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Heating by transverse waves in 3D simulations of turbulent coronal loops

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Our mysterious Sun: magnetic coupling between solar interior and atmosphere
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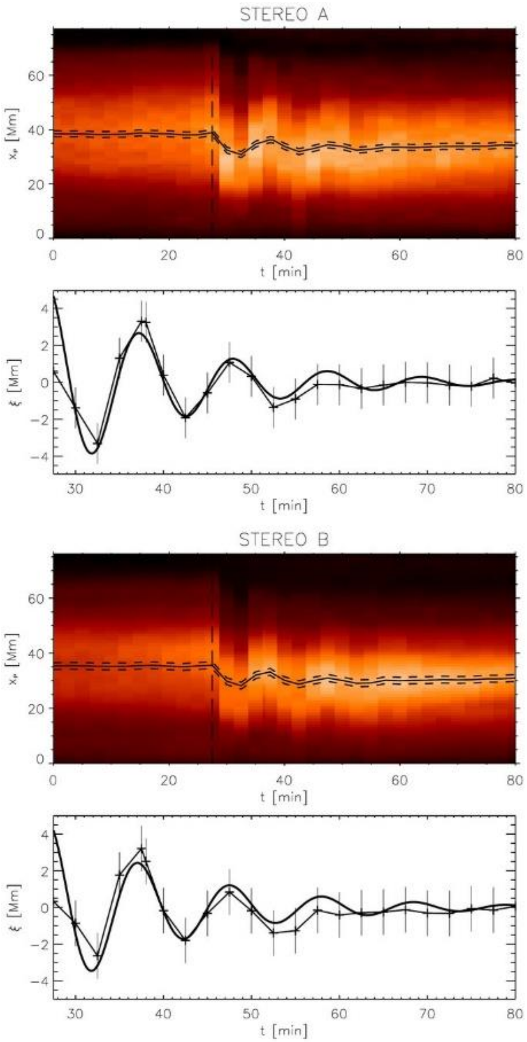
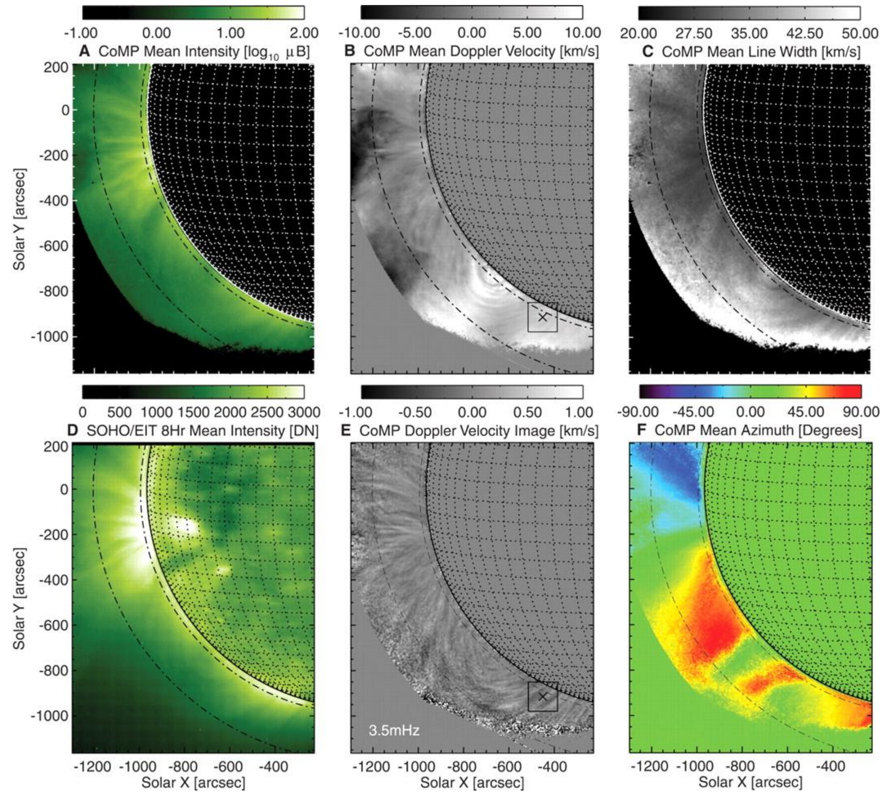
Outline of the presentation

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**

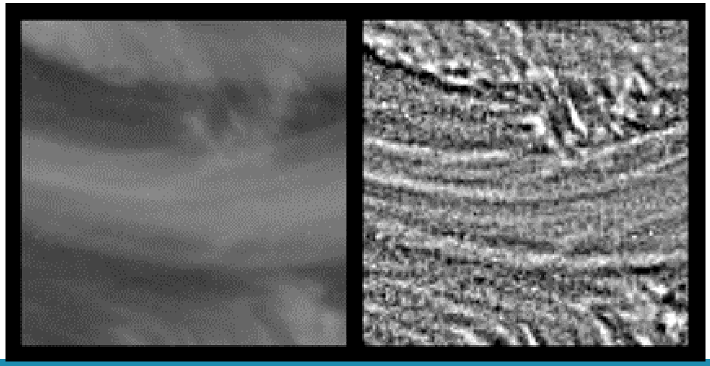
1. Ubiquitous transverse oscillations: Standing and Propagating waves



Verwichte et al. 2009



Tomczyk et al., 2007



McIntosh et al., 2011

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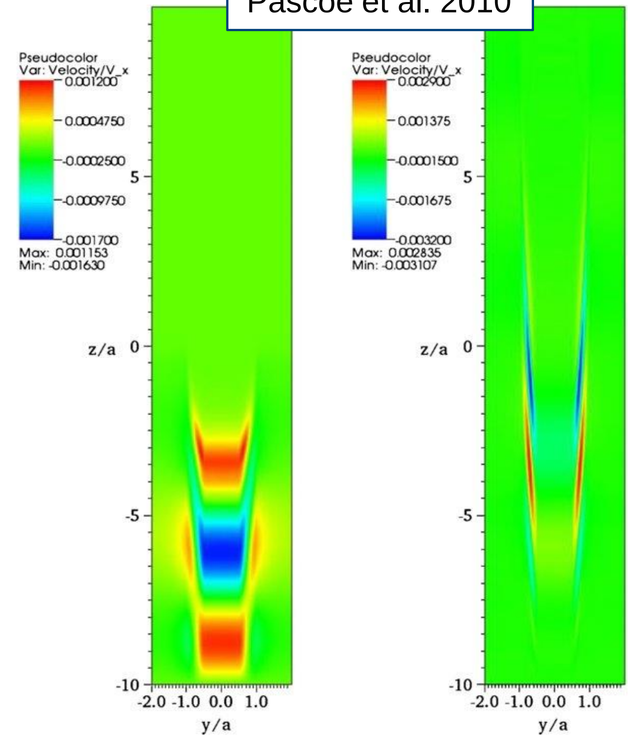
1. Damping of transverse oscillations

