l'Observatoire de Paris | LESIA
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

3D MHD simulations to model solar eruptive events

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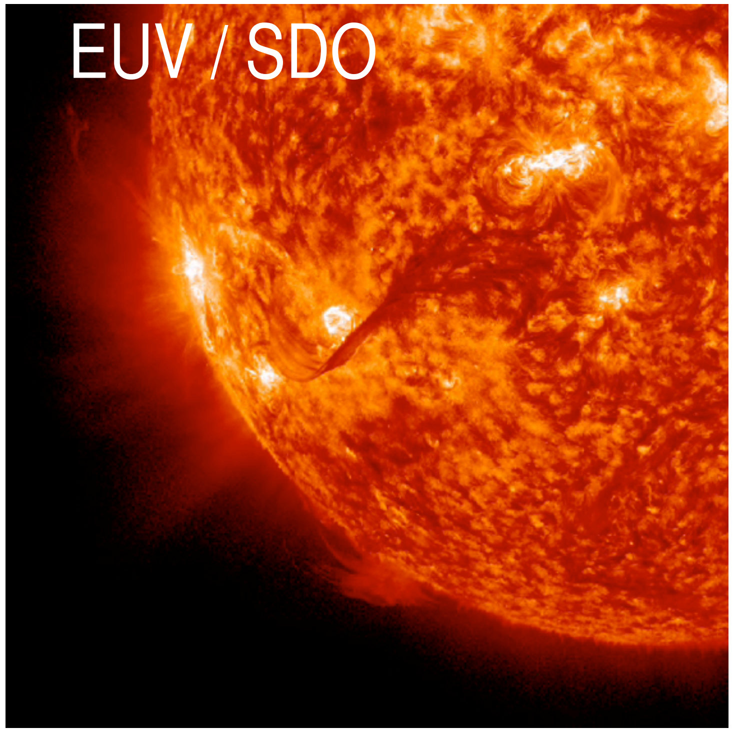
Outline

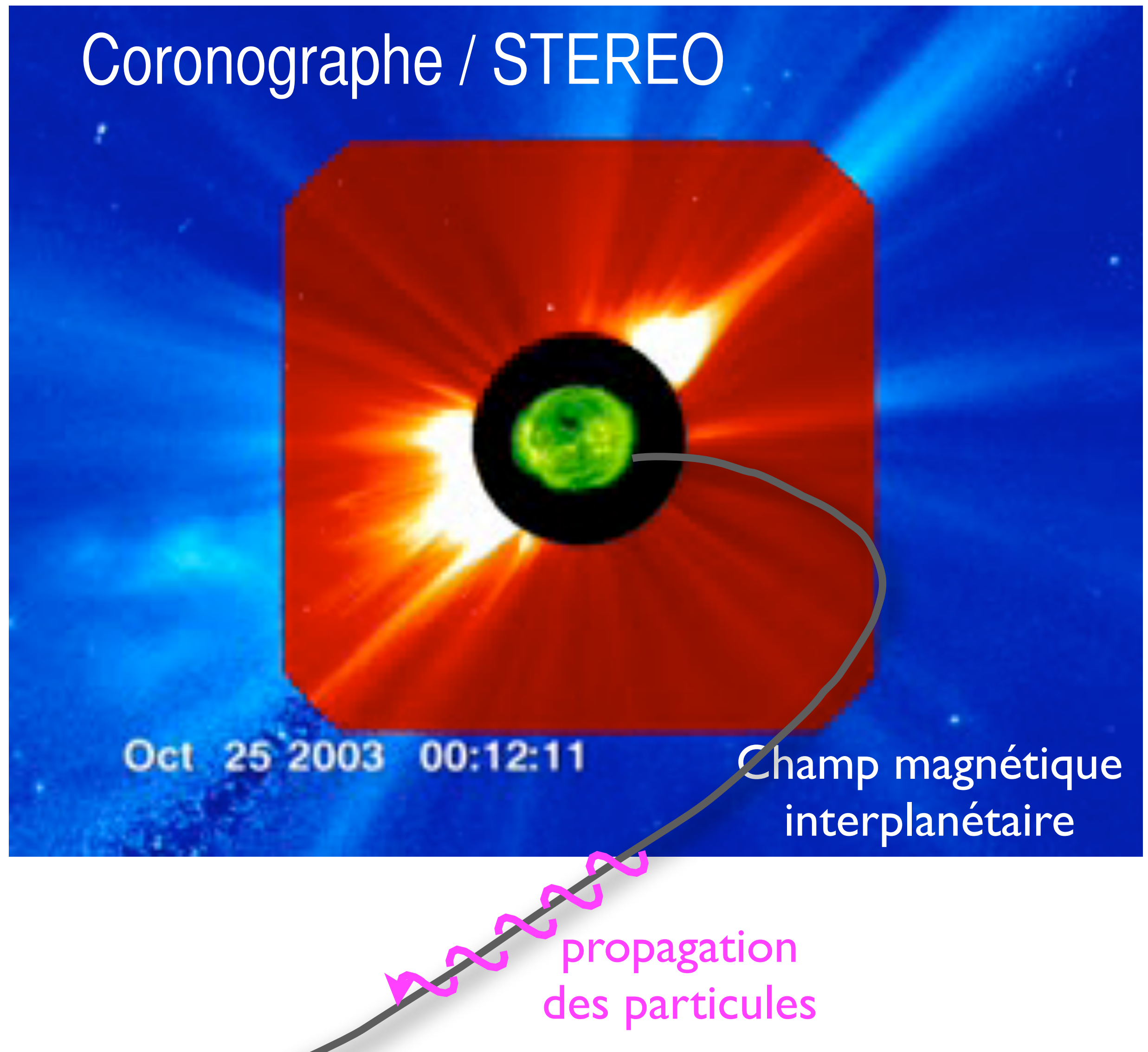
- Modeling solar eruptions
- Recent results on solar jets and coronal mass ejection
- Scientific and computational prospective

Modeling solar eruptions

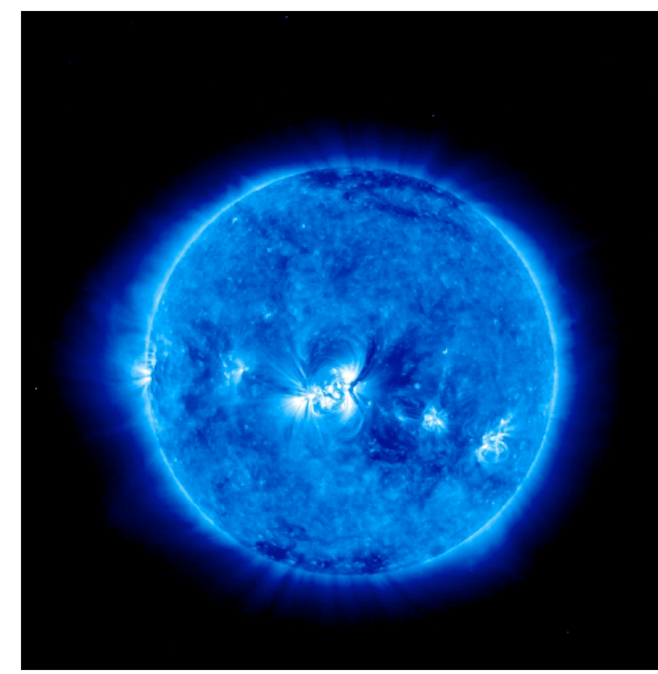
• Solar eruptions



• Coronal Mass Ejection (CME)



•Solar Jets



Energy release through magnetic reconnection :

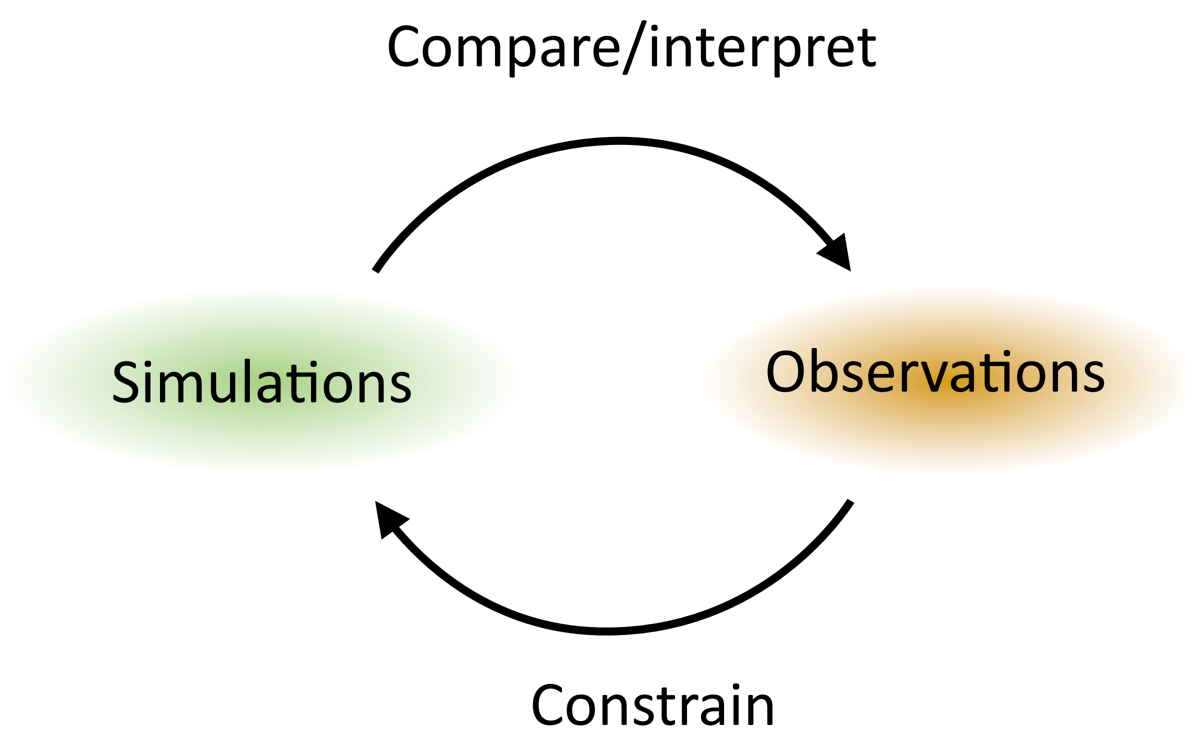
- Plasma heating and particle acceleration

- Magnetic reconfiguration

Modeling solar eruptions

Understanding the causes of the eruptive activity e.g. the physical mechanisms triggering the eruptions

