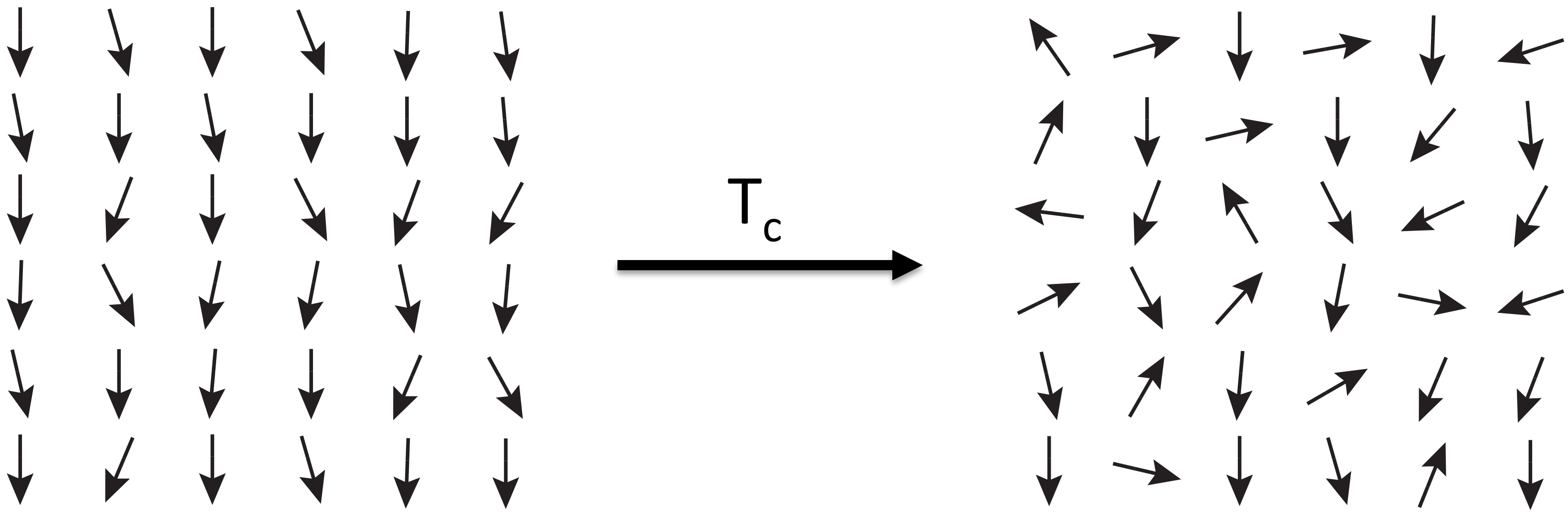
2D x-y model

low temperature ordered phase

high temperature disordered phase



energy favors aligned state

entropy favors disordered state

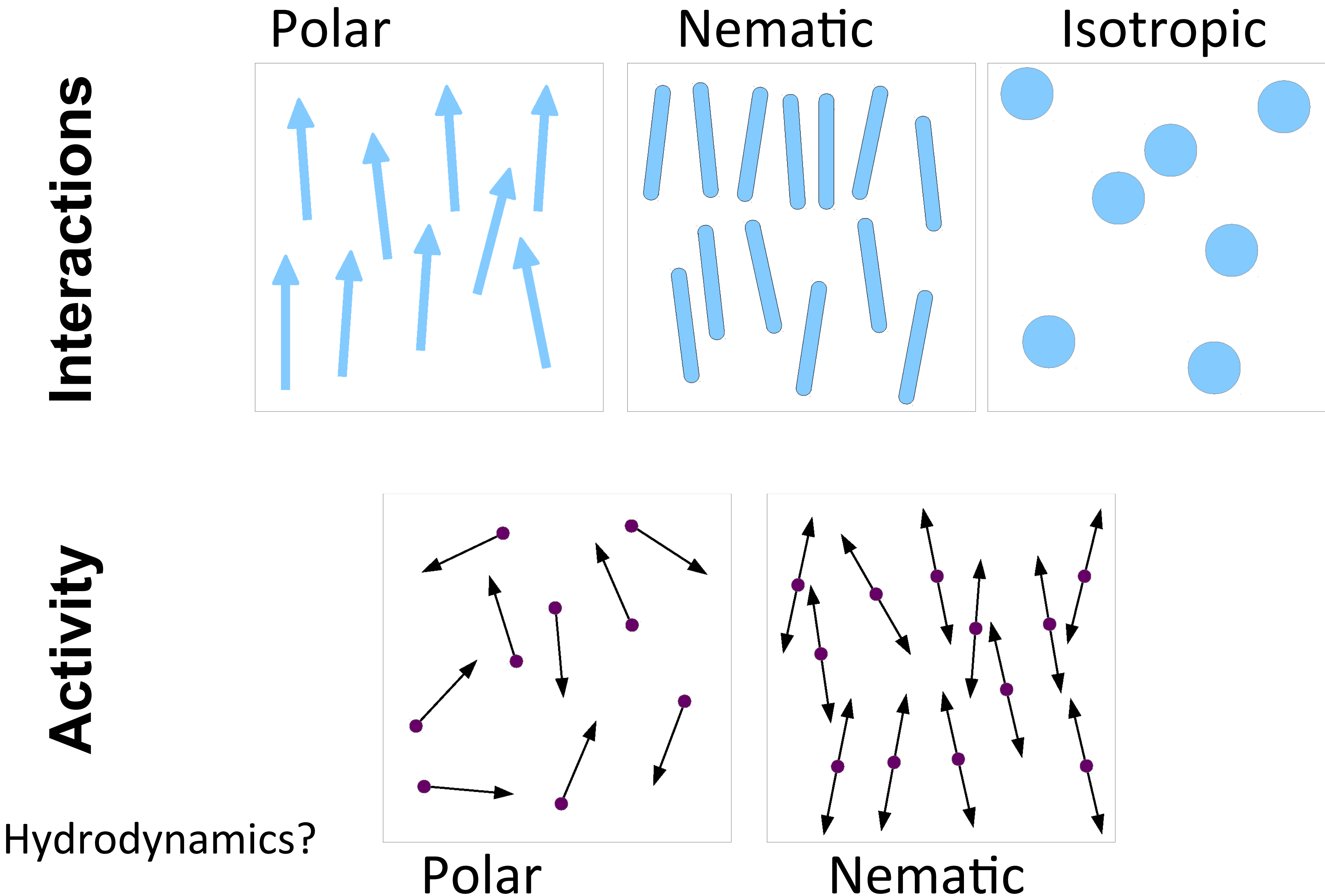
$$F=E-TS$$

Free energy, Energy, Temperature, Entropy

Minimizing free energy (F) determines equilibrium phase

What happens for a system away from equilibrium?

Symmetries in Active Systems



Active Materials

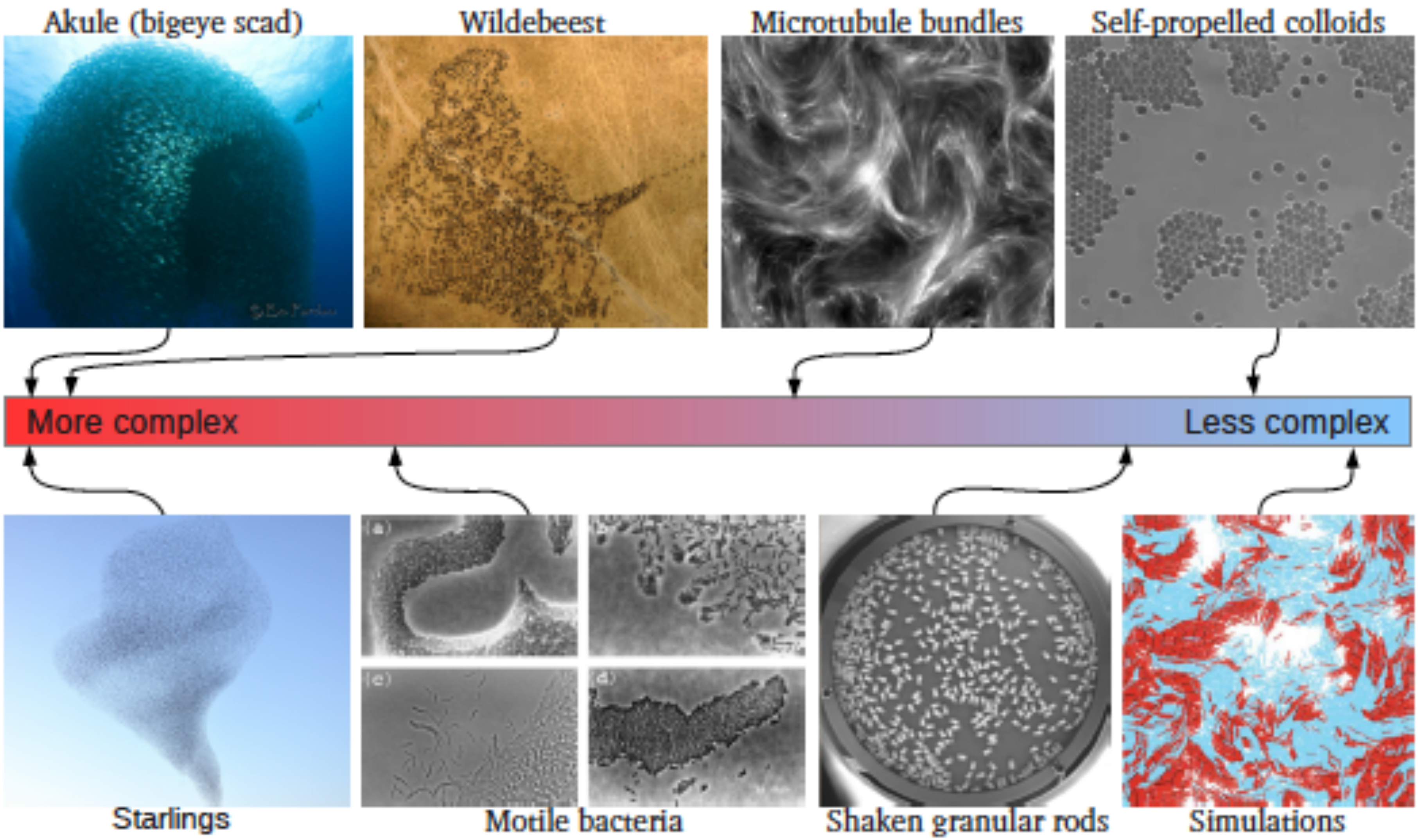


Image credits [top]: (1) Bo Pardau, Big Island, Hawaii, http://www.flickr.com/photos/bodiver/ (2) Wikipedia (3) T. Sanchez et. al. Nature, 491, 431. (2012) (4) J. Palacci et. al., Science 487, 33 (2013). [bottom] (1) http://webodysseum.com/videos/spectacular-starling-flocks-video-murmuration/ (2) R. Harshey, Annual review of microbiology 57, 249 (2003). (3) A. Kudrolli et. al. Phys. Rev. Lett. 100, 058001 (2008). (4) McCandlish et. al. Soft Matter, 8, 2527 (2012).

Overview of experiment active matter systems

Different categories of experimental model systems

Synthetic active swimmers – tunable shape and microscopic dynamics
very few microscopic mechanism that can power propulsion
orders of magnitude less efficient that biological swimmers
difficult to achieve long term steady state

Assemblages of Living Organism – robust long lived dynamics
evolution ensures high energy efficiency
microscopic activity, shape and interactions are not easily tunable
reproduction and death – number conservation
difficult to achieve long-term steady state dynamics

Biomimetic systems – assemblages of energy consuming biochemical building (molecular motors and microtubules)
high efficiency comparable to living organism while also tunable lie synthetic systems

No ideal system of active matter – each one has advantages and disadvantages

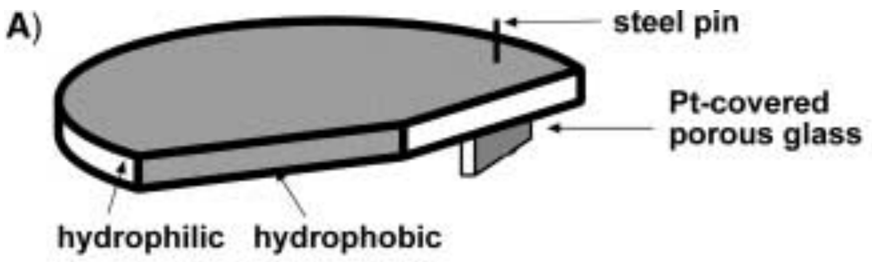
Outline

1. Isotropic interactions and polar active dynamics

2. Polar interaction and polar active dynamics

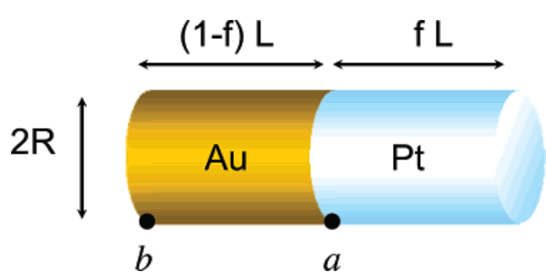
3. Apolar interaction and nematic active dynamics

Catalytic Swimmers



Ismagliov and Whitesides 2002

1 mm



~1 μm

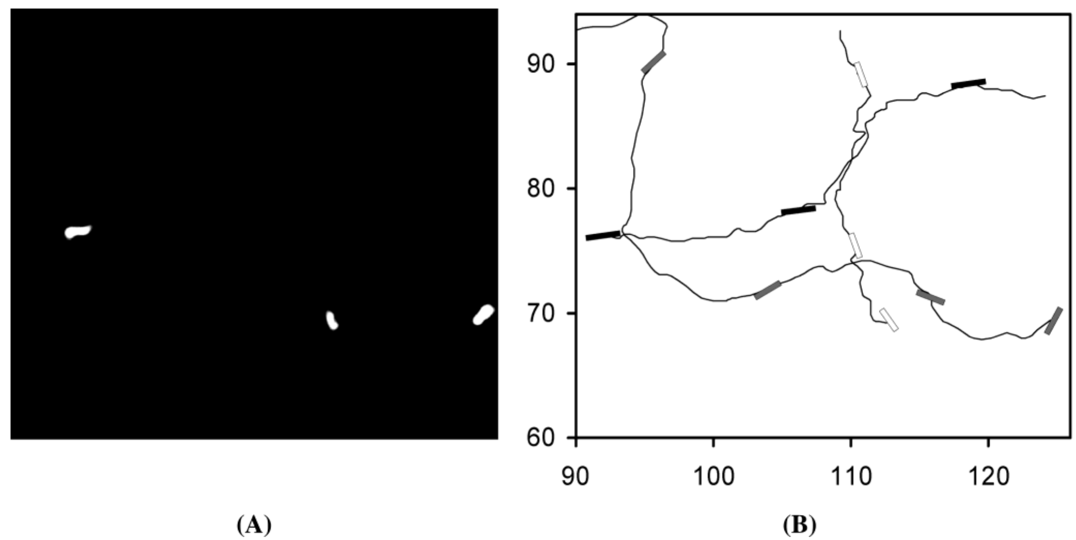


Figure 1. Trajectory plots of three 2 ím long platinum/gold rods identified in (A) over the next 5 seconds. (B) in 2.5% aqueous hydrogen peroxide.

