# Magnetic reconnection as the driver of eruptions in an emerging magnetic flux tube

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# 3D reconnection

Lots of what was leaned from 2D has to be almost completely reconsidered

2D breaking of field lines in a single point in space

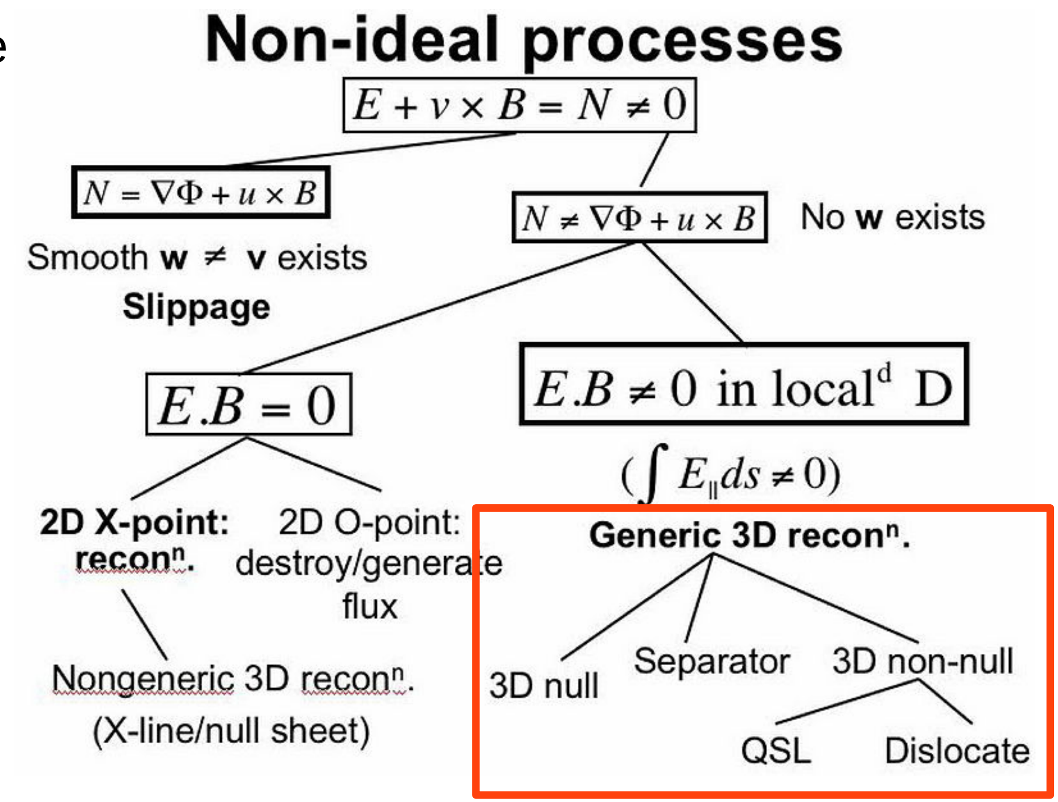
3D is different

At null locations

At no null locations

The electric field parallel to the magnetic field is important

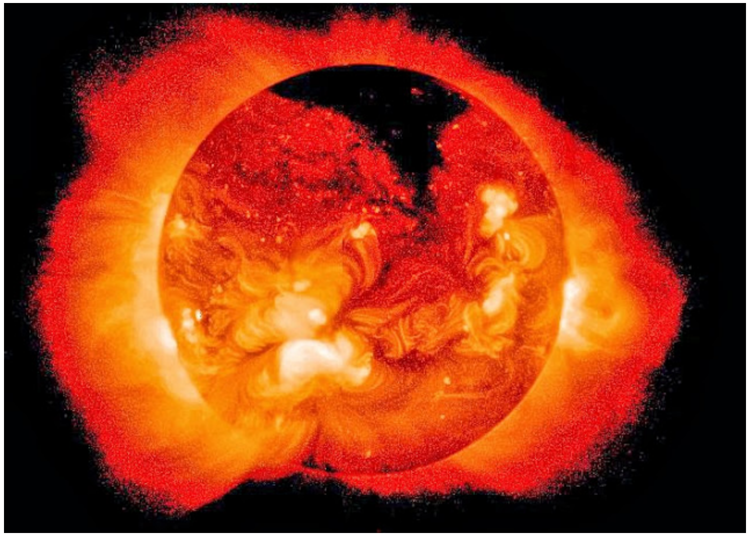
$$\boxed{\int E_{par}\, ds \neq 0}$$

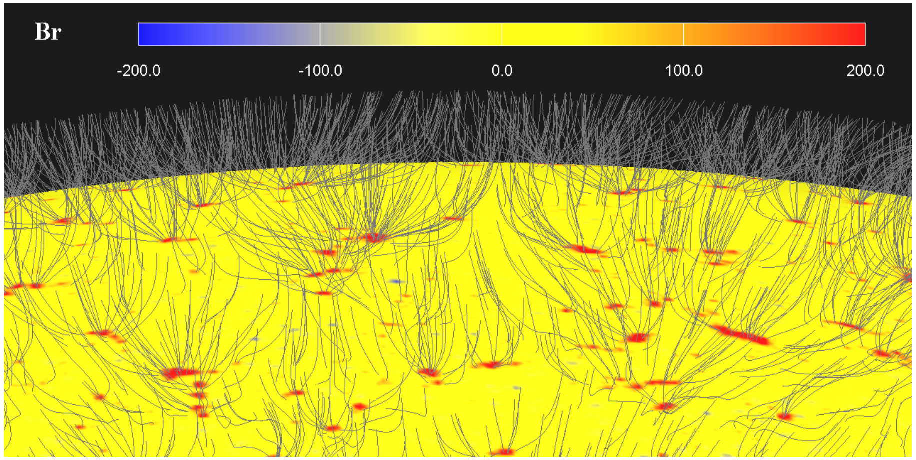



*Hesse, Birn, Schindler JGR 88ish*

# Observations

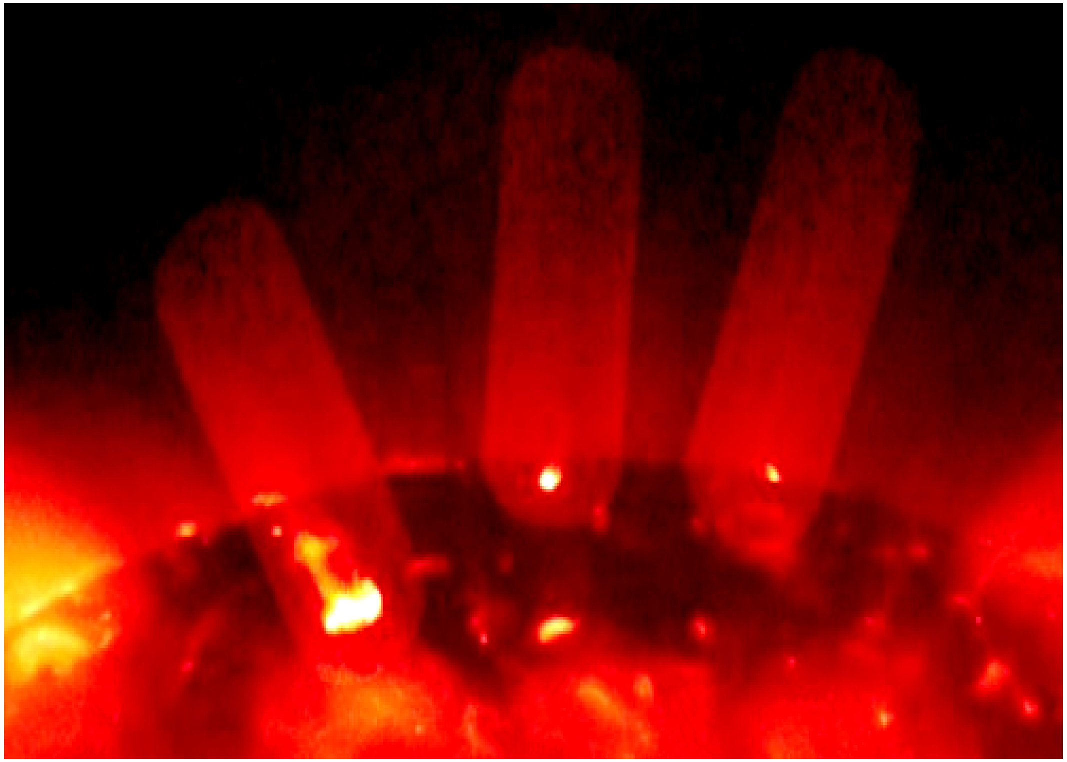
- EUV and X-ray observations of the Sun
  - Highlights the plasma in the upper atmosphere
  - Weak emission in the polar regions
    - Open field region (large scale dipolar field region)
- Extrapolation model





# Jets in Coronal Hole regions

- Hinode obs of CH, January 10, 1997
- Jets are associated with bright regions, indicating an interaction between a bipolar region and the open background field

