Propagation And Reflection Of Alfvén Waves In The Solar Wind

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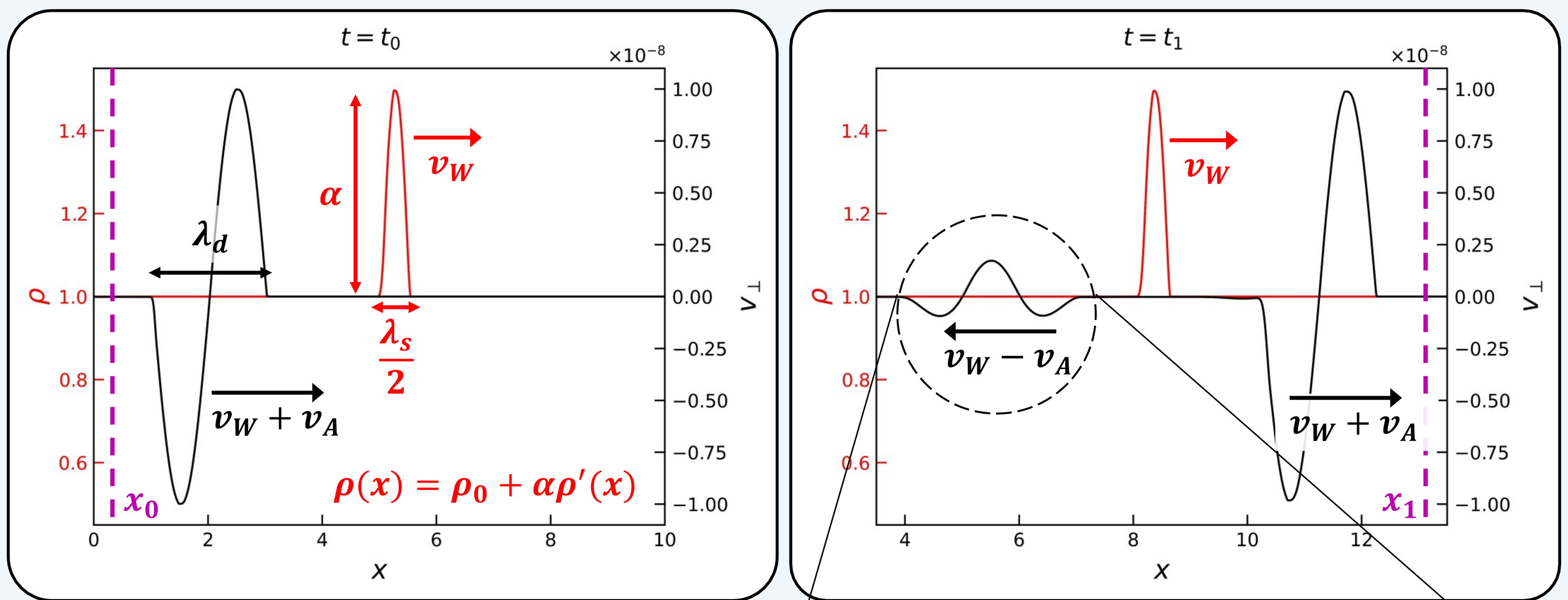
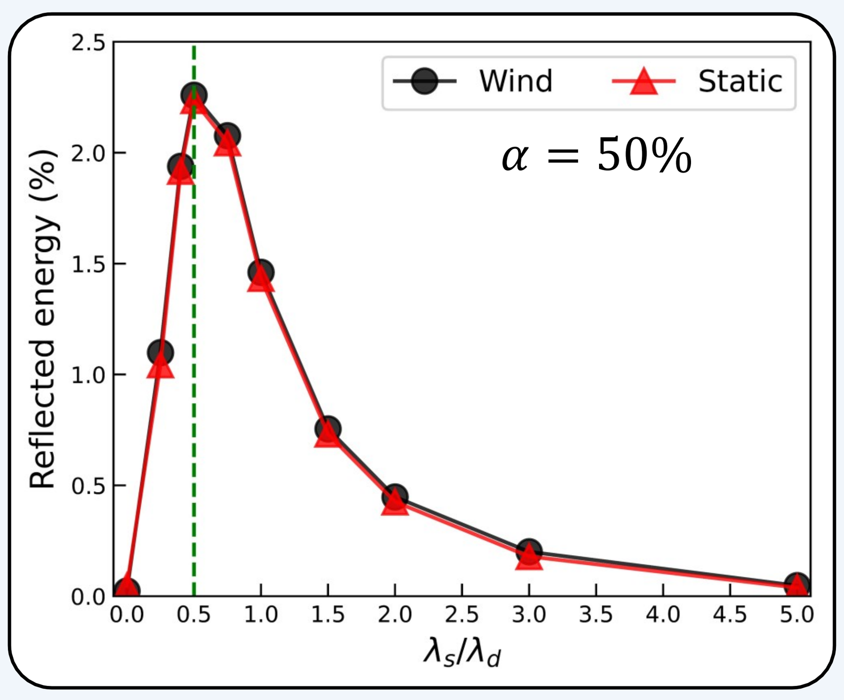
Introduction

