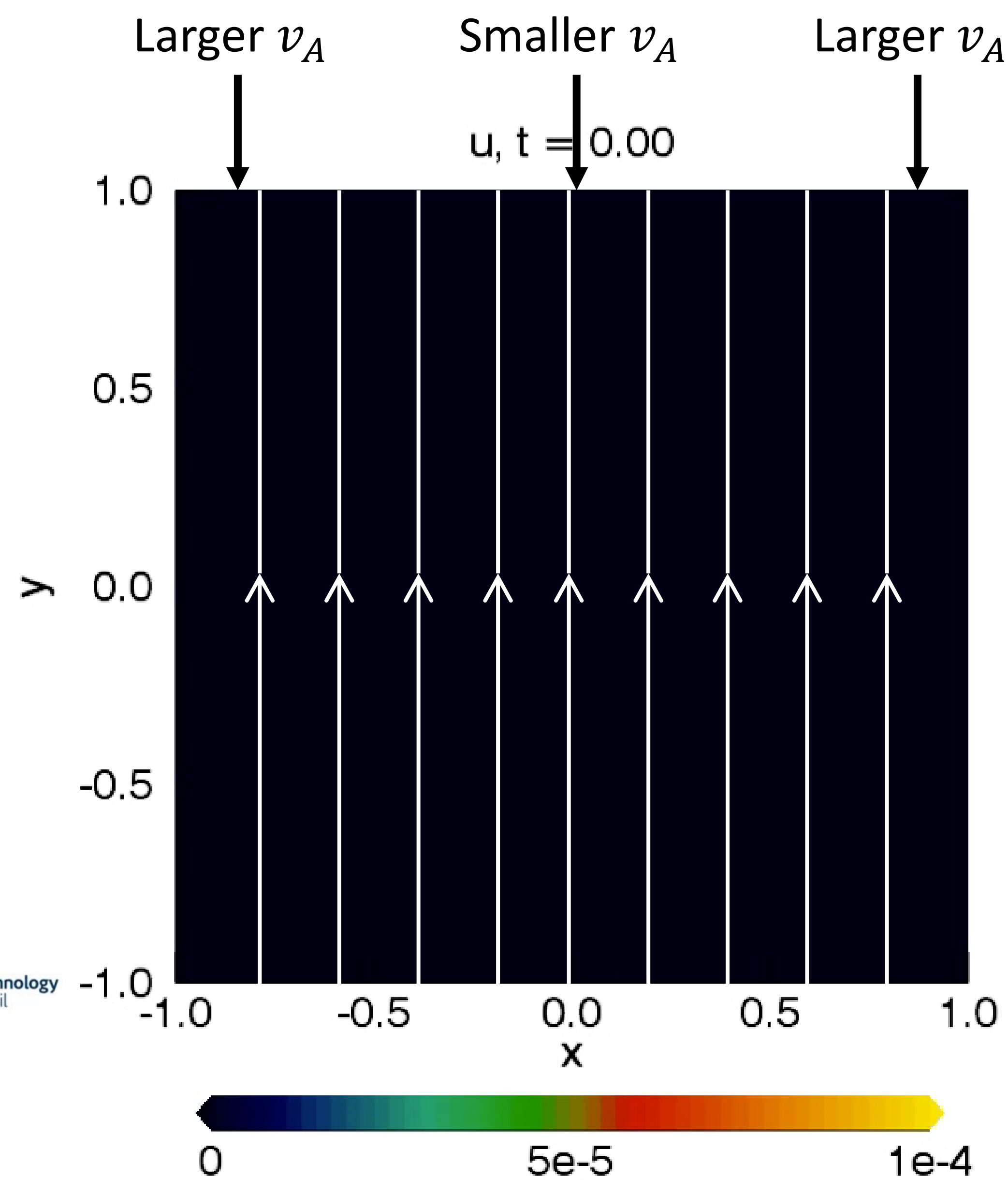
