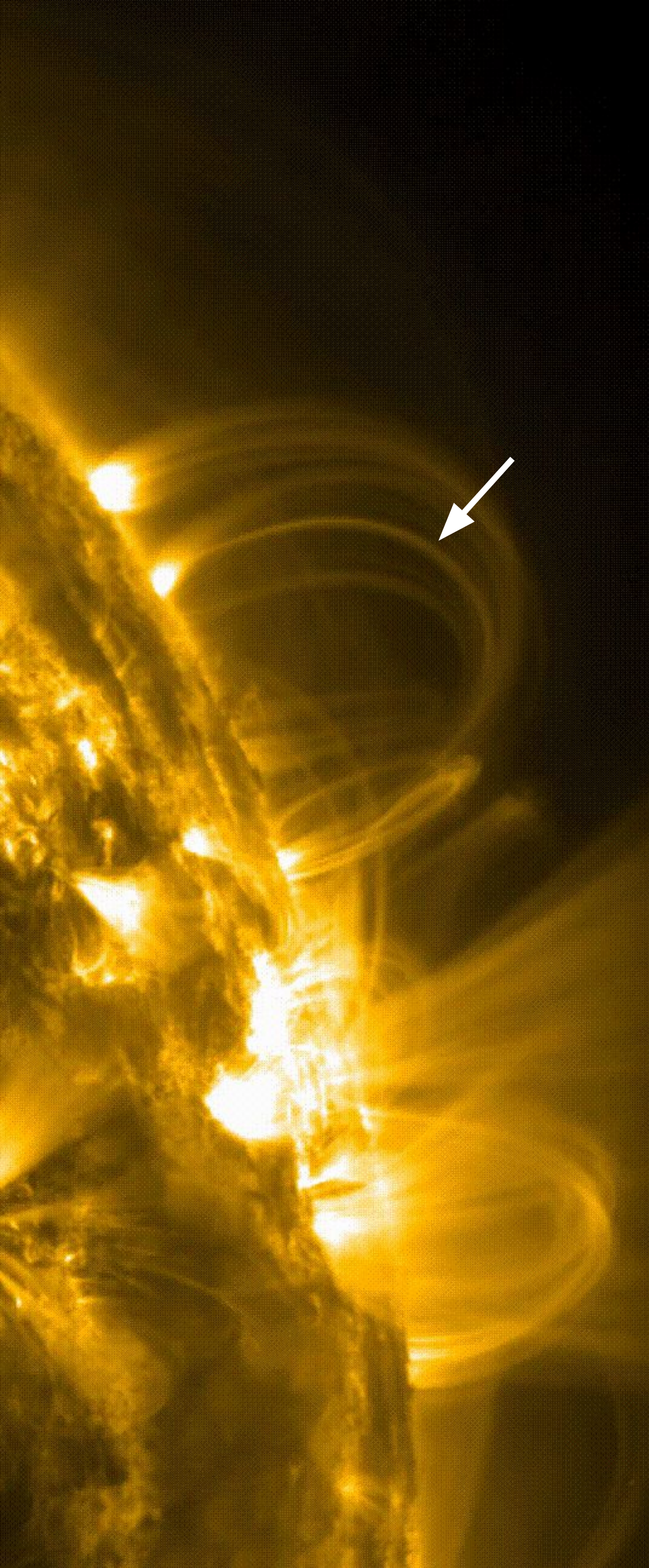


Cut-off of transverse waves through the solar transition region

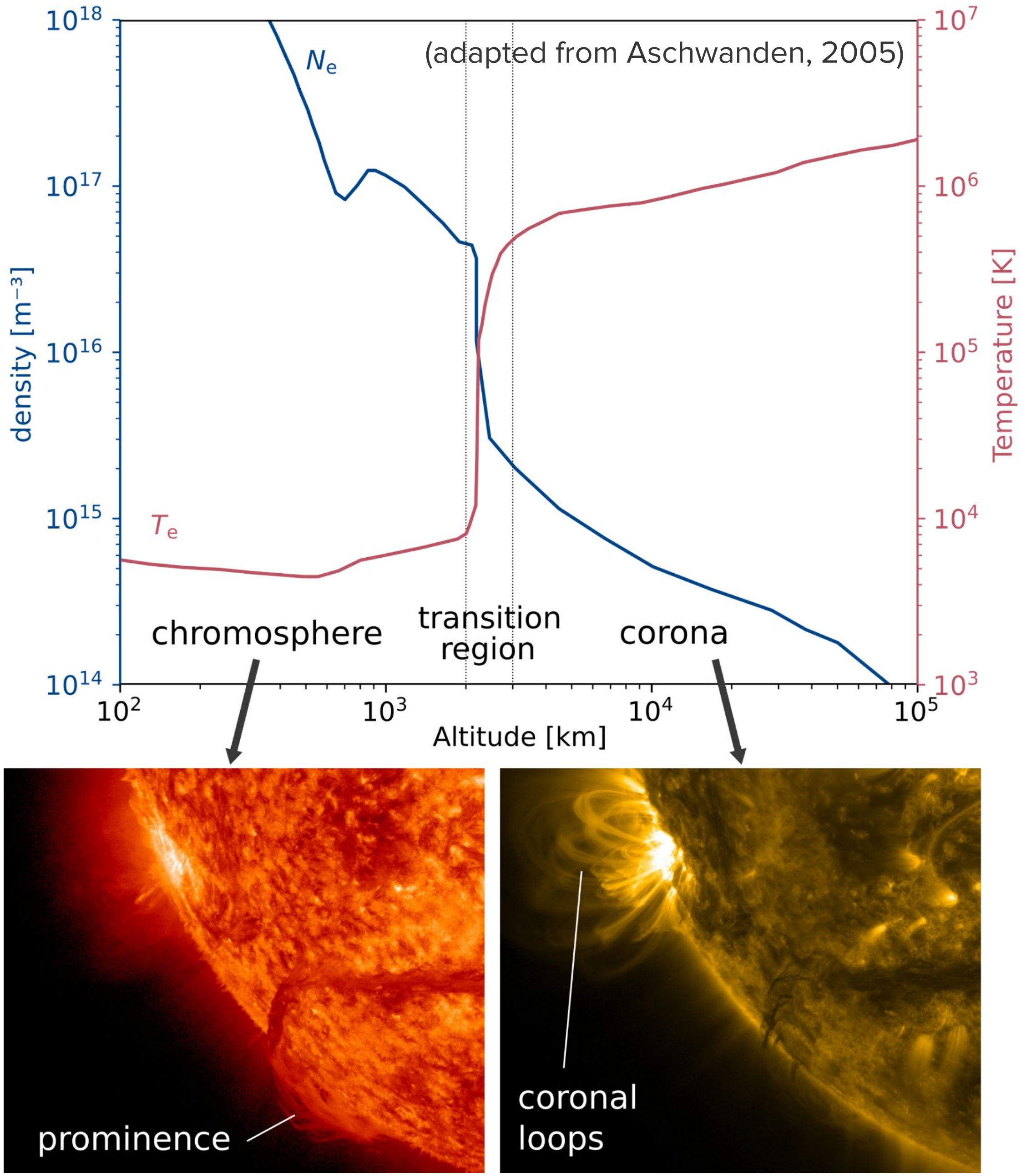
G. Pelouze, T. Van Doorsselaere,
K. Karampelas, J. M. Riedl,
& T. Duckenfield

IAS
Institut d'Astrophysique Spatiale
Orsay

KU LEUVEN

The coronal heating problem

Density and temperature in the solar atmosphere:



➜ How can we explain the heating of the solar corona?

