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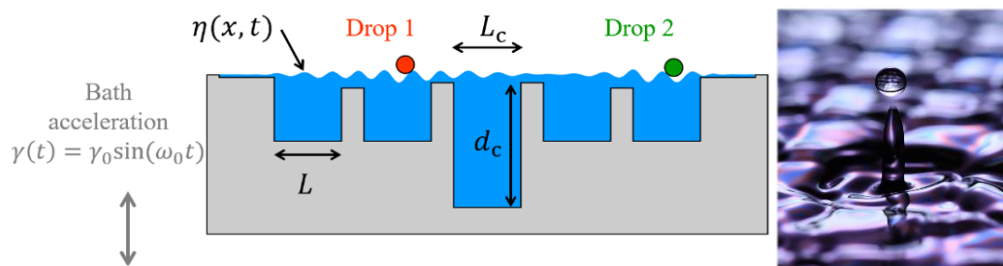
# Exploring Quantum Analogies: Superradiance, Bipartite Correlations, and static Bell Tests in Pilot-Wave Hydrodynamics

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Since its discovery in 2005<sup>1</sup>, the hydrodynamic pilot-wave system has provided a macroscopic realization of wave-particle duality, reproducing an increasing number of quantum-like effects<sup>2-6</sup>. A key question is how closely particle-particle correlations in this classical system can mimic those at the quantum scale. Here, we introduce a numerical model of cooperative tunneling in a bipartite pilot-wave system as a new platform for exploring this question.

We first establish bipartite hydrodynamic analogs of superradiance, both numerically and experimentally, demonstrating a sinusoidal modulation of the excited-to-ground state transition rate as a function of the separation between the two subsystems<sup>5-7</sup>. Additionally, we conduct a static Bell test, where the system's geometry remains fixed while the two subsystems are coupled through the intervening wave field. This wave-mediated coupling does not conform to the assumptions underlying Bell's theorem, providing a rationale for the observed violations. However, these violations are elusive, emerging only within a narrow region of parameter space<sup>8</sup>.



**Figure 1: a Numerical model of two coupled, 2-level systems.** The system consists of a pair of drops (red and green) walking on the surface of a vibrating fluid bath (blue) that spans the solid substrate (grey). Each drop is confined to a pair of wells separated by barriers across which they may tunnel unpredictably. **b** Experimental demonstration of a droplet generation due to interfacial breaking in a vibrationally excited hydrodynamic cavity. (Figure 1a and b are taken from [5] and [6]).

## References

- [1] Y. Couder and E. Fort. *Phys. Rev. Lett.*, 393, 97(154101), (2006).
- [2] J. W. M. Bush, K. Papatryfonos, and V. Frumkin, "The State of Play in Hydrodynamic Quantum Analogs," in *Advances in Pilot Wave Theory*, pp. 7–34. Boston Studies in the Philosophy and History of Science, vol 344, Cham: Springer International Publishing, (2024).
- [3] A. G. Lopez and R. N. Valani, *Phys. Rev. E* 111, L022201 (2025).
- [4] G. Pucci, A. Bellaigue, A. Cirimele, G. Ali, and A. U. Oza, *Phys. Rev. E* 111, L033101 (2025).
- [5] K. Papatryfonos, M. Ruelle, C. Bourdiol, A. Nachbin, J. W. M. Bush, and M. Labousse, *Commun. Phys.* 5, 142, (2022).
- [6] V. Frumkin, K. Papatryfonos, and J. W. M. Bush, *Phys. Rev. Lett.*, 130, 064002 (2023).
- [7] K. Papatryfonos, J. W. Schroder and V. Frumkin, arXiv: 2408.02620 (2024).
- [8] K. Papatryfonos, L. Vervoort, A. Nachbin, M. Labousse, J. W. M. Bush, *Phys. Rev. Fluids*, 9, 084001 (2024).