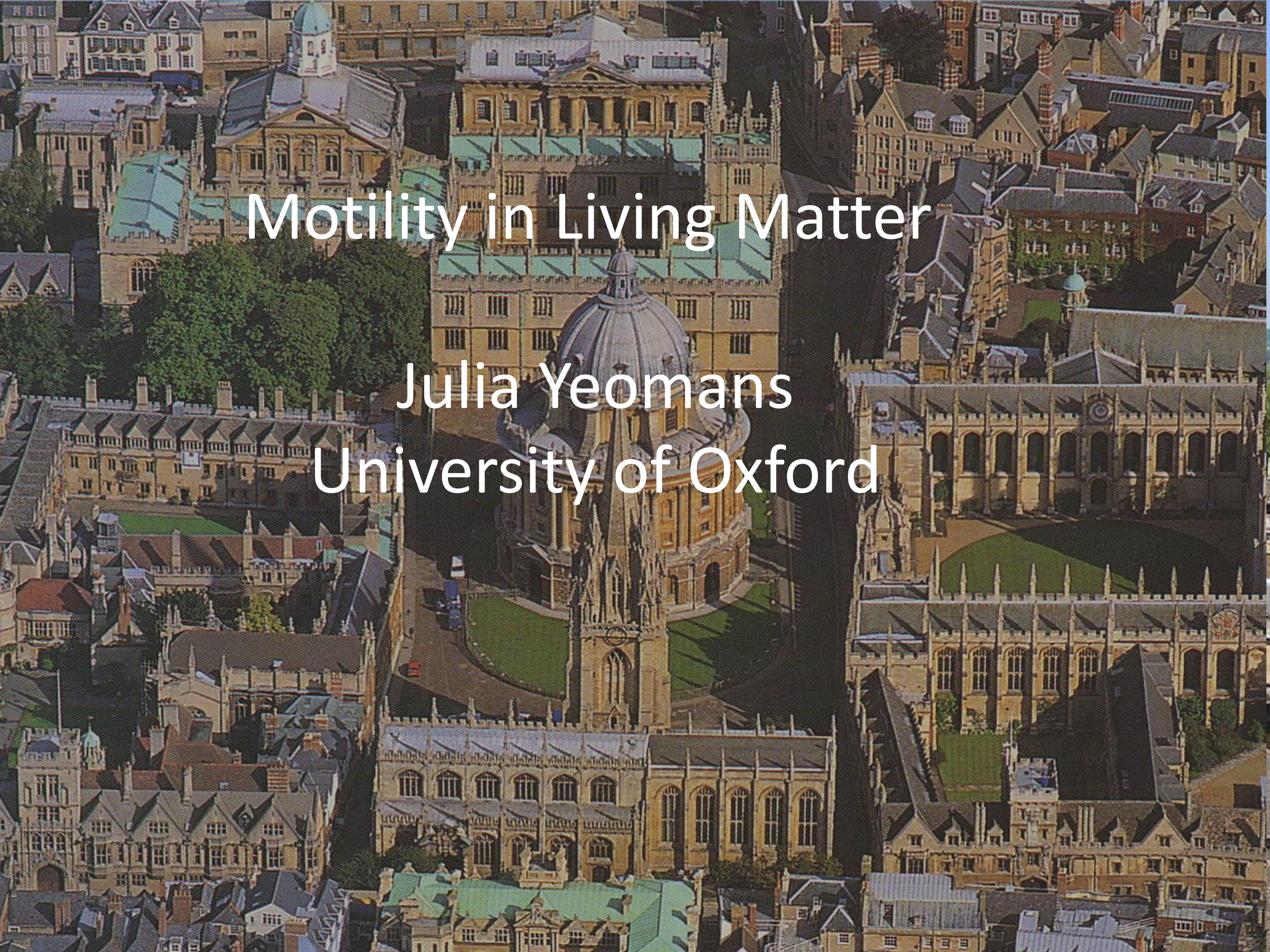
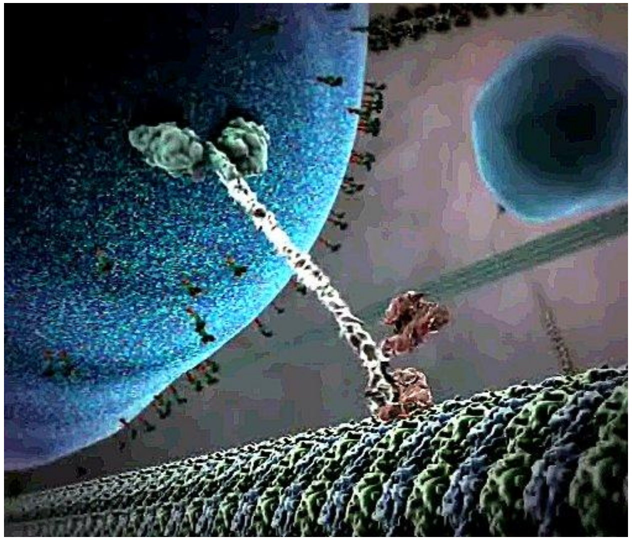
Motility in Living Matter

Julia Yeomans
University of Oxford

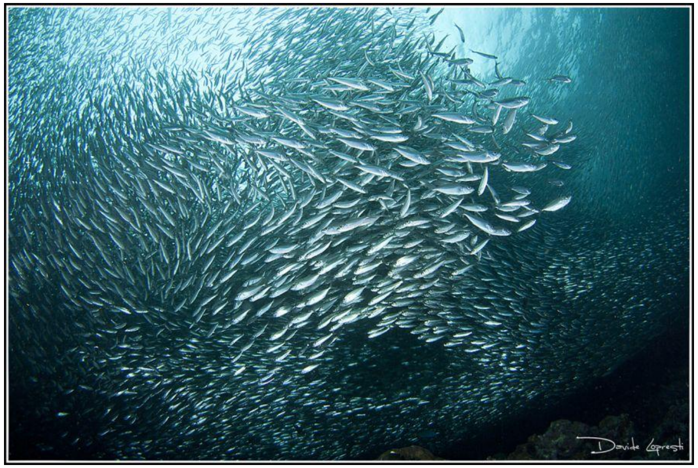


Active matter

bacteria, self-propelled colloids



molecular motors, cells



birds, fish

active systems operate out of thermodynamic equilibrium

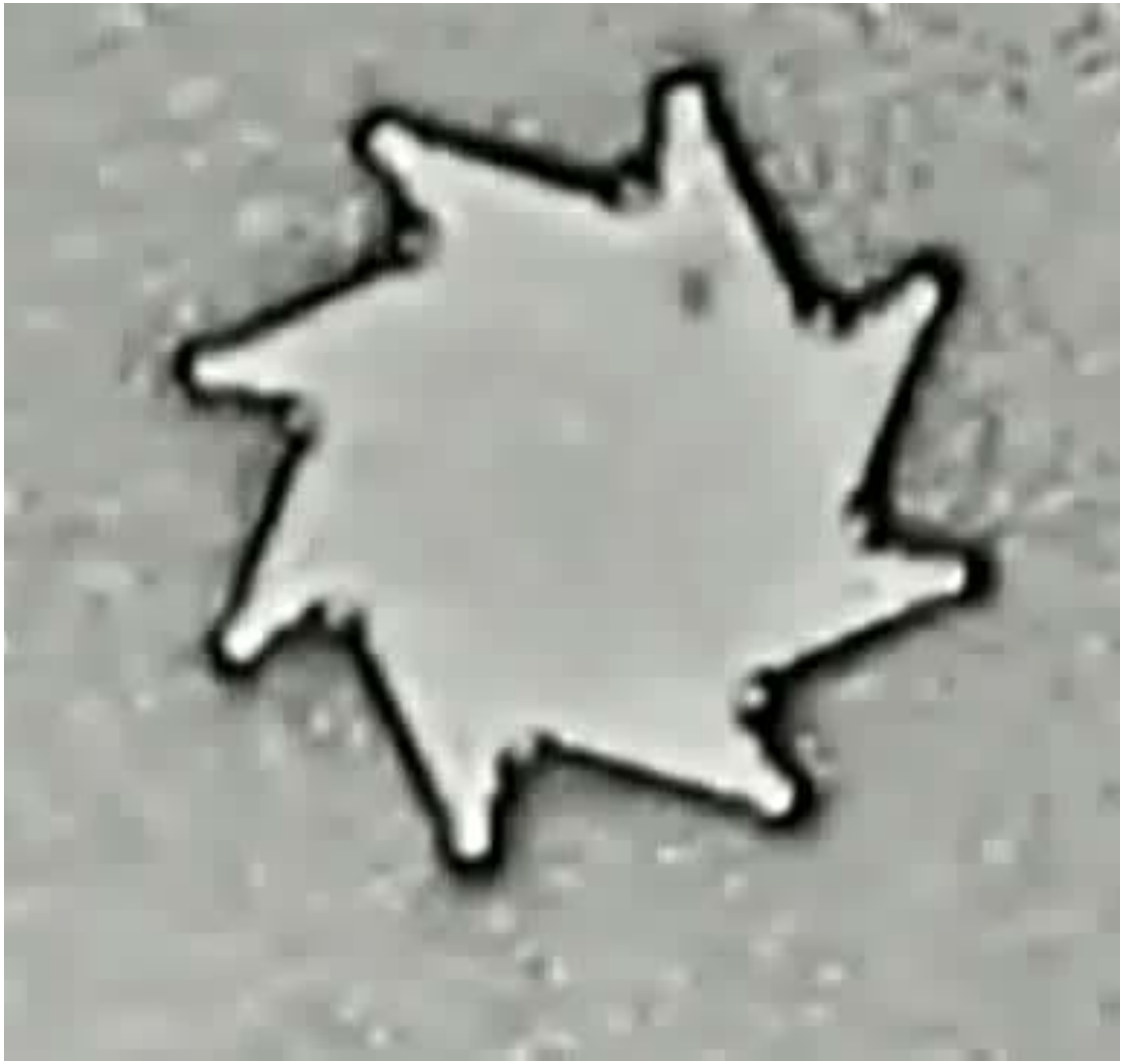
Active matter

Why is active matter interesting?

1. Statistical physics beyond Boltzmann

2. Engineering applications

3. Medical applications



L. Angelani, R. Di Leonardo, Ruocco G.,
Phys. Rev. Lett., ***102**, 048104, (2009)*

Active matter

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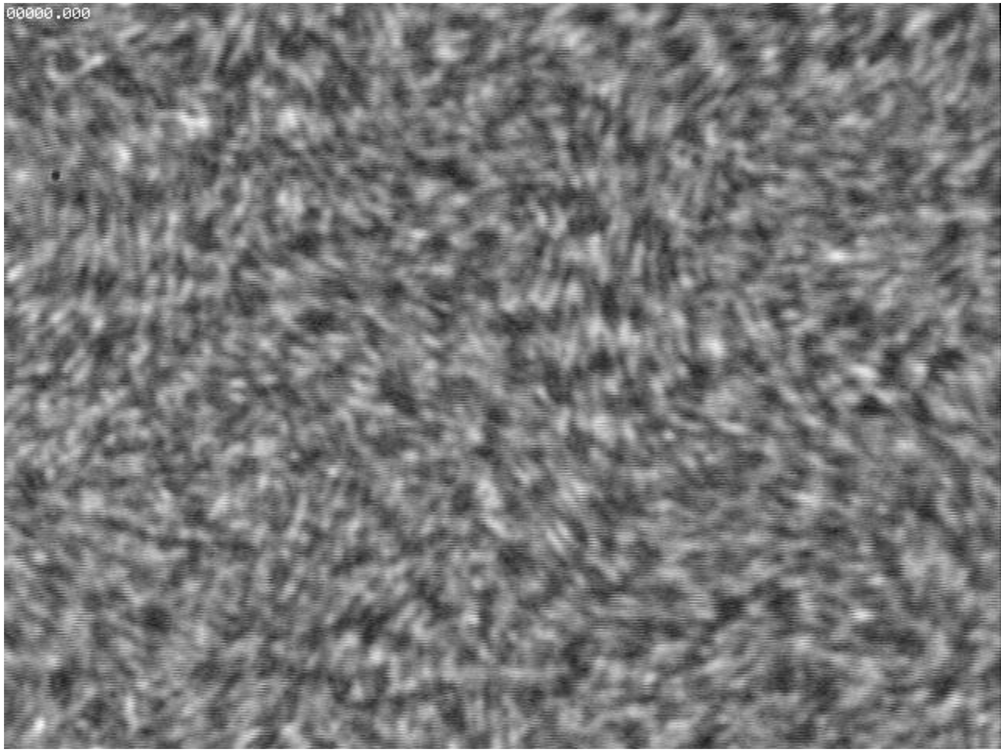


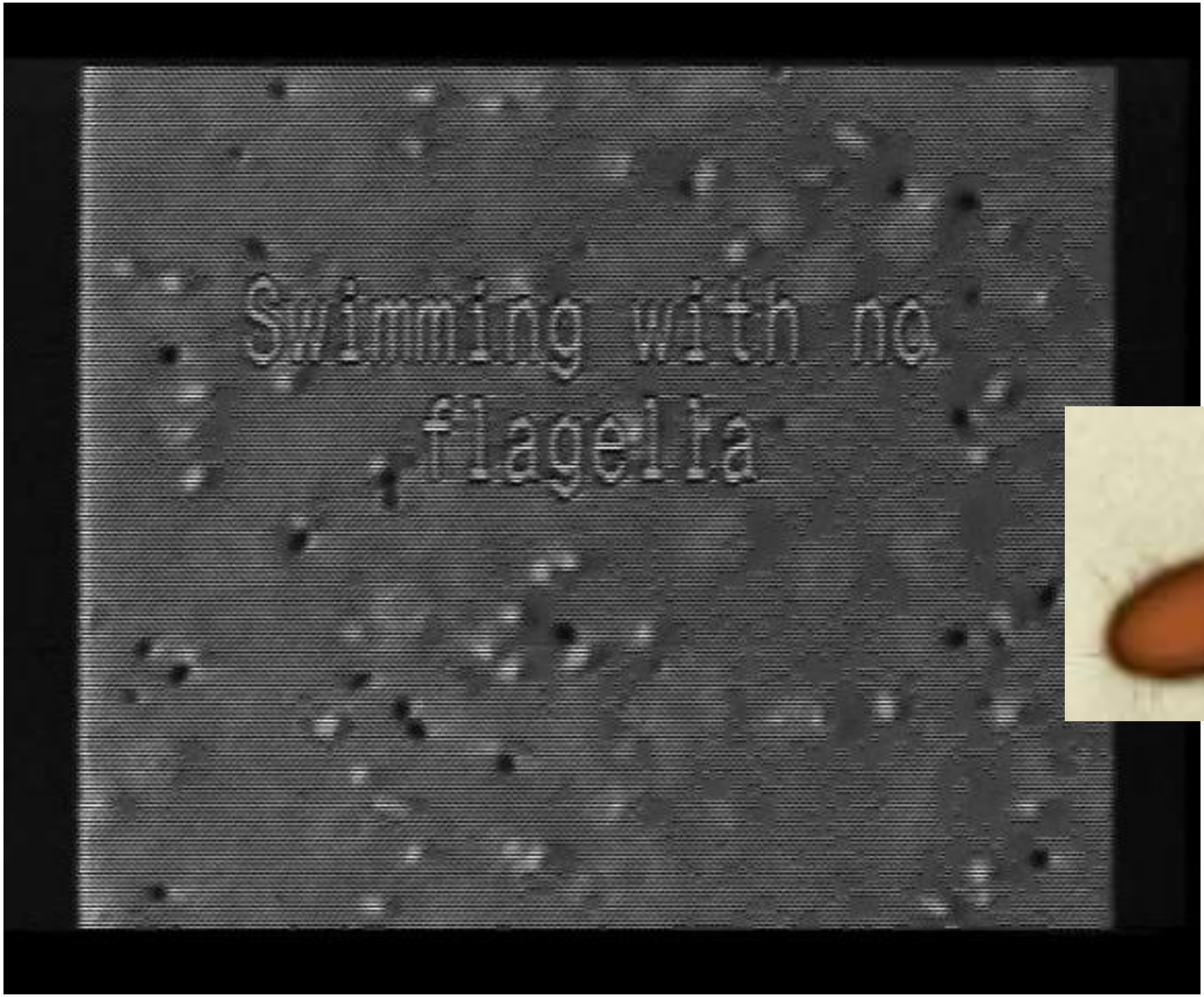
Why is it interesting now?

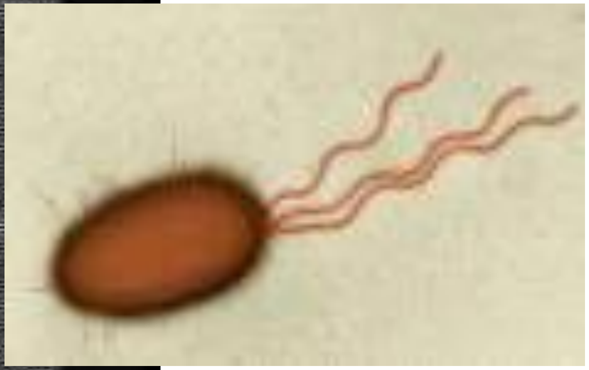
1. Better microscopy

2. Nanotechnology

3. Faster computers

Swimmers





http://mcb.harvard.edu/Faculty/Berg.html

$$\rho \left\{ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right\} = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f}$$

inertial terms

viscous terms

$$\mathrm{Re} = \frac{\text{inertial response}}{\text{viscous response}} \sim \frac{\rho L_0 V_0}{\mu}$$

$$\rho \left\{ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right\} = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f}$$

inertial terms

viscous terms

$$\mathrm{Re} = \frac{\text{inertial response}}{\text{viscous response}} \sim \frac{\rho L_0 V_0}{\mu}$$

10^{-6}

10^{-6}

10^{6}

Stokes equations

$$\nabla p = \mu \nabla^2 \mathbf{v} + \mathbf{f} \qquad \nabla \cdot \mathbf{v} = 0$$

Purcell's Scallop Theorem

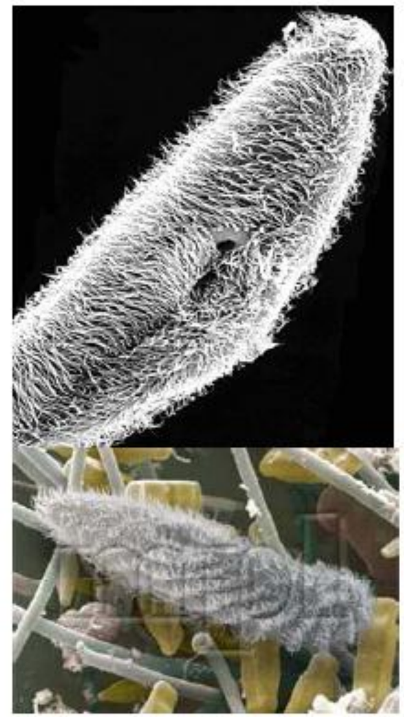
$$\nabla p = \mu \nabla^2 \mathbf{v} + \mathbf{f} \qquad \nabla \cdot \mathbf{v} = 0$$

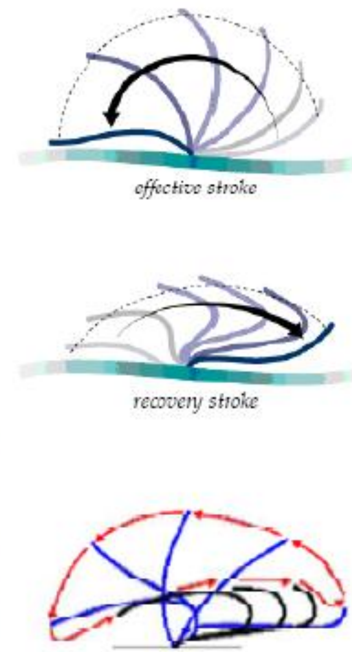
No time dependence implies the Scallop Theorem

