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Slide of the Seminar

The importance of fluid mechanics in the microbial world: From the transport of bacteria to the formation of biofilms

Prof. Roberto Rusconi

ERC Advanced Grant (N. 339032) "NewTURB"
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Università degli Studi di Roma Tor Vergata
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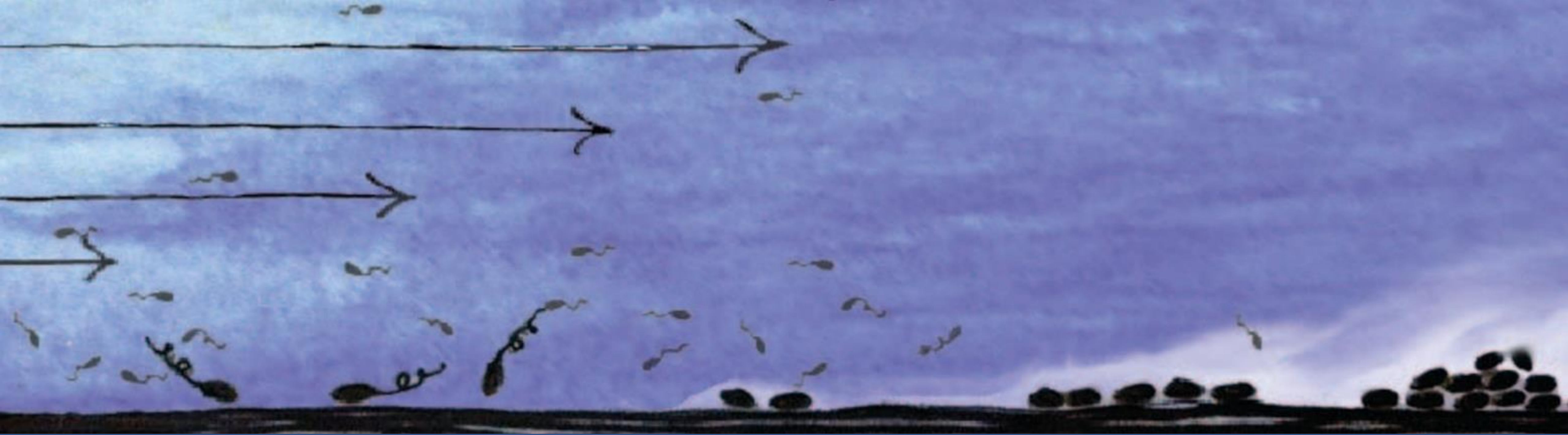

The importance of fluid mechanics in the microbial world:

From the transport of bacteria to the formation of biofilms

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Roberto Rusconi

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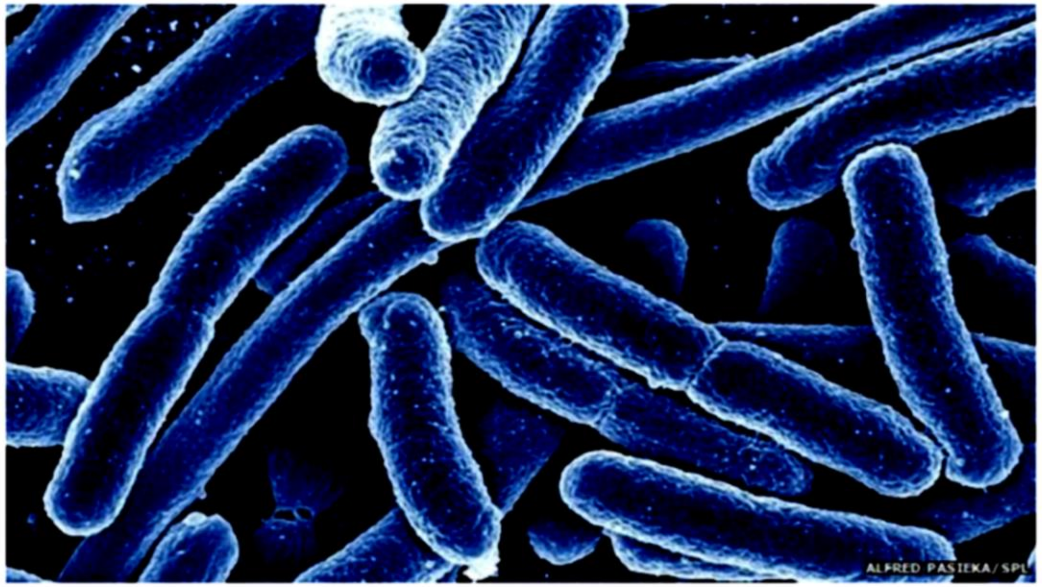
The “biofilm” threat

Superbugs to kill 'more than cancer' by 2050

Fergus Walsh
Medical correspondent

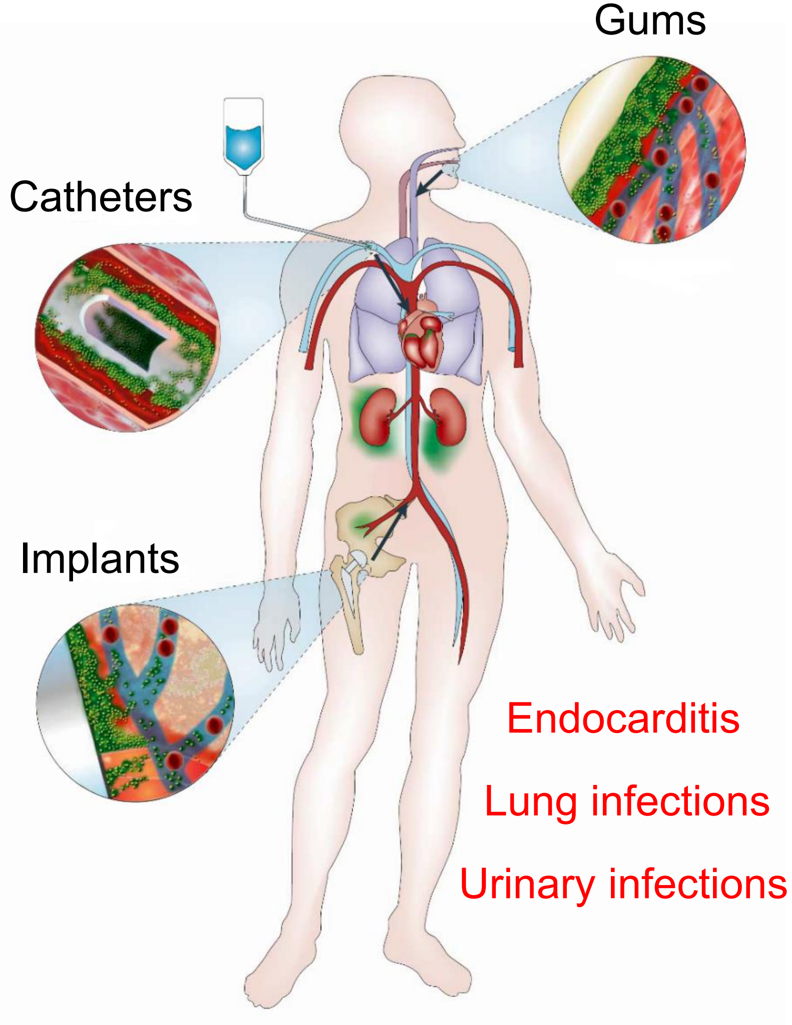
11 December 2014 | Health |



Drug resistant E.coli bacteria are already a significant problem in Europe

Drug resistant infections will kill an extra 10 million people a year worldwide - more than currently die from cancer - by 2050 unless action is taken, a study says.

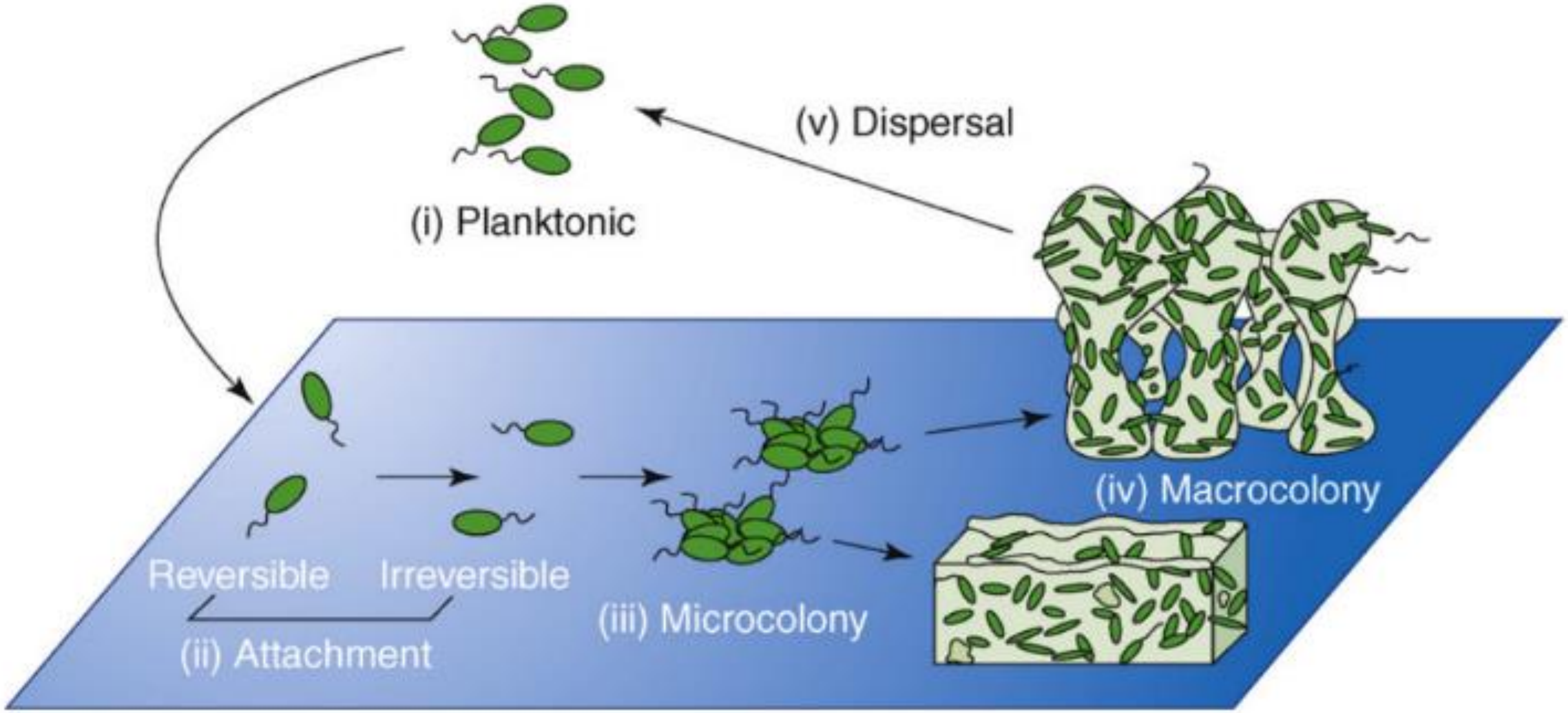
They are currently implicated in 700,000 deaths each year.



Hall-Stoodley et al. *Nat. Rev. Microbiol*. 2004

Bacteria within biofilms are up to 1000 times more resistant to antibiotics

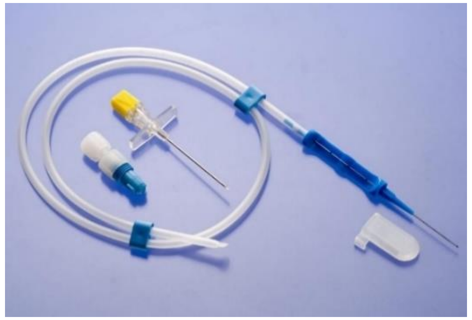
Biofilms form everywhere and often in the presence of flow



Monds & O'Toole. *Trends Microbiol.* 2009

Environment

Medical devices



Industrial applications

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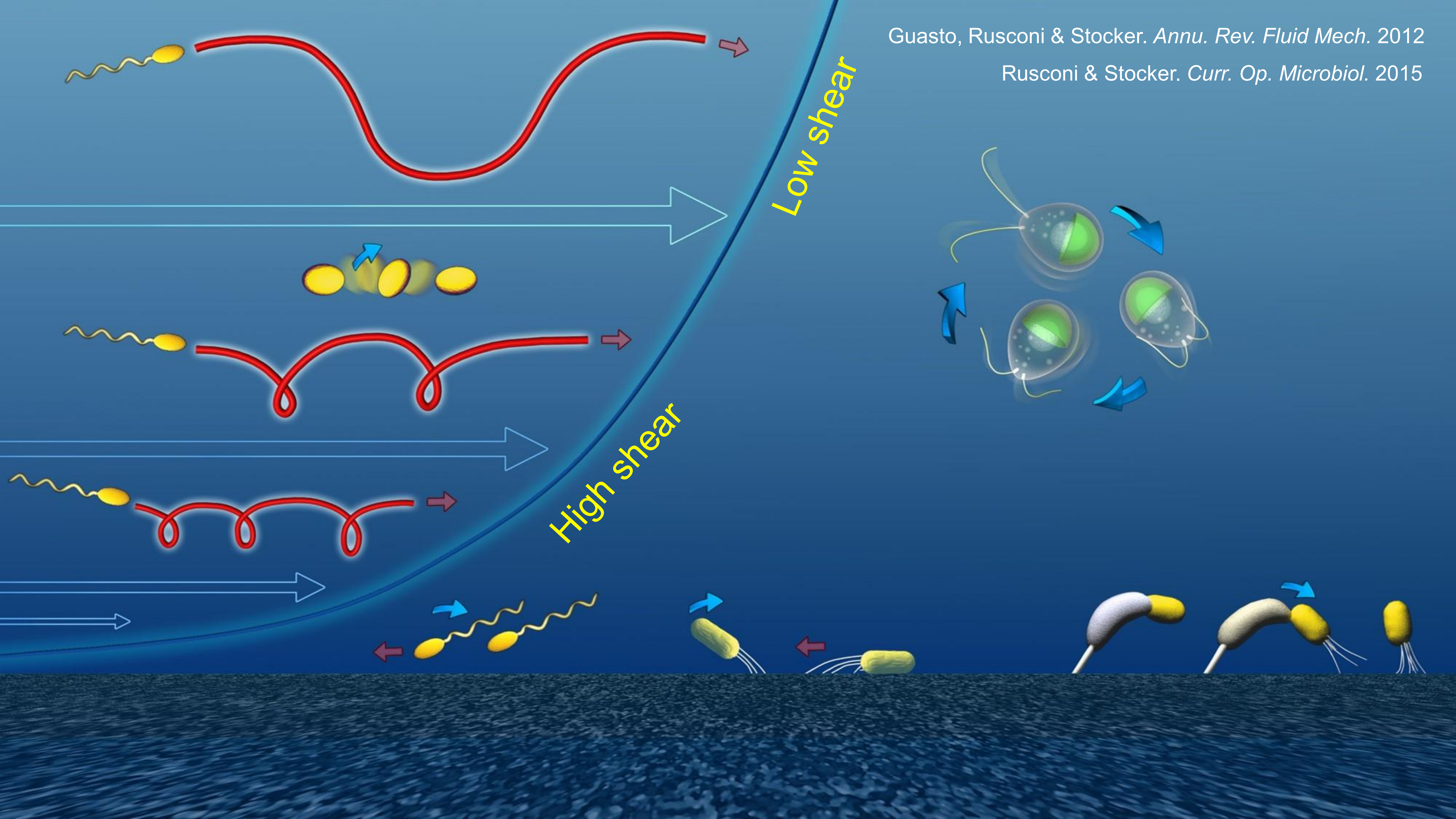
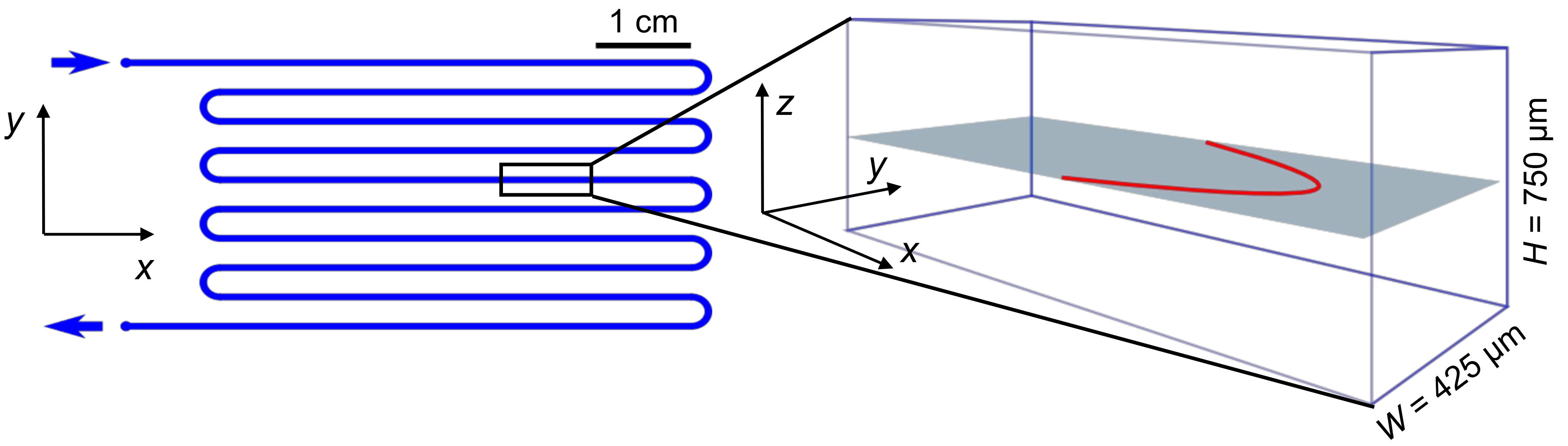
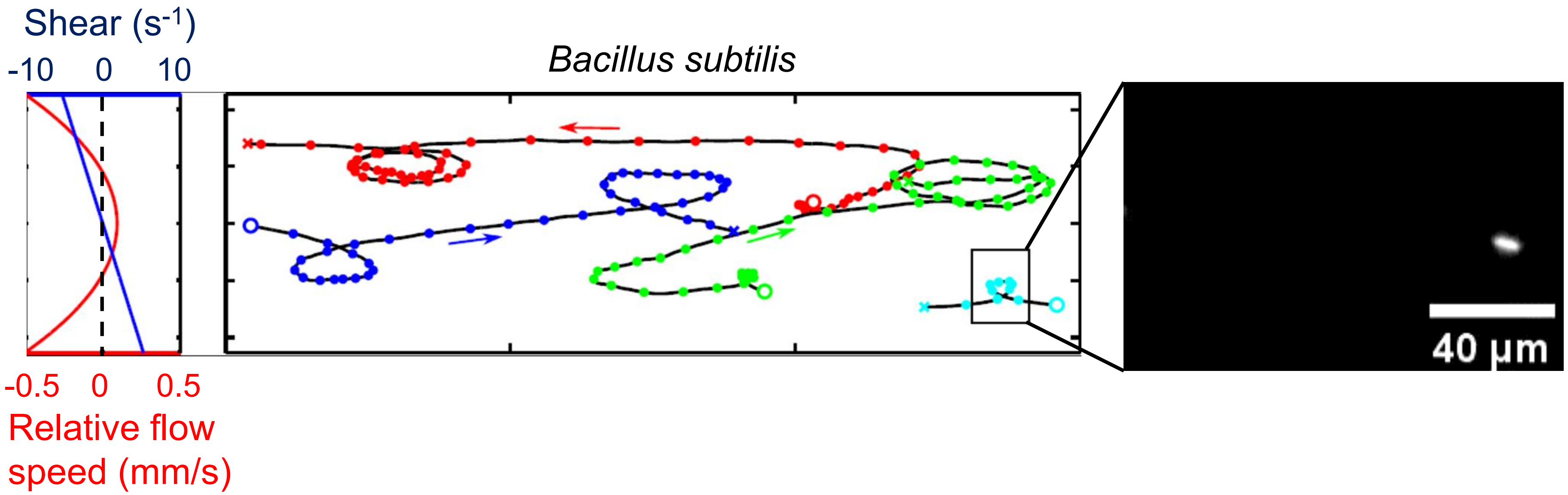
Guasto, Rusconi & Stocker. *Annu. Rev. Fluid Mech.* 2012