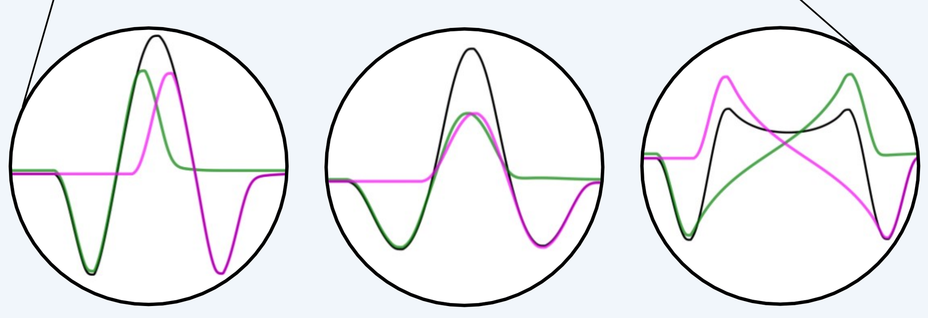
Alfvén waves play a crucial role in transporting magnetic energy from the solar interior that ultimately contributes to coronal heating and solar wind acceleration. Due to their incompressible nature, Alfvén waves can propagate over long distances and are therefore commonly observed in-situ either as propagating waves or switchbacks (*Kasper et al., 2019*). The dissipation of this energy requires small length scales to be formed where resistivity and viscosity dominate. In open structures, wave energy trapping may be possible by having field-aligned inhomogeneities in the medium. The hypothesis is tested using MHD simulations in PLUTO (*Mignone et al., 2007*) in 1D Cartesian geometry.

- **Optimal conditions for wave trapping?**
- **Typical reflection and transmission coefficients?**
- **How long are waves trapped for?**

