Active Particles With Social Interactions

Clemens Bechinger

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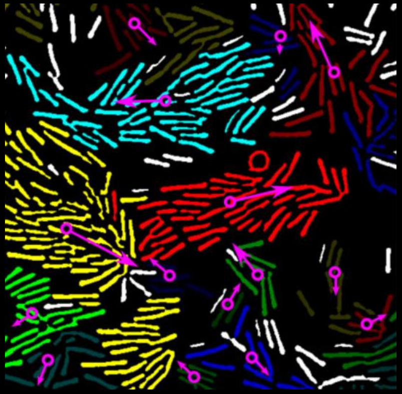
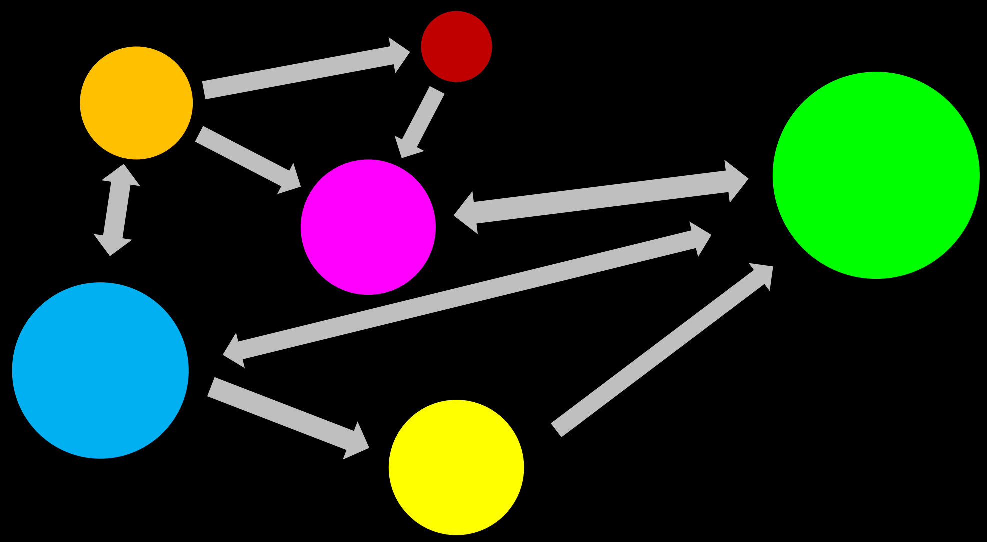


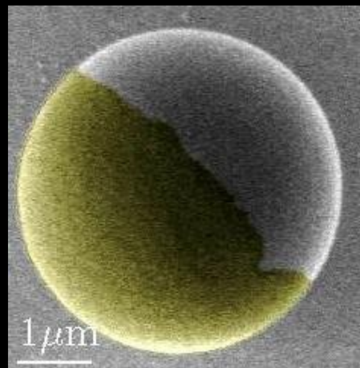
Jeckel et al PNAS (2019)

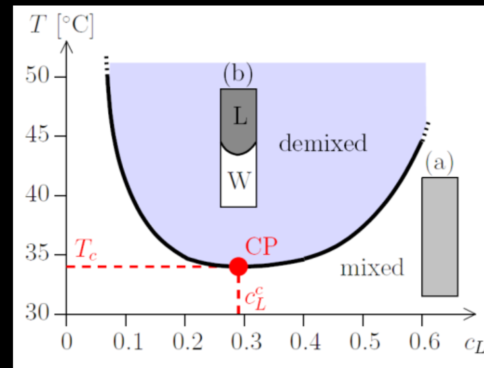
How living systems organize into complex spatio-temporal patterns ?

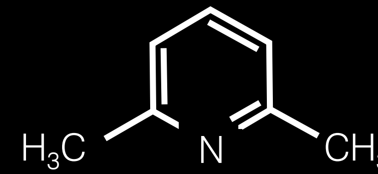


- what information is exchanged ?
- reciprocal vs. <u>non-reciprocal</u> (social) interactions ? ~~3rd Newton law~~
- spatial range of communication ?
- instantaneous vs. time-delayed response ?

Self-Propulsion by Local Demixing



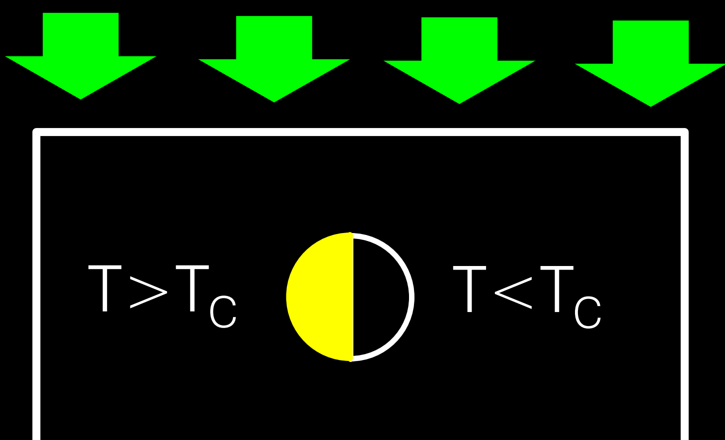


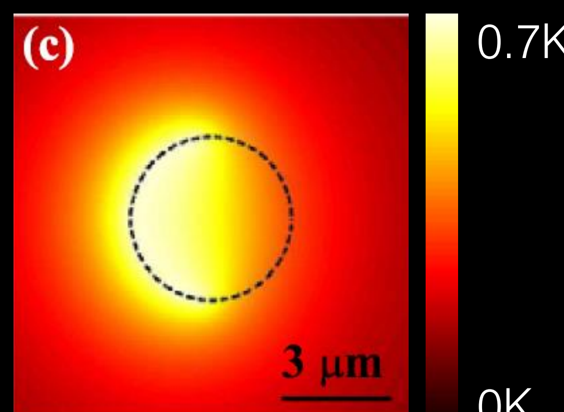


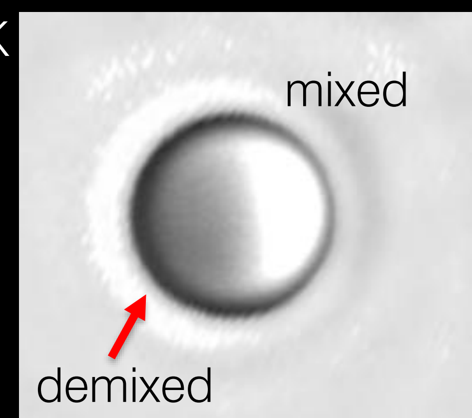
$T_C \approx$ 34°C

Hertlein, Helden, Gambassi, Dietrich, Bechinger, Nature 451, 172 (2008)

I < 1 μW/μm^2

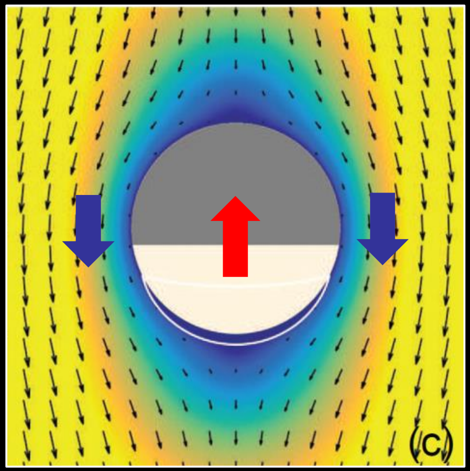






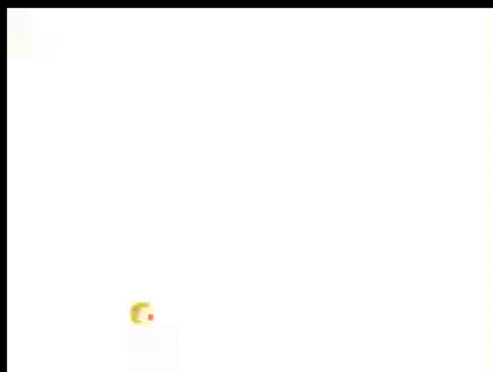
Volpe, Buttinoni, Vogt, Kümmerer, Bechinger, Soft Matter 7, 8810 (2011)