& the consequences : dynamics of the CME, bright ribbons, energetic particles



Modeling solar eruptions

- Magneto-hydrodynamic formalism

large scale modeling (>1s and > 1m)

no treatment of the particles

auto-consistent simulations of solar eruptions

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.\left(\rho \vec{u}\right) = 0$$

$$\frac{\partial T}{\partial t} = -(\vec{u}.\vec{\nabla})T - (\gamma - 1)T\left(\vec{\nabla}.\vec{u}\right)$$

$$\frac{\partial \rho \vec{u}}{\partial t} = -\vec{\nabla}\left(\rho \vec{u}\,\vec{u}\right) - \vec{\nabla}P + \mu^{-1}\left(\vec{\nabla} \times \vec{B}\right) \times \vec{B} + \rho \vec{g}$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times \left(\vec{u} \times \vec{B}\right) = 0$$

- The solar corona

- ionized plasma n~10^{14-16} m^{-3} (Hydrogen, Helium & heavy ions)

- Magnetized plasma : active regions with strong magnetic field ~ 1000 G

$\beta = P_{kin} / P_{mag} << 1$: structured by the magnetic field

- Small electric resistivity $R_m >> 1$: Reconnection develops at small scales

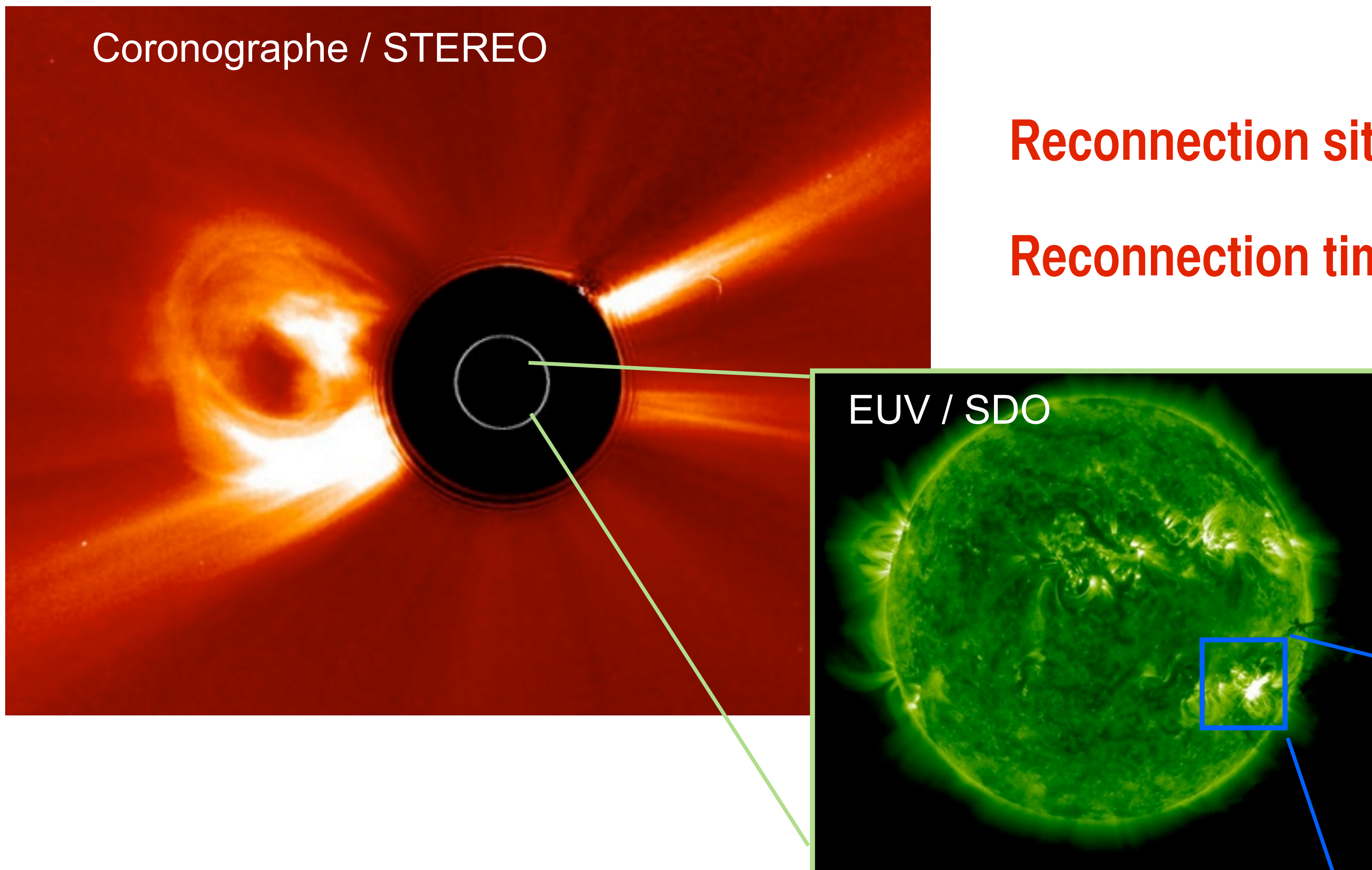
Eclipse August 2017

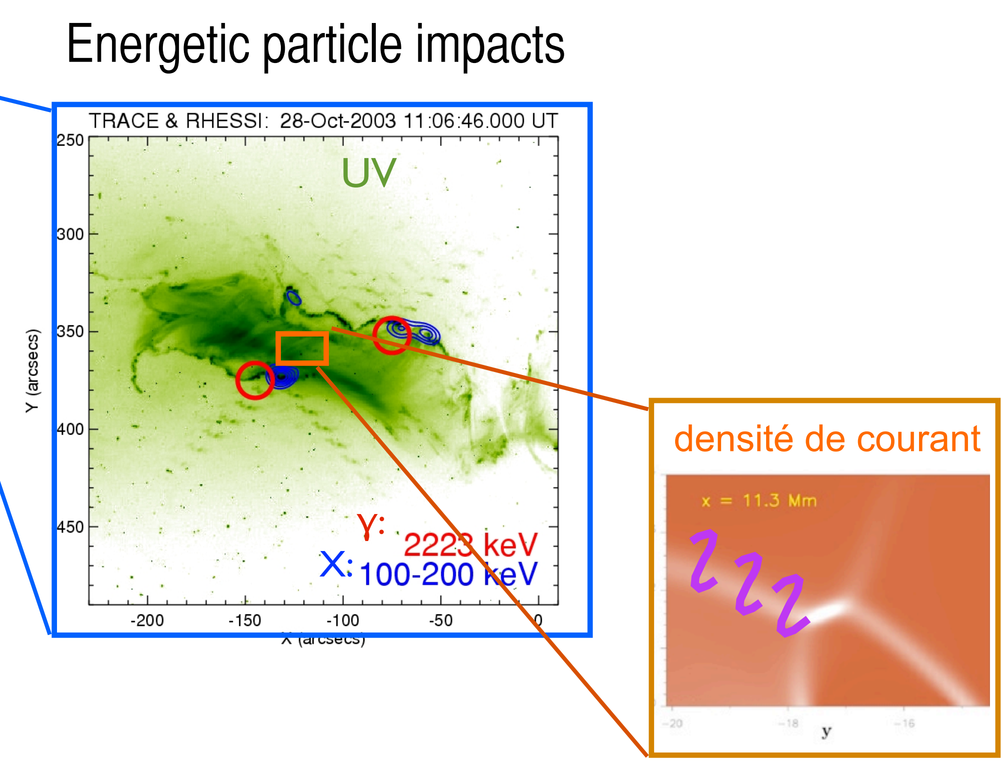
Modeling solar eruptions

- Scale challenges

Reconnection site ~ m to the size of the CME ~ Rs

Reconnection timescale ~ seconds to CME propagation ~ hours (CME)





Simulation numérique MHD

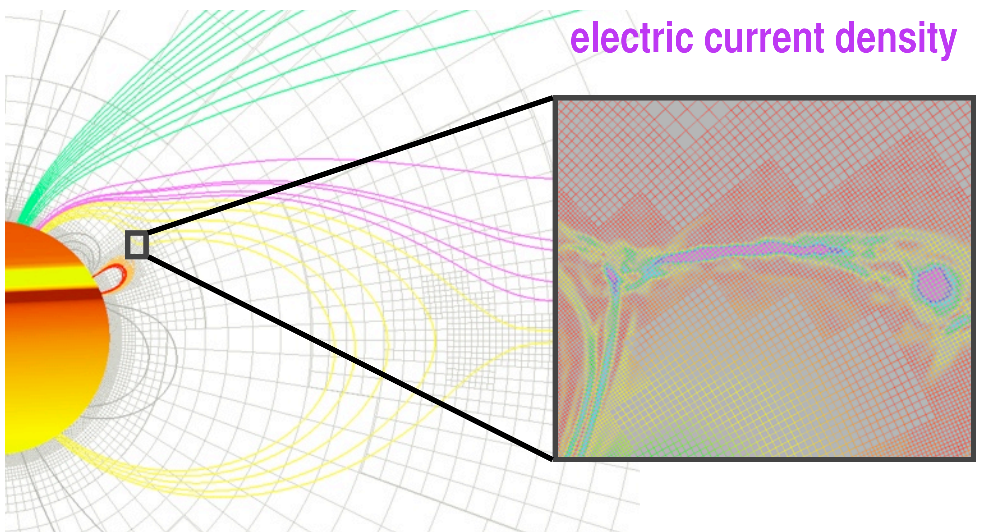
3D MHD Codes @ LESIA

ARMS Code

DeVore 1991; DeVore & Antiochos, 2008

- Cartesian and spherical
- Flux Corrected Transport algorythm: strong gradients resolution (e.g. schock capture)
- div B =0 => No Data-driven

Adaptive Mesh refinement Numerical resistivity



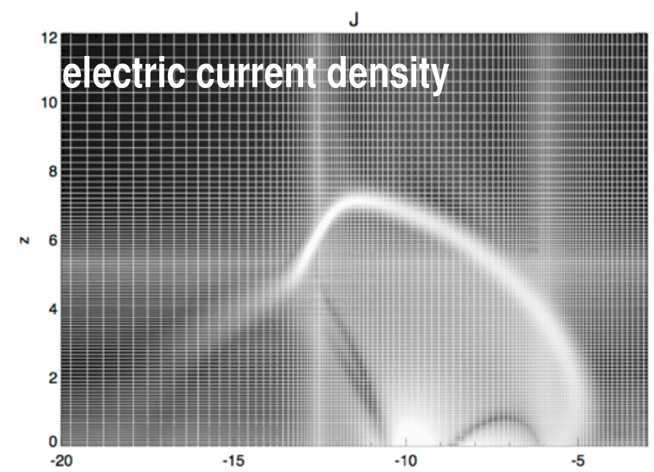
- Small & Large scale MHD simulation
- No limitation of the size and resolution of the system
- Structures at small scale (e.g. magnetic island)

OHM-MPI Code

Aulanier et al., 2005 **+ Collaboration with the LUTh**

- Cartesian
- high order scheme for derivatives
- Diffusive term to ensure the code stability
- div B $\neq$ 0 => Data driven

Non-unifom mesh Physical resistivity



- Small scale (active region) MHD simulation
- structures at small scale: increase the spatial resolution (in progress)
- Control of each diffusive term

Choose the most appropriate code !!

