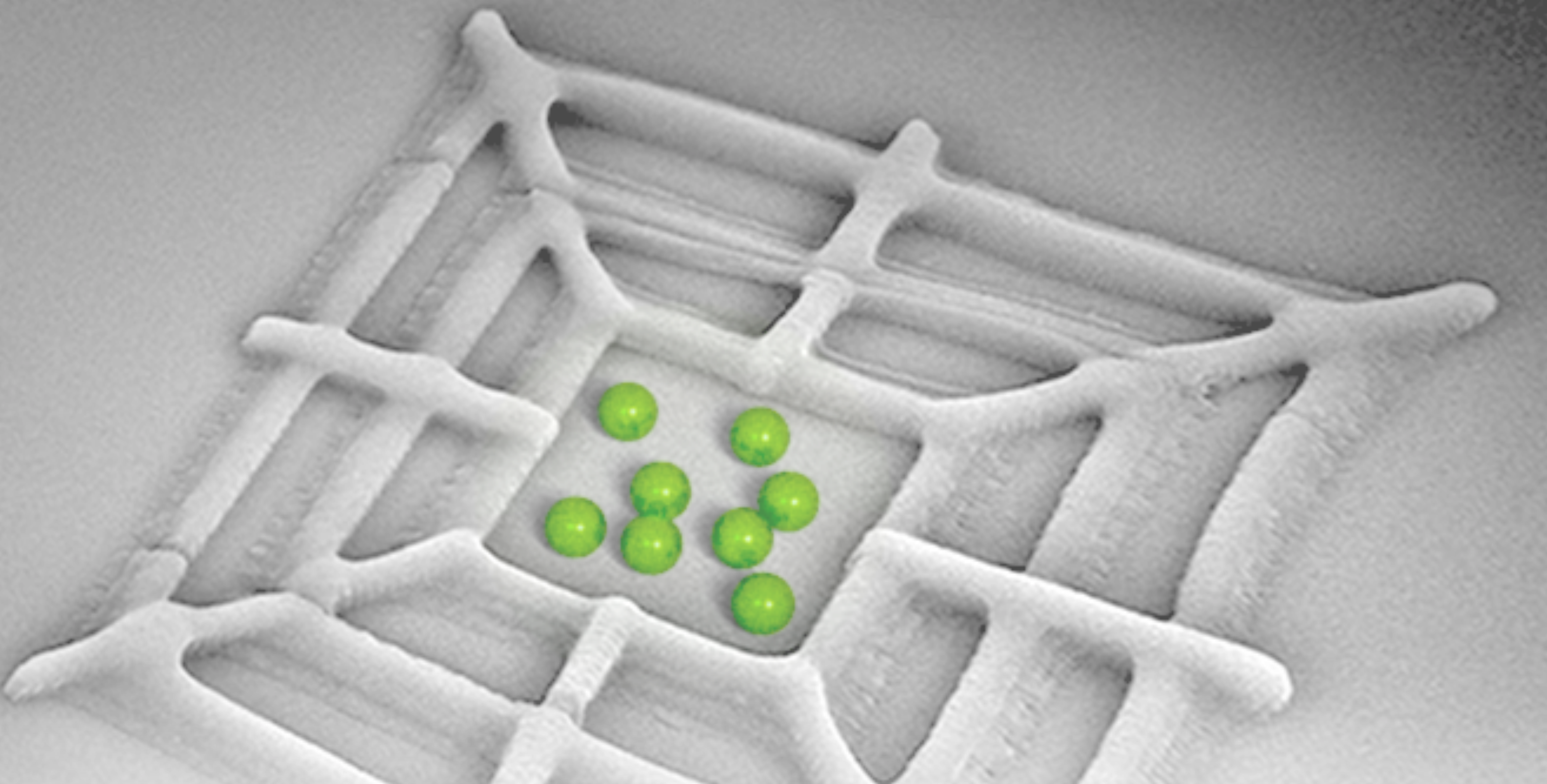
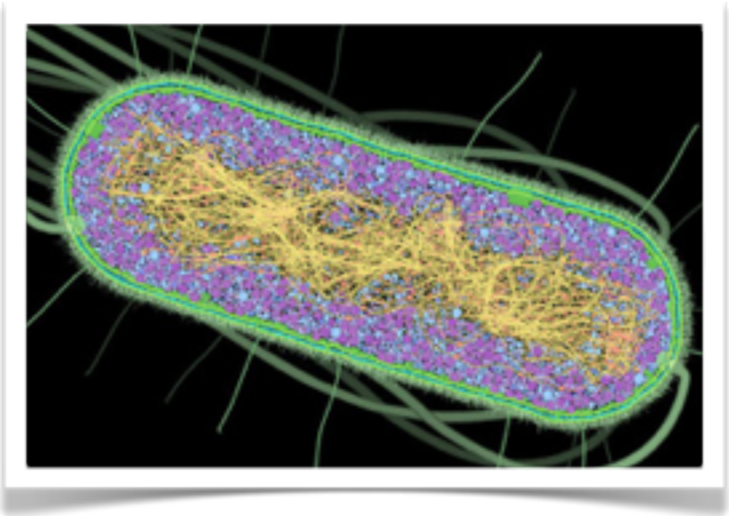


Swimming in complex environments: from biofilms to bacteria powered micro-devices

ROBERTO DI LEONARDO
Dip. Fisica, Sapienza Università di Roma, Italy
CNR-NANOTEC Soft and Living Matter Laboratory
School for Advanced Studies Sapienza

Plan

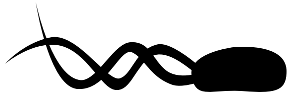
A SELF-PROPELLED MICRO-ORGANISM



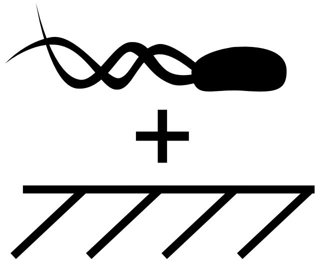
TODAY

Microhydrodynamics

a) SELF PROPELLING BACTERIA



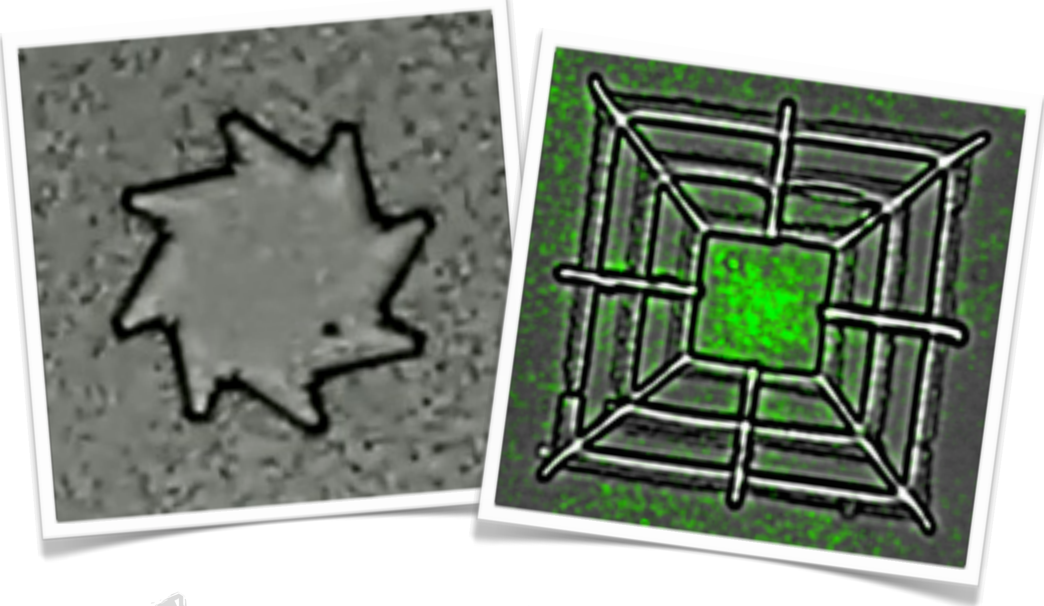
b) CONFINED SWIMMING



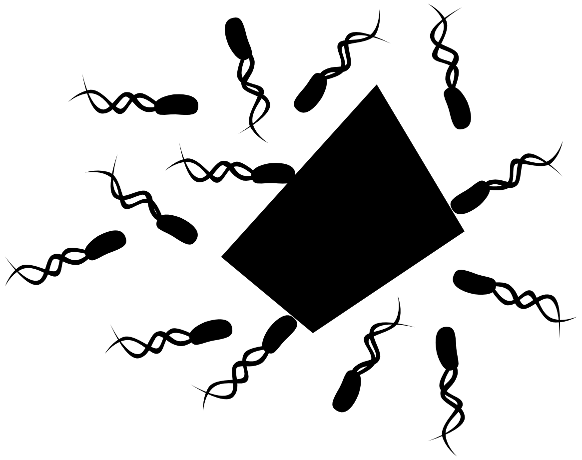
FRIDAY

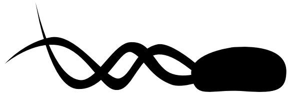
Statistical Mechanics

d) BACTERIA POWERED MICRODEVICES



c) STOCHASTIC DYNAMICS IN ACTIVE BATHS





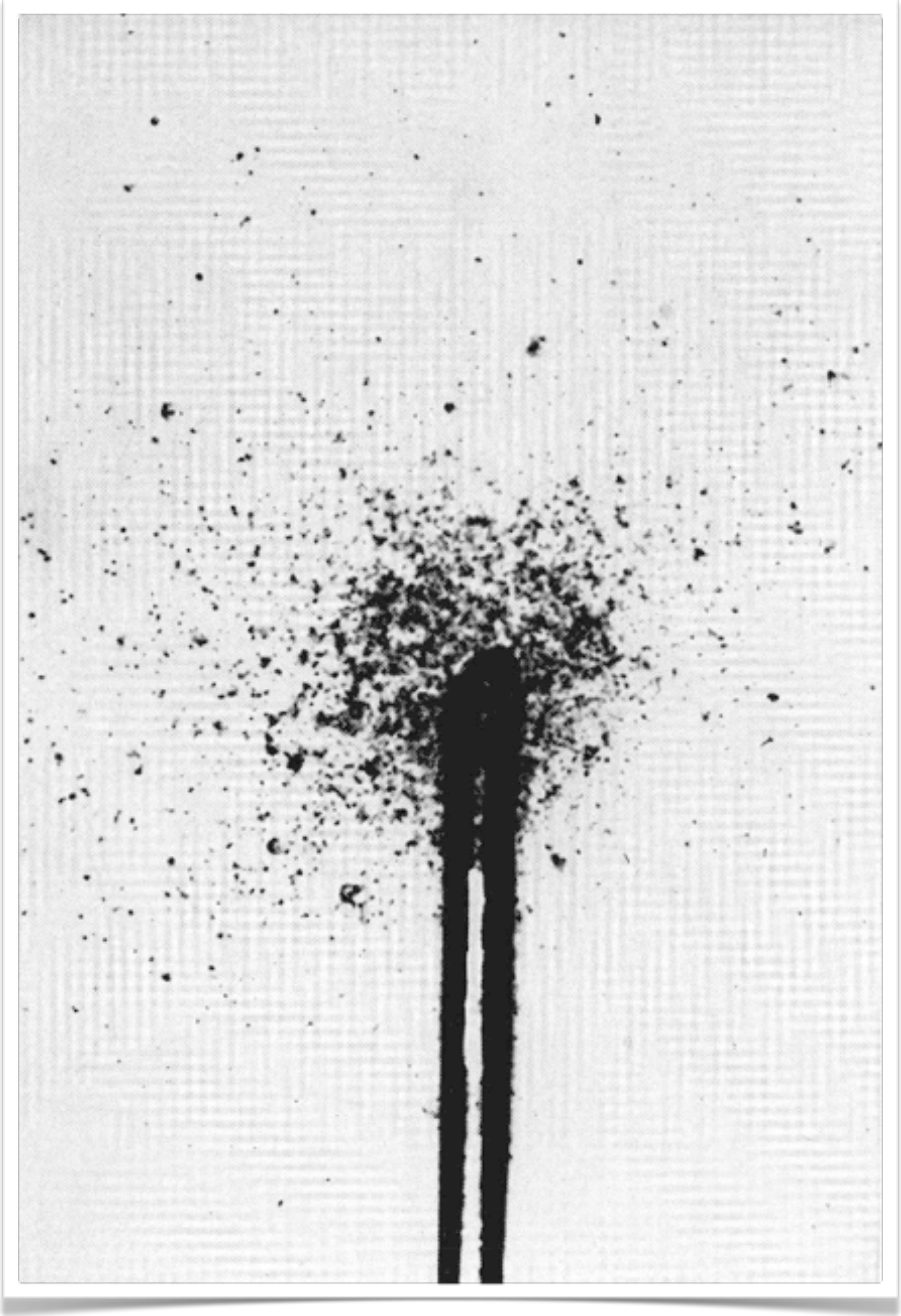
SELF-PROPULSION

swimming at the micron-scale

Swimming bacteria: why?

CHEMOTAXIS

J. ADLER, SCIENCE (1969)



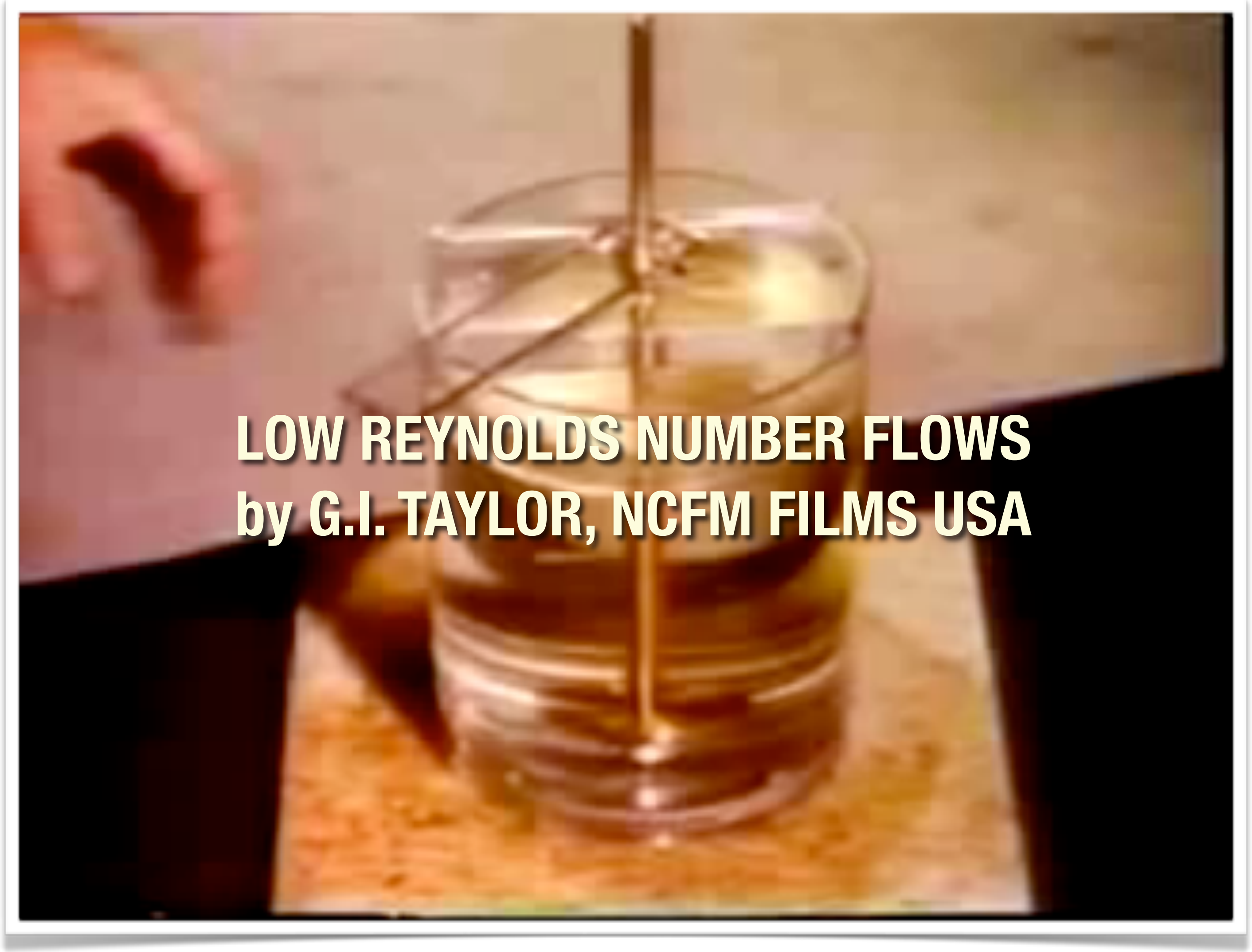
BACTERIA ARE COLLOIDS

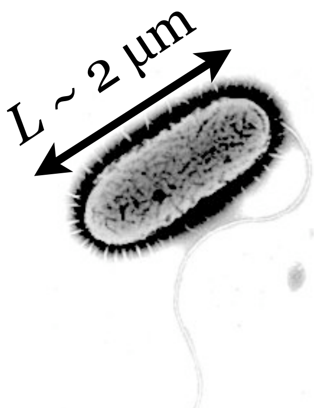
$$D \sim 0.2\ \mu\mathrm{m}^2/s$$

- **SELF-PROPULSION MECHANISM**
- **PERSISTENT MOTION**
- **“SNIFF” NUTRIENT GRADIENTS**

Problem 1: hydrodynamic reversibility

A PHYSICAL DEFINITION OF SWIMMING:
propel the body through a cyclic shape deformation