A swimming stroke must not be invariant under time reversal

Purcell's Scallop Theorem

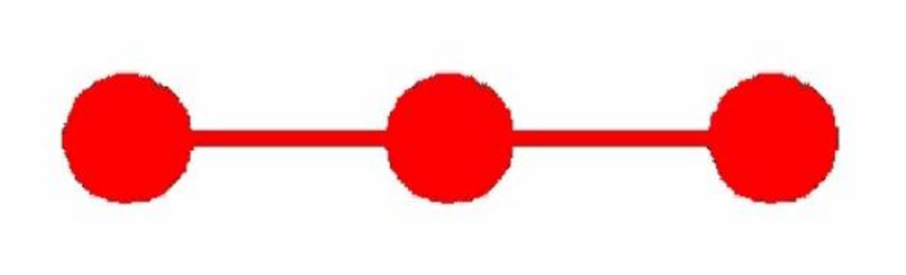
A swimmer strokes must be non-invariant under time reversal

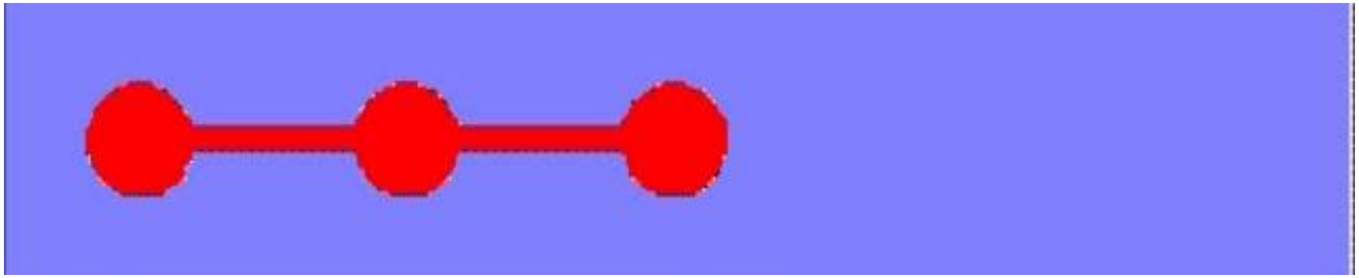




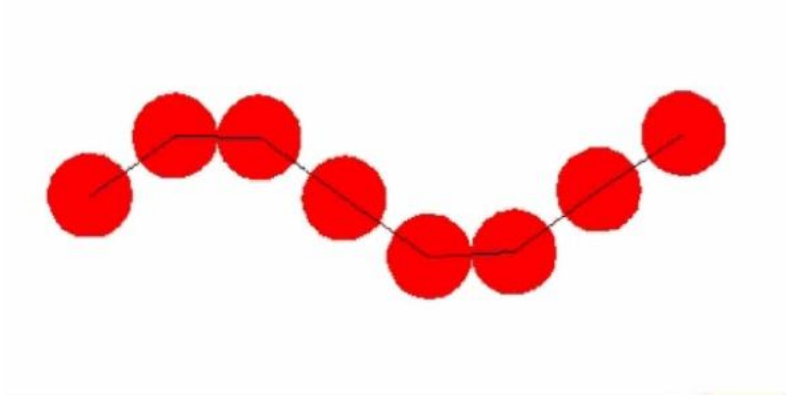
Model swimmers

three sphere swimmer
Najafi and Golestanian,





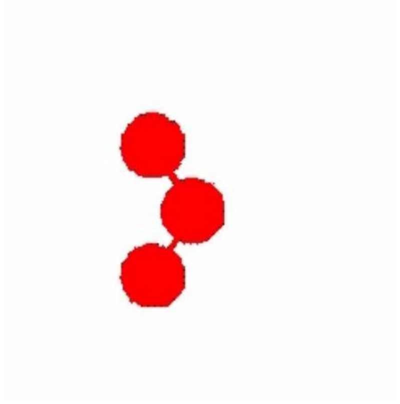
Snake swimmer

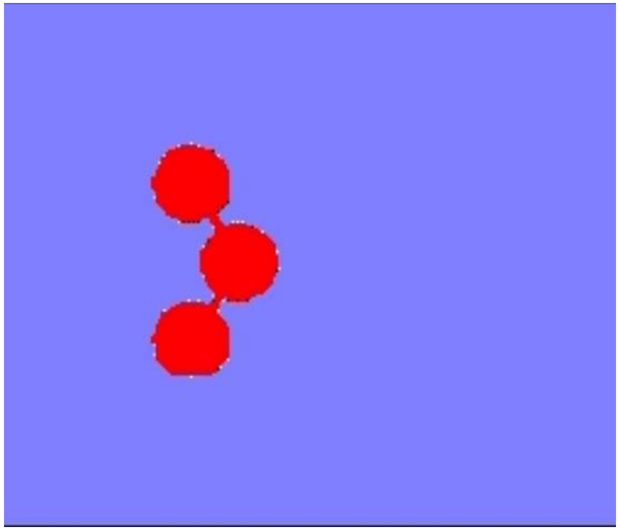


a generalised three sphere swimmer

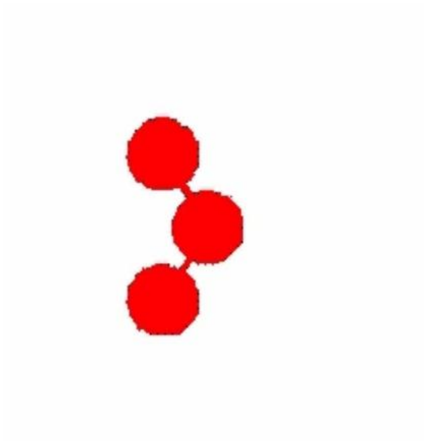
Radial and tangential motion

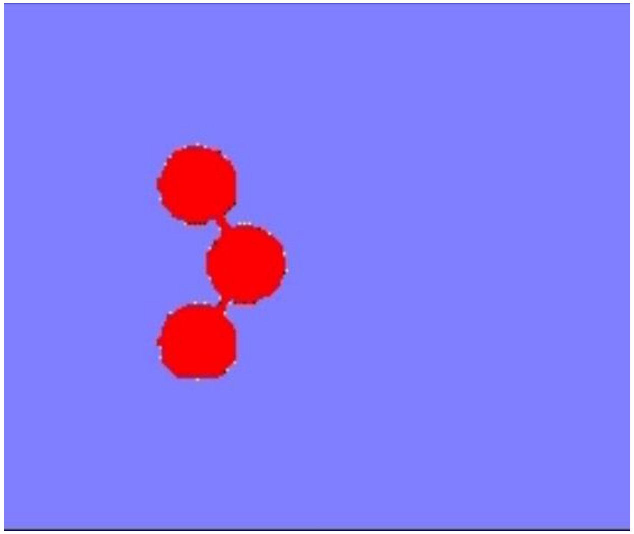
forward motion





turning motion





Green function of the Stokes equation

$$\nabla p = \mu \nabla^2 \mathbf{v} + \mathbf{f}\delta(\mathbf{r}) \qquad \nabla \cdot \mathbf{v} = 0$$

$$\mathbf{v} = \frac{\mathbf{f}}{8\pi\mu} \cdot \left(\frac{\mathbf{I}}{r} + \frac{\mathbf{rr}}{r^3} \right)$$

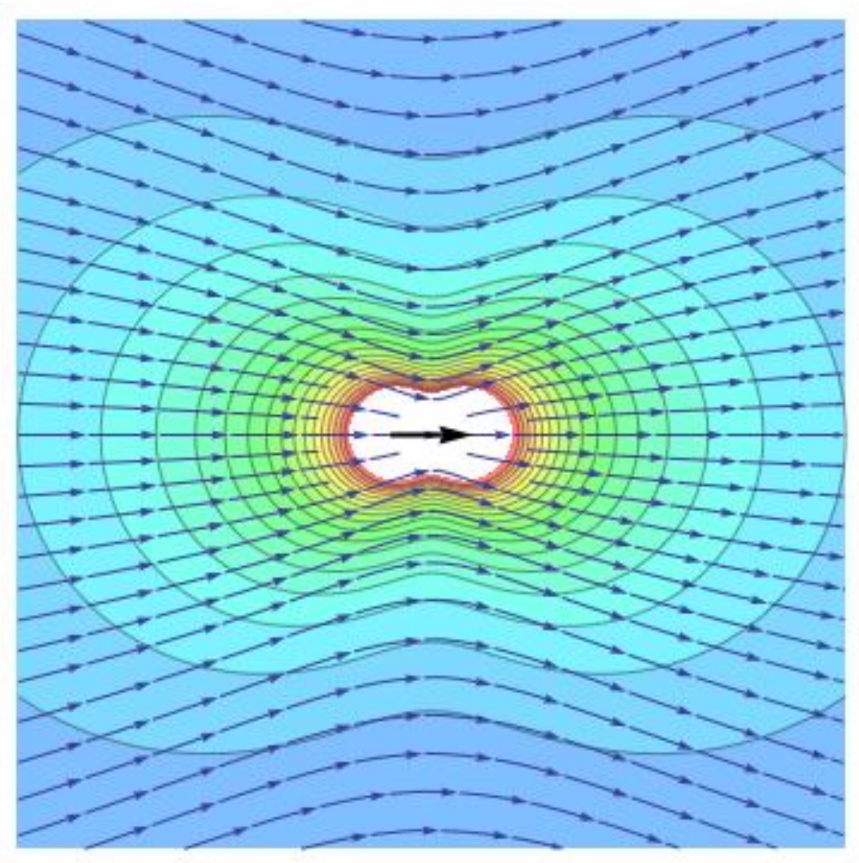
Stokeslet

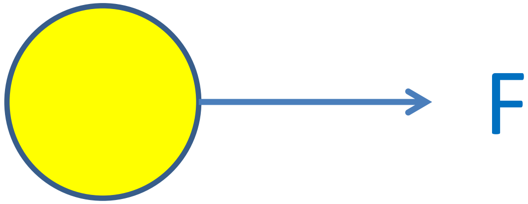
$$p = p_0 + \frac{\mathbf{f} \cdot \mathbf{r}}{4\pi r^3}$$

Maciej Lisicki http://www.fuw.edu.pl/~mklis/publications/Hydro/oseen.pdf

Green function of the Stokes equation

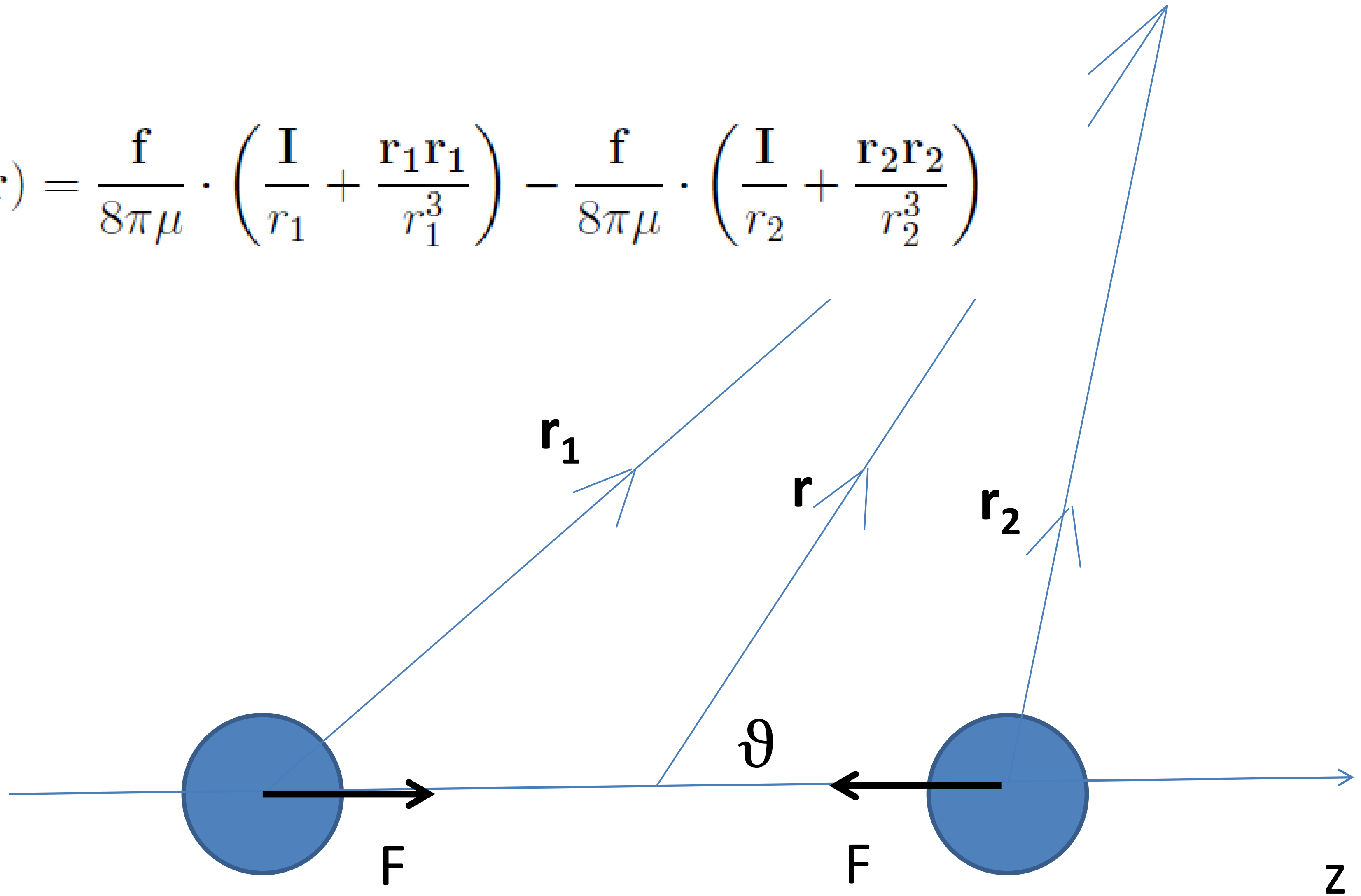
$$\mathbf{v} = \frac{\mathbf{f}}{8\pi\mu} \cdot \left(\frac{\mathbf{I}}{r} + \frac{\mathbf{rr}}{r^3} \right)$$





Dipolar far flow field

$$\mathbf{v}(\mathbf{r}) = \frac{\mathbf{f}}{8\pi\mu} \cdot \left(\frac{\mathbf{I}}{r_1} + \frac{\mathbf{r}_1\mathbf{r}_1}{r_1^3} \right) - \frac{\mathbf{f}}{8\pi\mu} \cdot \left(\frac{\mathbf{I}}{r_2} + \frac{\mathbf{r}_2\mathbf{r}_2}{r_2^3} \right)$$

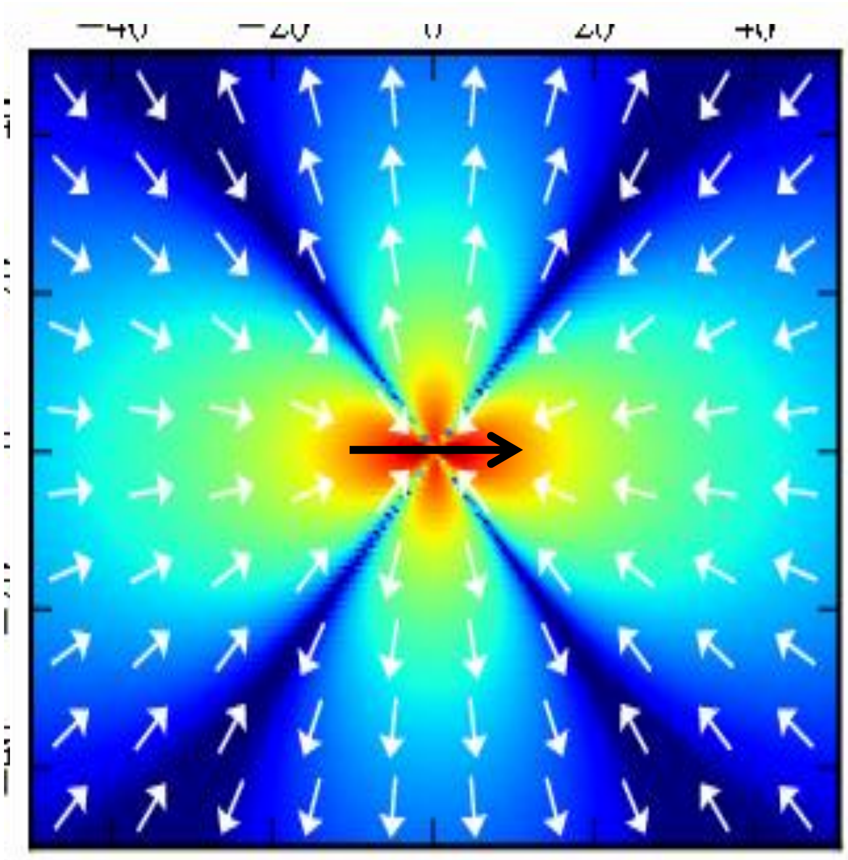


Far flow field of a swimmer

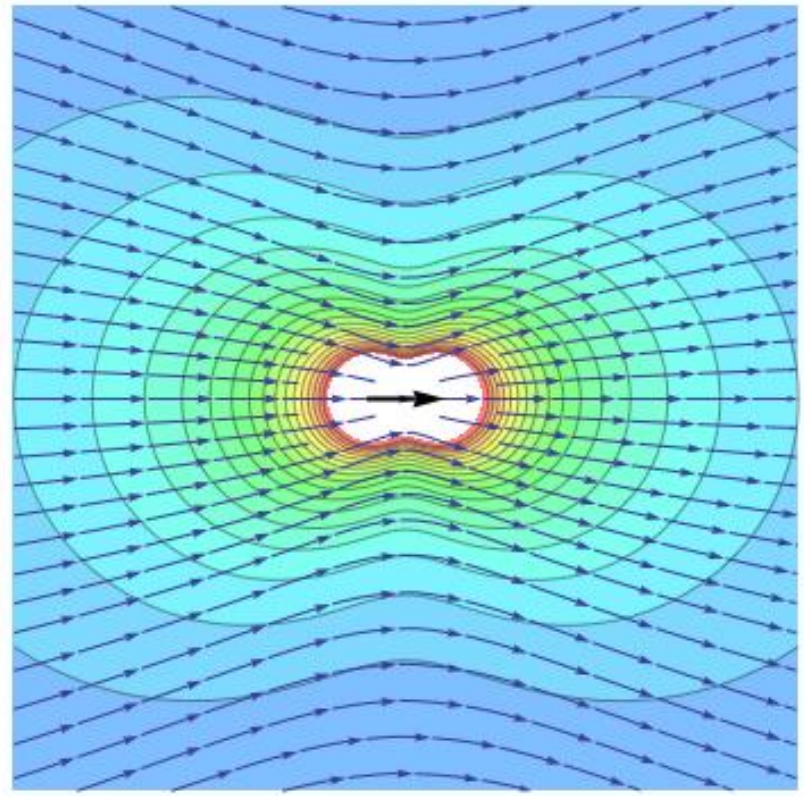
$$v_r = \frac{f}{4\pi\mu} \ \frac{L}{r^2} \ (3\cos^2\theta - 1)$$

Swimmers have dipolar far flow fields because they have no net force acting on them

