The Role of the Chromosphere in the Energization of the Corona

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James Leake [1]
Mark Linton [2]

[1] College of Science, George Mason University
[2] Space Science Division, Naval Research Laboratory

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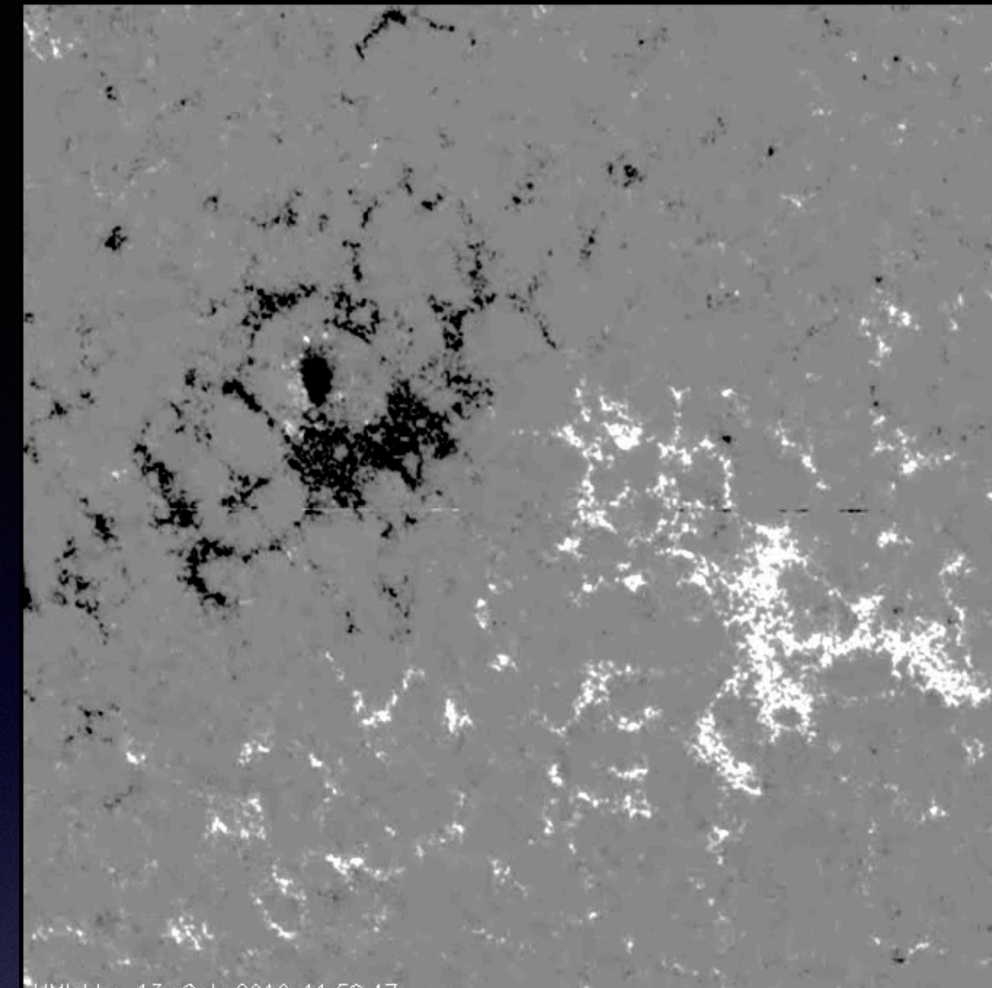
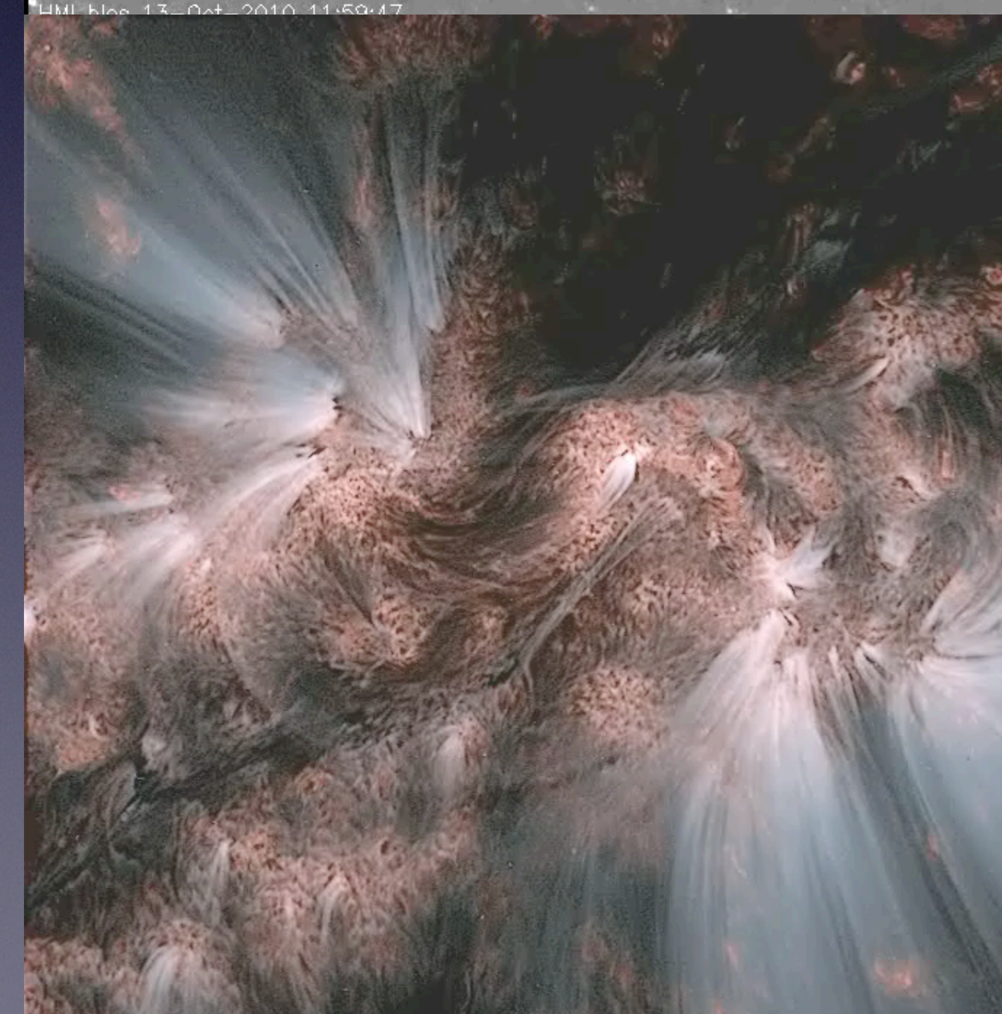
Content

- Motivation: The energization and destabilization of coronal magnetic field in active regions (ARs) driven by flux emergence
  - Others motivations: Supply of mass and energy to corona, solar wind, chromosphere and coronal heating, chromospheric reconnection, fundamental plasma physics (N. Murphy, M. Carlsson, J.Martinez-Sykora, Plenary session 3a, G. Crowley, S-19)
- Is the chromosphere just a transition twixt surface and corona?: Effects on the dynamic energization of the corona
- The physics of the chromosphere: A weakly ionized, stratified plasma with complex thermodynamics
- Including Chromospheric Physics in AR-scale studies: What are the consequences of adding chromospheric physics?

Motivation

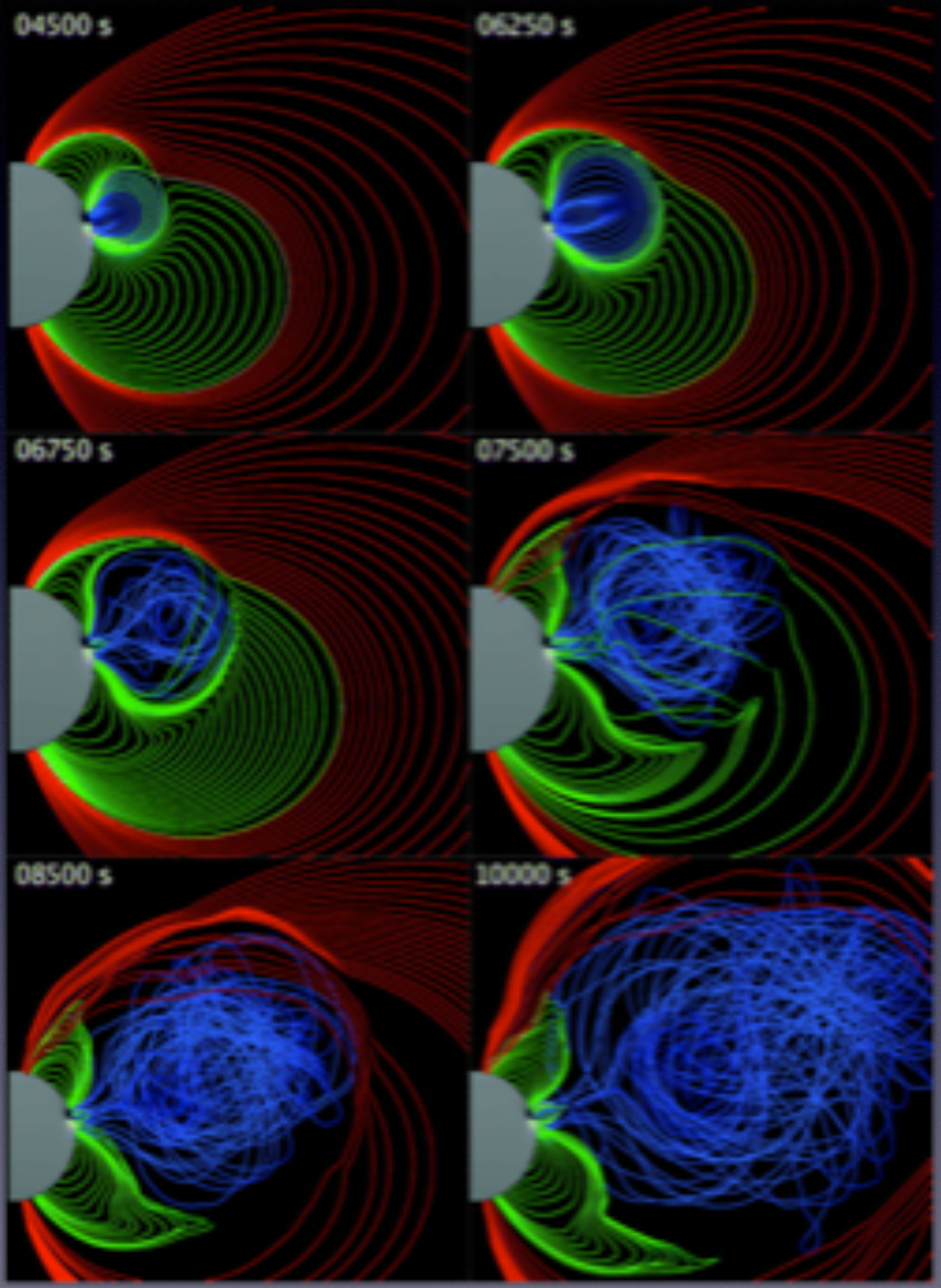
- Destabilization of magnetic field in the corona is source of major solar eruptions
  - Free energy (in non-potential field) built up and violently released
  - Built up by surface flows acting on potential field?
    - Flux Emergence/cancellation
    - Shearing and Sunspot Rotation
    - Differential rotation (longer times)
  - Are these flows consequence of the dynamic emergence of magnetic flux containing free energy?





