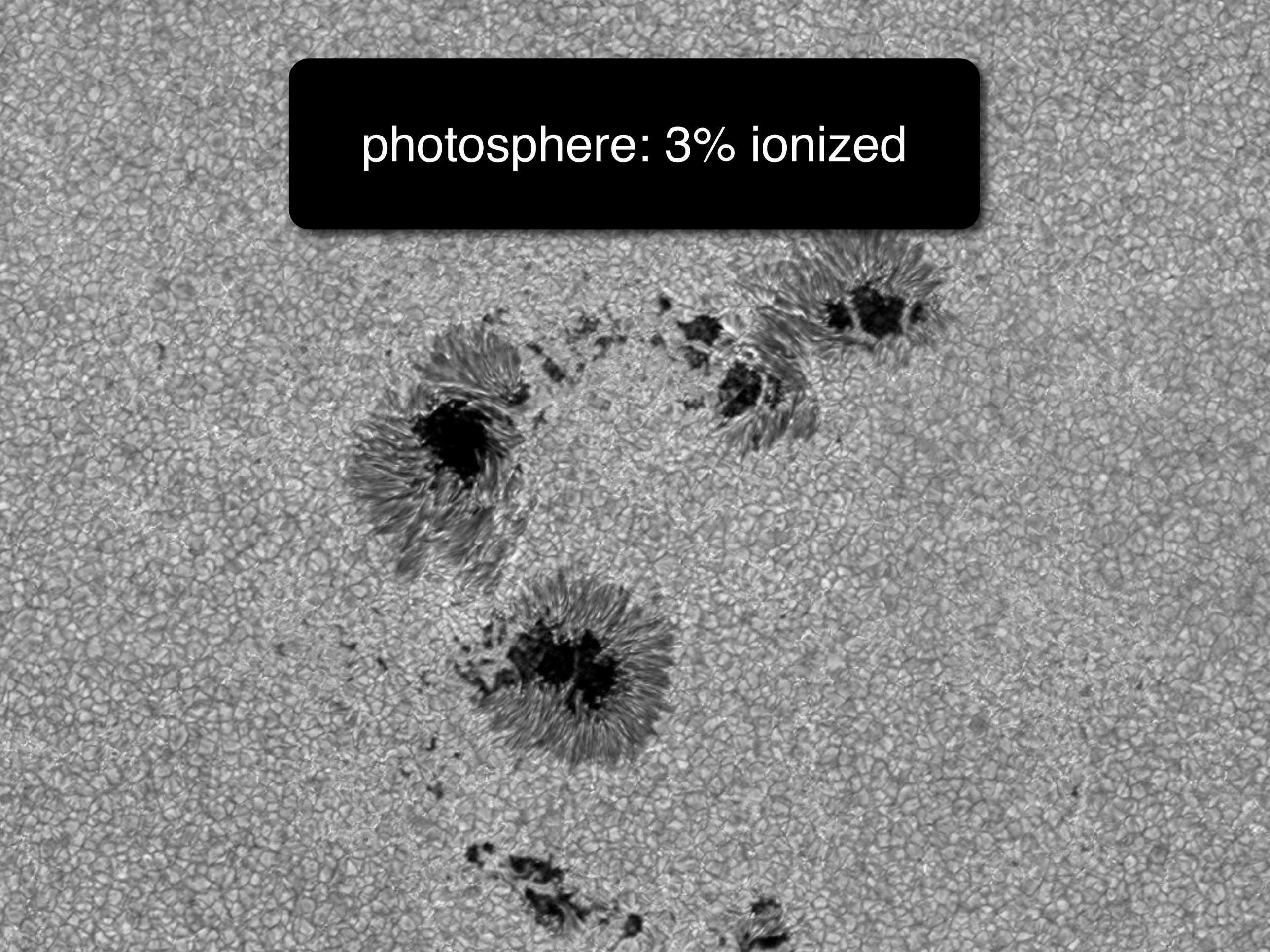
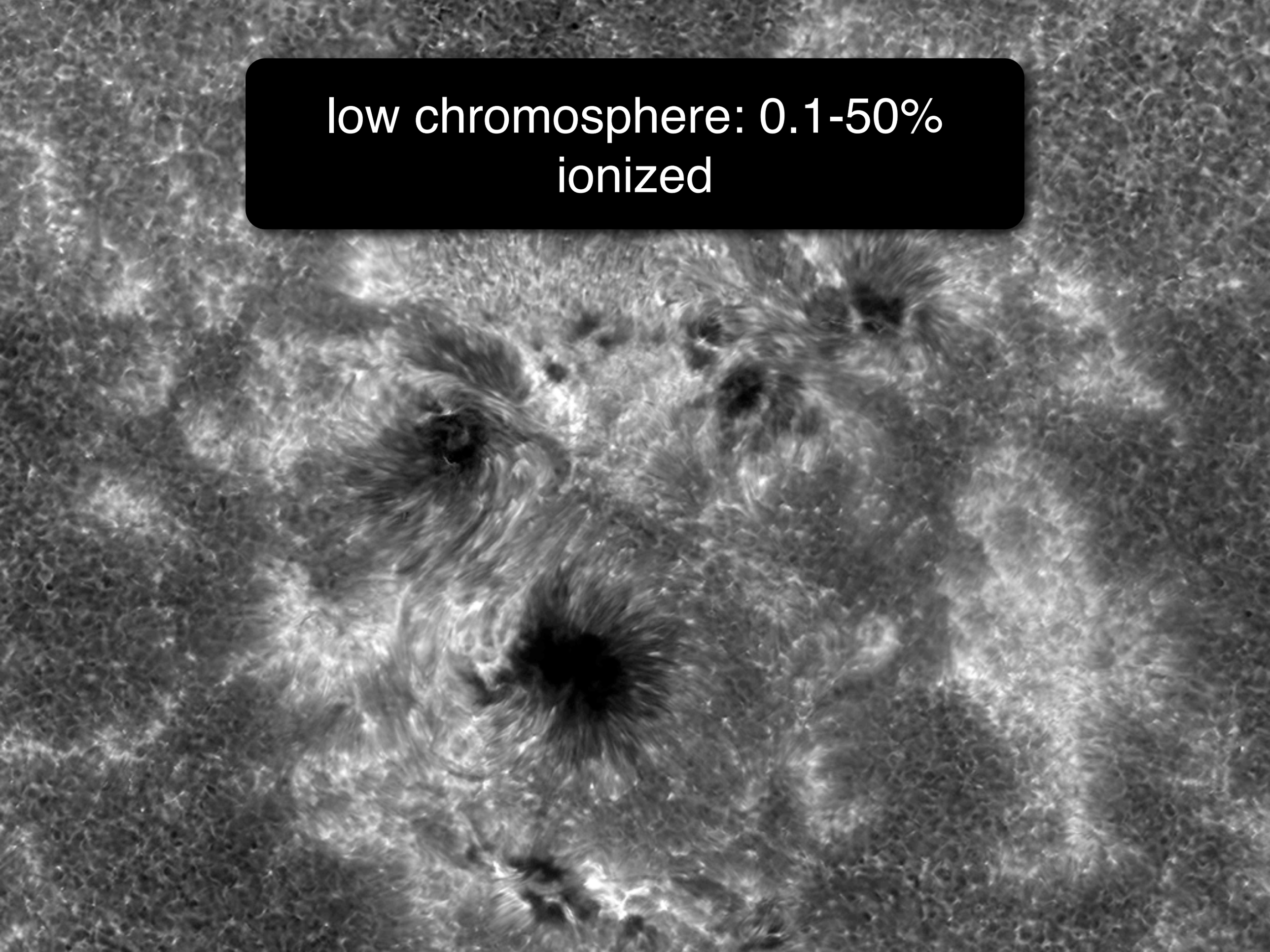
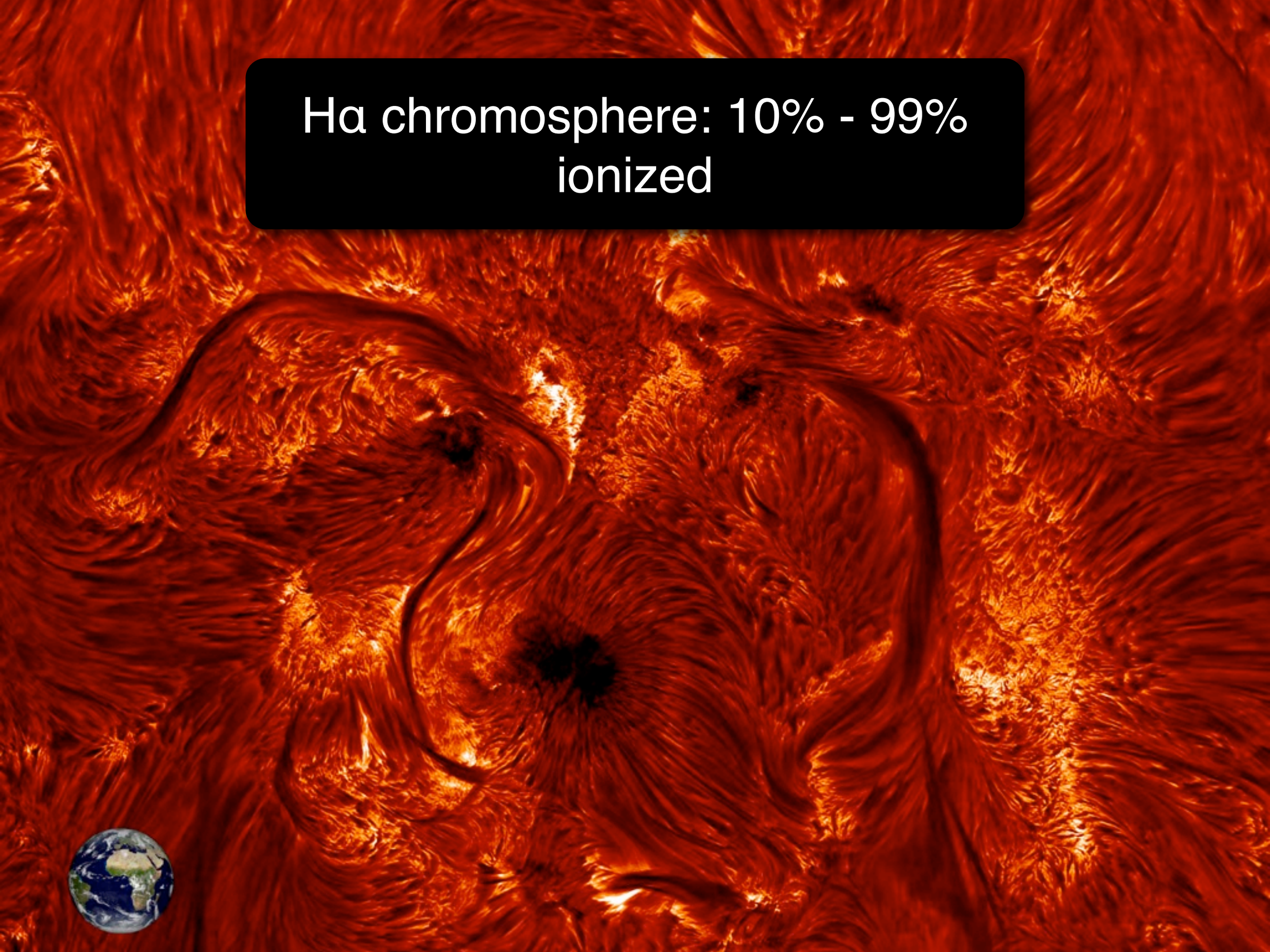
