Swarming behavior of microtubles driven by dyneins

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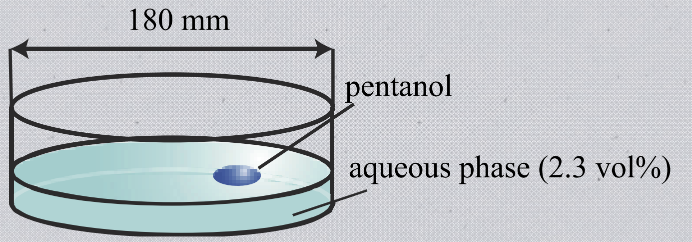
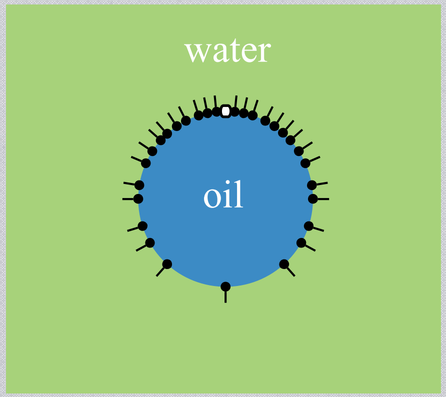
Self-propelled particle





•K. N., et al., *Phys. Rev. E* (2005).

•F. Takabatake, et al., *J. Chem. Phys.*(2009)

•K. H. N., et al. *Phys. Rev. E* (2013).

Main questions

- How to gain momentum without external force
- How to break symmetry
- Collective phenomena of active matters

Swarming behavior of active particles

T. Vicsek, *Phys. Rep.* (2012).

Swarming behavior through a short range interaction

$$x_i^{j+1} = x_i^j + (\mathbf{e}_x \cos\theta_i^j + \mathbf{e}_y \sin\theta_i^j)\Delta t$$
$$\theta_i^{j+1} = < \theta_k^j > + \xi_i$$

There is only short-range interaction about the direction of motion.

Univesal Characteristcs!

Nonequilibrium phase transition

Giant Fluctuation

•T. Vicsek, et al., *Phys. Rev. Lett.* (1995).

•G. Grégoire and H. Chaté, *Phys. Rev. Lett.* (2004).

Experimental evidence

J. Deseigne, et al., 2010.

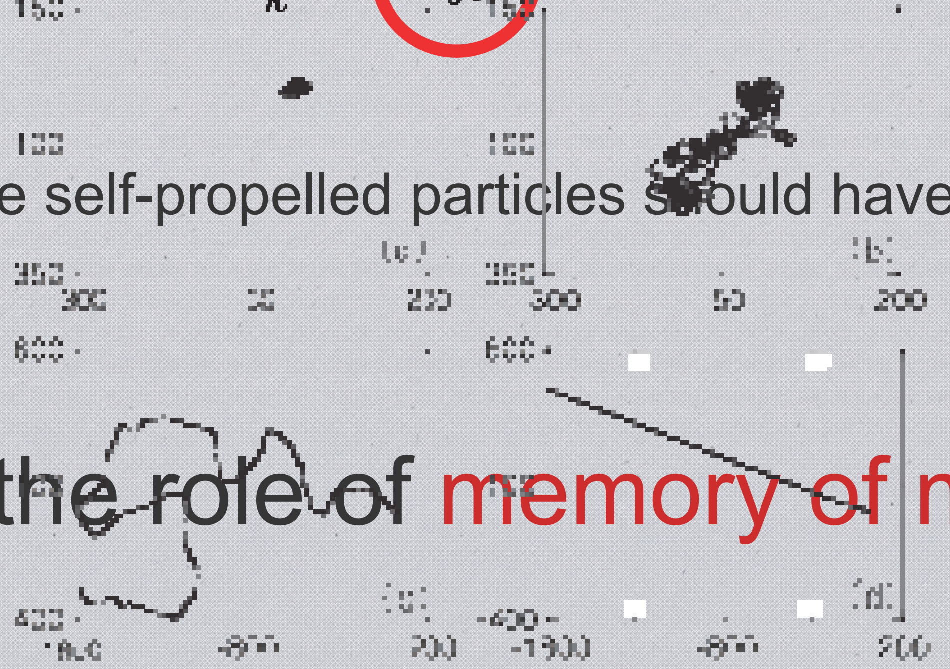
V. Schaller, A.Bausch, 2010.

Vicsek model does NOT have memory

$$x_i^{j+1} = x_i^j + (\mathbf{e}_x \cos\theta_i^j + \mathbf{e}_y \sin\theta_i^j)\Delta t$$

$$\theta_i^{j+1} = <\theta_k^j> + \xi_i$$

No memory (correlation)



Deformable self-propelled particles should have memory.

- What is the role of memory of motion?

T. Ohta, T. Ohkuma, *Phys. Rev. Lett.* (2009).

A. B. Verkhovsky, et al., *Curr. Biol.* (1999).

Mathematical model

$$\dot{\boldsymbol{x}}_i = v_0(\boldsymbol{e}_x \cos\theta_i + \boldsymbol{e}_y \sin\theta_i)$$

$$\dot{\theta}_i = \omega_i + \frac{\alpha}{n_i(t)} \sum_{|\boldsymbol{x}_i - \boldsymbol{x}_j| < l} \sin 2(\theta_j - \theta_i)$$

parallel alignment or anti-parallel alignment (short-range nematic interaction)

$$\dot{\omega}_i = -\frac{1}{\tau}(\omega_i - \omega_0) + \xi_i(t)$$

ω has a finite correlation time, τ.

$$\langle \xi(t) \rangle = 0, \langle \xi(t)\xi(t') \rangle = \sigma^2 \delta(t - t') \qquad \langle \omega^2 \rangle = \sigma^2 \tau / 2$$

v_0=8.75 μm/s, ω_0=-0.00624 rad/s, l=15.0 μm, α=0.0583 rad/s,
$\langle\omega^2\rangle$=2.48 × 10^{-4} rad^2/s^2

Order parameter

1. Nematic order parameter

$$S = \langle \exp 2i\theta_i \rangle$$

If all particles align parallel or anti-parallel (nematic order), S=1.