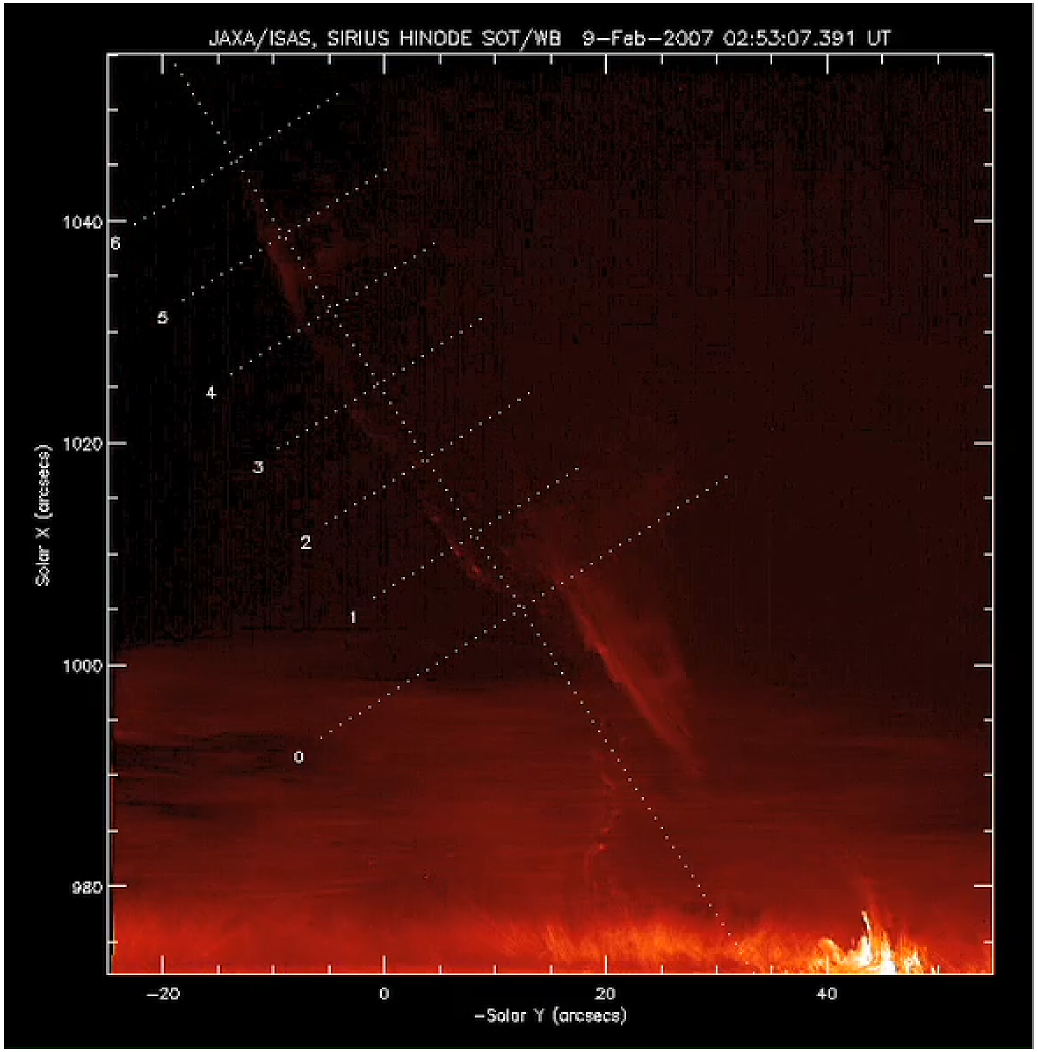


60 per day
10-15 minutes duration
Two types
    Eiffel tower
    Blowouts
V_jet order a few 100 km/s

# An eruptive CH jet

30 minutes duration

60.000x60.000 km



# The Standard or Eiffel-tower jet

- Order 13 minutes duration
- Bright point, Jet axis, position change of jet with time
- Reversed image – black is strong emission

*Moore et al. 2010*

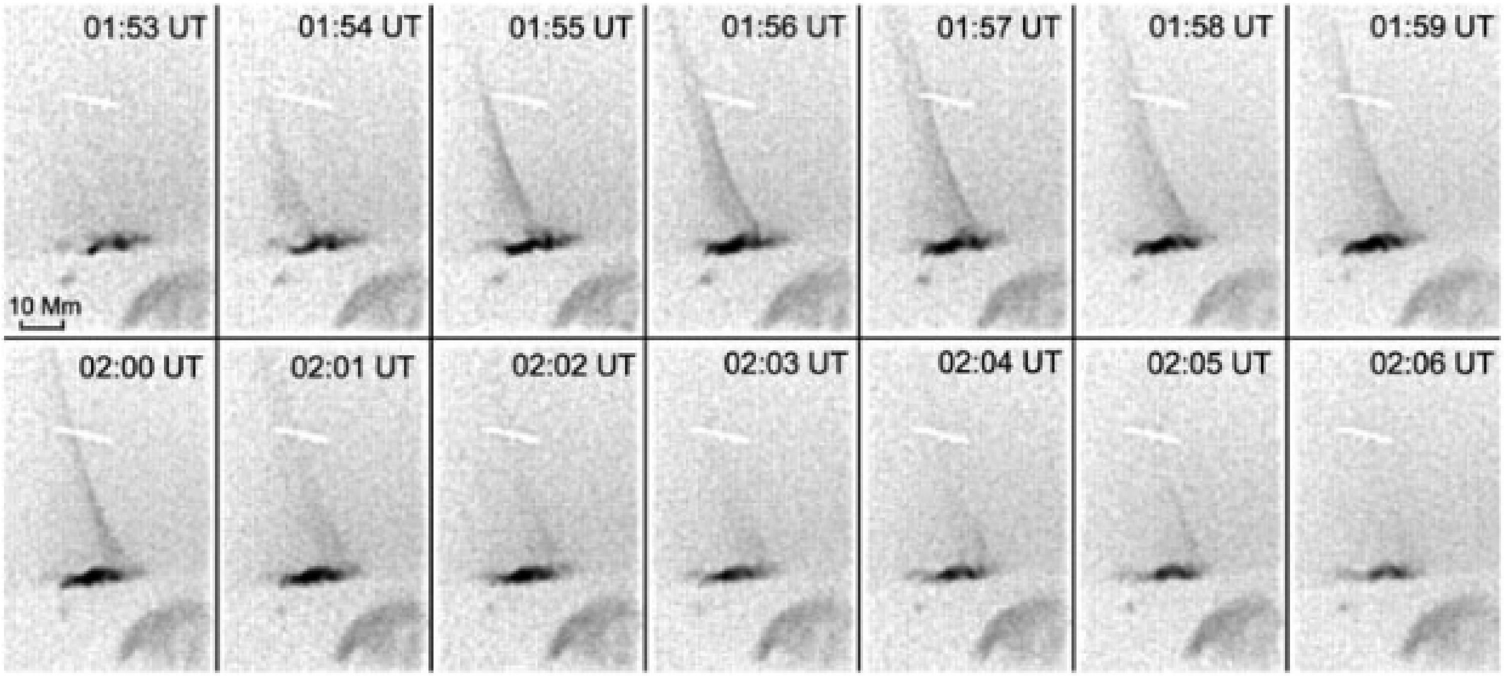
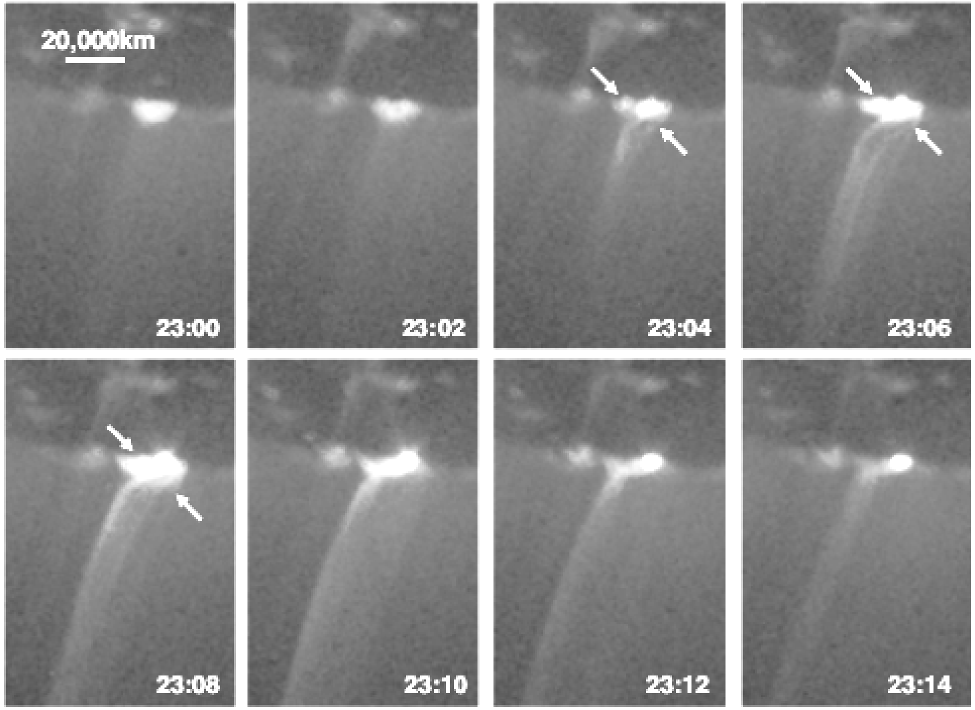



**Figure 2** Negative X-ray images showing the small jet evolution between 01:53 UT and 02:06 UT on 23 November 2006. This jet is visible in Figure 1, labeled A. The white segment at the top of each image is produced by a speck of dust in front of the CCD detector.

# "Blowout" jets

- Typically follows an Eiffel-tower jet period
- Eruption of the lower regions
- Looks like a mini CME
- Hot and cold plasma observed simultaneous



Moore et al. 2010

Eruptions found to occur several times from the same region.

Madjarska 2011 found 4 eruptions within 30 minutes

Innes et al. 2010 – *Mini CME*
Morre et al. 2010 – *jets*

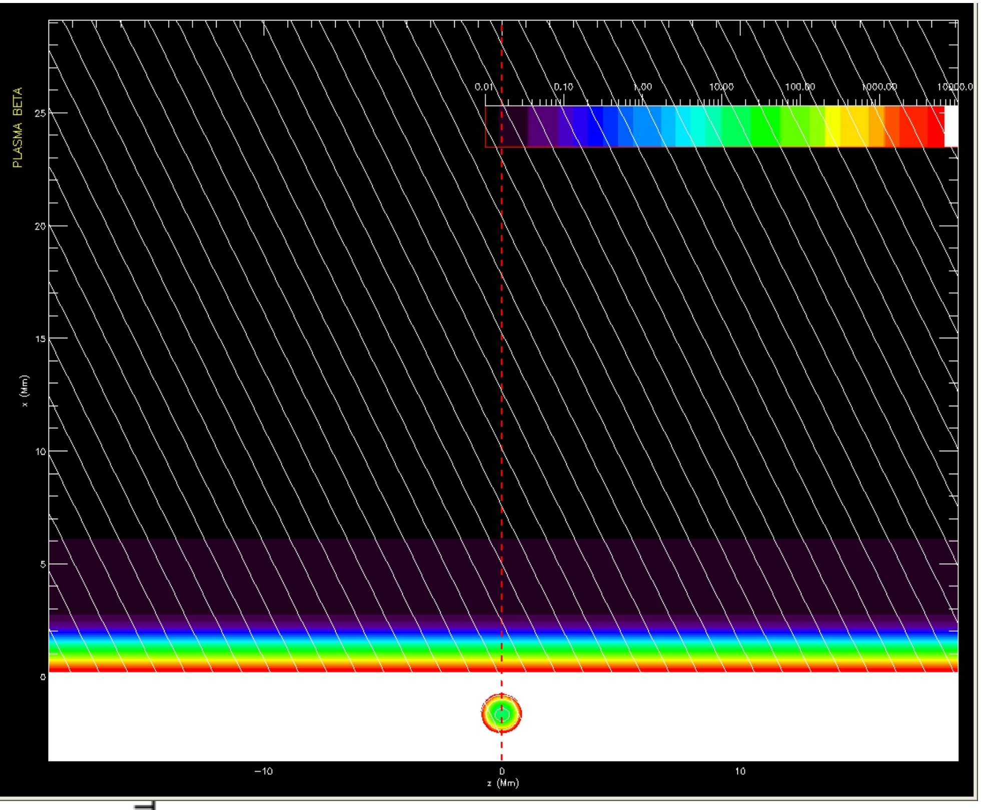
*Models:*
Pariat et al. 2009, 10,
Moreno-Insertis et al. 2010, 13
Archontis et al. 2013
Fang et al. 2015
Jui Lee et al. 2015
...

