# Non-equilibrium calcium ionisation in the solar atmosphere

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*in collaboration with M. Carlsson*

# INTRODUCTION

## CALCIUM

- Chemical abundance:
  - more than 5 orders of magnitude less abundant than hydrogen

- Ionisation stage in the (quiet) solar atmosphere:
  - mostly singly ionised (Ca II) *[partially ionised]*

➡ Calcium is a "minority species" and only minor electron donor

***BUT:***

- Significant part of the radiative losses in the chromosphere due to Ca lines
- Spectral lines of Ca II important and widely used diagnostics for chromospheric plasma
- Understanding properties of Ca needed for a detailed quantitative interpretation of observation and derivation of atmospheric properties

# INTRODUCTION

## CALCIUM

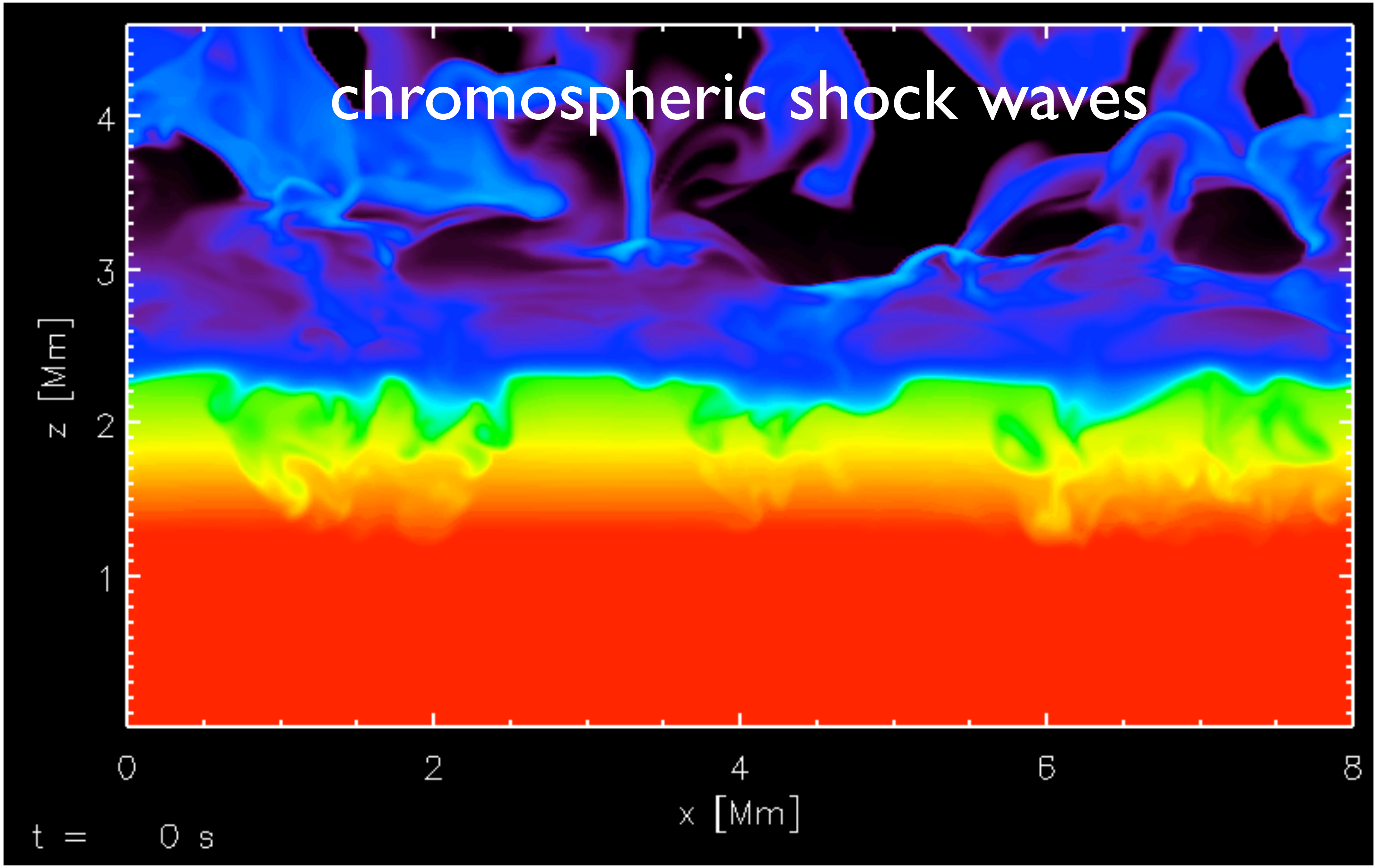
- Detailed numerical non-equilibrium treatment of a model atom (incl. time-dependence) can be computationally expensive.

➡ Modelling of calcium in the solar chromosphere mostly simplified:

- 1-D static (VAL-type)
- instantaneous equilibrium in 2-D/3-D simulations
  (often only indirectly included in equation of state, opacities)

# INTRODUCTION

- ***BUT:*** Solar chromosphere varies strongly on small spatial and temporal scales.




Wedemeyer-Böhm et al. (2008)

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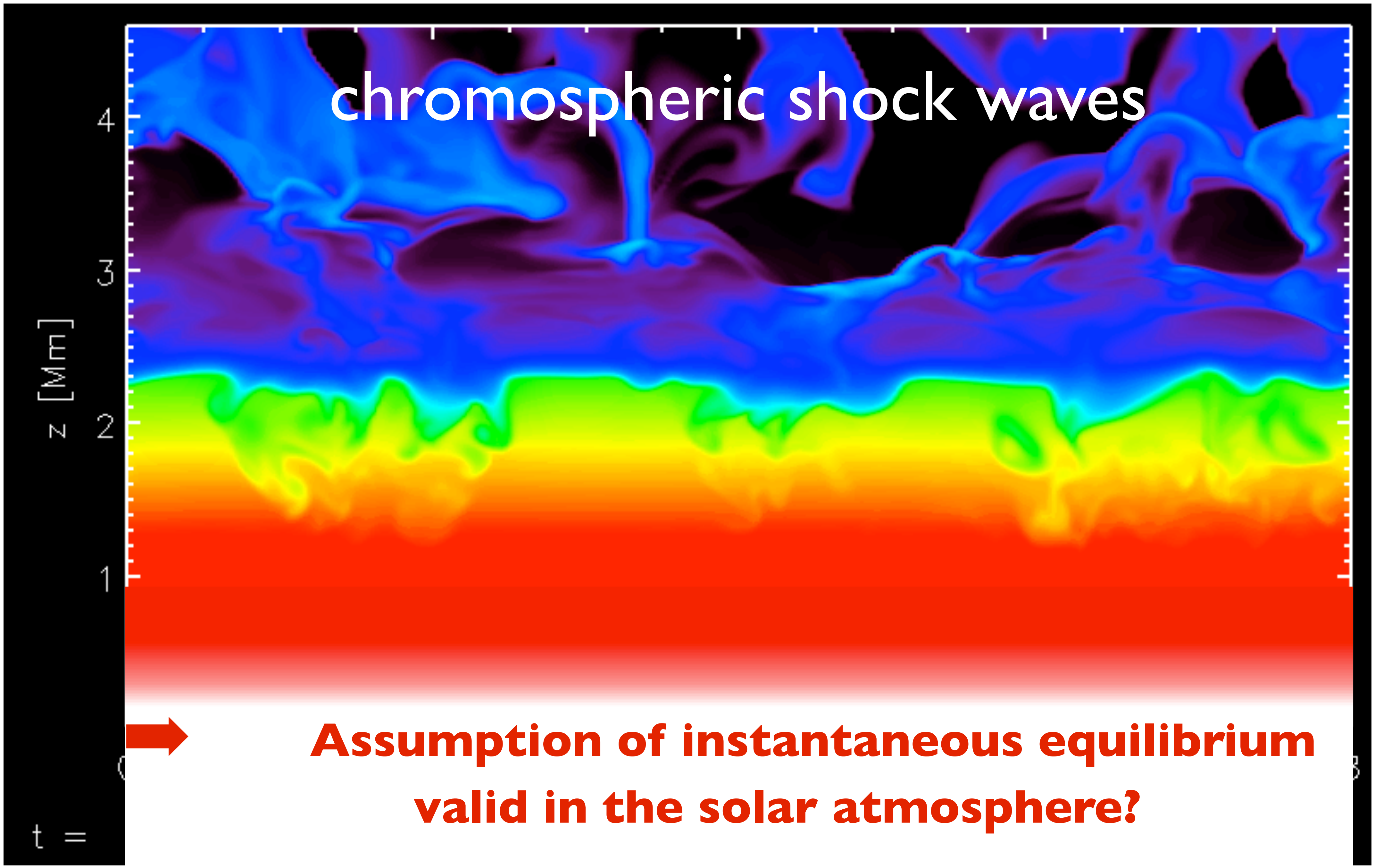



Wedemeyer-Böhm et al. (2008)

➡ **Assumption of instantaneous equilibrium valid in the solar atmosphere?**

# APPROACH

***Wedemeyer-Böhm & Carlsson 2011, A&A 528, A1***

- Numerical simulations of the solar chromosphere with detailed time-dependent treatment of Ca ionisation
  - computationally expensive
  - ➡ 1-D first, no magnetic fields(!)
  - similar to a study of the H ionisation *(Carlsson & Stein 2002, ApJ, 572, 626)*

- *Presented here:*
  - Resulting effect on the ionisation fraction of Ca
  - Relevant time scales

# NUMERICAL SIMULATIONS

***Simulation code RADYN*** *(Carlsson & Stein 1995)*

- solves
  - equations of mass, momentum, energy, and charge conservation
  - non-LTE radiative transfer
  - population rate equations
- takes into account
  non-equilibrium ionisation, excitation, and radiative energy exchange
  from the atomic species *H, He, and Ca*
  with back-coupling on the hydrodynamics
- adaptive mesh in one spatial dimension
- in the output:
  - population densities of all considered atomic levels

# NUMERICAL SIMULATIONS

***Simulation code RADYN*** *(Carlsson & Stein 1995)*

- lower and upper boundaries are both transmitting.

lower boundary

- located in the convection zone (z=-480 km below $\tau_{500}$ = 1)
- piston excites waves
- piston velocity based on observed Doppler-shifts
  *(FeI line at λ = 396.68nm, Lites et al. 1993)*

upper boundary condition

- at a height of 10 Mm
- represents a corona on top of the simulated layers
  *(T set to $10^6$ K + incident radiation; Tobiska 1991)*

# NUMERICAL SIMULATIONS

***Simulation code RADYN*** *(Carlsson & Stein 1995)*

***Model atoms:***

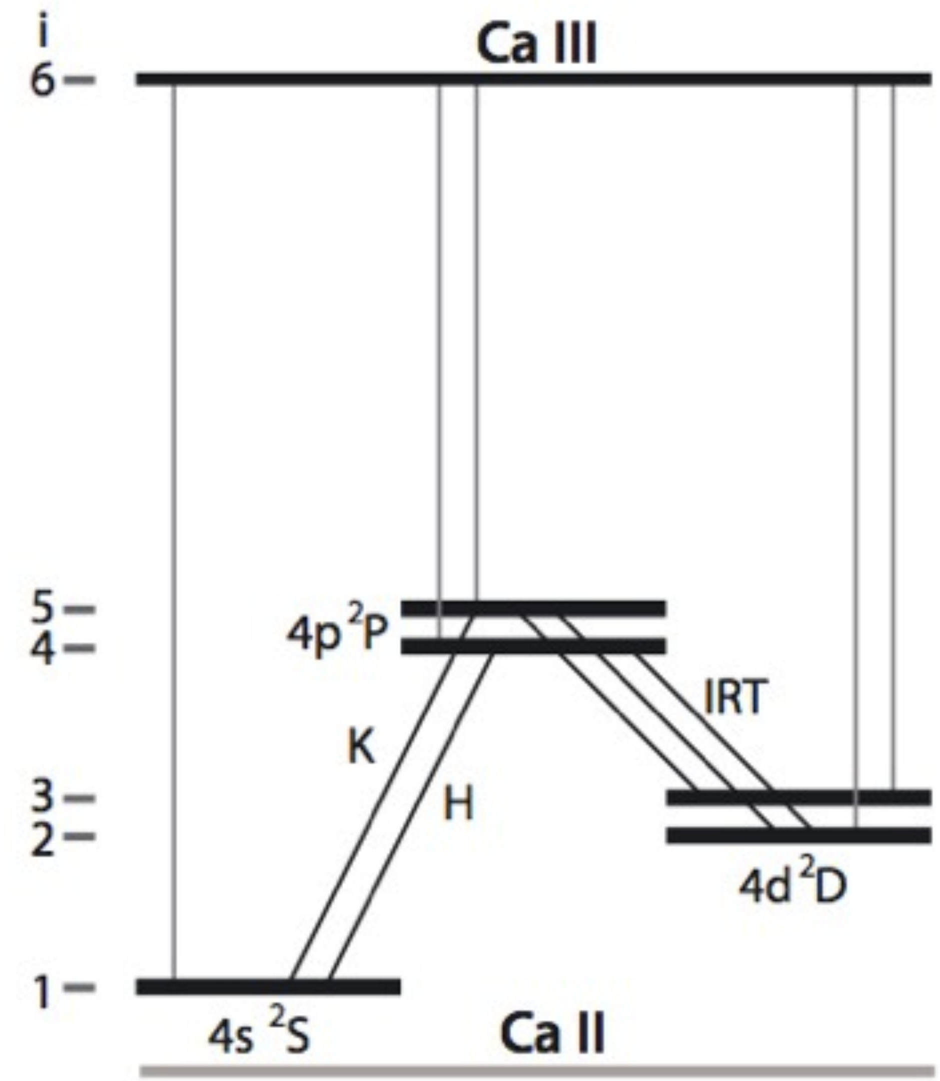
- 6-level atoms for H and Ca
- 9-level atom for He *(doubly ionised He included)*
- Transitions between all considered atomic levels treated in detail:
  - Radiative bound-bound transitions: 31−101 frequency points
  - Radiative bound-free transitions: 4−23 frequency points
- All other elements enter as background continua in LTE *(derived with the Uppsala atmospheres program; Gustafsson 1973)*

# NUMERICAL SIMULATIONS

## THE CALCIUM MODEL ATOM

***Energy levels:***

- 5 bound states of singly ionised Ca (Ca II)
  - lowest energy level *(i = 1)* is the ground state of Ca II (4s $^2$S)
  - two important energy level pairs
    - 4p $^2$P *(i = 2, 3)*
    - 4d $^2$D *(i= 4, 5)*
- continuum level *(i = 6)*
  - next ionisation stage (Ca III).



