

# Boundary-mediated phases of self-propelled Kuramoto particles

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Active agents are likely to accumulate near confining obstacles due to collective motion. Here we investigate how the nature of the microscopic drive—self-propulsion or velocity alignment—selects distinct accumulation patterns, leading to either delocalized or compact clustered states. We first characterize the dynamical regimes emerging from the interplay of these two driving mechanisms under perfectly reflective or smooth boundary conditions. We then introduce boundary friction and observe a drastic change in the accumulation patterns, with dynamical phases that are absent in the previous case. By connecting emergent macroscopic structures to their underlying interactions, this work provides a practical route to infer the dominant microscopic mechanism ruling boundary-mediated collective behavior, with potential applications ranging from single-cell migration to bioinspired robotics.

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## I. INTRODUCTION

From bacterial colonies in the intestinal lining [1] to self-propelled robots in circular arenas [2,3], active agents spontaneously form dynamic structures in response to the mechanical environment. Confinement imposed by obstacles and walls triggers collective behaviors such as different accumulation states and the spontaneous emergence of coherent flows [4,5]. These effects are not only central to understanding how collective reconfigurations shape the response of living organisms across multiple scales, from microbial transport in porous media [6] to threat reactions in large animal groups [7]; they also provide a theoretical basis for cytoskeletal remodeling in cell migration [8,9] and for harnessing bacteria as biological engines in micro-robotic applications [10].

The analysis of collective behavior in active matter typically relies on simplified models that capture the microscopic conversion and macroscopic redistribution of energy occurring on distinct length and time scales. A common mechanism is persistent self-propulsion, an internal force which drives motility at the level of individual agents; this is the case for certain bacteria able to migrate along nutrient gradients via chemotaxis [11] or algae moving toward light gradients via phototaxis [12]. Another mechanism underlying collective dynamics is velocity alignment, exemplified by the coordinated motion of bird flocks or insect swarms [13], and by epithelial cells forming confluent monolayers [14,15]. The dynamics of such polar active matter arise from local interactions that synchronize the direction of motion among self-propelled agents. Coarse-grained models of aligning

active matter, including the Vicsek and Kuramoto frameworks [16,17], capture this collective behavior through simple coupling rules that promote orientational order. For what follows, we adopt the Kuramoto formulation, where synchronization between agents is modeled by a reciprocal velocity coupling, which presents a continuous transition between disordered and ordered phases when alignment overcomes noise [18–21].

While self-propulsion and polar alignment are well established features of active matter, the phenomenology arising from their simultaneous action under confinement remains much less explored. For self-propelled particles without any explicit alignment interactions, a number of studies have focused on dense regimes where excluded-volume interactions compete with activity and lead to motility-induced phase separation (MIPS) between a dense and a dilute phase [22,23], the former being more prone to accumulate near surfaces than the latter. For alignment-dominated systems, research has instead concentrated on bulk flocking phenomena and the emergence of long-range order [13,24]. Confinement itself is known to induce clustering and ordering in certain colloidal suspensions and granular systems [25,26], yet it remains unclear how different driving forces interact in such settings, what types of boundary accumulation patterns emerge, and what is the role of boundary friction.

In this work, we show how accumulation patterns depend on the relative strength, or timescale, of self-propulsion and alignment. We first study self-propelled Kuramoto particles (SPKPs) confined by a frictionless circular boundary, where the two driving forces are independently tuned [20,27]. By systematically varying the timescales associated with self-propulsion reorientation and alignment relaxation, we identify two distinct clustering modes near boundaries: annular and compact dropletlike clusters. We then include boundary friction using a ring polymer to confine particles and observe how these accumulation modes are altered by boundary roughness. Friction counteracts alignment-mediated cohesion, so that

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annular clusters are largely replaced by a coexistence between boundary-bound aggregates and a gas of persistent particles in the bulk. Partially delocalized clusters survive only for strong alignment over a finite range of persistence time. We also identify a trapped gas phase where particles accumulate near the boundary with no net collective motion. Our results elucidate the interplay between mechanical confinement and emerging collective behavior, laying the groundwork for future studies on harnessing coordination in living and artificial confined active systems.

## II. NUMERICAL METHODS

We study a two-dimensional system of SPKPs confined within a circular wall of radius  $R$ . Particle diameters are drawn from a log-normal distribution with 20% polydispersity to suppress boundary-induced ordering [28]. The average particle diameter,  $\sigma$ , is taken as the unit of length, and all particle masses are set to  $m = 1$ . We fix the number of particles to  $N = 1024$  and limit the study to a very dilute system of area fraction  $\sum_i (\sigma_i/2)^2/R^2 = 0.014$ . The chosen area fraction lies within the dilute regime observed in suspensions of microbial communities [29,30] and active colloids [31,32]. Particles are evolved via driven overdamped dynamics

$$\frac{d\vec{r}_i}{dt} = -\mu \sum_{j \neq i} \vec{\nabla} U_{ij}^{\text{WCA}} + v_0 \hat{n}_i + \mu \vec{F}_i^w, \quad (1)$$

where steric interactions are modeled by the purely repulsive Weeks-Chandler-Andersen (WCA) potential

$$U_{ij}^{\text{WCA}} = \begin{cases} 4\epsilon \left[ \left( \frac{\sigma_{ij}}{r_{ij}} \right)^{12} - \left( \frac{\sigma_{ij}}{r_{ij}} \right)^6 \right] + \epsilon, & r_{ij} \leq 2^{1/6} \sigma_{ij}, \\ 0, & r_{ij} > 2^{1/6} \sigma_{ij}, \end{cases} \quad (2)$$

where  $r_{ij}$  is the distance between particle  $i$  and particle  $j$ , and  $\sigma_{ij} = (\sigma_i + \sigma_j)/2$  is the average particle diameter. We set the energy scale of the potential to  $\epsilon = 1$  and define  $\sigma \sqrt{m/\epsilon}$  as the unit of time,  $\tau_u$ . The mobility is set to  $\mu = 10^{-2} \tau_u/m$ , a value chosen such that the velocity autocorrelation decays over the inertial timescale  $m\mu$  in Brownian (white-noise) dynamics.