Compositional Current Flow Field



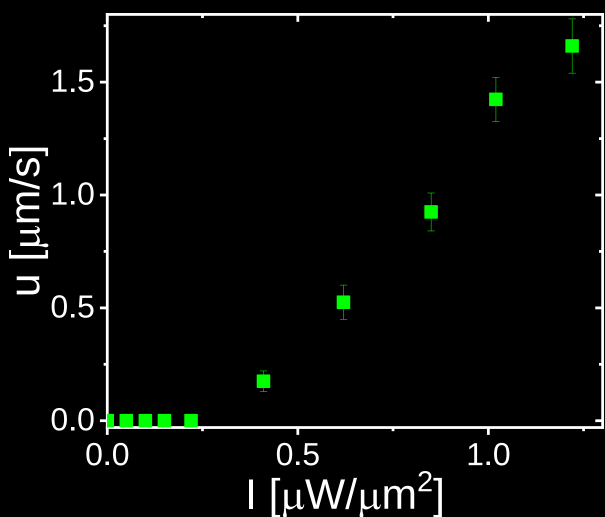
Gomez-Solano, Samin, Lozano, Ruedas-Batuecas, v. Roij, Bechinger Sci. Reports (2017).

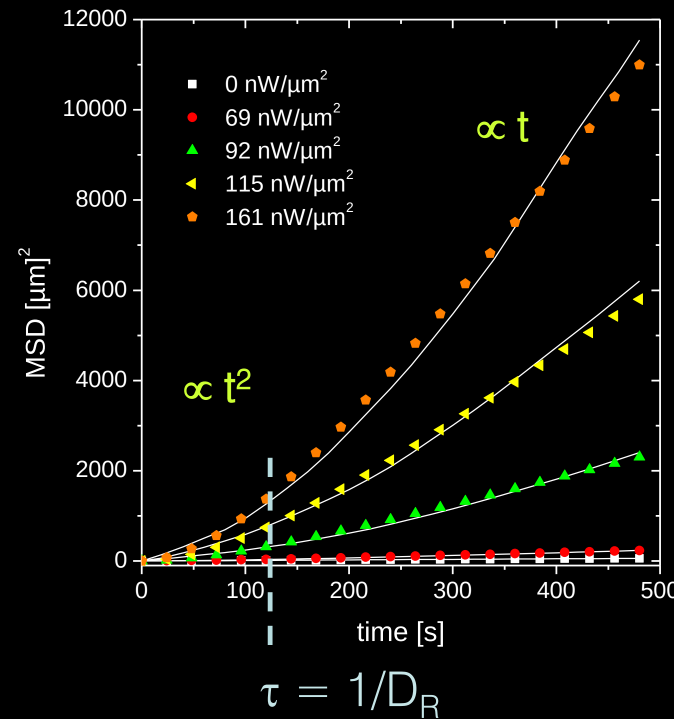
Light-induced Active Motion



persistent random walk:

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



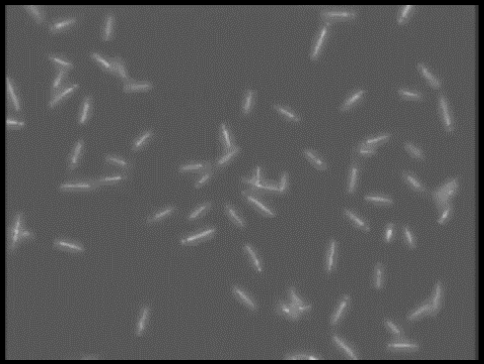


Response to external fields

Chemotaxis

Ribosome studio (2016)

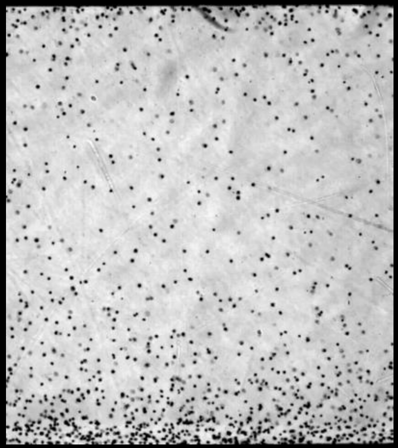
Phototaxis



Rheotaxis

Zaferani PNAS (2018)

Gravitaxis



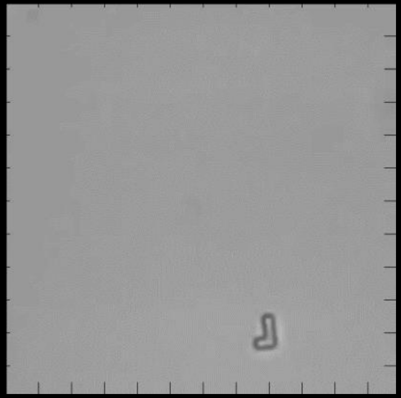
Burmeister Youtube (2016)

Response to External Fields

Gravitaxis

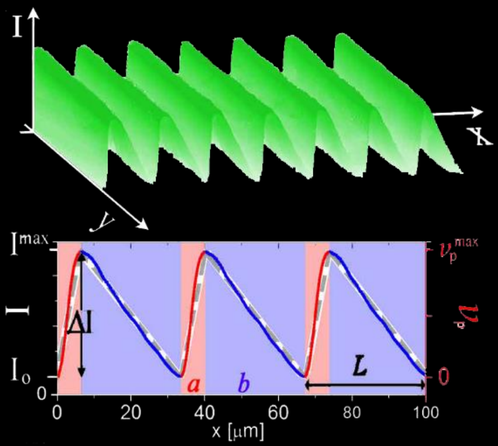
propulsion in plane

sedimentation



sedimentation and propulsion

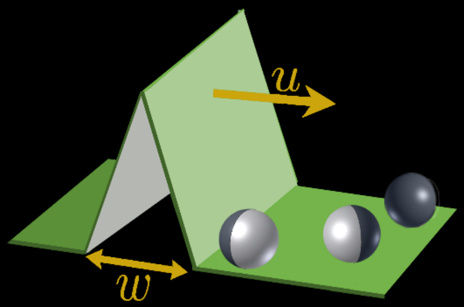
Phototaxis



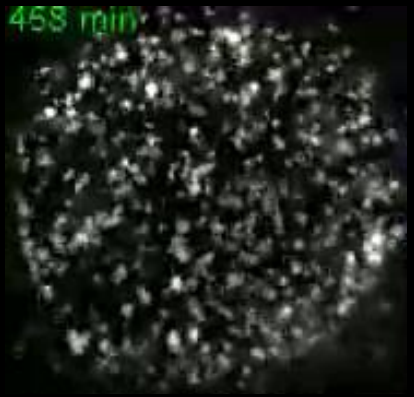
Hagen, Kümmel, Wittkowski, Takagi, Löwen, Bechinger Nat. Comm. **5,** *4829 (2015)*
Lozano, ten Hagen, Löwen, Bechinger Nat. Comm. **7**, 12828 (2016)

