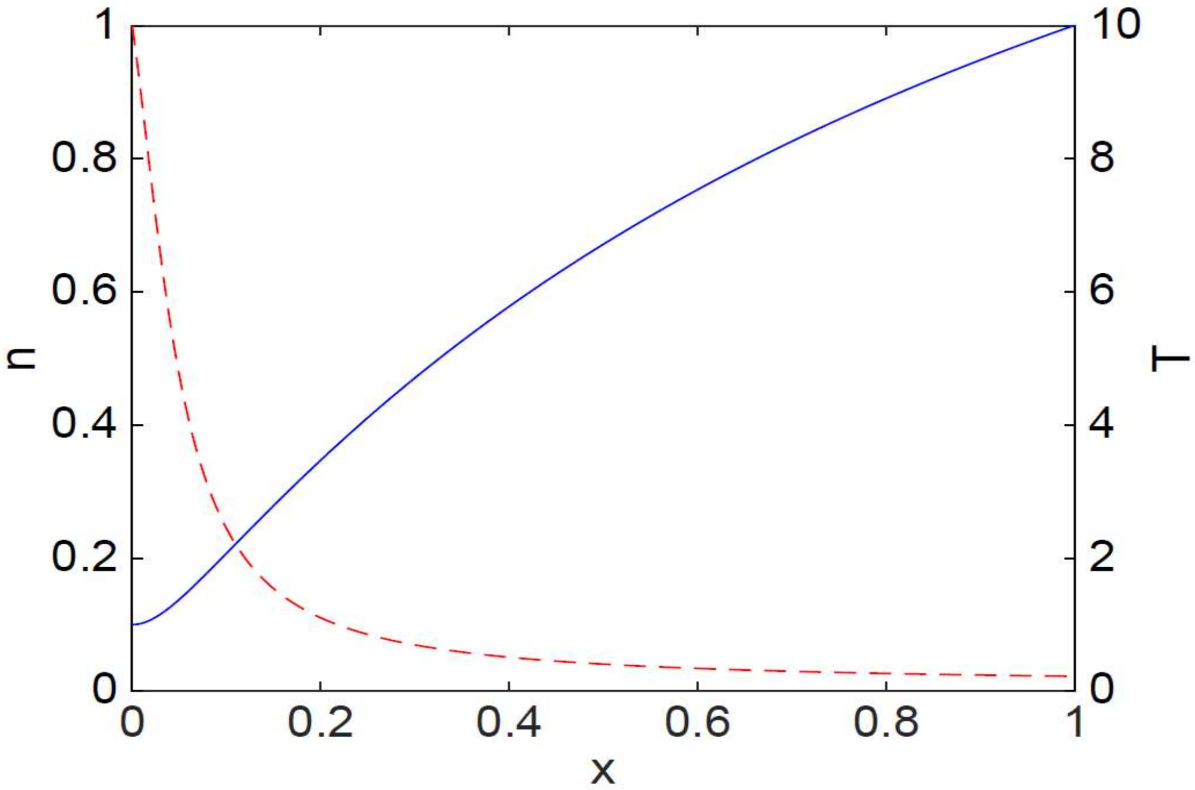
Temperature inversion in a gravitationally bound plasma: the case of the solar corona

