HPC MHD modelling of unstable reconnecting plasma in the solar corona and EUV diagnostics with the MUSE mission

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- Is **Parker's topological dissipation by nanoflare-storms** an effective mechanism for magnetic energy dissipation?
- **MHD modelling**: full 3D simulation of two interacting magnetic threads undergoing a global MHD instability.
- How can **MUSE spectrograph** improve our understating on coronal heating?

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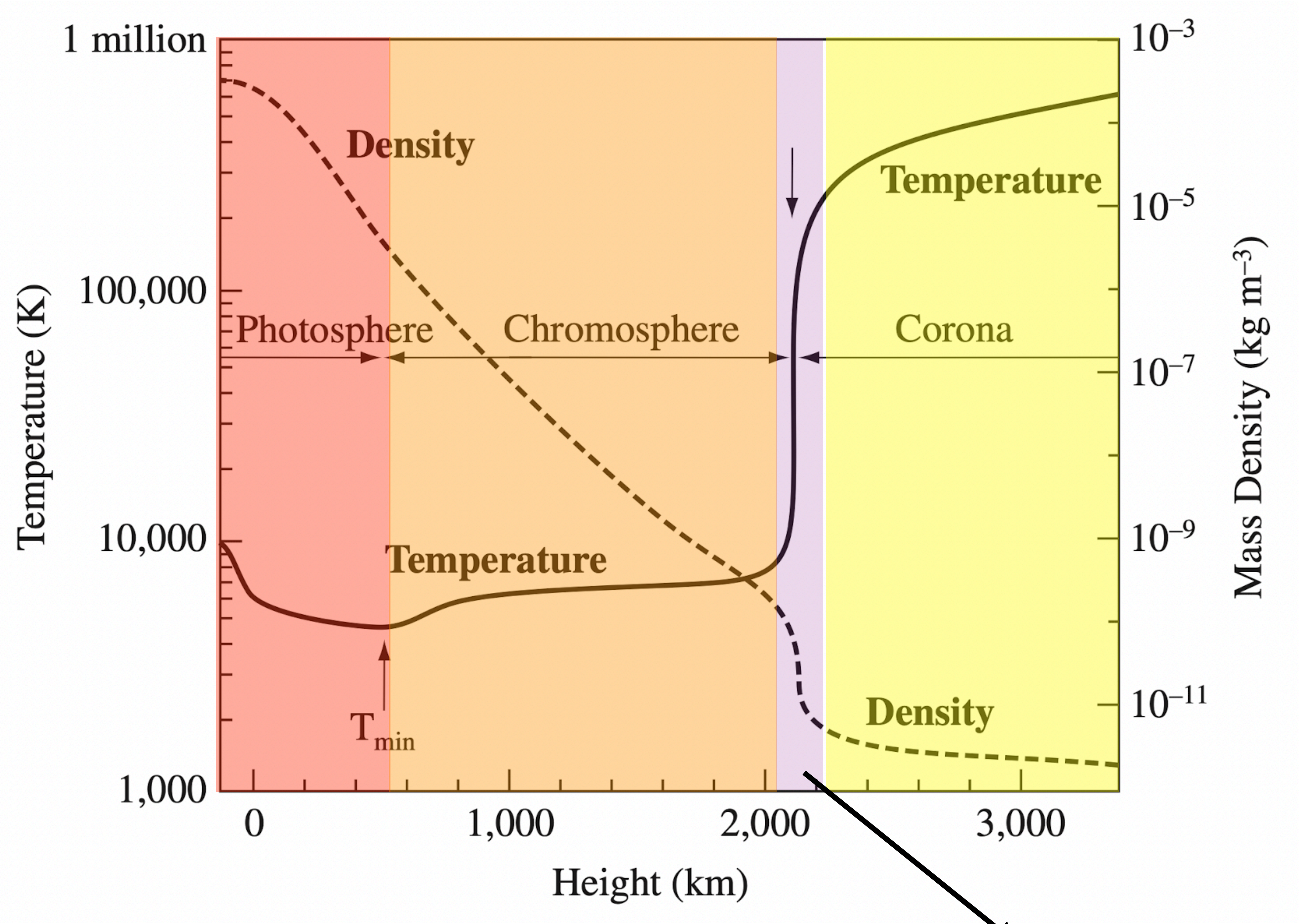
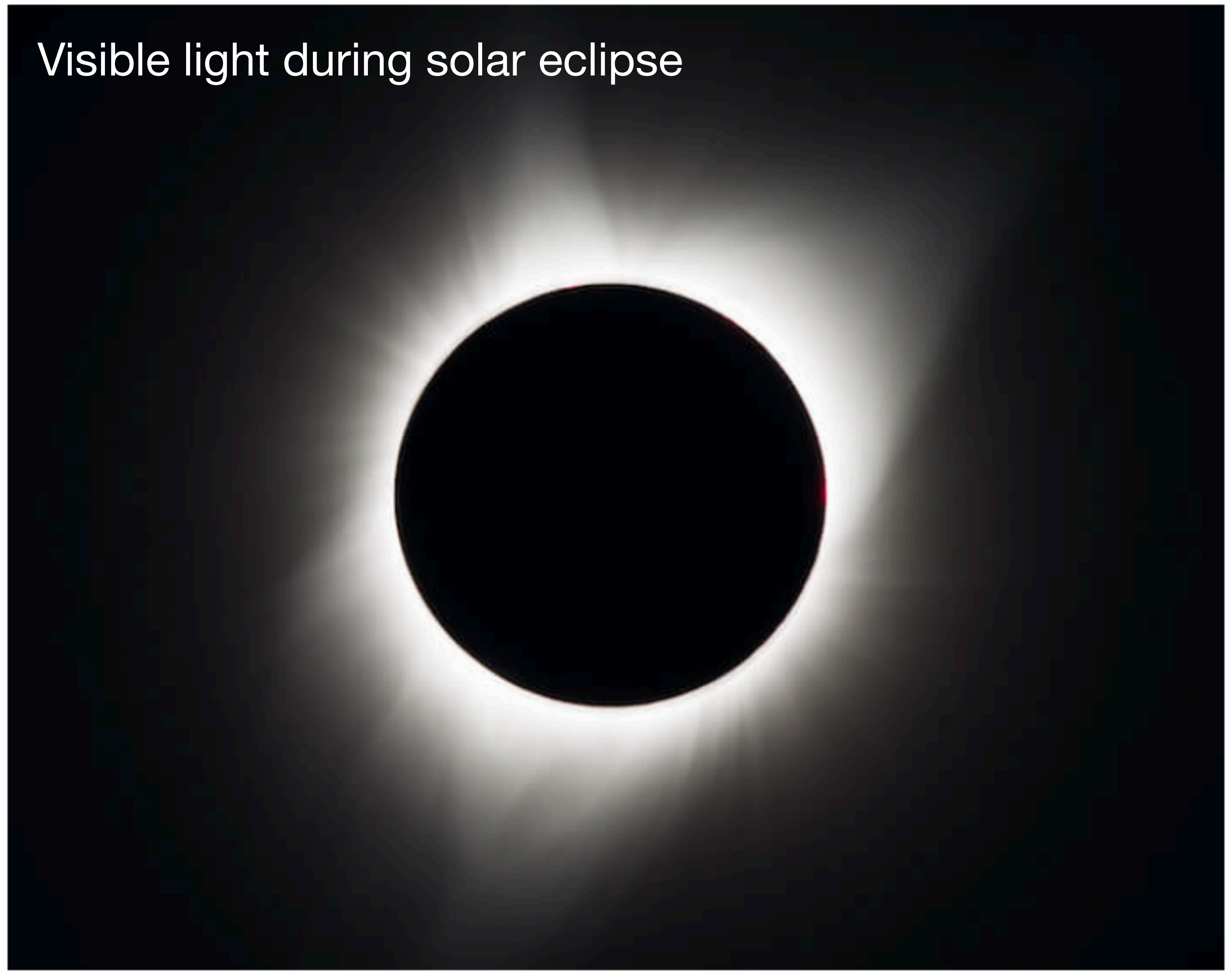
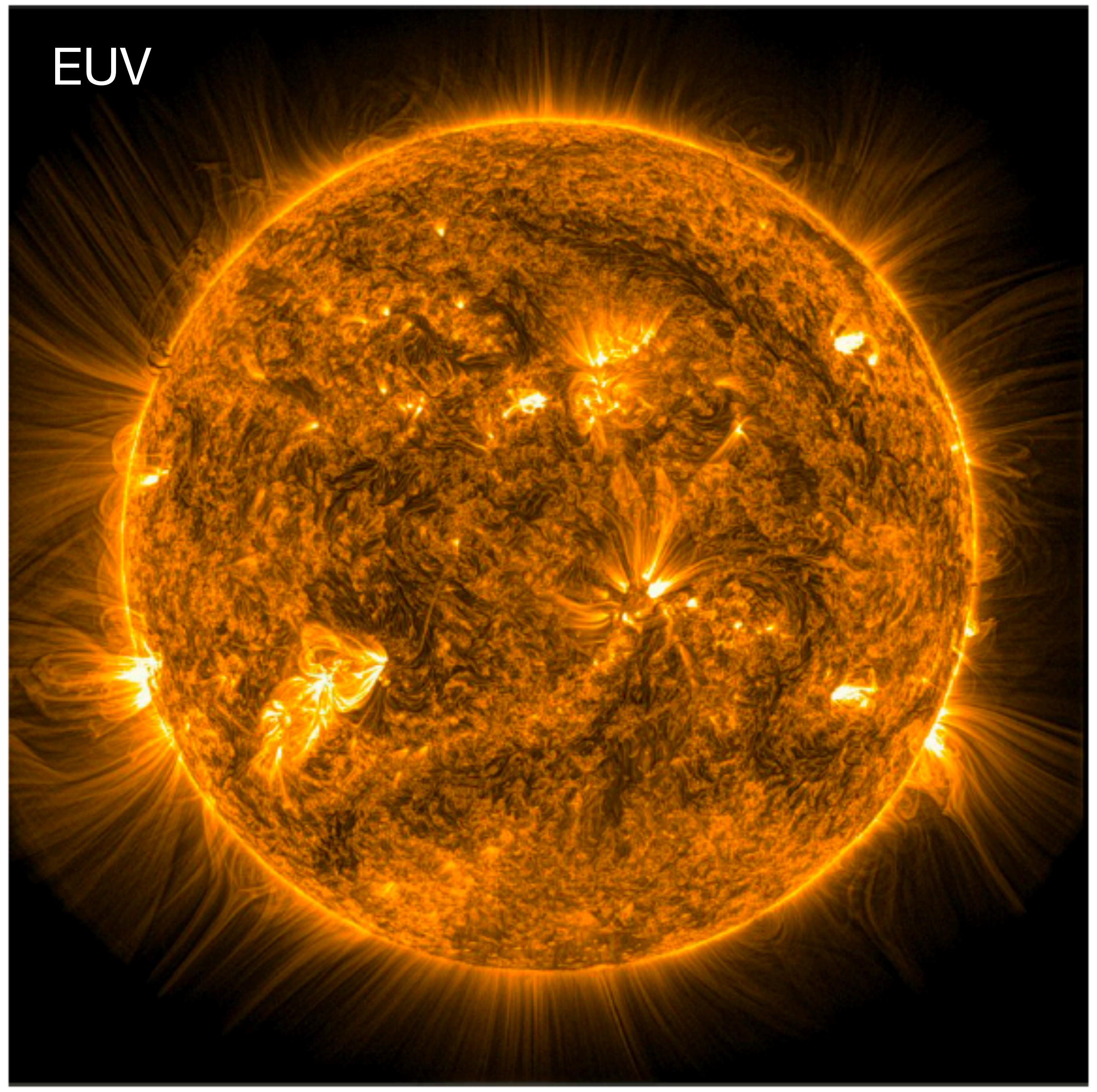
Addressing the coronal heating problem

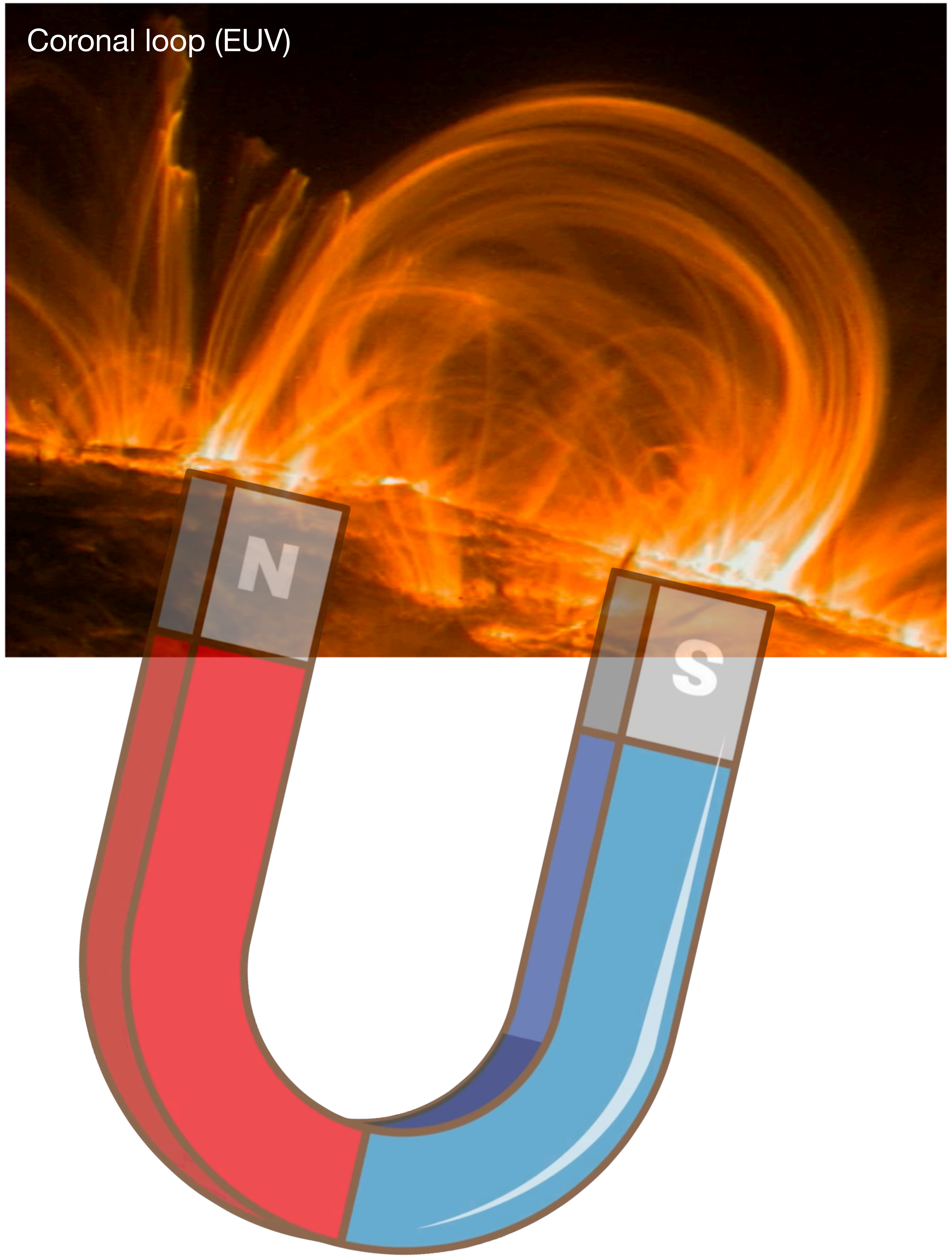


- **Photosphere**: ~ 6000 K hot, optically thick, absorption lines;
- **Chromosphere**: $\sim 10^4$ K hot, optically thick, emission features;
- **Corona**: $\sim 10^6$ K hot, optically thin, emission features,

