Synthetic Quorum Sensing in Colloidal Active Matter

Alberto Dinelli, T. Lefranc, C. Fernandez-Rico, R.P.A. Dullens, D. Bartolo, J. Tailleur

[T. Lefranc, AD et al., **Phys. Rev. X** 2025]

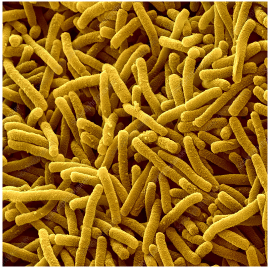
Université Paris Cité, Laboratoire MSC · Université de Genève

Jan 8th 2026

What is active matter?

Units that dissipate energy to exert non-conservative forces on their environment

↪ Complex agents



Motile bacteria

Birds

Humans

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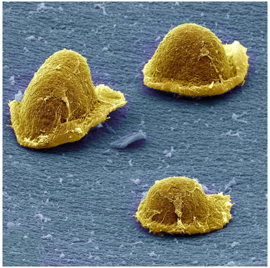
↪ Complex agents + interactions ⟶ Collective self-organization



Fruiting bodies in
M. Xanthus bacteria
[Kagle, **ChemTexts** 2020]

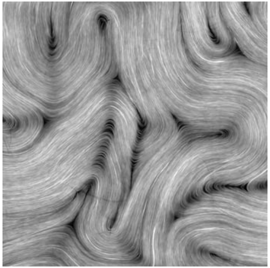
Flocks of birds
[Ballerini et al., **PNAS** 2008]

Collective motion in crowds
[Gu et al., Science 2025]

What is active matter?

Units that dissipate energy to exert non-conservative forces on their environment

- ↪ Complex agents + interactions ⟶ Collective self-organization
- ↪ Harvesting out-of-equilibrium properties ⟶ New soft materials



Active liquid crystals
[Sanchez et al., **Nature** 2012]

Portraits from light-controlled bacteria
[Frangipane et al., **eLife** 2018]

Autonomous robots
[Veenstra et al., **Nature** 2025]

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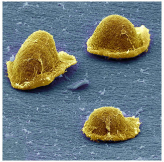   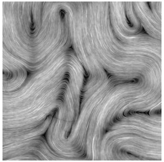  

- How to understand the self-organization of active systems?

Can we understand the large-scale phenomenology of active systems?

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  1/ Account for emergent self-organization in complex systems

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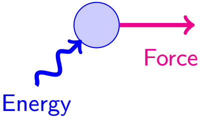
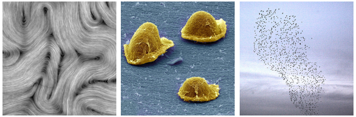
Dynamics of out-of-equilibrium units → Statistical physics → Collective behavior





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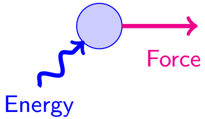

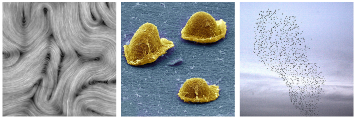

- Out of equilibrium ⟶ Need to develop new tools!

Quorum sensing: coupling activity $\leftrightarrow$ density

When running to catch a train...

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$\longrightarrow$

Adapt speed to density: $v(\rho)$

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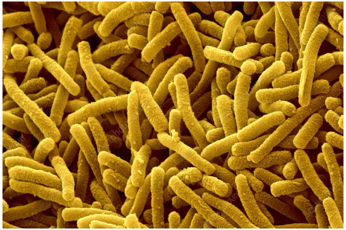
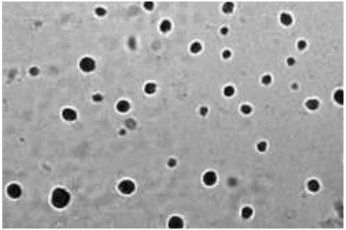


Bacteria exchanging chemical signals



Motility regulation based on density ρ

[Liu et al., **PRL** 2019]

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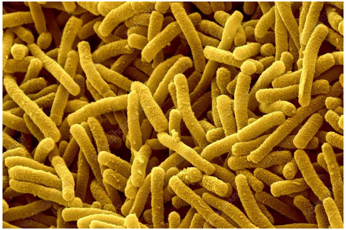

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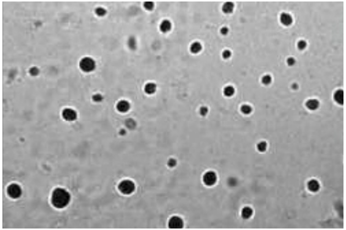

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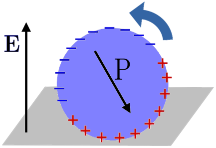
- Engineer synthetic particles with quorum sensing?