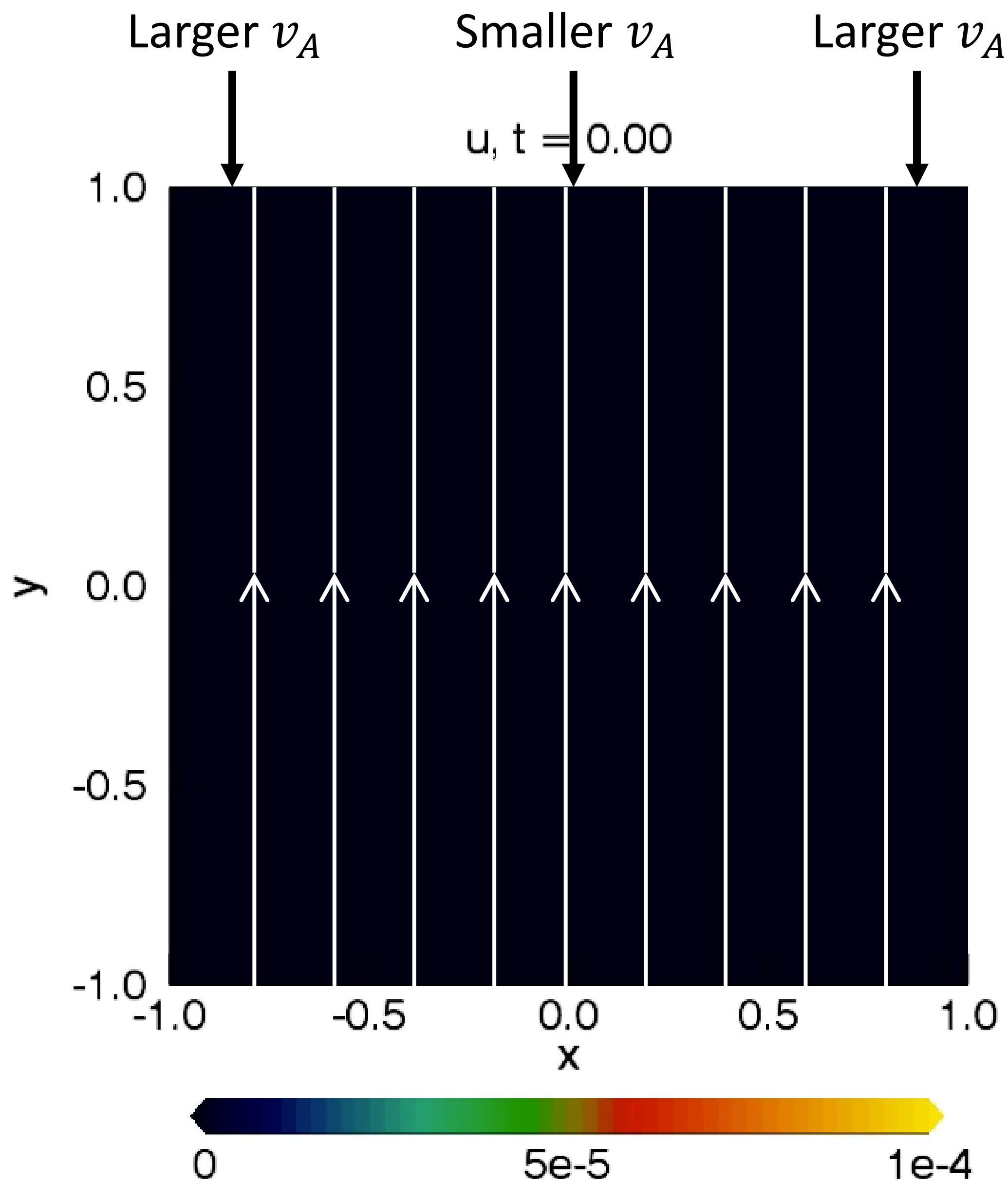
What is phase mixing?



