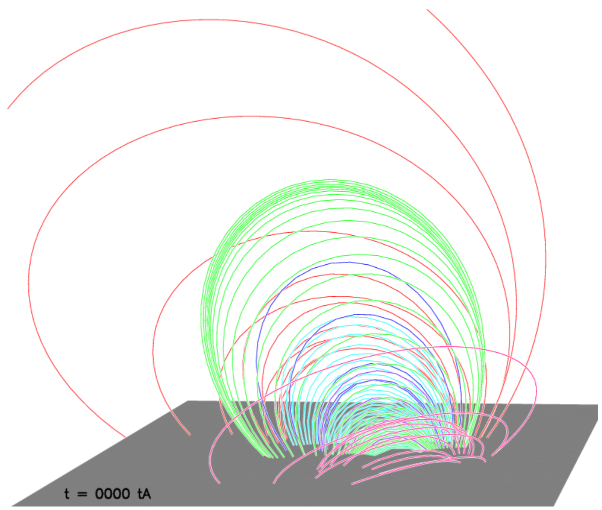
Numerical Simulations of Coronal Mass Ejections

Guillaume Aulanier & Stuart Gilchrist



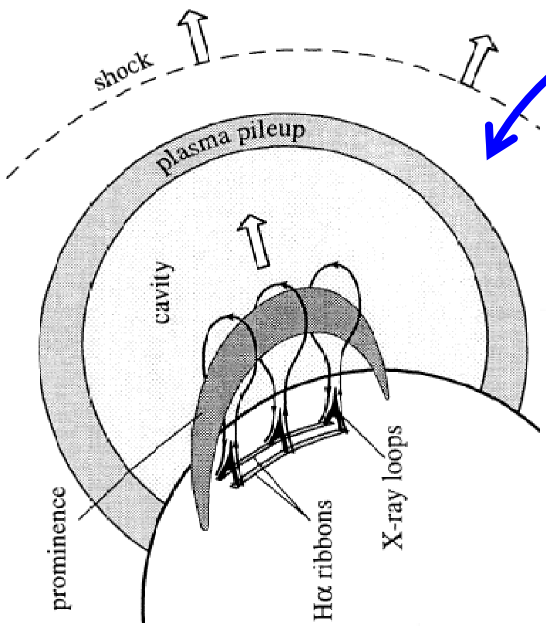
In collaboration with

F. Zuccarello, B. Schmieder, E. Pariat (LESIA),
M. Wheatland (Sydney Univ., Australia),
J. Zhao, H. Li (Purple Mountain, China)

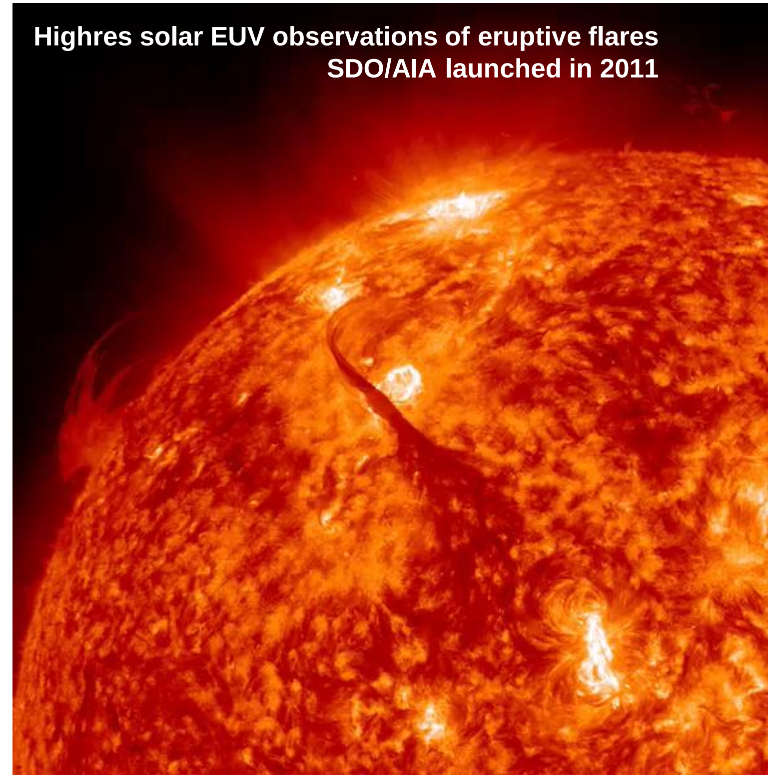
This work was supported by a grant from Région Ile-de-France

‘State of the art’ methodology in solar flare modeling

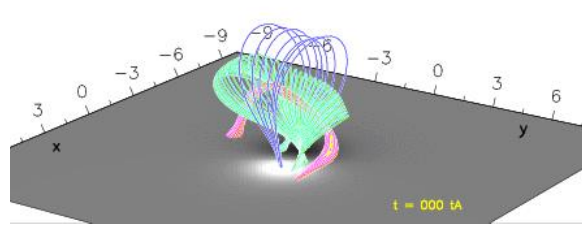
The so-called standard flare model (1960-90)



Observed phenomenology



OHM / MHD simulations (2008-09)



Physics constraints

Generic interpretation of observations

Beyond the 'state of the art' : data-initiated models

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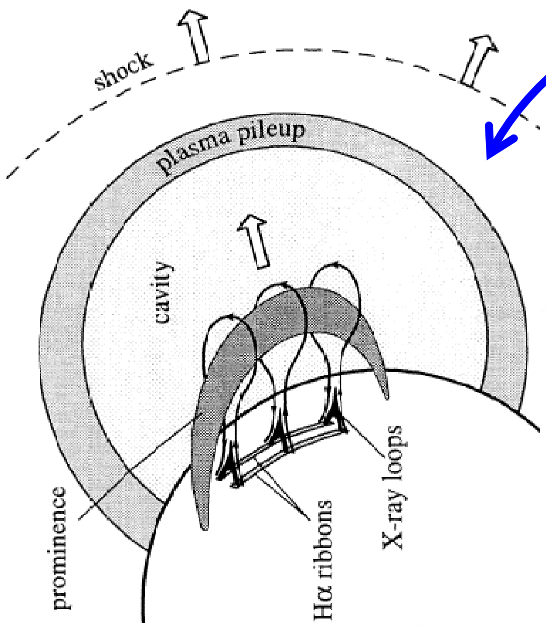

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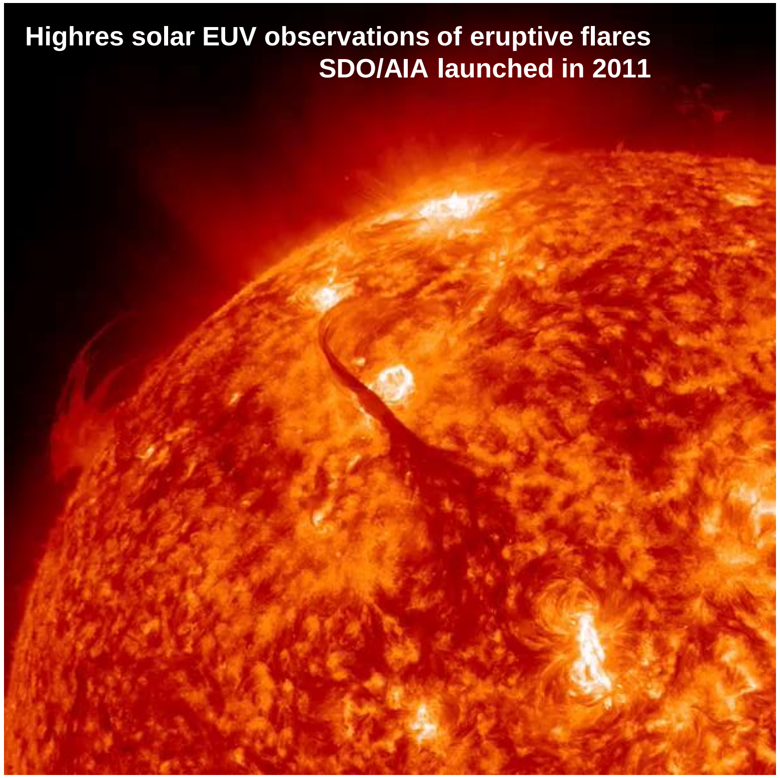
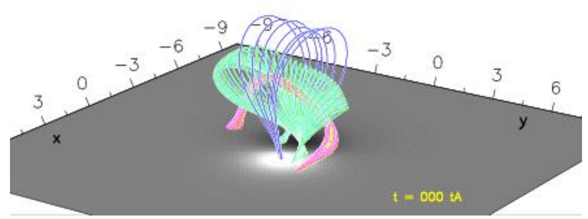


Data-initialized modeling ?

Physics constraints



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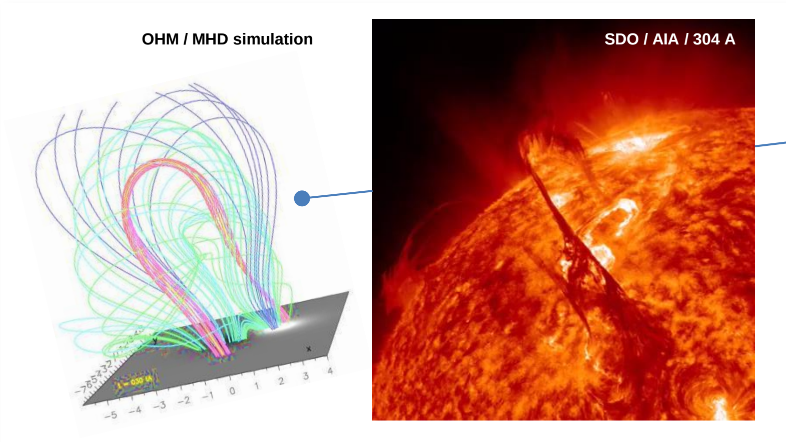
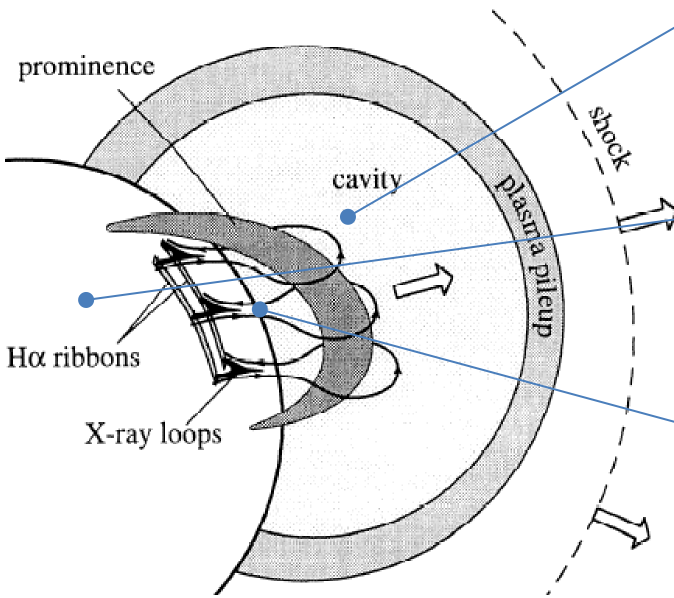
Going beyond the 'state of the art'





MHD code development

- Complete MPI parallelization of OHM code
- Integrate & parametrize generalized Ohm's law
- Optimize set-up for gravitational stratification

Building pre-eruptive B

- Use *observed* surface vertical B at boundary
- Couple NLFFF and MHD approaches
- Use *observed* surface horizontal B & coronal loops to constrain the solution