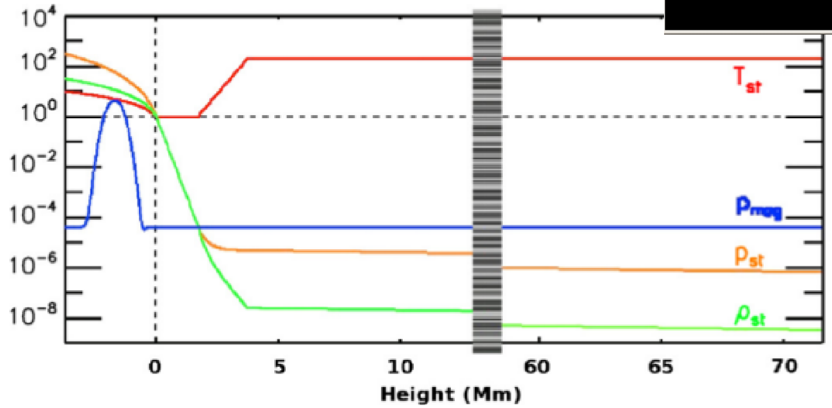
**There does not exist any unique theoretical model for this type of event**

# "Standard" 3D cartoon emergence setup

- Twisted flux loop inside the convection zone
- Tilted uniform background magnetic field
- Stratified hydrostatic model atmosphere

*Shibata et al.*
*Fan et al.*
*Manchester et al.*
*Archontis et al.*
*Magara et al.*
*Moreno-Insertis et al.*
*....*



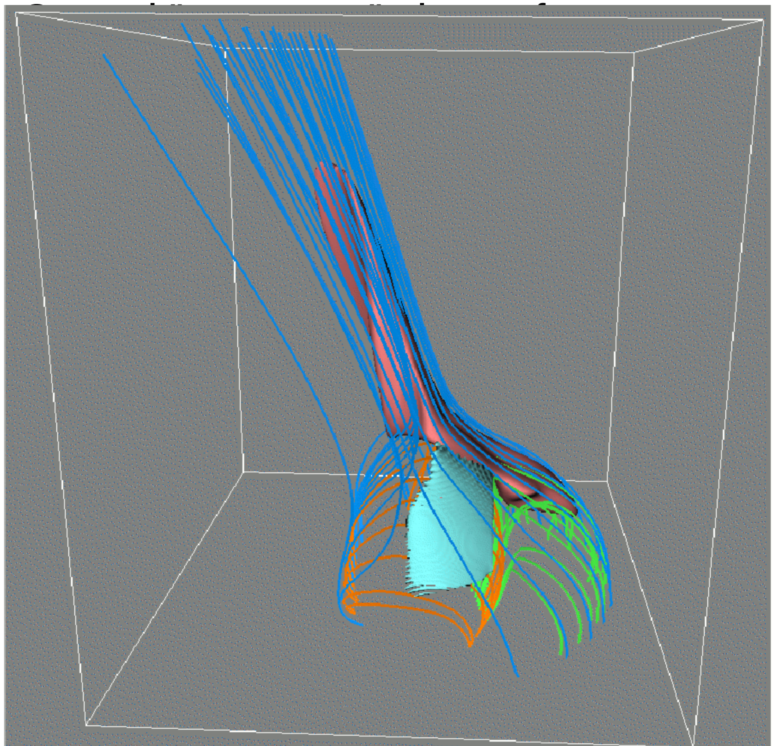



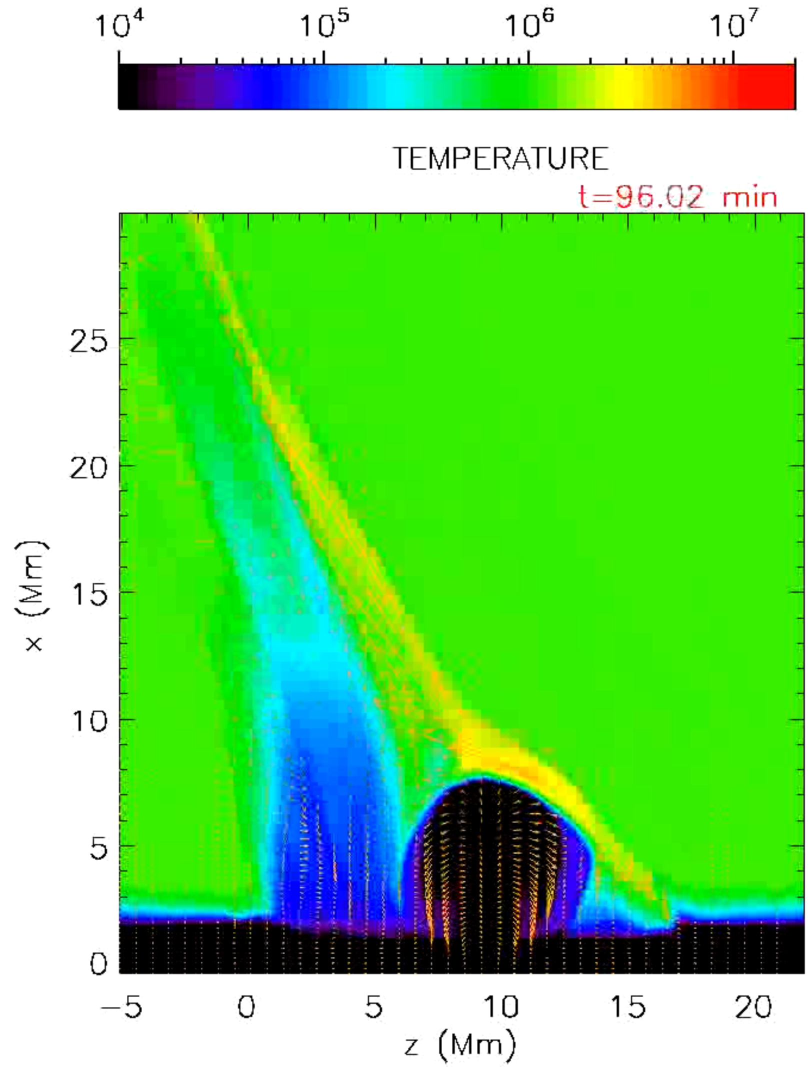
# Numerical approach

- 3D resistive MHD
- Simple energy equation
  - Ignoring radiation and heat conduction
- High order finite difference Copenhagen Stagger Code
  - Staggered grids
  - 6th order derivatives
  - 5th order interpolation
  - 3rd order time integration
  - High order numerical diffusion

