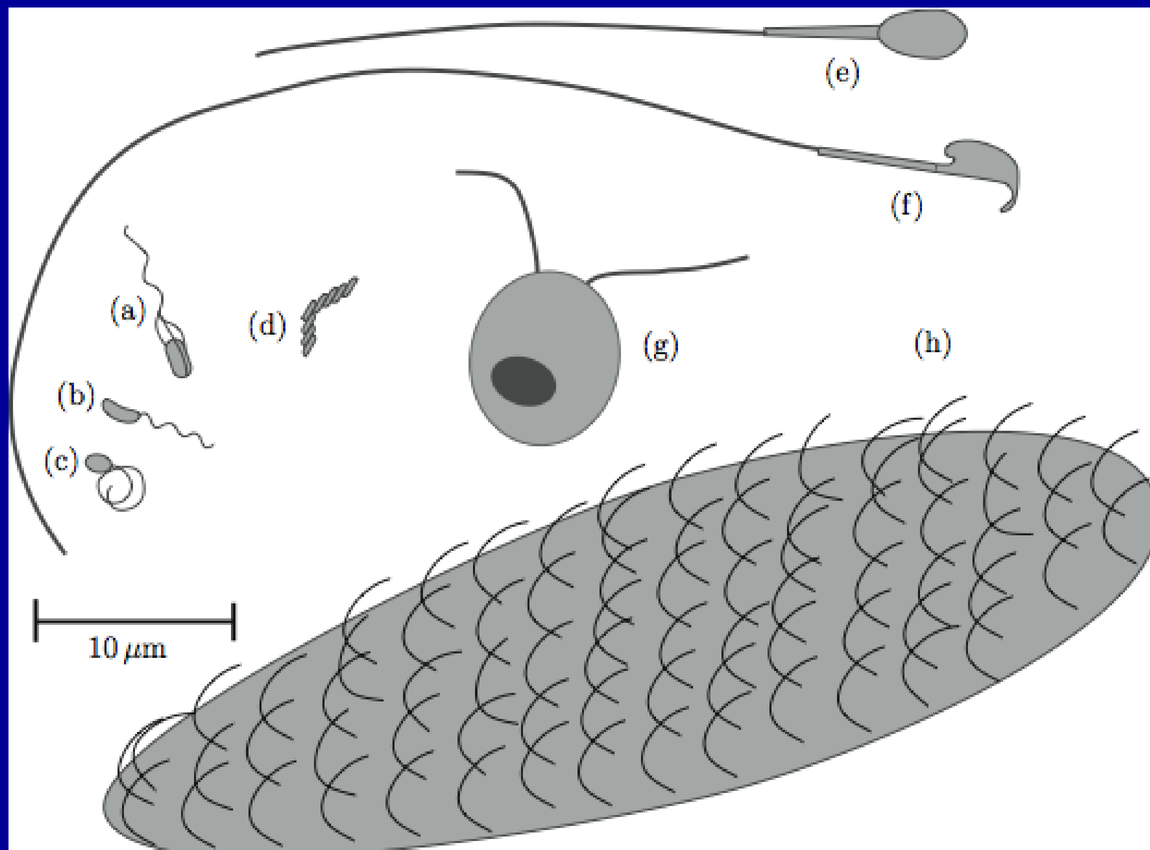
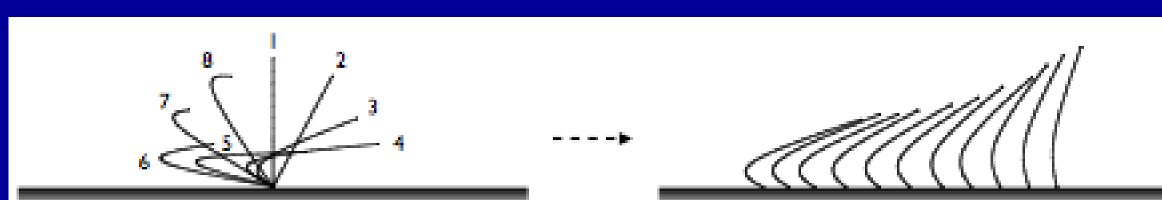
Microswimmers: hydrodynamics theory

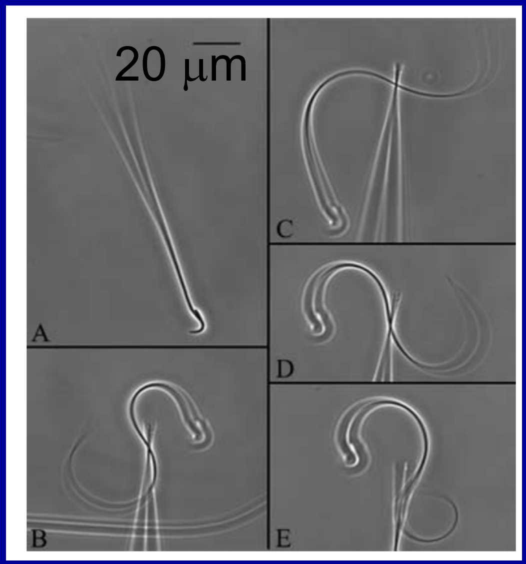
Tom Powers, Brown University

Lauga and Powers, 2009

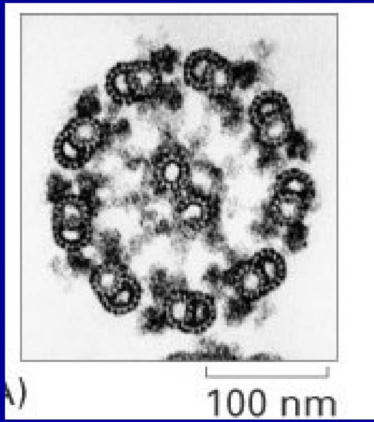




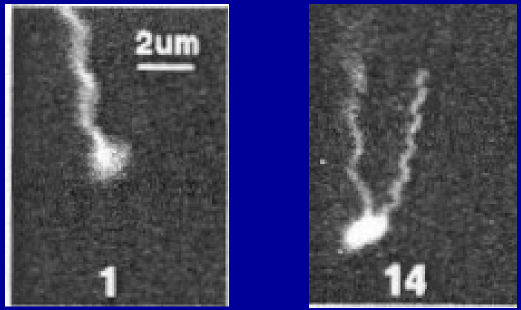
Eukaryotic & prokaryotic flagella are very different



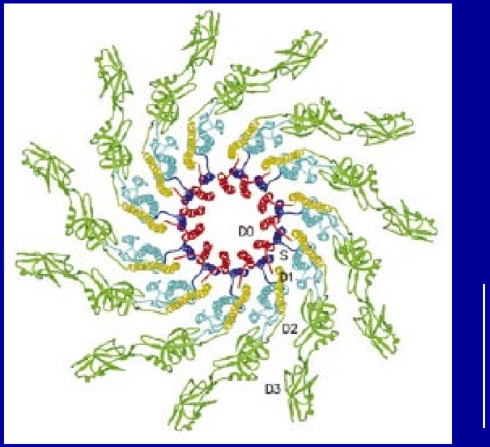
Lindemann, Macauley, & Lesich,
Biophysics J. 2005



