Heating by transverse waves in simulated coronal loops

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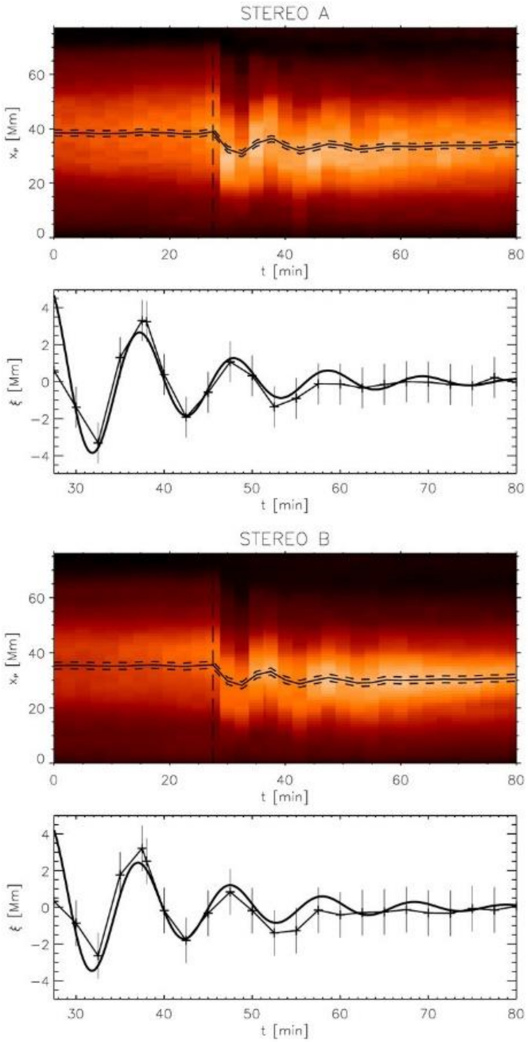
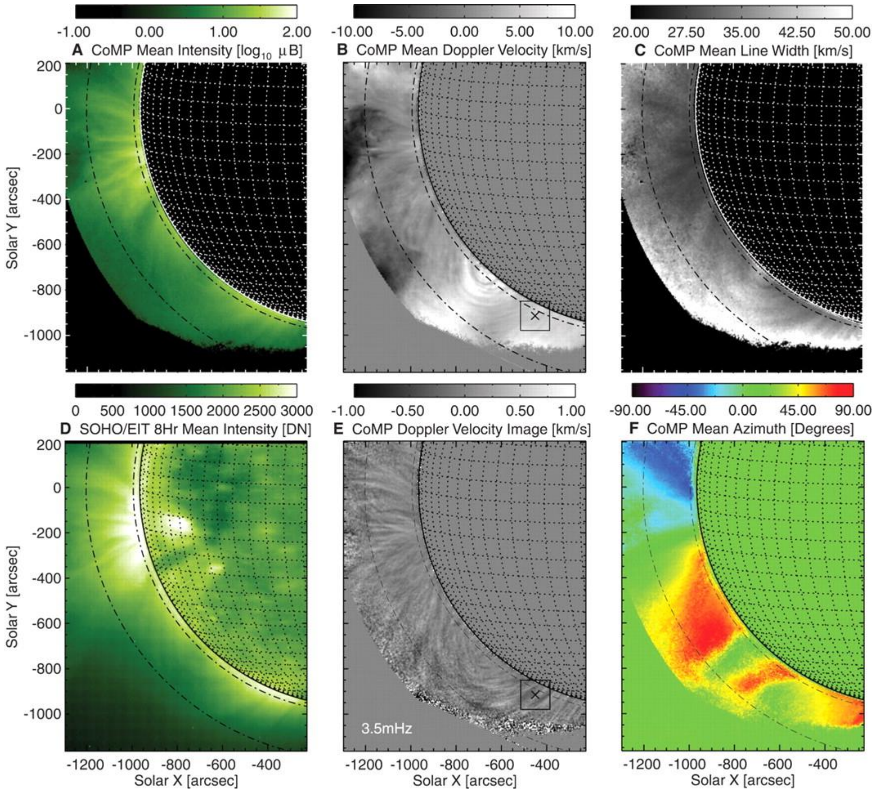
Outline of the presentation

1. **Introduction**
    - Ubiquitous transverse waves and oscillations
    - Damping and Dissipation mechanisms
    - Hypothesis: Wave heating
2. **Numerical models**
    - Setup
    - Density profile and driver
3. **Results and discussion**
    - Dynamical evolution of our models.
    - Current density and vorticity
    - Energy densities
    - Temperature profiles
4. **Conclusions and future work**

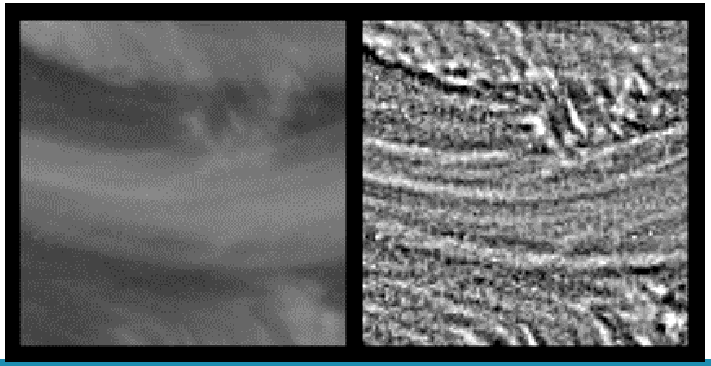
1. Ubiquitous transverse oscillations: Standing and Propagating waves



Verwichte et al. 2009



Tomczyk et al., 2007



McIntosh et al., 2011

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1. Damping of transverse oscillations