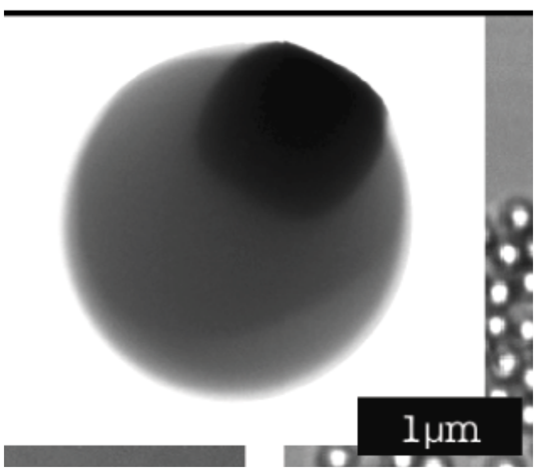
Sen et. al. JACS 2006

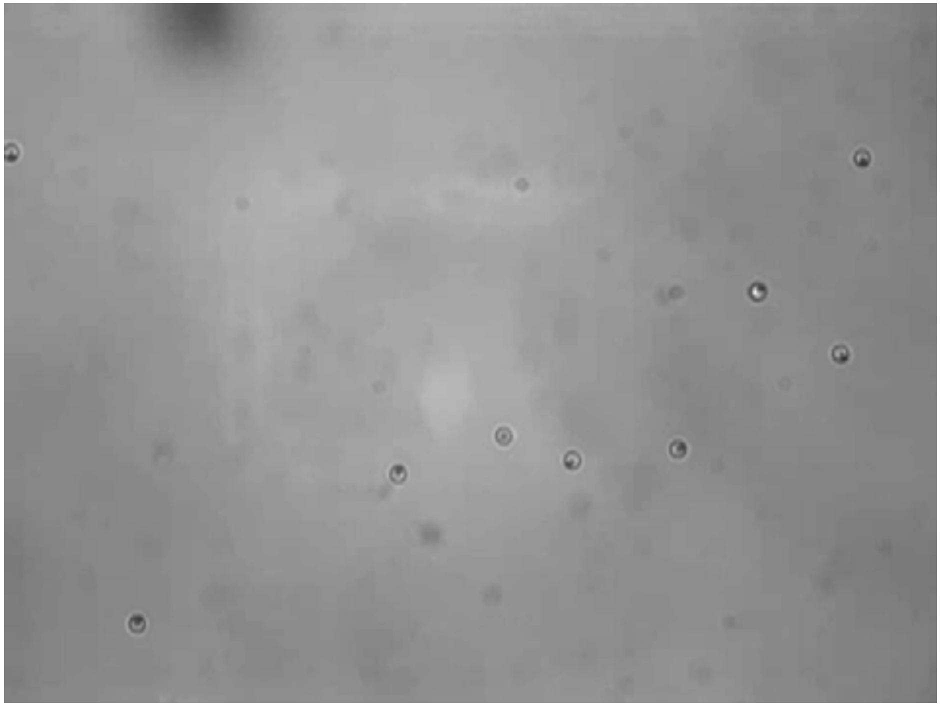
Isotropic synthetic swimmers

Light controlled particle motility – light catalyzes degradation of H_20_2

advantages – highly tunable
microscopy dynamics
(light and hydrogen peroxide concentration)

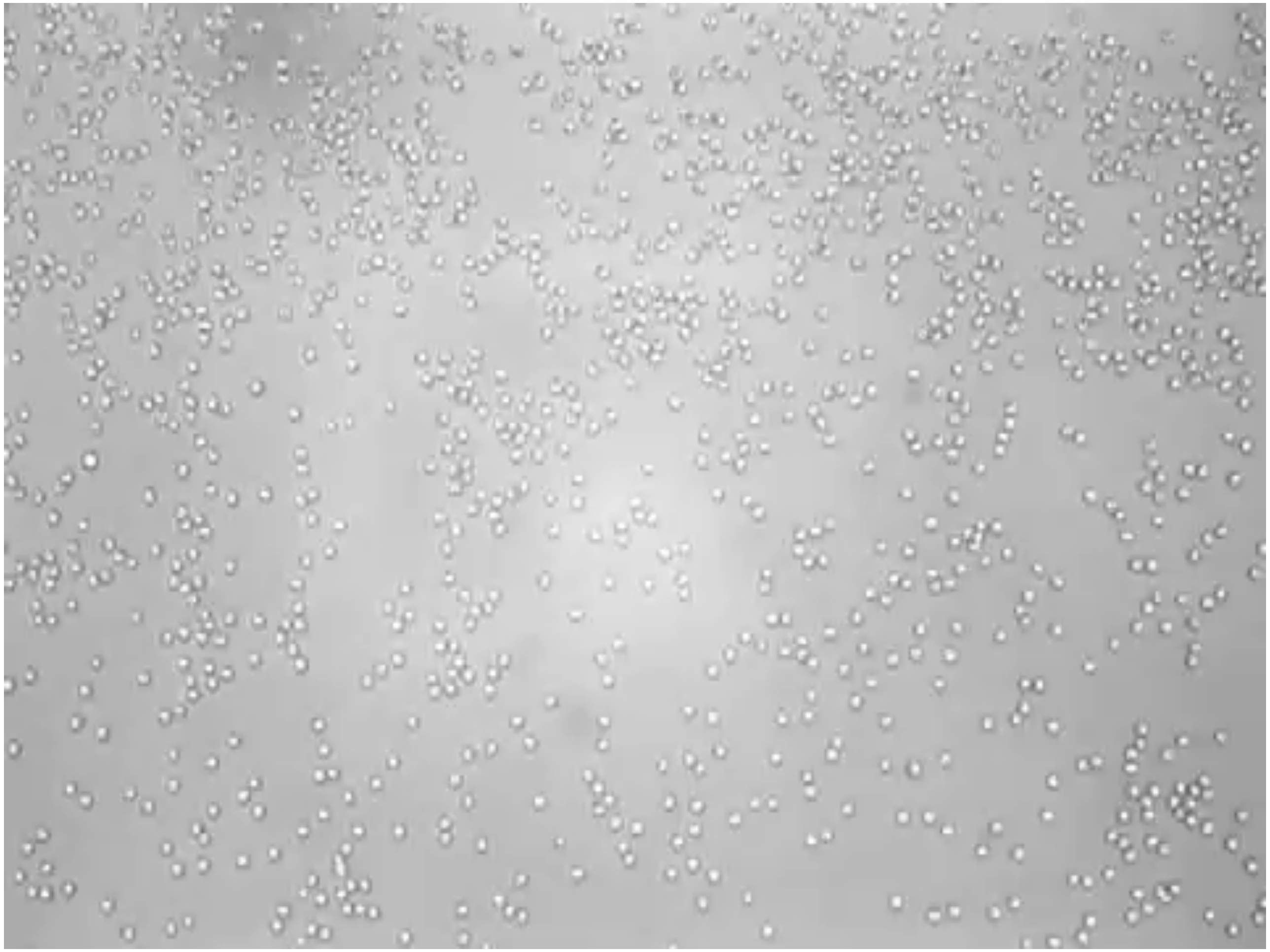
drawbacks – motility produces unwanted gas products – limited lifetime (tens of minutes)
complex swimming mechsims



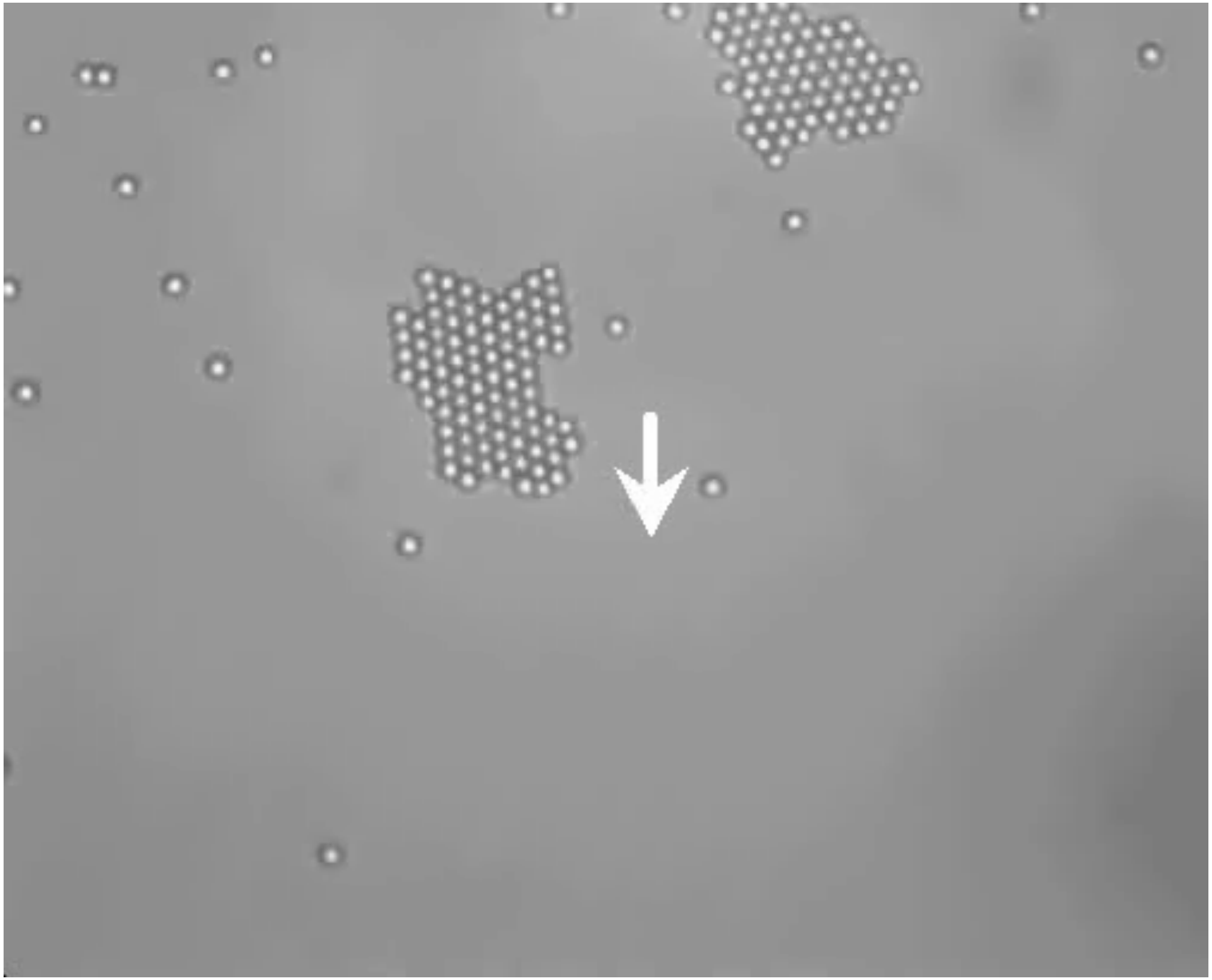


Jeramy Pallaci,Paul Chaikin and others 2013

Clustering of active isotropic swimmers

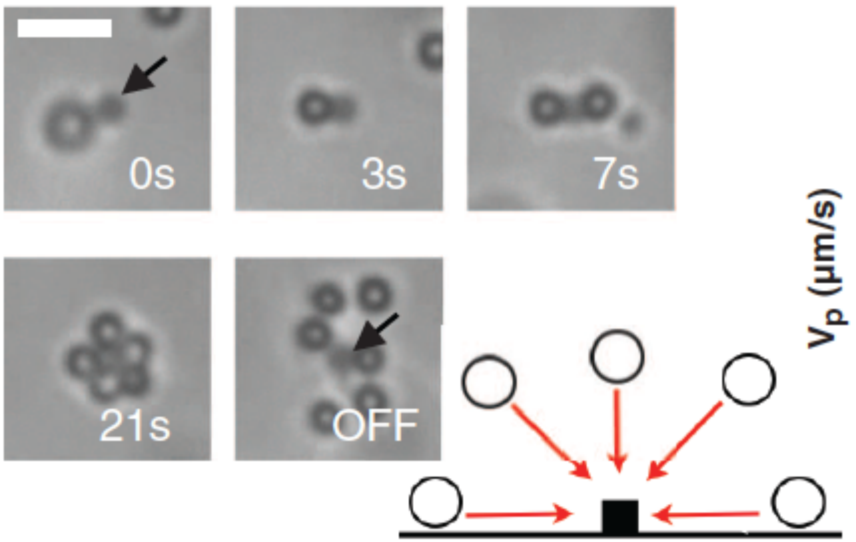


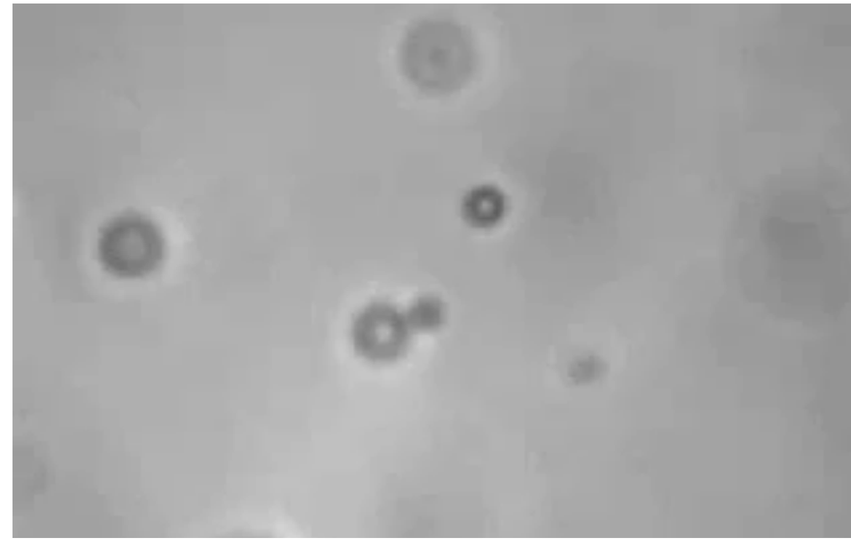
Clustering of active isotropic swimmers

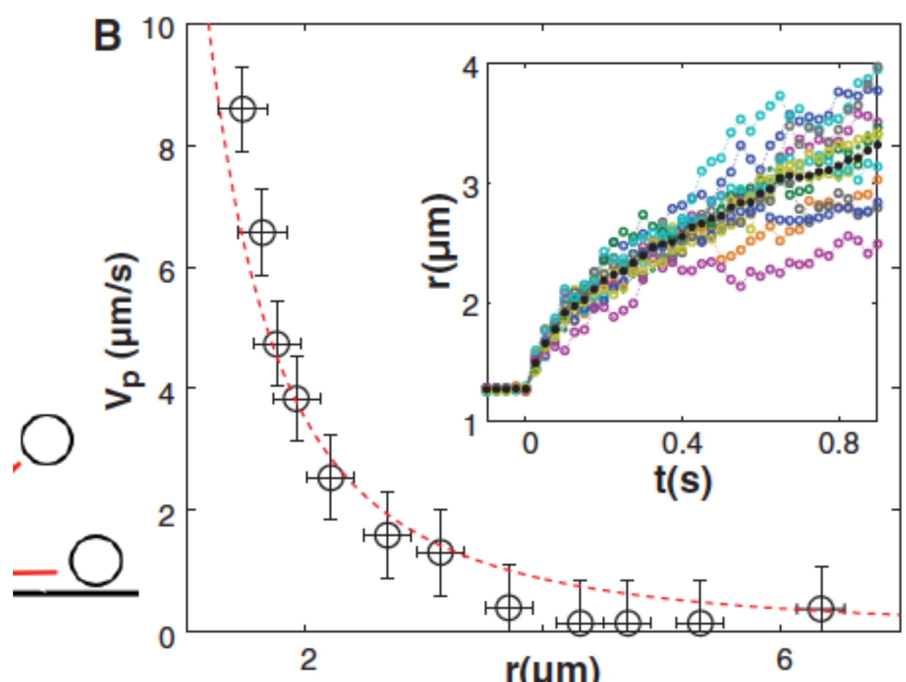


Clustering of active isotropic swimmers

light catalyzes degradation of H_2O_2
-induced chemical gradient
tracer beads swim up along the gradient

