MHD Wave Heating in Coronal Loops

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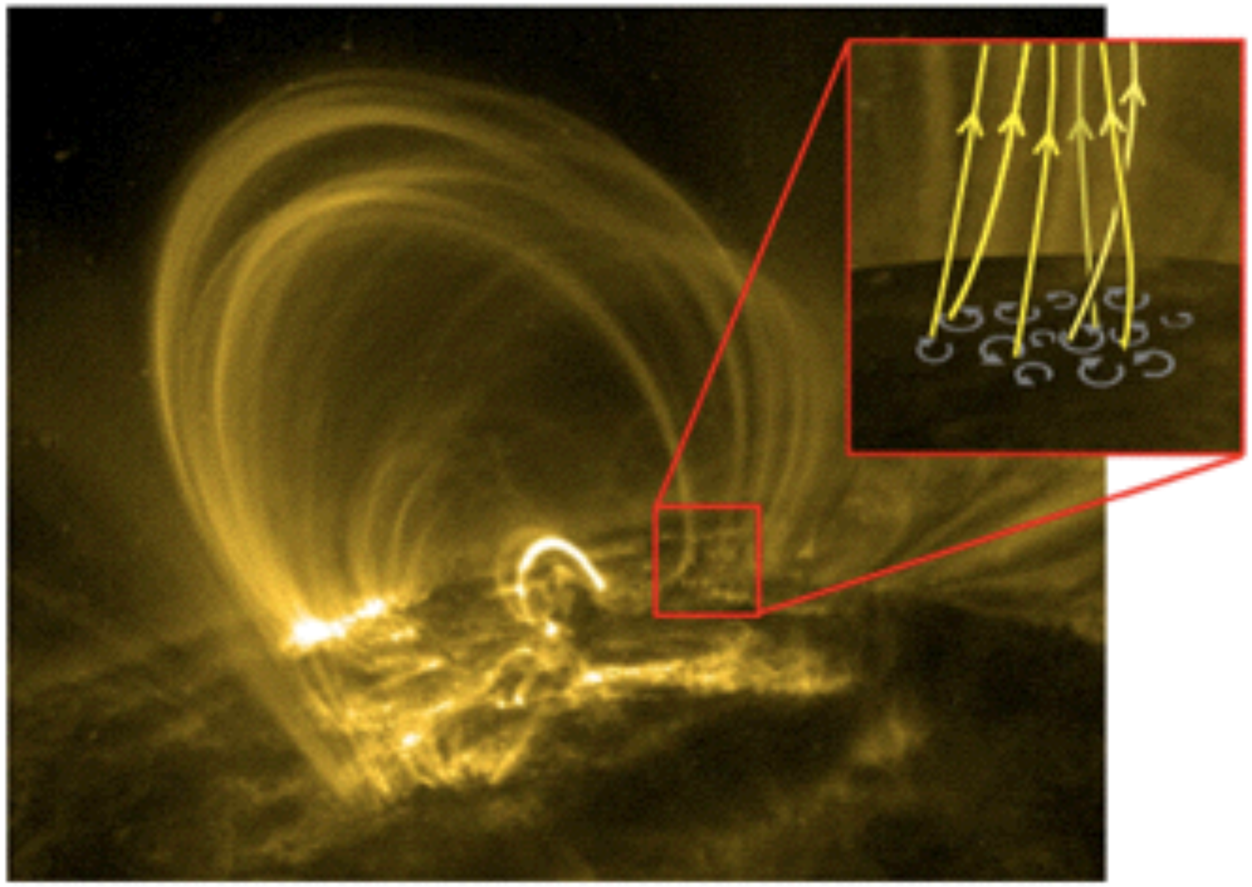
Wave Heating of the Solar Corona



Davila 1987

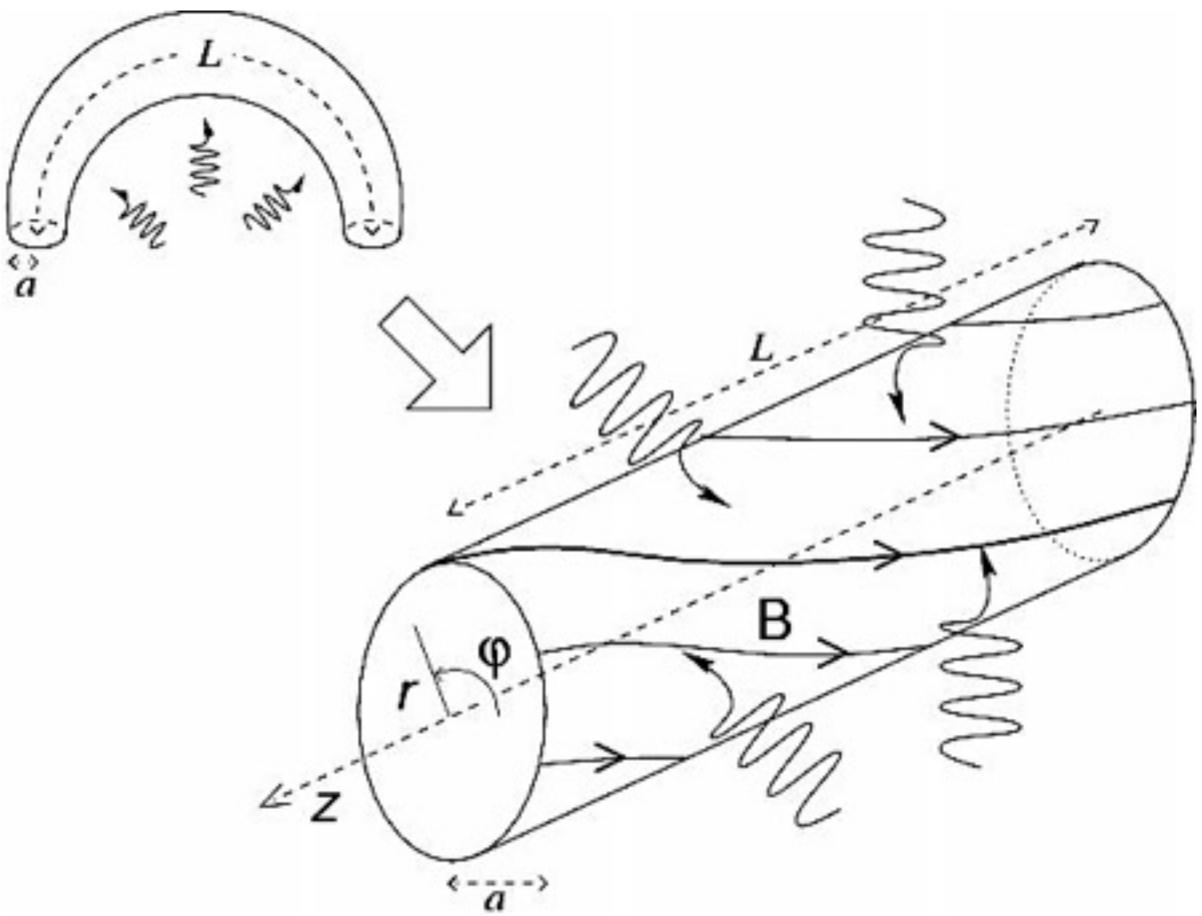
VII. Conclusion

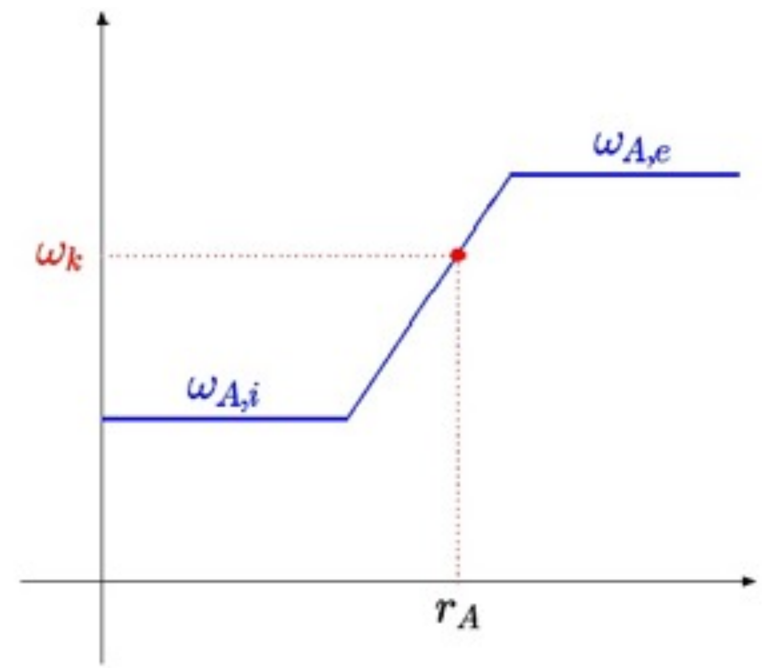
The calculation presented here demonstrates that it may be possible to heat the corona by the resonant absorption of Alfvén waves, and, although additional work is needed, it is reasonable to conclude that resonance absorption is a viable mechanism for heating the corona of the Sun and other late-type stars.

- Historically first suggested as heating mechanism *(Biermann 1946, 1948; Schwarzchild 1948)*
- (Some) Alfvén waves not reflected at chromosphere *(Hollweg 1978,1984,1985)* and hence could heat corona *(Wentzel 1974, 1976)*
  - Resonant absorption *(Ionson 1978; Goossens 2011)*
  - Phase mixing *(Heyvaerts & Priest 1983)*
- ***Vast literature…***

Resonant Absorption

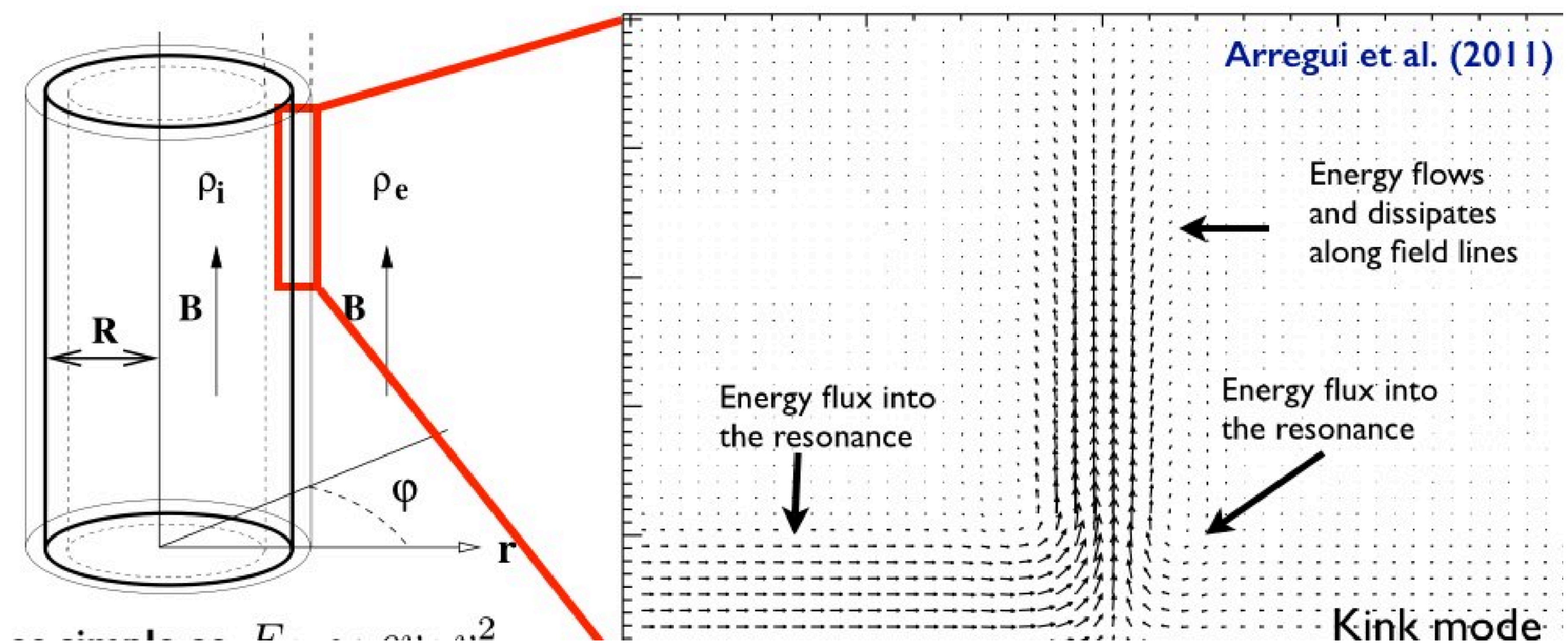
Goossens et al, 1992; Ruderman and Roberts, 2002):





$$t_R = \frac{2}{\pi}\frac{a}{l}\frac{(\rho_i/\rho_e+1)}{(\rho_i/\rho_e-1)}t_W$$

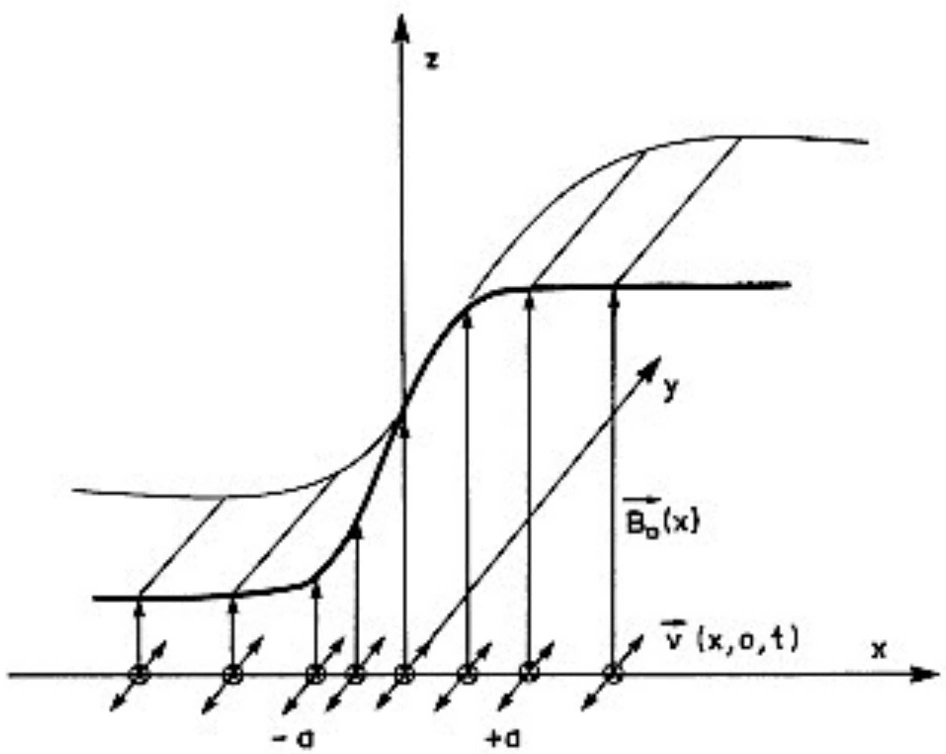
a = radius of loop
l= width of the layer
t_w= period of the global mode

