Modelling the Solar Transition Region using a Jump Condition

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Overview

Introduction:

- Solar Atmosphere
- Transition Region.
- Chromospheric Evaporation.
- Importance of Transition Region Resolution.

Modelling the Solar Transition Region using a Jump Condition:

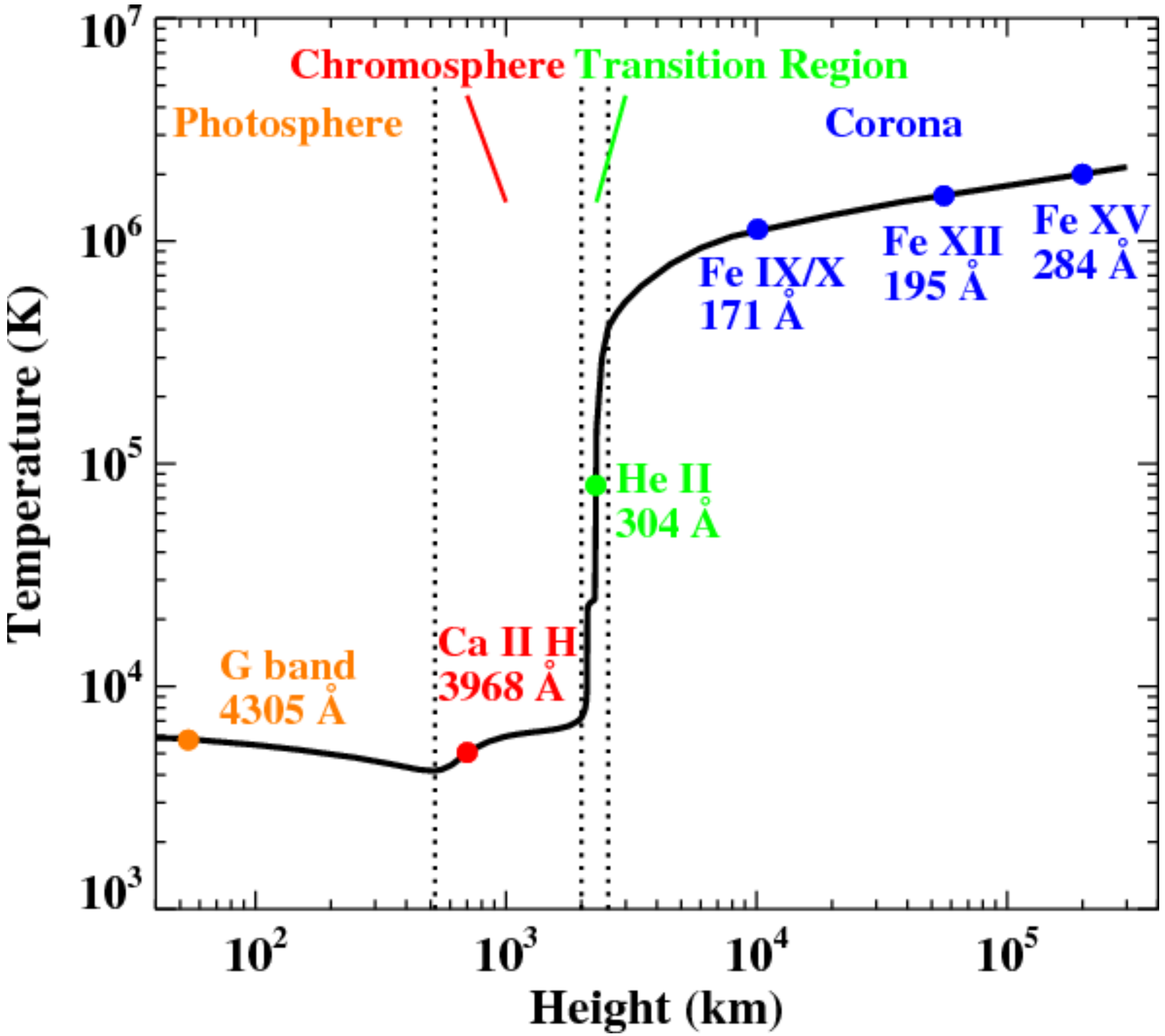
- Uniform Heating (Johnston et al. 2017a).
- Non-Uniform Heating (Johnston et al. 2017b).

Modelling Thermal Non-equilibrium & the Effect on TNE Cycles of :

- Spatial Resolution in the Transition Region (Johnston et al. 2018 *in prep*).
- Background Heating.

Conclusions.

The Solar Atmosphere



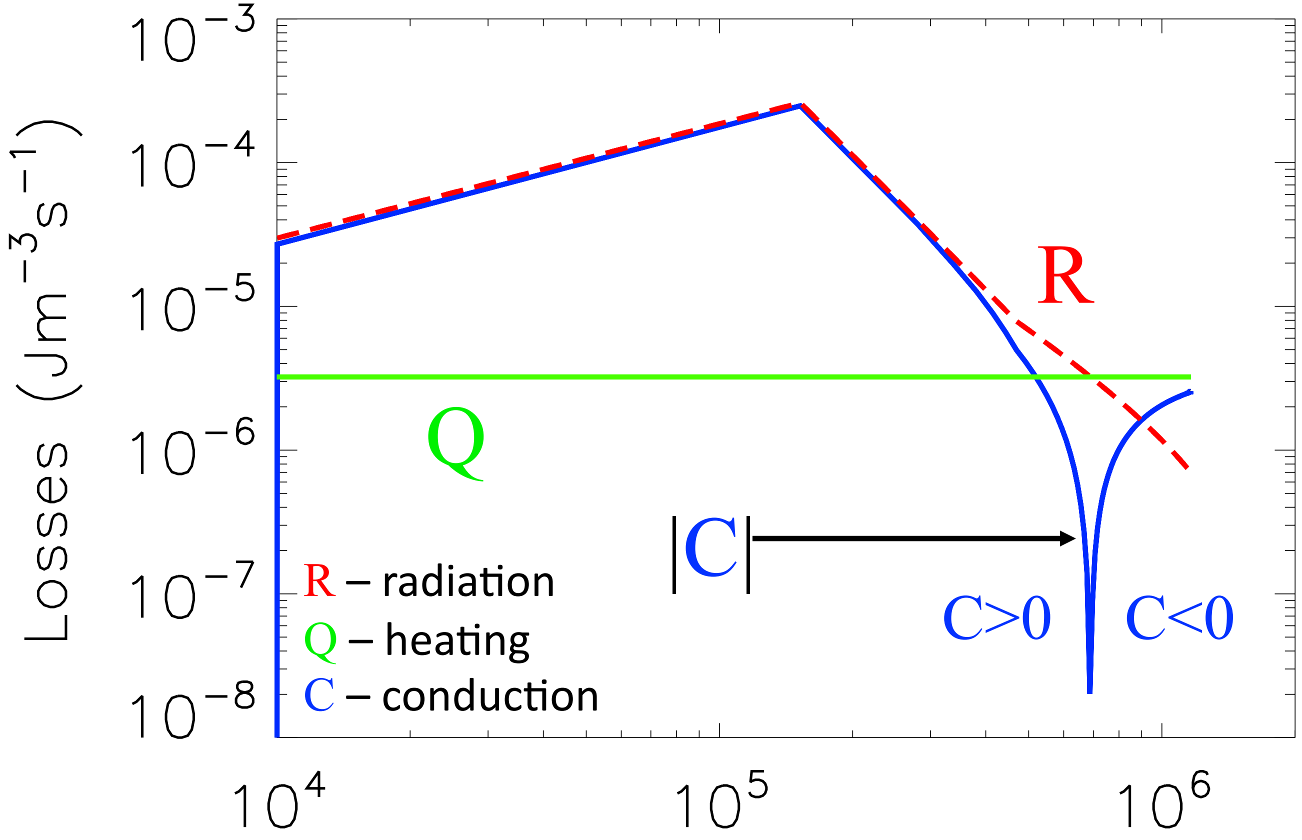
sdo.gsfc.nasa.gov

The Transition Region

TR radiative losses CAN BE more important than coronal losses.

Emission measure is proportional to n^2.

For a static loop, the top of the TR is where conduction changes from an energy loss to an energy gain.



Energy balance is between conduction and radiation, $\frac{\kappa_o T^{7/2}}{L_T^2} \sim n^2 \Lambda(T)$.

As radiation increases, T gradient must steepen so $\ell \ll L$. Difficult to resolve L_T^2 below $10^5 K$.

Changes in density can only be accounted for by mass exchange between the corona and chromosphere, controlled by the energy balance in the TR (chromospheric evaporation).

What is Chromospheric Evaporation?

Response of an equilibrium coronal loop to a heating event:

Coronal temperature increases rapidly.

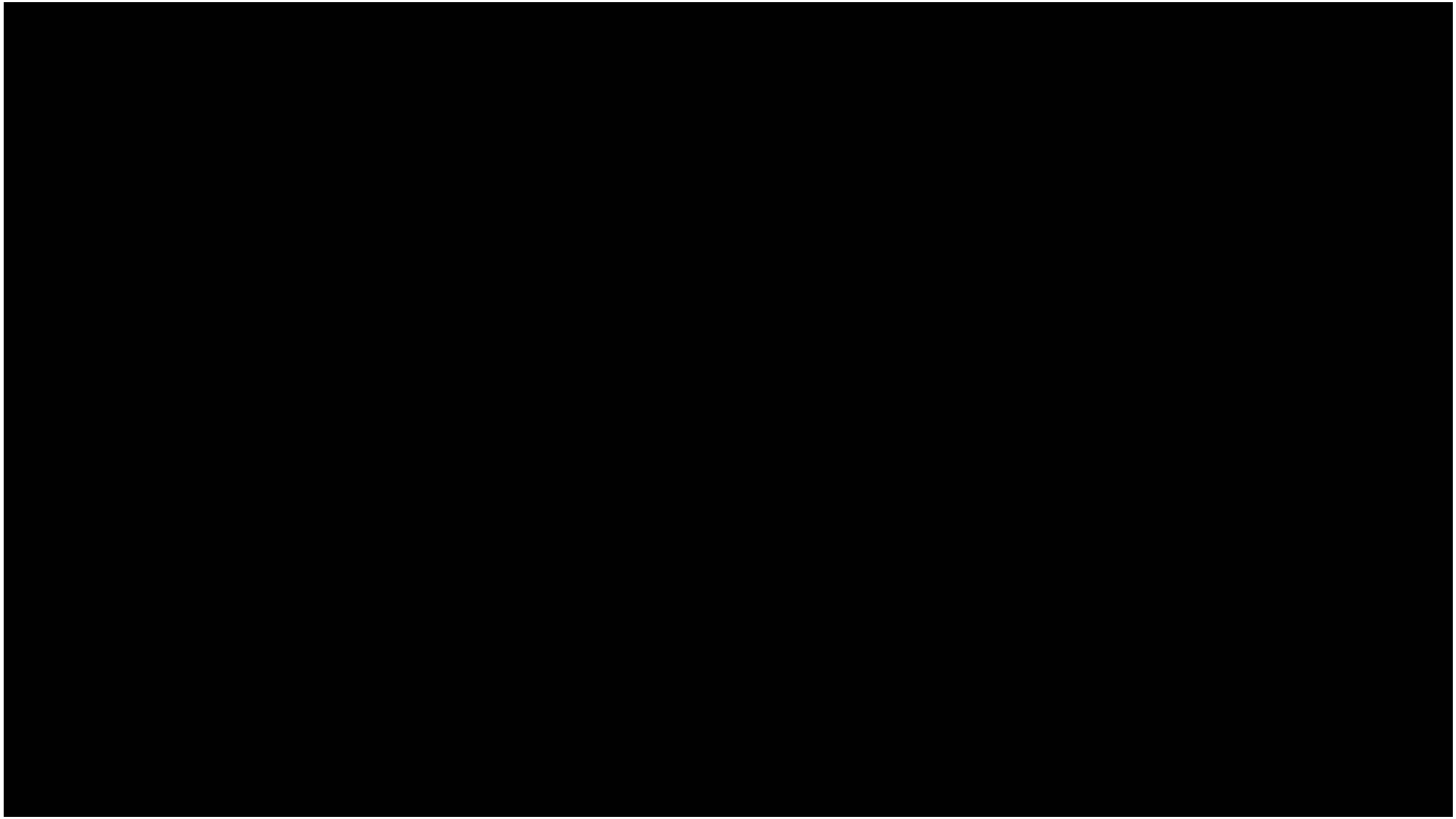
Drives an enhanced conductive flux downwards into the TR.

Upward pressure gradient exceeds gravity.

Transports density upwards (enthalpy flux).

Explanation for the observations of dense coronal loops that are draining.

nasa.gov/missions/trace



Post Flare Loops, 15th October 2014

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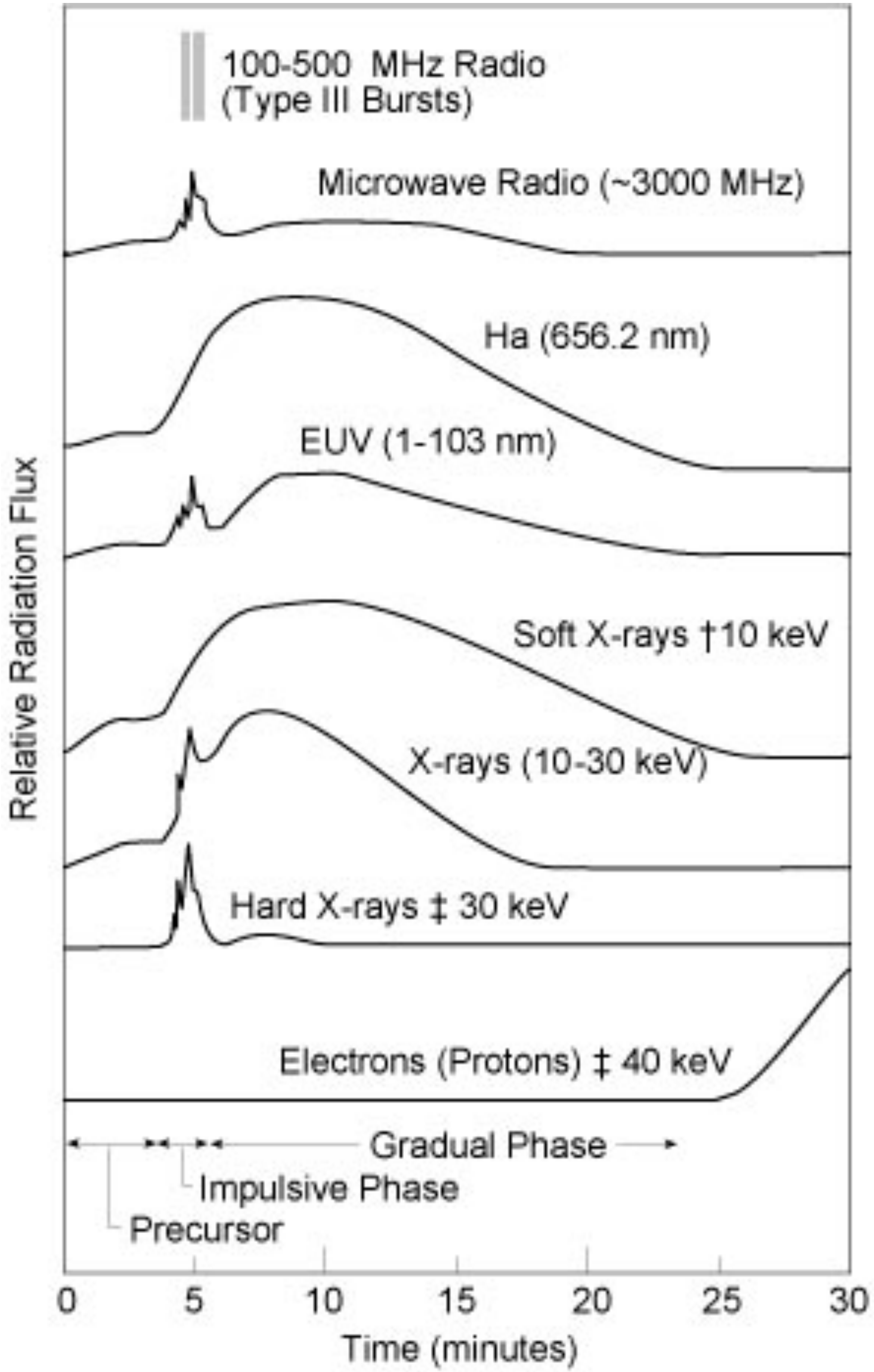
Solar Flare Emission

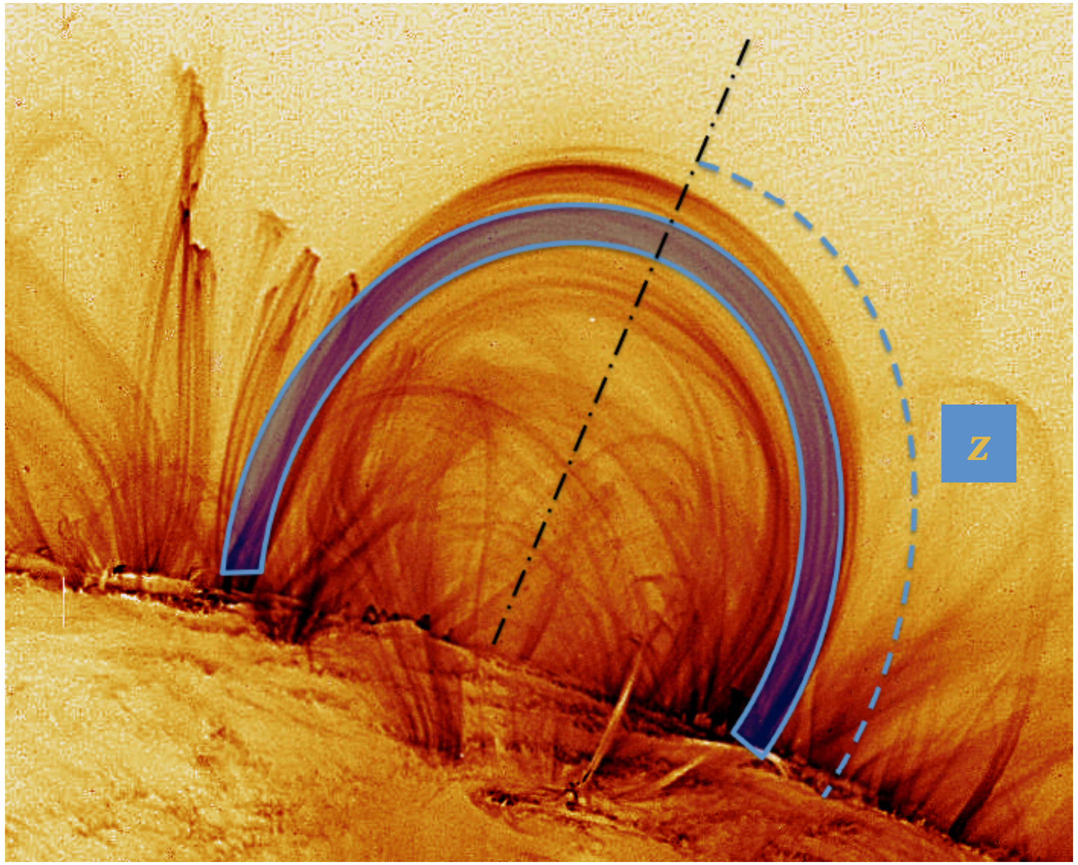
Hard X-rays are the response to the primary energy release.