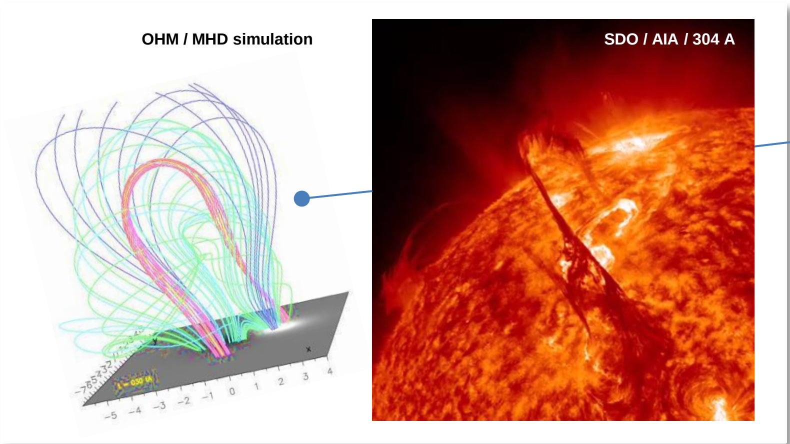
Role of observed solar drivers

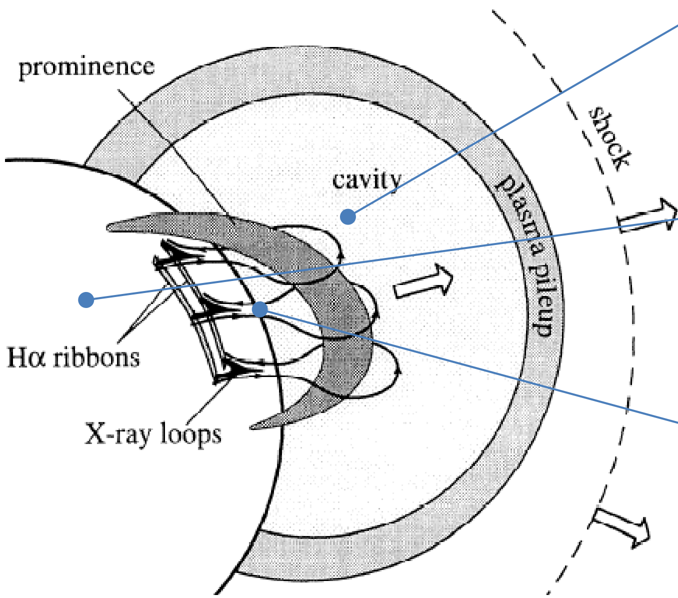
- Test the robustness of theoretical findings with data-driven simulations
- Contribute to international effort to test the prevalence of *torus instability* for initiating the majority of CME

Role of fast reconnection

- Quantify the feedback of fast reconnection on CME acceleration : Hall electric field & anomalous resistivity
- Accelerate / parellelize our topology visualization code TOPOTR

The DIM-ACAV project





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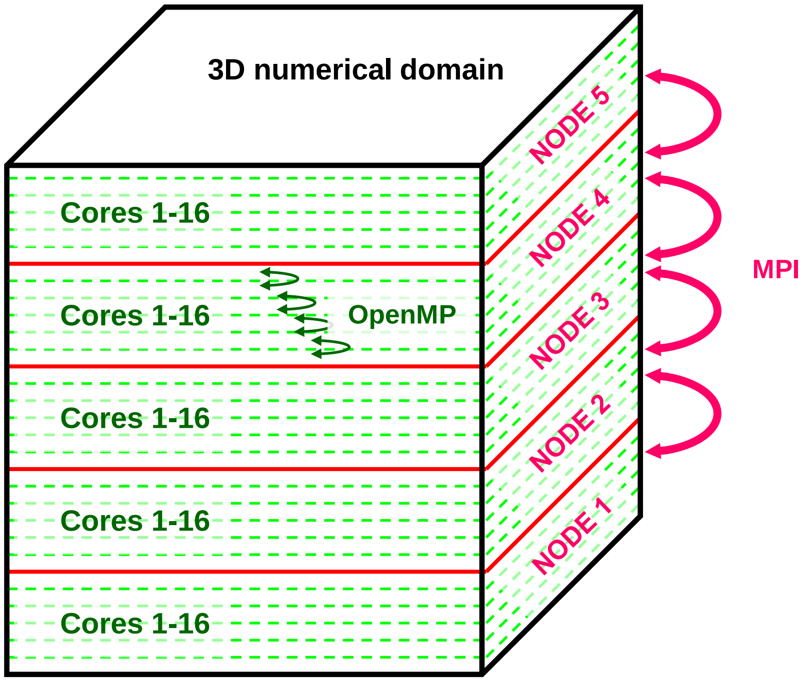
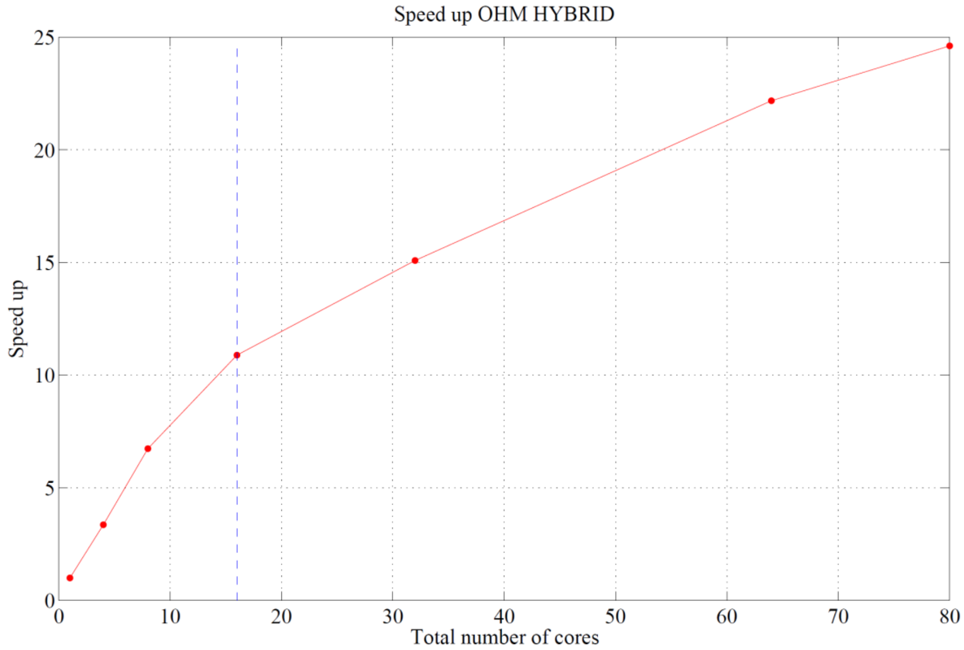
Hybrid slab parallelisation @ MesoPSL





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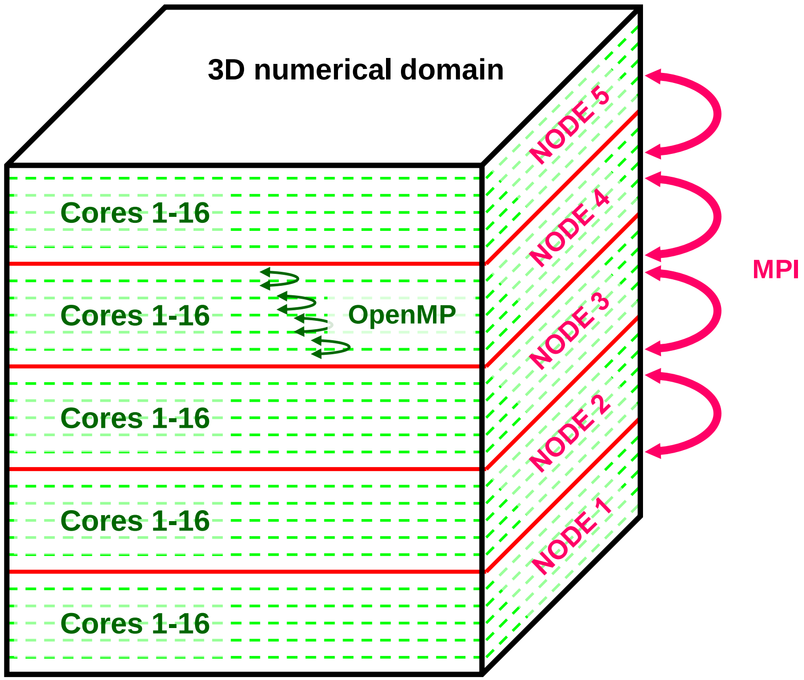
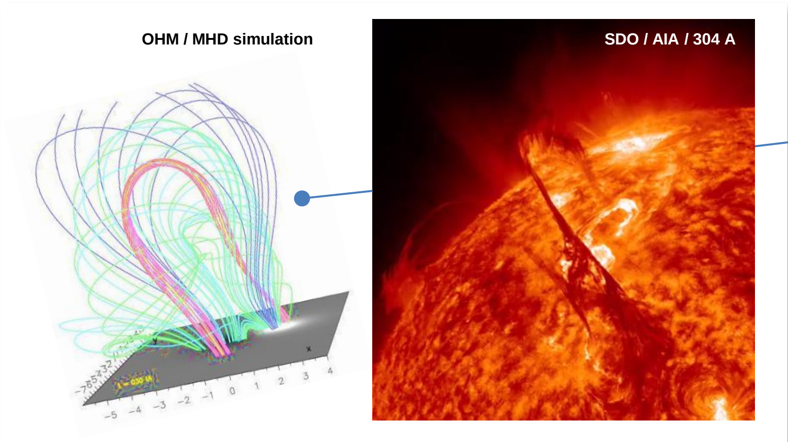


- Acceleration x25 with 80 cores allows :
  - ✓ Parametric explorations ;
  - ✓ Increasing nb of meshpoints ;
  - ○ Addition of new physics.
- Project towards 1000 cores :
  - ○ Aim for high-Rm plasma ;
  - ○ Requires block parallelisation ;
  - ○ Collaboration with LUTH (action fédératrice applications numériques de haute performance)

The DIM-ACAV project



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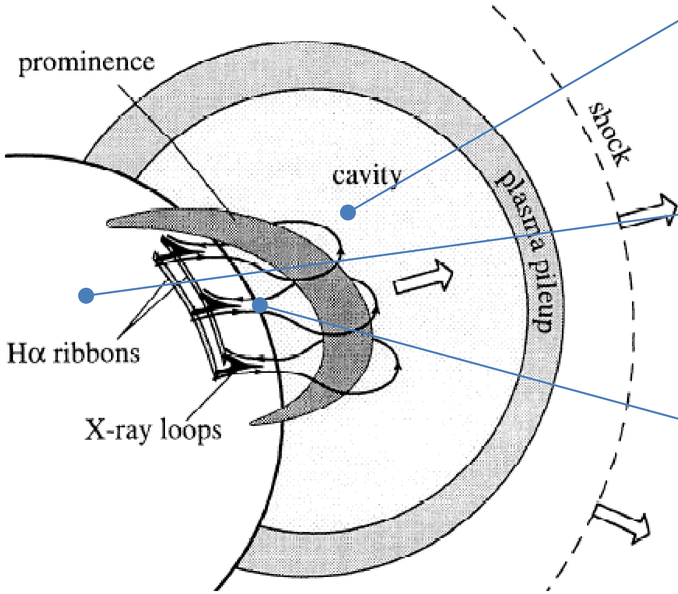