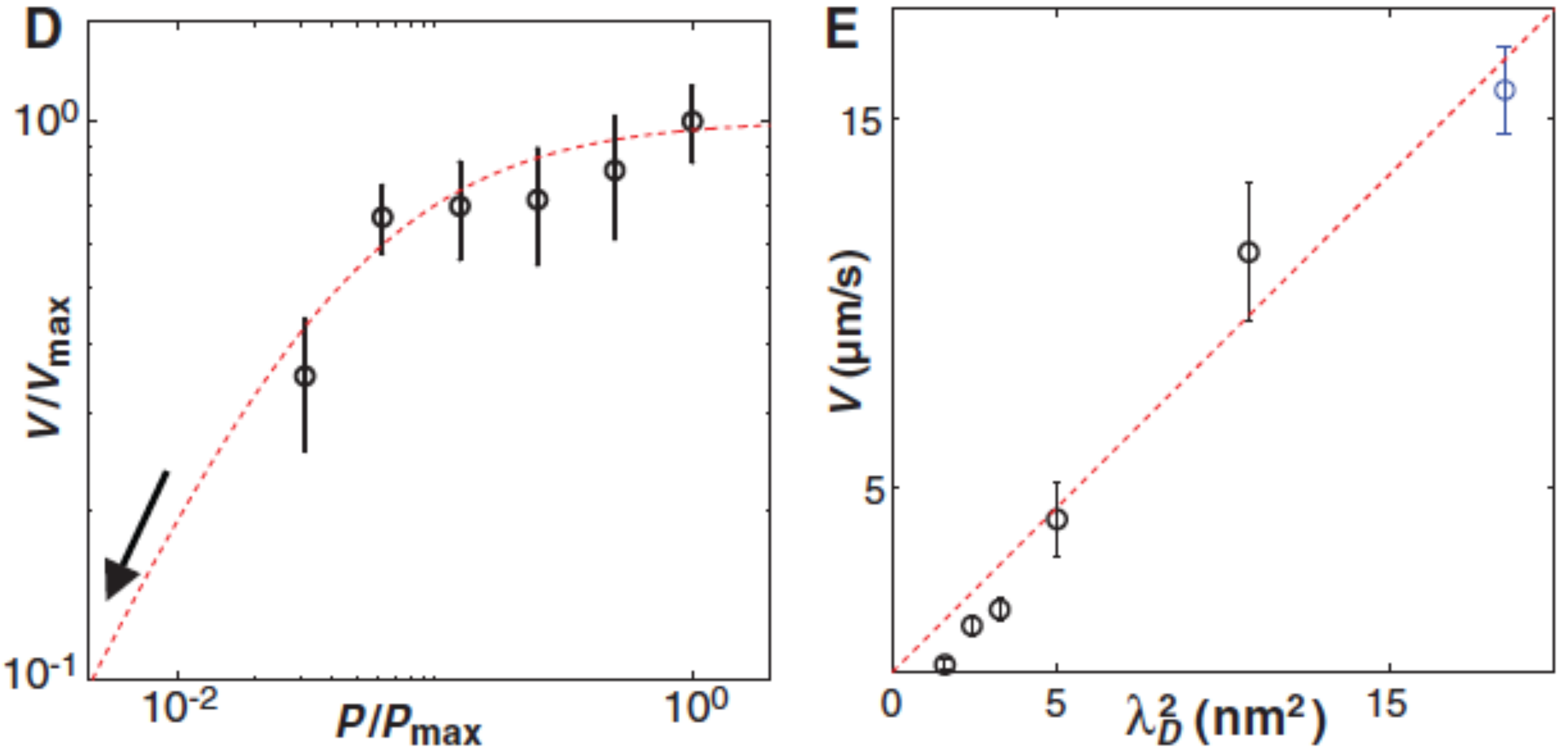






A/r^2 velocity profile is consistent with diffusive concentration gradient

Clustering of active isotropic swimmers

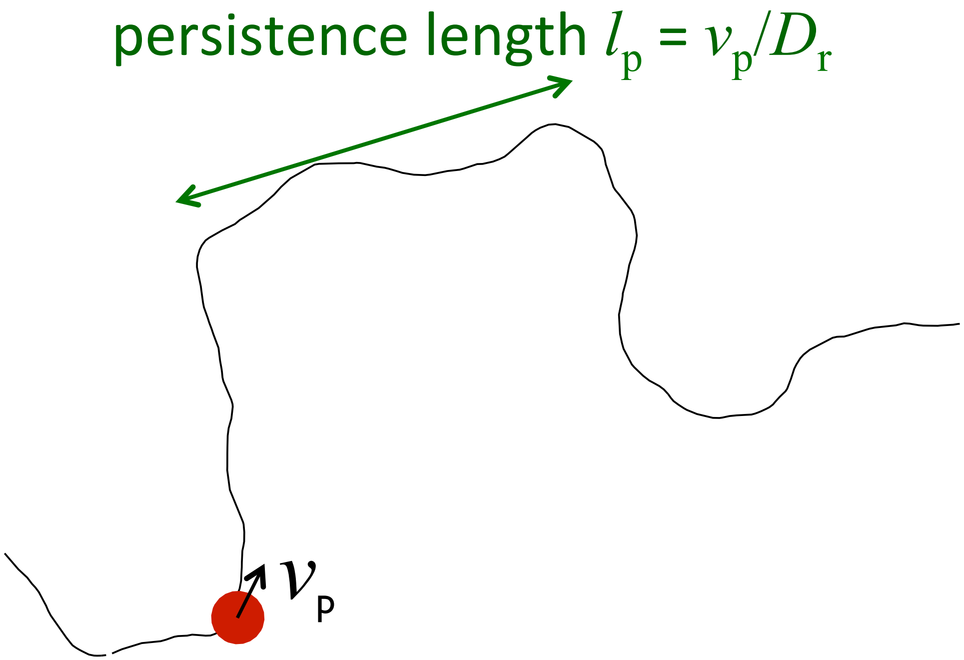


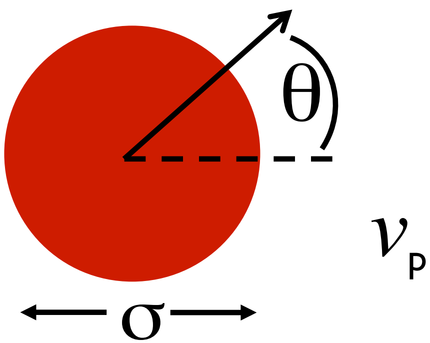
Tunable velocity of motile colloids

What is going on?

Redner, Hagan, and Baskaran PRL (2013)
see also:
Fily and Marchetti, PRL (2012)
Tailleur and Cates, PRL (2008).
A. G. Thompson et al. J Stat Mech (2011).
Bialke, Lowen, Speck, EPL 103, 30008 (2013).
Cates and Tailleur, EPL 101, 20010 (2013).
J. Stenhammar et al. PRL 111, 145702 (2013).
Redner, Baskaran, and MFH, PRE (2013).
T. Speck et al. arXiv:1312.7242(2013)
Fily, Henkes, and Marchetti, Soft Matter (2014).
J. Stenhammar et al. Soft Matter 10, 1489 (2014).
R. Wittkowski et al. arXiv:1311.1256 (2014)

Simulations of Self-Propelled Spheres



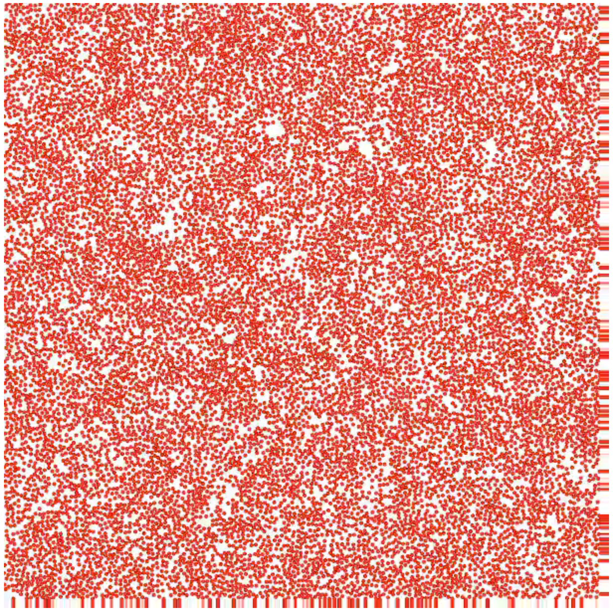


<u>Parameters:</u>

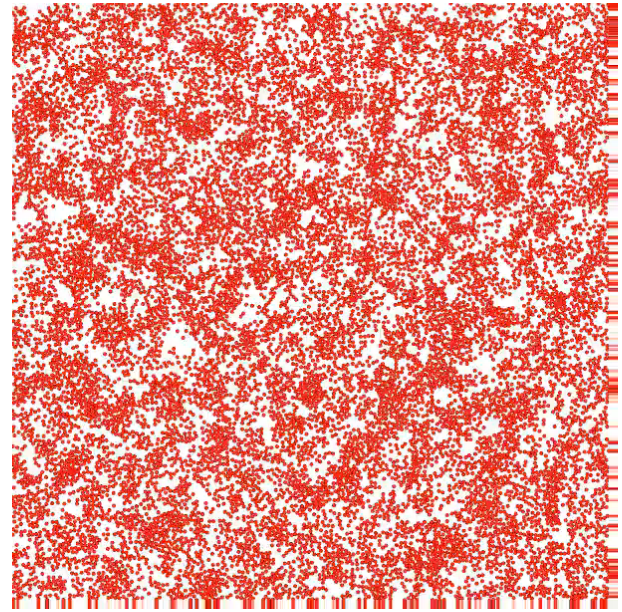
- density (ρ)
- $Pe = v_p\sigma/D \cong l_p/\sigma$

