

Emergent synchronization and defect dynamics in confined chiral active suspensions

Zaiyi Shen^{1,*}, Leilei Wang², Shishuang Zhang^{2,3}, Chenlu Li^{2,3}, Kaili Xie⁴, Xu Zheng^{2,†}, and Juho S. Lintuvuori^{5,‡}

¹State Key Laboratory for Turbulence and Complex Systems, School of Mechanics and Engineering Science, Peking University, Beijing 100871, China

²State Key Laboratory of Nonlinear Mechanics, Beijing Key Laboratory of Engineered Construction and Mechanobiology, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

³School of Building Services Science and Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China

⁴Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands

⁵Univ. Bordeaux, CNRS, LOMA, UMR 5798, F-33400 Talence, France

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Hydrodynamic interactions can generate rich emergent structures in active matter systems. Using large-scale hydrodynamic simulations, we demonstrate that inertial hydrodynamic coupling alone can drive spontaneous self-organization across a hierarchy of spatial and temporal scales in confined suspensions of torque-driven particles at moderate Reynolds numbers. Spinners first self-assemble into dimers, which crystallize into a hexatic lattice and subsequently undergo a collective tilting instability. The resulting tilted dimers rotate and synchronize through hydrodynamic repulsion, which can be tuned by the Reynolds number. Upon synchronization, the polar director develops splay and bend deformations and nucleates topological defects with charges of ± 1 . These defects induce long-wavelength concentration gradients and drive crystal vortex dynamics spanning hundreds of particle diameters. Our results reveal a purely hydrodynamic route to synchronization and defect-mediated dynamics in chiral active matter, without explicit alignment rules or long-range interparticle forces.

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I. INTRODUCTION

Active matter systems, composed of energy-consuming units, can exhibit a wealth of emergent behaviors [1,2], including flocking [3], turbulence [4], and motility-induced phase separation [5]. A particularly rich class involves chiral active matter, where rotational constituents can break mirror and time-reversal symmetries [6], enabling circulating flows [7–9], nonreciprocal interactions [10,11], and unconventional transport [12,13]. Recent studies with magnetically driven rotors have revealed edge currents and odd viscosity in spinner materials [14], self-healing lattices at fluid interfaces [15], and directional exchange under confinement [16,17], while simulations predict formation of helical structures by bi-functional patchy particles [18]. Biological examples include collective spinning and formation of mesoscale vortices by starfish embryos [19] and crystallization of spinning bacteria [20], while theoretical models predict rotor synchronization [21] via fluid-mediated interactions. Yet, most of these investigations either focus on the zero-inertia regime or rely on explicit alignment rules or external fields, leaving open

whether hydrodynamic flows alone can organize structure at finite Reynolds numbers.

At moderate Reynolds numbers, rotating particles have been observed to form vortex condensates [22], two-phase crystals [23], and other emergent structures [24–26]. Recently, it has been shown that fluid inertia can lead to propulsion [27–29] and flocking [27] of asymmetric spinning particles. Despite growing recognition of fluid inertia as a driver of self-organization, its full implications remain largely unexplored and may reveal a much broader spectrum of emergent behaviors in active matter.

Here, we demonstrate that weakly inertial hydrodynamics can serve as a stand-alone organizing principle in confined suspensions of torque-driven particles. Using large-scale simulations, we uncover a cascade of emergent structures: rotating dimers and their crystallization, robust phase synchronization between the dimers, the emergence of active topological defects, and ultimately vortex dynamics governed by defect-induced concentration gradients, spanning progressively larger spatial and temporal scales. All the central results, synchronization, defect proliferation, and vortex dynamics, arise solely from fluid-mediated interactions at finite inertia in Hele-Shaw-type confinements, and are distinct from swarming observed in Ref. [27].