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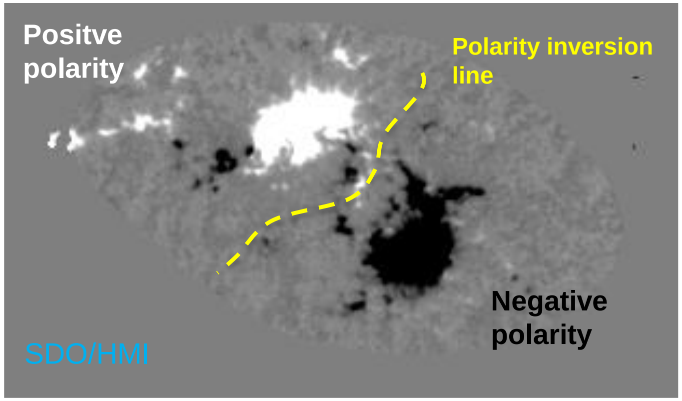
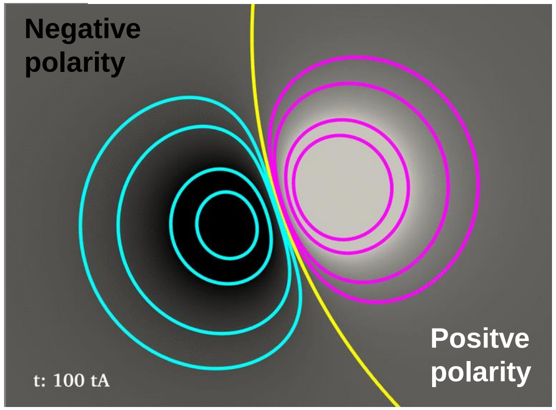
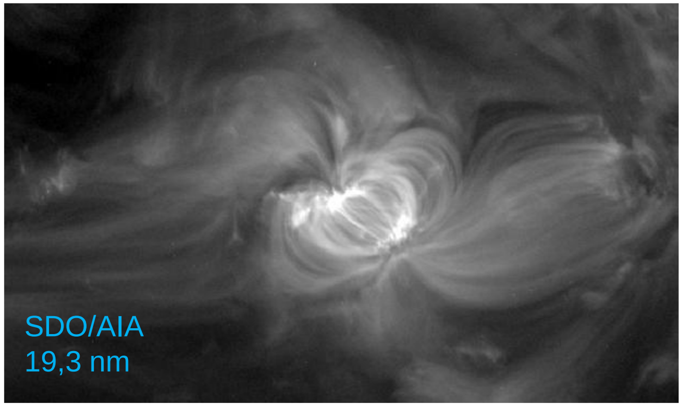
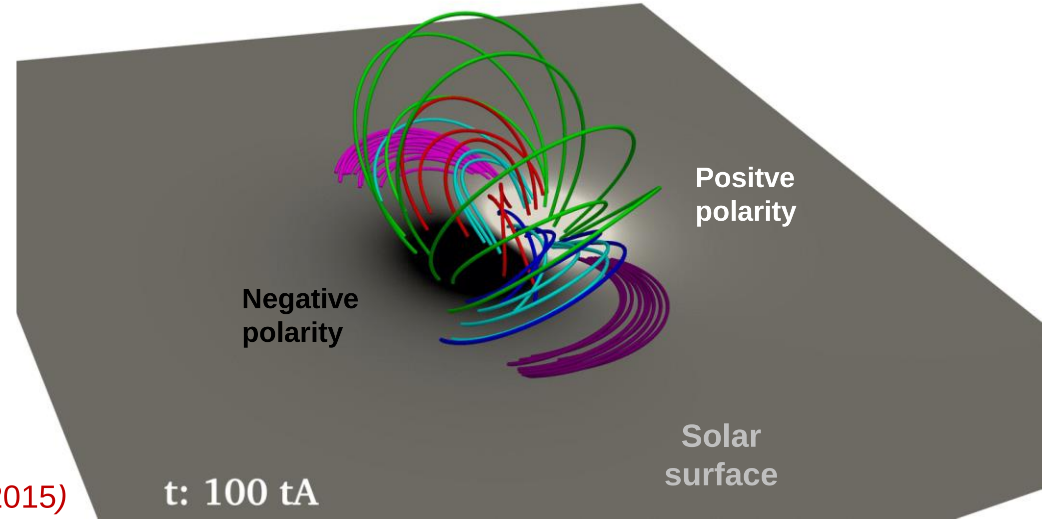
Data-inspired (not -initiated, yet) numerical models





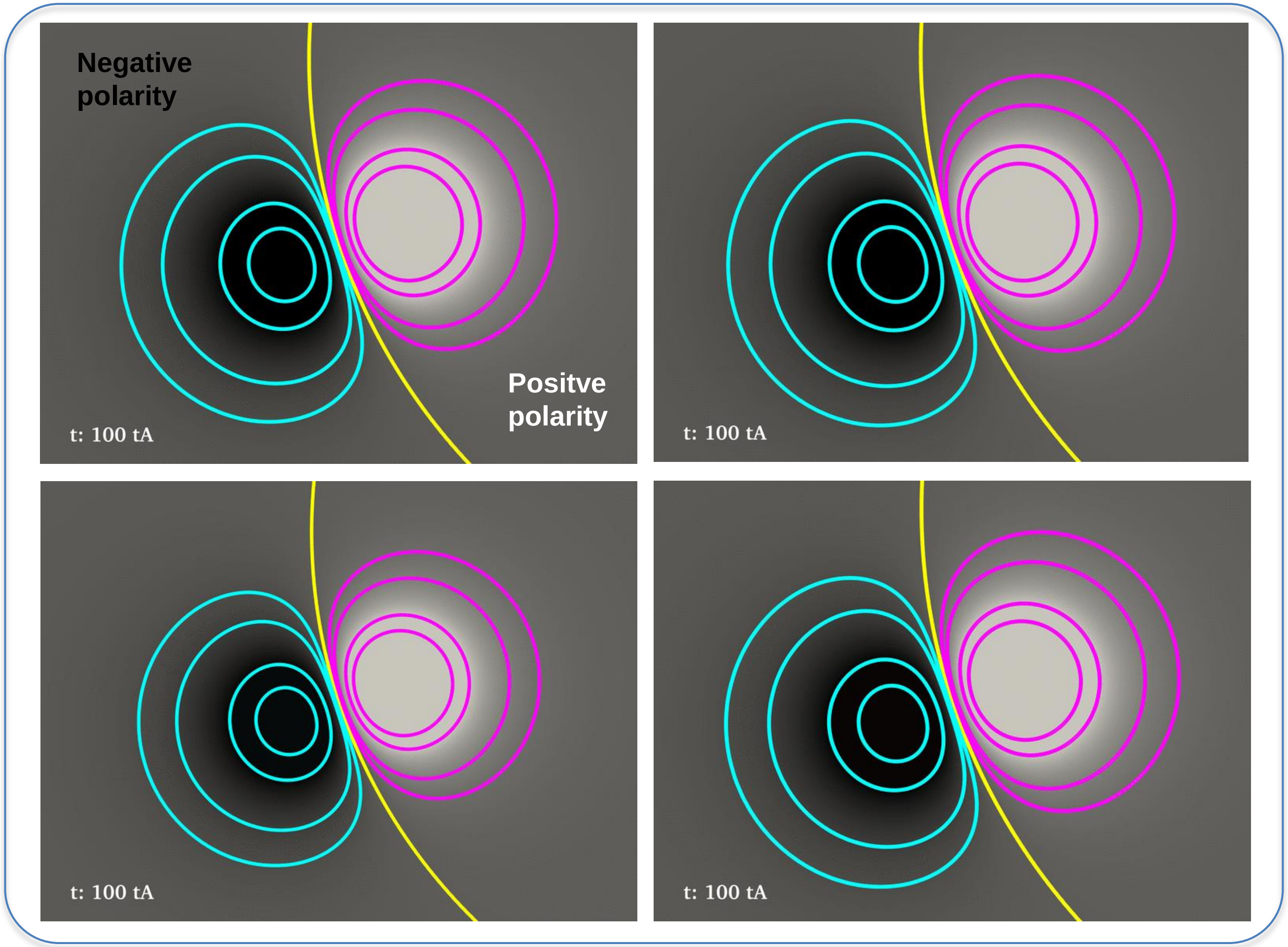


Code « OHM »



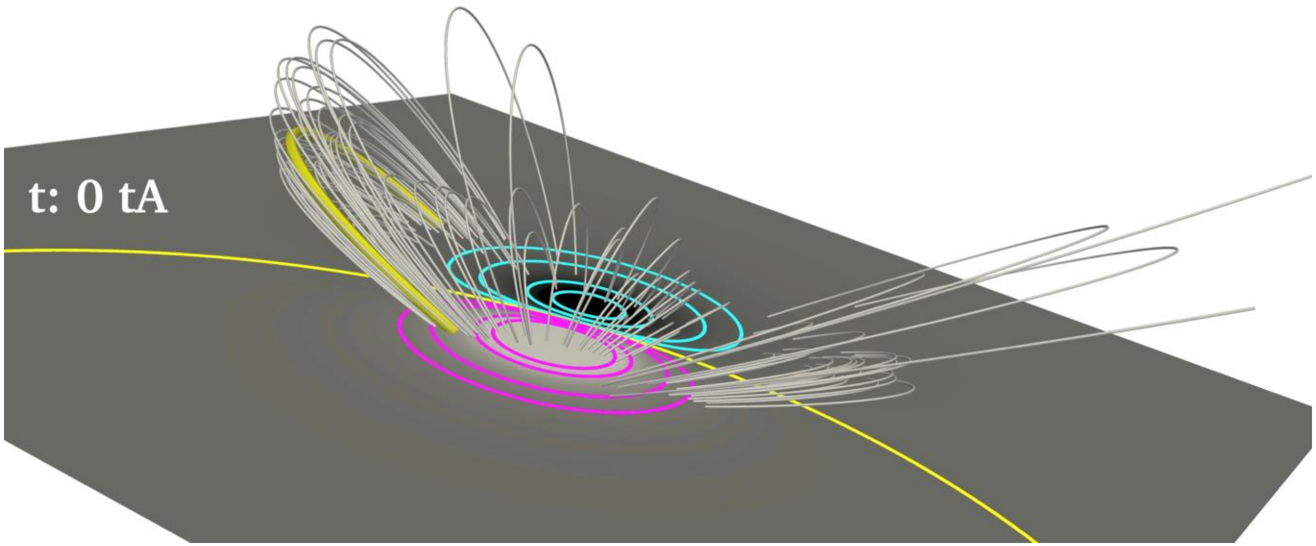
Zuccarello, Aulanier & **Gilchrist**, *ApJ* (2015)

Parametric exploration of solar drivers



- 4 different surface drivers, all inspired by observations :
  - Asymmetry of magnetic flux
  - Dispersion of the magnetic flux
  - Convergence and annihilation of flux polarity inversion line

Finding the time of the eruption onset … (many stress & relax runs)



- Magnetic field lines color-code : **black** = strong electric currents ;
  grey = weak electric currents

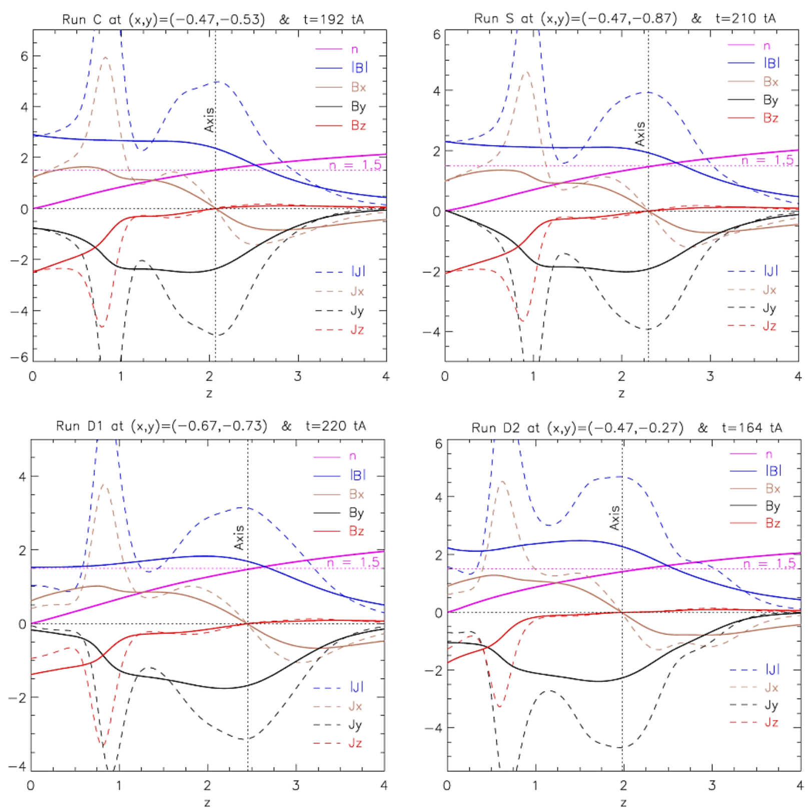
… and identifying common physical thresholds ? (many analyses)

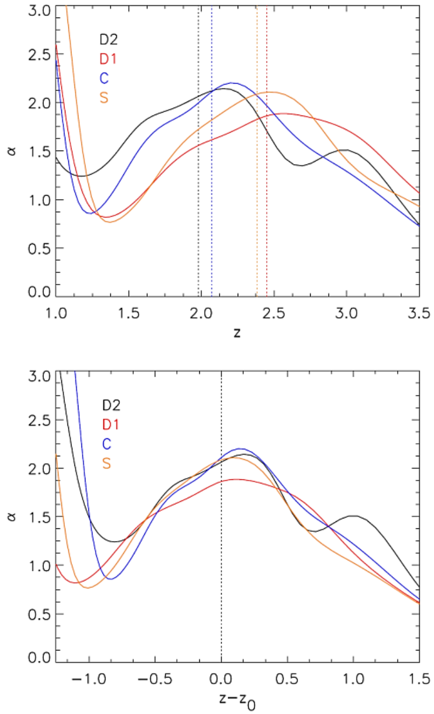
- The current profile normalised to the magnetic field ?