Resonant absorption:
for standing modes (Ionson 1978; Goossens et al. 1992; Arregui et al. 2005; Terradas et al. 2010; Goossens et al. 2011)

Mode coupling:
for propagating waves (Pascoe et al. 2010; De Moortel et al. 2016)

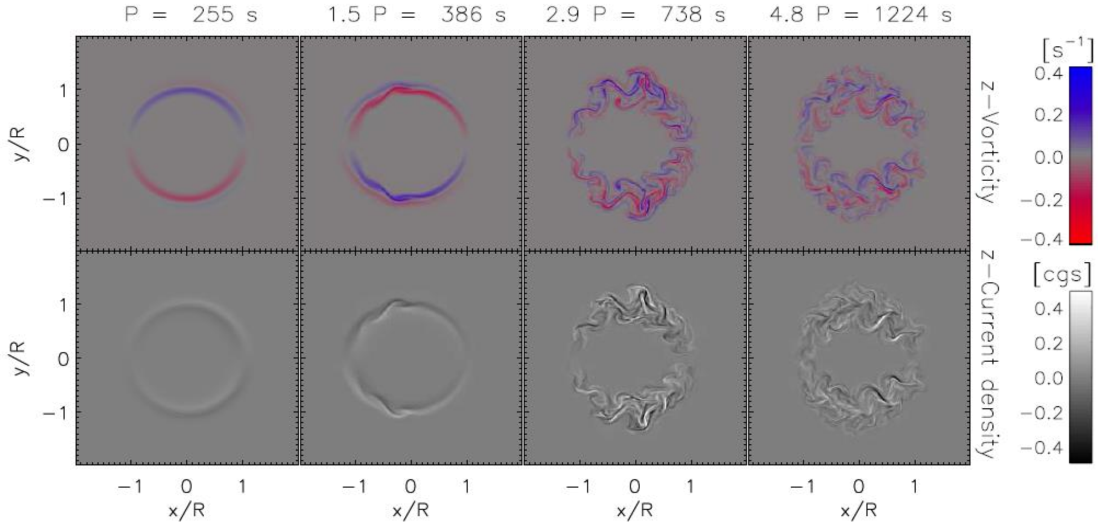
> Energy transfer of the global transverse motion, through resonance, to local azimuthal Alfvén modes in the boundary layer at the loop edges.

Kelvin-Helmholtz instability (KHI):
for standing modes (Heyvaerts & Priest 1983; Zaqarashvili et al. 2015).

- 3D simulations in straight flux tubes for driver generated azimuthal Alfvén waves (Ofman et al. 1994; Poedts et al. 1997),
- 3D simulations in straight flux tubes standing kink modes (Terradas et al. 2008; Antolin et al. 2014; Magyar et al. 2015; Magyar & Van Doorsselaere 2016, Howson et al. 2017)

Dissipation mechanisms: through resistivity or viscosity, resonant absorption and mode coupling can lead to heating (Poedts & Boynton 1996; Ofman et al. 1998).

1. Hypothesis: heating by K.H. induced turbulence



Antolin et al., 2014:

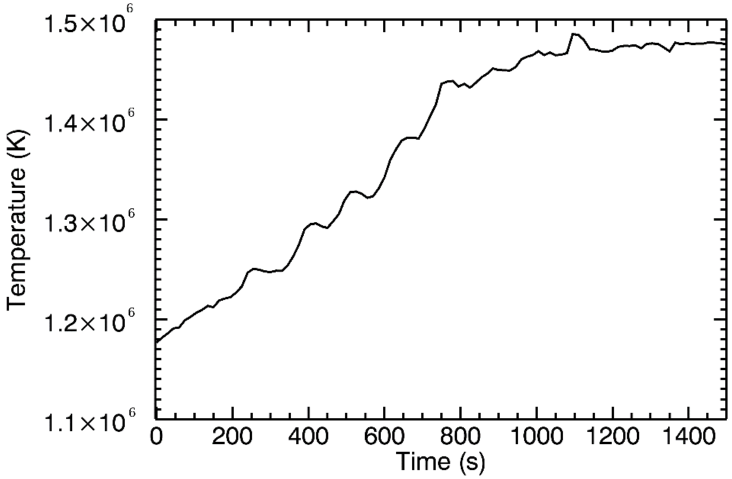
- Standing kink wave
- **T**ransverse **W**aves **I**nduced **K**elvin-**H**elmholtz rolls
- **TWIKH** rolls - heating due to viscous dissipation.
- Currents sheets - heating through ohmic dissipation.

Problem with current simulations!

Magyar & Van Doorsselaere 2016:

- Damping of nonlinear kink oscillations
- Increase of average internal energy density << Increase of average temperature.
- Mixing between colder loop plasma and hotter coronal plasma heats up the loop.

We can not distinguish between wave heating and the effects of mixing!



2. Numerical Models

From **Karampelas et al. 2017 (accepted):**

- 3D density enhanced, straight flux tube
- B_z magnetic field
- Numerical resistivity
- Spatially constant total pressure
- Setup with spatially changing temperature profile **(…-diffT model)**
- Setup with uniform temperature **(…-equalT model)**

Density profile (from **Antolin et al. 2014) :**

$$\rho(x,y) = \rho_e + (\rho_i - \rho_e)\,\zeta(x,y)$$

$$\zeta(x,y) = 0.5\left(1 - \tanh\left(\left(\sqrt{x^2+y^2}/R - 1\right)20\right)\right)$$