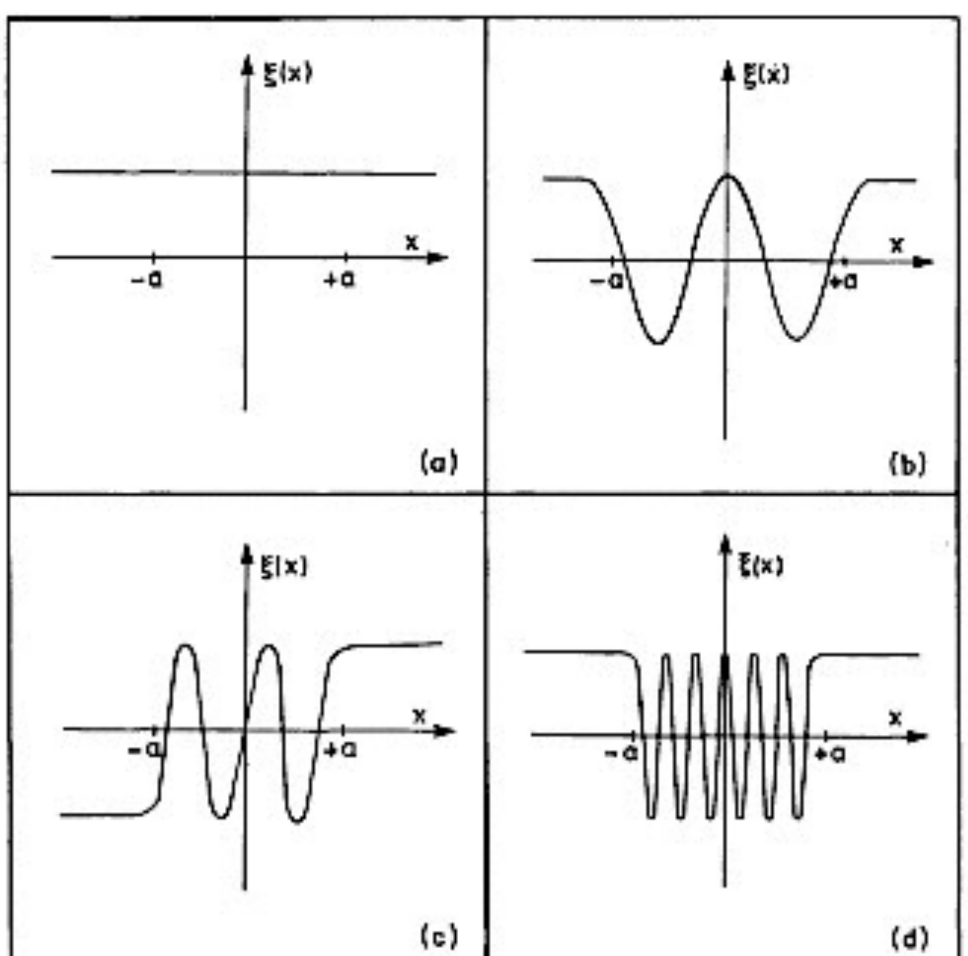


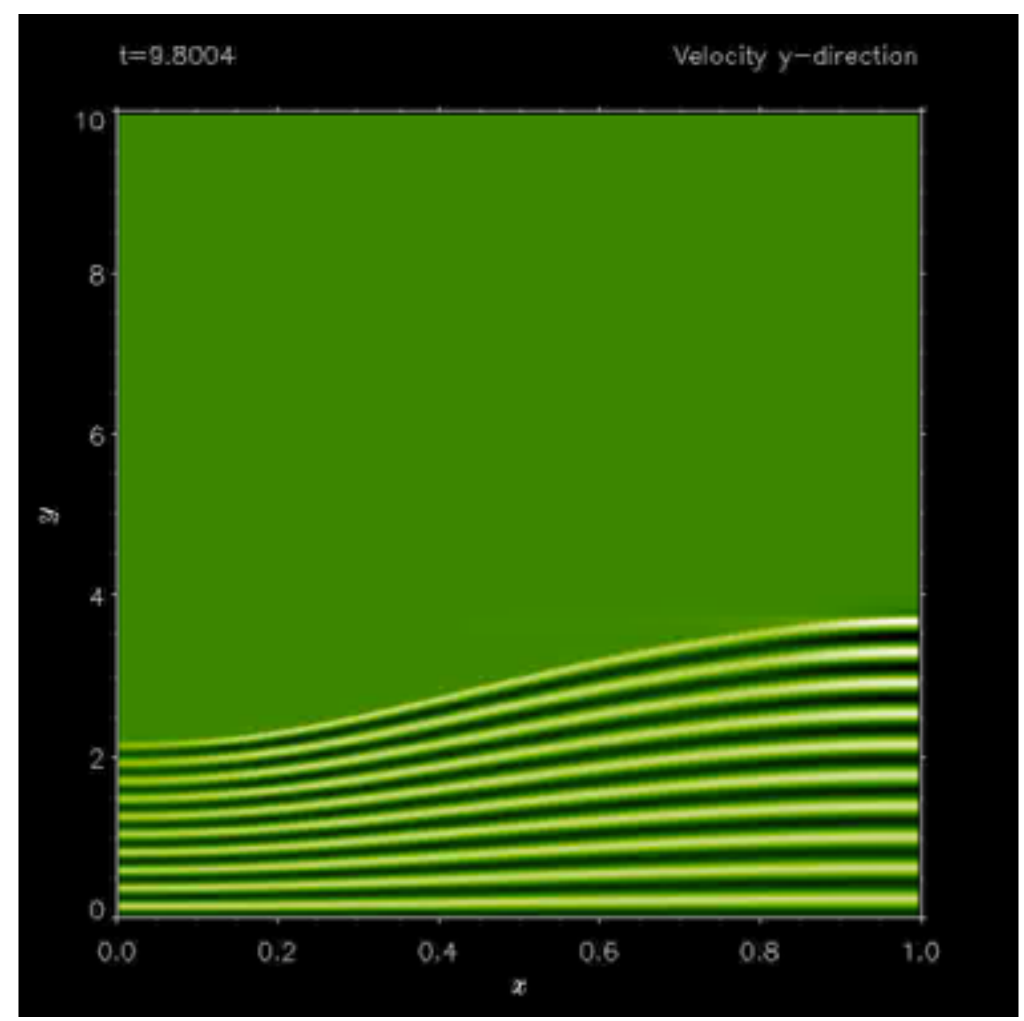
Alfven Wave Phase Mixing

e.g. Heyvaerts & Priest, 1983; Browning & Priest 1984

- Shear Alfven waves become quickly out of phase as they propagate along the field lines with large (perpendicular) gradients in the Alfven speed
- Small length scales are generated – dissipation is enhanced.
- Eventually, all the wave energy is dissipated.







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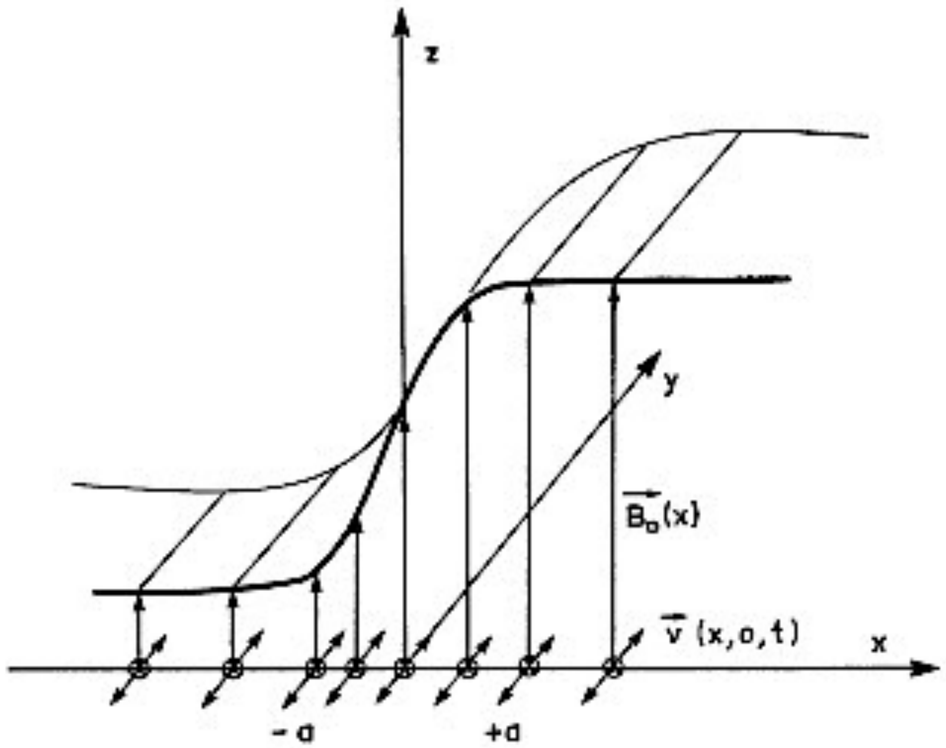