# Jet models 2D slice time view

Relevant fraction of the domain

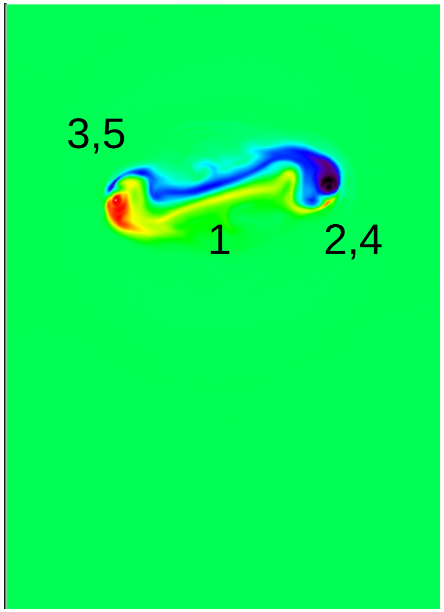


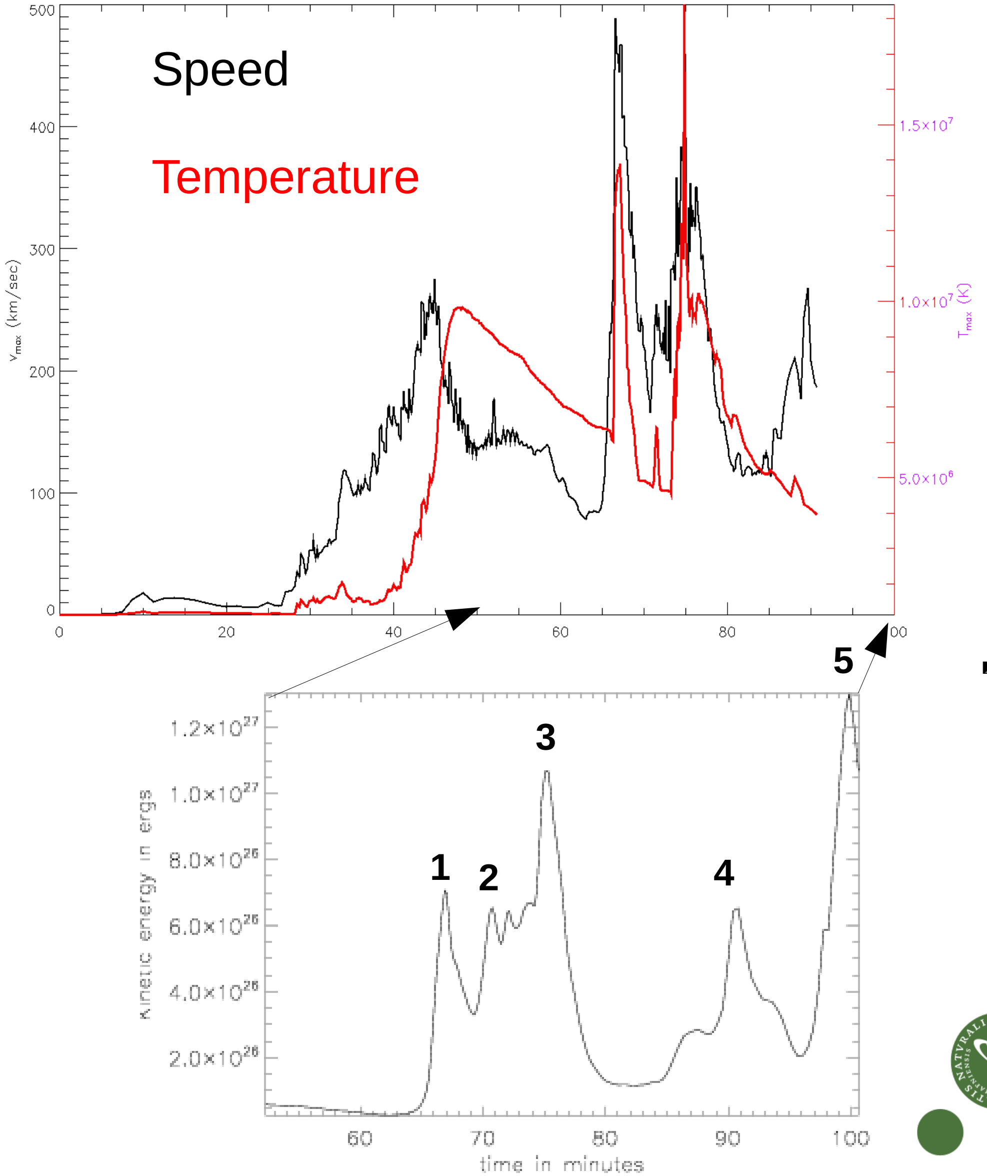



Moreno–Insertis & Galsgaard 2013

Later ones are not as clearly observed in this 2D plane

# 5 eruptions in about 35 minutes

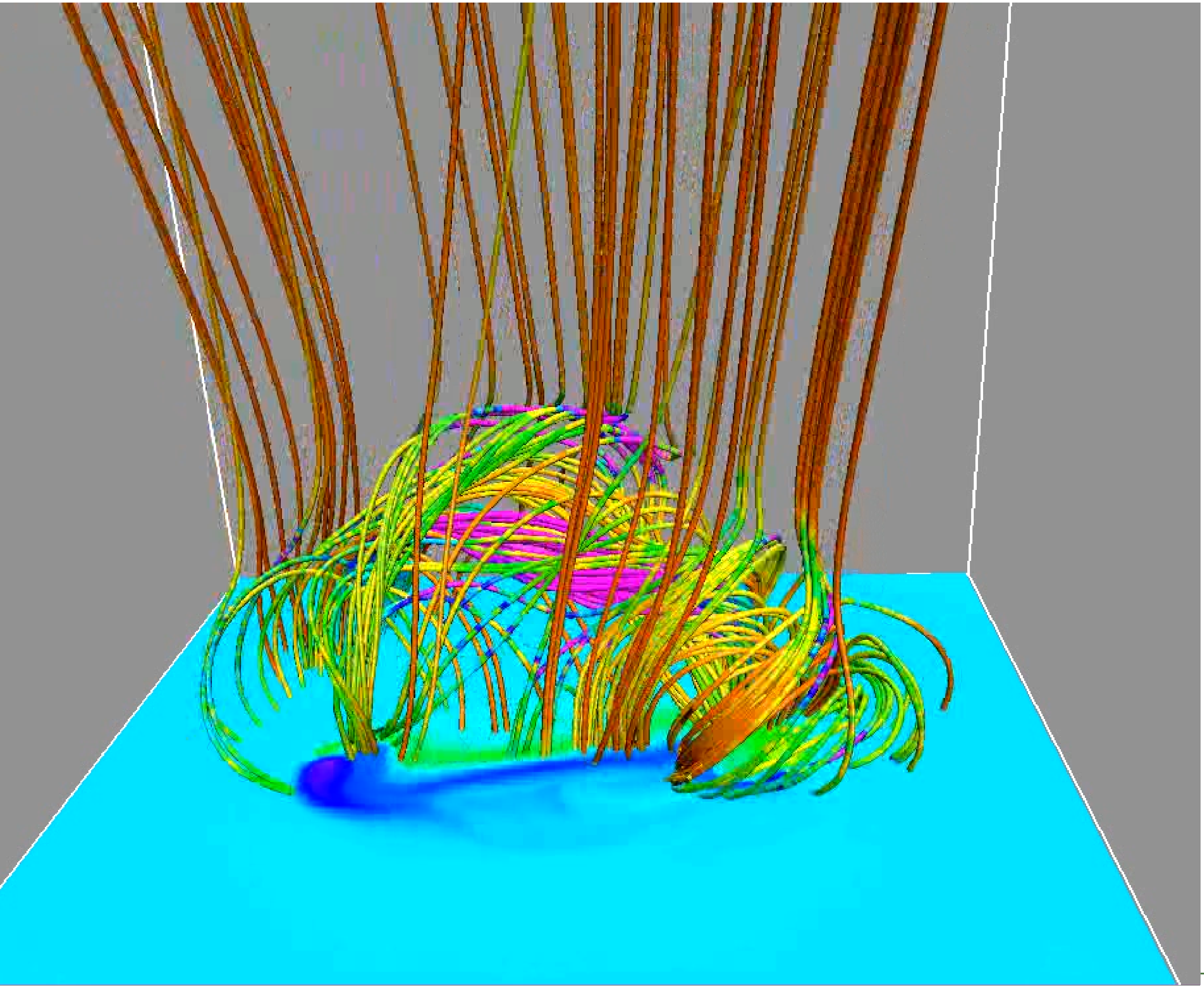



Magnetogram

Location of ERs

# Example of the field line evolution



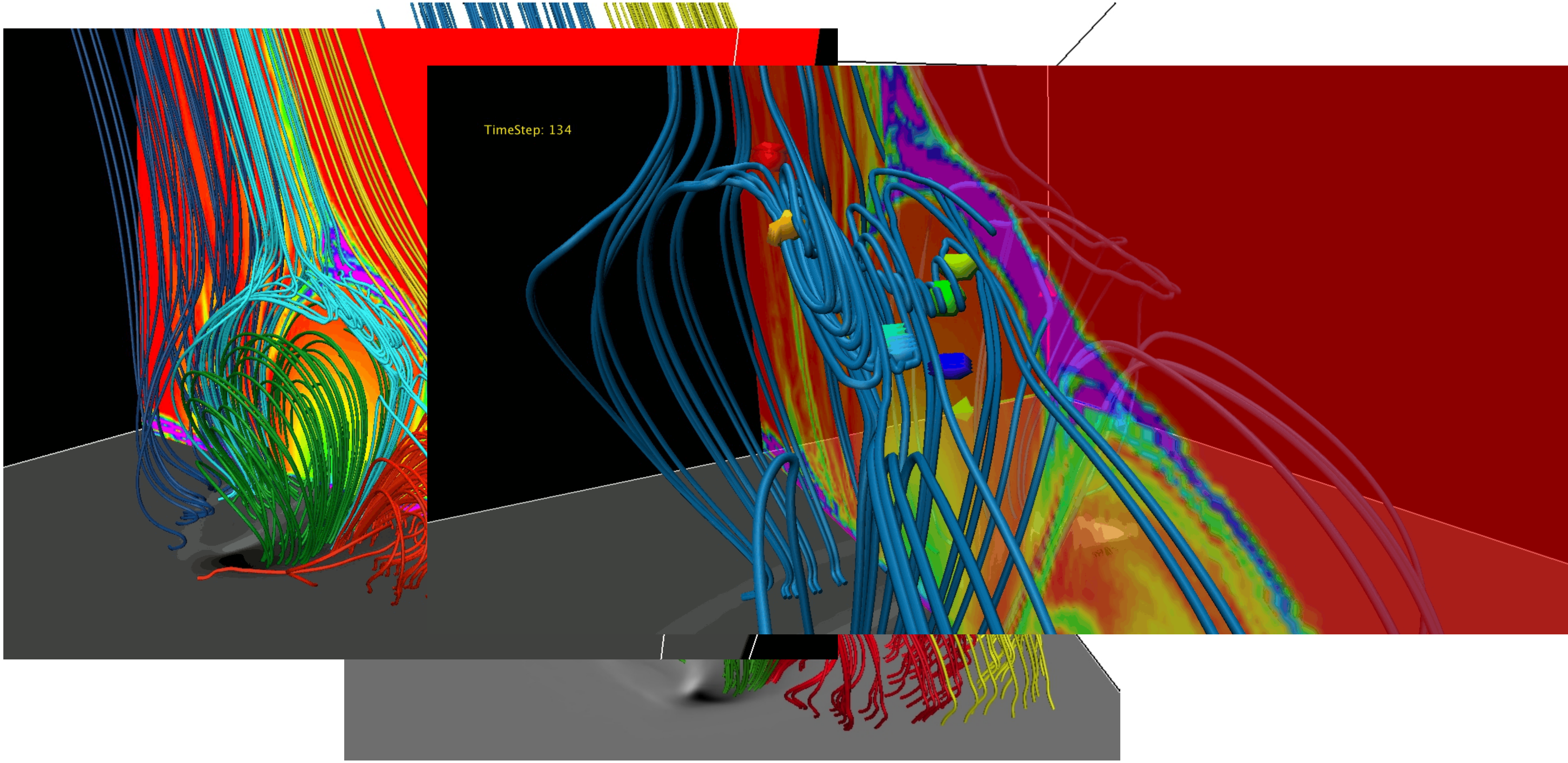
Field lines traced from fixed positions in space

Colour coded field lines: upflow speeds


Magnetogram at the base

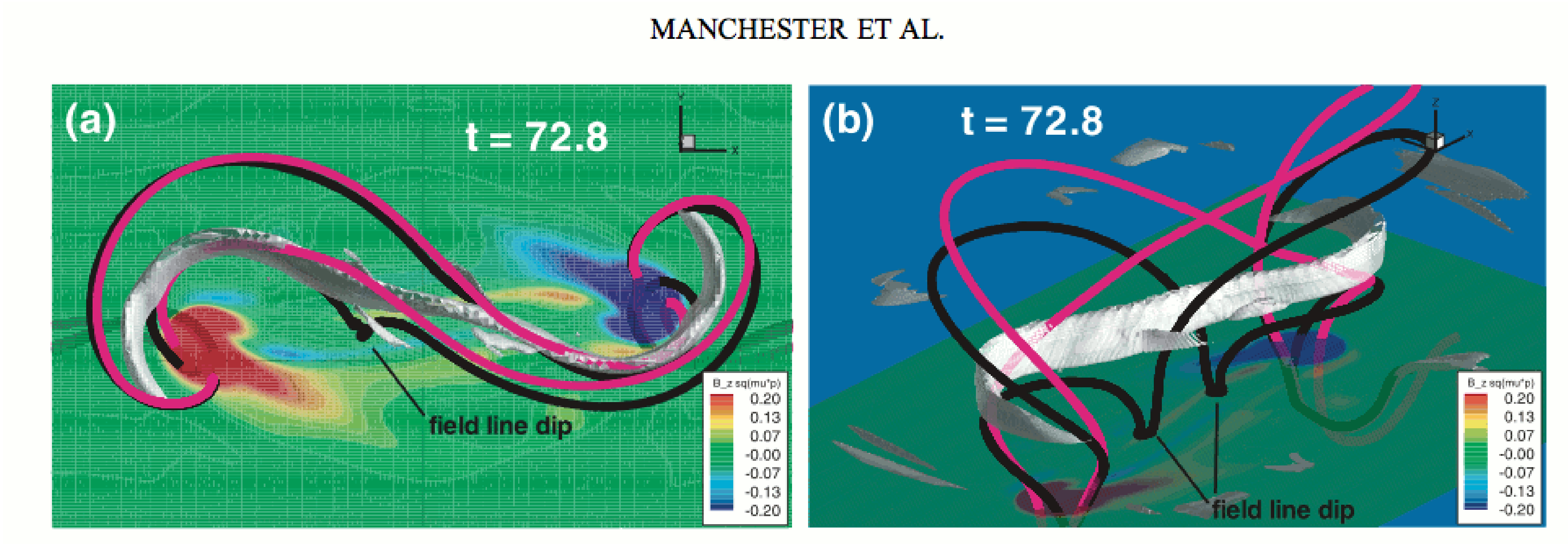
5 eruptions

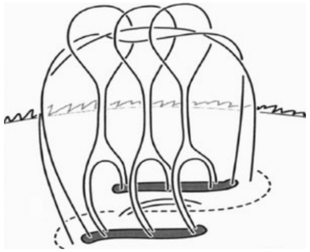
# Plasmoid formation in the current sheet