Luca Barbieri

In collaboration with: Lapo Casetti, Andrea Verdini and Simone Landi

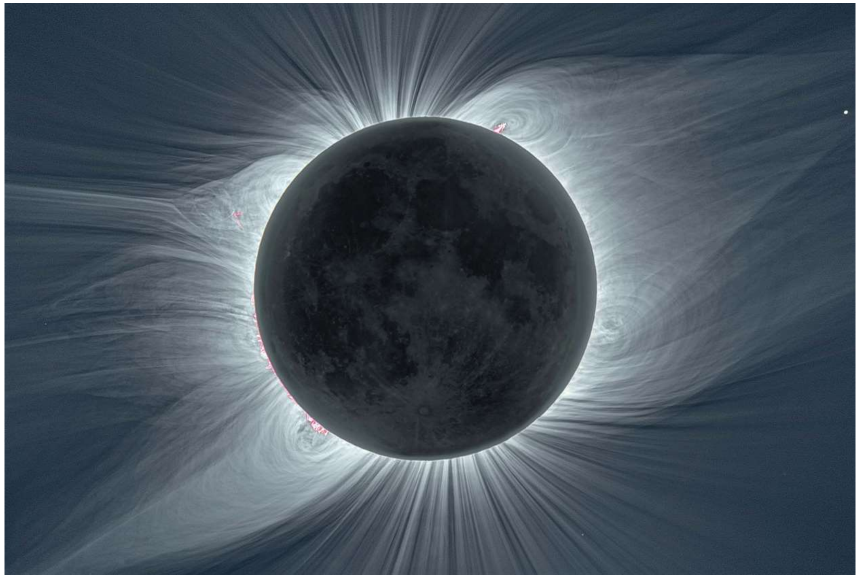
What is temperature inversion?

Non equilibrium stationary configuration (non isothermal)



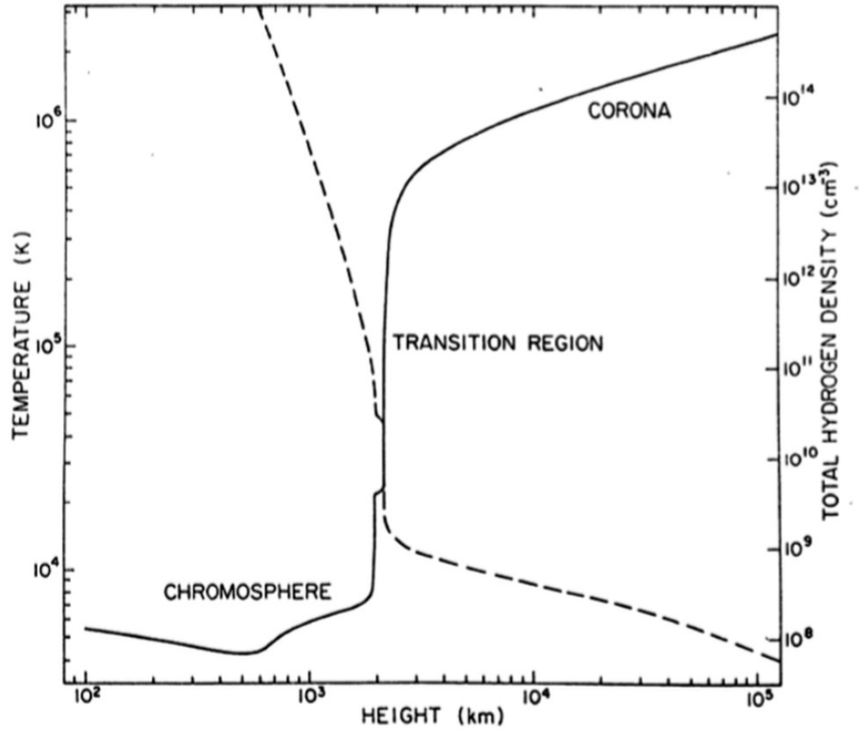
Number density and temperature are anticorrelated

The solar atmosphere: coronal heating problem (temperature inversion)



[M.Druckmuller eclipse August 2008]