Essential Cell Biology 2004



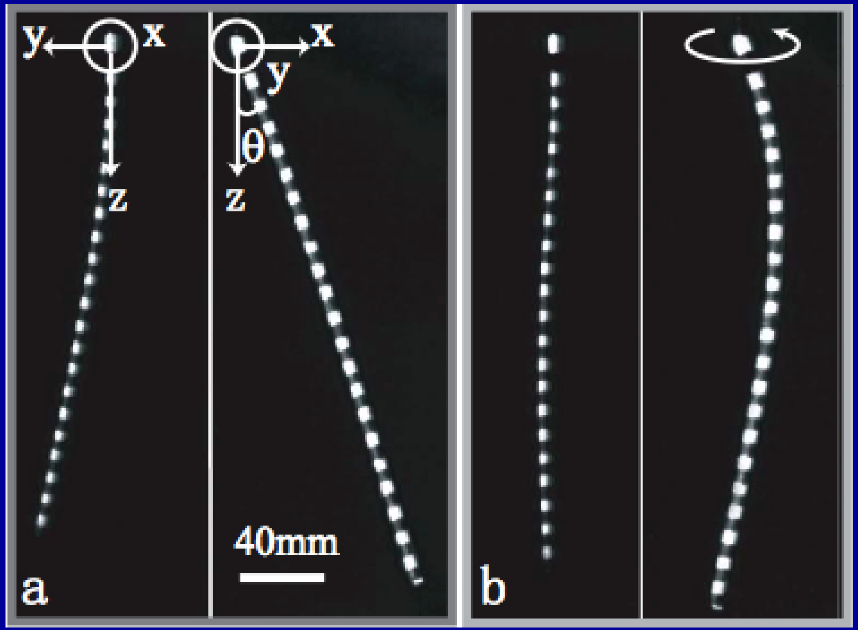
Turner, Ryu, & Berg, J. Bacteriology 2000



~10 nm

Yonekura, Maki-Yonekura, & Namba,
Nature 2003

Rotating Flexible Rod in a Viscous Fluid: Resistive force theory works well for small curvature



Just below critical torque

Just above critical torque

Inspired by Manghi, Schlagberger, & Netz (2006)

- Rotne-Prager theory for hydrodynamic interaction
- Transition between high/low drag states

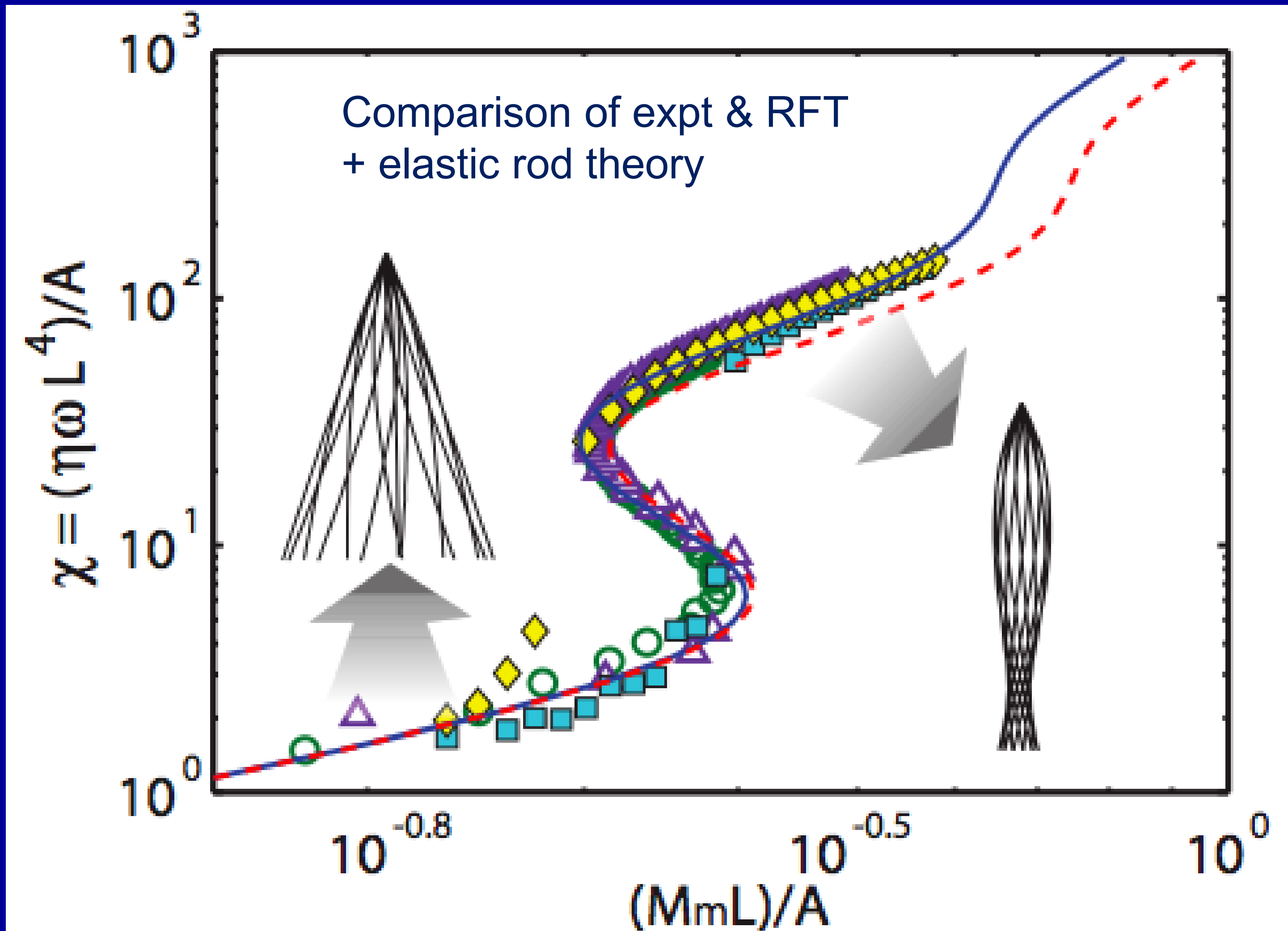
Other important work

- Machin 1958
- Wiggins & Goldstein 1998
- Yu, Lauga, & Hosoi 2006
- Coq, du Roure, Marthelot, Bartolo, Fermigier 2008

