Flocking through disorder

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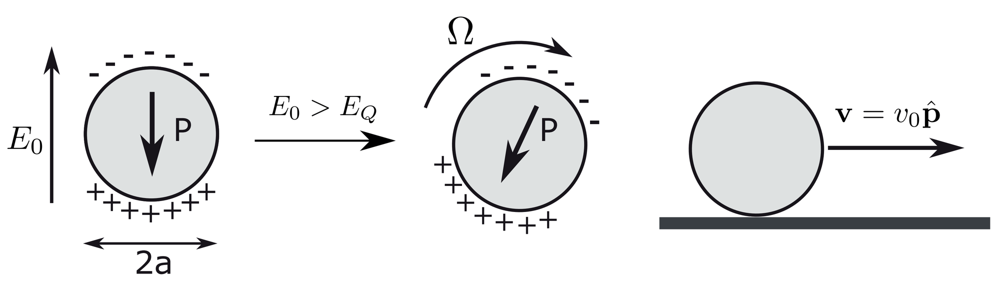
How do flocks, herds and swarms proceed through disordered environments? This question is not only crucial to the displacement of animal groups in the wild, but also to virtually all applications of collective robotics, and active materials composed of motile units. In stark contrast, apart from very rare exceptions, our physical understanding of flocking motion has been hitherto restrained to homogeneous media. Here, we elucidate how collective motion survives to geometrical disorder. Combining experiments on colloidal bots flocking through random repelling obstacles, and analytical theory, we establish two generic results: Firstly, we show how the bending elasticity of flocking phases restrains their flows to sparse channel networks akin those found beyond plastic depinning in driven condensed matter. Secondly, we demonstrate how further increasing disorder, collective motion is suppressed in the form of a first-order phase transition generic to all polar active materials.

Experimental system

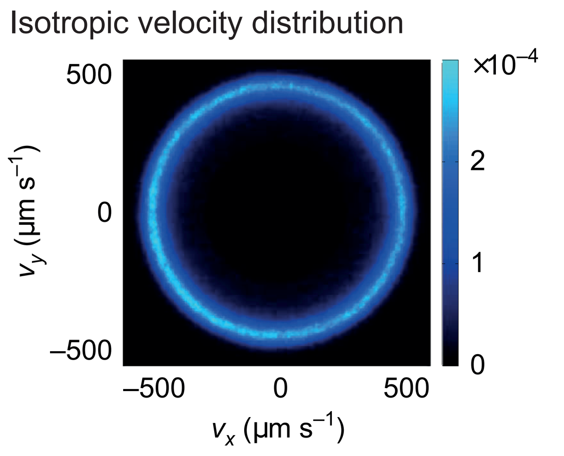
Making colloidal rollers

Basic principle: Quincke rotation

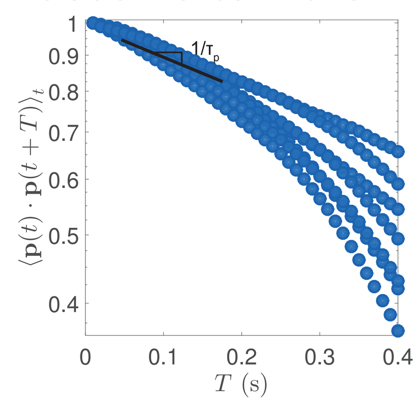


Self-propelled particles
- a = 2.5 µm — radius
- v_0 ~ 1 mm/s — translational speed
- τ_p ~ 1 s — persistance length

