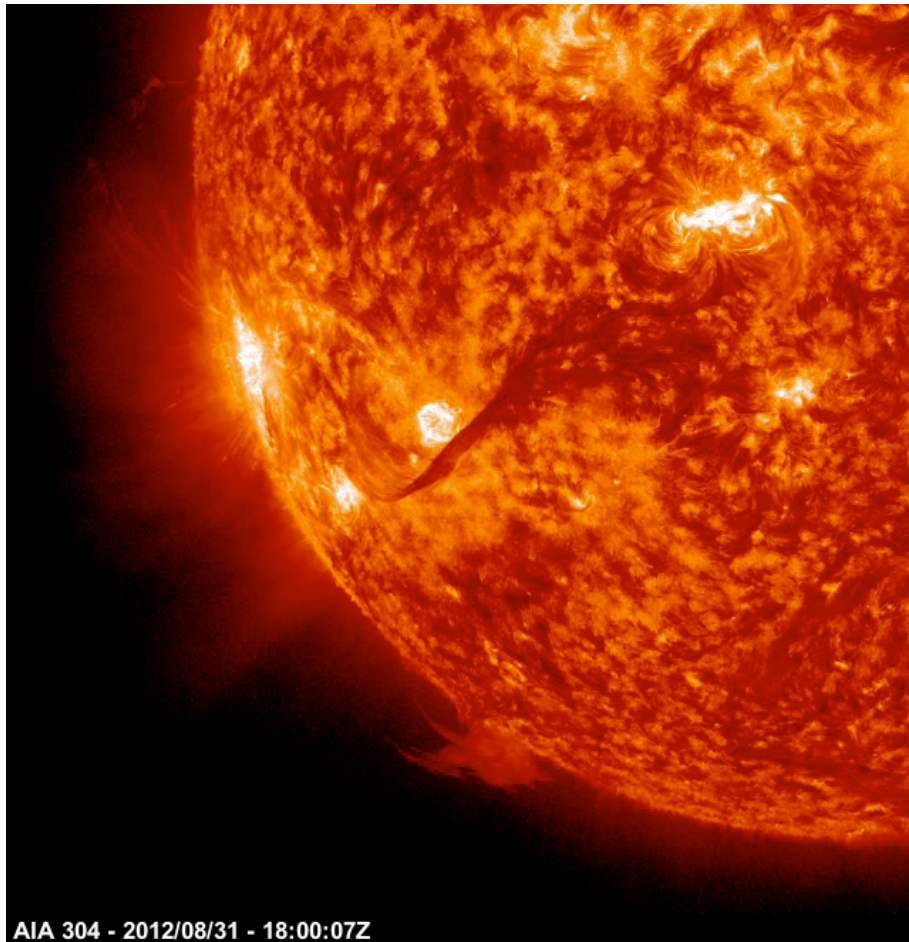


Towards a MHD instability tool for space weather forecasting

Francesco P. Zuccarello, Zakaria Meliani, Guillaume Aulanier

Centre for mathematical Plasma Astrophysics, KU Leuven, Belgium
LESIA, LUTH Observatoire de Paris, CNRS, PSL, UPMC, Univ. Paris Diderot

francesco.zuccarello@kuleuven.be



Quite often eruptive filaments display a two phases evolution:

1. Initial slow rise/evolution
2. Fast eruption

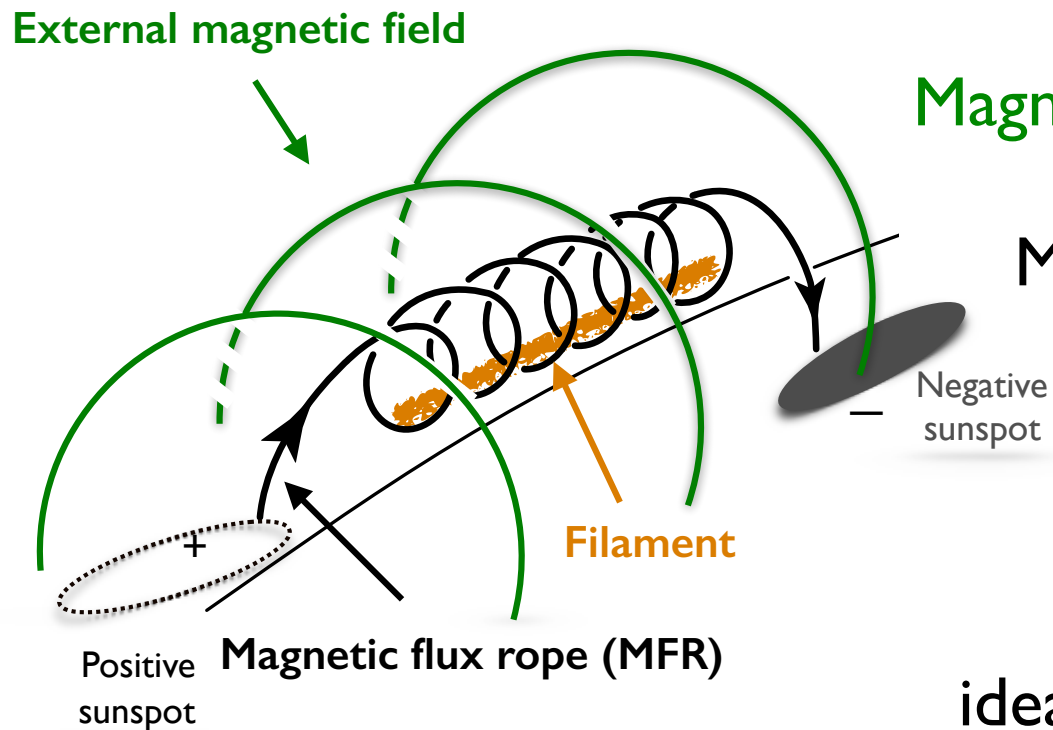
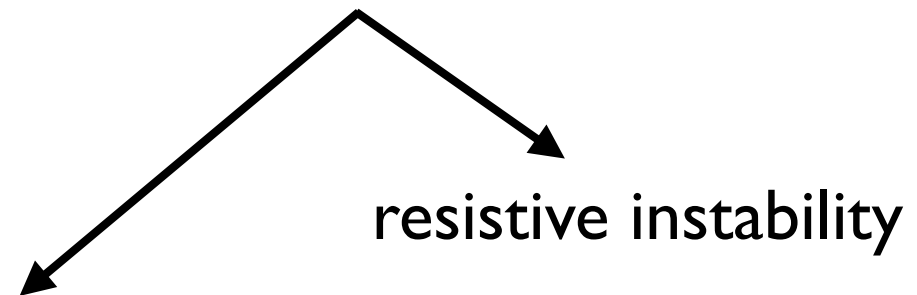
Rupture of equilibrium

Quite often eruptive filaments display a two phases evolution:

1. Initial slow rise/evolution
2. Fast eruption

Rupture of equilibrium

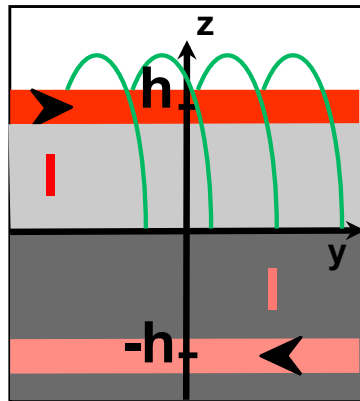
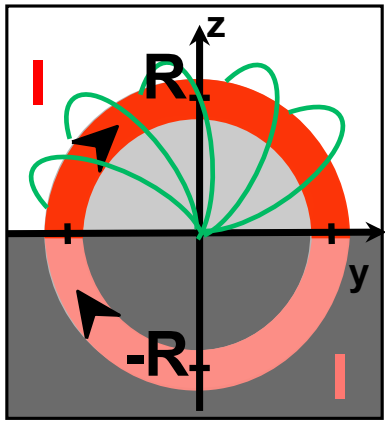
Magnetic tension of the external field
VS
Magnetic pressure of the MFR



