# Modeling the chromosphere: Beyond the Ideal MHD description

Given at

1. AOGS Meeting, Singapore, August 2015
2. IAU Meeting, Honolulu, HI, August 2015

James Leake [1]

Ack: T. Török (PSI), J. Martinez,-Sykora (LMSAL), Viggo Hansteen (Oslo)
M. Goodman (West Virginia), I. Ugarte-Urra (George Mason Univ.)

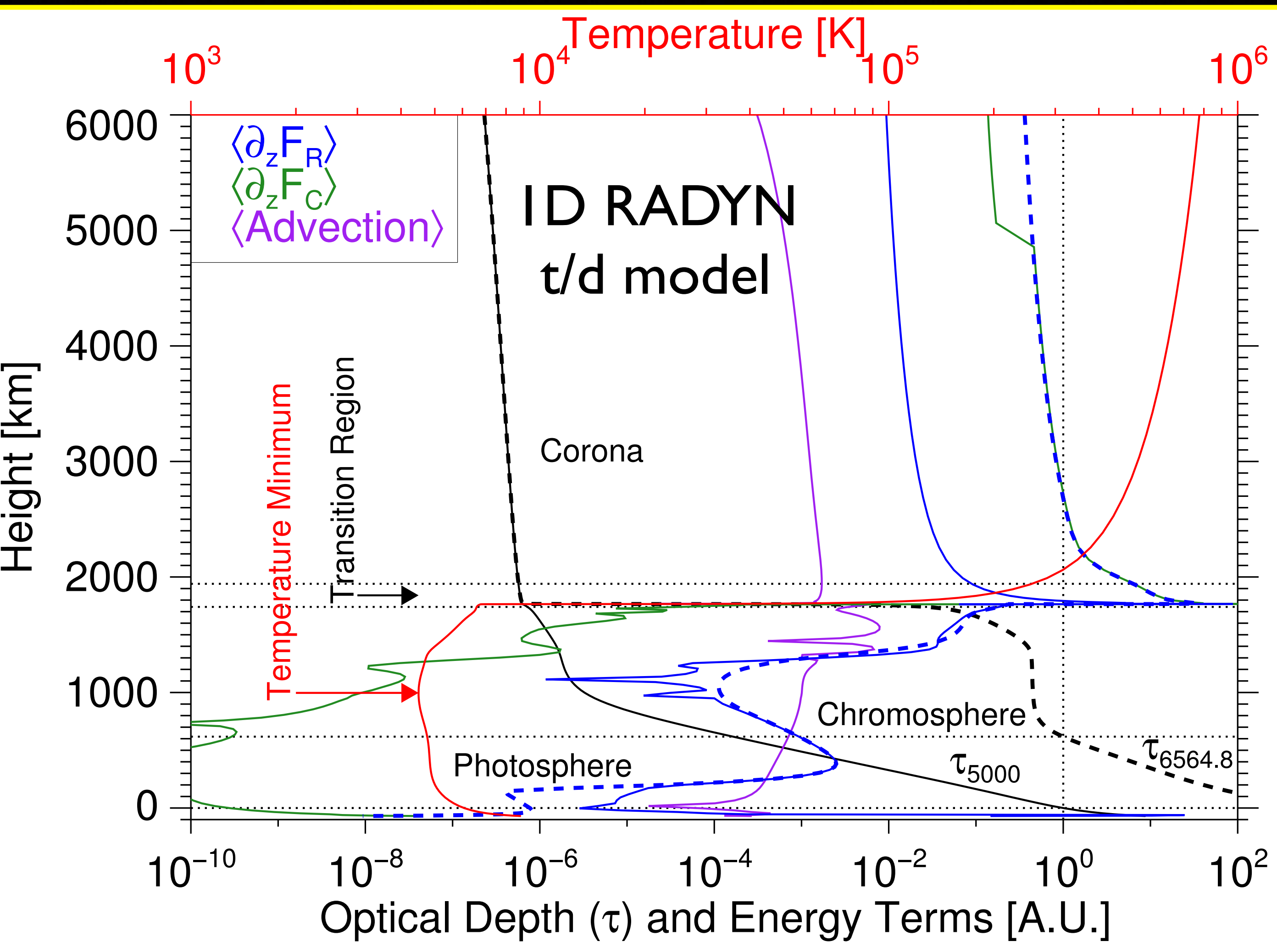
[1]Space Science Division, US Naval Research Laboratory

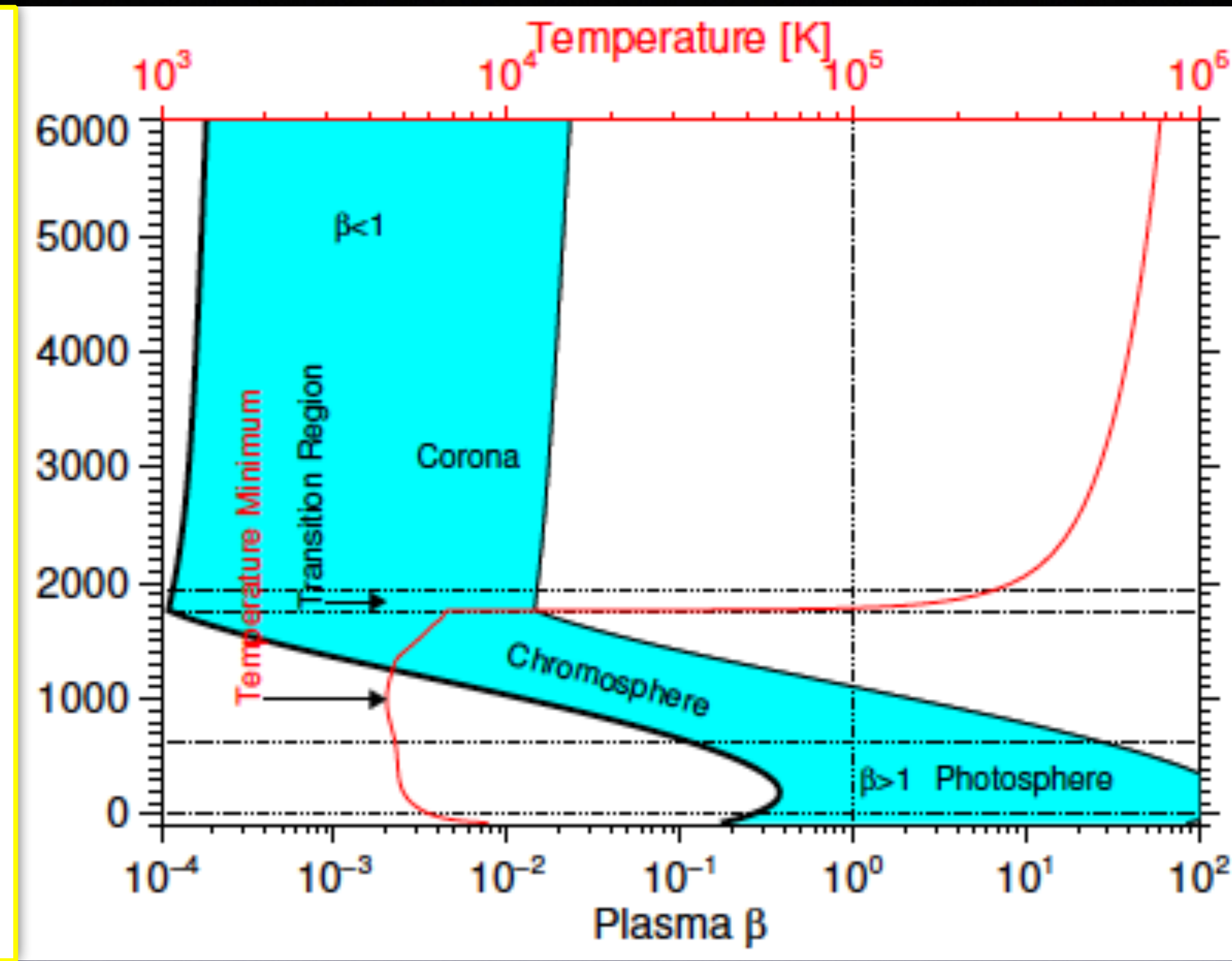
Funding:
NASA LWS TR&T program
Chief of Naval Research

# A review of recent developments in chromospheric modeling

- The chromosphere:
  - Dynamic region between surface and corona where number density drops many orders, involves many transitions (high to low $\beta$, unmagnetized to magnetized, weakly ionized to fully ionized)
- Motivation:
  - Improving our description of the chromosphere beyond a simple MHD transition betwixt high $\beta$ CZ and low $\beta$ corona
- Improving modeling of chromospheric physics
  - Within single-fluid MHD approx:
    - Electrodynamics
    - Thermodynamics
  - On small/fast scales
- What is the role of the chromosphere in the transfer of mass, energy, flux to the corona?
- What can we learn about what we observe in the chromopshere (IRIS) from improved simulations?

