
# MUSE diagnostics of coronal heating from MHD modeling of magnetically stressed coronal loops

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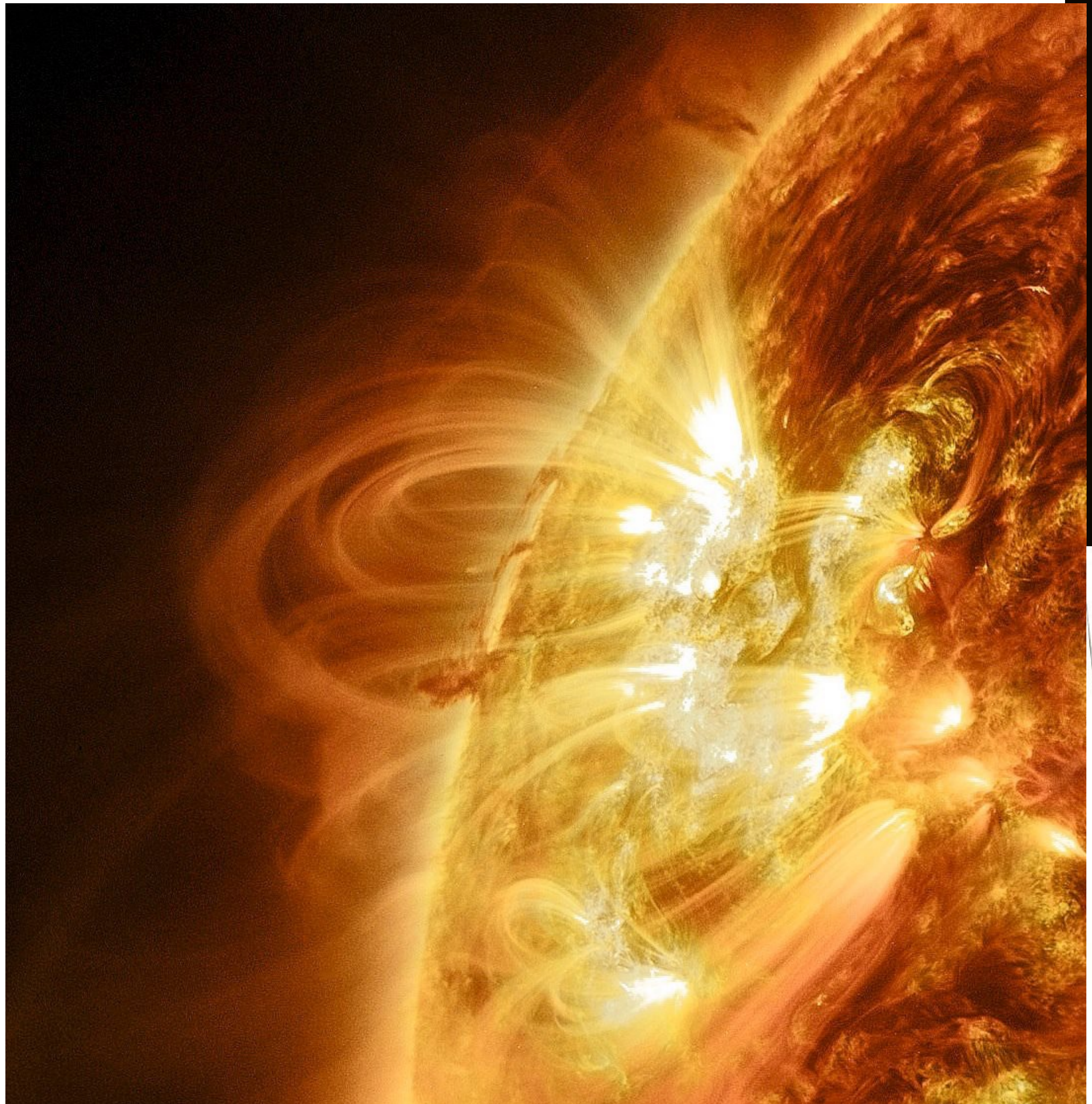
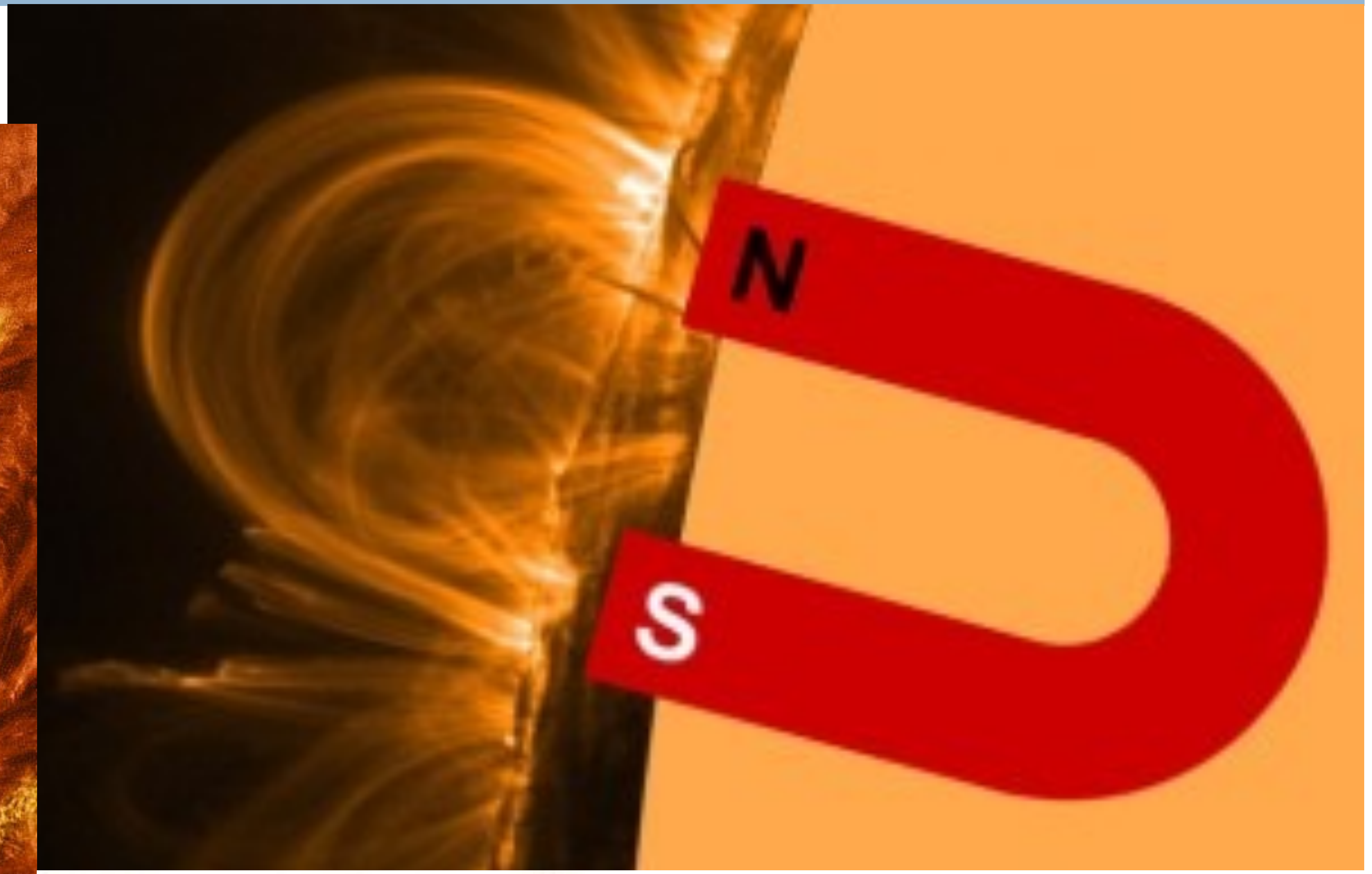
# Where we come from?

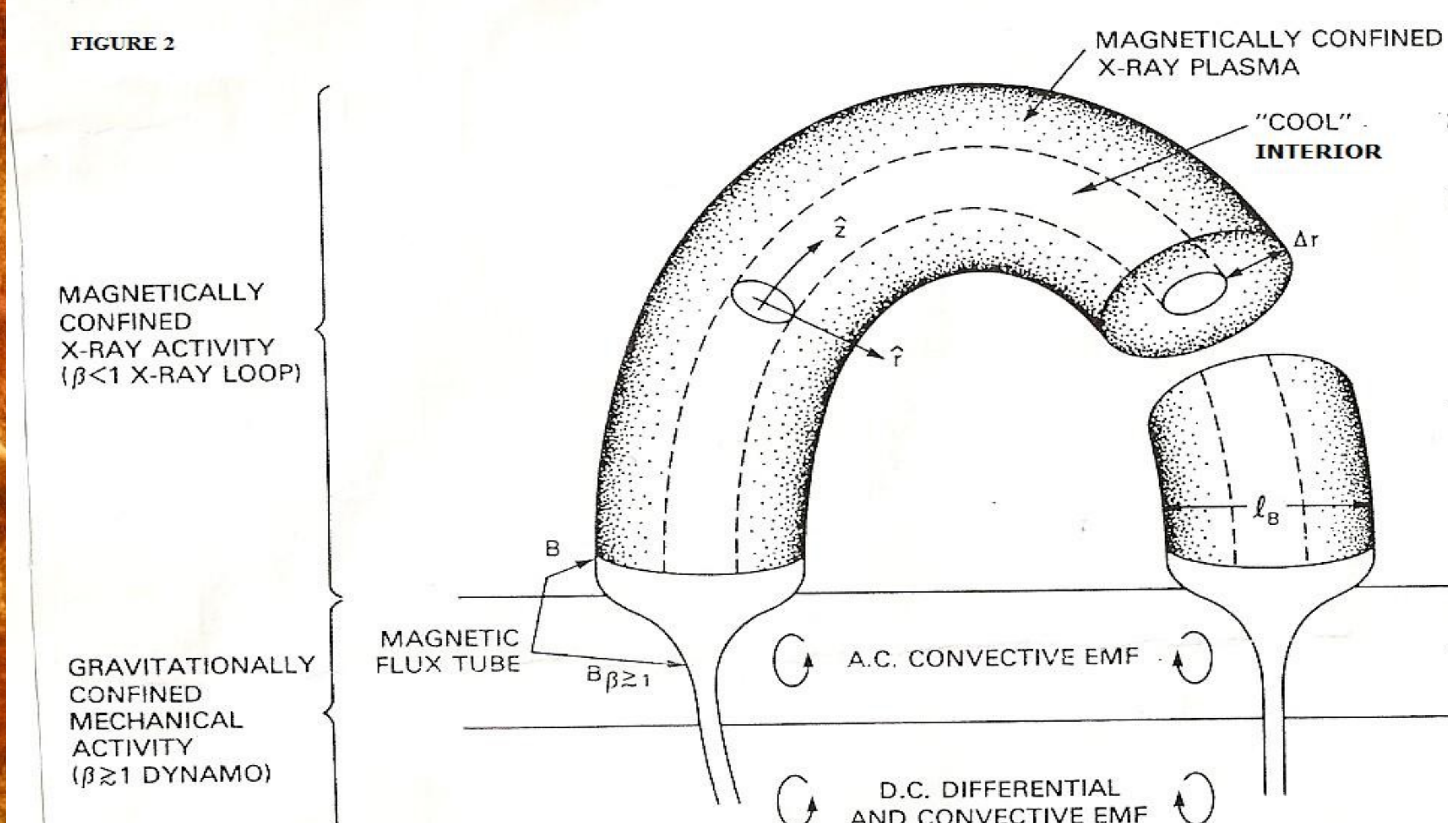
- Study single closed coronal magnetic structures
- 1D loop hydrodynamic modeling

# Coronal loop and magnetic field:

## plasma confined in closed magnetic tubes anchored in the chromosphere



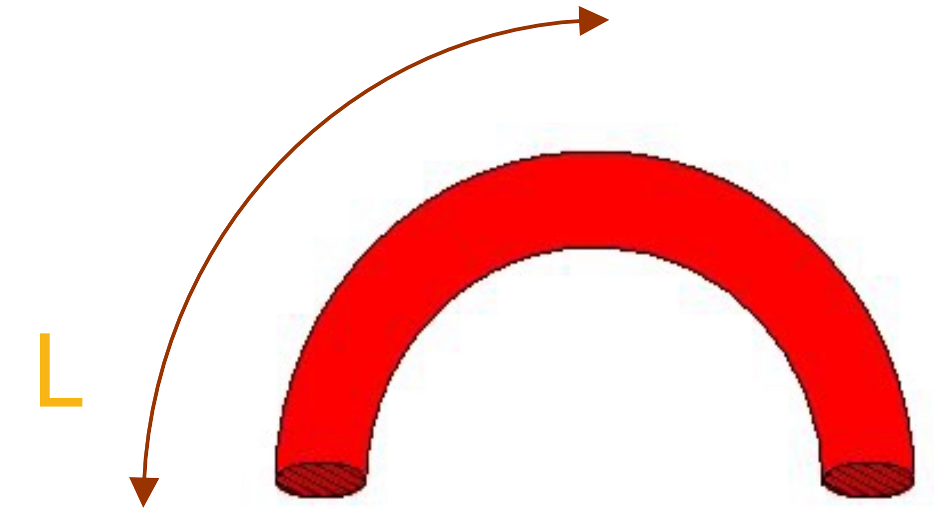


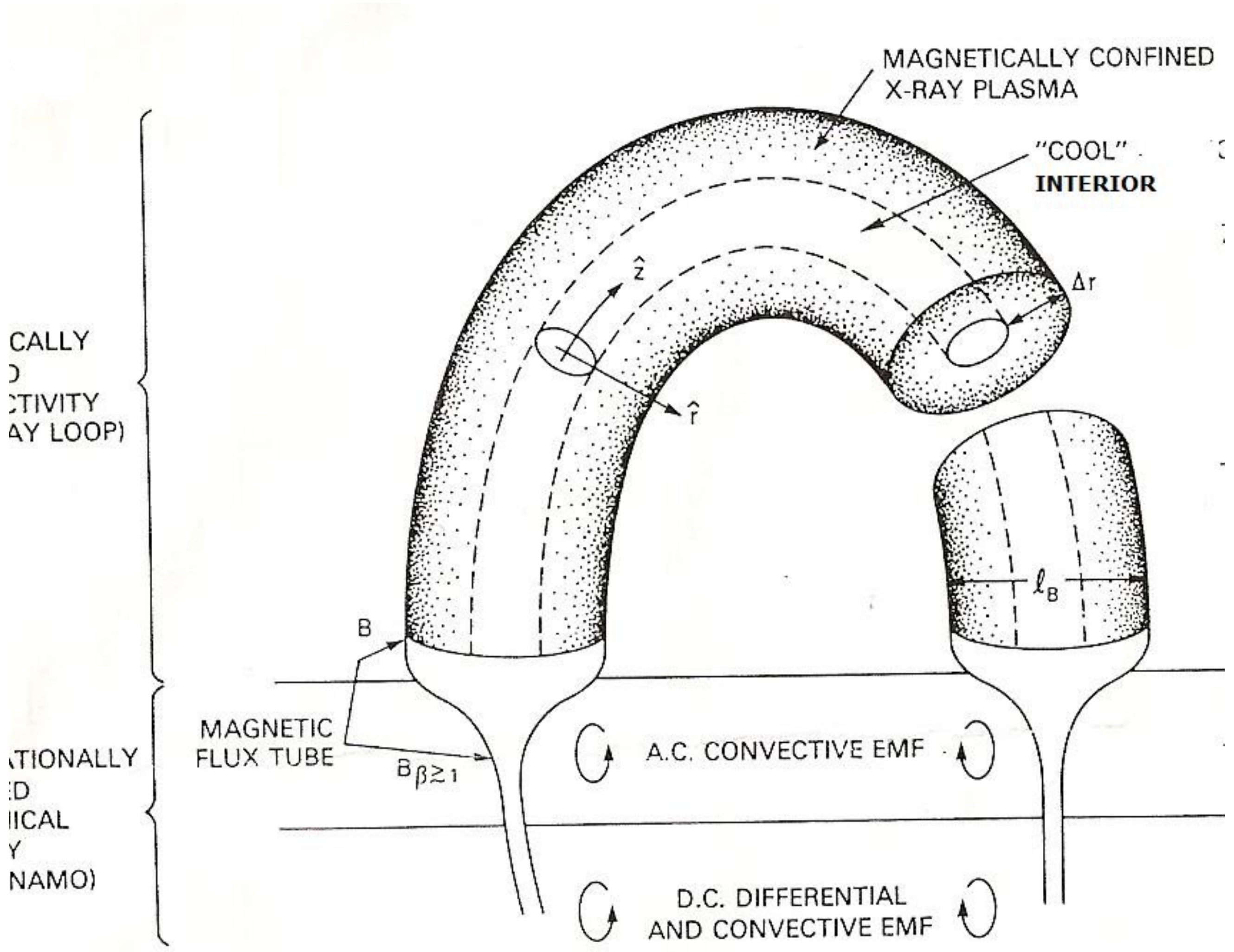



# The basic physics is non-linear:

## Time-dependent 1D hydrodynamic loop modeling and numerical simulations

Heat pulse (flares, nanoflares)