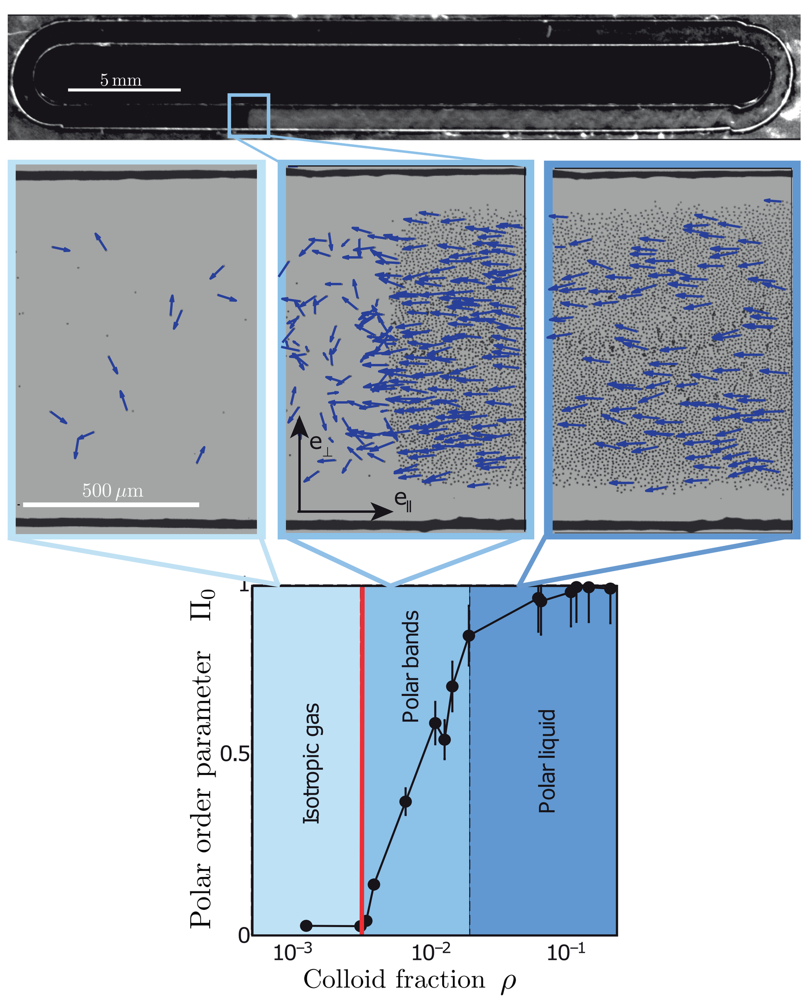
Isotropic velocity distribution



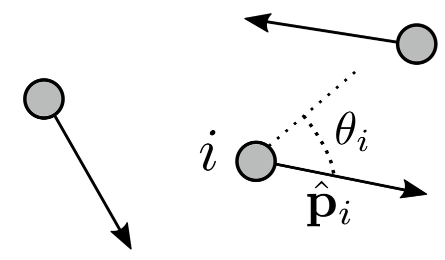
Persistant random walker



Flocking transition



Dynamics and interactions



$$\begin{cases} \partial_t \mathbf{r}_i(t) = v_0 \hat{\mathbf{p}}_i(\theta_i) & \text{(self-propulsion)} \\ \partial_t \theta_i(t) = -\partial_{\theta_i} \sum_{j \neq i} \mathcal{H}(\mathbf{r}_i - \mathbf{r}_j; \hat{\mathbf{p}}_i, \hat{\mathbf{p}}_j) + \sqrt{2D}\xi_i(t) \end{cases}$$

