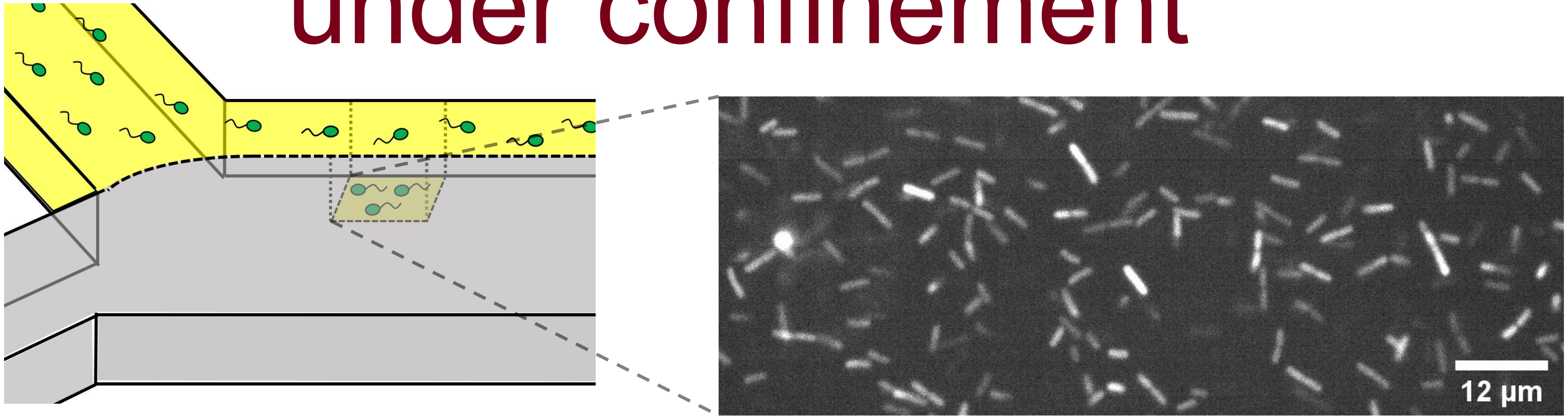
Rheology of bacterial suspensions under confinement



Zhengyang Liu

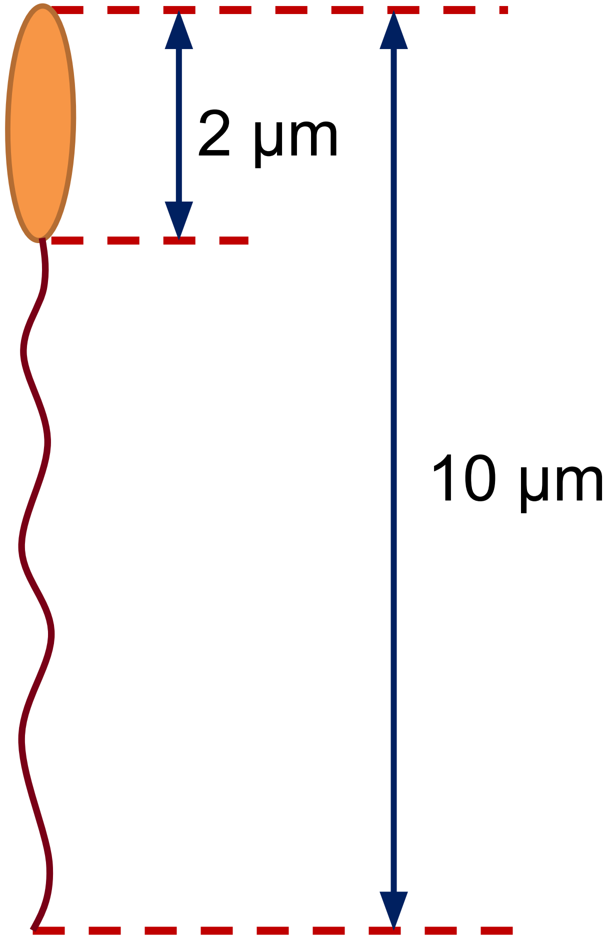
Advisor: Xiang Cheng

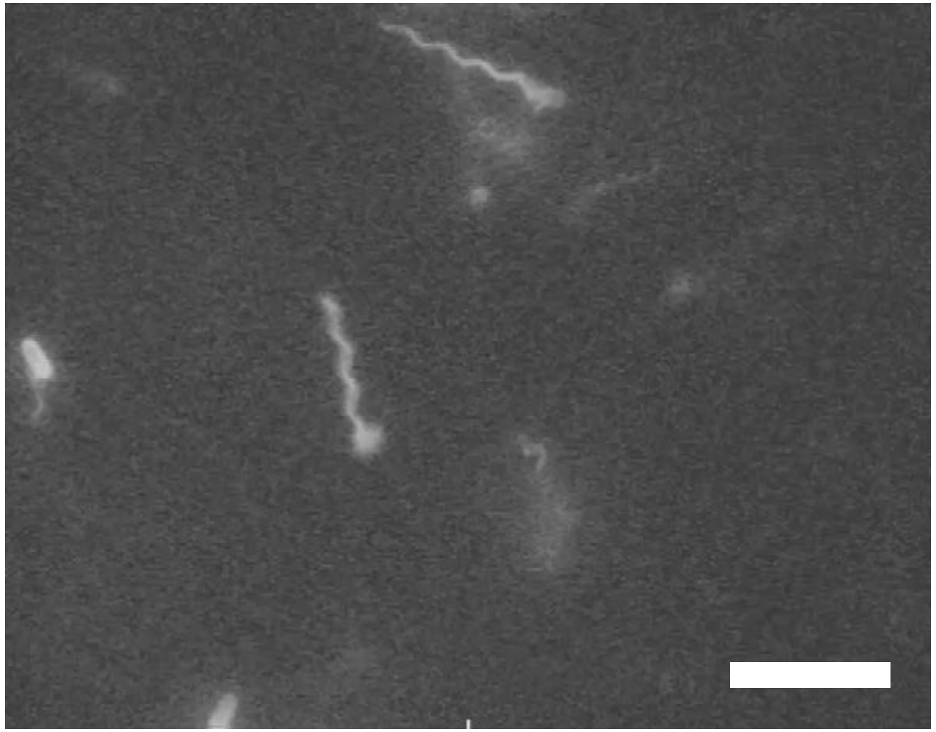
91st Society of Rheology Meeting, Raleigh, 2019

University of Minnesota

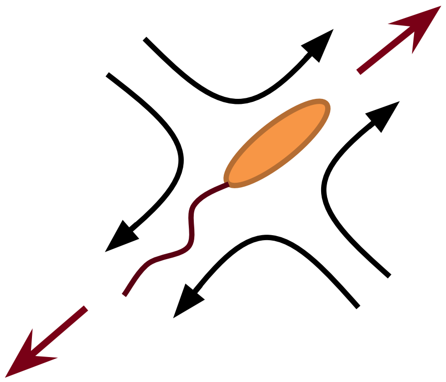
CEMS | Chemical Engineering & Materials Science

E. coli – a model pusher swimmer



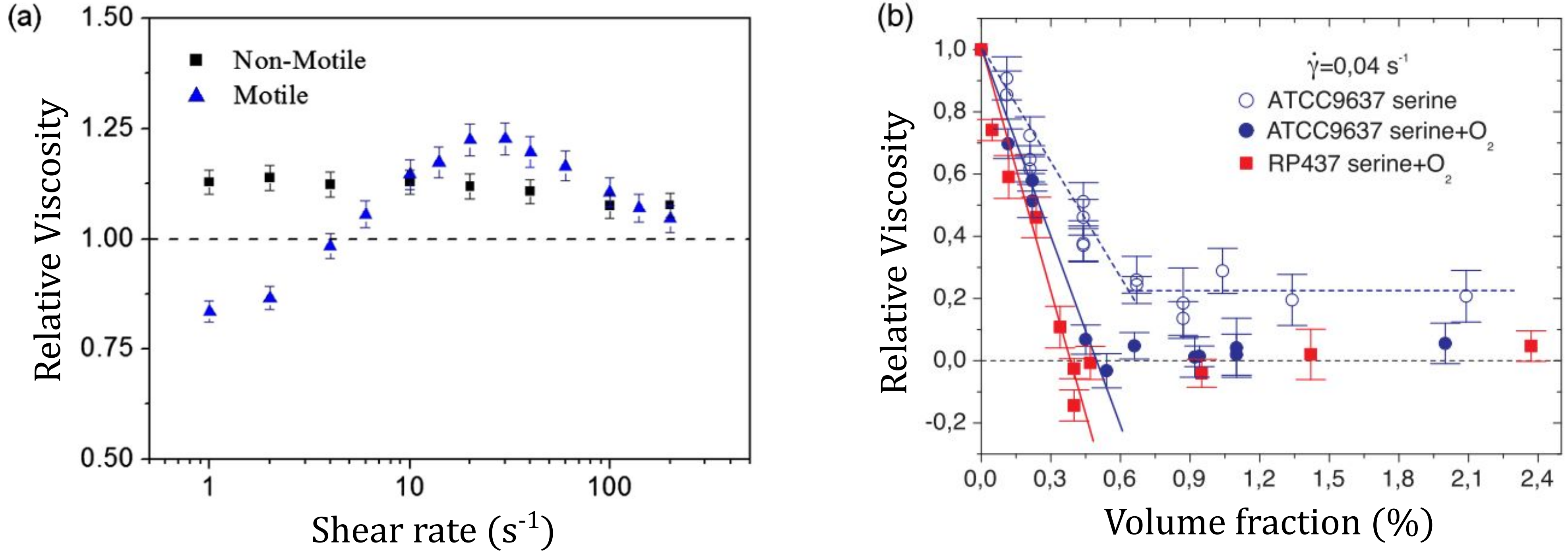


Turner et al., *J. Bacteriol.*, 2000 (Scale bar = 10 µm)



pusher flow field

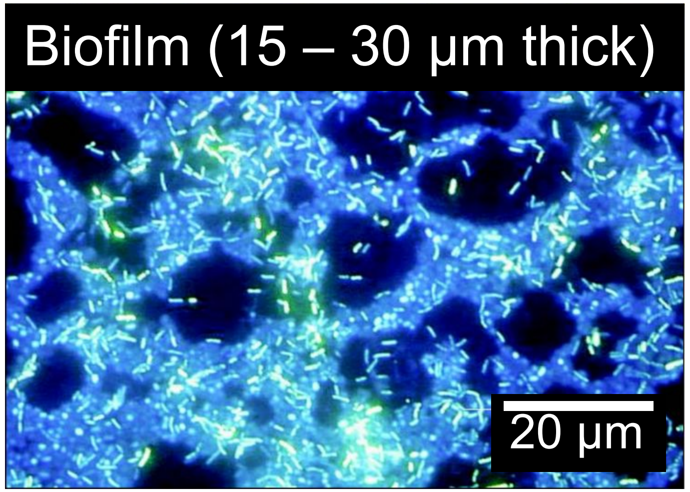
Pushers reduce viscosity of bulk suspensions



- In contrast to passive particle suspensions, bacteria can **reduce** the viscosity of their suspending fluids
- Zero apparent viscosity "bacterial superfluid" can be achieved

Bacterial suspensions under confinement

Natural processes

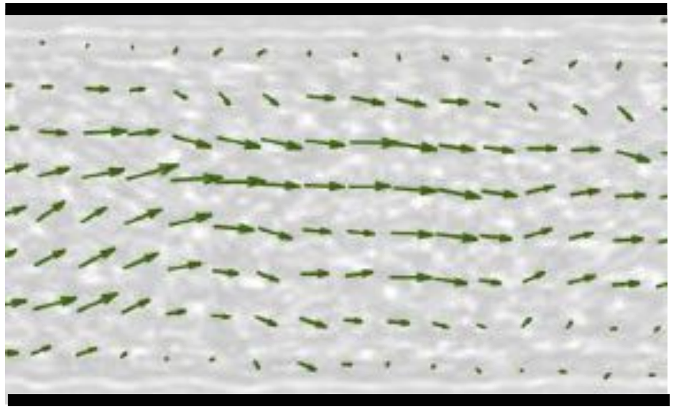


Donlan, *Emerg. Infect. Dis.*, 2002

https://sustainablepulse.com

Fundamental interest

Lushi et al., *PNAS*, 2014



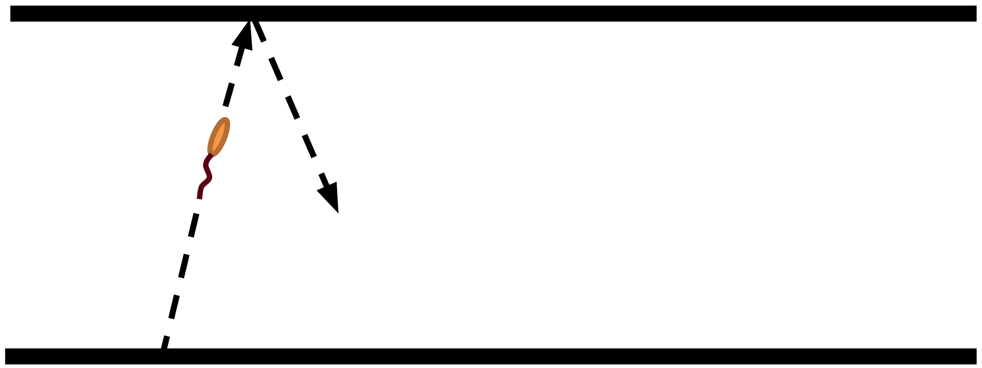
Wioland et al., *New J. Phys.*, 2016

Bacterial dynamics under confinement

- Competing length scales

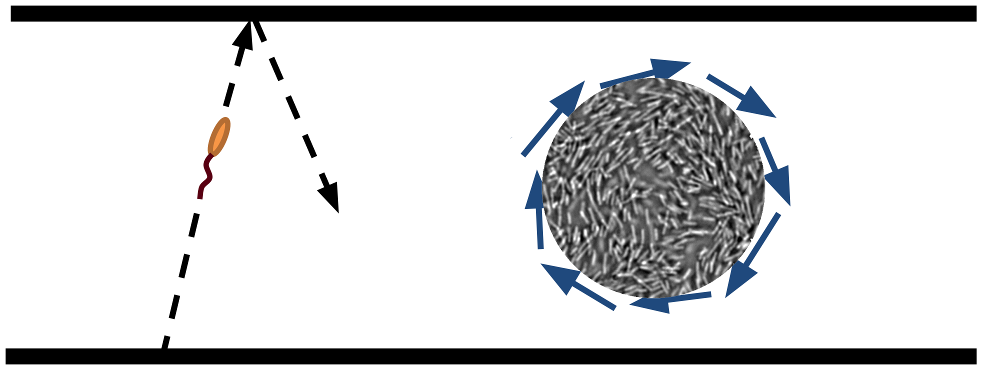
Bacterial dynamics under confinement

- Competing length scales
  - **run length**



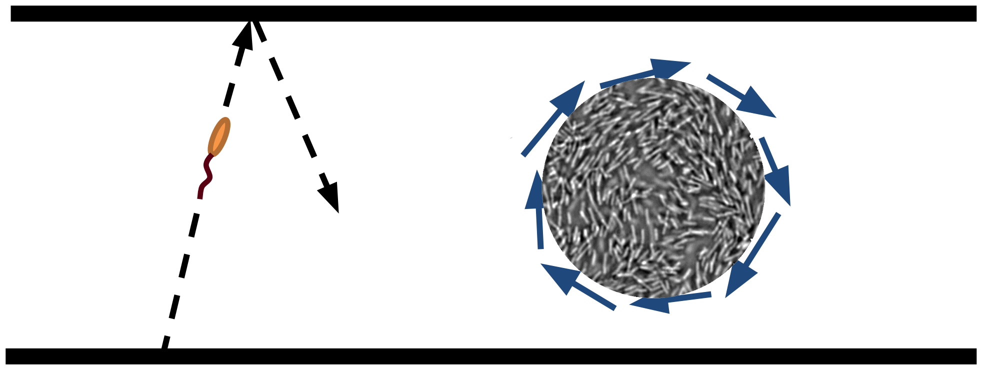
Bacterial dynamics under confinement

- Competing length scales
  - run length
  - **vortex size**



Bacterial dynamics under confinement

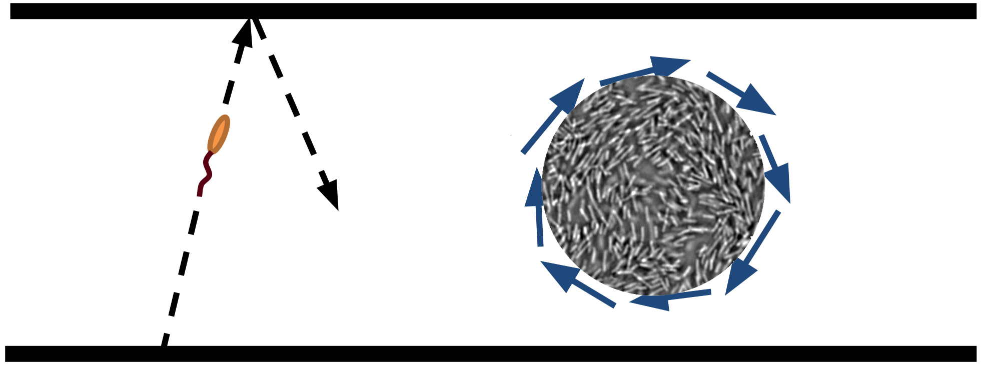
- Competing length scales
  - run length
  - vortex size
- Swimmer-boundary Interaction

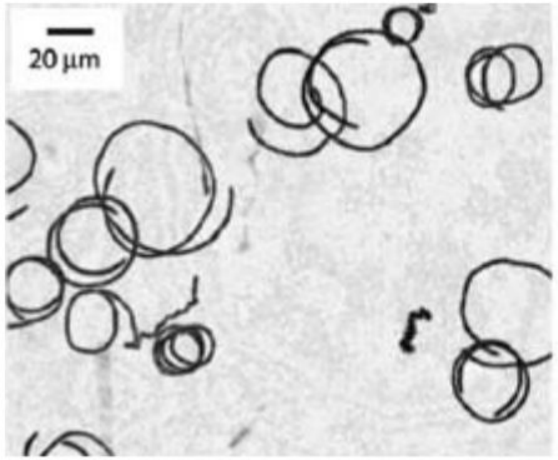


Bacterial dynamics under confinement

- Competing length scales
  - run length
  - vortex size

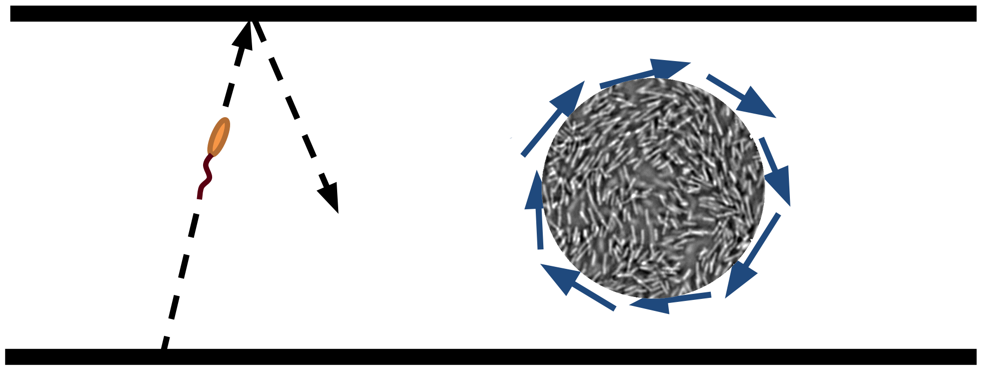
- Swimmer-boundary Interaction
  - **hydrodynamic trapping**

