Learning active matter

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

Nom Laboratoire : SPEC, CEA-Saclay, UMR 3680
e-mail : cesare.nardini@gmail.com
Téléphone : 06 32 33 27 70
Lieu du stage: Saclay and Jussieu
Stage uniquement : OUI
Thèse uniquement: NON
Stage pouvant déboucher sur une thèse : OUI
Financement proposé : OUI (stage)

In a nutshell: Developing theoretical tools to reliably learn models that describe active systems
Expected skills: Basic statistical mechanics methods and (ideally) interest towards numerical methods.

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.

Yet, active systems are very complex down to the scale of the single agent – think at the complexity inherent in single bacteria, cells, animals, or even micro-robots and other artificial active systems. In order to understand their large-scale self-organization properties, the current theoretical investigations mostly start from minimal microscopic descriptions where agents are represented by structureless entities (e.g. point particles that, for example, align their self-propulsion direction, or exert forces on each other) [2]. Alternatively field-theoretical models were proposed at the macroscopic level directly to describe mesoscopic observables such as the local density of particles, their polarization etc., and are based on symmetry arguments and conservation laws, [1,3]. However, in both cases, given the complexity of real active systems, it is impossible to tune the parameters of these minimal models via mechanistic arguments. Importantly, this does not only concerns our current inability of quantitatively describing experimental data – it is often even unclear whether qualitative theoretical results are applicable to a specific real active system. On the other hand, recent breakthroughs on data analysis based on sparse regression techniques [4-6] and causality detection [7] give hope that the crucial goal of quantitatively fit minimal models of active systems to experimental data can now be solved.

This internship is planned as a well-defined entry point in the subject and can naturally be continued in a Ph.D. You will focus on applying learning techniques to describe phase-separating active systems. This is one of the most intriguing phenomenologies found in active systems relevant for many diverse systems, from suspensions of self-propelled particles; biological tissues; biomolecular condensates in cells; granular materials, and even social dynamics, and ecology [3]. You will start from applying data analysis techniques to learn the minimal model that describe data that were produced from simulations of a phase-separating active system. You will then progress by comparing the field theories obtained from data analysis to those obtained from analytical coarse-graining and kinetic theories of minimal particle models. If the internship is continued in a Ph.D. you will further apply these techniques to experimental data that other groups have produced on biological tissues, self-propelled colloids and biomolecular condensates in cells. You will further be involved in other exciting projects that encompass both analytical and numerical work to describe active systems, such as: the examination of the role of leaders in determining collective behaviour, understanding the role of screened fluid interactions on the flocking transition, and the derivation of active stochastic field theories by coarse-graining microscopic active dynamics.

The skills required are a Master-level training in theoretical and statistical physics; no experience on active matter or biophysics is required. What you do not know and is needed, you will learn!

[1] C. Marchetti et al., Rev. Mod. Phys. **85**, 1143, 2013 ; [2] G. Gompper et al., J. Phys: Cond. Mat. **32**, 193001, 2020 ; [3] M.E. Cates, C. Nardini, Rep. Progr. Phys. **88**, 056601, 2025 ; [4] S. Rudy et al., Sci. Adv. **3**, e1602614, 2017 ; [5] S. Brunton, PNAS **113**, 3932, 2016 ; [6] C. Joshi, Phys. Rev. Lett. **129**, 258001, 2022 ; [7] V del Tatto et al., PNAS 121, e2317256121, 2024