If there is no global nematic order, S=0.

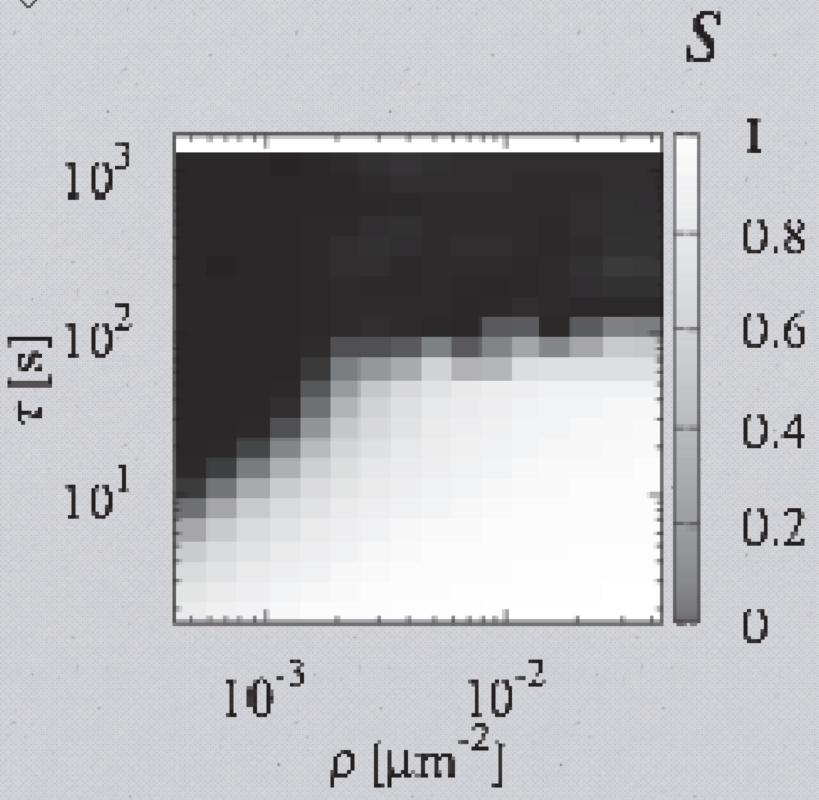
2. Density fluctuation

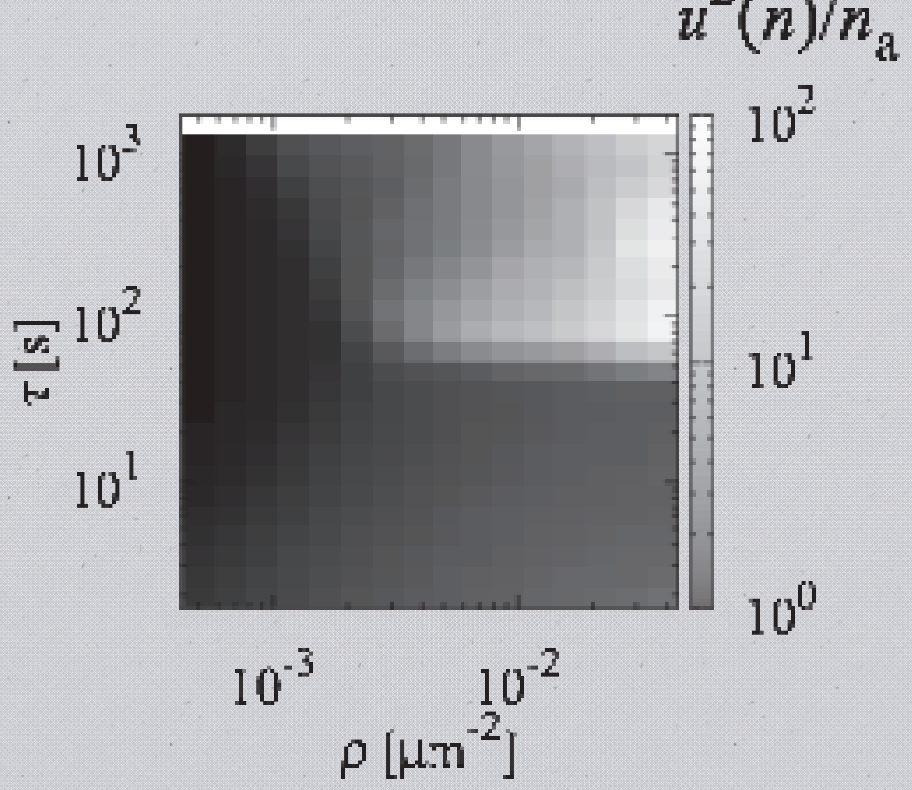
$$u^2(n)/n_{\mathrm{a}}$$

u^2 is the variance of density in a 60 μm^2 × 60 μm^2 region. n_{a} is the average number of particles in the same region.