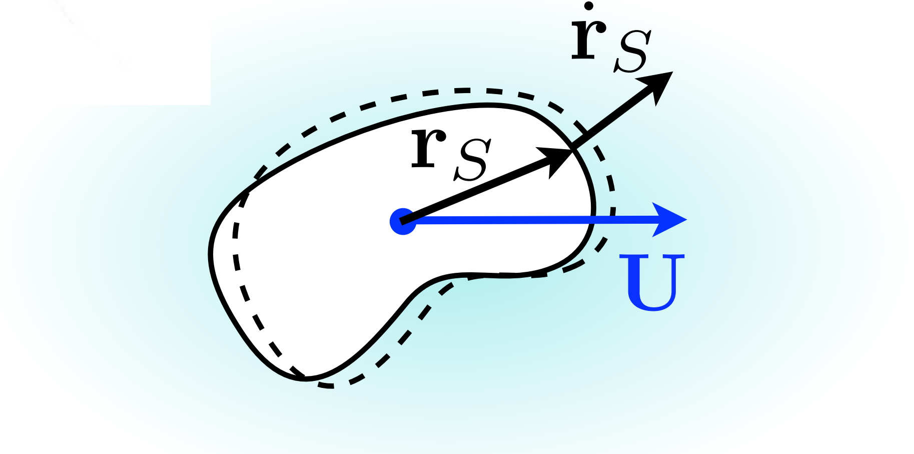
LOW REYNOLDS NUMBER

$$\Rightarrow \mathrm{Re} \sim 10^{-5}$$

$$\Downarrow$$

STOKES EQUATION

$$\mu\nabla^2\mathbf{u} - \nabla p = 0 \qquad \nabla\cdot\mathbf{u} = 0$$



TIME-DEPENDENT BOUNDARY

$$\mathbf{u}(\mathbf{r}_S, t) = \underbrace{\dot{\mathbf{r}}_S(t)}_{\text{PRESCRIBED}} + \underbrace{\mathbf{U}(t)}_{\text{UNKNOWN}}$$

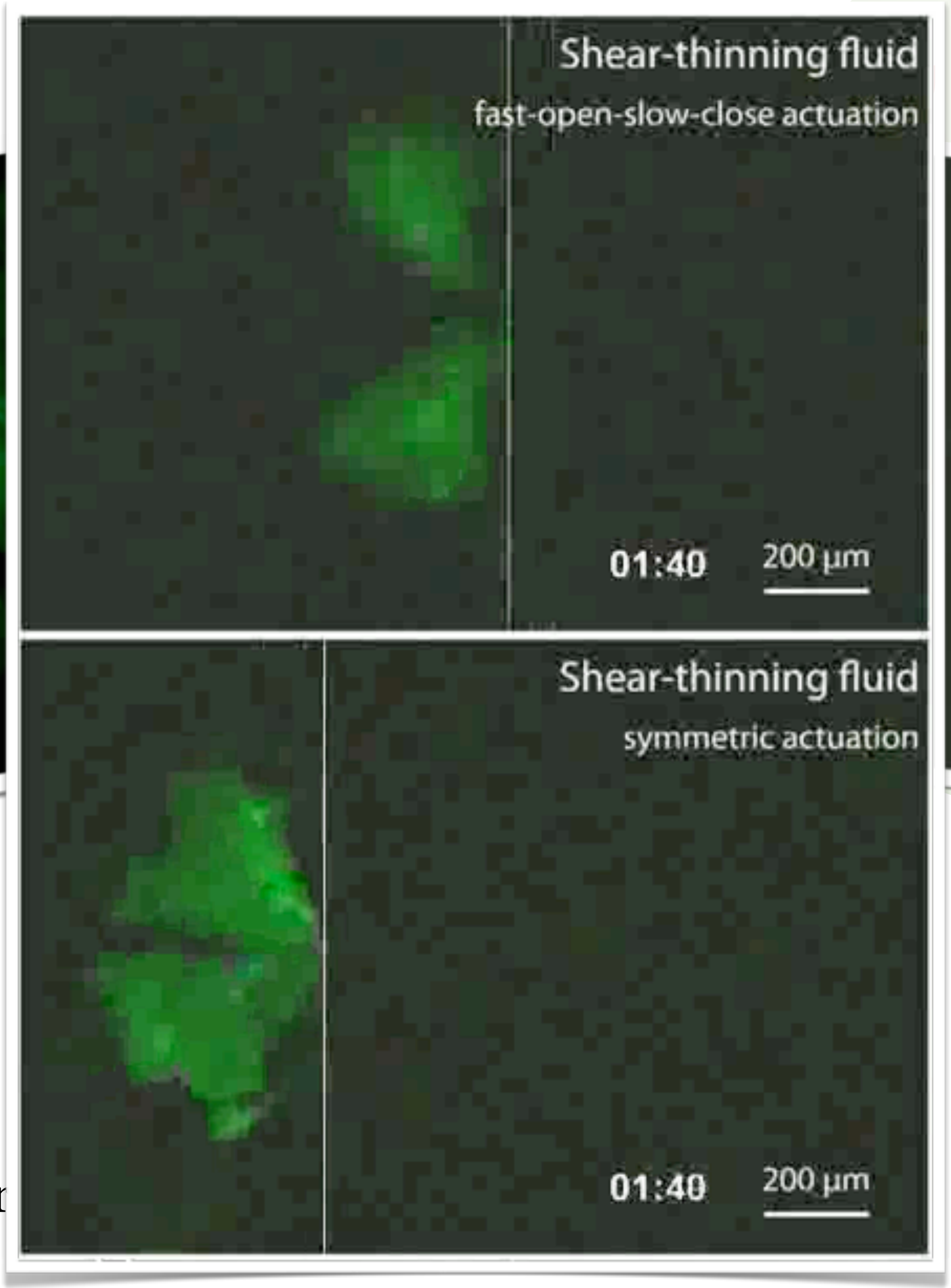
SOLVE FOR $\mathbf{u}, p$ AND IMPOSE FORCE-FREE CONDITION

$$\mathbf{F}(t) = 0 \Rightarrow \mathbf{U}(t)$$

$\alpha\dot{\mathbf{r}}_S \Rightarrow \alpha\mathbf{U}$ **HYDRODYNAMIC REVERSIBILITY**

Problem 1: hydrodynamic reversibility

HIGH Re



Re

QIU et al. NAT. COMM. (2014)

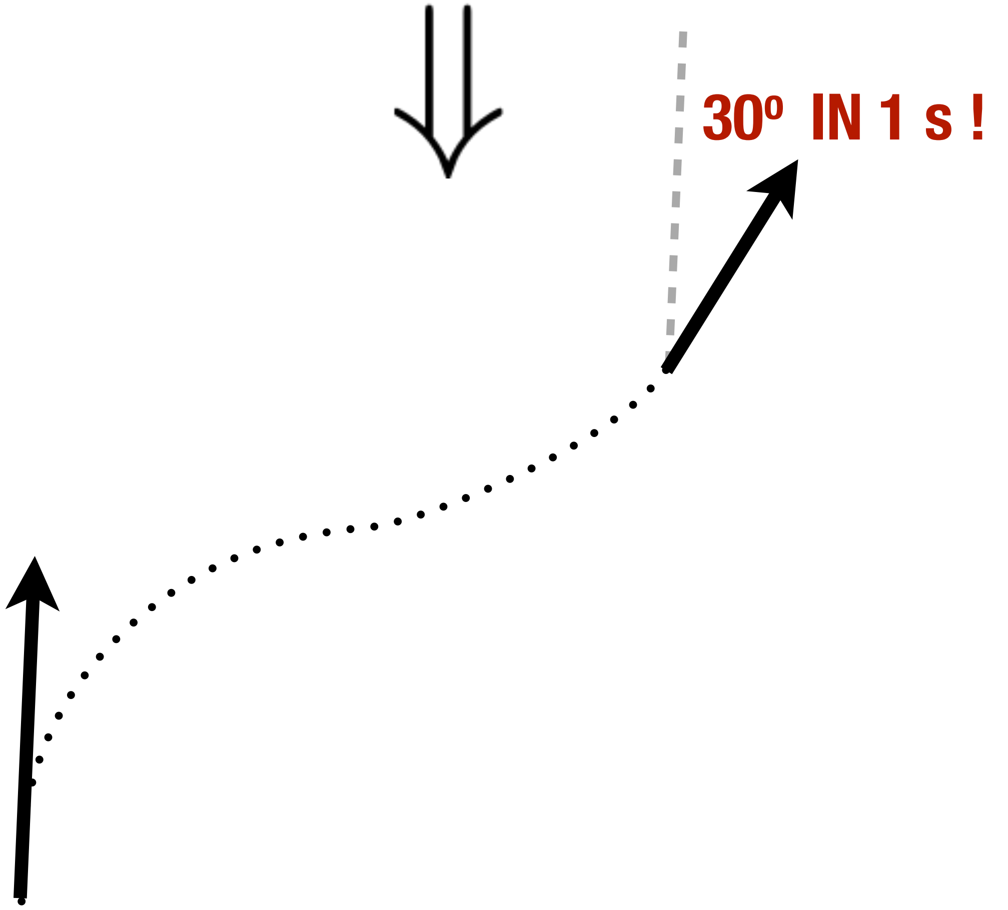
Problem 2: Brownian rotation

ROTATIONAL DIFFUSION

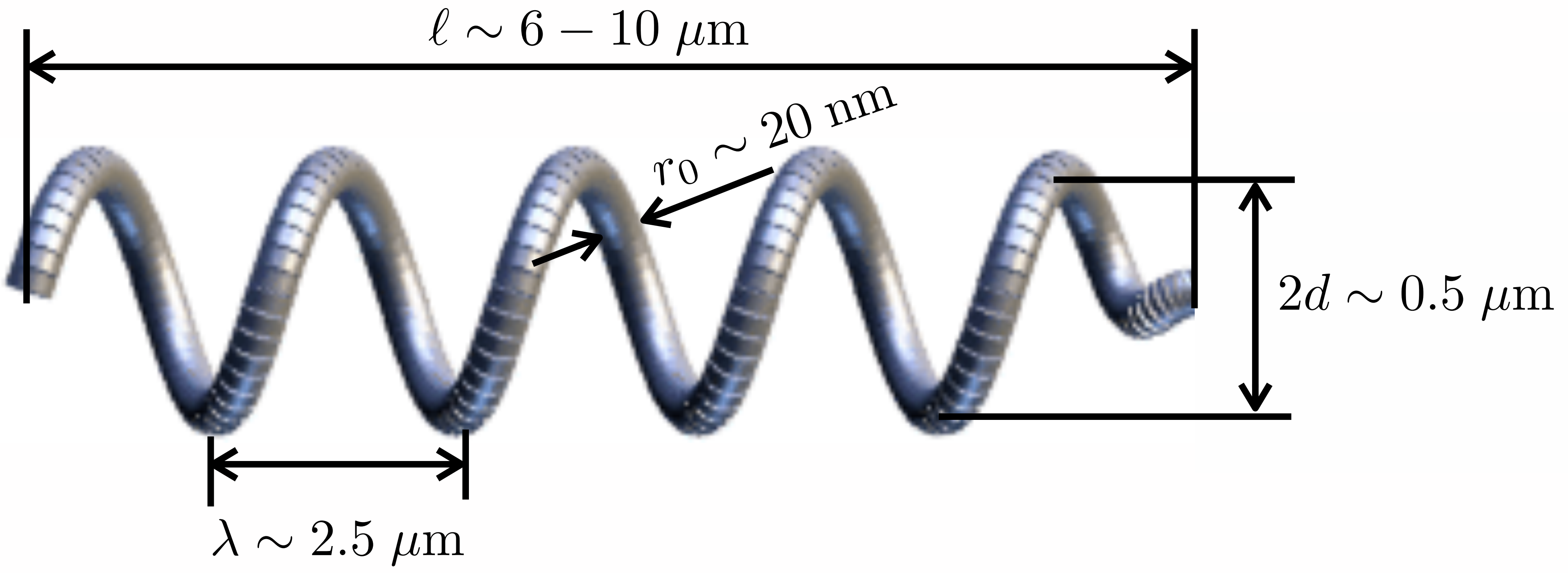
$$\langle \Delta\theta(t)^2 \rangle = 2D_r t$$