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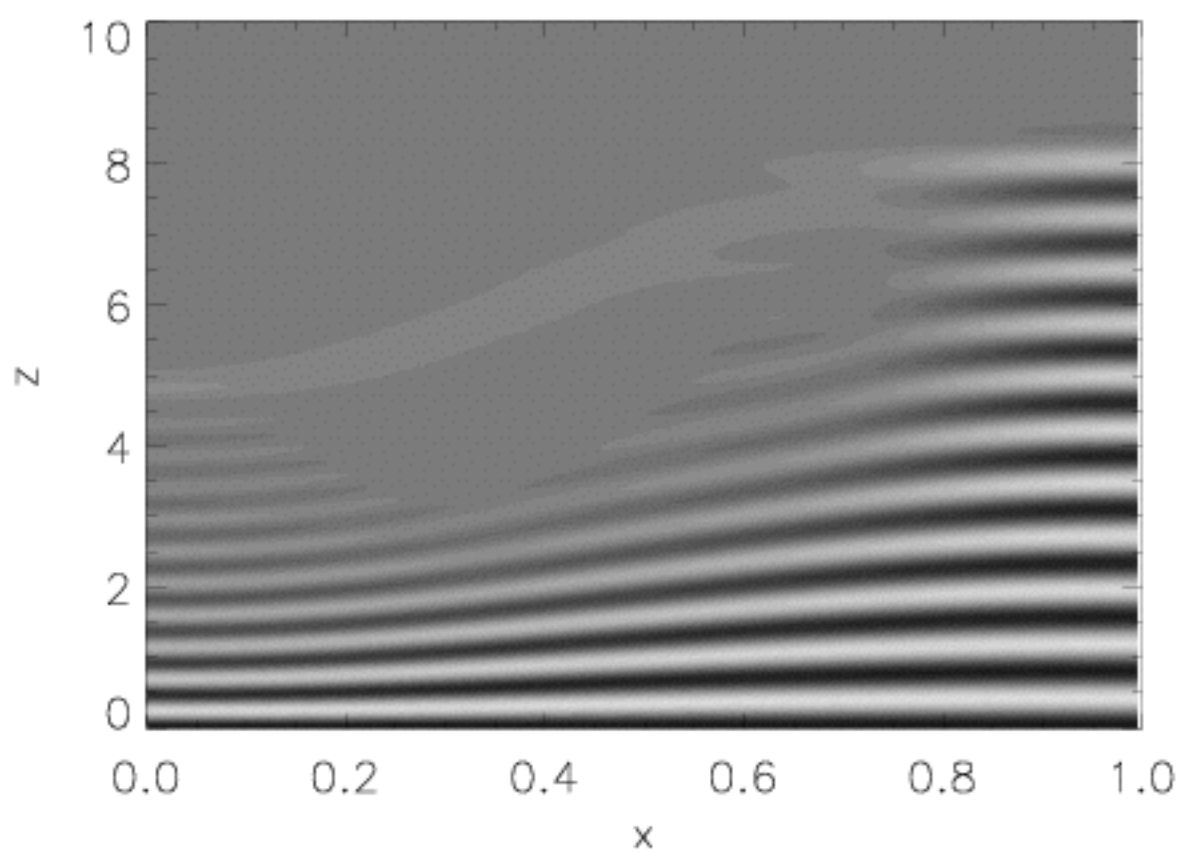
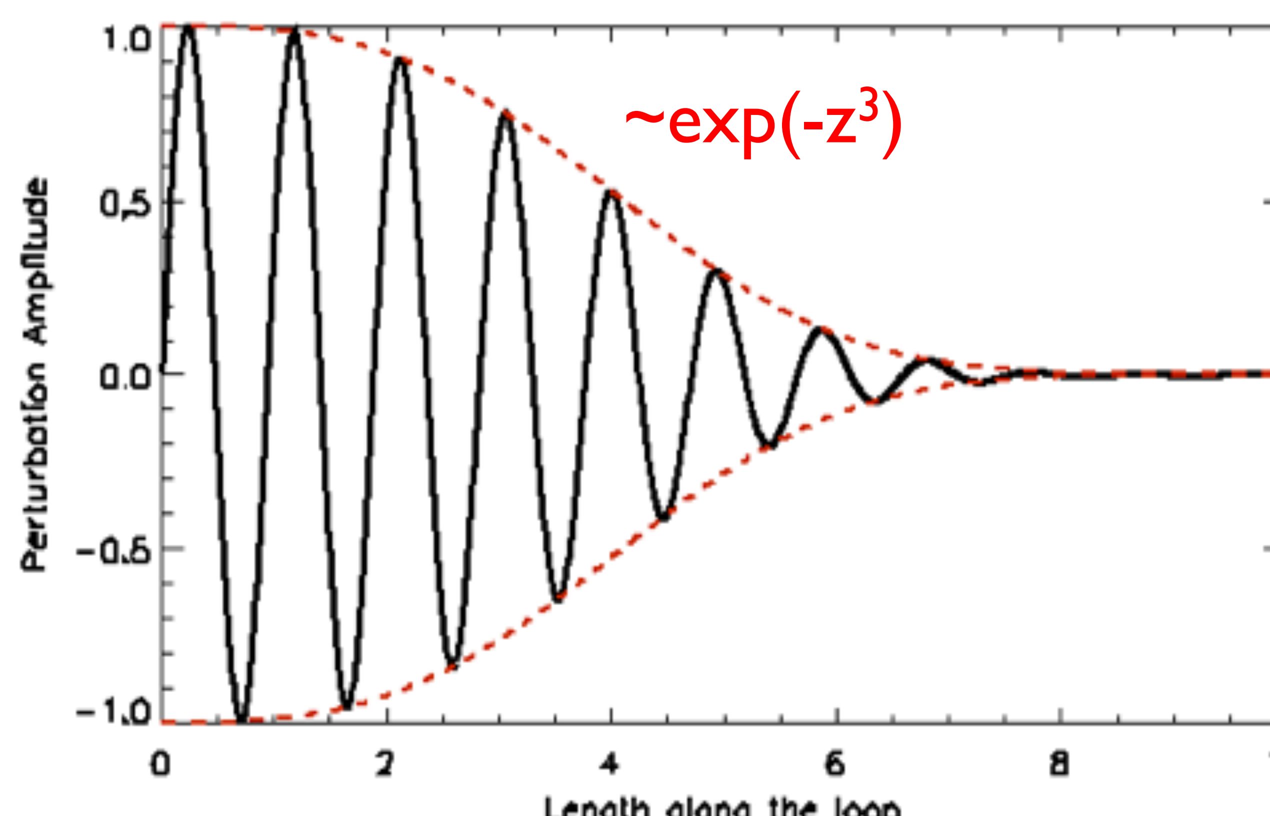
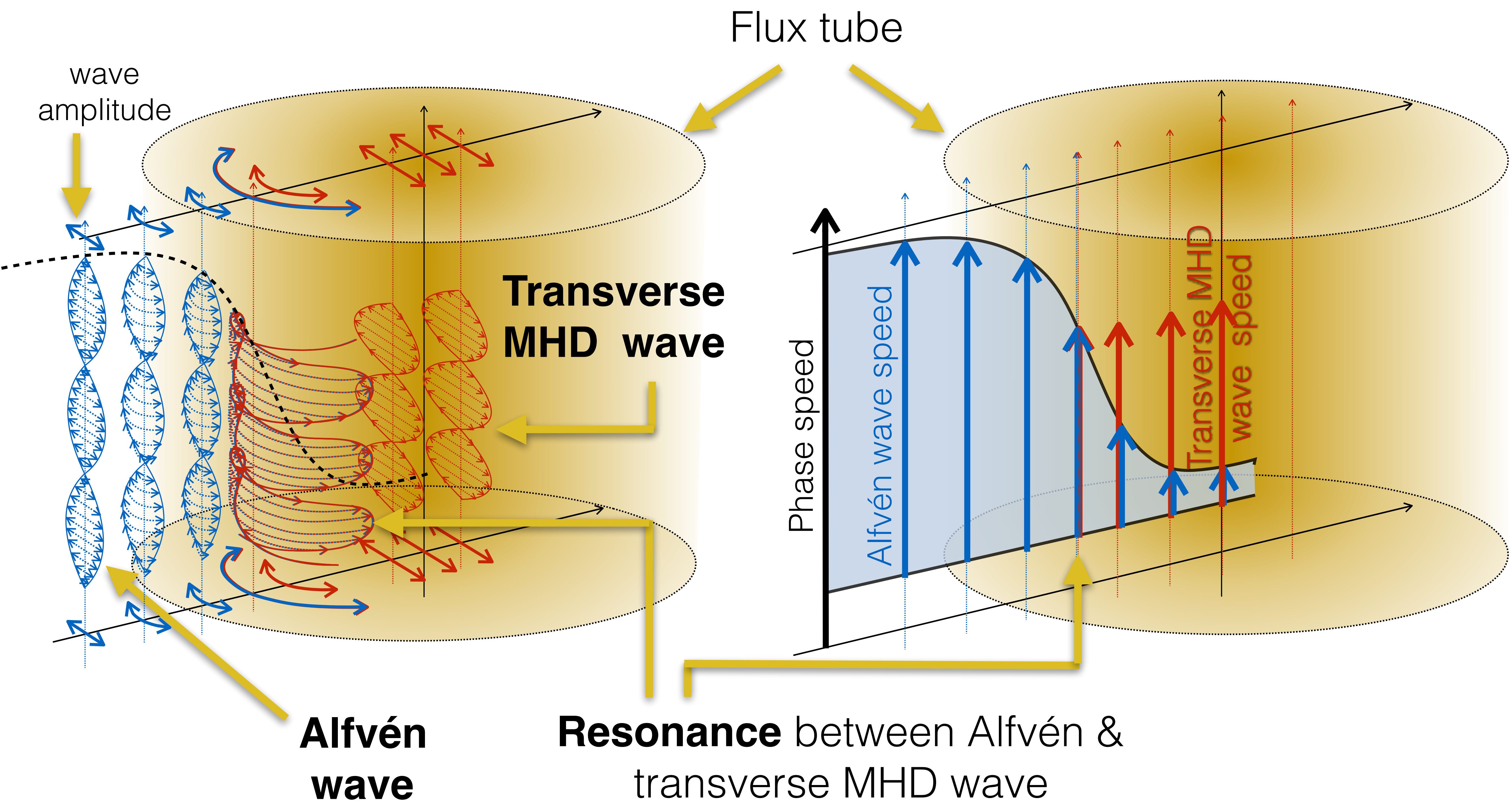


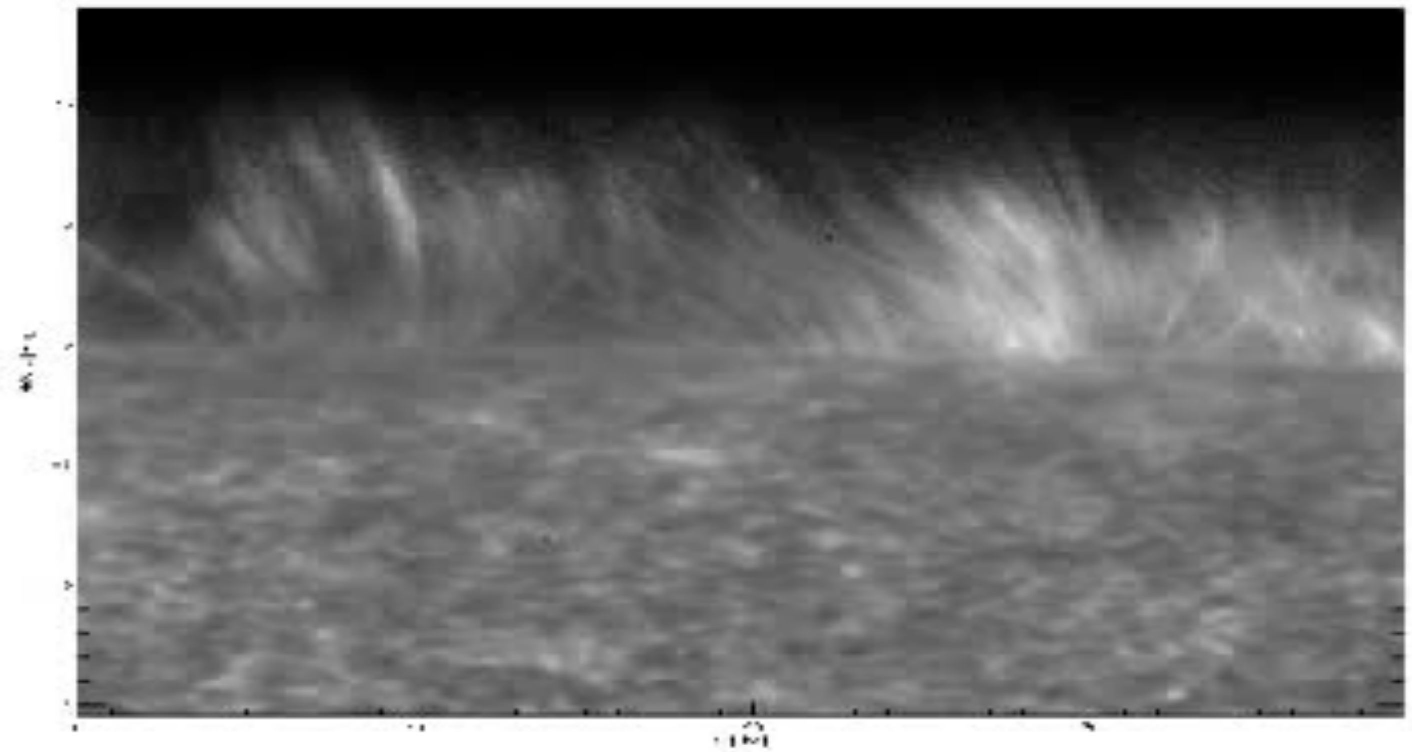


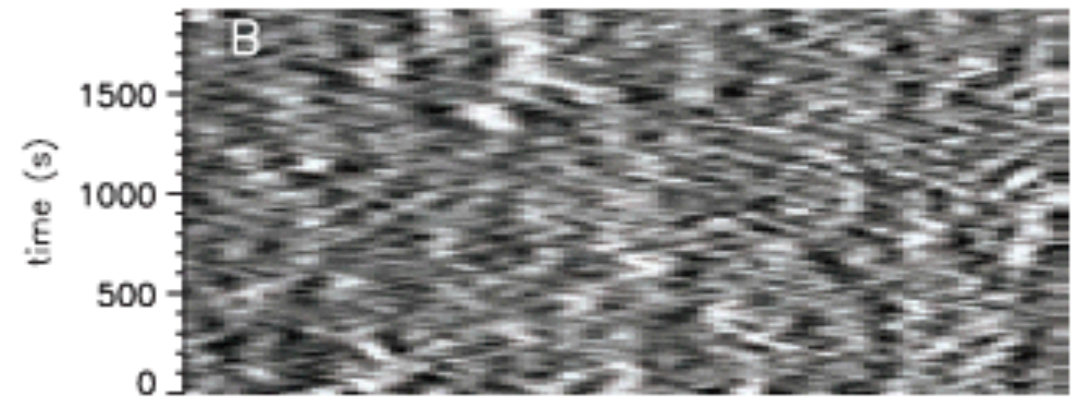
Resonant absorption & Phase Mixing

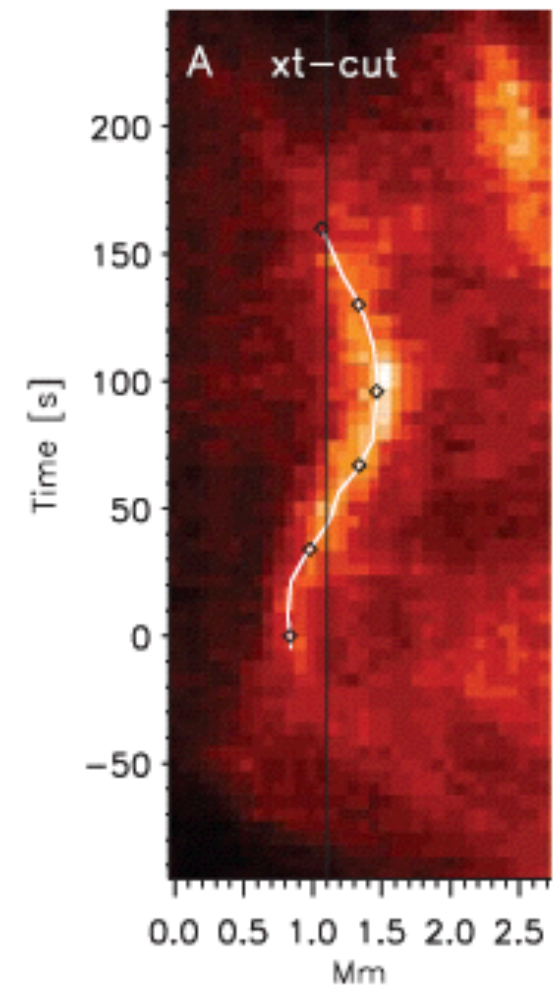


E.g. Ionson 1978, Hollweg+ 1990, Sakurai+ 1991, Goossens+ 1992, 2002, 2012; Van Doorsselaere+ 2004, Arregui+ 2008, 2011; Verth+ 2010, Soler+ 2010, 2012; Pascoe+ 2010, 2012

Alfvén(ic) Waves in the Chromosphere



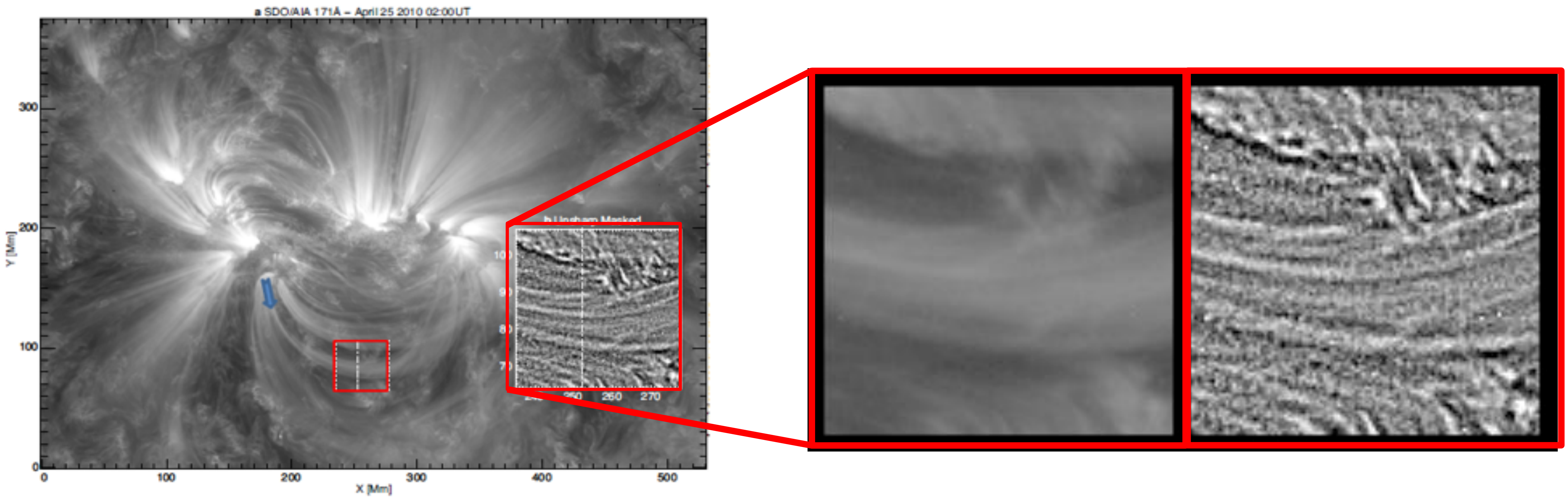




- "Swaying" spicules everywhere (Hinode/SOT)
  - Transverse motions ~ 500-1000km
  - Periods ~ few minutes
  - Chromospheric energy flux ~ 4-7 kW m^{-2}
  - Coronal energy flux ~ 120 W m^{-2} (transmission coefficient ~ 3%)
  - Sufficient to heat the Quiet Sun corona and/or drive the solar wind (~100 W m^{-2})
  - Additional torsional motions reported by De Pontieu et al (2012) → double energy budget?

