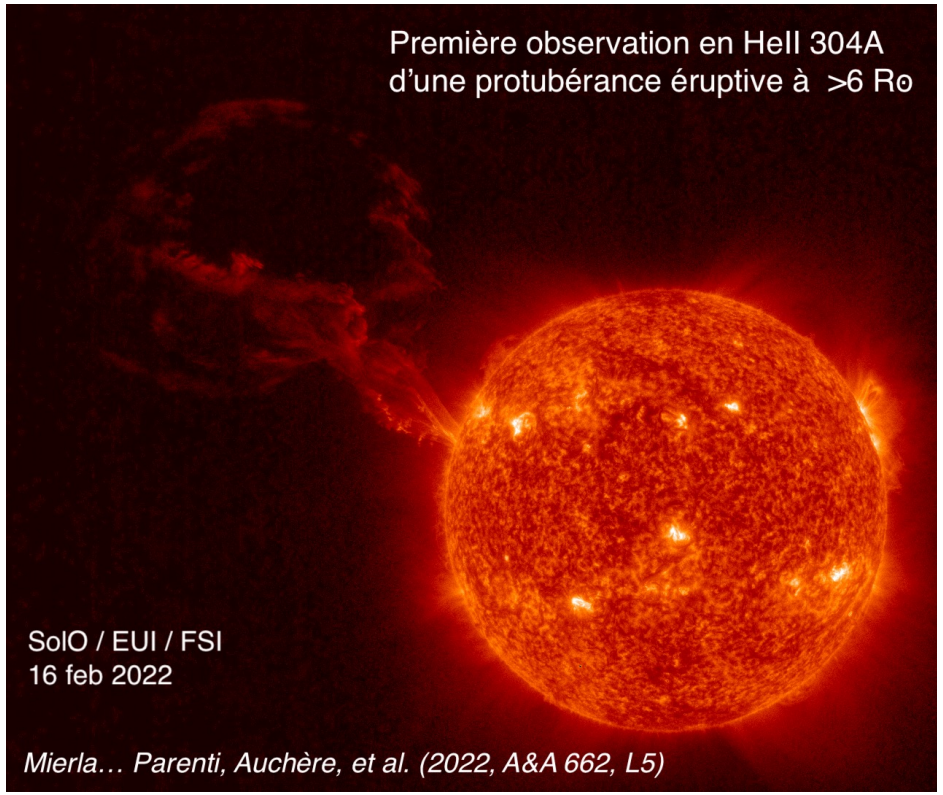
Coronal flux-rope formation through flux cancellation in a convectively-driven MHD simulation

Furuseth, S. V.[1] , Aulanier G.[2,1]

[1] Univ Oslo, Norway ; [2] LPP, France

Issue : The main CME onset mechanism requires a pre-eruptive flux rope

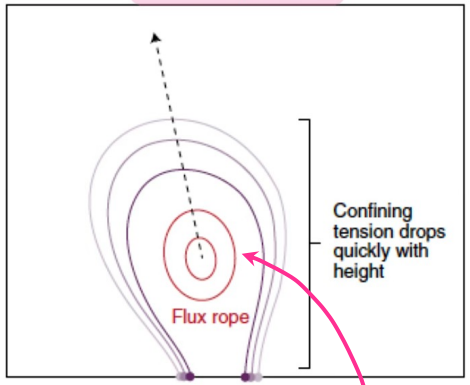
- The onset of CME's



- The 3 main CME onset models (Aulanier 2014, 2021)

van Tend & Kuperus (1978)
Kliem & Török (2006)
Démoulin & Aulanier (2010)

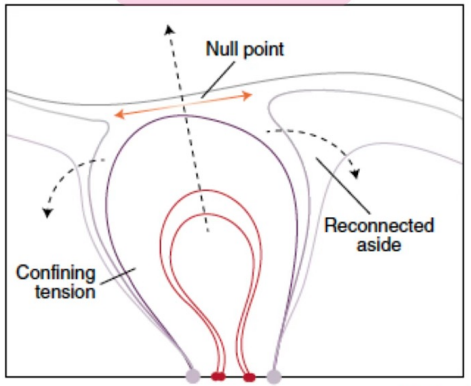
Torus instability
Loss of equilibrium



Robust and well-tested model ✓

Antiochos, DeVore & Klimchuk (1999)
DeVore & Antiochos (2005), Karpen et al (2012)
Lynch et al (2008), Masson et al (2019)

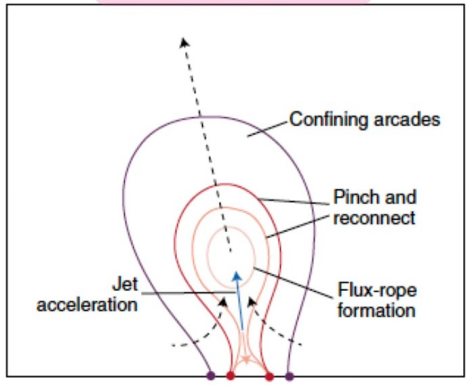
Magnetic breakout
Reconnection above



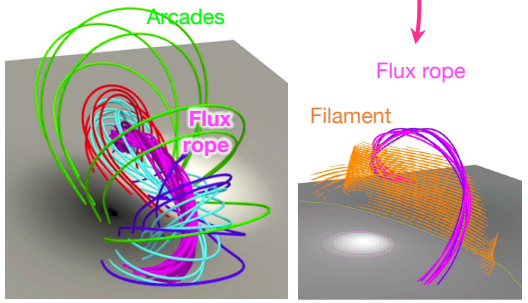
Requires similar relative magnetic fluxes above & below null-point

Moore & Roumeliotis (1992)
Mikic & Linker (1994), Amari et al (1996)
Jiang, Feng, Liu, Yan, Duan, Hu, Moore et al (2021)

Tether cutting
Reconnection — jet below



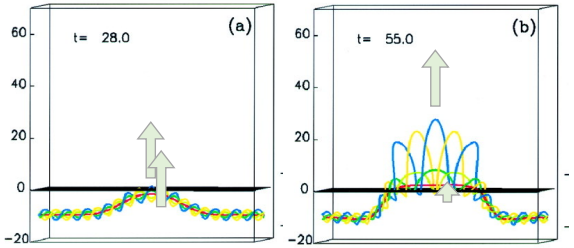
One group made it work in 3D, what is the parameter range ?



Zucarello, Aulanier & Gilchrist (2015, 2016),

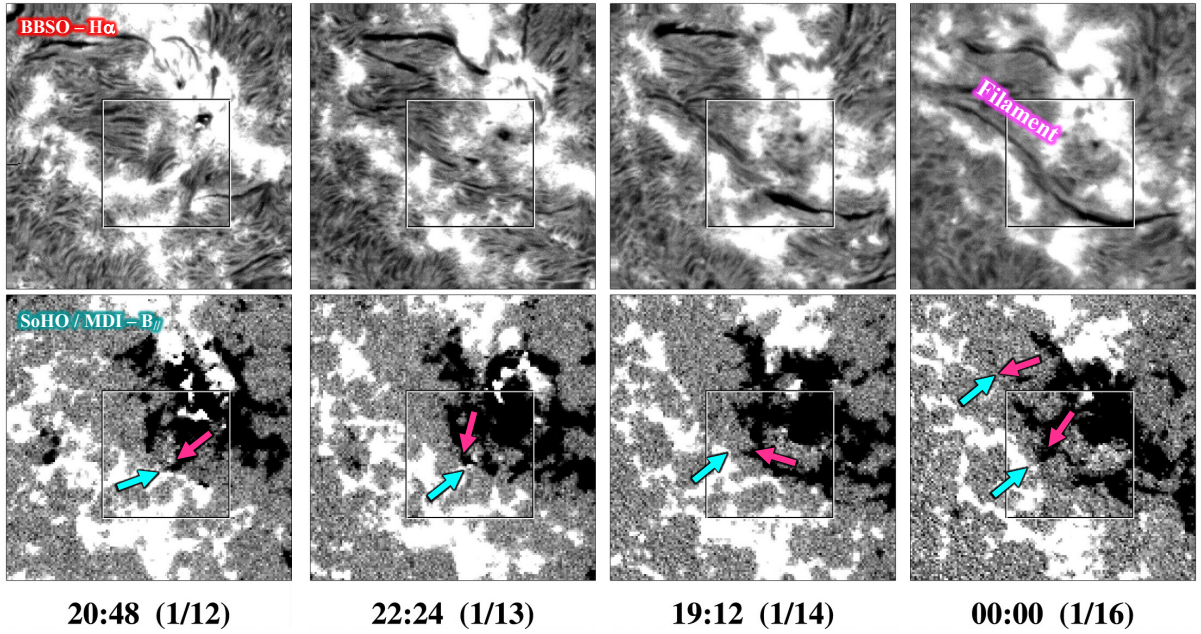
Problem : We are not sure how (if !!!) pre-eruptive flux-ropes really form

