Chromospheric modeling on ion-neutral interaction effects and non-equilibrium ionization

Using Bifrost

Juan Martinez-Sykora

Collaborators: B. De Pontieu, V. H. Hansteen, D. Nobrega-Sivero, M. Carlsson, F. Moreno-Insertis, B. Gudiksen. T. M. D. Pereira, J. Leenaarts

IRIS-9, Göttingen, 25-29 June 2018

Invited Talk

1. Fundamental physical processes and modeling

Chromospheric modeling on ion-neutral interaction effects and non-equilibrium ionization

Juan Martínez-Sykora[1]

[1] *Bay Area Environmental Research Institute, Moffett Field, CA 94035, USA*

In the chromosphere is governed by a variety of complex physical processes including ion-neutral interaction effects and non-equilibrium ionization. These two processes have never been combined in radiative MHD models. Although, recently, 2D radiative MHD numerical models using the Bifrost code have revealed the importance of the ion-neutral interaction effects for the formation of the type II spicules and chromospheric heating (Martinez-Sykora et al 2017, Science). However, this work assumed ionization in statistical equilibrium. In addition, non-equilibrium ionization must be also taken into account in IRIS observations for Si IV and O IV. In this talk, focusing on Bifrost models, we will reveal the importance of combining ion-neutral interaction effects and non-equilibrium ionization in order to properly address chromospheric energetics as well as the interpretation of IRIS observations.

Chromospheric modeling on ion-neutral interaction effects and non-equilibrium ionization

Using Bifrost

Juan Martinez-Sykora

Collaborators: B. De Pontieu, V. H. Hansteen, D. Nobrega-Sivero, M. Carlsson, F. Moreno-Insertis, B. Gudiksen. T. M. D. Pereira, J. Leenaarts

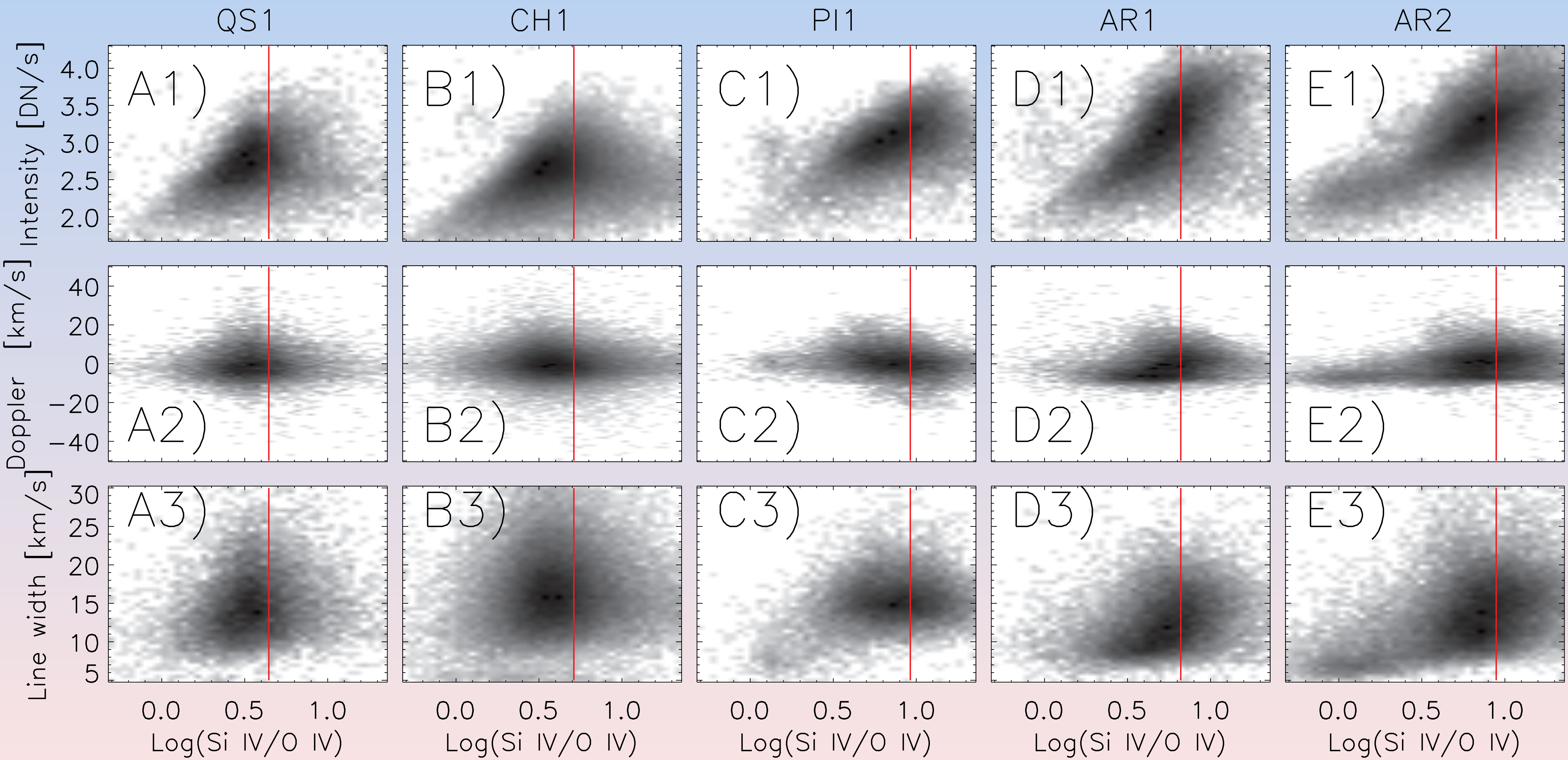
Two main topics:

- NEQ ionization of oxygen and silicon
  - Observables

- NEQ ionization of hydrogen and helium + ambipolar diffusion
  - Impact on chromospheric thermo-thermodynamics

Ratio of Si IV 1402 Å and O IV 1401 Å increases with Si IV intensity

- The ratio is correlated with intensity.
- The correlation differs between each observed region.
- The Doppler shift barely shows any dependence with the ratio.
- The line width increases (no strong correlation) with the ratio.

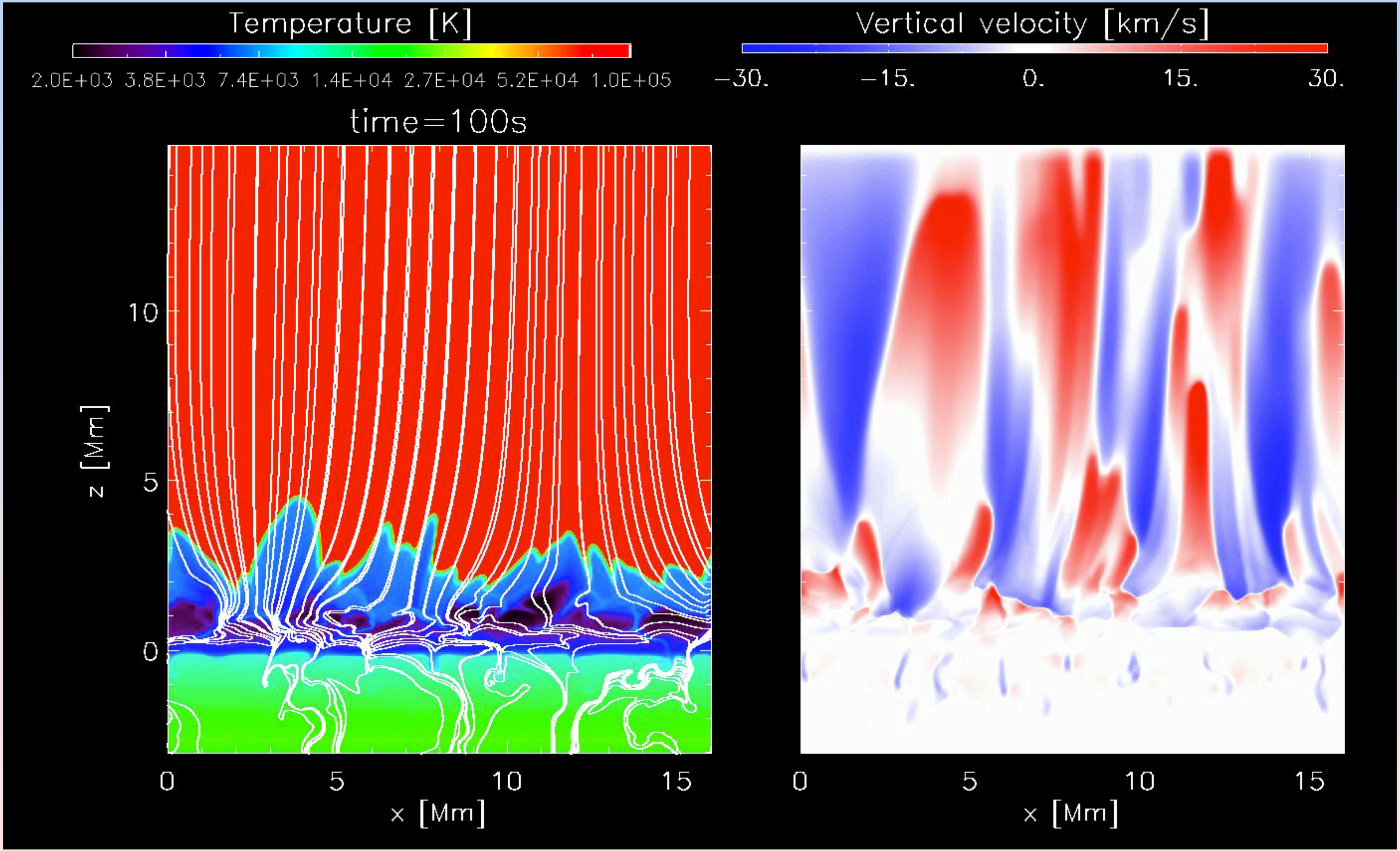


Martinez-Sykora et al. 2016

2D radiative MHD coronal hole (no type II spicules)

- MHD, radiative losses with scattering, and thermal conduction along the magnetic field lines.
- NEQ ionization for oxygen and silicon (Olluri et al 2013).
- 2D with initial unipolar vertical magnetic field (~5G in the corona)
- Open boundary conditions and constant entropy at the bottom boundary in order to have convection

Martinez-Sykora et al. 2016



Non-Equilibrium ionization

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (\mathbf{u} n_i) = \sum_{j \neq i} n_j P_{ji} - n_i \sum_{j \neq i} P_{ij}$$

- Transition probabilities: $P_{ij} = R_{ij} + C_{ij}$
  - radiative rates introduce global coupling through the radiation field
- Approximations
  - Optically thin atmosphere

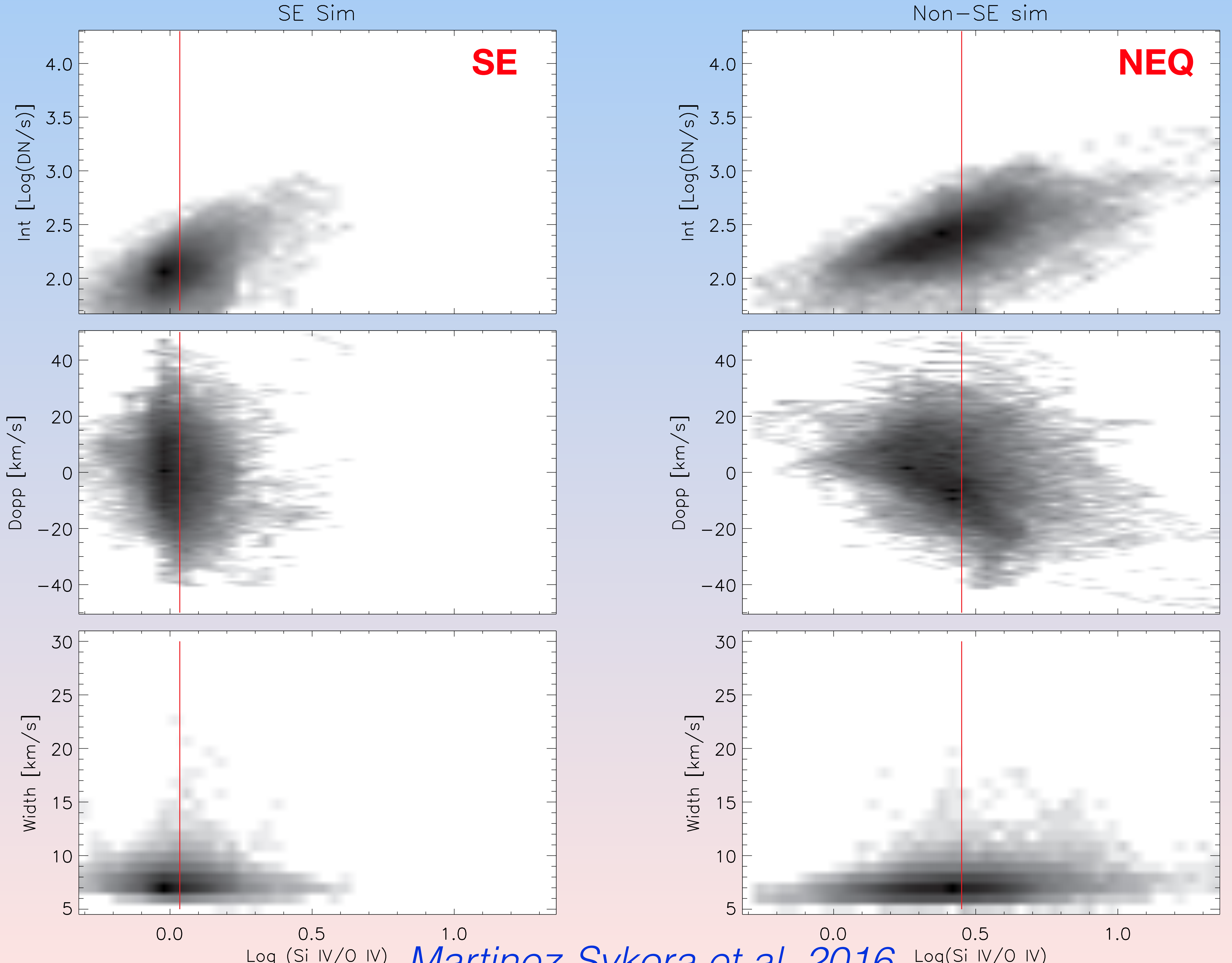
Using DIPER*

The transition rates (P) ;