Reflections Due To Inhomogeneities In A 1D Medium







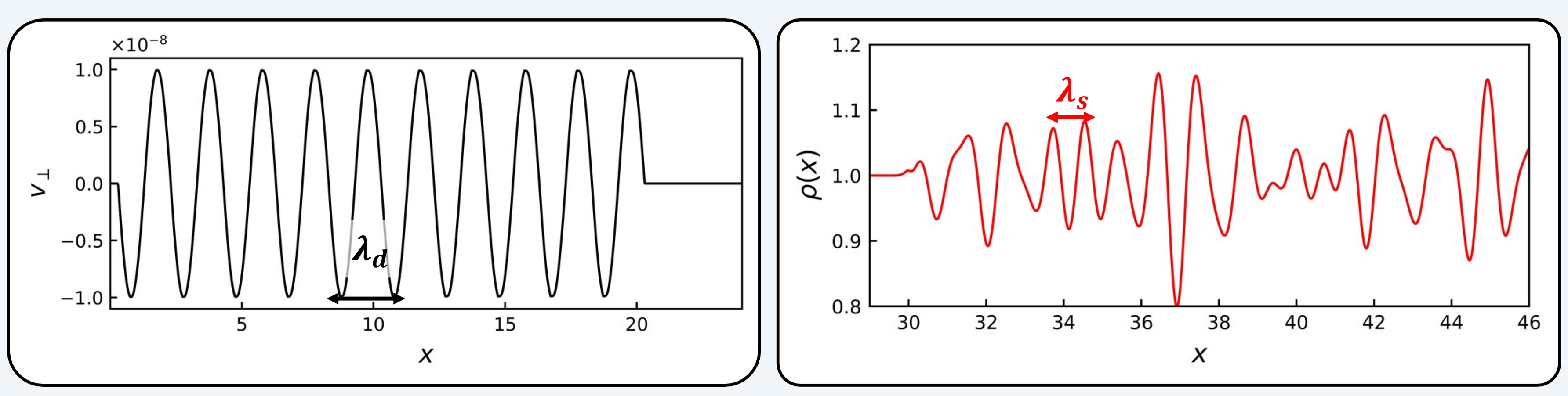
Increasing λ_s

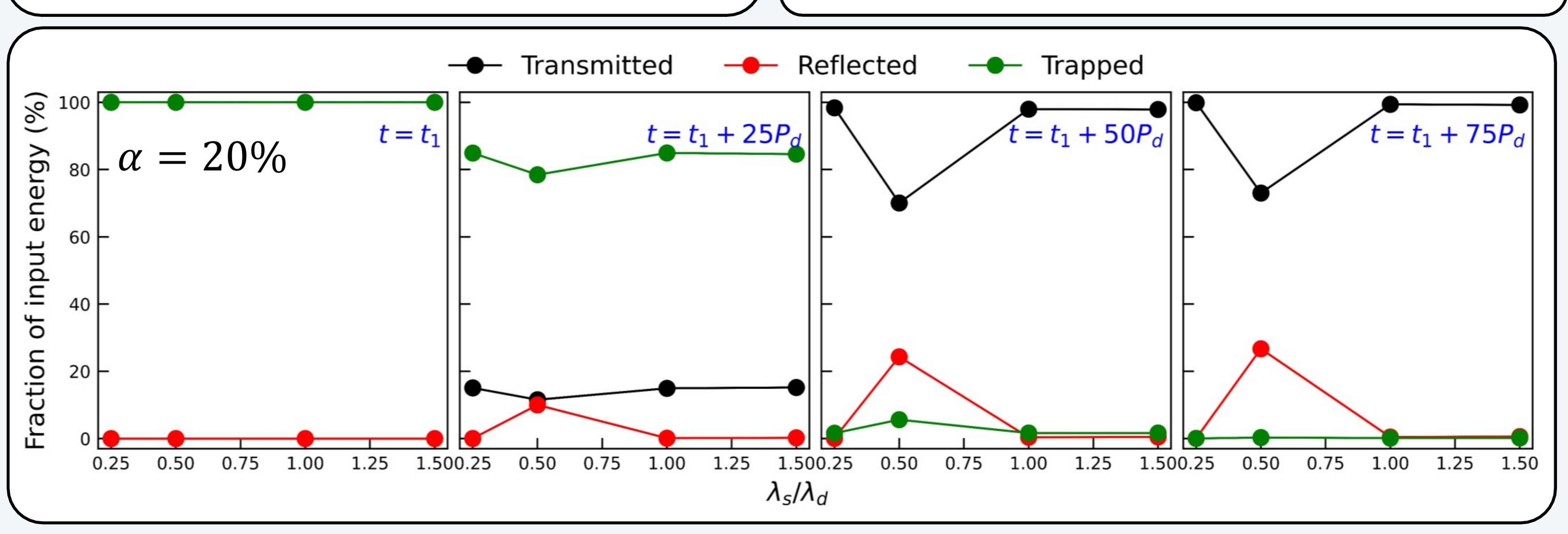
There are reflections in general, but significant reflections occur only when the reflected wave packets interfere constructively for each half wave in the wave packet (green and magenta lines).

