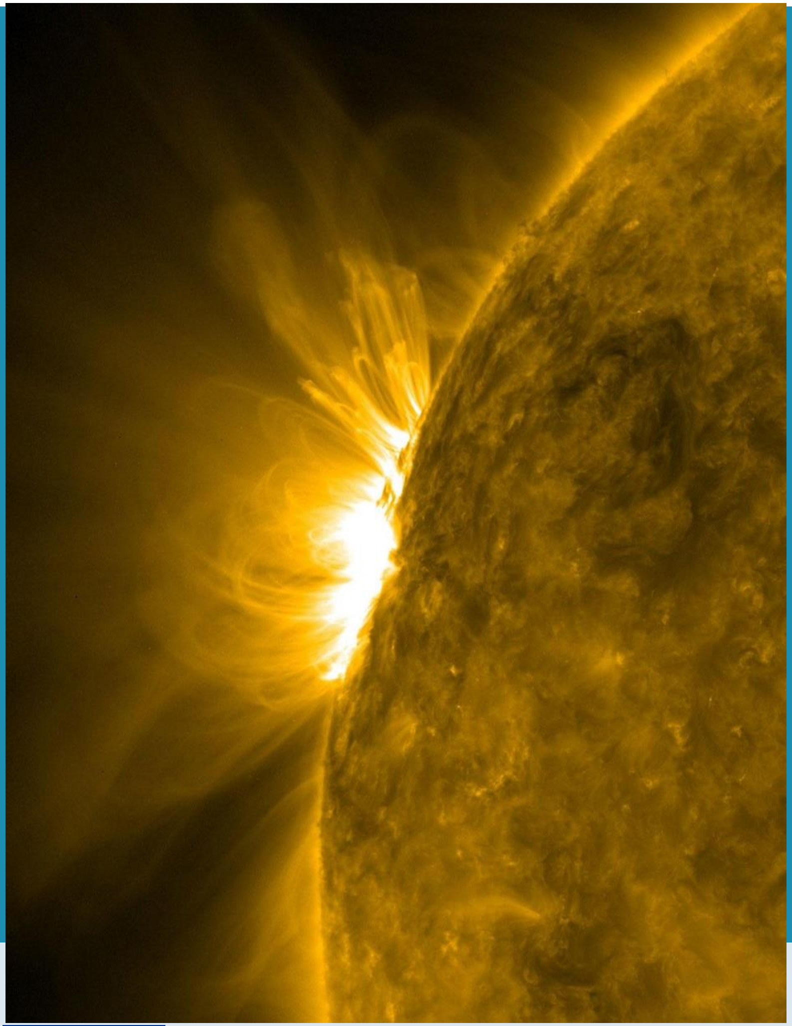
Transverse waves in a coronal loop: effect of a transition region



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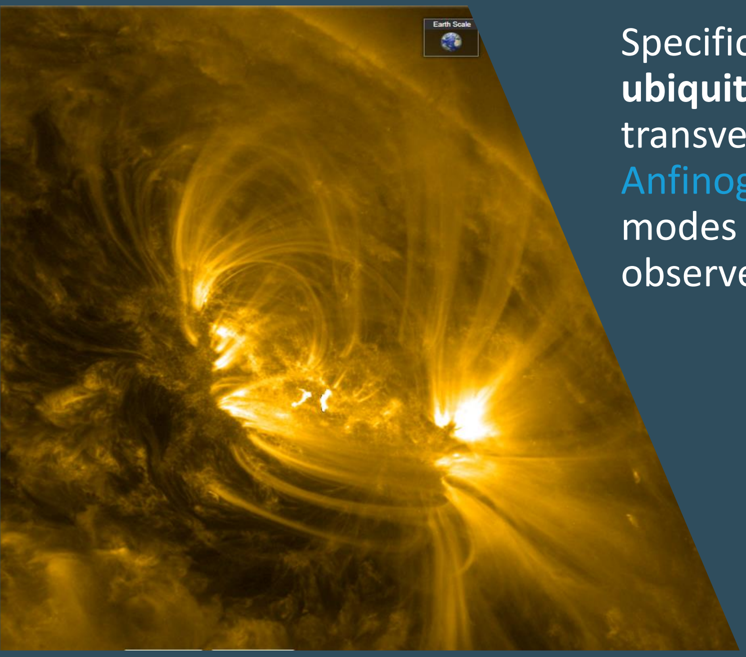
Motivation