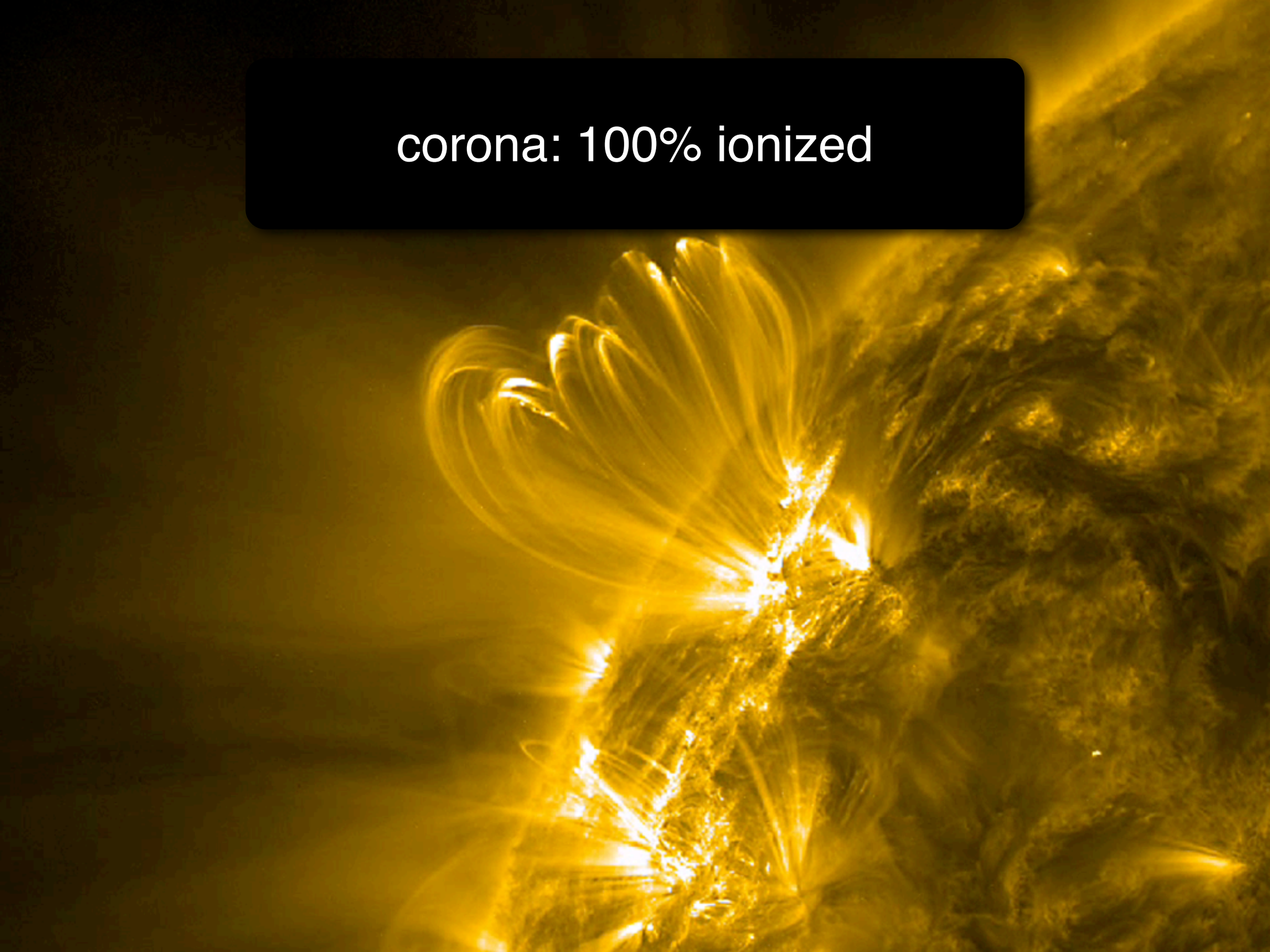
Hydrogen ionization in the solar atmosphere