Motivation

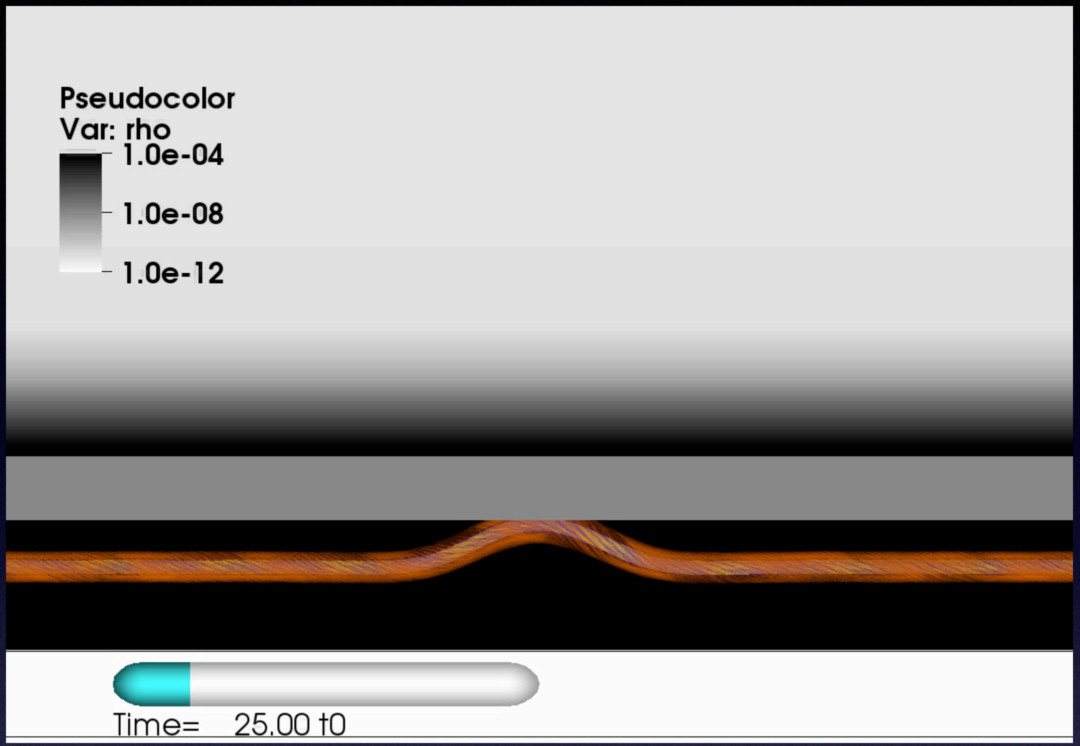
- Why care about dynamic emergence?
- Let's use surface signatures to influence lower boundary conditions in CME models
  - Torus Instability, Magnetic Breakout
- Let's assume free energy observed at surface reaches corona
  - Are we missing some important physics?
  - We need to include dynamic emergence to answer fundamental questions about CME initiation?
    - Flux rope formation,mechanism for impulsive release?

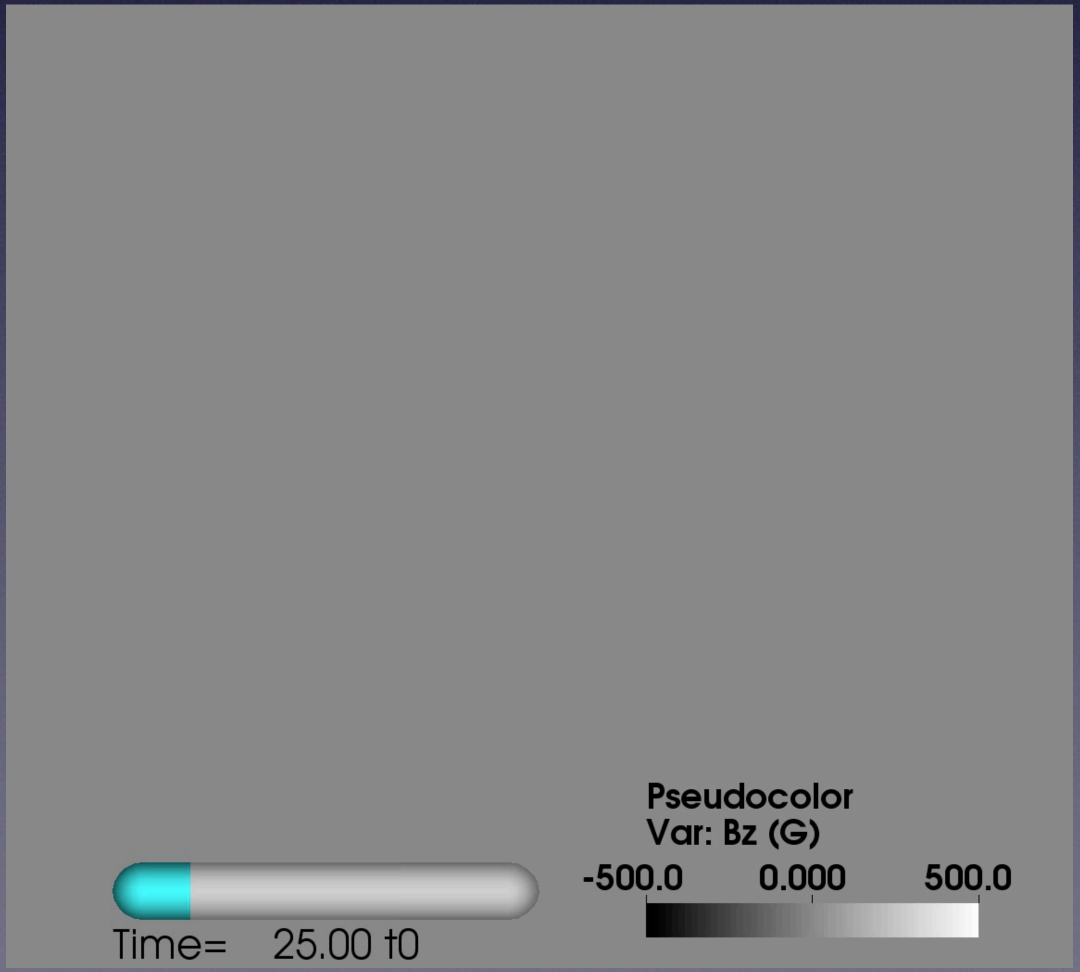


Lynch et al. 2008

The chromospheric transition

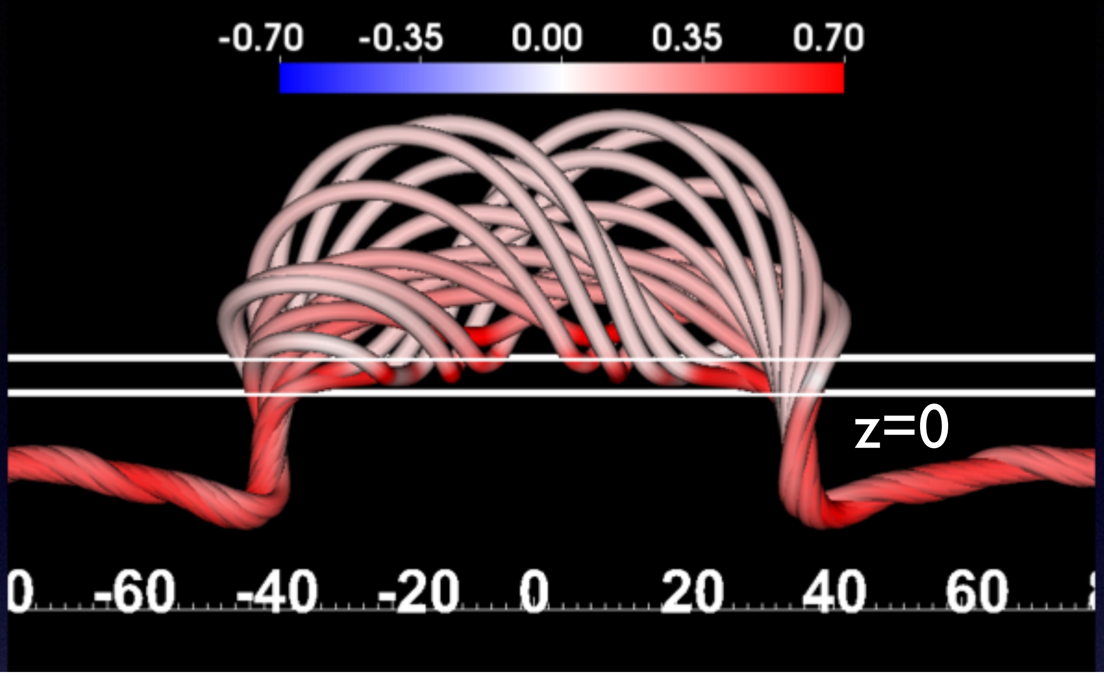
- Dynamic simulations of flux emergence from the convection zone (Leake et al., 2013, 2014)
- Based on theory and simulations of dynamo actions in the solar interior - twisted flux tubes
- Chromosphere is a transitional layer where stratification is stable to buoyancy and density drops
- Self consistent create energization mechanisms (shearing, rotation, flux cancellation) at surface - able to initiate CME in the B/O scenario
- Presence of chromosphere - Complex transfer of free energy to the corona