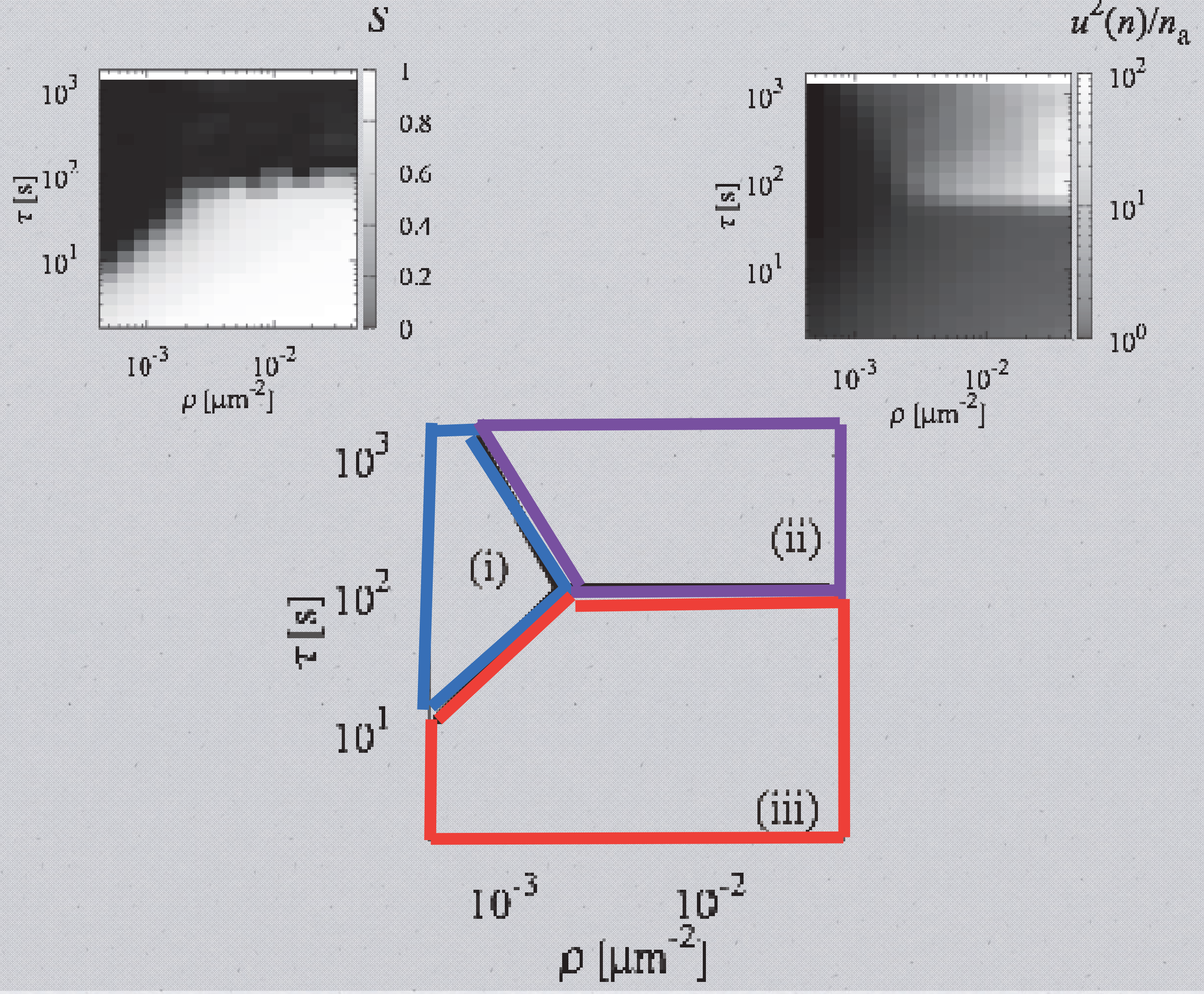
If the density is not uniform, this value is large.