$$\frac{dn}{dt} = -n\frac{\partial v}{\partial s}$$

$$nm_H\frac{dv}{dt} = -\frac{\partial p}{\partial s} + nm_H g + \frac{\partial}{\partial s}\left(\mu\frac{\partial v}{\partial s}\right)$$

$$\frac{d\mathcal{E}}{dt} + w\frac{\partial v}{\partial s} = \mathcal{Q} - n^2\beta\mathcal{P}(T) + \mu\left(\frac{\partial v}{\partial s}\right)^2 + \frac{\partial}{\partial s}\left(\kappa\frac{\partial T}{\partial s}\right)$$

$$p = (1+\beta)nk_BT \qquad \mathcal{E} = \frac{3}{2}p + n\beta\chi \qquad w = \frac{5}{2}p + n\beta\chi$$

$n$ hydrogen particle density, $s$ coordinate along the loop, $v$ plasma velocity, $T$ temperature, $p$ pressure, $g$ gravity, $m_H$ hydrogen atomic mass, $\mu$ viscosity, $\beta$ ionization fraction, $\kappa$ thermal conductivity, $\chi$ hydrogen ionization potential, $k_B$ Boltzmann constant, $\mathcal{P}(T)$ radiative losses p.u.e.m., $\mathcal{Q}(s,t)$ input heating power per unit volume.

# Concept of 1D HD modeling

- Isolate structures and effects
- Detailed comparison w/ observations
- Time-dependent agreement not easy
- Two examples:
    - Modulated light curves of hot interacting loops as the footpoints of IRIS SiIV hot spots (Testa et al. 2019)
    - Impulsive light curves and spectral lines of microflaring interacting loops (Testa & Reale 2020)

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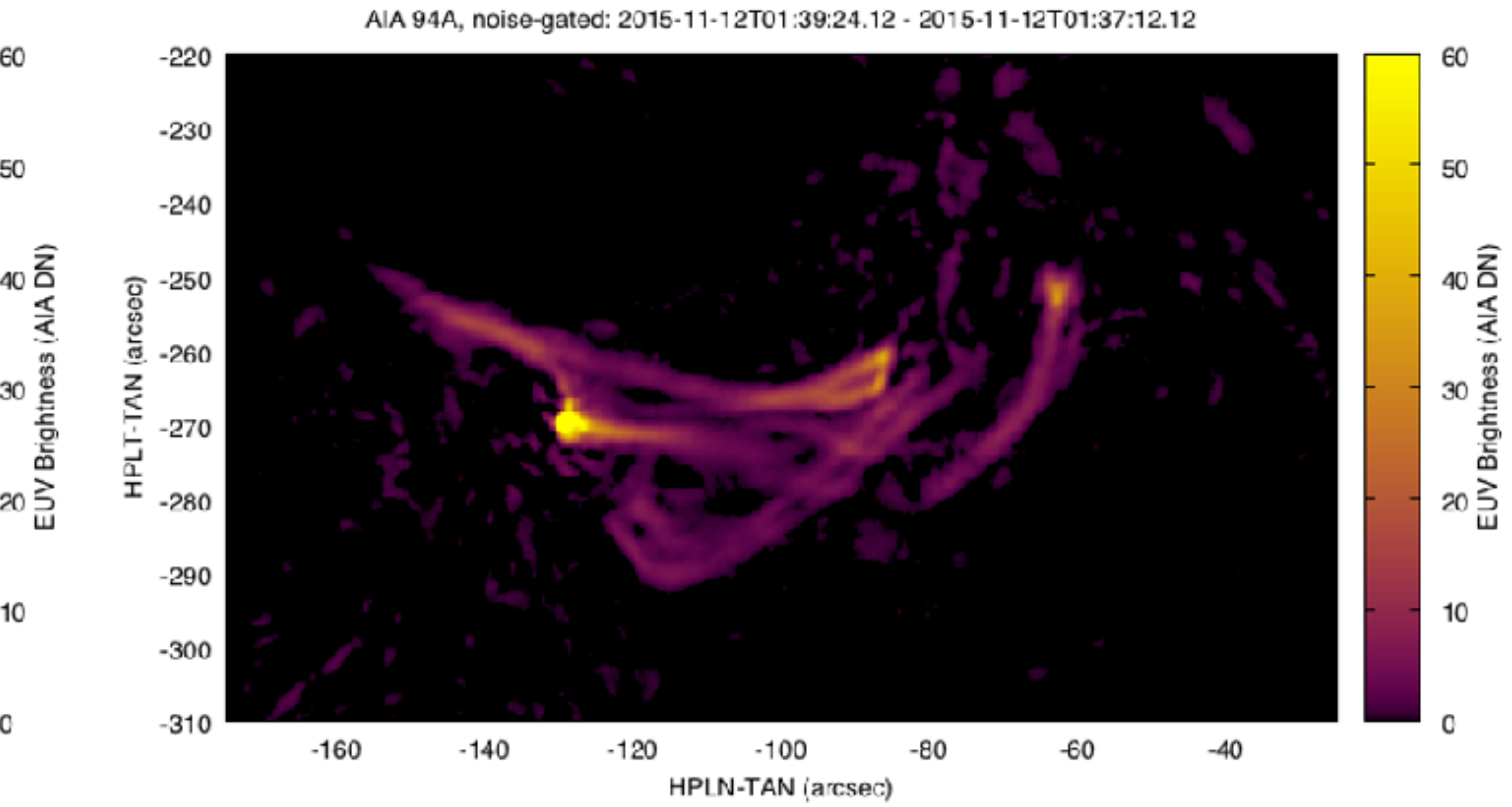
# Impulsive Coronal Heating from Large-scale Magnetic Rearrangements: From IRIS to *SDO*/AIA

Fabio Reale[1,2], Paola Testa[3], Antonino Petralia[2], and David R. Graham[4]

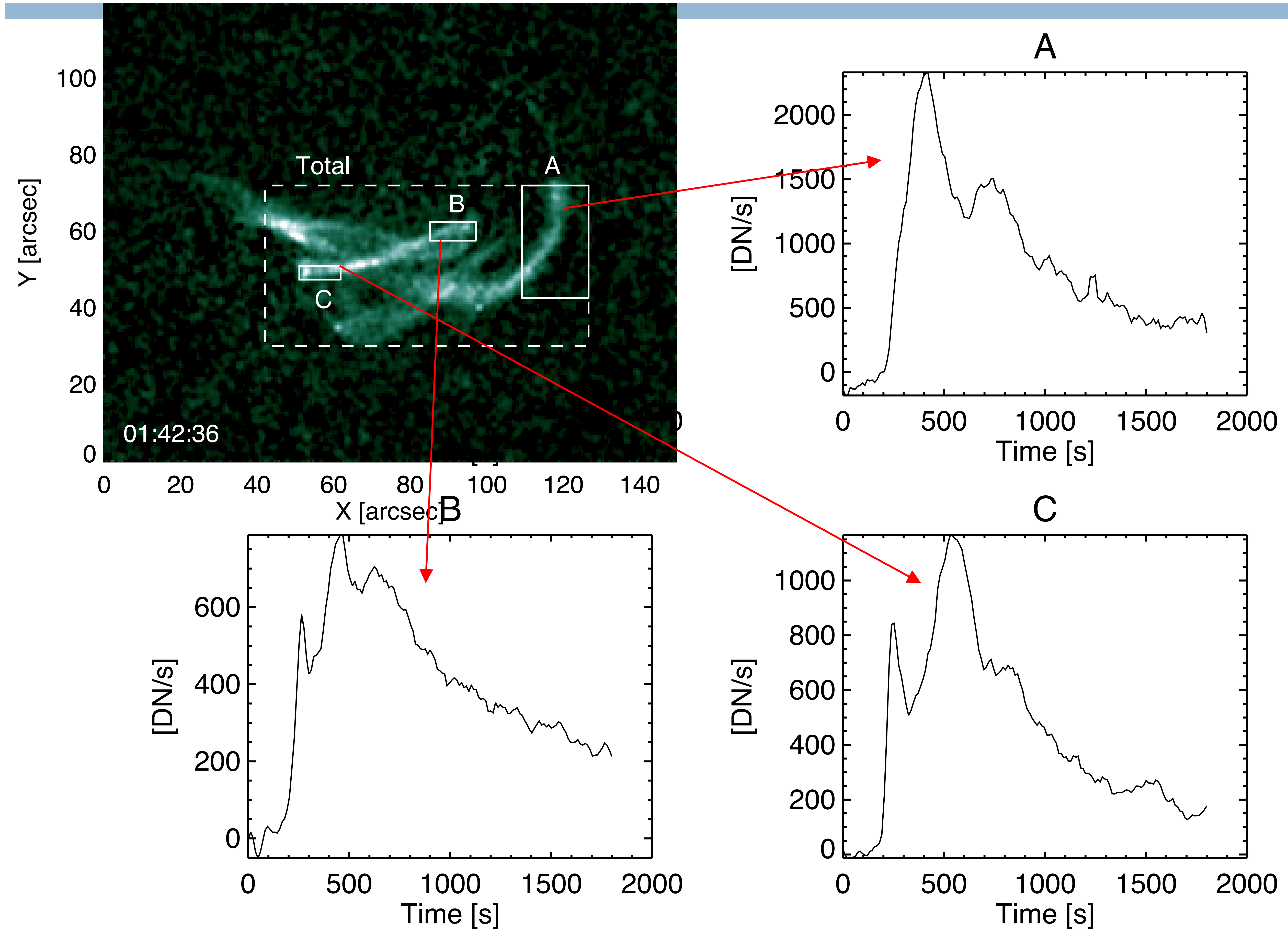
**Credit: Craig De Forest**



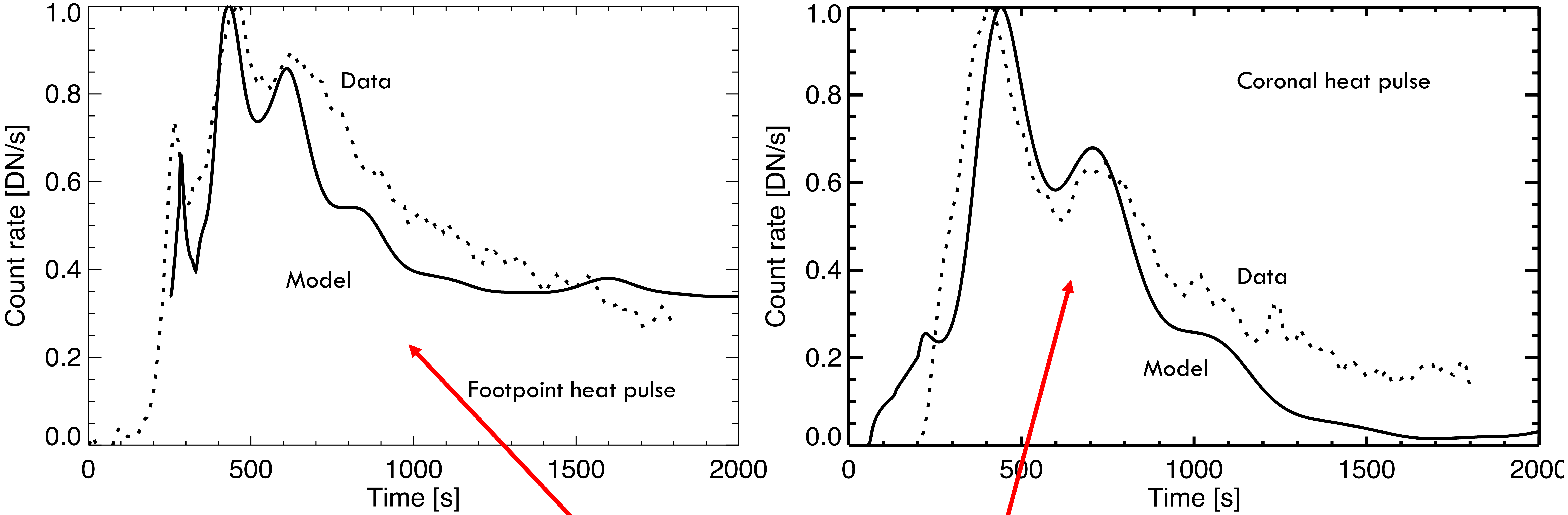

AIA 94A (background subtracted)

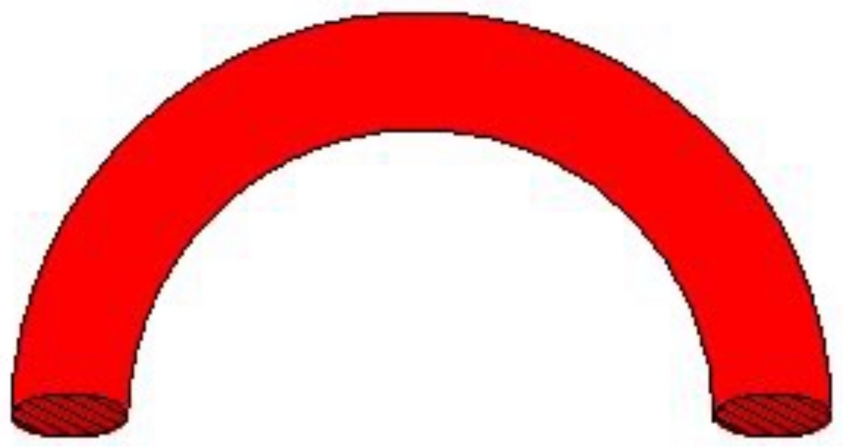
THE ASTROPHYSICAL JOURNAL, 884:131 (9pp), 2019 October 20
https://doi.org/10.3847/1538-4357/ab4270