Emission measure is proportional to n^2.

Need correct density (n) to get the time evolution of the soft X-rays and EUV. Therefore, need correct link between chromosphere and corona.



Modelling Chromospheric Evaporation



The plasma confined in a loop can be described with a 1D hydrodynamic model, with a single coordinate (z) along the loop (e.g. Reale 2014).

1D field-aligned model.

Global 3D MHD models.

$$\frac{\partial \rho}{\partial t} + v\frac{\partial \rho}{\partial z} = -\rho\frac{\partial v}{\partial z},$$

$$\rho\frac{\partial v}{\partial t} + \rho v\frac{\partial v}{\partial z} = -\frac{\partial P}{\partial z} - \rho g_{\parallel},$$

$$\rho\frac{\partial \epsilon}{\partial t} + \rho v\frac{\partial \epsilon}{\partial z} = -P\frac{\partial v}{\partial z} - \frac{\partial F_c}{\partial z} + Q(t) - n^2\Lambda(T),$$

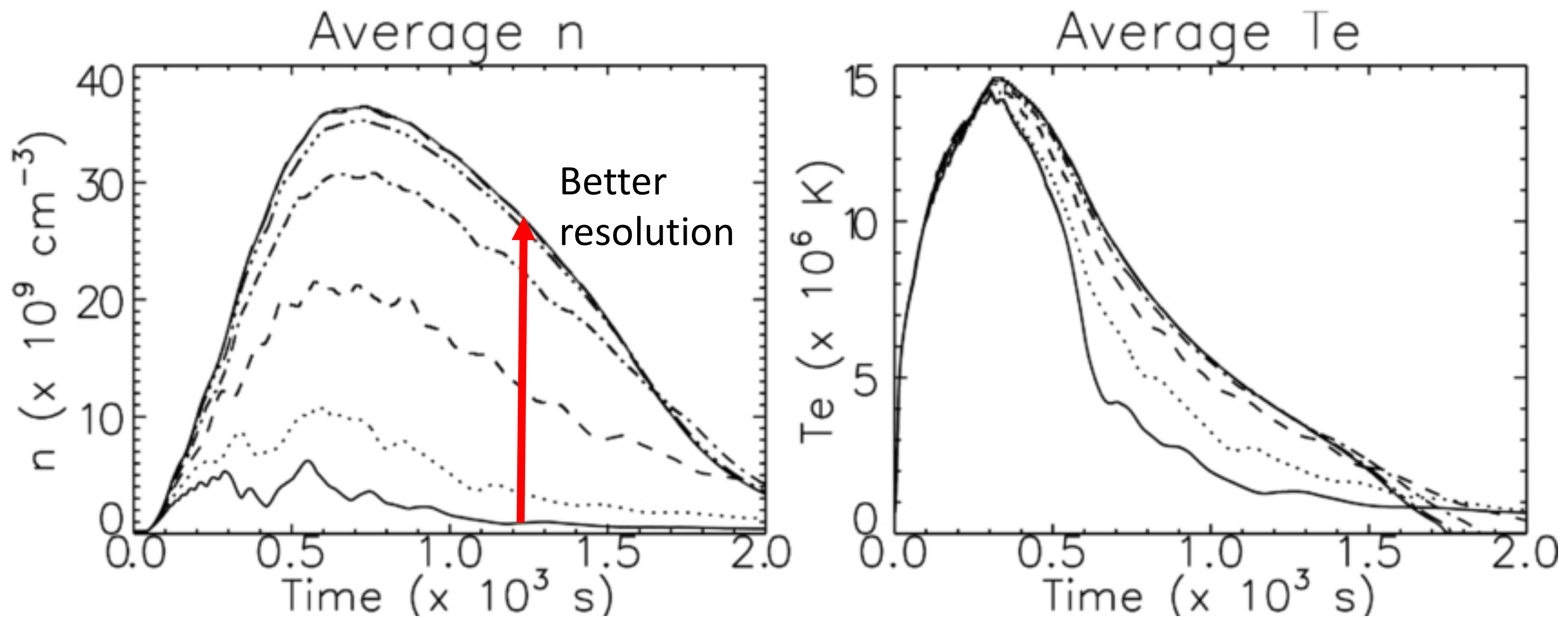
$$P = 2k_B nT,\ \epsilon = \frac{P}{(\gamma-1)\rho}.$$

$F_c = -\kappa_0 T^{5/2}\frac{\partial T}{\partial z}$ is the Spitzer heat flux.

Solved using a Lagrangian remap approach (Arber et al, 2001), adapted for 1D field-aligned hydrodynamics.

The Importance of TR Resolution (Bradshaw & Cargill, 2013)

Emission measure is proportional to n^2.



Difficulty of resolving downward heat flux is well known,

$$L_T \sim \sqrt{\frac{\kappa_o T^{7/2}}{n^2 \Lambda(T)}} \, .$$

Quantitative description by B&C (2013).

Heat flux jumps across the TR.

HYDRAD – fully resolved 1D model with an adaptive grid.

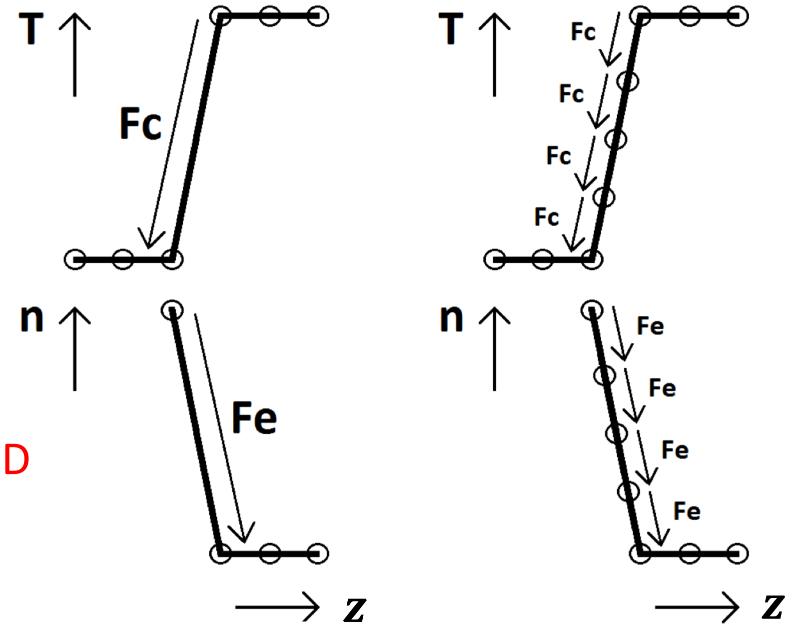
Showed that lack of spatial resolution leads to coronal densities that are far too low.

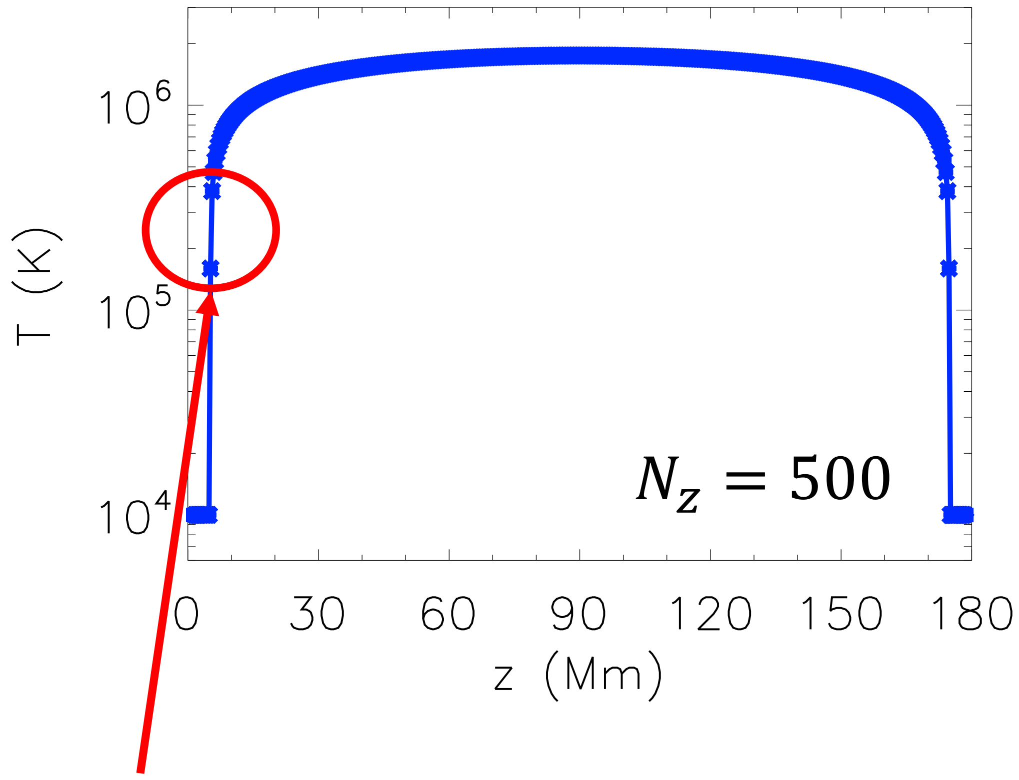
TR Resolution can be brute-forced in 1D.

But not in 3D. So develop approximate methods for use in 3D.

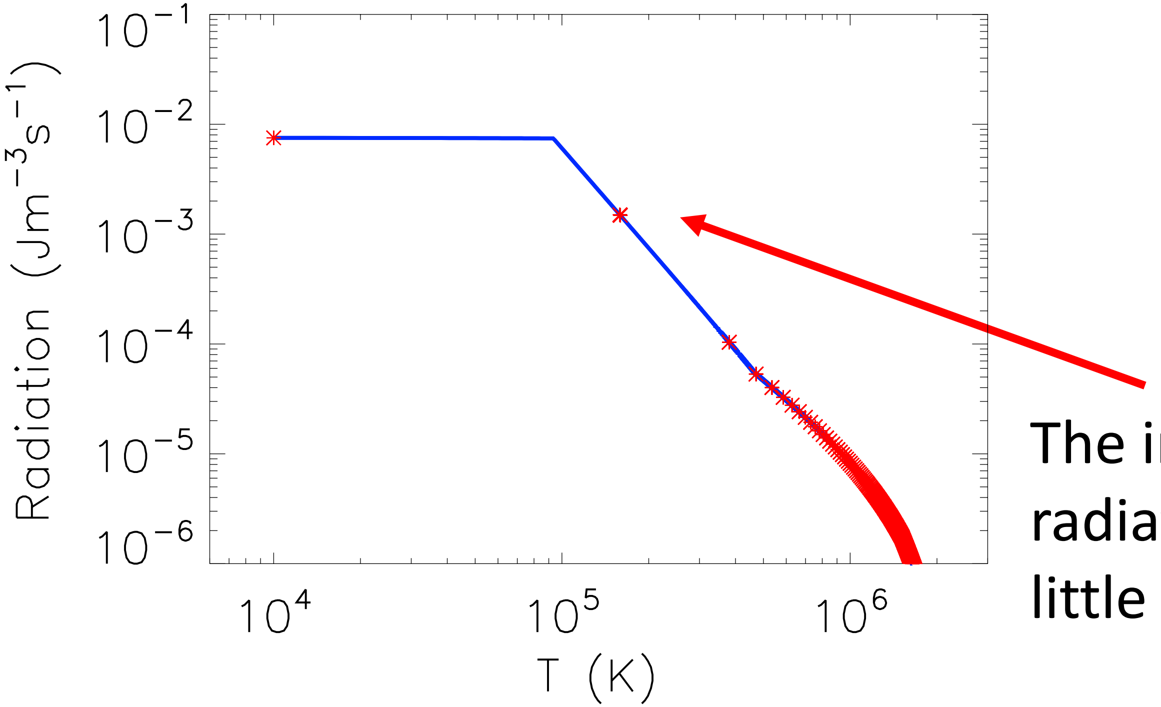
The Influence of Poor Resolution

$N_z = 500$ is reflective of the number of grid points a 3D MHD code can run in a realistic time (500^3).





Rather than passing through the TR continuously in a series of steps, the heat flux jumps across the TR.



The incoming energy is then strongly radiated (Bradshaw & Cargill, 2013), leaving little excess energy to drive the upflow.

Jump Condition Approach (Johnston et al, 2017a,b)

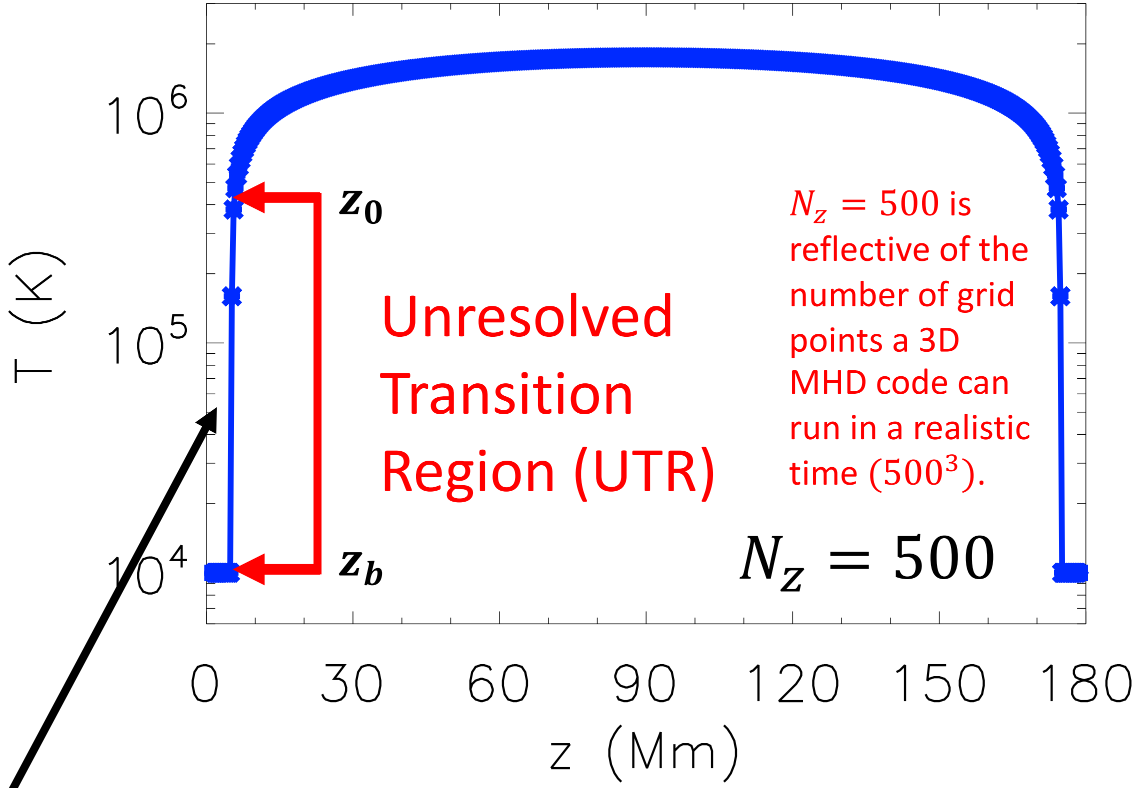
Model the unresolved transition region as a discontinuity using a jump condition.

The 1D field-aligned MHD equations can be written in conserved form for the total energy,

$$\frac{\partial E}{\partial t} = -\frac{\partial}{\partial z}\left(\frac{\gamma}{\gamma-1}Pv + \frac{1}{2}\rho v^3 + \rho\Phi v + F_c\right) + Q - n^2\Lambda(T),$$

where,

$$E = \frac{P}{\gamma - 1} + \frac{1}{2}\rho v^2 + \rho\Phi.$$



Integrate over the UTR, neglecting LHS and z_b flux terms.

z_b is the base of the TR.

z_0 is the top of the UTR.

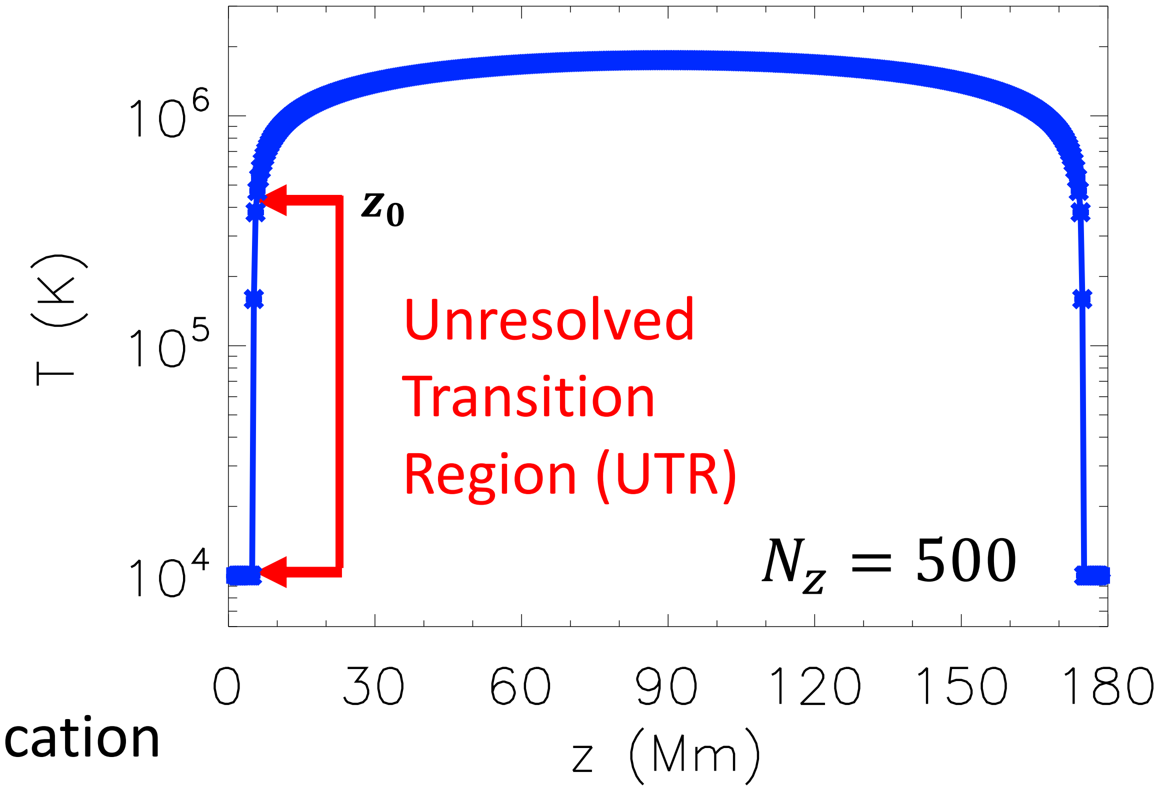
Unresolved Transition Region (UTR)

Define the temperature length scale,

$$L_T = \frac{T}{|dT/dz|} = \frac{\kappa_0 T^{7/2}}{|F_c|}.$$

With a uniform grid the simulation resolution is given by,

$$L_R = \frac{2L}{N_z - 1}.$$



Define the top of the UTR (z_0) to be the final location at which the temperature resolution criteria,

$$\frac{L_R}{L_T} \leq \delta \leq 1,$$ is satisfied. ⟶ Shift upwards.

Take $\delta = 1/4$.