The other terms on the r.h.s. of Eq. (1) describe the velocity imposed by the active driving,  $v_0 \hat{n}_i$ , and the interaction with the boundary,  $\mu \vec{F}_i^w$ . The magnitude of the active velocity  $v_0$  is fixed to  $2\sigma/\tau_u$  corresponding to a kinetic energy scale  $mv_0^2/2 = 2\epsilon$ , making it comparable to the interaction energy scale  $\epsilon$ . Particle velocity components are initialized from a Gaussian distribution with zero mean and variance  $v_0^2/2$ . The orientation of the active force acting on particle  $i$  is defined by a unit vector  $\hat{n}_i(t) = (\cos \theta_i(t), \sin \theta_i(t))$ , where the angle  $\theta_i(t)$ , initially chosen at random, evolves following the equation

$$\frac{d\theta_i(t)}{dt} = \sqrt{\frac{2}{\tau_p}} \xi_i(t) - \frac{1}{\tau_K} \sum_{\substack{j \\ r_{ij} < R_K}} \sin(\varphi_{v,i}(t) - \varphi_{v,j}(t)). \quad (3)$$

Here, the first term on the r.h.s. of the equation is a scalar white noise, where  $\tau_p$  is the persistence time, i.e., the typical time needed to change the direction of self-propulsion, and

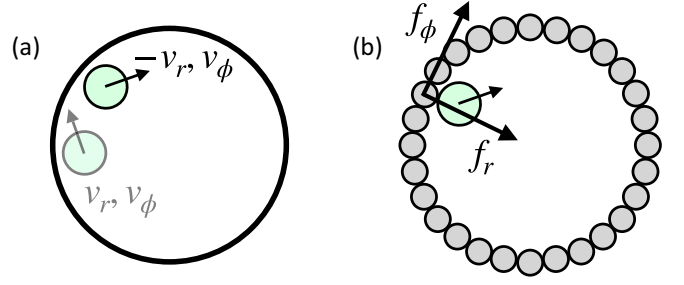


FIG. 1. (a) A particle before and after collision with a smooth boundary. (b) Particle-monomer interaction in a rough boundary with radial  $f_r$  and tangential  $f_\phi$  components.

$\xi_i(t)$  is a Gaussian random process of mean zero and correlation  $\langle \xi_i(t) \xi_i(t') \rangle = \delta(t - t')$ . The second term is the Kuramoto interaction, where  $\tau_K = \pi R_K^2/K$  is the alignment time, i.e., the timescale for the interaction to become effective, with  $K$  being the coupling strength and  $R_K$  the interaction radius. In the following, we will vary  $\tau_K$  by varying the coupling strength  $K$ , while keeping the interaction radius equal to  $1.5\sigma$ . Particles align by minimizing the sine of the difference between their velocity orientations, namely  $\varphi_{v,i} = \arctan(v_{i,y}/v_{i,x})$ . In the absence of the Kuramoto term, the model reduces to a system of active Brownian particles which may acquire local velocity alignment from persistent collisions in the MIPS regime [33–35]. However, this phenomenon is observed in much denser systems than those studied here, so we can attribute alignment solely to the Kuramoto term. Equations (1) and (3) are numerically integrated using the Euler-Maruyama scheme with a time step  $\Delta t = 5 \times 10^{-5}$ .

By varying the particle-wall interaction  $\vec{F}_i^w$  we model two types of boundaries schematically shown in Fig. 1: (i) smooth, implemented as a perfectly reflective circle, where the radial velocity component  $v_r$  of a particle colliding with the boundary is reversed upon collision while the tangential component  $v_\theta$  remains unchanged; and (ii) rough, implemented as a ring polymer made of monomers that interact with particles via the WCA potential with energy scale  $\epsilon_w$ . We set  $\epsilon_w = 10\epsilon$  to ensure a significantly stiffer boundary compared to particle-particle interactions. More details are reported in Sec. IV.

## III. PHASES OF CONFINED SELF-PROPELLED KURAMOTO PARTICLES

We now examine how the interplay between self-propulsion and velocity alignment influences the collective dynamics of SPKPs confined by a smooth boundary. Particles move under a constant driving force, and the higher their persistence, the longer they reside near the boundary before reorienting. Alignment interactions may then trigger the formation of groups of particles that slide along the boundary. As a result, clustering and collective motion spontaneously emerge.

By varying  $\tau_p$  and  $\tau_K$ , we identify three distinct phases reported in Fig. 2. At short persistence time and weak alignment (large  $\tau_K$ ), particles reorient more rapidly than they can align with their neighbors, leading to a homogeneous, weakly correlated gas of self-propelled particles. As  $\tau_p$  increases at

