Investigation of collective states using programmable active matter

Clemens Bechinger

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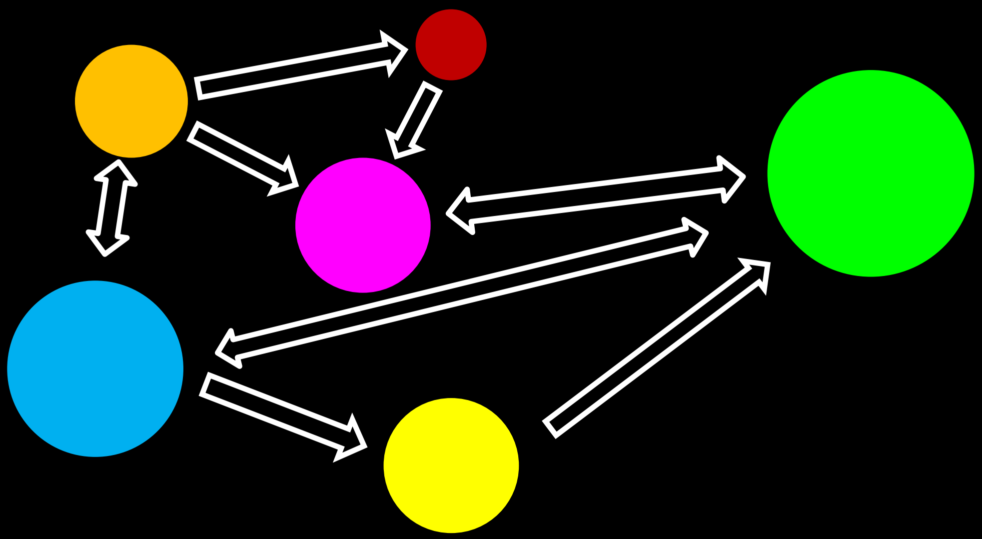
Organization of collective states



- information flows coupled to behaviours of individuals (interaction rules)
- reciprocal and non-reciprocal interactions
- robustness to noise and variations of environment
- stability towards uninformed and misbehaving individuals

Interaction rules

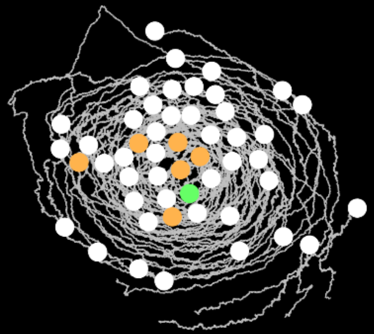
living systems

top - down

1. measure
2. search for correlations (velocity, positions, ..)

→ infer interaction rules & communication flows

synthetic/robotic systems

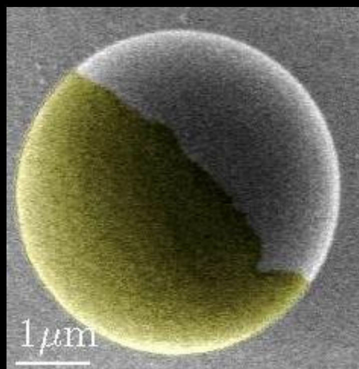


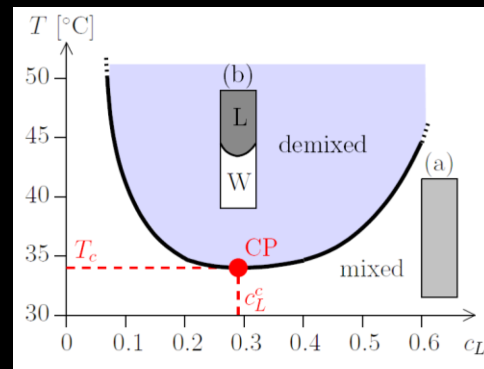
bottom - up

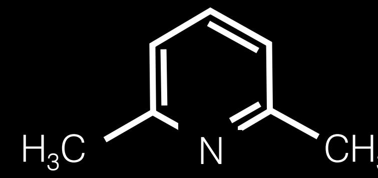
1. impose known interaction rule to each agent
2. observe resulting behavior
3. compare with living system

<u>systematic variations</u> of interaction rules possible !

Self-propulsion by local demixing

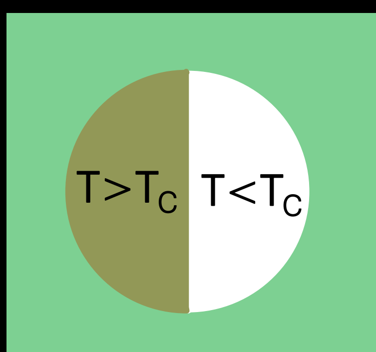


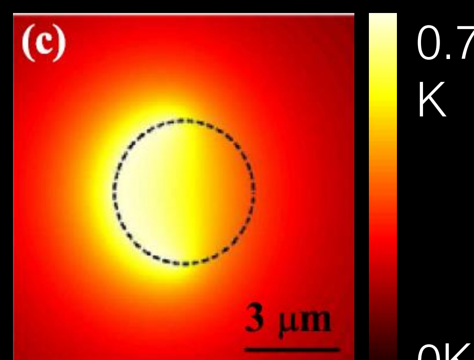


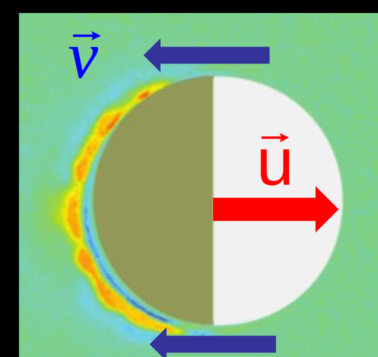


$T_C \approx$ 34°C

Lozano, Gomez-Solano, Bechinger Nature Mat. **18**, 1118 (2019)

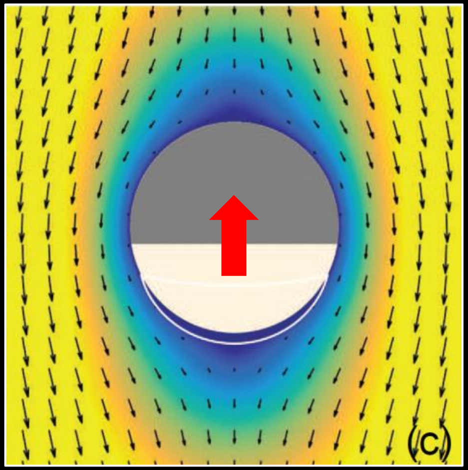




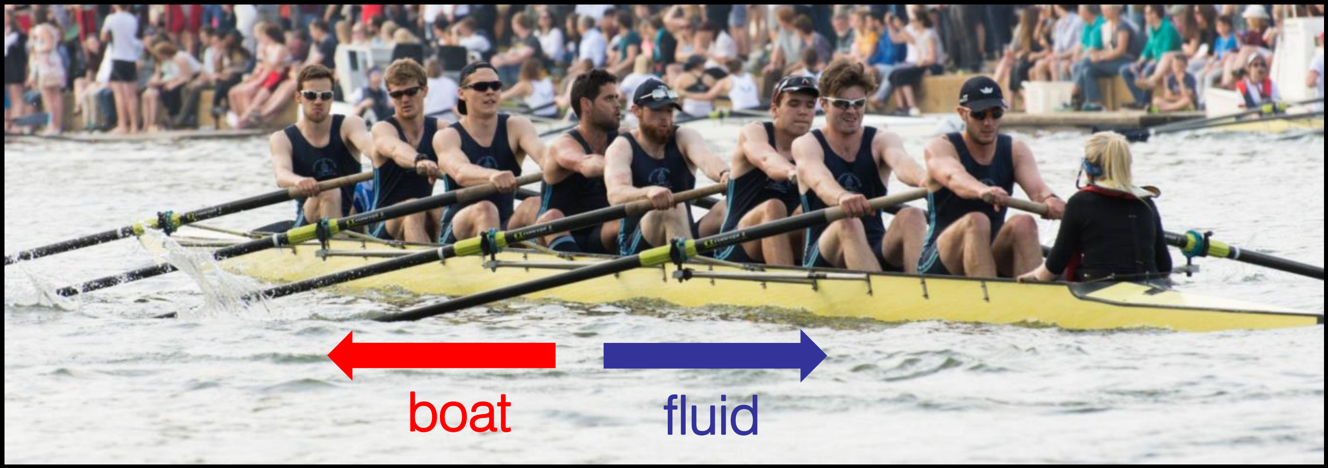


Volpe, Buttinoni, Vogt, Kümmerer, Bechinger, Soft Matter 7, 8810 (2011)
Gomez-Solano, Roy, Araki, Dietrich, Maciolek, Soft Matter 16, 8512 (2020)