Jorrit Leenaarts


photosphere: 3% ionized


low chromosphere: 0.1-50%
ionized


Hα chromosphere: 10% - 99% ionized


corona: 100% ionized

Ionization is a substantial buffer of energy

Ionization strongly affects thermal evolution

H: 90% of nuclei

He:10% of nuclei

- $E(H \rightarrow H_2) / E_{th} = 22$ @ 2 kK
- $E(H\ I \rightarrow H\ II) / E_{th} = 17$ @ 8 kK
- $E(He\ I \rightarrow He\ II) / E_{th} = 3$ @ 10 kK
- $E(He\ II \rightarrow He\ III) / E_{th} = 2$ @ 30 kK

Ionization is slow in the chromosphere

rate equations:

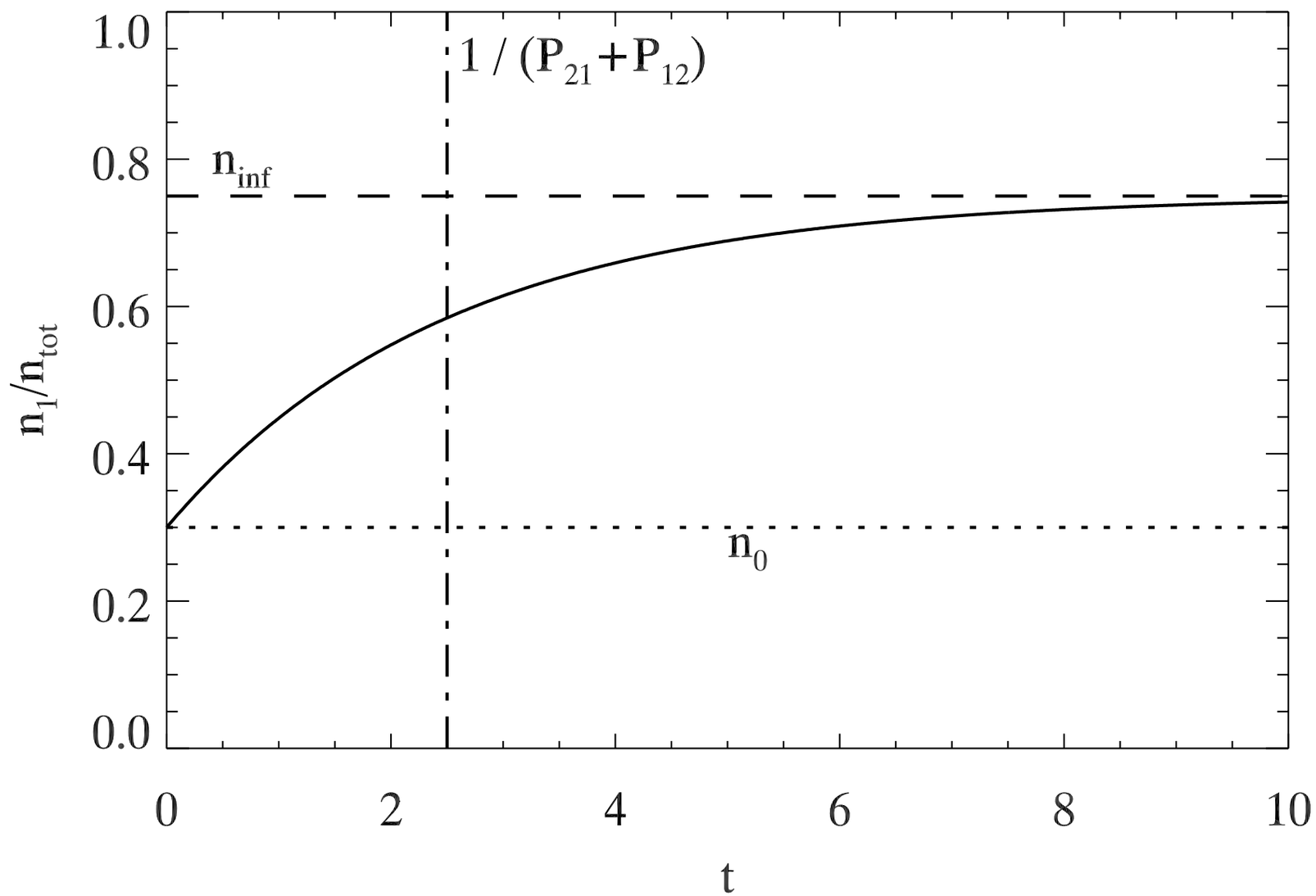
$$\begin{aligned}
\frac{\mathrm{D}n_1}{\mathrm{D}t} &= n_2 P_{21} - n_1 P_{12} \\
\frac{\mathrm{D}n_2}{\mathrm{D}t} &= n_1 P_{12} - n_2 P_{21} \\
n_{\mathrm{H}} &= n_1 + n_2
\end{aligned}$$

solution:

$$\begin{aligned}
n_1(t) &= n_1(\infty) + [n_1(0) - n_1(\infty)]\mathrm{e}^{-t(P_{12}+P_{21})} \\
n_1(\infty) &= \frac{n_{\mathrm{H}} P_{21}}{P_{12} + P_{21}}
\end{aligned}$$

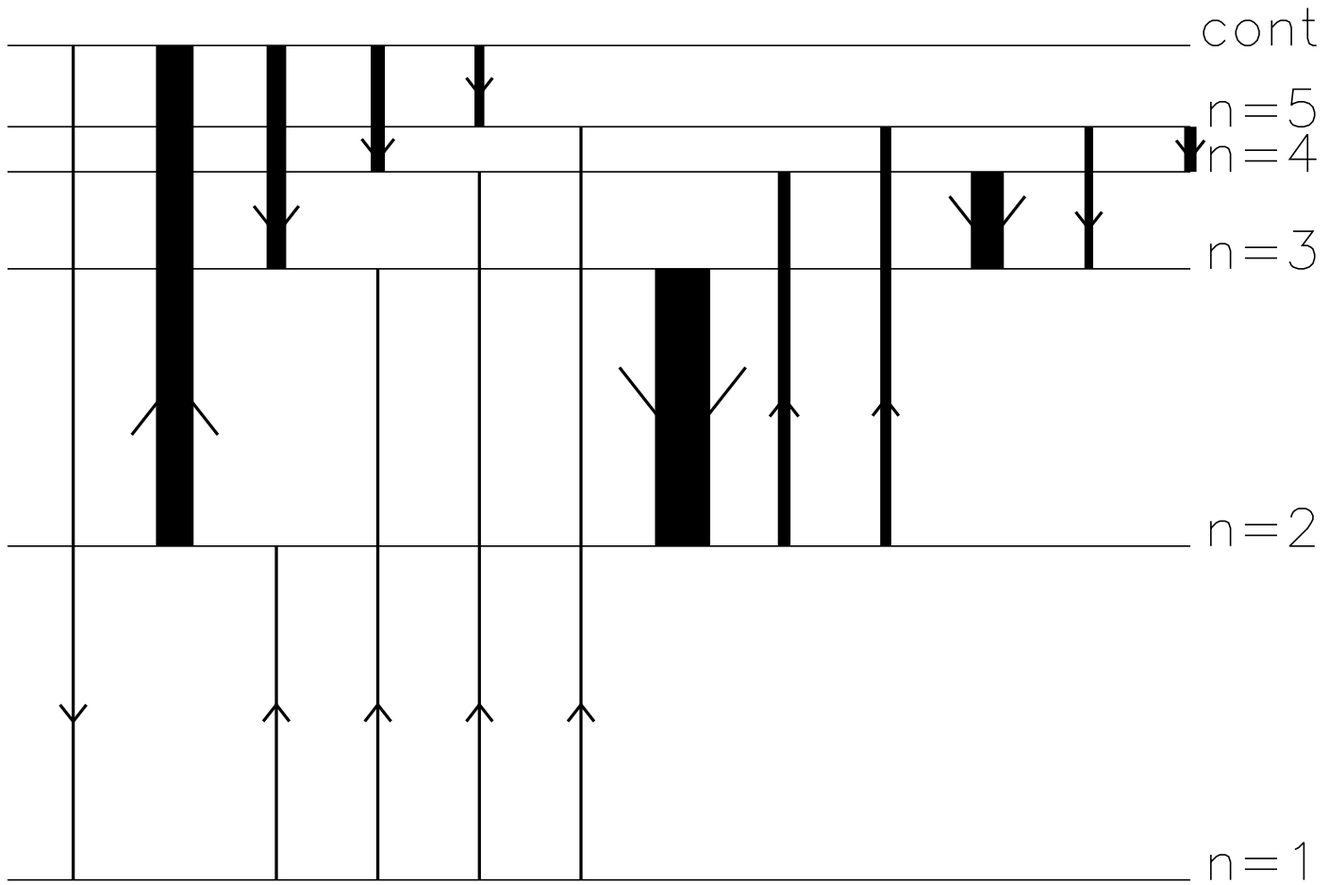
Ionization is slow in the chromosphere

$$n_1(t) \quad = \quad n_1(\infty) + [n_1(0) - n_1(\infty)]\mathrm{e}^{-t(P_{12}+P_{21})}$$



How does hydrogen ionize?

see Carlsson & Stein, 2002, ApJ, 572, 625



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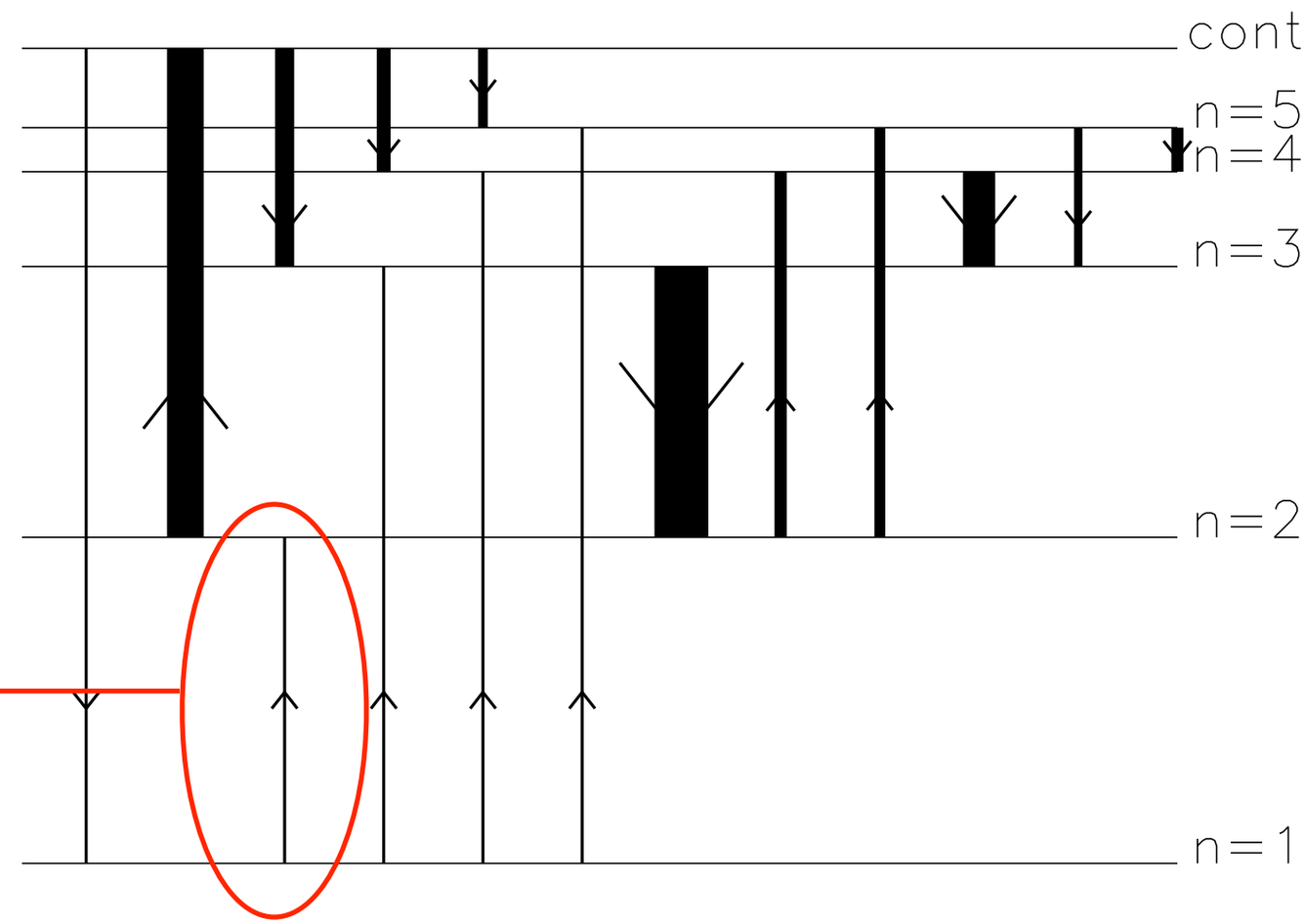