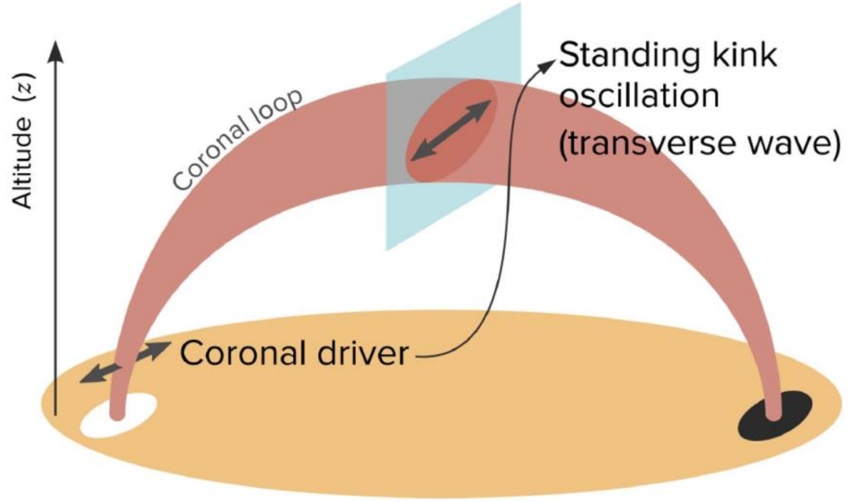
Magnetohydrodynamic waves in the corona are crucial to the energy budget.

- Transports energy from low down in the solar atmosphere up to corona
- Can create small scales via nonlinear processes such as Kelvin-Helmoltz instability, leading to dissipation of energy into heat
- Can be used via seismology to remotely diagnose the plasma



Specifically look at *decay-less oscillations*, **ubiquitous** small amplitude standing transverse waves (Wang+2012, Nistico+2013, Anfinogentov+2015), and propagating kink modes (Tomczyk+2007, Morton+2015) observed everywhere in the corona.

Interested in how the energy transported + dissipated via *kink waves* (transverse waves) by the inclusion of a mass reservoir at the loop base.



Schematic of a curved coronal loop undergoing a kink oscillation

Create a density-enhanced stable loop incorporating a chromosphere + transition region, and **driver in the chromosphere** to lead to decay-less kink oscillations.

Extension of Karampelas+ 2019, written in the 3DMHD *PLUTO* code (Mignone+ 2012).

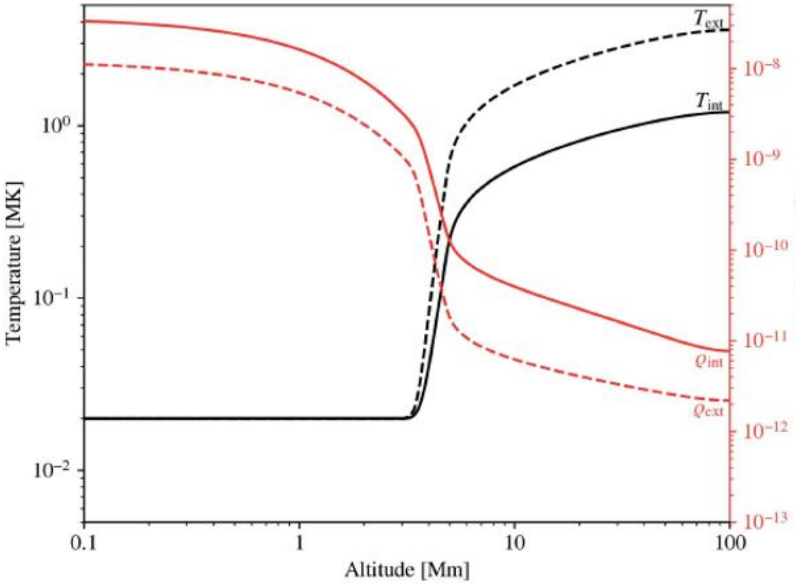
Physics included: Gravitational stratification
Mass reservoir
Transition region
Thermal conduction
[No heating function or radiation]
[Straight untwisted cylinder]
[Neglect two-fluid effects]
[Does not start turbulent]

