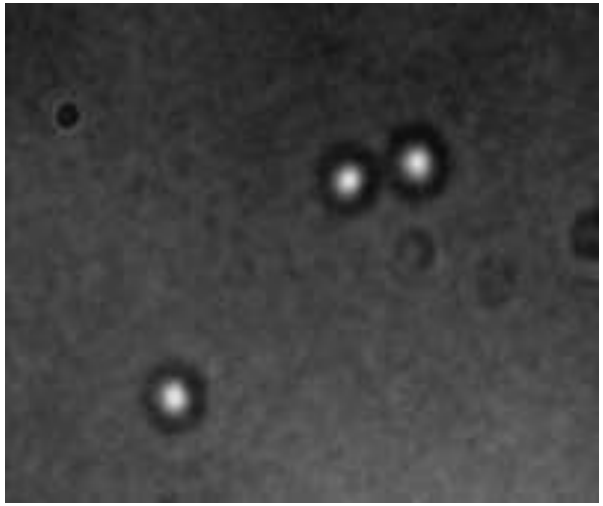
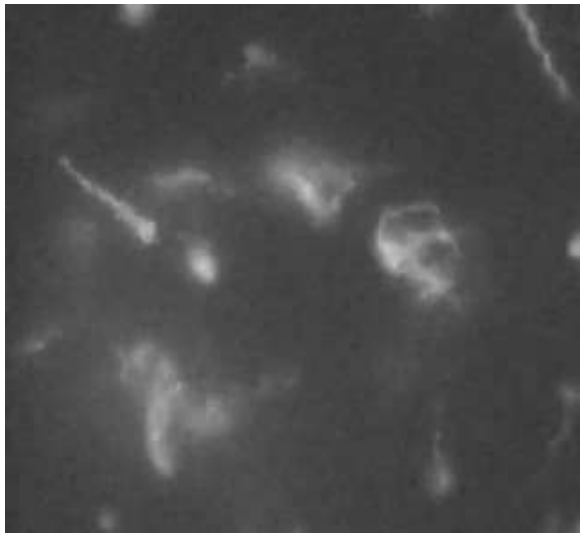
中国科学院物理研究所
Institute of Physics Chinese Academy of Sciences

活性物质的涌现集群行为

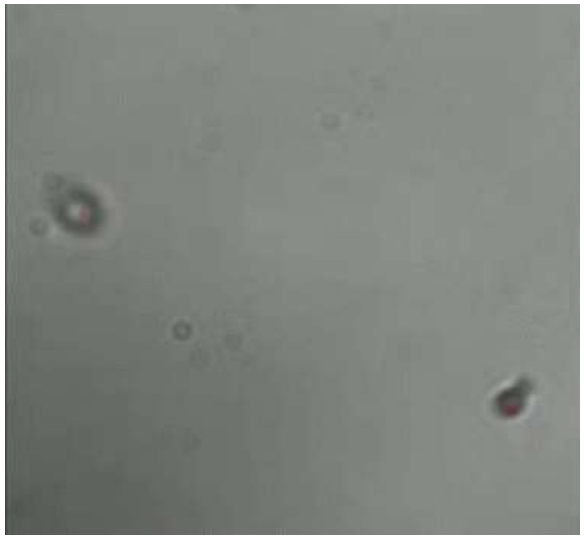
杨明成
中国科学院物理研究所



Brownian motion



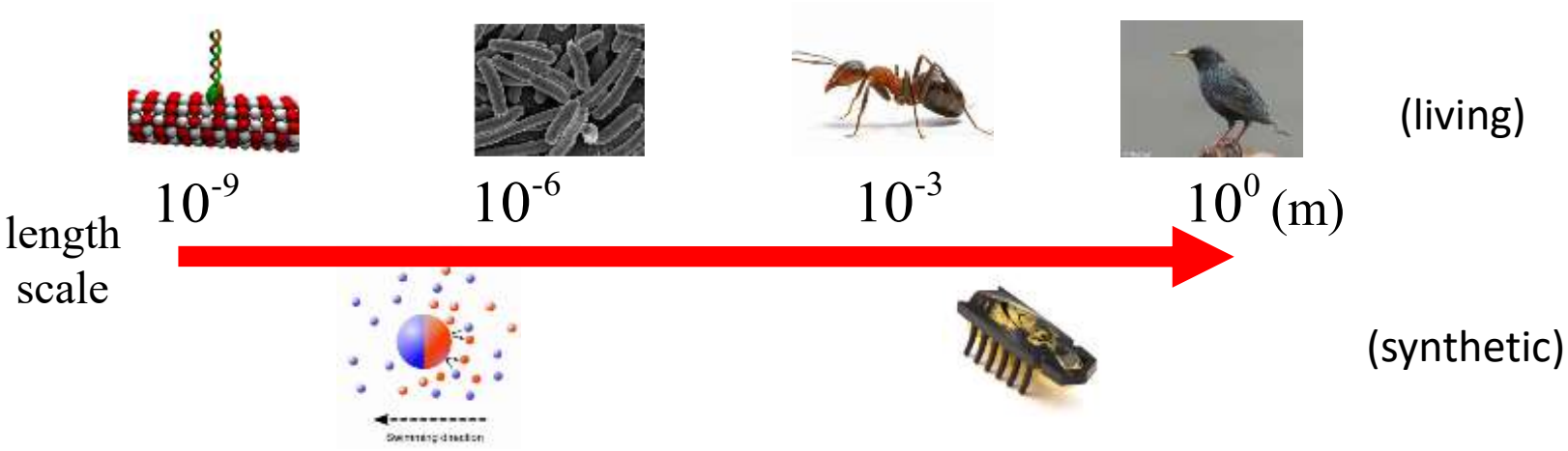
Bacteria (E. Coli)



self-propelling colloid

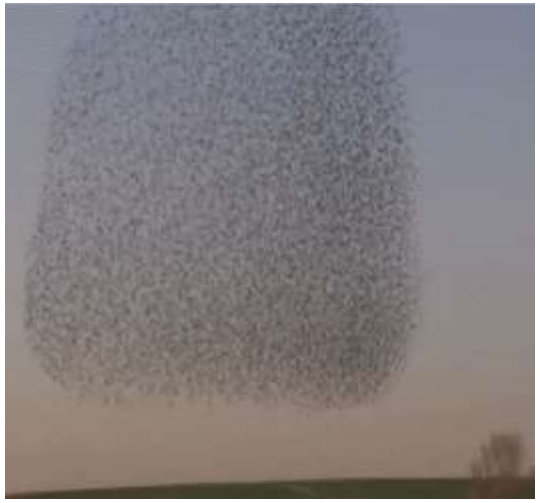
Active Matter

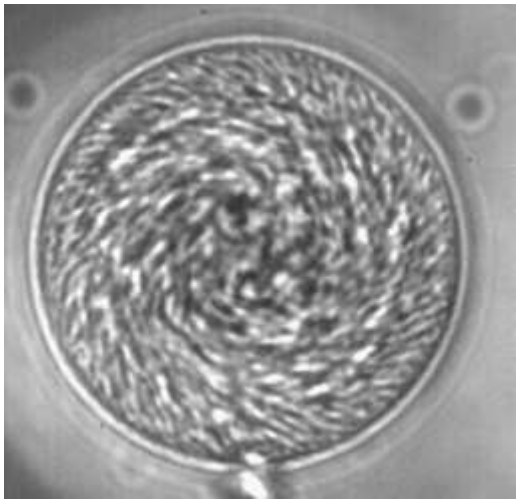
- Self-propelled units, Intrinsically nonequilibrium, Novel phenomena



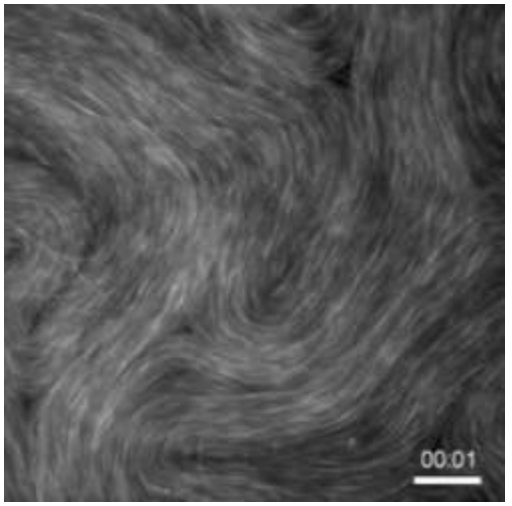
- **Collective behavior**

Intrinsic out-of-equilibrium state



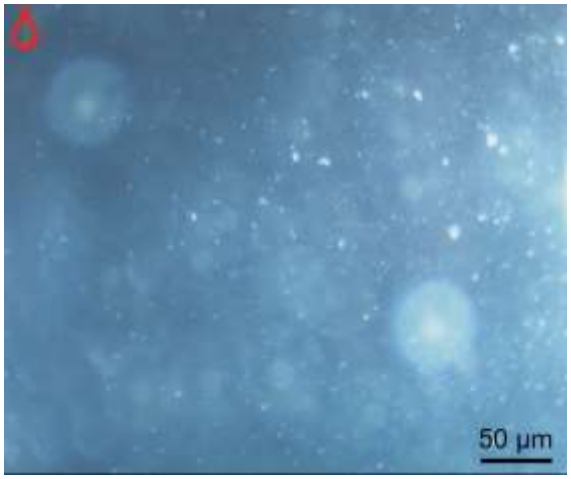


Bacterial spontaneous vortex
Wioland et al. **PNAS** (2014)

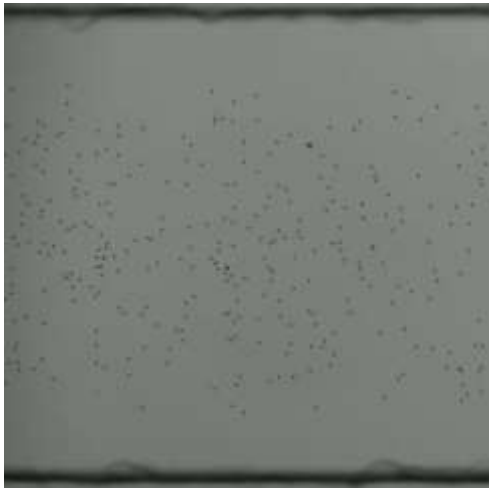


kinesin + microtubule
Sanchez *et al.* **Nature** (2012)

Swarming colloid
Nat. Nanotechnol. 16, 288 (2021)



Phototactic colloidal vortex
PNAS 118, e2104481118 (2021)



Colloidal roller flocking
Bricard, *et al.* **Nature** (2013)

Novel nonequilibrium physics

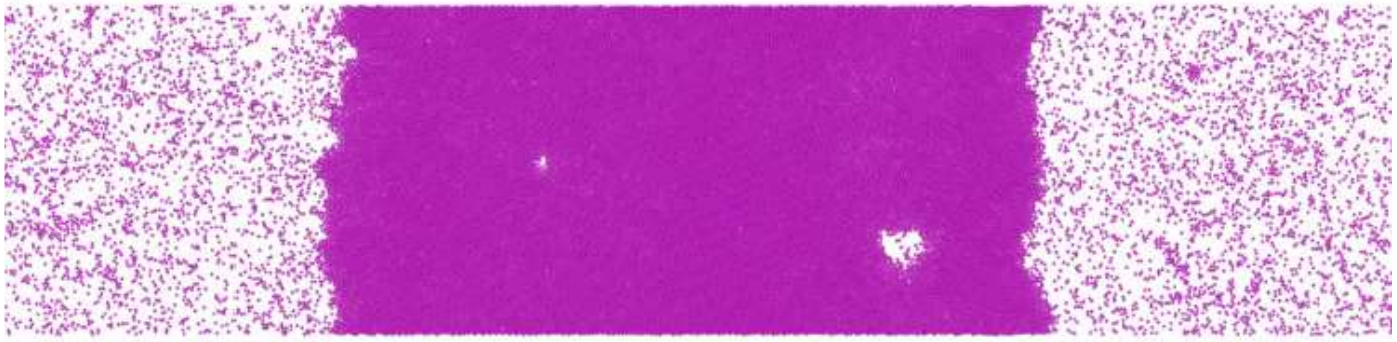
- Breaking the Mermin-Wagner theorem (there is no long-range ordered state in 2D systems with continuous symmetry).