# The chromosphere

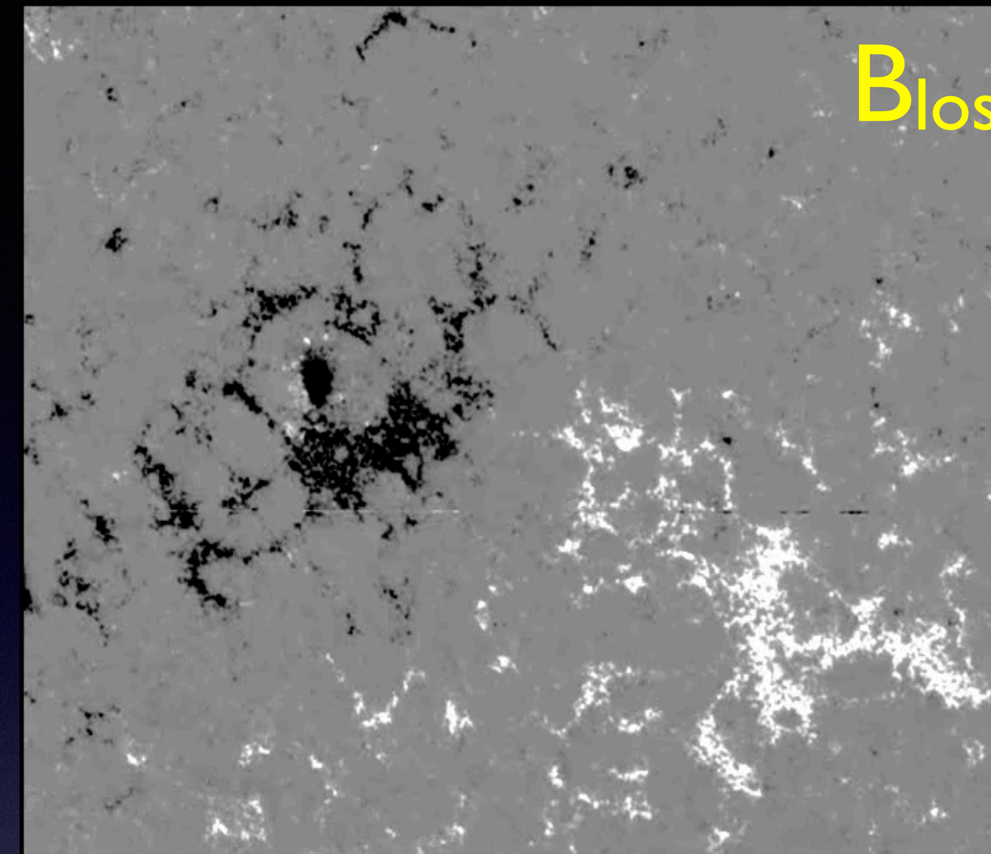


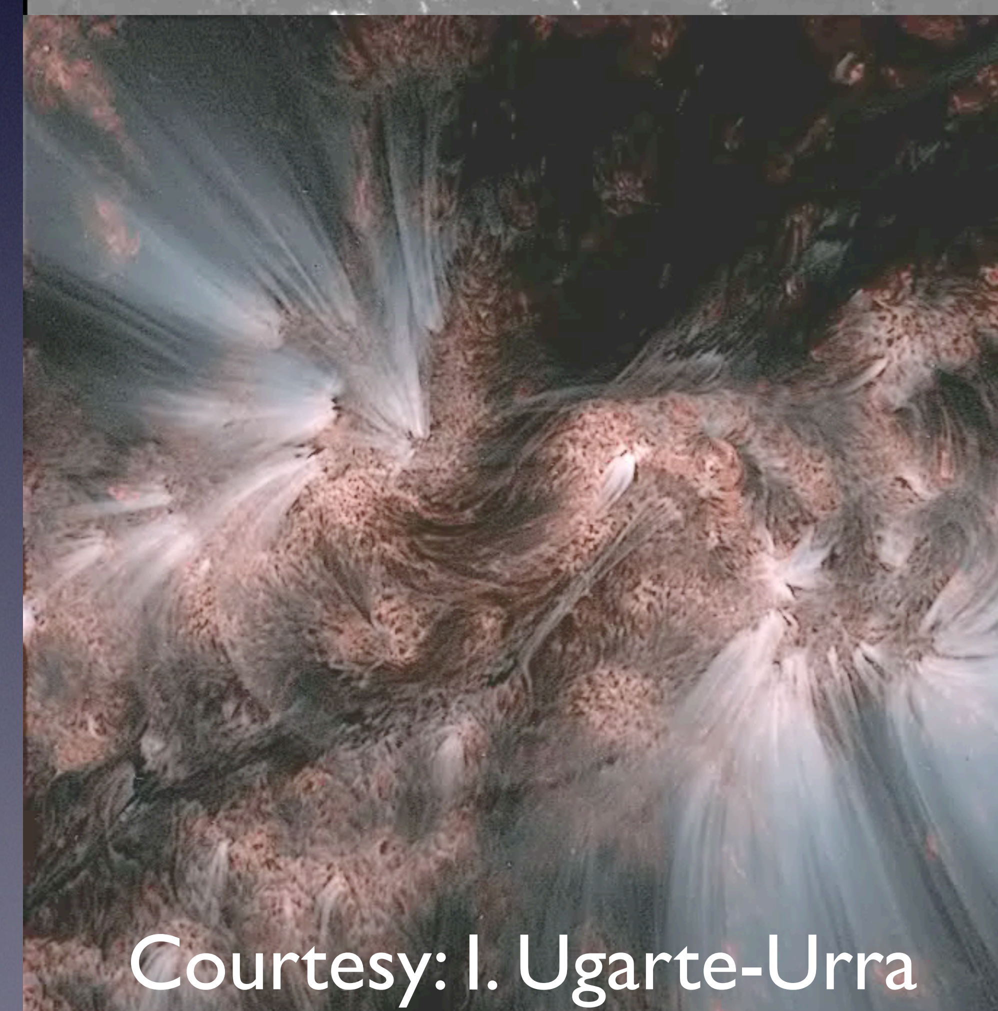




- Define in similar way as photosphere ($\tau_{5000} = 1$)
- Radiative flux from photosphere excites transitions in chromosphere - $H_\alpha$ 6564.8
- Define base of chromosphere as ($\tau_{6564.8} = 1$) ~ 600 km
- Chromosphere extends below temperature minimum to TR
- How is chromosphere heated? Fch ~ 100 Fcor
- In AR modeling chromosphere is transition from high to low β

# Motivation

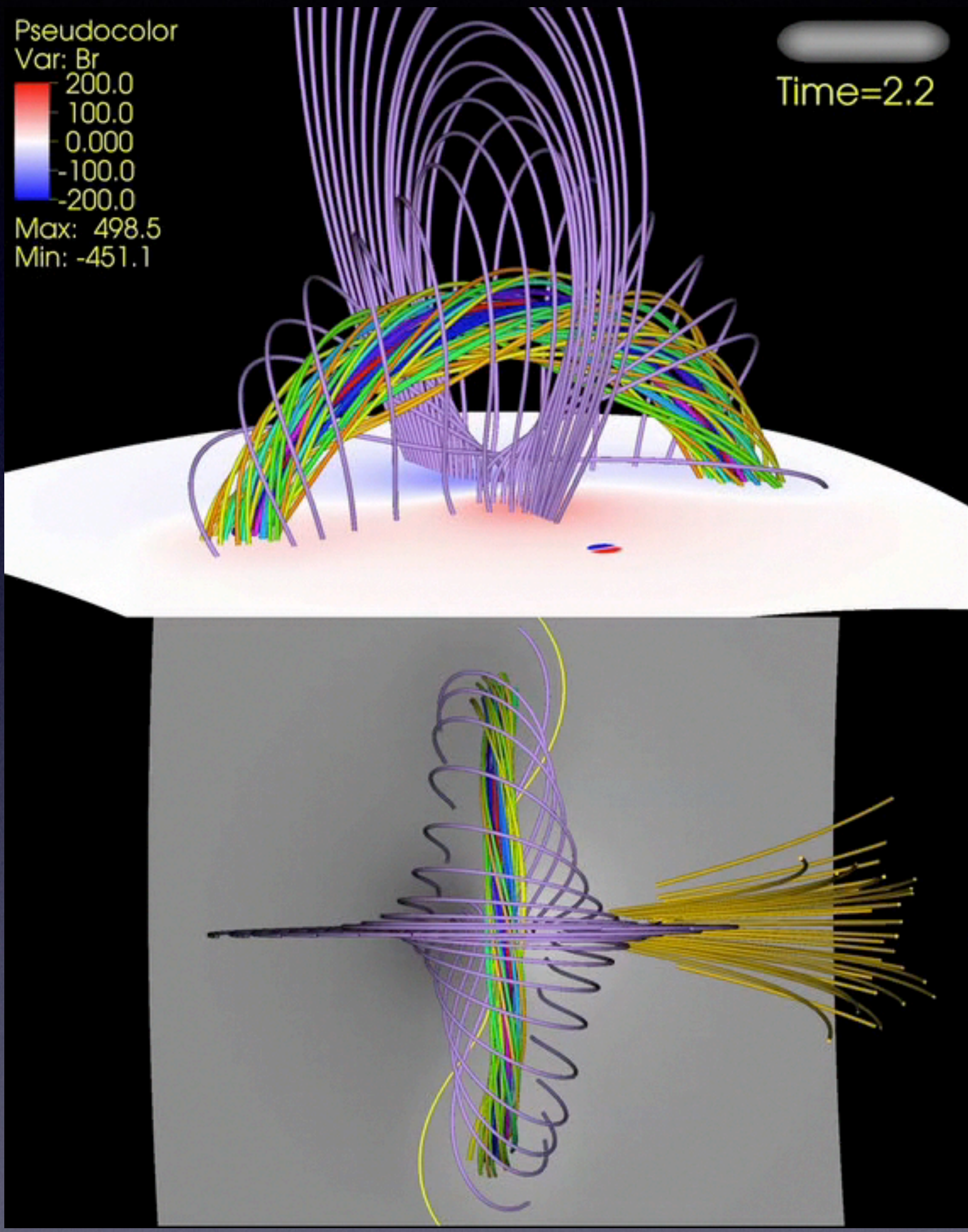
- Space weather:
  - Energy of CMEs/flares stored in electric currents of coronal field
  - How is energy/mass/field transferred to the corona?
  - Observations of B at surface (forced)
  - Currently we use surface data to drive global coronal models (force-free)
  - Or we use models from CZ/surface to drive global coronal models
  - In these studies, chromosphere is usually ignored, or included as a simple stratified MHD transition from CZ to corona
- But chromosphere is weakly ionized, radiatively complex, and has important physics which need to be included



# Motivation

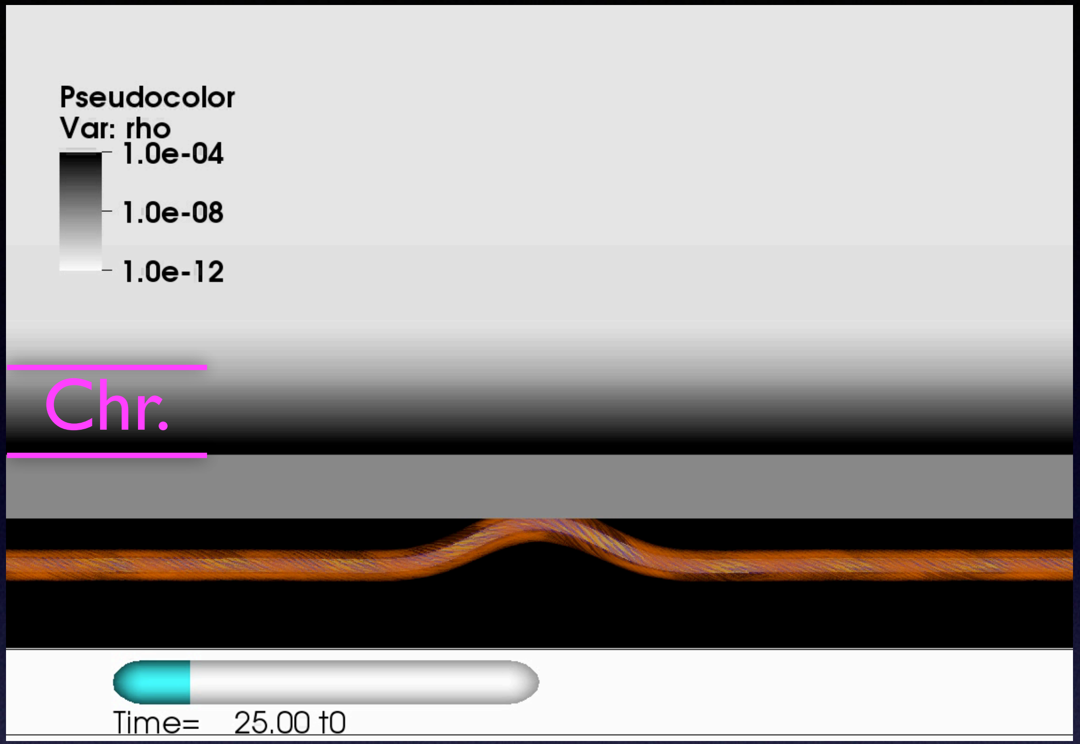
- Space weather:
  - Energy of CMEs/flares stored in electric currents of coronal field
  - How is energy/mass/field transferred to the corona?
  - Observations of B at surface (forced)
  - Currently we use surface data to drive global coronal models (force-free)
  - Or we use models from CZ/surface to drive global coronal models
  - In these studies, chromosphere is usually ignored, or included as a simple stratified MHD transition from CZ to corona
- But chromosphere is weakly ionized, radiatively complex, and has important physics which need to be included

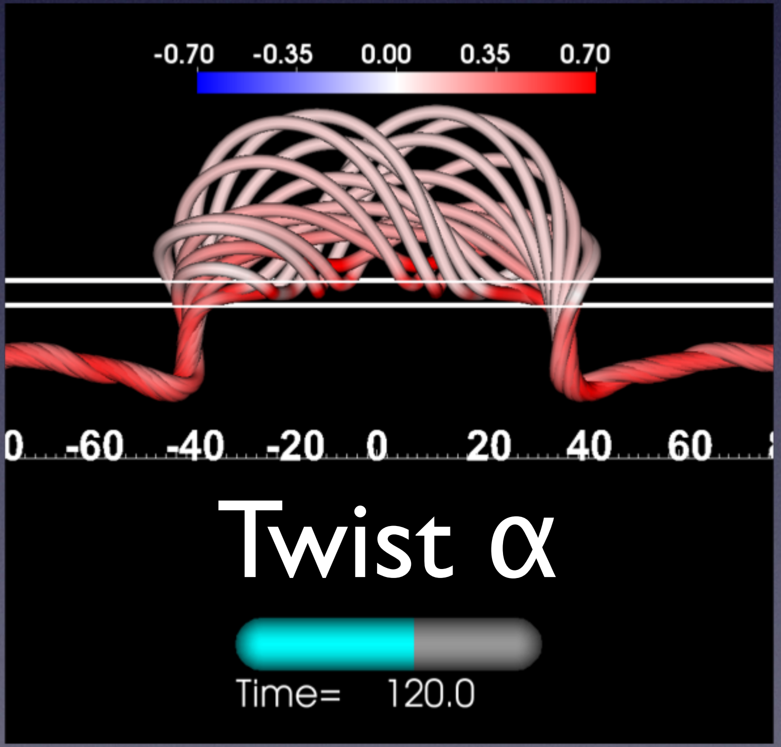


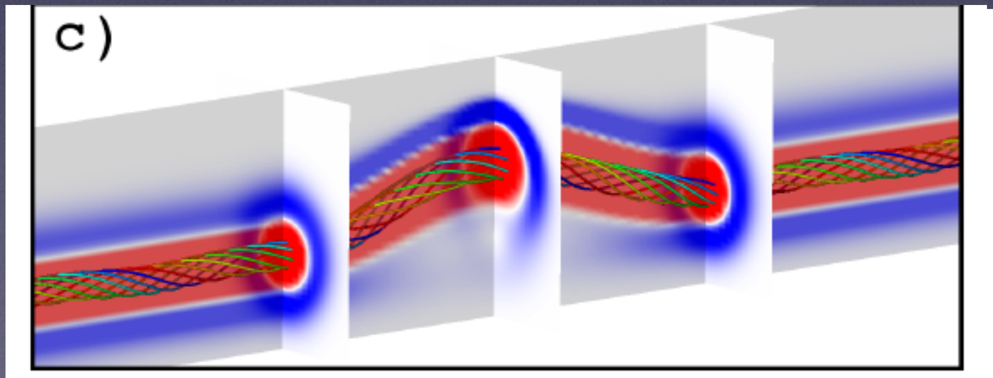

Courtesy: T. Török
Eruption due to destabilization of existing flux rope by emerging flux