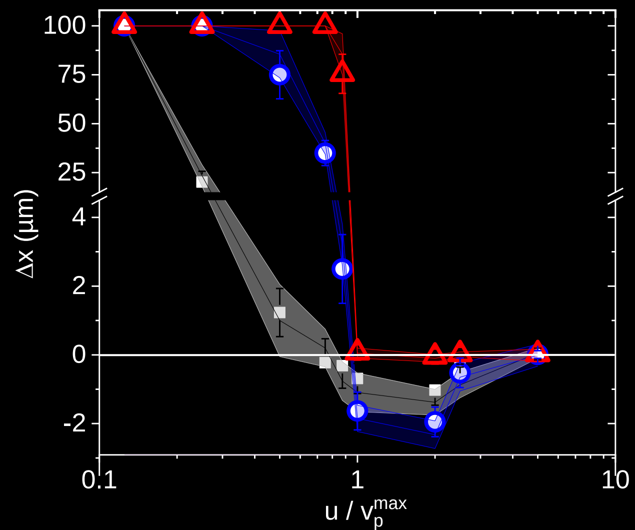
Diffusing Wave Paradox

Response of chemotacting amoebae to travelling chemical pulses



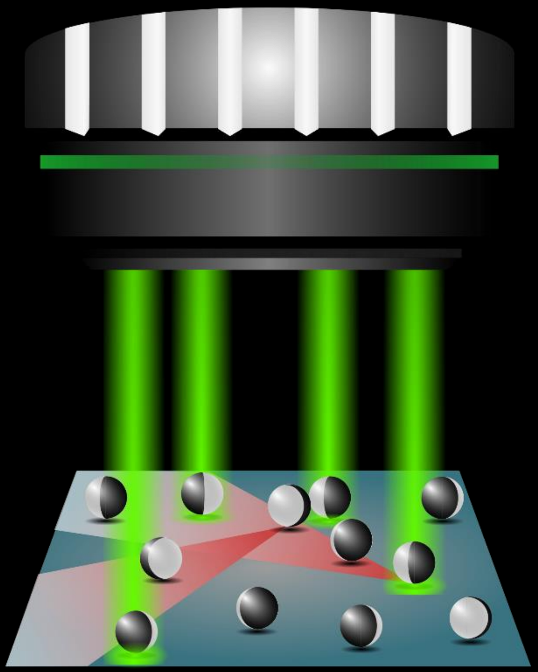
Dictyostelium



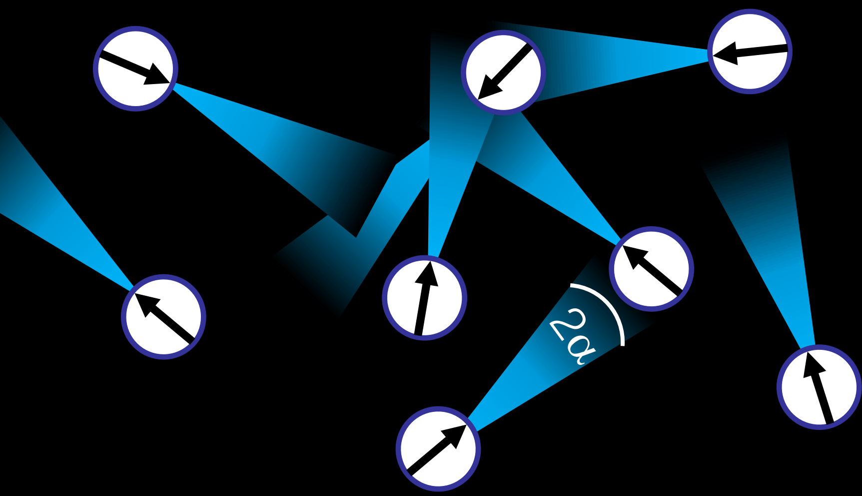


Lozano, Bechinger Nat. Comm. **10**, 2495 (2019)
Geiseler, Hänggi, Marchesoni Sci. Rep. (2017)

Group formation and cohesion by visual perception-dependent motility



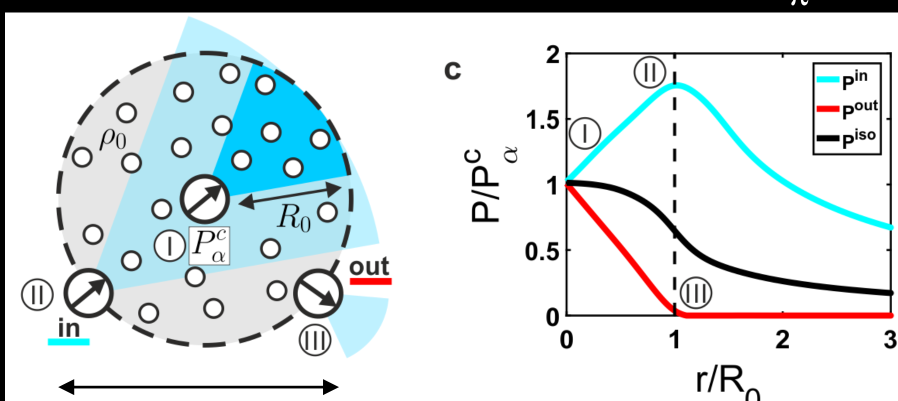
Visual Perception



visual perception:

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

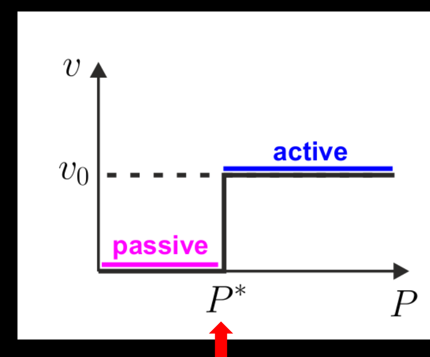
$$P^c_\alpha = \frac{\alpha}{\pi} \rho_0 R_0$$



