# The current state of wave-based heating mechanisms

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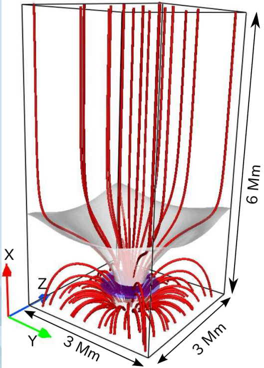
# Current state-of-the-art in wave heating

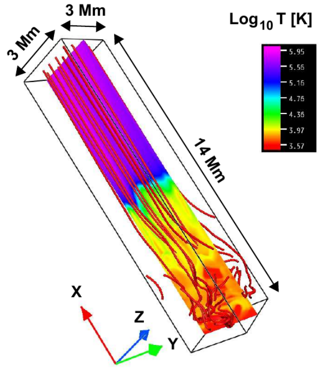
Can waves heat loops to coronal temperatures?

- Yes

# Heating with Alfvén waves

Matsumoto (2018): 3D incarnation of Alfvén wave heating models (building on Moriyasu et al. 2004, Antolin & Shibata 2010, Van Ballegooijen et al. 2011)

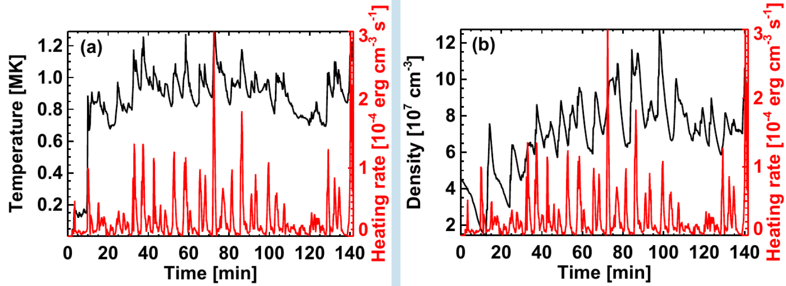



Drive at footpoint with random convective buffeting.

# Heating with Alfvén waves

Matsumoto (2018): Alfvén wave packets steepen, reflect & collide, leading to turbulence & heating

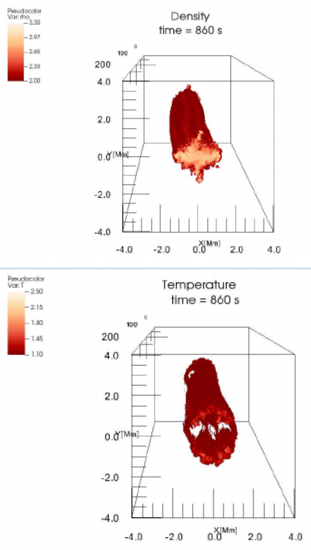



- Loop heated to coronal temperature, and density of $10^8 \mathrm{cm}^{-3}$.
- Similar to nanoflare heating
- But not perp. density structuring: forward model → no loop

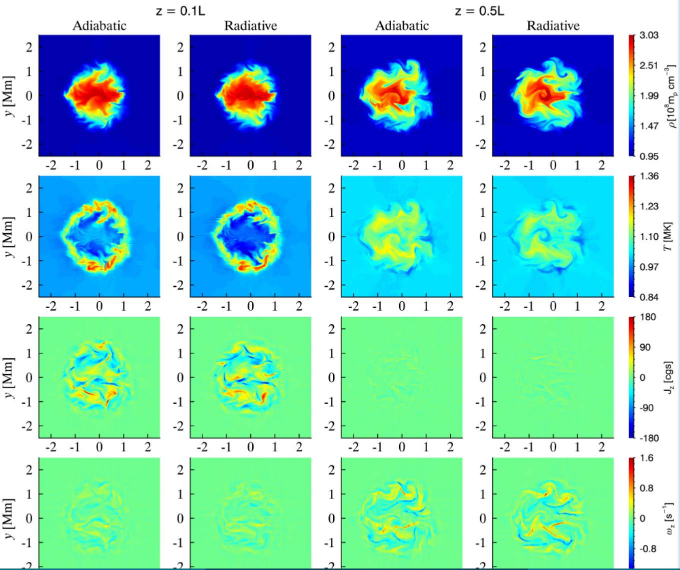
# Kink heating against radiative losses

Shi et al. (2021):