ideal-MHD instability

Introduction

Current-wire models



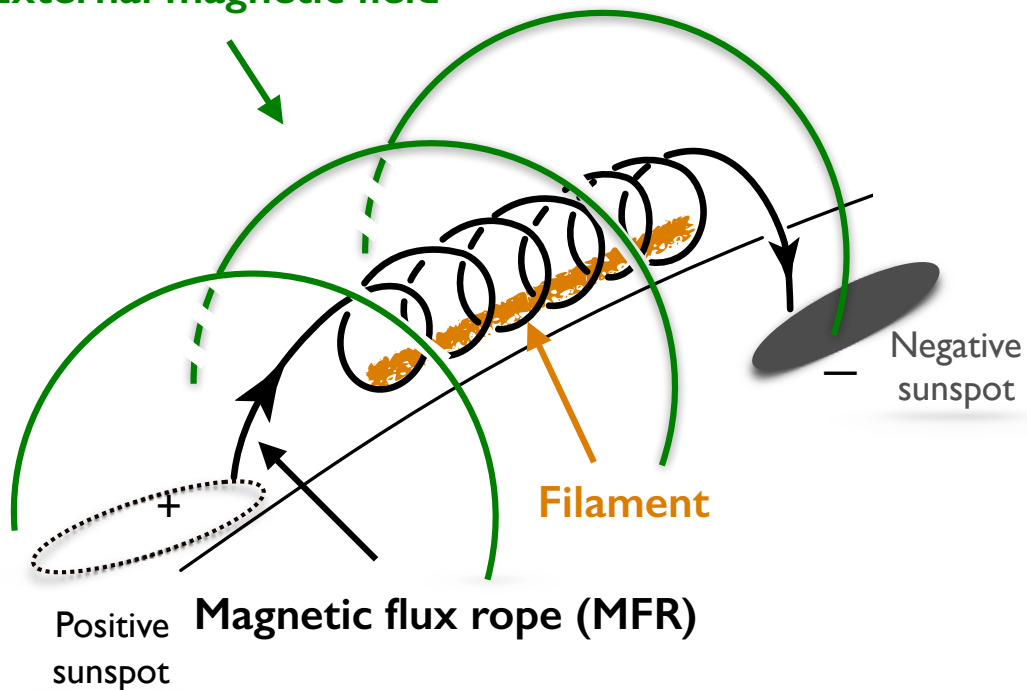
coronal B_{ex}
coronal current
image current

Instability if

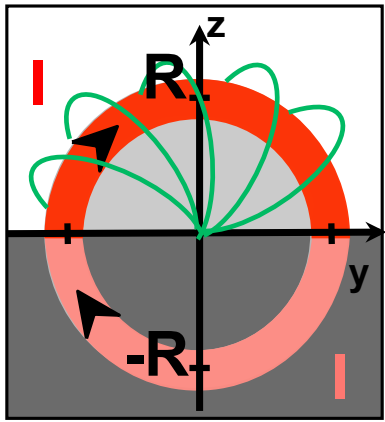
$$n = -d(\ln B^{ex}) / d(\ln z) \geq 1-1.5$$

based on morphology

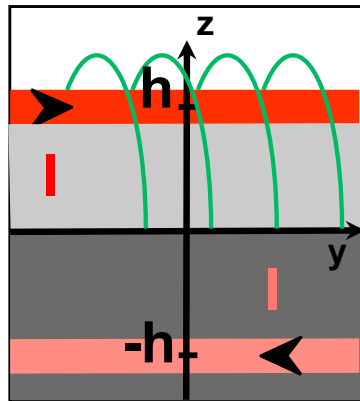
External magnetic field



Introduction



Current-wire models



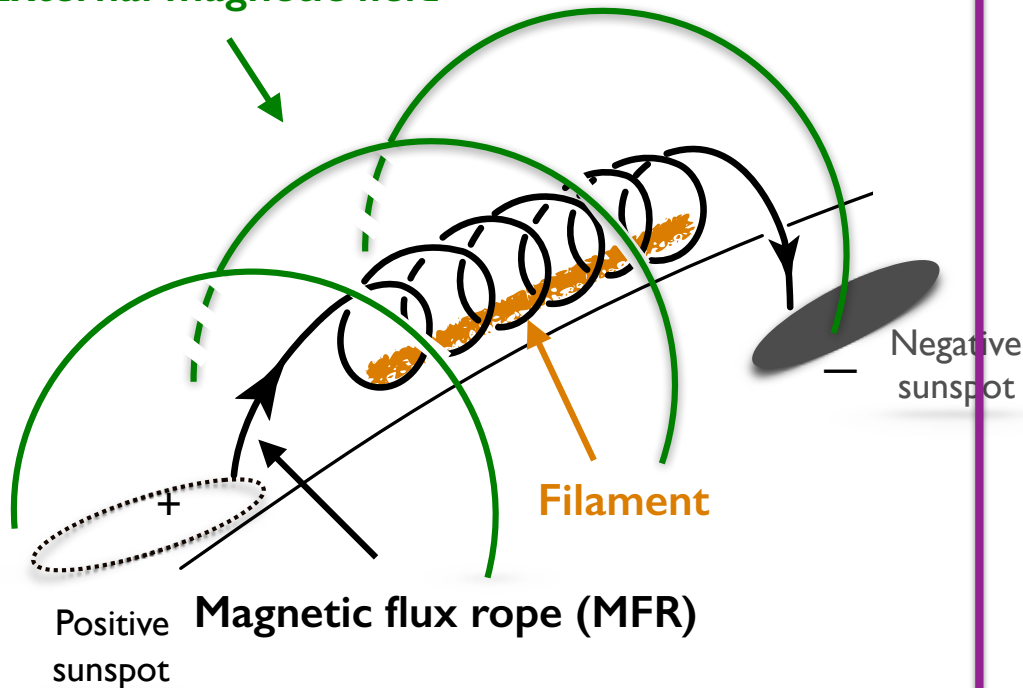
coronal B_{ex}
 coronal current
 image current

Instability if

$$n = -d(\ln B^{ex}) / d(\ln z) \geq 1.5$$

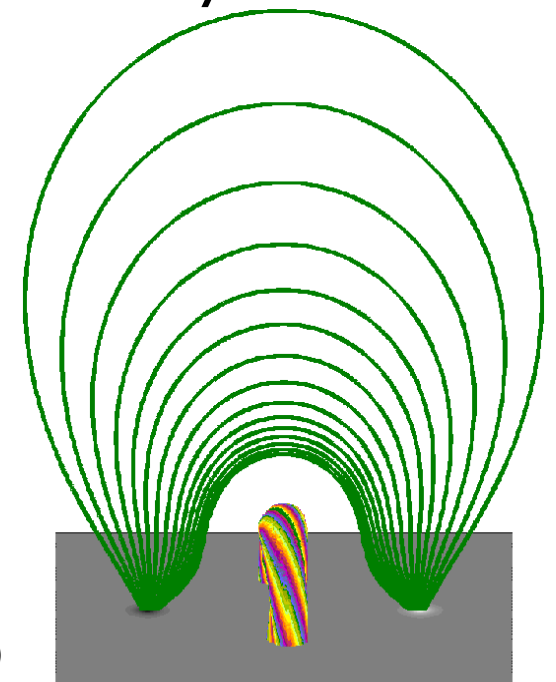
based on morphology

External magnetic field



MHD relaxation of analytical MFR

$$\rightarrow n_{crit} = 1.5$$



Török & Kliem (2005, 2007)