$2R_0$

R_0: initial group size

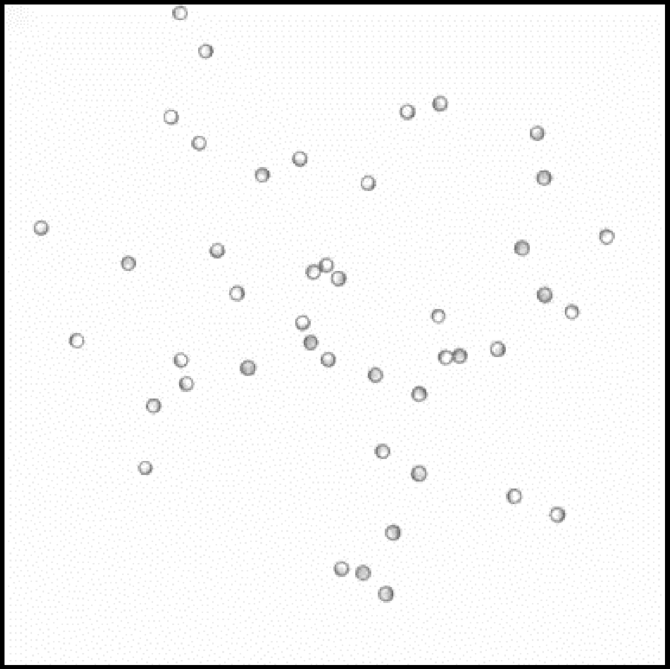
decision-making: *„social behavior“*



reaction threshold

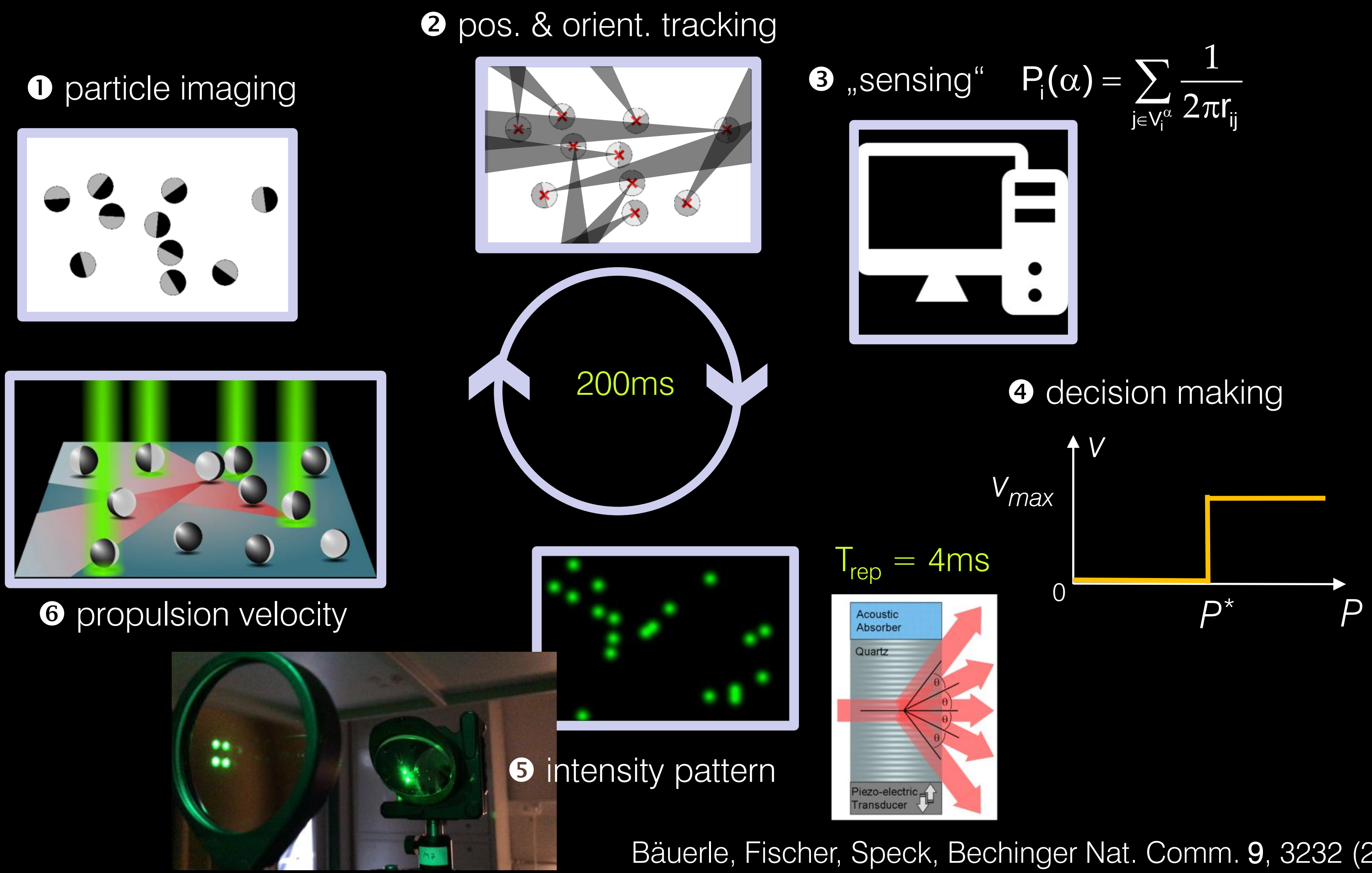
<u>No active realignment of APs !</u>

$$\alpha = 45^\circ$$
$$P^* = P^c_\alpha$$



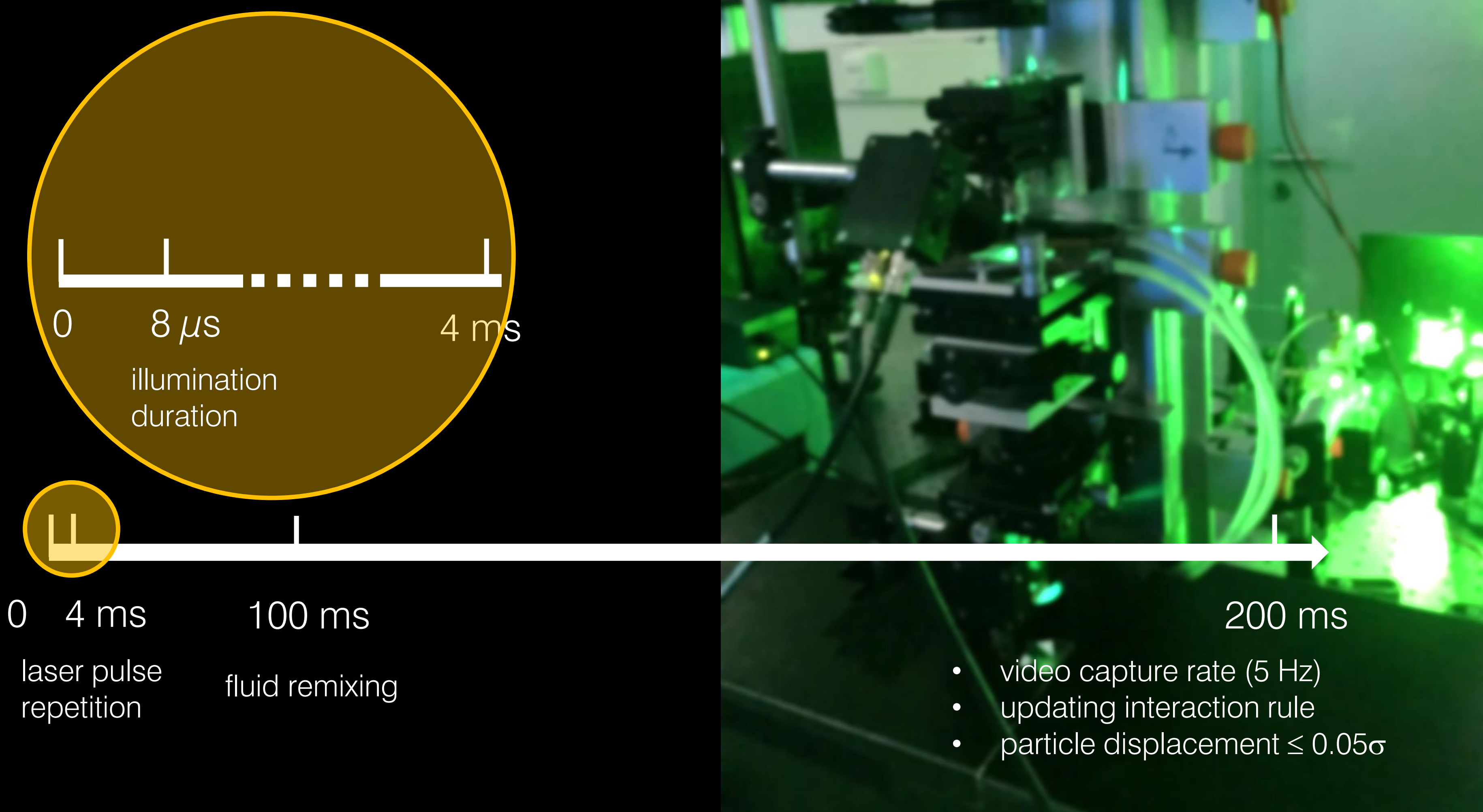
cohesive groups without alignment interactions
(no coexistence with dilute phase !!)

