

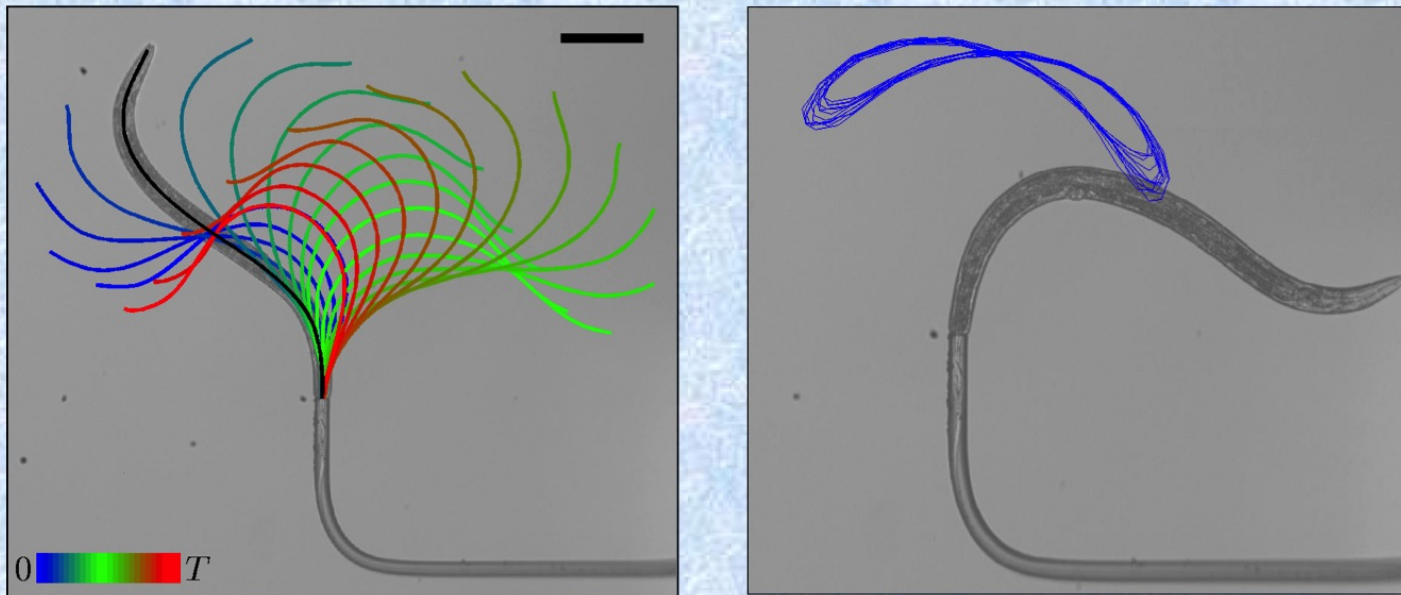
Title: Dynamic Force Patterns of an Undulatory Microswimmer

Date: Dec 05, 2013 03:30 PM

URL: <http://pirsa.org/13120038>

Abstract: C. elegans is a millimeter-sized nematode which has served as a model organism in biology for several decades primarily due to its simple anatomy. Using an undulatory form of locomotion this worm is capable of propelling itself through various media. Due to the small length scales involved swimming in this regime is qualitatively different from macroscopic locomotion because the swimmers can be considered to have no inertia. In order to understand the microswimming that this worm exhibits it is crucial to determine the viscous forces experienced during its motion. Using a micropipette deflection technique in conjunction with high speed imaging we have directly measured the time-varying forces generated by C. elegans during swimming. Furthermore by analyzing the body's kinematics over time and applying a simple model of locomotion we can compute the theoretical force curves. We observe excellent agreement between the measured and calculated forces. The success of this simple model has important implications in the understanding of microswimming in general.

# The Dynamic Force Measurements on the Nematode *C. elegans*



**Rafael Schulman, Matilda Backholm, and Kari Dalnoki-Veress**

Department of Physics and Astronomy, McMaster University

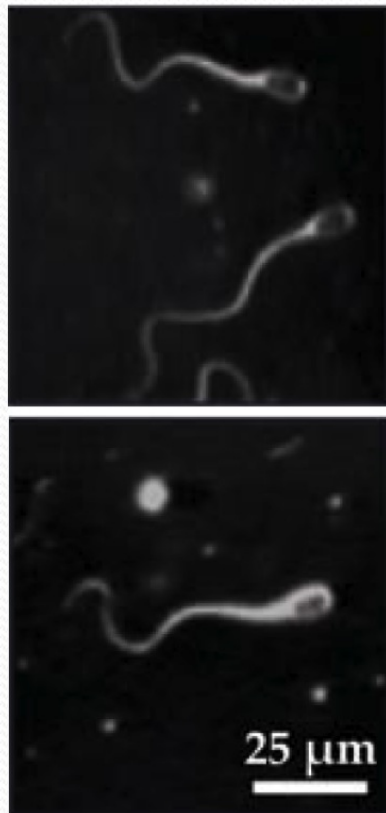
**William S. Ryu**

Department of Physics, University of Toronto

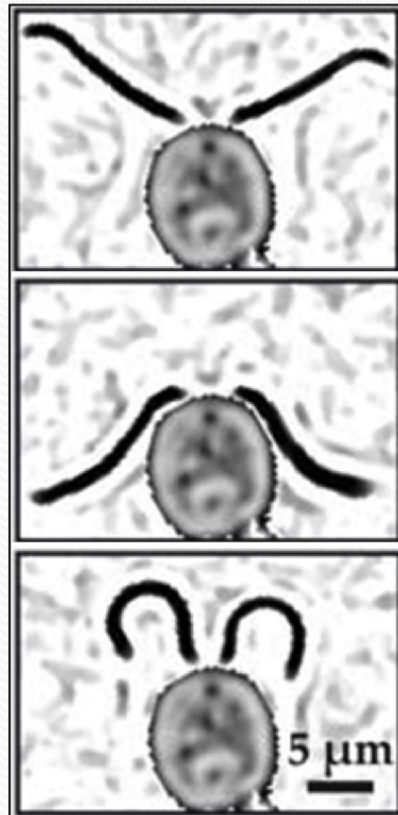


# Microswimmers

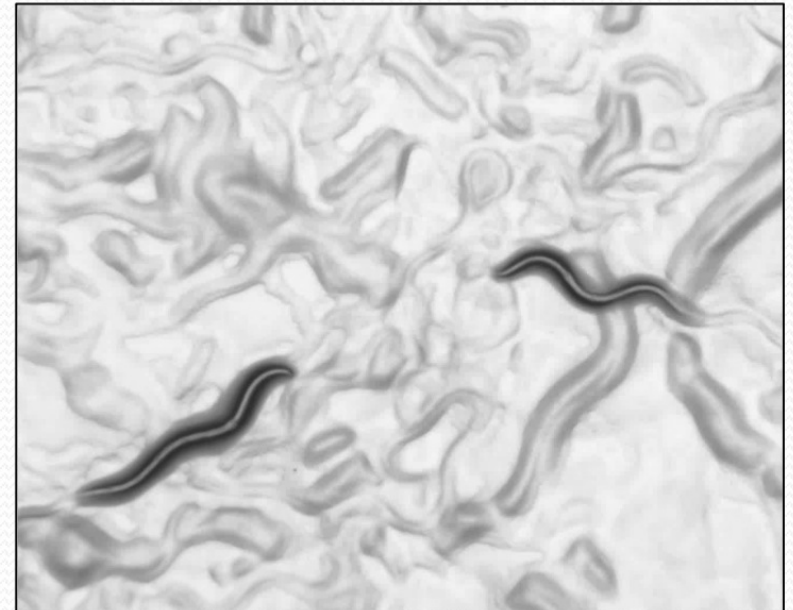
Helical beating  
of flagellum



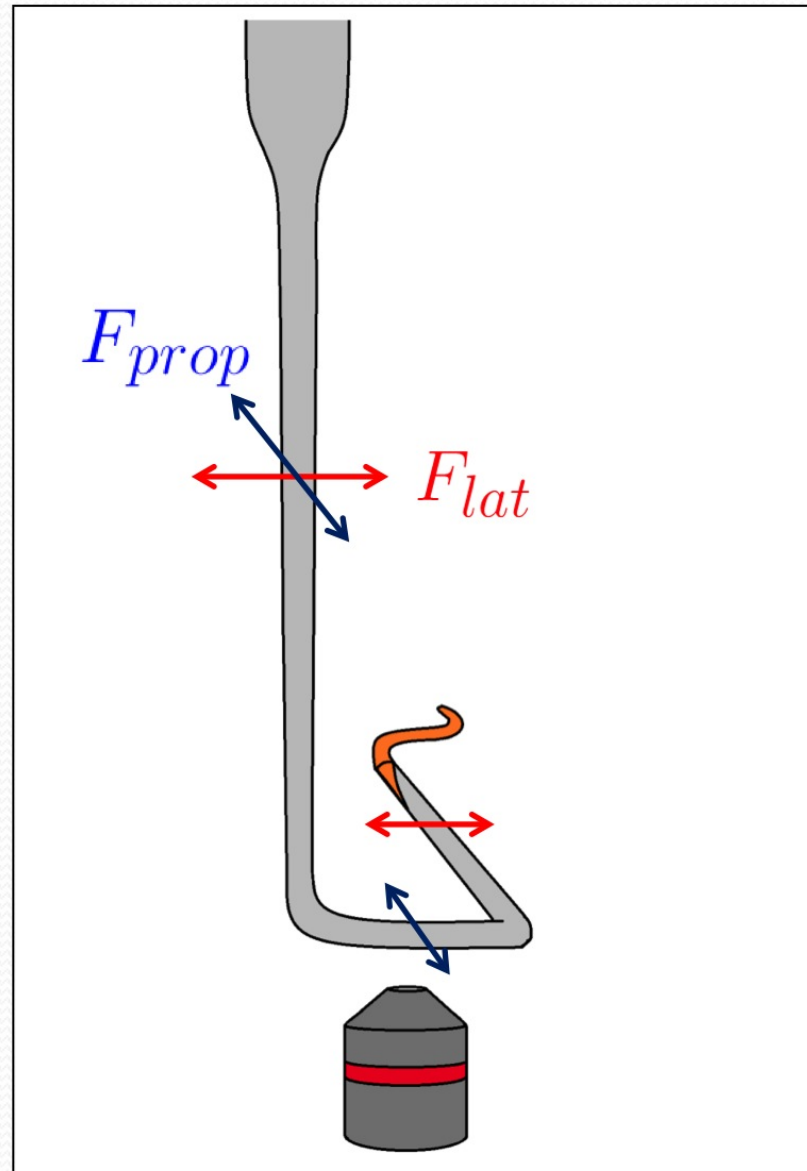
“Breast stroke”



