# Micro-robots and bacteria swimming in a supercomputer


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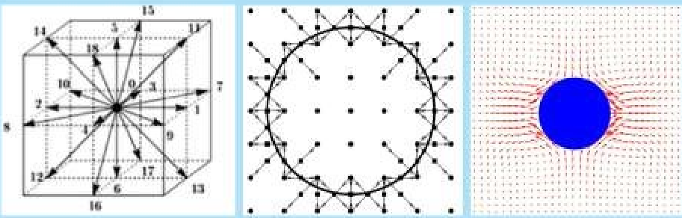
## Abstract


We studied the fundamental role that the hydrodynamic interactions have in the collective motion of micro-swimmers. We have used the squirmer model to describe how the microorganisms interact with the fluid and made used of the Lattice Boltzmann Method (LBM) to simulate the fluid dynamics [1]. Such collective behaviour has inspired researchers to deepen the understanding of the physics of motility to engineer complex emergent behaviours in model systems that promise advances in technological applications. Such a fundamental understanding will help to identify new routes to design micro-robots that can imitate micro-organisms.


## Model

Ludwig Boltzmann's kinetic theory of gases → LBM

$$\frac{\partial f}{\partial t} + \boldsymbol{u}\cdot\nabla f = \Omega \quad \rightarrow \quad \frac{\partial f_i}{\partial t} + \boldsymbol{c}_i \nabla f_i = \frac{\Omega_i[f(\mathbf{x},t)]}{\Delta t}$$




LBM is modified to incorporate the BC imposed on the fluid by the solid particles. Solid Particle = Boundary Surface.

$$\mathbf{u}_b = \mathbf{U} + \boldsymbol{\Omega}\times(\mathbf{r}_b - \mathbf{R}), \qquad \mathbf{r}_b = \mathbf{r} + \tfrac{1}{2}\mathbf{c}_b$$

Squirming motion **model for the flow generated by the beating of cilia**. We threat squirmers as spherical solid bodies embedded in the fluid with a slip velocity $\mathbf{u}_S$ (the simplest squirmer model) [2].

$$\mathbf{u}_S = [B_1 \sin\theta + B_2 \sin\theta\cos\theta]\,\mathbf{t}, \qquad \beta \equiv B_2/B_1$$

**Slip velocity as a local bounce-back condition**

## Swimming in bulk

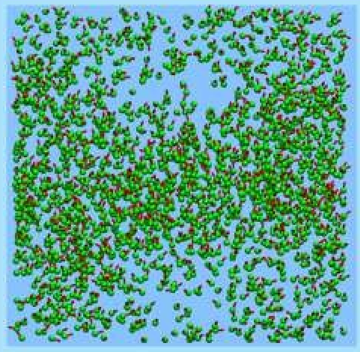
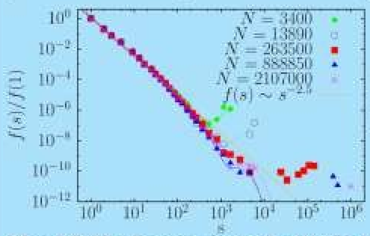
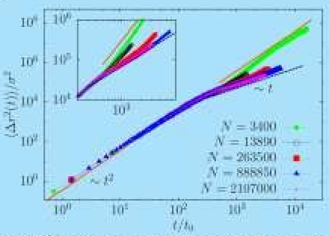


Figure on the left shows a 3D simulated squirmer suspension with $\beta = 0.5$. Long range spatial-correlations have been observed. Anomalous diffusion was also founded. We further characterize the system by measuring the cluster size distribution (CSD) and the mean square displacement (MSD). We used HPC to reach large-scale systems.

For large enough systems, a macroscopic cluster of size comparable to the system size emerges, when $\beta = 0.5$

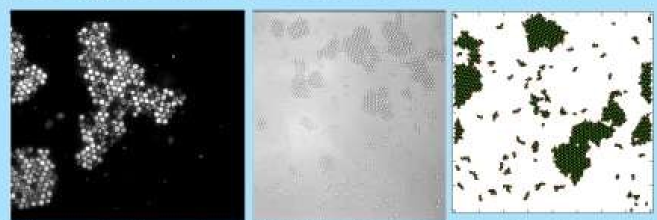



The MSD change from ballistic to diffusive motion at the same time for every size, the 2nd crossover is driven by the long range hydrodynamic flows generated by the same particles.

## Swimming confined in a plane

Here we compare among some experiments with swimming bacteria, photo-active particles and our simulations.



Left panel: Snapshot of *Thiovulum majus* swimming bacteria [3]. Center panel: Living crystals formed by photoactive colloids [4]. Right panel: Snapshot of one of our simulations of interacting squirmers swimming in 2D.

## References


[1] K. Stratford and I. Pagonabarraga, *Computers & Mathematics with Applications*, **55**, (7), 1585, 2008.

[2] M. J. Lighthill, *Communications on Pure and Applied Mathematics*, **5**, (2), 109, 1952.

[3] A.P. Petroff, X-L. Wu and A. Libchaber *Phys. Rev. Lett.* **114**, 158102, 2015.

[4] J. Palacci et al. *Science* **339**, 936 (2013).


## Take-home message

- Microswimmers can generate two collective motions (CM): **polar order and the emergency of a macroscopic cluster that percolates.** We have proved that both effects depend only on the hydrodynamic signature of the squirmers.
- Thanks to the versatility of LBM to simulate different geometries. **We were able to reproduce the morphology and the dynamics of living cystals observed in experiments**, using the squirmer model with direct interactions.

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