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Using data-driven time-dependent Magnetofrictional modeling to initiate MHD simulations of coronal active regions

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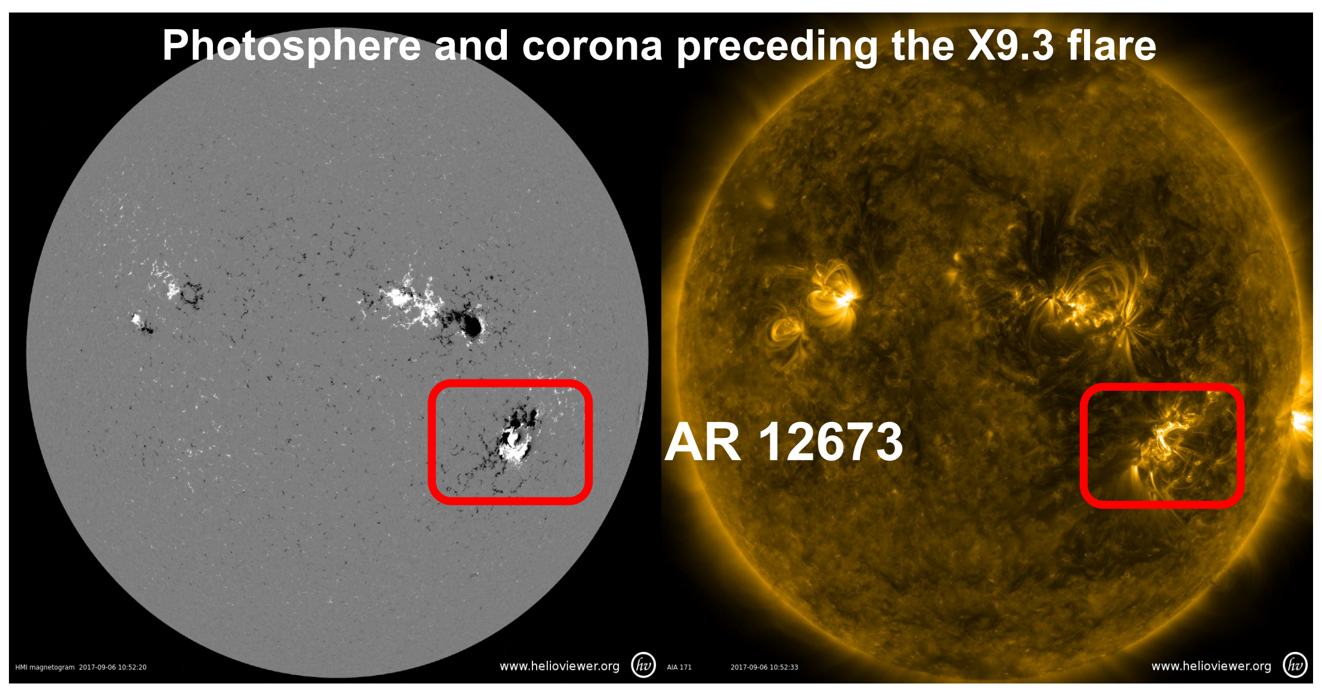
Introduction

- The **time-dependent magnetofrictional model** (TMFM), when driven by accurate photospheric electrograms, can capture the evolution of active regions (ARs) over multiple days [1, 4].
- TMFM can self-consistently produce localized highly sheared magnetic fields as well as flux-ropes, that can evolve to become eruptive (***see talk by A. Wagner***)
- However, the simplified momentum equation that does not include inertia, makes TMFM inadequate for modeling fast eruptions [1, 2].
- Premise of this study: use TMFM to simulate an active region up to a given point in time (close to expected eruption), then transfer the system to a more realistic model that includes inertia, in this case ideal zero-β magnetohydrodynamics (MHD), to study and assess the subsequent dynamics.