Pascoe et al. 2010



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

Phase mixing: Creation of smaller scales from the interacting out-of-phase Alfven waves in an inhomogeneous plasma (Heyvaerts & Priest 1983; Soler & Terradas 2015).

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 & Van Doorsselaere 2016)

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

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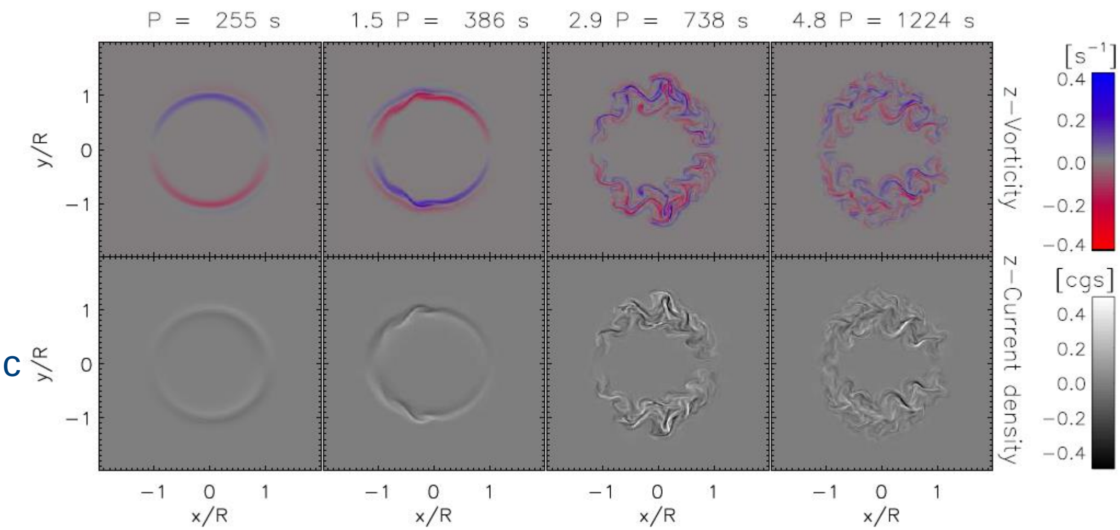
1. Hypothesis: heating by K.H. induced turbulence

Antolin et al., 2014:

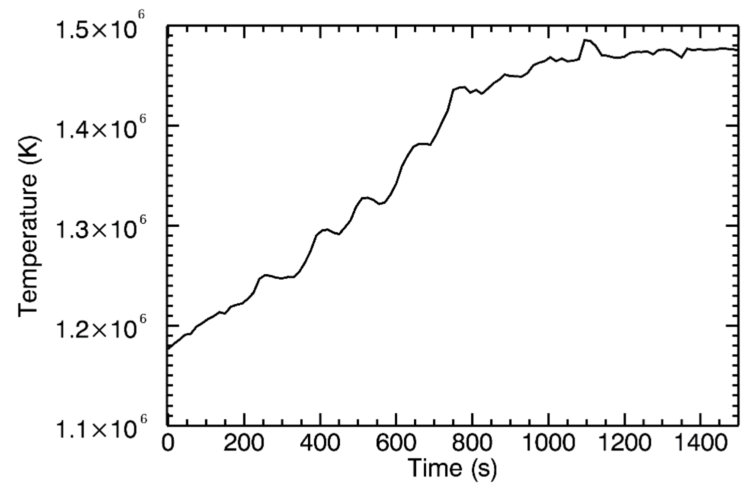
- Standing kink wave
- **T**ransverse **W**aves **I**nduced **K**elvin-**H**elmholtz rolls
- **TWIKH** rolls - heating due to viscous dissipation.
- Currents sheets - heating through ohmic dissipation.