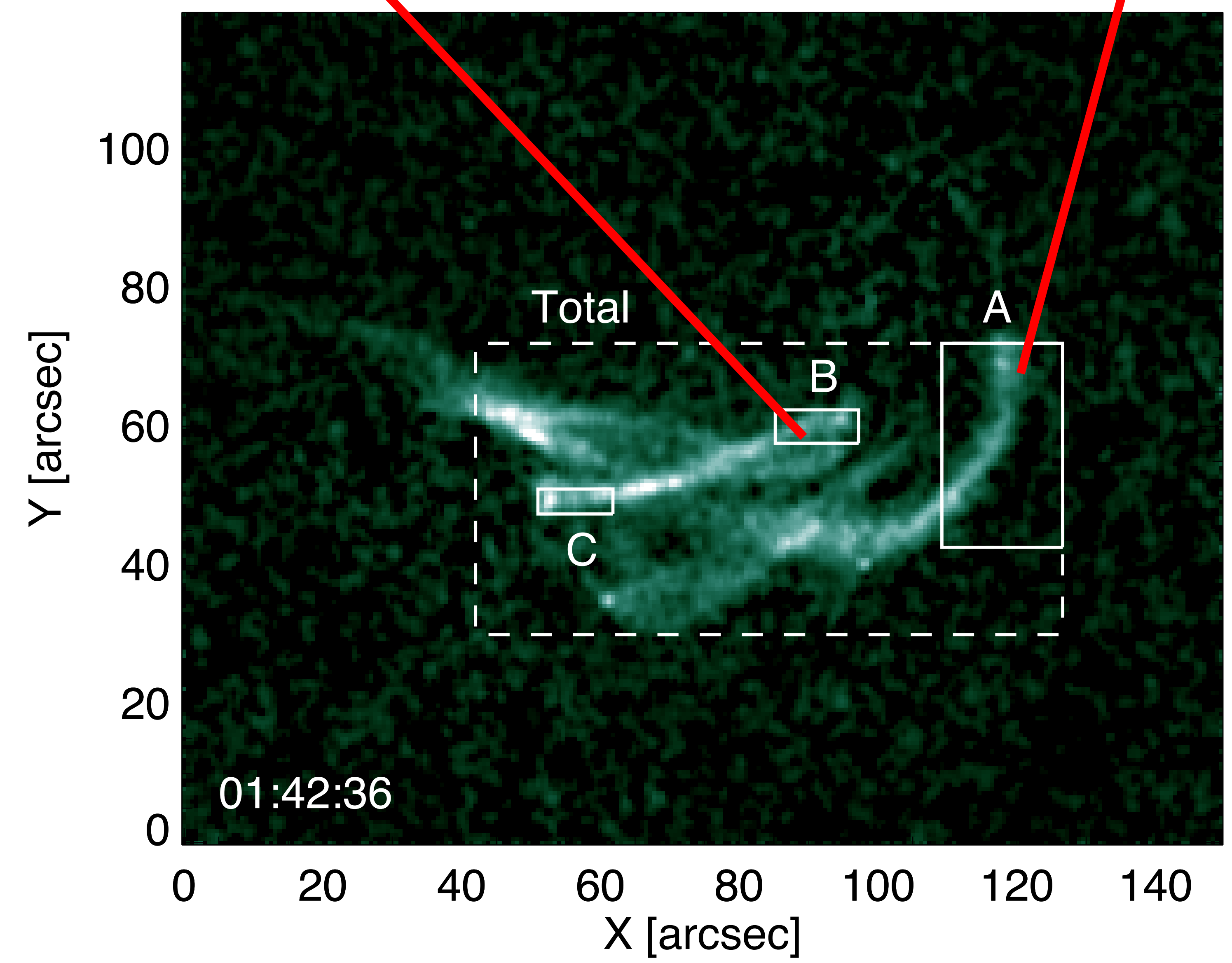

# Large-amplitude Quasiperiodic Pulsations as Evidence of Impulsive Heating in Hot Transient Loop Systems Detected in the EUV with *SDO*/AIA