Swimmer and colloidal flow fields

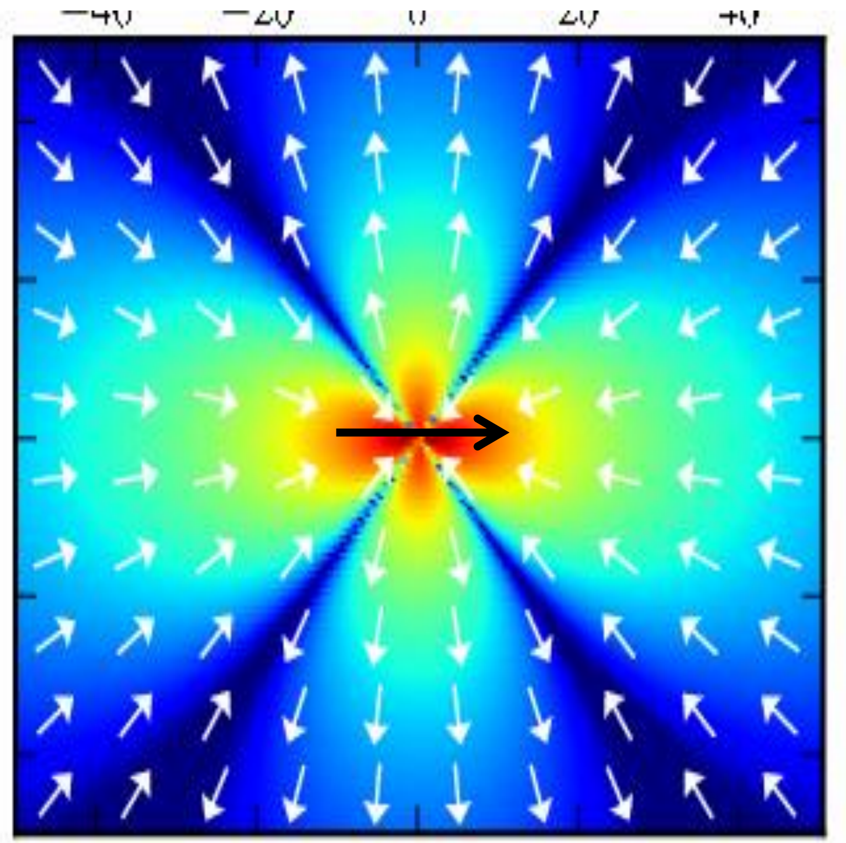


$$v \sim \frac{1}{r^2}$$

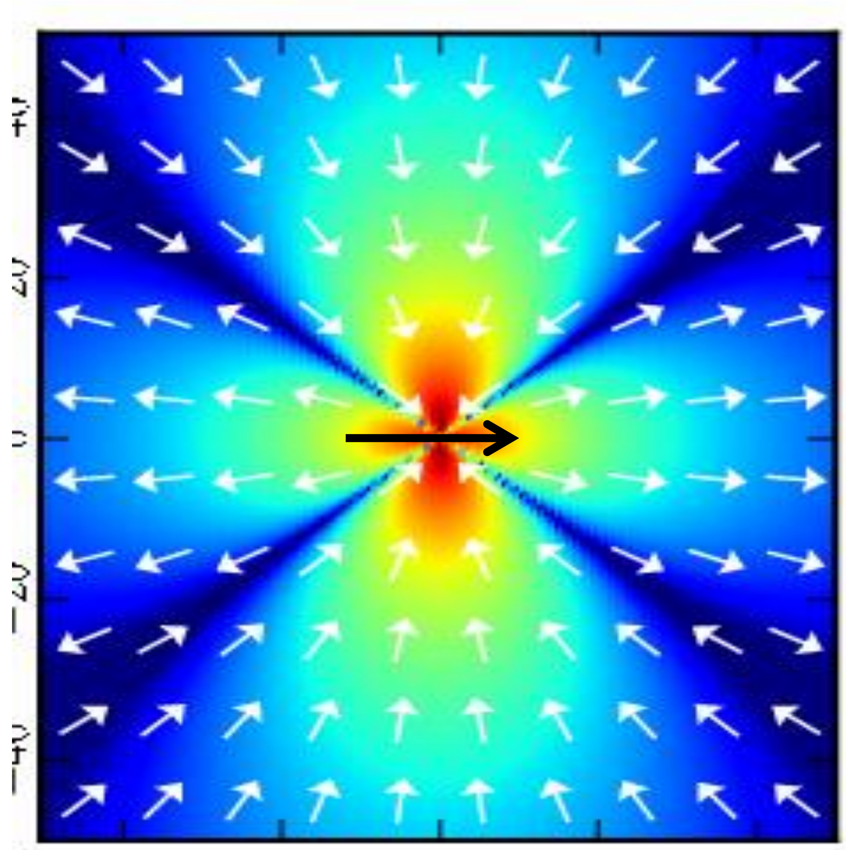


$$v \sim \frac{1}{r}$$

Dipolar flow field

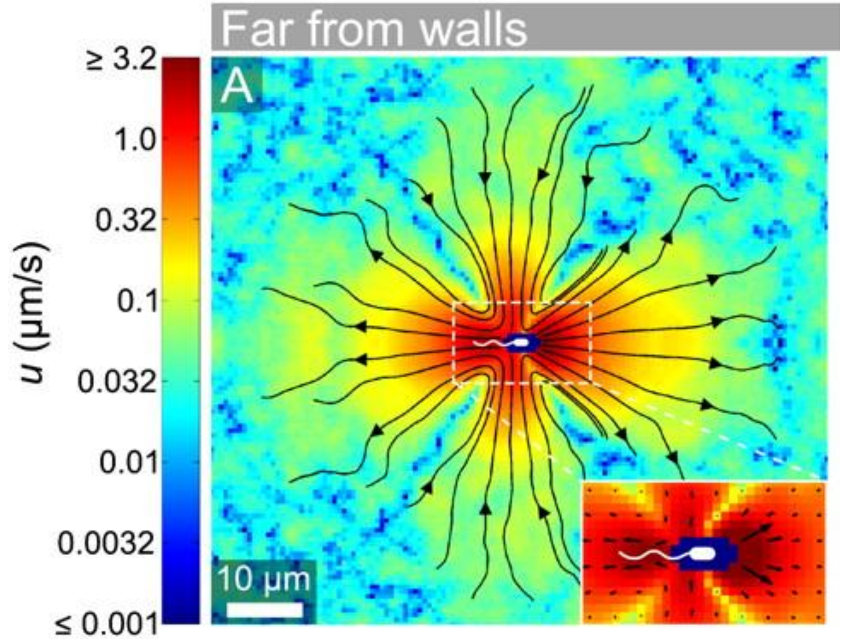


puller (contractile)

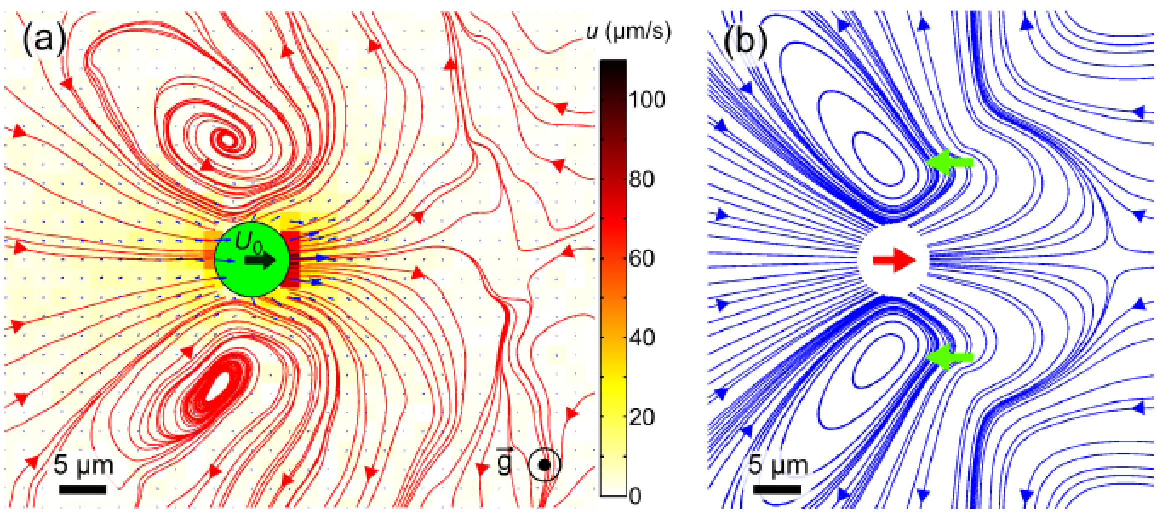


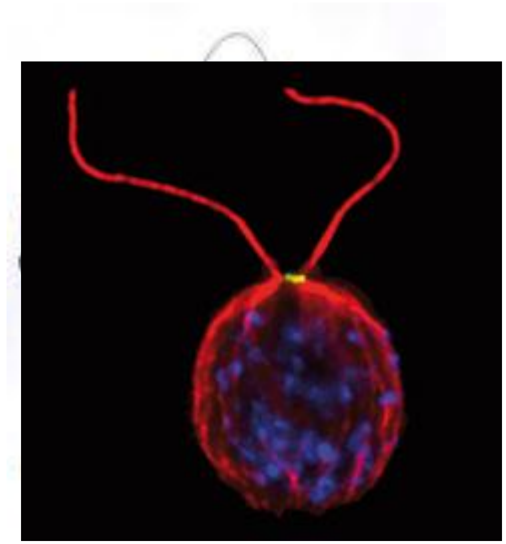
pusher (extensile)

$$v_r = \frac{f}{4\pi\mu} \; \frac{L}{r^2} \; \left(3\cos^2\theta - 1\right)$$



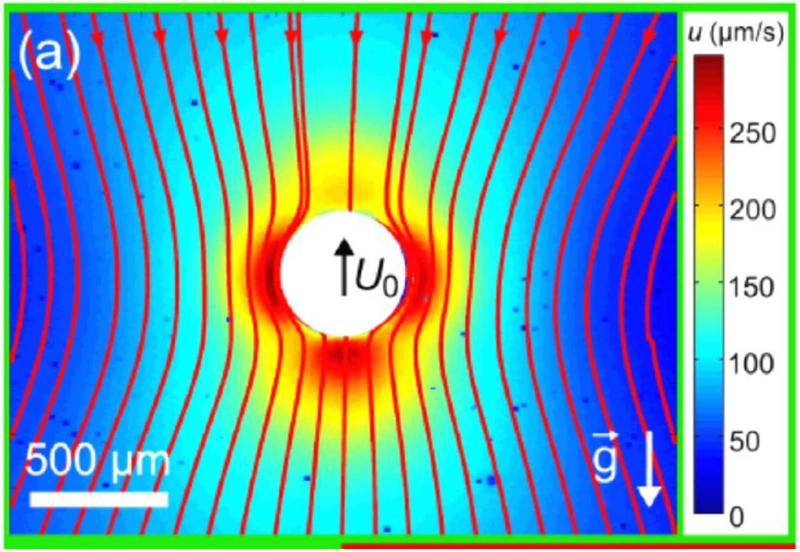
E-coli



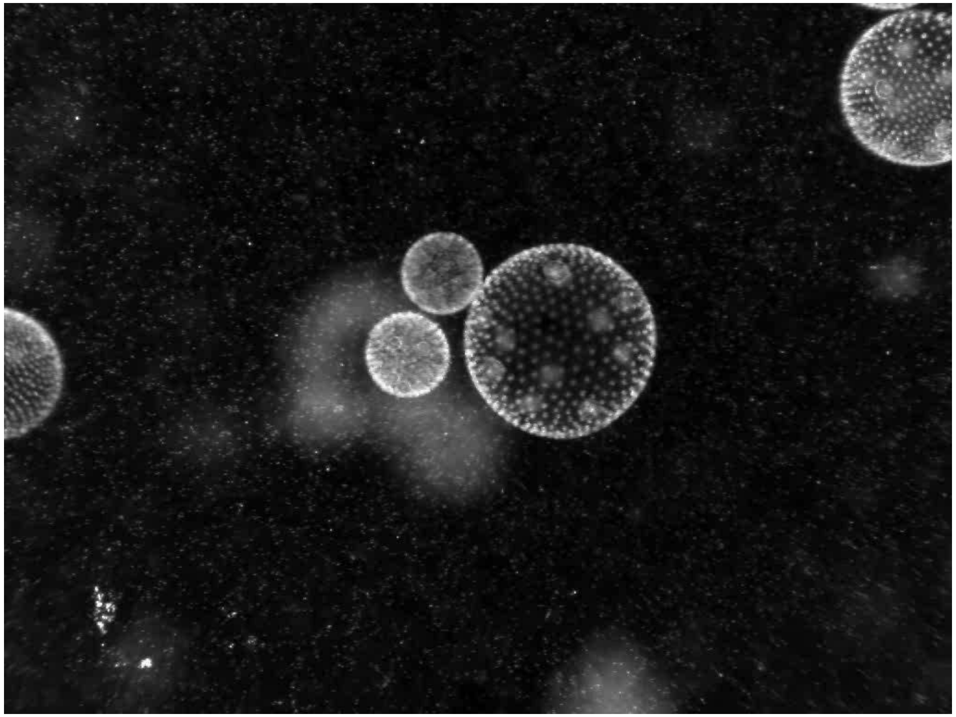


Chlamydomonas

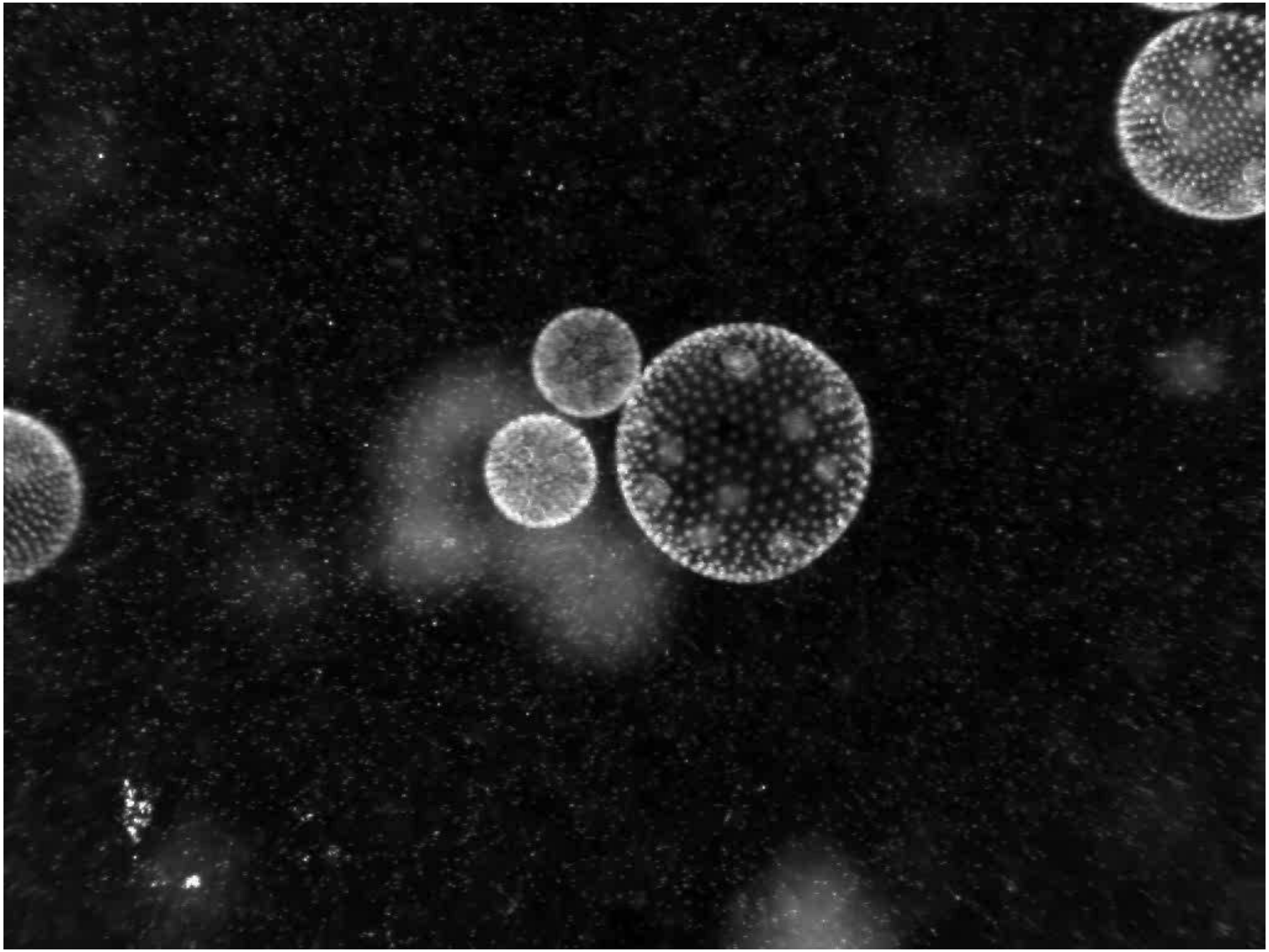
Goldstein group, University of Cambridge



Volvox



Dresher et al,   PRL 105 (2010)
PNAS 108 (2011)