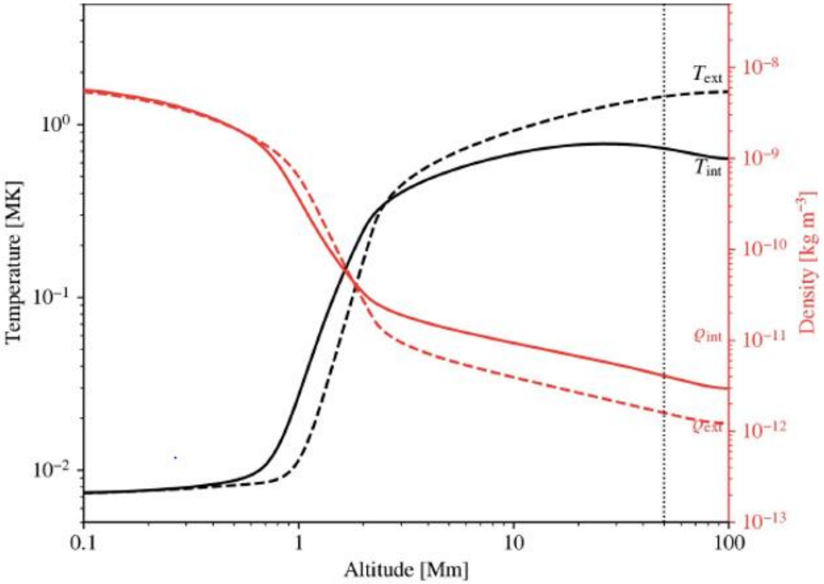
Setting up an equilibrium

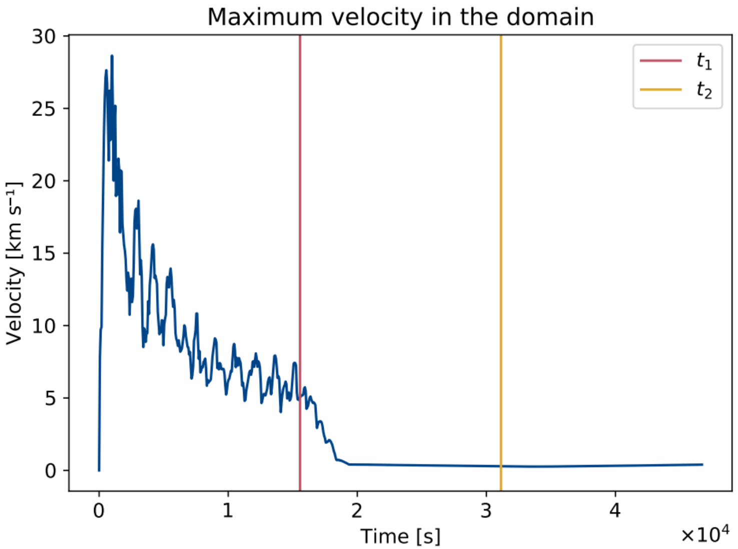
- We begin by considering the 1D equilibrium along the field. Have uniform vertical magnetic field ($B = 42$ G), impose a temperature profile from Aschwanden & Schrijver 2002.
  - Solve hydrostatic equilibrium numerically, since have gravity
- Then we relax in 2D (bottom left -> bottom right). The radial profile follows a 1 - tanh function to transition smoothly from inside the loop to out, with a density contrast of ~3.