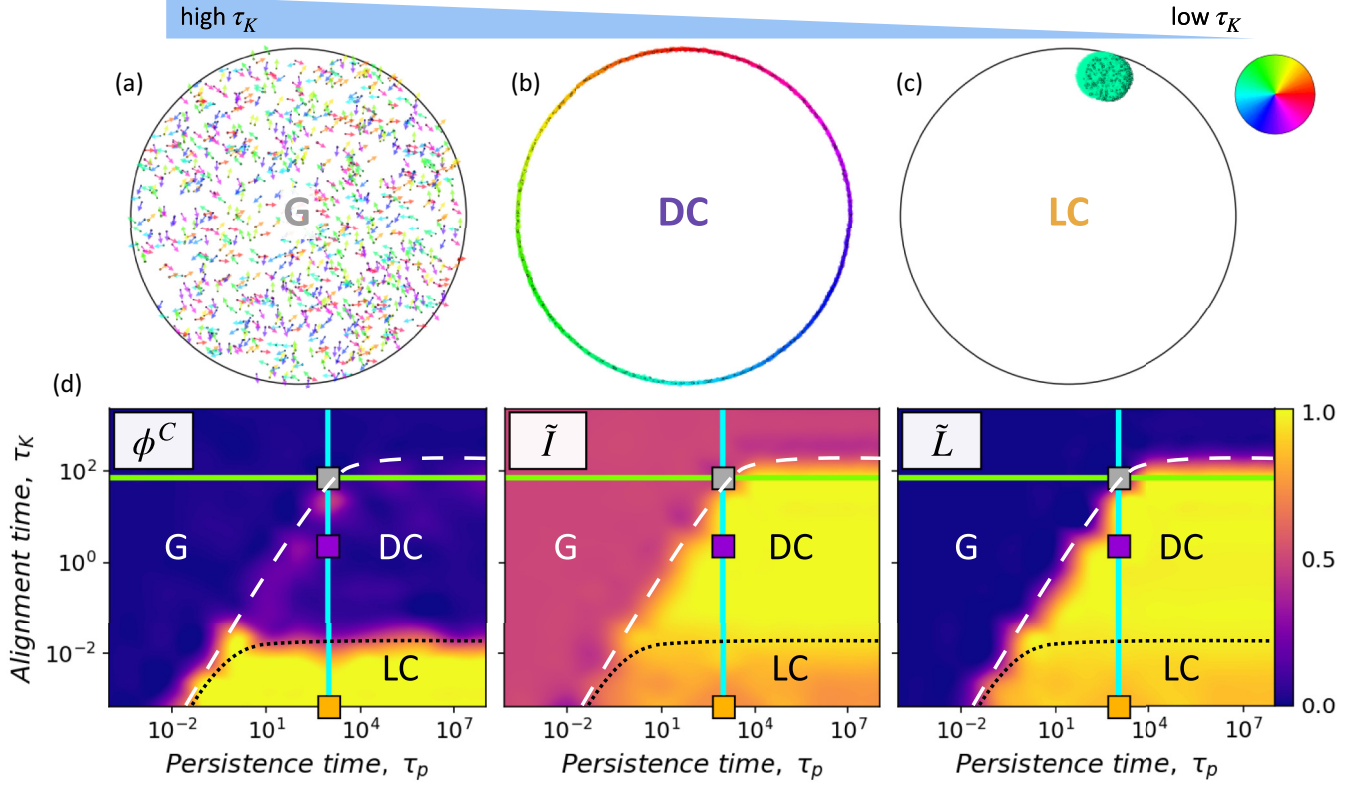


FIG. 2. Phases of SPKPs confined by a smooth boundary at fixed persistence time  $\tau_p = 10^3$ . Here and in the following, values of  $\tau_p$  and  $\tau_K$  are reported in units of  $\tau_u$ . (a) Gas (G) phase at  $\tau_K = 7.1 \times 10^1$ . (b) Delocalized clustered (DC) phase at  $\tau_K = 2.4$ . (c) Localized clustered (LC) phase at  $\tau_K = 7.1 \times 10^{-4}$ . Particles and velocity arrows are color coded according to  $\phi_v$ . (d) Diagrams in the plane  $(\tau_p, \tau_K)$  color coded by  $\phi^C$ ,  $\tilde{I}$ , and  $\tilde{L}$ , defined in the text. The vertical line at  $\tau_p = 10^3$  and the horizontal line at  $\tau_K = 7.1 \times 10^1$  refer to the coordinate axes of Fig. 4(a). Dashed and dotted lines distinguish phases, while squares indicate the configurations shown in (a)–(c).

fixed  $\tau_K$ , particles are pushed to travel longer along a fixed direction before reorienting. This enhances collisions between neighboring particles, promoting alignment and cluster formation. When a cluster reaches the boundary, particles nearest to the wall experience forces that reverse their direction of motion, while innercore particles are forced to align with both reflected and wall-approaching particles. The cluster eventually aligns tangentially to the boundary with no preferential direction of rotation.

Notably, for sufficiently small  $\tau_K$ , or sufficiently strong coupling, a delocalized clustered (DC) phase emerges where particles form a single annular cluster (roughly  $2\sigma$  thick) that spans the whole circumference of the wall and rotates around its center. As  $\tau_K$  decreases (alignment increases) while keeping  $\tau_p$  fixed, particles tend to sit at the interaction distance  $R_K$  with respect to one another, leading to the localized clustered (LC) phase where particles form one or more compact aggregates that slide along the boundary. Delocalized and localized clusters select a direction of rotation which has equal probability of being clockwise or counterclockwise. In particular, when multiple rotating clusters come into contact, particles align with the direction of the largest cluster. This merging dynamics is spontaneously breaking the symmetry of the confining geometry. We note that, when persistence is low ( $\tau_p < 1$ ), the cluster direction of motion rapidly reorients and clusters are not bound to slide along the wall; see Video 3 in the Supplemental Material [36]. We checked the

occurrence of the different phases in a larger system composed of  $N = 32\,768$  particles and observed no significant variations.

Similar phases have been reported in Ref. [37], where Vicsek-like self-propelled particles are confined by a radially symmetric trapping potential. There, compact dropletlike structures emerge when the potential softens, reducing the accessible space and promoting collision-driven condensation. In our model, by contrast, the dropletlike phase is driven by strong alignment rather than collisions, with typical interparticle distances exceeding the interaction cutoff.

To distinguish the observed dynamical patterns, we identify three quantities whose behavior is summarized in Fig. 2(d). The first is the localization parameter [38],

$$\phi \equiv \left| \frac{1}{N} \sum_{i=1}^N e^{i\varphi_{r,i}} \right|, \quad (4)$$

where  $\varphi_{r,i}$  denotes the angular coordinate of particle  $i$ , defined by  $\vec{r}_i = r_i(\cos \varphi_{r,i}, \sin \varphi_{r,i})$  and  $i = \sqrt{-1}$ . The localization parameter approaches zero when particles have a uniform distribution of angular coordinates, and is equal to one if they share the same exact angular coordinate. Since we observe that clusters always appear at the border,  $\phi$  is sufficient to indicate the formation of a single cluster. However, it fails to detect multiple localized clusters [38], which occur for  $\tau_K > 2.4 \times 10^{-3}$ ; see Video 4

in the Supplemental Material [36]. To give an example, two clusters of equal size moving at an angular distance of  $\pi$  would yield  $\phi = 0$ . To avoid this limitation, we compute the localization parameter for the largest cluster,  $\phi^*$ , identified using the DBSCAN algorithm [36,39]. When the largest cluster contains more than 30% of the particles we use  $\phi^*$ , and  $\phi$  otherwise; both are denoted by  $\phi^C$ . In summary,  $\phi^C$  is close to zero in the G and DC phases, and close to one in the LC phase.