Compositional Current Flow Field

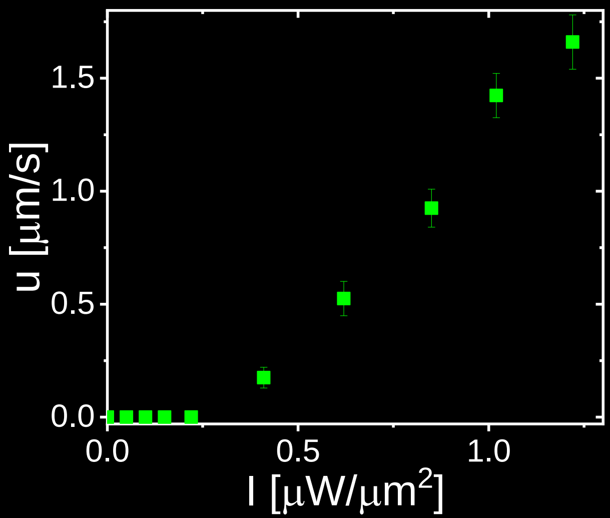


Cahn Hilliard & Nav. Stokes



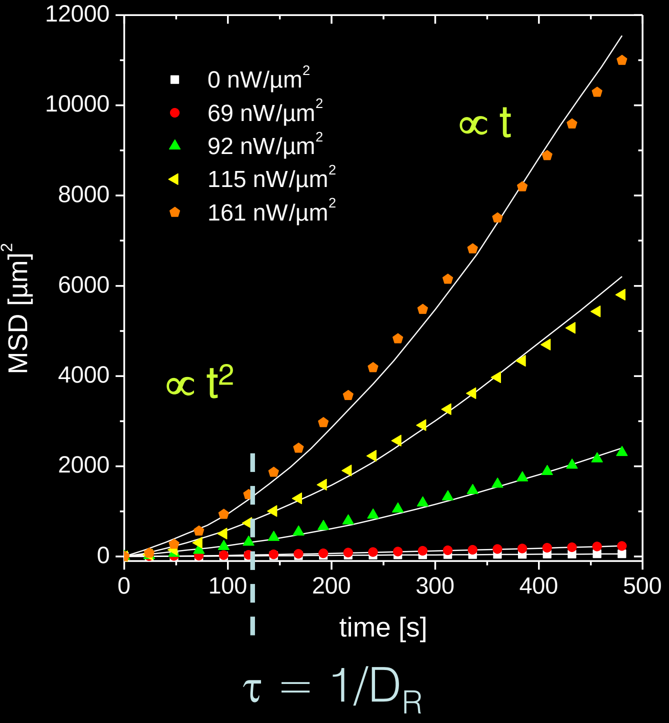
Gomez-Solano, Samin, Lozano, Ruedas-Batuecas, v. Roij, Bechinger Sci. Reports (2017).

Light-induced Active Motion

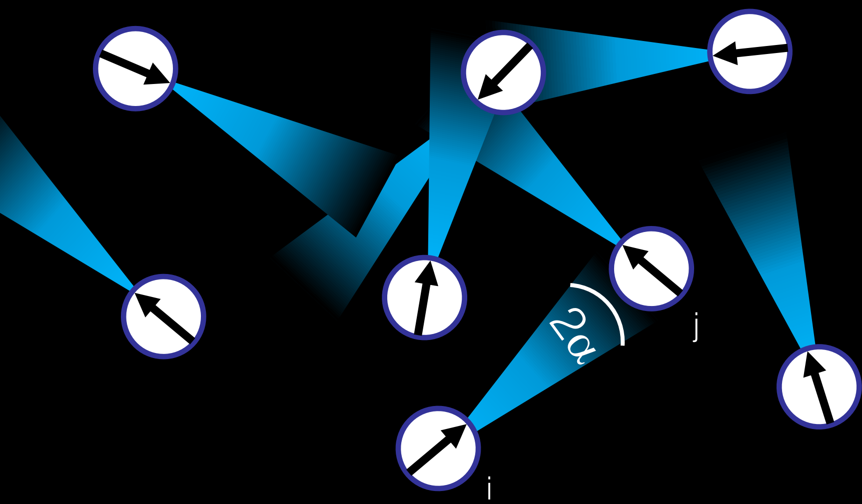


persistent random walk:

$$\Delta r^2 = \left[4D_0 + \frac{L^2}{\tau}\right]t + \frac{L^2}{2}\left[\exp\left(-\frac{2t}{\tau}\right) - 1\right]$$



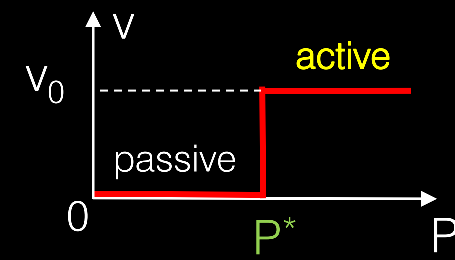
Group formation by visual perception



visual perception:

$$P_i(\alpha) = \sum_{j \in V_i^\alpha} \frac{1}{2\pi r_{ij}} \quad ; \quad \{\alpha < \pi\text{: non-reciprocal}\}$$

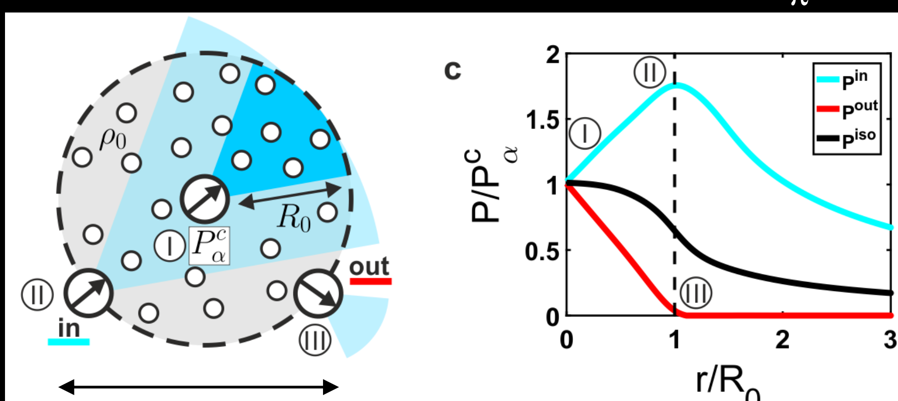
behavioral change:



reaction threshold

Particle alignment not affected!

$$P_\alpha^c = \frac{\alpha}{\pi} \rho_0 R_0$$



$2R_0$

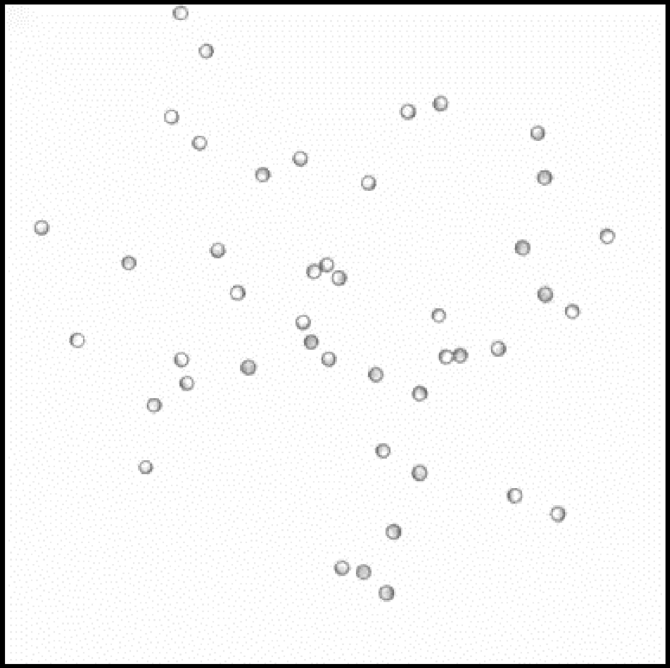
R_0: initial group size

<u>non-monotonic</u> perception vs. distance to group (opposed to typically decaying physical forces)