Phase diagram

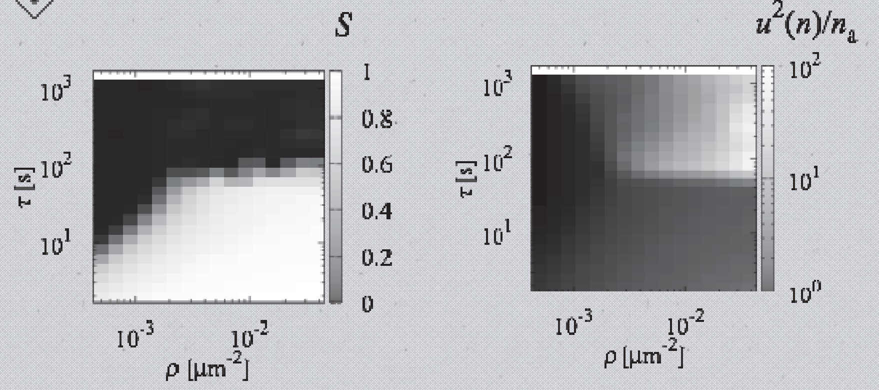




Phase diagram

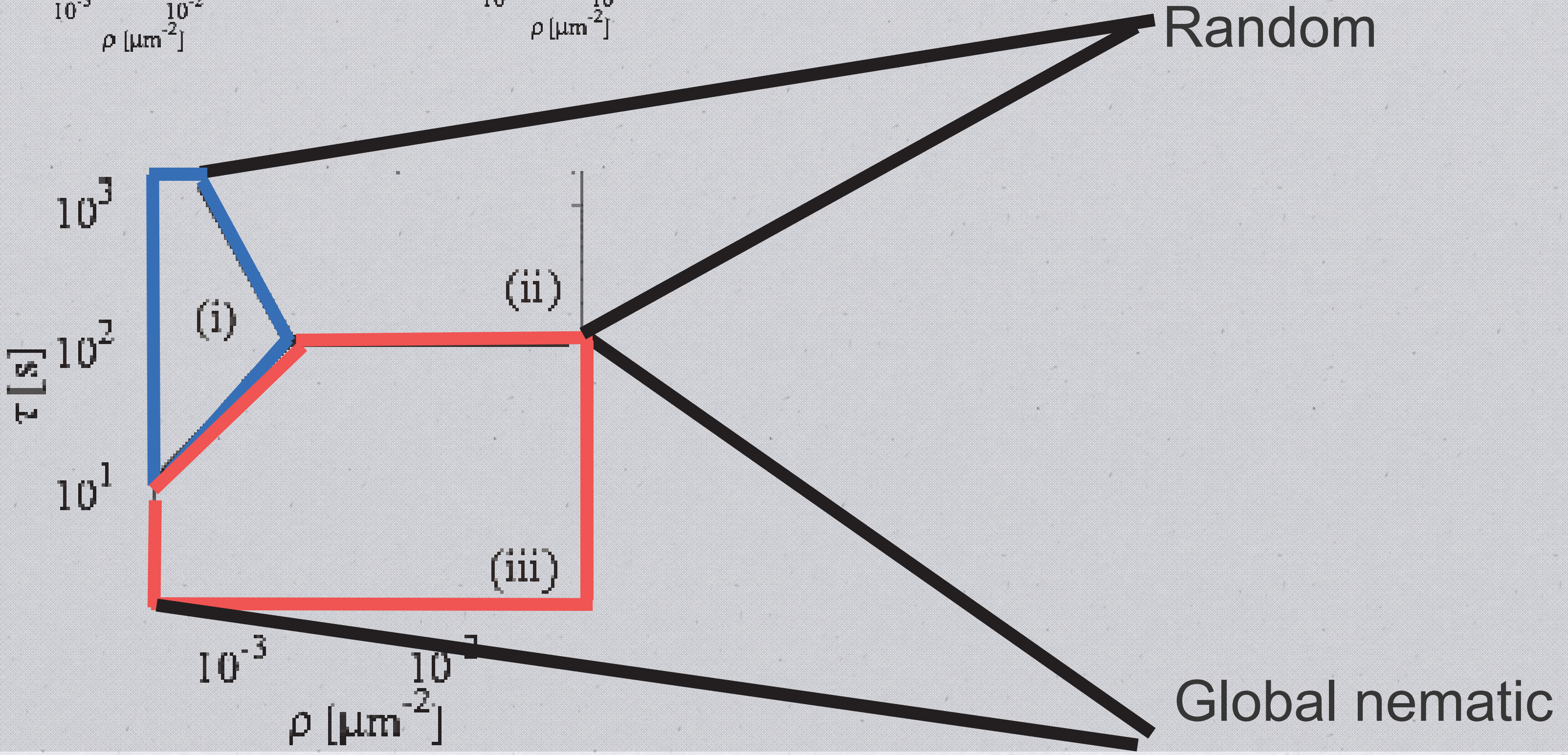


Phase diagram

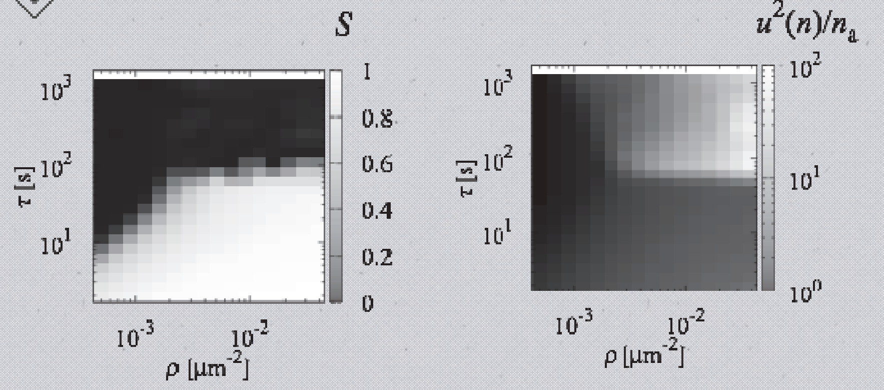


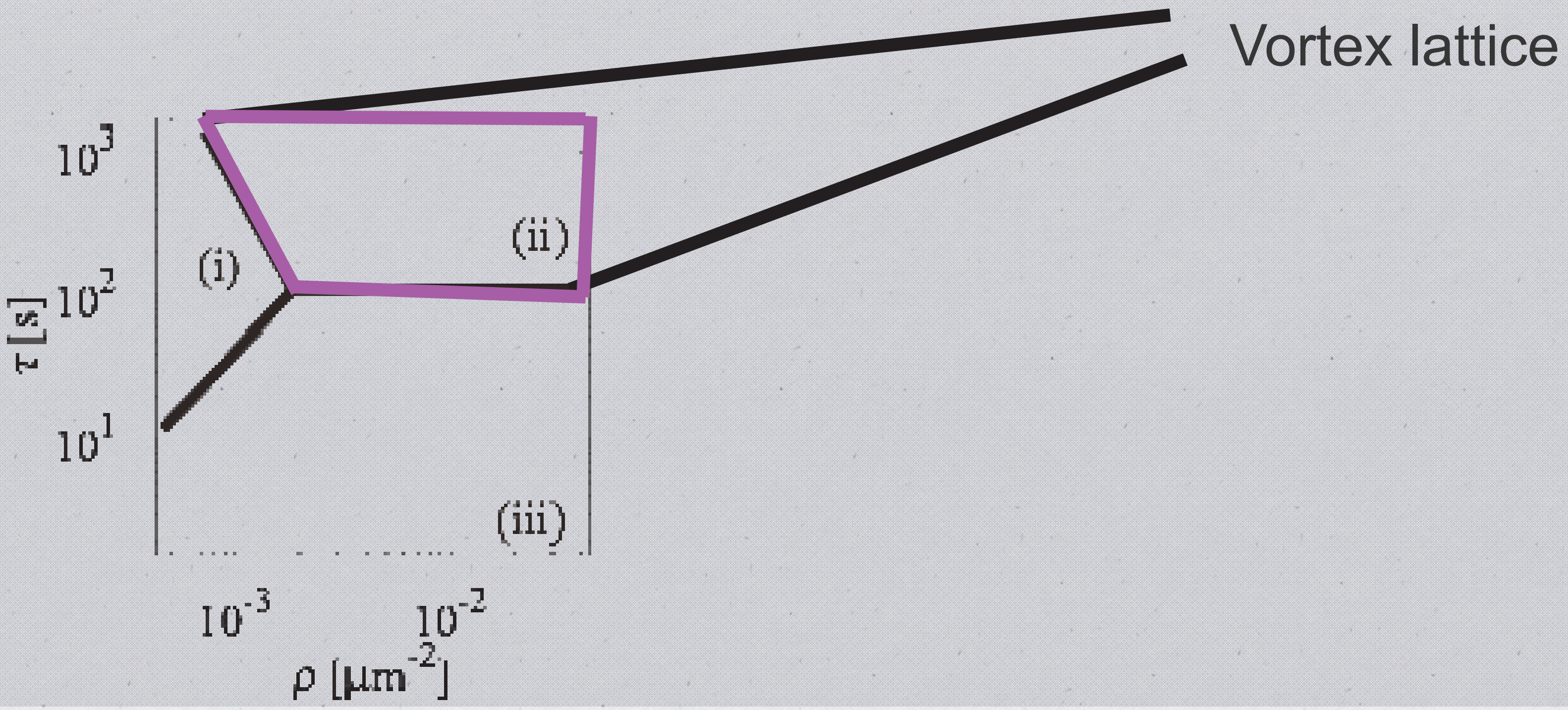
F. Ginelli, et al, 2010.