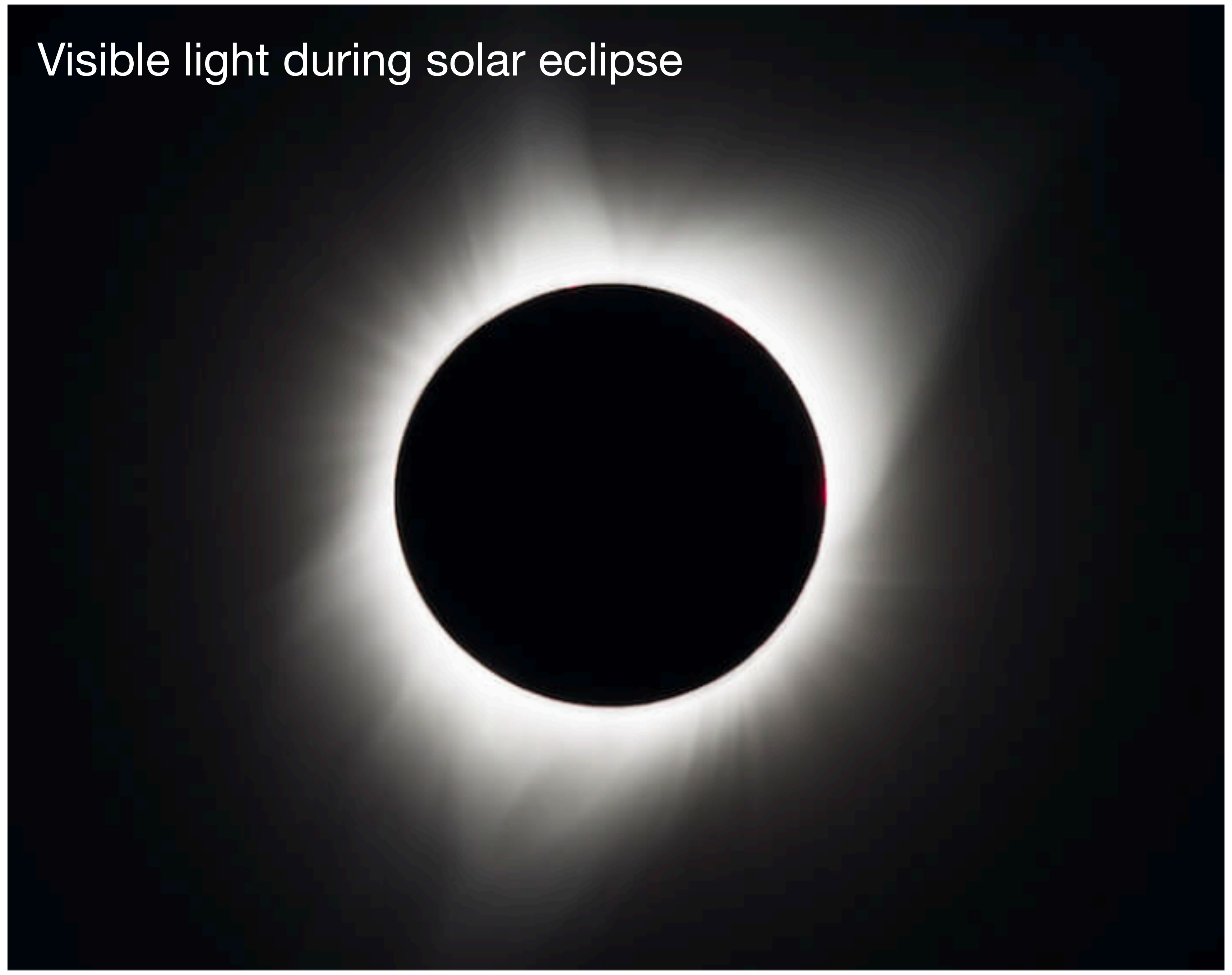
Transition region (< 100 km).

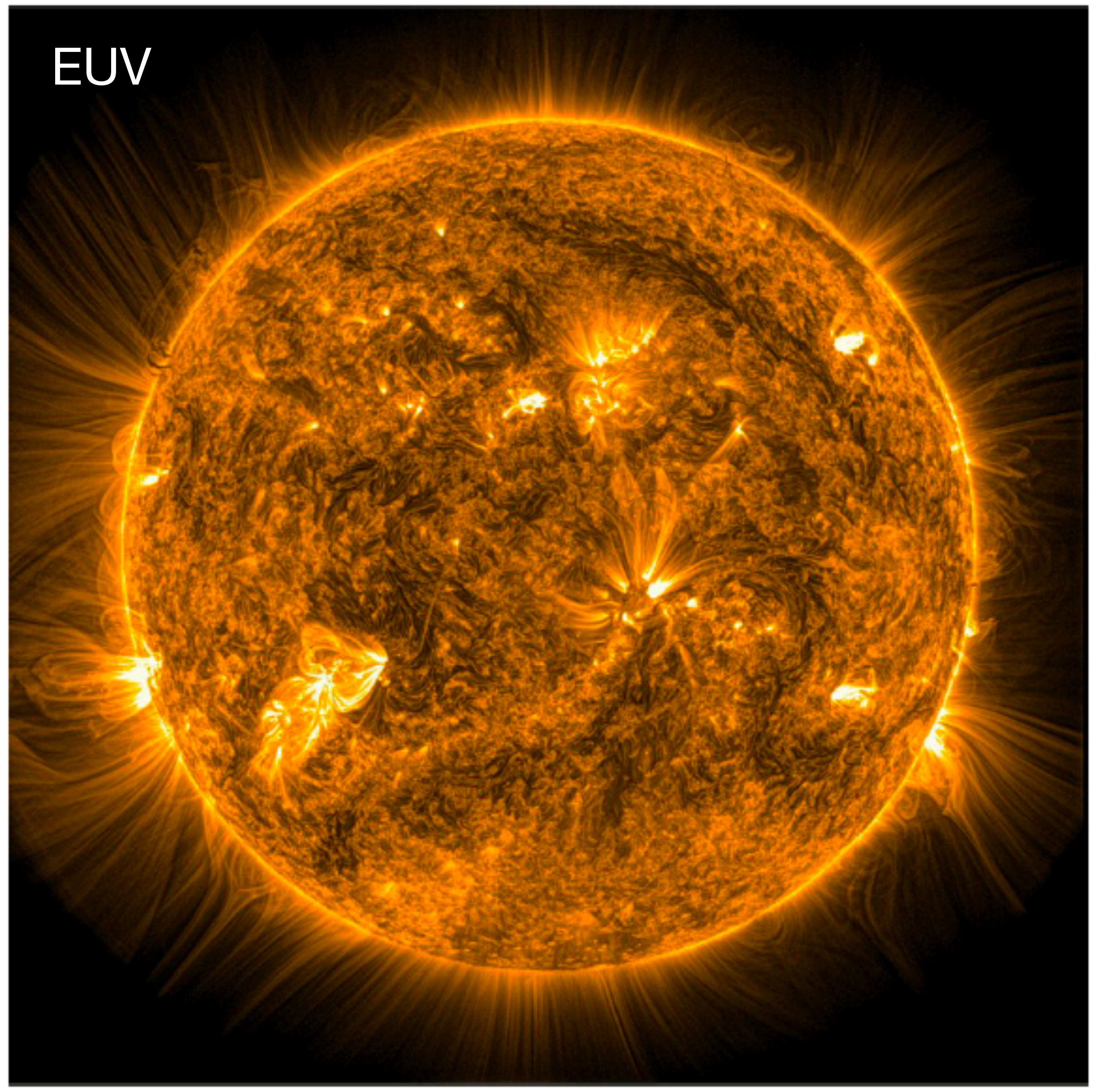


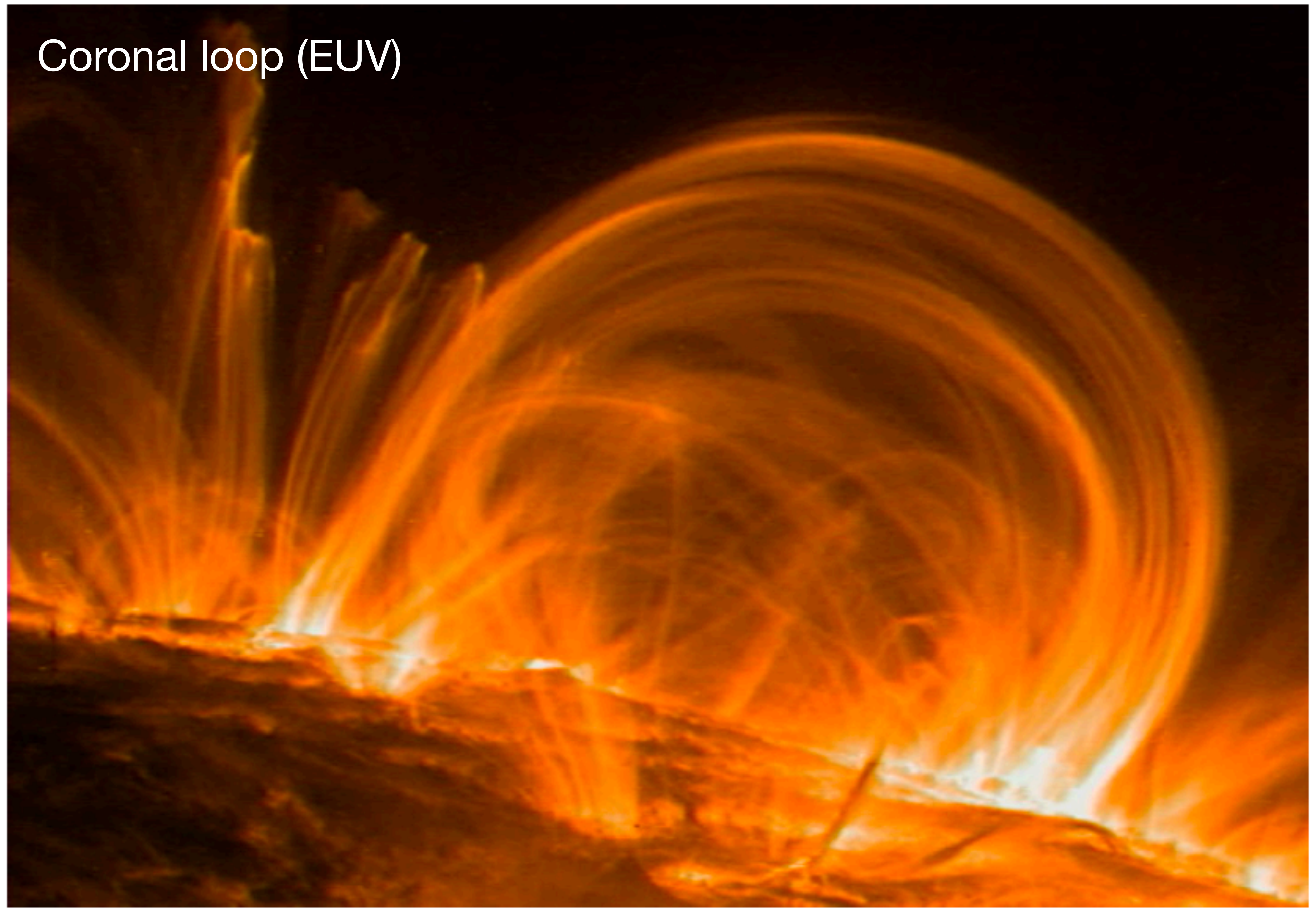




- **How the solar corona is heated to millions Kelvin degrees?**





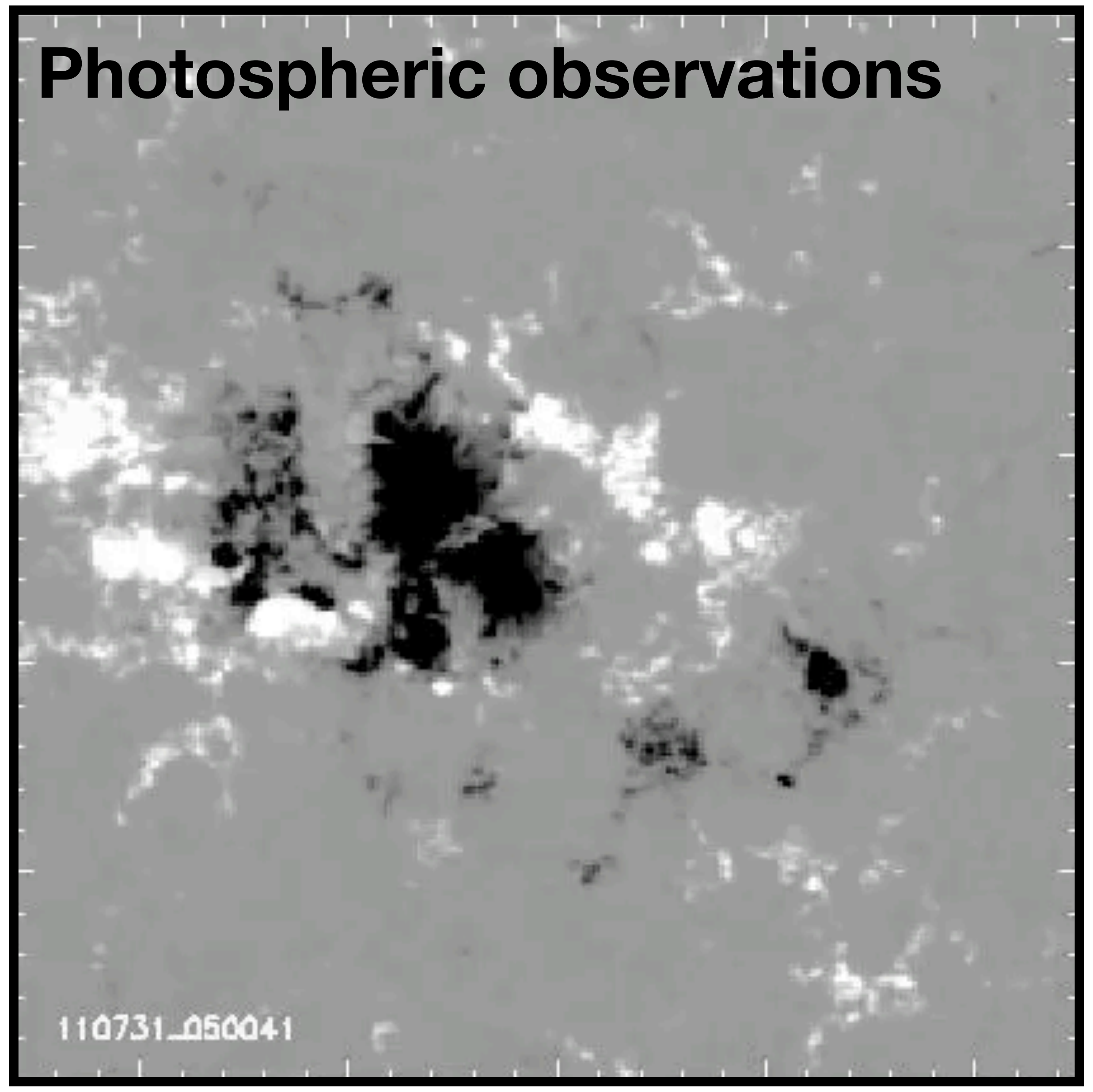


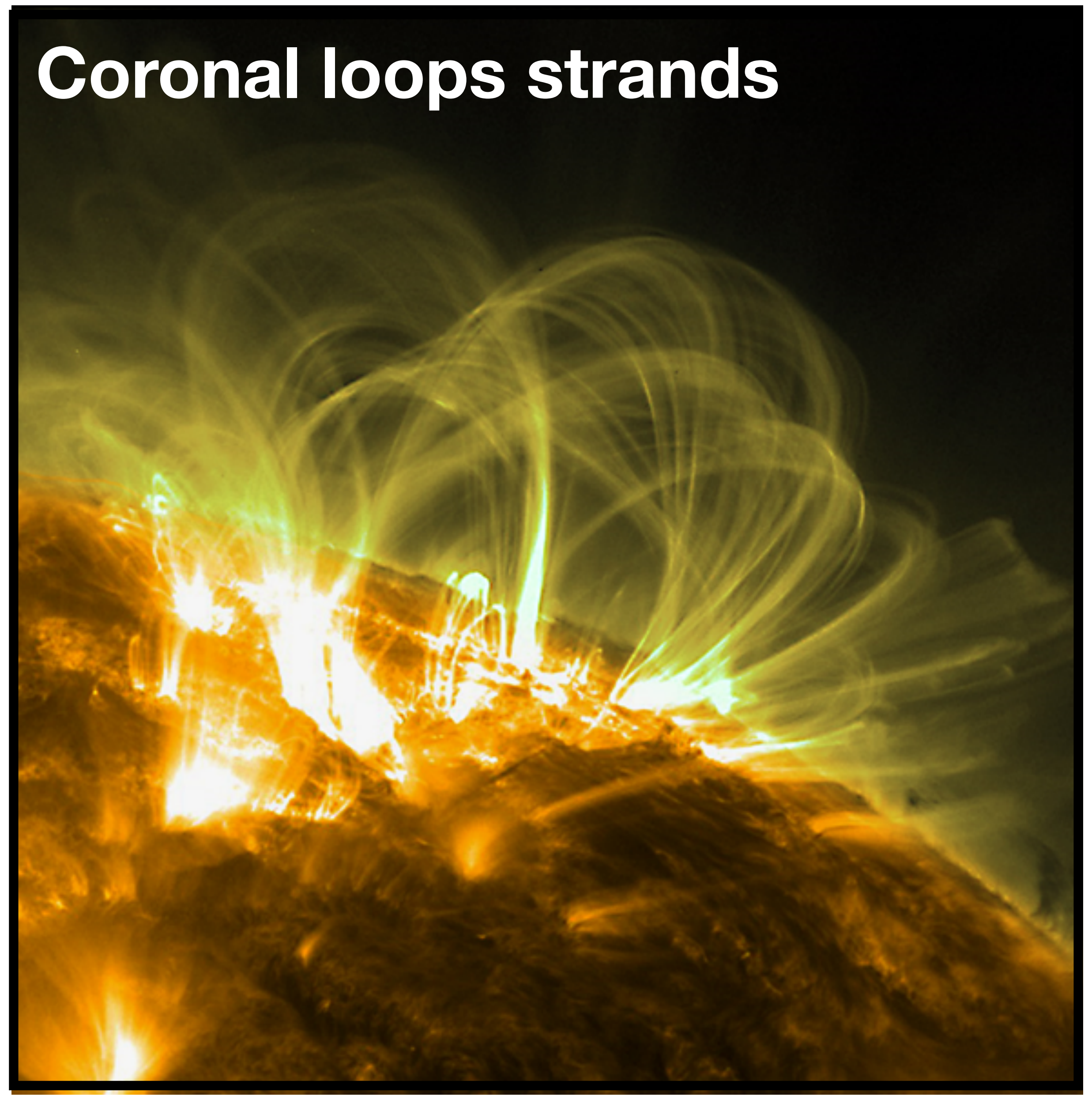
○ **How the solar corona is heated to millions Kelvin degrees?**