Loop length: $L = 100\ M$

Loop Radius: $R = 1\ Mm$

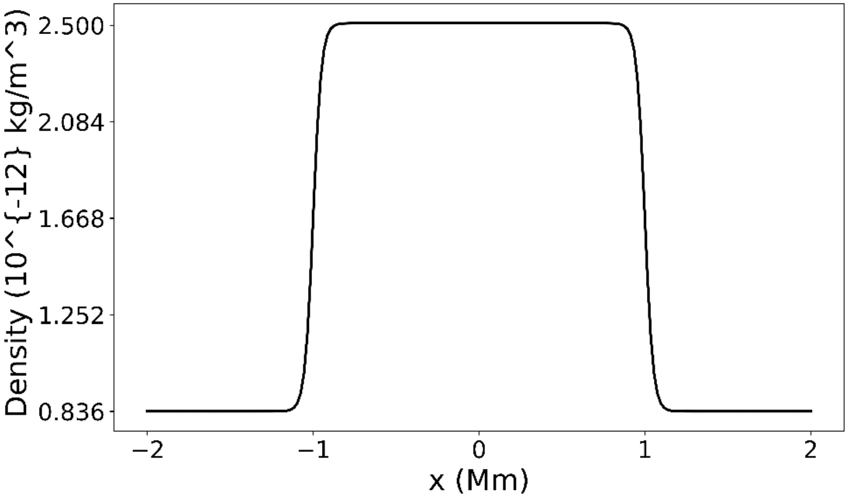
Plasma beta: $\beta = 0{,}018$

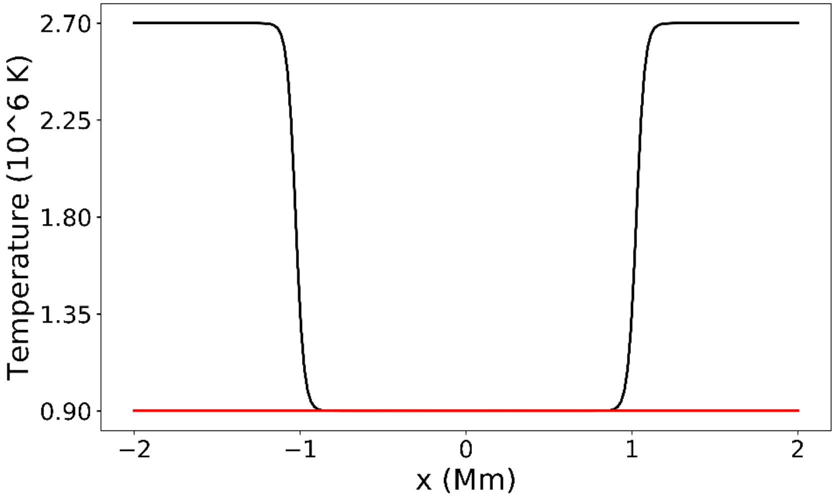
Numerical domain: $(x,y,z) = (16{,}8{,}100)\ Mm$

Maximum resolution:

$$(\delta x, \delta y, \delta z) = (31.5, 31.5, 1526.5)\ km$$

Lundquist number: $S \sim 10^4$





2.Density profile and driver

Two types of models:

1. **Stand-equalT** model (initial velocity perturbation):

$$V_{x0} = \left(25\frac{km}{s}\right)\cos\left(\frac{\pi z}{L}\right)\zeta(x,y)$$

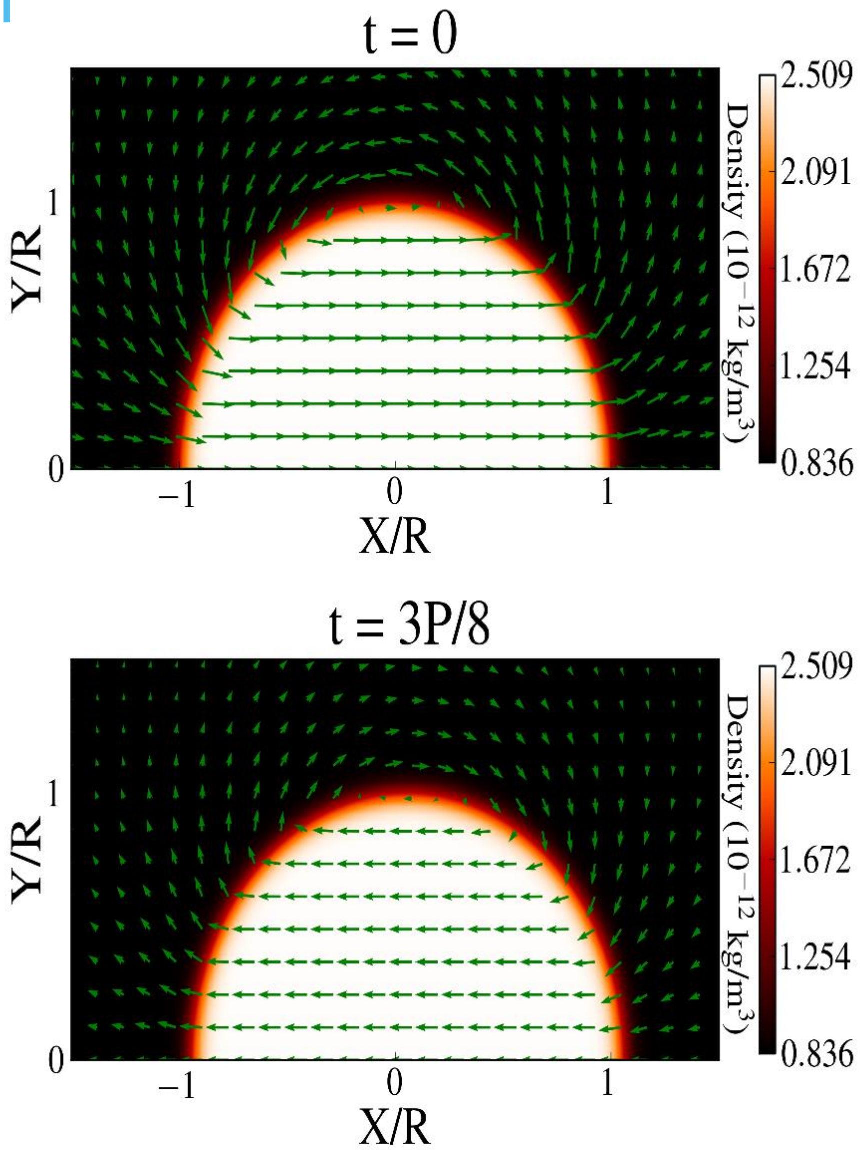
2. **Driven-equalT** and **Driven-diffT** models (Footpoint driver (from **Pascoe et al., 2010**):

$$\{v_x, v_y\} = \{v(t), 0\} = \{\left(2\frac{km}{s}\right)\cos\left(\frac{2\pi t}{P}\right), 0\}$$