$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t)\Delta t$$

$$\theta(t+1) = \langle\theta(t)\rangle_r + \Delta\theta$$

PRL 75, 1226 (1995)

- Gas-liquid phase transition without attraction

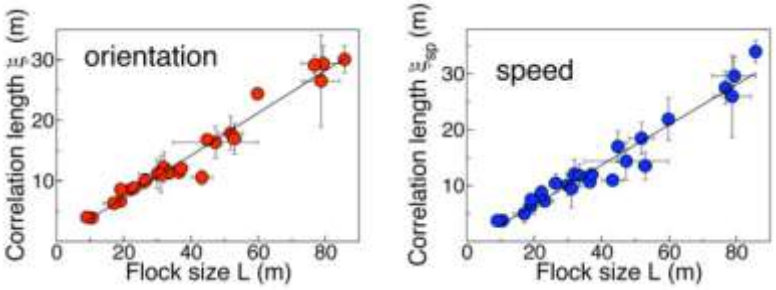


PNAS 122, e2505010122 (2025)

Collective behavior of active systems

2021 Nobel Physics Prize

Giorgio Parisi, "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."



Scale-free correlations in starling flocks

PNAS 107, 11865 (2010)

2021 IgNobel Physics Prize

Alessandro Corbetta, et al, "for conducting experiments to learn why pedestrians do not constantly collide with other pedestrians."

Pedestrian traffic is a fascinating case study in dynamic collective behavior. Physicists typically model such systems as interacting particles, with social forces acting on people in similar ways to physical forces. Corbetta et al. set up a six-month pedestrian-tracking experiment, and collected about 5 million trajectories, and used that data to build a better model for pedestrian.

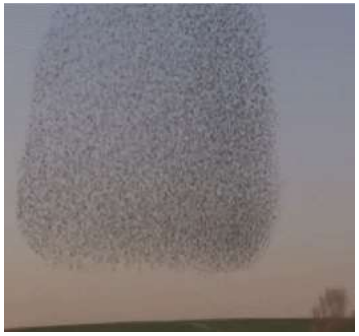
PRE 98, 062310 (2018)

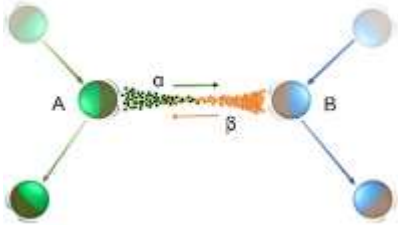
(1) Collective dynamics of active colloids with chemical ***communication***

Artificial active colloid with communication

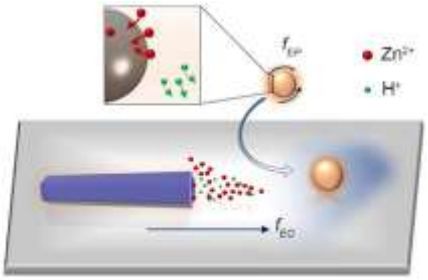
Biological active particles often communicate with each other, and change their self-propelled velocities accordingly.

Artificial active colloid generally cannot do so.





- Consider two types of chemically-powered active particles, whose reaction products are each other's food or "catalyzer", so their activities (motility) depend on their separation.



- ZnO nanorod self-propels by self-diffusiophoresis (depending on PH)

$$ZnO_{(s)} + H_2O_{(1)} \rightleftharpoons Zn^{2+}_{(aq)} + 2OH^-_{(aq)}$$

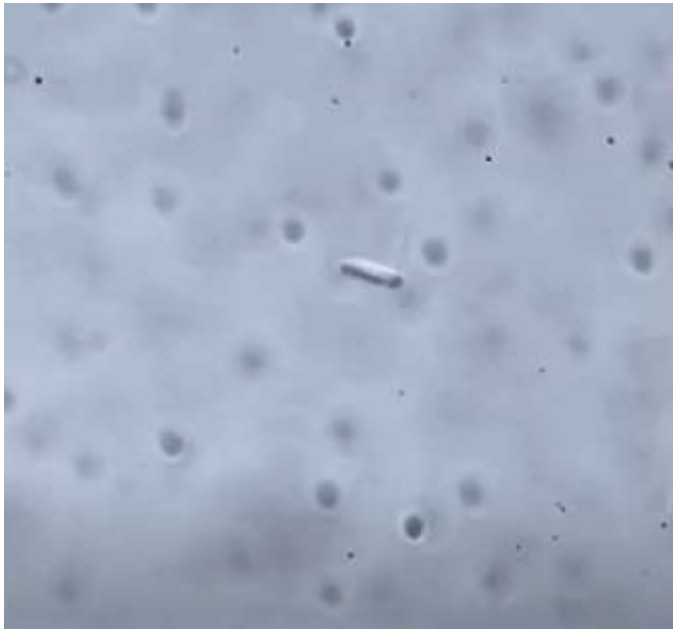
- Chemically active sulfonated PS microbead (depending on cation)

$$PS - SO_3H + M^+ \rightleftharpoons PS - SO_3M + H^+$$

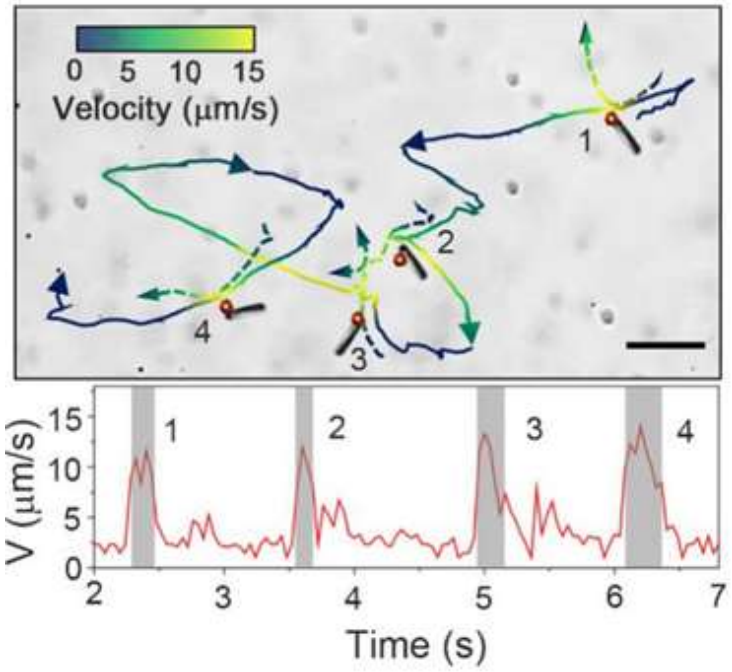
Ion-exchange reaction enables chemical communication!

Artificial active colloid with communication

ZnO and SPS mixture



ZnO nanorod motility changes with its separation from SPS microbead.

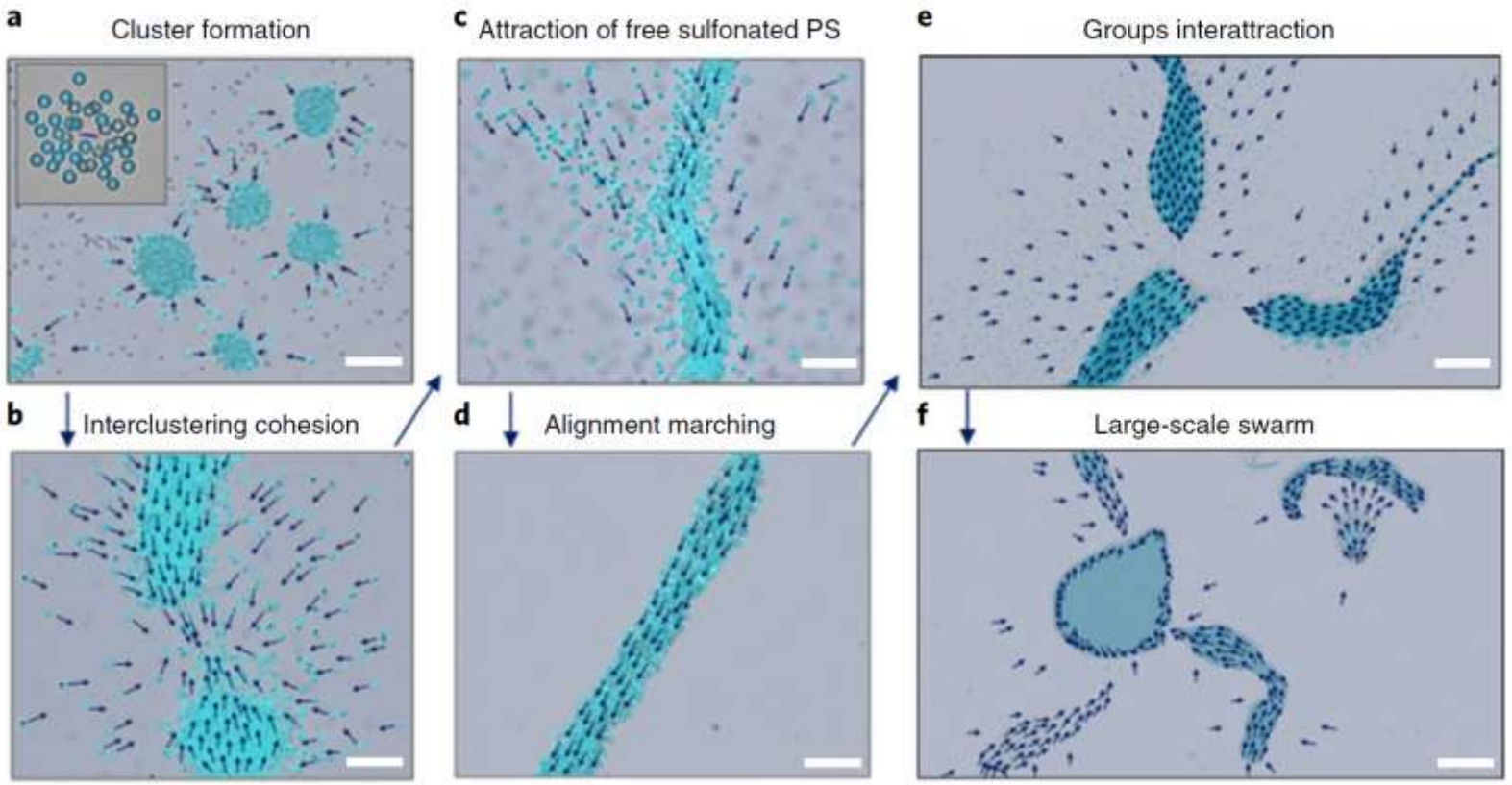


- Chemical communication between active particles induces separation-dependent self-propelled velocity.