Magnetic field as reservoir of energy:

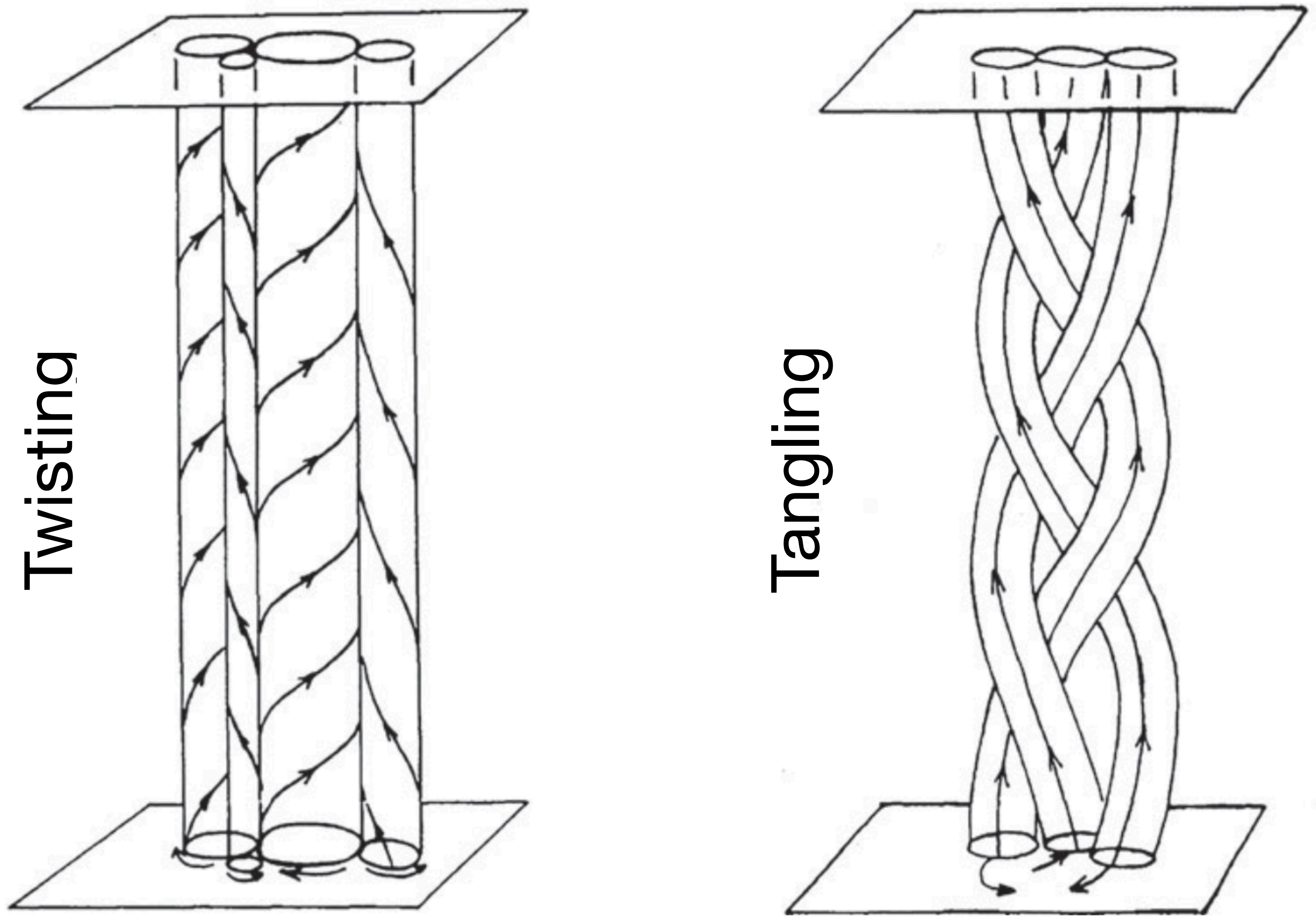
- What kind of mechanisms can efficiently convert magnetic energy into heat?
- How this different processes cooperate with each other?
- How the problem can be addressed by including the unavoidable and continuous interactions between corona, photosphere and chromosphere?

From Large scales …





Magnetic stress based heating mechanisms



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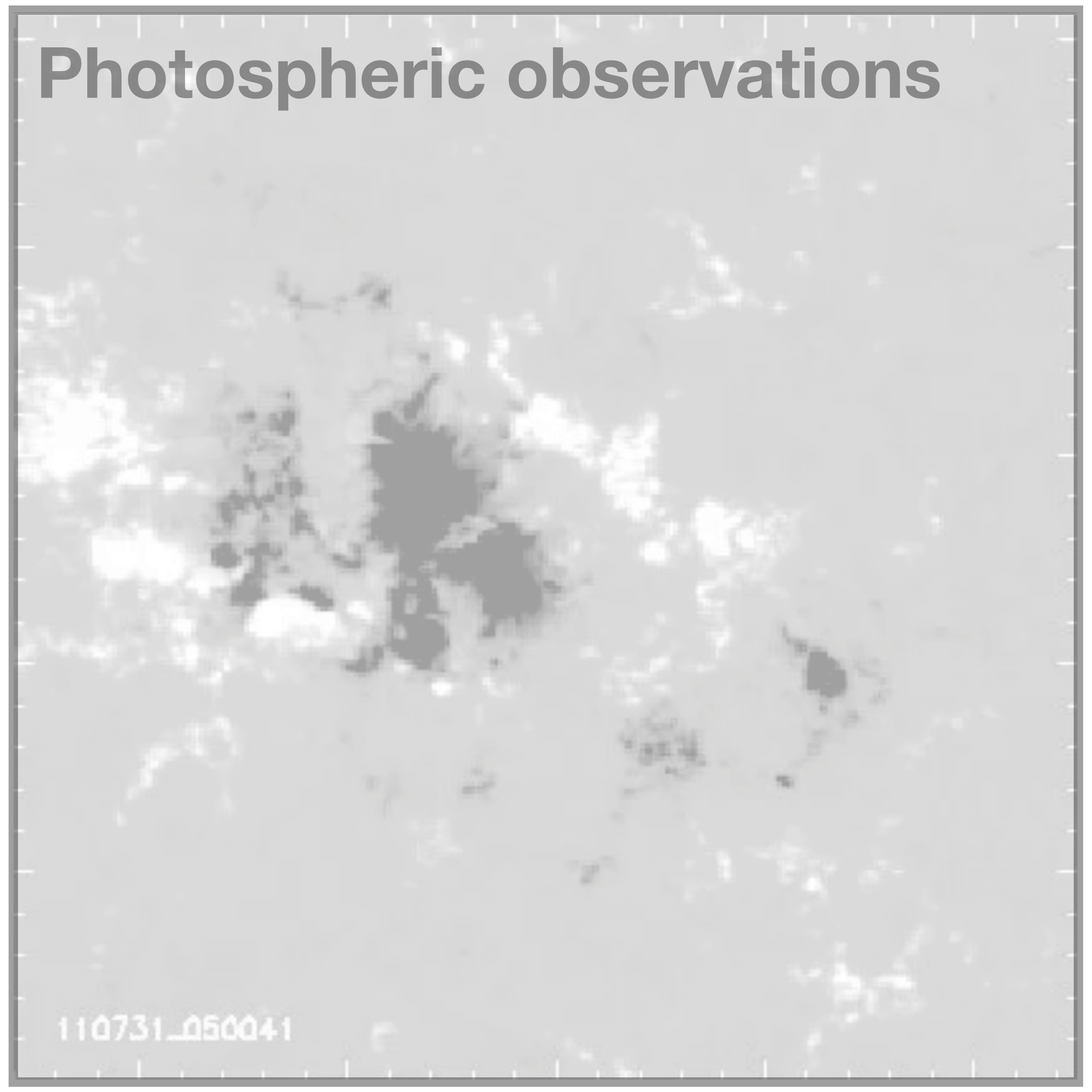