Case-study: Intensely flaring AR12673

- Intense flaring AR.
- On September 6, 2017, a failed X2.2 flare on 8:57 UT was followed by X9.3 flare at 11:53 UT and a fast CME.
- The AR evolution from emergence to eruption was studied using TMFM by [3].
- Same AR studied by many using different methods


Photosphere and corona preceding the X9.3 flare

TMFM snapshot as initial condition to MHD

- TMFM models only the evolution of the magnetic field: need additional info when transferring TMFM to MHD.
- We set:

$$\boldsymbol{B}_{\mathrm{MHD}}(\boldsymbol{x}, t=0) = \boldsymbol{B}_{\mathrm{MF}}(\boldsymbol{x}, t=t_c) \quad (1)$$

$$\boldsymbol{V}_{\mathrm{MHD}}(\boldsymbol{x}, t=0) = \boldsymbol{0} \quad (2)$$

$$\rho_{\mathrm{MHD}}(\boldsymbol{x}, t=0) = \frac{B^2_{\mathrm{MHD}}(\boldsymbol{x}, t=0)}{\mu_0 v_A^2} \quad (3)$$

$$v_A = 300\ \mathrm{km\ s^{-1}}\ \text{(constant)}$$

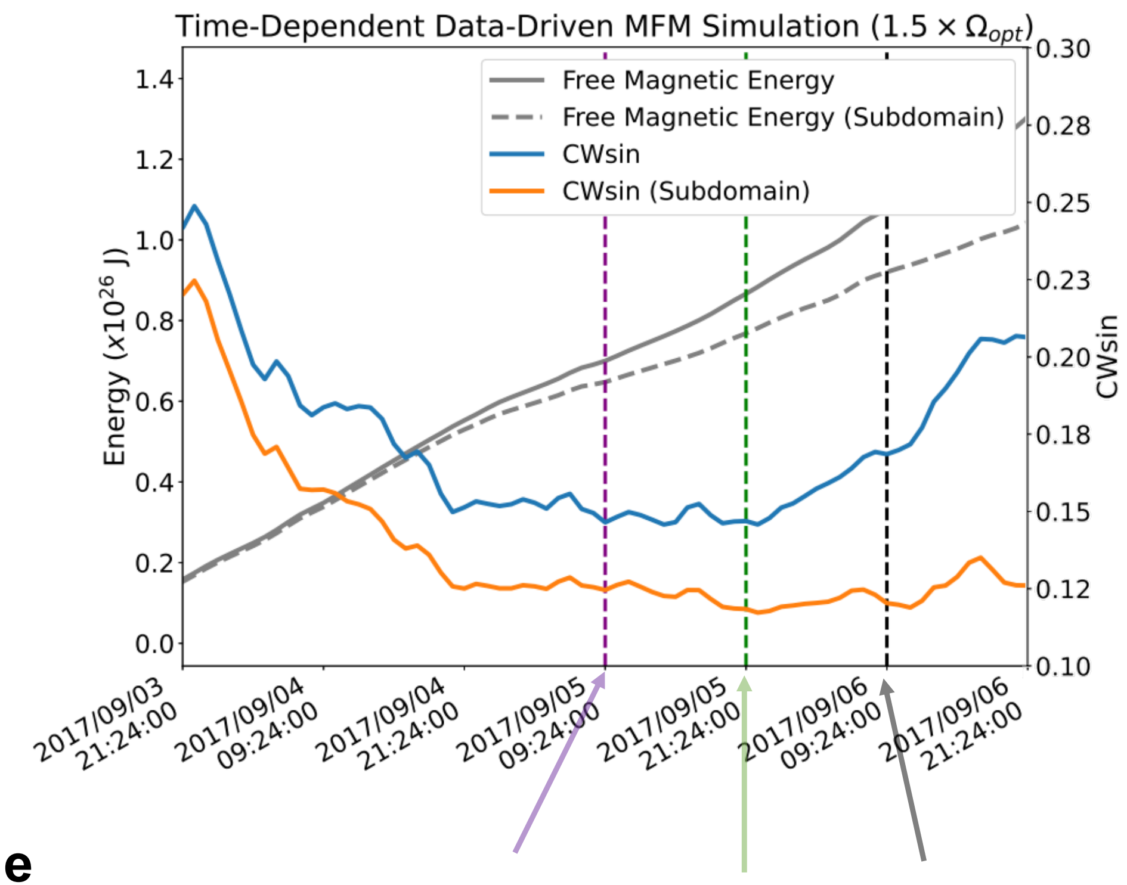
- From this construction follows that at $t = 0$