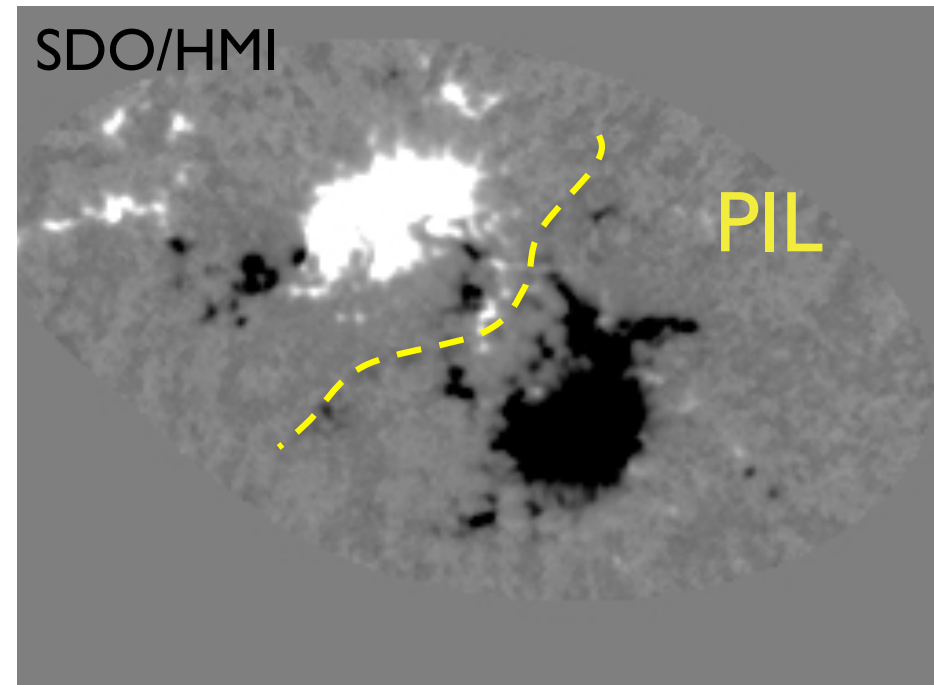
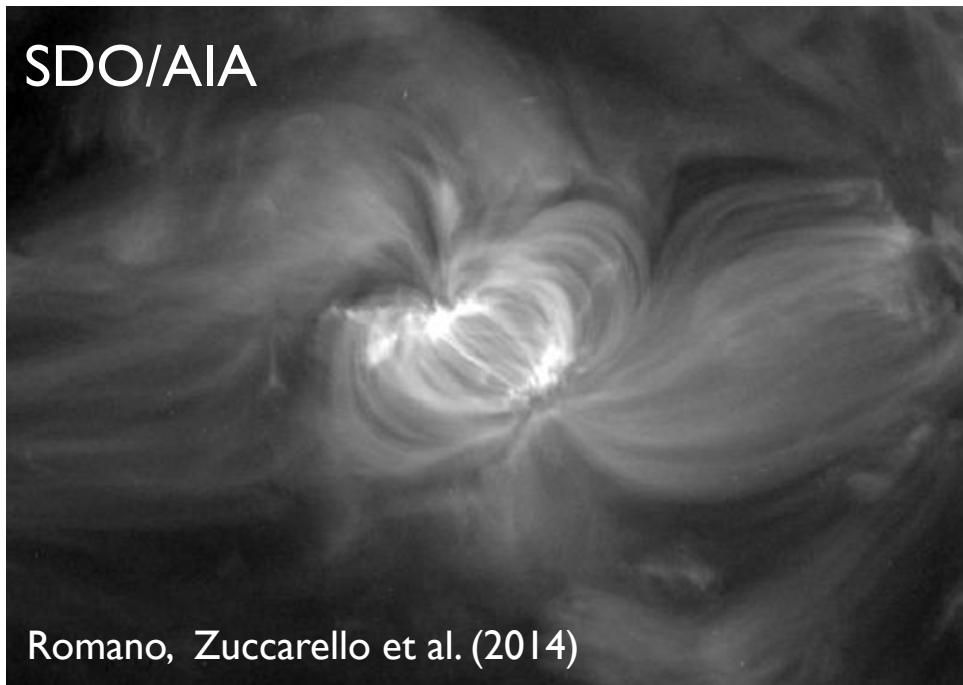
Towards observation inspired MHD simulations

... filaments are seen to form over days,

does this affect the eruption's onset ?

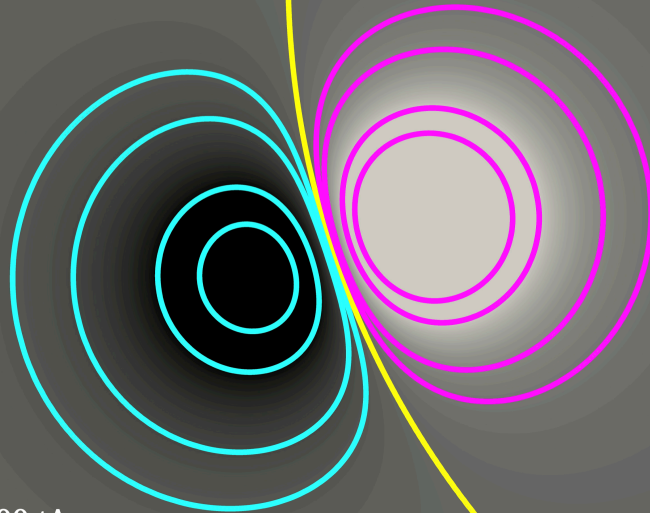
how to define the shape of a (non-analytical) MFR ?

→ line-tied photospheric motions (shearing/twisting)
+ flux cancellation by diffusion or convergence motions