Lavergne, Wendehenne, Bäuerle, Bechinger, Science **364**, 70 (2019)

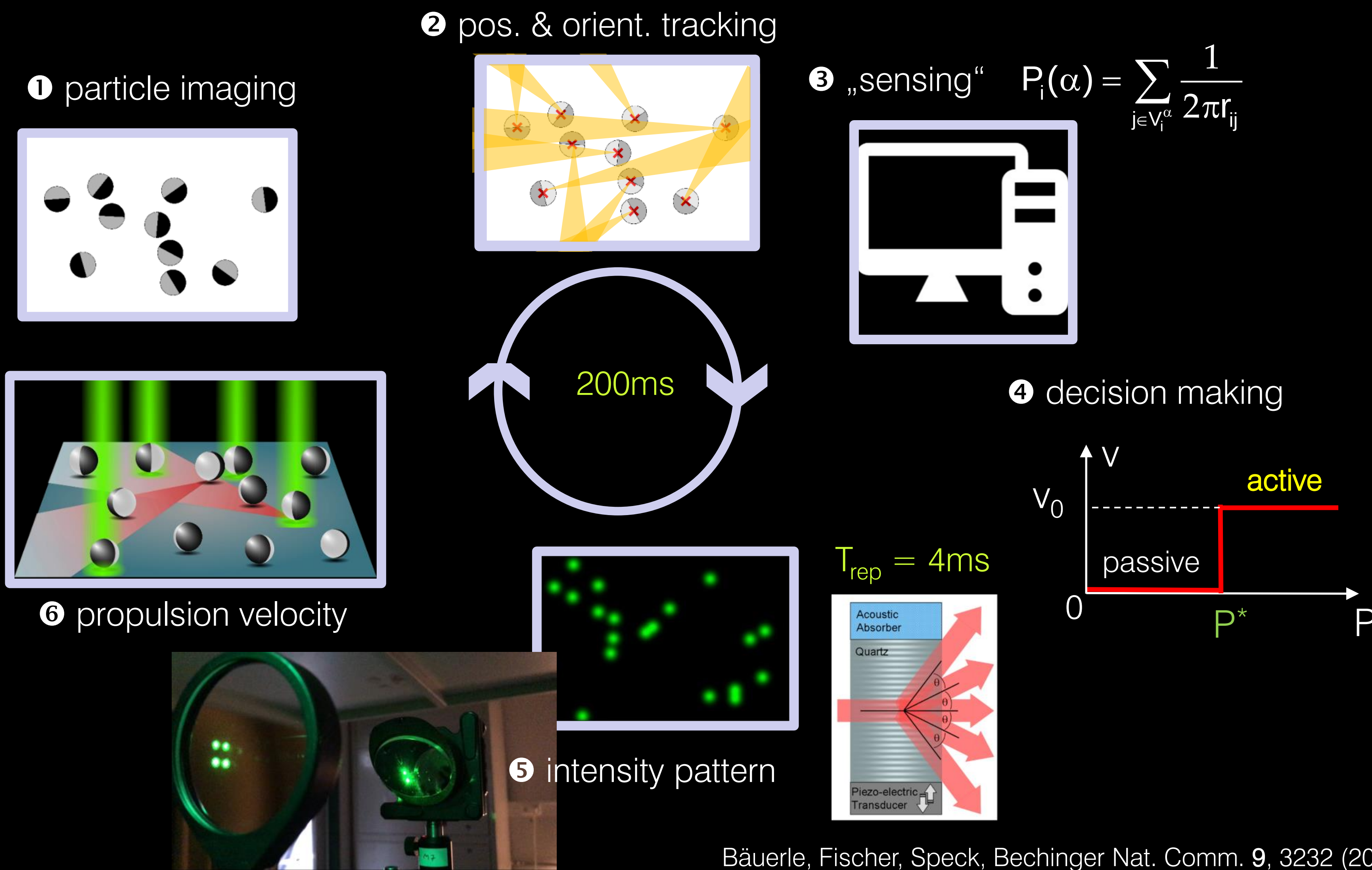
Cohesive groups in free space

$$\alpha = 45^\circ$$
$$P^* = P_\alpha^c$$



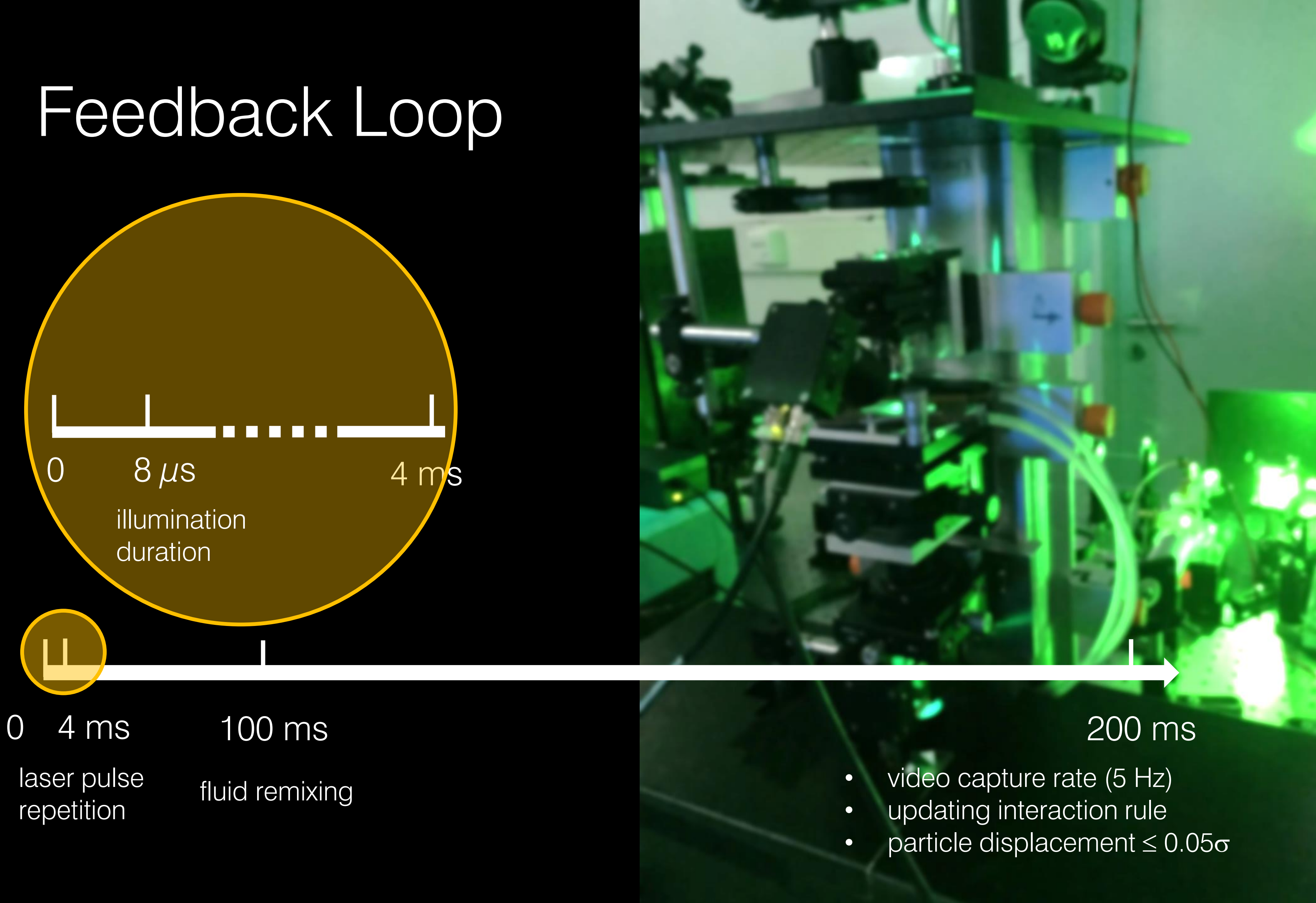
x 40

Feedback-control

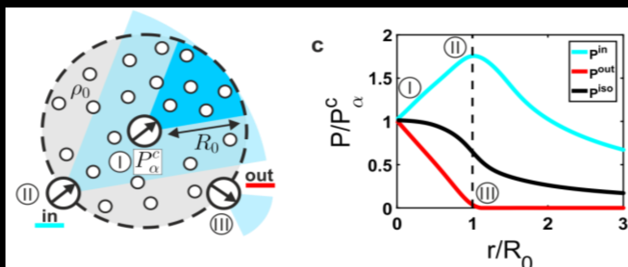


Bäuerle, Fischer, Speck, Bechinger Nat. Comm. **9**, 3232 (2018)

