An MHD Model of a Solar Eruption Starting from NLFFF Initial Conditions

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For more details see:

Observations and Magnetic Field Modeling of the Flare/coronal Mass Ejection Event on 2010 April 8; Su, Y., Surges, V., van Ballegooijen & DeLuca, E.E., 2011 ApJ 734, 53.

Magnetohydrodynamic Modeling of the Solar Eruption on 2010 April 8; Kliem, B., Su, Y., van Ballegooijen, A. & DeLuca, E.E. 2013 ApJ in Press (arXiv:1304.6981v2)

Intent

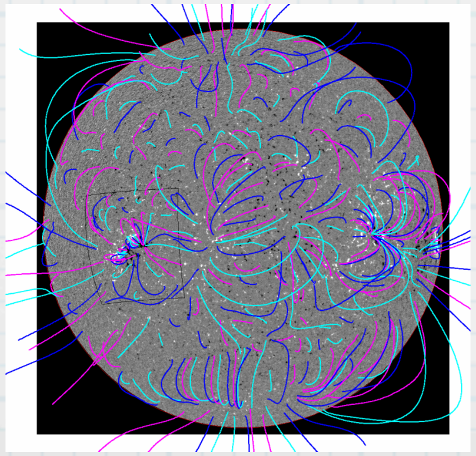
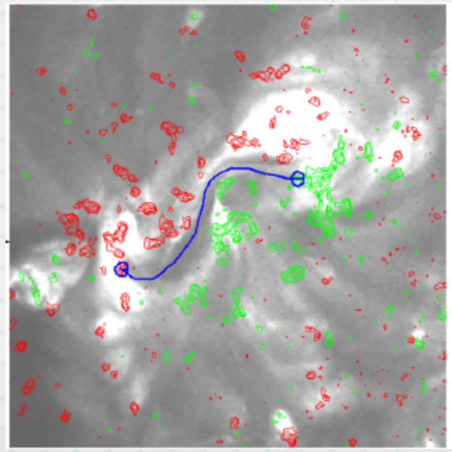
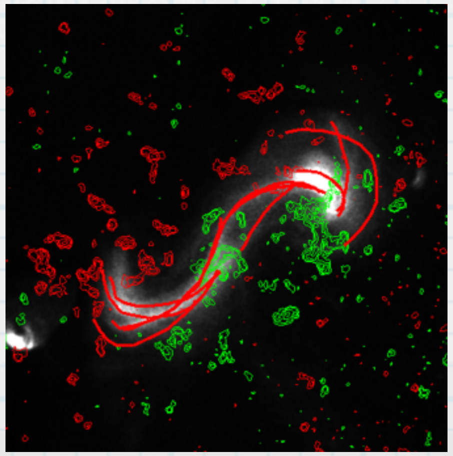
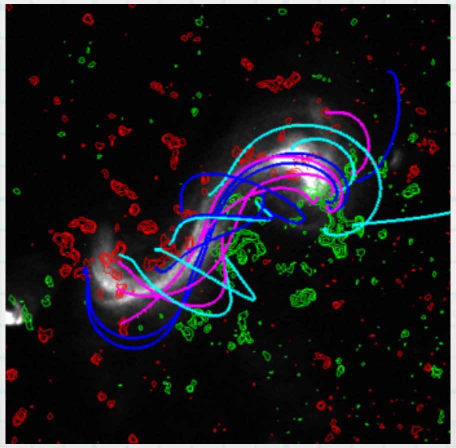
* Demonstrate that well constrained non-linear force free magnetic field models can be used as initial conditions for zero-beta MHD code.
* Use the MHD evolution to understand physical processes that result in instability

Why Bother

* Data Driven MHD Codes are challenging. Is there a way to initiate an MHD simulation with a realistic solar condition?
* Can we forward model AR evolution without a global simulation?

Intro to Flux Insertion NLFFF Models

* Assume that the only important NLFFF fields are associated with the flux rope in the active region. Essentially, we produce the simplest NLFFF structure that is consistent with the observations.
* See Savcheva S4-P-15 for a discussion of the sigmoid catalogue, statistics and evolution
* Coronal Modeling System flux insertion magneto-frictional code (van Ballegoojien, 2004)
    * Start with a global potential field
    * Identify a flux rope path: Length, direction of field.
    * Insert a flux rope, parameters: Axial flux, Poloidal flux, width
    * Relax the solution
    * Compare solution field lines with observed coronal features
    * Modify parameters and repeat until consistent solution is found

Kliem & Torok MHD Code

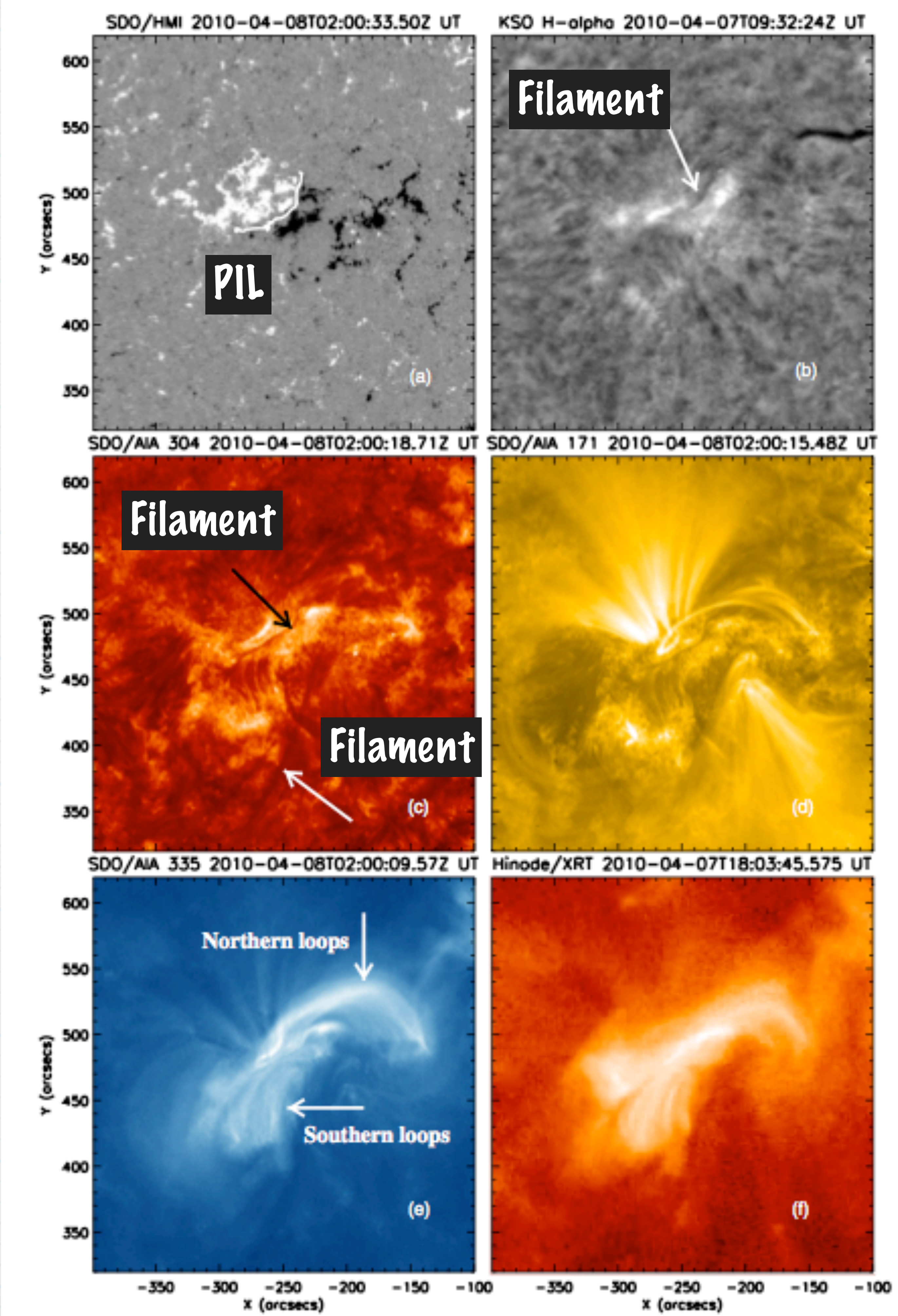
* Zero-Beta approximation: uncouples energy equation from dynamics.
* Modified two-step Lax-Wendroff scheme with adjustable numerical diffusivity (Torok & Kliem 2003)
* Cartesian geometry with non-constant grid spacing

Process

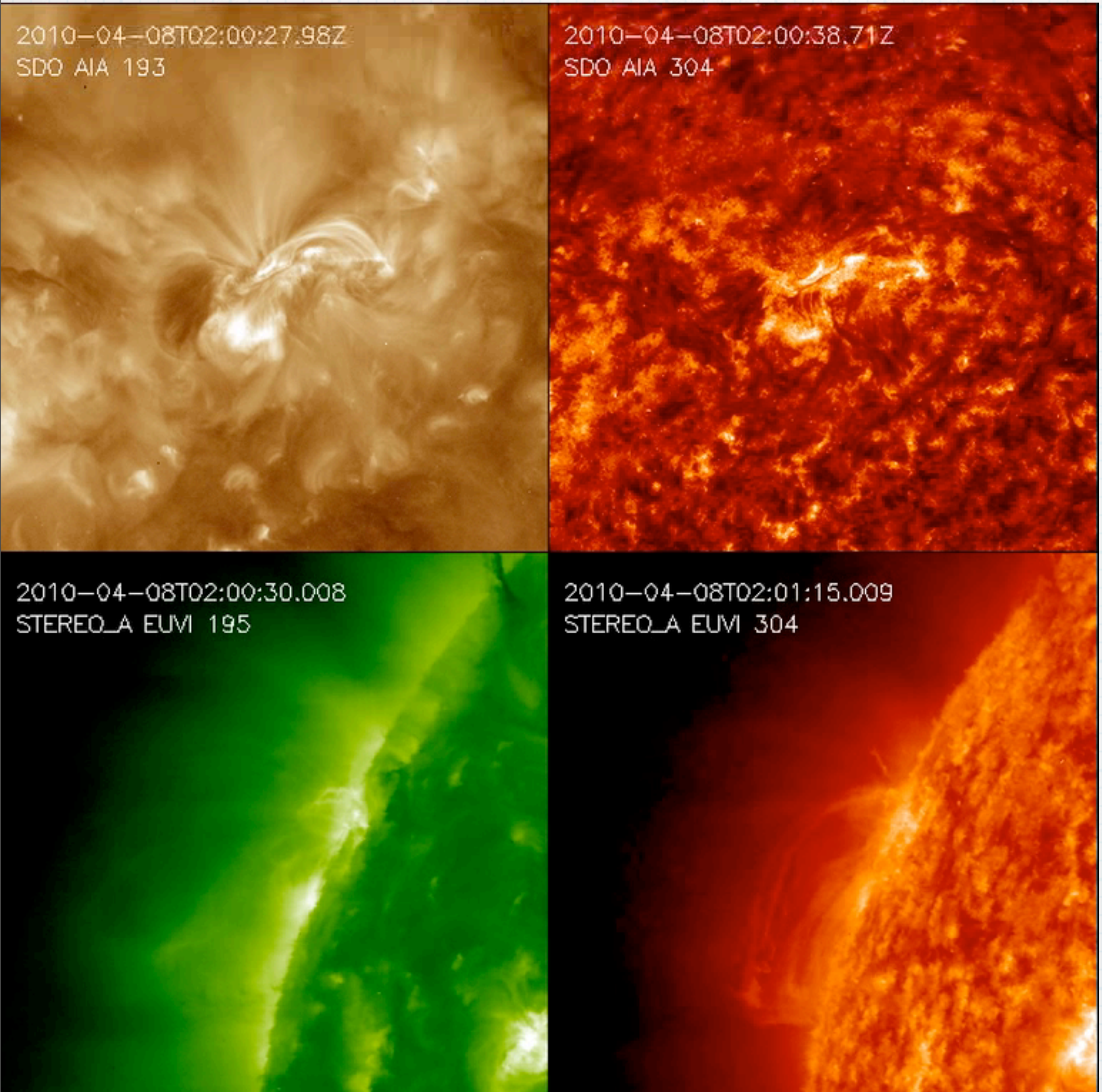
* Choose an AR that is well modeled by our NLFFF flux insertion models (Su et al 2011)
    * Produce a set of three models that are stable, marginally stable and unstable
* Save the NLFFF solutions in a form that is acceptable for the MHD code.
* Evolve the MHD code for each case and determine the evolution.