We study the collective dynamics of spherical spinners confined between two flat walls [Fig. 1(a)], using lattice Boltzmann simulations [30]. The particles, density-matched with the surrounding fluid, are subjected to a constant torque T around the axis perpendicular to the confining walls [Fig. 1(a)], resulting in steady spinning with a frequency ω . Periodic boundary conditions are applied along the directions

*Contact author: zaiyi.shen@pku.edu.cn

†Contact author: zhengxu@lnm.imech.ac.cn

‡Contact author: juho.lintuvuori@u-bordeaux.fr

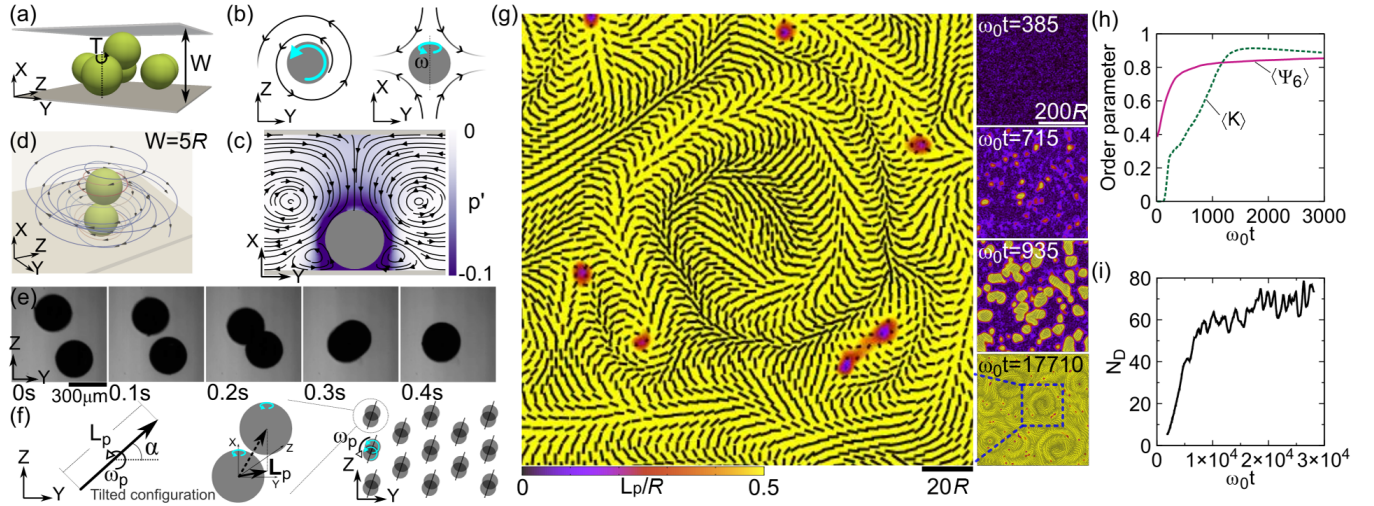


FIG. 1. Multiscale self-organization of confined spinners. (a) Schematic of the system. (b) Schematic representation of the streamlines generated by a spinner at $Re \sim 10$. (c) Simulated flow field of an isolated spinner at $Re \approx 7$ confined between walls separated by $W \approx 5R$. A recirculating flow arises due to the confinement, as indicated by the streamlines. The color map shows the pressure field, with low-pressure regions appearing near the spinner surface. (d) Example of spinner pairing and the surrounding streamlines of a stable vertical dimer under confinement ($W \approx 5R$). (e) Experimental time series showing the self-pairing process of spinning magnetic particles at $Re \approx 8$ ($W \approx 4.2R$). (f) Schematic illustrating the crystallization of tilted dimers and rotational synchronization. Here, we define the upper spinner as the *head* and the lower spinner as the *tail*; the dimer axis is the vector pointing from tail to head, and $\mathbf{L}_p$ is its in-plane projection. Black lines (magnified $\times 4$) represent the alignment vector $\mathbf{L}_p$. (g) Right: Time series of snapshots showing the evolution of tilted dimer configurations. At early times, the dimers are vertical ($L_p \approx 0$). Spontaneous tilting ($L_p > 0$) emerges and spreads across the system. The color map indicates the spatial distribution of $L_p = |\mathbf{L}_p|$. Left: Enlarged view of the boxed area in the right panel. Black lines show the alignment of the dimers given by $\mathbf{L}_p$ (magnified $\times 4$). Darker regions highlight defect locations, where vertical pairing persists ($L_p \approx 0$). Simulation corresponds to $N = 30\,720$ spinners at $Re \approx 10$, confined within a computational domain of $5R \times 480R \times 480R$. (h) Time evolution of the hexatic order parameter Ψ_6 and the Kuramoto order parameter K . (i) Time evolution of the total number of defects N_D .