slow leakage between n=1and n=2 because of 10.2 eV jump

How does hydrogen ionize?

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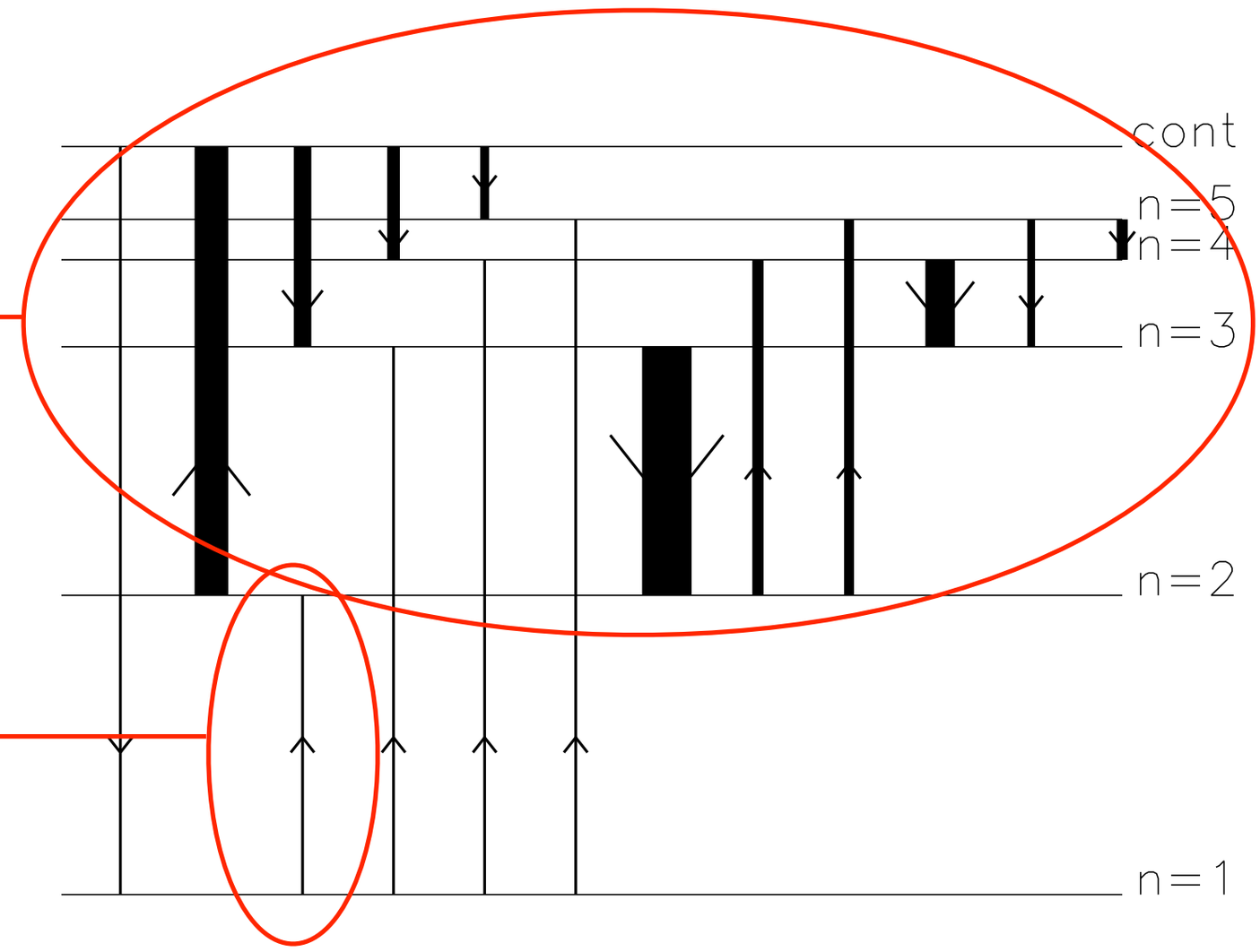
fast equilibration of excited states and continuum

slow leakage between n=1and n=2 because of 10.2 eV jump



Bifrost

see Gudiksen et al.,2011, A&A,531,154

3D MHD code,
MPI parallelized

photospheric radiation

thermal conduction

non-equilibrium ionization

etc...

How to deal with H ionization

- 9 extra variables + 8 MHD variables = 17 variables
- 7 hydrogen populations are advected

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \boldsymbol{u}) = \sum_{j, j \neq i}^{n_1} n_j P_{ji} - n_i \sum_{j, j \neq i}^{n_1} P_{ij}$$

$$\frac{\partial n_{\mathrm{H2}}}{\partial t} + \nabla \cdot (n_{\mathrm{H2}} \boldsymbol{u}) = R_{\mathrm{f}} n_1^3 - R_{\mathrm{b}} n_1 n_{\mathrm{H2}}$$

- n_{e} and T_{g} are not advected
- close system with energy, particle and charge conservation

How to deal with H ionization

energy conservation:

$$F_2 = 1 - \frac{1}{e_{\mathrm{i}}}\left(\frac{3kT}{2}\left[n_{\mathrm{e}} + n_{\mathrm{noH}} + n_{\mathrm{H2}} + \sum_{i=1}^{6} n_i\right]\right.$$
$$\left. + n_{\mathrm{H}}^{\mathrm{tot}}\, e_{\mathrm{noH}} + n_{\mathrm{H2}}\, e_{\mathrm{H2}} + \sum_{i=1}^{6} n_i \chi_i\right) = 0,$$

How to deal with H ionization

charge conservation:

$$F_1 = 1 - \frac{1}{n_\mathrm{e}}\left(n_6 + n_\mathrm{H}^\mathrm{tot} n_\mathrm{e}^\mathrm{noH}\right) = 0.$$

pressure follows:

$$P = kT\left(n_\mathrm{e} + n_\mathrm{H2} + \sum_{i=1}^{n_\mathrm{l}} n_i + n_\mathrm{o}\right),$$

H ionization acts as an equation-of-state.