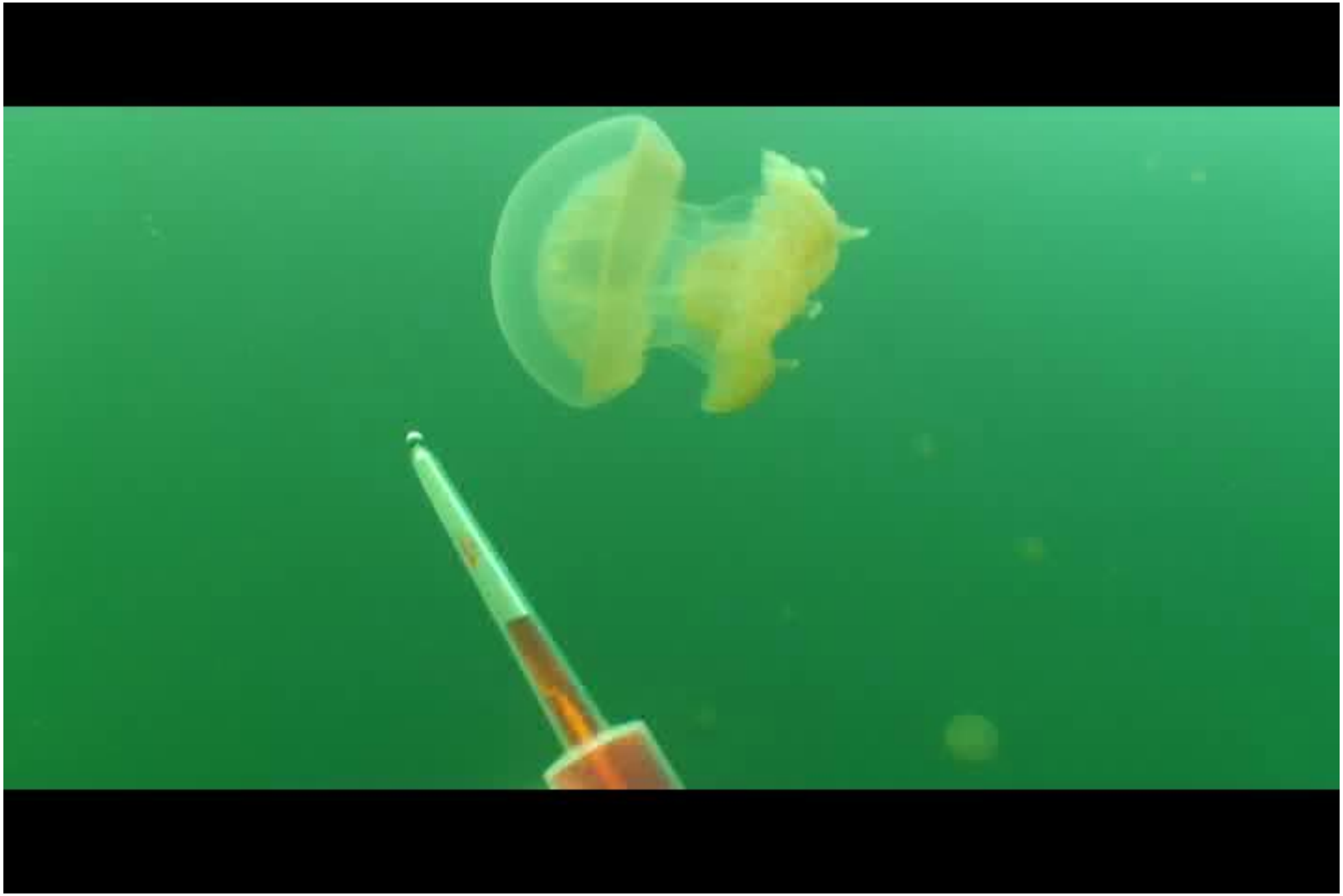


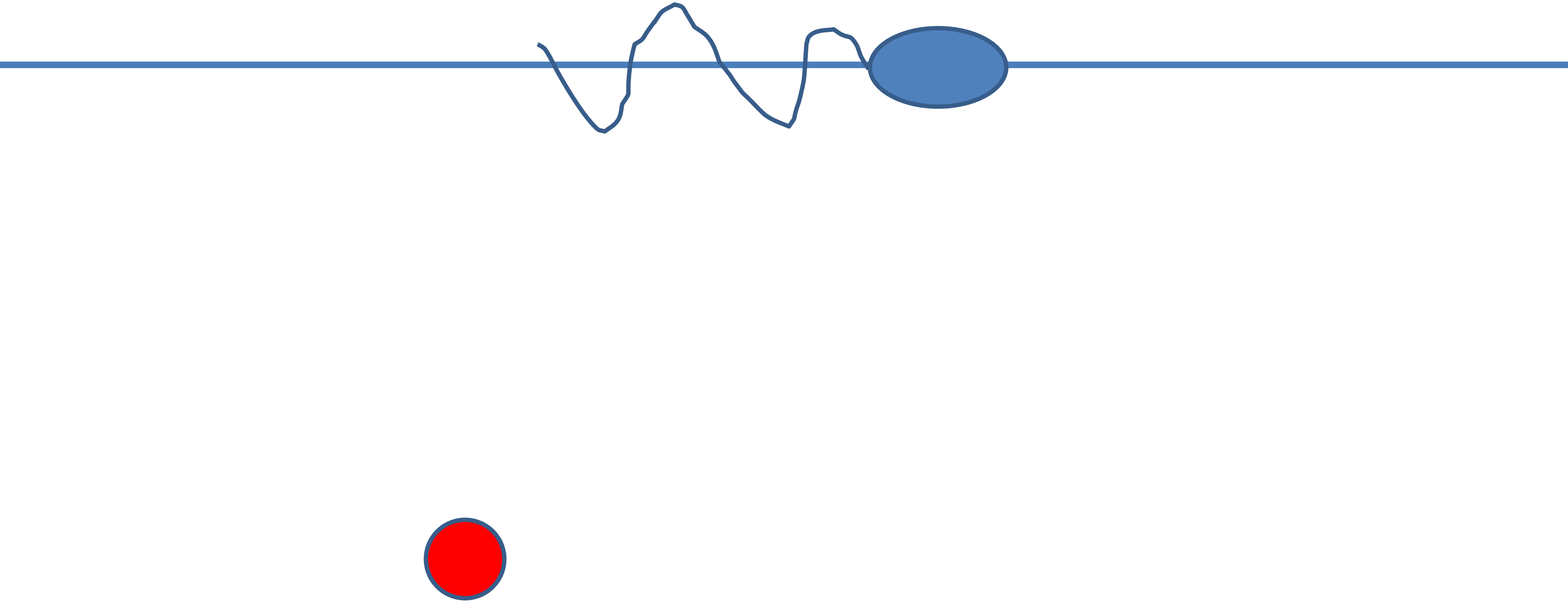
Volvox

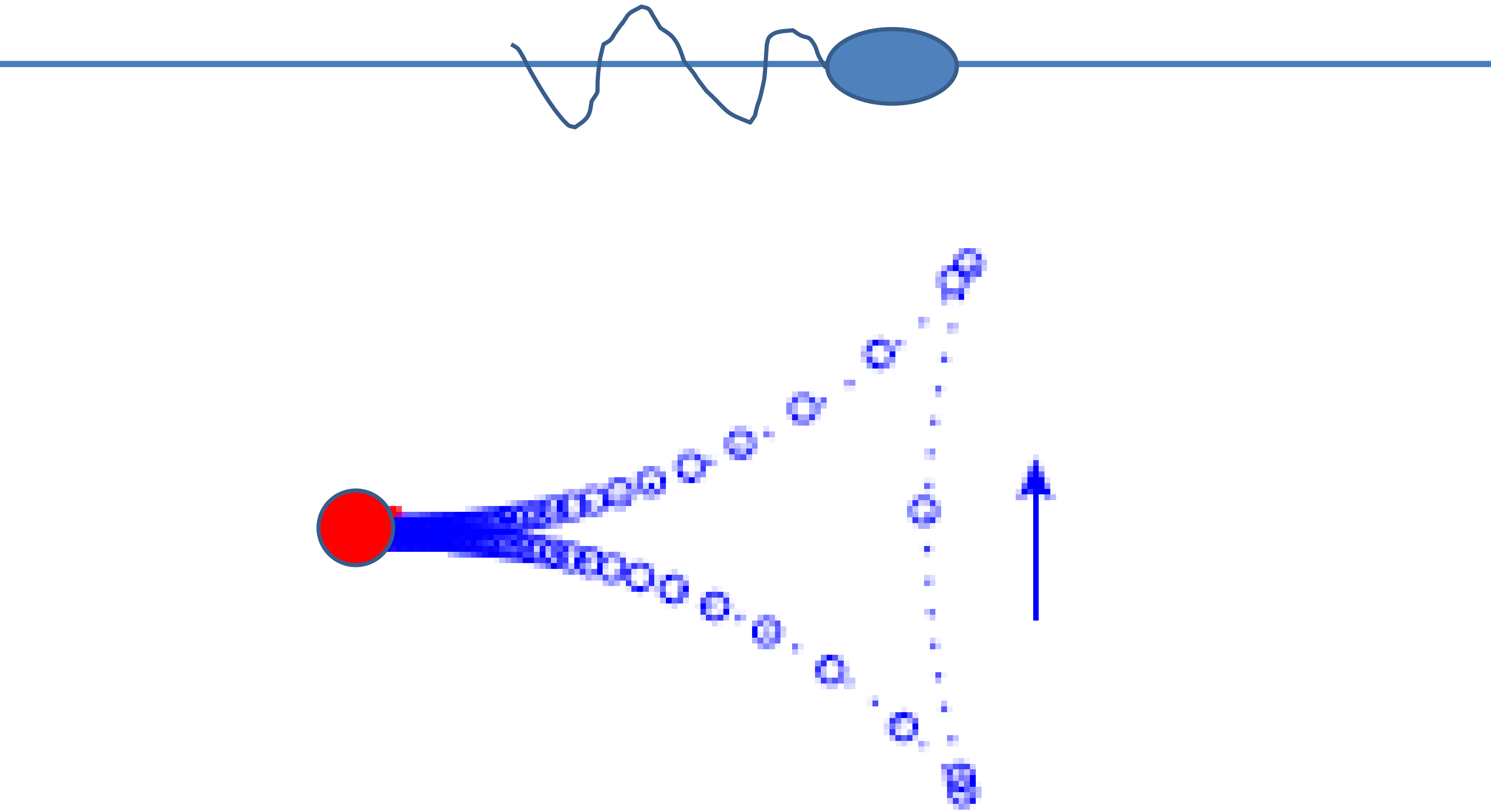
Goldstein group, Cambridge

Do small swimmers mix the ocean?

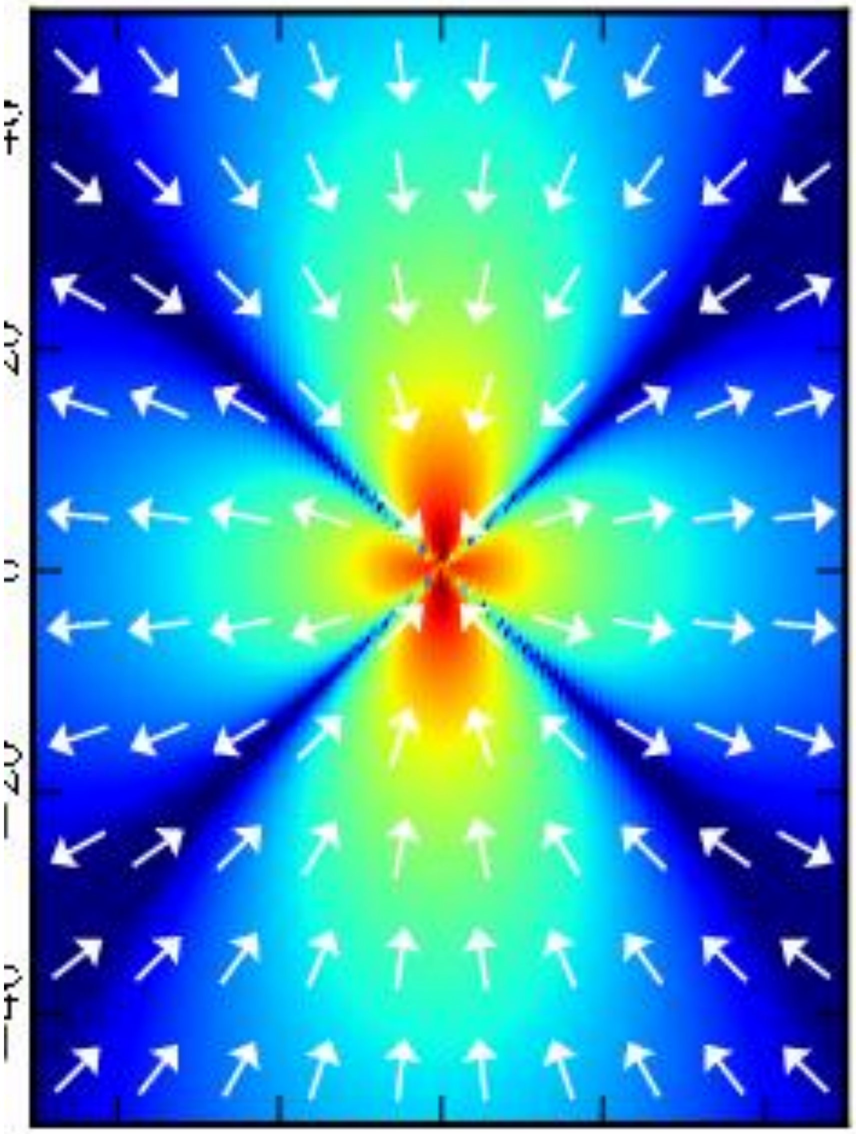
K. Katija, J.O. Dabiri, G. Subramanian,
A.M. Leshansky, L.M. Pismen, A.W. Visser