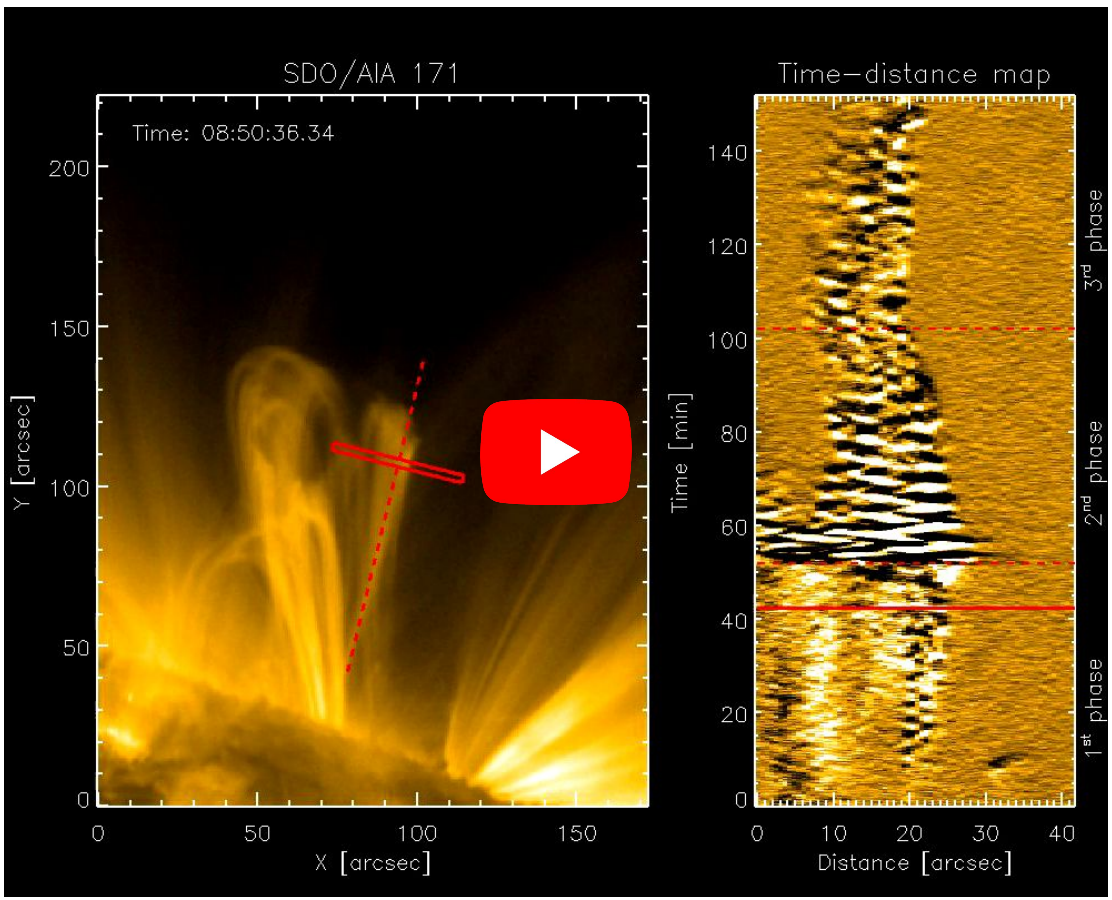
- Energy **source:** photospheric motion
- Energy is **transported** by the magnetic field, and **deposited** in the corona:
  - magnetohydrodynamic (MHD) waves,
  - magnetic reconnection,
  - mixed mechanisms.

We still don't know which mechanism is predominant

Transverse waves are **widely observed** in the corona

- **Propagating** kink waves:
  - **In loops** (e.g. Tomczyk et al. 2007; Tomczyk & McIntosh 2009; Thurgood et al. 2014)
  - **In open flux tubes** (Morton et al. 2015)
- **Standing** kink waves:
  - **Impulsively excited:** decaying oscillations (e.g. Nakariakov et al. 1999; Van Doorsselaere et al. 2007)
  - **Continuously driven:** decayless oscillations (e.g. Wang et al. 2012; Nisticò et al. 2013; Anfinogentov et al. 2013, 2015)

Nisticò et al. (2013)