Experimental Realization

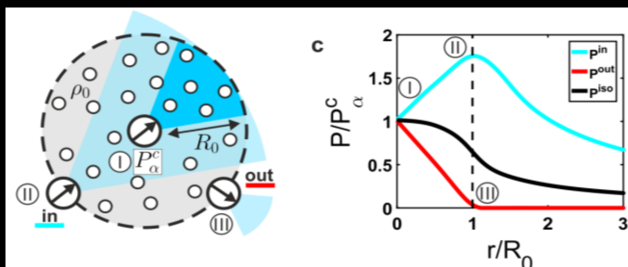


Bäuerle, Fischer, Speck, Bechinger Nat. Comm. **9**, 3232 (2018)

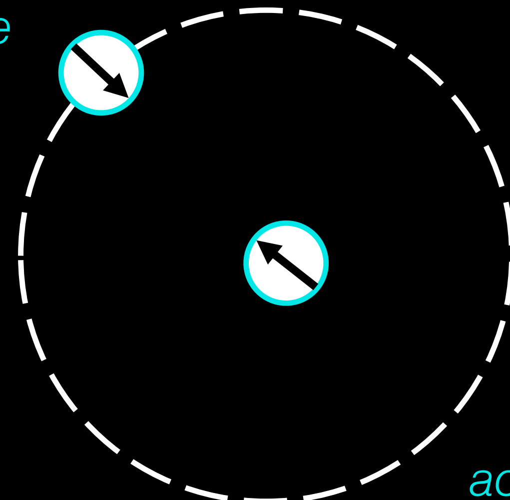
Feedback Loop



Cohesion Mechanism

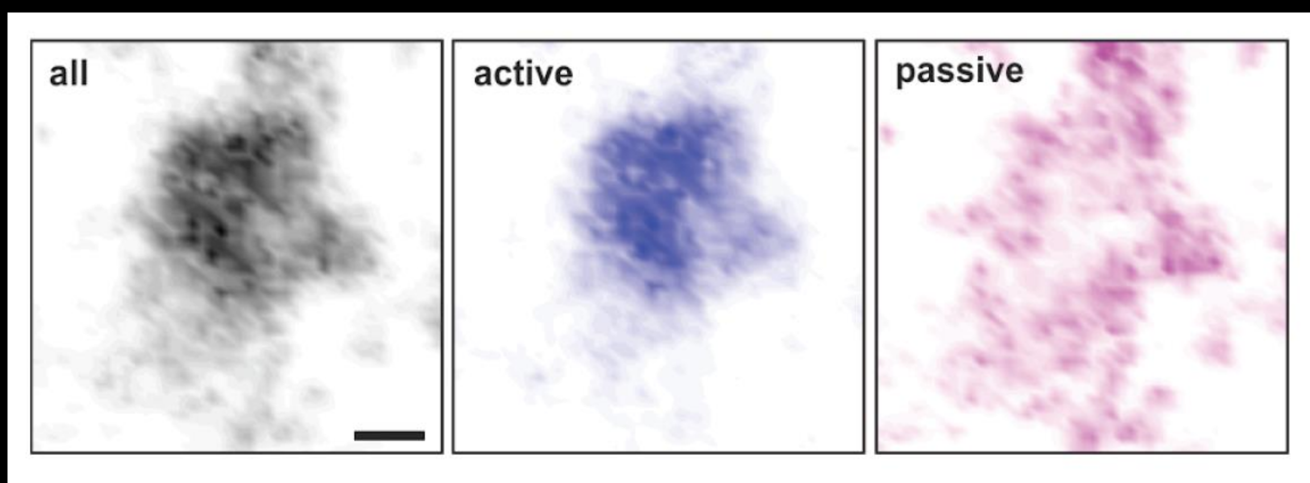


active



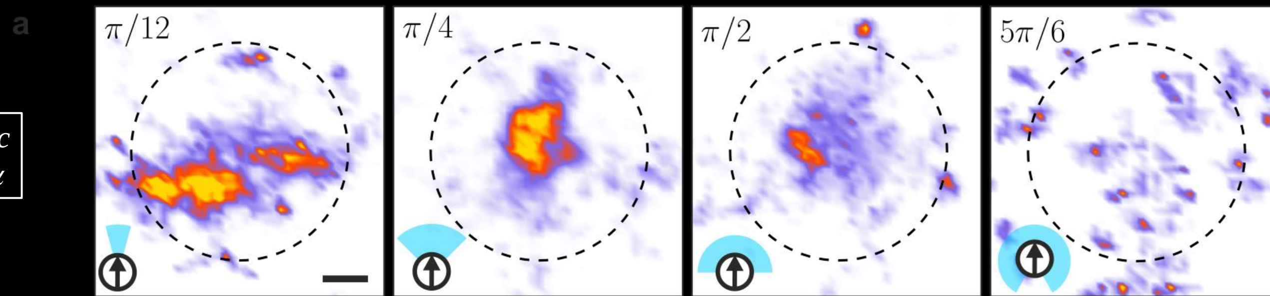
$$P^* = P^c_\alpha$$

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



Variation of vision cone

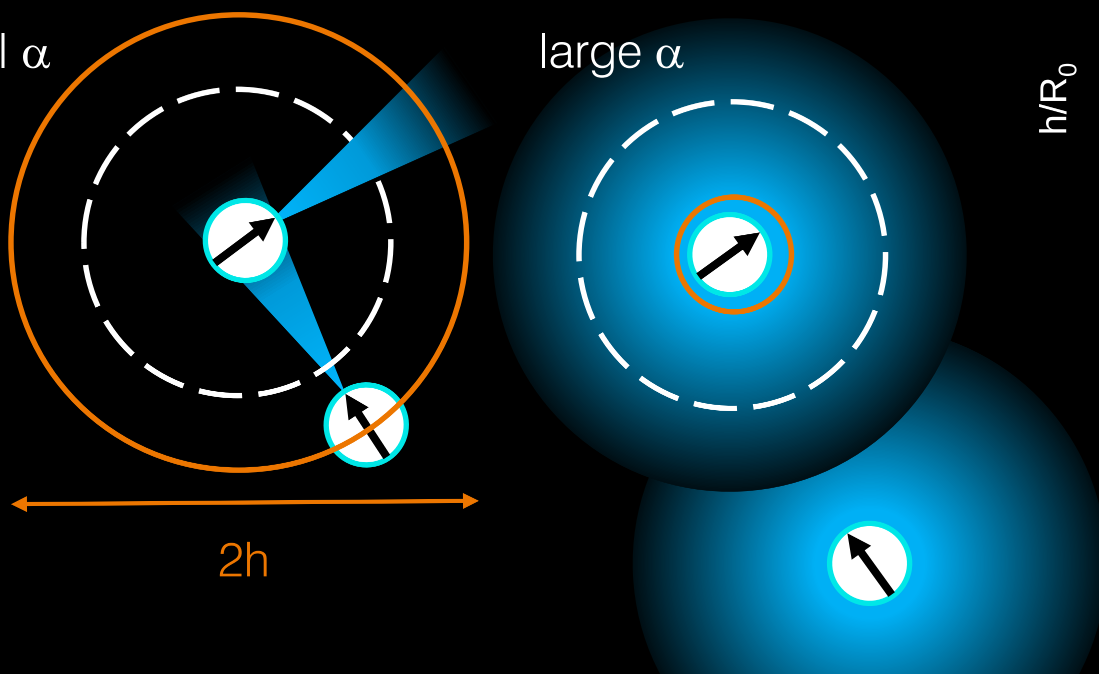
$$P^* = P^c_\alpha$$

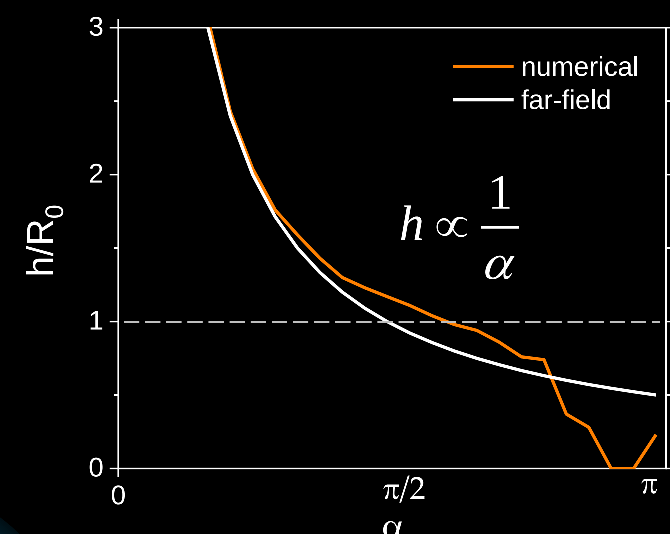


← cohesion → no cohesion