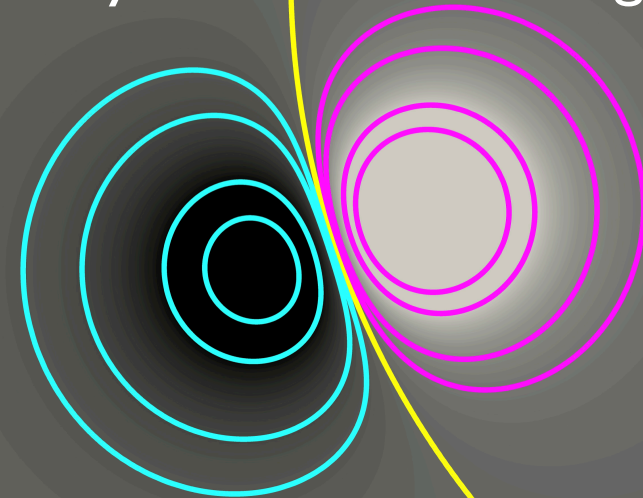
4 different photospheric flows

Minor flux cancellation



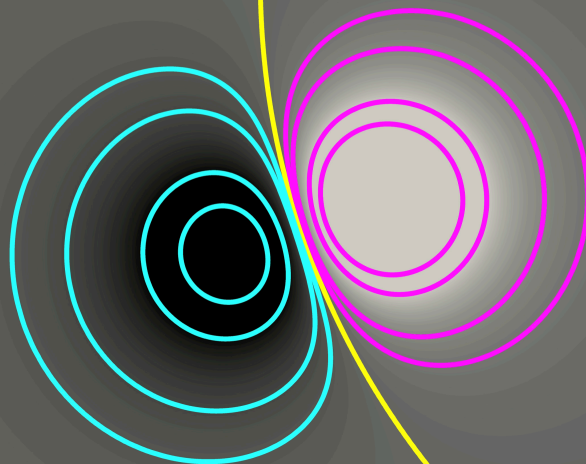
t: 100 tA

Asymmetric stretching



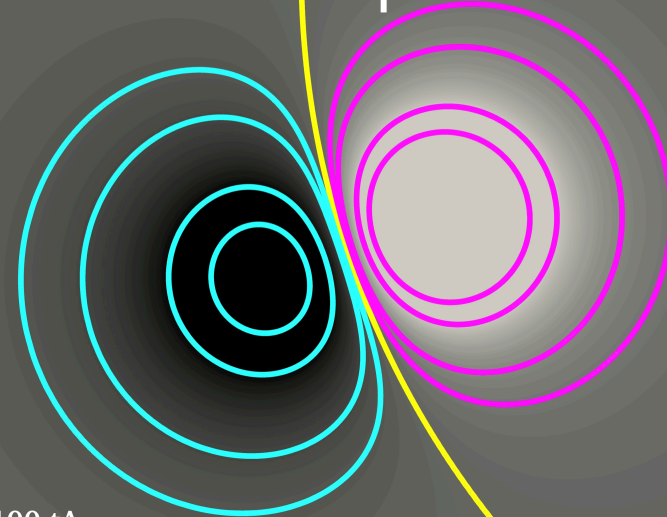
t: 100 tA

Peripheral dispersion



t: 100 tA

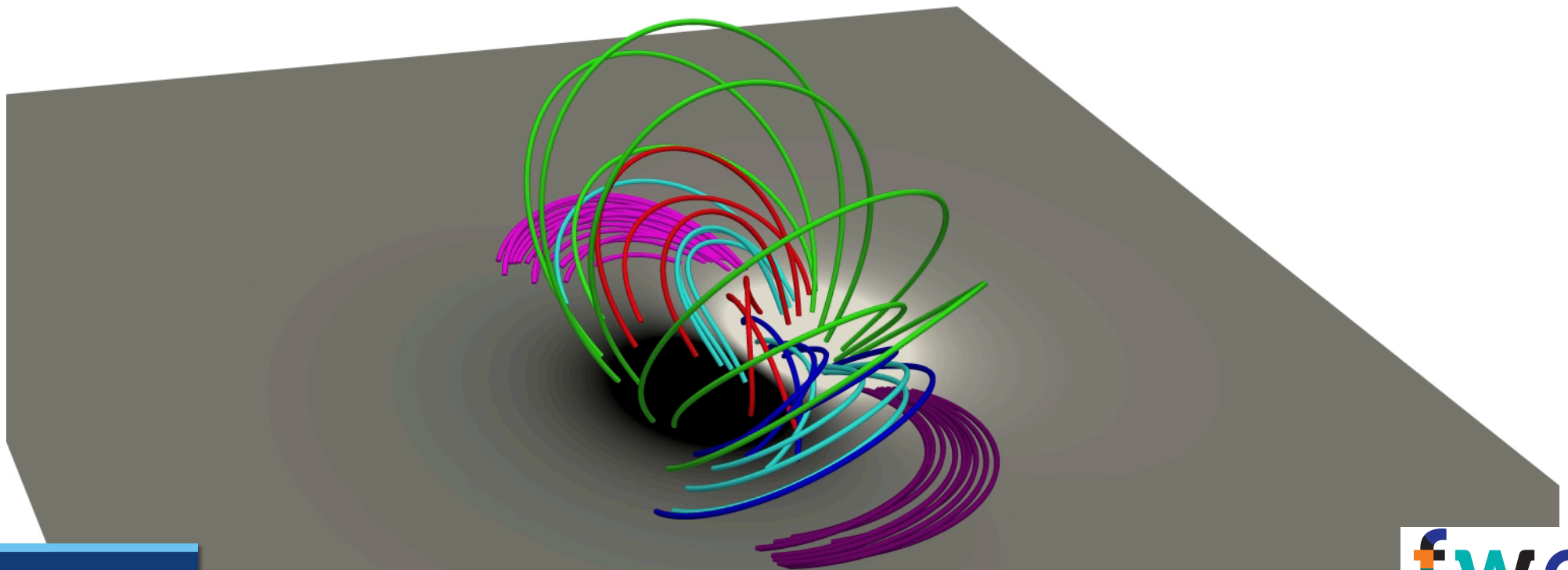
Global dispersion



t: 100 tA

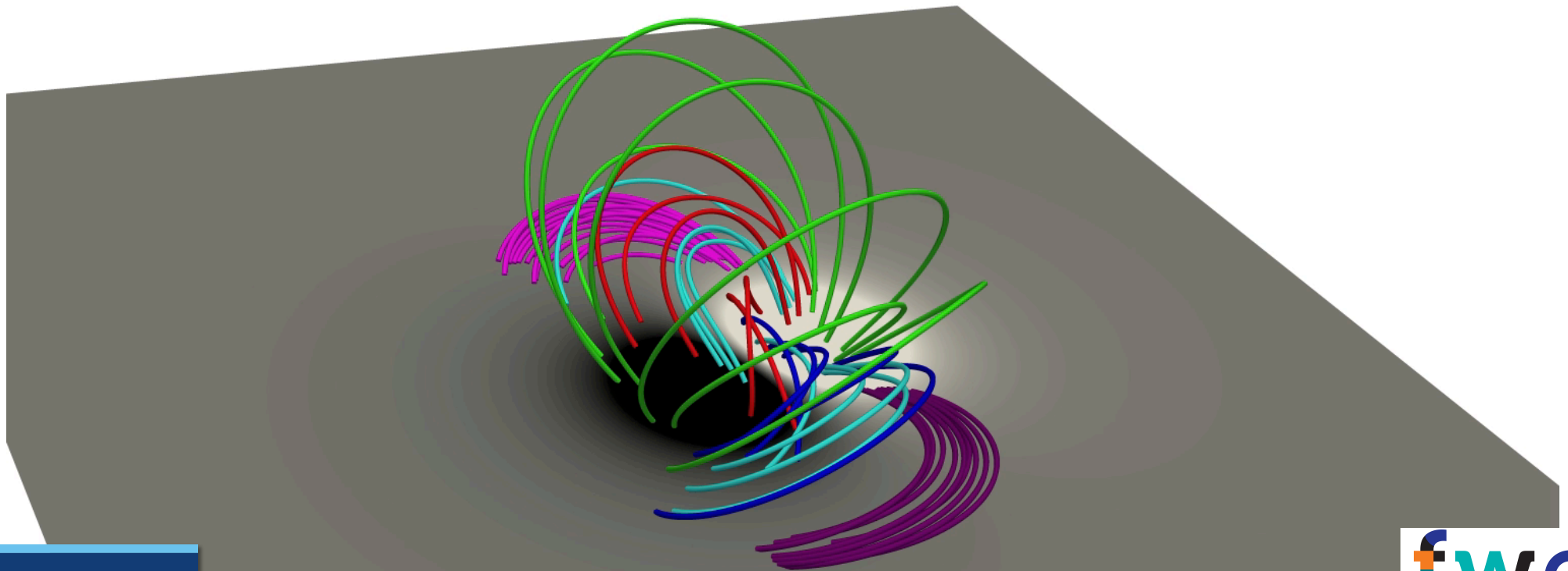
Coronal response

(tether-cutting) magnetic reconnection between highly sheared bald-patches field lines sets-in resulting in the formation of a magnetic flux rope and a sigmoid



Coronal response

Perform relaxation runs to determine the time of the onset of the eruptions

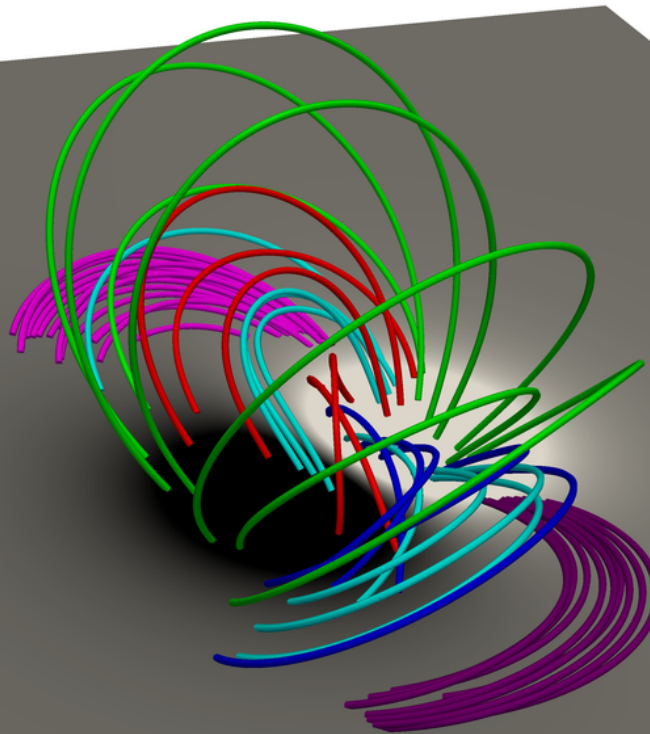


Coronal response

From the different photospheric flows and coronal resistivities

$$\rightarrow n_{\text{crit}} = 1.4 \pm 0.1$$

Zuccarello, Aulanier & Gilchrist (2015)

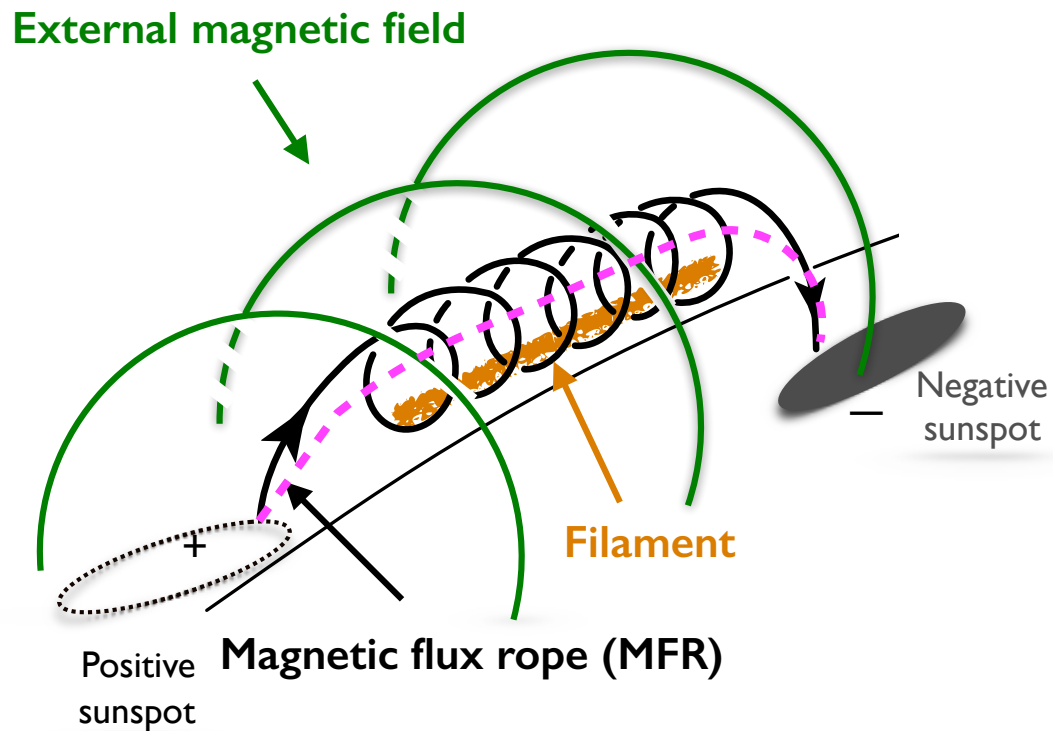


How to use this criterion in observations ?

