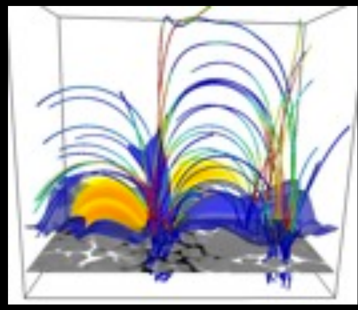

Simulations of the Impact of Partial Ionization on the Chromosphere

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Introduction

Most works and state-of-the-art simulations use an MHD model consistent with fully-ionized plasmas, but plasma in the photosphere and chromosphere is mostly weakly ionized (mass fraction mainly dominated by neutral atomic H, He and molecular hydrogen).

A large number of papers in recent years have investigated effects of ion-neutral interactions on MHD. Mostly theoretical work that use some 1D semi-empirical profile (e.g. VAL-C) of the solar atmosphere e.g.

- Leake & Arber (2006), Arber, Haynes & Leake (2007) - flux emergence simulation with 1d profile of ionization degree.
- De Pontieu & Haerendel (1998), Goodman (2000), Leake, Arber & Khodachenko (2005), Pandey & Wardle (2008), Singh & Krishnan (2010) - Alfvén wave dissipation.
- Khomenko & Collados (2012) studied the impact of the Pedersen dissipation in the chromosphere using different simplified scenarios.

These studies typically conclude that the Hall effect can be important in magnetized photosphere and Pedersen dissipation is dominant in the magnetized chromosphere.

- Cheung & Cameron (2012) preformed full magneto-convection simulations of an umbra taking into account partial ionization effects

Multi-dimensional nonlinear MHD simulations by groups in Kyoto, Tenerife, USA, and Oslo.

State-of-the-art simulation: Bifrost

Gudiksen et. al. 2011

$$\boxed{\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0}$$

$$\boxed{\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})} - \nabla \times \eta (\nabla \times \mathbf{B})$$

$$\boxed{\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}} + \tau) = \boxed{-\nabla p + \mathbf{j} \times \mathbf{B} - \mathbf{g}\rho}$$

$$\boxed{\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{u}) + p\nabla \cdot \mathbf{u}} = \nabla \cdot \mathbf{F}_r + \nabla \cdot \mathbf{F}_c + \eta j^2 + Q_{visc}$$

- Scheme: 6th order differential operator in a stagger mesh
- 3rd order Runge-kunta

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+ Eq. of state

Look up table, using the LTE basic assumption

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Without time dependent ionization

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From multifluid (3) problem to Generalized Ohm's law

$$\boxed{\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta_c \nabla \times \mathbf{B}} - \boxed{\eta_H (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{|B|}} + \boxed{\eta_A (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{|B|} \times \frac{\mathbf{B}}{|B|})}$$

$$\eta_c = \frac{1}{\sigma} = \frac{m_e \nu_e}{q_e^2 n_e}$$

$$\eta_H = \frac{|B|}{q_e n_e}$$

$$\eta_A = \frac{(|B| \rho_n / \rho)^2}{\rho_i \nu_{in}}$$

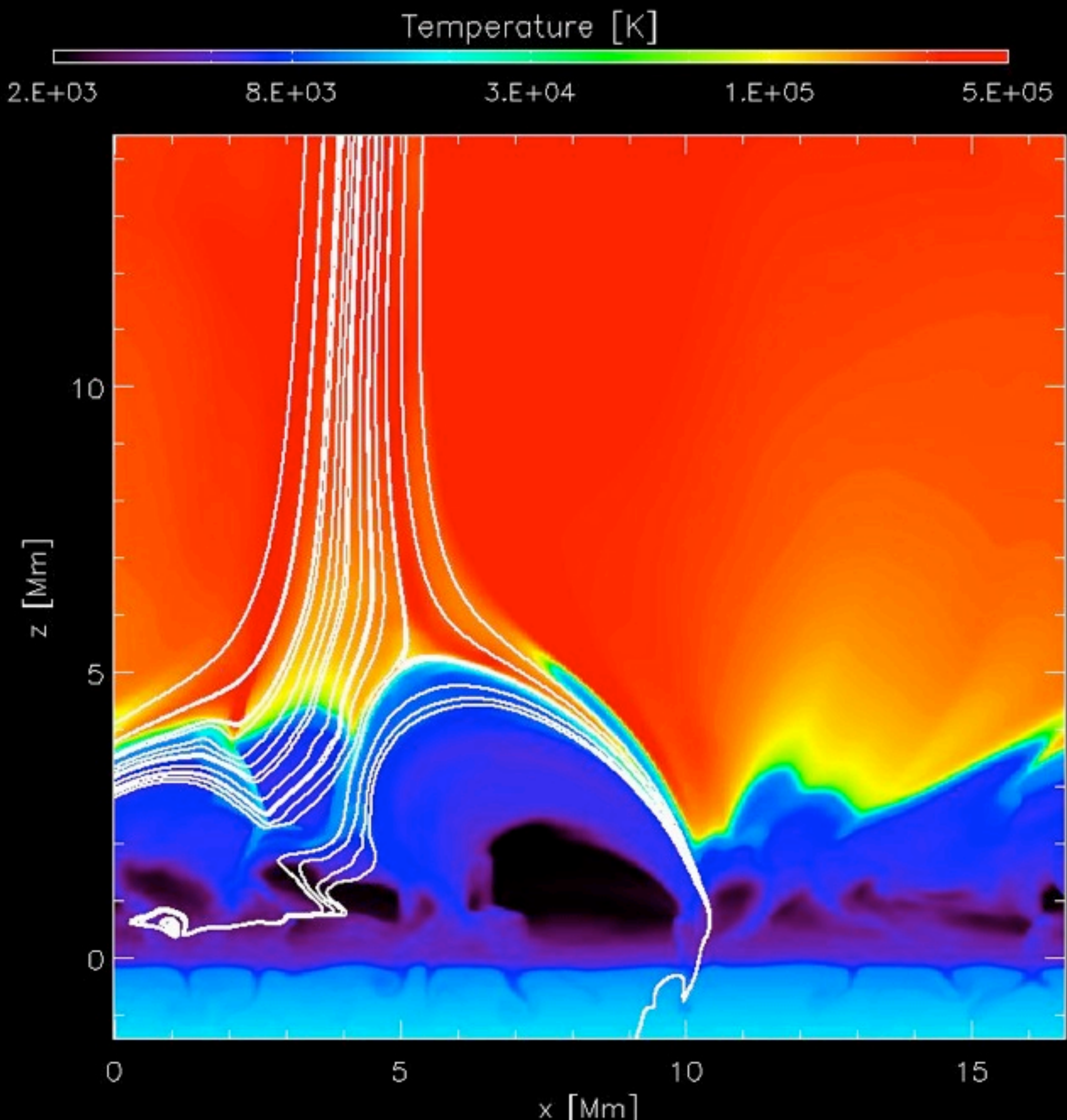
- Still one particle problem, but it includes effects of 3 fluid approach (e, n & p). Therefore, it is a single-fluid model, but with two additional effects captured by a generalized Ohm's Law for the electric field E.
- These two new terms in the induction equation take into account the effects of the collision between ions and neutrals in the MHD Equations.
- Timescale >> collision times

• Electron inertia, electron pressure gradient and Biermann's battery are negligible

• Pedersen dissipation is neglected when plasma is highly ionized.