Nature Nanotechnology 16, 288 (2021)

Collective behavior of ZnO-SPS mixture

- Communication and separation-dependent motility induce hierarchal and dynamic swarming motion.
  - ZnO nanorod produces repulsive osmotic flow
  - SPS microbead produces attractive osmotic flow

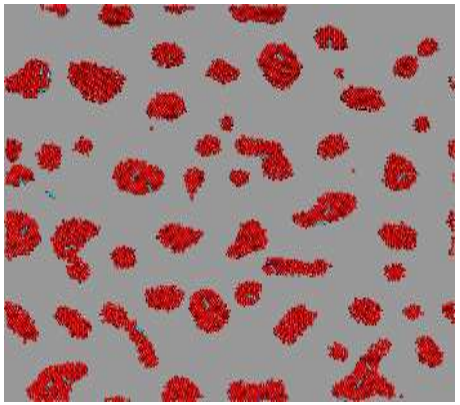


Nature Nanotechnology 16, 288 (2021)

Collective behavior of ZnO-SPS mixture

- Communication, separation-dependent motility and osmotic effect induce hierarchal and dynamic emergent collective motion.

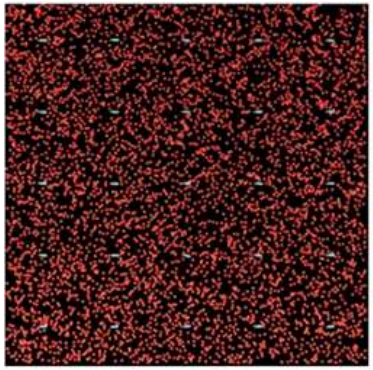
Exp

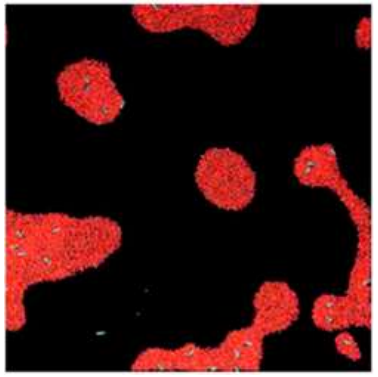


Sim

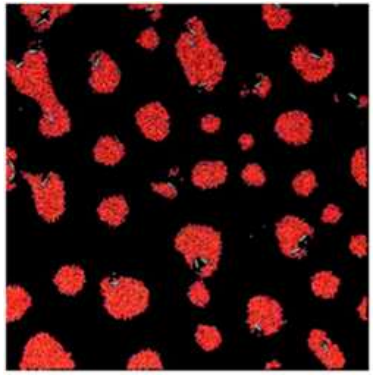
ZnO-SPS mixture

With communication





No communication



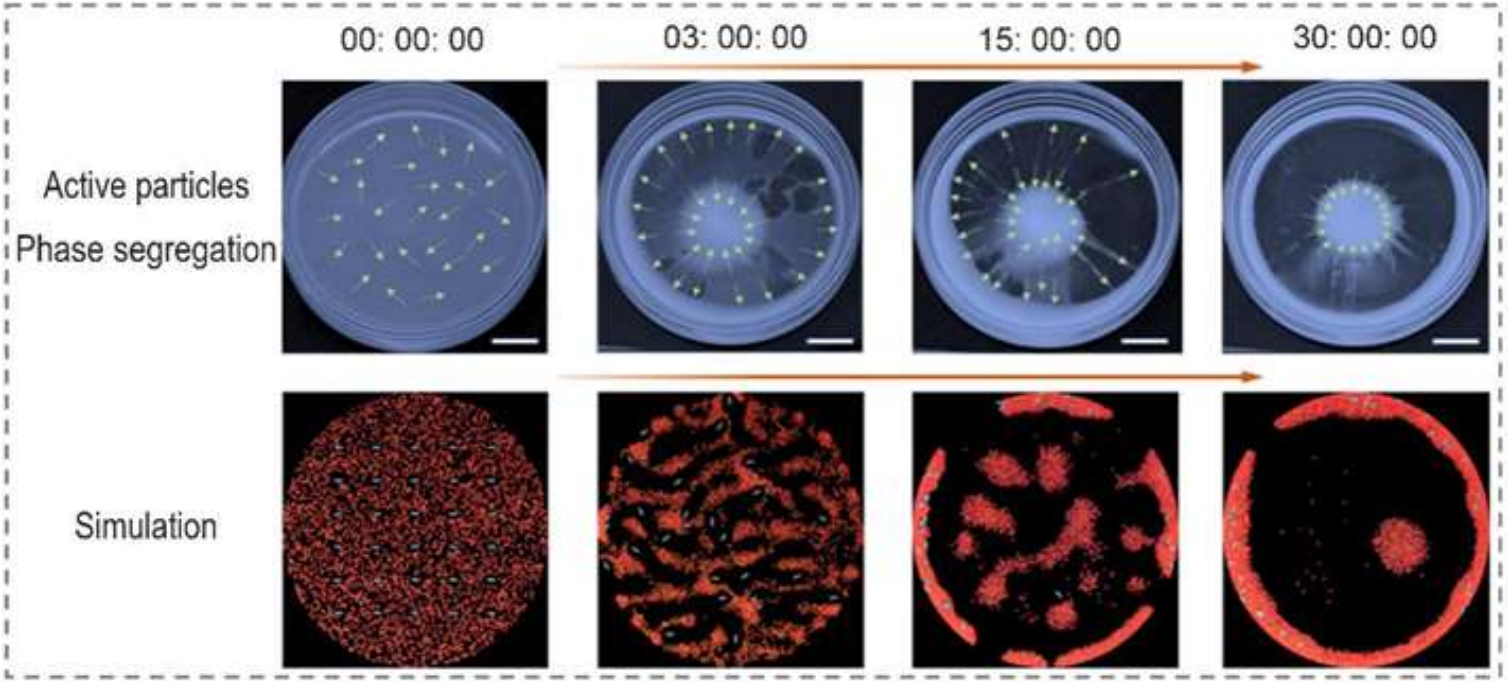
Brownian dynamics simulation

Nature Nanotechnology 16, 288 (2021)

Macroscopic segregation and quorum sensing

Boundary wall impedes ion diffusion, leading to macroscopic segregation and quorum “decision-making”：

Evolution over time



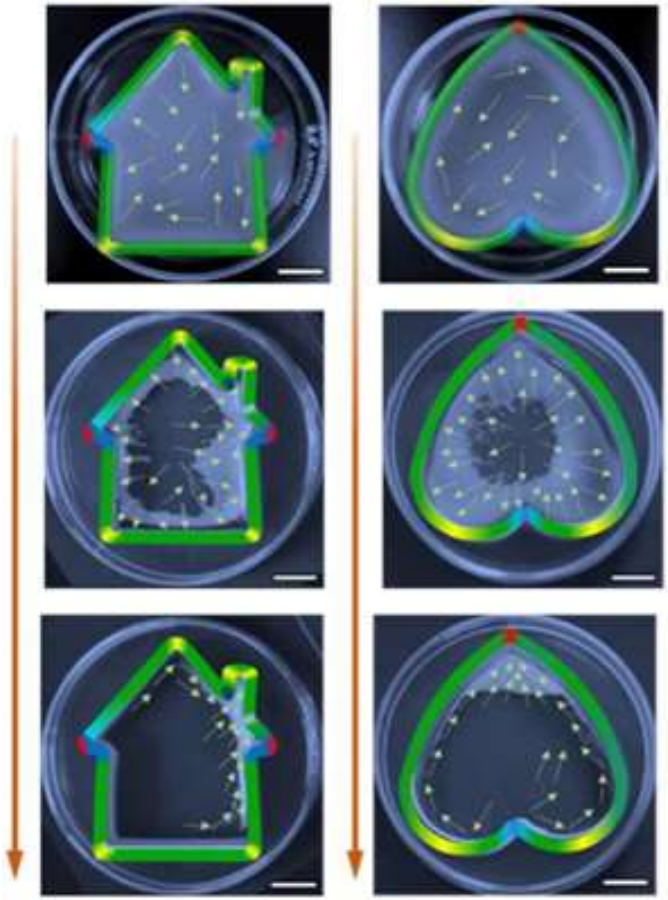
Accumulate at the boundary wall

Different from motility-induced trapping at the boundary!

Macroscopic segregation and quorum sensing

Boundary wall impedes ion diffusion, leading to macroscopic segregation and quorum “decision-making”：

Evolution over time

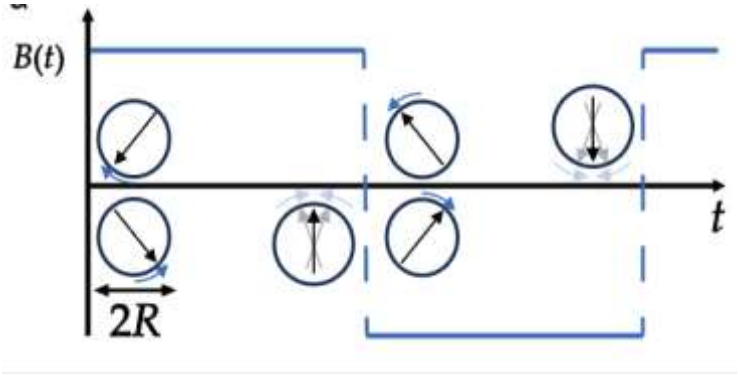


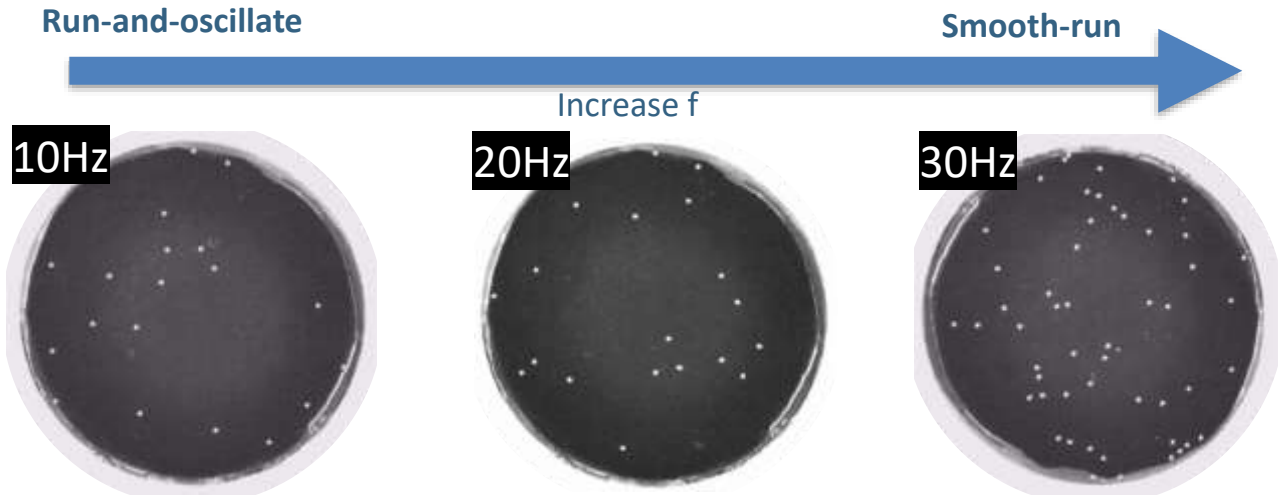
Accumulate at sharp corner

(2) Flocking phase separation of ***inertial*** active rollers

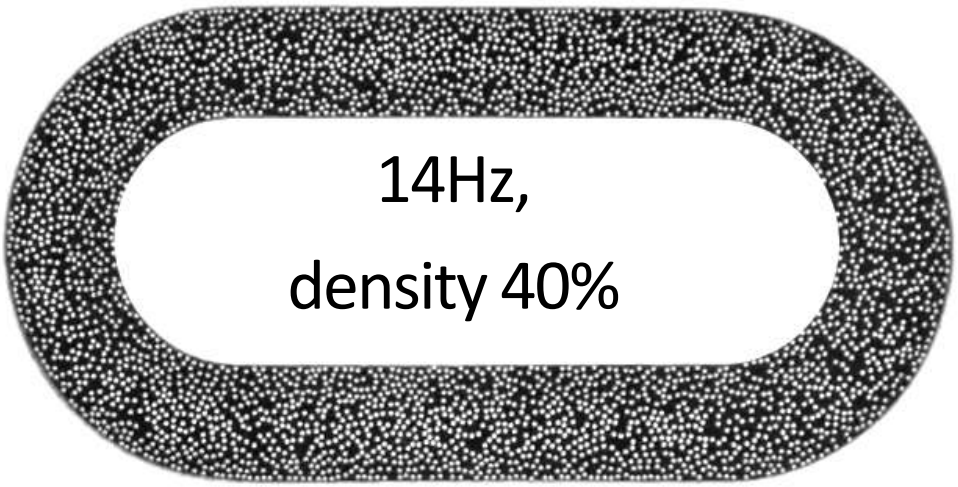
Magnetic-field-driven granular rollers

Ferromagnetic spheres of diameter 0.5mm under AC squared-wave magnetic field, with **well-known physical interactions** and **tunable motile behaviors**