... and for space weather tools ... ?

Key ingredients:

- Potential field extrapolations to compute the decay index
- The height of the axis of the magnetic flux rope



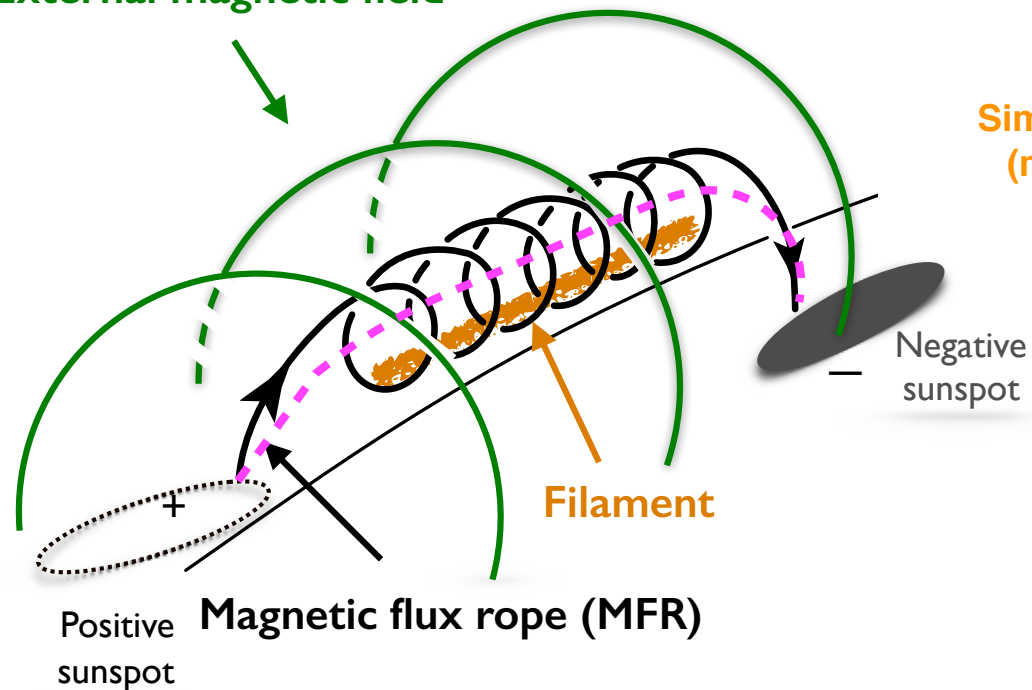
Key ingredients:

- Potential field extrapolations to compute the decay index
- The height of the axis of the magnetic flux rope

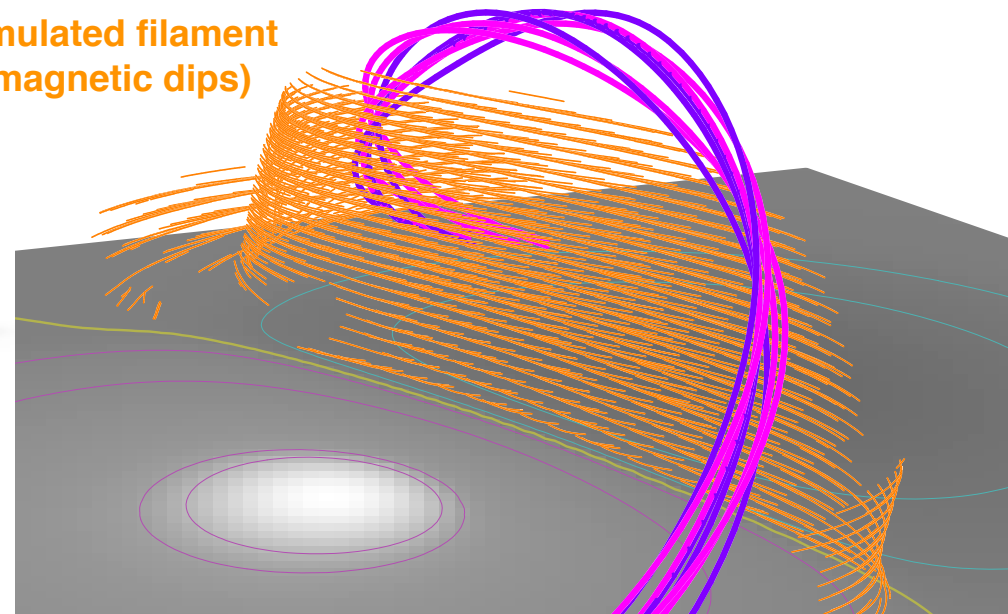
From observations we have info on the filament not on the MFR

→do the same with the MHD simulation

External magnetic field



Simulated filament
(magnetic dips)



Key ingredients:

- Potential field extrapolations to compute the decay index
- The height of the axis of the magnetic flux rope

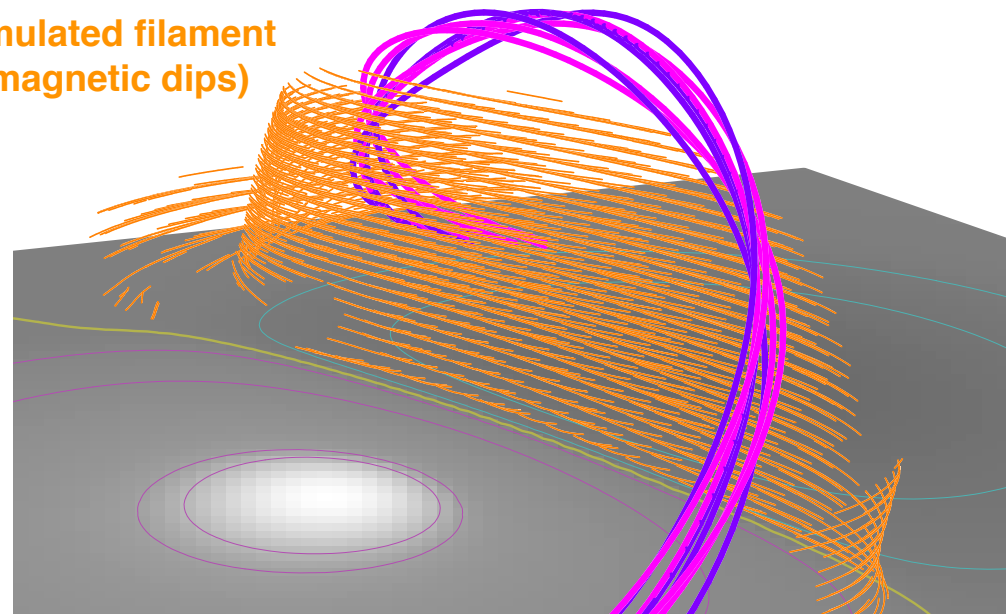
From observations we have info on the filament not on the MFR

→ do the same with the MHD simulation

→ apparent $n_{\text{crit}} = 1.1 \pm 0.1$

Zuccarello, Aulanier & Gilchrist (2016)

Simulated filament
(magnetic dips)

