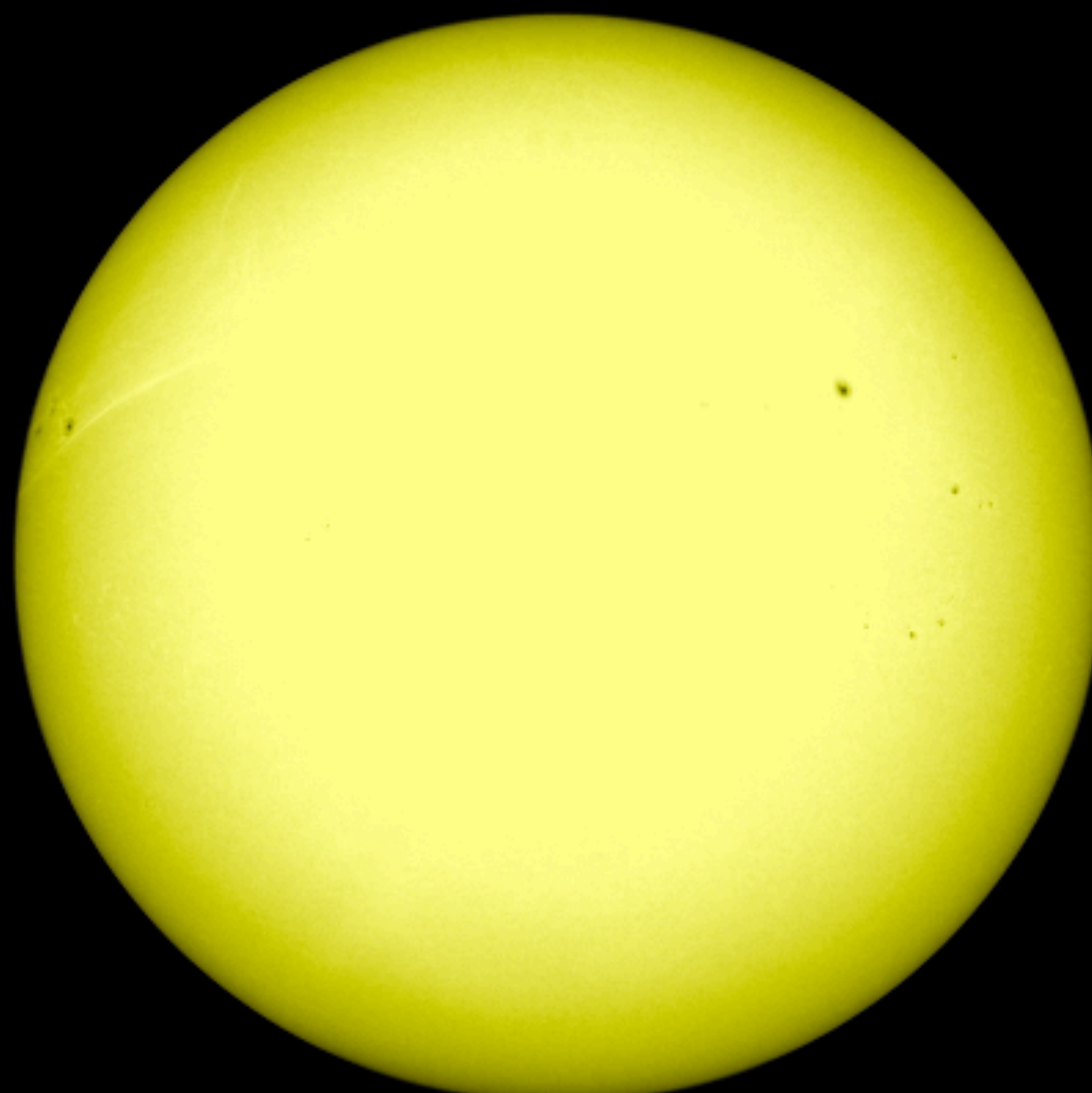
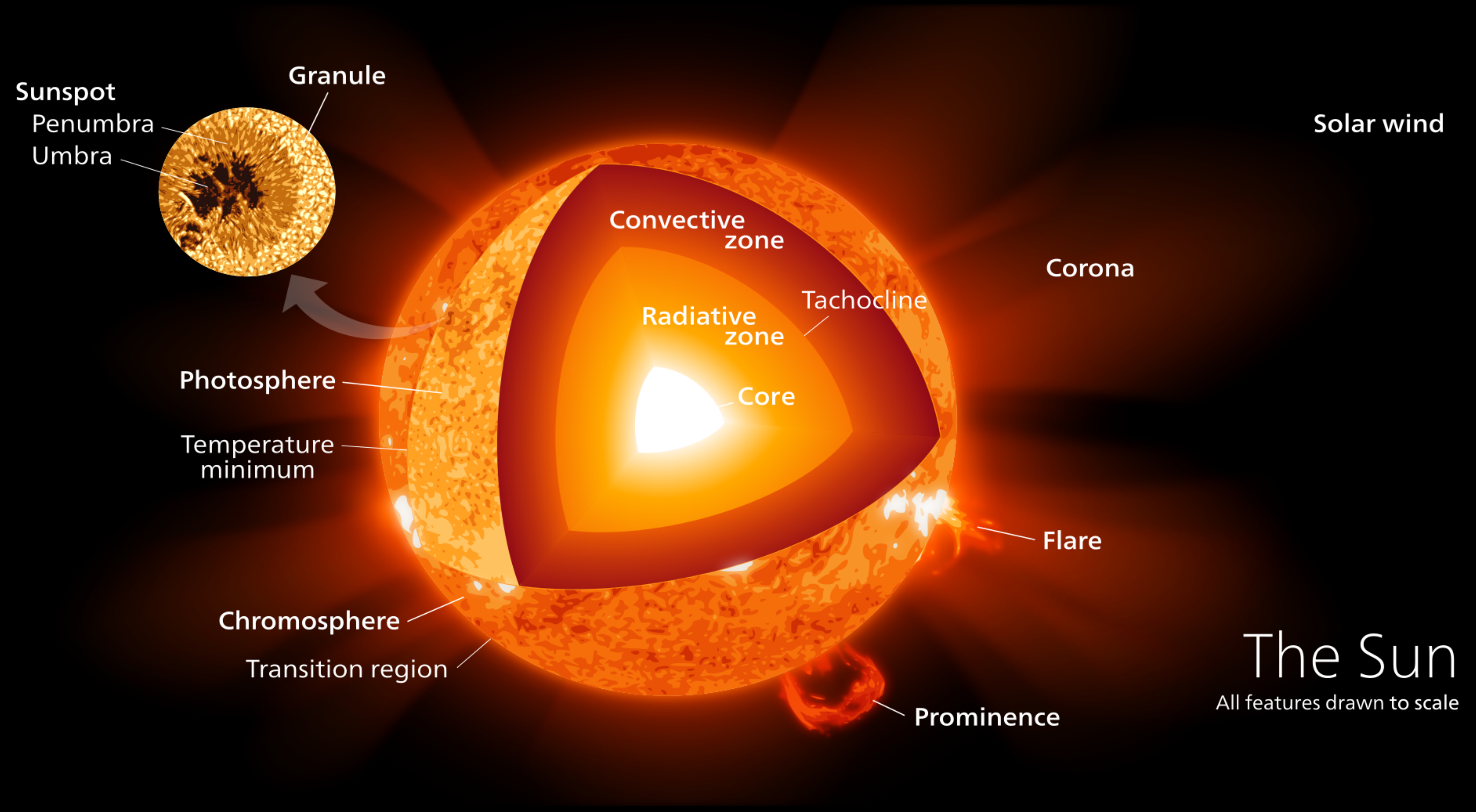
Non-equilibrium helium ionization in the solar atmosphere