Modeling solar eruptions

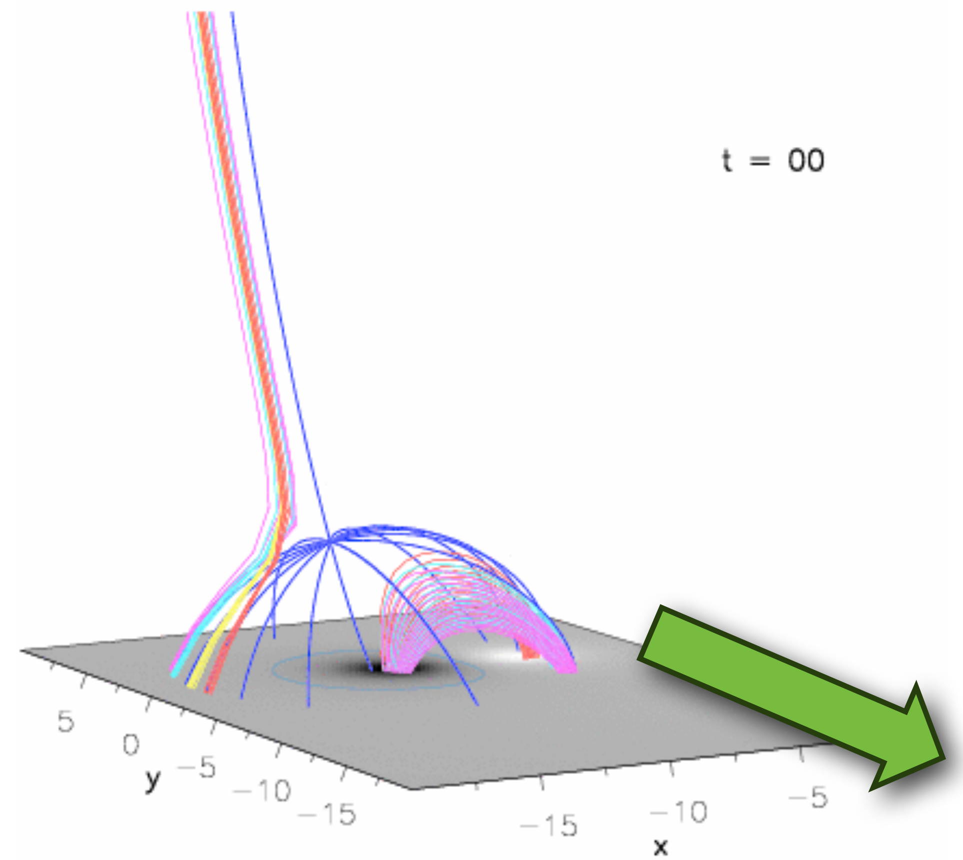
Initiation

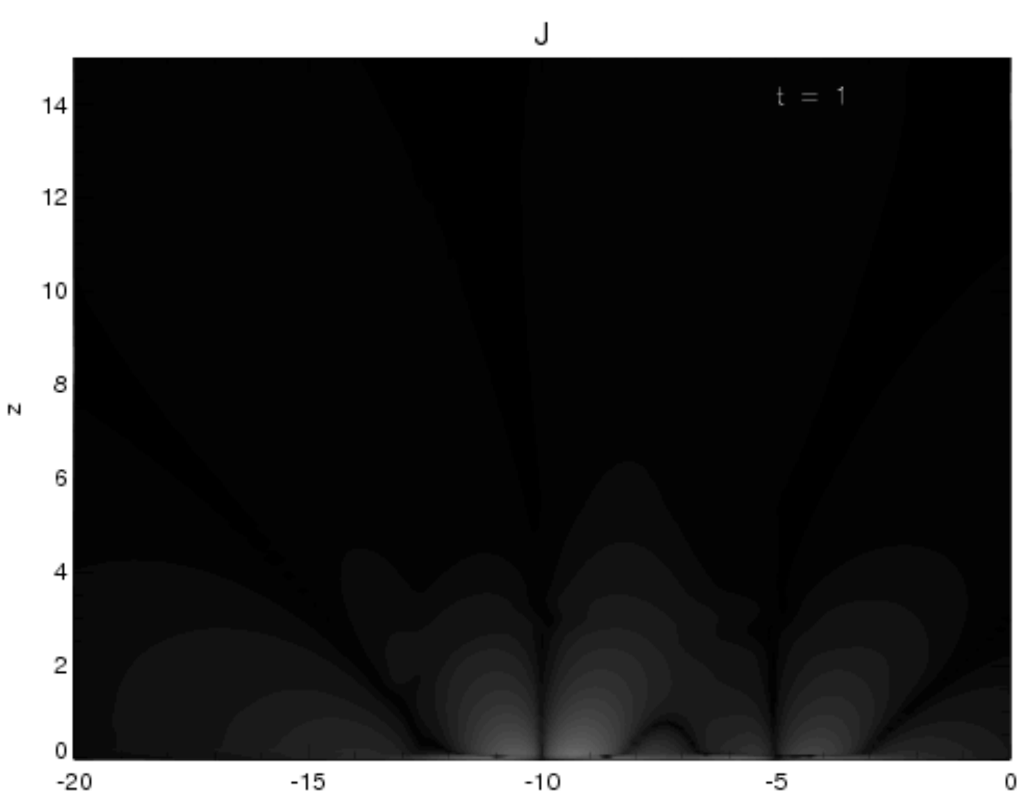
magnetic field (observed)
+ atmosphere

Destabilize the system

Apply slow flows at the solar surface

line-tying => inject magnetic stress and energy





Dynamics of the solar eruption

Current sheet formation

Magnetic reconnection: change of **field lines connectivity**

Outline

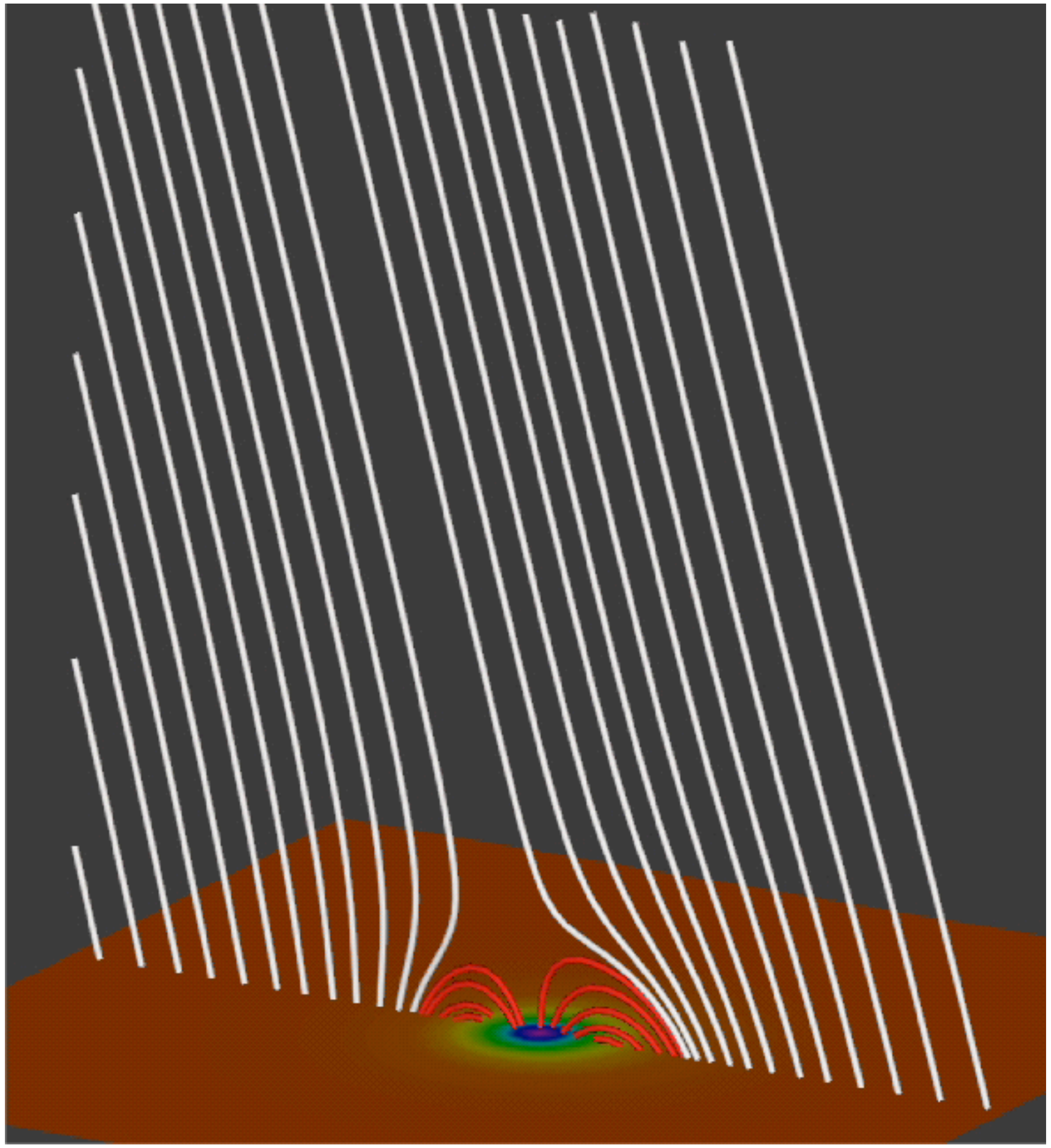
- Modeling solar eruptions
- Recent results on solar jets and coronal mass ejection
- Scientific and computational prospective

3D MHD simulations of solar eruptions

- Effect of the plasma-β on solar jet properties (ARMS)

Pariat, DeVore & Antiochos, ApJ 2009

Pariat, Dalmasse, et al. ApJ, 2015



- **Solar jet model** : magnetic reconnection between closed & twisted field and open field.