Rusconi & Stocker. *Curr. Op. Microbiol.* 2015



How does fluid flow affect bacterial swimming dynamics?





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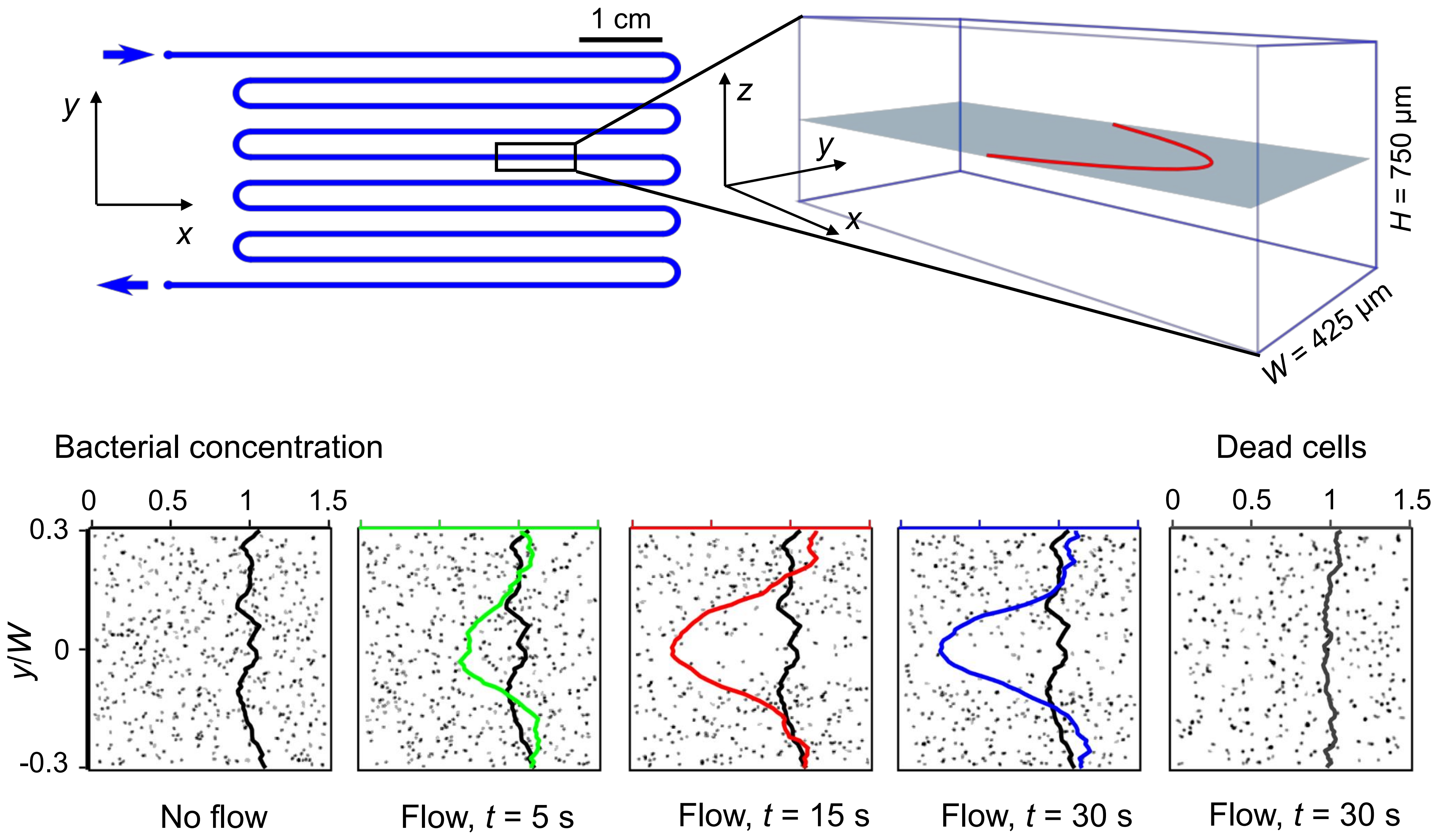

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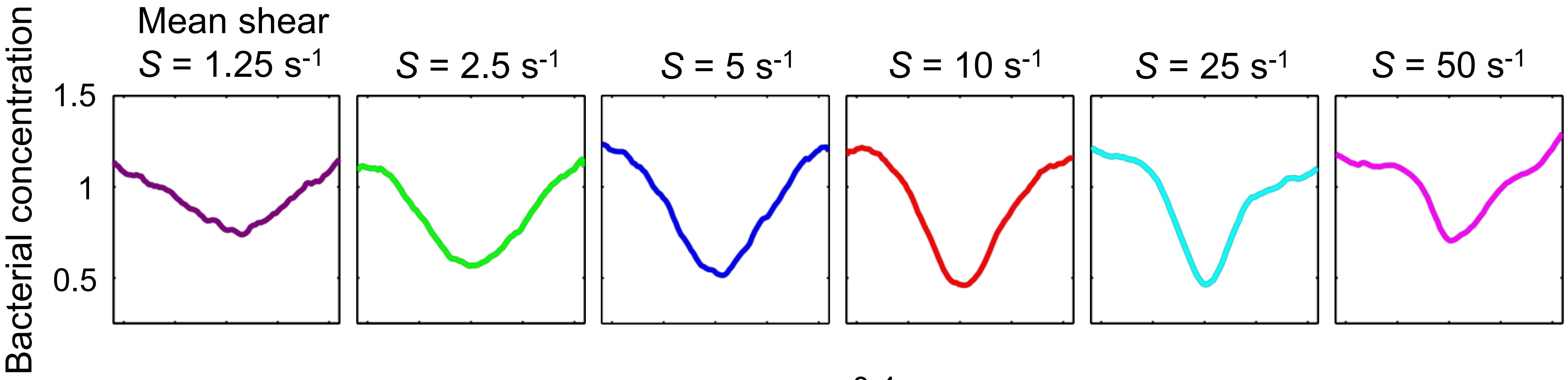
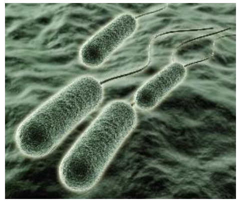
Maximal depletion occurs at intermediate shear



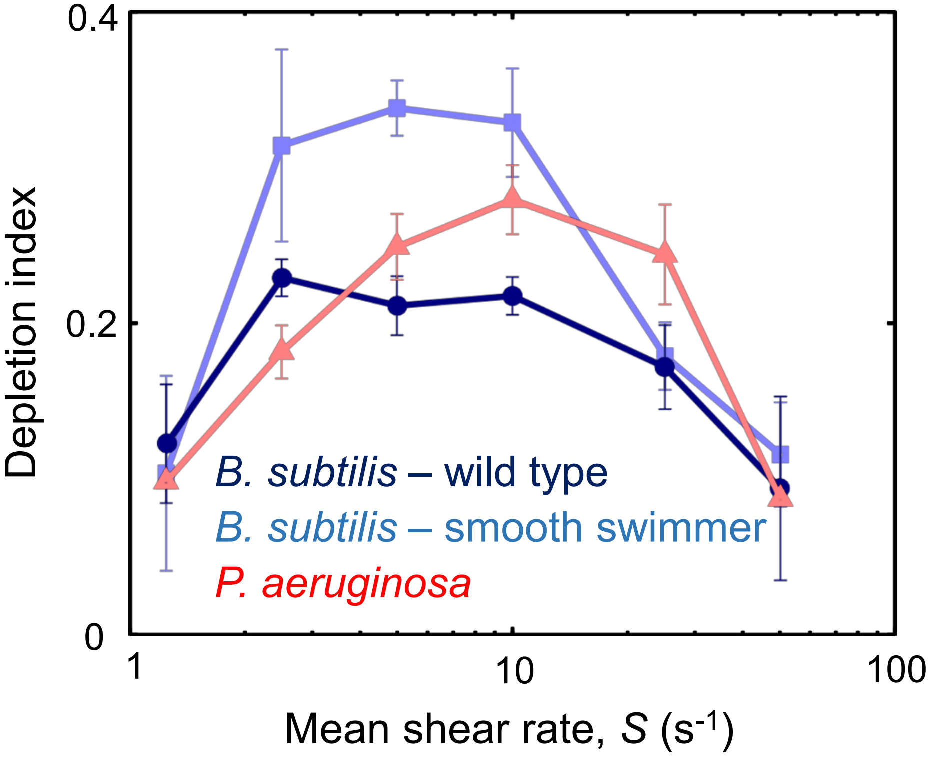
Bacillus subtilis

- Rod shape (1µm x 3µm)
- Multiple flagella

Pseudomonas aeruginosa



- Rod shape (0.5µm x 1.5µm)
- Single flagellum



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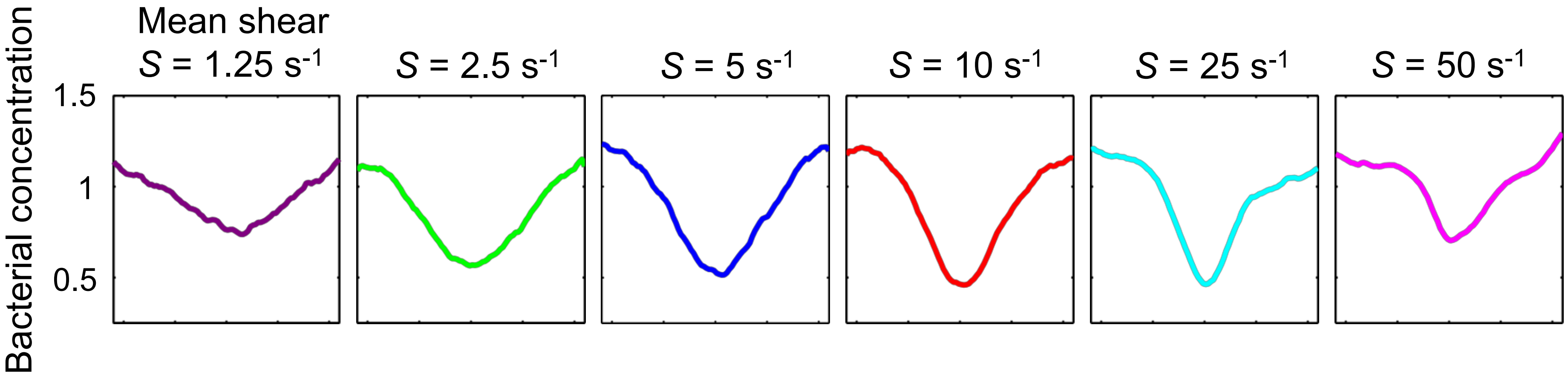
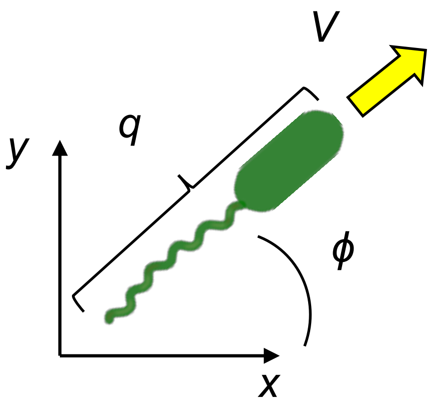




$$\dot{x} = -V\cos\phi + u(y)$$

$$\dot{y} = -V\sin\phi$$

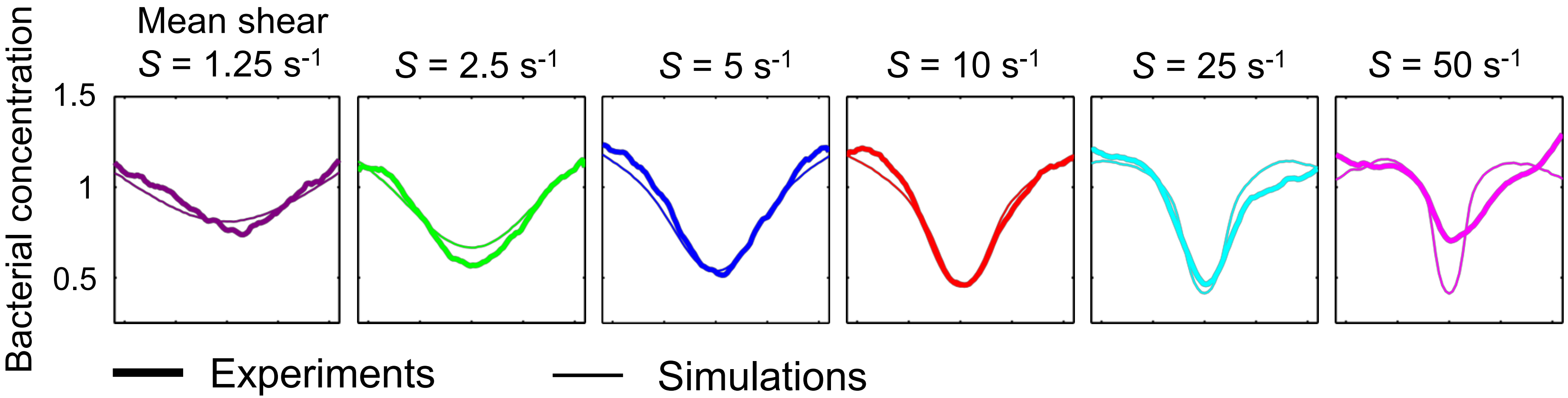
$$\dot{\phi} = \frac{4yU}{W^2}\left[1 + \left(\frac{1-q^2}{1+q^2}\right)\cos 2\phi\right] + \xi_R$$