Same!



Phase diagram





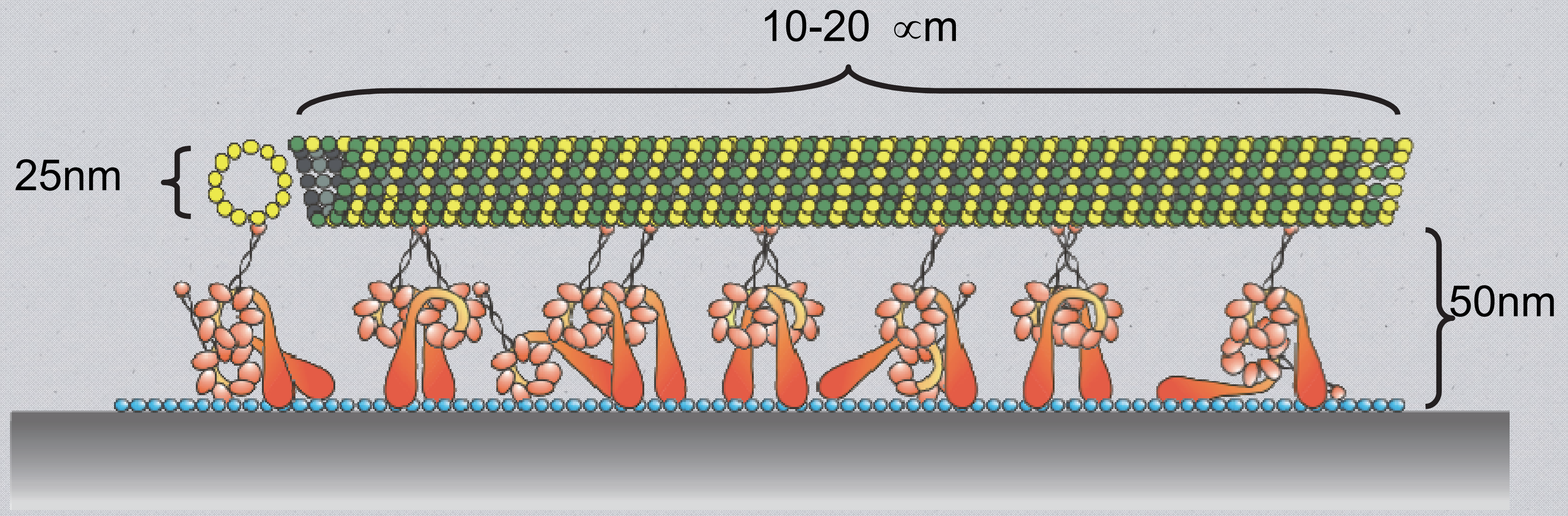
Microtubule

- No polymerization and depolymerization (stabilized with taxol)
- Microtubules were labeled with Cy3.

Dynein-c

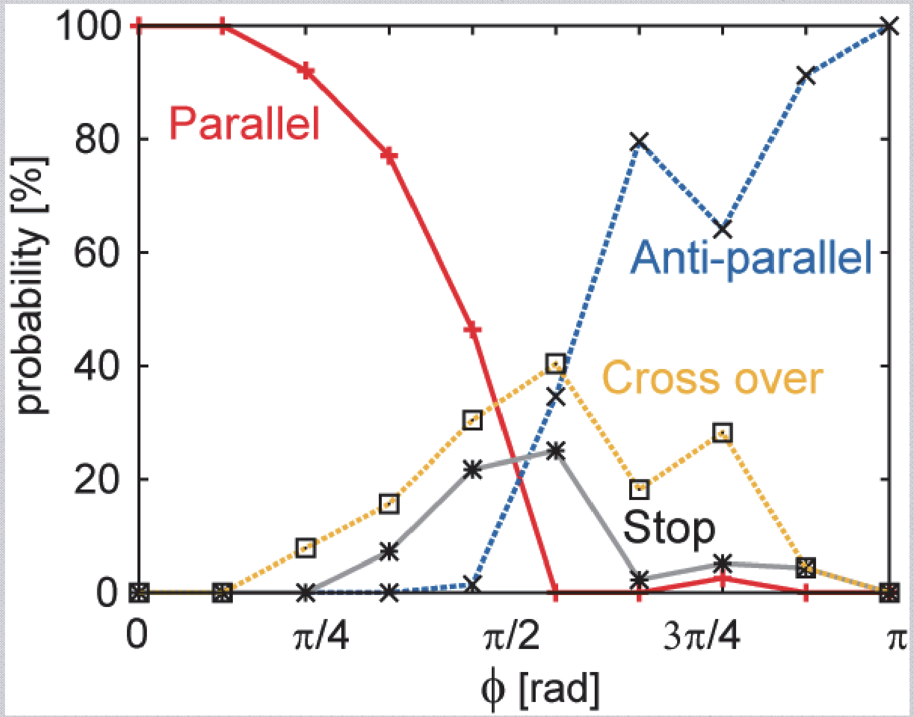
Inner-arm dynein purified from Chlamydomonas flagella

Experimental setup



- ATP concentration was 1 mM.
- In vitro motility assay consisted of dynein grafted to glass surface and to microtubules.
- Density of dyneins was 750-2,500/μm^2.
- Average speed of a microtubule was 8.75 µm/s.