Qian, TRP, Breuer, Phys Rev Lett 2008

☒

Qian, TRP, Breuer, Phys Rev Lett 2008

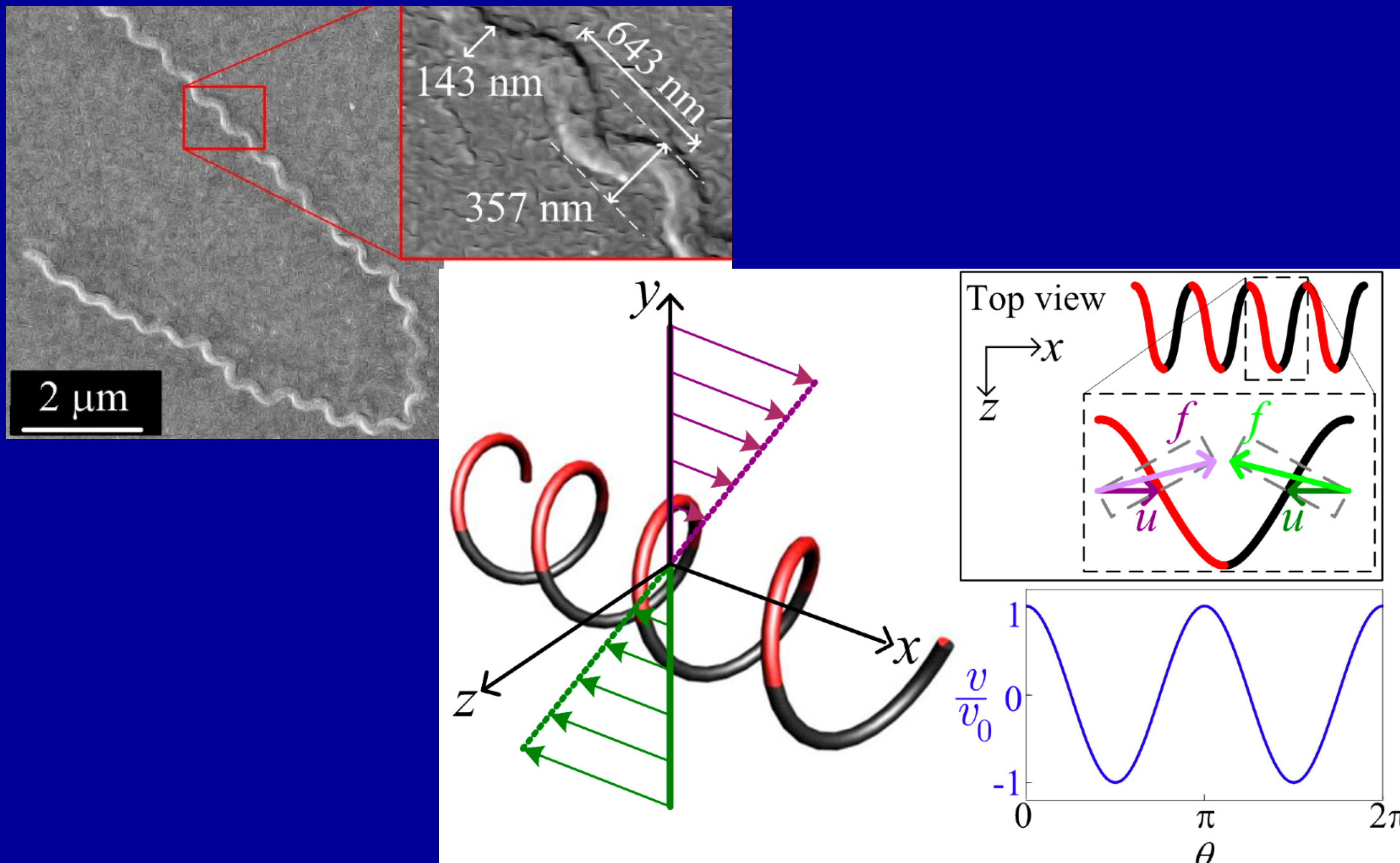


Dashed red line: small deflection elastic theory

$$-EI\frac{\partial^4 \mathbf{r}_\perp}{\partial z^4} + \zeta_\perp \omega \hat{\mathbf{z}} \times \mathbf{r}_\perp = \mathbf{0}$$

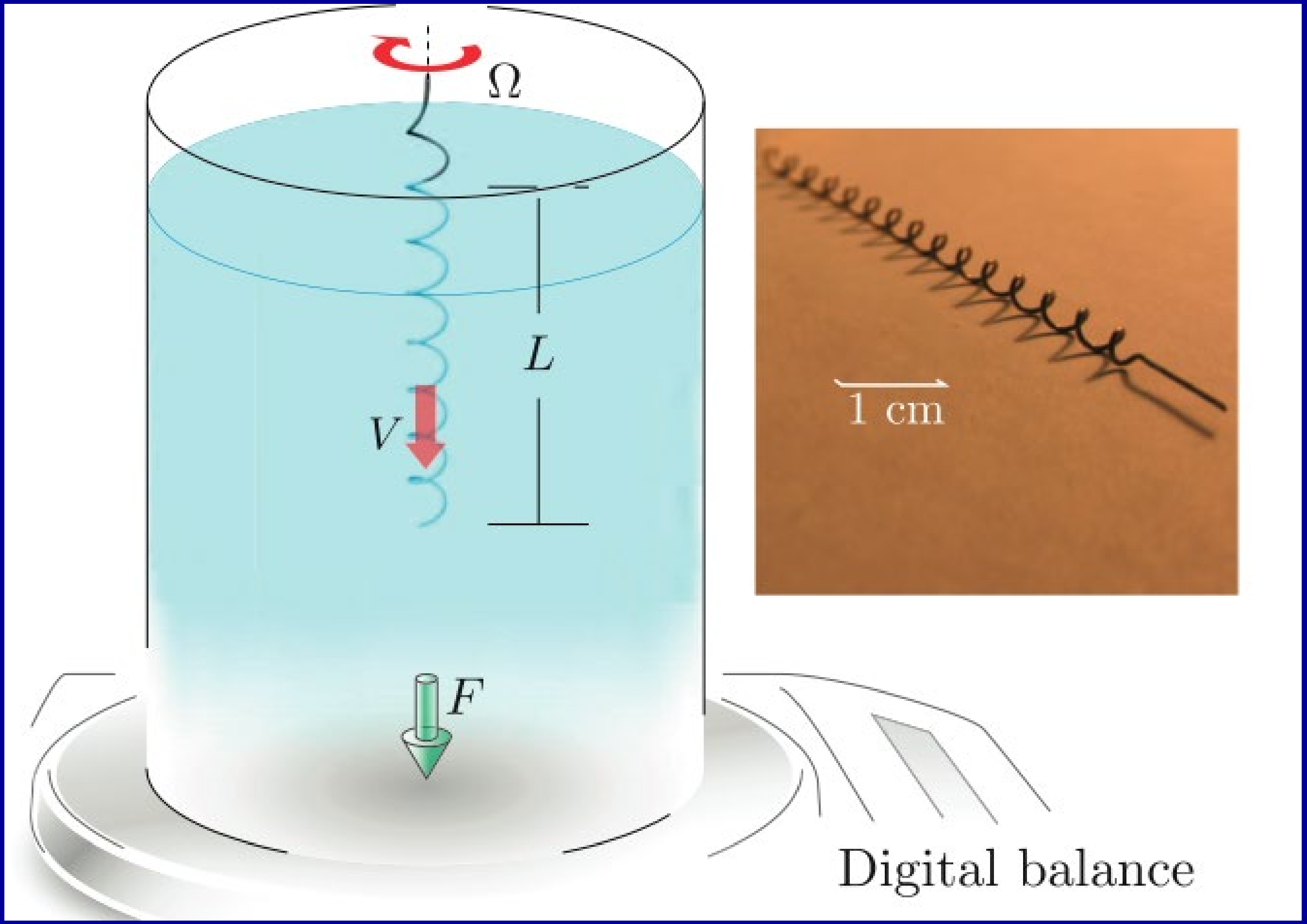
Solid blue line: large deflection elastic theory

Neat RFT example: a helix in the shear plane moves along or against the vorticity direction in shear flow, with the direction depending on handedness



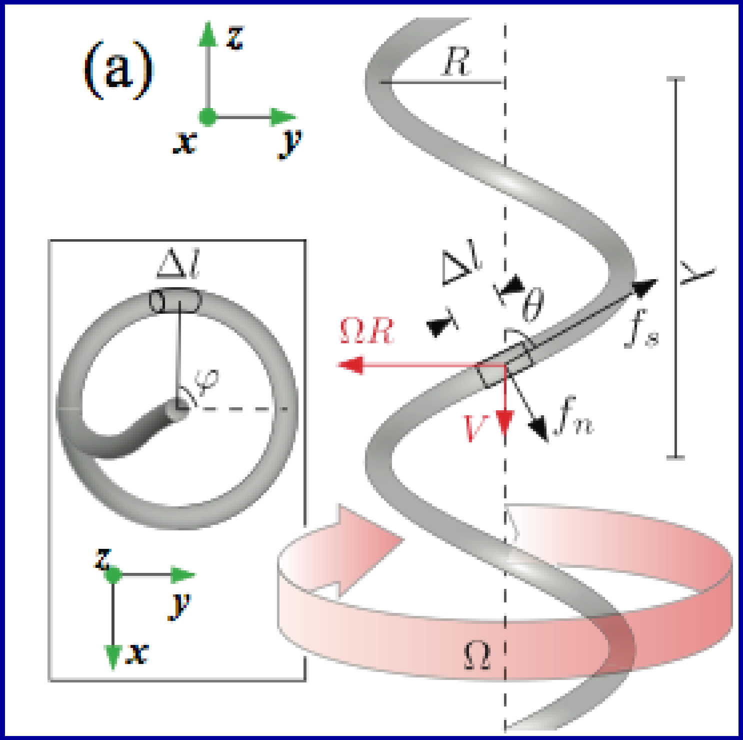
Marcos, Fu, TRP, Stocker, Phys Rev Lett 2009
⌧