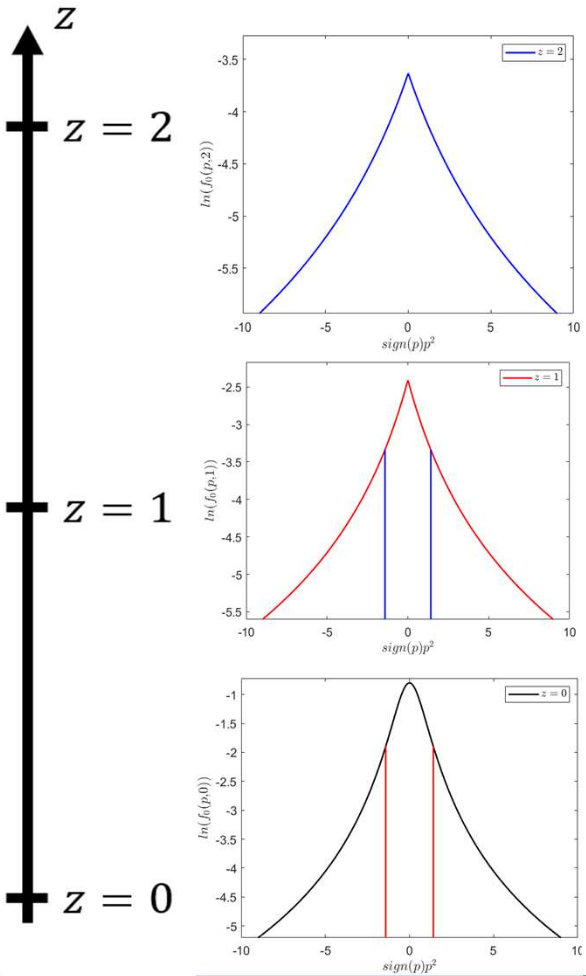
Temperature inversion



Standard approaches: fluid dynamics approaches
The hypothesis of LTE (local thermal equilibrium)

Number density and temperature are anticorrelated

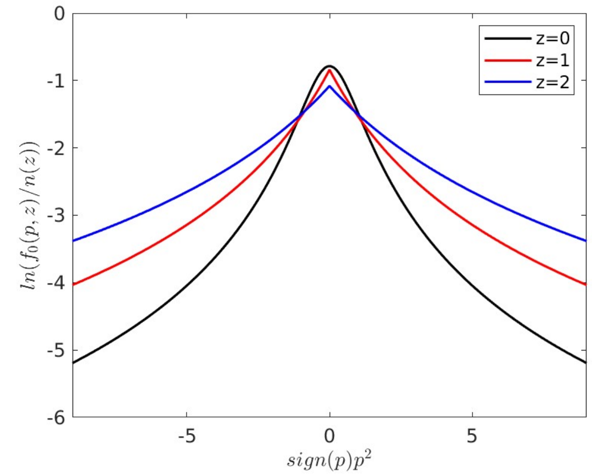
Non-equilibrium approach: velocity filtration (J.D. Scudder 1992)

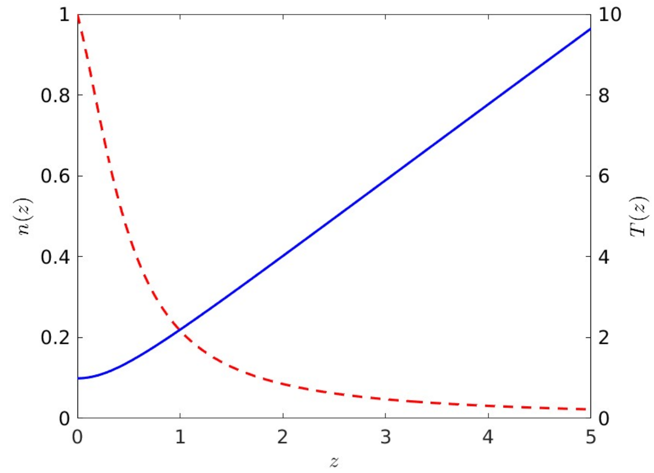


The Model

- One-dimensional model.
- Non interacting particles.
- Stationary suprathermal VDF at the base.

$$f_0(p) = \frac{\sqrt{2}}{\pi(1+p^4)}$$





What did we do?

The kinetic (numerical) model

- Self-electrostatic interactions (an electrostatic plasma).
- **Thermal contact with the Chromosphere (a thermostat)**.

Fluctuating temperature of the Chromosphere

- **Fluctuating temperature of the Chromosphere (thermostat)**→ Temperature inversion.
- Theoretical model to explain the results of the simulations.