- Straight density enhanced (contrast $= 3$, internal density 3e8 $\text{cm}^{-3}$)
- temperature uniform loop (1MK)
- 200Mm, 30G
- Footpoint periodic velocity driver (8km/s, P=86s)
- Driving from $t = 0s$, radiative losses from $t = 600s$
- Background heating to keep exterior



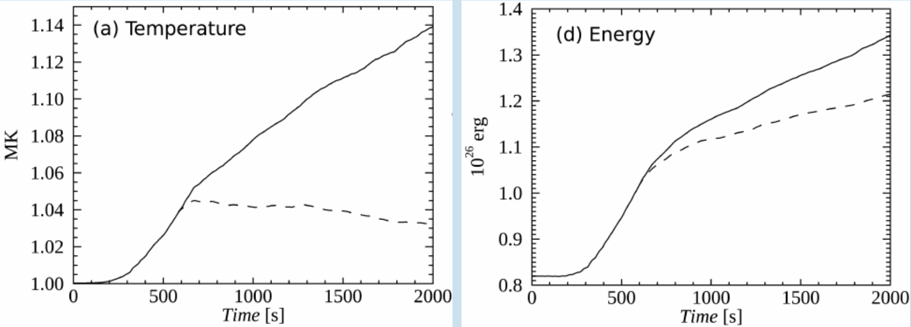
# Kink heating against radiative losses




Forward modelling

# Kink heating against radiative losses

Shi et al. (2021): evolution of loop temperature and energy

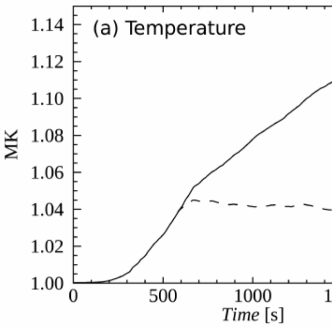


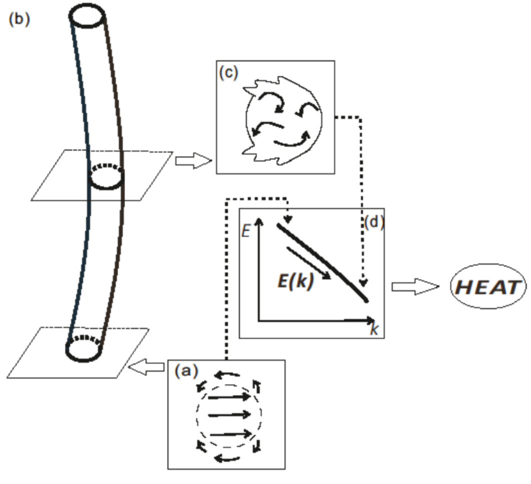

Wave heating

- supports (low density) loop against radiative losses,
- extends cooling time significantly,
- matches observed long cooling times (e.g. Viall & Klimchuk 2012)

# Kink heating against radiative losses

Shi et al. (2021): evolu




(a) Footpoint driver
(b) Fundamental standing kink wave
(c) KHI and Turbulence structure

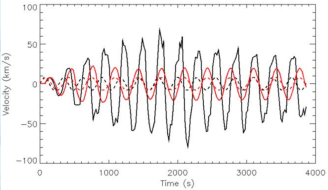
Wave heating

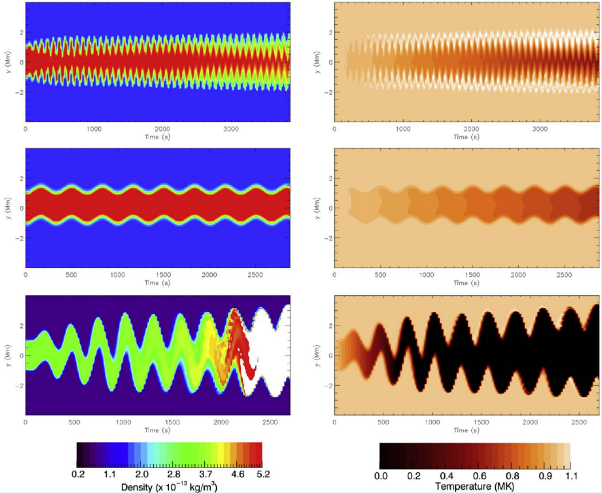
- supports (low dens
- extends cooling tin
- matches observed l
2012)