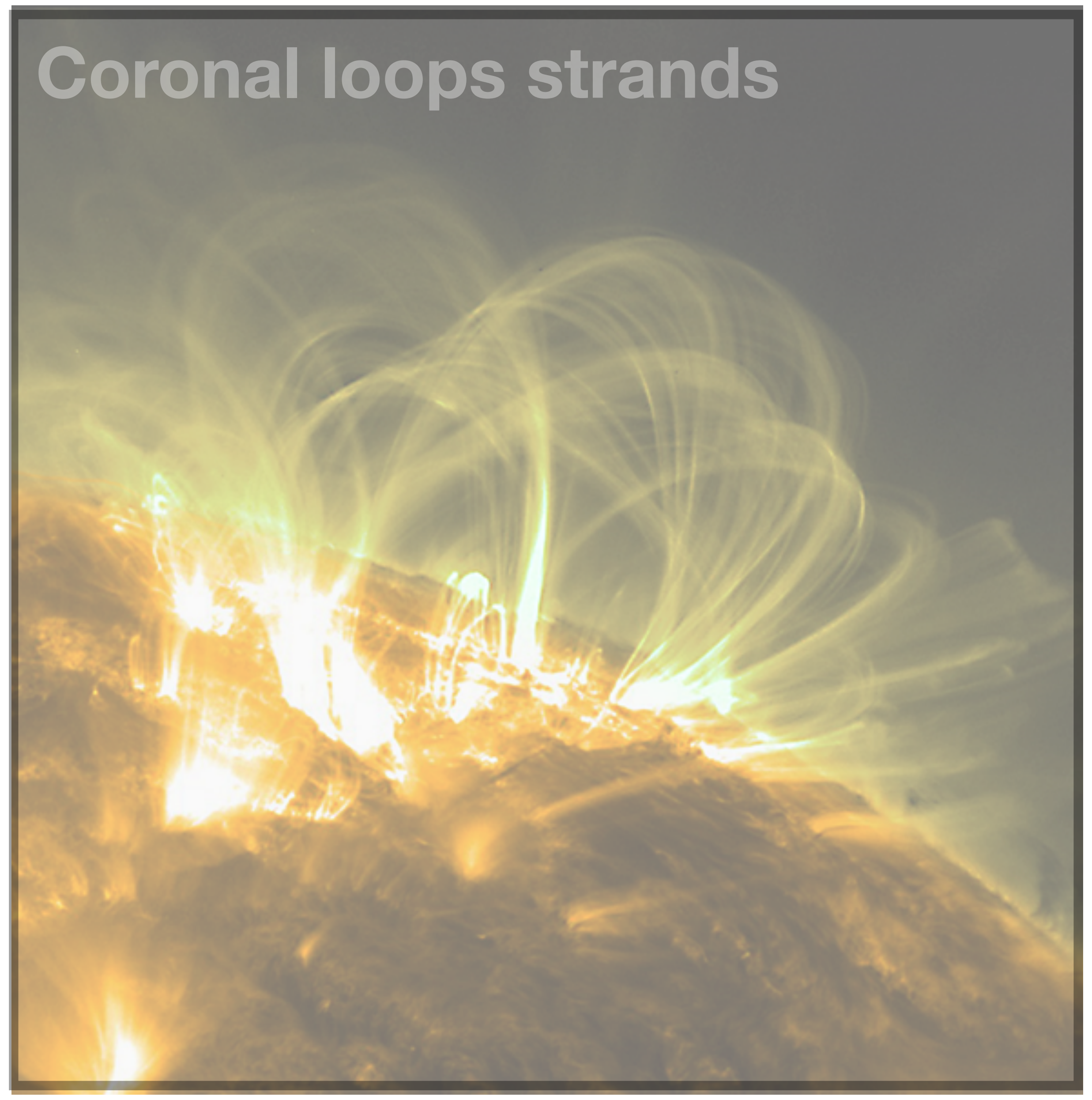

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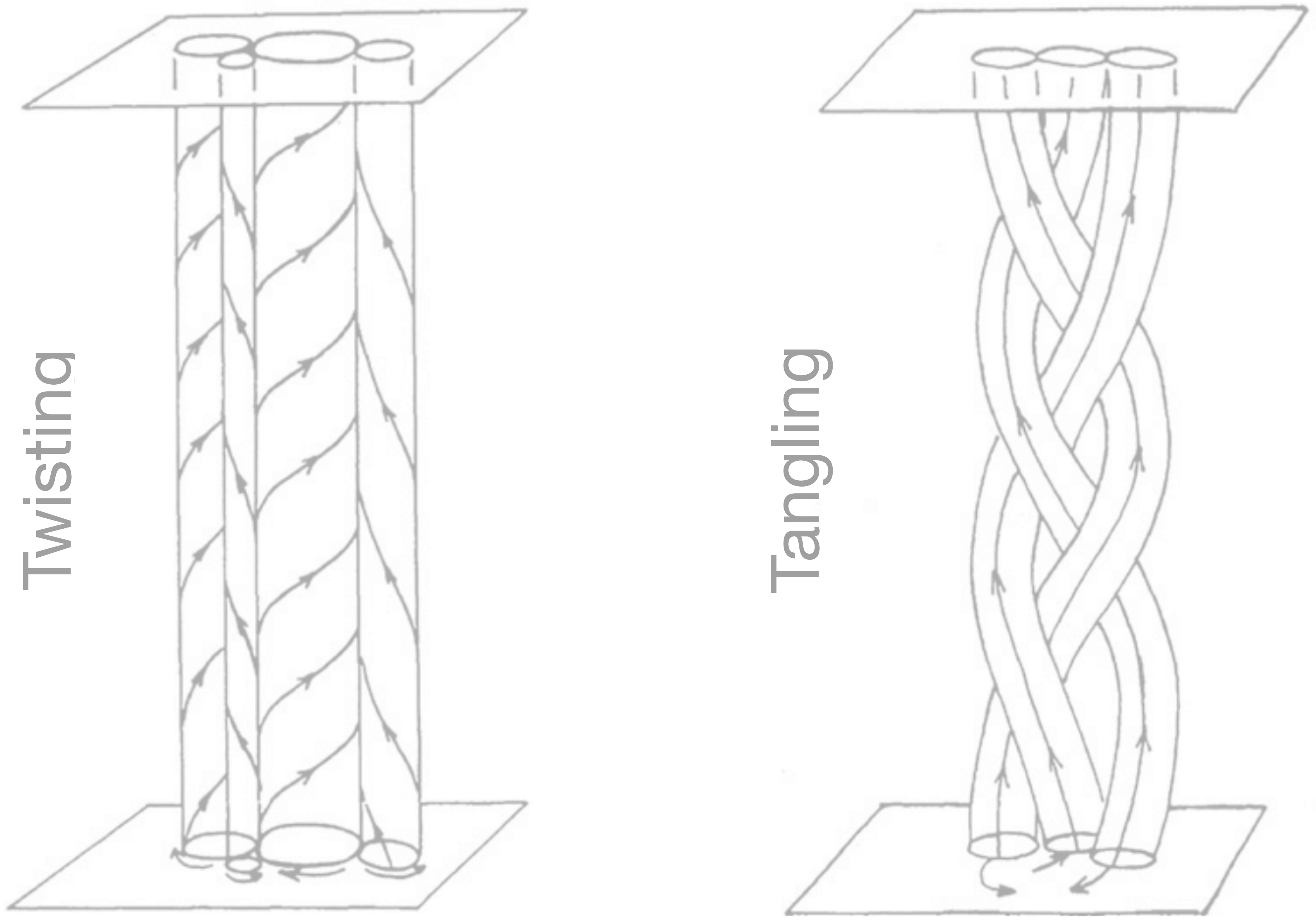
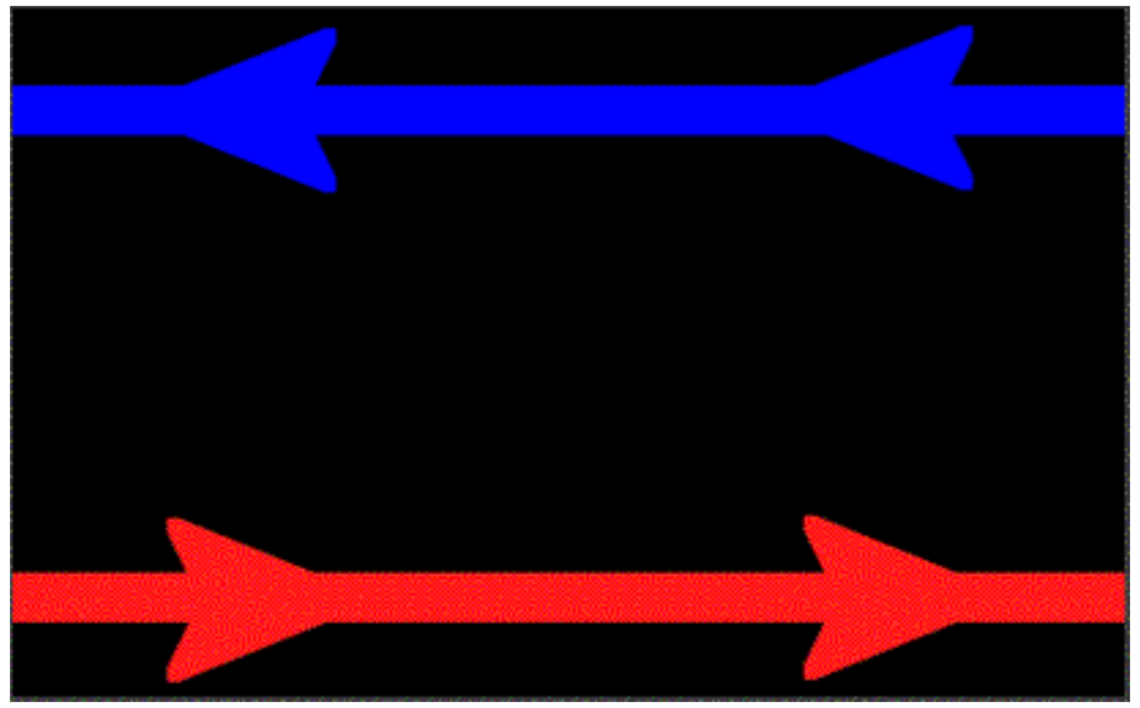
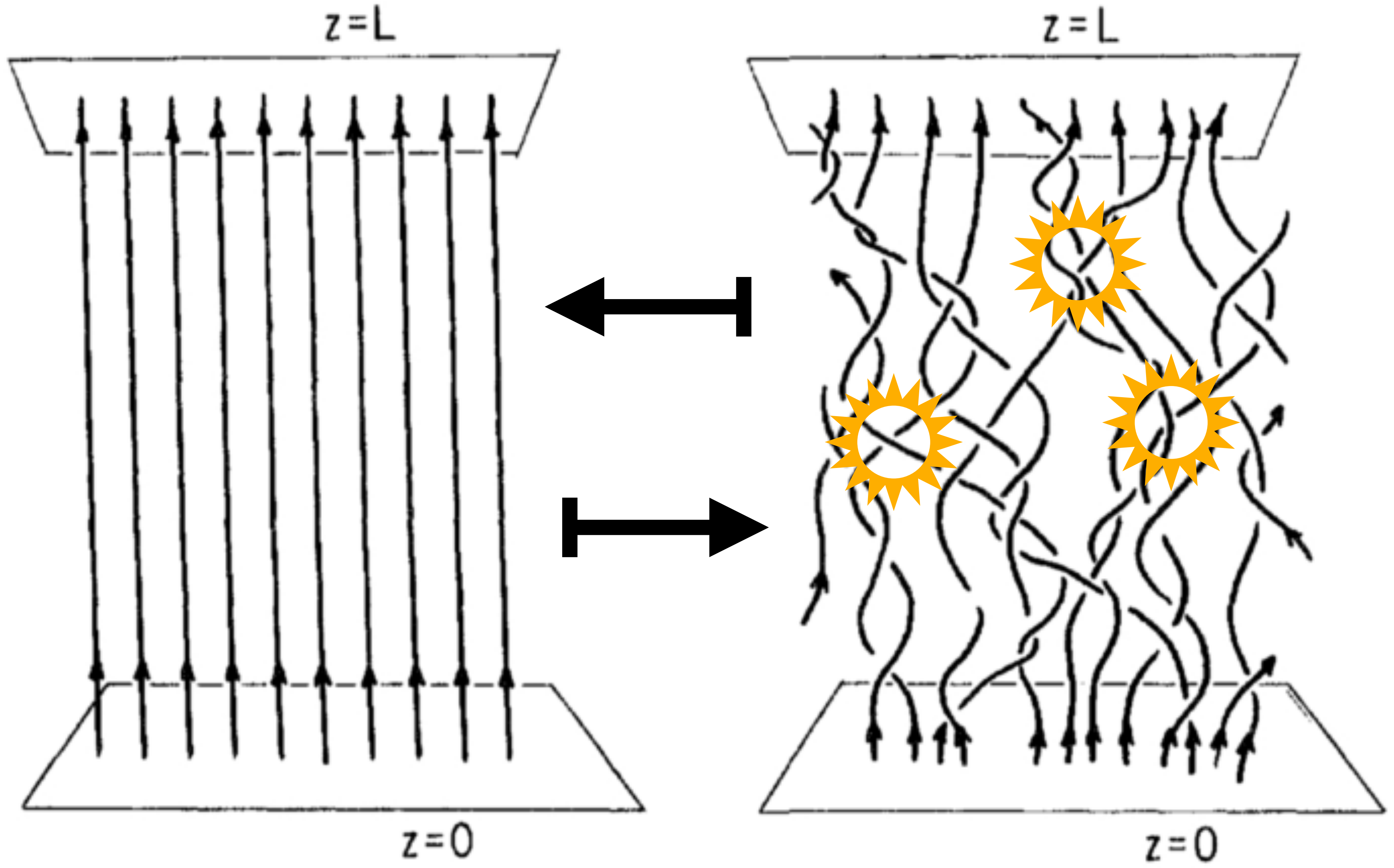


... to small scales

Topological dissipation (Parker, 1971): *large-scale magnetic field possesses a hydrostatic equilibrium only if the pattern of small-scale variations is uniform along the large-scale field […] The result is rapid dissipation and field-line merging, which quickly reduces the topology to the simple equilibrium form.*





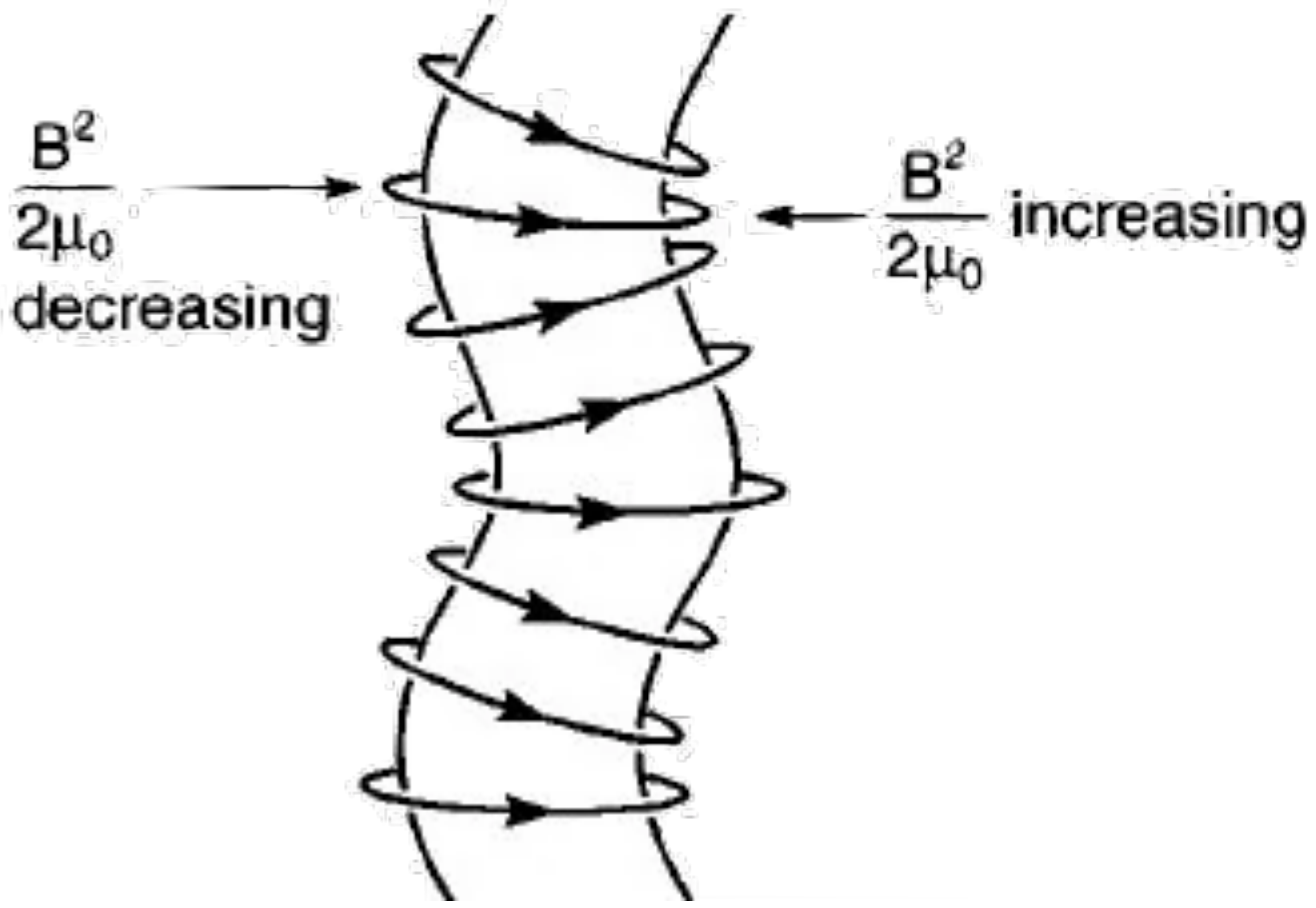
Key points

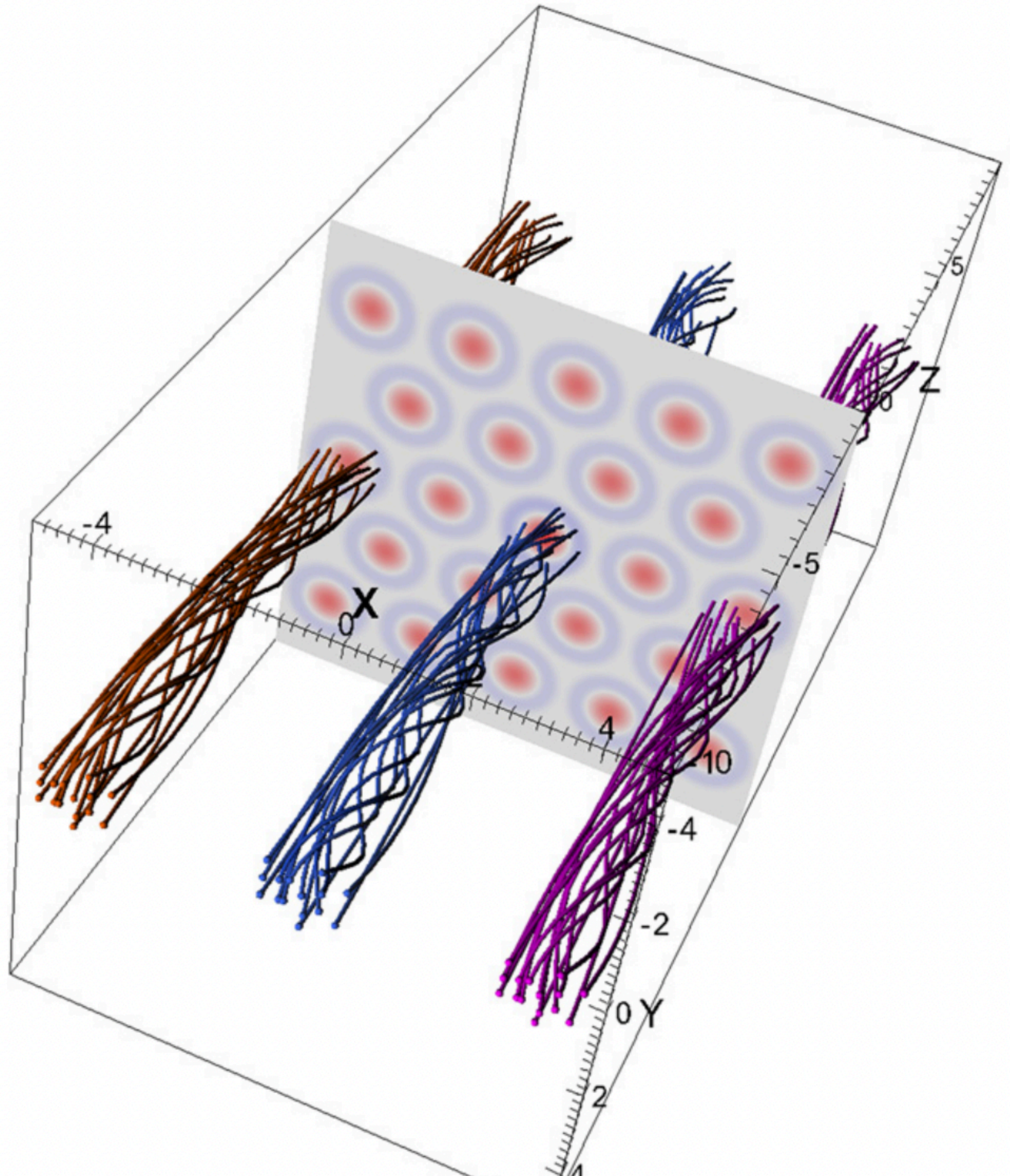
- Large scale magnetic structures;
- Irregular ad structured photospheric motions;
- Multi-thread structuring;
- Small scales, diffused heating.

MHD avalanches

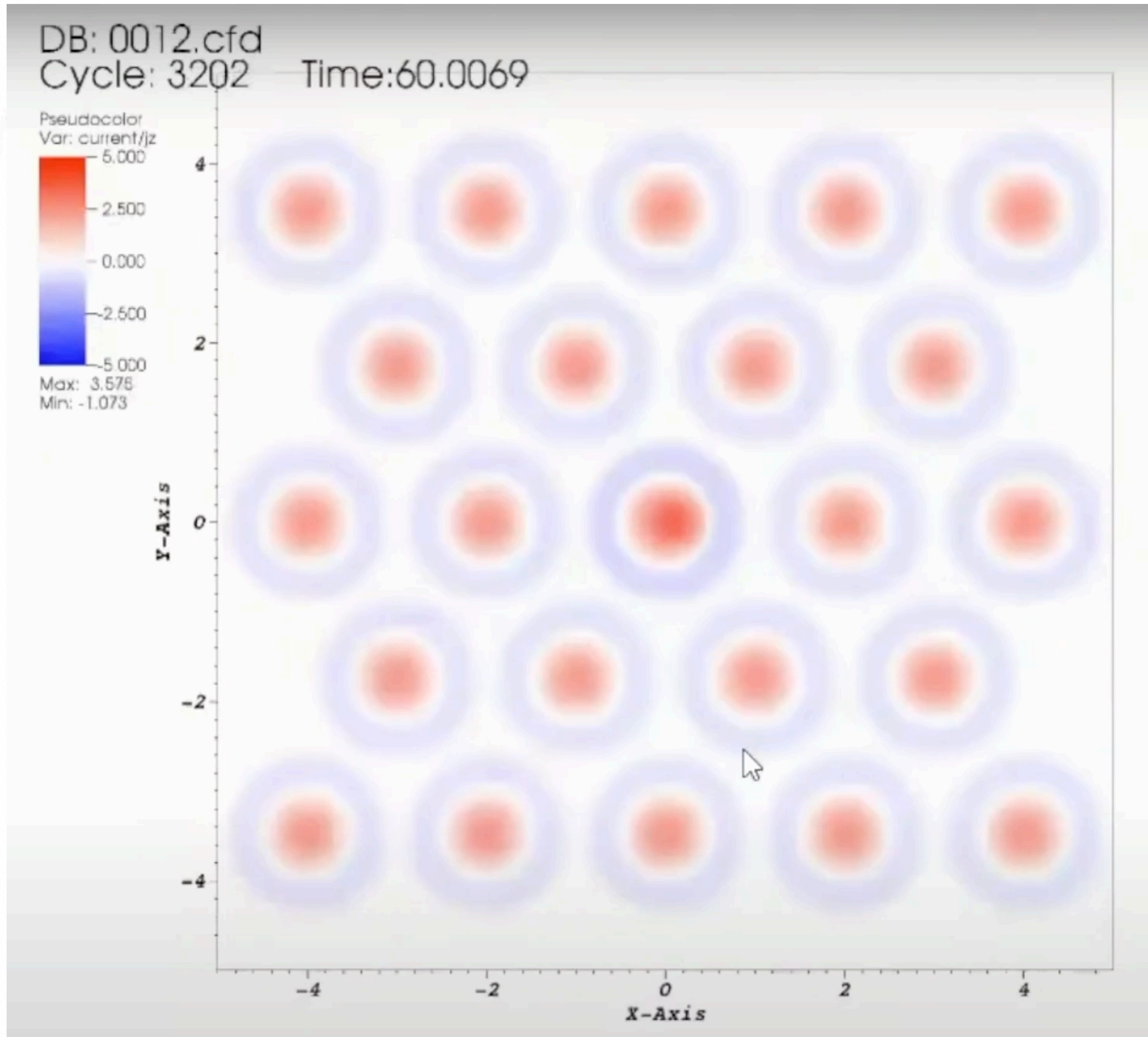
- **Initial condition**: multi threaded, highly twisted magnetic structure;
- **Domino effect**: localised instability leading to a large heating event;
- **Kink Instability** as key element for large scale energy release: initial helical perturbation fragments in a turbulent way. Can trigger an MHD avalanche.
- **Topological dissipation** (Parker, 1971): large-scale magnetic field resulting in rapid dissipation and field-line merging, to restore the topology to the simple equilibrium form;
- **State of the art:** Tam et al 2015, Hood et al 2016, Reid et al 2018, 2020 with relatively simple homogeneous atmosphere.