J/B = 2.2 ☺

$fwhm_{J/B}$ = 1 ☺

- The peak in the electric current ? **J = 3 to 5** ☹
- The altitude of the rope axis ? **Z = 1.95 to 2.45** ☹





… and identifying common physical thresholds ? (many analyses)

- The current profile normalised to the magnetic field ?

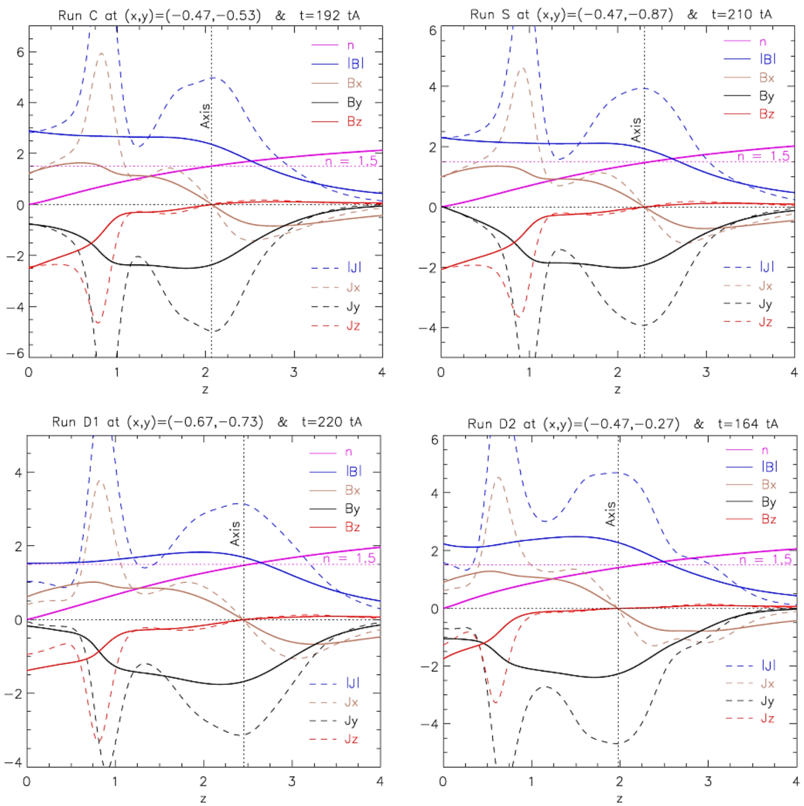
  J/B = 2.2 ☺ but one at **1.9** ☹

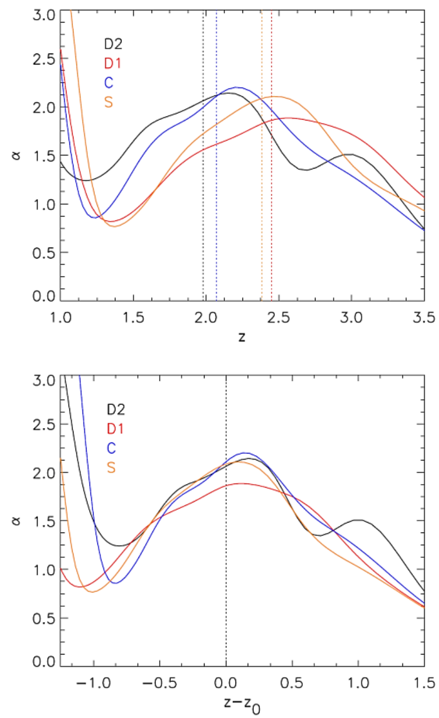
  $fwhm_{J/B}$ = 1 ☺ but one at **2** ☹

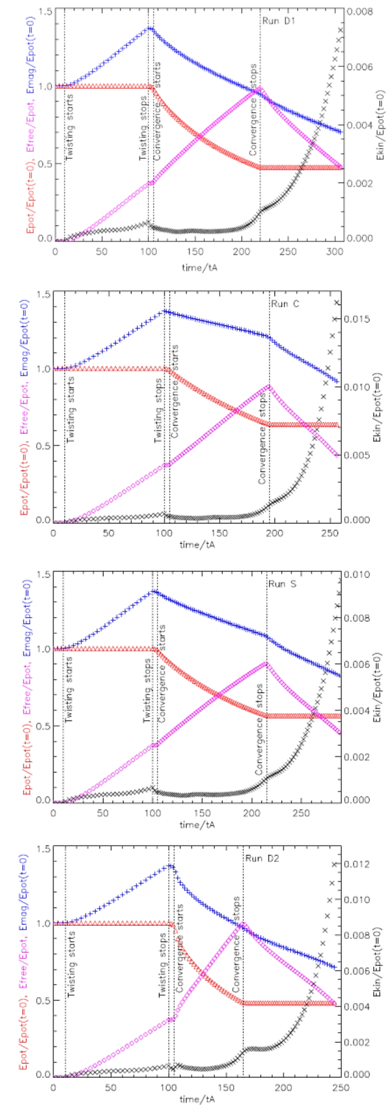
- The magnetic energy normalized to the current-free energy ?

  E_{free}/E_{pot} = 0.9 to **1.1** ☺ **?**

- The peak in the electric current ? **J = 3** to **5** ☹
- The altitude of the rope axis ? **Z = 1.95** to **2.45** ☹



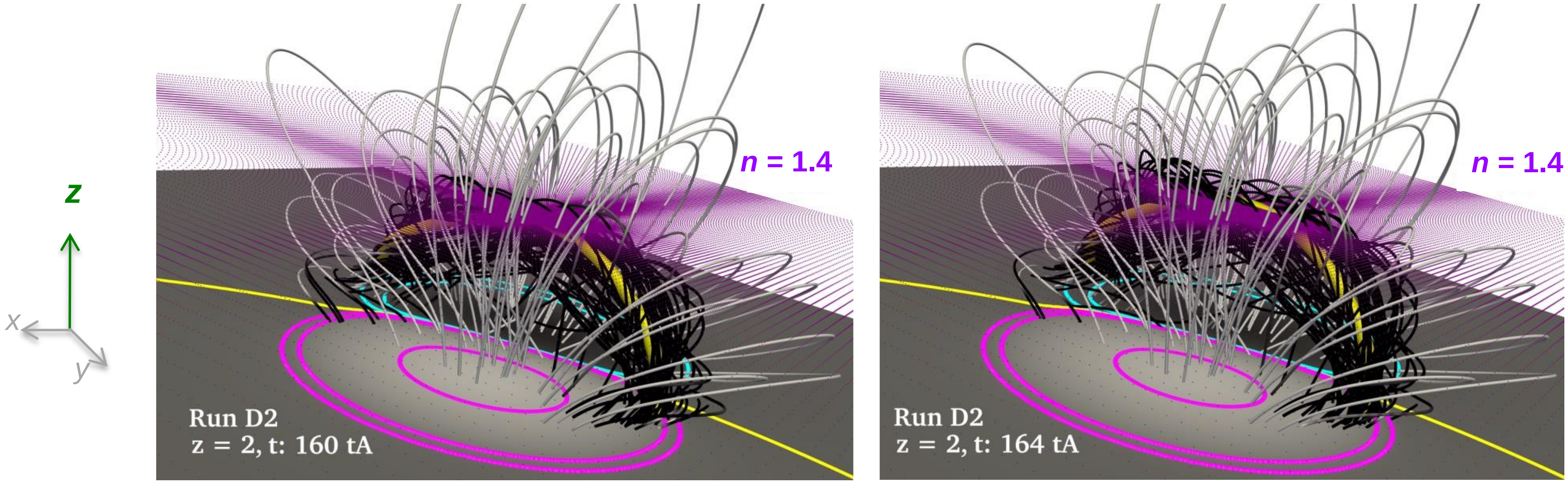




A unique criterion (!) on the eruption threshold

Twisted magnetic flux ropes

… stable … eruptive

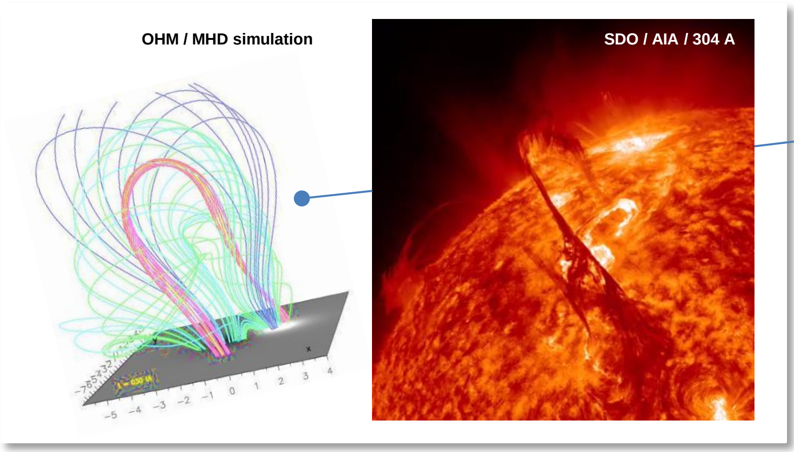


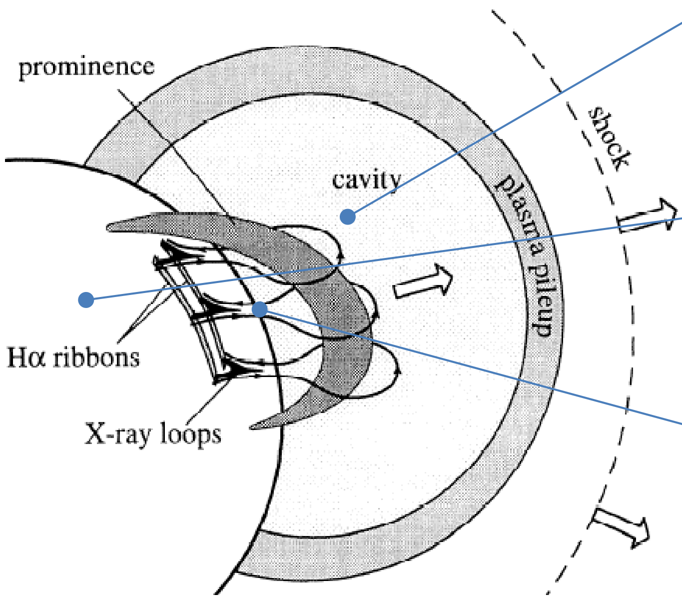
- Instability threshold uniquely determined by :

  - ➢ Altitude ***z*** of the **axis** of magnetic flux rope
  - ➢ Critical altitude z_c above which the magnetic field ***B*(*z*)** decreases faster than (*1/**z***)^{n}
    (analogy with the *T(z)* criterion for thermal convection)
  - ➢ ***n* = 1.3 - 1.5** (depends on resistivity η : diffusion and/or reconnexion?)