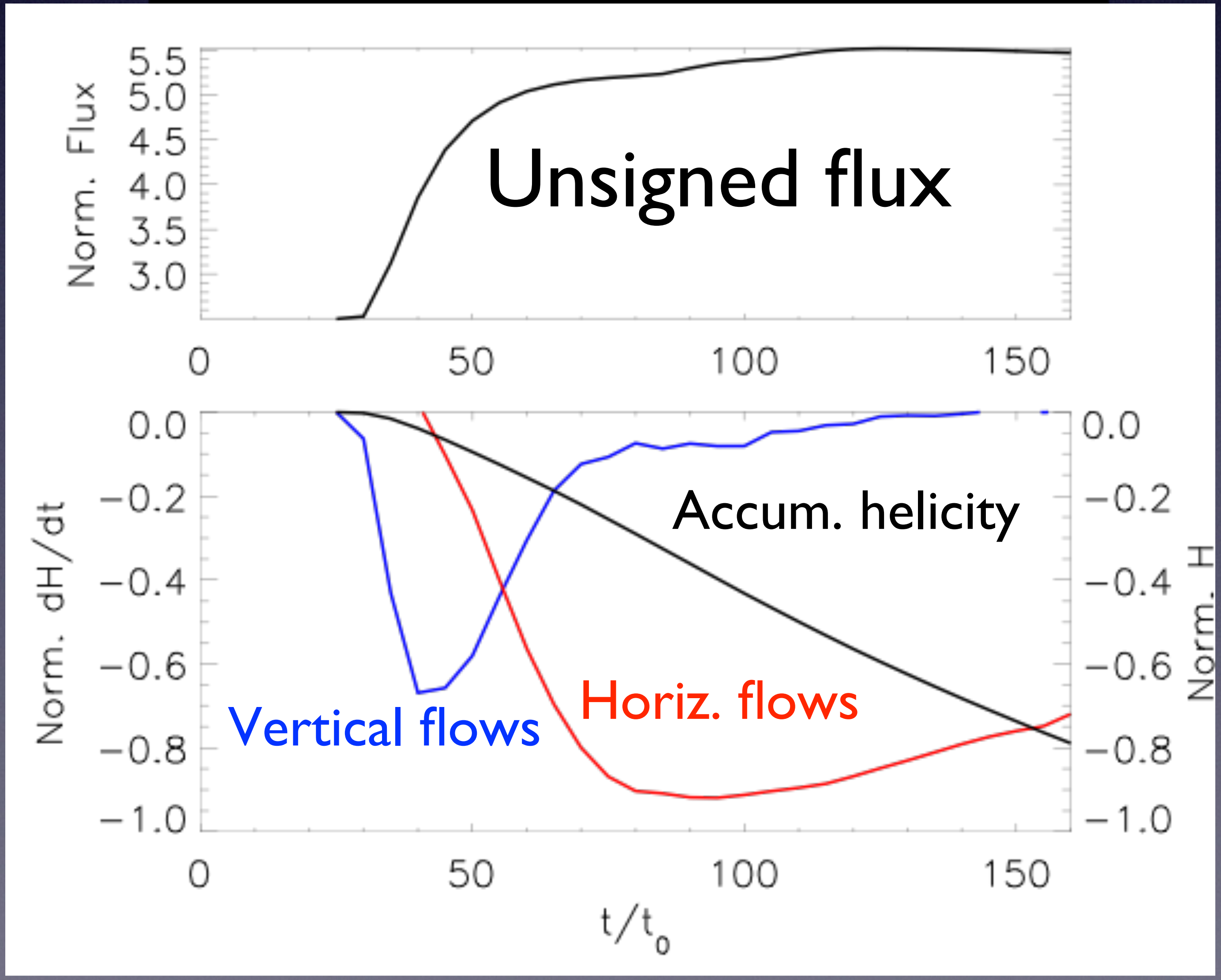




The chromospheric transition

- Partial emergence
  - bodily emergence to just above surface
  - outer fieldlines expand into corona, lengthen
    - gradient in twist per unit length
    - propagation of twist (Manchester 2004, Fan 2009)
  - Leads to differing contribution of vertical and horizontal flows to helicity injection at different surfaces





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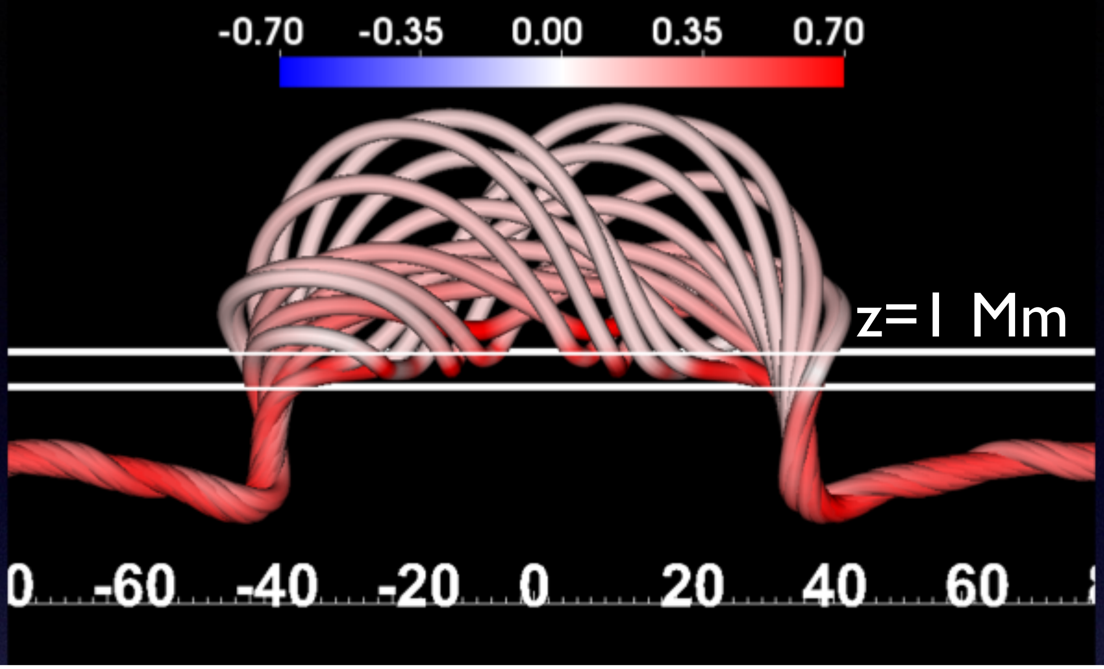
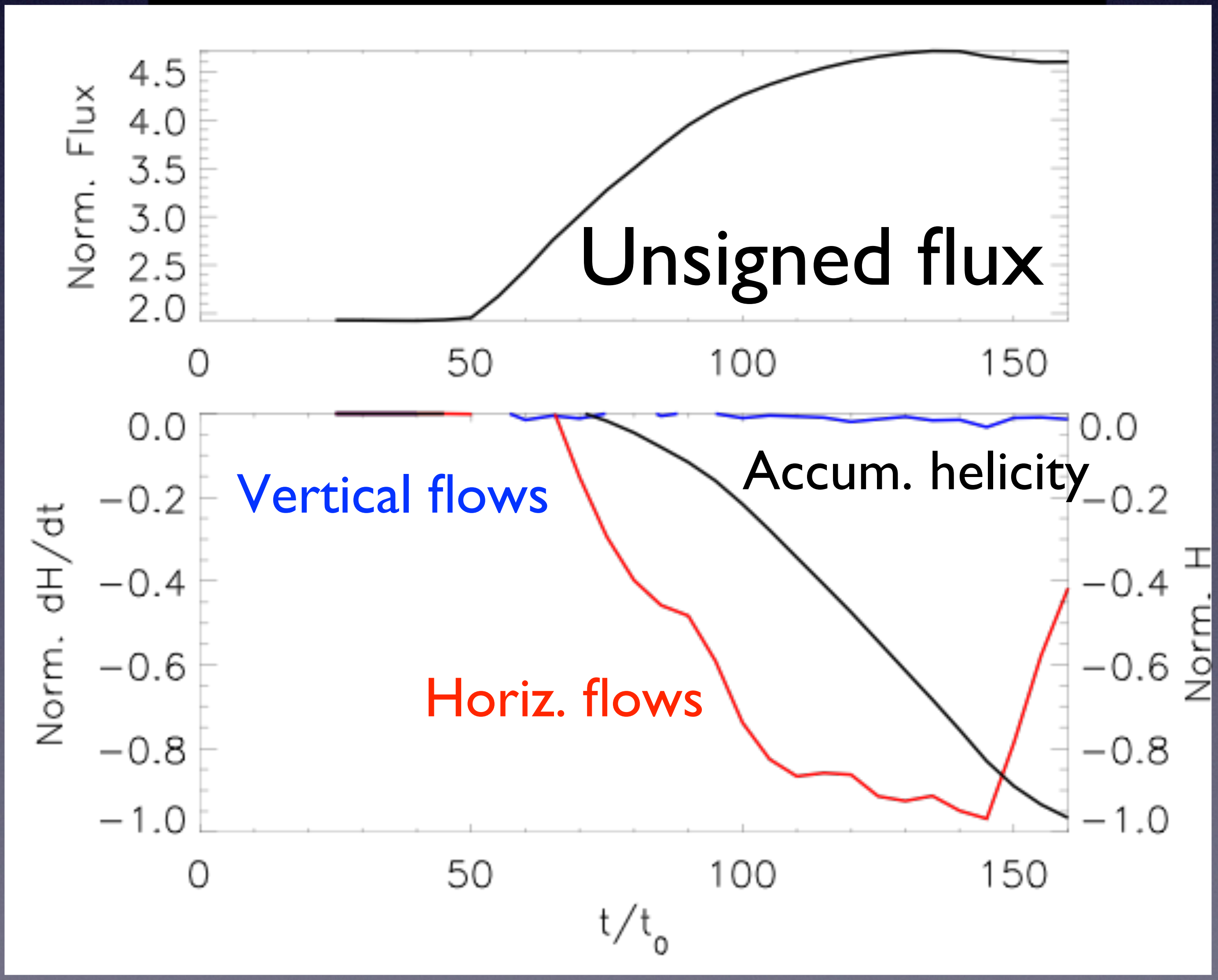
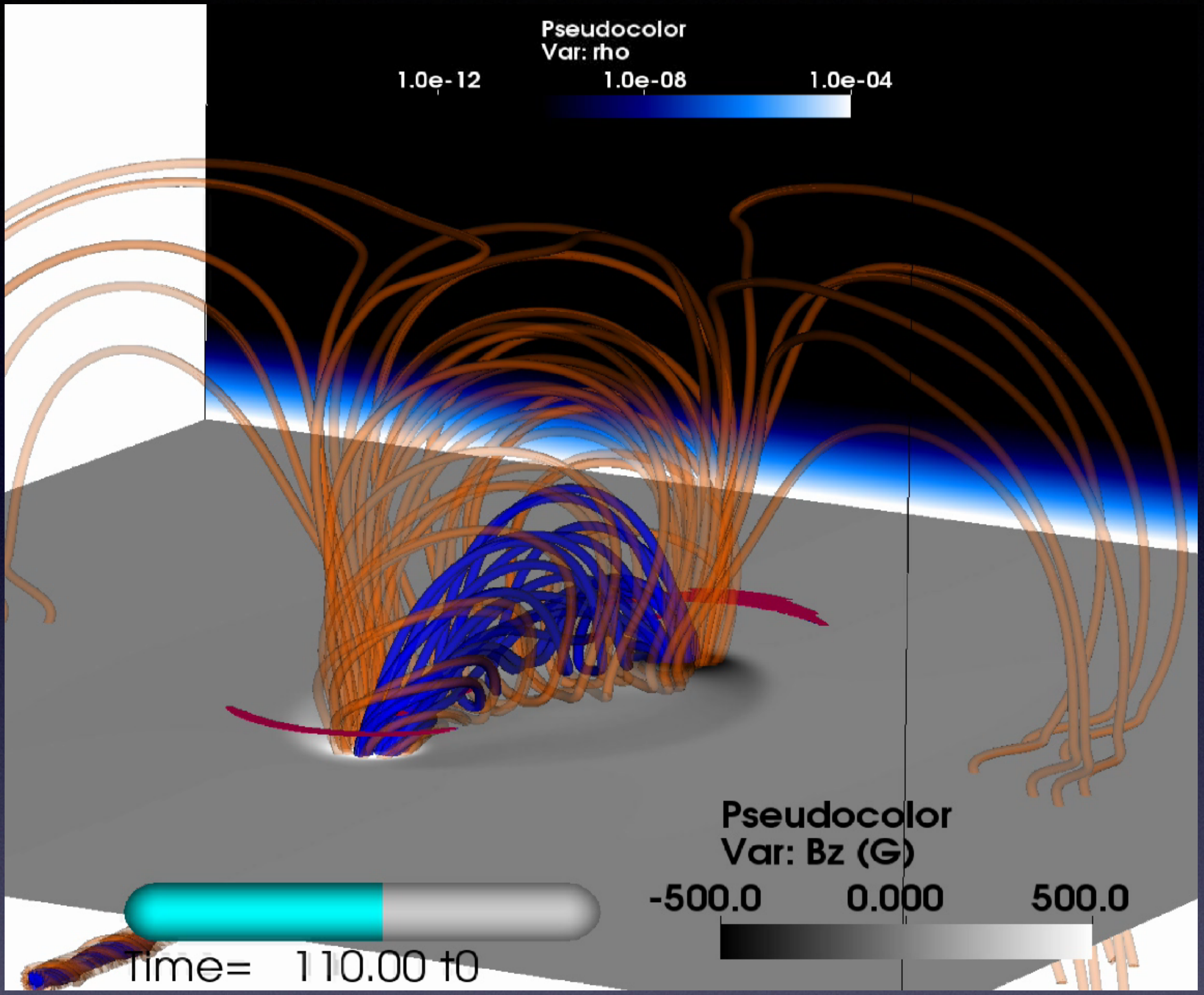