$$Pe=\sigma v_p / D$$

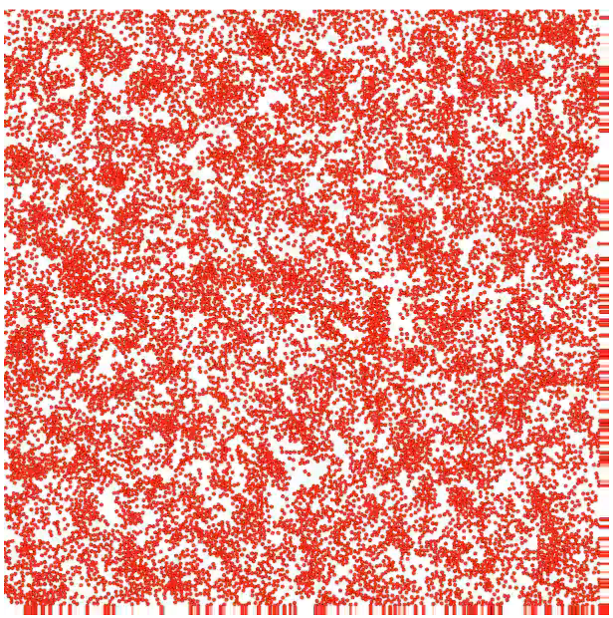
Pe=10



Pe=60



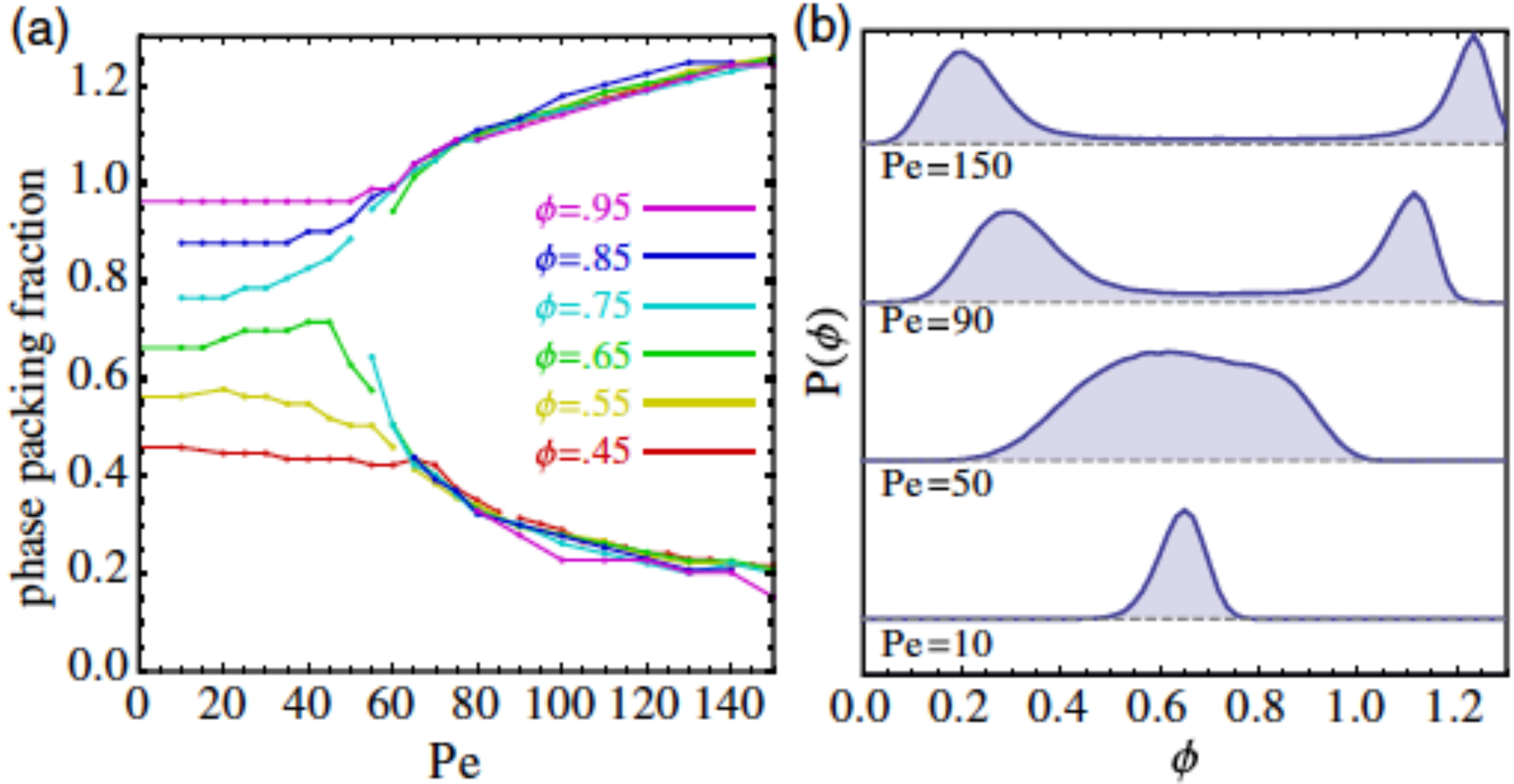
Pe=80



Simulations of Self-Propelled Spheres

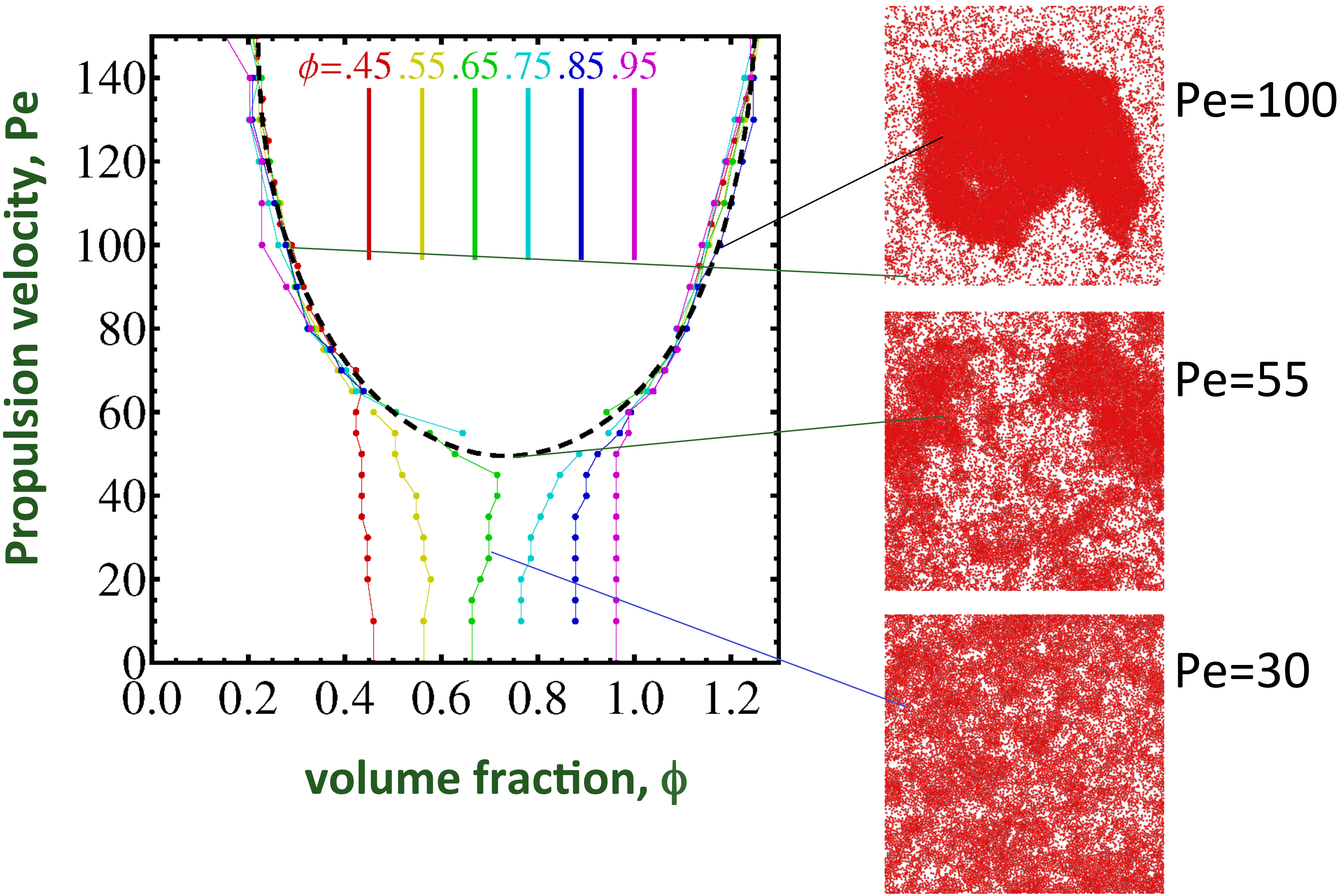
Stop the presentation now – exit powerpoint

Simulations of Self-Propelled Spheres



- phase diagram analogous to equilibrium system of attracting particles undergoing phase separation,
- Pe playing the role of an attraction strength
- increasing activity induced phase separation
- "effective temperature" does not make sense.