parallel to the walls. Hydrodynamic interactions are fully resolved by solving the Navier-Stokes equations, with no-slip conditions enforced via the bounce-back method [31]. The particle Reynolds number is defined as $Re = \rho \omega_0 R^2 / \mu$, where $\omega_0 = T / 8\pi \mu R^3$ is the Stokes-limit spinning frequency, with R , ρ , and μ denoting the particle radius, fluid density, and viscosity, respectively. The Reynolds number serves as the primary control parameter. A short-range repulsive potential is implemented to prevent solid surface overlaps, including particle-particle and particle-wall interactions [32]; this does not set the interparticle spacing nor the observed emerging dynamics [33]. To validate our simulations, we tested experimentally the two first steps of our self-assembly: dimer formation and their crystallization [33].

II. MULTISCALE SELF-ORGANIZATION

Starting from randomly distributed spinners [Fig. 1(a)], we observe a remarkable hierarchy of self-organized states (Fig. 1). A single spinner generates a secondary flow [Fig. 1(b)] consisting of a radial component that advects fluid inward near the poles and outward along the equatorial plane [34], while the azimuthal component remains axisymmetric [22,35]. Confinement breaks the pole symmetry, leading to an effective attraction along the spinning axis [36]. When placed between two parallel walls, the flow field of a single spinner develops a recirculating pattern, pumping fluid from the equator toward the pole farther from the nearby wall [Fig. 1(c)], and two nearby particles rapidly trap one another and orbit

around a common center, eventually stabilizing into a steady vertical configuration [Fig. 1(d) and Movie S1 in Supplemental Material [33]]. Experiments with magnetically driven spinners under similar confinement reproduce the dimer formation [Fig. 1(e) and Movie S2 in Supplemental Material [33]]. The final structure of the dimer depends on the wall separation W (Movie S1 in Supplemental Material [33]). For a moderate confinement ($W \approx 5R$), sufficient vertical space allows the spinners to align vertically with negligible lateral displacement [Fig. 1(d)]. Now, the dimer center can be slightly offset from the midplane, depending on which spinner contacted the nearby wall first.

At larger scales, the dimers spontaneously self-organize into a hexatic crystal [Fig. 1(f)]. At zero Reynolds number, it is known that a combination of steric repulsion and mixing driven by azimuthal (rotational) flows promotes the rapid crystallization of spinners [37]. Here, at a finite Reynolds number, the effective repulsion needed for crystallization emerges naturally from the inertia-induced secondary flow generated by each spinner [Fig. 1(b)], leading to a hexatic ordering of the dimers without any long-range thermodynamic repulsion. The dimer crystallization is reproduced in our spinner experiments [33].

At sufficiently high concentrations, hydrodynamic interactions from the surrounding dimers can trigger a collective tilting instability. Considering an initially vertical configuration, local perturbations in spinner positions grow and lead to spontaneous tilting that propagates throughout the system (Movie S3 in Supplemental Material [33]). The dimers adopt

tilted configurations characterized by an orientation field $\mathbf{L}_p$ corresponding to the projection of the center-to-center separation of the two spinners onto the plane of rotation [left panel in Fig. 1(f)]. Each spinner orbits its partner around a shared center of mass with a characteristic angular speed $\omega_p < \omega_0$, while the overall crystalline order of the dimer centers is maintained. The rotation of dimers tends to synchronize with their neighbors, and at larger scales, this local phase locking gives rise to spiral structures in the orientation field $\mathbf{L}_p$, punctuated by the nucleation of topological defects [Fig. 1(g)].