Zuccarello, Aulanier & **Gilchrist**, *ApJ* (2015 ; & another paper in prep)

The DIM-ACAV project





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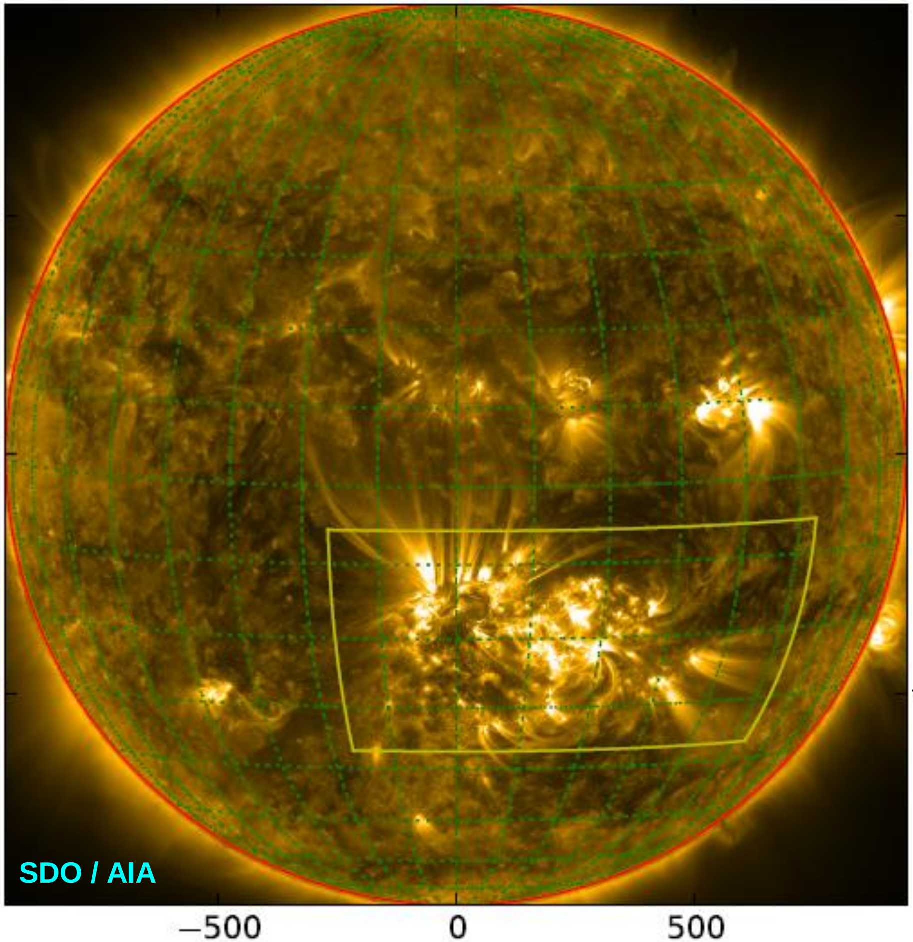
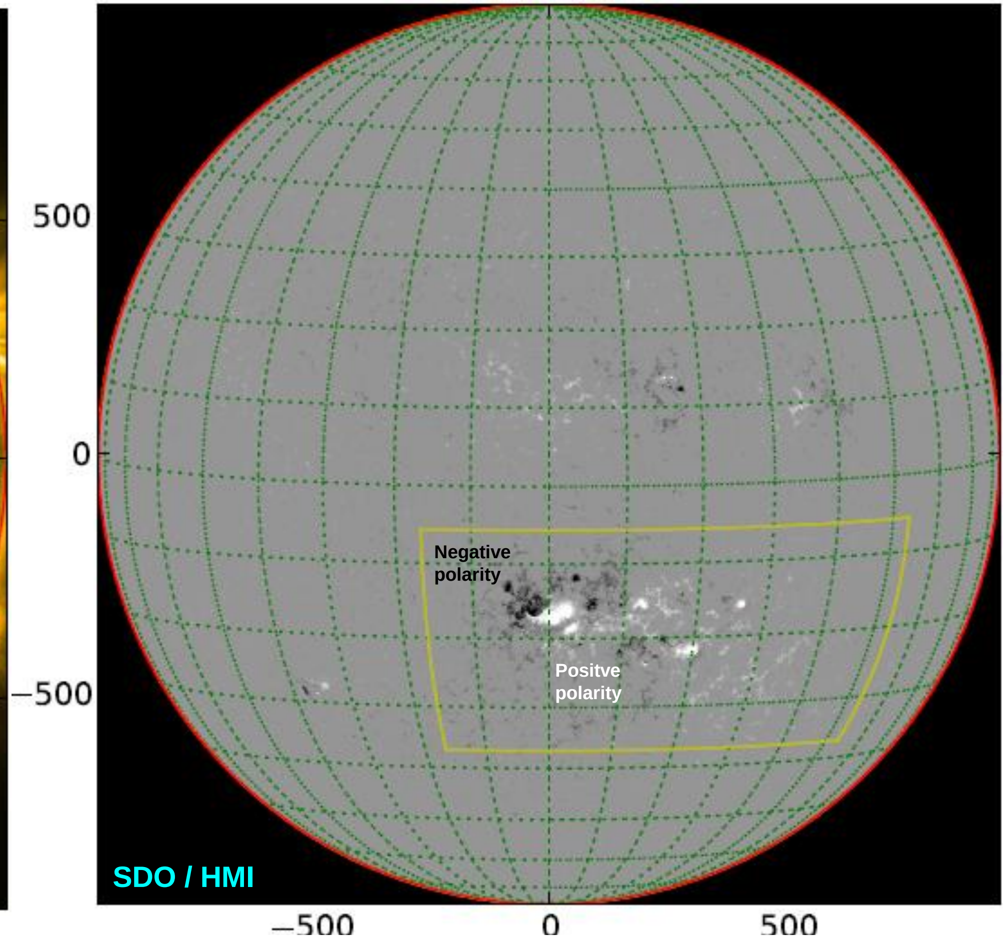
Spherical non-linear force-free fields : Grad-Rubin method

Equation solved : $\mathbf{J} \times \mathbf{B} = 0,$

Boundary conditions : $\alpha_0 = \mu_0 \left.\frac{J_r}{B_r}\right|_{r=R_\odot}, \quad B_r|_{r=R_\odot},$

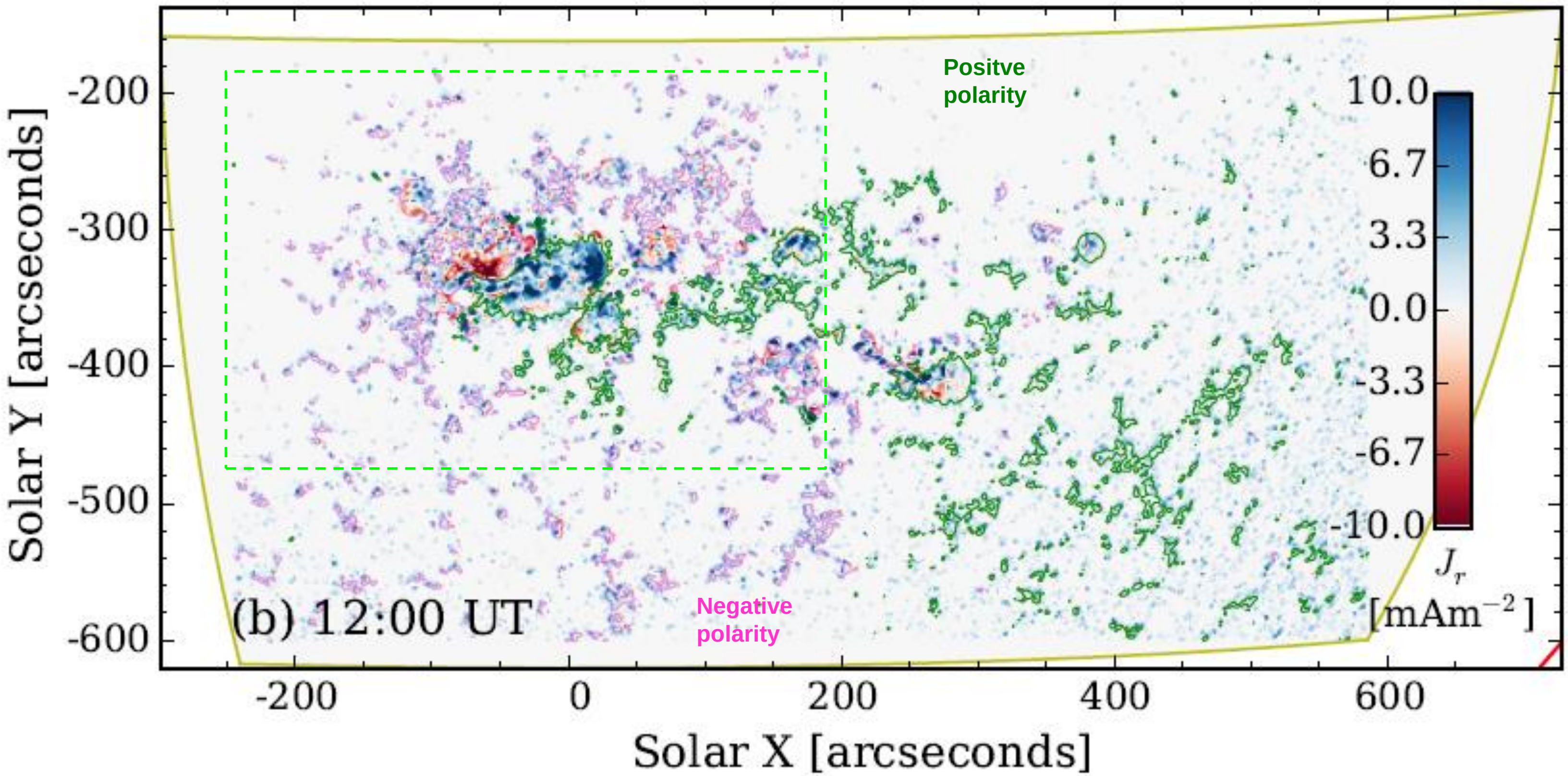




Code « CIFTS » : **Gilchrist**, & Wheatland (2014)