# The chromosphere as a stratified MHD transition

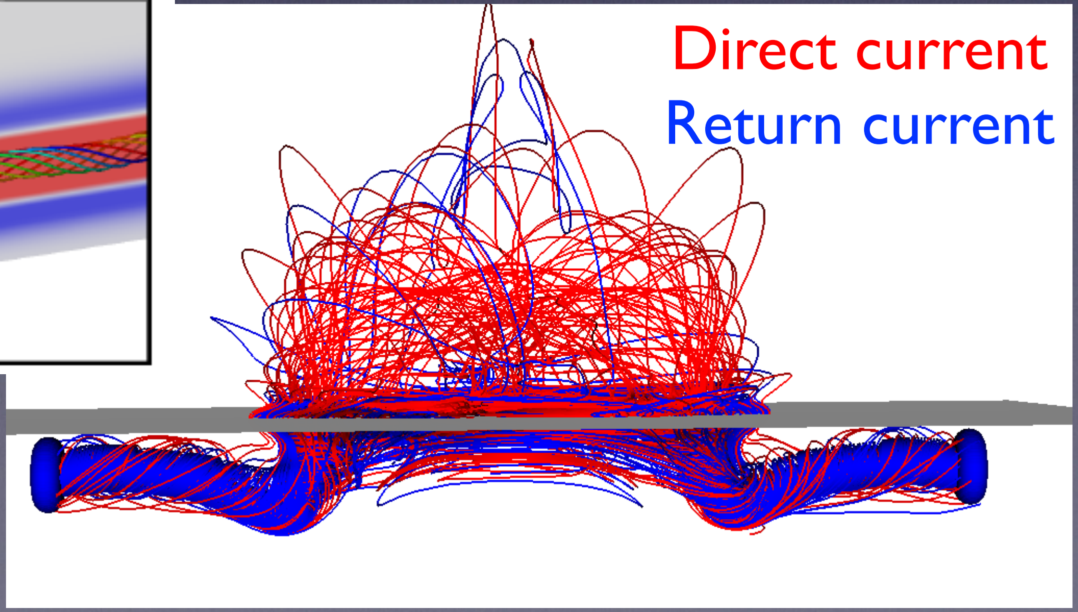
- Look at flux emergence from CZ through chromosphere (Leake et al. 2013,2014)
- Chromosphere is just stratified transition
- Fieldlines expand into low β corona
  - Gradient in twist along fieldlines
  - Propagation of torsional Alfven waves
  - Complicated transfer of helicity into corona
- Initially curent neutralized flux tube (zero-I)
  - return currents are stripped off at base of chromosphere
  - leads to net-current in corona



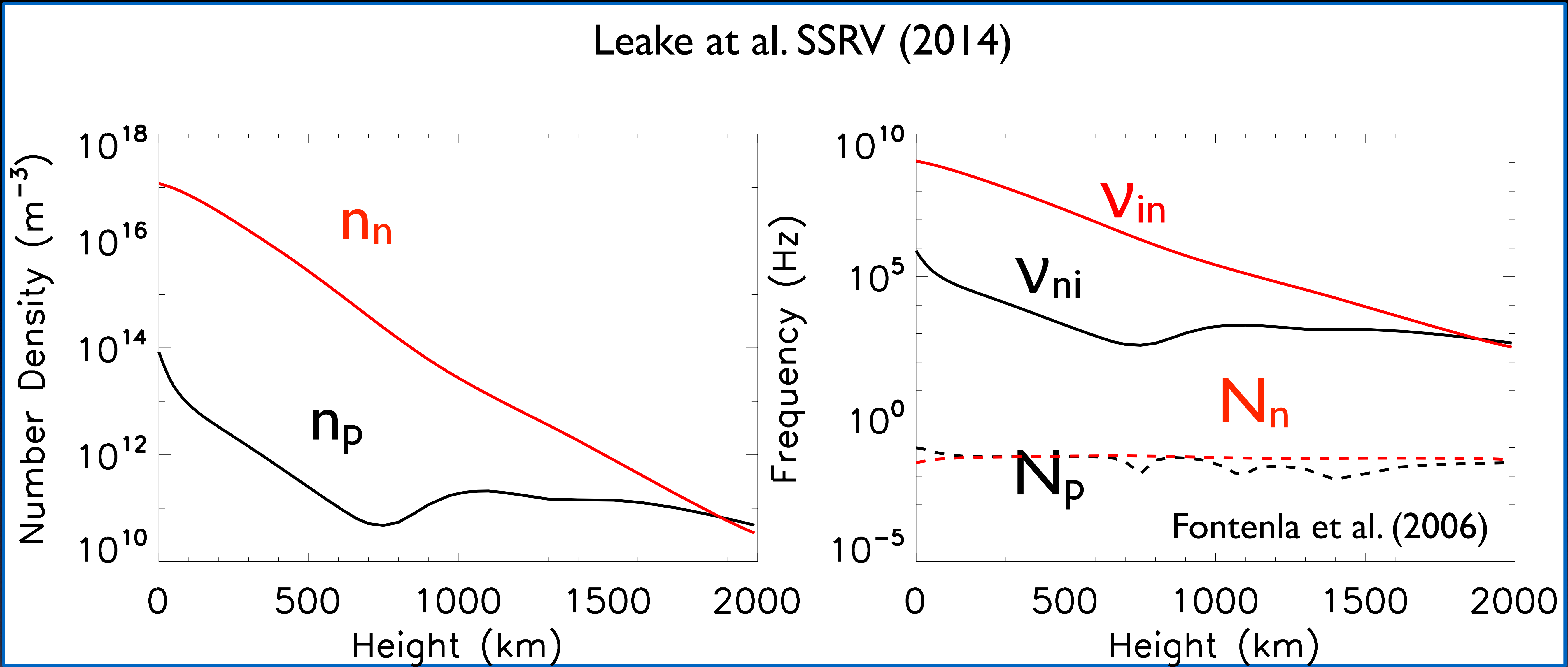




Török et al. (2014)



# The chromosphere




- Varies from very weakly ionized to fully ionized
- For frequencies ~ BV frequency (N) chromosphere is a coupled mixture
- Relatively high plasma density - collisional - mostly ideal MHD

# Chromospheric Physics within single-fluid approx

- Partially ionized single-fluid MHD valid when

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

- Neutrals and plasma highly coupled - single-fluid (c.f. ionosphere/ thermosphere - low ion density - not coupled)

- Cannot use when plasma and neutral decouple on small scales (e.g. reconnection in chromopshere - Leake et al, 2012 2013, waves of high frequency - Soler at al. 2012)

- 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 within single-fluid approx

- 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 electron momentum equation (E = $-V_e$xB + collisions)
- 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 $\mathbf{E}^{\mathbf{V}_P} = \eta \mathbf{J}$
    - leads to Ohmic or Joule heating $\mathbf{E}^{\mathbf{V}_P} \cdot \mathbf{J} = \eta \mathbf{J}^2$
- In partially ionized plasma, collisions between plasma and neutrals can increase E in the rest frame of the mass-averaged flow ($V_T$)

$$\mathbf{E}^{\mathbf{V}_T} = \mathbf{E} + \mathbf{V}_T \times \mathbf{B} = \eta_{\|} \mathbf{J}_{\|} + \eta_{\perp} \mathbf{J}_{\perp} \longrightarrow \mathbf{E}^{\mathbf{V}_T} \cdot \mathbf{J} = \eta_{\|} \mathbf{J}_{\|}^2 + \eta_{\perp} \mathbf{J}_{\perp}^2$$

- 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: anisotropic electrodynamics

- Perpendicular (Pedersen) resistivity

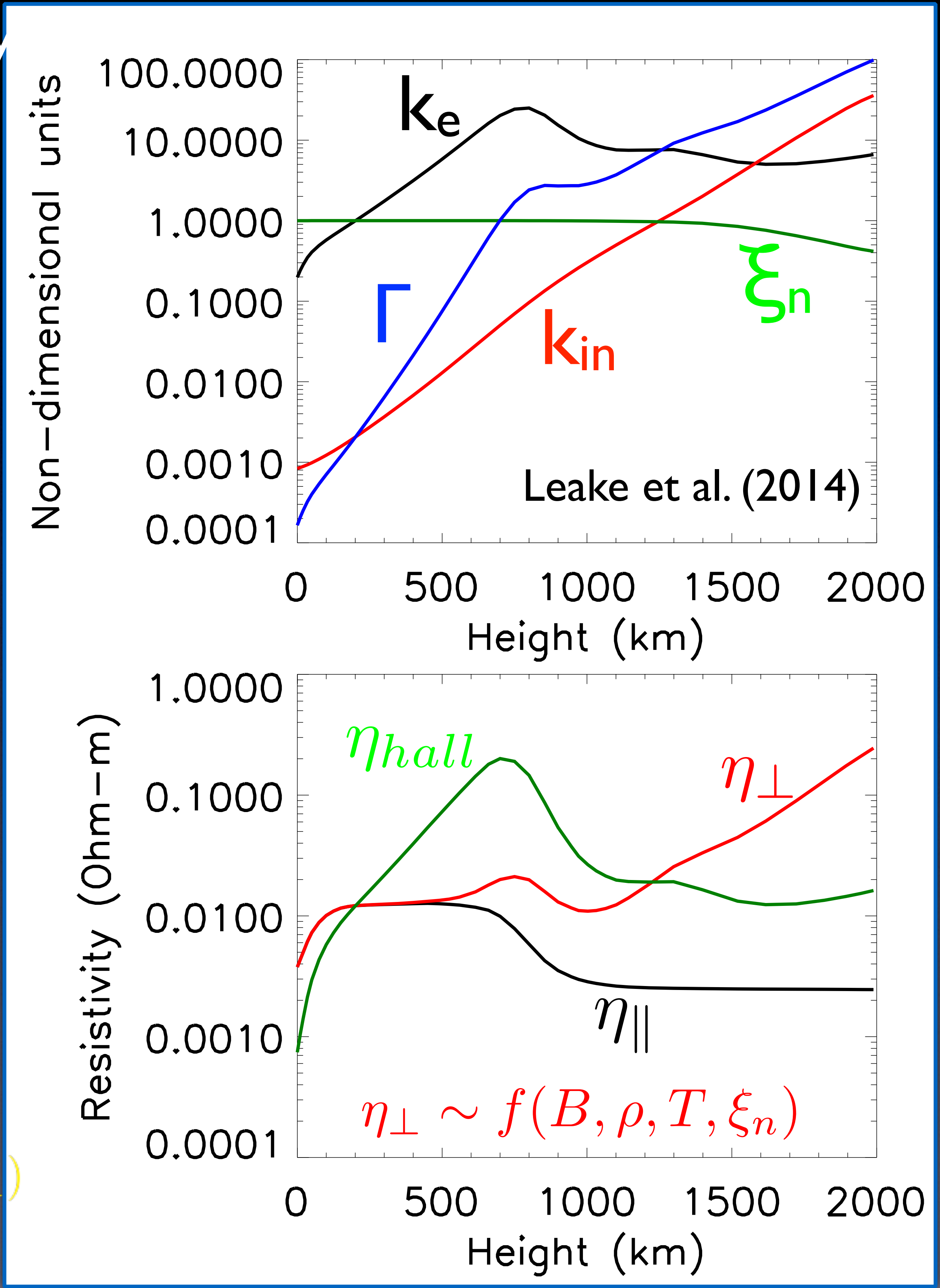
$$\frac{\eta_\perp}{\eta_\|} = \Gamma \equiv \xi_n^2 k_{in} k_e$$
$$k_{in} = \Omega_i / \nu_{in}$$
$$k_e = \Omega_e / (\nu_{ei} + \nu_{en})$$