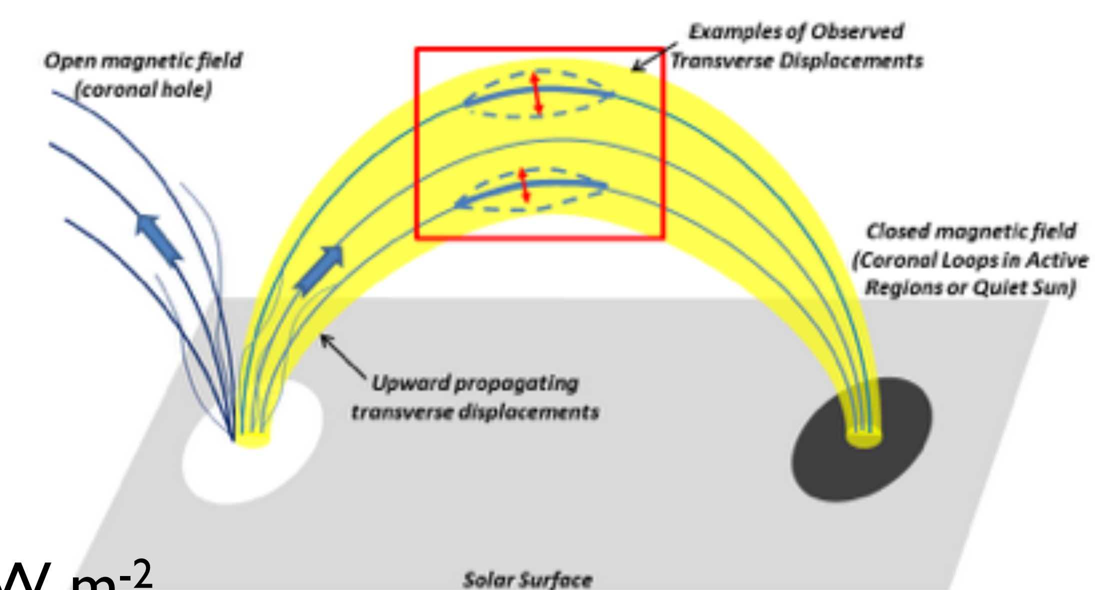
De Pontieu et al (2007, 2012)

Alfvén(ic) Waves in the Corona



➢ Alfvénic motions everywhere (SDO/AIA)

- Amplitudes ~ 5-20 km/s
- Periods ~ 100 – 500 sec (lifetimes ~ 50-500 sec)
- Energy flux Quiet Sun & Coronal Holes ~ 100 – 200 W m^{-2}
- Active Region Loops ~ 100 W m^{-2} (2000 W m^{-2} needed)

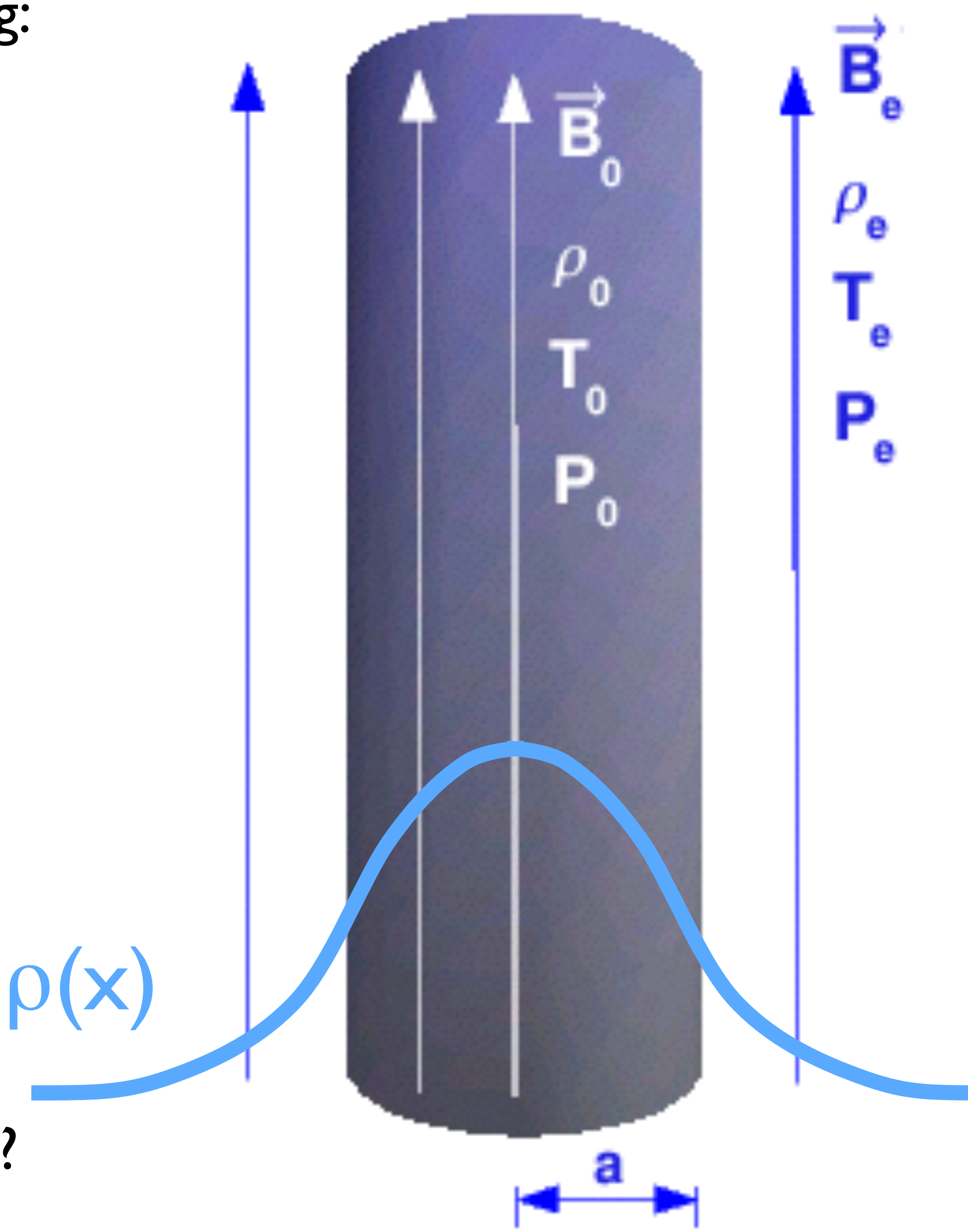


McIntosh et al 2011

Wave Energy vs Wave Heating

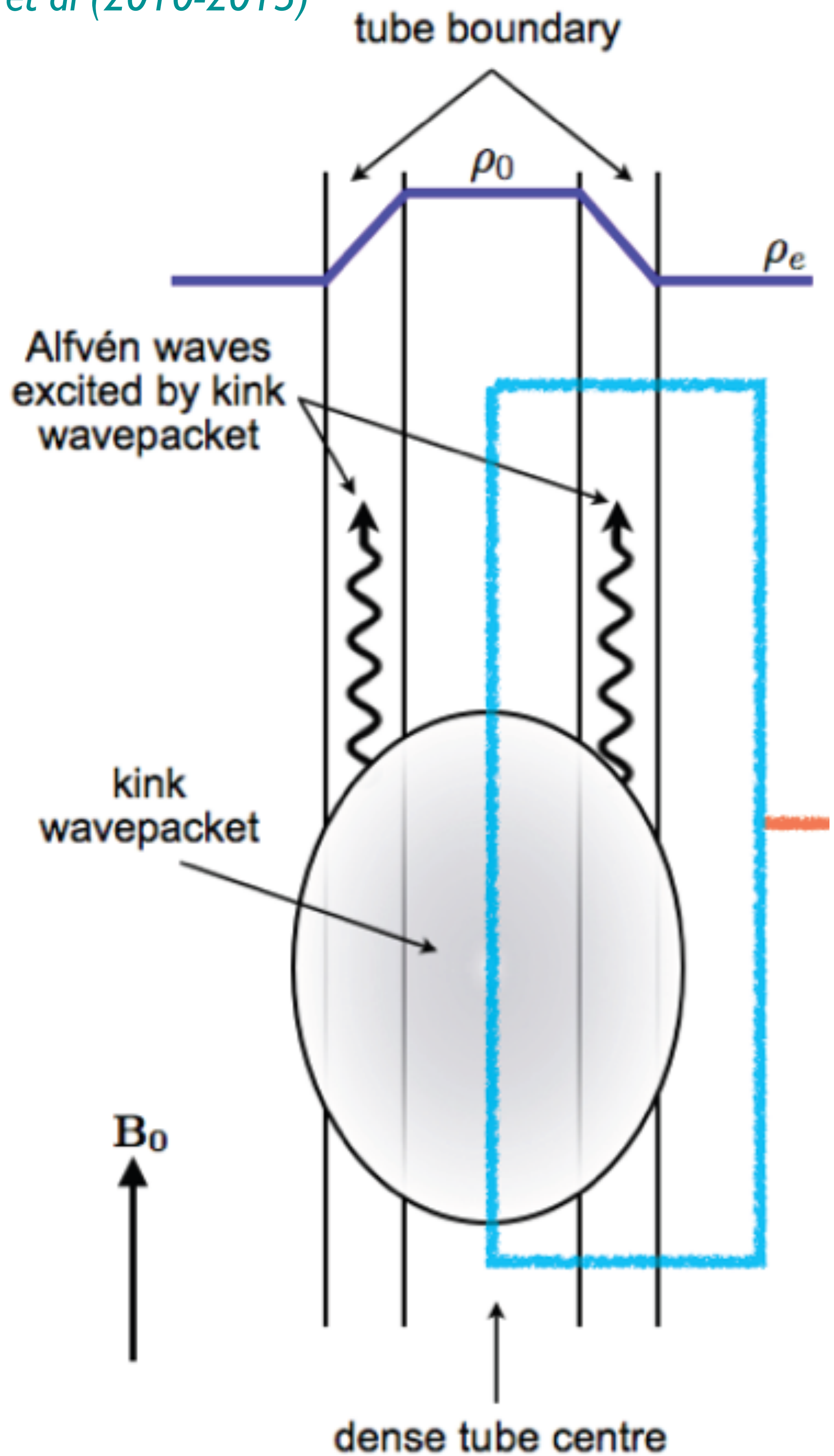
➢ **Recent observations suggest a substantial amount of wave power is "available".**