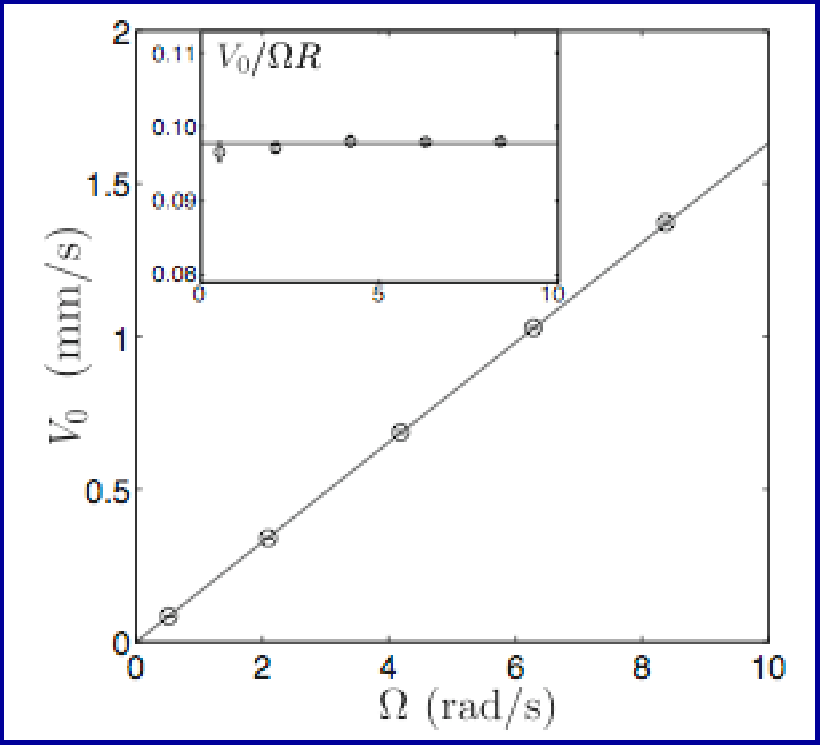
Bin Liu's experiment: Measure the thrust on a rotating helix



Liu, Powers, Breuer PNAS 2011

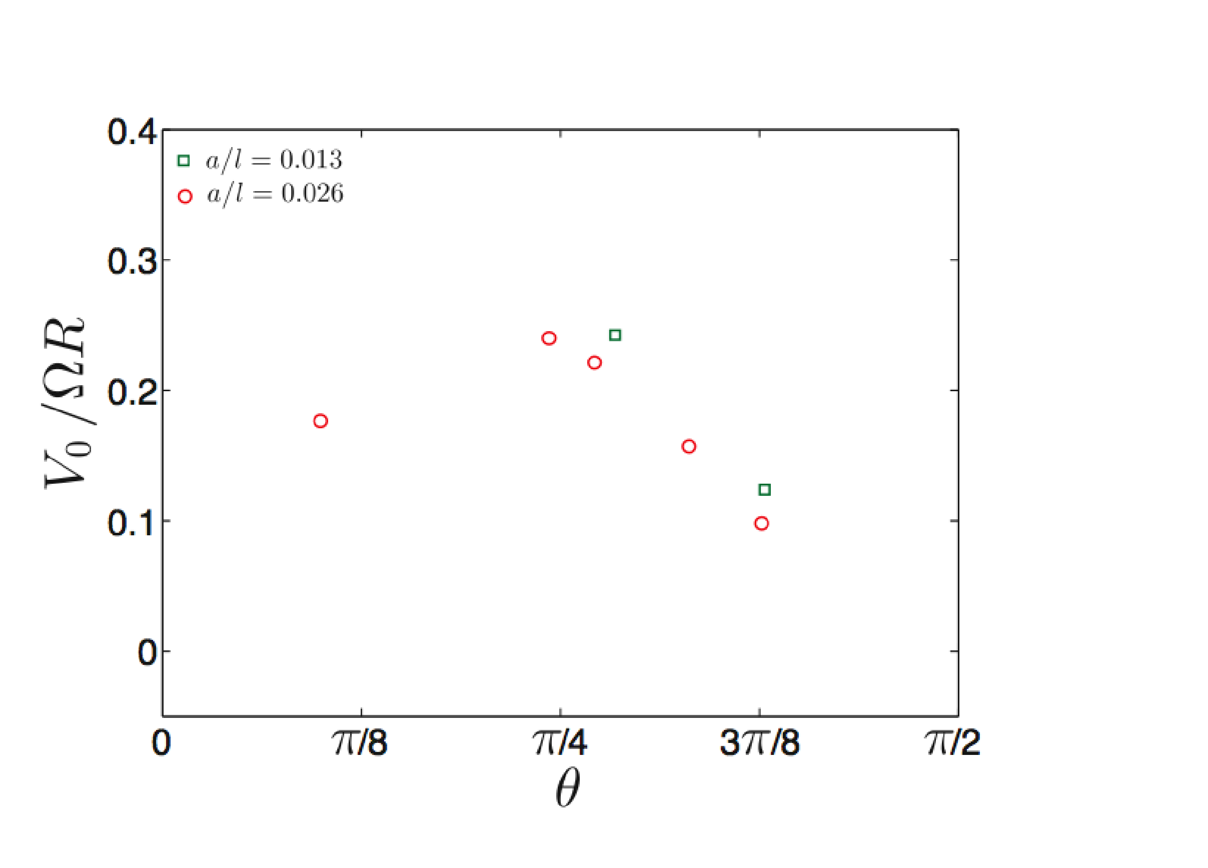
(Force-free) speed is linear in rotation rate





Liu, Powers, Breuer PNAS 2011

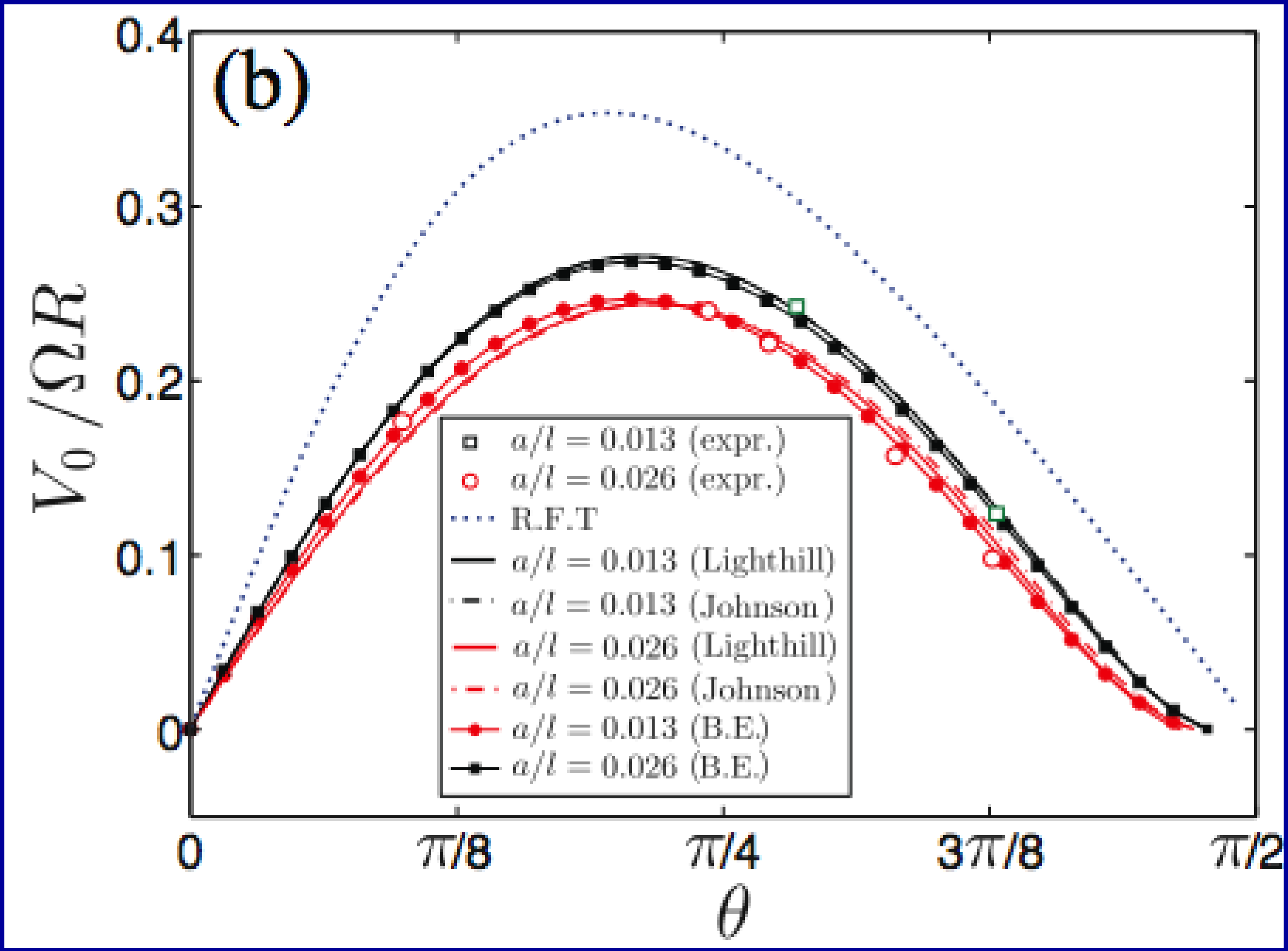
Ratio of swimming speed to rotation rate depends on pitch angle and slenderness