- Sub-surface rope : lower windings cannot emerge



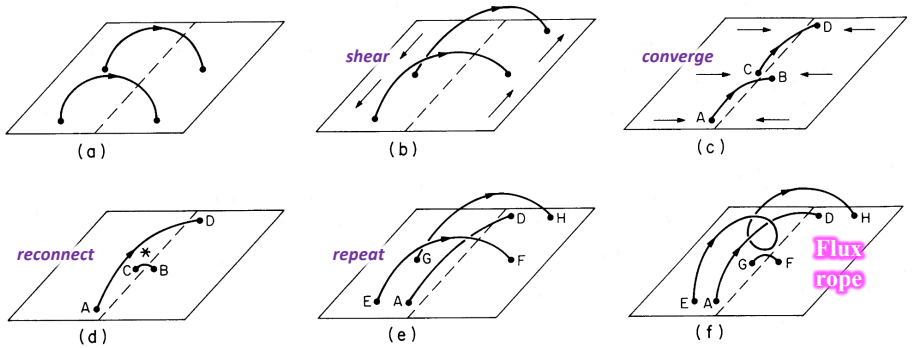
Fan (2001), Magara & Longcope (2001), Archontis et al (2004, 2009)

- Filament formation and flux-cancellation : **NOT** smooth



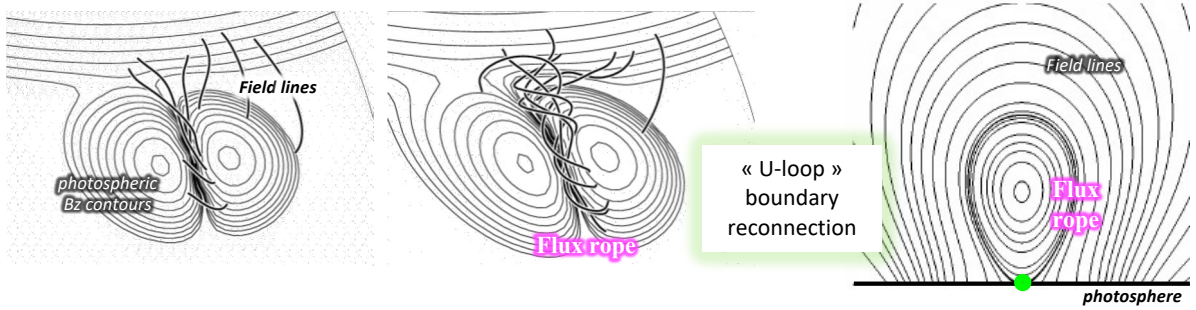
Harvey & Martin (1973), Martin & Harvey (1979), Wang (1989), Livi et al (1989), van Driel-Gesztelyi et al (2003), Green et al 2011), Wang & Muglach (2013)

- The original cancellation model : concept & smooth



van Ballegooijen & Martens (1989)

- Boundary-driven cancellation in line-tied simulations : smooth & U-loop/boundary reconnection …



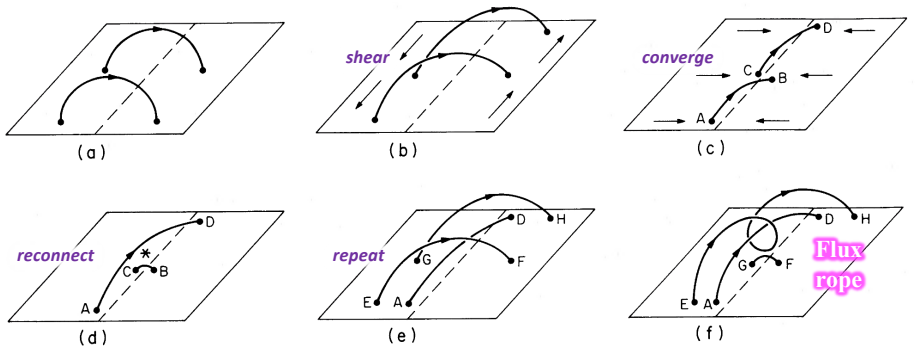
van Ballegooijen et al (2000), Amari et al (2003, 2011), MacKay & van Ballegooijen (2006), Yeates & MacKay (2009), Aulanier et al (2010, 2012), Pagano et al (2013), Zuccarrello, Aulanier et al (2015), Jiang et al (2024), Xing et al (2024, 2025)

A broader stake : A fundamental question ahead of space weather

- Designing setup for flux-cancellation **with a realistic photosphere**

  No line-tied treatment

  No boundary reconnection



van Ballegooijen & Martens (1989)

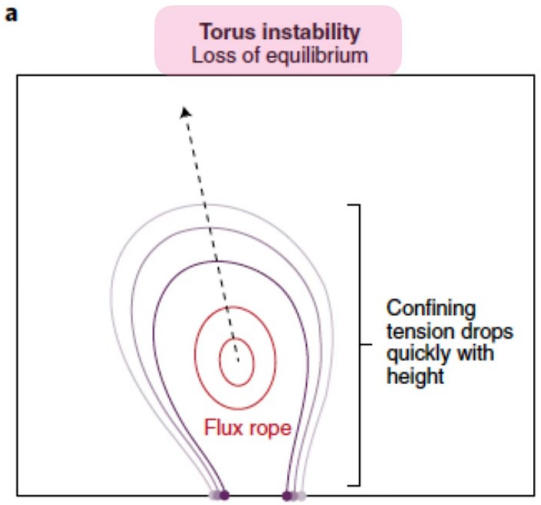
- Torus-instability **CME-onset model at risk ?**

  Model needs pre-eruptive flux rope build-up

  The only model with a quantitative threshold

  Relevant for space weather

van Tend & Kuperus (1978)
Kliem & Török (2006)
Démoulin & Aulanier (2010)



Plugging the analytical B-field in a Quiet-Sun MHD simulation

Linear force-free magnetic fields (LFFF)

$$\nabla^2 \mathbf{B} = -\alpha^2 \mathbf{B}.$$

$$B_x = -\sum_{n=1}^{n_h} \frac{B_n l_n}{k_{nx}} \cos(k_{nx} x) \exp[l_n (z - z_{CZ})],$$

$$B_y = +\sum_{n=1}^{n_h} \frac{B_n \alpha}{k_{nx}} \cos(k_{nx} x) \exp[l_n (z - z_{CZ})],$$

$$B_z = -\sum_{n=1}^{n_h} B_n \sin(k_{nx} x) \exp[l_n (z - z_{CZ})],$$

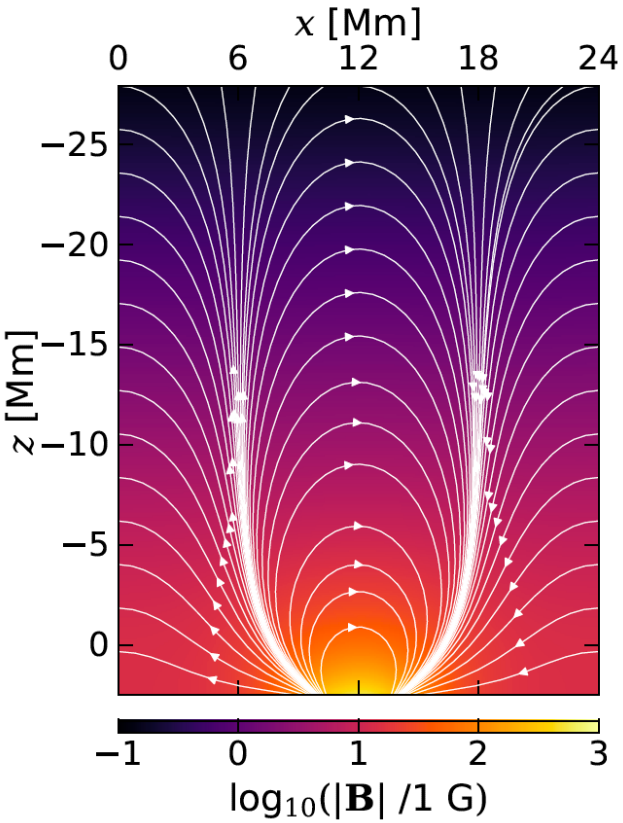
$$k_{nx} = \frac{2\pi}{L_x} n,$$

$$l_n = \sqrt{k_{nx}^2 - \alpha^2} = \frac{2\pi}{L_x} \sqrt{n^2 - \alpha_{\text{norm}}^2}$$