- Jets are observed over a broad spatial range:

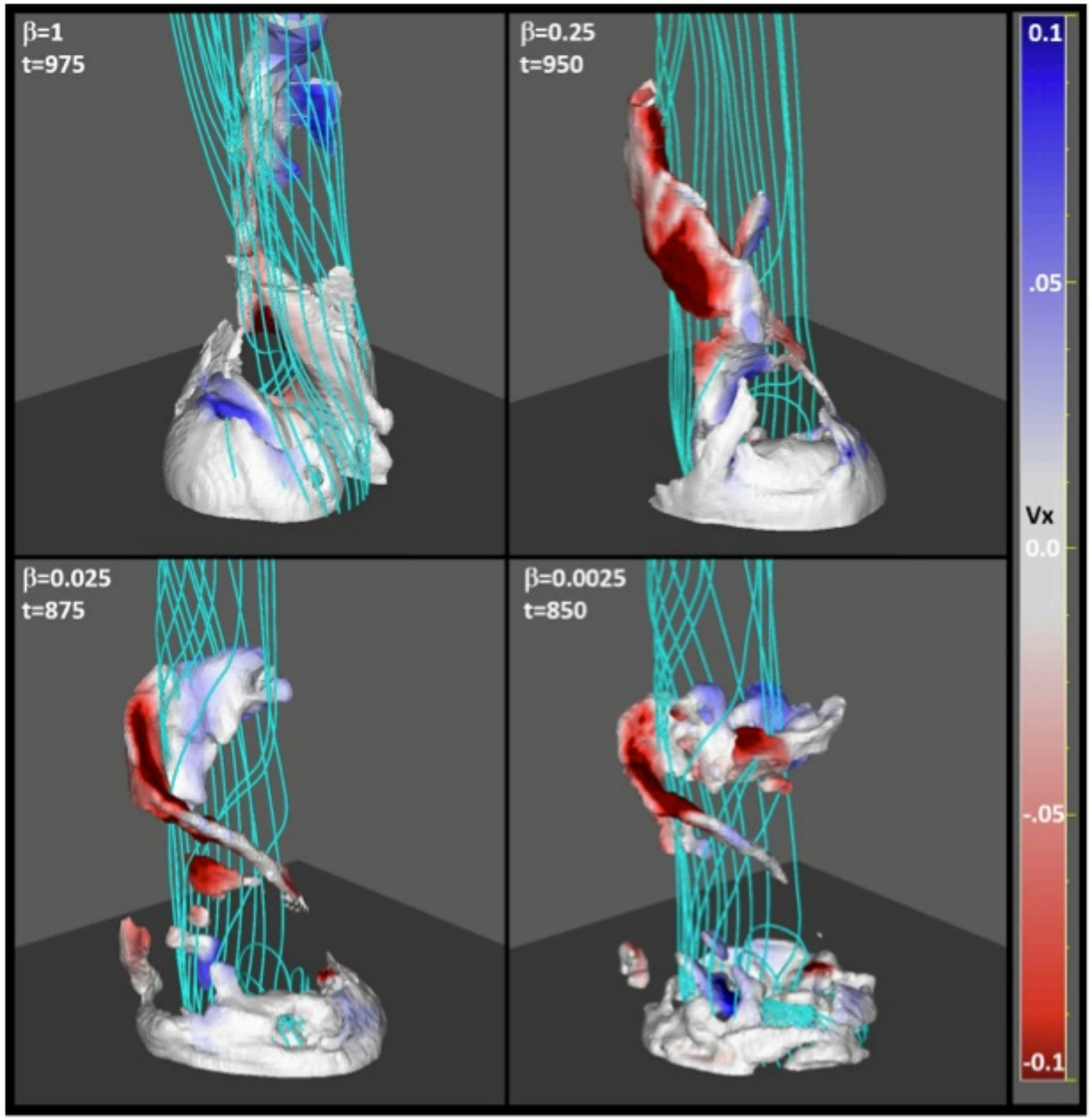
  -small scale chromospheric jets
  -large scale coronal jets

Varying the plasma-β to interpret the observations of the observed jet-like events :

Common property : Helicoidal structures

3D MHD simulations of solar eruptions

- Effect of the plasma-β on solar jet properties (ARMS)



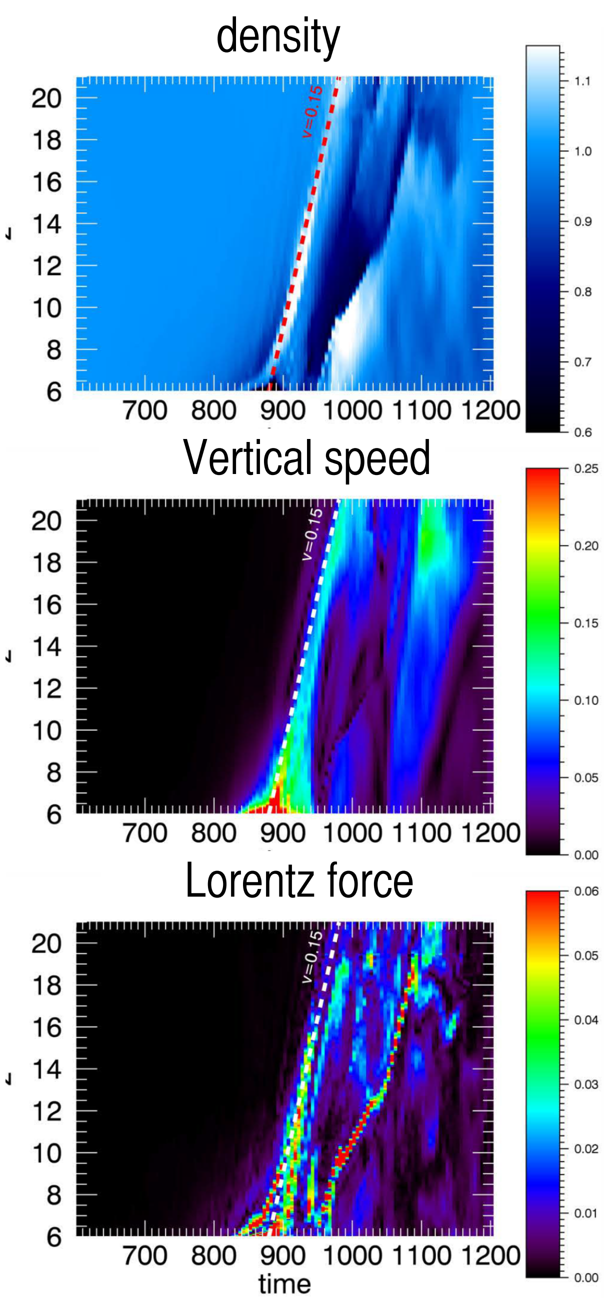
Pariat, Dalmasse, et al. ApJ, 2015

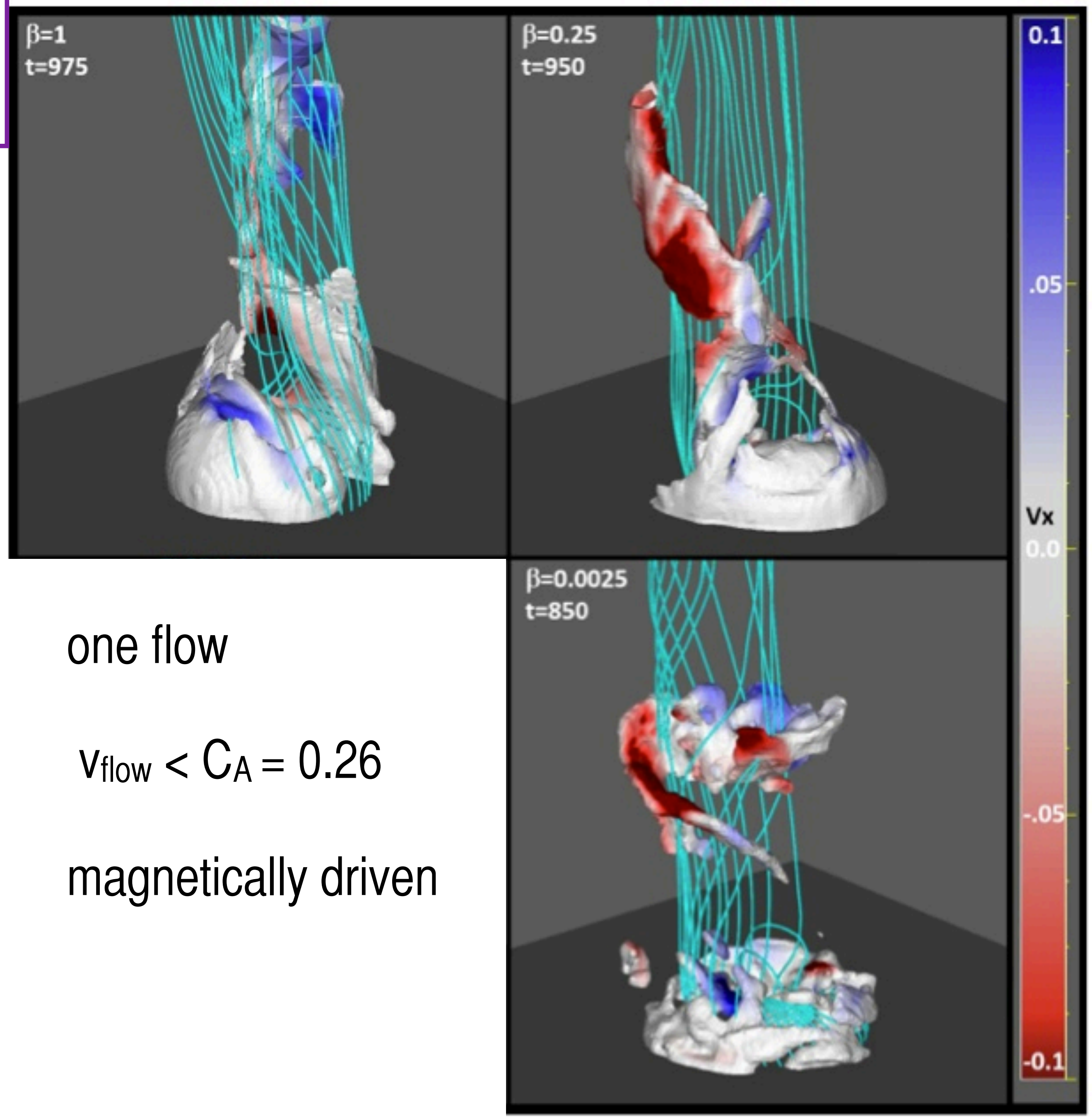
3D MHD simulations of solar eruptions

- Effect of the plasma-β on solar jet properties (ARMS)