Liu, Powers, Breuer PNAS 2011

The two slender-body theories make almost indistinguishable predictions (which are very accurate!)

Liu, Powers, Breuer PNAS 2011



Helical LH filaments bundle when the motors turn CCW when viewed from outside the cell

Turner, Ryu, Berg, J. Bact. 2000

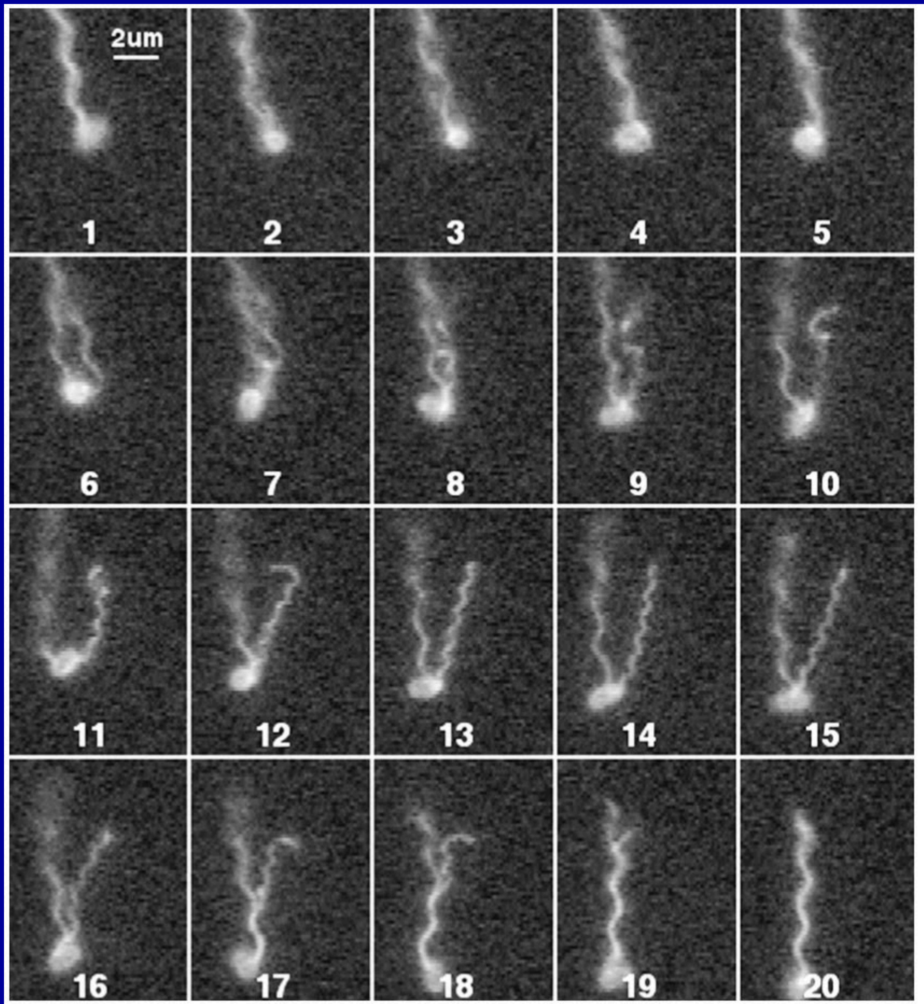
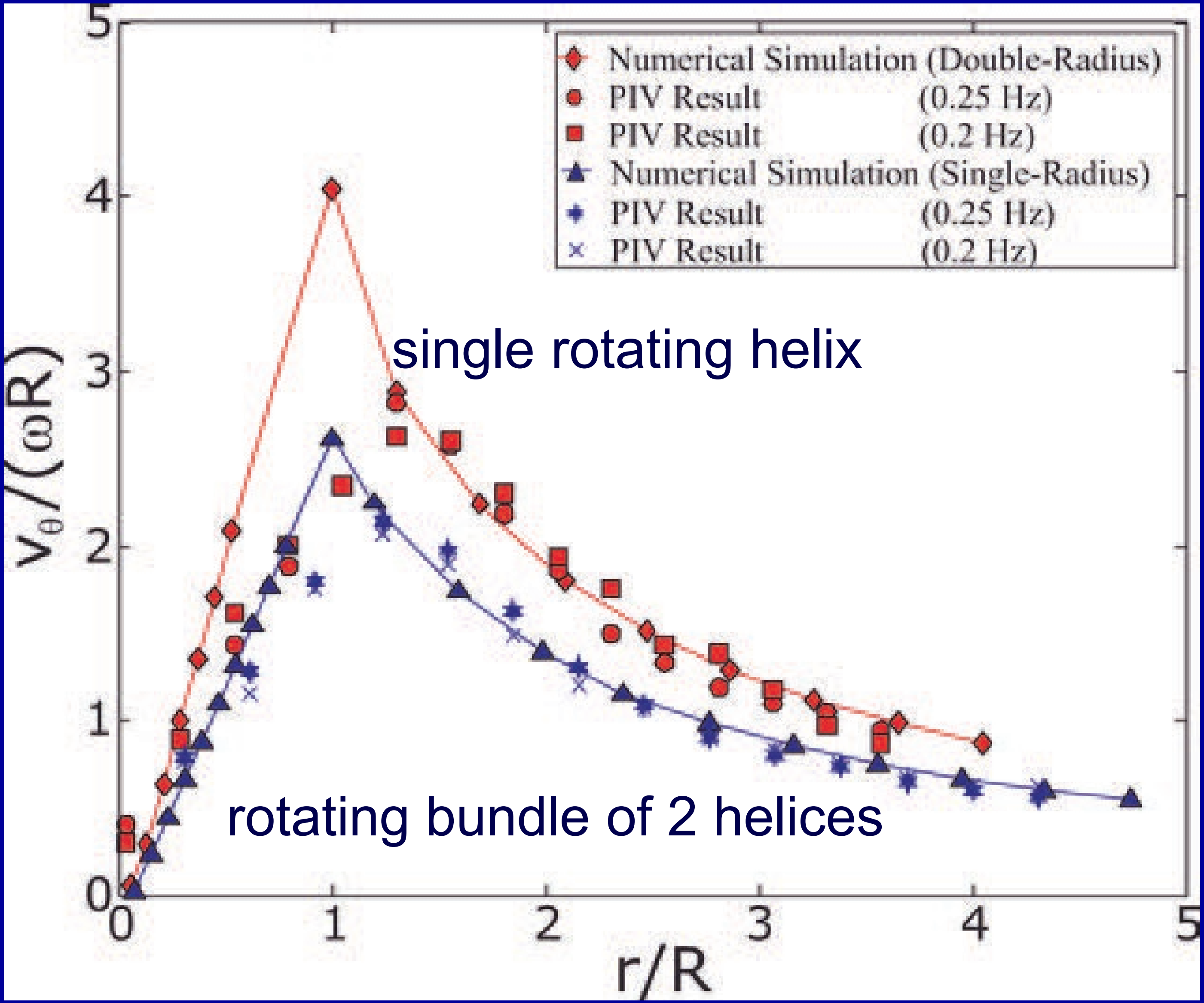


FIG. 7. *E. coli* with two flagellar filaments, one undergoing a polymorphic transformation. Successive fields are shown.

