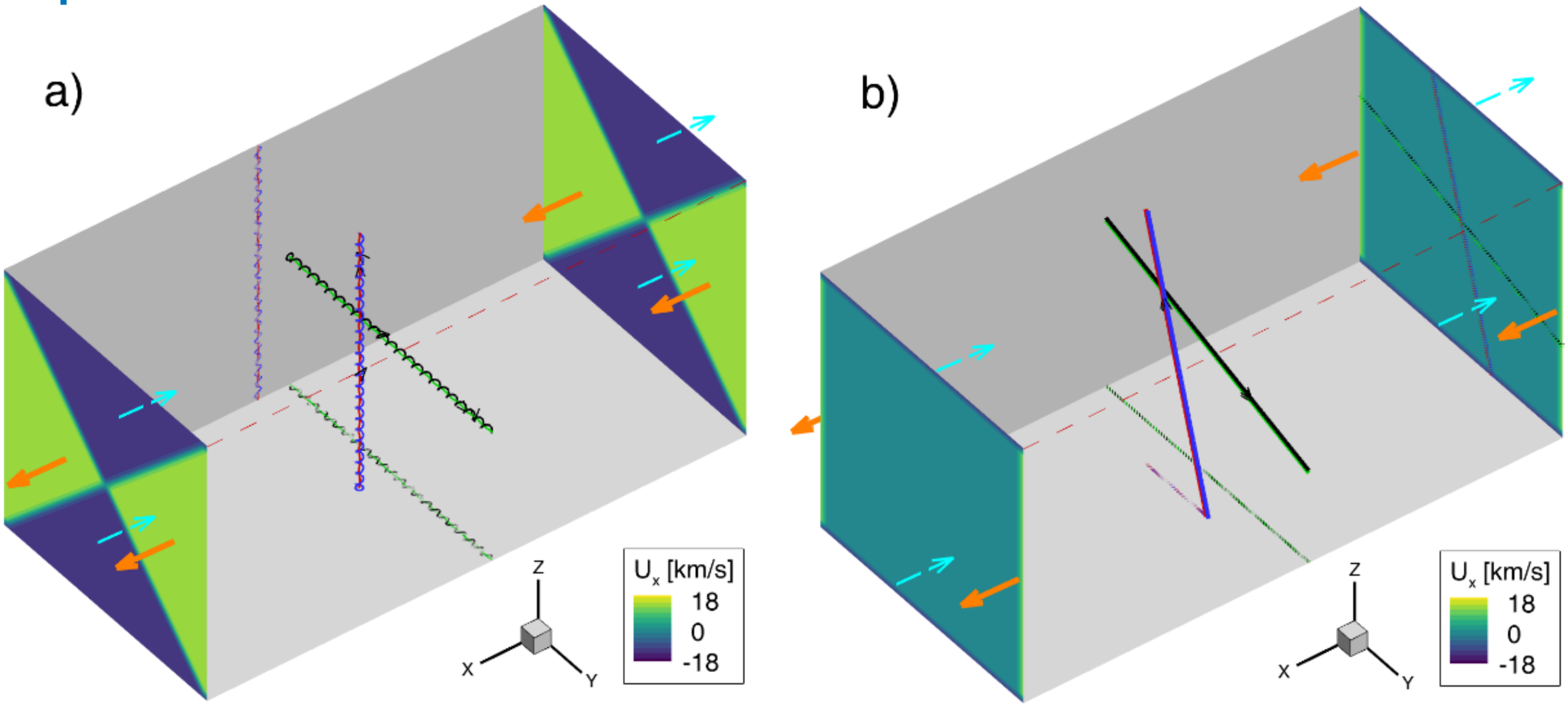
3D Cartisien Nx*Ny*Nz = 160*80*80
Number particles/cell = 200
Lx*Ly*Lz = 80*60*60 (d_i)
β=4, Corresponding to B_0=10nT, n_i=10/cc T_i=100eV

Initial setup: plasma = uniform Ni & Ti
Magnetic field = zero background + flux tubes
Boundary condition: x fix; y & z periodic
Driven flow velocity=0.2V_{A0}