Continuously driven

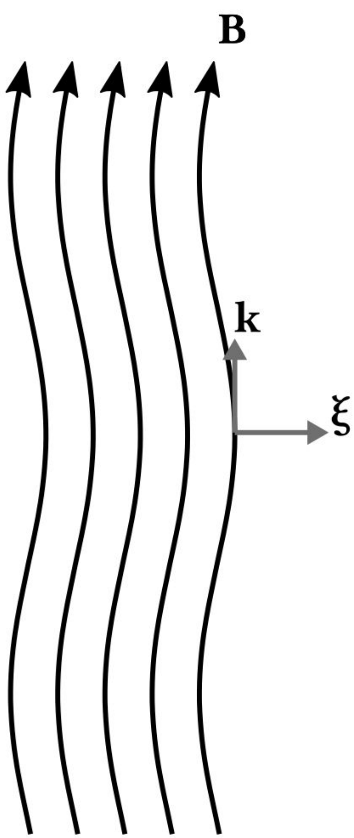
Impulsively-driven

Eruption

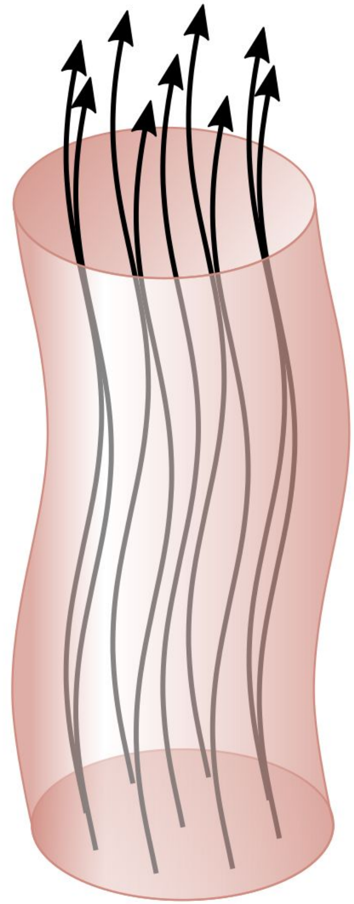
Continuously driven

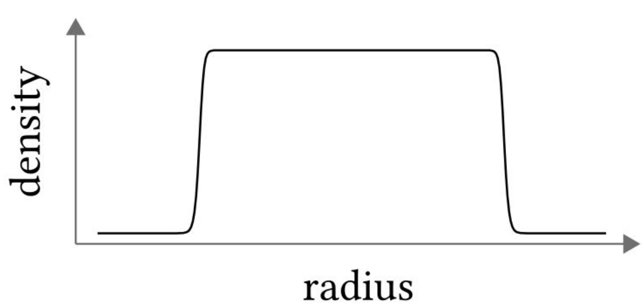
What are these transverse waves?

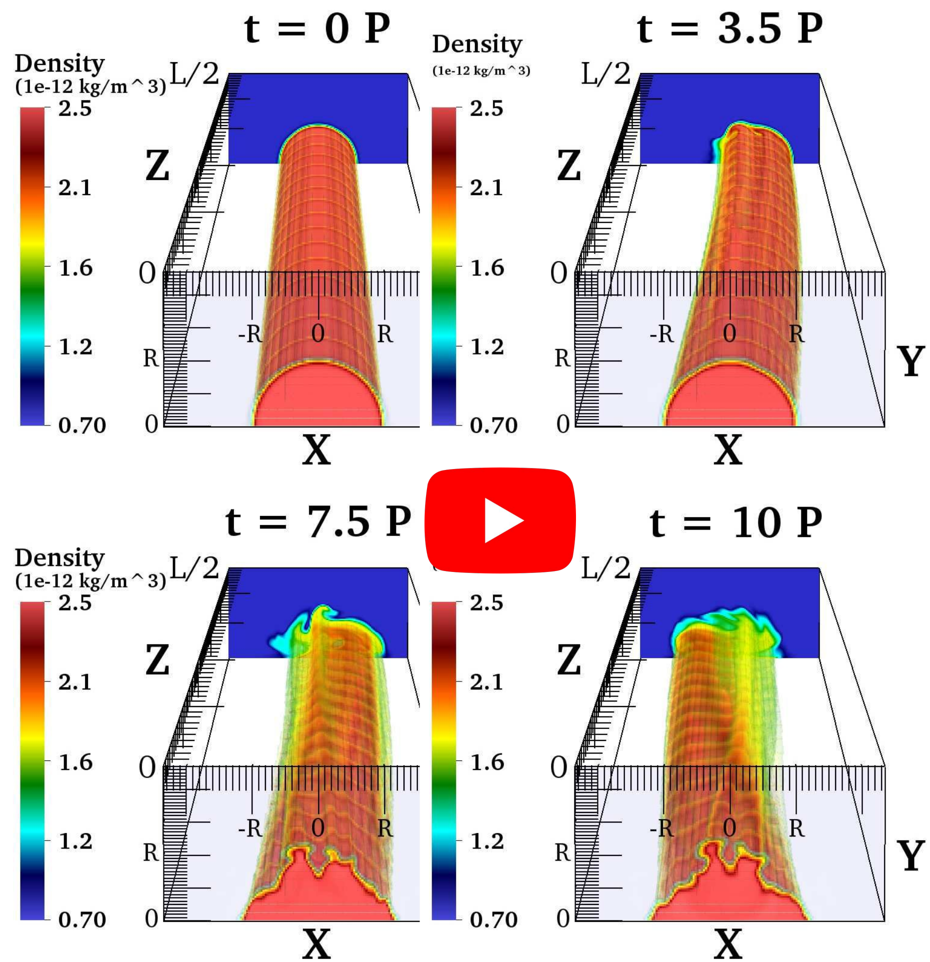
Alfvén waves
(magnetic tension)



Kink waves
(mag. tension + density cylinder)





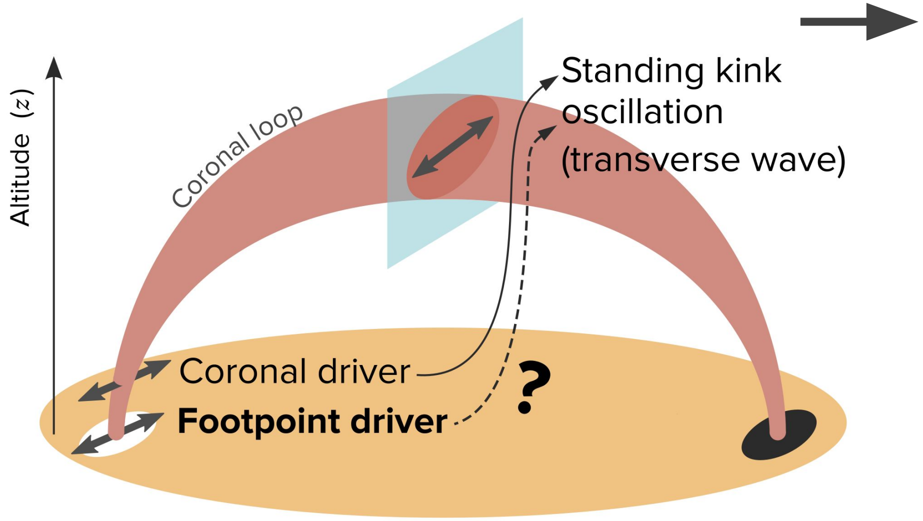


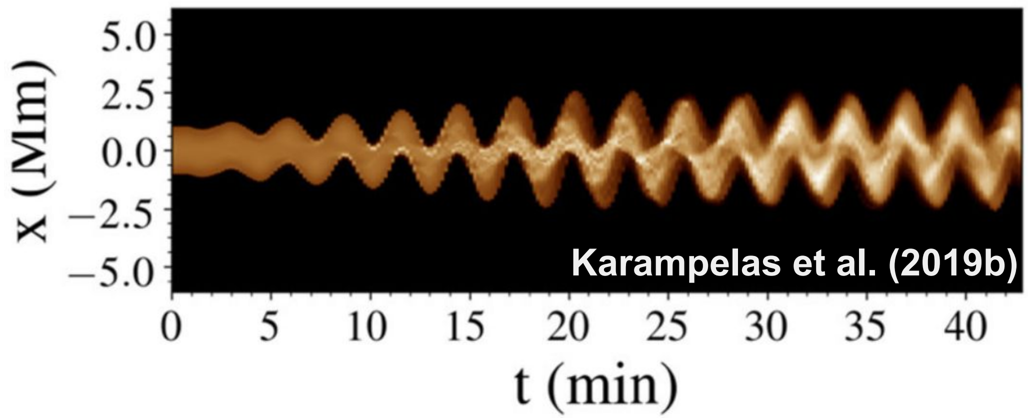
Karampelas & Van Doorsselaere (2018)