Small coloured squares are 3D null points, mainly complex nulls
Twisted magnetic field lines, |J|/|B| surface
Complicated magnetic reconnection processes
Null points slow down the reconnection

# Eruption 1: Tether cutting of emerging loop system

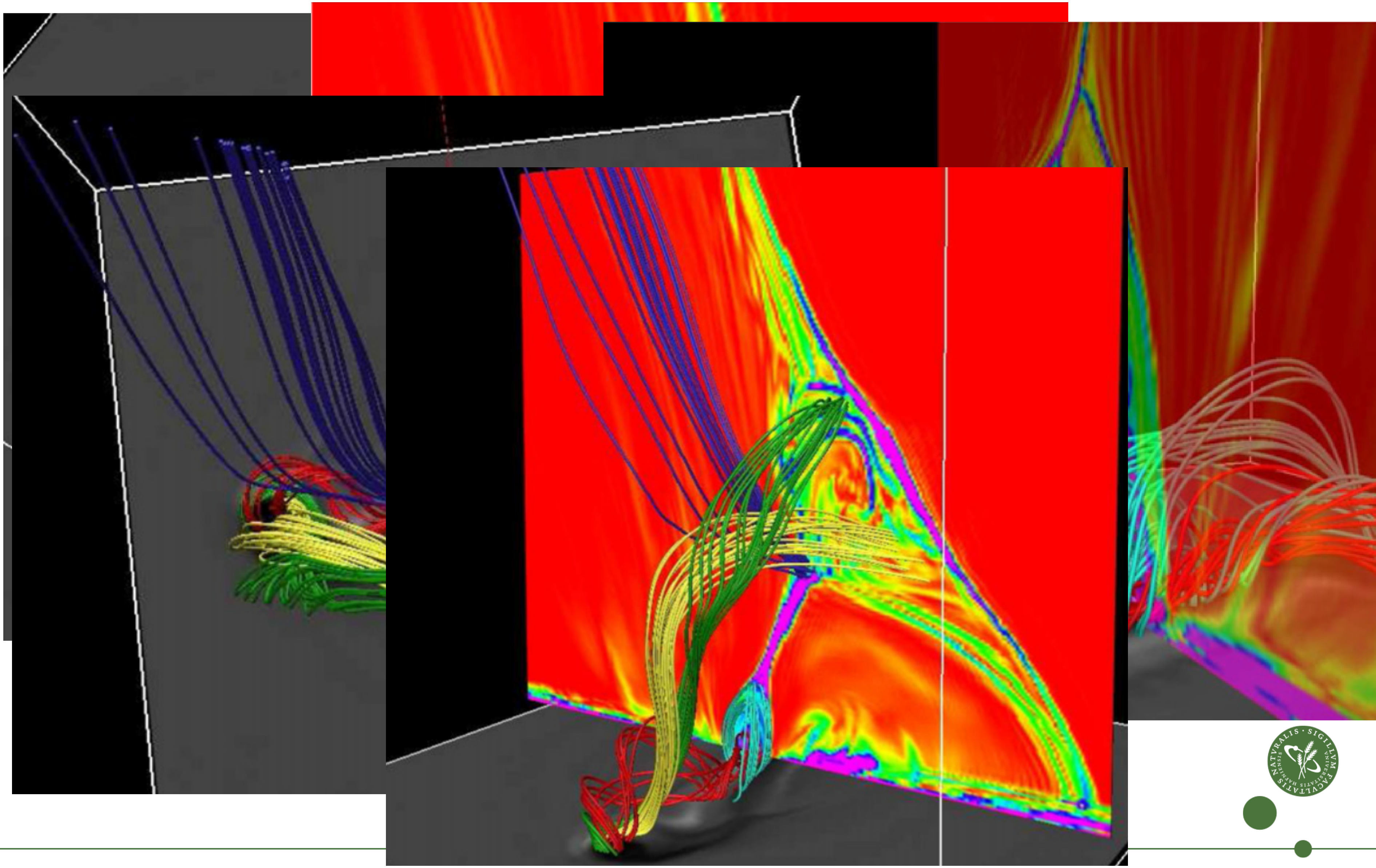


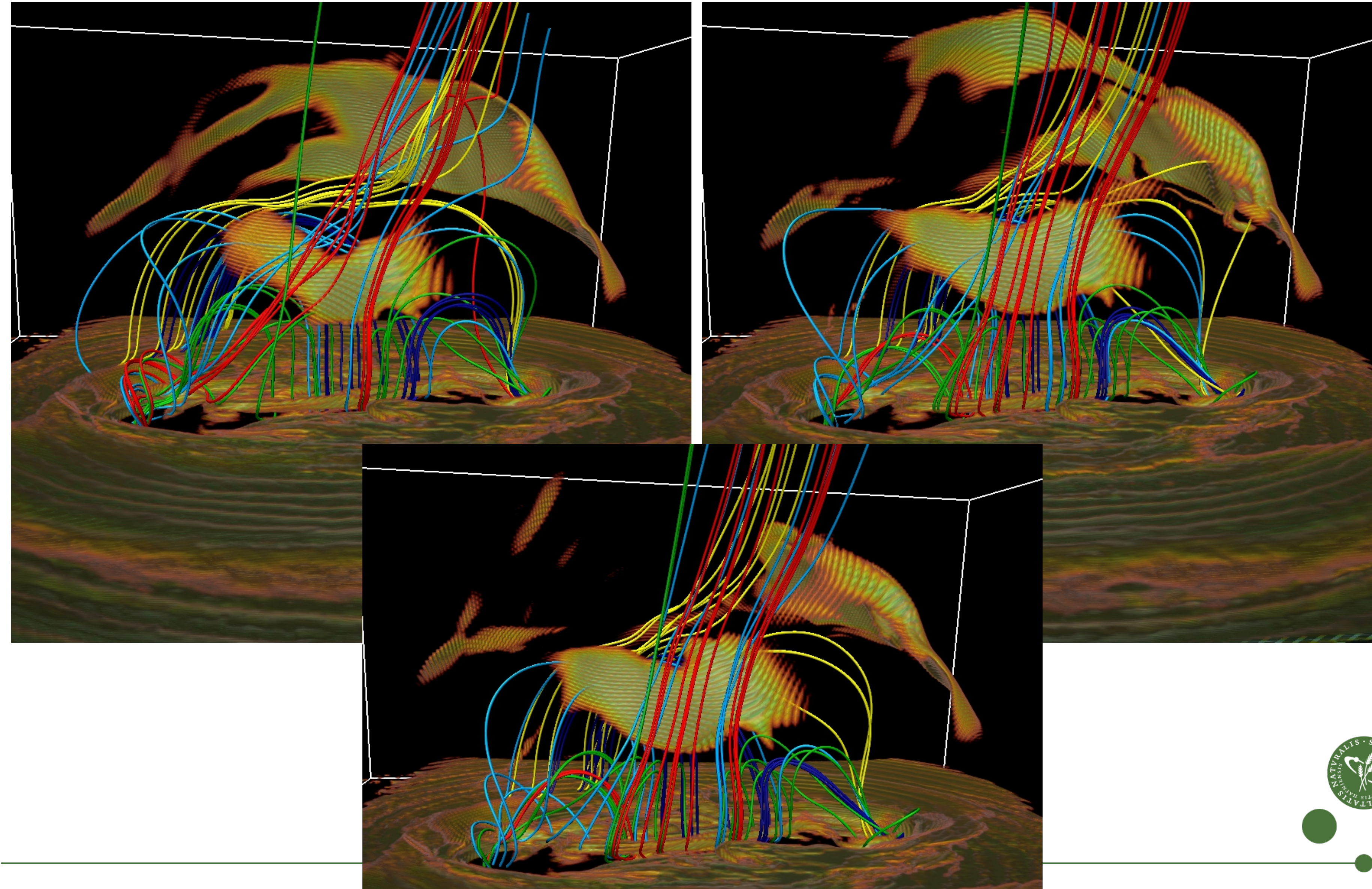
Yan Xu et al 2010

Creates a twisted flux rope above the rec site
Near potential loop system below the rec site
Increases the twist of the remaining loop system