$$D_r \sim \frac{k_B T}{8\pi\mu a^3} = 0.2\ \mathrm{s}^{-1}$$

$$\Downarrow$$

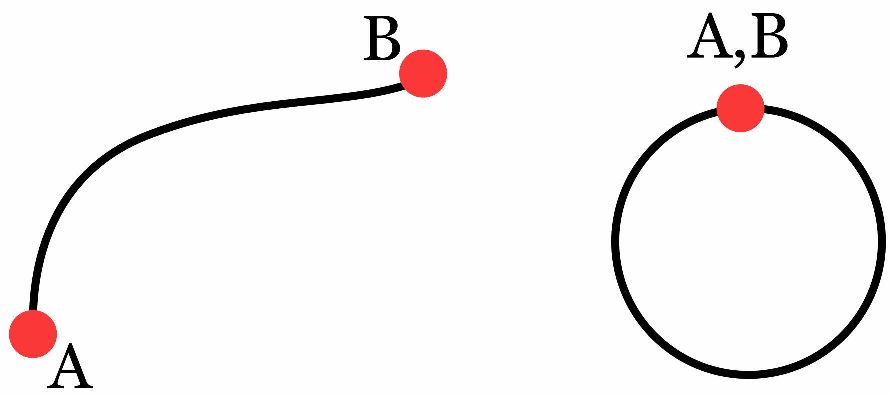


The procaryotic flagellum



PROBLEM 1

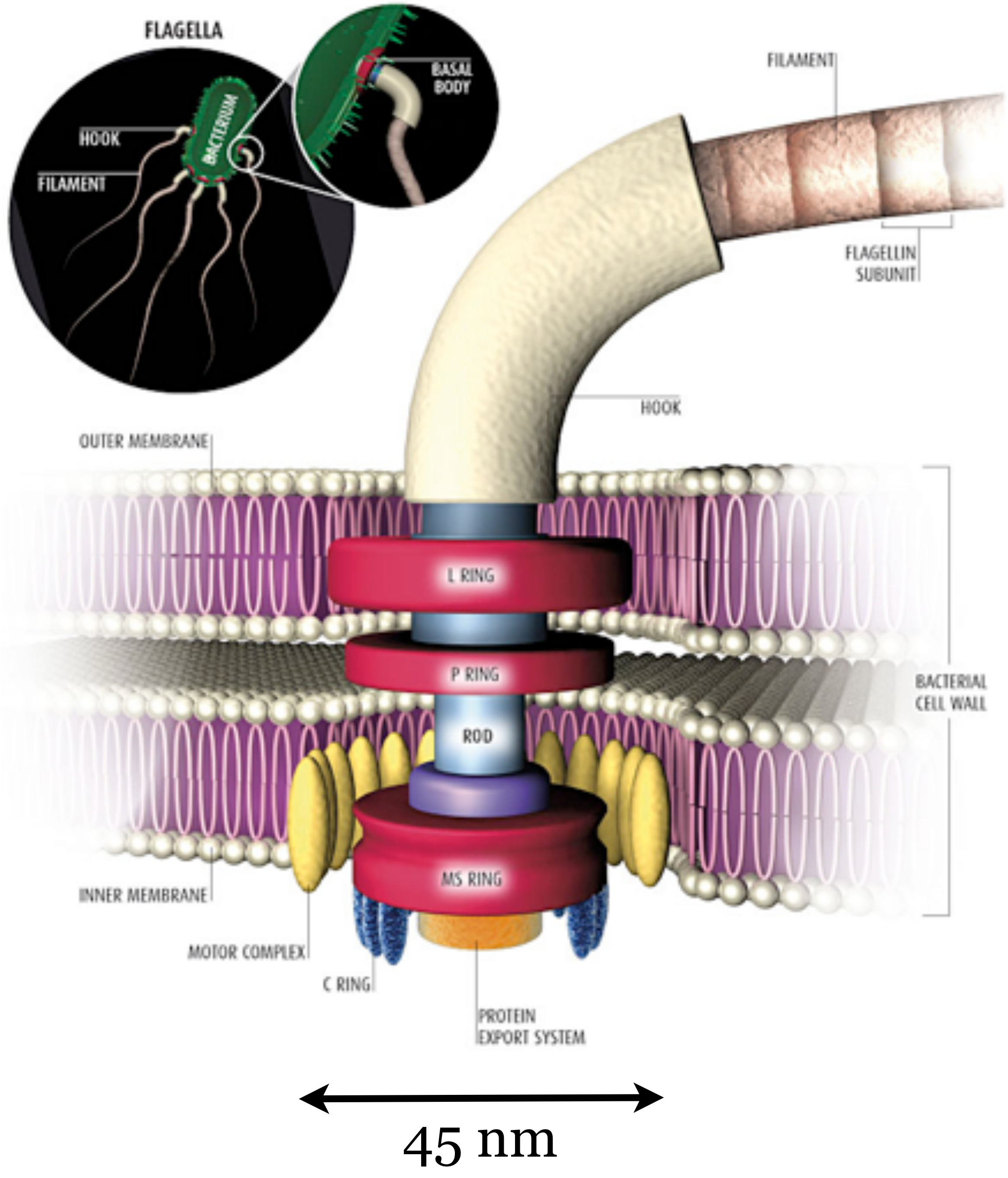
CYCLIC NON RECIPROCAL MOTION
USING ONE DEGREE OF FREEDOM



PROBLEM 2

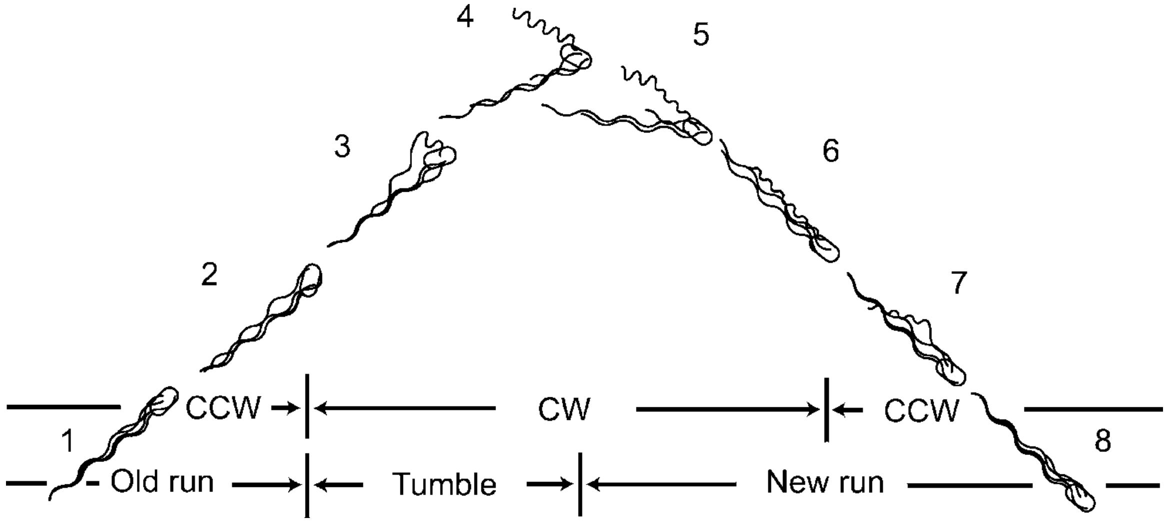
TOTAL LENGTH INCREASE BY ~5
ROTATIONAL DIFFUSION DECREASE BY 5^3=125

Flagellar propulsion



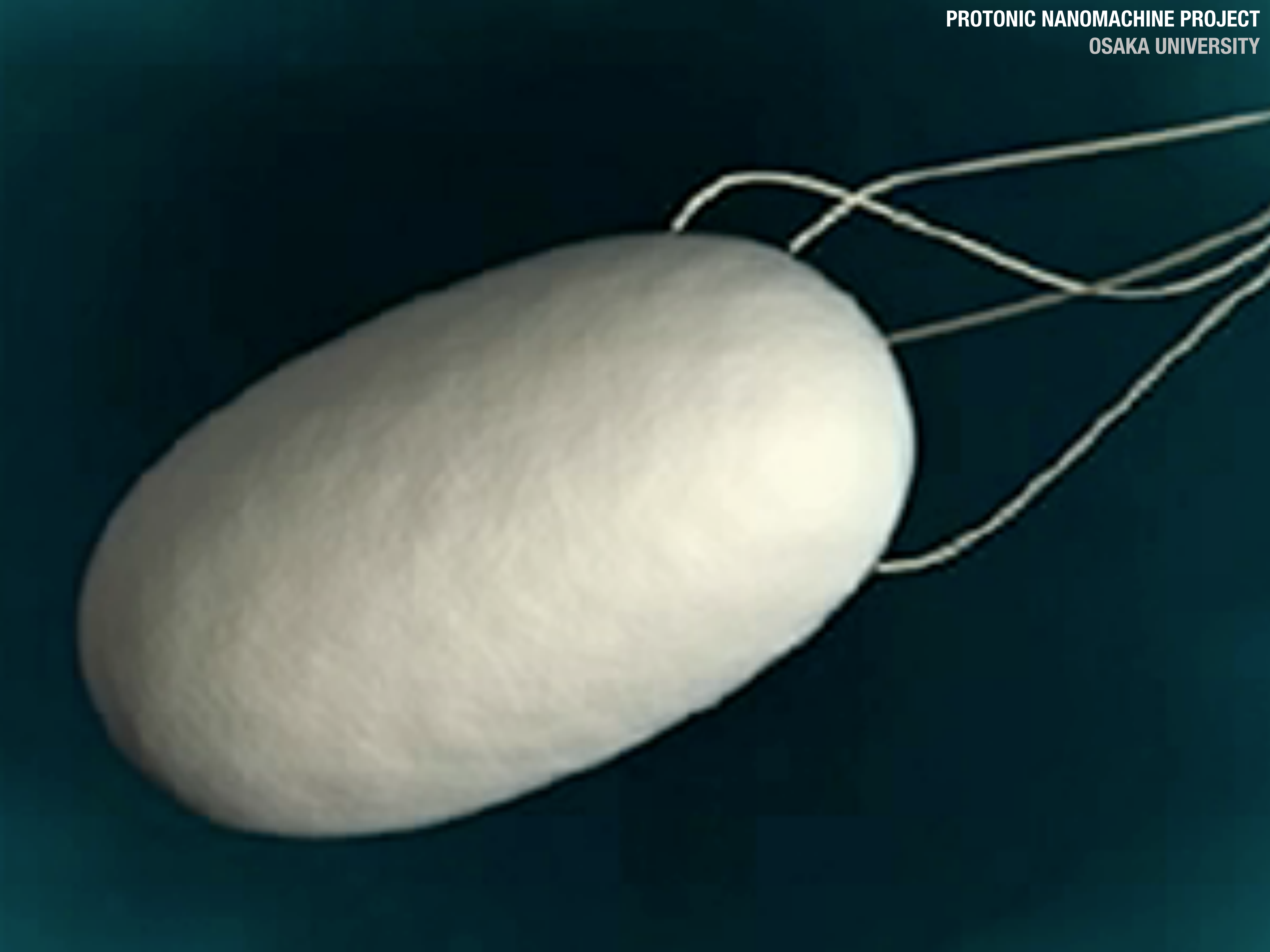
FLAGELLAR MOTOR

RUN AND TUMBLE DYNAMICS



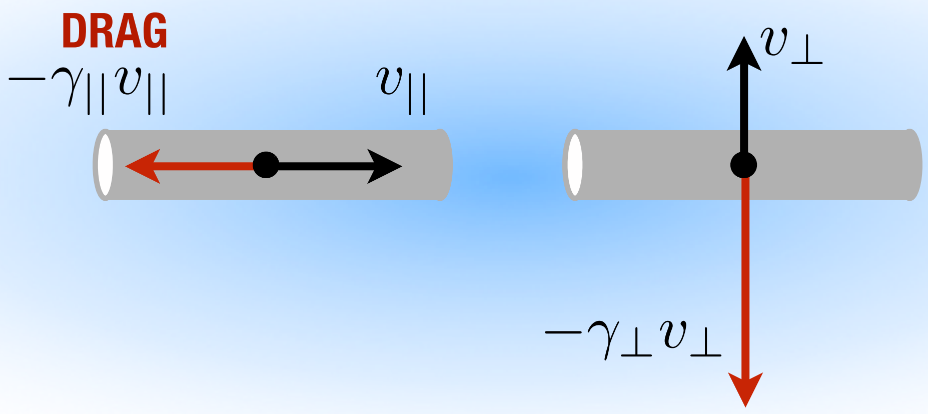
DARNTON et al., J. BACTERIOL. 2007

ESCHERICHIA COLI, BERG LAB HARVARD



PROTONIC NANOMACHINE PROJECT
OSAKA UNIVERSITY

Propulsion matrix



$$\gamma_{\perp} > \gamma_{||}$$

$$F_z = \Gamma^{F\Omega}_{zz}\,\Omega_z$$

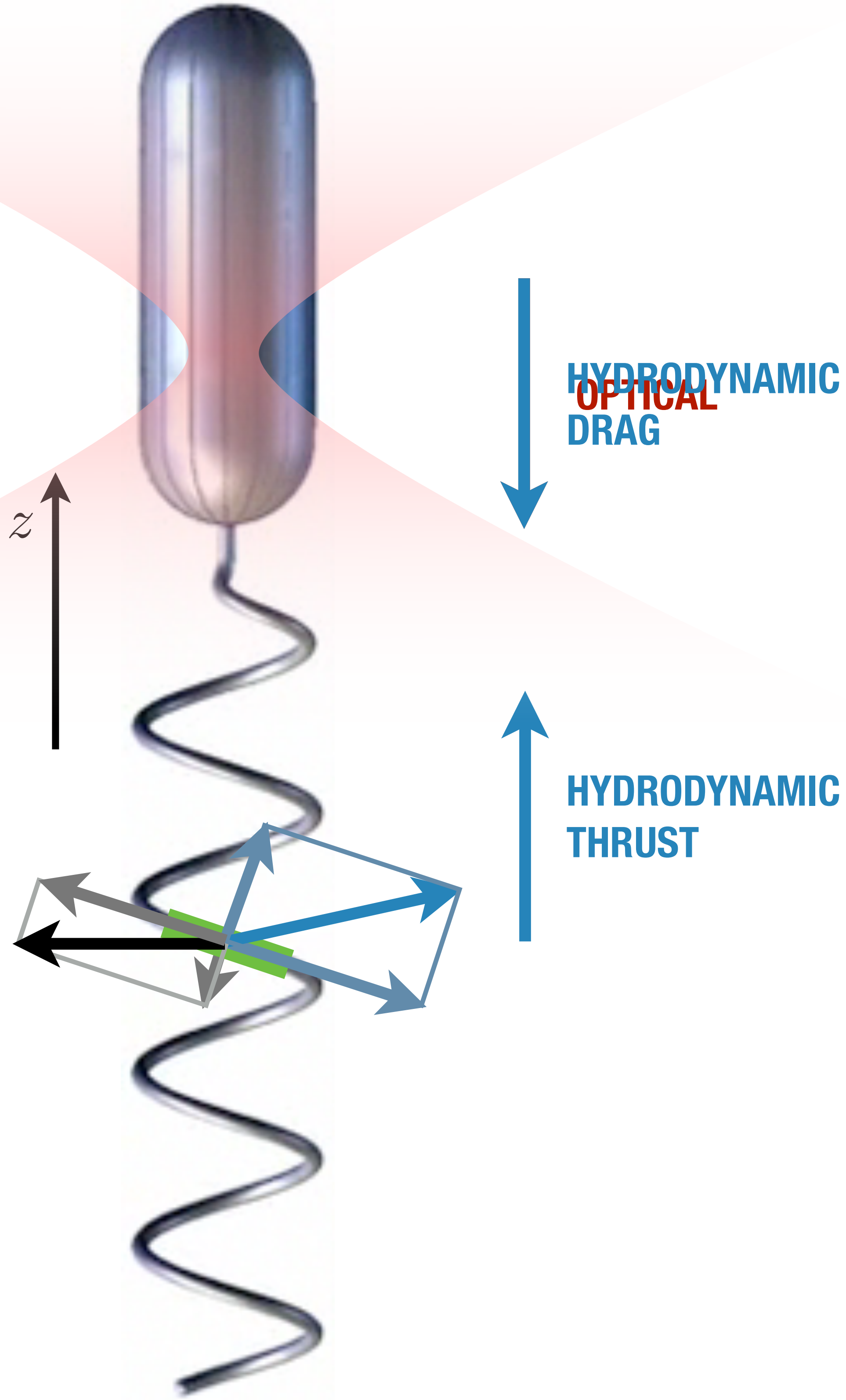
$$\Gamma^{F\Omega}_{zz} \propto \ell d(\gamma_{\perp} - \gamma_{||})$$

RESISTANCE EQUATIONS

$$\begin{pmatrix} \mathbf{F} \\ \mathbf{T} \end{pmatrix} = \begin{pmatrix} \mathbf{\Gamma}^{FU} & \mathbf{\Gamma}^{F\Omega} \\ \mathbf{\Gamma}^{F\Omega^{\intercal}} & \mathbf{\Gamma}^{T\Omega} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{U} \\ \mathbf{\Omega} \end{pmatrix}$$

MOBILITY EQUATIONS

$$\begin{pmatrix} \mathbf{U} \\ \mathbf{\Omega} \end{pmatrix} = \begin{pmatrix} \mathbf{M}^{UF} & \mathbf{M}^{UT} \\ \mathbf{M}^{UT^{\intercal}} & \mathbf{M}^{\Omega T} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{F} \\ \mathbf{T} \end{pmatrix}$$