Undulatory

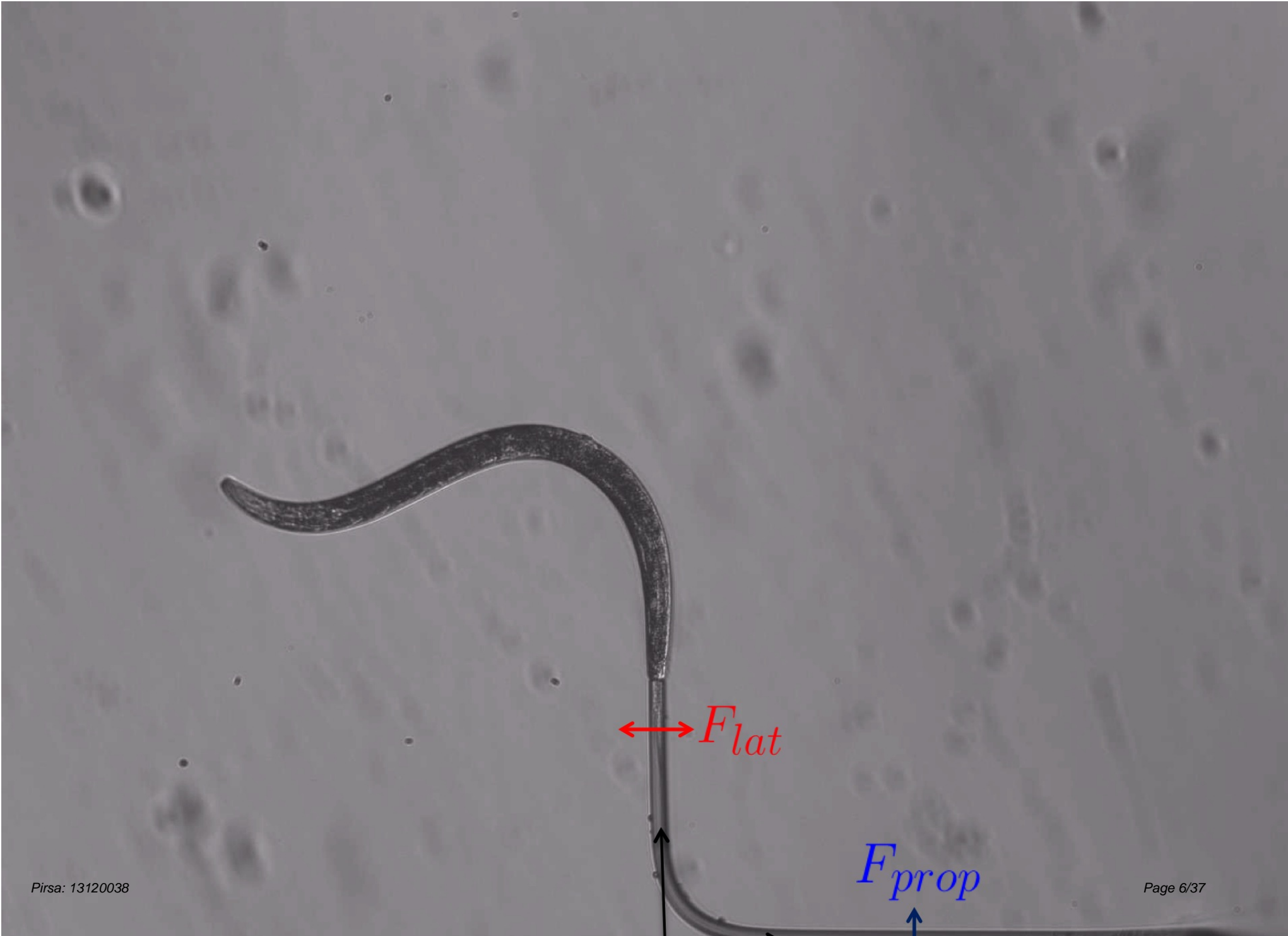


# Lateral and Propulsive Forces



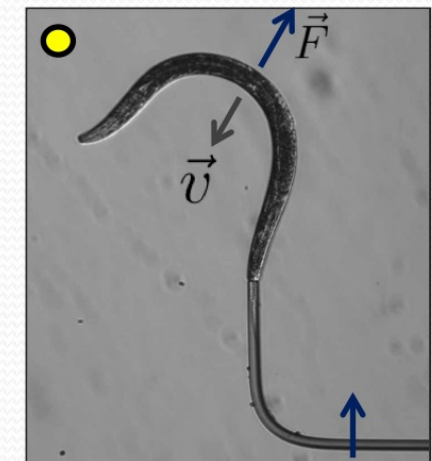
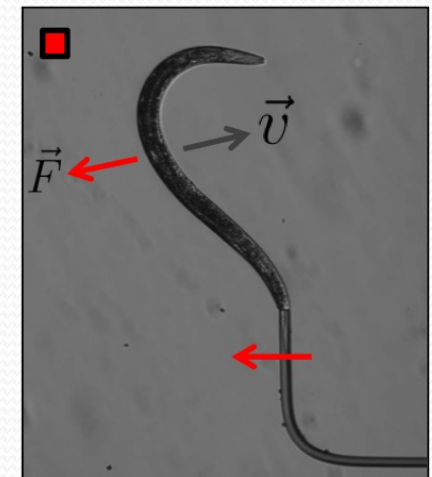
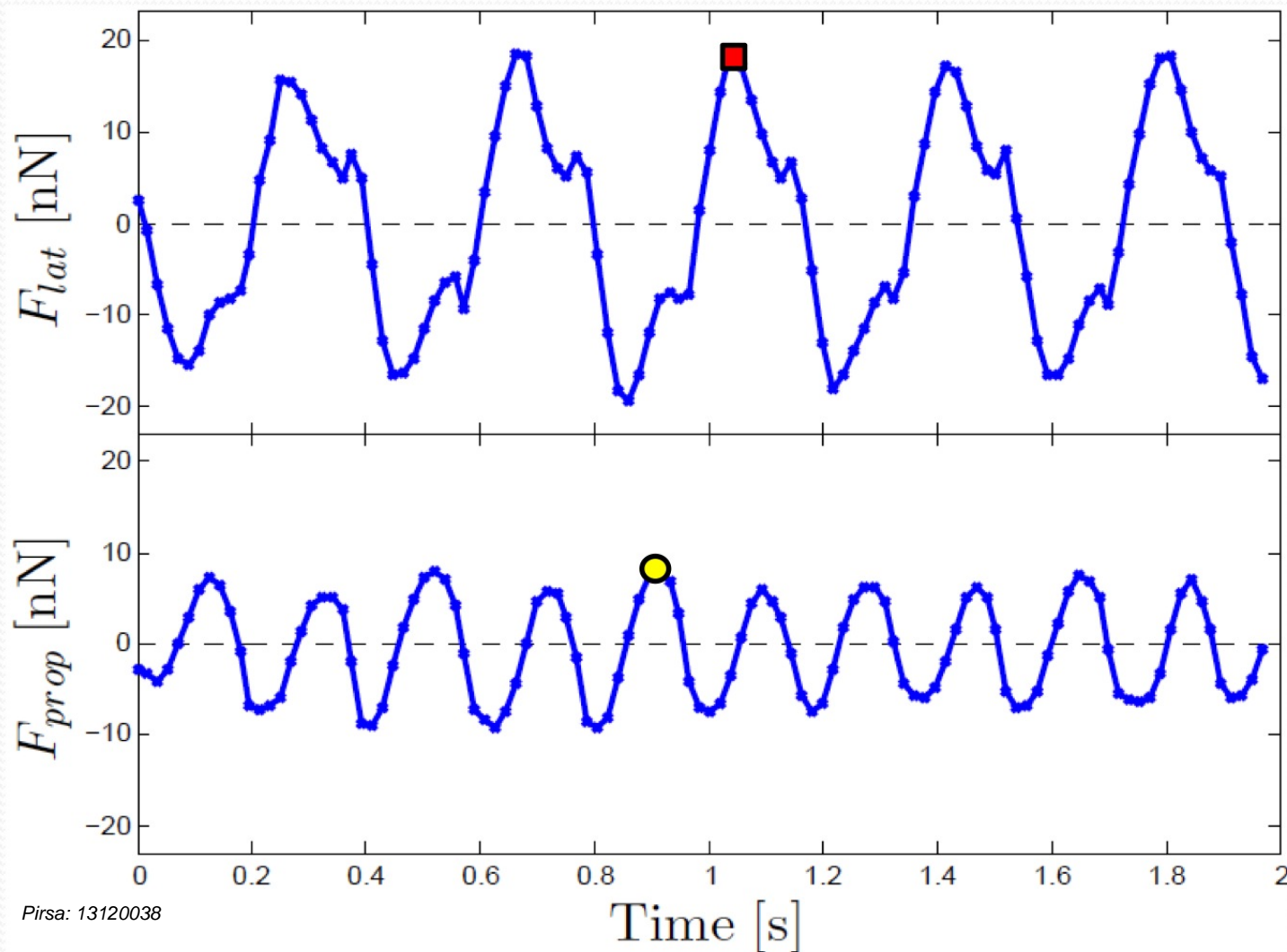




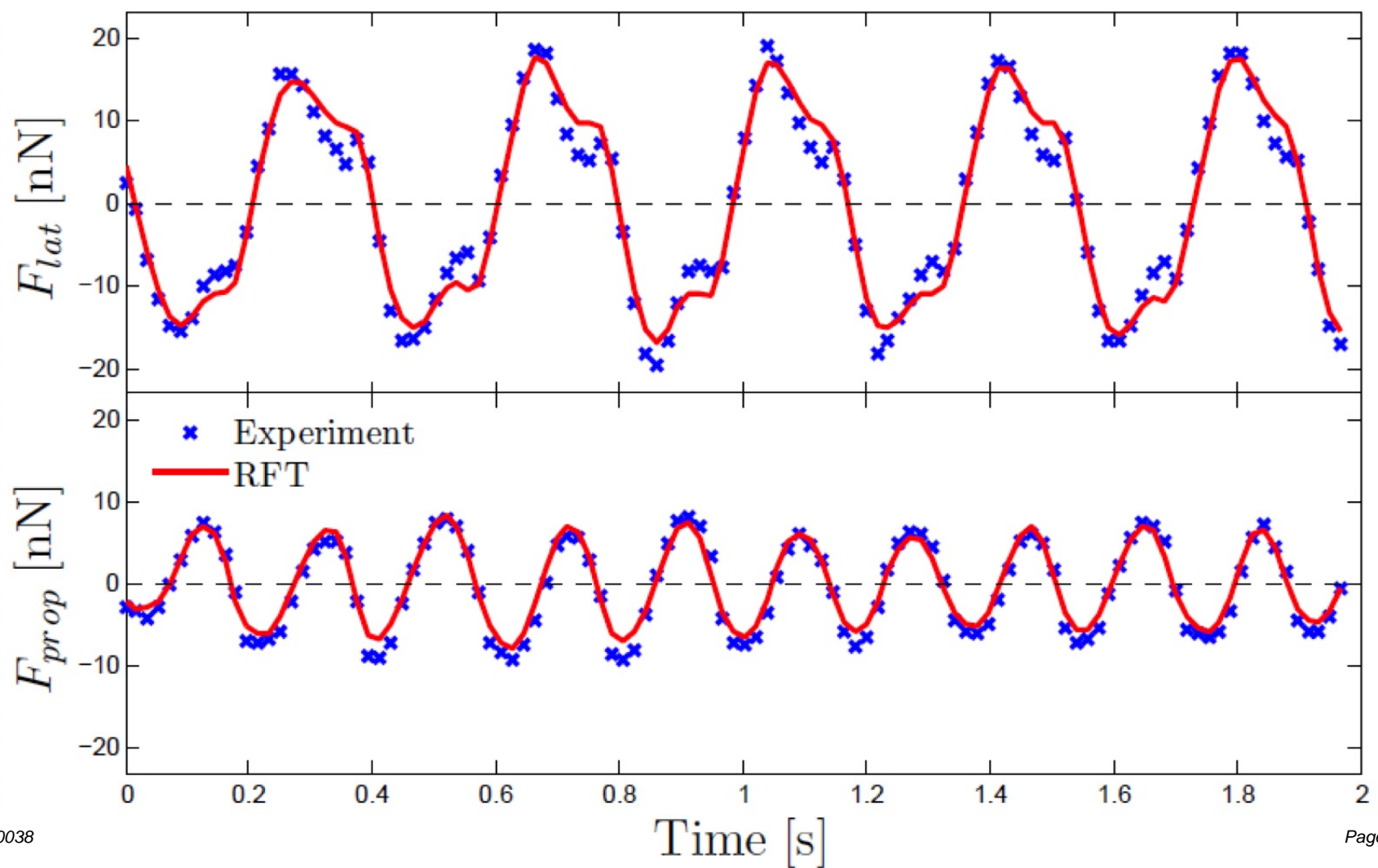




# Lateral and Propulsive Forces

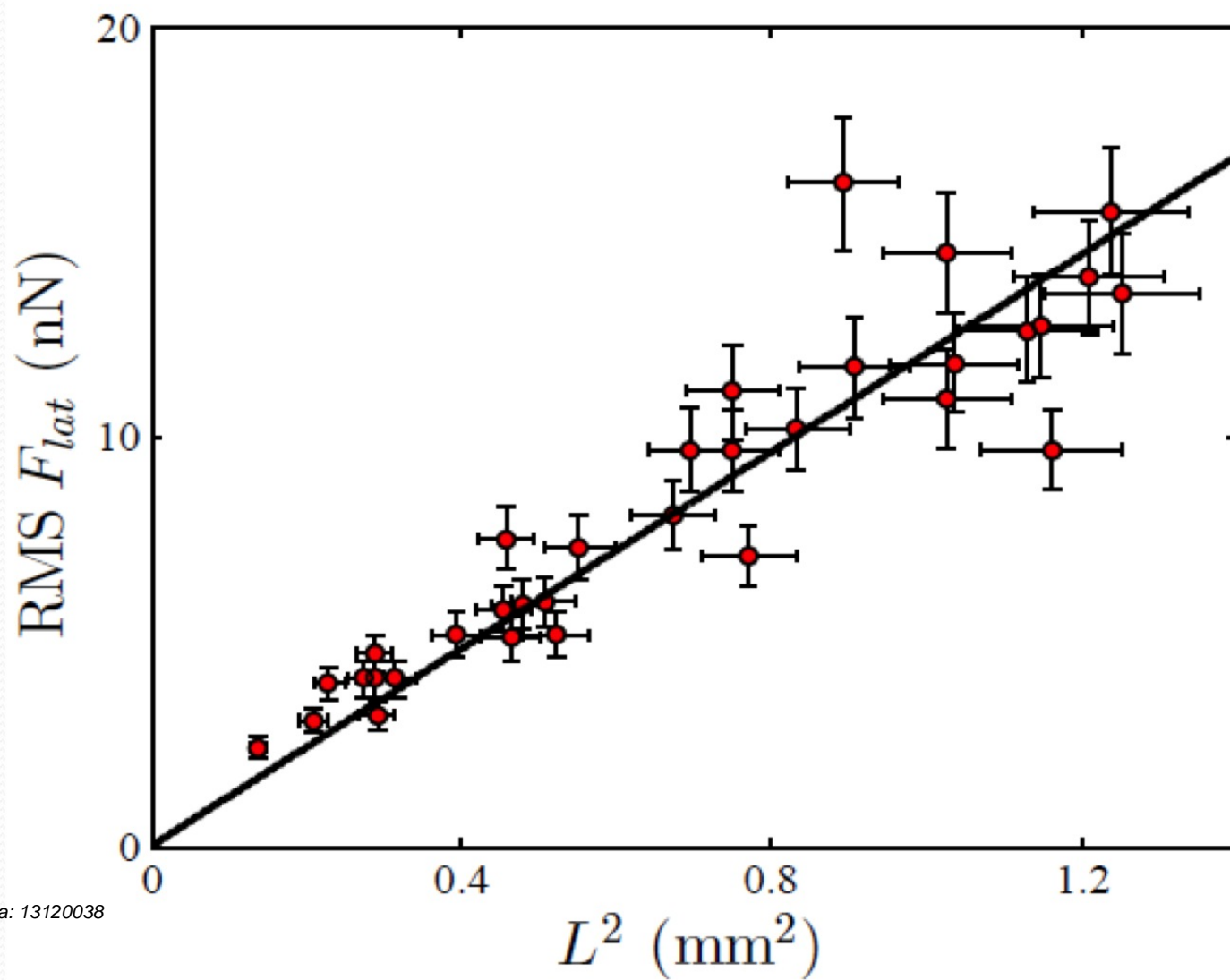


# Resistive Force Theory (RFT)





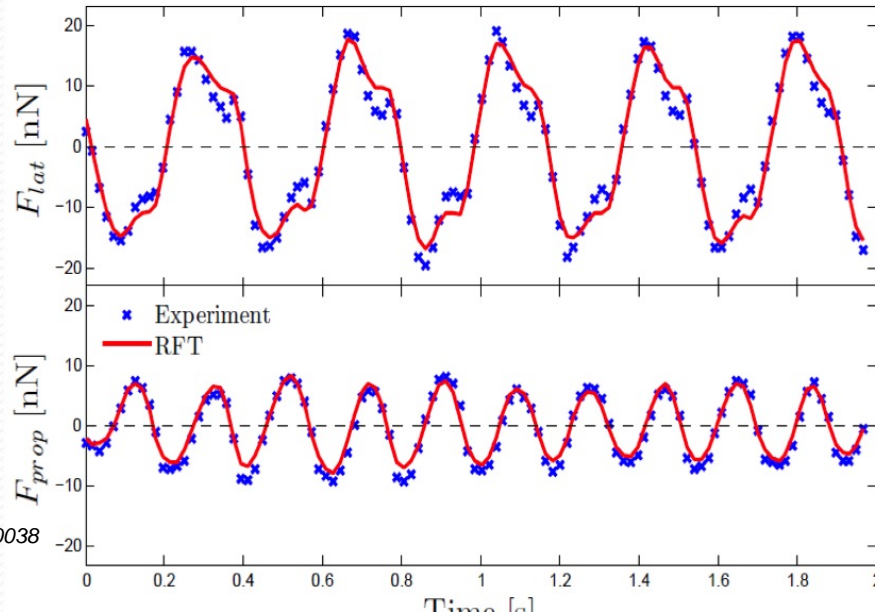
## Size Dependence: Lateral



$$|F| \propto L^2$$

# Conclusions

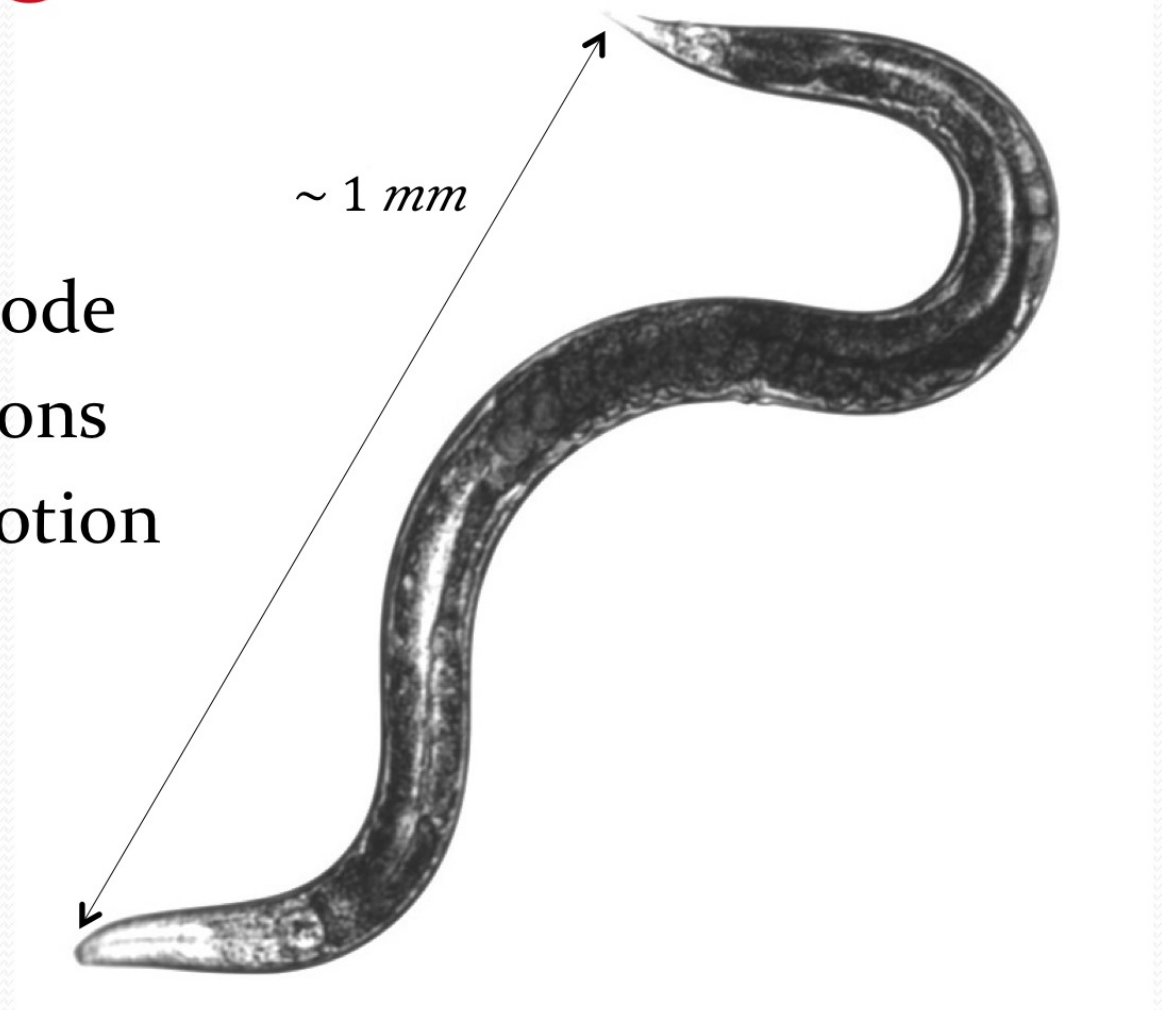
- Measured forces felt by *C. elegans* during swimming using micropipette deflection
- Resistive Force Theory describes force pattern well
- Forces scale as  $L^2$