Quasi-periodic pulsations are detected in loop legs of this loop system



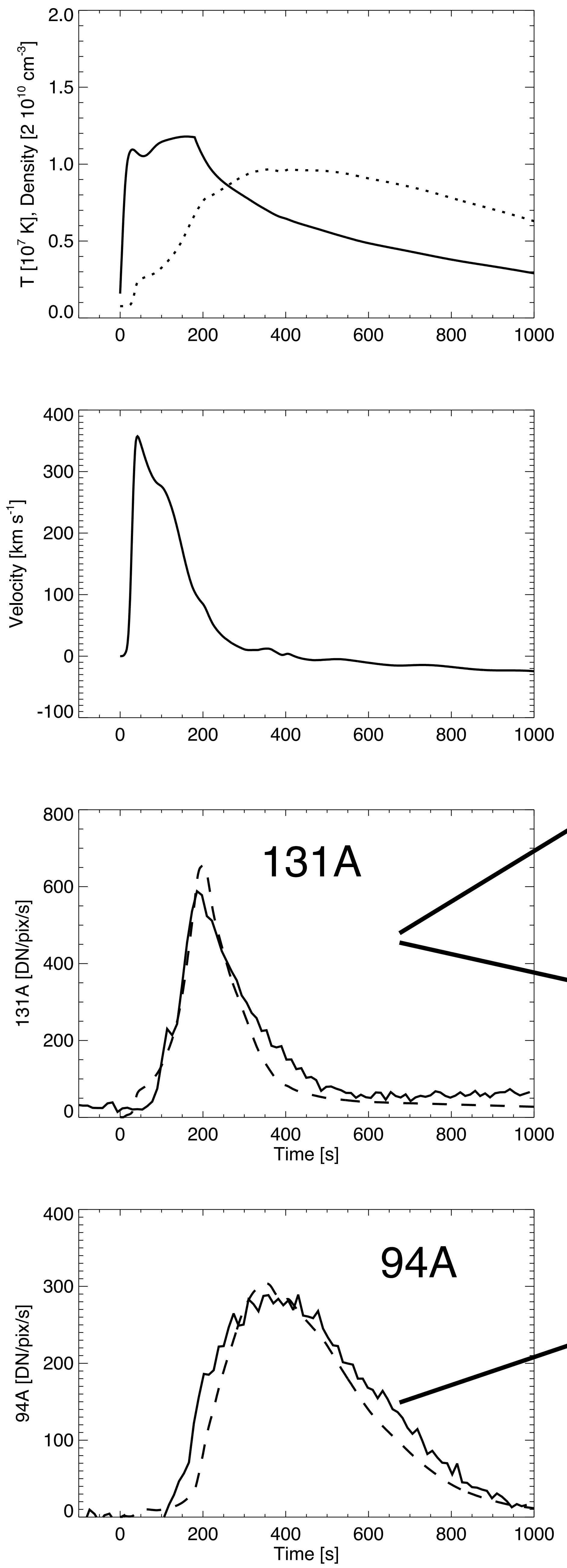



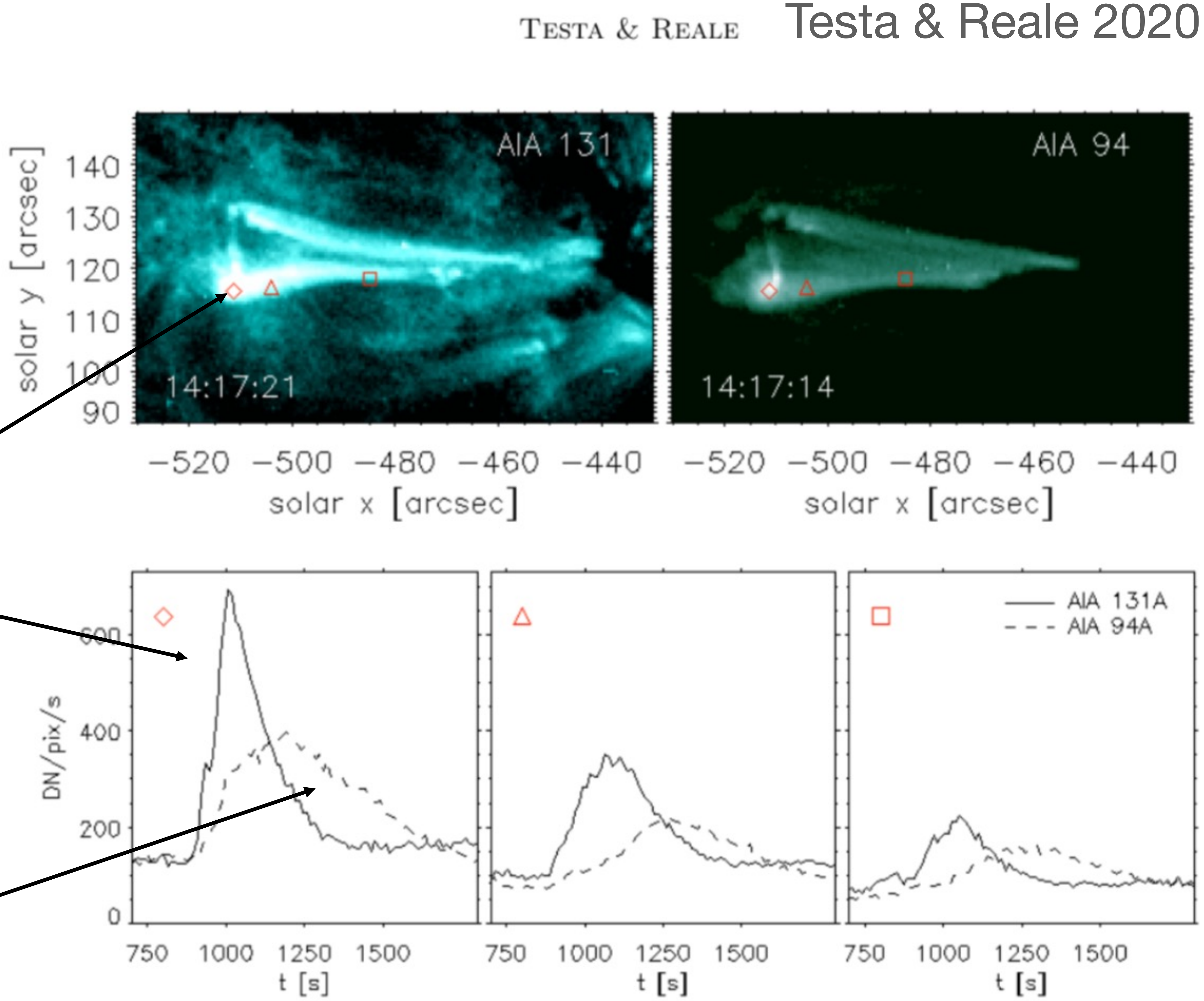


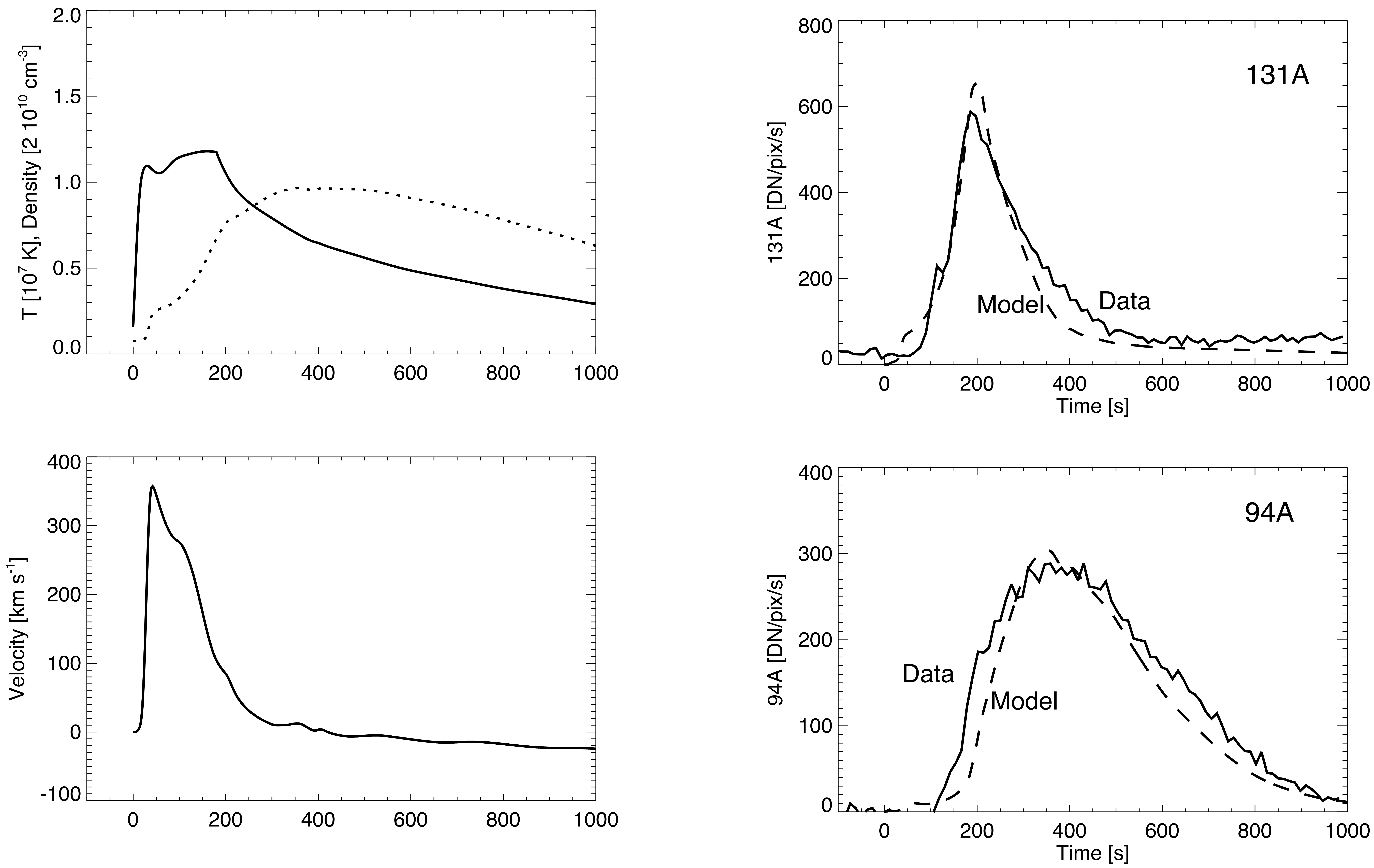

1D heat-pulsed loop model reproduces the light curves in detail

# Coronal heat pulse
## (left pixel)

Testa & Reale 2020

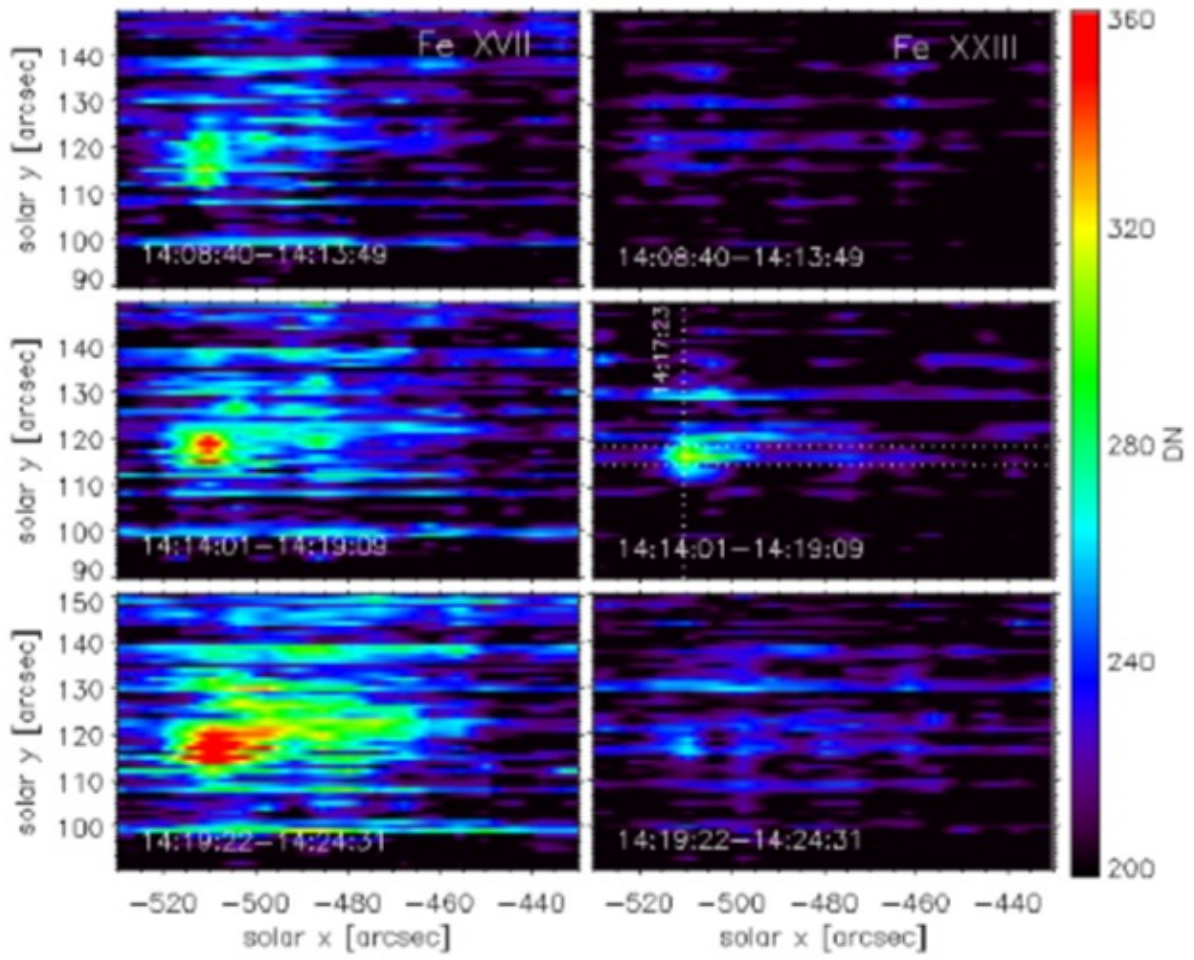


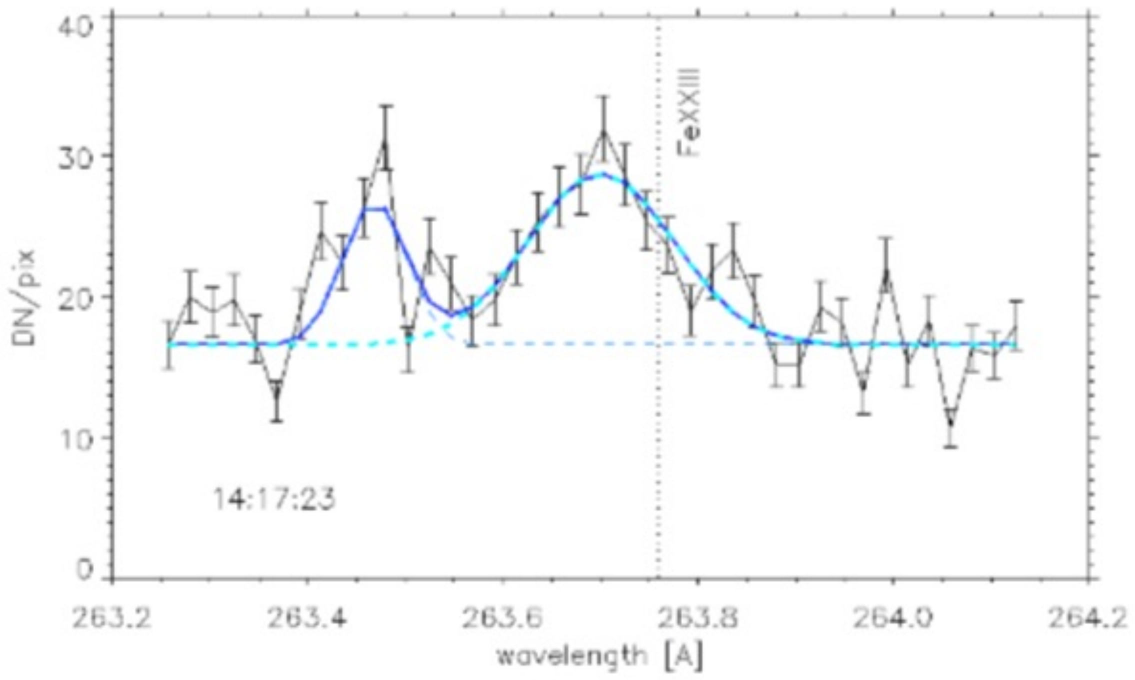


T [$10^7$ K], Density [2 $10^{10}$ cm$^{-3}$]
Velocity [km s$^{-1}$]
131A
131A [DN/pix/s]
Model
Data
Time [s]
94A
94A [DN/pix/s]
Data
Model
Time [s]

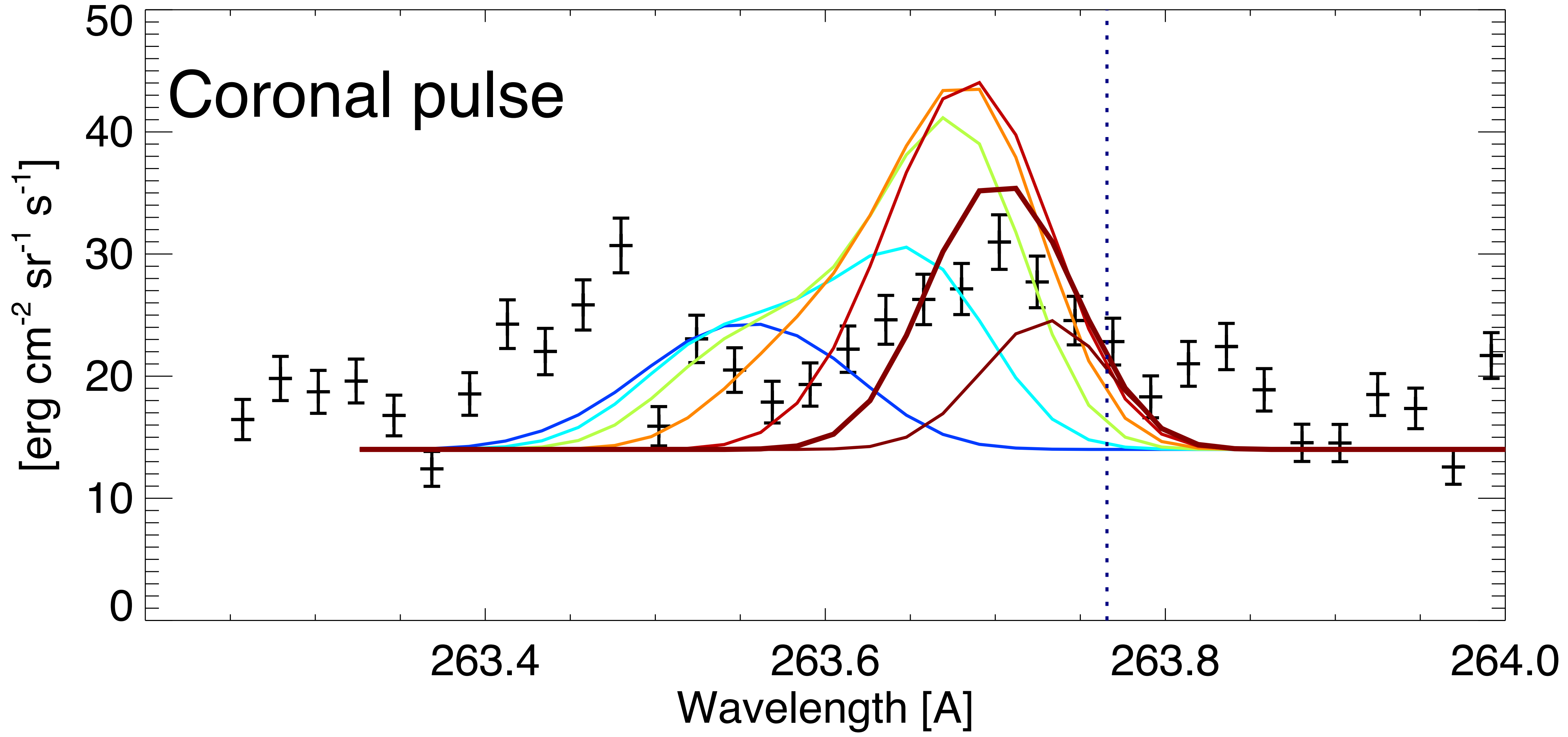
# Fe xxiii



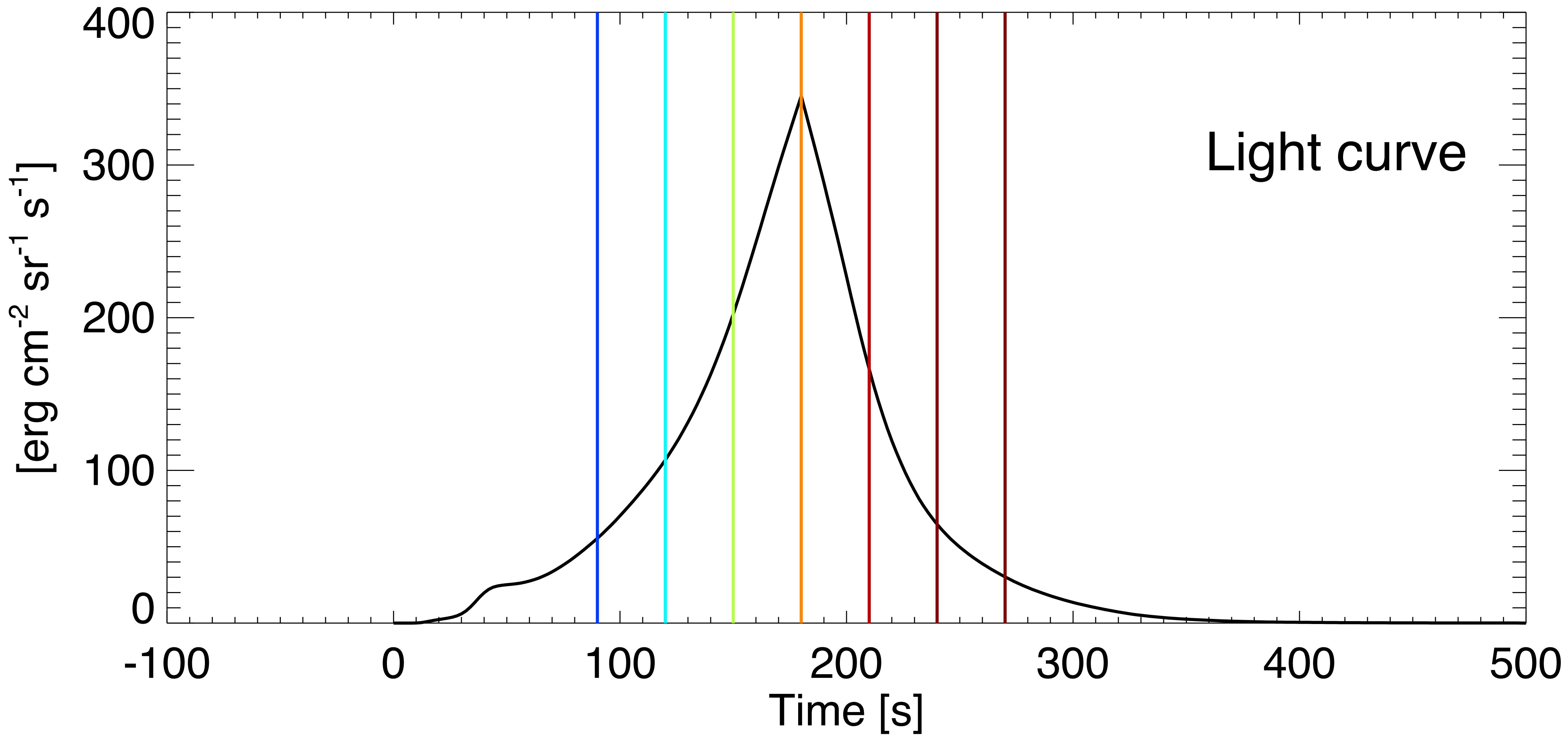
Fe XVII
Fe XXIII
14:08:40–14:13:49
14:08:40–14:13:49
14:14:01–14:19:09
14:14:01–14:19:09
14:19:22–14:24:31
14:19:22–14:24:31
14:17:23
solar y [arcsec]
solar x [arcsec]
DN

FeXXIII
14:17:23
DN/pix
wavelength [A]

Coronal pulse
[erg cm$^{-2}$ sr$^{-1}$ s$^{-1}$]
Wavelength [A]
263.4
263.6
263.8
264.0

Light curve
[erg cm$^{-2}$ sr$^{-1}$ s$^{-1}$]
Time [s]

# Investigating triggering mechanisms

## Plasma-magnetic field interaction

- MHD required
- PLUTO code (Mignone et al. 2007 and follow-ups) set up for loop modeling (Guarrasi+ 2014, Reale+ 2016, Antolin+ 2020)
- *Possible observables with MUSE*
  - MHD kink avalanches (Cozzo et al., 2023, in prep)
  - Nanojets from magnetic reconnection (Antolin et al. 2020, De Pontieu et al. 2022, Pagano et al., 2023, in prep)