Interaction of microtubules

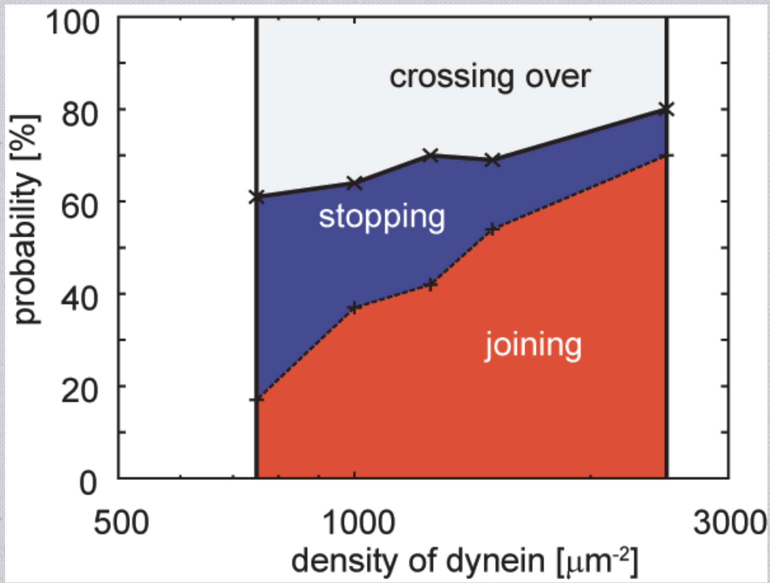


Microtubule aligns parallel or anti-parallel through collision

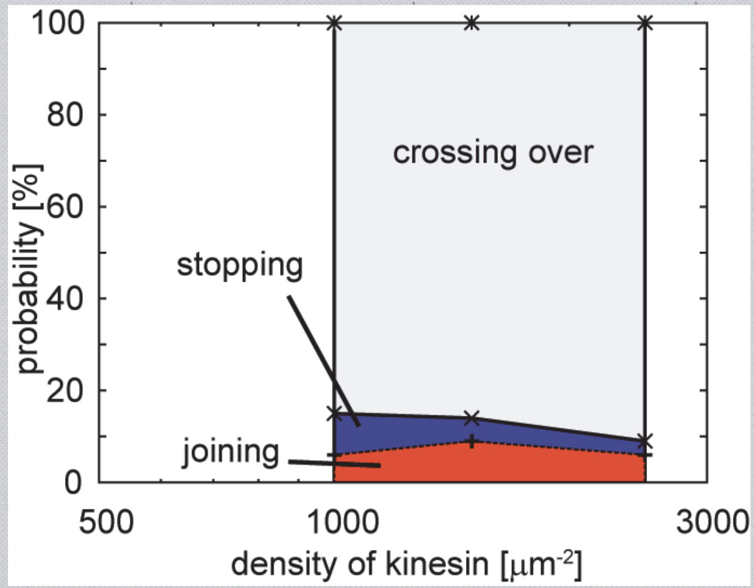
(Short-range nematic interaction)

Difference between dyneins and kinesins

Dynein

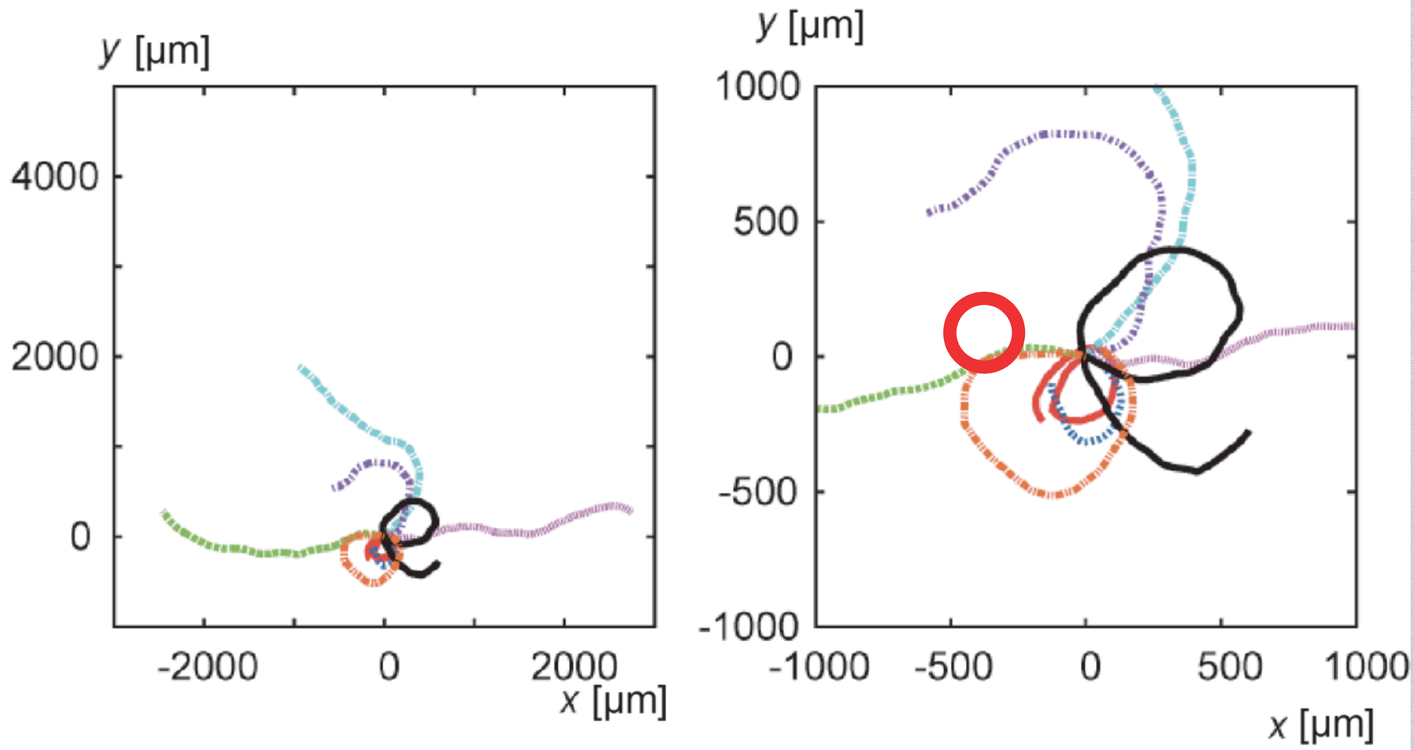


Kinesin



- Most microtubules does not change the direction.