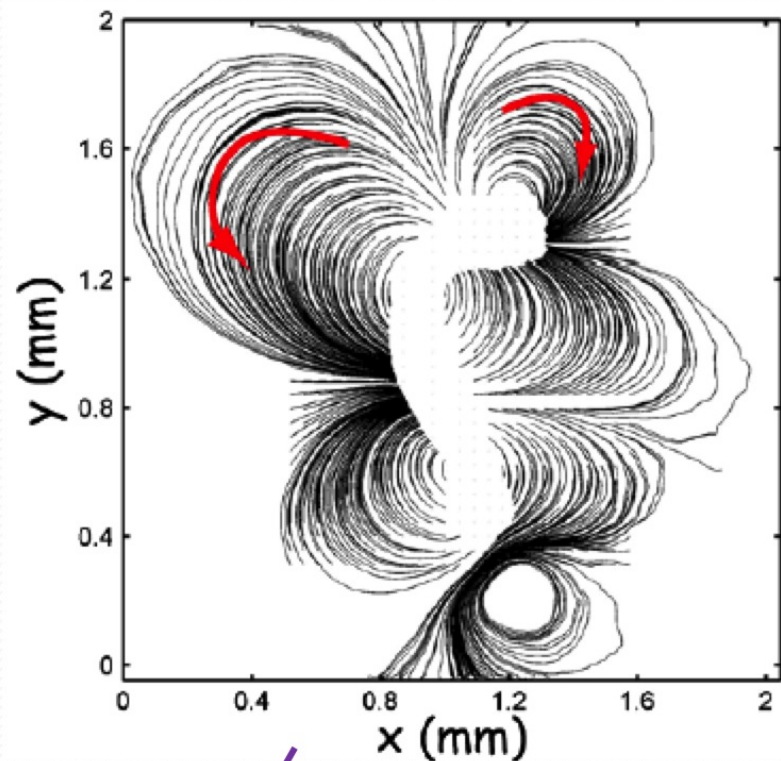


# *C. elegans*

- Hermaphroditic, transparent nematode
- 959 cells, 302 neurons
- Undulatory locomotion
- Swimming and crawling gaits



# Measuring Forces

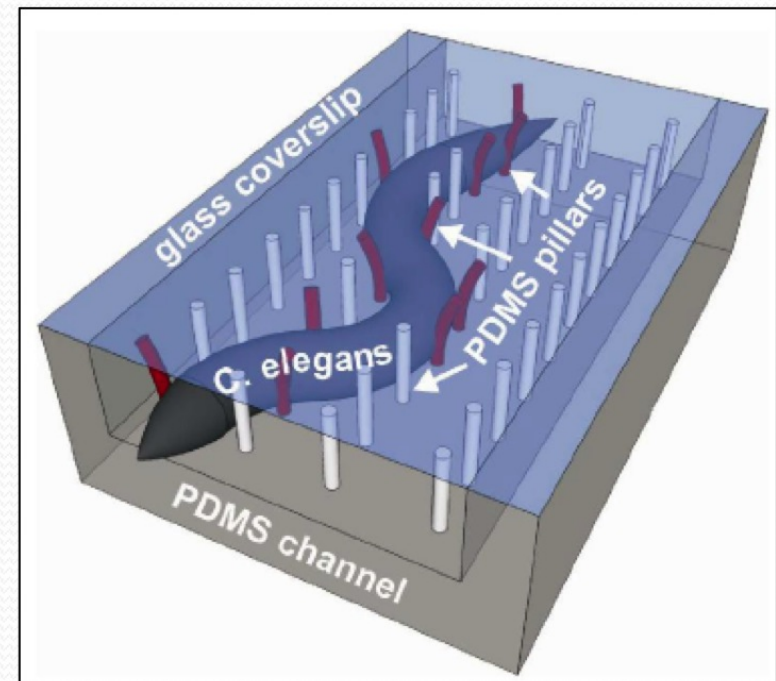


Shen and Arratia, PRL 2011

Fluid velocities → Calculate forces

Pirsa: 13120038

INDIRECT



Ghanbari, et al., M2VIPo8 2008

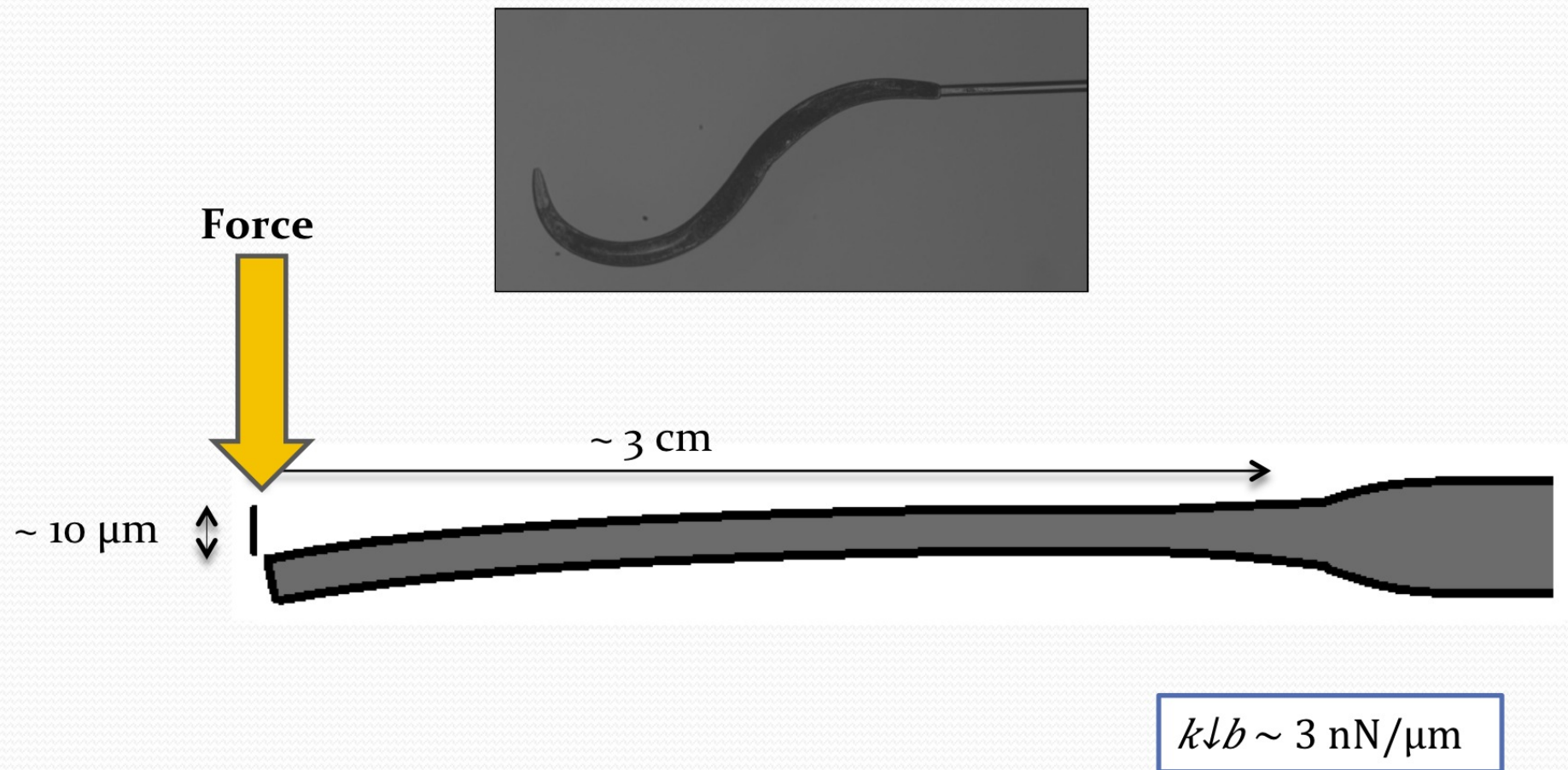
Pillar deflections → Calculate forces

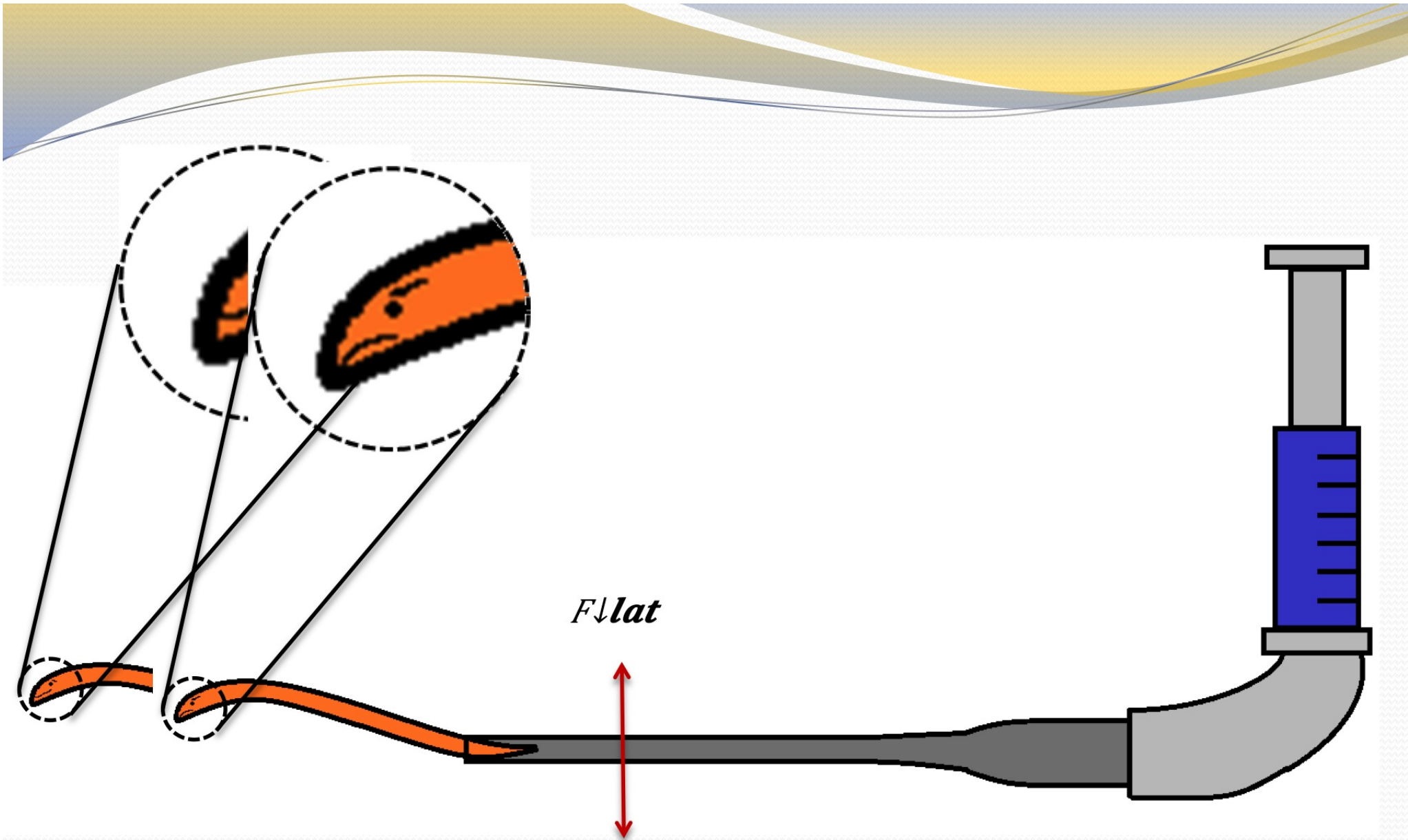
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DIRECT



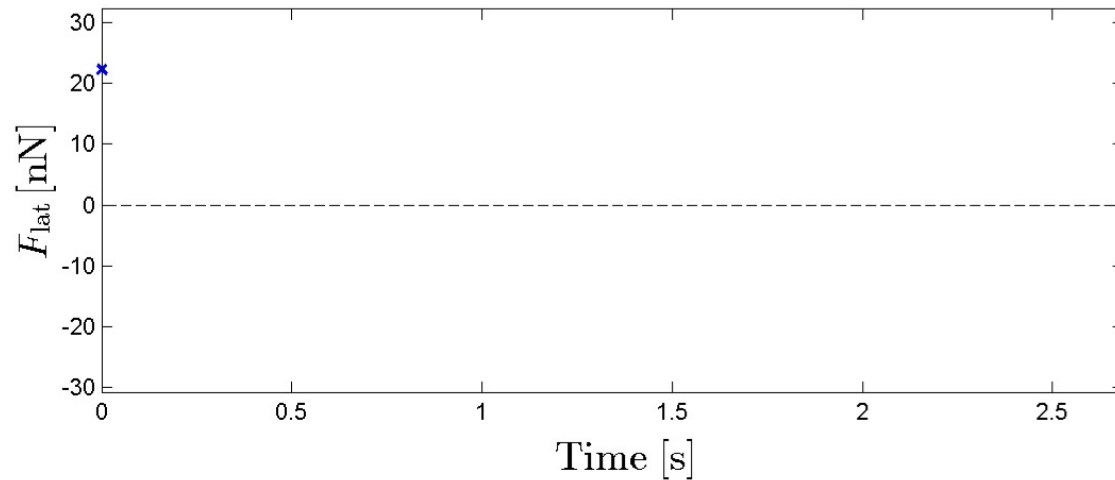
# Micropipette Deflection (MD)