The chromospheric transition

- Chromospheric physics will affect emergence
- "Flare"-like reconnection leads to formation of erupting flux rope (Archontis and Torok 2008, Archontis et al., 2012, Leake et al., 2014)
- As a result of expansion driven by 'breakout reconnection'
- This reconnection is occurring in the chromospheric transition
- Magnetic reconnection is affected by plasma-neutral decoupling (Leake et al. 2012, 2013)
- In cases where no B/O reconnection?
- Need improved MHD model of the chromosphere

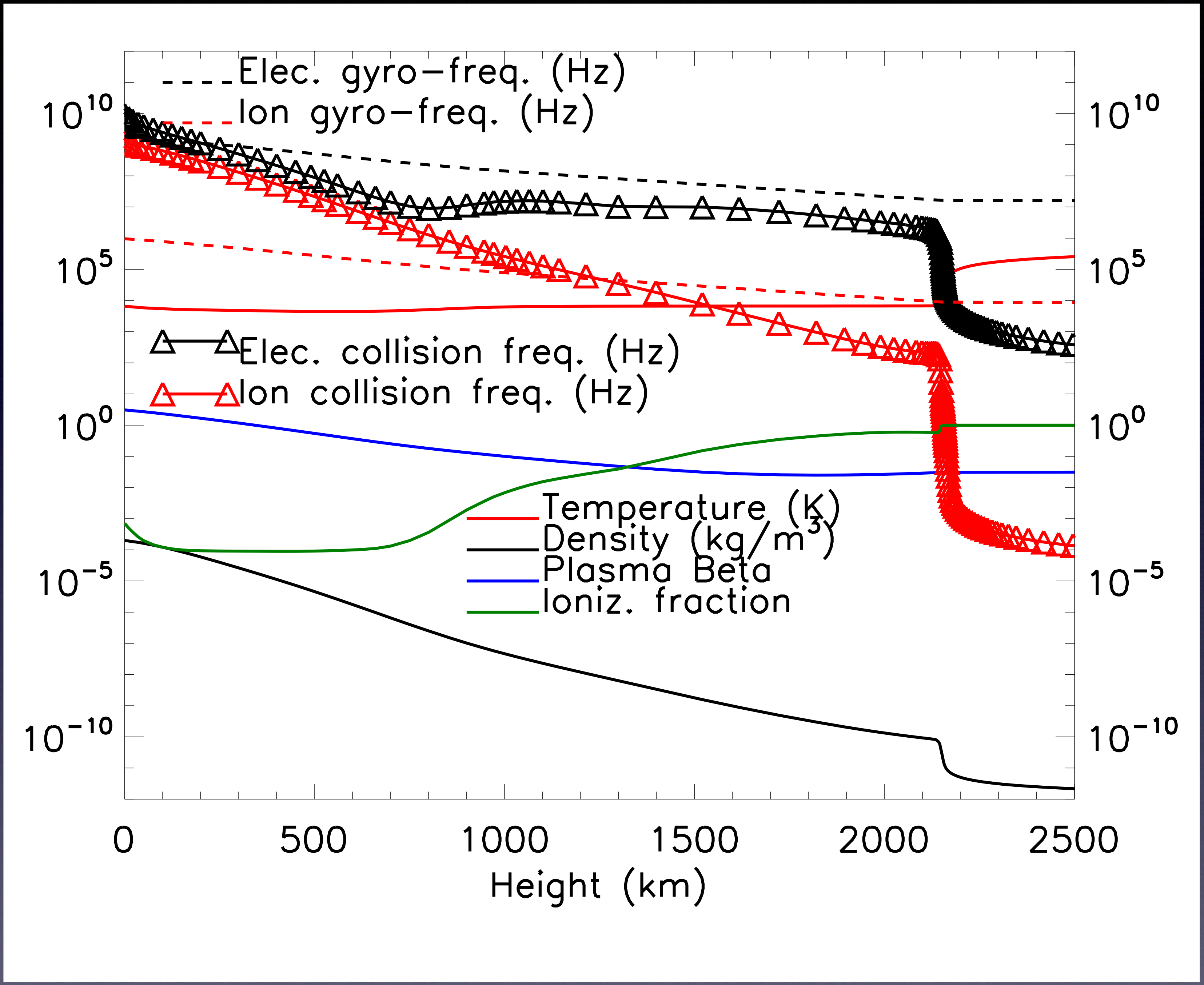


Chromospheric Physics

- Not a layer in space but based on optical thickness

  $$\tau_{6564.8} = 1$$

- Other transitions
  - high to low beta
  - Nearly neutral to fully ionized
  - unmagnetized to magnetized
  - isotropic to anisotropic electrodynamics
- Need to include relevant physics in MHD simulations



Chromospheric Physics

- Partially ionized single-fluid MHD valid when

$$\nu_{ab}, \nu_{aa}, \nu_{ion}, \nu_{recomb} >> f_0$$

- Neutrals and plasma highly coupled - single-fluid
- Cannot use when plasma and neutral decouple on small scales (e.g. reconnection in chromopshere - Leake et al, 2012 2013
- Fluid equations, continuity, momentum, energy:

$$\begin{aligned}
\frac{\partial}{\partial t}(\rho_T) + \nabla \cdot (\rho_T \mathbf{V}_T) &= 0 \\
\frac{\partial}{\partial t}(\rho_T \mathbf{V}_T) + \nabla \cdot (\rho_T \mathbf{V}_T \mathbf{V}_T) &= -\nabla \cdot \mathbb{P}_T + \mathbf{J} \times \mathbf{B} + \mathbf{F}_{ext} \\
\frac{\partial \epsilon_T}{\partial t} + \nabla \cdot (\epsilon \mathbf{V}_T)) &= -\nabla \cdot (\mathbf{h}_T) + \mathbb{P}_T : \nabla \mathbf{V}_T \\
&+ \mathbf{E}^{\mathbf{V}_T} \cdot \mathbf{J} + Q_{rad} + H
\end{aligned}$$