chromospheric-like jets

bulk flow





one flow

$v_{flow} < C_A = 0.26$

magnetically driven

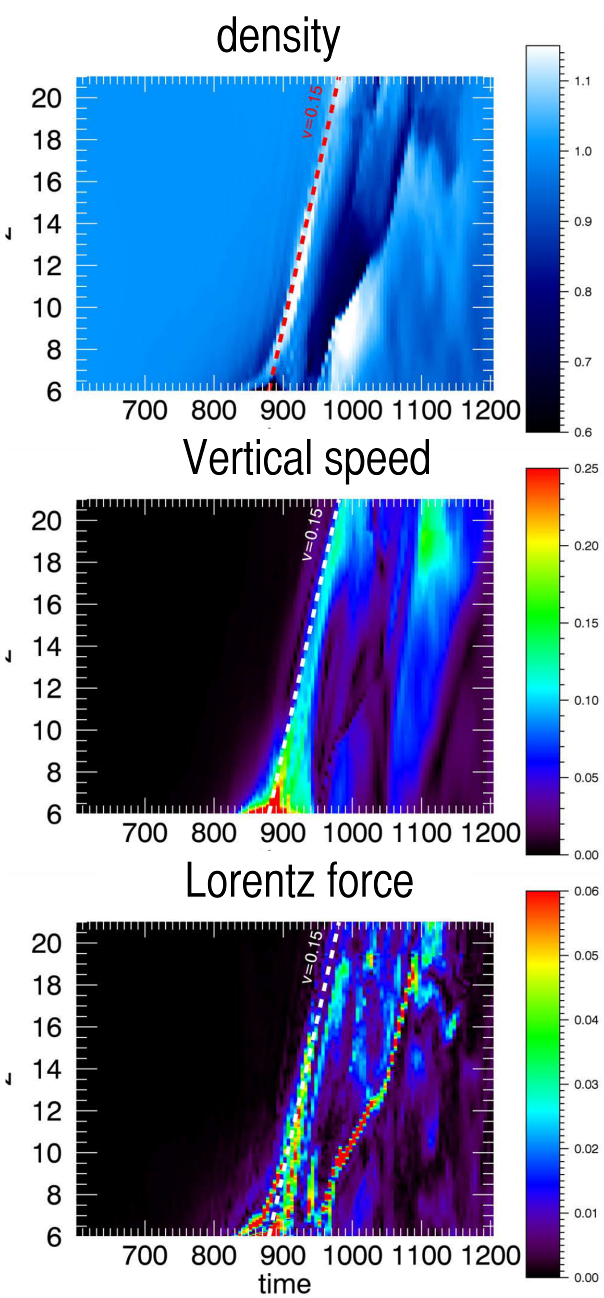
Pariat, Dalmasse, et al. ApJ, 2015

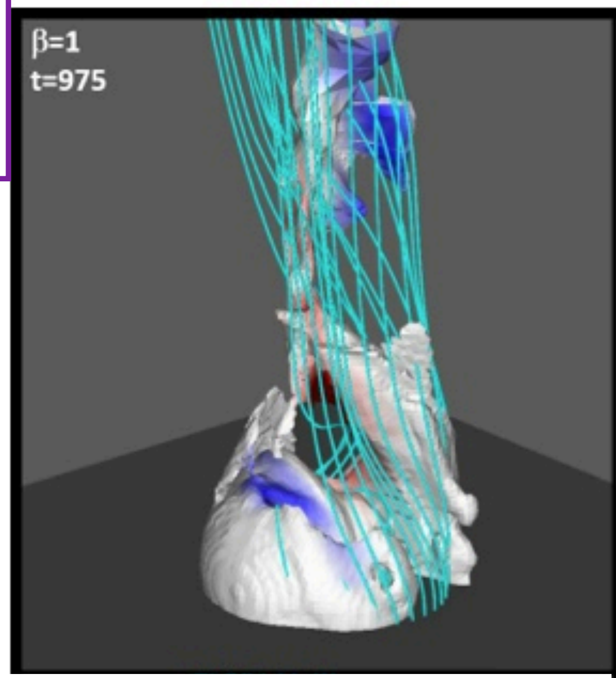
3D MHD simulations of solar eruptions

- Effect of the plasma-β on solar jet properties (ARMS)

chromospheric-like jets

bulk flow





one flow

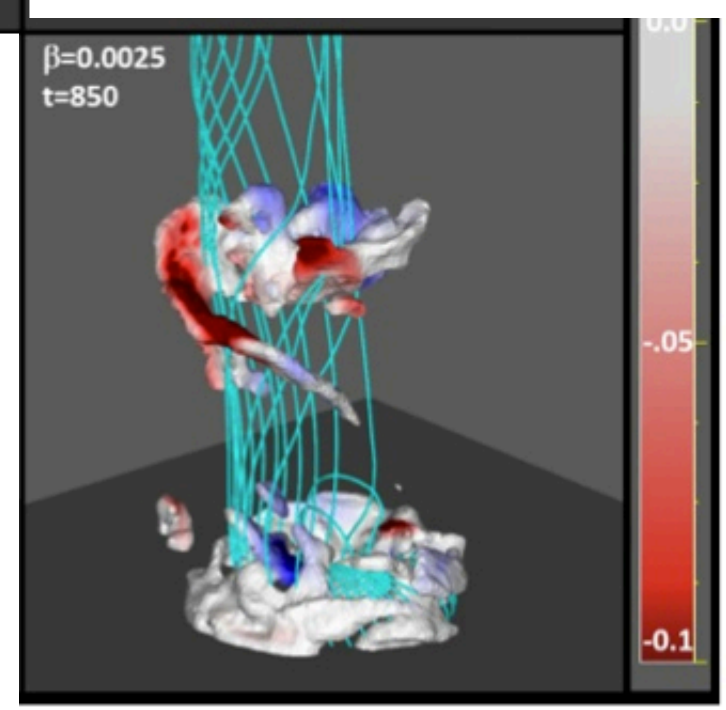
$v_{flow} < C_A$

magnetically driven

two flows

$v_{flow} \sim C_A$

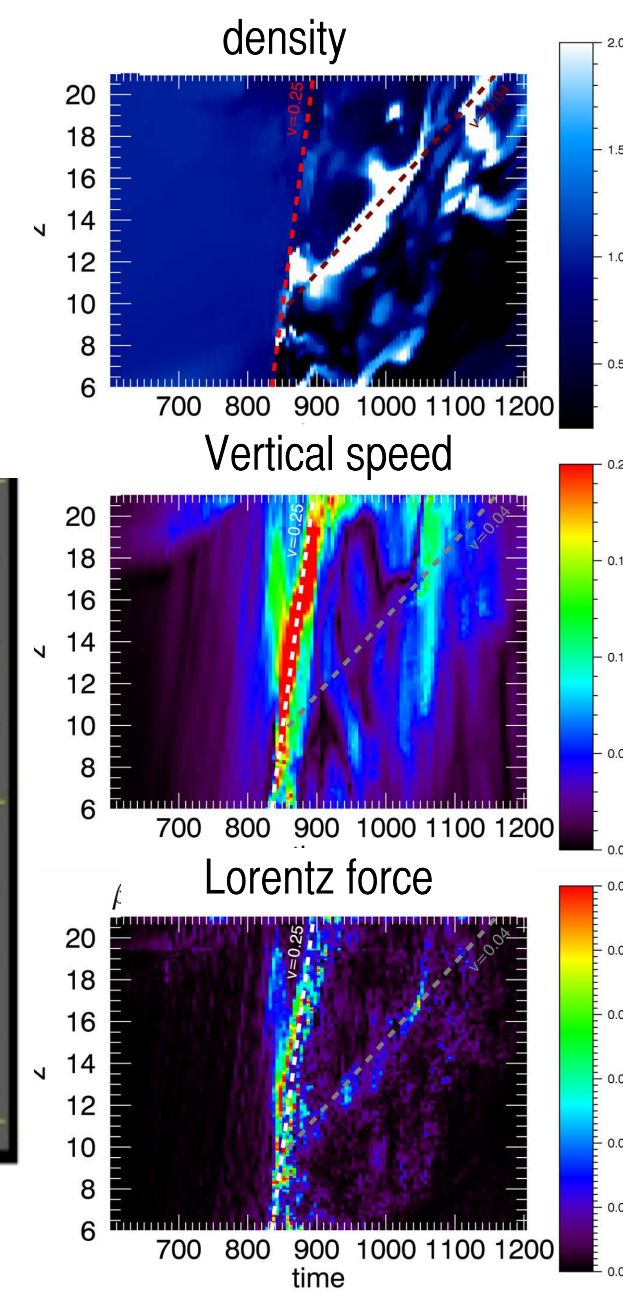
magnetically driven



coronal-like jets

fast untwisting Alfvèn waves

+ slow bulk flow

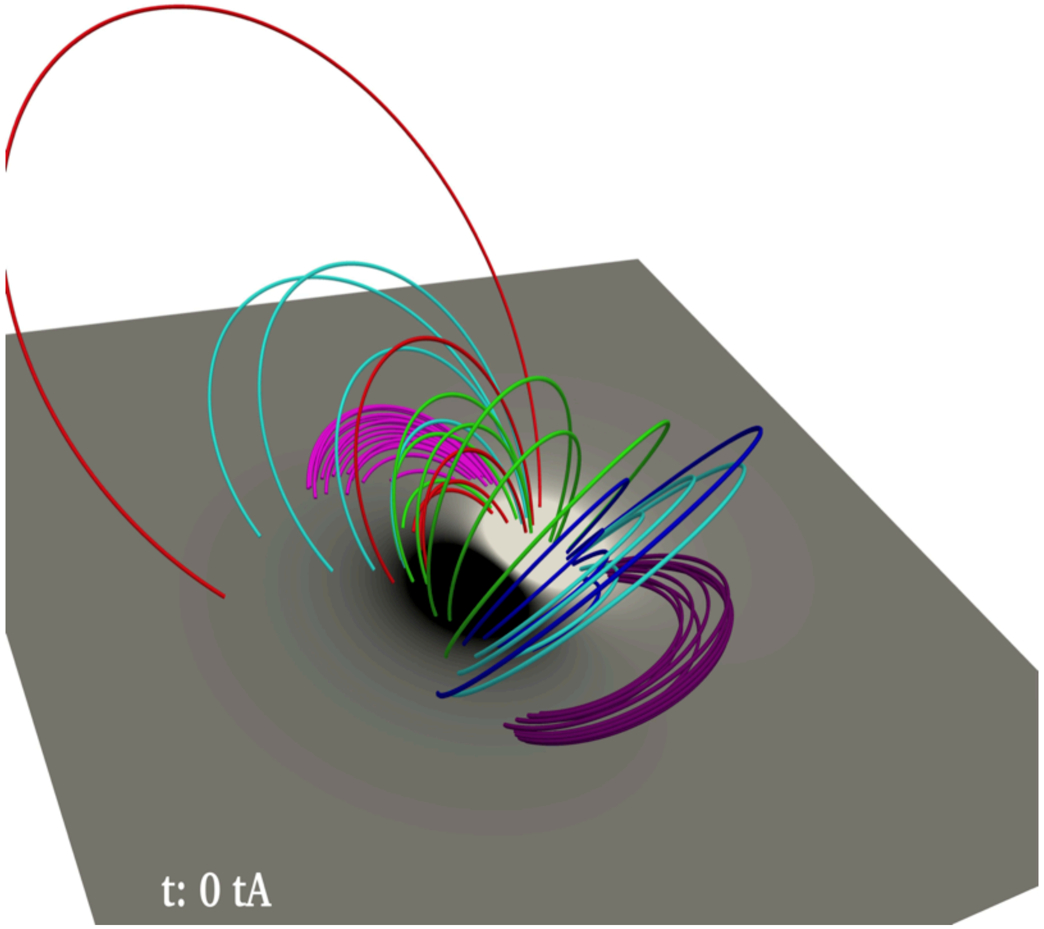


Pariat, Dalmasse, et al. ApJ, 2015

3D MHD simulations of solar eruptions

- Triggering mechanism of coronal mass ejections (OHM-MPI)

