Statistical mechanics of wet active systems

Nom des responsables du stage ou thèse: Cesare Nardini
(Theoretical & numerical internship, possibly leading to a Ph.D.)

Nom Laboratoire : SPEC, CEA-Saclay, and LPTMC, Jussieu
e-mail : cesare.nardini@gmail.com **Téléphone** : 06 32 33 27 70
Lieu du stage: Saclay and Jussieu **Stage pouvant déboucher sur une thèse** : OUI

In a nutshell: Study theoretically the effect of hydrodynamic interactions on active systems
Expected skills: Basic statistical mechanics methods. Interest in performing analytical and some numerical work

Active systems are formed of units that are able to extract energy from the environment and dissipate it while producing work, as for example by self-propelling. Examples are found everywhere in nature: flocks of birds, animal swarms, suspensions of bacteria and tissues are all biological active systems [1]. Artificial active systems have also been engineered in the lab using catalytic colloidal particles or micro-robots. A strong research activity emerged attempting at describing their collective behavior, with fundamental applications in understanding and controlling biological systems, and the long-term goal of engineering self-assembling materials using active units.

Most active particles do move in a fluid ('wet' systems) and, because of their size (typically in the μm-range), the Reynold's number is very small. This means that, by moving, a microswimmer creates a fluid flow which affects the motion of other swimmers. However the majority of theoretical description of active systems, especially those focusing on their collective behavior, neglect the presence of the surrounding fluid ('dry' systems). While this approximation has the notable advantage of simplicity, it is not controlled: even when swimmers move close to a substrate, fluid-mediated interactions are long-ranged and it is natural to expect that the resulting phenomenology is deeply affected by hydrodynamics. Furthermore, even the collective properties of fully wet active systems are much less understood than those of their dry counterparts. For example, wet active systems with nematic alignment generically self-organize in a chaotic state known as active turbulence [4]. However, the size of the vortices is observed to be scale-free experimentally, a conclusion that currently lacks any theoretical explanation [9].

In this project, you will develop theories for wet active systems for describing how hydrodynamics modifies their collective behavior. We will focus on the fact that most active systems are neither fully dry nor fully wet, and ask whether this implies different phenomenologies with respect to the two limiting situations. The work will employ both analytical and numerical techniques, ranging from large-deviations theory, statistical field theories, hydrodynamics and kinetic theories [10] to coarse-grain particle models to their large-scale description. The internship is thought as a well-defined entry point in the subject and can be naturally continued in a PhD.

Questions you will address encompass: the emergence of super-diffusive regime of passive tracers [5,6]; the novel phenomenology emerging when systems are neither fully dry nor fully wet [11,12]; the formation of coherent structures in quasi two-dimensional geometries [7], and the scale-free nature of the active turbulent state [9]. Within a PhD, we will further consider the impact of hydrodynamic interactions on other active phenomenologies, including phase separating systems and flocking. The skills required are a Master-level training in statistical physics; no experience on active matter or biophysics is expected: What you don't know, you will learn.

[1] C. Marchetti et al., Rev. Mod. Phys. **85**, 1143 (2013). [2] D. Saintillan, et al., Phys. Fluids **20**, 12 2008. [3] HM López, et al., PRL, **115**, 028301, 2015. [4] J. Stenhammar, et al., PRL **119**, 028005 (2017). [5] XL Wu, et al., PRL **84**, 3017 (2000). [6] A. Lagarde, D. Bartolo, Soft Matter **16**, 7503 (2020). [7] M. Nejad, et al., PRL **128**, 048001, 2022. [8] CA Weber, et al., Rep. Progr. Phys. **82**, 064601, 2019. [9] B. Perez-Estay, et al., PNAS **123**, e2600266123, 2026. [10] S. Burekovic, PRR **8**, 033141, 2026. [11] D. Bárdfalvy et al., Comm. Phys. **7**, 93, 2024. [12] Y. Yin et al., PRL **136**, 138301, 2026.