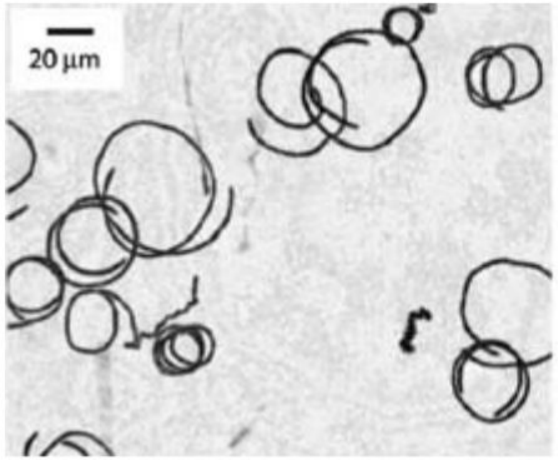


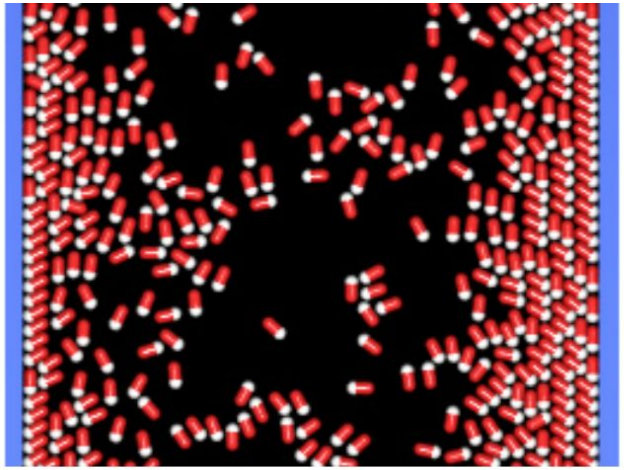


Bacterial dynamics under confinement

- Competing length scales
  - run length
  - vortex size
- Swimmer-boundary Interaction
  - hydrodynamic trapping
  - **upstream swimming**







Bacterial dynamics under confinement

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  - run length
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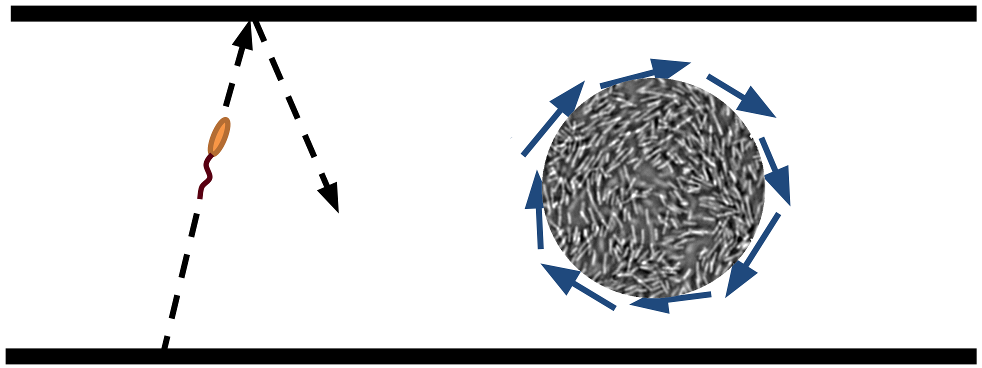
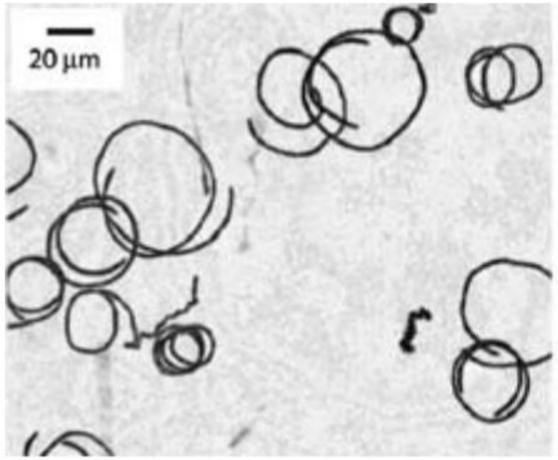
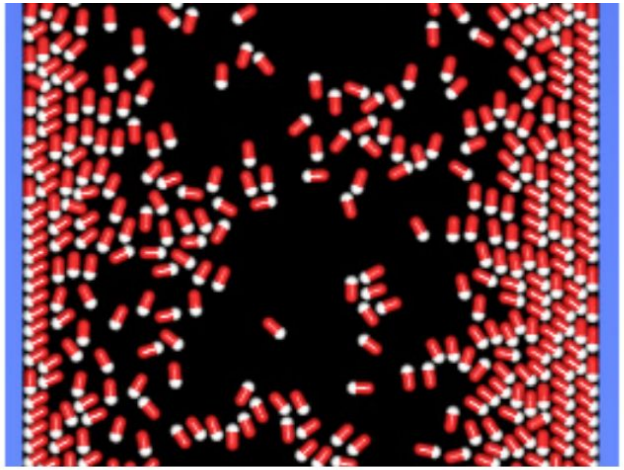


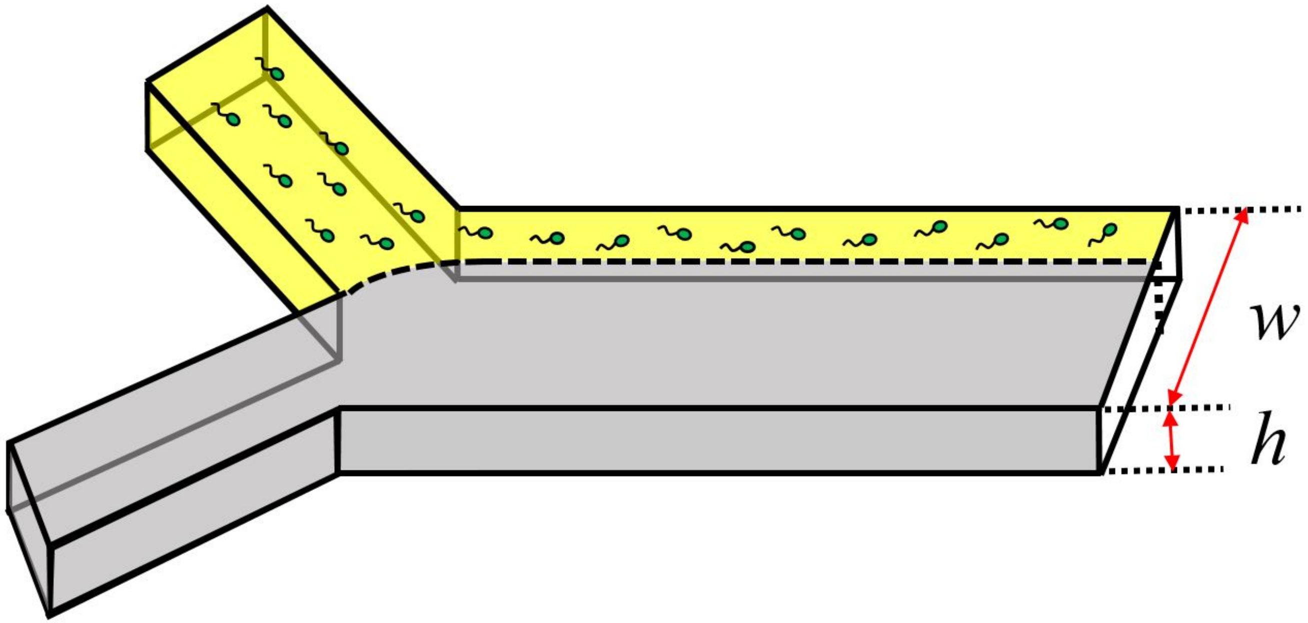
- Swimmer-boundary Interaction
  - hydrodynamic trapping
  - upstream swimming



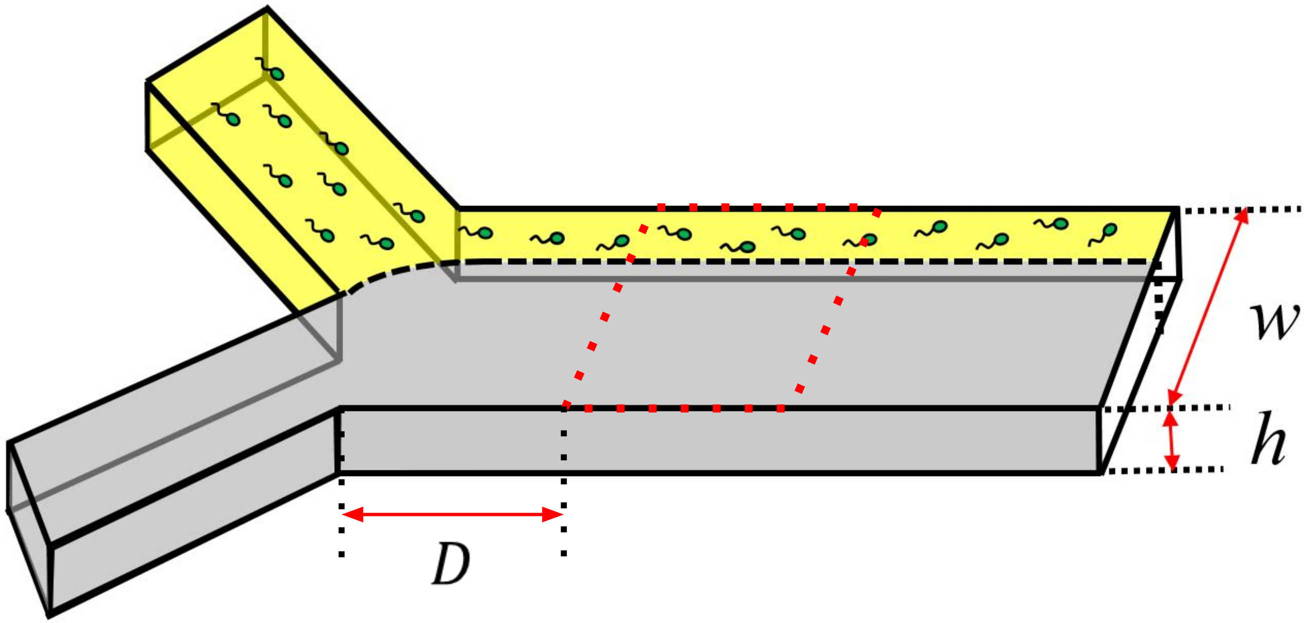


Different rheology under confinement?

Microfluidic channel viscometer



Microfluidic channel viscometer



$w = 600\ \mu\text{m}$

$h = 25\sim128\ \mu\text{m}$

$D = 500\sim1000\ \mu\text{m}$

$n = 1.6 \times 10^{10}\ \text{ml}^{-1}$

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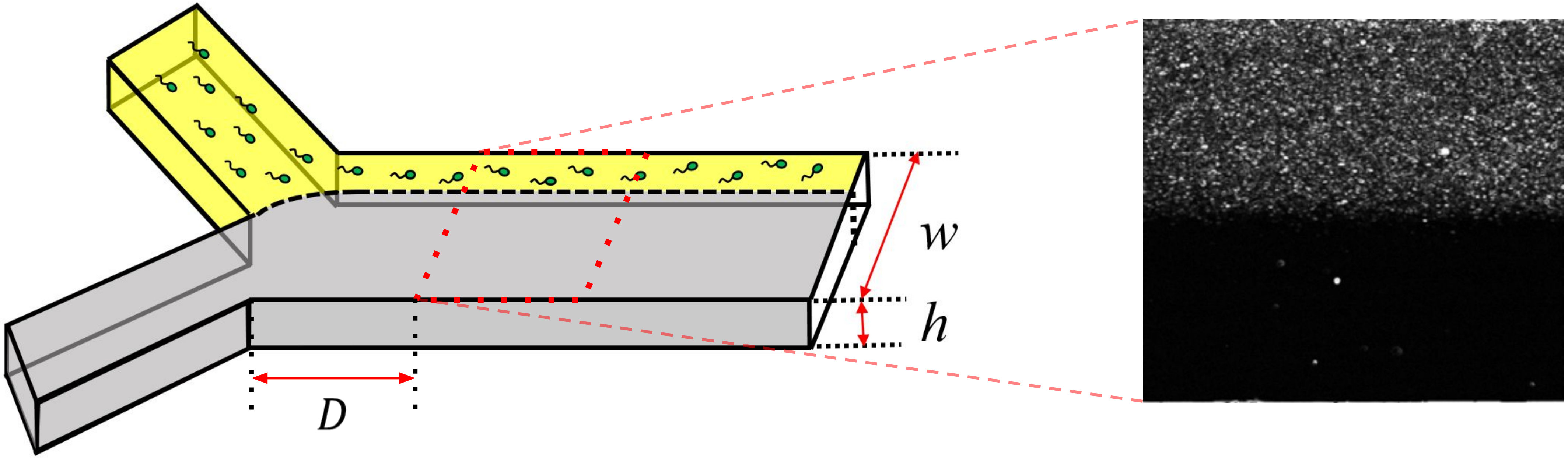

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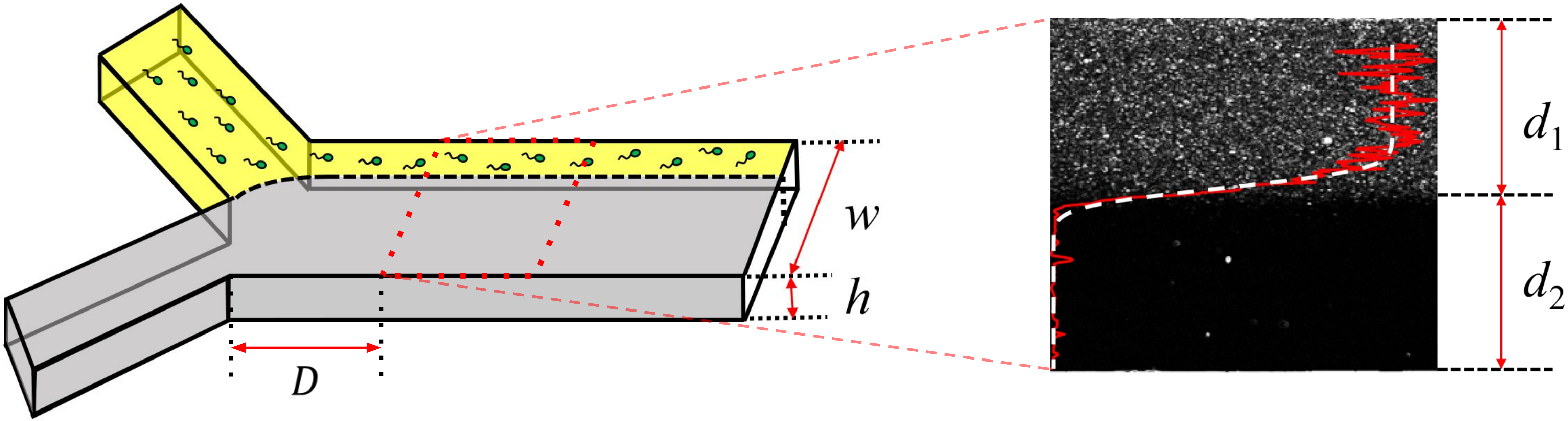

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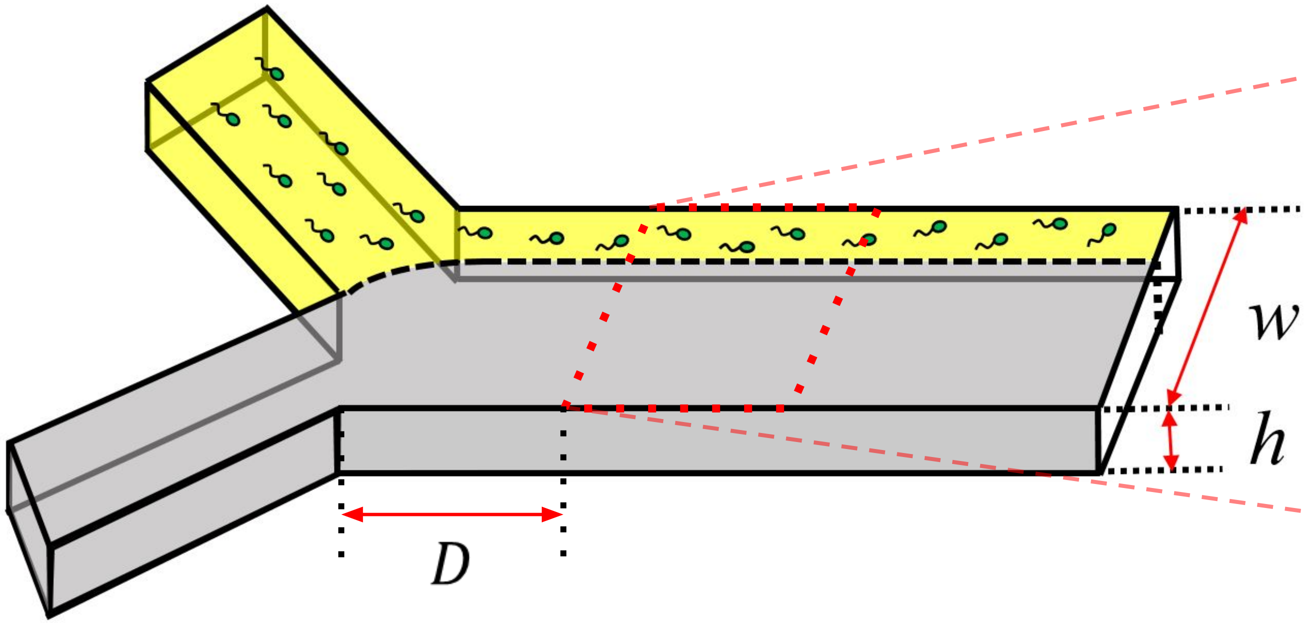

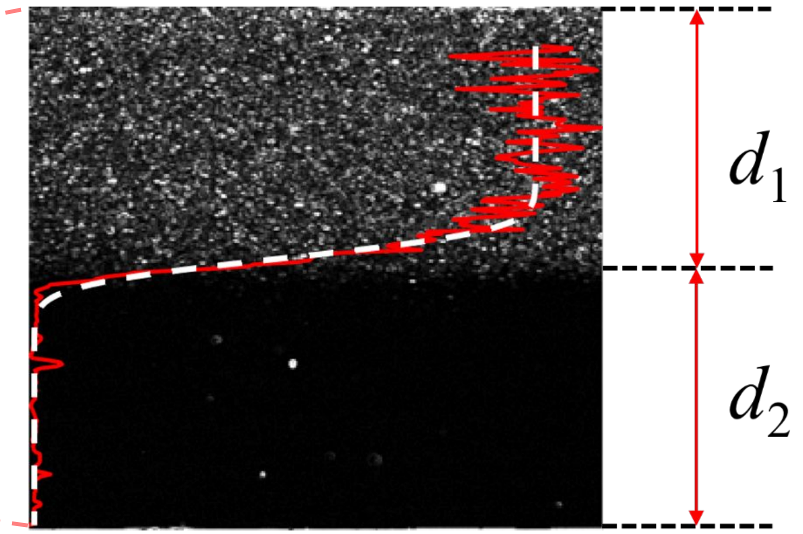

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$h = 25\sim128\ \mu m$
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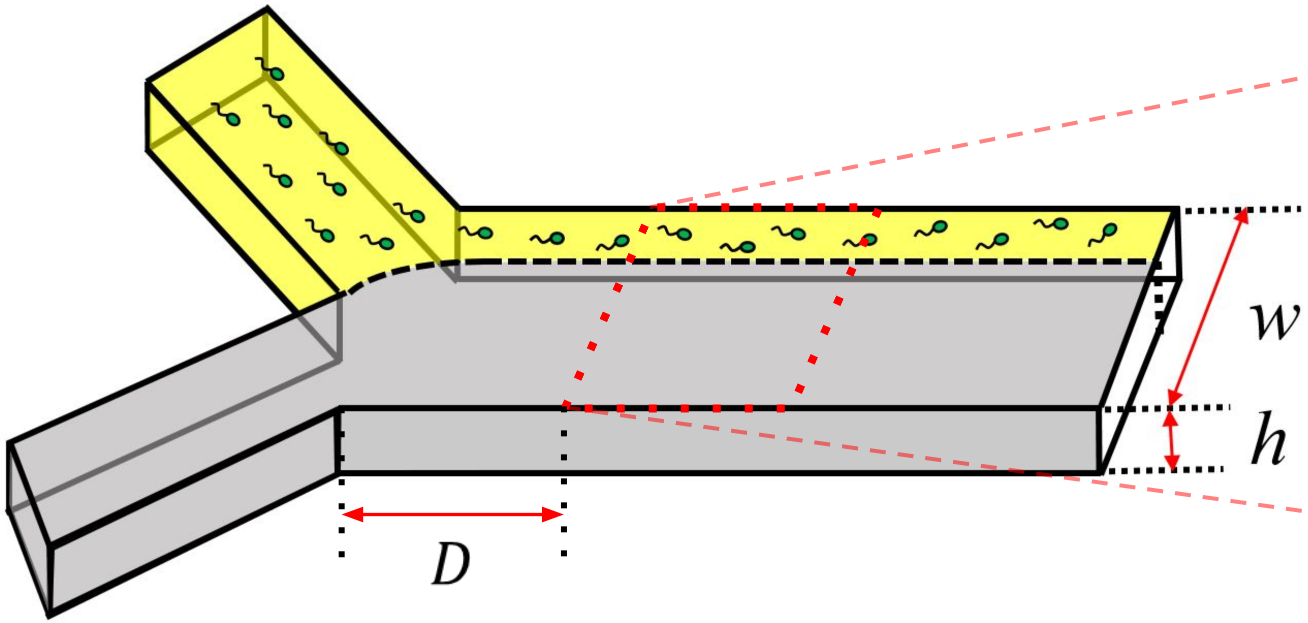
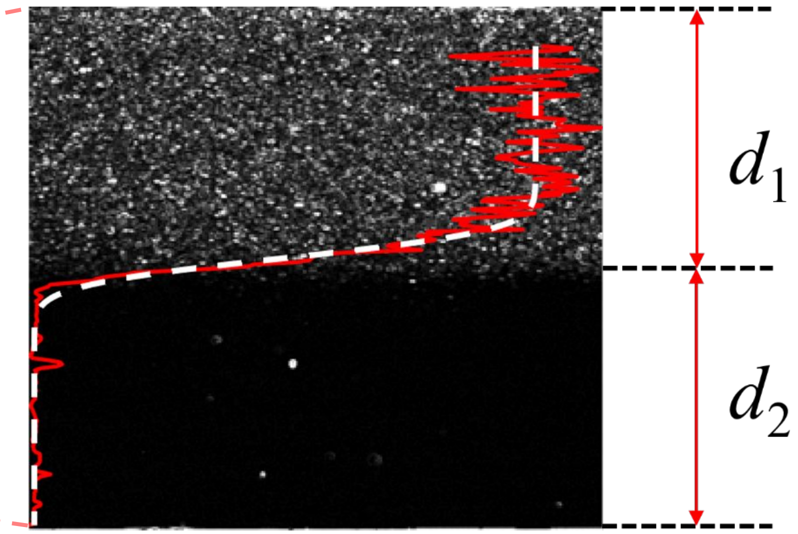
Relative viscosity $= \frac{\eta_1}{\eta_2} = \frac{d_1}{d_2}$