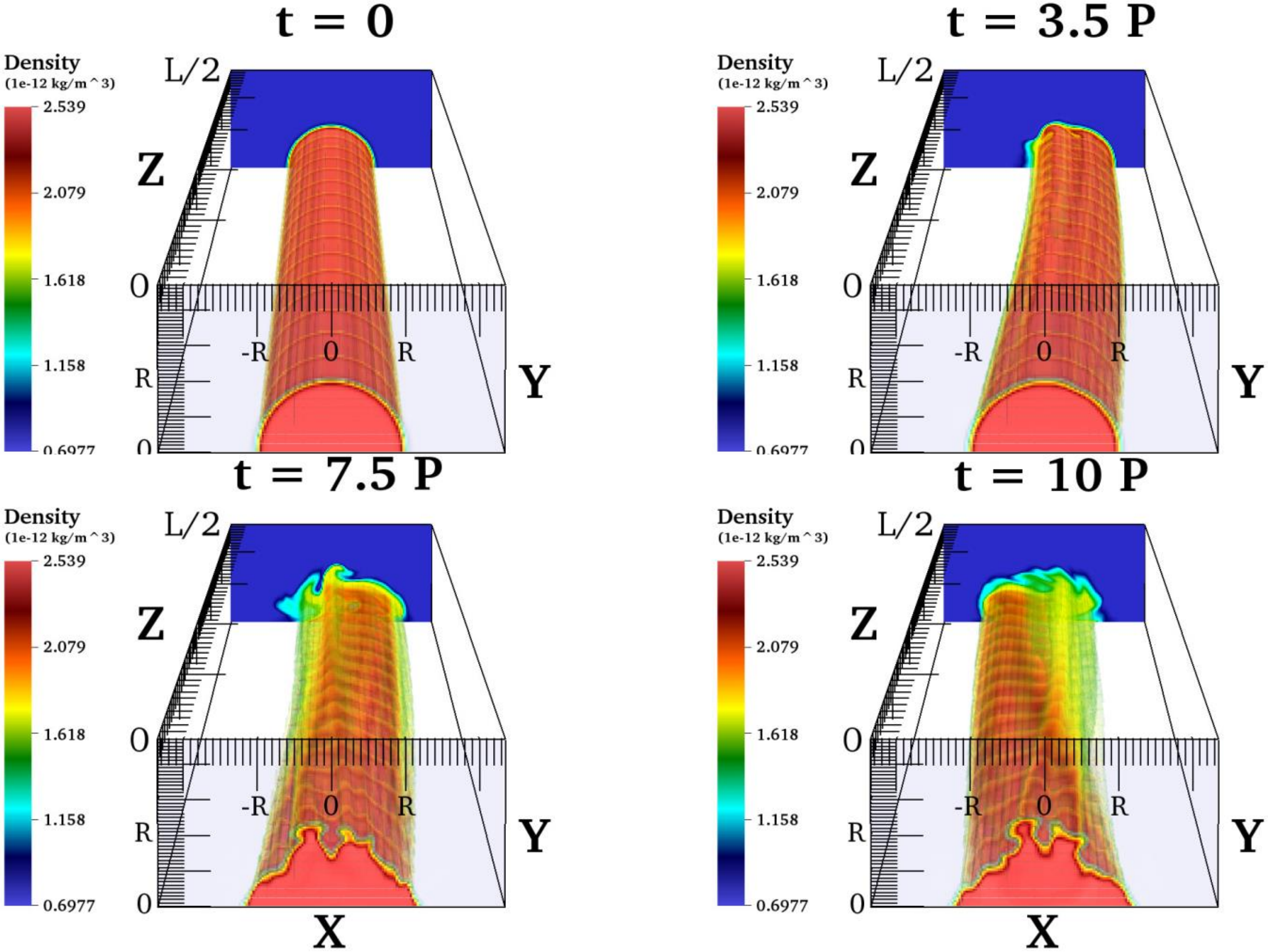
$$\{v_x, v_y\} = v(t)R^2\{\frac{x^2-y^2}{(x^2+y^2)^2}, \frac{2xy}{(x^2+y^2)^2}\}$$

$P = 254\ s$ is the driver period, and is equal to the period of the fundamental standing kink mode (Edwin & Roberts 1983).

We use the **MPI-AMRVAC** code (Porth et al. 2014), with the Powell's scheme for the solenoidal constraint on the magnetic field.