Kelvin-Helmholtz instability
→ **Energy dissipation**

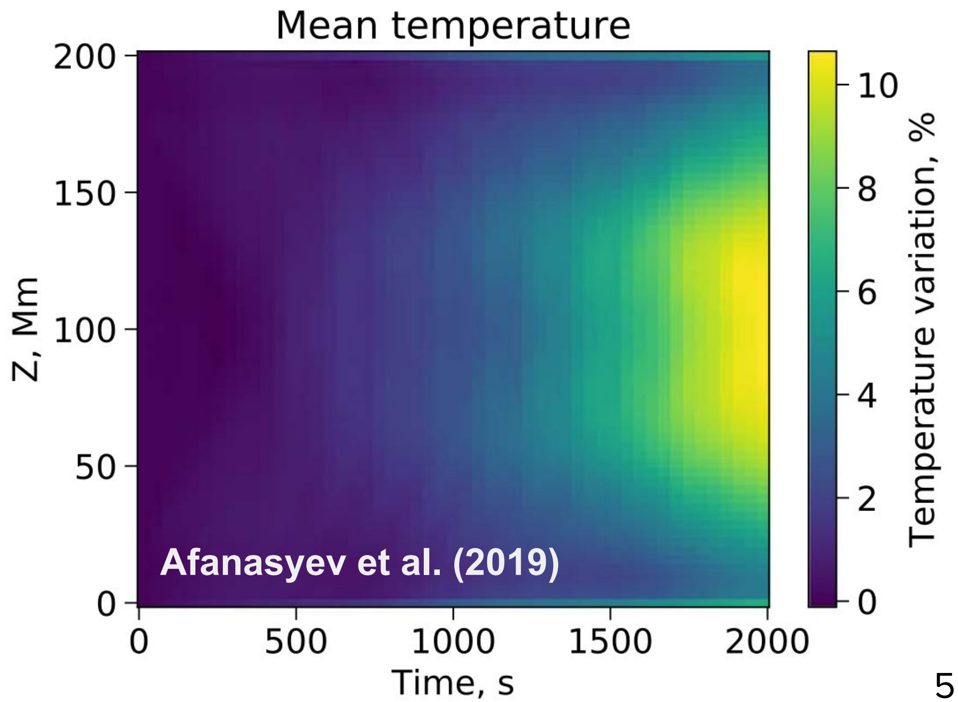
Standing kink waves lead to heating in simulations

➔ **Simulations with driver at the bottom of the corona**
(e.g. Karampelas et al. 2017, 2019a,b, Guo et al. 2019a, Afanasyev et al. 2019)



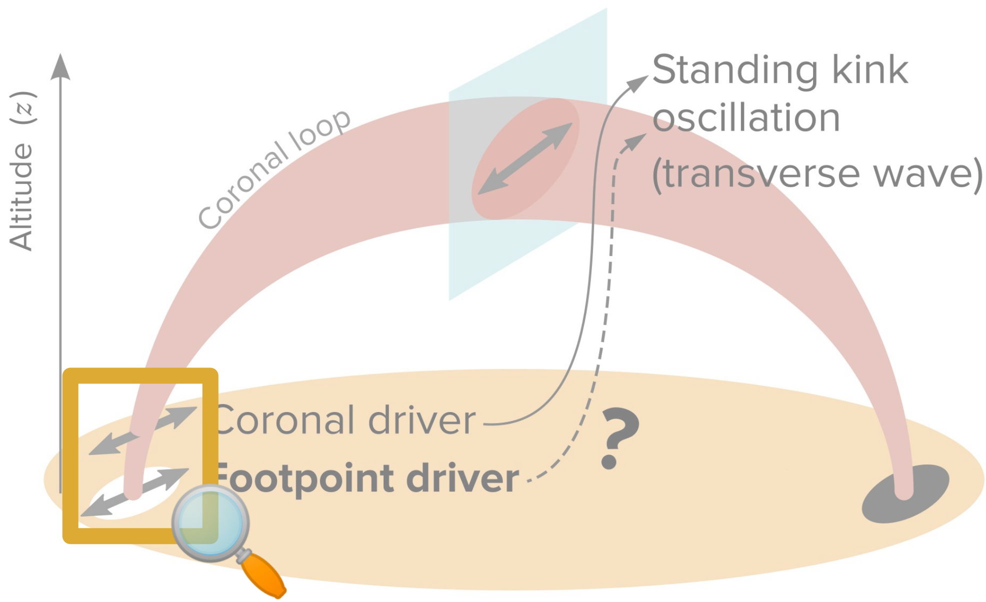


- ➔ **Reproduce observations**
- ➔ **Lead to heating** through the Kelvin-Helmholtz instability