8-April-2010 2-ribbon B3.7 flare occurred in NOAA 11060

Pre-Flare Observations from AIA, XRT and KSO a

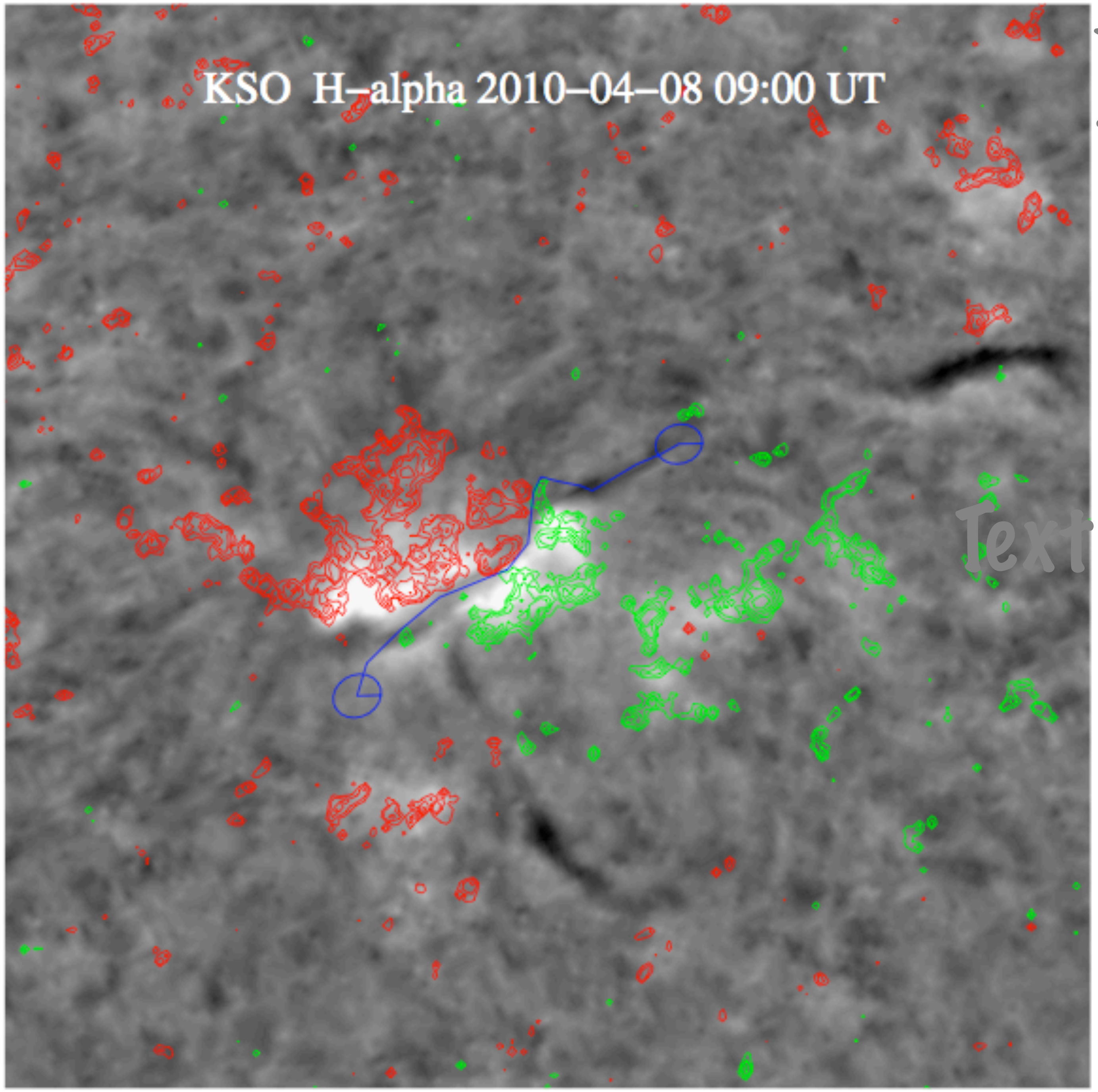


Su et al 2011



Flare & CME Seen by AIA and STEREO

Note southward direction of CME as seen in STEREO



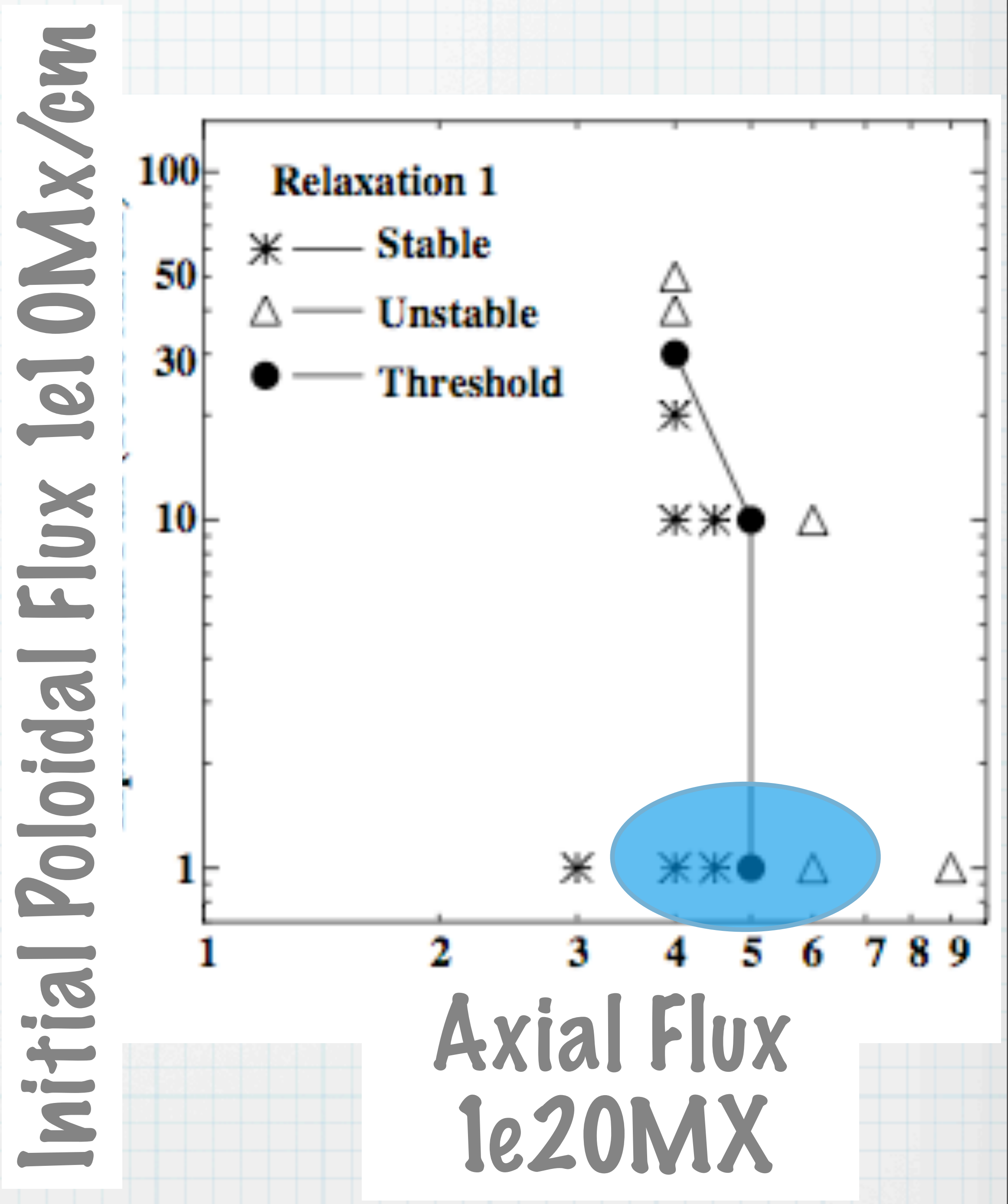
Flux rope path is determined from the magentogram and the location of the H-alpha filament

Su et al 2011 produced 14 different flux rope models. Compared them to the observed loops. Varying the poloidal and toriodal flux and the relaxation parameters

The stability boundary for the solutions was determined.