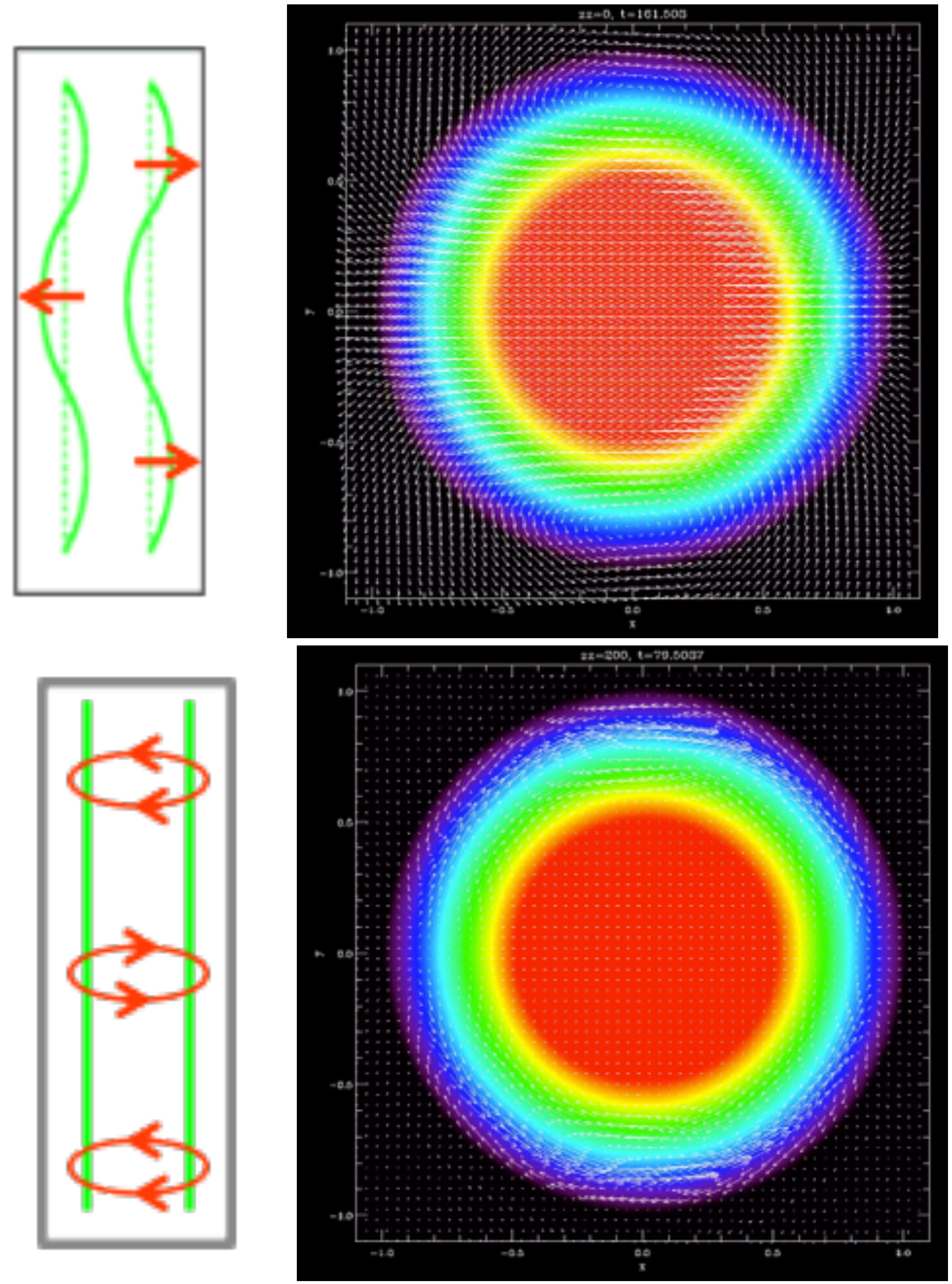
- It is not clear if/how/when these waves contribute to heating:
  - Sufficient flux ≠ (right) heating
    - (1) Damping ≠ Dissipation –e.g. mode coupling
    - *(e.g. Lee & Roberts 1986)*
    - (2) Timing? (dissipation time?)
- Phase mixing and resonant absorption:
  - Require a transverse density structure. Self-consistent?
    - (3) Is this sustainable by wave heating?
    - (4) Does the wave heating change the density profile?



(1) Damping vs Dissipation - Mode Coupling/Resonant Absorption

Pascoe et al (2010-2015)





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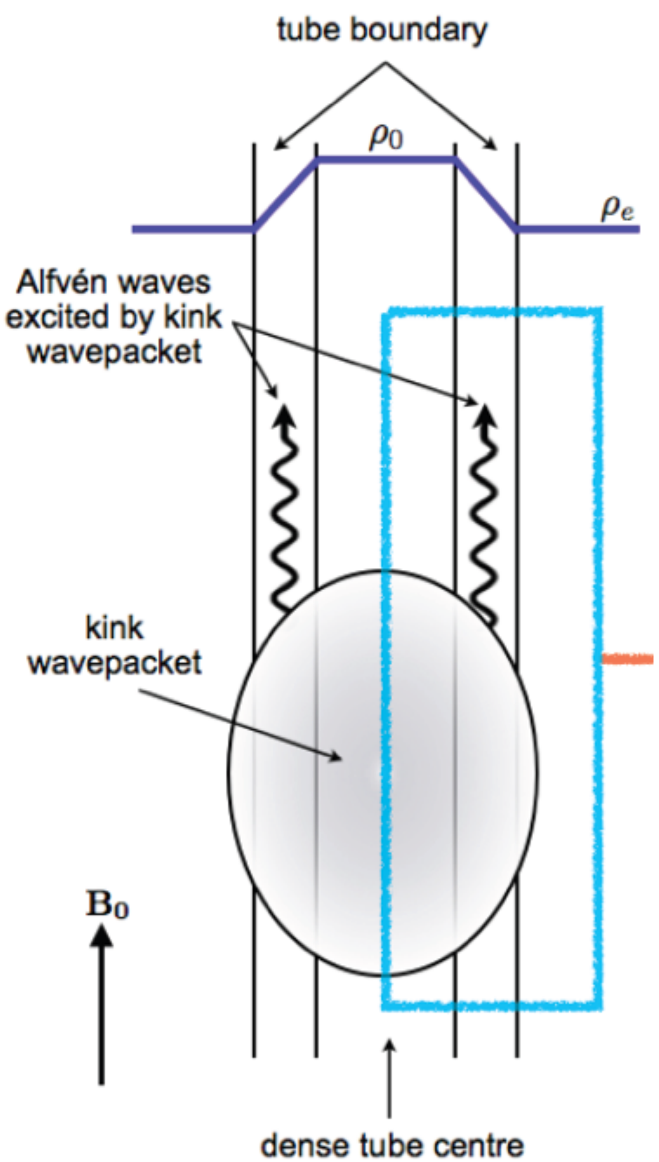
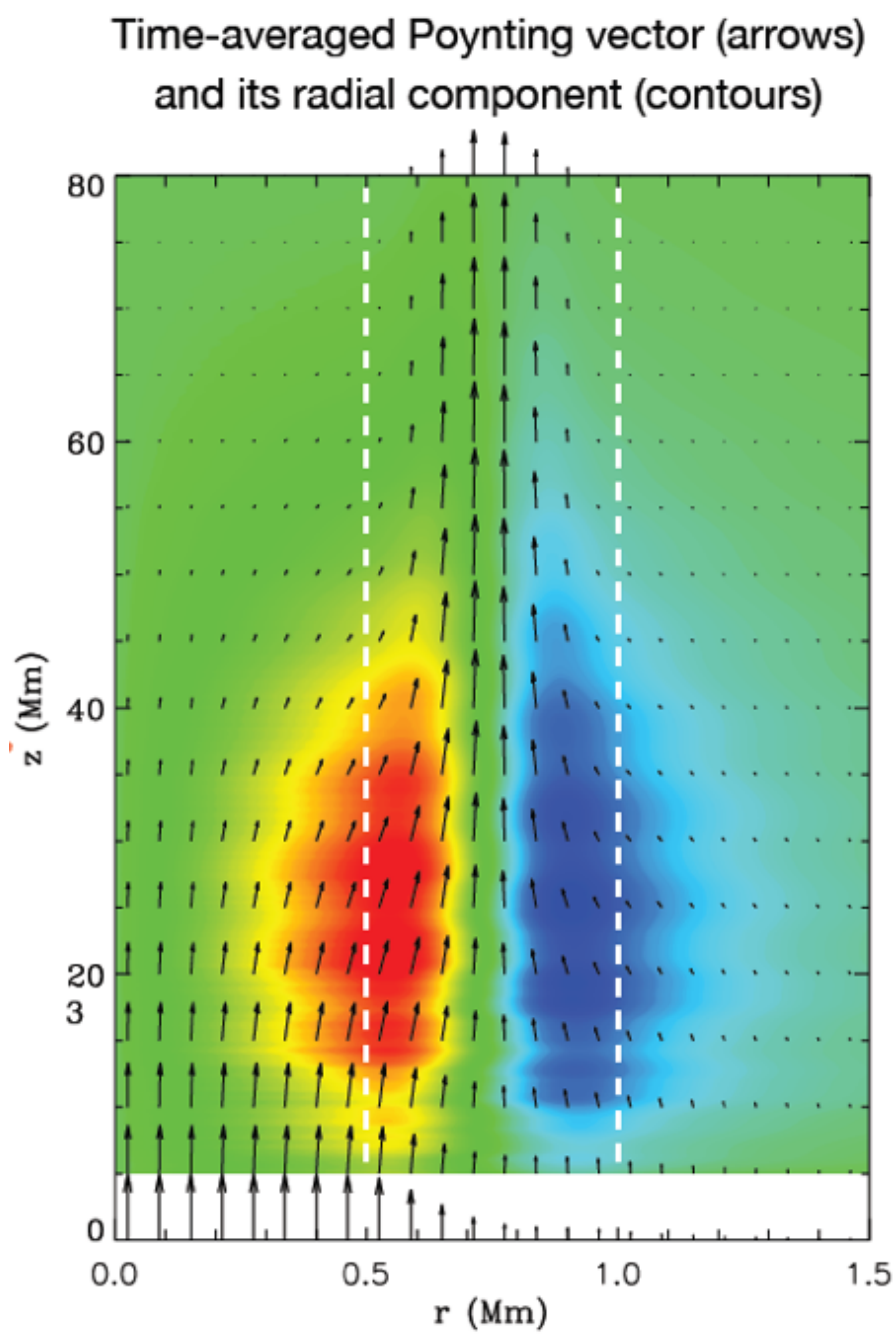




Kink mode propagating along coronal loop

↓

Mode conversion to Alfvén wave

↓

Damping of original kink mode (NOT dissipation!)

(2) Relevant time and spatial scales for wave heating

From Arregui (2015)

Resonant damping

$\zeta = \frac{\rho_i}{\rho_e}$

$$\tau_{\rm damping} \sim \frac{R}{l}\left(\frac{\zeta+1}{\zeta-1}\right)P$$

Phase-mixing > creation of small scales

$$L_{pm} = 2\pi/(t|\omega'_{\rm A}|)$$

Resistive dissipation important when

$$l_{ra} =\sim (R_{\rm m}|\omega'_{\rm A}|)^{-1/3}$$

This scale is reached in a time

$$t_{ra} = 1/(l_{\rm la}|\omega'_{\rm A}|) = R_{\rm m}^{1/3}|\omega'_{\rm A}|^{-2/3}$$

$R_{\rm m} = 10^{12}$	$R_{\rm m} = 10^4$
$l/R = 0.1$	$l/R = 0.1$
$\tau_{damping}/P = 13$	$\tau_{damping}/P = 13$
$t_{\rm diff}/P = 170$	$t_{\rm diff}/P = 0.36$
$l/R = 0.5$	$l/R = 0.5$
$\tau_{damping}/P = 3$	$\tau_{damping}/P = 3$
$t_{\rm diff}/P = 500$	$t_{\rm diff}/P = 1$
NO heating during oscillation	Heating during oscillation

Resonant absorption (mode coupling) followed by dissipation through phase mixing: no heating during lifetime of (observed) oscillation

See also Lee & Roberts (1986); Davila (1987)

(3) Can wave heating sustain the required density profiles?

Cargill et al (2016)

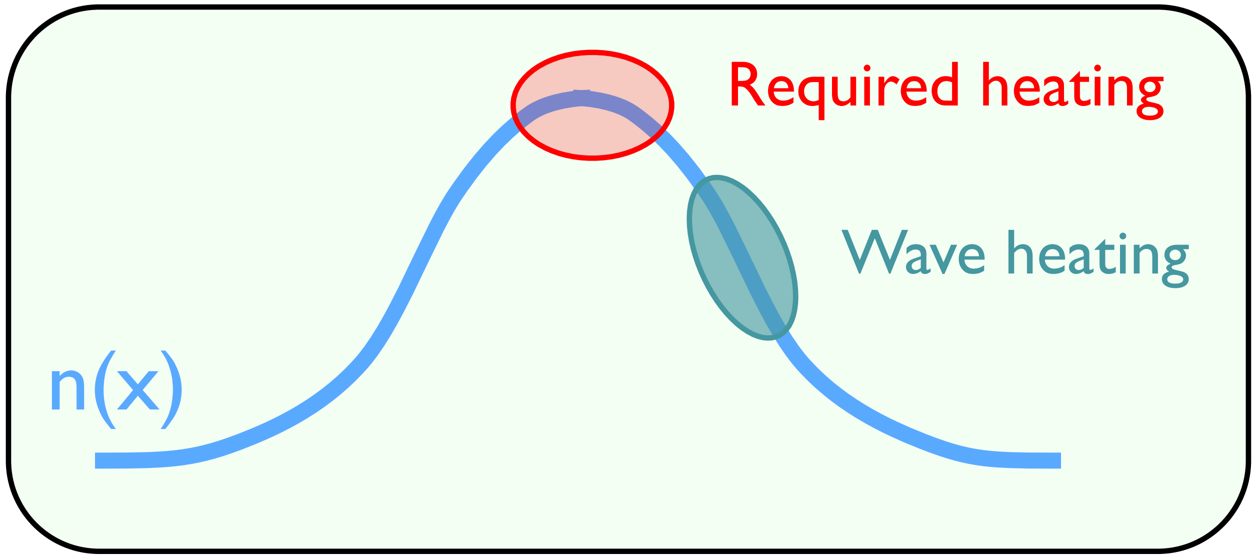
- Consider steady state with a radiative loss function $\Lambda(T)=\chi T^{\alpha}$:

$$\frac{d}{ds}\left(\kappa_0 T^{5/2}\frac{\partial T}{\partial s}\right) = n^2 \chi T^{\alpha} - H$$

- Scaling laws: $T^{7/2} \sim H L^2$, $nL \sim T^{(7-2\alpha)/4}$, $n \sim H^{(7-2\alpha)/14} L^{-2\alpha/7}$