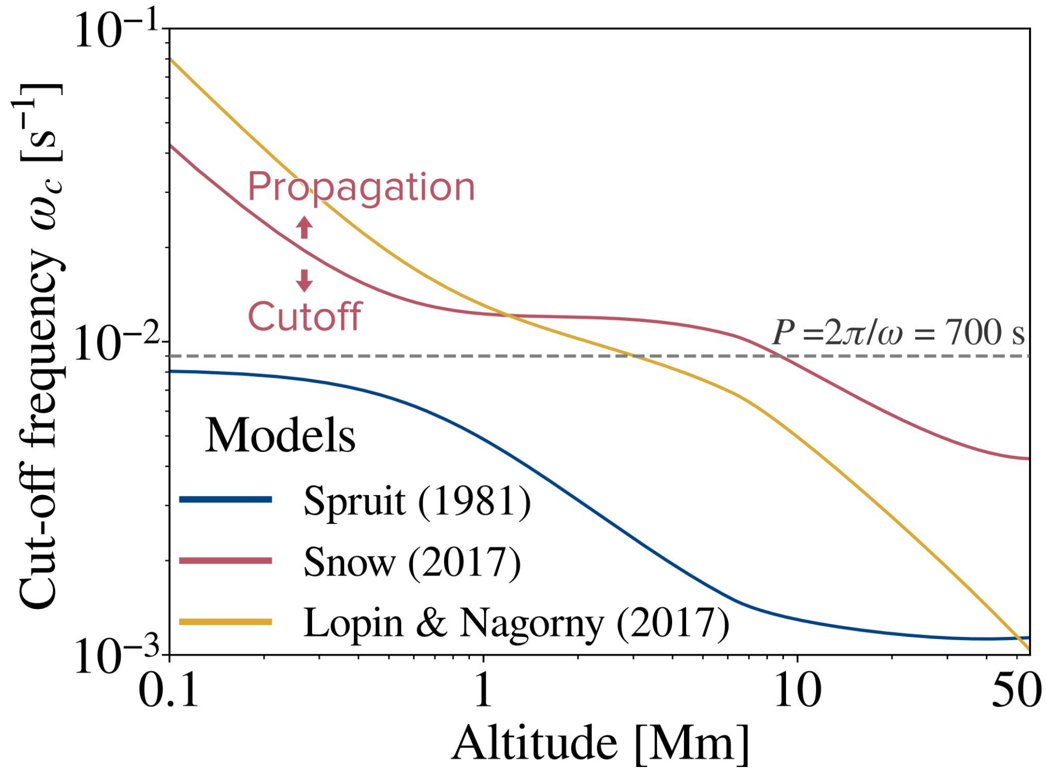


➔ **Is it still true if the driver is in the chromosphere?**

Transverse wave cut-off in the transition region



Analytically-predicted cut-off frequencies (several inconsistent expressions)



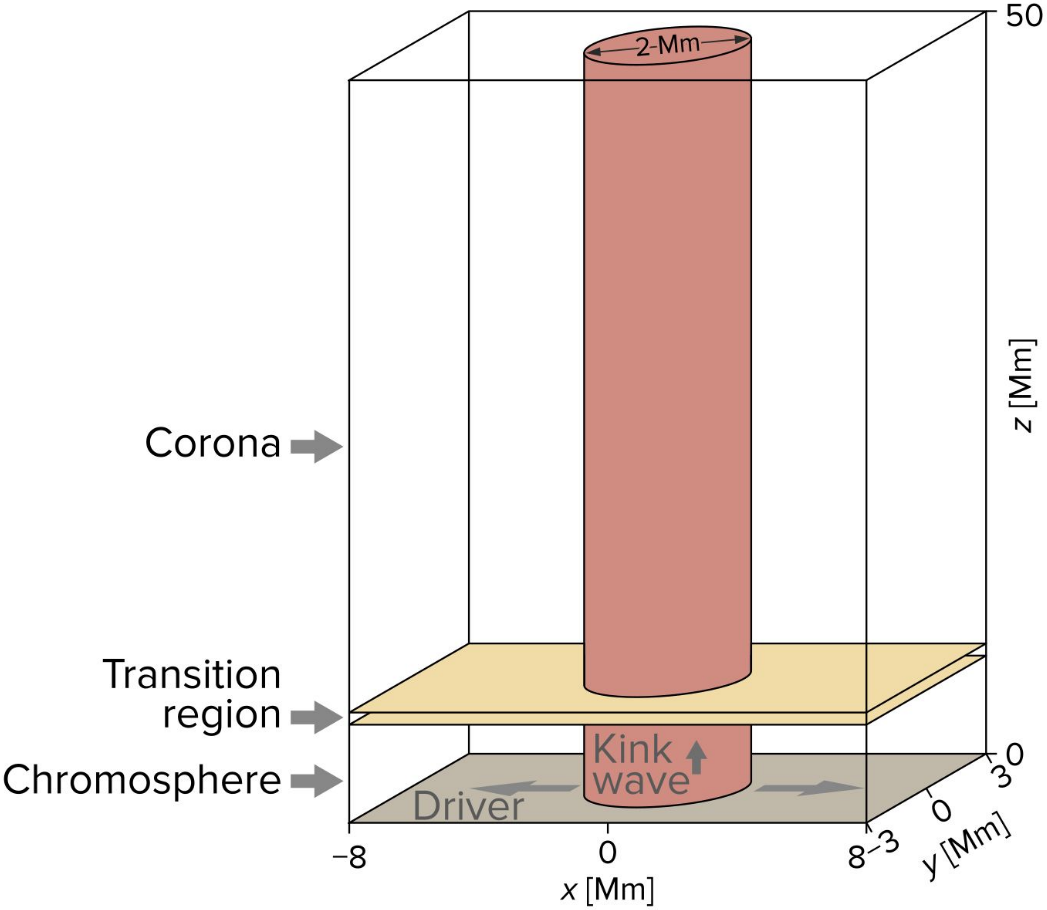
→ Not observed or simulated

→ Can transverse waves reach the corona?