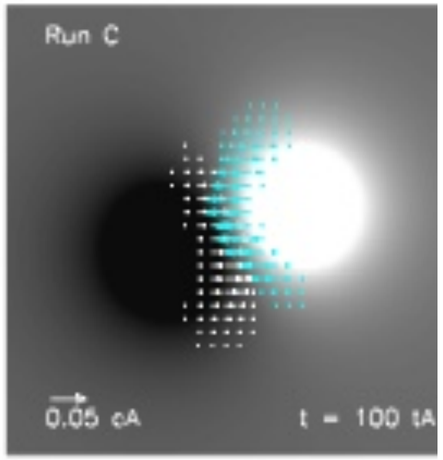
Torus instability = When the filament reaches the height at which the external B field decreases $\propto R^{-n}$



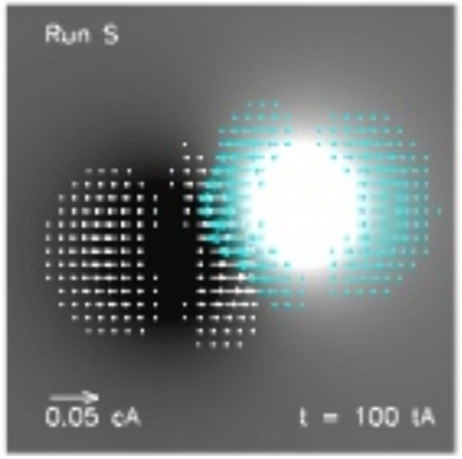
Does the critical decay index vary with respect to the property in the filament?

Zuccarello, Aulanier, Gilchrist, ApJ, 2015

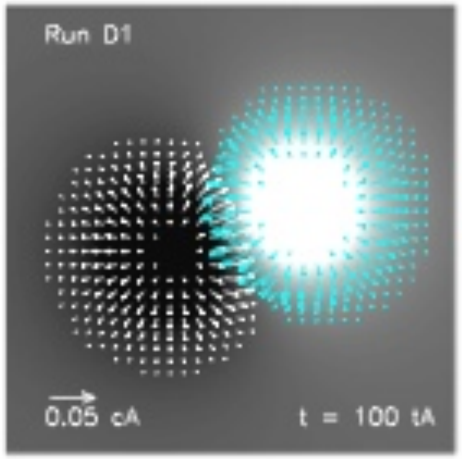
Apply 4 different photospheric forcing => Build up the filament with different properties



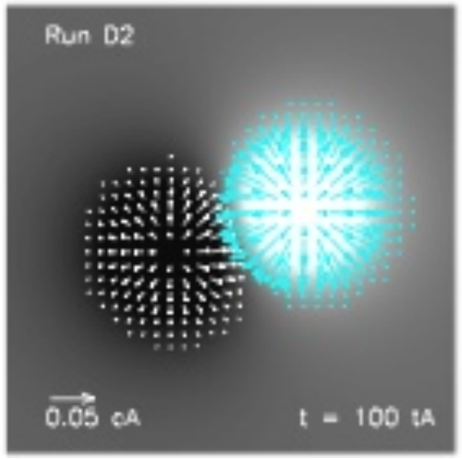
convergence



stretching



outer dispersal

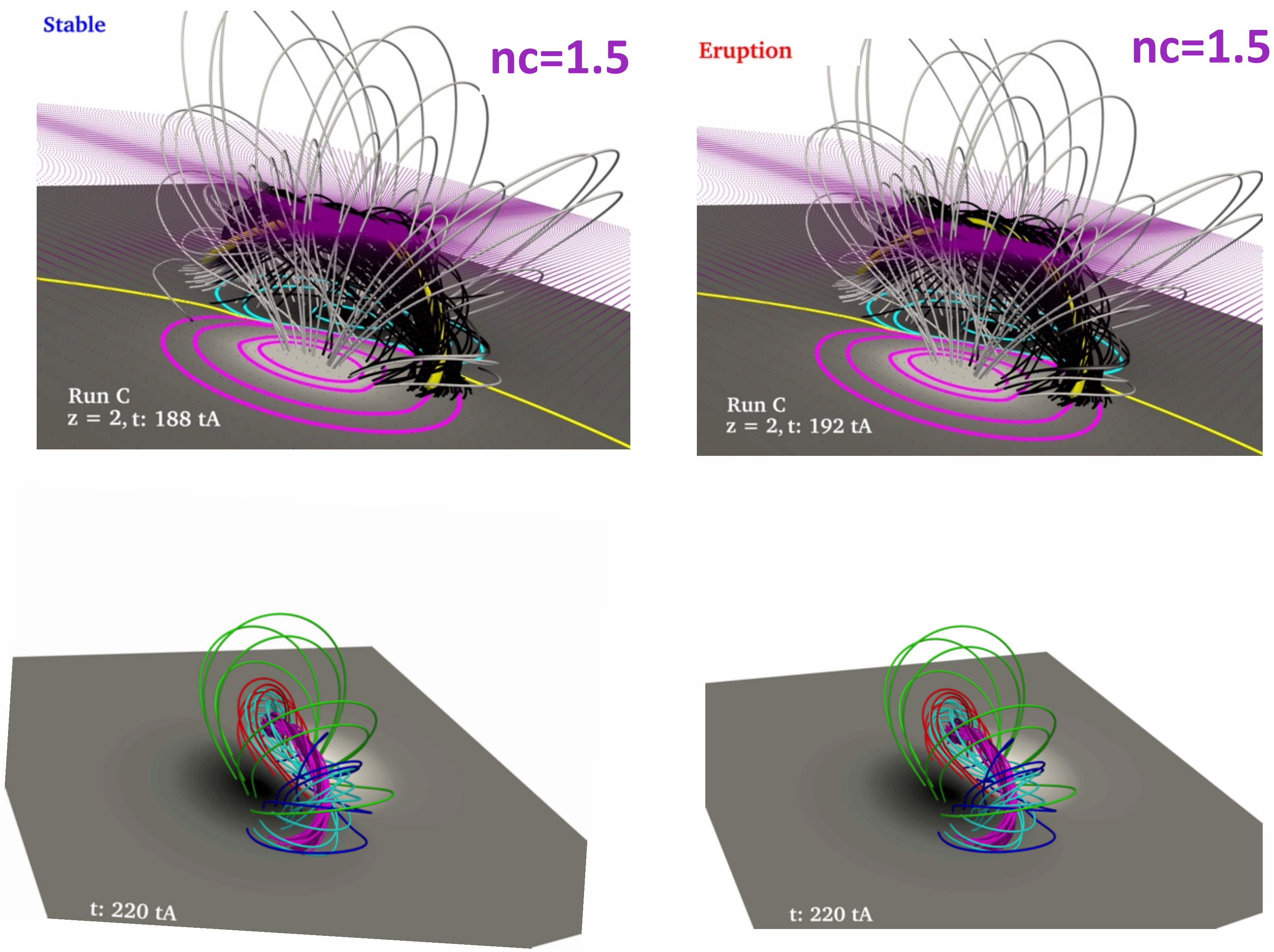


full dispersal

3D MHD simulations of solar eruptions

- Triggering mechanism of coronal mass ejections (OHM-MPI)

To determine the onset of the eruption: Stop the forcing earlier



Flux rope axis reaches the height (nc = 1.5)

=> erupts

4 different forcing :

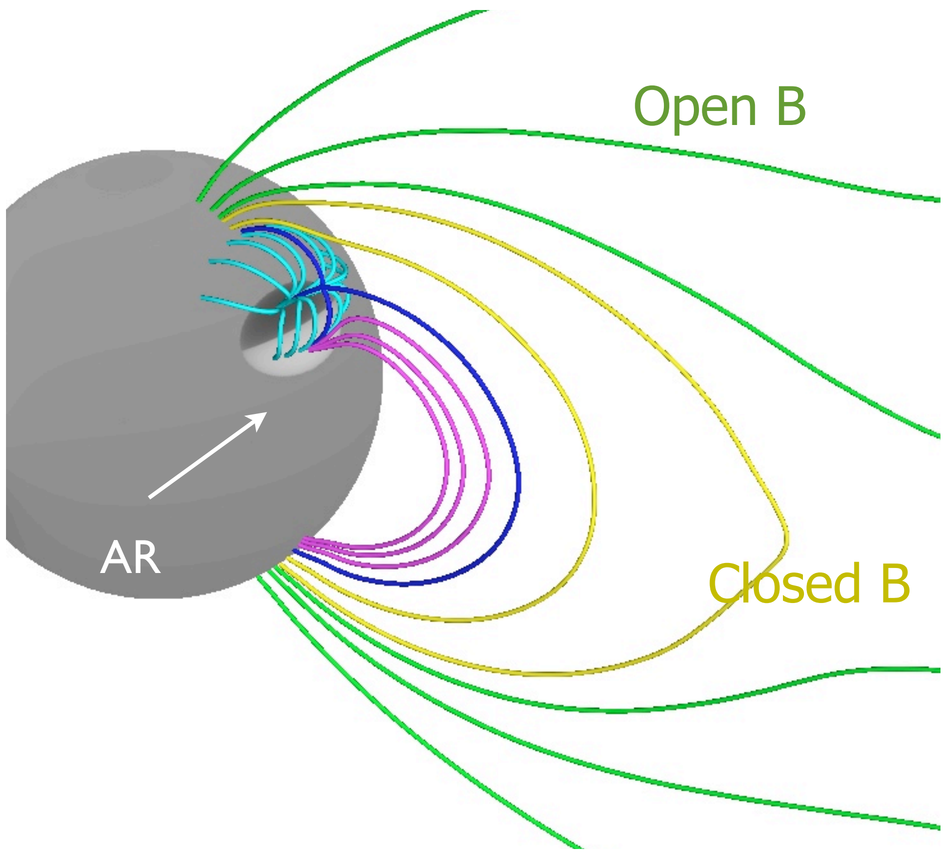
The critical index ~ 1.4 – 1.5

Universal condition for eruptivity

Zuccarello, Aulanier & Gilchrist, ApJ, 2015

3D MHD simulations of solar eruptions

- CME eruption into a more realistic environment (ARMS)



Large scale background B field :