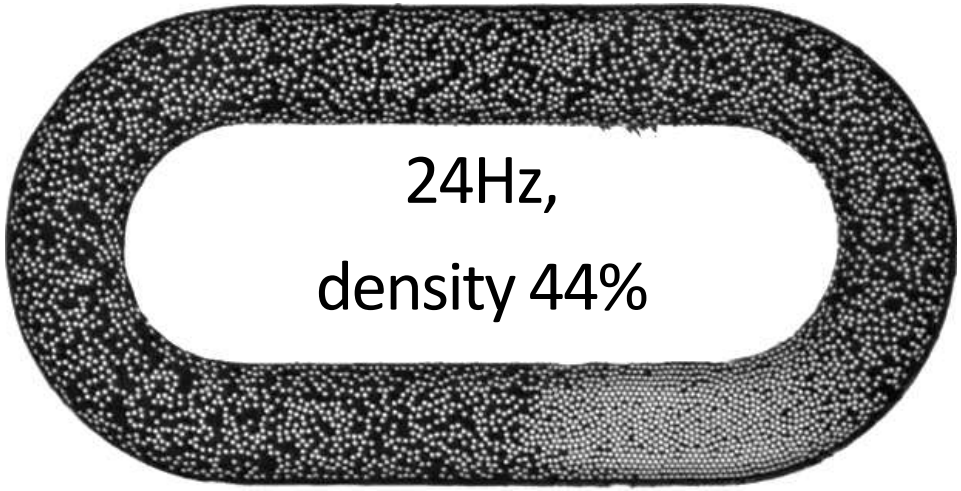


Collective behavior of magnetic rollers



Isotropic gaseous phase

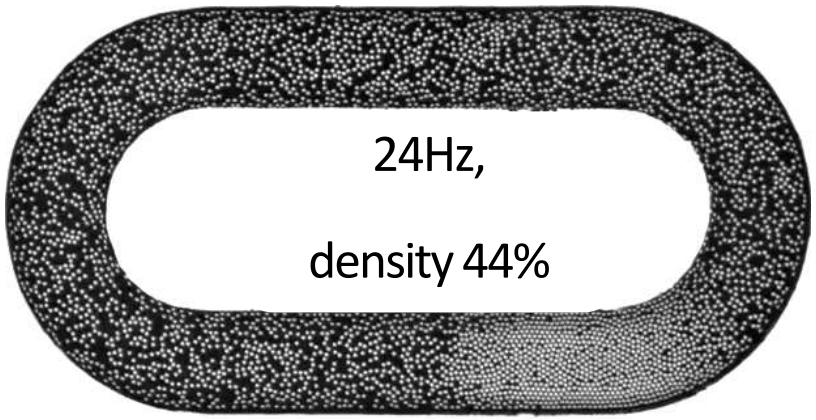
Increase density



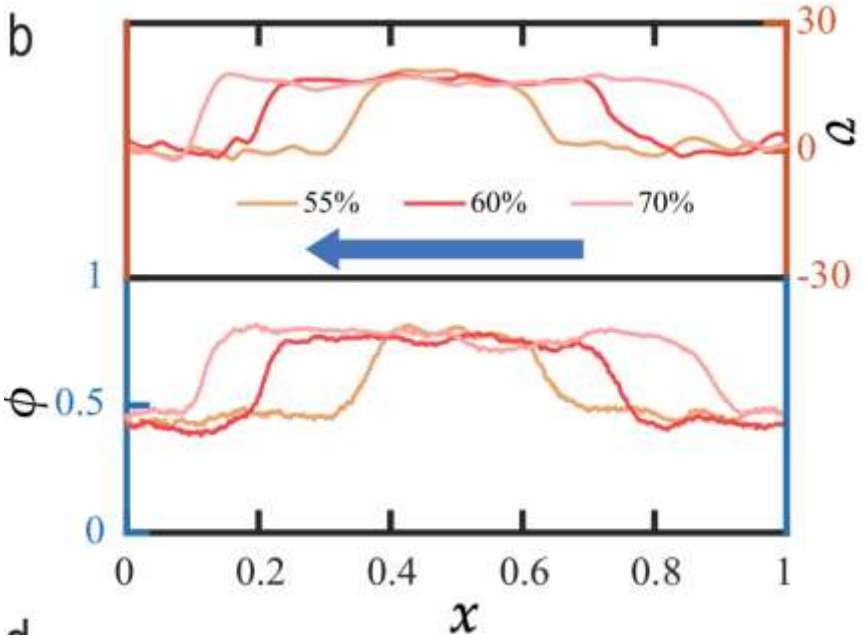
Flocking phase separation

Phys. Rev. Lett. 135, 178301 (2025)

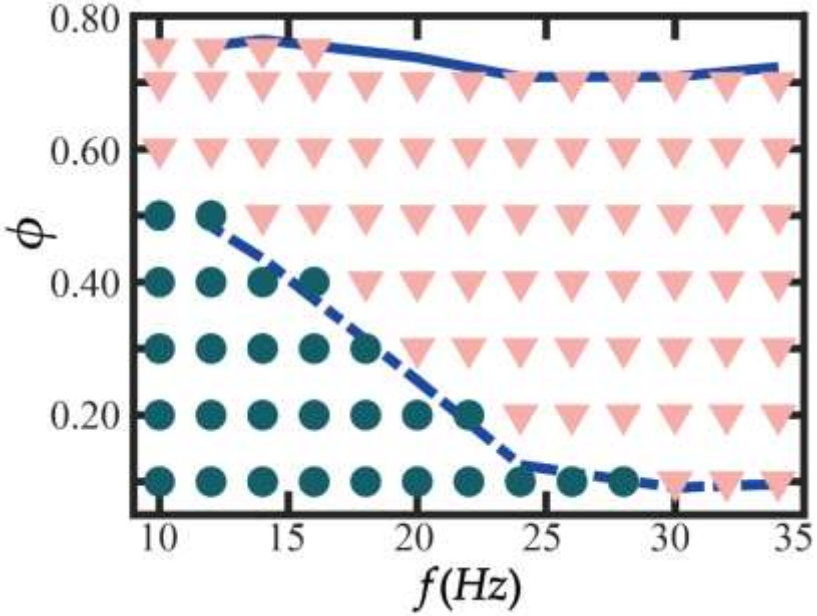
Flocking phase separation



Profile of velocity and density



Phase diagram

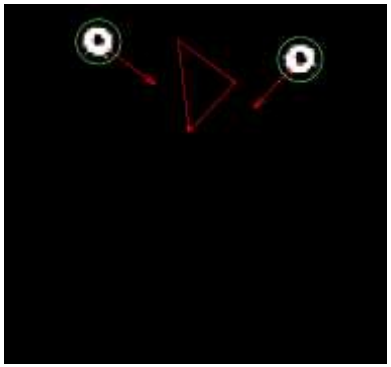


Phases exhibit intrinsic densities and velocities, independent of mean system density, follow the lever rule.

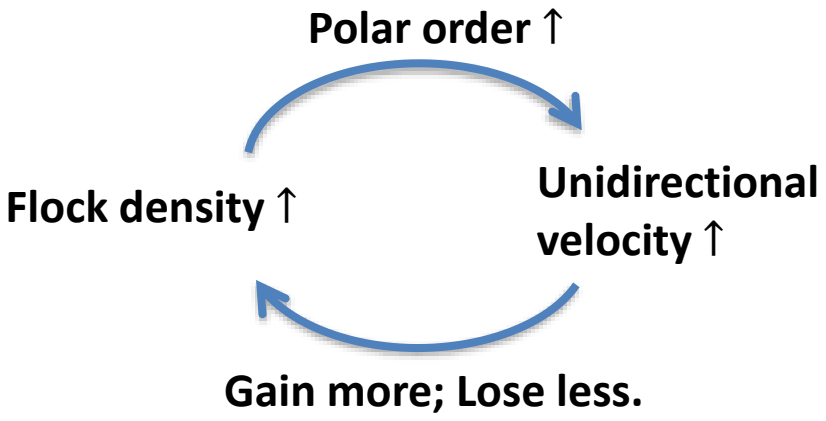
Phys. Rev. Lett. 135, 178301 (2025)

What leads to flocking phase separation?

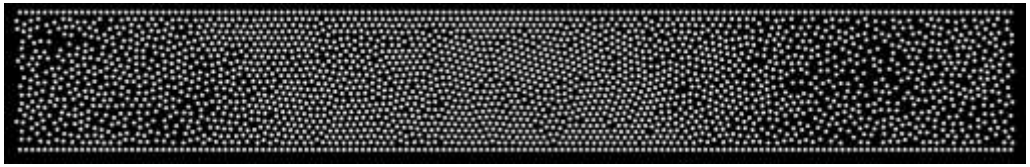
Inelastic collision and inertia dominate



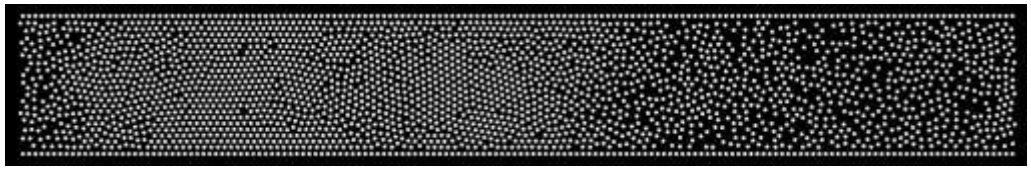
Positive feedback:



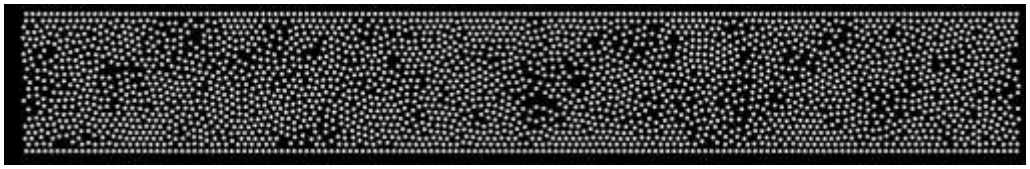
Inelastic collision+dipole interaction

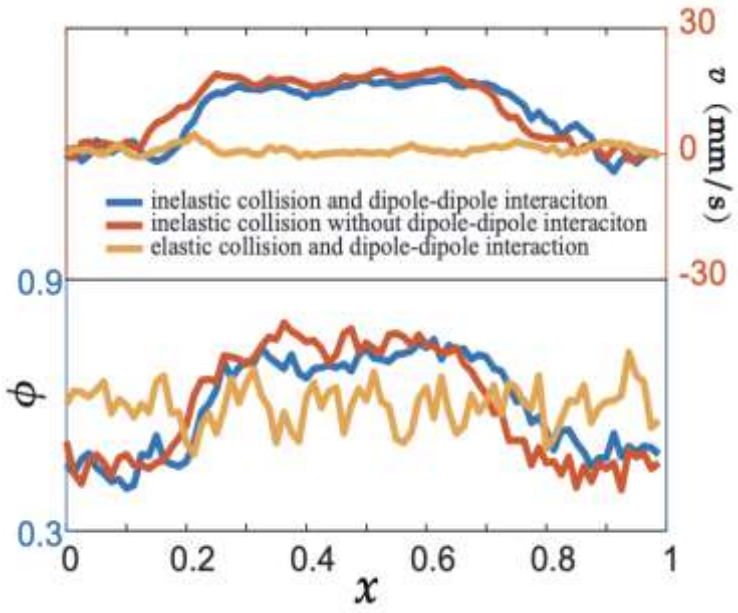


Inelastic collision



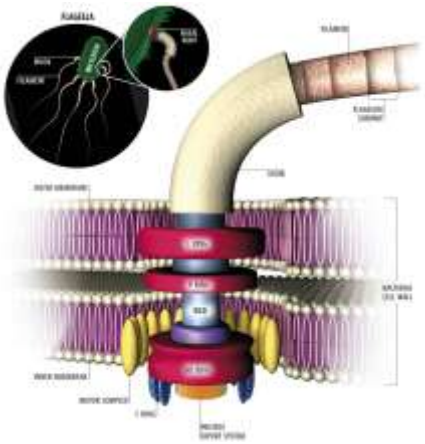
elastic collision+dipole interaction



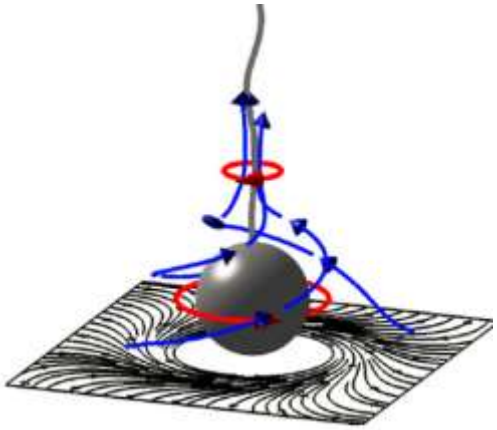


(3) Edge flow of ***chiral*** active matter and cargo transportation

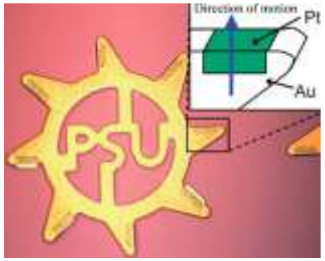
Active rotors in experiments

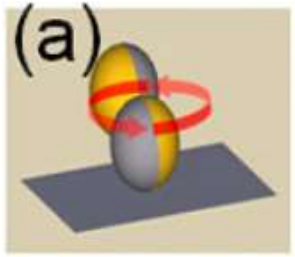


Rotary biological motor

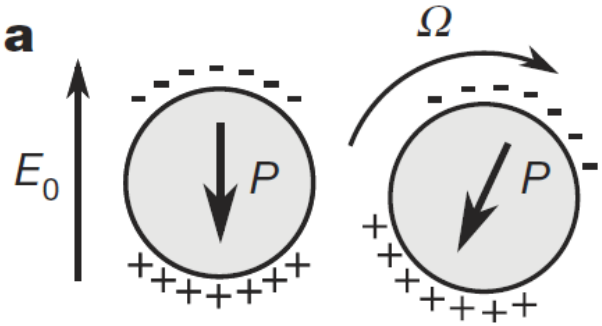


Spinning bacteria
Petroff et al (2015) PRL

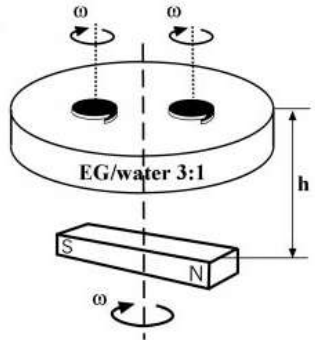




Chemcal and thermal powered rotors
Catchmark et al (2005) Small
Jiang et al (2010) PRL



Quincke rotation

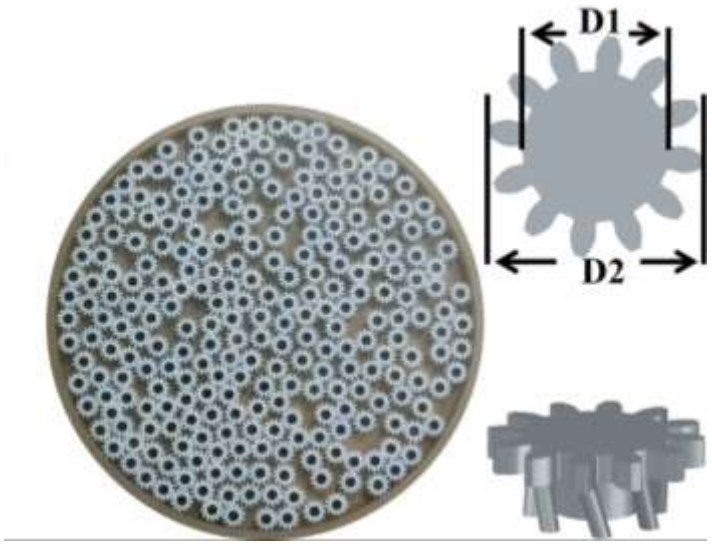


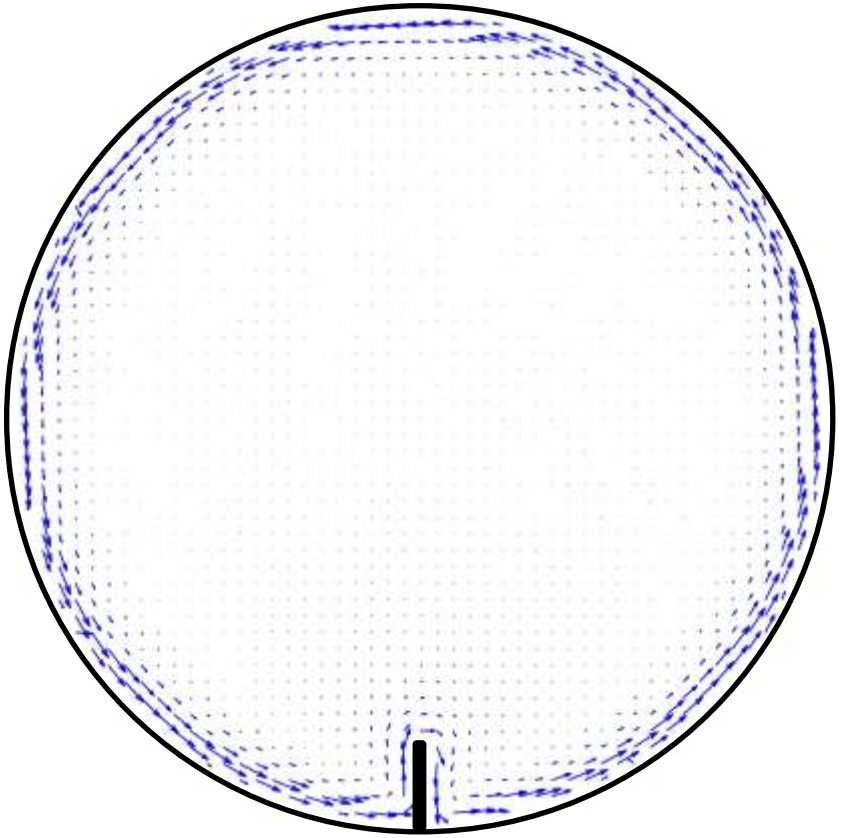
Magnetic field driven rotor
Grzybowski et al (2002) Science

Spinning grannular
Tsai et al (2005) PRL

Breaking both time-reversal and chiral symmetries

Active spinners and edge flow



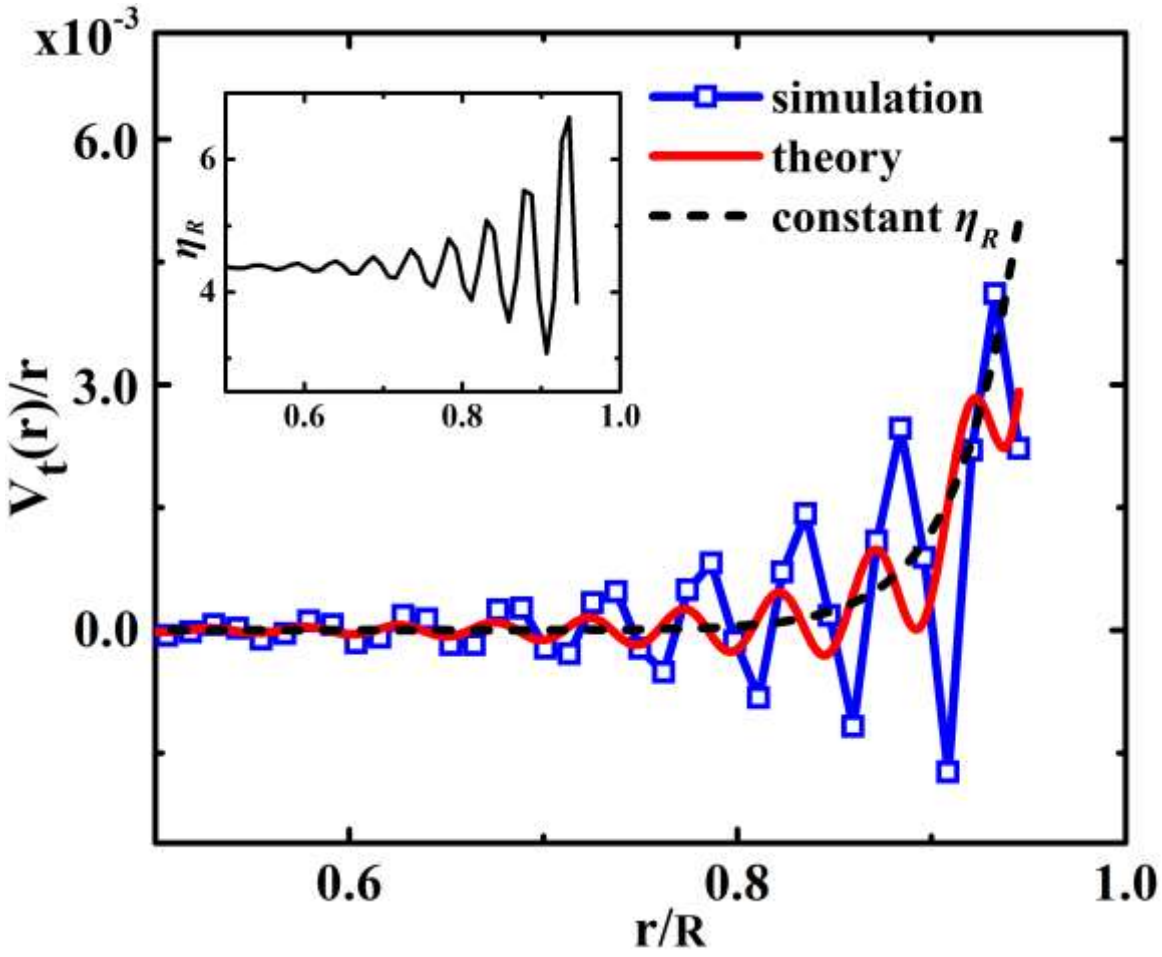


Spontaneous edge flow along the boundary.