- Collisional Ionization
- Excitation auto-ionization
- Dielectric recombination
- Three-body recombination
- Spontaneous emission
- Radiative recombination
- Collisional excitation
- Collisional de-excitation

**DIPER: HAO Spectral Diagnostic Package for Emitted Radiation (Judge and Meisner 1994, Judge: 2007)*

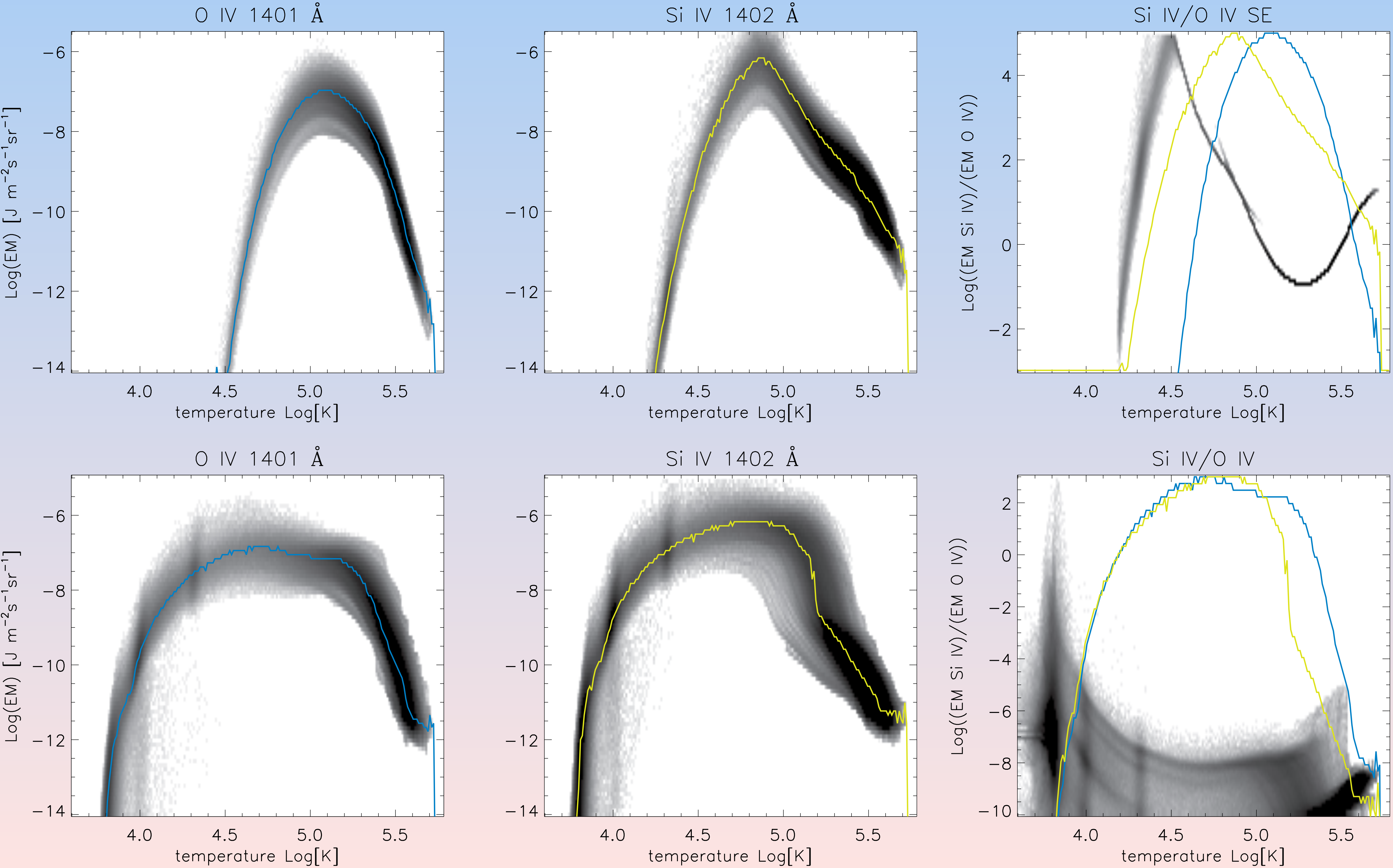
Variations of the ratio as a function of intensity, Doppler shift and line-width vary in SE and NEQ



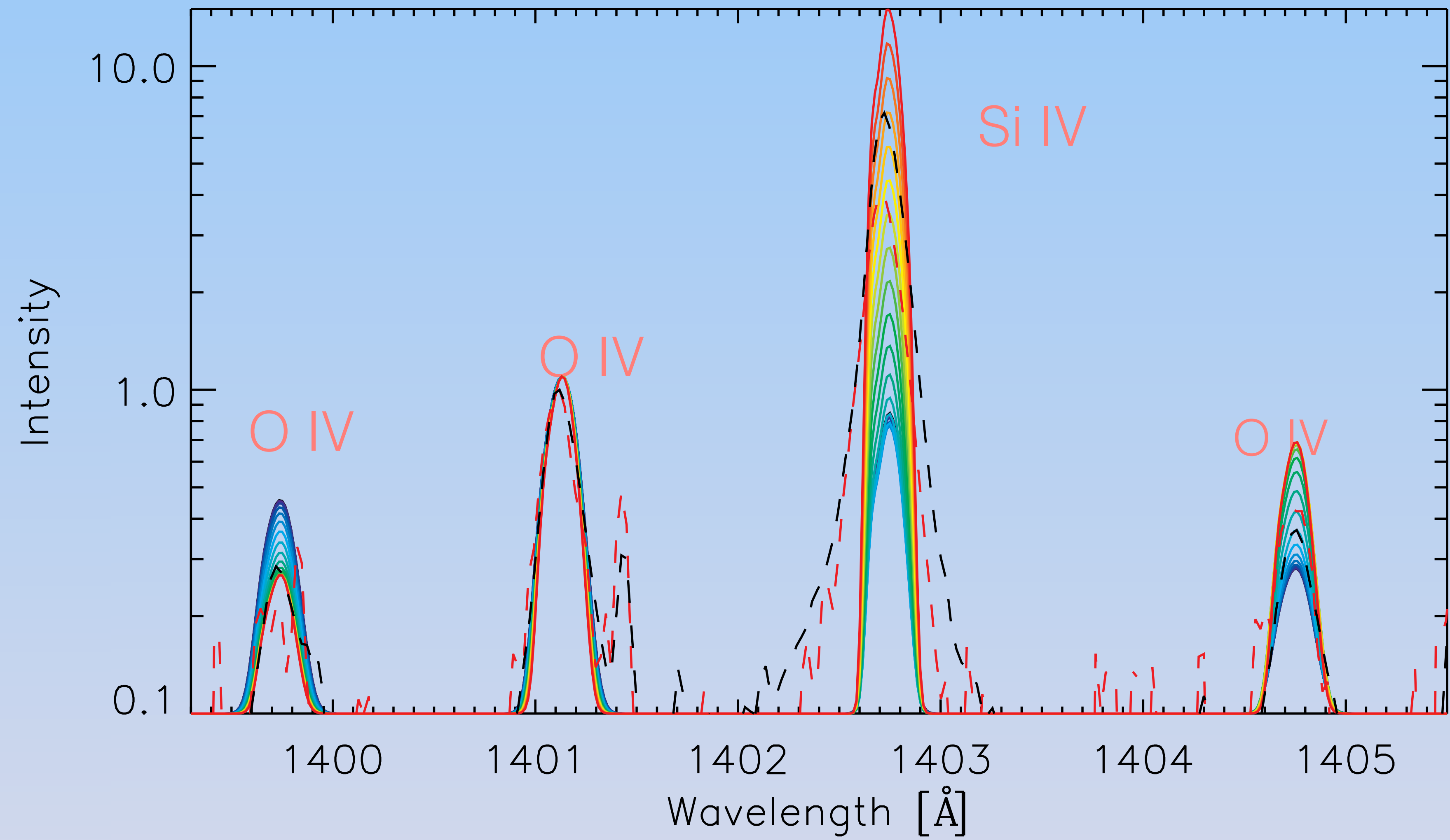
Martinez-Sykora et al. 2016

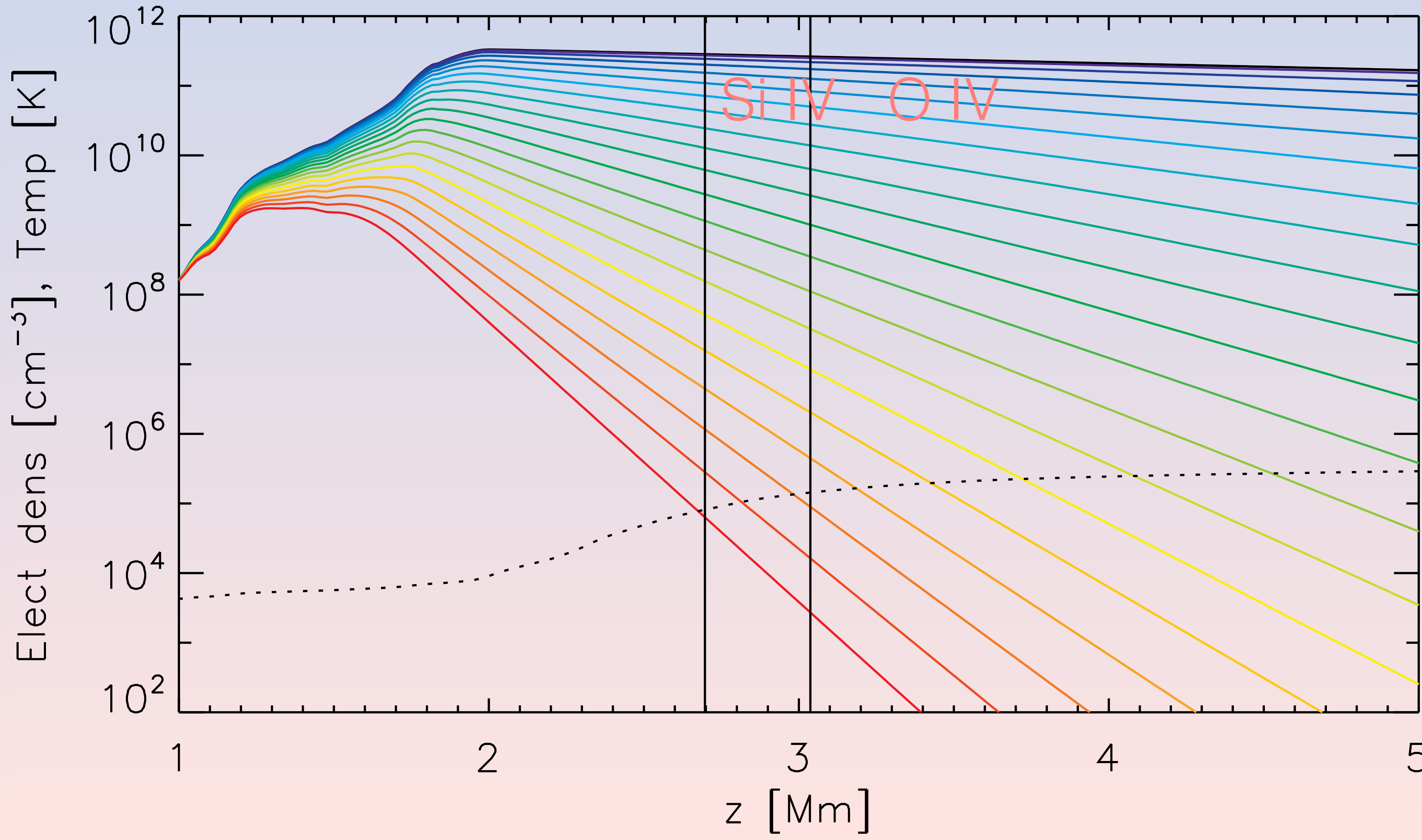
NEQ - Not nicely correlated with temperature
NEQ vs SE- different temperature range

