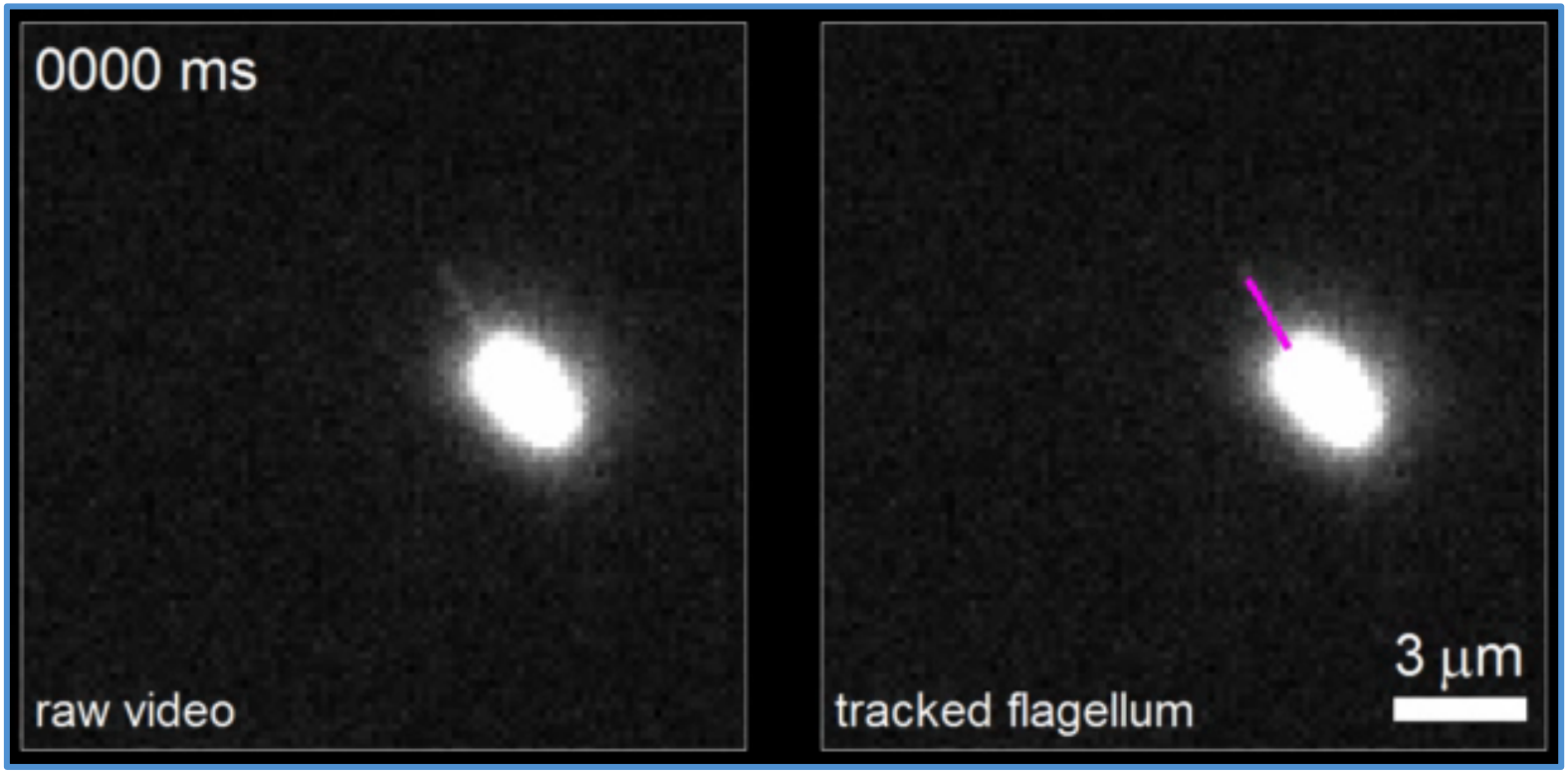
The acrobatics of swimming bacteria



Son, Guasto, & Stocker, *Nat Phys* 2013

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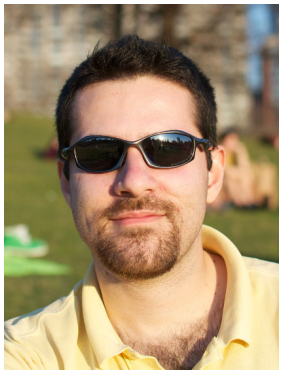
F.Menolascina, MIT


Peko Hosoi, MIT


Lisa Burton, MIT


Jerry Gollub, HC


Karl Johnson, HC


H. Gadelha, Oxford


Orr Shapiro, Weizmann

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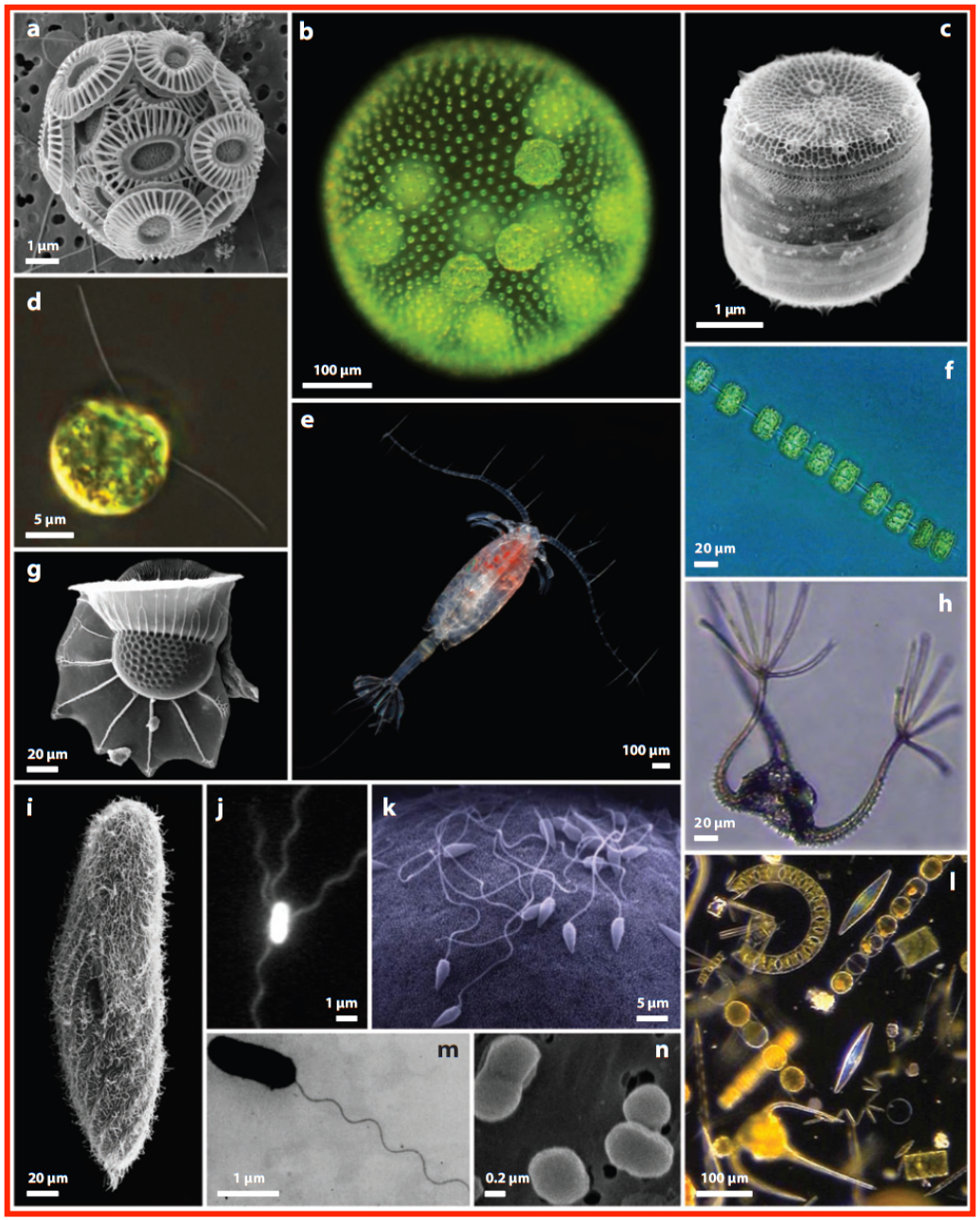
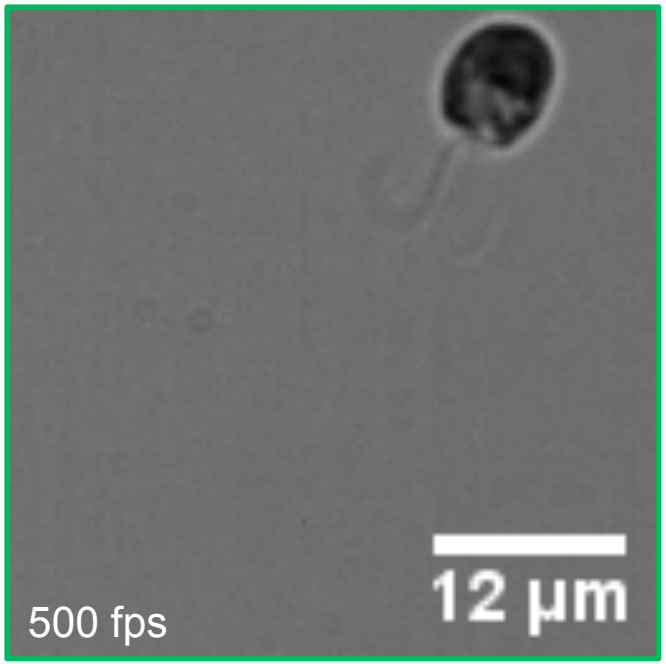
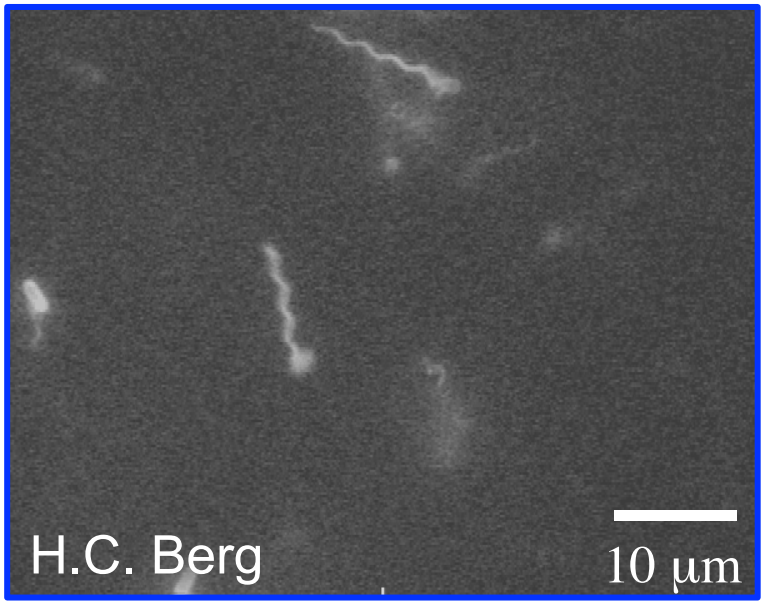
Why study the biophysics of motile single cells?