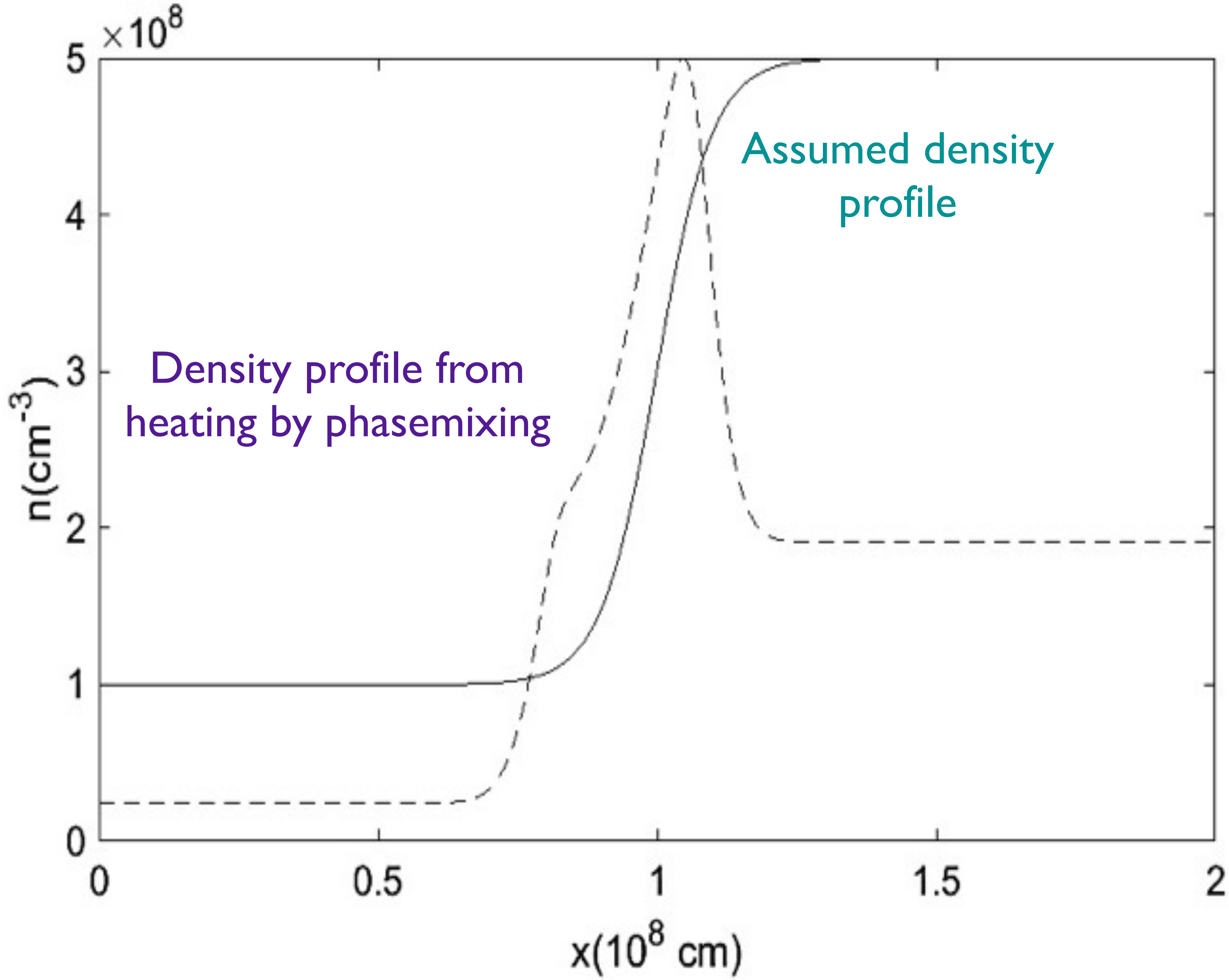
  ➢ High density region requires more heating.

➢ **For both phasemixing and resonant absorption, heating is situated near the maximum density *gradient*.**



Example Phase mixing Density Profiles

- Damping due to phase mixing & scaling laws → density profile due to heating by phasemixing

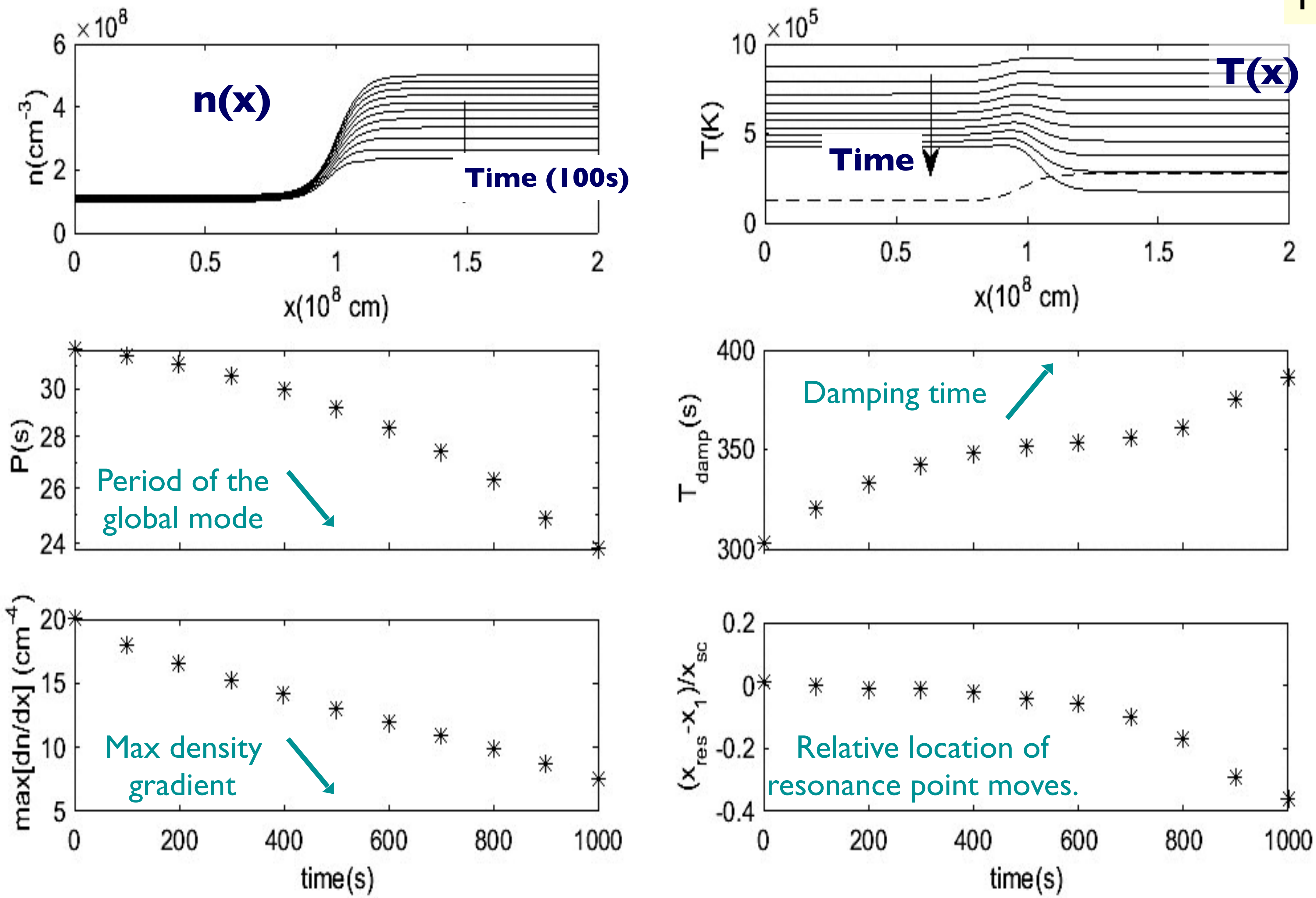


➢ The imposed density profile is incompatible with the density implied by the wave heating.

(4) Temporal Evolution of the Density Profile (no heating)

- **Temporal evolution of density profile on timescale needed for wave heating?**

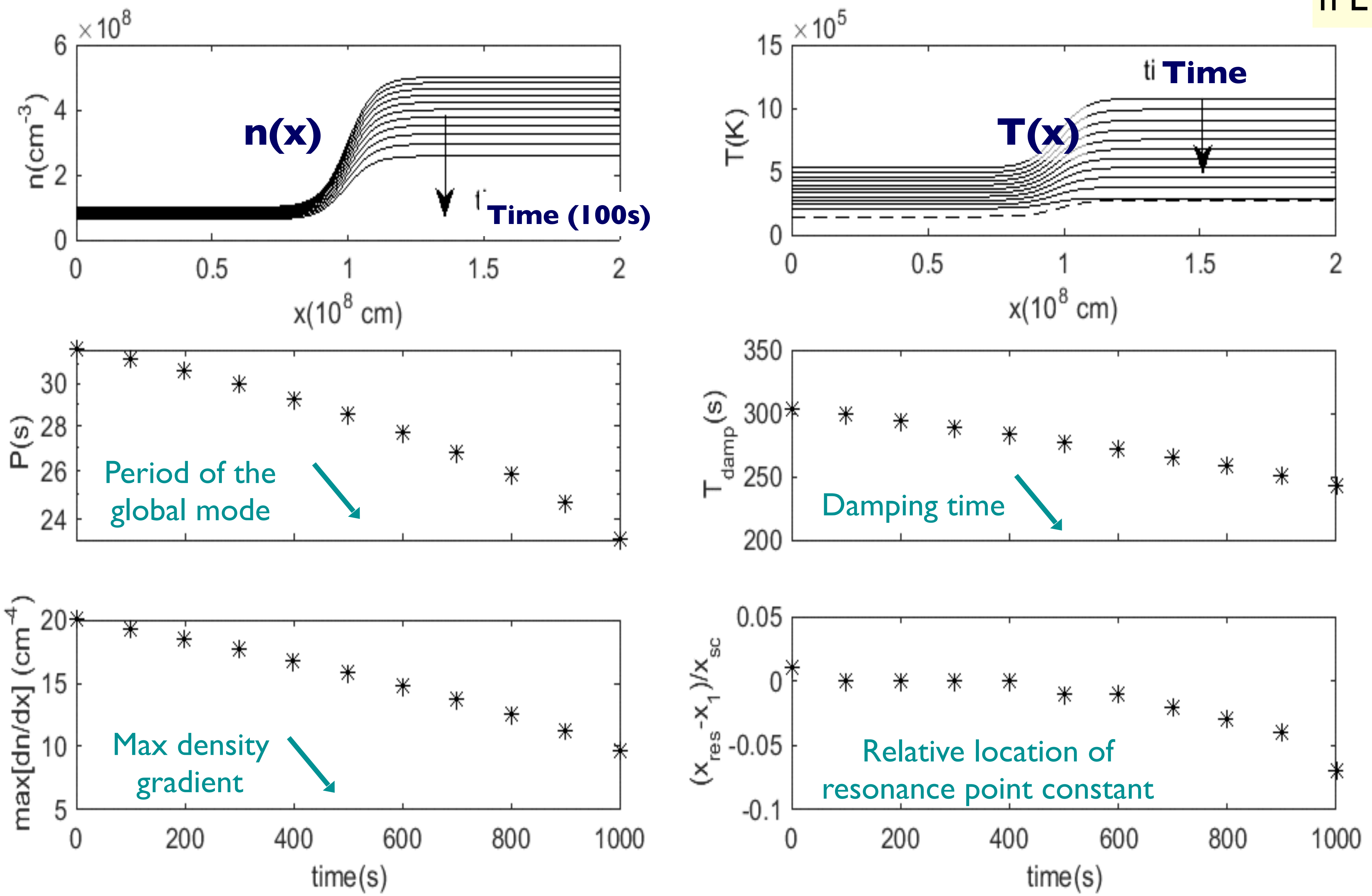
T~constant



- High density region cools rapidly → density gradient decreases and location of the resonance point changes.

(4) Temporal Evolution of the Density Profile (no heating)

$n\ L \sim T^{(7-2\alpha)/4}$



- Still some reduction in density gradient but location of the resonance point remains the same.

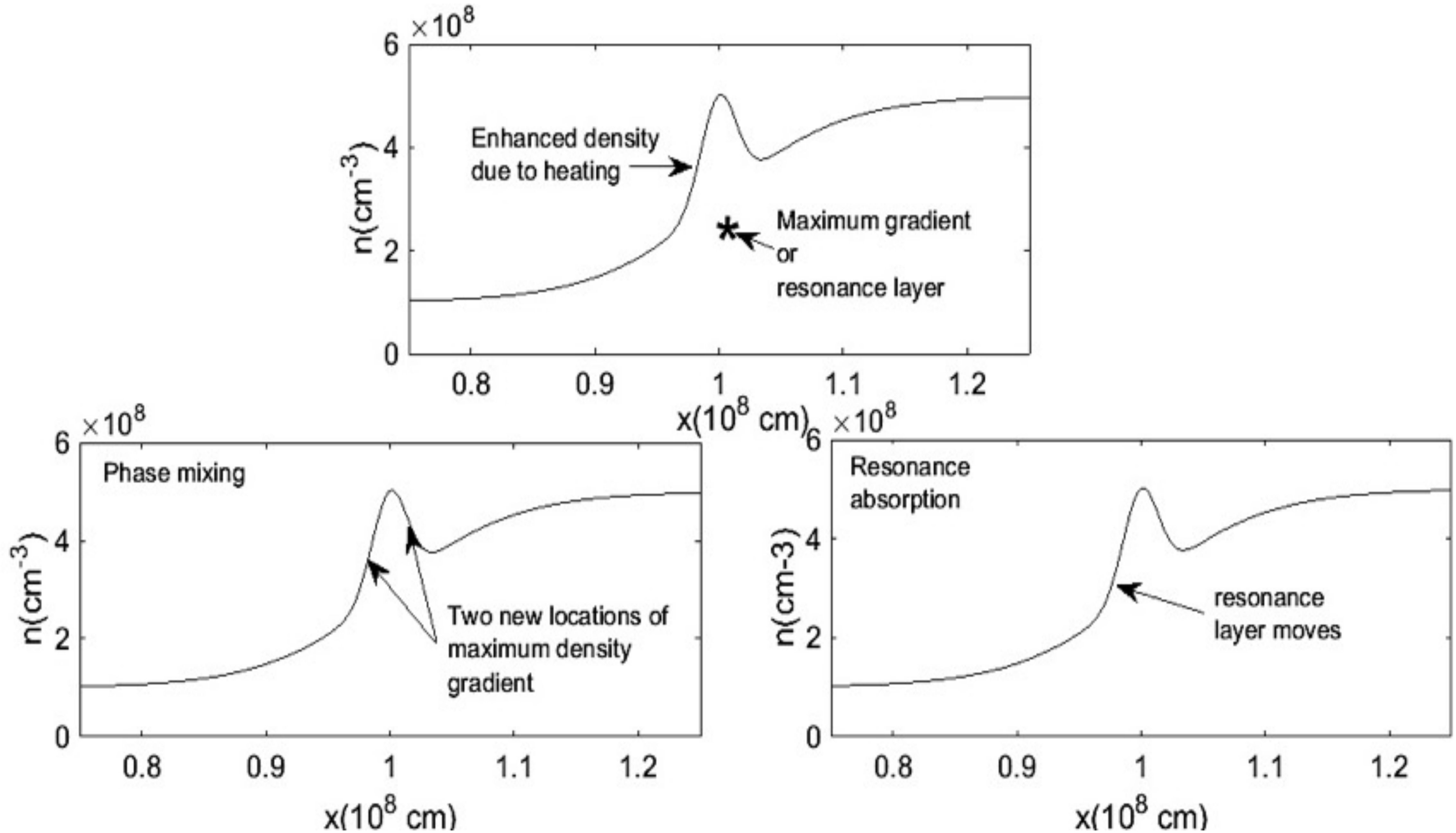
Temporal Evolution – no heating

- Phase mixing:
  - Density gradient decreases: *damping time ~ (density gradient)*$^{2/3}$
    - **Damping becomes weaker/slower**

- To maintain fixed (background) density profile needed for wave heating mechanisms:
  - Need dissipation time << draining time where $\tau_{drain} = n\left(\frac{dn}{dt}\right)^{-1} = \frac{2kT\gamma}{\left[(\gamma - 1)nR_L(T)\right]} \sim 1000\,\mathrm{sec}$
  - Phase mixing: need very large transport coefficients

(4) Temporal Evolution of the Density Profile

- Heating leads to chromospheric evaporation:
    - Modification of the density profile
    - Drifting of the heating layer?

