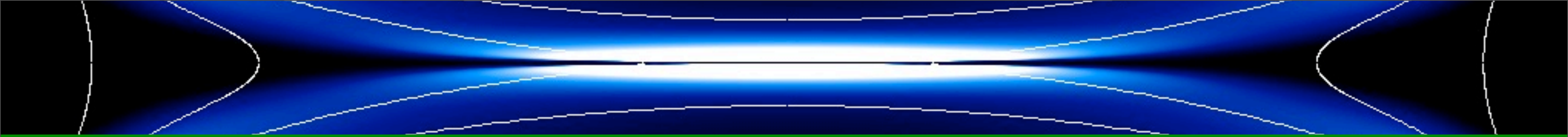

Multi-fluid simulations of chromospheric magnetic reconnection

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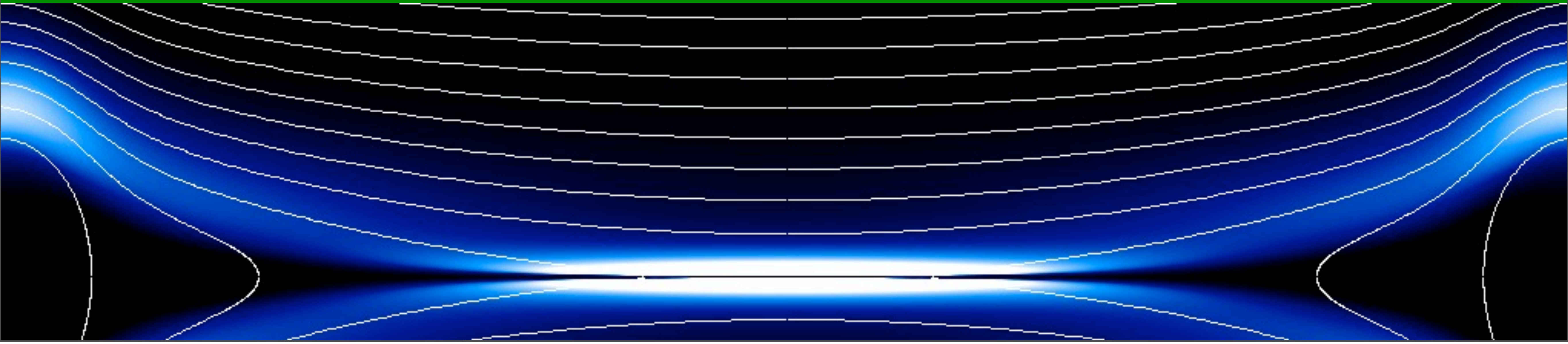
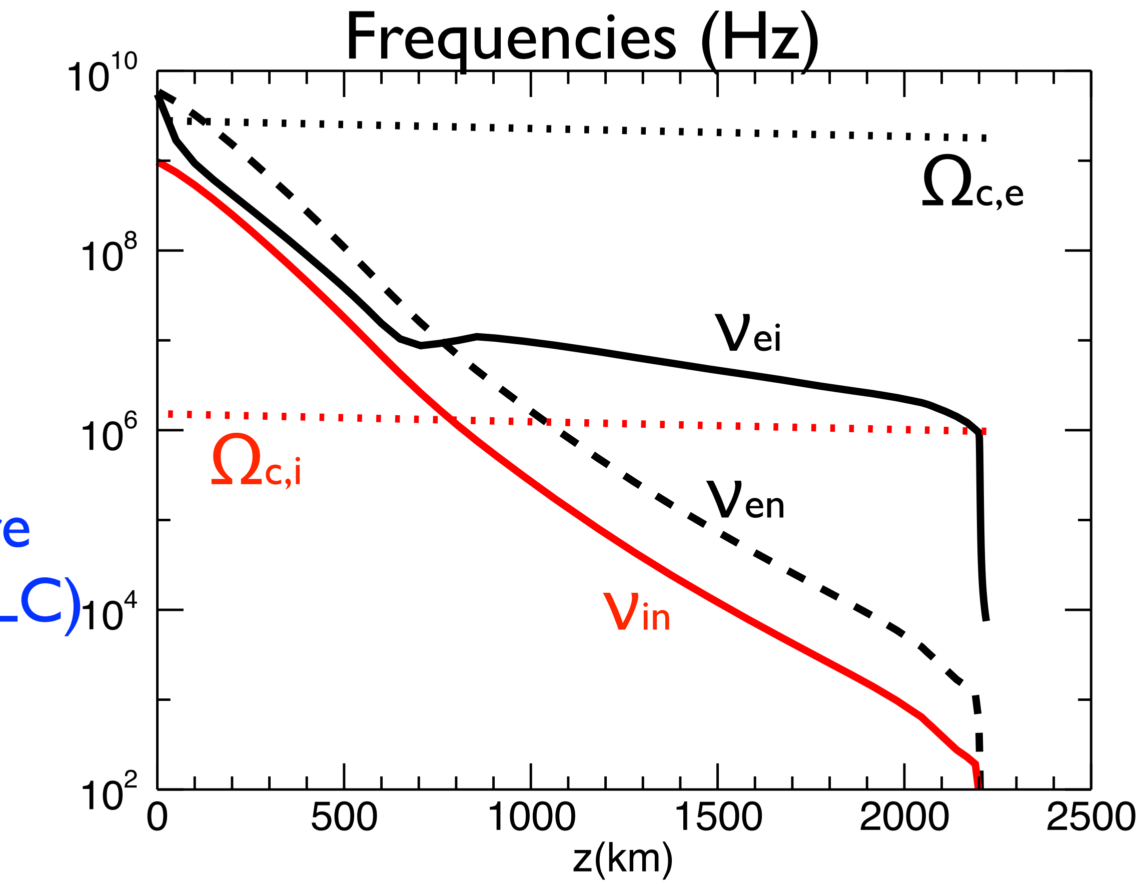
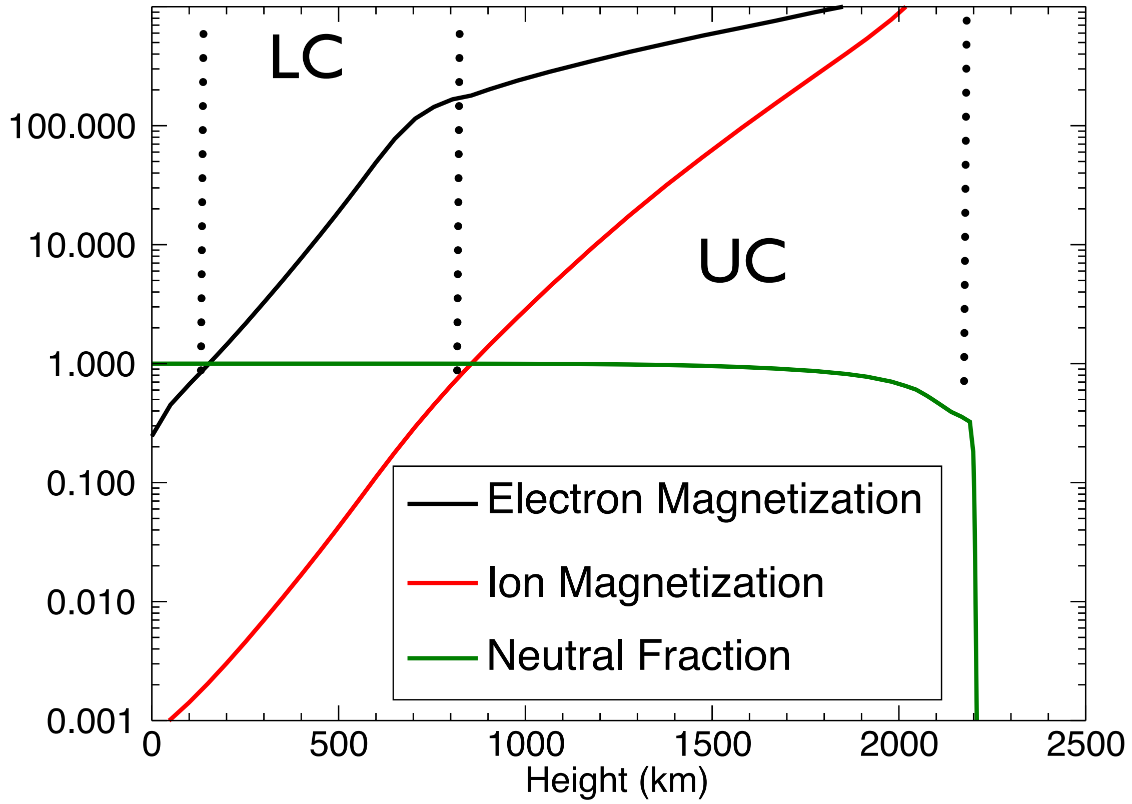