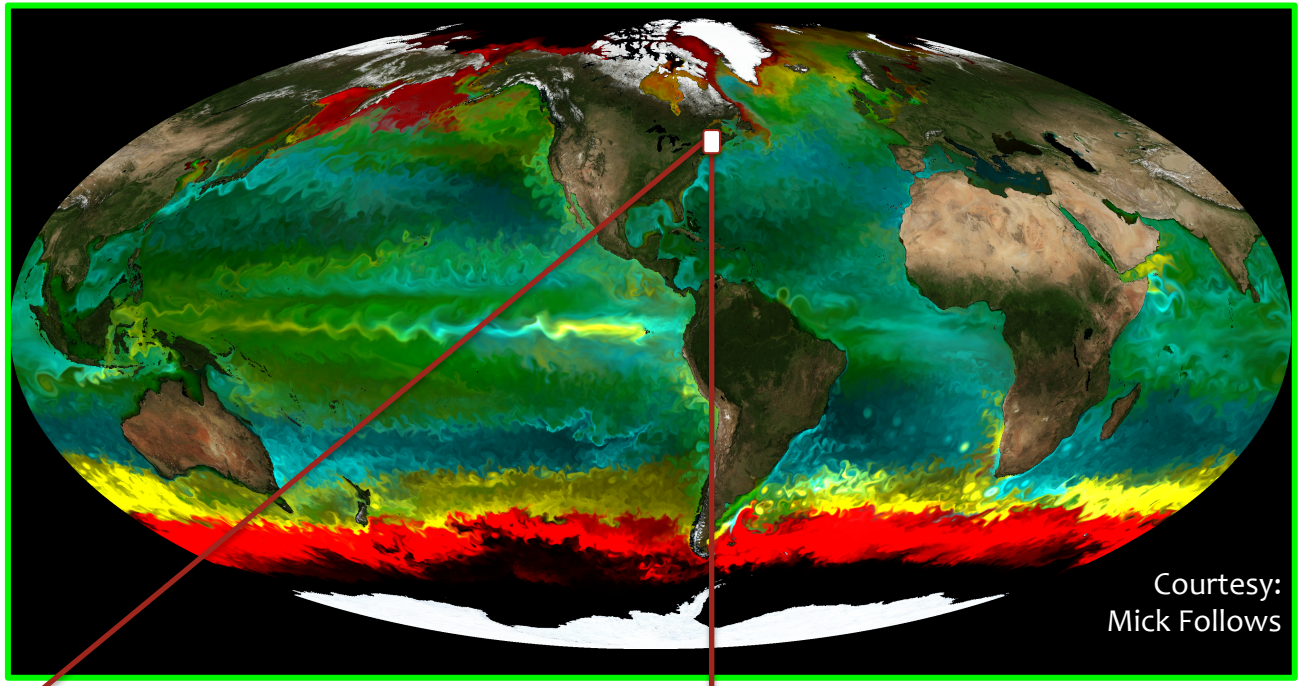


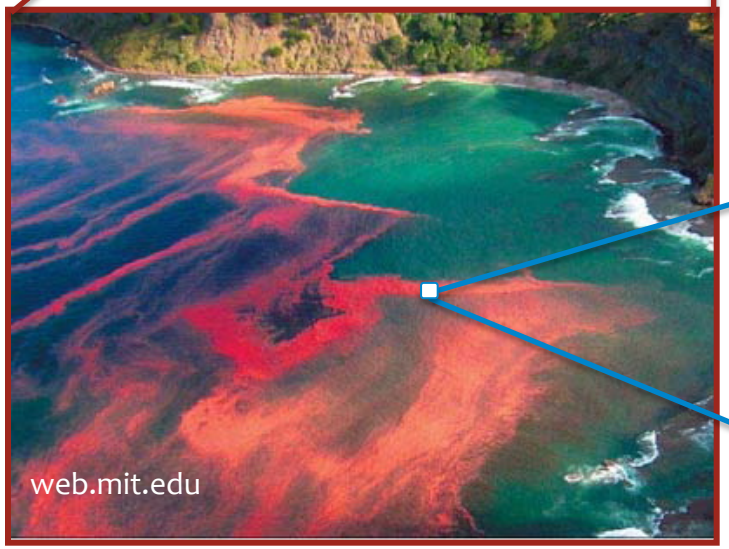
Guasto et al, *ARFM* 2012

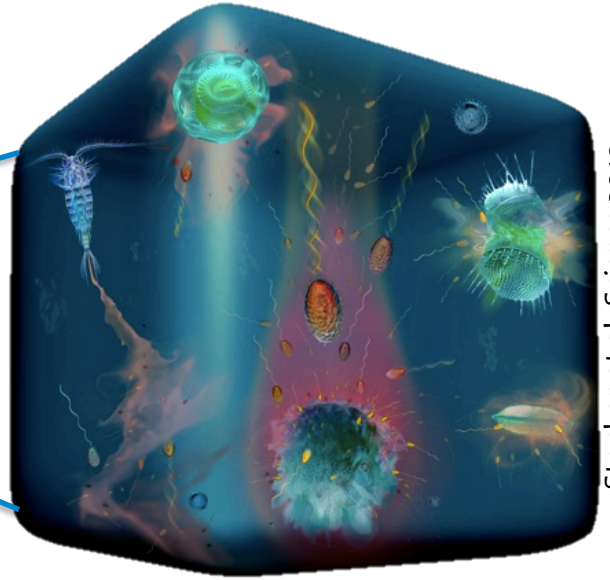




Swimming microorganisms in the environment







Stocker et al, *Science* 2010

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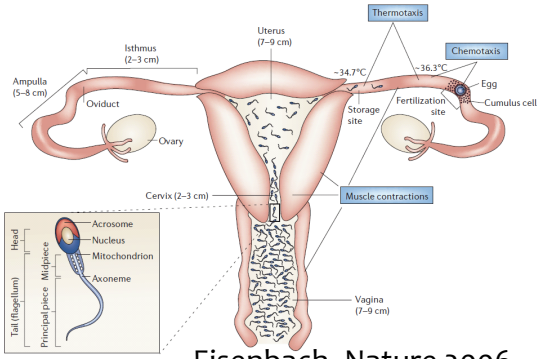
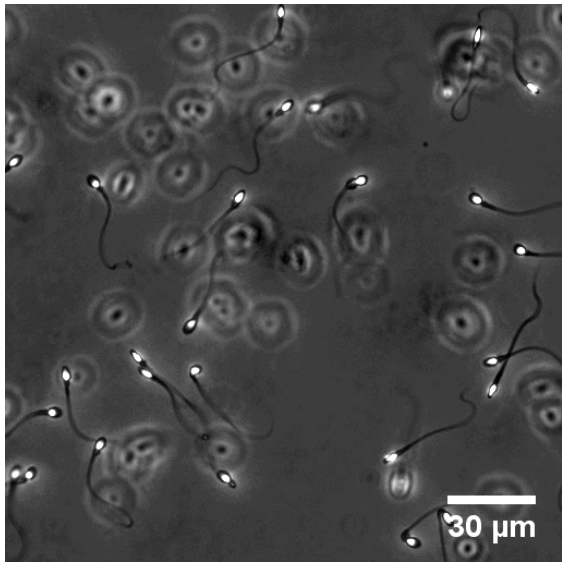
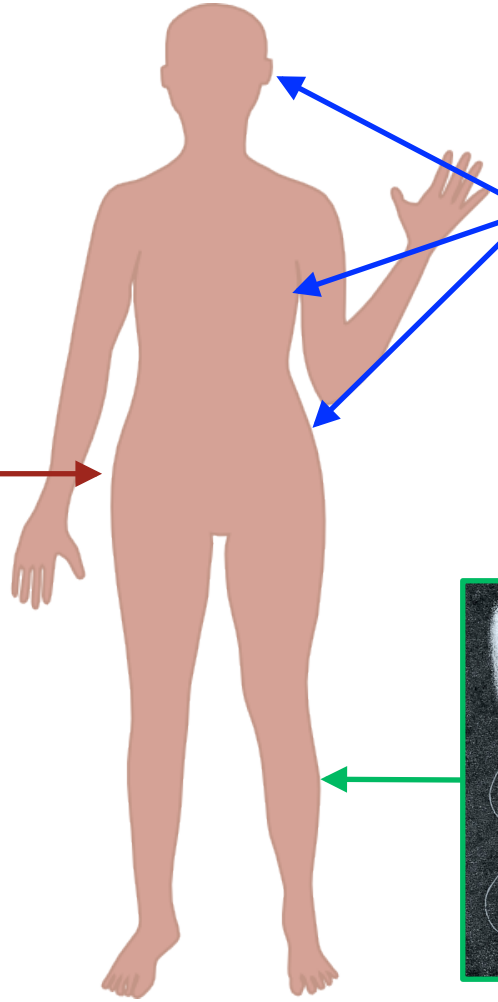
Swimming cells in the human body

Reproduction & fertilization

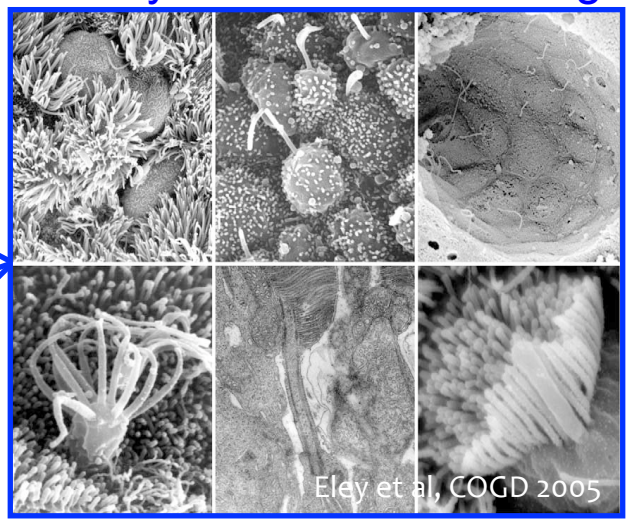


Eisenbach, Nature 2006



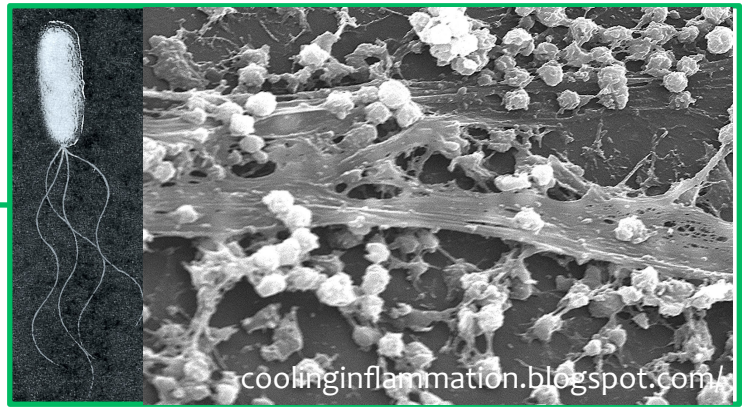


Ciliary actuation & sensing



Eley et al, COGD 2005

Infectious disease



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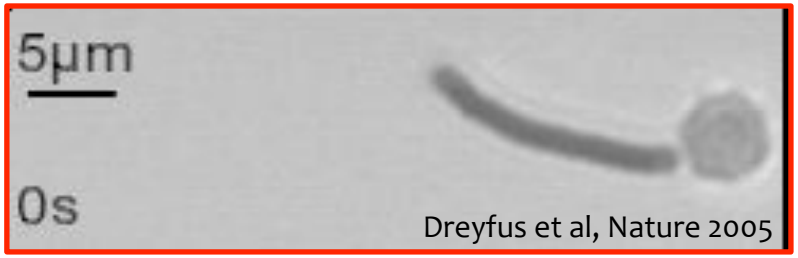
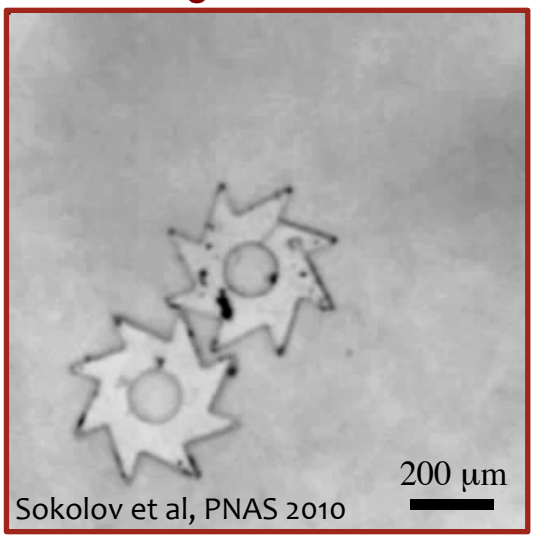
“There’s plenty of room at the bottom!” -Feynman

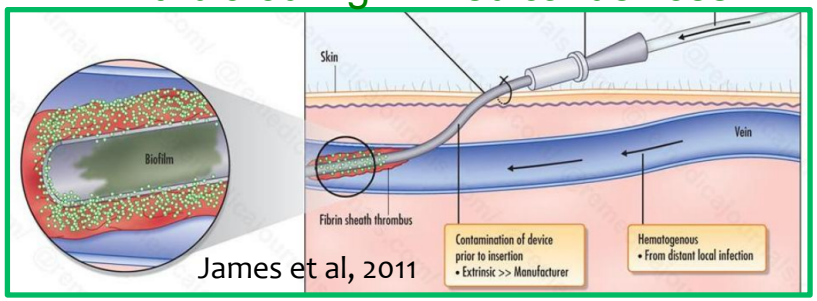
Robots for nano-medicine & drug delivery



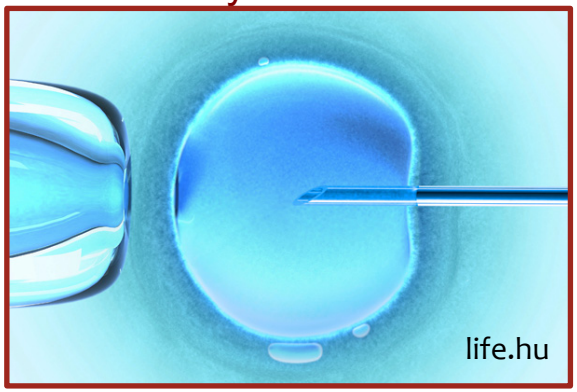
Powering micro-machines



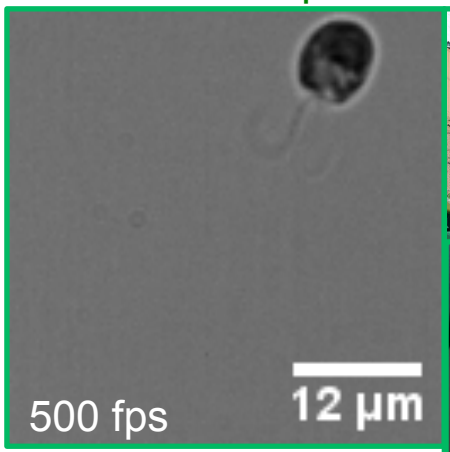
Anti-biofouling in medical devices



Fertility treatments



Biofuel production & bioreactors



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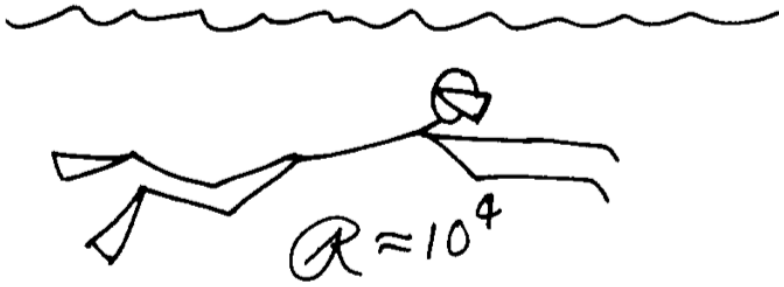
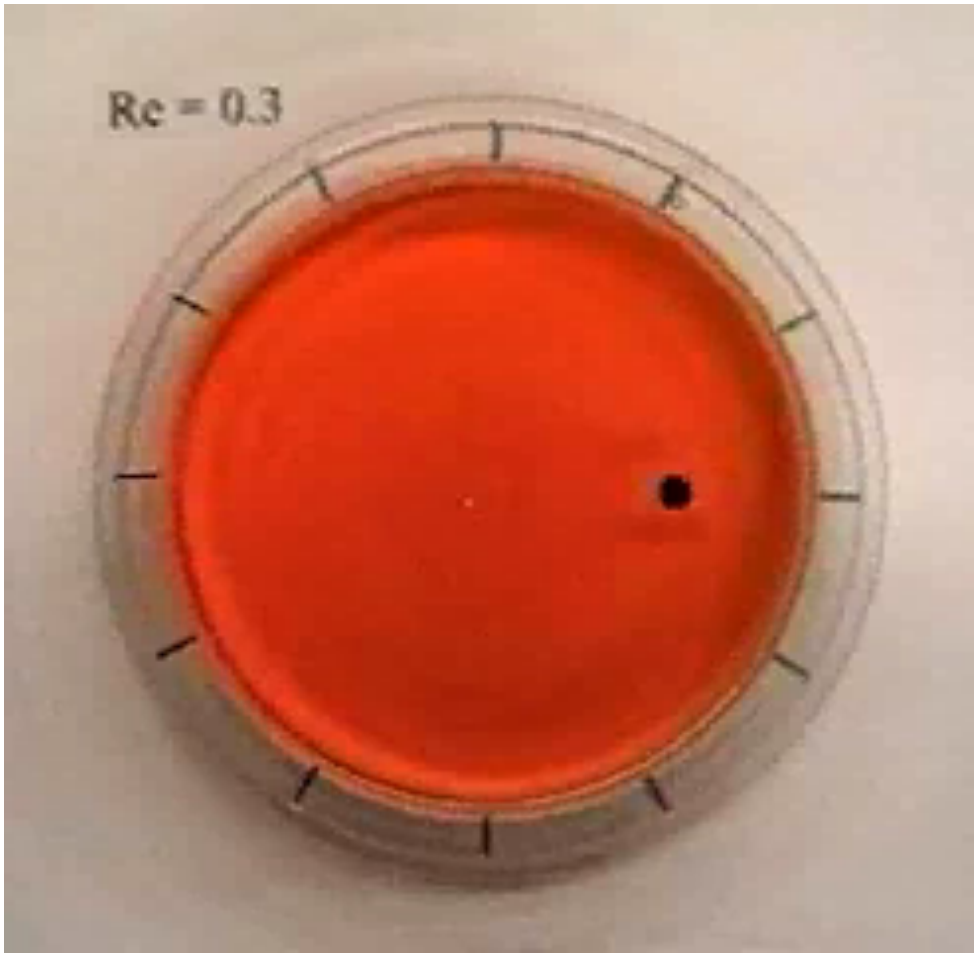
Fluid mechanics: The physical rules of the game

- The Reynolds number, *R*
- No coasting!!



$$R \equiv \frac{avp}{\eta} = \frac{av}{\nu}$$

$\nu = 10^{-2}\ \frac{cm^2}{sec}$ for water



Purcell, *Am J Phys* 1977

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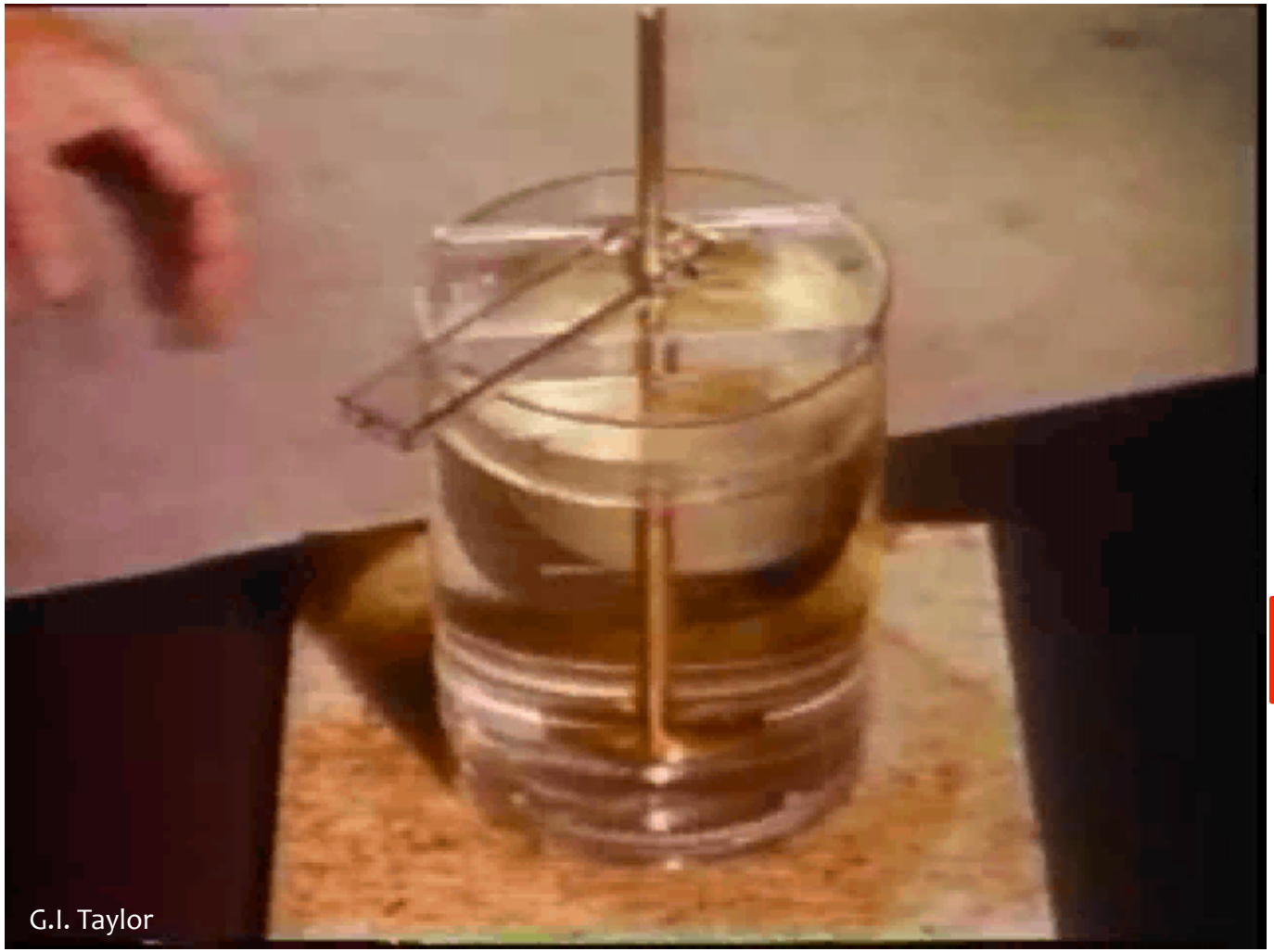
Life in the slow lane

- Motion is perfectly ‘reversible’

$$R \equiv \frac{avp}{\eta} = \frac{av}{\nu}$$



Organism	*R*
Whale	10^{8}
Tuna	10^{7}
Michael Phelps	10^{5}
Goldfish	100
House Fly	10
← This Expt.	0.01
Bacterium	10^{-4}

Vogel, 1994

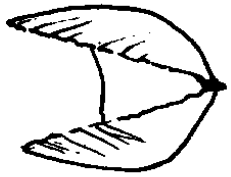
What does this mean for locomotion?