The kinetic (numerical) model

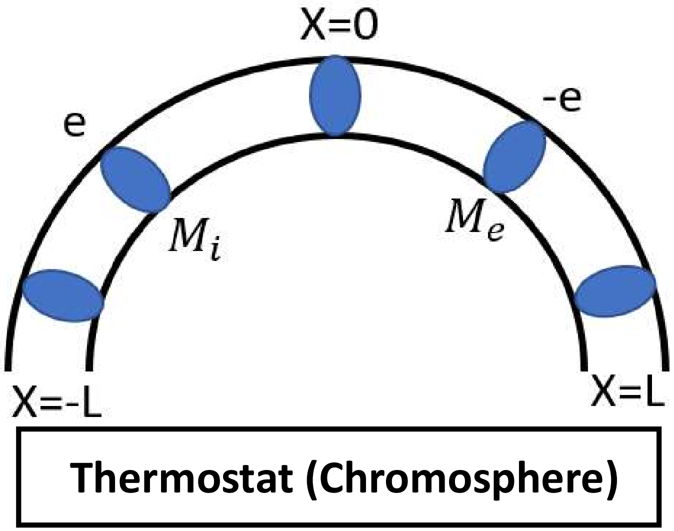
- Loop (Semicircular tube).
- External gravitational field plus the Pannekoek-Rossland field.
- Thermal contact with the Chromosphere (thermostat).
- Cylindrical symmetry (one-dimensional model).
- HMF (Hamiltonian mean-field) assumption to treat the self-electrostatic field (only the first Fourier mode).

$$M_e \ddot{x}_{j,e} = -eE(x_{j,e}) + g\frac{M_e + M_i}{2} \sin\left(\frac{\pi x_{j,e}}{2L}\right)$$

$$M_i \ddot{x}_{j,i} = eE(x_{j,i}) + g\frac{M_e + M_i}{2} \sin\left(\frac{\pi x_{j,i}}{2L}\right)$$

$$E(x) = \frac{4eN}{S} q \sin\left(\frac{\pi x}{L}\right)$$

$$q = q_i - q_e \quad q_{e/i} = \frac{1}{N}\sum_{j=1}^{N} \cos\left(\frac{\pi x_{j,e/i}}{L}\right)$$



The system of units

All the quantities are normalized as

$$L_0 = \frac{L}{\pi} \quad v_0 = \sqrt{\frac{k_B T_0}{M_e}} \quad M_0 = M_e$$

The equations of motion in dimensionless units

$$\ddot{\theta}_{j,e} = -Cq[\{\theta_{j,e/i}\}]\sin\theta_{j,e} + \tilde{g}\sin\left(\frac{\theta_{j,e}}{2}\right)$$

$$M\ddot{\theta}_{j,i} = Cq[\{\theta_{j,e/i}\}]\sin\theta_{j,i} + \tilde{g}\sin\left(\frac{\theta_{j,i}}{2}\right) \quad \theta_{j,e/i} = \frac{\pi x_{j,e/i}}{L}$$

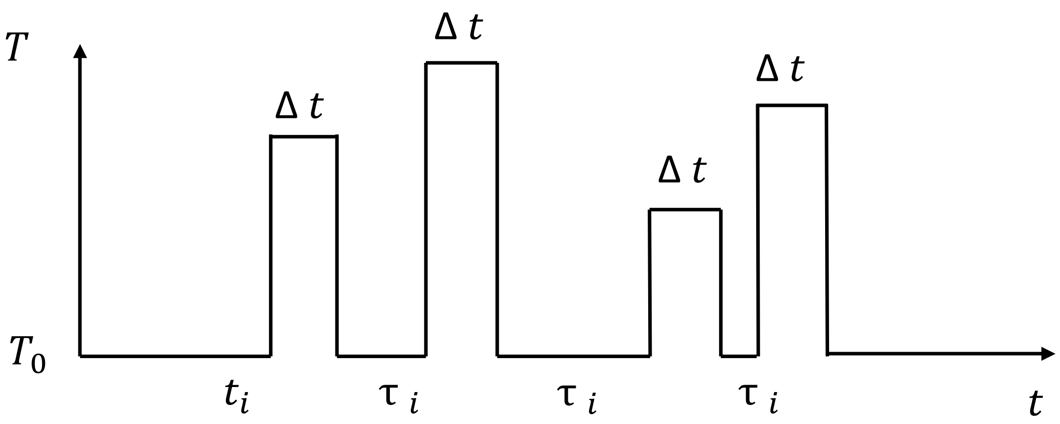
$$q[\{\theta_{j,e/i}\}] = q_i[\{\theta_{j,i}\}] - q_e[\{\theta_{j,e}\}] \quad q_{e/i}[\{\theta_{j,e/i}\}] = \frac{1}{N}\sum_{j=1}^{N}\cos\theta_{j,e/i}$$

$$M = \frac{M_i}{M_e} \quad C = 2\left(\frac{t_0}{t_{p,e}}\right)^2 \quad \tilde{g} = \frac{gL_0(M_i + M_e)}{2k_B T_0}$$