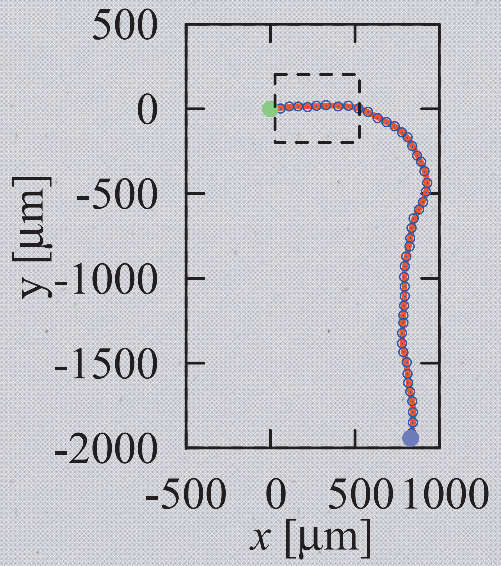
Trajectory of an isolated microtubule



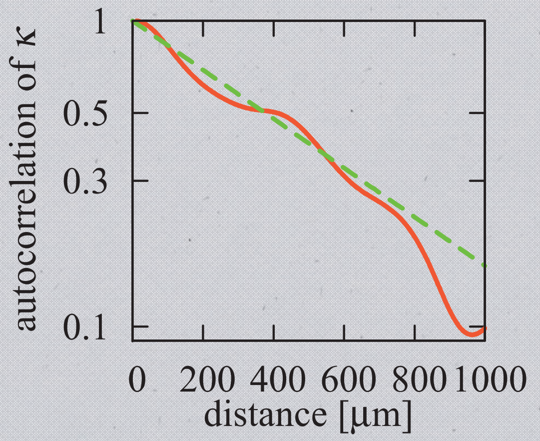
- Smooth trajectory (finite correlation time of direction of motion)
- ω_i/v_0 is the curvature of trajectory.

Analysis of trajectory

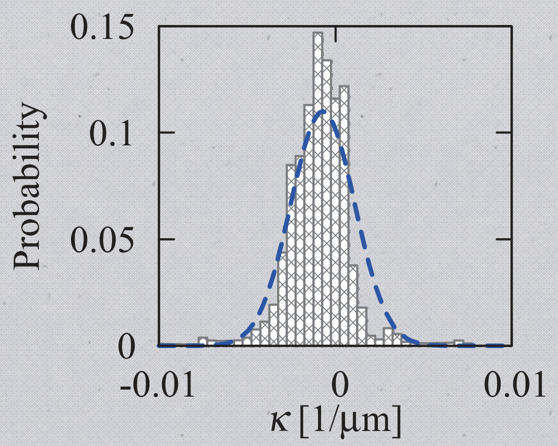
Trajectory



Autocorrelation of curvature

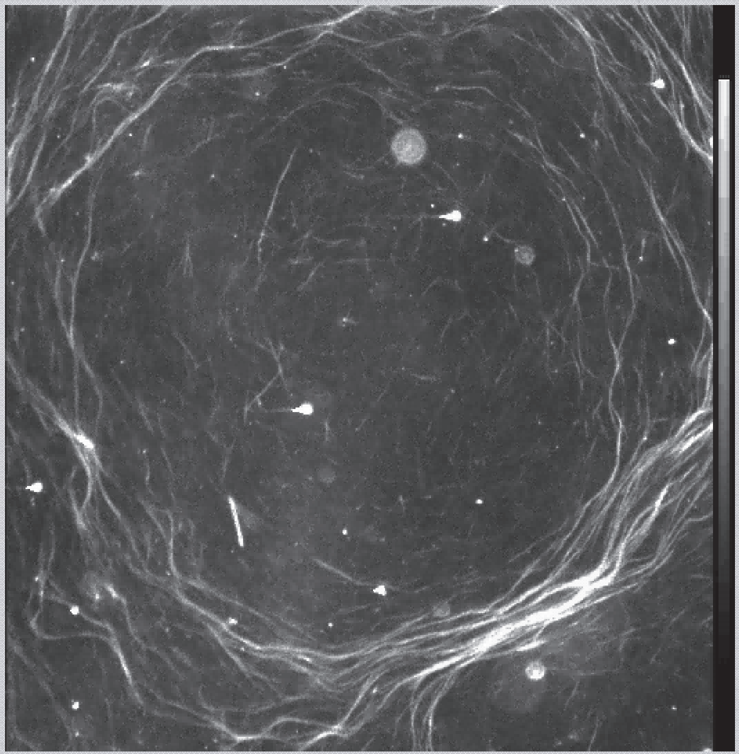


Distribution of curvature



- Correlation length along the trajectory was 542±4 µm (>>microtubule length (10 µm))!
- Average curvature was -7.1×10^{-4} µm^{-1} (clockwise rotation).
- Standard deviation of curvature was 1.8×10^{-3} µm^{-1}.