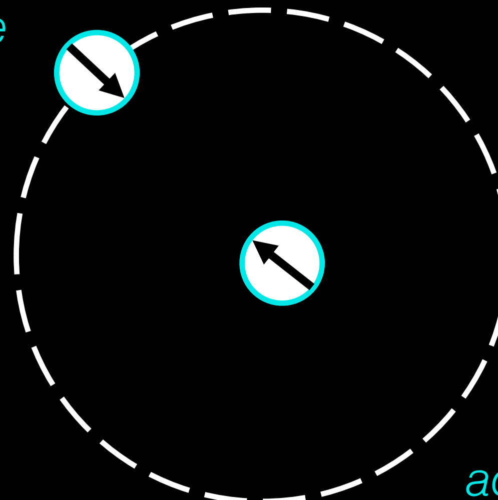
Feedback Loop



Cohesion Mechanism

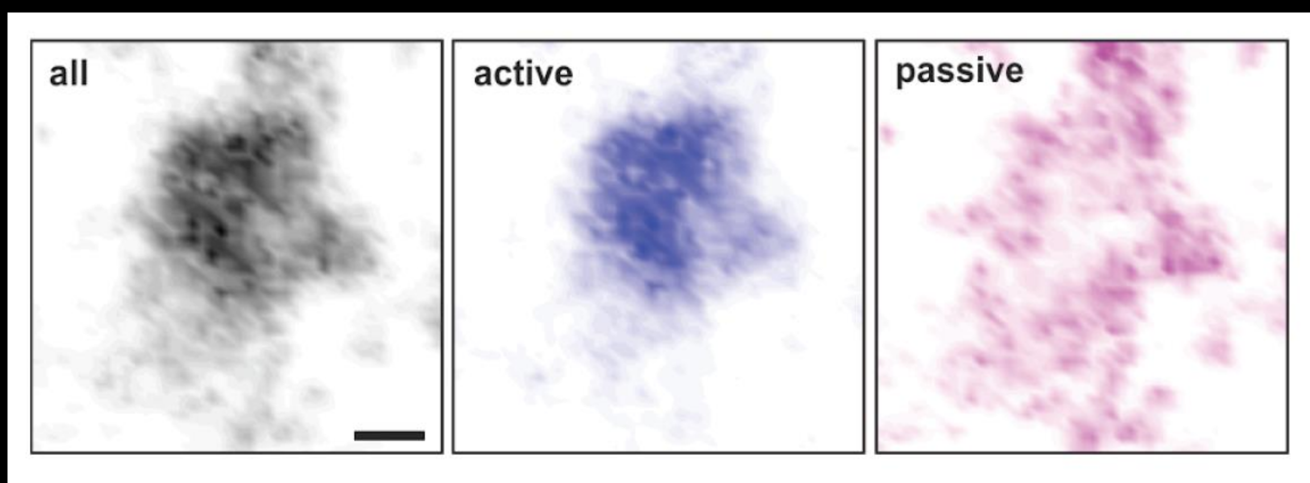


active



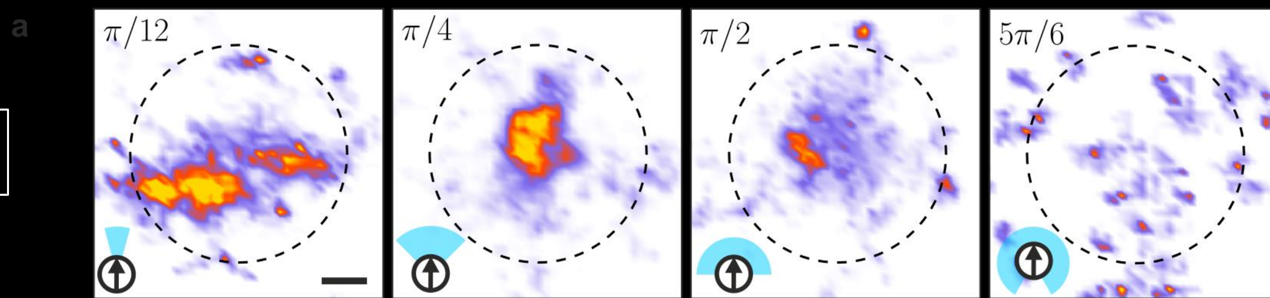
$$P^* = P^c_\alpha$$

active $(P_\alpha^{R_0} > P^*)$

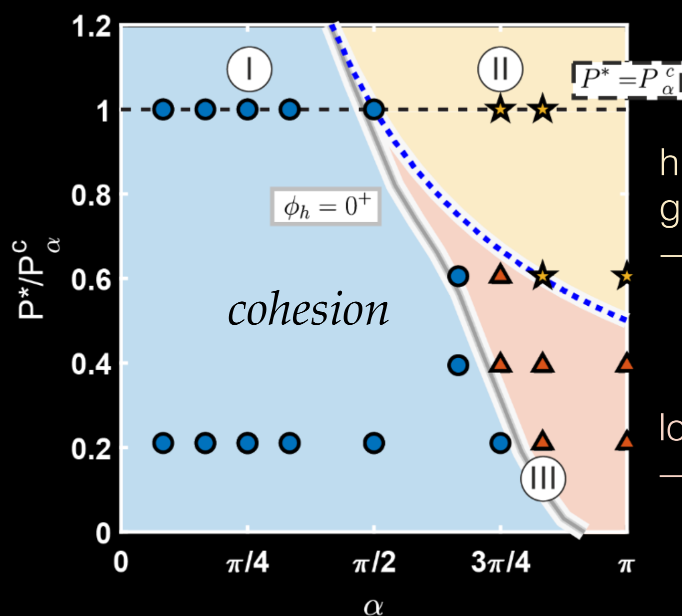


Variation of vision cone

$$P^* = P^c_\alpha$$



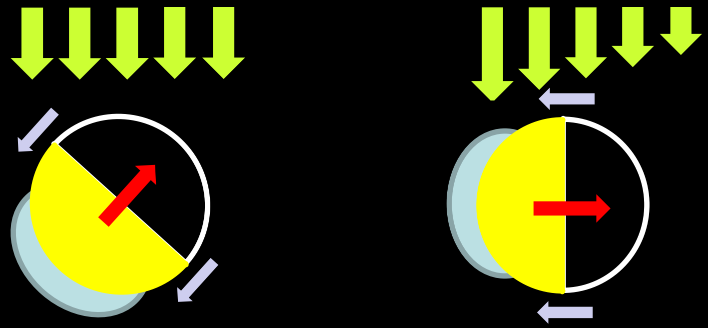
← *cohesion* → *no cohesion*



high threshold: APs remain diffusive outside group
→ no cohesion

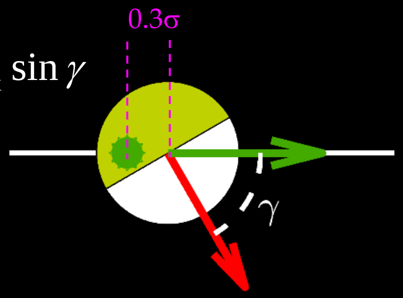
low threshold: APs ≈ permanently active
→ no cohesion (MIPS)