- Chromosphere transitions from

$$k_{in} << 1 \quad \text{to} \quad k_{in} >> 1$$
$$\eta_\perp = \eta_\| \quad \text{to} \quad \eta_\perp >> \eta_\|$$

- Isotropic to anisotropic e/d
- Increased Joule* heating $\mathbf{E}^{V_T} \cdot \mathbf{J}$
- Dissipation of cross-field currents, force-free field

$$\frac{\partial B}{\partial t} = \nabla \times (\mathbf{V}_T \times \mathbf{B}) - \nabla \times (\eta_\| \mathbf{J}_\|) - \nabla \times (\eta_\perp \mathbf{J}_\perp)$$



# Chromospheric Physics: Pedersen heating

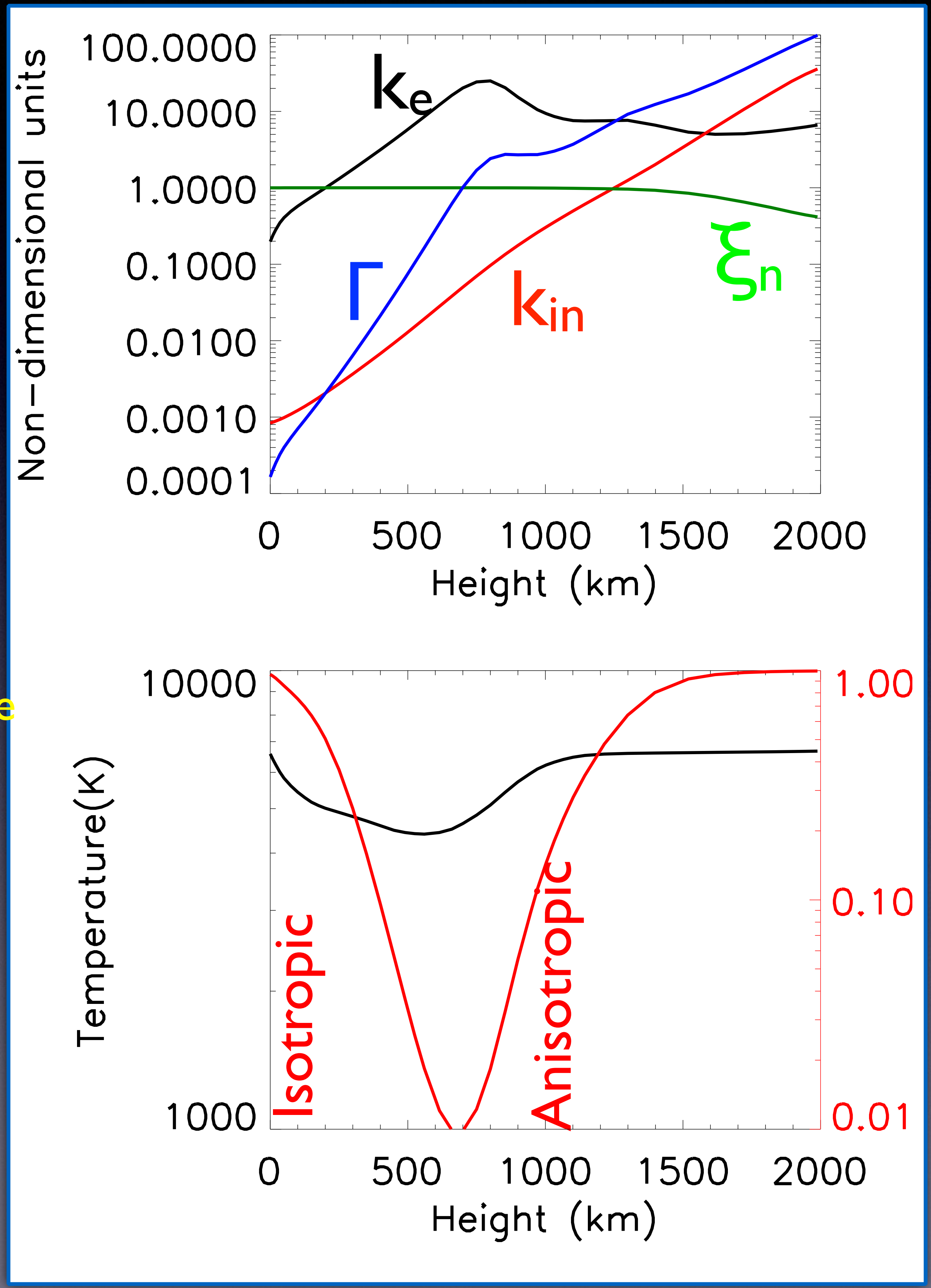
- How efficient is Pedersen heating (Goodman et al.)?

$$Q_p = \mathbf{E}_\perp^{\mathbf{V}_T} \cdot \mathbf{J}_\perp$$
$$\epsilon = Q_p / Q_{p,max}$$

- $Q_{p,max}$ is $Q_p$ when all of perpendicular current is Pedersen currents

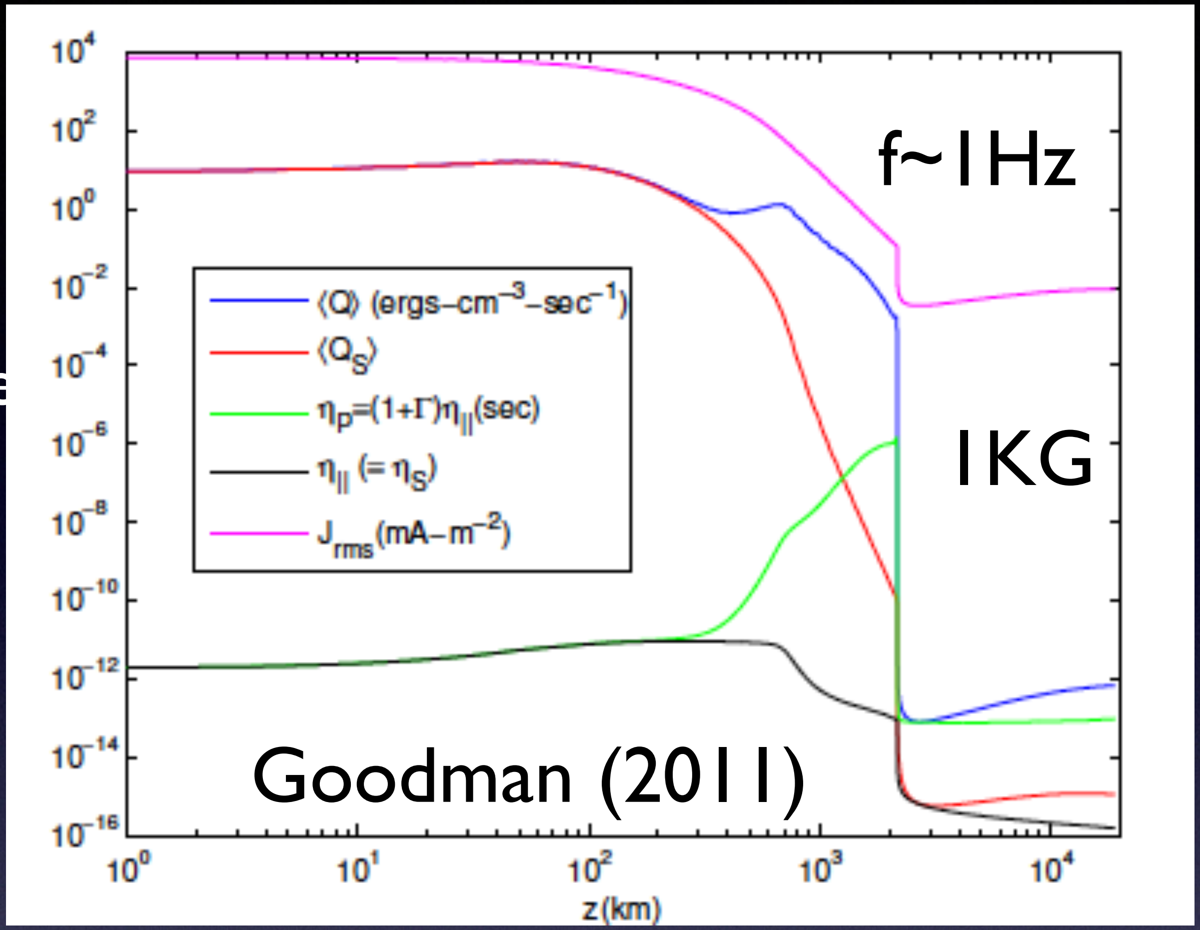
$$J_\perp = J_{Pedersen} + J_{Hall}$$

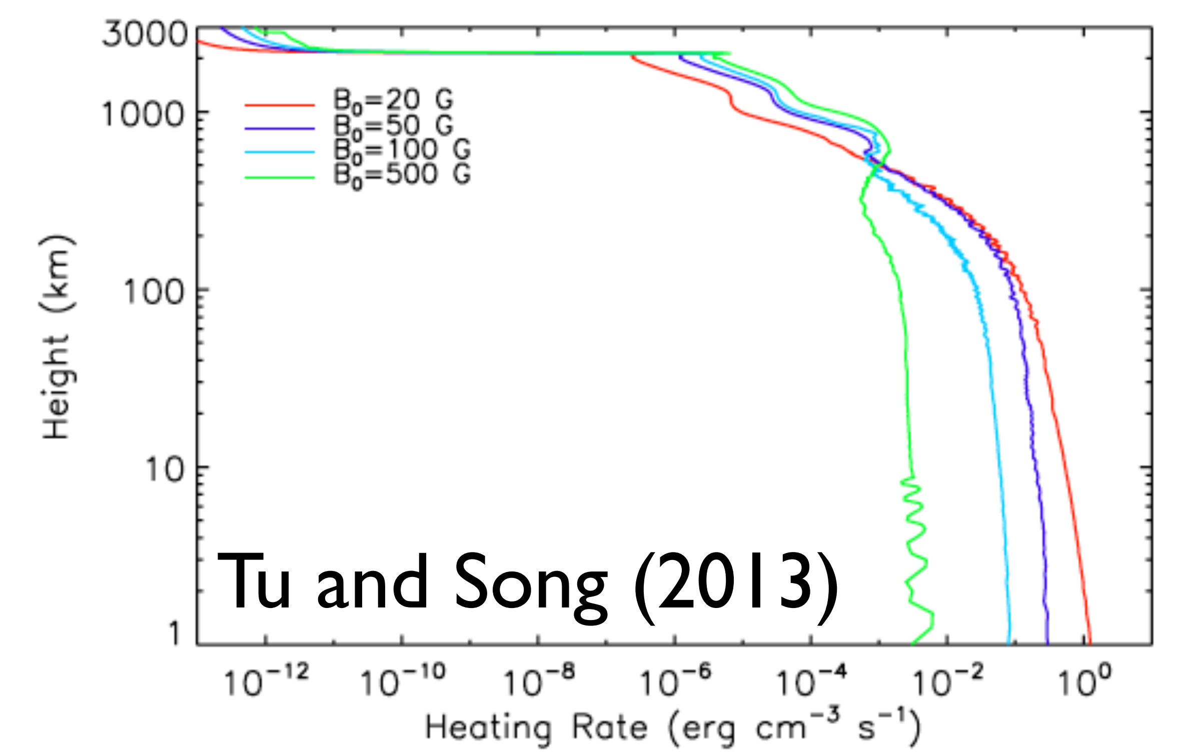
  - This occurs when
    - a) everything is unmagnetized (isotropic)
    - b) ions become magnetizes
- Increased Joule heating can heat the chromosphere
- To get actual value of heating, need model for E generation mechanism
  - Bulk flows -see Khomenko et al. (2014)
  - waves - see Goodman (2000-2010) papers (Tu and Song 2014)
  - reconnection (Judge (2012)
  - Models need to include mechanism for E generation, as well as relevant e/d and t/d