Microfluidic channel viscometer





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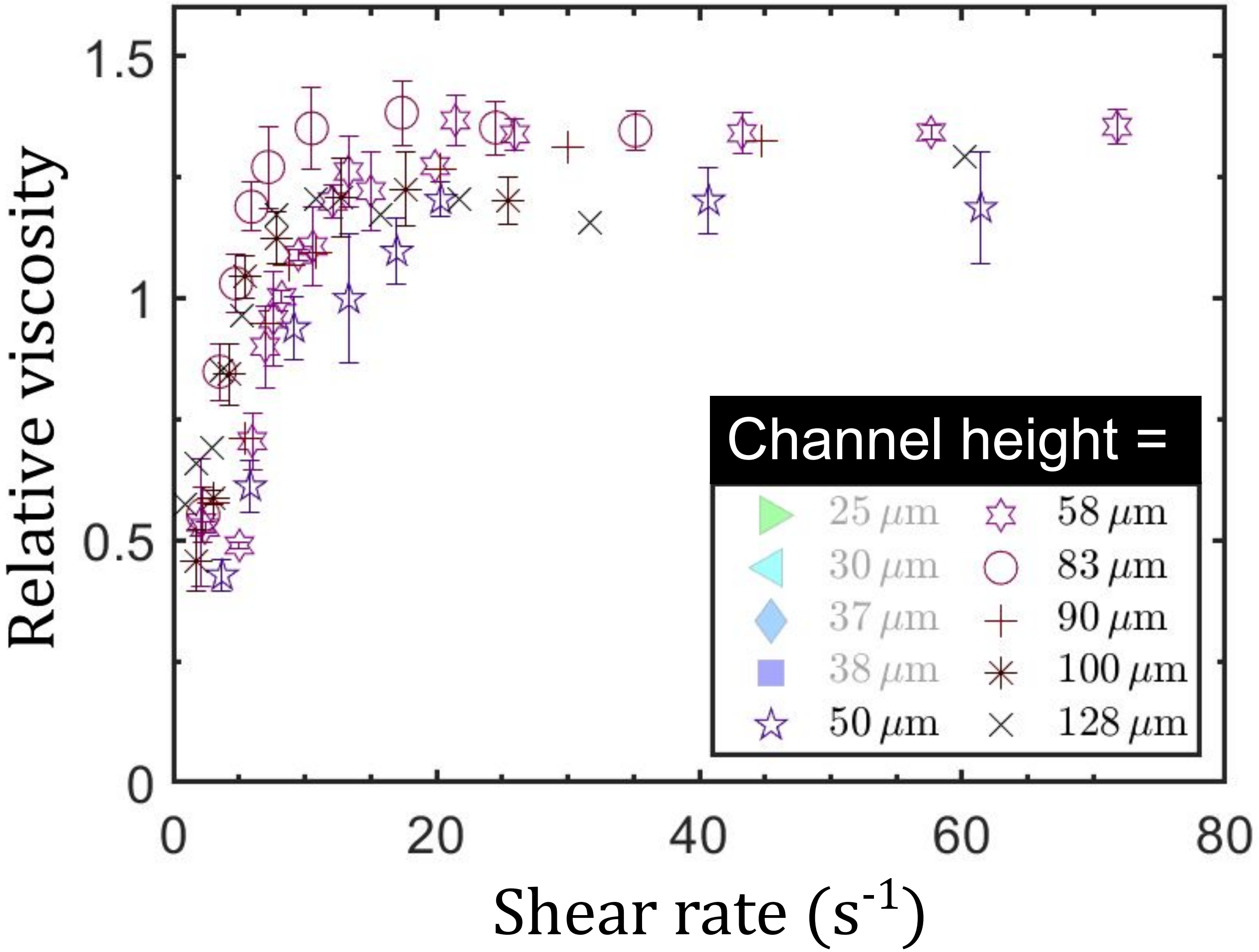
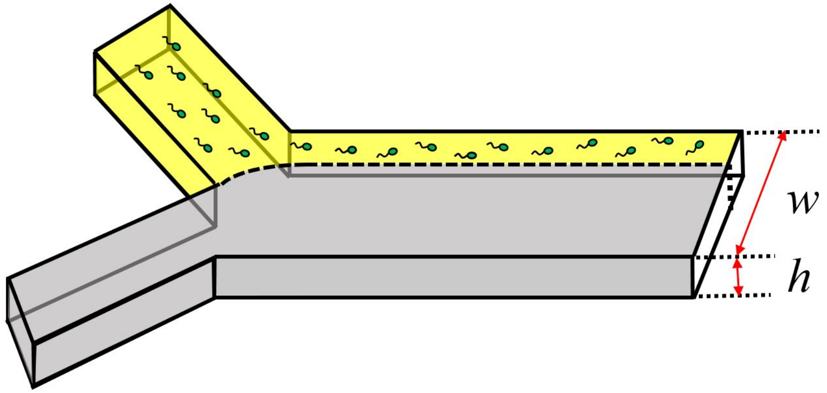
Relative viscosity $= \dfrac{\eta_1}{\eta_2} = \dfrac{d_1}{d_2}$

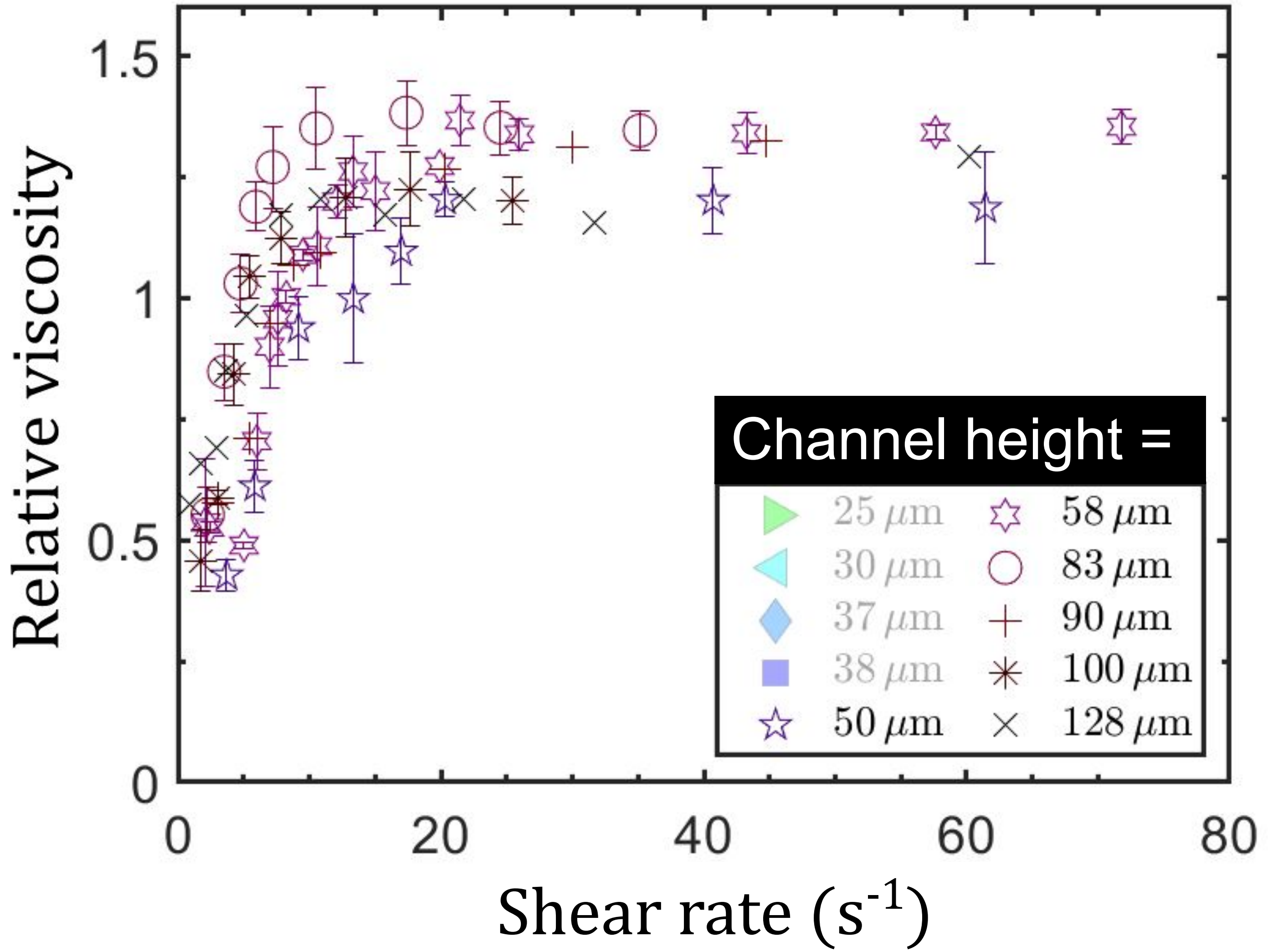
Viscosity under confinement

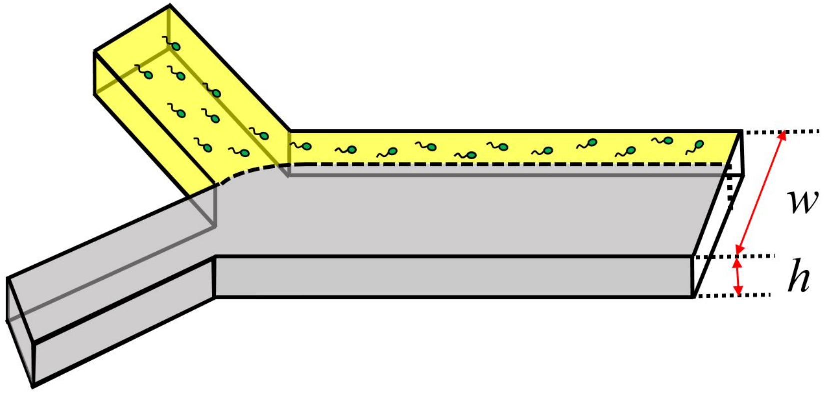




$h \geq 50\ \mu m$

Viscosity under confinement

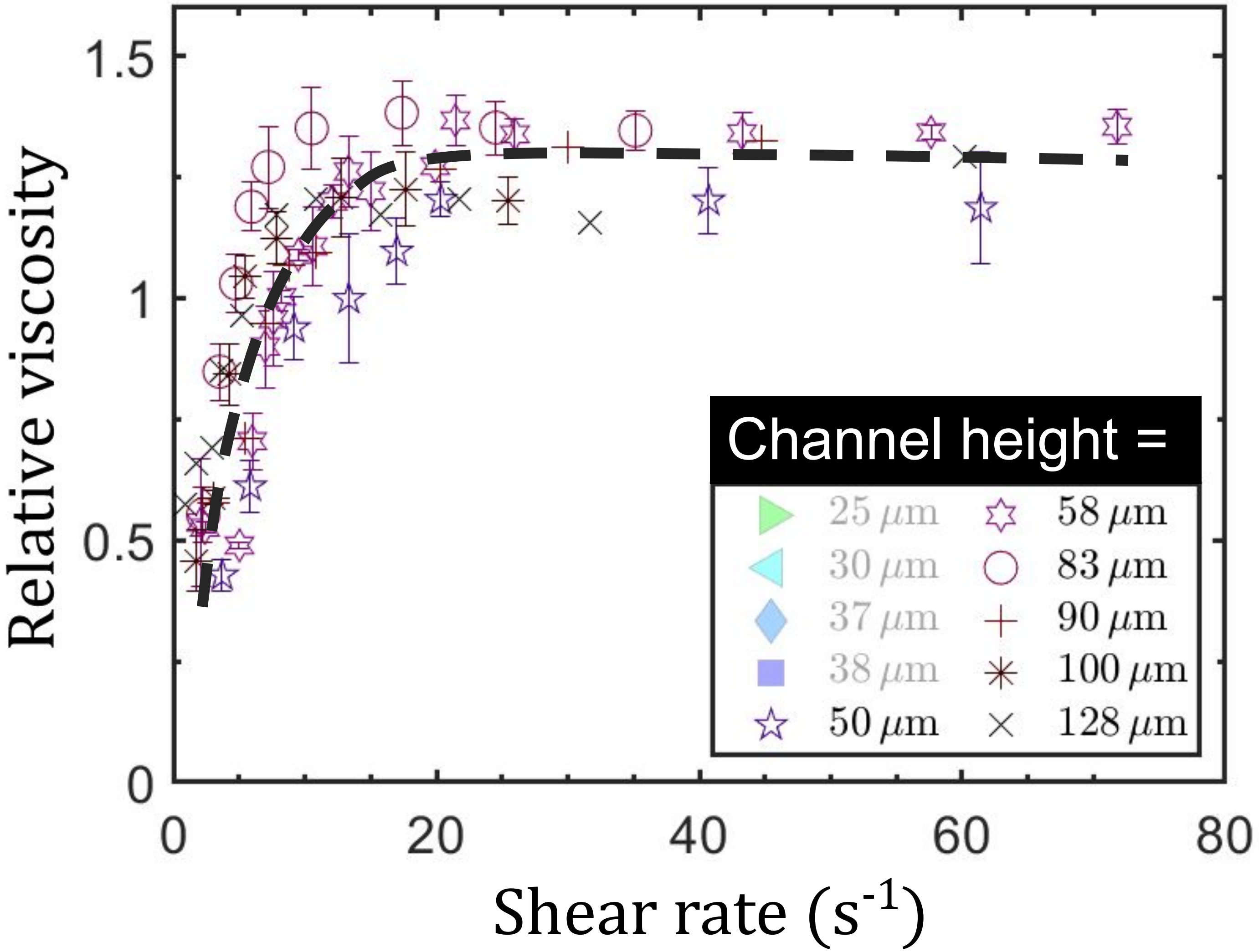


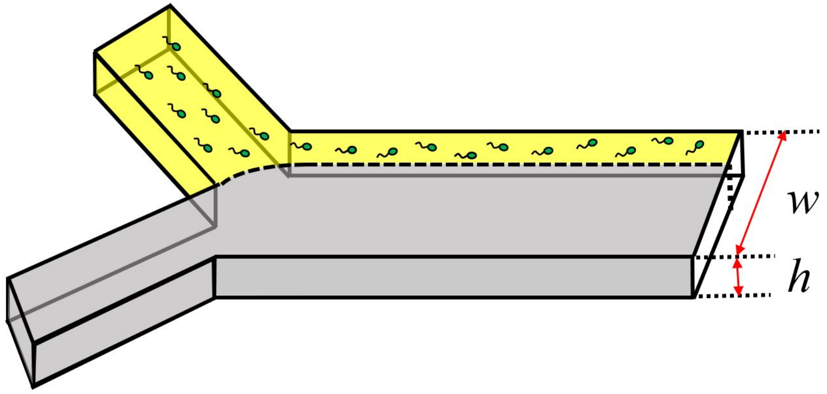


$h \geq 50\ \mu m$

- Viscosity reduction at low shear rate

Viscosity under confinement

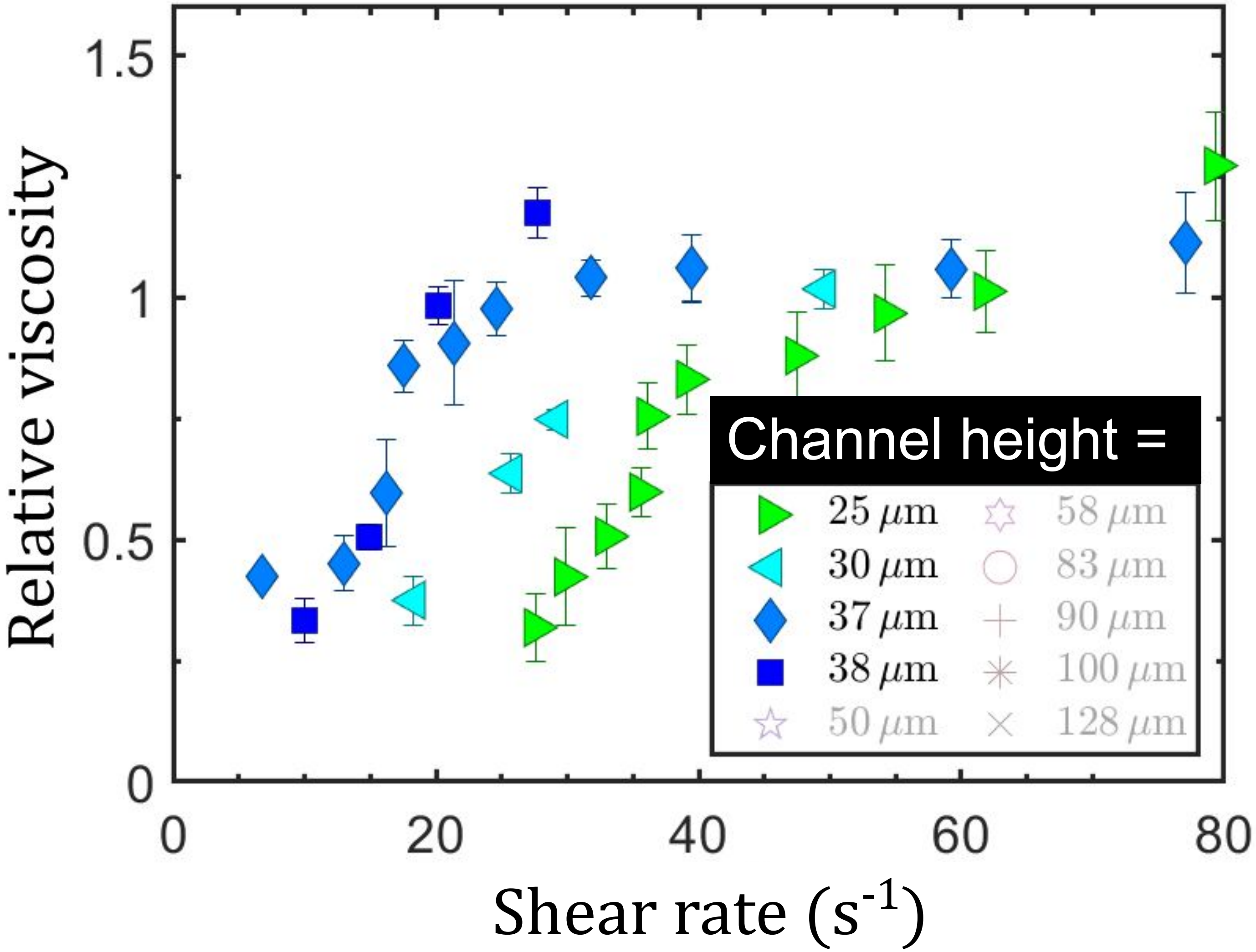


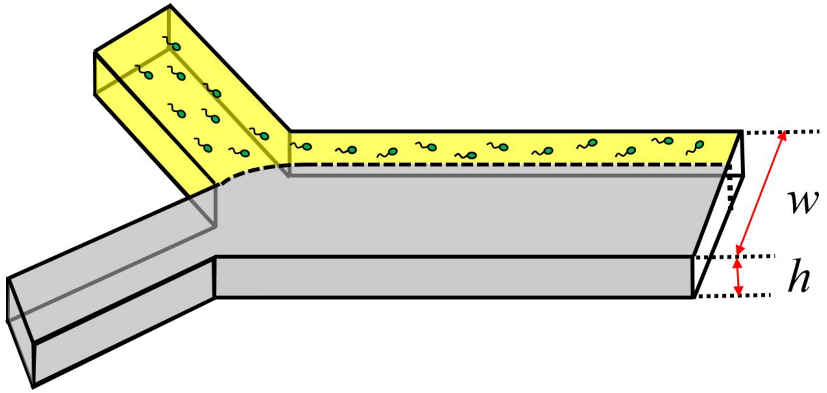


$h \geq 50\ \mu m$

- Viscosity reduction at low shear rate
- Fall on a same master curve: no confinement effect