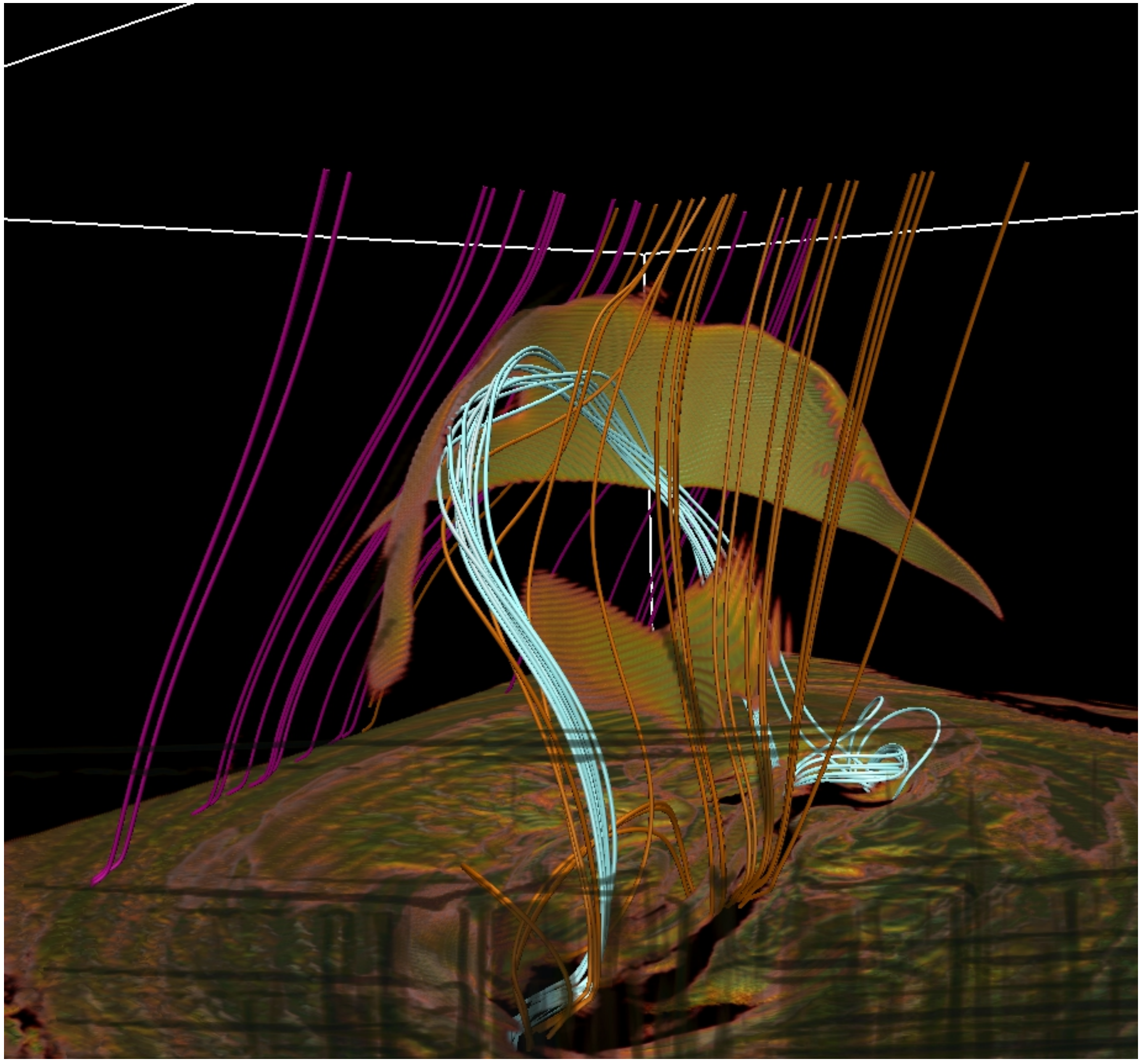
# Eruption 1: Field line structures - Domains



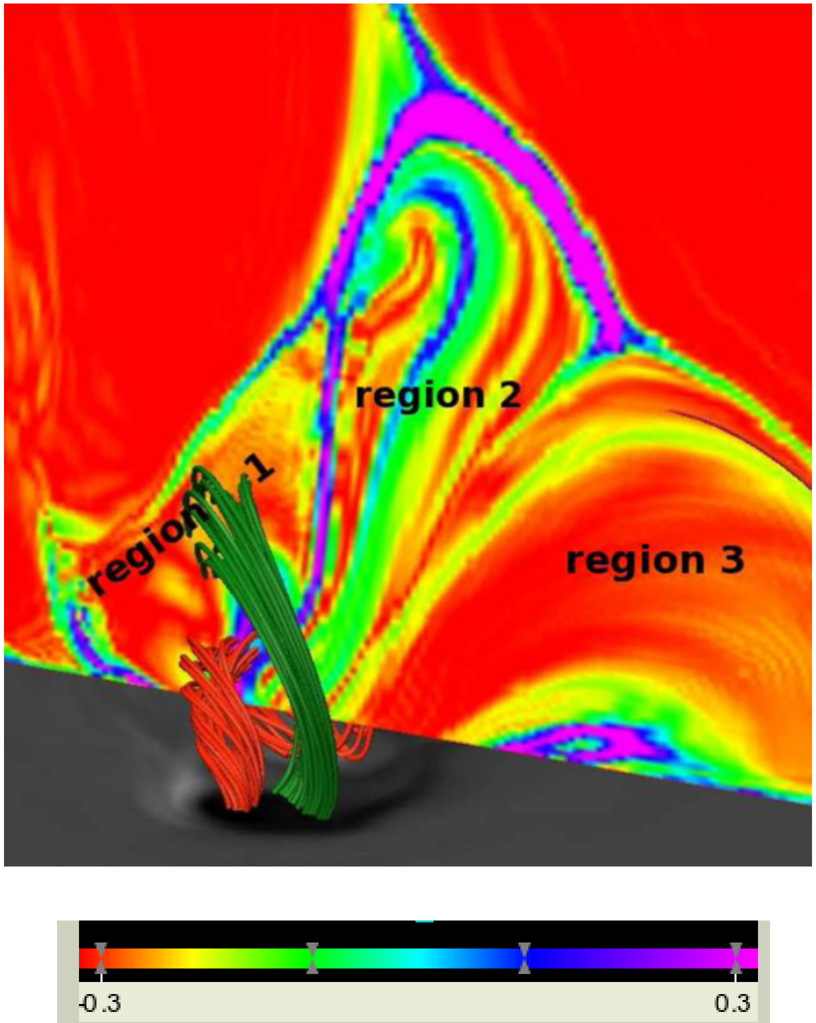
# Tether cutting evolution



# Destruction of the rising flux robe



# Eruption 2: ”Domain decomposition”




Located above the negative polarity flux concentration

Loop system partly grown by eruption 1

Region 1: origin of 2nd eruption
Region 2: perturbed flux after 1st eruption
Region 3: hot loop system after the steady state jet phase

|J|/|B| surface

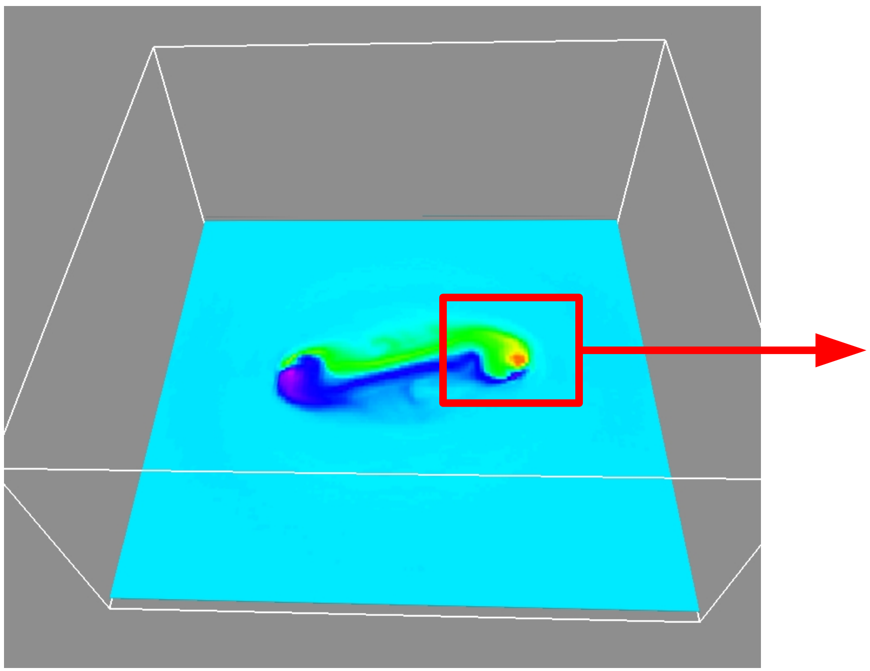
Flux into the area from above
Twisted rope low down (red)