# Numerical model

## PLUTO

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot \left(\rho \vec{v}\vec{v} - \vec{B}\vec{B} + p_t \mathbf{I}\right) = \rho \vec{g},$$

$$\frac{\partial \vec{B}}{\partial t} \nabla \cdot \left(\vec{v}\vec{B} - \vec{B}\vec{v}\right) = -\nabla \times \left(\eta \cdot \vec{J}\right)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left(\left(E + p_t\right)\vec{v} - \vec{B}\left(\vec{v} \cdot \vec{B}\right)\right) = \rho \vec{v} \cdot \vec{g} - n_e n_{II} \Lambda(T) + H - \nabla \cdot F_c - \nabla \cdot \left[\left(\eta \cdot \vec{J}\right) \times \vec{B}\right]$$

$$E = \frac{p}{\rho(\gamma - 1)} + \frac{1}{2}\vec{v}^2 + \frac{\vec{B}^2}{8\pi\rho},$$

$$\eta = \begin{cases} \eta_0 & \left(|\vec{j}| \geq J_0\right) \\ 0 & \left(|\vec{j}| < J_0\right) \end{cases}$$

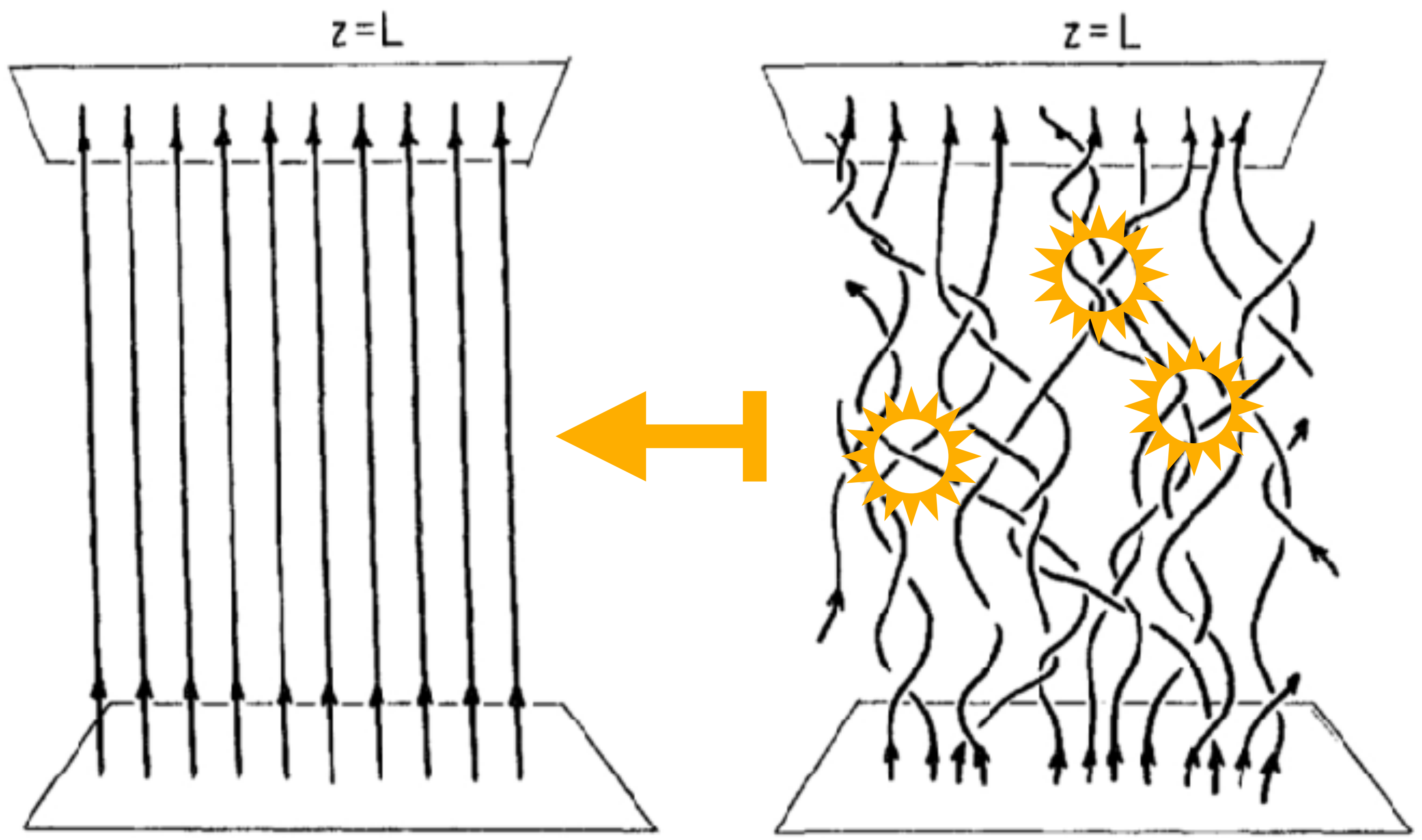
$$J_0 = 250 \text{ G s}^{-1}$$
$$\eta_0 = 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$$

$k(T)\Lambda(T)$ constant

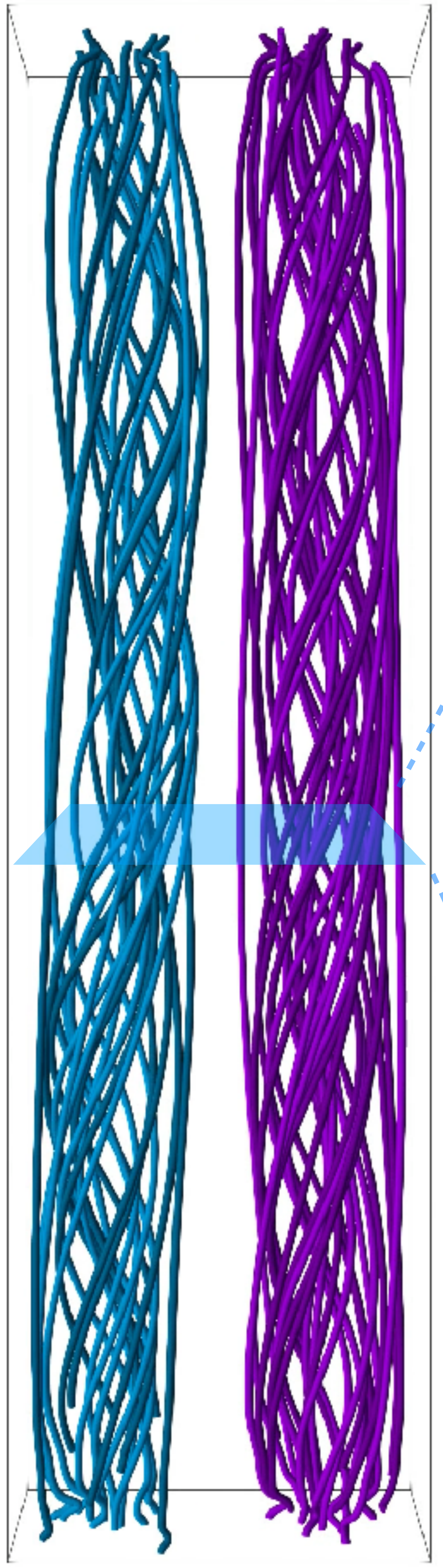
H= $\Lambda(T)$ (t=0)

# Ongoing work: MHD avalanches (Cozzo, Hood, et al. 2023, in prep)

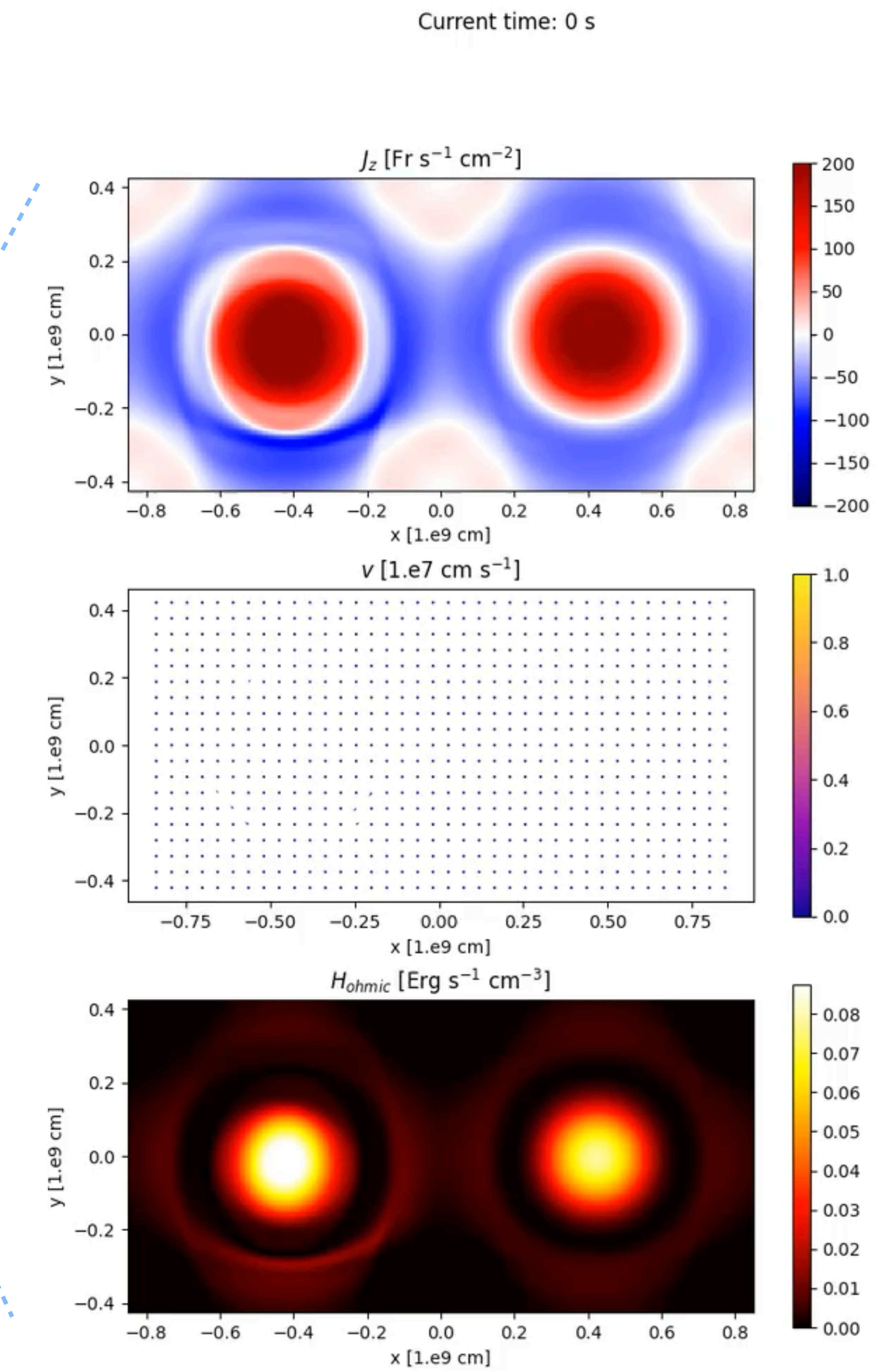
- Localised instability leading to a large heating event (Tam et al 2015, Hood et al 2016, Reid et al 2018, 2020);
- Stratified atmosphere (chromosphere + TR + corona), magnetic field tapering, thermal conduction, radiative cooling, anomalous diffusivity, gravity in curved loop;
- **Kink Instability** can trigger an MHD avalanche.