- Magnetic dipole at the Sun center + Isothermal solar wind

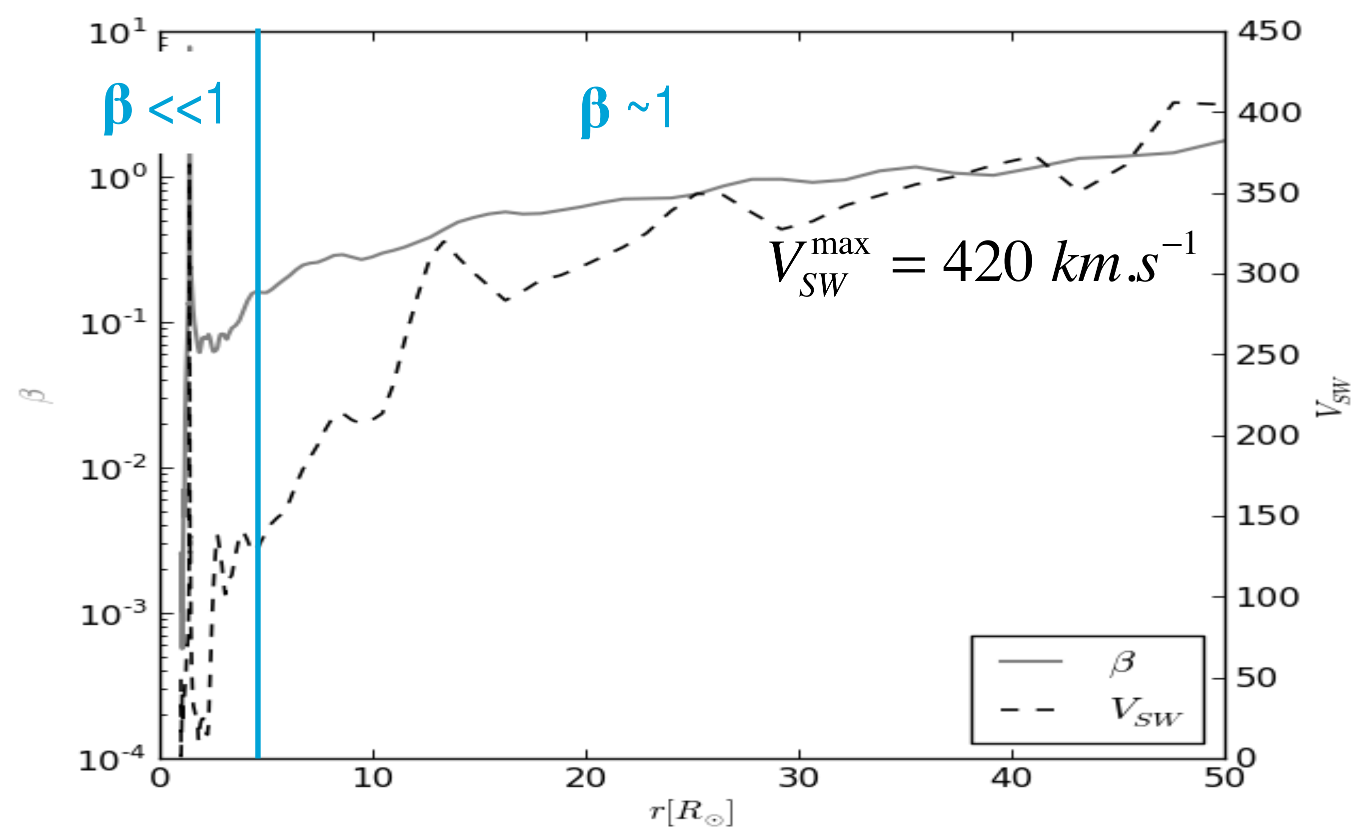
Masson et al., 2013

➡ Define the open/closed field domain

Dipolar active region

➡ More realistic – large scale magnetic configuration

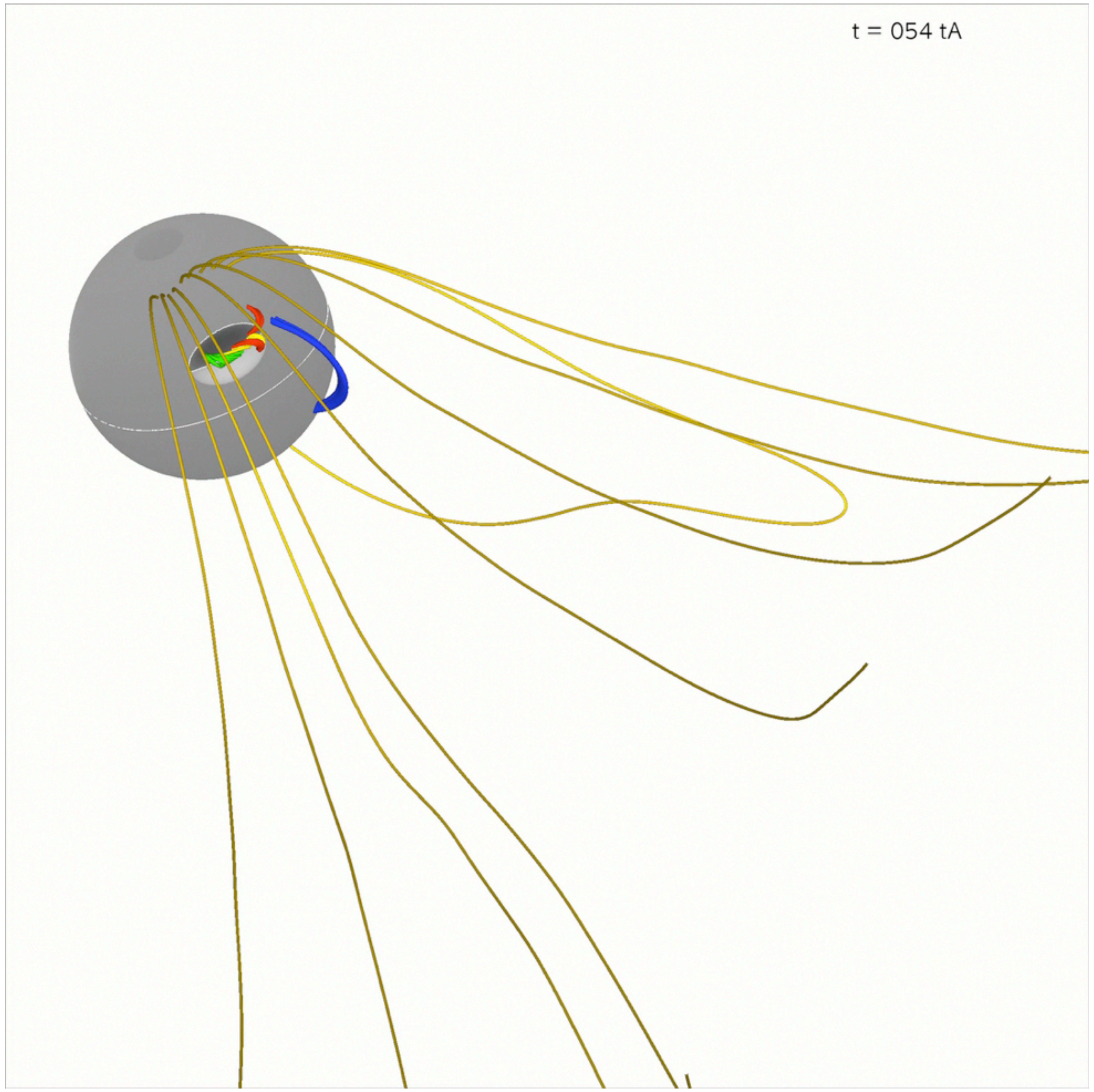
Realistic atmosphere :



3D MHD simulations of solar eruptions

• CME eruption into a more realistic environment (ARMS)

Masson, DeVore & Antiochos, submitted



Magnetic reconnection with the surrounding field

- At least **4 reconnection sites/episodes** versus 1 in the small scale simulation.

  → corona reconfiguration
  → particle acceleration

- **Coupling the filament and the open IMF**

  → Injection of particles into the IMF

3D MHD simulations of solar eruptions

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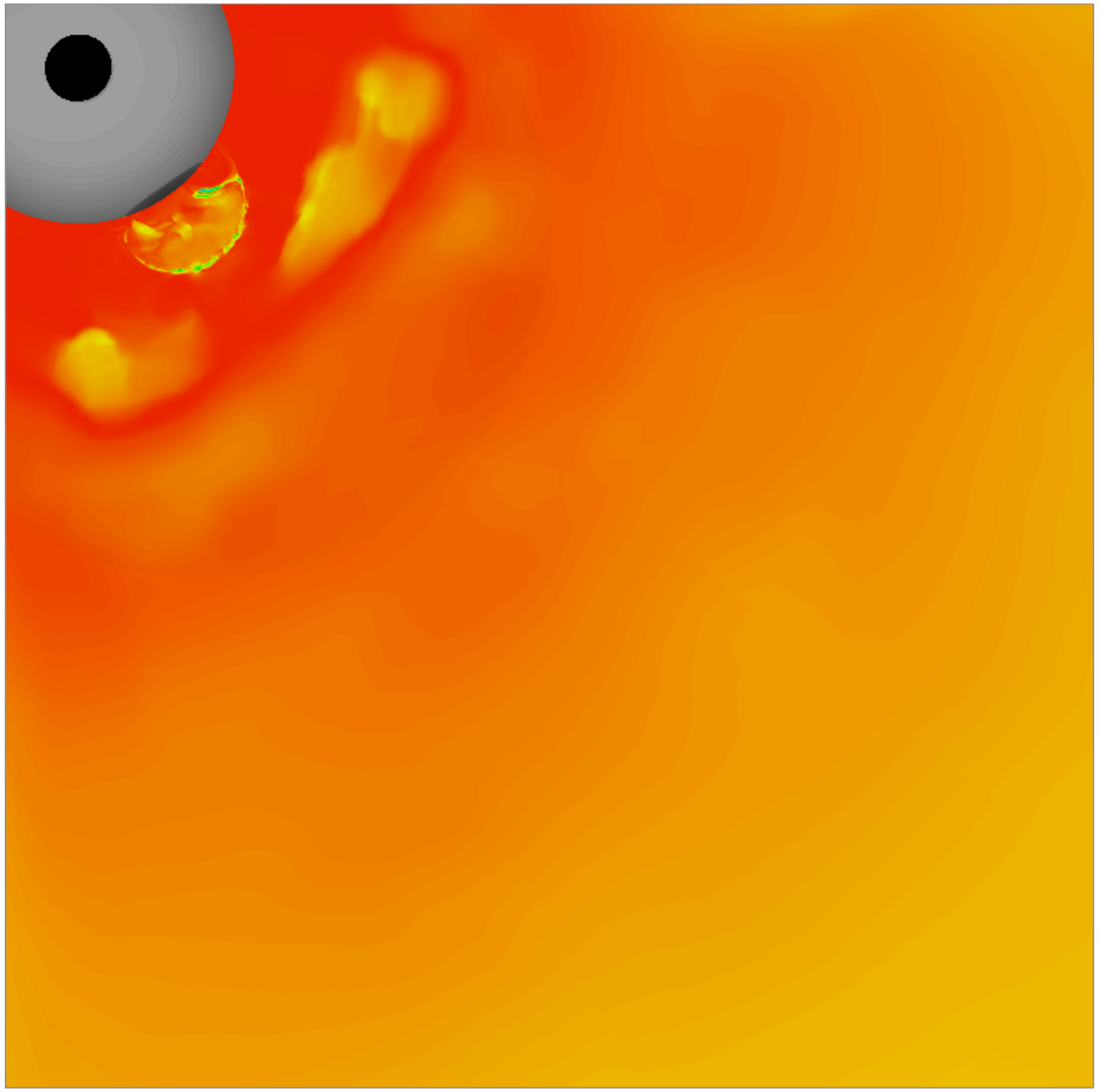


Magnetic reconnection with the surrounding field

• At least **4 reconnection sites/episodes** versus 1 in the small scale simulation.