Martinez-Sykora et al. 2016



Density stratification leads also to different ratios





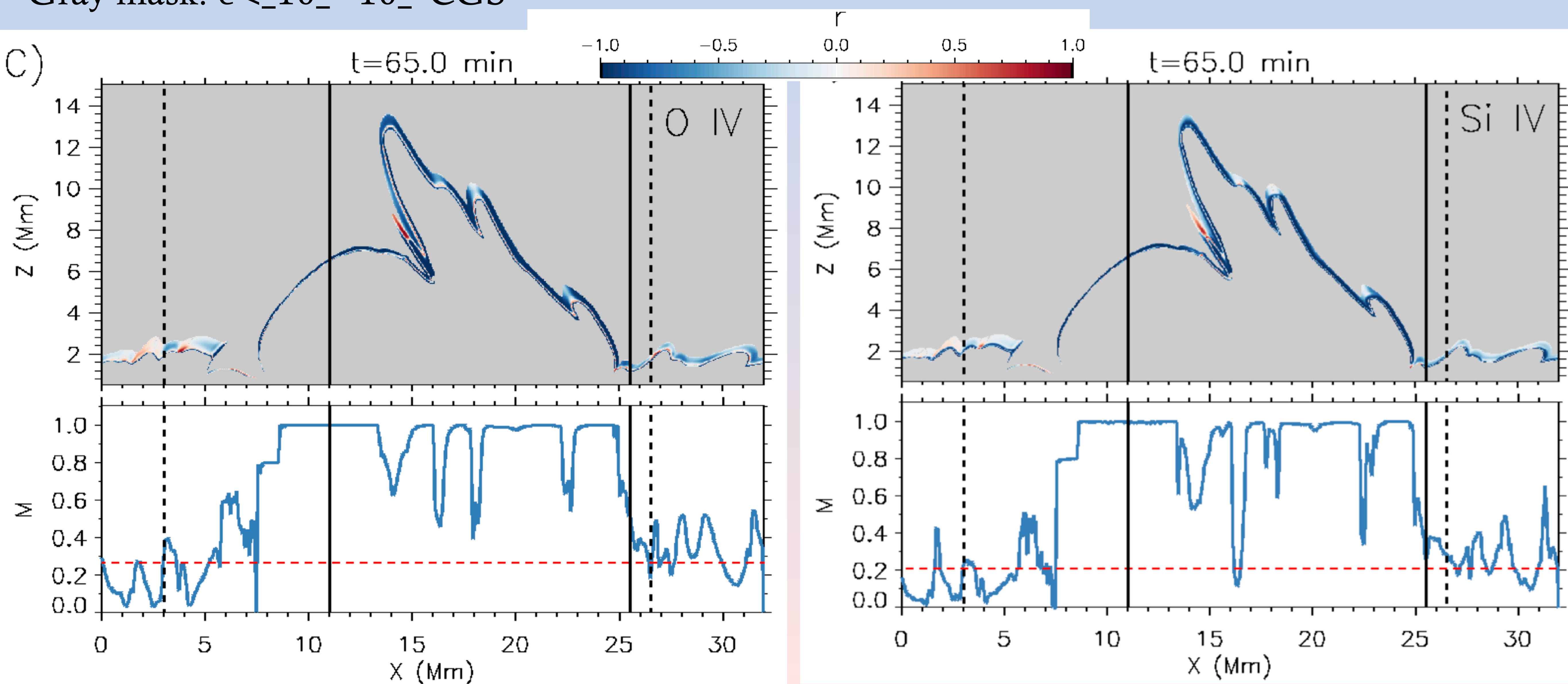
Martinez-Sykora et al. 2016

NEQ in Surges and flux emergence

- **NEQ ionization of Si IV and O IV are important, and its effects are massive in the surge and emerged region**
- **SE seriously underestimate the number density values**

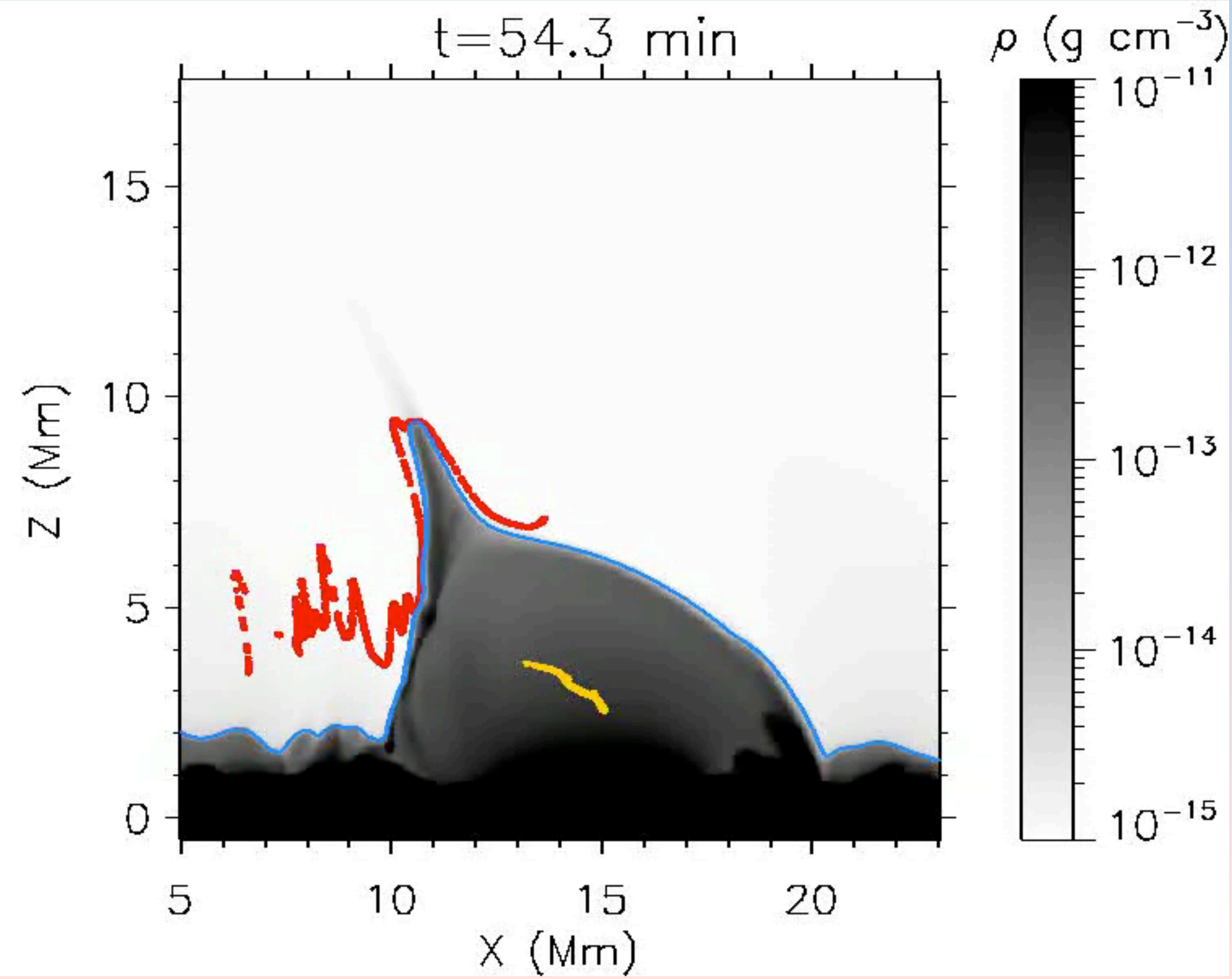
Nobrega-Siverio et al. 2018

Gray mask: ϵ<_10_−10_ CGS



NEQ in Surges and flux emergence

Lagrangian tracing

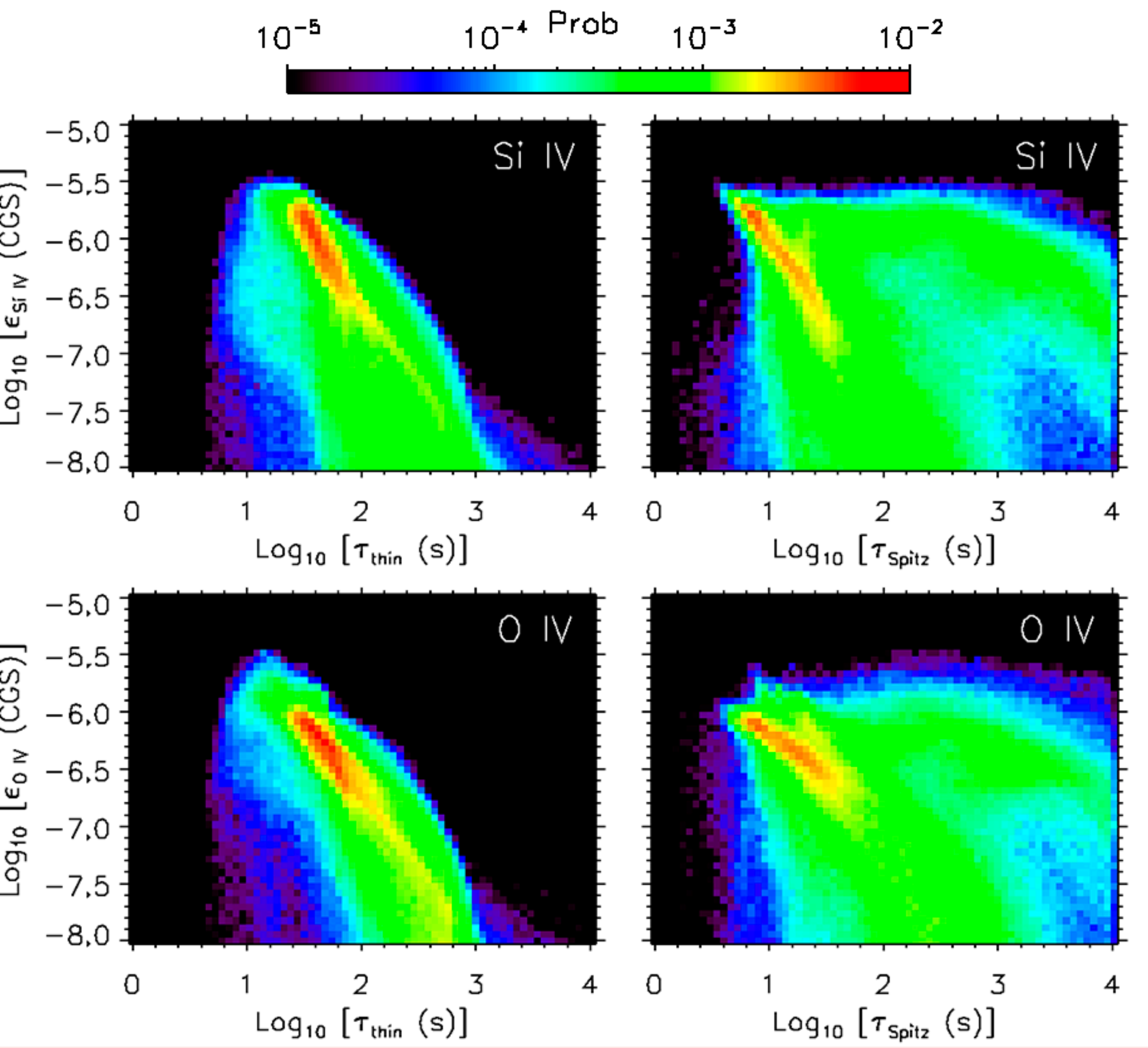


Two populations with different origin:
red = corona
yellow = dome

Nobrega-Siverio et al. 2018

NEQ in Surges and flux emergence

Lagrangian tracing

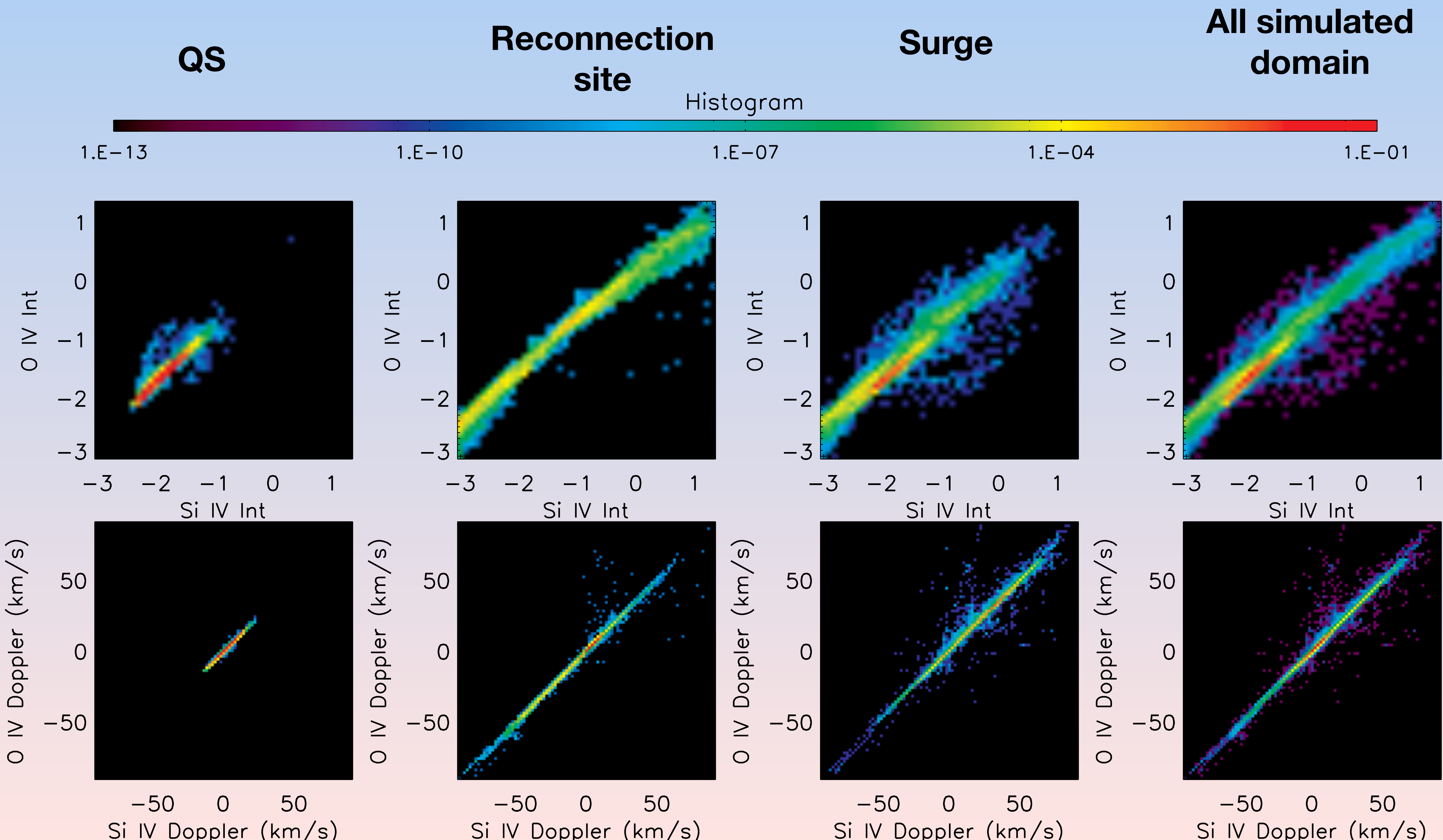


- Large values of emissivity corresponds to **short characteristic times**:
  - Optically thin losses (20 - 100 s)
  - Thermal conduction (4 – 40 s)