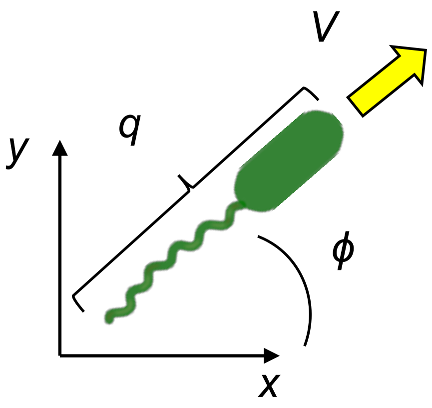
Swimming speed, $\boldsymbol{V}$ **= 50 μm/s**

Rotational diffusion, $\boldsymbol{D_R}$ **= 1 rad²/s**

Aspect ratio, $\boldsymbol{q}$ **= 10**

Maximal depletion occurs at intermediate shear





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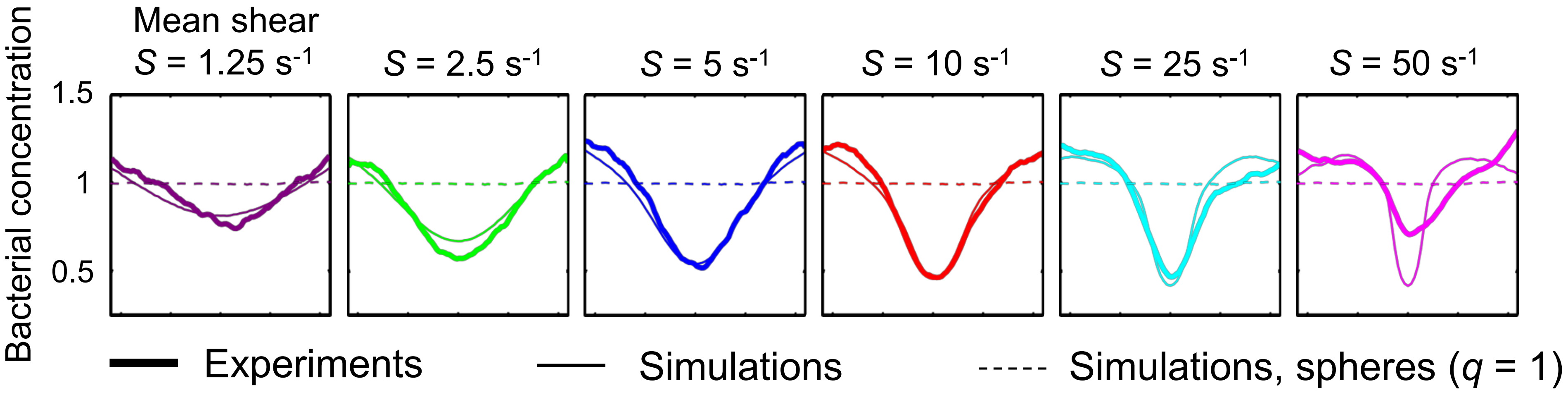

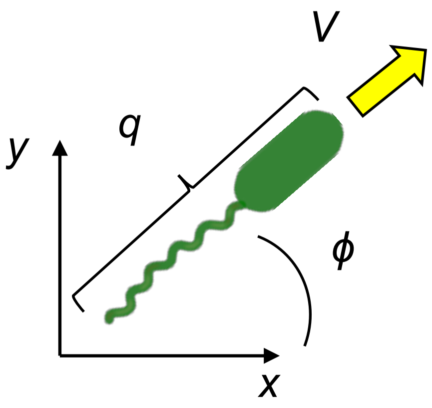

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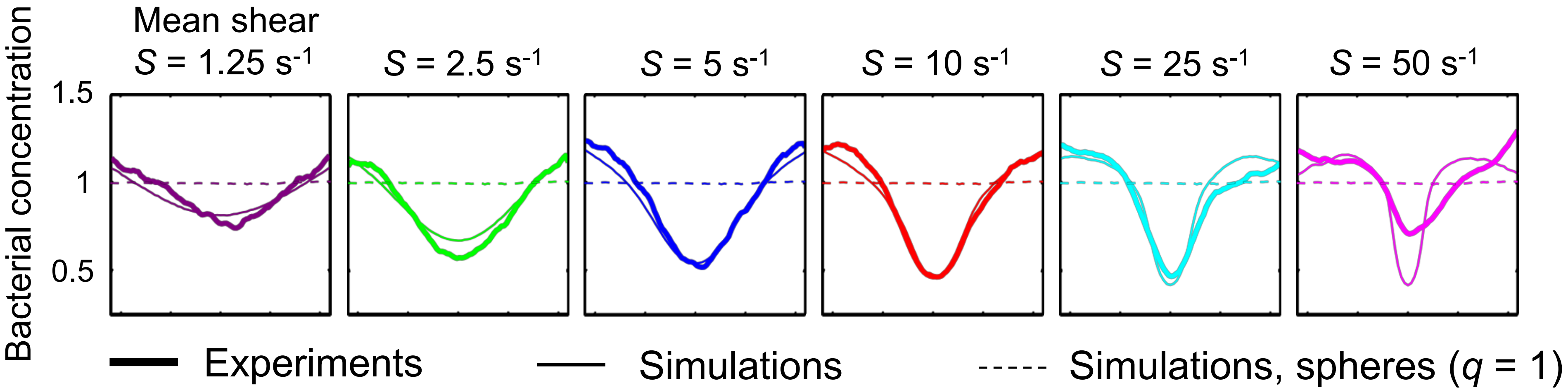
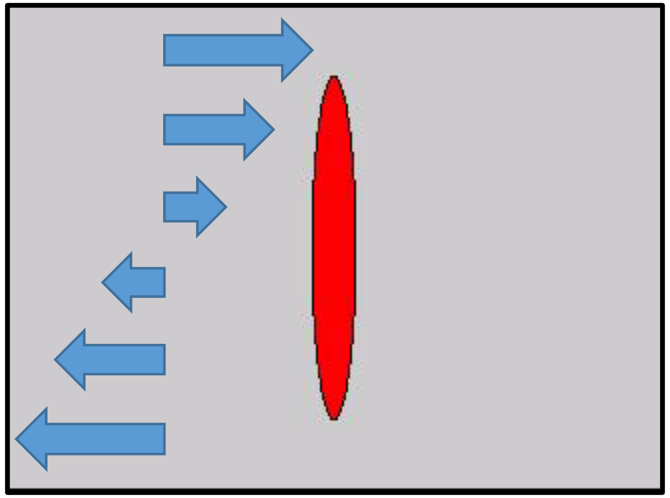


Elongated particle in shear flow



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Swimming speed, ***V* = 50 μm/s**

Rotational diffusion, ***D*$_R$ = 1 rad^2/s**

Aspect ratio, ***q* = 10**

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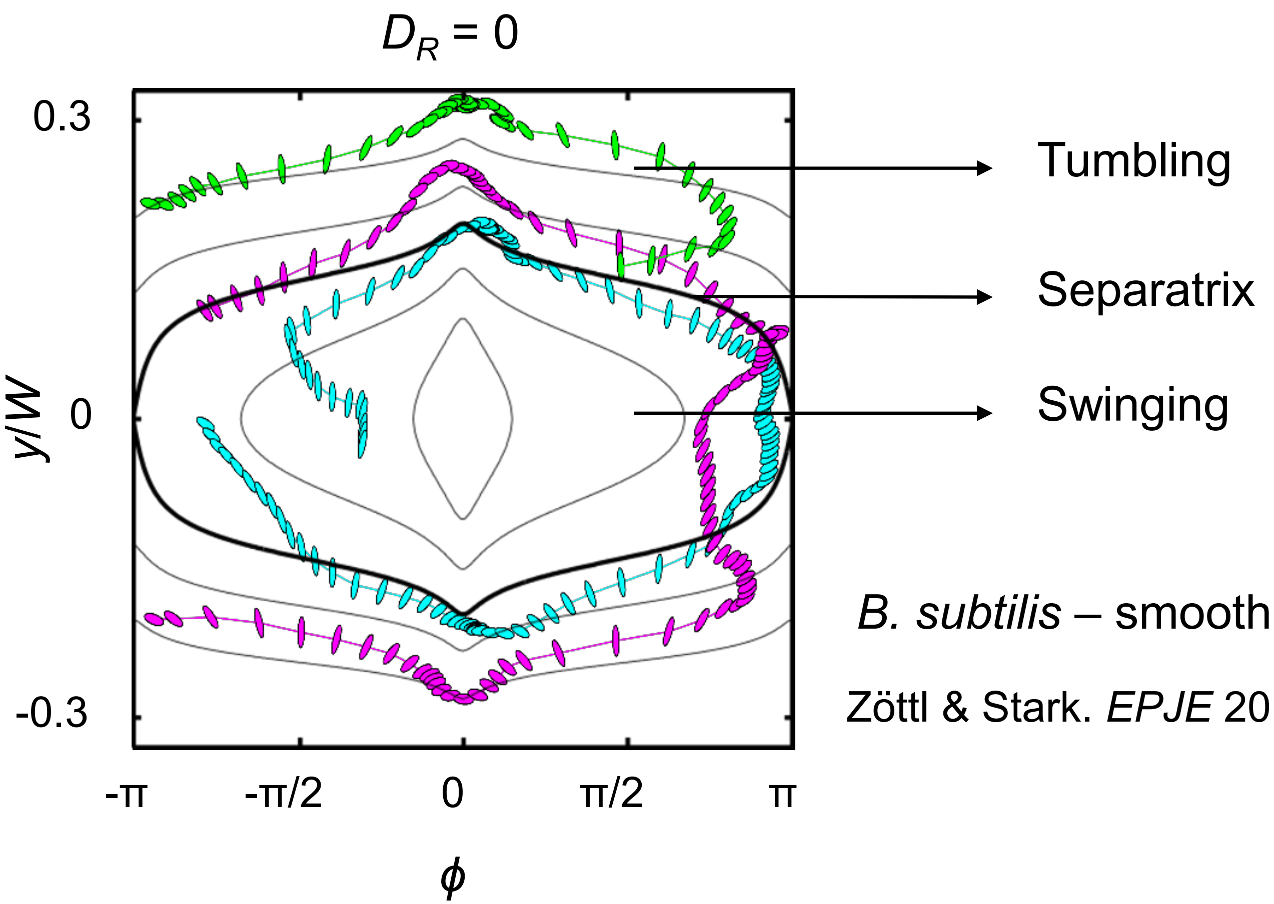
Elongation and rotational diffusion control bacterial depletion in flow



B. subtilis – smooth swimmer

Zöttl & Stark. *EPJE* 2013

Rusconi et al. *Nat. Phys.* 2014

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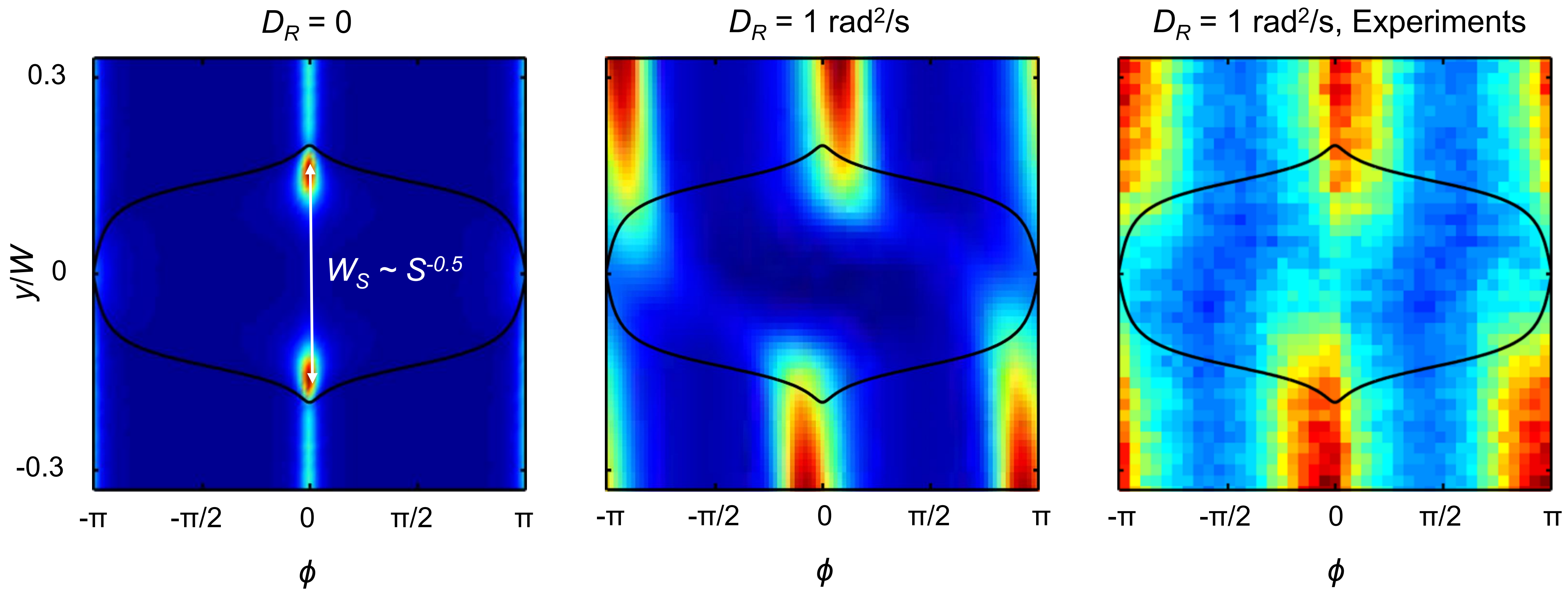

Rusconi et al. *Nat. Phys.* 2014

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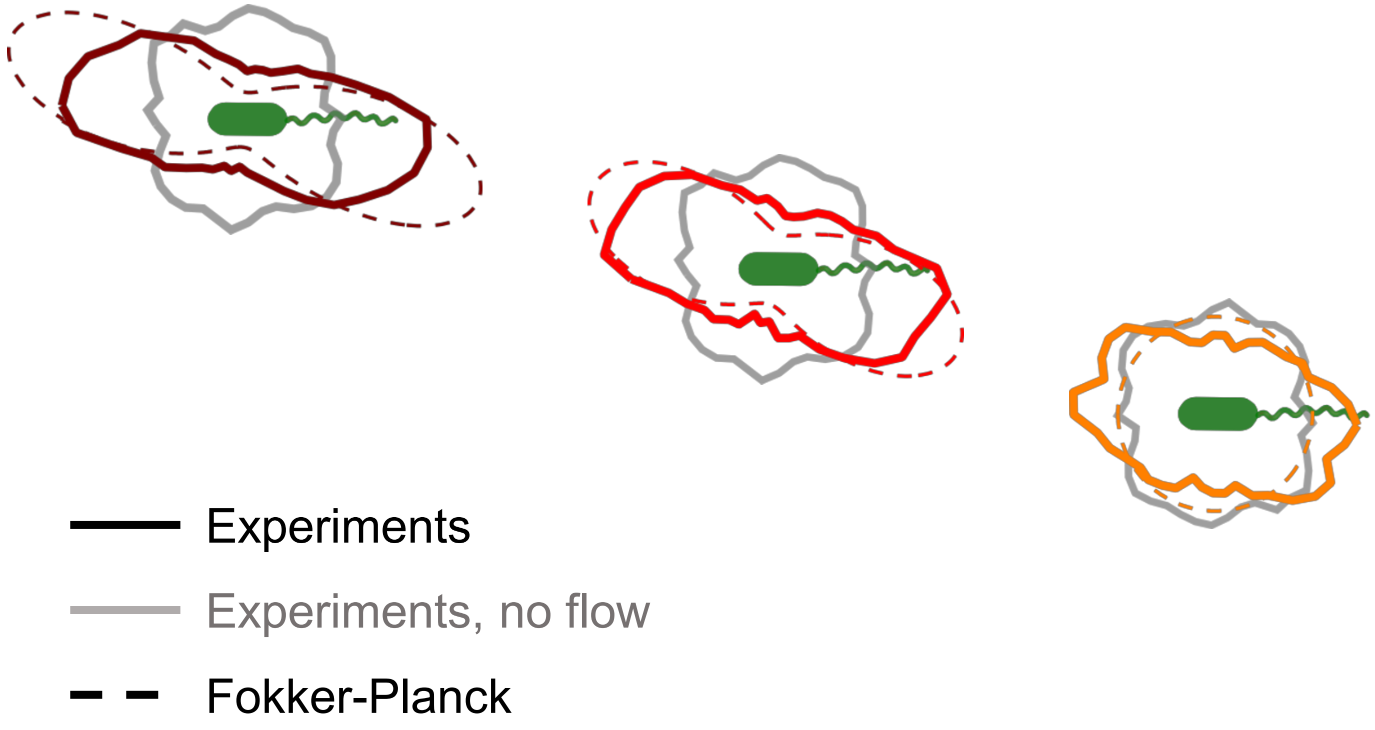