The solar atmosphere

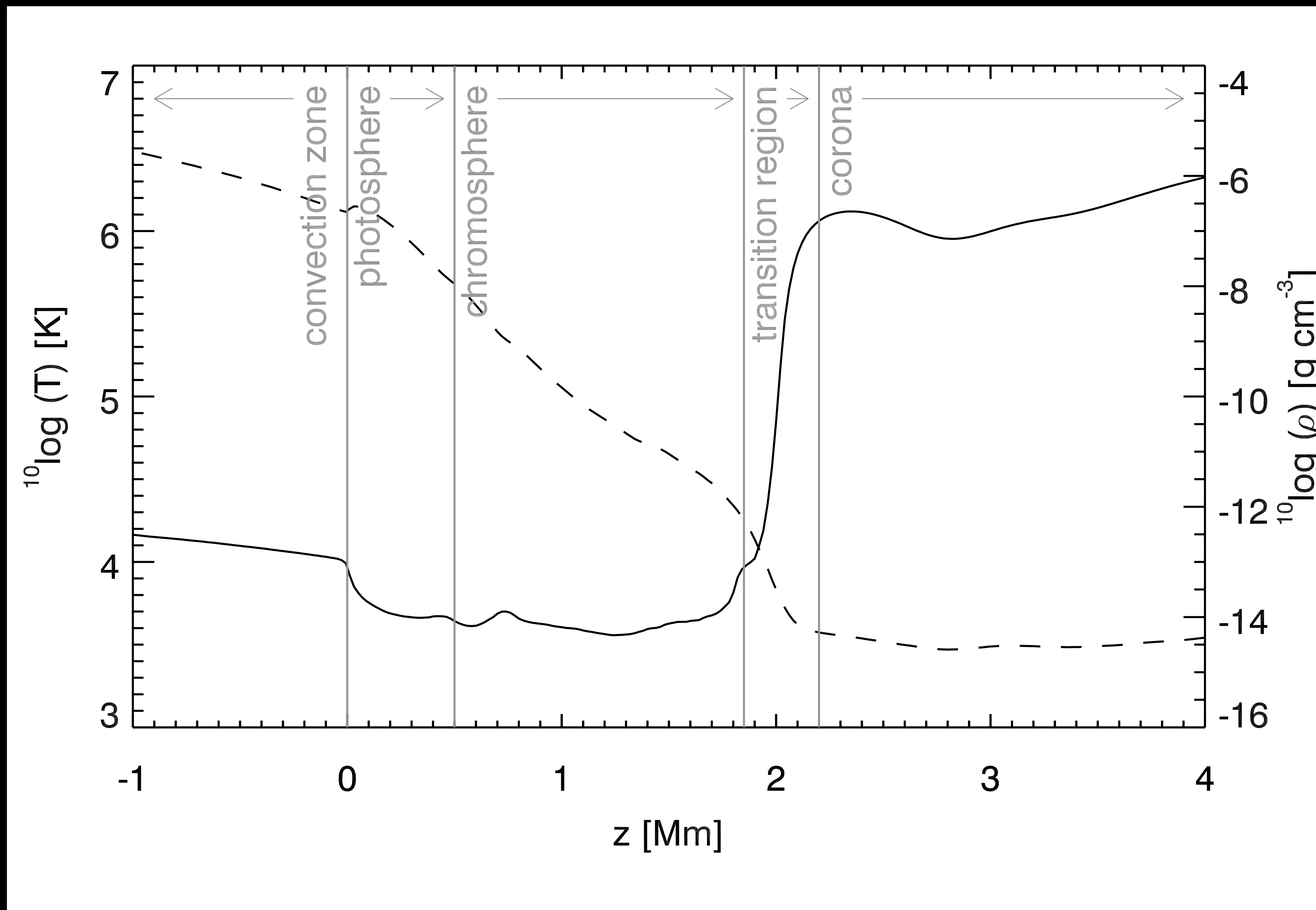
- where the light we see come from



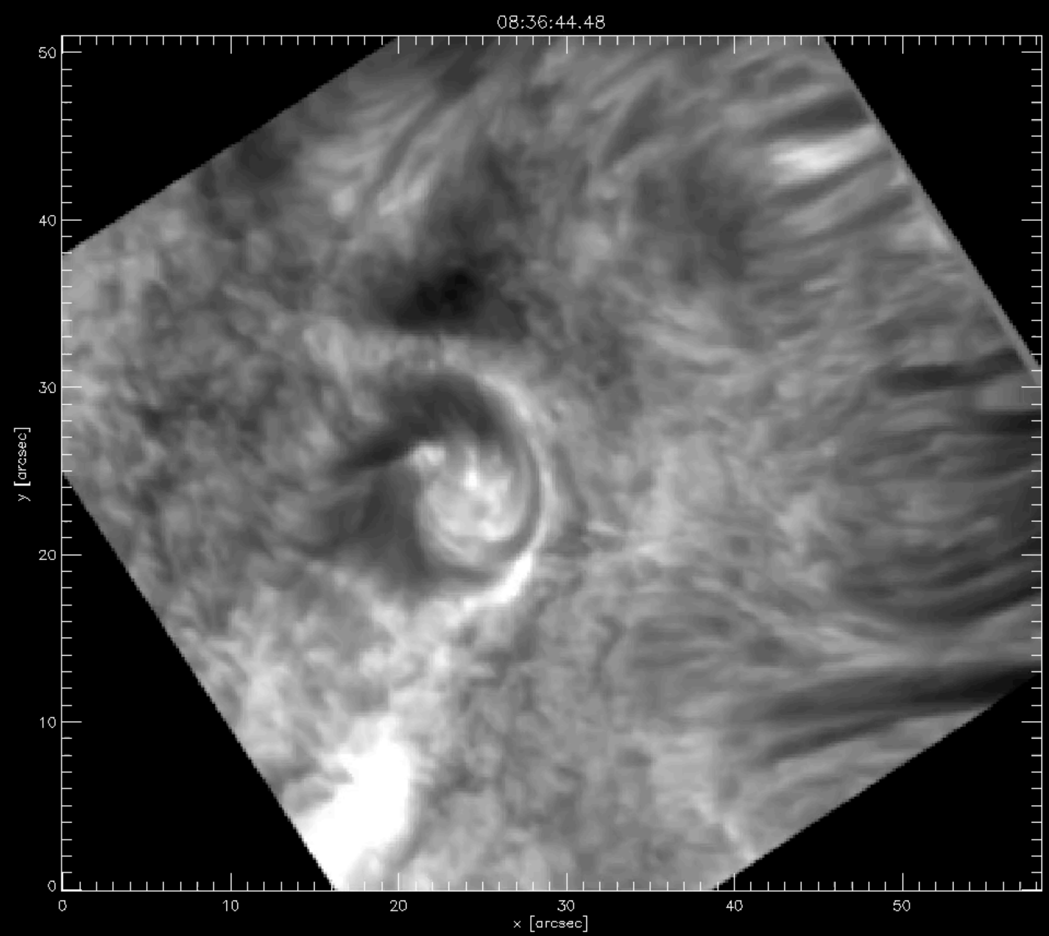
Internal structure



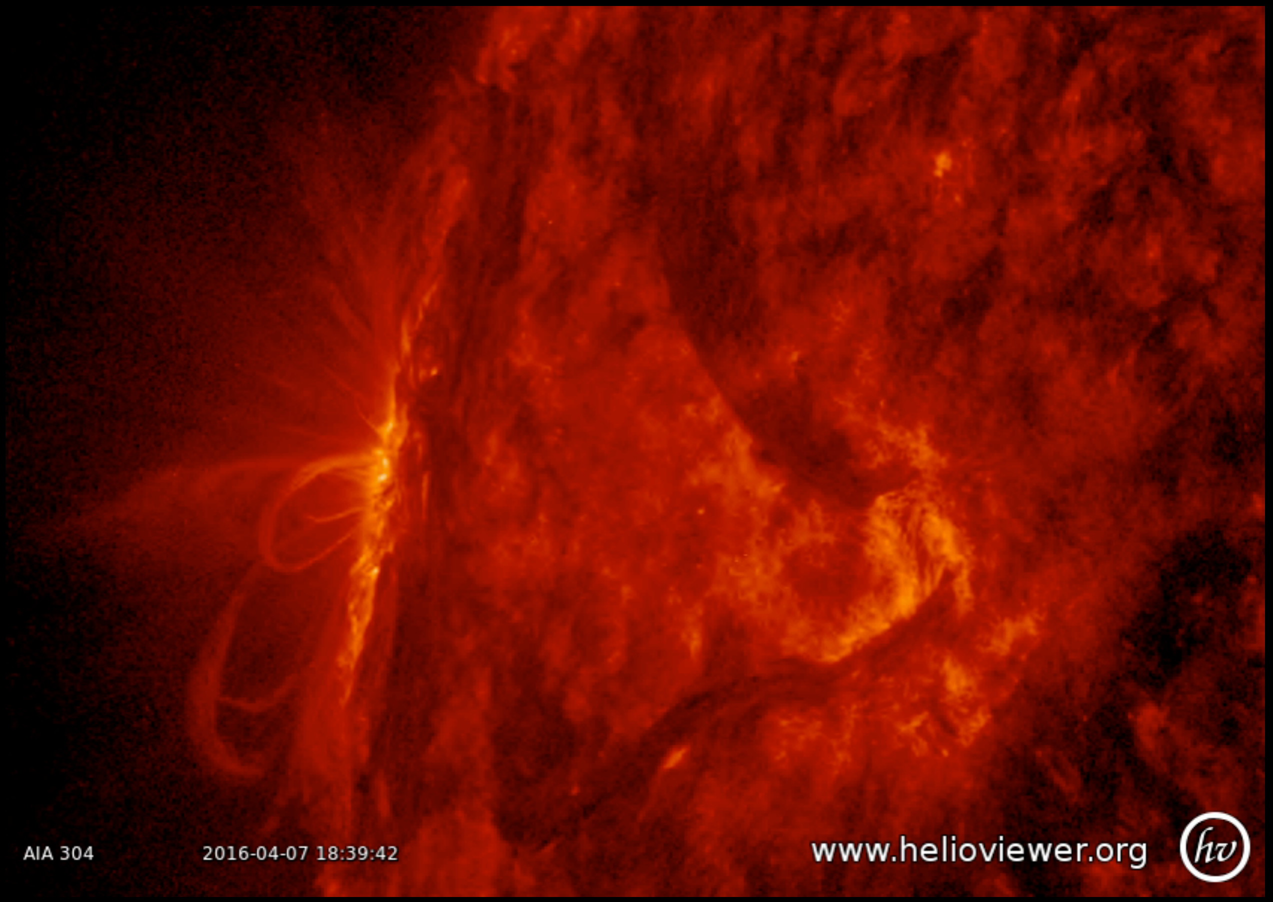
Basic model atmosphere