Unresolved Transition Region (UTR)

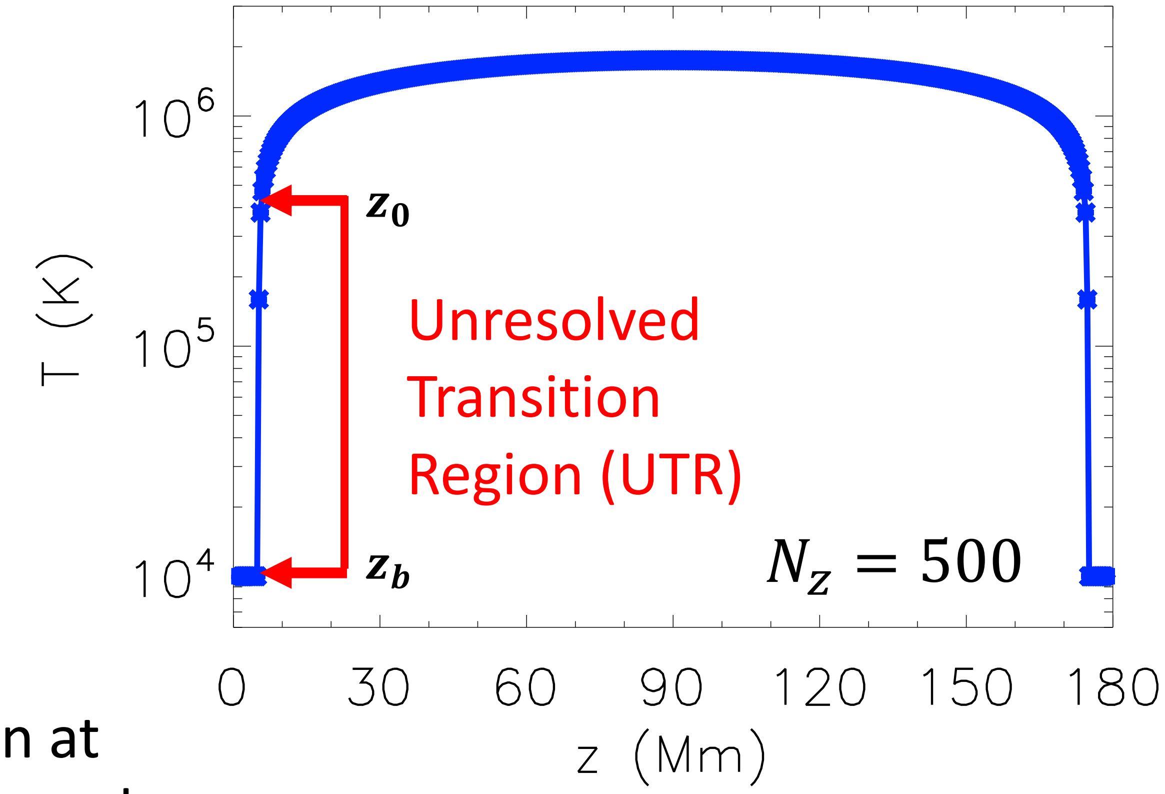
Define the temperature length scale,

$$L_T = \frac{T}{|dT/dz|} = \frac{\kappa_0 T^{7/2}}{|F_c|}.$$

With a uniform grid the simulation resolution is given by,

$$L_R = \frac{2L}{N_z - 1}.$$

Define the base of the TR (z_b) to be the location at which the temperature first reaches or falls below the chromospheric temperature (10,000K) .



Modelling the UTR using a jump condition

$$\frac{\partial E}{\partial t} = -\frac{\partial}{\partial z}\left(\frac{\gamma}{\gamma-1}Pv + \frac{1}{2}\rho v^3 + \rho\Phi v + F_c\right) + Q - n^2\Lambda(T),$$

Integrate over the UTR,

$$\int_{z_b}^{z_0} \frac{\partial E}{\partial t}\, dz = -\int_{z_b}^{z_0} \frac{\partial}{\partial z}\left(\frac{\gamma}{\gamma-1}Pv + \frac{1}{2}\rho v^3 + \rho\Phi v + F_c\right) dz + \int_{z_b}^{z_0} Q - n^2\Lambda(T)\, dz,$$

$$= -\left[\frac{\gamma}{\gamma-1}Pv + \frac{1}{2}\rho v^3 + \rho\Phi v + F_c\right]_{z_b}^{z_0} + \ell\bar{Q} - \int_{z_b}^{z_0} n^2\Lambda(T)\, dz,$$

$$\ell\frac{\partial \bar{E}}{\partial t} = -\frac{\gamma}{\gamma-1}P_0 v_0 - \frac{1}{2}\rho_0 v_0^3 - \rho_0\Phi_0 v_0 - F_{c,0} + \ell\bar{Q} - \mathcal{R}_{utr}.$$

Only important over short intervals.

Very difficult to calculate accurately.

∴ Neglect term.

UTR Jump Condition

$N_z = 500$ is reflective of the number of grid points a 3D MHD code can run in a realistic time (500^3).

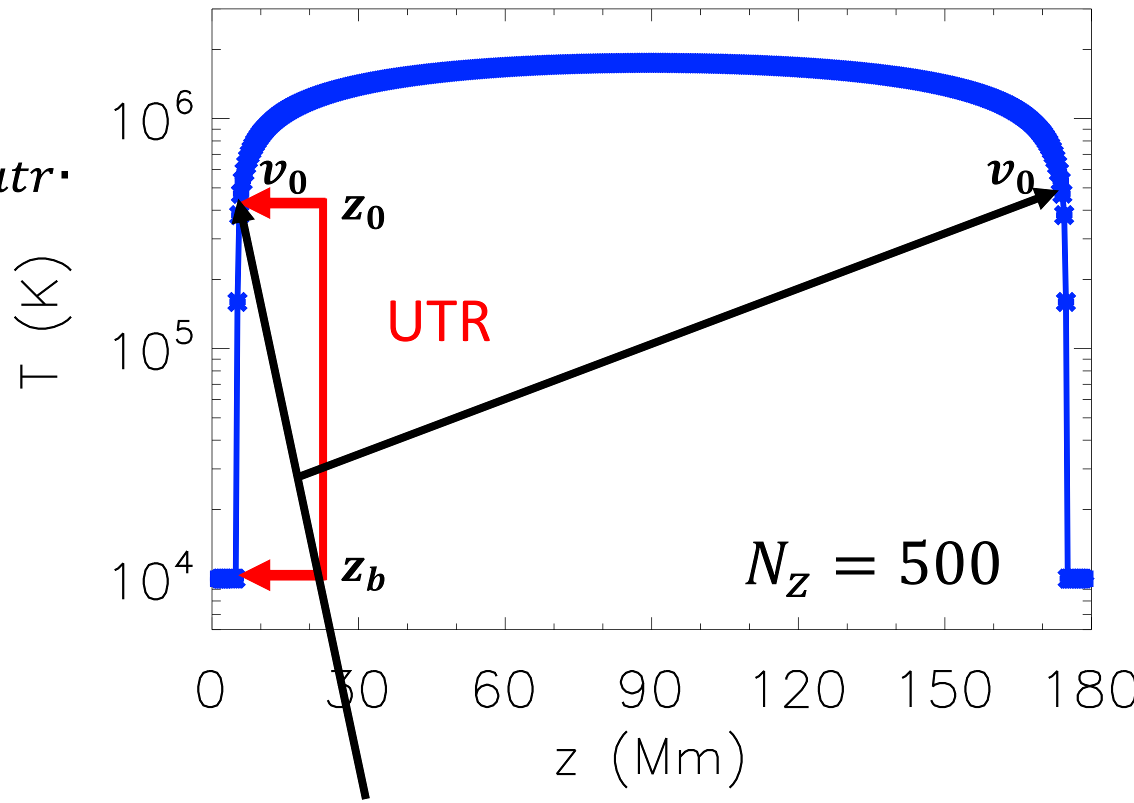
$$\frac{\gamma}{\gamma - 1} P_0 v_0 + \frac{1}{2}\rho_0 v_0^3 + \rho_0 \Phi_0 v_0 = -F_{c,0} + \ell \overline{Q} - \mathcal{R}_{utr}.$$

Need to approximate $$\mathcal{R}_{utr} = \int_{z_b}^{z_0} n^2 \Lambda(T)\, dz.$$

Then solve for the velocity v_0.

Three scenarios:

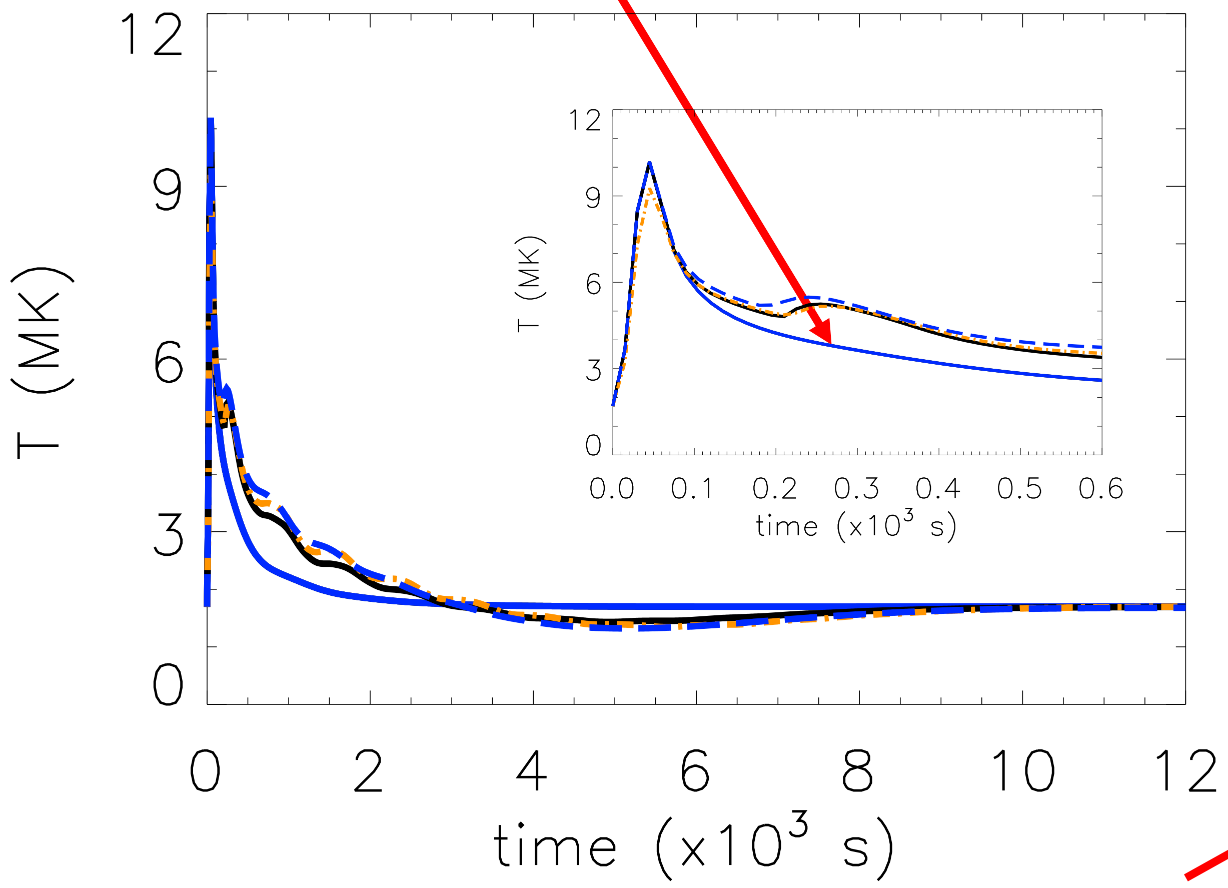
Equilibrium ($v_0 = 0$).
Evaporation ($v_0 > 0$).
Draining ($v_0 < 0$).



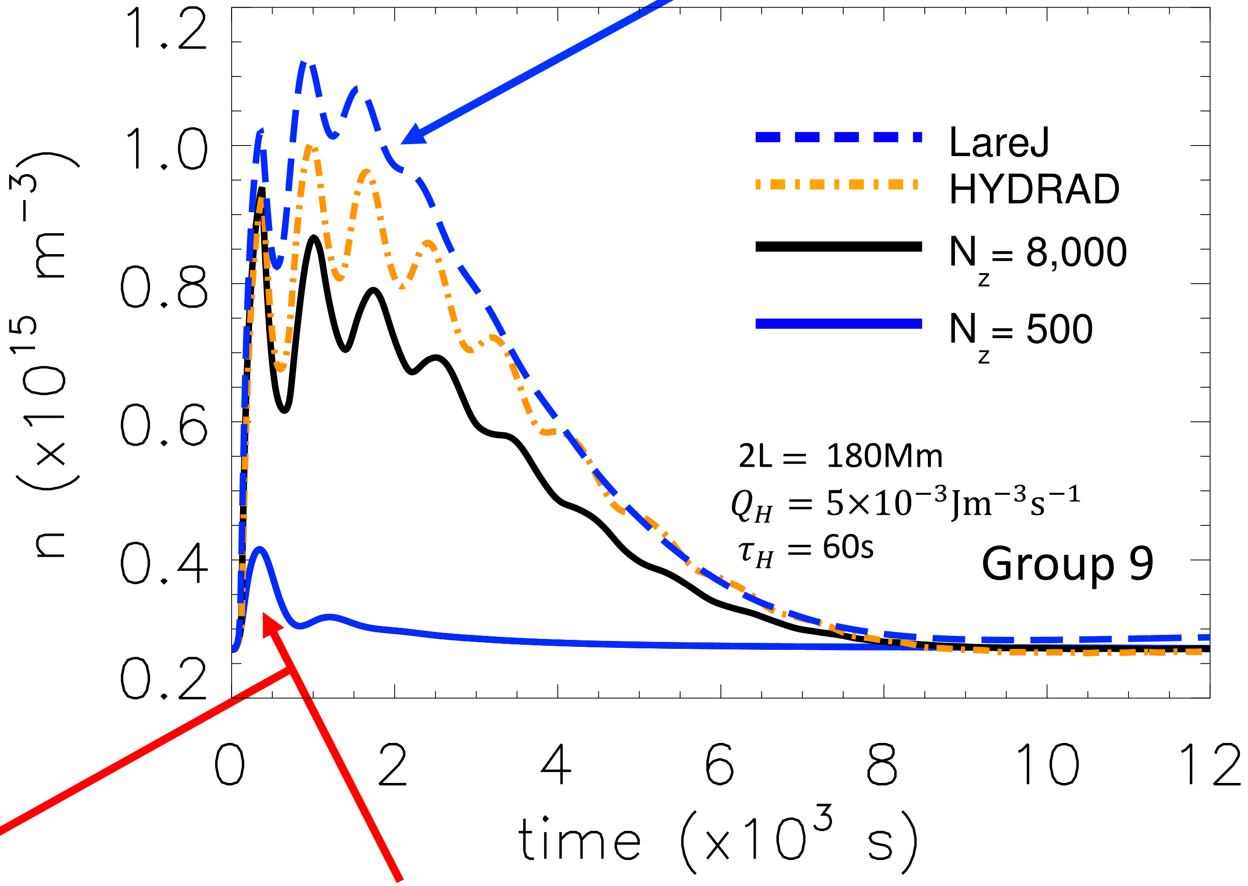
Impose corrected velocity at the top of the UTR to compensate for the jumping of the heat flux (Johnston et al, 2017a,b).

Uniform Heating - Long Loop, Short Pulse, Strong Heating.

Rapid cooling since conductive cooling timescale scales as $n/T^{5/2}$.



Jump condition solution provides a much improved approximation.



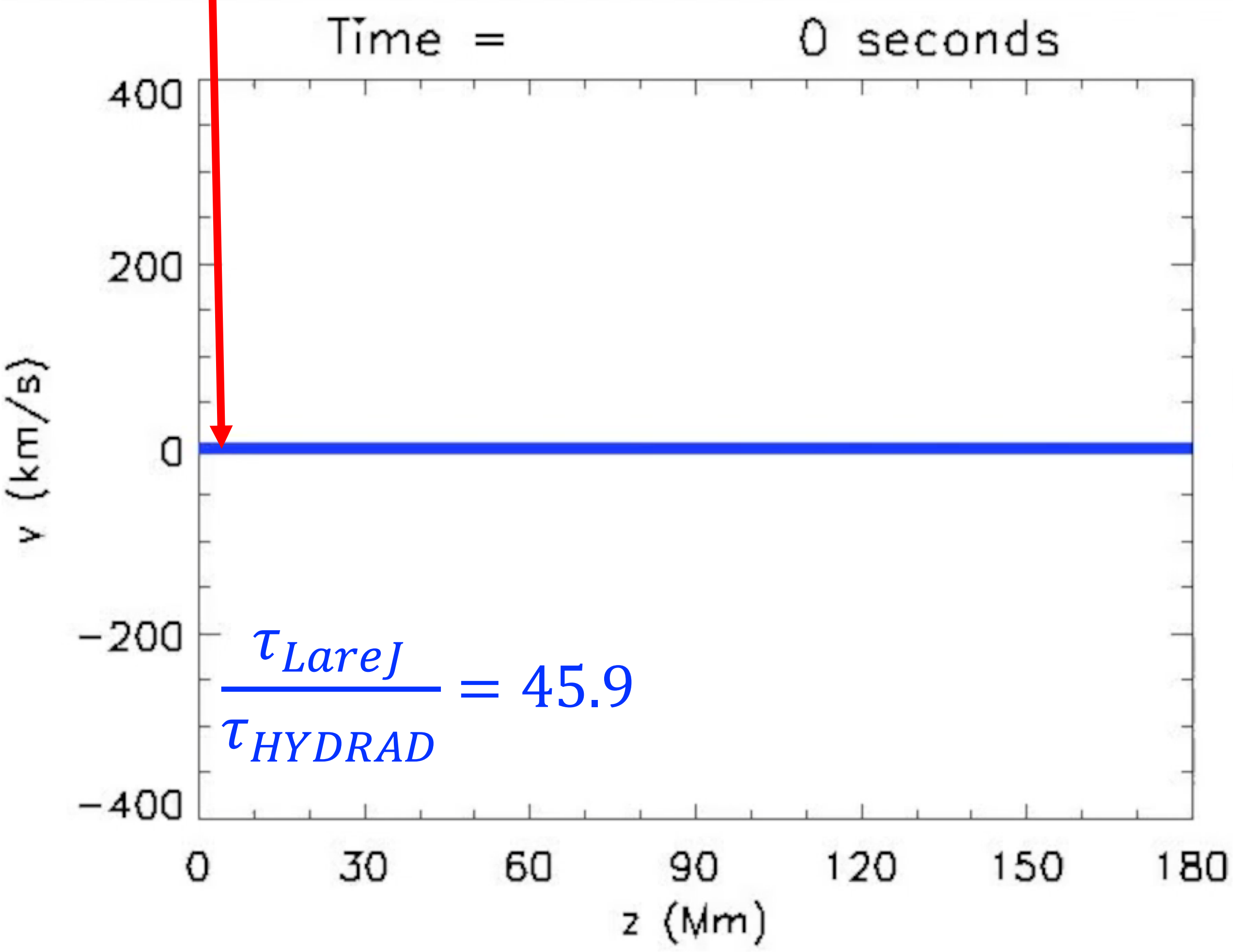
1D or 3D simulations would give very low density with $N_z = 500$.

