

Confinement-induced collective motion in suspensions of run-and-tumble particles

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(Dated: 12 November 2025)

Collective motion is ubiquitous in active systems at all length and time scales. The mechanisms behind such collective motion usually are alignment interactions between active particles, effective alignment after collisions between agents or symmetry-breaking fluctuations induced by passive species in active suspensions. In this article, we introduce a new type of collective motion in the shape of a traveling band induced purely by confinement, where no explicit or effective alignment are prescribed among active agents. We study a suspension of run-and-tumble particles confined in microchannels comprising asymmetric boundaries: one flat wall and one array of funnel-like obstacles. We study the phase behavior of the confined active suspension upon changes in the packing fraction and the persistence length to define the stability region of the traveling band. We characterize the traveling band structurally and dynamically and study its stability with respect to the tilt angle of the obstacles. Lastly, we describe the mechanism of motion of the band, which resembles the tracked locomotion of some heavy vehicles like tractors, finding that a counter-flux of active particles in the lower part of the band, explained in terms of source-sink and vacancy diffusion mechanisms, is the facilitator of the traveling band and sustains its motion. We name this new collective phenomenon *confinement-induced tracked locomotion*.

I. INTRODUCTION

Collective motion is ubiquitous in Nature at different length and time scales¹, ranging from genetic material migration during cell division², to bacterial swarming^{3,4}, the mesmerizing collective migration of *Dictyostelium*⁵, the phototactic response of the green micro-algae *C. reinhardtii*⁶⁻⁹, swarms of insects^{10,11}, schools of fish¹²⁻¹⁴, flocks of birds^{15,16}, herds of sheep¹⁷, and crowds of people¹⁸, among other examples.

Thirty years ago, Vicsek and collaborators proposed a model to mimic the collective behavior of aligning active particles: a simple aligning mechanism between point-like agents moving in a noisy environment, affecting the agents' orientation¹⁹. In particular, at intermediate densities and noise intensities, the Vicsek model predicted the formation of traveling bands (dense regions of aligning particles)²⁰⁻²³. The alignment between particles was the underlying mechanism of such traveling bands. The effects of confinement on the collective motion of active particles with alignment interactions have recently been addressed. Aligning self-propelled particles confined in arrays of obstacles with different shapes and distributions has revealed trapping and subdiffusive behavior^{24,25}. On the other hand, confinement in ordered arrays of obstacles can induce a re-entrant collective behavior, leading from self-organization into traveling bands to a disordered state and, as the packing fraction of obstacles increases, to a new synchronous collective behavior²⁶.

Although the Vicsek model can qualitatively explain many collective phenomena observed in organisms with evolved sensory organs and complex signal processing systems, it cannot do the same for their microscopic counterparts. This

is due to colloids or motile microorganisms usually exhibiting collective motion as a response to light or chemical stimuli^{7-9,27-31} or due to hydrodynamic interactions³²⁻³⁴, rather than through an explicit alignment mechanism among agents. Thus, systems exhibiting collective motion that arises without aligning interactions between agents and without the action of external fields are highly appreciated in the active matter community and provide a platform for understanding the physics behind this emergence.

Some examples of systems with no explicit aligning interactions that exhibit collective motion in bulk are "energy-depot" active disks which form traveling bands as a consequence of an effective alignment mechanism mediated by collisions³⁵, and active-passive mixtures of Brownian particles that form propagating interfaces as a result of a complex combined mechanism involving source/sink effects and oriented displacements of particles modulated by density fluctuations induced by the presence of passive particles^{36,37}.

Geometrical confinement has proven to be an efficient mechanism in rectifying³⁸⁻⁴¹, trapping and sorting⁴²⁻⁴⁵ active particles, especially configurations comprising concave regions in which the active particles tend to accumulate, such as funnels or chevrons⁴⁶. Moreover, the shape of the confining boundaries may induce jamming states⁴⁷ or destroy phase separation⁴⁸ in active systems. In this article, we present a simulation study of a two-dimensional suspension of run-and-tumble particles confined in asymmetric microchannels with one flat wall and one wall made of funnel-like obstacles (see Fig. 1).

To the best of our knowledge, we report for the first time the emergence of a dense traveling band whose formation and motion are completely induced and sustained by confinement, with neither explicit alignment between agents, nor effective alignment induced by particle shape or collisions, nor by the presence of passive particles in the suspension. We discov-

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ered such a traveling structure serendipitously, while performing the analysis of the results published in Ref.⁴⁹ by some of the present authors. The mechanism of the band's motion resembles the tracked locomotion of some heavy vehicles such as tractors, and thus we have named it *confinement-induced tracked locomotion*.

This article is organized in the following way. In section II, we introduce the model and the analysis tools. Section III contains the results and the discussion, and Section IV includes a summary and the conclusions. Finally, Section V has an index for the **Supplementary Information**.

II. MODEL AND METHODS

A. Model

The system under consideration is a two-dimensional suspension of active particles (type 1, in pink in Fig. 1) following run-and-tumble dynamics confined in microchannels composed of frozen particles (type 2, in yellow in Fig. 1).

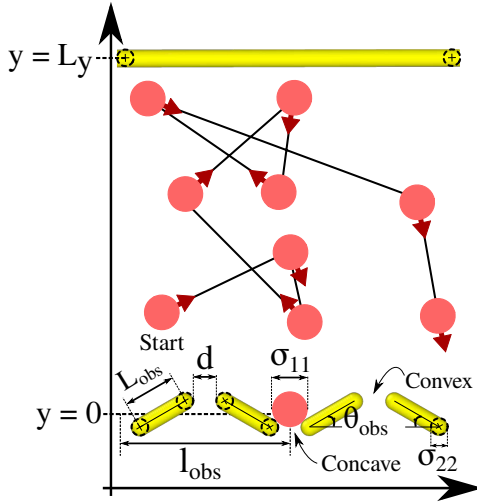


FIG. 1. Scheme of the geometry of the system. The top boundary of the microchannel is a flat wall, and the bottom boundary of an array of funnel-like obstacles with period $l_{\text{obs}} = 2(L_{\text{obs}} \cos \theta_{\text{obs}} + d + \sigma_{22})$, where $d = 1.25\sigma_{22}$ is the gap size, $L_{\text{obs}} = 3.0\sigma_{22}$ is the length of the obstacles and θ_{obs} the angle formed between the obstacles and the x -axis. The walls of the microchannel are composed of frozen particles (in yellow) of diameter σ_{22} , with a lattice constant, $l_w = 0.12\sigma_{22}$. The axis $y = 0$ is placed at the center of the obstacles. The active particles (i pink) follow the run-and-tumble phenotype observed in different motile microorganisms.

Run-and-tumble motion is implemented following Langevin dynamics:

$$m_i \frac{d^2 \mathbf{r}_i}{dt^2} = F_a \mathbf{n}_i - \nabla_i U - \gamma \mathbf{v}_i + \sqrt{2\gamma m_i k_B T} \mathbf{W}_i. \quad (1)$$

Here, $\mathbf{r}_i$, $\mathbf{n}_i$ and $\mathbf{v}_i$ are the position vector, unit orientation vector and velocity vector of particle i , respectively. The

active self-propulsion force is set to $F_a = 10$, the friction coefficient, $\gamma = 10$, the mass of the particles $m_i = 1.0$, and the thermal energy, $k_B T = 1.0$. The self-propulsion speed of the particles is, thus $v_0 = F_a/\gamma = 1.0$. With such a choice of parameters, the inertia of the particles' motion is only significant at very small length scales, so we can consider the system follows an overdamped regime⁴⁹. The thermal bath applies a stochastic force, $\mathbf{W}_i = (W_i^x, W_i^y)$, on the i th particle, given by the standard Gaussian white noise with zero mean and correlation $\langle W_i^x(t) W_i^y(t') \rangle = \delta_{ij} \delta_{xy} \delta(t - t')$.