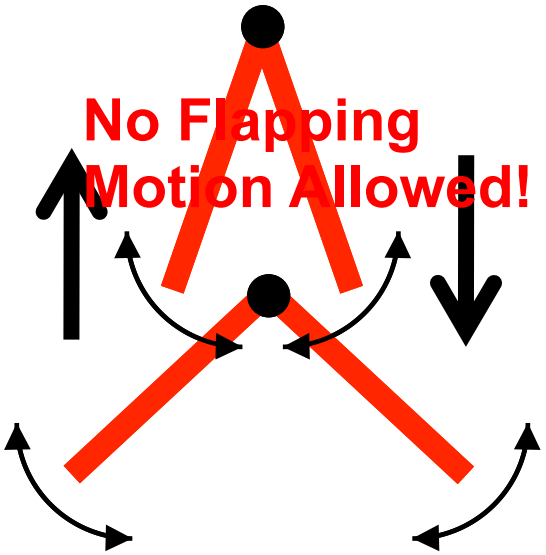
- Purcell's "Scallop" Theorem

Time doesn't matter. The pattern of motion is the same, whether slow or fast, whether forward or backward in time.

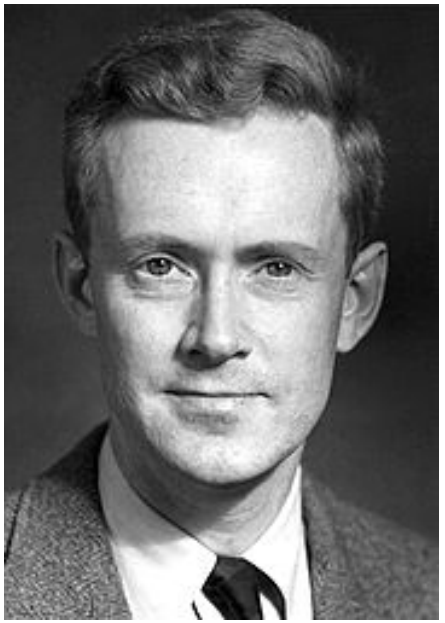
The Scallop Theorem

Purcell, AJP 1977



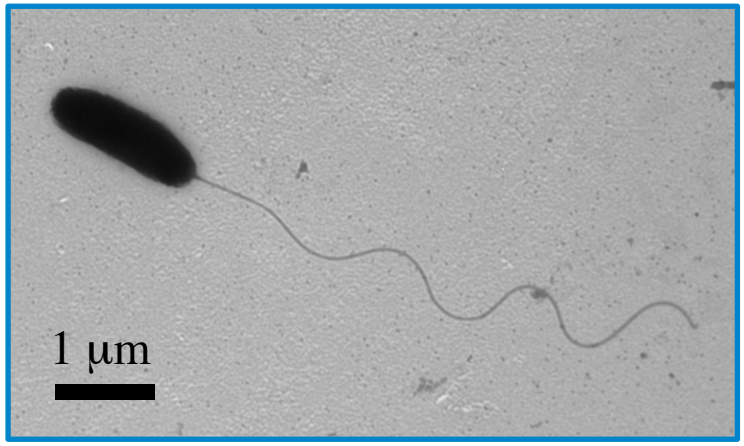


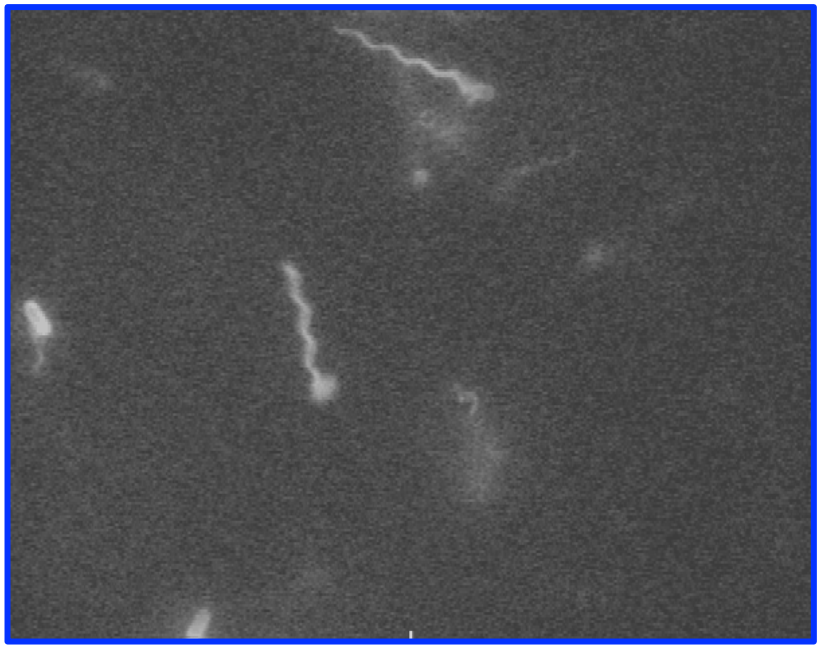
- Ed Purcell (Harvard)
  - 1952 Nobel Prize (physics)
  - Discovered nuclear magnetic resonance (NMR), which is the basis for MRI

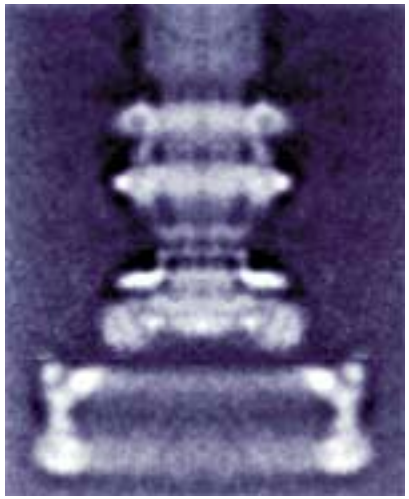


Nature's solutions for motility

- Rigid flagella (prokaryotes)

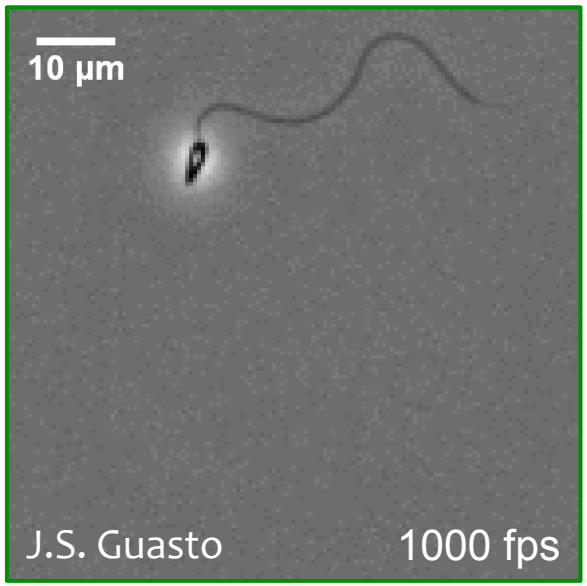


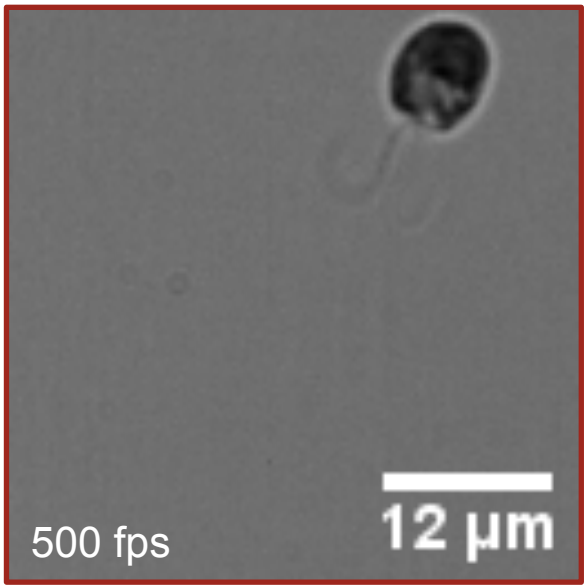




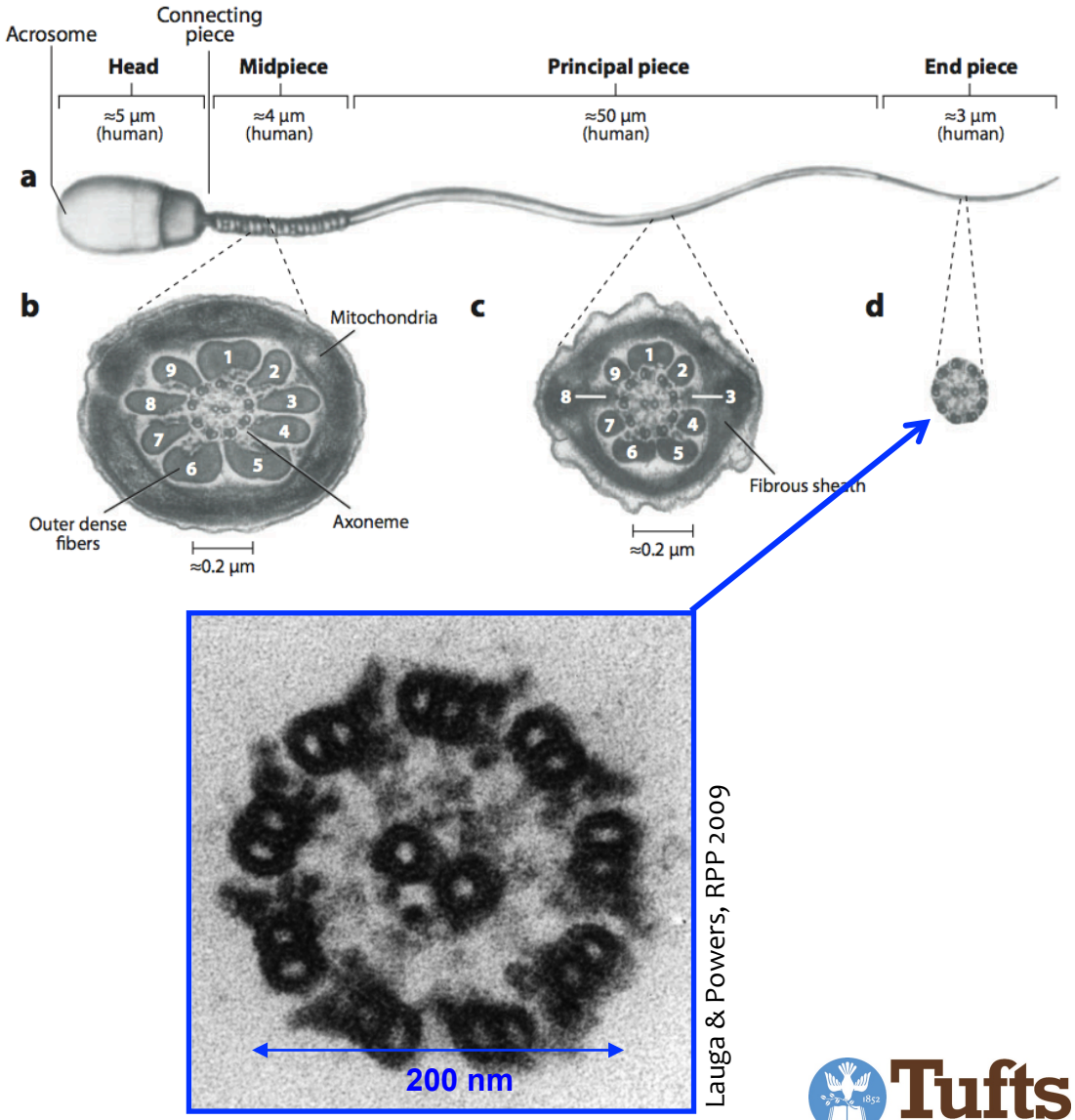
Nature's solutions for motility

- Flexible flagella (eukaryotes)





Guasto et al, *PRL* 2010



Lauga & Powers, RPP 2009

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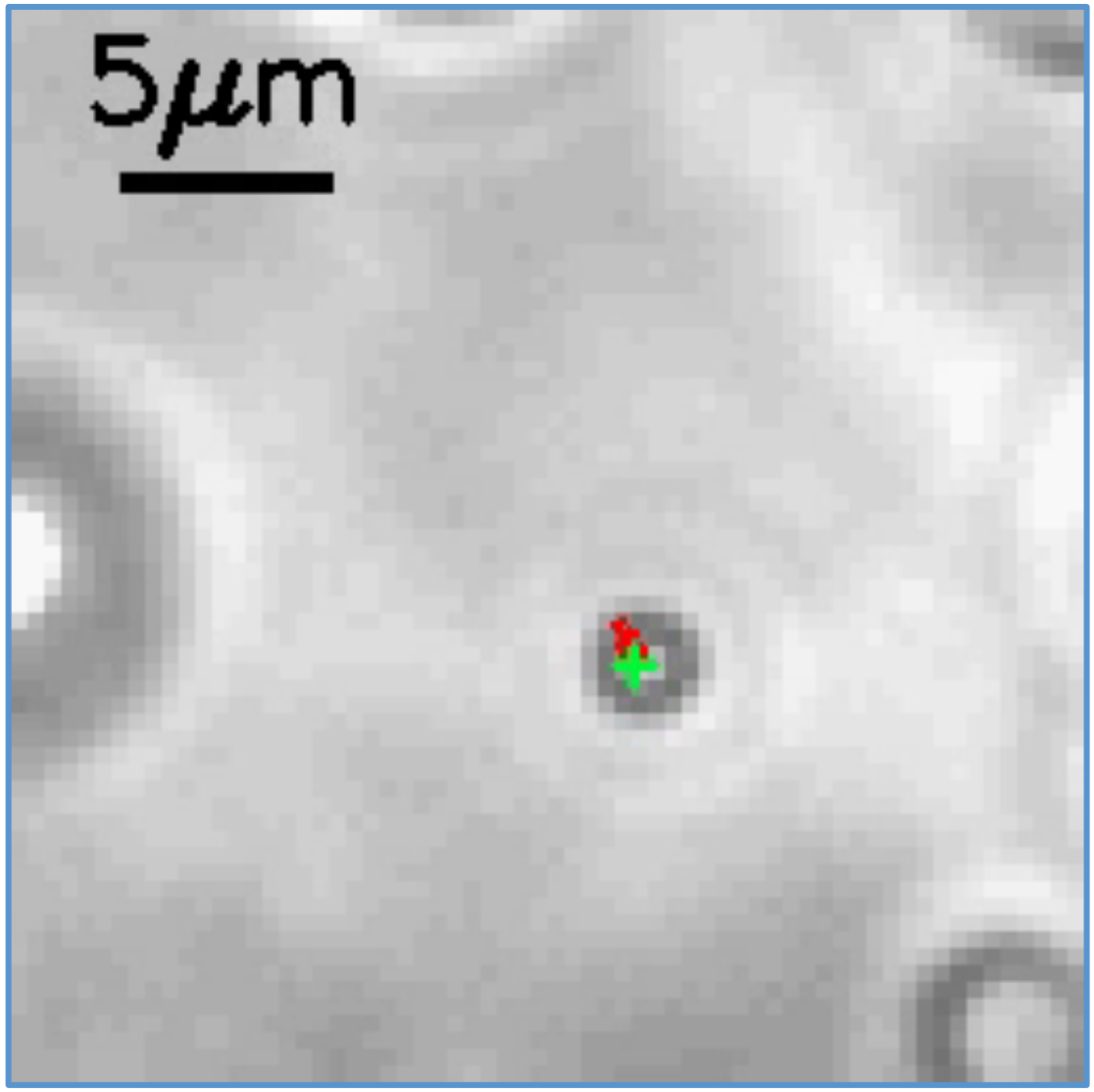
Fluid flows generated by cells