Unstable loop v.s. nearby stable loop



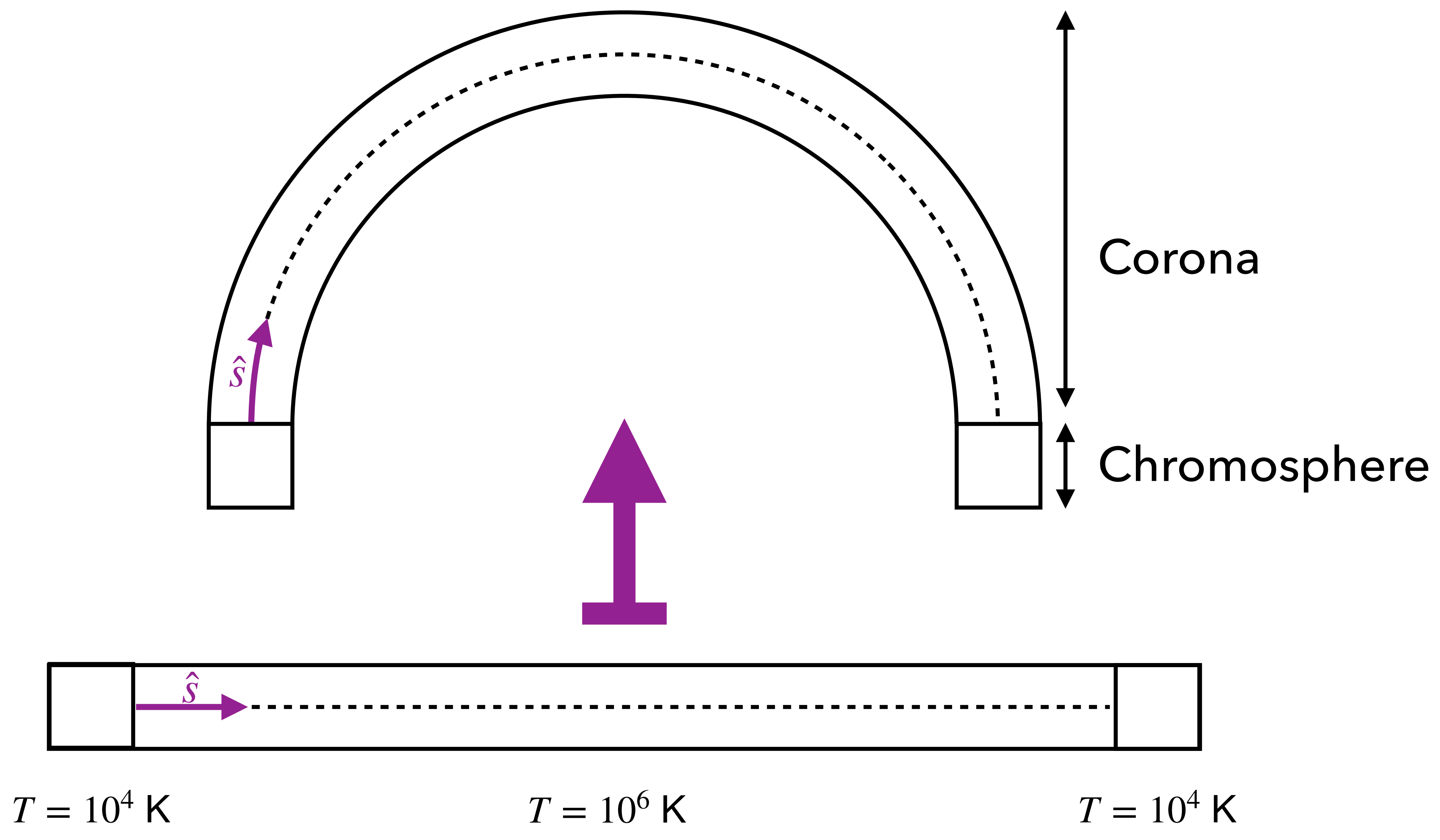
Full 3D multi threaded coronal loops



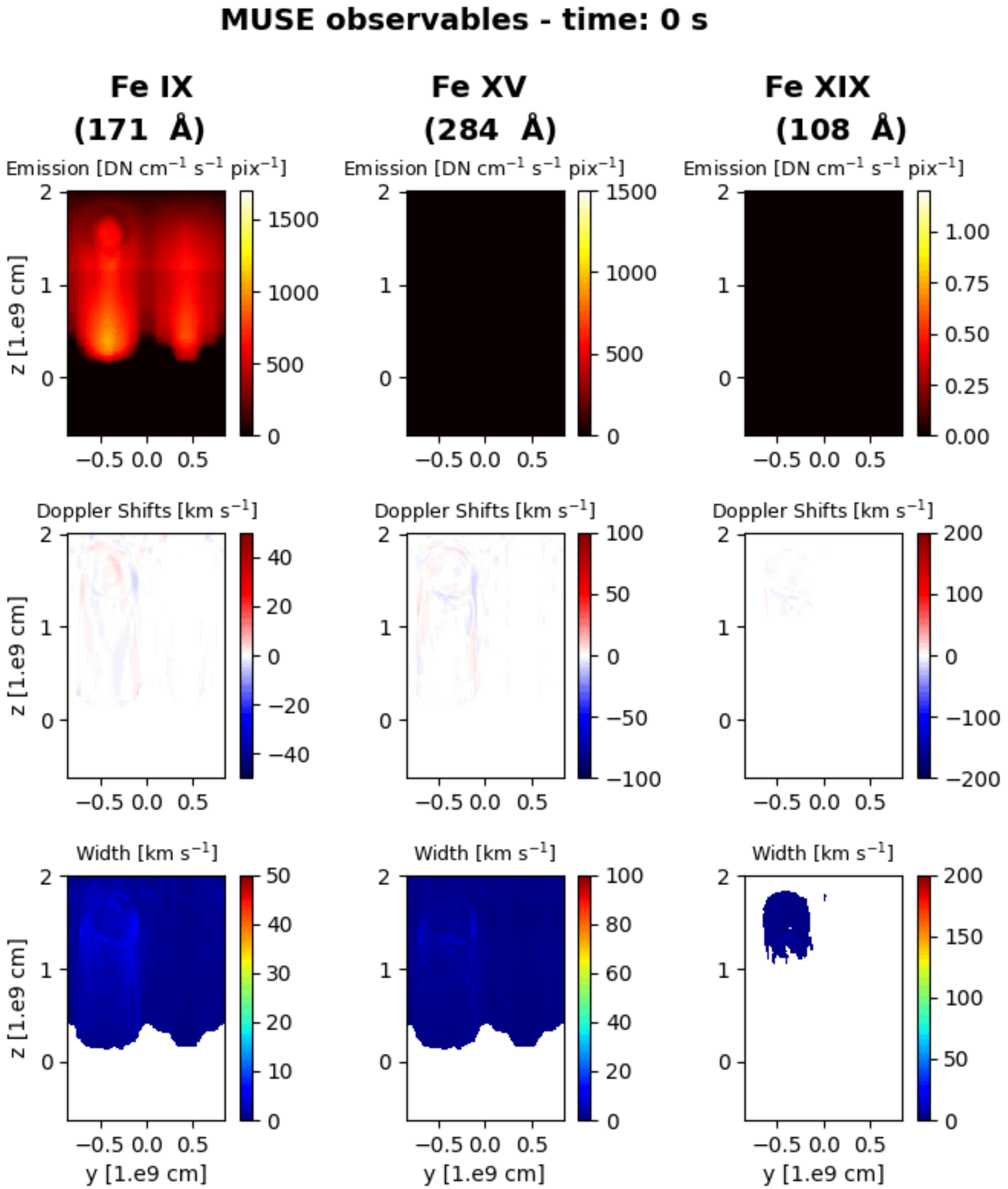

Horizontal cut: current density / velocity / heating

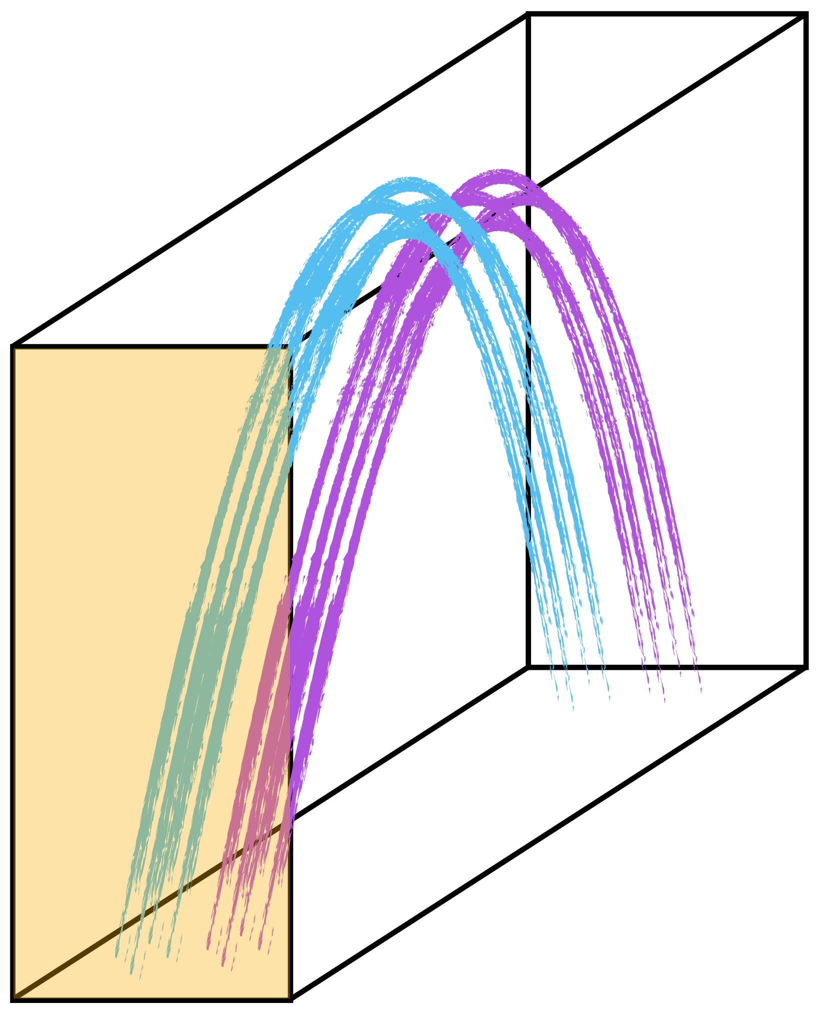
# **MHD avalanches:** *onset of the instability*

- **Instability trigger**: twisting by localised foot-point rotation;
- **During instability onset:** formation of current sheets, plasma heating;
- **After instability onset:** heat diffusion, chromospheric evaporation

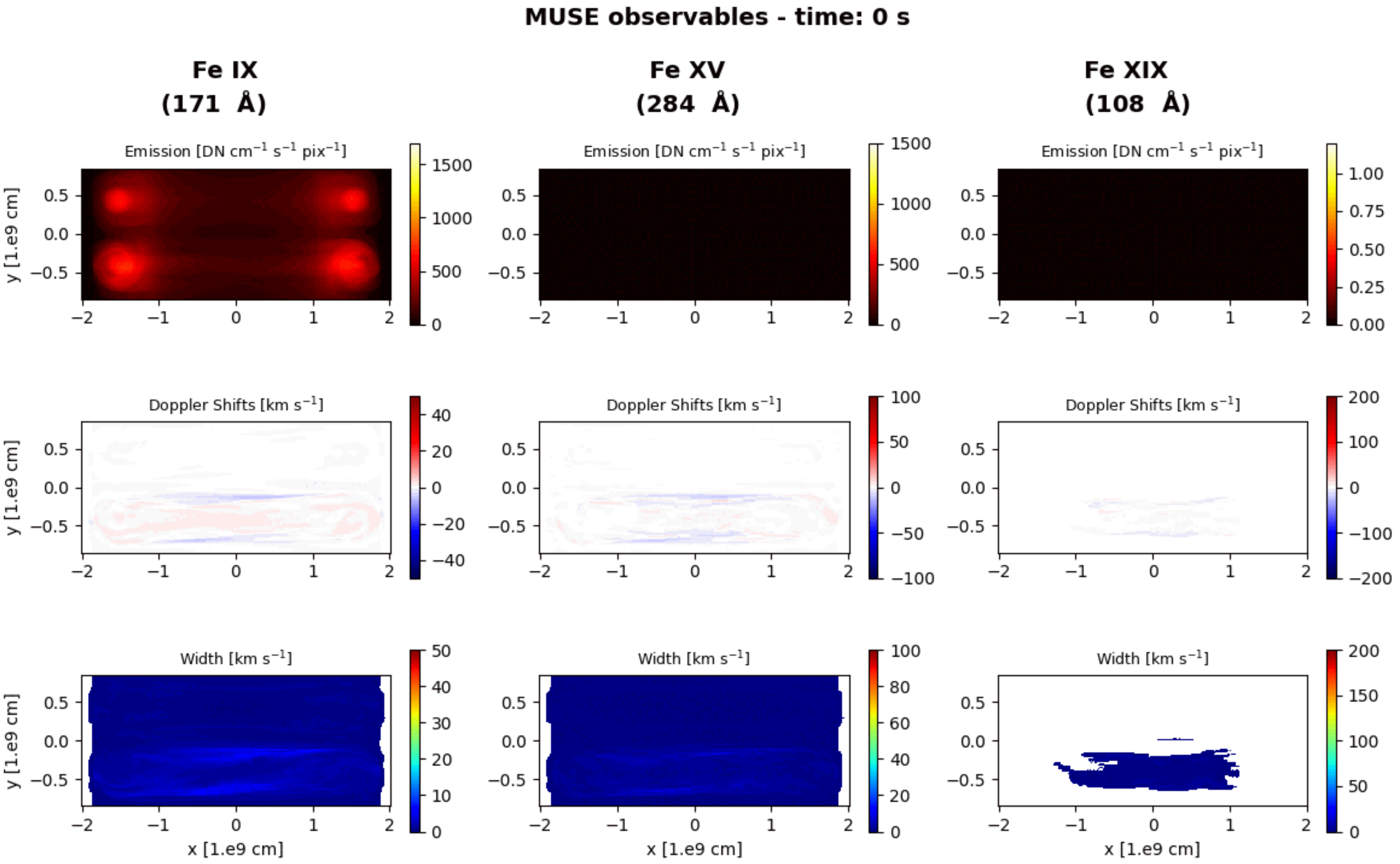


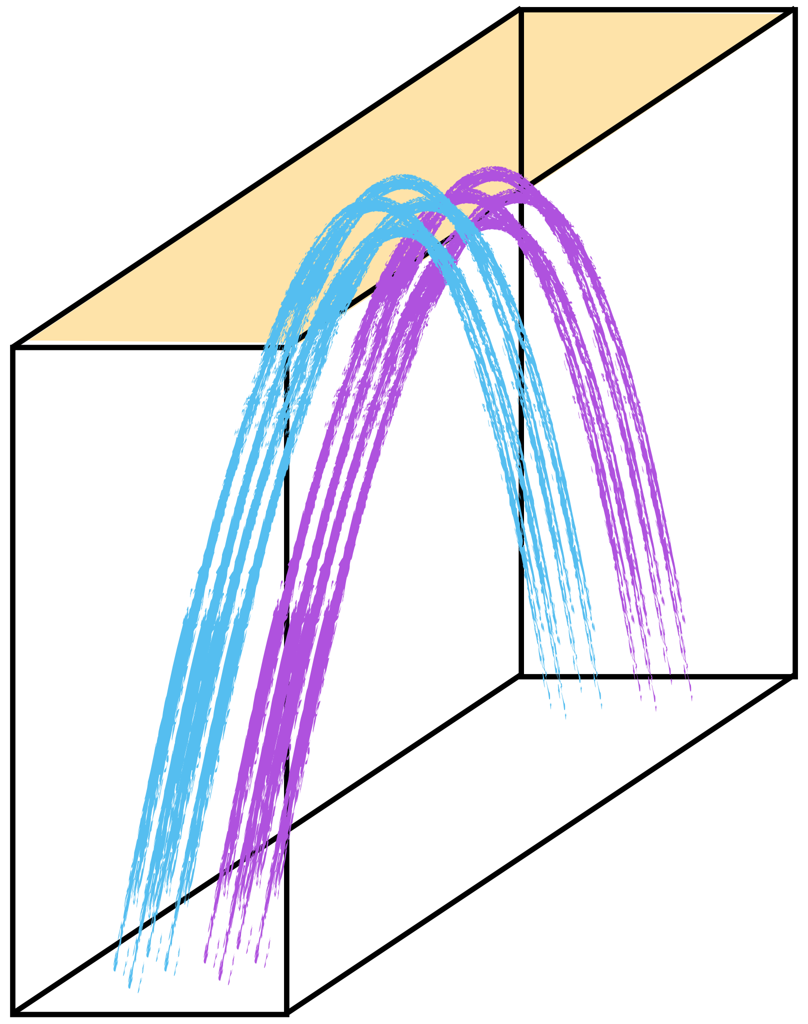

**Temperature** **Plasma density** **Current density**



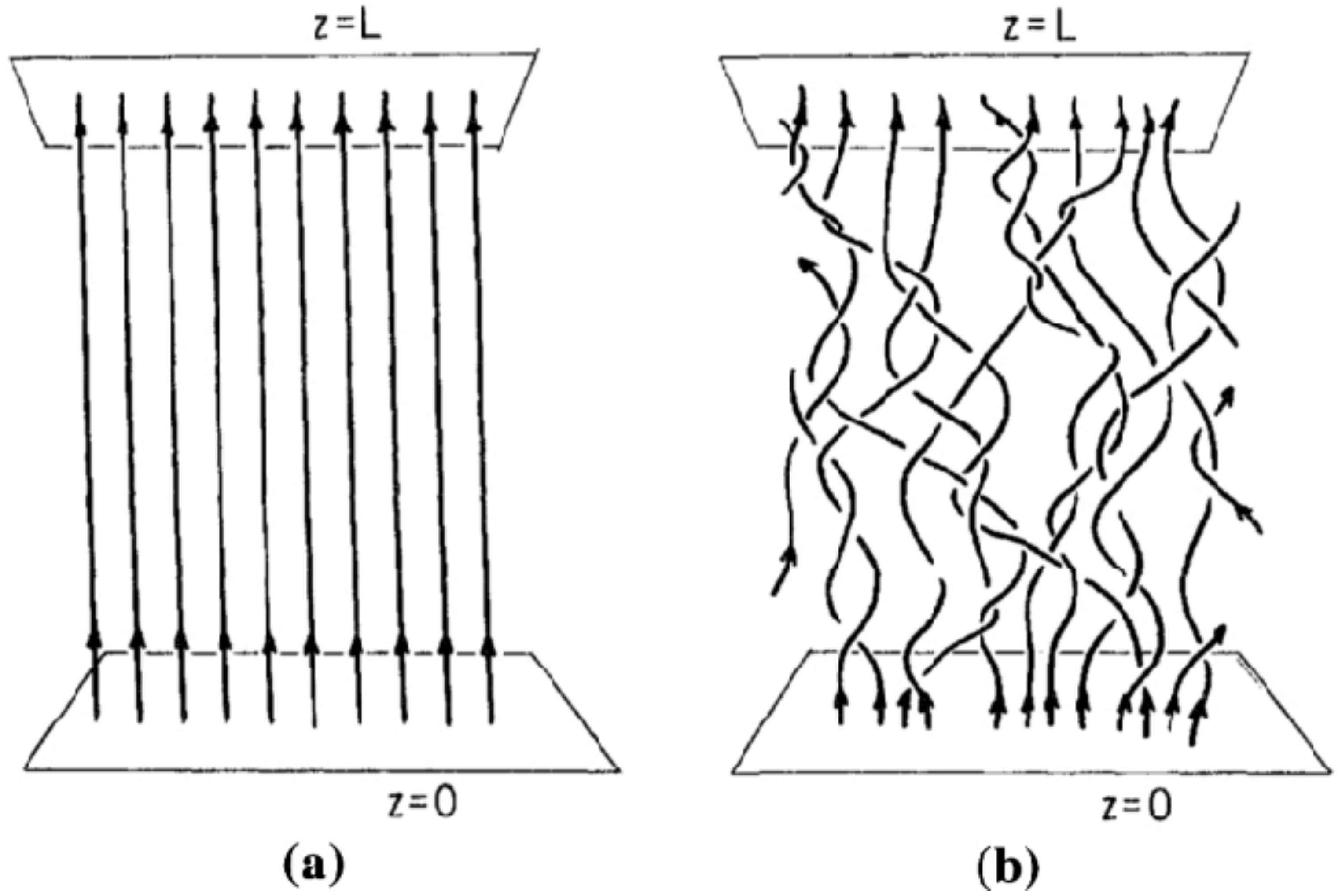
- **Edge-on POV**;
- **Fe IX** ($\log T[k] \sim 5.9$): heated upper TR;
- **Fe XV** ($\log T[k] \sim 6.4$): heated coronal plasma after chromospheric evaporation;
- **Fe XIX** ($\log T[k] \sim 7.1$): coronal plasma heated by magnetic reconnection during instability onset.