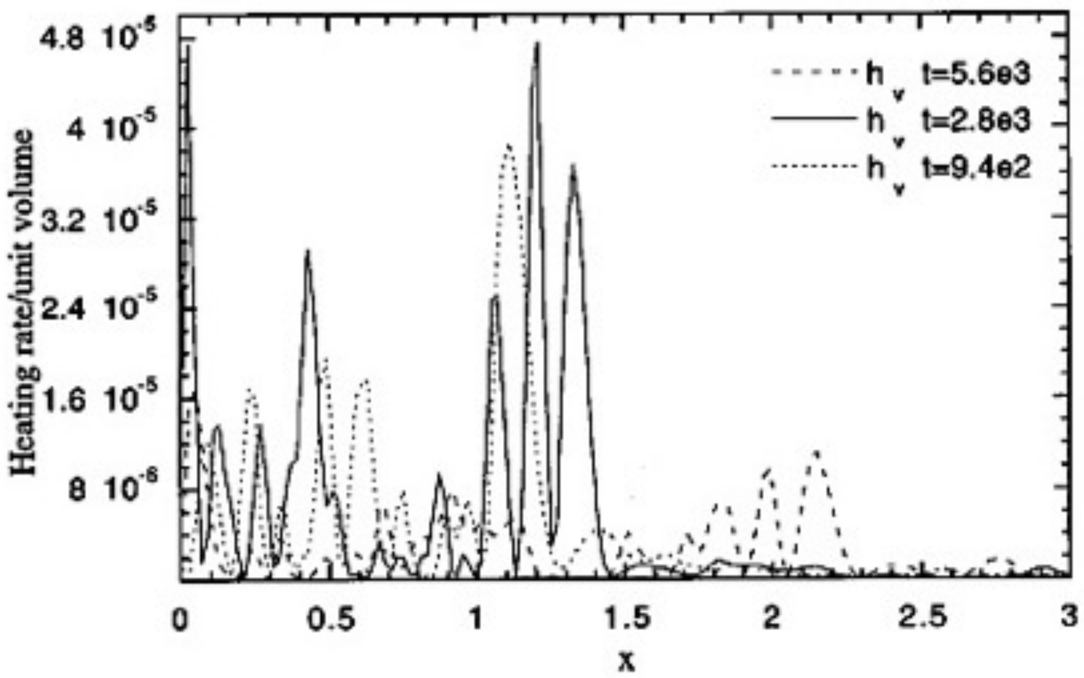


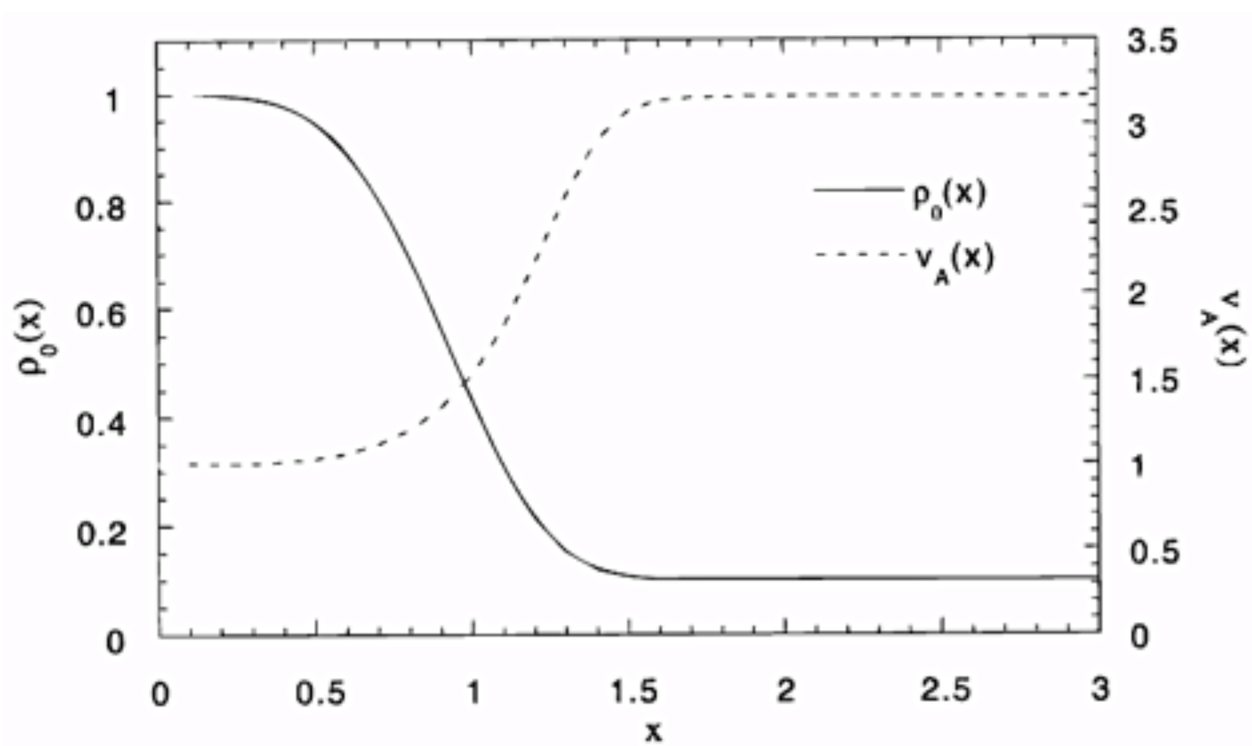
Density Feedback Resonant Absorption

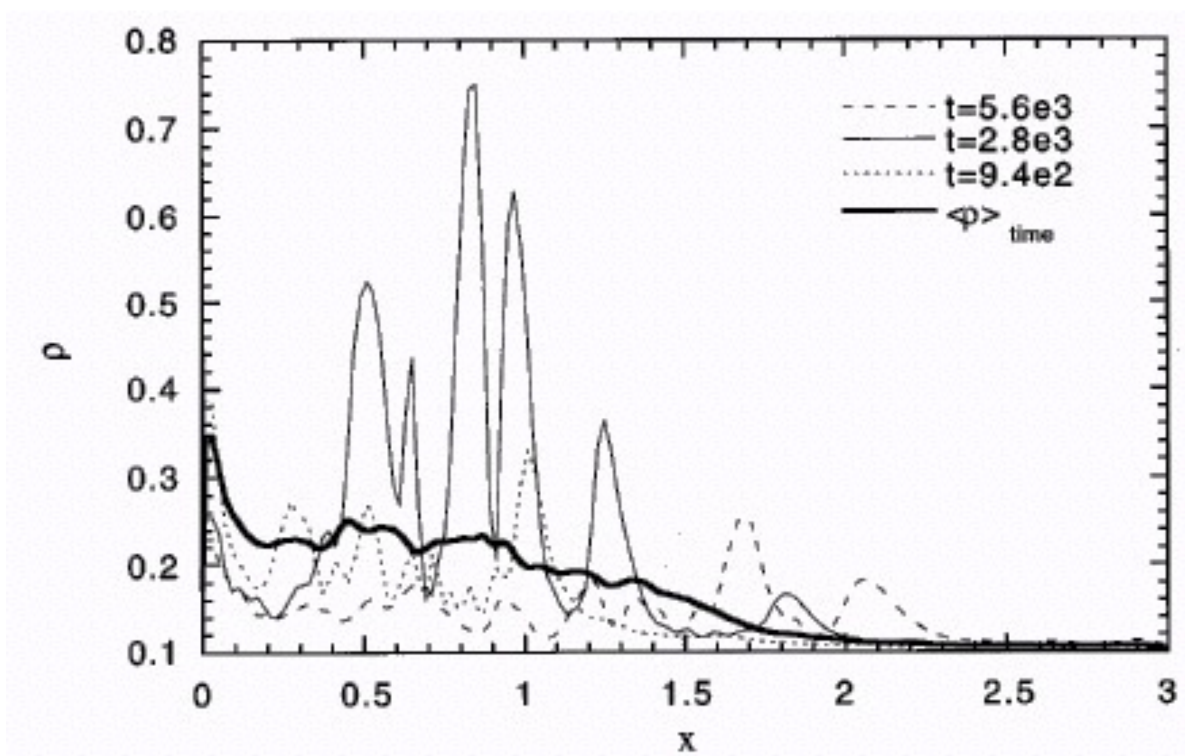
- *Ofman et al (1998):* simulations of resonant absorption
  - Scaling laws for quasi-static heating & volumetric heating rate

$$Q \approx \frac{3}{7}\kappa_0 \frac{T^{7/2}}{L^2} \approx \frac{3}{4}\rho_0^2 \Lambda(T)$$

➢ Smooth initial density → spiky structure



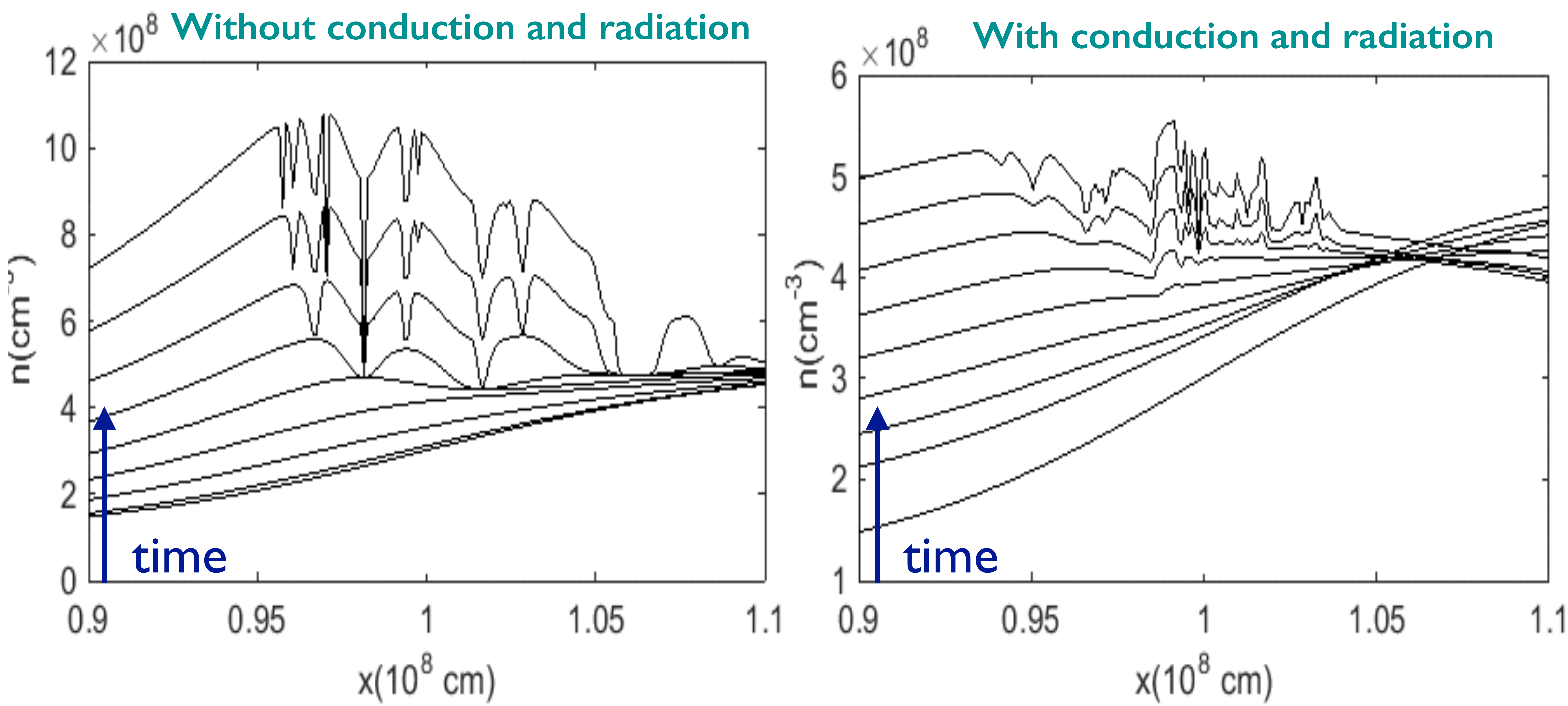




➢ Resonance 'detunes' – no heating – loop cooled and drained.