A. P. K. Prokopyszyn, A. W. Hood,
I. De Moortel

What is phase mixing?

- Phase mixing is the process by which a build-up in $\nabla_\perp$ occurs due to $\nabla_\perp v_A$.
- Introduced by Heyvaerts and Priest (1983).
- $\boldsymbol{v}$ & $\boldsymbol{b}$ shear $\Longrightarrow$ KHI & tearing instability $\Longrightarrow$ turbulence (possibly).
- We consider just laminar phase mixing.

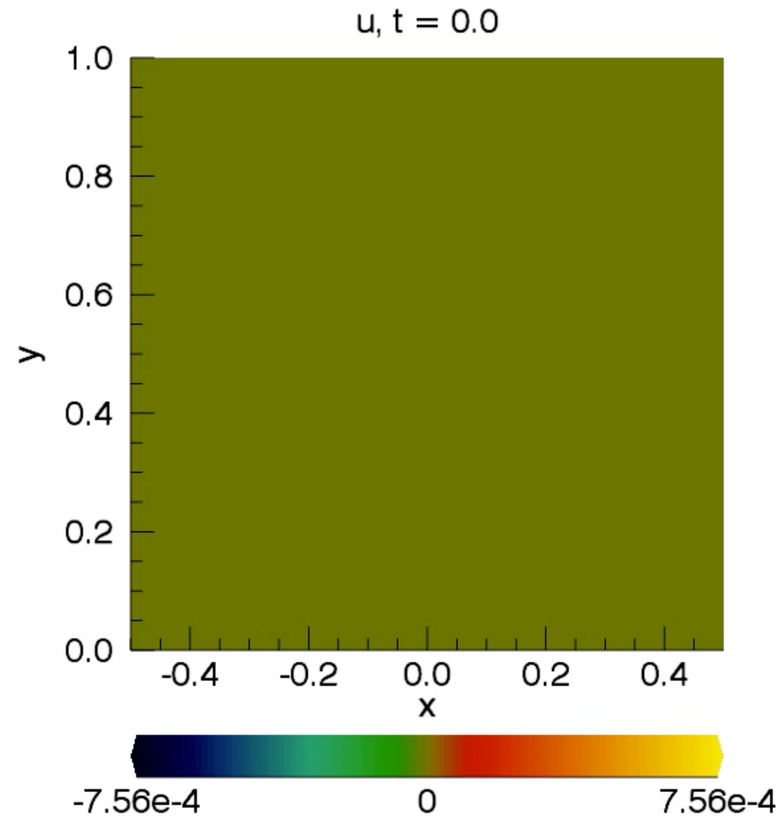


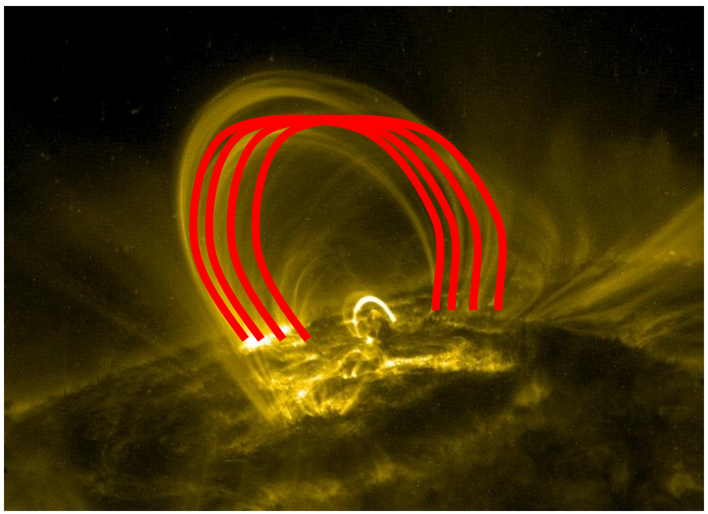
Aims

- Provide an argument that the damping rate (γ) of laminar, phase mixed Alfvén waves is too small to heat coronal loops.
- Leakage though the TR reduces γ by ≈ 2 orders of magnitude.

Model

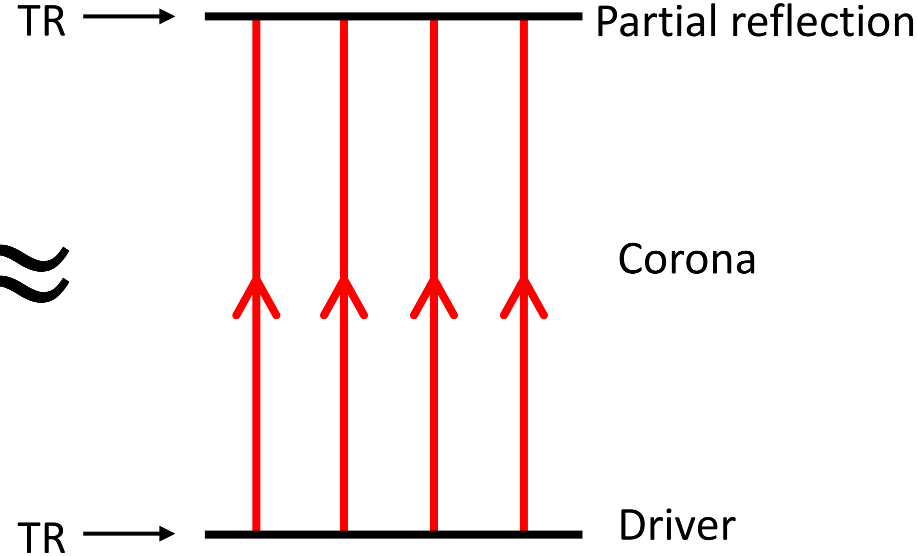
- Model loops as straight.
- Footpoint, sinusoidal driver.
- Linear Alfvén waves.
- Model in 2.5D.
- Partial reflection.