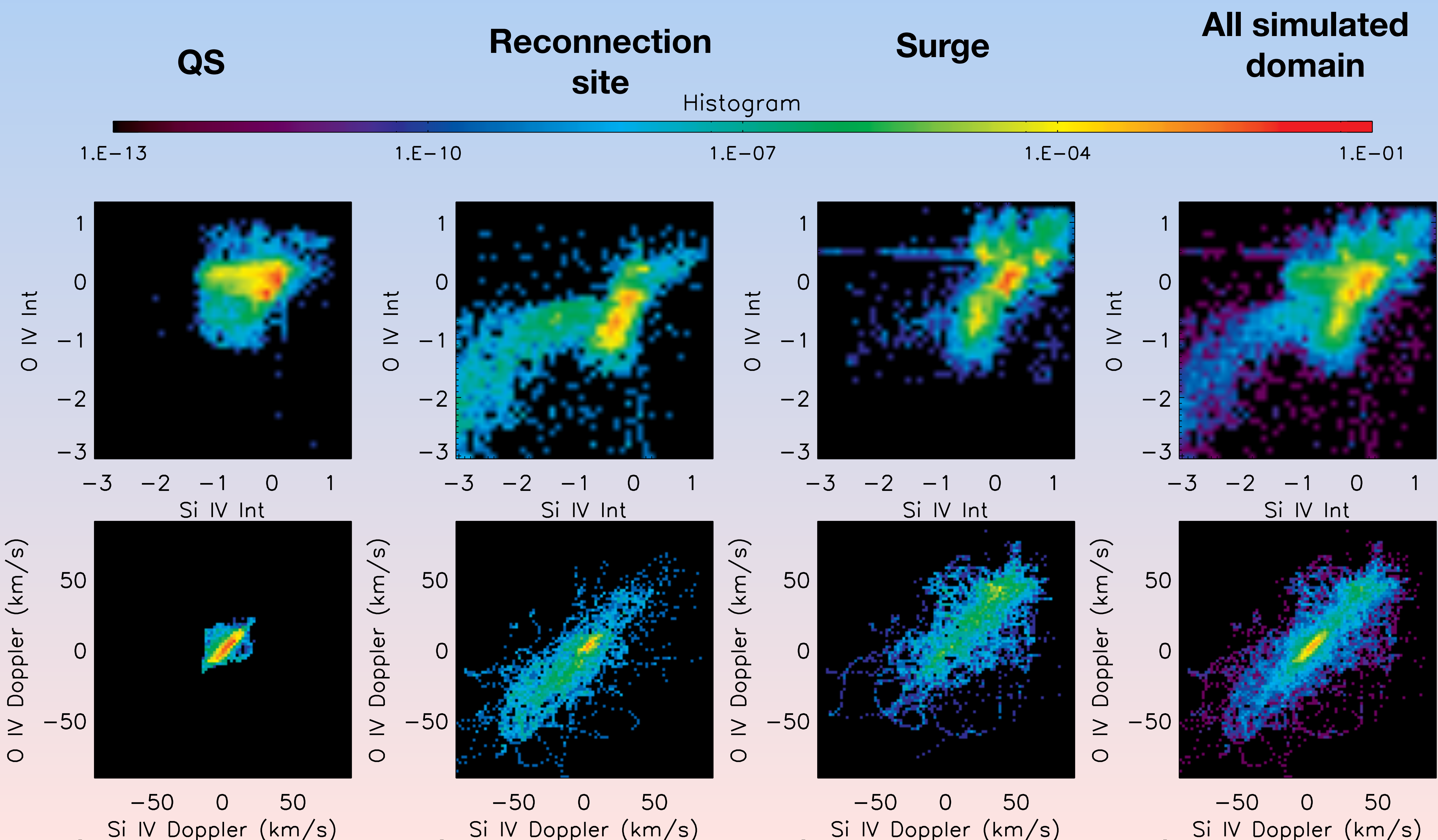
- Compatible with theoretical estimations (10-100 s) for NEQ ionization in the TR by Smith & Hughes (2010)

Nobrega-Siverio et al. 2018

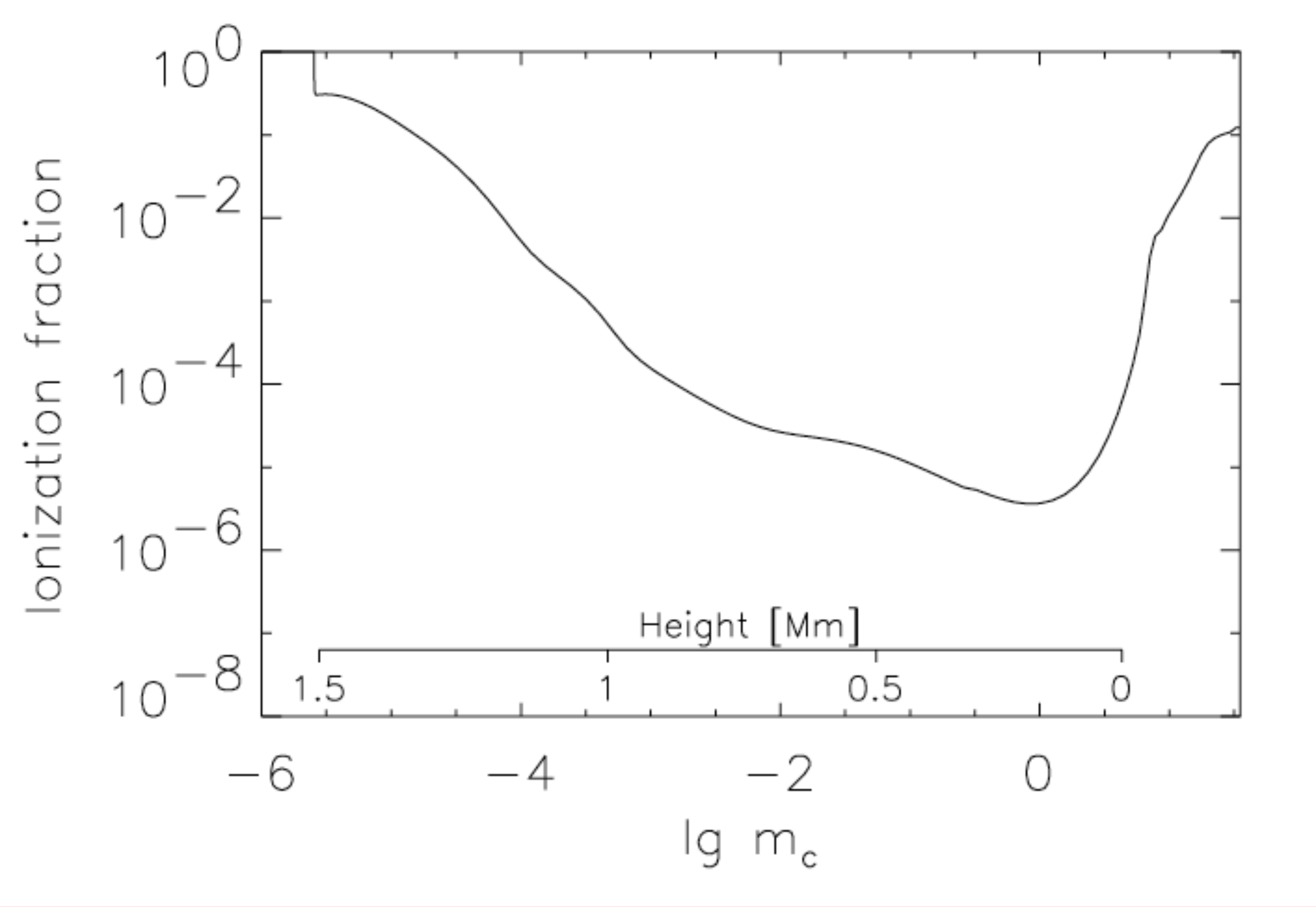
SE has highly strong correlations



If Si and/or O depart from SE very weak correlations

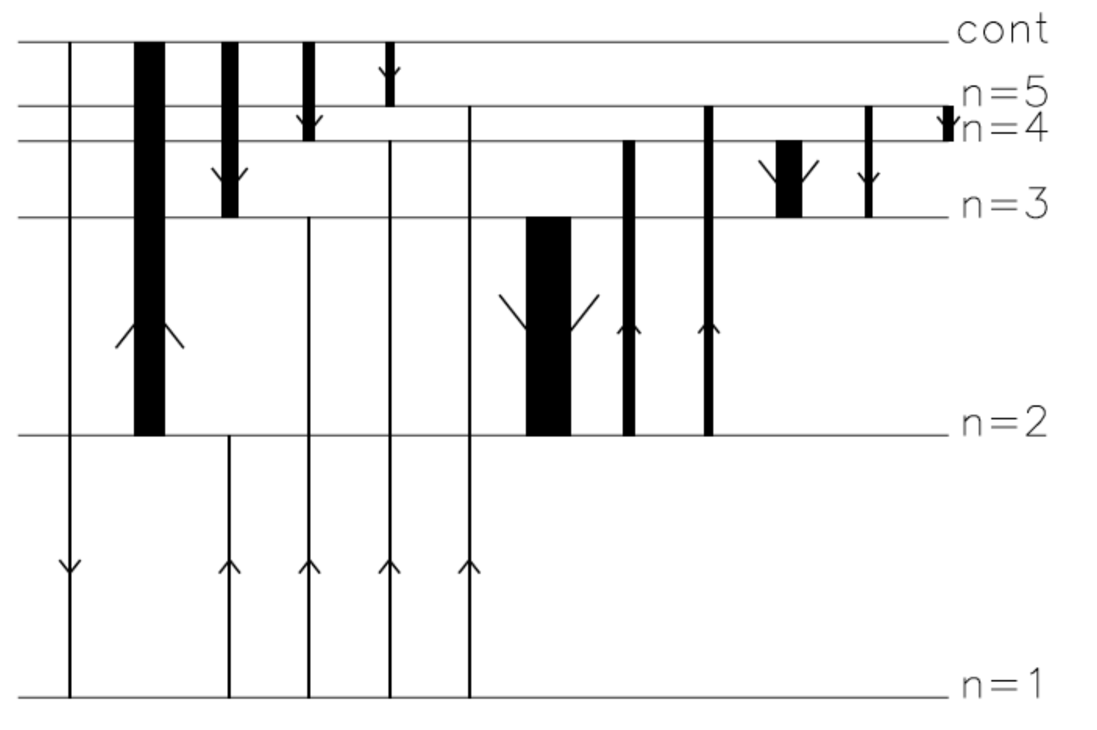


Hydrogen and Helium
Non-Equilibrium ionization
and ion-neutral interaction effects (ambipolar diffusion)