NLFFF Solutions/Initial Conditions

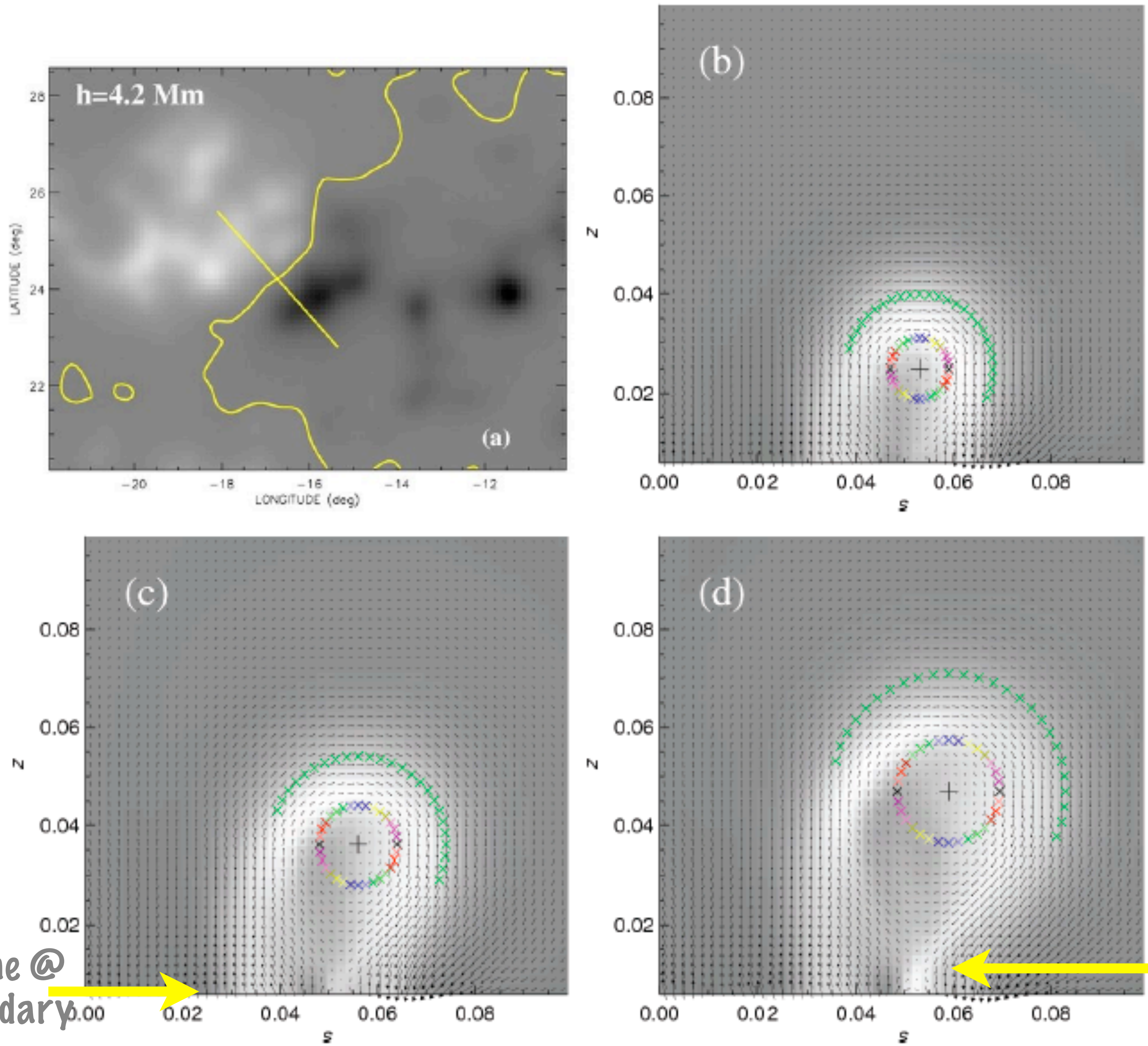
* The critical parameters for the NLFFF solutions are the axial and poloidal field and the relaxation parameters.
  * The axial flux largely controls the stability in our models.
  * For the MHD code we use 3 solutions that span the stability boundary, with axial fluxes of 4, 5, 6 e20 MX and poloidal flux of 1e10Mx/cm



Using the NLFFF Solutions: What is the MHD Evolution?

* We run the MHD code starting from each of the three NLFFF solutions: Stable, marginally stable and unstable.
* Each solution relaxes as MHD code accommodates the mapped NLFFF initial conditions.
* The stability boundary identified in the NLFFF simulations is reproduced by the MHD simulations.

Three NLFFF initial conditions



4e20MX,
1e10Mx/cm

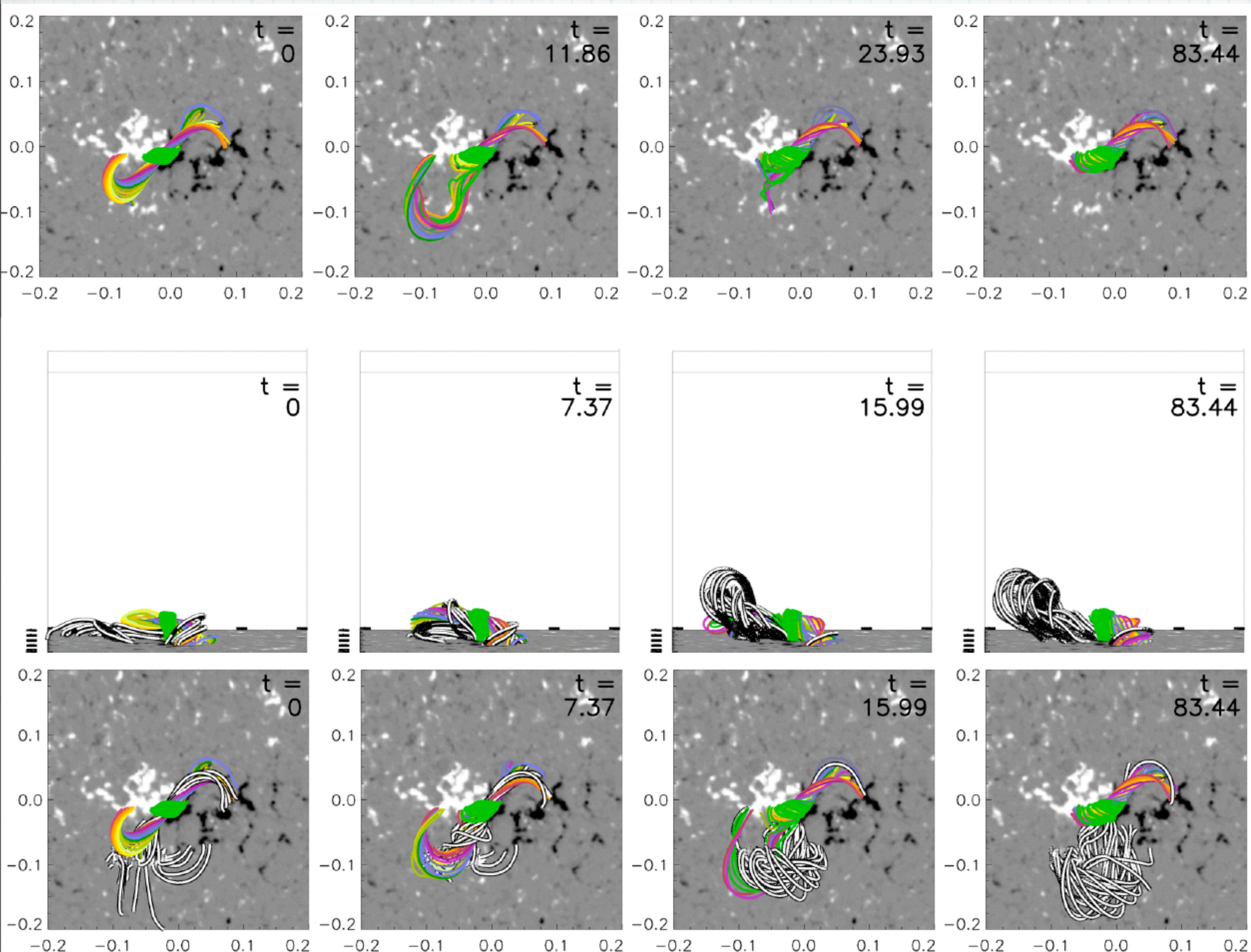
Field lines initial points are indicated by the x's

X-line @ Boundary

X-line above Boundary

5e20MX,
1e10Mx/cm

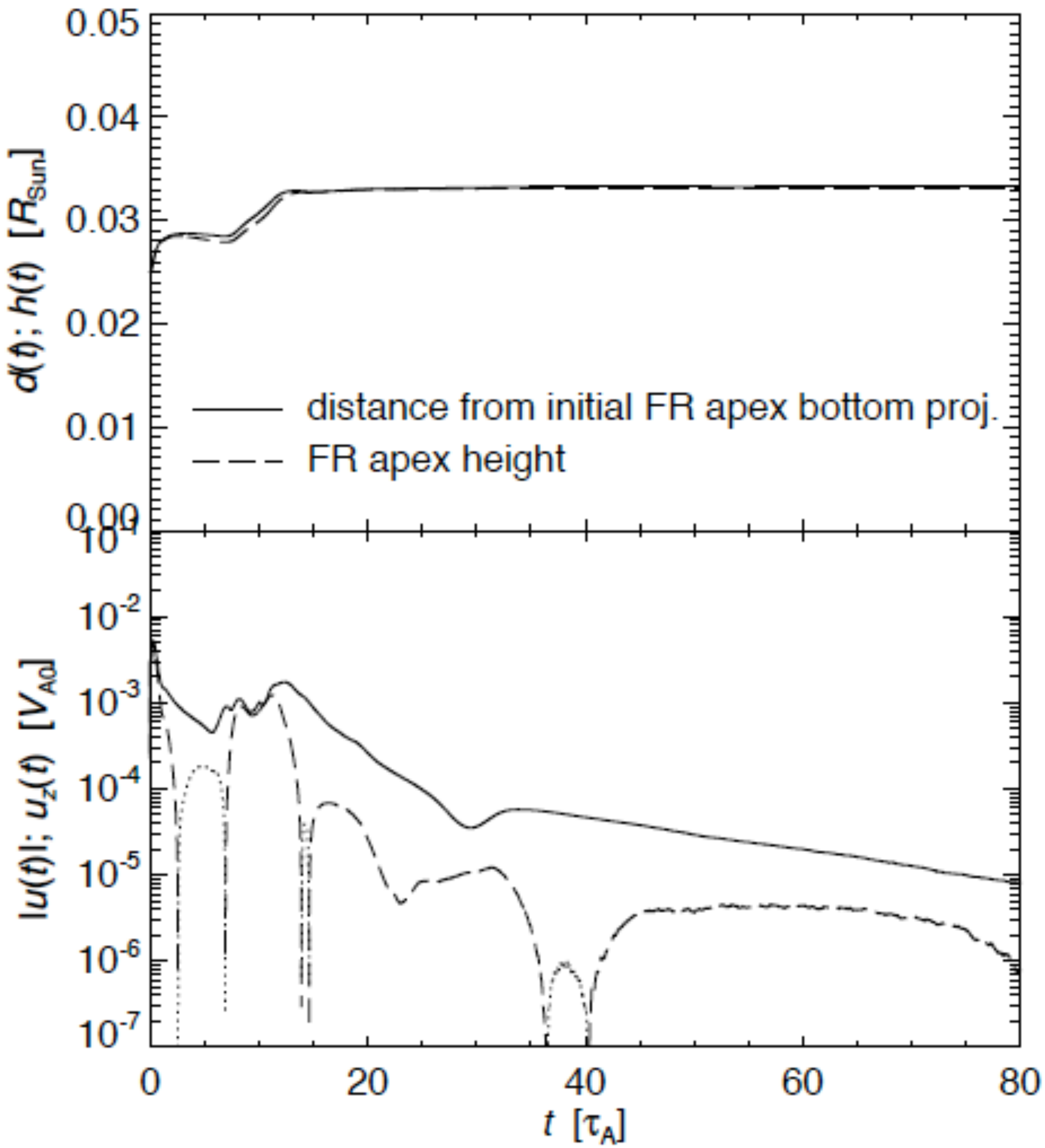
6e20MX,
1e10Mx/cm



A: 4e20MX Stable solution

Solution evolves as the NLFFF flux rope interacts with field lines South and East of the active region.