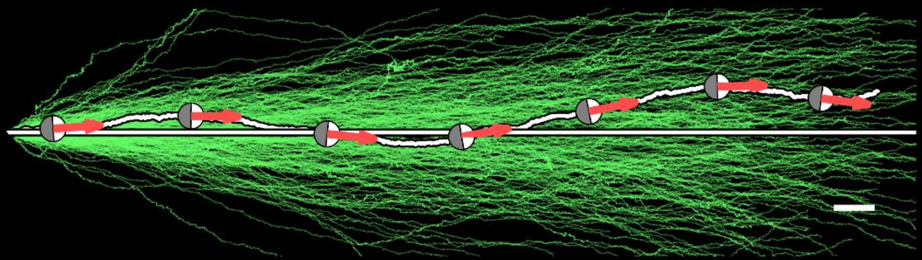
Alignment-Control



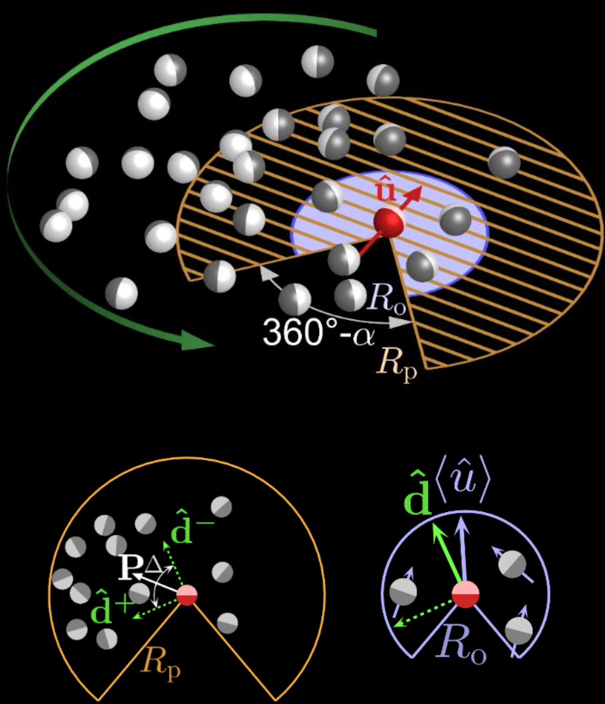
Lozano, ten Hagen, Löwen, Bechinger Nat. Comm. **7**, 12828 (2016)

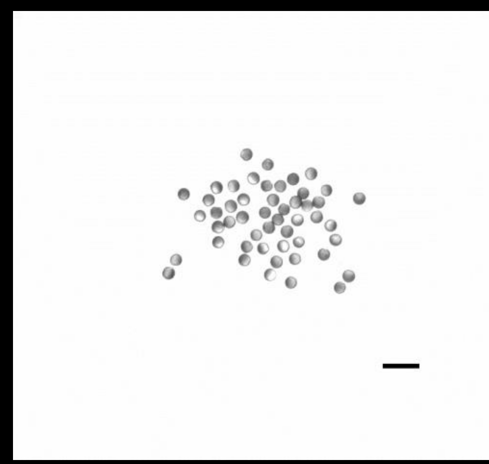
$$\Gamma(\gamma) = -\Gamma_{max} \sin\gamma$$





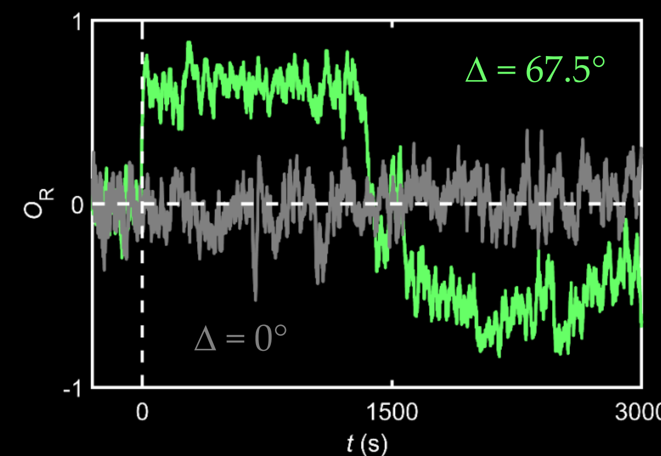
Swirl formation





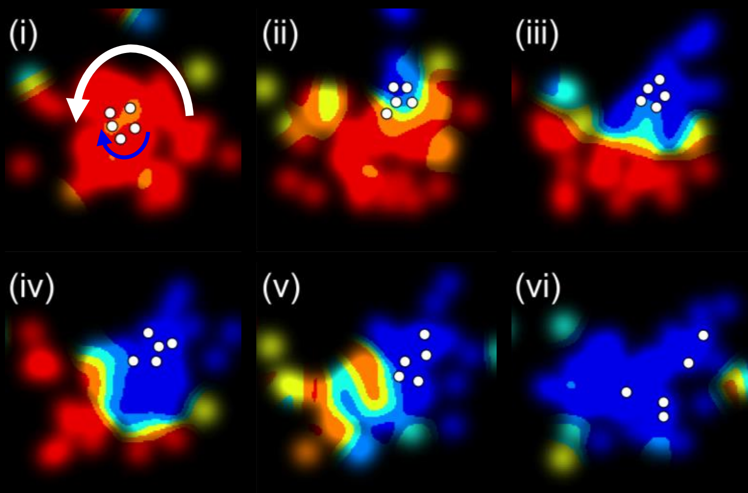
x 40

$$O_R = \frac{1}{N} \sum_{i=1}^{N} (\hat{r}_i \times \hat{u}_i) \cdot e_z$$

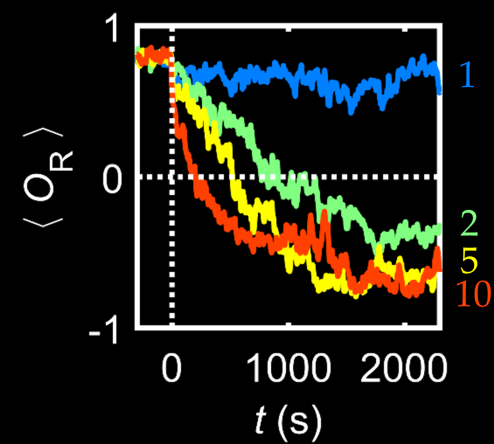


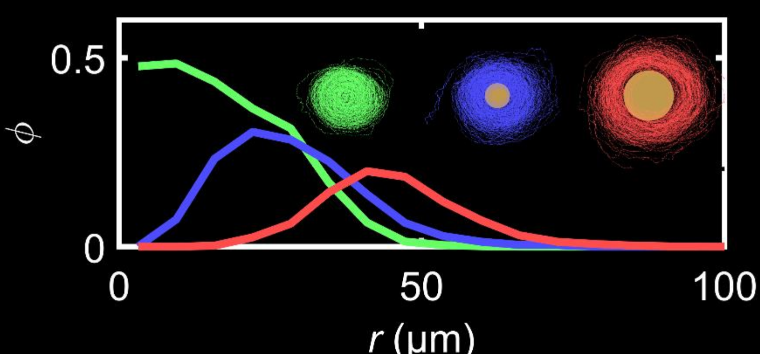
Bäuerle, Löffler, Bechinger, Nature Comm. **11**, 2547 (2020)