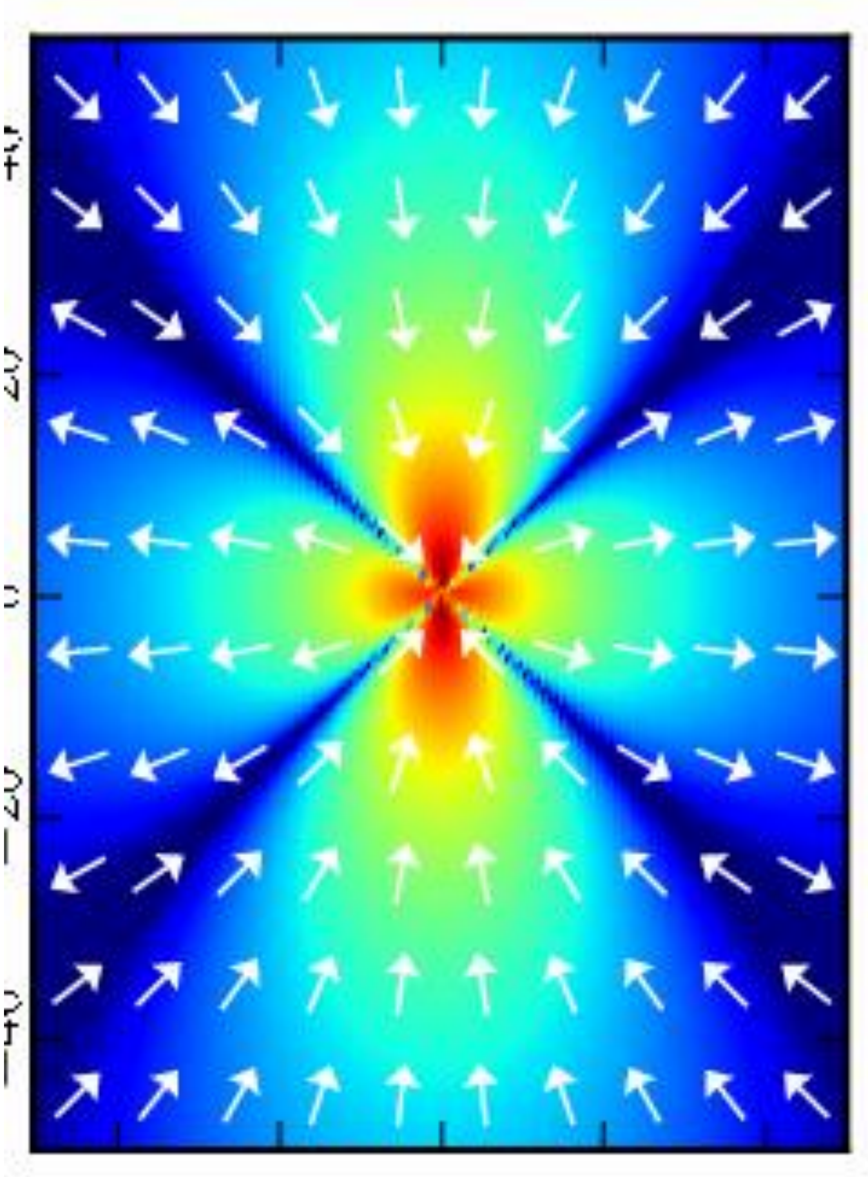


Multipole flow fields

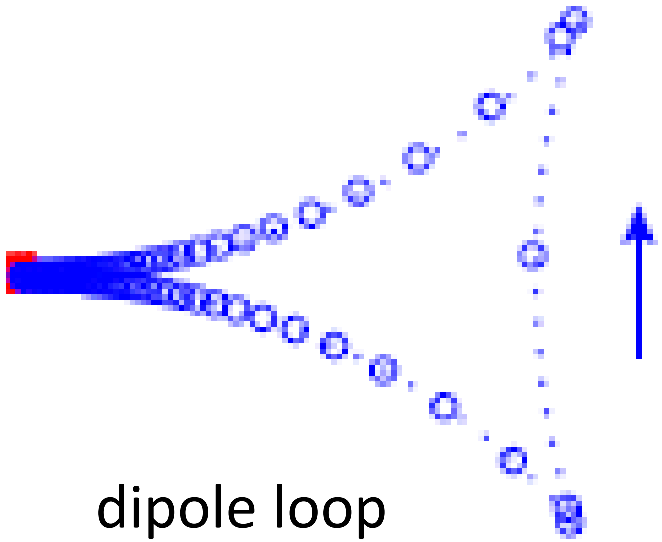


Dipole flow field

Multipole flow fields

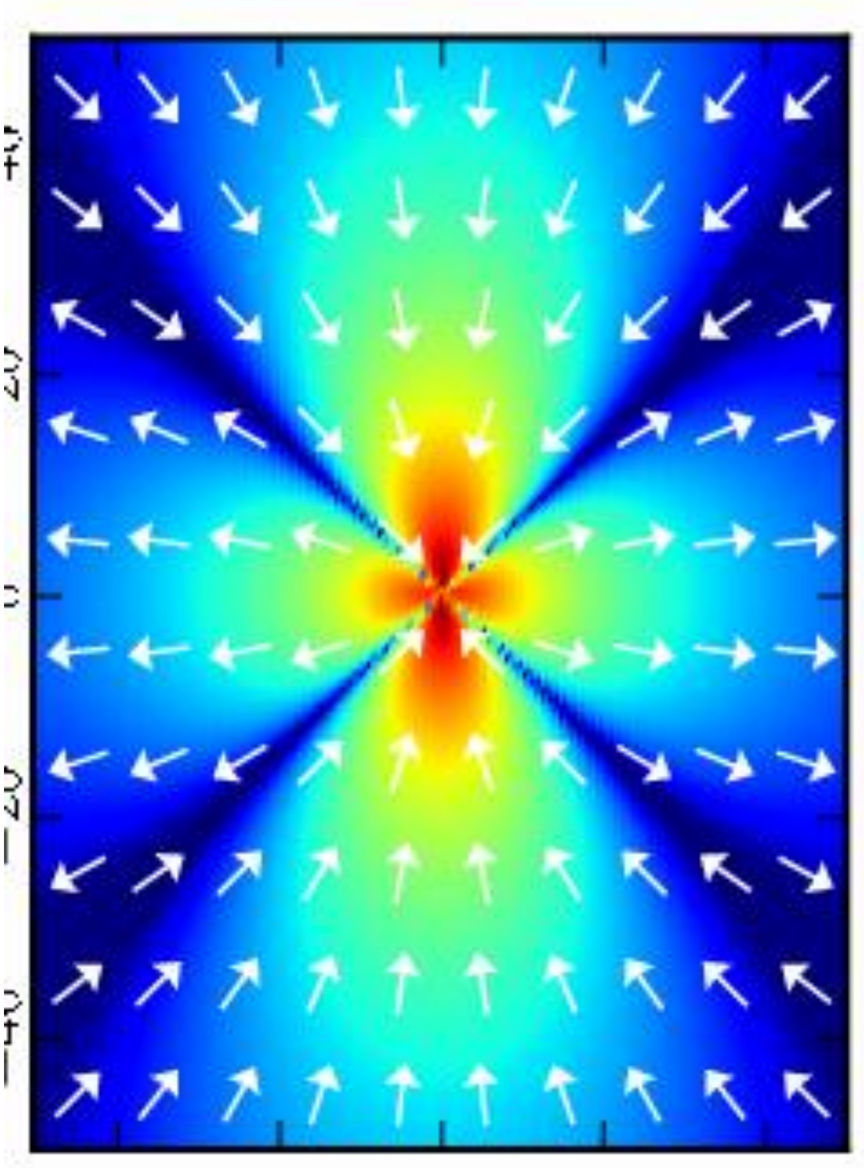


Dipole flow field

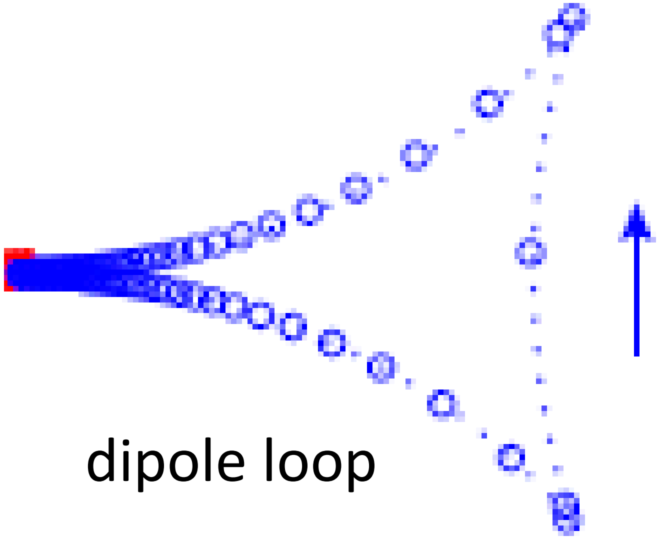


dipole loop

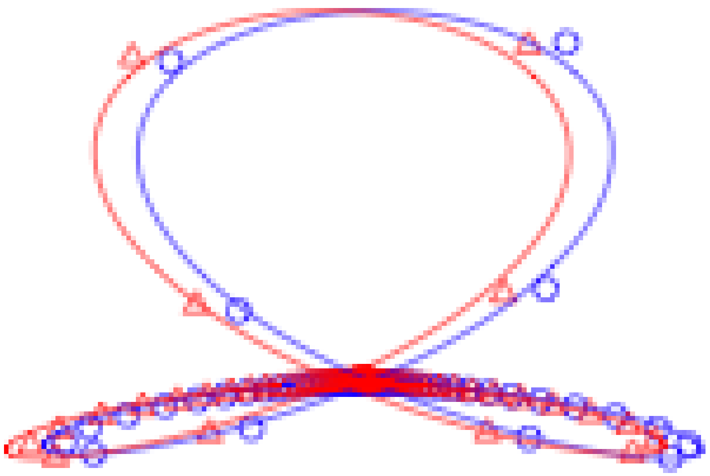
Multipole flow fields



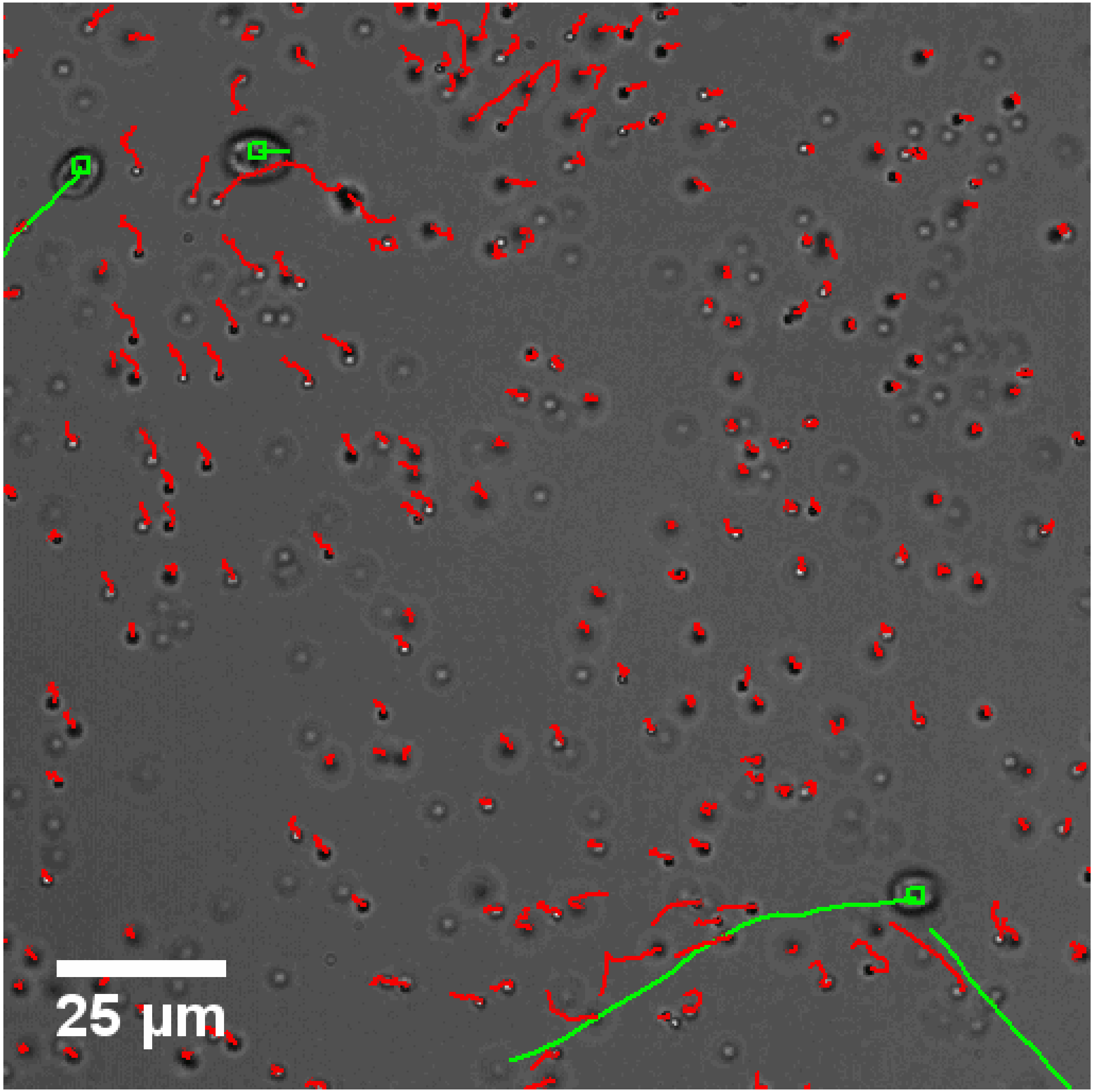
Dipole flow field



dipole loop

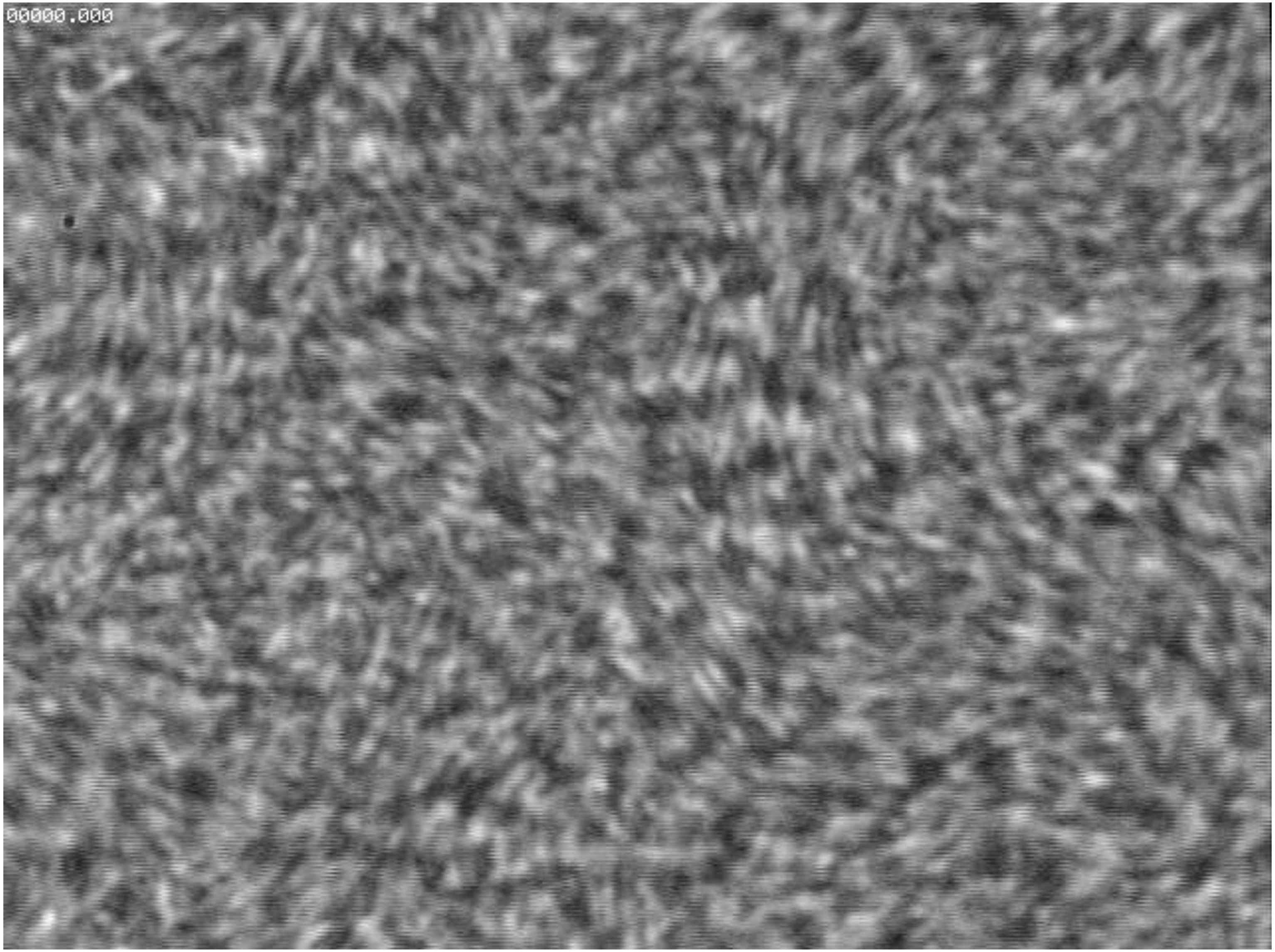


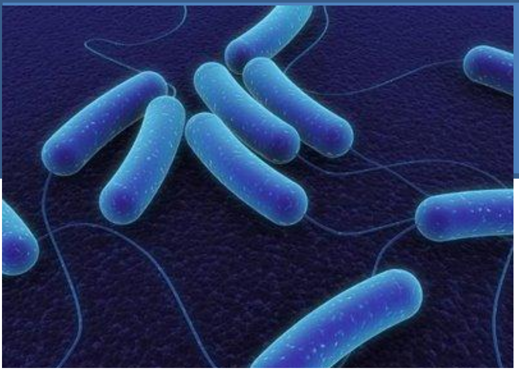
quadrupole loop



Guasto website

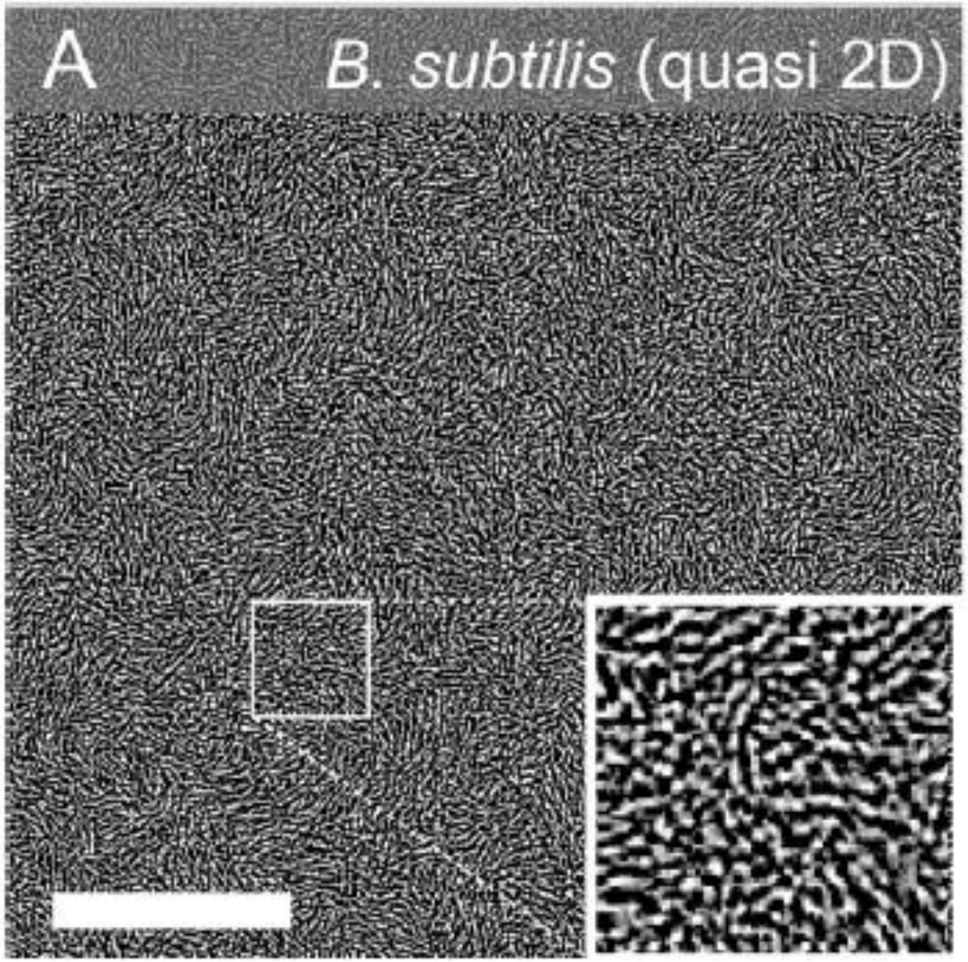