Chromospheric conditions

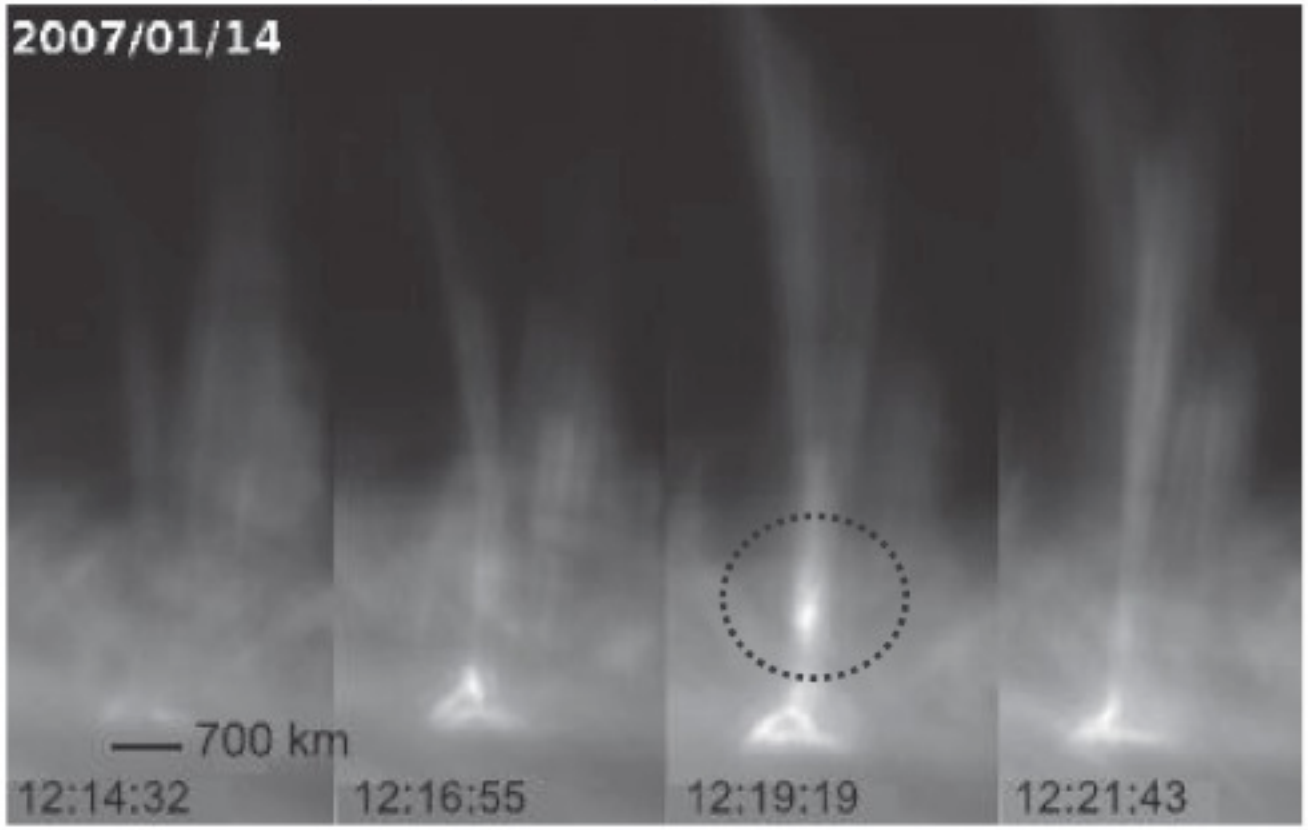
- Transitions
  - Plasma-β
    $\beta>1$ in convection zone and photosphere
    $\beta<1$ in corona
  - Magnetization
    Ions and electrons unmagnetized in photosphere
    Electrons magnetized in lower chromosphere (LC)
    Both magnetized in upper chromosphere (UC)
  - Varies from optically thick to optically thin
  - Emission lines formed in non-LTE
- Weakly ionized, highly collisional
  - c.f. corona - fully ionized, collisionless
  - Typically strongly coupled, $t_{collisions} \sim$ ms
  - On small time-scales/length-scales ions and neutrals can decouple





Chromospheric reconnection

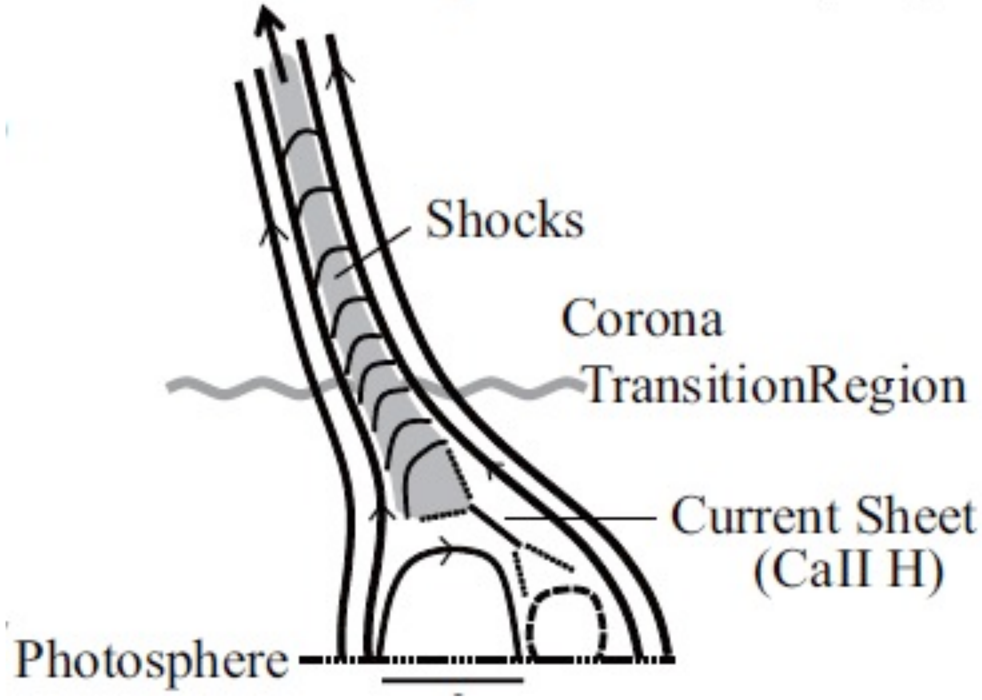
Chromospheric anenome jet observed with SOT/Hinode (Singh 2011)