$n_h = 30$

$\alpha_{\text{norm}}^2 = 0.5$

$\theta \leq 45°$ magnetic shear along PIL



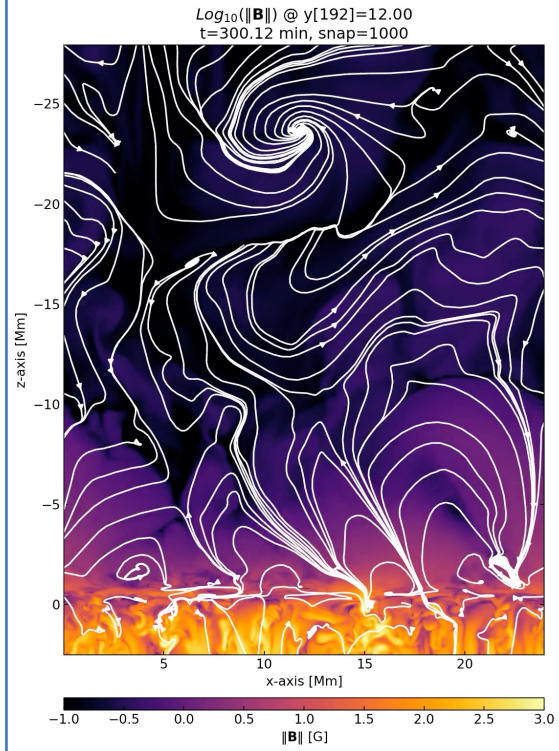
Bifrost QS simulation

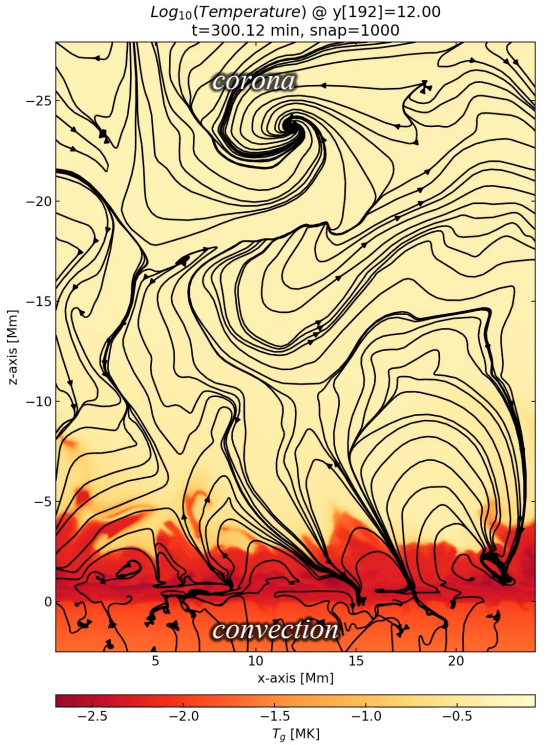
Gudiksen, Carlsson, Hansteen et al. (2011)

768^3 grid cells $\quad L_x = L_y = 24$ Mm

$< B_y >$ = 100 G bottom ; 10 G photosphere

$< B_z >$ photosphere = 20 G mean unsigned ; 0 no net flux



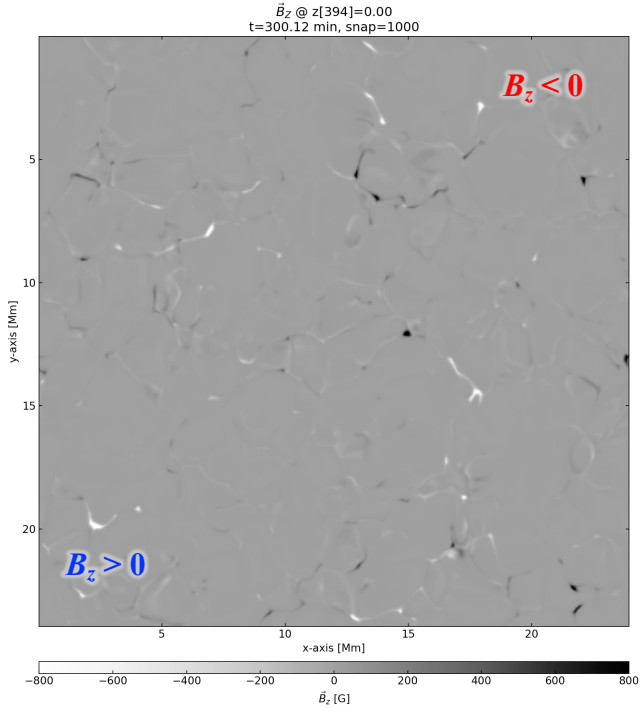


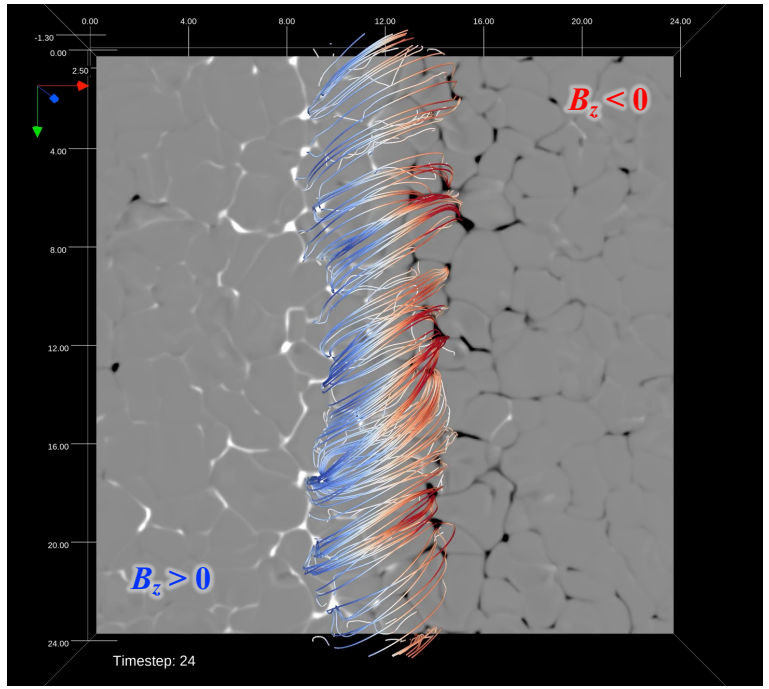
Convectively-driven arcade transformation into a flux rope