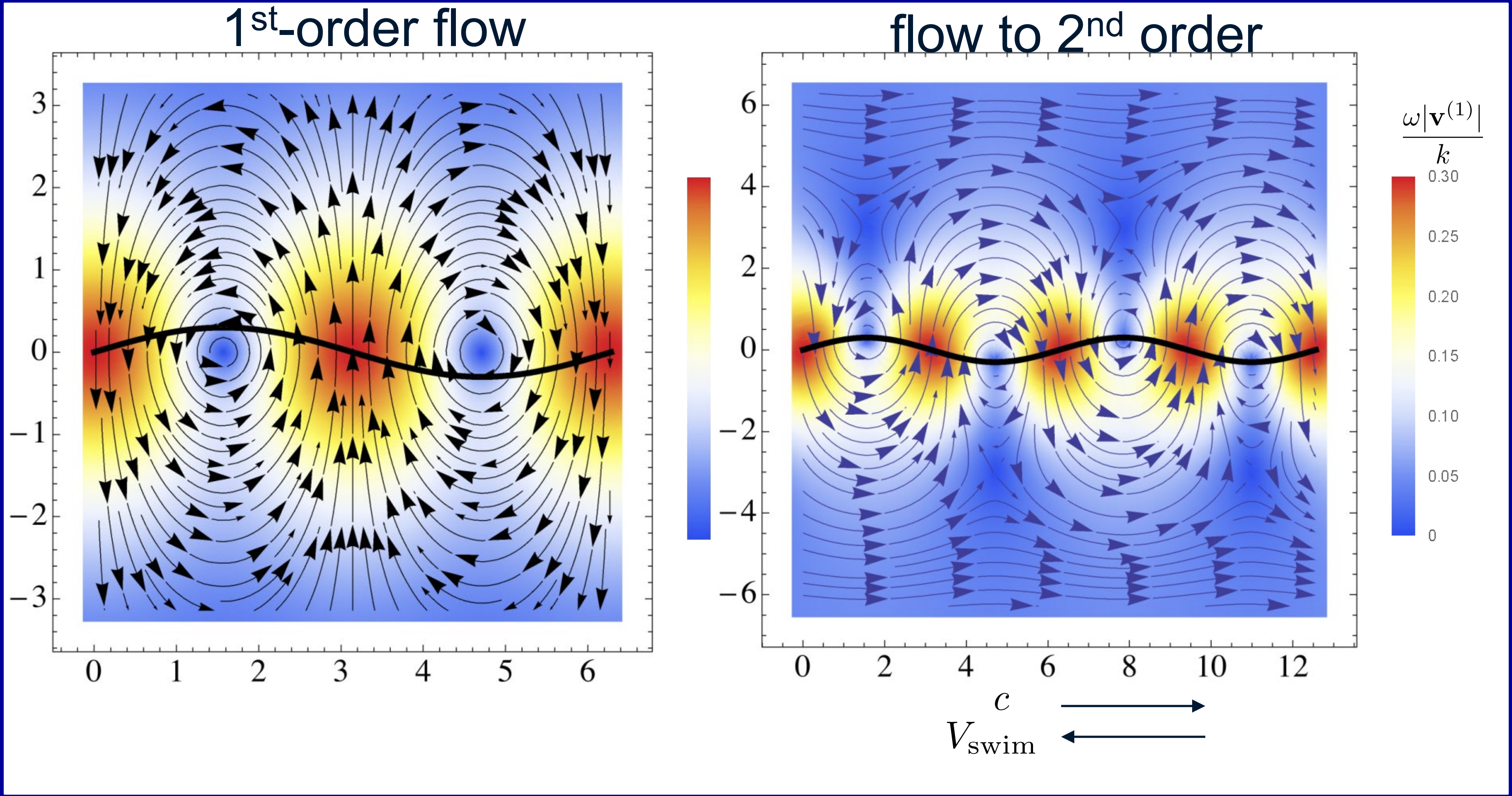
We made a scale model (Kim et al. PNAS 2003)
See the movie!
https://www.pnas.org/doi/suppl/10.1073/pnas.2633596100/suppl_file/3596Movie1.mov

Comparison of SBT calculations & PIV measurements

Kim et al., Expts in Fluids 2004

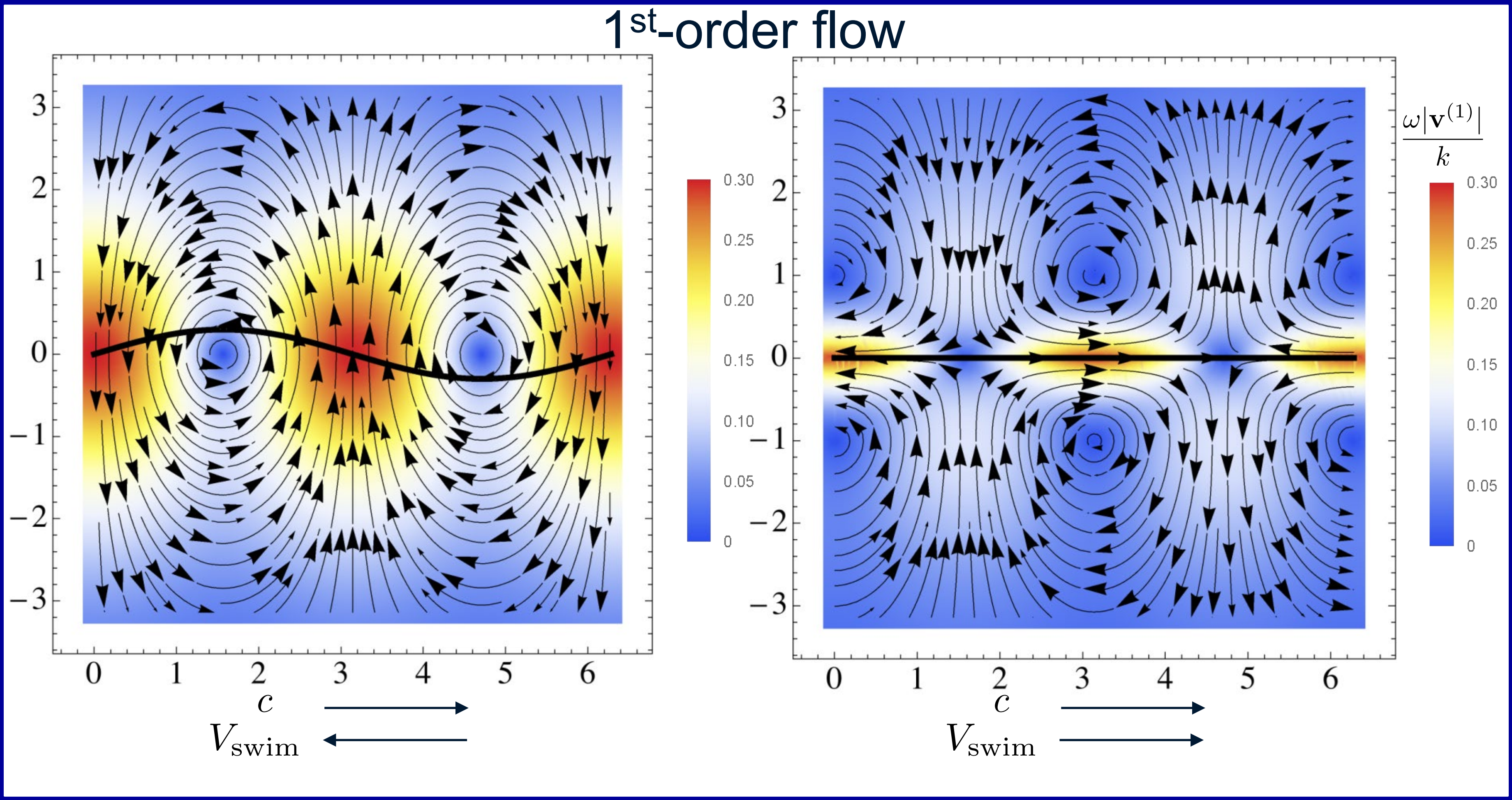


The swimming direction is determined by the 2nd order disturbance flow required to correct the error induced by the 1st order no-slip BC