interaction torque — angular noise

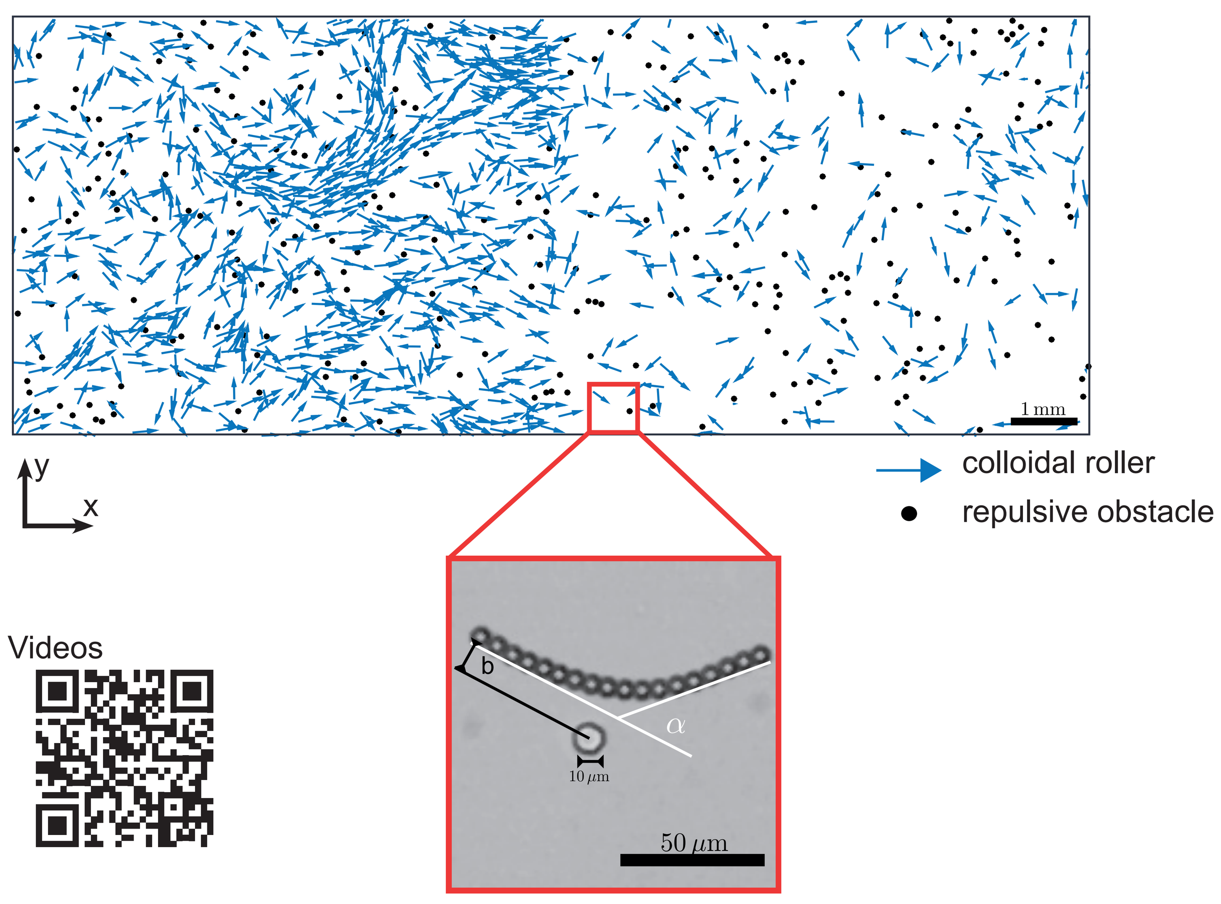
$$\mathcal{H}(\mathbf{r}; \hat{\mathbf{p}}_i, \hat{\mathbf{p}}_j) = A(r)\hat{\mathbf{p}}_i \cdot \hat{\mathbf{p}}_j + B(r)\hat{\mathbf{p}}_i \cdot \mathbf{r} + C(r)\hat{\mathbf{p}}_j \cdot (2\mathbf{r}\mathbf{r} - \mathbb{I}) \cdot \hat{\mathbf{p}}_i$$

alignment — repulsion — alignment in a dipolar field

ALIGNMENT *VS* NOISE => FLOCKING

Question: How much disorder is needed to melt a flock?