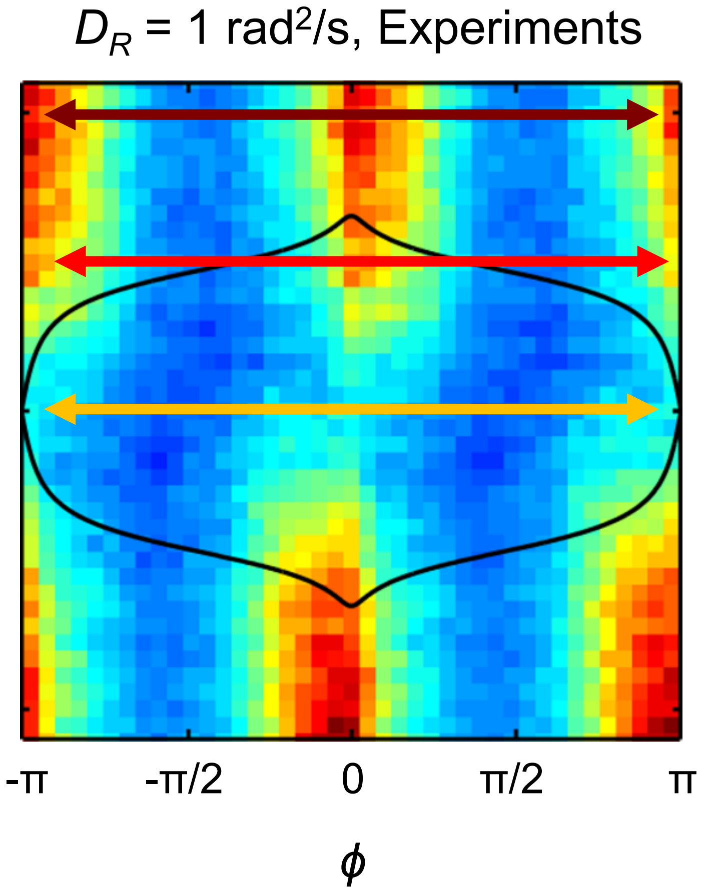

Rusconi et al. *Nat. Phys.* 2014

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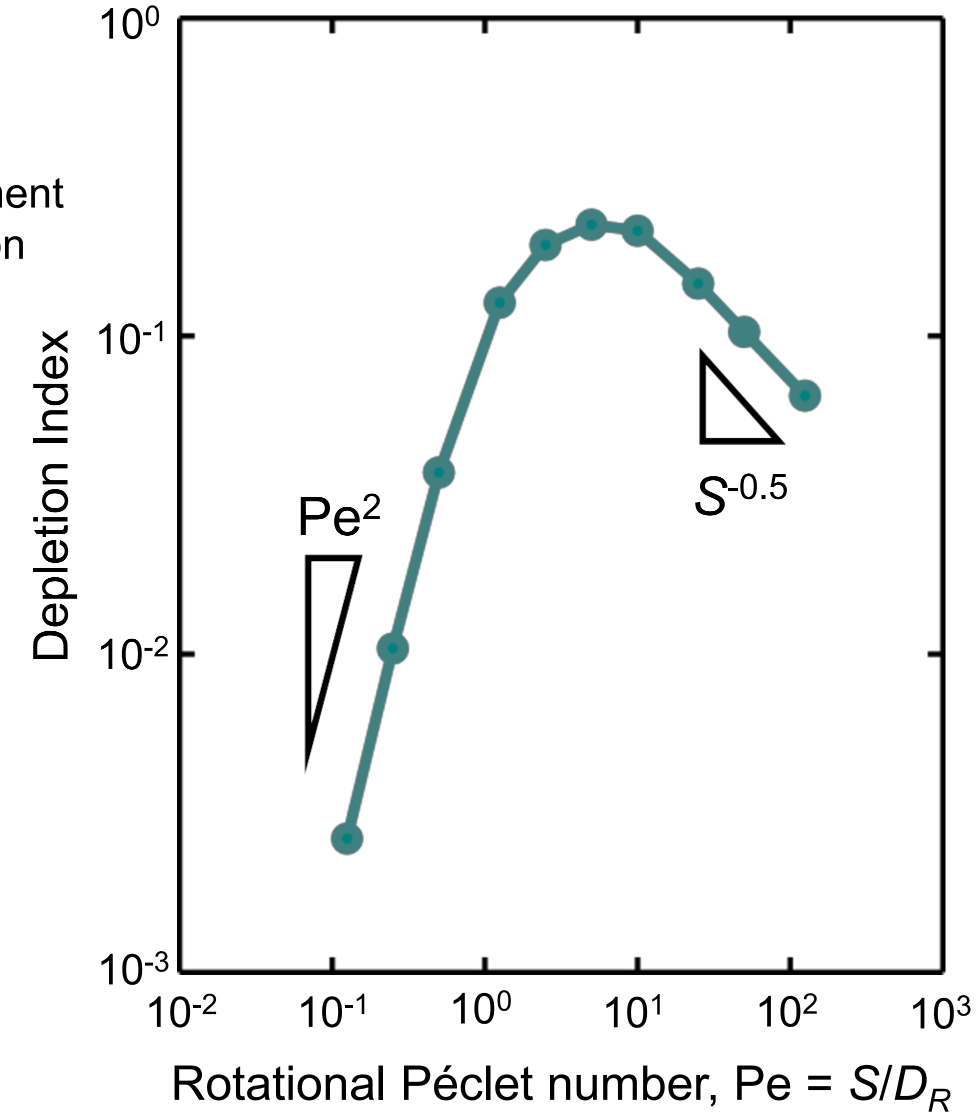
Elongation and rotational diffusion control bacterial depletion in flow

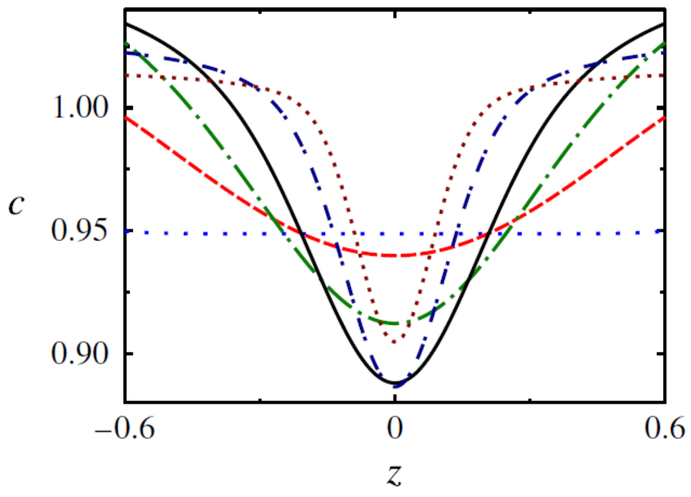
Pe<<1

Competition between shear-induced alignment and rotational diffusion



Pe>>1

Depletion effect is limited by the distance between the separatrices



Ezhilan & Saintillan. *J. Fluid Mech.* 2015

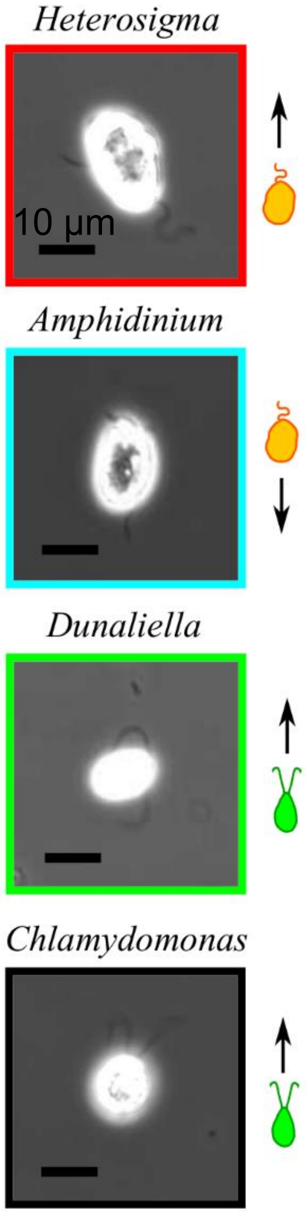
Rusconi et al. *Nat. Phys.* 2014

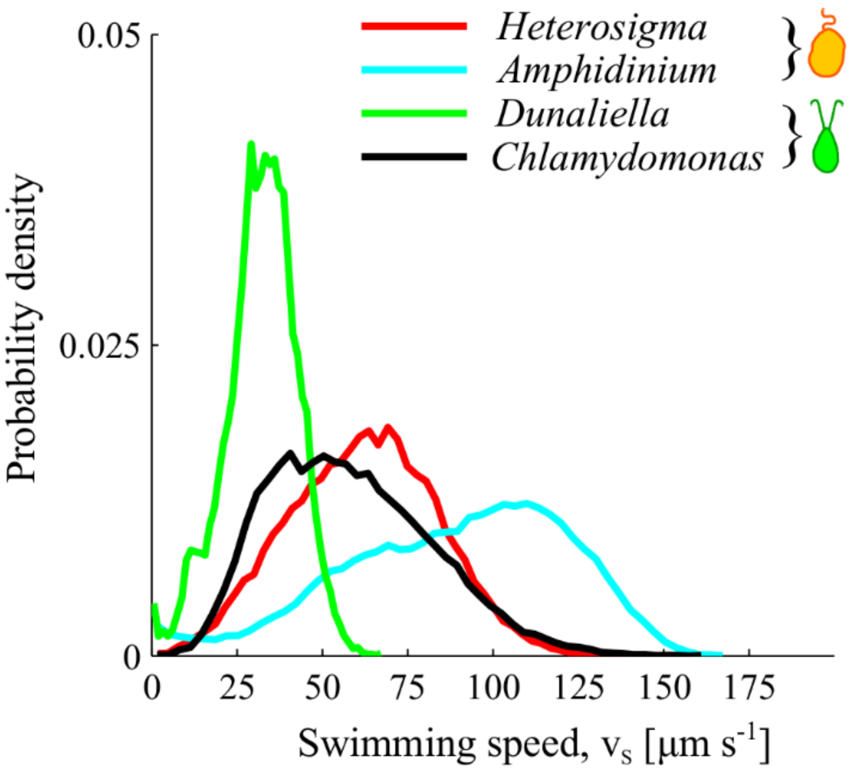
Spatial heterogeneity in suspensions of phytoplankton cells

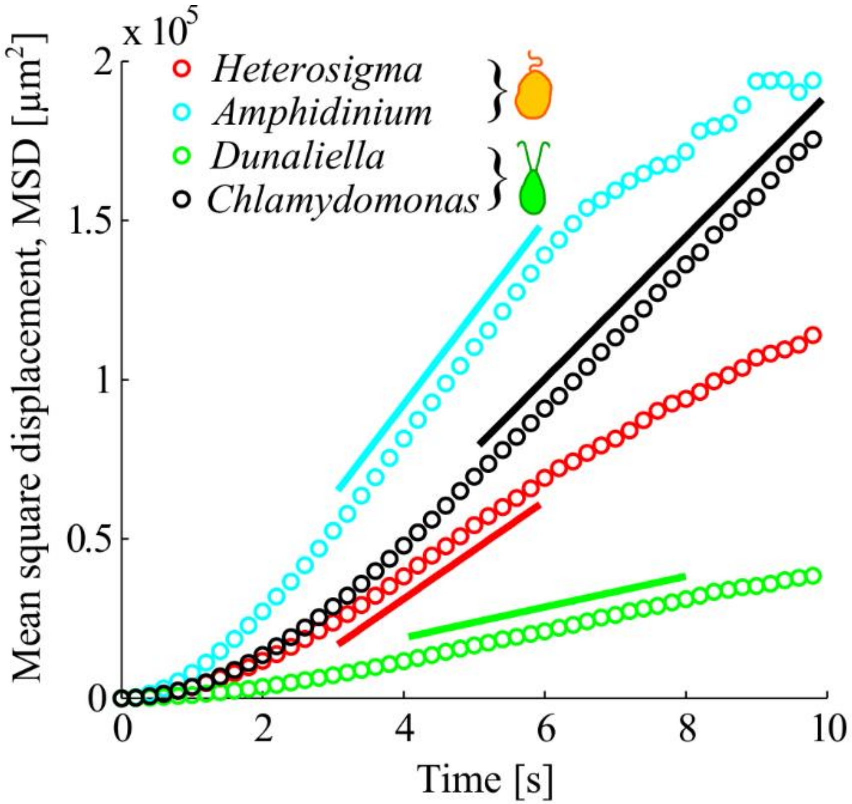
t=0 s

S=0.5 s^{-1} S=2.5 s^{-1} S=12.5 s^{-1}

Spatial heterogeneity in suspensions of phytoplankton cells







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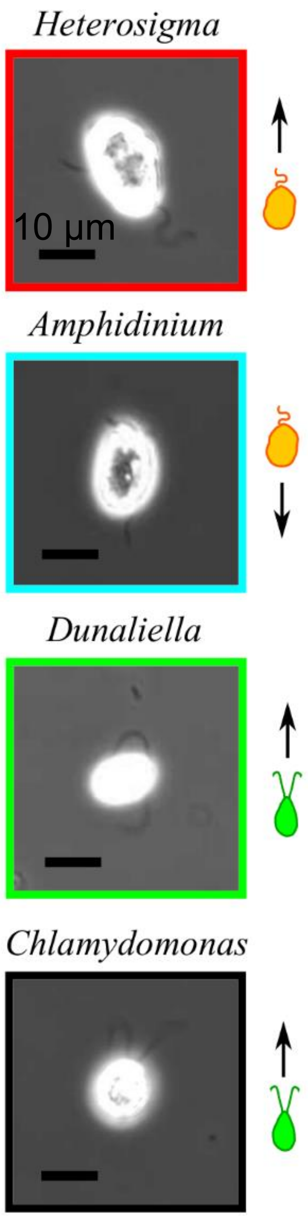