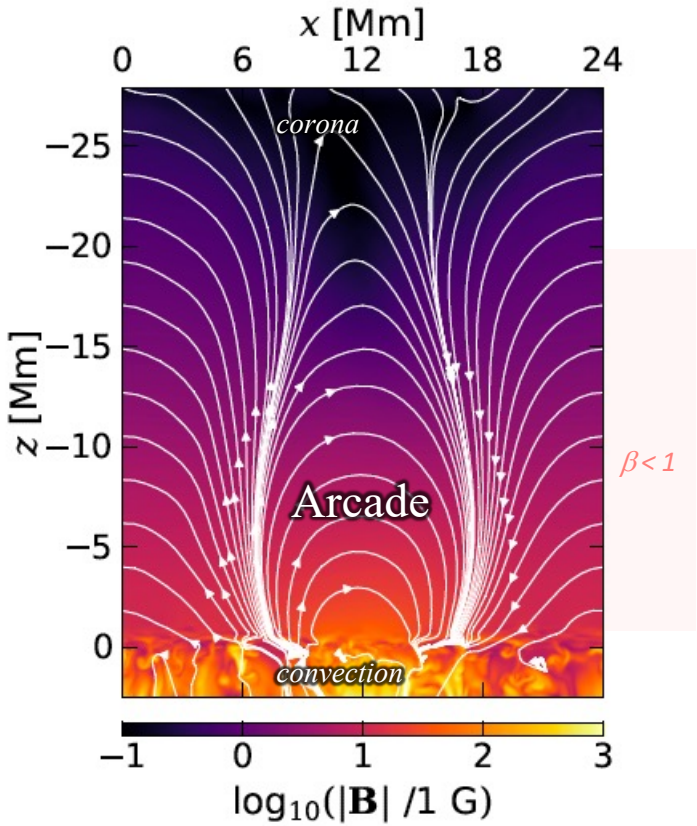
Bifrost simulation

768^3 grid cells $\quad L_x = L_y = 24\,\mathrm{Mm}$

$< B_z >^{\text{photosphere}} = 50\ \mathrm{G}$ mean unsigned ↗



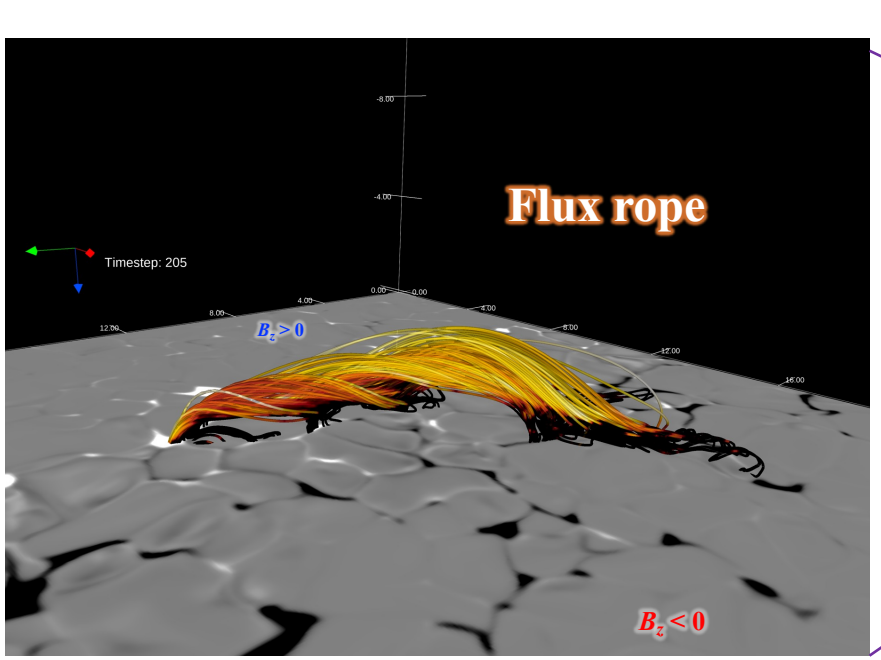


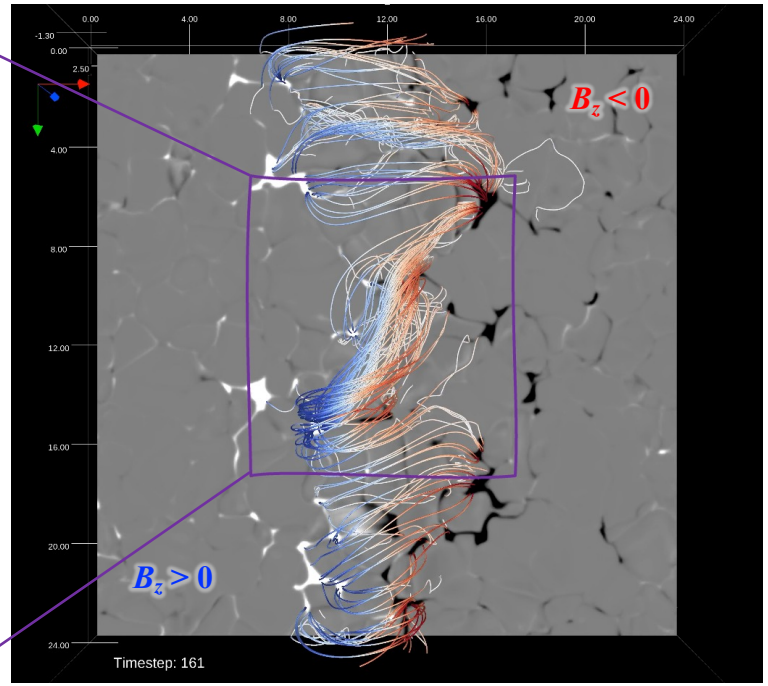


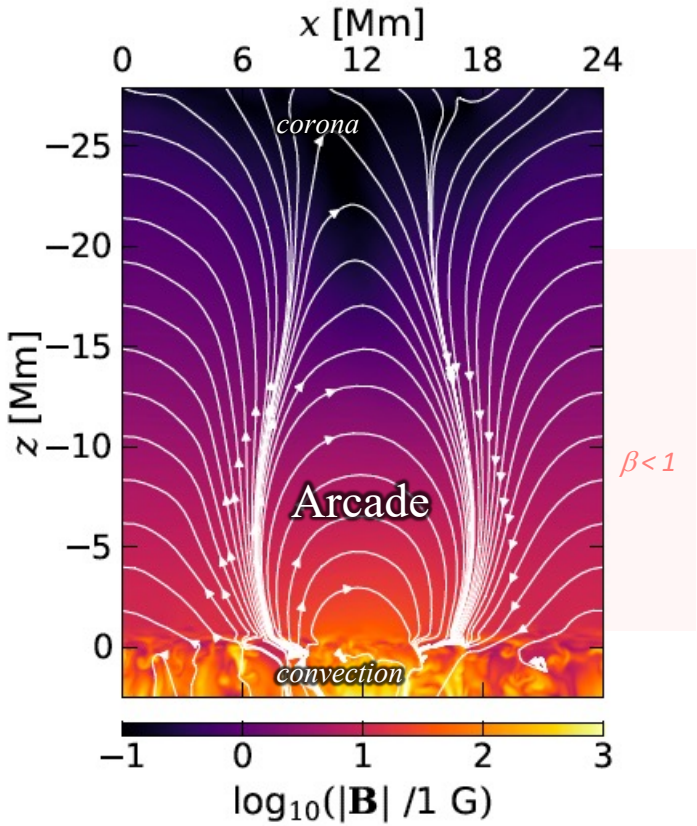
Convectively-driven arcade transformation into a flux rope

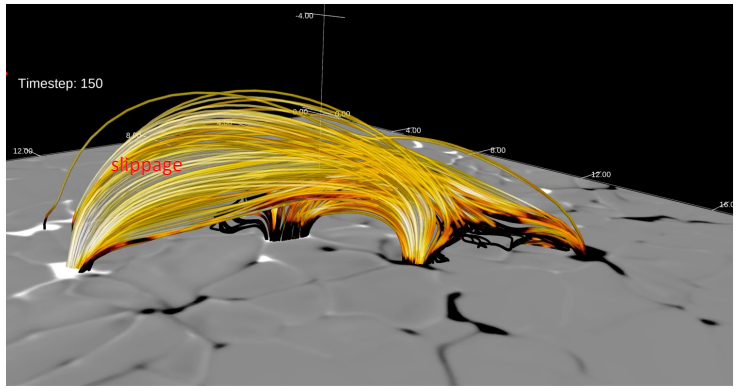
Bifrost simulation

Free convection
turns 2.5D LFFF arcade
into 3D NLFFF flux rope





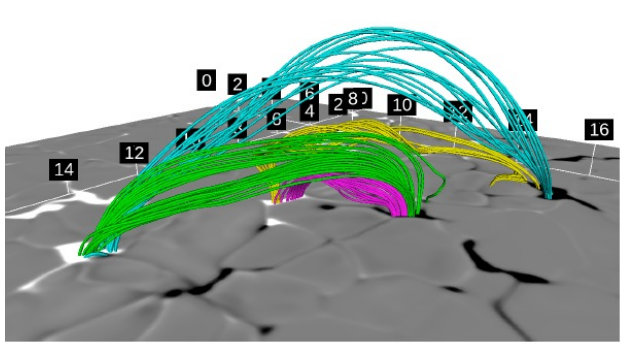




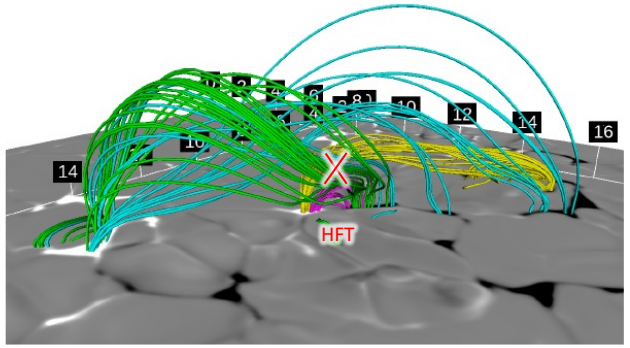
Cancellations driving slip-running reconnection

1° Low-altitude HFT

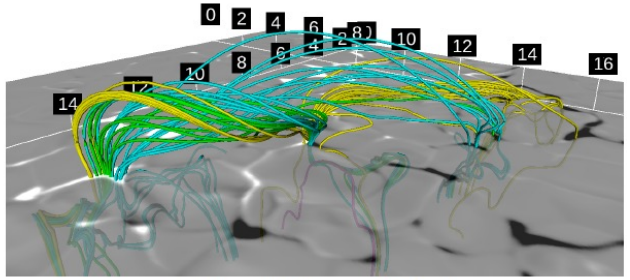
« Tether-cutting reconnection »