Microscopic colloids undergoing autonomous phase separation

- Insulating bead + conducting medium + Electric field

  ⤷ Self-propelled motion! [Bricard et al., **Nat. Comm.** 2015]



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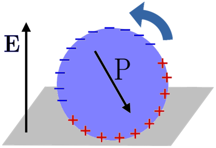
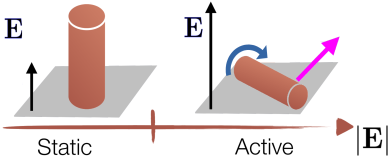


- μm-size rod → 2 states:



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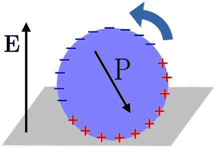

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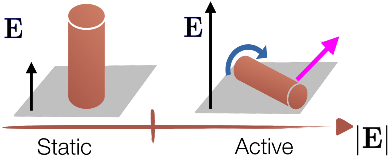
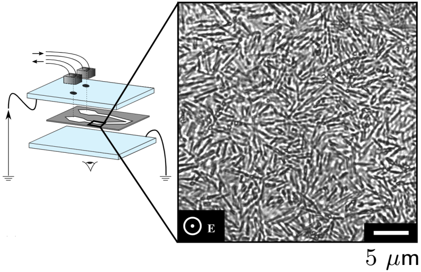


- Collective behavior of $\sim 10^3 - 10^4$ rods



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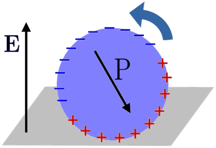

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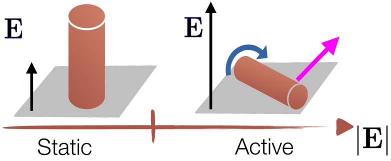

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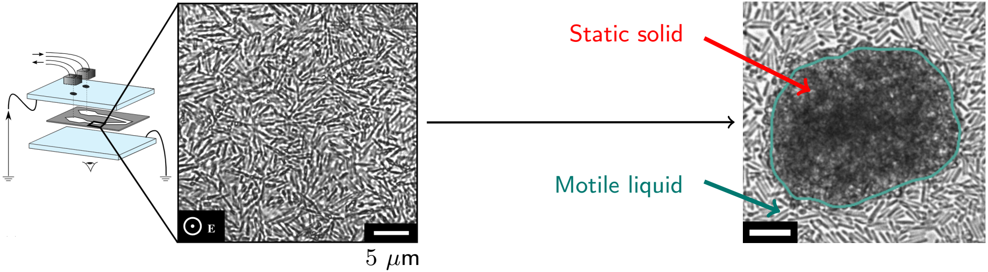
Phase separation!



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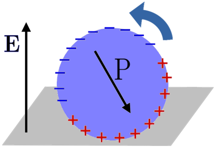

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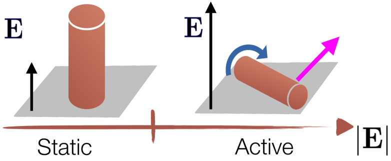

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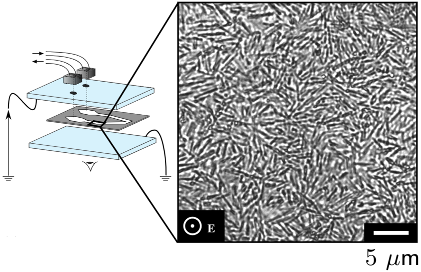

