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How do anisotropic active particles collectively organize?

In collaboration with A. Altieri & J. Tailleur

Collective behavior of self-propelled particles.– The motion of a self-propelled particle rests on the consumption of an energy source (mostly of chemical nature in the real world) that is converted into directed random motion. An important physical feature is that, unlike a colloid in water experiencing thermal fluctuations due to the collisions with the water molecules, and for which the energy dissipated through viscous friction is returned to the energy reservoir (the water molecules), for self-propelled partciles, the injection and dissipation mechanisms are based on different physical channels. The particles we have in mind (synthetic colloids, bacteria) are usually big enough so that inertial effects can be discarded. Their dynamics balances out direct forces (caused by other particles or by an external field) with viscous damping, and a self-propulsion force. The latter, while random, is neither Gaussian nor with a white spectrum. Because of the properties of the self-propulsion force, such active particles live out the realm of equilibrium statistical physics. And this is enough to lead to spectacular collective behaviors such as the celebrated alignement transition [11] or to the possibility of phase separation in the absence of attractive interactions [6].

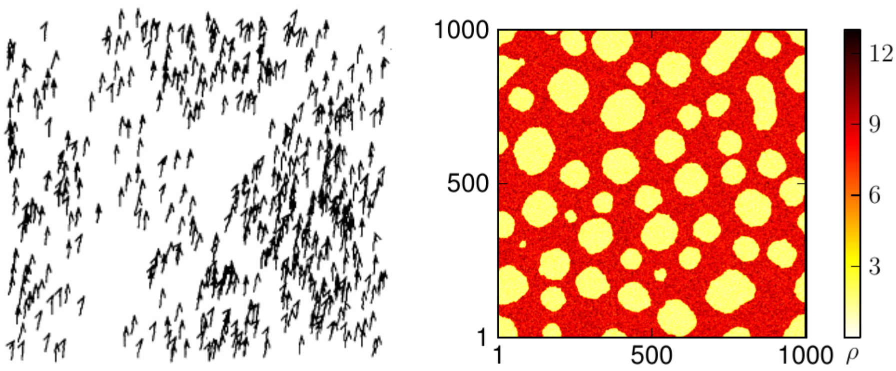

Figure 1: Left: Emergence of ordered and directed motion at high density and small noise, taken from [11]. Right: Motility-induced phase separation in a two-dimensional system of run-and-tumble particles, taken from [6].

What we do know.– It is fair to say that the Vicsek alignement transition or that motility-induced phase separation are by now pretty well-understood phenomena. While both continue to stimulate a steady stream of works, existing theoretical approaches, based on numerical simulations, on phenomenological coarse-grained theories, on more or less controled analytical approximations, concur to shape a pretty clear physical picture of the phase diagrams of systems of interacting self-propelled particles.

What are the open questions?– In equilibrium physics, it was realized in the last 25 years that the shape of the particles itself would play a key role in the ordering at high density or low temperature. The complexity of these macroscopic phases was interpreted as resulting from entropic effects [4, 7, 13]. It turns out that in physical (experimental) realizations, active particles are seldom ideal hard spheres (think of the rod shaped E. Coli). Hence the physical reality lies somewhere in between active hard-spheres and point-like spins. Simulations of such systems are hard, and few results exist, except for hard rods [2, 3, 12, 10]. These are exclusively of numerical or phenomenological nature, and the influence of shape itself (known to be a crucial feature in equilibrium [8]) has not been investigated so far.

What are the possible ways to take up these questions?– It has been very recently realized [1] that, much like equilibrium simple liquids, embedding an active fluid in a space of high dimensionality allowed for great analytical progress (this is actually the only exactly solvable model of an active fluid known so far). For equilibrium fluids, it has been shown that hard-rods [5] or hard-disks [14] could, as much as hard spheres (see [9] for a review) lend themselves to a high-dimensional analysis. Our goal is to endow such anisotropic particles with an active dynamics by incorporating a self-propulsion force and an aligning torque, and to explore their collective phase behavior using the statistical mechanical tools developped in the infinite-dimensional limit. Further questions dealing with the onset of crowding and with the role of geometry in jamming the dynamics will naturally emerge.

What are the prerequisites?–

1. a strong background education in statistical mechanics, in and out of equilibrium, including stochastic calculus and field-theoretic approaches;

2. a strong interest for theoretical questions many people have stumbled on;

3. a certain taste for mathematical elegance.

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