Kink-instability





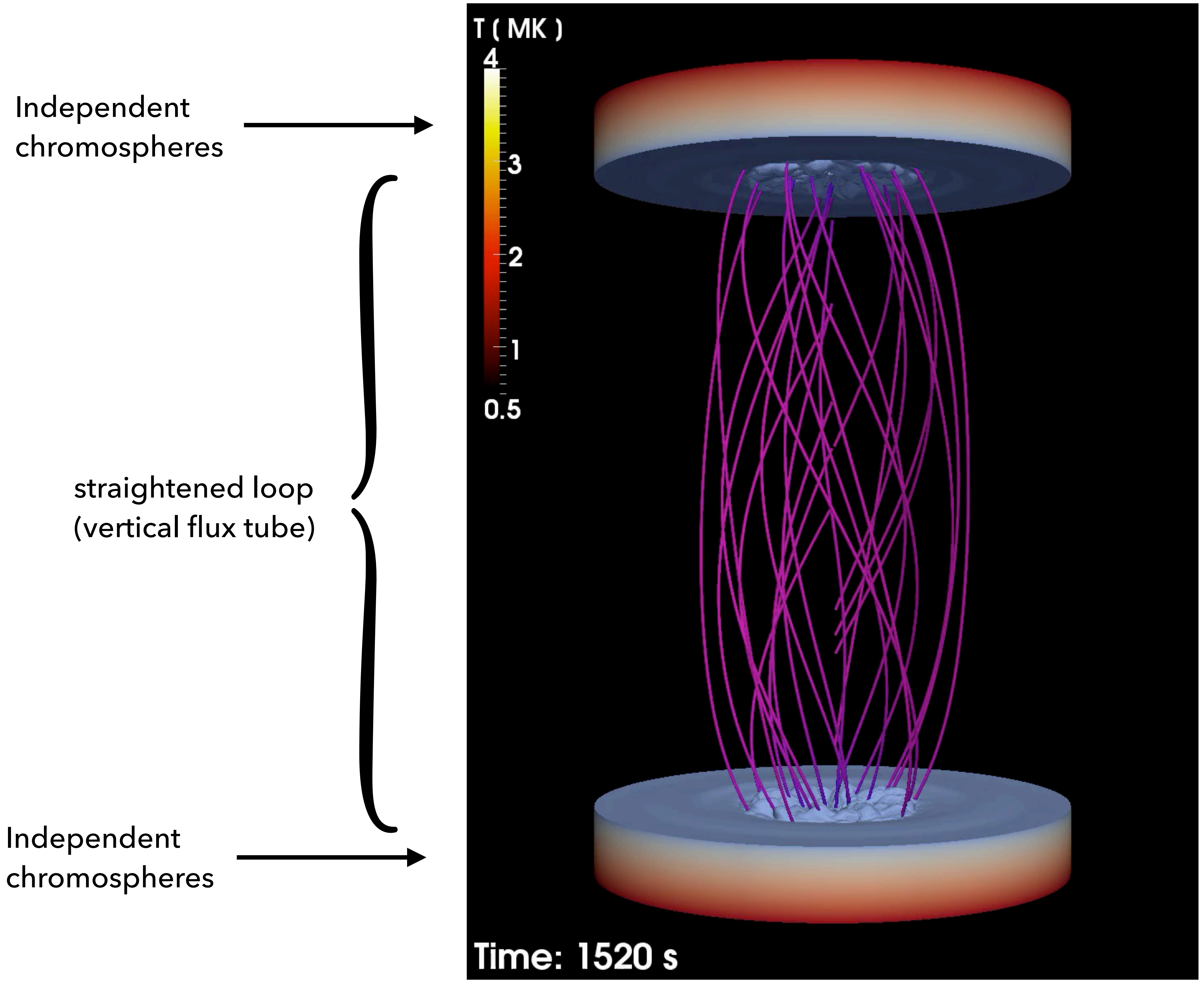
Hood et al. 2016: 23 threads, mid plane current



Goals

- Address **multiple strands interaction and instabilities** as in Hood et al 2016;
- Include **Chromosphere-TR-Corona Interactions** (stratified atmosphere): Reale et al 2016 model of a twisted coronal loop;

Reale et al. 2016: temperature



Coronal energy release by MHD avalanches

Effects on a structured, active region, multi-threaded coronal loop

G. Cozzo[1], J. Reid[2], P. Pagano[1,3], F. Reale[1,3], and A. W. Hood[2]

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Full MHD equations:

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

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \boldsymbol{v}) = -\nabla \cdot \left(P \mathbf{I} + \frac{B^2}{8\pi} \mathbf{I} - \frac{\boldsymbol{B} \boldsymbol{B}}{8\pi}\right)$$

Gravity → $+\rho \boldsymbol{g},$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = \eta \nabla^2 \boldsymbol{B},$$

$$\frac{\partial}{\partial t}\left(\frac{B^2}{8\pi} + \frac{1}{2}\rho v^2 + \rho \epsilon + \rho g h\right) + \nabla \cdot \left[\frac{c}{4\pi} \boldsymbol{E} \times \boldsymbol{B} + \frac{1}{2}\rho v^2 \boldsymbol{v} + \frac{\gamma}{\gamma - 1} P \boldsymbol{v} + \boldsymbol{F}_c + \rho g h \boldsymbol{v}\right] = -\Lambda(T) n_e n_H + H_0,$$

Radiative losses

Thermal conduction

$$P = (\gamma - 1)\rho \epsilon = \frac{2 k_B}{\mu m_H} \rho T,$$

$$\boldsymbol{j} = \frac{c}{4\pi} \nabla \times \boldsymbol{B},$$

$$\boldsymbol{E} = -\frac{\boldsymbol{v}}{c} \times \boldsymbol{B} + \frac{\boldsymbol{j}}{\sigma},$$

Numerical approach

- **Pluto Code** (Mignone et al. 2007);
- MHD equation in eulerian conservative form;
  - Mass continuity equation
  - Momentum Equation
  - Energy Equation
  - Magnetic Induction Equation + CS
  - Ideal gas law
- Stretched geometry (loop length >> width);
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- Stratified atmosphere (chromosphere + TR + corona),
  - back ground heating,
  - thermal conduction,
  - radiative cooling,
  - plasma beta variation,
  - magnetic field tapering,
- Boundary conditions:
  - smooth rotational plasma motions at photospheric boundaries;
  - periodic lateral BC;

PLUTO: A NUMERICAL CODE FOR COMPUTATIONAL ASTROPHYSICS

A. Mignone,[1,2] G. Bodo,[2] S. Massaglia,[1] T. Matsakos,[1] O. Tesileanu,[1] C. Zanni,[3] and A. Ferrari[1]

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ABSTRACT

We present a new numerical code, PLUTO, for the solution of hypersonic flows in 1, 2, and 3 spatial dimensions and different systems of coordinates. The code provides a multiphysics, multialgorithm modular environment particularly oriented toward the treatment of astrophysical flows in presence of discontinuities. Different hydrodynamic modules and algorithms may be independently selected to properly describe Newtonian, relativistic, MHD, or relativistic MHD fluids. The modular structure exploits a general framework for integrating a system of conservation laws, built on modern Godunov-type shock-capturing schemes. Although a plethora of numerical methods has been successfully developed over the past two decades, the vast majority shares a common discretization recipe, involving three general steps: a piecewise polynomial reconstruction followed by the solution of Riemann problems at zone interfaces and a final evolution stage. We have checked and validated the code against several benchmarks available in literature. Test problems in 1, 2, and 3 dimensions are discussed.

Subject headings: hydrodynamics — methods: numerical — MHD — relativity–shock waves

Online material: color figures

1. INTRODUCTION

Theoretical models based on direct numerical simulations have unveiled a new way toward a better comprehension of the rich and complex phenomenology associated with astrophysical plasmas.

Finite difference codes such as ZEUS (Stone & Norman 1992a, 1992b) or NIRVANA+ (Ziegler 1998) inaugurated this novel era and have been used by an increasingly large fraction of researchers nowadays. However, as reported in Falle (2002), the lack of upwinding techniques and conservation properties have progressively moved scientist's attention toward more accurate and robust methods. In this respect, the successful employment of the so-called high-resolution shock-capturing (HRSC) schemes have revealed a mighty tool to investigate fluid dynamics in nonlinear regimes. Some of the motivations behind their growing popularity is the ability to model strongly supersonic flows while retaining robustness and stability. The unfamiliar reader is referred to the books of Toro (1997), LeVeque (1998), and references therein for a more comprehensive overview.

Implementation of HRSC algorithms is based on a conservative formulation of the fluid equations and proper upwinding requires an exact or approximate solution (Roe 1986) to the Riemann problem, i.e., the decay of a discontinuity separating two constant states. This approach dates back to the pioneering work of Godunov (1959), and it has now become the leading line in developing high-resolution codes examples of which include FLASH (Fryxell et al. 2000 for reactive hydrodynamics), the special relativistic hydro code GENESIS (Aloy et al. 1999), the versatile advection code (VAC; Tóth 1996), or the new NIRVANA (Ziegler 2004).

Most HRSC algorithms are based on the so-called reconstruct-solve-average (RSA) strategy. In this approach volume averages are first reconstructed using piecewise monotonic interpolants inside each computational cell. A Riemann problem is then solved at each interface with discontinuous left and right states, and the solution is finally evolved in time. It turns out that this sequence of steps is quite general for many systems of conservation laws, and therefore, it provides a general framework under which we have developed a multiphysics, multialgorithm, high-resolution code, PLUTO. The code is particularly suitable for time-dependent, explicit computations of highly supersonic flows in the presence of strong discontinuities, and it can be employed under different regimes, i.e., classical, relativistic unmagnetized, and magnetized flows. The code is structured in a modular way, allowing a new module to be easily incorporated. This flexibility turns out to be quite important, since many aspects of computational fluid dynamics are still in rapid development. Besides, the advantage offered by a multiphysics, multisolver code is also to supply the user with the most appropriate algorithms and, at the same time, provide interscheme comparison for a better verification of the simulation results. PLUTO is entirely written in the C programming language and can run on either single processor or parallel machines, the latter functionality being implemented through the message passing interface (MPI) library. The code has already been successfully employed in the context of stellar and extragalactic jets (Bodo et al. 2003; Mignone et al. 2004, 2005a), radiative shocks (Mignone 2005; Massaglia et al. 2005), accretion disks (Bodo et al. 2005; Tevzadze et al. 2006), magneto-rotational instability, relativistic Kelvin-Helmholtz instability, and so forth.

The paper is structured as follows: in § 2 we give a description of the code design; in § 3 we introduce the physics modules available in the code; in § 4 we give a short overview on source terms and nonhyperbolicity; and in § 5 the code is validated against several standard benchmarks.

2. CODE DESIGN

PLUTO is designed to integrate a general system of conservation laws that we write as

$$\frac{\partial \boldsymbol{U}}{\partial t} = -\nabla \cdot \mathbf{T}(\boldsymbol{U}) + \boldsymbol{S}(\boldsymbol{U}). \qquad (1)$$

Here $\boldsymbol{U}$ denotes a state vector of conservative quantities, $\mathbf{T}(\boldsymbol{U})$ is a rank 2 tensor, the rows of which are the fluxes of each component

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[3] Laboratoire d'Astrophysique de l'Observatoire de Grenoble, 414 Rue de la Piscine, 38041 Grenoble Cedex 09, France.

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Numerical approach

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  - thermal conduction,
  - radiative cooling,
  - plasma beta variation,
  - magnetic field tapering,
- Boundary conditions:
  - smooth rotational plasma motions at photospheric boundaries;
  - periodic lateral BC;

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) &= 0 \\
\frac{\partial m_x}{\partial t} + \nabla \cdot (m_x \boldsymbol{v} - B_x \boldsymbol{B}) + \frac{\partial p_t}{\partial x} &= \rho \left(g_x - \frac{\partial \Phi}{\partial x} \right) \\
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$$\nabla \cdot \overrightarrow{B} = 0$$

$$P = (\gamma - 1)\rho\epsilon = \frac{2k_b}{\mu m_H}\rho T$$

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$$\frac{\partial B_x}{\partial t} + \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = 0$$

$$\frac{\partial B_y}{\partial t} + \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = 0$$

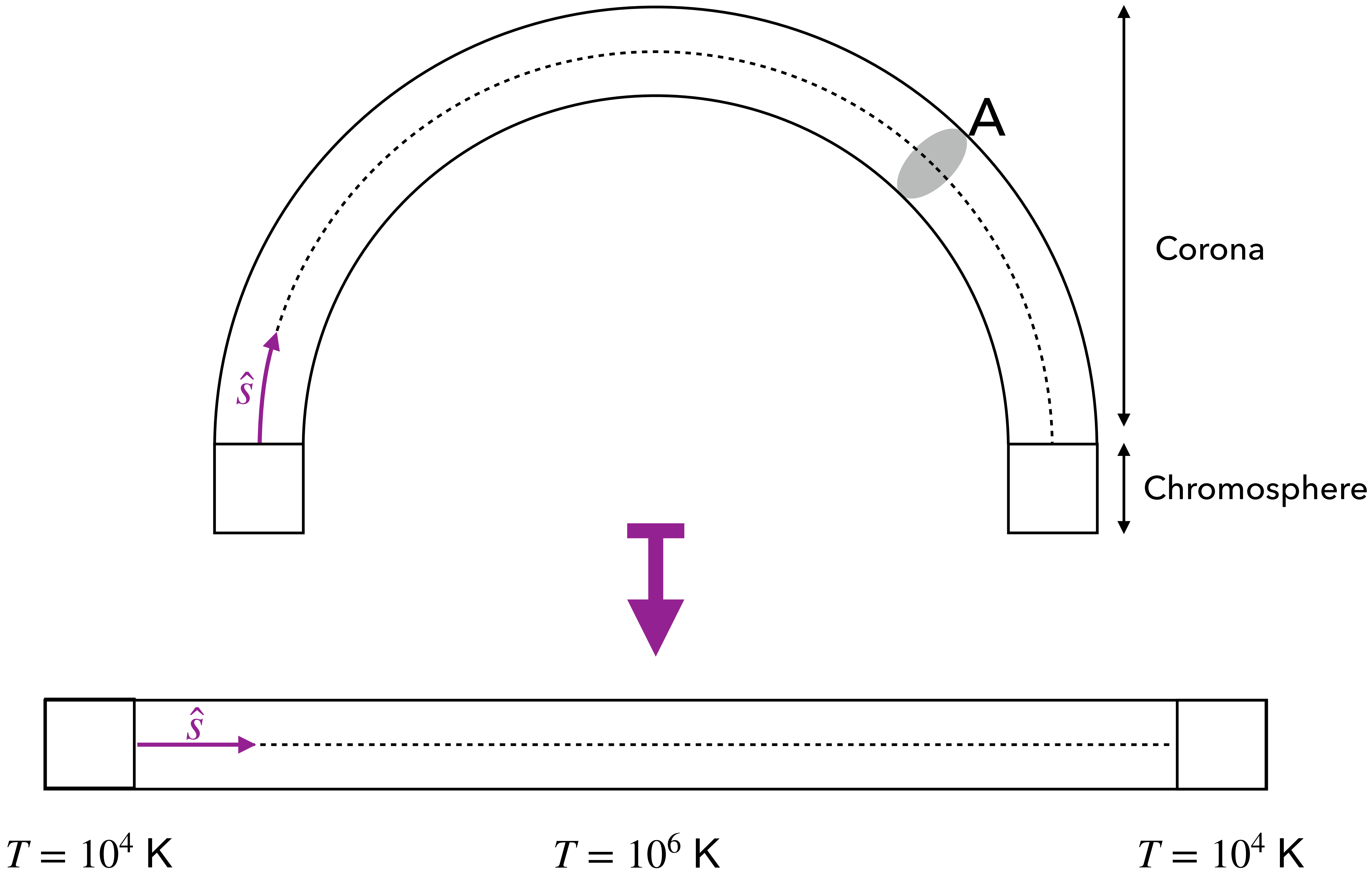
$$\frac{\partial B_z}{\partial t} + \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = 0$$