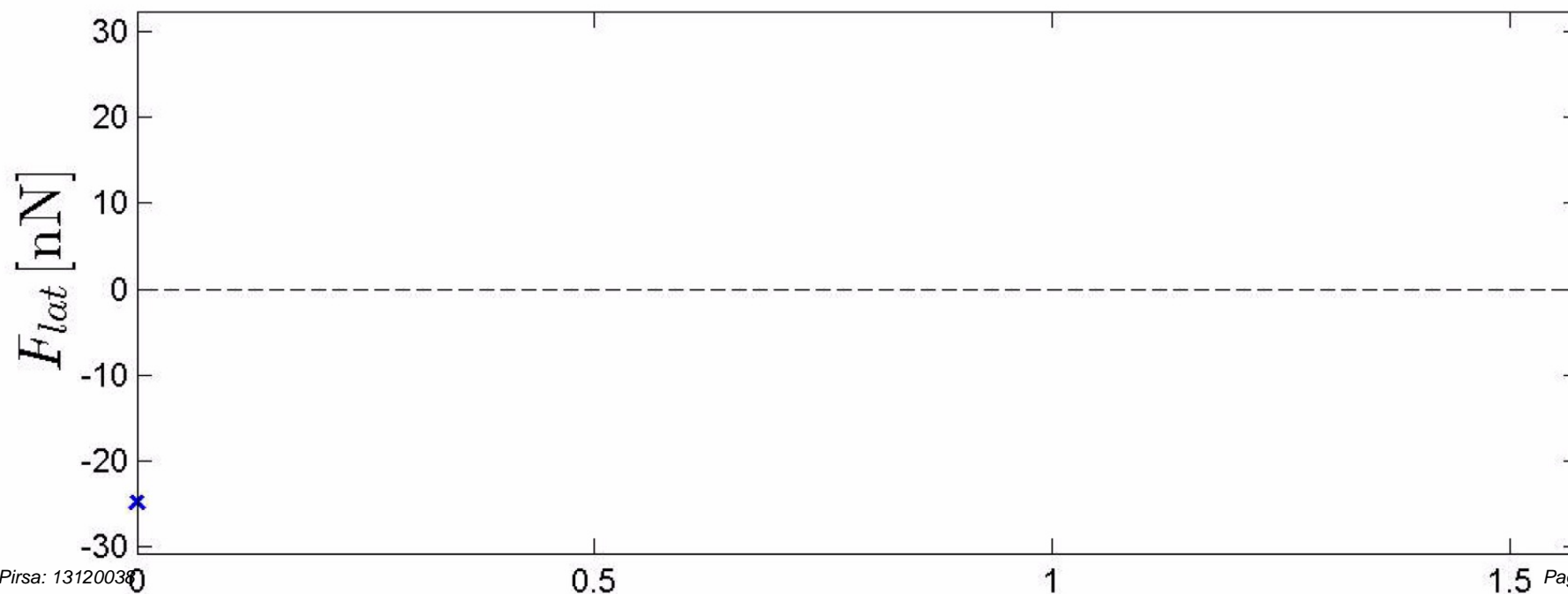






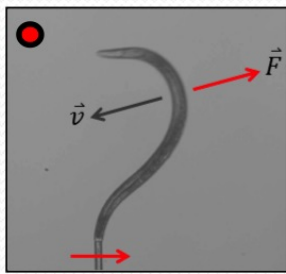
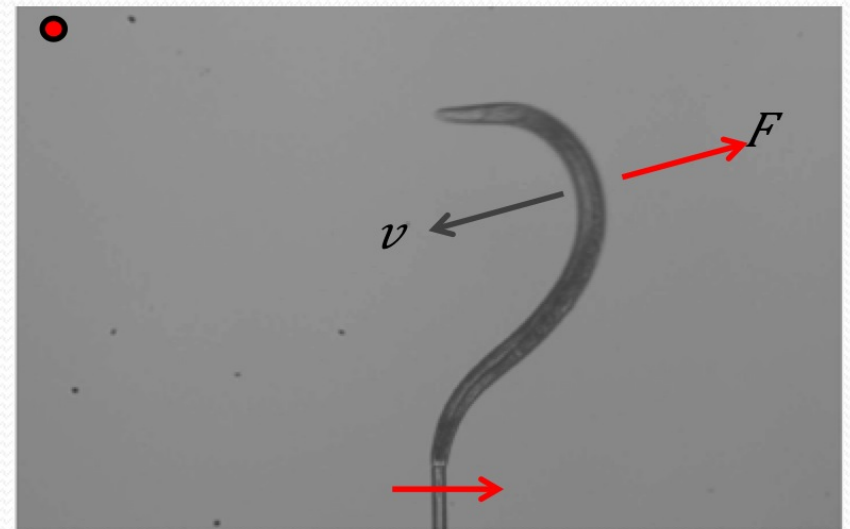
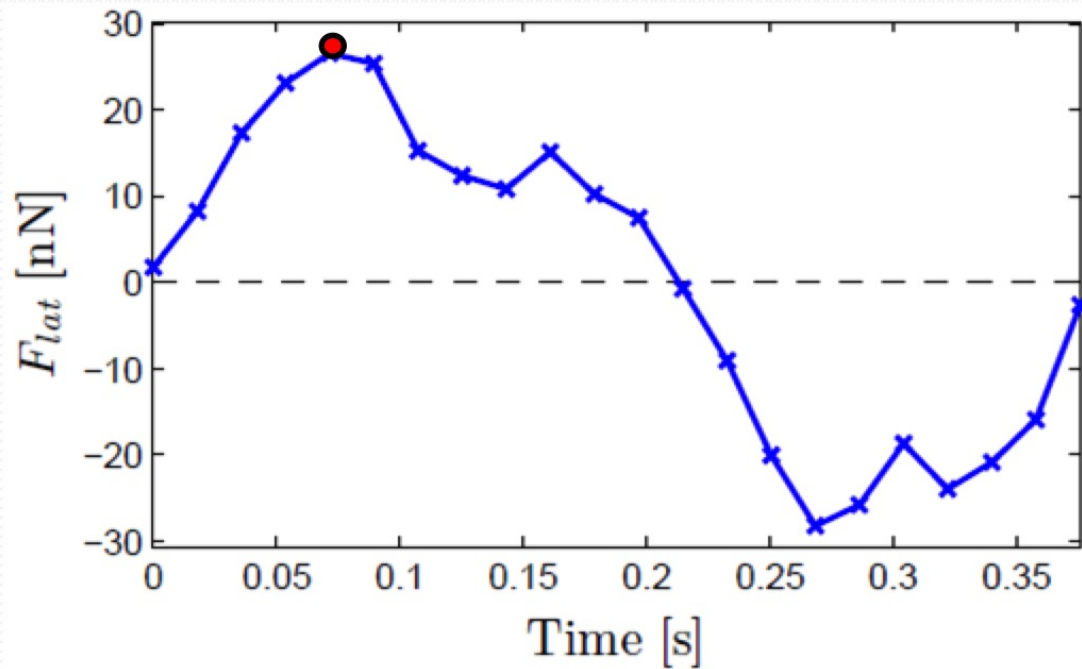
# Lateral Force Measurement



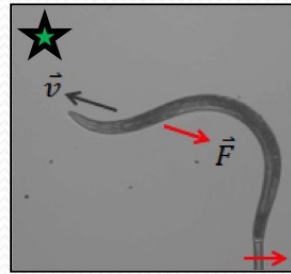
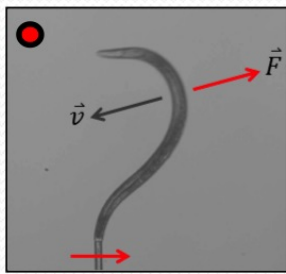
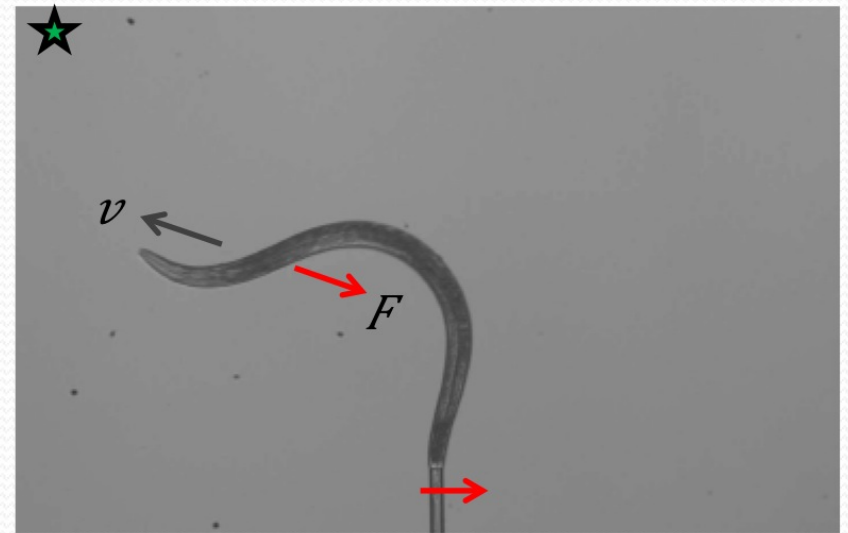
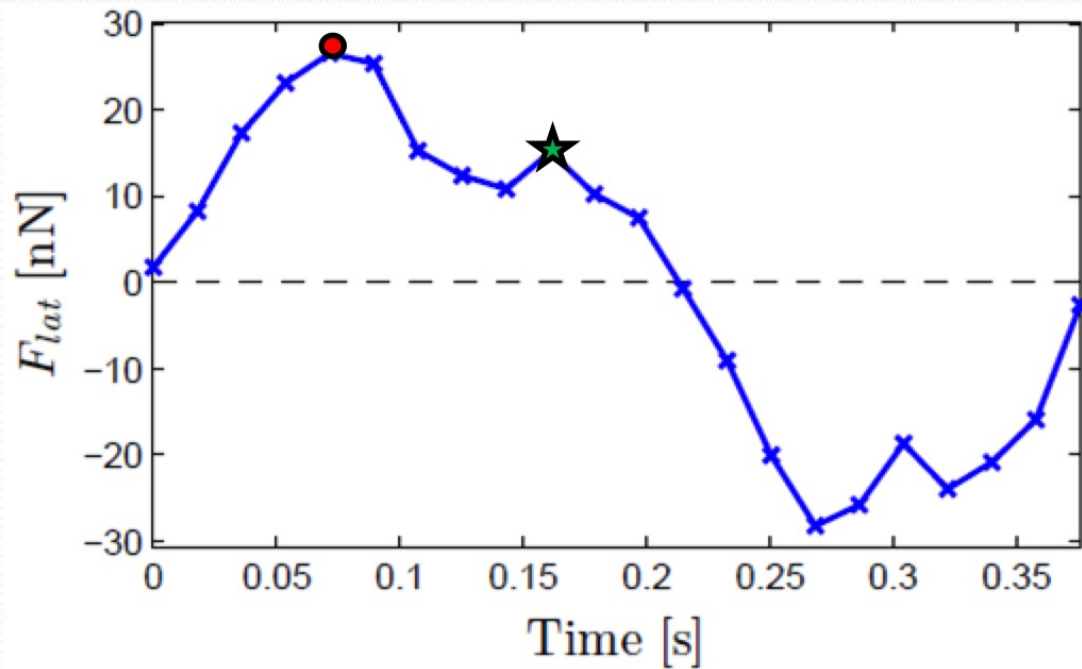




# Lateral Force Measurement

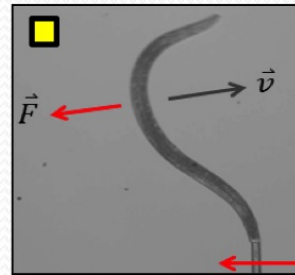
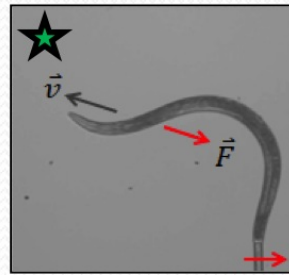
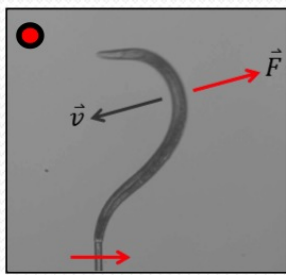
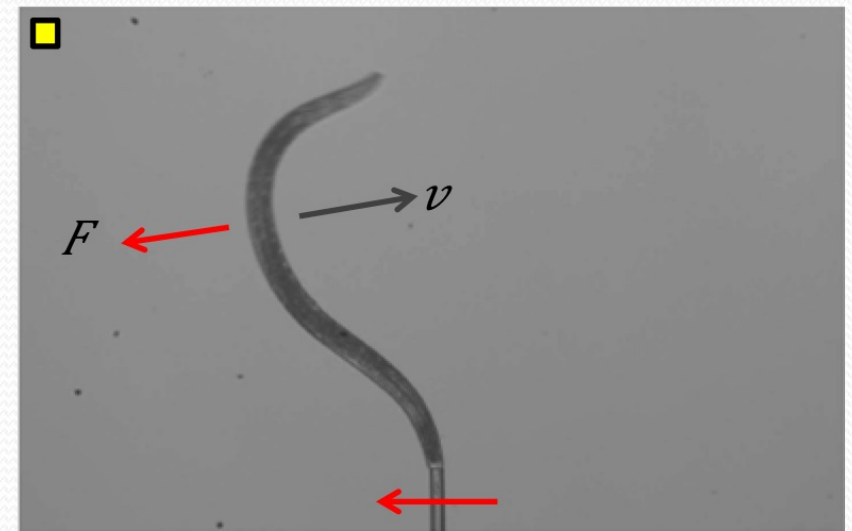
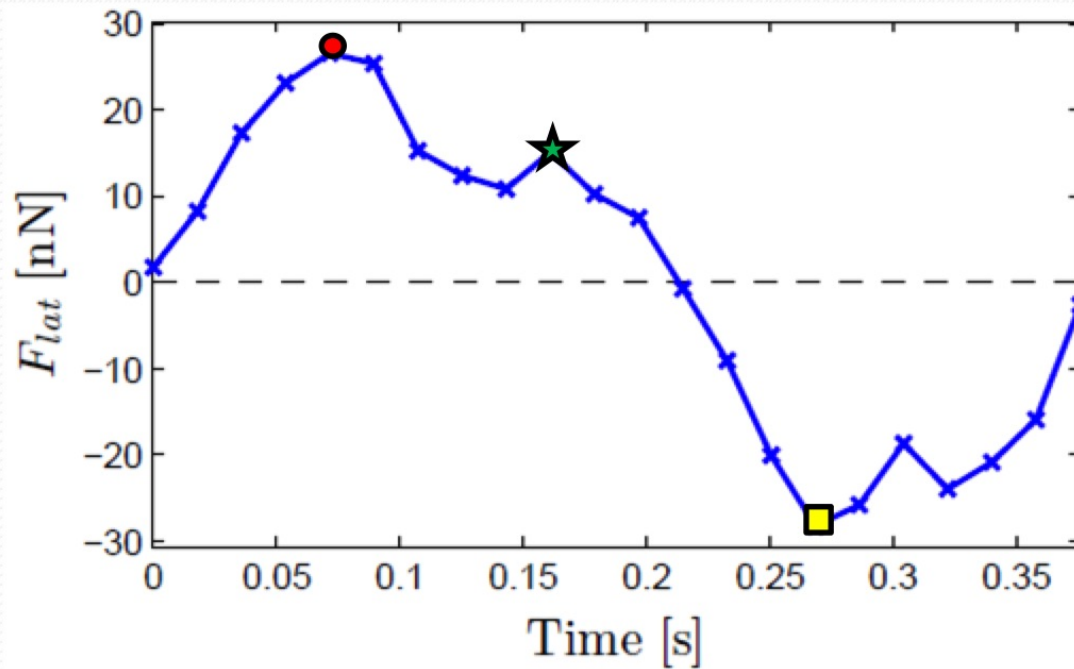