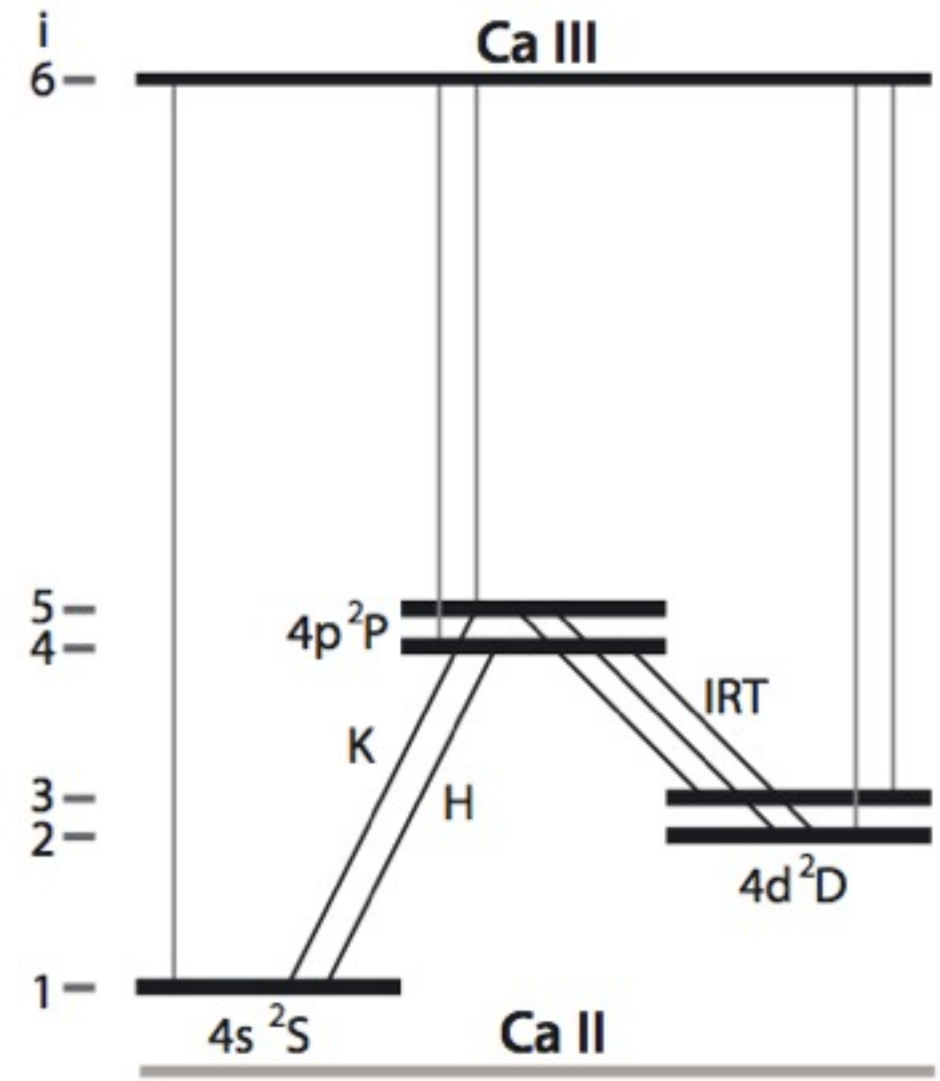
# NUMERICAL SIMULATIONS

## THE CALCIUM MODEL ATOM

**Radiative transitions:**

- all 5 allowed radiative bound-bound (b-b) transitions:
  - H + K resonance lines
  - infrared triplet (IRT)

- all 5 radiative bound-free (b-f) transitions
  with corresponding photoionisation continua from the 5 lowest levels to continuum level *i* = 6



# NUMERICAL SIMULATIONS

- (TD) Detailed time-dependent simulation
- (SE) large number of additional short simulation runs, starting from a statistical equilibrium solution (*used for timescale analysis*)

# IONISATION FRACTION

- ionisation fraction $$\chi_{\mathrm{Ca}} = \frac{n_{\mathrm{Ca\,III}}}{n_{\mathrm{Ca\,II}} + n_{\mathrm{Ca\,III}}} = \frac{n_6}{\sum_{i=1}^{6} n_i}$$

  *$n_i$ : population densities of the energy levels*

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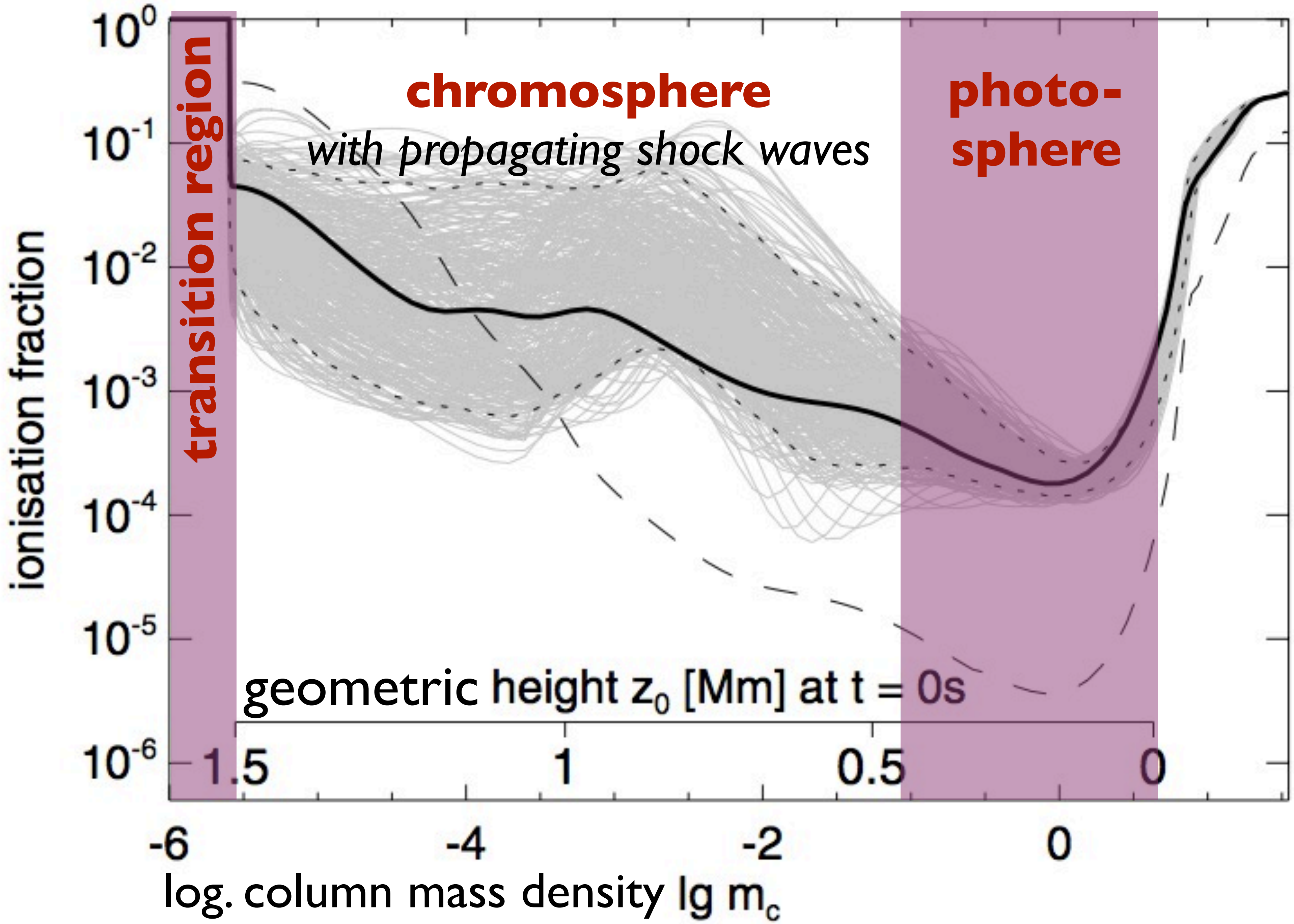

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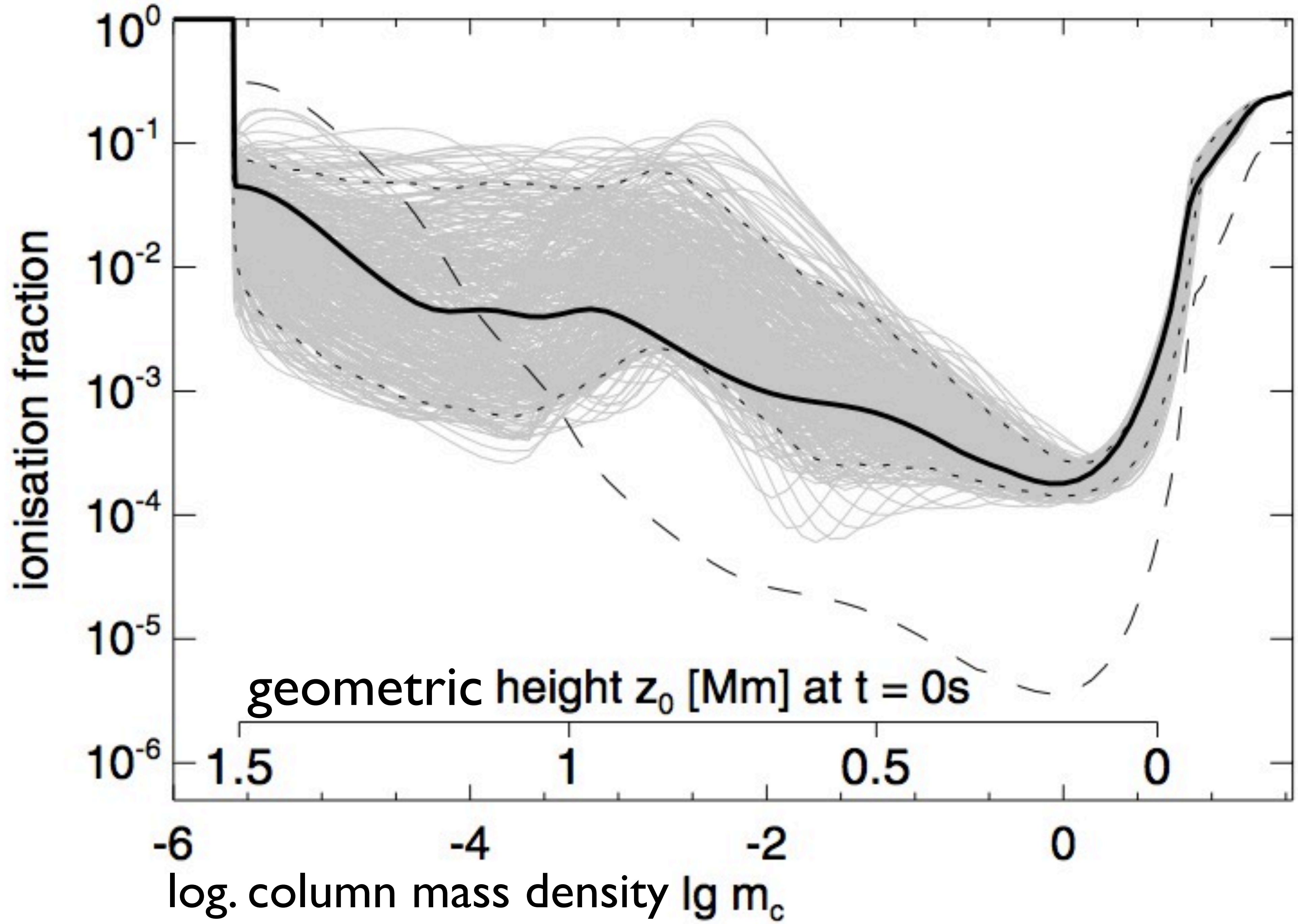