$\nabla \cdot \overrightarrow{B} = 0$ **(constrained transport approach)**

$$P = (\gamma - 1)\rho\epsilon = \frac{2k_b}{\mu m_H}\rho T$$

Numerical approach

- Pluto Code (Mignone et al. 2007);
- MHD equation in eulerian conservative form;
    - Mass continuity equation
    - Momentum Equation
    - Energy Equation
    - Magnetic Induction Equation + CS
    - Ideal gas law
- **Stretched geometry** (loop length >> width);
- Gravity for curved loops;
- Stratified atmosphere (chromosphere + TR + corona),
    - back ground heating,
    - thermal conduction,
    - radiative cooling,
    - plasma beta variation,
    - magnetic field tapering,
- Boundary conditions:
    - smooth rotational plasma motions at photospheric boundaries;
    - periodic lateral BC;



Loop structure: stretched flux tube

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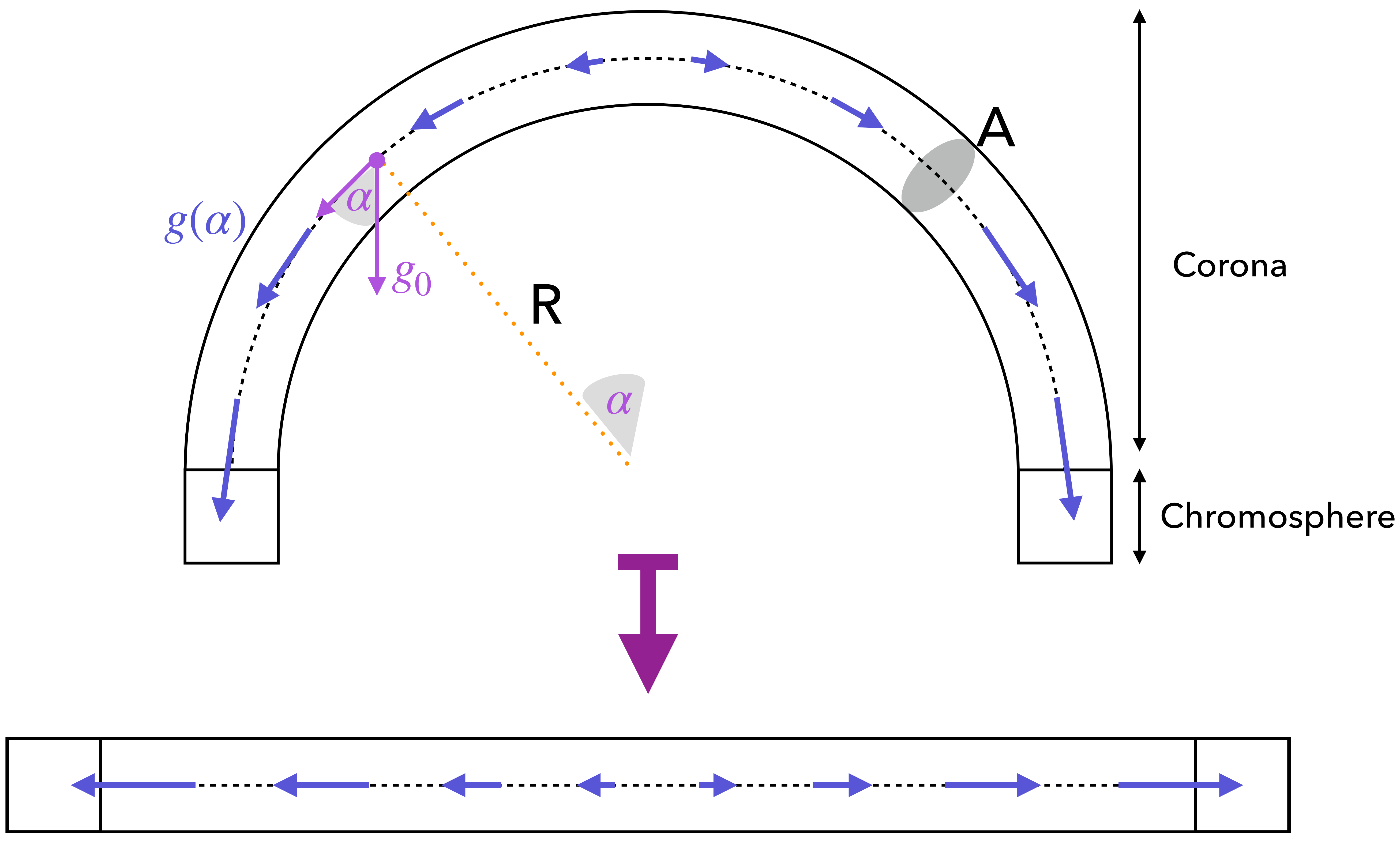

$$g(s)\hat{s} = -\,g_{\odot}\hat{s} \qquad g(s)\hat{s} = g_{\odot}\cdot\sin\left(\pi\frac{s}{R}\right)\hat{s} \qquad g(s)\hat{s} = +\,g_{\odot}\hat{s}$$

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Energy equation:

$$\frac{\rho E}{\partial t} + \nabla \cdot [\vec{u}(\rho E + P_t) + \overrightarrow{B}(\vec{u} \cdot \overrightarrow{B})] = \\ = \rho \vec{u} \cdot \vec{g} - n_e n_H P(T) - \nabla Fc + H_0$$

Background heating: $H_0 = 10^{-3} T_6^{3.5} L_9^{-2}$

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Background heating: $H_0 = 10^{-3} T_6^{3.5} L_9^{-2}$

Thermal conduction: $F = \frac{F_{sat}}{F_{sat} + |F_{class}|} |F_{class}|$

Anisotropic heat transport:

$$F_{class} = k_{||} \hat{b}(\hat{b} \cdot \nabla T) + k_{\perp}[\nabla T - \hat{b}(\hat{b} \cdot \nabla T)]$$

Heat flux saturation: $F_{sat} = 5\phi\rho c_s^3$

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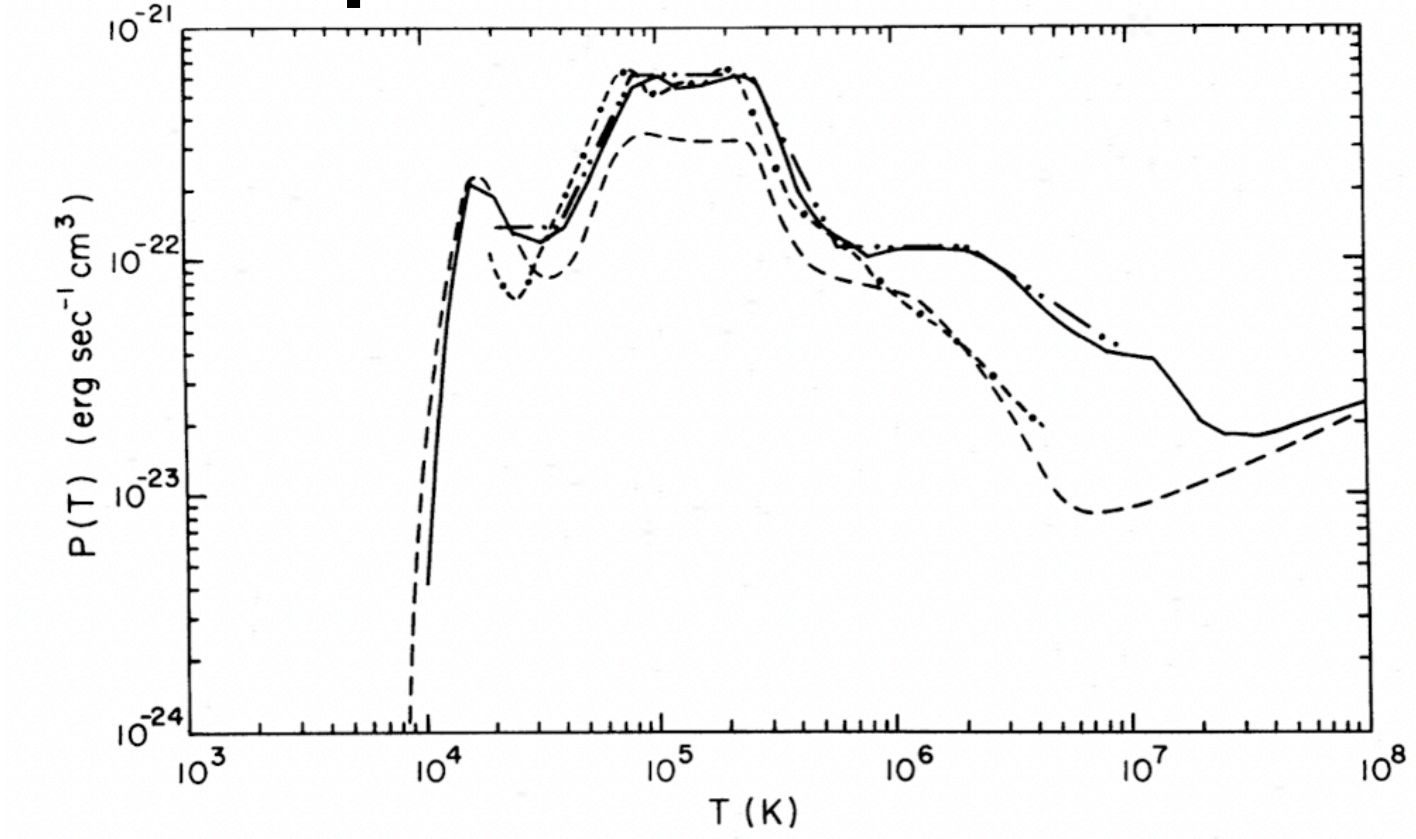
Radiative losses per unit E.M. : CHIANTI



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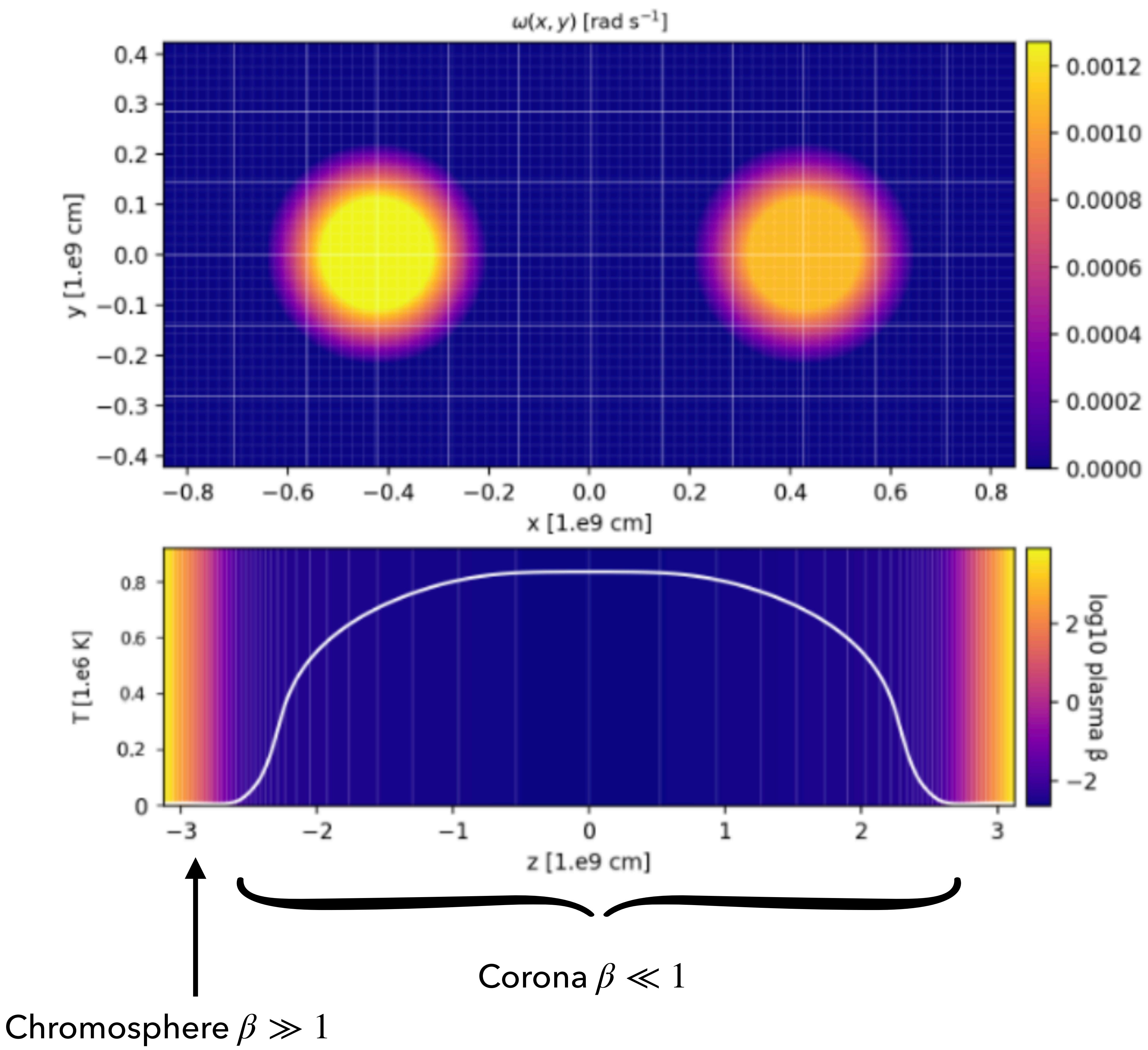