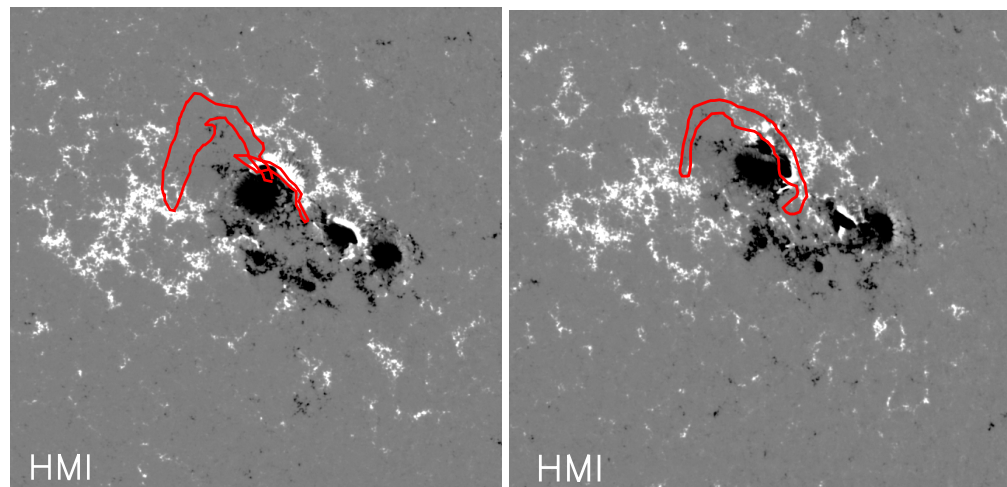


Application to observed filament eruptions

Torus instability criterion can be tested from observations

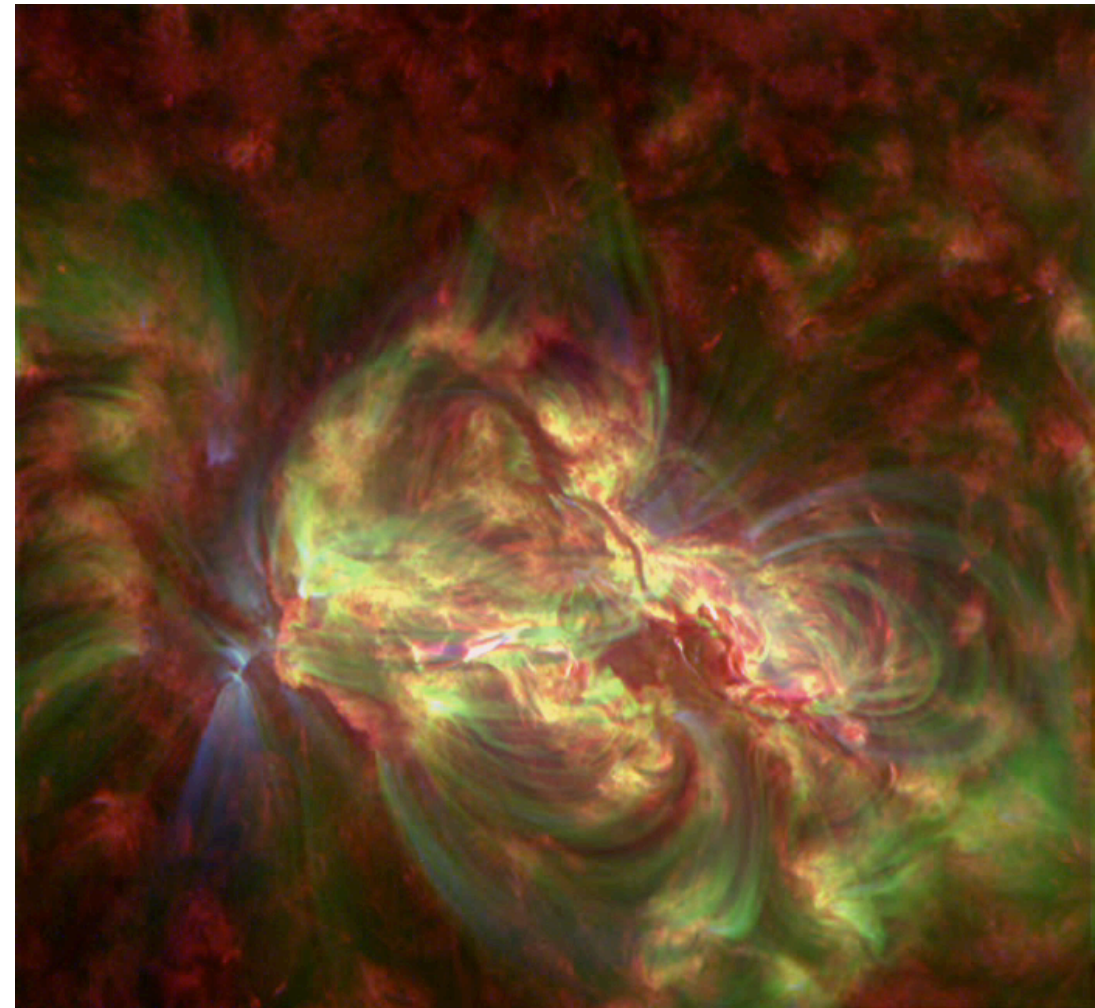
→ limb observations

→ stereoscopic observations



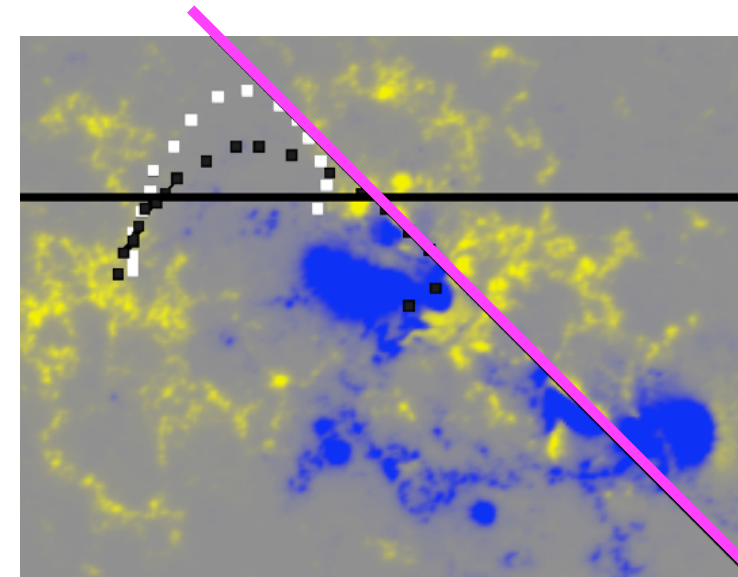
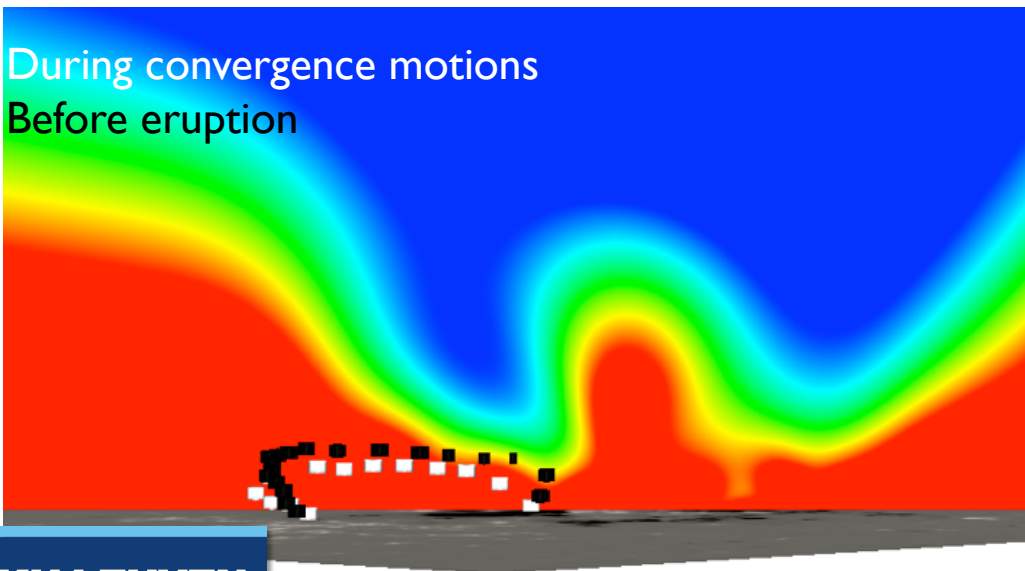
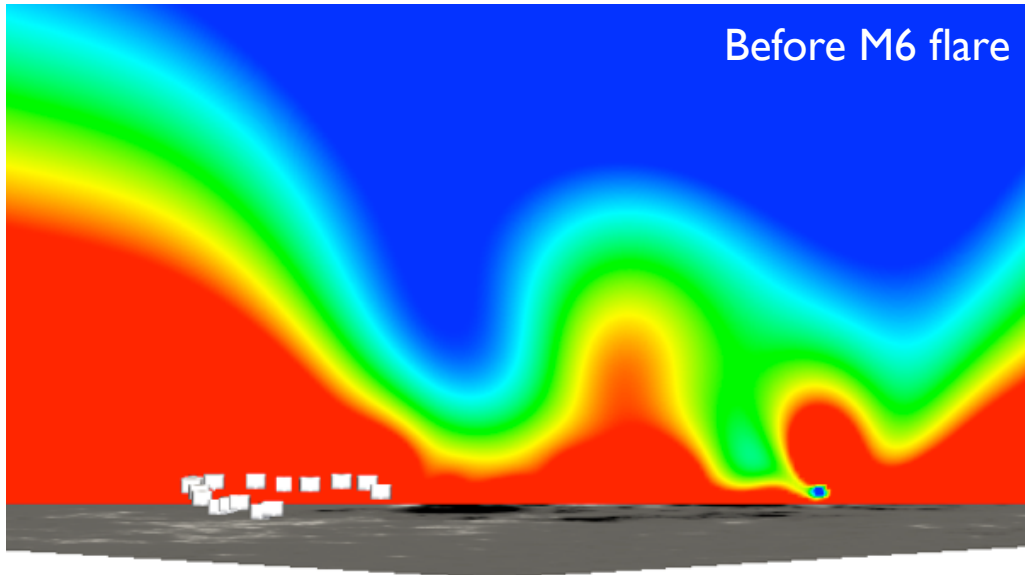
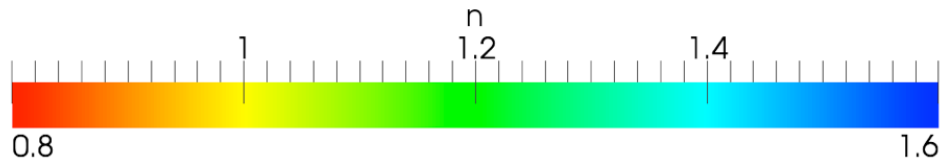
Before the M6 flare