The second observable is the normalized moment of inertia,

$$\tilde{I} \equiv \frac{m}{MR^2} \sum_{i=1}^N r_i^2, \quad (5)$$

where the normalization  $MR^2$  is the moment of inertia of a ring with radius  $R$  and mass  $M = Nm$ . This observable is  $\tilde{I} \approx 0.5$  in the gas phase where the mass is uniformly distributed within the circle, and  $\tilde{I} \approx 1$  in the DC phase where particles form a single ringlike cluster. The LC phase instead is characterized by intermediate values of  $\tilde{I}$ . Specifically, a circular cluster of radius  $R_c$  and mass  $M$  located at a distance from the center equal to  $R - R_c$ , has a normalized moment of inertia equal to

$$\tilde{I} = \left(1 - \frac{R_c}{R}\right)^2 + \frac{1}{2} \left(\frac{R_c}{R}\right)^2. \quad (6)$$

The correspondence between  $\tilde{I}$  and  $R_c/R$  provides a way of estimating the area fraction, or density, within the cluster. For example, the configuration reported in Fig. 2(c) corresponds to  $\tilde{I} \approx 0.74$ , and by inverting (6) we get  $R_c/R \approx 0.15$ , i.e., a cluster radius of about 15% of the wall radius. Thus, computing the number density as  $n_c = N/\pi R_c^2$  yields an area fraction equal to  $n_c a_p \approx 0.61$ , where  $a_p = \pi(\sigma/2)^2$  is the average particle area. Since the ratio between kinetic and potential energy scales is  $mv_0^2/2\varepsilon = 2$ , comparison with the literature on self-propelled aligning particles [20,27] suggests that localized clusters at this density are in a polar liquid state with no structural order and long-range velocity correlations that are explicitly induced by the alignment.

The third parameter we use to describe the phases of confined SPKPs is the normalized angular momentum,

$$\tilde{L} \equiv \frac{m}{Mv_0R} \left| \sum_{i=1}^N \tilde{r}_i \times \tilde{v}_i \right|, \quad (7)$$

where  $Mv_0R$  is the angular momentum of a system with all the mass concentrated at a distance  $R$  from the center, rotating with angular velocity  $\omega = v_0/R$ . We focus on the absolute value of the angular momentum to disregard whether clusters rotate clockwise or counterclockwise. Figure 2(d) clearly shows that  $\tilde{I}$  and  $\tilde{L}$  are strongly correlated in smooth boundary conditions. In particular, this implies that whenever particles are distributed close to the boundary, whether in DC or LC structures, they exhibit collective rotation. This behavior changes when boundary friction is included.

#### IV. INFLUENCE OF BOUNDARY ROUGHNESS

We now focus on rough boundary conditions and quantify the influence of roughness on the dynamical phases identified so far. To this end, we replace the reflective wall with an inextensible ring polymer composed of  $N_m$  monomers of diameter  $\sigma_m$  equal to half of the average particle diameter. The number of monomers is set to  $N_m = 2\pi R/\sigma_m$  (rounded to the nearest integer) so that adjacent monomers are just in contact. Starting from stationary or cyclostationary configurations (according to the parameter values) within smooth boundaries, we slightly reduce the radial particle coordinates by 0.01% to prevent discontinuities in the interaction with the border. We then let the system relax to its rugged-boundary steady conditions.

Rough boundaries lead to new dynamical phases reported in Fig. 3. Importantly, we observe that collisions with boundary monomers cause particles to detach from clusters. While this has little effect on the LC phase, as only a subextensive fraction of particles slides along the boundary at any given time, ringlike clusters in the DC phase are strongly disrupted because almost every particle interacts with boundary monomers. As a consequence, moving along the vertical line at  $\tau_p = 10^3$  in Fig. 3(d), we observe that the DC phase is typically replaced by a partially delocalized clustered (PDC) phase. At  $\tau_K = 7.1 \times 10^{-2}$ , where alignment interactions are strong enough to counteract particle detachment from the rotating cluster, the partially delocalized structure spans roughly 30% of the boundary and is approximately  $10\sigma$  thick [see Figs. 3(c) and 4(a)]. Note that we observe the PDC phase only in the range  $10^1 < \tau_p < 10^5$ : below this range, persistence is too short to maintain clusters at the boundary, while above it, reflections from the rough boundary enhance directional dispersion, leading to the formation of multiple small clusters with different orientations. The rest of the phase space that was once occupied by the DC phase is now divided into two other phases: a coexistence between the PDC phase along the boundary and the G phase in the bulk (PDC + G), and another phase where particles are stuck near the boundary but the rotation of the system center of mass is close to zero. This trapped gas (TG) phase takes over a portion of the prior gas phase as well: for sufficiently high  $\tau_p$ , as  $\tau_K$  increases and the alignment strength weakens, the system does not recover the homogeneous gas. Here, moderate-to-high persistence drives particles toward the boundary, where their finite interaction time with monomers enables transient clustering. However, the weak alignment strength prevents cluster growth, resulting in clusters that continuously form and dissolve. Crucially,  $\tilde{I}$  and  $\tilde{L}$  are no longer strictly correlated as in the case of smooth boundary conditions, and the TG phase is found for  $\tilde{I} \approx 1$  and  $\tilde{L} \approx 0$ . Thus, these observables are complementary for identifying the TG phase, and only when combined with the localization parameter do they fully capture all the phases of SPKPs in rough boundary conditions.

To better quantify the differences between the phases observed for smooth and rough boundaries, we compare time averages of  $\tilde{I}$  and  $\tilde{L}$ , indicated with  $\langle \tilde{I} \rangle$  and  $\langle \tilde{L} \rangle$ , as functions of  $\tau_K$  and  $\tau_p$  for the two boundary types in Fig. 4(a). Focusing on smooth boundary conditions, we notice