Reconnection signatures of chromospheric jets

Jet flow ~ Alfven speed

Alfven waves created (T~200 s)



Recent evidence of reconnection using SOT obs of jets (Shimizu, 2011, Shimizu et al. 2009)

Chromosphere: Collisional reconnection (Sweet-Parker Width >> λi) due to ion-neutral collision

c..f corona - Width < λi - collisionless

Q. How do we get fast reconnection in the highly collisional chromosphere?

Two-fluid physics model

- Reacting, ion-neutral model, (Meier and Shumlak 2012, PoP submitted), implemented with HiFI
  - Two-fluid approach, one fluid is ions (i), the other is neutrals (n)
  - Electron impact ionization, radiative recombination

$$\begin{aligned}
\text{Ion continuity: } & \frac{\partial n_i}{\partial t} + \nabla.(n_i \mathbf{v}_i) = \Gamma_i^{ion} - \Gamma_n^{rec} \\
\text{Ion momentum: } & \frac{\partial}{\partial t}(m_i n_i \mathbf{v}_i) + \nabla.(m_i n \mathbf{v}_i \mathbf{v}_i + pI + \pi) = \\
& \mathbf{j} \wedge \mathbf{B} + R_i^{in} + \Gamma_i^{ion} m_i \mathbf{v}_n - \Gamma_n^{rec} m_i \mathbf{v}_i \\
\text{Ohm's law: } & \mathbf{E} + (\mathbf{v}_i \wedge \mathbf{B}) = \eta \mathbf{j}
\end{aligned}$$

  - Energy (pressure) equation contains ionization/recombination exchange, collisional heating and thermal transfer between plasma and neutrals and thermal conduction
- ‘Ambipolar Diffusion’ - consequence of taking single-fluid approach
  - we follow dynamics of neutrals and ions separately, η is electron collisions (Spitzer) only

Initial conditions

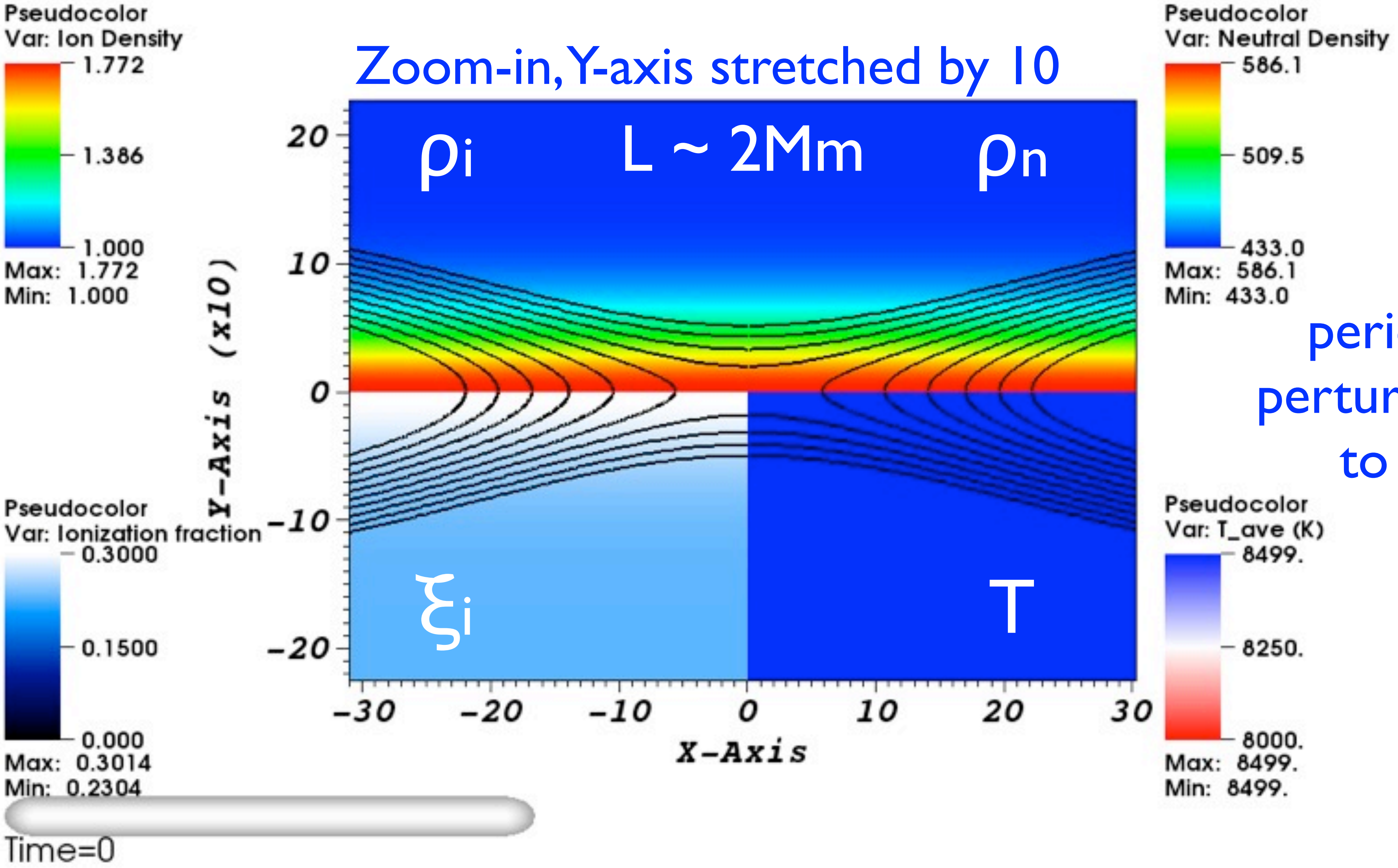
Weakly ionized plasma, n~1.4x10^{19} m^{-3}
Ionization balance ~ 0.2%
Harris Current sheet, β_{total} ~1, β_i~0.001
perturb both neutral and ionized pressures
add flow to couple pressure gradients