We demonstrate the formation of these dynamic states in a large-scale simulation of $N = 30\,720$ spinners (volume fraction $\phi \approx 11\%$) confined between parallel walls separated by $W = 5R$ at a Reynolds number $\text{Re} \approx 10$ [Figs. 1(g)–1(i)]. Randomly initialized spinner dimers rapidly self-organize into a hexatic crystal, quantified by the local hexatic order parameter $\Psi_6 = \frac{1}{n_j} \sum_k \exp(i6\theta_{jk})$, where n_j is the number of nearest neighbors of the dimer j and θ_{jk} is the angle between the vector connecting the dimers j and k and a fixed horizontal axis. The spatial average $\langle \Psi_6 \rangle$ quickly rises to 0.85 [Fig. 1(h)], indicating rapid crystallization after $\omega_0 t \approx 500$, driven by hydrodynamic repulsion.

At the initial stage, the particle pairs are vertical ($L_b \sim 0$) [see, e.g., $\omega_0 t \approx 385$ in the insets of Fig. 1(g)]. The hydrodynamic interactions gradually induce tilting ($L_b > 0$) and consequently dimer rotation that propagates through the system [$\omega_0 t \approx 715$ and $\omega_0 t \approx 935$ in the insets of Fig. 1(g) and Movie S4 in Supplemental Material [33]]. This propagation is subsequently followed by spontaneous rotational synchronization, corresponding to the alignment of the tilted dimers [Fig. 1(g) and Movie S4 in Supplemental Material [33]].

To evaluate the synchronization, we calculate averaged local Kuramoto order parameter $\langle K \rangle = \langle \frac{1}{m_j} |\sum_k \exp(i\alpha_k)| \rangle$, where α_k is the in-plane orientation angle of the dimer k [left panel in Fig. 1(f)] within a circular region of radius $10R$ centered on the dimer j and m_j is the total number of dimers within the region. The value of $\langle K \rangle$ rises steadily and reaches approximately 0.9 after $\omega_0 t \approx 1200$ [Fig. 1(h)], indicating a high degree of local rotational synchronization.

At large scales, global synchronization of dimer rotations is not attained. Instead, the system self-organizes into multiple locally synchronized domains separated by finite phase lags. To accommodate smooth phase variation between these regions, the orientation field develops bend and splay deformations and formation of active defects. The defects can be identified as regions where the bond length L_p is significantly reduced [dark red regions in Fig. 1(g), corresponding to $L_p \sim 0$]. In the bend and splay zones, L_p remains finite [yellow areas in Fig. 1(g)]. By tracking the spatial distribution of L_p , we estimate the total number of defects N_D , which fluctuates between approximately 60 and 80 in the steady state [Fig. 1(i)].

The deformations and defects are reminiscent of those found in nematic liquid crystals. However, unlike conventional nematics, the dimers rotate persistently; thus, the resulting orientation field $\hat{\mathbf{n}} = \cos\alpha\hat{\mathbf{y}} + \sin\alpha\hat{\mathbf{z}}$ is polar rather than headless [Fig. 2(a)], where α is the angle between y axis and the projected dimer alignment vector $\mathbf{L}_p$ [Fig. 1(f)]. The formation of topological defects with charges of ± 1 is observed [Fig. 2(a)]. In the steady state, most defects exhibit