Effect of the data-smoothing on the recovery of a flux rope

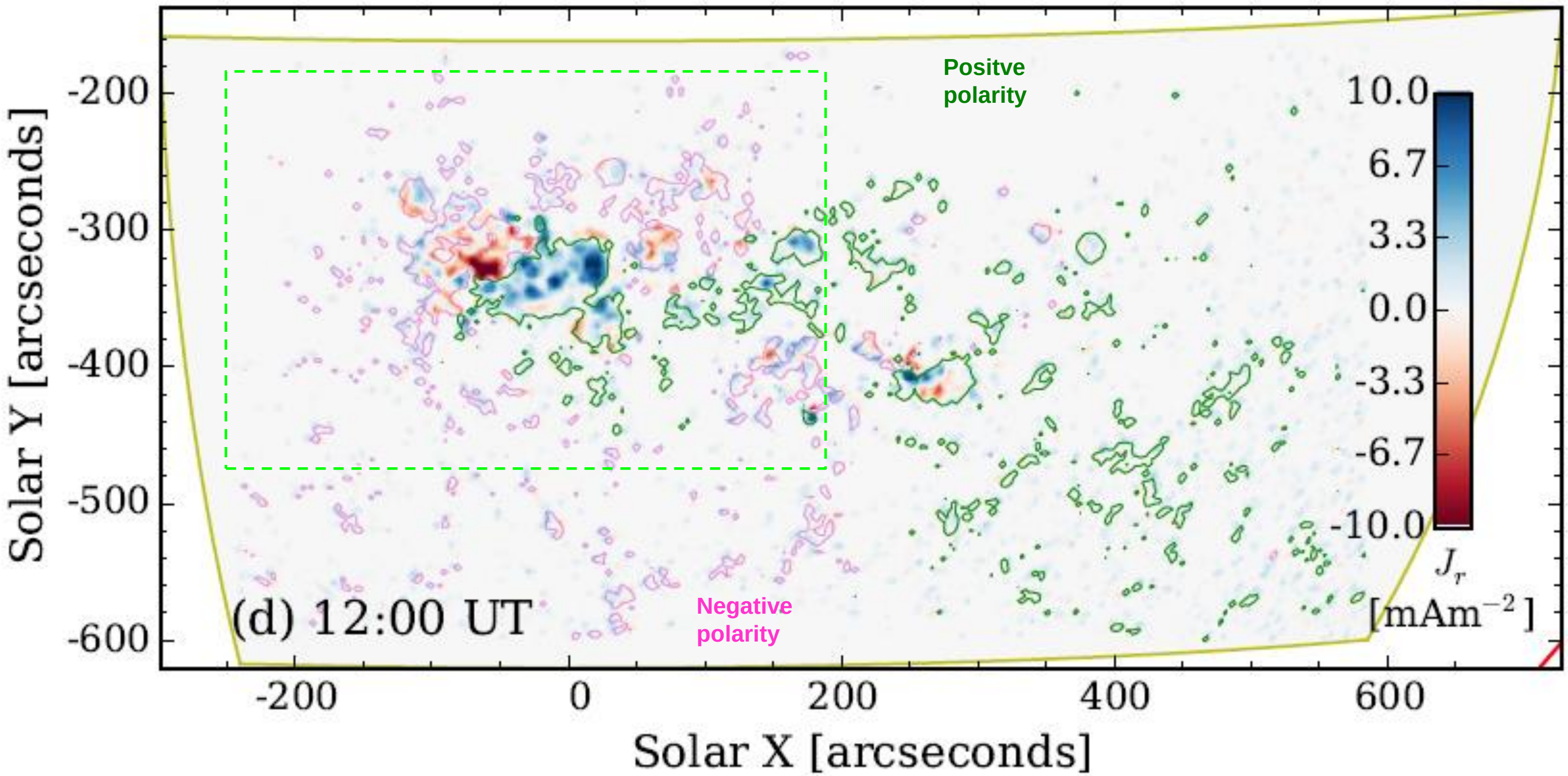
Observed Jz (original data, with 4x4 binning ; still noisy & spiky)



Gilchrist, Aulanier, Wheatland, Schmieder & Janvier (in prep)

Effect of the data-smoothing on the recovery of a flux rope

Observed Jz (8x8 binning + « smoothing » treatment)



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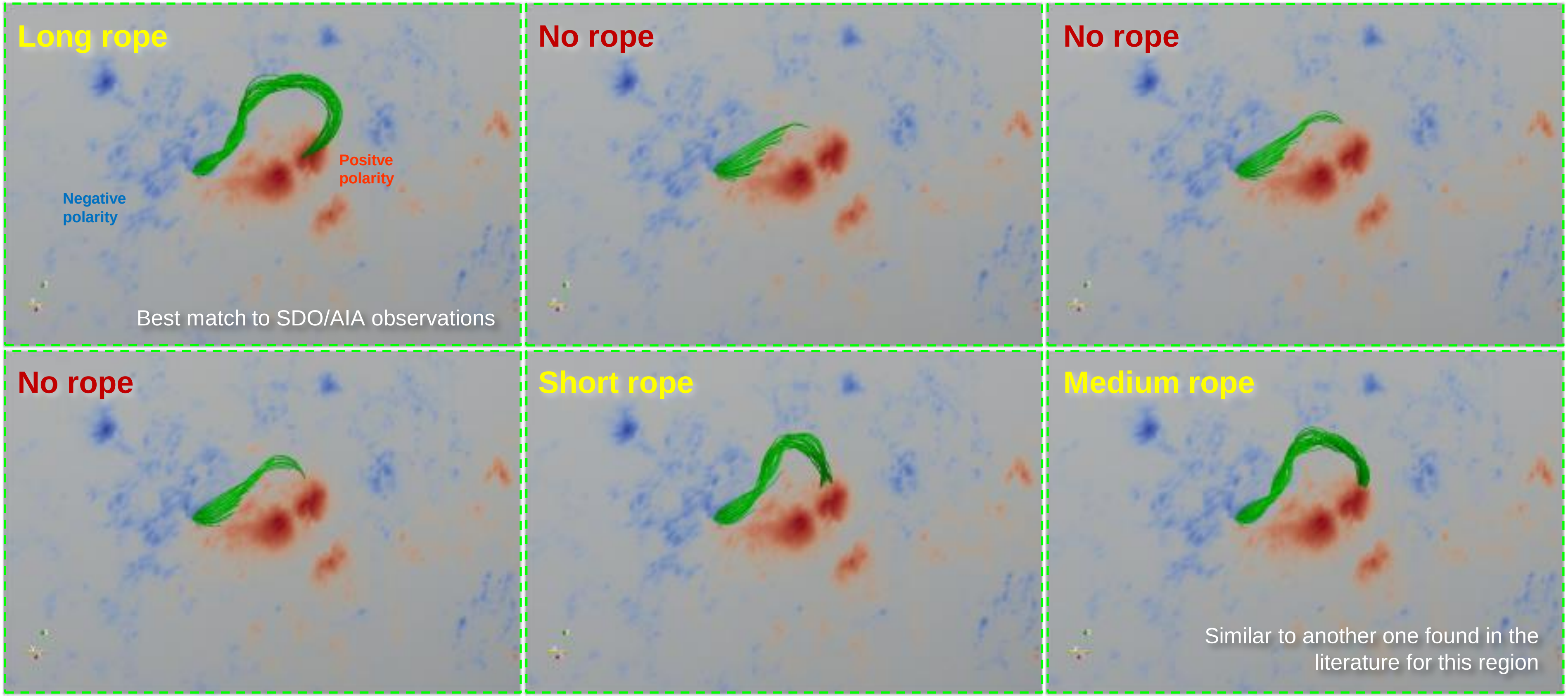

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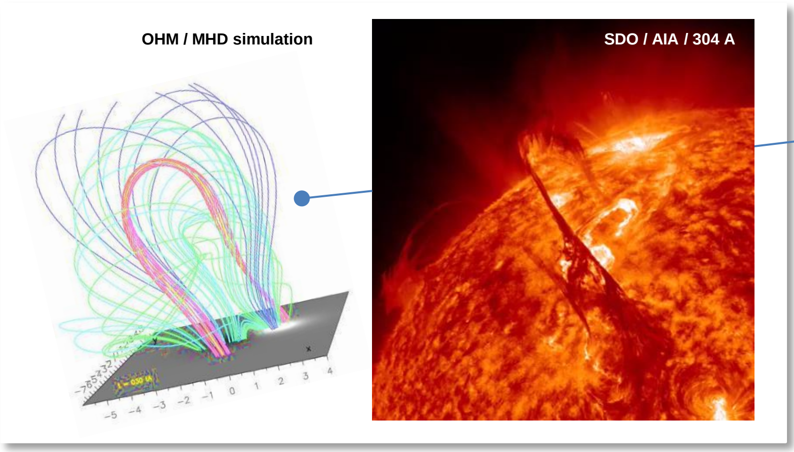

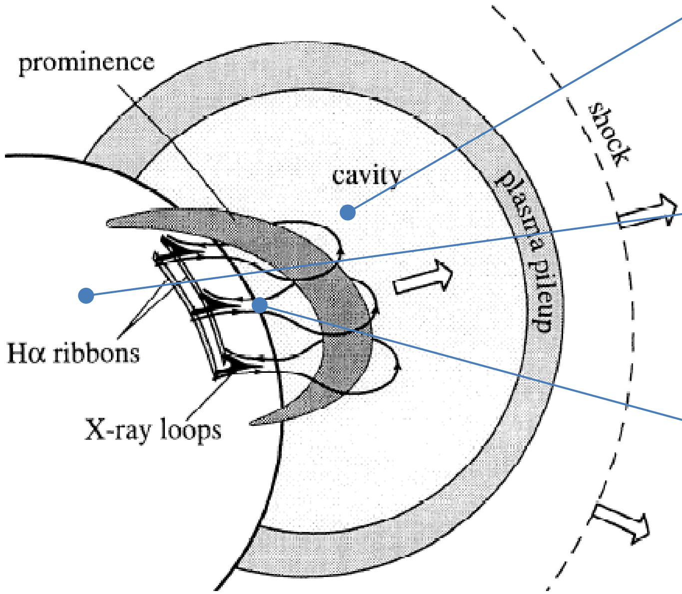

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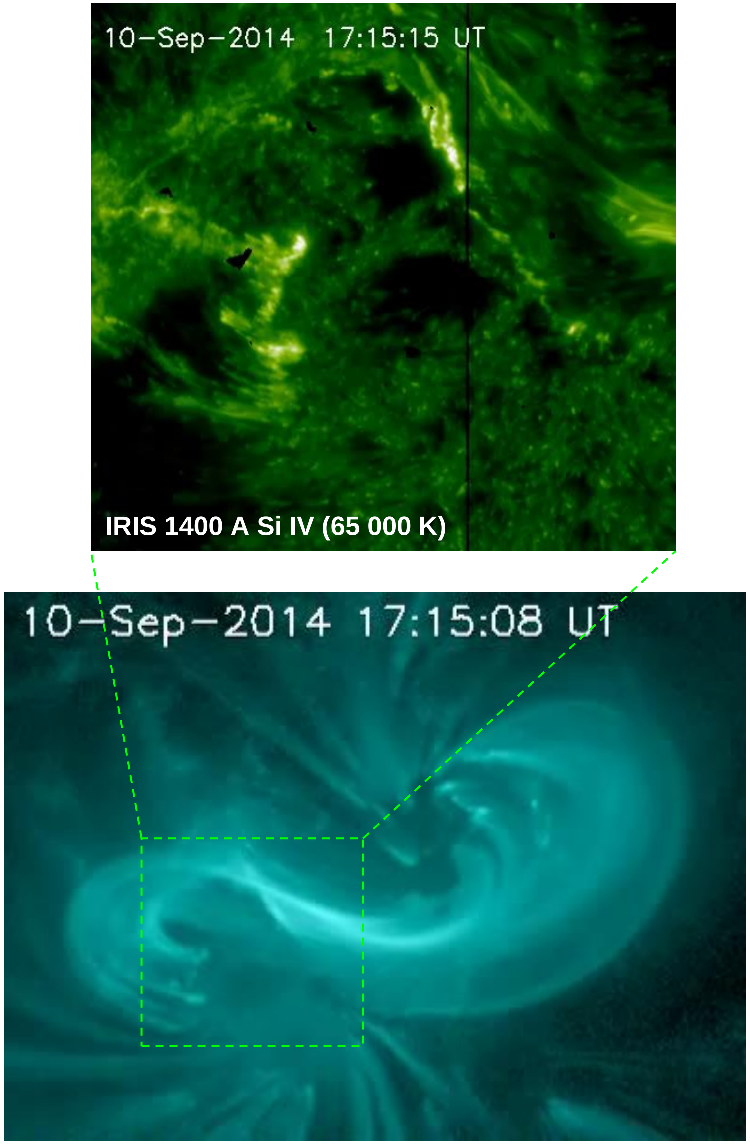
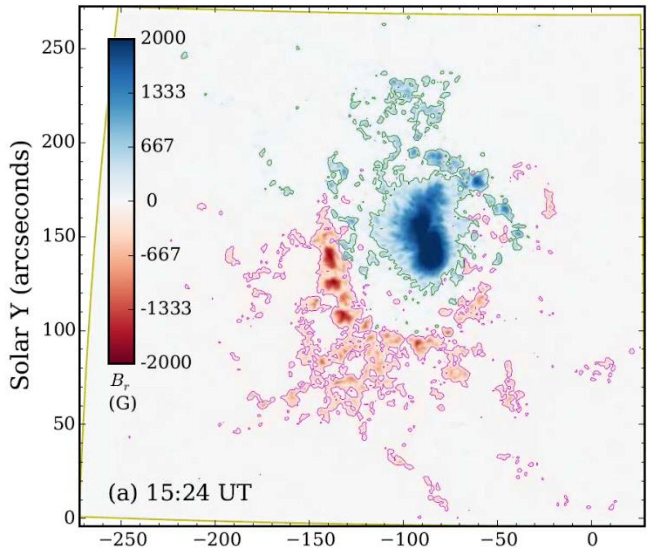
Origin of fast-slipping coronal loops, during an eruption ?