$$-\nabla P_i + \mathbf{j} \wedge \mathbf{B} = -R_i^{in}$$

$$-\nabla P_n = R_i^{in}$$

$$-\nabla(P_n + P_i) + \mathbf{j} \wedge \mathbf{B} = 0$$

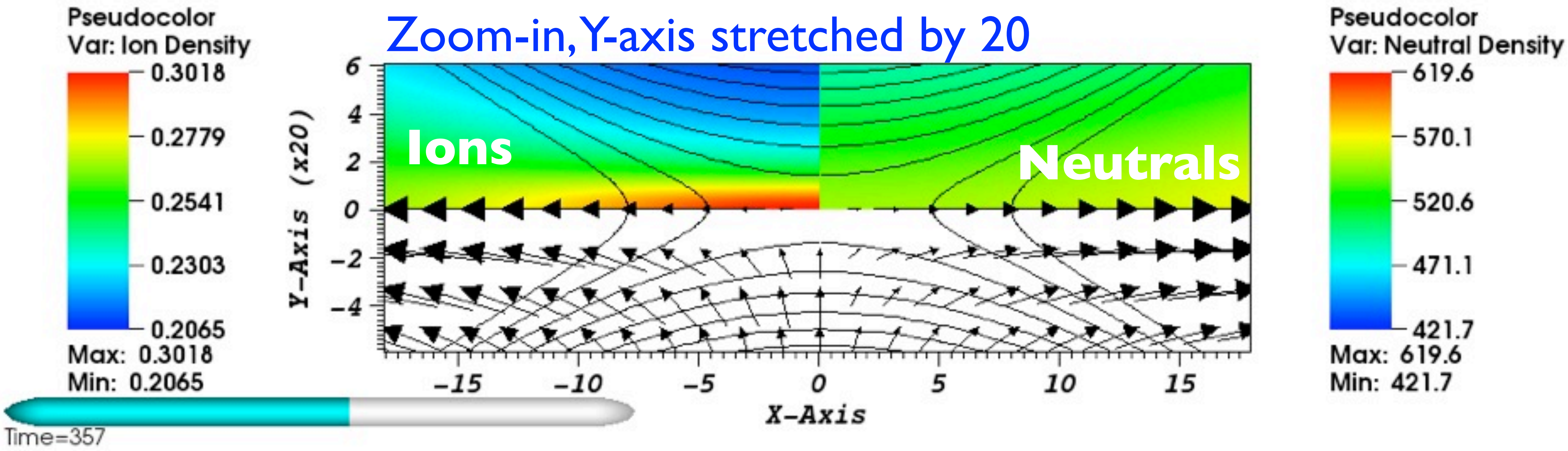
Zoom-in, Y-axis stretched by 10



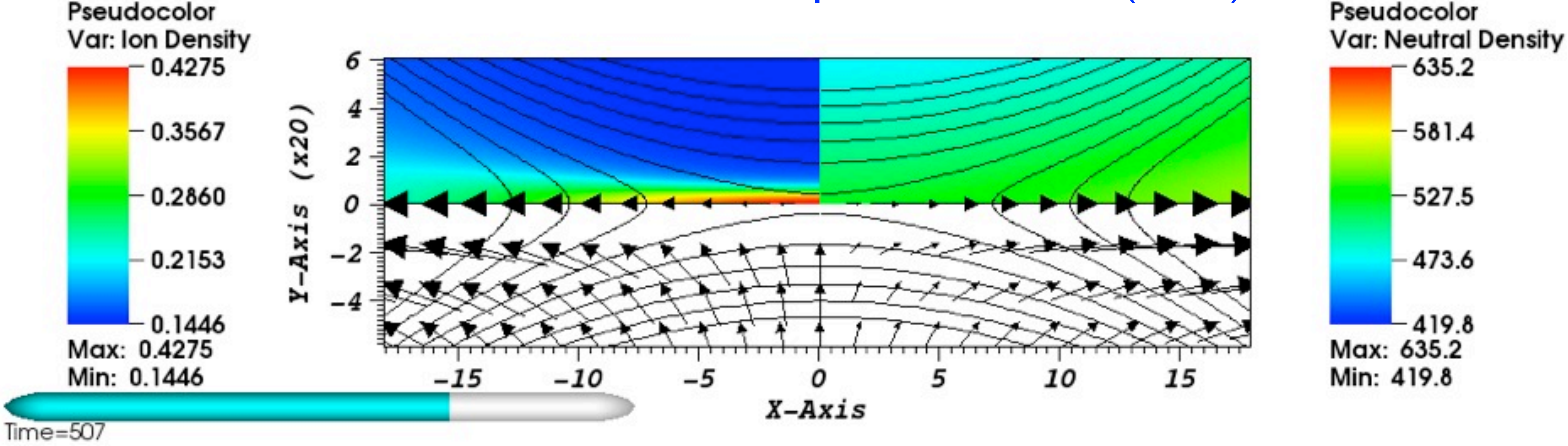
periodic
perturbation
to Az

Decoupling of inflow

Zoom-in, Y-axis stretched by 20

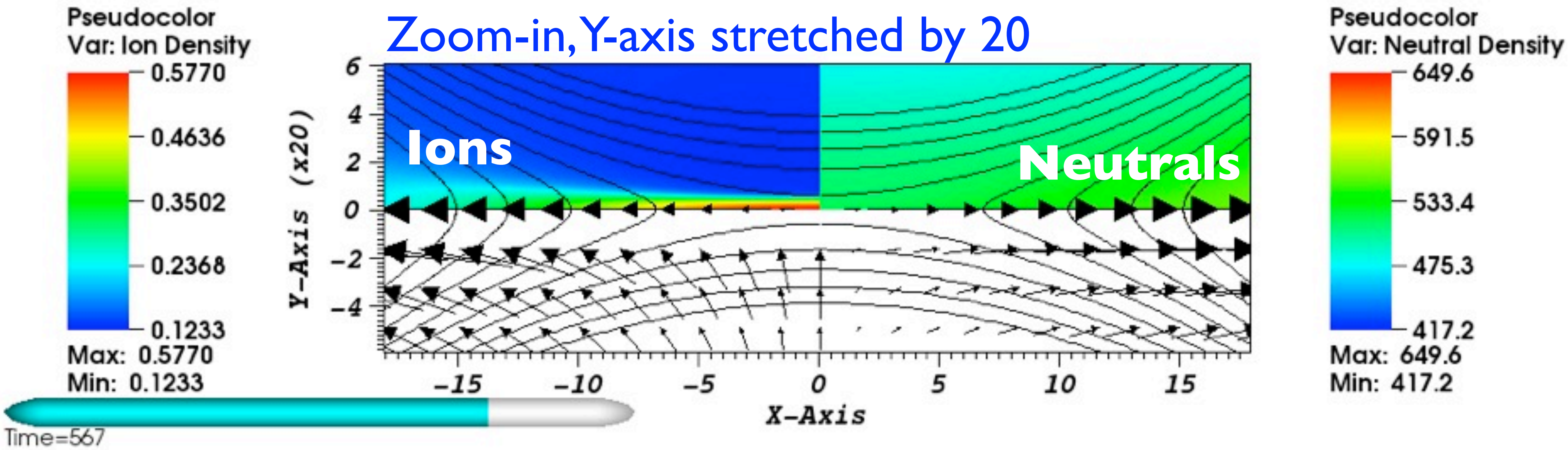


Outflow remains coupled $v_{out} = v_a$ (total)