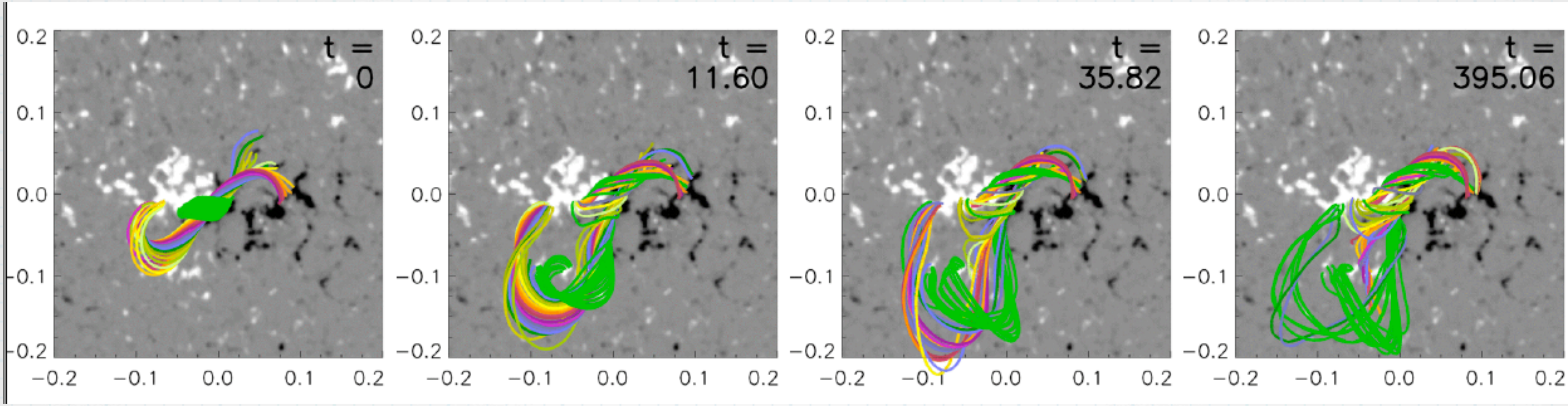
A new stable solution is found.

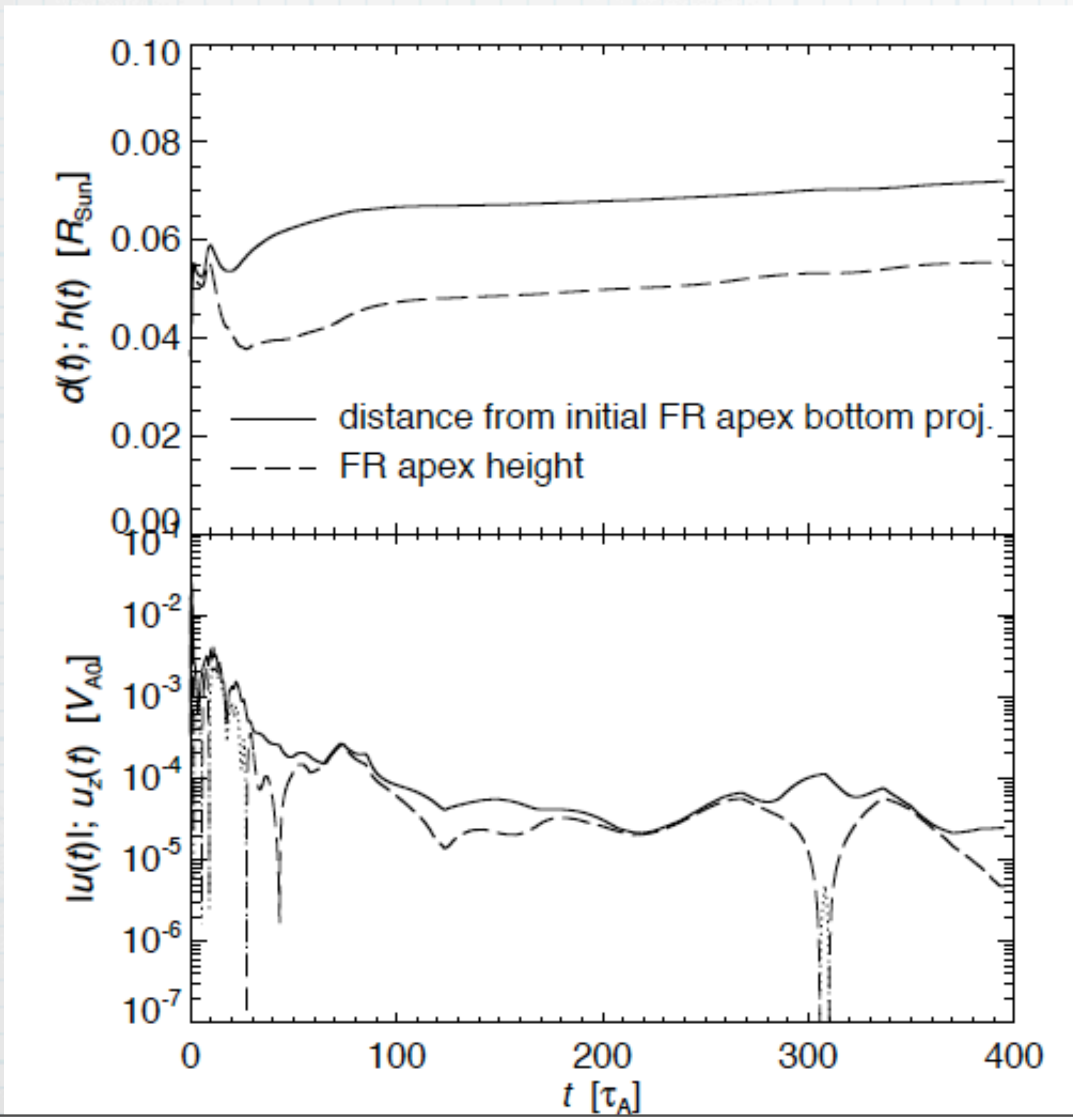


Height time plot and velocity time plot.

Initial jump is likely due to inconsistencies between the NLFFF code and the MHD code.

Secondary is probably due to incomplete relaxation in the NLFFF code.