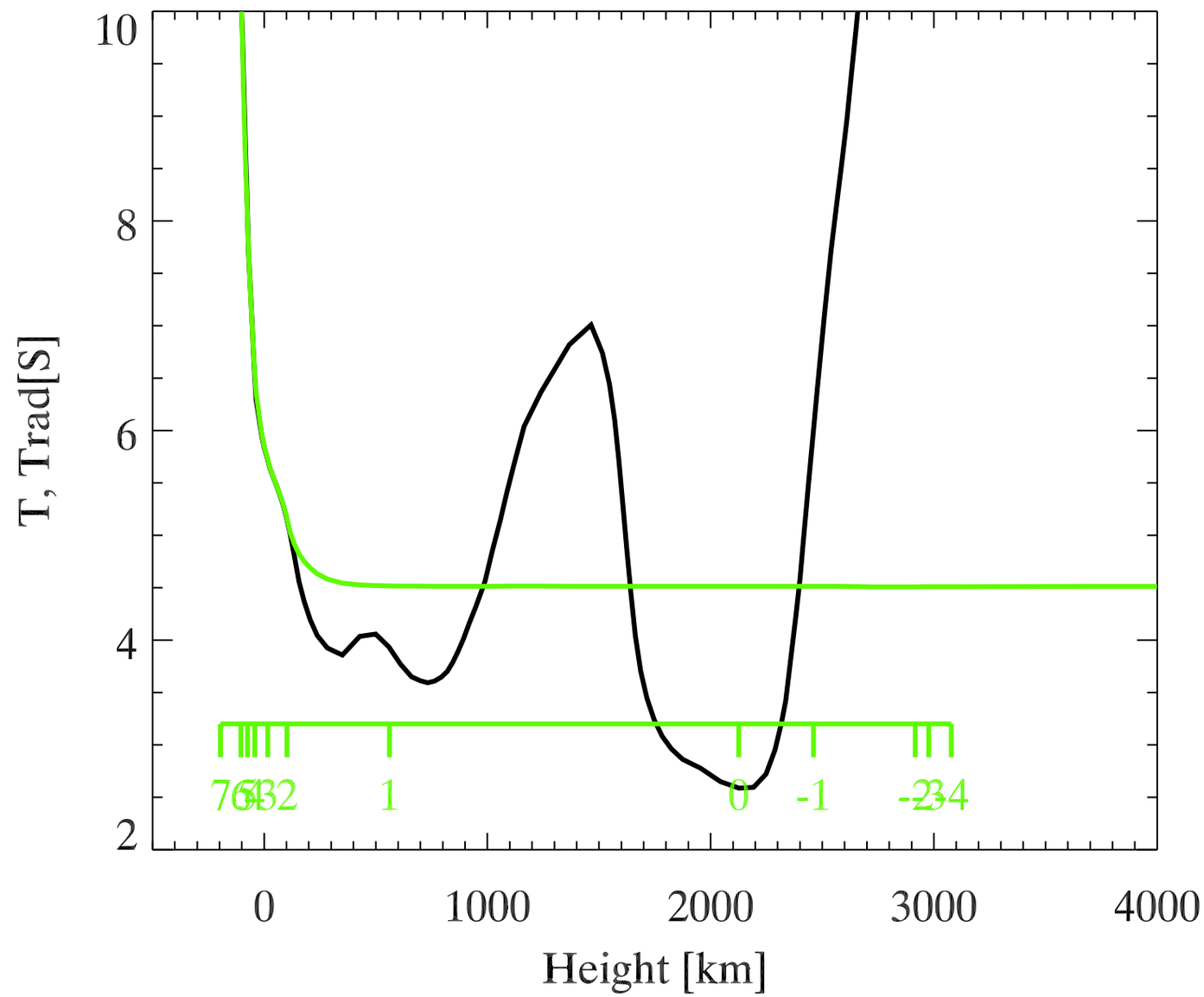
Radiation field

- detailed evaluation of radiation field J_ν computationally expensive
- but needed for rate equations:

  $$P_{ij} = C_{ij}(n_\mathrm{e}, T_\mathrm{e}) + R_{ij}(J_\nu, n_\mathrm{e})$$

- Sollum (1999): fixed radiative rates can be used as confirmed in detailed 1D simulations

Radiation field



- specify T_{rad} in each transition
- rate coefficients are local

$$P_{ij} = C_{ij}(T_{\mathrm{e}}, n_{\mathrm{e}}) + R_{ij}(T_{\mathrm{rad}}, n_{\mathrm{e}})$$