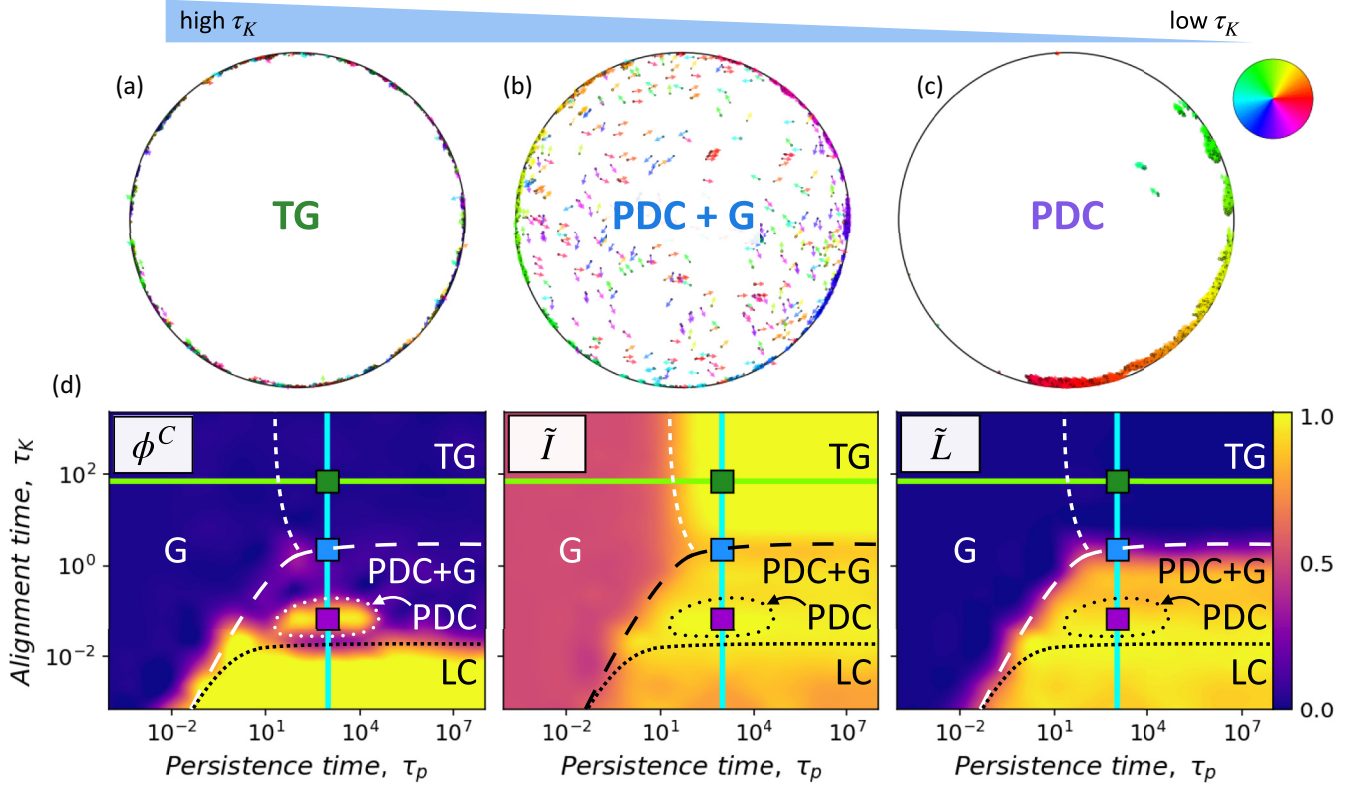


FIG. 3. Dynamical regimes of SPKPs confined by a rough boundary at fixed persistence time  $\tau_p = 10^3$ . (a) Trapped gas (TG) phase at  $\tau_K = 7.1 \times 10^1$ . (b) Coexistence between partially delocalized clustered (PDC) phase and gas at  $\tau_K = 2.4$ . (c) PDC phase at  $\tau_K = 7.1 \times 10^{-2}$ . (d) Diagrams in the plane  $(\tau_p, \tau_K)$  color coded by  $\phi^C$ ,  $\tilde{I}$ , and  $\tilde{L}$ . The vertical line at  $\tau_p = 10^3$  and the horizontal line at  $\tau_K = 7.1 \times 10^1$  refer to the coordinate axes of Fig. 4(a). Dashed and dotted lines distinguish phases, while squares indicate the configurations shown in (a)–(c).

a sharp transition between the G and the DC phase as previously observed for other active systems with Kuramoto-type alignment [21]. On the contrary, when going from the DC to the LC phase,  $\langle \tilde{I} \rangle$  and  $\langle \tilde{L} \rangle$  show a gradual crossover as the system assumes complex dynamical patterns such as ripples to switch from ringlike to dropletlike structures.

When roughness is introduced, it is clear that the TG phase takes over a portion of the G phase where  $\langle \tilde{I} \rangle$  and  $\langle \tilde{L} \rangle$  were both nearly zero in smooth boundary conditions (see left panels for high  $\tau_K$ ), and a portion of the DC phase where instead  $\langle \tilde{I} \rangle$  and  $\langle \tilde{L} \rangle$  were both close to one (see right panels for high  $\tau_p$ ). The G phase within rough boundary conditions is recovered by decreasing persistence time at fixed  $\tau_K$ . We further examine the dependence of  $\langle \tilde{L} \rangle$  on boundary roughness by defining the nondimensional roughness parameter as  $\sigma_m/\sigma$  [see Fig. 4(b)]. Interestingly, only the coexistence regime PDC + G shows an appreciable dependence on roughness as  $\tilde{L}$  monotonically increases with  $\sigma_m/\sigma$ . This rise in angular momentum is caused by a growing cluster population along the border, driven by increasing friction, since larger monomers increase the tangential components of the forces exchanged at the boundary. This effect is visible only in the PDC + G phase, where bulk particles regularly collide with the boundary, maximizing the angular momentum transfer. In other phases, particles either slide along the boundary with little tangential force exchange (PDC and LC

phases) or remain in the bulk with insufficient collisions (G phase).

We conclude our study by performing a cluster analysis which employs the same method used for computing  $\phi^C$ . Figure 5 shows steady-state averages of the number of clusters,  $\langle N_c \rangle$ , and the average fraction of particles within a cluster, or cluster fraction,  $\langle N_p \rangle/N$ . For both smooth and rough boundaries, the gas phase is identified by negligible values of  $\langle N_p \rangle/N$ . At fixed  $\tau_p$  (left panels), and low  $\tau_K$ , the LC phase, found in both boundary types, corresponds to  $\langle N_c \rangle \approx \langle N_p \rangle/N \approx 1$ , meaning that all particles form a single cluster. As alignment strength decreases ( $\tau_K$  increases), the number of clusters grows and the cluster fraction decreases, signaling the presence of multiple clusters. When  $\tau_K \geq 7.1 \times 10^{-2}$ , clusters start to spread along the wall and boundary friction enters the game. While smooth boundaries allow the formation of a single ringlike cluster where the condition  $\langle N_c \rangle \approx \langle N_p \rangle/N \approx 1$  is met once again, particle-boundary friction leads to the PDC + G coexistence where  $\langle N_c \rangle$  is maximum and  $\langle N_p \rangle/N$  is minimum. When  $\tau_K$  is large at fixed  $\tau_p$  (left panels) and  $\tau_p$  is large at fixed  $\tau_K$  (right panels), the system within rough boundaries is in the TG phase which is characterized by several small clusters each containing approximately 2–3% of the total number of particles. For smooth boundary conditions instead, when  $\tau_p$  is large at fixed  $\tau_K$ , the system is in the DC phase but the clustering algorithm fails to capture the presence