Source: TRACE, 171 Å,
Characterstic temperature $\approx 6 \times 10^5 \mathrm{K}$

$\approx$



Analytic solution

- Heyvaerts and Priest (1983) gives the soln in an open field.

$$u = u_0 \exp\left[-\left(\frac{s}{l_{ph}}\right)^3\right] \exp\left[i\omega\left(t - \frac{s}{v_A}\right)\right]$$

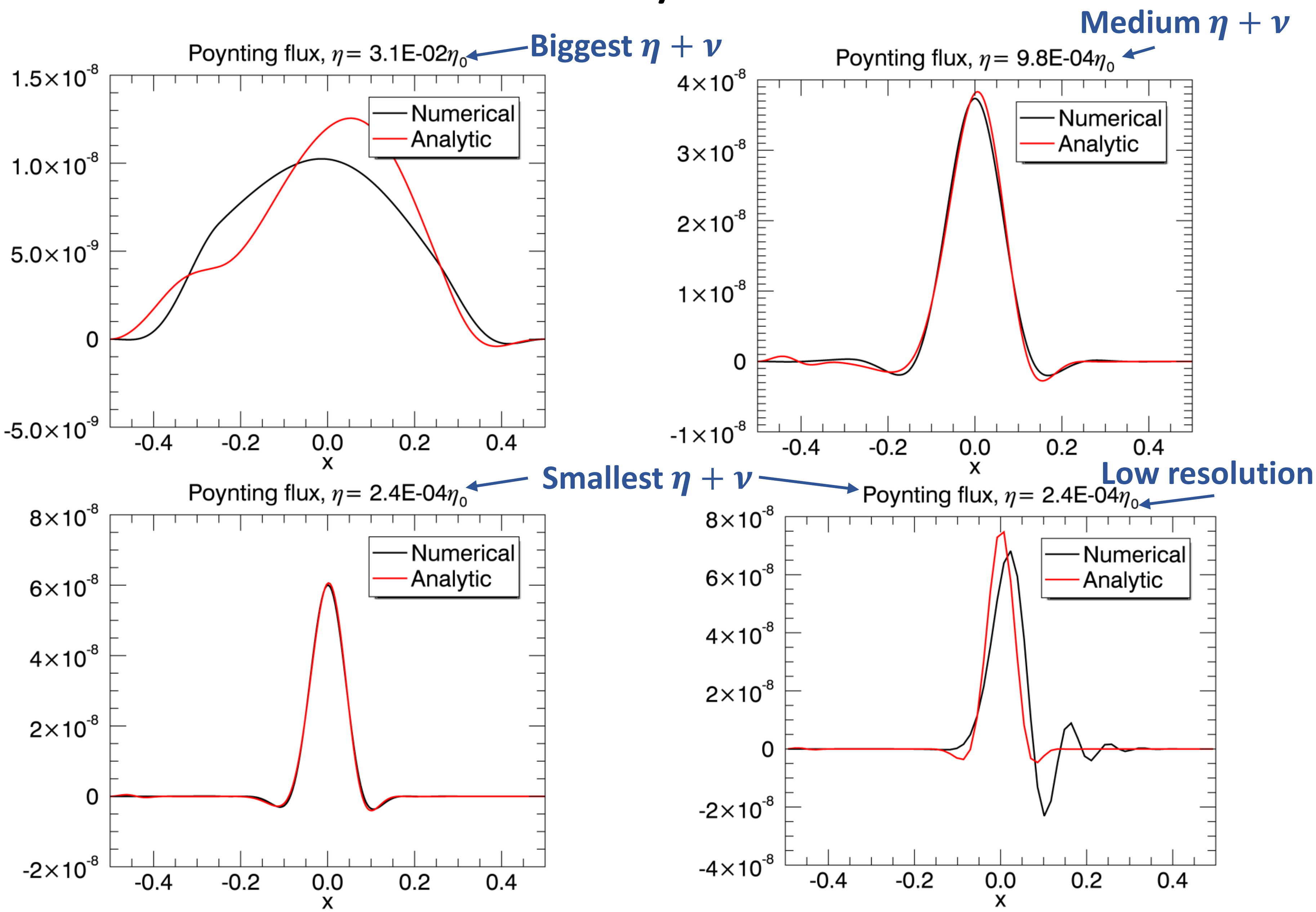
$$l_{ph} = \left(\frac{(\nu + \eta)\omega^2}{6v_A^5}(\nabla_\perp v_A)^2\right)^{-1/3}$$

- Steady-state soln with partial reflection.

$$u = u_0 \exp[i\omega t] \sum_{k=0}^{\infty} (-1)^k R^k \exp\left[-\left(\frac{s_k}{l_{ph}}\right)^3\right] \exp\left[-i\omega \frac{s_k}{v_A}\right]$$

$$s_k = (-1)^k s + (2k + 1)l$$

Numerical vs Analytic



Damping rate (γ)

- We define as

$$\gamma = \frac{\text{Steady state heating rate}}{\text{Kinetic wave energy}},$$

$$= \frac{\oint\!\!\oint_{\partial V} \boldsymbol{E} \times \boldsymbol{B} \cdot \boldsymbol{dS}}{\iiint_V \frac{1}{2}\rho\, v^2 dV}.$$