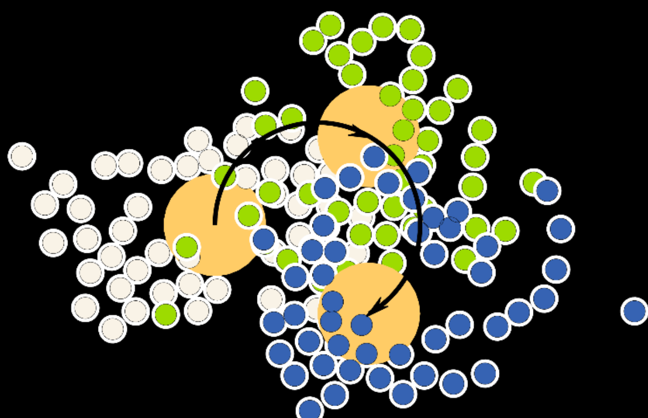
Stability against perturbations



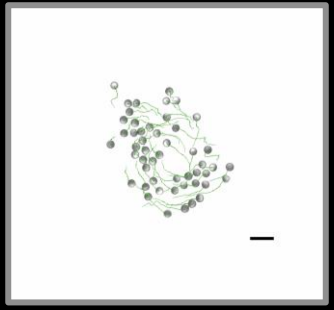
$\Delta = 67.5°$

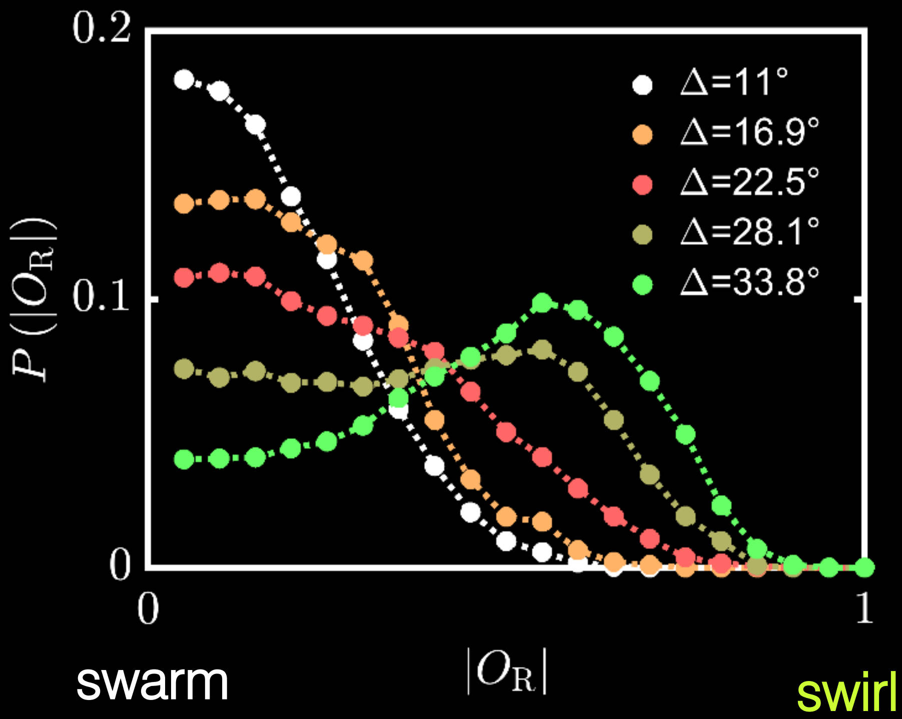


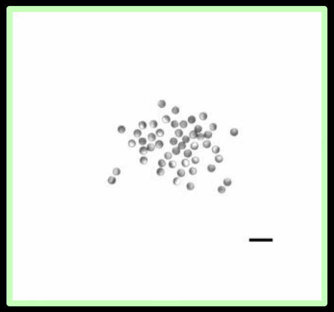




Transition between swarms & swirls



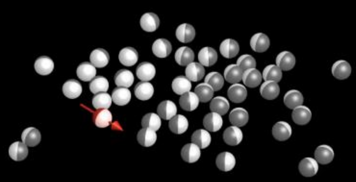




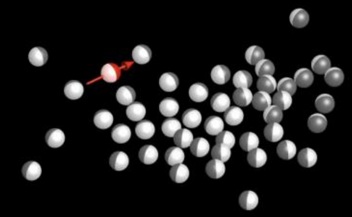
critical transition?

Order parameter dynamics

$$O_R = \frac{1}{N}\sum_{i=1}^{N}(\hat{r}_i \times \hat{u}_i)\cdot e_z$$

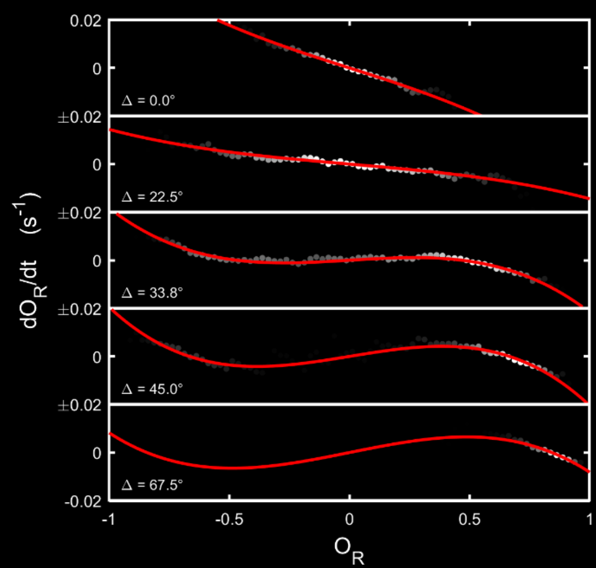


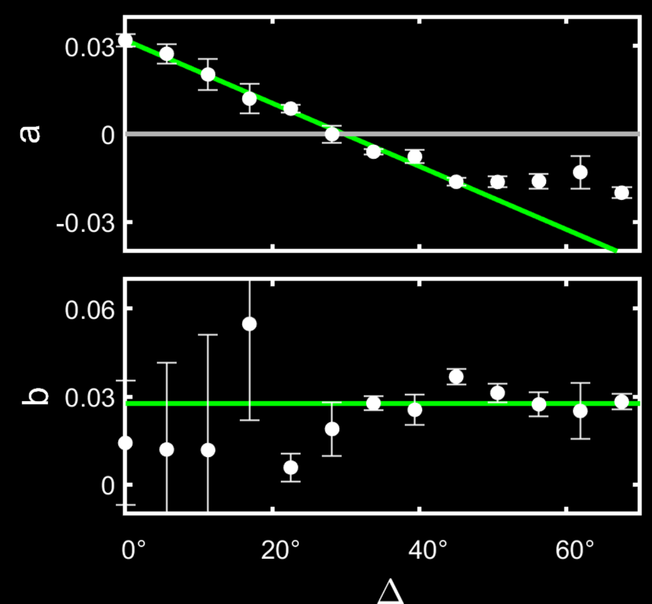
$$t \to -t$$



- odd time-reversal symmetry
- O_R not conserved

$$\frac{\partial}{\partial t}O_R = -aO_R - bO_R^3 + \eta(t)$$



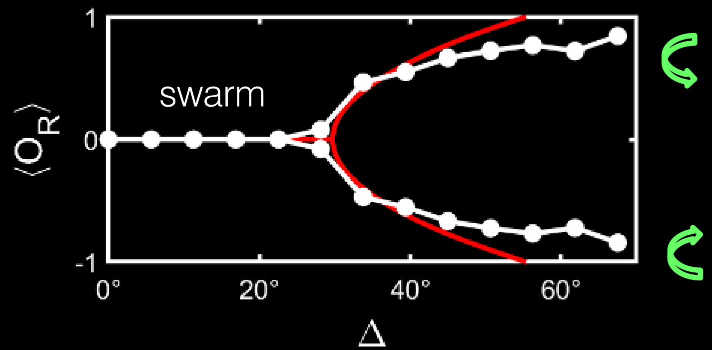


Signatures of critical behaviour

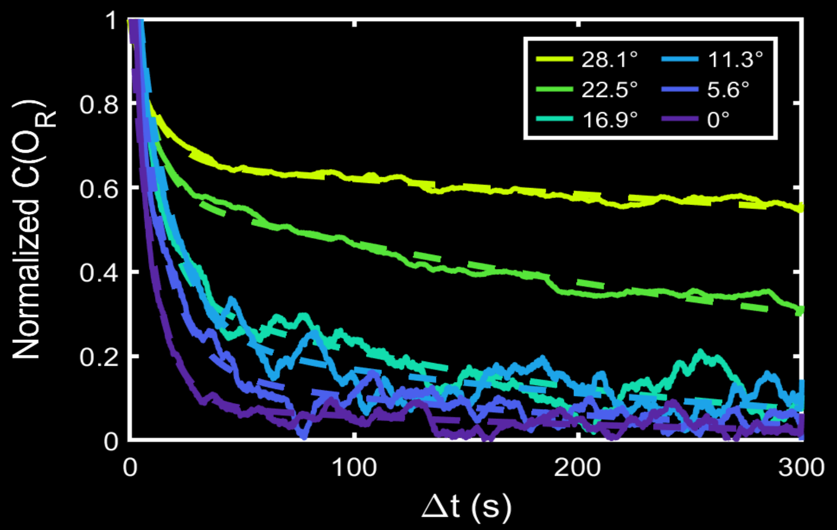
- Bifurcation

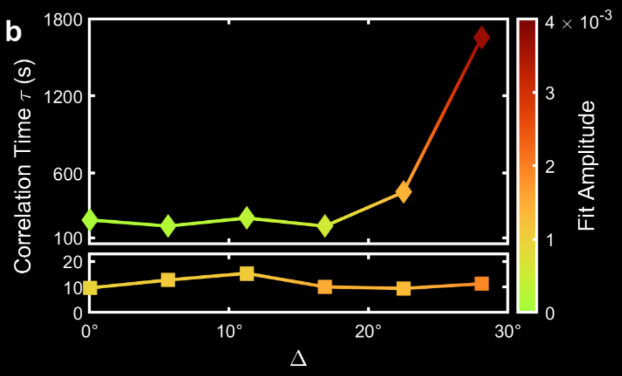
$$\frac{\partial}{\partial t} O_R = -aO_R - bO_R^3 + \eta(t)$$