Cowling 1957

2D Initial condition: 2 simulations



1) Without Partial ionization effects
2) With Pedersen dissipation and Hall term

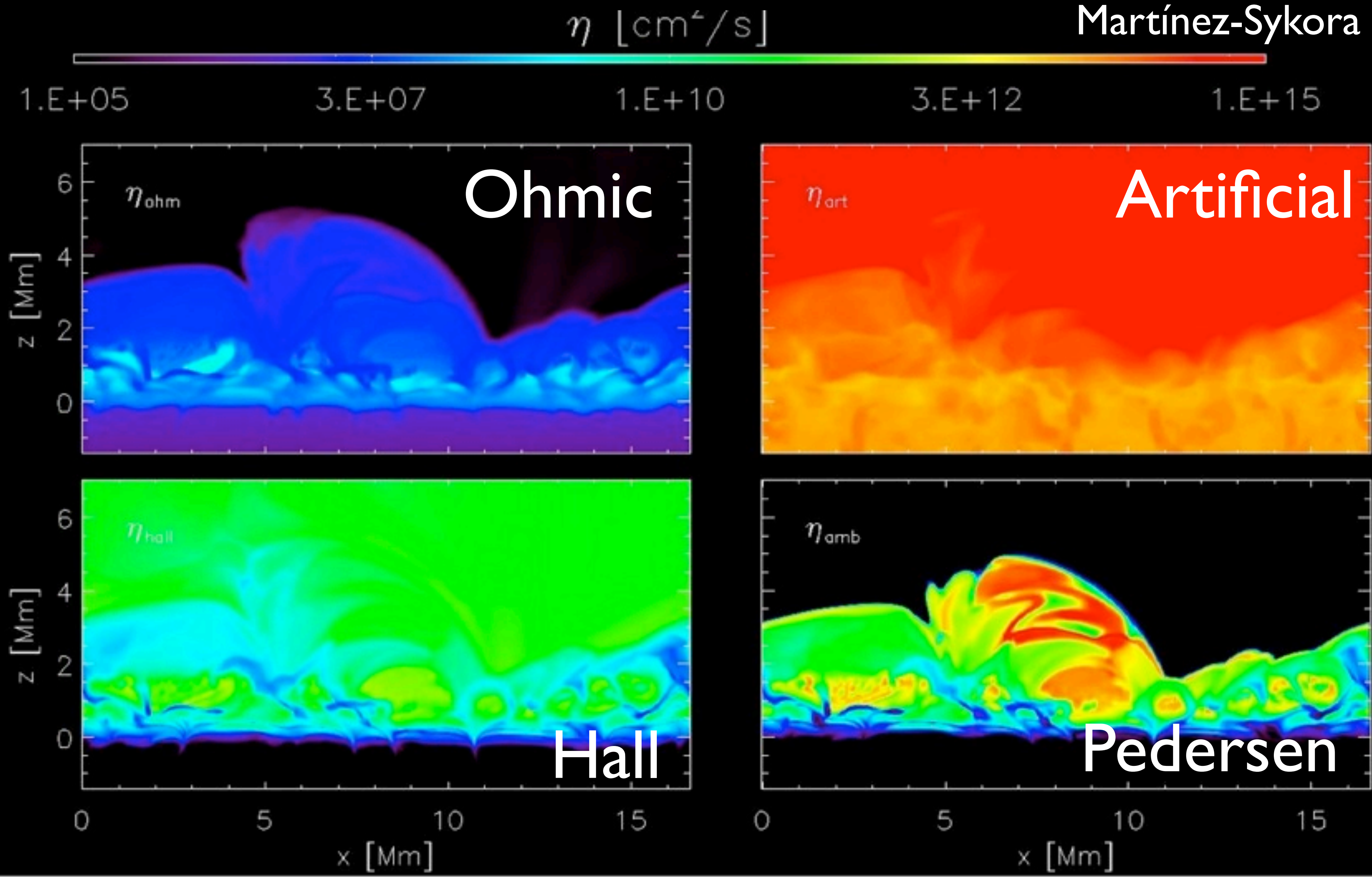
Unipolar field with unsigned flux of ~100 G at the photosphere

Reconnection X point in the proximities of the transition region

Comparison of diffusivities

- Ohmic diffusion is negligible compare to the artificial diffusion
- Hall diffusion important in the upper-photosphere and cold chromospheric bubbles.
- In certain regions in the chromosphere, Pedersen dissipation is of the same order as the artificial diffusion!