Lyα is special

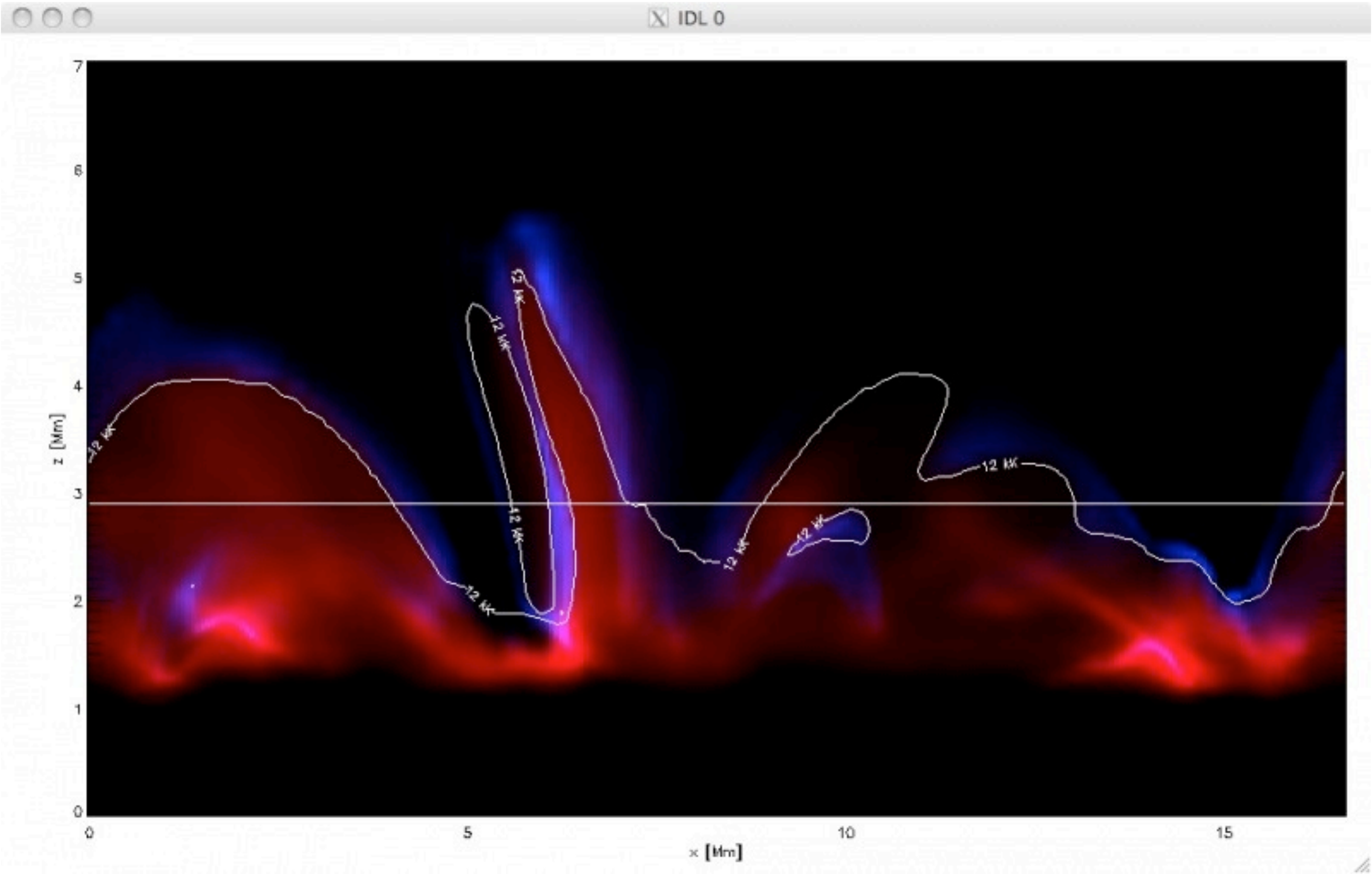
see Carlsson & Leenaarts, 2012, A&A

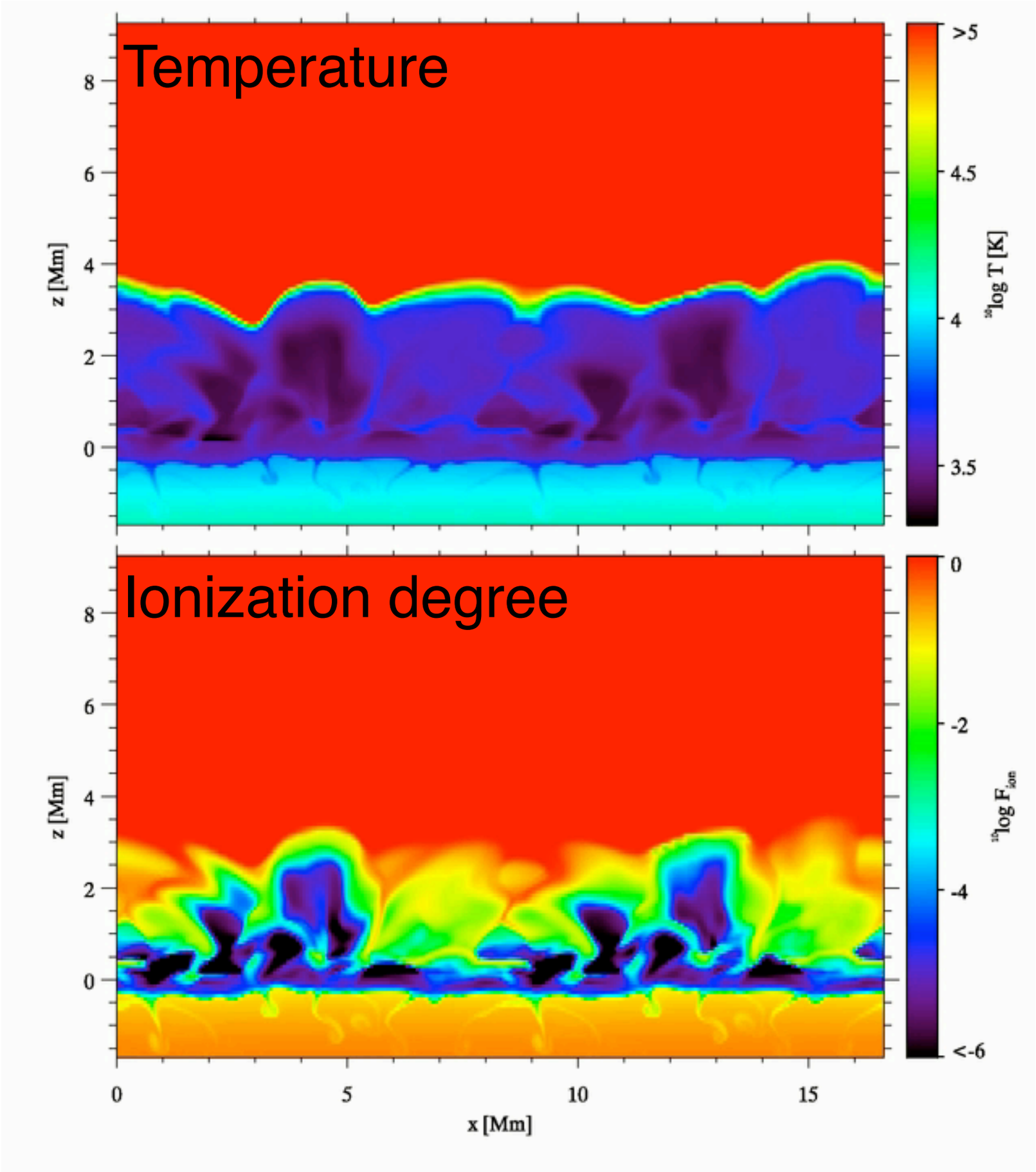
- Use detailed computations to compute the Lyα downward rate:

$$R_{21} = L(T)\, E(\tau)\, n_{\mathrm{e}}\, n_1$$

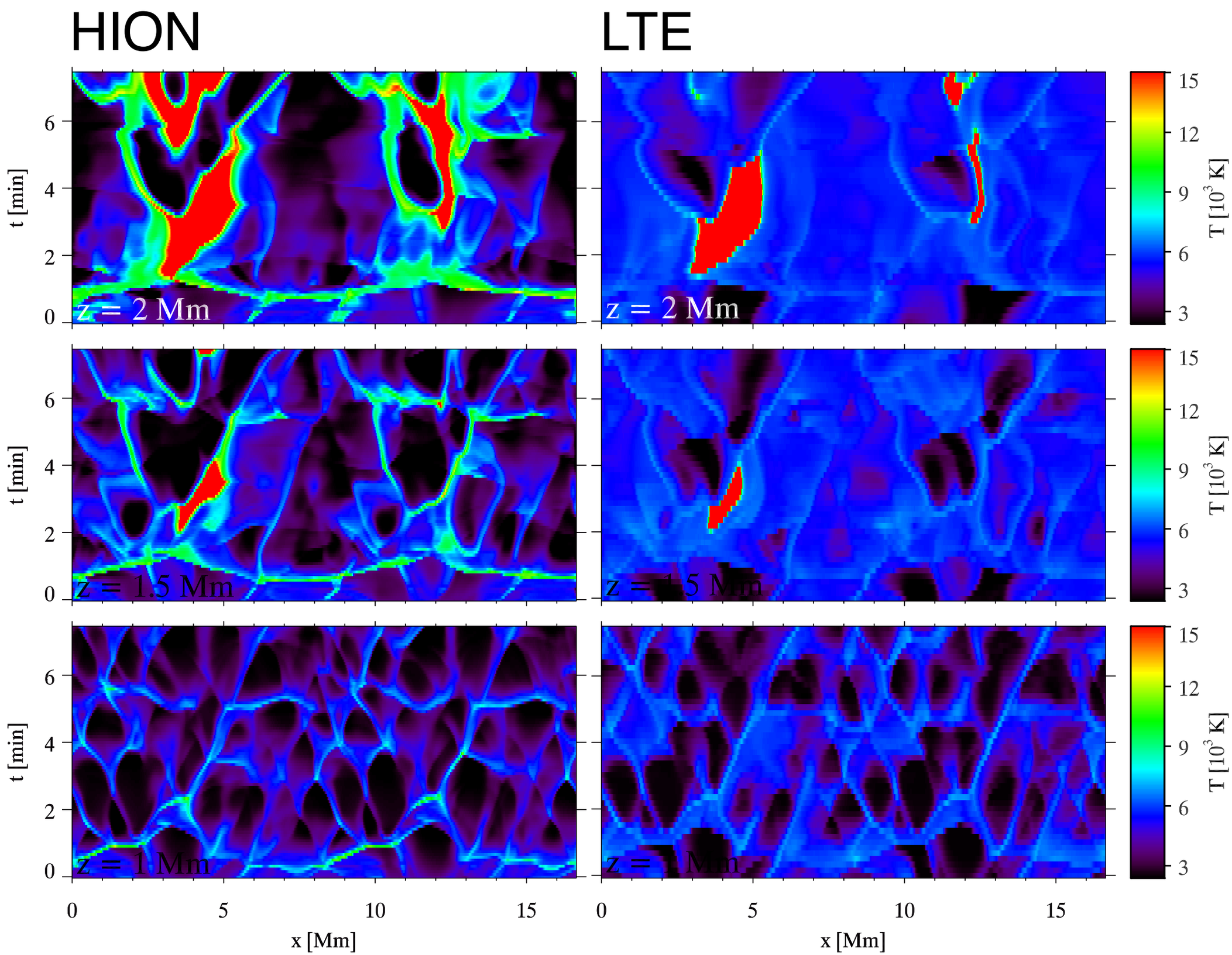
- Solve the transfer equation using rate and n_1 populations to provide source function and (fudged, poor man's scattering) opacity
- Obtain upward rate from J
- Rates not implicit, possible source of problems