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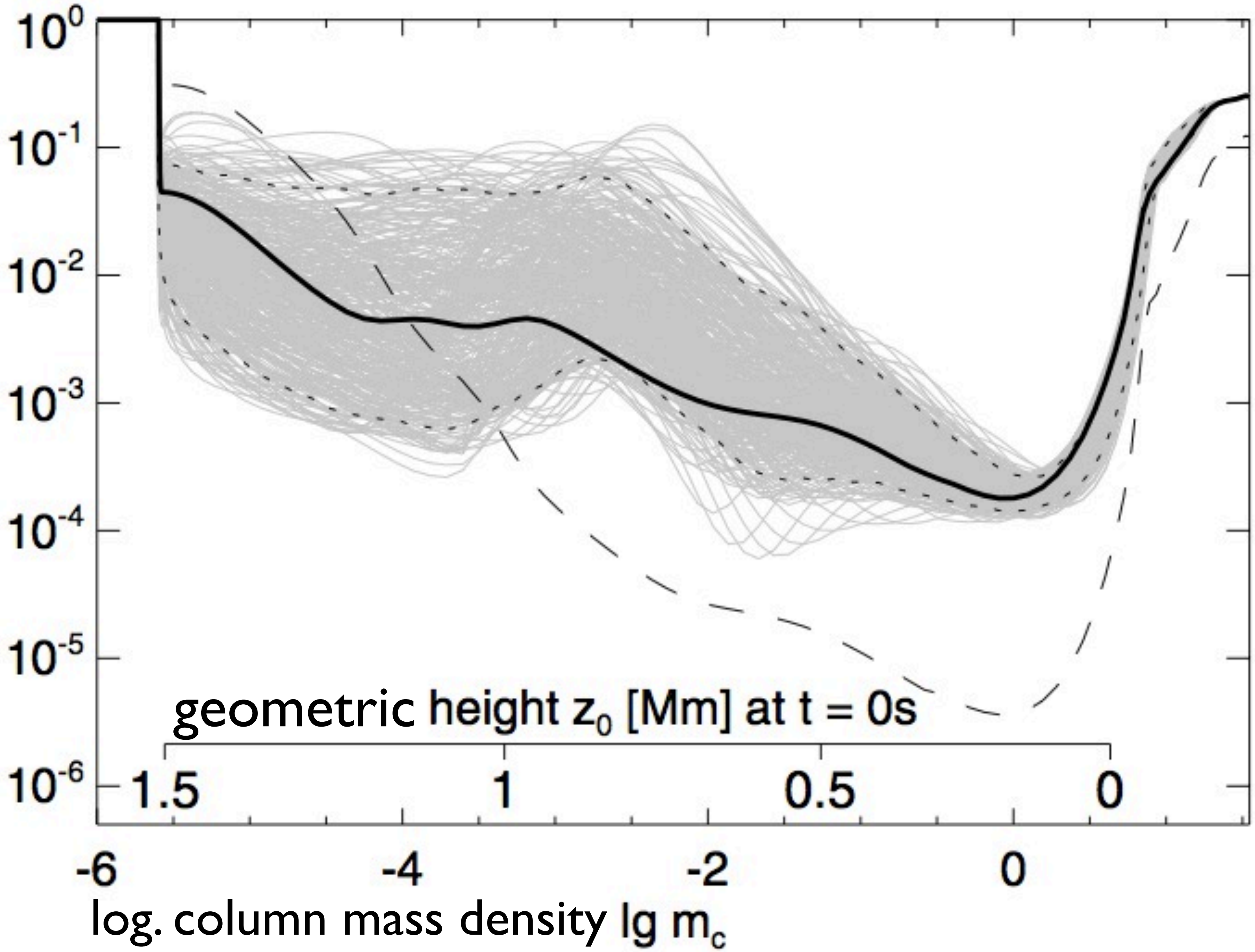


***thick solid:*** *initial radiative equilibrium atmosphere*

***grey lines:*** *all simulation snapshots (here with cadence 10s)*

*dashed: H ionisation fraction (in initial atmosphere)*

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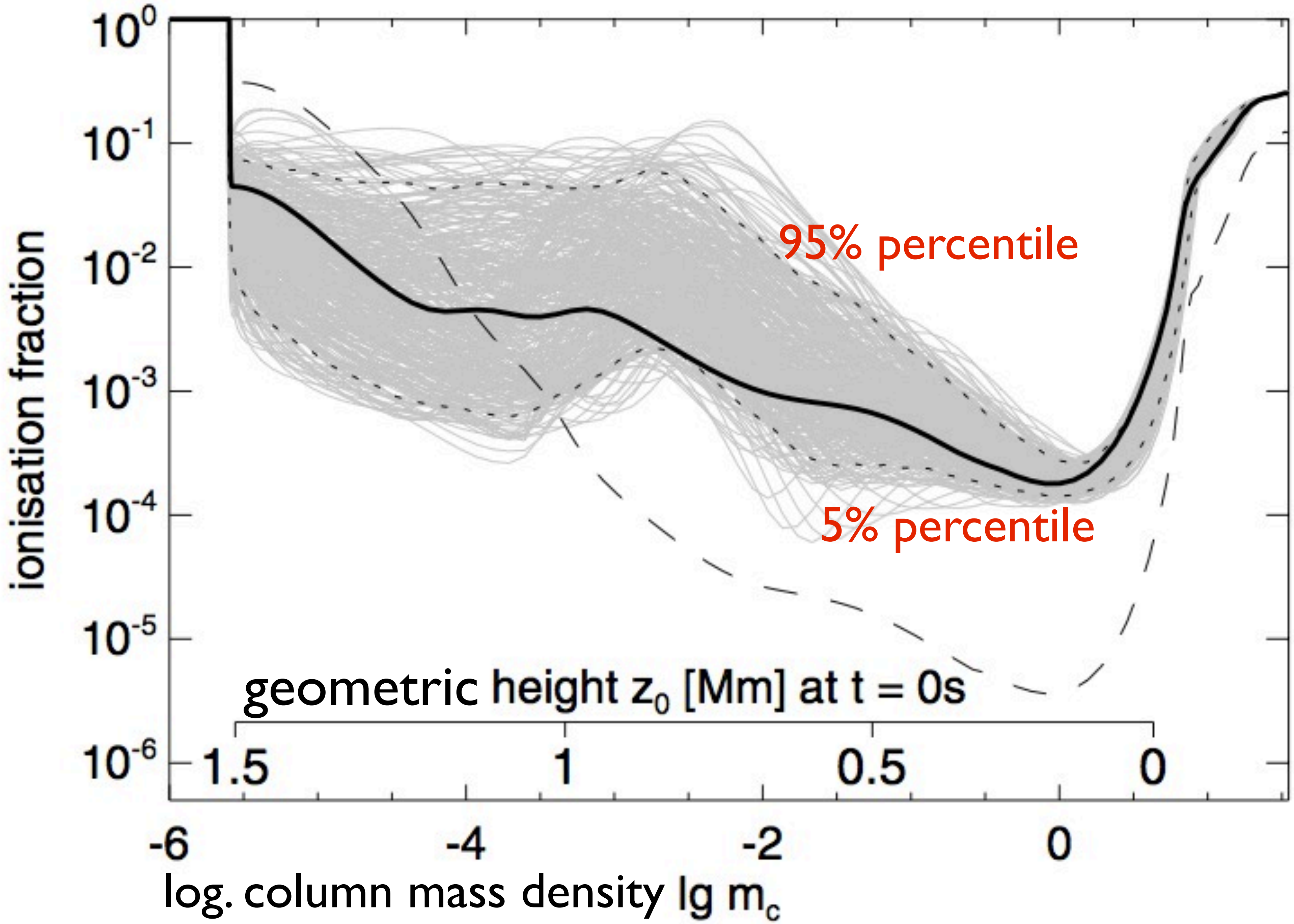


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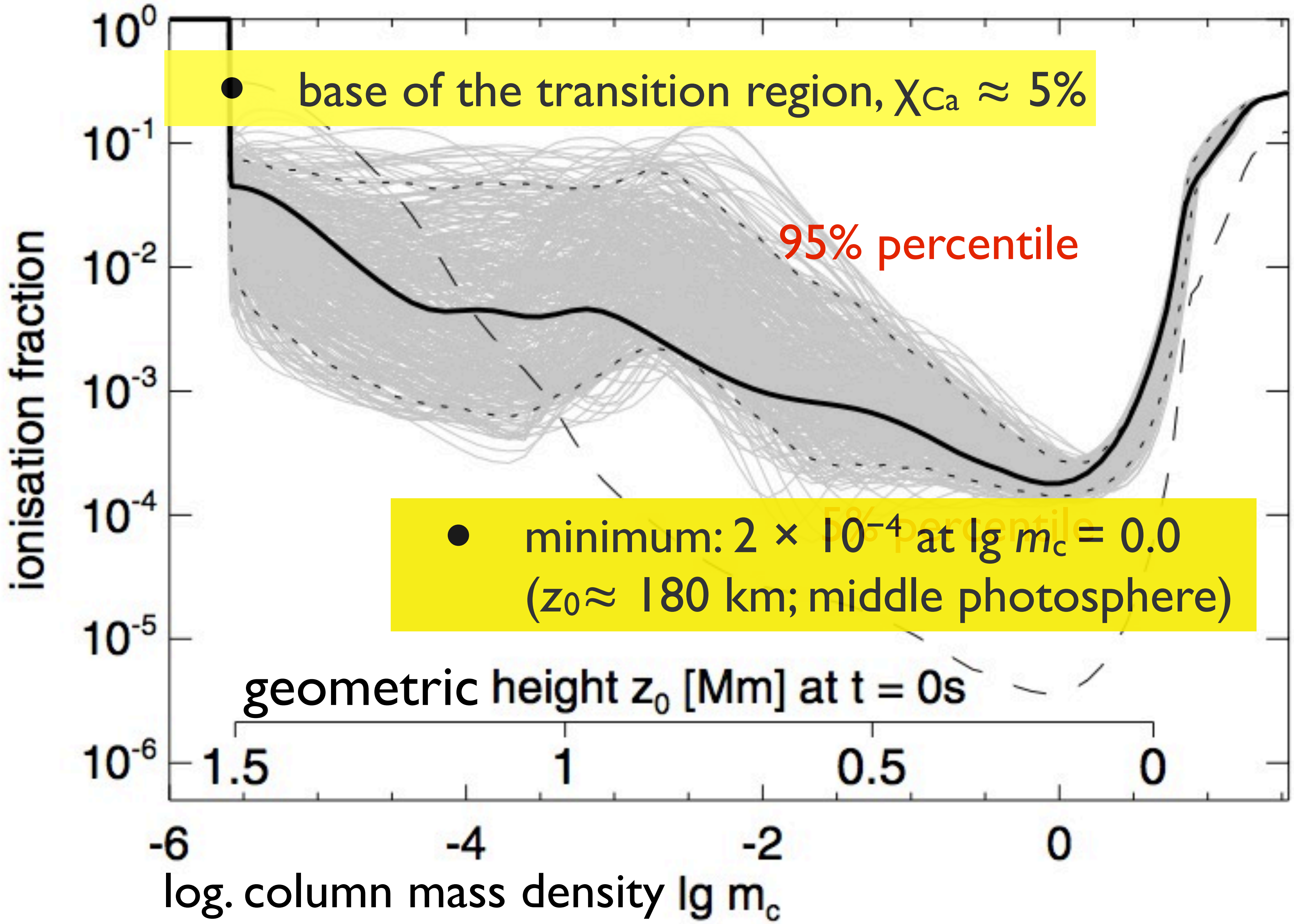