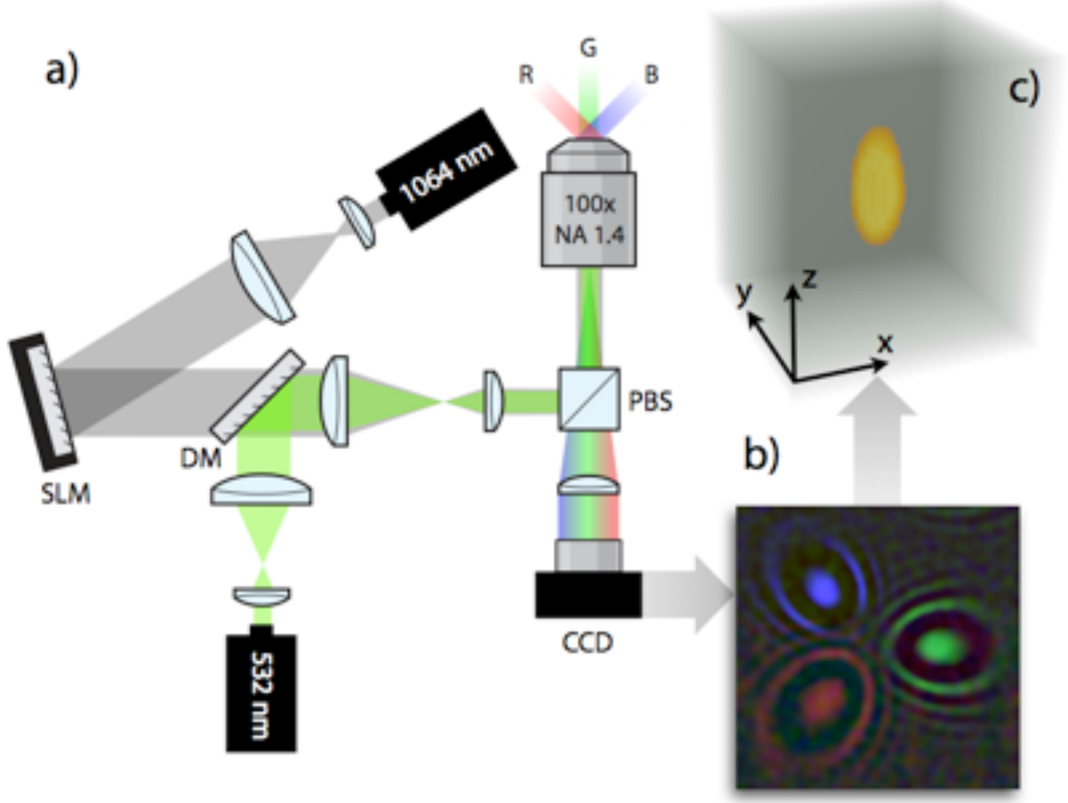


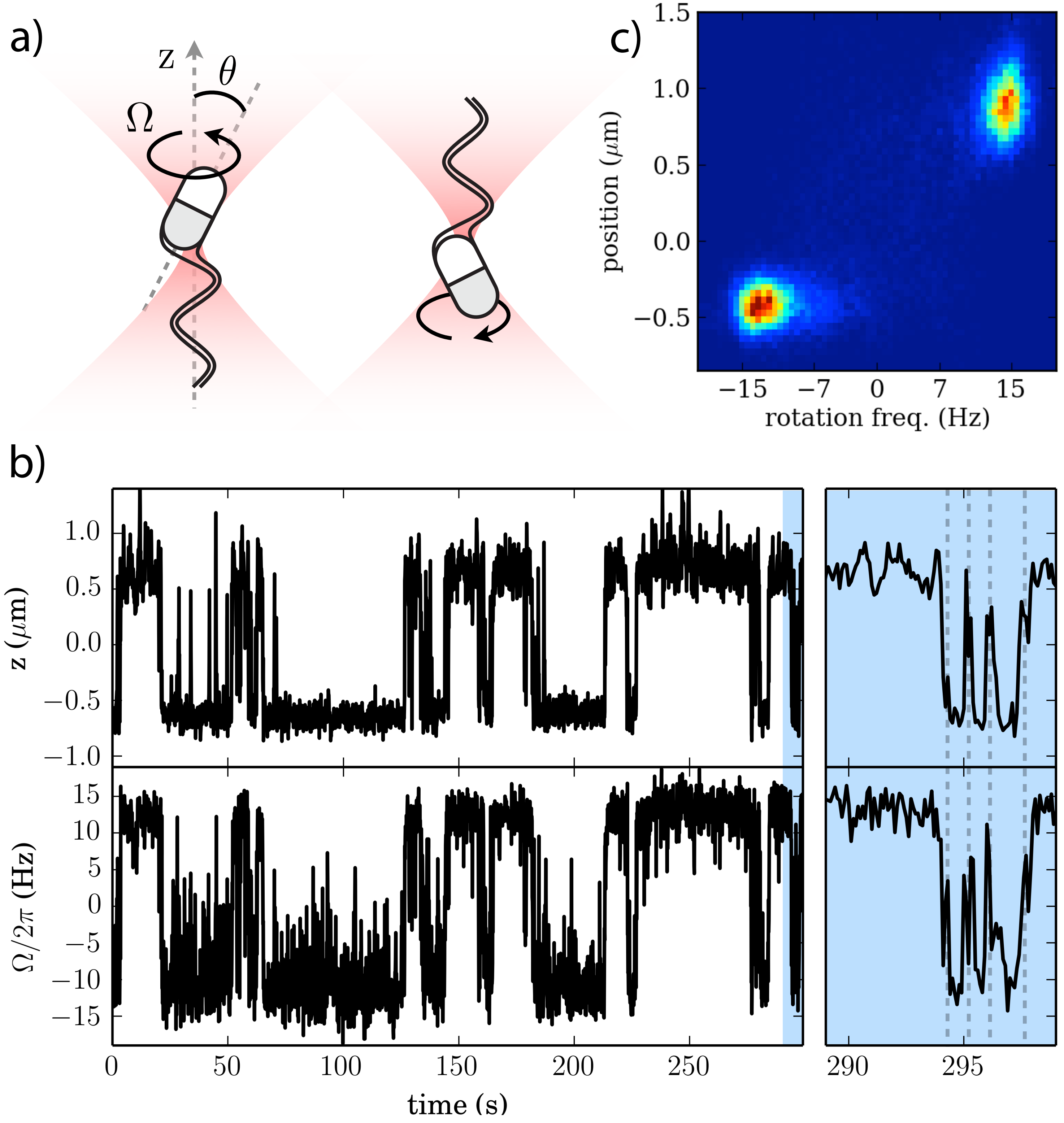
S. CHATTOPADHYAY et al. PNAS (2006)

Measuring propulsion matrix

BIANCHI, SAGLIMBENI, LEPORE, DI LEONARDO
Opt. Express (2014)

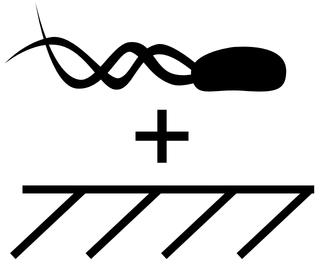
BIANCHI, SAGLIMBENI, LEPORE, DI LEONARDO
under review





BUNDLE REVERSALS GIVE RISE TO TWO RUN STATES WITH VERY DIFFERENT PROPELLING FORCES

$$\frac{|F_+ - F_-|}{(F_+ + F_-)/2} = 0.35$$

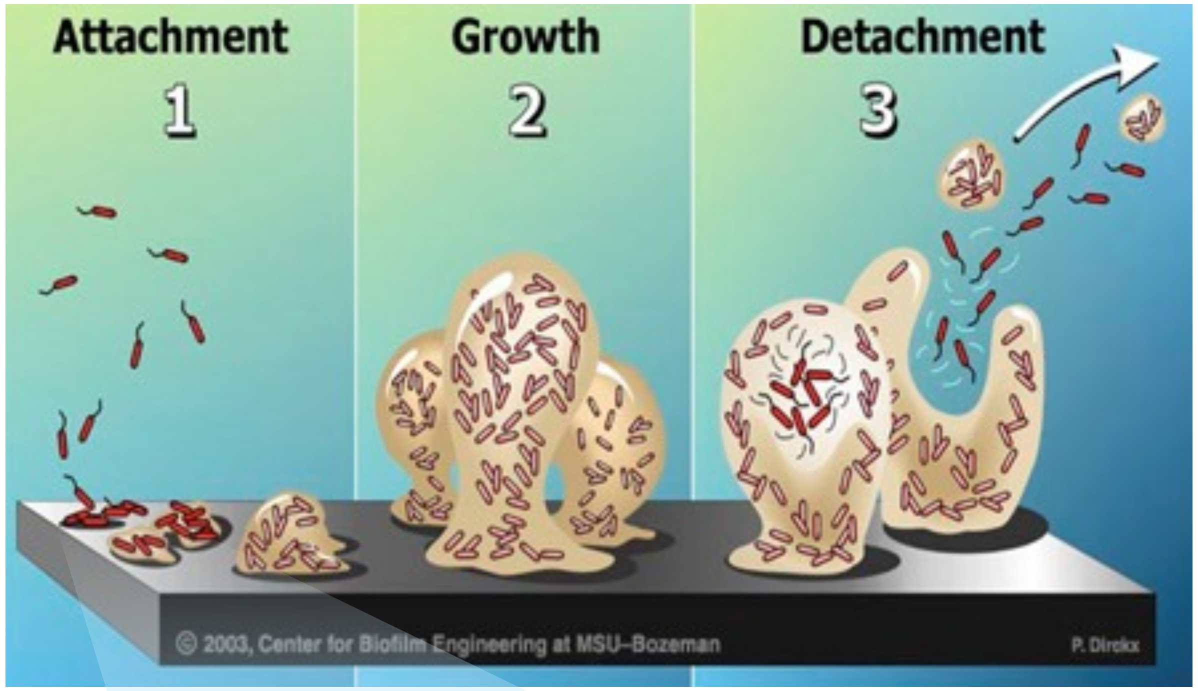


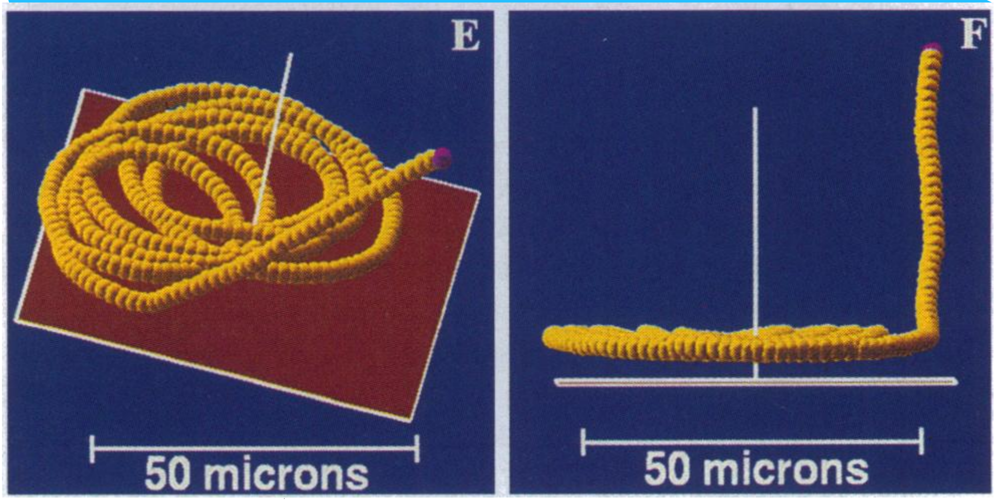
CONFINED SWIMMING

wall entrapment

Wall entrapment

BIOFILM





FRYMIER et al. PNAS (1995)

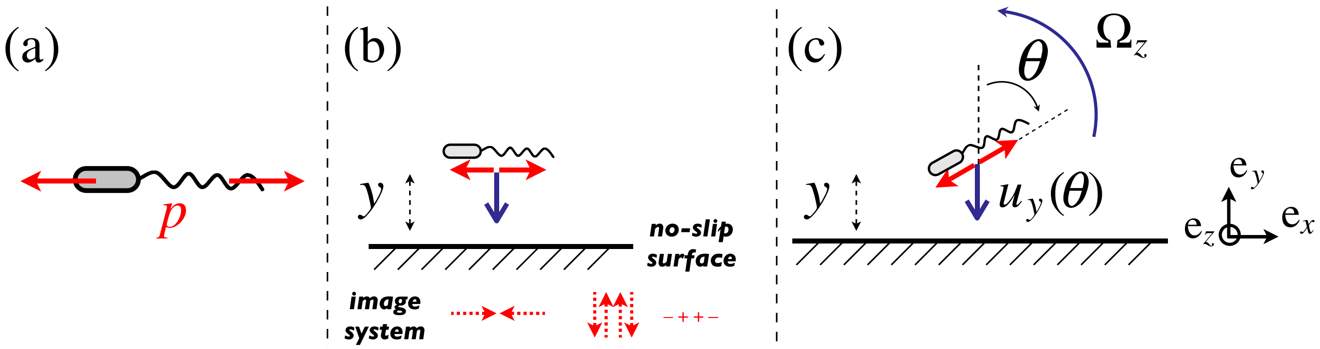
HYPOTHESIS 1: DLVO

VIGEANT, FORD APPL. ENVIRON. MICROB. (1997).

NO DLVO, HYPOTHESIS 2: HYDRODYNAMICS

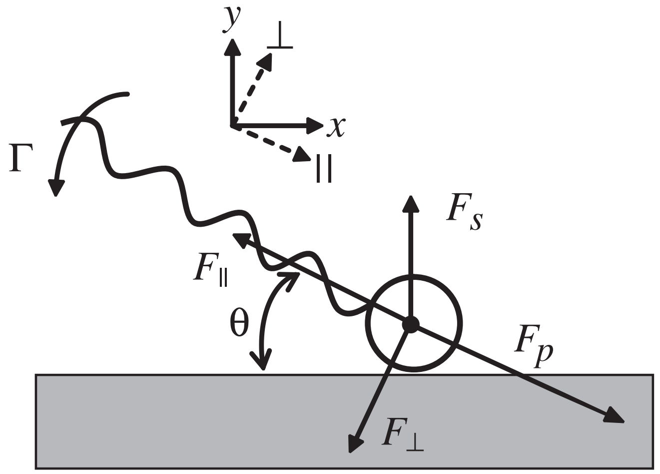
BERKE et al. PRL (2008)

HYPOTHESIS 2A: HYDRODYNAMICS (FAR FIELD)



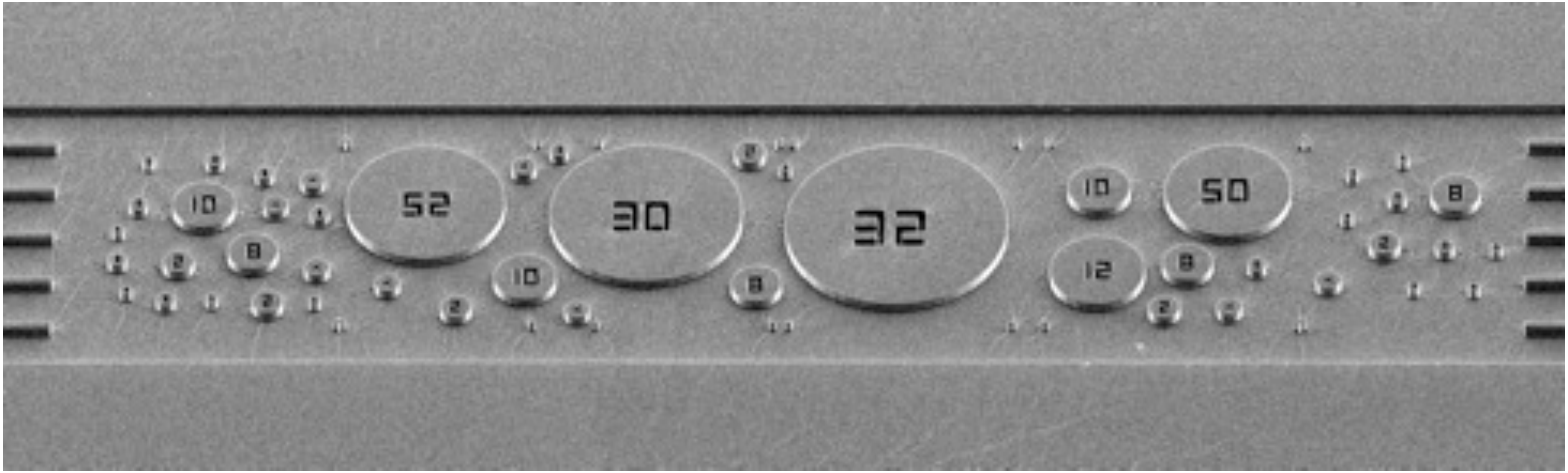
LI, TANG PRL (2009)

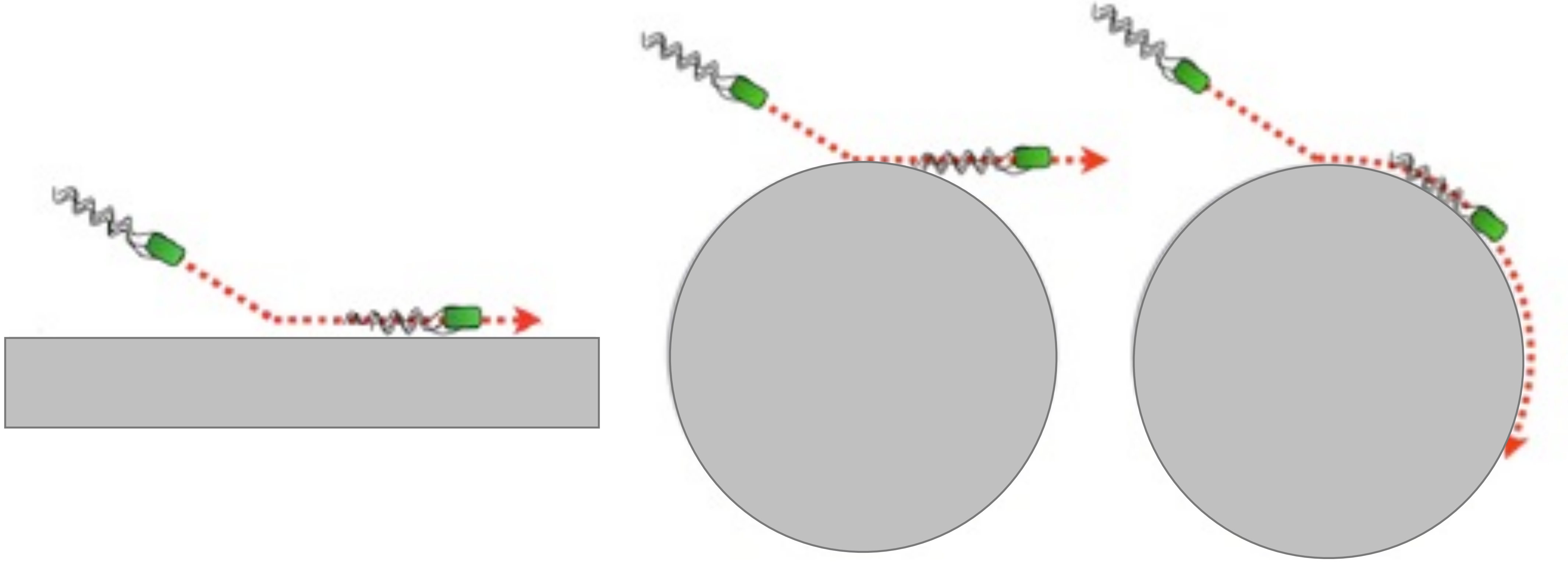
HYPOTHESIS 3: STERIC REPULSION (NO HYDRODYN.)