1. **Maximum reflections occur when $\lambda_d = 2\lambda_s$ (*Pascoe et al., 2022*).**
2. **A background wind does not affect the reflection or transmission coefficients.**

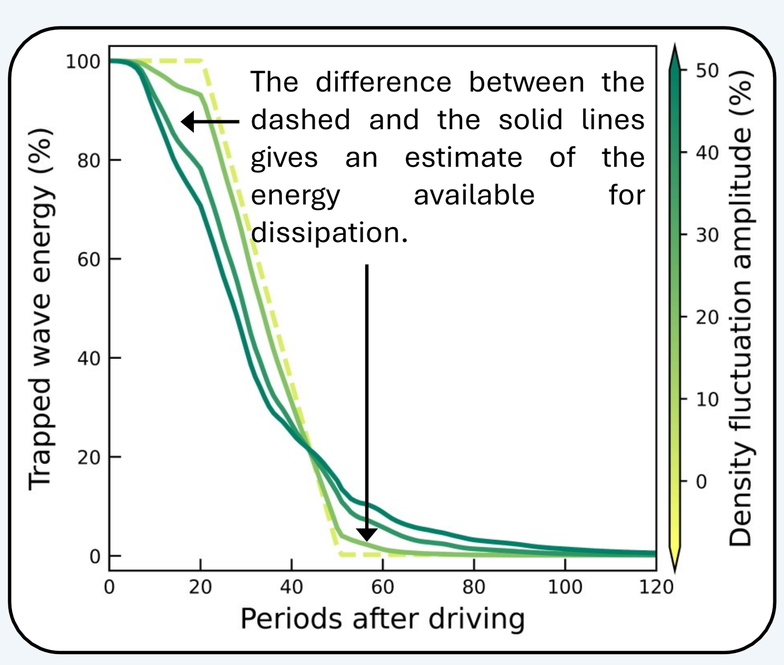
Alfvén Waves In A Randomly Structured, Static Medium: Length Scale Selectivity And Energy Trapping

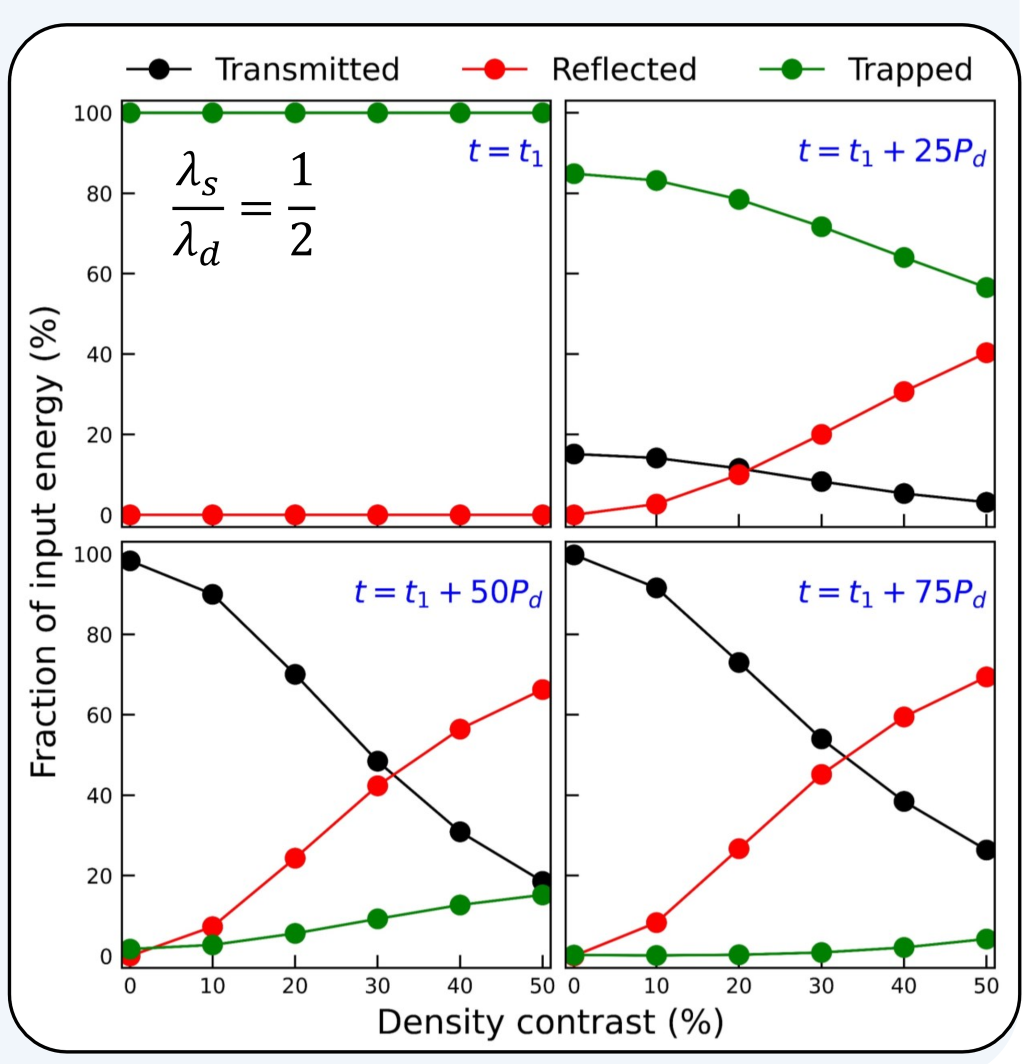
A long duration, monochromatic Alfvén wave train is injected into a region with random density fluctuations, with a mean fluctuation width of λ_s. Through a parameter space study – varying λ_s and the density contrast – the goal is to find out conditions for wave trapping in a more *realistic* scenario that could be applied to the solar atmosphere.