# Chromospheric Physics: Pedersen wave heating

- Typical estimated net radiative loss measurements for the chromosphere are $10^7$ ergs/cm$^2$/s
- Convection creates spectrum of waves with Poynting flux sufficient to heat the chromosphere
- 1D models of wave heating
  - Pre-existing T,dens profile
  - Goodman (2011) - single-fluid
    - drive with single f < collision frequency
  - Tu and Song (2013) - multi-fluid (also Soler 2015)
    - Use spectra of waves
  - Include  reflections and NL interaction
  - Missing acoustic shocks in 2D
  - Missing thermodynamics



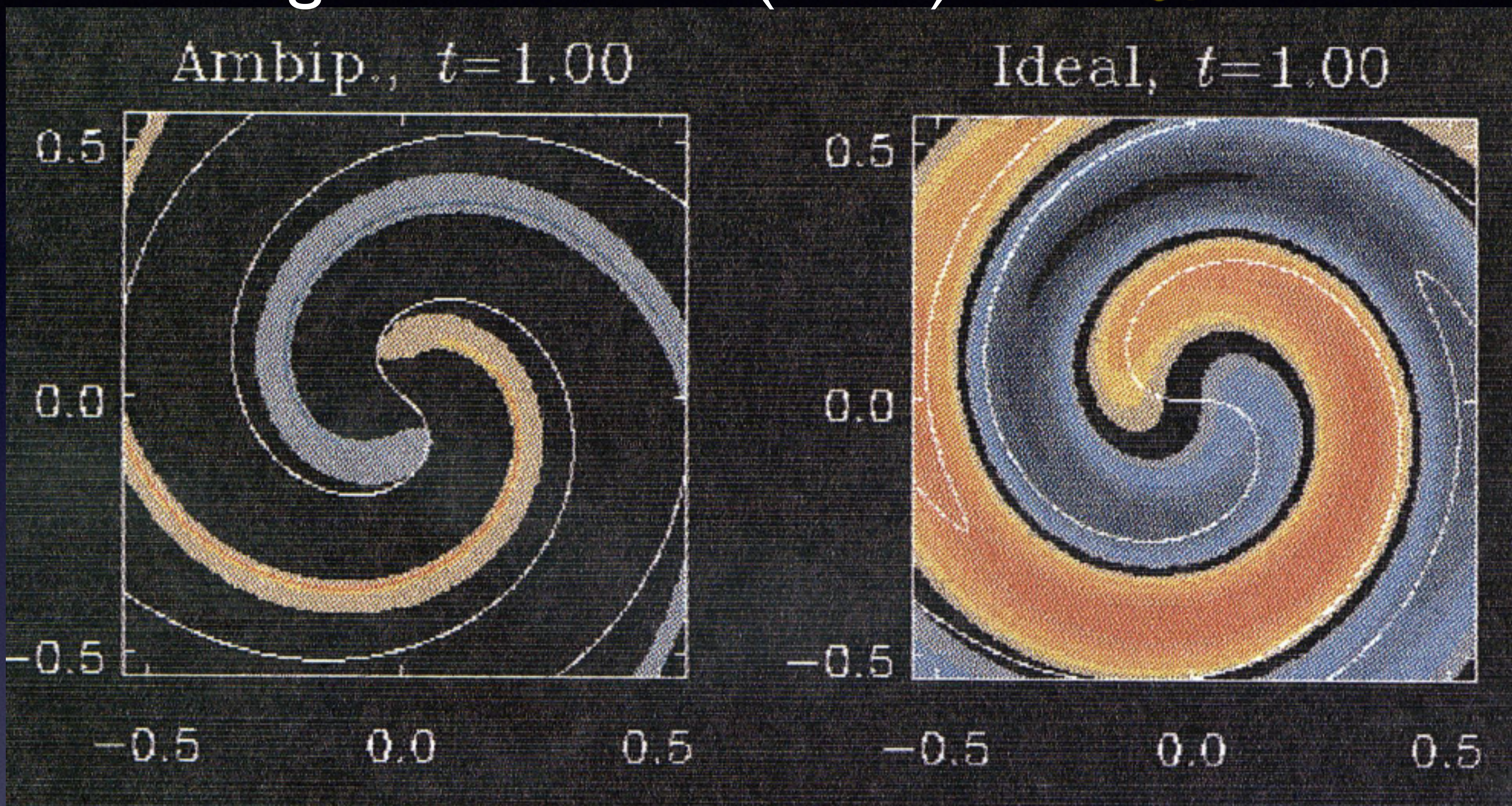



# Chromospheric Physics: Pedersen Dissipation

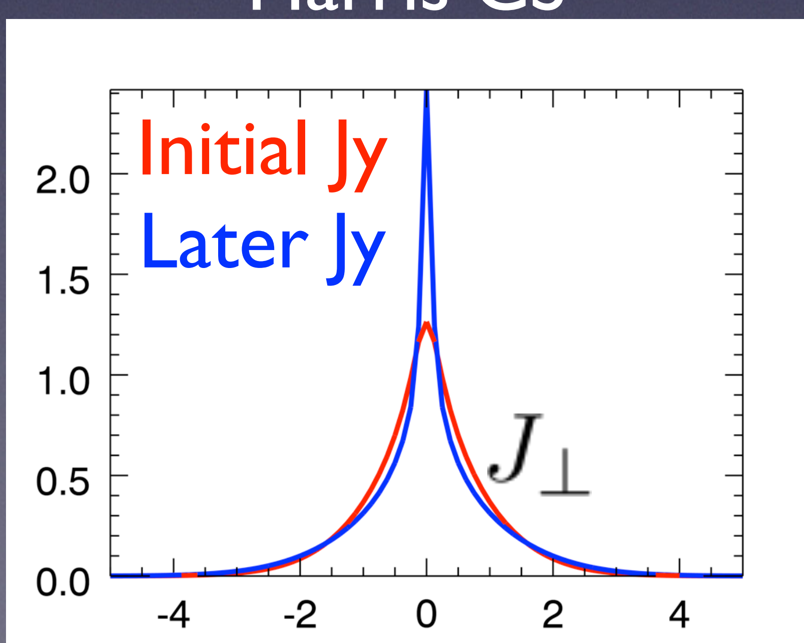
- Pedersen dissipation acting on simple structures

Brandenburg and Zwiebel (1994)

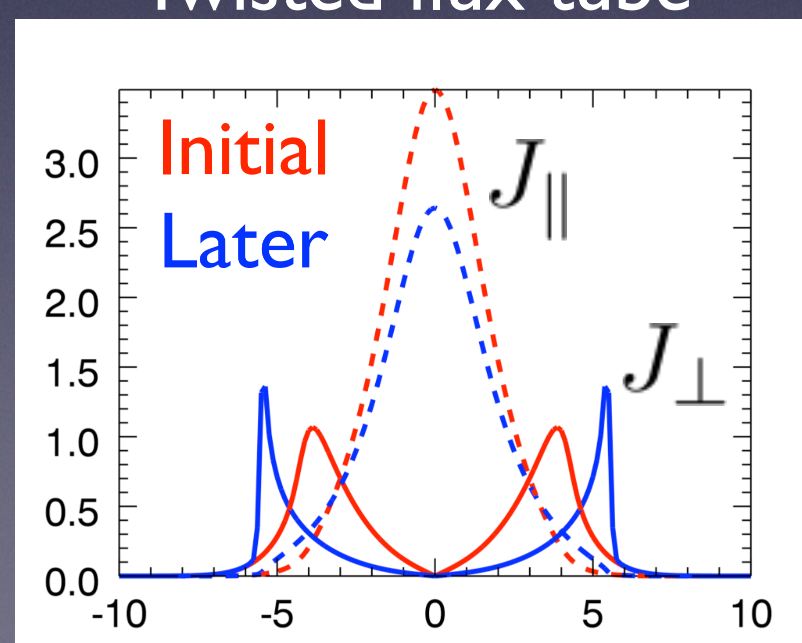
$$\frac{\partial B}{\partial t} = \nabla \times (\mathbf{V}_T \times \mathbf{B}) - \nabla \times (\eta_{\parallel} \mathbf{J}_{\parallel}) - \nabla \times (\eta_{\perp} \mathbf{J}_{\perp})$$




Harris CS




Twisted flux tube




$$B \to 0, \ \eta_P \to 0$$

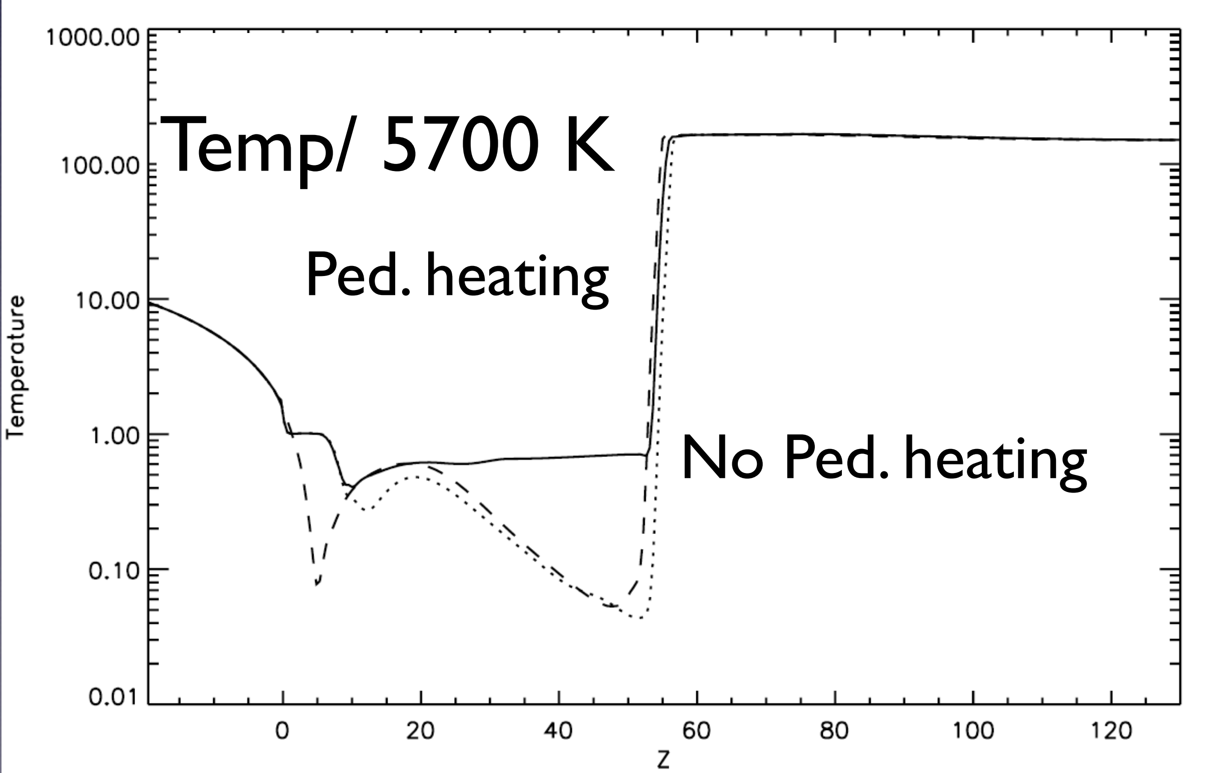
- Pedersen resistivity tends to dissipate regions of perpendicular current