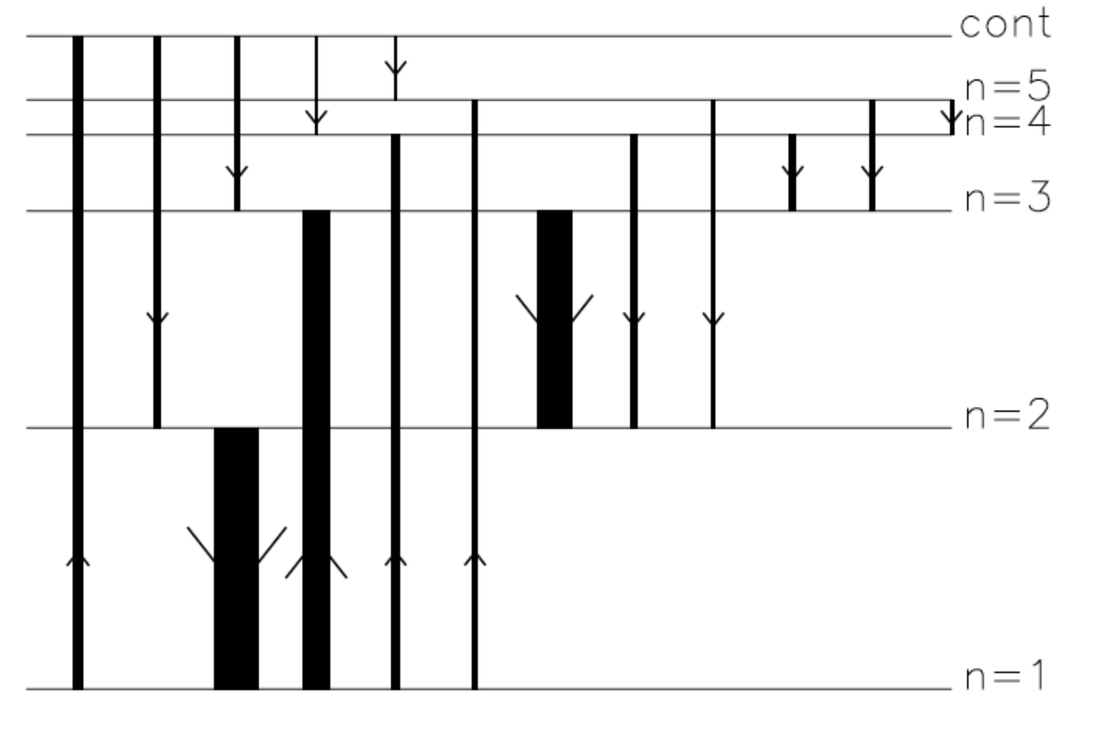


6 level Hydrogen

net rates in chromosphere



net rates in TR



Leenaarts et al. 2007 A&A 473, 625

3 level Helium

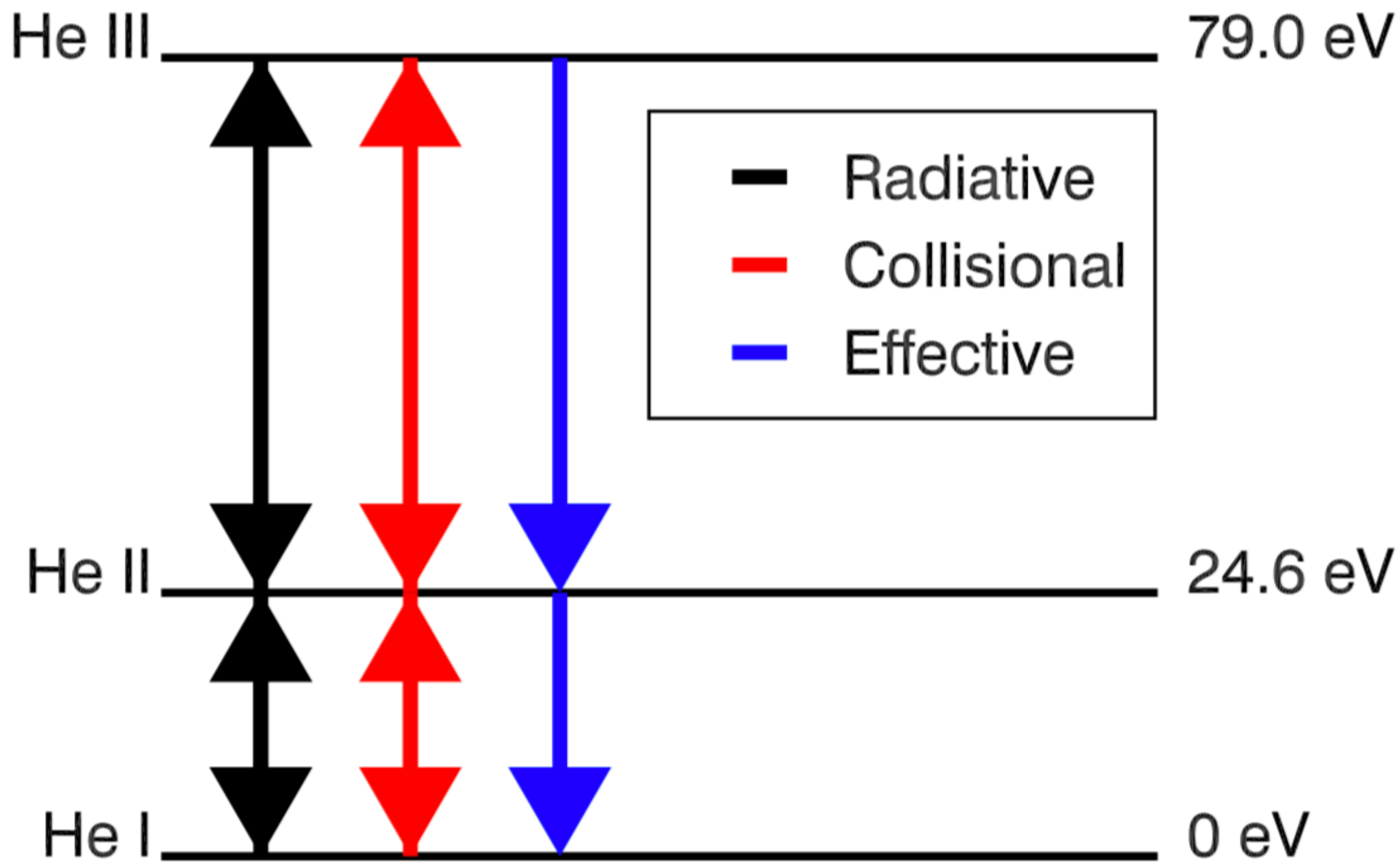


Figure 1. Simplified helium three-level model atom. It consists of the ground states of each ion stage. Transitions taken into account are photoionization, radiative recombination, collisional ionization by electrons, three-body recombination, and an effective recombination modeling recombination to excited states and the subsequent radiative cascade to the ground state.

Golding et al. 2016

Insertion in a 3d code

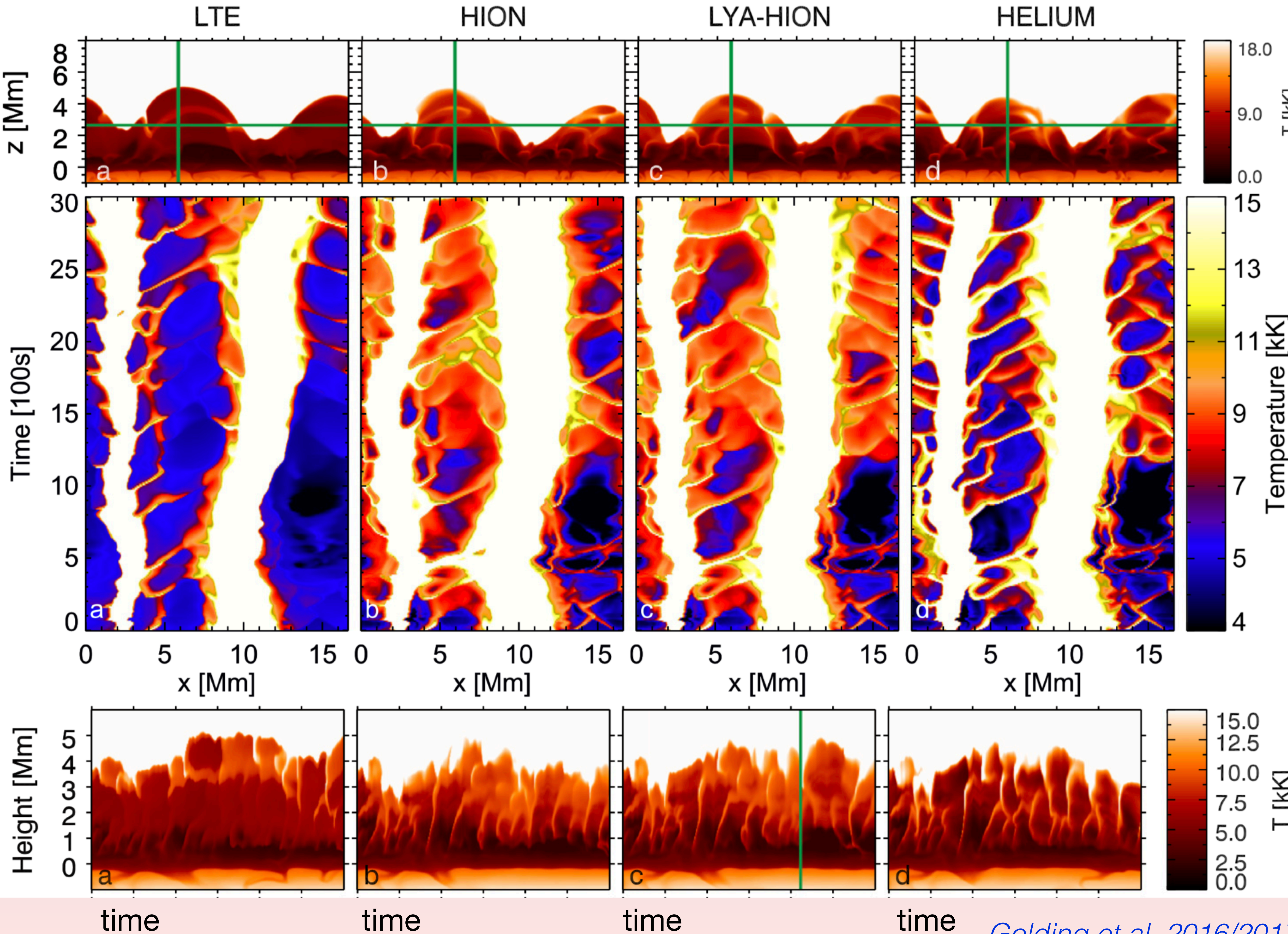
Solve the advective part of the equation along with the other MHD equations; use lower order discretization

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{u})$$

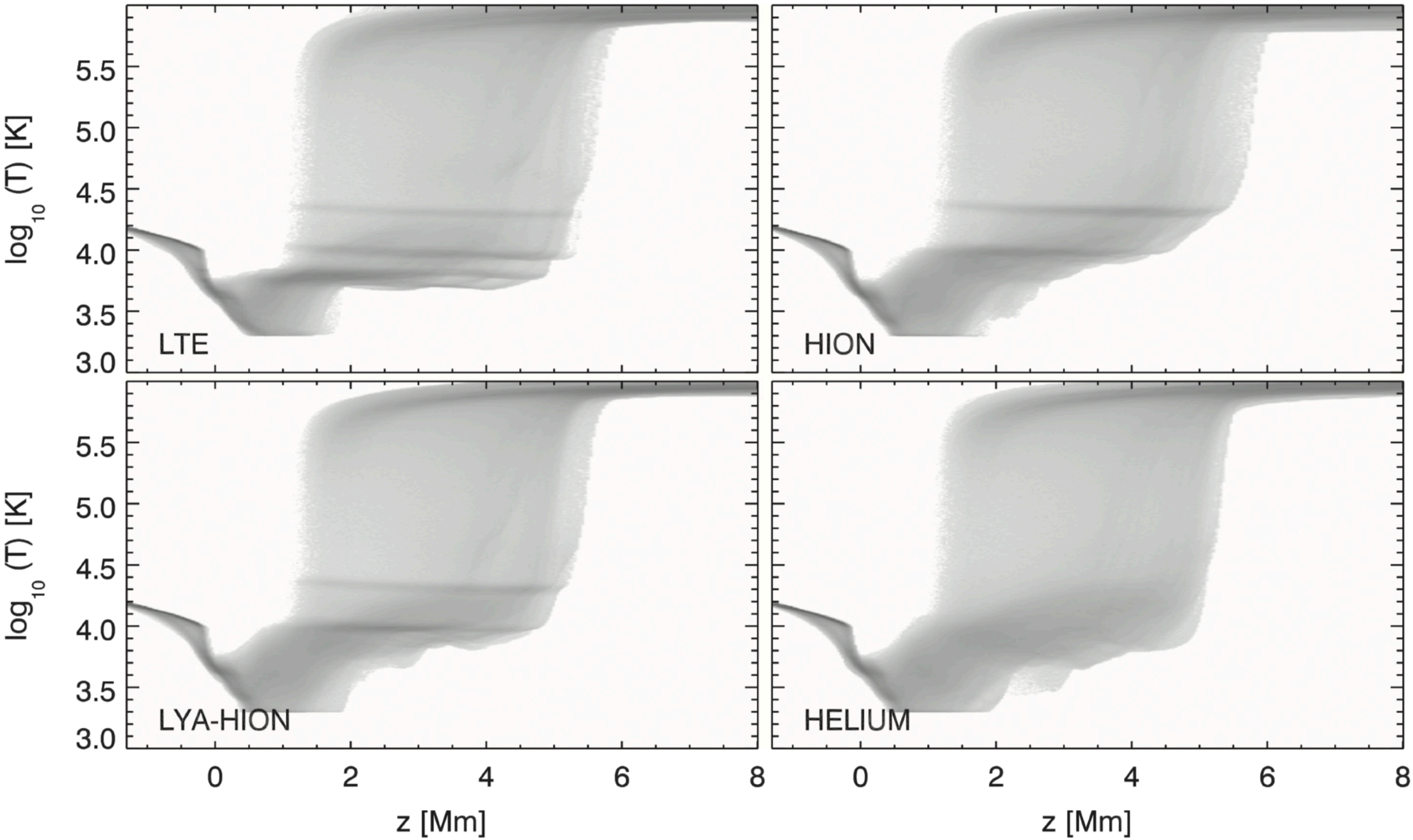
Then solve the rate matrix (along with charge and particle conservation) with Newton-Raphson

$$n_i^{new} - n_i^{old} = \Delta t(\sum_j n_j P_{ji} - n_i \sum_j P_{ij})$$

Leenaarts et al. 2006 & 2007



Golding et al. 2016/2017



Golding et al. 2016/2017

What is ambipolar Diffusion?

