

Collective dynamics of inertial active matter

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Theoretical models of active matter (systems that use a local energy influx to drive persistent motion) often focus on mesoscopic particles whose inertia is negligible. However, in many experimental realizations of active matter inertia turns out to be significant. This holds for both very macroscopic (birds, robots) and microscopic (atomic) realizations of active matter. Moreover, the combination of activity with inertia can give rise to a plethora of interesting effects, such as the spontaneous formation of temperature gradients or collective dynamics reminiscent of that of quantum systems. Finally, as shown by the phenomenon of velocity correlations, even in the overdamped system the particle velocity is an independent and important degree of freedom in active systems.

In this talk, I will discuss the role of inertia in active matter systems — a topic that has received increasing attention as experiments reveal that inertial effects are not negligible in many real-world settings. I will begin by giving a general introduction to inertial active matter, highlighting how inertia changes the dynamical structure of active systems compared to the overdamped case. I will explain why, even when inertia is small, velocity remains a dynamically relevant variable, as demonstrated by velocity correlations that persist even in systems where friction dominates.

I will then present a theoretical model for continuum descriptions of inertial active matter. This model is designed to capture thermodynamic properties and to reveal structural similarities to quantum mechanics. This analogy provides a useful mathematical and conceptual framework for analyzing and predicting the behavior of inertial active systems. Next, I will show how machine learning methods can be used to analyze the collective dynamics of active systems, with a specific focus on studying their velocity fields. Finally, I will present an experimental case study on quantum-mechanical active particles. I will describe the system, the observed dynamics, and how they relate to the theoretical models discussed earlier. I will also discuss possible applications for realizing intelligent quantum systems — systems that can adapt, self-organize, or respond collectively to external stimuli — based on the principles of active matter.

This talk aims to bridge theory, simulation, and experiment in the study of inertial active matter, and to highlight how combining activity with inertia opens new avenues for understanding and engineering complex non-equilibrium systems.