Decoupling of inflow

Zoom-in, Y-axis stretched by 20



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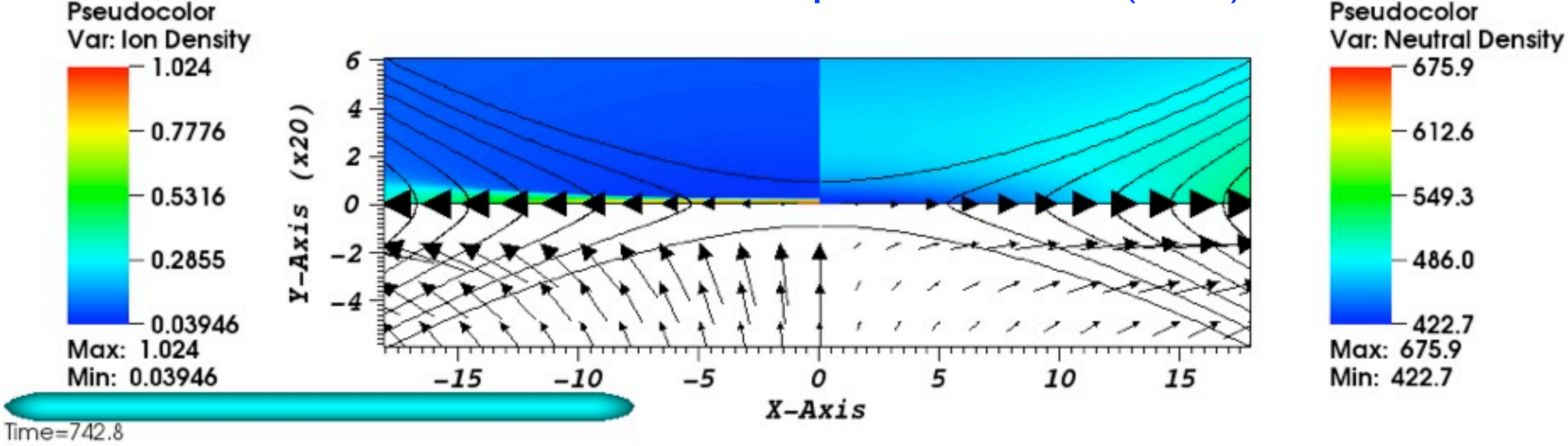
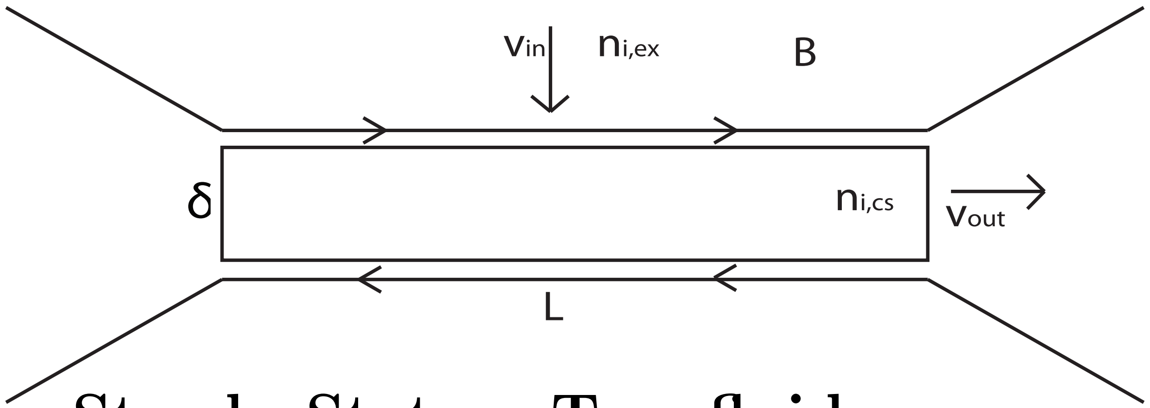


Scaling



Steady State, Two fluid

Ion continuity: $n_{i,ex} v_{in} L = n_{i,cs}(v_{out}\delta + \delta L \tau_{recomb} - \delta L \tau_{ioniz})$

$$: \quad \boxed{\tau_{inflow} = \frac{n_{i,cs}}{n_{i,ex}}(\tau_{outflow} + \tau_{recomb} - \tau_{ioniz})}$$

$$\tau_{inflow} = v_{in}/\delta, \;\; \tau_{outflow} = v_{out}/L$$

Ohm's law: $v_{in} B = \eta j \sim \dfrac{\eta B}{\mu_0 \delta}$

Inflow: $v_{in} = \sqrt{\dfrac{\eta}{\mu_0} \dfrac{n_{i,cs}}{n_{i,ex}} (\tau_{outflow} + \tau_{recomb} - \tau_{ioniz})}$

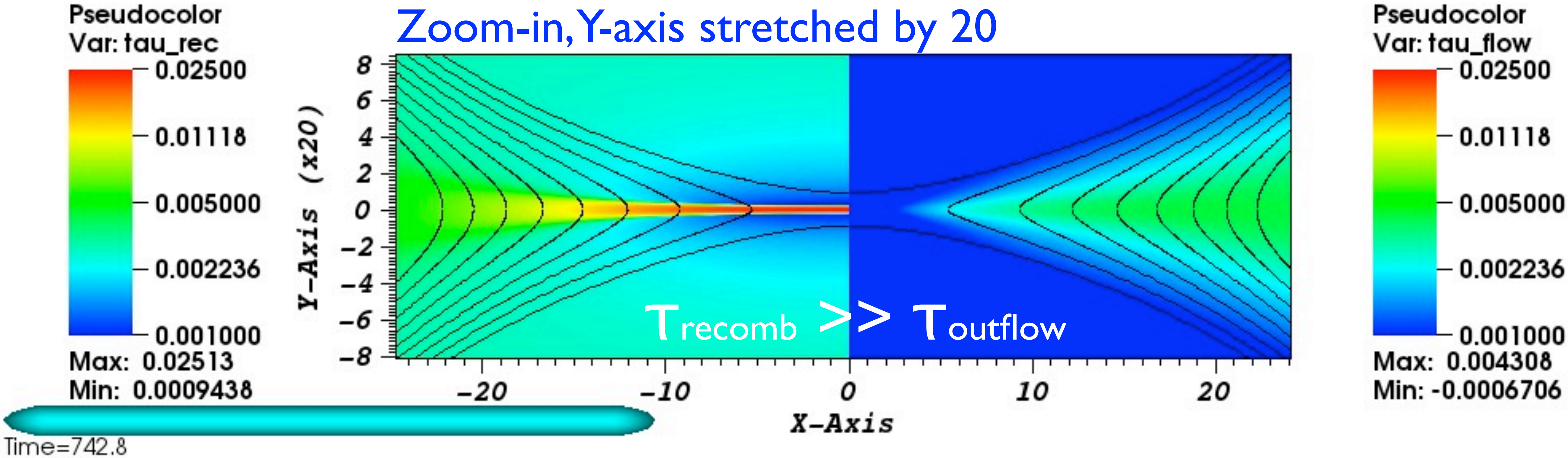
If ionization balance: $\tau_{ioniz} = \tau_{recomb}, \;\; v_{out} = v_A(\text{total}), \;\; n_{i,cs} \sim n_{i,ex}$

$$: \quad \frac{v_{in}}{v_A} = \sqrt{\frac{\eta}{\mu_0 L v_A}} = \sqrt{\frac{1}{S}}, \text{or: } M = \frac{\eta j}{v_A B} = \frac{\delta}{L}.$$