All particles interact via a WCA⁵⁰ repulsive potential,

$$U(r) = \begin{cases} 4\epsilon_{mn} \left[\left(\frac{\sigma_{mn}}{r} \right)^{12} - \left(\frac{\sigma_{mn}}{r} \right)^6 \right] + \epsilon_{mn}, & r < 2^{1/6} \sigma_{mn}, \\ 0 & r \geq 2^{1/6} \sigma_{mn}. \end{cases} \quad (2)$$

with indexes m and n running over the two particle types. We set $\sigma_{11} = 2$, $\sigma_{22} = 1$ and $\epsilon_{11} = \epsilon_{22} = 1$. The crossed interactions are given by the Lorentz-Berthelot mixing rules^{51,52}: $\sigma_{mn} = (\sigma_{mm} + \sigma_{nn})/2$ and $\epsilon_{mn} = \sqrt{\epsilon_{mm}\epsilon_{nn}}$. Particles constituting the microchannel walls are placed at a distance $l_w = 0.12\sigma_{22}$ from each other.

Run-and-tumble motion is simulated as a discrete stochastic process, where the tumbling events are described by:

$$\theta_i(t + dt) = \begin{cases} \theta_i(t), & \alpha < \zeta(t) \\ \theta_i(t) + \Phi(t) & \alpha > \zeta(t) \end{cases}, \quad (3)$$

being θ_i the angle formed between the orientation vector $\mathbf{n}_i$ and the positive x -axis. $\alpha = t_{\text{trial}}/\tau_r$ is the probability of occurrence of a tumbling event, t_{trial} being the time between trials, and τ_r the mean time between tumbling events or re-orientation time. Here we use $t_{\text{trial}} = dt$, i.e. tumbling trials are performed at every step. Thus, the tumbling rate is $\alpha_r = \alpha/t_{\text{trial}} = 1/\tau_r$. $\zeta \in [0, 1]$ is a uniformly distributed random number generated at each step and $\Phi \in [0, 2\pi]$ is a uniformly distributed random angle. Note that, in this formulation the tumbling rate, α , is the probability that a particle performs a tumbling in the current timestep, and thus it is dimensionless.

The particles' level of activity is thus characterized by the persistence length, $l_p = \frac{F_a}{\alpha_r \gamma}$, which is the average distance an active particle travels before tumbling. In our work, we vary the suspension's packing fraction, $\phi = \frac{N\pi\sigma_{11}^2}{4L_x L_y} \in [0.20, 0.40]$, with N the number of active particles and L_x and L_y the edge lengths of the rectangular simulation box. We fix $L_y = 20\sigma_{22}$. The system contains $N \in (1000, 20000)$ active particles, depending on the packing fraction and the system's size, thus L_x is chosen accordingly. The initial condition is defined as a random distribution of active particles inside the microchannel with a uniform random distribution of orientations. Periodic boundary conditions are imposed on the x -axis. The confining channel comprises funnel-like obstacles in the lower part and a flat wall in the upper part (See Fig. 1). The obstacles feature gaps that do not allow the passage of the active particles. The gaps provide two stable resting positions for the active particles, since they can fit in the gaps (but cannot go through them). In Fig. 1, we present the geometry of the funnel-like

obstacles: we set their length to $L_{obs} = 3.0\sigma_{22}$, forming an angle θ_{obs} with respect to the x -axis which will be varied in the range $[7.5^\circ, 52.5^\circ]$ in steps of 7.5° . The width of the gaps is fixed to $d = 1.25\sigma_{22}$. The period of the obstacle array is given by $l_{obs} = 2(L_{obs}\cos\theta_{obs} + d + \sigma_{22})$. As a comparison, we also consider two different channels: one with two flat parallel walls and another consisting of a flat wall and corrugations with no gaps (See **Fig S1 of Supplementary Information**).

All quantities in the manuscript are expressed in reduced simulation units, using $k_B T$, σ_{22} , and m as units of energy, distance and mass, respectively. The simulations are performed using the open-source Molecular Dynamics package LAMMPS^{53,54}, in which we have implemented the run-and-tumble dynamics in equation 3. The equations of motion are integrated using the NVE integrator and the Langevin's thermostat with $dt = 0.001\tau$, where $\tau = \sqrt{\frac{m\sigma_{22}^2}{k_B T}}$ is the simulation time unit. Simulations are run for up to 30000τ .

B. Analysis tools

1. Identifying dense structures: Percolation

To start with, we characterize the internal structure of the system and, by analyzing the instantaneous particle configurations, we identify structures such as travelling bands and clogs: the former consist of a large percolating clusters moving along the channel, while the latter are large percolating immobile clusters. For each configuration, the set of pairwise particle distances was evaluated under periodic boundary conditions along the longitudinal direction of the channel (x -axis), and fixed boundaries along the y -axis. Two particles were considered connected if their separation was smaller than a prescribed cutoff distance $r_{cut} = \sigma_{11}$, chosen slightly above the mean interparticle spacing within the dense phase as shown in the radial distribution function (see **Fig. S2, Supplementary Information**). From this connectivity criterion, a percolation network was constructed, where each particle represents a node and pairwise connections define edges. Clusters were then identified as the connected components of this network and the system is considered in a percolated state when the network connects particles from one extreme $y = 0$ to the other $y = L_y - \sigma_{12}$ along y -axis. Having established the largest connected cluster in the system, this will correspond to the traveling band or the clog case for the following analysis. This procedure provides a robust identification of the collective structure and allows one to extract statistical quantities such as the temporal evolution of the band size and the distribution of orientation angles within the dense region.

2. Following the structures: Band velocity

The propagation speed of the traveling band was determined from the evolution of its center of mass (CM) along the

channel axis. Given that the system is periodic in the longitudinal direction, the CM position was computed using an angular (circular-mean) formulation that prevents discontinuities when the band crosses the periodic boundaries. Each particle position x_i was mapped to a phase angle $\theta_i = 2\pi(x_i - x_{min})/L_x$, from which the mean direction in angular space was calculated as

$$\tan \theta_{CM} = \frac{\langle \sin \theta_i \rangle}{\langle \cos \theta_i \rangle}.$$

The corresponding CM coordinate was then obtained by inverting this transformation back to real space. The coordinate $x_{CM}(t)$ thus obtained provides a smooth measure of the band's translational motion, from which the instantaneous and mean propagation velocities were extracted. As shown later, the CM velocity seems to be well defined with a constant value close to $\langle V \rangle \approx \frac{1}{3}v_0$. We will use this value to characterize the mechanism of the motion.

3. Motion mechanism: Fluxes and internal particle displacements in the travelling band

Finally, to quantify the microscopic dynamics within the traveling band, we evaluated the local flux and density profiles, as in Ref.³⁶. We employ a coarse-grained formulation based on Smoluchowski's equation for the instantaneous density and current fields in two dimensions. The microscopic density is defined as $\rho(\mathbf{r}, t) = \langle \sum_i \delta(\mathbf{r} - \mathbf{r}_i(t)) \rangle$ and currents are defined as $\mathbf{j}(\mathbf{r}, t) = \langle \sum_i \delta(\mathbf{r} - \mathbf{r}_i(t)) \mathbf{v}_i(t) \rangle$, where $\langle \dots \rangle$ denotes an ensemble average. These fields satisfy the Smoluchowski continuity equation, $\frac{\partial \rho(\mathbf{r}, t)}{\partial t} + \nabla \cdot \mathbf{j}(\mathbf{r}, t) = 0$. During the steady propagation of the traveling band, the center of mass of the dense phase moves with an average constant velocity $\langle V \rangle \approx \frac{1}{3}v_0$ along the longitudinal direction of the channel. Assuming that the band profile is self-averaging in the comoving frame, the coarse-grained density can be written as $\rho(\mathbf{r}, t) \simeq \tilde{\rho}(\tilde{\mathbf{r}})$, where $\tilde{\mathbf{r}} = \mathbf{r} - \langle \mathbf{V} \rangle t = (x - \langle V \rangle t, y)$ and $\tilde{\rho}(\tilde{\mathbf{r}})$ is the stationary density distribution in the reference frame of the traveling band. In this frame, the continuity equation reduces to a balance between the advective and diffusive fluxes, $\nabla_{\tilde{\mathbf{r}}} \cdot \mathbf{j}(\tilde{\mathbf{r}}) = \langle \mathbf{V} \rangle \cdot \nabla_{\tilde{\mathbf{r}}} \tilde{\rho}(\tilde{\mathbf{r}})$, which can be formally integrated to obtain the local current density as

$$\mathbf{j}(\tilde{\mathbf{r}}) = \langle \mathbf{V} \rangle \tilde{\rho}(\tilde{\mathbf{r}}) - \Delta(\tilde{\mathbf{r}}), \quad (4)$$

where $\Delta(\tilde{\mathbf{r}})$ represents a counter-current term that compensates the advective transport produced by the collective motion of the band, and must satisfy $\nabla_{\tilde{\mathbf{r}}} \cdot \Delta(\tilde{\mathbf{r}}) = 0$. Due to the fact that the system is traveling mainly along the x -direction of the channel, we can focus only on the longitudinal component of the previous equation, averaging out its dependence in x to explore the fluxes of the band along the perpendicular axis

$$j_x(y) = \langle V \rangle \rho(y) - \Delta_x(y) \quad (5)$$

In contrast with previous cases, where the counter-current is a constant³⁶, we observe a dependency with y due to the