After the M6 flare



AIA 131 - 2011/08/03 - 00:06:33Z
AIA 193 - 2011/08/03 - 00:06:43Z
AIA 304 - 2011/08/03 - 00:06:44Z

Application to observed filament eruptions



Decay index along the magenta plane

Yellow-green: region where $n \approx 1.1 \pm 0.1$

When the M6.0 flare occurred the filament was in a **torus stable region and did not erupt**

The filament erupts when reaches the height where $n \approx 1 \pm 0.1$

Agreement between selected observational cases and MHD simulations

Zuccarello et al. (2012, 2014, 2015, 2016)

... but how to make it operational ?

Essentially ones needs:

- **Potential field extrapolations** to compute the decay index at different heights
 - LOS magnetograms (lat $\pm 30^\circ/35^\circ$)
- A way to estimate/track the height of the axis of the **magnetic flux rope**
 - Stereoscopic observations (L5 mission)
 - Ground based H α observations

Stereoscopic observations

'Hand-made' (L3 student's project) stereoscopic reconstructions

SOLAR ERUPTION DATA BASE

FILTER TABLE

BEGINNING OF THE PERIOD END OF THE PERIOD

(AAAA-MM-JJ HH:MM:S) (AAAA-MM-JJ HH:MM:S)

Search

| Date | Coordinates (x,y) arcsec | SDO/AIA 171 Å | SDO/AIA 193 Å | SDO/AIA 304 Å | Potential field extrapolation | Filament reconstruction |
|------|-----------------------------|------------------|------------------|------------------|----------------------------------|----------------------------|
|------|-----------------------------|------------------|------------------|------------------|----------------------------------|----------------------------|

Stereoscopic observations

'Hand-made' (L3 student's project) stereoscopic reconstructions

SOLAR ERUPTION DATA BASE

HELIO Introduction Sign Up

DATE

| Date | Coordinates (x,y) arcsec | SDO/AIA 171 Å | SDO/AIA 193 Å | SDO/AIA 304 Å | Potential field extrapolation | Filament reconstruction |
|---------------------|--------------------------|---------------|---------------|---------------|-------------------------------|-------------------------|
| 2011-09-08 04:00:00 | (510,320) | | | | | |
| 2011-09-19 07:25:00 | (100,290) | | | | | |
| 2011-09-26 14:30:00 | (-490,130) | | | | | |
| 2011-09-30 03:30:00 | (-200,90) | | | | | |
| 2011-10-01 08:45:00 | (610,190) | | | | | |

Stereoscopic observations

'Hand-made' (L3 student's project) stereoscopic reconstructions

SOLAR ERUPTION DATA BASE

FILTER TABLE

| Date | Coordinates (x,y) arcsec | SDO/AIA 171 Å | SDO/AIA 193 Å | SDO/AIA 304 Å | Potential field extrapolation | Filament reconstruction |
|---------------------|--------------------------|---------------|---------------|---------------|-------------------------------|-------------------------|
| 2011-09-08 04:00:00 | (510,320) | | | | | |
| 2011-09-19 07:25:00 | (100,290) | | | | | |
| 2011-09-26 14:30:00 | (-490,130) | | | | | |
| 2011-09-30 03:30:00 | (-200,90) | | | | | |
| 2011-10-01 08:45:00 | (610,190) | | | | | |

Stereoscopic observations

'Hand-made' (L3 student's project) stereoscopic reconstructions

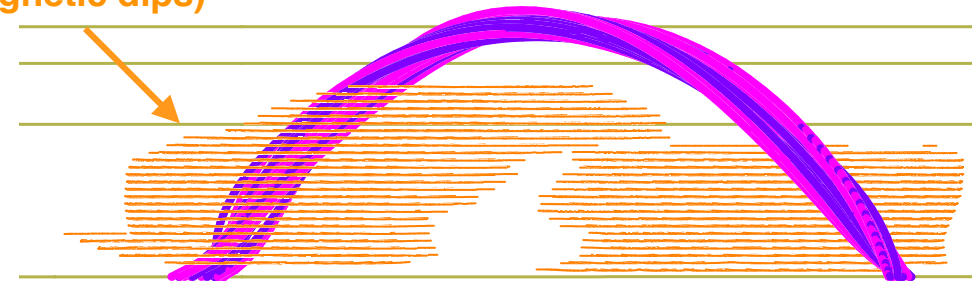
| Date | Coordinates (x,y) arcsec | SDO |
|---------------------|--------------------------|-----|
| 2011-09-19 07:25:00 | (1 | |
| 2011-09-26 14:30:00 | (- | |
| 2011-09-30 03:30:00 | (- | |
| 2011-10-01 08:45:00 | (610,190) | |

Ground based H α observations

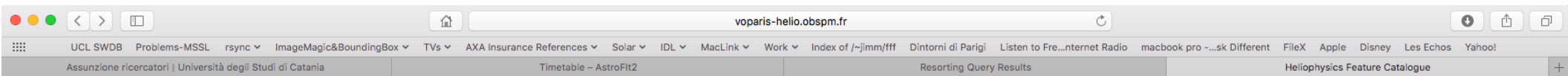
Ground based H α observations to estimate the height of the filament

Filament extent to estimate foot point location + a shape model for the MFR's the height of its axis

Simulated filament
(magnetic dips)



Ground based H α observations



Heliophysics Feature Catalogue



The Heliophysics Feature Catalogue (HFC) provides access to existing solar and heliophysics feature data, extracted from images by automated recognition codes.

The catalogue contains geometrical (e.g., gravity center coordinates, contours, area, etc.) and photometric feature parameters (e.g., average, minimum, and maximum intensity, etc.) , but also tracking information to identify co-rotating feature on the solar disc.

- [Query form](#)
- [Database and fields description](#)
- [Database content](#)
- [Free SQL query](#)
- [Helio Front End](#)

Query form

- 1 - Date and time selection**
- 2 - Features selection
- 3 - Output options

If 'From' and 'to' are empty, date selection is ignored and query applies to the whole database!

From to Or Duration between 0 and 60 days

Or [Upload dates sample from VOTable](#)

[Submit](#) ?