Chromospheric Physics

- MHD - E/M fields $t_0 \gg L_0/c, \ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \ \frac{\nabla \times \mathbf{B}}{\mu_0} = \mathbf{J}$
- V-B paradigm
- Need equation between E and J, Generalized Ohm's law (GOL)
  - In plasma, this involves velocity, as E is frame-dependent
    - GOL comes from individual momentum equations
- Gradients in B - J drives E, plasma moves to drive E in plasma frame to zero
  - small leftover E due to collisions and electron pressure gradients
    - leads to Ohmic heating $\mathbf{E}^{\mathbf{V}} \cdot \mathbf{J}$
- In partially ionized plasma, collisions between plasma and neutrals can

increases E in the rest frame of the mass-averaged flow

$$\mathbf{E}^{\mathbf{V}_T} = \mathbf{E} + \mathbf{V}_T \times \mathbf{B} = \eta_{||}\mathbf{J}_{||} + \eta_{\perp}\mathbf{J}_{\perp}$$

- Anisotropic (Pedersen or ambipolar) dissipation of currents
- $$\frac{\partial B}{\partial t} = \nabla \times (\mathbf{V}_T \times \mathbf{B}) - \nabla \times (\eta_{||}\mathbf{J}_{||}) - \nabla \times (\eta_{\perp}\mathbf{J}_{\perp})$$

Chromospheric Physics

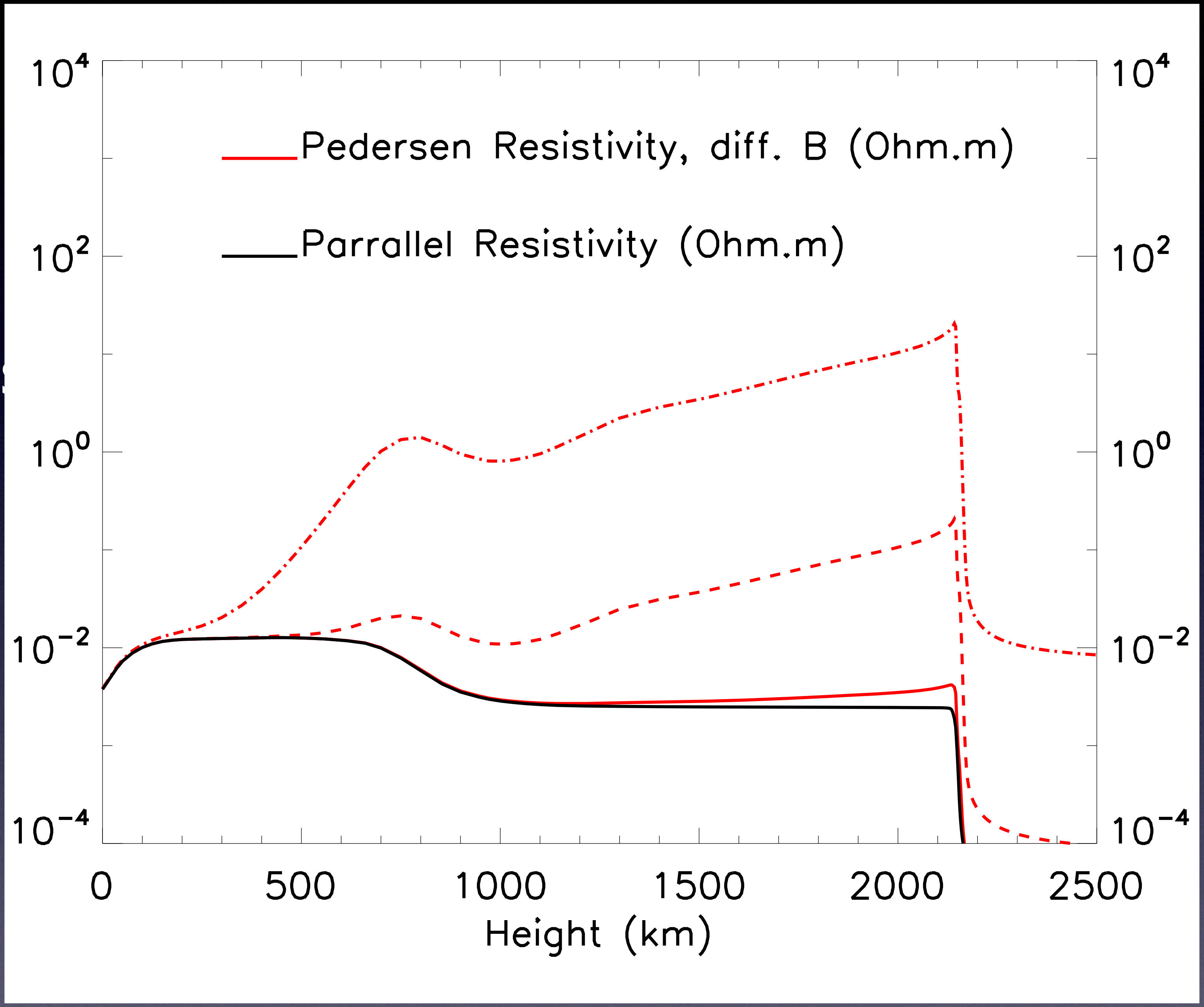
- Pedersen resistivity

$$\eta_\perp = \frac{B}{en}\xi_n^2 k_{in}, \quad k_{in} = \Omega_i/\nu_{in}$$

- Chromosphere transitions from

$$k_{in} << 1 \quad \text{to} \quad k_{in} >> 1$$

$$\eta_\perp = \eta_\parallel \quad \text{to} \quad \eta_\perp >> \eta_\parallel$$



- Dissipation of cross-field currents, force-free field

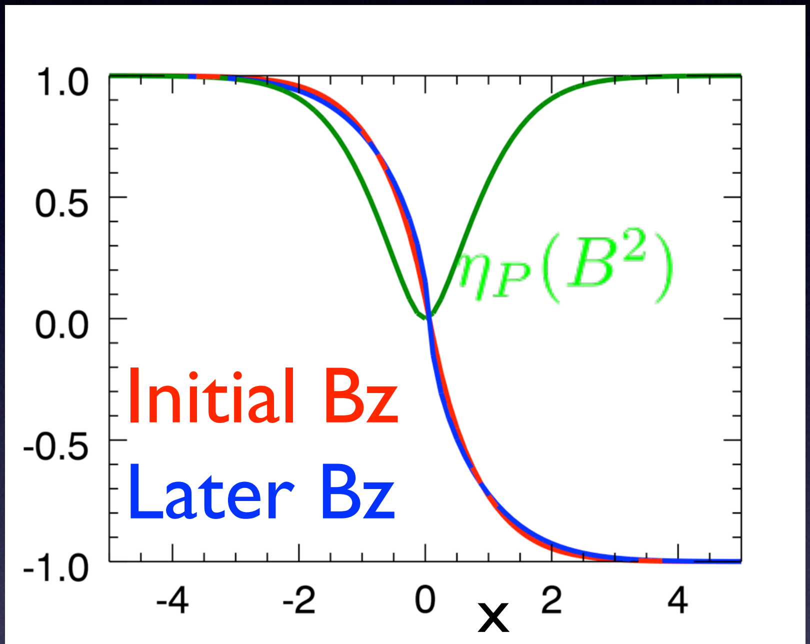
- Increased Joule heating

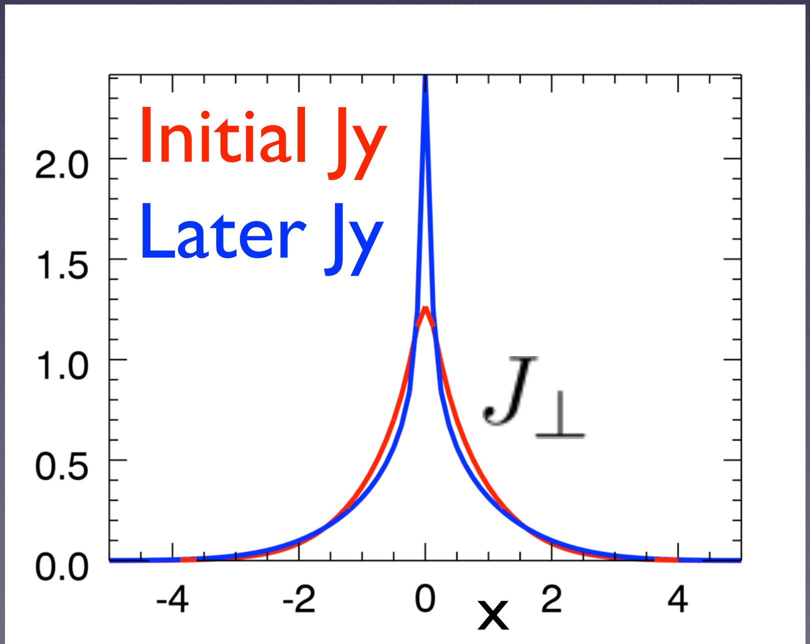
$$\mathbf{E}^{\mathbf{V}} \cdot \mathbf{J}$$

Chromospheric Physics

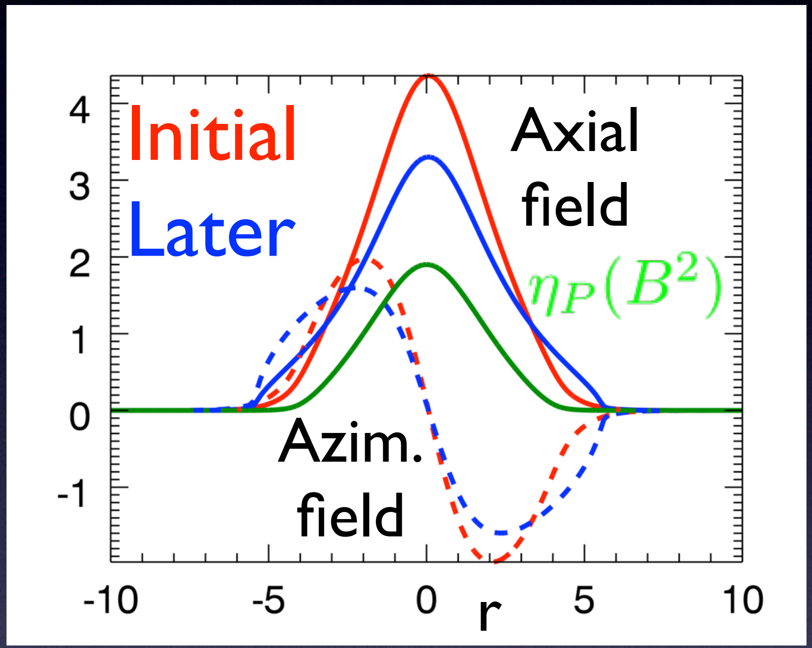
- Pedersen dissipation acting on simple structures $B \to 0, \ \eta_P \to 0$