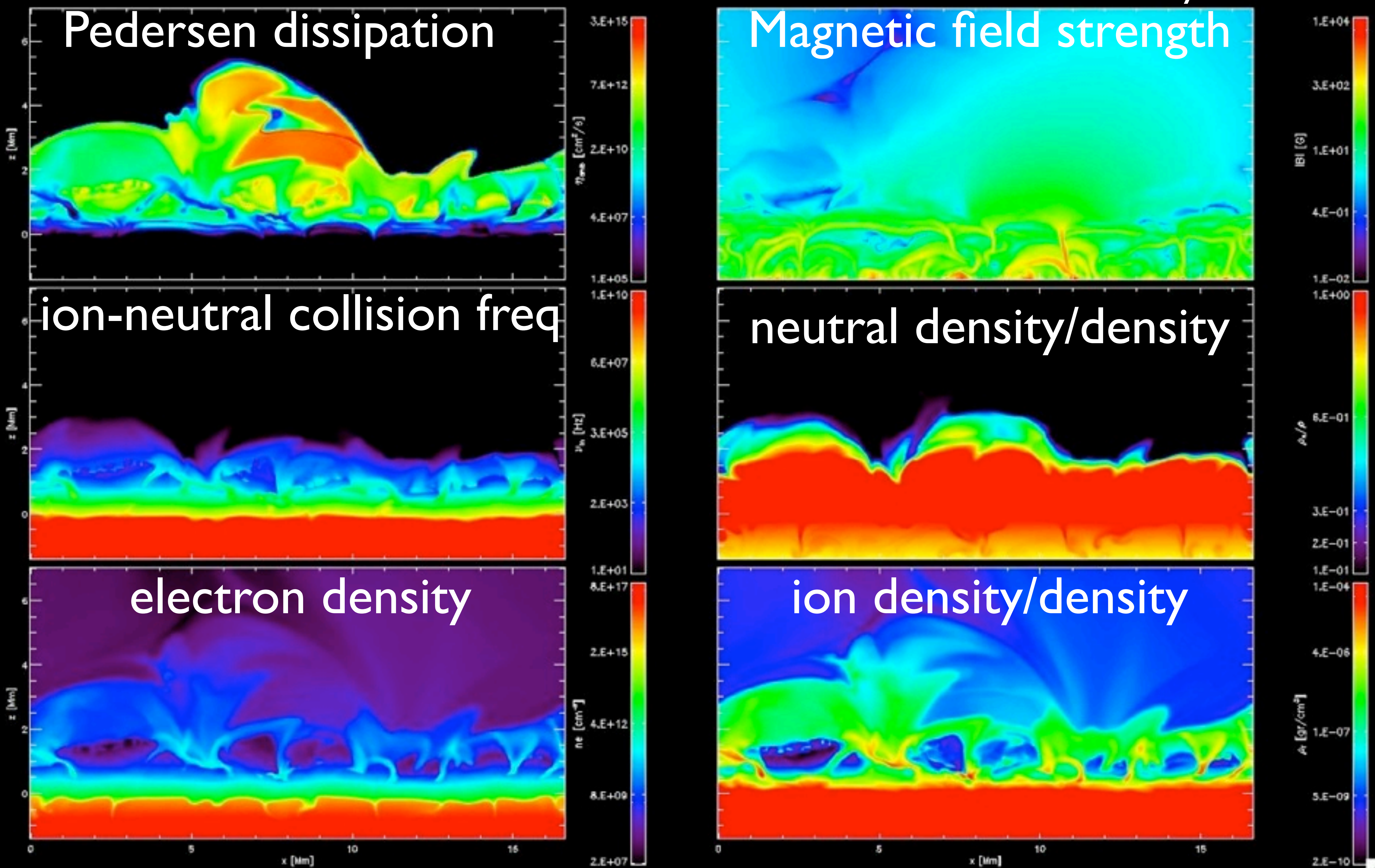
Martínez-Sykora et al. 2012



Dependence of the Pedersen dissipation

Reminder: $\eta_A = \frac{(|B|\rho_n/\rho)^2}{\rho_i \nu_{in}}$

Martínez-Sykora et al. 2012



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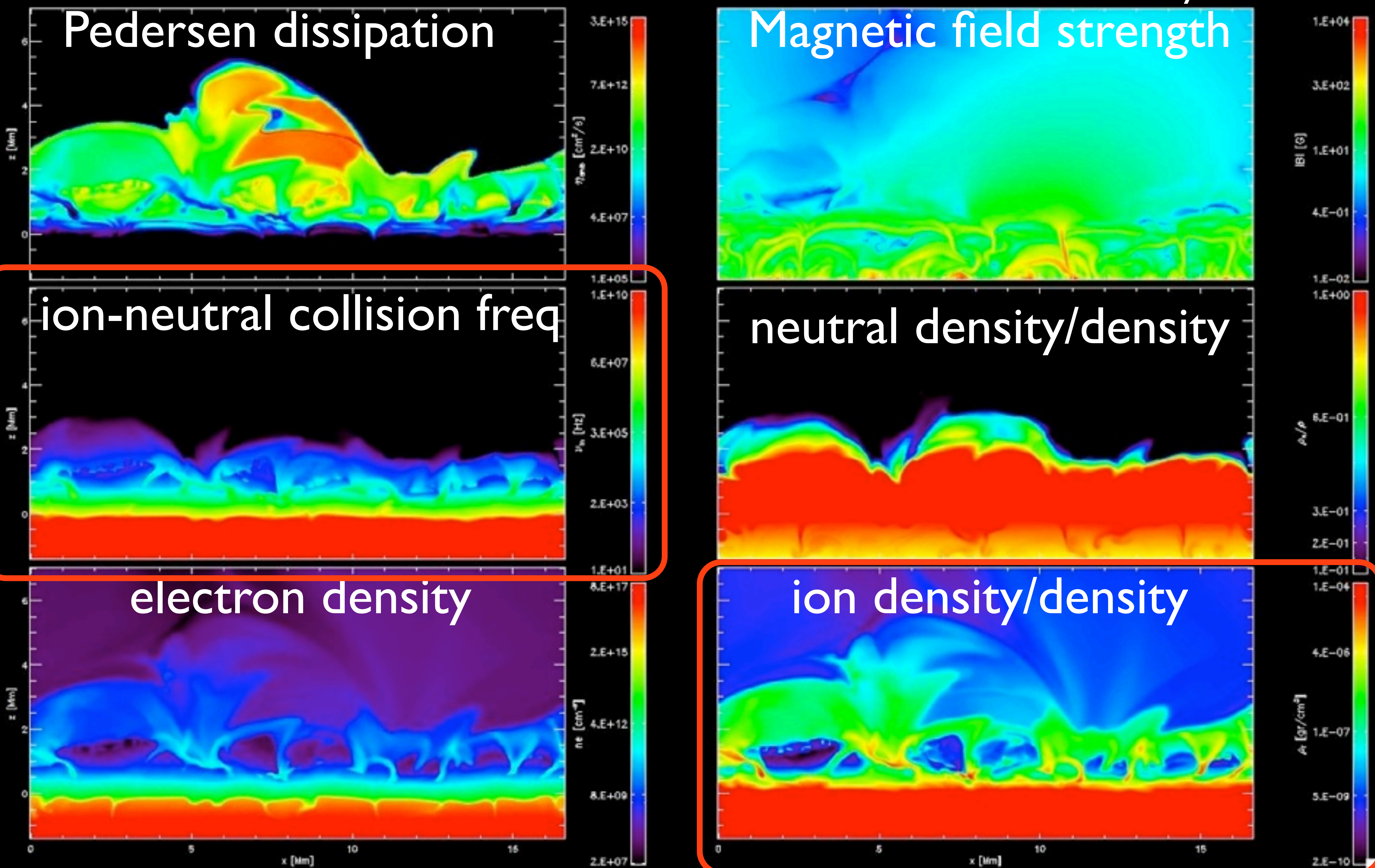
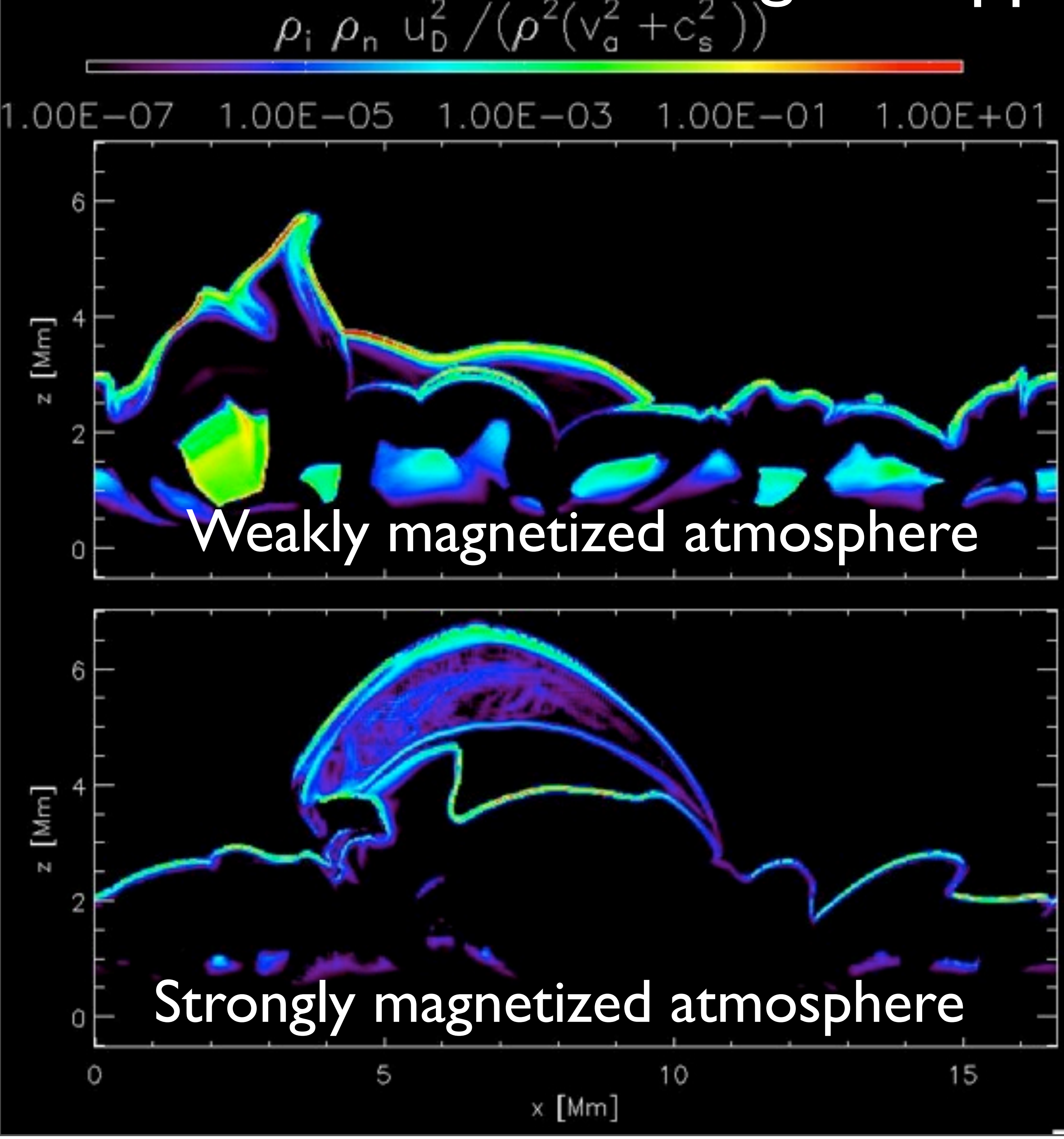


In some regions in the proximities to the transition region and in the cold chromospheric bubbles (weakly magnetized) the plasma is strongly decoupled: generalized ohm's law is not a good approximation

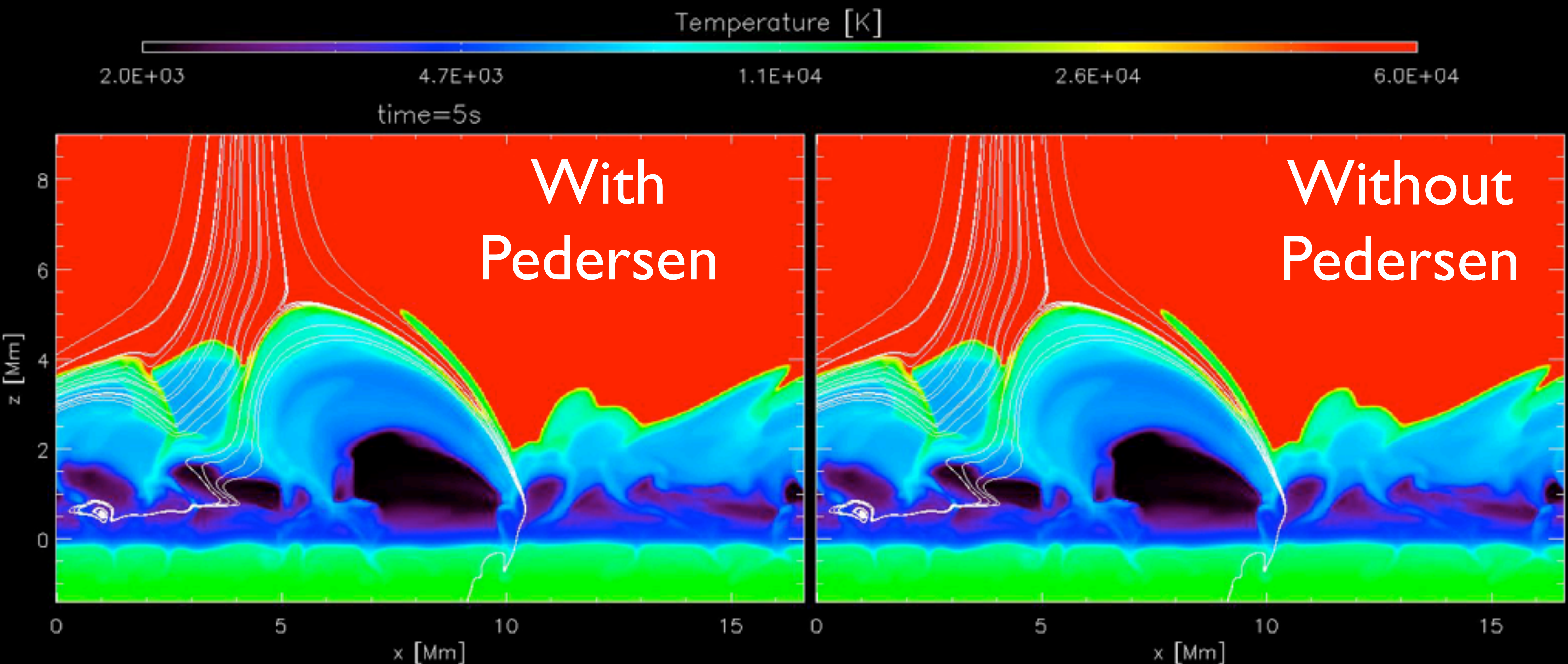


We compare the drift momentum vs the momentum of the fast speed

It may be necessary to include extra equation(s): as consider 2 fluid or at least the velocity drift equation