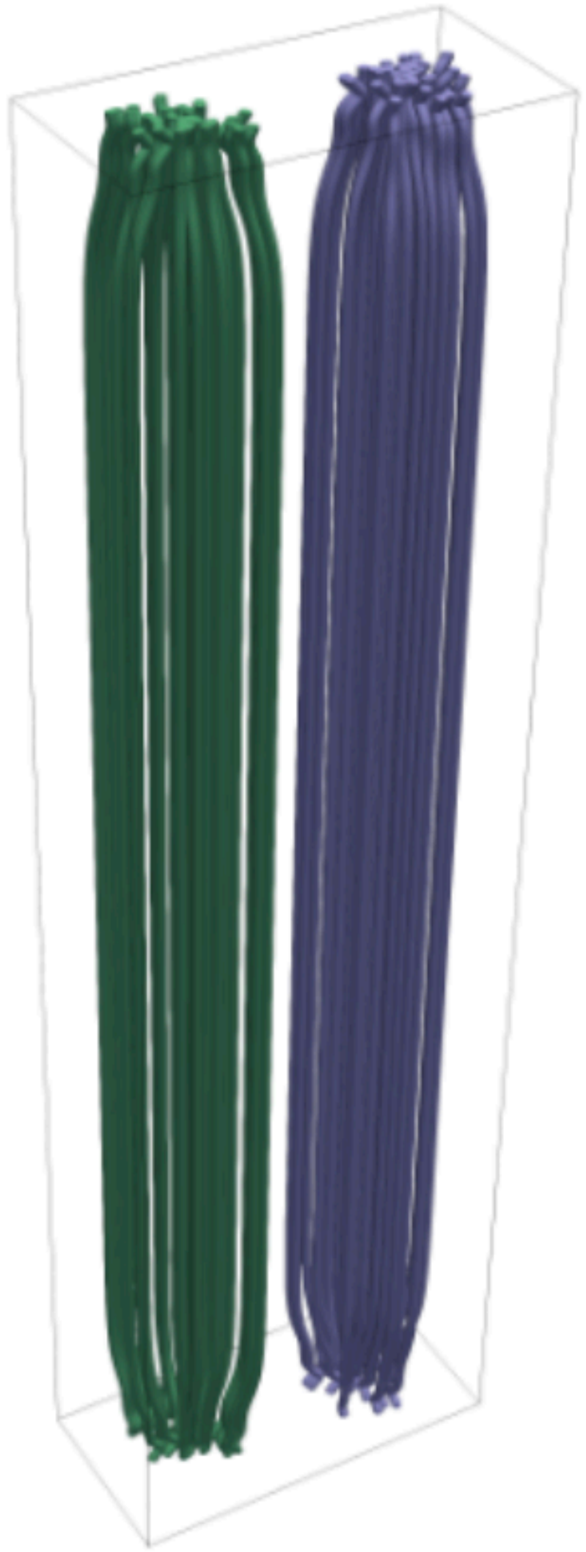

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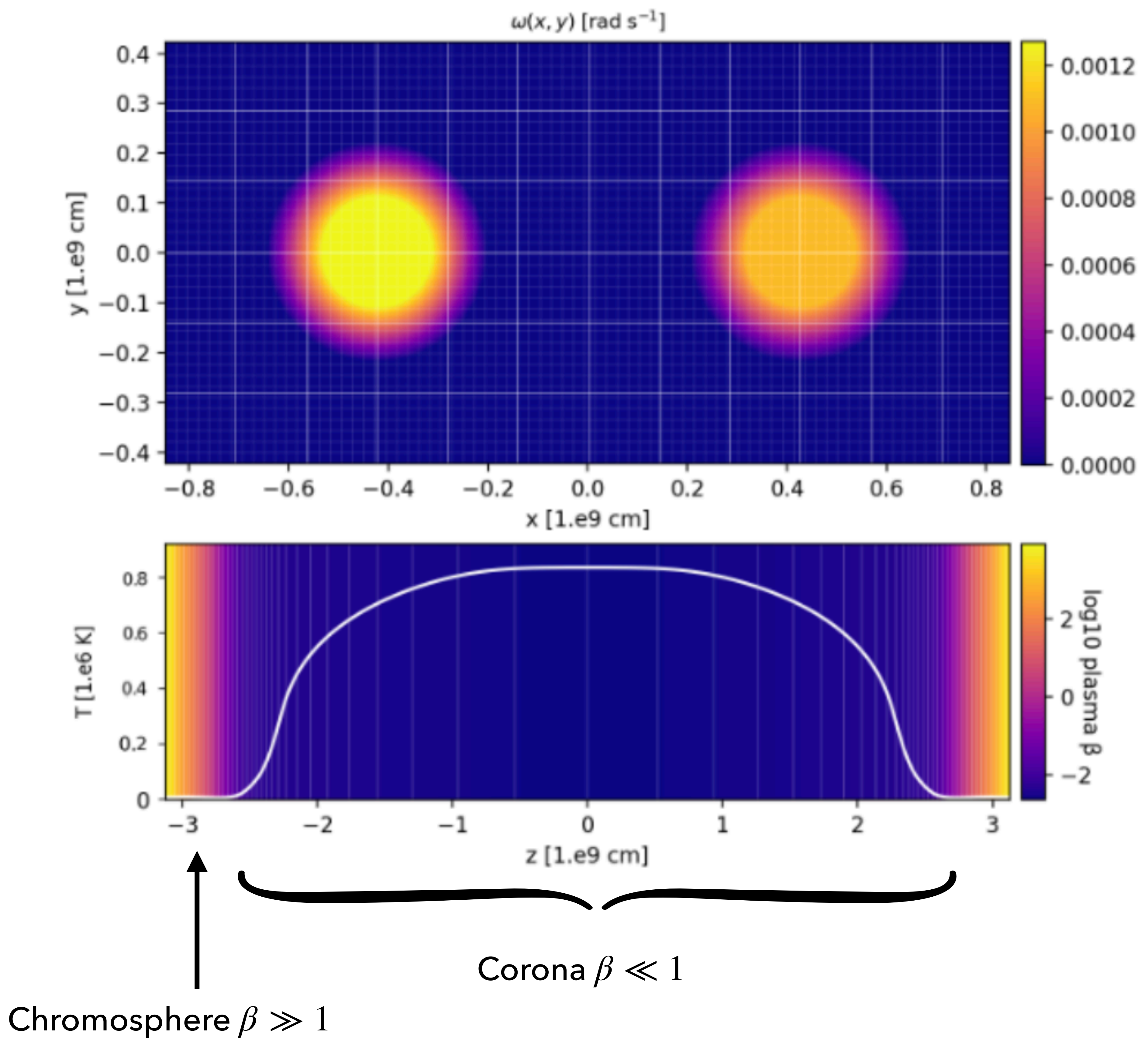

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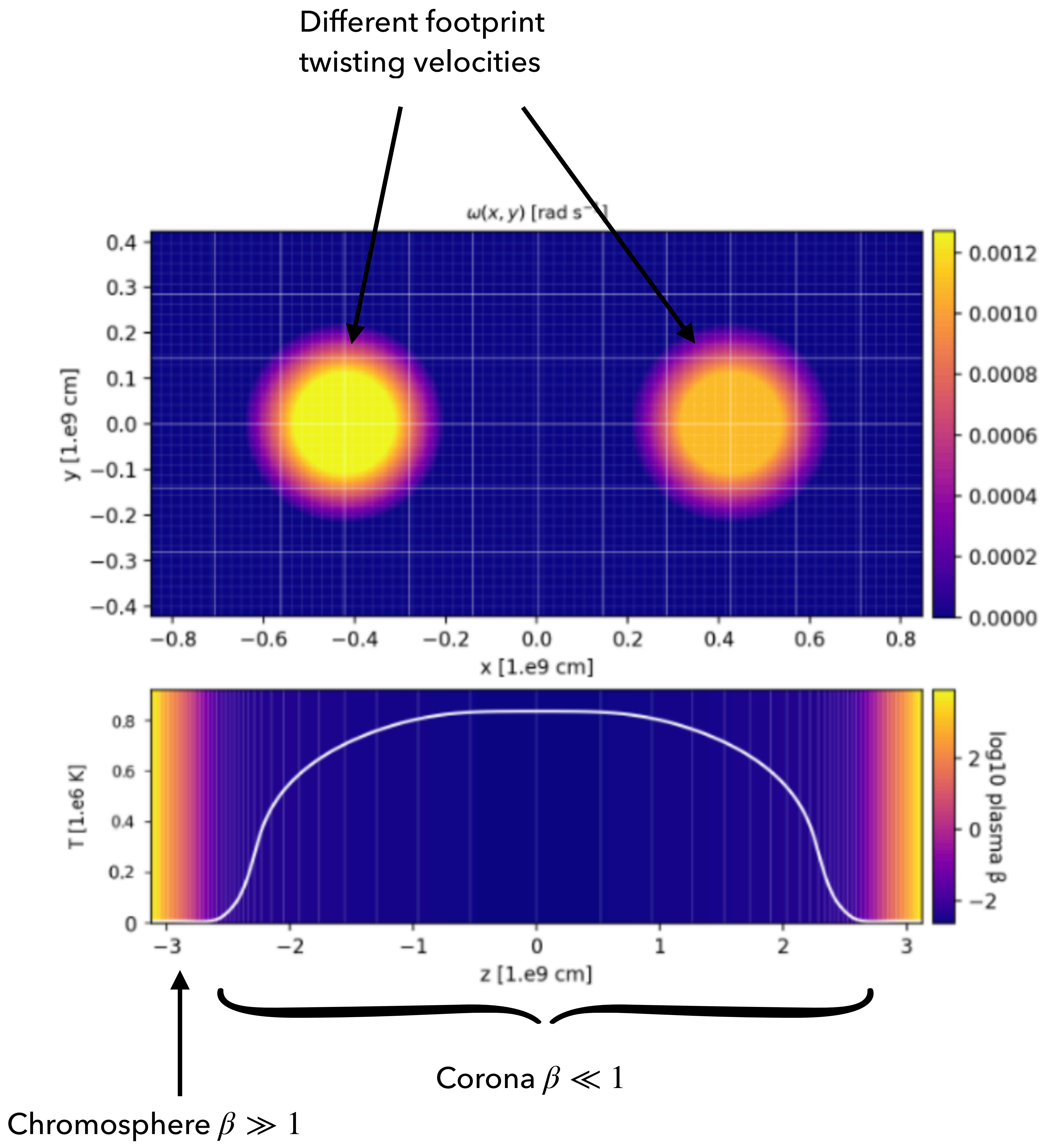

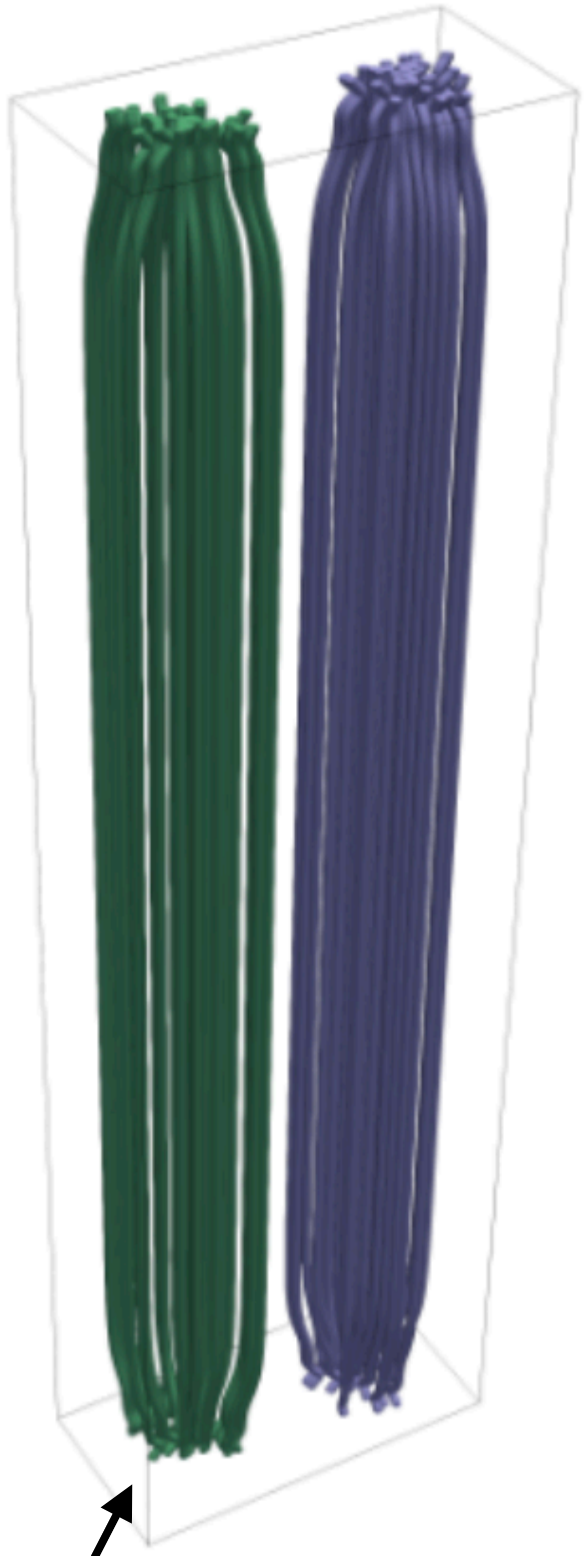

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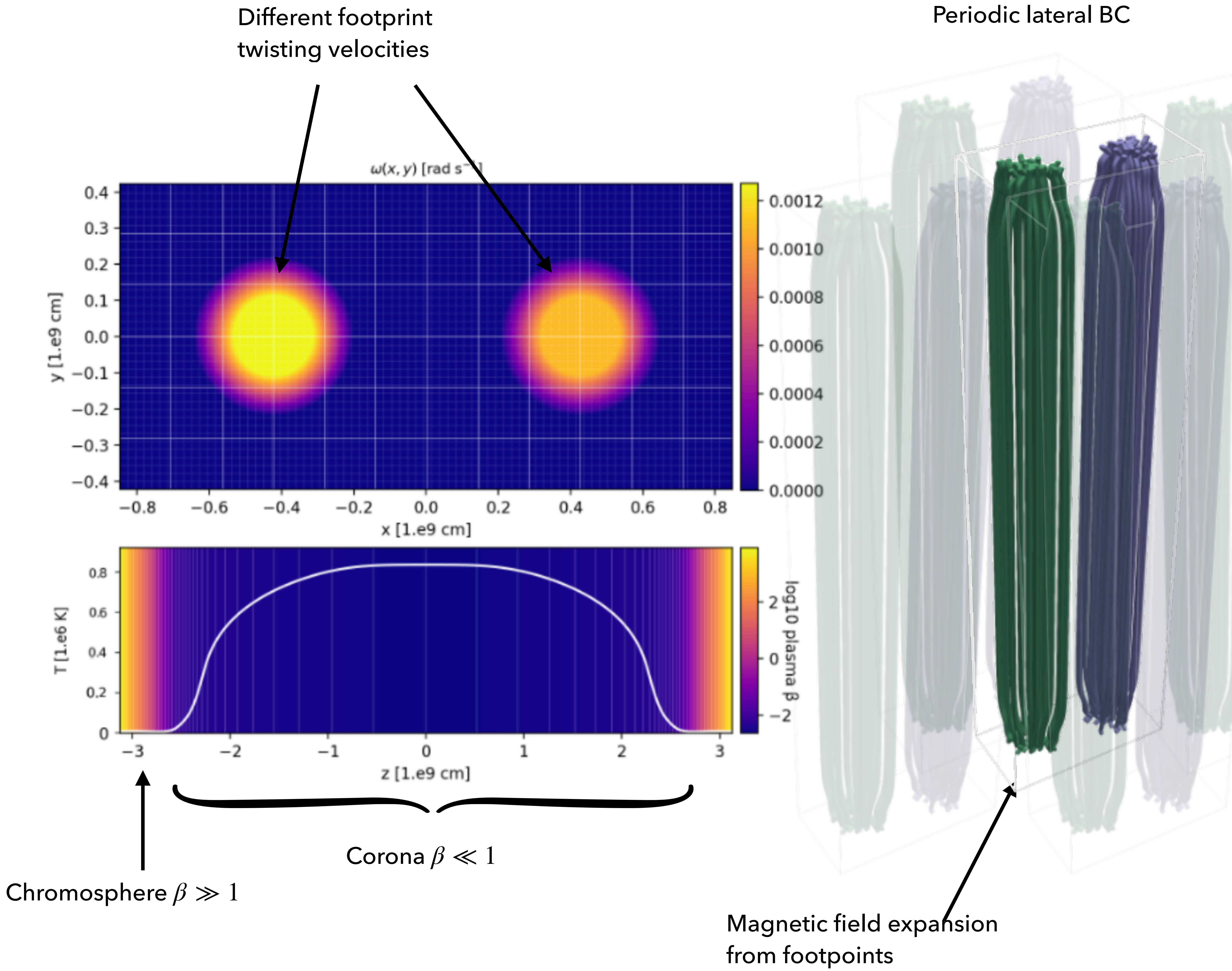

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Numerically challenging!

- Full 3D problem (256 $\times$ 512 $\times$ 512 pixels);
- Magnetic field, thermal conduction;
- Fine spatial resolution (to appropriately resolve the transition region);
- Fine temporal resolution (high efficient thermal conduction + strong temperature gradients);
- Physically long process.

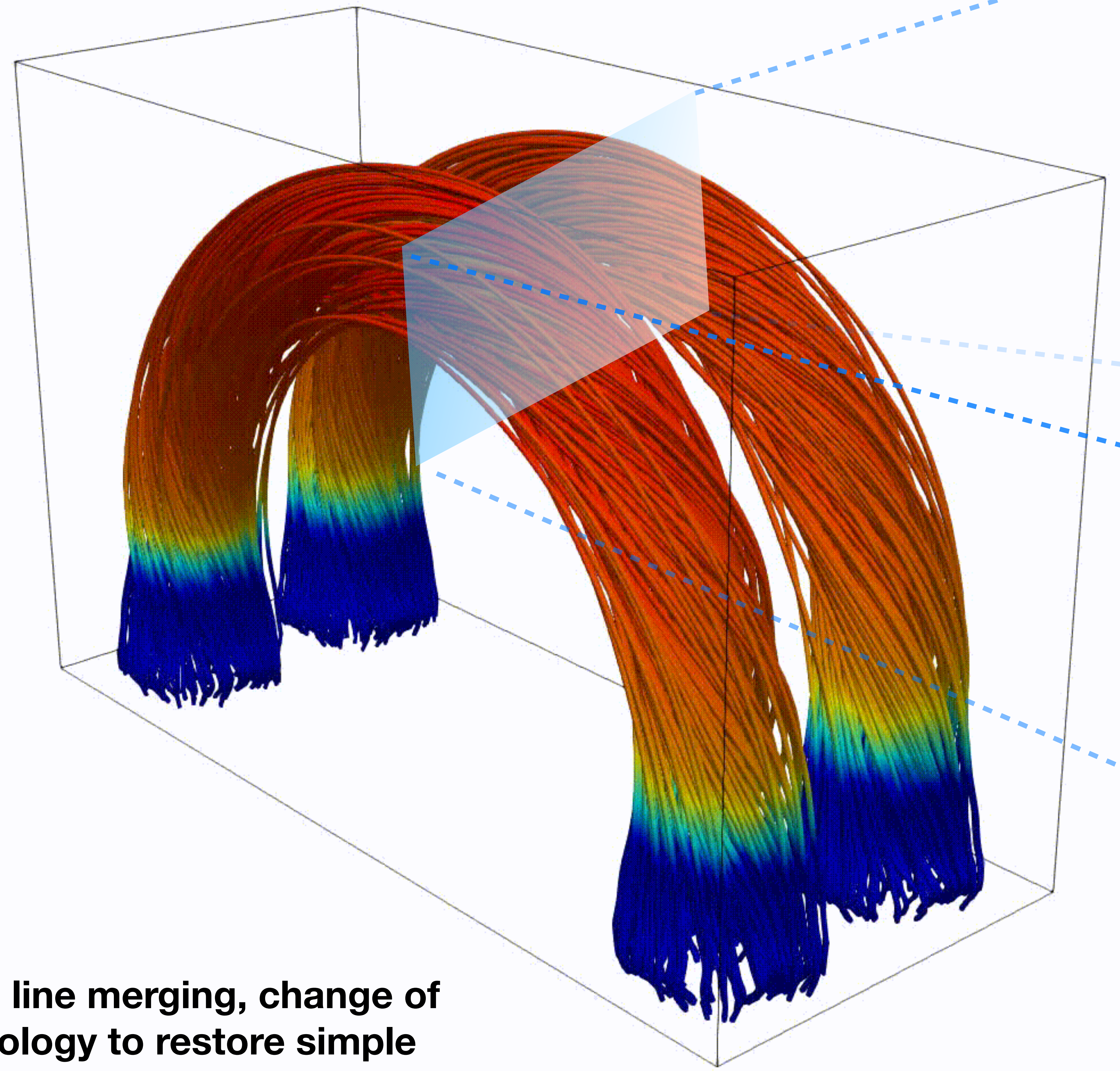
MEUSA - OAPa

Galileo 100 - Cineca

- Single run: 250000 h on Cineca Galileo 100

Results

This work therefore confirms, in more realistic conditions, that avalanches are a viable mechanism for the storing and release of magnetic energy in plasma confined in closed coronal loops, as a result of photospheric motions.