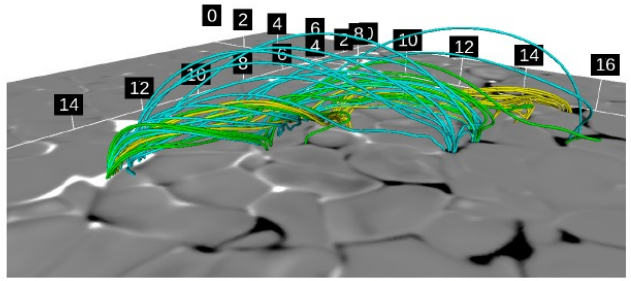
(a) Snap 1750, t = 291m40s



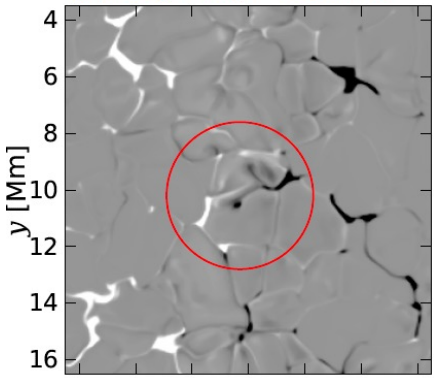
(b) Snap 1850, t = 308m20s

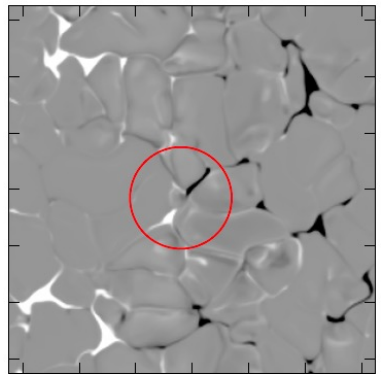


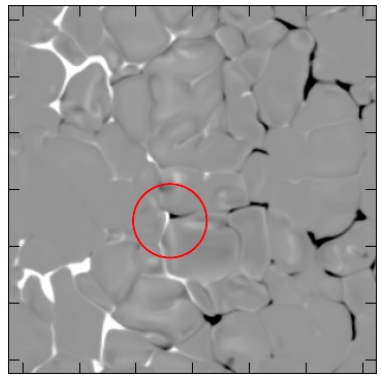
(c) Snap 1950, t = 325m0s

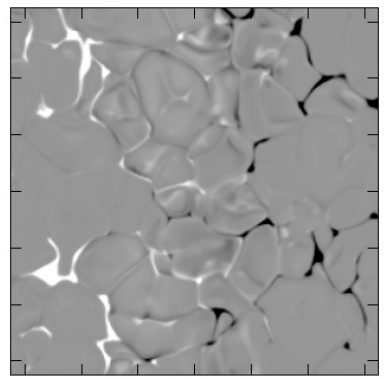


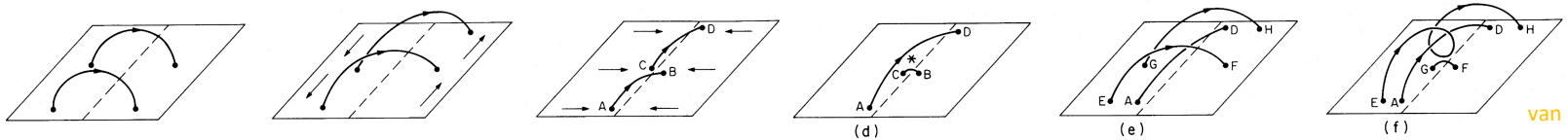
(d) Snap 2000, t = 333m20s









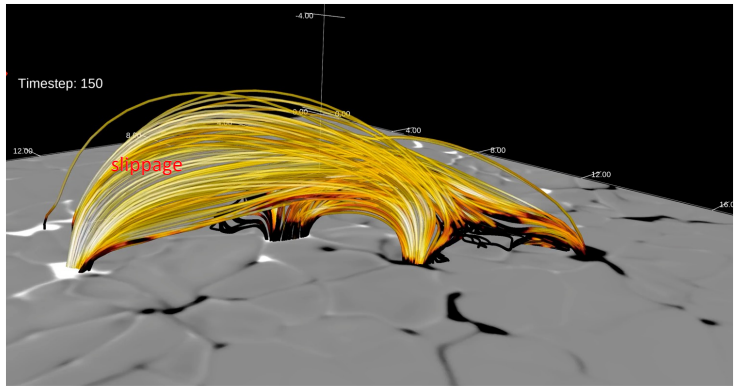


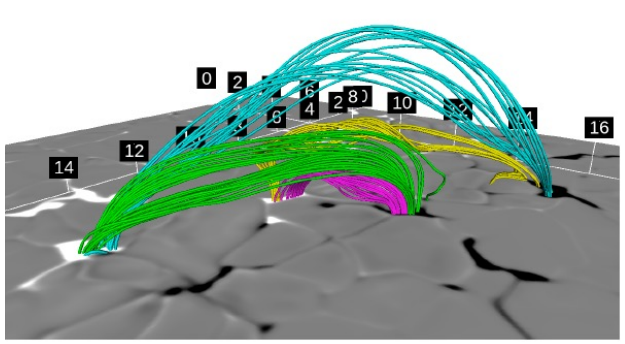
van Ballegooijen & Martens (1989)

Cancellations driving slip-running reconnection

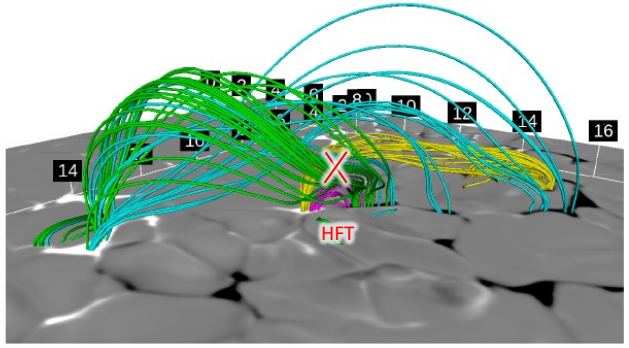
1° Low-altitude HFT

« Tether-cutting reconnection »