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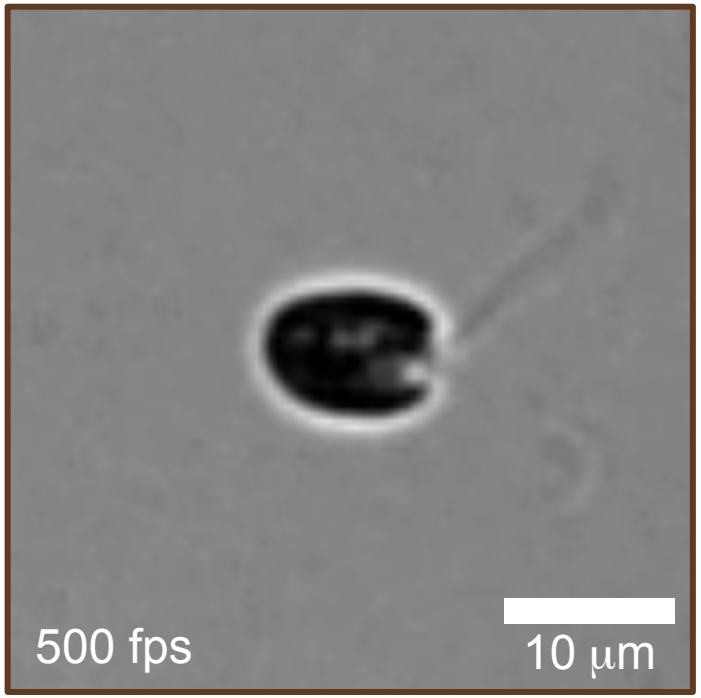
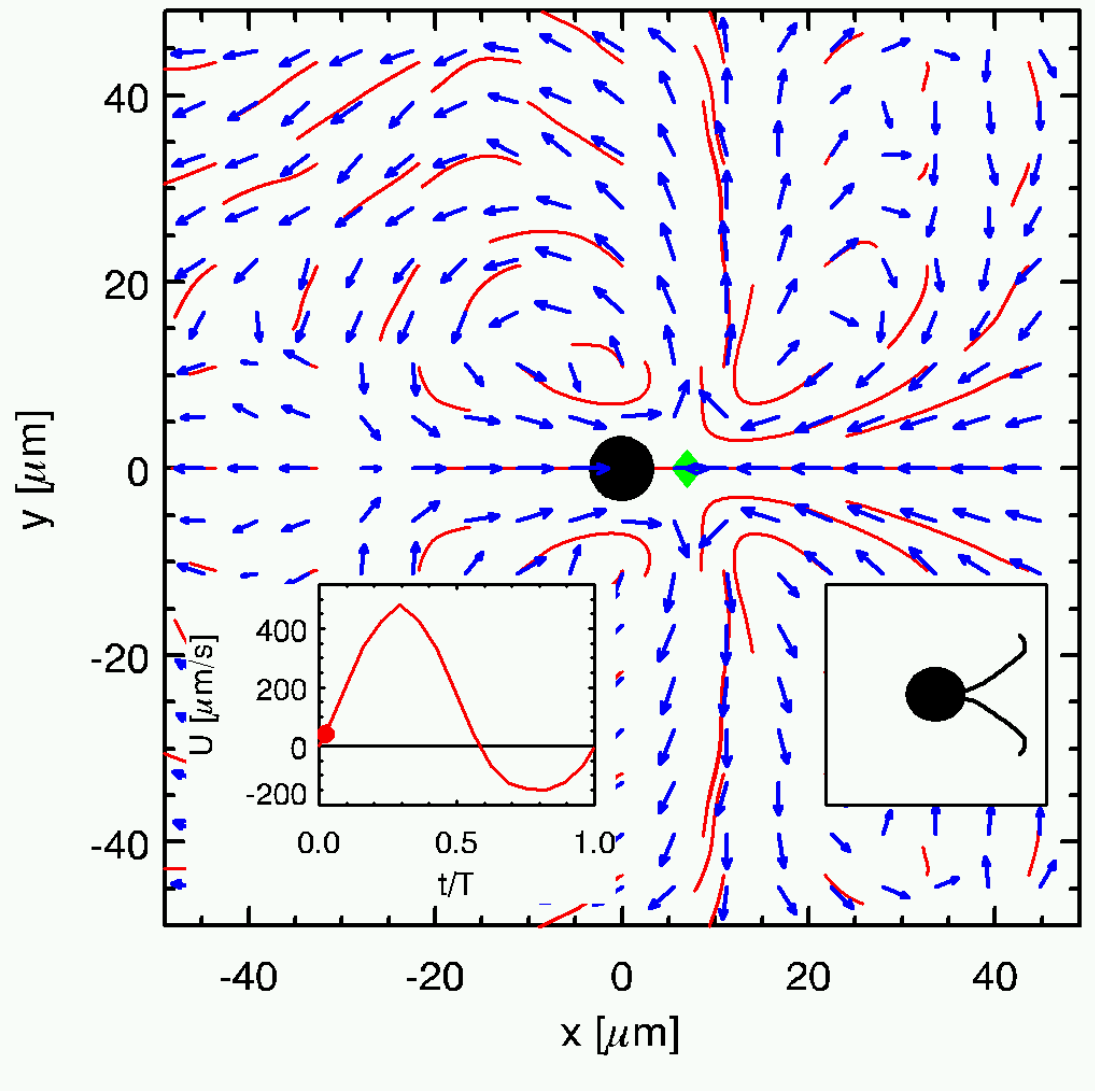
Swimming microalgae (*Chlamydomonas*)





Guasto et al, *PRL* 2010
Leptos et al, *PRL* 2009
Kurtuldu et al, *PNAS* 2011

- Beat period = 19 ms (50 Hz)

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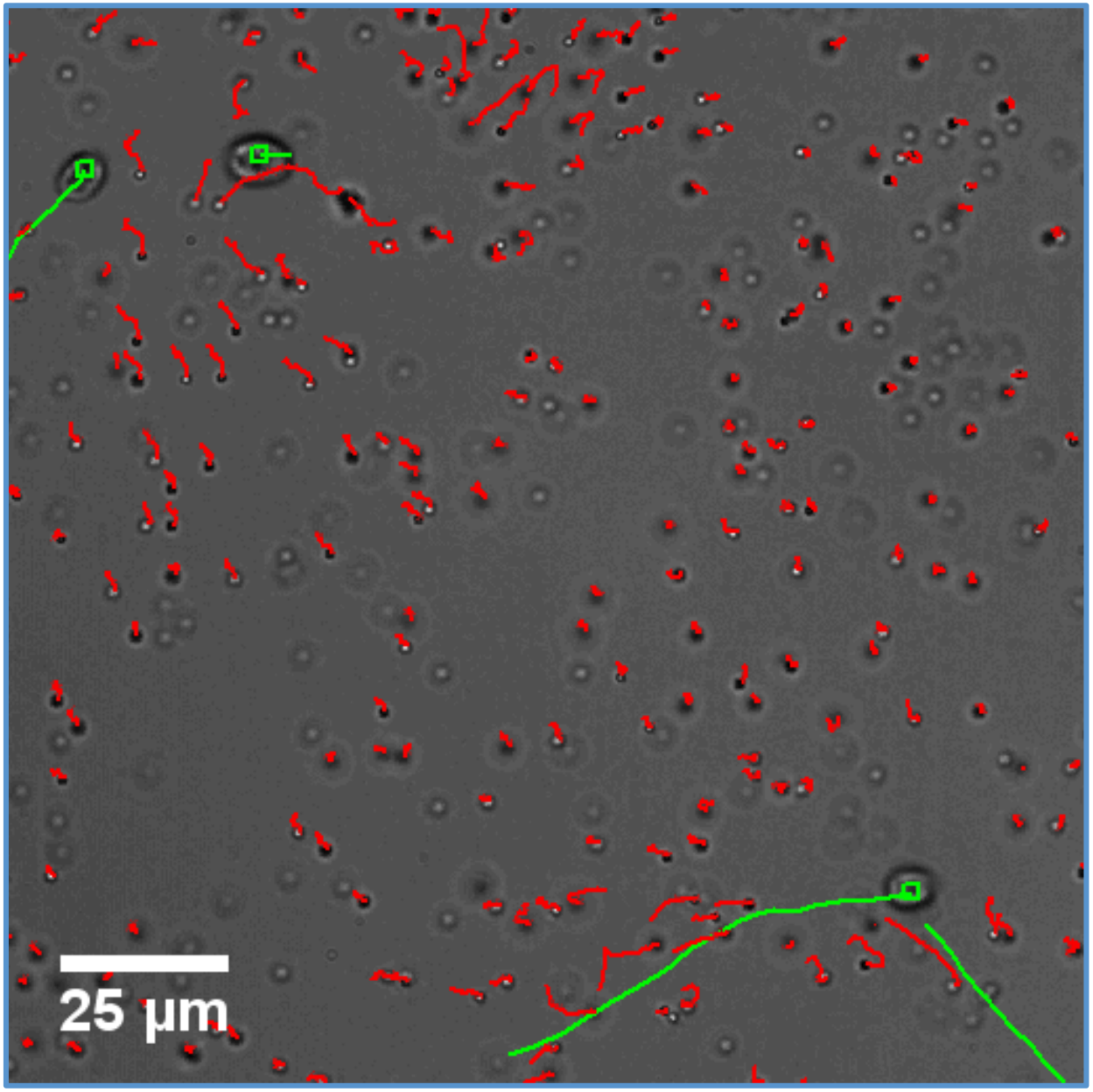
Mixing in active suspensions



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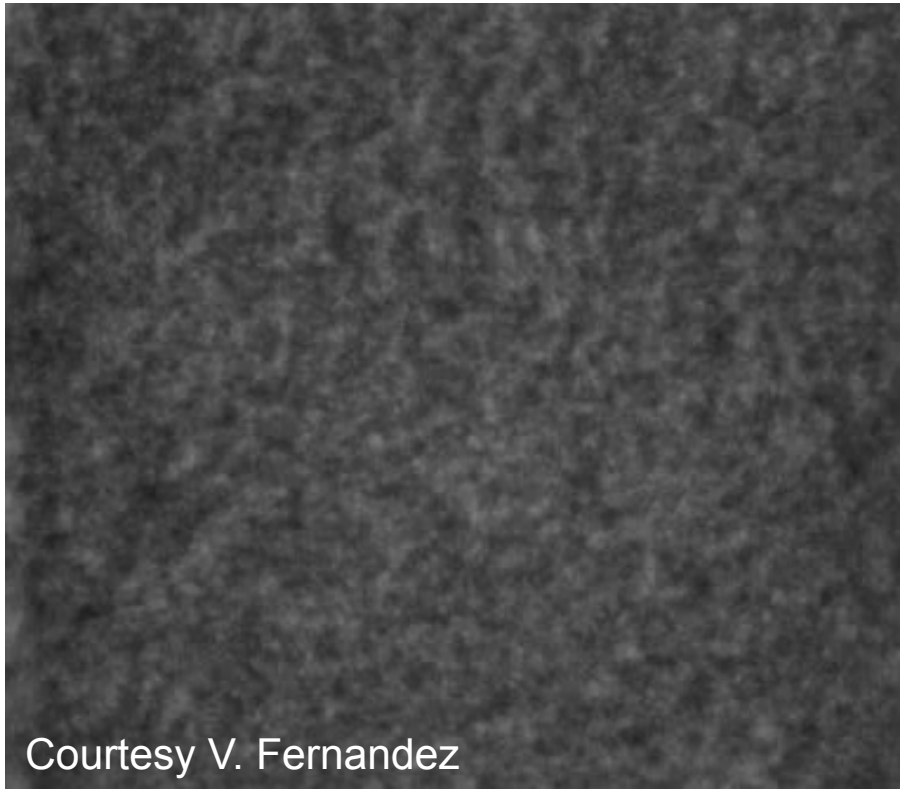
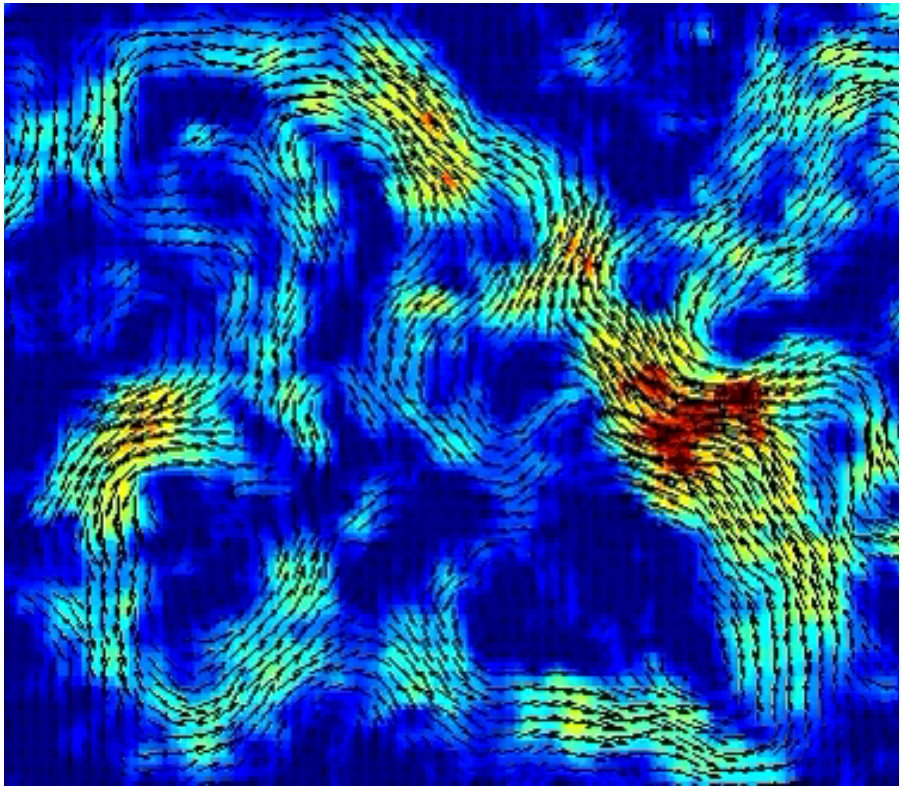
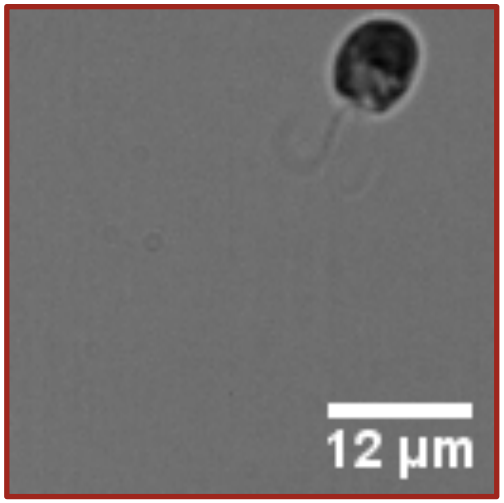
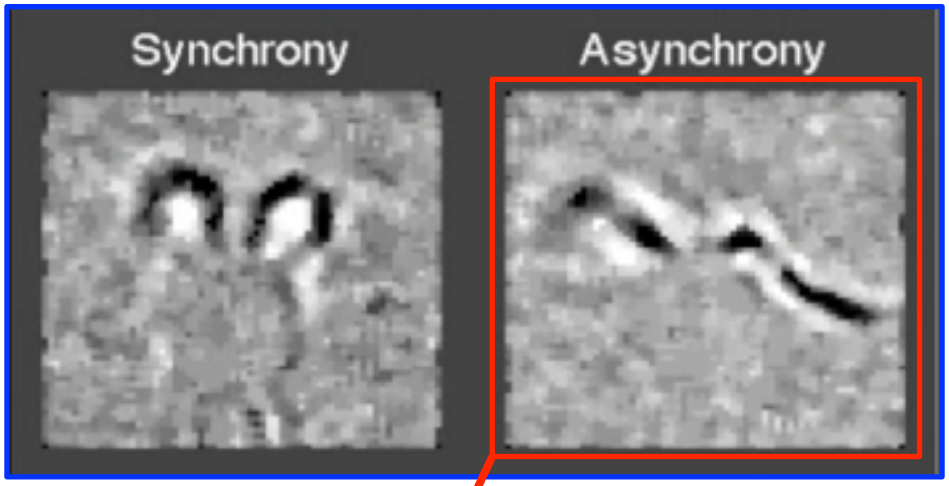
Collective bacterial motion (high cell concentration)