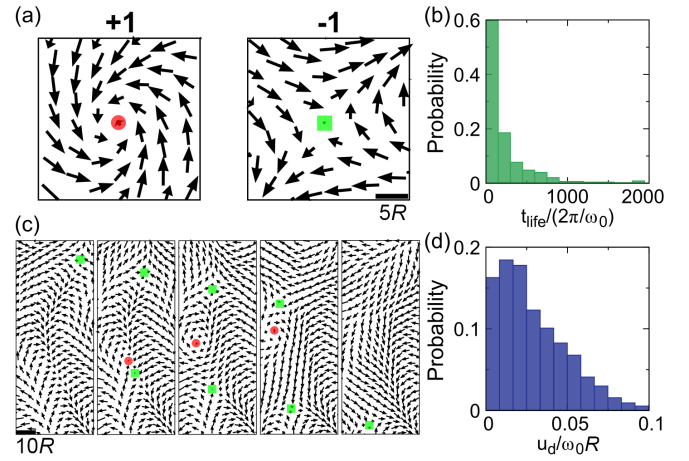


FIG. 2. Active defects. (a) Instantaneous orientation structures around a $+1/-1$ defect. (b) Probability distribution of defect lifetimes. (c) Example of a short-lived $+1/-1$ defect pair undergoing spontaneous nucleation, movement, and annihilation. (d) Probability distribution of defect speeds.

lifetimes $t_{\text{life}} < 100 \times 2\pi/\omega_0$ [Fig. 2(b)] and undergo continuously migration, annihilation, or nucleation through local reconfigurations of the orientation field [Fig. 2(c) and Movie S5 in Supplemental Material [33]]. Their migration velocity ($\sim 0.01\omega_0 R$) is significantly slower than the tangential surface velocity of the spinners [Fig. 2(d)]. Due to the periodic boundary conditions, topologically equivalent to a torus, the total topological charge remains conserved at $q = 0$ throughout the dynamics.

The defects not only shape the orientation field, but also induce concentration gradients in the particle distribution. We observe a strong relationship between the number of local defects and the local particle concentration [Fig. 3(a)]. Regions with more defects exhibit lower dimer density.

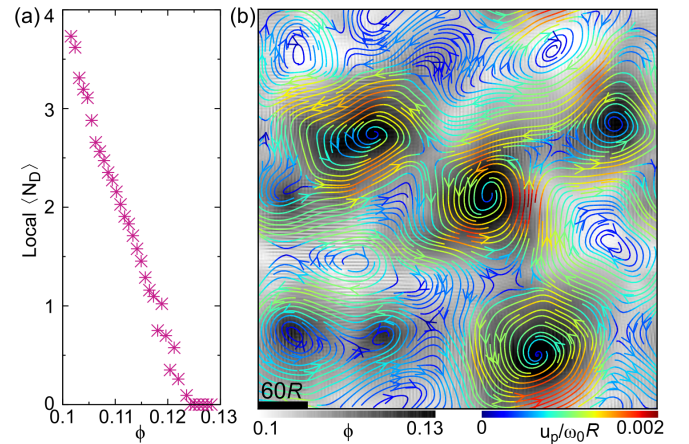


FIG. 3. Vortex dynamics. (a) The average number of defects N_D decreases with increasing local volume fraction ϕ , indicating that defect-rich regions are systematically more dilute. (b) Regions with high (black) or low (white) local volume fraction exhibit slow vortical motion. The black-and-white shading indicates the local volume fraction. The motion of the dimer centers is represented by streamlines, color coded by the observed speed. Dense domains rotate in the same sense as the individual spinners (counterclockwise), while dilute domains exhibit an opposite (clockwise) recirculation.

As a result, the system develops long-wavelength density modulations [Fig. 3(b)]. Intriguingly, the concentrated regions rotate in the same direction as the individual spinners, while depleted regions exhibit counterrotating vortices [Fig. 3(b)]. We attribute this two-sense circulation to a hierarchy of couplings. The collective rotation is driven by the transverse forces between the spinners [flow field v_t in Fig. 1(b)]. The defect-poor domains are denser, which amplifies the collective transverse force [37] and gives rise to particle vortices rotating in the same direction as the spinners (counterclockwise). This rotation creates opposite turning fluid vortex in the dilute region, advecting the particles creating clockwise rotating vortices [Fig. 3(b)]. We note that vorticity reversal has been observed at grain boundaries of rotating crystallites in odd crystals [11], which is different from the approximately equal sized oppositely rotating vortices reported here. These emergent vortex structures span hundreds of particle diameters and remain stable within the duration of the simulations, highlighting the robustness of the observations.