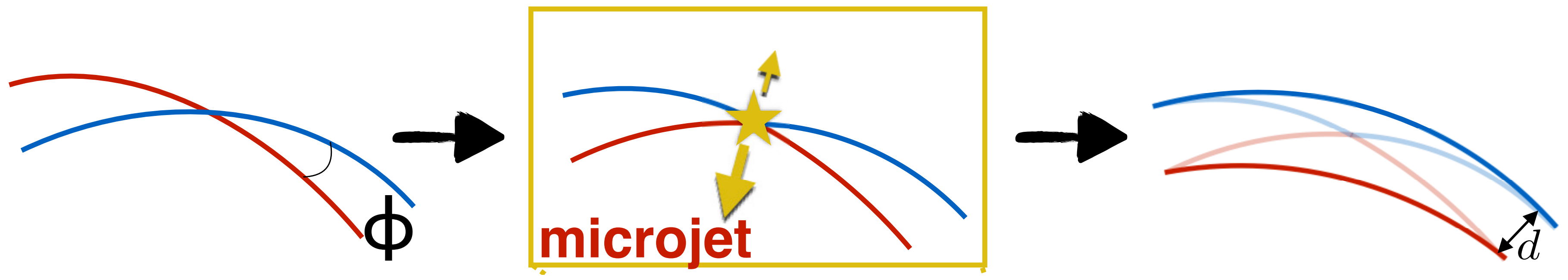


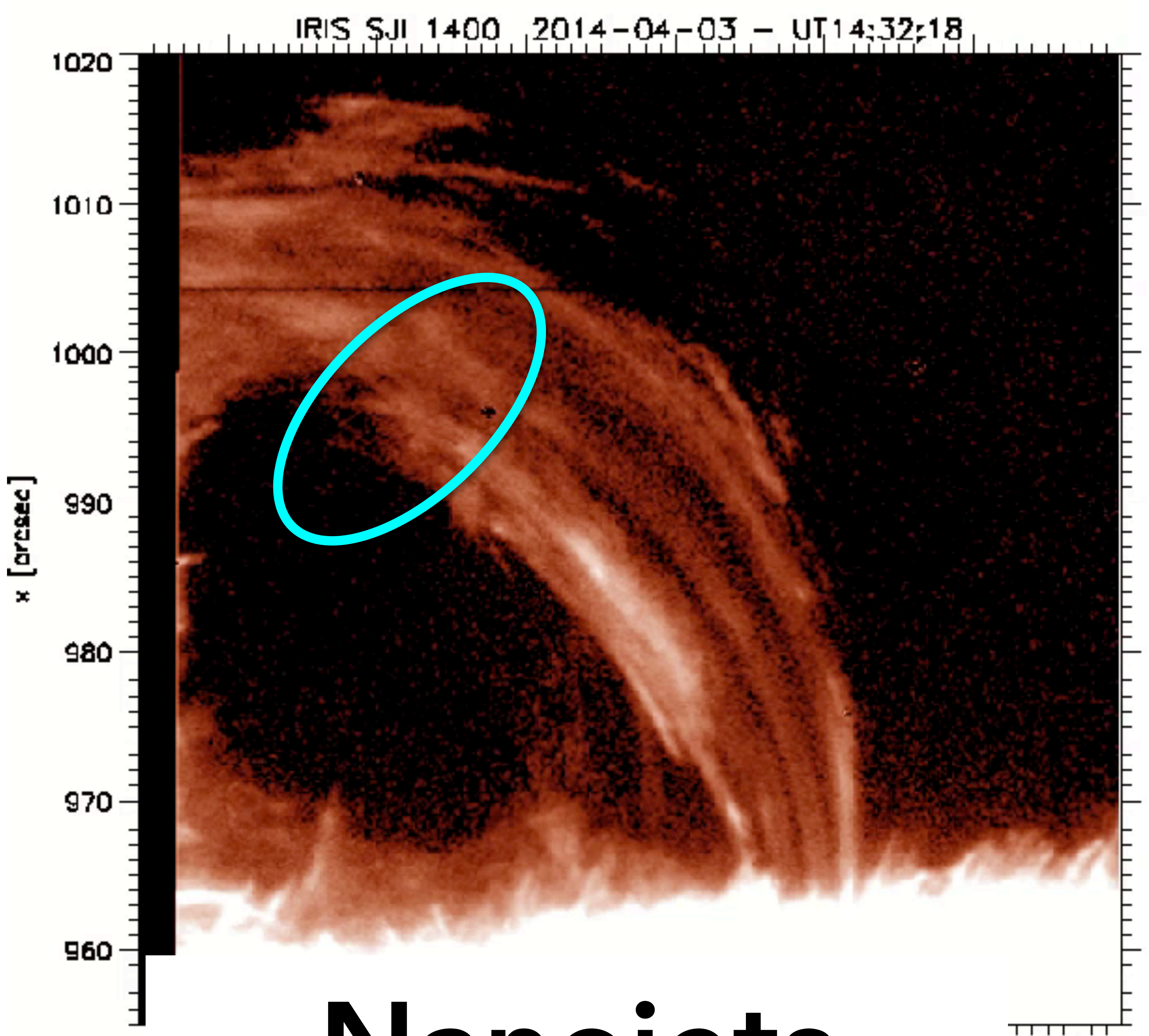



- **From the top POV;**
- Helical patterns above TR: *smoking gun* of the kink instability;
- Doppler shifts as evidence of chromospheric evaporation.

# Nanoflares and nanojets (Antolin+ 2020, Pagano+ 2023, in prep)




## Nanojets

**Antolin et al. 2020**

- Intensity bursts
- Very short lived (<10 s - 15 s)
- V ~ 100-200 km/s
- 1000-2000 km in length
- ~500 km in width

## Nanoflares

- Impulsive energy release ~ $10^{24}$ erg
- Small /short, spatial /temporal scales
- Significant localised heating: 5-10 MK
- Magnetic reconnection

# Numerical model

## PLUTO

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot \left( \rho \vec{v} \vec{v} - \vec{B}\vec{B} + p_t \mathbf{I} \right) = \rho \vec{g},$$

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$$\frac{\partial E}{\partial t} + \nabla \cdot \left( (E + p_t)\, \vec{v} - \vec{B} \left( \vec{v} \cdot \vec{B} \right) \right) = \rho \vec{v} \cdot \vec{g} - n_e n_H \Lambda(T) + H - \nabla \cdot F_c - \nabla \cdot \left[ \left( \eta \cdot \vec{J} \right) \times \vec{B} \right]$$

$$E = \frac{p}{\rho(\gamma - 1)} + \frac{1}{2}\vec{v}^2 + \frac{\vec{B}^2}{8\pi\rho},$$

$$\eta = \begin{cases} \eta_0 & \left( |\vec{j}| \geq J_0 \right) \\ 0 & \left( |\vec{j}| < J_0 \right) \end{cases}$$

90K CPU hours
@CINECA
Galileo 100
2021 1.1 PFlops

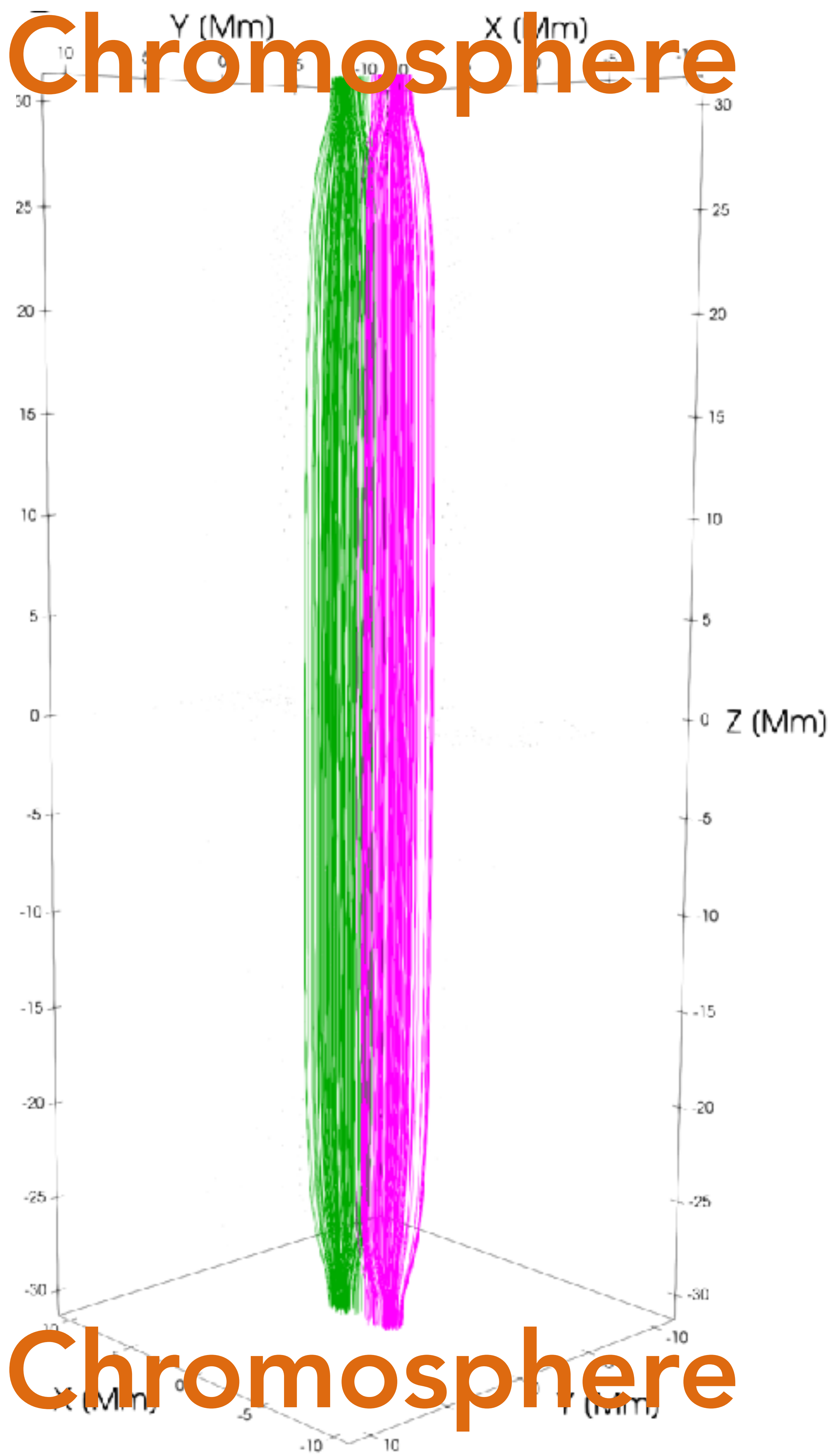
$$J_0 = 250 \text{ G s}^{-1}$$

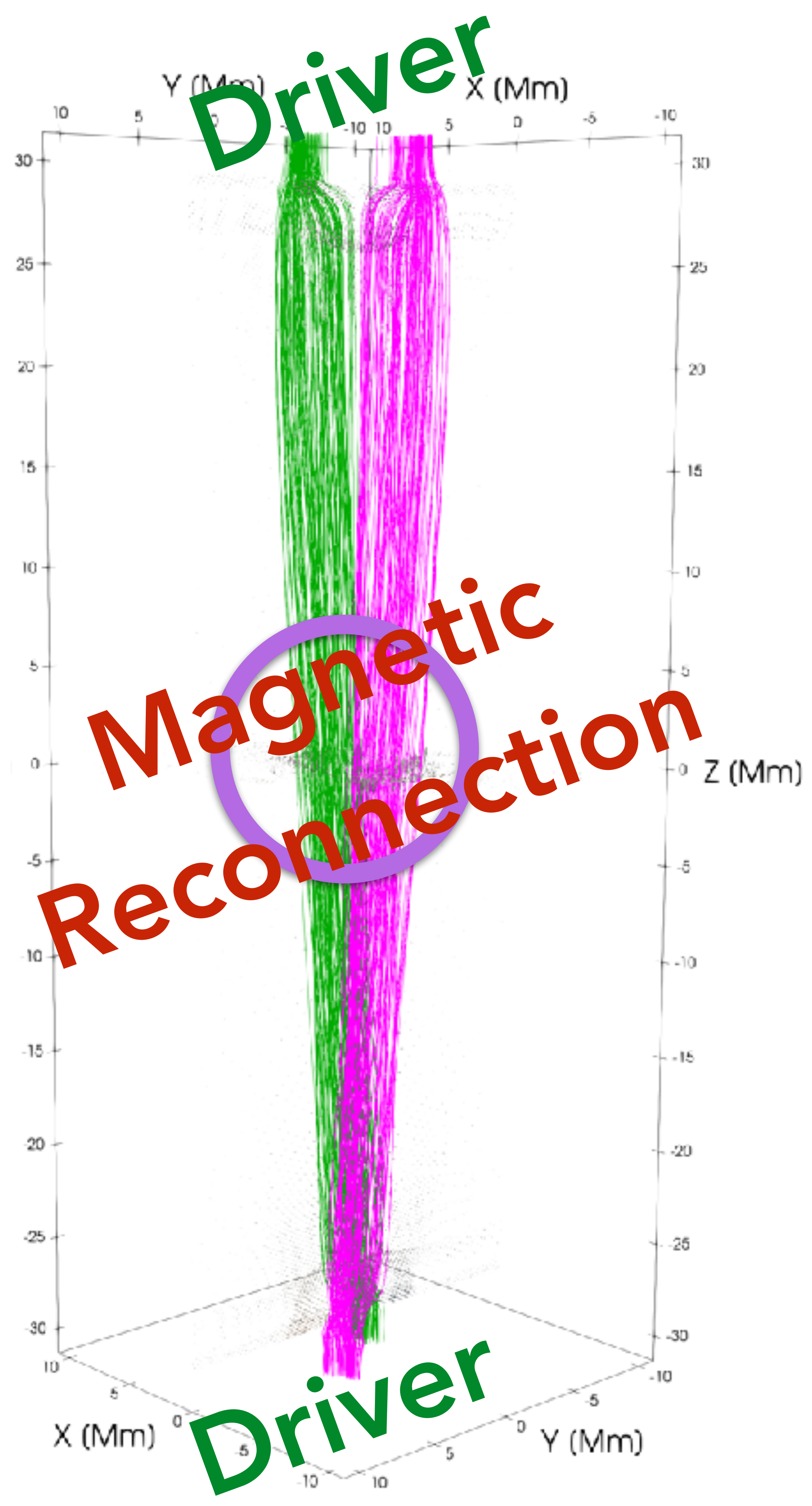
$$\eta_0 = 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$$