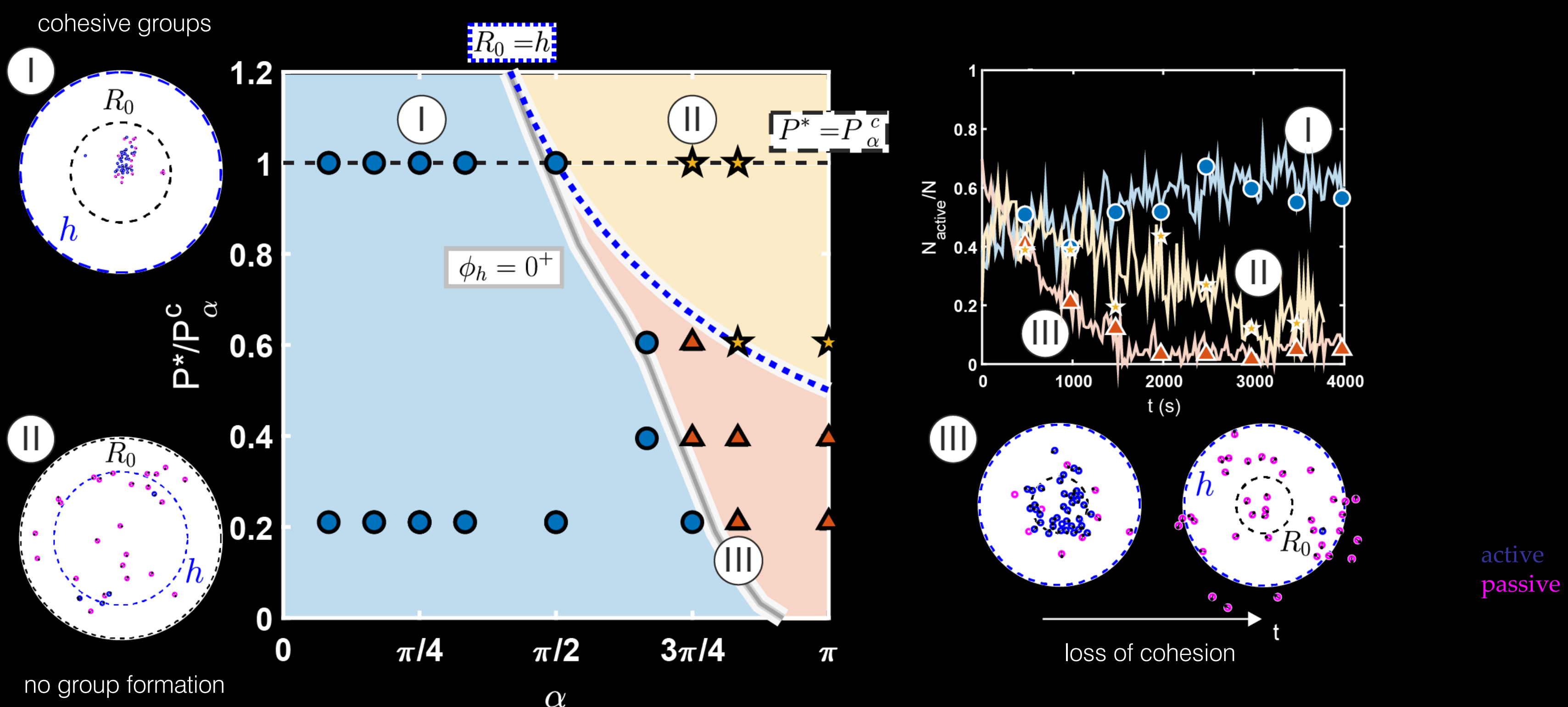
activity horizon h: $P^{in}(h) \equiv P^* = P^c_\alpha$

r < h: particles join group





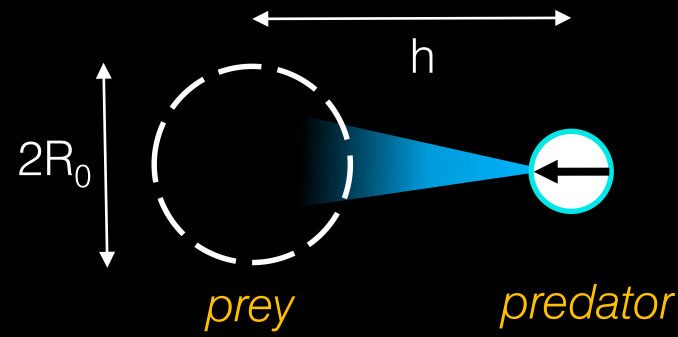
Variation of reaction threshold

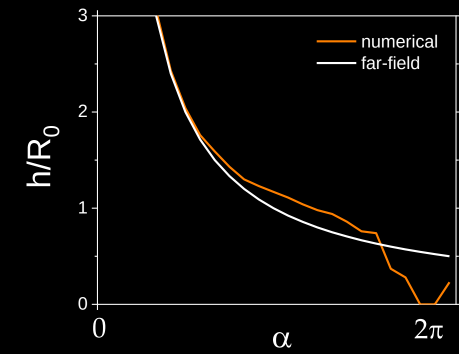


Lavergne, Wendehenne, Bäuerle, Bechinger, Science **364**, 70 (2019)

Relation to Predator-Preys Interactions

Predators: small binocular field of vision α, round or vertically elongated pupils

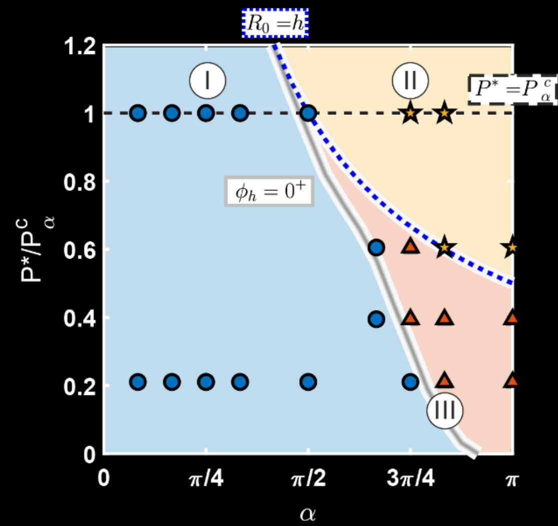




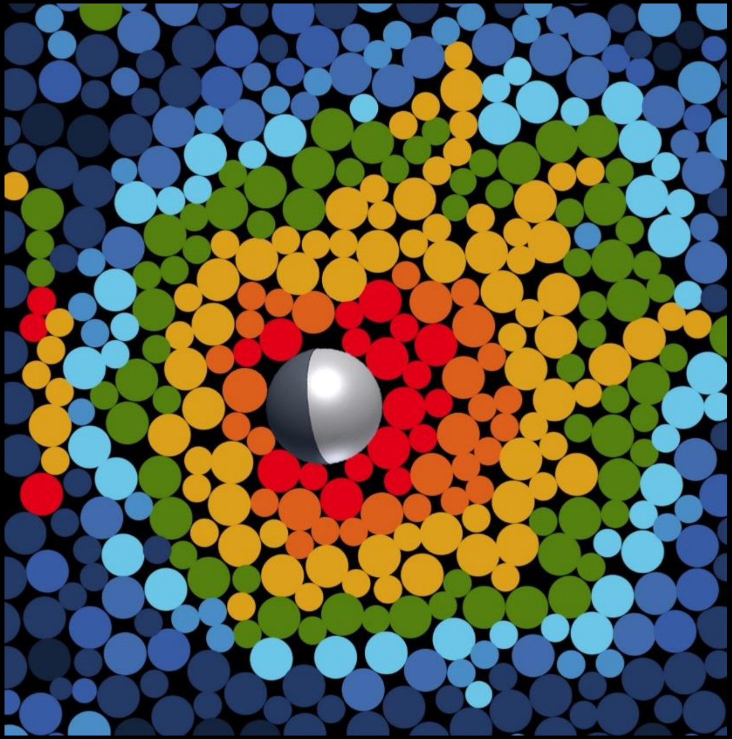
h>>R_0: response to group triggered far away