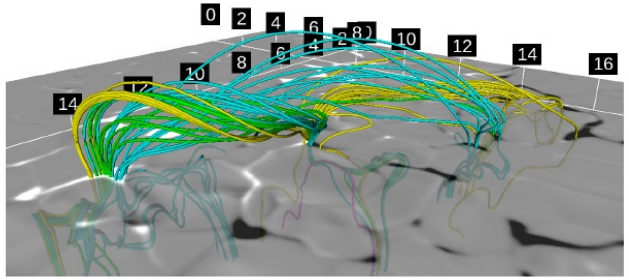




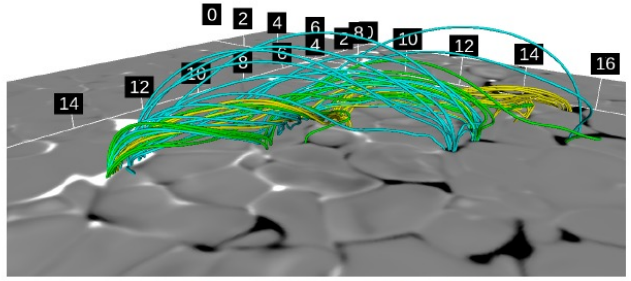
(a) Snap 1750, t = 291m40s



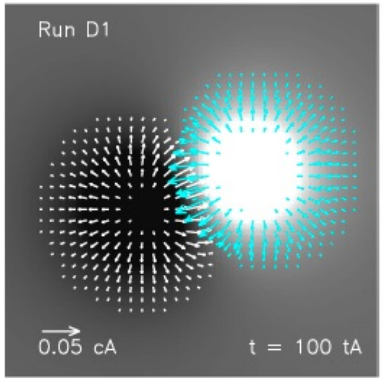
(b) Snap 1850, t = 308m20s

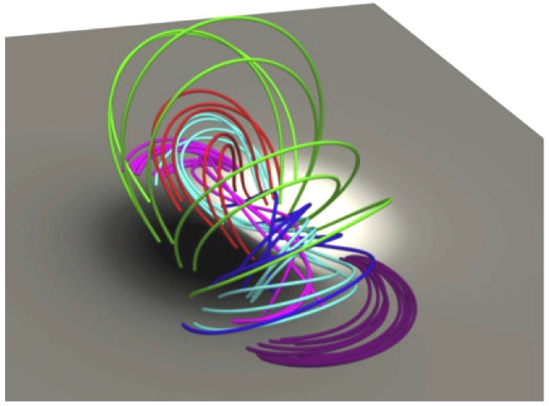


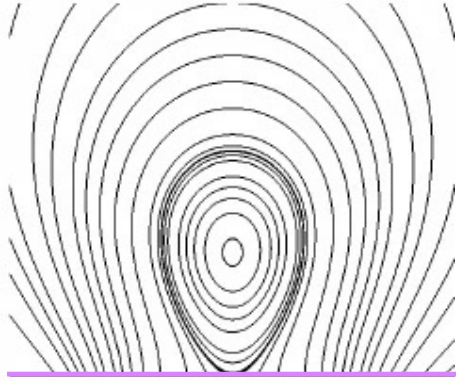
(c) Snap 1950, t = 325m0s



(d) Snap 2000, t = 333m20s







Bald Patch
boundary-reconnection

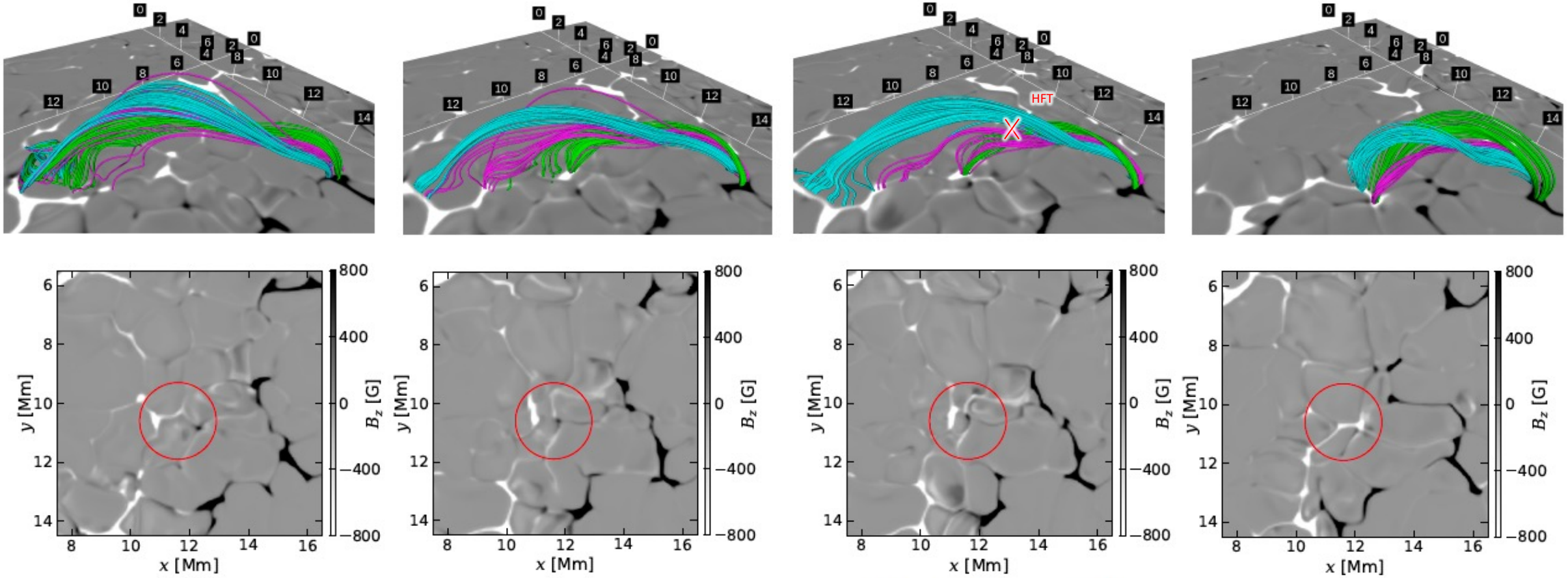
photospheric plane

van Ballegooijen et al (2000), Amari et al (2003, 2011), MacKay & van Ballegooijen (2006), Yeates & MacKay (2009), Aulanier et al (2010, 2012), Pagano et al (2013), Zuccarrello, Aulanier et al (2015), Jiang et al (2024), Xing et al (2024, 2025)

Cancellations driving slip-running reconnection

2° Coronal HFT

« component reconnection »



(a) Snapshot 1390, $t = t_a - 14$ min

(c) Snapshot 1414, $t = t_a - 10$ min

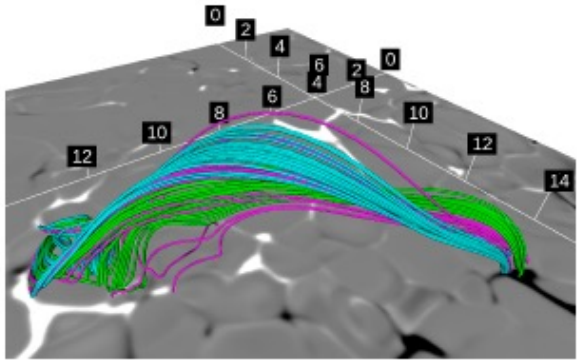
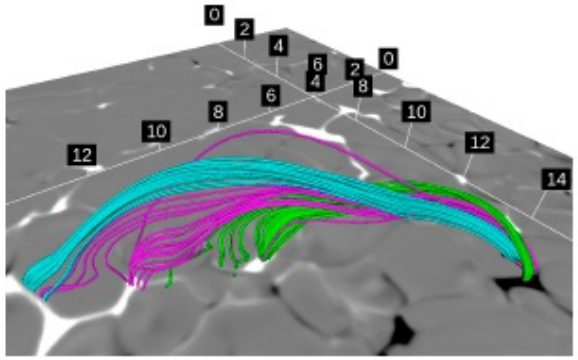
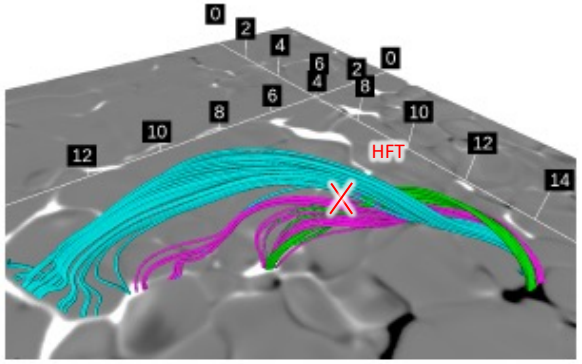
(d) Snapshot 1426, $t = t_a - 8$ min

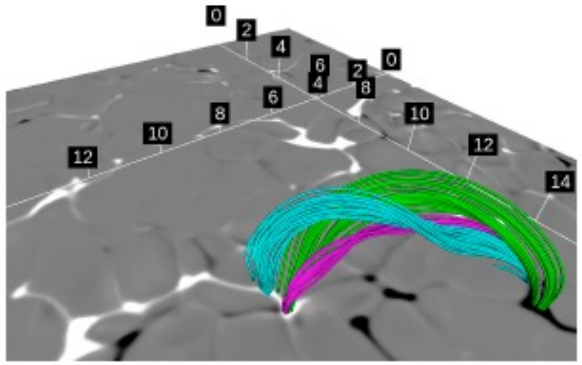
(f) Snapshot 1474, $t = t_a = 245$m40s

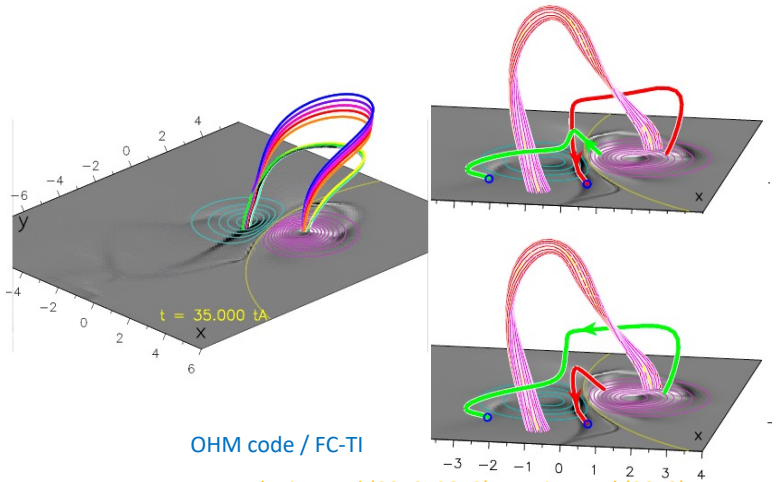
Cancellations driving slip-running reconnection

2° Coronal HFT

« component reconnection »

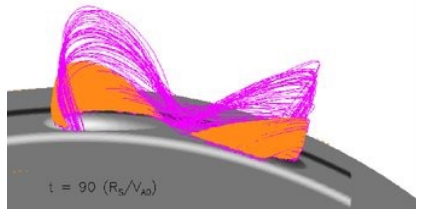




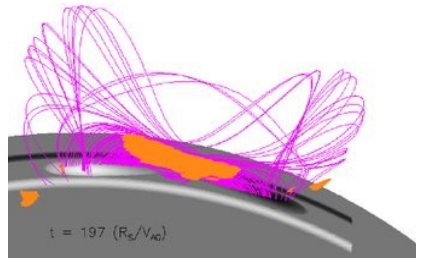




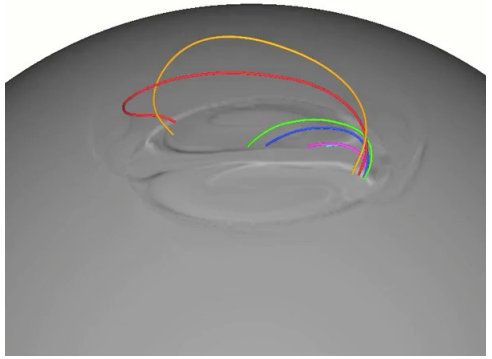
OHM code / FC-TI

Aulanier et al (2010, 2012), Janvier et al (2013)