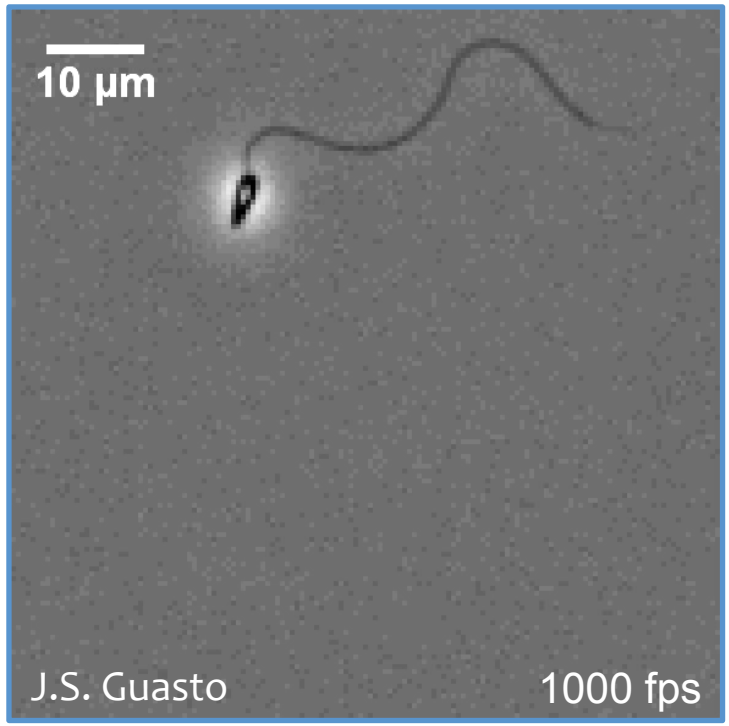


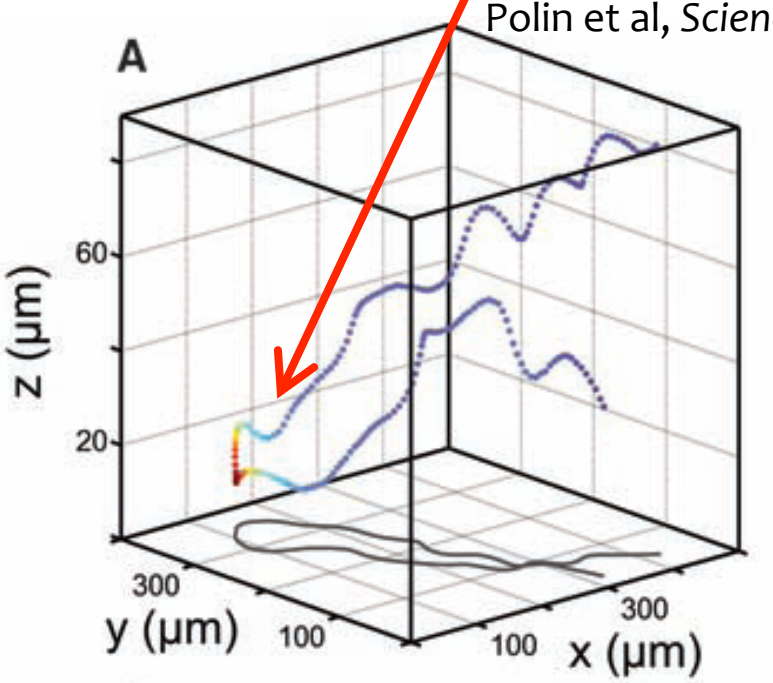
Propulsion is only half of the story





Polin et al, *Science* 2009





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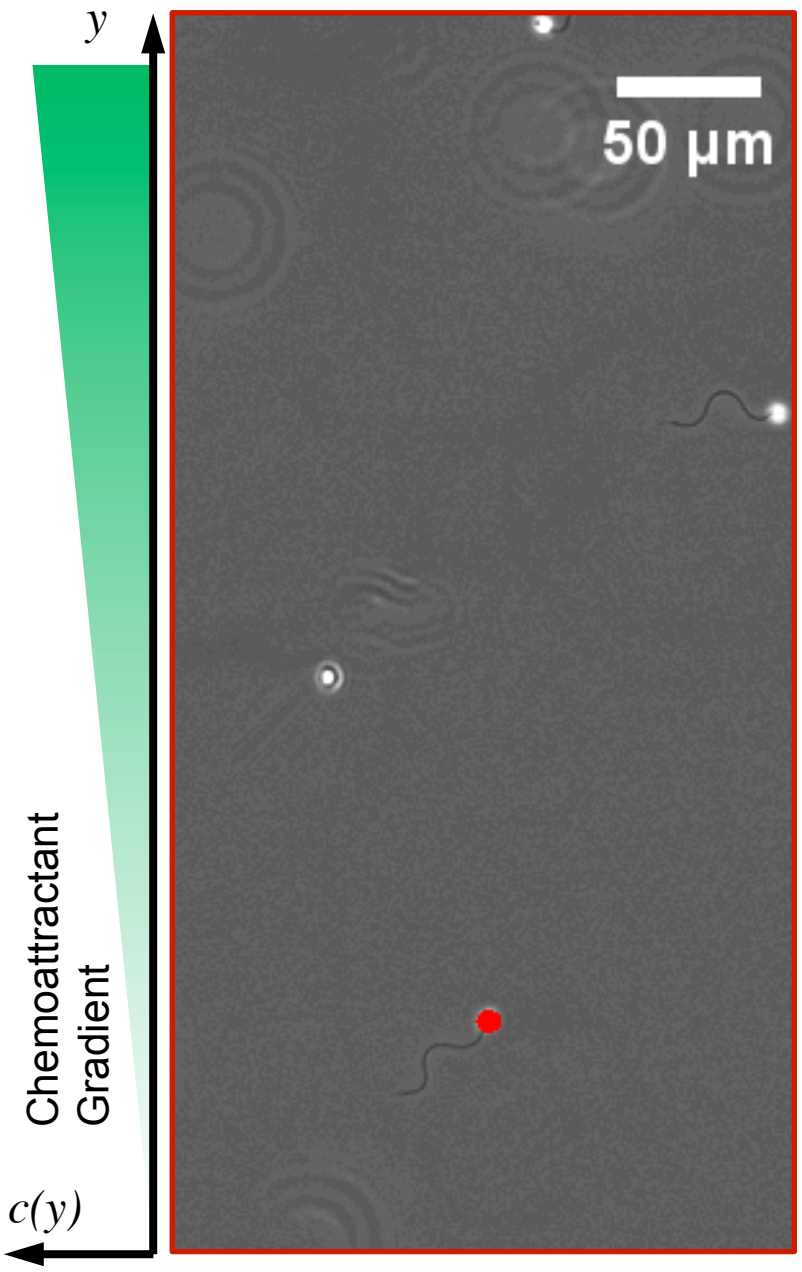
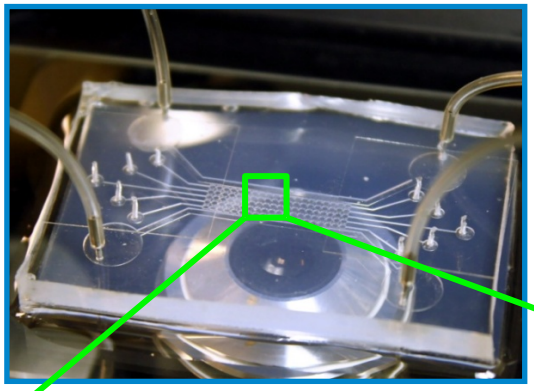
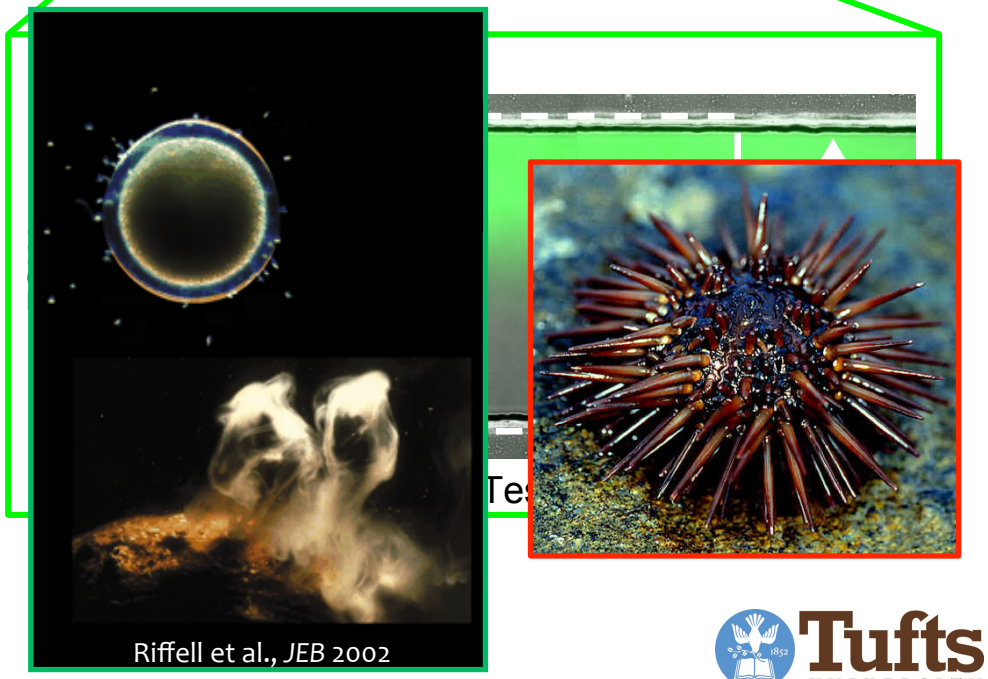
Chemotactic turning of sperm

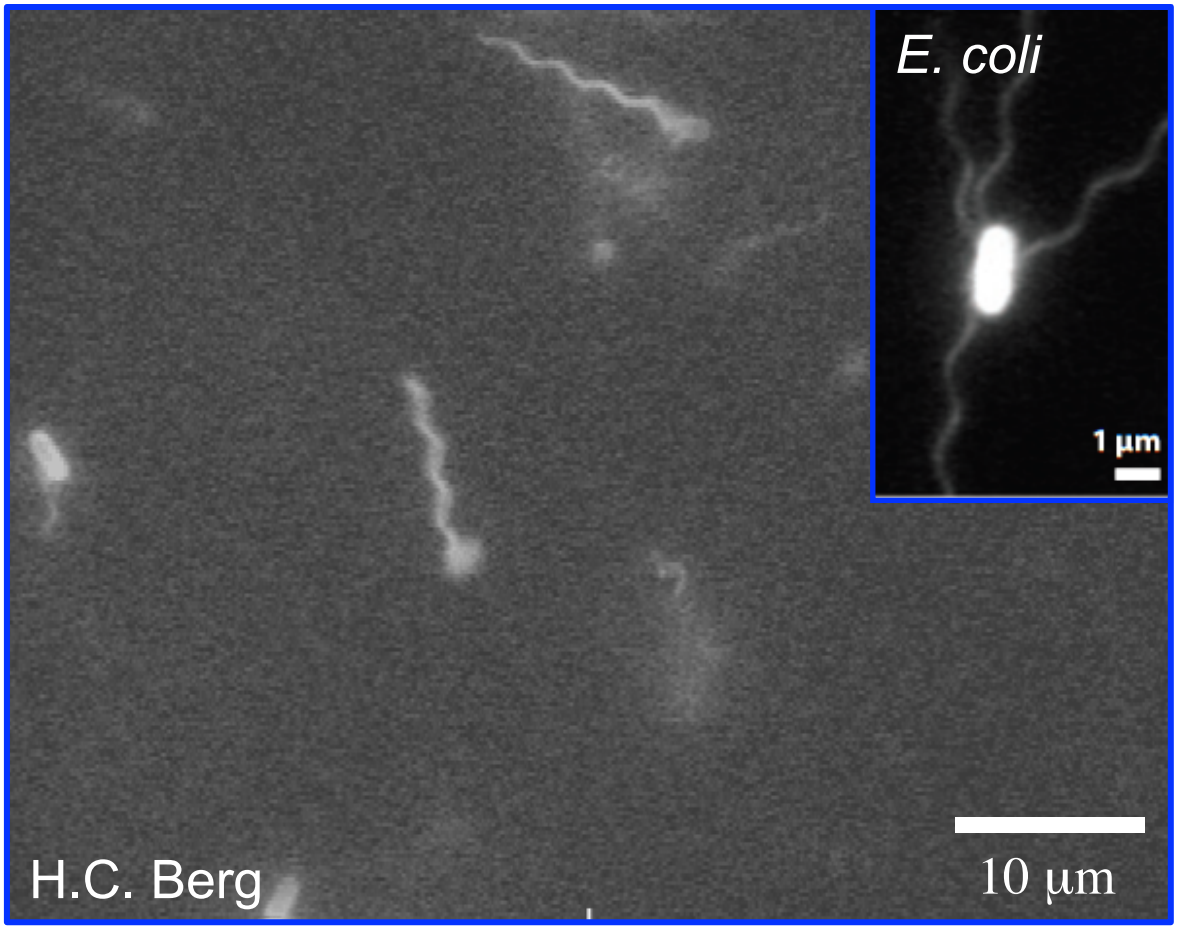


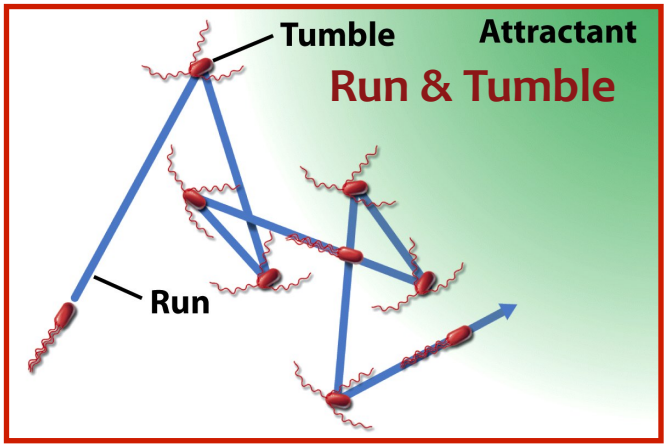


Microfluidics enable the precise **engineering** of microscale **fluid** and **chemical** conditions



Turning is crucial for bacterial survival





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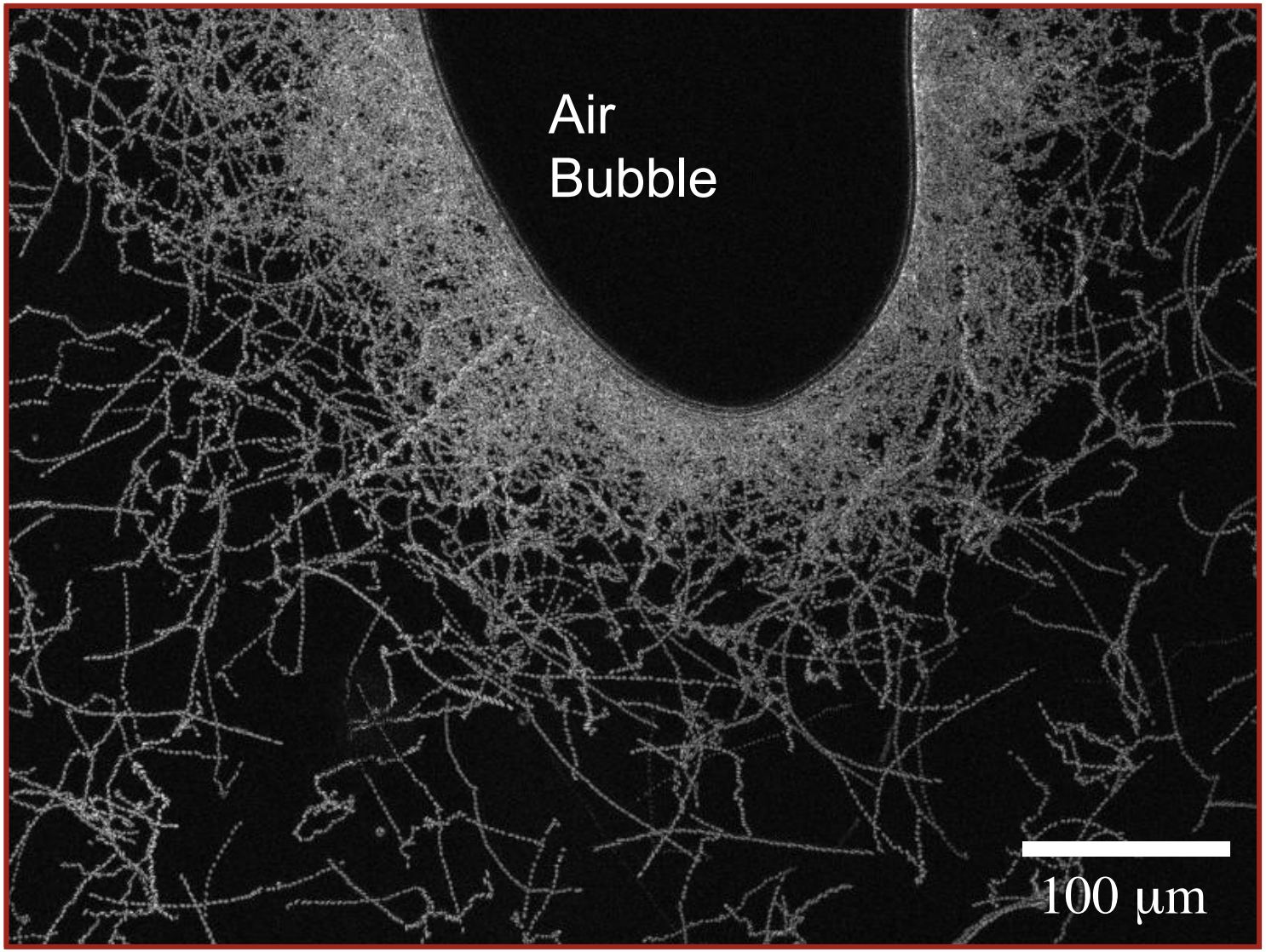
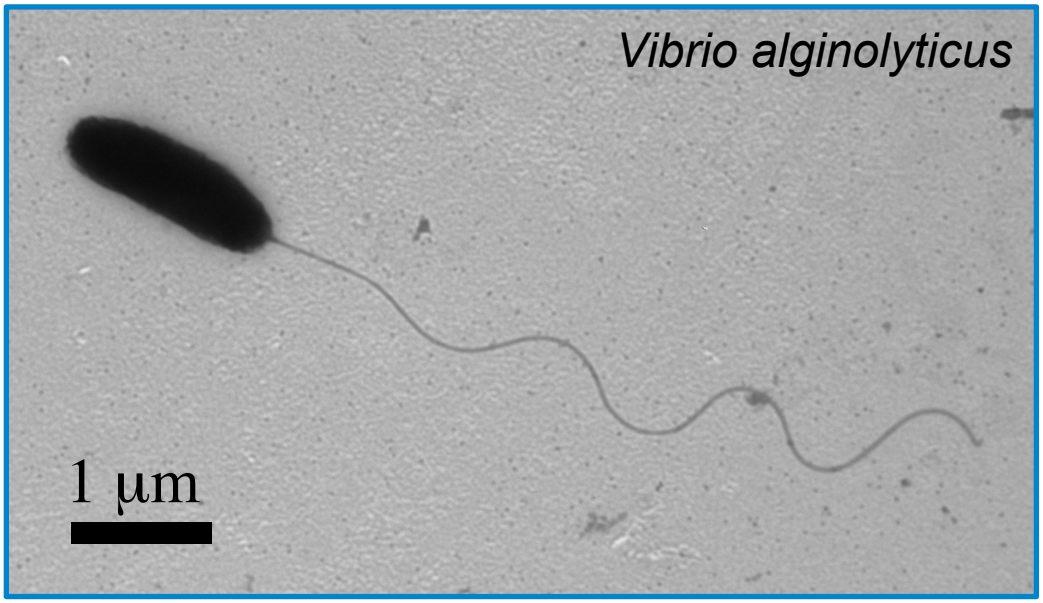
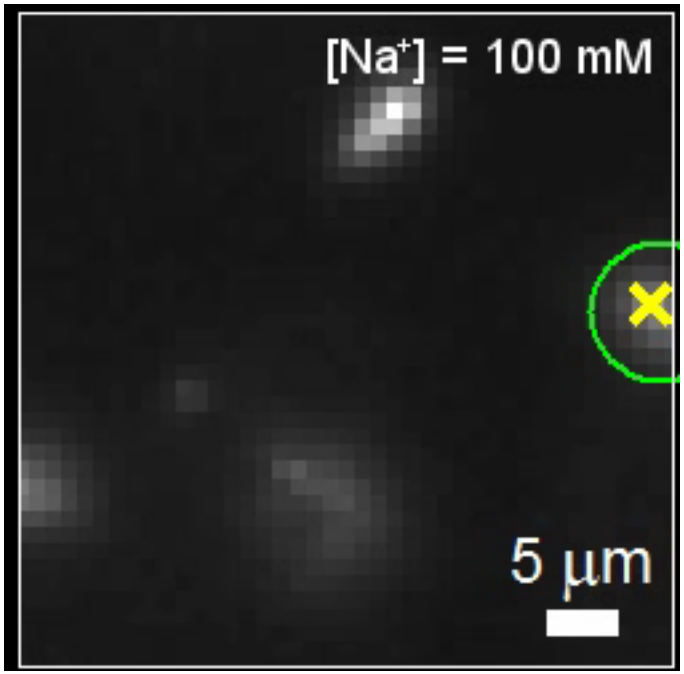
Turning allows cells to find resources (chemotaxis)