The solar atmosphere is dynamic and 3 dimensional



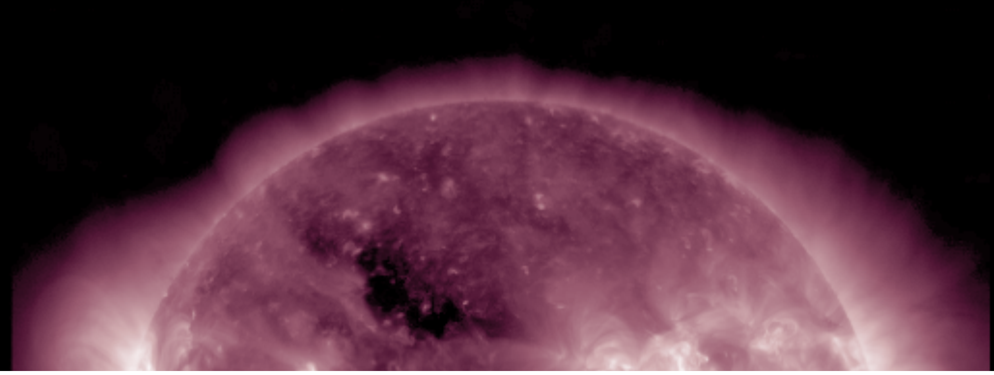
Chromosphere



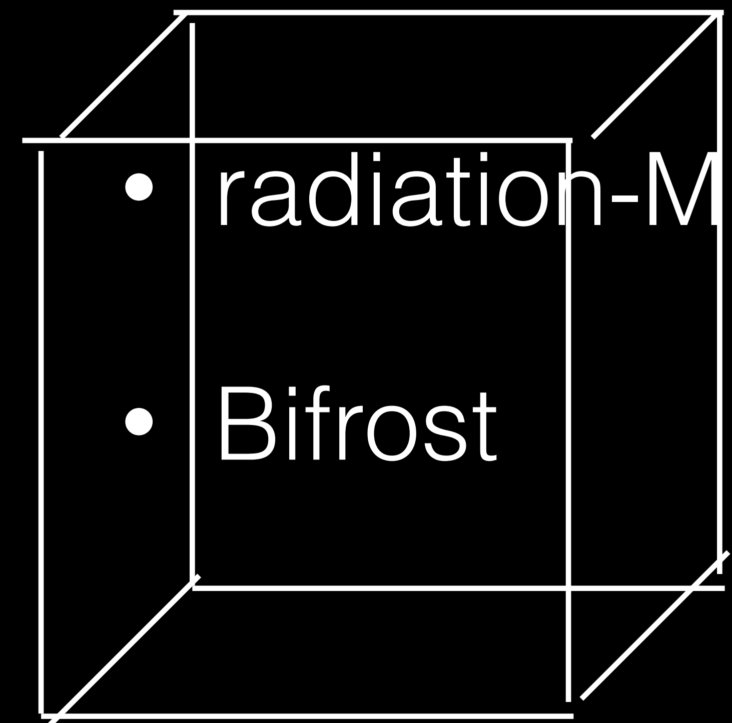
Transition region

Models are useful to interpret observations such as these.