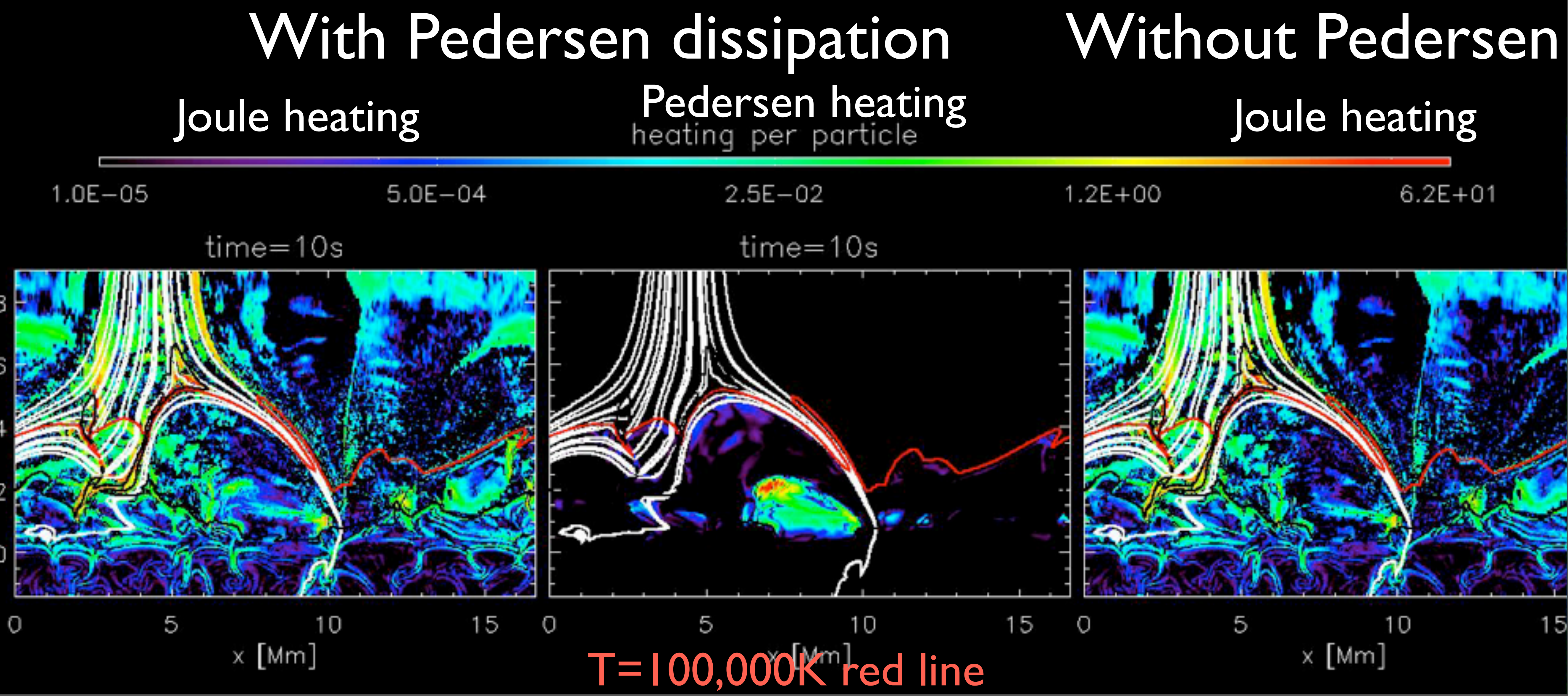
Temporal evolution of temperature

- The cold chromospheric bubbles have higher temperatures with Pedersen dissipation than without
- The transition region is less sharp and hotter the upper chromosphere with Pedersen dissipation than without
- The reconnection process is different with and without Pedersen dissipation