Many bacteria have only *one* flagellum





- **95%** of marine bacteria:
  - *Vibrio alginolyticus*
  - *Vibrio cholerae*
  - *Shewanella putrefaciens*
  - *Pseudoalteromonas haloplanktis*

- Previous view:
  - Cells **only** swim **forward and backward** ('run and reverse') via rotary motor control

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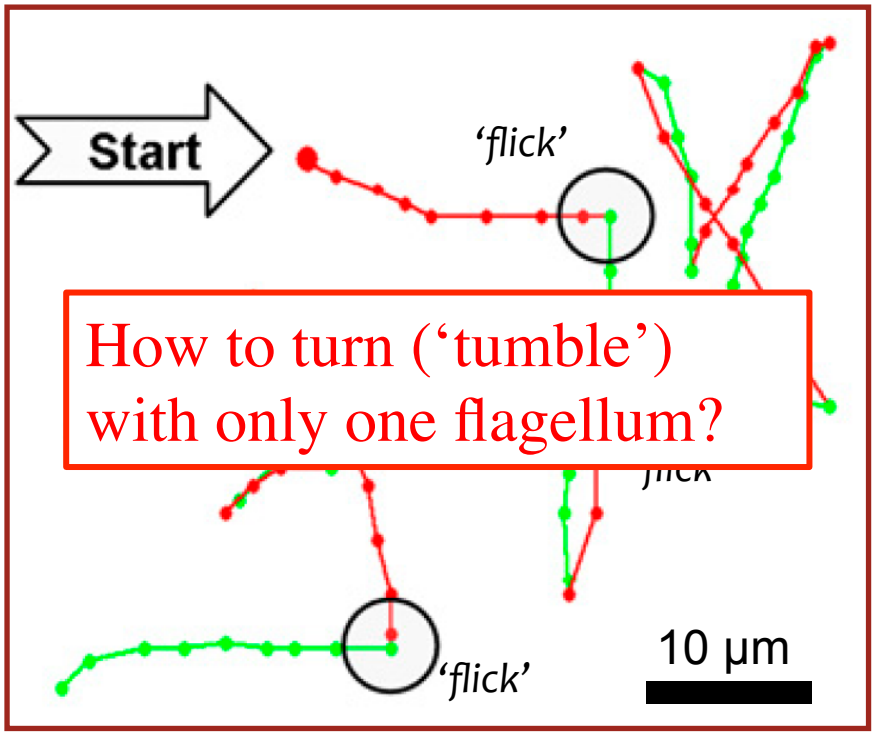
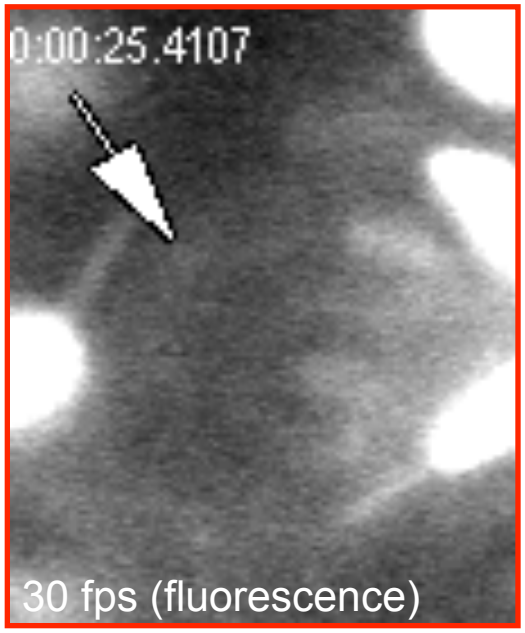
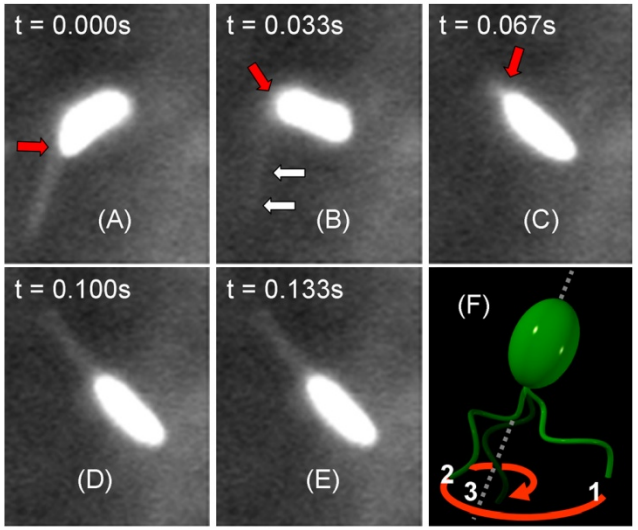
Run, reverse, & flick motility



Xie et al, PNAS 2011
Stocker, PNAS 2011





- Flagellum = propeller + rudder
- Mean angle change = 90°

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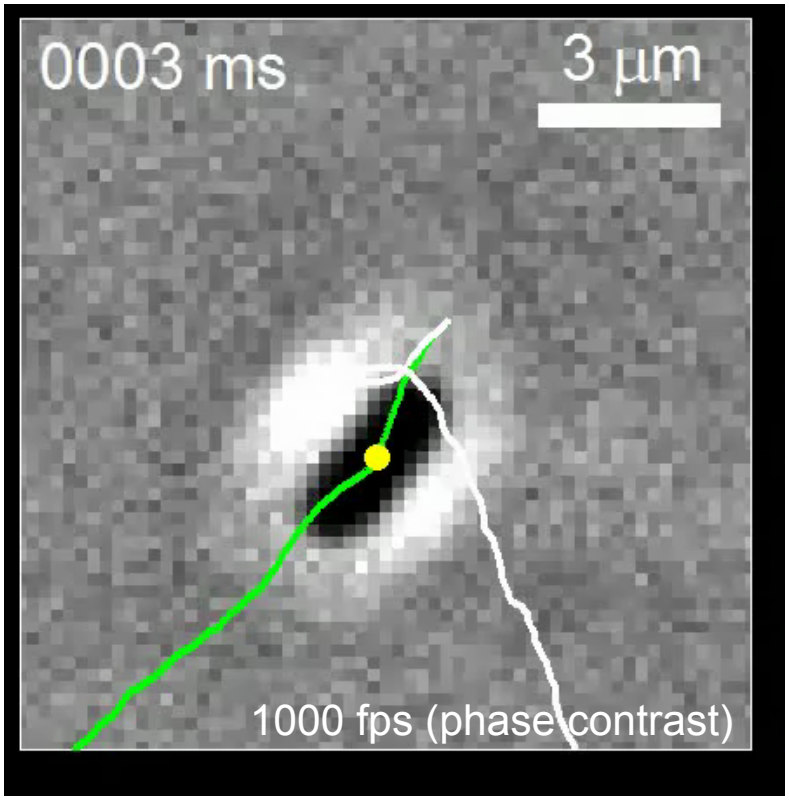
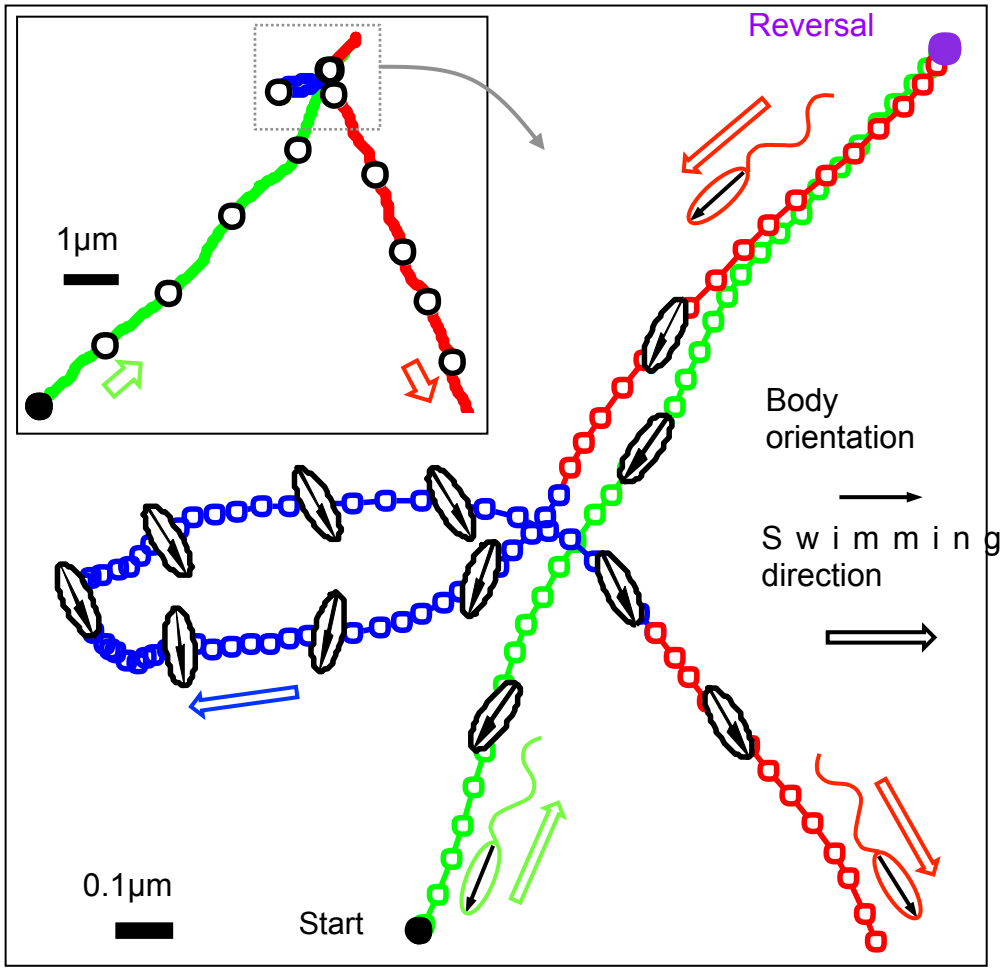
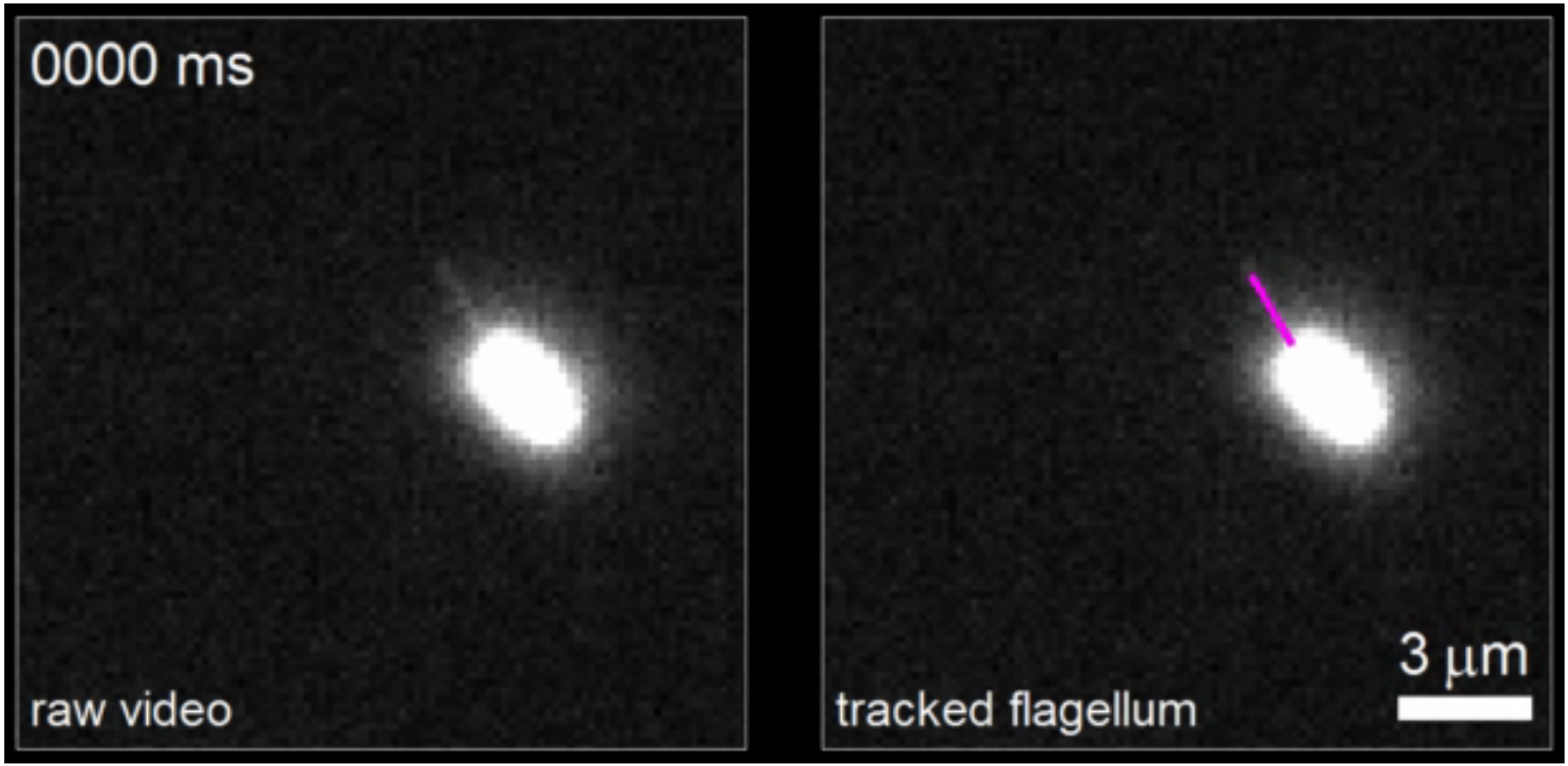
Cells swim forward prior to ‘flick’