The thermostat temperature fluctuations

The system

- A two-component plasma in an external field.
- Fluctuating temperature at the base.



$\Delta t \ll t_{r,1}$ $\quad$ $t_{r,1}$ thermal relaxation time to T

$\tau_i \ll t_{r,2}$ $\quad$ $t_{r,2}$ thermal relaxation time back to T_0

τ sorted from an exponential distribution

$$f(\tau) = \frac{1}{\langle\tau\rangle} e^{-\frac{\tau}{\langle\tau\rangle}}$$

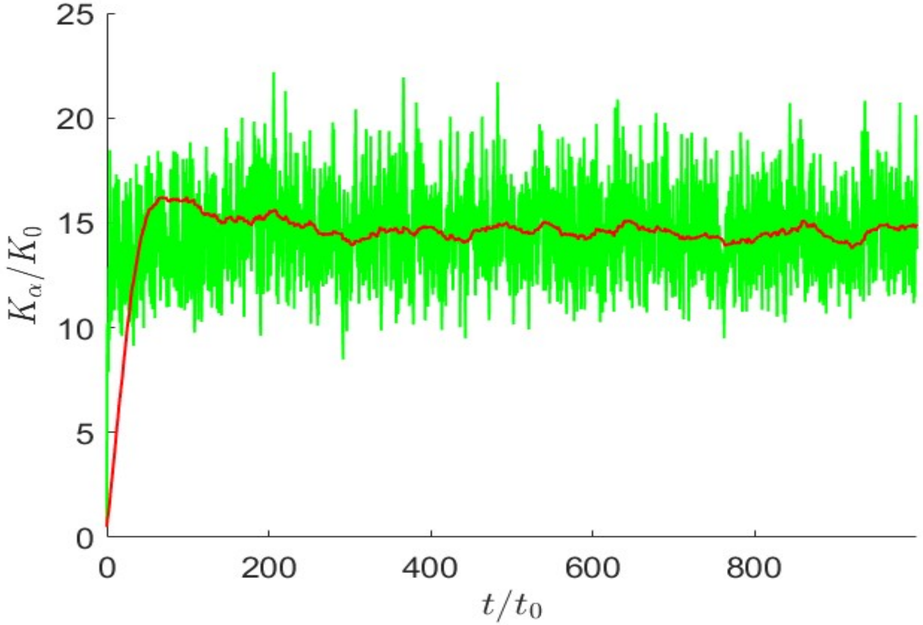
T sorted from an exponential distribution