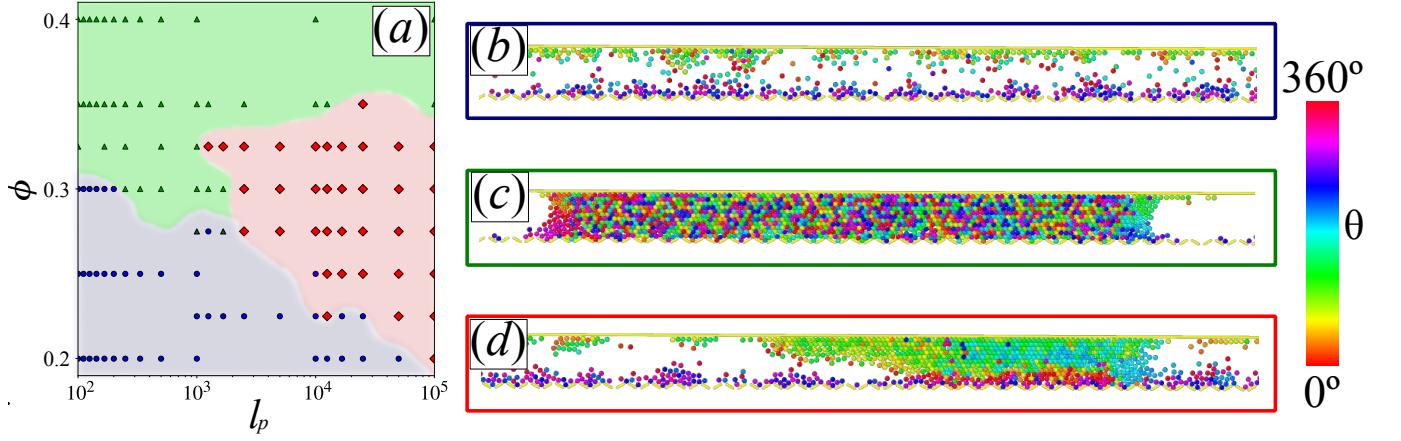


FIG. 2. Phase behavior of the confined active suspension. (a) Dynamic phase diagram in the plane $\phi - l_p$ for the active suspension confined in a microchannel with funnel-like obstacles configured at $\theta_{obs} = 30^\circ$. The different phases are represented by symbols and colors: (b) non-percolated system (blue circles); (c) clogging (green triangles); and (d) traveling band (red diamonds). The color code of the active particles in b-d represent the orientation angle, θ , with respect to the x -axis, according to the color bar on the right. All the graphics of trajectories of simulations presented in this article were generated in part using the visualization software OVITO⁵⁵.

symmetry-breaking in the bottom of the channel. This is an educated assumption based on direct observations and preliminary analysis of the traveling band trajectories. The counter-current accounts for the internal rearrangements and local diffusive fluxes of particles within the dense region, which reduce the apparent current below the purely advective value $\langle \mathbf{V} \rangle \bar{\rho}$. Therefore, the spatial dependence of $\Delta(\bar{\mathbf{r}})$ provides direct information on the internal dynamics and flux balance inside the traveling band.

To measure the flux, successive configurations separated by a fixed time interval $\Delta t = 1 \tau$ were used to estimate particle velocities from finite differences of their positions. Particles were binned along the transverse (y) direction into strips of thickness $\delta y = \sigma_{11}$, and for each bin we computed the local density $\rho(y)$ and the longitudinal flux component $j_x(y)$. The counter-current, defined as the difference between the advective and self-propulsive contributions to the flux, $\Delta_x(y) = \langle \mathbf{V} \rangle \rho(y) - j_x(y)$, was used to characterize the degree of internal rearrangement within the band. Averaging these quantities over time yields stationary profiles that provide detailed information on the internal mass transport and collective motion in the traveling structure.

III. RESULTS

A. Phase behavior

We start by exploring the phase behavior of the active suspension confined in microchannels with $\theta_{obs} = 30^\circ$ in the $l_p - \phi$ plane (Figure 2a), where the different phases are: non-percolating clustering state (blue circles, panel b), clogging (green triangles, panel c) and traveling band (red diamonds, panel d). Videos of these states are available in the **Supplementary Video 1**.

To classify, from a structural perspective, the different self-

organized steady states observed in the active suspension, we determine the probability of finding a percolating configuration along the y -axis at the steady state, P_p . Thus, high values of P_p indicate states where a big dense cluster spans the system in the y -direction, whereas small values correspond to states in which the active particles are not forming such structures. The dense structures may correspond to clogs or traveling bands. To distinguish between these two, we monitor the speed of the center of mass of the whole system in the x direction. States corresponding to a clog are characterised by velocities close to zero, in contrast to states corresponding to traveling bands. Combining the percolation and the center of mass velocity criteria, we build the phase diagram in Fig. 2a.

The clustering state consists of active particles accumulating at the funnels or at the flat wall of the microchannel and takes place at low l_p and ϕ (see Fig. 2b). The clog state mainly occurs for suspensions with high l_p and ϕ (see Fig. 2c). It also appears when confining the suspension in channels with two flat walls (with the same l_p and ϕ), and can be acknowledged as the confined equivalent of motility-induced phase separation (MIPS) in a bulk suspension with periodic boundary conditions^{56,57} (See **Figure S1a (bulk) and S1b (confinement between flat walls) and Supplementary Video 2**). The traveling band is observed in persistent active suspensions ($l_p > 4 \times 10^3$) and intermediate to low packing fractions ($0.30 \leq \phi \leq 0.20$), and consists of a big cluster of active particles that moves persistently towards left or right. In the example shown in Fig. 2d, it moves to the left.

Interestingly, the traveling band is only stable under confinement in microchannels featuring either funnel-like obstacles with gaps or corrugations. Neither in bulk nor in confinement within channels with two flat walls the band is stable, suggesting that its formation is induced by the asymmetry of the obstacles in one of the confining walls See **Figure S1 and Supplementary Video 2**. We also observe that, at low packing fractions, ($\phi \leq 0.25$), the system exhibits a cluster-

ing state for low l_p that directly becomes a traveling band as l_p increases. Contrastingly, at higher packing fractions, ($\phi \geq 0.275$), the system shows clogging behavior before the traveling band is formed as l_p increases (See Fig 2a).

B. Characterization of the traveling band

Having explored the phase behavior of the system, we now focus on the features of the traveling band. First, we calculate the speed of the center of mass in the x direction of the system, V_{CM} , for cases in which a clog or a traveling band is formed. Note that the center of mass of the system roughly matches that of the largest cluster when the system is in a clogging or a traveling state.