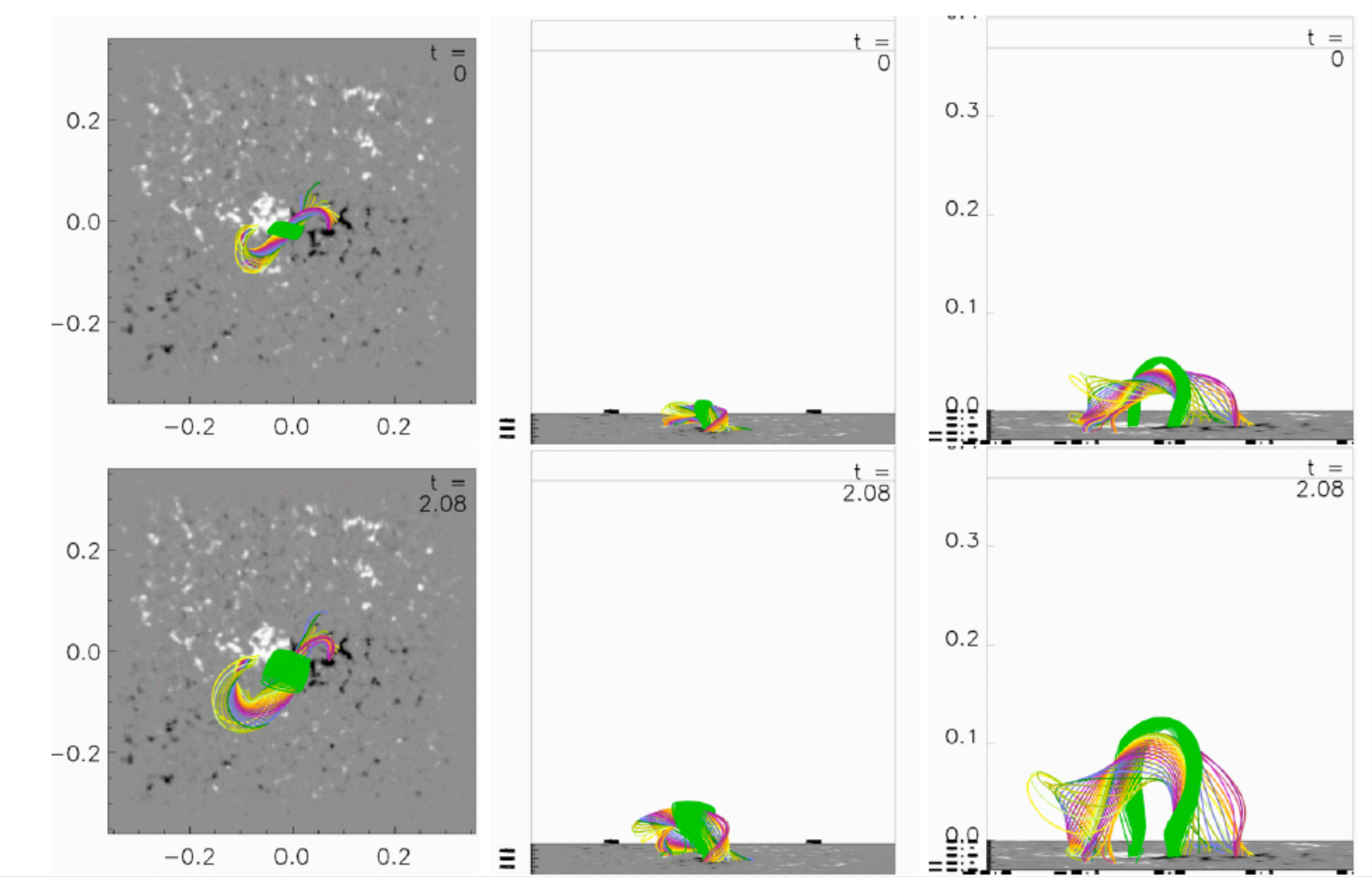


A: 5e20Mx Marginally Stable

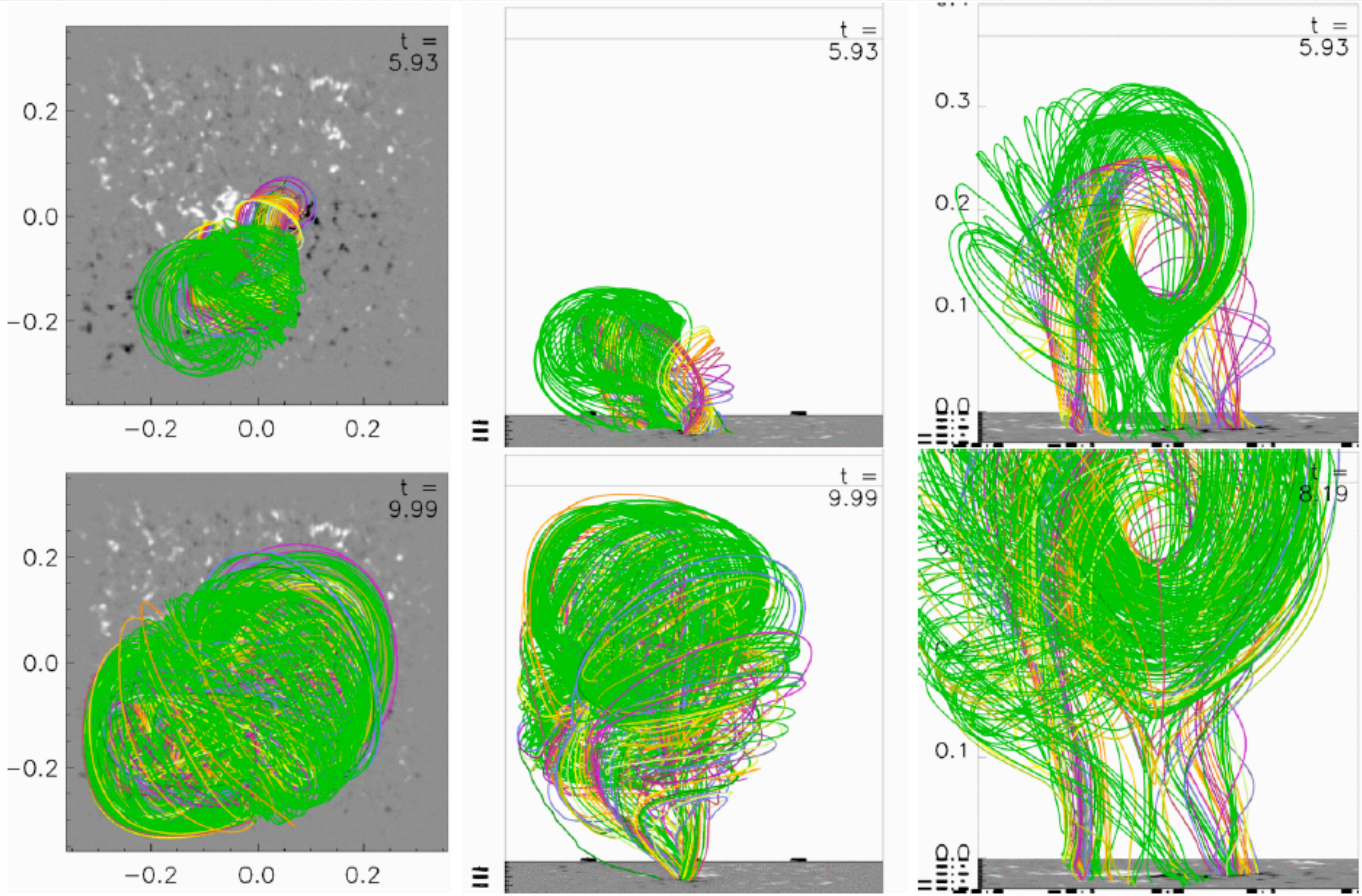
Flux rope evolves very slowly over 400 Alfvén crossing times

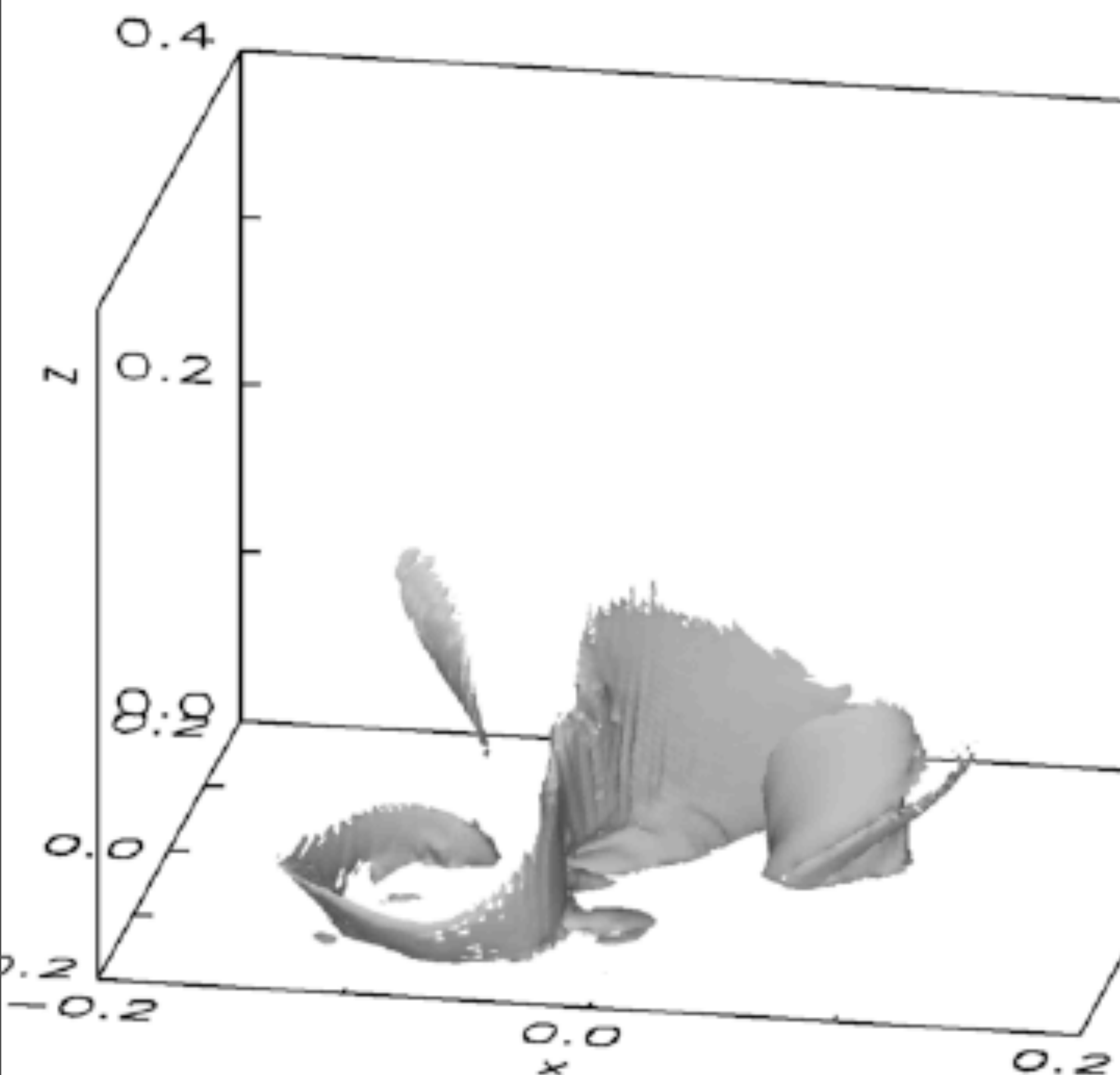
Can be driven to instability by driving reconnection across the PIL.