$$f(T) = \frac{1}{T_p} e^{-\frac{T-T_0}{T_p}}$$

The temperature inversion

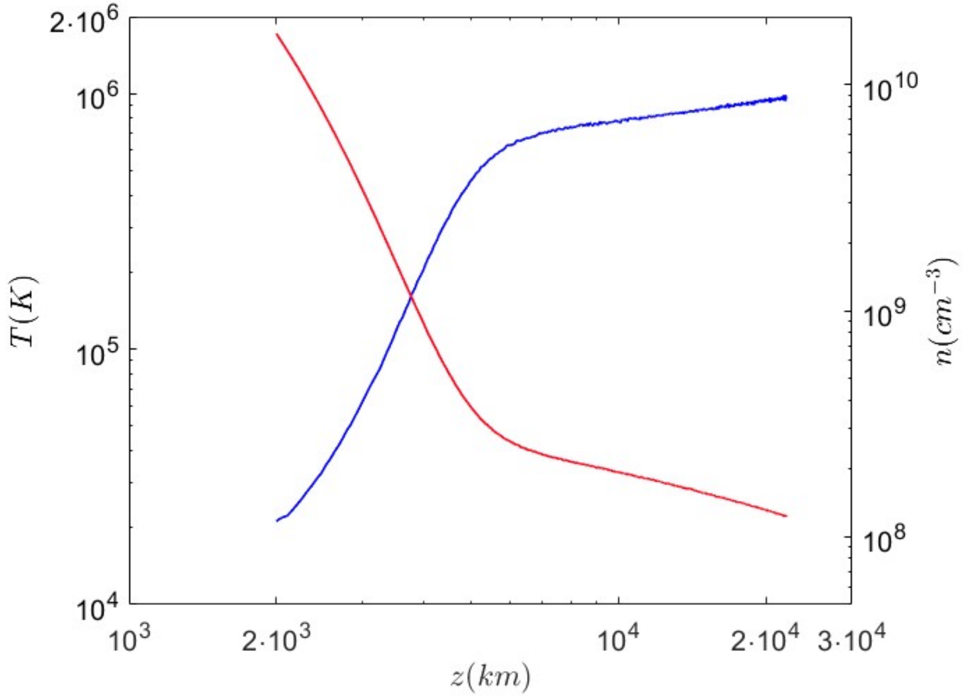
Electrons
Ions

$$C = 400 \quad M = \frac{M_i}{M_e} = 1836 \quad T_0 = 10000K \quad z_{top} - z_{bottom} = 2 \cdot 10^4 km \quad T_p = 900000K \quad A = \frac{\Delta t}{\Delta t + \langle \tau \rangle} = 0.1$$

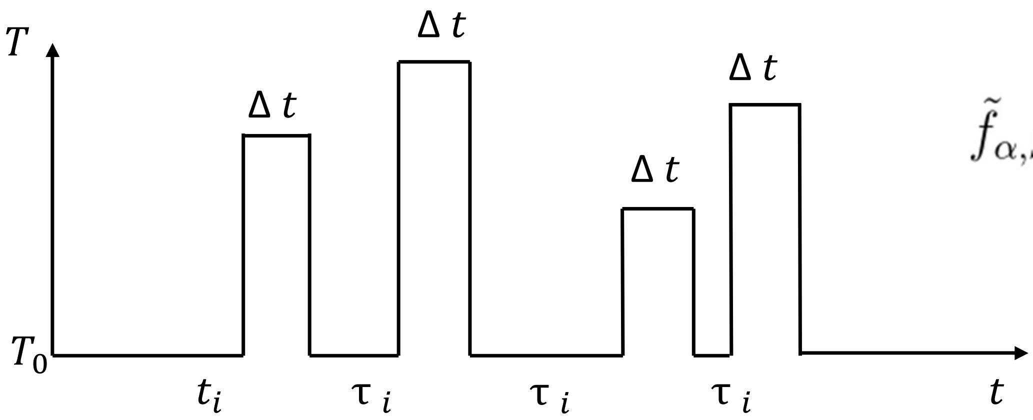


$$K_0 = k_B T_0 \quad t_0 = \frac{L_0}{v_T} \quad L_0 = \frac{z_{bottom} - z_{top}}{2} \quad v_T = \sqrt{\frac{k_B T_0}{M_e}}$$

Temperature
Density



The theoretical model: temporal coarse-graining



Coarse-grained Vlasov dynamics

$$\tilde{f}_{\alpha,SS}(\theta,p) = D\left(A\int_1^{+\infty} dT\,\frac{f(T)}{TM_\alpha}e^{-\frac{H_\alpha}{T}} + \frac{(1-A)}{M_\alpha}e^{-H_\alpha}\right)$$

$$H_\alpha = \frac{p^2}{2M_\alpha} + \tilde{g}z \qquad z = 2\cos\left(\frac{\theta}{2}\right)$$