Entrapment by convex walls

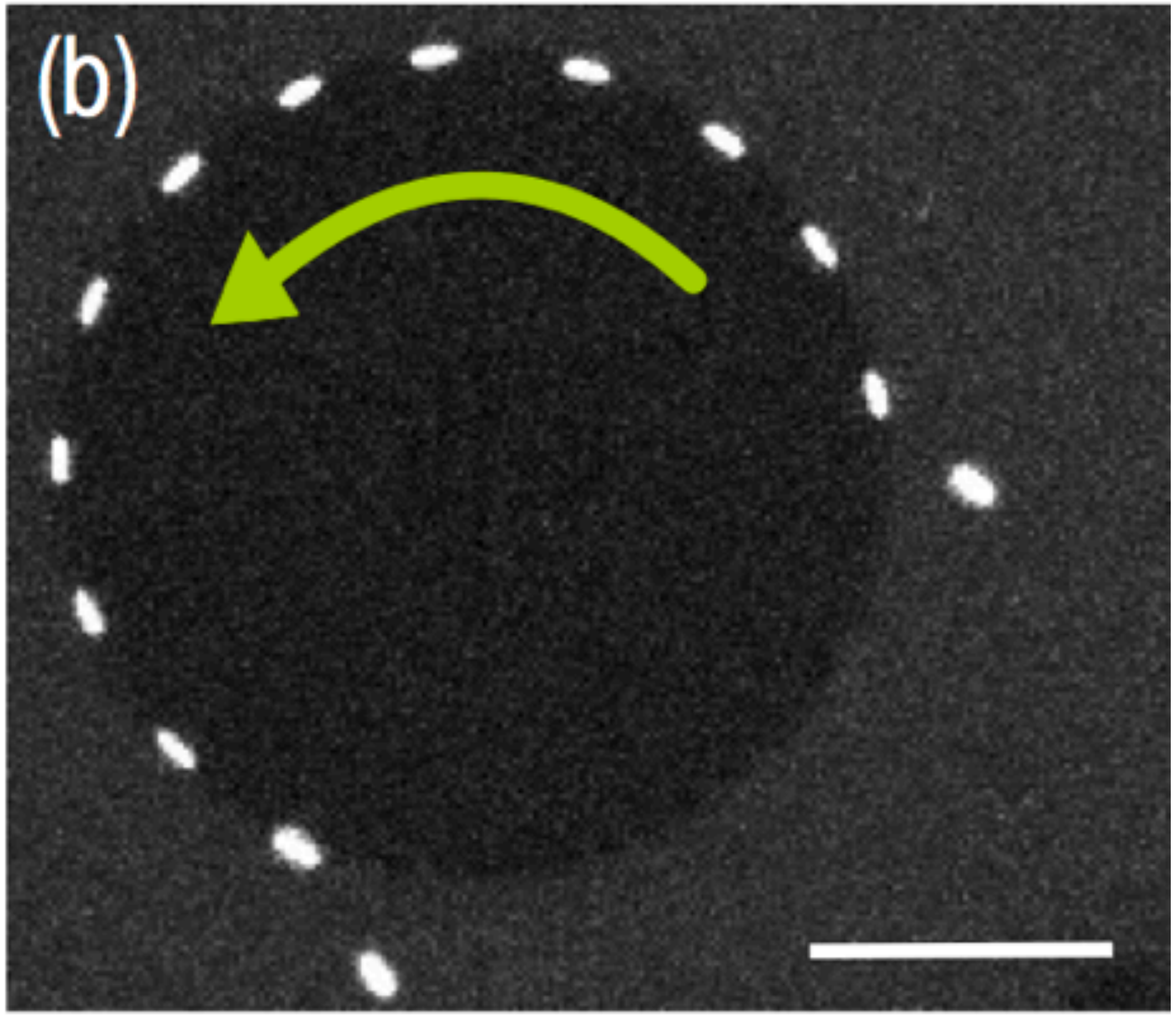
O. SIPOS , K. NAGY, RDL, P. GALAJDA, under review

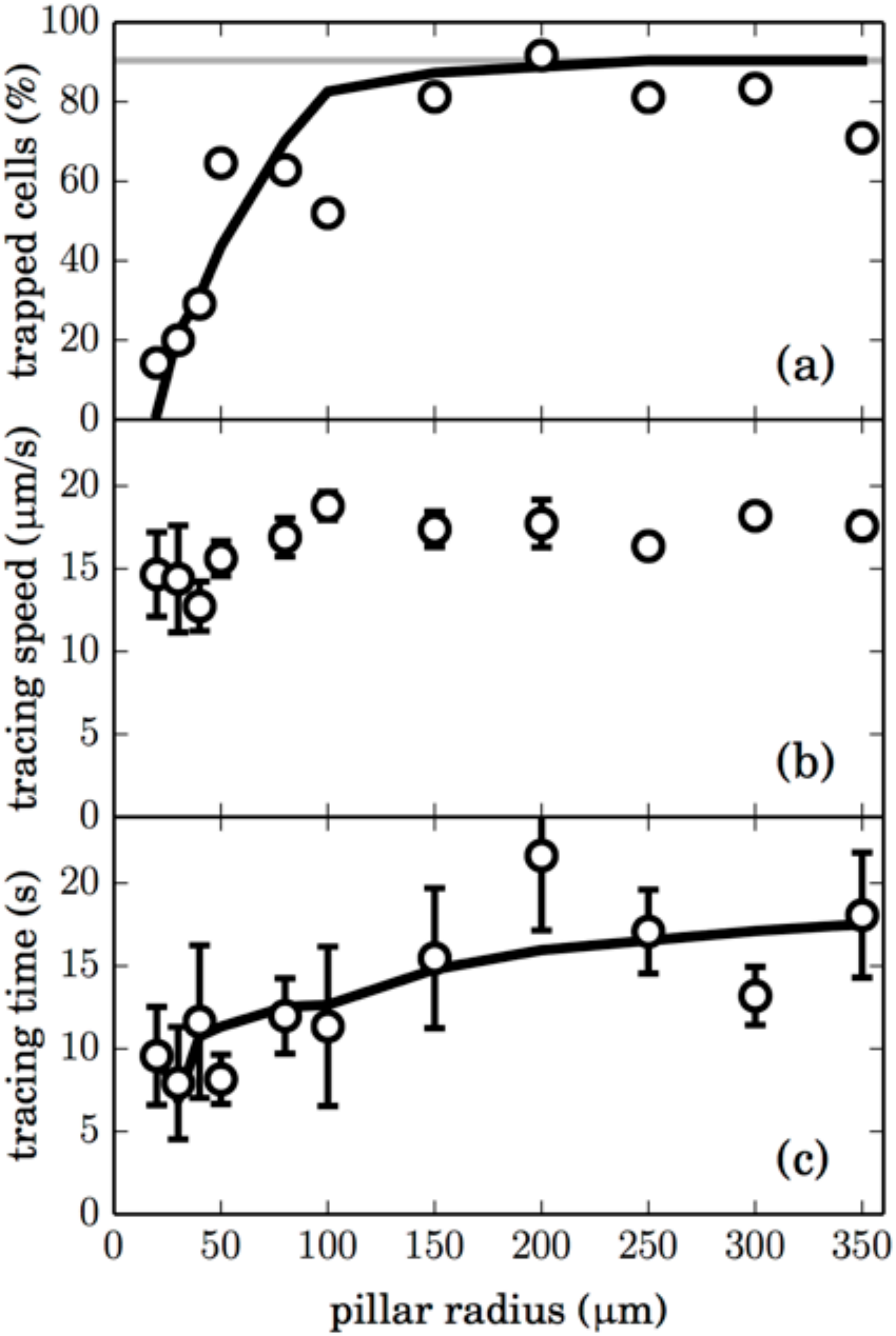




Entrapment by convex walls

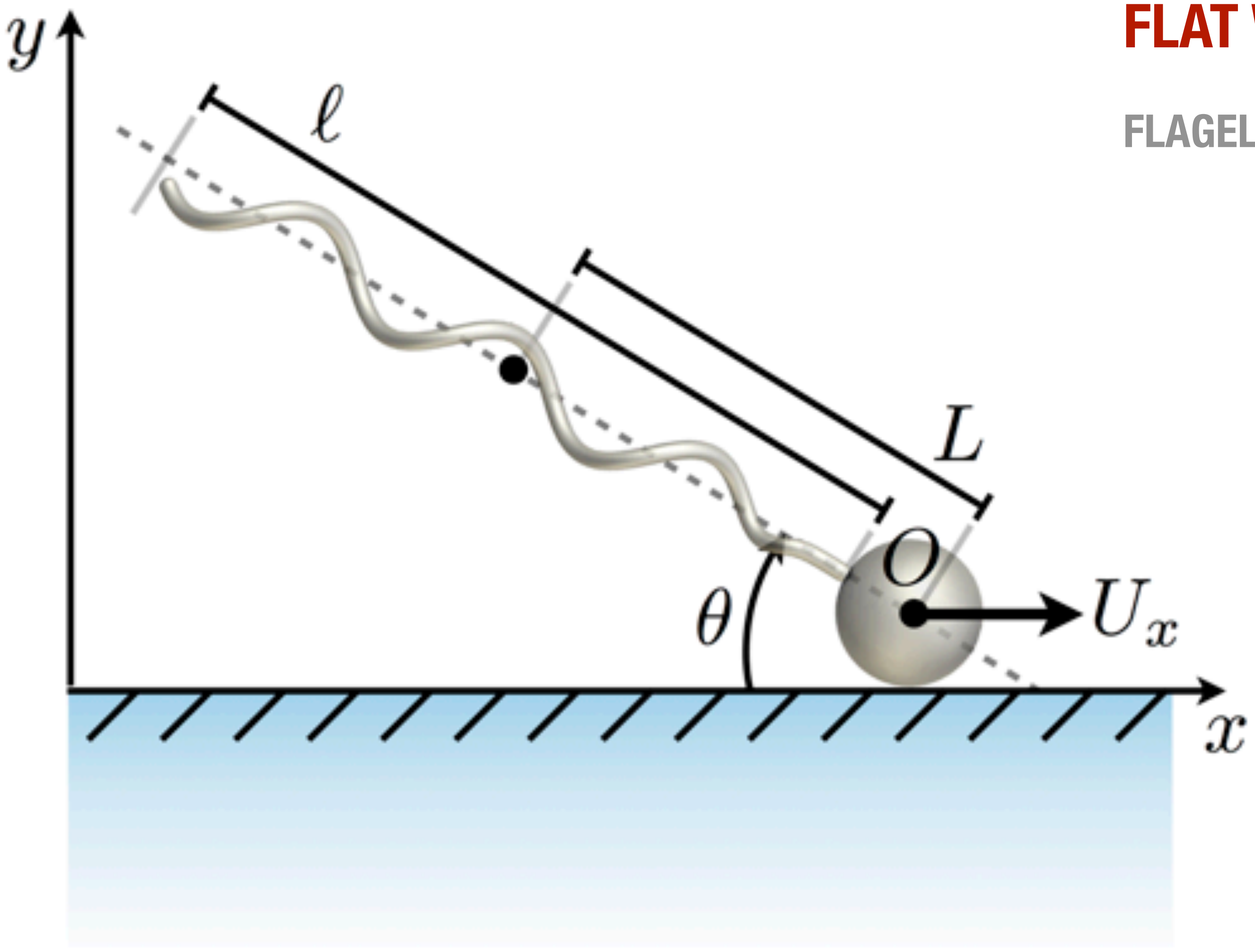
O. SIPOS , K. NAGY, RDL, P. GALAJDA, under review





Hydrodynamic origin

O. SIPOS , K. NAGY, RDL, P. GALAJDA, under review



FLAT WALL

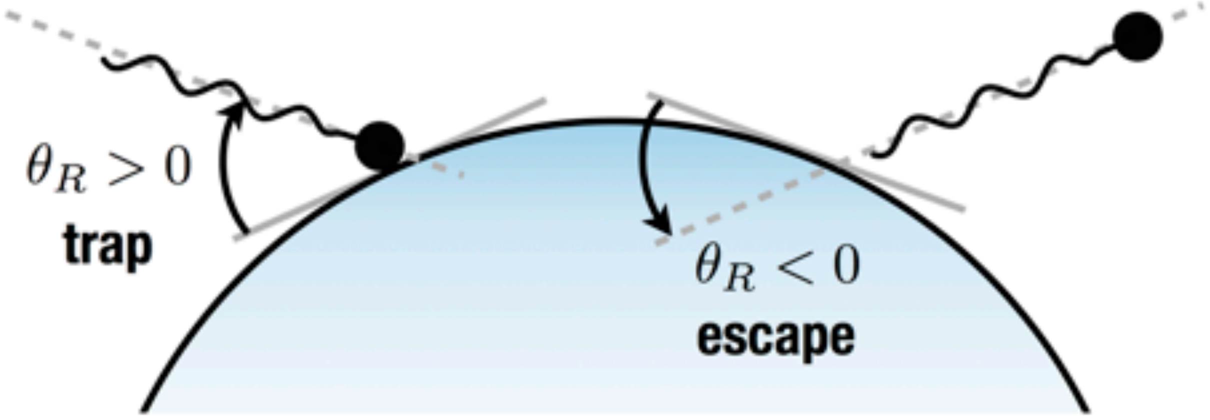
$L\gamma_{\perp}^{FU}\sin\theta$

FLAGELLAR BUNDLE $\tau_z = -\gamma_{zz}^{T\Omega}\Omega_z + \gamma_{zx}^{TU}U_x$

CELL BODY $T_z = -\Gamma_{zz}^{T\Omega}\Omega_z - \Gamma_{zx}^{TU}U_x$

$$\tau_z + T_z = 0$$

$$\dot{\theta} = -\Omega_z = 0 \Rightarrow \sin\theta_\infty = \frac{\Gamma_{zx}^{TU}}{L\gamma_{\perp}^{FU}}$$



CONVEX WALL

$$\dot{\theta} = -\Omega_z - U_x/R = 0$$

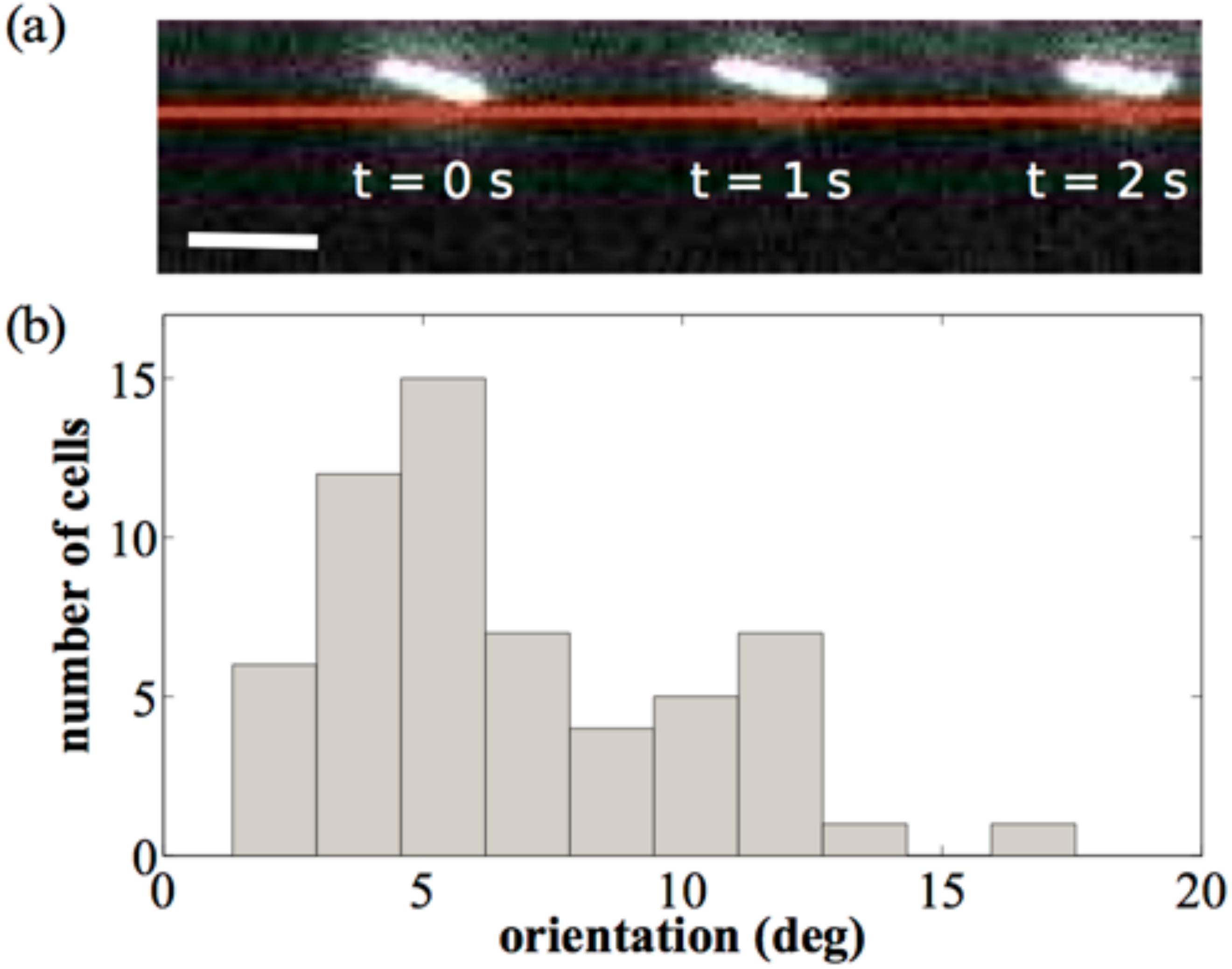
$$\sin\theta_R = \sin\theta_\infty - \frac{\Gamma_{zz}^{T\Omega} + \gamma_{zz}^{T\Omega}}{LR\gamma_{\perp}^{FU}}$$