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

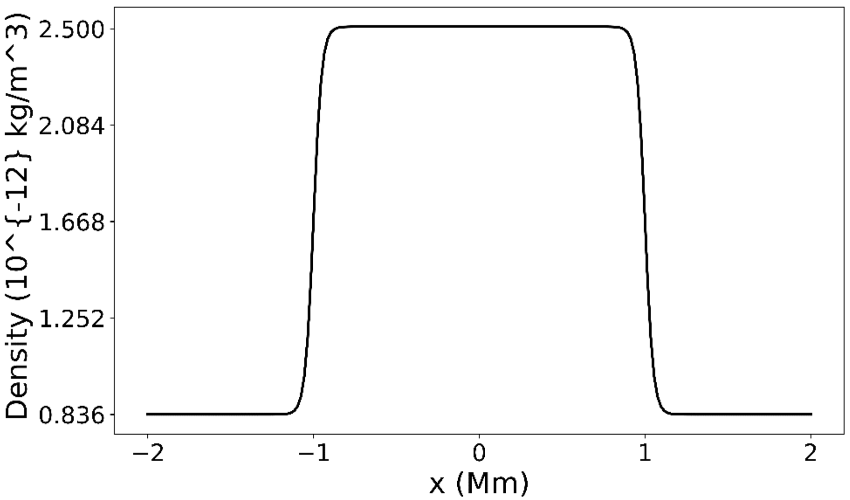
From **Karampelas et al. 2017:**

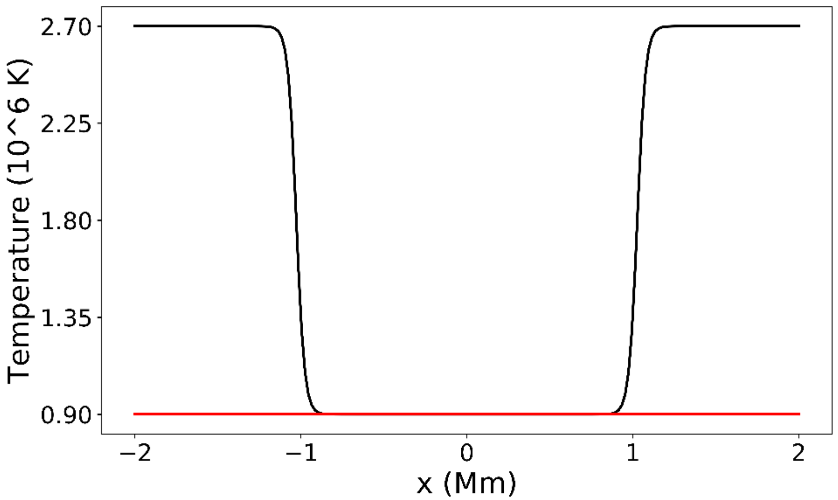
- 3D density enhanced, straight flux tube
- B_z magnetic field
- Numerical dissipation
- Spatially constant total pressure
- Setup with spatially changing temperature profile **(…-diffT** model**)**
- Setup with uniform temperature **(…-equalT** model**)**

Density profile (also see **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):

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

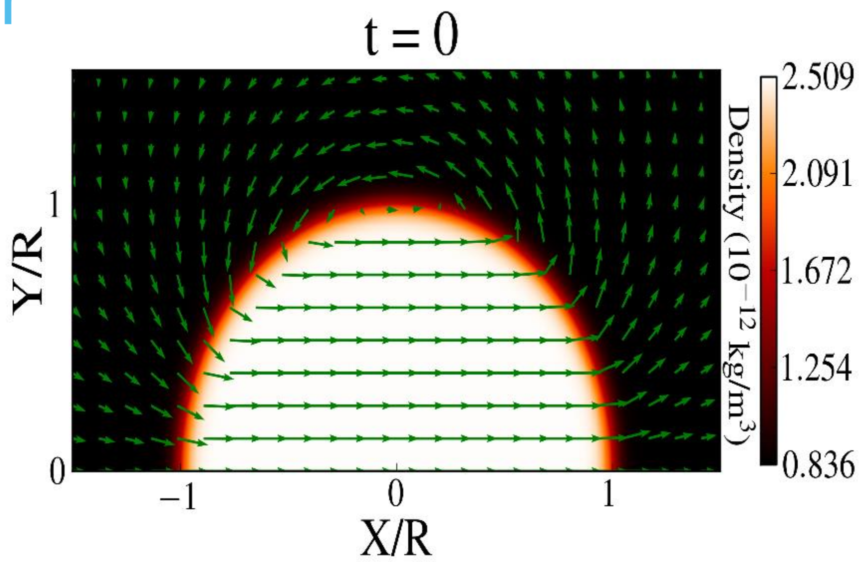
2. **Driven-equalT** and **Driven-diffT** models (Footpoint driver (from **Pascoe et al., 2010**):

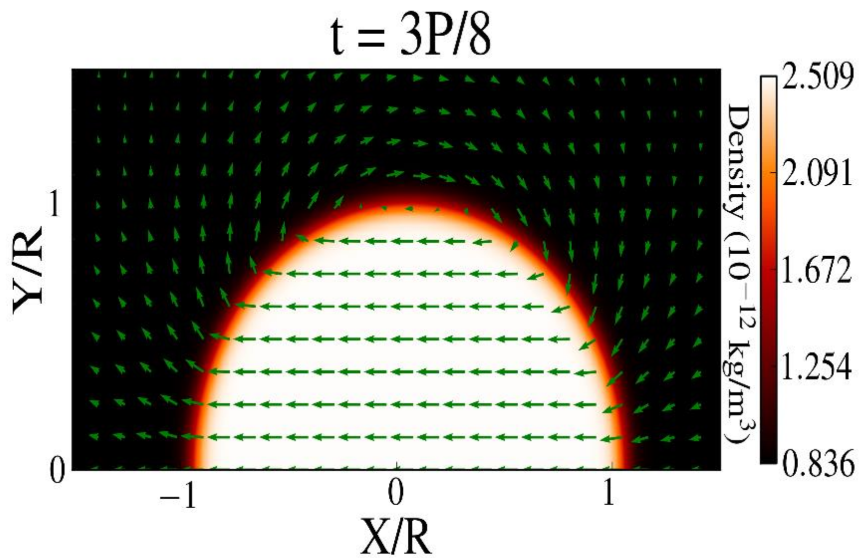
$$\{v_x, v_y\} = \{v(t), 0\} = \{\left(2\frac{km}{s}\right)\cos\left(\frac{2\pi t}{P}\right), 0\}$$

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

$P = 254\ s$ is the driver period, approximately 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.