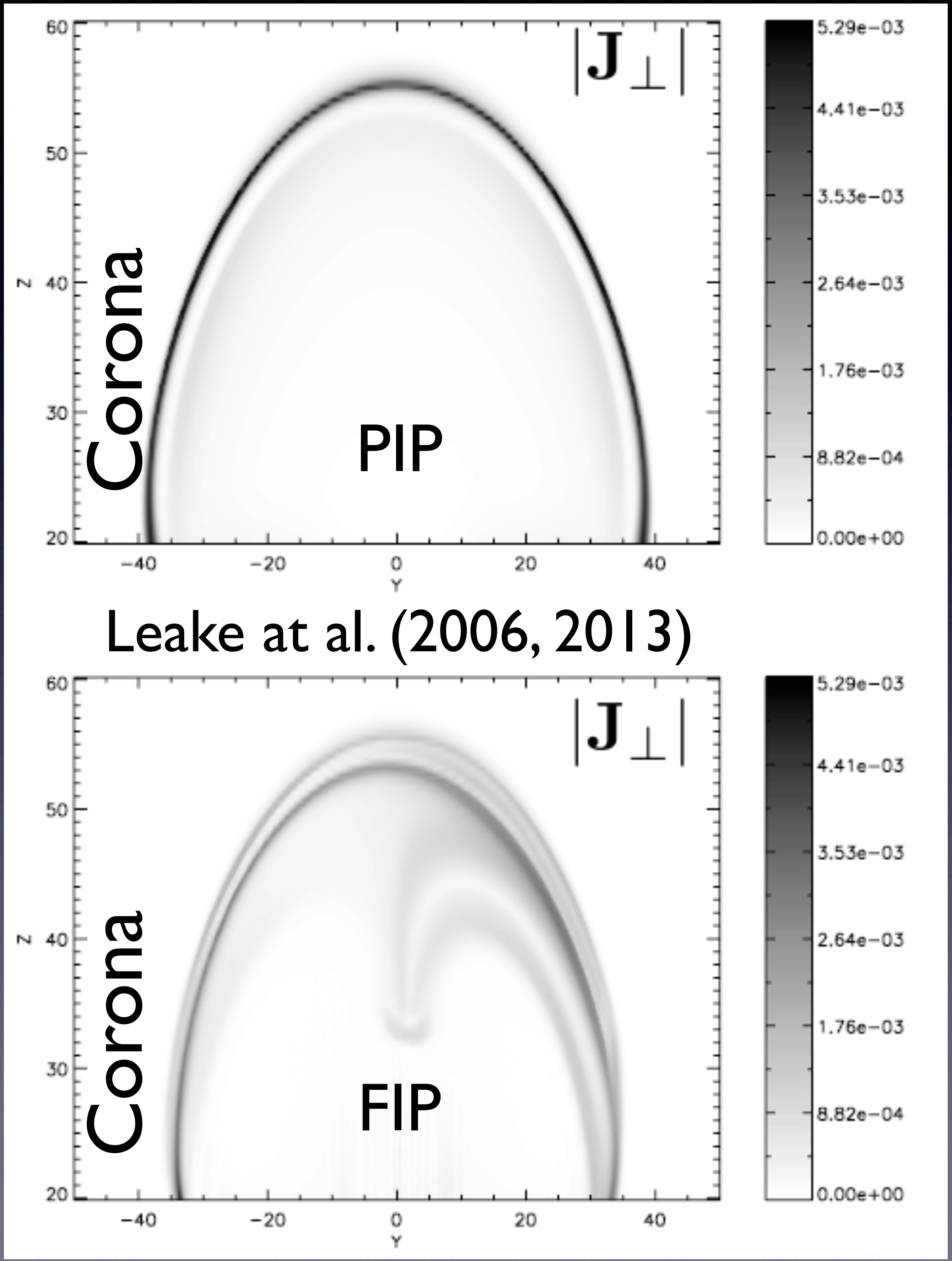
$$J_\perp \to 0, \ \mathbf{J} \times \mathbf{B} \to 0$$

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

# Chromospheric Physics: Pedersen Dissipation

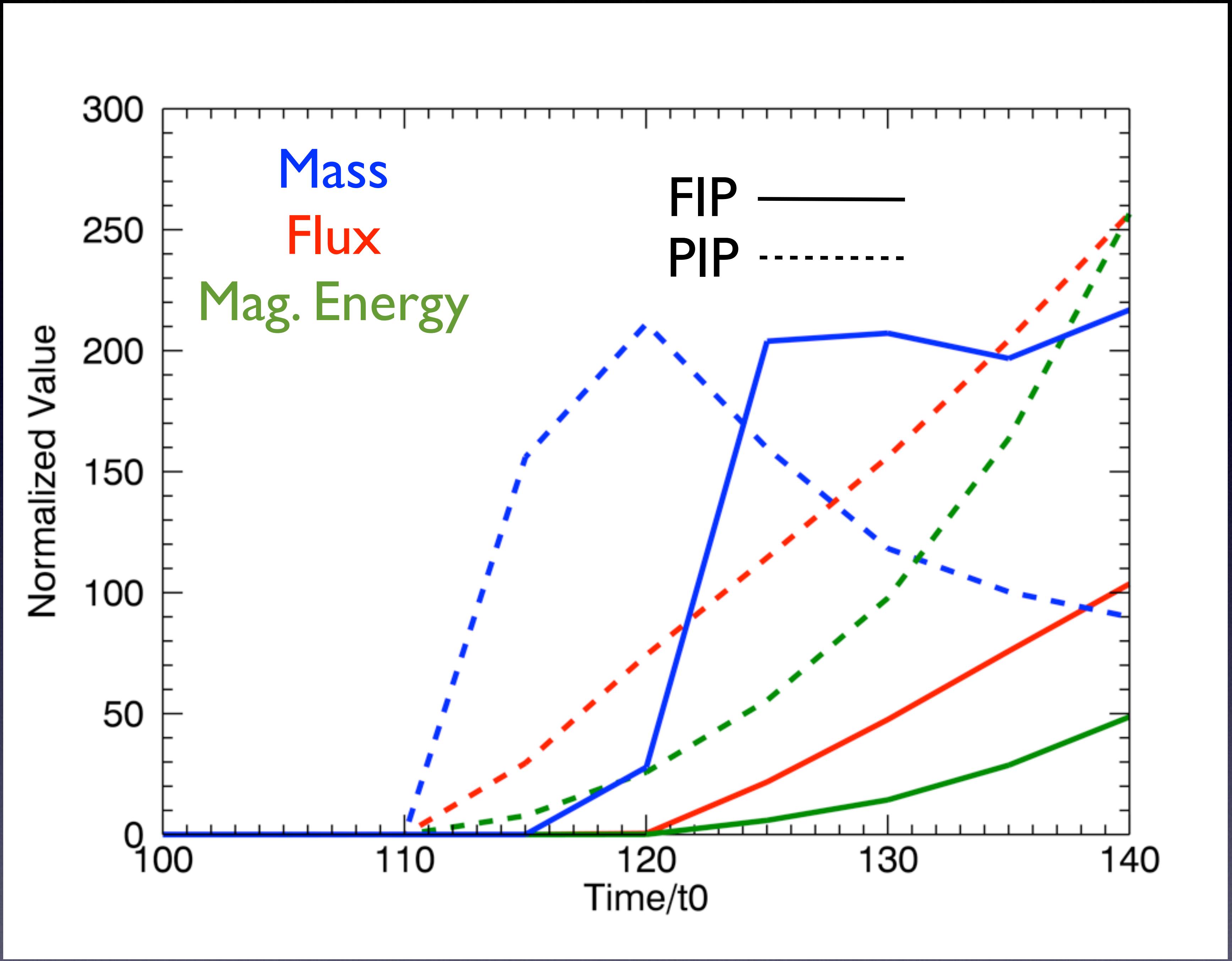
- Simple MHD simulations + Pedersen heating
- Look at currents in emerging active region magnetic field
- Compare fully ionized plasma (FIP) and partially ionized plasma (PIP)
- dissipation of perp.current (force-free) and thinning of current sheets
- How does this affect current closure?
- Heating of AR by Ped, dissipation



# Chromospheric Physics: Pedersen Dissipation

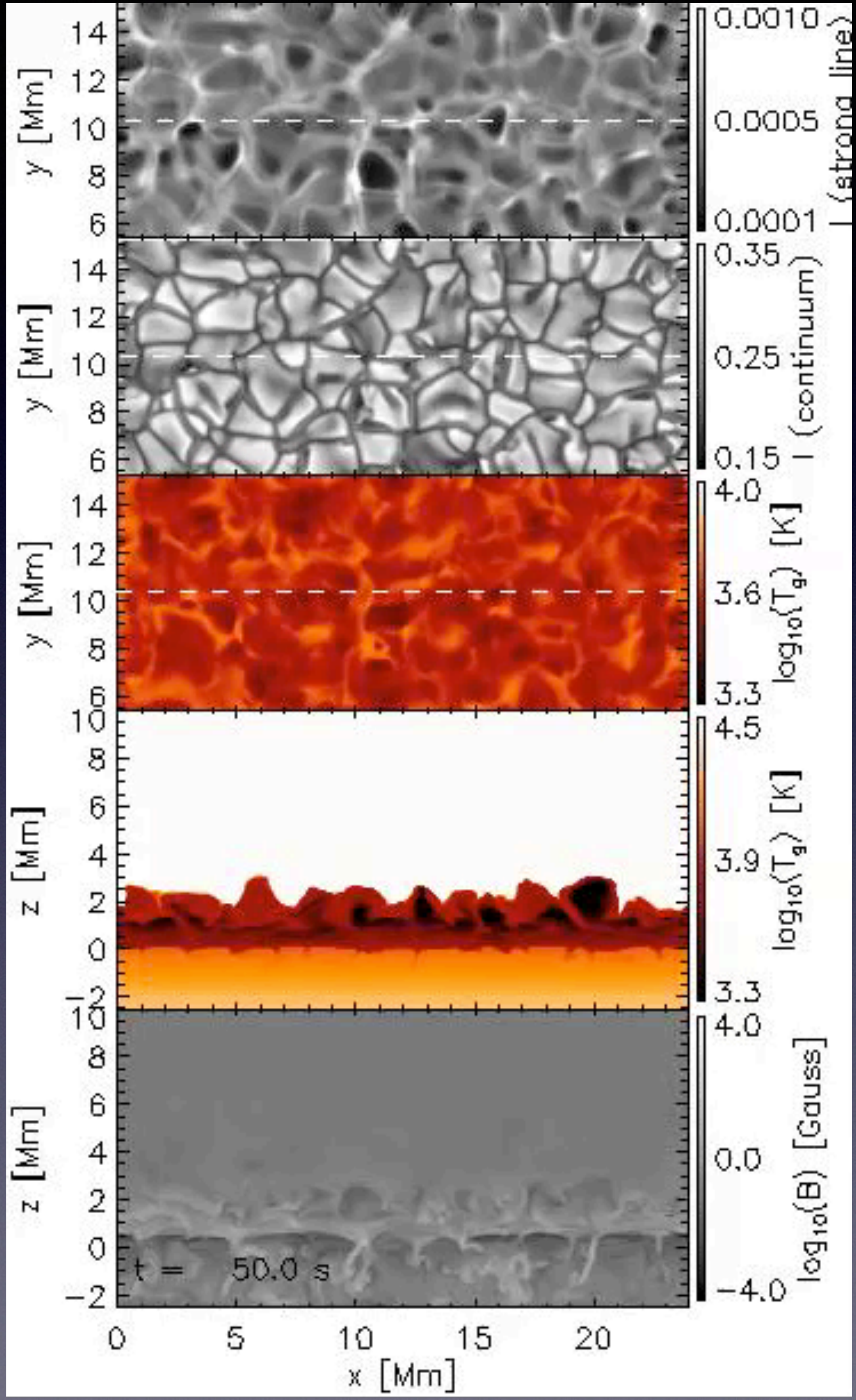
- MHD simulations with partial ionization and Pedersen dissipation
- Ionization fraction from Saha equation
  - Not valid in the chromosphere
- Compare fully ionized plasma (FIP) to partially ionized plasma (PIP)
- Increase in magnetic energy in corona
- Increase in unsigned flux in corona, decrease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