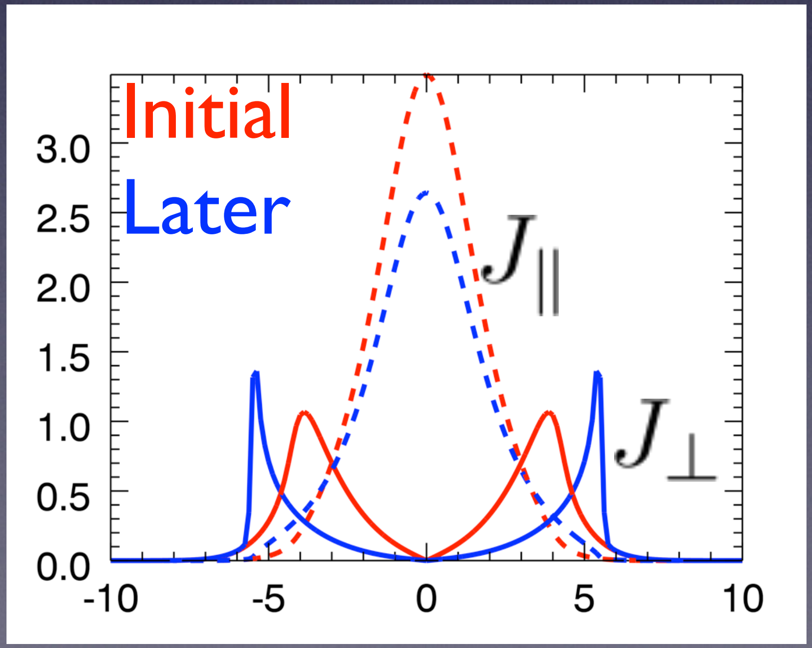
Simple Harris Current Sheet





Twisted CZ tube





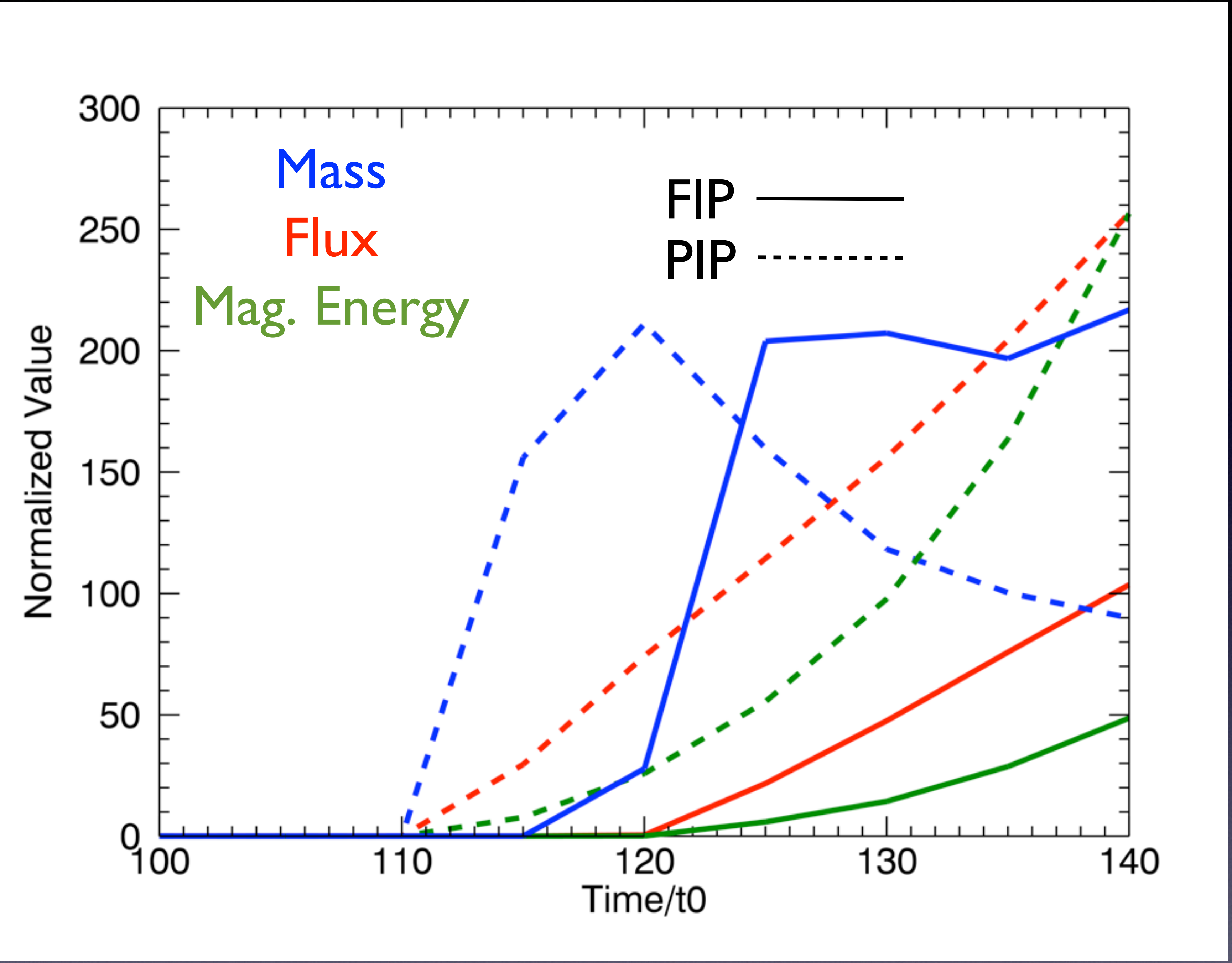
- Pedersen resistivity tends to dissipate regions of perpendicular current

$$J_\perp \to 0, \ \mathbf{J} \times \mathbf{B} \to 0$$

- But sharpens currents at null points (B=0)
- Also dissipates parallel currents via coupling to perpendicular
- How will it affect emerging flux?

Chromospheric Physics in AR-studies

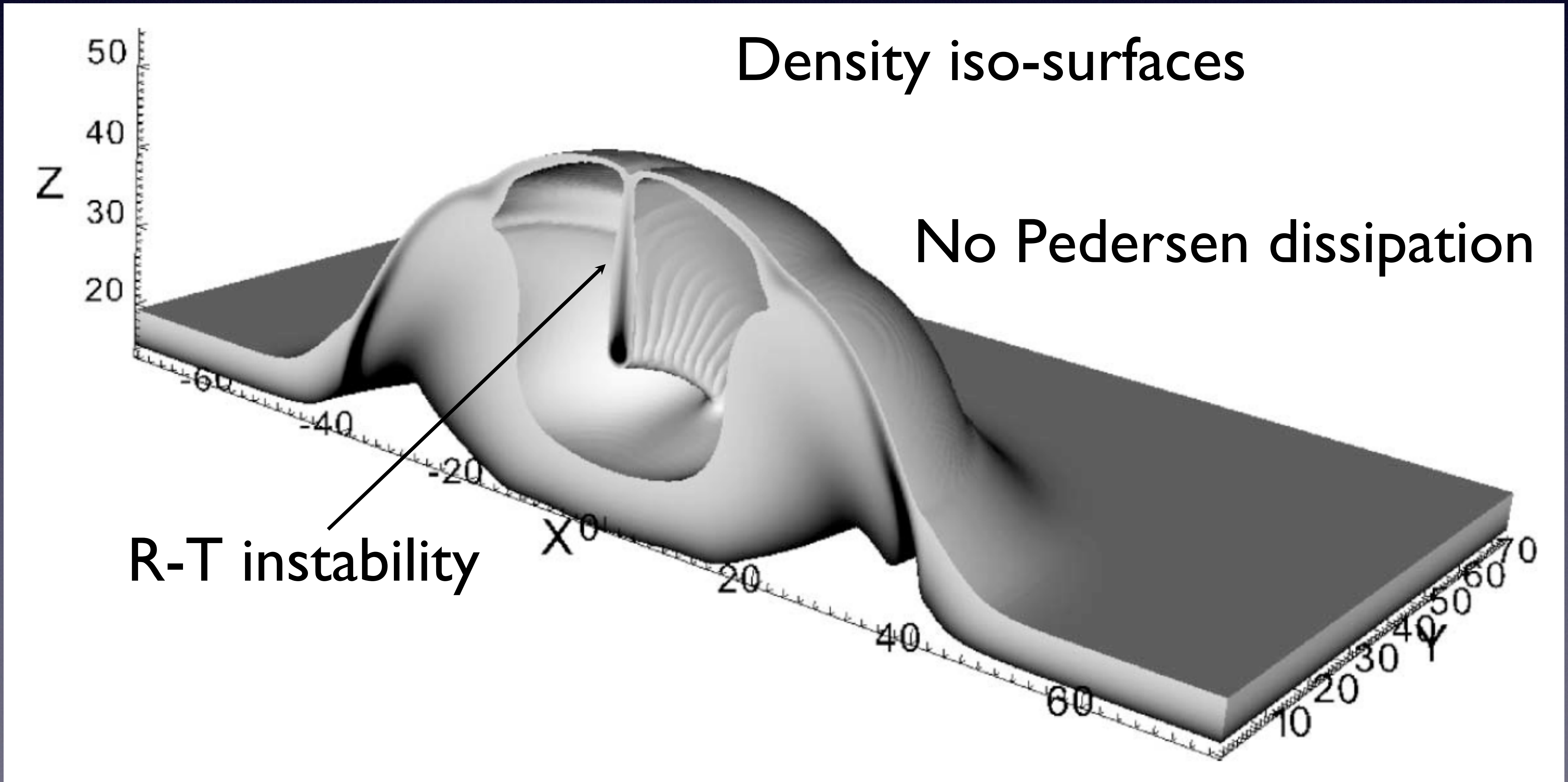
- MHD simulations with partial ionization and Pedersen dissipation
- Ionization fraction from Saha equation
  - Not valid in the chromosphere
- Compare fully ionized plasma (FIP) to partially ionized plasma (PIP)
- Increase in magnetic energy in corona
- Increase in unsigned flux in corona, decrease in mass supplied to corona