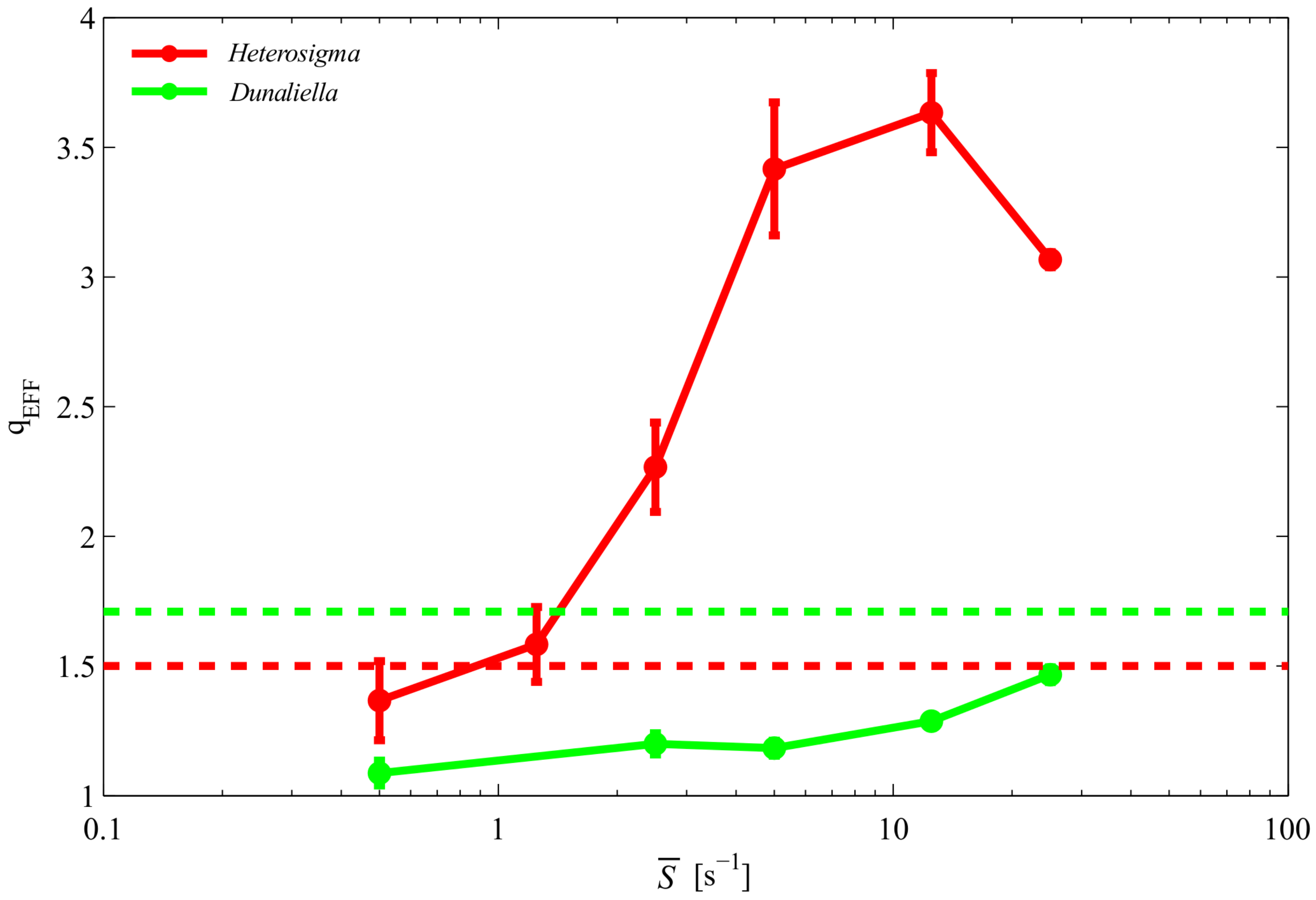

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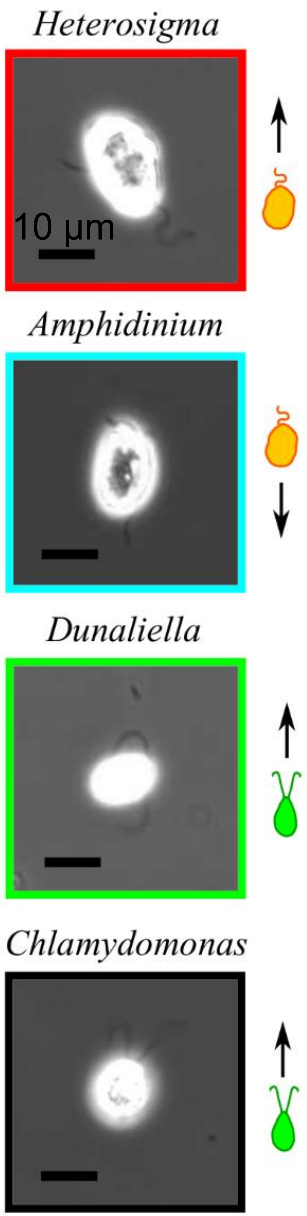

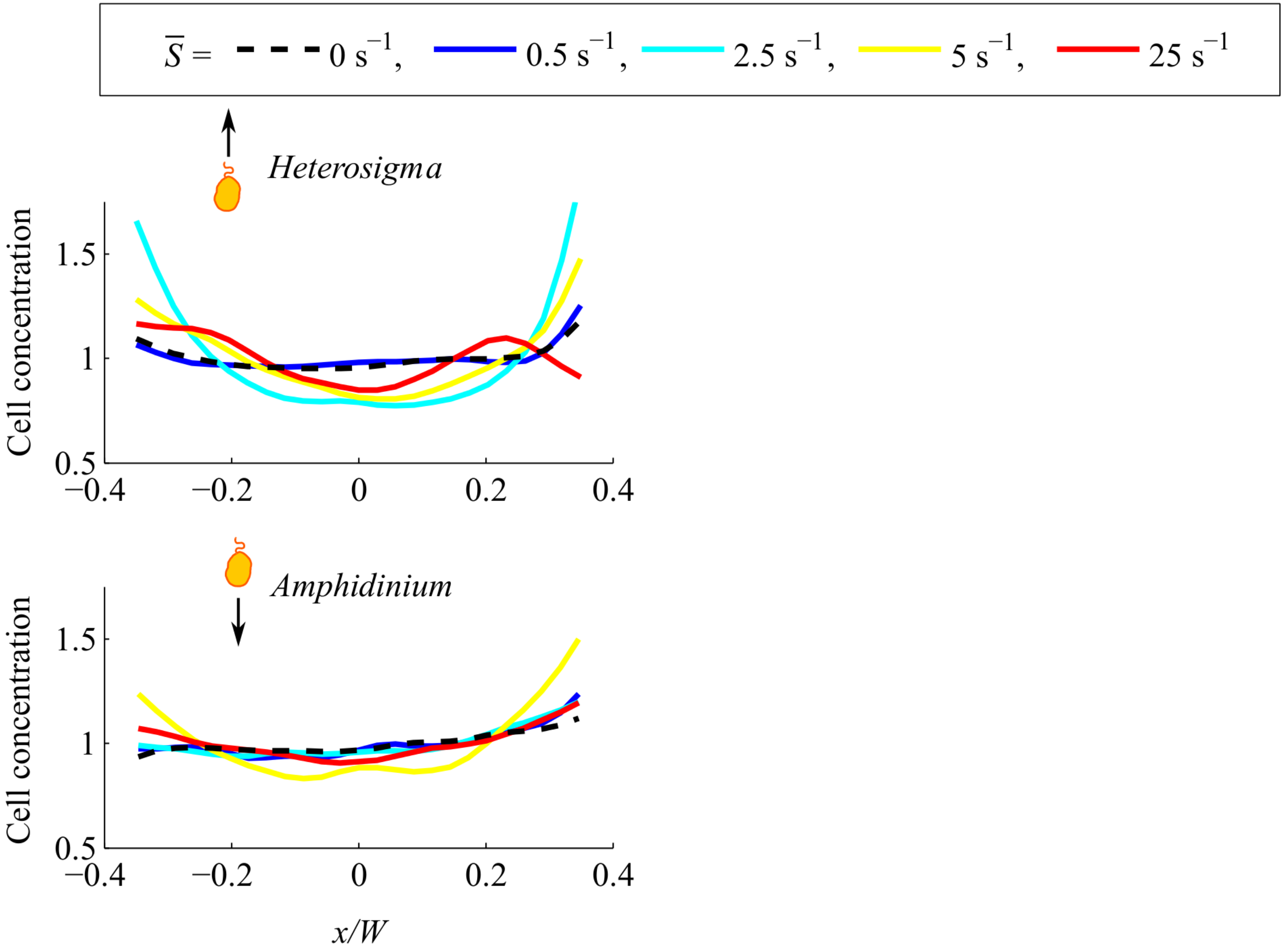

Barry, Rusconi et al. *J. Roc. Soc. Interface* 2015

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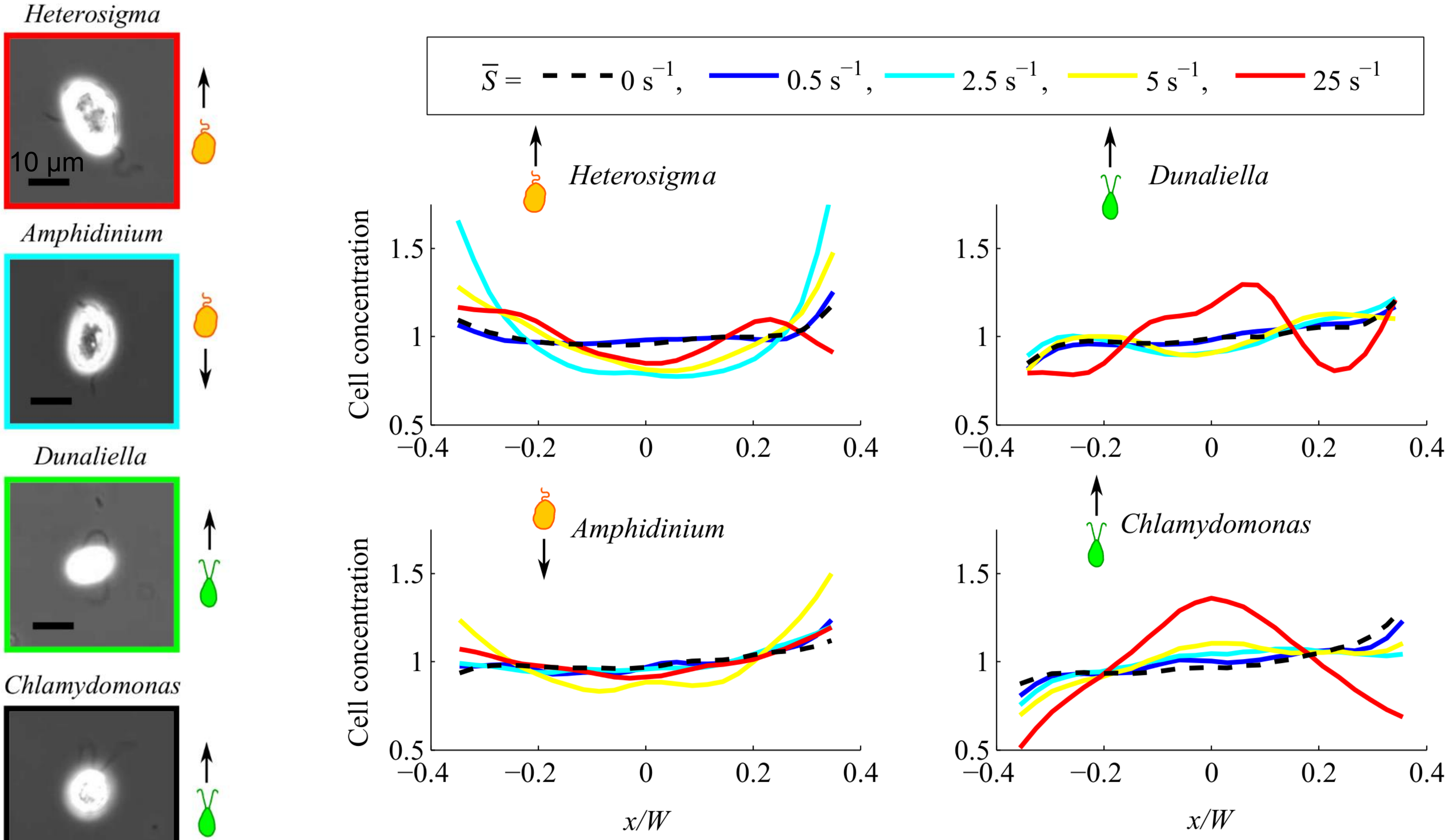
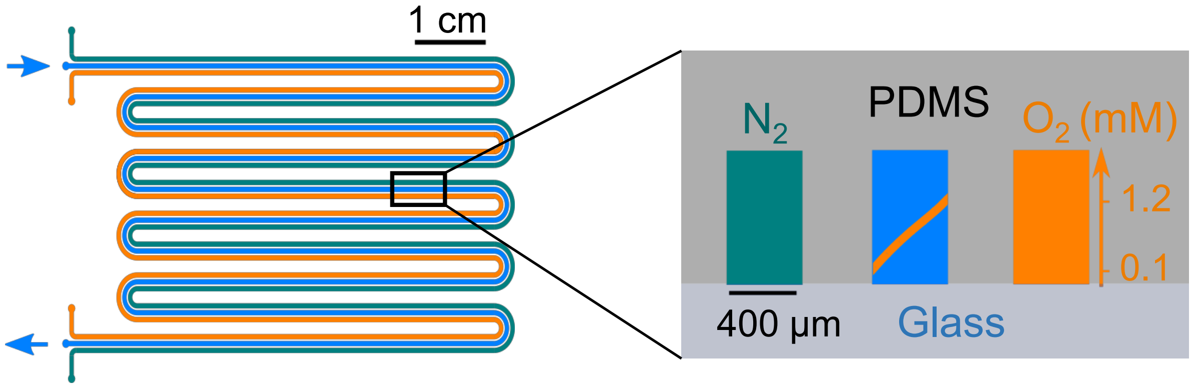
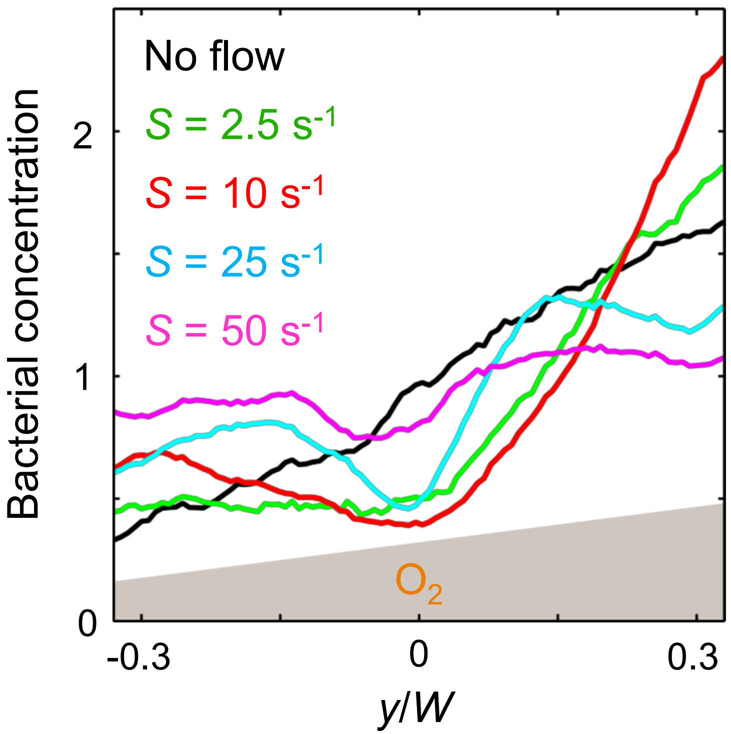
Spatial heterogeneity in suspensions of phytoplankton cells