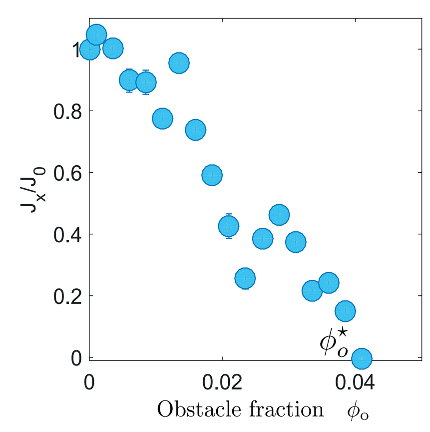
Flocking through heterogeneous media



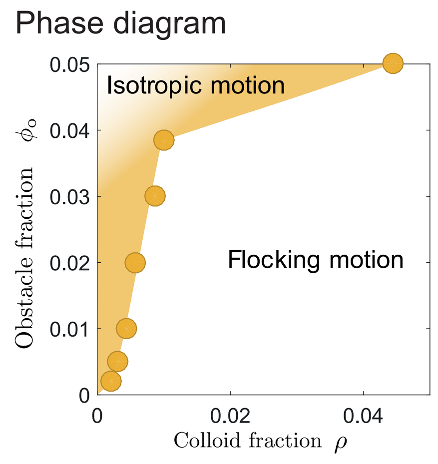
Videos

Disorder induces melting

Space-time averaged current

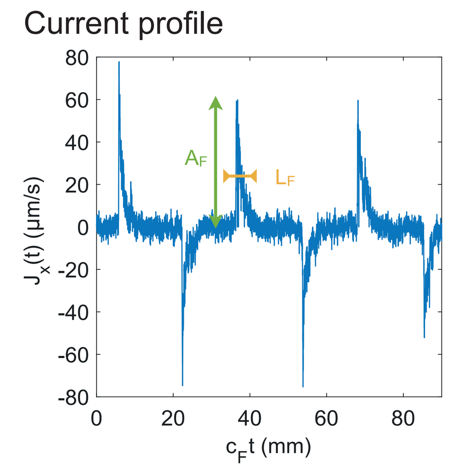


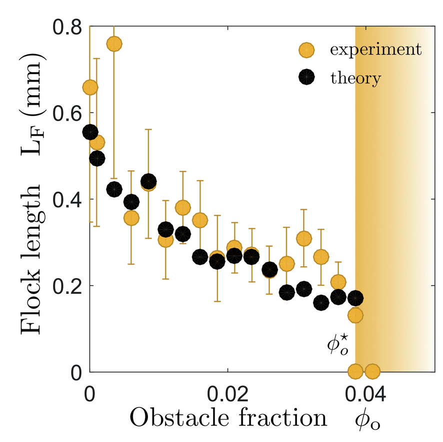
Phase diagram

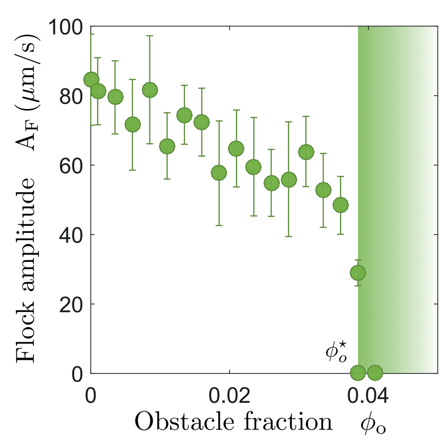


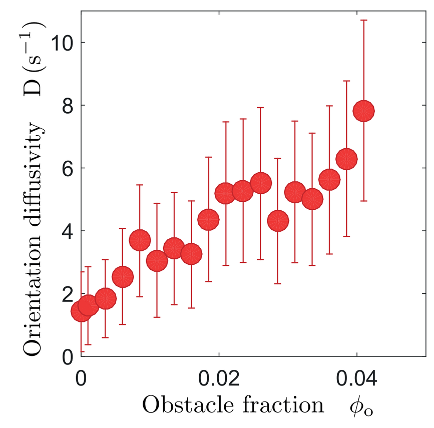
Nature of the transition: 1st order

Current profile









$$\partial_t \theta_i(t) = -\partial_{\theta_i} \sum_{j \neq i} A\hat{\mathbf{p}}_i \cdot \hat{\mathbf{p}}_j + \ldots + \sqrt{2D}\xi_i(t)$$

Quenched disorder + Motility = *Time* dependent angular noise

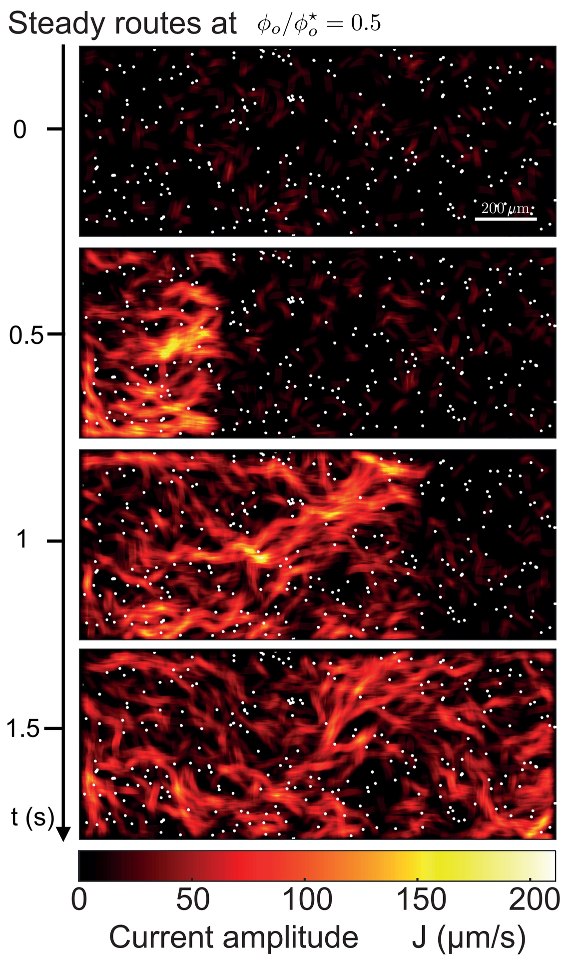
Theory prediction $L_F = f^{\circ}(\phi_o)$ agrees with experiments.