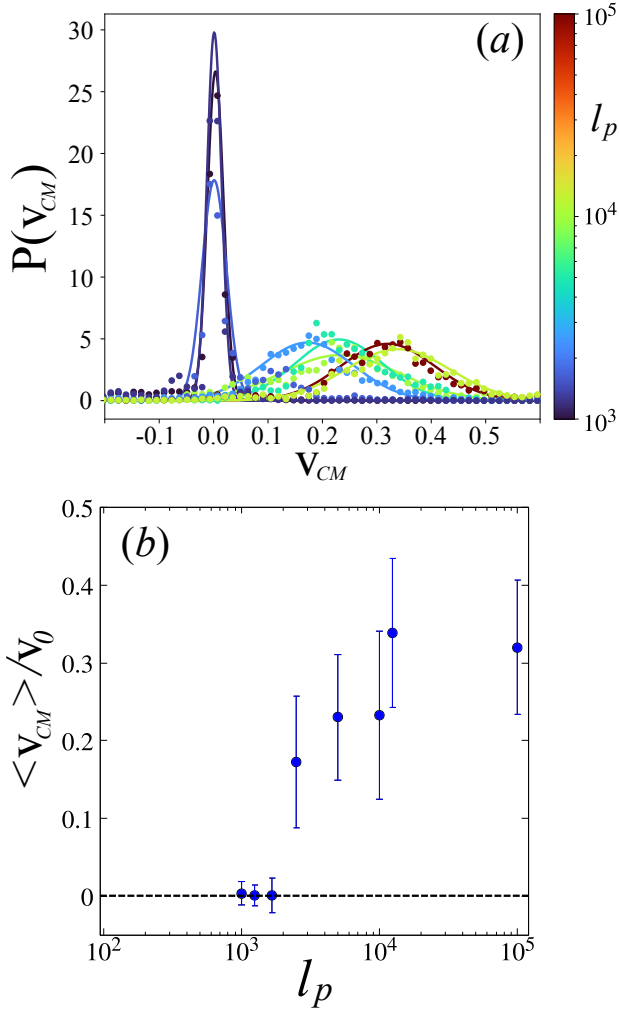


FIG. 3. Center of mass velocity of the system (a) Probability distributions of the Center-of-mass velocity of the system for $\phi = 0.3$ and $\theta_{obs} = 30^\circ$, at different values of l_p , for clogging and traveling states. (b) Average Center-of-mass velocity of the system as a function of the persistent length, l_p .

In Fig. 3a, we present the probability distributions of V_{CM} . The distributions calculated from simulations (circles) fit well

to Gaussian distributions (solid lines). The color bar represents the persistence length, l_p . For clogging states, $P(V_{CM})$ is centered at 0 with a small standard deviation, whereas, for traveling states, the distributions are shifted to non-zero values with higher standard deviations. Clearly, the mean speed of the center of mass, $\langle V_{CM} \rangle$, can be used as an order parameter to monitor the transition from clogging to traveling states, as presented in Fig. 3b. Remarkably, the traveling band reaches average speeds, $\langle V_{CM} \rangle$, of up to 35% as high as the active particles' self-propulsion speed (See Fig. 3b).

With the goal of unraveling the mechanism behind the traveling band's motion at the macroscopic level, we calculate and compare the orientation distributions, $P(\theta)$, of the active particles in clogging and traveling states (see Fig. 4).

In Fig. 4a we report the $P(\theta)$ for clogging states at different l_p and ϕ , observing, as could be expected, that the distributions are rather uniform. This is already visible from the snapshot presented in Fig. 2c, where, at the clog boundaries, active particles point in opposite directions, while inside the clog they are oriented at random. The profile of the clog boundaries seems parabolic, which could be due to the effective attraction towards the walls induced by activity. On the other hand, the $P(\theta)$ for traveling states in Fig. 4b, also at different l_p and ϕ , exhibits two distinctive peaks around $\theta = 90^\circ$ and $\theta = 180^\circ$. We have chosen cases in which the traveling structure moves to the right as shown in Fig. 4c, although the simulations show no clear preference for any direction. As seen in Fig. 4b, despite the different values of l_p and ϕ , as long as those values are within the stability region of the traveling band, the distribution of orientations inside the band remains the same, indicating the same underlying mechanism.

Figure 4c shows a typical snapshot of the traveling band, with the orientation vectors of the particles colored according to the angle they form with respect to the x -axis. We identify four domains corresponding to the features of the $P(\theta)$ shown in Fig. 4b. Domain I is composed of particles mainly pointing upwards and roughly containing half of the band's particles, thus corresponding to the peak around $\theta = 90^\circ$. Domain II is also composed of approximately half of the band's particles; the particles in this domain point in the direction of motion of the band (the peak around $\theta = 0^\circ$ and 360° due to periodicity of θ) and thus represent the propulsion force of the band. In other words, domain II pushes domain I. Domain III is composed of the particles below domains I and II, that form a thin layer that spans the whole band along its x -axis and points in the opposite direction of the band, corresponding to a short peak around $\theta = 180^\circ$. Finally, domain IV is mainly composed of particles trapped in the concave region of the gaps which are pointing downwards. Particles that belong to domain IV are reflected in the $P(\theta)$ as the flat region in the range $225^\circ < \theta < 325^\circ$.

C. Mechanism of travelling band's motion

The well-defined internal structure consisting of four domains is maintained as long as the band moves. Any drastic modification of this structure leads to the formation of a clog

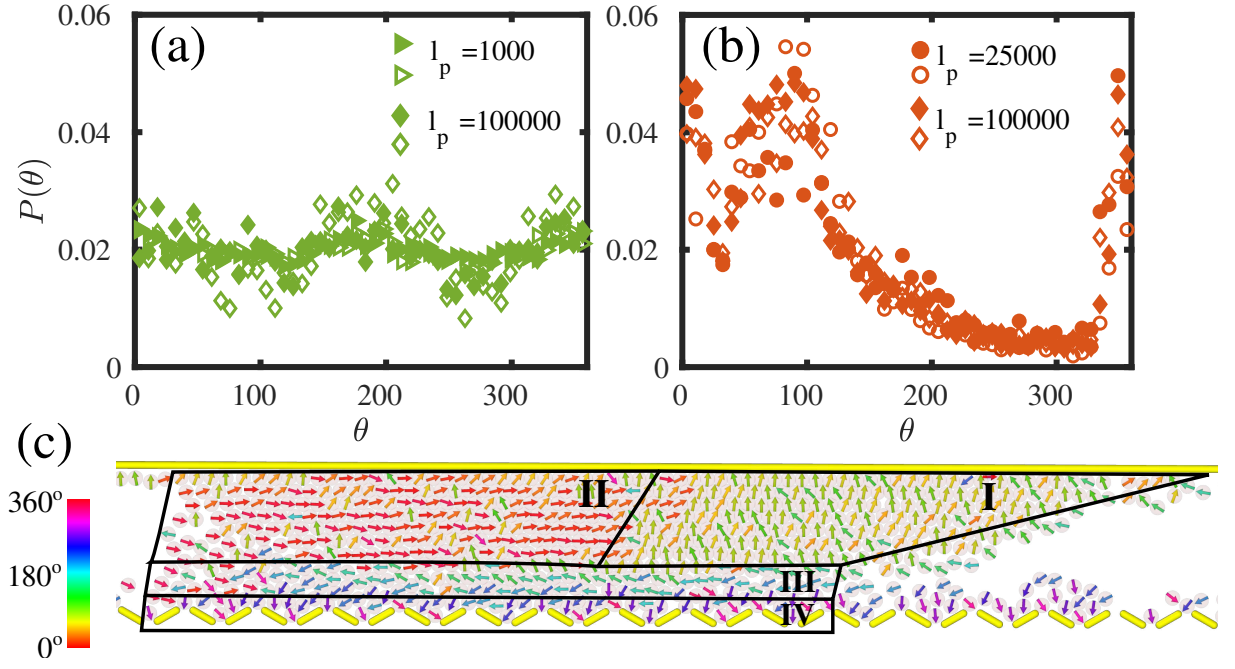


FIG. 4. Probability distributions of the orientation angle, θ , of active particles for four selected cases. (a) Clogging states. Filled markers correspond to $\phi = 0.40$, and empty to $\phi = 0.35$. (b) Traveling states. Filled markers correspond to $\phi = 0.275$ and empty to $\phi = 0.25$. (c) Orientation domains within the band. **I**: Particles pointing mainly upwards. **II**: Particles pointing towards the direction of motion of the traveling band, constituting the thrust. **III**: Particles forming a thin layer in the lower part of the band pointing opposite to the band's motion. This domain is the facilitator of the collective motion. **IV**: Particles trapped in the funnels mainly pointing downwards. The distributions are computed using only the orientations of the largest cluster in the system. The band moves to the right and $\theta_{obs} = 30^\circ$.

(high ϕ) or a clustering state (low ϕ), depending on the packing fraction.

Although it is clear that the band's motion relies on domain **II** pushing domain **I**, the dynamics of domains **III** and **IV** are also crucial for understanding the mechanism that sustains this motion. As the band moves, there is an inflow of particles directed opposite to the band's motion. As shown in Fig. 4c, the profile of the boundary of the traveling band, which faces the above-mentioned inflow of particles, can be described as a straight line whose slope has the same sign as the band's direction of motion. Thus, the inflow of particles can move down along the band's linear boundary to reach its lowest part, filling the gap between the top domains (**I** and **II**) and the particles trapped in the obstacles. The band keeps moving on top of the particles that constitute the inflow (now domain **III**), which, in turn, are arranged on top of the particles trapped in the gaps (now domain **IV**). Particles in domain **III** find their way out, hopping through vacancies opened due to the relocation of particles induced by the motion of domains **I** and **II**, and the sliding along the obstacles. Finally, particles of domain **III** leave the band from behind. Following the described mechanism, the same particles populate **I** and **II** for extended periods, with low exchange rate, whereas domains **III** and **IV** are always composed of different particles. In the **Supplementary Video 3**, we present a movie with the details of the band's motion.