Prey: large field of vision α, horizontally elongated pupils

cohesion requires small P^*
$\rightarrow$ high alertness

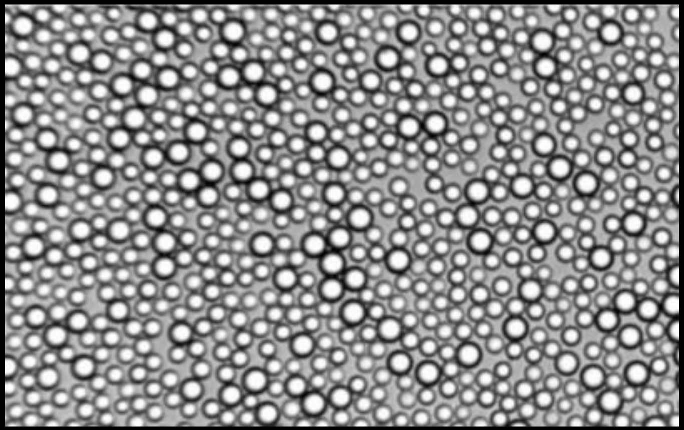


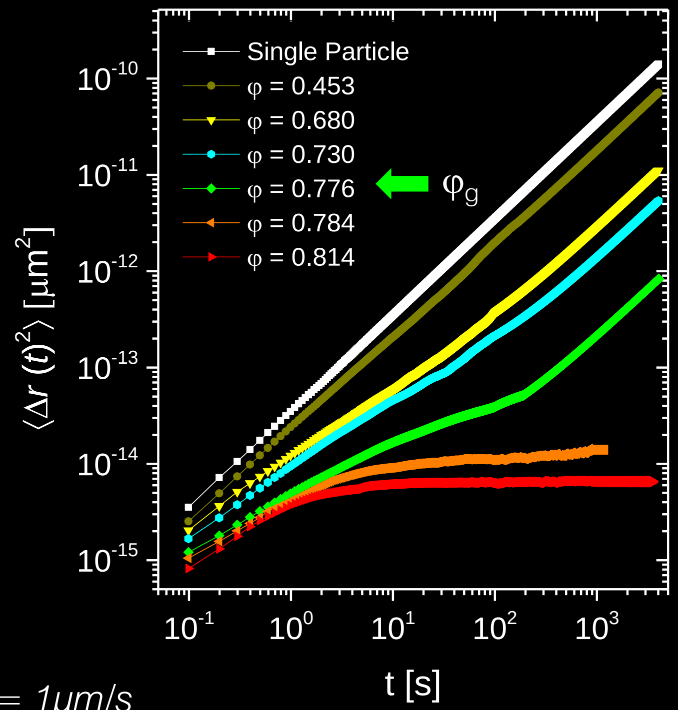
Active particles as mechanical probes of glassy environments



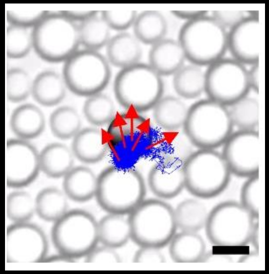
ABM in crowded/glassy materials

50:50 mixture, 6.3μm & 4.4μm

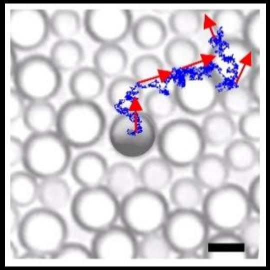




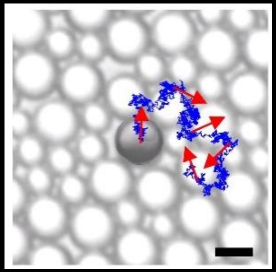
$\varphi = 0.73, \; v = 0\mu m/s$



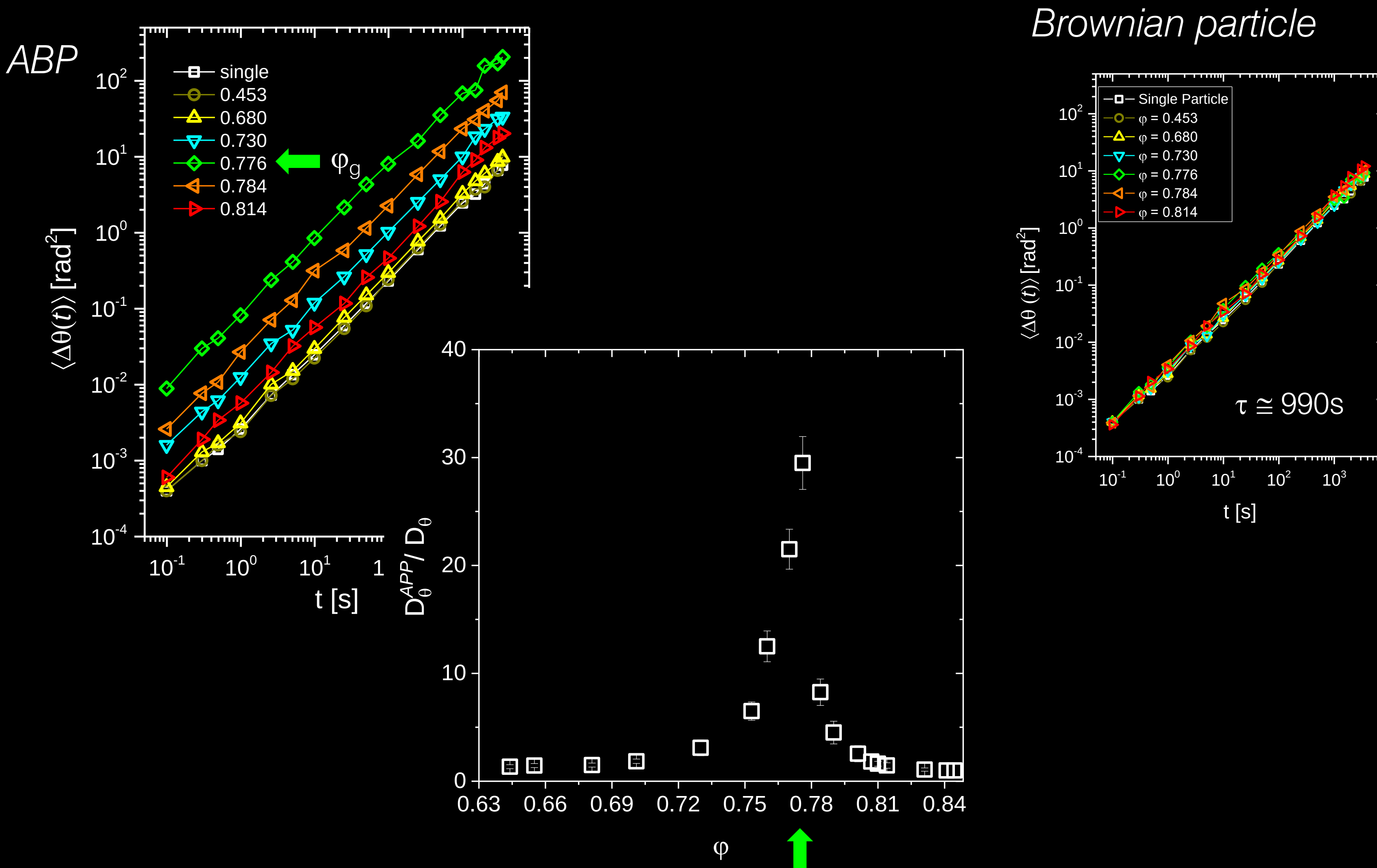
$\varphi = 0.73, \; v = 1\mu m/s$



$\varphi = 0.776, \; v = 1\mu m/s$



Rotational Diffusion Coefficient



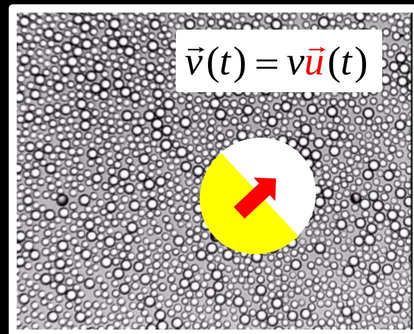
Lozano, Gomez-Solano, Bechinger Nat. Mat. (2019)