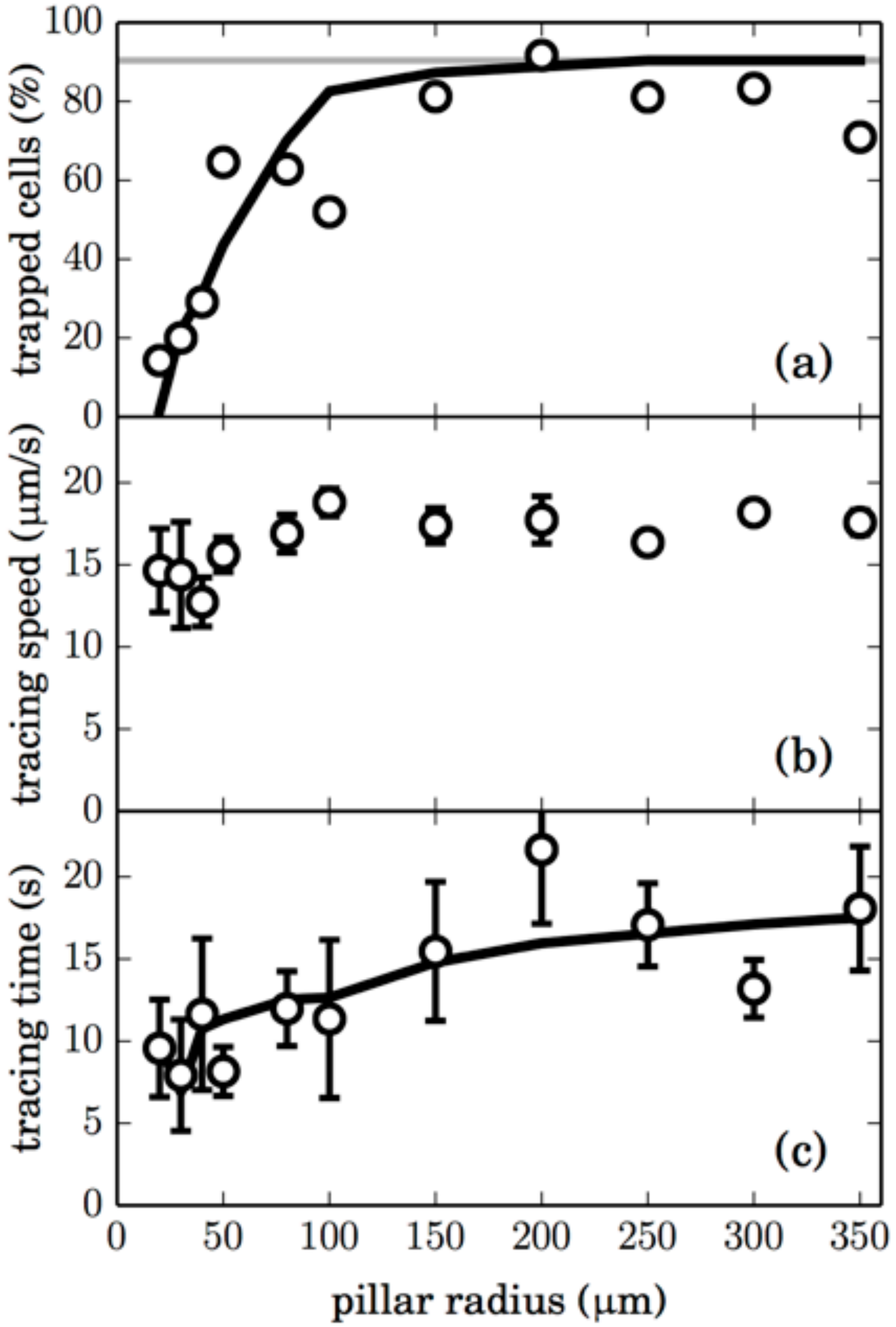
$$R^* \approx \frac{2}{3}\frac{\ell}{\sin\theta_\infty}$$

Swimming angle depends on pillar radius

O. SIPOS , K. NAGY, RDL, P. GALAJDA, under review

FLAT WALL





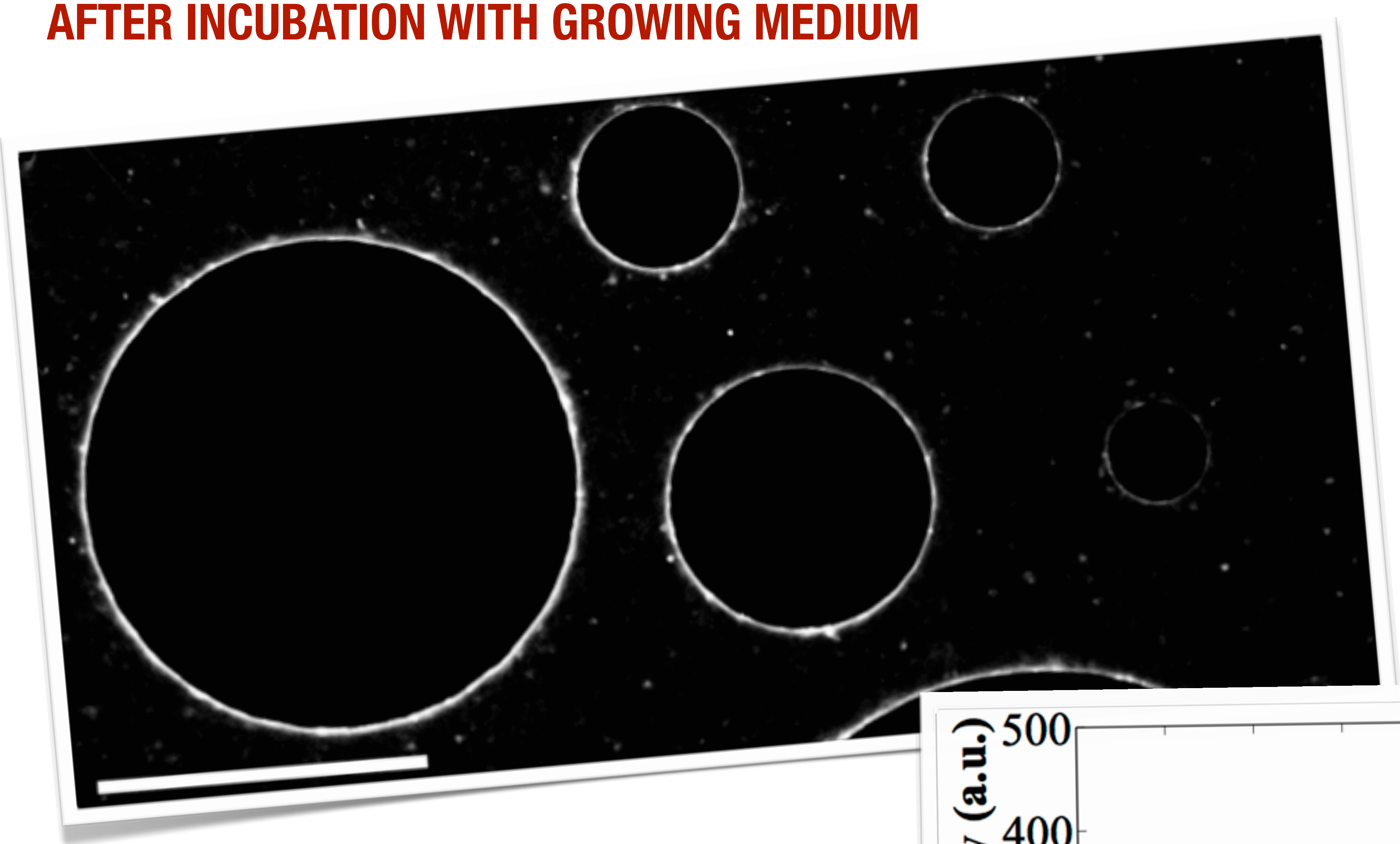
$$R^* \approx \frac{2}{3} \frac{\ell}{\sin \theta_\infty}$$

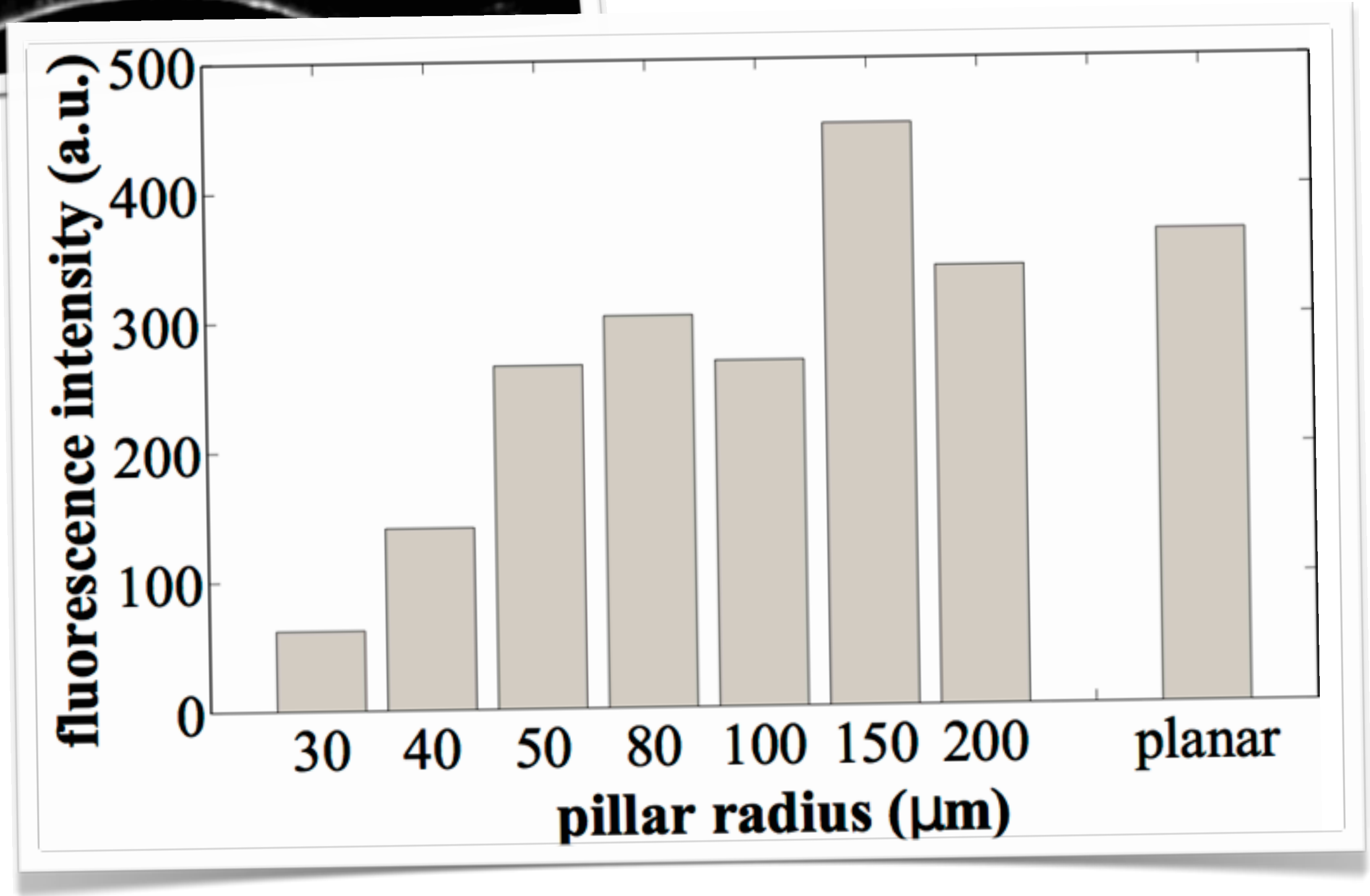
$$\ell = 8, \quad \theta_\infty = 5^\circ \rightarrow R^* = 60\ \mu\mathrm{m}$$

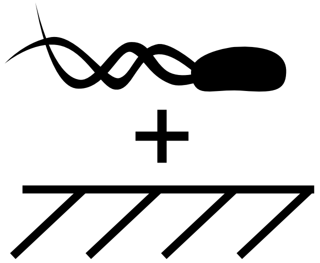
Reduced colonization of small pillars

O. SIPOS , K. NAGY, RDL, P. GALAJDA, under review

AFTER INCUBATION WITH GROWING MEDIUM







CONFINED SWIMMING

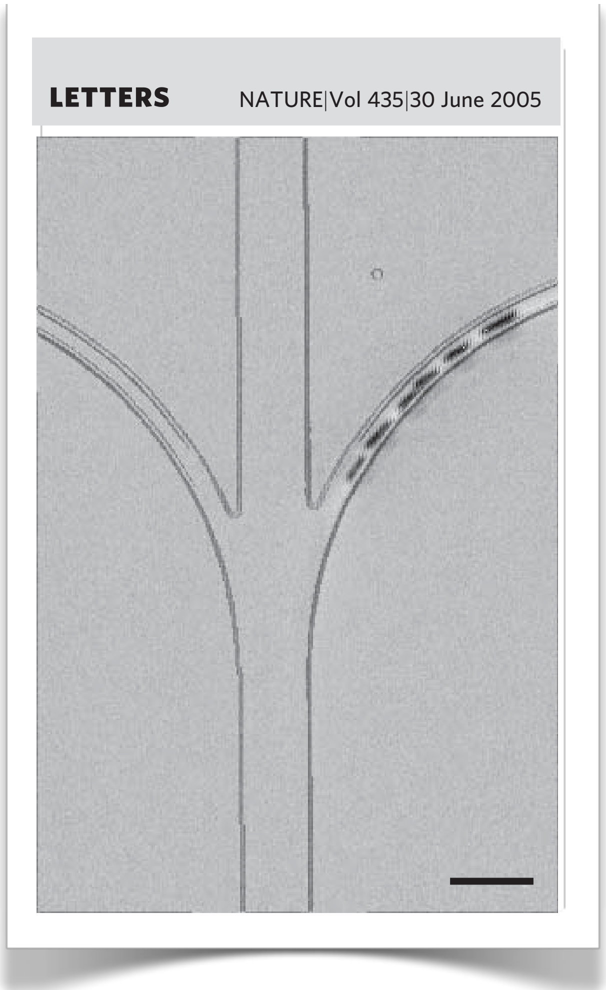
swimming with an image

Swimming at a wall

Escherichia coli swim on the right-hand side

Willow R. DiLuzio[1,2], Linda Turner[3], Michael Mayer[1], Piotr Garstecki[1], Douglas B. Weibel[1], Howard C. Berg[3,4] & George M. Whitesides[1]

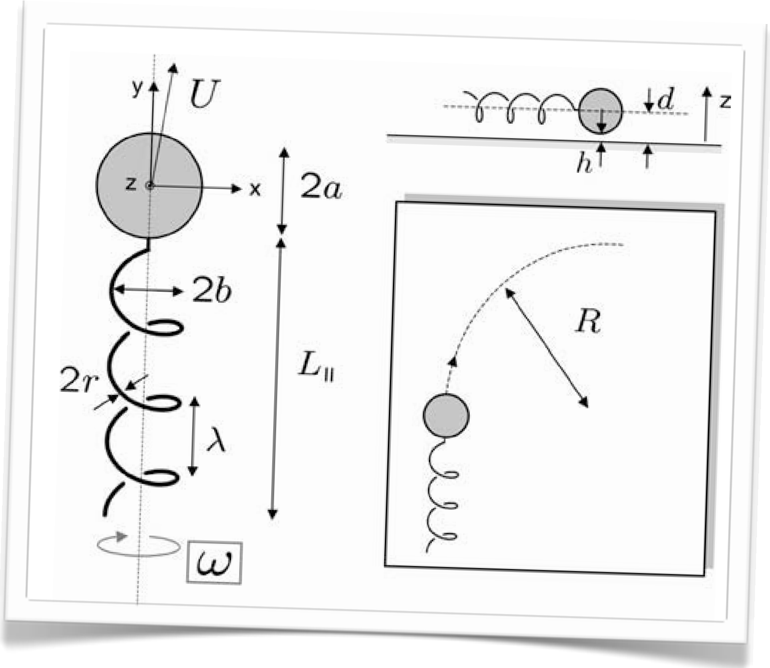
“The flagellar bundle rolls to the left near the surface, and the cell body rolls to the right near the surface. These two motions cause the cell to swim in a clockwise, circular trajectory”