- 'Slippage' of magnetic field through the weakly ionized chromosphere

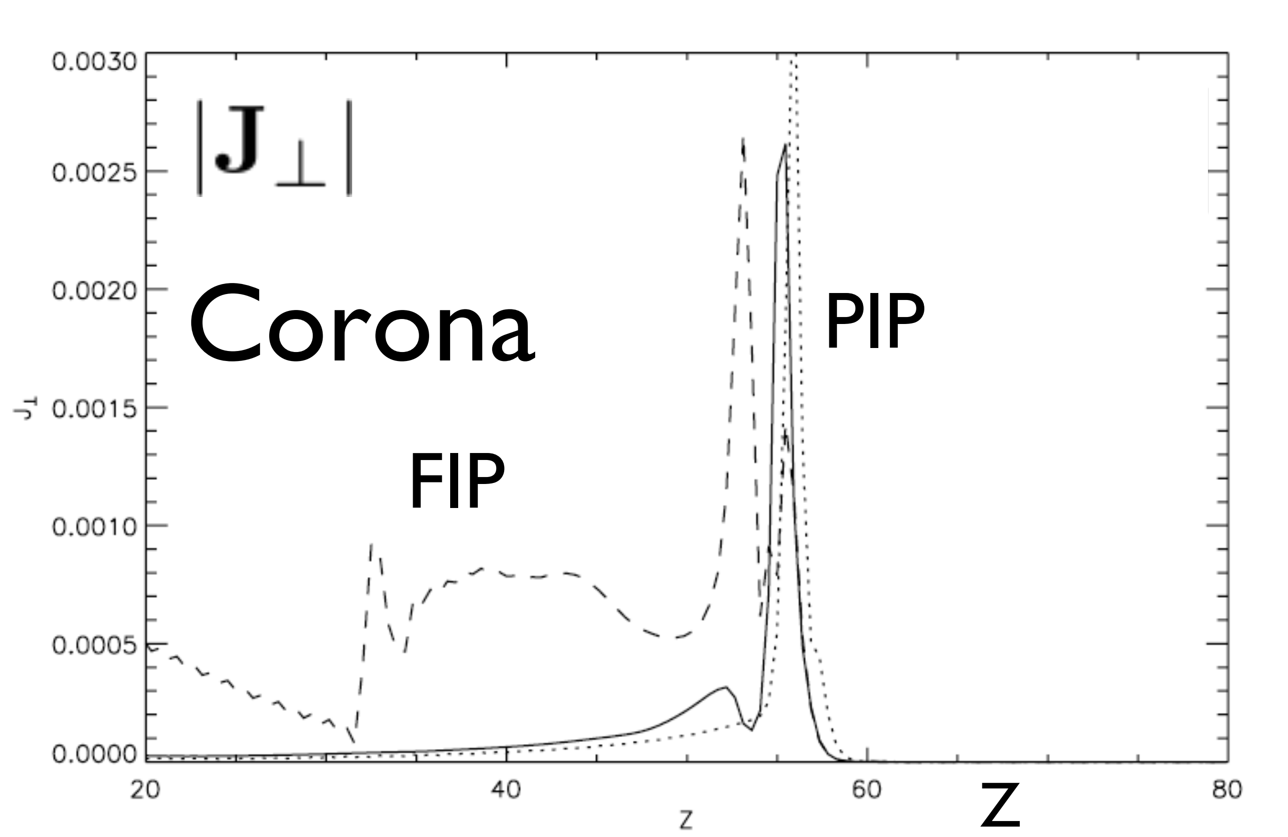
Chromospheric Physics in AR-studies

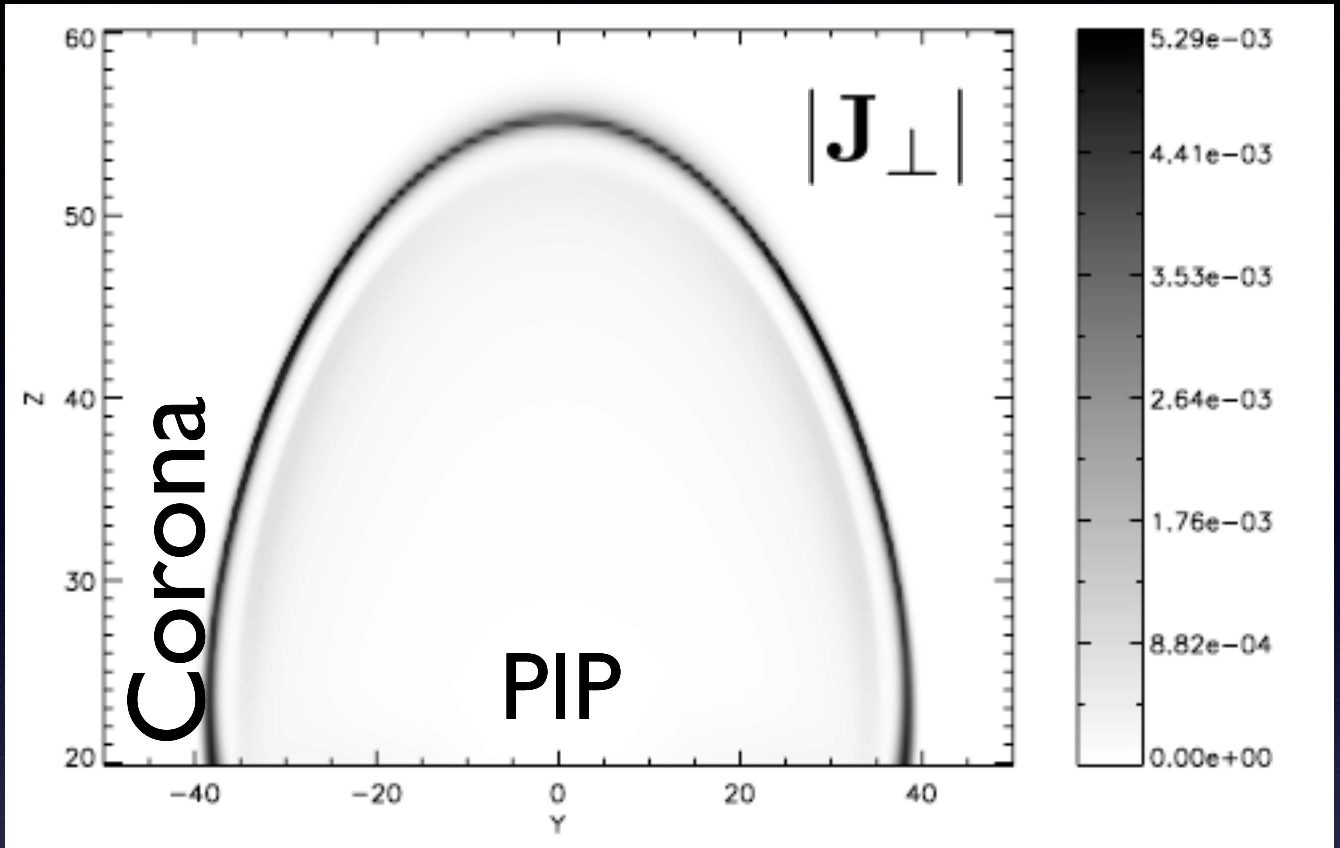
- Pedersen dissipation (ambipolar diffusion) lifts less mass into corona on emerging fields
- Without partial ionization effects get Rayleigh-Taylor inst. due to mass lifting
- With Pedersen dissipation, field slips through chromosphere, lifts less mass

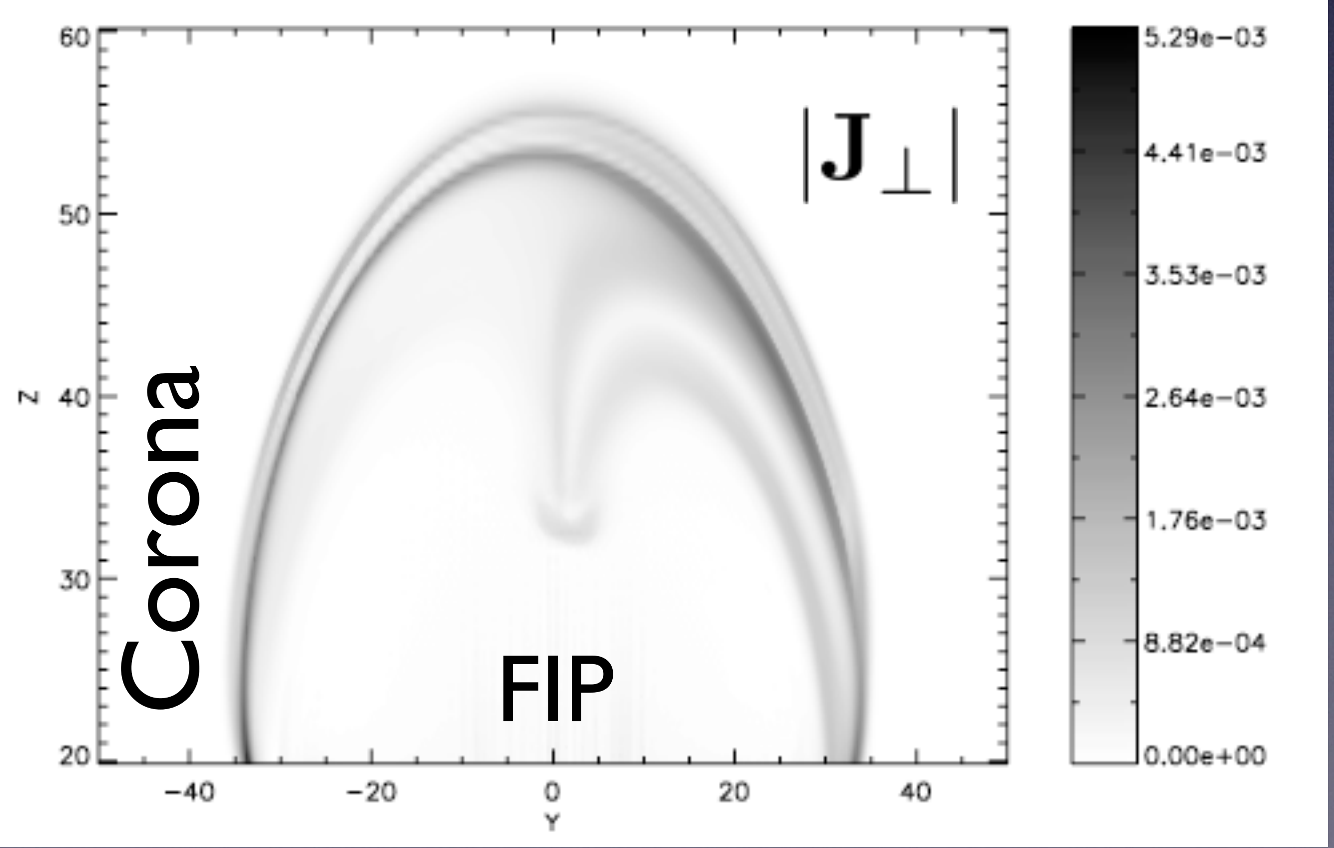


Chromospheric Physics in AR-studies

- Look at currents in emerging active region magnetic field
- Compare fully ionized plasma (FIP) and partially ionized plasma (PIP)
- As with simple test:
    - dissipation of perp.current and thinning of current sheets