Bacteria

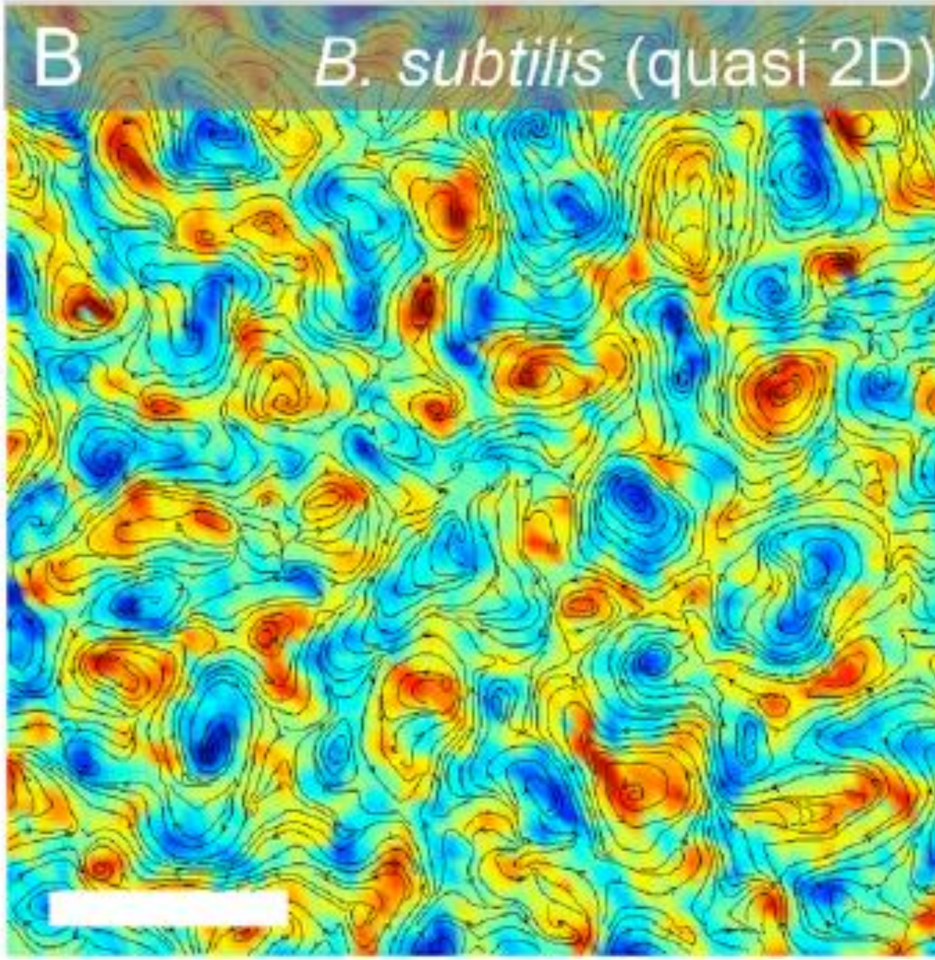




Bacteria

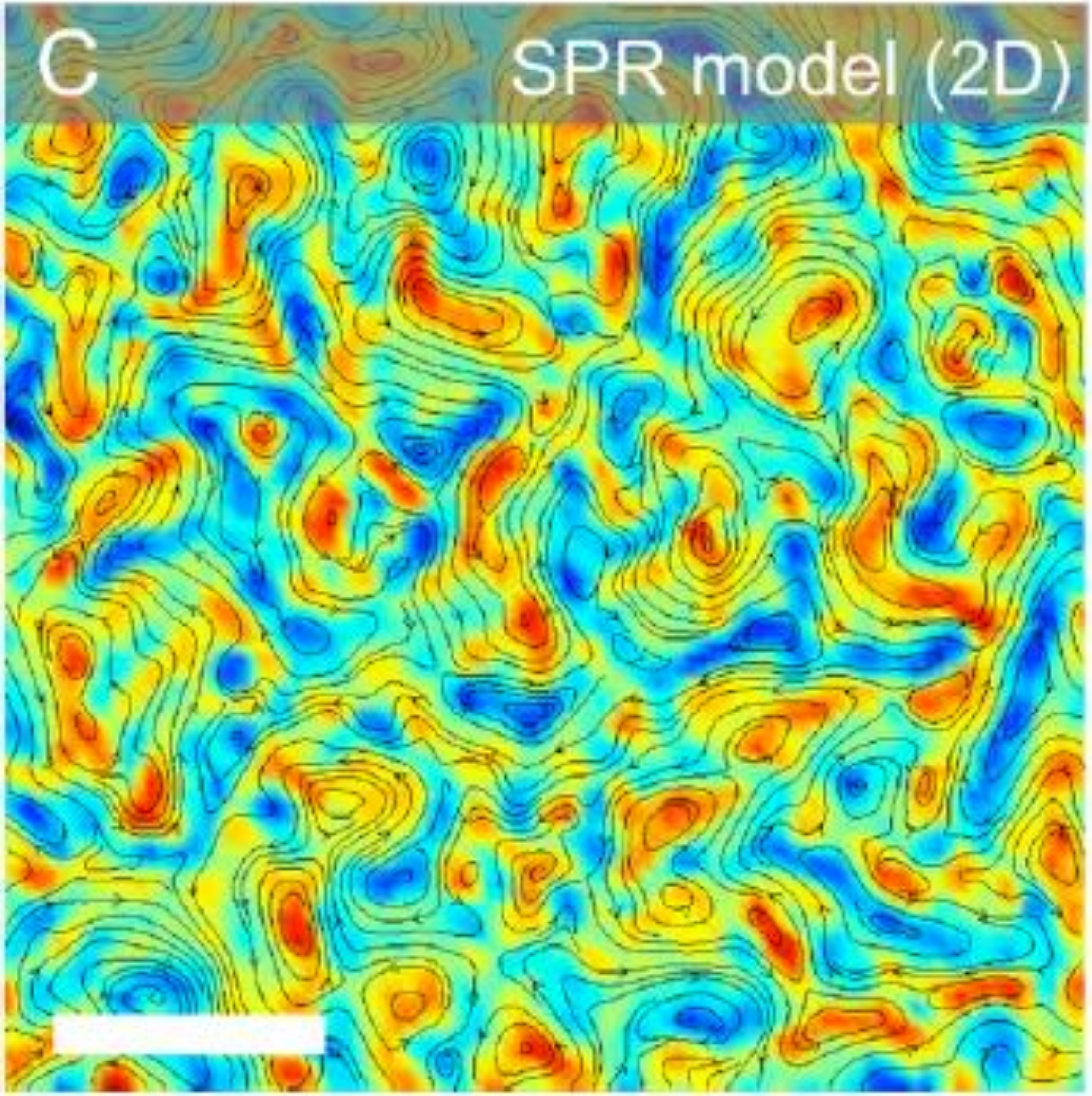
vorticity





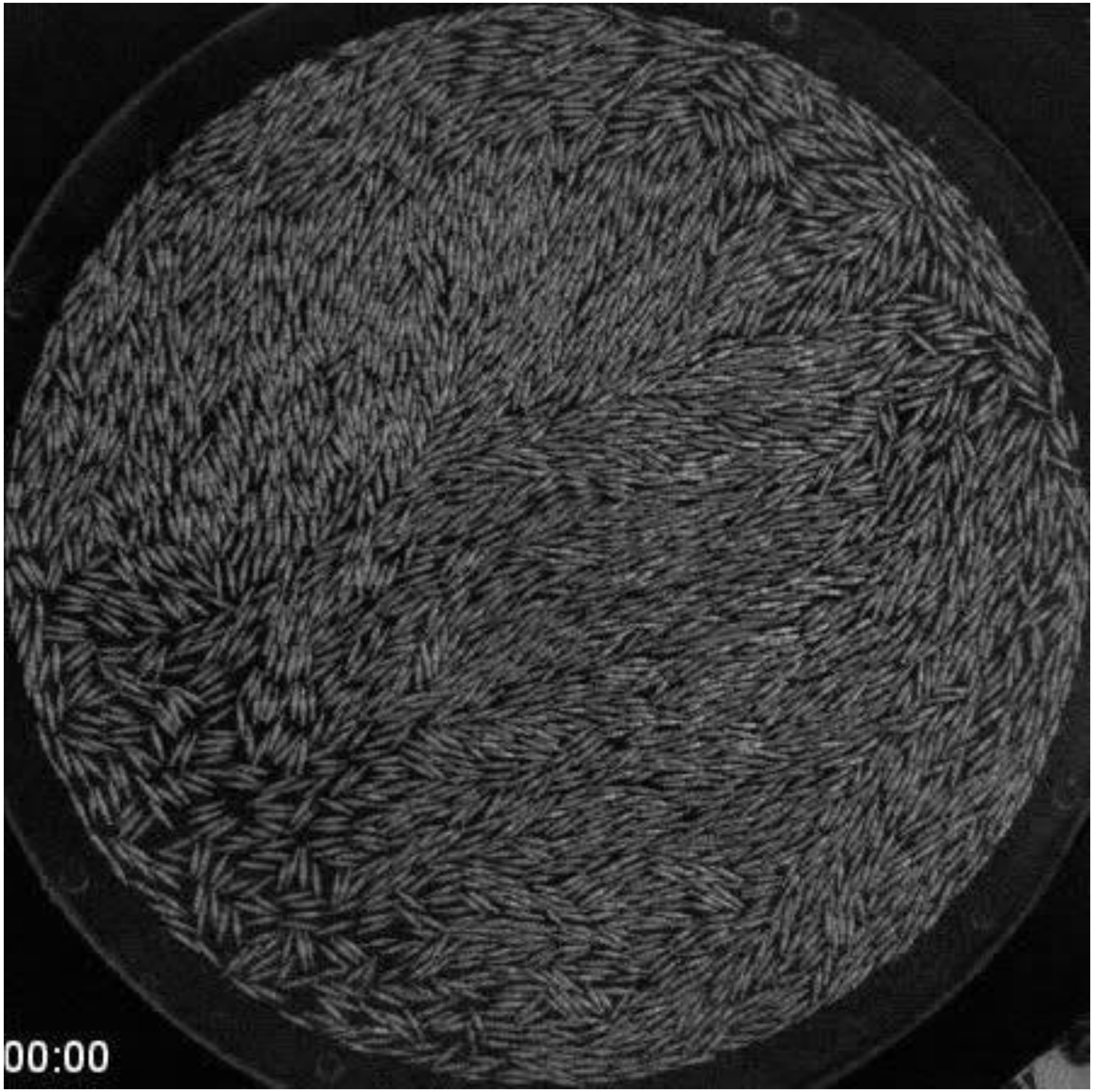
Wensink, Dunkel, Heidenreich, Dresher, Goldstein, Lowen, Yeomans, PNAS 2012

Discrete simulations



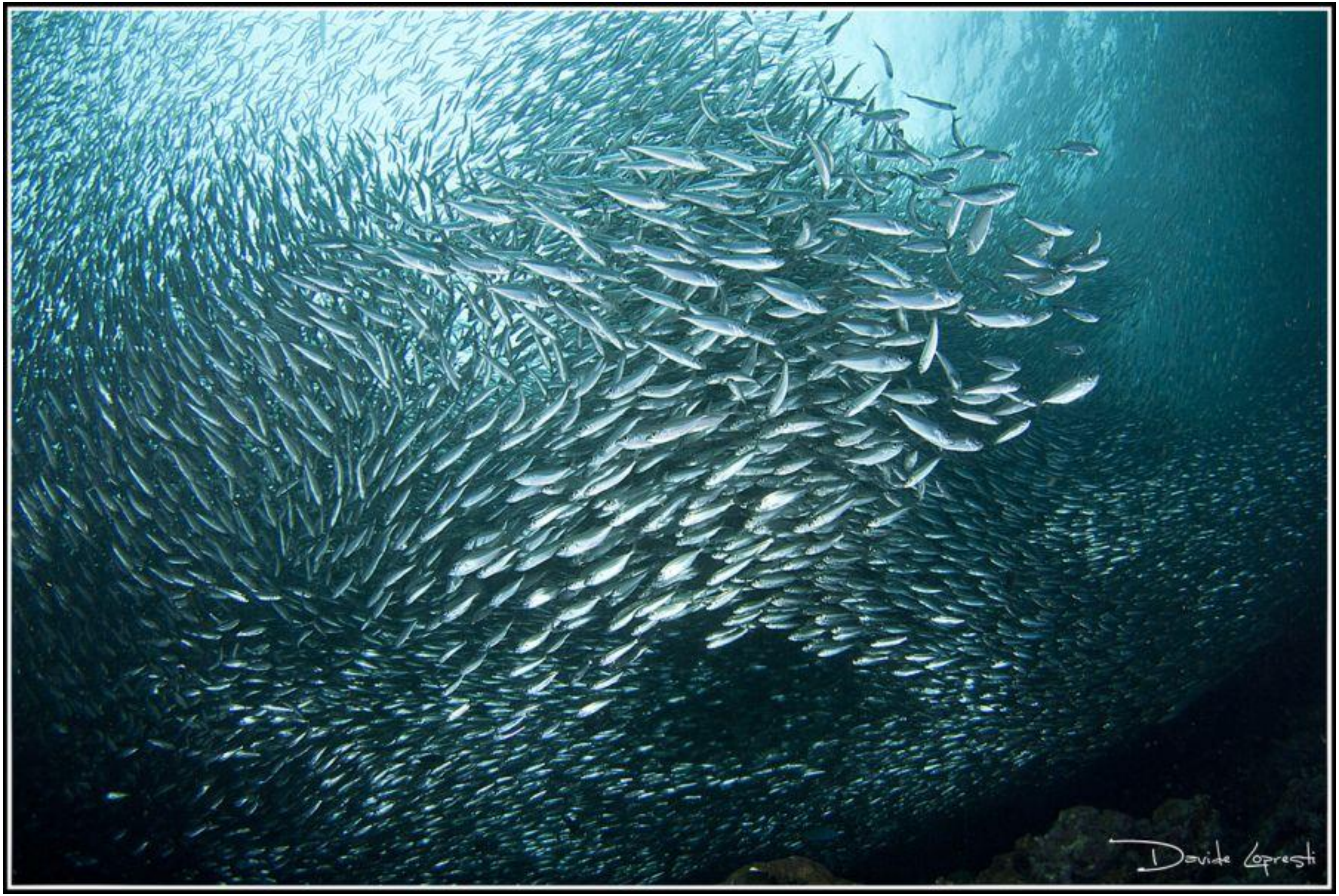
Wensink, Dunkel, Heidenreich, Dresher, Goldstein, Lowen, Yeomans, PNAS 2012

Driven grains

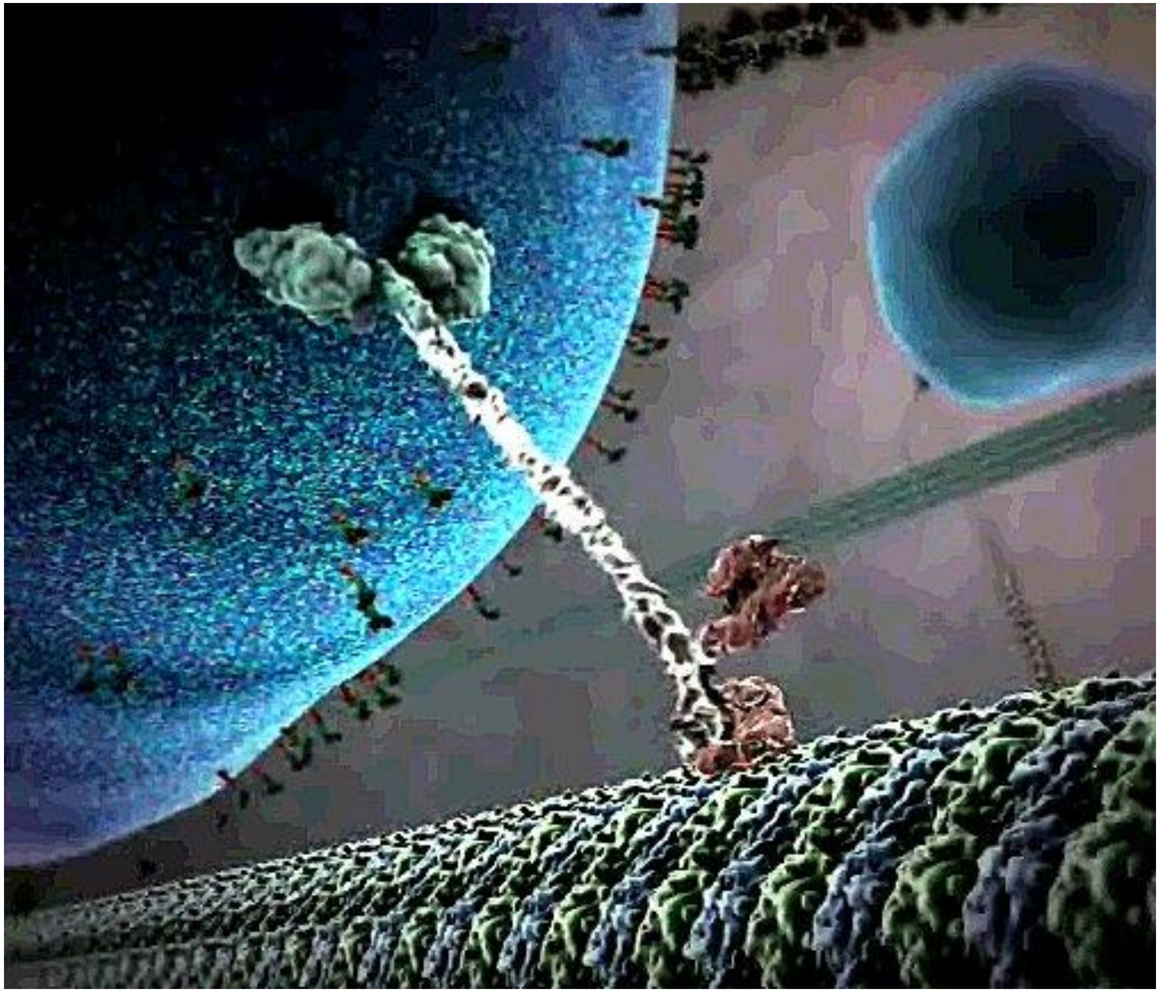


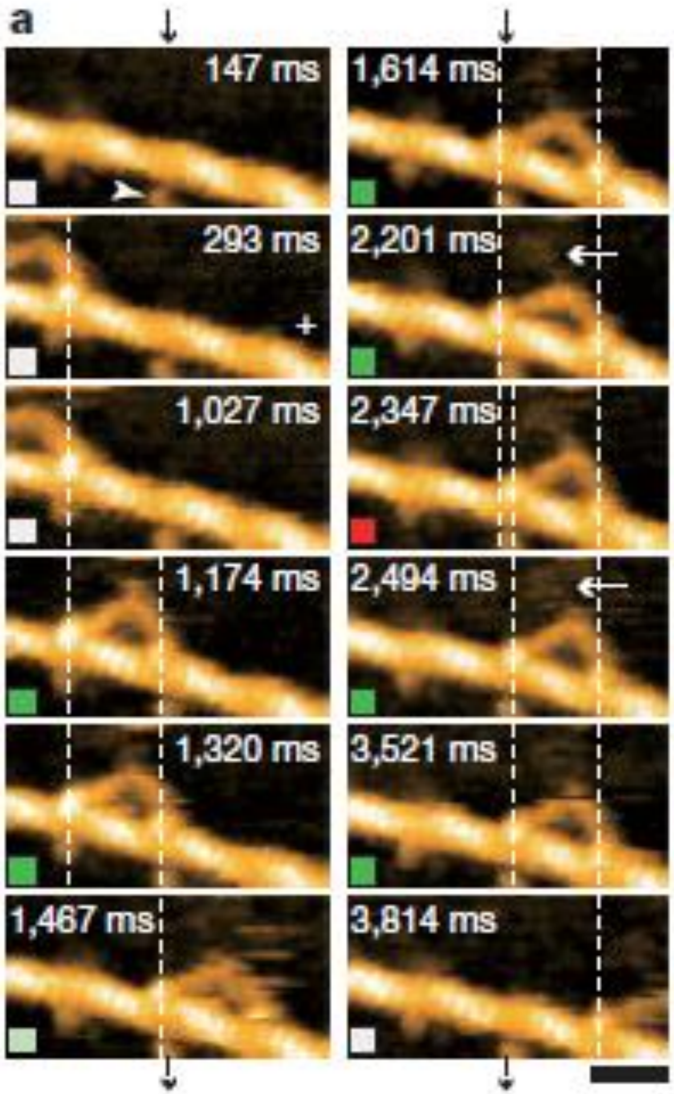
V Narayan, S Ramaswamy, N Menon - Science, 2007

Fish?