$$\tau, \Delta t << \tilde{t} << t_R$$

$$\tilde{f}_\alpha = \frac{1}{\tilde{t}}\int_{\tilde{t}} dt\, f_\alpha$$

Thermal contribution

$$\frac{e^{-H_\alpha}}{M_\alpha}$$

Weight

$$A = \frac{\Delta t}{\Delta t + \langle\tau\rangle}$$

Suprathermal (multitemperature) contribution

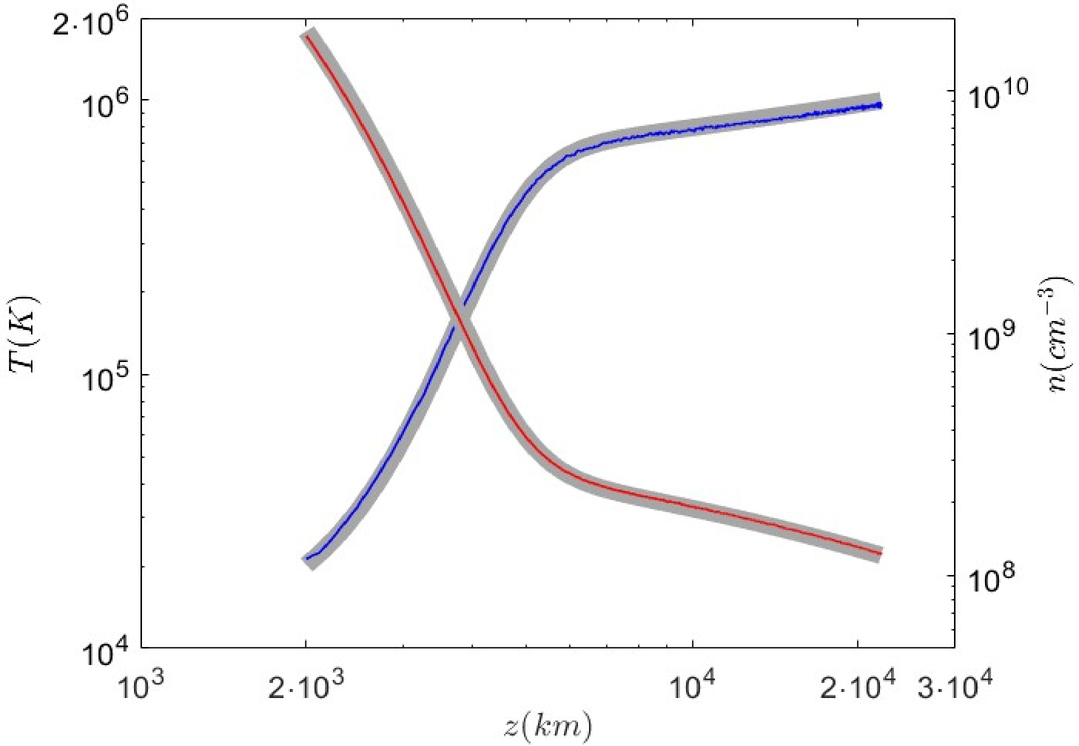
$$\int_1^{+\infty} dT\,\frac{f(T)}{TM_\alpha}e^{-\frac{H_\alpha}{T}}$$