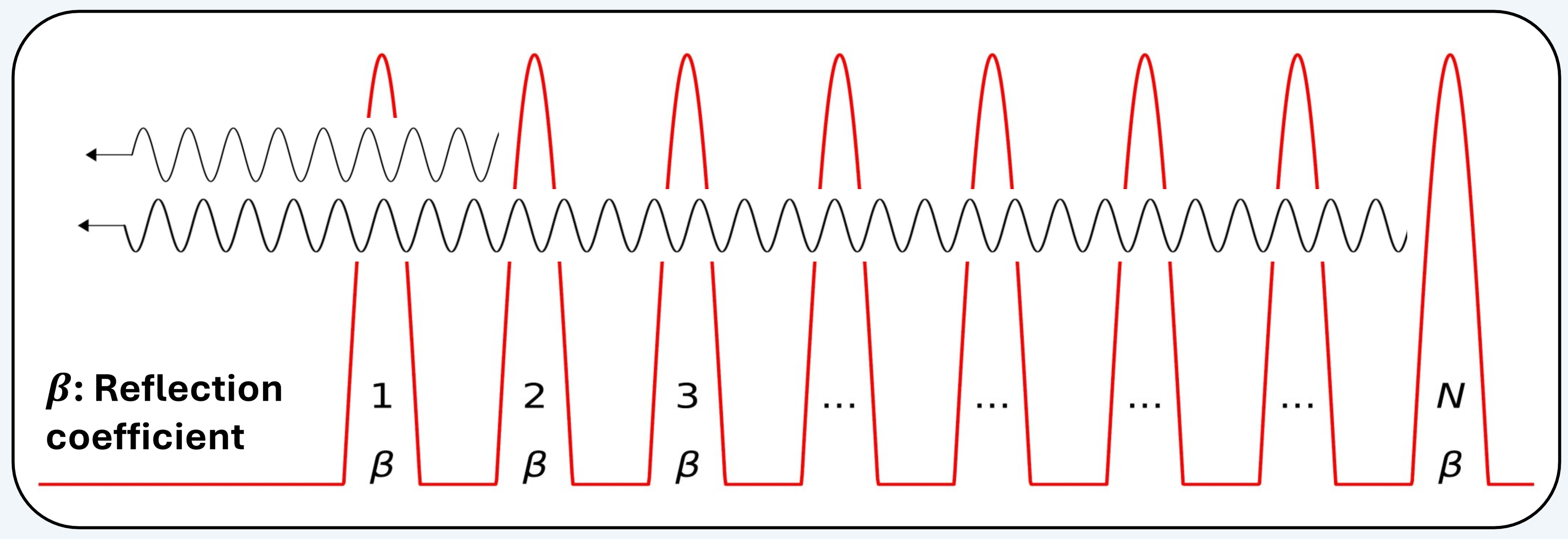
The energy trapped in between the density fluctuations eventually leaves the domain from one of the boundaries. However, the trapping duration can be increased by increasing the density contrast that also facilitates greater reflections.