$k(T)\Lambda(T)$ constant

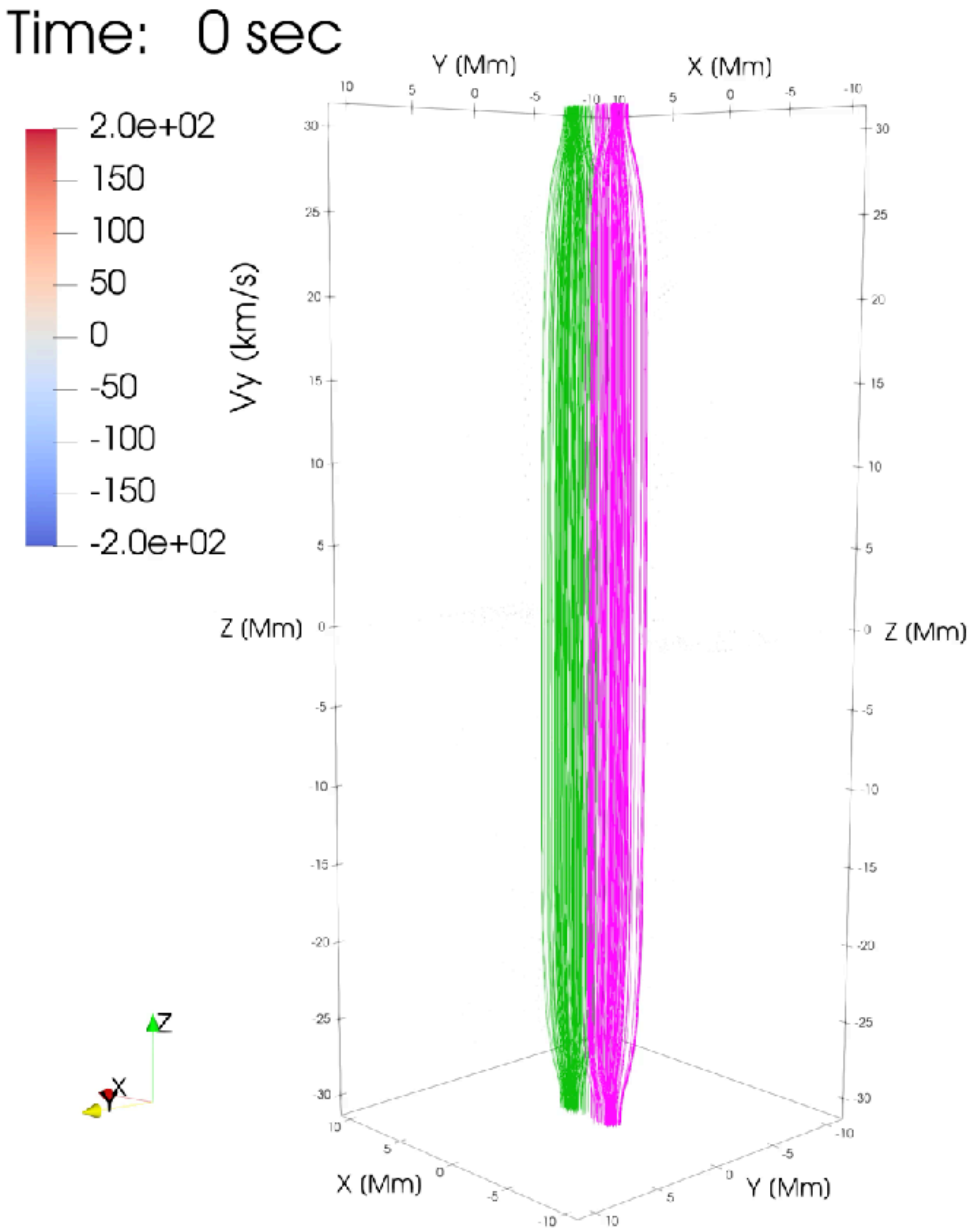
H= $\Lambda(T)$ (t=0)

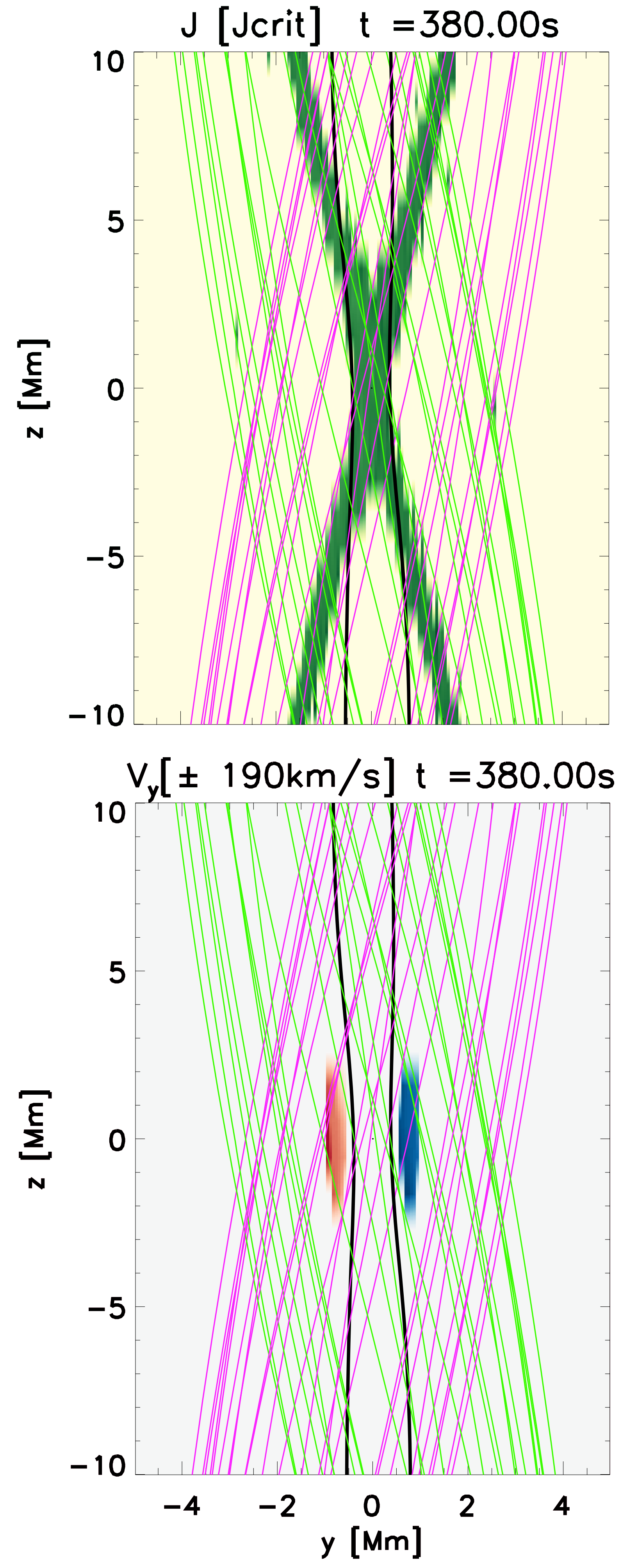
# Numerical model
# Reconnection and jets



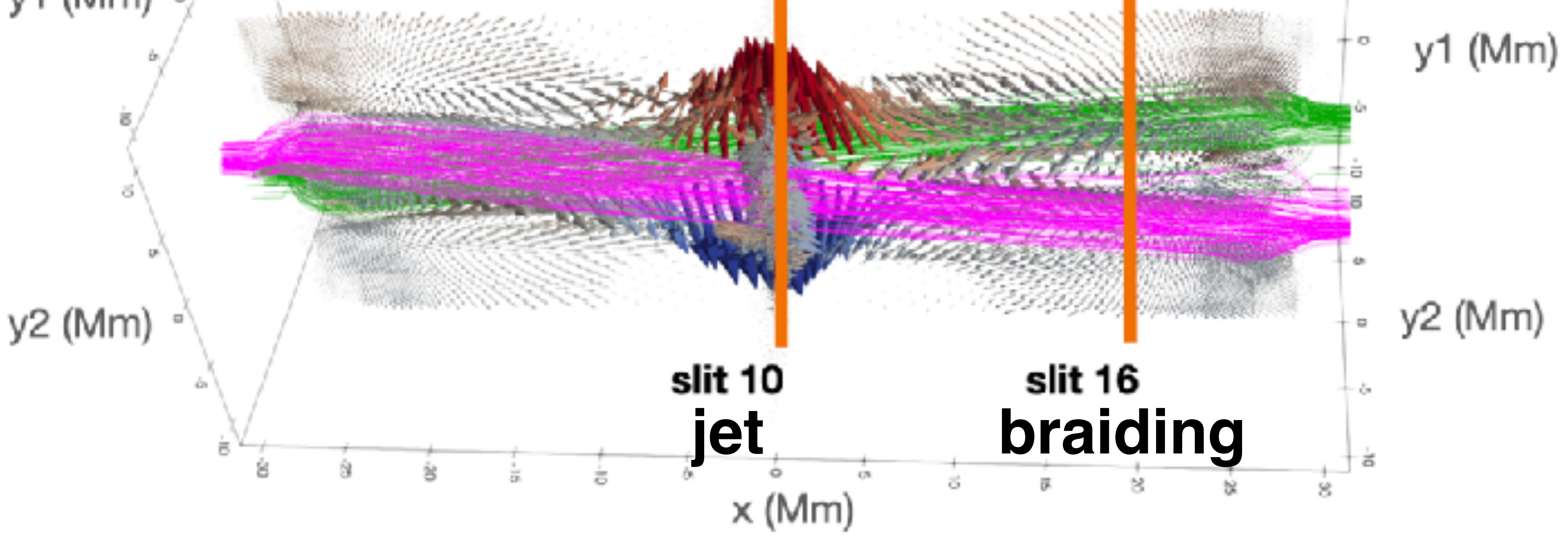



# Numerical model
# Reconnection and jets

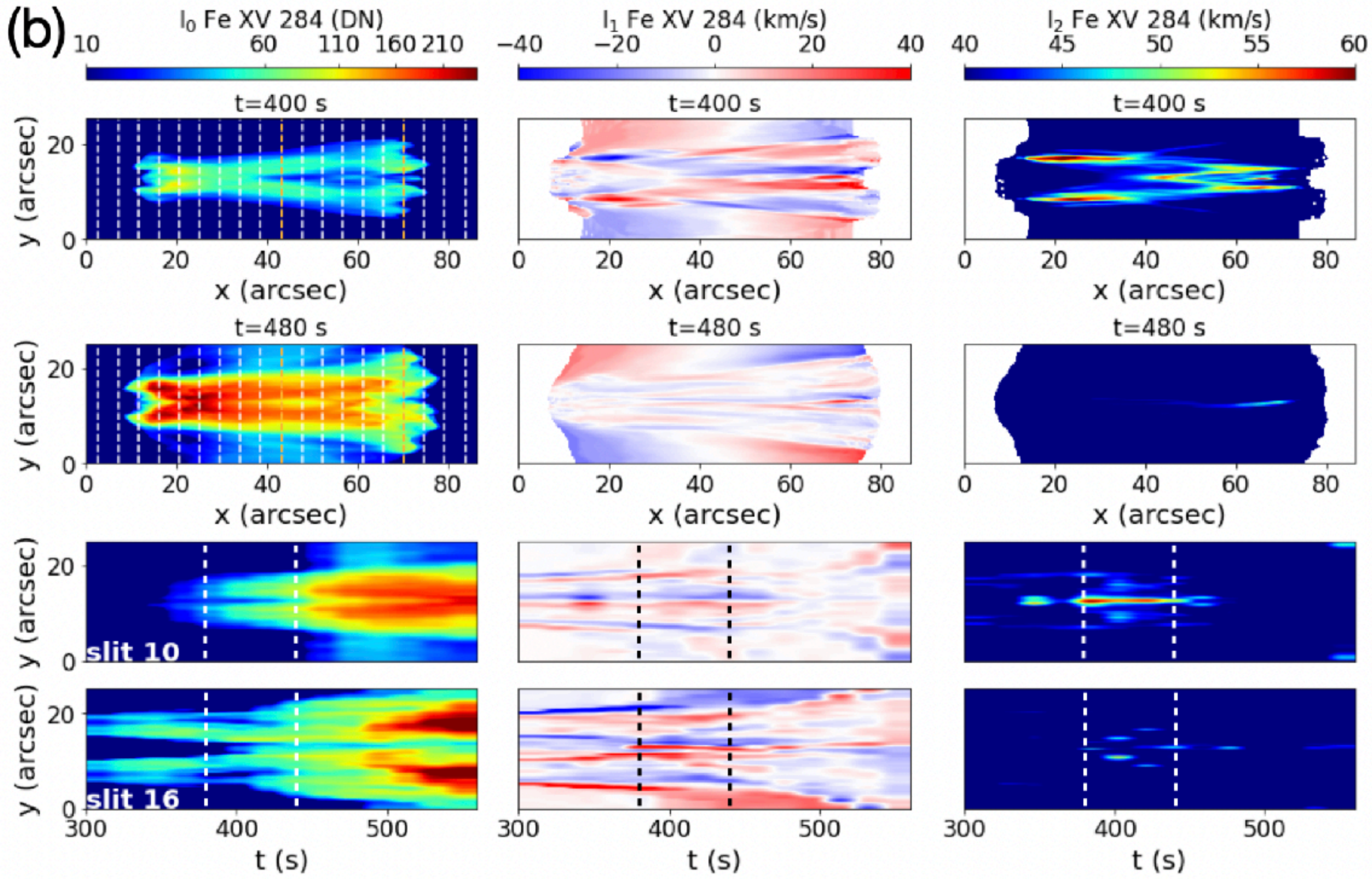


# MUSE observables




Line intensity | Doppler shift | Line width




**MUSE Fe XV 284 line**