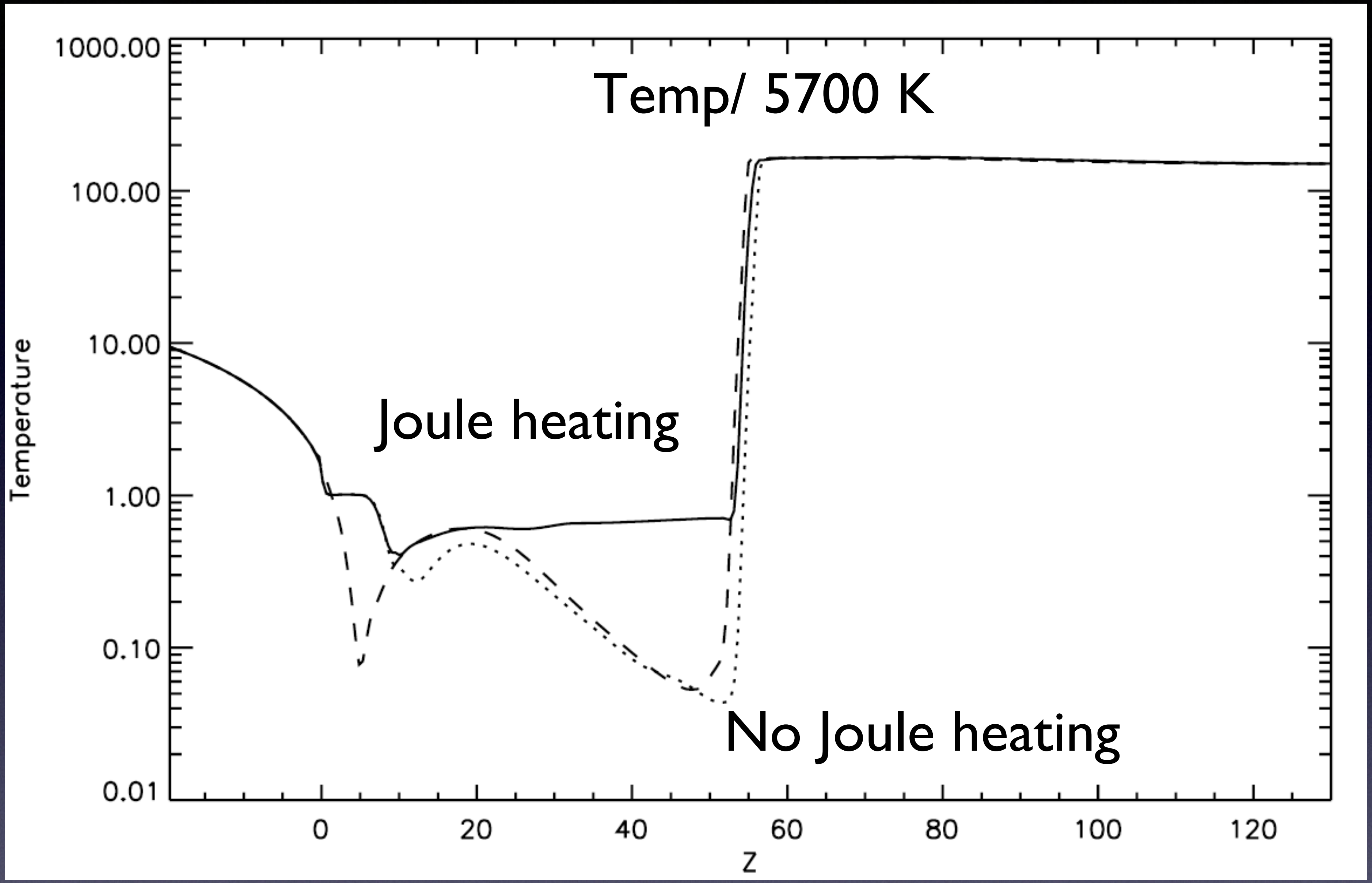






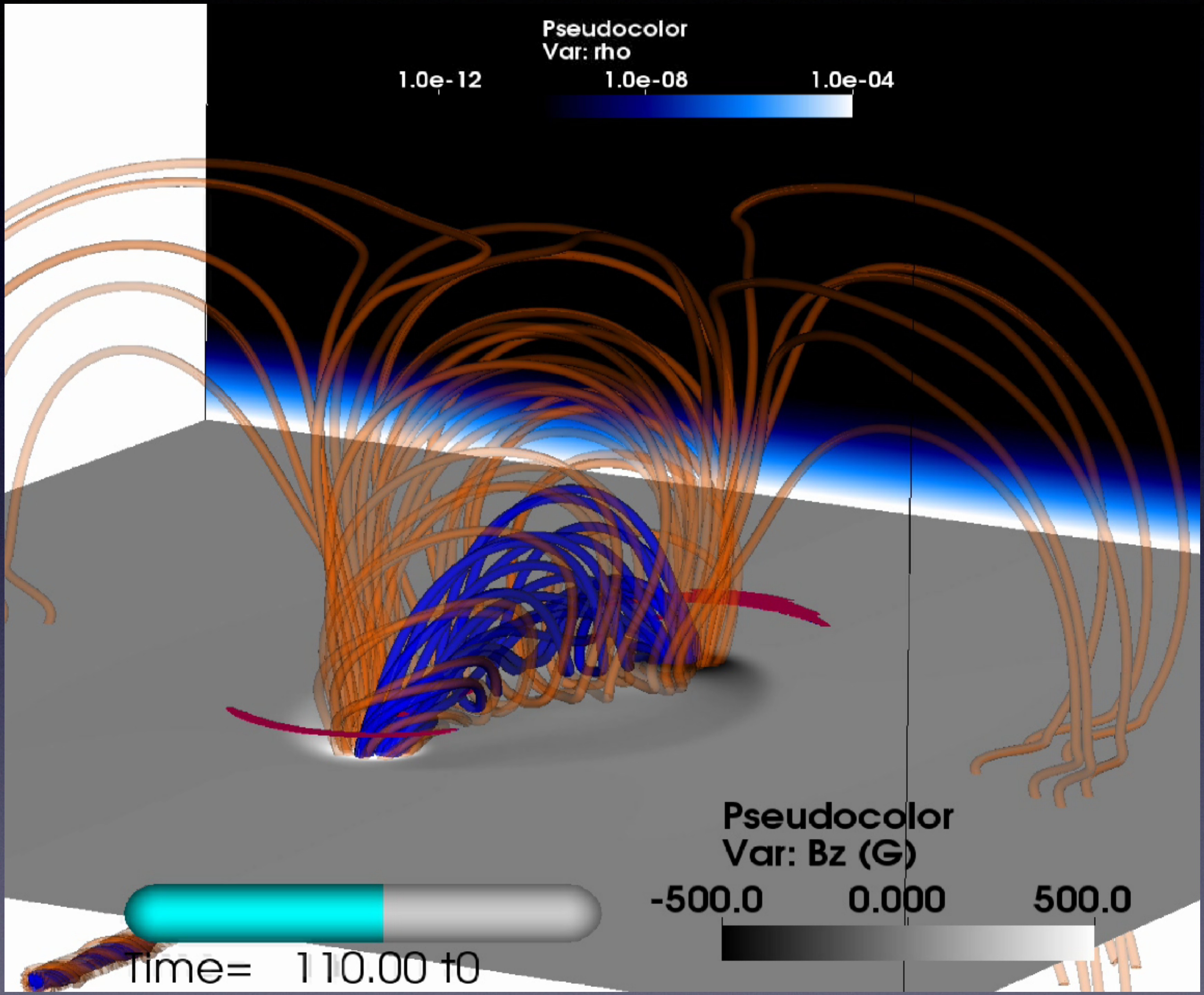
Chromospheric Physics in AR-studies

- During emergence of field into atmosphere:
  - Strong expansion and cooling
- Pedersen heating counteracts this cooling



- Additional collisional heating maintains surface temperatures in emerging active regions

Chromospheric Physics in AR-studies



How will Pedersen dissipation affect internal "flare"-like reconnection?

Discussion

- Chromosphere is oft-ignored, weakly ionized, radiatively complex, region between surface (observations) and corona (models)
- Even included as a simple stratified transition is is important for free energy and helicity transfer into the corona
- In single-fluid model (low frequency limit), effect of partial ionization is the anisotropic dissipation of currents
- Pedersen resistivity
  - perpendicular currents are preferentially dissipated (force-free), but can create sharp structures at null points
  - slippage of field through plasma-neutral mix (or vice-versa)
- In emerging simulations, Pedersen effects reduce mass supplied to corona (slippage), but increases magnetic energy
- Is internal ("flare"-like) reconnection in chromosphere, and resultant flux rope eruption, affected by chromospheric physics?
- Important to get thermodynamics sufficiently accurate to trust calculation of Pedersen dissipation - radiation, thermal conduction

Chromospheric Physics

- Efficiency of pedersen (Joule) heating
- For generic mechnaism which creates E in atmosphere, efficiency increases from near temp minimum to TR
- To get actual value of heating, need model for the E generation mechanism (waves, reconnection etc)