$$\frac{\partial \boldsymbol{V}}{\partial t} = \frac{1}{\rho} \boldsymbol{J} \times \boldsymbol{B} = \mu_0\, v_A^2 \frac{|\boldsymbol{J}|}{|\boldsymbol{B}|} \boldsymbol{j} \times \boldsymbol{b}.$$

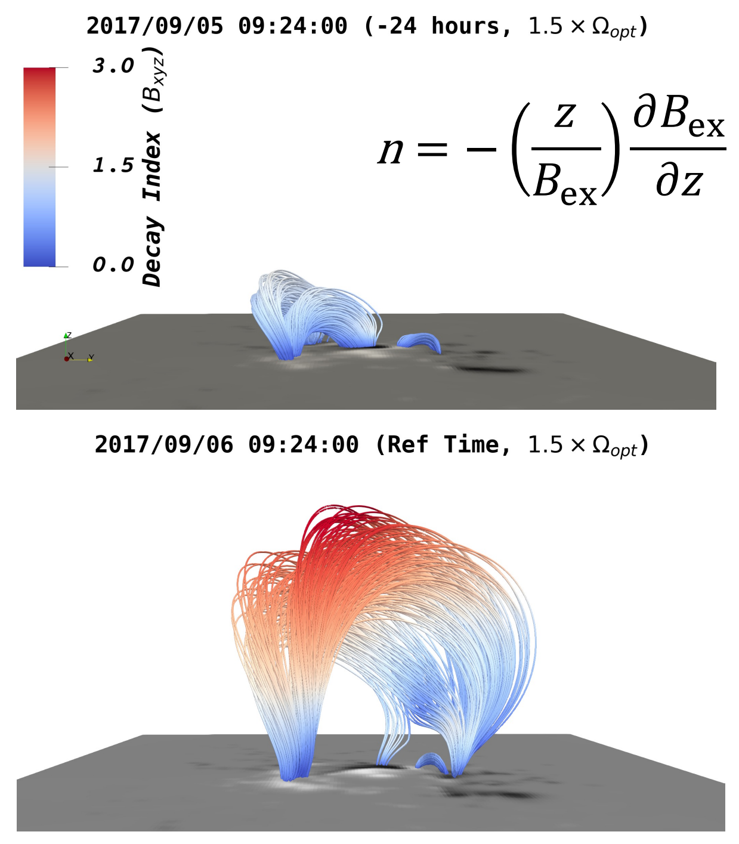
Thus, immediate evolution determined **solely by the Lorentz force in the TMFM state used as input.**

- Choice of v_A was not found to be important as expected from scale invariance.

Lorentz force evolution quantified using $CWsin = \frac{\Sigma_l |\boldsymbol{J}_l||sin\theta_l|}{\Sigma_l |\boldsymbol{J}_l|}$ in the TMFM simulation and MHD simulation:



$t_{\mathrm{ref}} - 24\mathrm{h}$ $t_{\mathrm{ref}} - 12\mathrm{h}$ t_{ref}: time of X9.3 flare



$$n = -\left(\frac{z}{B_{\mathrm{ex}}}\right) \frac{\partial B_{\mathrm{ex}}}{\partial z}$$