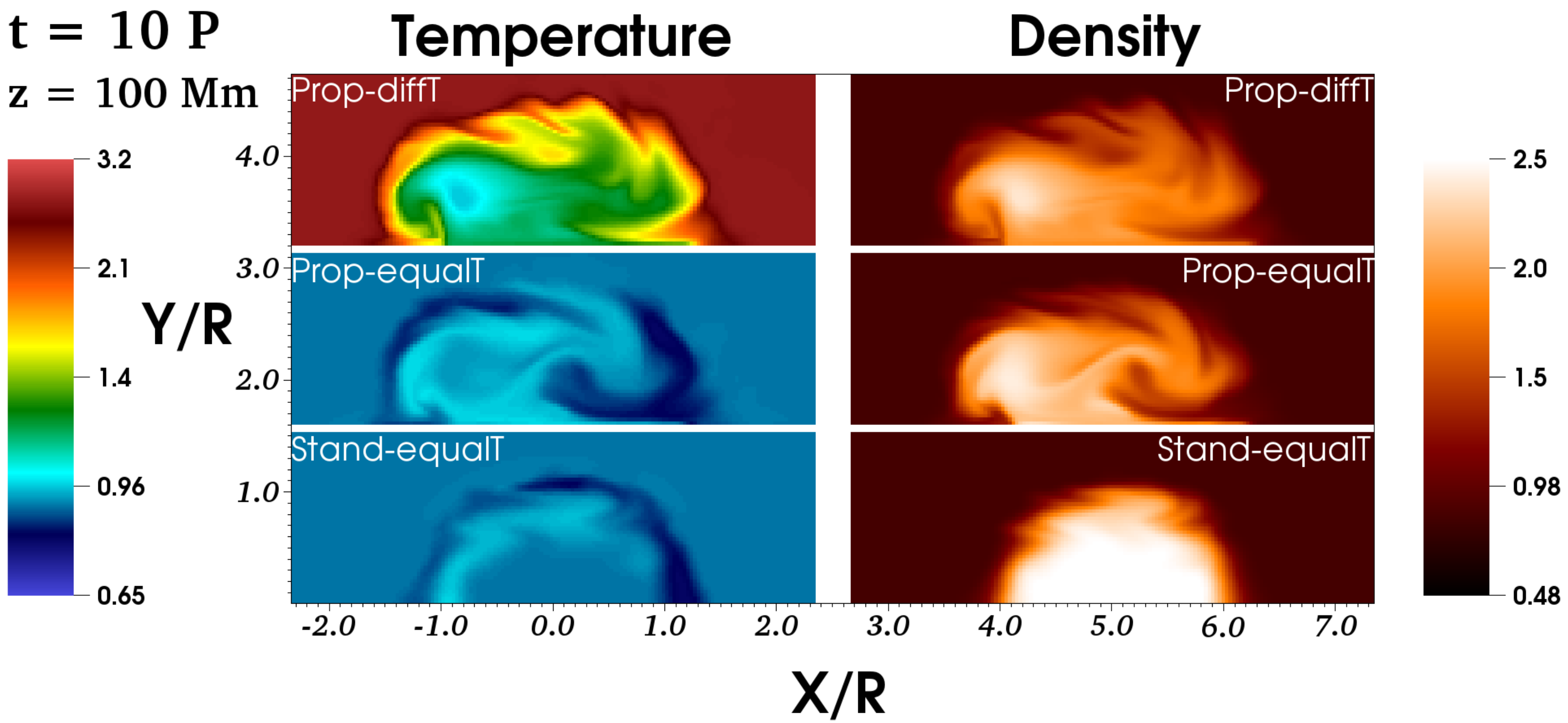
3. Dynamical evolution of our models.



Snapshots (movies in the .pptx) of a driven standing wave at different times:

- For the **Driven** models, the propagating waves superpose creating a standing mode. This mode resembles the fundamental kink oscillation.
- **Bonus observation:** The creation of elongated density structures (“apparent strands”) along the loop length (see also Antolin et al. 2014, 2016).

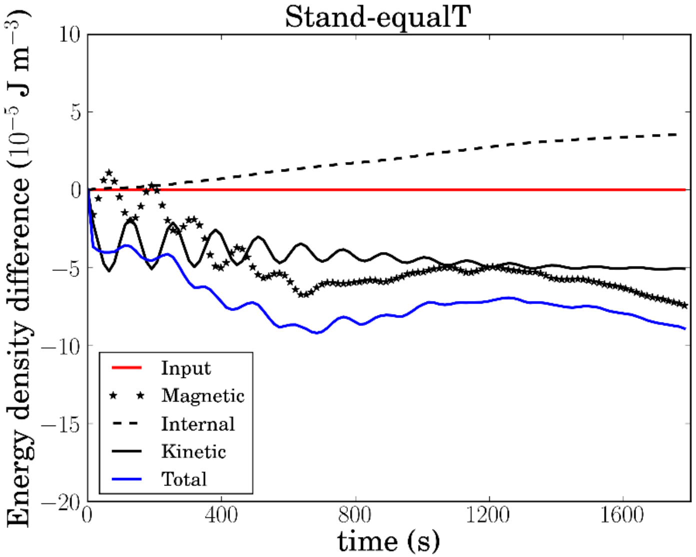
3. Dynamical evolution of our models.

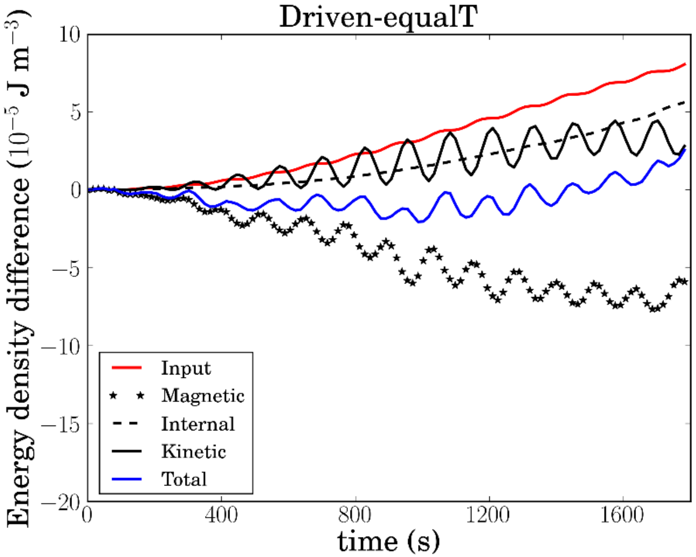


Snapshots (movies in the .pptx) of the cross-section of the models, at the apex. The maximum centre of mass velocity for the **Stand-equalT** model is $25\ km/s$, while the peak centre of mass velocity for the **Driven**-models is $\sim 13\ km/s$.