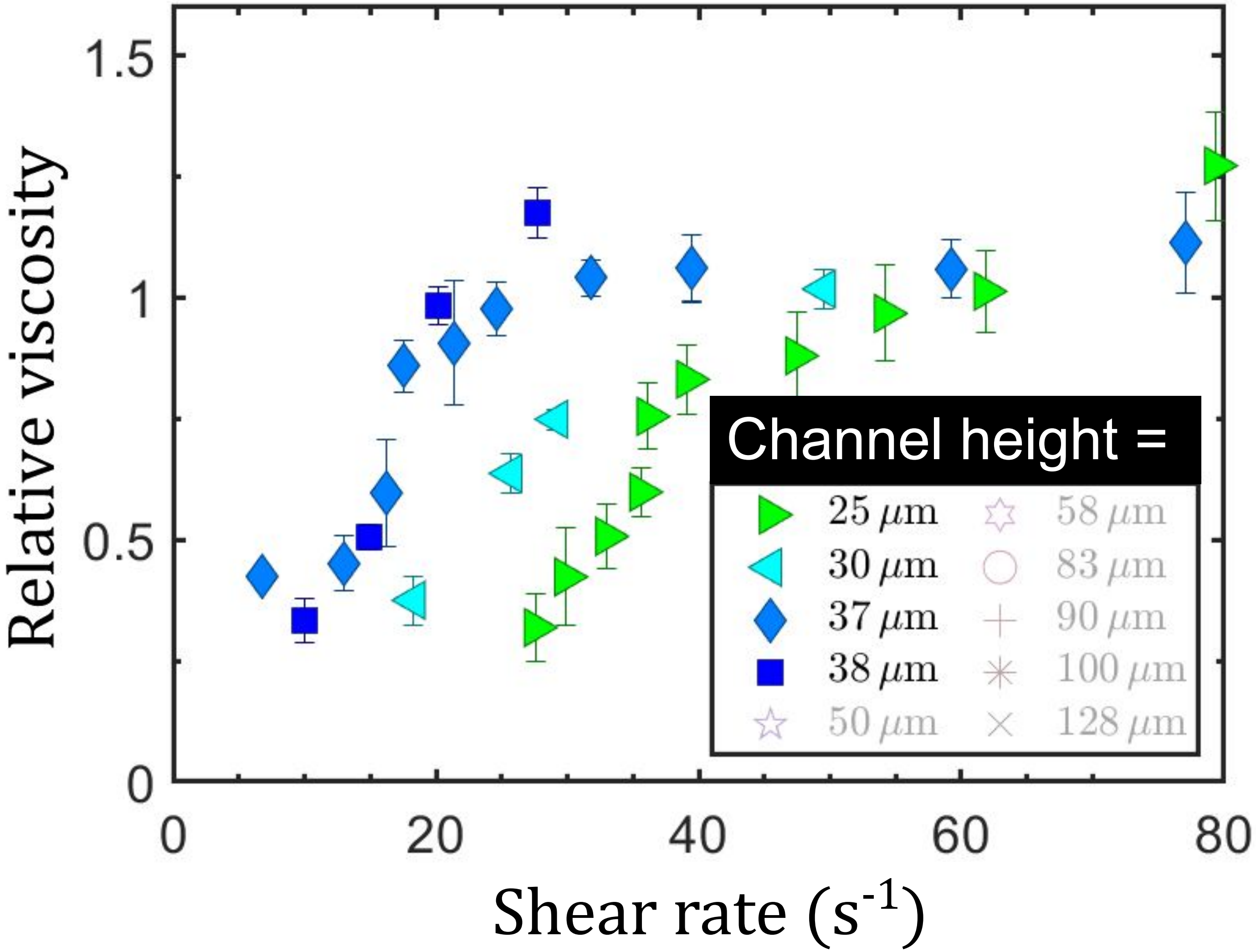
Viscosity under confinement

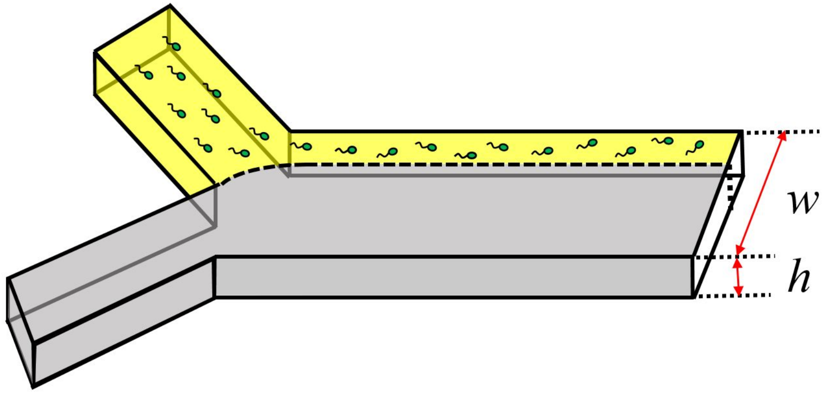




$h < 50\ \mu m$

Viscosity under confinement

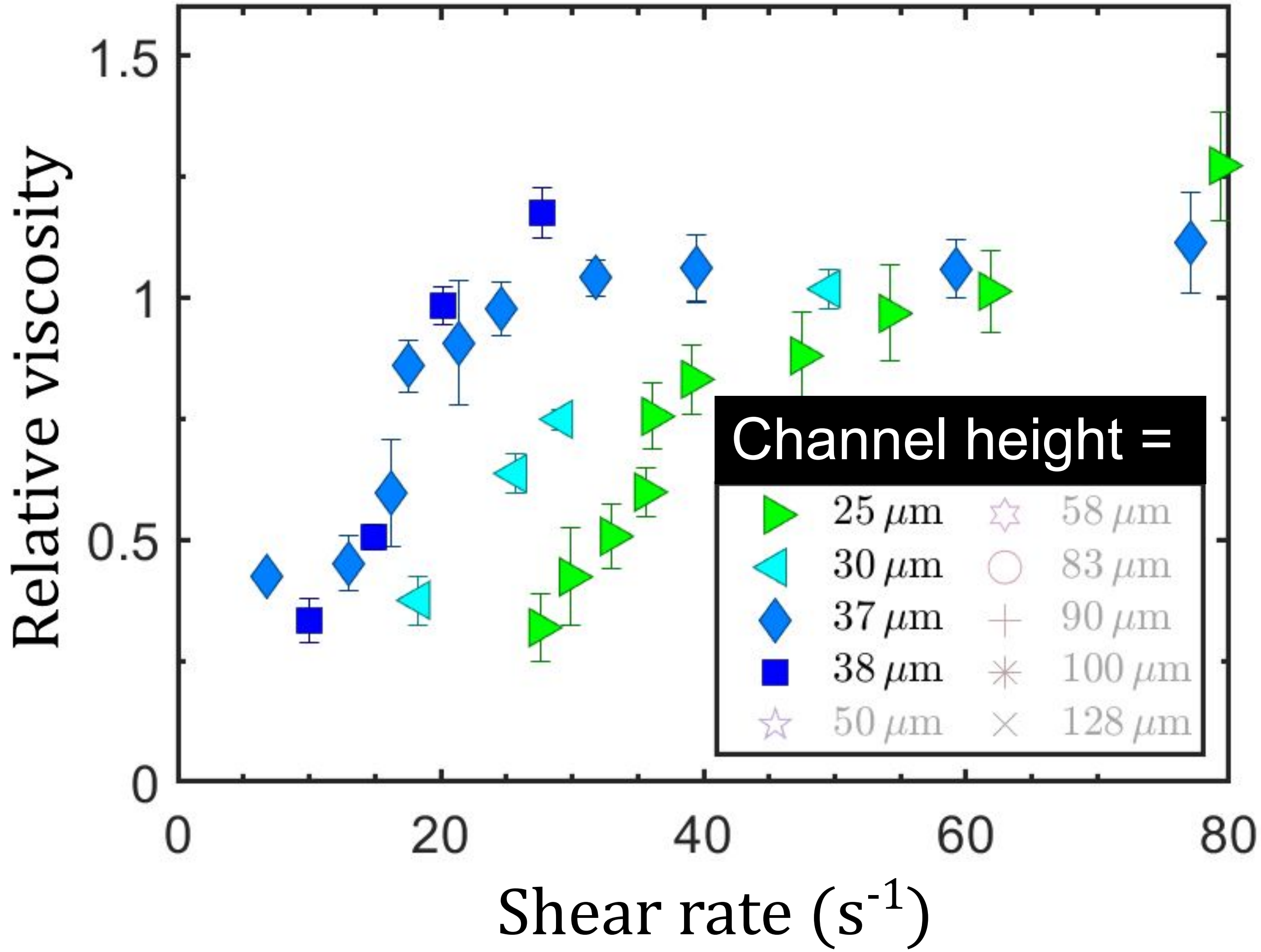


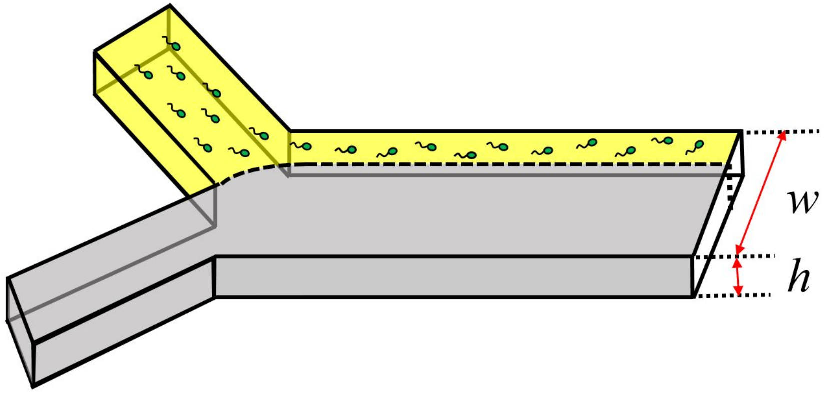


$h < 50\ \mu m$

- Viscosity reduction at low shear rate

Viscosity under confinement

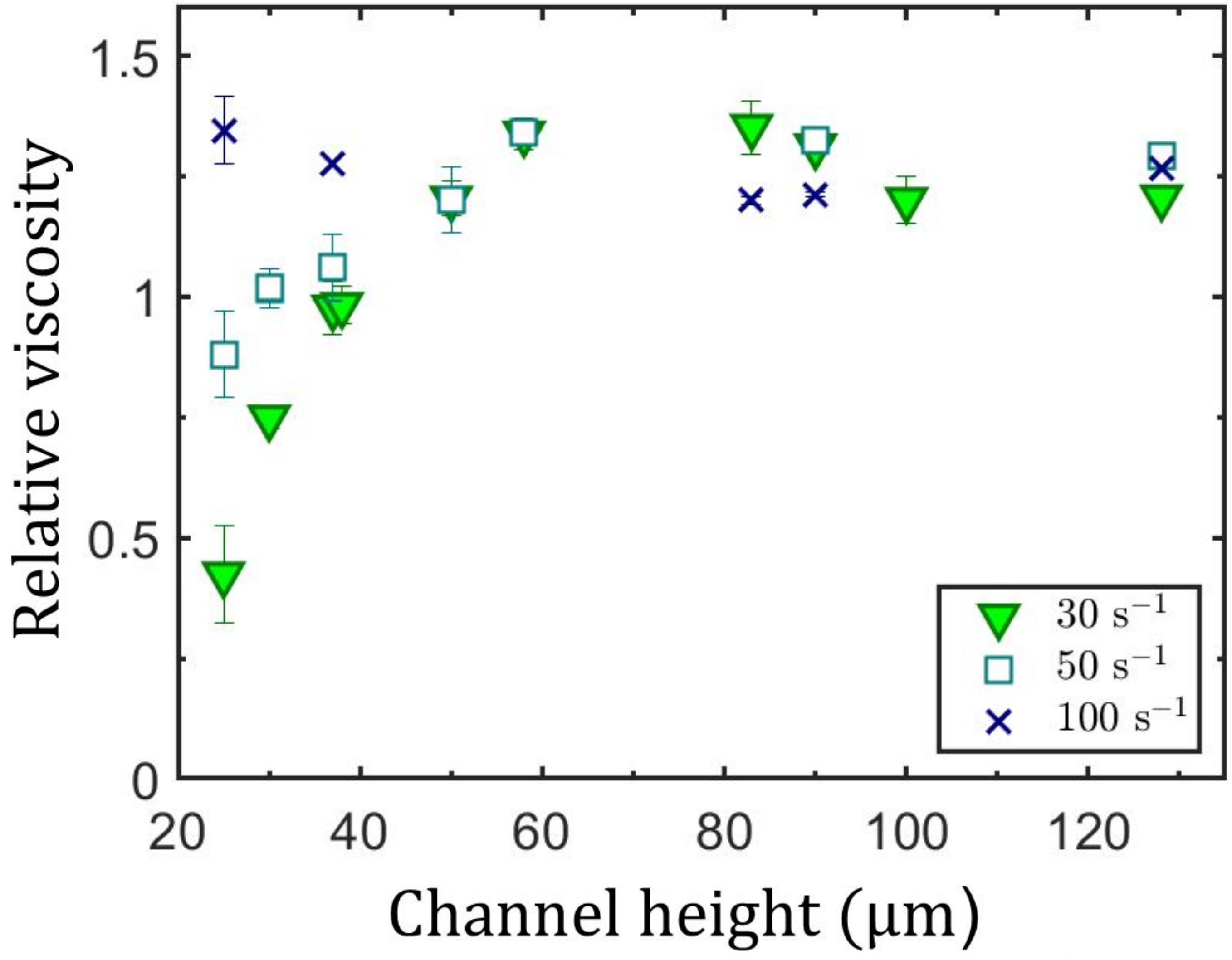




$h < 50\ \mu m$

- Viscosity reduction at low shear rate
- Separated: a sign of confinement effect

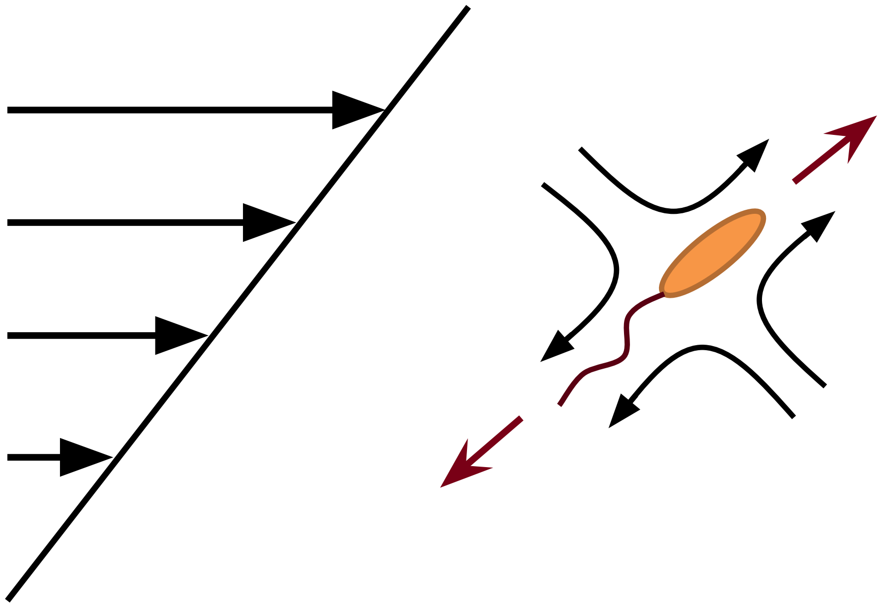
Viscosity under confinement



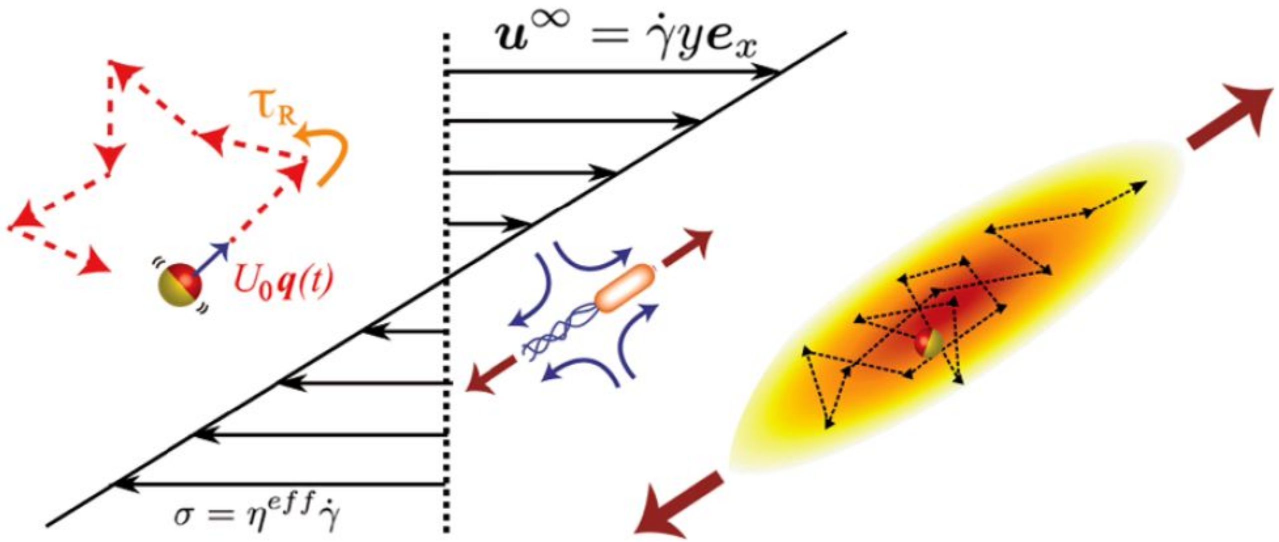
- At low shear rate, confinement **reduces** viscosity