# Conditions for heating with kink waves

De Moortel & Howson (2022):

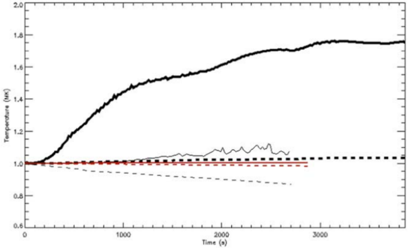
- started from Shi et al. (2021)
- changed driver frequency: no match with fundamental mode
- changed density to $10^9 \mathrm{cm}^{-3}$

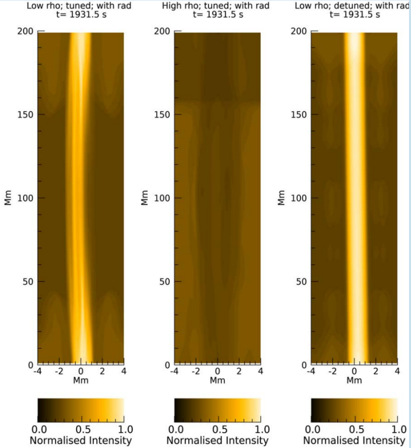


# Conditions for heating with kink waves

De Moortel & Howson (2022)



# Current state-of-the-art in wave heating

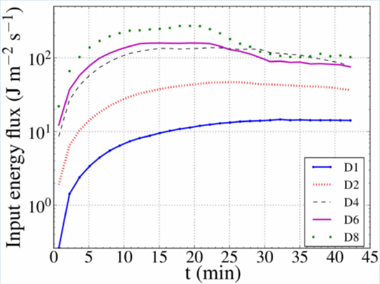
Can waves heat loops to coronal temperatures?

- Yes, due to the formation of small scales in turbulence

  but:
  - only quiescent loops (with densities $\sim 10^8 \text{cm}^{-3}$)
  - only when driven at resonant frequencies
  - leads to stable $T$ or long cooling time (observed!)
- No

# Reasons for non-heating

- Energy input too low to compensate radiative losses (Karampelas et al. 2019)




  - high amplitude → high Doppler shifts (unobserved)
  - high amplitude → shredding of loop

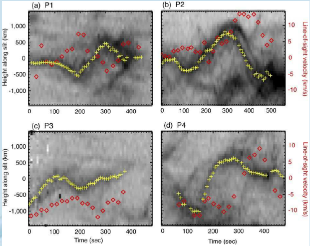
How to solve?

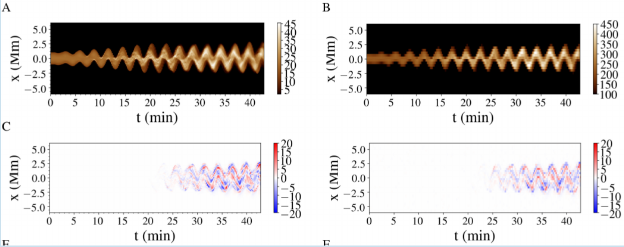
At least allow comparison with observations!

# Doppler shift in prominence

Okamoto et al. (2015): found peculiar Doppler shifts in oscillating prominence

Antolin et al. (2015): made model with resonant absorption & turbulence in prominence thread → explaining phase shift



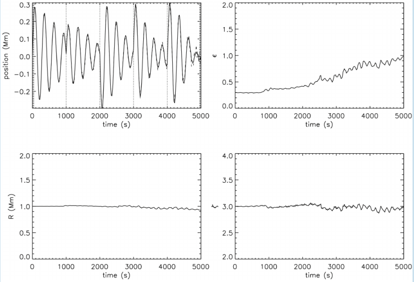

Same physics in loop models (Karampelas et al. 2019, RHS)