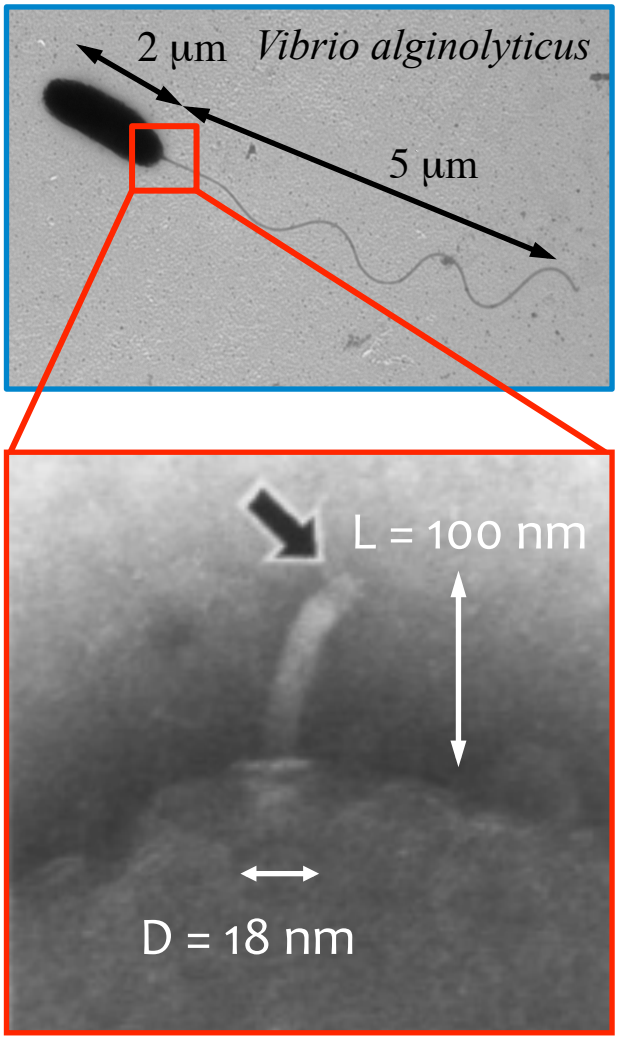


Flagellar bending concentrated at base

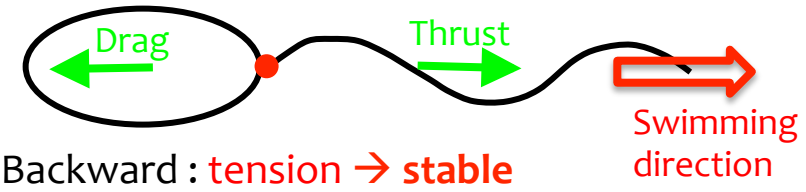


- 20 nm diameter flagellum

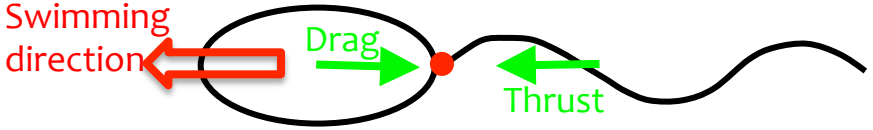
Forward swimming implies compression



Nishioka et al 1998



Backward : tension → **stable**



Forward : compression → **unstable**

H.C. Berg

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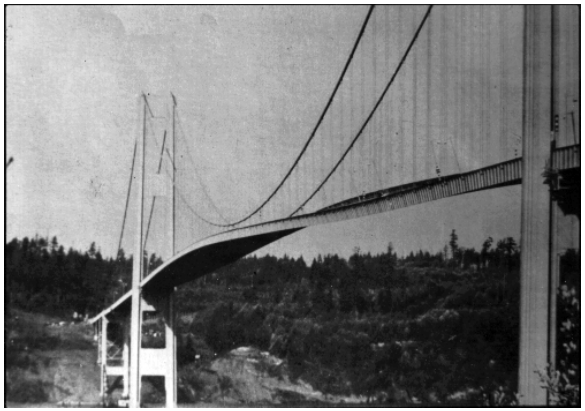
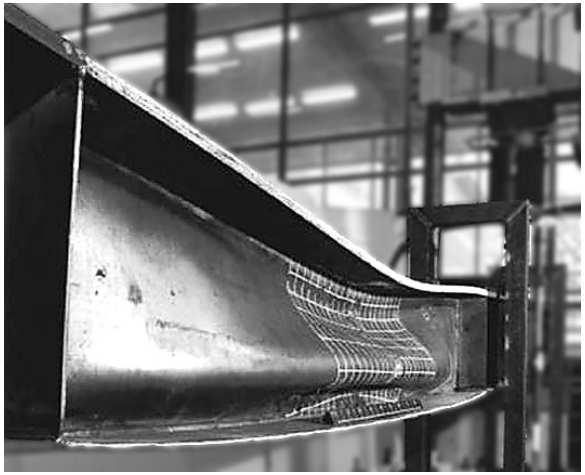
But, buckling is bad … right?





$$P_{cr} = \pi^2 \frac{EI}{L^2}$$

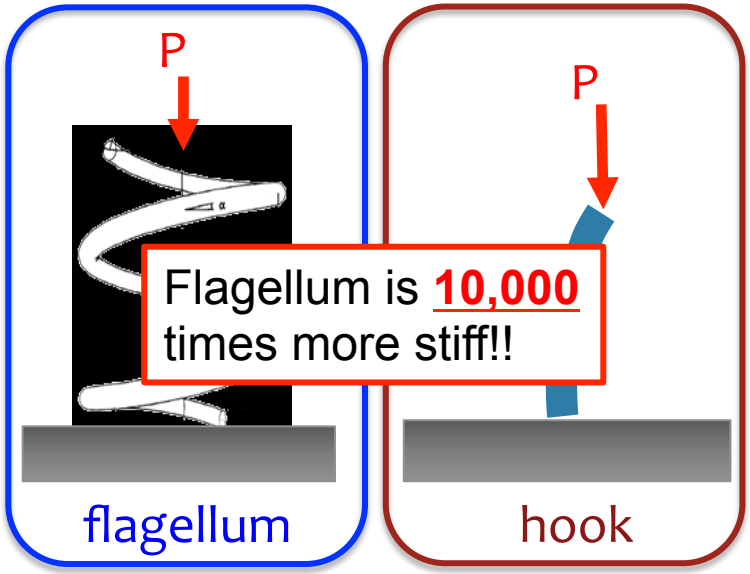
Turning by buckling

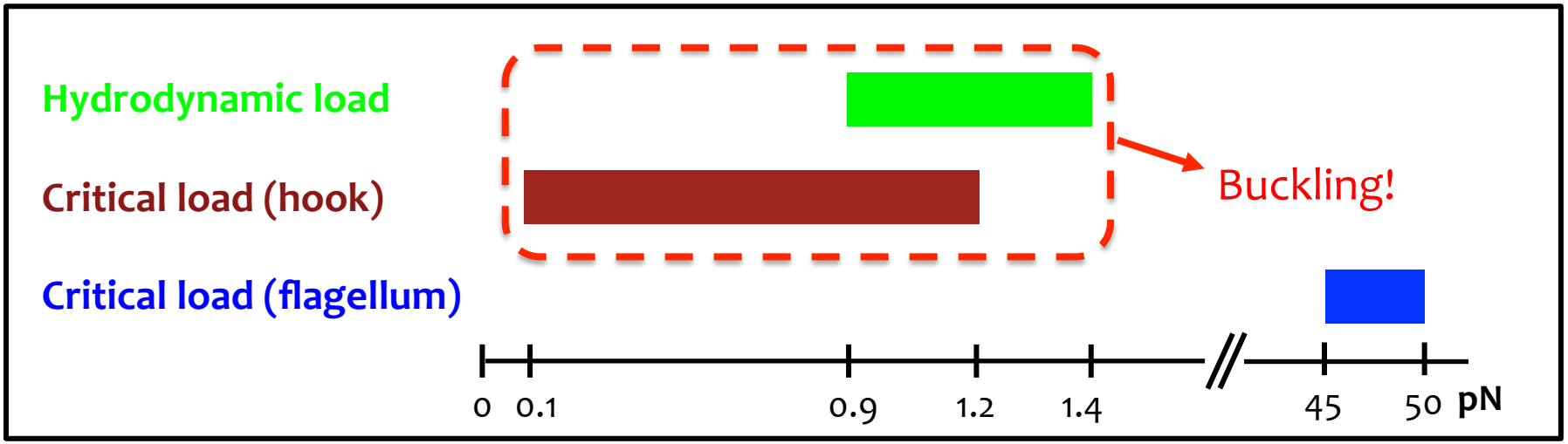
- **Hydrodynamic force**
  - given by swimming speed

$$P_{visc} = 6\pi\mu a V$$

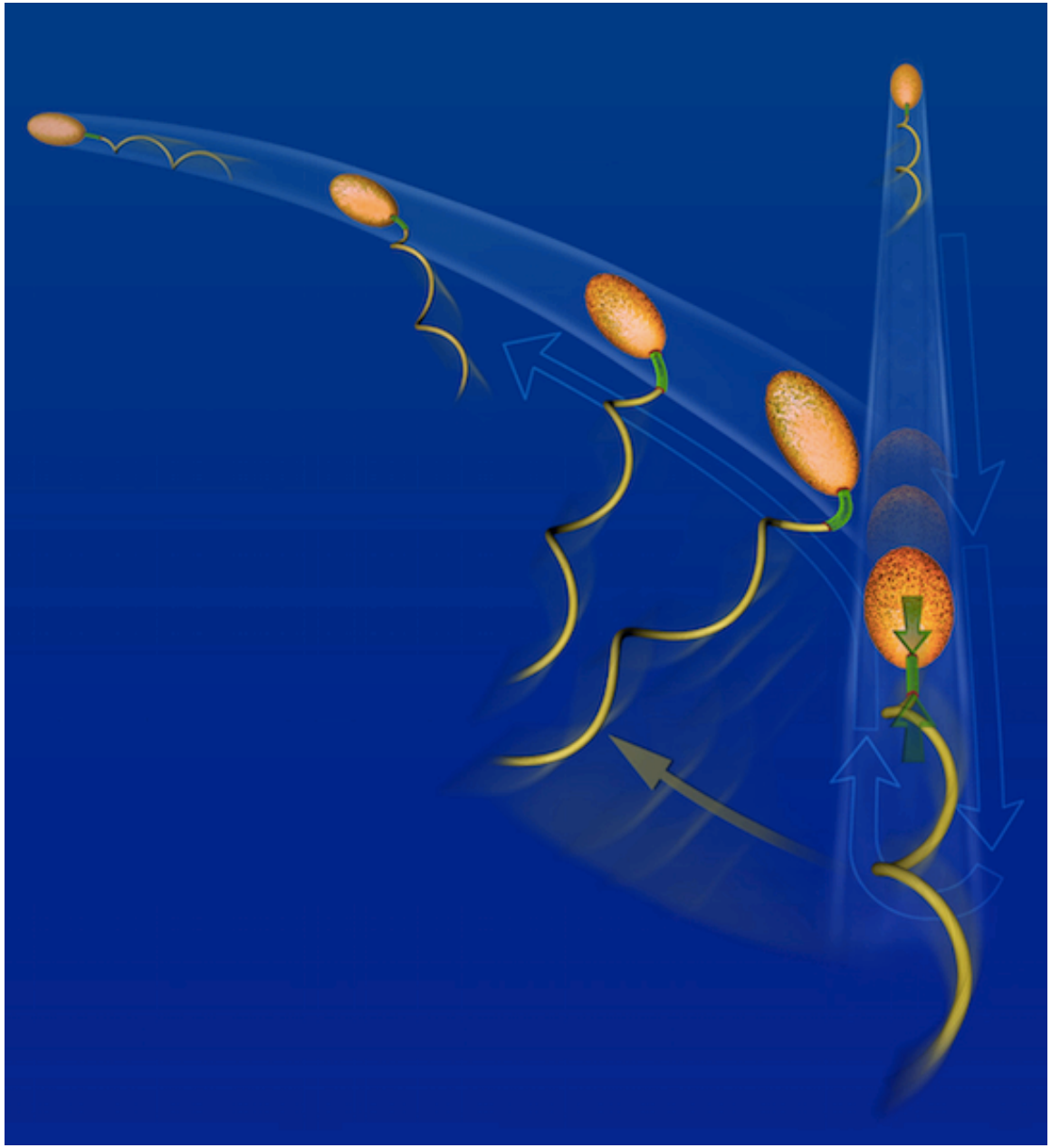
- **Critical buckling force**
  - beam theory, given by bending rigidity, EI

$$P_{cr} = \pi^2 \frac{EI}{L^2}$$





Hypothesis: Turning by buckling of the ‘hook’



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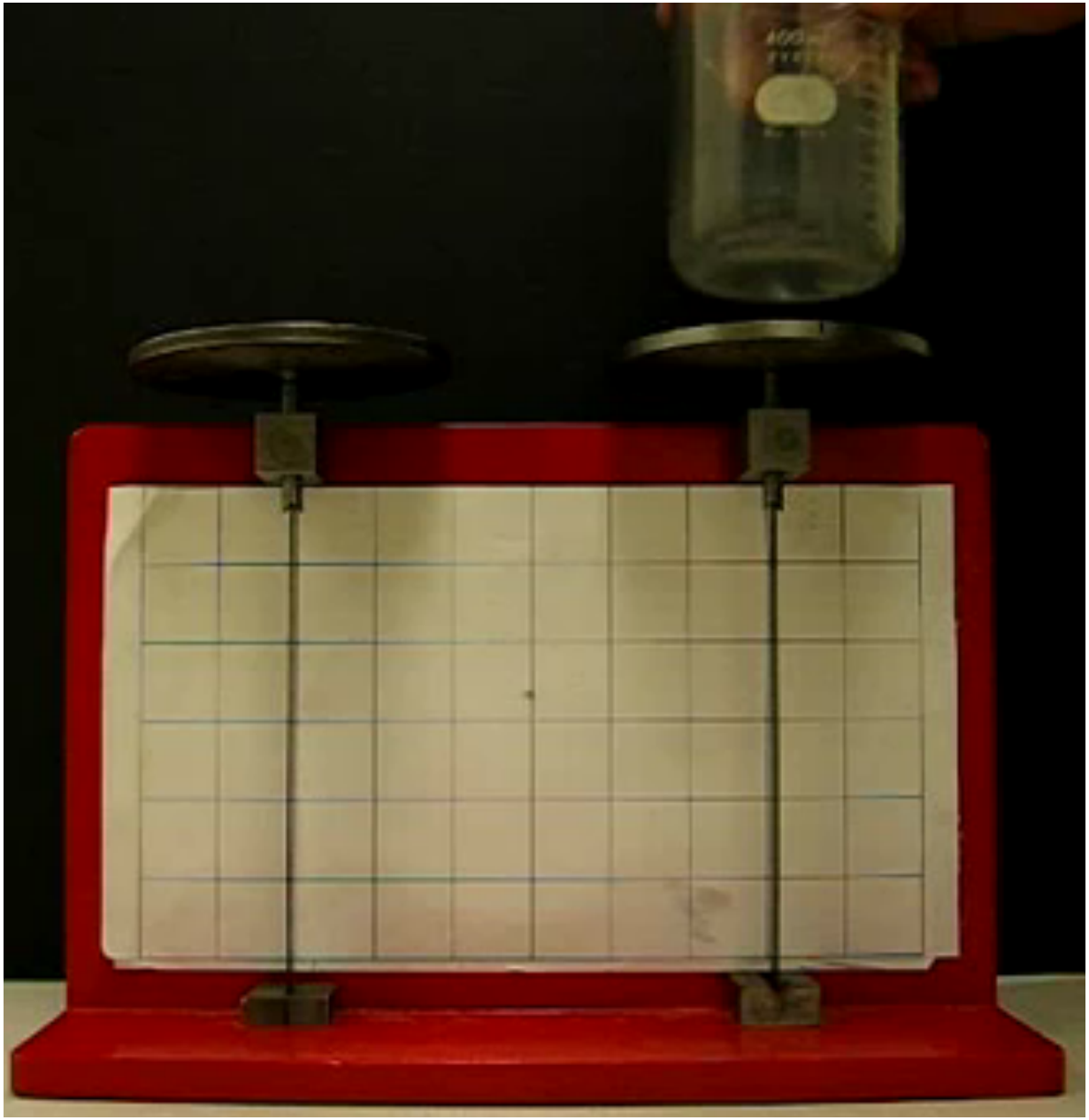
How to test for buckling at the nanometer scale?