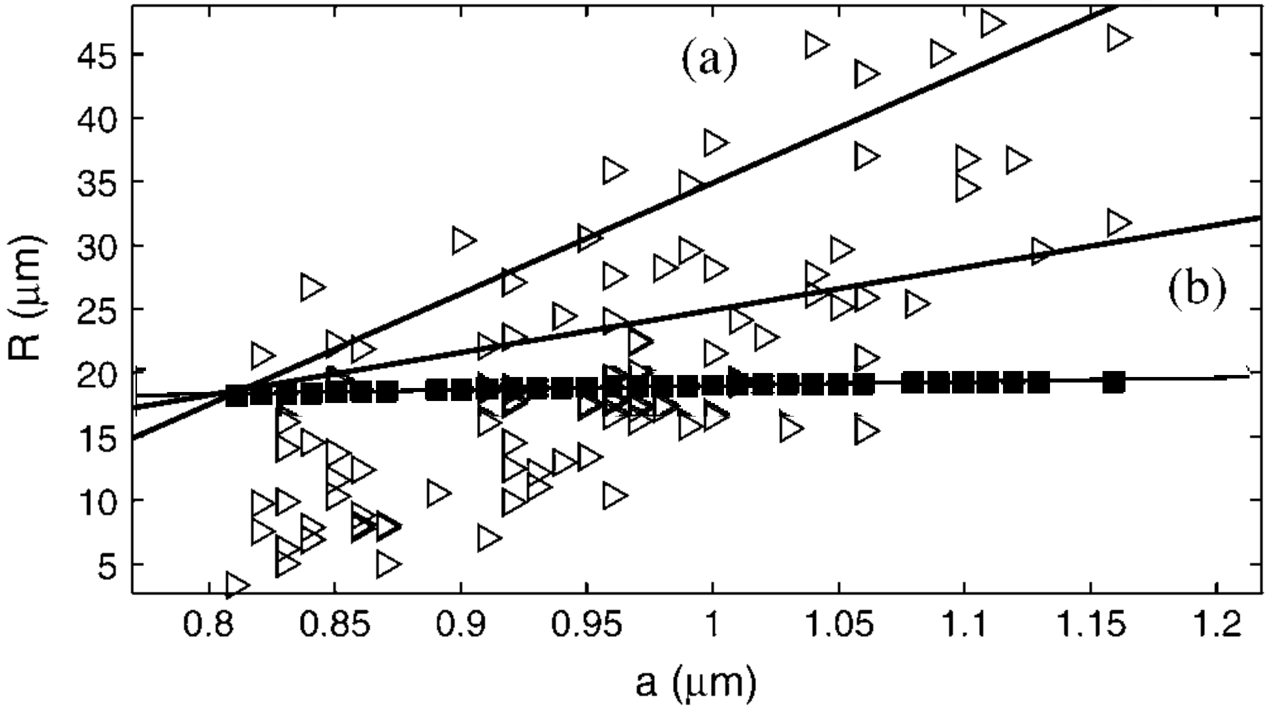

LETTERS NATURE|Vol 435|30 June 2005

TOP VIEW

SORTING IN MICROFLUIDIC CHANNELS
Choosing the right materials we can have bacteria swimming closer to the floor and then preferentially on the right

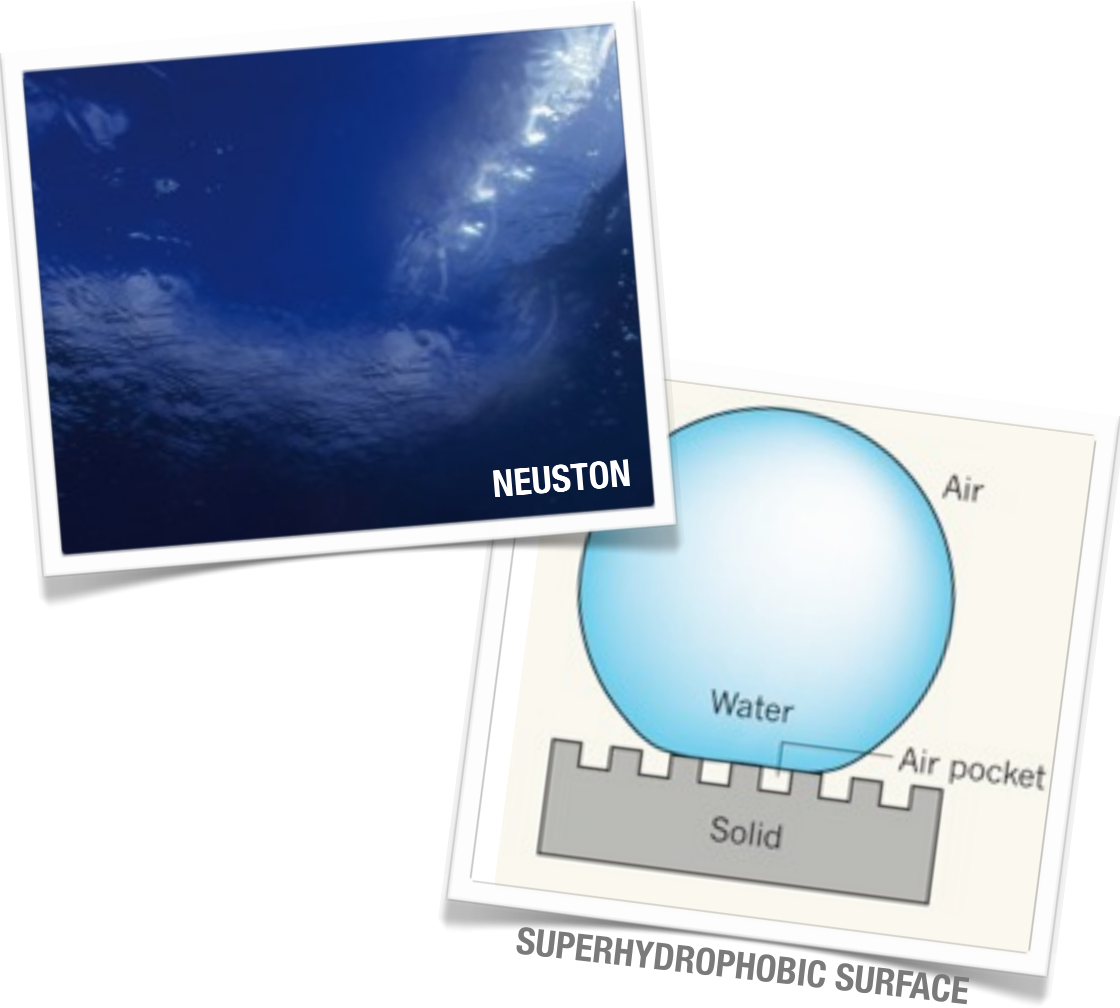
E. Lauga et al. Biophysical Journal 90(2) 400–412





Hydrodynamic images

WHAT HAPPENS ON A LIQUID-GAS INTERFACE?