Constructing a dynamic 3D solar atmosphere model



$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= -\boldsymbol{\nabla} \cdot \rho \boldsymbol{u} \\
\frac{\partial \rho \boldsymbol{u}}{\partial t} &= -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{u} \boldsymbol{u} - \tau) - \boldsymbol{\nabla} P + \boldsymbol{J} \times \boldsymbol{B} + \rho \boldsymbol{g} \\
\mu \boldsymbol{J} &= \boldsymbol{\nabla} \times \boldsymbol{B} \\
\boldsymbol{E} &= \eta \boldsymbol{J} - \boldsymbol{u} \times \boldsymbol{B} \\
\frac{\partial \boldsymbol{B}}{\partial t} &= -\boldsymbol{\nabla} \times \boldsymbol{E} \\
\frac{\partial e}{\partial t} &= -\boldsymbol{\nabla} \cdot e \boldsymbol{u} - P \boldsymbol{\nabla} \cdot \boldsymbol{u} + Q
\end{aligned}
$$



- radiation-MHD
- Bifrost

Energy balance

$$\frac{\partial e_{\mathrm{i}}}{\partial t} = -\nabla \cdot (\mathbf{u} e_{\mathrm{i}}) - p \nabla \cdot \mathrm{u} + Q_{\mathrm{c}} + Q_{\mathrm{v}} + Q_{\mathrm{ohm}} + Q_{\mathrm{rad}}$$

Radiation

Very costly

The temperature can be determined from the internal energy:

$$e_i = e_{\mathrm{thermal}} + e_{\mathrm{ion}}$$

Equilibrium + only collisional = LTE

How wrong is LTE?

Photosphere:
- high density
- high opacity

-> LTE is reasonable

Chromosphere:
- medium density
- medium opacity

-> far from LTE

Corona
- low density
- zero opacity
- high temperature

-> completely ionized

Consider a parcel of neutral chromospheric gas at 10 000K. The following possibilities require the same amount of heating:

- doubling the temperature
- ionize 10% of the hydrogen
- ionize 50% of the helium

Keeping track of the time dependent ionization state with a set of non-equilibrium rate equations

Radiative transfer equation

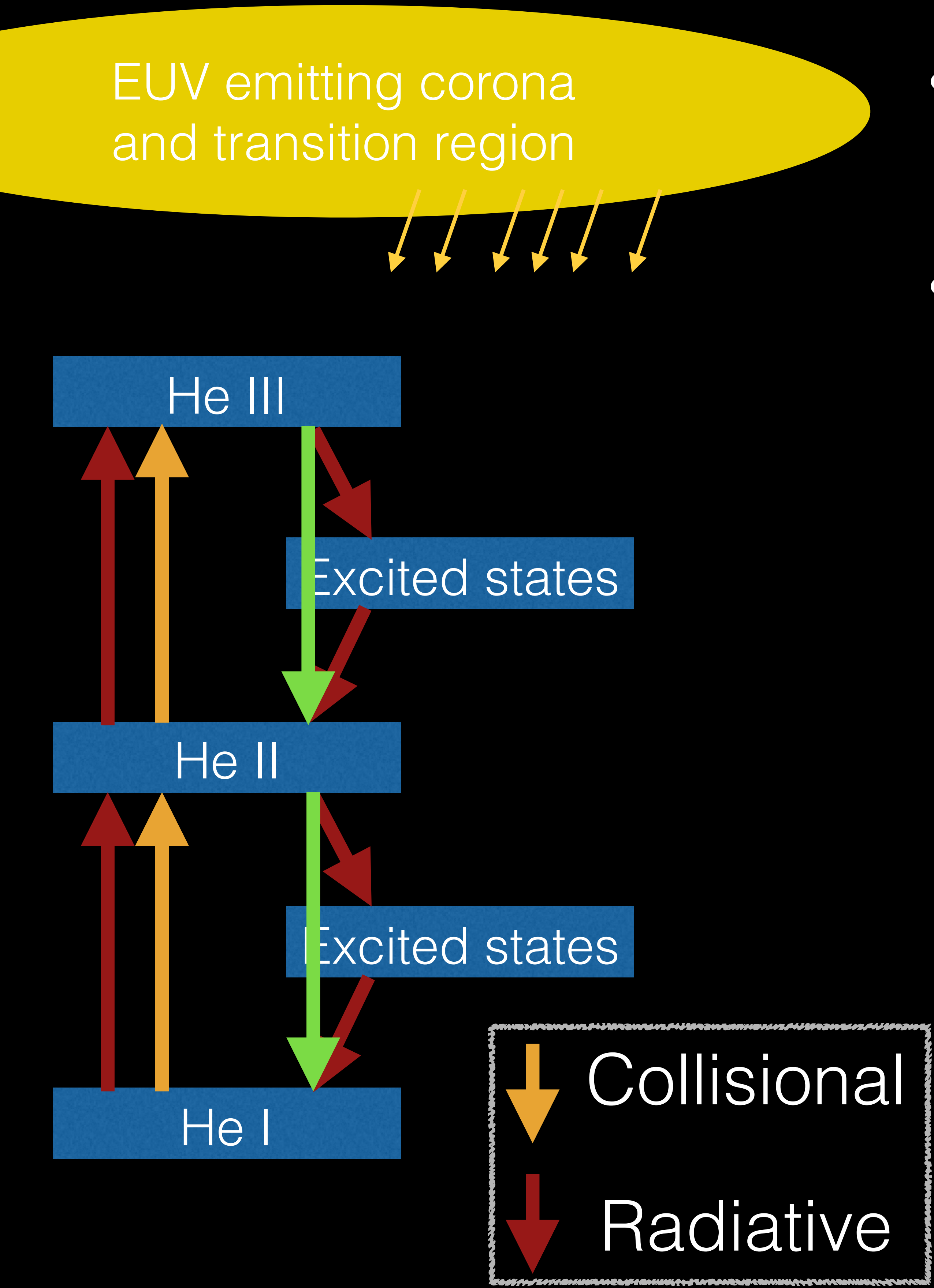
$$\frac{\mathrm{d}I}{\mathrm{d}s} = \eta - I\chi$$

Non-equilibrium rate equations

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

- Aspects to consider:
  - number of levels in the model atom = number of rate equations
  - how to treat the radiative transition rate coeffs

Helium ionization in the solar atmosphere



- Photo+collisional ionisation from ground state.
- Radiative recombination through the excited states