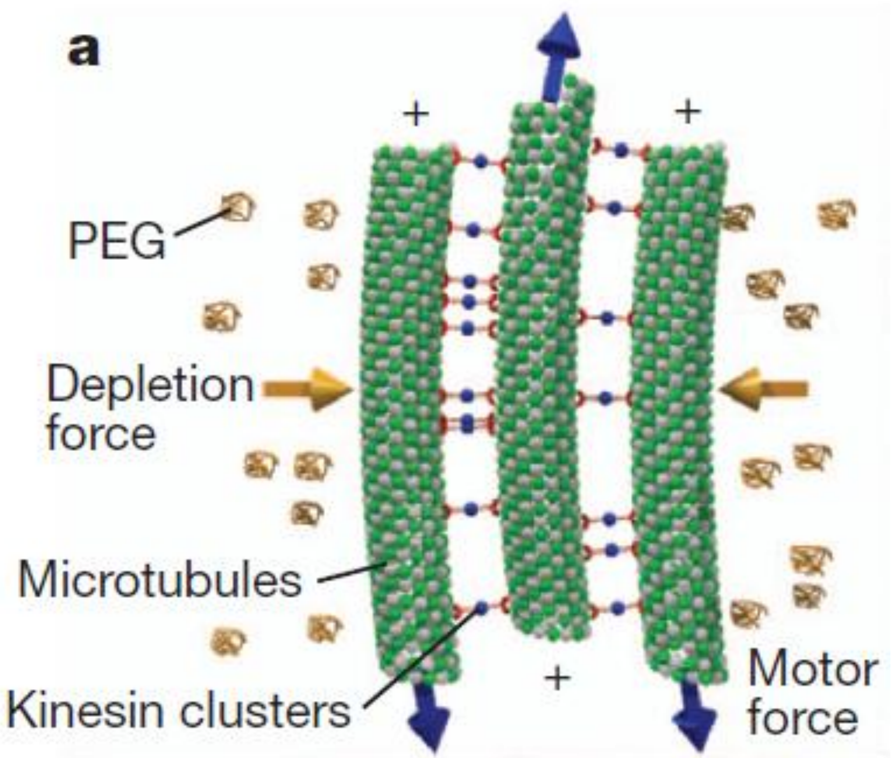
Molecular motors

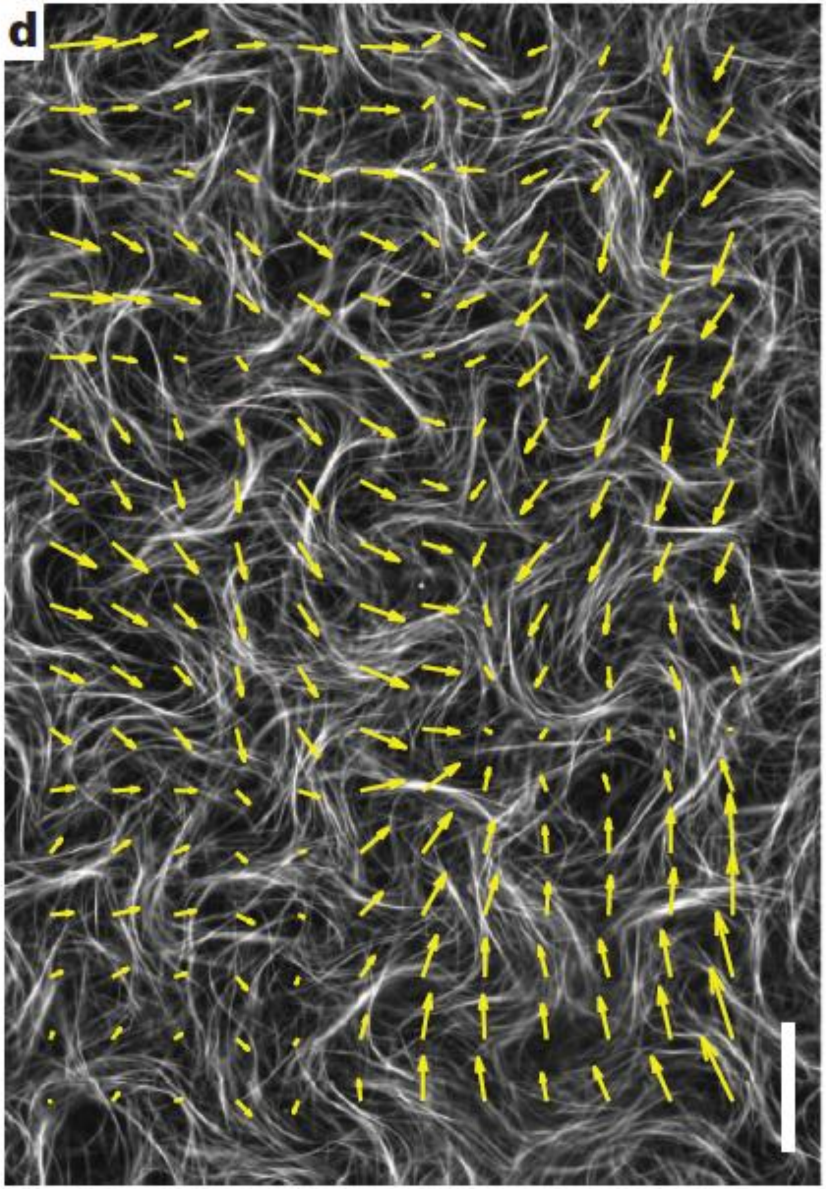




Inner life of a cell You tube

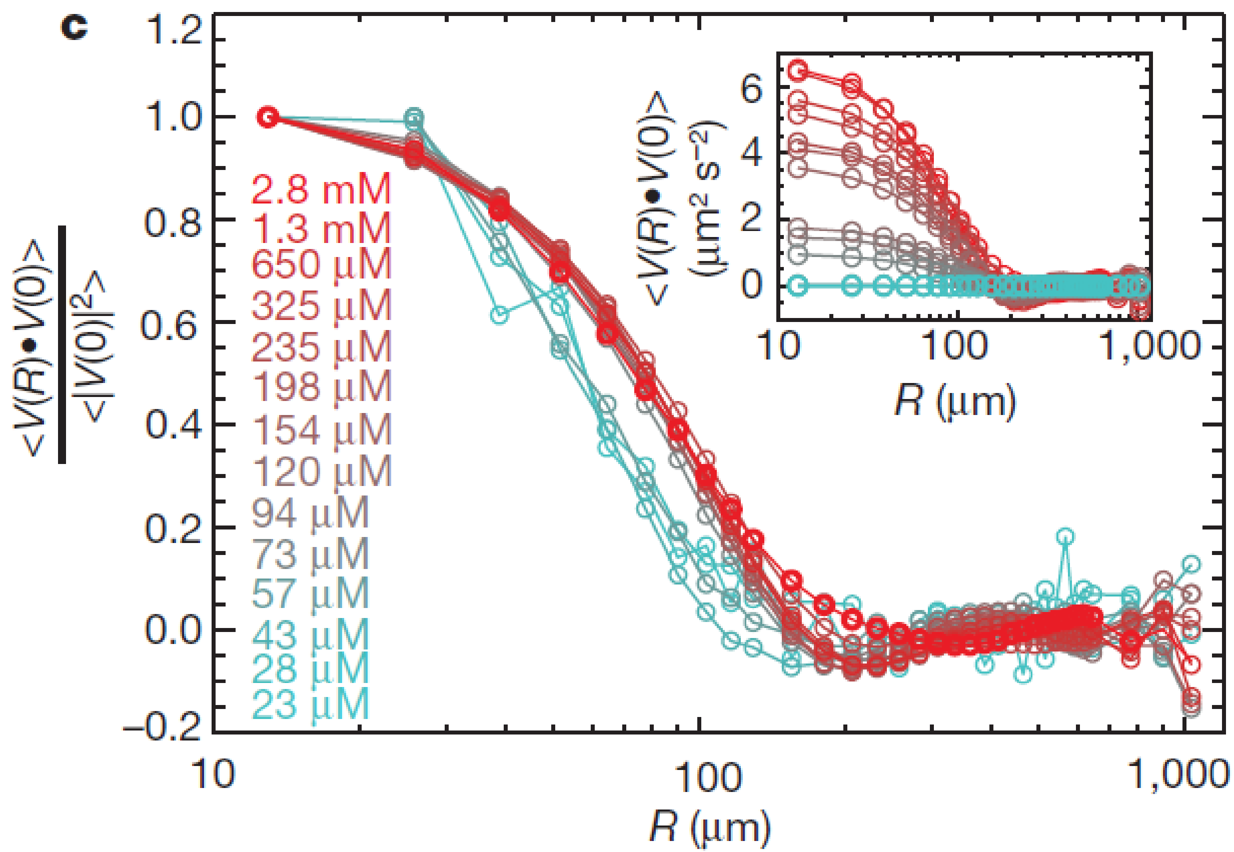
Molecular motors





Sanchez, Chen, DeCamp, Heymann, Dogic, Nature 2012

Molecular motors

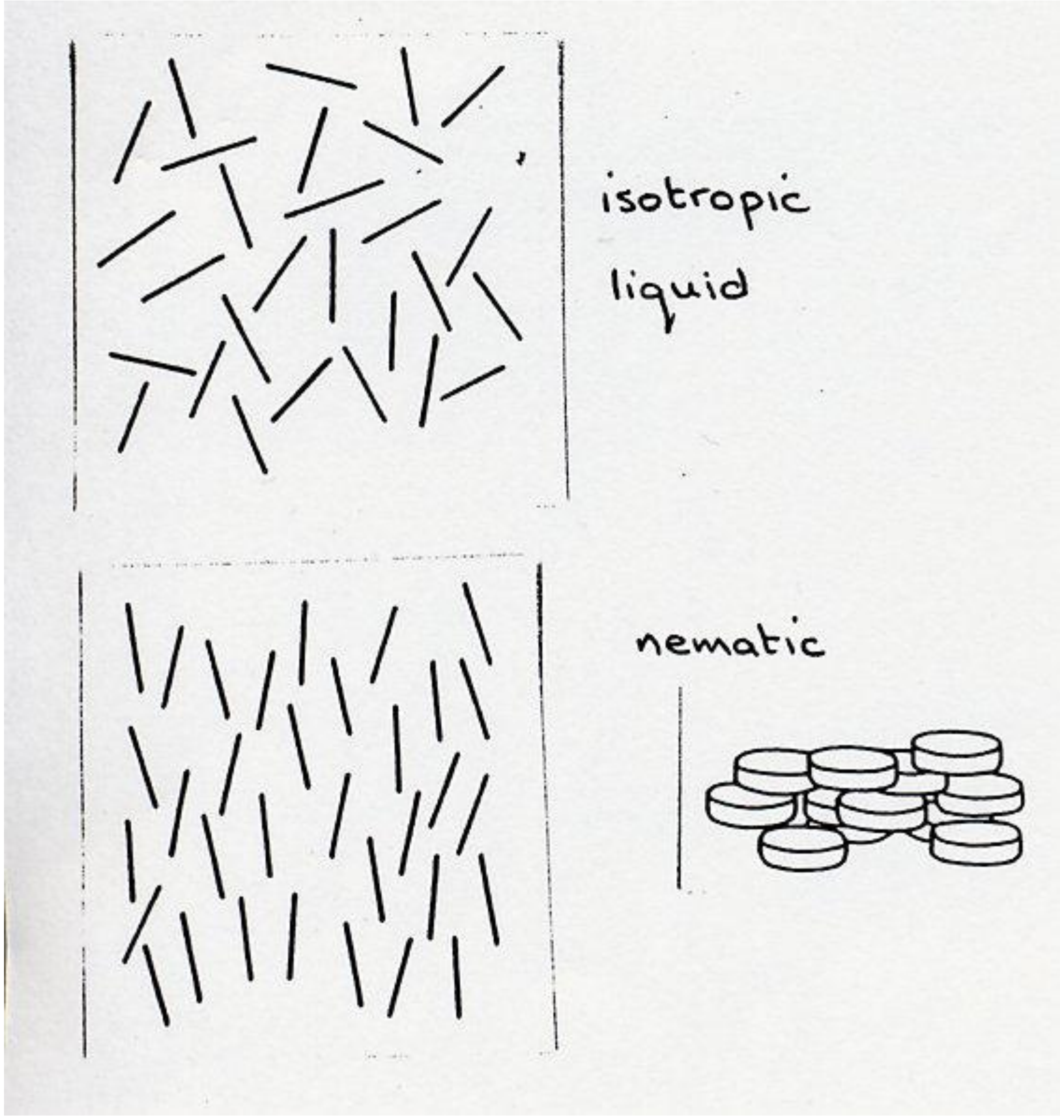


Velocity increases with activity

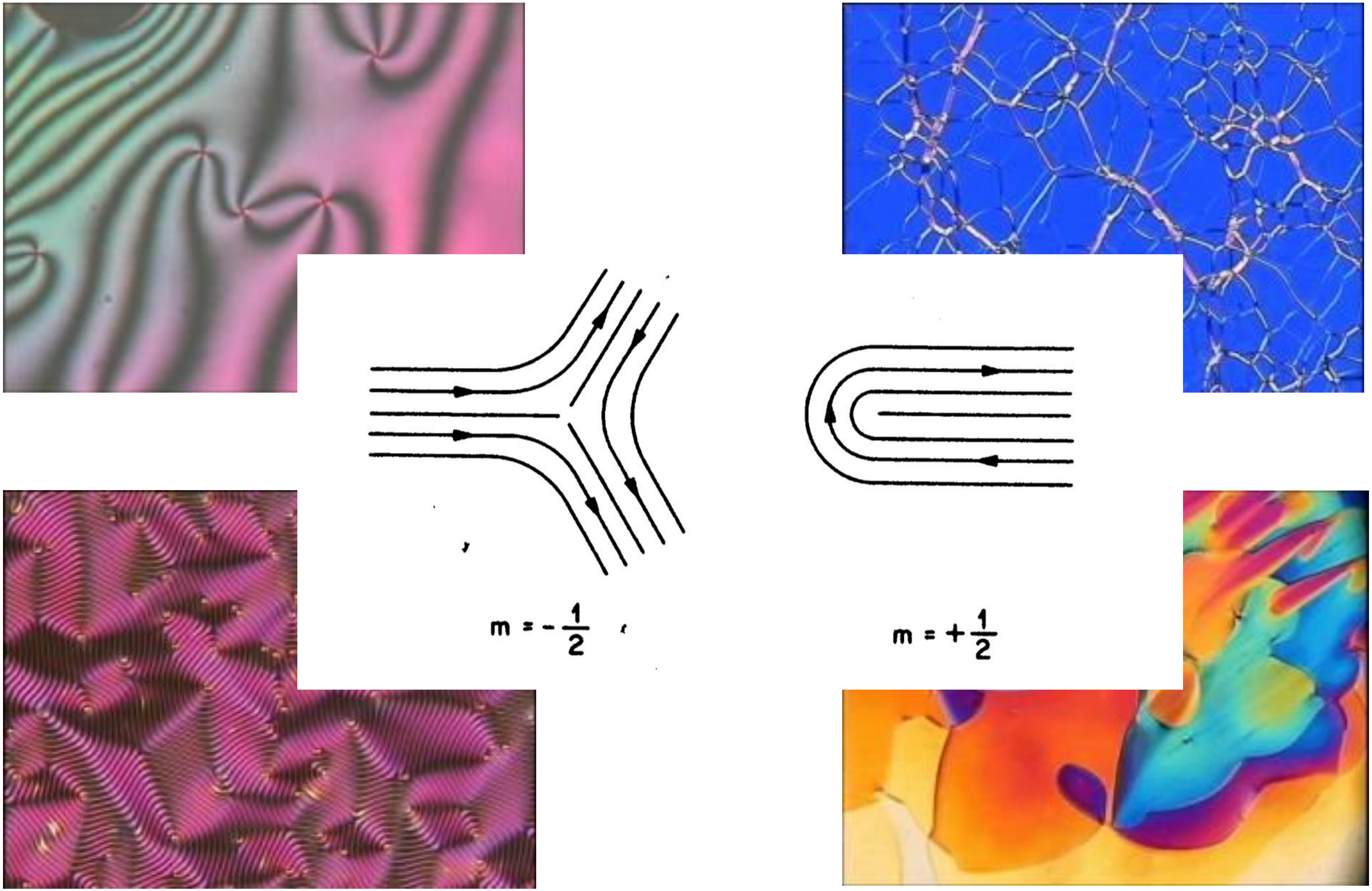
Length scale controlling decay of <vv> independent of activity

Sanchez, Chen, DeCamp, Heymann, Dogic, Nature 2012

Liquid crystals



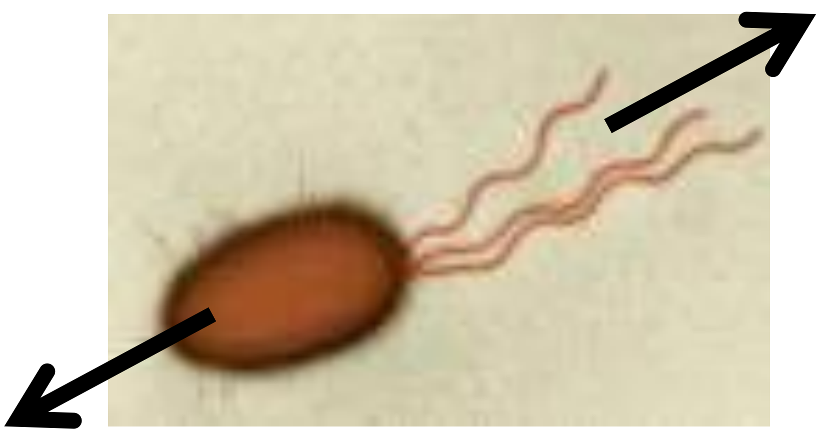
Topological defects

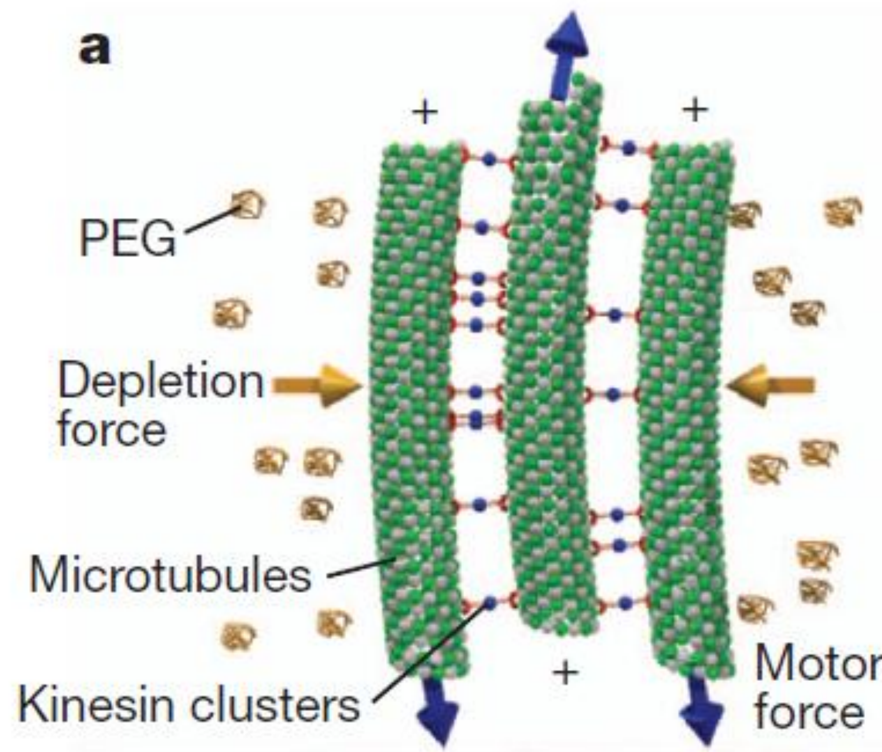


Continuum equations of active nematics

Liquid crystal equations of motion +
additional term in the stress tensor

Consequence of a dipolar source term





Hatwalne, Ramaswamy, Rao, Simha, PRL 2003

Continuum equations of active nematics

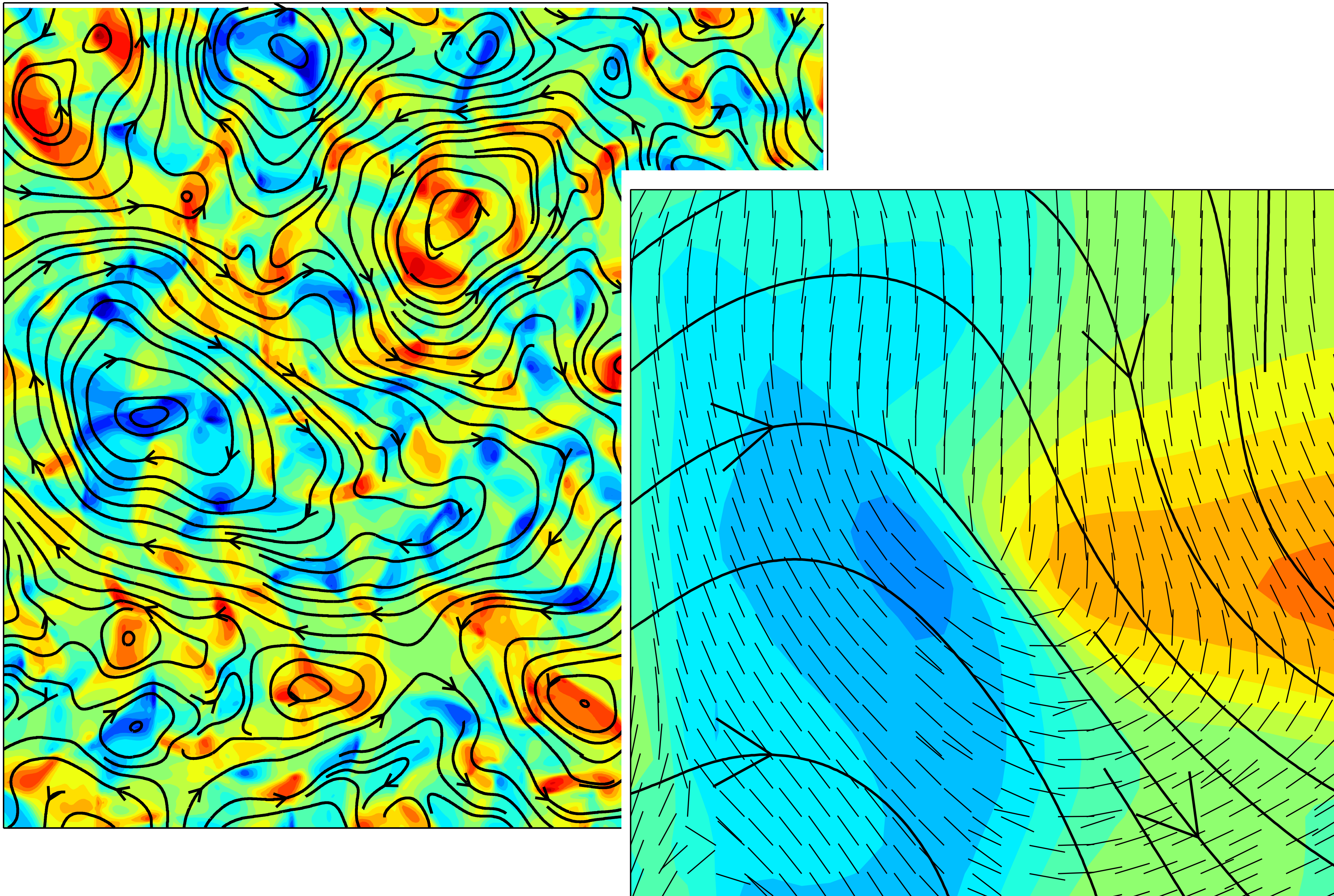
Liquid crystal equations of motion +
additional term in the stress tensor