→ Simulate propagation of kink waves in an open tube with chromosphere and TR

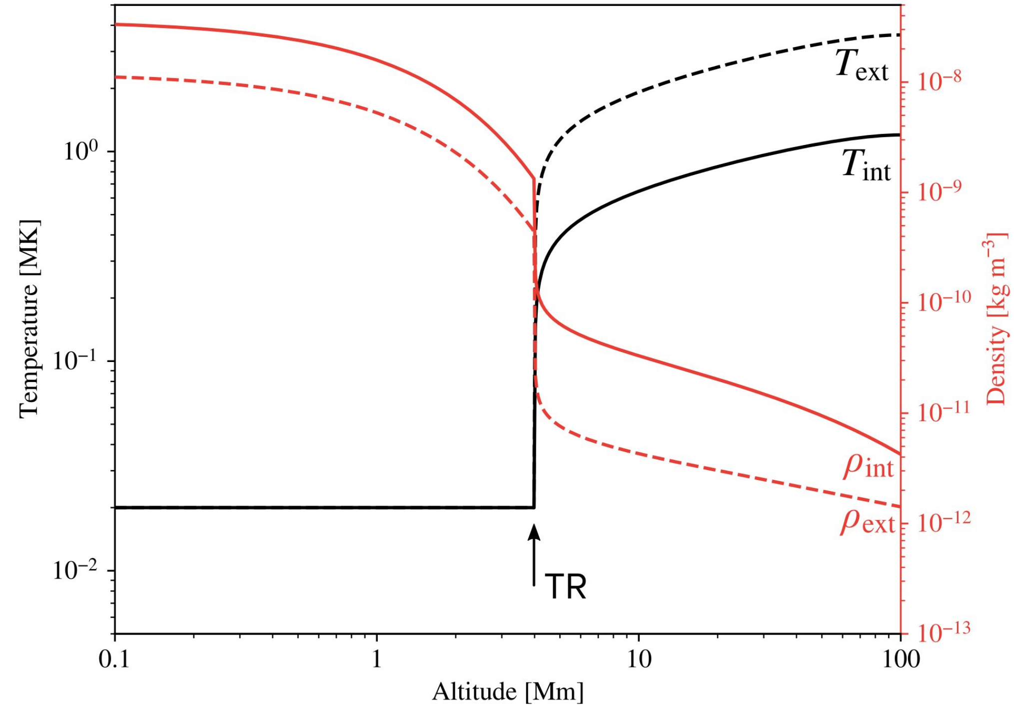
3D MHD numerical model

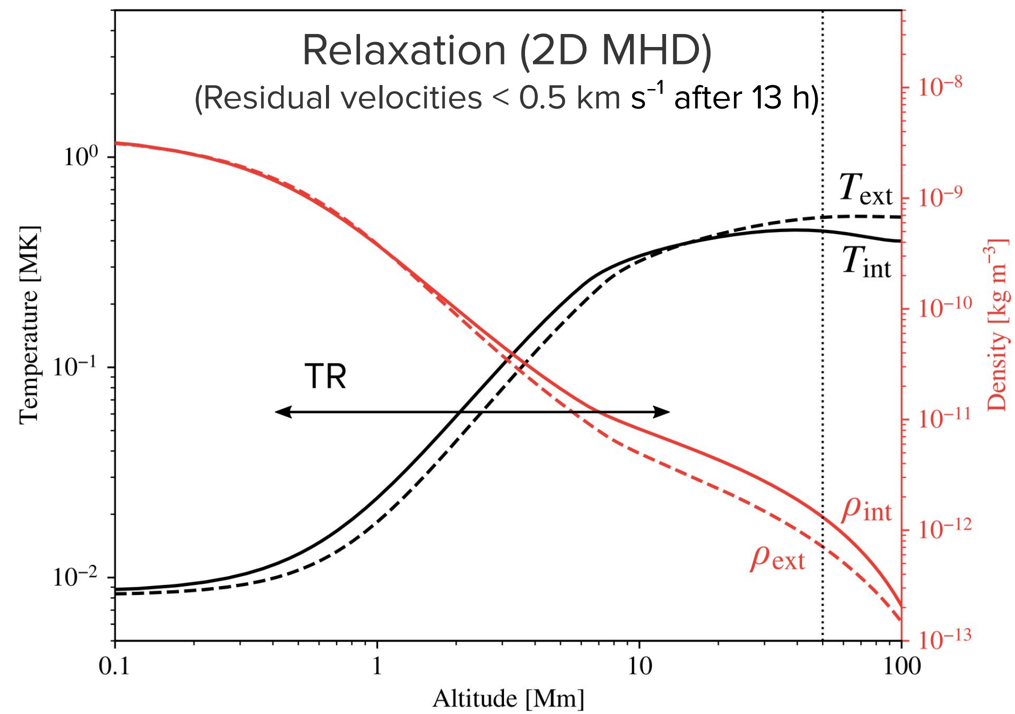
Magnetic flux tube in chromosphere, transition region and corona



- PLUTO MHD code (Mignone et al. 2012)
- Thermal conduction
  ➔ modified conductivity below 0.25 MK to broaden the TR (Lionello et al. 2009)

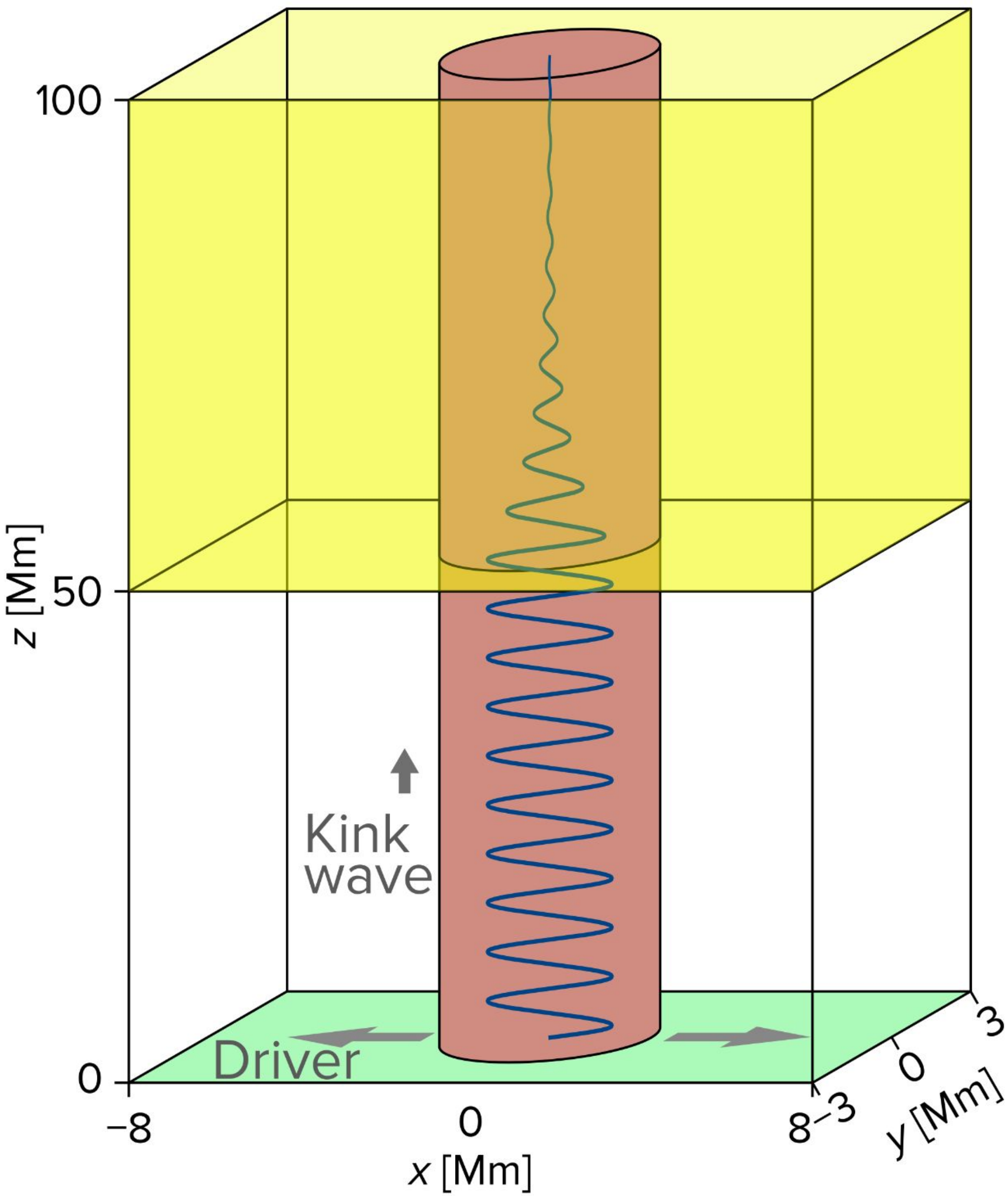
Initial conditions: field-aligned hydrostatic eq.