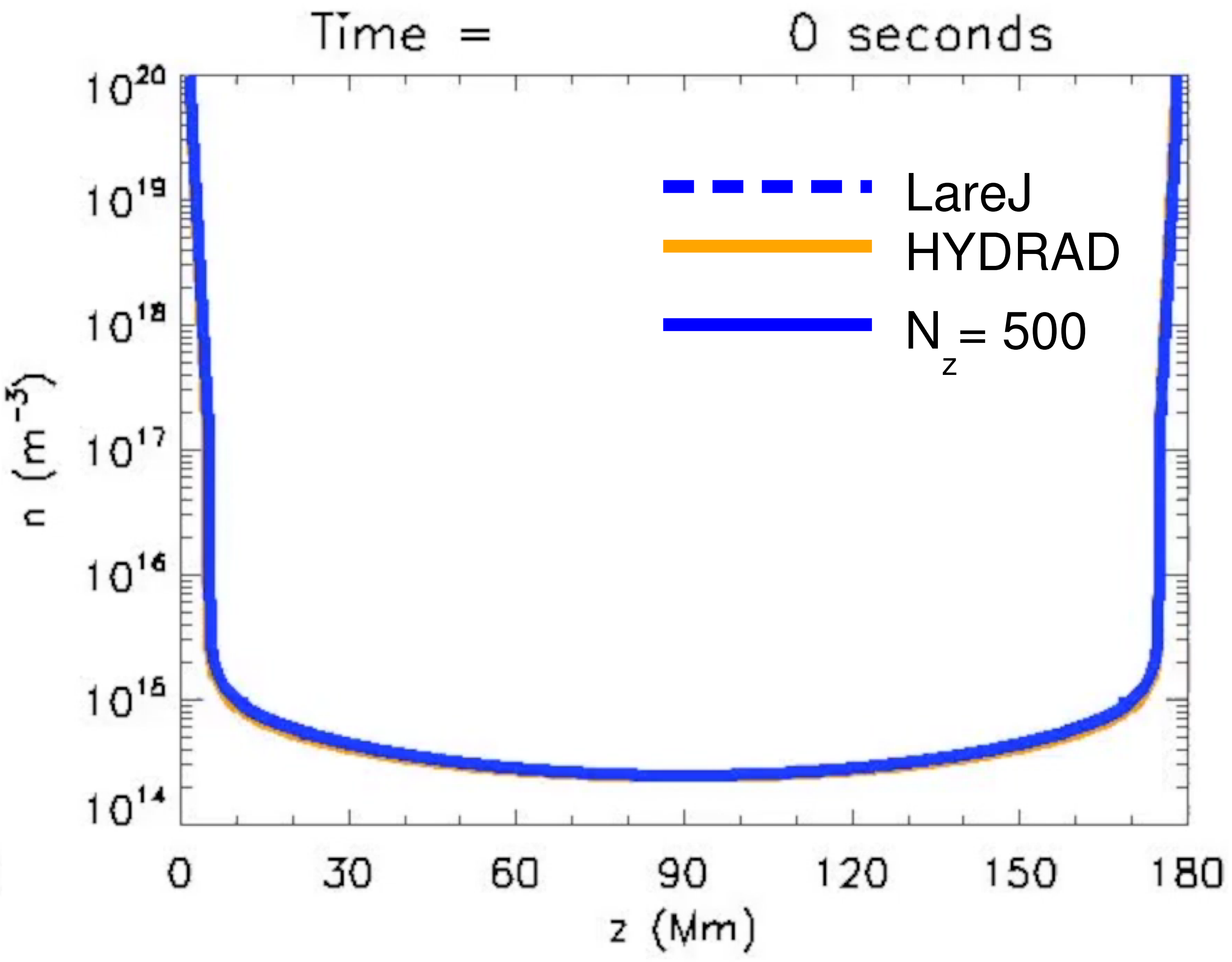
The peak is premature and there is no significant draining phase.

(Johnston et al, 2017a)

The corrected velocity ensures that the energy from the heat flux goes into driving the upflow.

Time Evolution of the Velocity & Density (Evaporation)



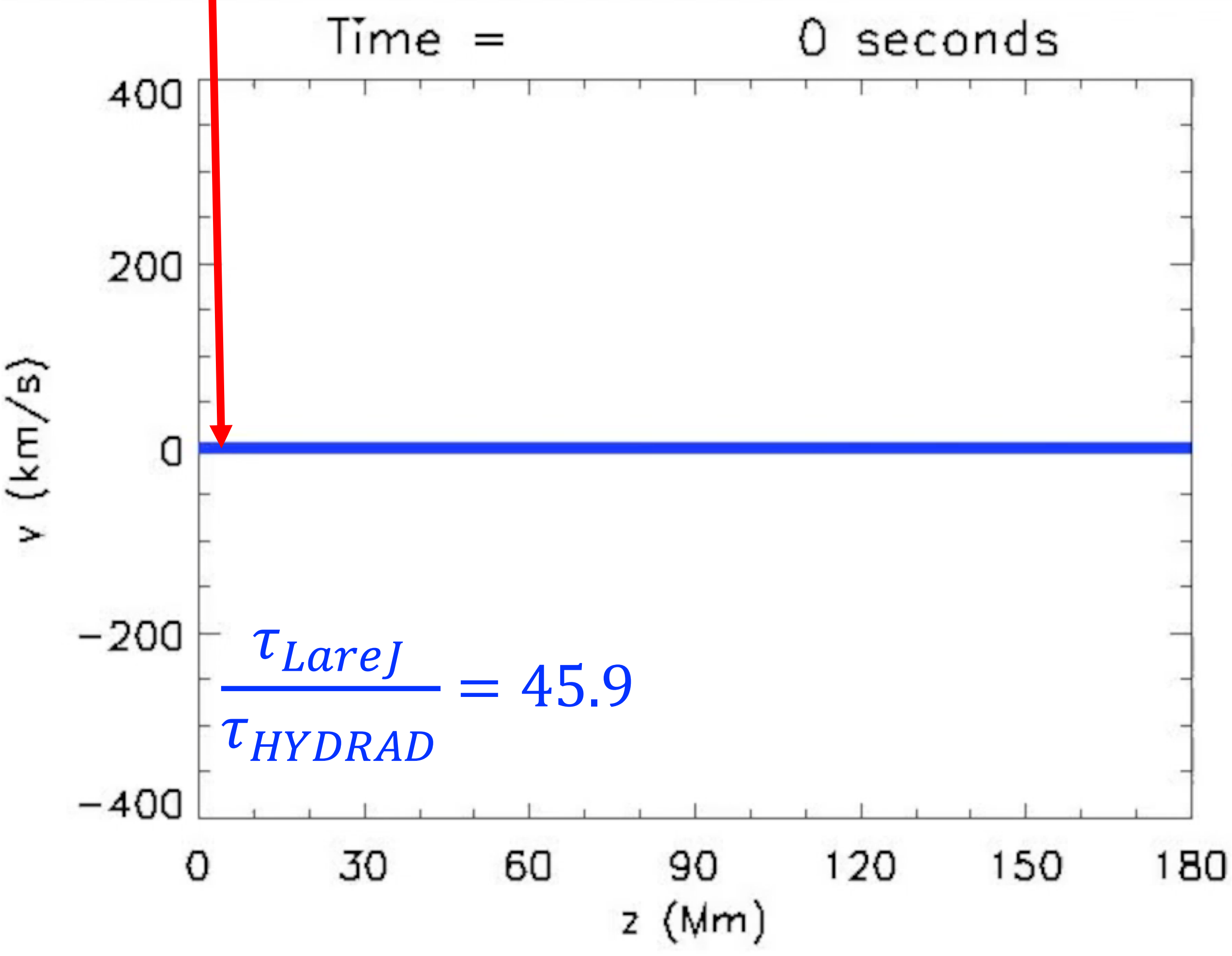


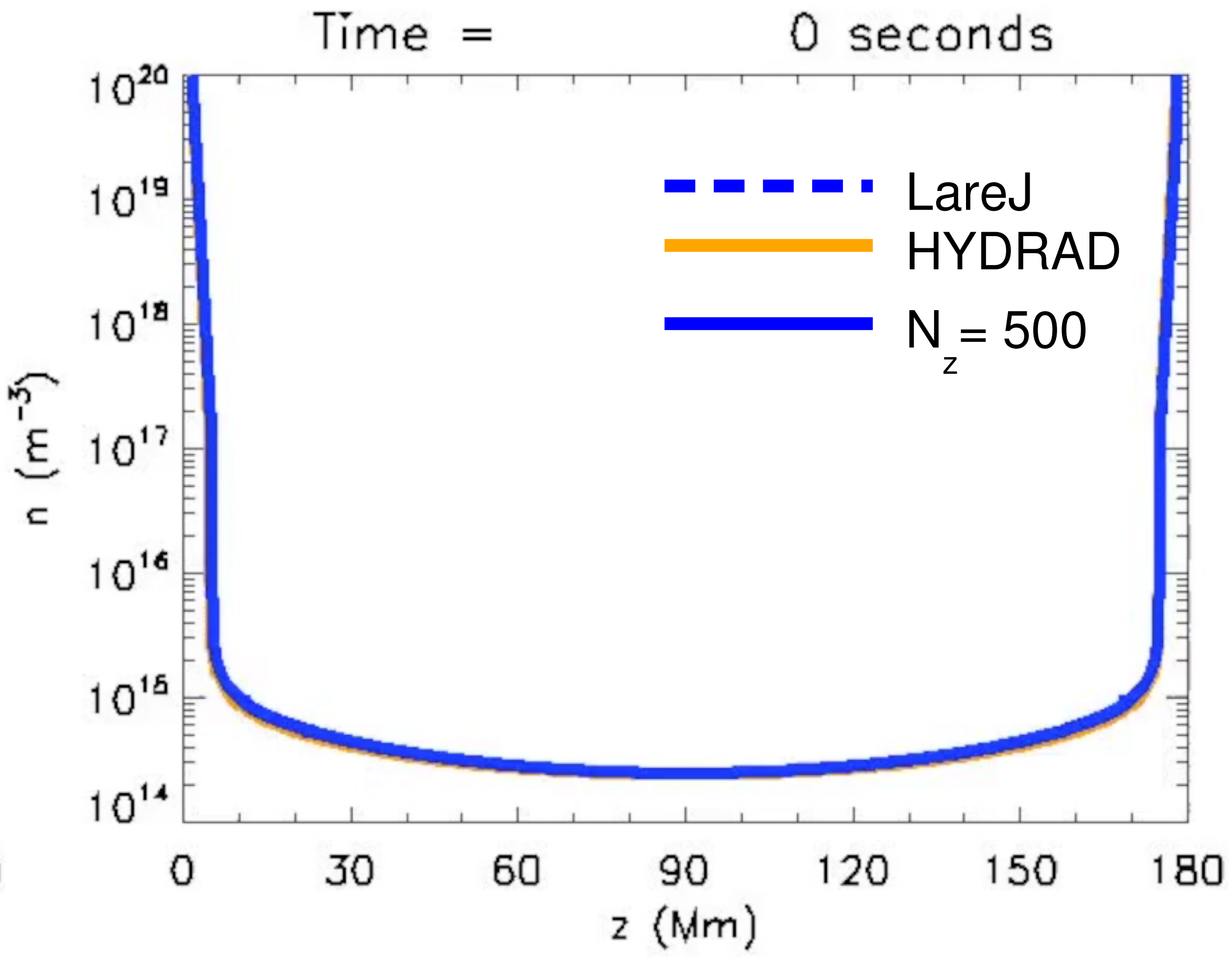
(Johnston et al, 2017a)

Long Loop, Short Pulse, Strong Heating.

Time Evolution of the Velocity & Density (Evaporation)

The corrected velocity ensures that the energy from the heat flux goes into driving the upflow.

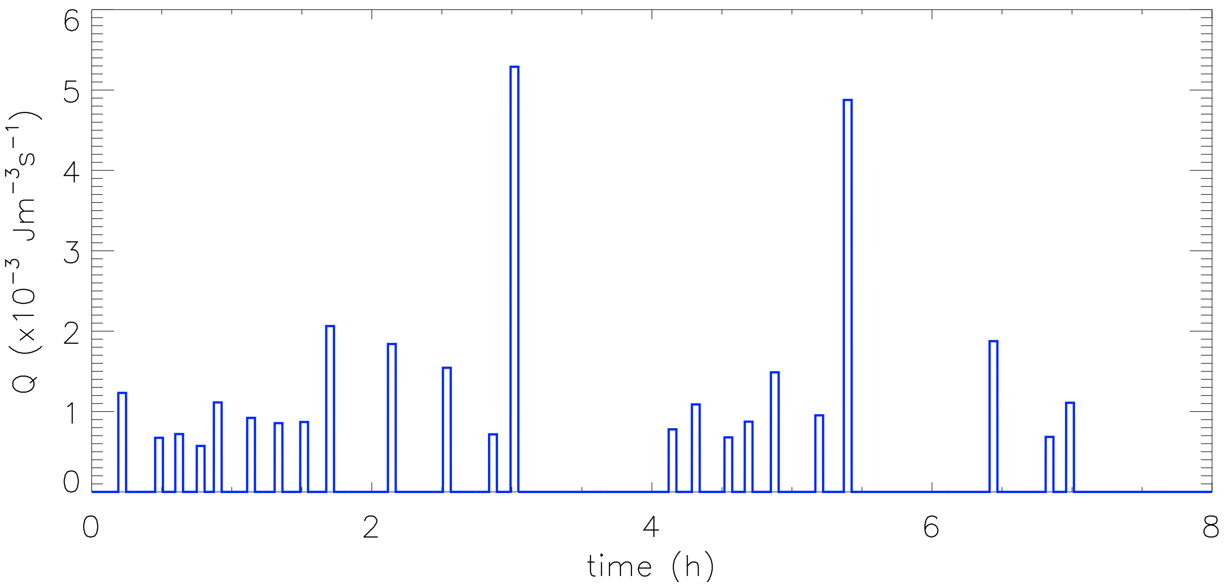


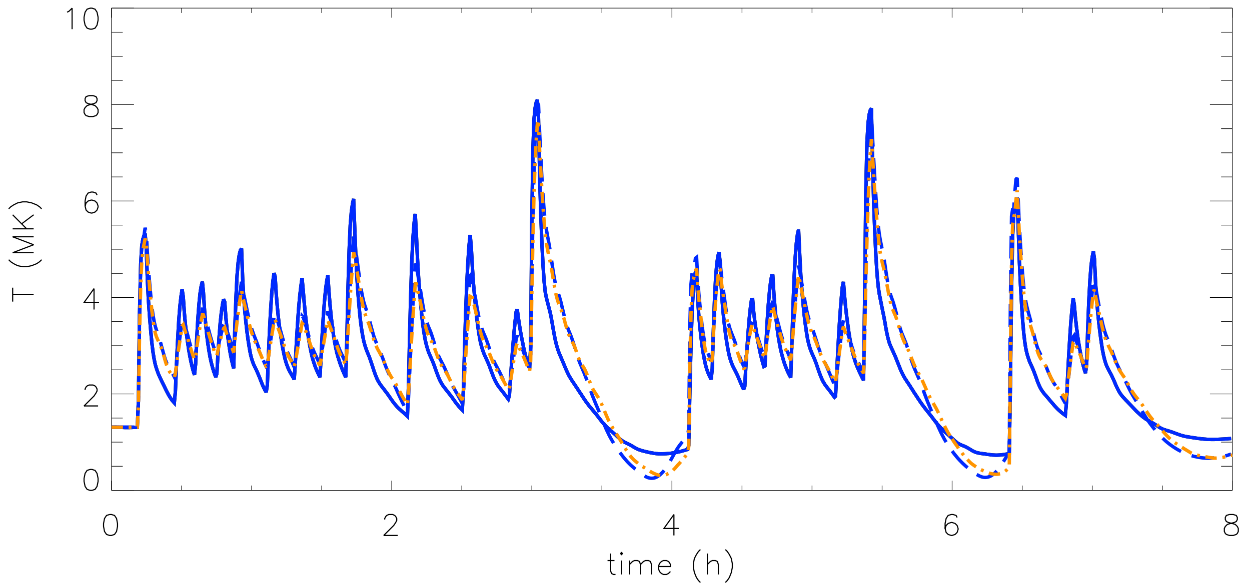


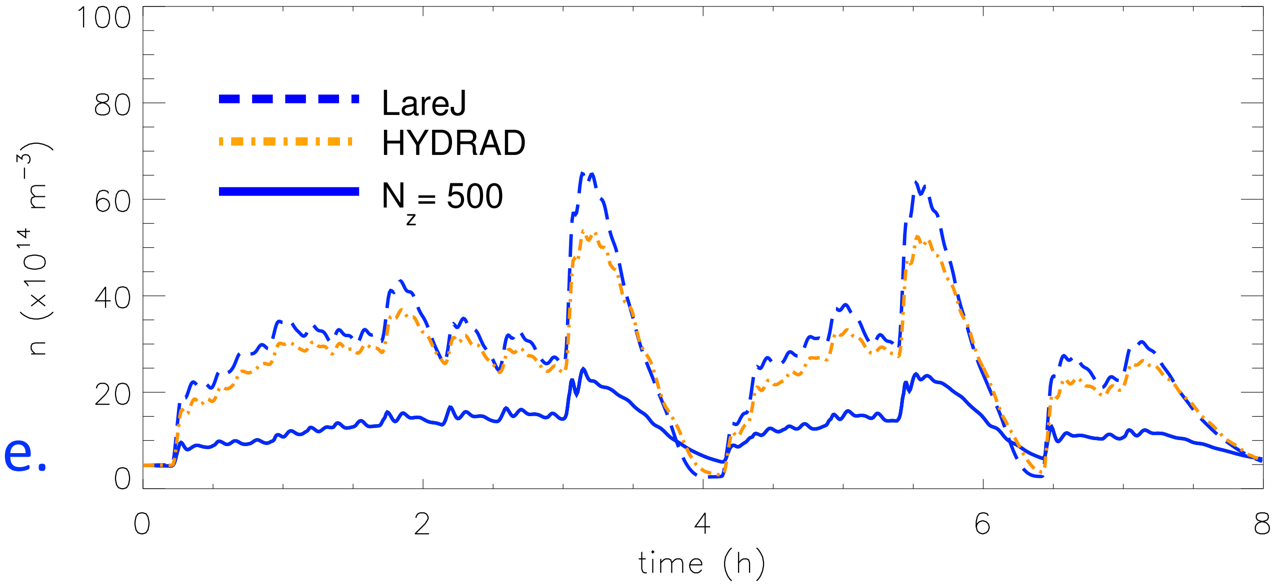
(Johnston et al, 2017a)

Long Loop, Short Pulse, Strong Heating.

Non-Uniform Heating – Nanoflare Train.