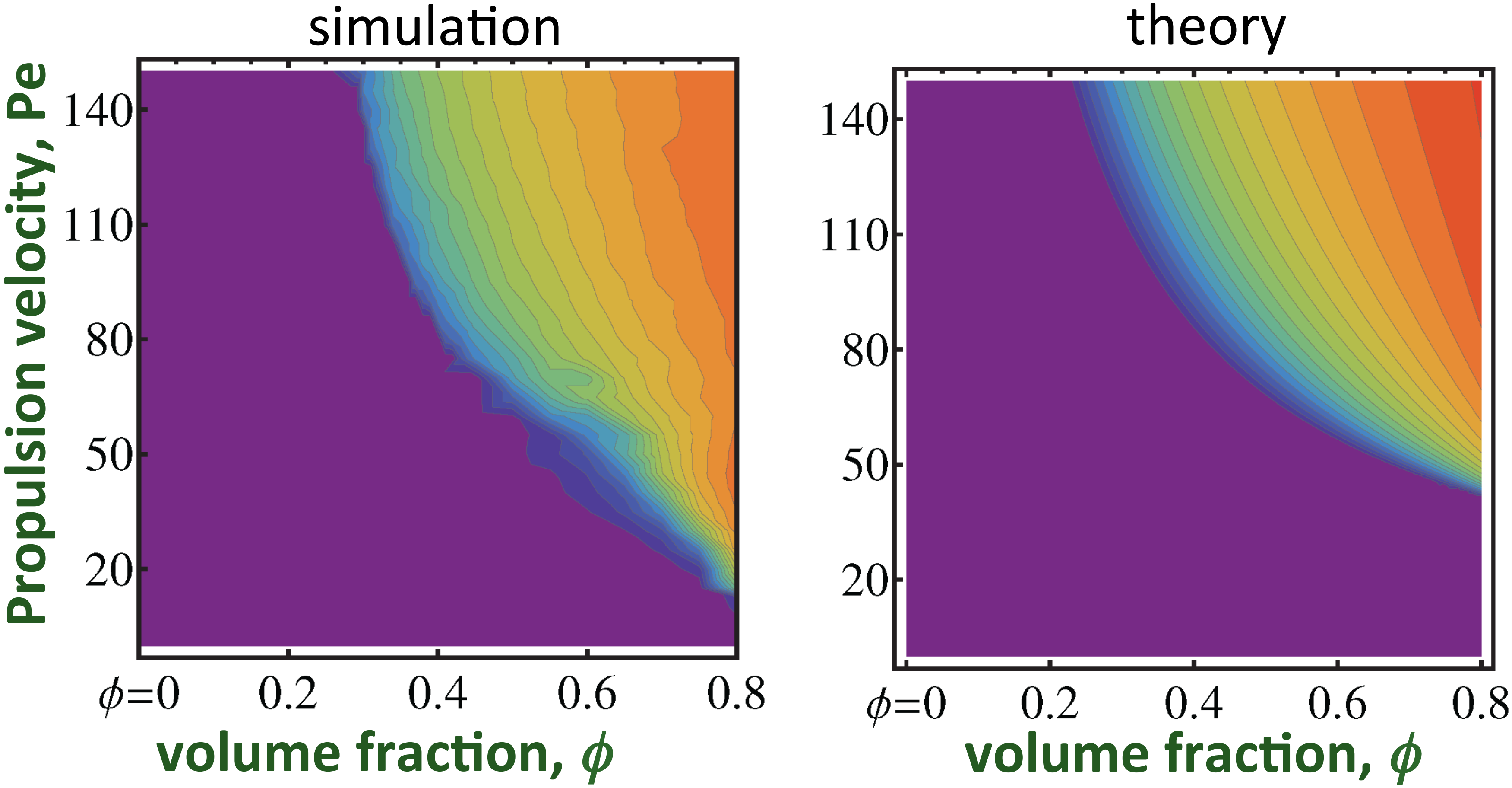
Phase Coexistence



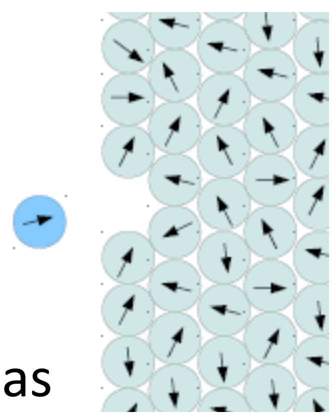
Simulations of Self-Propelled Spheres

Stop the presentation now – exit powerpoint

fraction in clusters

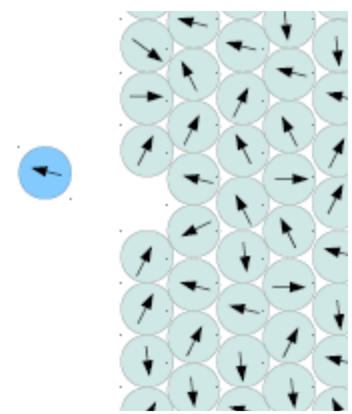


$$k_{\mathrm{on}} = \frac{\rho_{\mathrm{gas}} v_{\mathrm{p}}}{\pi}$$



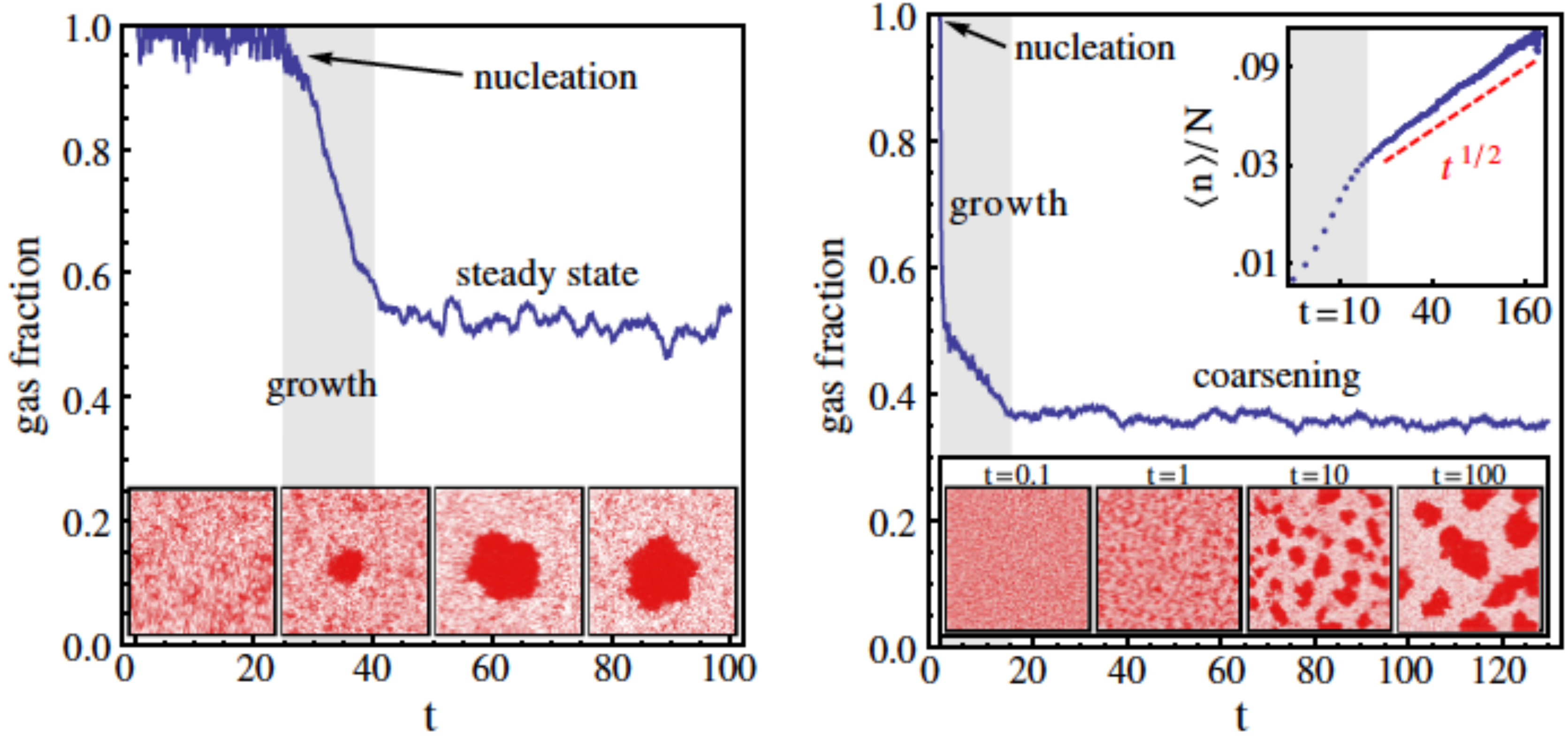
ρ_{gas} = density in gas

$$k_{\mathrm{off}} = \frac{\kappa D_{\mathrm{r}}}{\sigma}$$



κ= fit parameter

Simulations of Self-Propelled Spheres



Nucleation and spinodal decomposition of self-propelled spheres

Outline

1. Isotropic interactions and polar active dynamics

Dynamical clustering and phase separationof purely repulsive particles

2. Polar interaction and polar active dynamics

3. Apolar interaction and nematic active dynamics

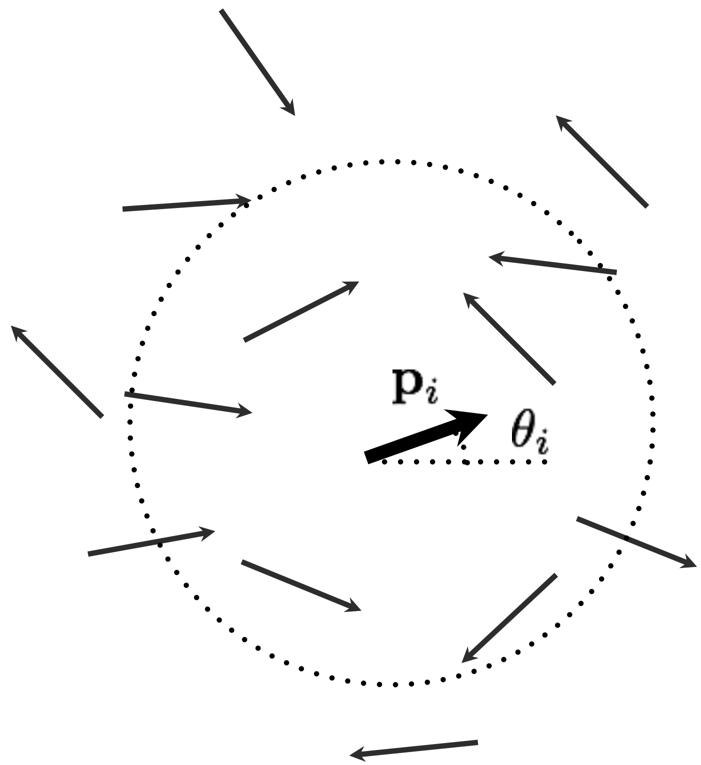
Vicsek model(s): Two ingredients

Self-propelled

$$\mathbf{v}_i = v_0 \mathbf{p}_i$$

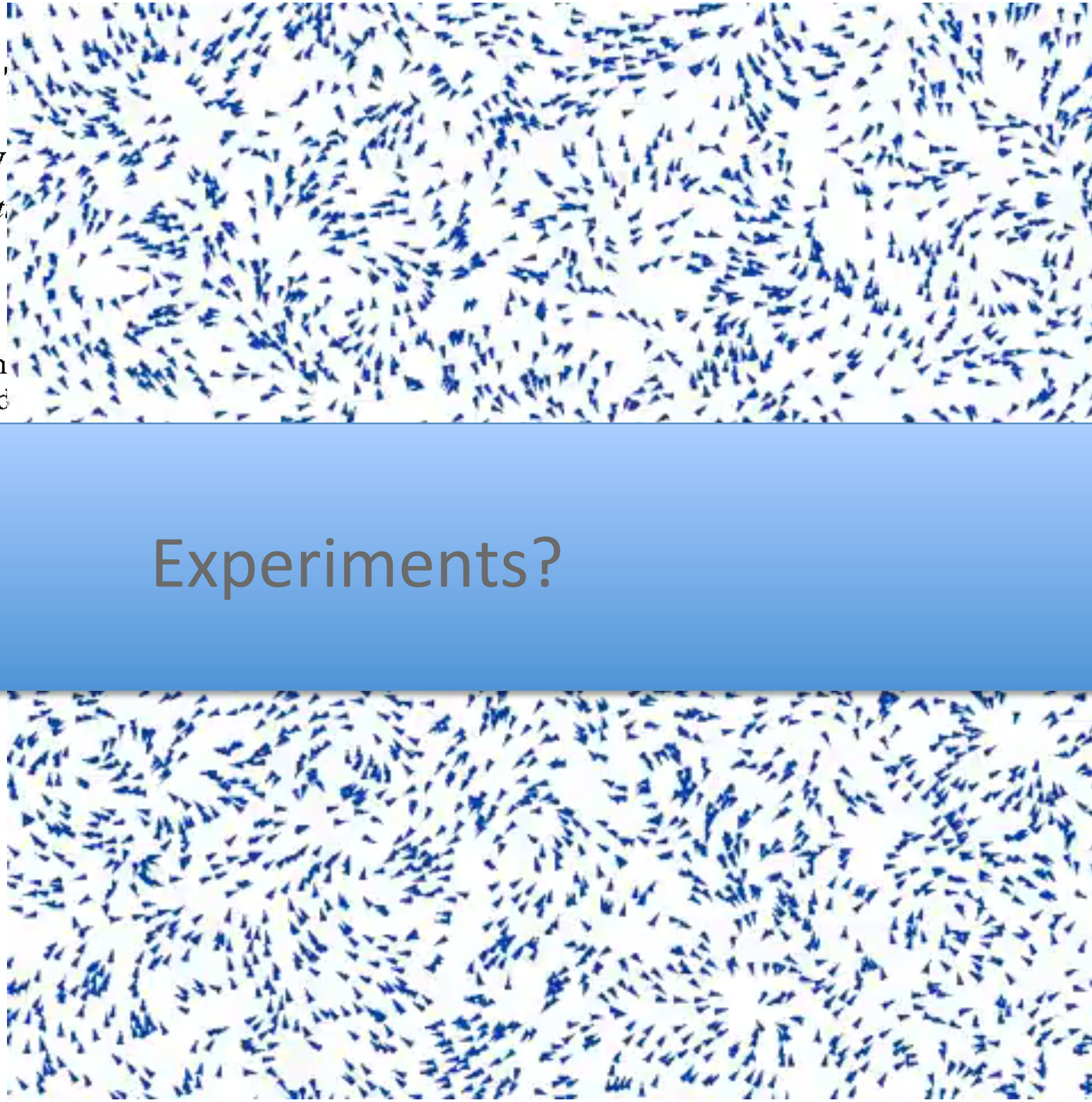
Polar interaction

$$\theta_i(t+1) = \langle \theta_i(t) \rangle_R + \xi_i(t)$$



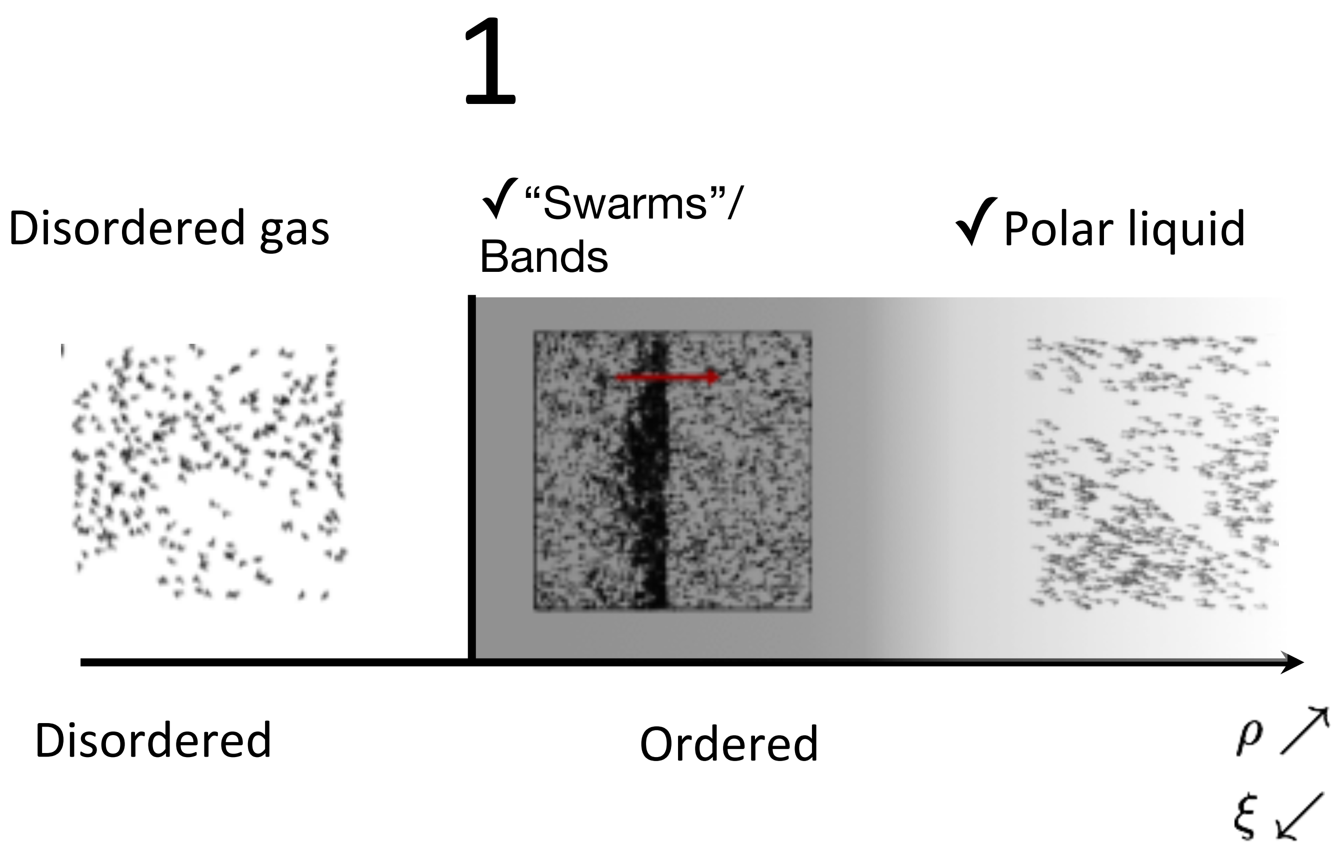
Vicsek et al PRL 95

Vicsek dynamical transition



Experiments?

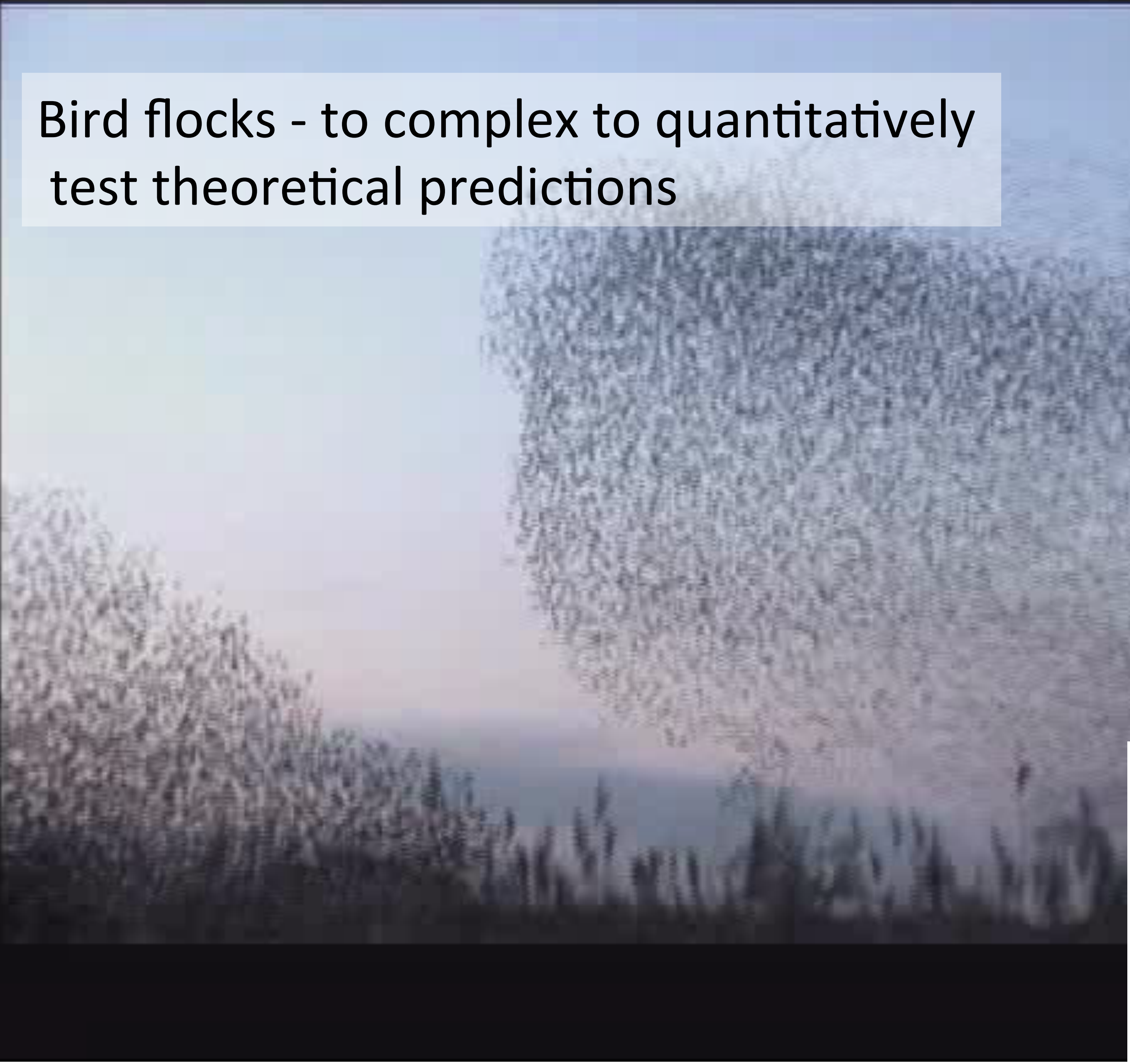
Hallmarks of polar active matter



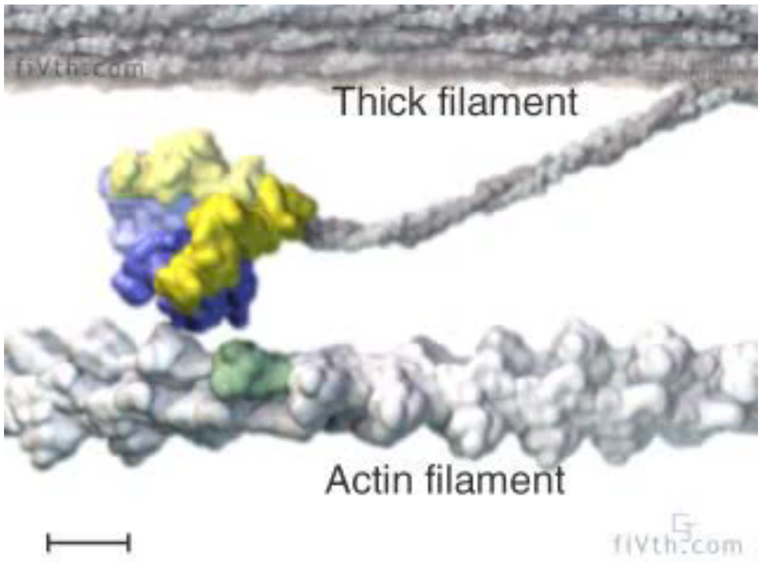
NO ATTRACTION
yet phase separation
at the onset of collective motion

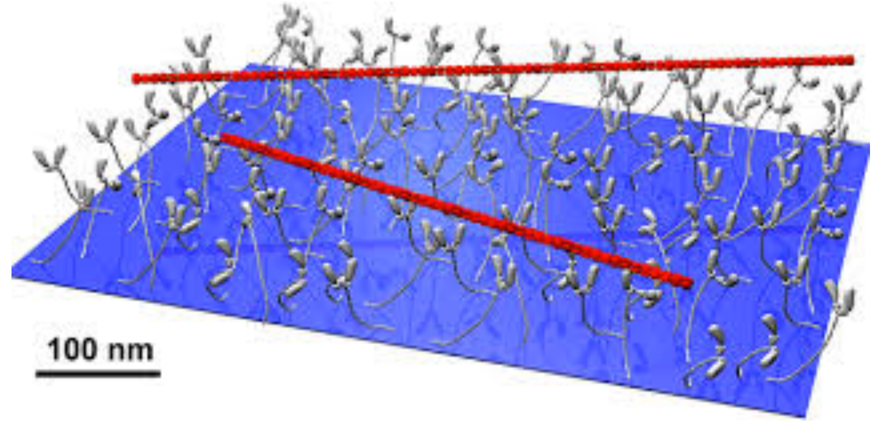
Vicesk 95, Gregoire 04,
Solon 15

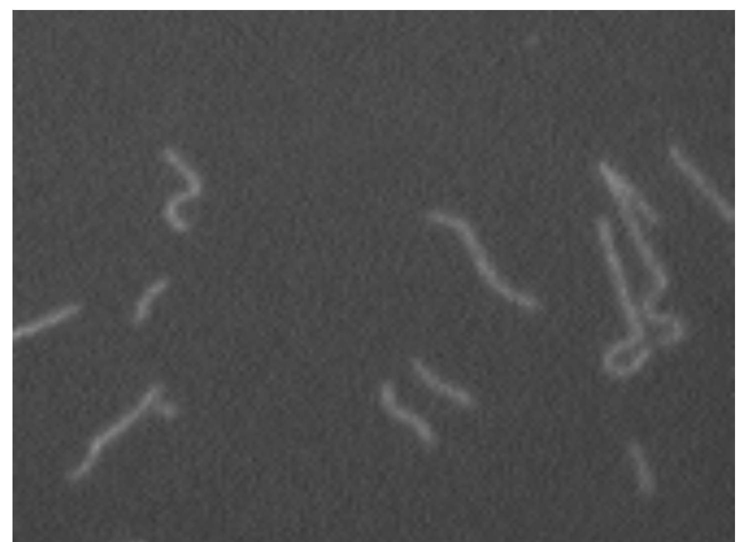
Bird flocks - to complex to quantitatively test theoretical predictions