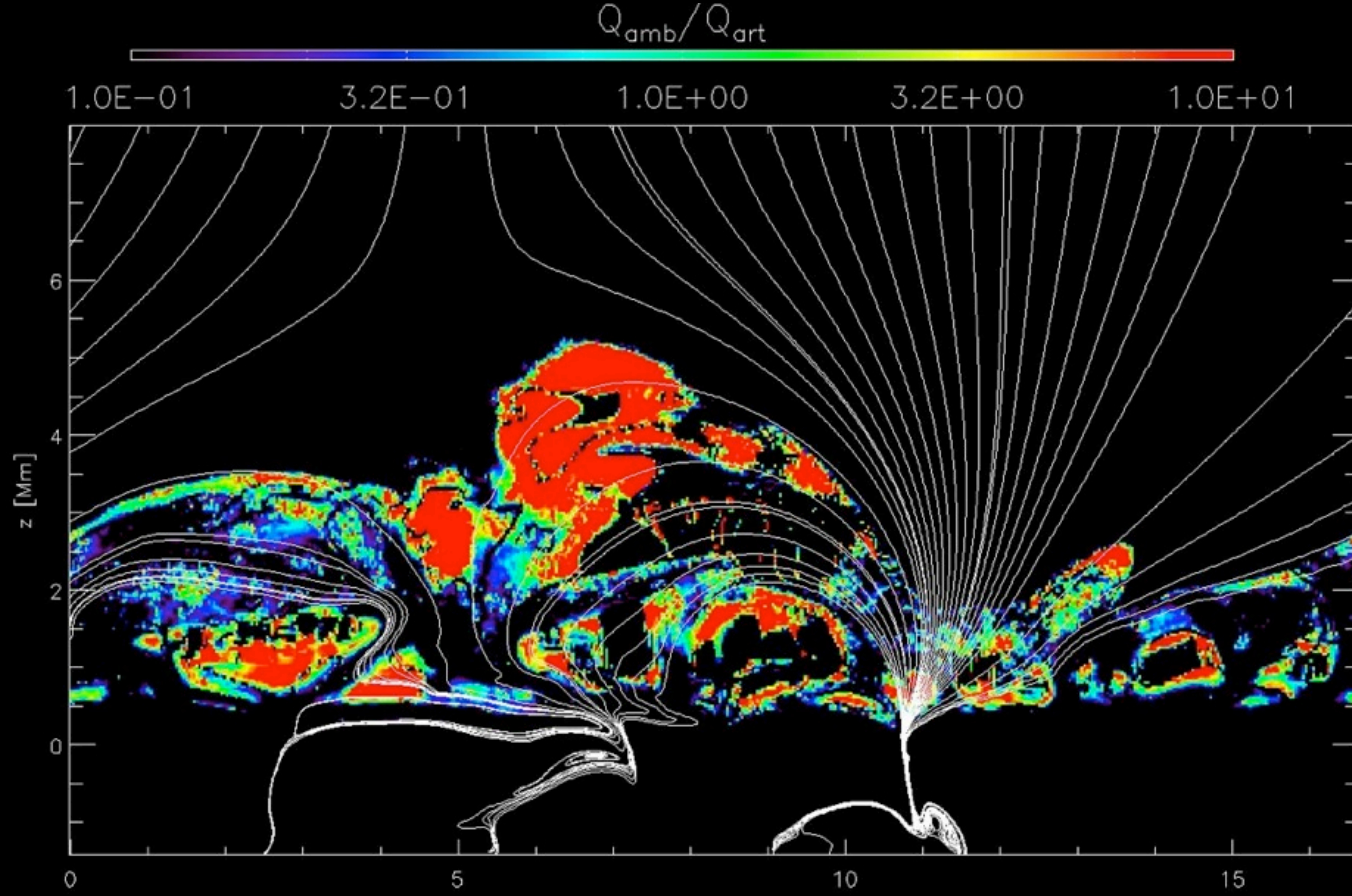


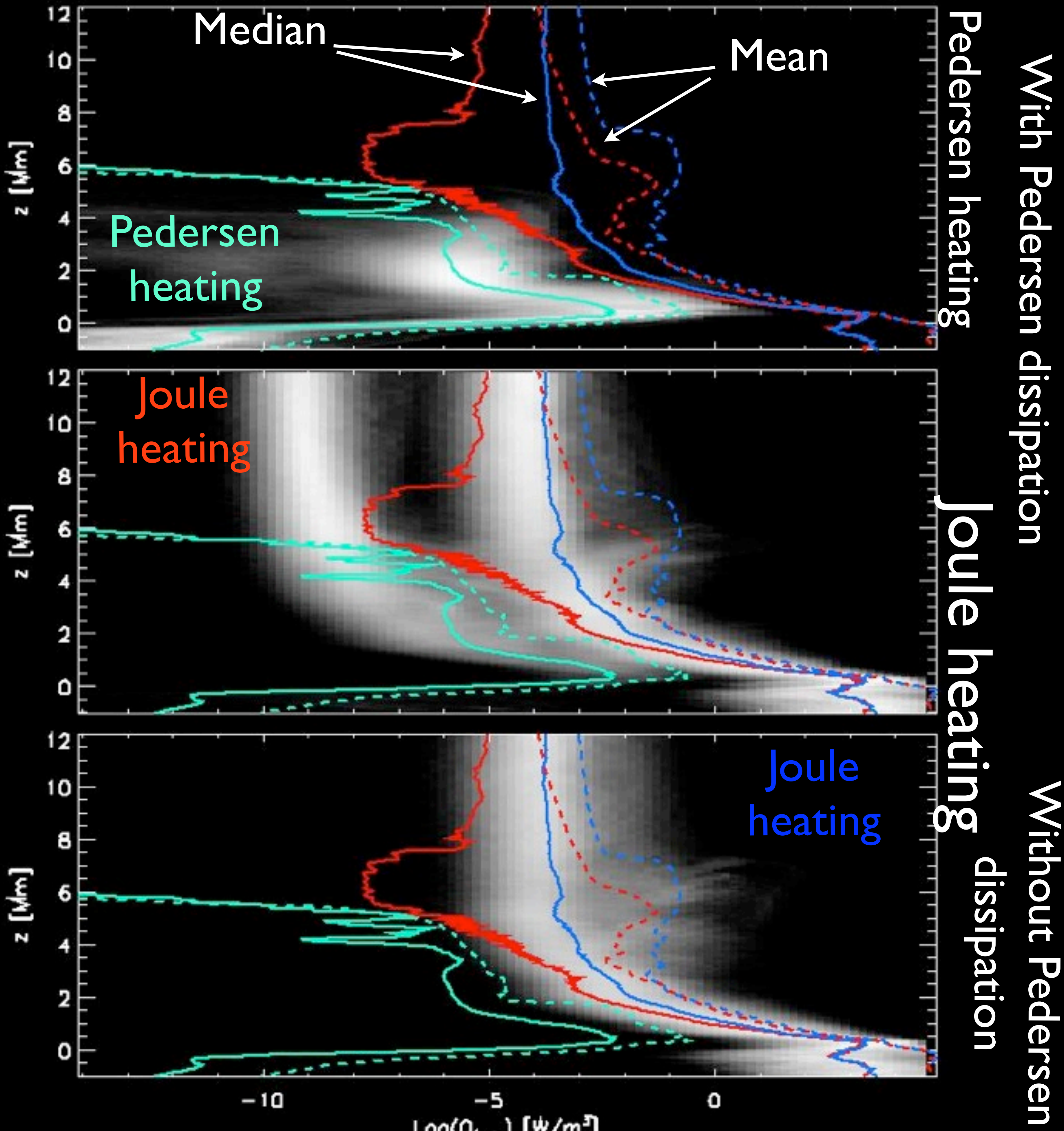
- The cold chromospheric bubbles and upper chromosphere are heated by Pedersen heating.

- The Joule heating is reduced in the corona with Pedersen dissipation



Pedersen heating is important in cold regions and upper chromosphere in contrast to Joule heating!



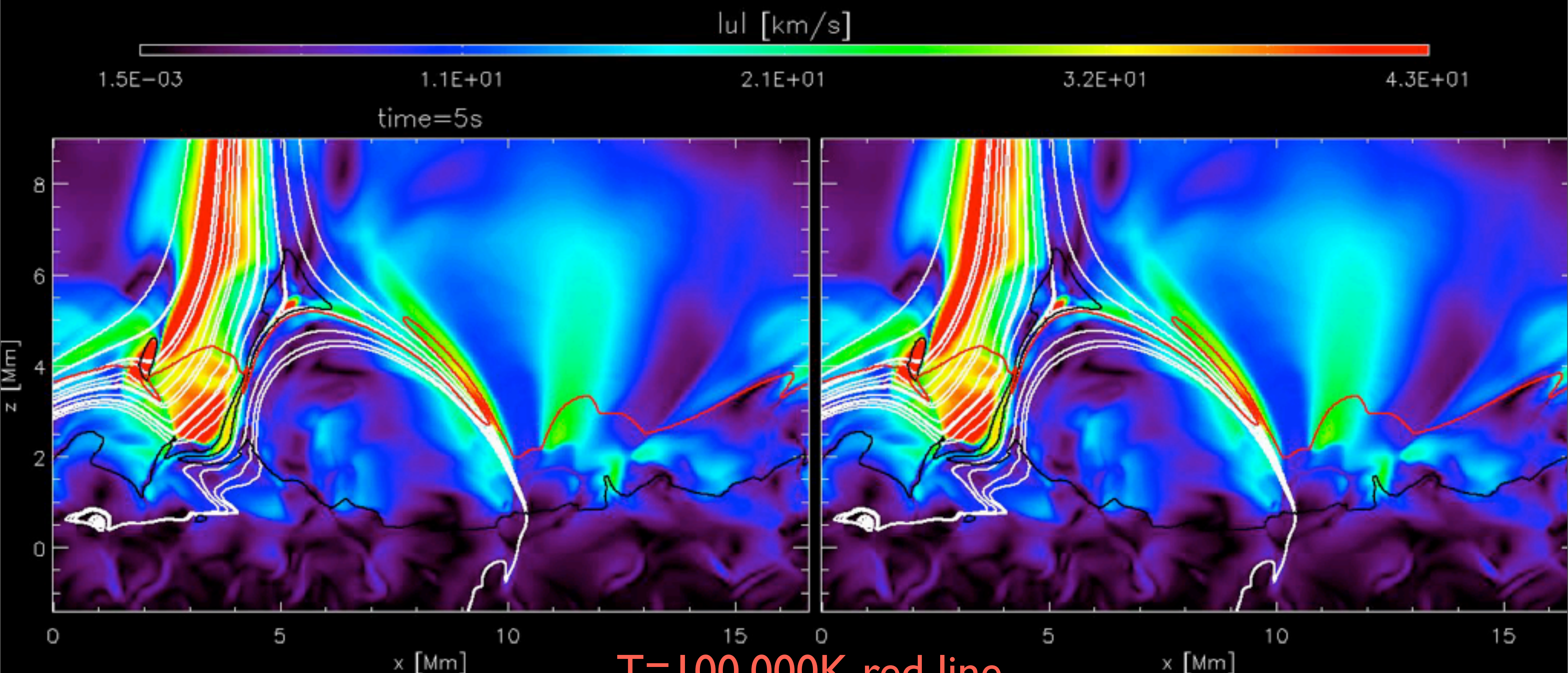


- In the chromosphere Pedersen heating is important
- In the upper chromosphere and in the corona the Joule heating is less important when Pedersen dissipation is taken into account