- When starting the 2d relaxation, find residual pressure waves being launched along the tube + reflecting off the density gradients. Although small amplitude (~5 km/s), these need to be removed for study.
- Use *velocity rewriting*, an unphysical transformation of velocity $v_{i+1}(x,y,z) = \alpha_v(t) v_i(x,y,z)$ for some timesteps between t_1, t_2, and $\alpha_v = 0.995$.

The final state is rotated to 3D by axisymmetry.

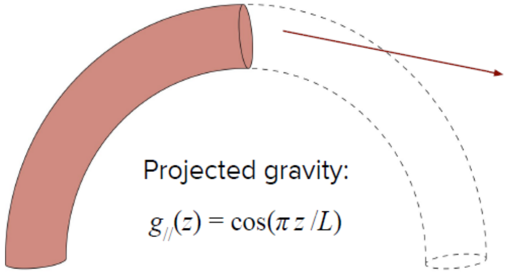


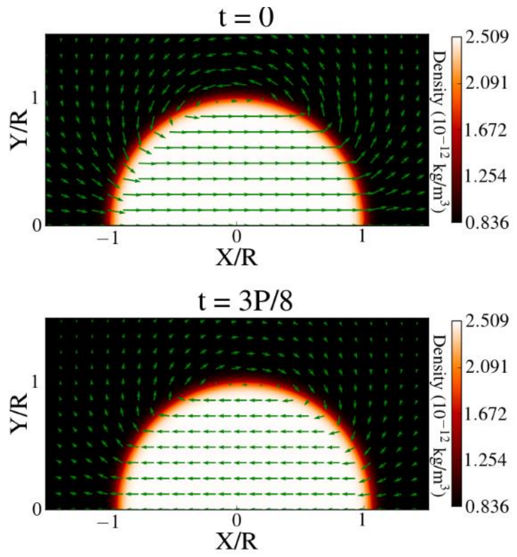




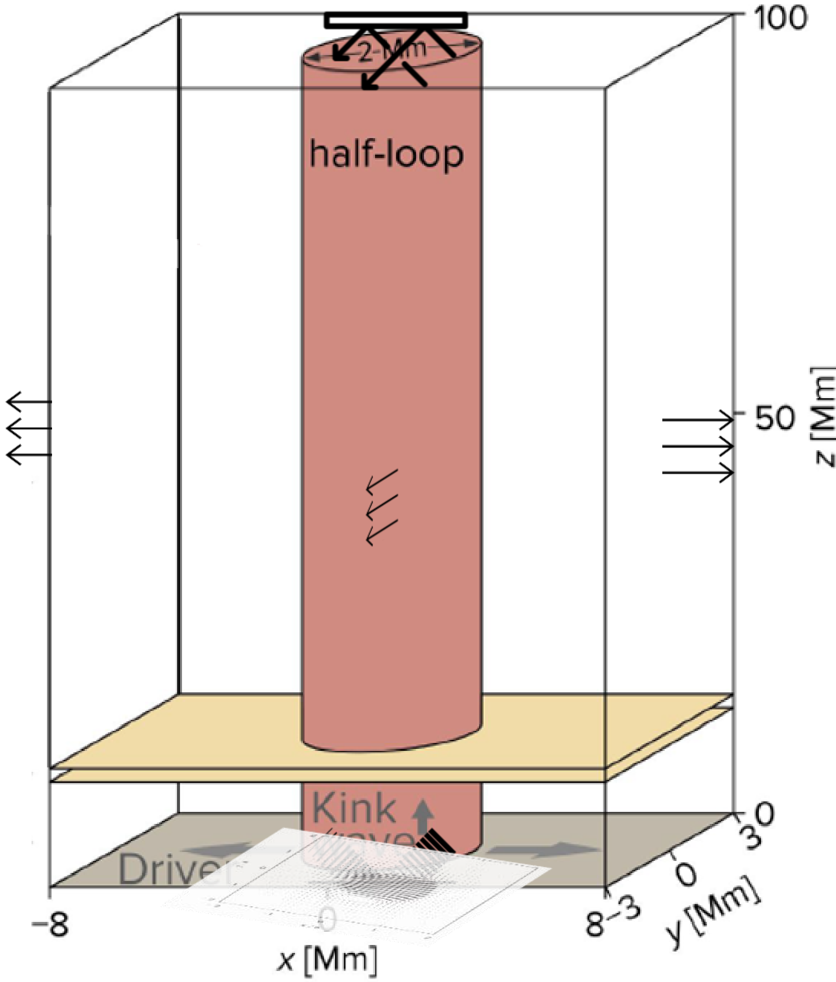
Driving the 3D simulation

- The full 3D simulation has 400x150x1024 cells, so resolution along the loop is ~100 km and 40 km across. The chromosphere has approximate width $\Delta_{CH} = 4Mm$.
- Use the Transition Region Adaptive Conduction (TRAC) method (Johnston+ 2019, 2020) to broaden the steep gradients in TR, whilst keeping energy equation terms.
- Density contrast of $N_{int}/N_{ext} = 3$, with electron densities $N_{CH} \approx 7 \cdot 10^{18}$ m^{-3} down to $N_{apex} \approx 10^{15}$ m^{-3}
- Temperature contrast $T_{int}/T_{ext} = 1/3$ where $T_{CH} = 20kK, T_{max} = 3.6MK$.
- Uniform magnetic field ~22 G along axis direction z.
- 'Kick' with cosine(z) velocity impulse mimic the fundamental kink mode, find the natural period of the loop is 288 seconds.
- Drive with a dipole like driver (Pascoe+ 2010) along x at the bottom boundary (chromosphere). Due to the reflection boundary condition at loop apex + symmetry, sets up a standing mode.