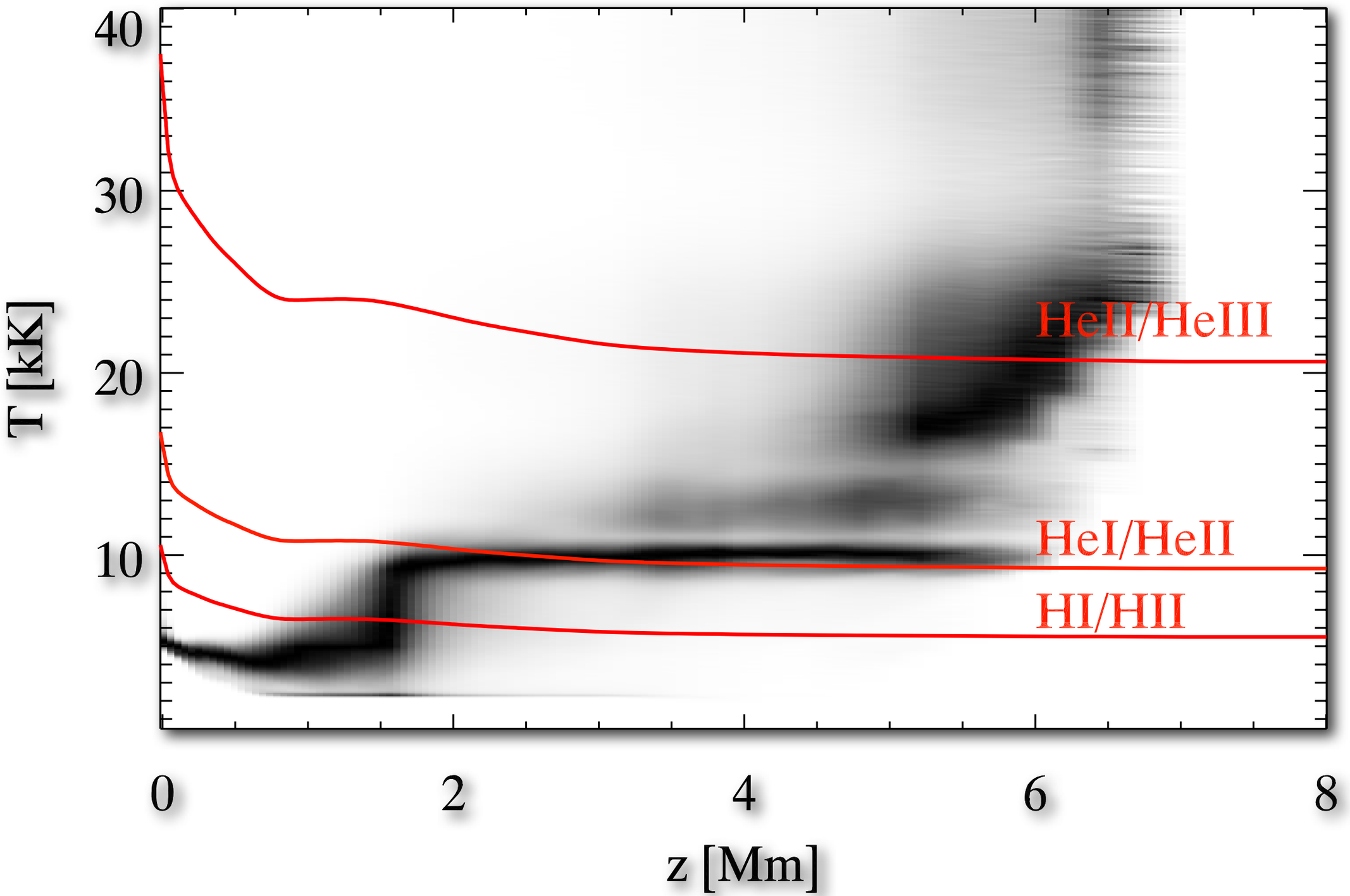
Lyα is special



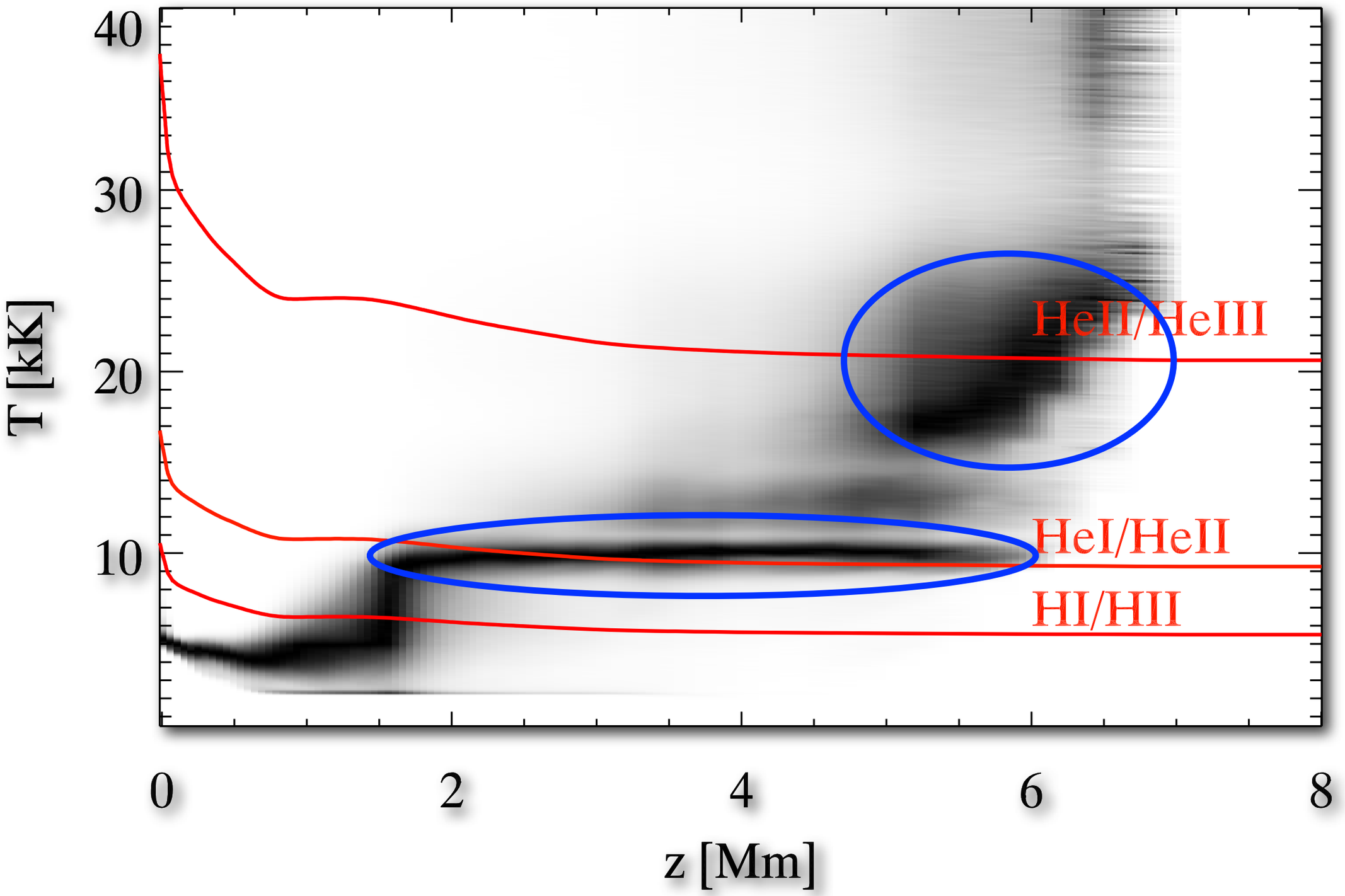

Temperature
Ionization degree
z [Mm]
x [Mm]
0
2
4
6
8
0
5
10
15
>5
4.5
4
3.5
^{10}log T [K]
0
-2
-4
<-6
^{10}log F_{ion}

Increased temperature fluctuations

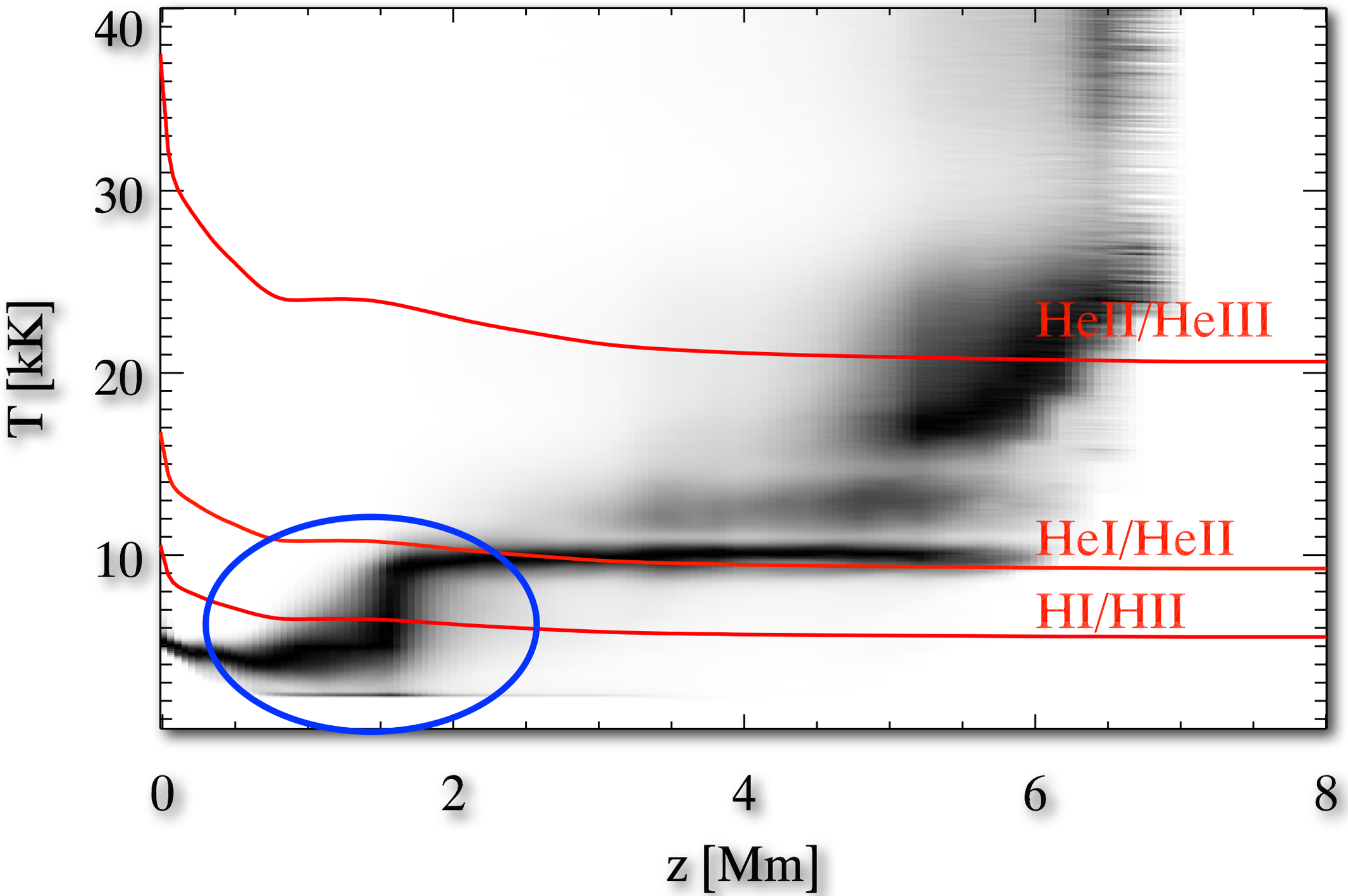



40
30
20
10
T [kK]
HeII/HeIII
HeI/HeII
HI/HII
0
2
4
6
8
z [Mm]