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*dashed:*
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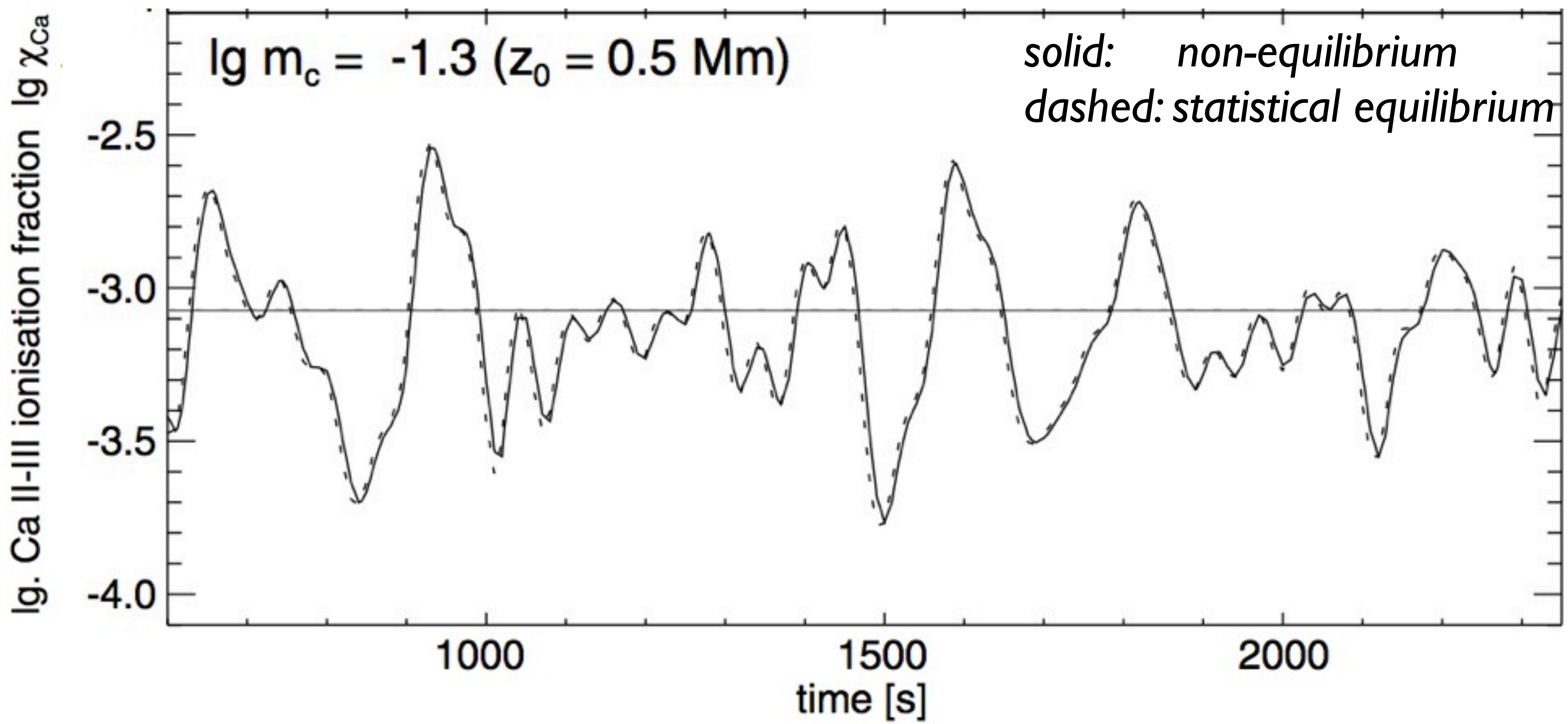
# IONISATION FRACTION

## *Temporal evolution at a fixed height*

### *top of photosphere/low chromosphere*

- Variation of one order of magnitude (min. to max.)
- Essentially ***no*** difference between equilibrium and detailed non-equilibrium solution



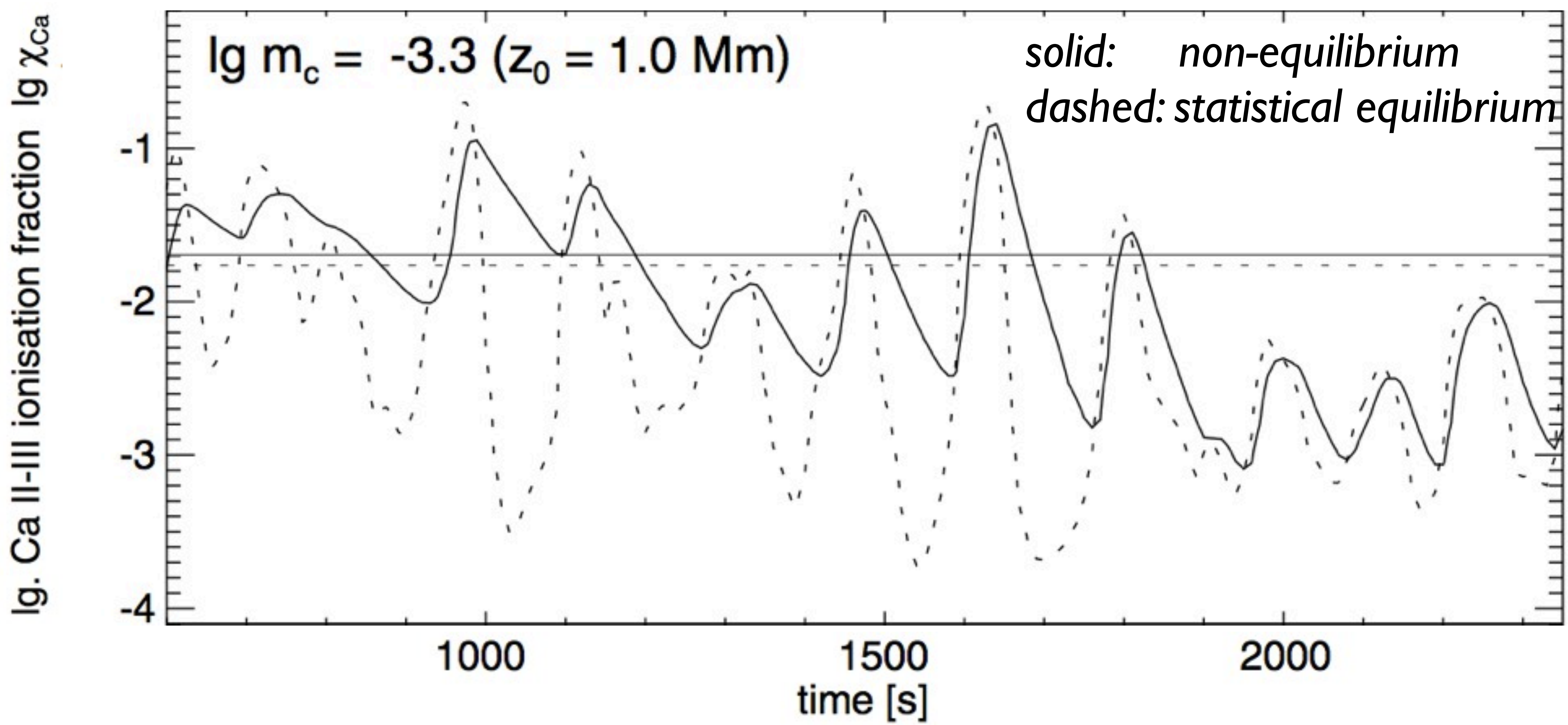
# IONISATION FRACTION

## *Temporal evolution at a fixed height*

### *middle chromosphere*

- Variations: two (or more) orders of magnitude
- Non-equilibrium ion. fraction decreases slower after shock wave passage

➡ Does not reach as small values as in equilibrium case

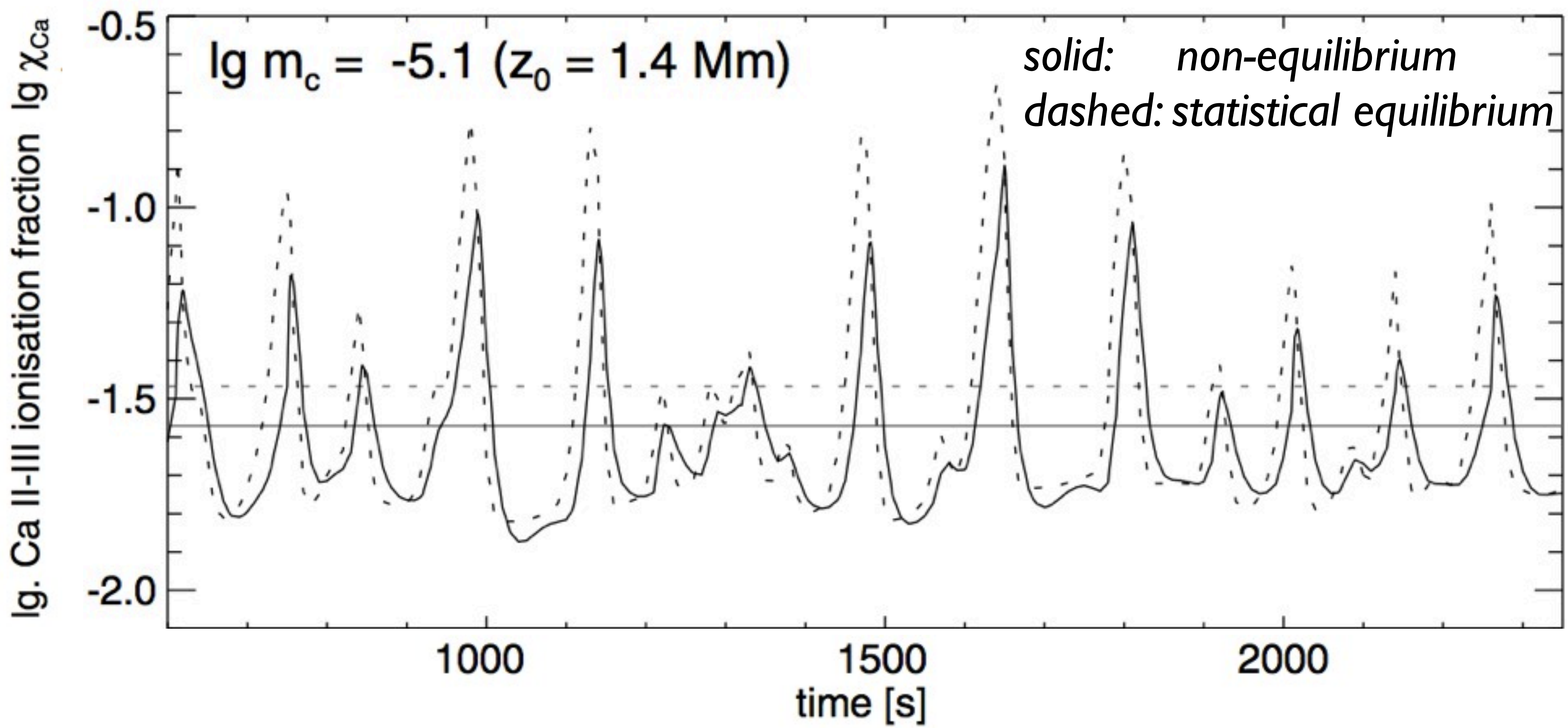


# IONISATION FRACTION

## *Temporal evolution at a fixed height*

### *middle-upper chromosphere*

- Variations: up to one order of magnitude
- small differences between equilibrium and non-equilibrium solutions
- non-equilibrium: peaks smaller and with a small time delay (few s)



# IONISATION FRACTION

## *Summary*

***low atmosphere (below the middle photosphere)***

- small variations
- minimum of $2 \times 10^{-4}$ in the middle photosphere
- Statistical equilibrium assumption valid.

***chromosphere***

- varies strongly in chromosphere due to the passage of shock waves (two orders of magnitude)
- rises with height but less steep than for H
- Relaxes slower after shock wave passage *(compared to statistical equilibrium)*

***transition region***

- reaches maximum $\chi_{Ca} \approx 5\%$ at the base of the transition region

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Relaxation time scale?