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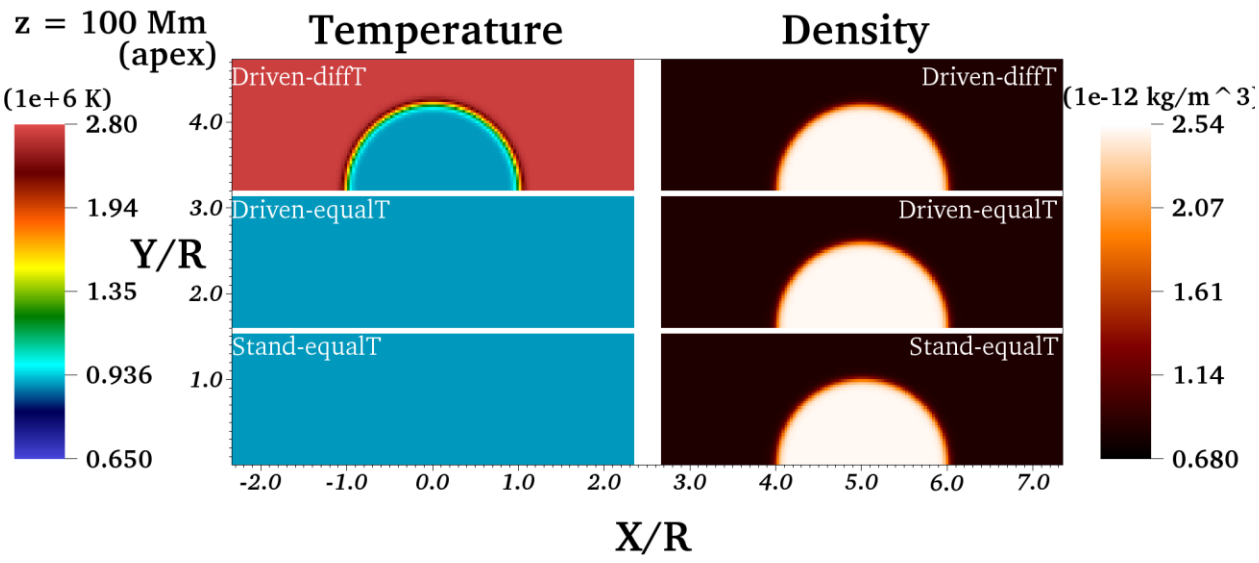
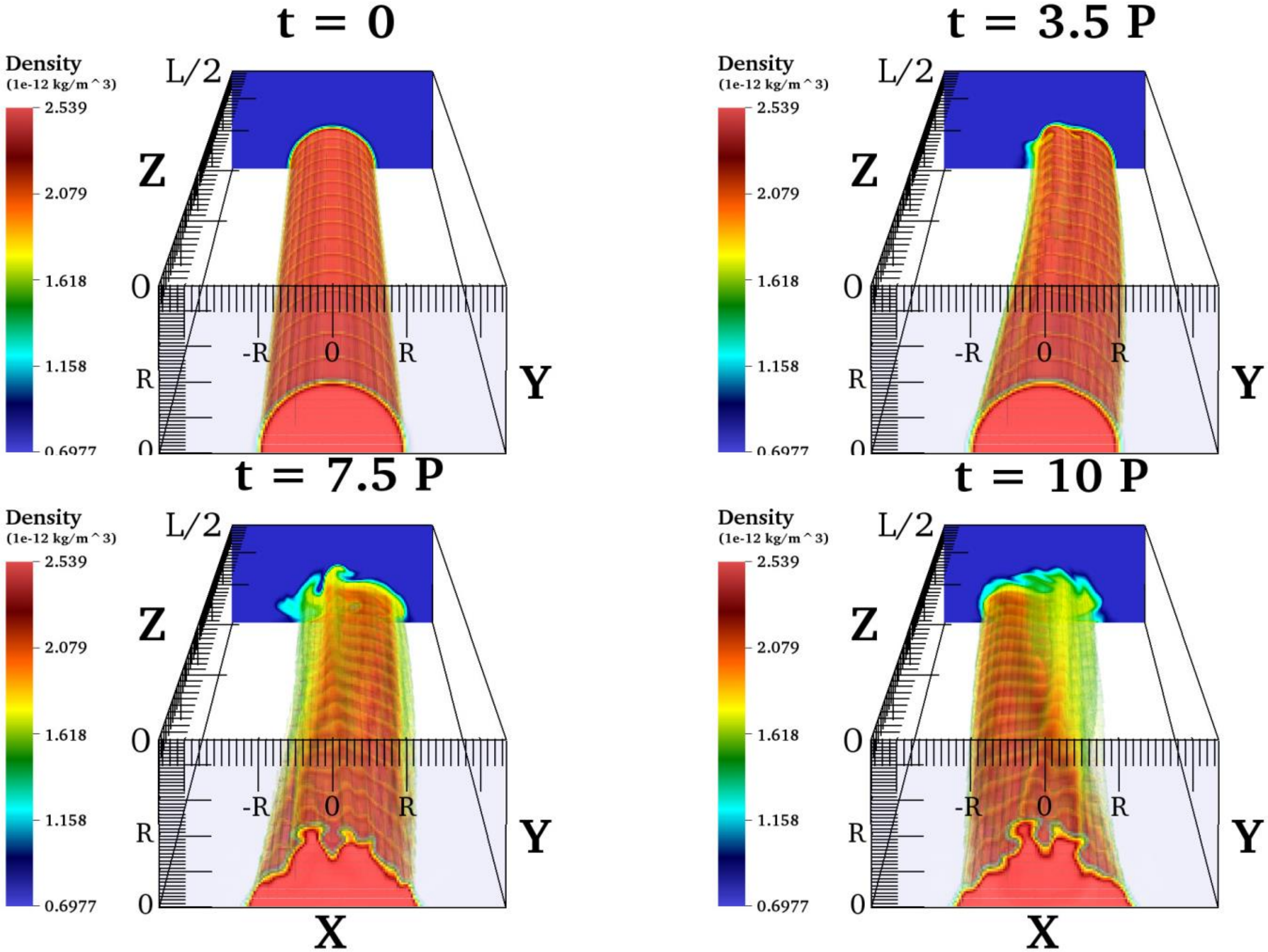
2.Summary of the different setups

	Uniform Temperature	Temperature gradient
Driver	Driven-equalT	Driven-diffT
Initial Pulse	Stand-equalT	-



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**).