- At high shear rate, viscosity is **independent** of confinement

Existing mechanisms for bulk suspensions



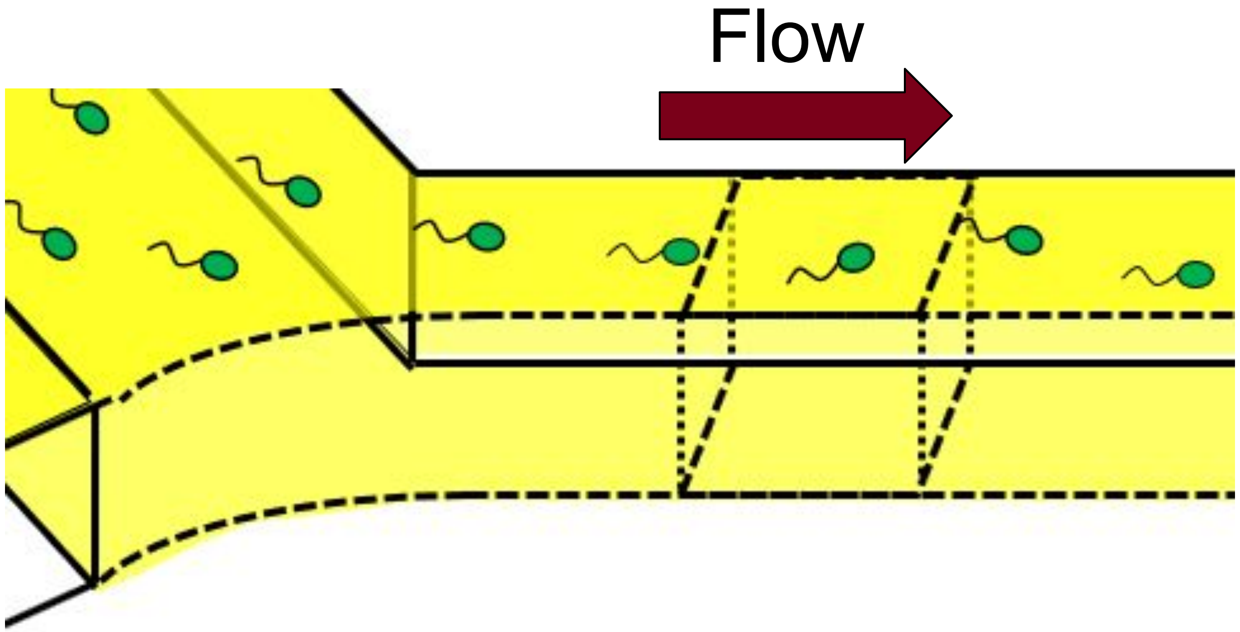
hydrodynamic stress



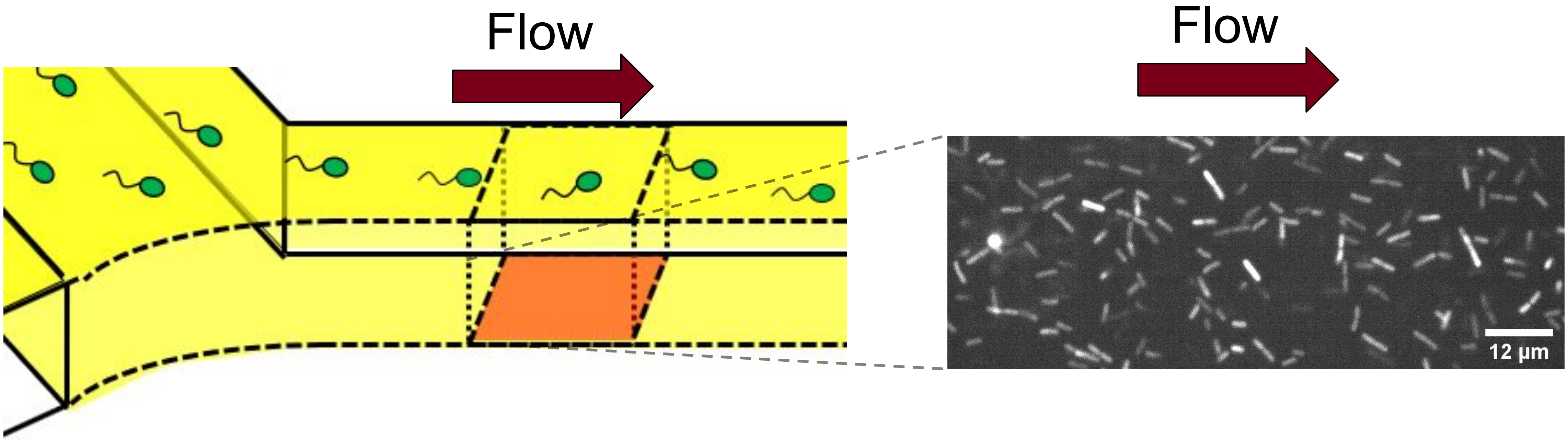
$$\sigma_{xy}^{\mathrm{swim}} = -n\zeta D_{xy}^{\mathrm{swim}}$$

swim stress

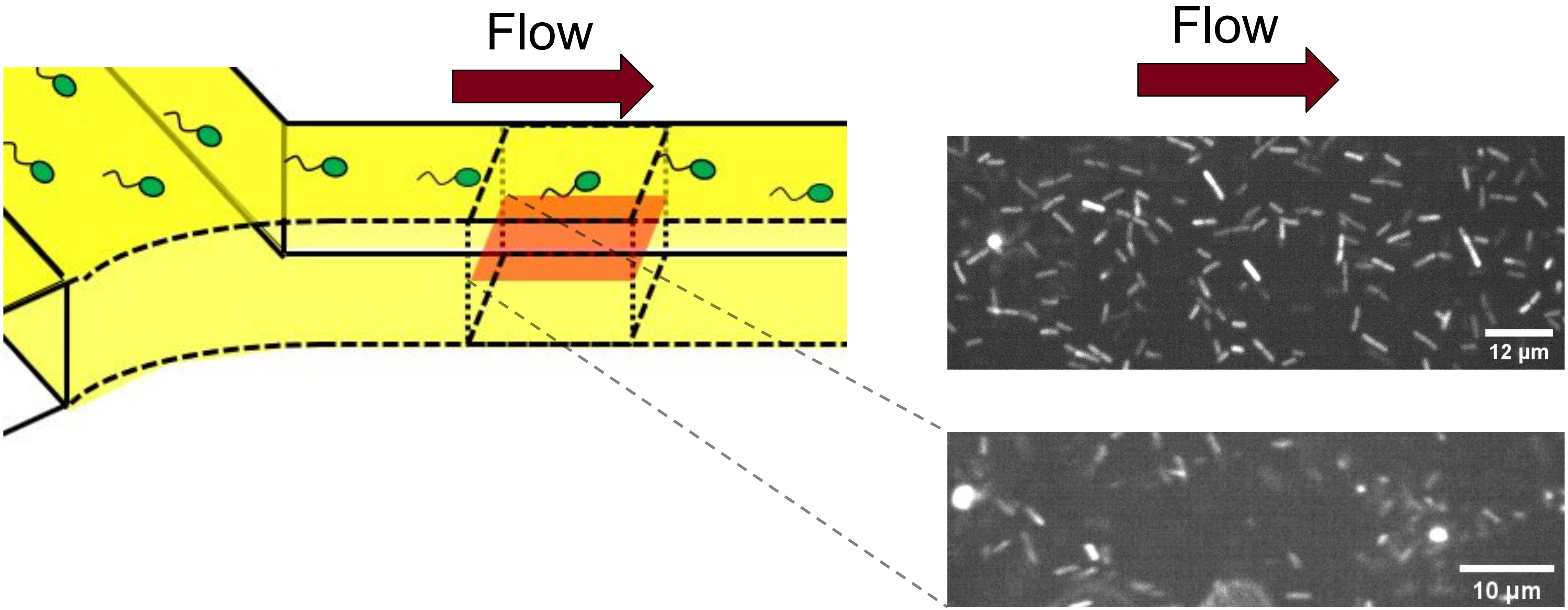
Relative motion near boundary



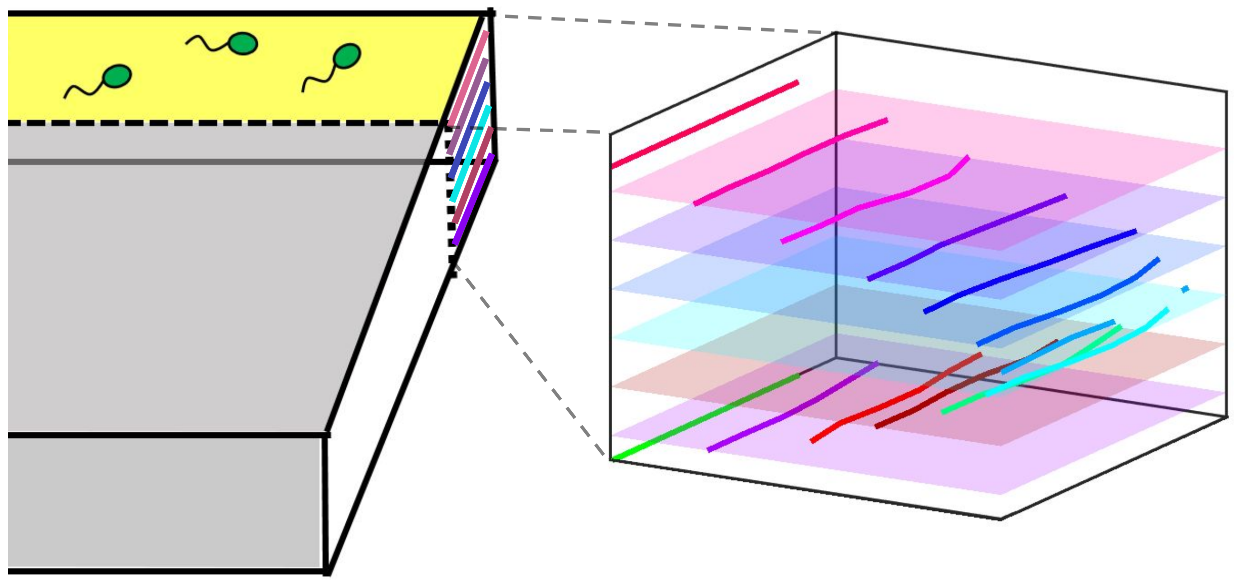
Relative motion near boundary



Relative motion near boundary

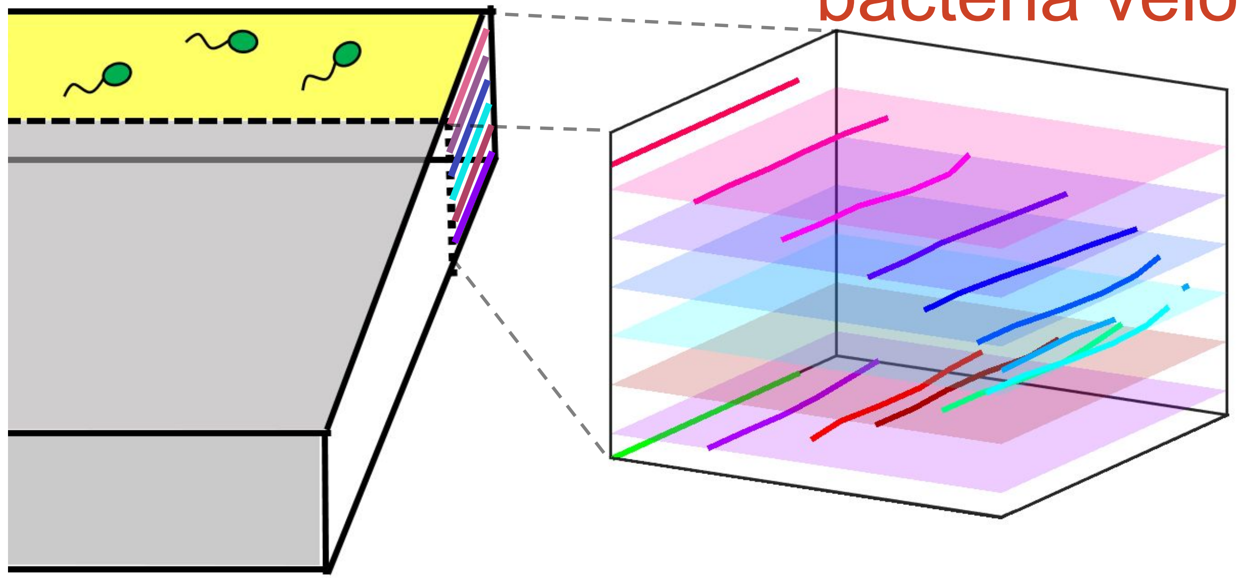


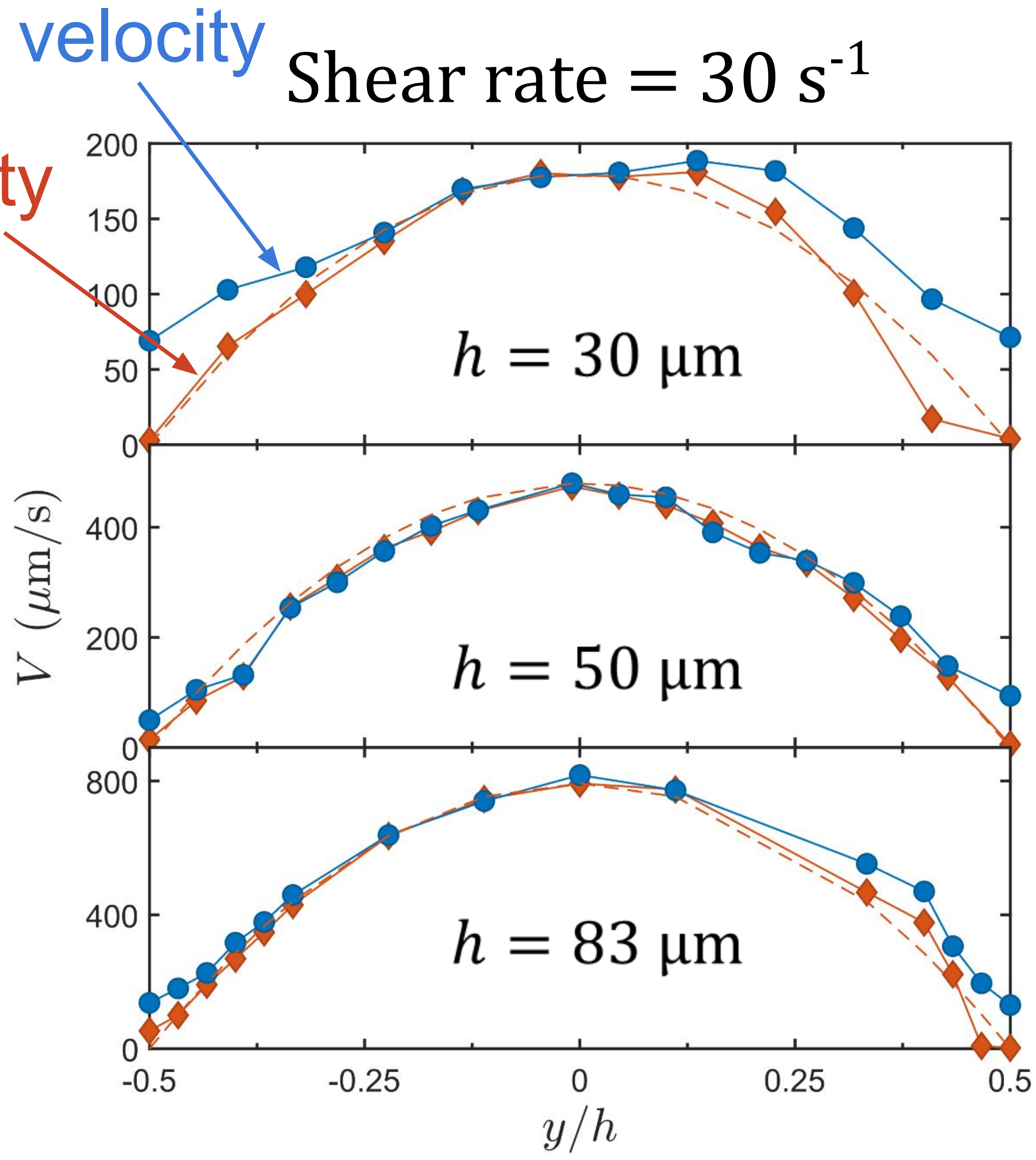
Velocity profile



Get velocity profile by imaging layer by layer using confocal microscopy

Velocity profile





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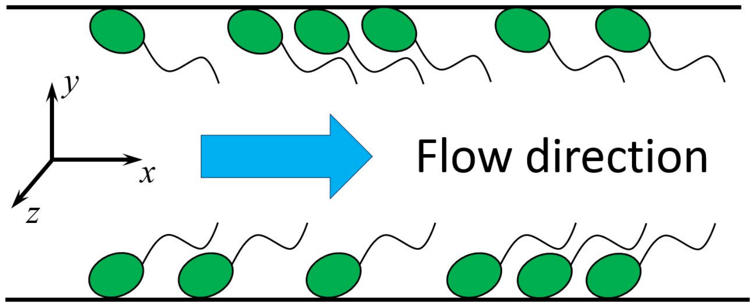
Boundary bacteria push fluid forward



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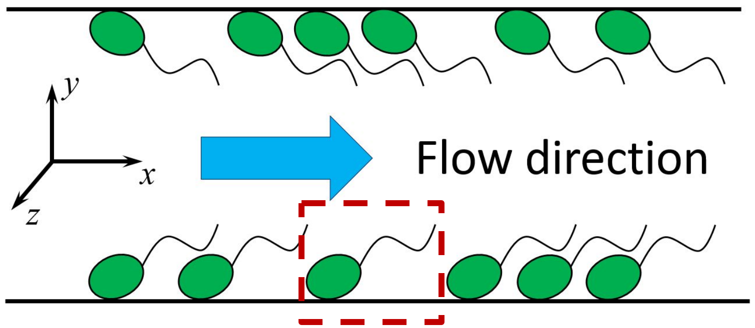
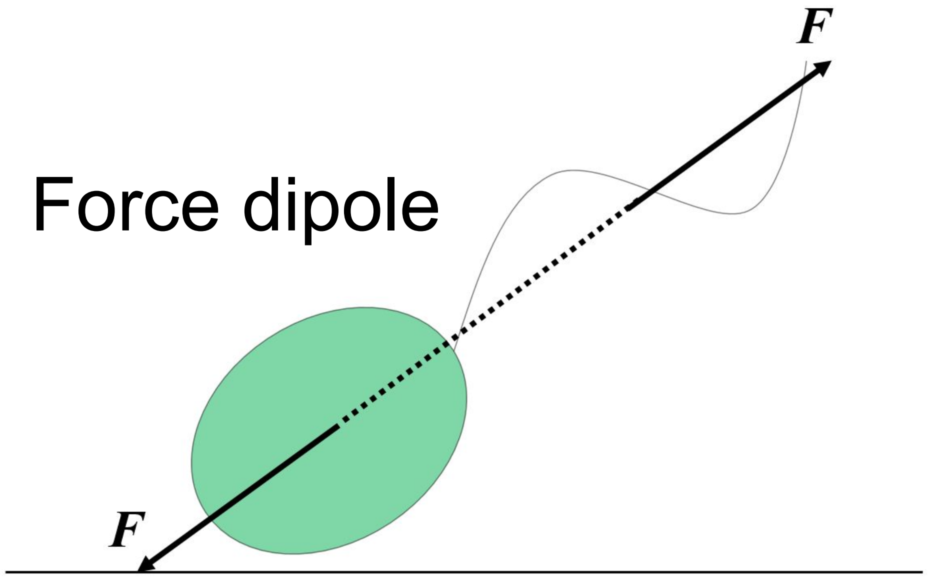