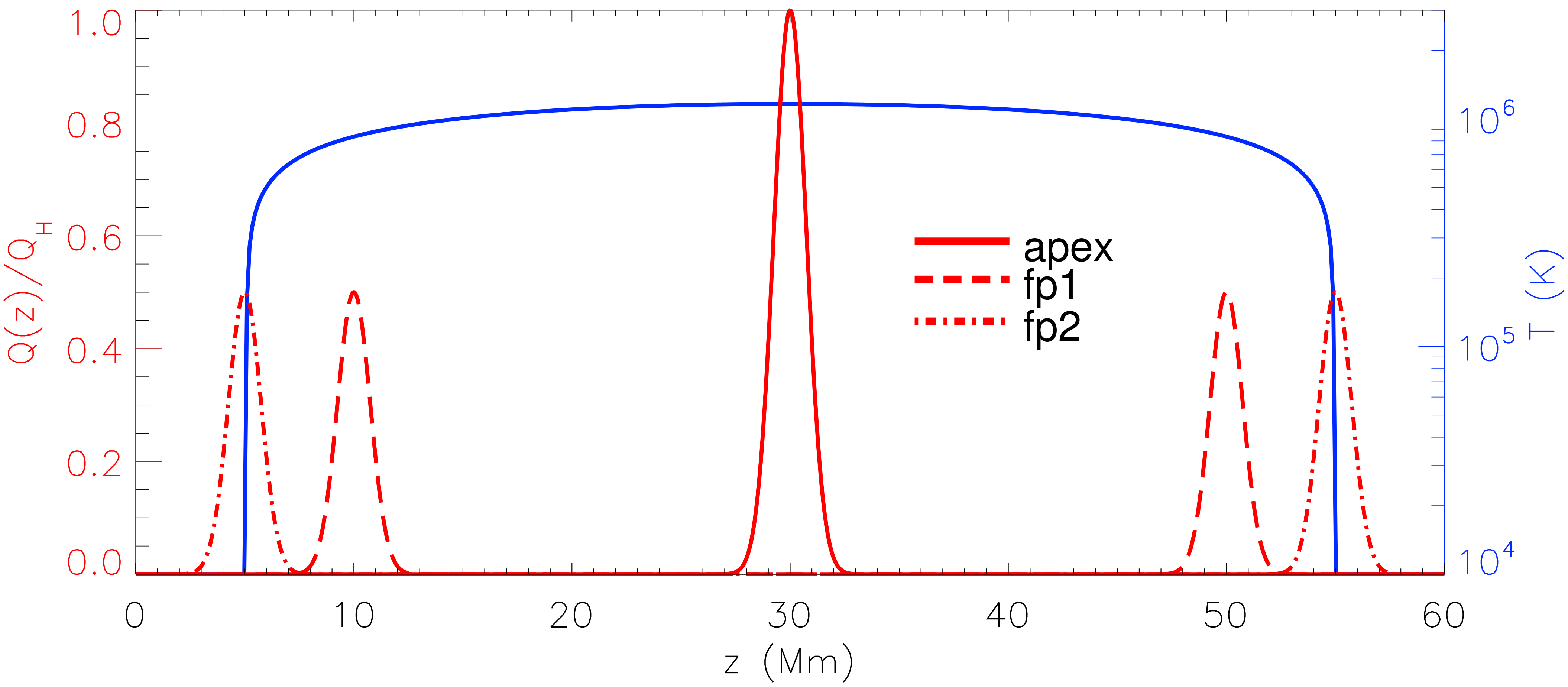
90Mm loop.

Spatial profile of the heating is uniform.

Application of the jump condition is not limited to a single heating and cooling cycle.

(Johnston et al, 2017b)

Non-Uniform Heating – Apex and Footpoint Heating.



fp1 heating - footpoint heating at the base of the corona.

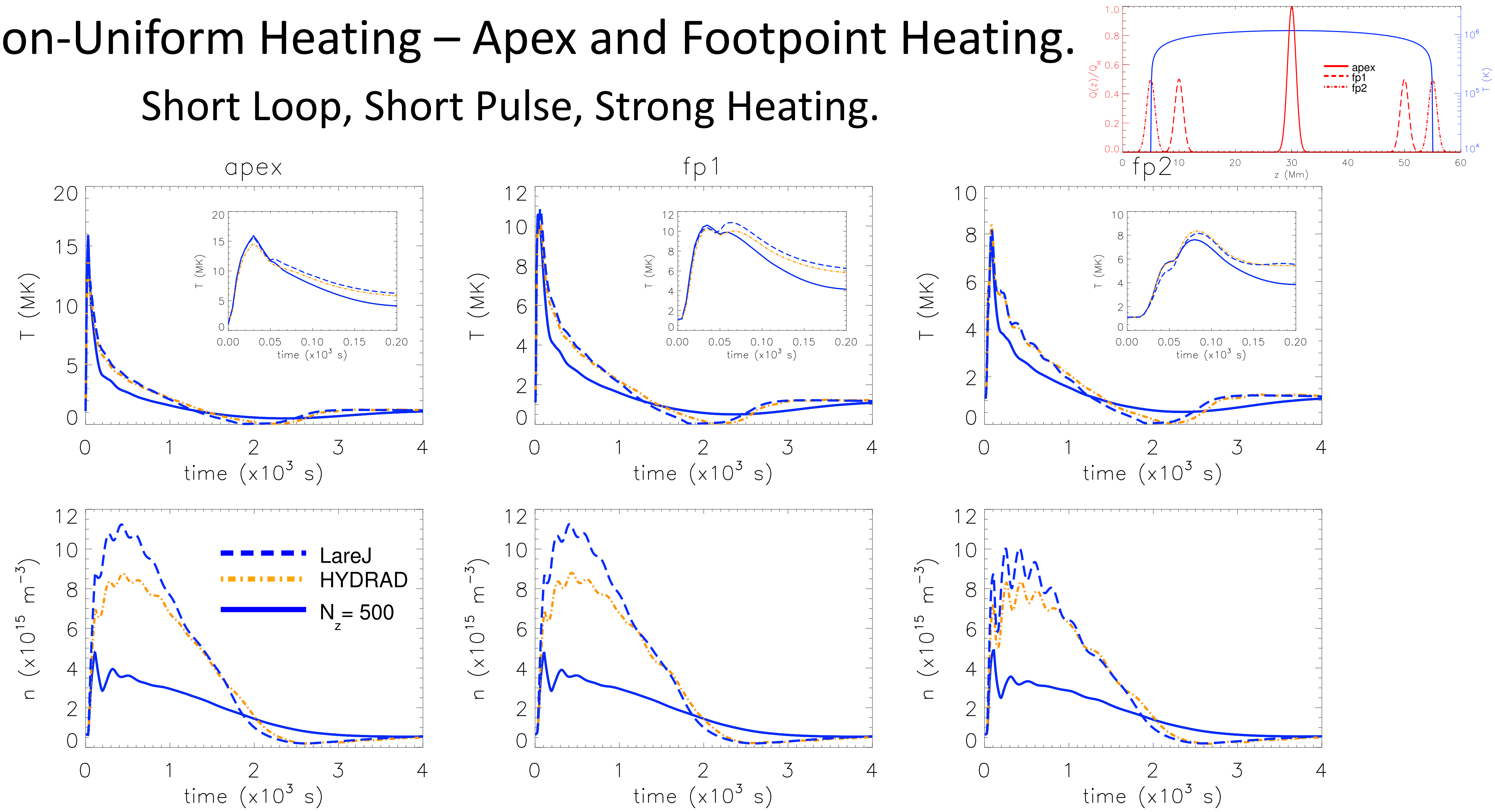
fp2 heating - footpoint heating at the base of the TR.

$$Q_H(z) = Q_{H_0} \exp\left(\frac{-(z - z_0)^2}{2z_H^2}\right).$$

(Johnston et al, 2017b)

Non-Uniform Heating – Apex and Footpoint Heating.

Short Loop, Short Pulse, Strong Heating.



Despite the complexity of the type of heating considered the jump condition still performs well (Johnston et. al 2017b).

Summary Part I

Detailed Analysis of the Jump Condition Approach (Johnston et al. 2017a,b).

1. The method is physically motivated. — Based on energy conservation.

2. Computationally efficient and easy to implement. The jump condition approach is between 1-2 orders of magnitude faster than fully resolved 1D models. — Eliminates the need for very short time steps since we do not need to resolve the TR. Good accuracy is obtained with resolutions compatible with 3D MHD simulations.

3. Get the correct coronal T & n response. — Ensures accurate comparisons between simulations and observations.

4. Can be used for active region modelling. — Applicable for the required T range and simulation box size (loop length).

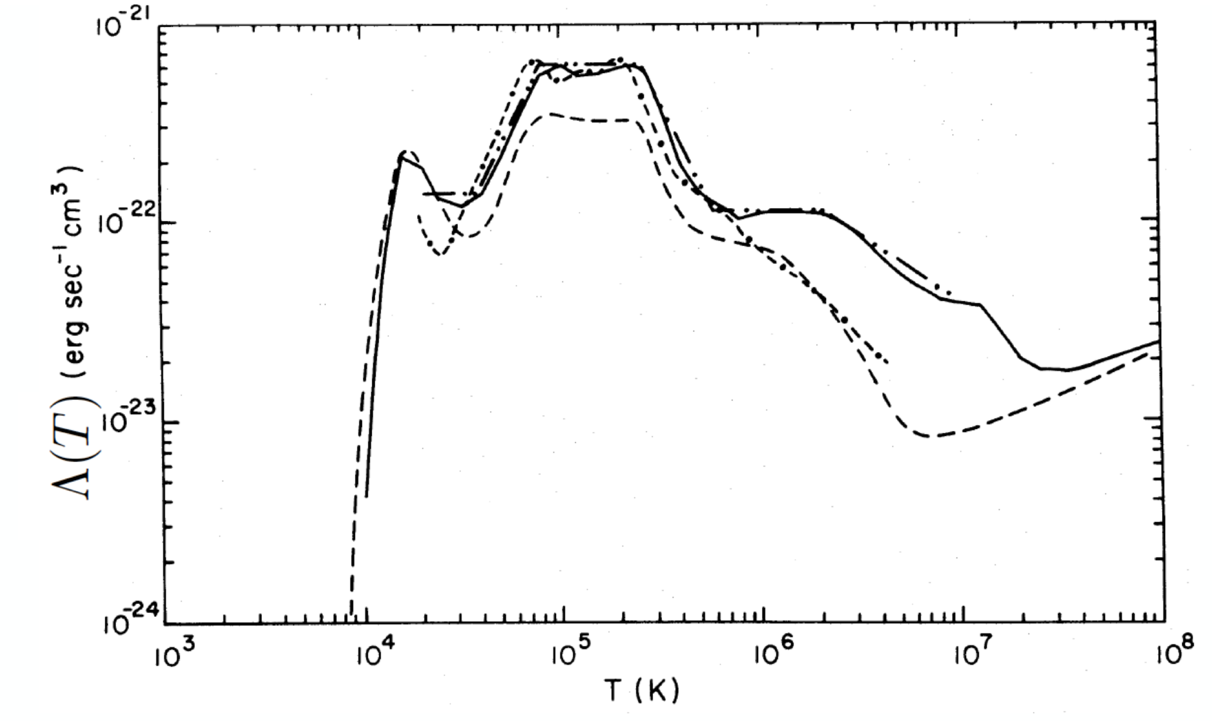
This project has received funding from the Carnegie Trust for the Universities of Scotland, the Science and Technology Facilities Council (UK) through the consolidated grant ST/N000609/1 and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 647214).

Thermal Instability

$$\rho \frac{\partial \epsilon}{\partial t} + \rho v \frac{\partial \epsilon}{\partial z} = -P \frac{\partial v}{\partial z} - \frac{\partial F_c}{\partial z} + Q(t) - n^2 \Lambda(T),$$

Compressive heating. Conductive heating. Background (coronal) heating. Radiative cooling.

Rosner et al. 1978



If radiative cooling > heating,

then runaway cooling can occur.

Condensation – thermal mode.

Parker (1953), Field (1965), Goldsmith (1971) …

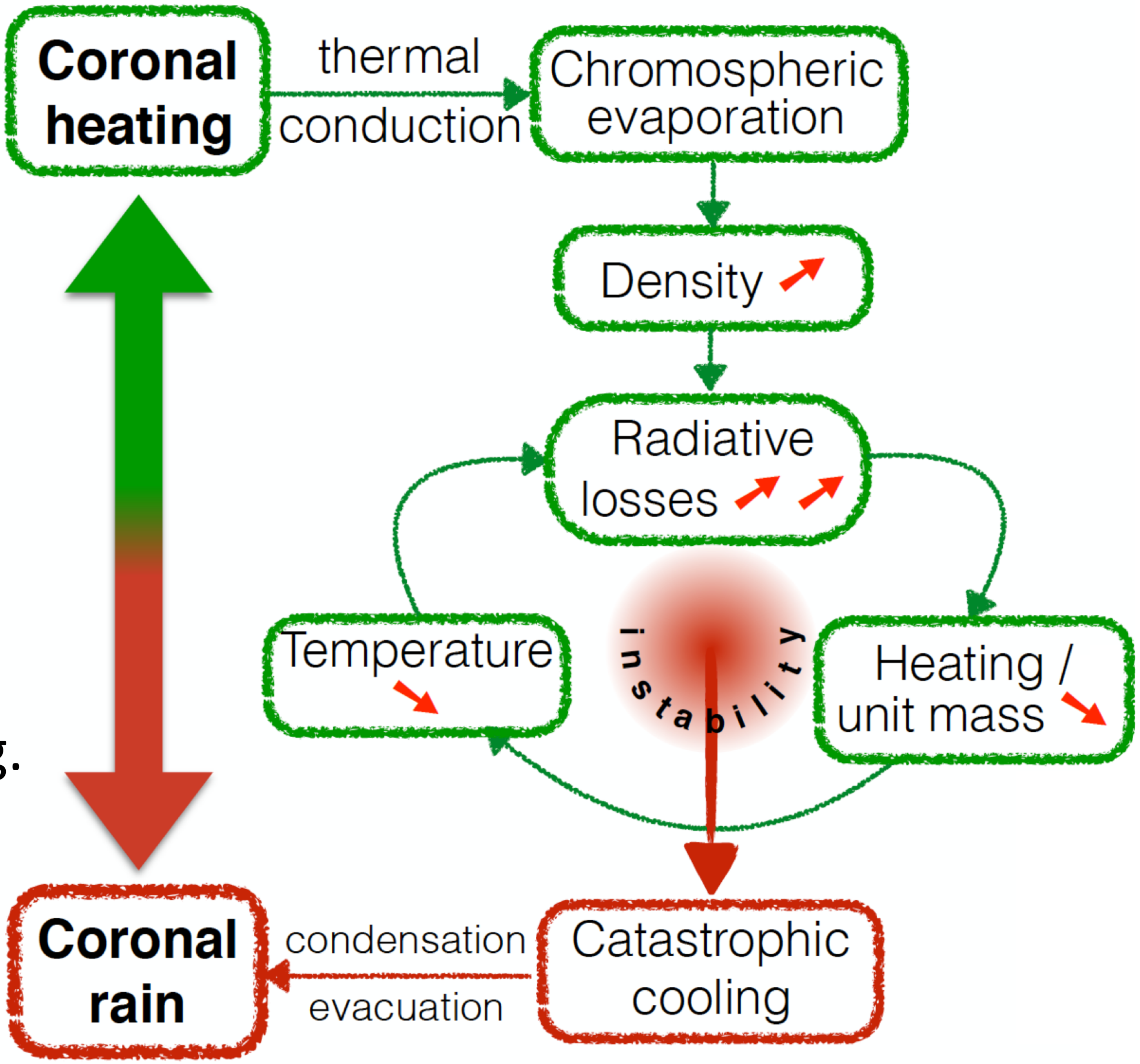
Thermal Instability in Coronal Loops

The thermal instability in coronal loops (thermal non-equilibrium) is strongly linked to how the loop structure is heated.

E.g. Müller et al. 2003; Antolin et al. 2010; Peter et al. 2012; Mikic et al. 2013; Froment et al. 2018:

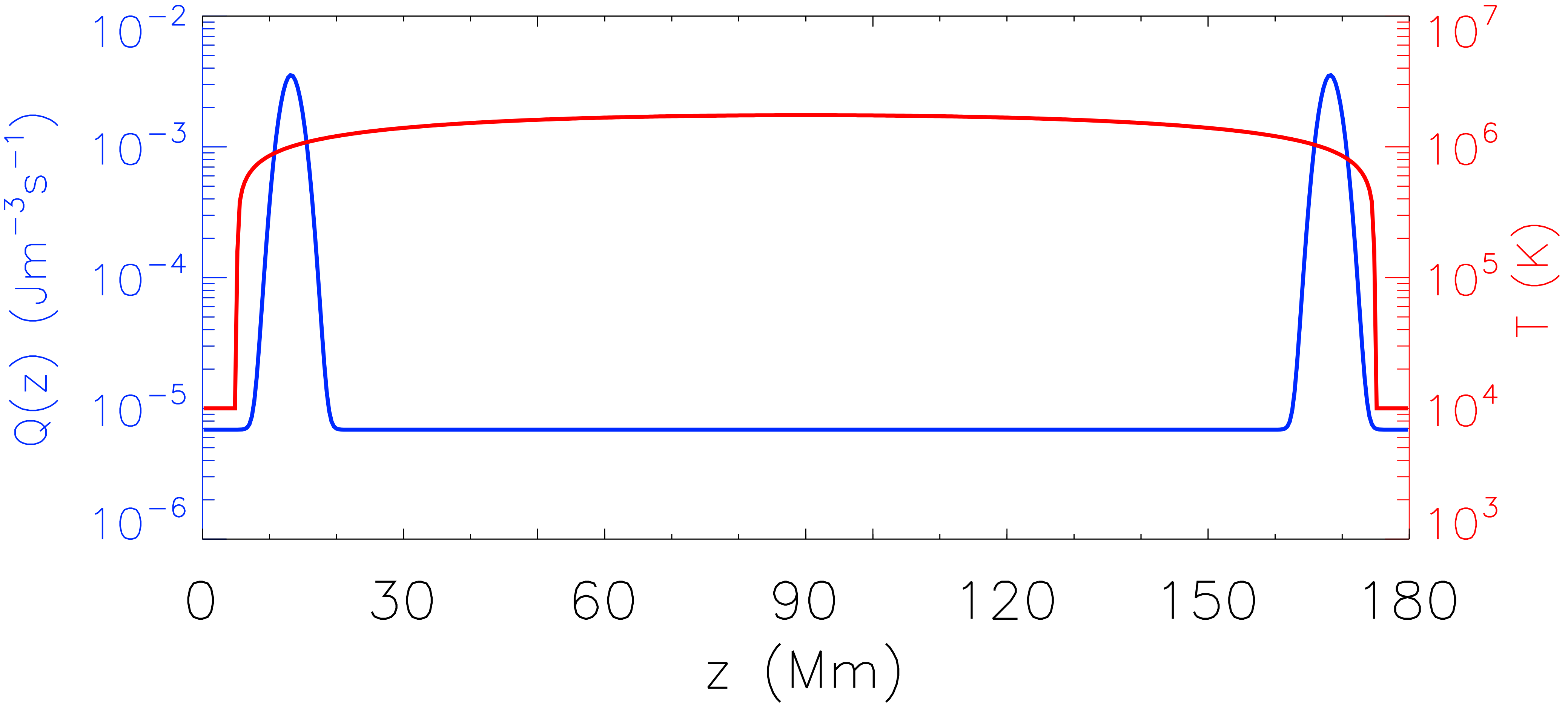
Uniform heating. → No coronal rain.

Steady footpoint heating. → Coronal rain.



Modelling TNE: Steady Footpoint Heating.

Preliminary results that only cover a small range of the large parameter space.



Maximum at 12.5Mm (between fp1 & fp2 heating).

Uniform $Q_{bg} = 6.8682\times10^{-6}\mathrm{Jm}^{-3}\mathrm{s}^{-1}$.

$Q_{H_0} = 3.5273\times10^{-3}\mathrm{Jm}^{-3}\mathrm{s}^{-1}$.