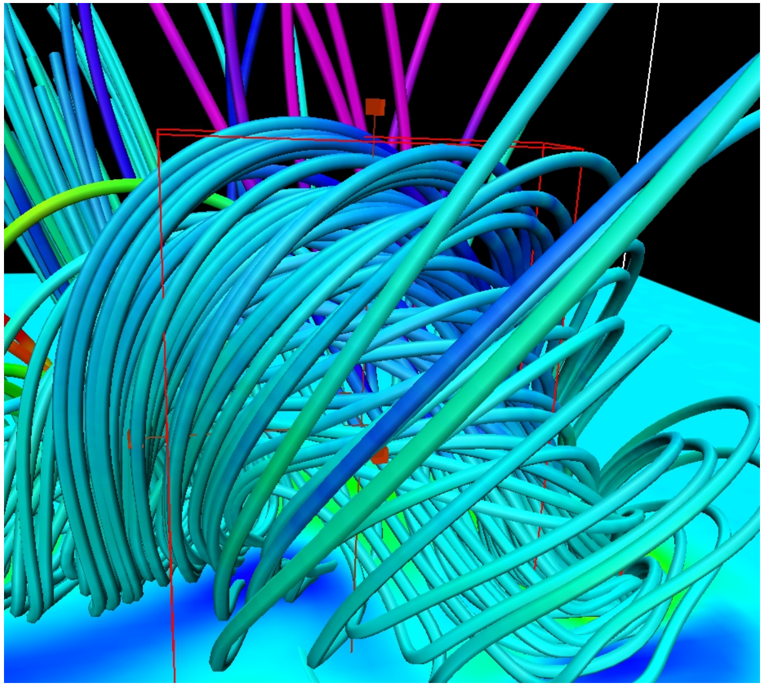
Magnetogram at the base

Region closely related to the negative flux concentration

# Eruption 2: ”initial configuration”

- Structure of the magnetic field of the erupting region

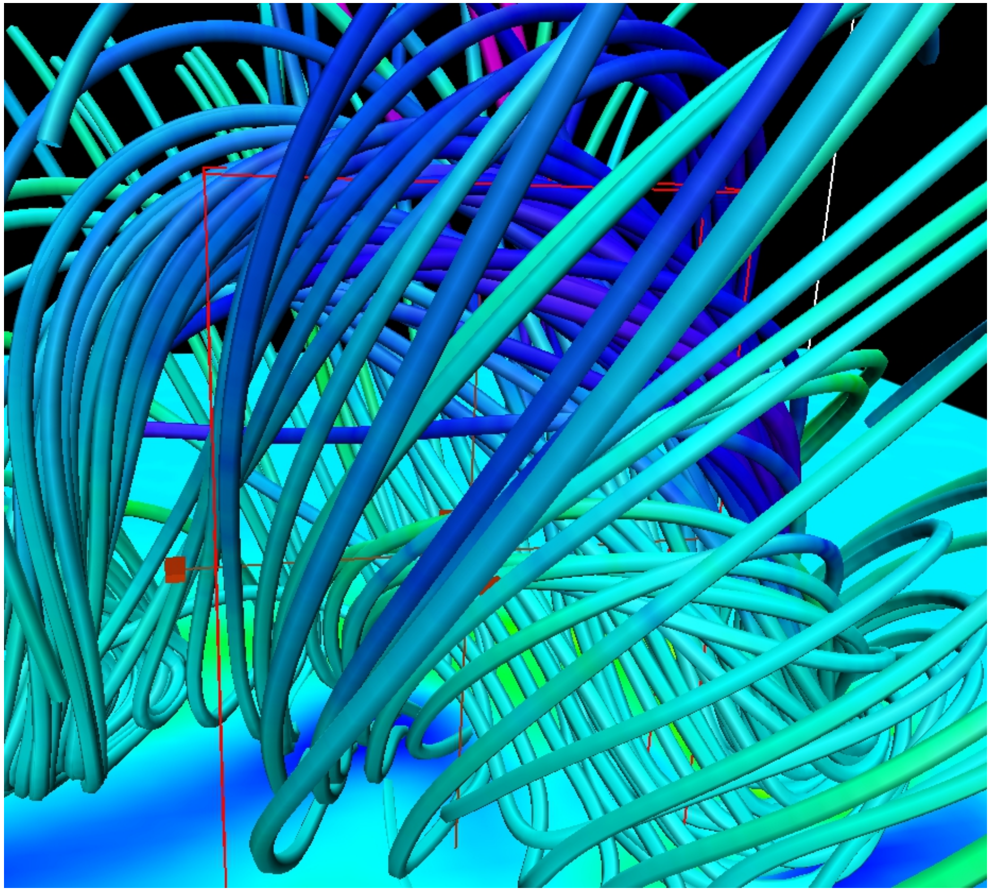


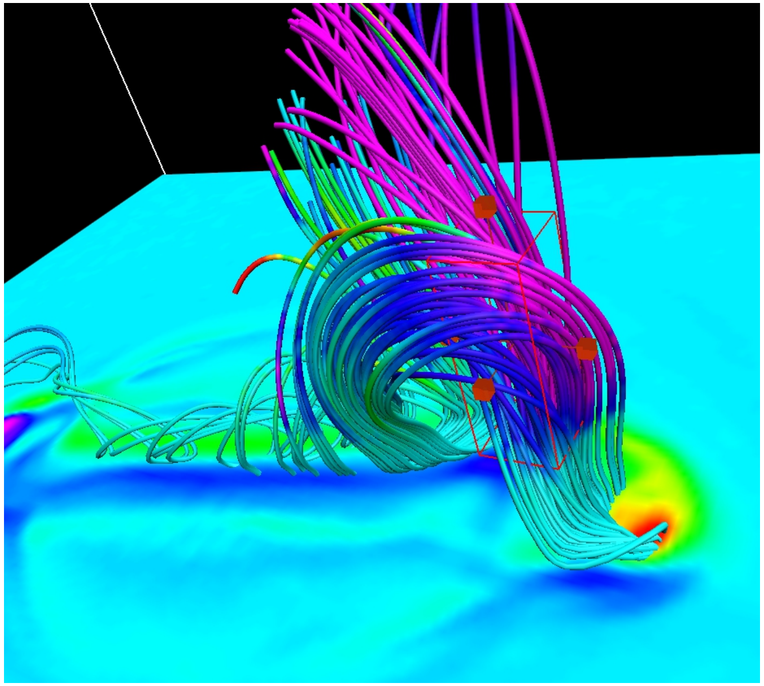


Magnetogram

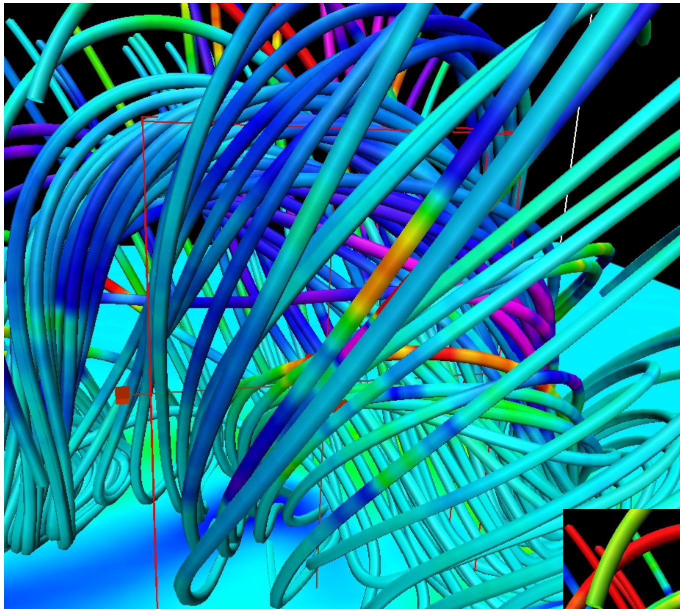

Field lines traced from within
the red box
Coloured with vertical flow speed

# Eruption 2: Vertical flow speed at a later time

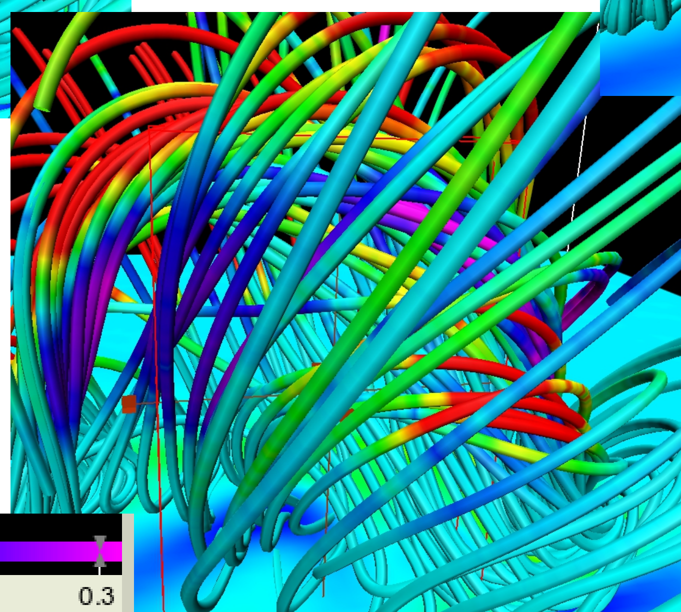




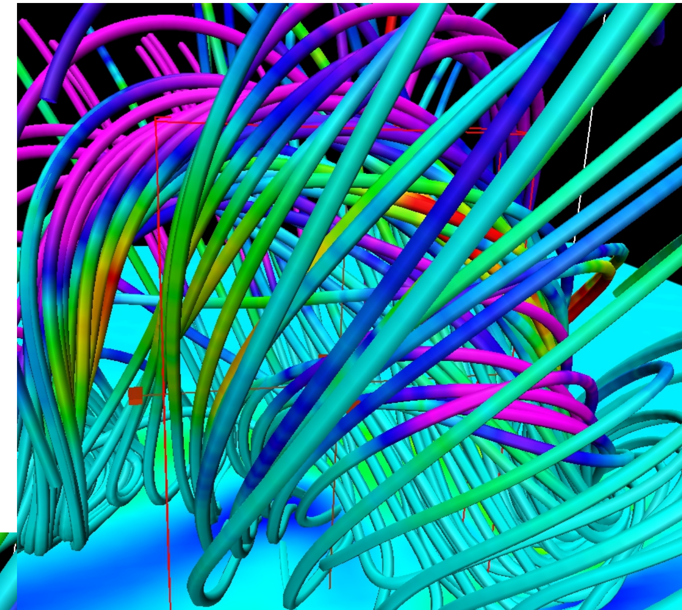
# Eruption 2: Acceleration terms



Total acceleration



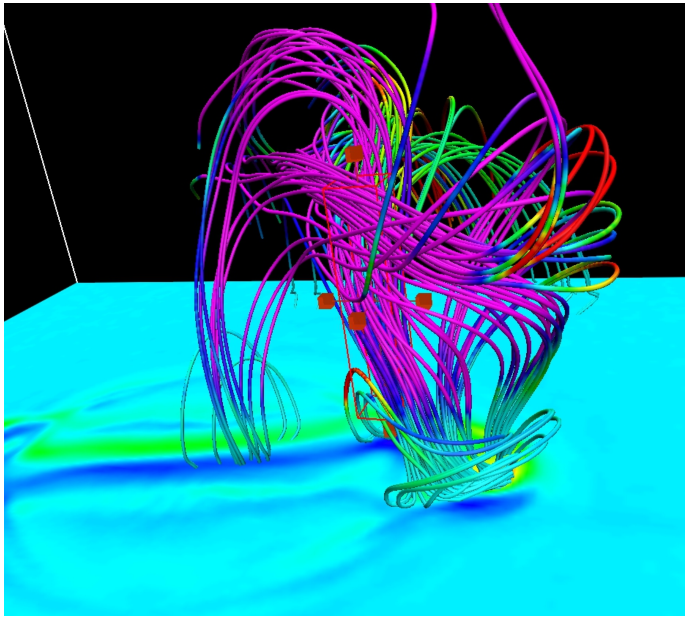
Lorentz force

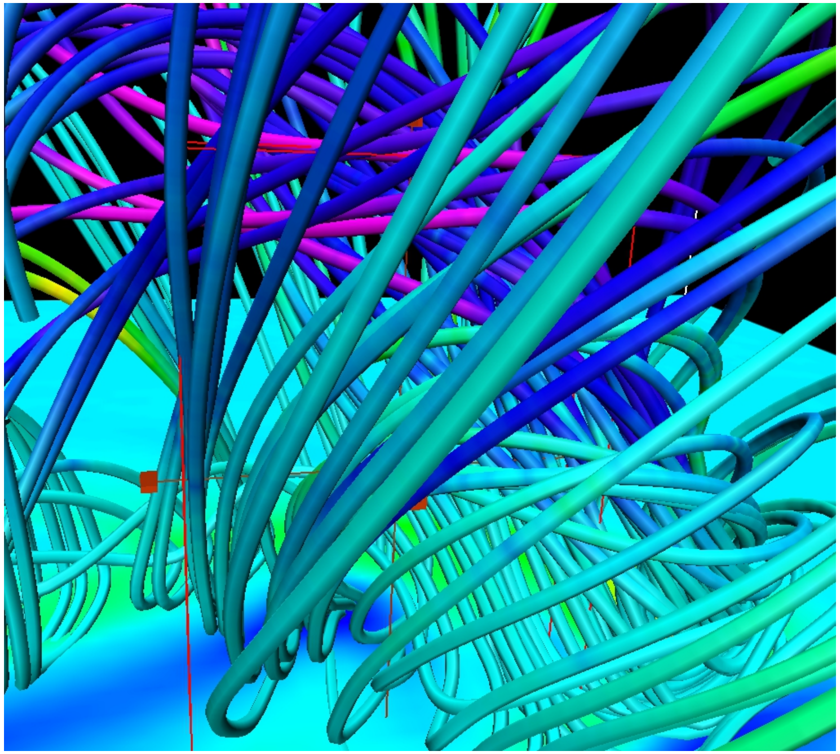


Pressure gradient

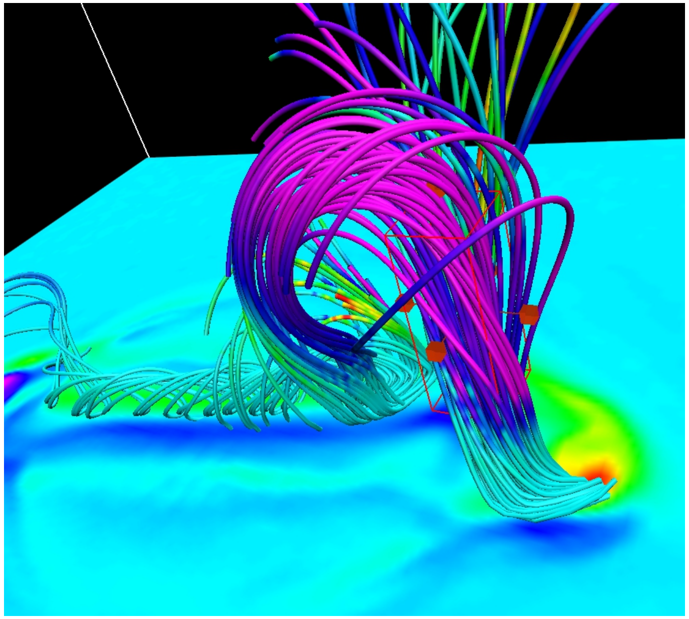
Corrected for the hydrostatic contribution