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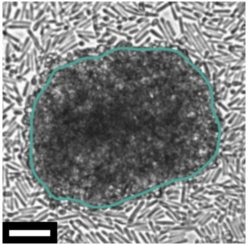
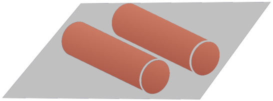


Effective density sensing in colloids

- Friction between rods ⟶ Electric torque insufficient to sustain self-propulsion



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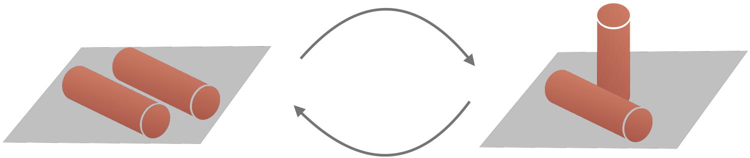

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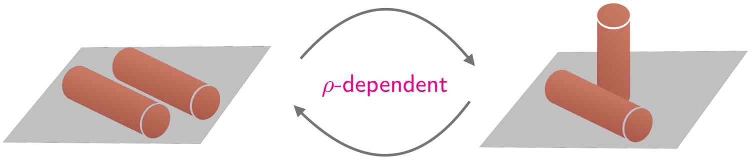

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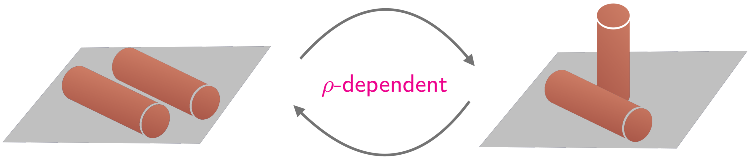

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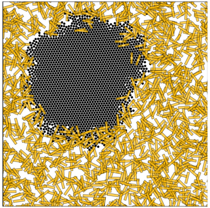

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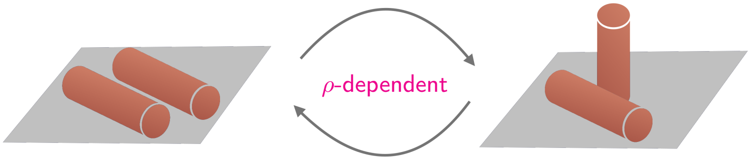

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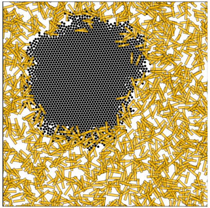

- Hydrodynamics: $\partial_t \rho(\mathbf{r}, t) = \ldots$

  ↪ Physical understanding of phase separation

An unconventional phase separation

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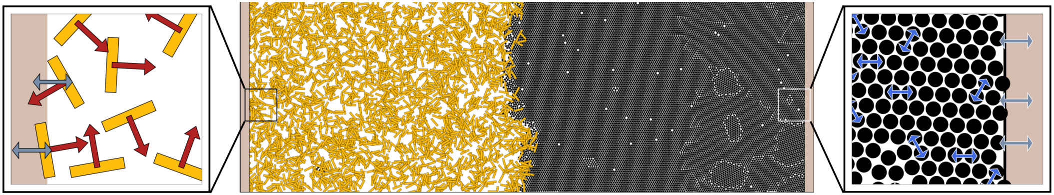
- In active systems: Phase separation can occur at unequal pressure!



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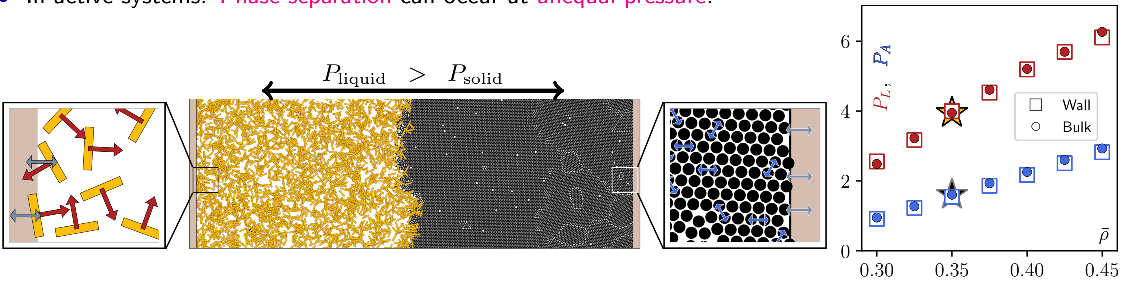

↪ Wall pressure = Pressure in bulk phases

↪ However: Different bulk pressures in the two phases!