- We require

$$\gamma = \frac{H_c}{\frac{1}{2}\rho v^2},$$
$$\approx 10^{-1}\mathrm{s}^{-1}.$$

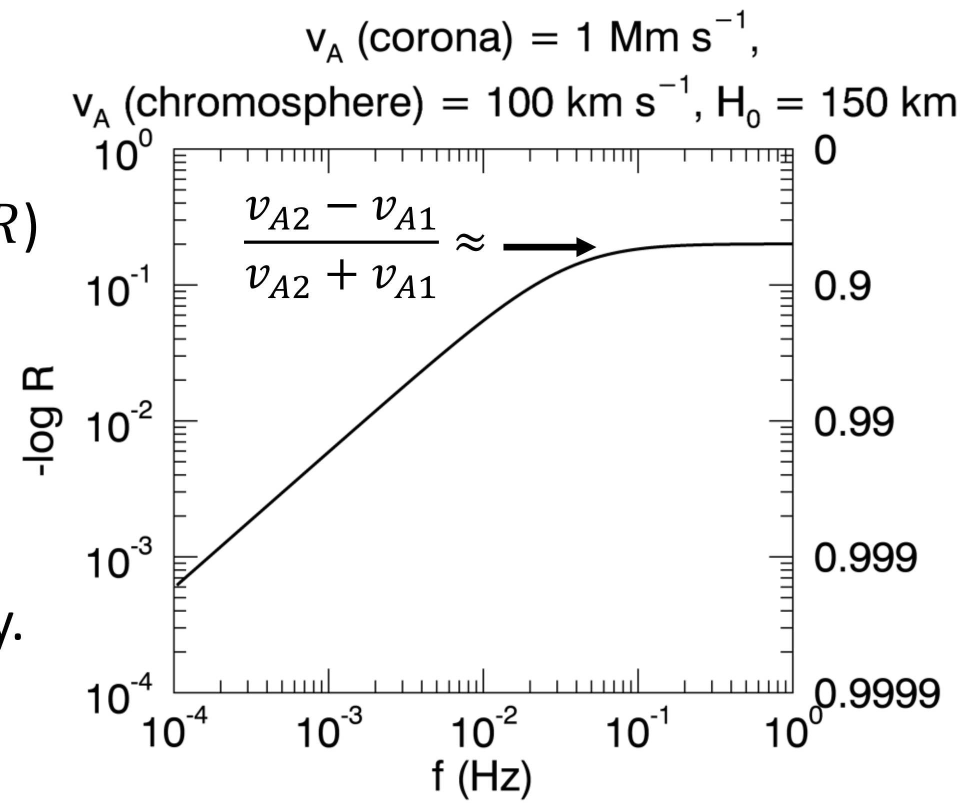
Coronal heating rate $\approx$ $10^{-5}\ \mathrm{Wm}^{-3}$

Coronal kinetic transverse wave energy

Observed amplitudes $\sim$ 20 km s^{-1} (quiet sun) (McIntosh et al. 2011).

Leakage

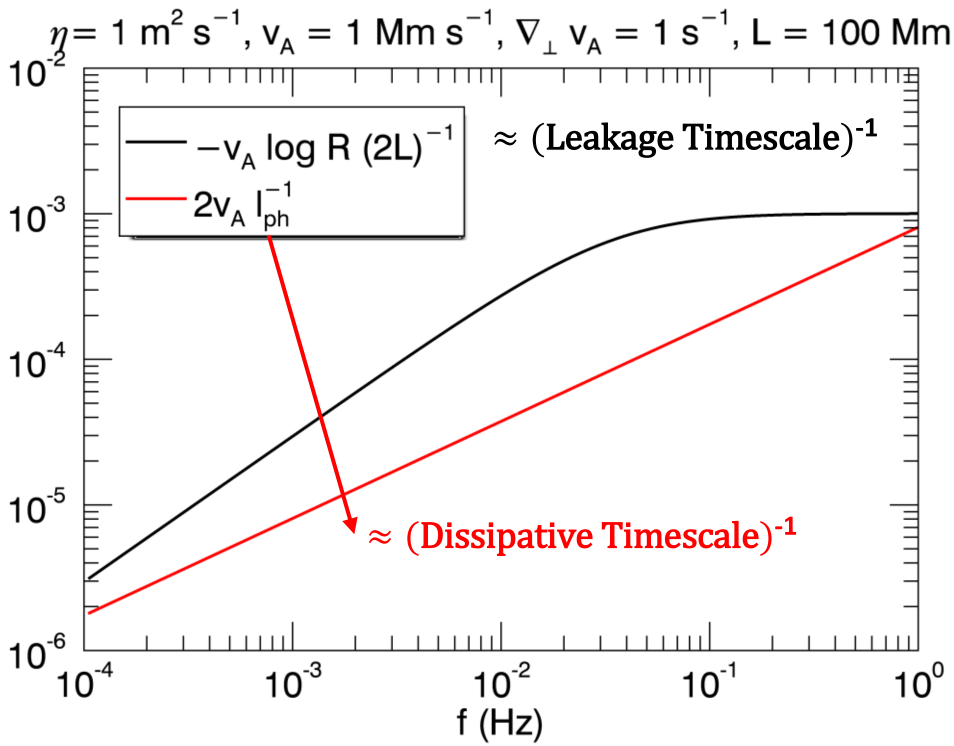
- Waves can leak through the TR.
- We use the reflection coefficient (R) estimated analytically in Hollweg (1984).
- Hydrostatic chromosphere.
- Uniform corona.
- We model the TR as a discontinuity.