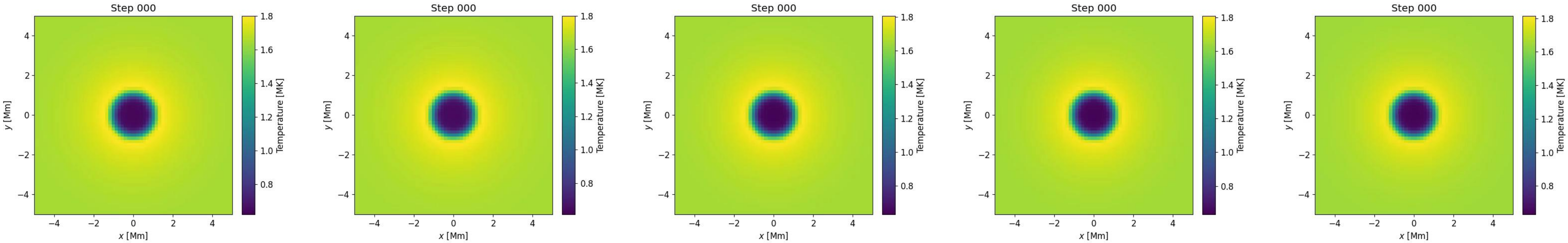


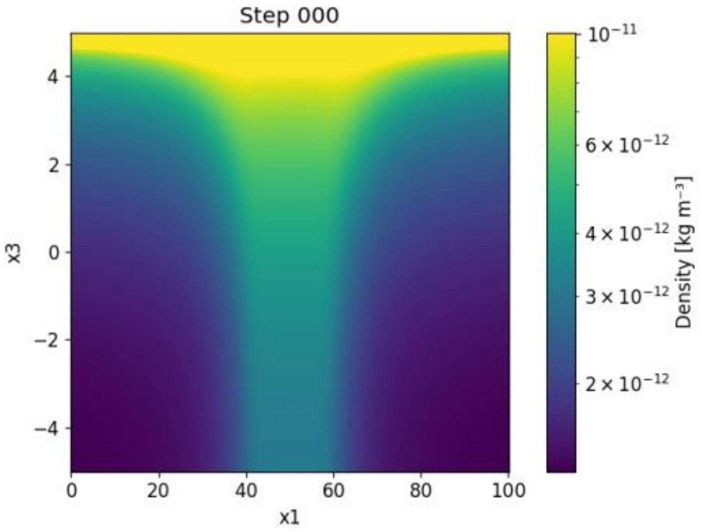


Use same driver as Karampelas+ 2017 (Fig 2)



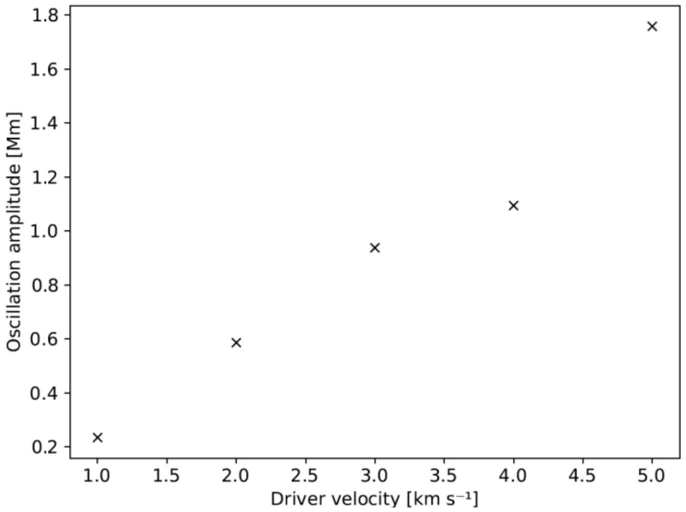
Results: loop oscillation





Only a small velocity amplitude (of order 1 km/s) needed to drive full loop oscillation (see right).

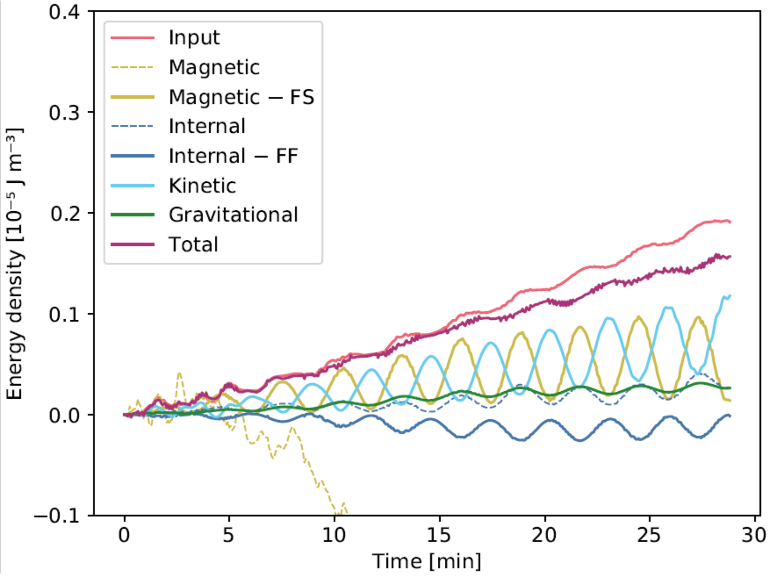
Compare: observations + simulations show photospheric average horizontal (neutral gas) flow speeds of around 2 km/s; supergranulation horizontal flows typically 0.3 km/s; transverse waves in fibrils + spicules have typical amplitudes < 10 km/s (see review Jess+ 2015).