Conclusions

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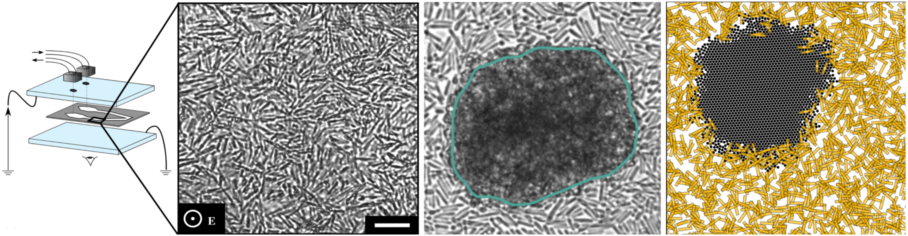

Thank you!

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A motility-induced phase separation

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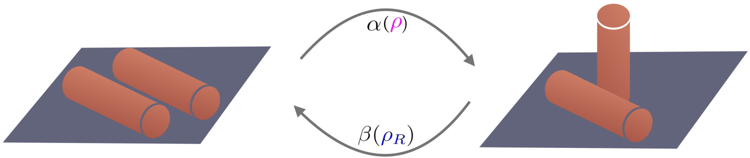
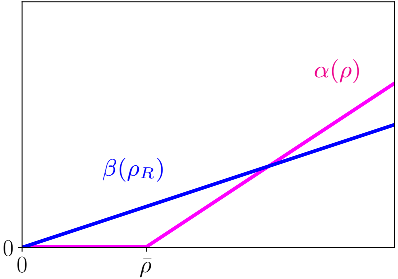


- The denser the system, the easier it is to arrest
  $\rightarrow$ Stopping rate $\alpha(\rho)$

- Static rods resume motion only upon collision with rolling rods ρ_R $\rightarrow$ Resuming rate $\beta(\rho_R)$



Microscopic model for active rods

- $2d$ Active Brownian particles in 2 states:

- Rolling (R):

$$\dot{\boldsymbol{r}}_i = v_0 \boldsymbol{u}(\theta_i) - \mu \sum_j \nabla_{\boldsymbol{r}_i} V(r_{ij})$$

$$\dot{\theta}_i = \sqrt{2D_r}\,\eta_i(t)$$

$\alpha(\rho)$ →

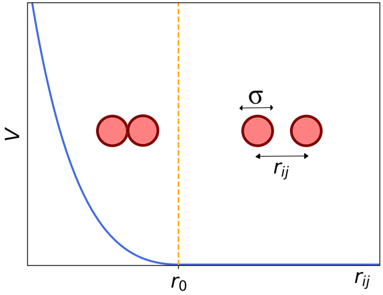
← $\beta(\rho_R)$

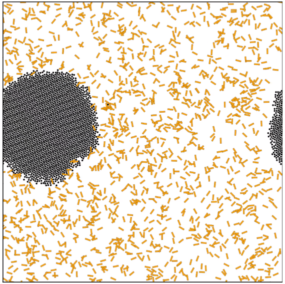
- Stopping (S):

$$\dot{\boldsymbol{r}}_i = -\mu \sum_j \nabla_{\boldsymbol{r}_i} V(r_{ij})$$

- WCA repulsive potential

- Steric repulsion stabilizes phase coexistence





Re-connecting with experiments

- Cluster area fraction: $\Phi_S \equiv \dfrac{\mathcal{A}_{\text{solid}}}{L_x L_y}$

- In experiments: modulate powering tension V

  $\hookrightarrow$ Modulate activity $\longrightarrow$ Control Φ_S

- Modulate activity in simulations:

  $\hookrightarrow$ Self-propulsion speed $v_0 \propto V$

  $\hookrightarrow$ Arrest threshold $\bar{\rho} \propto V$

- Activity competes against phase separation!