Leakage vs dissipative timescale

- Heyvaerts and Priest (1983) give a value for $\nu + \eta \approx 1$ (for 10 G field).
- Although $\nu \propto \frac{1}{B_0^2}$.
- Leakage timescale < phase mixing dissipative timescale.

(Timescale)$^{-1}$ (s^{-1})



Damping rate (γ) vs leakage

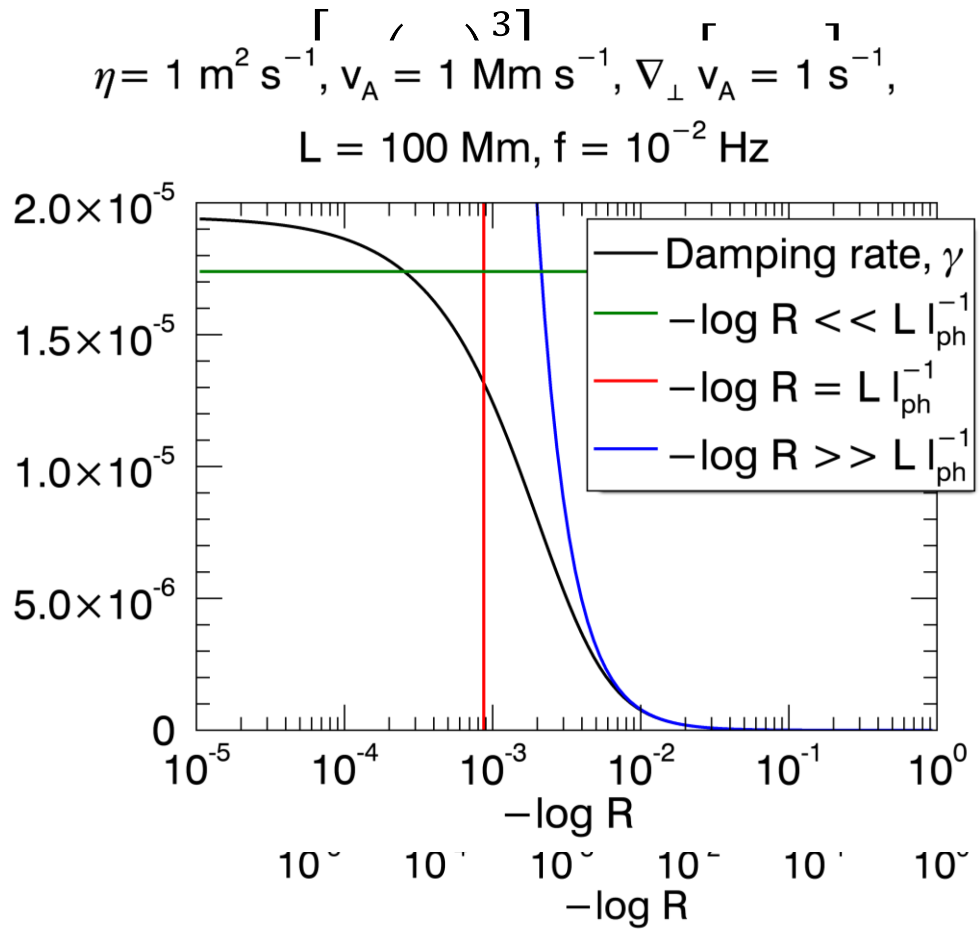
- Leakage reduces γ.
- Caused by the e^{-s^3} nature of phase mixing.
- For $-\log R \ll L\, l_{ph}^{-1}$:

$$\gamma \approx \left(\frac{4}{3} \frac{(\nu+\eta)\omega^2}{v_A^2} (\nabla_\perp v_A)^2 \right)^{1/3}.$$