- Development of **T**ransverse **W**aves **I**nduced **K**elvin-**H**elmholtz rolls **(TWIKH)** rolls
- Spatially extended TWIKH rolls for the Driven-models.
- Plasma mixing and deforming of the initial density (and temperature) profile – **Turbulent Loops (Karampelas and Van. Doorsselaere, in prep.)**.

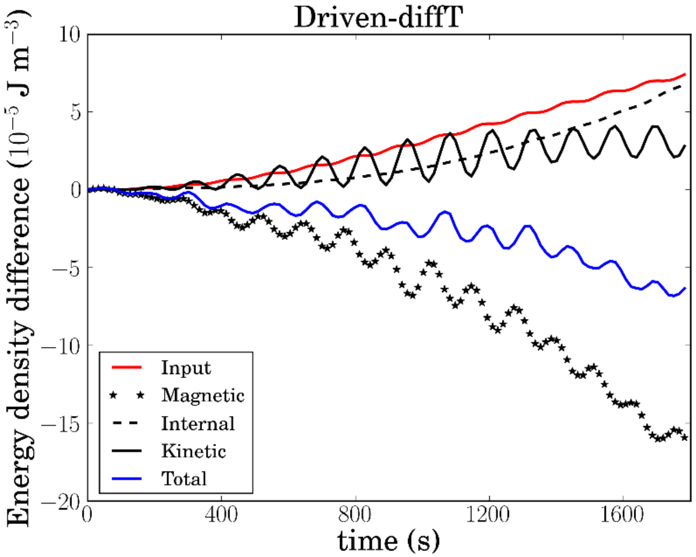
3. Energy densities



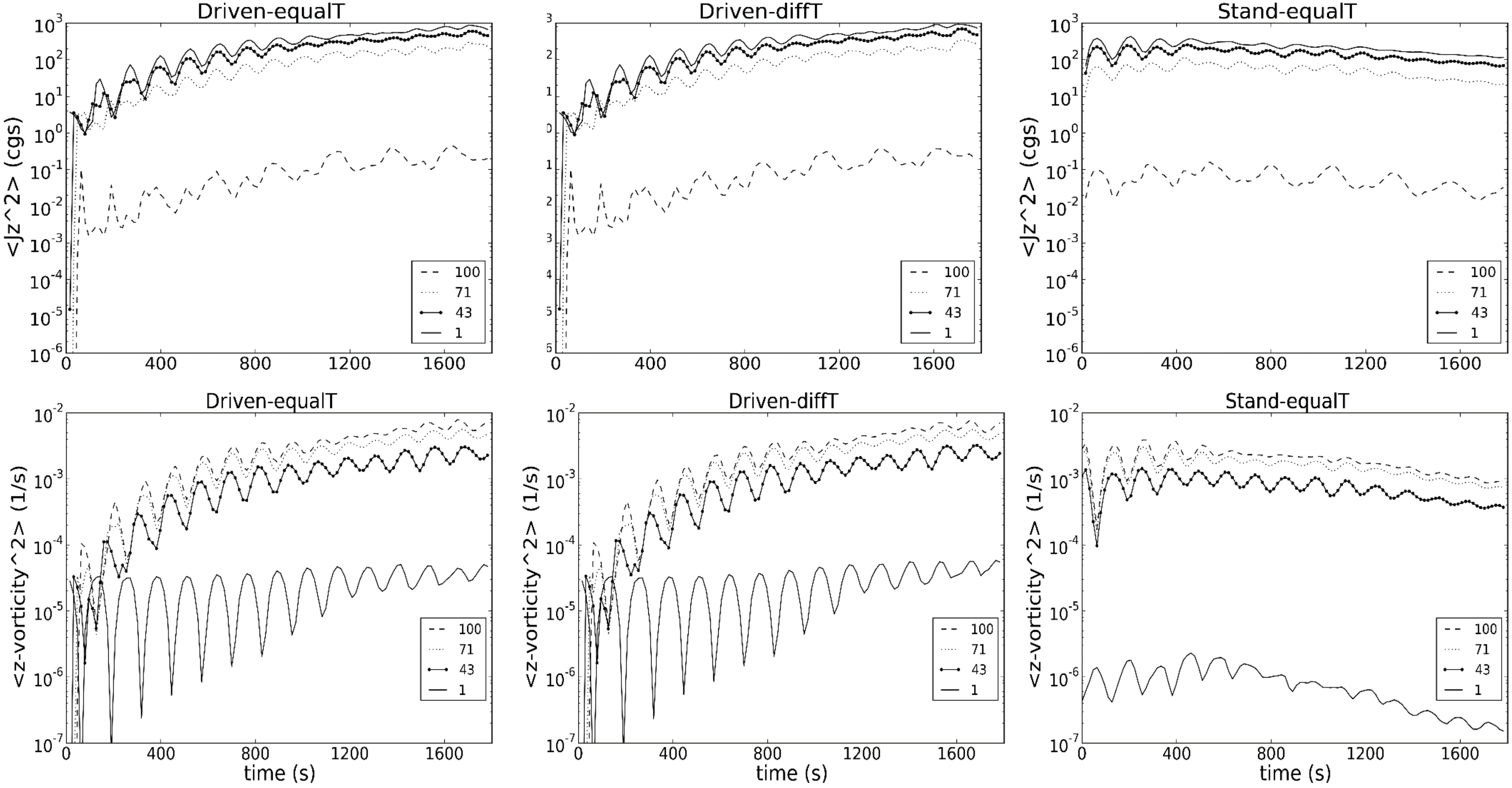


Internal **(I)** and magnetic **(M)** energy density variations relative to the initial state.
Kinetic **(K)** energy density.
Total **(T=M+I+K)** energy density.
Energy (density) provided by the driver **(Input)**.