A VICSEK 1ST ORDER TRANSITION

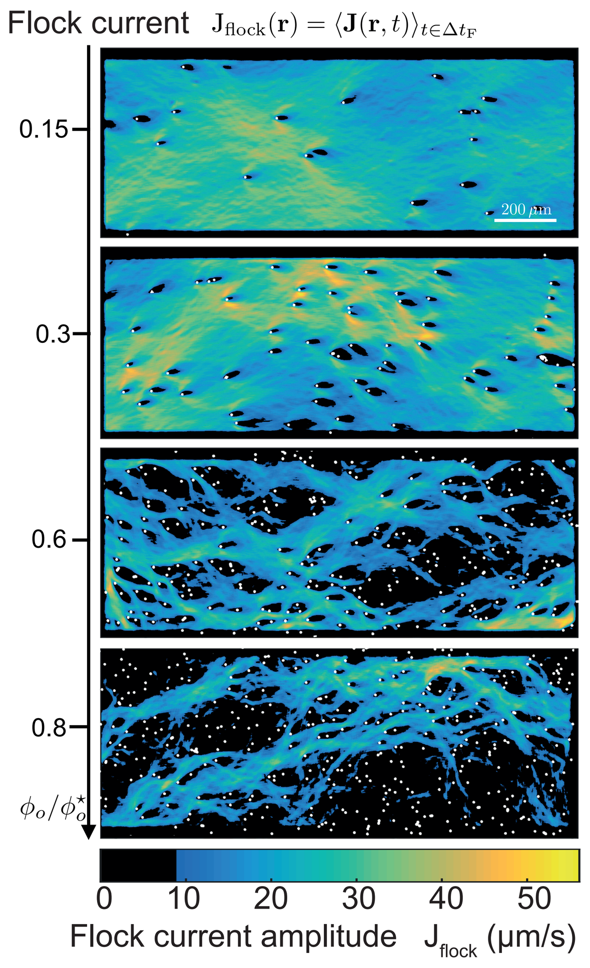
Question: Spatio-temporal fluctuations?

Emergence of sparse flowing networks as $\phi_o \to \phi_o^*$

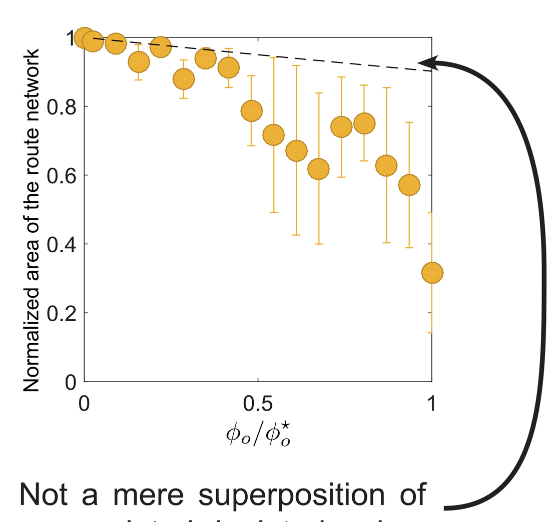
Steady routes at $\phi_o/\phi_o^* = 0.5$



Flock current $\mathbf{J}_{\text{flock}}(\mathbf{r}) = \langle \mathbf{J}(\mathbf{r}, t) \rangle_{t \in \Delta t_F}$



Network area



Not a mere superposition of uncorrelated depleted wakes

Active fluid in a random potential

$$\partial_t \mathbf{\Pi} + v_0 \mathbf{\Pi} \cdot \nabla \mathbf{\Pi} = \mathbb{P} \cdot \left[-\beta \nabla \rho + \alpha_2 \nabla^2 (\rho \mathbf{\Pi}) + \gamma \tilde{\Delta} \cdot (\rho \mathbf{\Pi}) + \mathbf{F}_o \right]$$

pressure — elasticity — random force $\mathbf{F}_o \sim -\nabla \phi_o$

BENDING BY A RANDOM POTENTIAL

$$\overline{|\partial \theta_{\mathbf{q}}|^2} = \frac{\beta_o^2 \phi_o}{v_o^2 + q_x^2(\alpha_2 - \gamma)^2 \bar{p}^2} \left(\frac{q_y}{q_x} \right)^2$$

disorder — elasticity

ELASTICITY *VS* DISORDER => SPARSE NETWORK

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ENS DE LYON

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