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

# Chromospheric Physics: Improved thermodynamics

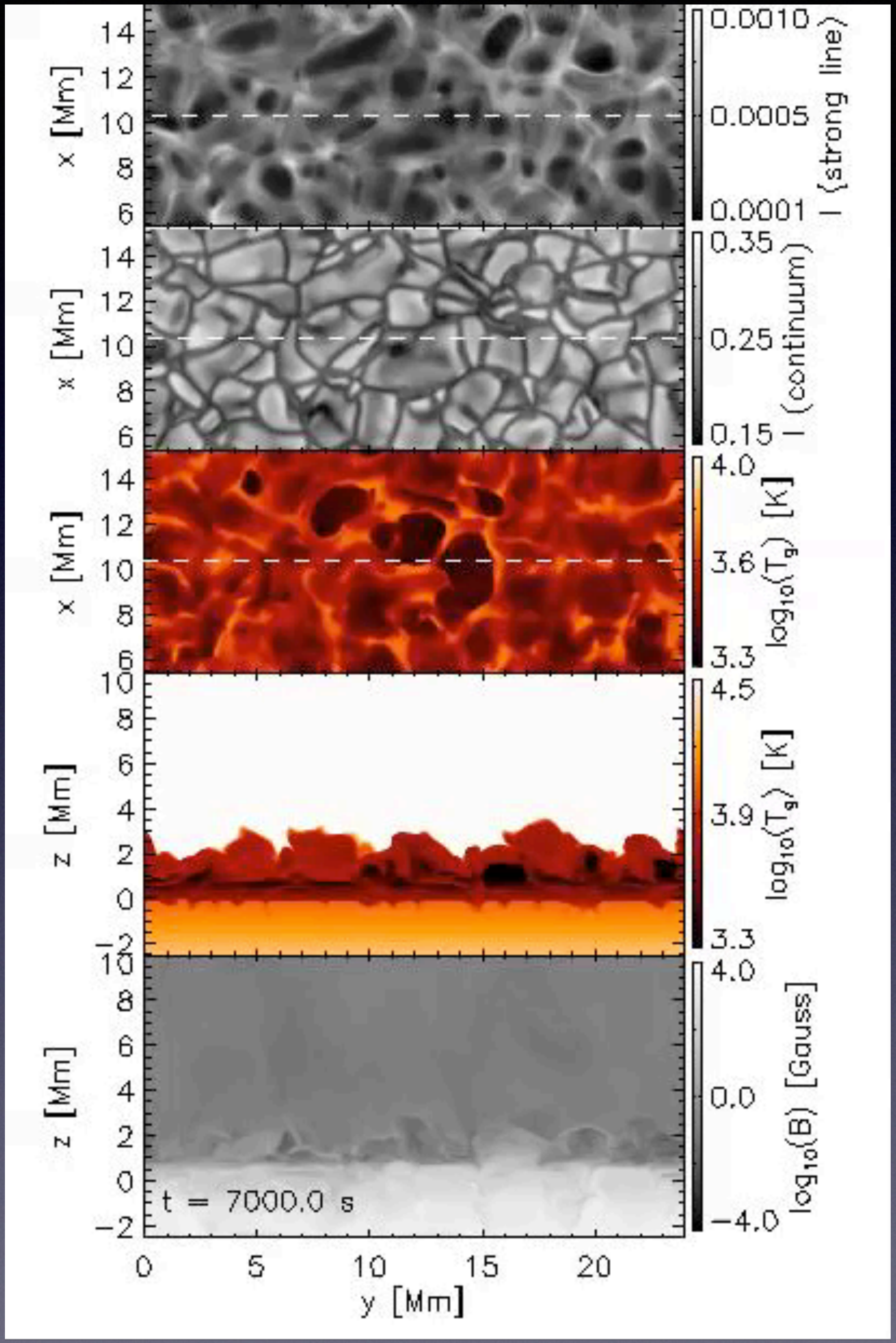
- Bifrost — Hansteen 2004, Hansteen, Carlsson, Gudiksen 2007, Martínez Sykora, Hansteen, Carlsson 2008, Gudiksen et al 2011
- Single-fluid MHD equations 6th order scheme, with "artificial viscosity/diffusion"
- "Realistic" EOS
- Detailed radiative transfer along 48 rays
  - Multi group opacities (4 bins) with scattering
- NLTE radiative losses in the chromosphere, optically thin in corona
- Conduction along field lines
  - Operator split and solved by using multi grid method
- Insert field at base of CZ, bubbles to surface and expands into corona
- Coronal heating by art. diffusion -
  - thermal conduction + radiation give chromospheric structure




Courtesy: V. Hansteen and Ada Ortiz

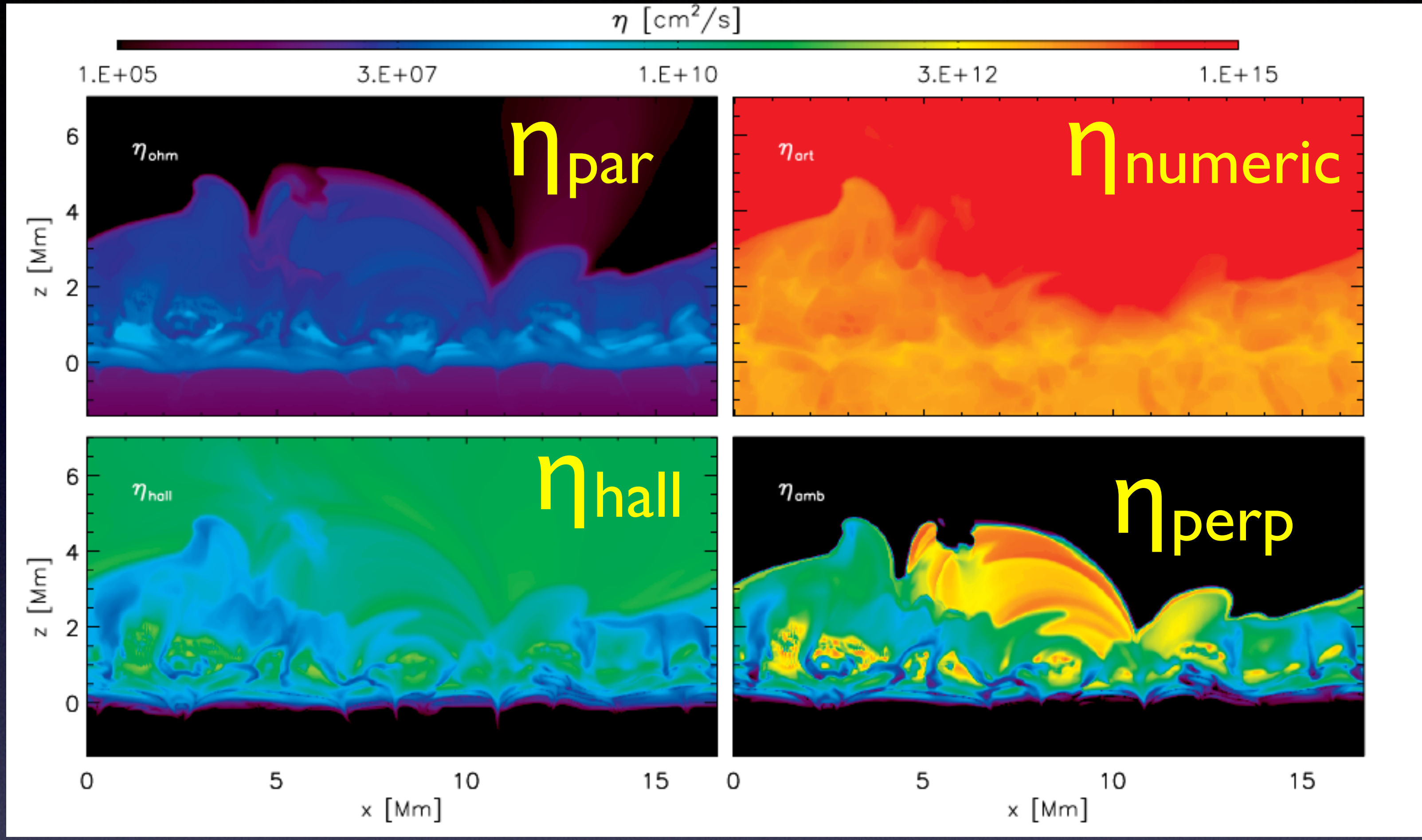
# Chromospheric Physics: Improved thermodynamics

- Simulation with magnetic field inserted at base of convection zone
- Convection 'scrambles' up field - some of it bubbles up to surface
- Magnetic field "pushes" pre-existing corona away filling coronal volume with cold high density plasma. Reheating occurs at reconnection sites.
- Once past the photospheric barrier (several) magnetic field bubbles rapidly fill the chromosphere and corona, where they eventually abut each other.
- Without additional heating, these bubbles get very cold.
  - Pedersen heating?



# Chromospheric Physics: Joule* heating

- Add time-dependent ionization and Pedersen heating to previous simulation
- Still an issue resolving the resistivities
- Pedersen res >> parallel res.
  - Leads to additional heating in cool bubbles
  - Values of Pedersen resistivity dependent on B, dens, T, and hence need for reliable estimates of radiation in chromosphere

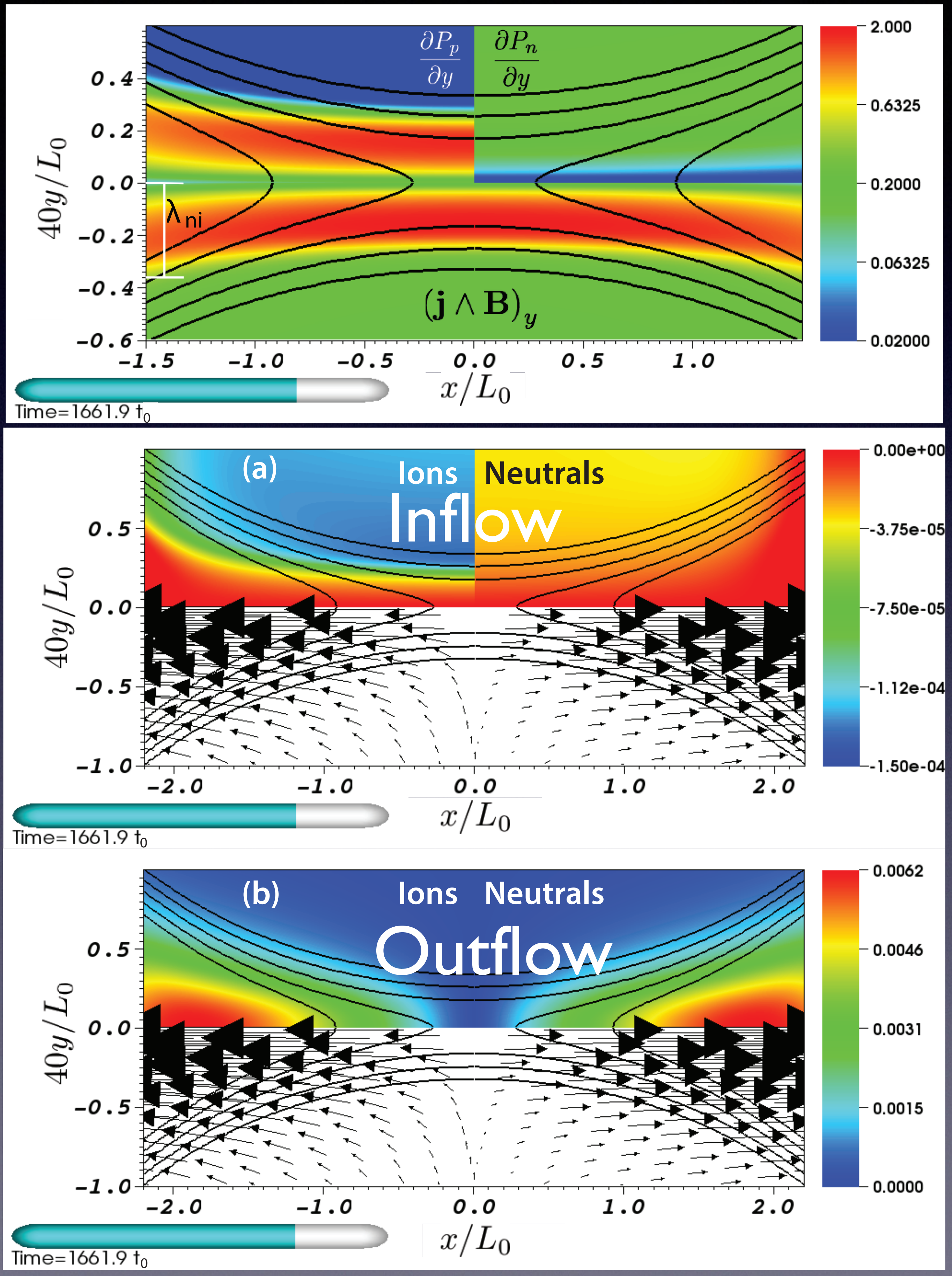



Martinez-Sykora et al. (2012)