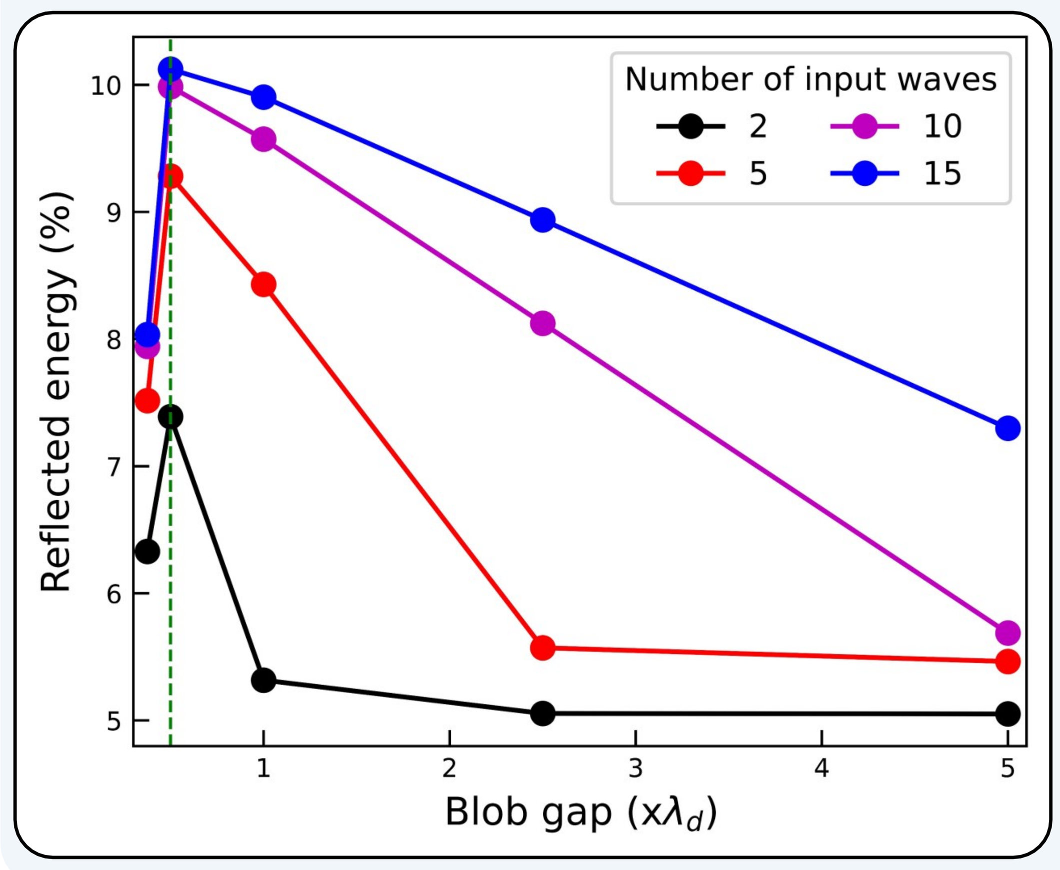


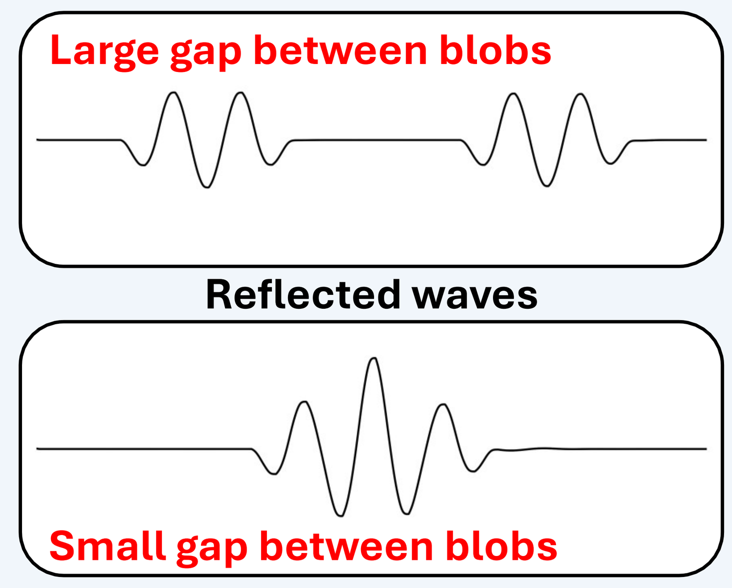
Reflection Coefficients Due To An Array Of Density Blobs