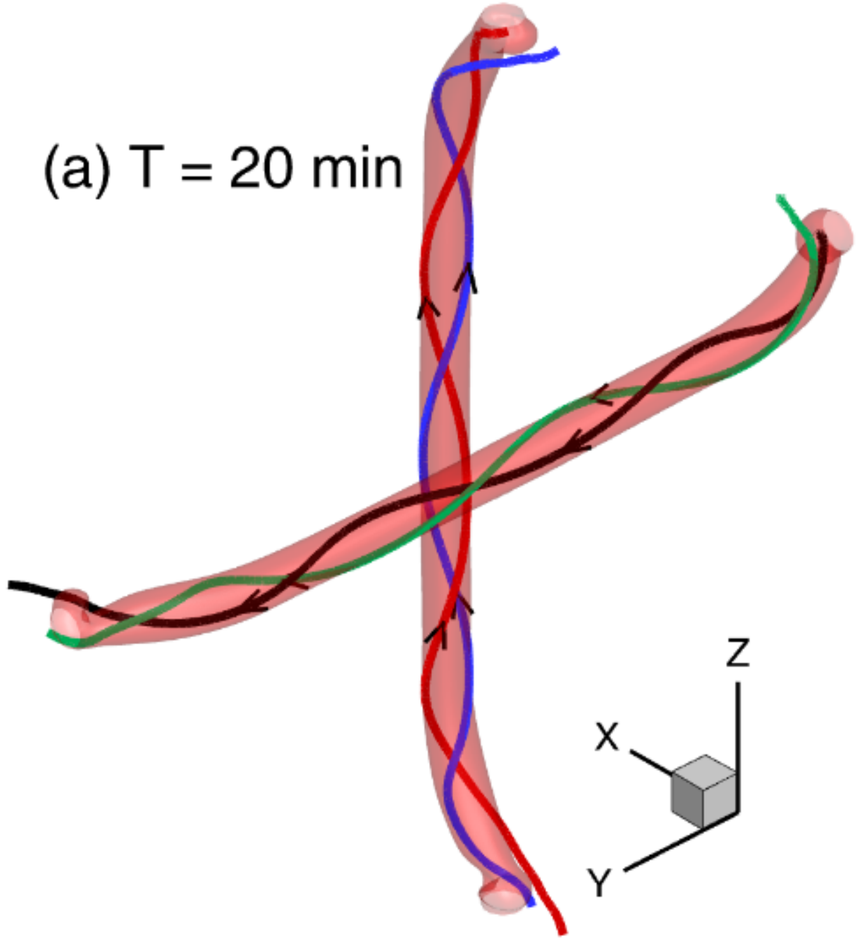
$\Omega_i t$ =4 44 88 132 176 280

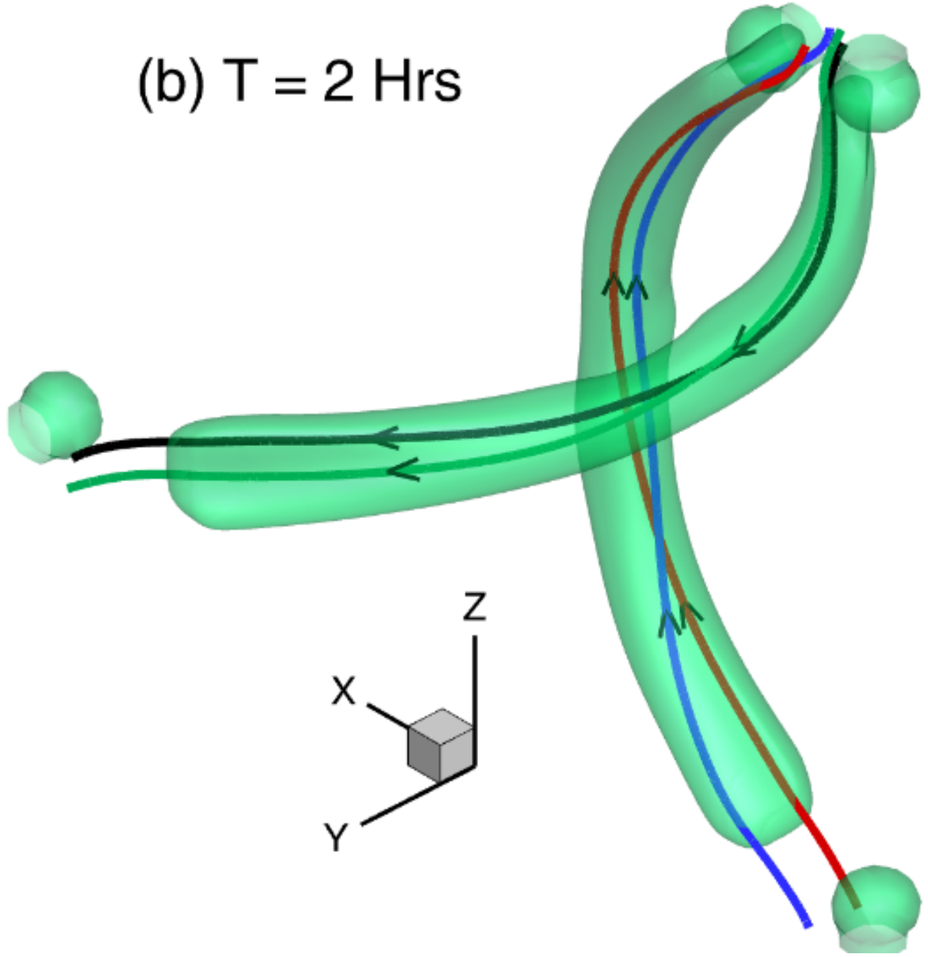


Cases 3 and 4: Different Boundary