Unrealistic clustering at temperatures where He ionizes

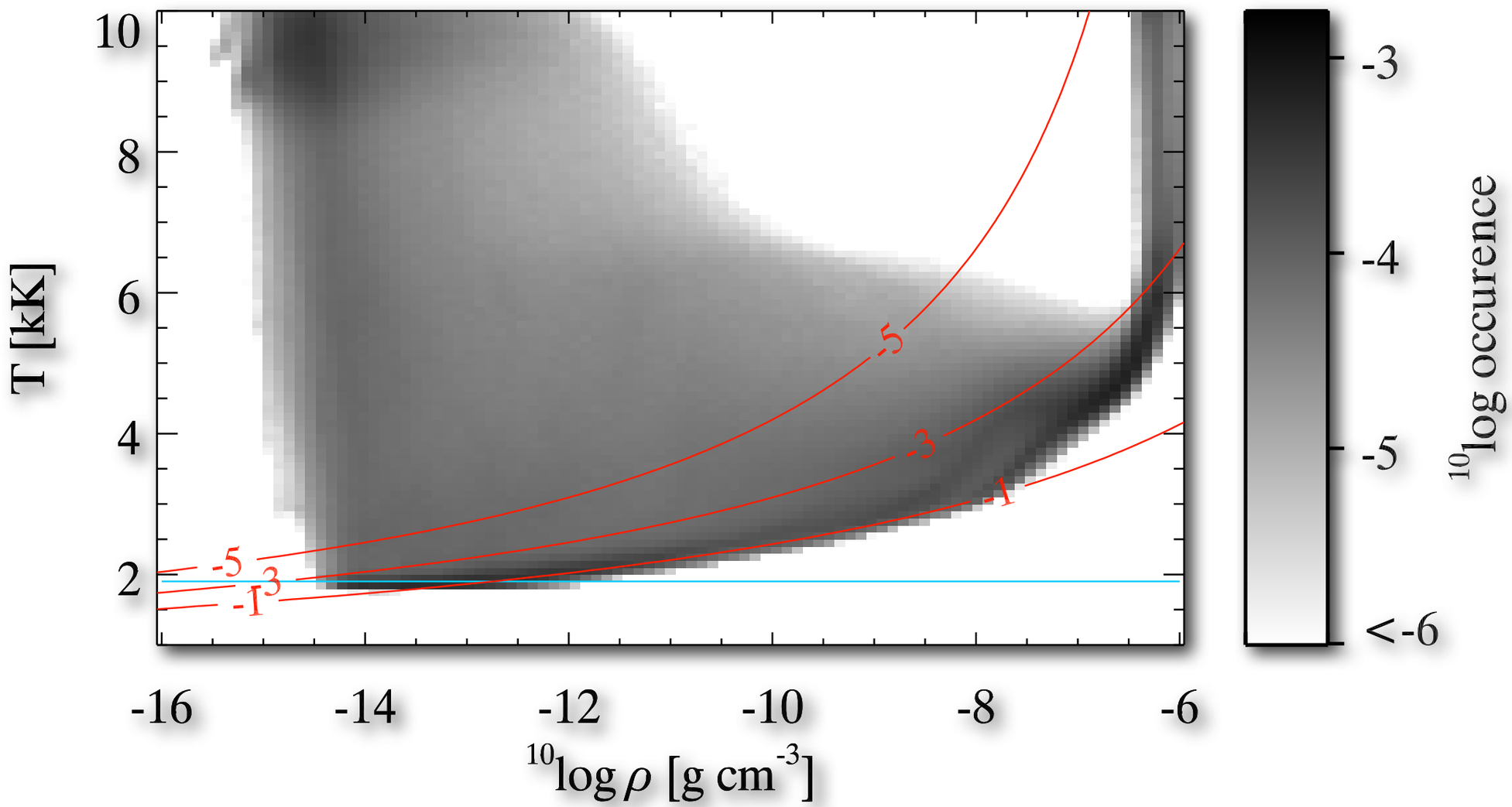


No such clustering for hydrogen



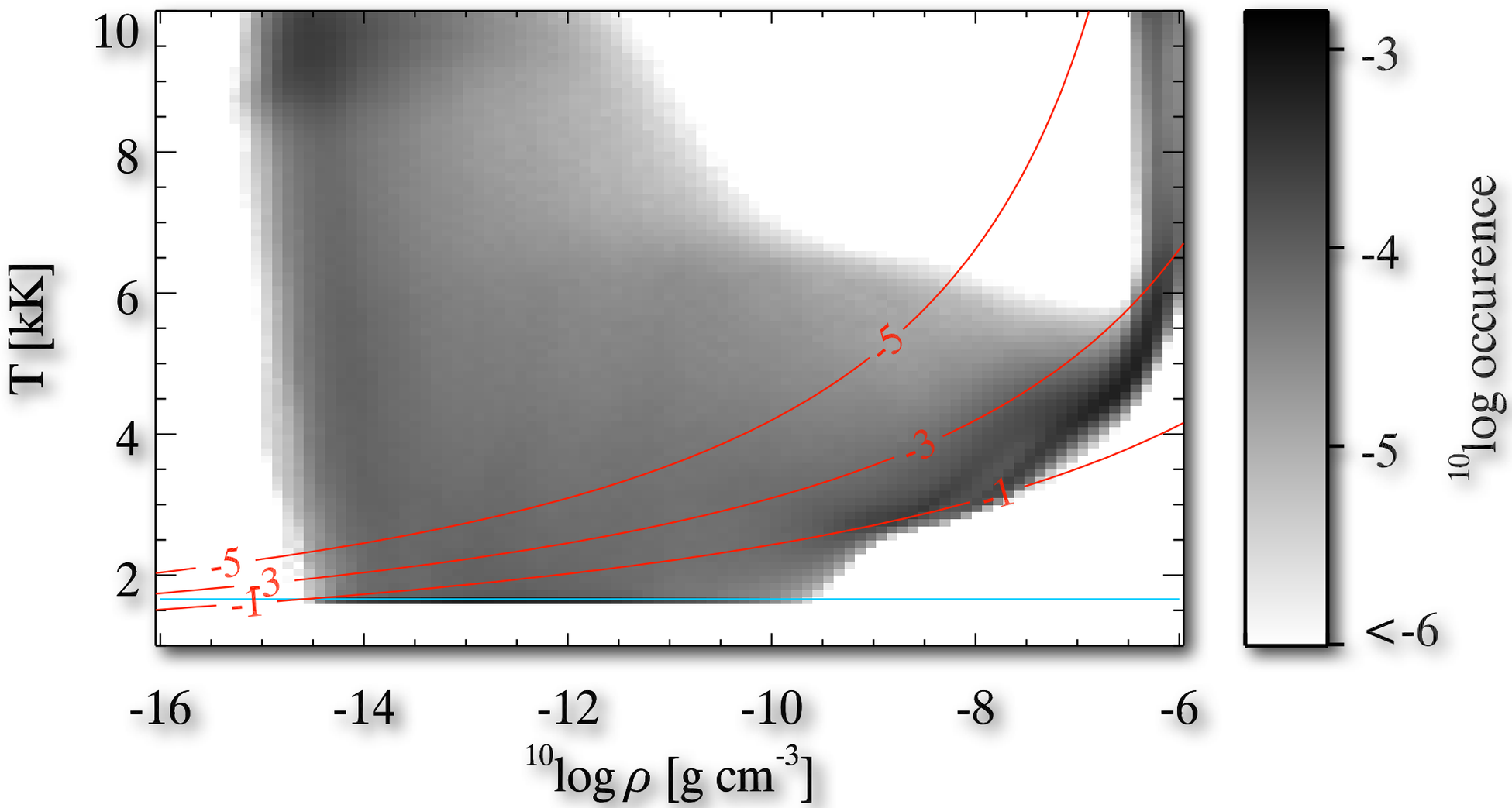
Low temperature end

H_2 molecules provide lower limit in LTE



Low temperature end

Time-dependent chemistry removes lower limit below $\rho=10^{-9}$



Conclusions (1)

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- clumping of gas at 10 kK and 30kK is an artifact of LTE Helium ionization
  - real temperature structure in upper chromosphere unknown, He ionization should be modeled better
- time-dependent H_2 chemistry removes lower limit of temperature in expansion bubbles

Conclusions (2)

- Conclusions (1) are generally valid
- Magnetized chromosphere influenced by ionization-dependence of neutral-ion effects
- See Juan's (and others) talk for details