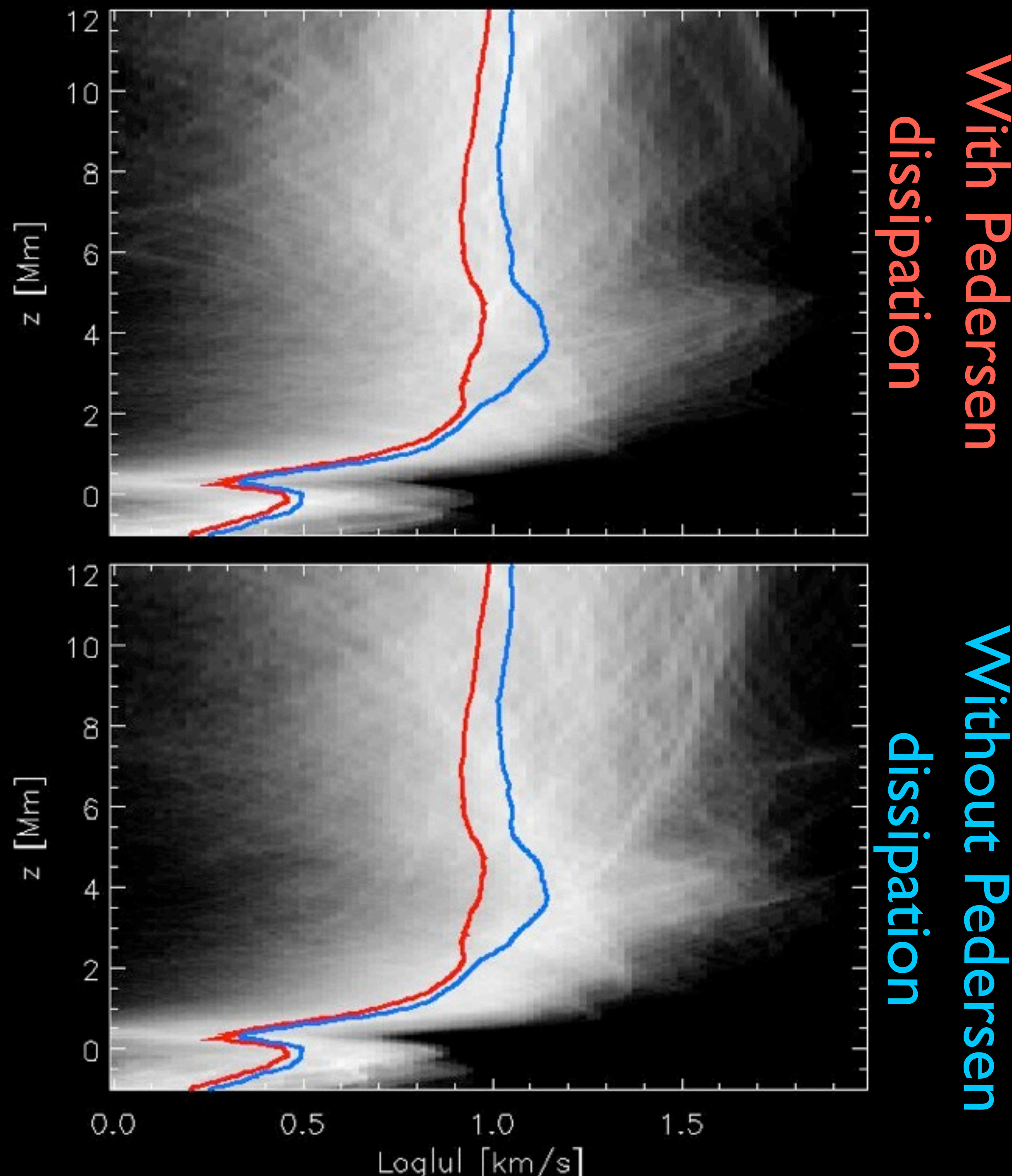
Dynamics

The simulation with Pedersen dissipation (unfortunately?) shows less dynamics than without in:

- In the upper chromosphere
- In the corona
- At the reconnection X point.