As domain **I** is the thrust of the band, the counter-flow of particles represented in domain **III** is the facilitator of its mo-

tion. If particles in domain **III** could not flow through the lower part of the band, it would lead to the accumulation of particles opposing to the band's motion in its frontal part, ending up in a clogging state. Particles in domain **III** are able to find their way out of the band due to the presence of the obstacles that comprise two stable positions for active particles with a height difference (convex and concave gaps), which facilitate hopping and sliding. This is confirmed by simulations of confined active suspensions inside channels with two flat walls, where only clogging states form (See **Figure S1**).

Since the motion of the bands implies two currents of particles moving in opposite directions- domains **I** and **II** in the band's direction and **III** in the opposite direction - it somehow resembles the tracked locomotion performed by some vehicles, although both currents move at different speeds (as will be discussed later in Fig. II B 3). Thus, we name this new type of collective motion *confinement-induced tracked locomotion*.

Active systems are well known to exhibit strong finite size effects, especially those forming traveling structures^{36,58,59}. With the intention of testing the robustness of our results, we perform simulations setting the conditions we expect a traveling band, but for channels with $l_p < L_x < 10l_p$. We observe that the traveling bands are still formed and move following the same mechanism described above. However, the traveling bands are stable in a shorter length scale and thus more difficult to analyze See **Fig. S3**. We are interested in characterizing and unraveling the mechanism of *confinement-induced tracked locomotion*, so we set the simulations at con-

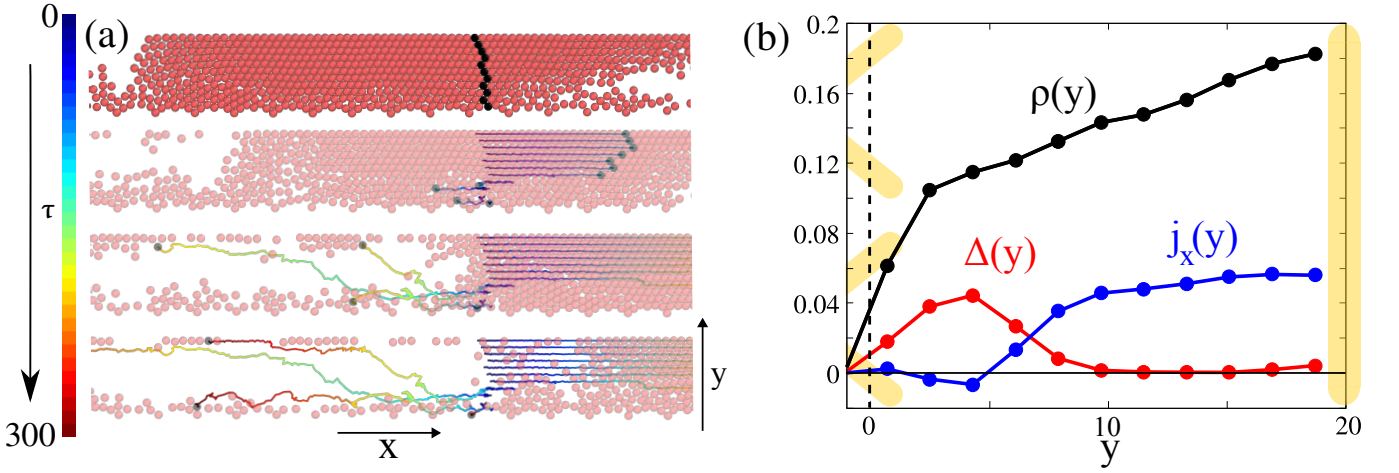


FIG. 5. (a) Representative particle trajectories depending on their initial positions along the y -axis inside the traveling band, for $l_p = 10^5$, $\phi = 0.3$ and $\theta_{obs} = 30^\circ$. The wall particles are not shown for the sake of clarity. (b) Corresponding local density profiles $\rho(y)$, total flux $j_x(y)$, and counter-current $\Delta(y)$ along the y -axis. The channel walls are depicted in yellow for reference.

ditions at which we can observe it for longer time scales ($L_x \in [790, 1000]$) to have statistically significant results.

Aiming to characterize, at the quantitative level, the mechanism of *confinement-induced tracked locomotion*, we calculate the internal fluxes of particles within the traveling band with respect to its center of mass as described in Section II B 3, following the integrated version of the Smoluchowski's continuity equation presented in equation 5. In Figure 5a, we present the trajectories of particles belonging to the band placed along the y -axis. We observe that particles in the top part of the band, those belonging to domains I and II, follow approximately horizontal trajectories in the direction of the band's motion, and are kept inside the band. On the other hand, particles in the lower part of the band (domains III and IV) also describe horizontal trajectories, in the opposite direction of the band's motion, but at a lower speed. Their trajectories exhibit the characteristic pattern of vacancy diffusion. Such vacancies appear due to the rearrangement of particles caused by the motion of the upper part of the band. Particles also take advantage of sliding along the obstacles to occupy the vacancies, as shown in some of the trajectories depicted in Fig. 5a. Finally, the majority of particles in domain III leave the band, whereas some of them get trapped in the gaps.

In Figure 5b, we present the three averaged quantities involved in equation 5, for a typical system exhibiting *confinement-induced tracked locomotion*: local density profile, $\rho(y)$ (in black); flux of particles in the x direction along the y -axis, $j_x(y)$ (in blue); and the counter-current of particles, $\Delta(y)$ (in red). The funnel-like obstacles and the top wall of the channel are depicted in the figure in yellow, for reference. In the concave regions of the obstacles, $\rho(y)$ adopts values close to zero. This is because only one particle per l_{obs} is counted due to the shape of the obstacles. Then, $\rho(y)$ grows fast, up to positions just above the convex gaps of the obstacles (spanning domains IV and II), and then it grows linearly, with a smaller slope, up to the top wall of the microchannel (domains I and II).

As expected, $j_x(y)$ shows a small but negative value in the region that corresponds to the flow of particles belonging to domain III in the opposite direction of the band's motion, whereas the region comprising domains I and II ($y \geq 7.5$) shows a constant high flux of particles in the same direction of the band's motion. Both the tendencies of $\rho(y)$ and $j_x(y)$ are consistent with the structure and dynamics of the band as shown in Fig. 5a (see also **Supplementary Video 2**).

Finally, $\Delta_x(y)$ shows a peak centered at the region corresponding to domain III, whereas it vanishes in the rest of the microchannel. As shown in a previous work³⁶, a non-zero counter-current term, $\Delta_x(y)$, signals a source-sink effect that, in the case of *confinement-induced tracked locomotion*, occurs in the lower part of the band and reflects the dynamics of domain III: particles are captured from at front end of the band and expelled from the back end of the band. Additionally, $\Delta_x(y)$ contains all the contributions that oppose to the advective transport represented by the collective motion of the band ($\langle V_{CM} \rangle \neq 0$), thus accounting for the vacancy diffusion of particles due to rearrangements within the band and facilitated by sliding along the obstacles. The vacancy diffusion mechanism that contributes to the motion of particles in domain III is justified since the particles inside the band are arranged in a hexagonal lattice that is continuously distorted, generating empty lattice spaces that are subsequently occupied by other particles.

D. Stability of the band with respect to θ_{obs}

With the goal of understanding the role of θ_{obs} in *confinement-induced tracked locomotion*, we perform simulations at $\phi = 0.30$ and $l_p = 10^5$ for $\theta_{obs} \in [0^\circ, 75^\circ]$. In Fig. 6, using $\langle V_{CM} \rangle$ as order parameter, we observe the existence of a range $15^\circ \leq \theta_{obs} \leq 45^\circ$ which allows the formation of traveling structures.