Conditions: only move the foot points of the tubes



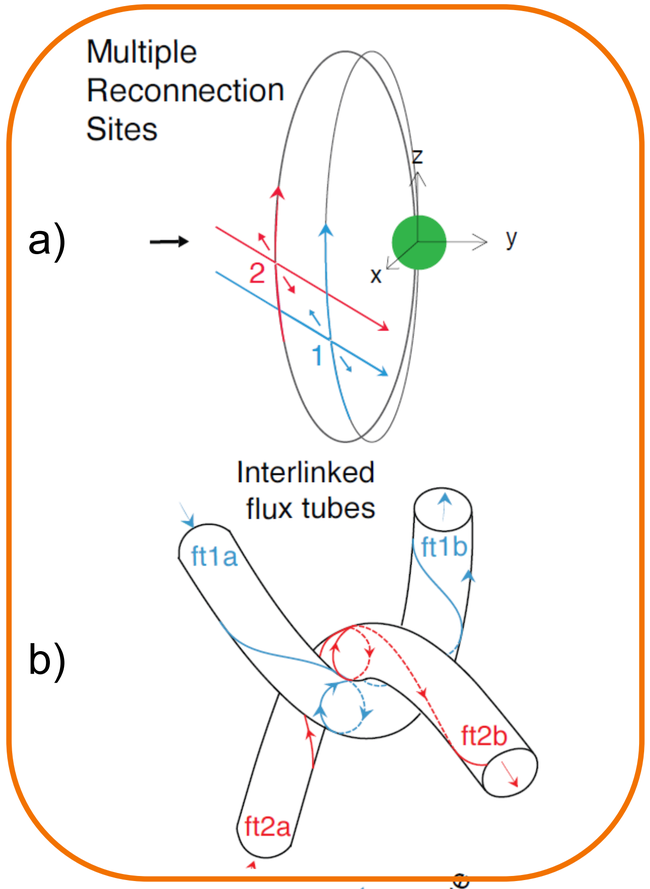
Reconnection happens but cannot fully resolve the entanglement