Proc. Natl. Acad. Sci. U.S.A. 117, 11901 (2020).

Spatially oscillatory edge flow

$$\eta_R(\rho) = A\rho^2 \left[\frac{1 - 7\rho/16}{(1-\rho)^2} - \frac{\rho^3/16}{8(1-\rho)^4} \right]$$



Proc. Natl. Acad. Sci. U.S.A. 117, 11901 (2020).

Continuum hydrodynamic theory

Momentum conservation:

$$\varrho(\partial_t + \mathbf{v}\cdot\nabla)v_i = \partial_j\sigma_{ij} - \Gamma v_i$$

$$\sigma_{ij} = -p\delta_{ij} + \eta(\partial_i v_j + \partial_j v_i) + \epsilon_{ij}\eta_R(2\omega - \Omega)$$

Rotational viscosity:

$$\eta_R(\rho) = A\rho^2\left[\frac{1-7\rho/16}{(1-\rho)^2} - \frac{\rho^3/16}{8(1-\rho)^4}\right]$$

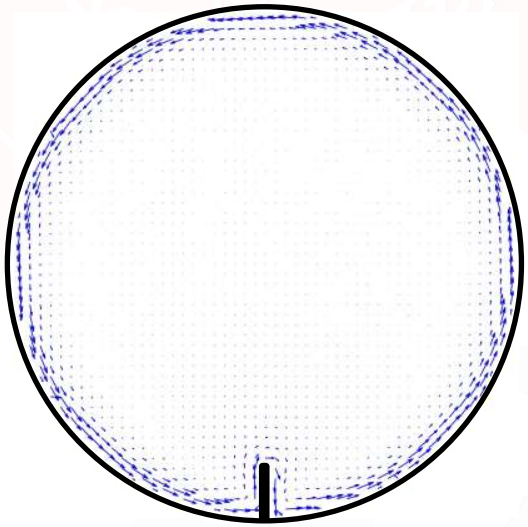
Angular momentum conservation:

$$I(\partial_t + \mathbf{v}\cdot\nabla)\omega = -\Gamma_r\omega - 2\eta_R(2\omega - \Omega) + D_\omega\nabla^2\omega + \tau$$

$$\beta\partial_r^2 v_t + \frac{\partial_r(\beta r)}{r}\partial_r v_t - \frac{(\beta - r\partial_r\beta + r^2\Gamma)}{r^2}v_t - 2\partial_r\beta' = 0$$

$$\beta = \eta + \Gamma_r\eta_R(\Gamma_r + 4\eta_R)^{-1} \text{ and } \beta' = \beta\tau(\Gamma_r + 4\eta_R)^{-1}$$

Topological transport of an intruder



Can this topological edge flow robustly and unidirectionally transport a cargo ?

Three requirements:

- Nonvanishing edge flow
- Can stay cling to the boundary
- Cargo can be controllably released from boundary

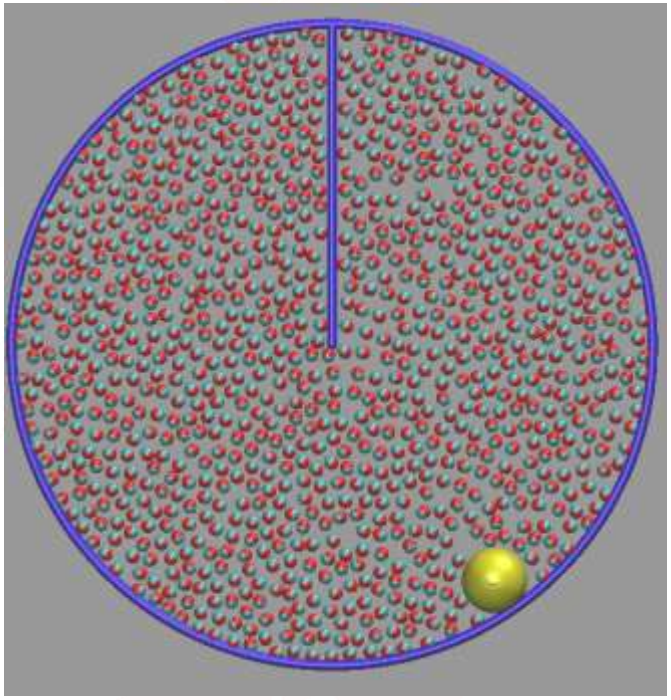
Topological edge transport of an cargo

spinner

spinner

cargo

Experiment



Simulation

➢ Edge flow combined with depletion-like interaction induce topological transport.

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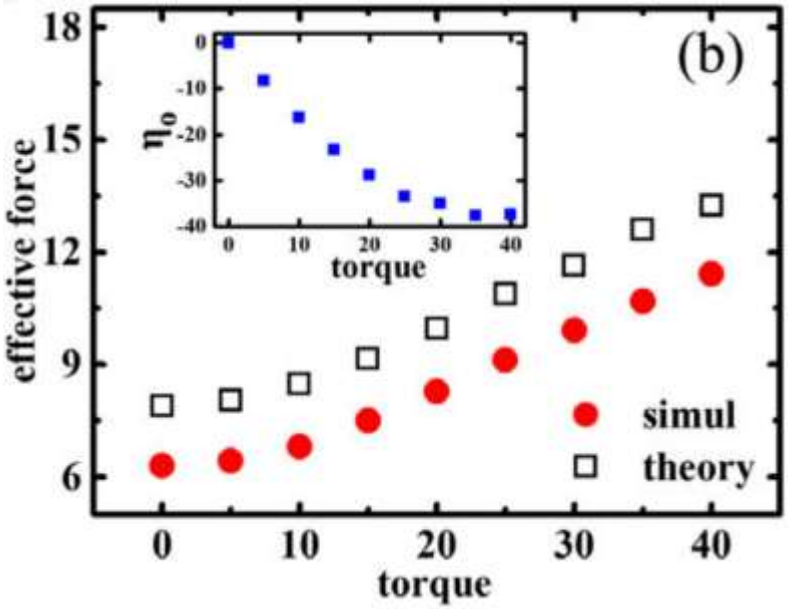
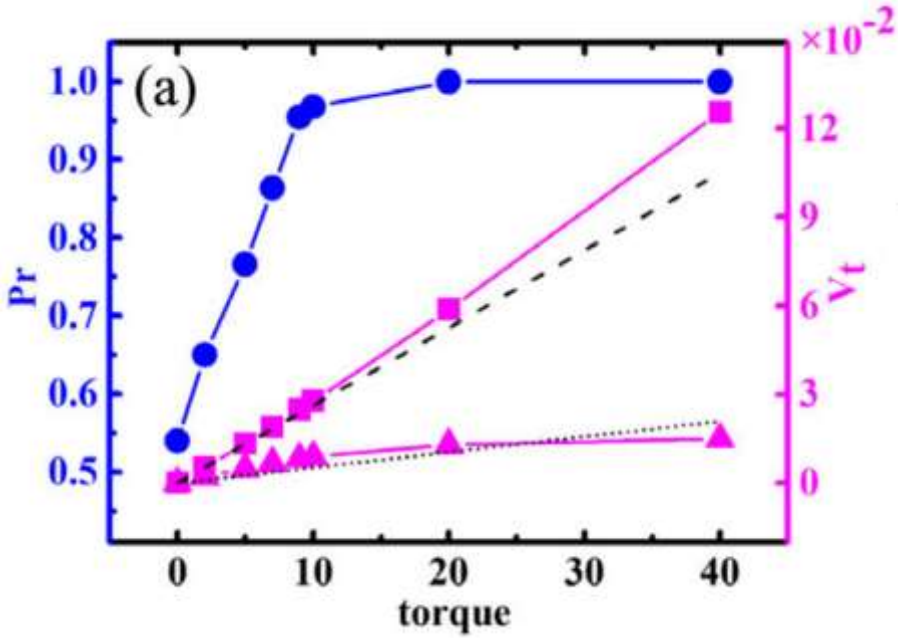
Transport velocity and dwell probability



Effective attraction between cargo and boundary increases with the activity. (entropic force + odd viscosity effect)

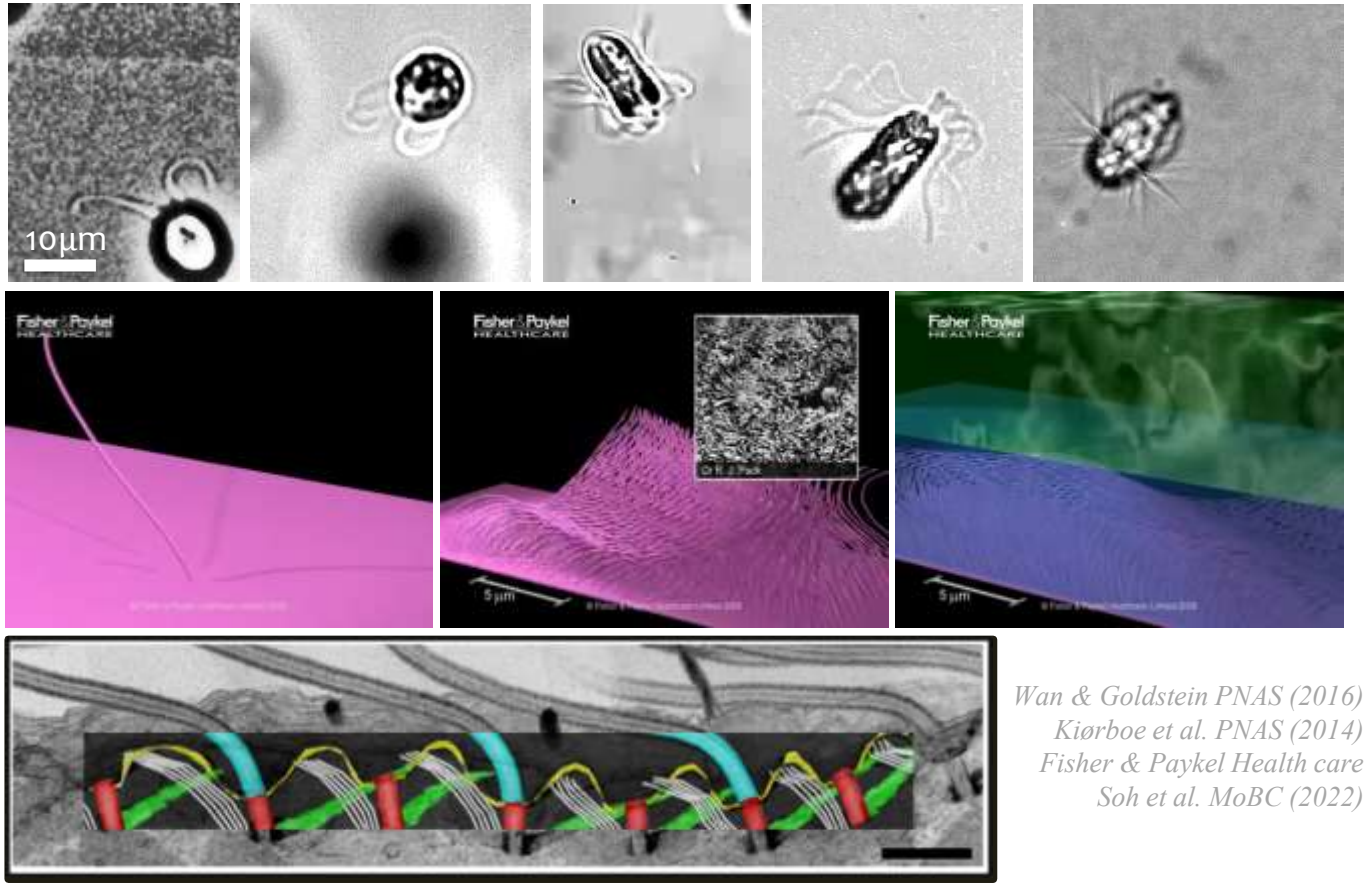


Dwell probability and transport velocity increase with the activity. (controllable)