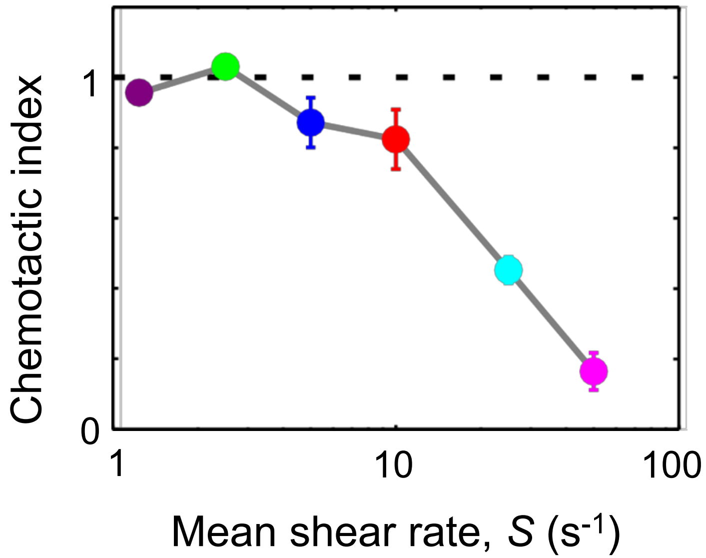


Barry, Rusconi et al. *J. Roc. Soc. Interface* 2015

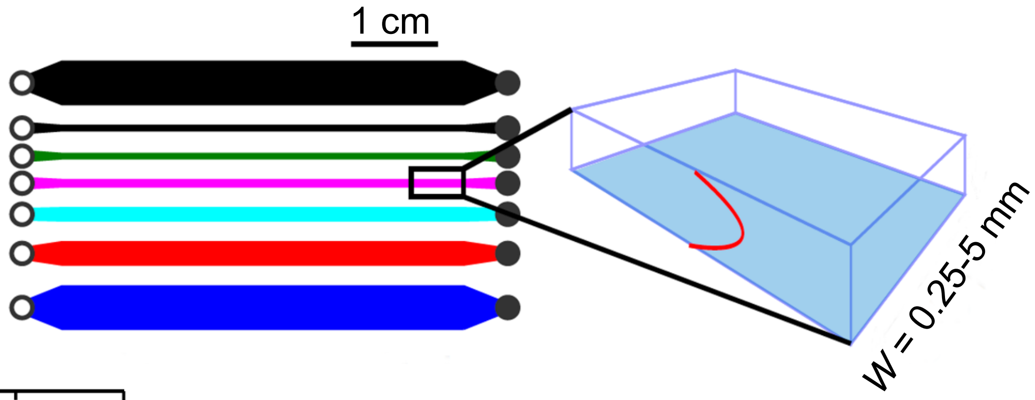
Shear suppresses bacterial chemotaxis

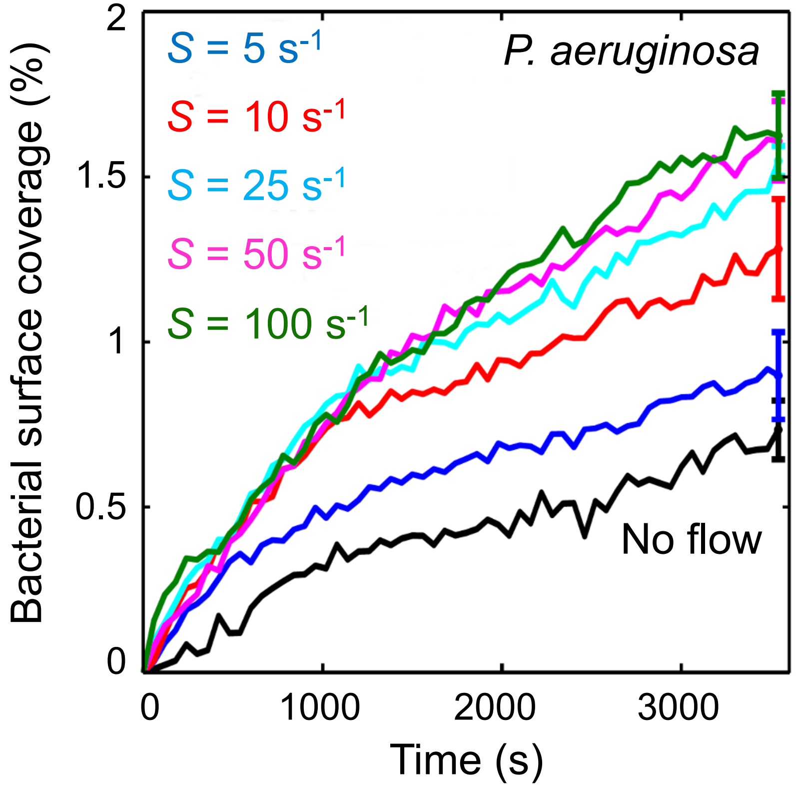


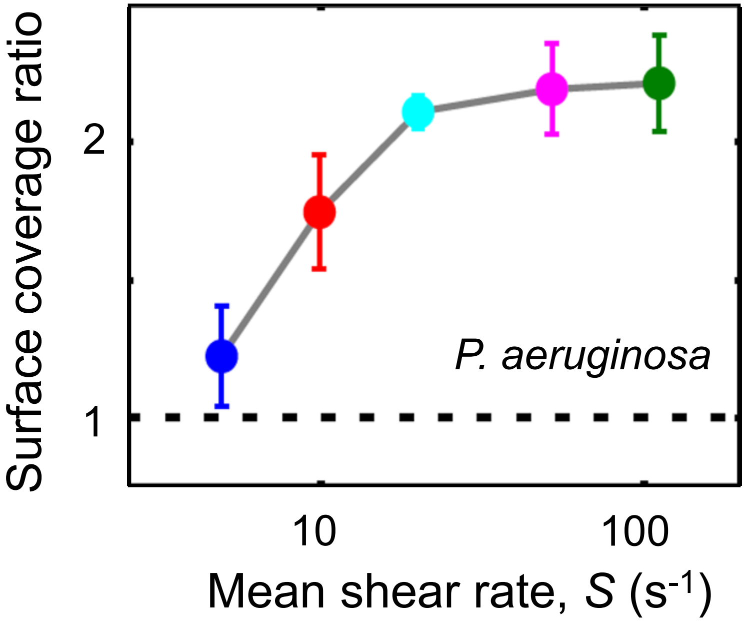


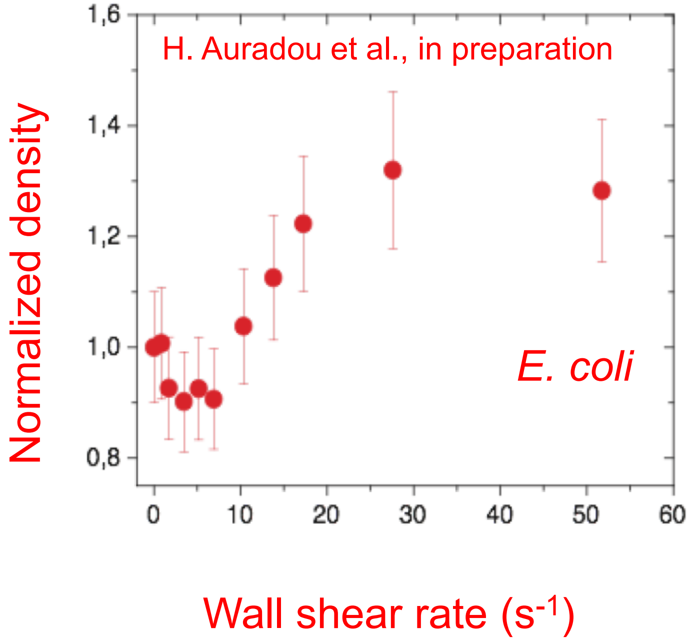


Shear promotes surface attachment









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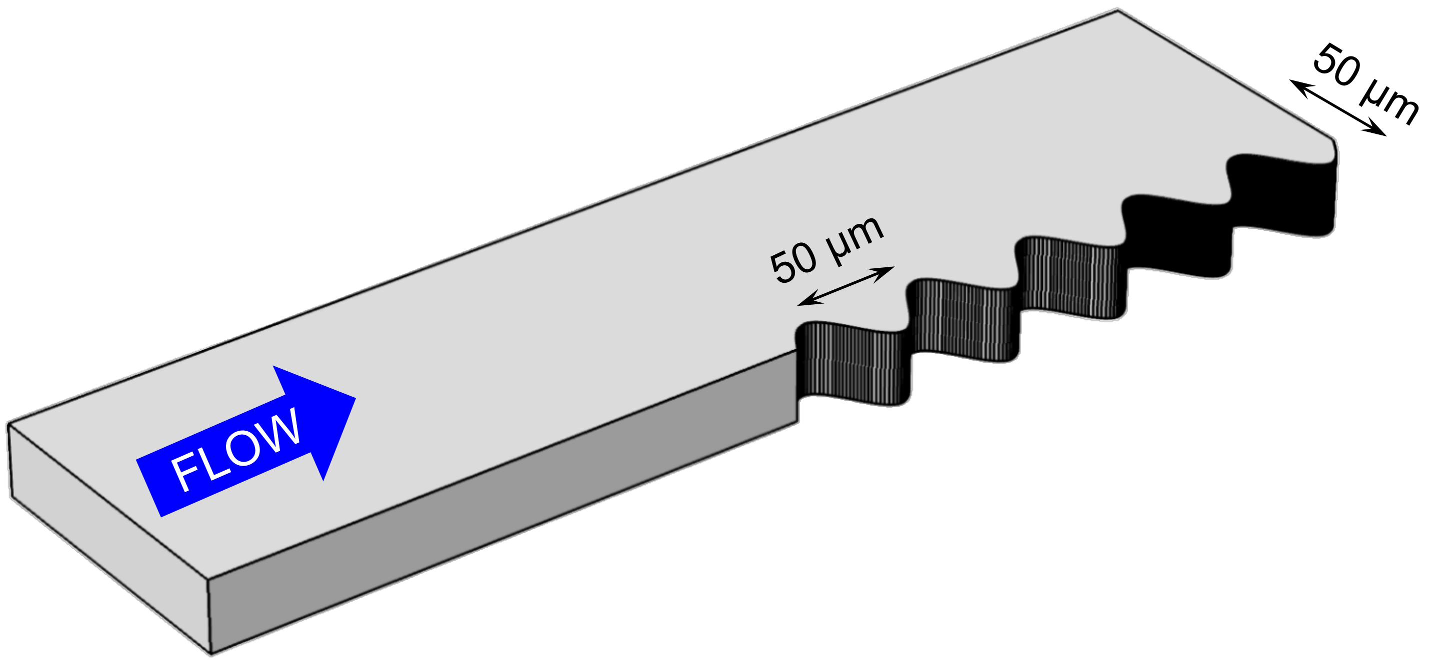
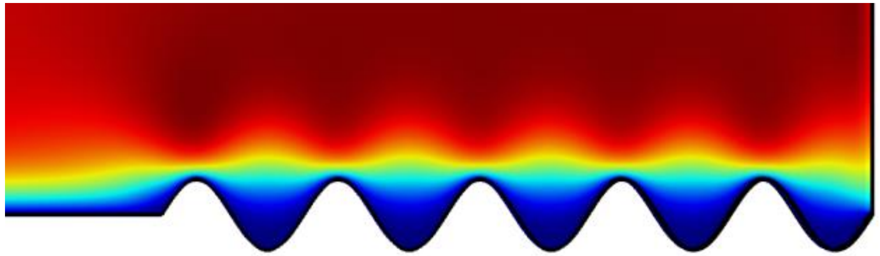
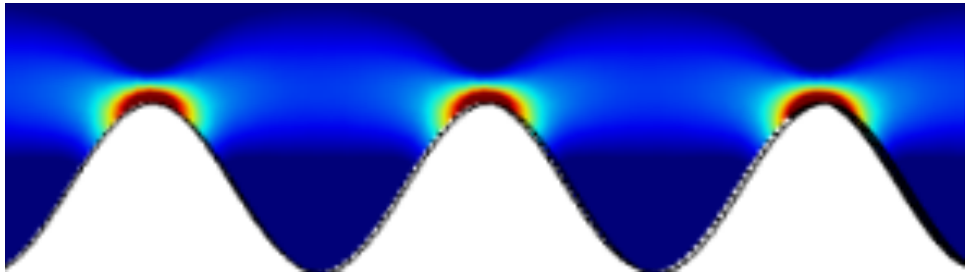
Shear induces preferential attachment to corrugated surfaces



Flow velocity



Shear rate



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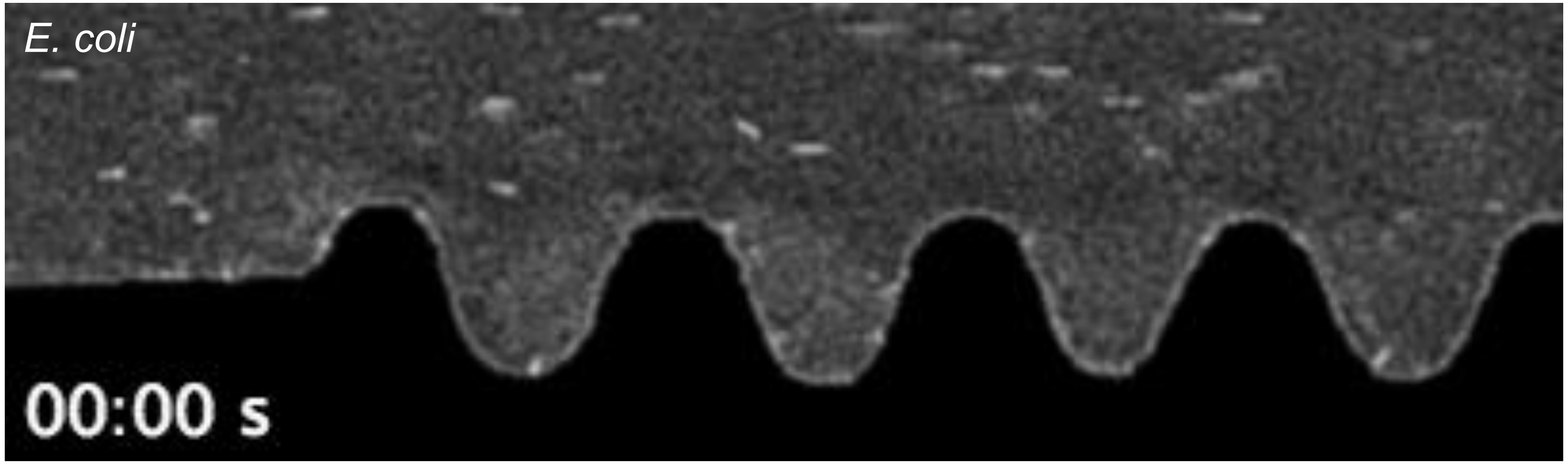
Experiments



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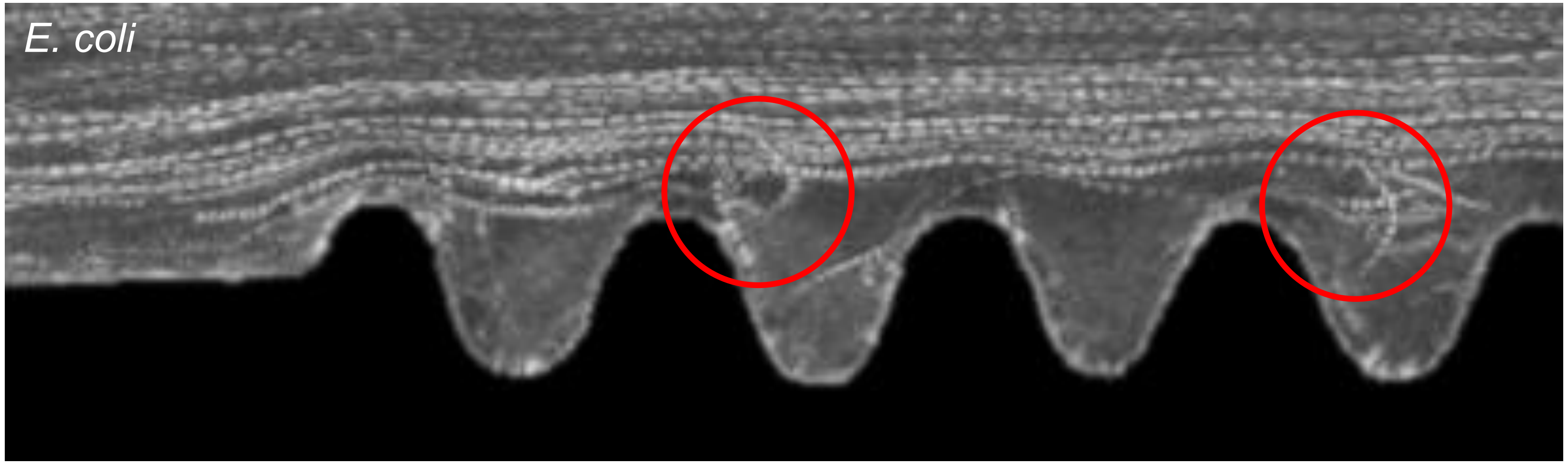
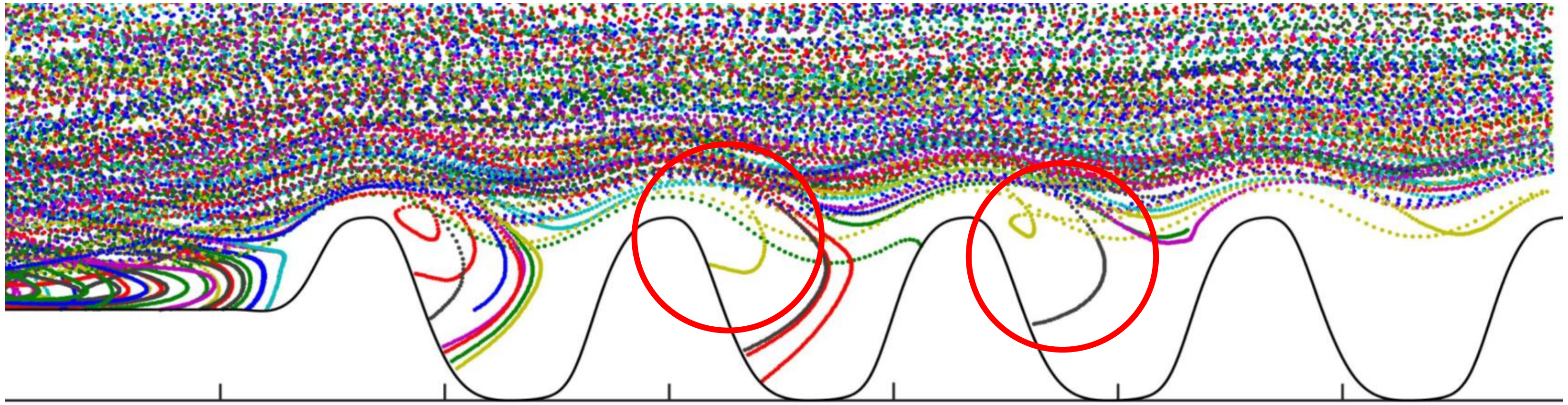