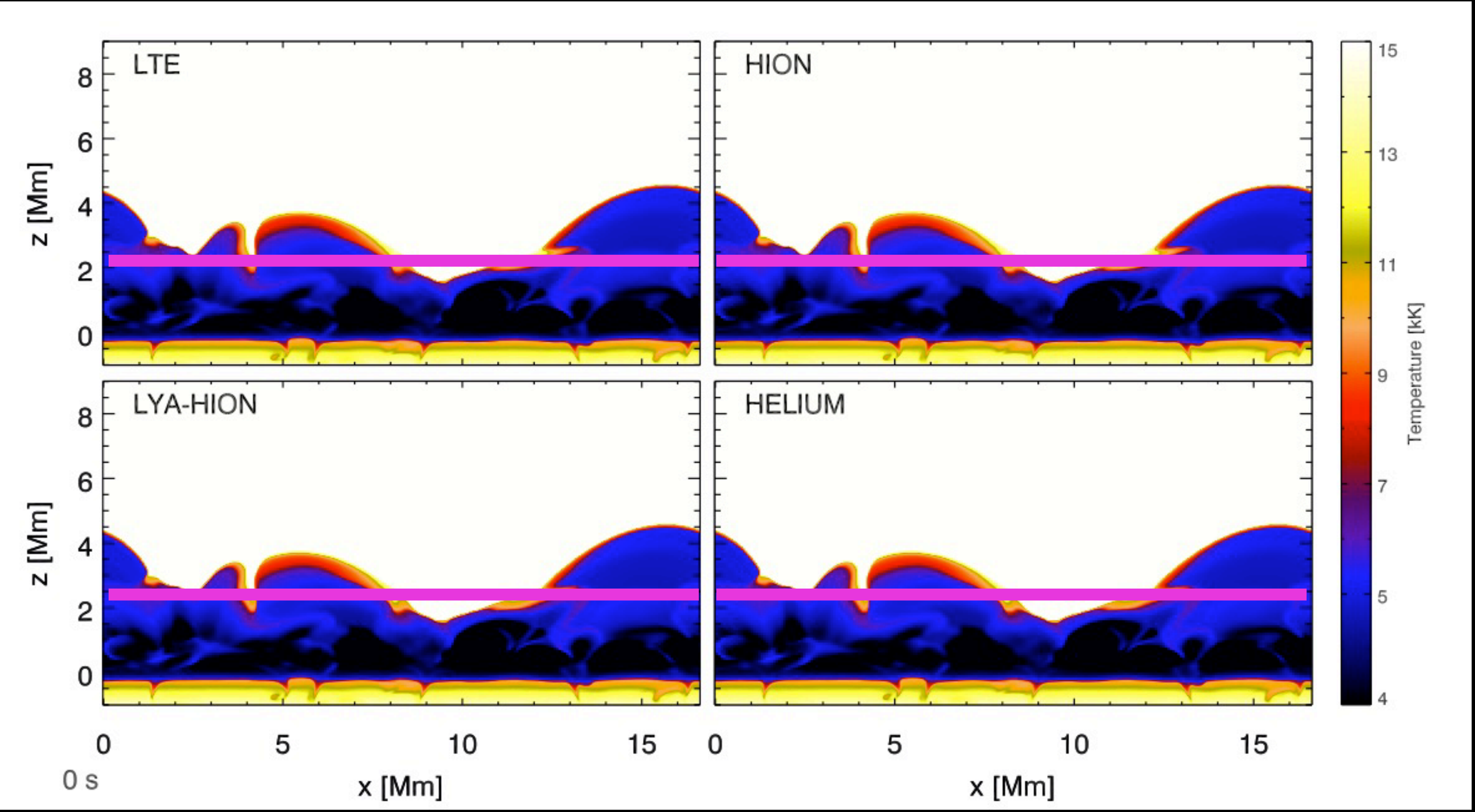
Approximate solution for Bifrost:

- 3 level model atom
- effective recombination
- radiative transfer in a couple of frequency bins only

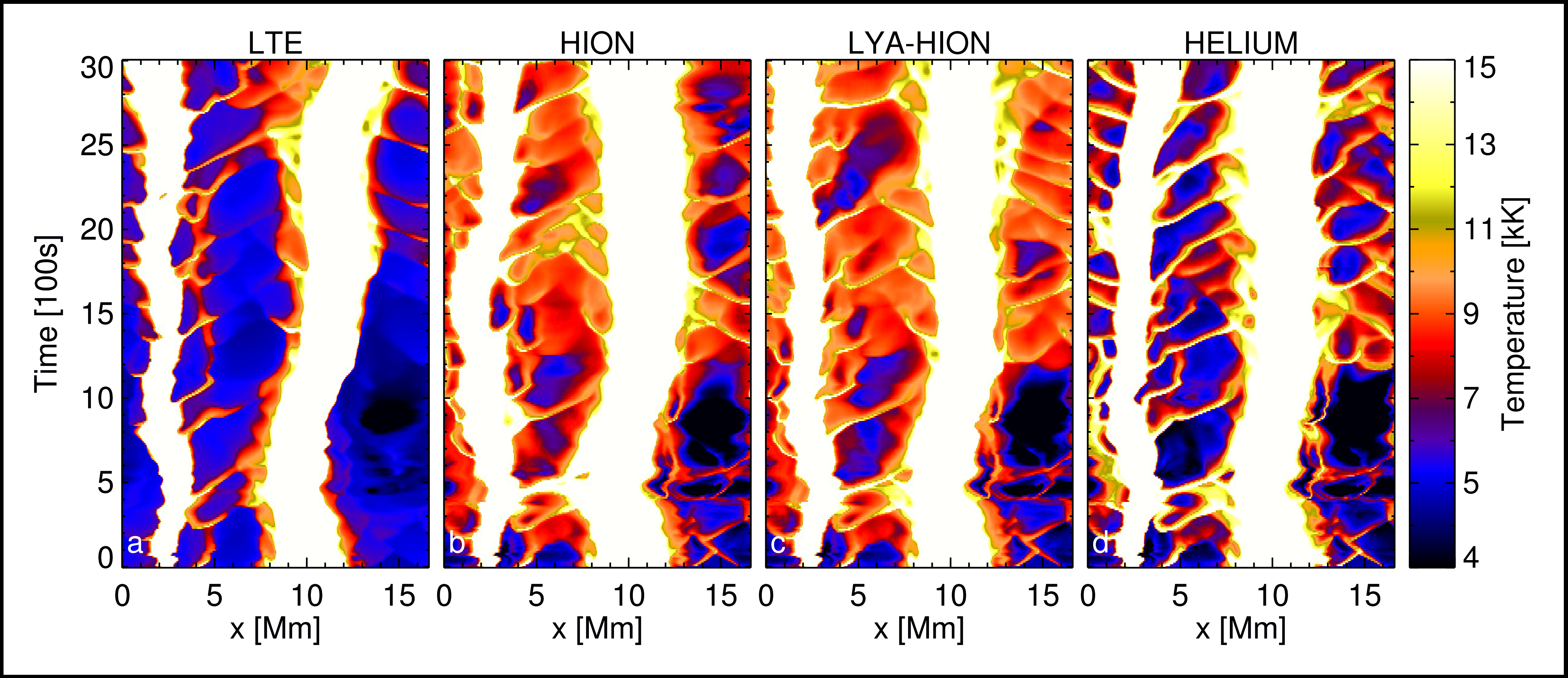
Bifrost with non-equilibrium H and He

	LTE	HION	LYA-HION	HELIUM
Hydrogen	LTE	Non-eq	Non-eq + Ly-alpha	Non-eq + Ly-alpha
Helium	LTE	LTE	LTE	Non-eq.
All other elements	LTE	LTE	LTE	LTE