steady state: $\langle O_R \rangle = \pm \mathrm{Re}\left(\sqrt{-a/b}\right)$

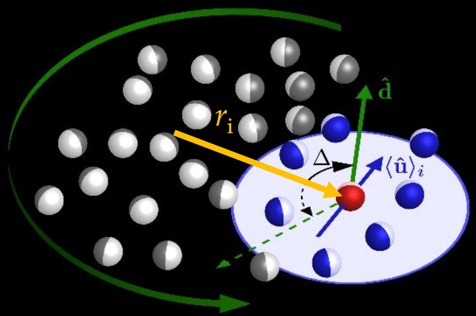


- Critical slowing down



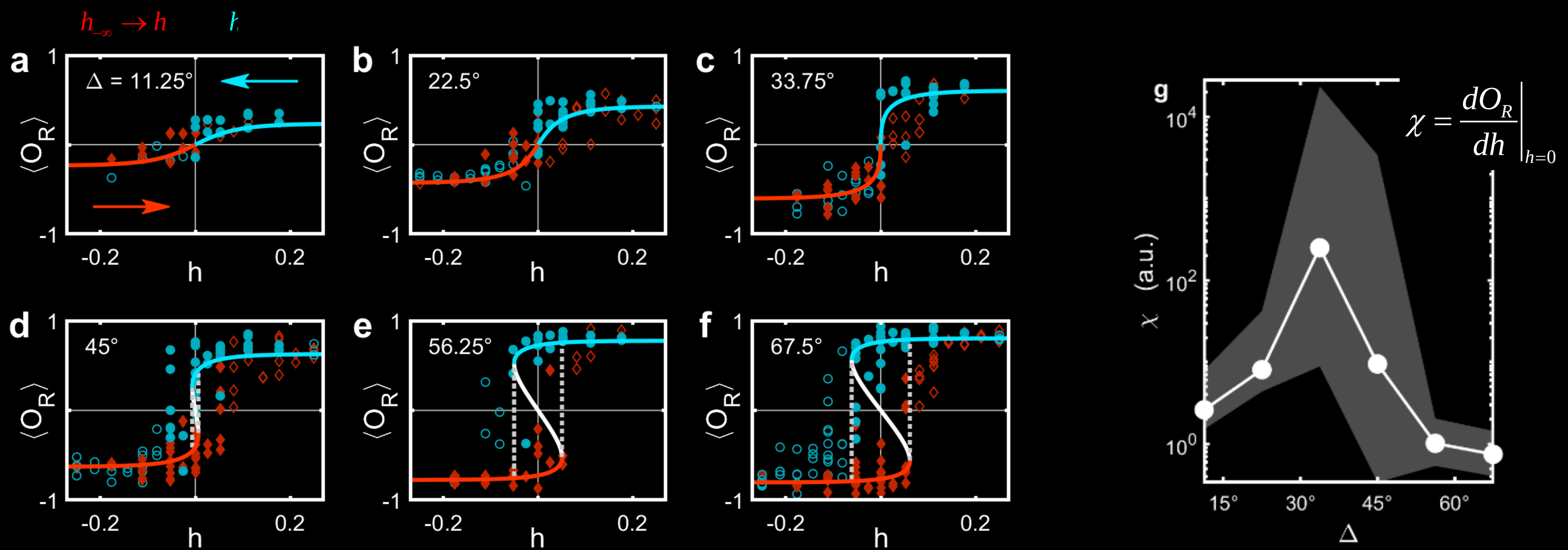


Breaking rotation symmetry



$$\langle \hat{u}_i \rangle \rightarrow \langle \hat{u}_i \rangle - h \langle \hat{r}_i \times \hat{e}_z \rangle$$

bias towards ccw (h>0) or cw (h<0) rotation



R. Löffler, T. Bäuerle, M. Kardar, C. Rohwer, C. Bechinger, EPL 134, 64001 (2021)

Collectivity ↔ Criticality ?

living systems: variation of group density

- scale-free behavior in flocks of starlings

Social interactions dominate speed control in poising natural flocks near criticality

William Bialek[a,1], Andrea Cavagna[b,c], Irene Giardina[b,c], Thierry Mora[d], Oliver Pohl[b,c,2], Edmondo Silvestri[b,c], Massimiliano Viale[b,c], and Aleksandra M. Walczak[e]

PNAS, **111** (2014)

- maximizing susceptibility near critical point

Are Biological Systems Poised at Criticality?

Thierry Mora · William Bialek

J Stat Phys, **144 (2011)**

- critical slowing down as early warning signals

Generic Indicators for Loss of Resilience Before a Tipping Point Leading to Population Collapse

Lei Dai,[1]* Daan Vorselen,[2]* Kirill S. Korolev,[1] Jeff Gore[1]†

Theory predicts that the approach of catastrophic thresholds in natural systems (e.g., ecosystems, the climate) may result in an increasingly slow recovery from small perturbations, a phenomenon called critical slowing down. We used replicate laboratory populations of the budding yeast *Saccharomyces cerevisiae* for direct observation of critical slowing down before population collapse. We mapped the bifurcation diagram experimentally and found that the populations became more vulnerable to disturbance closer to the tipping point. Fluctuations of population density increased in size and duration near the tipping point, in agreement with the theory. Our results suggest that indicators of critical slowing down can provide advance warning of catastrophic thresholds and loss of resilience in a variety of dynamical systems.

Science, **336** (2012)

- critical slowing between disordered and aligned motion

From Disorder to Order in Marching Locusts

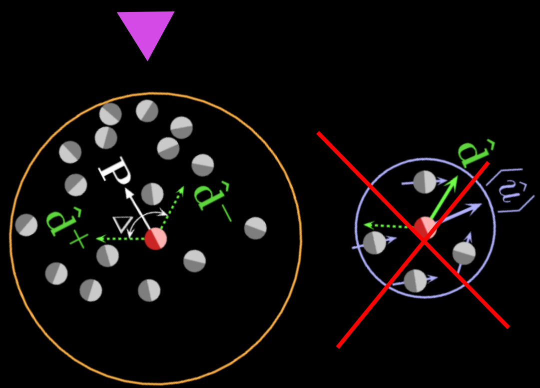
J. Buhl,[1,2]* D. J. T. Sumpter,[1] I. D. Couzin,[1,3] J. J. Hale,[1] E. Despland,[1]† E. R. Miller,[1] S. J. Simpson[1,2]

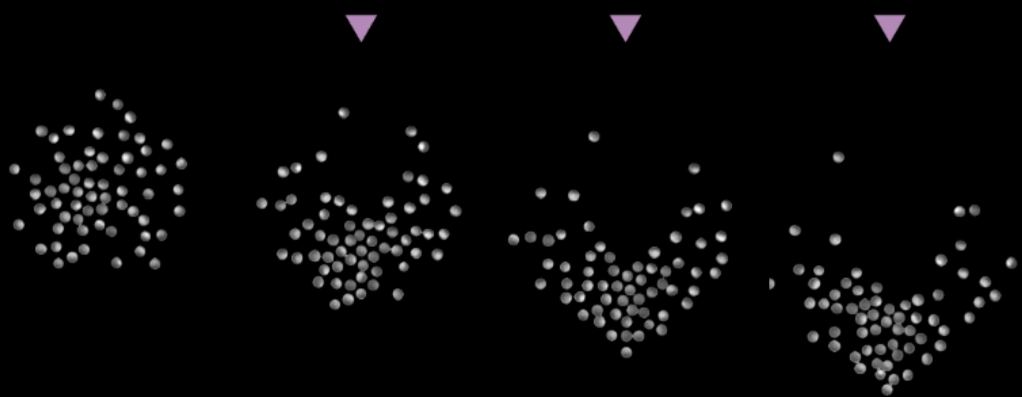
Recent models from theoretical physics have predicted that mass-migrating animal groups may share group-level properties, irrespective of the type of animals in the group. One key prediction is that as the density of animals in the group increases, a rapid transition occurs from disordered movement of individuals within the group to highly aligned collective motion. Understanding such a transition is crucial to the control of mobile swarming insect pests such as the desert locust. We confirmed the prediction of a rapid transition from disordered to ordered movement and identified a critical density for the onset of coordinated marching in locust nymphs. We also demonstrated a dynamic instability in motion at densities typical of locusts in the field, in which groups can switch direction without external perturbation, potentially facilitating the rapid transfer of directional information.