- Three different transfer times t_c from data-driven TMFM to MHD were considered as indicated above

Model equations

Magnetofriction

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$$

$$\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B} + \eta \mu_0 \boldsymbol{J}$$

$$\boldsymbol{V} = \frac{1}{\nu} \frac{\mu_0 \boldsymbol{J} \times \boldsymbol{B}}{B^2}$$

Ideal zero-β MHD

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0$$

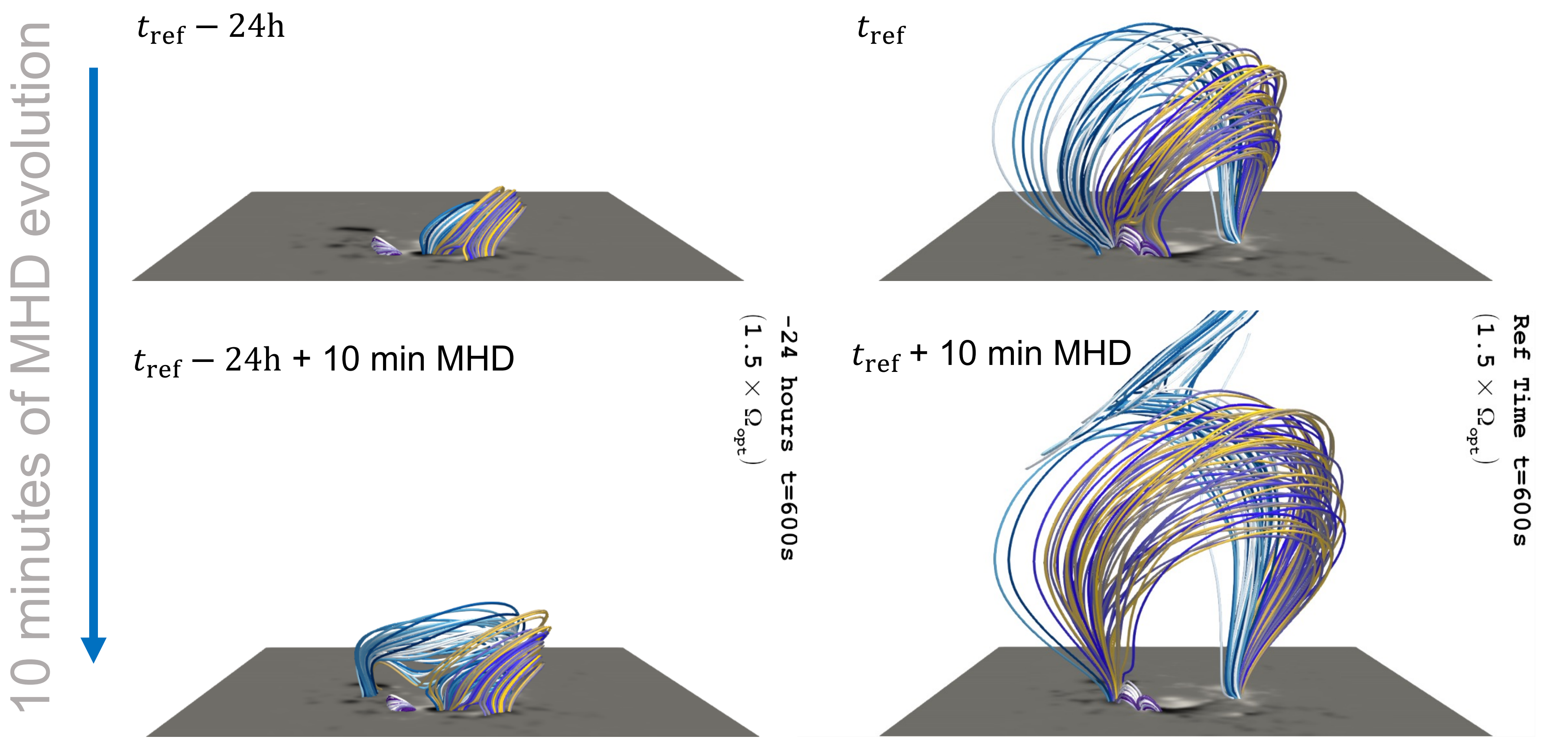
$$\frac{\partial (\rho \boldsymbol{V})}{\partial t} = -\nabla \cdot \left(\rho \boldsymbol{V}\boldsymbol{V} + \frac{B^2}{2\mu_0} \boldsymbol{I} - \frac{1}{\mu_0} \boldsymbol{B}\boldsymbol{B} \right)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$$