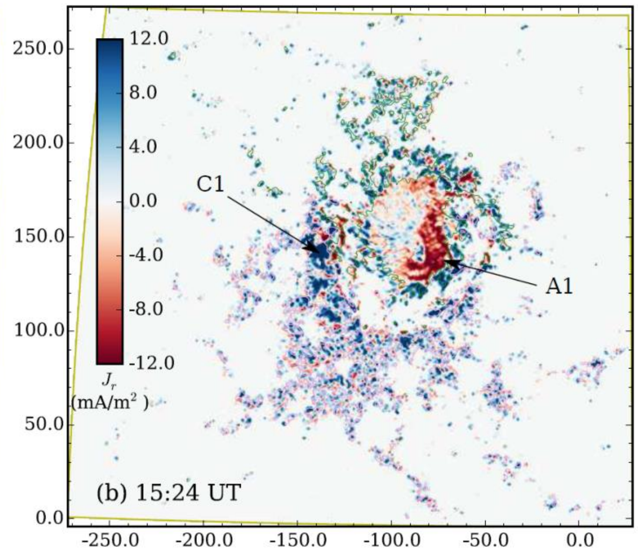


Li & Zhang (2015) Dudik, Polito, Janvier, et al (submiited)

Exploit SDO/HMI full-vector magnetographic data

Observed Bz

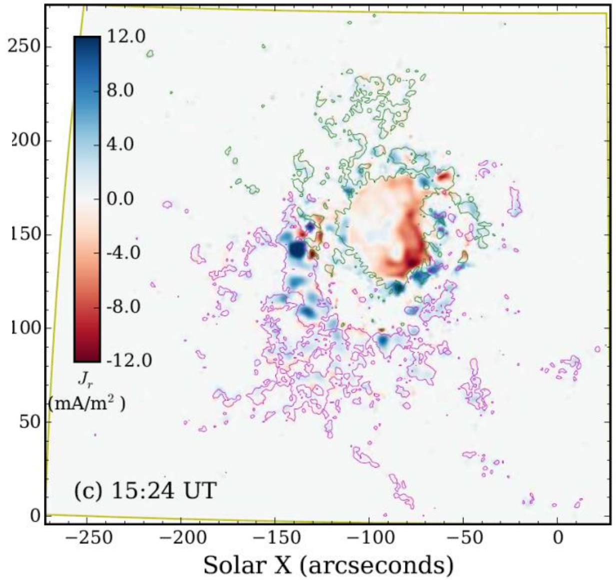




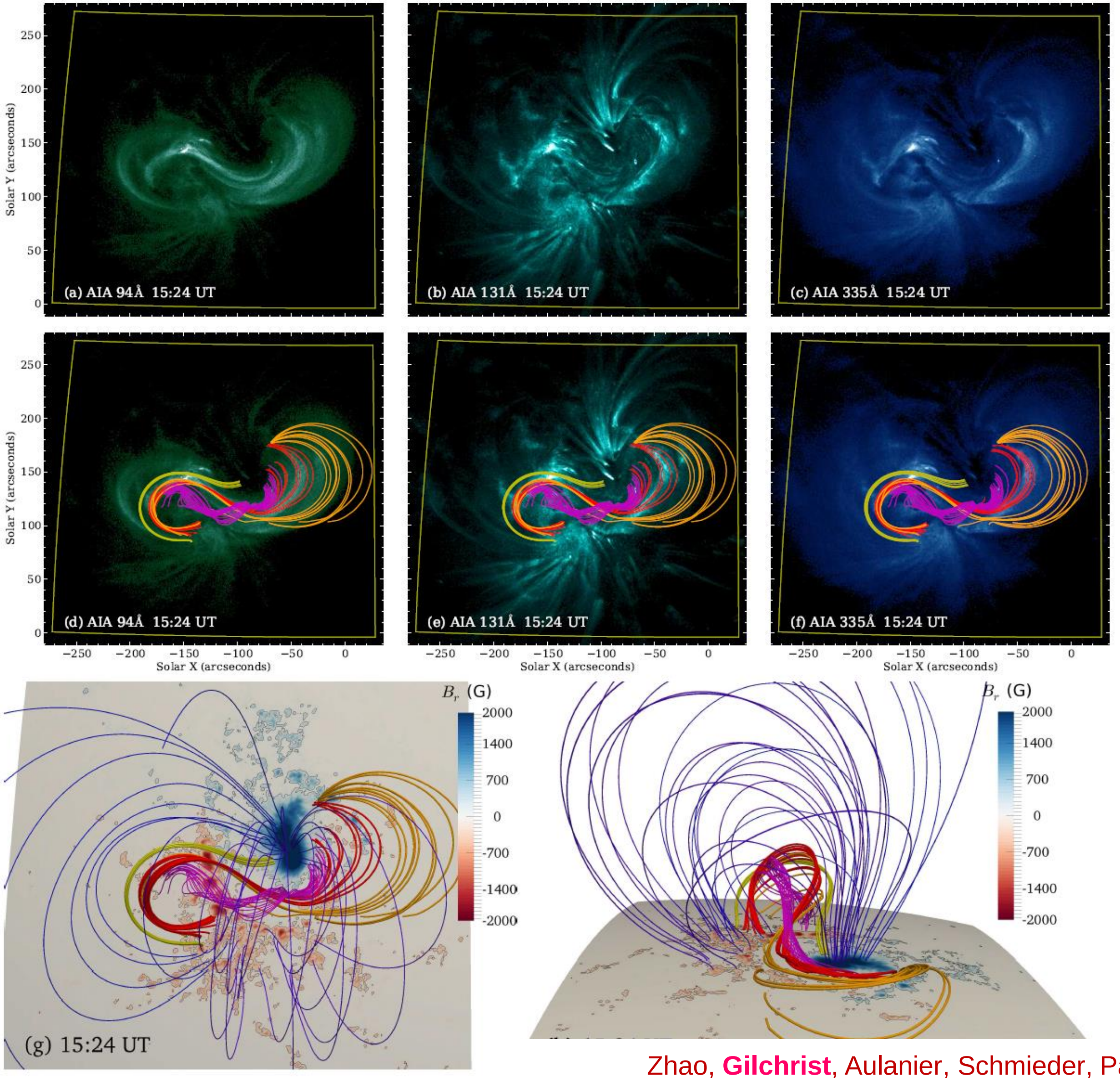
Observed Jz

Smoothed Jz

(only prescribed where Bz> 0)



Solving the non-linear force-free field equation



Zhao, **Gilchrist**, Aulanier, Schmieder, Pariat & Li, *ApJ* (submitted)

Exploit SDO/HMI full-vector magnetographic data

Observed Bz

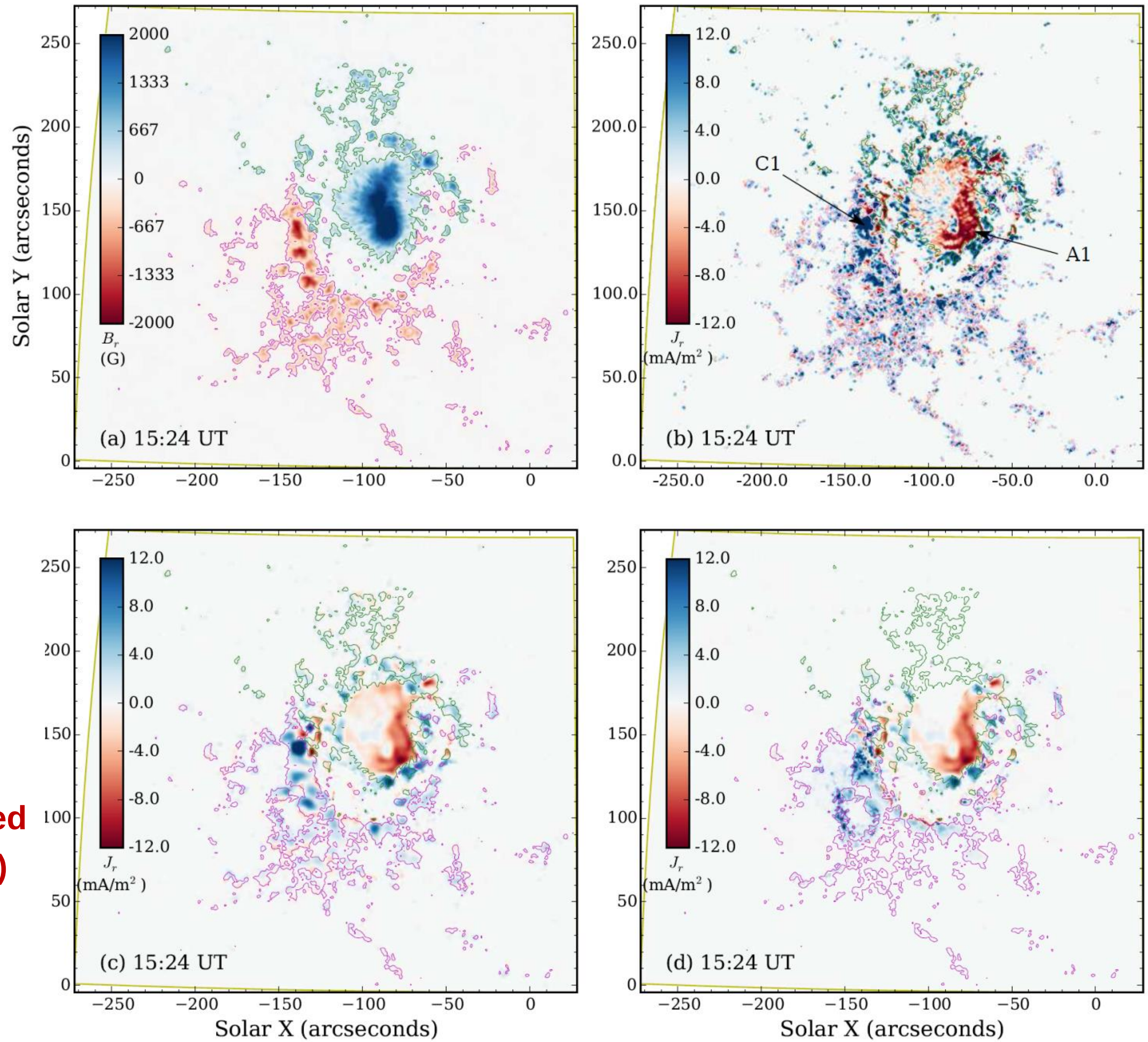
Observed Jz

Smoothed Jz

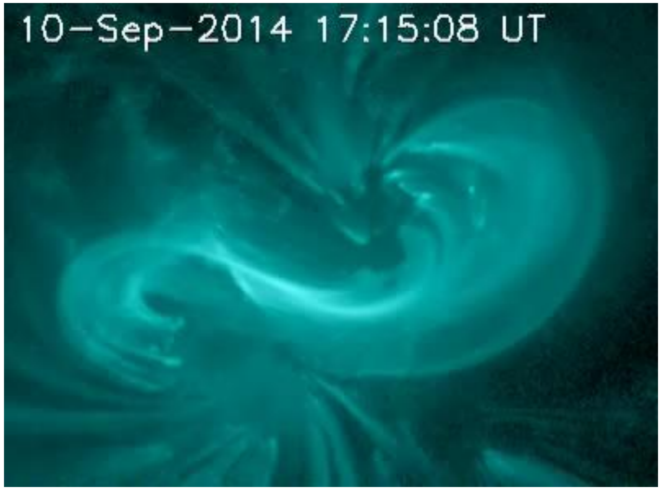
(only prescribed where Bz> 0)