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\mathbf{u} \times \mathbf{B} - \eta_o \mathbf{J} - \frac{\eta_H}{|B|} \mathbf{J} \times \mathbf{B} + \frac{\eta_A}{|B^2|} (\mathbf{J} \times \mathbf{B} \times \mathbf{B} \right]$$

Neutrals do not experience the Lorentz force, then neutrals decouple from magnetic field lines and allow to diffuse magnetic field line through neutral gas.

Neutrals drift from ions with velocities of

$$\mathbf{u_A} = \eta_A \frac{\mathbf{J} \times \mathbf{B}}{|B|^2}$$

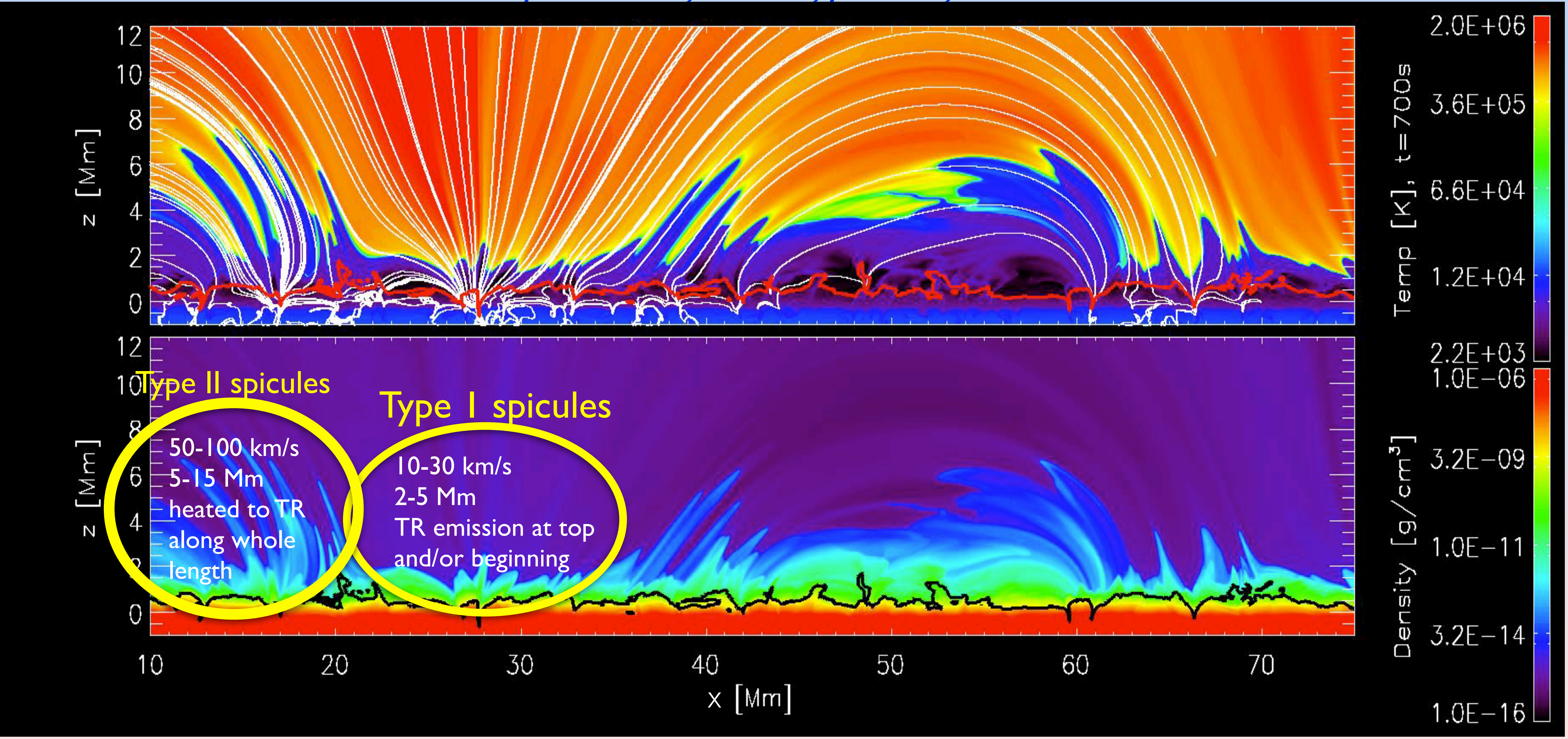
Ambipolar diffusion can not change the magnetic field topology, but it can accelerate reconnection processes. In addition, it dissipates magnetic energy into thermal energy.

Martinez-Sykora et al. 2012/2017

Ambipolar diffusion plays a big role on type II spicule formation and thermal properties of the chromosphere.

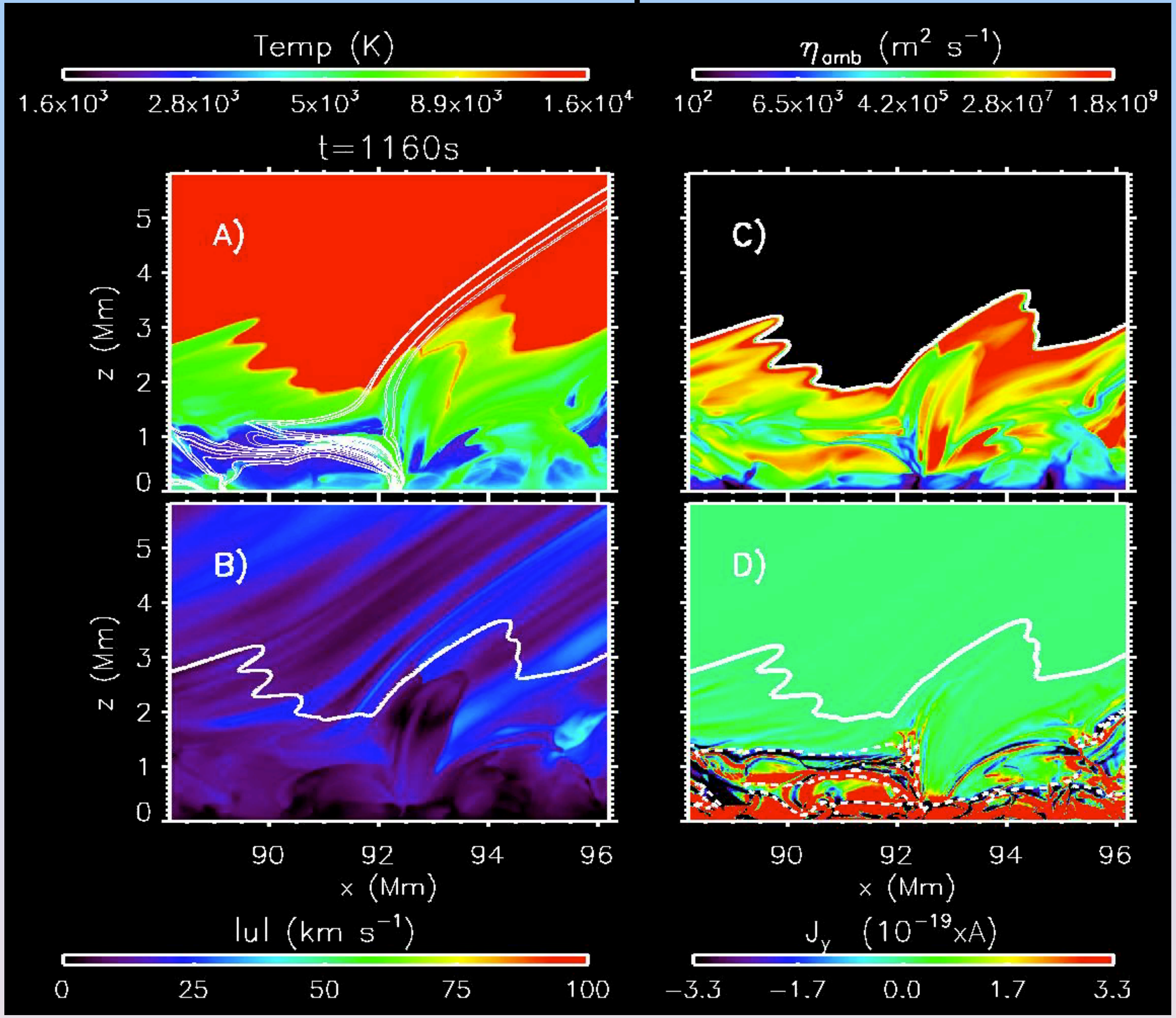
- 2.5D MHD, radiative losses with scattering, thermal conduction along the magnetic field lines **and Ion-Neutral Interaction Effects (INIE) produce self-consistently type II-like spicules**

Martinez-Sykora et al., Science, June 23, 2017



Martínez-Sykora et al ApJ. 2012/2017/2018

Strong flows driven by magnetic tension that diffuses into upper chromosphere because of ambipolar diffusion



1. created by interaction of weak and network/plage fields in photosphere
2. diffusion of weak fields/tension into chromosphere through ambipolar diffusion
3. ambipolar diffusion concentrates currents further amplifying tension
4. violent release of tension above β=1 layer

Martínez-Sykora et al Science. 2017 *see also Leake & Arber (2006/2017): flux emergence with ambipolar di*

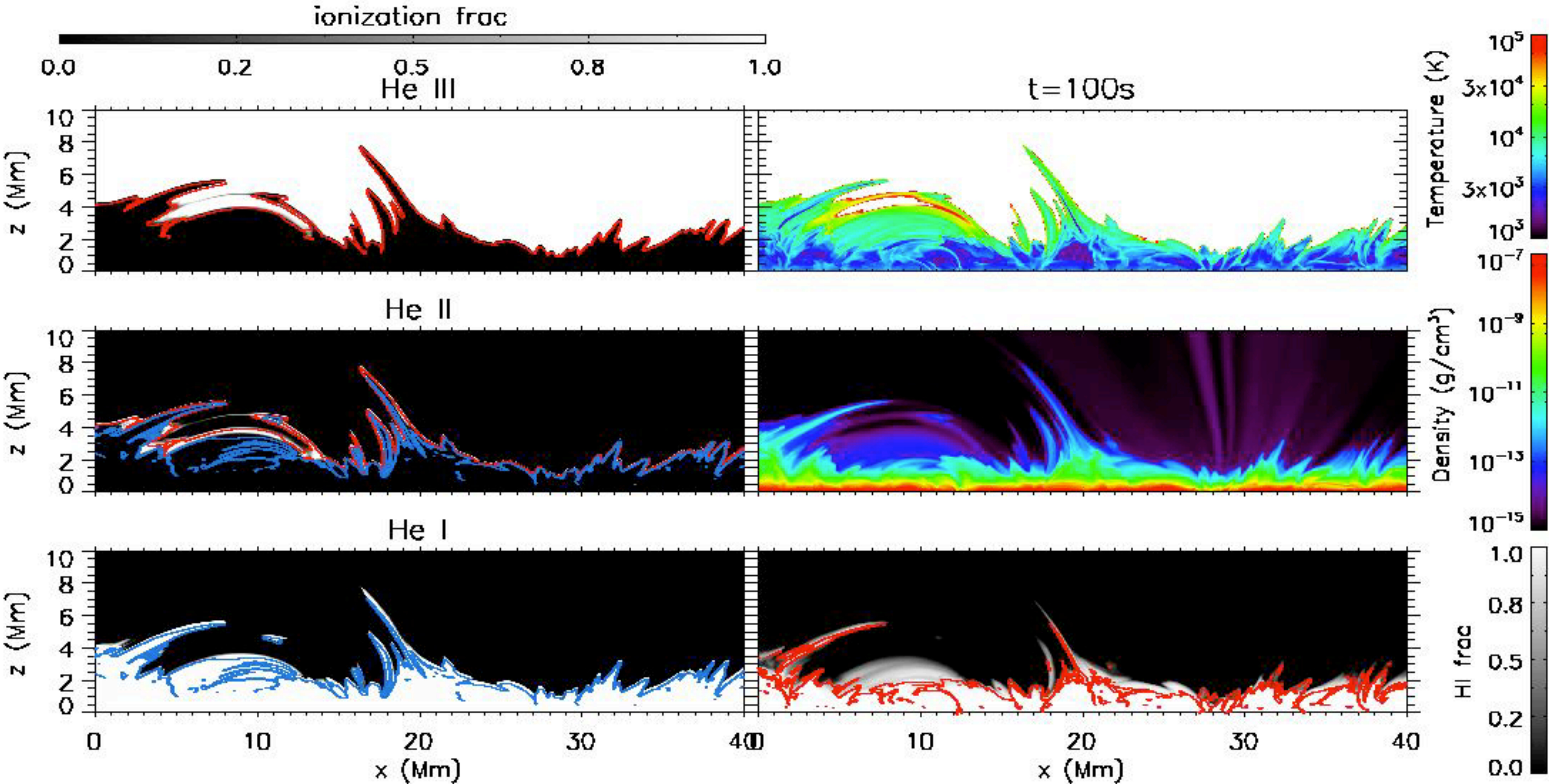
Importance on combining H and He NEQ ionization + Ambipolar diffusion