***Under which conditions is a detailed non-equilibrium treatment necessary?***

# RELAXATION TIME SCALE

## *Calculation of the relaxation time scale*

- ***Method 1:*** numerically from the temporal evolution of an initially perturbed atmosphere
- ***Method 2:*** eigenvalue analysis of the rate matrices

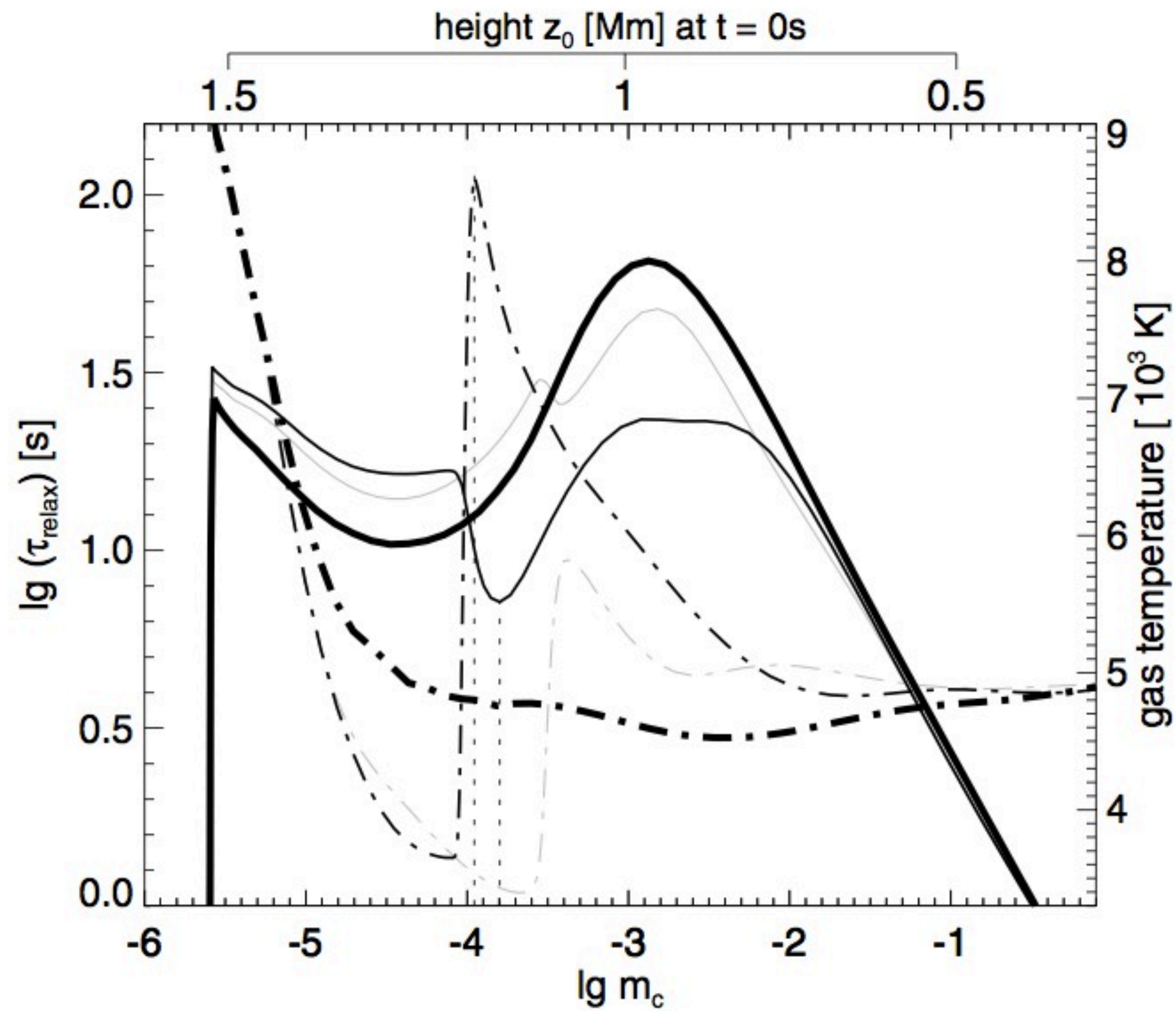
# RELAXATION TIME SCALE

## *Calculation of the relaxation time scale*

- ***Method 1:*** numerically from the temporal evolution of an initially perturbed atmosphere

- Large number of additional short simulation runs
- Each run starts from a snapshot of the non-equilibrium (TD) sim.
- Initial atmosphere with statistical equilibrium (SE) solution
- Next time step: atmosphere perturbed by increasing the gas temperature by 1%
- Time-evolution followed for 50 s
- *In addition, calculation of the SE state of the perturbed atmosphere.*

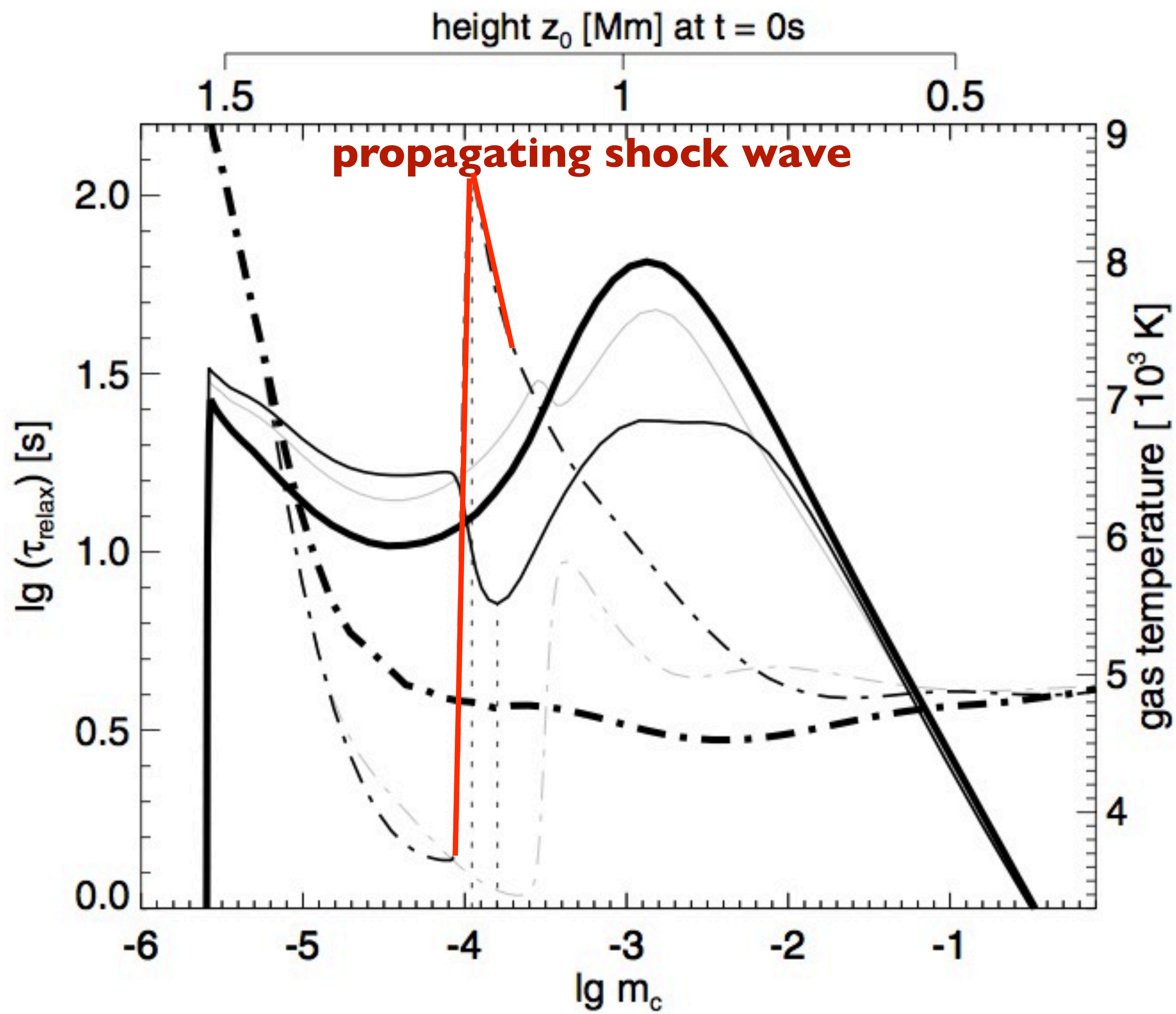
# RELAXATION TIME SCALE




dot-dashed: gas temperature
solid: log. relaxation time scale

thin: exemplary snapshot
thick: temporal average

# RELAXATION TIME SCALE

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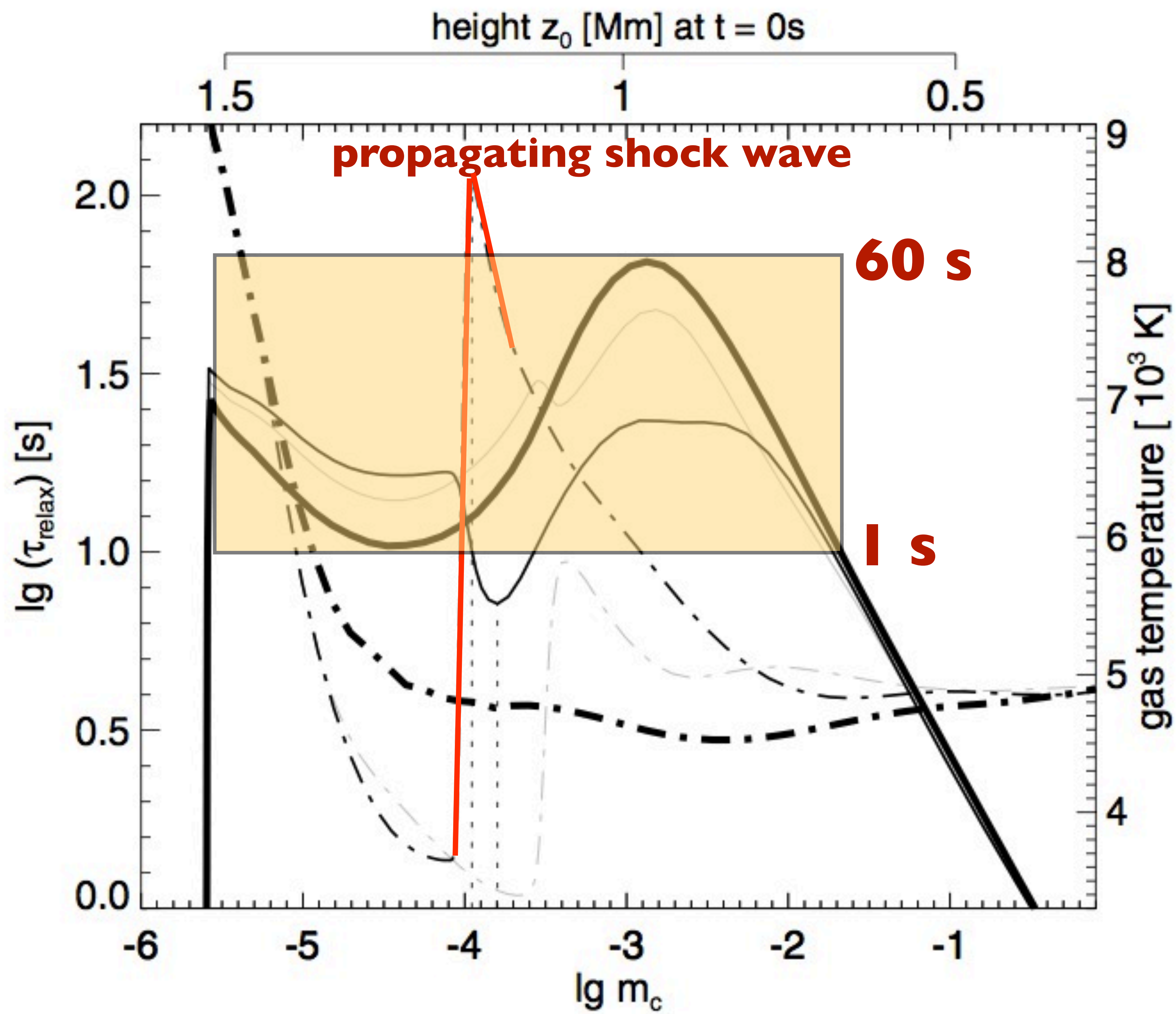
# RELAXATION TIME SCALE

- photosphere:
  well below 1 s
- chromosphere:
  mostly between 1s and 60s
- interval between consequent shock waves ~120 -180s

➡ 60s "critical"