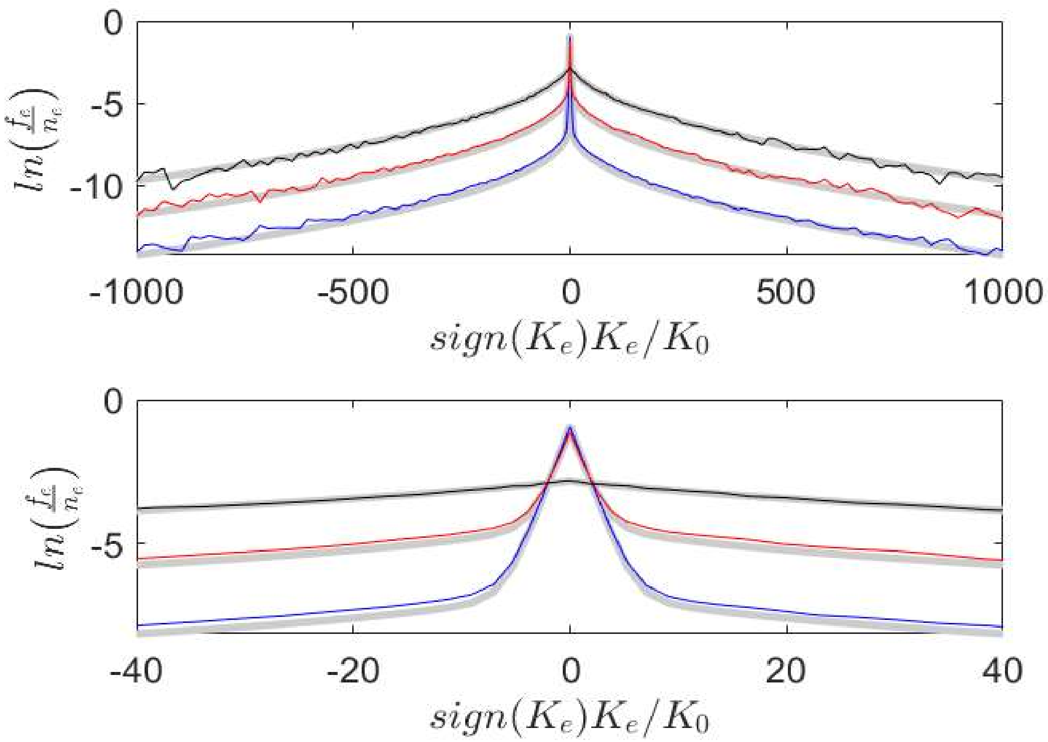
Why temperature inversion?: the theoretical model vs numerics

$$C = 400 \quad M = \frac{M_i}{M_e} = 1836 \quad T_0 = 10000K \quad z_{top} - z_{bottom} = 2 \cdot 10^4 km \quad T_p = 900000K \quad A = \frac{\Delta t}{\Delta t + \langle \tau \rangle} = 0.1$$

Theoretical model

$z_1 = 2.3 \cdot 10^3 km$ $z_2 = 3.9 \cdot 10^3 km$ $z_3 = 1.1 \cdot 10^4 km$



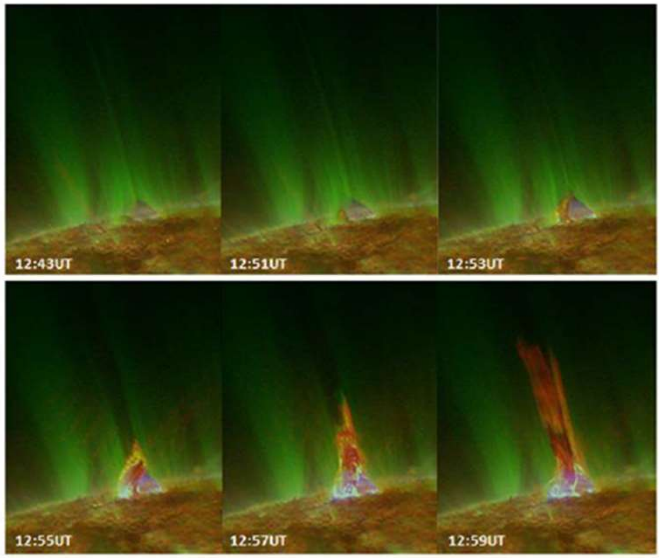


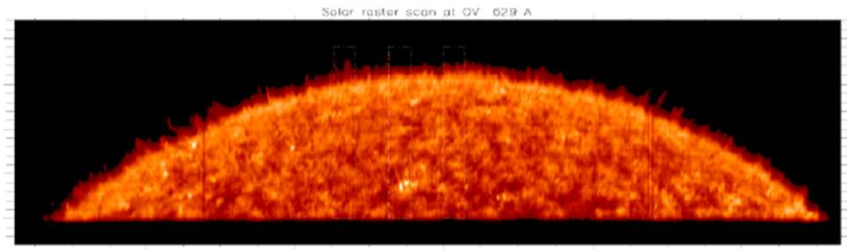
Conclusions

- We have shown with a kinetic (numerical) model how temperature fluctuations in the high Chromosphere are able to bring the plasma towards a non-thermal configuration with temperature inversion.
- We have a theoretical model able to explain the results of the simulations.

Why the fluctuating temperature of the Chromosphere (thermostat)?

Jets and spicole





Magnetic reconnection