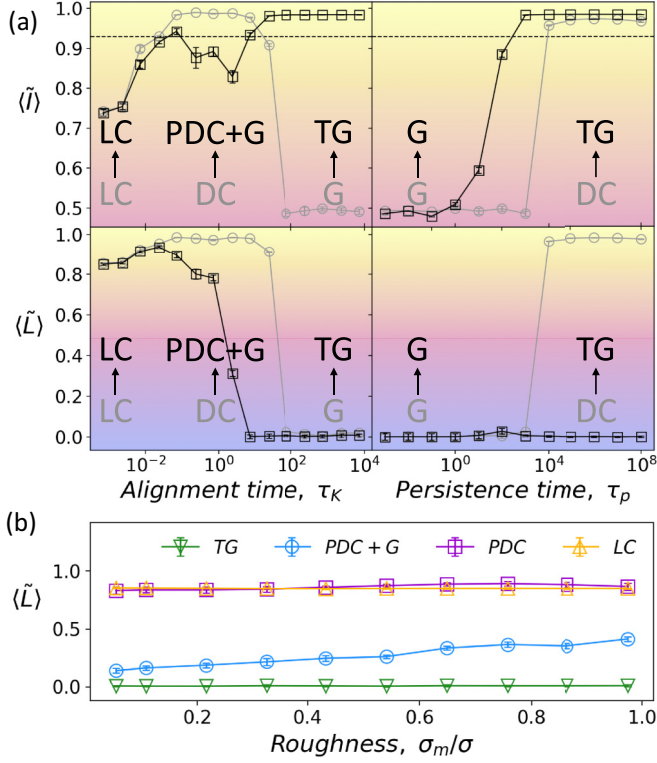


FIG. 4. (a) Time averages of  $\tilde{I}$  and  $\tilde{L}$  as functions of  $\tau_K$  and  $\tau_p$  for smooth (gray circles) and rough (black squares) boundaries. Left panels correspond to  $\tau_p = 10^3$  and right panels to  $\tau_K = 7.1 \times 10^1$ , representing two cuts of the diagrams in Figs. 2(d) and 3(d) indicated by the horizontal and vertical lines. The dashed line in the top panels corresponds to the value of  $\tilde{I}$  for an annulus of thickness  $10\sigma$ . The background is colored according to the color maps used in Figs. 2(d) and 3(d). (b) Dependence of  $\langle \tilde{L} \rangle$  on  $\sigma_m/\sigma$  for the phases observed in rough boundary conditions at  $\tau_p = 10^3$ : LC (upward triangles,  $\tau_K = 7.1 \times 10^{-4}$ ), PDC (squares,  $\tau_K = 7.1 \times 10^{-2}$ ), coexistence between PDC and gas phases (circles,  $\tau_K = 2.4$ ), and TG (downward triangles,  $\tau_K = 7.1 \times 10^1$ ).

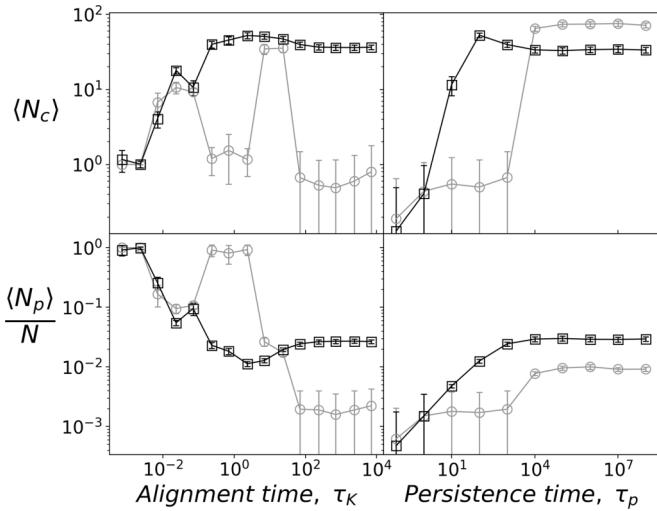


FIG. 5. Time averages of the number of clusters,  $\langle N_c \rangle$ , and the cluster fraction,  $\langle N_p \rangle / N$ , as functions of  $\tau_K$  and  $\tau_p$  for smooth (gray circles) and rough (black squares) boundaries. Data are obtained from the same simulation runs as those reported in Fig. 4(a).

of a single delocalized cluster, which is instead identified by  $\langle N_c \rangle \approx \langle N_p \rangle / N \approx 1$ . More specifically, data reported in the right panels of Fig. 5 correspond to relatively weak alignment compared to self-propulsion, leading to sparse delocalized clusters (see Video 5 in the Supplemental Material [36]). To retain the detection of a single cluster, the DBSCAN algorithm must be tuned to account for longer interparticle distances, as described in [36]. However, the parameter  $\phi^C$  and the phase diagrams of Figs. 2 and 3 are robust against this technical limitation.

## V. CONCLUSIONS

We have characterized the collective dynamics of SPKPs confined within circular boundaries by systematically exploring the combined effects of self-propulsion and velocity alignment under either smooth or rough boundary conditions. For a purely reflective wall, the interplay between persistence and alignment leads to three distinct dynamical regimes: a gas phase, a delocalized clustered phase characterized by a single ringlike cluster, and a localized clustered phase signaled by the presence of one or more disklike clusters. Notably, the moment of inertia and the angular momentum are tightly correlated and both are maximized in the delocalized clustered phase. The introduction of boundary roughness fundamentally alters this phenomenology: friction destabilizes delocalized clusters, giving rise to a coexistence regime between multiple clusters on the boundary and the gas phase. Friction also triggers the emergence of a trapped gas phase, where persistent particles form small groups near the boundary that are not able to merge into larger clusters and thus have negligible center-of-mass angular momentum. These effects can be traced back to momentum exchange between particles and boundary monomers, which disrupts alignment and consequently coherent tangential motion along the wall.