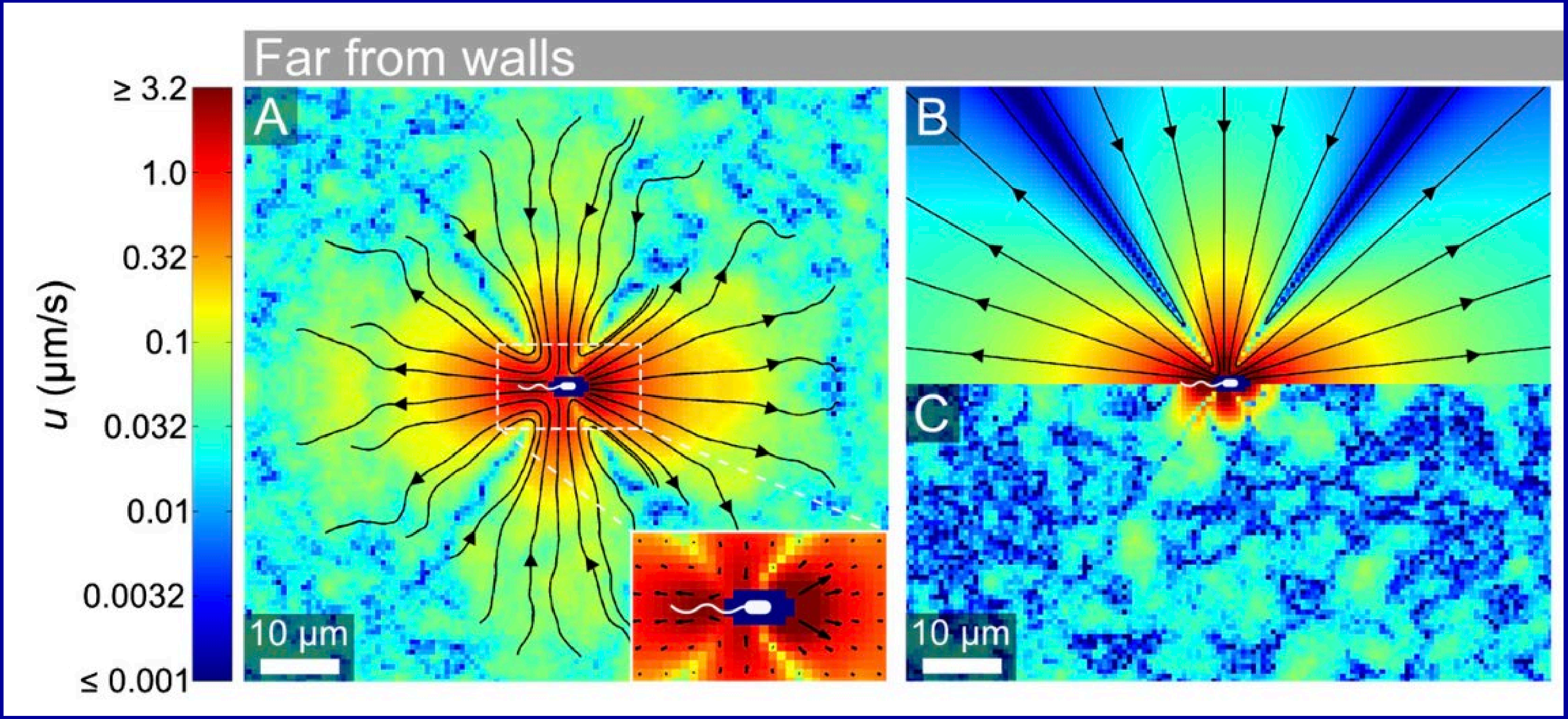
Krieger, Spagnolie, TRP, PRE 2014

The swimming direction is determined by the 2nd order disturbance flow required to correct the error induced by the 1st order no-slip BC



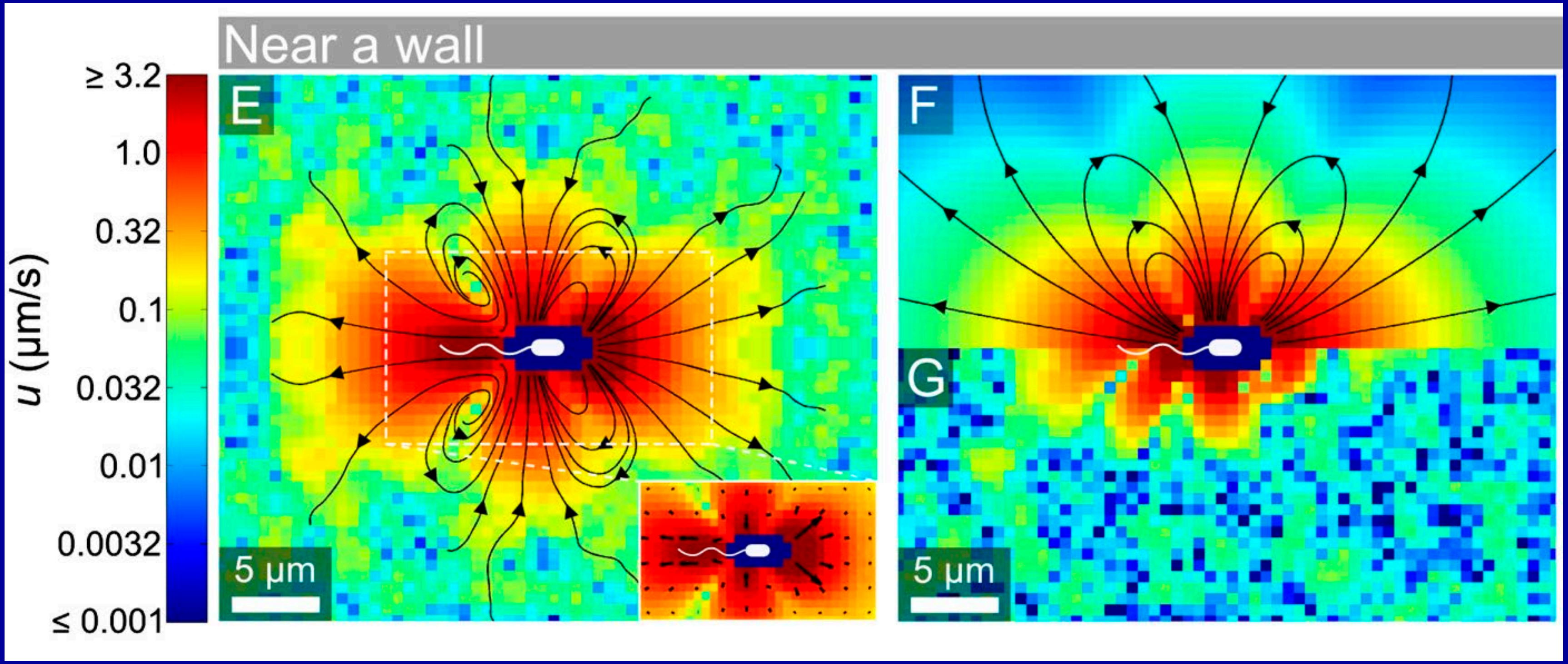
Krieger, Spagnolie, TRP, PRE 2014

The flow field induced by a swimming bacterium is well-approximated by the stresslet