Simulations



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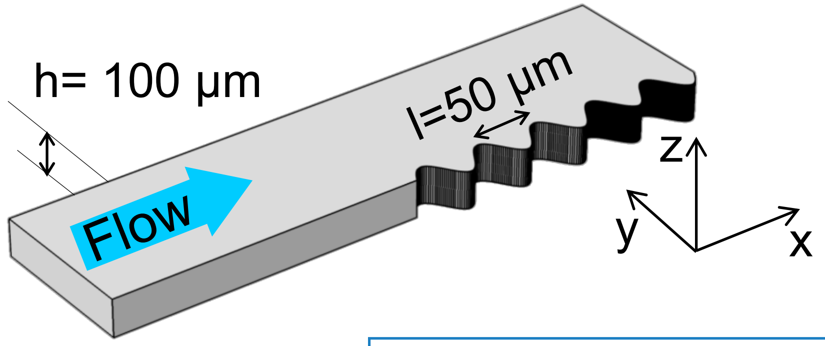
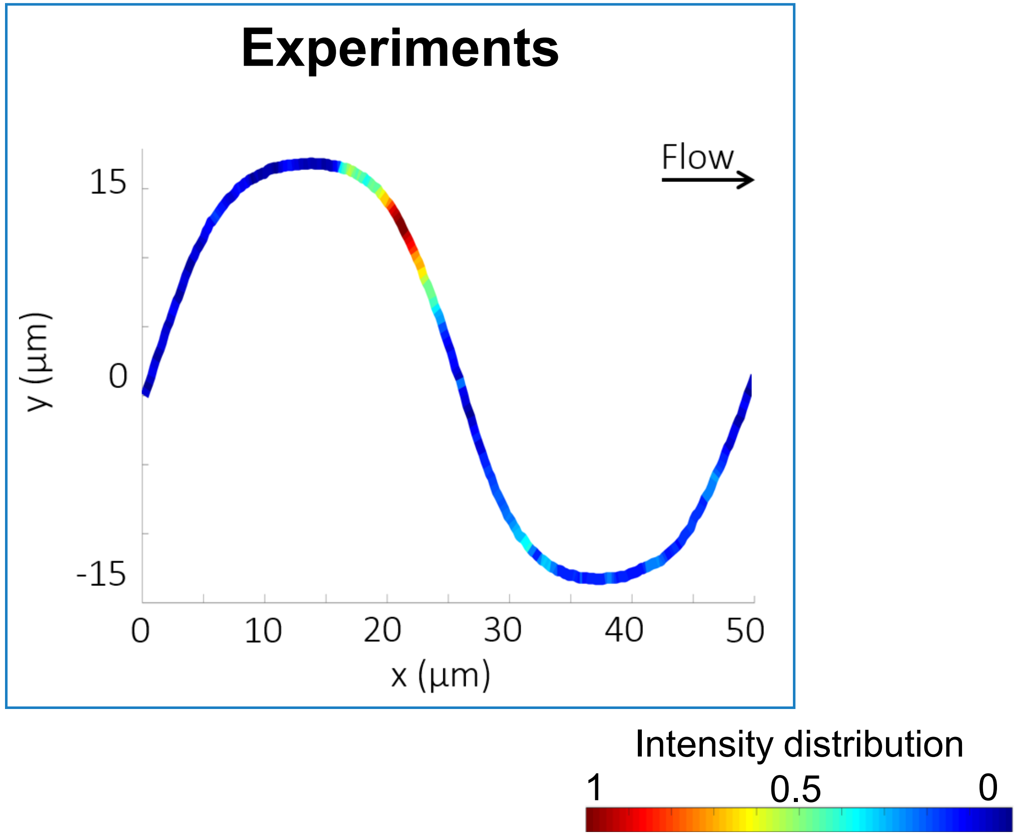


Escherichia coli GFP

$q = 8$, $V = 22\ \mu m/s$,
$D_R = 0.5\ rad^2/s$



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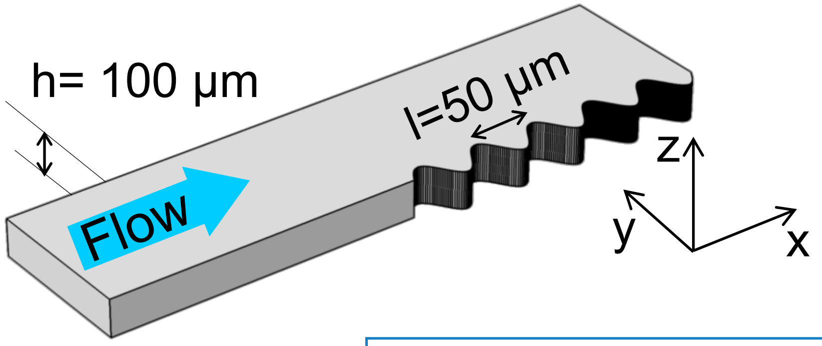

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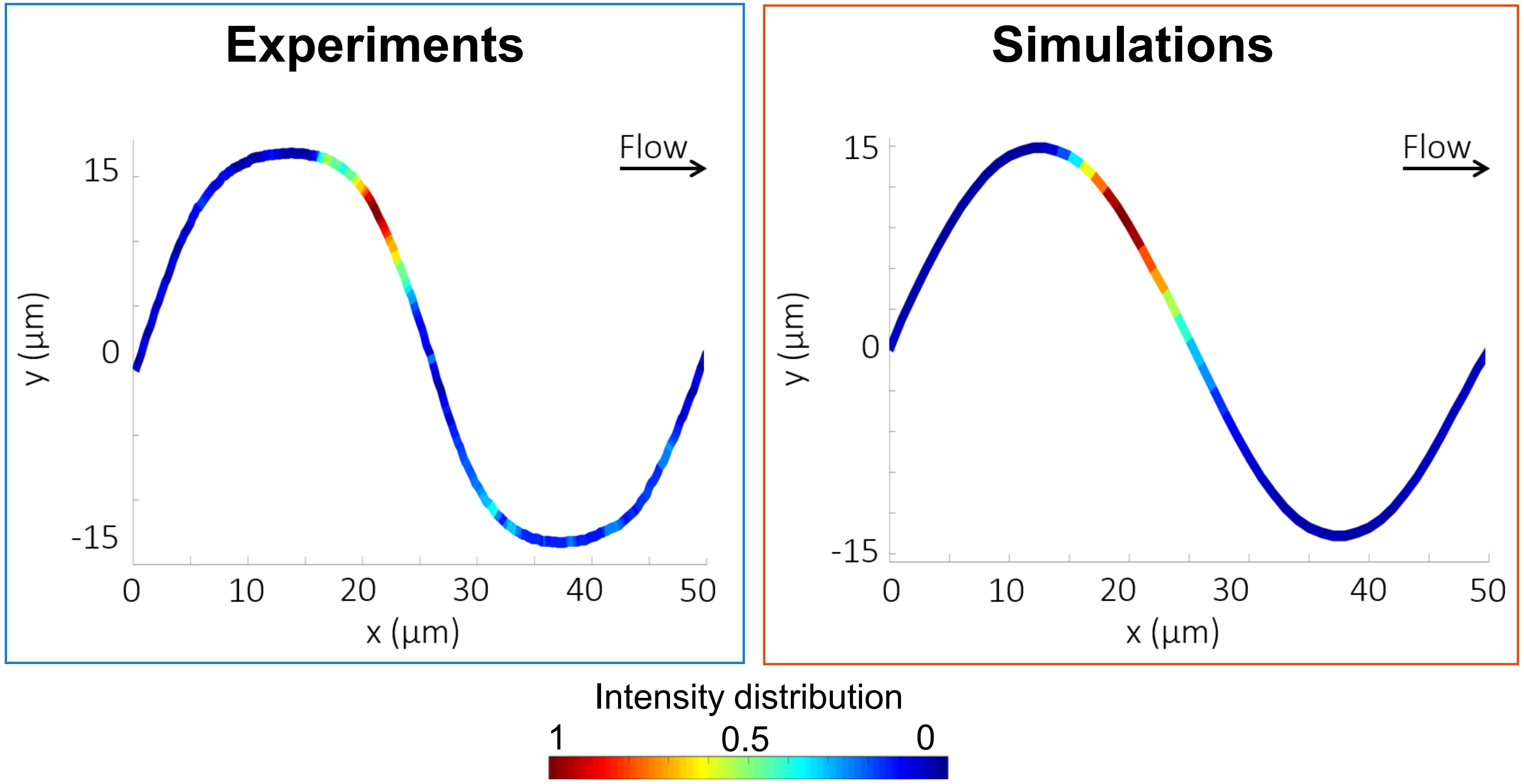

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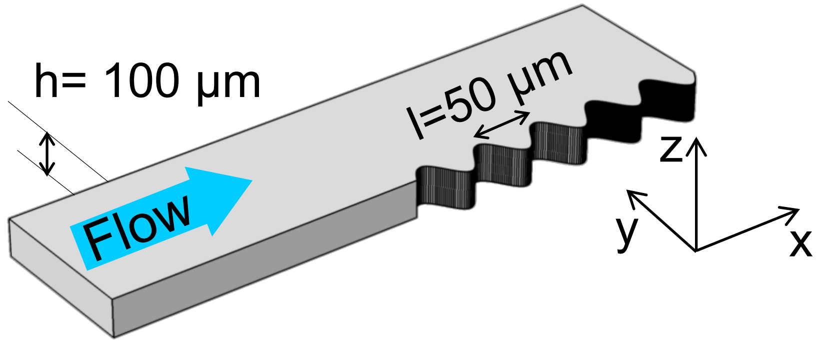