III. HYDRODYNAMIC MECHANISM FOR SYNCHRONIZATION

To isolate the mechanism leading to synchronization, we investigate a slightly stronger confinement ($W = 4R$), where the geometry imposes tilted configuration (Movie S1 in Supplemental Material [33]). This constraint suppresses variations in the dimer geometry, so that we can focus on the in-plane rotational (phase) dynamics of an ensemble of tilted dimers.

Simulations of $N = 3200$ spinners in the domain of $4R \times 240R \times 240R$ ($\phi \approx 5.8\%$) show that at $Re \approx 25$, the orientation field $\hat{\mathbf{n}}(\mathbf{r})$ exhibits extended nematic domains with well-defined alignment, accompanied by high local synchronization measured by the Kuramoto order parameter ($K \approx 1$) [Fig. 4(a)]. In contrast, at low Reynolds number ($Re \approx 1$), the orientation field becomes isotropic and disordered, indicating the absence of synchronization [Fig. 4(a)].

The flow field around a single spinner features both radial (v_r) and tangential (v_t) components in the equatorial plane [Fig. 1(b)]. These generate effective in-plane radial repulsion (f_r) and transverse forces (f_t) between neighboring spinners. From simulations of two interacting spinners near a wall under the same confinement ($W = 4R$), we extract the force scaling as $f_t = 4.56F_0(r/R)^{-3.85}$ and $f_r = 0.08F_0Re(r/R)^{-2.9}$, where $F_0 = 6\pi\mu\omega_0R^2$ [33]. In what follows, we use the pair interaction as a leading-order approximation. We note that a full dimer-dimer interaction involves multipair superposition as well as wall-induced corrections and may renormalize the effective coefficients at the dimer level [33].

To isolate the role of these interactions, we construct a minimal model in which rotating dimers are fixed on hexagonal lattice sites [Fig. 4(b)]. The dimer positions are fixed (only the in-plane phases/orientations evolve); therefore, structural measures such as the hexatic order parameter Ψ_6 and the (local) packing fraction ϕ are not defined within the model and are evaluated only in the hydrodynamic simulations. Each dimer rotates with a natural angular velocity ω_d and experiences both radial and transverse forces from its neighbors (given above). Assuming an overdamped regime, the

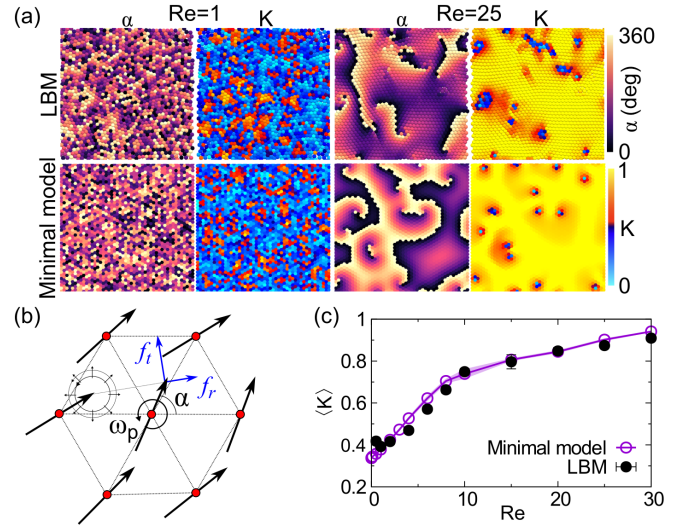


FIG. 4. Rotational synchronization driven by hydrodynamic interactions. (a) Spatial fields of dimer orientation angle α and local synchronization parameter K . (b) Schematic of the minimal model describing rotational dynamics of dimers arranged on a hexatic lattice. Each dimer is represented by a rotating vector, and hydrodynamic interactions are modeled via transverse f_t and repulsive f_r forces. (c) Mean Kuramoto order parameter (K) as a function of Reynolds number Re . Results from both hydrodynamic simulations and the minimal model show a consistent increase in synchronization with Re .