Our study proves that boundary friction mediates phases of self-propelled aligning objects. This indicates that the underlying mechanism giving rise to collective motion in confined active systems can be inferred from the macroscopic structures and dynamical patterns that emerge near mechanical obstacles. Delocalized structures signal self-propulsion-dominated motility with weak interparticle coordination, as observed in *E. coli* performing run-and-tumble motion and self-propelled Janus particles in the dilute regime [22]. By contrast, when self-propulsion is coupled with neighbor-to-neighbor alignment, cohesive collective structures emerge—a mechanism whose universality transcends length scales, from large animal groups, e.g., bird flocks, insect swarms, and fish schools, to active colloids. Of particular relevance are experiments on confined Quincke rollers, where vortexlike structures emerge above a critical density threshold [25,40]. Moreover, our finding that condensed, polarized structures form once alignment dominates over self-propulsion is consistent with the hydrodynamic theory developed for active colloids confined by geometric boundaries in the absence of repulsion: indeed, in the LC phase cohesion is maintained even as repulsive interactions become negligible. In addition, we show that boundary friction can act as a regulatory switch, enabling the system to adapt its accumulation

patterns in response to external modifications, such as surface coatings in microfluidic essays of active nematics [41], and rough geometries in experiments of granular active matter [2,4,42]. Our results establish a framework for future studies on active systems that are mechanically coupled to their environment, where accumulation near boundaries may trigger rotation as for bacteria in ratchet geometries [10] or deformation as in neural crest cells during development [43].

We close by outlining two natural extensions of this work. First, relaxing the overdamped approximation would allow the study of inertia-dominated systems, such as active granular matter [2,4]. Preliminary simulations suggest that reducing viscous drag progressively spreads accumulation structures, indicating that inertia modulates the morphology of active wetting. Second, explicitly incorporating hydrodynamic

interactions would enable the study of fluid-mediated long-range alignment [10,32,40], potentially modifying the dynamical phases reported here and providing a more direct connection with microscopic active systems. A systematic investigation of both effects is left for future work.

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### DATA AVAILABILITY

Data were generated using the in-house developed package CUDASOFT, available at [44]. The analysis code and a guide to reproduce the findings of this study is openly available at [45].

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- [1] H. Wioland, F. G. Woodhouse, J. Dunkel, J. O. Kessler, and R. E. Goldstein, Confinement stabilizes a bacterial suspension into a spiral vortex, *Phys. Rev. Lett.* **110**, 268102 (2013).
  - [2] J. Deseigne, S. Léonard, O. Dauchot, and H. Chaté, Vibrated polar disks: Spontaneous motion, binary collisions, and collective dynamics, *Soft Matter* **8**, 5629 (2012).
  - [3] C. A. Weber, Long-range ordering of vibrated polar disks, *Phys. Rev. Lett.* **110**, 208001 (2013).
  - [4] L. Caprini, D. Breoni, A. Ldov, C. Scholz, and H. Löwen, Dynamical clustering and wetting phenomena in inertial active matter, *Commun. Phys.* **7**, 343 (2024).
  - [5] G. S. Ugolini, M. Wang, E. Secchi, R. Pioli, M. Ackermann, and R. Stocker, Microfluidic approaches in microbial ecology, *Lab Chip* **24**, 1394 (2024).
  - [6] P. de Anna, A. A. Pahlavan, Y. Yawata, R. Stocker, and R. Juanes, Chemotaxis under flow disorder shapes microbial dispersion in porous media, *Nat. Phys.* **17**, 68 (2021).
  - [7] J. Deng and D. Liu, Spontaneous response of a self-organized fish school to a predator, *Bioinspir. Biomim.* **16**, 046013 (2021).
  - [8] D. Zhang, K. D. Grode, S. F. Stewman, J. D. Diaz-Valencia, E. Liebling, U. Rath, T. Riera, J. D. Currie, D. W. Buster, A. B. Asenjo, H. J. Sosa, J. L. Ross, A. Ma, S. L. Rogers, and D. J. Sharp, Drosophila katanin is a microtubule depolymerase that regulates cortical-microtubule plus-end interactions and cell migration, *Nat. Cell Biol.* **13**, 361 (2011).
  - [9] S. Feng, Y. Song, M. Shen, S. Xie, W. Li, Y. Lu, Y. Yang, G. Ou, J. Zhou, F. Wang, W. Liu, X. Yan, X. Liang, and T. Zhou, Microtubule-binding protein FOR20 promotes microtubule depolymerization and cell migration, *Cell Discov.* **3**, 17032 (2017).
  - [10] R. 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, *Proc. Natl. Acad. Sci. USA* **107**, 9541 (2010).
  - [11] J. P. Moore and T. Emonet, Physics of bacterial chemotaxis, *Curr. Biol.* **34**, R972 (2024).
  - [12] A. C. H. Tsang and I. H. Riedel-Kruse, Light-dependent switching between two flagellar beating states selects versatile phototaxis strategies in microswimmers, *Proc. Natl. Acad. Sci. USA* **121**, e2408082121 (2024).
  - [13] A. Cavagna, L. Del Castello, I. Giardina, T. Grigera, A. Jelic, S. Melillo, T. Mora, L. Parisi, E. Silvestri, M. Viale, and A. M. Walczak, Flocking and turning: A new model for self-organized collective motion, *J. Stat. Phys.* **158**, 601 (2015).
  - [14] J.-A. Park, L. Atia, J. A. Mitchel, J. J. Fredberg, and J. P. Butler, Collective migration and cell jamming in asthma, cancer and development, *J. Cell Sci.* **129**, 3375 (2016).
  - [15] O. Ilina, P. G. Gritsenko, S. Syga, J. Lippoldt, C. A. M. La Porta, O. Chepizhko, S. Grosser, M. Vullings, G.-J. Bakker, J. Starrau, P. Bult, S. Zapperi, J. A. Käs, A. Deutsch, and P. Friedl, Cell-cell adhesion and 3D matrix confinement determine jamming transitions in breast cancer invasion, *Nat. Cell Biol.* **22**, 1103 (2020).
  - [16] T. Vicsek, A. Czirók, E. Ben-Jacob, I. Cohen, and O. Shochet, Novel type of phase transition in a system of self-driven particles, *Phys. Rev. Lett.* **75**, 1226 (1995).
  - [17] J. A. Acebrón, L. L. Bonilla, C. J. P. Vicente, F. Ritort, and R. Spigler, The Kuramoto model: A simple paradigm for synchronization phenomena, *Rev. Mod. Phys.* **77**, 137 (2005).
  - [18] A. A. Chepizhko and V. L. Kulinskii, On the relation between Vicsek and Kuramoto models of spontaneous synchronization, *Physica A* **389**, 5347 (2010).
  - [19] S. Gupta, A. Campa, and S. Ruffo, Kuramoto model of synchronization: Equilibrium and nonequilibrium aspects, *J. Stat. Mech.* (2014) R08001.
  - [20] A. Martín-Gómez, D. Levis, A. Díaz-Guilera, and I. Pagonabarraga, Collective motion of active Brownian particles with polar alignment, *Soft Matter* **14**, 2610 (2018).
  - [21] D. Levis, I. Pagonabarraga, and B. Liebchen, Activity induced synchronization: Mutual flocking and chiral self-sorting, *Phys. Rev. Res.* **1**, 023026 (2019).
  - [22] I. Buttinoni, J. Bialké, F. Kümmel, H. Löwen, C. Bechinger, and T. Speck, Dynamical clustering and phase separation in suspensions of self-propelled colloidal particles, *Phys. Rev. Lett.* **110**, 238301 (2013).