Force dipole



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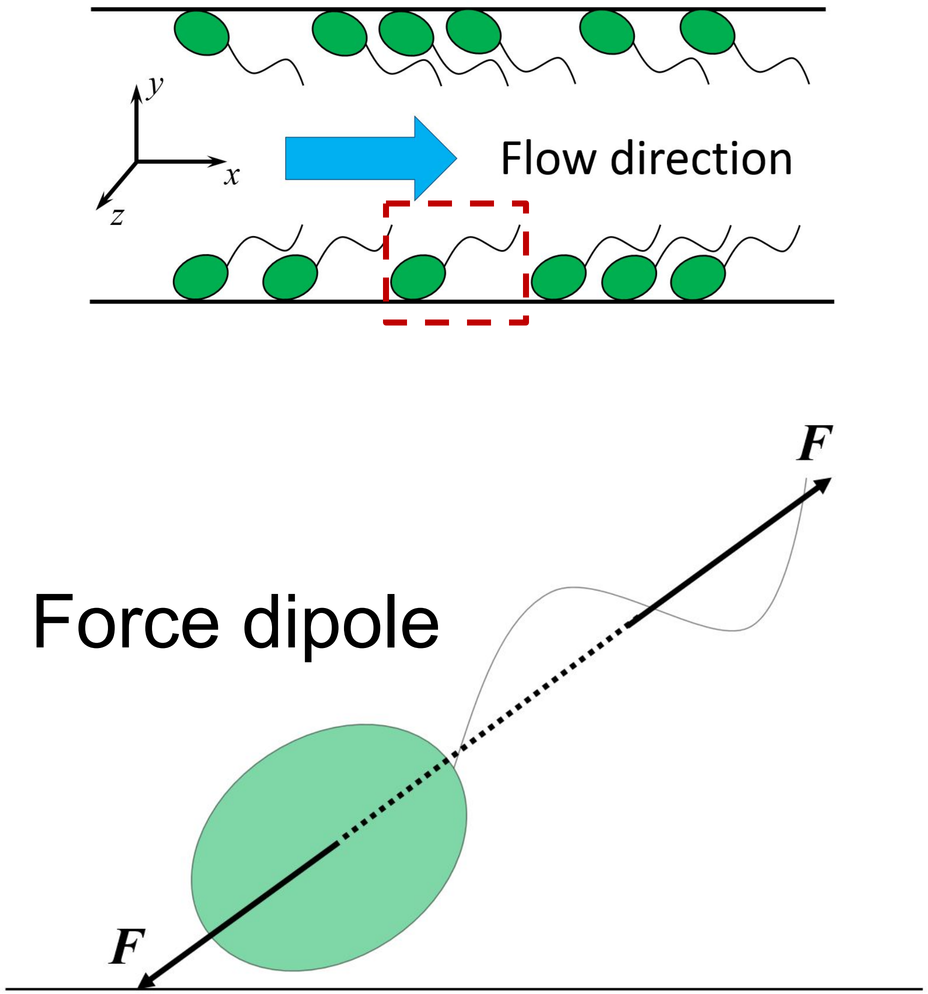

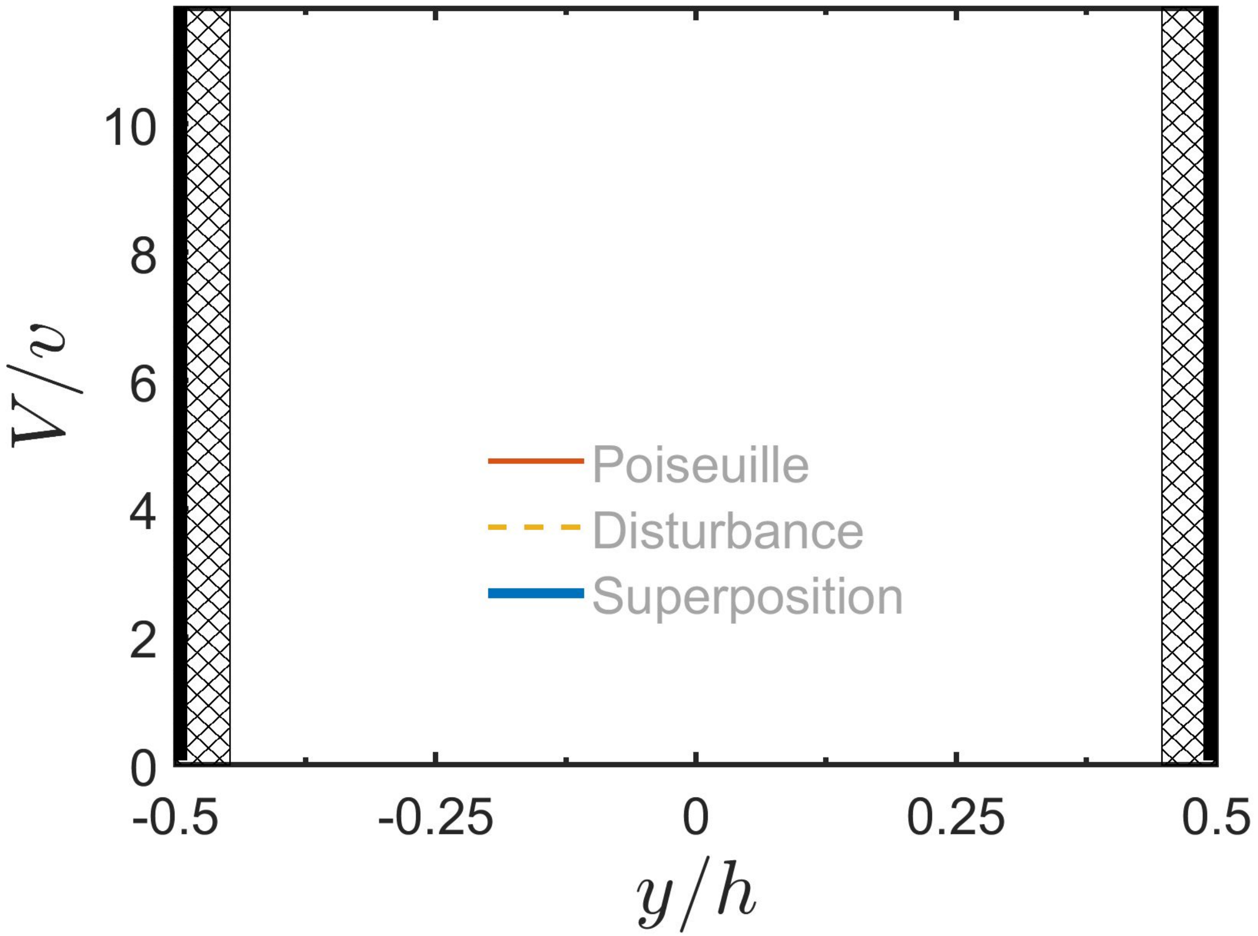

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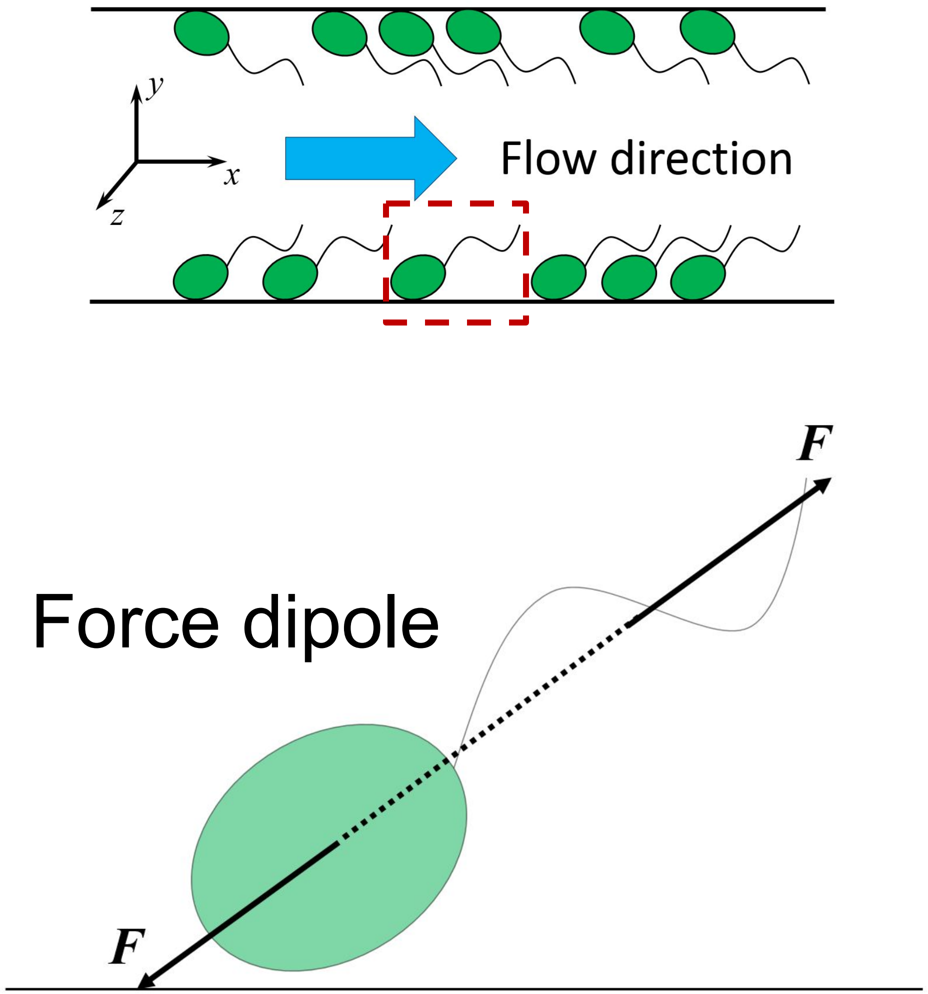

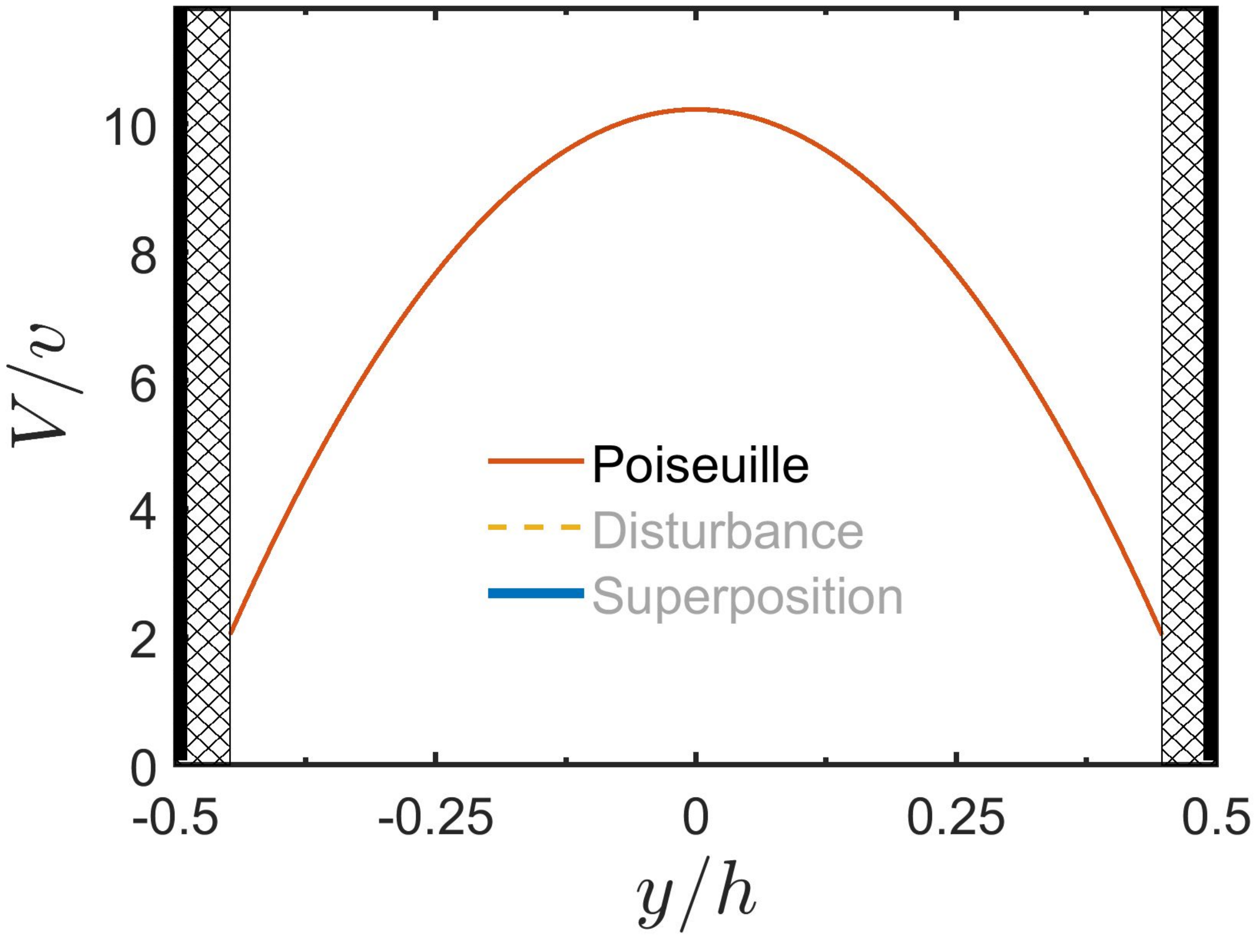

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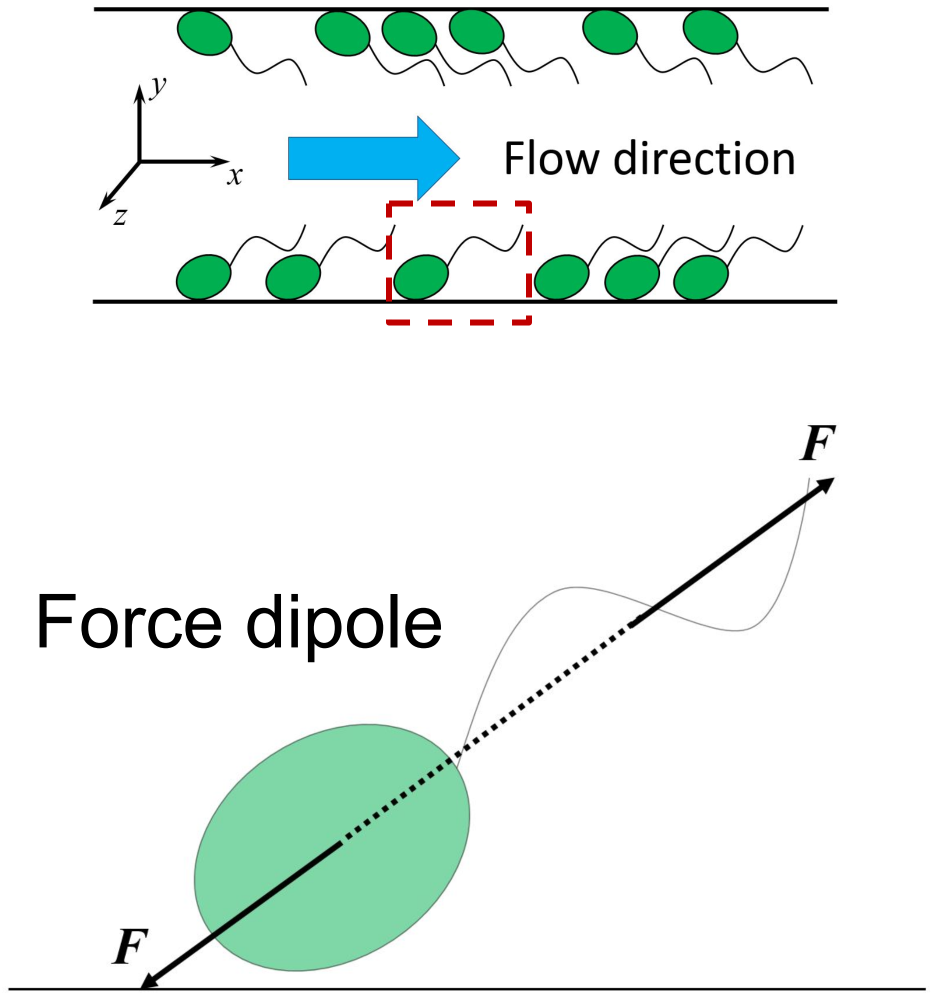