Actin-myosin motility







Motility assay at intermediate filament densities – spontaneous clustering

cluster movement

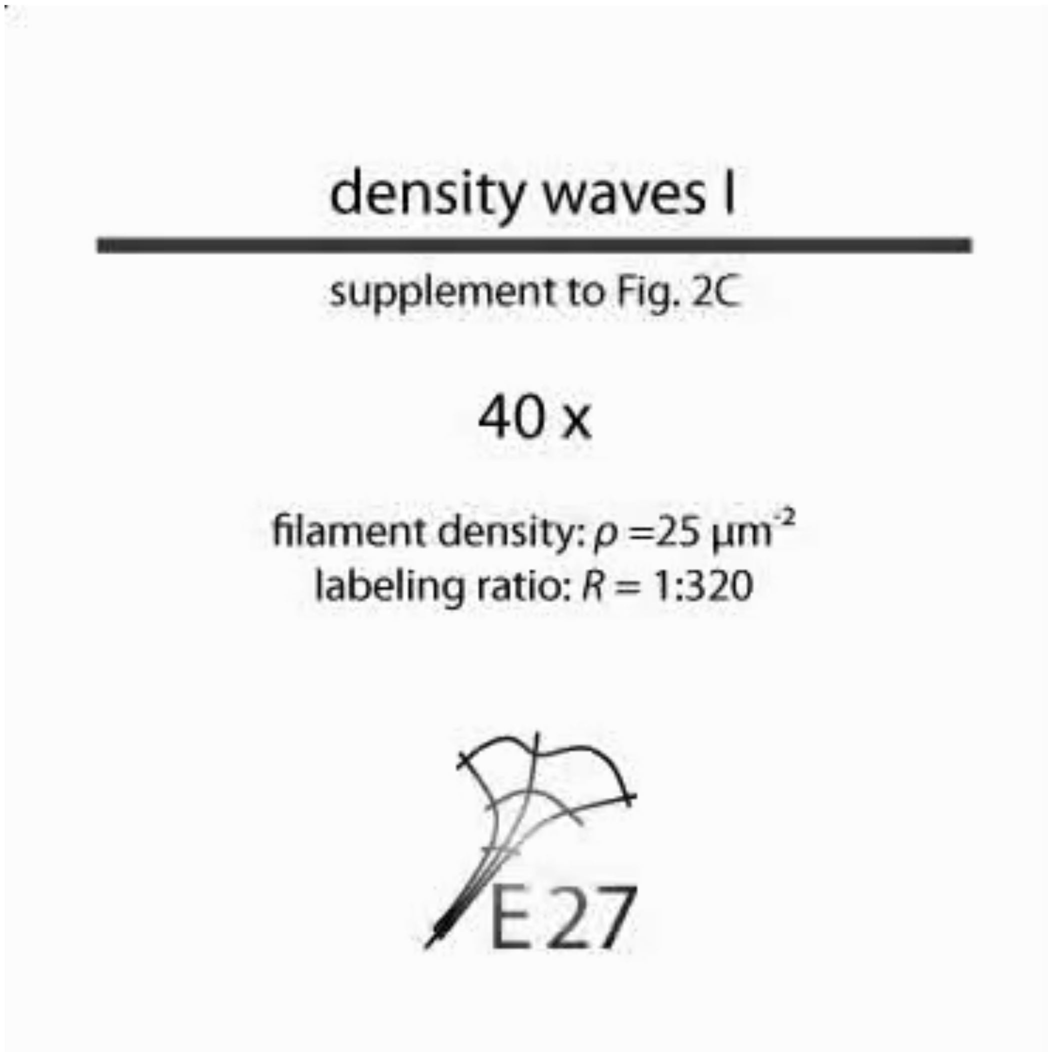
video1 - supplement to Fig. 2A

filament density: $\rho = 5.5\ \mu m^{-2}$
labeling ratio: $R = 1{:}200$

E27

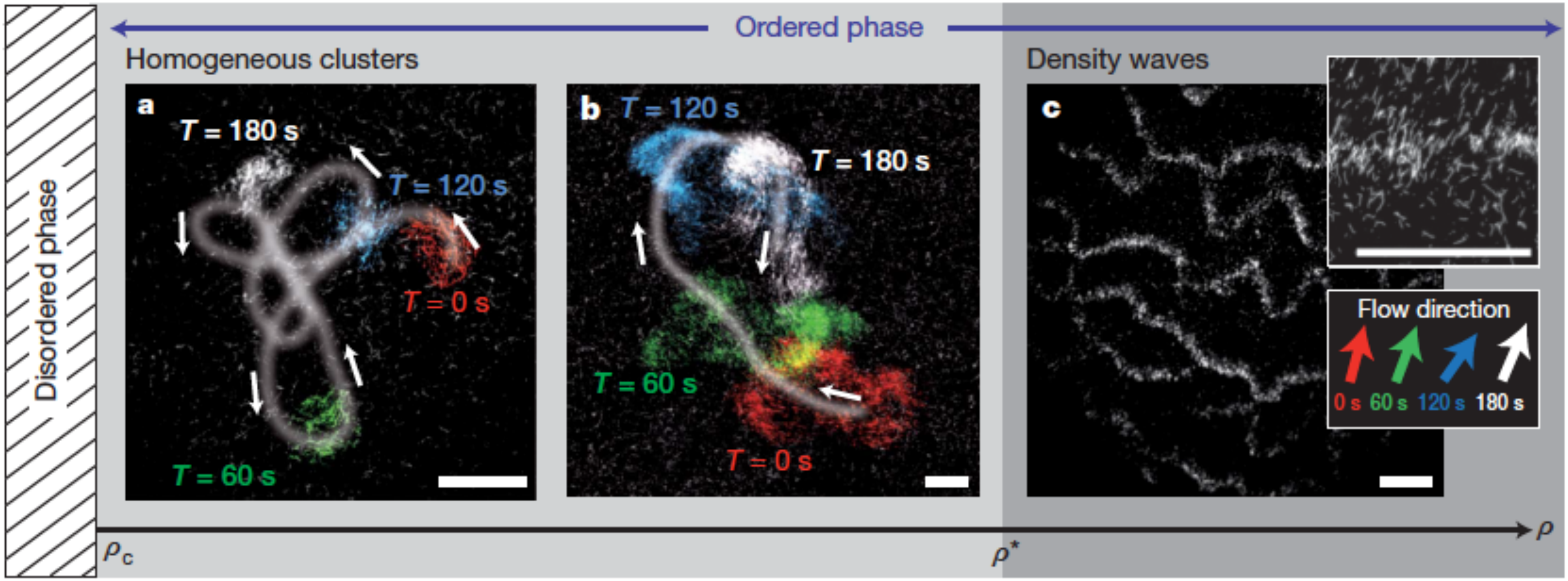
ratio of unlabeled to labeled filaments → 1:200

Motility assay at intermediate filament densities – spontaneous clustering



ratio of unlabeled to labeled filaments → 1:200

Phase diagram of motile 2D actin filaments



polar microscopic dynamics — role of hydrodynamics?

what is the nature of interfilament interactions?

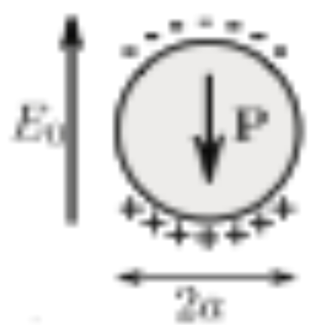
Interactions are very weak – 5% of the collisions results in filament reorientation