Strongly depends on the ionization fraction

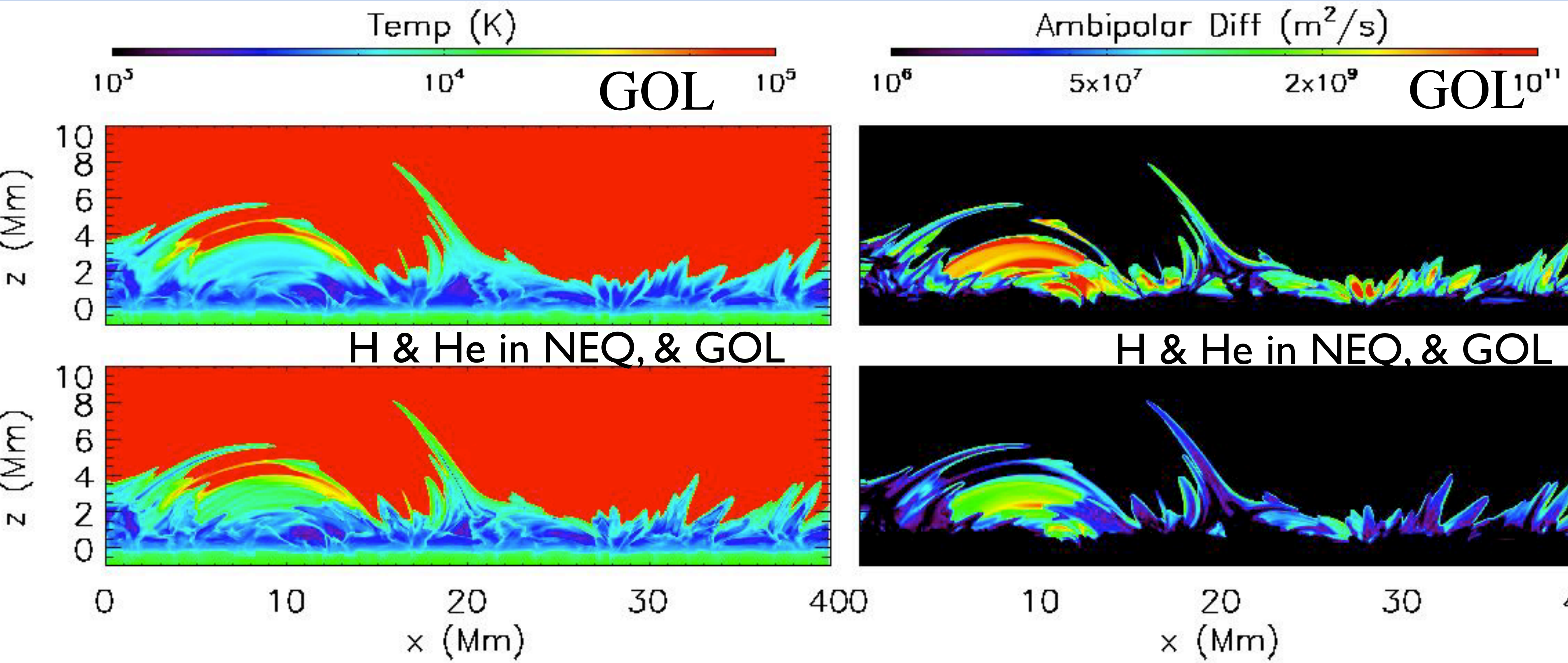
$$\eta_{amb} = \frac{(|B|\rho_n/\rho)^2}{\rho_i \nu_{in}}$$

So… Would we still have simulated spicules once we include H and He NEQ ionization? and/or is the chromosphere hot enough?

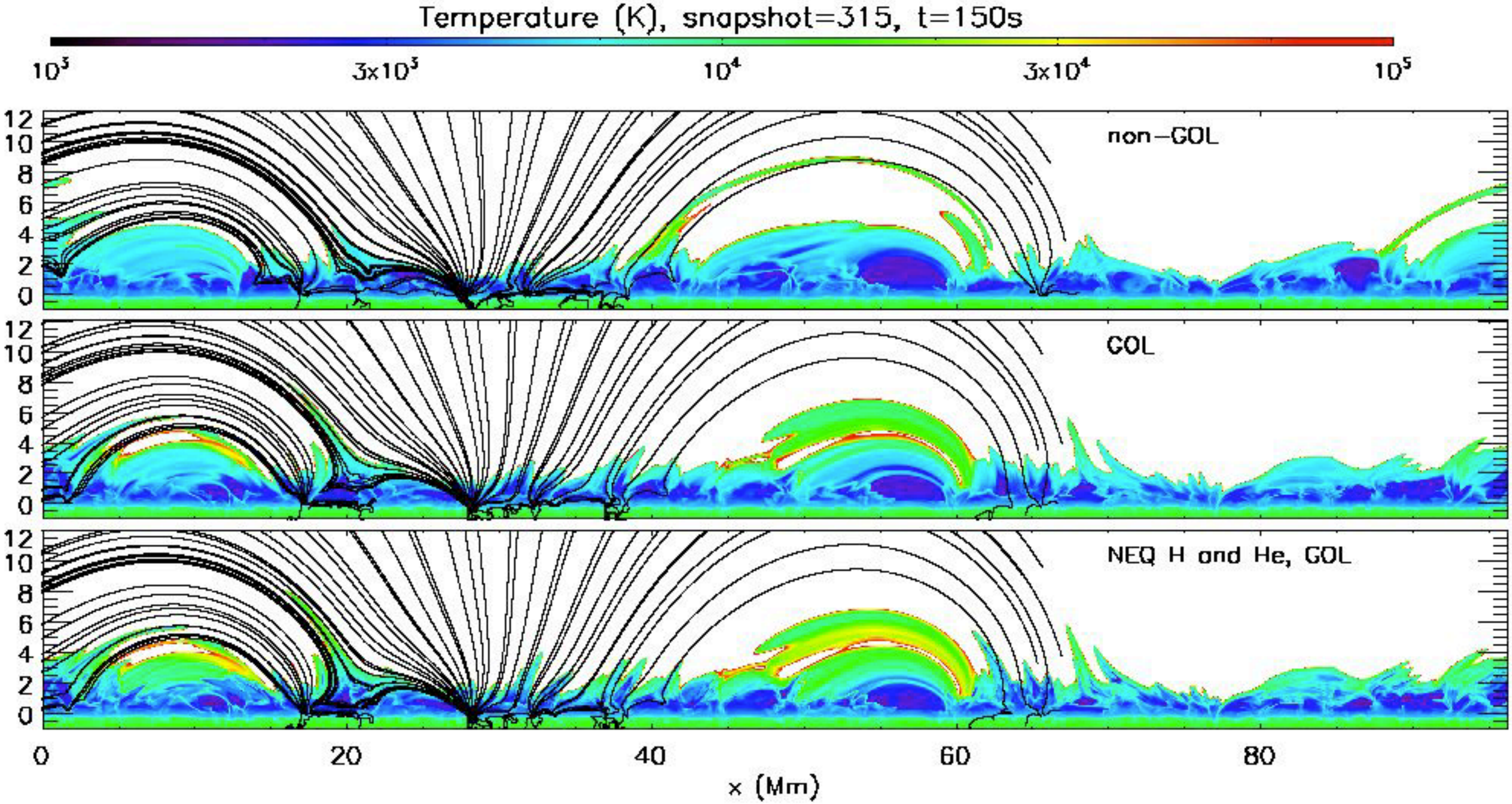
Importance on combining H and He NEQ ionization + Ambipolar diffusion



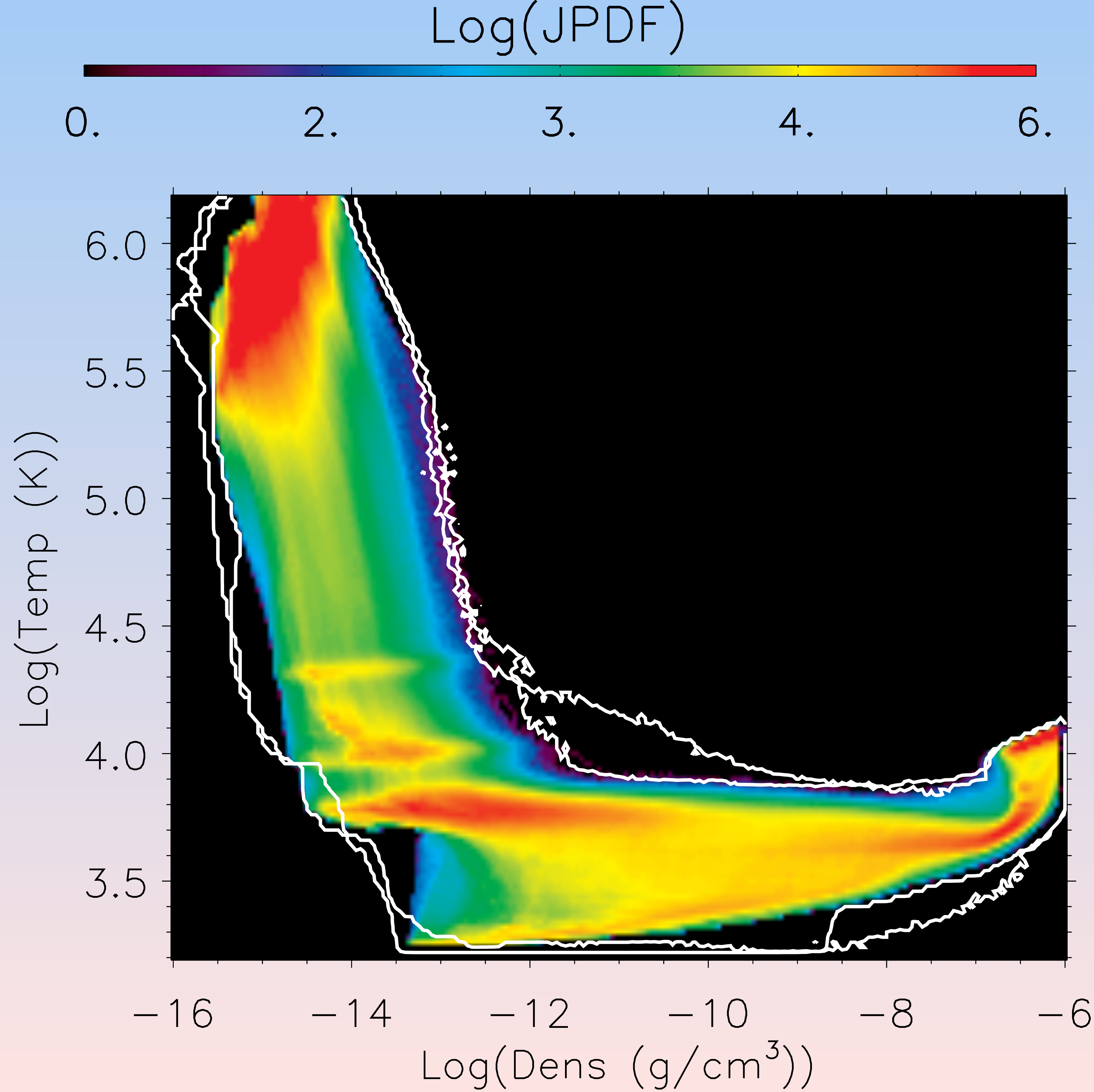
Importance on combining H and He NEQ ionization + Ambipolar diffusion



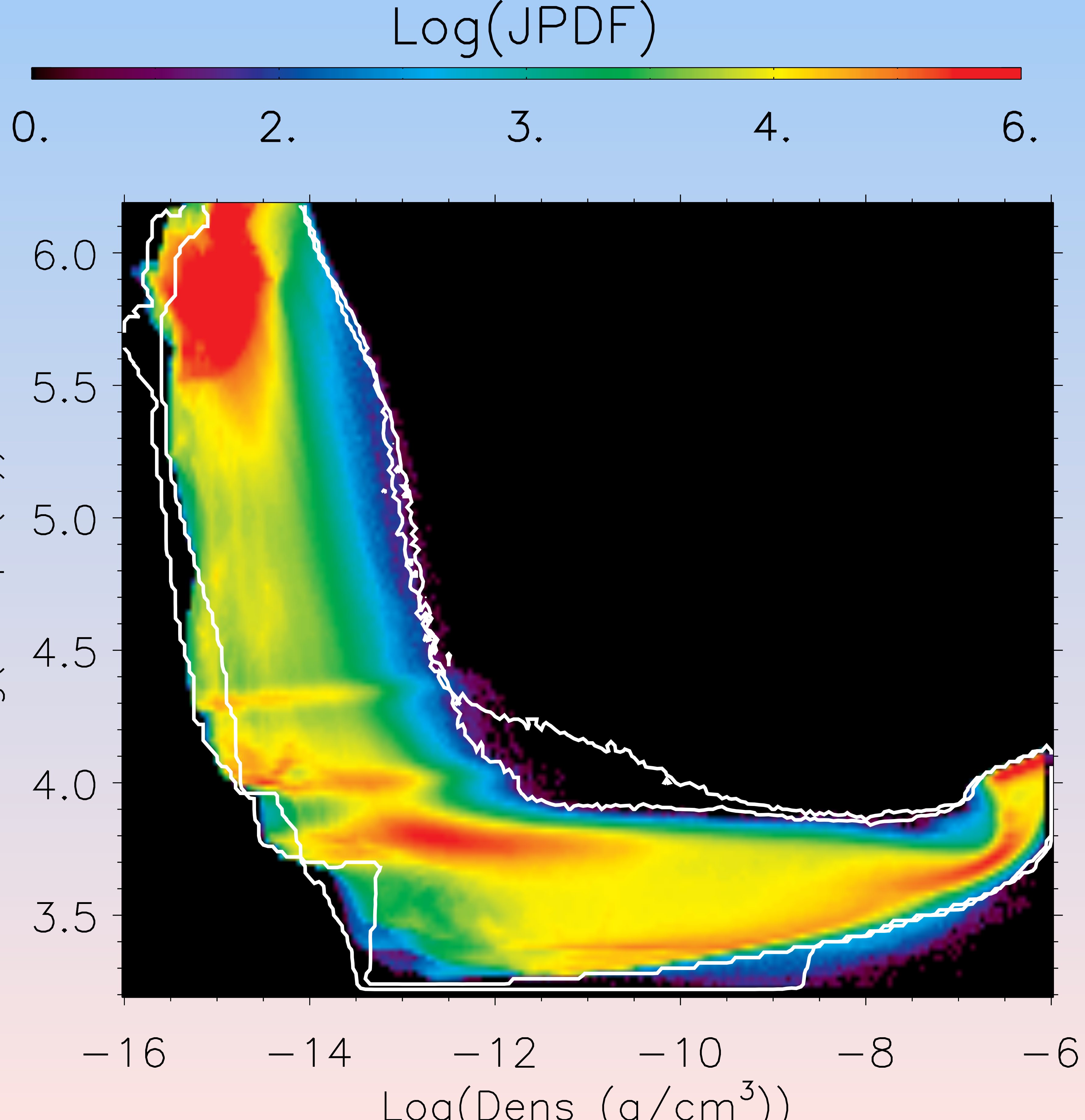
SE, only GOL, and H & He in NEQ & GOL have different chromospheric properties