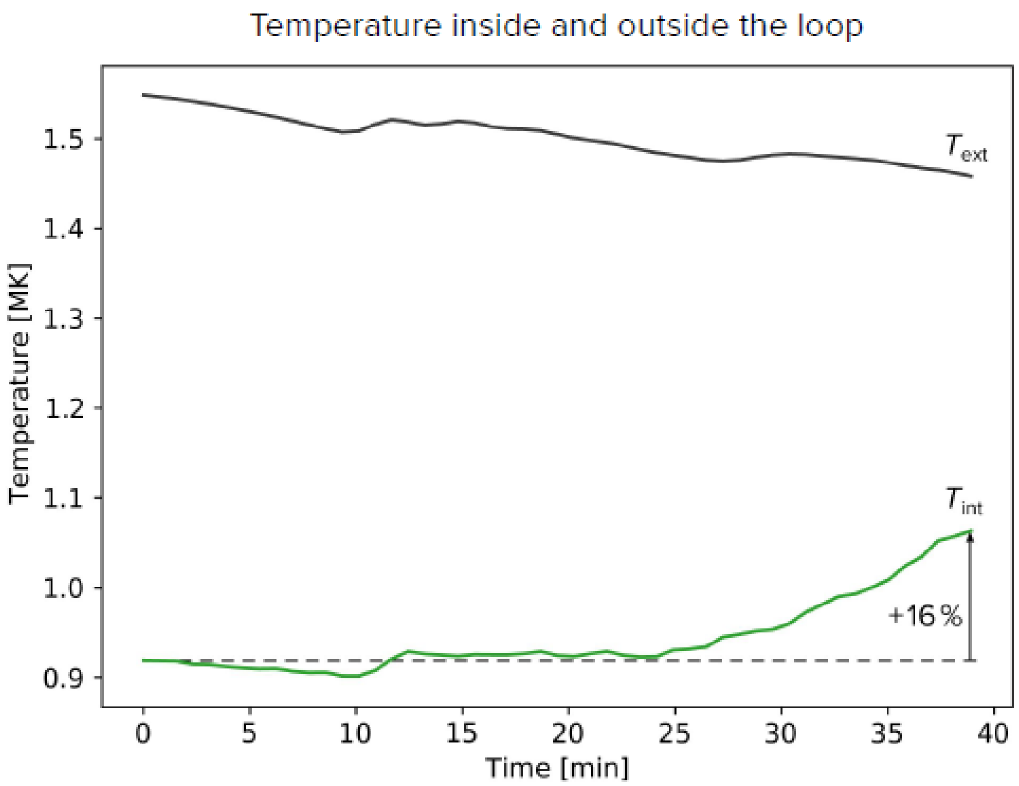


Results: heating

- Advected energy flux is positive at top of TR, negative at base of chromosphere – implies chromosphere is acting as a mass reservoir as intended!
- Looking at temperature inside and outside loop, defined simply as $\rho > (\max_{xy}(\rho(z)) + \min_{xy}(\rho(z))/2$, can see there is **heating beyond mixing**.

Difference in energy between a driven + undriven simulation. Can see the internal energy begins to grow, whilst the magnetic/kinetic energy alternate 'through' apex boundary.