Well controlled system – unlike bird flocks

Second example: Synthetic model system of model active polar colloids

Quincke Rotation

G. Quincke, Ann. Phys. Chem. **59**, 417 (1896).



Unstable

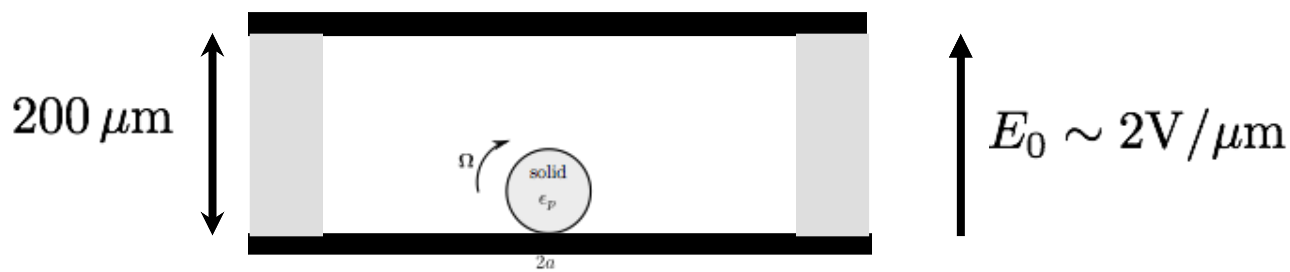
$E > E_{\mathrm{Q}}$

$$\mathbf{\Omega} \sim \mathbf{P} \times \mathbf{E}$$

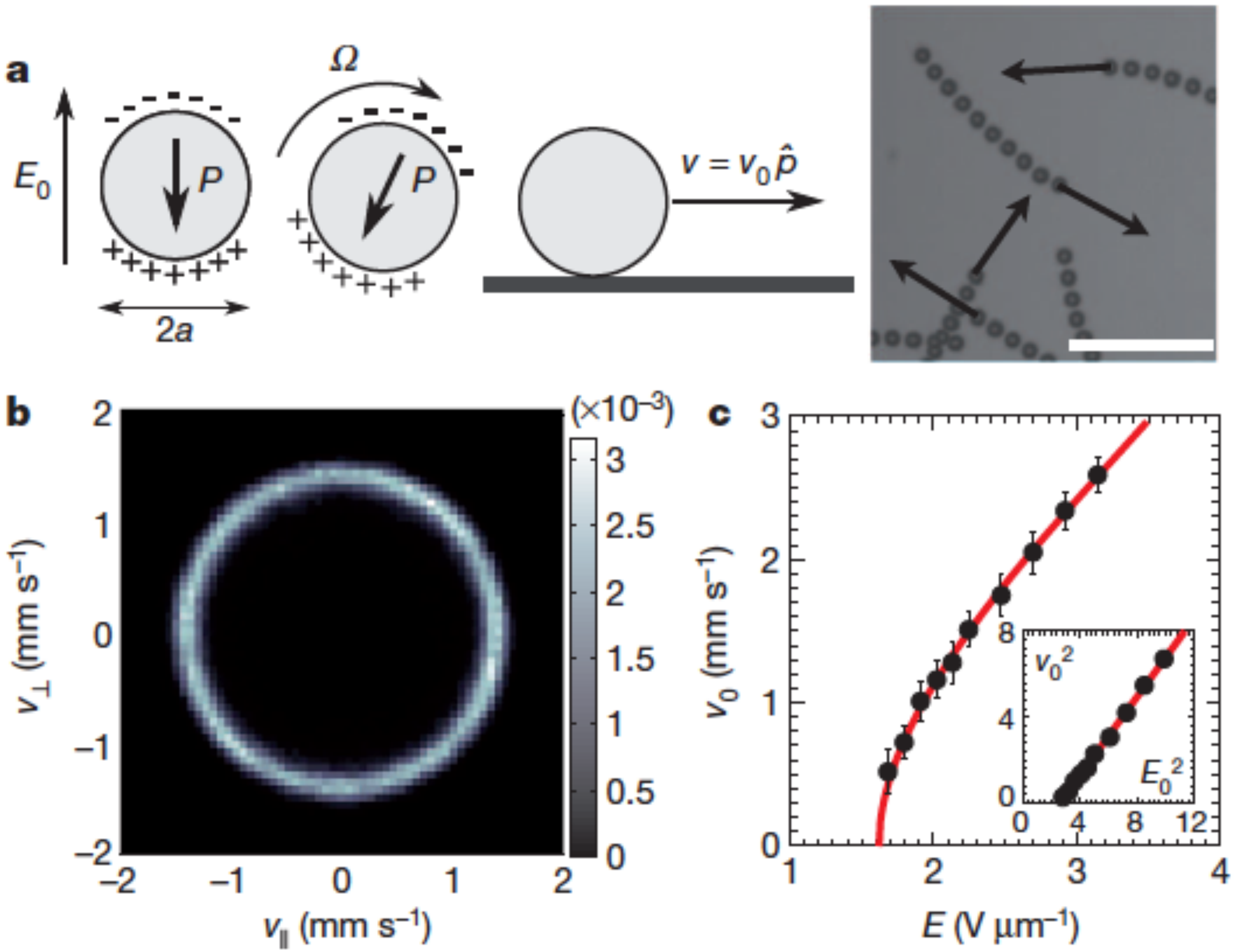
Quincke rollers

PMMA colloids
Hexadecane oil+AOT salt

Microfluidic channel:
ITO coated glass

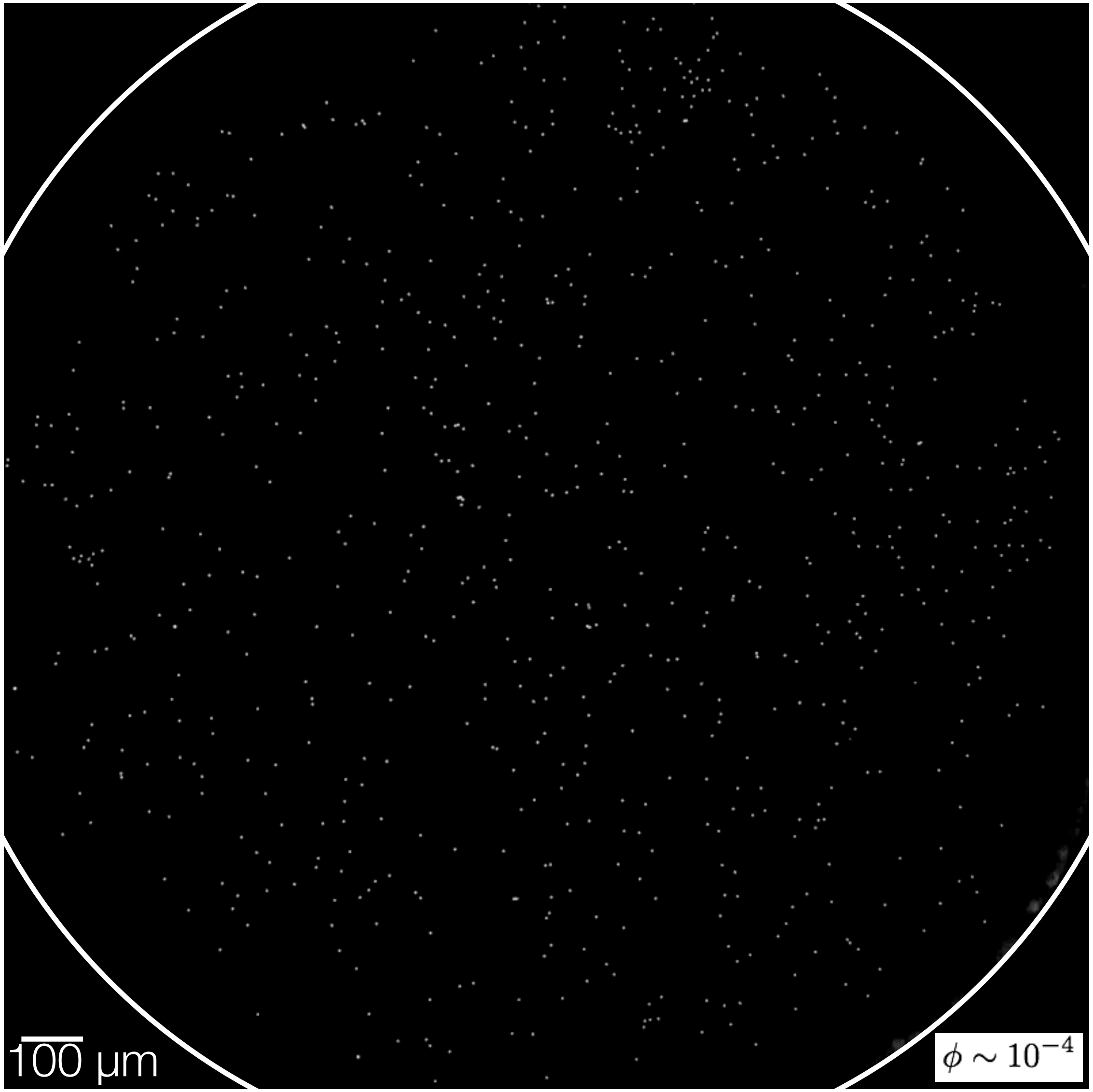


$2a = 5\,\mu\mathrm{m}$

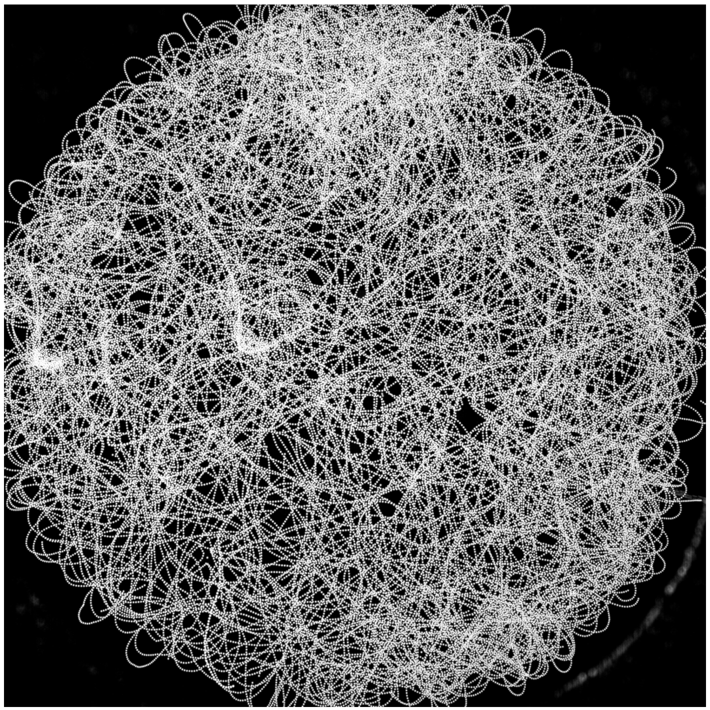


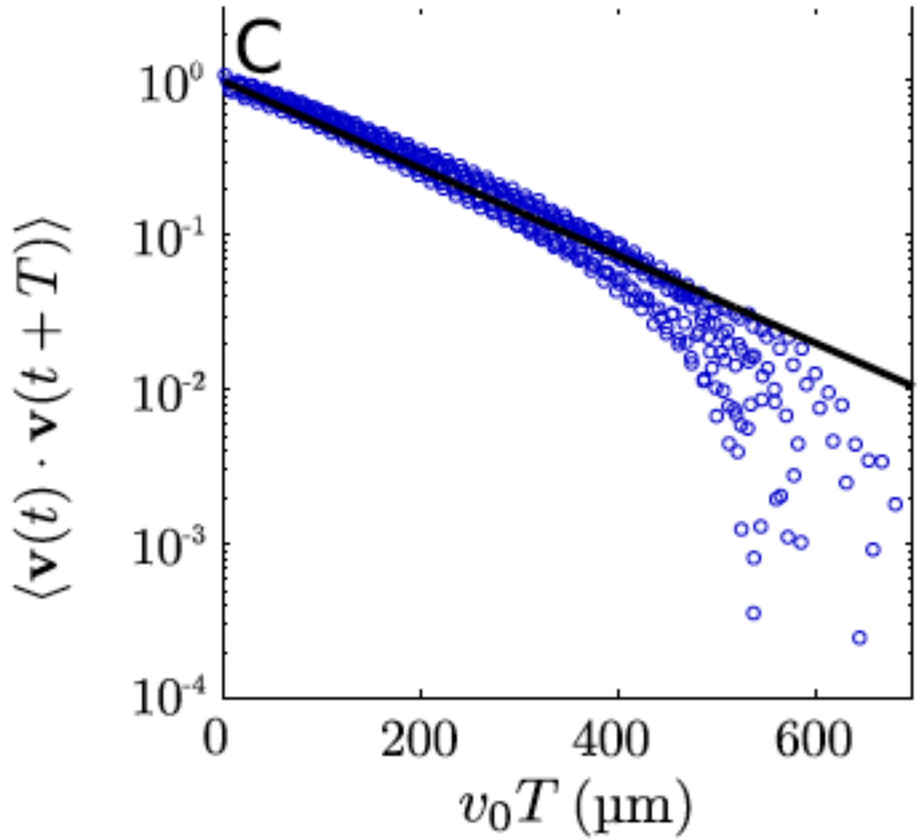
a
Ω
E_0
P
P
2a
$v = v_0\hat{p}$
b
(×10^−3)
$v_\perp$ (mm s^−1)
$v_\parallel$ (mm s^−1)
c
v_0 (mm s^−1)
E (V μm^−1)
v_0^2
E_0^2

Colloidal rolling robots



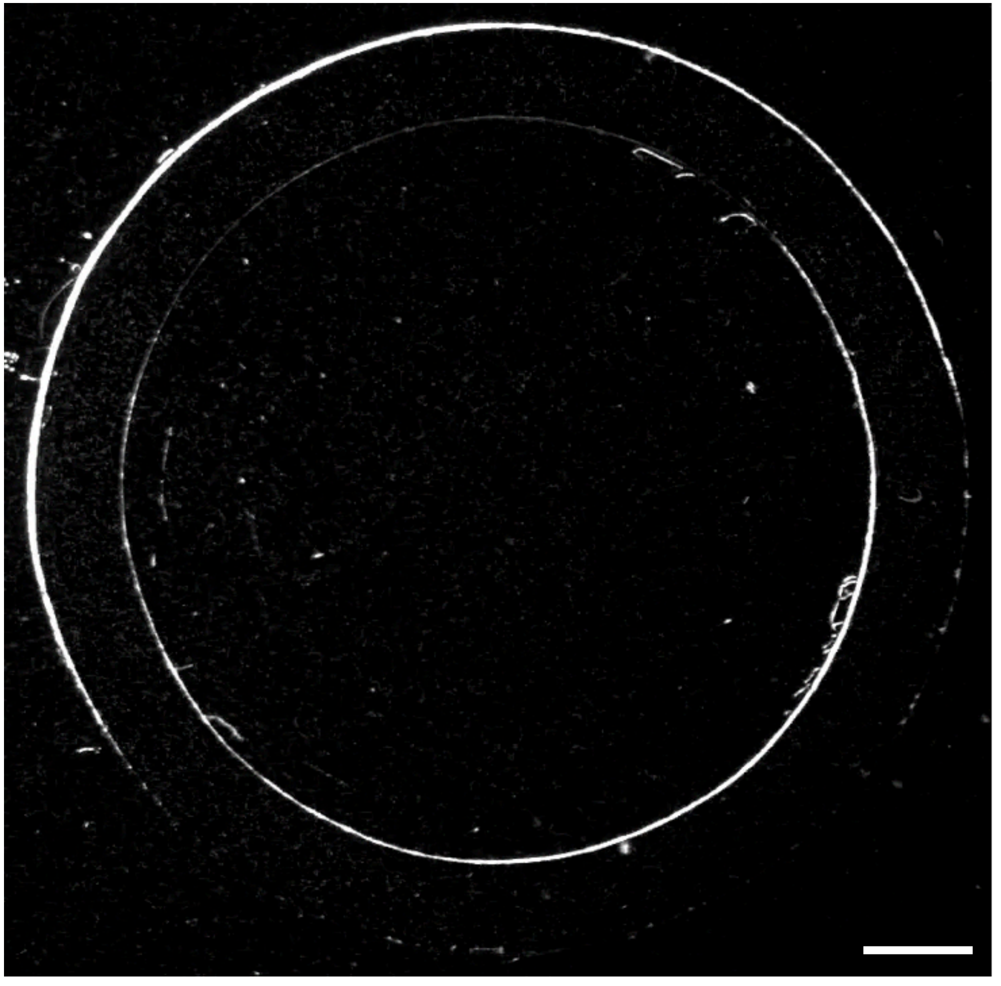
Persistent random walks





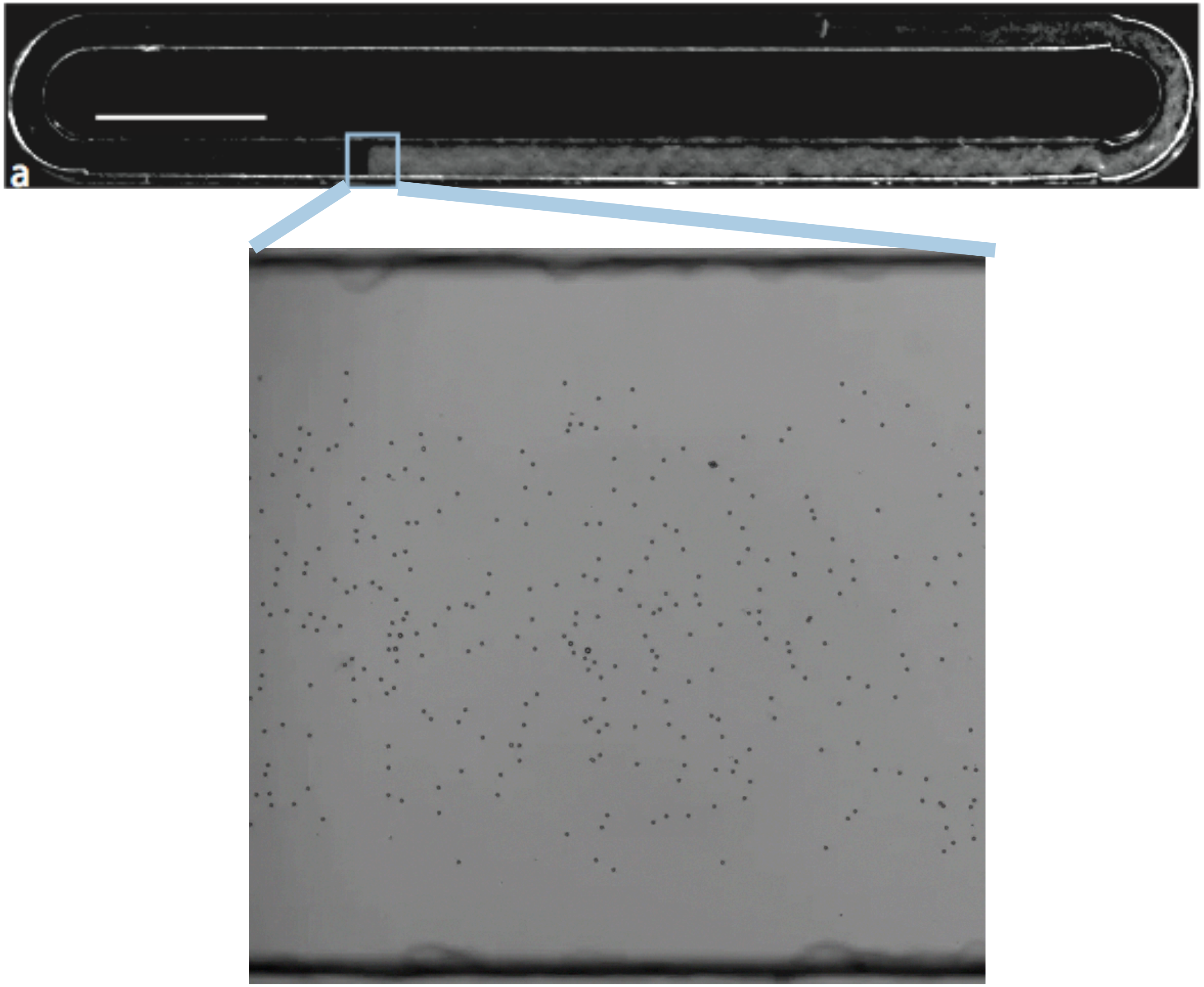
Collective motion?