$$\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$$

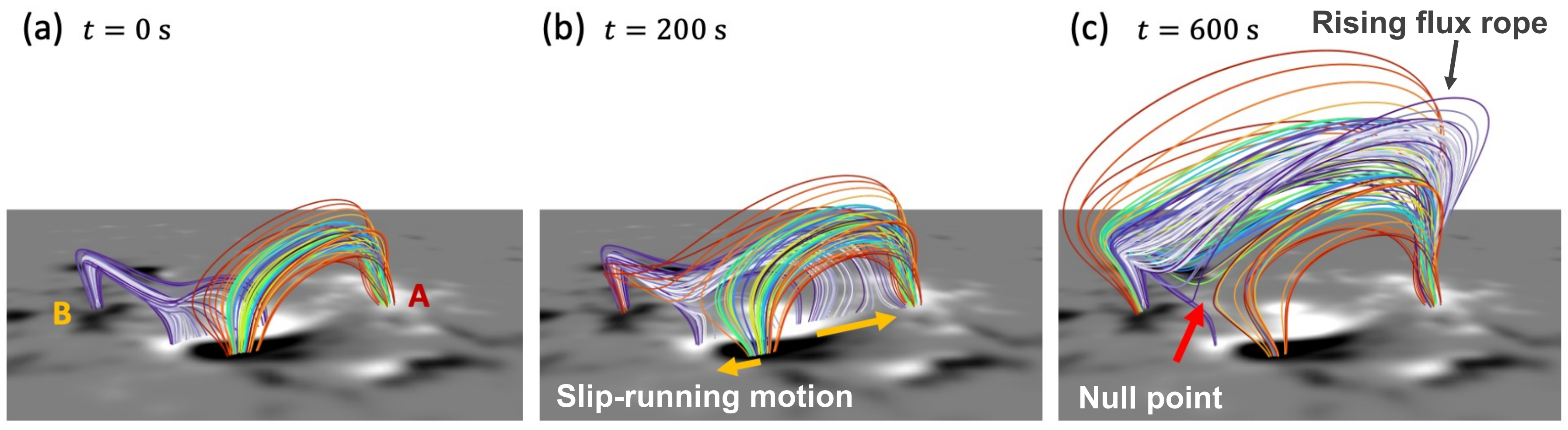
Eruptive and non-eruptive evolution

- All MHD initial conditions were to the same degree force-free close to the AR.
- For the simulation initialized at time $t_{\mathrm{ref}} - 24\mathrm{h}$, the magnetic field of the AR experiences only minor evolution and does not erupt. In contrast, the simulation at t_{ref} shows clear eruptive behavior.
- With a TMFM run using a larger helicity and energy injection, also $t_{\mathrm{ref}} - 24\mathrm{h}$ becomes more dynamic and the simulation at t_{ref} results in a faster eruption.



What causes the eruption?