The following table provides the list of the features for which data are currently available in the HFC.

| Feature | Instrument | Recognition code | Bibliography | Tracking information |
|------------------------|--|-------------------|---|----------------------|
| Active Region | SOHO/MDI SOHO/EIT (171/195 A) SDO/AIA (171/193 A) | SMART | Higgins et al., 2010 | No |
| | | SPOCA-AR | Barra et al., 2009 | Yes |
| | | SPOCA-AR | Barra et al., 2009 | Yes |
| Coronal Hole | SOHO/MDI + SOHO/EIT (195 A) SOHO/EIT (171/195 A) SDO/AIA (193 A) | CHARM | Krista and Gallagher, 2009 | No |
| | | SPOCA-CH | Barra et al., 2009 | Yes |
| | | SPOCA-CH | Barra et al., 2009 | Yes |
| Filament | Meudon H Alpha Spectroheliograph | SoSoft & TrackFil | Fuller et al., 2005 - Bonnín et al., 2013 | Yes |
| Prominence | Meudon CAIL K3 Spectroheliograph | SoSoPro | N. Fuller | No |
| Sunspot | SOHO/MDI SDO/HMI | MDISS | Zharkov et al., 2005 | No |
| | | SDOSS | Zharkov et al., 2005 | Yes |
| Type III | Wind/Waves, STEREO/Swaves | RABAT3 | X. Bonnín | No |
| Coronal radio emission | Nancay Radio Heliograph | NRH2D | C. Renié, X. Bonnín | Yes |

- [Query form](#)
- [Database and fields description](#)
- [Database content](#)
- [Free SQL query](#)
- [Helio Front End](#)

- [API](#)
- [Web Services](#)
- [About HFC](#)



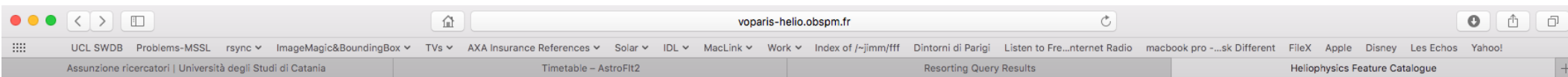
LESIA



Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

FP7, project No. 238969

Ground based H α observations



Heliophysics Feature Catalogue



The Heliophysics Feature Catalogue (HFC) provides access to existing solar and heliophysics feature data, extracted from images by automated recognition codes.

The catalogue contains geometrical (e.g., gravity center coordinates, contours, area, etc.) and photometric feature parameters (e.g., average, minimum, and maximum intensity, etc.), but also tracking information to identify co-rotating feature on the solar disc.

[Query form](#) [Database and fields description](#) [Database content](#) [Free SQL query](#) [Helio Front End](#)

Query form

1 - Date and time selection 2 - Features selection 3 - Output options

If 'From' and 'to' are empty, date selection is ignored and query applies to the whole database!

From 2011-10-01T00:00 to 2011-10-16T00:00 Or Duration between 0 and 60 days 15

Or [Upload dates sample from VOTable](#)

Submit

The following table provides the list of the features for which data are currently available in the HFC.

| Feature | Instrument | Recognition code | Bibliography | Tracking information |
|------------------------|--|-------------------|---|----------------------|
| Active Region | SOHO/MDI SOHO/EIT (171/195 A) SDO/AIA (171/193 A) | SMART | Higgins et al., 2010 | No |
| | | SPOCA-AR | Barra et al., 2009 | Yes |
| | | SPOCA-AR | Barra et al., 2009 | Yes |
| Coronal Hole | SOHO/MDI + SOHO/EIT (195 A) SOHO/EIT (171/195 A) SDO/AIA (193 A) | CHARM | Krista and Gallagher, 2009 | No |
| | | SPOCA-CH | Barra et al., 2009 | Yes |
| | | SPOCA-CH | Barra et al., 2009 | Yes |
| Filament | Meudon H Alpha Spectroheliograph | SoSoft & TrackFil | Fuller et al., 2005 - Bonnín et al., 2013 | Yes |
| Prominence | Meudon CAIL K3 Spectroheliograph | SoSoPro | N. Fuller | No |
| Sunspot | SOHO/MDI SDO/HMI | MDISS | Zharkov et al., 2005 | No |
| | | SDOSS | Zharkov et al., 2005 | Yes |
| Type III | Wind/Waves, STEREO/Swaves | RABAT3 | X. Bonnín | No |
| Coronal radio emission | Nancay Radio Heliograph | NRH2D | C. Renié, X. Bonnín | Yes |

[Query form](#) [Database and fields description](#) [Database content](#) [Free SQL query](#) [Helio Front End](#)

[API](#) [Web Services](#) [About HFC](#)



LESIA



Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

FP7, project No. 238969

Ground based H α observations

Ground based H α observations to estimate the height of the filament

The screenshot displays the Heliophysics Feature Catalogue (HFC) interface. At the top, the title "Ground based H α observations to estimate the height of the filament" is overlaid. The website header includes the "HELIO" logo and the text "Heliophysics Feature Catalogue". Below the header, there are navigation buttons: "Query form", "Database and fields description", "Database content", "Free SQL query", and "Helio Front End".

The main content area shows the results of a query for a filament. It indicates "Number of features retrieved: | Filament: 297 VOTable" and "Page: | 1". A date range selector is set to "2011-10-01". Below this, a "Filament: results per hour at 2011-10-01" section shows three time intervals: "07:36:10", "11:00:01", and "15:22:52".

Two circular images are displayed side-by-side, showing the filament's structure. The left image is a white background with colored features, and the right image is a grayscale image with blue features. Both images have a dashed crosshair. Below the images is a "Tabular result" button.

At the bottom of the interface, there are additional navigation buttons: "API", "Web Services", and "About HFC". The footer contains logos for "Observatoire de Paris - LESIA" and "IAS", along with the text "Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique" and "FP7, project No. 238969". The "KU LEUVEN" logo is in the bottom left corner, and the "fwo" logo is in the bottom right corner.

A red box highlights a "Submit" button on the right side of the page.

Ground based H α observations

The screenshot displays the Heliophysics Feature Catalogue website. The main content area shows a search for filaments on 2011-10-01. The interface includes a search bar, a list of dates, a 'Submit' button, and a large image of the Sun with filament features highlighted in blue and green. A 'Tabular result' section shows a circular plot of filament locations.

Number of features retrieved: | Filament: 297 VOTable

Page: | 1

2011-10-01 2011-10-02 2011-10-03 2011-10-04 2011-10-07 2011-10-13 2011-10-14 2011-10-15

Filament: results per hour at 2011-10-01

07:36:10 11:00:01 15:22:52

Submit

Tabular result

Query sameup

SQL log

Query form Database and fields description Database co

API Web Services Ab

Observatoire de Paris LESIA IAS

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique
FP7, project No. 238969

Fuller, Aboudarham et al. (2005)

ku LEUVEN

fwo

Conclusion

- Torus instability is a **robust mechanism** to trigger filament eruptions
- **Consistent results** with different approaches: analytical, observational & 3D MHD
- n_{crit} depends on **MFR's** morphology, photospheric flows and coronal diffusion,
→ for *usable* onset criterion a **critical decay index range** [1.1-1.5 ?] should be used
- An instability-likelihood approach that depends on different combinations of **n_{crit} values/MFR's morphologies**

| | FR1 | FR2 |
|----|--------|--------|
| n1 | Medium | Low |
| n2 | High | Medium |

Conclusion

- Torus instability is a **robust mechanism** to trigger filament eruptions
- **Consistent results** with different approaches: analytical, observational & 3D MHD
- n_{crit} depends on **MFR's** morphology, photospheric flows and coronal diffusion,
→ for *usable* onset criterion a **critical decay index range** [1.1-1.5 ?] should be used
- An instability-likelihood approach that depends on different combinations of **n_{crit} values/MFR's morphologies**

| | FR1 | FR2 |
|----|--------|--------|
| n1 | Medium | Low |
| n2 | High | Medium |

- **Key ingredients:**
 - **LOS (or vector) magnetic field** for potential field extrapolations
→ **already available**
 - Height of the **MFR's axis**
 - Automatic filament recognition + different MFRs shapes
→ **already available + easy to implement**
 - Automatic prominence recognition for, not yet existing, L5 mission data
→ **promising, but ...**

Thank you !

Francesco P. Zuccarello, Zakaria Meliani, Guillaume Aulanier

Centre for mathematical Plasma Astrophysics, KU Leuven, Belgium
LESIA, LUTH Observatoire de Paris, CNRS, PSL, UPMC, Univ. Paris Diderot

francesco.zuccarello@kuleuven.be