Out of ionization balance: $\tau_{recomb} >> \tau_{ioniz}, \tau_{outflow}$

(Heitsch and Zweibel 2003)

Ionization imbalance: recombination rate vs outflow rate



Zoom-in, Y-axis stretched by 20

$\tau_{recomb} >> \tau_{outflow}$

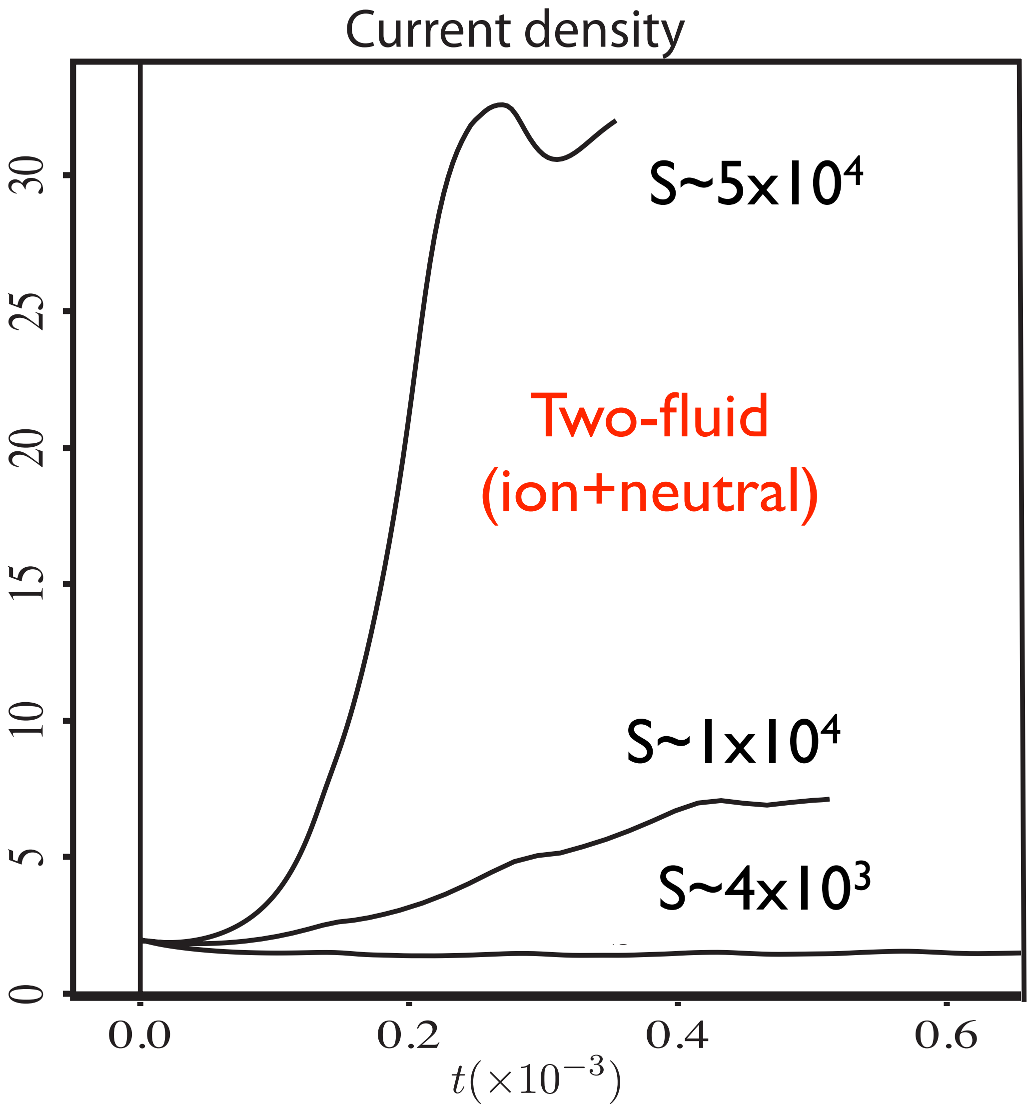
Ions dragged in - decouple from neutrals - loss of ionization balance

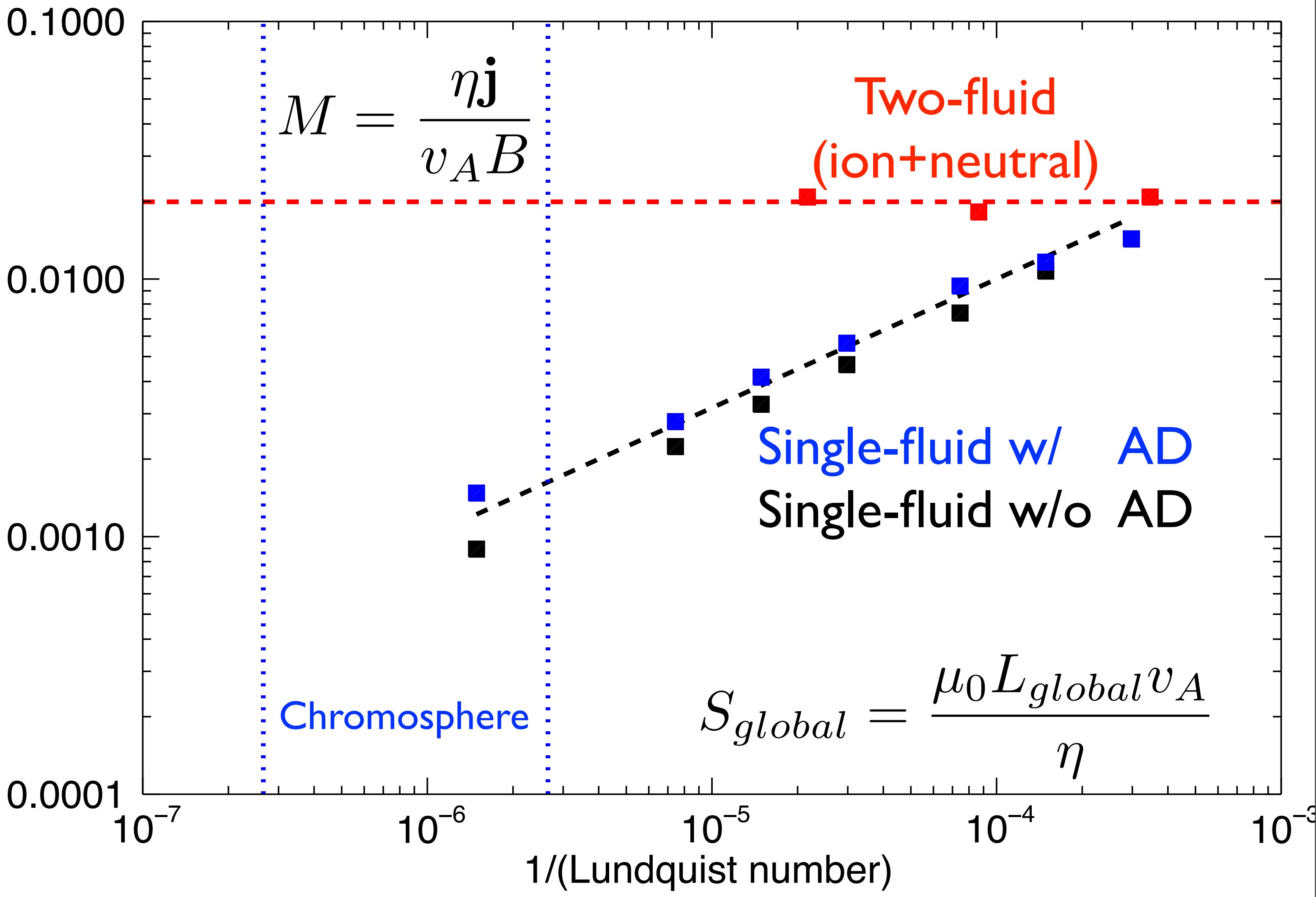
$$\tau_{inflow} = \frac{n_{i,cs}}{n_{i,ex}} (\tau_{outflow} + \tau_{recomb} - \tau_{ioniz})$$