→ corona reconfiguration
→ particle acceleration

• **Coupling the filament and the open IMF**

→ Injection of particles into the IMF

Fast auto-consistent filament eruption into an interplanetary field structured by the solar wind

Outline

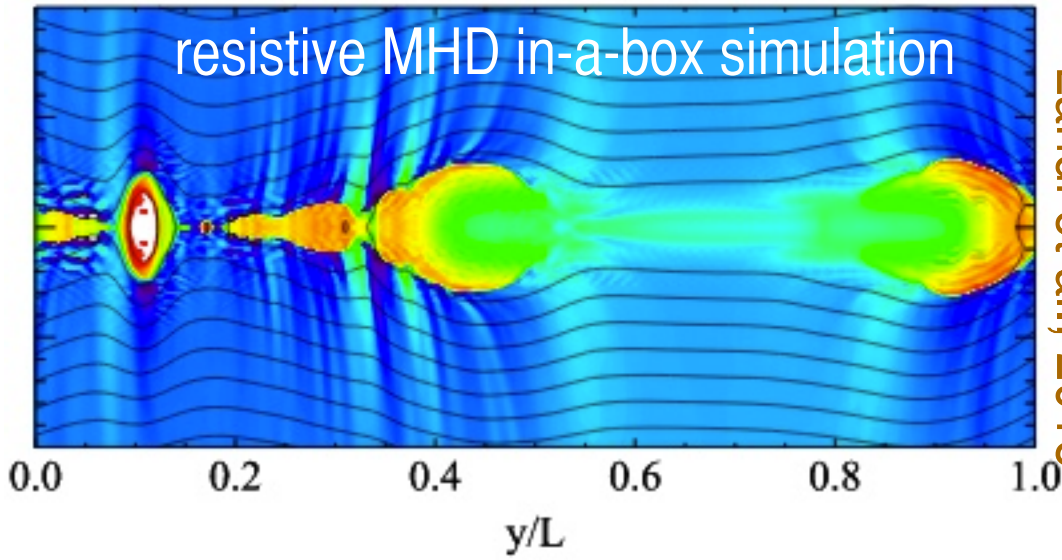
- Modeling solar eruptions
- Recent results on solar jets and coronal mass ejection
- Scientific and computational prospectives

Scientific & computational prospectives

- Going to smaller scales

3D MHD simulations : reproduce the global dynamics of the eruption, but it is too slow compare to the reality

Include some small scale MHD processes !!



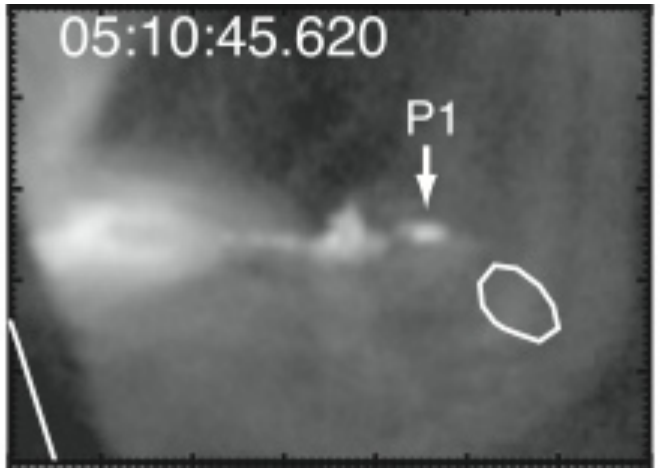
Landi et al., 2015

- Multi-reconnection sites in the current sheet
- Petscheck reconnection regime

→ **Reconnection rate increase**

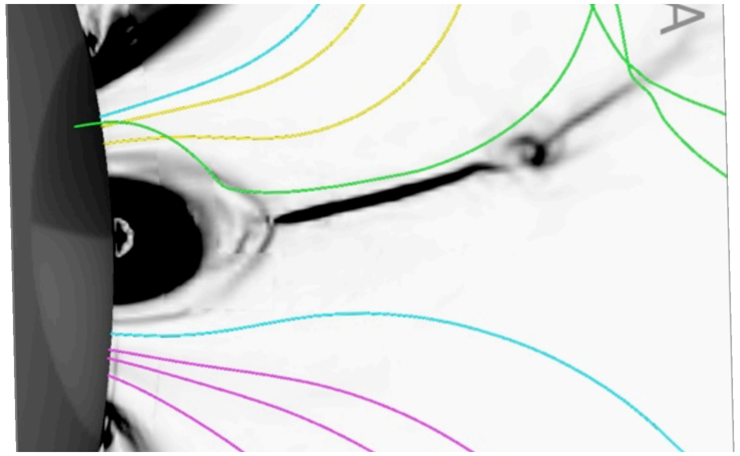
- Plasmoids'role in reconnection and flares

Plasma blobs in observation



Takasao et al., 2016

Plasmoids in simulation (ARMS)



Preliminary

How do islands form and evolve in 3D flare current sheet ?

How does it affect the eruption characteristic (dynamics radiative signatures,...) ?

Scientific & computational prospectives

- Increase the spatial and temporal resolution

To identify magnetic islands and study their dynamics

OHM-MPI : non-uniform mesh	ARMS : Using the adaptive mesh refinement
~8 GB / output file (1 vector)	~3 GB / output file (3 vectors & 4 scalar)

+ output files every $t < t_A$ over a long period of time (>20 tA)

- **OHM-MPI allows us to control the resistivity in the system ≠ ARMS has a numerical resistivity**

→ OHM-MPI needs a fine-tuning of parameters during the simulation

→ test several parameters within a day : need to decrease the time spending in the queue

- Use ‘homemade’ softs taylored to analyse solar eruption simulations :

Size of high resolution runs → Difficult to analyse the results locally

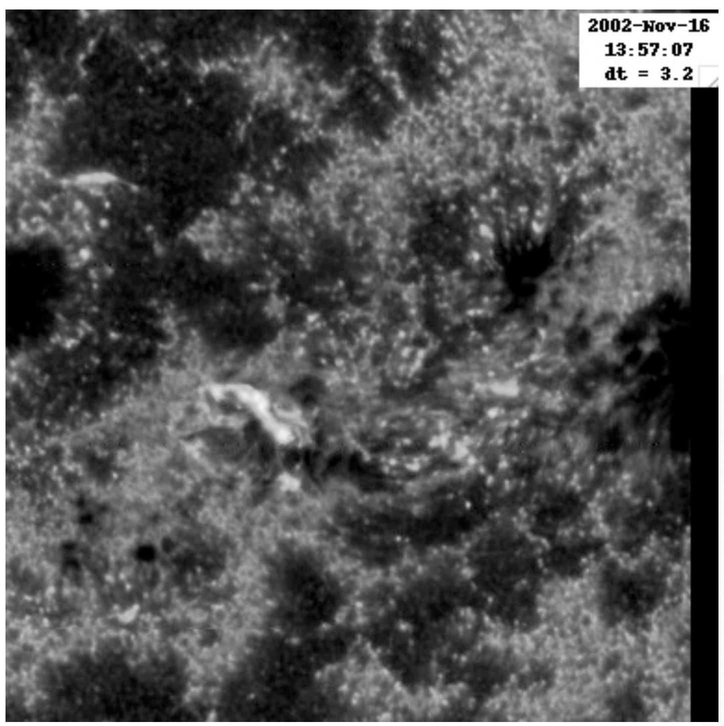
Help to parallelize & export the visualisation softs to analyse the results on clusters

Scientific & computational prospectives

- Including particles

How those particles are accelerated during the eruptions ?

precipitate toward the solar surface
→ EUV bright ribbons / X-rays

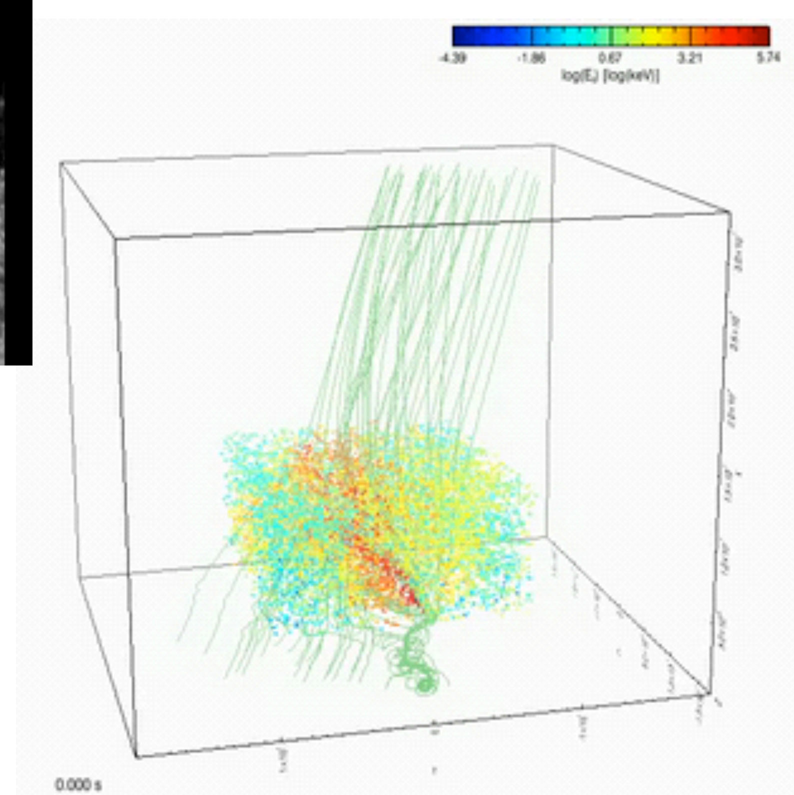


Masson et al., 2009

Compare the radiative signature with simulations including particles → new constrain on the model

Test particles in a dynamic B resulting from 3D MHD simulation

→ Shape & dynamics of the radiative signatures



Rosdahl & Galsgaard, 2010

Large scale simulations (ARMS)

Developp the particle code

Run the MHD & the particle codes in parallel