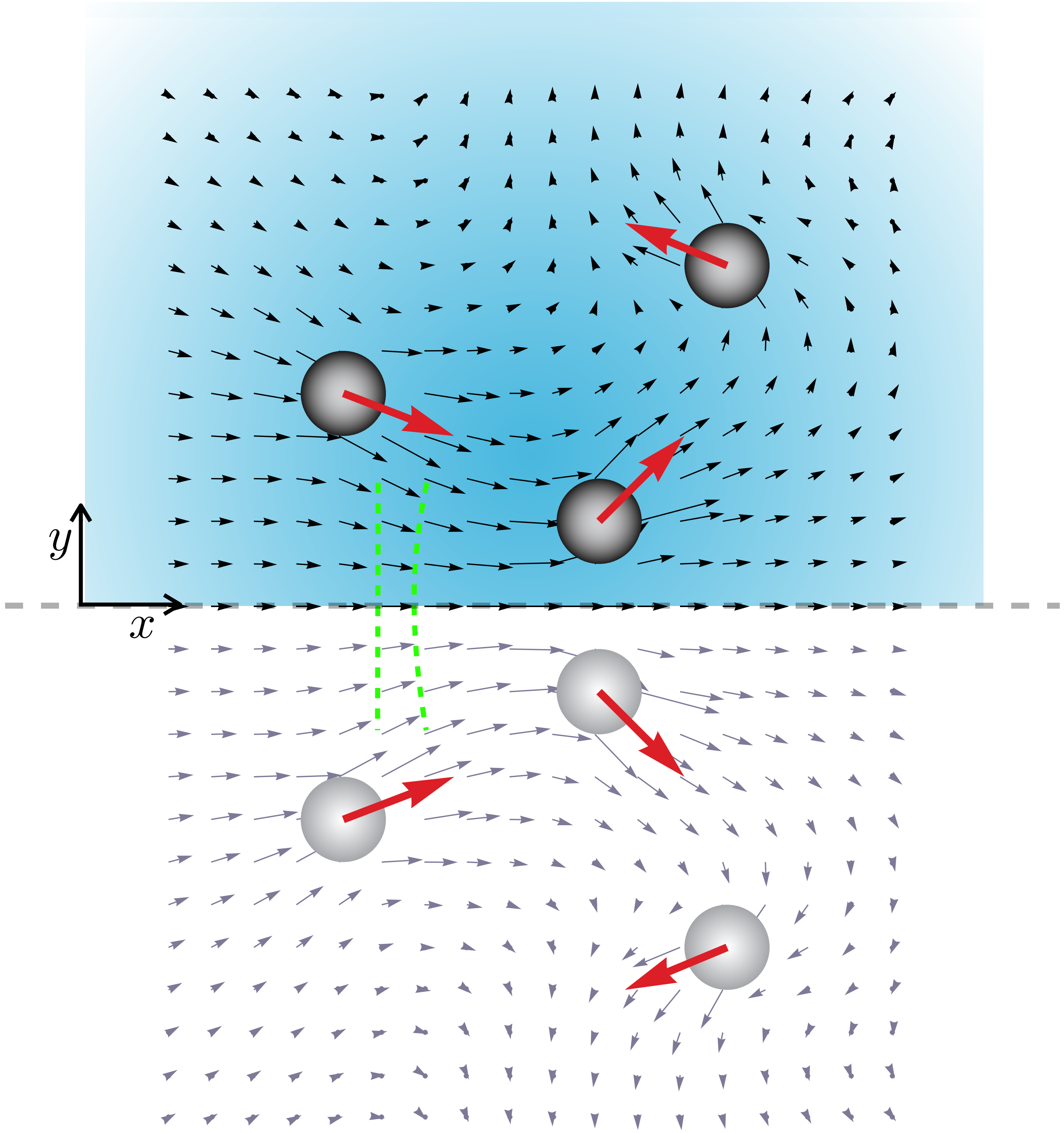
SUPERHYDROPHOBIC SURFACE

REFLECTION SIMMETRY

$$\Downarrow$$

$$u_y = 0 \qquad \frac{\partial u_x}{\partial y} = 0$$

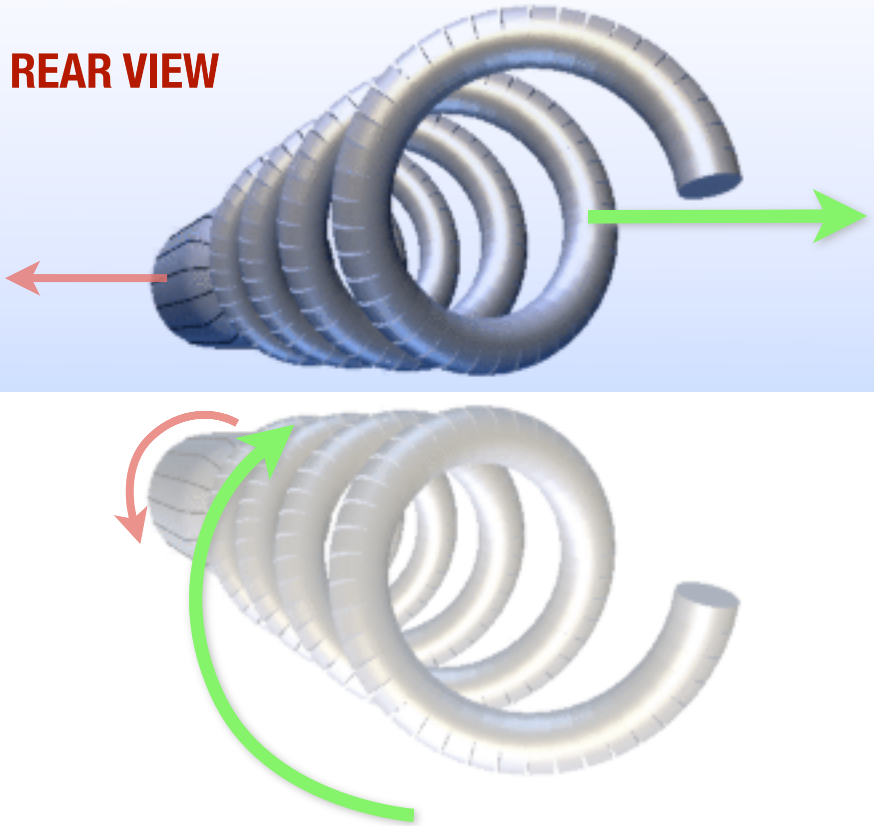
PERFECT SLIP BOUNDARY CONDITIONS



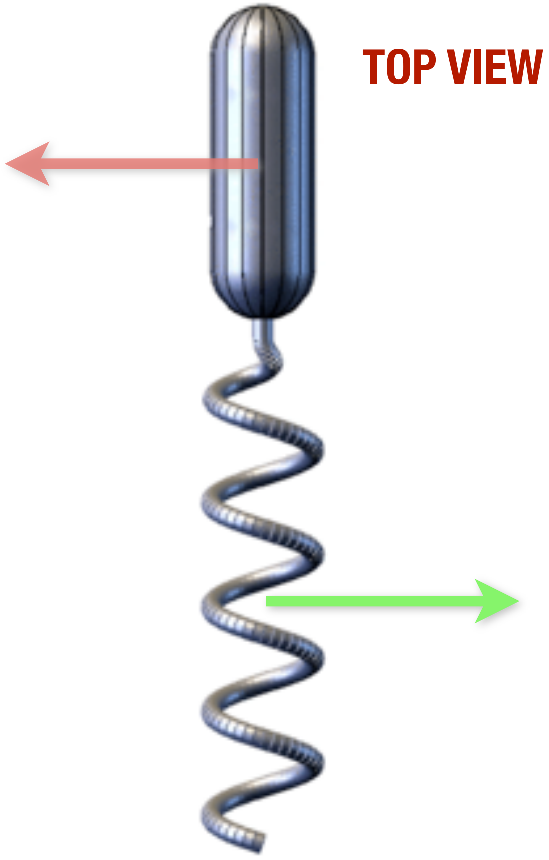
Swimming with an image

SIDE VIEW

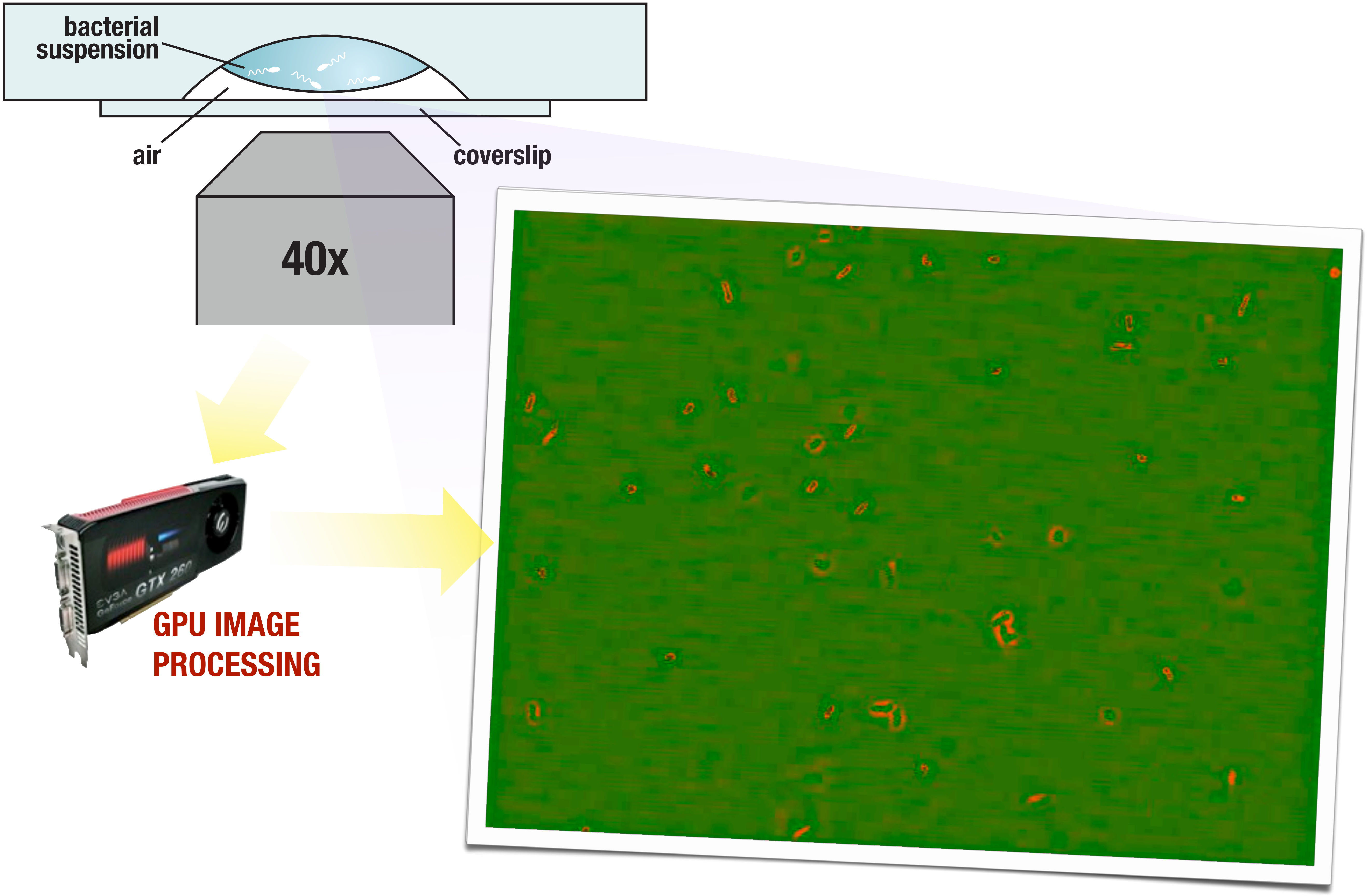
REAR VIEW



TOP VIEW



Swimming with an image



bacterial suspension

air

coverslip

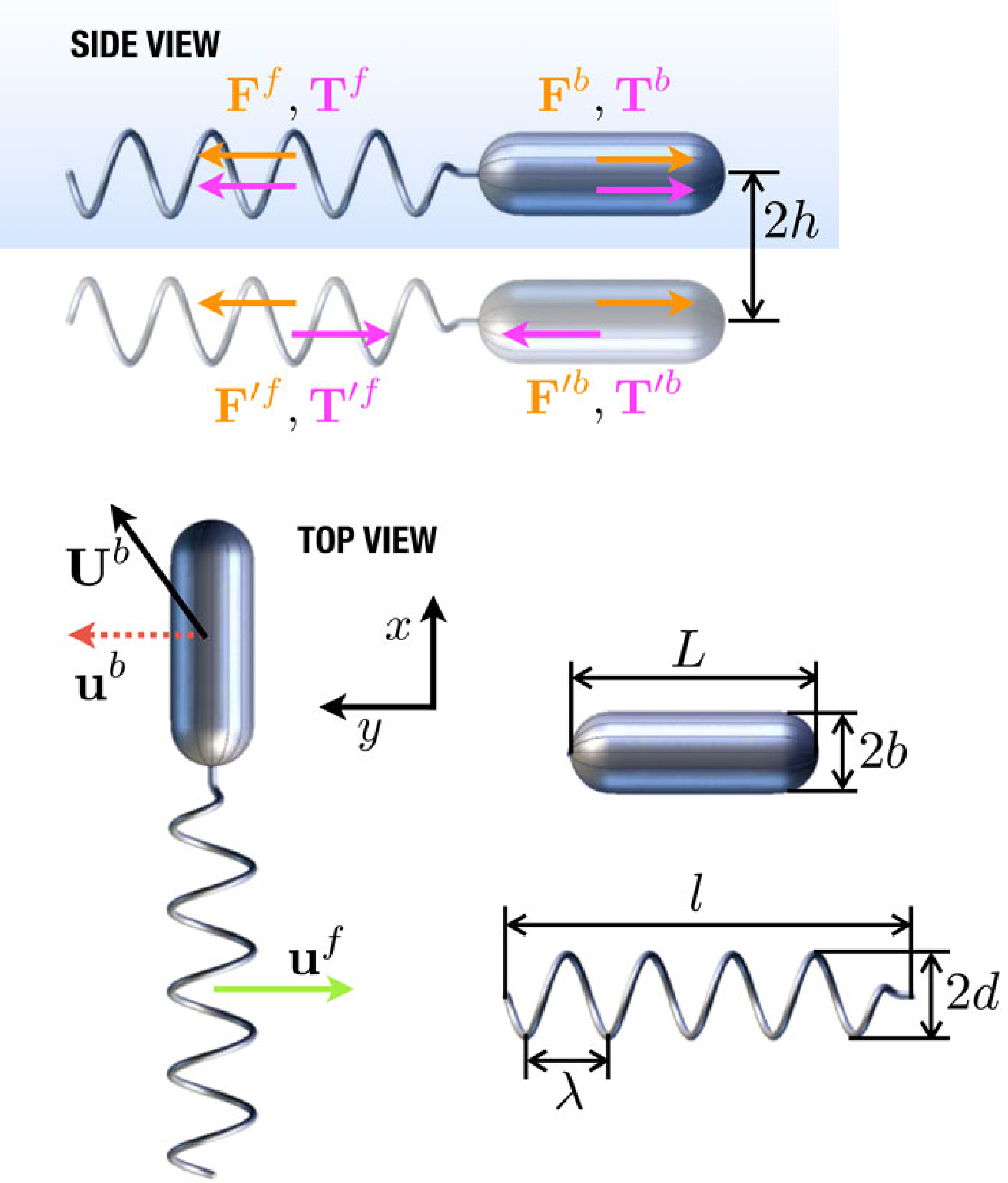
40x

GPU IMAGE PROCESSING

Swimming with an image

R. DI LEONARDO et al. PRL 106, 038101 (2011)

Science NOW



$$\alpha = \begin{cases} b & \text{BODY} \\ f & \text{FLAGELLUM} \end{cases}$$

$$\mathbf{U}^{\alpha} = \mathbf{M}^{\alpha} \cdot \mathbf{F}^{\alpha} + \mathbf{D}^{\alpha} \cdot \mathbf{T}^{\alpha}$$

$$\boldsymbol{\Omega}^{\alpha} = \mathbf{K}^{\alpha} \cdot \mathbf{T}^{\alpha} + (\mathbf{D}^{\alpha})^{T} \cdot \mathbf{F}^{\alpha}$$

+RIGIDITY CONSTRAINTS

IMAGE BODY AND FLAGELLUM GENERATE A “BACKGROUND FLOW”

$$\mathbf{u}^{\alpha} = \mathbf{G}^{uF} \cdot \mathbf{F}'^{\alpha} + \mathbf{G}^{uT} \cdot \mathbf{T}'^{\alpha},$$

$$\boldsymbol{\omega}^{\alpha} = \mathbf{G}^{\omega T} \cdot \mathbf{T}'^{\alpha} + \mathbf{G}^{\omega F} \cdot \mathbf{F}'^{\alpha}$$

$$\mathbf{G}^{uT}_{yx} = \frac{1}{8\pi\mu h \ell^{\alpha}} \longrightarrow$$

LONGER IMAGE BODY

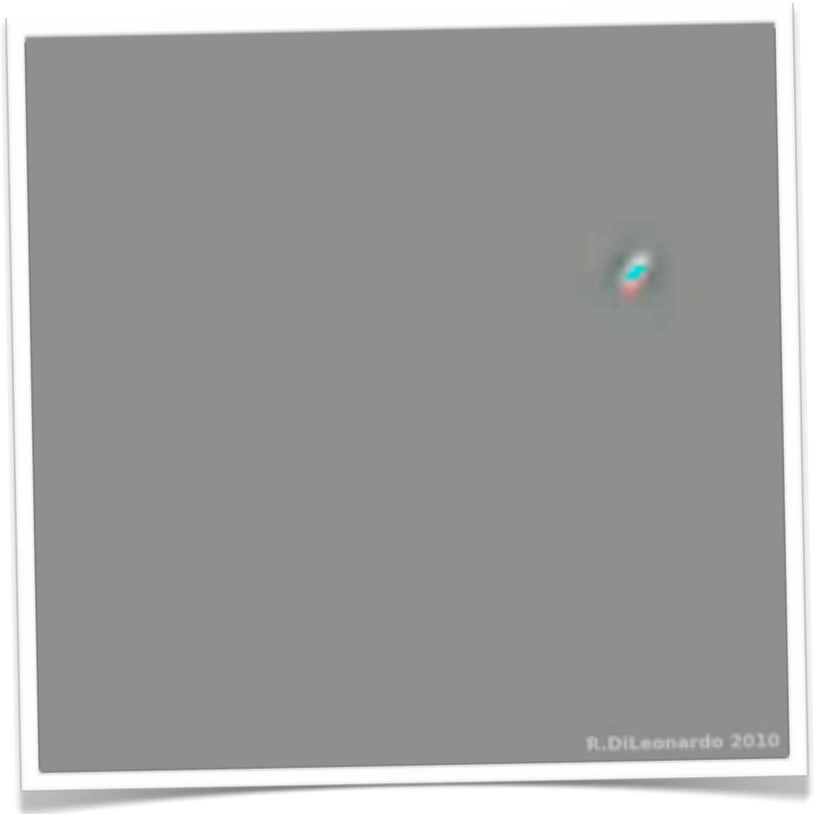
$\Downarrow$

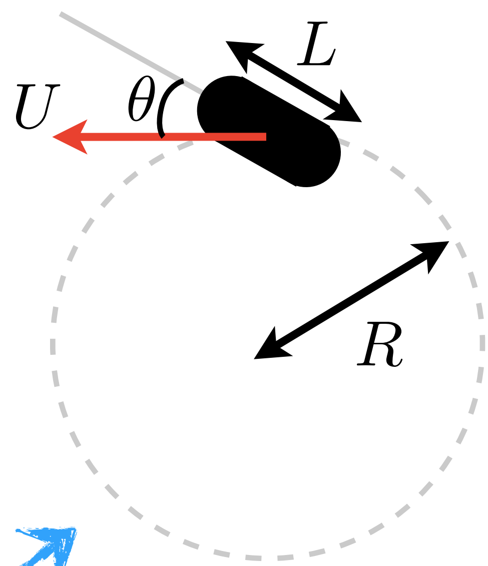
SMALLER “BACKGROUND” FLOW

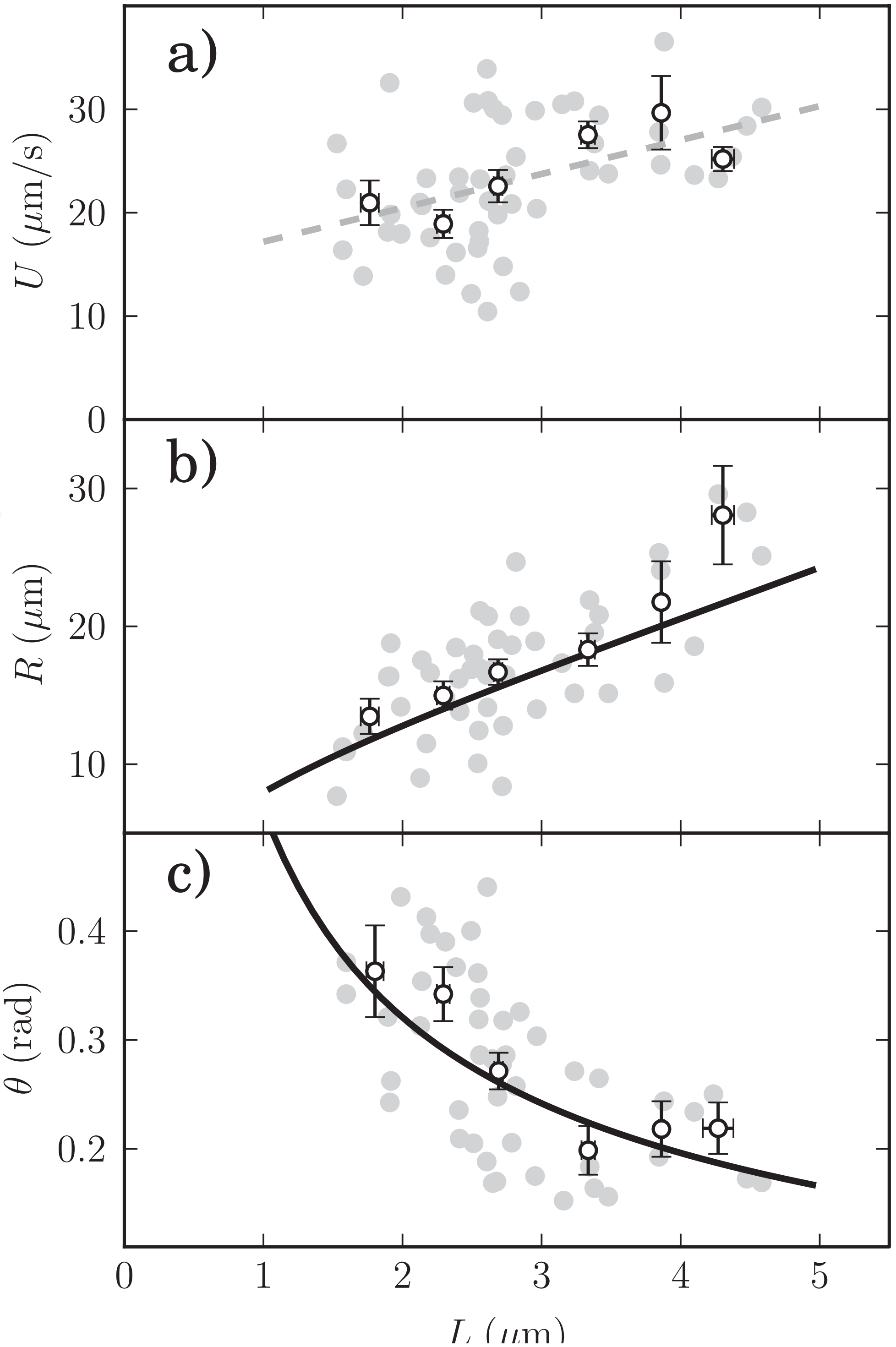
$\Downarrow$

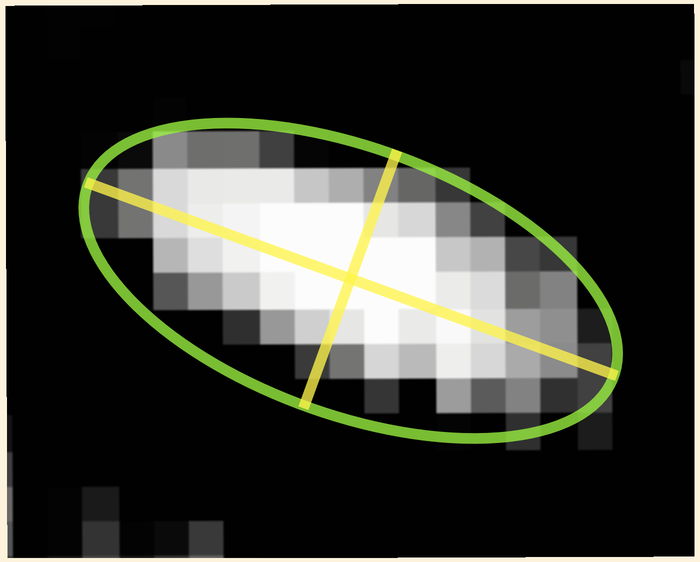
LARGER CURVATURE RADIUS

Video tracking bacteria









SPATIAL MOMENTS

0 , 1

center of mass
↓
position

covariance matrix
↓
shape (eigenvalues)
orientation (eigenvectors)

Summary 1

SELF-PROPULSION

- flagellar propulsion provides a simple strategy for swimming in low Re and fluctuating environments

CONFINED SWIMMING

- wall entrapment is hydrodynamic in origin and can be reduced using convex walls with small curvature radius

- wall-trapped bacteria swim to either right or left hand depending on the surface boundary condition (stick/slip)