(4) Synchronization of active ***cilia***

Ciliary synchronization

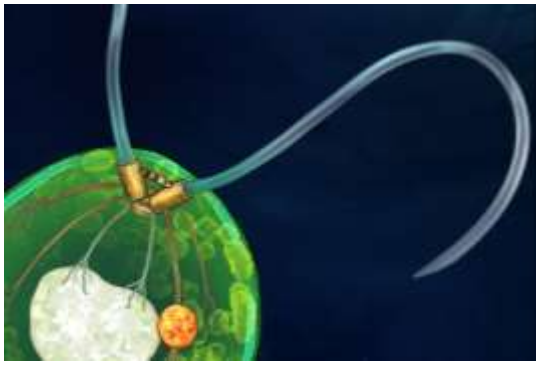
- Cilia are everywhere
- Be synchronized to be effective
- Coupling through **Fluid** and/or **Fiber**

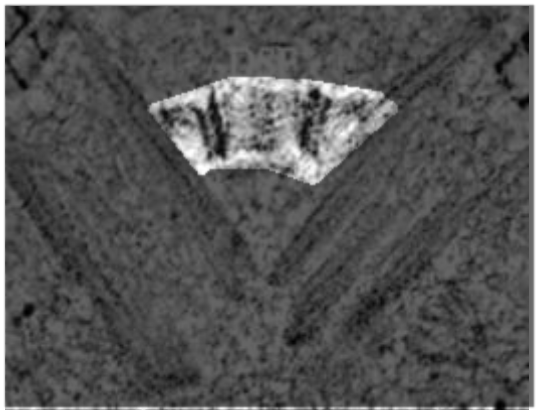


Wan & Goldstein PNAS (2016)
Kiørboe et al. PNAS (2014)
Fisher & Paykel Health care
Soh et al. MoBC (2022)

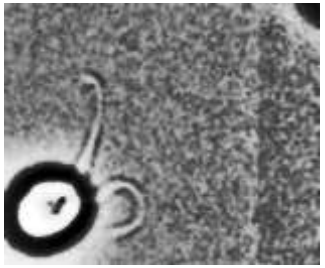
Biciliate synchronization

Chlamydomonas reinhardtii

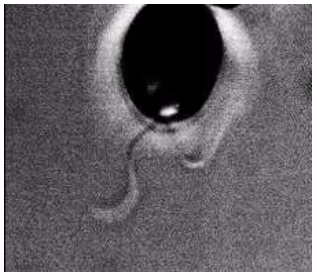




Fiber connections in biciliates



breaststroke

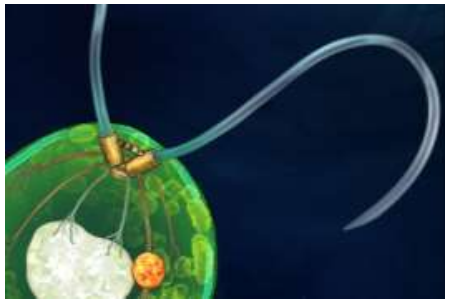


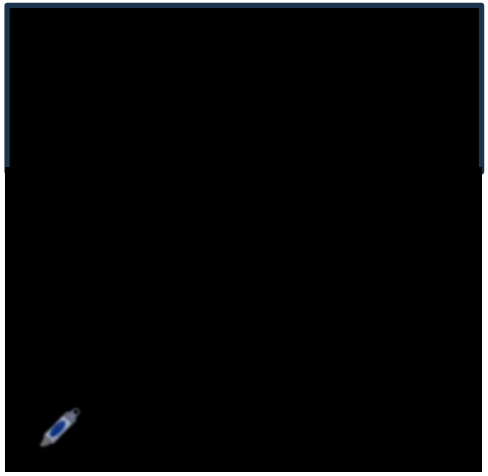
No fiber, no sync.

freestyle

- How different ciliary dynamics emerges via mechanical connection?
- A perspective from the non-equilibrium thermodynamics.

Artificial robotic cilium

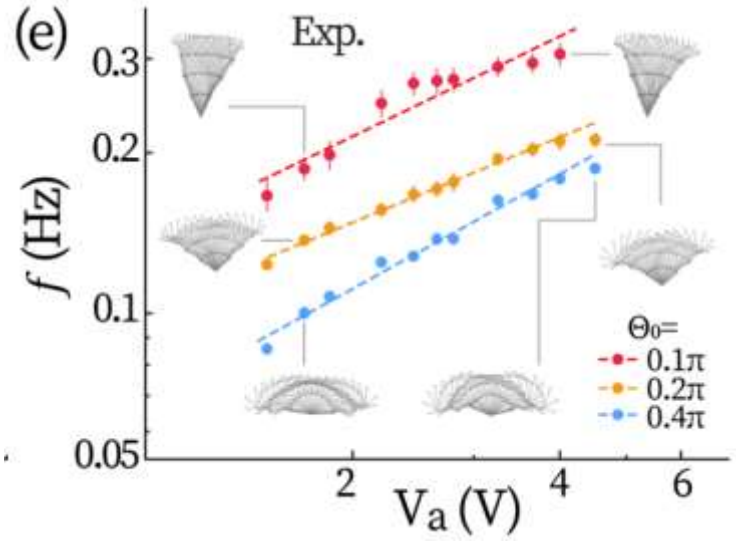




A toy robot

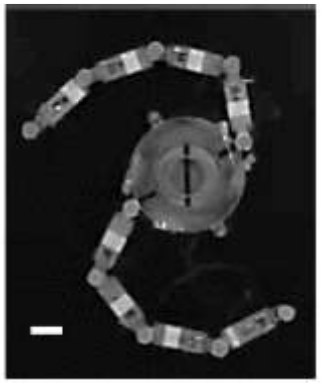
A artificial cilium

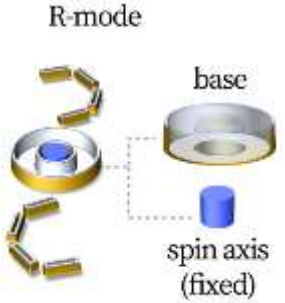
Single-cilium frequency and two-cilia coupling



Frequency vs driving

Coupling strength: translational friction



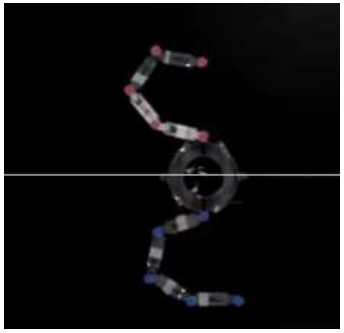


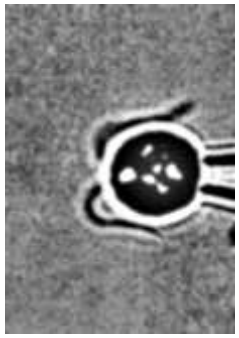
Coupling strength: rotational friction

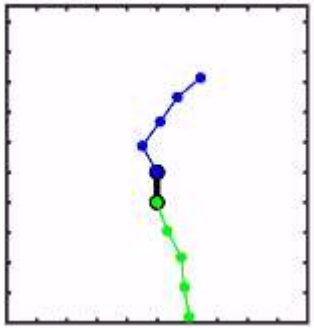
Synchronization of two coupled artificial cilia

Translational constraints (X-mode): breaststroke

Coupling strength: translational friction



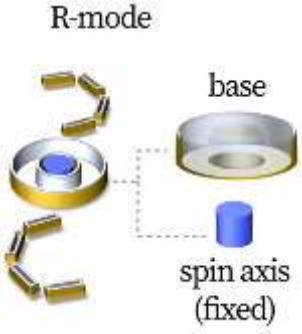


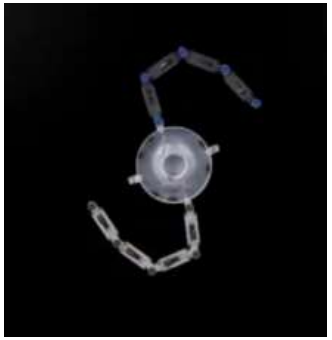


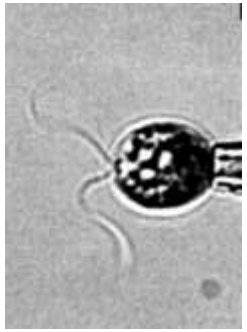
Simulation

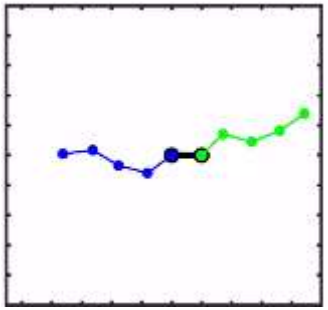
Rotational constraints (R-mode): freestyle

Coupling strength: rational friction









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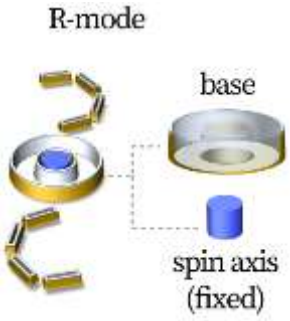
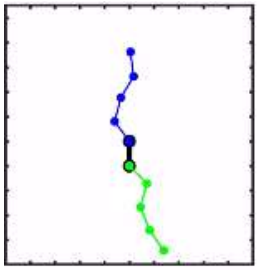
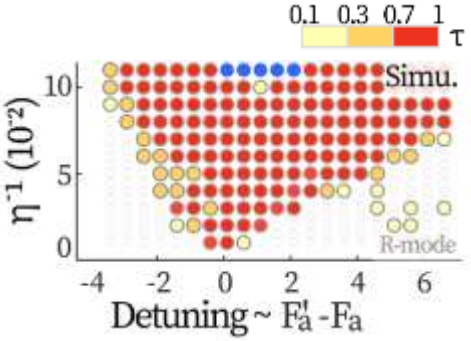
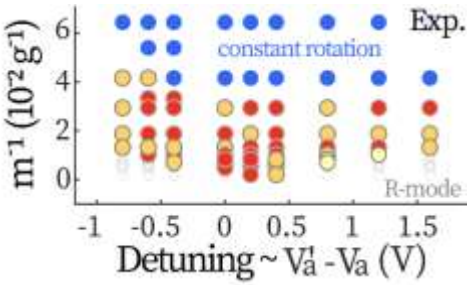
Coupling strength: “Arnold Tongue” diagram