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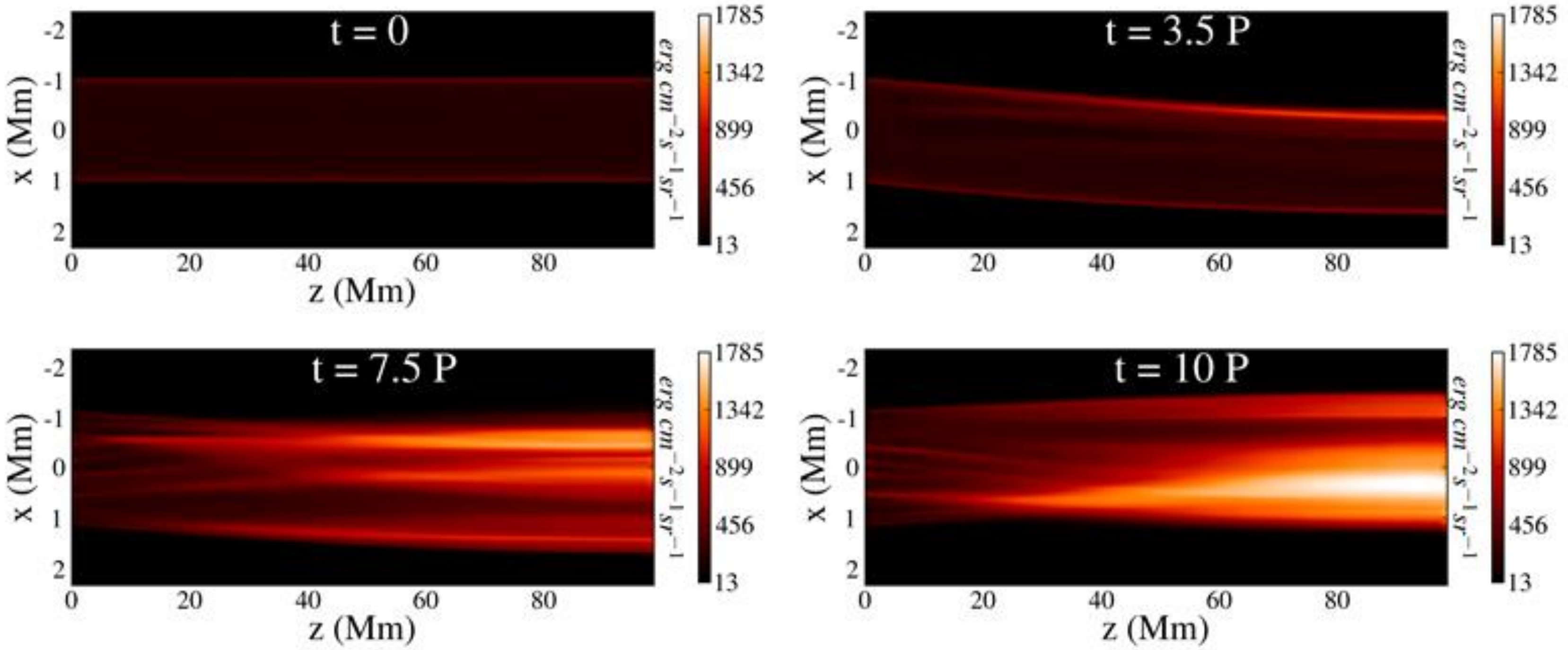
3. Dynamical evolution of our models.



(Karampelas and Van. Doorsselaere, submitted.)

- Forward modeling of the **Driven-diffT** model, with the use of the **FoMo** code (**Van Doorsselaere et al. 2016**). The spectral lines of *Fe XII 19.3* nm are shown, mapping the evolution of the tube outer layer.
- The emission images highlight the aforementioned turbulent state of the flux tubes, caused by the Kelvin-Helmholtz instability.

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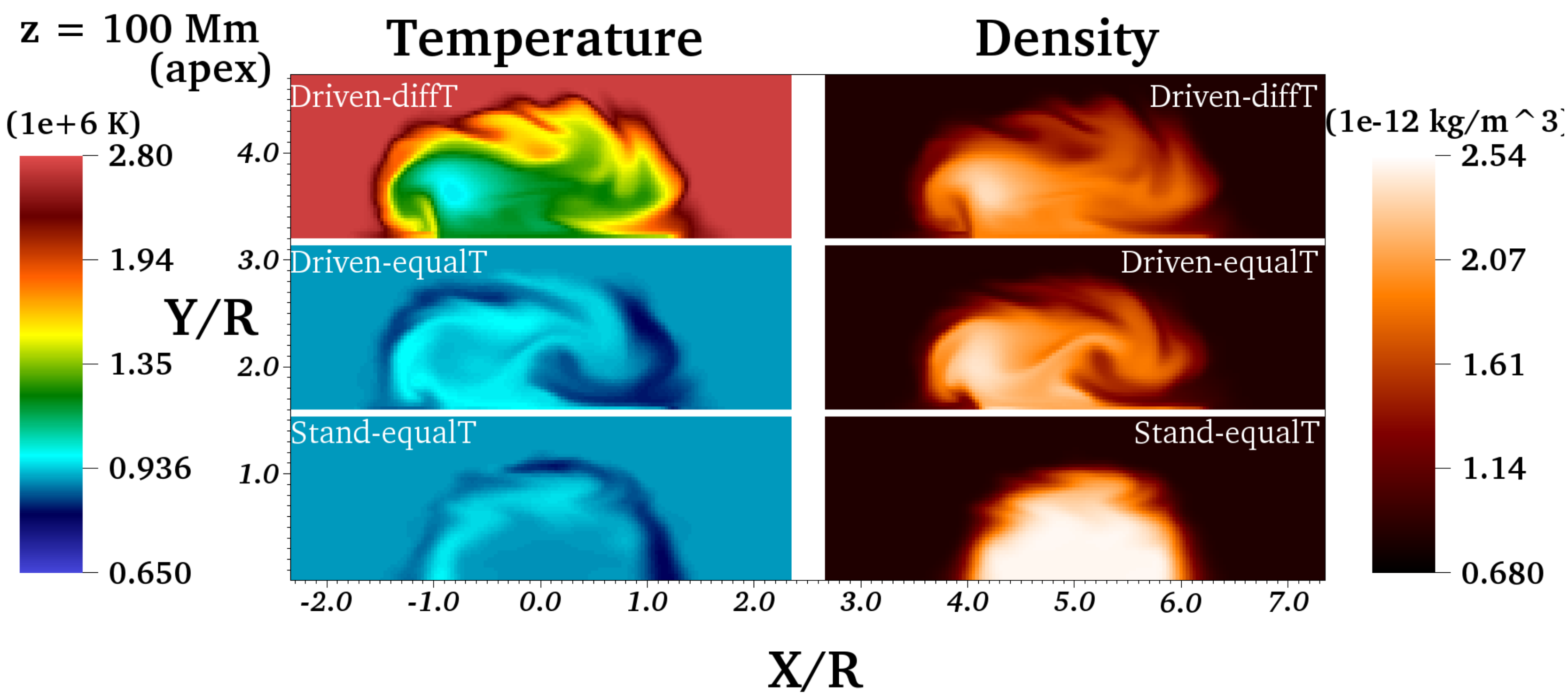
3. Dynamical evolution of our models.



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, submitted)**.