# Lateral Force Measurement

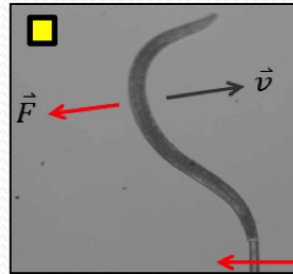
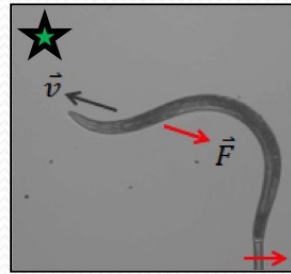
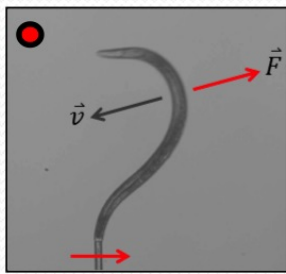
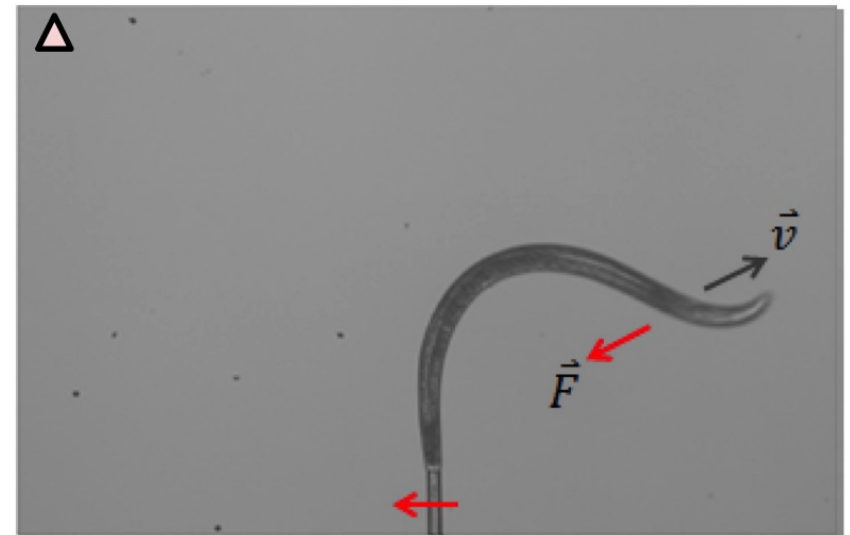
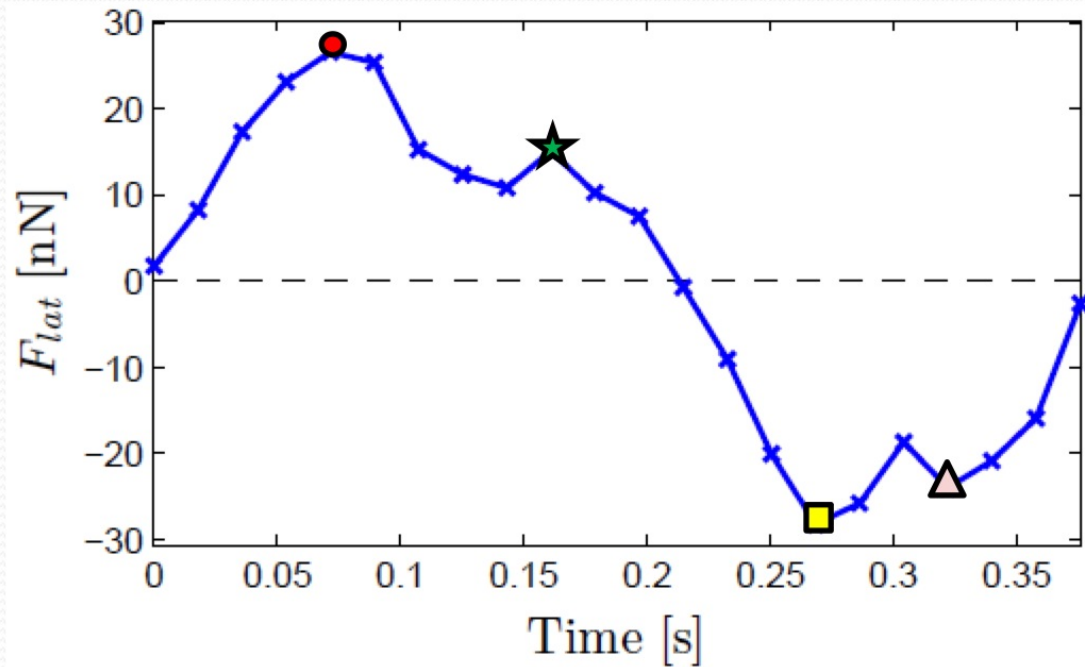




# Lateral Force Measurement

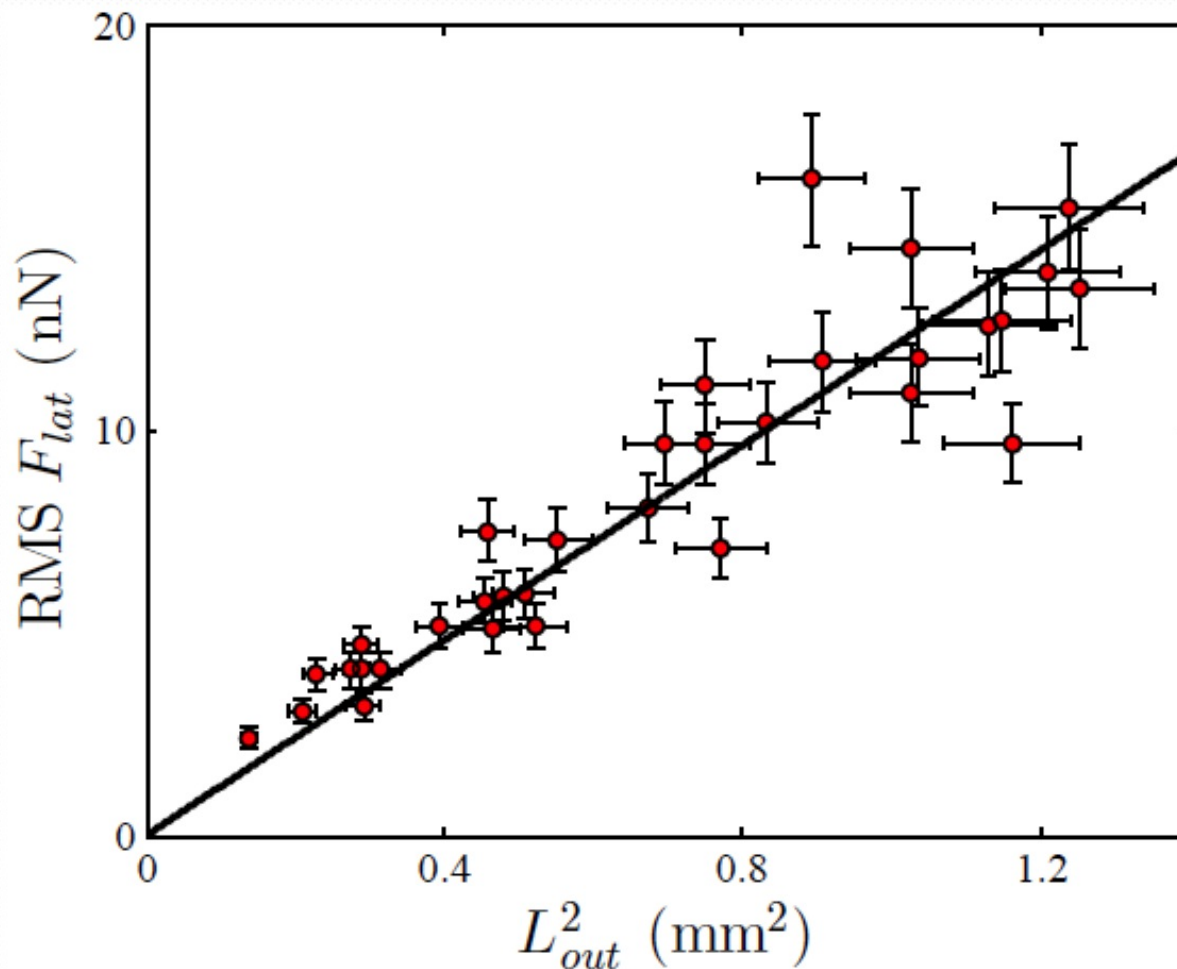


# Lateral Force Measurement





# Size Dependence: Lateral



$$|dF| \sim c v dL$$

$c$  independent of  $L$

$$|F| \propto vL$$

$$v \sim A/T/2, \quad |F| \propto AL/T$$

$$A \propto L$$

$T$  independent of  $L$

$$|F| \propto L^2$$

# Size Dependence: Lateral

$$|F| \sim cvL$$

$c$  independent of  $L$

$$|F| \propto vL$$

$$v \sim A/T/2, \quad |F| \propto AL/T$$

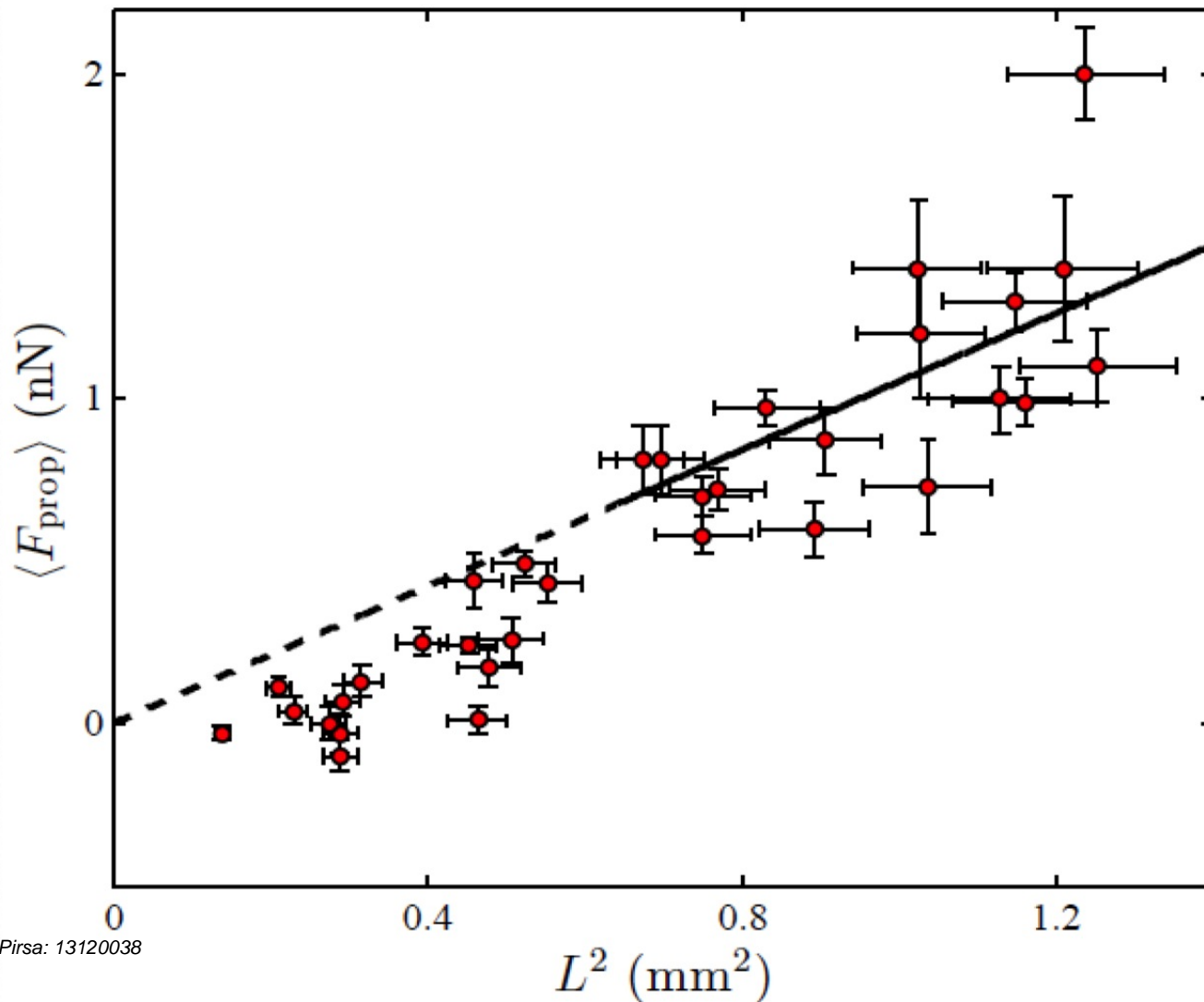
$$A \propto L$$

$T$  independent of  $L$

$$|F| \propto L^2$$



# Size Dependence: Propulsive



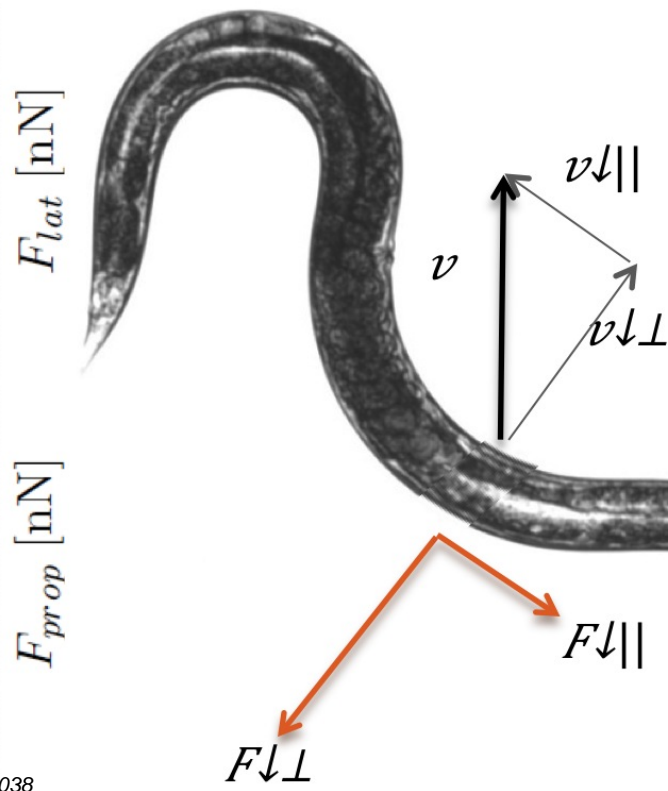
$$\langle F_{prop} \rangle \propto L^2$$