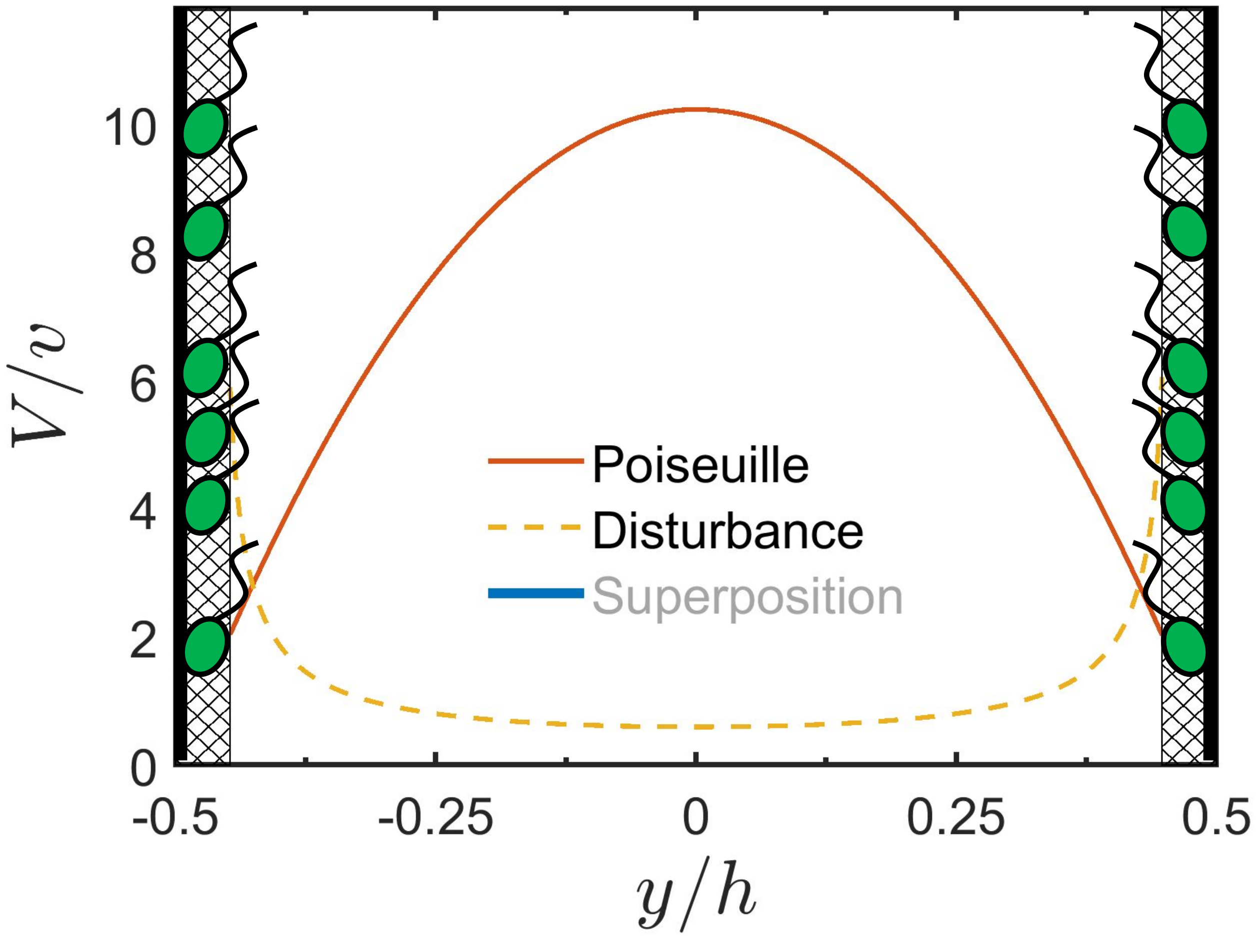

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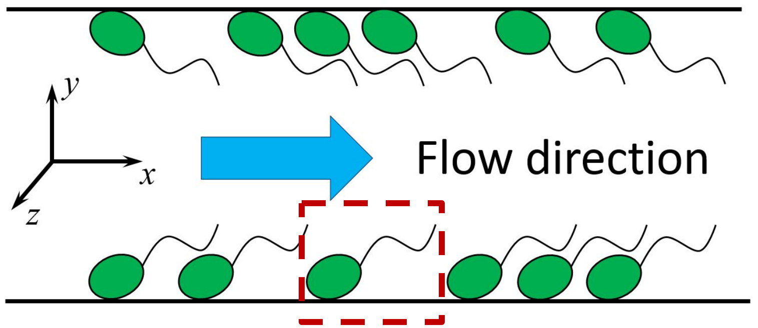
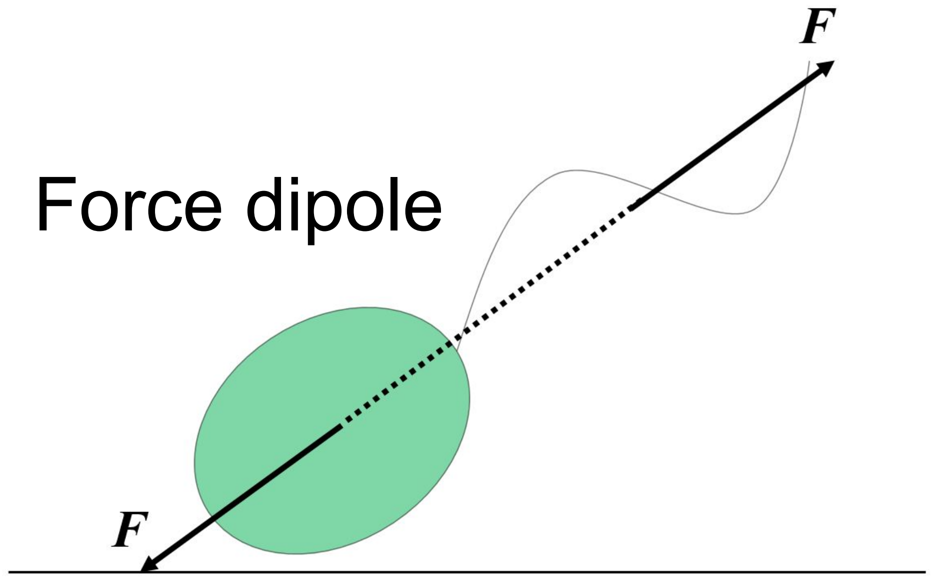
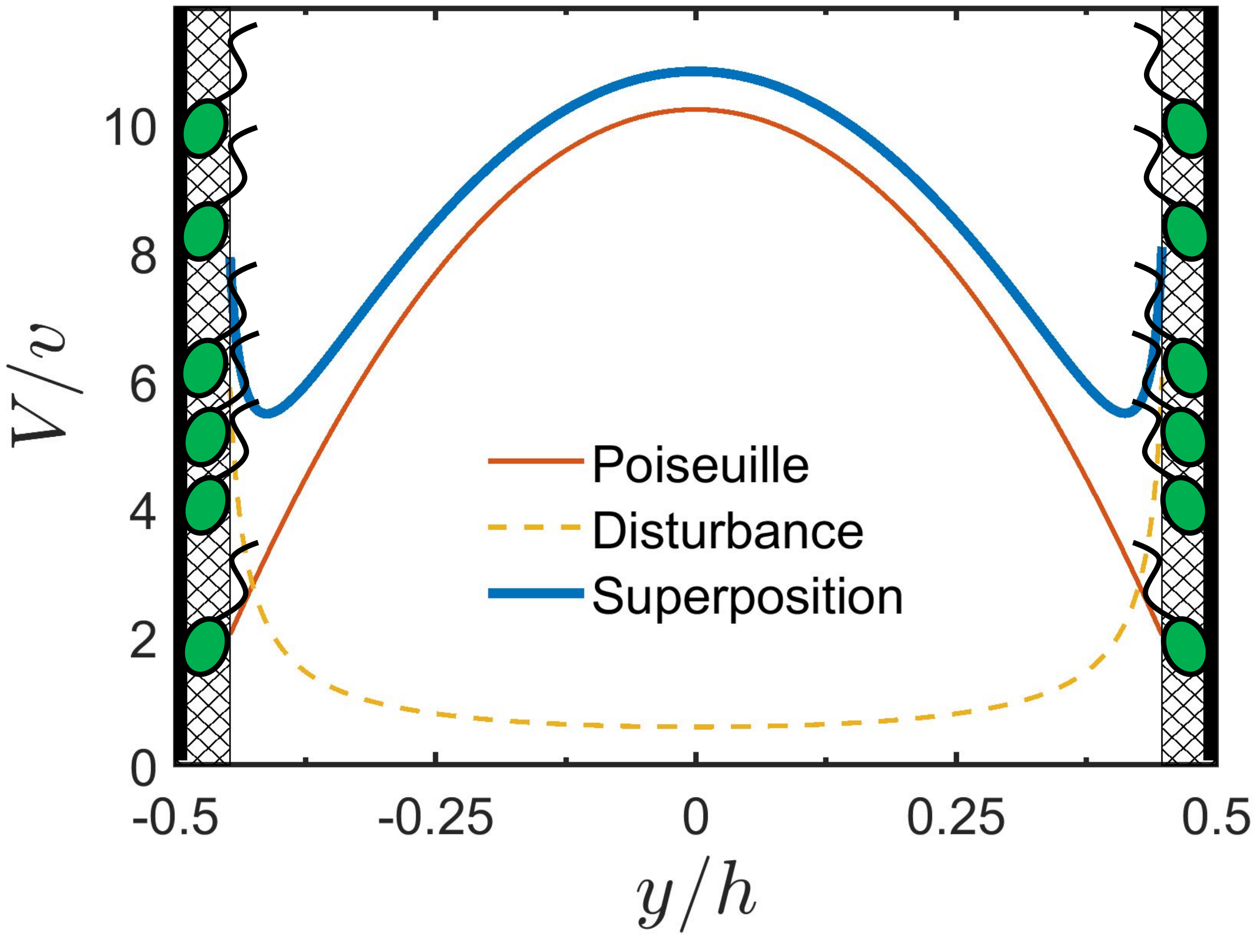
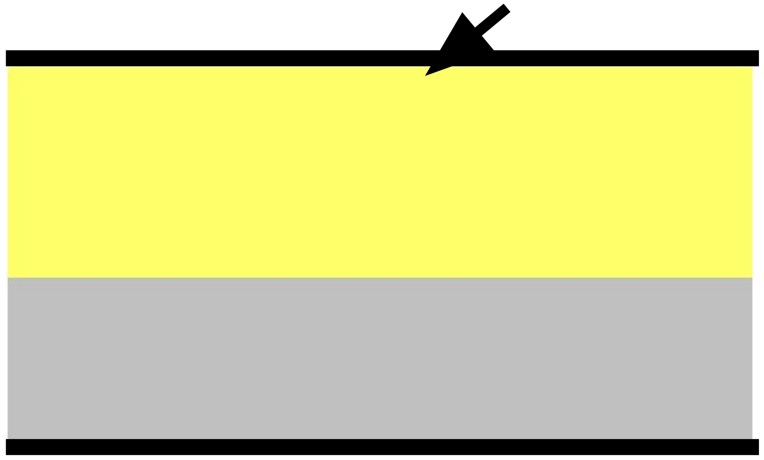


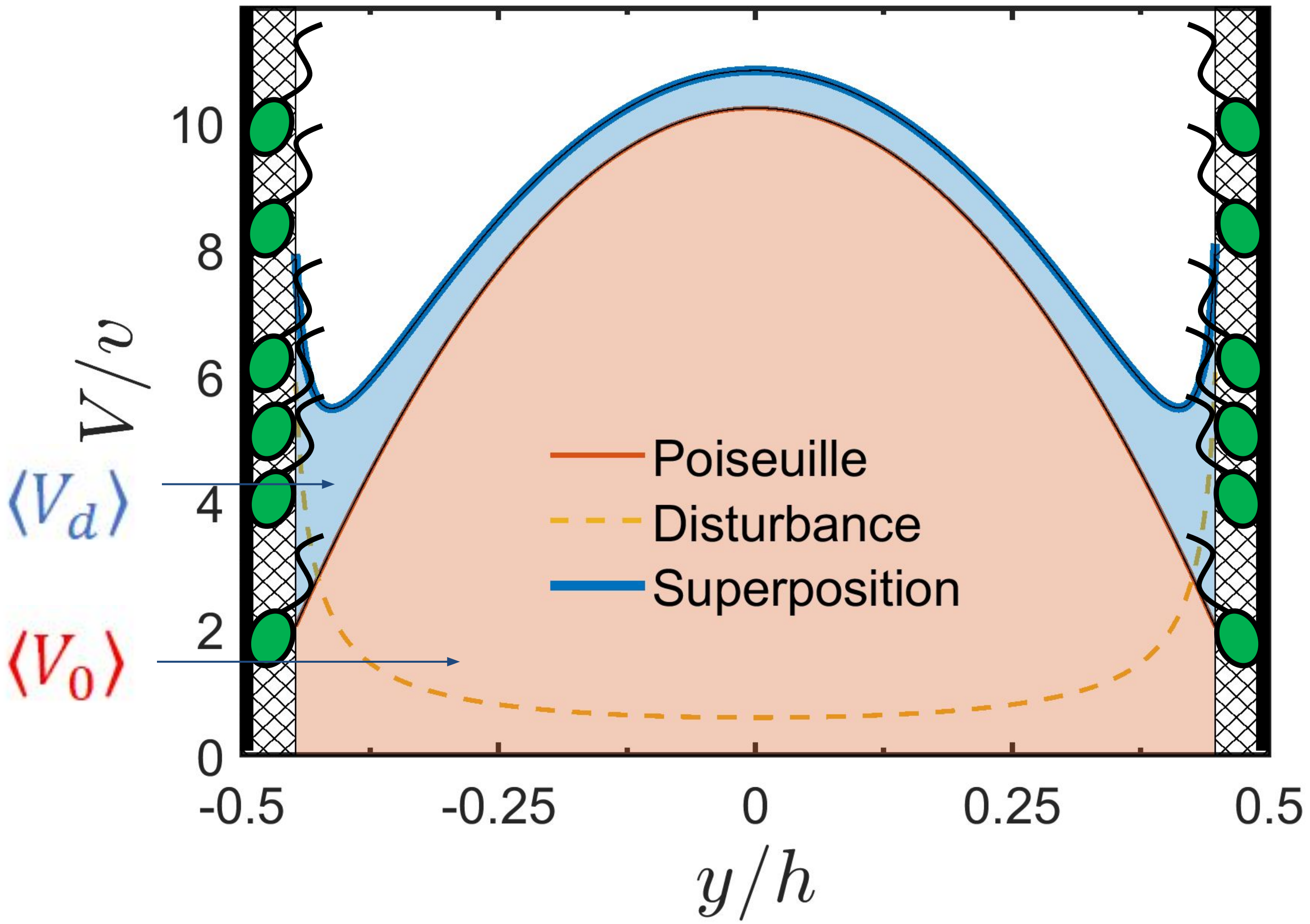




Disturbance velocity leads to reduced viscosity

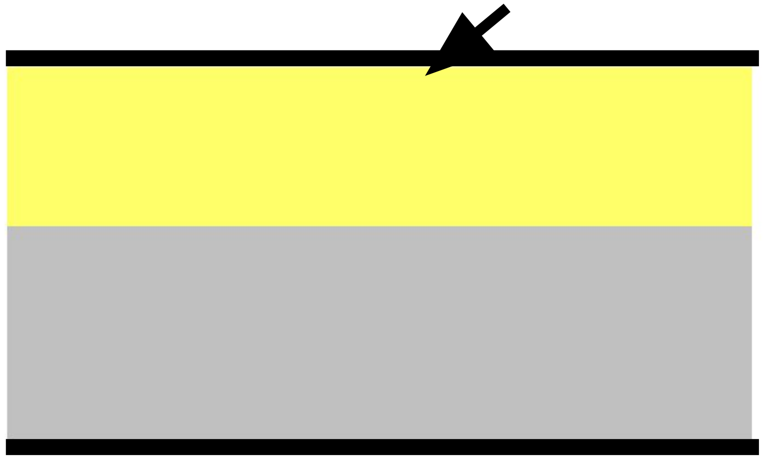
$$\langle V \rangle = \langle V_0 \rangle$$

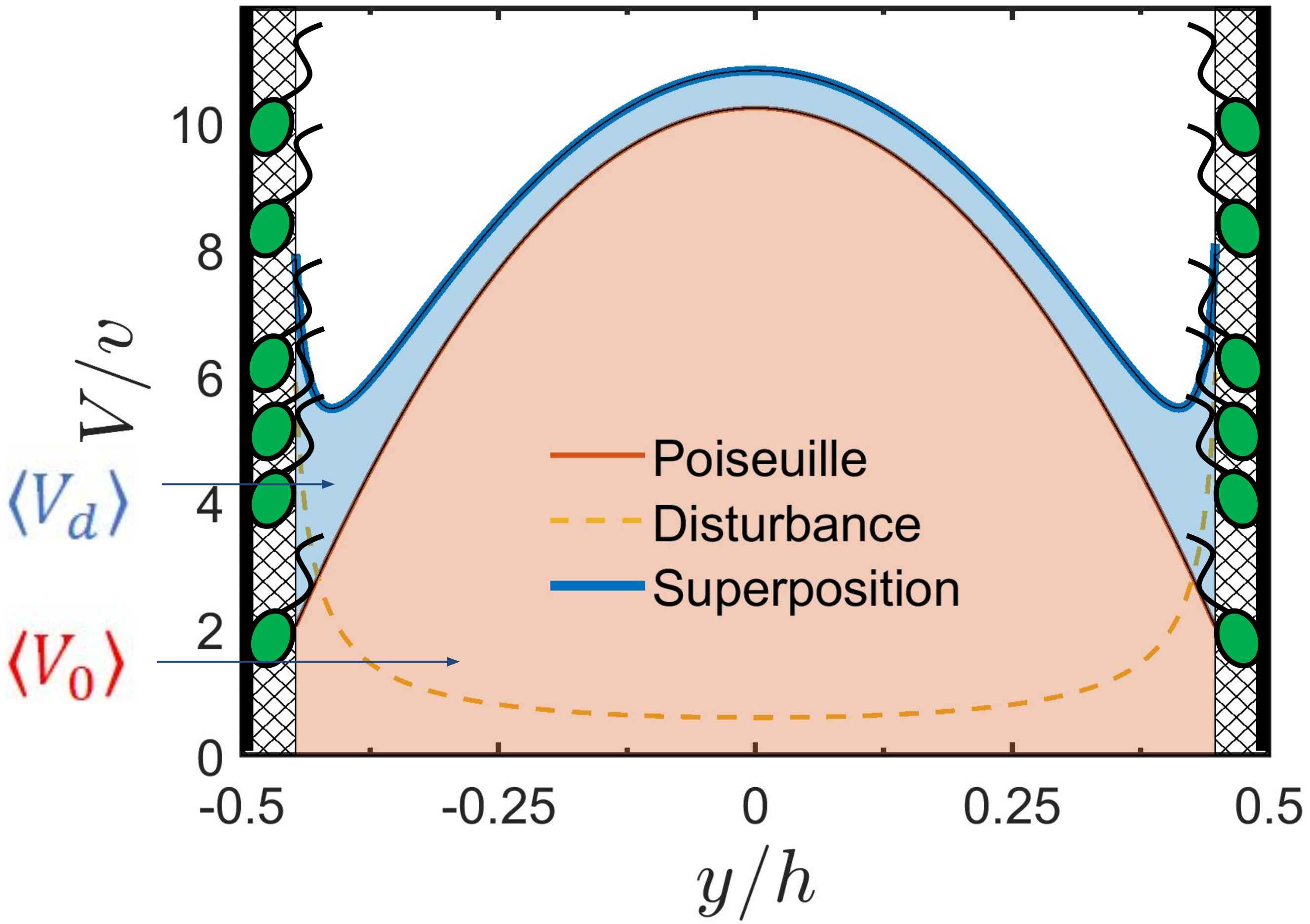




Disturbance velocity leads to reduced viscosity

$$\langle V \rangle = \langle V_0 \rangle + \langle V_d \rangle$$





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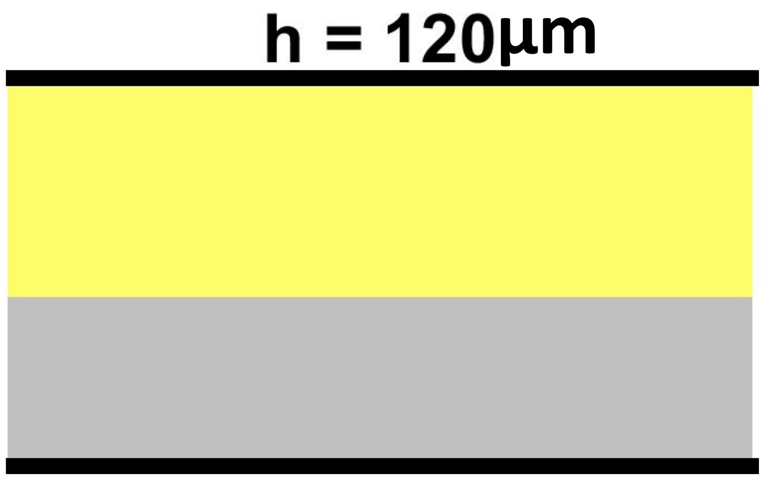
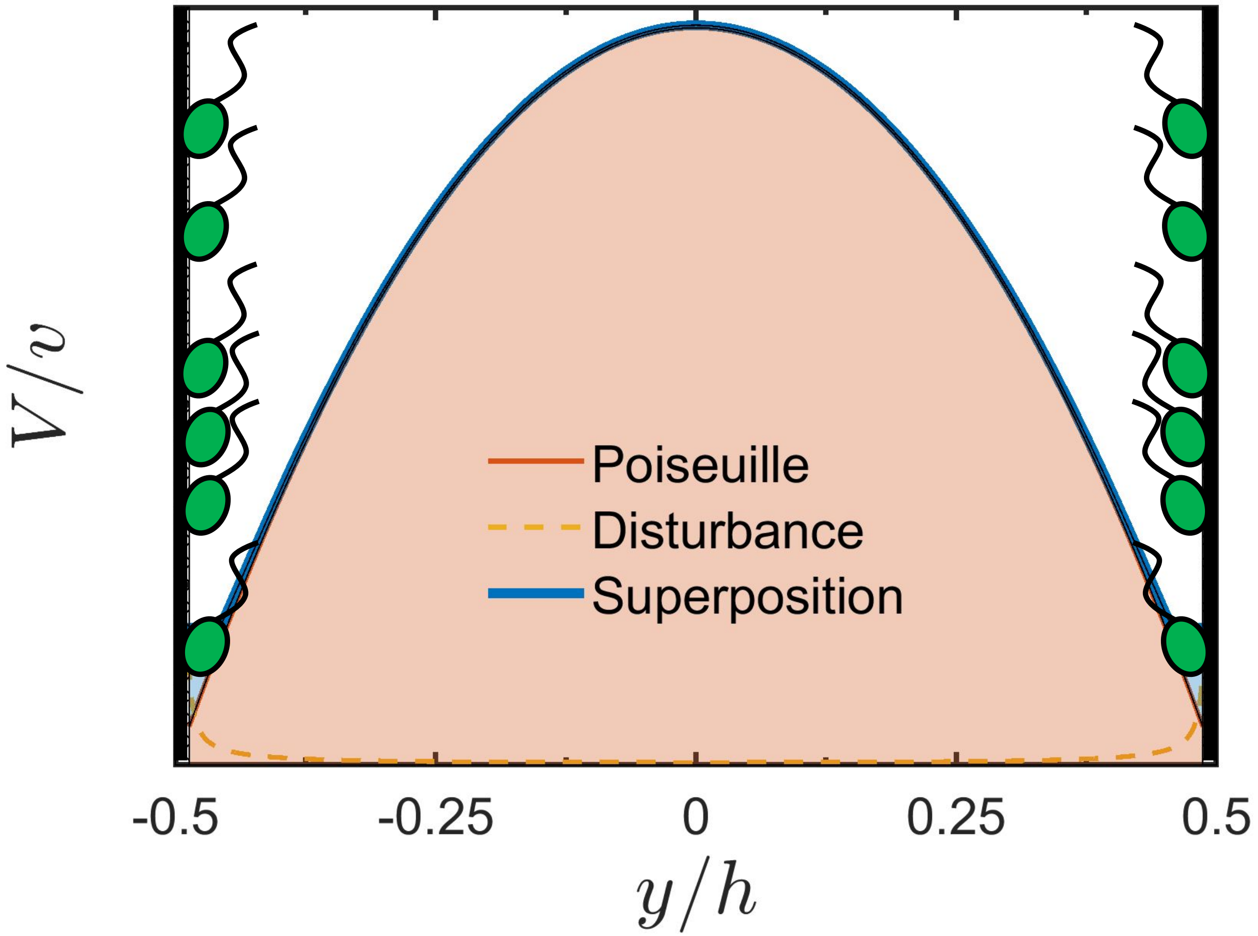
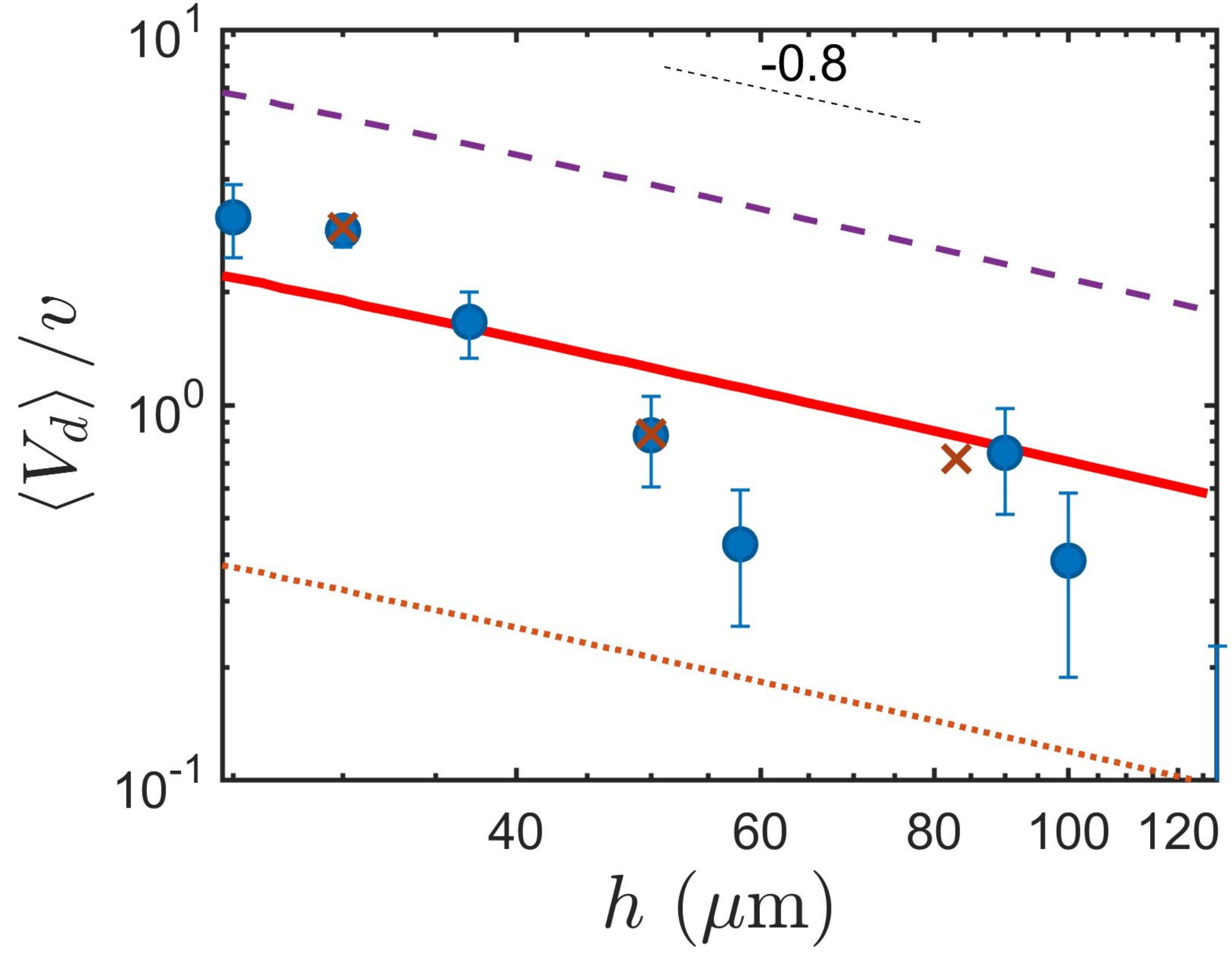