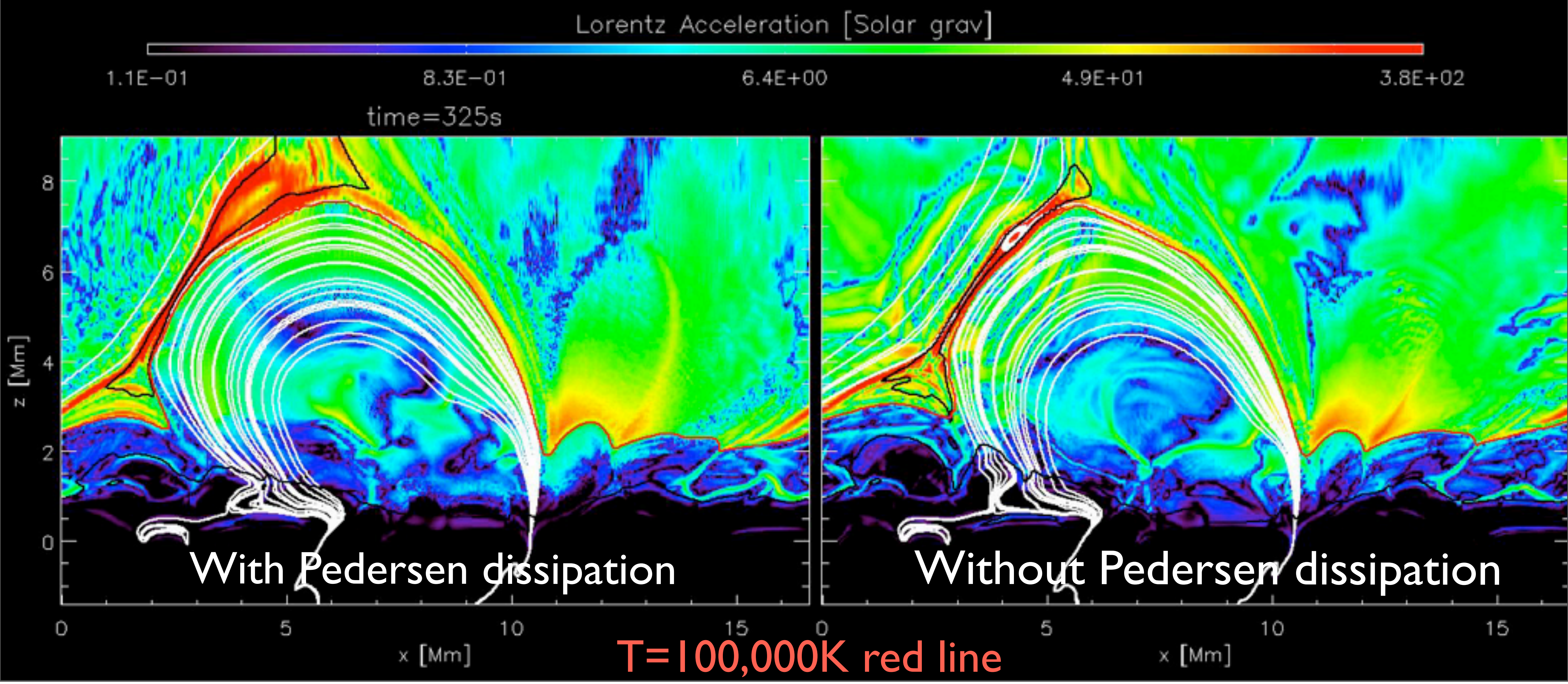
T=100,000K red line

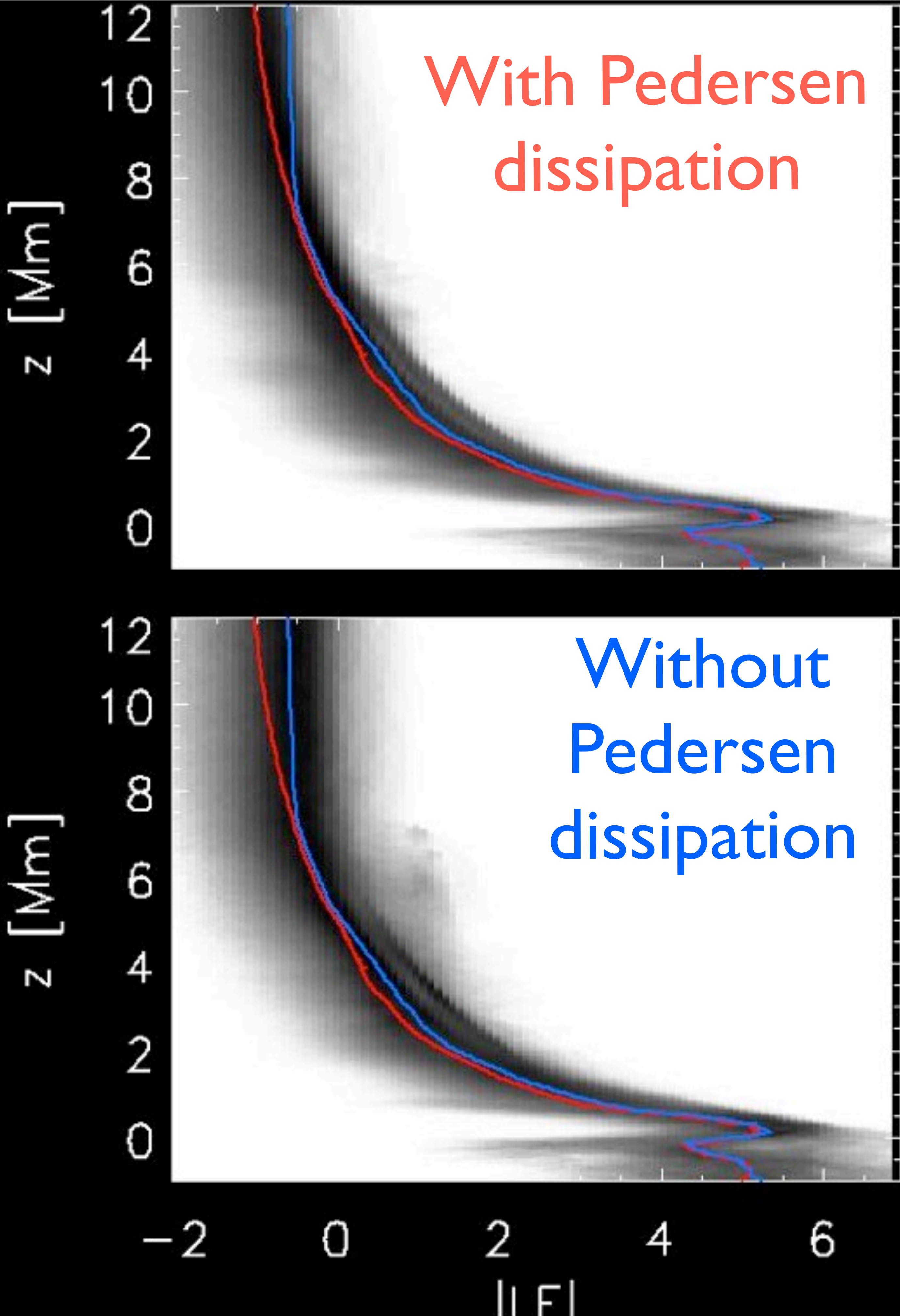


The simulation with Pedersen dissipation shows less dynamics than without in the upper chromosphere and corona

• The simulation with Pedersen dissipation shows less dynamics than without in the upper chromosphere and corona because the Lorentz force is also smaller.

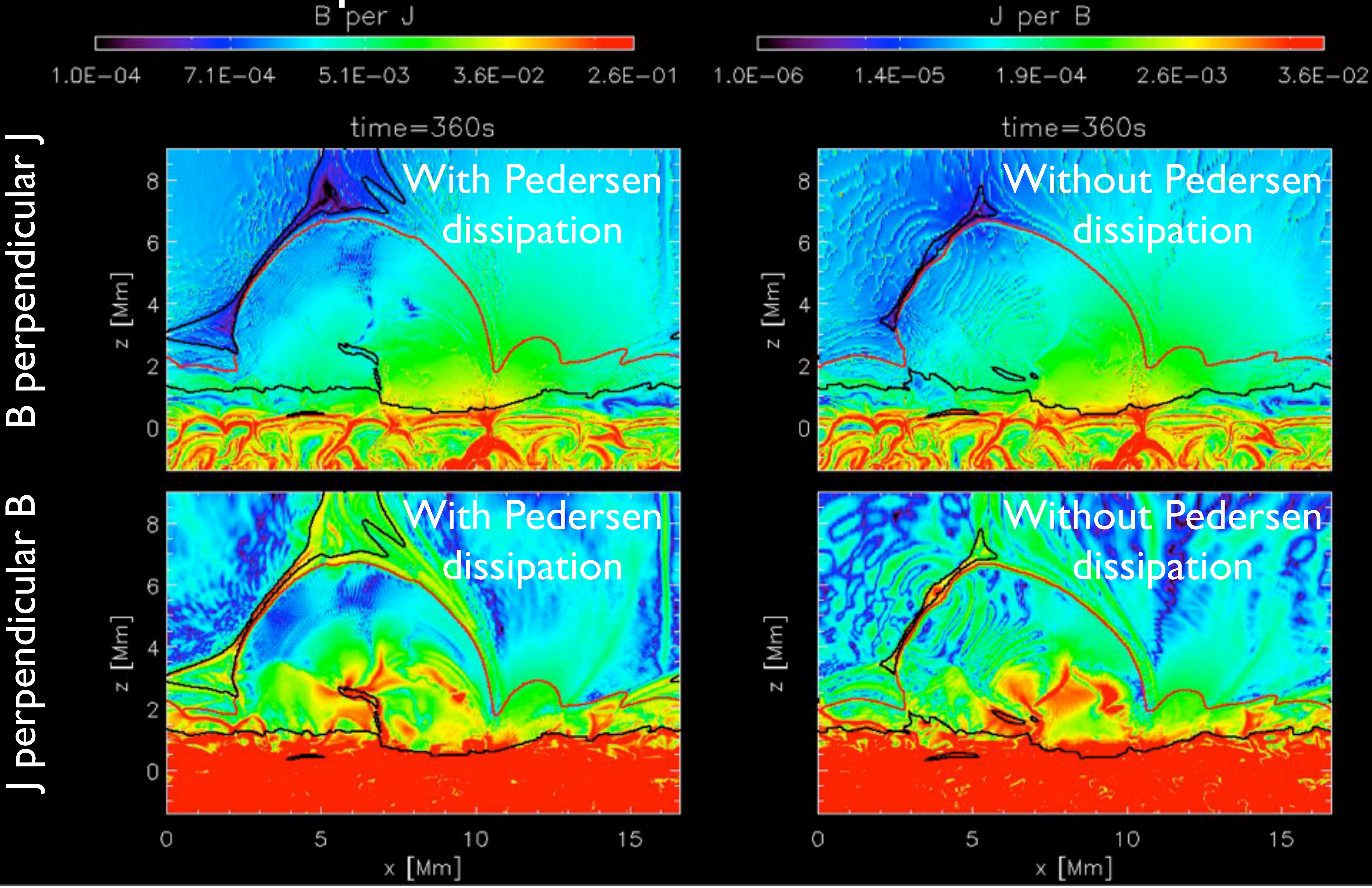
• The reconnection X is not as fast as with Pedersen dissipation because less tension is involved.





- The simulation with Pedersen dissipation shows less dynamics than without in the upper chromosphere and corona because the Lorentz force is also smaller.

The Lorentz force is smaller in these regions because the current (perpendicular to B) is removed in the lower chromosphere and B is more force free