- For $-\log R \gg L\, l_{ph}^{-1}$:

$$\gamma \approx 2 \frac{\eta \omega^2 L^2 (\nabla_\perp v_A)^2}{v_A^4 \log(R)^2}.$$

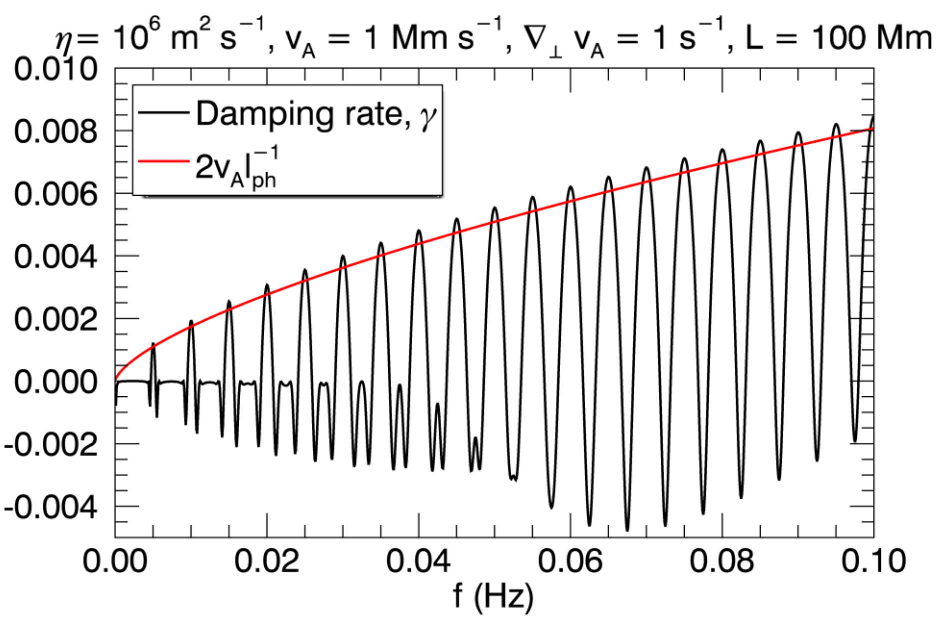
Damping rate for a resonant field line

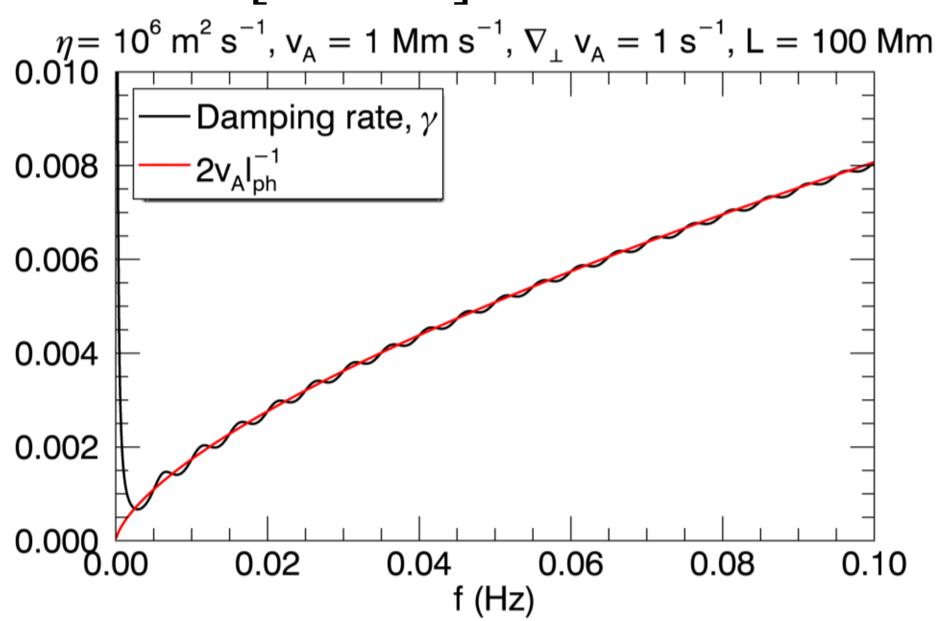


Damping rate (γ) vs frequency

- Damping rate is largest at resonance.
- Error mainly caused by e^{-s^3} nature of phase mixing.

$$\exp\left[-\left(\frac{s}{l_{ph}}\right)^3\right] \rightarrow \exp\left[-\frac{s}{l_{ph}}\right]$$