Drescher, Dunkel, Cisneros, Ganguly & Goldstein, PNAS 2011

The flow field induced by a swimming bacterium near a wall is well-approximated by the stressle and its image



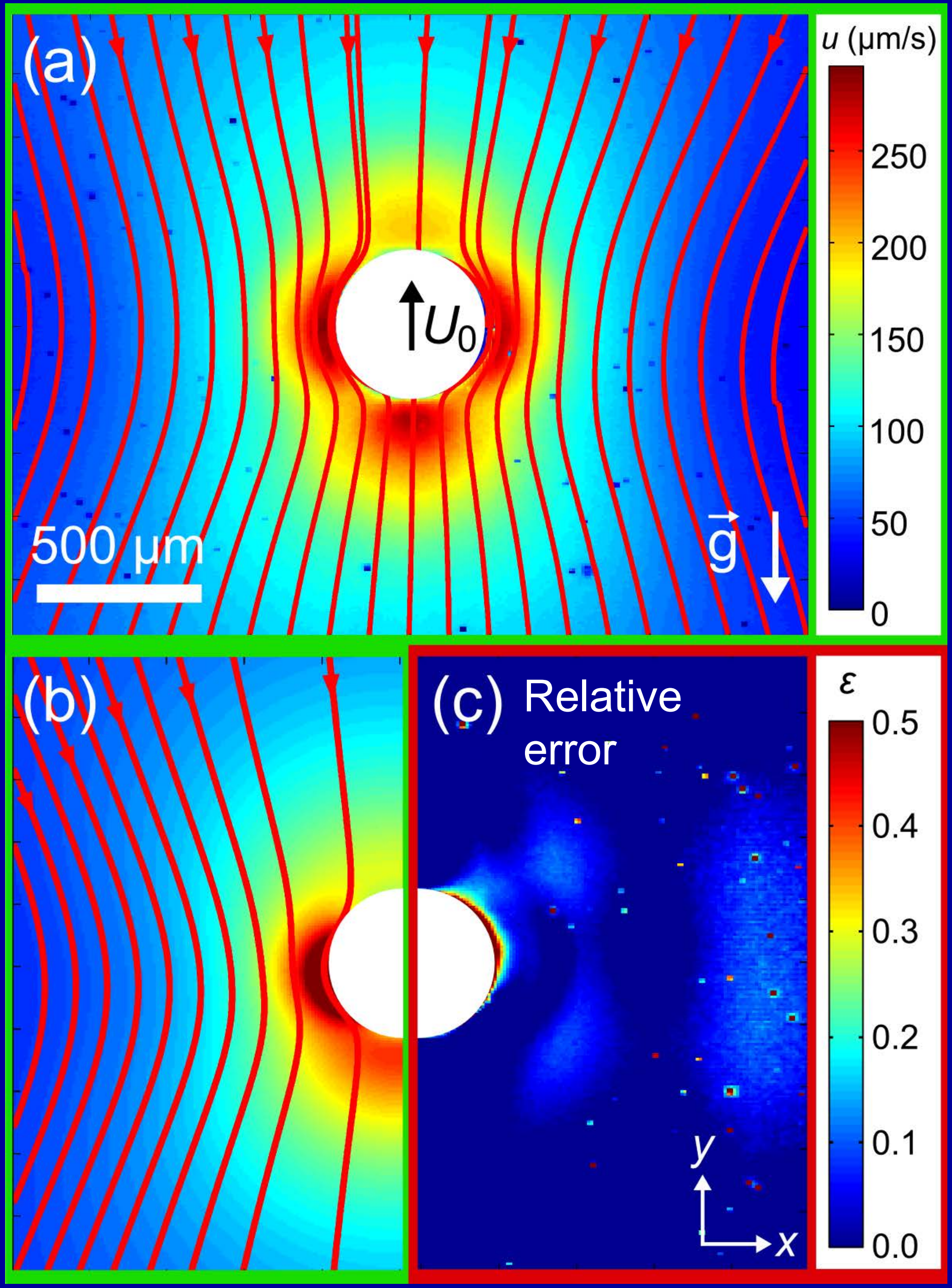
Drescher, Dunkel, Cisneros, Ganguly & Goldstein, PNAS 2011

Volvox is not neutrally buoyant; the swimming-induced flow field has a Stokeslet

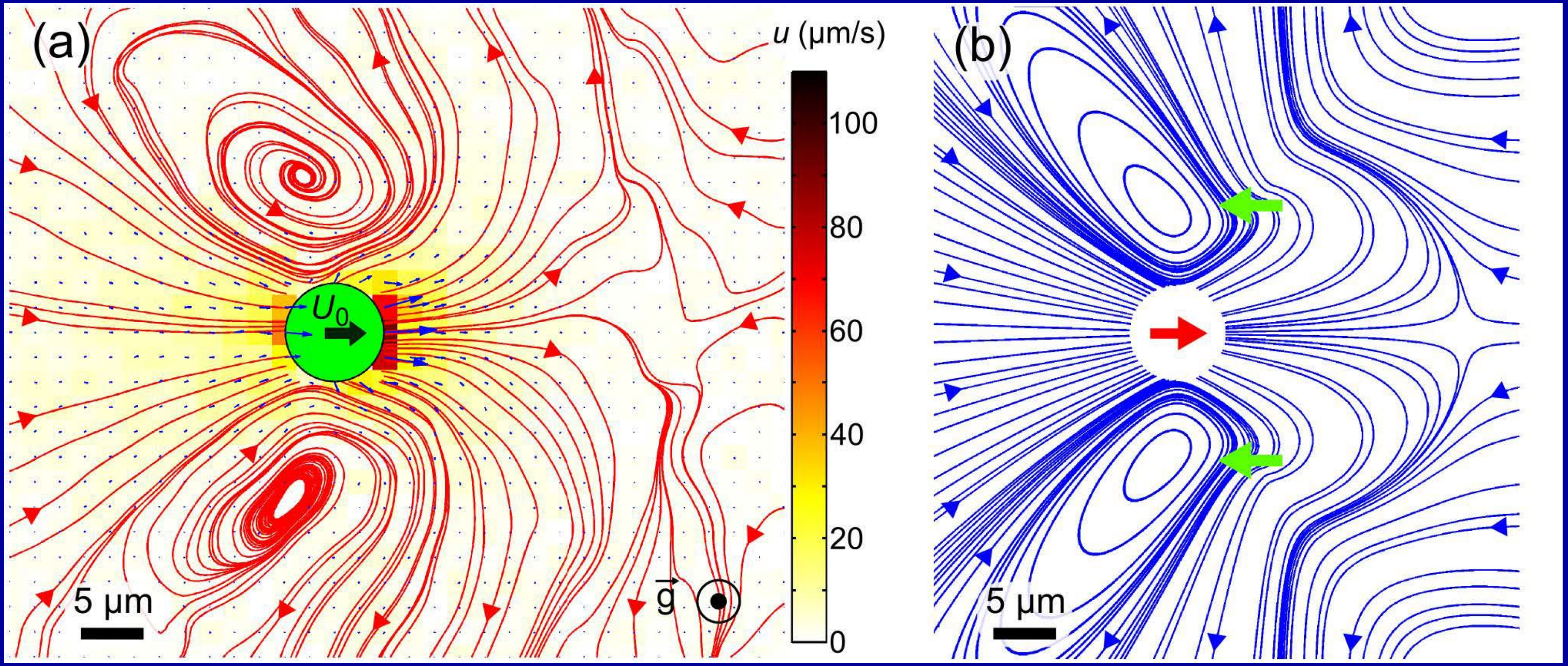
Measurement

Fit to a Stokeslet + stresslet + potential dipole

Drescher, Goldstein, Michel, Polin & Tuvan 2010



A three-Stokeslet model captures much of the nar field of *Chlamydomonas*



Drescher, Goldstein, Michel, Polin & Tuvan 2010