$$\tau_{inflow} \sim \frac{n_{i,cs}}{n_{i,ex}} \tau_{recomb}$$

Q. How does τ_{recomb} affect the scaling with Lundquist number (S)?

Reconnection rates





- Single-fluid: ~ Sweet Parker scaling (M~√(1/S), δ~√η)
- Two-fluid:
    - Reconnection rate, M, 'fast' - independent of S, δ~η
        - Dependent on transport coefficients

Comparison to previous analytic work (Heitsch and Zweibel 2003)

- Astrophysical magnetic current sheets (protoplanetary disks)
- Two-fluid (reacting) model, no thermal conduction

- 1D steady state (no need for outflow if $T_{recomb} >> T_{outflow}$)
- Cover Lundquist number (S) 10^4-10^{12}

$$Z \sim \frac{\beta_{0,i}^{3/\gamma}}{10} \frac{t_{recomb} t_{\Omega}}{t_{AD}^2}$$

Fast (independent of S) reconnection when:

$$Z << 10^{-4}(\text{simulation}),\ Z << 10^{-2}(\text{theory})$$

Our 2D simulations

$$t_{\Omega} \sim 5 \times 10^4 s$$

$$t_{AD} \sim 5 \times 10^2 s$$

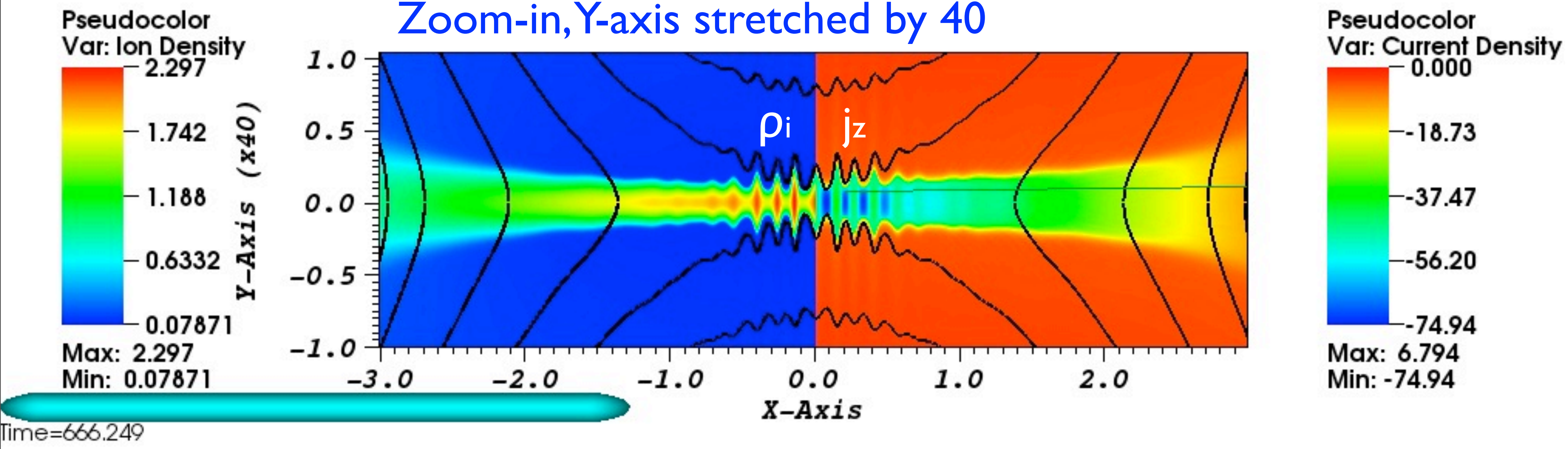
$$t_{recomb} \sim 2 \times 10^2 s$$

$$Z \sim 1 \times 10^{-5}$$

What about higher S, and plasmoid instability (2D)?