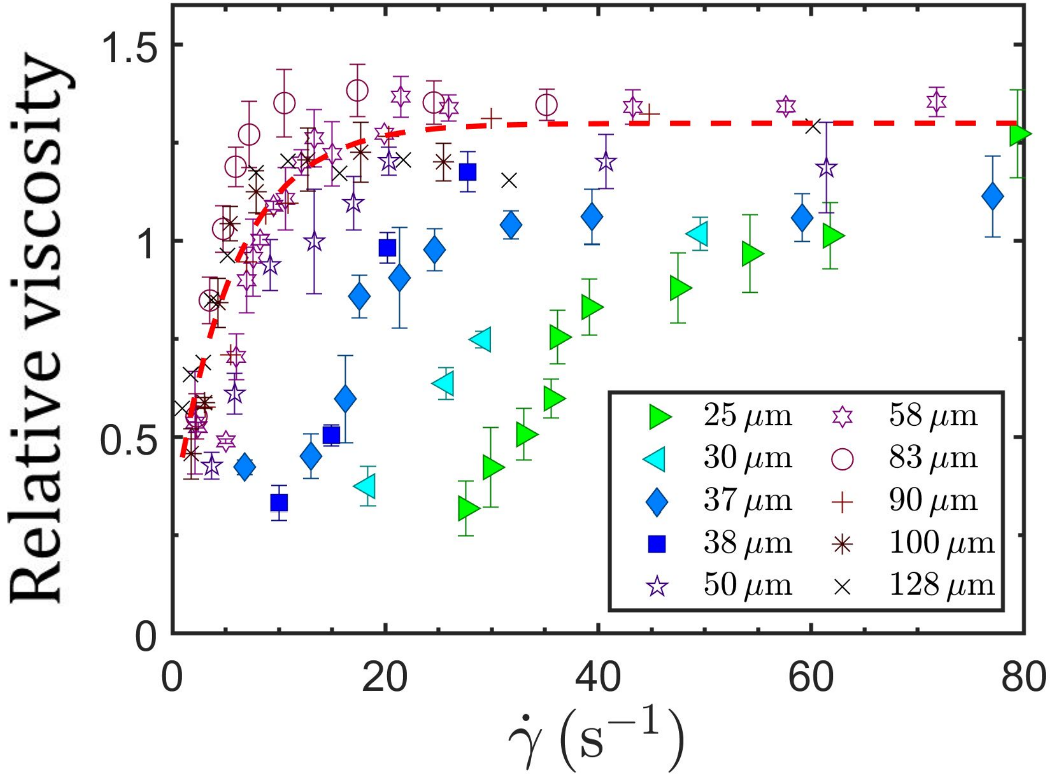


Disturbance velocity leads to reduced viscosity



Disturbance velocity leads to reduced viscosity

$$\eta = \eta_b \left(1 - \frac{6\langle V_d \rangle}{\dot{\gamma} h}\right)$$



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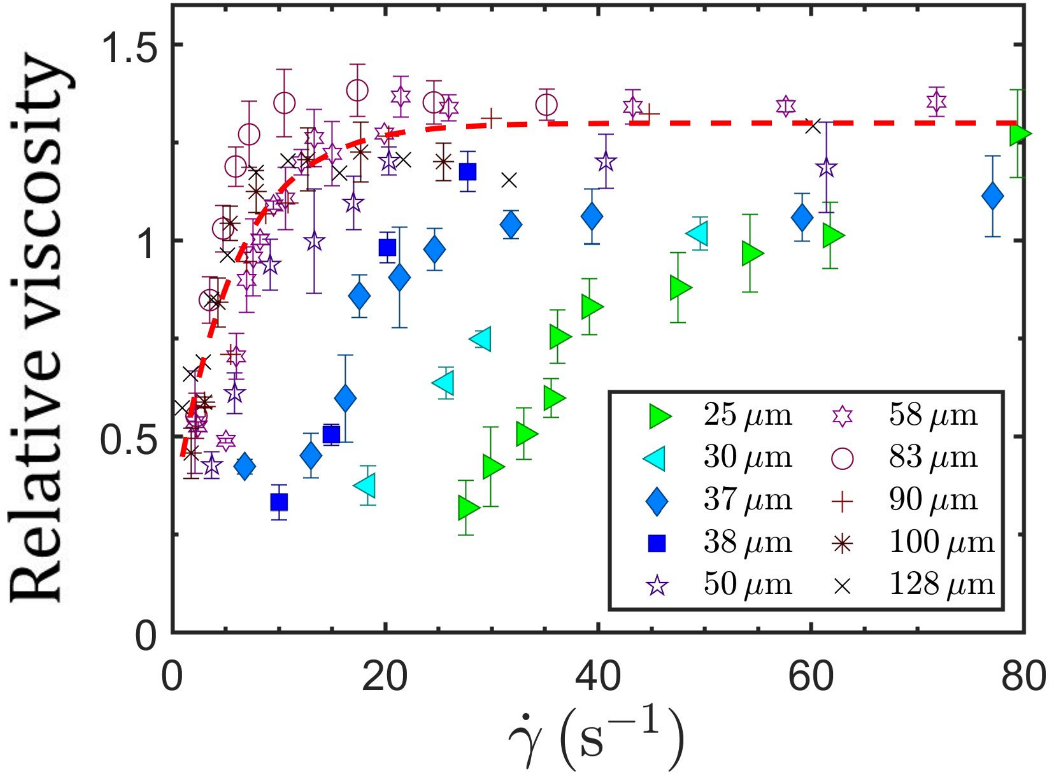
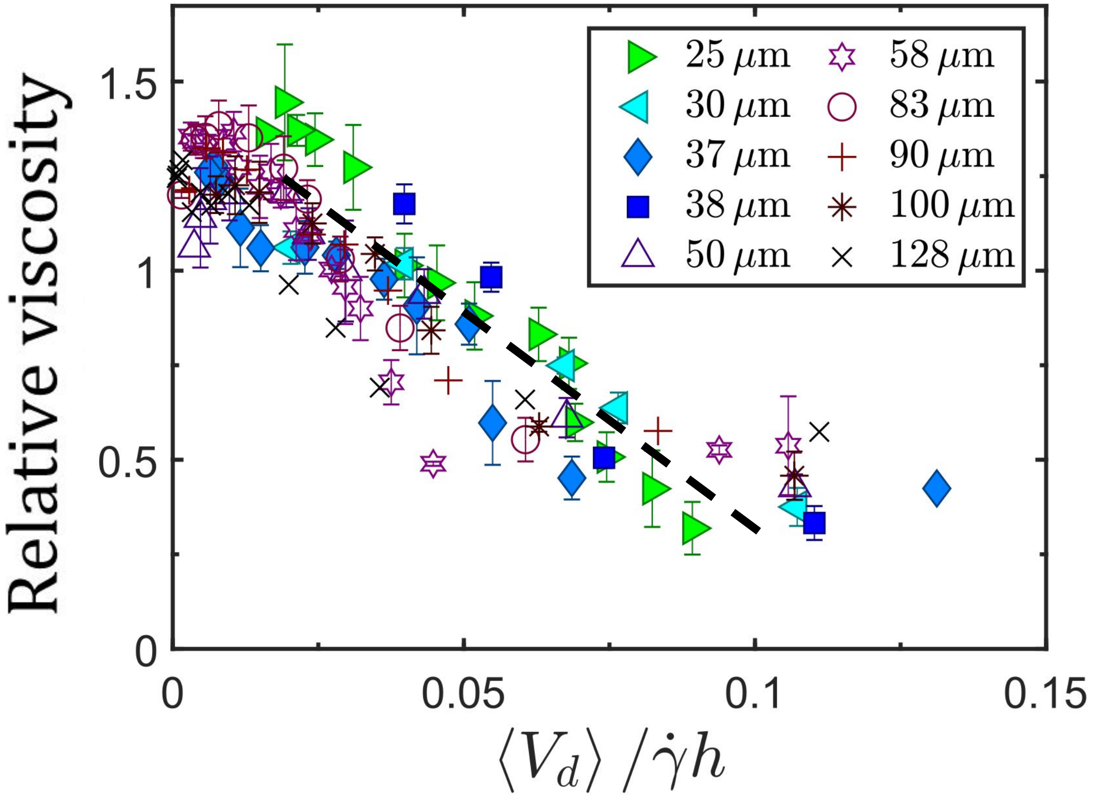
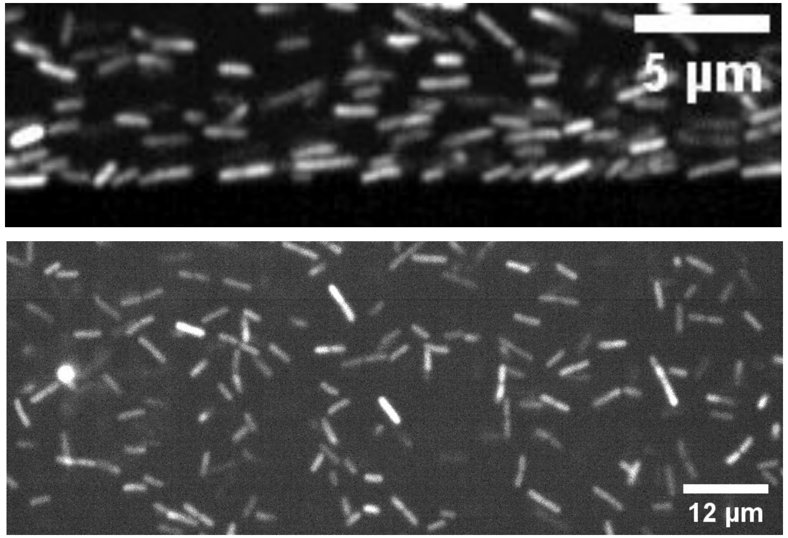




Conclusions

- Confinement **reduces** the viscosity of *E. coli* suspensions
- A new mechanism of viscosity reduction due to **upstream swimming boundary layer** of *E. coli*



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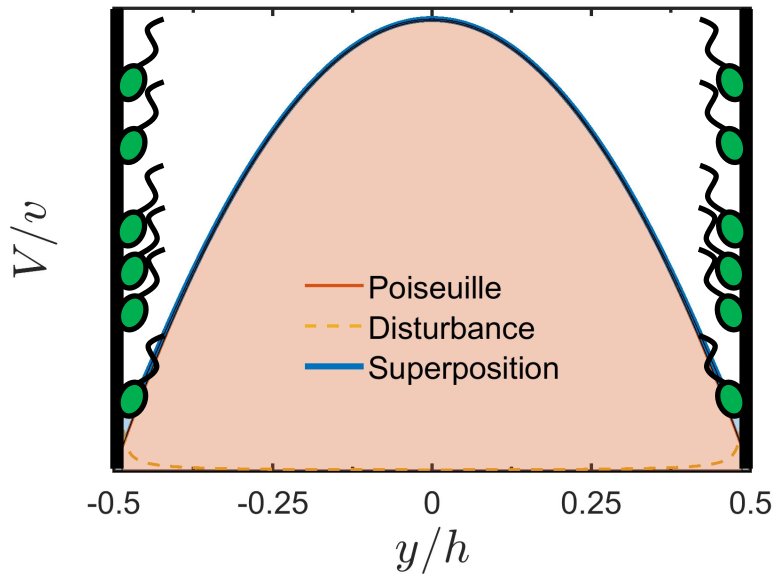

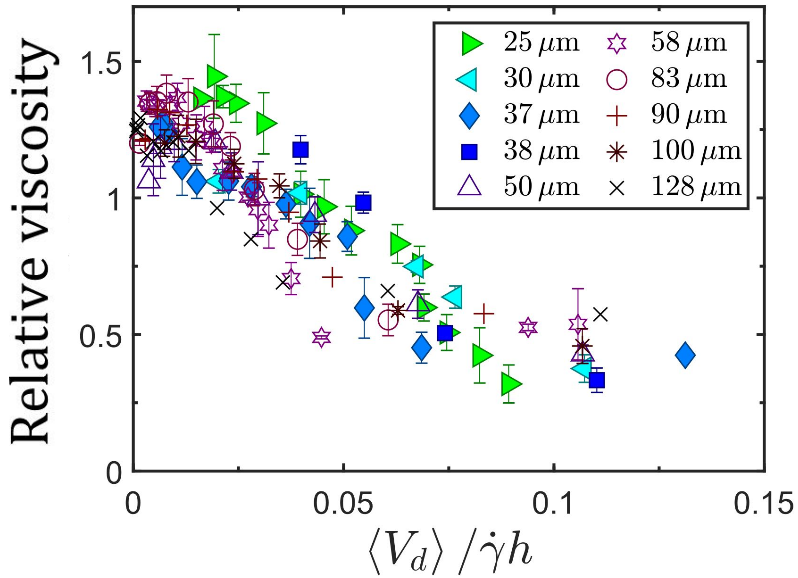

Acknowledgment

<u>Group members</u>

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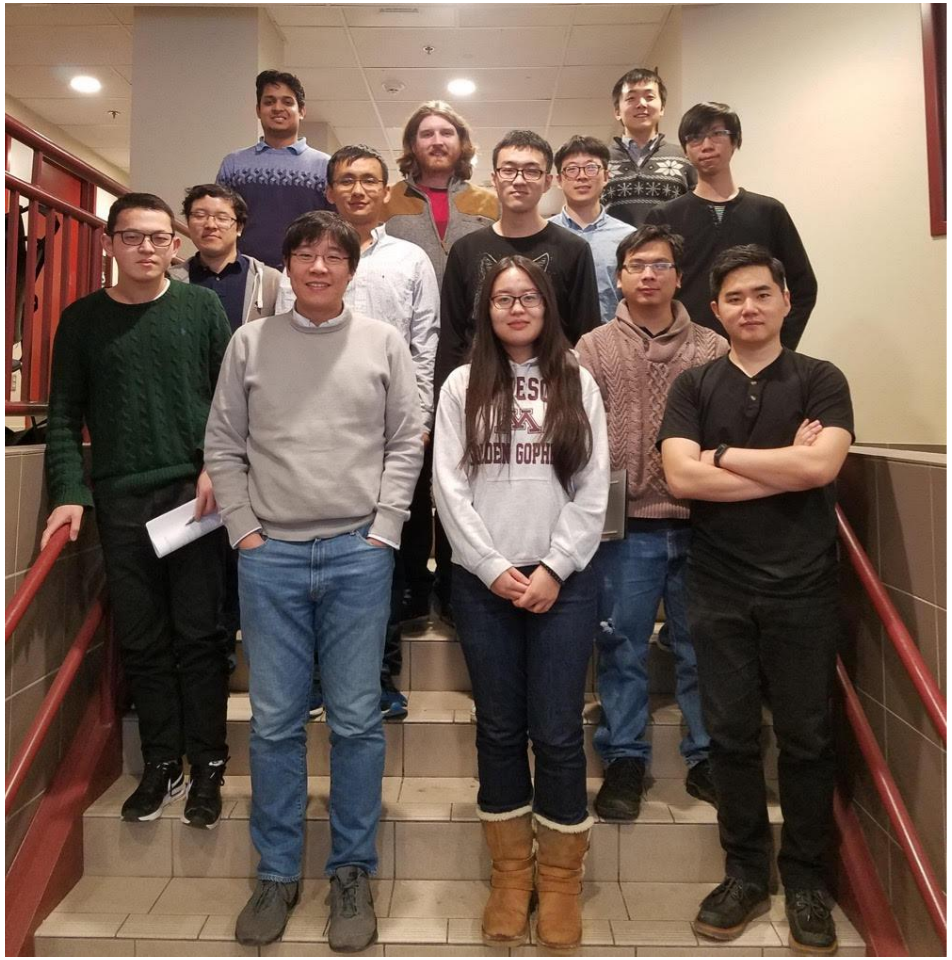

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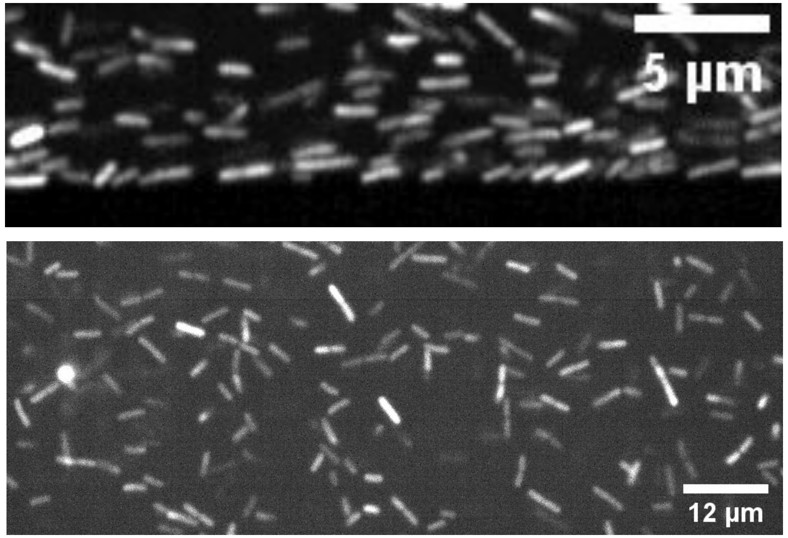

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