# Resistive Force Theory (RFT)

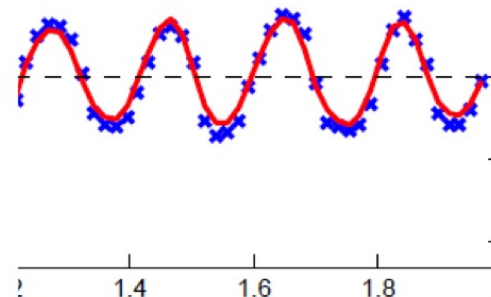
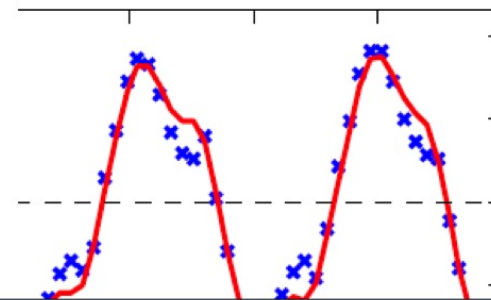
$$F_{\parallel} \propto -c_{\parallel} v_{\parallel}$$

$$F_{\perp} \propto -c_{\perp} v_{\perp}$$

$$K = c_{\perp} / c_{\parallel} \approx 1.5$$



Velocity data + RFT  
Force



$$c_{\parallel} = 3.4 \pm 0.2$$

$$c_{\perp} = 5.1 \pm 0.3$$

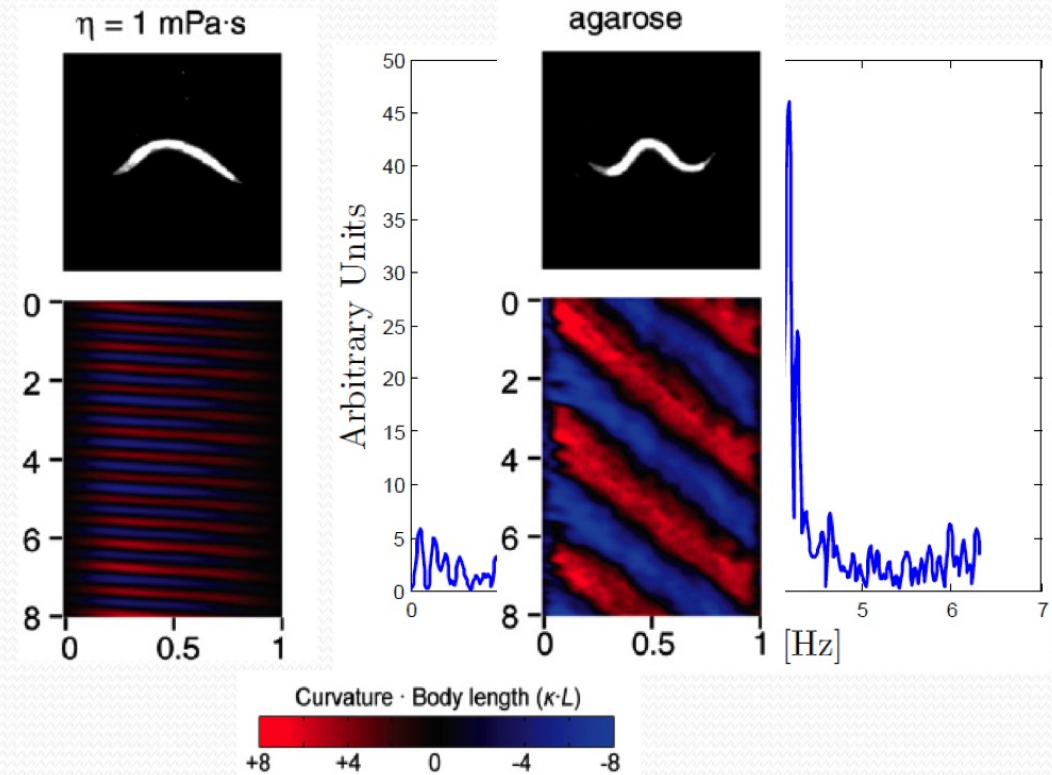
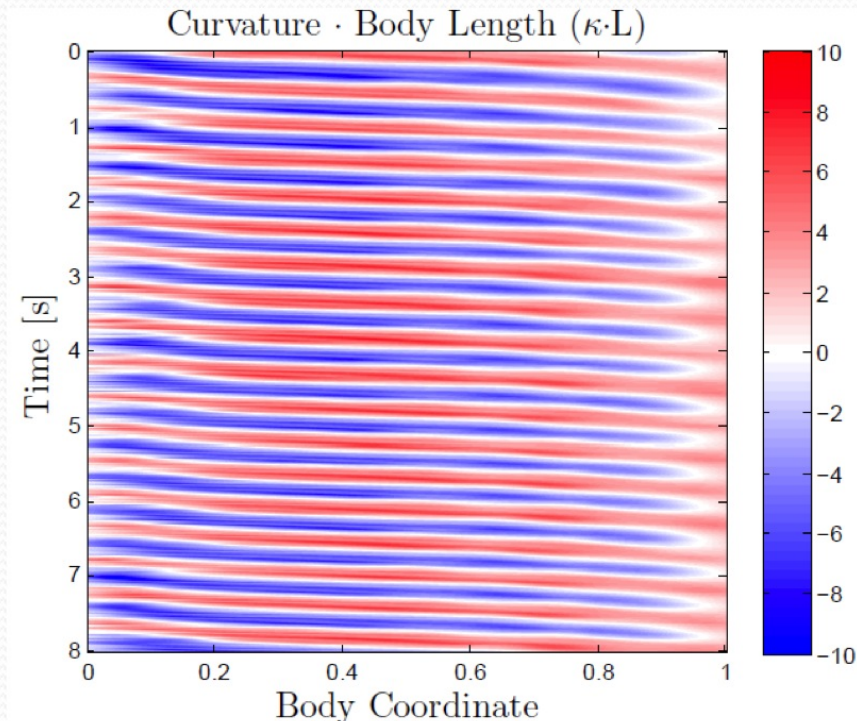


# Trajectory



# Swimming?

- Forcing a node at tail

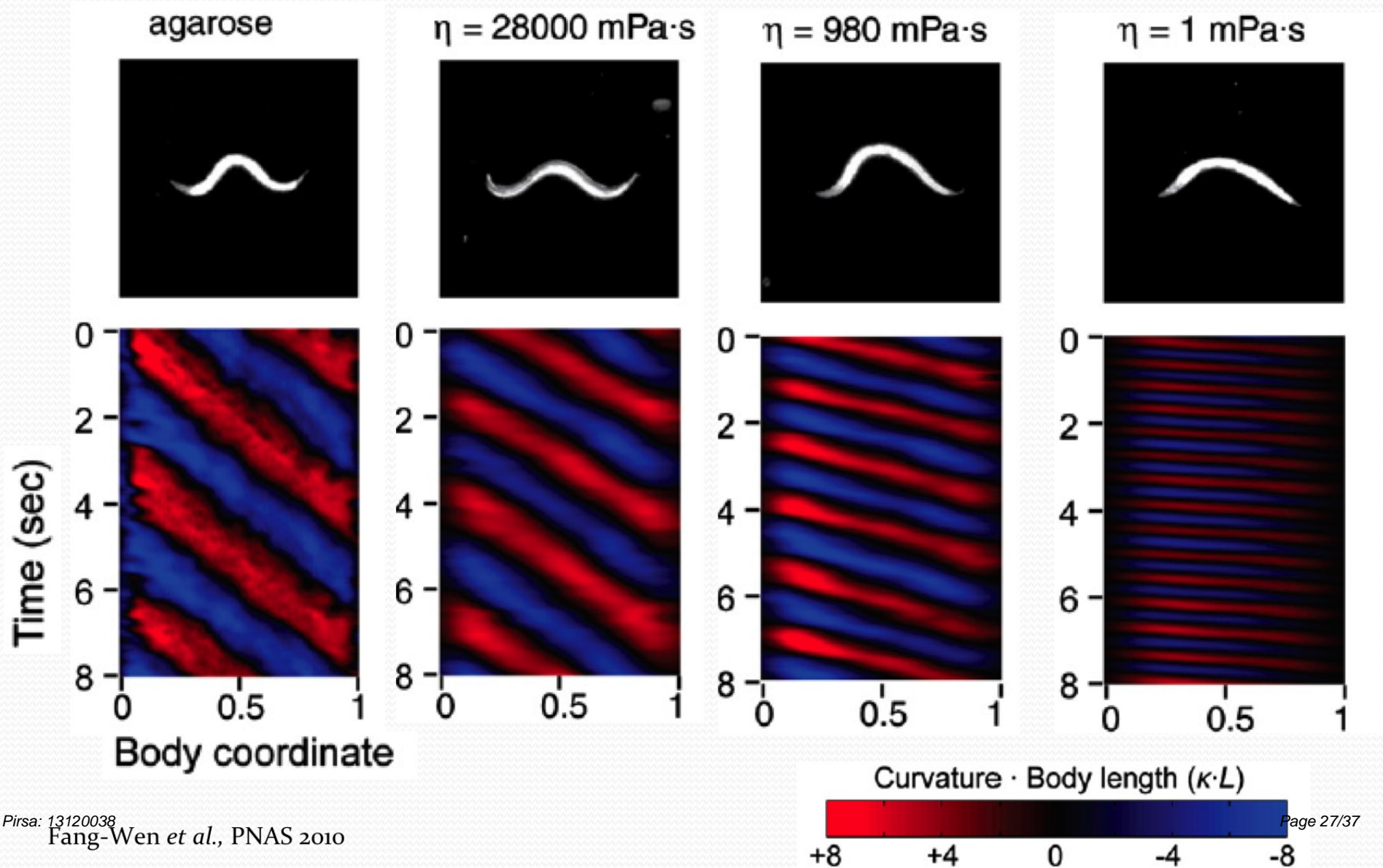


Fang-Yen *et al.*, PNAS 2010

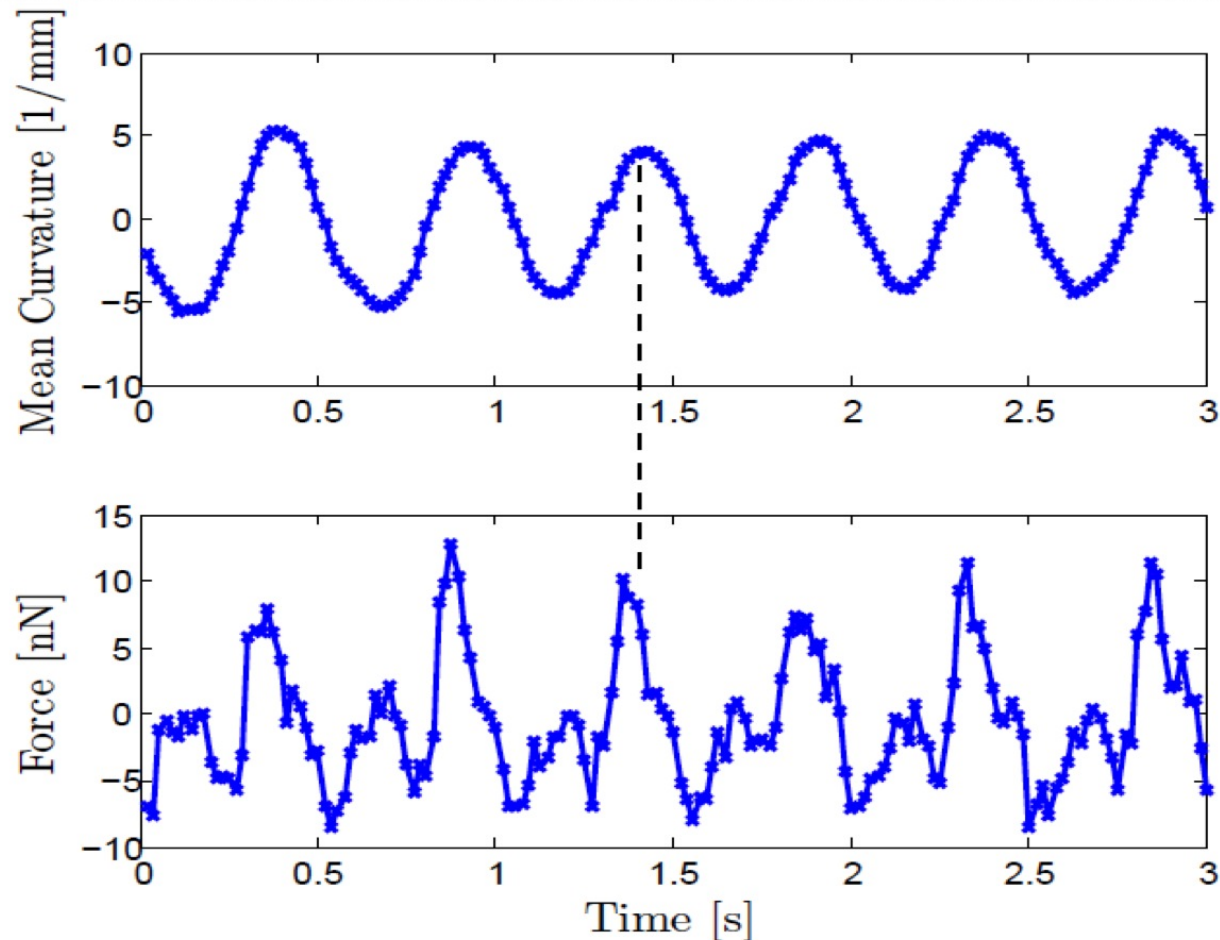
- Similar curvature pattern and frequency ✓