Periodic boundary conditions



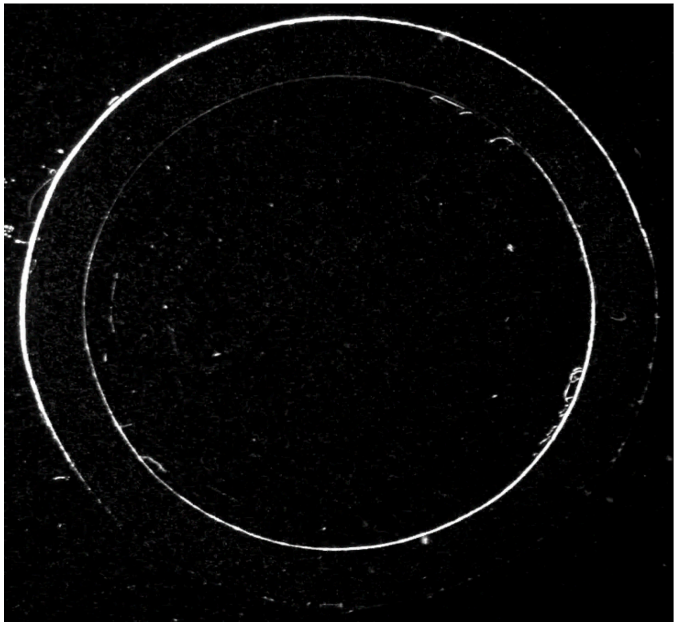
1 mm

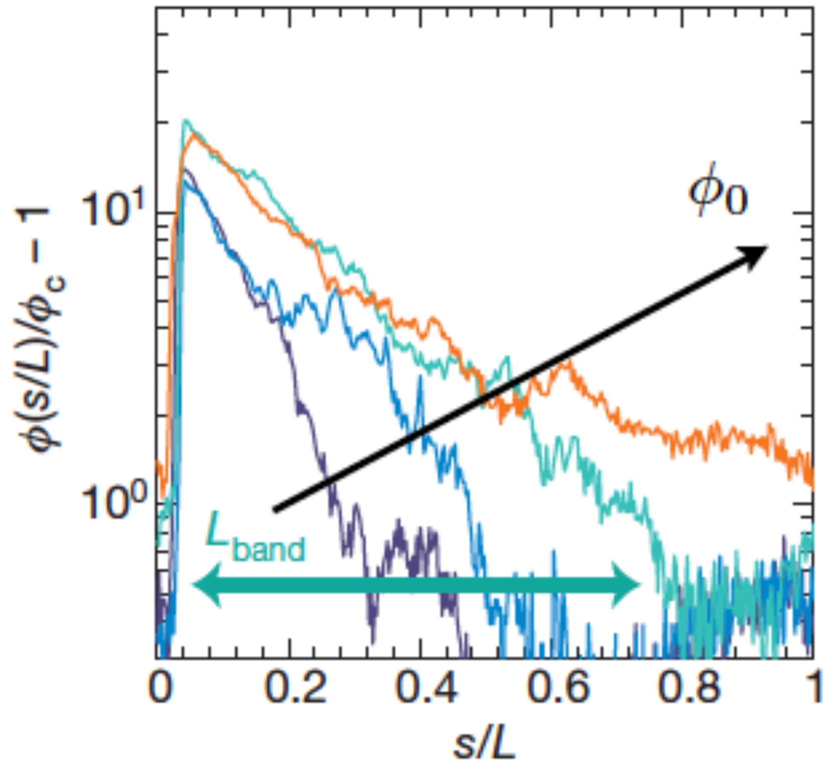
Flocking



$\phi \sim 10^{-2}$

Shape of the colloidal swarms





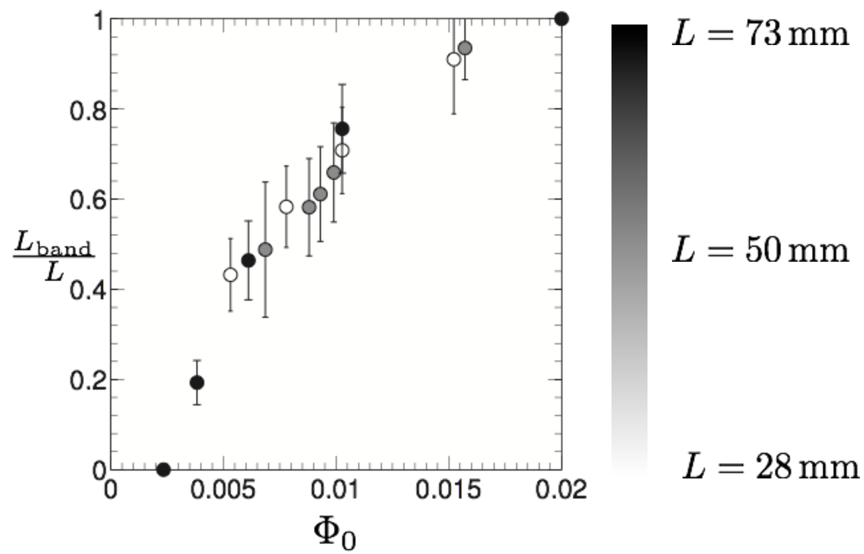
Exponential tail

$\phi_\infty \sim \phi_c$

$L_{\mathrm{band}} \nearrow \quad \phi_0 \nearrow$

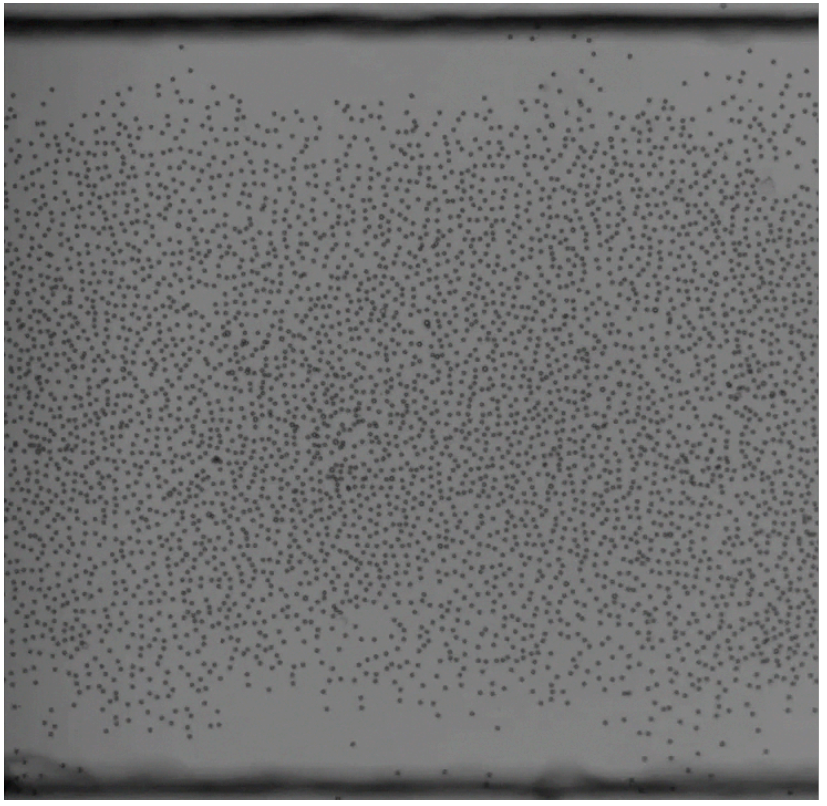
Phase separation at the onset of collective motion

No intrinsic length scale



Consistent with a
phase separation picture

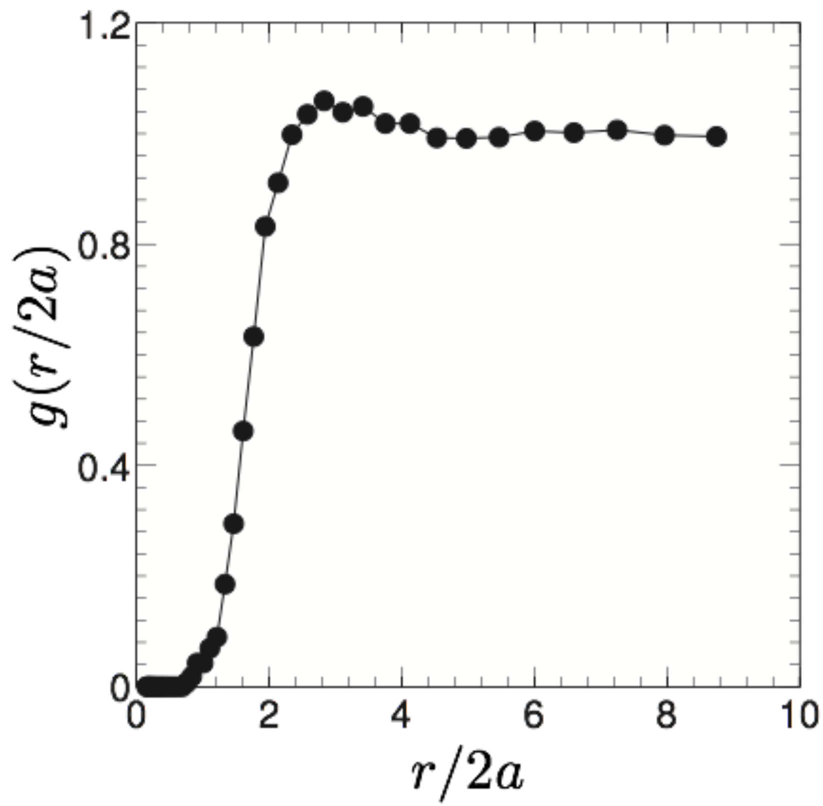
Polar-liquid phase



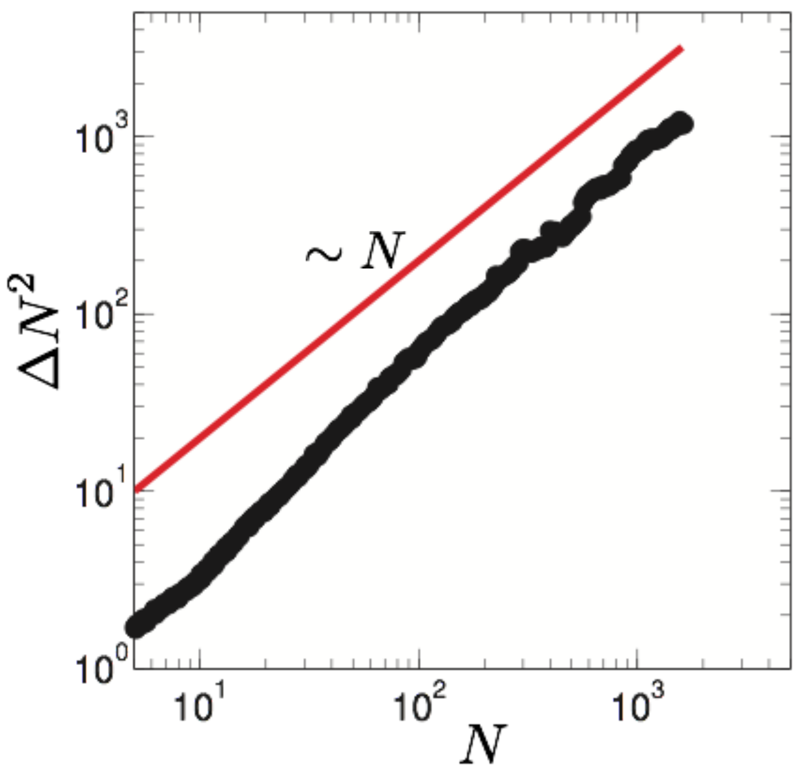
$\phi \sim 1.8 \times 10^{-1}$

Spontaneously flowing liquid

Polar liquid: polar gaz…

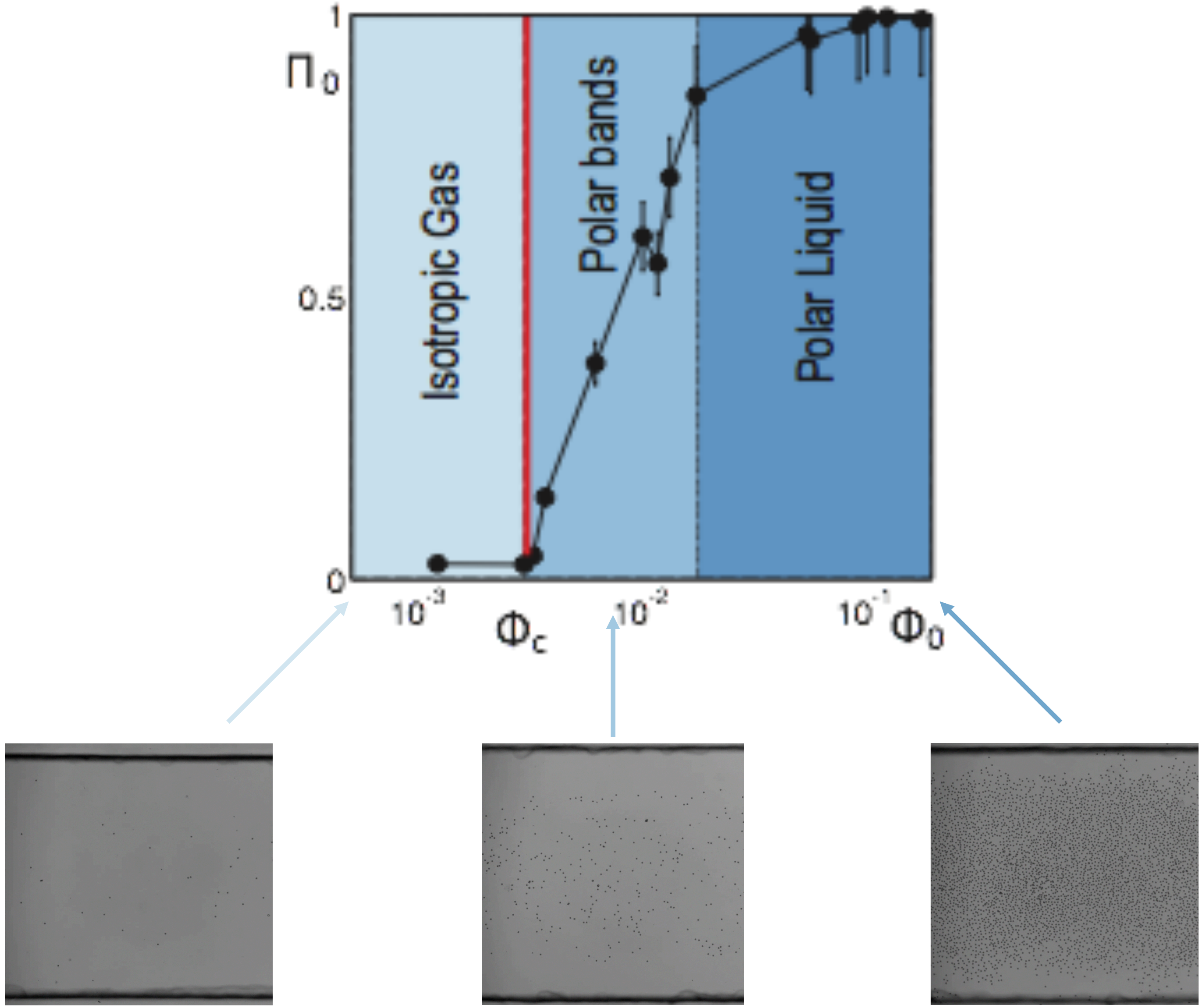


Polar liquid: Normal Number Fluctuations



No Giant-Number Fluctuations

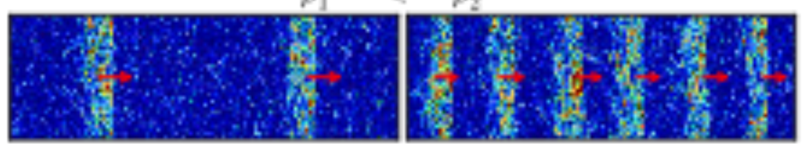
Phase behavior: Vicsek like



Vicsek like?

Not really…

No intrinsic swarm scale/No multiple-band states



Solon et al PRL 15

No giant-density fluctuation

Open questions:
What does set the band shape?
Phase separated?
…

Outline

1. Isotropic interactions and polar active dynamics

dynamical clustering and phase separation of purely repulsive particles

2. Polar interaction and polar active dynamics

3. Apolar interaction and nematic active dynamics

- **complex living organisms (dry)**
- simple shaken granular rods (dry)
- active nematics reconstituted from biochemical components (wet)