➔ Converted to 3D

Numerical model (3D): boundary conditions



Upper layer (z > 50 Mm)
Velocity rewrite layer ➔ **absorb waves**
$\forall\ t$ rewrite velocity:

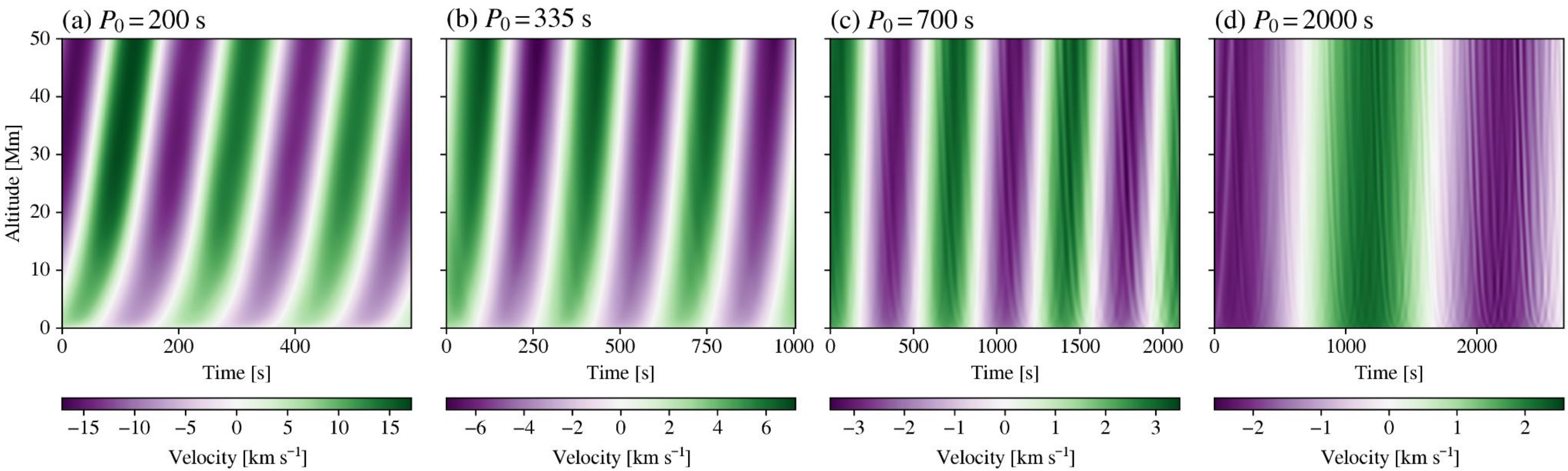
$$v\,(x,\,y,\,z) \leftarrow \alpha\,(z)\,v\,(x,\,y,\,z)$$

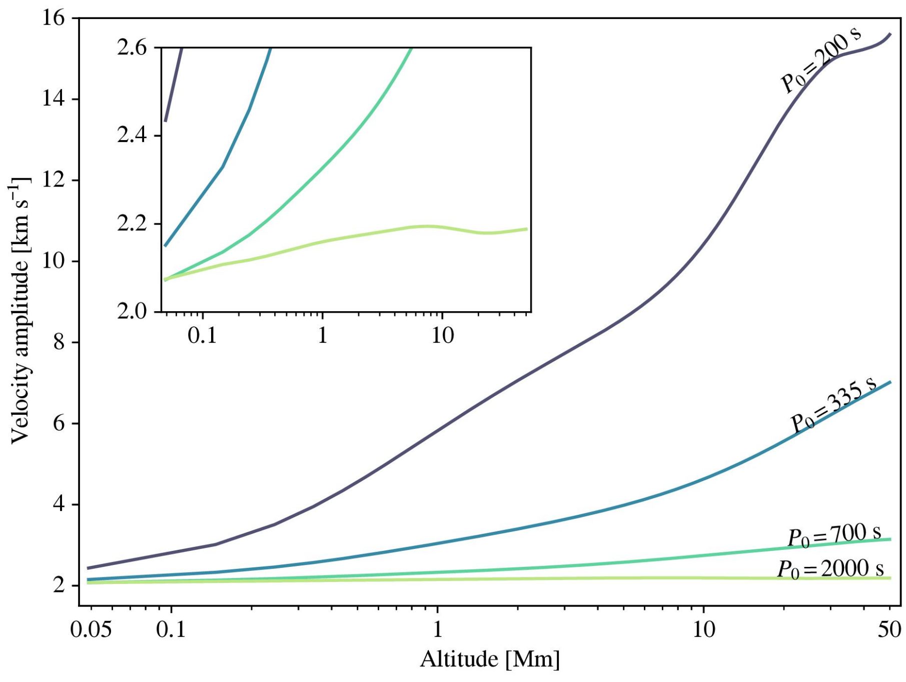
where $\alpha\,(z)$ varies linearly from 1 to 0.9995 between 50 Mm and 100 Mm.

Lower boundary (z = 0)