- [23] M. E. Cates and J. Tailleur, Motility-induced phase separation, *Annu. Rev. Condens. Matter Phys.* **6**, 219 (2015).
- [24] G. Baglietto and E. V. Albano, Nature of the order-disorder transition in the Vicsek model for the collective motion of self-propelled particles, *Phys. Rev. E* **80**, 050103(R) (2009).
- [25] A. Bricard, J.-B. Caussin, N. Desreumaux, O. Dauchot, and D. Bartolo, Emergence of macroscopic directed motion in populations of motile colloids, *Nature (London)* **503**, 95 (2013).
- [26] C. O. Solano-Cabrera, P. Castro-Villarreal, R. E. Moctezuma, F. Donado, J. C. Conrad, and R. Castañeda-Priego, Self-assembly and transport phenomena of colloids: Confinement and geometrical effects, *Annu. Rev. Condens. Matter Phys.* **16**, 41 (2025).
- [27] B. Liebchen and D. Levis, Chiral active matter, *Europhys. Lett.* **139**, 67001 (2022).
- [28] C. S. O'Hern, S. A. Langer, A. J. Liu, and S. R. Nagel, Random packings of frictionless particles, *Phys. Rev. Lett.* **88**, 075507 (2002).
- [29] M. Brun-Cosme-Bruny, E. Bertin, B. Coasne, P. Peyla, and S. Rafai, Effective diffusivity of microswimmers in a crowded environment, *J. Chem. Phys.* **150**, 104901 (2019).
- [30] D. Ghosh and X. Cheng, To cross or not to cross: Collective swimming of *Escherichia coli* under two-dimensional confinement, *Phys. Rev. Res.* **4**, 023105 (2022).
- [31] A. Morin, N. Desreumaux, J.-B. Caussin, and D. Bartolo, Distortion and destruction of colloidal flocks in disordered environments, *Nat. Phys.* **13**, 63 (2017).
- [32] K. J. Modica, Y. Xi, and S. C. Takatori, Porous media microstructure determines the diffusion of active matter: Experiments and simulations, *Front. Phys.* **10**, 869175 (2022).
- [33] P. Digregorio, D. Levis, A. Suma, L. F. Cugliandolo, G. Gonnella, and I. Pagonabarraga, Full phase diagram of active Brownian disks: From melting to motility-induced phase separation, *Phys. Rev. Lett.* **121**, 098003 (2018).
- [34] L. Caprini, U. M. B. Marconi, and A. Puglisi, Spontaneous velocity alignment in motility-induced phase separation, *Phys. Rev. Lett.* **124**, 078001 (2020).
- [35] F. Turci and N. B. Wilding, Wetting transition of active Brownian particles on a thin membrane, *Phys. Rev. Lett.* **127**, 238002 (2021).
- [36] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/2184-9hg3> for videos illustrating the observed phases and additional details on the cluster analysis and boundary friction.
- [37] S. Rana, M. Samsuzzaman, and A. Saha, Tuning the self-organization of confined active particles by the steepness of the trap, *Soft Matter* **15**, 8865 (2019).
- [38] S. Gil, Y. Kuramoto, and A. S. Mikhailov, Common noise induces clustering in populations of globally coupled oscillators, *Europhys. Lett.* **88**, 60005 (2009).
- [39] M. Hahsler, M. Piekenbrock, and D. Doran, DbSCAN: Fast density-based clustering with R, *J. Stat. Software* **91**, 1 (2019).
- [40] A. Bricard, J.-B. Caussin, D. Das, C. Savoie, V. Chikkadi, K. Shitara, O. Chepizhko, F. Peruani, D. Saintillan, and D. Bartolo, Emergent vortices in populations of colloidal rollers, *Nat. Commun.* **6**, 7470 (2015).
- [41] J. Hardouin, R. Hughes, A. Doostmohammadi, J. Laurent, T. Lopez-Leon, J. M. Yeomans, J. Ignés-Mullol, and F. Sagués, Reconfigurable flows and defect landscape of confined active nematics, *Commun. Phys.* **2**, 121 (2019).
- [42] A. Kudrolli, G. Lumay, D. Volfson, and L. S. Tsimring, Swarming and swirling in self-propelled polar granular rods, *Phys. Rev. Lett.* **100**, 058001 (2008).
- [43] E. Scarpa, A. Szabó, A. Bibonne, E. Theveneau, M. Parsons, and R. Mayor, Cadherin switch during EMT in neural crest cells leads to contact inhibition of locomotion via repolarization of forces, *Dev. Cell* **34**, 421 (2015).
- [44] cudaSoft, GitHub, 2026, <https://github.com/farceri/cudaSoft>.
- [45] F. Arceri, Software documentation and analysis code for manuscript “Boundary-mediated phases of self-propelled Kuramoto particles”, Zenodo, 2026, doi: 10.5281/zenodo.19664818.