Viscous vs. viscoelastic fluids

viscous fluids

$$\vec{F}_{drag}(t) = -6\pi\eta a\dot{\vec{r}}(t)$$

$$\vec{F}_{prop}(t) = 6\pi\eta a v\vec{u}(t)$$



viscoelastic fluids

$$\vec{F}_{drag}(t) = -\int_{-\infty}^{t} \Gamma(t-t')\dot{\vec{r}}(t')dt'$$

$\Gamma(t) = 6\pi a G_{\varphi}(t)$;

$G_{\varphi}(t)$ *stress relaxation modulus*

$$\vec{F}_{prop}(t) = v\int_{-\infty}^{t} \Gamma(t-t')\vec{u}(t')dt'$$

$$\vec{F}_{drag}(t) + \vec{\xi}(t) + \vec{F}_{prop}(t) = 0$$

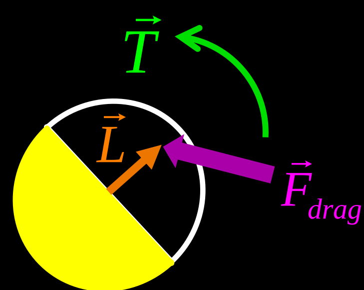
force-free conditions $(\vec{F}_{drag} \parallel -\vec{F}_{prop})$

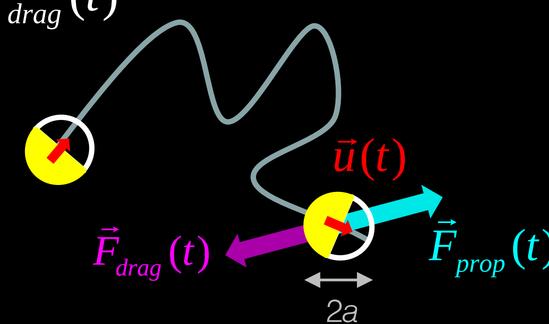
$$\rightarrow \vec{F}_{drag} \parallel -\vec{u}$$

$$\vec{F}_{drag}(t) = -v\int_{-\infty}^{t} \Gamma(t-t')\vec{u}(t')dt' - \vec{\xi}(t)$$

$$\rightarrow \vec{F}_{drag} \nparallel -\vec{u}$$

$$\vec{T}(t) = \underbrace{\mu a\vec{u}(t)}_{\vec{L}} \times \vec{F}_{drag}(t)$$





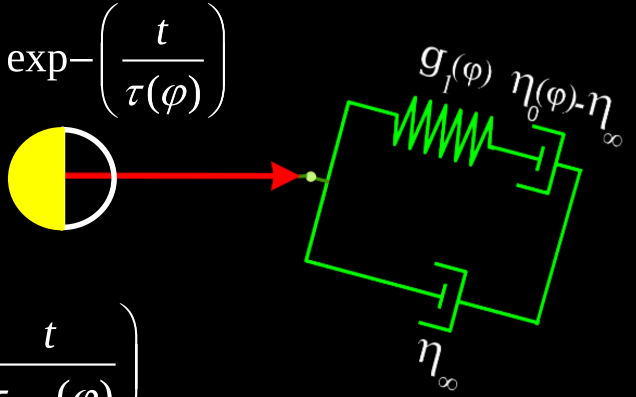
$$\pi\sigma^3\eta_\Theta\dot{\vec{\Theta}}(t)+\vec{\xi}_\Theta(t)+\vec{T}(t)=0$$

$$D_\Theta=\frac{k_BT}{8\pi\eta_\Theta a^3}$$

Jeffrey fluid ($\varphi<\varphi_g$)

$$G(t)=2\eta_\infty\delta(t)+\frac{\eta_0(\varphi)-\eta_\infty}{\tau(\varphi)}\exp-\left(\frac{t}{\tau(\varphi)}\right)$$

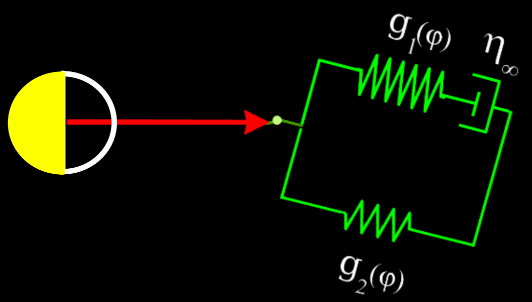
$$\tau(\varphi)=\frac{\eta_0(\varphi)-\eta_\infty}{g_1(\varphi)}$$

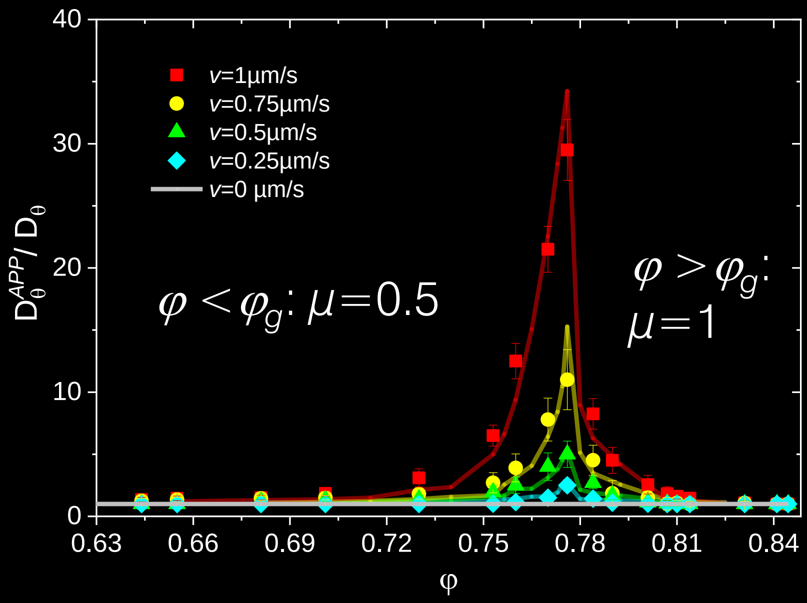


Viscoelastic solid ($\varphi>\varphi_g$)

$$G(t)=g_2(\varphi)+g_1(\varphi)\exp-\left(\frac{t}{\tau_{SLS}(\varphi)}\right)$$

$$\tau_{SLS}(\varphi)=\frac{\eta_\infty}{g_1(\varphi)}$$





Summary

- Laser feed-back system to implement user-defined interactions rules in experimental system (variations of velocities, alignment interactions, time-delays, …): social interactions

- Hybrid method between simulations and experiments
  - a priori knowledge of interaction rules required (as in numerical sim.)
  - equations of motion must not be known (opposed to simulations)

→ all physical interactions (hydrodynamics, phoretic, steric) are taken into account.

→ extension to viscoelastic fluids (non-Markovion baths) which provide the natural habitat of bacteria and other microorganisms.

→ development of minimal rules for self-organization of microrobots without central control

erc MICRO-SWIMMERS DFG