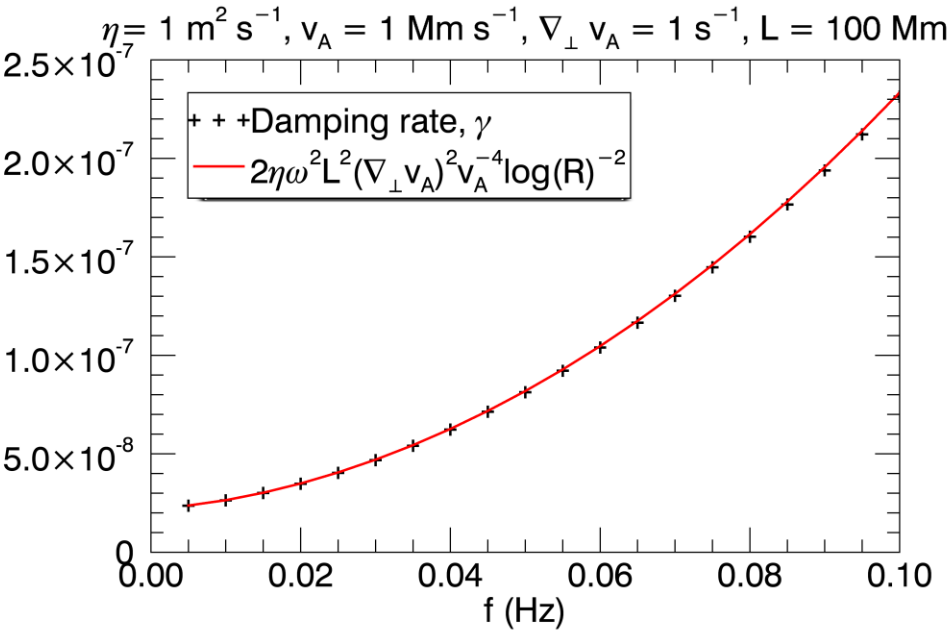




Leakage vs no leakage

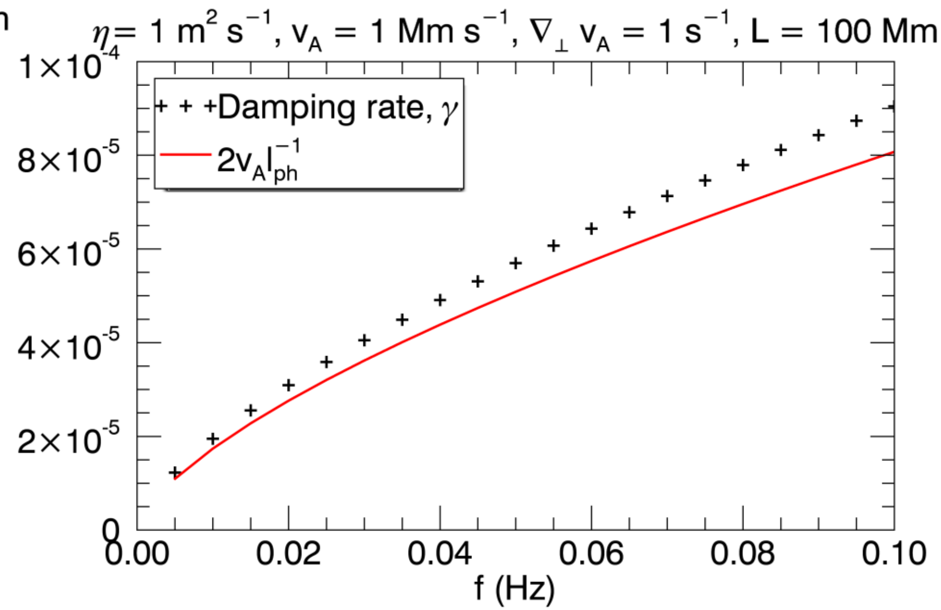
Leakage

(R given by Hollweg 1984)



$$\gamma \approx 2\frac{\eta\omega^2 L^2(\nabla_\perp v_A)^2}{v_A^4\log(R)^2}$$

No leakage



$$\gamma \approx \left(\frac{4}{3}\frac{(\nu+\eta)\omega^2}{v_A^2}(\nabla_\perp v_A)^2\right)^{1/3}$$

$\Longrightarrow$ **Leakage reduces damping rate by ~2 orders of magnitude**

Summary

- Require $\gamma \approx 10^{-1}\ \mathrm{s}^{-1}$.
- $R = 1 \Longrightarrow \gamma$ insufficient by approximately 3 orders of magnitude.
- R given by Hollweg (1984) $\Longrightarrow \gamma$ insufficient by approximately 5 orders of magnitude (for $\nu + \eta = 1\ \mathrm{m}^2\mathrm{s}^{-1}$).
- $\Longrightarrow$ Laminar phase mixing is unlikely to be a viable heating mechanism.
- However, this has not been proven for all parameters.

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