Recent results: Onset of the plasmoid instability at higher S

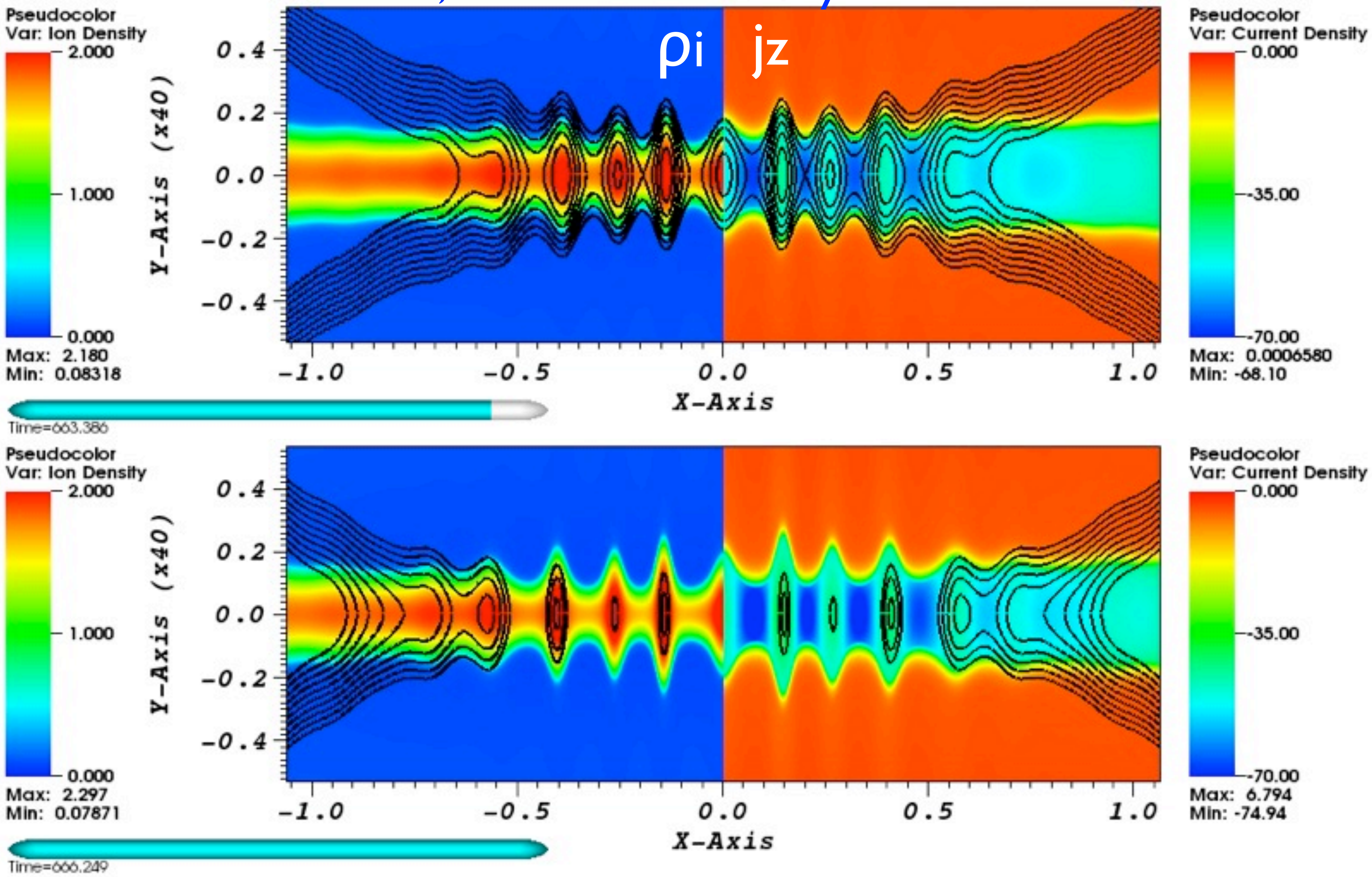
Zoom-in, Y-axis stretched by 40



- Plasmoid instability sets in for higher S, when $\delta/L \sim 1/300$ (Loureiro et al. 2007, Huang and Battacharjee 2010)
- As we increase S (decrease η):
  - For two-fluid model $\delta \sim \eta$ (single-fluid $\delta \sim \sqrt{\eta}$)
    - plasmoid instability sets in at higher η (lower S) than single-fluid

Recent results: What happens to the plasmoids?

Zoom-in, Y-axis stretched by 40



- Recombination dominates over outflow in resistive region
- Plasmoids lose flux rather than get ejected by outflows

Conclusions

- Multi-fluid simulations of chromospheric reconnection in weakly ionized reacting plasma
- Reconnection rates independent of S, even at low S: 10^4 - 10^5
  - decoupling of inflow creates ionization imbalance
  - recombination of incoming ions dominates over outflow
- Onset of plasmoid instability occurs as S is increased 10^6
  - onset occurs at lower S than single fluid, due to 'fast scaling'

Questions

- How does 'fast' reconnection rate depend on (neutral) transport coefficients?
- How do plasmoids affect weakly ionized reconnection (scaling)?
  - early work sees continuation of S-independent rate for higher S
- How does decoupling of ions from neutrals affect the decoupling of ions from electrons? (Malyshkin and Zweibel 2011)

'Multi-fluid simulations of magnetic reconnection in a weakly ionized reacting plasma'
Leake, Lukin, and Linton 2012, in prep

Funded by the Living with a Star (LWS) Targeted Research and Technology (TRT) Program

Appendix: Literature

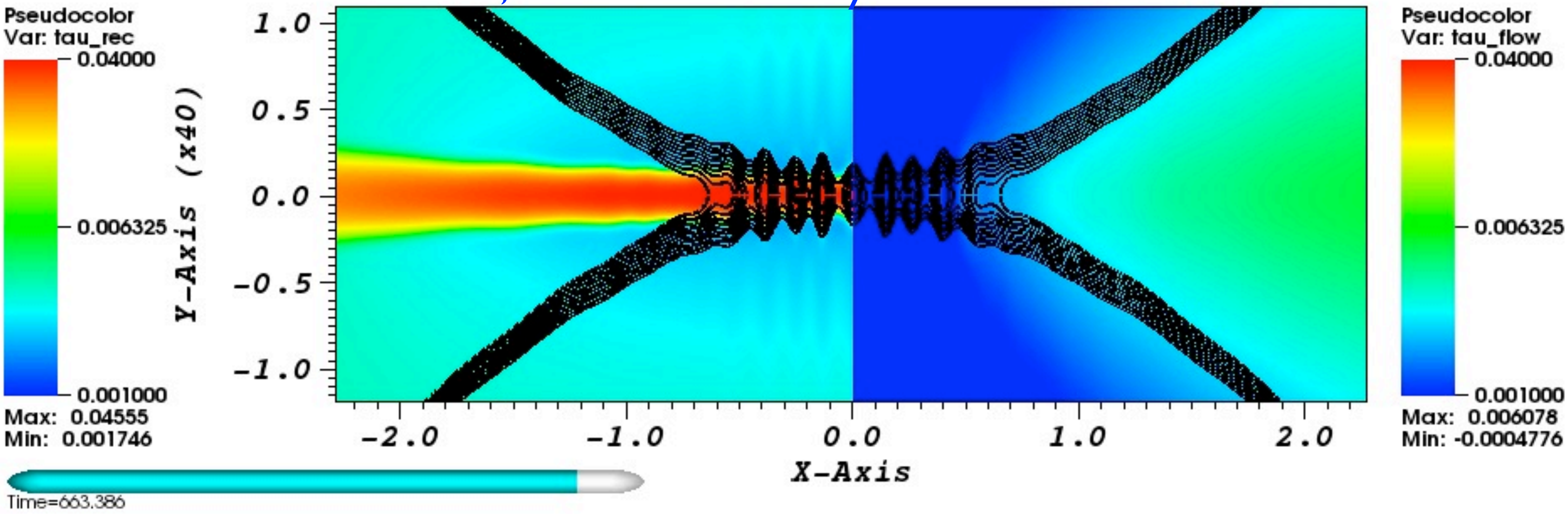
- Zweibel 1989
  - For $t < 1/\tau_{in}$, $C_A \sim B/\sqrt{\rho_{tot}}$
  - For $t > 1/\tau_{in}$, $C_A \sim B/\sqrt{\rho_i}$
  - ionization rate and amount of decoupling affect growth of tearing mode
- Brandenburg and Zweibel 1994,1995
  - ‘Ambipolar diffusion’ (effect of ion-neutral collisions in a single-fluid approach) can lead to steepening of current sheets in ISM
- Vishniac and Lazarian 1999, Heitsch and Zweibel 2003, Lazarian et al. 2004
  - Recombination of inflowing plasma can increase reconnection rates
- Smith and Sakai 2008
  - Reconnection rates between two flux system are dependent on proton density to neutral Hydrogen density ratio
- Malyshkin and Zweibel 2011
  - Ion neutral collisions increases effective skin depth, so Hall reconnection is important at larger scales

Appendix: HiFi numerical code

- Main developers: V.Lukin (NRL), A. Glasser (Univ. of Washington)
- PDE Formulation: generic flux-source form of the equations
- Spatial discretization: high order C0 spectral elements - low numerical dispersion + adaptable grid + domain decomposition + semi-structured grid
- Time step: fully implicit 2nd-order accurate, Newton iteration, direct or iterative solvers
- PDE Formulation: generic flux-source form of the equations
- User-specified physics file: transparent modification of equations

Appendix: Recombination of ions in plasmoids

Zoom-in, Y-axis stretched by 40



$T_{\text{recomb}} >> T_{\text{outflow}}$