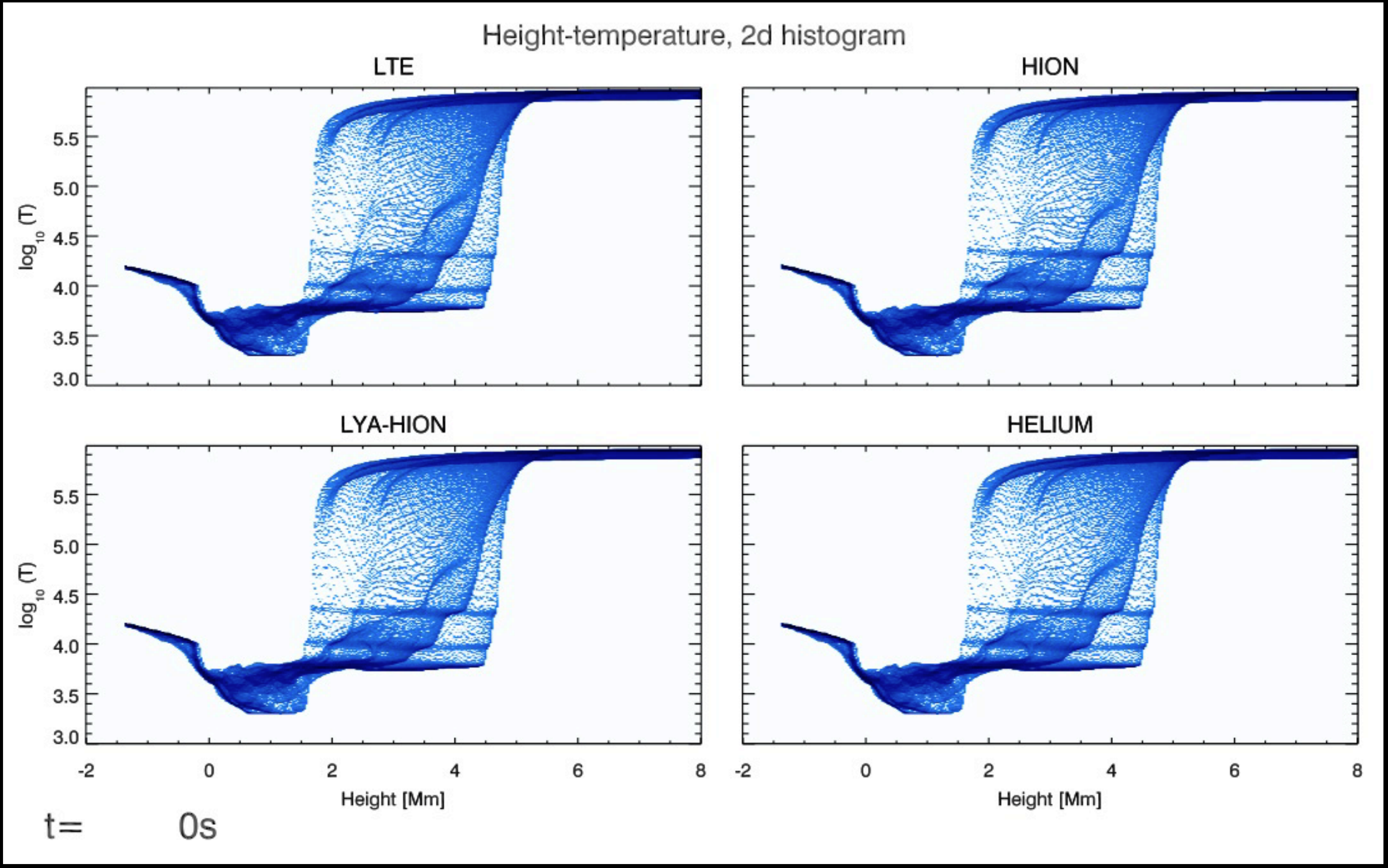
Results


LTE
HION
LYA-HION
HELIUM
z [Mm]
x [Mm]
Temperature [kK]
0 s
0
2
4
6
8
0
5
10
15
4
5
7
9
11
13
15

Hotter in shocks, colder between shocks



Temperature plateaus vanish



Part two: modeling line formation

Radiative transfer equation $$\frac{\mathrm{d}I}{\mathrm{d}s} = \eta - I\chi$$

Statistical equilibrium rate equations $$0 = \sum_j n_j P_{ji} - n_i \sum_j P_{ij}$$

- 10 atomic levels + 500 frequency points x 24 angles = 12 010 equations
- Not possible to solve in a time-dependent Bifrost simulation
- Solve on one snapshot: Statistical equilibrium NLTE
- Multi3D

Classical modeling of emission in spectral lines forming at temperatures > 10 kK.

- DEM = Differential emission measure = how much material do I have at a given temperature

- From theory: probability of an atom emitting a photon at a given temperature

- Line intensity = DEM * probability integrated over temperature.

Application: the helium resonance line intensity problem

- Carol Jordan 1975:
  - constructed DEM models which successfully predicted EUV line intensities of many transition region lines, but not for those of helium
- Papers published up until recently show the same thing:
  - McPherson & Jordan 1999, Pietarila & Judge 2004, Giunta et. al. 2015

Method used in the studies

- Observe EUV intensities from lines forming in the transition region and corona

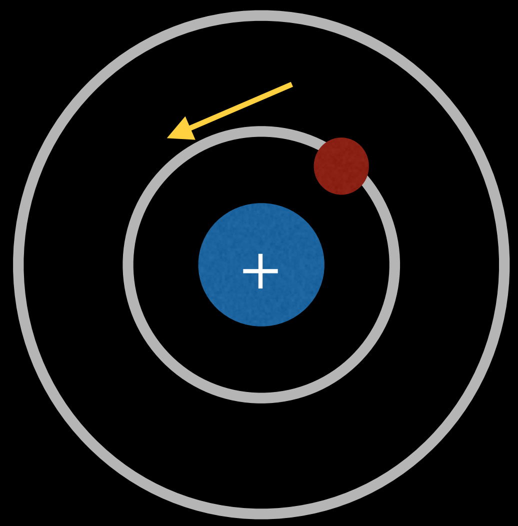
- Determined a DEM model from a subset of the line intensities

- Compare intensities computed with the DEM model with observed values

- Conclusion: DEM model predict most line intensities, except for helium line intensites who are roughly a factor of 10 lower than the observed values