Interestingly, for $22.5^\circ \leq \theta_{obs} \leq 30^\circ$ the traveling band is

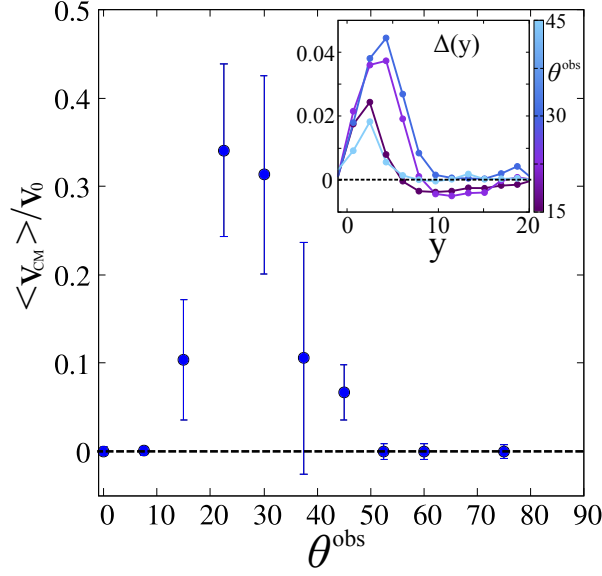


FIG. 6. Center-of-mass velocity as a function of corrugation tilt angle. Inset represents the dependence of the x-component of the counter-current y-axis $\Delta_x(y)$ on tilt angle, when the traveling band appears.

fully formed and reaches its top speed. As we highlighted before, the counter-current of active particles in domain **III** is the facilitator of the collective motion, and thus, when we monitor $\Delta_x(y)$ as θ_{obs} varies, we observe a non-monotonic behavior that perfectly correlates with the behavior of $\langle V_{CM} \rangle$, exhibiting the highest peaks, precisely, for $\theta_{obs} = 22.5^\circ$ and 30° . Thus, the larger the counter-current the faster the traveling band, which might seem counter-intuitive in the first place. However, since $\Delta_x(y)$ accounts for rearrangement and diffusive fluxes opposing to the band's motion, we suggest that those angles favor particles' rearrangements at the lower part of the band by enhancing sliding and thus producing more vacancies for particles in domain **III** to diffuse into.

IV. SUMMARY AND CONCLUSIONS

In the reported work, we have studied the collective behavior of persistent active suspensions confined in asymmetric channels. The top boundary of the channel is a flat wall and its bottom boundary is composed of an array of funnel-like obstacles (see Fig. 1). The active particles follow translational overdamped Langevin's dynamics and rotational run-and-tumble dynamics. Our numerical results show a new type of collective motion in the shape of a wide and dense traveling band induced by the symmetry-breaking of funnel-like obstacles. Such traveling band has not been observed neither in bulk nor under confinement in channels bounded by two flat walls.

By characterizing the mechanism of the traveling band's motion qualitatively and quantitatively, we identify its similarity with the motion of the tracks of vehicles, reason why we name this collective motion *confinement-induced tracked*

locomotion. While the band is moving, its internal structure can be described by 4 domains (see Fig. 4c). The mechanism relies on two key aspects: 1.) Particles in domain **II** constitute the thrust of the band by pushing domain **I**. 2.) Particles in domain **III** counter-flow in the lower part of the band via source-sink and vacancy diffusion mechanisms mediated by sliding along the obstacles. The existence of this counter-flow of particles facilitates the band's motion. Without it, the traveling band ends up in a clogging state.

Interestingly, we found the existence of a narrow range of obstacles tilt angles, θ_{obs} which promotes the emergence of the traveling state. We discuss the preferred θ_{obs} in terms of an enhanced counter-current, $\Delta_x(y)$, as a consequence of an improved sliding along the obstacles for such angles.

We suggest that a possible experimental realization of the system might consist in a concentrated suspension of the motile microalgae *Chlamydomonas reinhardtii* confined into a ring-shaped microfluidic device with one asymmetric boundary (with the shape of corrugations or funnels). It has been shown that a single cell of *C. reinhardtii* persistently follows the curvature of a circular chamber⁶⁰, which suggests that a collection of cells might behave in a similar way as described in the article. The ring-shaped chamber should have a perimeter of the same order of magnitude of the persistence length of the microalgae. To achieve high persistence lengths and concentrate the cells in specific regions within the ring, *C. reinhardtii* phototaxis can be leveraged. Another possible experimental realization of the proposed mechanism consists in Janus particles confined into rings. A recent study has reported clustering of Janus particles in ring-shaped soft confinement⁵⁷. Such clustering effect might be the basis for a traveling structure when the width of the ring and the packing fraction of the active suspension are correctly tuned. A potential technological application of the *confinement-induced tracked locomotion* could be fast steered one-dimensional transport of passive particles in narrow channels.

V. SUPPLEMENTARY INFORMATION

- **SI** containing additional figures and discussions. **Figure S1:** bulk, channels with 2 flat walls and channels with corrugations with no gaps. **Fig. S2:** pair correlation functions to choose the correct cut-off radius for the percolation criterion. **Figure S3:** Finite size effects, proof that in long channels the traveling band is still formed.
- **Supplementary Video 1:** containing a video version of Figs. 2 c,d and e.
- **Supplementary Video 2:** movie from simulations of the active suspension in bulk, confined within flat walls, and within channels with corrugations with no gaps.
- **Supplementary Video 3:** a movie showing the microscopic details of the motion of the traveling band.
- **Supplementary Data:** LAMMPS configurations of a

system exhibiting *confinement-induced tracked locomotion* in a long channel with $L_x = 10l_p$.

ACKNOWLEDGMENTS

C.V. acknowledges fundings IHRC22/00002 and Proyecto PID2022-140407NB-C21 funded by MCIN/AEI /10.13039/501100011033 and FEDER, UE. C.V. and H.S. acknowledge fundings from the European Union's Horizon research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101108868 (BIOMICAR). H.S. and J. M-R. thanks the insightful discussions with Rodrigo Fernández-Quevedo García. H. S. and C. V. acknowledge the discussions with Sujeet Kumar Choudhary and Marco Polin.

AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

- ¹T. Vicsek and A. Zafeiris, "Collective motion," *Physics reports* **517**, 71–140 (2012).
- ²J. M. Scholey, I. Brust-Mascher, and A. Mogilner, "Cell division," *Nature* **422**, 746–752 (2003).
- ³D. B. Kearns, "A field guide to bacterial swarming motility," *Nature reviews microbiology* **8**, 634–644 (2010).
- ⁴N. C. Darnton, L. Turner, S. Rojevsky, and H. C. Berg, "Dynamics of bacterial swarming," *Biophysical journal* **98**, 2082–2090 (2010).
- ⁵H. Hashimura, Y. V. Morimoto, M. Yasui, and M. Ueda, "Collective cell migration of dictyostelium without camp oscillations at multicellular stages," *Communications biology* **2**, 34 (2019).
- ⁶G. B. Witman, "Chlamydomonas phototaxis," *Trends in cell biology* **3**, 403–408 (1993).
- ⁷J. Arrieta, A. Barreira, M. Chioccioli, M. Polin, and I. Tuval, "Phototaxis beyond turning: persistent accumulation and response acclimation of the microalga *chlamydomonas reinhardtii*," *Scientific reports* **7**, 3447 (2017).
- ⁸S. K. Choudhary, A. Baskaran, and P. Sharma, "Reentrant efficiency of phototaxis in *chlamydomonas reinhardtii* cells," *Biophysical journal* **117**, 1508–1513 (2019).
- ⁹S. K. Choudhary, Y. Ma, A. Baskaran, and P. Sharma, "Transient state dynamics of *chlamydomonas reinhardtii* cells during phototaxis," *Physical Review Research* **7**, 033282 (2025).
- ¹⁰C. M. Topaz, A. J. Bernoff, S. Logan, and W. Toolson, "A model for rolling swarms of locusts," *The European Physical Journal Special Topics* **157**, 93–109 (2008).
- ¹¹G. Ariel and A. Ayali, "Locust collective motion and its modeling," *PLOS computational Biology* **11**, e1004522 (2015).
- ¹²H.-S. Niwa, "Self-organizing dynamic model of fish schooling," *Journal of theoretical Biology* **171**, 123–136 (1994).
- ¹³U. Lopez, J. Gautrais, I. D. Couzin, and G. Theraulaz, "From behavioural analyses to models of collective motion in fish schools," *Interface focus* **2**, 693–707 (2012).
- ¹⁴L. Liu, Z. Liu, J. Lin, Y. Tao, Z. Ge, and F. Meng, "Collective motion model inspired by fish school based on deep attention mechanism," *Bioinspiration & Biomimetics* **20**, 056012 (2025).
- ¹⁵W. Bialek, A. Cavagna, I. Giardina, T. Mora, E. Silvestri, M. Viale, and A. M. Walczak, "Statistical mechanics for natural flocks of birds," *Proceedings of the National Academy of Sciences* **109**, 4786–4791 (2012).
- ¹⁶A. Cavagna and I. Giardina, "Bird flocks as condensed matter," *Annu. Rev. Condens. Matter Phys.* **5**, 183–207 (2014).
- ¹⁷A. Garcimartín, J. Pastor, L. Ferrer, J. Ramos, C. Martín-Gómez, and I. Zuriguel, "Flow and clogging of a sheep herd passing through a bottleneck," *Physical Review E* **91**, 022808 (2015).
- ¹⁸F. Gu, B. Guiselin, N. Bain, I. Zuriguel, and D. Bartolo, "Emergence of collective oscillations in massive human crowds," *Nature* **638**, 112–119 (2025).
- ¹⁹T. Vicsek, A. Czirók, E. Ben-Jacob, I. Cohen, and O. Shochet, "Novel type of phase transition in a system of self-driven particles," *Physical review letters* **75**, 1226 (1995).
- ²⁰H. Chaté, F. Ginelli, G. Grégoire, and F. Raynaud, "Collective motion of self-propelled particles interacting without cohesion," *Physical Review E—Statistical, Nonlinear, and Soft Matter Physics* **77**, 046113 (2008).
- ²¹H. Chaté, F. Ginelli, G. Grégoire, F. Peruani, and F. Raynaud, "Modeling collective motion: variations on the vicsek model," *The European Physical Journal B* **64**, 451–456 (2008).
- ²²A. P. Solon, J.-B. Caussin, D. Bartolo, H. Chaté, and J. Tailleur, "Pattern formation in flocking models: A hydrodynamic description," *Physical Review E* **92**, 062111 (2015).
- ²³F. Ginelli, "The physics of the vicsek model," *The European Physical Journal Special Topics* **225**, 2099–2117 (2016).
- ²⁴O. Chepizhko and F. Peruani, "Diffusion, subdiffusion, and trapping of active particles in heterogeneous media," *Physical review letters* **111**, 160604 (2013).
- ²⁵O. Chepizhko and F. Peruani, "Active particles in heterogeneous media display new physics," *The European Physical Journal Special Topics* **224**, 1287–1302 (2015).
- ²⁶H. Serna, B. Li, and W. T. Gózdź, "Influence of obstacles on collective motion of self-propelled particles forming traveling bands," *Physica A: Statistical Mechanics and its Applications* **658**, 130303 (2025).
- ²⁷E. O. Budrene and H. C. Berg, "Dynamics of formation of symmetrical patterns by chemotactic bacteria," *Nature* **376**, 49–53 (1995).
- ²⁸Y. Wu, "Collective motion of bacteria in two dimensions," *Quantitative Biology* **3**, 199–205 (2015).
- ²⁹R. Erban and H. G. Othmer, "From individual to collective behavior in bacterial chemotaxis," *SIAM Journal on Applied Mathematics* **65**, 361–391 (2004).
- ³⁰B. Liebchen and H. Lowen, "Synthetic chemotaxis and collective behavior in active matter," *Accounts of chemical research* **51**, 2982–2990 (2018).
- ³¹E. F. Keller and L. A. Segel, "Traveling bands of chemotactic bacteria: a theoretical analysis," *Journal of theoretical biology* **30**, 235–248 (1971).
- ³²F. Alarcón and I. Pagonabarraga, "Spontaneous aggregation and global polar ordering in squirmer suspensions," *Journal of Molecular Liquids* **185**, 56–61 (2013).
- ³³F. Alarcón, C. Valeriani, and I. Pagonabarraga, "Morphology of clusters of attractive dry and wet self-propelled spherical particle suspensions," *Soft matter* **13**, 814–826 (2017).
- ³⁴A. Zöttl and H. Stark, "Hydrodynamics determines collective motion and phase behavior of active colloids in quasi-two-dimensional confinement," *Physical review letters* **112**, 118101 (2014).
- ³⁵J. P. Miranda, D. Levis, and C. Valeriani, "Collective motion of energy depot active disks," *Soft Matter* **21**, 1045–1053 (2025).
- ³⁶R. Fernandez-Quevedo, E. Chacon, P. Tarazona, and C. Valeriani, "Dynamics and rupture of doped motility induced phase separation," *Soft Matter* (2025).
- ³⁷A. Wysocki, R. G. Winkler, and G. Gompper, "Propagating interfaces in mixtures of active and passive brownian particles," *New journal of physics* **18**, 123030 (2016).
- ³⁸S. Anand, X. Ma, S. Guo, S. Martiniani, and X. Cheng, "Transport and energetics of bacterial rectification," *Proceedings of the National Academy of Sciences* **121**, e2411608121 (2024).
- ³⁹J. Tailleur and M. Cates, "Sedimentation, trapping, and rectification of dilute bacteria," *Europhysics Letters* **86**, 60002 (2009).
- ⁴⁰M. Wan, C. Olson Reichhardt, Z. Nussinov, and C. Reichhardt, "Rectification of swimming bacteria and self-driven particle systems by arrays of asymmetric barriers," *Physical review letters* **101**, 018102 (2008).
- ⁴¹R. Di Leonardo, L. Angelani, D. Dell'Arciprete, G. Ruocco, V. Iebba, S. Schippa, M. P. Conte, F. Mecarini, F. De Angelis, and E. Di Fabrizio, "Bacterial ratchet motors," *Proceedings of the National Academy of Sciences* **107**, 9541–9545 (2010).
- ⁴²P. Galajda, J. Keymer, P. Chaikin, and R. Austin, "A wall of funnels concentrates swimming bacteria," *Journal of bacteriology* **189**, 8704–8707 (2007).

- ⁴³R. Martinez, F. Alarcon, J. L. Aragonés, and C. Valeriani, “Trapping flocking particles with asymmetric obstacles,” *Soft matter* **16**, 4739–4745 (2020).
- ⁴⁴A. Kaiser, H. Wensink, and H. Löwen, “How to capture active particles,” *Physical review letters* **108**, 268307 (2012).
- ⁴⁵N. Kumar, R. K. Gupta, H. Soni, S. Ramaswamy, and A. Sood, “Trapping and sorting active particles: Motility-induced condensation and smectic defects,” *Physical Review E* **99**, 032605 (2019).
- ⁴⁶C. O. Reichhardt and C. Reichhardt, “Ratchet effects in active matter systems,” *Annual Review of Condensed Matter Physics* **8**, 51–75 (2017).
- ⁴⁷Š. Pajger and F. Slanina, “Jamming of active particles in narrow pores: implications for ratchet effect and diffusion coefficient,” *Journal of Statistical Mechanics: Theory and Experiment* **2025**, 083201 (2025).
- ⁴⁸Y. Ben Dor, S. Ro, Y. Kafri, M. Kardar, and J. Tailleur, “Disordered boundaries destroy bulk phase separation in scalar active matter,” *Physical Review E* **105**, 044603 (2022).
- ⁴⁹H. Serna, C. M. Barriuso G., I. Pagonabarraga, M. Polin, and C. Valeriani, “Sorting of binary active–passive mixtures in designed microchannels,” *Soft Matter*, – (2025).
- ⁵⁰J. D. Weeks, D. Chandler, and H. C. Andersen, “Role of repulsive forces in determining the equilibrium structure of simple liquids,” *The Journal of chemical physics* **54**, 5237–5247 (1971).
- ⁵¹H. A. Lorentz, “Ueber die anwendung des satzes vom virial in der kinetischen theorie der gase,” *Annalen der physik* **248**, 127–136 (1881).
- ⁵²D. Berthelot, “Sur le mélange des gaz,” *Compt. Rendus* **126**, 15 (1898).
- ⁵³S. Plimpton, “Fast parallel algorithms for short-range molecular dynamics,” *Journal of computational physics* **117**, 1–19 (1995).
- ⁵⁴A. P. Thompson, H. M. Aktulga, R. Berger, D. S. Bolintineanu, W. M. Brown, P. S. Crozier, P. J. in ’t Veld, A. Kohlmeyer, S. G. Moore, T. D. Nguyen, R. Shan, M. J. Stevens, J. Tranchida, C. Trott, and S. J. Plimpton, “LAMMPS - a flexible simulation tool for particle-based materials modeling at the atomic, meso, and continuum scales,” *Comp. Phys. Comm.* **271**, 108171 (2022).
- ⁵⁵A. Stukowski, “Visualization and analysis of atomistic simulation data with ovito—the open visualization tool,” *Modelling and simulation in materials science and engineering* **18**, 015012 (2009).
- ⁵⁶M. E. Cates and J. Tailleur, “Motility-induced phase separation,” *Annu. Rev. Condens. Matter Phys.* **6**, 219–244 (2015).
- ⁵⁷T. Knippenberg, A. Jayaram, T. Speck, and C. Bechinger, “Motility-induced clustering of active particles under soft confinement,” *Physical Review Letters* **133**, 048301 (2024).
- ⁵⁸R. Kürsten and T. Ihle, “Dry active matter exhibits a self-organized cross sea phase,” *Physical Review Letters* **125**, 188003 (2020).
- ⁵⁹H. Chaté, “Dry aligning dilute active matter,” *Annual Review of Condensed Matter Physics* **11**, 189–212 (2020).
- ⁶⁰S. A. Bentley, H. Laeverenz-Schlogelhofer, V. Anagnostidis, J. Cammann, M. G. Mazza, F. Gielen, and K. Y. Wan, “Phenotyping single-cell motility in microfluidic confinement,” *Elife* **11**, e76519 (2022).