A:6e20Mx, Unstable Case

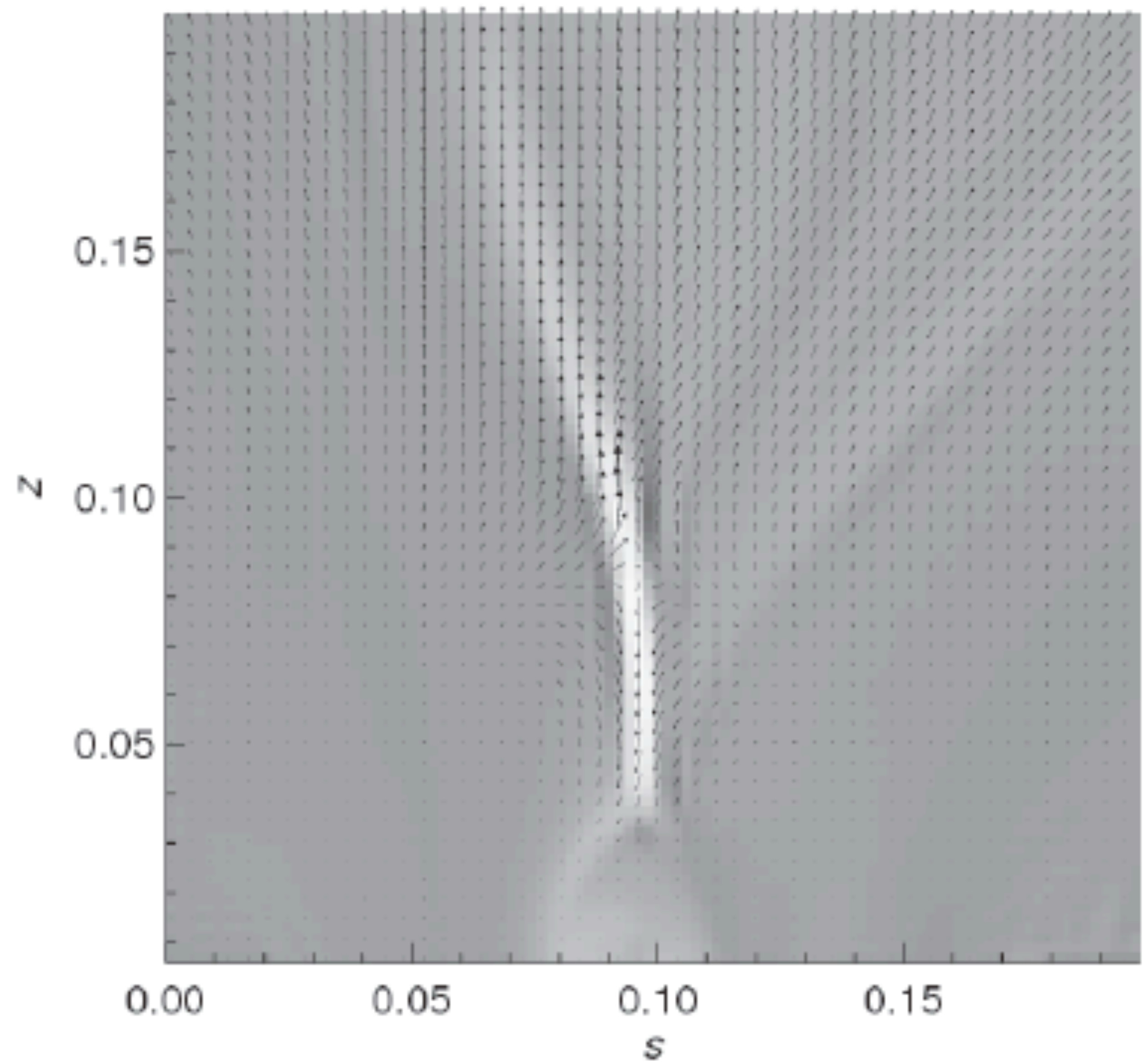


A:6e20Mx, Unstable Case



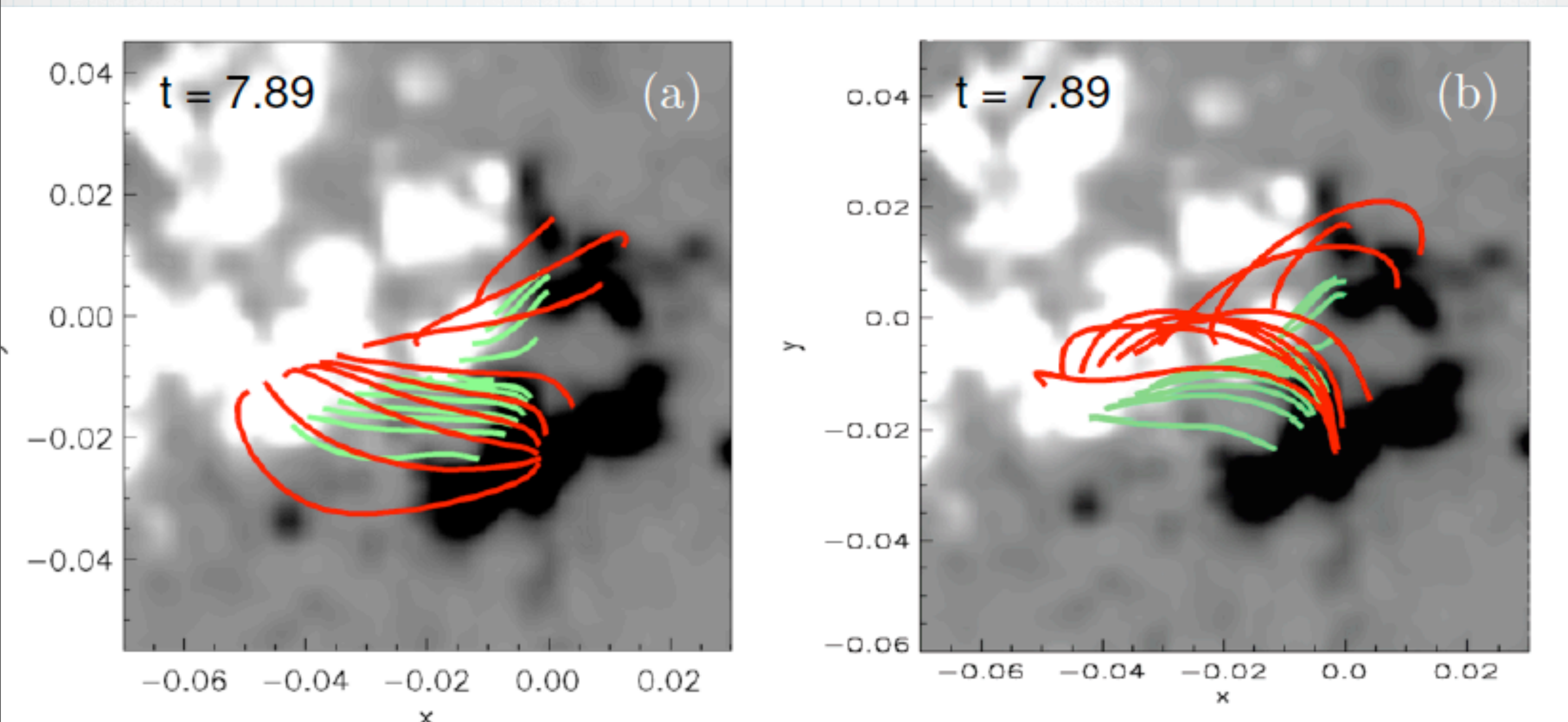


Current Sheet

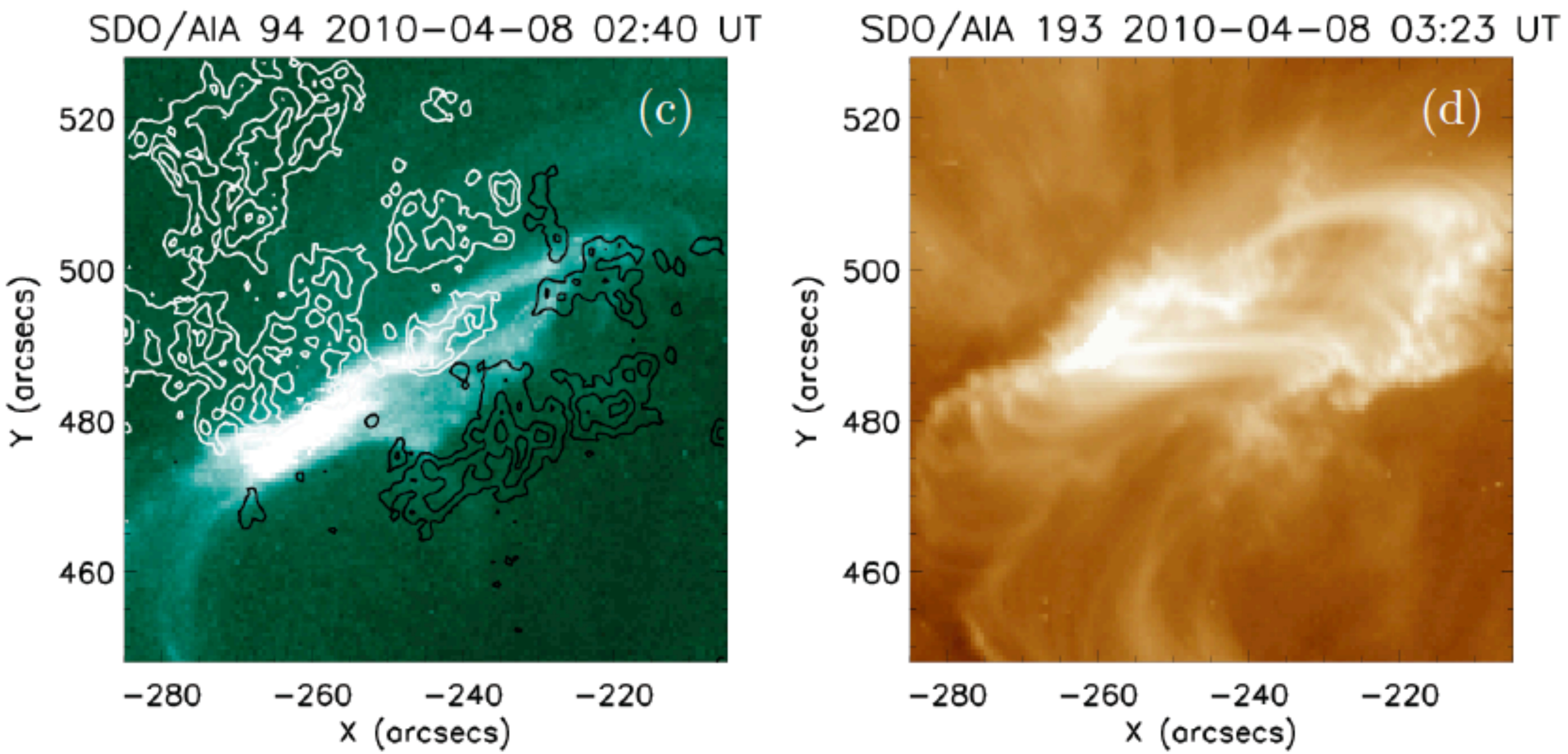


Current Cross Section

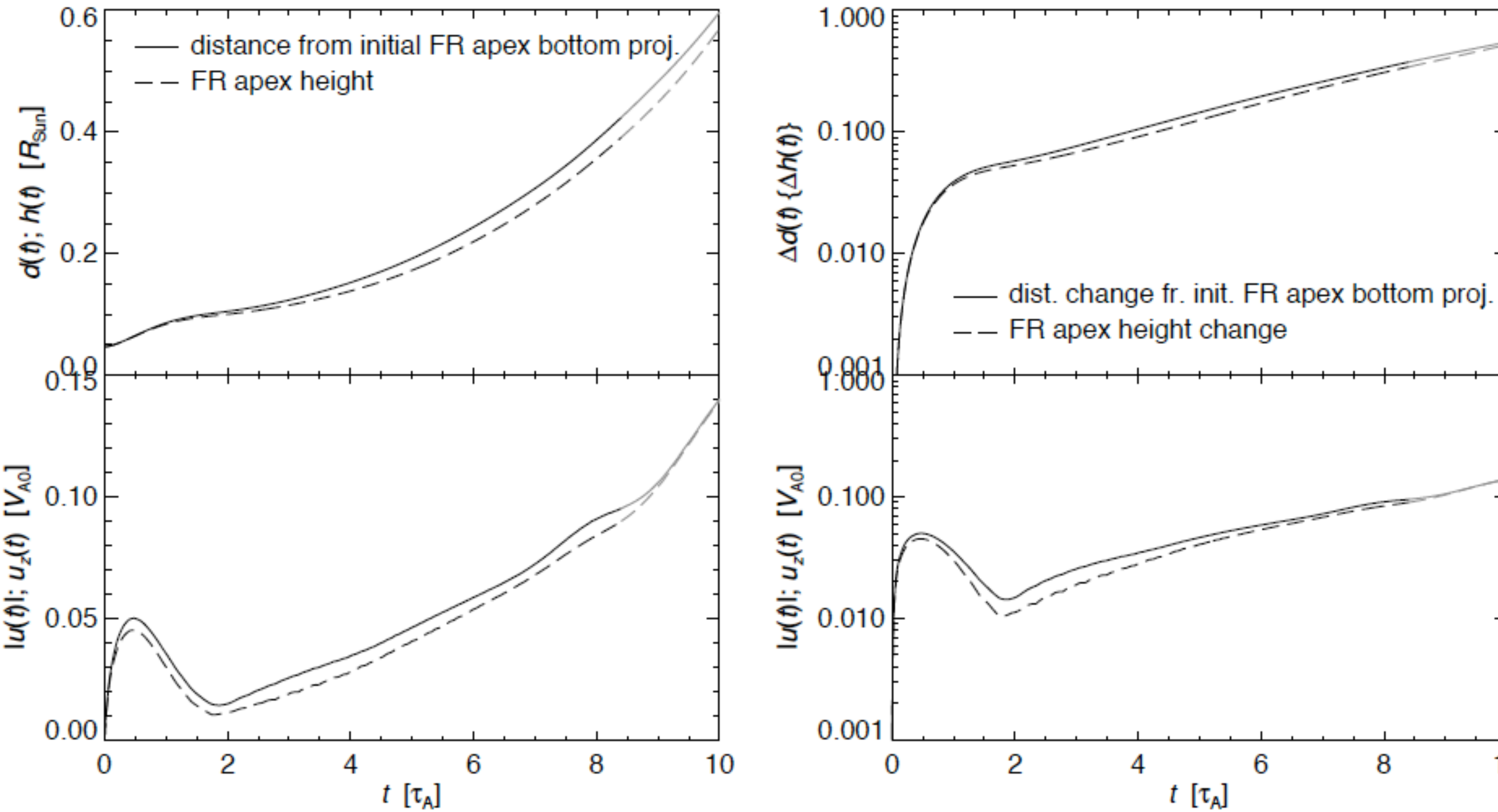
Reconnected Post Flare Loops



Reconnected Post Flare Loops

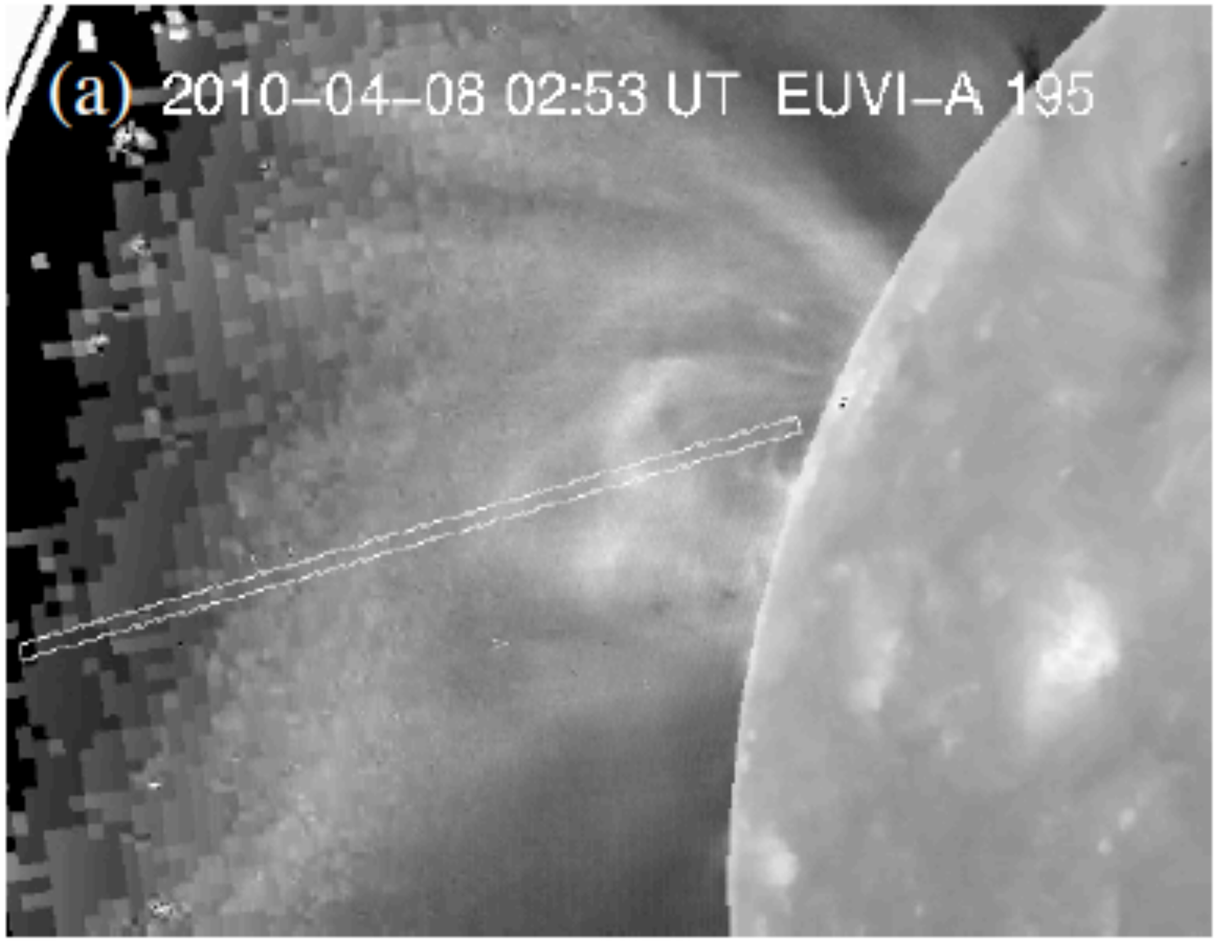


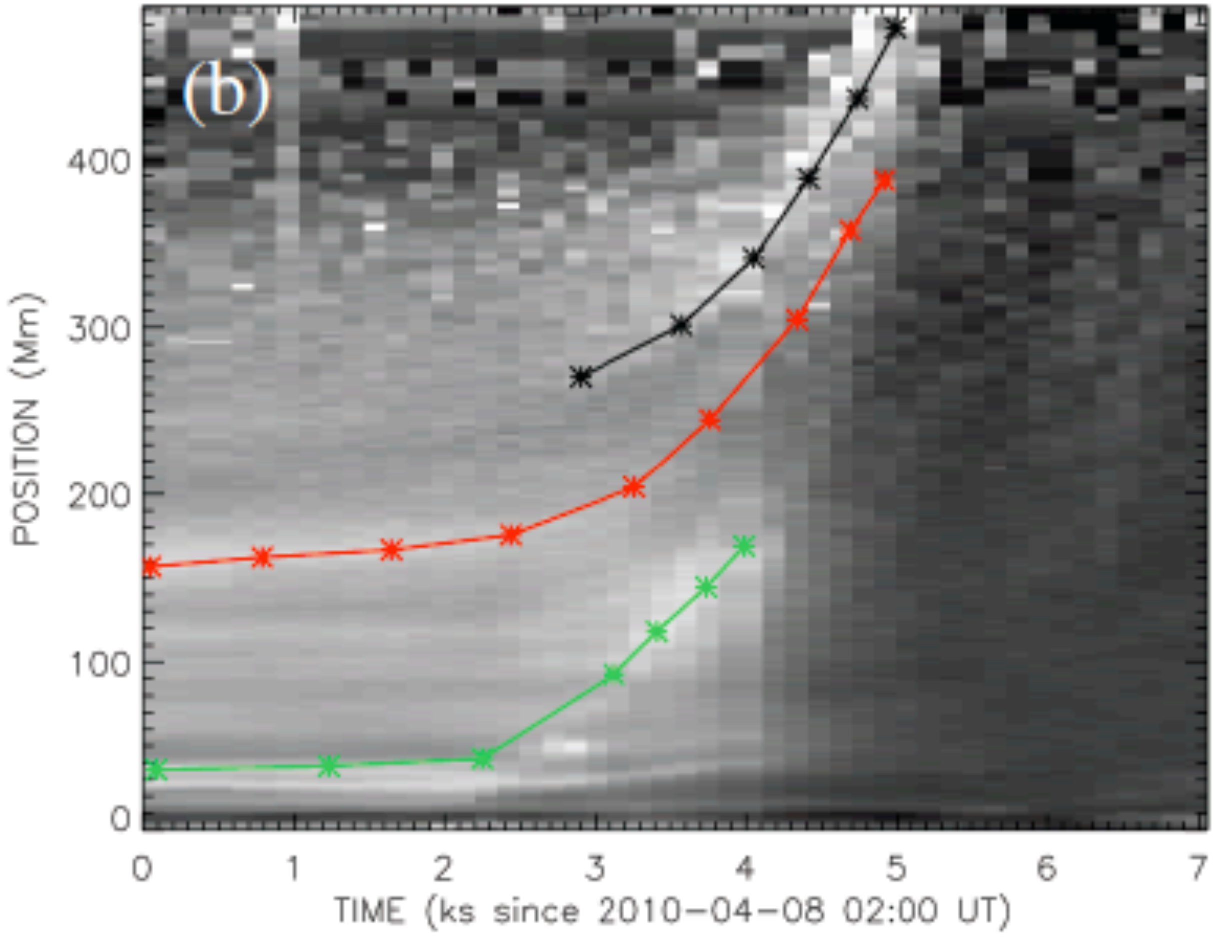
Rise of Flux Rope



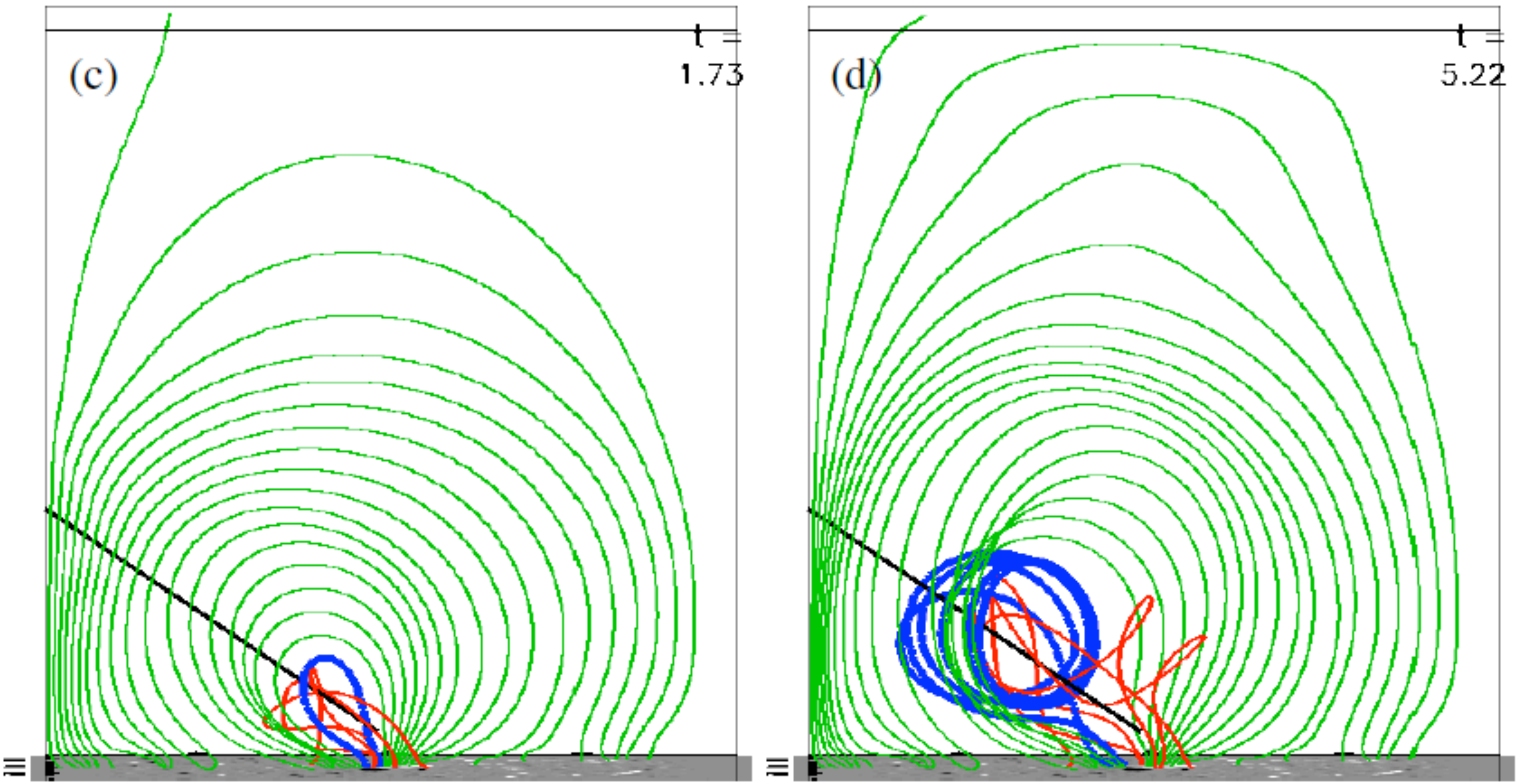
Linear　　　　　　　　Log

CME Direction and Height Time Profile



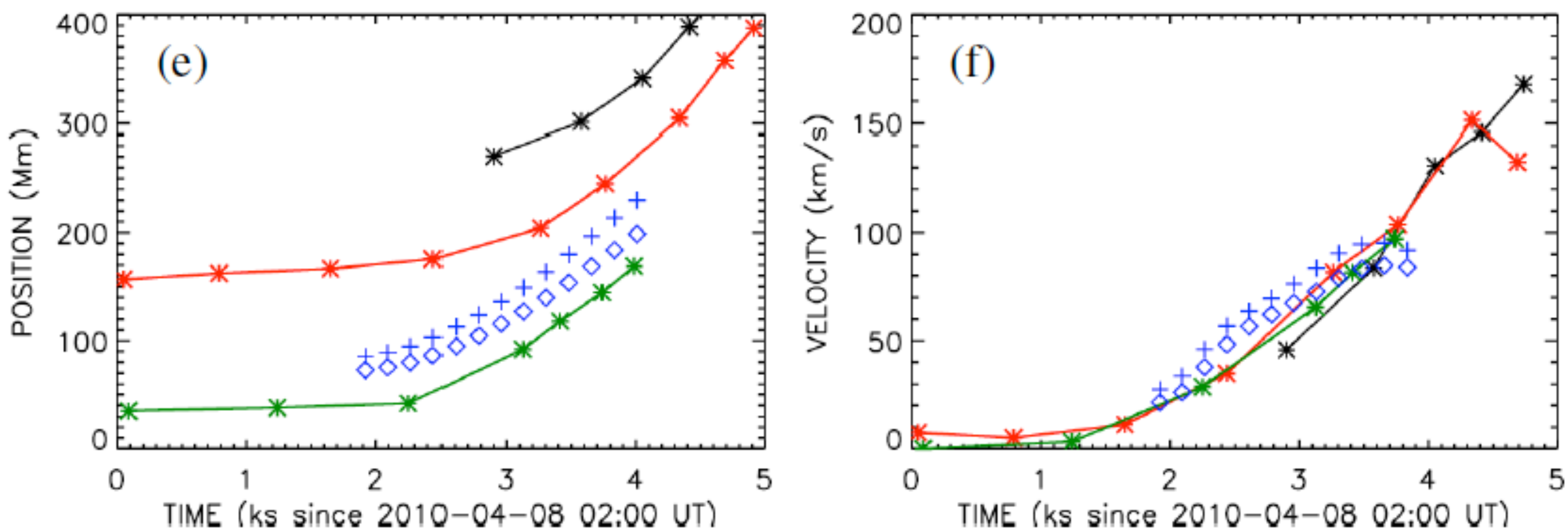


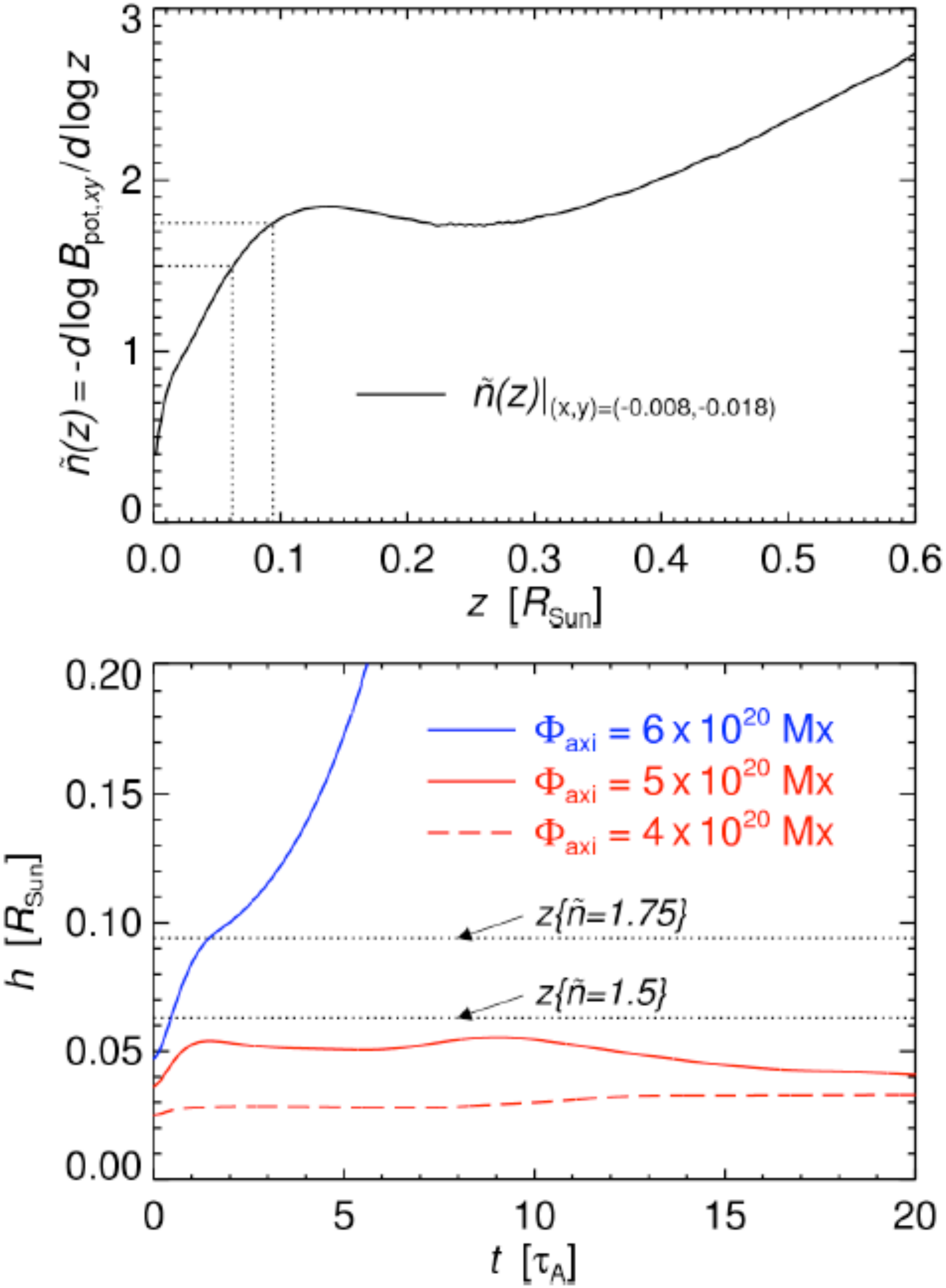
Flux Rope Eruption



Flux Rope Velocity and Acceleration

Blue points simulation data, green, red and black curves are from the observations. Scaling of the Alfvén speed to about 730km/s in the flux rope (density ~1-4e10cm^{-3}) yields good agreement.





van Tend & Kuperus (1978), Kliem & Török (2006), Démoulin & Aulanier (2010)