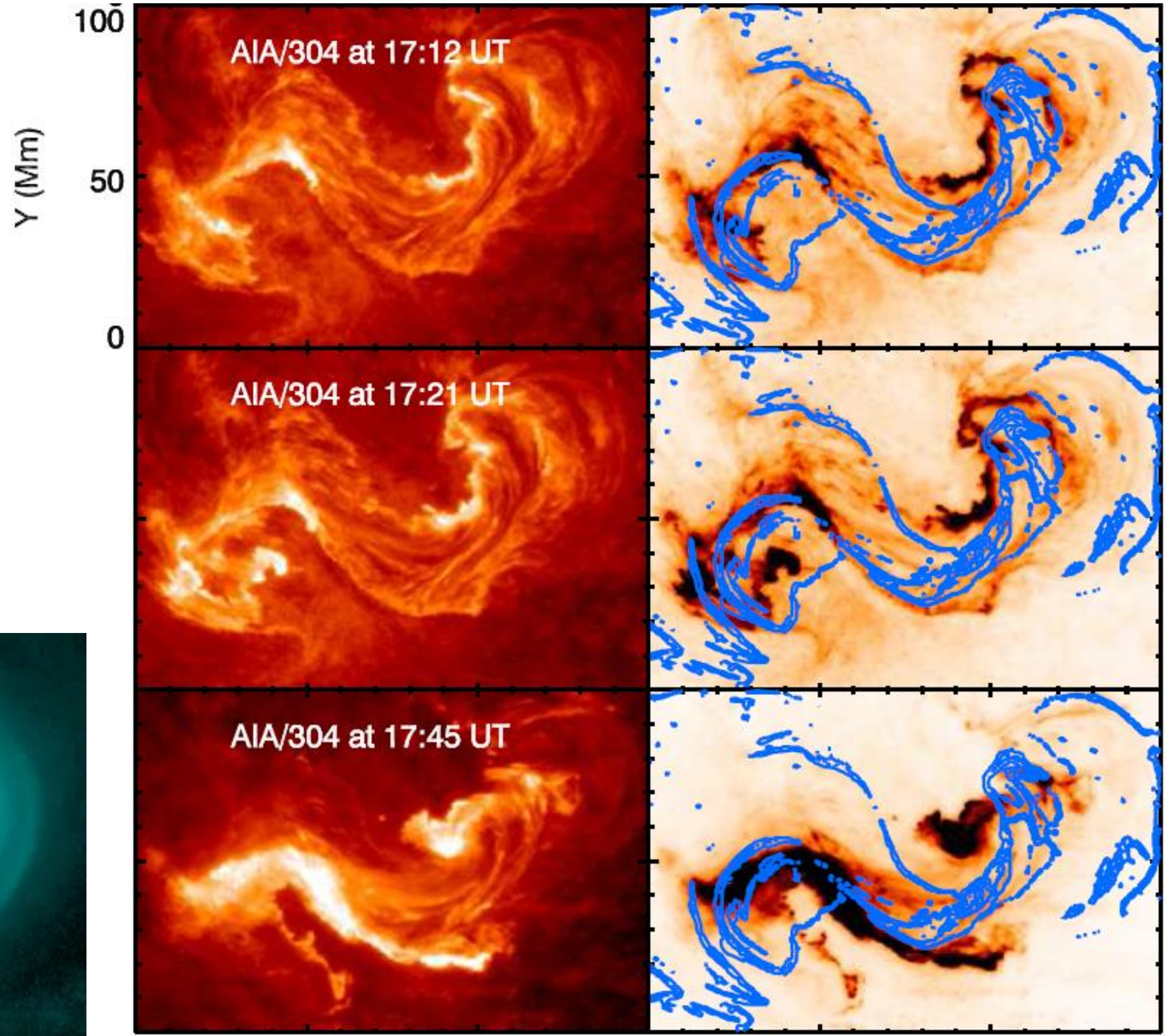
Recovered Jz

(in Bz< 0 where where it was not prescribed)



Loops slip along flare ribbons = connectivity gradients





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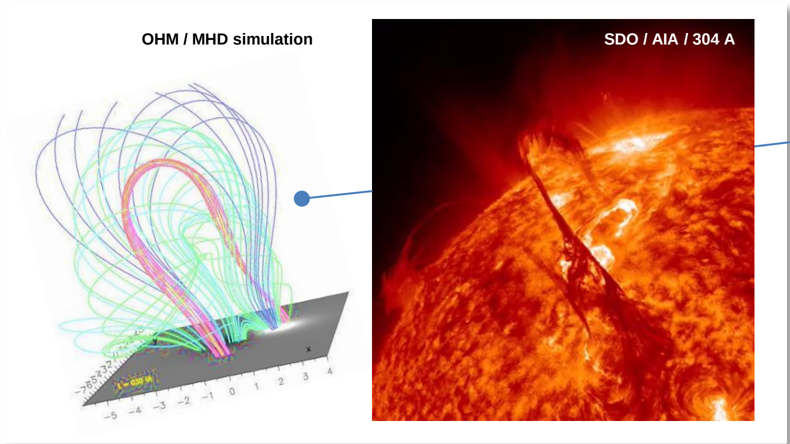

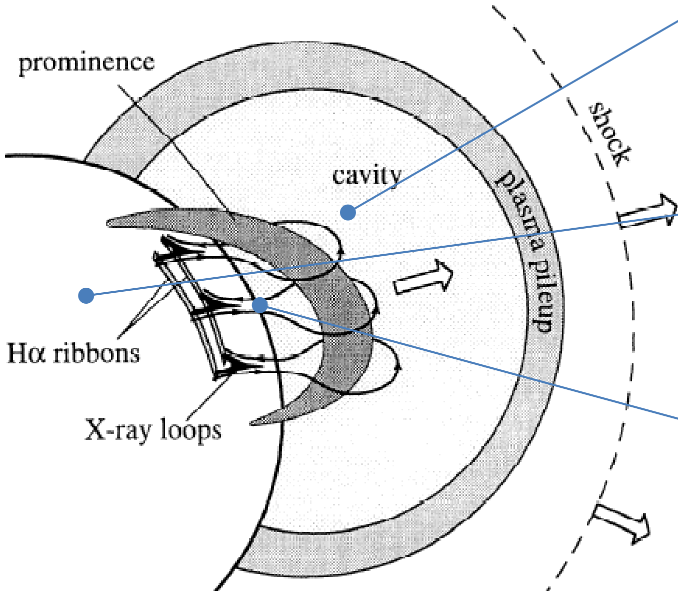

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NLFFF-stability vs. MHD eruption-threshold ?

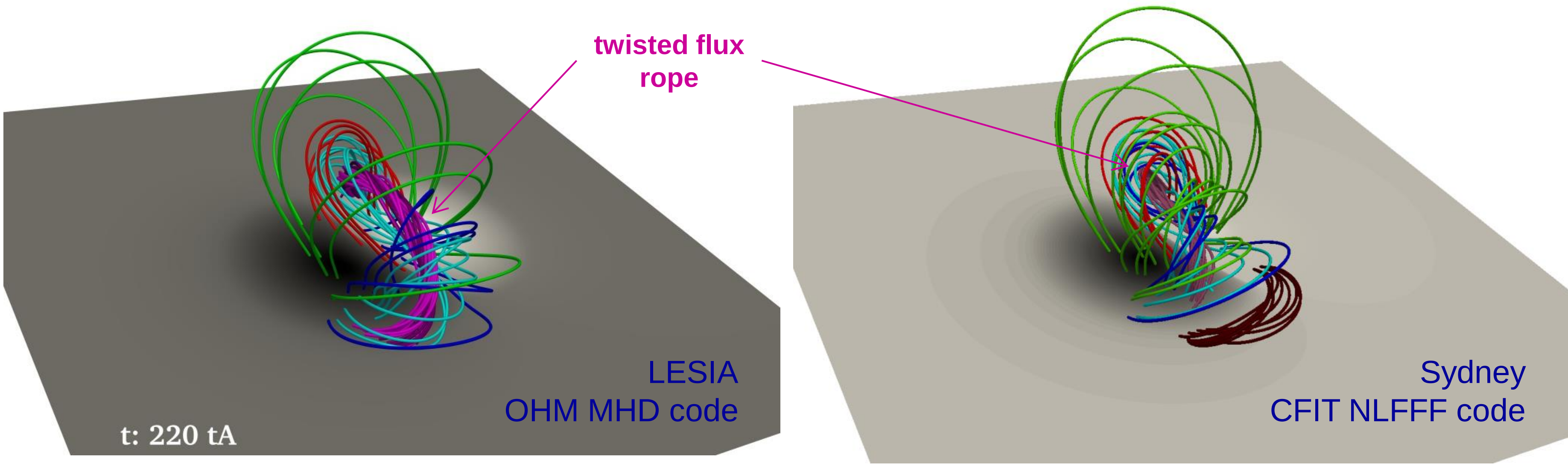
- Ongoing project :

  ✓ Re-mapping the MHD nonuniform-mesh onto a NLFFF uniform-mesh ;

  ✓ Using re-mapped MHD surface-B as boundary conditions,

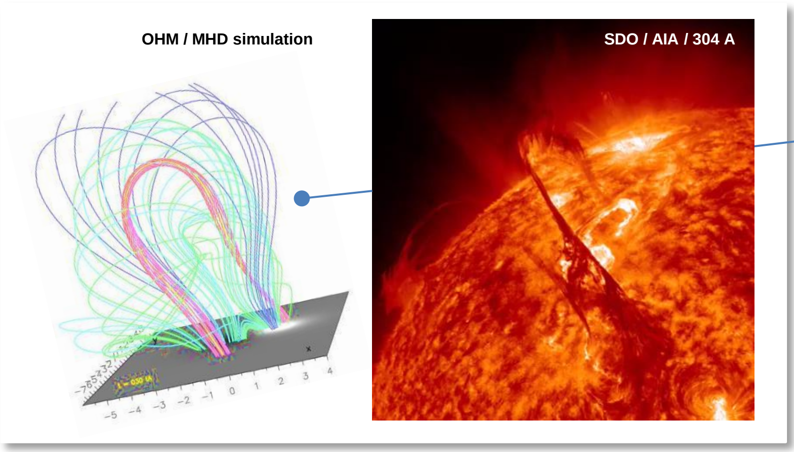
  recover (?) MHD coronal twisted flux rope with NLFFF reconstruction ;

  ○ Repeat at various times of an MHD simulation.



Gilchrist, Zuccarello, Aulanier & Wheatland (work in progress)

Where do we stand (the project was ambitious for only 1 year ½)



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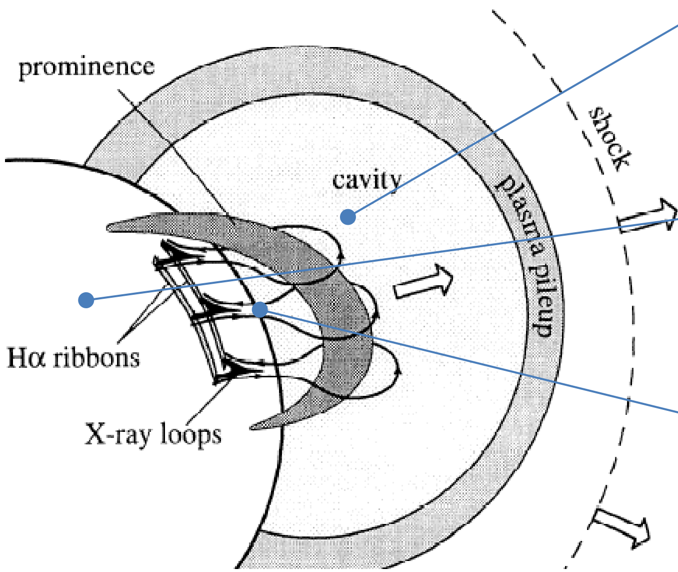

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4 refereed papers : published = 1 on MHD ; submitted = 1 on NLFFF ; in preparation = 2 (1 on MHD + 1 on NLFFF) +1 work in progress