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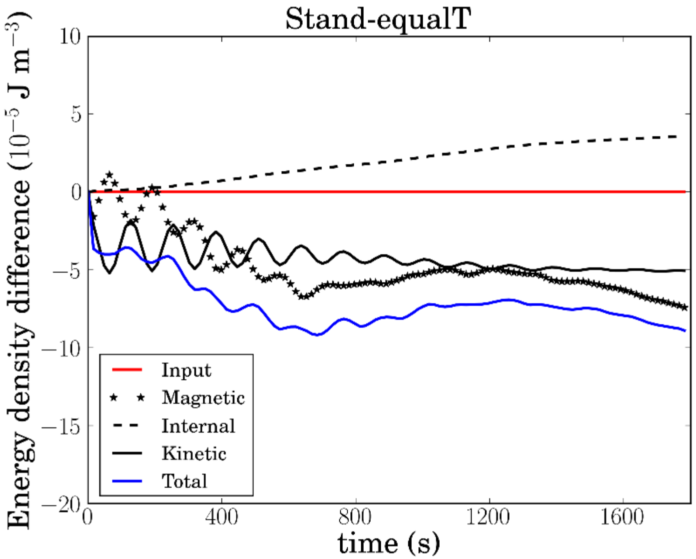
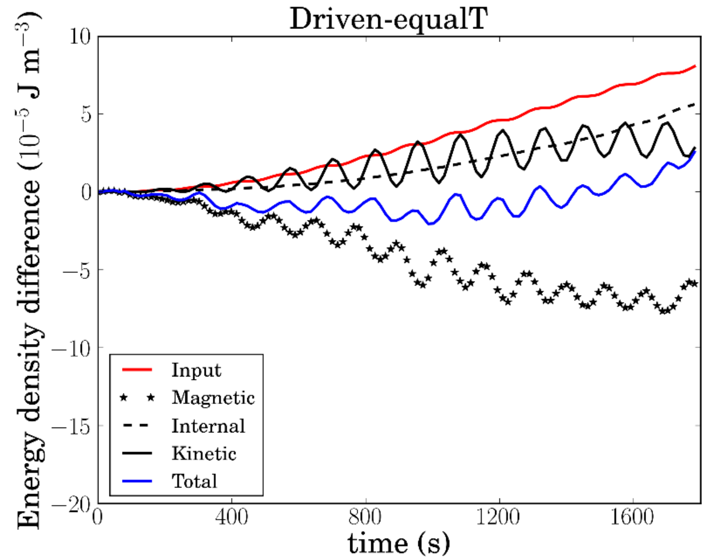
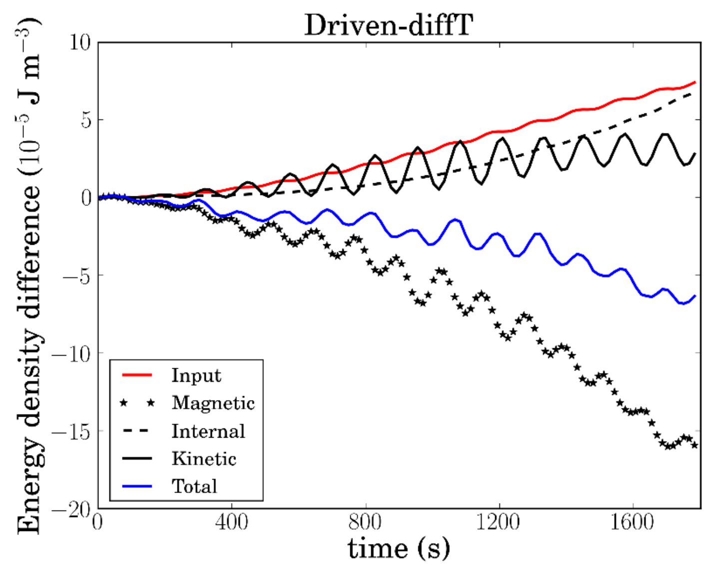
3. Energy densities