Alfvén waves trains of different durations are injected into a medium with different number of identical density blobs such that $\lambda_d = 2\lambda_s$ with 50% density enhancement. Each blob acts as source of a reflected wave train that interfere with each other constructively or destructively depending on their relative phases. The phase difference depends on the background medium as well as the distance between individual blobs.



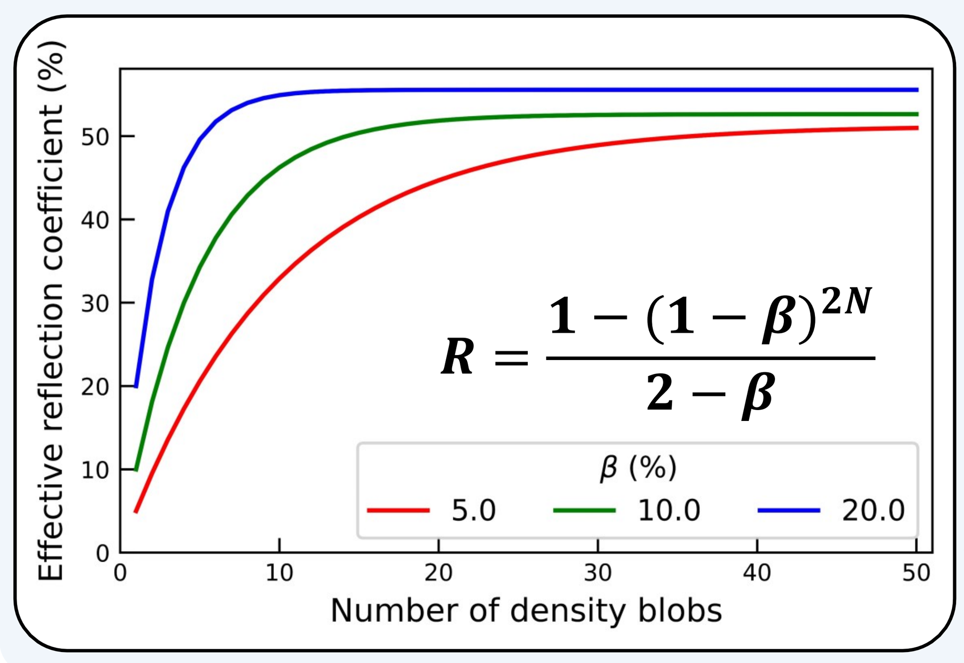
Case Of Varying Gaps Between Two Density Blobs For Different Wave Train Lengths





A shorter gap between blobs facilitates greater interaction between the reflected wavefronts, which are otherwise separated and distinguished for larger gaps.