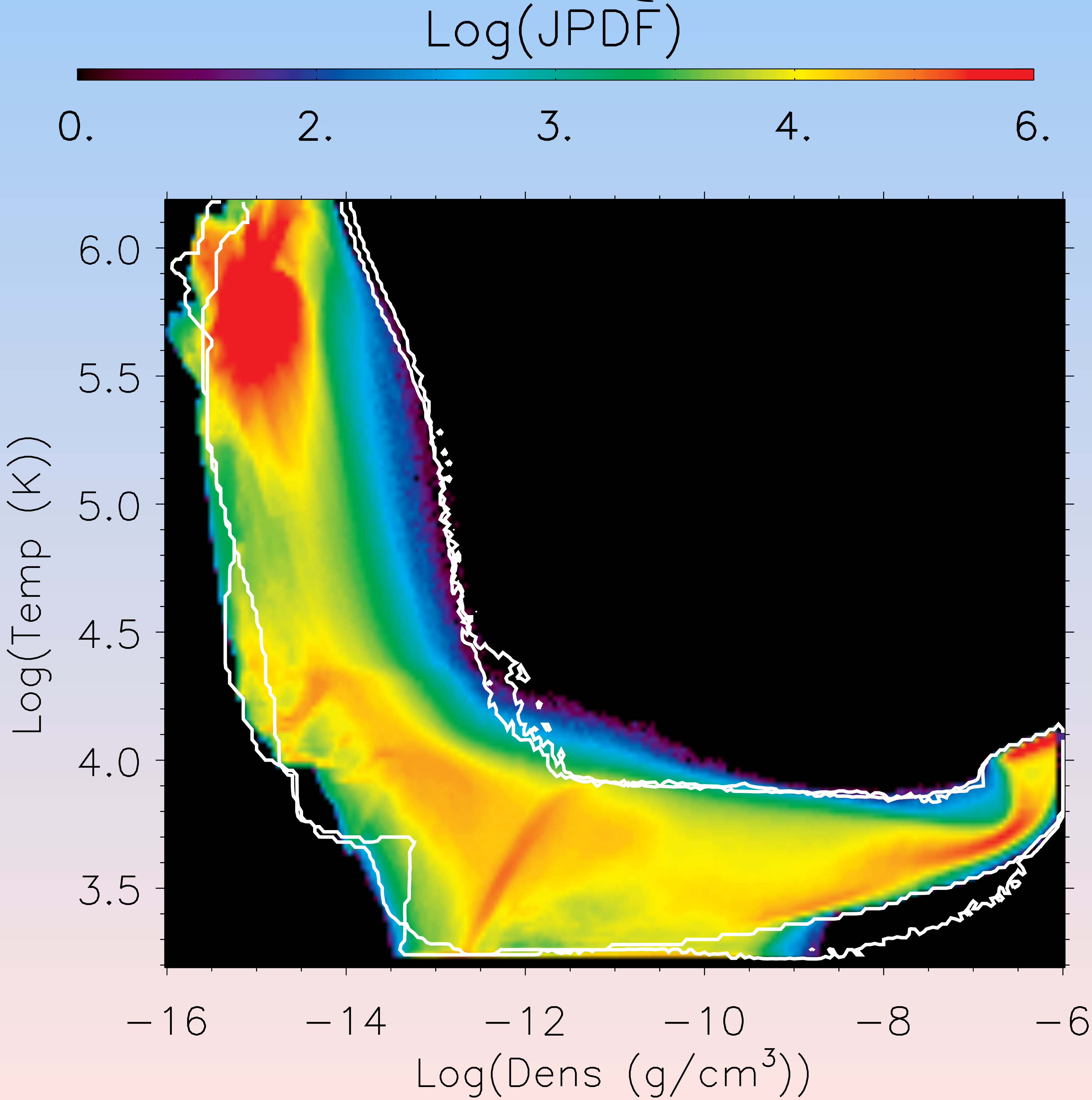
H and He in SE and Non-GOL



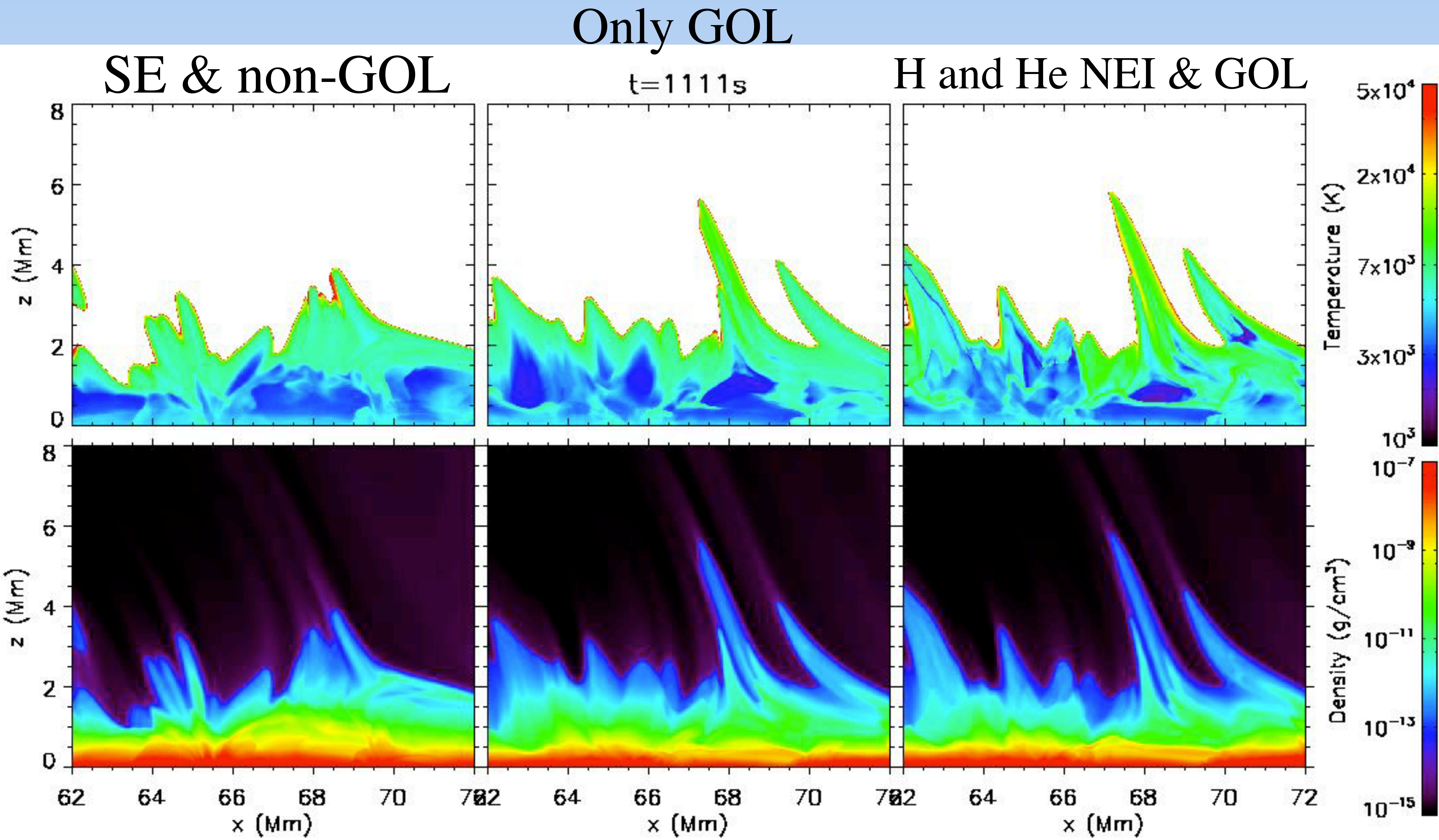
H and He in SE and GOL



H and He in NEQI and GOL



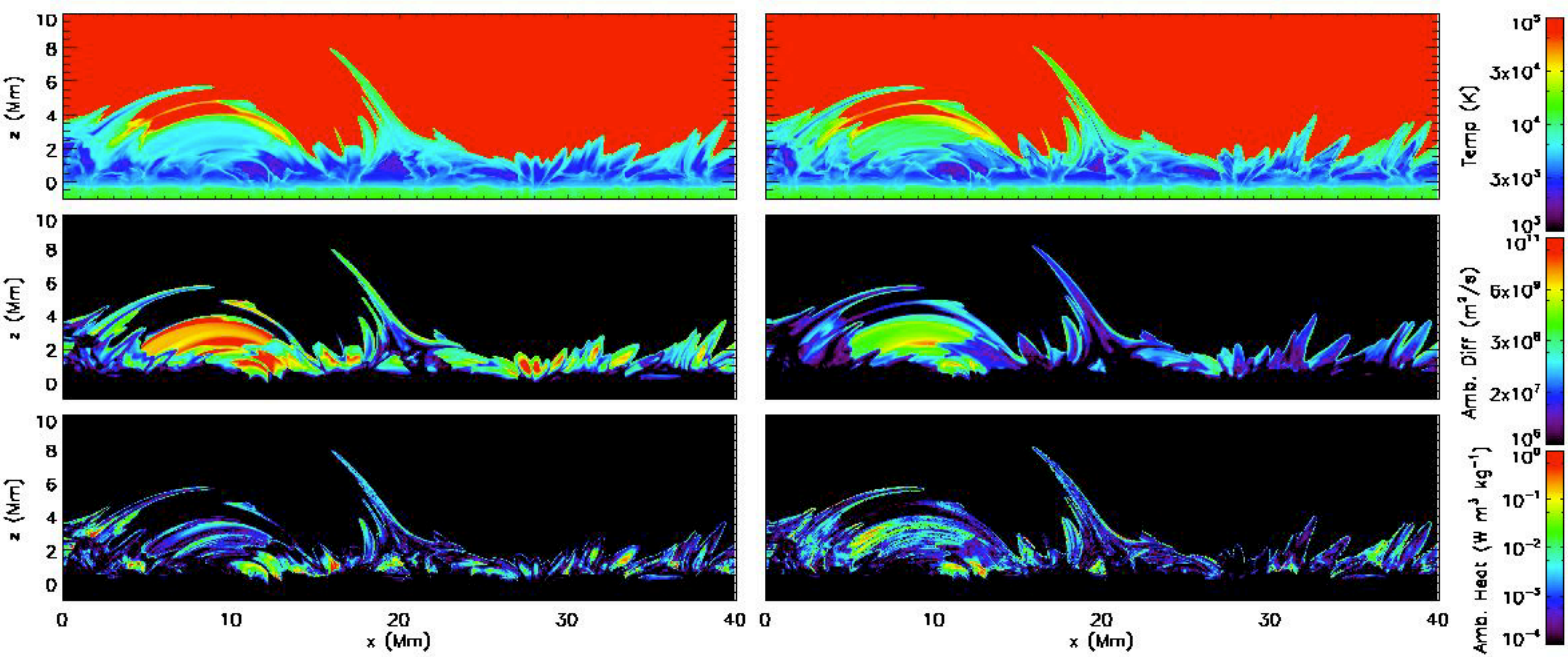
NEQ in H & He and GOL have greater temperature variation within structure.



NEQ in H & He impact largely the ambipolar diffusion and heating in the lower chromosphere and low temperatures.

Only GOL

H & He in NEQ, & GOL



Summary

- Si IV and O IV usually are out of equilibrium
- Doppler shift and non-thermal width are highly correlated between for Si IV and O IV in SE.
- O IV and Si IV in flux emergence and surges are drastically out of equilibrium due to radiative losses and thermal conduction.
- In simulations thermal chromospheric properties are largely affected when H and He are calculated in NEQ including ambipolar diffusion.
- Still we have spicules but temperatures can be rather low chromosphere.