➡ explains the noticeable influence of the non-equilibrium treatment

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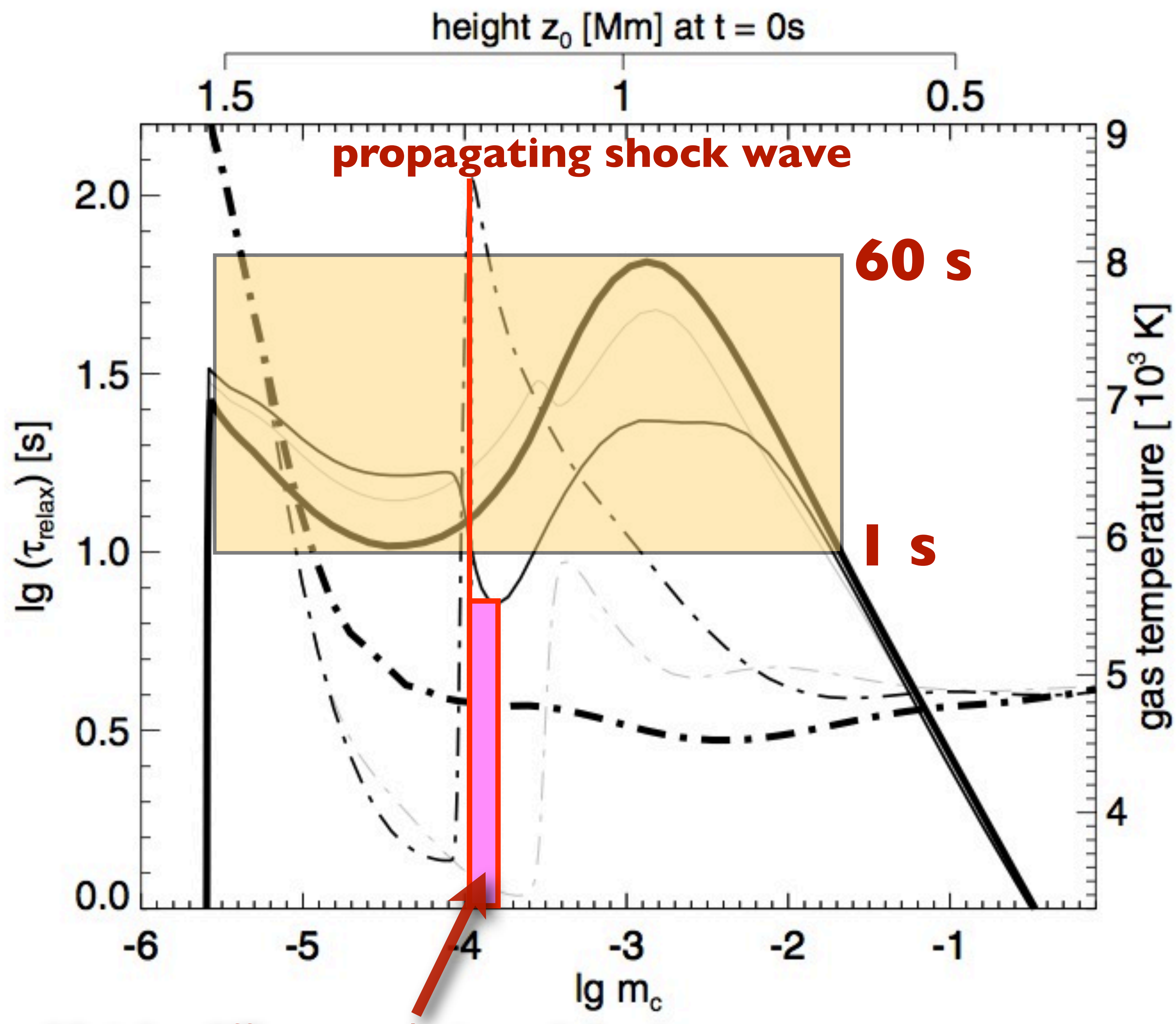


Height difference / time delay between temperature peak and minimum relaxation time scale

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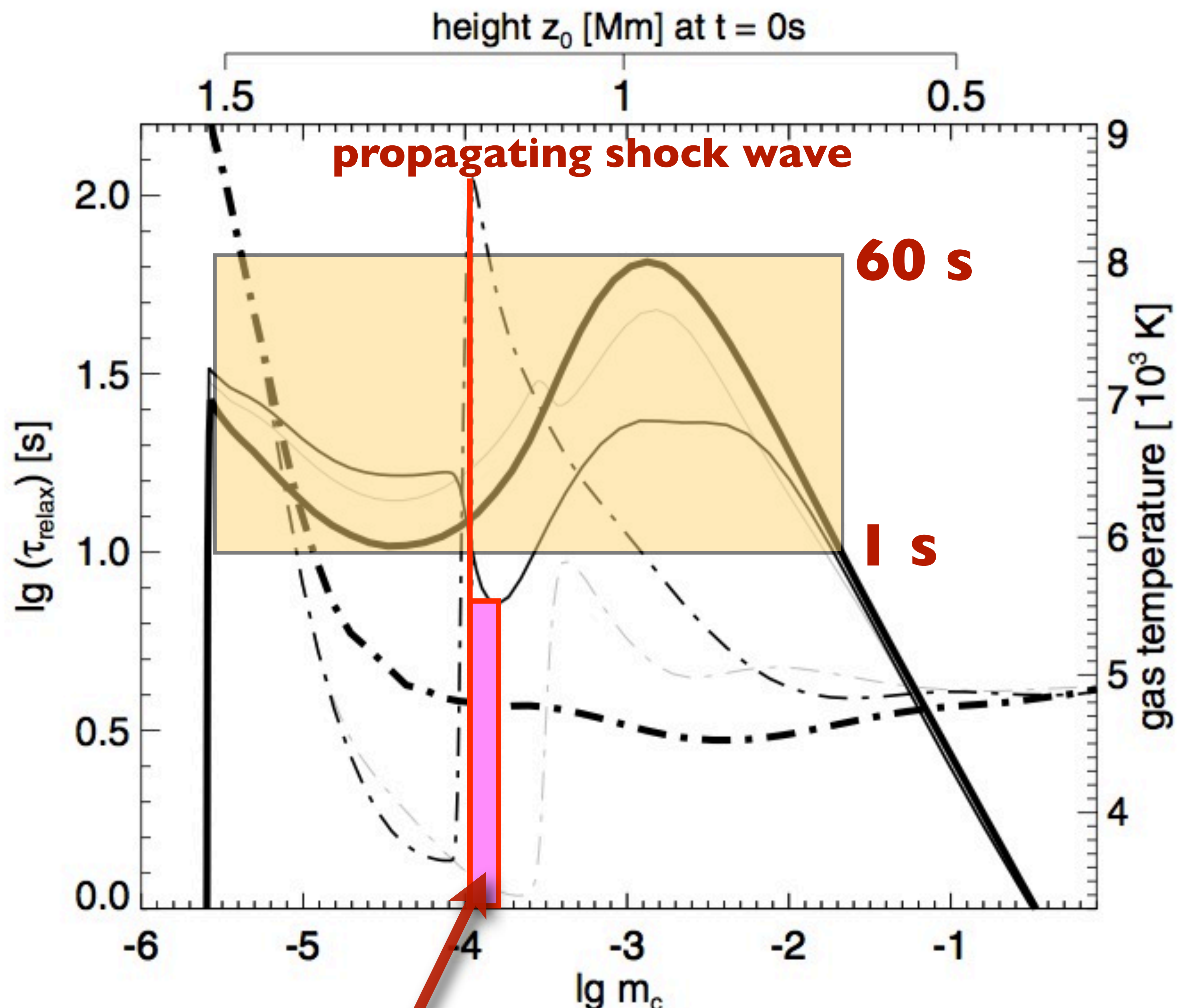


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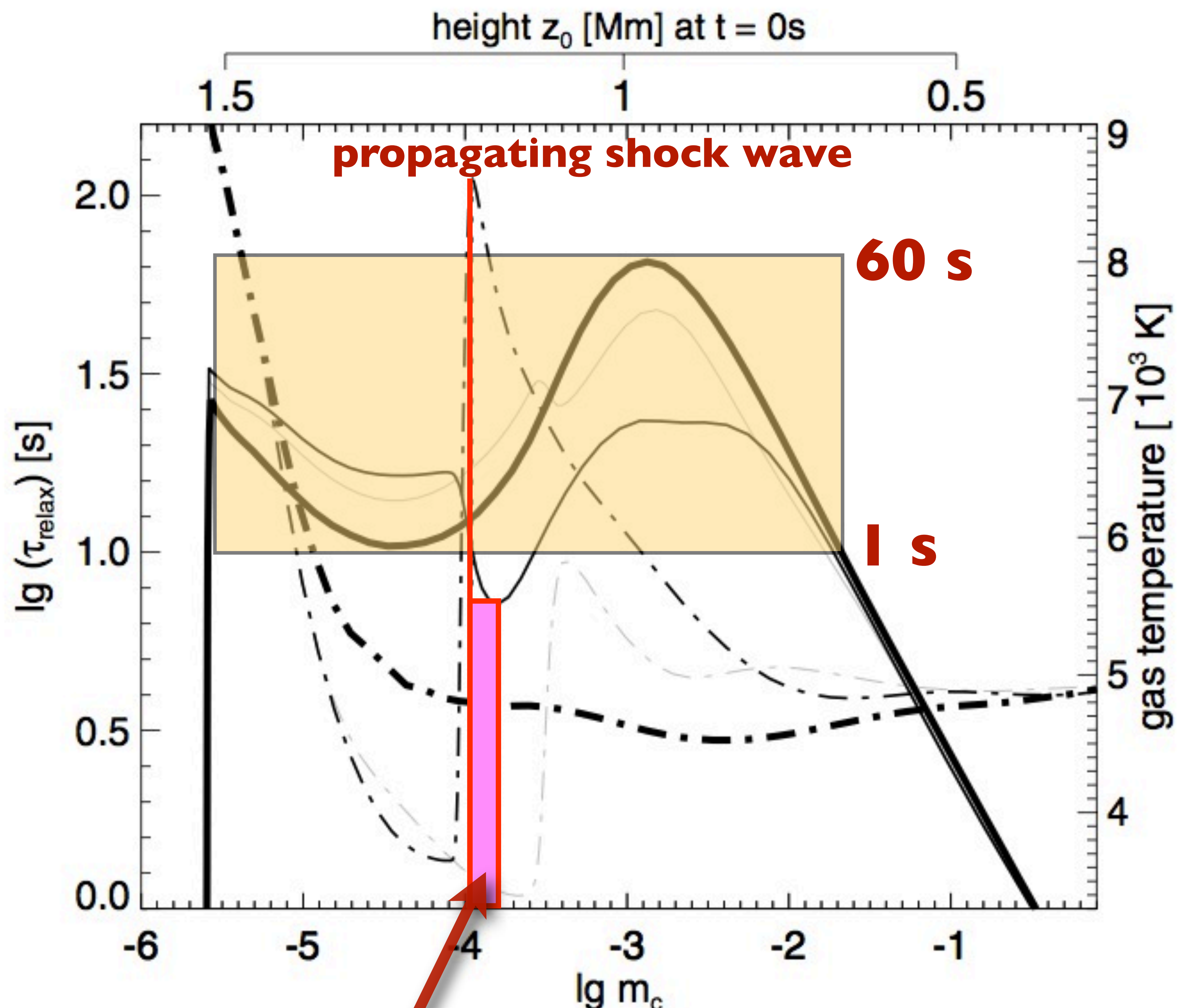
# RELAXATION TIME SCALE

What is causing this offset?

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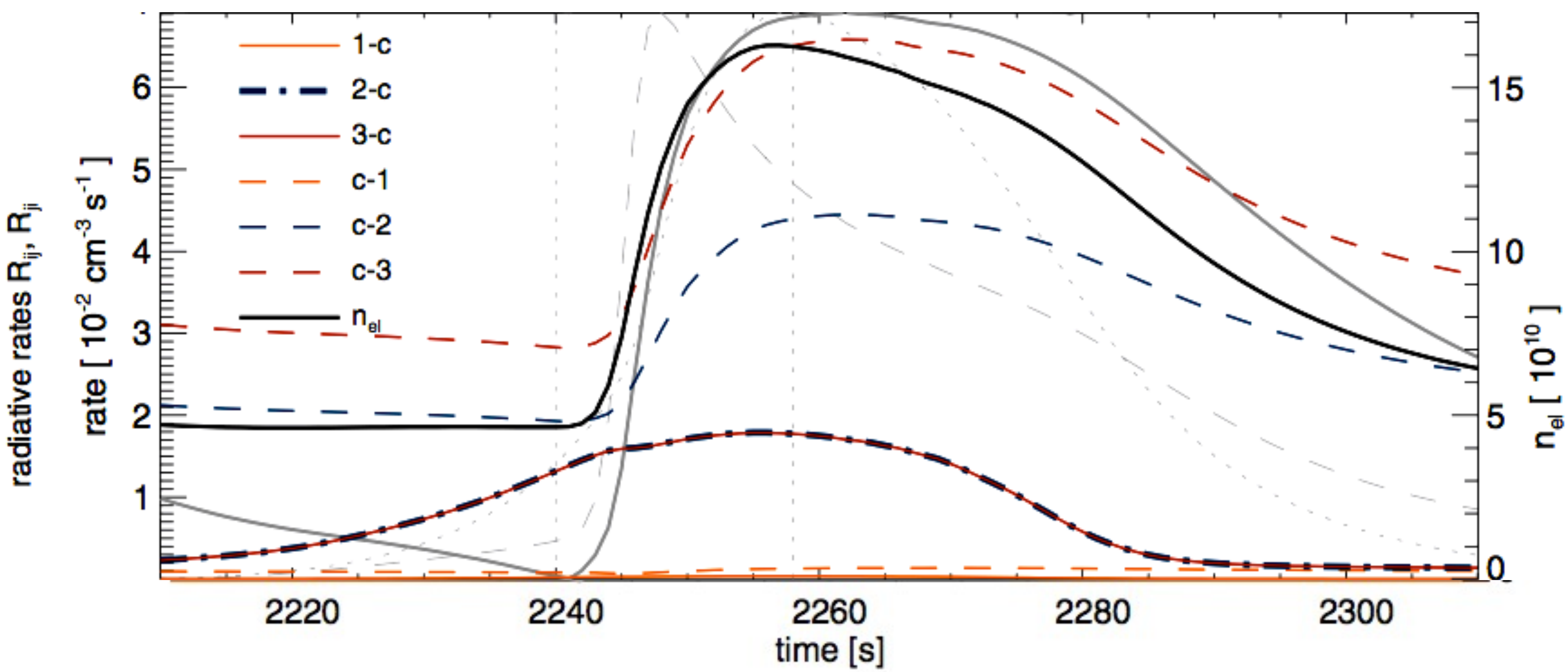
# TRANSITION RATE ANALYSIS