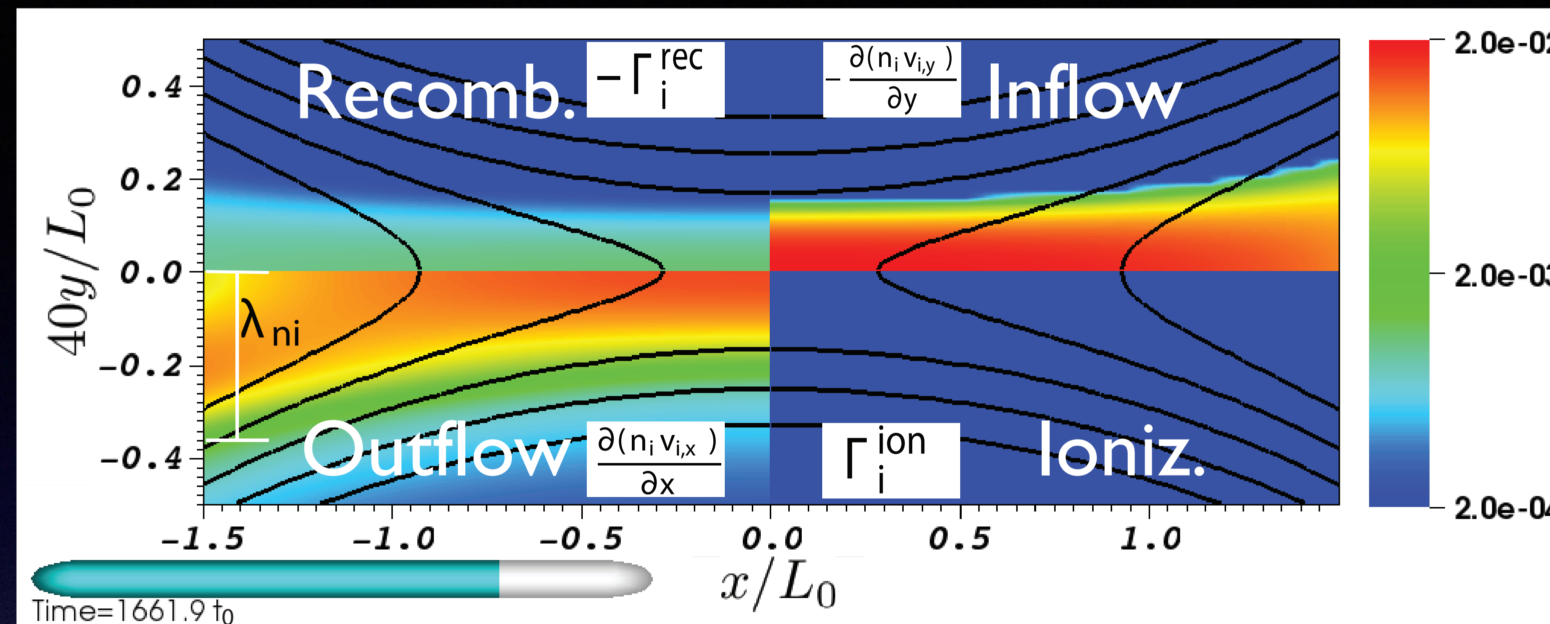
As in Leake et al. (2006,2013) - Pedersen heating is important in emerging regions of B - maintains chromospheric temperatures

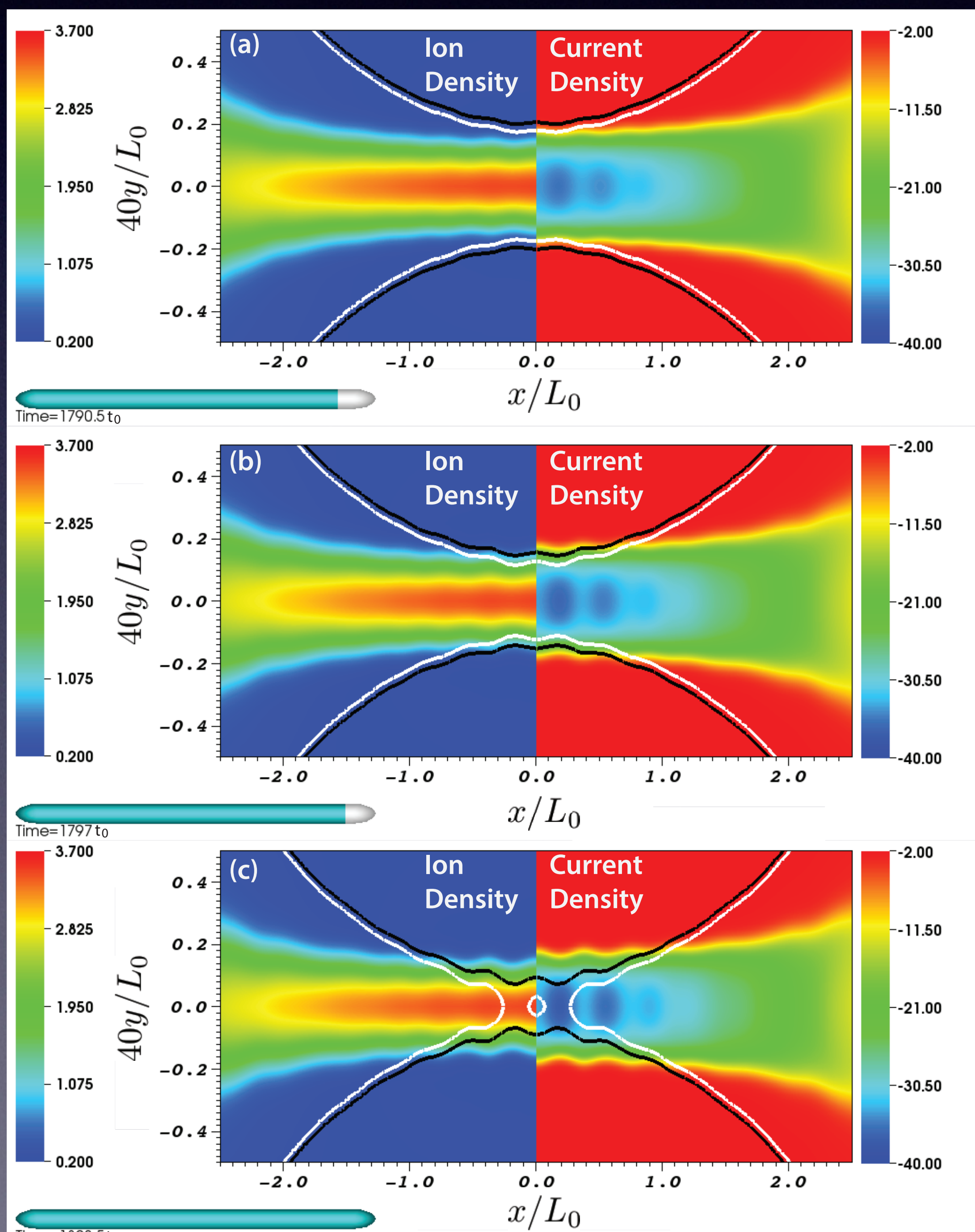
# Chromospheric Physics at smaller scales ($L<\lambda_{ni}$)

- 2D Harris current sheet
- Weakly ionized chromospheric plasma
- Two-fluid (neutrals and plasma) numerical model includes cont., mom, energy equation for both fluids, Ohm's law with Hall term and electron pressure
- Initially, width $w>\lambda_{ni}$ - Sweet Parker scaling - current sheet thins and lengthens
- Ions and neutrals coupled
- When $w \sim \lambda_{ni}$ ion and neutrals decouple on inflow, remain coupled on outflow $L>\lambda_{ni}$
- Leads to build up of ions in current sheet



# Example of multi-fluid physics when $L<\lambda_{ni}$

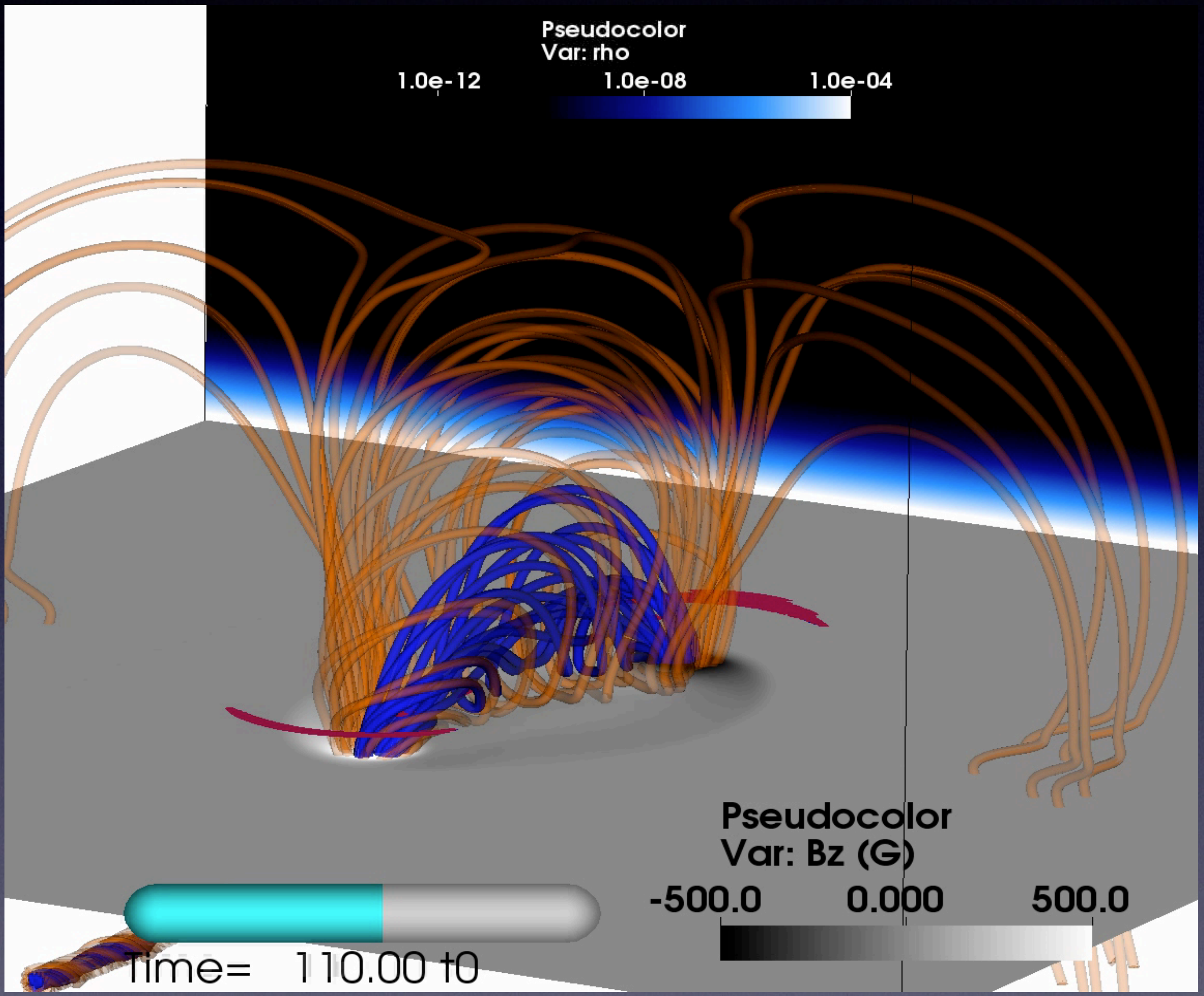



- Build up of ions leads to ionization/ recombination imbalance
- Recombination can dominate over reconnection for removing ions from diffusion region
- Leads to rapid thinning of current sheet and faster reconnection
- Eventually 2D sheet becomes plasmoid unstable
- Decoupling at scales $\sim\lambda_{ni}$ allows for fast reconnection quicker than in resistive MHD
- See also Ni et al. (2015)

# Open Questions

- Can Pedersen heating by waves explain net radiative losses in chromosphere?
    - Need to couple e/d and t/d models
- How important is Pedersen heating in emerging active regions?
    - Need to cover AR scales and resolve Pedersen resitivity
        - easier to do than for Spitzer!
- How important is dissipation of perpendicular currents for stability?
    - How does it affect reconnection
        - overlying reconnection
        - flare-like reconnection
- How does dissipation of perpendicular currents in emerging structures affect the current closures in active regions?



# Conclusion

- Chromosphere is oft-ignored, weakly ionized, radiatively complex, region between surface (observations) and corona (models)
- Even included as a simple stratified transition it is important for free energy, twist, current, 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 - slippage of field through plasma-neutral mix (or vice-versa)
    - Dissipates perpendicular currents
    - Increases transfer of magnetic energy into the corona
    - Increase Joule heating due to non-zero electric field (model dependent)
        - may explain heating requirement of chromosphere but need better models
        - simple 1D wave models without thermodynamic feedback are suggestive
- When single-fluid model breaks down (current sheets, high frequency waves - Soler 2015) - need to follow neutrals and plasma separately
- Important to get thermodynamics sufficiently accurate to trust calculation and consequences of Pedersen dissipation (radiation, thermal conduction)