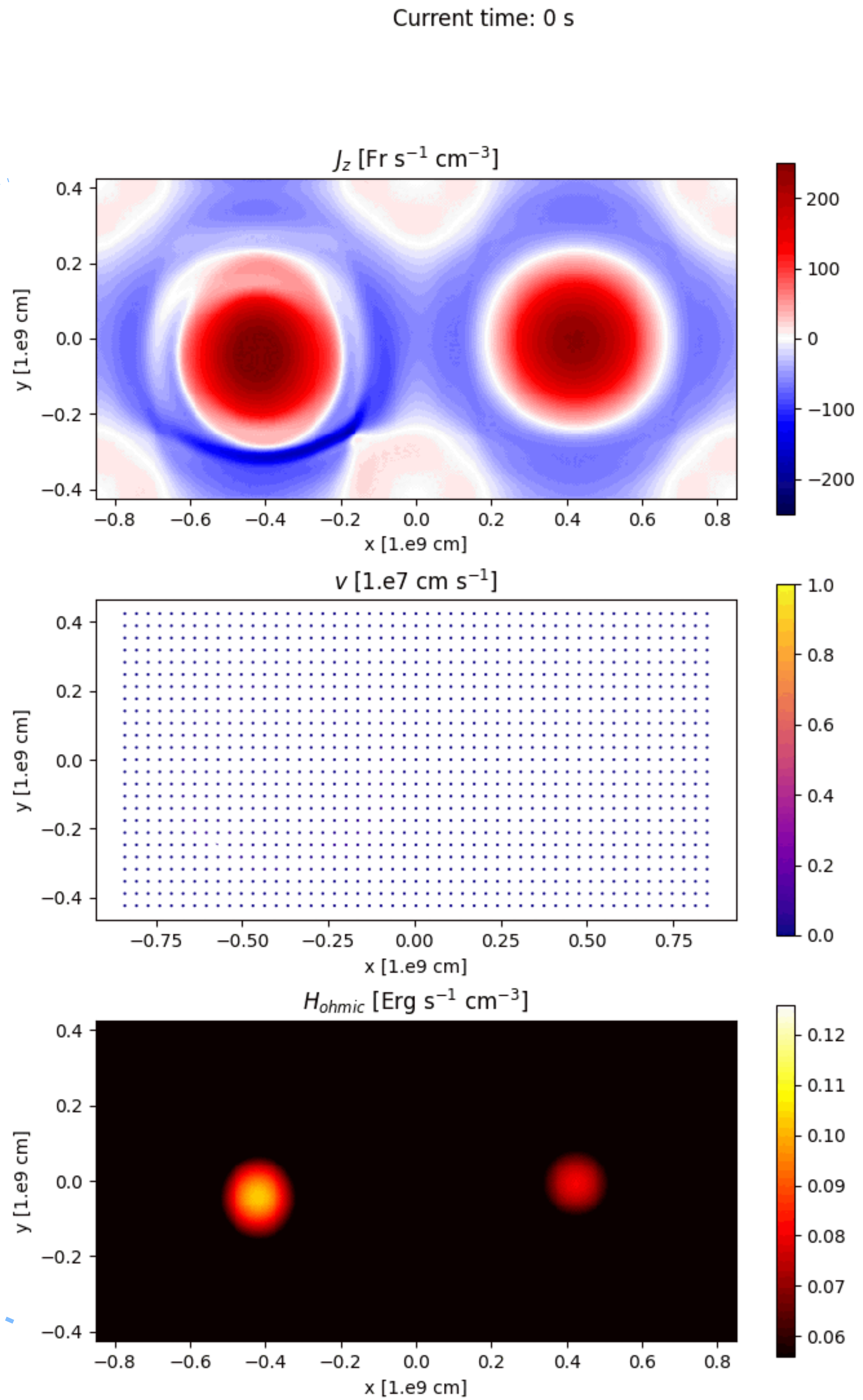


Current density fragmentation into current sheets

Turbulent behaviour of flaring plasma

Widespread, impulsive heating

Field line merging, change of topology to restore simple equilibrium form



MUSE Diagnostics

- **Multi-slit Solar Explorer**;
- **Medium Class** Explorer proposed by **NASA**;
- **ASI** participation;
- **Launcing**: 2027
- **Heritage**: IRIS, SDO, Hinode
- EUV **multi-slit spectrograph** (Δpixel $\sim 0.167''$; Δt $\sim$ 10 s)
- EUV **context imager**;

Observables:

- Zero-momentum (emission maps)

$$I_0 = \sum_j F_j \qquad F_j = \Lambda(T_j) n_j^2 \Delta z[j]$$

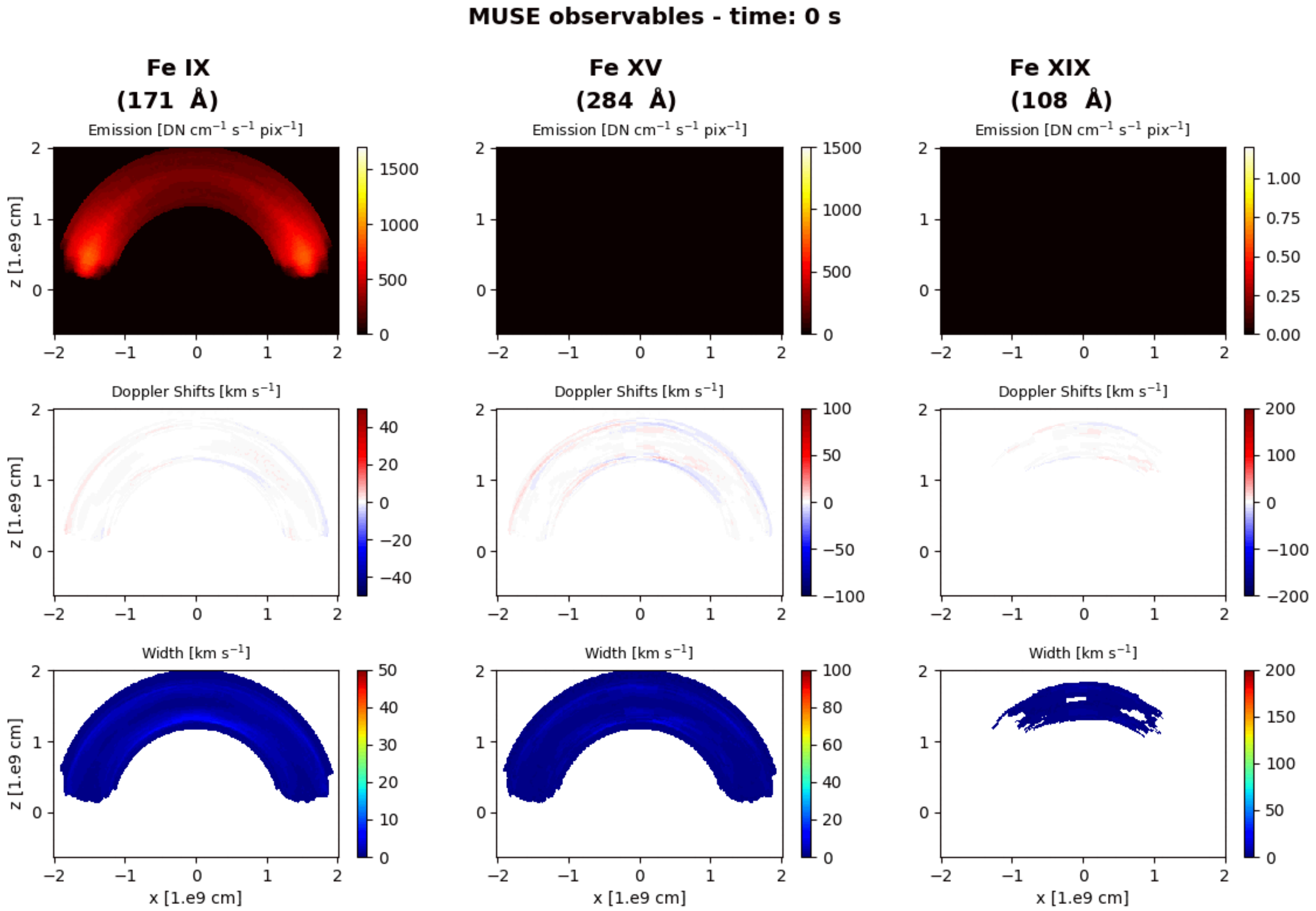
- First-momentum (Doppler shifts)

$$I_1 = \frac{\sum_j F_j v_j}{I_0}$$

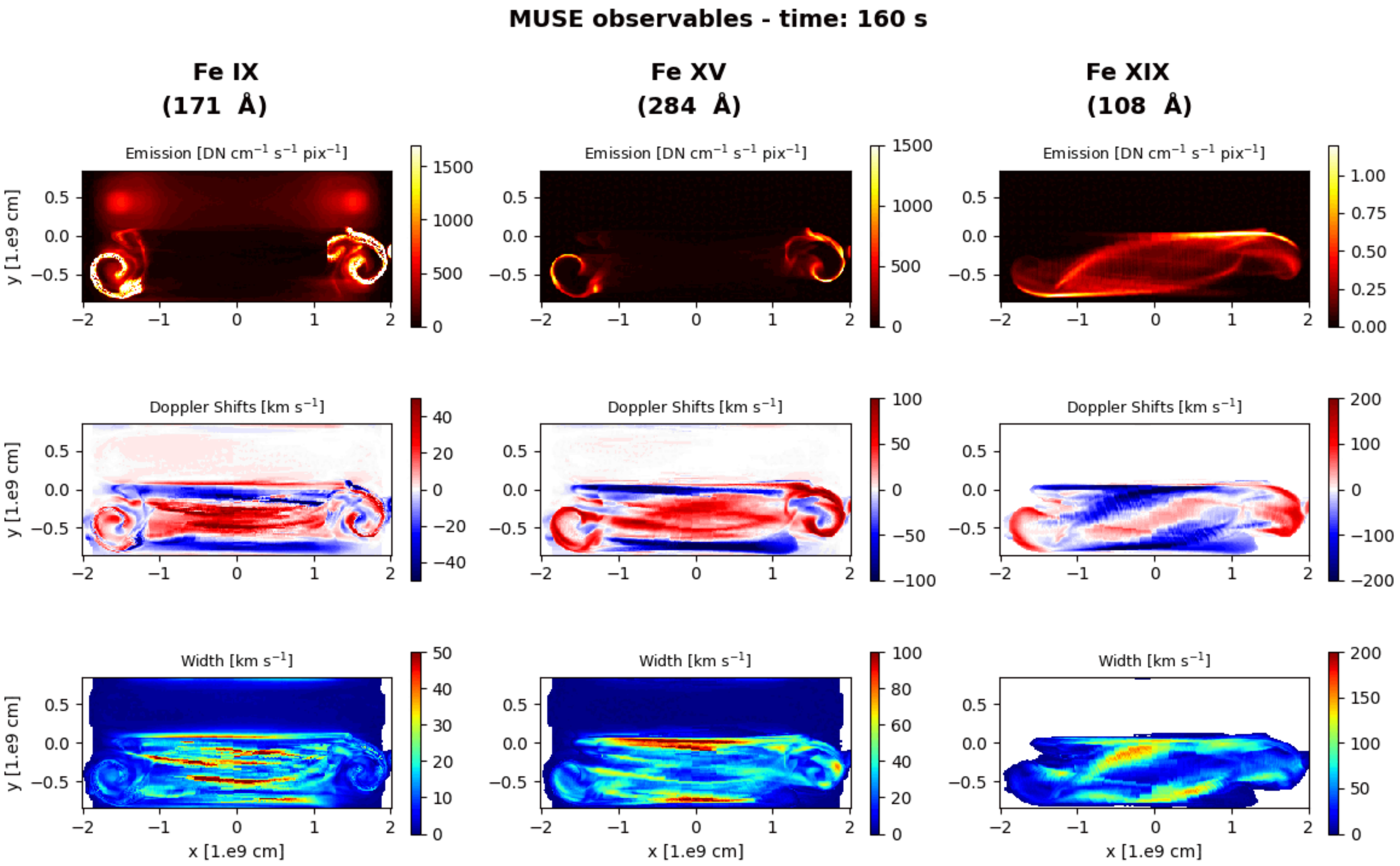
- Second-momentum (line widths)

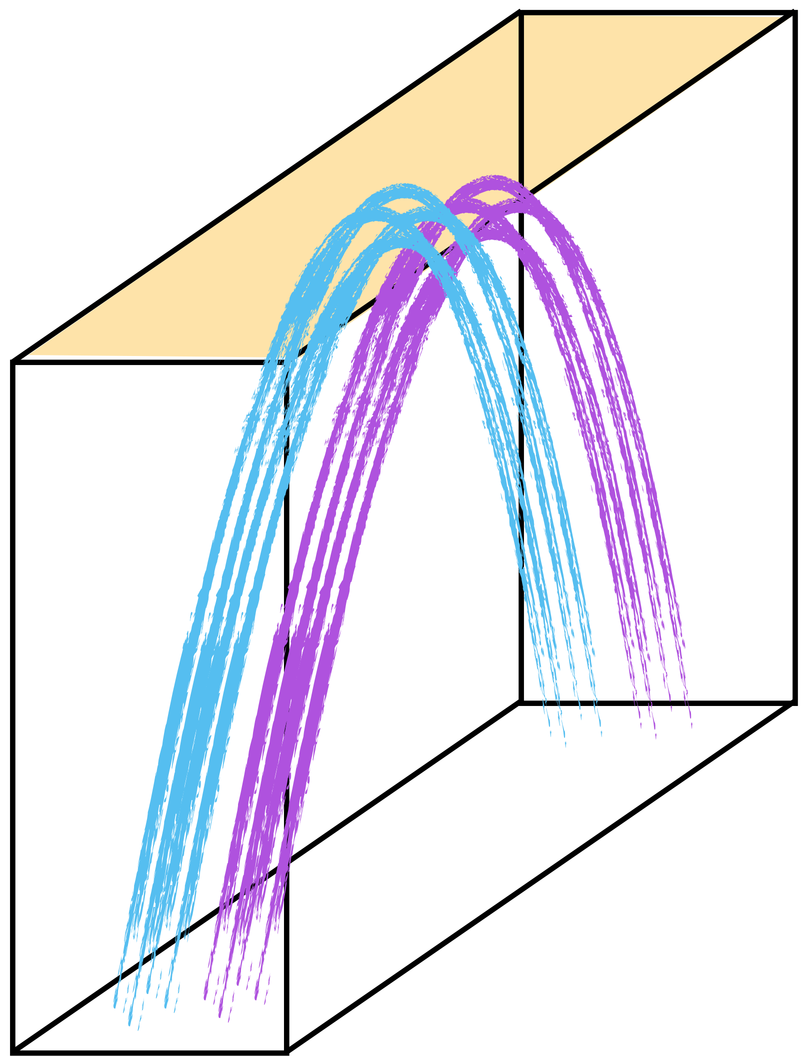
$$I_2 = \sqrt{\frac{\sum_j F_j (v_j - I_1)^2}{I_0}}$$

MUSE SG LINES	WAVE LENGTH	TYPICAL REGION	LOG10 T [K]
Fe IX	171 Å	quiet corona / upper transition region	5.9
Fe XV	284 Å	active-region corona	6.4
Fe XIX	108 Å	hot flare plasma	7.0/7.1



Any chances to corroborate the model?





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