- At approx. $t_{\mathrm{ref}} - 12\mathrm{h}$, the eruptive dynamics is facilitated by slip-running reconnection mediated by a null-point at the edge of the main PIL of the AR:

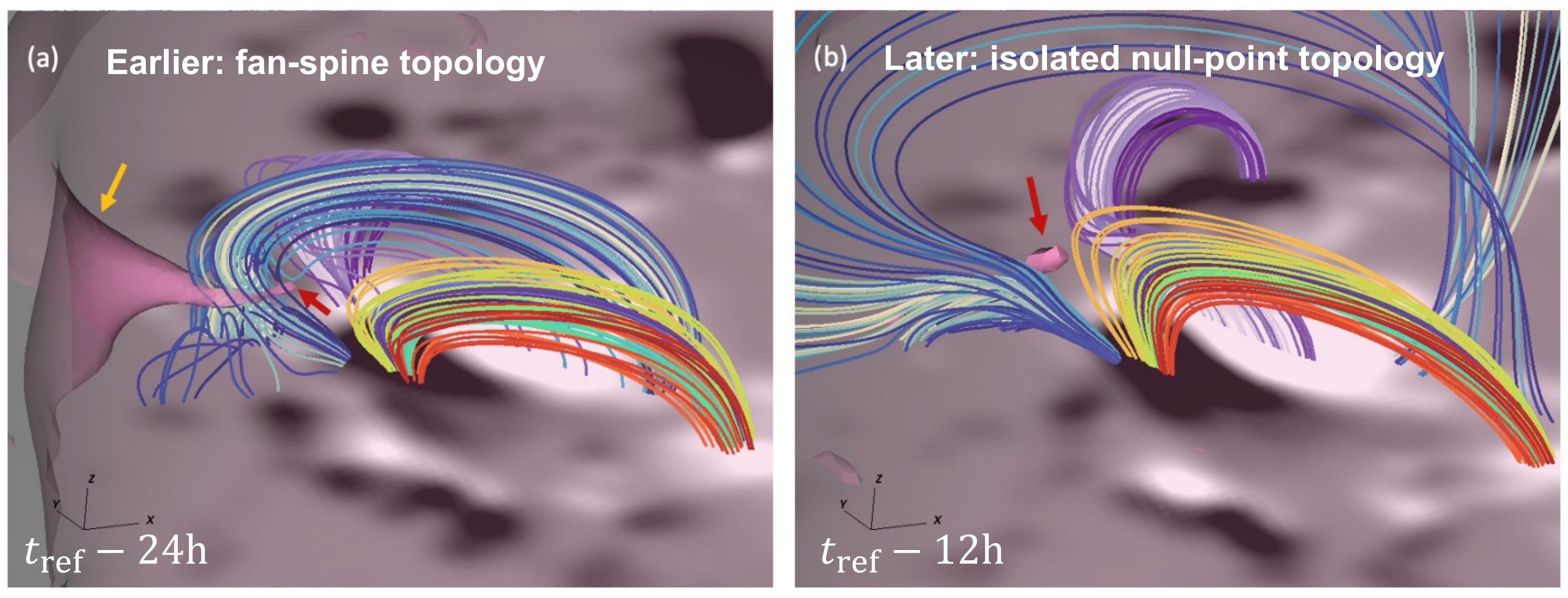


Flux systems **A** and **B** are initially unconnected.

A sharp change in connectivity occurs, resulting in **A** and **B** sharing common foot points.

The change in connectivity is a result of slip-running reconnection that is mediated by the null point.

- The change in magnetic topology that enables the slip-running reconnection to take place becomes apparent between $t_{\mathrm{ref}} - 24\mathrm{h}$ and $t_{\mathrm{ref}} - 12\mathrm{h}$.
- The field transitions from a fan-spine configuration to become an isolated null-point:



The transparent magenta surface: iso-contour of $|B| = 30$ G

Conclusions

- We successfully used TMFM snapshots as initial condition for zero-β MHD simulations.
- The dynamics depends on the chosen snapshot, and not on the change of the model.
- Prior to the eruption, the main flux system undergoes a topological change that allows slip-running reconnection to take place.
- MFRs, once formed, were susceptible to the torus instability.

References

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