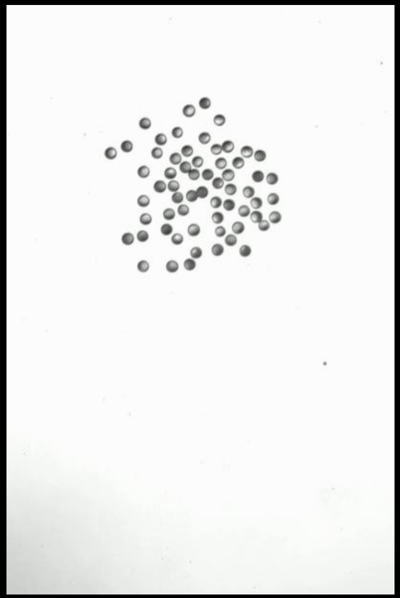
Science, **312** (2006)

Here: critical behavior achieved by variation of <u>social interactions</u>

Response to external threats

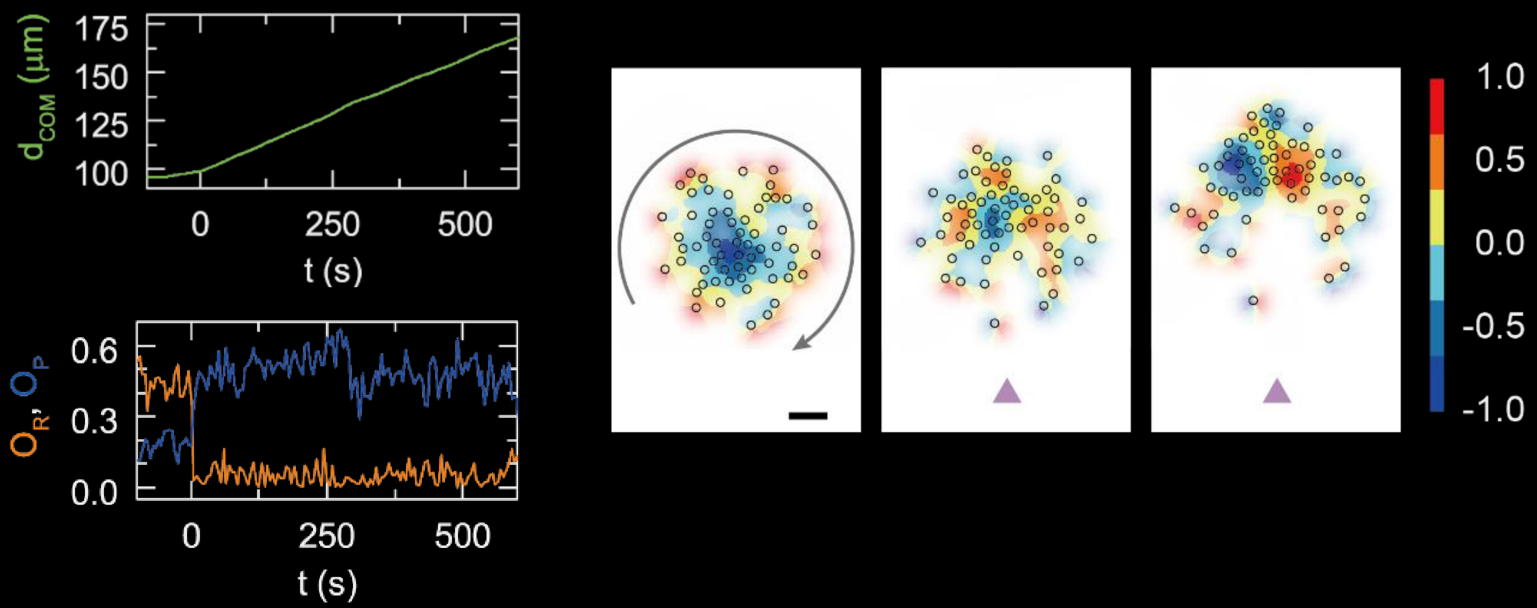






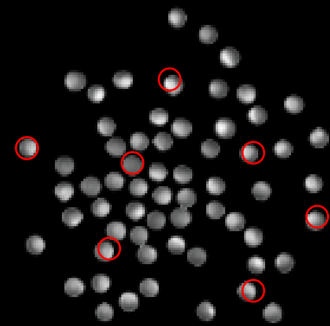
x 50

Escape by collective decision-making

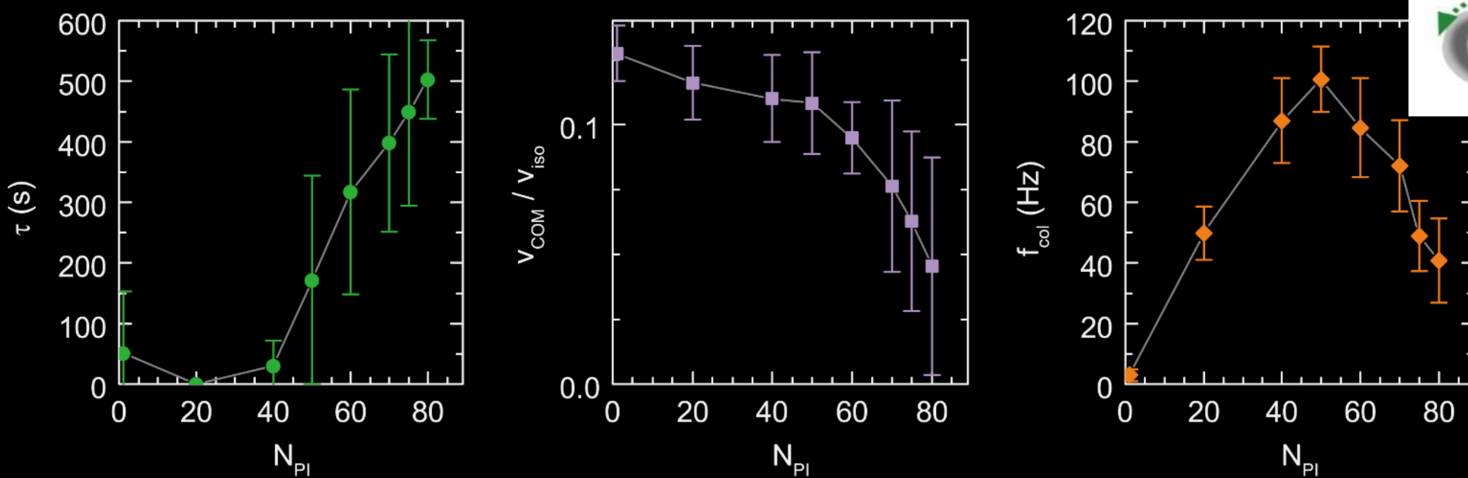


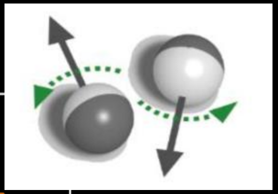
Enhanced vigilance of groups

attentive N_A
inattentive N_{PI}



N = 85





C.-J. Chen, C. Bechinger (under review)

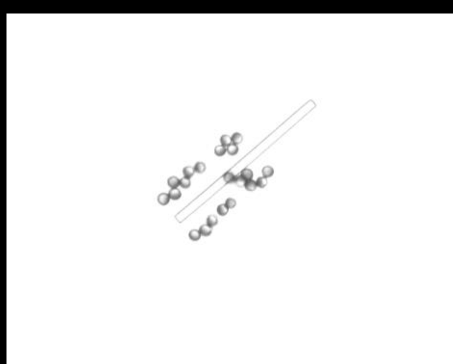
High tolerance regarding sensorial failures in microrobotic systems

Summary

- Laser feed-back system to implement user-defined interactions rules in experimental system (variations of velocities, alignment interactions, time-delays, …): social interactions
- well-defined interaction rules (as in simulations)
  but: - no equations of motions required, coupling to <u>real and noisy environment</u>
  - no knowledge of interactions required (hydrodynamic, lubric, phoretic, viscoelastic)
- Cohesive swarms without attraction
- Evidence for relation between collective states and critical behavior

- Implementation of reinforcement learning (RL) by dynamic interaction rules
- Motion through constricitons

Veit-Lorenz Heuthe



Timo Knippenberg