***Cause of the time delay?***

***Detailed analysis of temporal behaviour of the radiative rates of all b-f transitions.***



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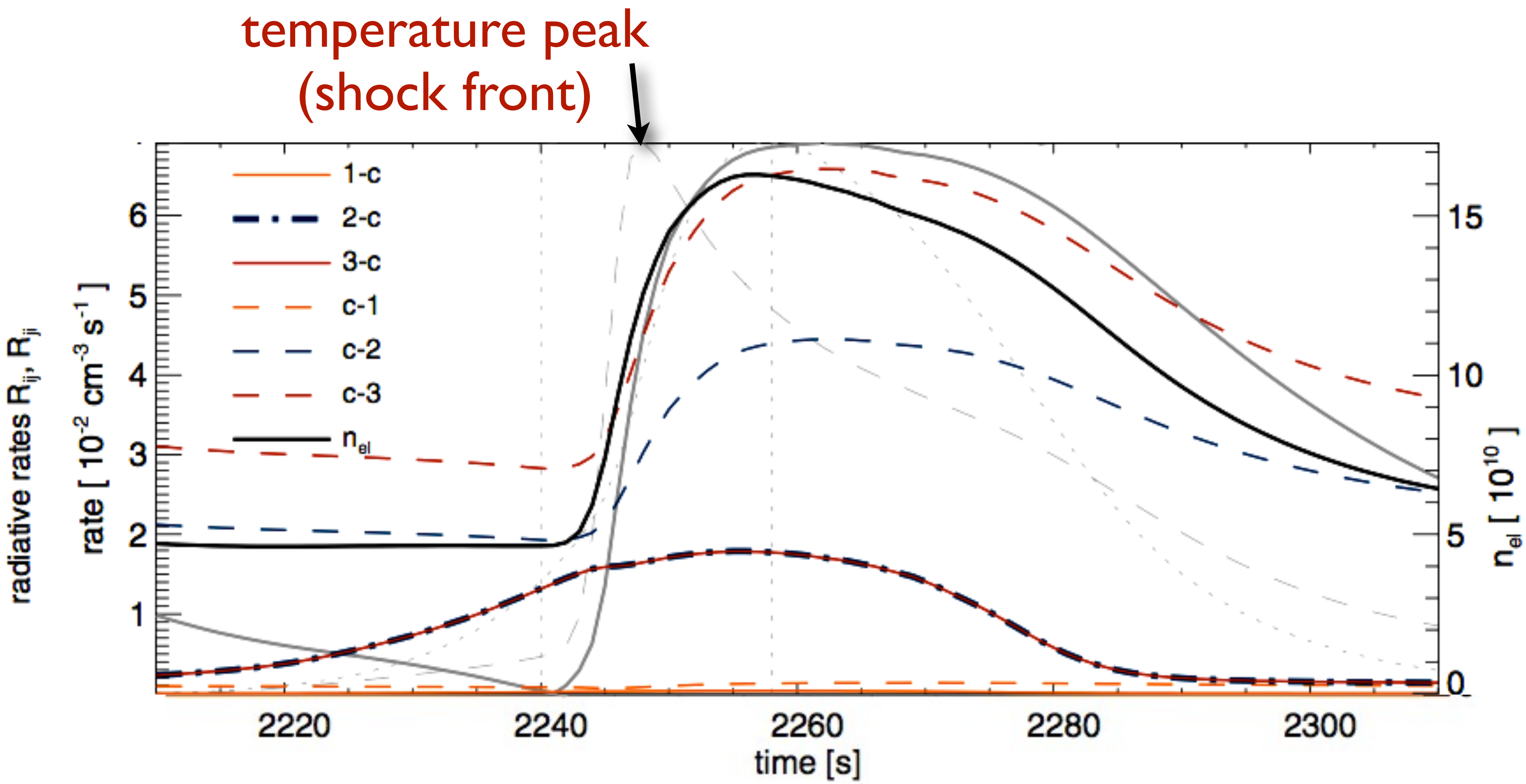

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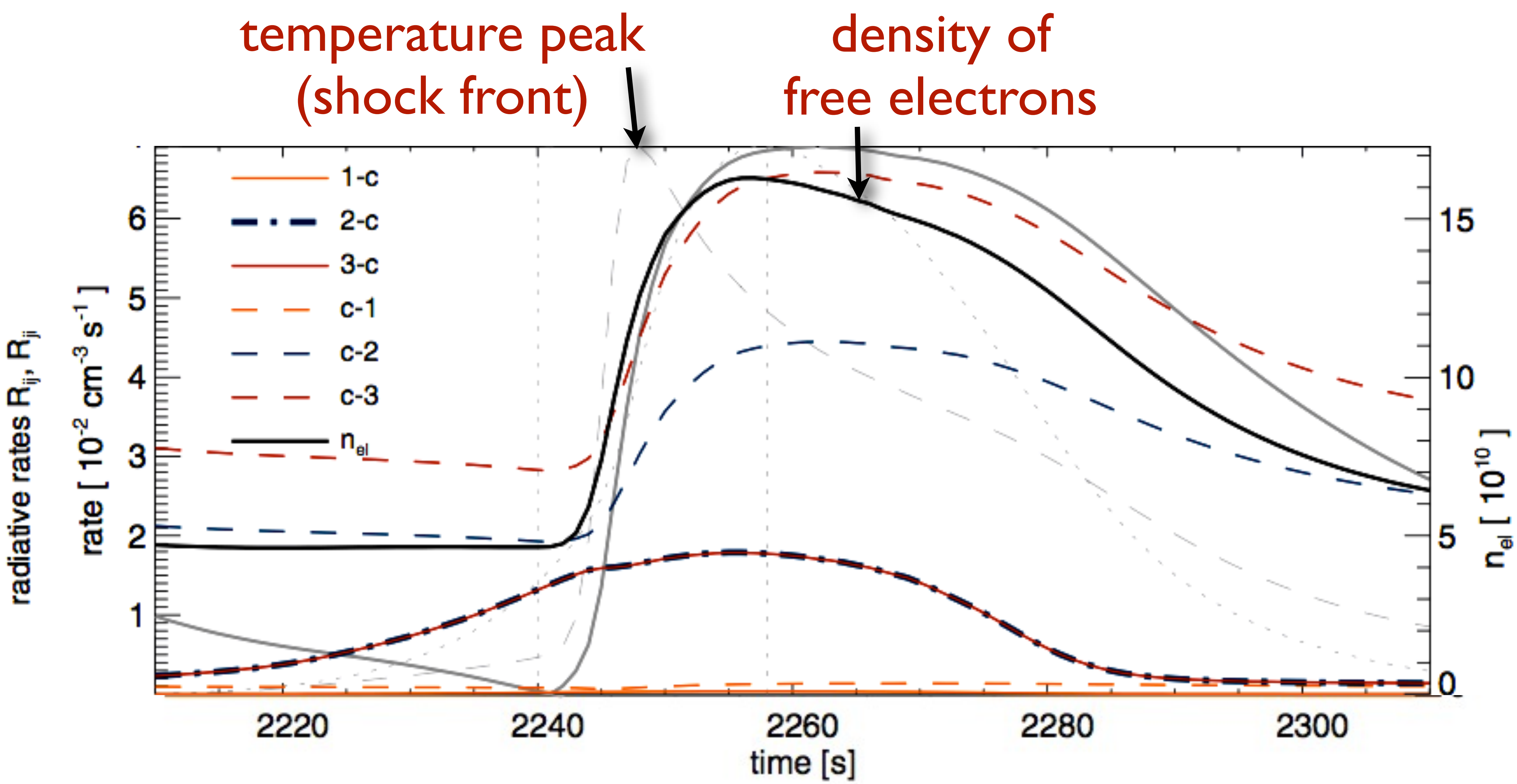

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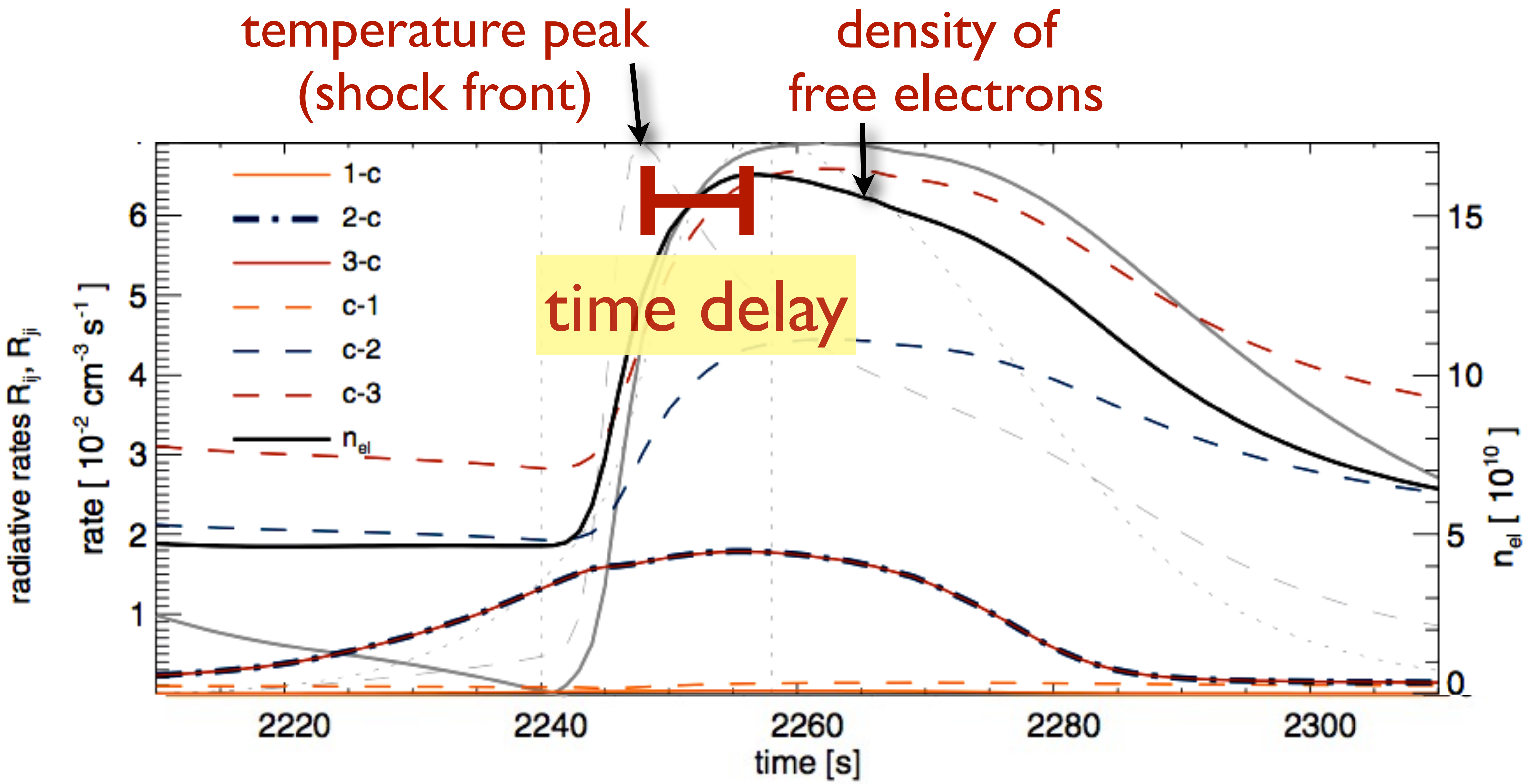


# TRANSITION RATE ANALYSIS

***Cause of the time delay:***

- recombination process involves a collision between a free electron and a Ca III ion *(see, e.g., Mihalas 1978, p. 130f)*

- ***free electrons:***
  - Ca only a minor electron donor
  - Small changes in H ionisation fraction can lead to significant fluctuations of the electron density.