In our models, we observe a drop in the magnetic energy density, as well as an increase in the internal energy.



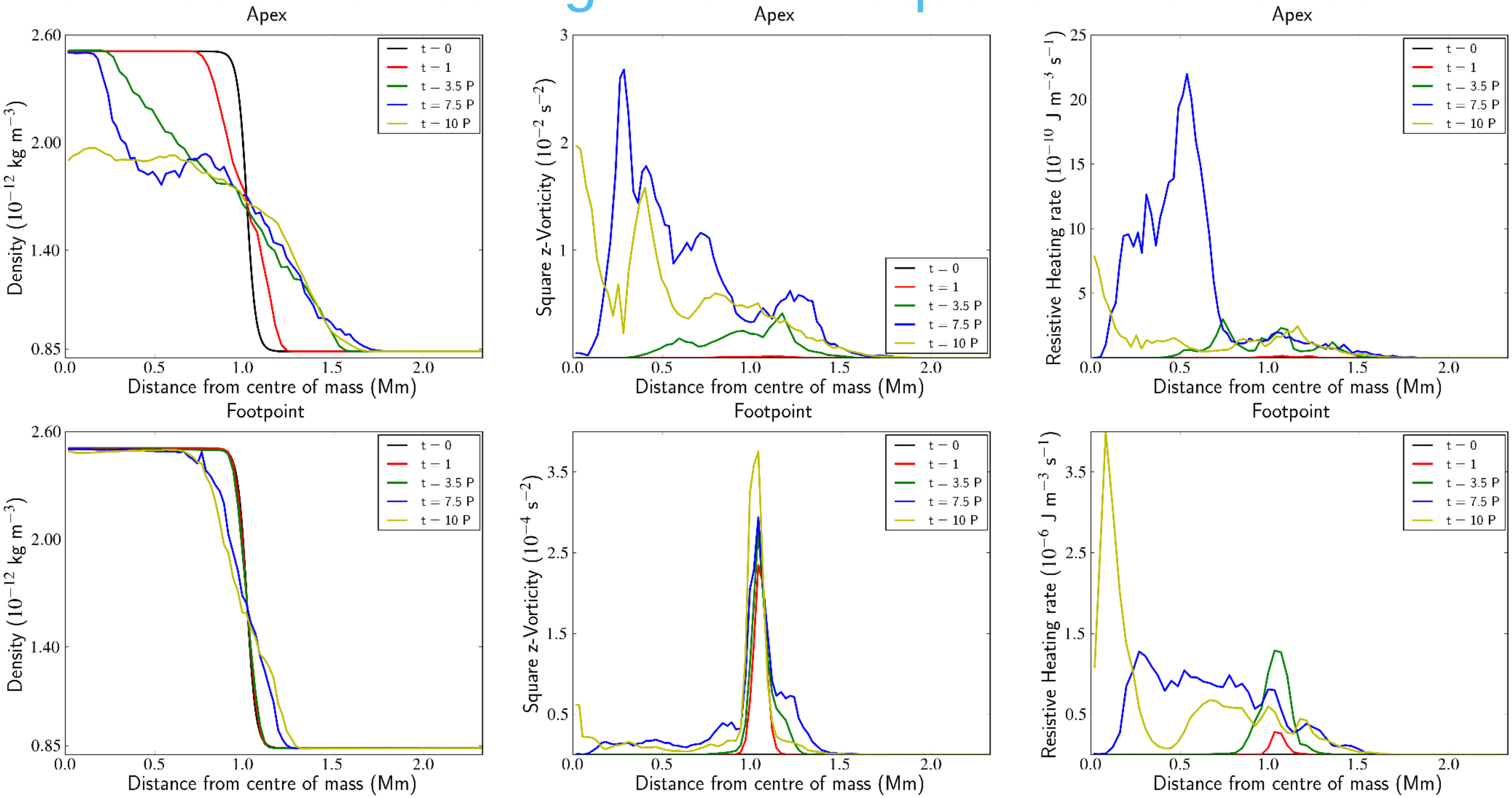
3. Square z-current densities and square z-vorticities



For all three models:

- Profiles of the average: square z-current densities (J_z^2) **(top)** and square z-vorticity (ω_z^2) **(bottom)**.
- Higher values of J_z^2|| ω_z^2 near the footpoint || apex hint towards ohmic || viscous dissipation as a potential heating mechanism.