Gradients in the order parameter field induce a flow

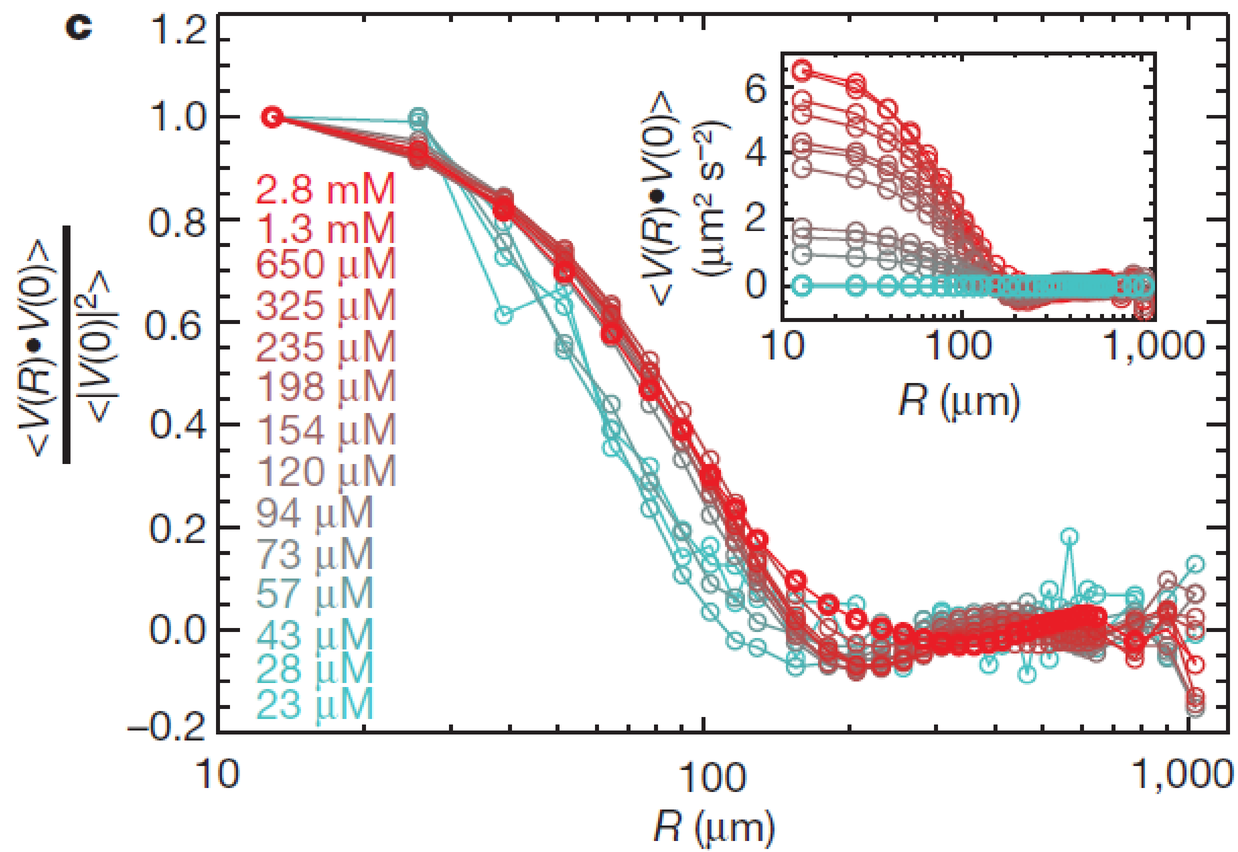
Nematic state is unstable

Hatwalne, Ramaswamy, Rao, Simha, PRL 2003

Active turbulence in extensile suspensions



Molecular motors

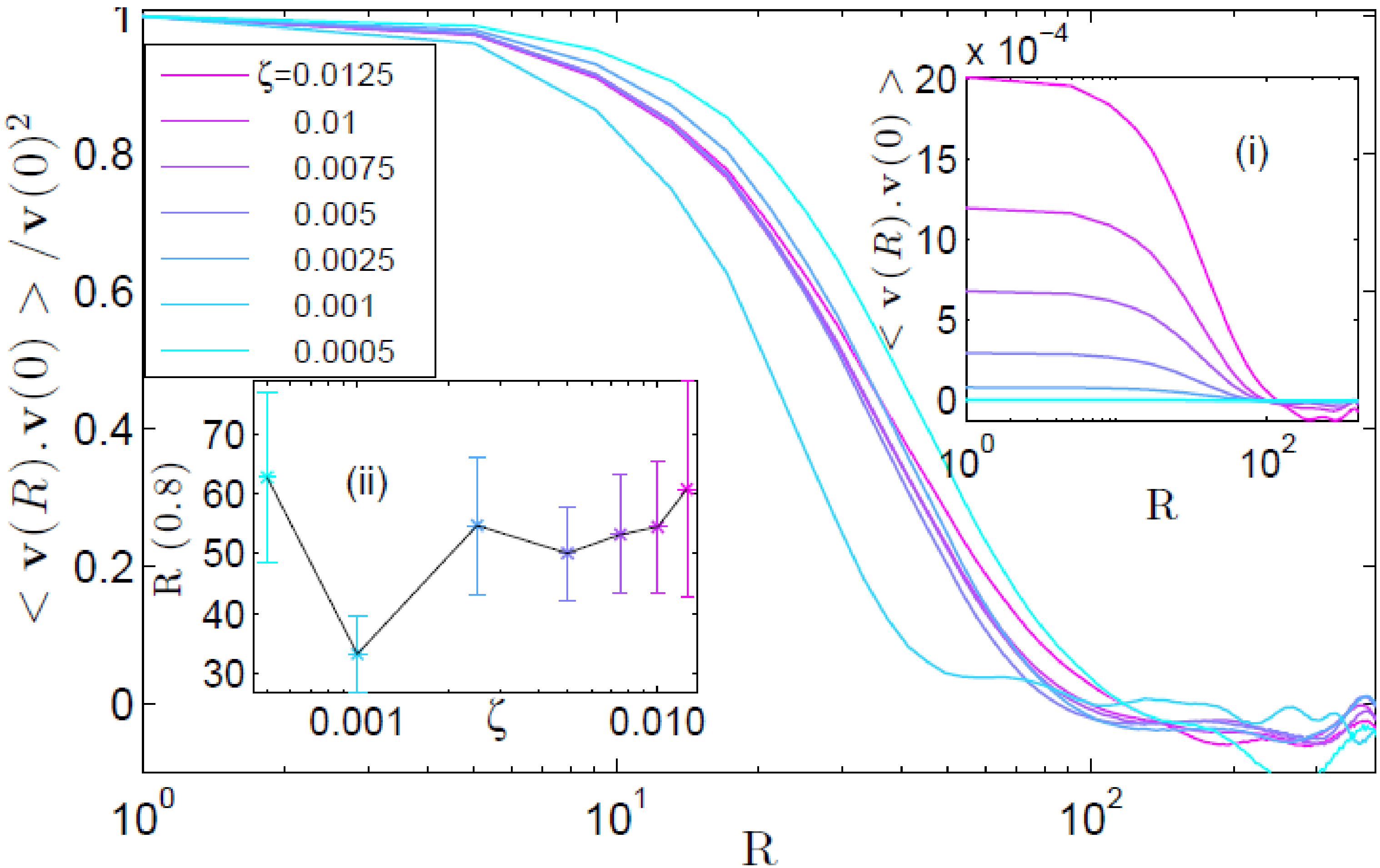


Velocity increases with activity

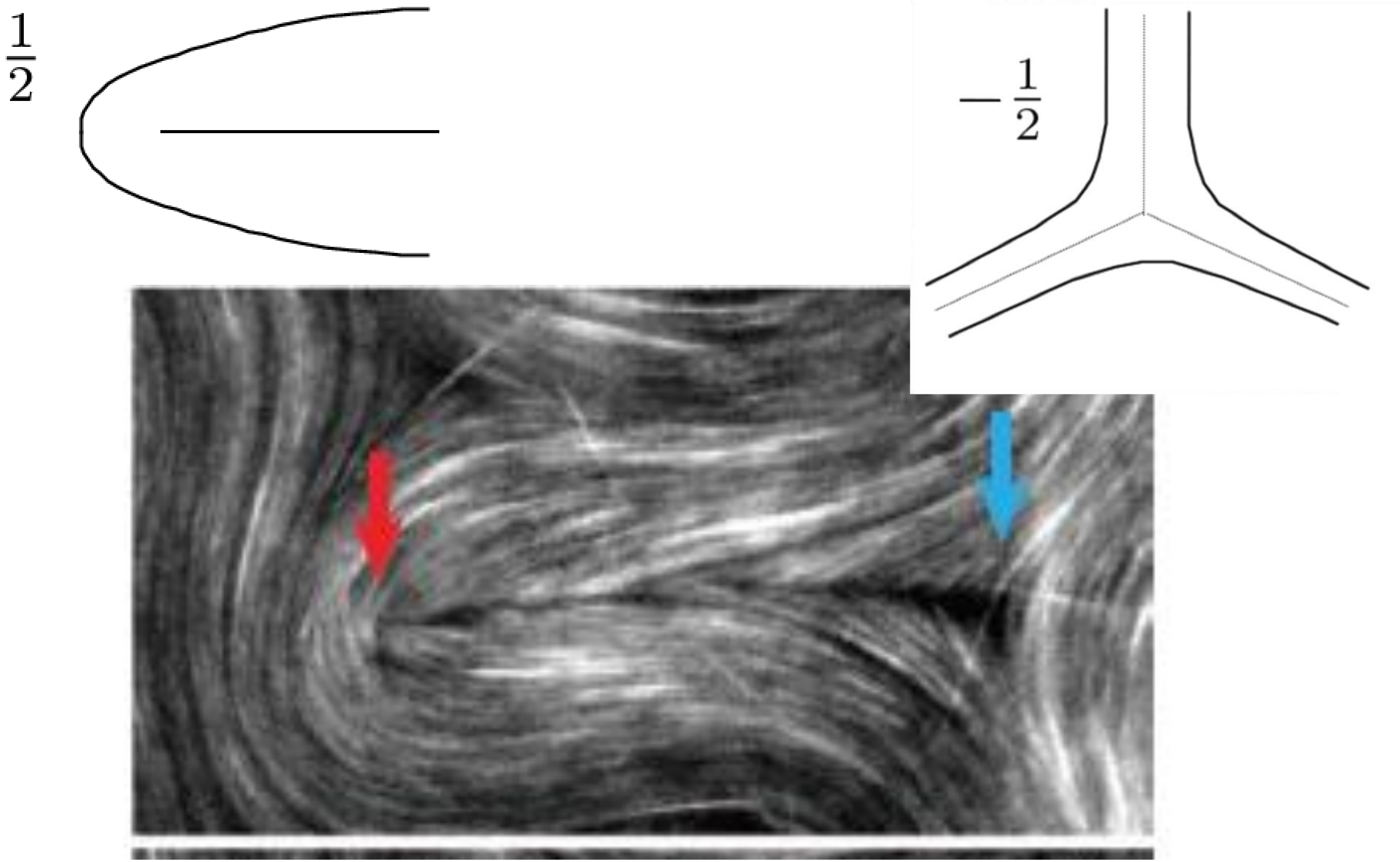
Length scale controlling decay of <vv> independent of activity

Sanchez, Chen, DeCamp, Heymann, Dogic, Nature 2012

<vv>: simulations

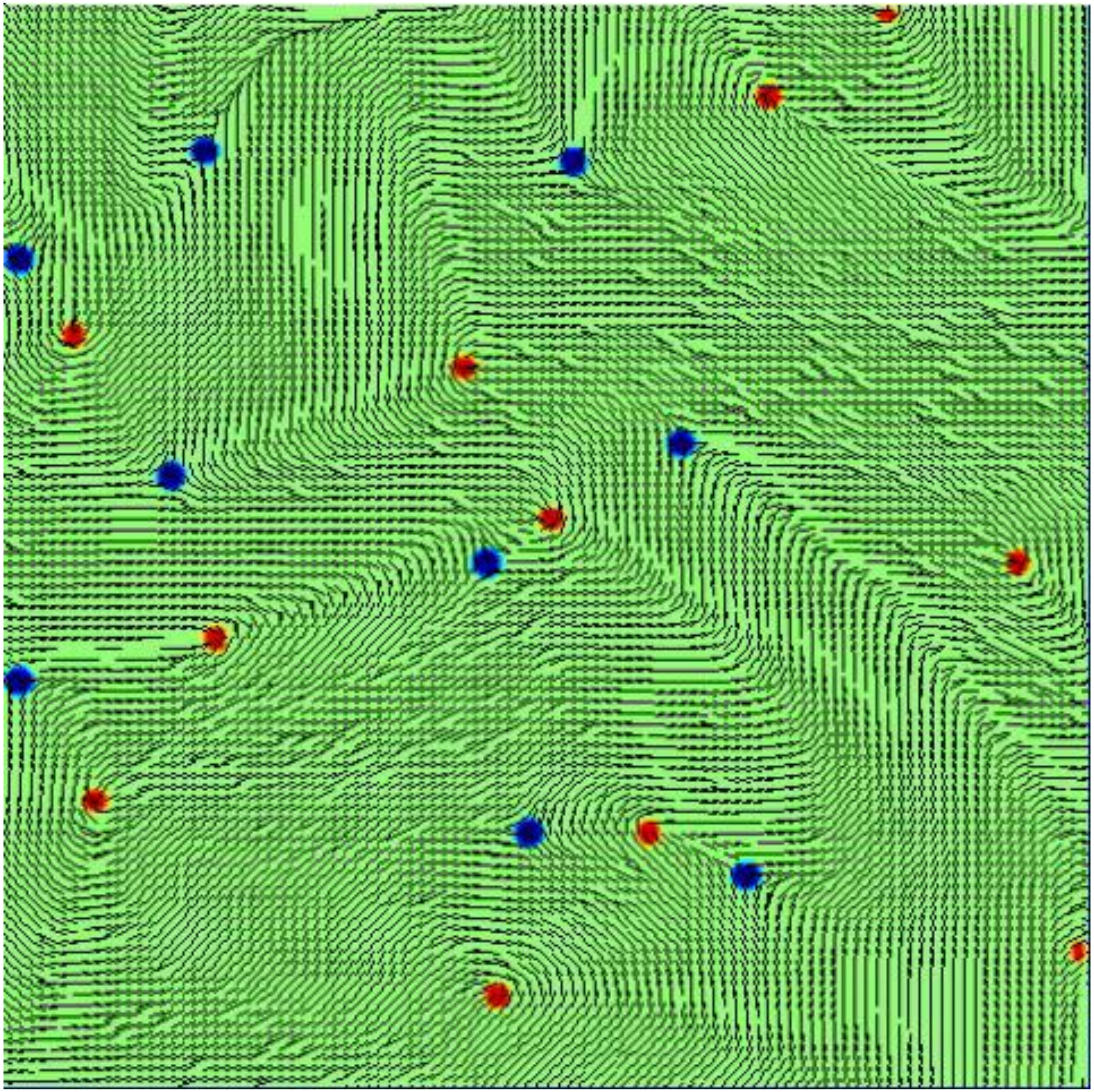


Topological defects in active systems



microtubule bundles driven by molecular motors

L. Giomi, M.J. Bowick, Ma Xu, M.C. Marchetti, PRL 110, 228101
Sanchez, Chen, DeCamp, Heymann, Dogic, Nature 2012



Defect dynamics: steady state

$$\alpha \frac{\zeta}{K} = \beta \frac{\sigma \zeta \ell Q n^2}{\mu}$$

ℓ independent of activity

Active nematics

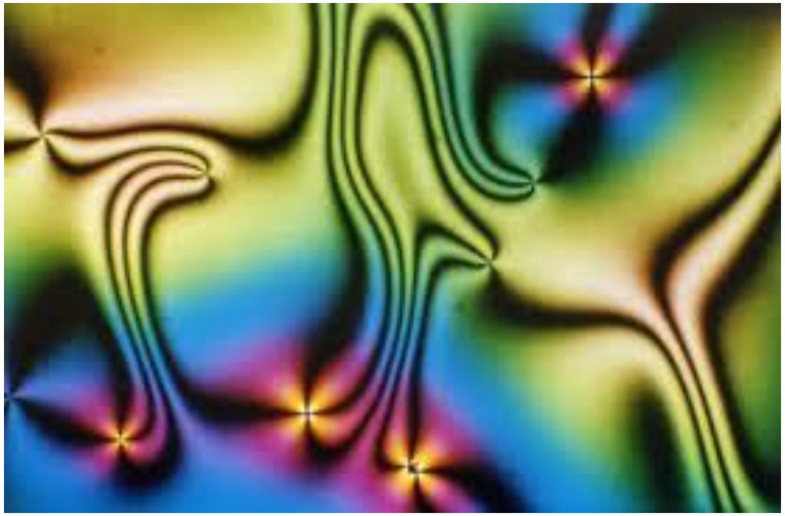
Experimental and simulation evidence that defects control active turbulence

Predicting the rate of defect formation?

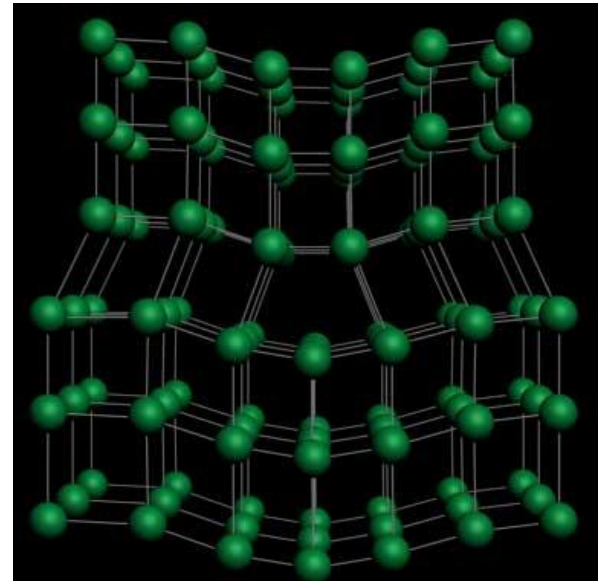
Predicting the cross section for annihilation?

Varying concentration?

How generic is this picture?



liquid crystals

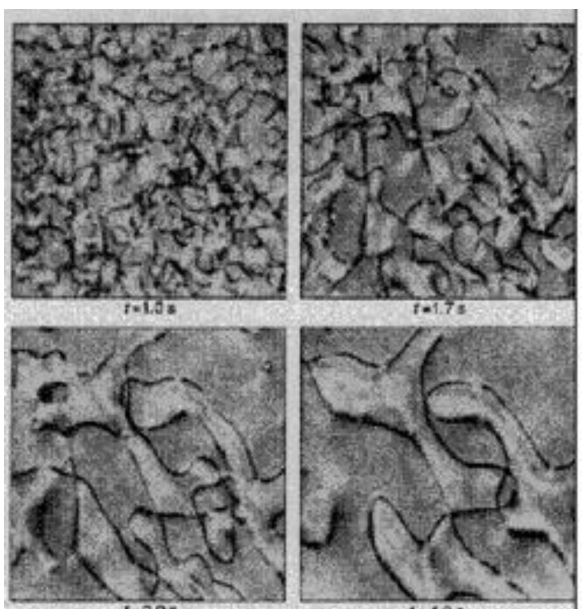


crystal dislocations

magnetic monopoles in spin ice

topological insulators

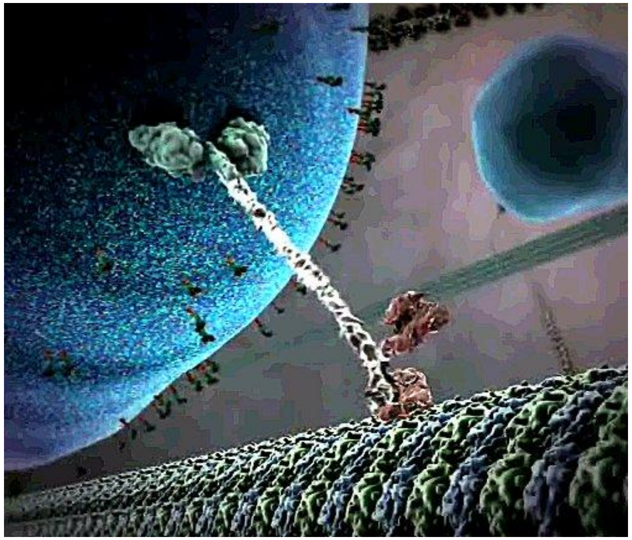
quantum vortex in a superfluid



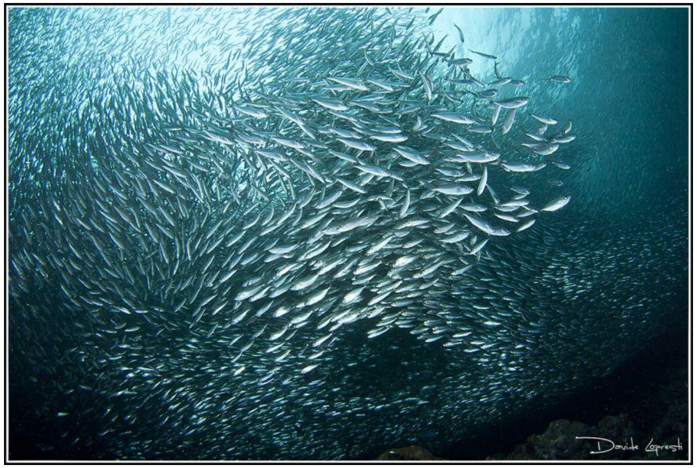
cosmic strings in the early universe

Active matter

bacteria, self-propelled colloids



molecular motors, cells



birds, fish

active systems operate out of thermodynamic equilibrium

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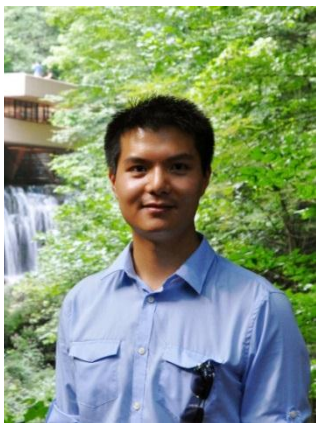

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