- ***H ionisation***/recombination timescale in the chromosphere:
  - on average on the order of one to several hours
  - strongly reduced in hot shock fronts, down to 10 s to 20 s.

➡ delayed release of electrons

➡ direct effect on the recombination rates of Ca

➡ related timescales reach minimum only shortly after the occurrence of temperature peak

# SPECTRUM SYNTHESIS

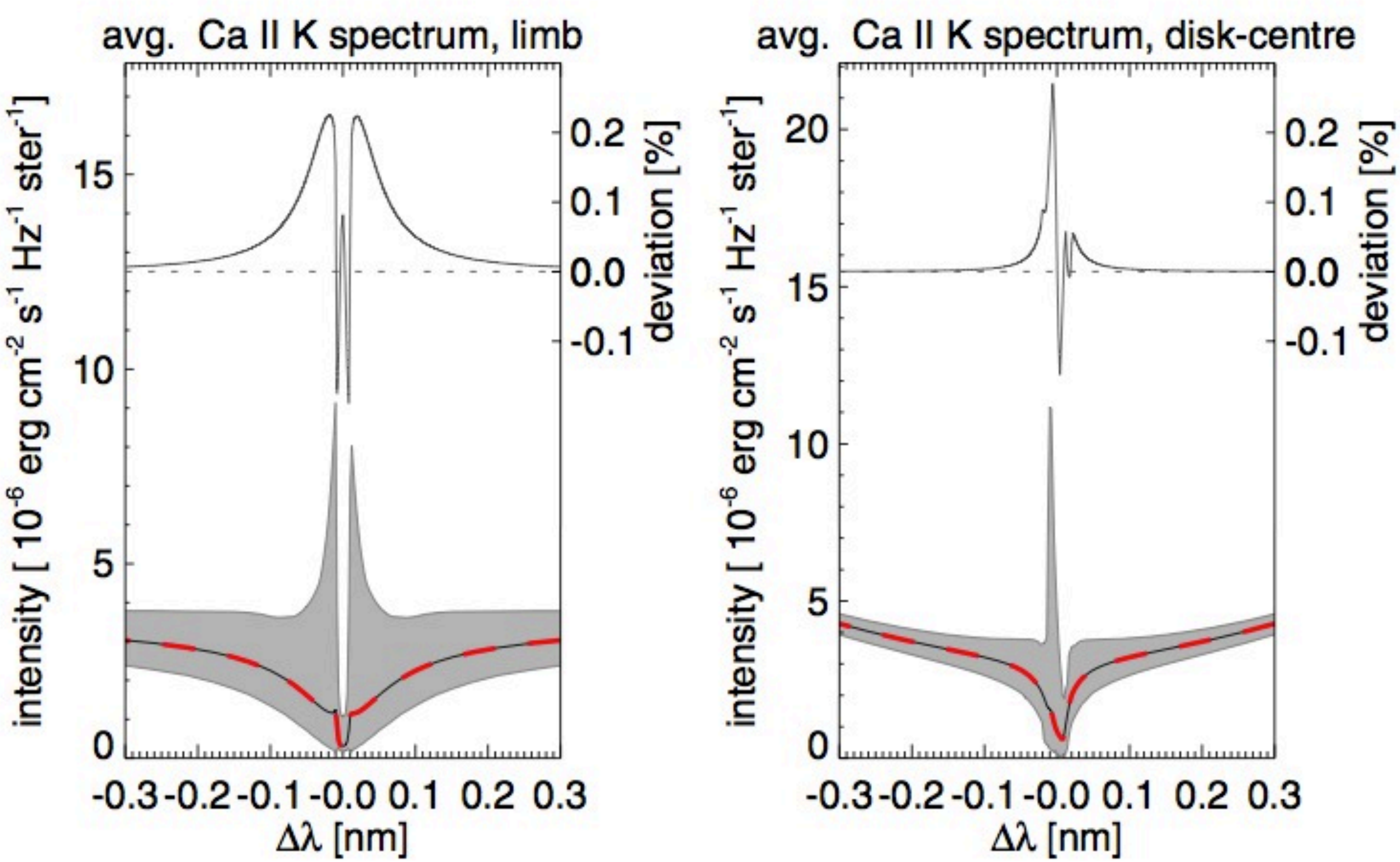
- Are the non-equilibrium effects measurable?
- Comparison of the spectral line profiles (here Ca K) based on the non-equilibrium and equilibrium solution

time-average

black:
avg. non-equilibrium

grey area:
full intensity range covered during the time sequence

red dashed:
avg. equilibrium



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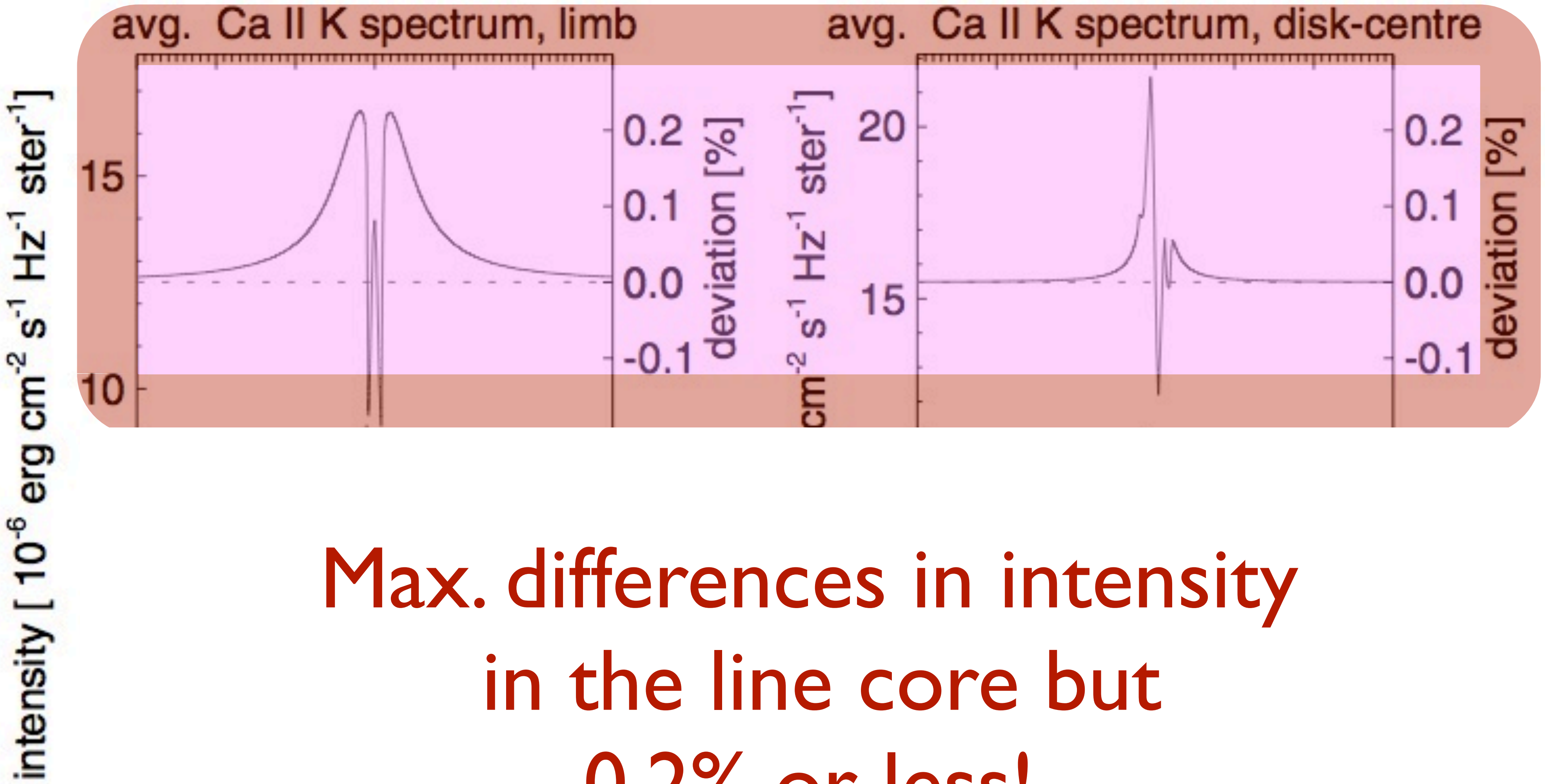
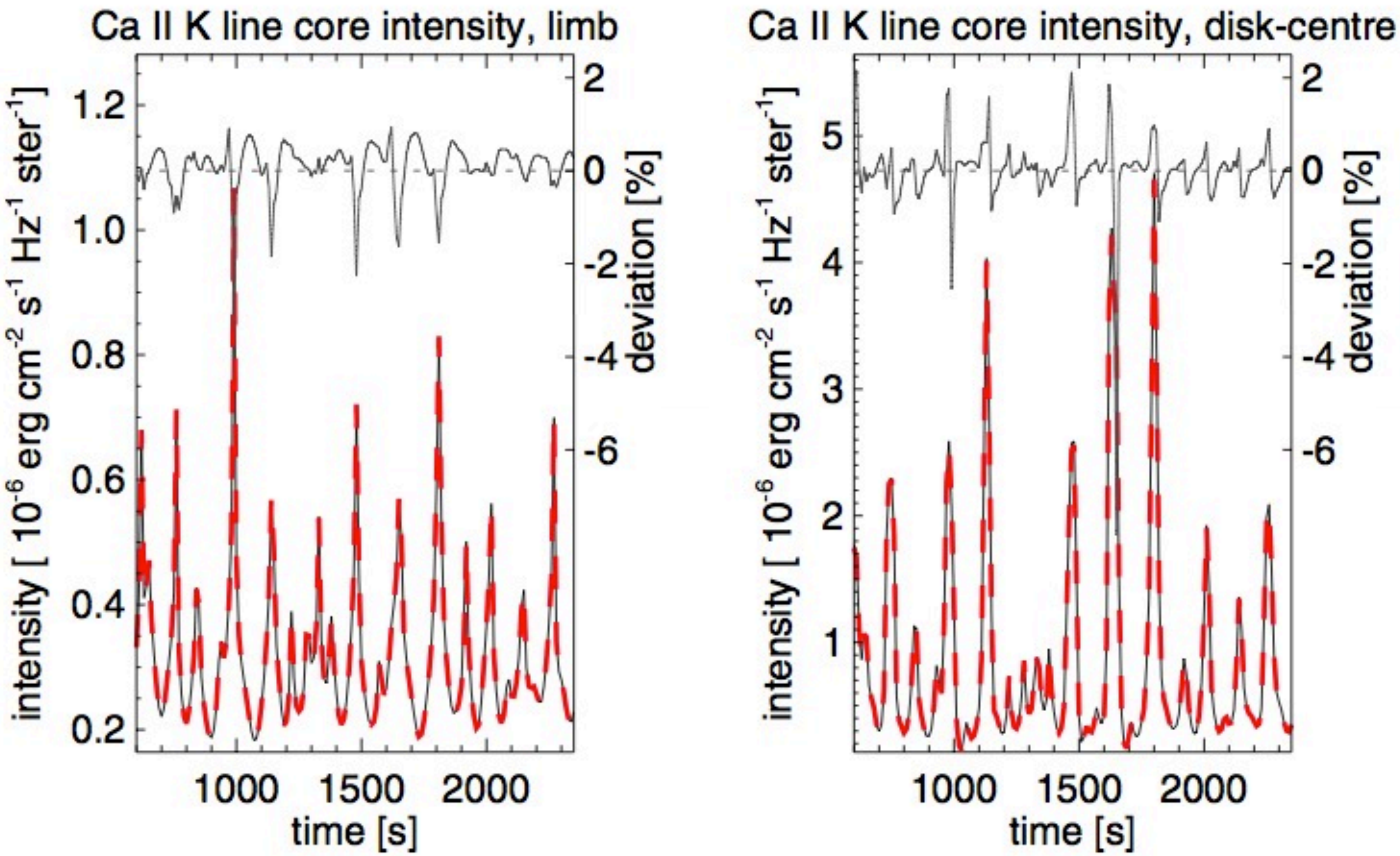



Max. differences in intensity in the line core but 0.2% or less!

# SPECTRUM SYNTHESIS

- same for the time evolution of the line core intensity:
- differences very small *(peaks with a few percent)*



# CONCLUSIONS

- ***Ionisation/recombination timescales too long for assumption of instantaneous ionisation equilibrium but not long for the assumption of a constant ionisation fraction***
  *(for the considered conditions in the quiet solar chromosphere)*

- Ca II-III ionisation fraction generally small
- BUT noticeable deviations from ionisation equilibrium in the middle chromosphere
- error due to assumption of statistical equilibrium is therefore negligible for most applications
- e.g. , effect barely visible in synthesized intensity for the diagnostically important spectral lines of Ca II, i.e., the H and K lines and the infrared triplet