orientation of the i th dimer evolves according to

$$\dot{\omega}_p^i = \frac{d\alpha_i}{dt} = \omega_d + \sum_j \frac{\mathbf{f}_{ij} \times \hat{\mathbf{n}}_i}{\xi a}, \quad (1)$$

where $\mathbf{f}_{ij}$ is the hydrodynamic force exerted by the j th dimer on the i th, decomposed into transverse ($f_t \hat{\mathbf{t}}_{ij}$) and radial ($f_r \hat{\mathbf{r}}_{ij}$) components. Here, $\hat{\mathbf{n}}_i$ is the director of the i th dimer, a is the distance from the lattice site to the spinner within a dimer, and ξ is the viscous drag coefficient, given by Stokes drag $\xi = 6\pi\mu R$. The phase angle α_i is the in-plane orientation of $\hat{\mathbf{n}}_i$.

Using the lattice distance $d \approx 6.4R$ (calculated from a hexatic arrangement of a dimer monolayer corresponding to $\phi \approx 5.8\%$ with $W = 4R$ in hydrodynamic simulations), together with $a = 0.75R$ and a natural dimer rotation rate $\omega_d = 0.15\omega_0$ inferred from the two-spinner dynamics [33], this minimal model captures the essential features of the full hydrodynamic simulations: It exhibits large-scale nematic domains and strong local synchronization at $Re \approx 25$, and transitions to an isotropic, disordered state at $Re \approx 1$ [Fig. 4(a)], in excellent agreement with the full simulations [Fig. 4(c)].

The ratio between the radial and transverse interactions scales linearly with the Reynolds number $f_r/f_t \sim Re$. Comparison across simulations reveals that radial repulsion promotes phase locking and synchronization at higher Re , while transverse forces induce phase divergence and disorder at lower Re , for various concentrations and confinement ratios [33]. To examine the generality of this behavior, we formulated generalized interaction forms unrelated to fluid flow $f_t = \xi\omega Rr^{-3}$ and $f_r = \beta\xi\omega Rr^{-3}$, where $\beta = f_r/f_t$

defines the ratio between repulsive and transverse forces. The numerics demonstrate that purely radial interactions ($f_r/f_t \rightarrow +\infty$) consistently stabilize synchronization, whereas purely transverse interactions ($f_r/f_t \rightarrow 0$) destabilize it [33].

IV. CONCLUSION

Our findings establish moderate Reynolds number flows coupled with confinement as a powerful organizing tool in chiral active matter. Starting from torque-driven spinners, the system spontaneously develops a sequence of emergent states: stable rotating dimers, and their hexatic ordering, active chiral polar nematics, topological defects, and ultimately large-scale vortex dynamics. The physics is boundary selected: The reported sequence relies on a Hele-Shaw-type confinement that stabilizes vertical pairing and shapes the inertial secondary flows that provide effective hydrodynamic repulsion. Within this class of confinements, the phenomenology is robust across the range tested ($W/R \approx 4, 4.5$, and 5) and persists under substantial boundary-condition variations [33]. For very large wall separations, or sedimented monolayers, we expect different behavior [22,23]. Finally, while odd responses may also arise, as typical in chiral active fluids [14,19,38,39], we attribute the ordering and density modulations primarily to inertia-induced secondary flows.

Our results suggest strategies for engineering tunable multiscale order in synthetic active materials, microrobotic swarms, and biologically inspired systems. More broadly, they

reveal a general framework in which nonequilibrium structure emerges naturally from the interplay of chirality, inertia, and confinement—offering routes to controlling active matter through hydrodynamic interactions.

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DATA AVAILABILITY

The code used in this study is available in Ref. [40]. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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