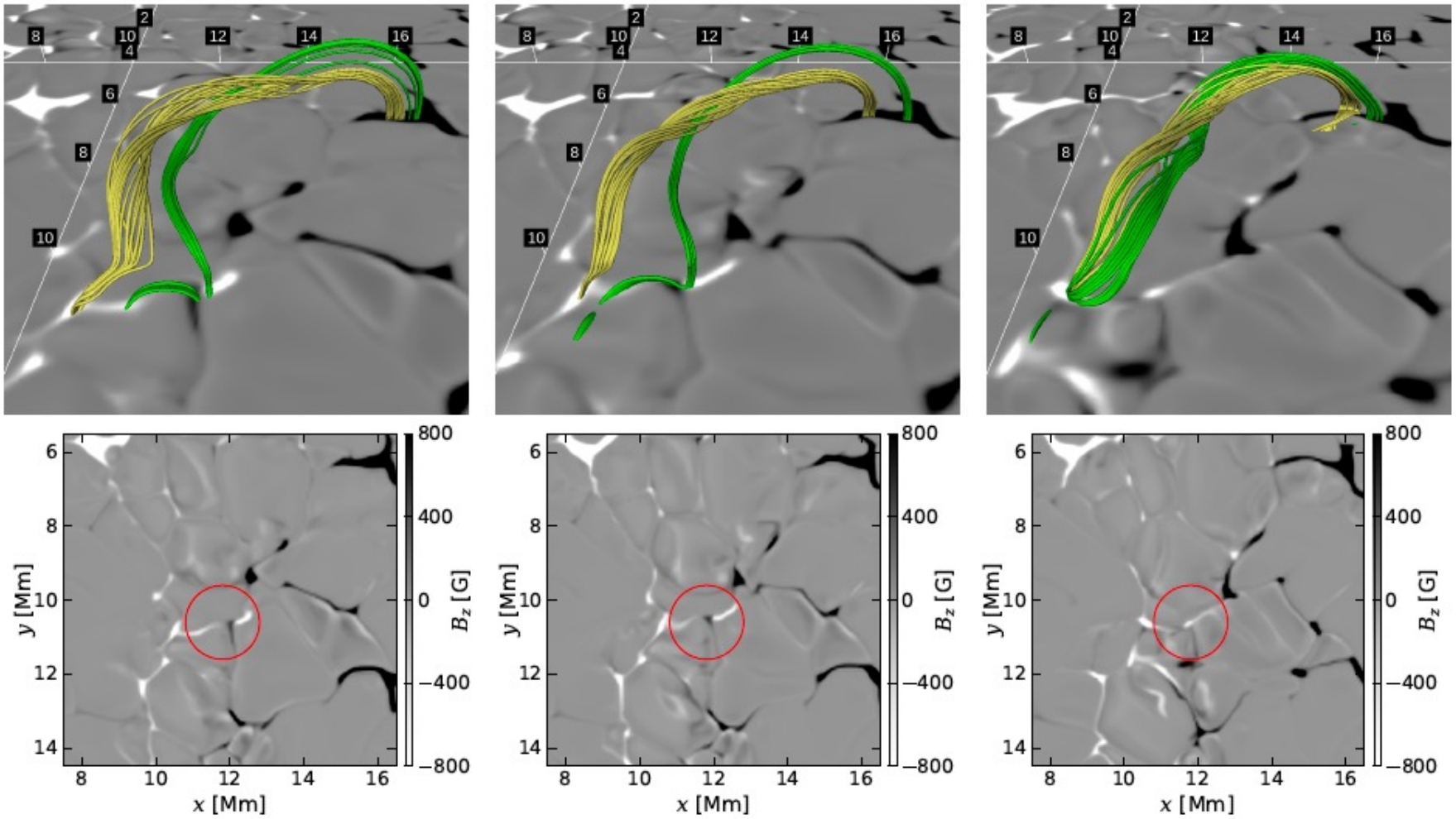


ZEUS-adapted code / Emergence-TI Fan (2010)



ARMS code / Breakout Masson et al (2019)

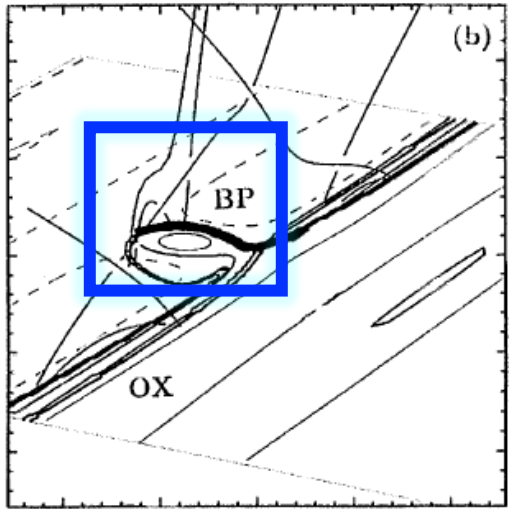
Other cancellations are U-loop emergence without reconnection



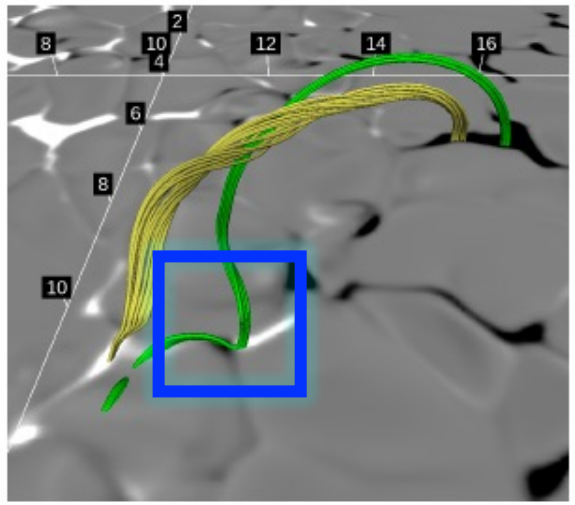
(a) Snapshot 1575, $t = t_b - 100\,\mathrm{s}$ (b) Snapshot 1585, $t = t_b = 264\mathrm{m}10\mathrm{s}$ (c) Snapshot 1605, $t = t_b + 200\,\mathrm{s}$

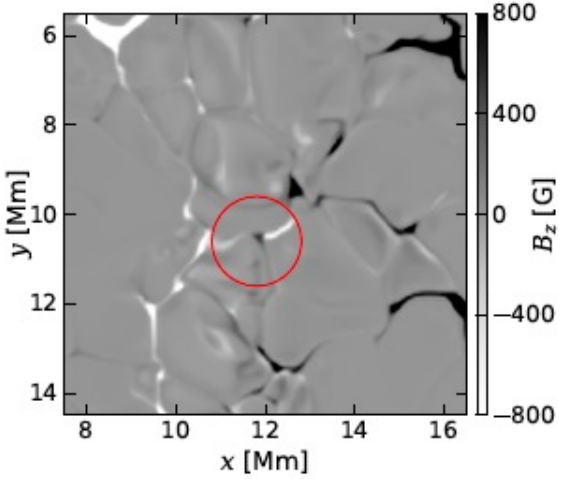
Other cancellations are U-loop emergence like filament feet

without reconnection

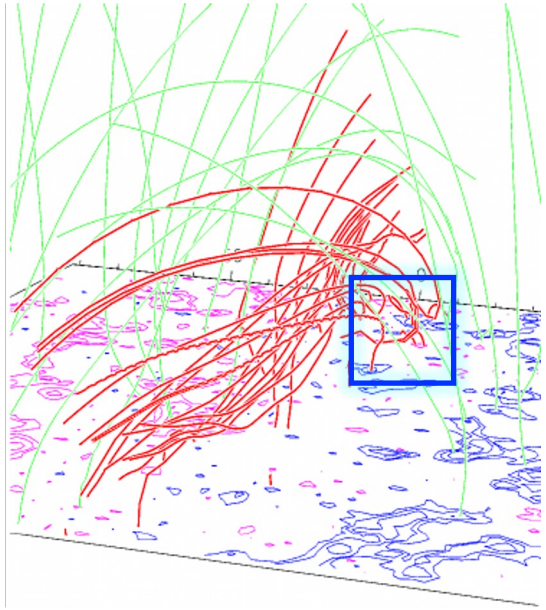


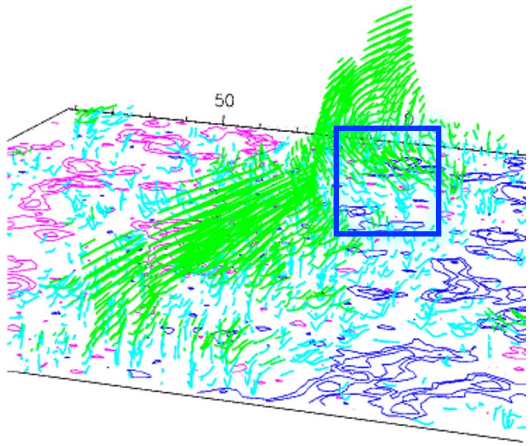
Aulanier, Démoulin, et al (1998)