→ prominence observation indirect evidence of existence of turbulent loop models

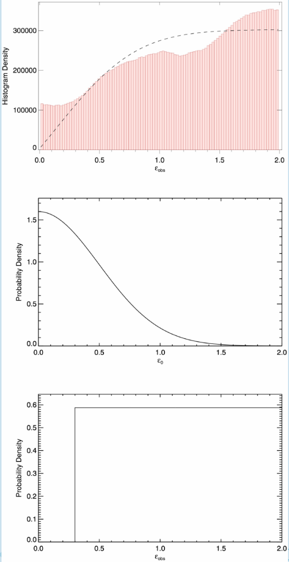
# Observational evidence of turbulent loops

Pascoe et al. (2020):

- Consider evolution of loop "sharpness" $\epsilon$



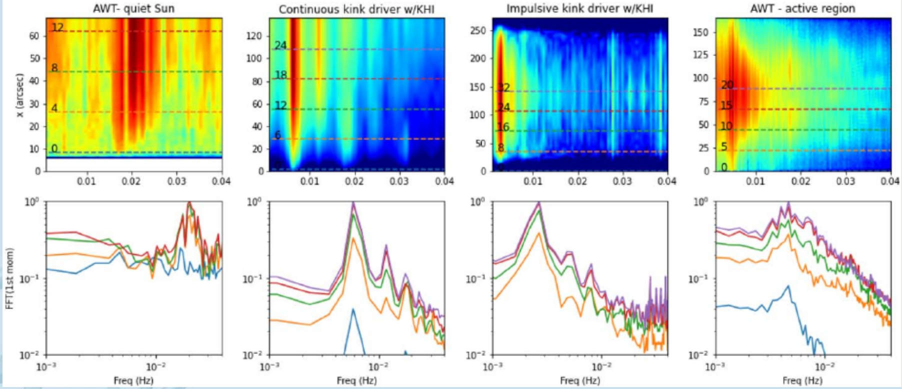

- Compare with observations (red)
- Born with Gaussian sharpness $\epsilon$
- Evolved due to transverse motions $\epsilon > .3$
- Predicted dashed line in top panel (right)



# Observational differences waves heating models

De Pontieu et al. (2022): prospection for MUSE mission. Can MUSE differentiate between (wave) heating models?

Matsumoto ('18) | Karampelas et al. ('19) | Antolin & VD ('19) | Van Ballegooijen et al. ('17)




Very clear spectral (FFT) differences!

# Observational differences waves heating models

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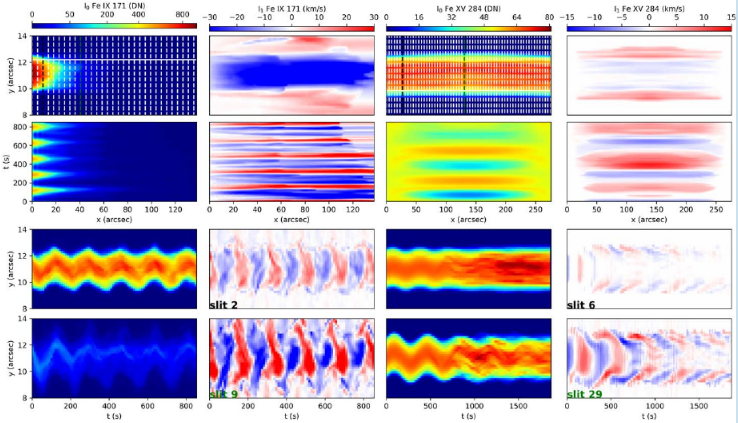


Spectral resolution → differ between standing and propagating

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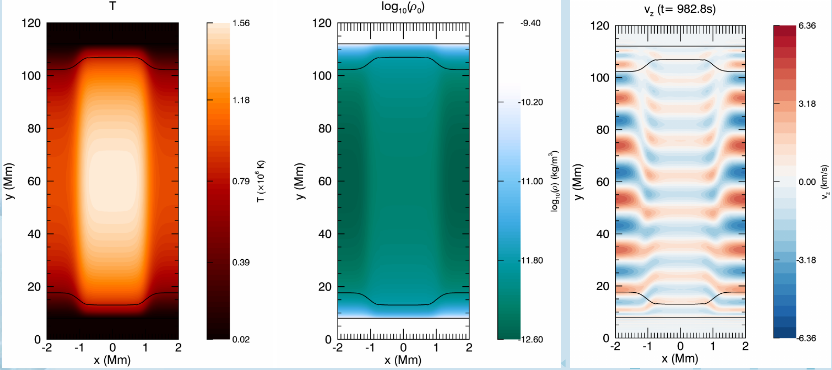
  - leads to stable $T$ or long cooling time (observed!)
- No, but:
  - driver not energetic enough
  - only circumstantial observational evidence
  - lower atmosphere missing