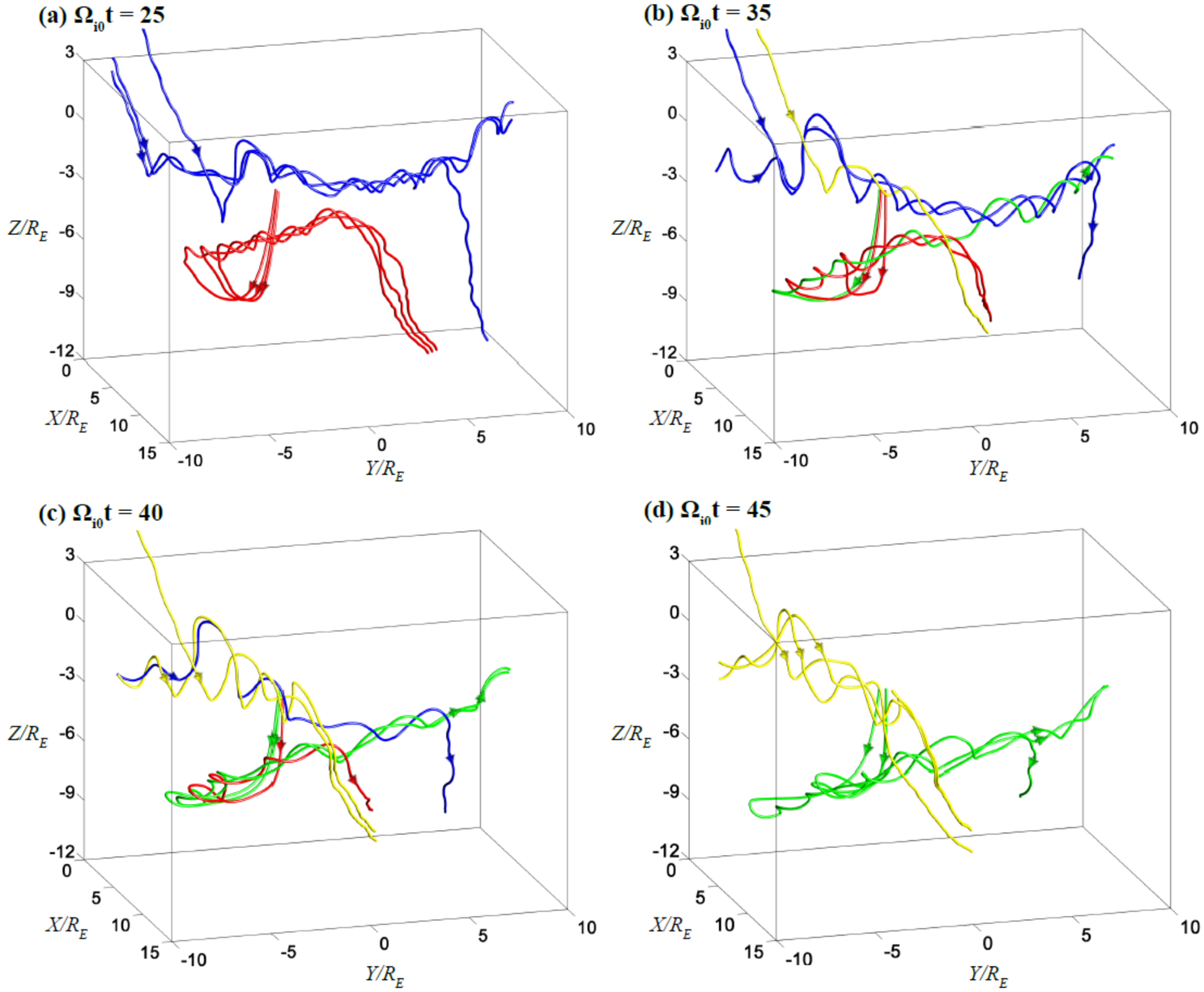




Guo, Jin; Lu, San et al. in prep

Global hybrid simulation: step (a) -> (b)





Summary

- MMS observations:
  (Qi, Y., Russell, C. T., Jia, Y. & Hubbert, M. ***Temporal Evolution of Flux Tube Entanglement at the Magnetopause as Observed by the MMS Satellites****. Geophys Res Lett* ***47****, (2020))*
  - 17 flux tube entanglement events using MMS
  - 8 out of 17 events show characteristics of three temporal evolutionary stages of entanglement
  - As the entanglement evolves, a new pair of flux ropes with different connectivity than that of the initial pair is eventually produced. Of this new flux rope pair, one has both ends in the magnetosphere while the other has both ends connected to the magnetosheath.
- Hall MHD simulations:
  (Jia, Y., Qi, Y., Lu, S. & Russell, C. T. ***Temporal Evolution of Flux Rope/Tube Entanglement in 3-D Hall MHD Simulations.*** *J Geophys Res Space Phys (2021) doi:10.1029/2020ja028698.)*
  - Flux rope reconnection has been modeled at different conditions (helicity, beta, flow velocity…)
  - Previously entangled flux tubes reconnect into untangled ropes.
  - This process is mainly driven by the momentum of converging plasma
- Hybrid simulations *(Guo, Jin; Lu, San et al. in prepin preparation)*
  - The generation of entanglement
  - Details at the entanglement interface

Future work

- Expand the study and compare various plasma environments:

Enviroments	**Magnetosphere**	**Solar corona**
Observation	MMS, planetary missions	EUV imagers
Global simulation	MHD + Hybrid	MHD
Small scale details	Hybrid	Hybrid