Basic line formation process

- Electron excites helium atom
- Spontaneous de-excitation releasing an EUV photon



Suggested enhancement mechanisms

- increase number of collisional excitations by cold atoms mixing with hot electrons
  - ⁕ microturbulent motions
  - ⁕ non-maxwellian electron distributions
  - ⁕ macroscopic velocity fields
- Photoionization-recombination (PR)

NE-NLTE line formation

Radiative transfer equation

$$\frac{\mathrm{d}I}{\mathrm{d}s} = \eta - I\chi$$

Statistical equilibrium rate equations

$$0 = \sum_j n_j P_{ji} - n_i \sum_j P_{ij}$$

Use NE helium ion fractions from Bifrost to constrain solution

$$n_{\mathrm{HeI}} = \sum_{i=\mathrm{HeI}} n_i$$

$$n_{\mathrm{HeII}} = \sum_{i=\mathrm{HeII}} n_i$$

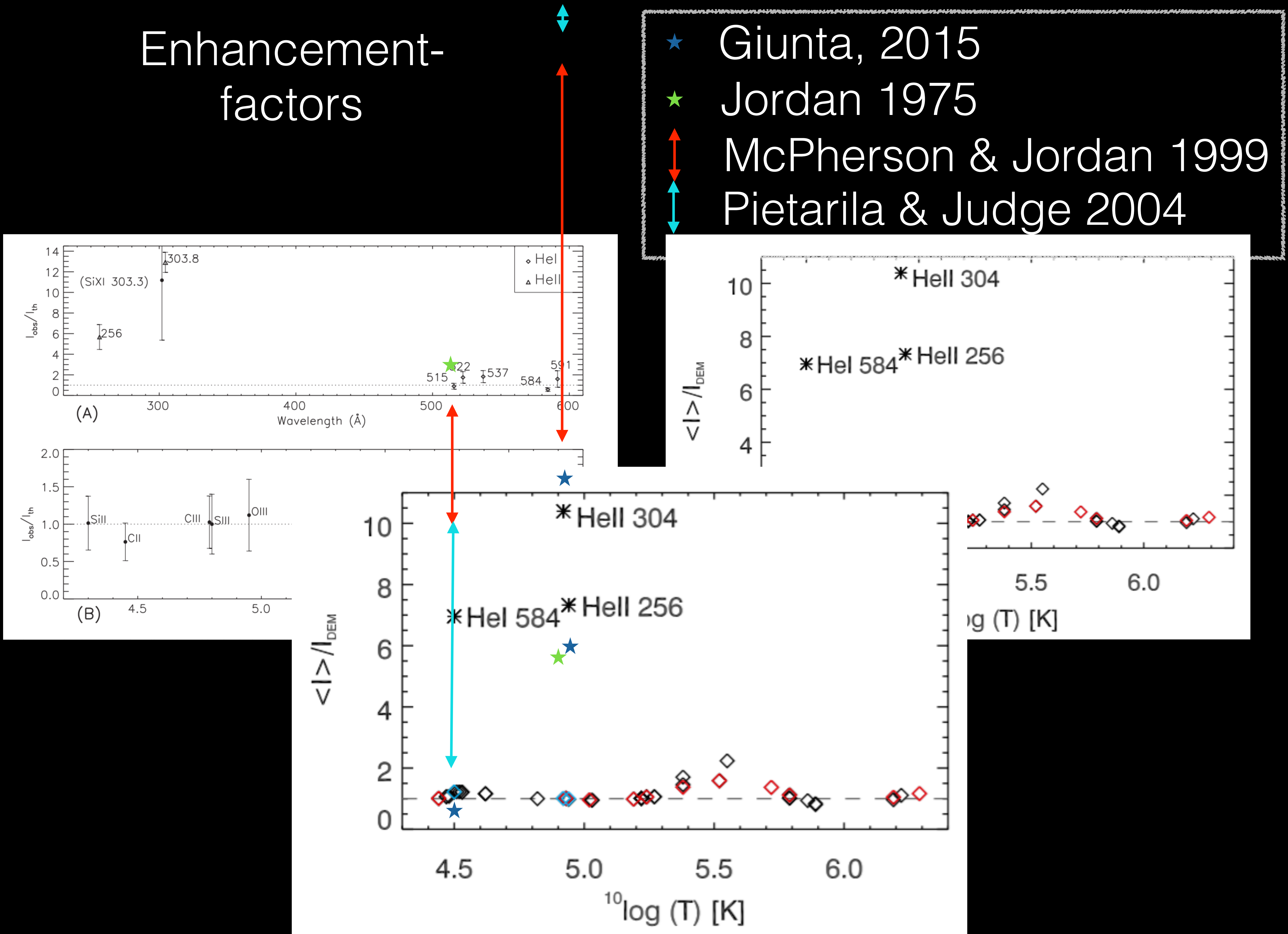
$$n_{\mathrm{HeIII}} = n_i$$

- Assumption: number density balancing of the excited states equilibrate instantaneously to ionization state
- Desired outcome: line intensities equal to those obtained by solving the time-dependent rate equations
- NE-NLTE performs well in test cases.

Experimental setup: copy Giunta, 2015

- Use Bifrost snapshot
- Compute synthetic observations for the same lines as Giunta, assuming optically thin, ionization equilibrium conditions
- Compute synthetic helium line intensity observations using the NE-NLTE method
- Derive a DEM from a subset of the thin lines
- Compute line intensities using the DEM model
- Compare these DEM line intensities with the “observations”: enhancement factor = observed intensity / synthesised intensity