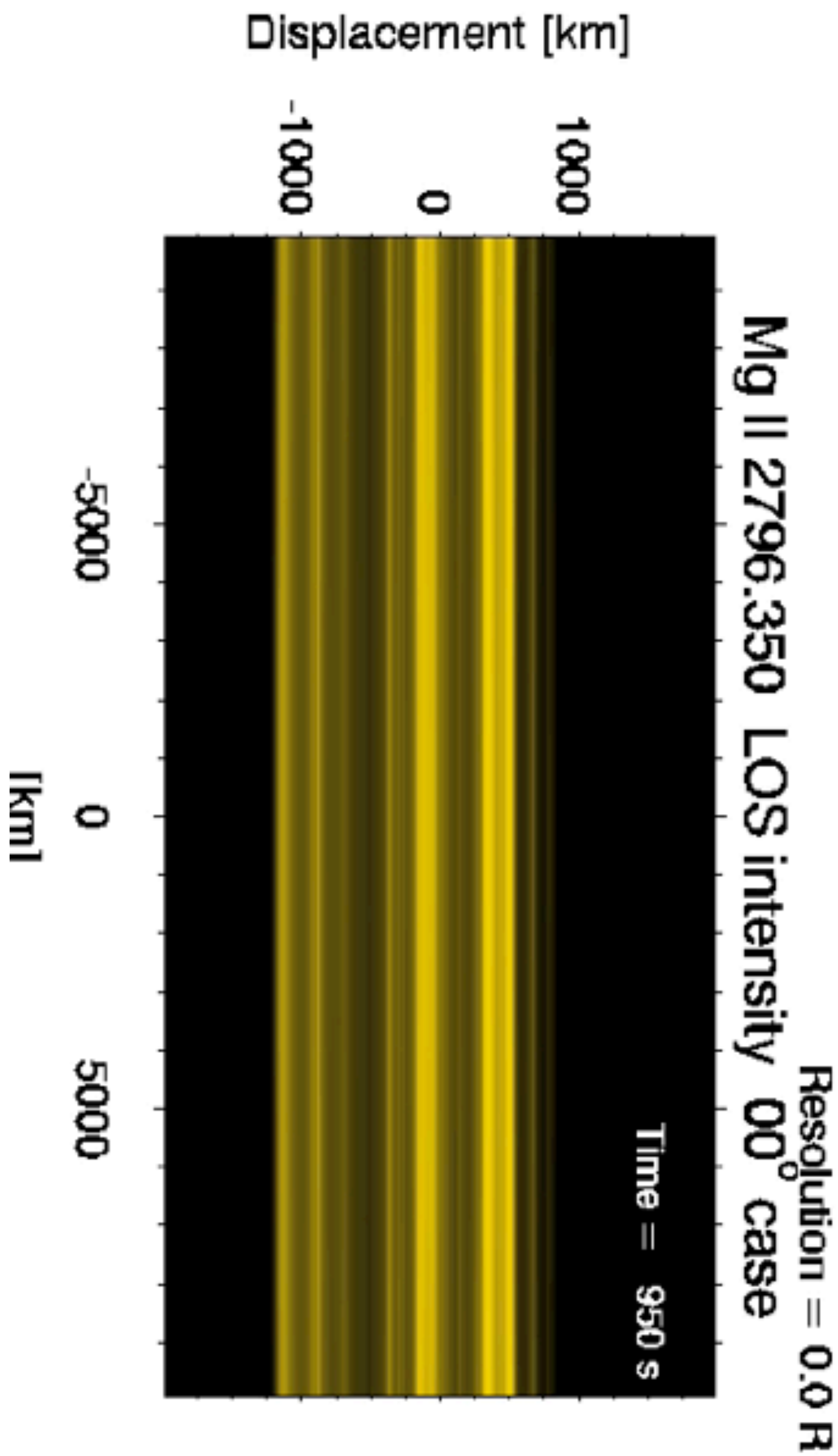
Density feedback

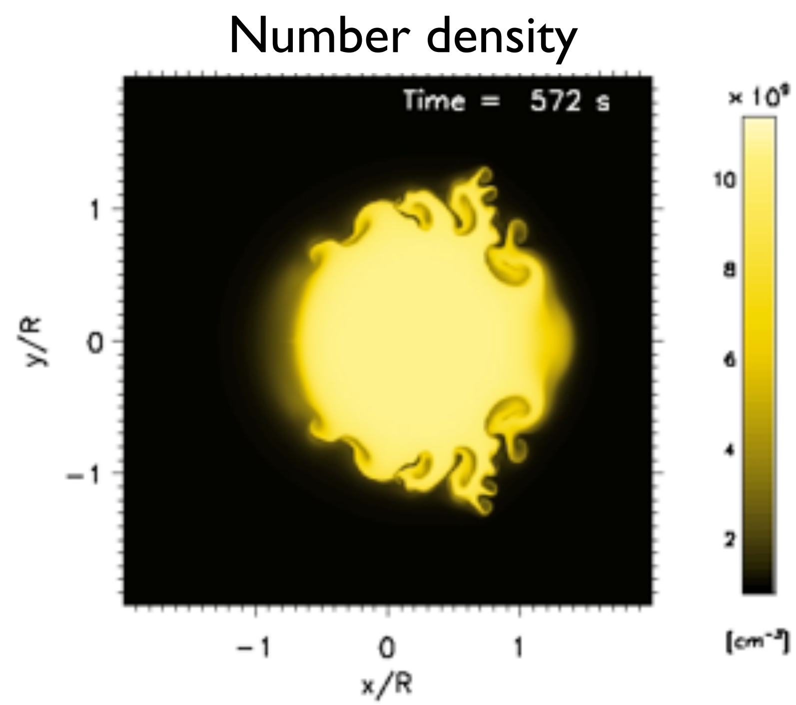
- Instantaneous adjusting of density too fast – detuning takes some time
  - Overestimates breakdown of resonant absorption
- Use EBTEL (solid line) or scaling laws averaged over 200 sec intervals (dashed line)

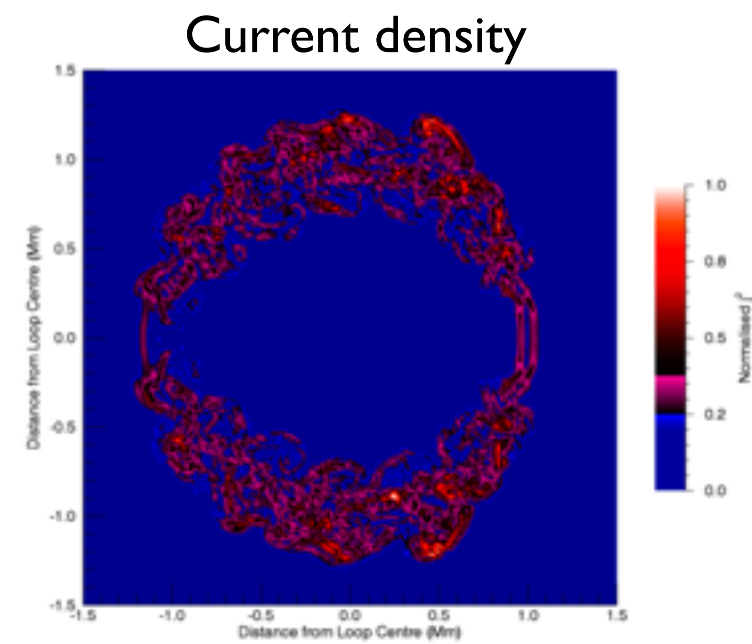


With full energetics included: density feedback dominated by loop thermal evolution.

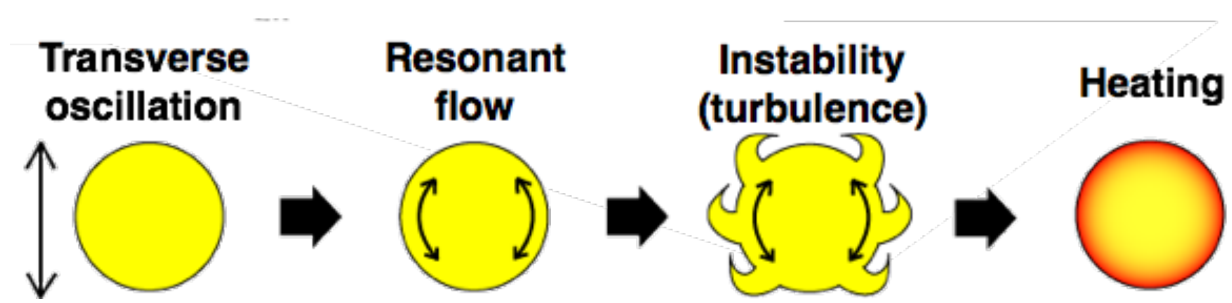
Resonant Absorption + KH Instability: turbulent dissipation?







- Resonant absorption transfers energy from the transverse wave to azimuthal waves in the boundary shell
- KHI could lead to increase dissipation into heat through turbulent dissipation

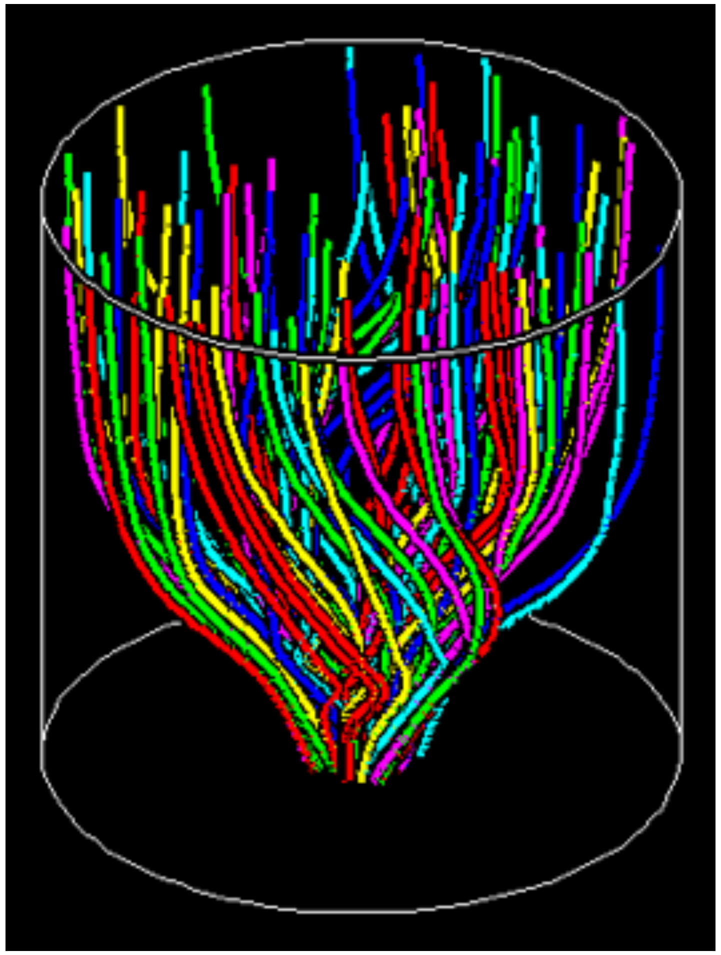


Talks by Antolin, Howson, Karampelas, Pagano, Van Doorsselaere

(Alfvénic) Turbulence

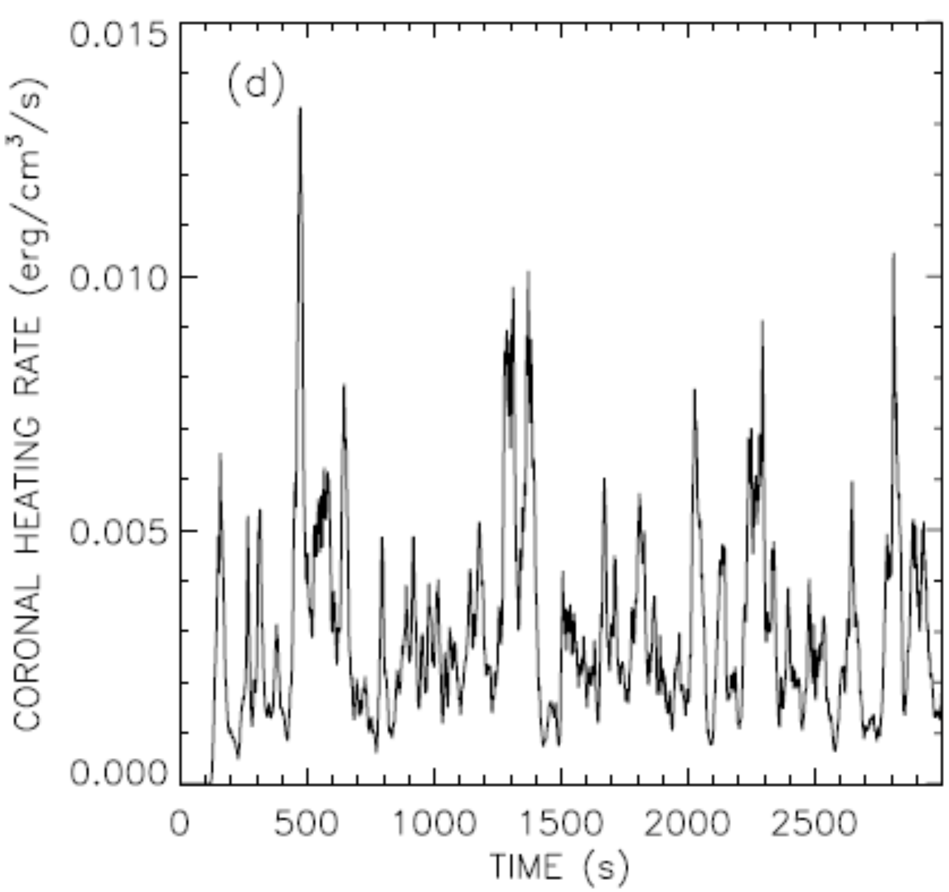
Van Ballegooijen et al 2011

- Small scale footpoint motions (< 100 km) - incompressible
- Assume AR flux tube maintains identity
- Strong reflection of chromosphere and TR - Complex pattern of counter-propagating waves —> Alfvénic turbulence
- Reduced MHD (—> coupling to slow modes —> shocks?)



z = 0 - 2 Mm

z = 2 - 50 Mm



Conclusions/Future Directions

Cargill, De Moortel, Kiddie (2016) + Arregui (2015)

- Observations: waves are present beyond doubt in a wide range of structures in all layers of the solar atmosphere.

➢ **Can heating be "delivered" by these waves in the right locations and on the right timescales?**

- Damping ≠ Dissipation –e.g. mode coupling & resonant absorption
- Dissipation time >> damping time – no heating during oscillations
- Assumed density profile (gradients) destroyed by plasma cooling on timescales faster than wave heating.
- "Structuring" of density profile through feedback only on timescales comparable to draining/cooling time.

- Resonant absorption/mode coupling combined with phase mixing and KH instability in the boundary layer?
- Internal reflections of Alfvenic waves leading to cascade to smaller scales?

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