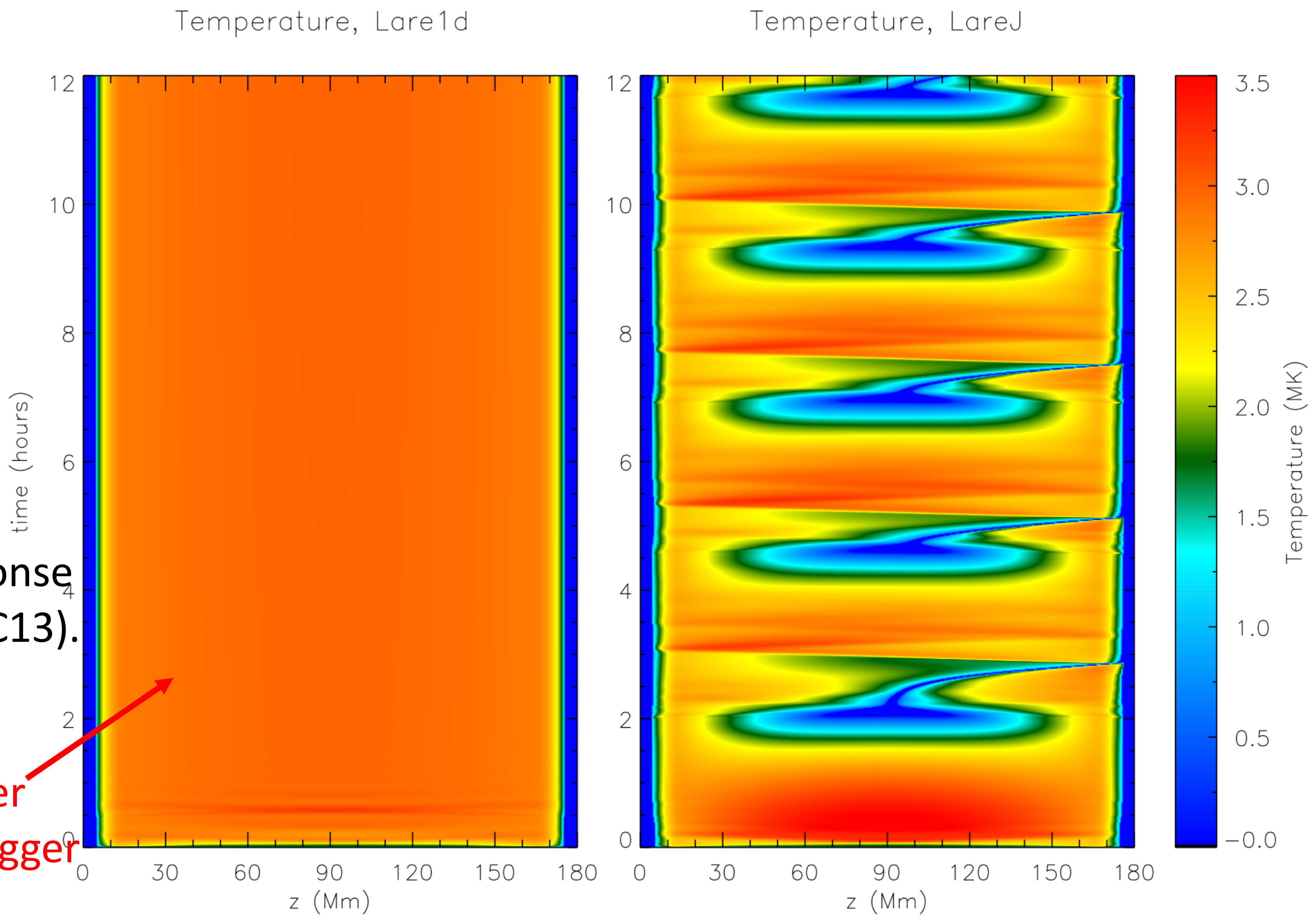
$$Q(z) = Q_{bg} + Q_{H_0}\exp\left(\frac{-(z-z_0)^2}{2z_H^2}\right).$$

The Effect on TNE Cycles of Spatial Resolution in the Transition Region.

Steady Footpoint Heating.

If the TR is under-resolved then the evaporative response can be underestimated (BC13).

This results in steady state solutions because the lower density is insufficient to trigger the thermal instability.

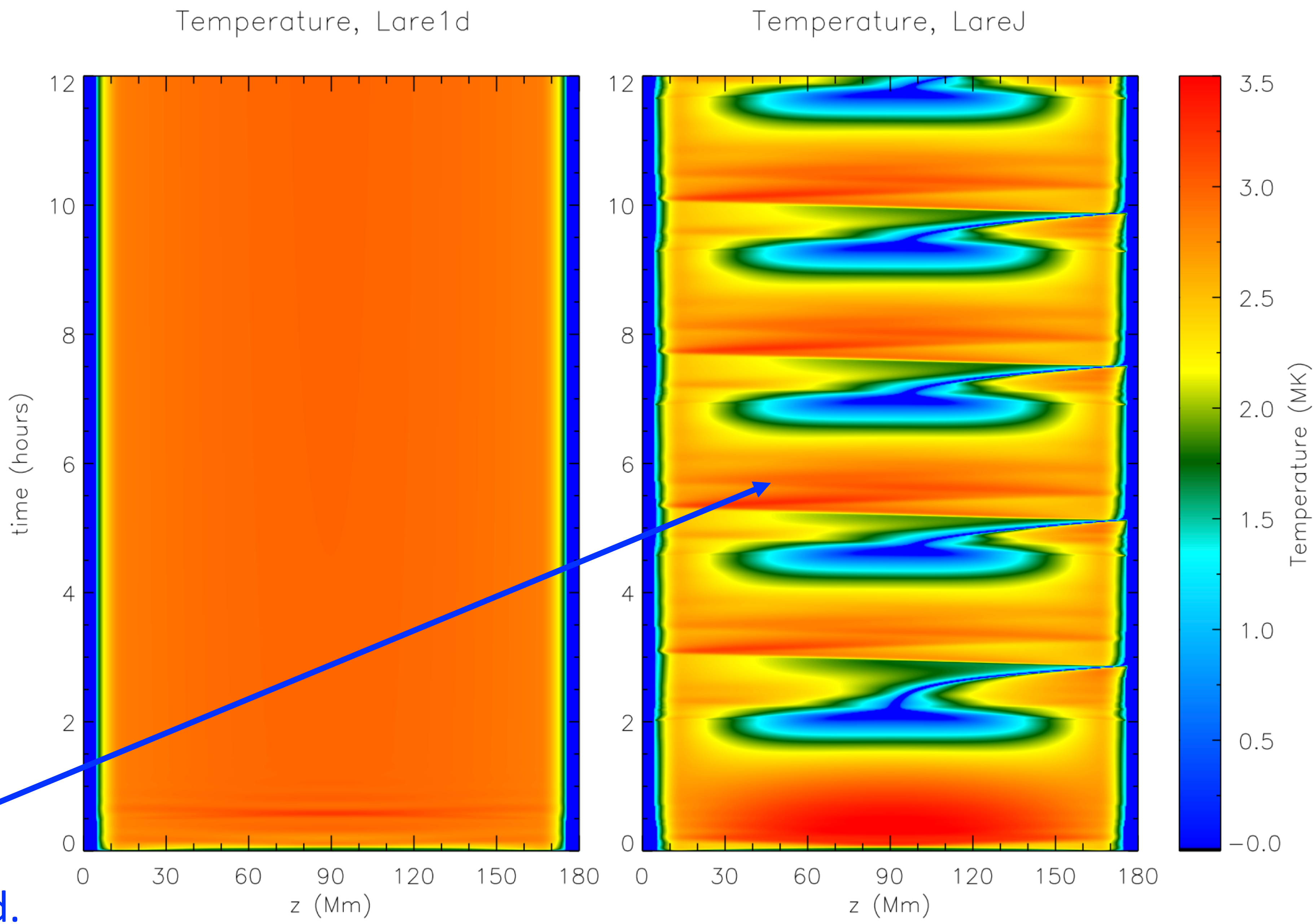


The Effect on TNE Cycles of Spatial Resolution in the Transition Region.

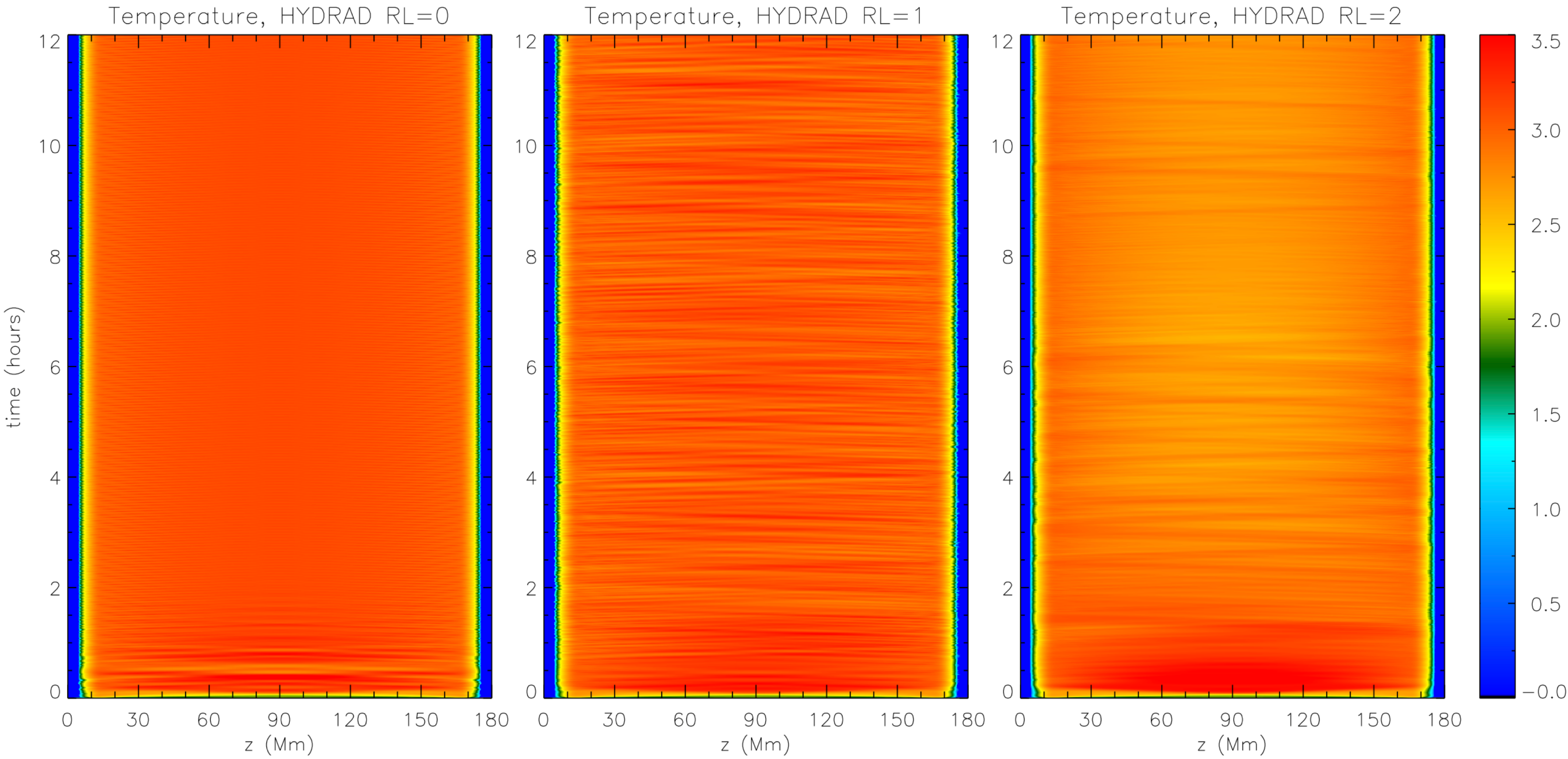
Steady Footpoint Heating.

Loop computed with the jump condition employed obtains the “correct” evaporative response.

Undergoes TNE with complete condensations and a 2.5 hour cycle period.



The Effect on TNE Cycles of Spatial Resolution in the TR.



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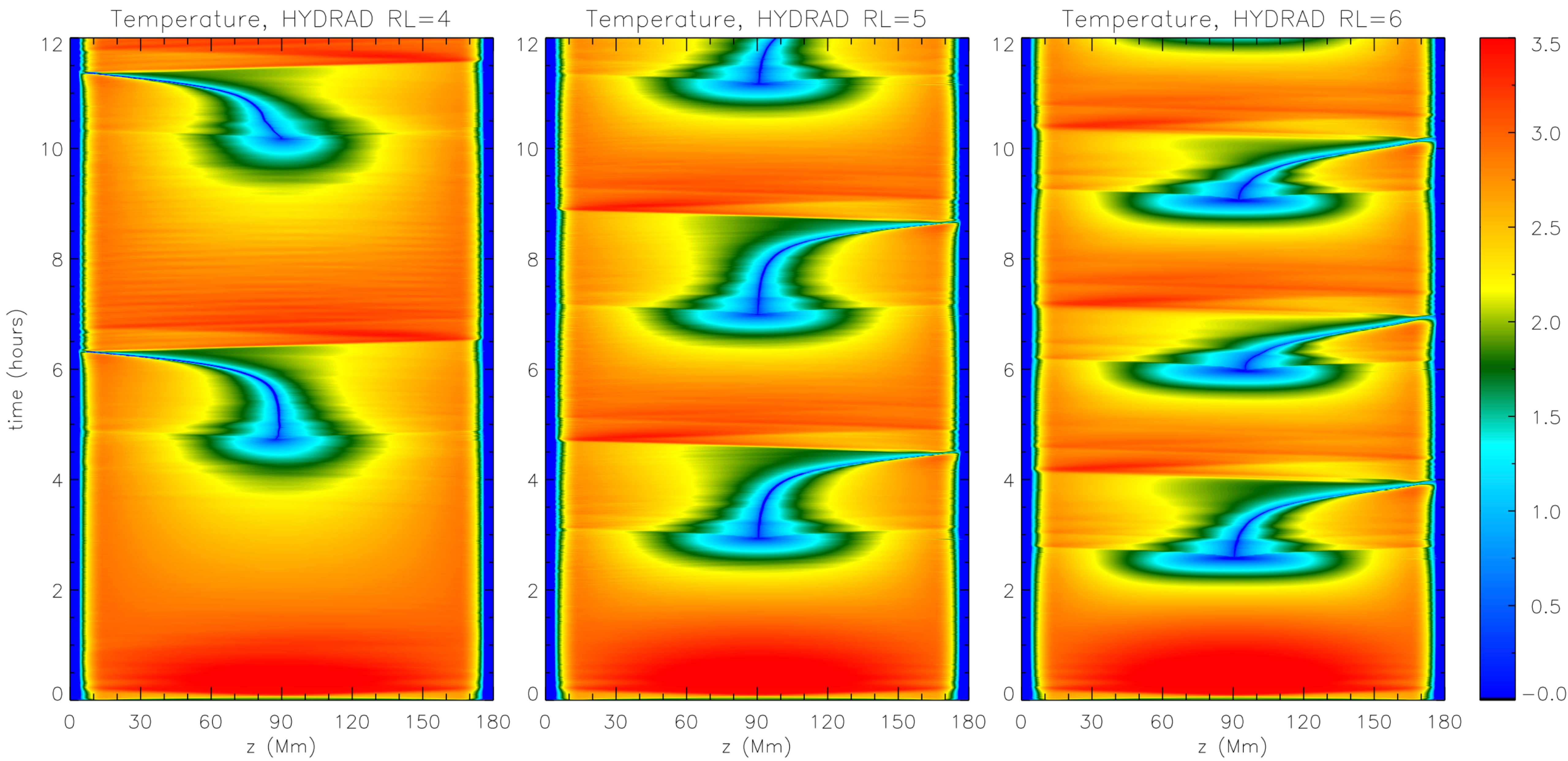