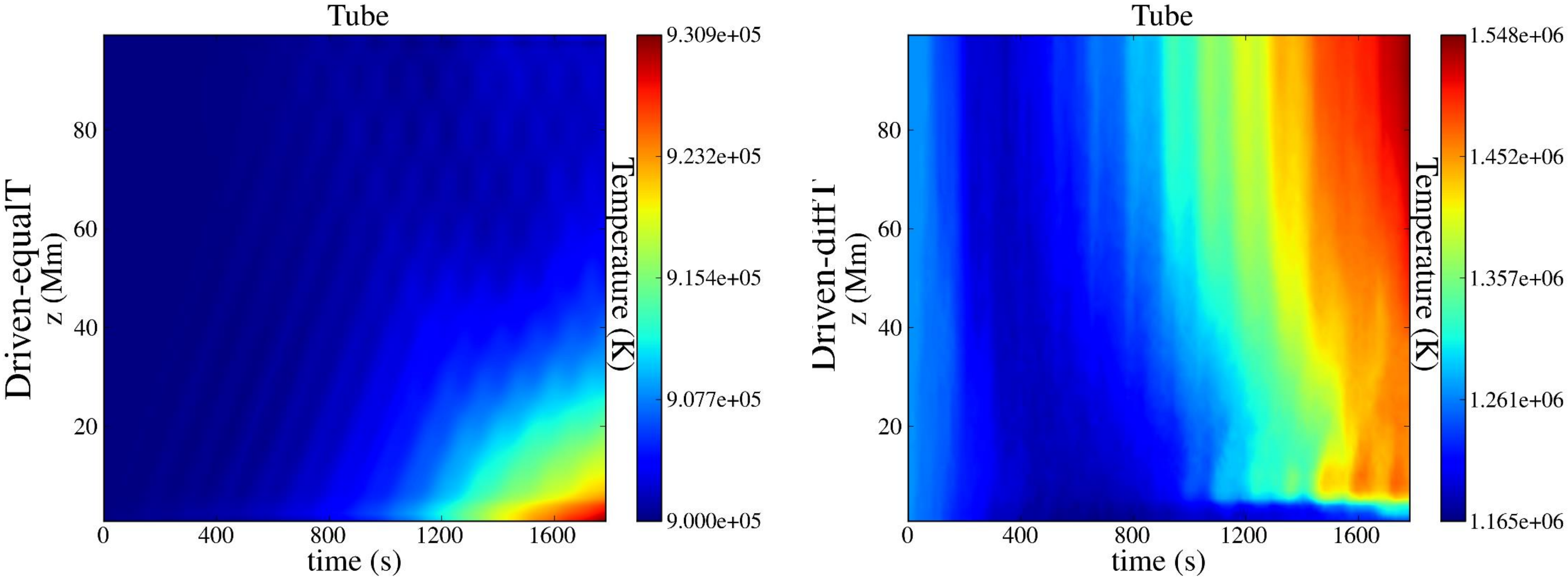
3. Resistive heating rate and square z-vorticities



Driven-diffT model **(Karampelas and Van. Doorsselaere, in prep.):**

- Profiles of the average density, square z-vorticity (ω_z^2) and resistive heating rate (H_r).
- Higher values of H_r || ω_z^2 near the footpoint || apex hint towards ohmic || viscous dissipation as a potential heating mechanism.

3. Temperature profiles



Time – height plot for the average temperature for the two models with the footpoint driver. We focus only on the flux tube (for density $\boldsymbol{\rho} \geq \mathbf{0.335}\, \boldsymbol{\rho_i}$). .

- The larger final temperatures near the footpoint for the **Driven-equalT** model, point towards ohmic over viscous dissipation as the main heating mechanism.
- For the **Driven-diffT** model, the larger final temperatures near the apex, are the result of mixing between the cold loop and the warmer corona (**apparent heating,** see also Magyar & Van Doorsselaere 2016).

Summary – Next steps…

Flux tube dynamics:

- Driver induced propagating waves superpose, forming a standing mode.
- Emergence of Kelvin - Helmholtz instability (K.H.I) at magnetic field node (apex).
- The development of TWIKH rolls leads to the appearance of strands-like structures in our loop.

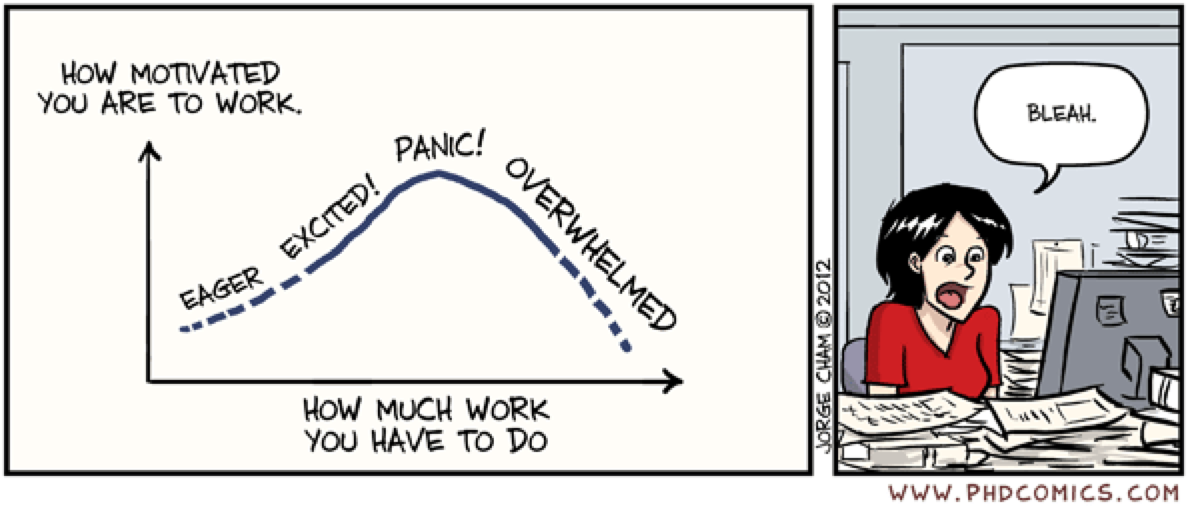
Flux tube energetics:

- Increase of internal energy, decrease of magnetic energy.
- K.H. vortices lead to extensive mixing of plasma between different layers, causing the apparent heating of the loop.
- Strong currents develop at the loop footpoints, leading to ohmic (actual) heating, in presence of (effective) numerical resistivity.

Future steps:

- Effects of physical resistivity and thermal conduction?
- Gravity.
- Use of a realistic atmosphere.

Thank you



99 little bugs in the code.
99 little bugs.
Take one down, patch it around.

127 little bugs in the code...