# Eruption 2: Onset of the eruption





Flow speeds

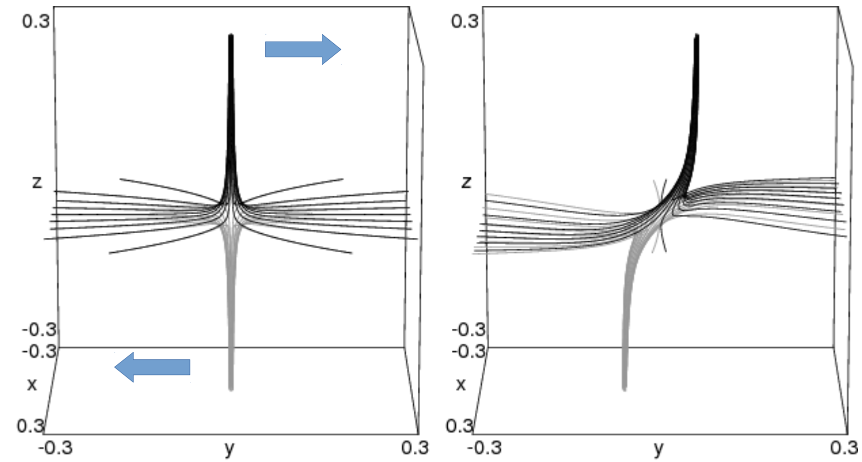



# Shear driven collapse of a 2D null

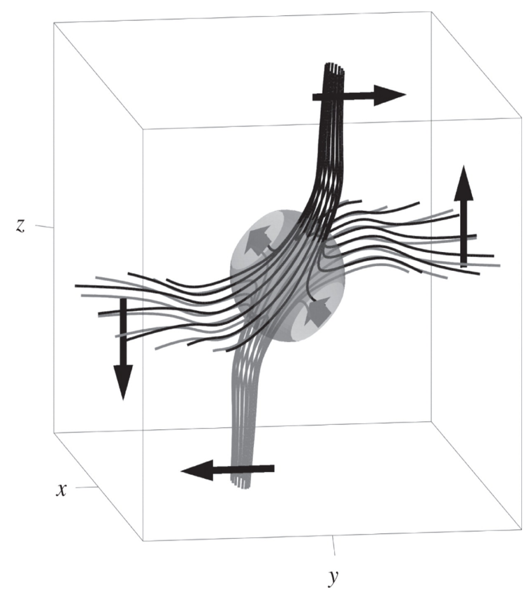
Two potential ways to perturb a single null

- Shear motion  (the most generic)
  - Across the spine or fan plane

- Rotation
  - Spine or fan plane



(a) (b)



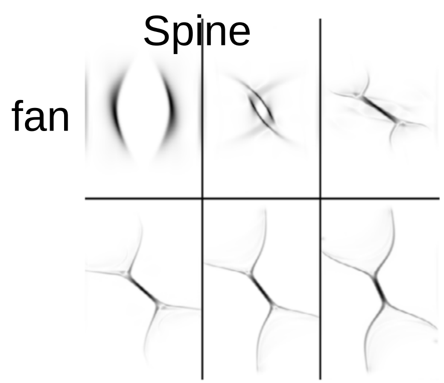
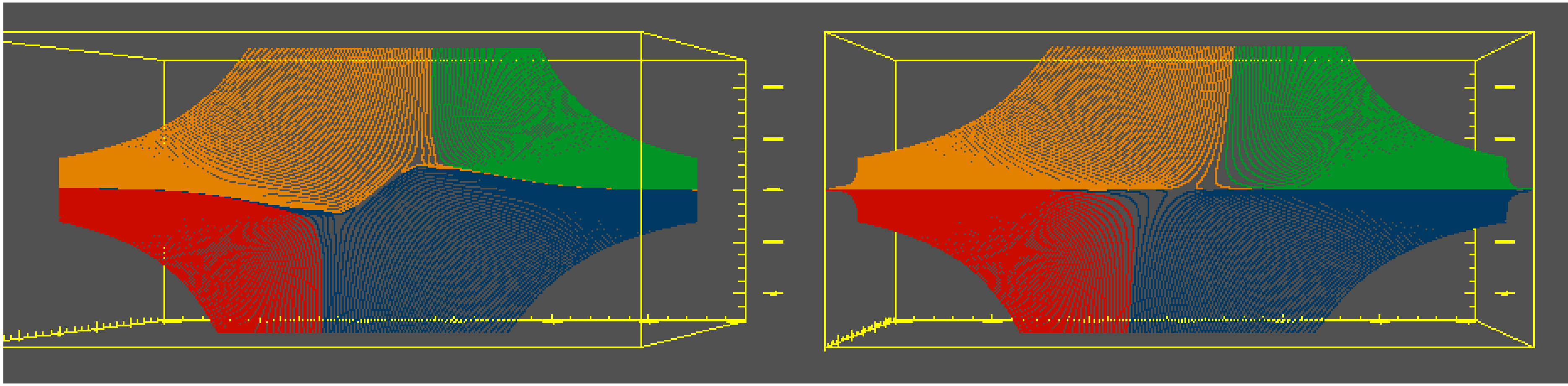



**Fig. 4.** Current amplitude at a number of characteristic instances in the dynamical evolution. The individual frames are scaled to their local dynamical range to enhance the visual appearance. The images represent the $z = 0$ plane for run "C3" at times $t = (0.4, 1.0, 2.2, 4.4, 9.2, 19.0)$.


(c)

# Symmetric null Continued driving

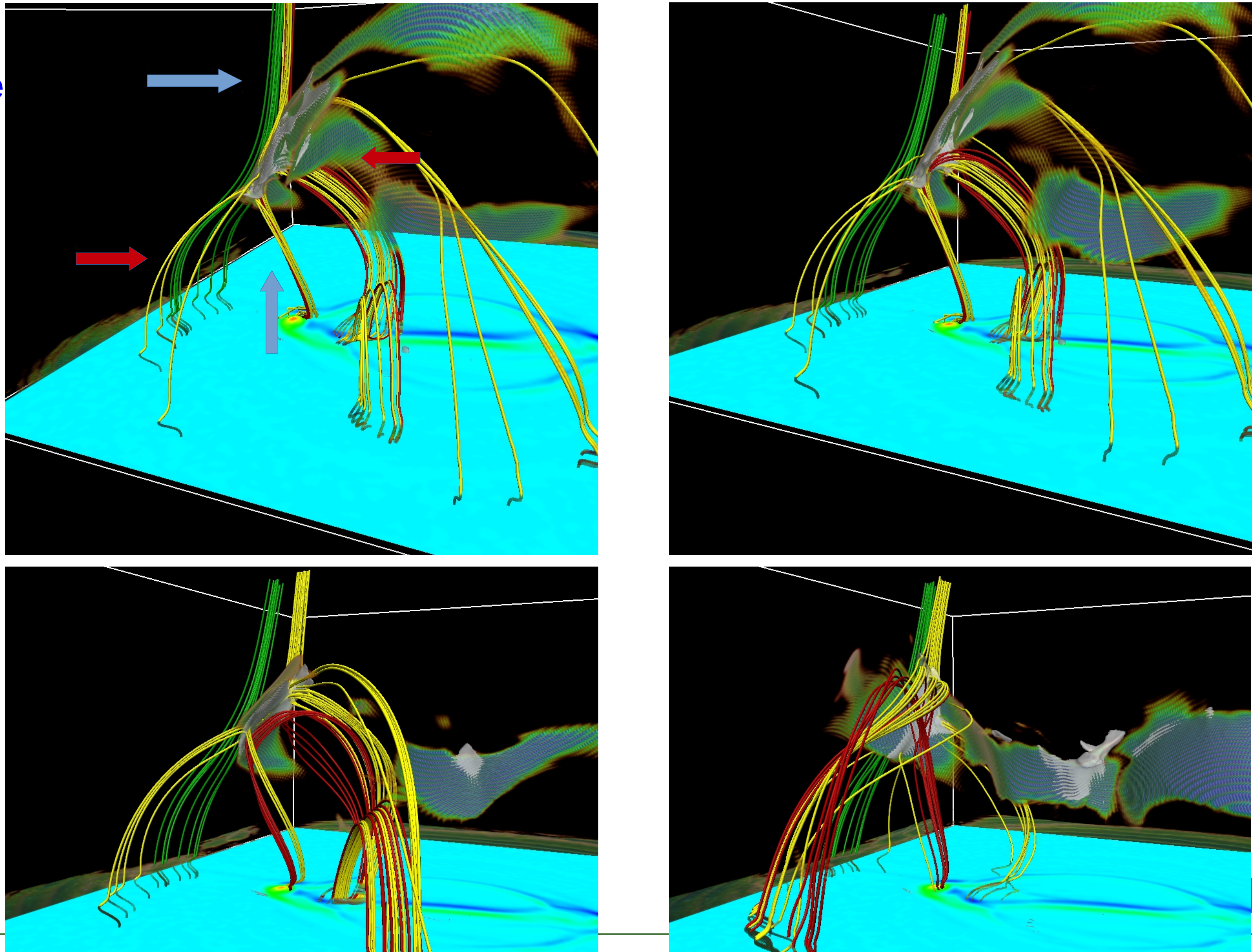


Null region seen from the side
Different distance from the symmetry line
Four colours, two above/below fan plane

# Topology evolution of the null point

Spine

Fan



# Summary

- Simple initial magnetic model
- Complicated dynamical evolution
- Several reconnection scenarios
    - No null reconnection
        - Tether cutting of various types of magnetic field lines
    - Null reconnection
        - Spine – fan reconnection type
            - Bifurcation of the single null when dynamically stressed
            - Complicated magnetic field region
- Takes place on a dynamical time scale
    - Fast magnetic reconnection