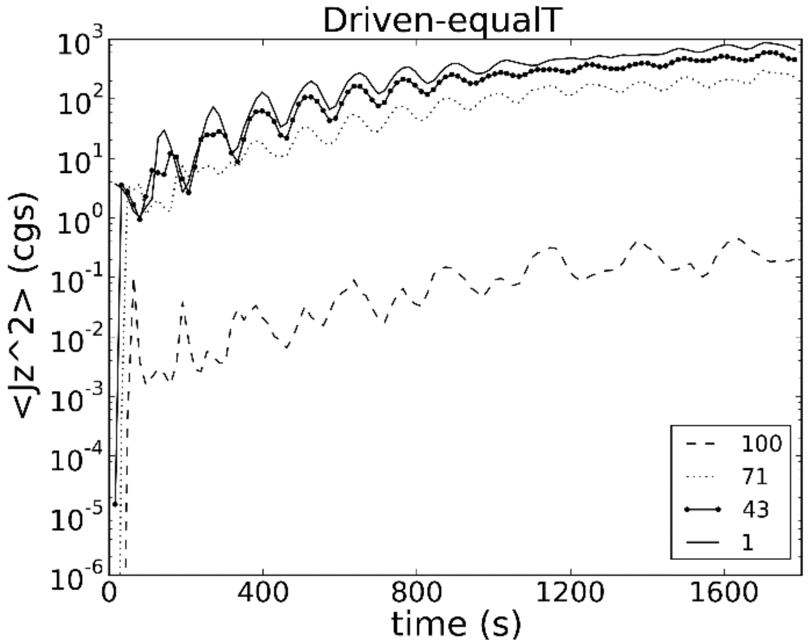


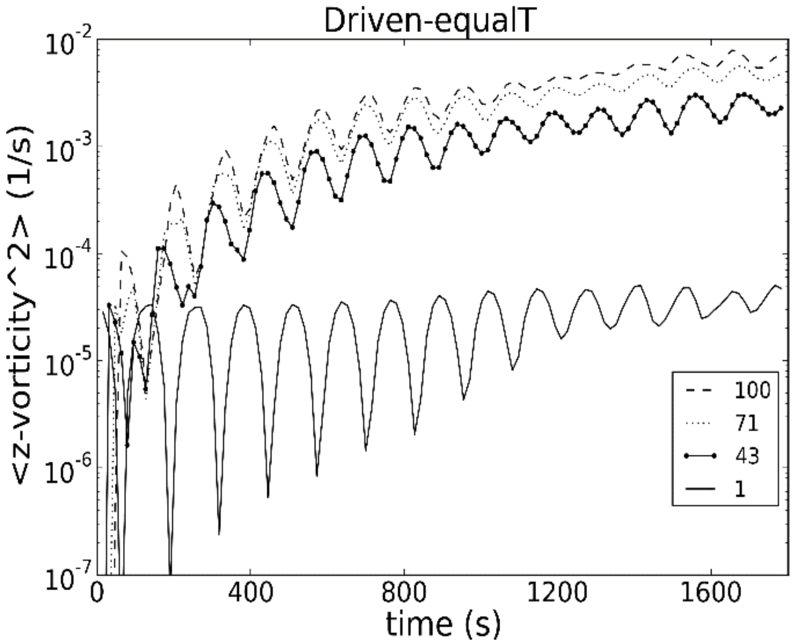


Internal **(I)** and magnetic **(M)** energy density variations relative to the initial state.
Kinetic **(K)** energy density variations relative to the initial state.
Total **(T=M+I+K)** energy density.
Energy (density) provided by the driver **(Input)**.

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





Driven oscillation with uniform initial temperature:

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

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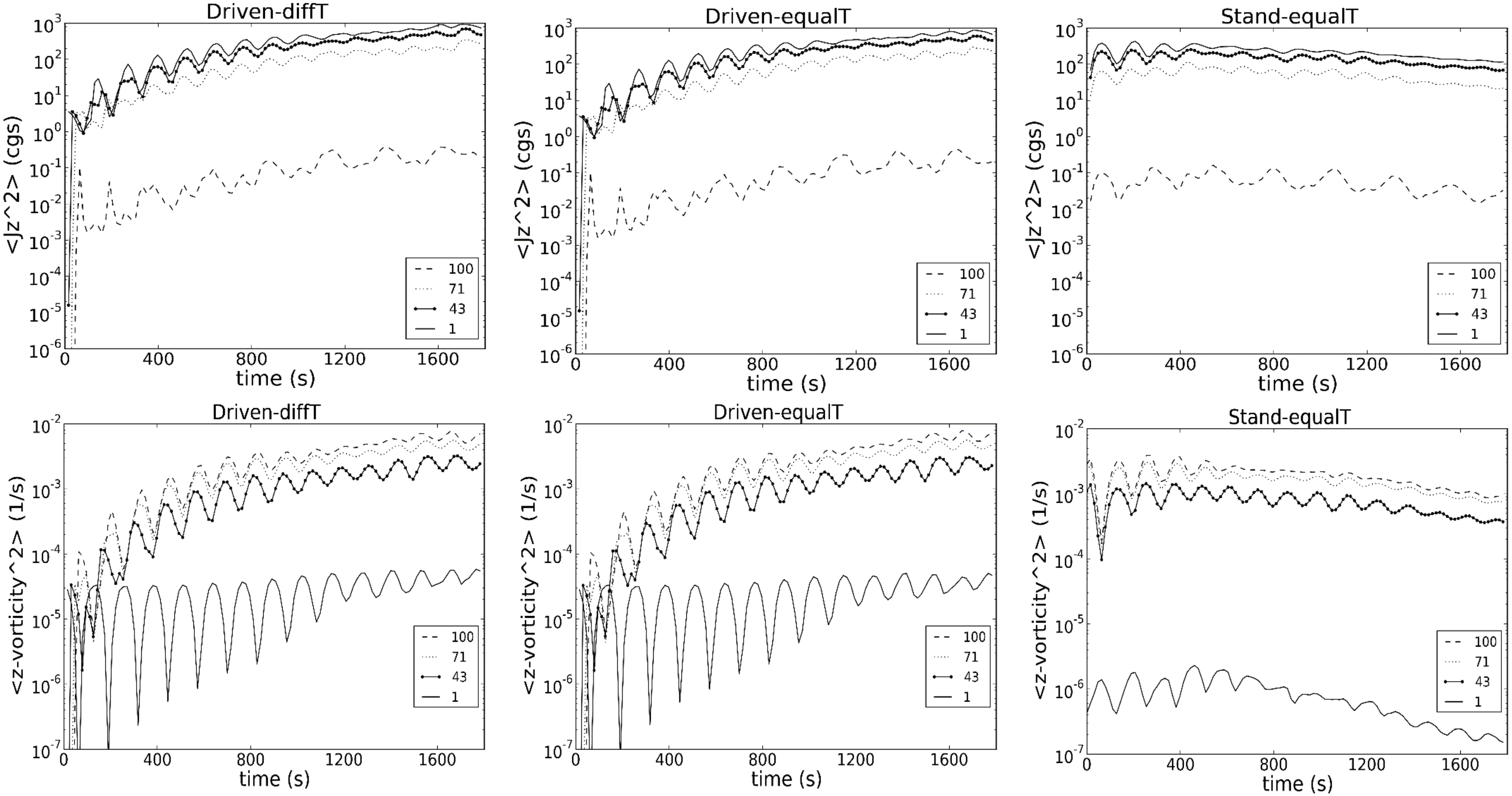
3. Square z-current densities and square z-vorticities



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.