Supplementary Information: *Confinement-induced collective motion in suspensions of run-and-tumble particles*

1 The traveling band is only observed under confinement in asymmetric channels

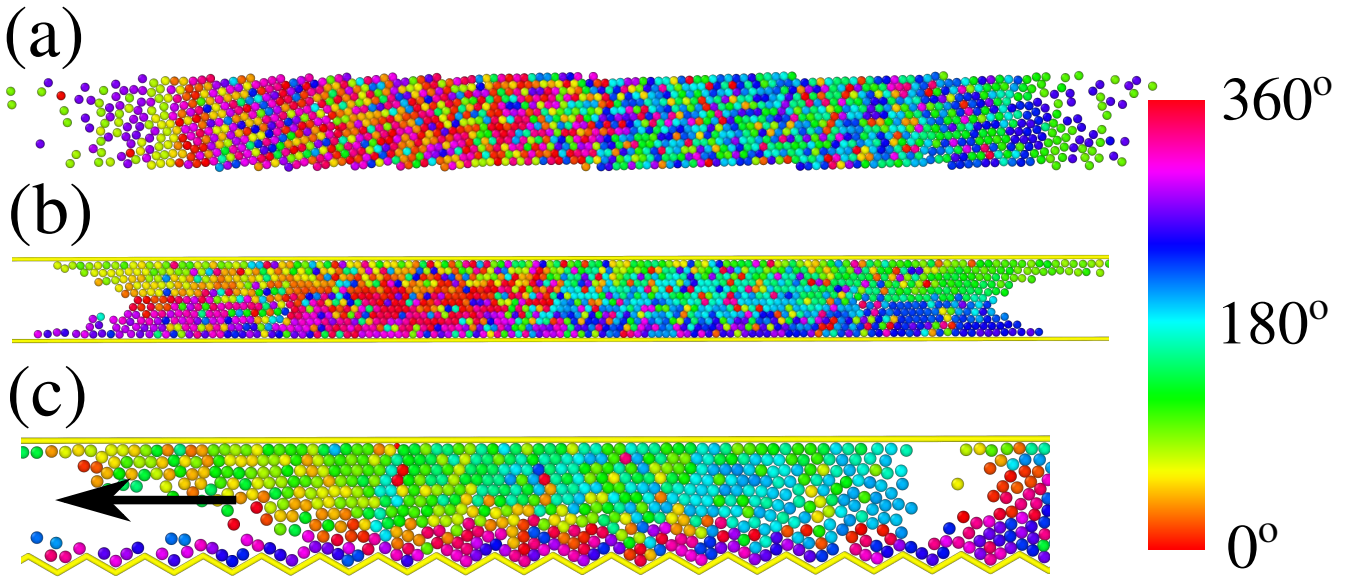


Figure S1: Configurations of active particles at the steady state with $\phi = 0.30$, $l_p = 10^5$. **(a)** Bulk: the system exhibits MIPS, and the band does not move persistently; **(b)** Confinement in a channel with flat walls: The system always evolves towards a clogging state; **(c)** Confinement in a channel with asymmetric boundaries (flat wall + corrugations with $\theta_{obs} = 30^\circ$): the system self-organizes into a traveling band whose mechanism of motion is similar to the cases discussed in the main text, *confinement-induced tracked locomotion*. This Figure is complemented with the **Supplementary Video 1**.

2 Choosing r_c for the percolation criterion

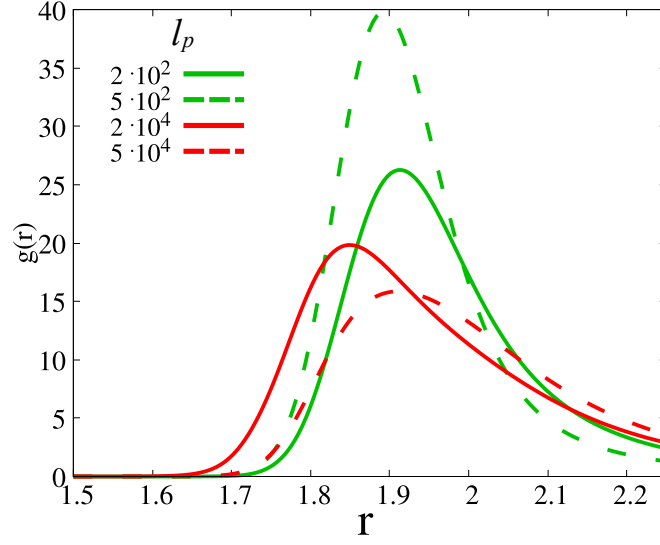


Figure S2: Radial distribution functions, $g(r)$, for $\phi = 0.325$ and different persistent lengths when either a clogging state (green) or a traveling state (red) is observed. Aiming to only detect dense structures with the percolation criterion described in the main text, we choose $r_c = \sigma_{11} = 2\sigma_{22}$, which is the nominal contact distance between active particles, but is far above the real effective contact distance due to some overlapping of the particles

3 Finite Size Effects

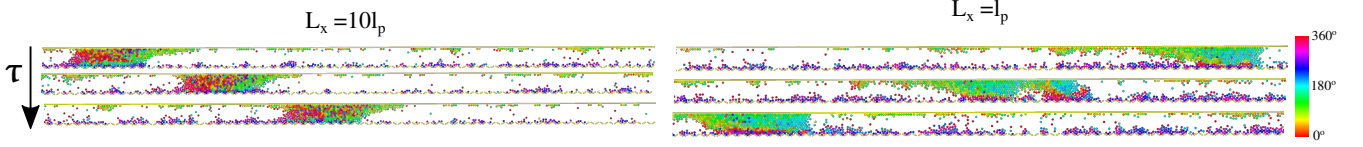


Figure S3: The *confinement-induced tracked locomotion* is still observed in long channels, whose length is of the same order of magnitude (right panel) of the persistence length of the active particles, or even one order of magnitude higher (left panel). the mechanism of motion is exactly the same described in the main text. However, in long channels, dense structures (traveling or not) may appear simultaneously at different positions and thus the chances of encounters between two traveling structures moving in opposite directions to form clogs, or traveling structures merging with clogs are much more higher. For such reasons, the traveling structures survive for shorter length scales in longer channels. We add as **Supplementary Data** some LAMMPS configurations in which the traveling structure can be observed in a channel of $L_x = 10l_p$, initially formed at $x \approx 4200$, then it moves to the right until it merged with a clog. They can be visualized using OVITO or any other standard program for visualizing molecular simulation trajectories. As discussed in the main text, an experimental approach to realize short channels with PBC, is by confining the active suspension in ring-shaped chambers with perimeters of the order of magnitude of the persistence length of motile microorganisms. To achieve high persistence lengths, we can leverage the photo- or chemotaxis of the microorganisms.