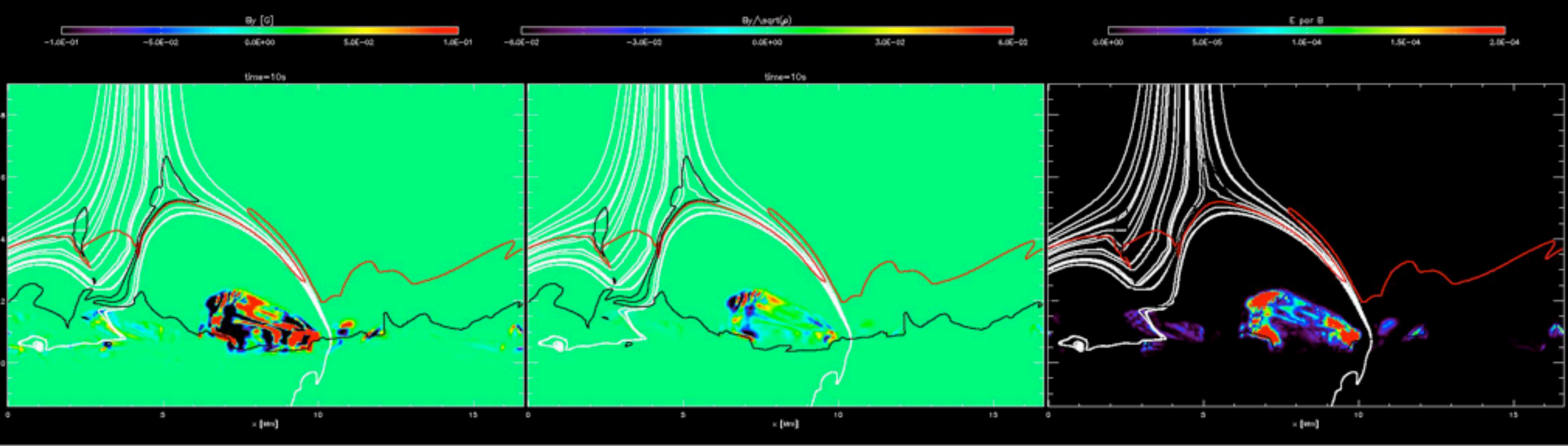
From 2D to 2.5D

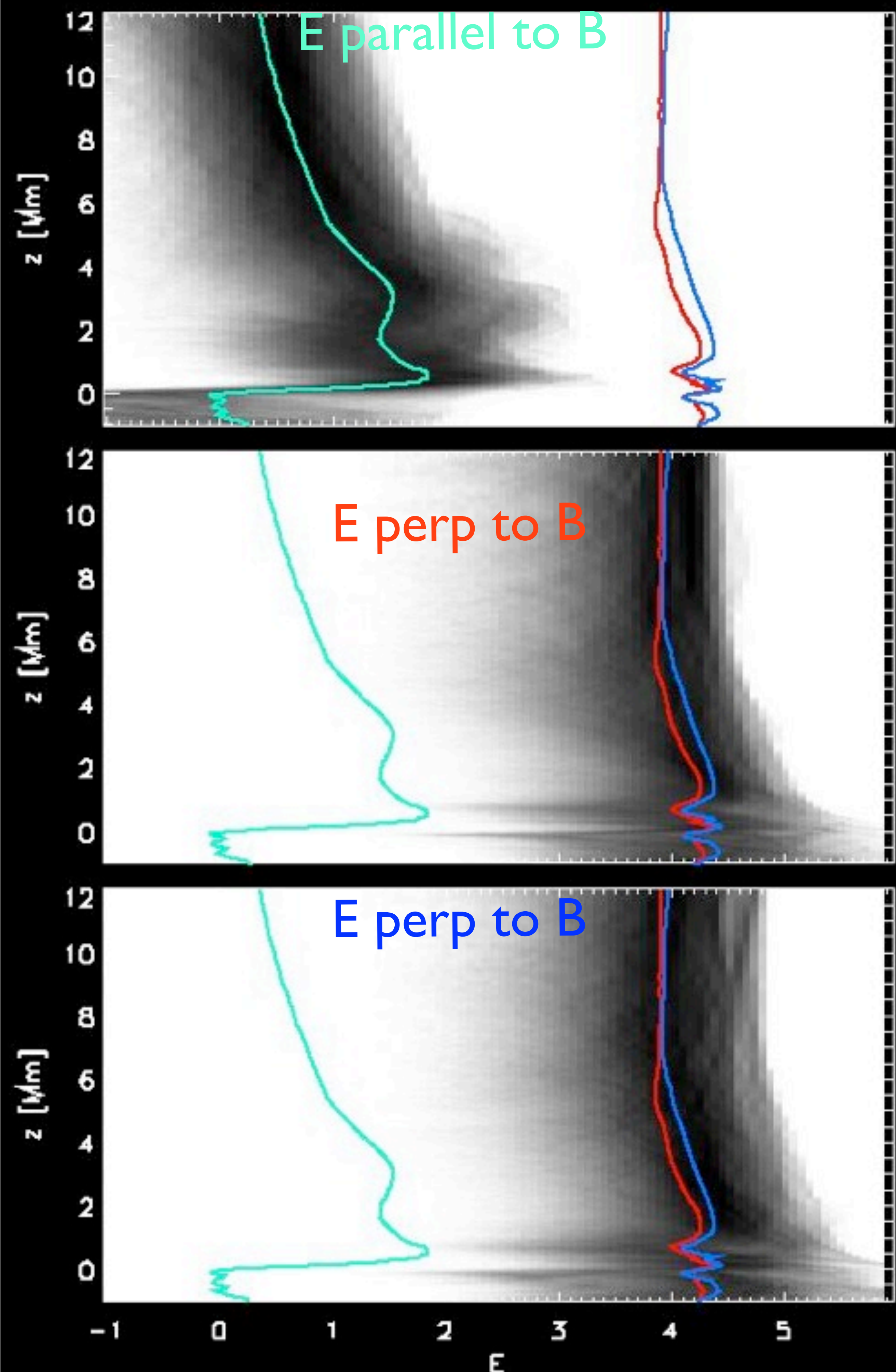
Magnetic field perpendicular to the plane is created triggered by the Hall term and increased by the Pedersen dissipation

With Pedersen dissipation can generates Electric field perpendicular to the currents

In the lower chromosphere

$B_y \sim 10^{-2} B_{||plane}$ $\qquad B_y/\sqrt{\rho}$ $\qquad$ E parallel to B





E parallel to B

With Pedersen dissipation

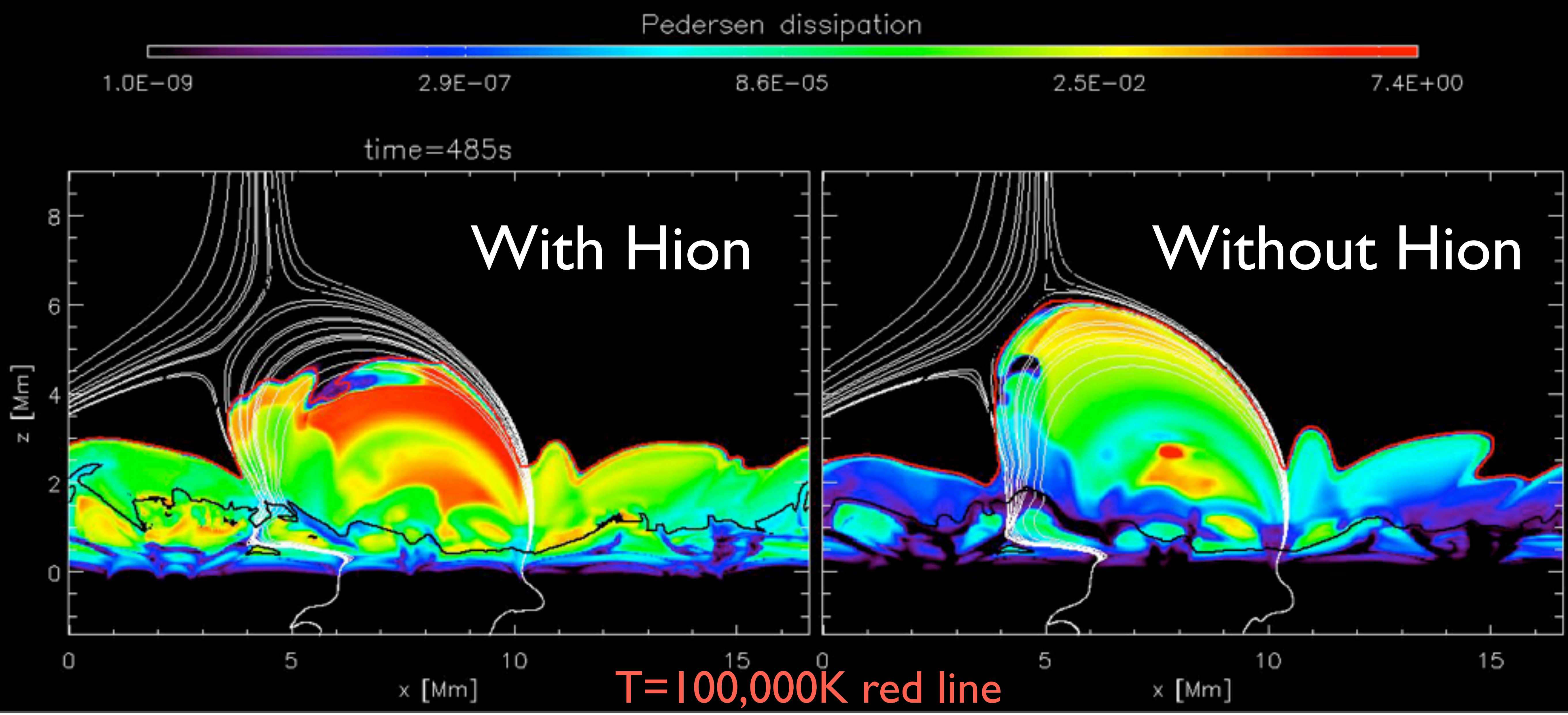
E perpendicular to B

Without Pedersen dissipation

Electric field perpendicular to J is created and Electric field parallel to J decreases in the upper chromosphere and a bit in the corona

Importance of solving the time dependent ionization with generalized Ohm's law

Pedersen dissipation shows less variation in the lower chromosphere when time dependence ionization is taken into account.
The upper chromosphere shows larger dissipation when time dependent ionization
If flows goes into the corona, Pedersen dissipation may be present in regions with temperatures above 100,000K!



Summary

- Pedersen dissipation is extremely sensitive to ionization degree: crucial to consider effects of time dependent ionization on Pedersen dissipation (Work in progress).
- Pedersen dissipation plays an important role in the energy balance of the chromosphere and transition region:
  - The minimum temperatures in the chromosphere are higher.
  - The mean temperature in the upper chromosphere is higher.
  - The TR structure with height is changed.
  - Reconnection processes are different.
- The simulation are less dynamics in the upper chromosphere, corona and in the reconnection X point because:
  - The Lorentz force is weaker in average in the upper chromosphere and corona.
  - As result of having less current perpendicular to B.
  - Because it has been removed by the Pedersen dissipation ("more force free") in the lower chromosphere.
- Electric field parallel to J is generated and the third component of the magnetic field is created (combination of Hall and Pedersen dissipation).