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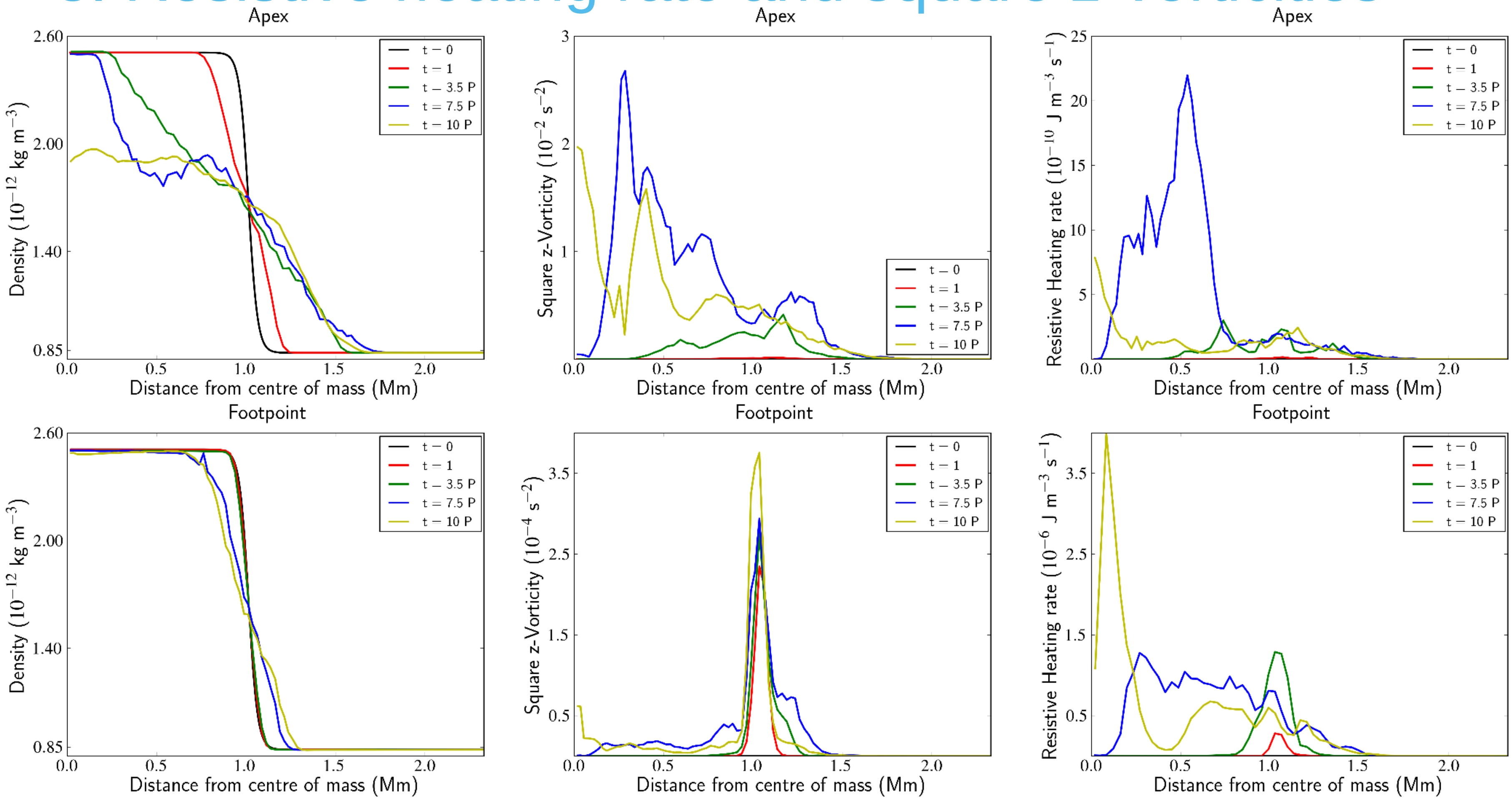
3. Resistive heating rate and square z-vorticities



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

- 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.

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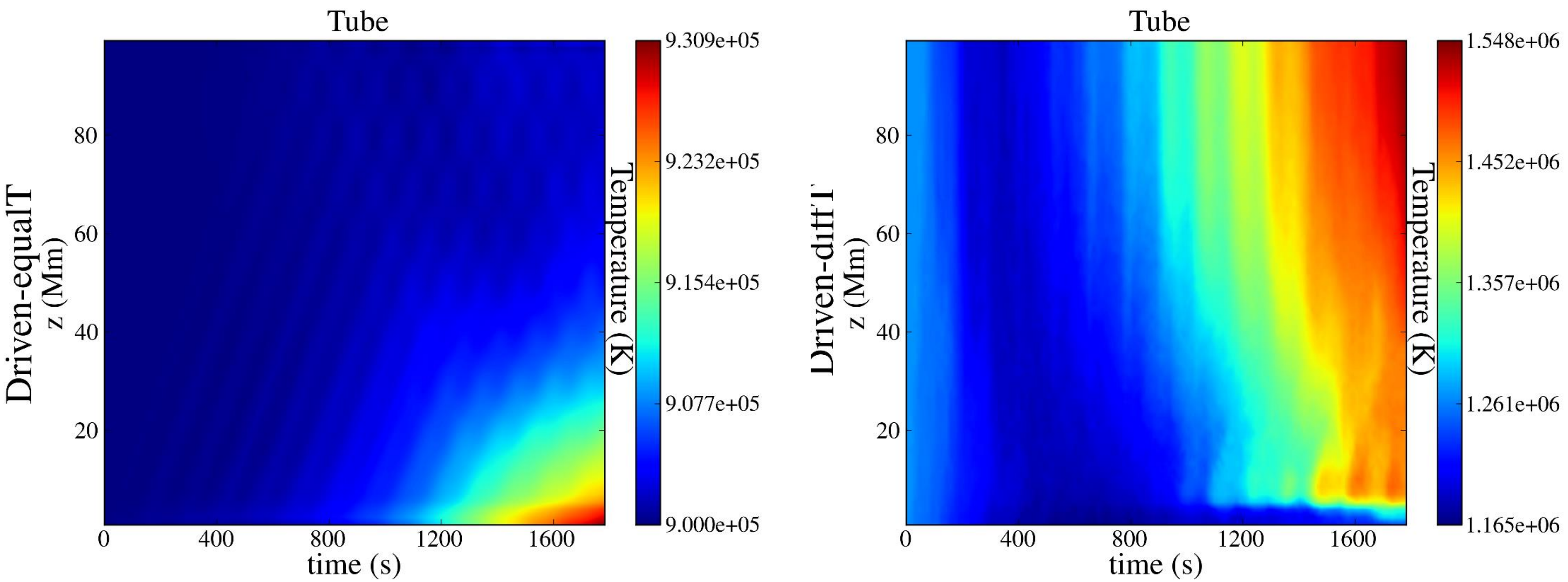
3. Temperature profiles



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

- 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).

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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:

- Physical resistivity and viscosity
- Thermal conduction
- Gravity
- A more realistic atmosphere + radiation
- A realistic energy injection mechanism

Thank you!