# Crawling to Swimming



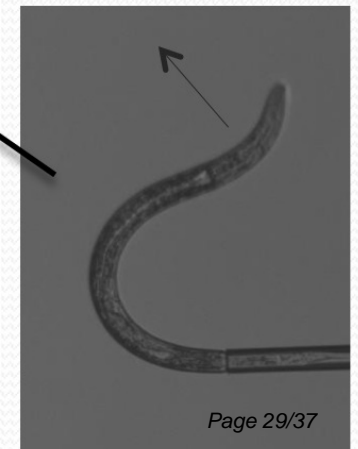
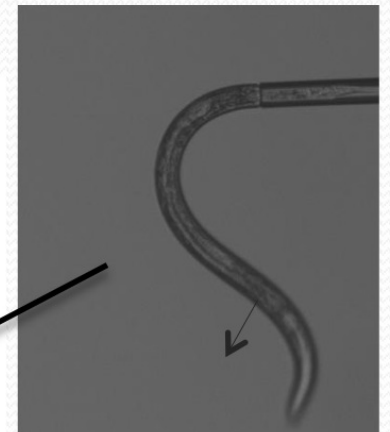
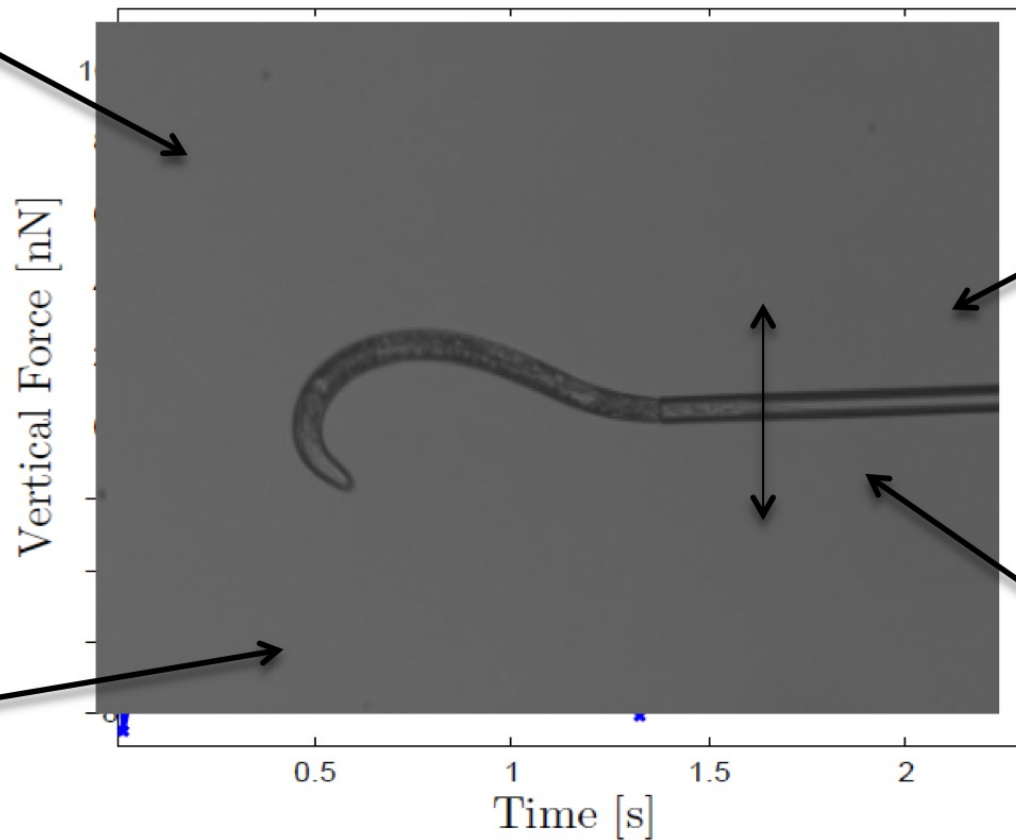
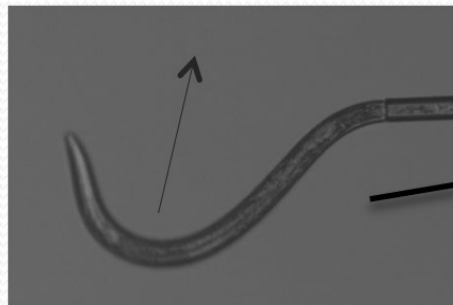
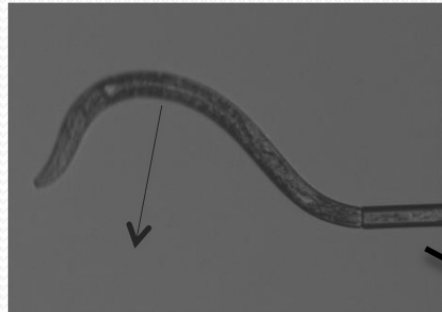
# Curvature and Force



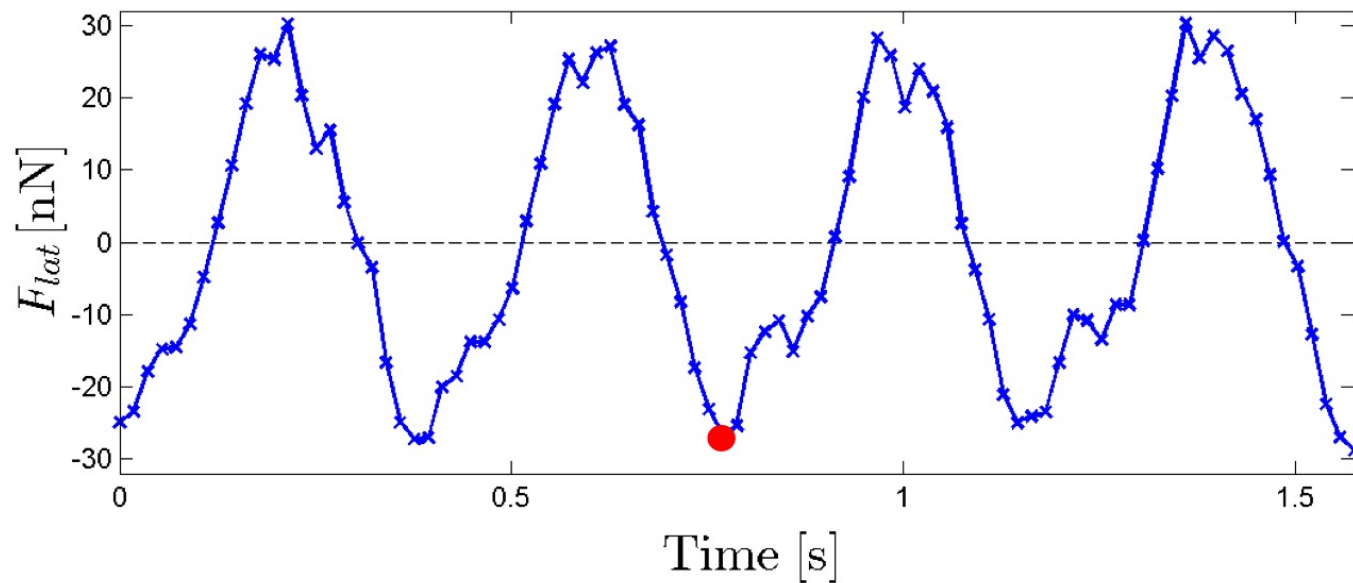
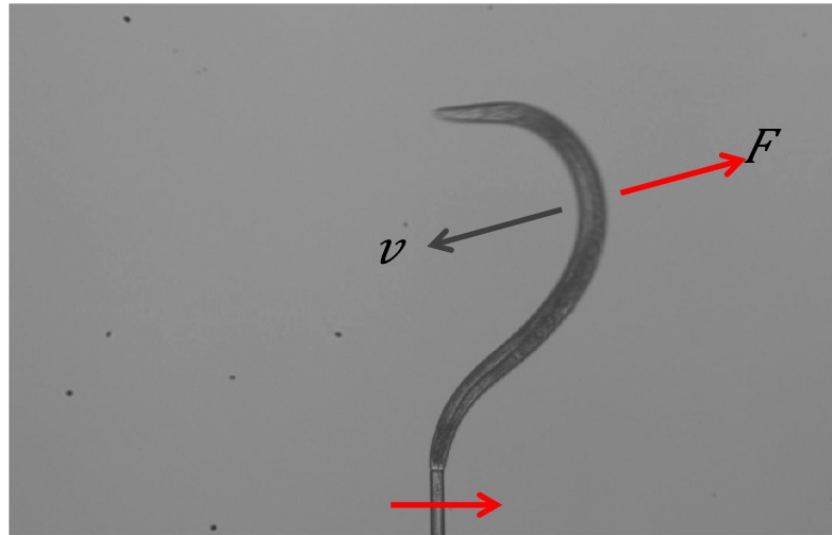
- Asymmetry in force but not curvature  
→ Pipette interaction?



# Vertical Forces

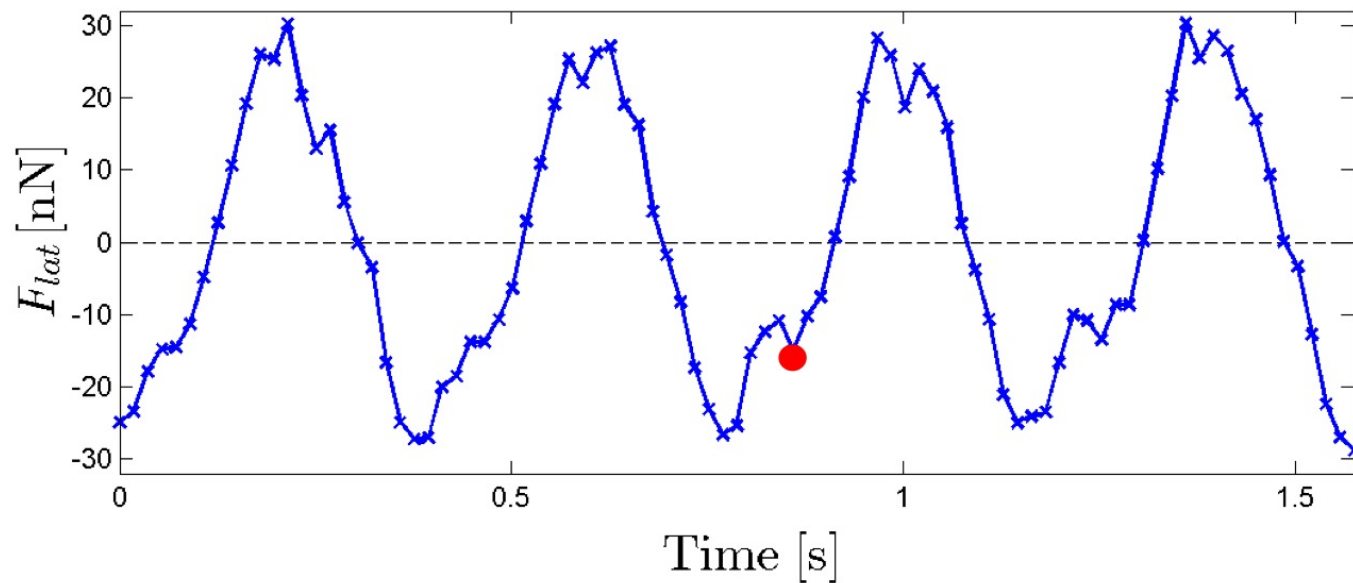
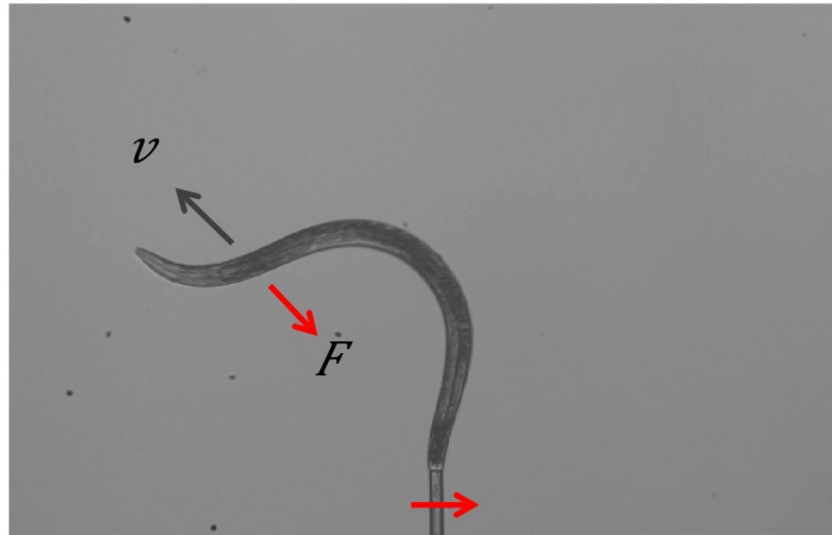


# Lateral Force Measurement

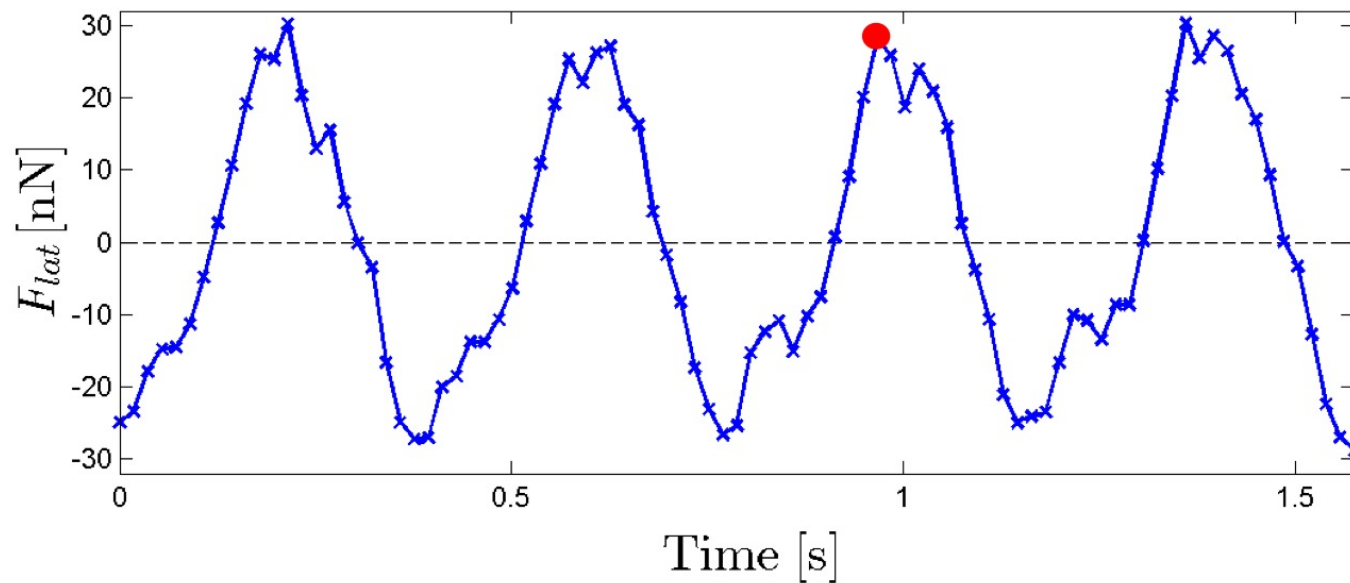
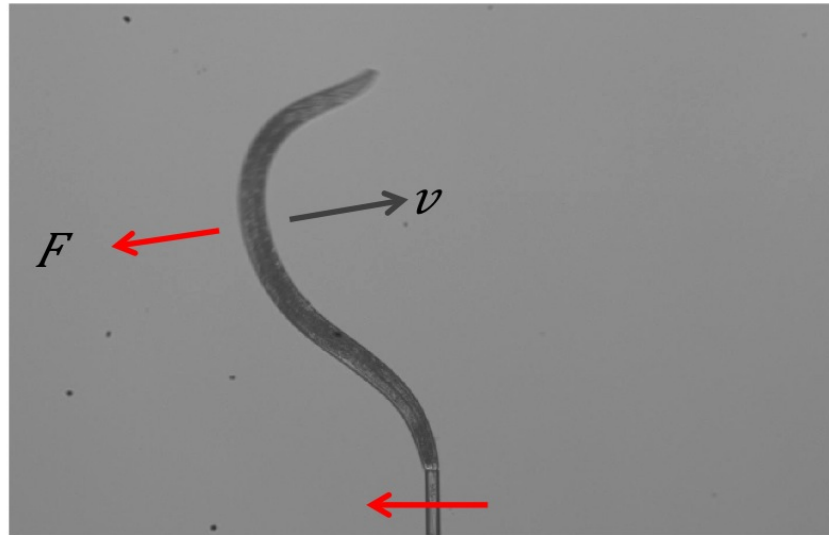