— Dipole-like driver (Pascoe et al. 2010)
➔ **propagating kink wave**

Results: wave amplitude decreases with frequency

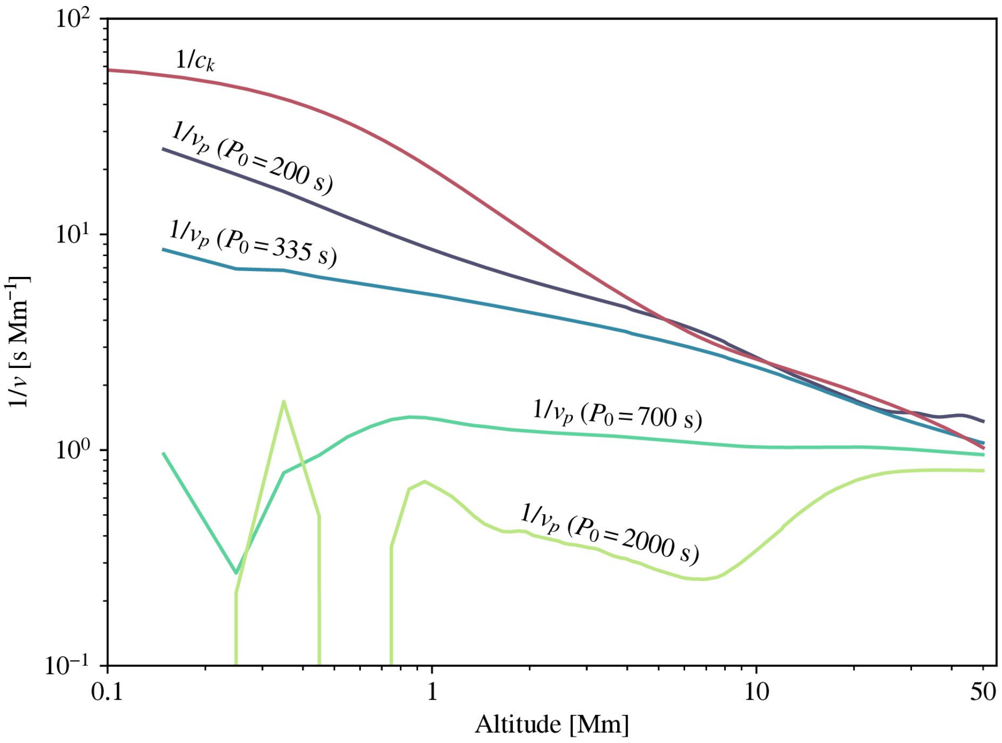




- Drive magnetic flux tube ($v_0 = 2$ km s^{-1}) in the chromosphere, at different periods
- Measure velocity amplitude as a function of altitude

- Velocity amplitude decreases with frequency
- **Higher frequencies propagate better** through the transition region
- **Consistent with analytical models** that predict a low frequency cut-off

Results: phase speed shows cut-off



- Measure **phase speed** as a function of altitude
  Compute the maximum cross-correlation between $v_x(z - \Delta z/2)$ and $v_x(z + \Delta z/2)$ to obtain time delay, and in turn phase difference.
- The inverse of the phase speed tells us whether a wave is propagating or not:

$$\frac{1}{v_p(z)} = \frac{\Delta\phi(z)}{\omega \Delta z}$$

- $\sim 1/c_k$ propagating → **no damping**
- $<< 1/c_k$
  - standing
  - evanescent → **damping**

→ **Transverse waves are cut-off through the transition region**

Results: cut-off altitude matches analytical model

- Compute the **cut-off altitude** $z_c(\omega)$:
  Altitude at which c_k/v_p goes above threshold $t_r < 1$.
- Compare to analytical models:

Spruit (1981)

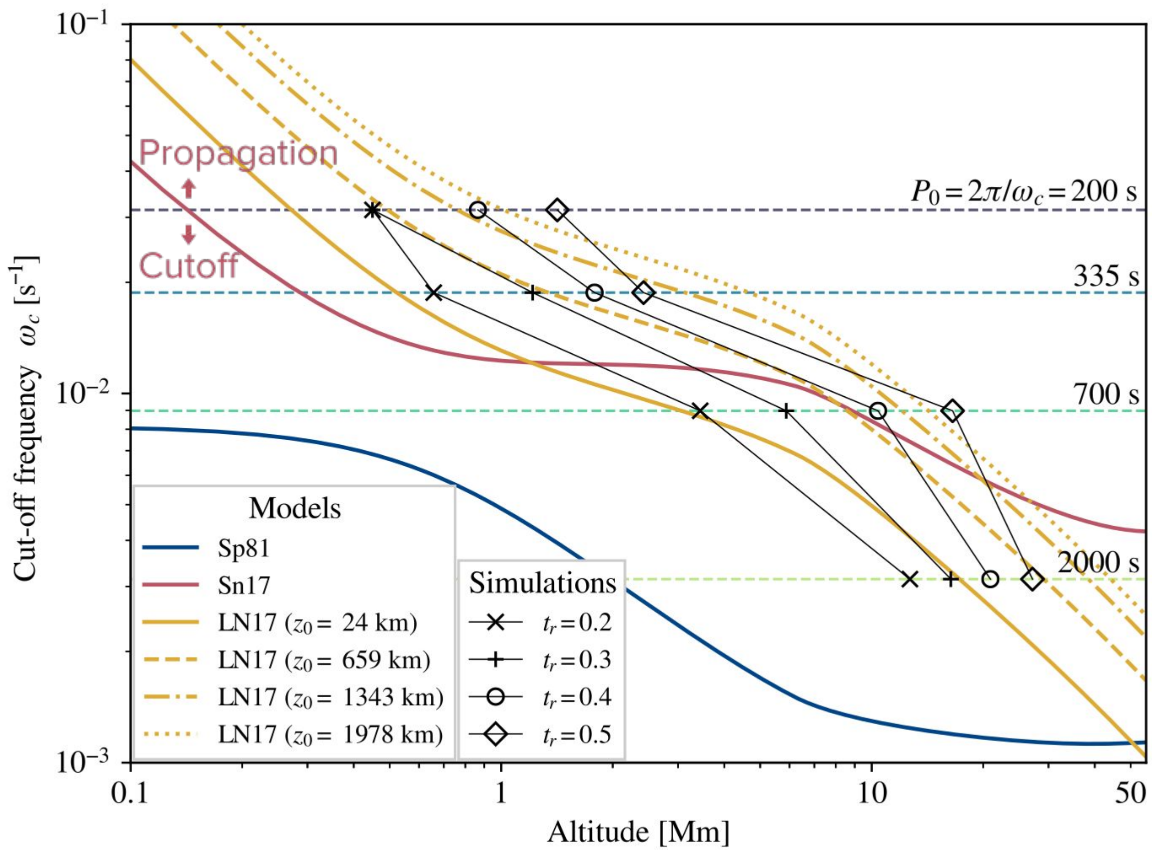
$$\omega_c^2 = \frac{g}{8H}\frac{1}{2\beta+1}$$

Snow (2017, NAM)

$$\omega_c^2 = \frac{v_A^2}{4z^2}$$

Lopin & Nagorny (2017)

$$\omega_c^2 = \frac{c_{k0}^2}{4H_0H(z)}\left(\delta_B^2\frac{\mathrm{d}H(z)}{\mathrm{d}z} + \frac{H^2(z)}{z^2}\right)$$



➔ The cut-off frequency is best predicted by Lopin & Nagorny (2017)

➔ High-frequency waves can reach the corona by tunnelling

Conclusions: **kink waves cut-off**

(Pelouze et al. 2022, in prep)

- **Transverse waves are cut-off in the transition region, as predicted by analytical models**
- **Identified the analytical model that best predicts the cut-off frequency** (Lopin & Nagorny 2017)
- **Cut-off waves can still reach the corona through tunnelling**

Perspectives: **heating by kink waves**

Coronal loop with chromosphere and TR

Density at loop apex