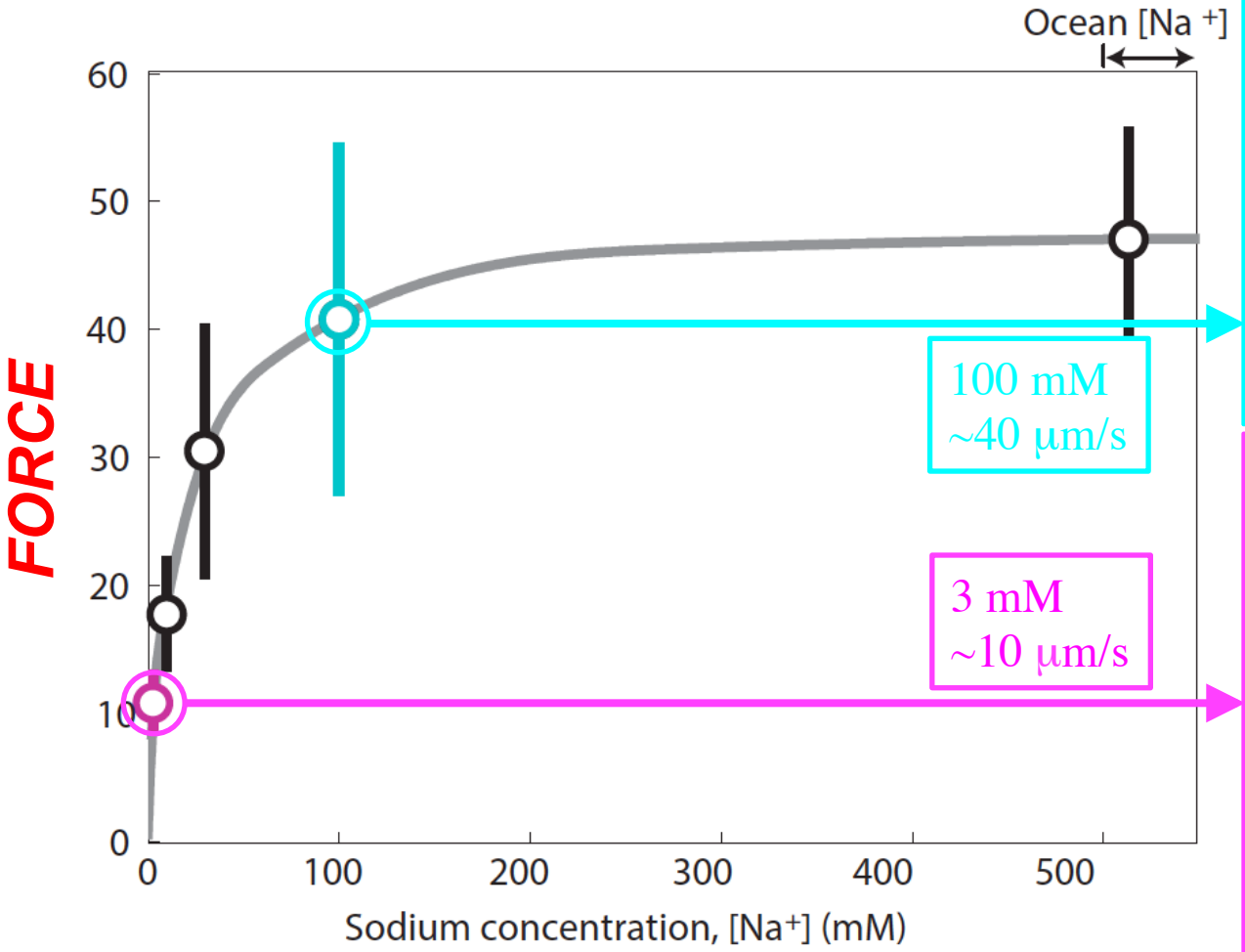


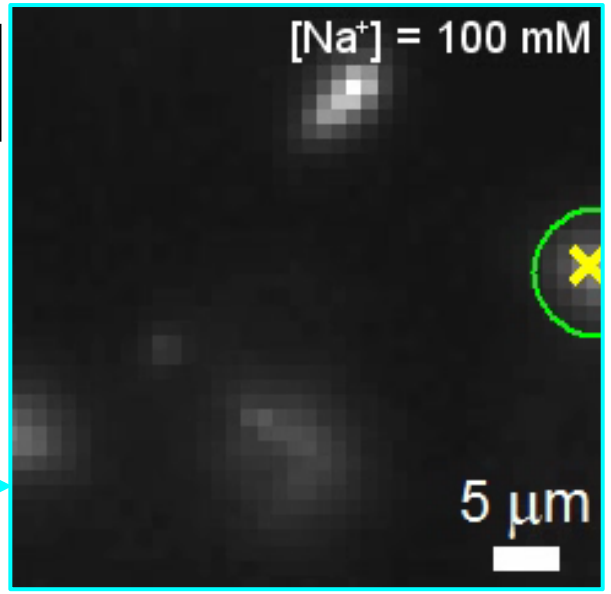
$$P_{cr} = \pi^2 \frac{EI}{L^2}$$

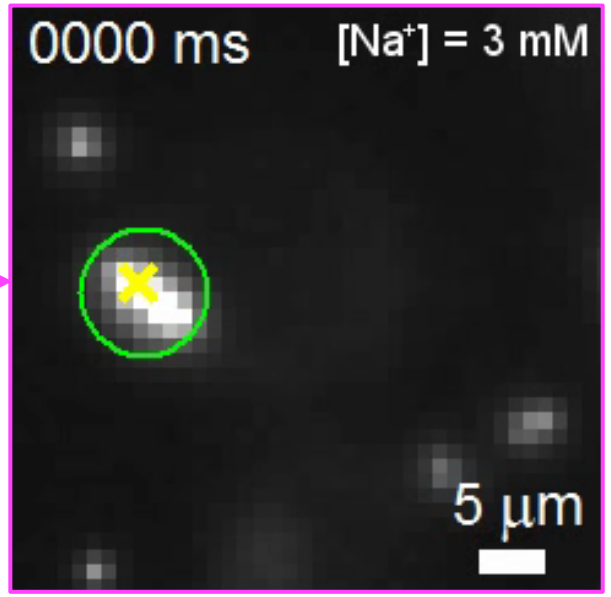
$$P_{visc} = 6\pi\mu a V$$

Test for buckling by slowing down bacteria

Swimming speed ↓ → Hydrodynamic force ↓ → Flicks ↓







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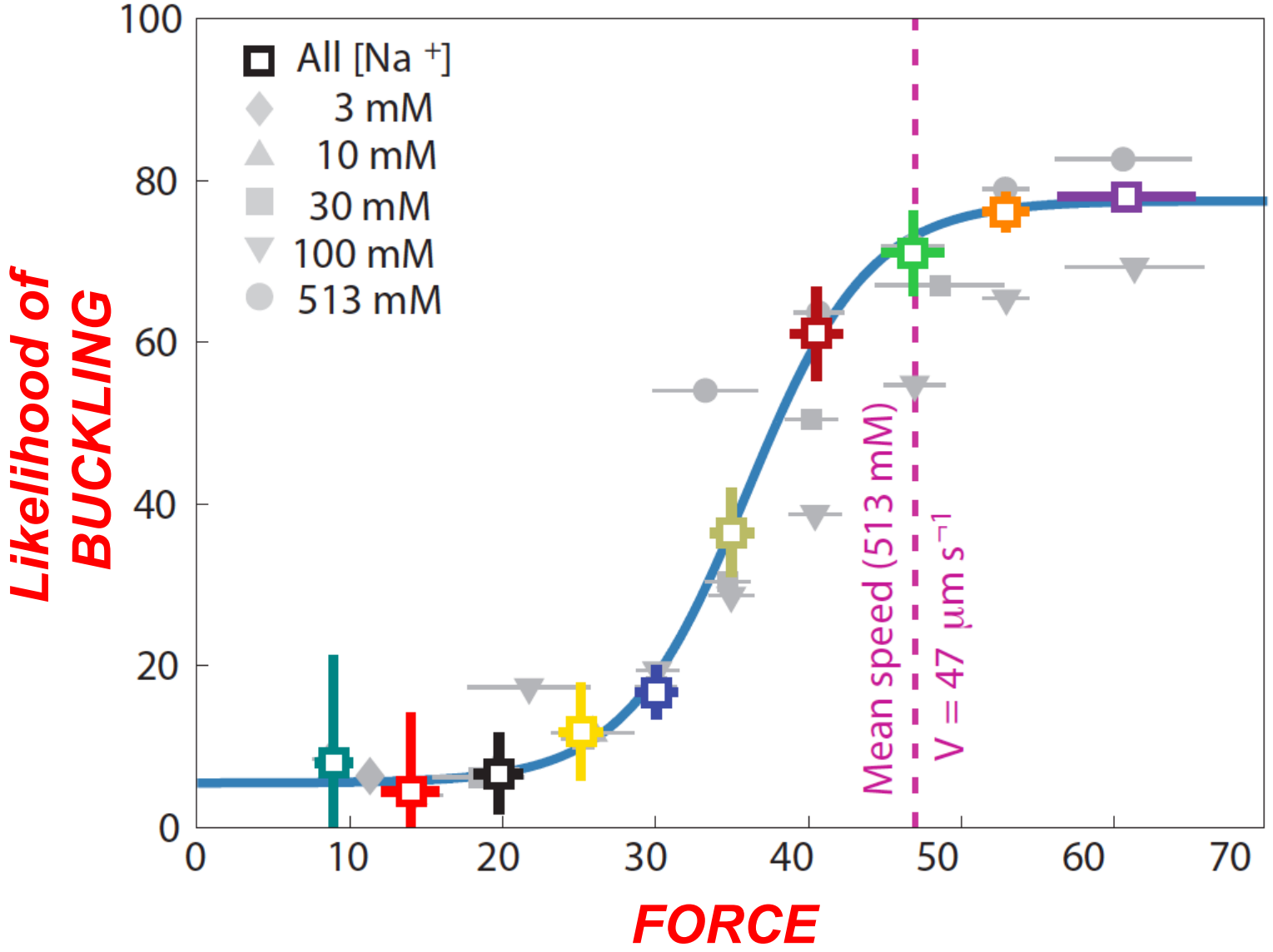
The sudden onset of buckling



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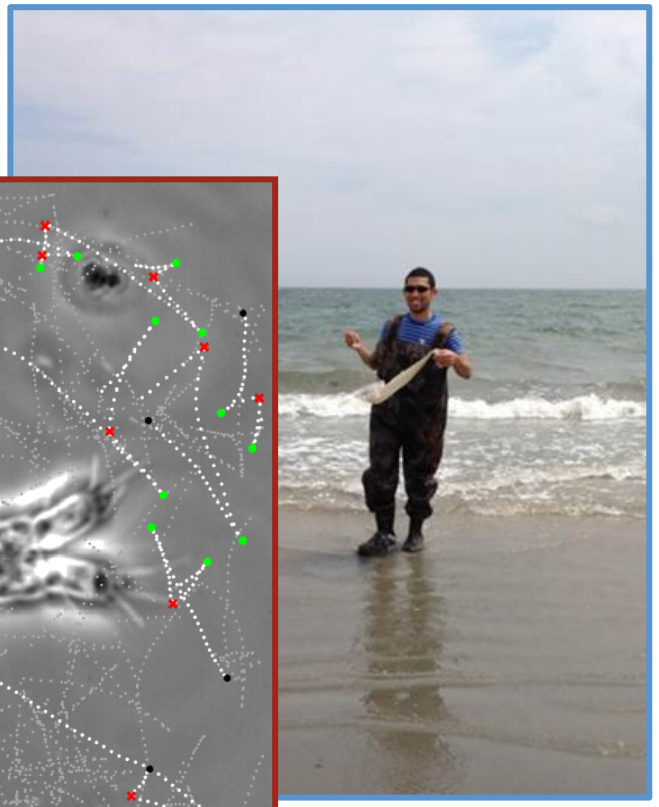
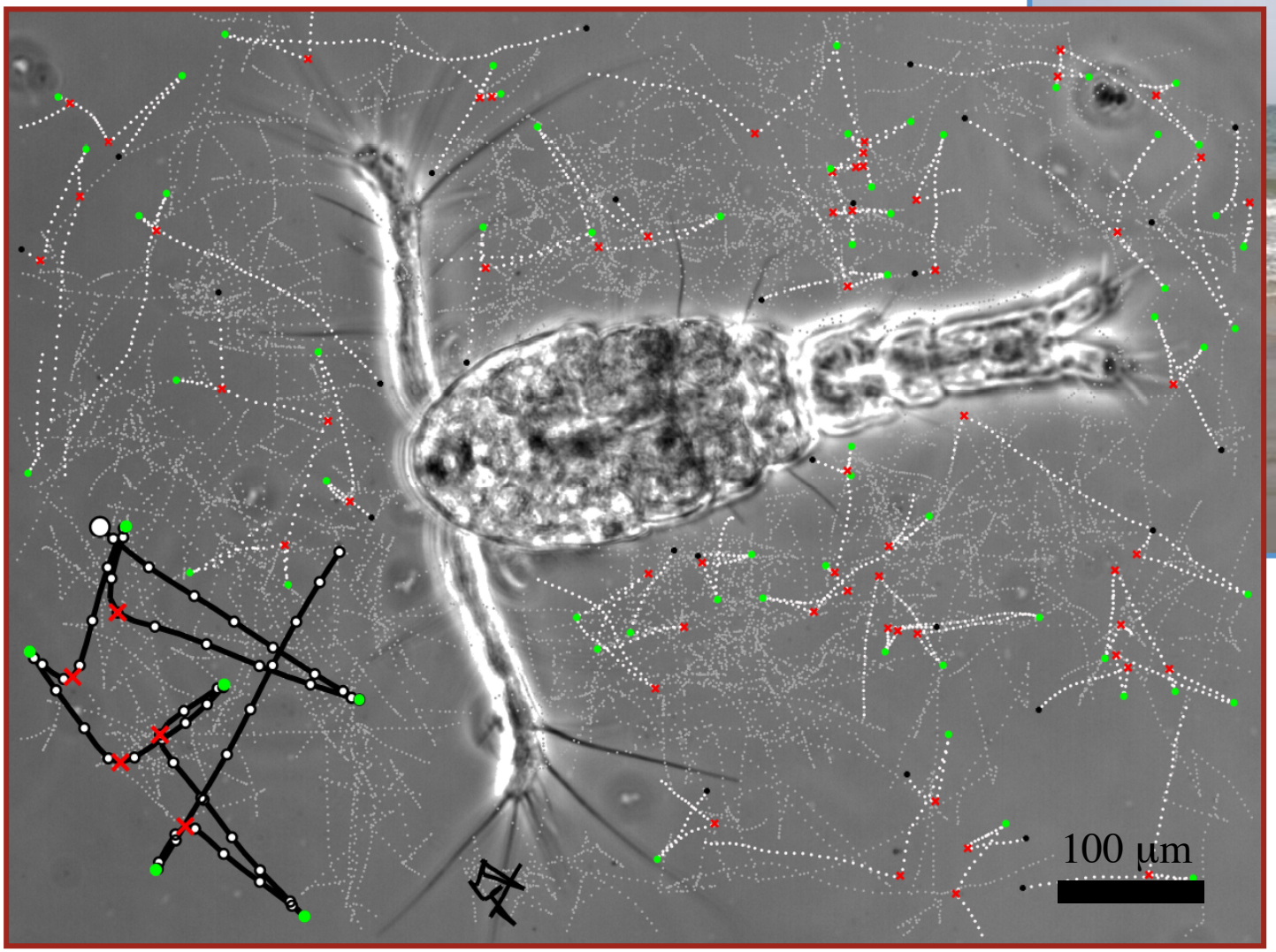
Turning by buckling appears to be VERY common

- Observed in 60-70% of cells





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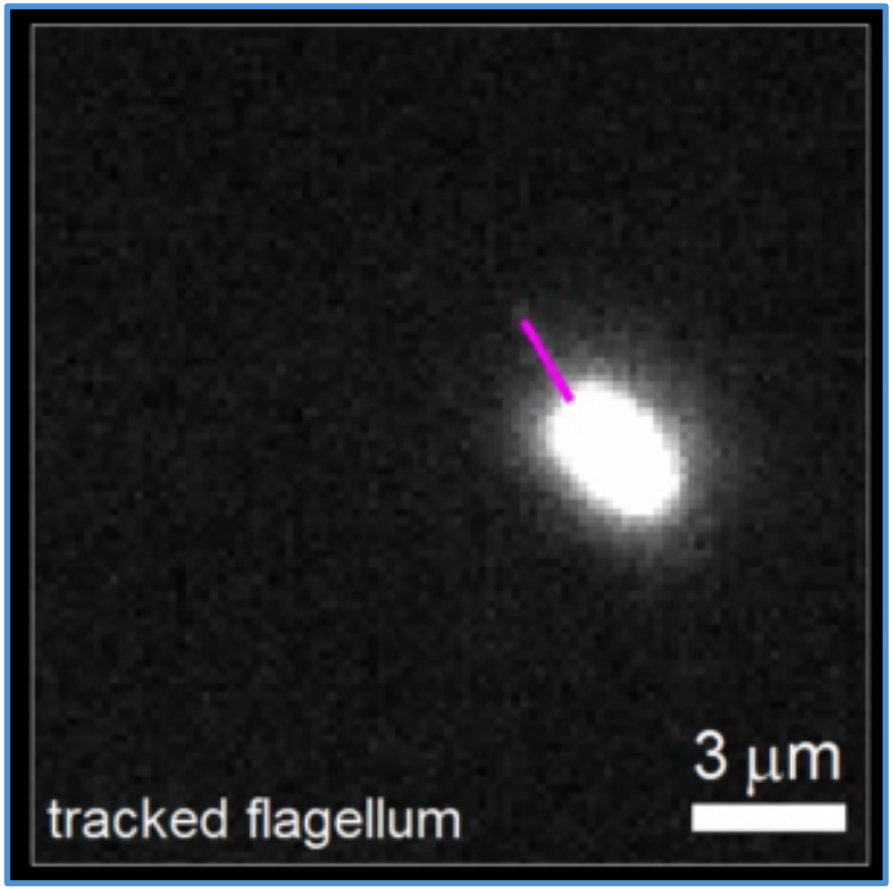
What lessons do we learn from turning by buckling?

- **Engineered materials:**
  biological structures provide inspiration for advanced engineered materials
- **Micro-robotics:**
  under-actuated dynamics use the flagellum as both a ‘motor and rudder’
- **Evolution:**
  common and biologically ‘cheap’ motility strategy



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Bacteria can exploit a flagellar buckling instability to change direction

Kwangmin Son[1], Jeffrey S. Guasto[2] and Roman Stocker[2]*

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