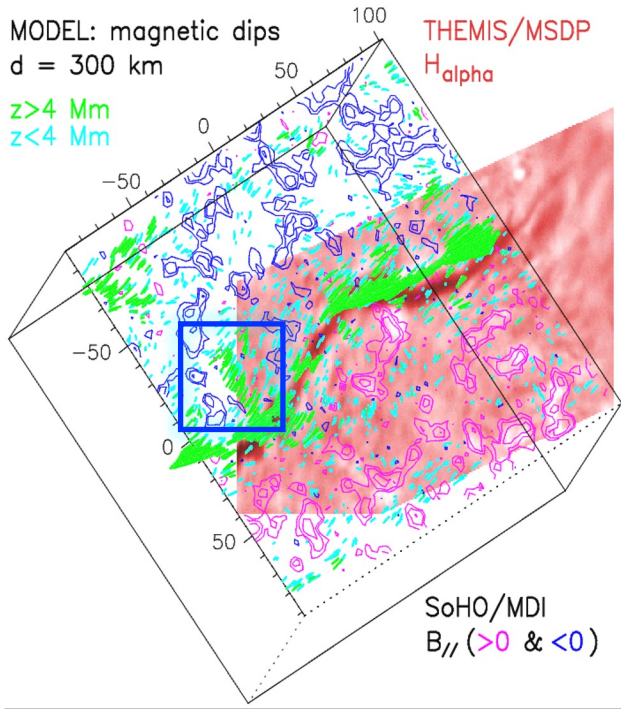




(b) Snapshot 1585, $t = t_b = 264$m10s







Aulanier & Schmieder (2002)

First realistic self-consistent simulation of formation of stable pre-eruptive flux-ropes

- Coupling solar layers

  Eruptions are purely coronal BUT

  ➔ energy buildup involves convection

- Torus-instability CME-onset model OK

  Model with quantitative threshold

  ➔ Relevant for space weather

- Small-scale photospheric B's matter

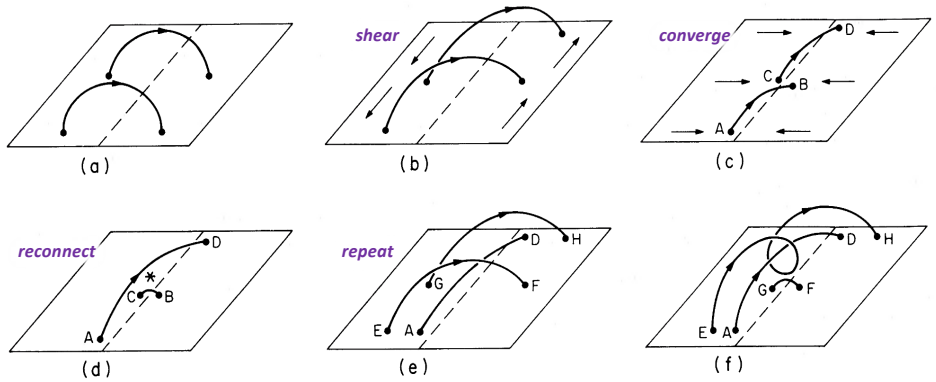
  Seeds of torus-unstable CME progenitors

  ➔ Sparse surface flux-cancellations

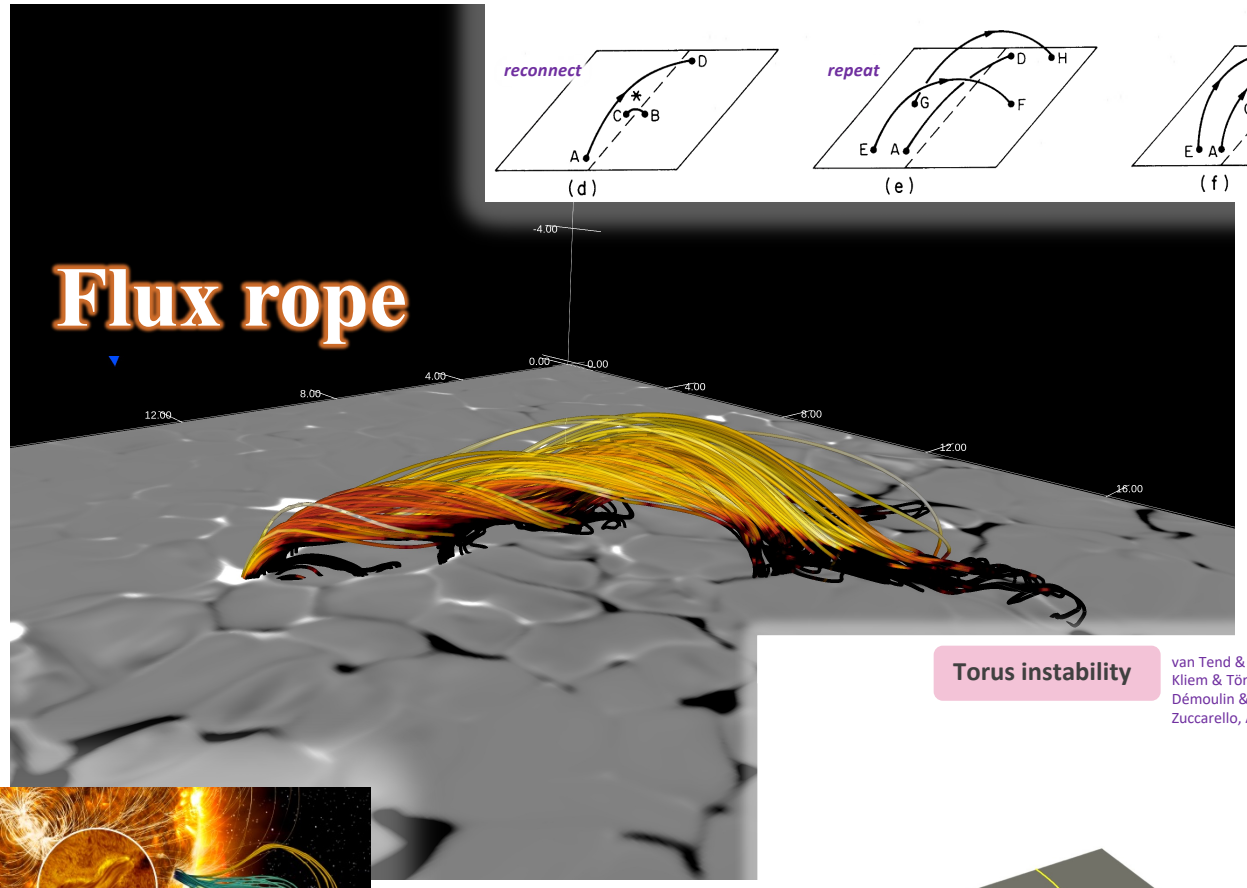
  Requires highres continuous obsdervations

  ➔ European Solar Telescope

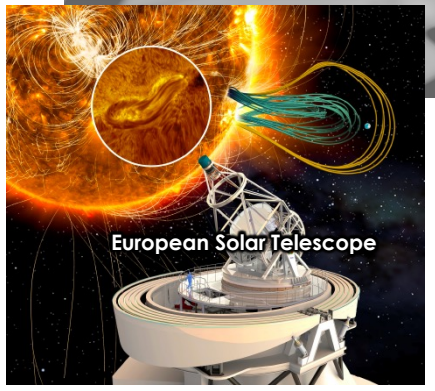
Flux cancellation model van Ballegooijen & Martens (1989)



Furuseth & Aulanier (2026, A&A)



Torus instability van Tend & Kuperus (1978), Kliem & Török (2006), Démoulin & Aulanier (2010), Zuccarello, Aulanier & Gilchrist (2015)



see Pariat's talk