Collective behavior of microtubules

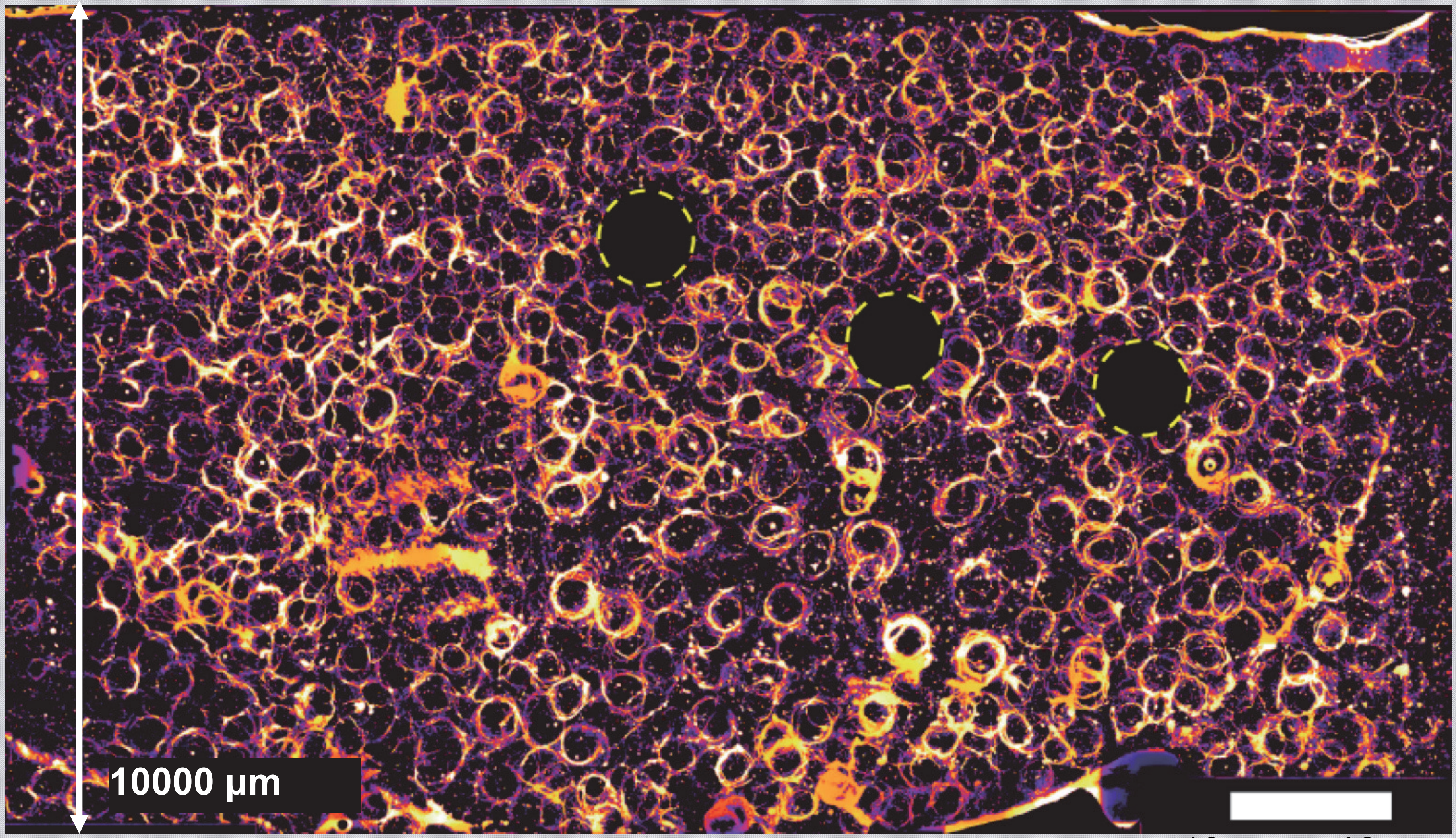


100 μm

- Density was 40 μg/ml (5 MT in 100 μm^2).
- The size of a vortex was 443±64 μm (major axis)

(>>microtubule length (10 μm))!

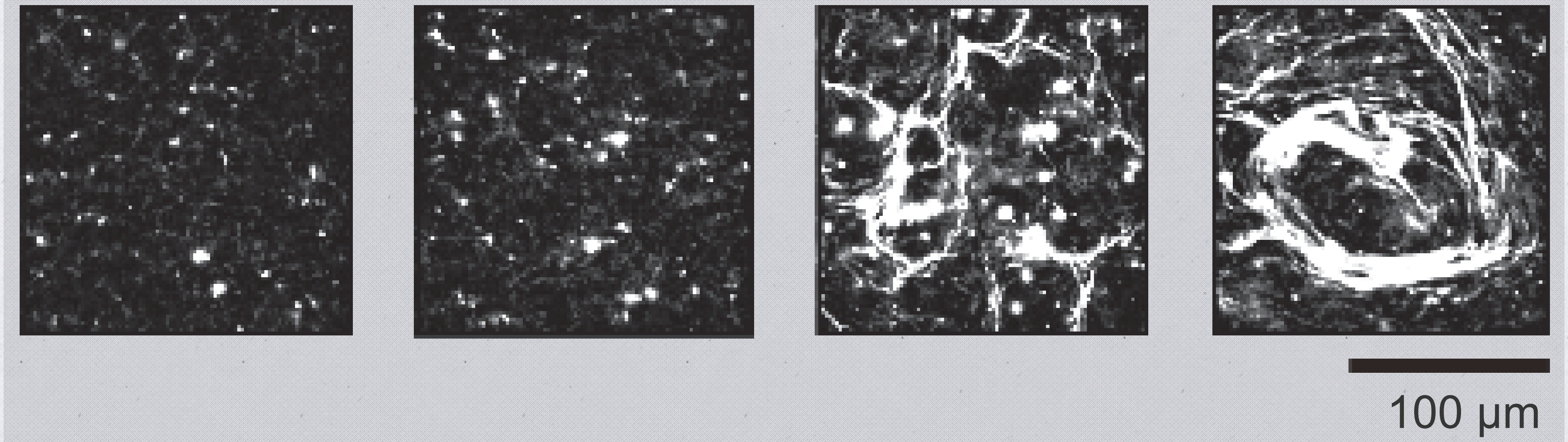
Whole view



10 mm x 18 mm

Density Dependence

14.3 µg/ml 28.6 µg/ml 57.2 µg/ml 114.5 µg/ml



Situation corresponding to the experiments

τ=171 s, L=7.68 mm, ρ=4.44 × 10^{-2} μm^2, N=2621440

Vortex lattice!

Conclusion and remarks

- Using a mathematical model, we found long correlation time of motion and high density leads to vortex lattice of active particles. Only short-range nematic interaction is needed for vortex lattice (not hydrodynamical one (I. H. Riedel, et al., Science (2005))).

- We experimentally confirmed this type of swarming behavior using motility assay consisted of dynein proteins grafted to glass surface and to microtubules.

- The macroscopical meaning of the finite correlation time of the curvature of microtubule's trajectory are being analyzed.

- Y. S, K. H. N., et al., *Nature* (2012).