An Analytical Model Estimating The Limiting Behaviour



$$R = \frac{1 - (1 - \beta)^{2N}}{2 - \beta}$$

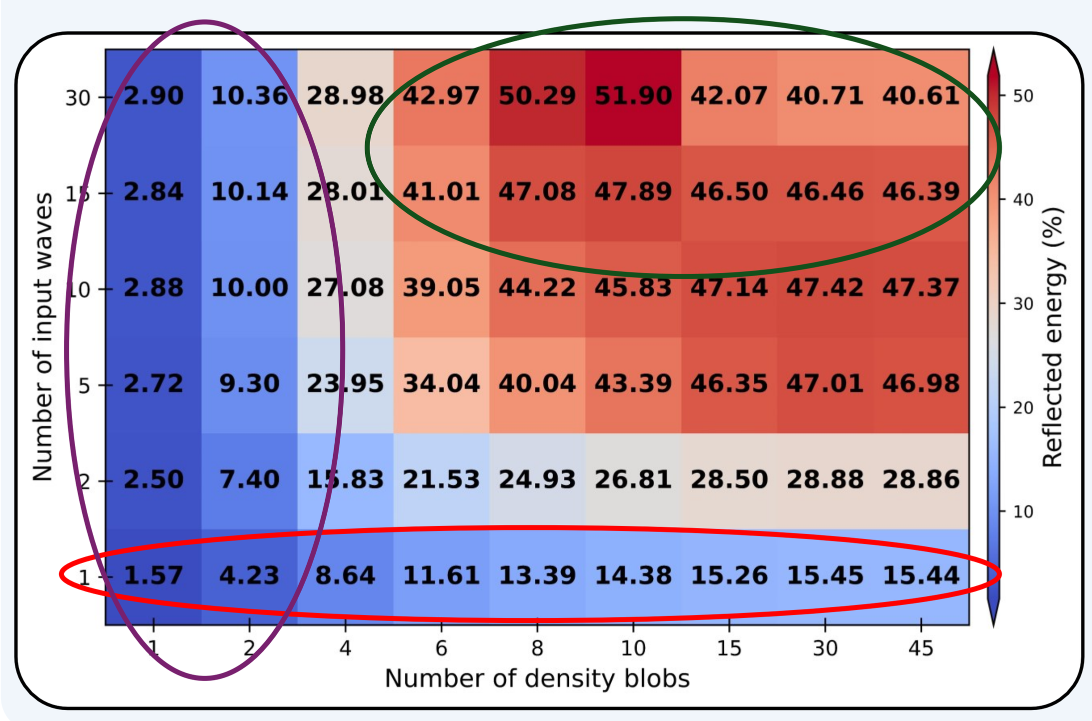
Assumptions

1. Single reflection from each blob.
2. The reflection coefficient of each blob is spatially independent across its width.

Limitations

1. The model does not account for the interaction or the phase difference between the reflected wavefronts.
2. The length scales – wavelength and blob width – are not of the same order, unlike the case under consideration.

Parameter Space Study For A Best-Case Scenario For Wave Trapping



Number of input waves \ Number of density blobs	1	2	4	6	8	10	15	30	45
30	2.90	10.36	28.98	42.97	50.29	51.90	42.07	40.71	40.61
15	2.84	10.14	28.01	41.01	47.08	47.89	46.50	46.46	46.39
10	2.88	10.00	27.08	39.05	44.22	45.83	47.14	47.42	47.37
5	2.72	9.30	23.95	34.04	40.04	43.39	46.35	47.01	46.98
2	2.50	7.40	15.83	21.53	24.93	26.81	28.50	28.88	28.86
1	1.57	4.23	8.64	11.61	13.39	14.38	15.26	15.45	15.44

Sudden dip in reflection coefficient for more input waves and more density blobs.

Non-linear increase in the reflection coefficient for more input waves, because of superposition of reflected waves which increases the Poynting flux non-linearly.

Saturating reflection coefficient for large number of blobs because transmission dominates reflection for higher blob numbers.

Summary

- Wave interference is an important phenomenon that governs the reflection and transmission coefficients.
- Maximum reflections occur when Alfvén wave wavelength is twice the size of the density fluctuation length scale in the medium.
- A background wind has no effect on the reflection and transmission coefficients. It only controls whether the reflected wave is trapped ($M_A < 1$) or not ($M_A > 1$).
- Increasing the interaction region between the waves and density enhancements may not always increase the net reflected energy as the added path difference may lead to destructive interference.

Extension To Spherical Geometry: Requirements And Challenges

- In a *realistic* scenario, Alfvén waves must be reflected in the sub-alfvénic regime for them to trap close to the chromosphere.
- A combination of thermodynamic, gravitational and spherical expansion effects often lead to non-linearities even for 10-15% density contrasts.
- For an accelerating and spherically expanding solar wind, significant density contrasts with coherent length scales are challenging to maintain.

References

1. Kasper, J.C., Bale, S.D., Belcher, J.W., Berthomier, M., Case, A.W., Chandran, B.D., Curtis, D.W., Gallagher, D., Gary, S.P., Golub, L. and Halekas, J.S., 2019. *Nature*.
2. Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O.E., Zanni, C. and Ferrari, A., 2007, *The Astrophysical Journal Supplement Series*.
3. Pascoe, D.J., De Moortel, I., Pagano, P. and Howson, T.A., 2022, *MNRAS*.