Onset of instability is consistent with the conditions of the Torus (lateral kink) instability.

Top Figure is the gradient of the overlying potential field as a function of height. Conditions for instability arise between the dotted lines

Bottom figure show the axis for the flux rope as a function of time. The heights of the instability conditions as shown.

Conclusions

* With some effort, NLFFF solutions can be used as an initial conditions for an MHD code.
* NLFFF solutions accurately identify the stability boundary for this event. Stable/Unstable NLFFF solutions are stable/unstable in the MHD code
* The MHD solutions confirm that the onset of the instability is due to the torus instability as suggested by the NLFFF solutions.
* The solutions agree with the observations to a remarkable degree.

What next

* Remove model inconsistencies: Spherical (sector) MHD code, open side boundaries, global model...
* Combine NLFFF initial conditions with magnetic field driving.
    * Can we identify the dynamics that result in energy build up in the flux rope?
    * Can we follow the evolution to eruption?
    * Does it erupt at the right time?

Personal Observations

* The flux insertion magneto-frictional method is time consuming and cumbersome, but it has the advantage of reminding the user and the reader that the final solution is one realization of a set of possible solutions - there is no uniqueness.

* When discussing our inversions or extrapolations we need to be clear that they are at best consistent with the observations. The sun is more complex than our models.

* Remain humble and hopeful. Five years from now we will be watching our spectro-polarimeter colleagues present magnetic field measurements of active regions filaments. These models will likely appear simplistic.