Rotational constraints (R-mode): freestyle

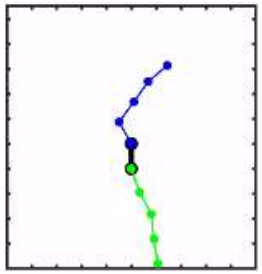


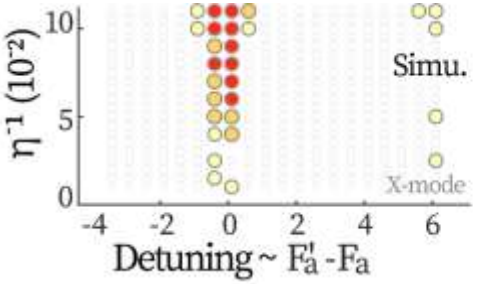


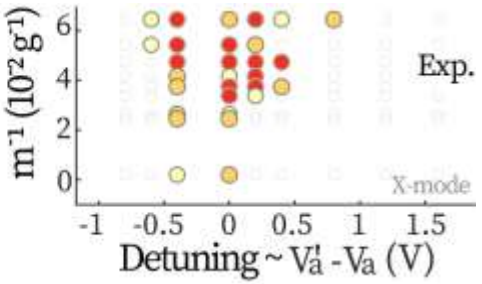




Translational constraints (X-mode): breaststroke







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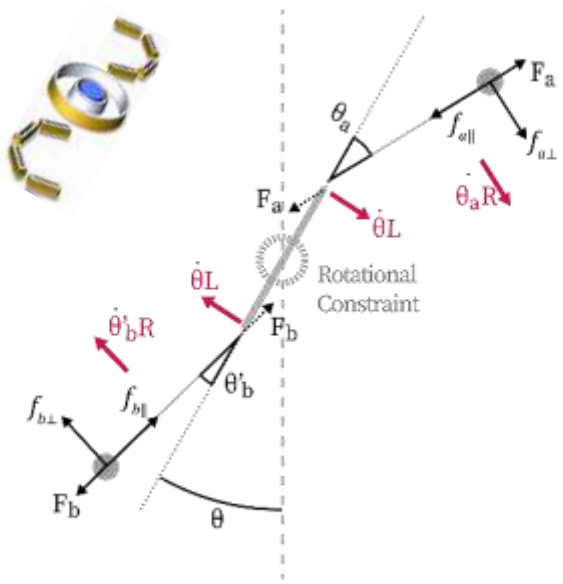
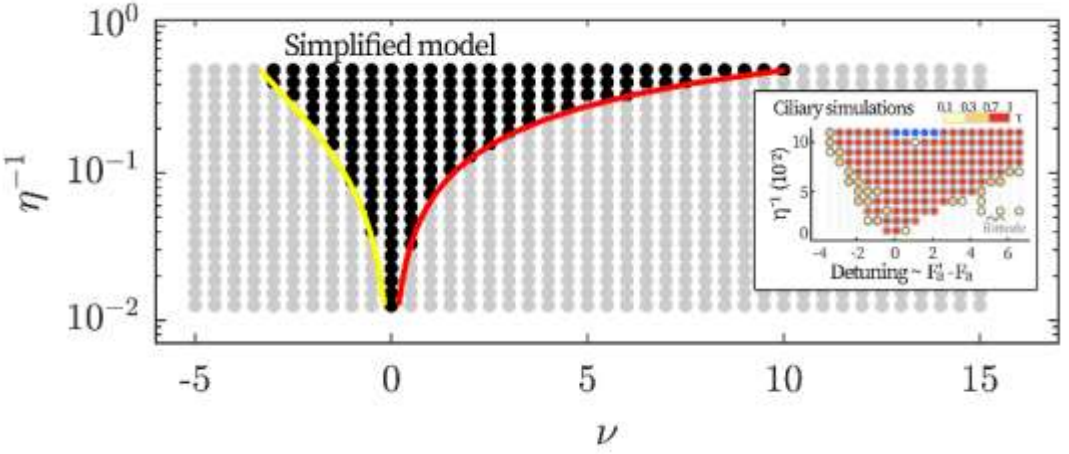
How does the base induce synchronization?

A minimal model



$$\nu = \Omega_b - \Omega_a = \frac{f_{b\perp} - f_{a\perp}}{R\eta_0}$$



$$\begin{cases} f_{a\perp} = \eta_a\left(\dot{\theta_a}R + \dot{\theta}L\cos\theta_a\right) \\ f_{b\perp} = \eta_b\left(\dot{\theta'}_bR + \dot{\theta}L\cos\theta'_b\right) \\ f_{a\parallel} - F_a = -\eta_a\dot{\theta}L\sin\theta_a \\ f_{b\parallel} - F_b = -\eta_b\dot{\theta}L\sin\theta'_b \\ F_a\sin\theta_a + F_b\sin\theta'_b = -\eta_R\,\dot{\theta}/L \end{cases}$$

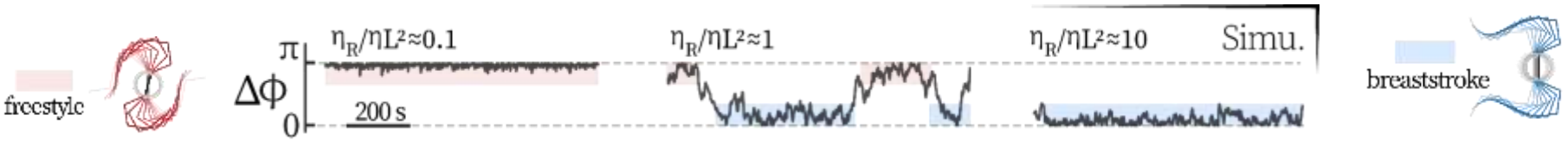
Adler-type equation:

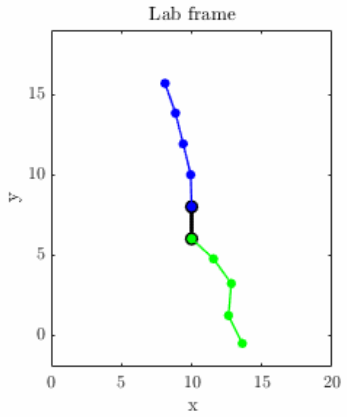
$$\dot{\theta_a} - \dot{\theta'}_b = (\Omega_a - \Omega_b) - \frac{L^2\left(f_{a\parallel} + f_{b\parallel}\right)}{2R\tilde{\eta}_R}\sin(\theta_a - \theta'_b),$$

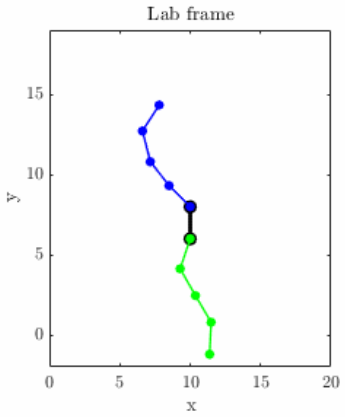
Coupling strength

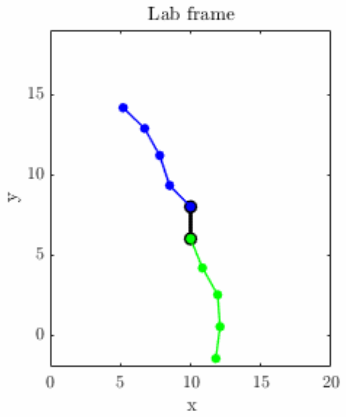
Competition between sync. Modes with free base

1. Make both modes possible with a free base
2. Decouple rotational friction, increase rotational friction (η_R)



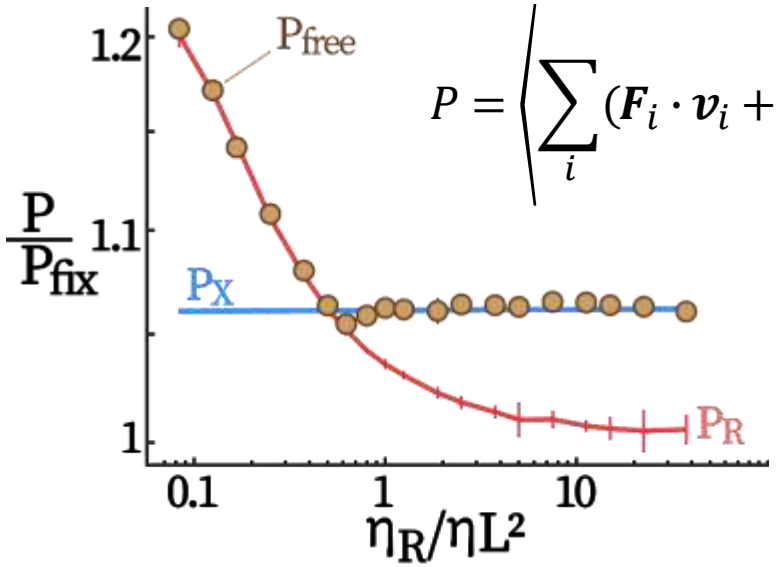






Energetics behind mode switching

Increase rotational friction (η_R)



$$P = \left\langle \sum_i (\boldsymbol{F}_i \cdot \boldsymbol{v}_i + M_i \omega_i) \right\rangle$$

Stochastic thermodynamics: $\dot{q}(\tau) = F(x, \lambda)\dot{x} \equiv T\dot{s}_{\mathrm{m}}(\tau)$, $\quad \dot{s}_{\mathrm{tot}}(\tau) = \dot{s}_{\mathrm{m}}(\tau) + \dot{s}(\tau)$

medium entropy **total entropy (max)** $(\dot{s} = 0)$

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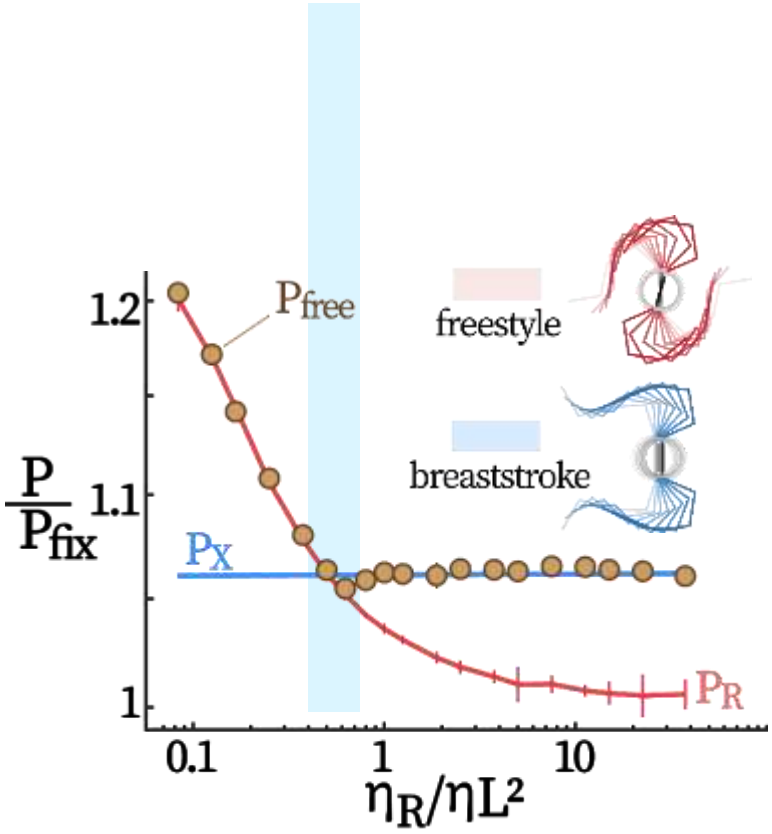
Energetics behind mode switching

Transitions of mode take place at the dissipation crossovers



Dominant state ≈ the more dissipative (entropy production) state

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Summary

- Active matter exhibits rich, novel and intriguing collective behaviors.
- Understand its universal *nonequilibrium* physical law and mechanism ?
- Design, control and apply collective behavior ?

谢谢大家，祝学业顺利！