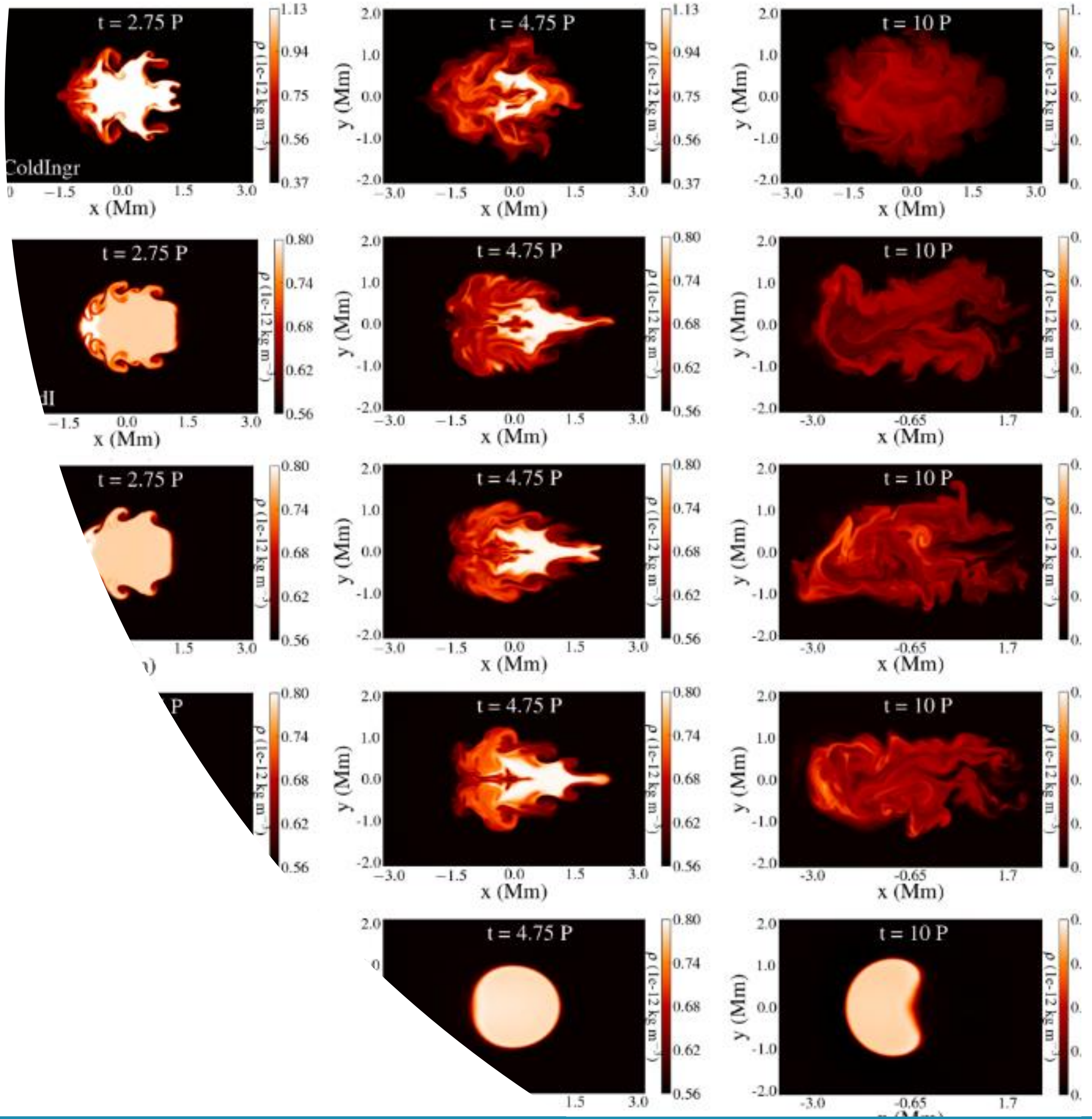




Temperature difference calculated at apex. The heating is the result of KHi, seen clearly at the loop apex. Note the exterior temperature decreases due to thermal conduction down to chromosphere.

Results (forthcoming!)

- By computing 1d hydrostatic equilibrium and a 2d relaxation with velocity rewrite, a stable (enough) loop with transition region and chromosphere is successfully created.
- The eigenfunction of the loop is not significantly changed by the presence of the chromosphere. Standing kink waves can be driven from below the transition region, though much lower amplitudes needed than in corona (on the order of 1 km/s is sufficient).
- Initial results show that, in line with previous work, heating occurs once KHi has `set in'.
- Enthalpy flux does play a role in the energetics after some time. However, issues from scaling with resolution + sufficient duration mean I am hesitant to share results yet. Please stay tuned!



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Thank you for your time!

Please feel free to come + chat,
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