# Lateral Force Measurement

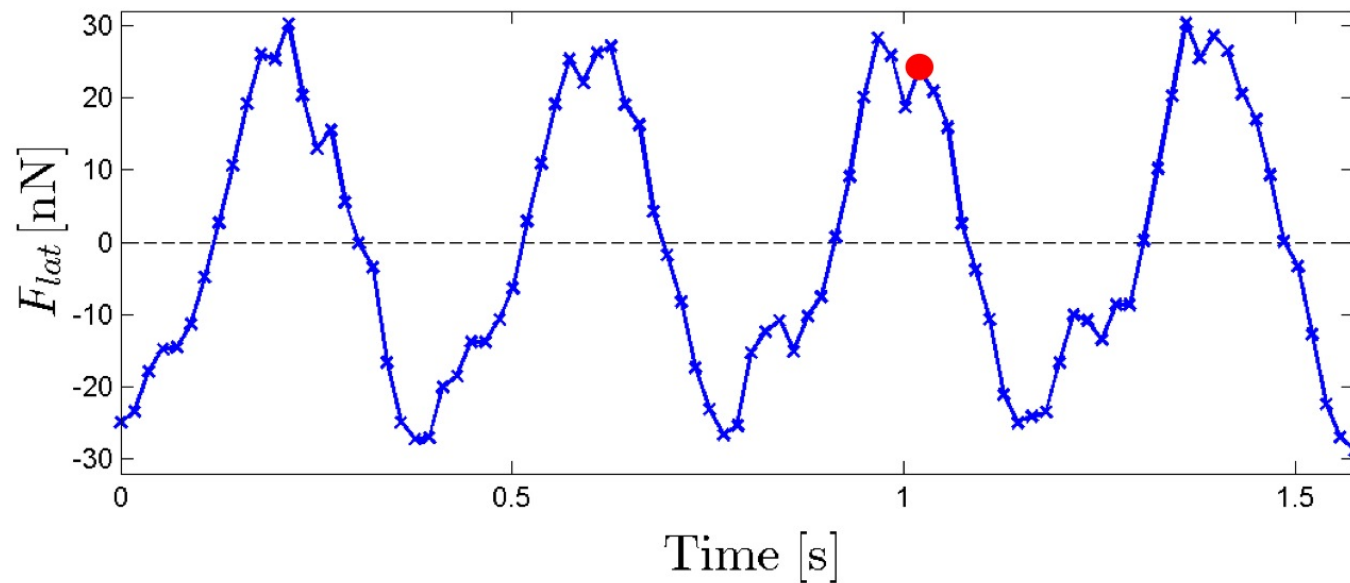
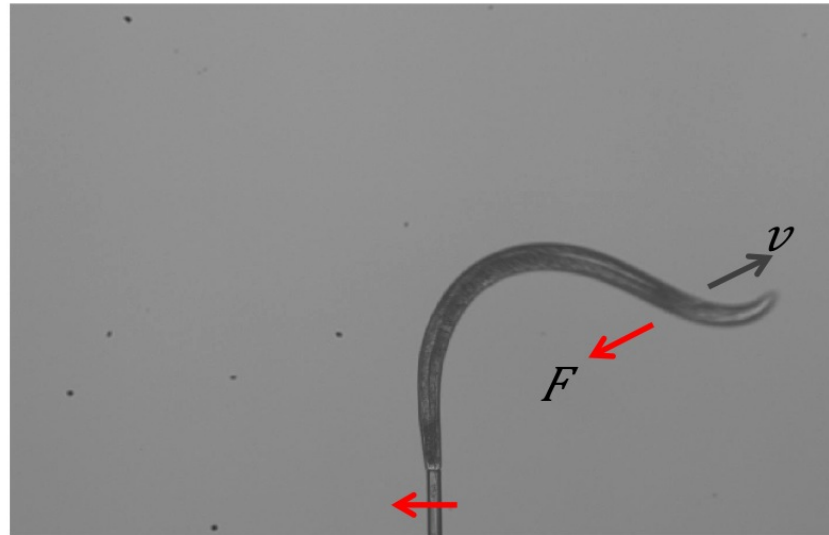


# Lateral Force Measurement

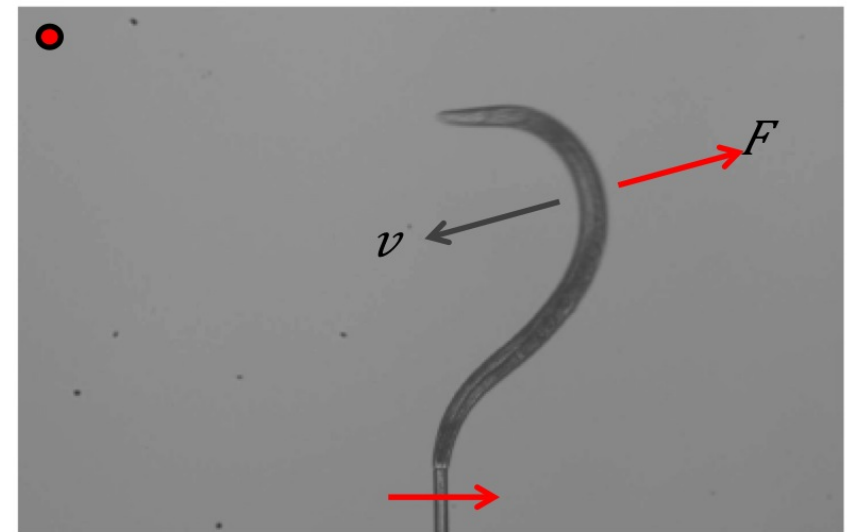
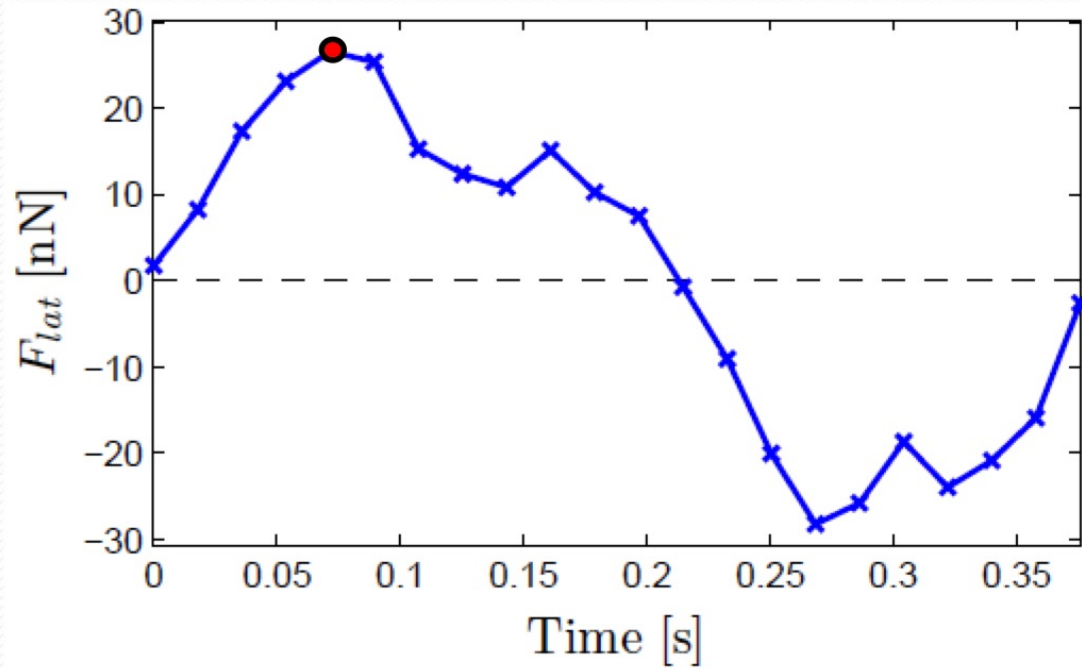




# Lateral Force Measurement

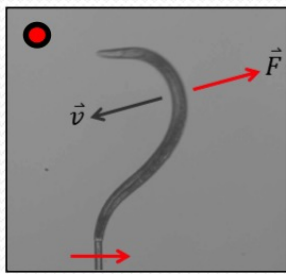
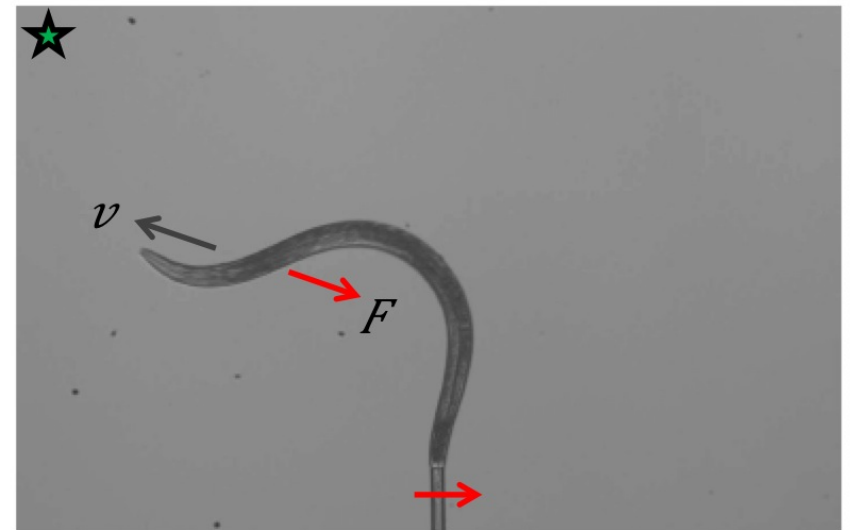
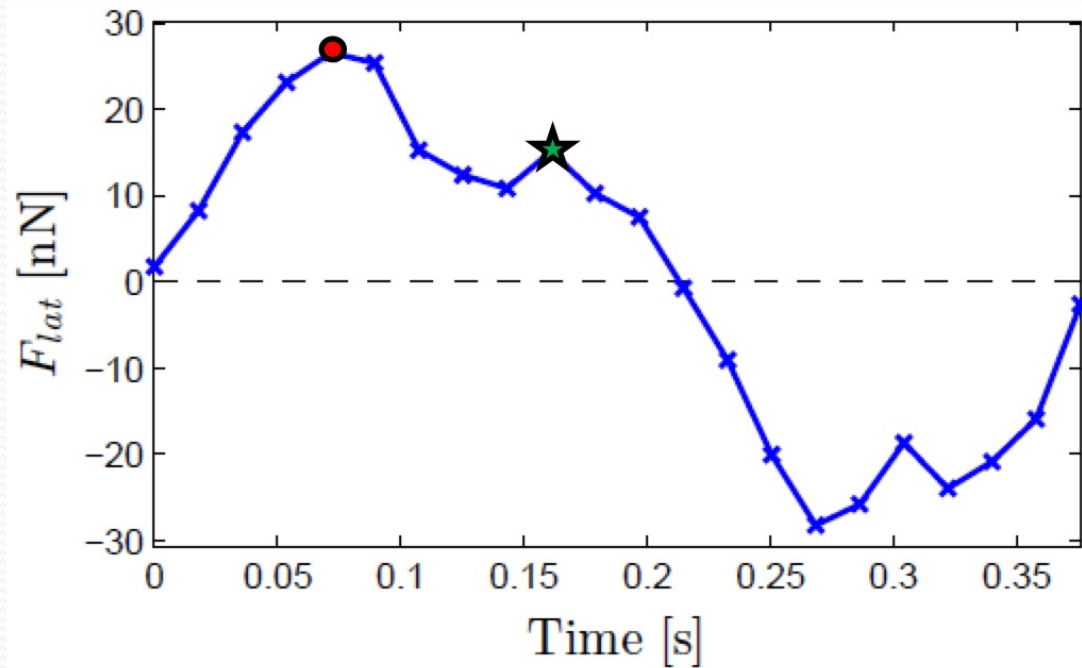


# Lateral Force Measurement

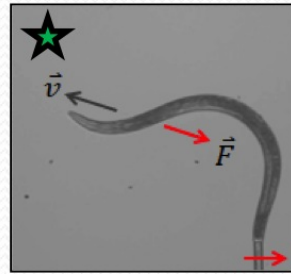
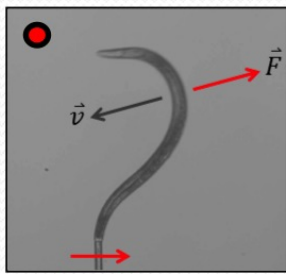
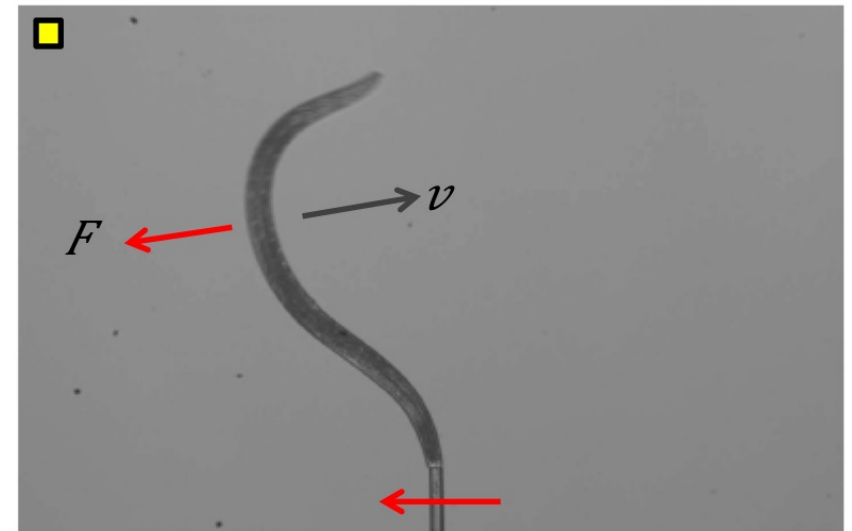
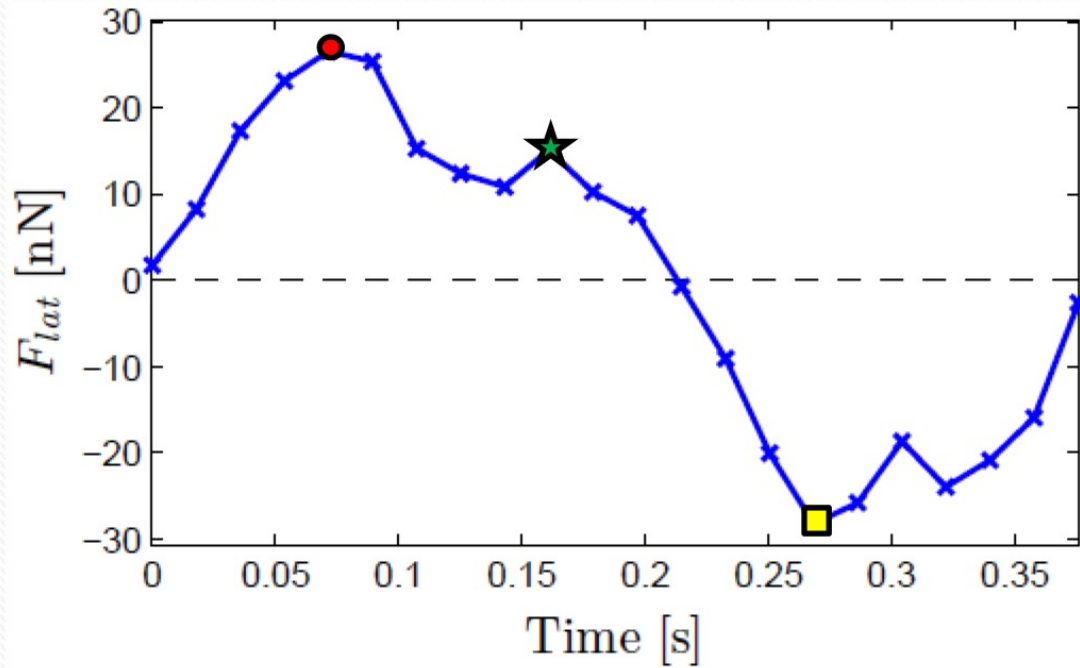




# Lateral Force Measurement



# Lateral Force Measurement





# Lateral Force Measurement