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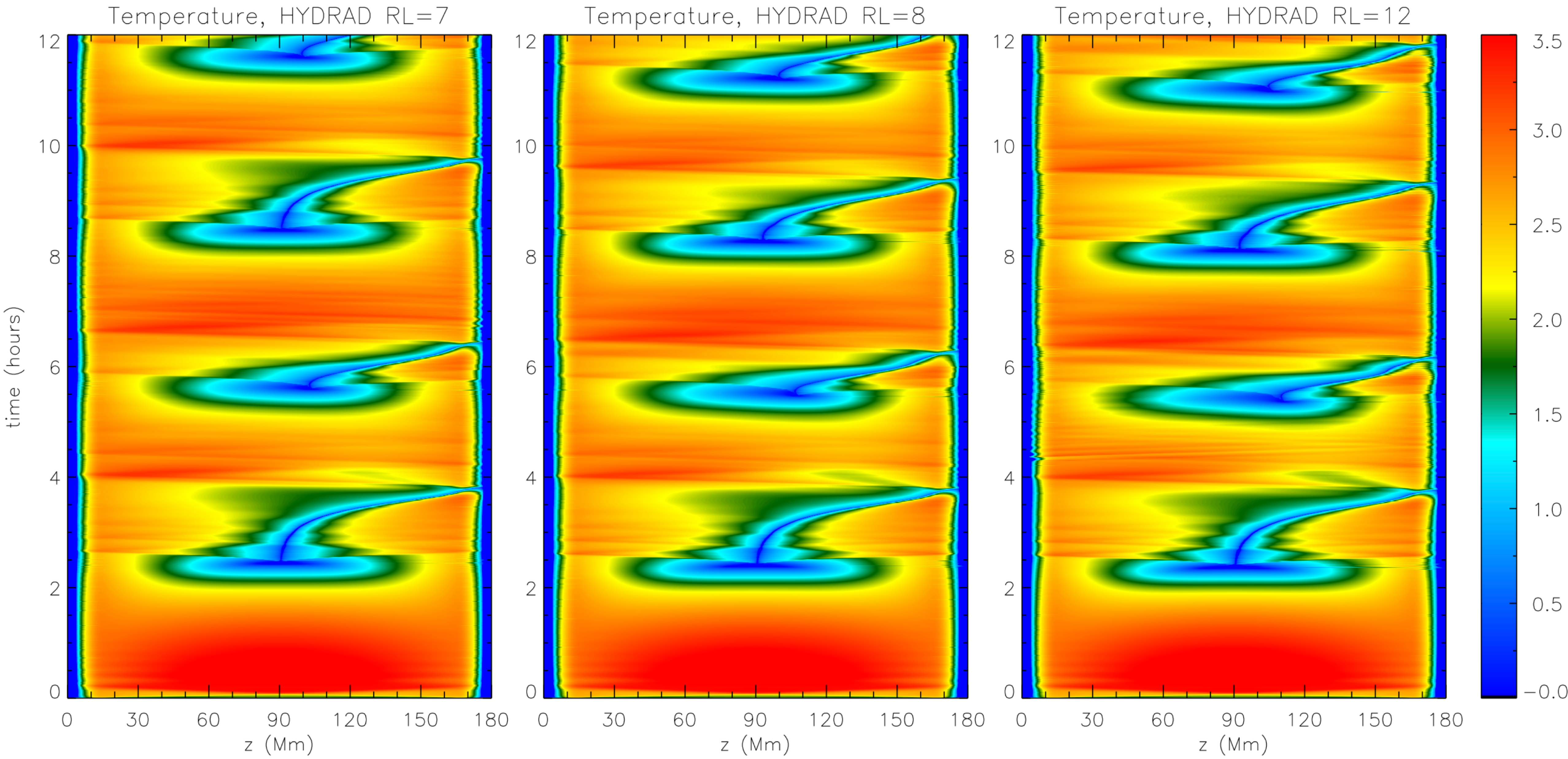
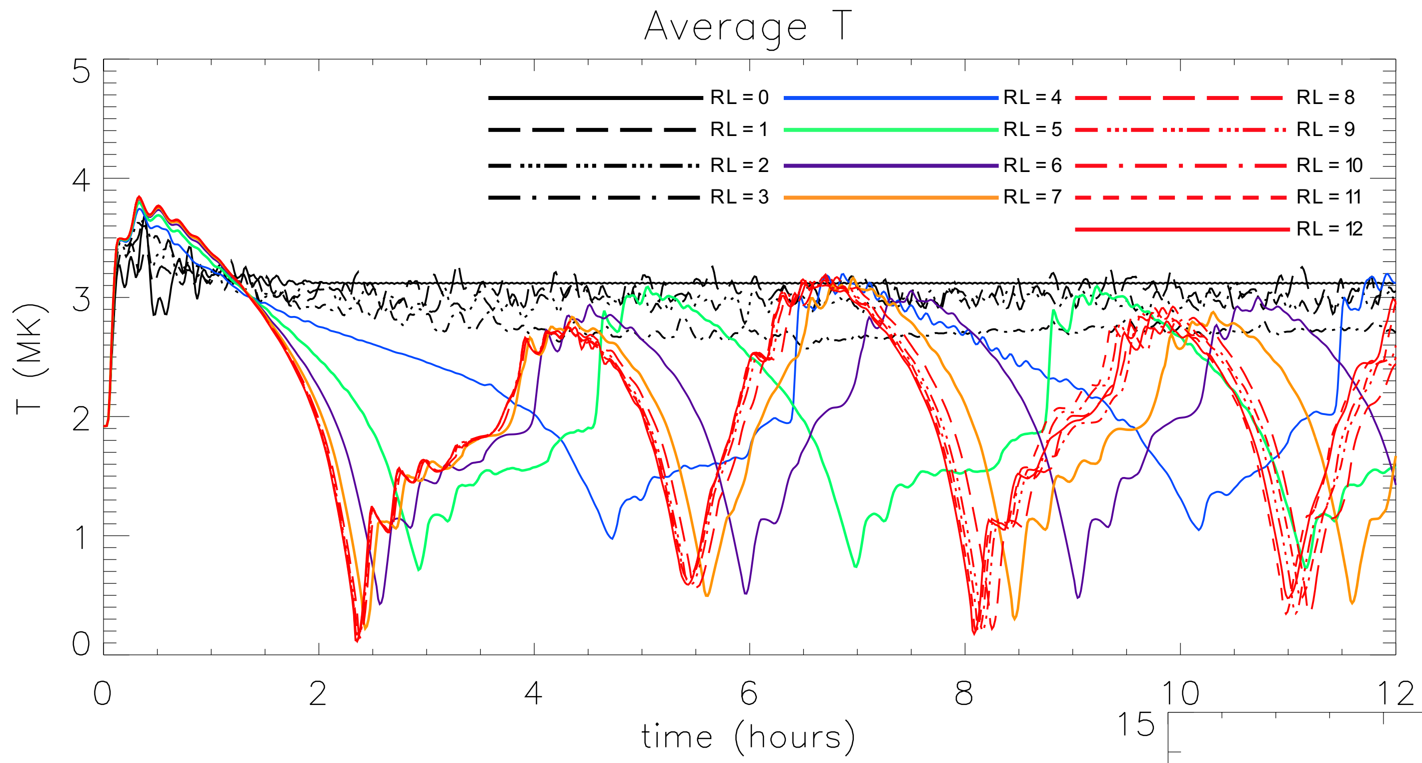
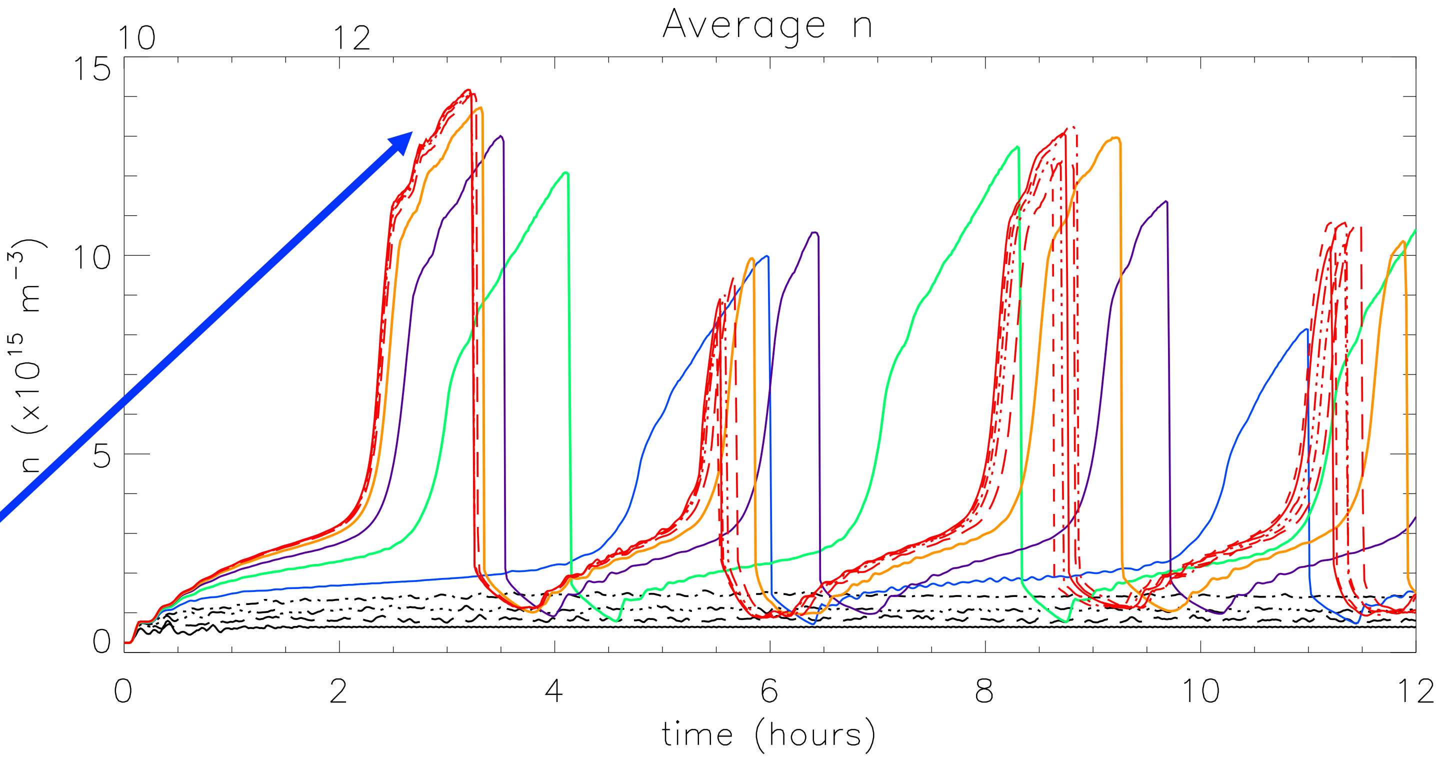


The Effect on TNE Cycles of Spatial Resolution in the Transition Region.

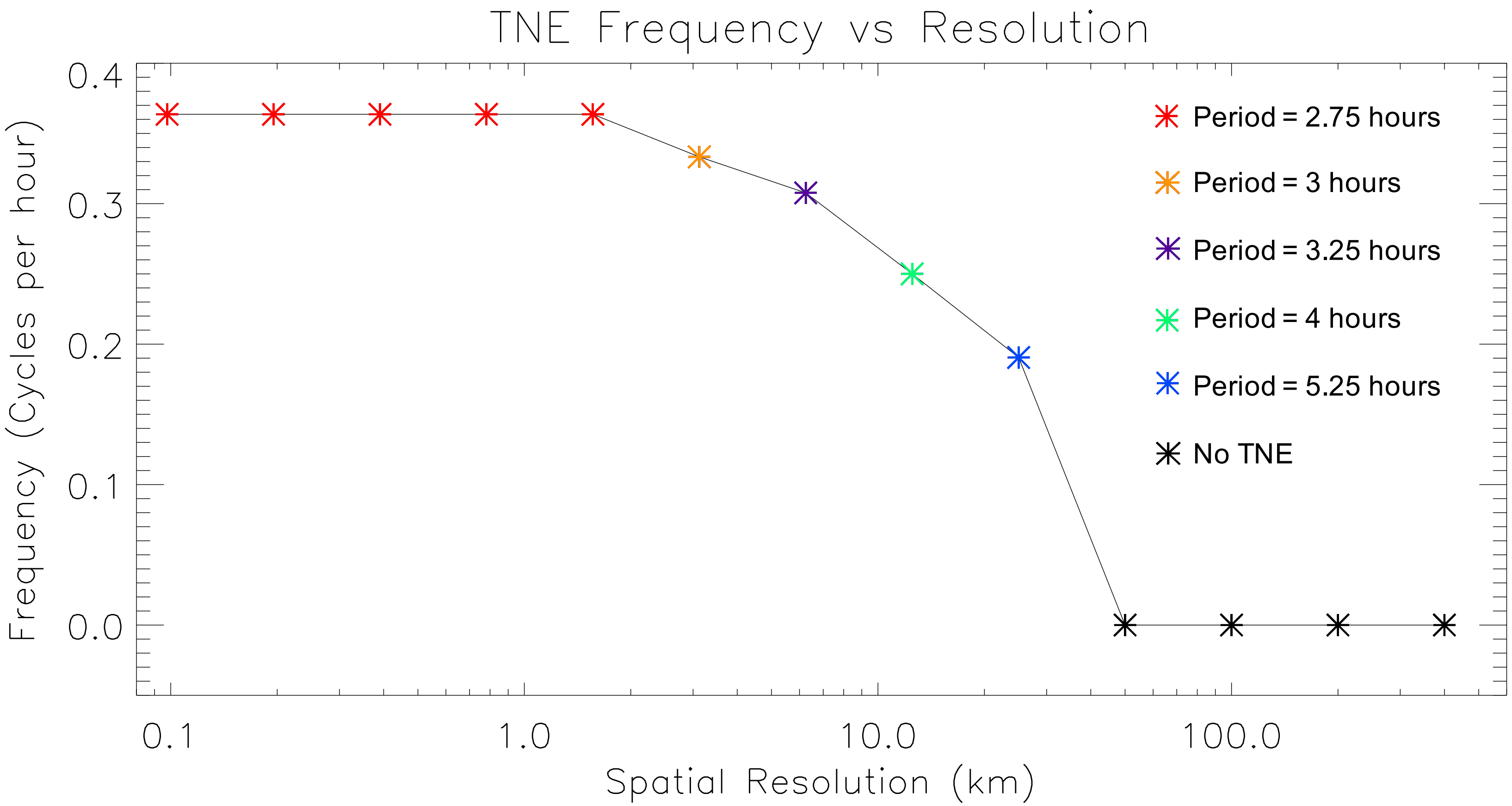


Estimate the TNE cycle period from the troughs in the coronal averaged temperature.

Convergence of the period requires a TR resolution of at least 1.5625 km (RL >= 8, red lines).



The Effect on TNE Cycles of Spatial Resolution in the TR.

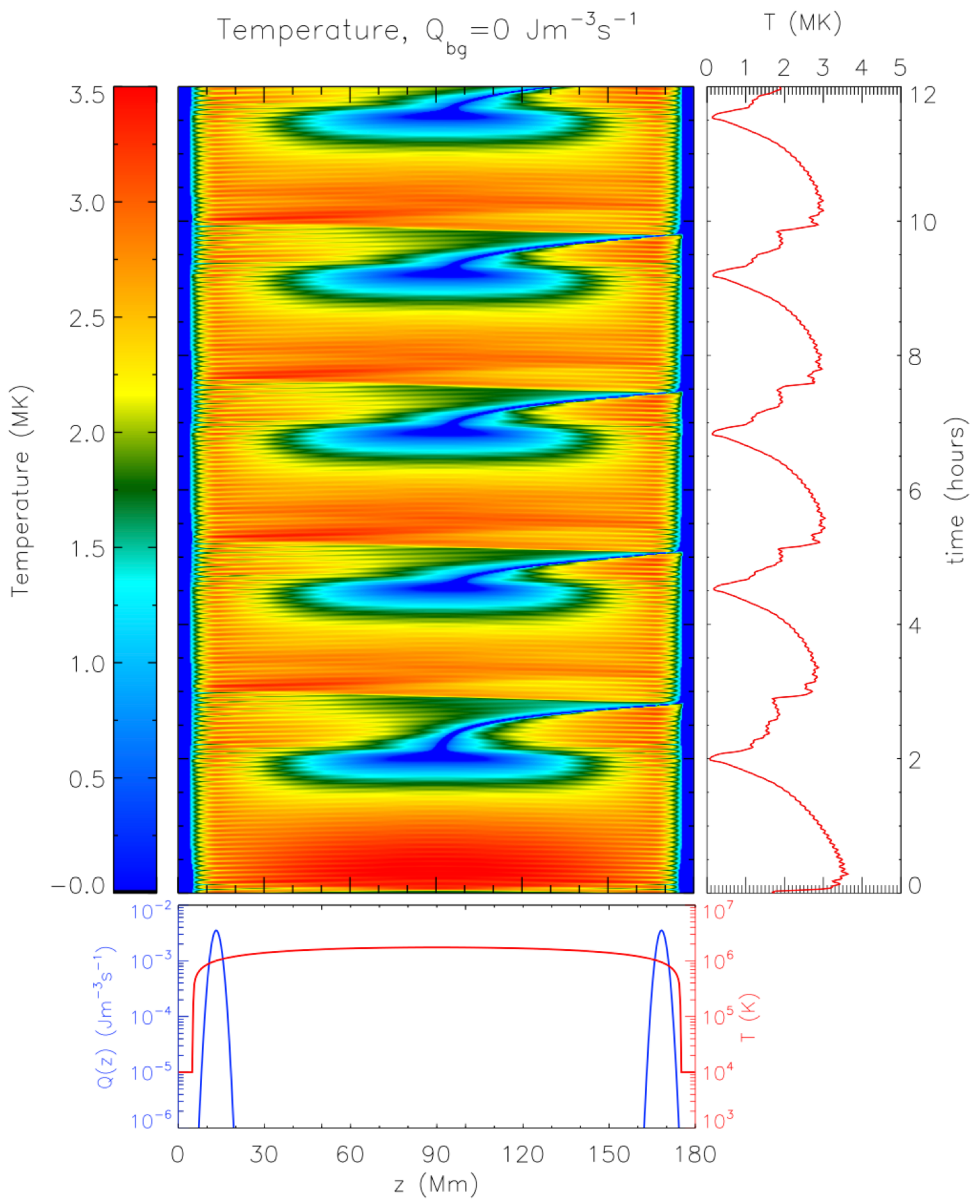


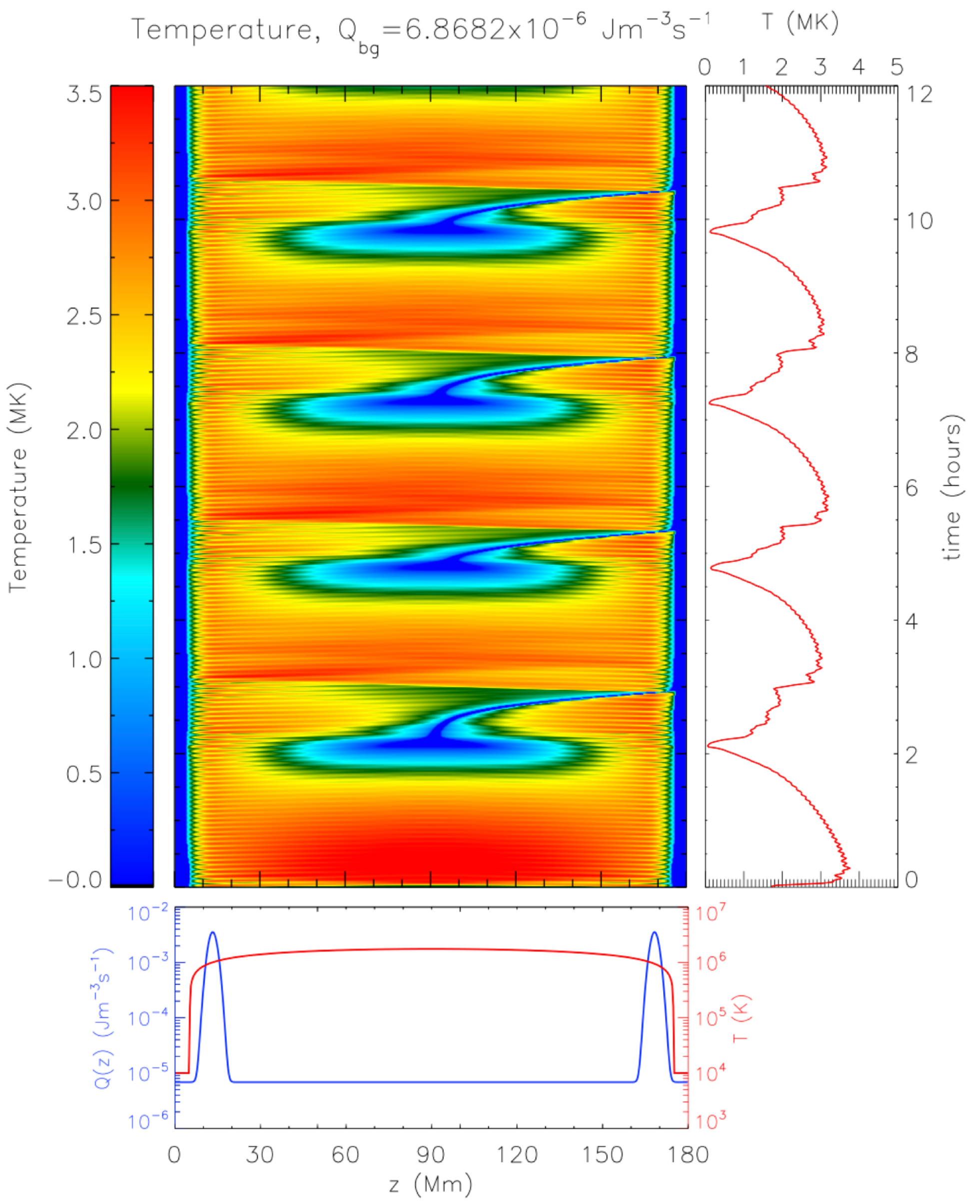
The existence and period of TNE limit cycles in coronal loop models are strongly dependent on the numerical spatial resolution used.

If the TR is under-resolved then the evaporative response can be underestimated (BC13). This results in either (i) steady state solutions because the lower density is insufficient to trigger the thermal instability or (ii) enhancements in the limit cycle periods because the reduced evaporation rate requires an extended time to trigger the runaway cooling.