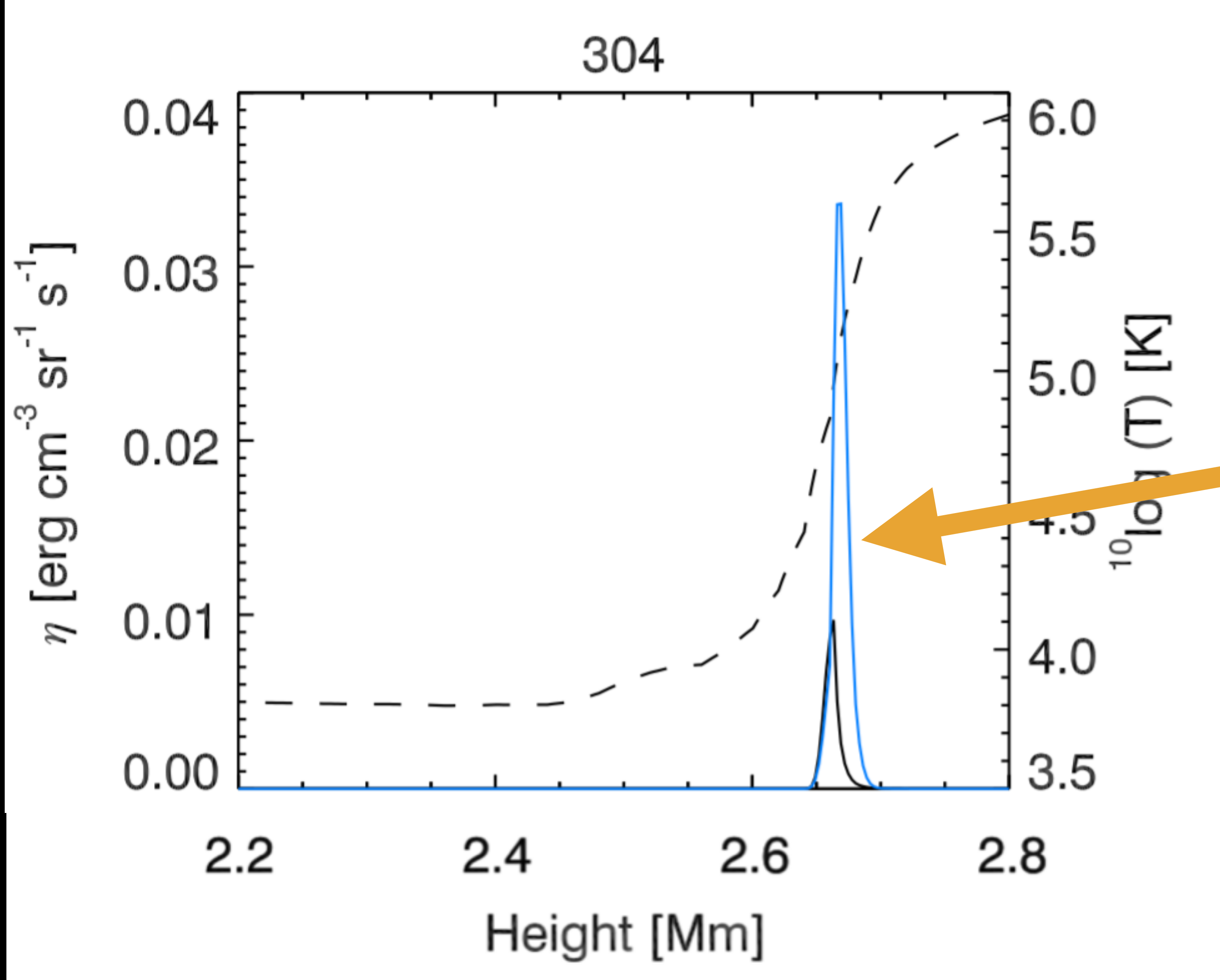
Enhancement-factors



We reproduce enhancement factors

- Our synthetic observations give results similar to real observations
- Our model includes physics suitable to explain the helium EUV line intensity enhancement

He II lines: NE-ionization



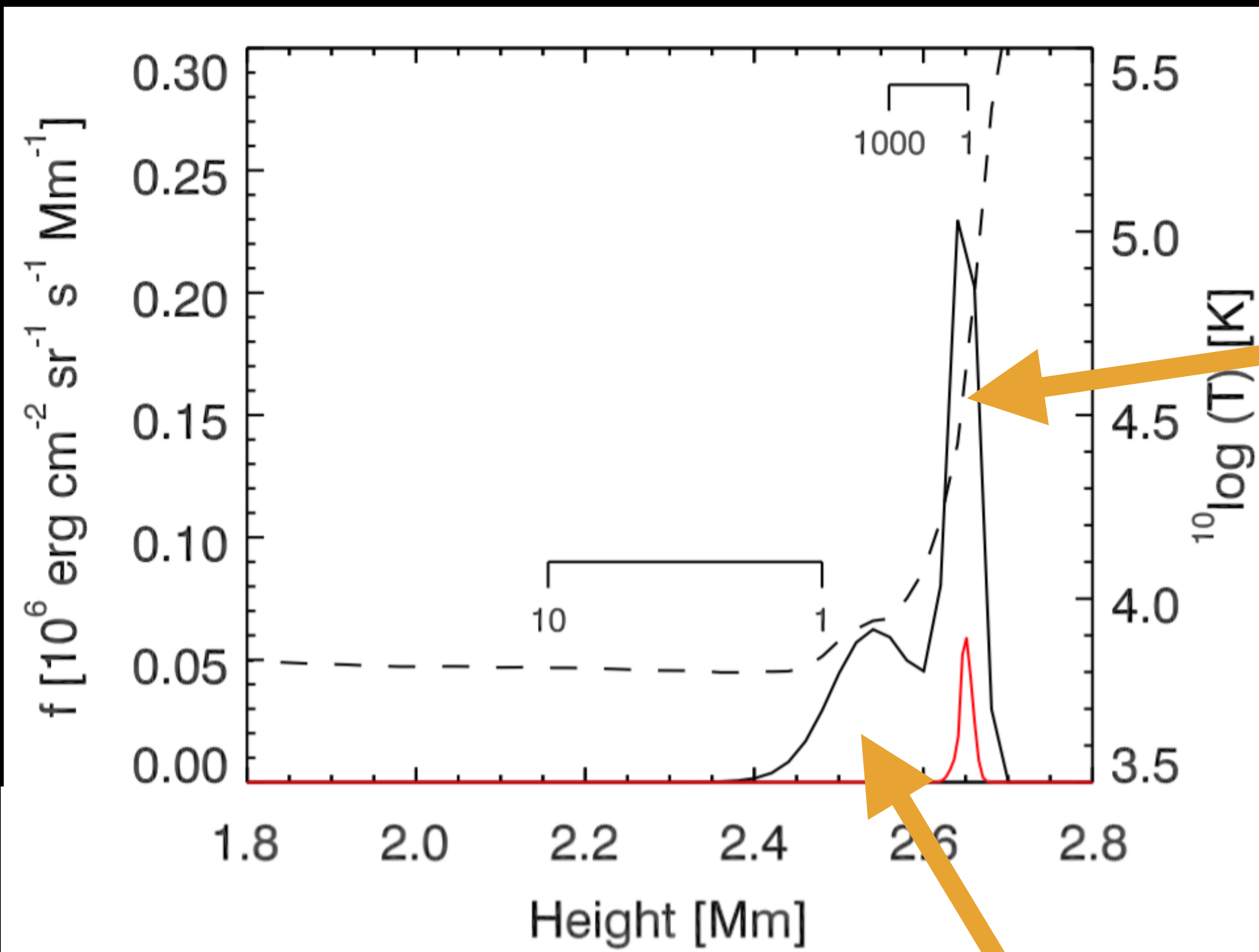
NE emissivity higher than EQ emissivity

$$\eta \sim n_{\mathrm{HeII}} n_{\mathrm{e}} C(T)$$

NE: significant amount of He II ions in hot region:

He I 584

- Thick transfer important



Thick NE-NLTE: contribution function significant also in cold regions

Extra photons produced are due to recombination cascades

Summary

- The helium ionization state is important for the energy balance of the chromosphere
- Helium is photoionized by EUV radiation from transition region and corona
- He I 10830: the opacity primarily set by He II recombining into the triplet He I system
- Structures in 10830 images: emitting transition region structures result in localized regions of He II
- He I 584: Primarily formed in recombination cascades
- He II 256 and 304: Formed by collisions (cold atoms, hot electrons) and RT effects

Thank you