# Coupling to chromosphere

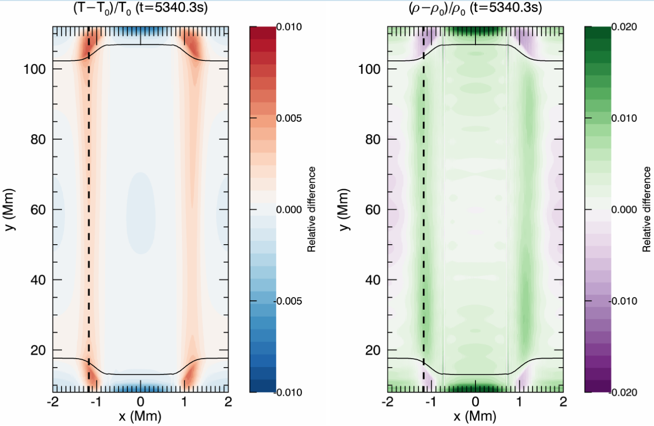
Van Damme et al. (2020): effect of phase mixing on evaporation from chromosphere

- Drive Alfvén waves ($v_z$)
- in relaxed loop with $\nabla_\perp v_\mathrm{A}$
- phase mixing → heating → evaporation



# Coupling to chromosphere

Van Damme et al. (2020): wave induced evaporation

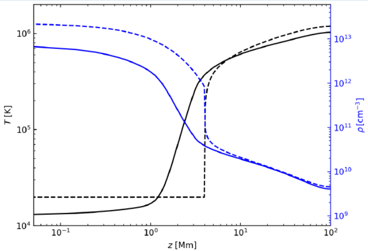


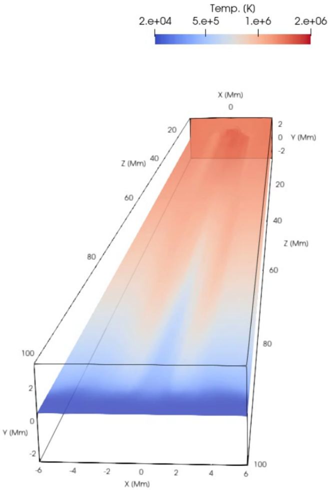

Wave heating indeed leads to evaporation

But low energy input → low heating → “insignificant evaporation”

# Coupling to chromosphere

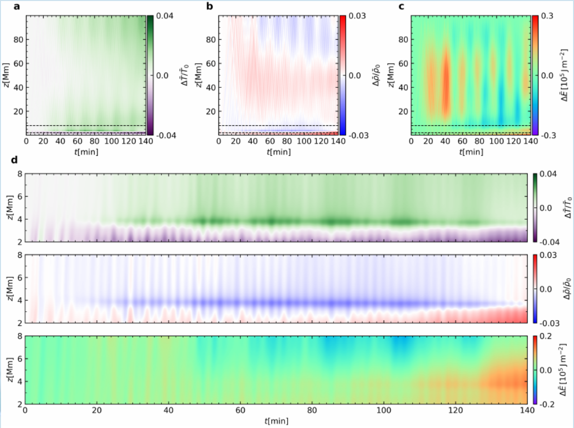
Guo et al. (2023, upcoming): Kink wave & turbulence heating, coupling to chromosphere



# Coupling to chromosphere

Guo et al. (2023, upcoming): kink heating → (gentle) evaporation




Sustaining loop for longer term? Long term loop evolution?

Forward modelling ↔ observations (MUSE)

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  - only when driven at resonant frequencies
  - leads to stable $T$ or long cooling time (observed!)
- No, but:
  - driver not energetic enough
  - only circumstantial observational evidence
  - lower atmosphere missing
- What is needed?
  - Connection with lower atmosphere, in models (hard!) and observations (MUSE!)
  - How to inject energy at rates compatible with radiative losses?
- Wave heating still has potential!
- From 1D $\rightarrow$ 3D in last decade.