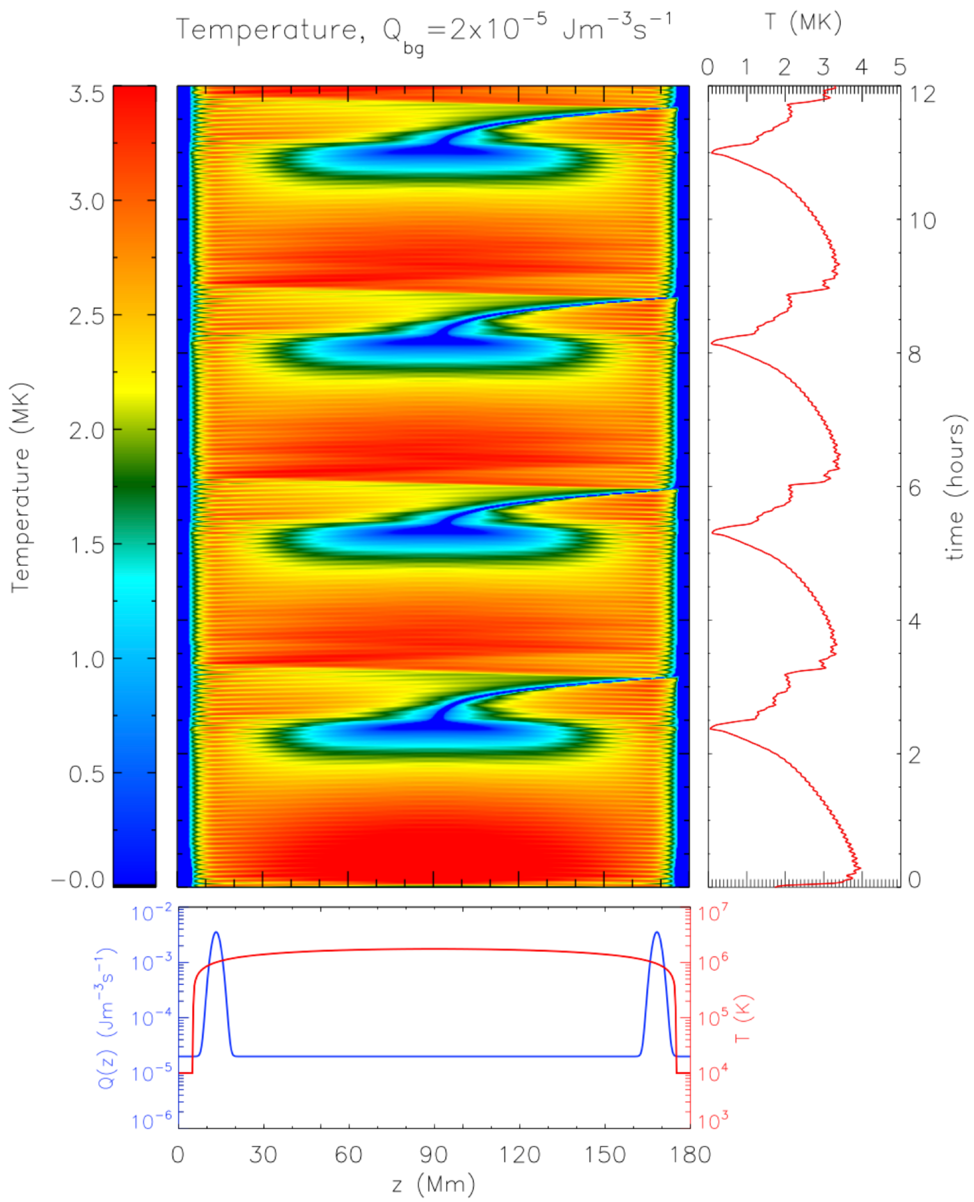
When interpreting the observed intensity pulsations and cyclic coronal rain as TNE cycles with condensations, the precise characteristics of these cycles become important (Auchère et al. 2018).

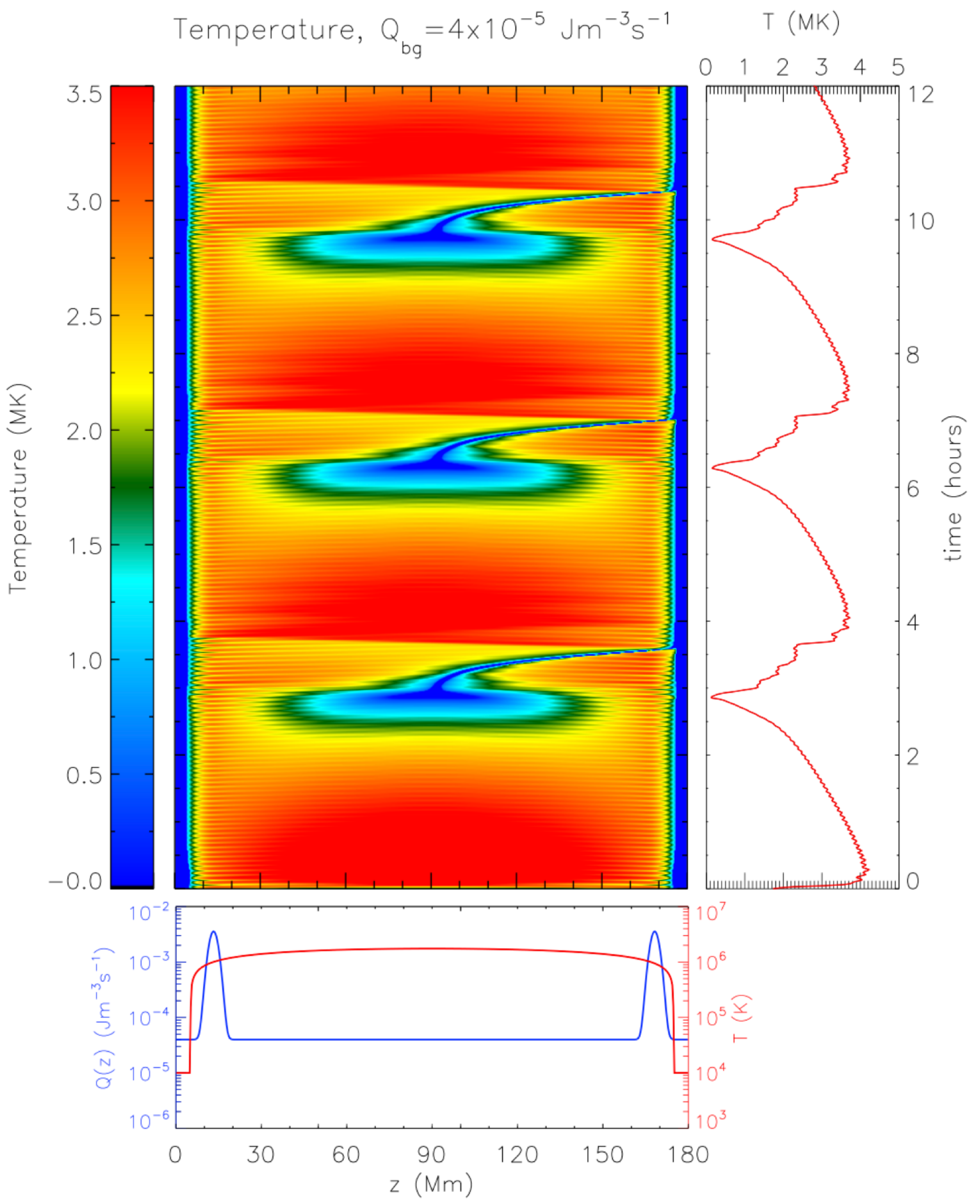
The Effect on TNE Cycles of the Background Heating.





The Effect on TNE Cycles of the Background Heating.





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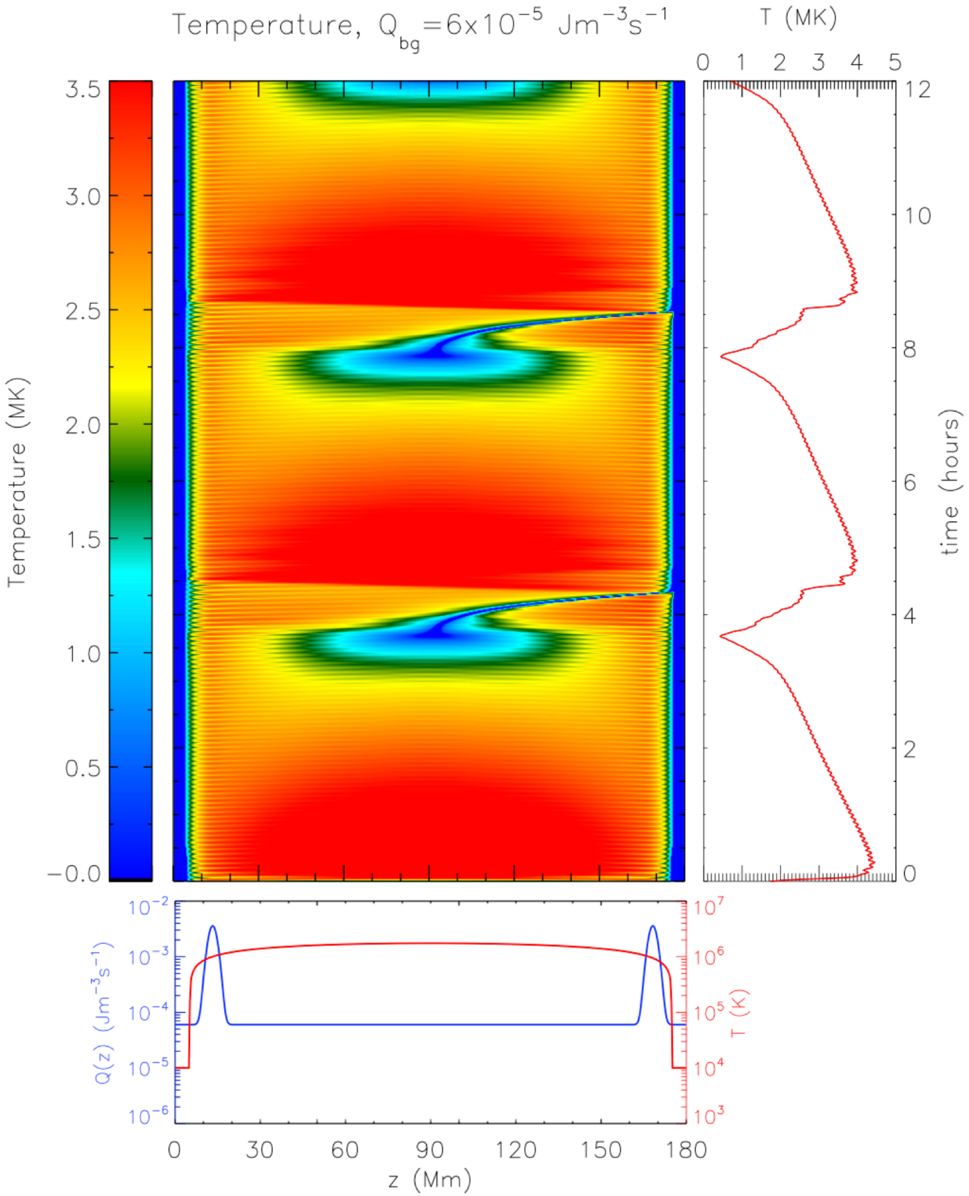
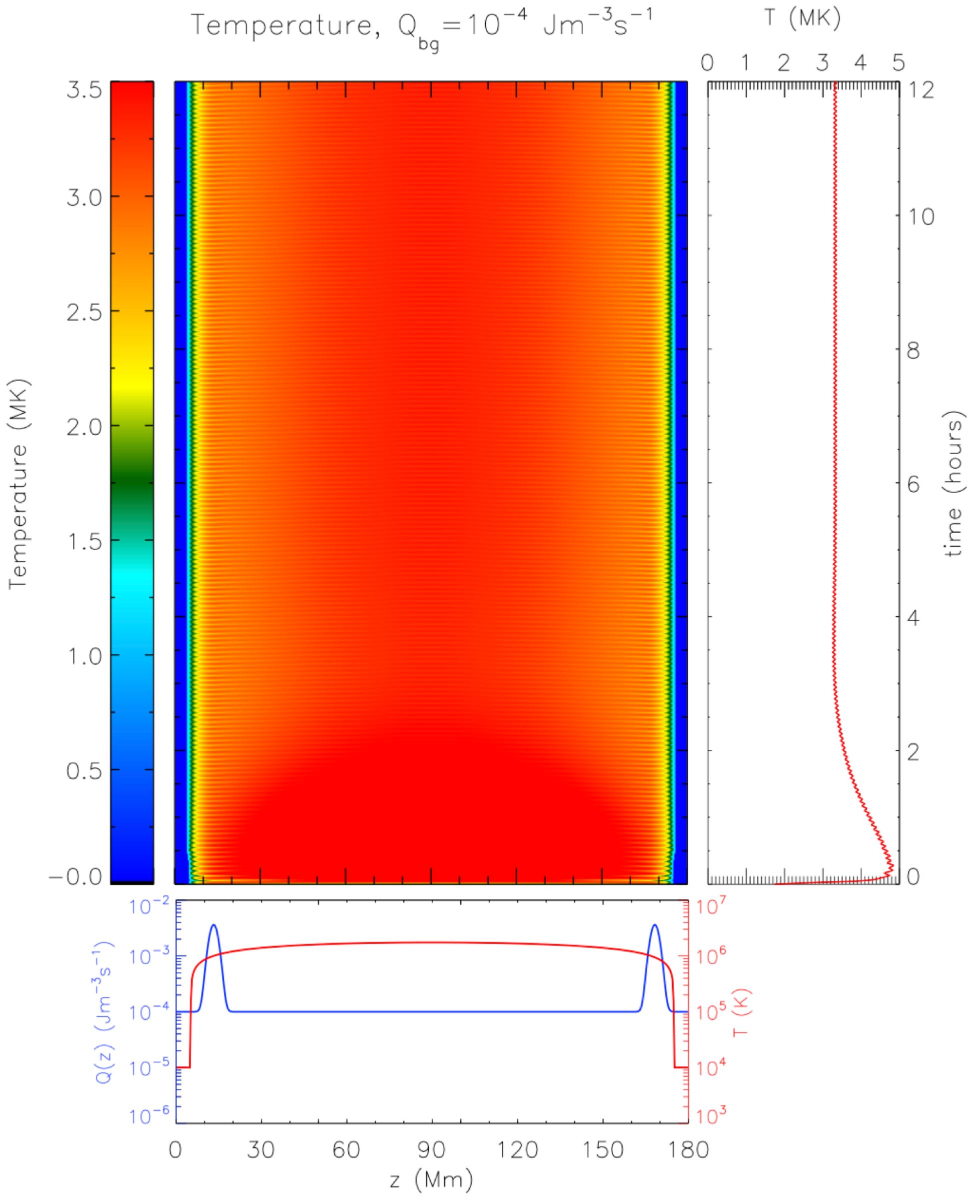
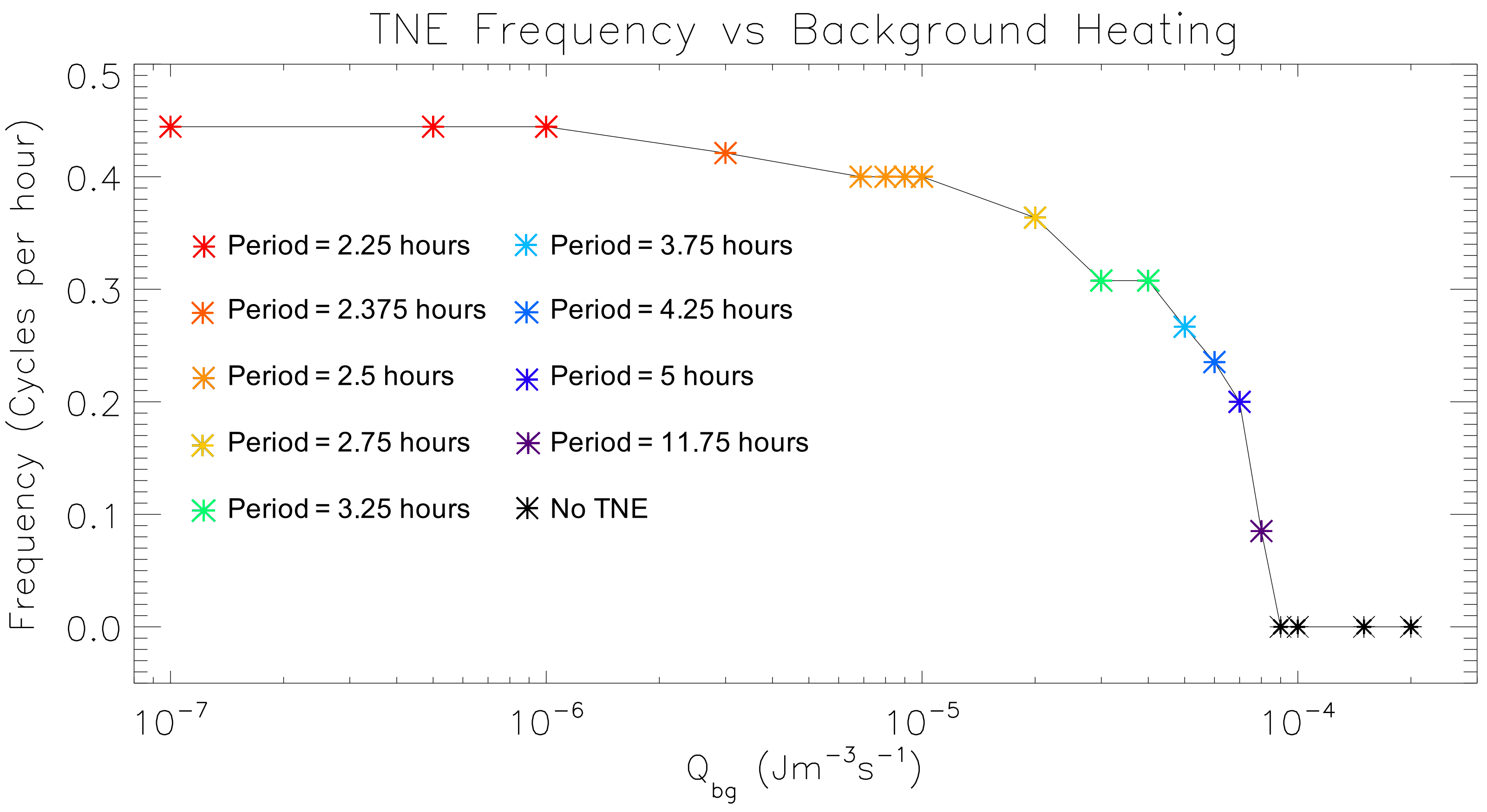




The Effect on TNE Cycles of the Background Heating.



The use of a background heating term can either (i) significantly change the period of the TNE cycles observed in coronal loop models or (ii) act to suppress the thermal instability and the existence of such limit cycles.

If the background heating value is increased, then in order for radiative cooling to overcome the heating and trigger the onset of TNE, the evaporative response must also be increased.

When interpreting the observed intensity pulsations and cyclic coronal rain as TNE cycles with condensations, the precise characteristics of these cycles become important (Auchère et al. 2018).

Conclusions Part II

1. The existence of TNE cycles in coronal loop models is strongly dependent on obtaining the "correct" plasma response to the energy deposition at the "footpoints" of the loop. If the TR is under-resolved then the evaporative response can be underestimated, resulting in either (i) steady state solutions because the lower density is insufficient to trigger the thermal instability or (ii) enhancements in the limit cycle periods because the reduced evaporation rate requires an extended time to trigger the runaway cooling.

1. The use of a background heating term can either (i) significantly change the period of the TNE cycles observed in coronal loop models or (ii) stabilize the thermal instability and suppress the existence of such cycles.

2. Preliminary results that only cover a small range of the large parameter space. Other factors such as the the loop geometry and area expansion and stochasticity of the heating events also play an important role.

(Johnston et al. 2018, *in prep*)

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