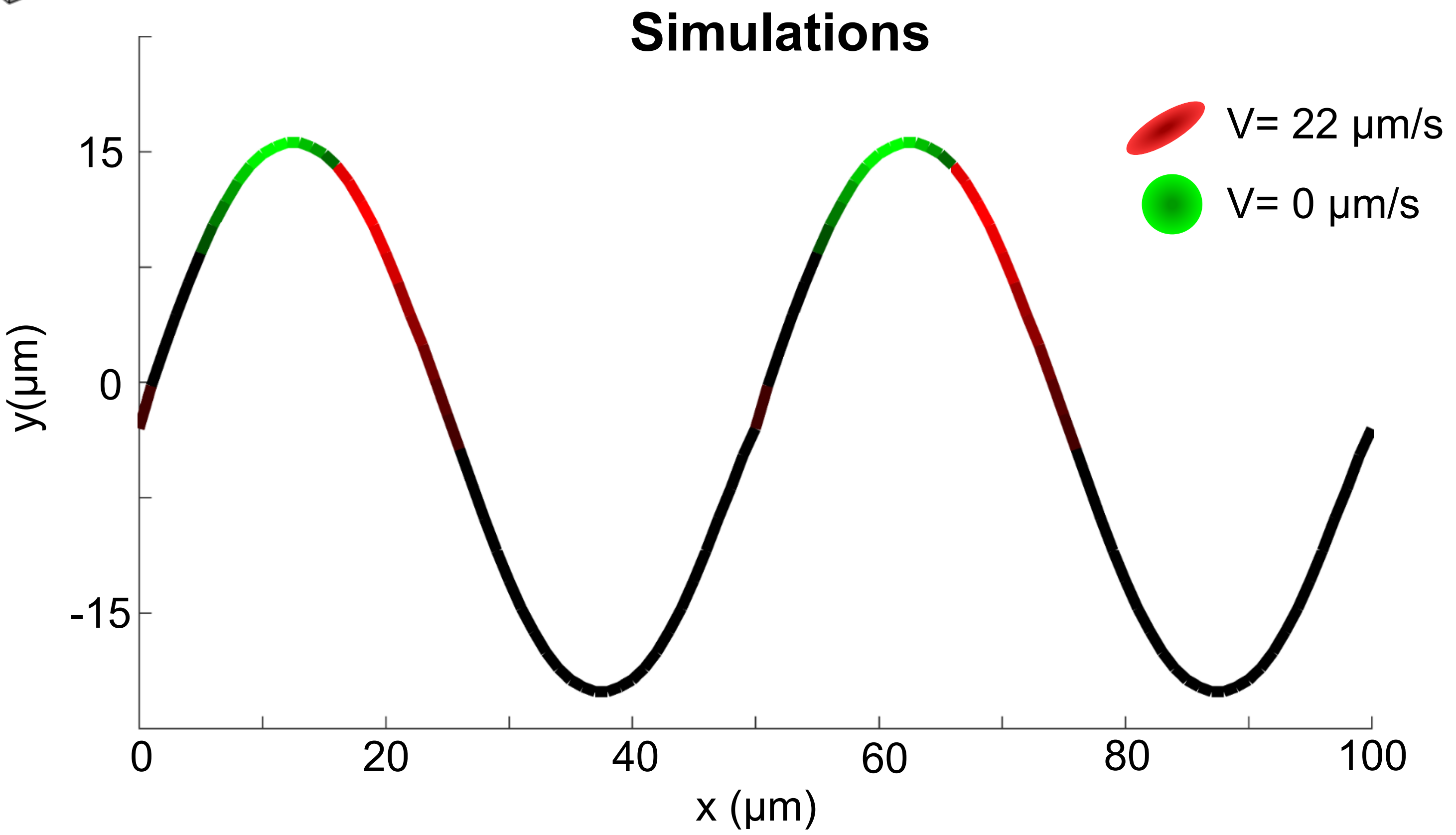

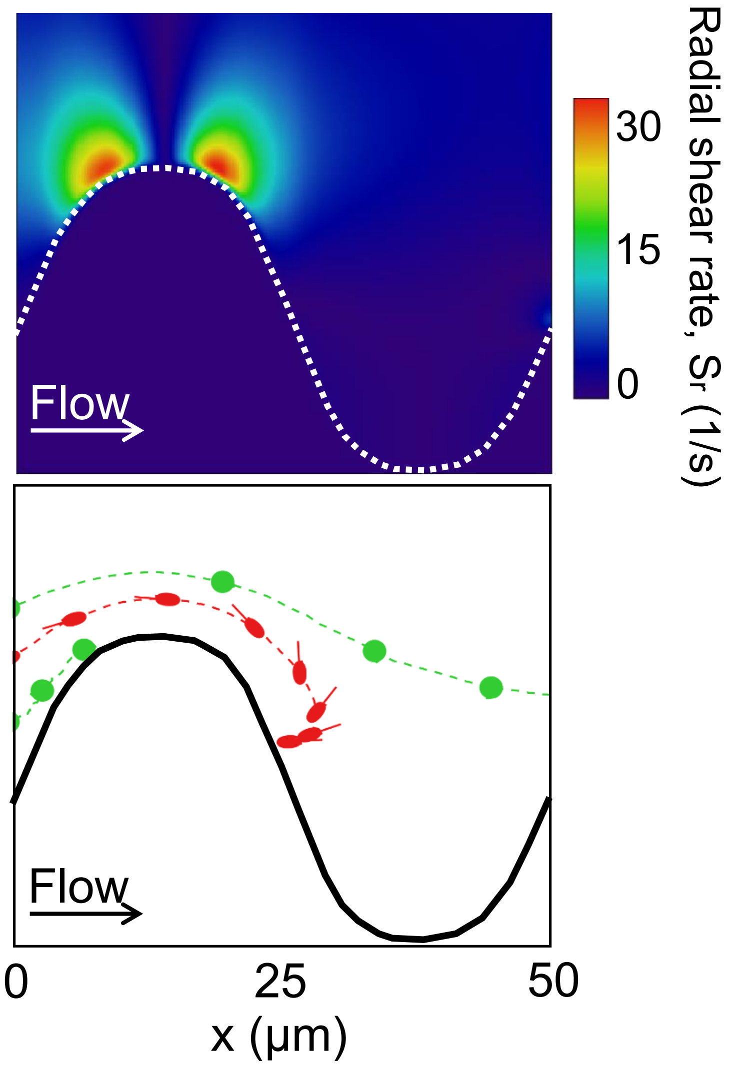

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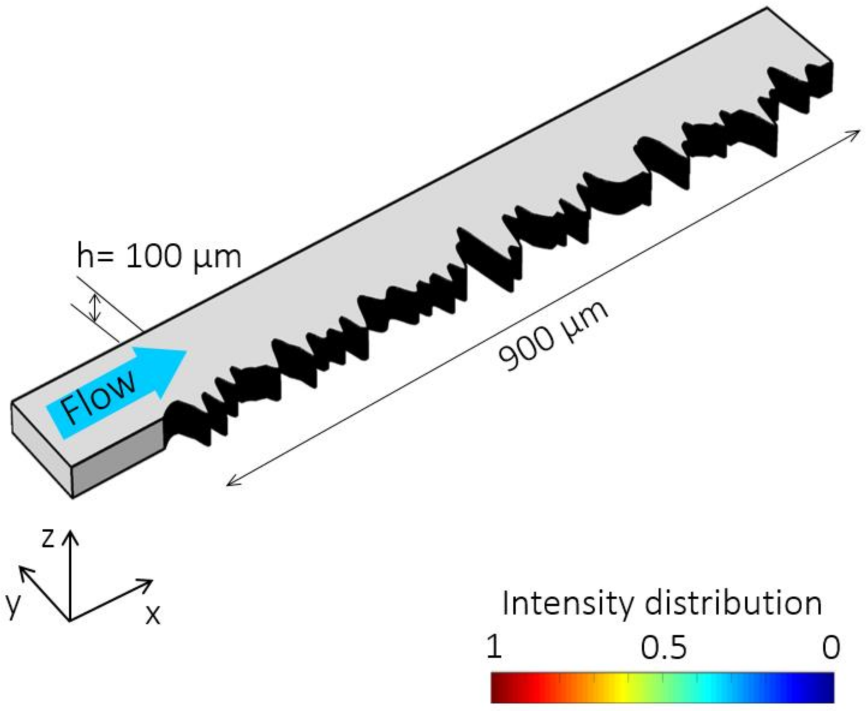

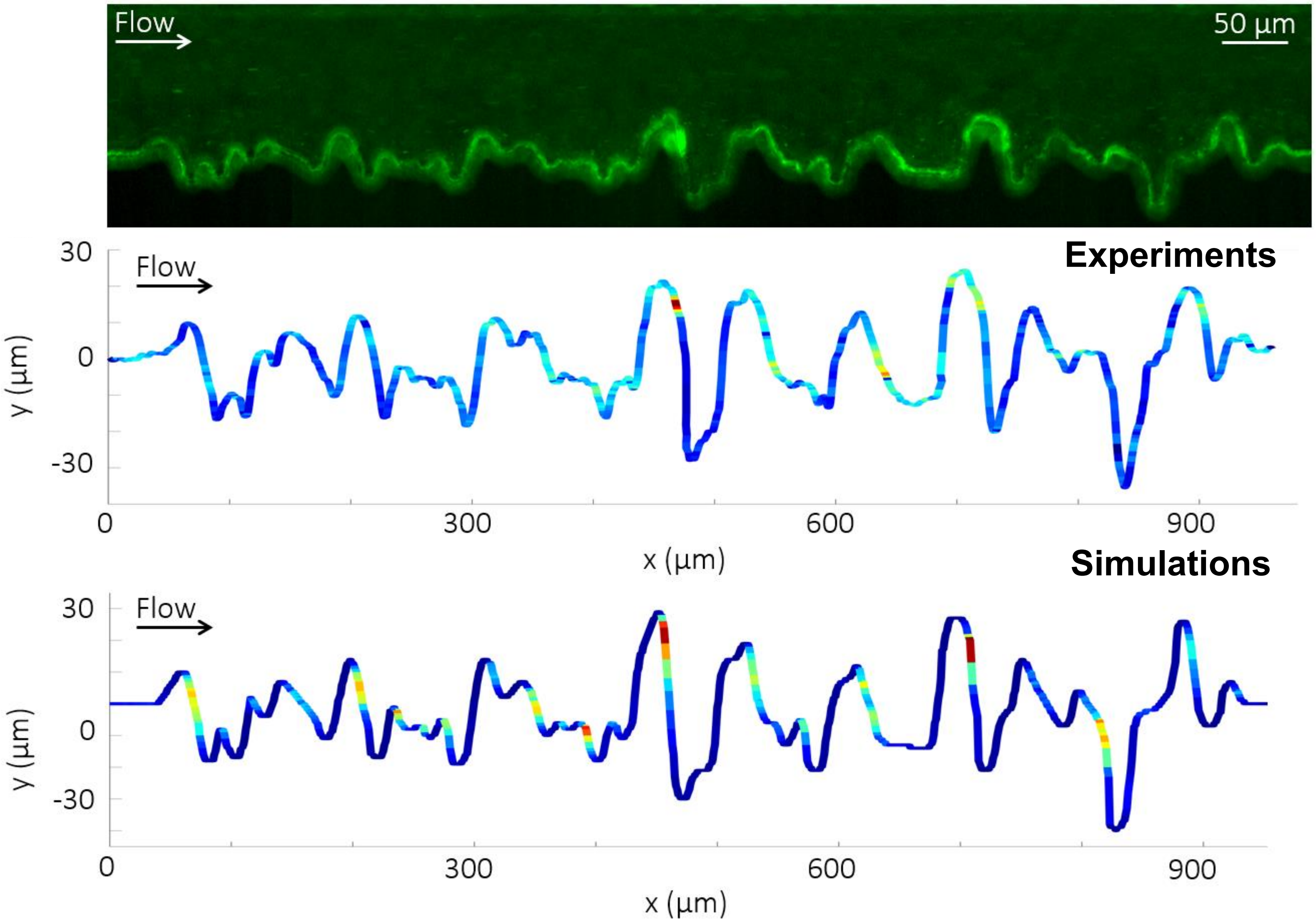

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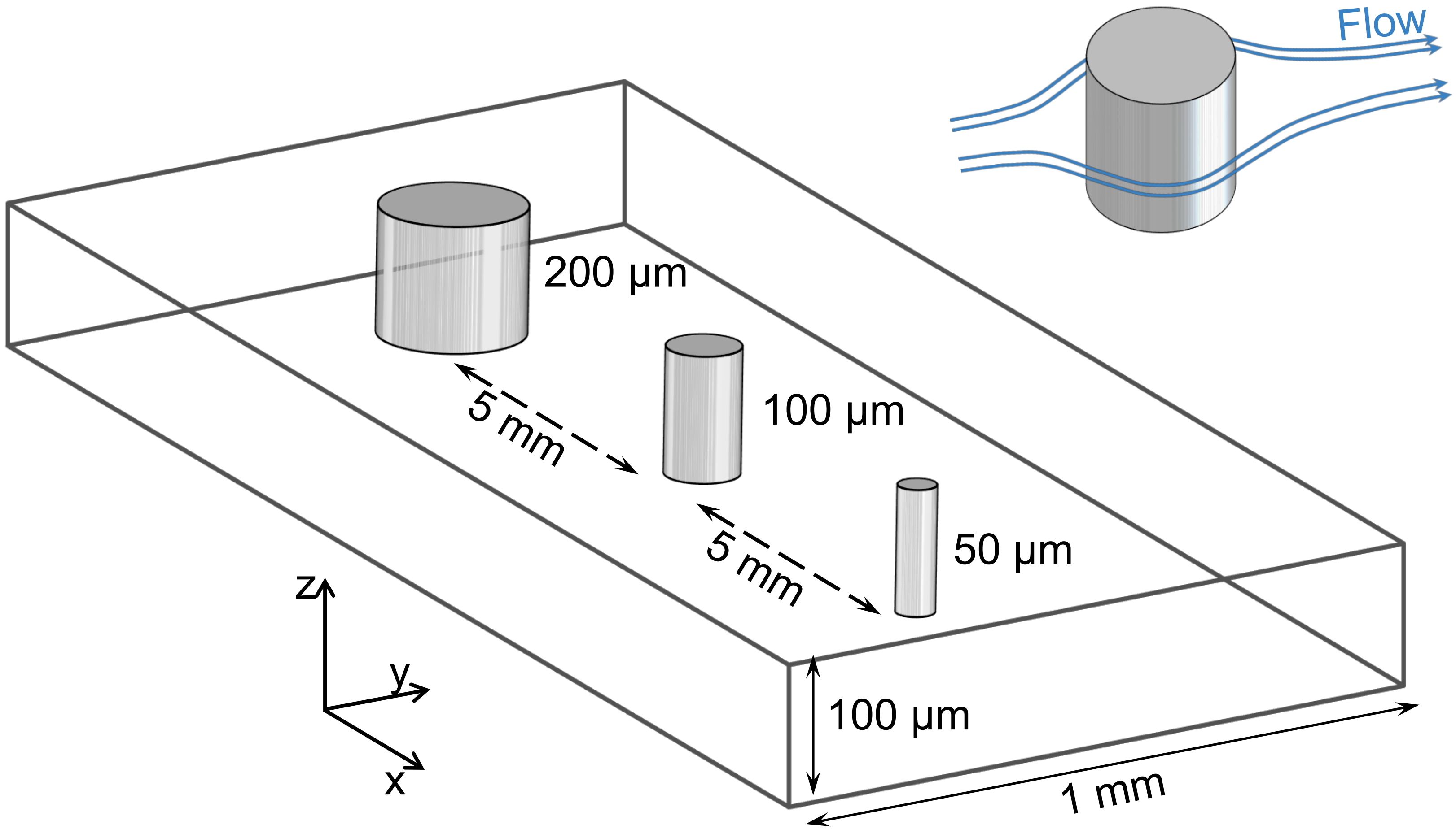
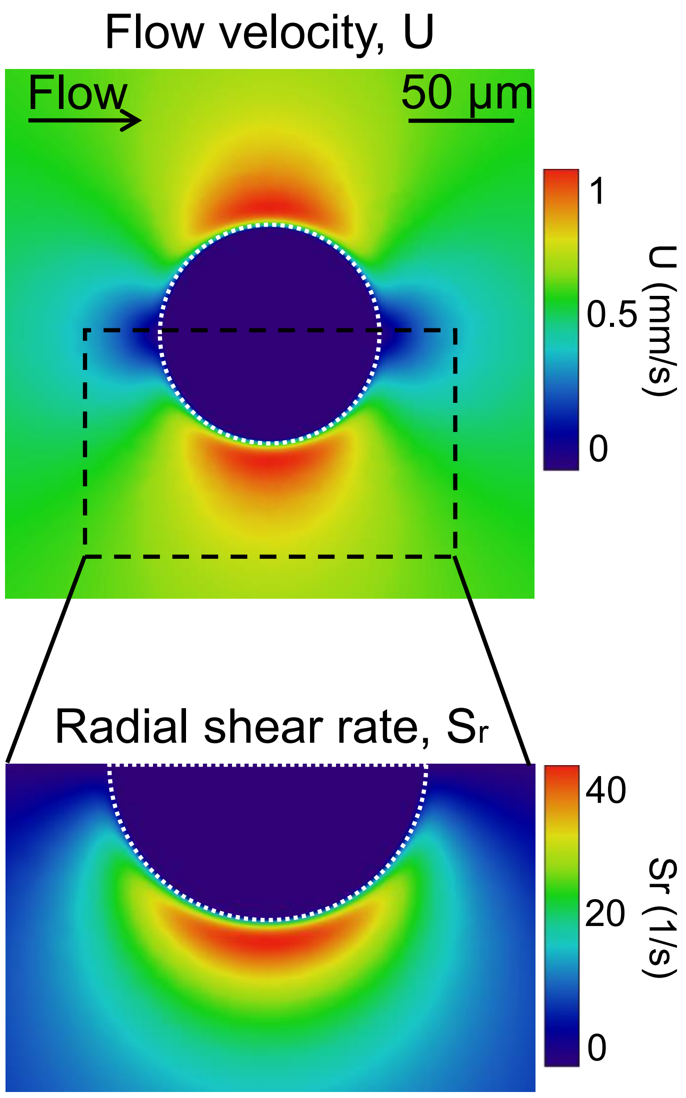
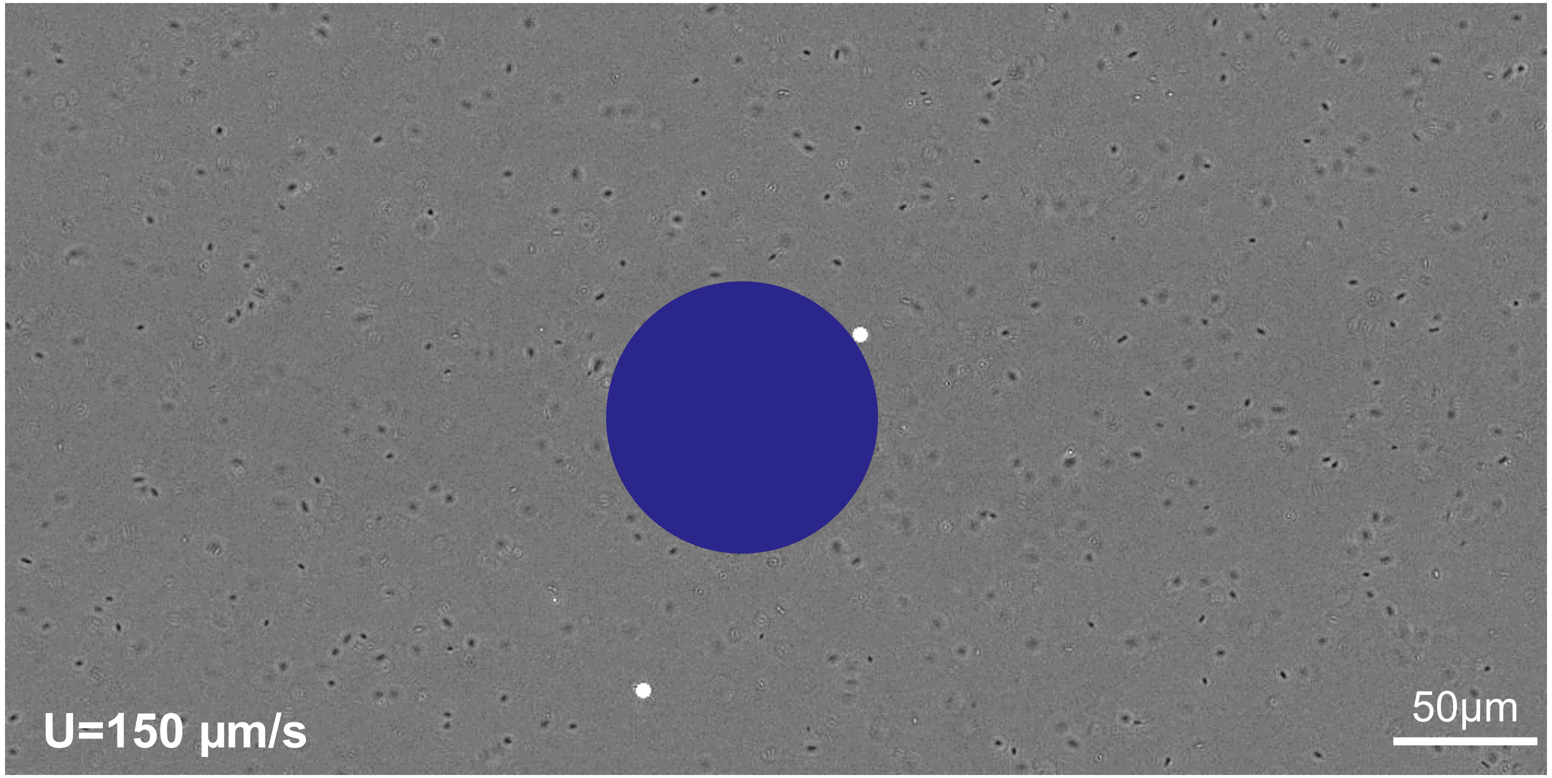
Motility and flow control bacterial transport and attachment around pillars

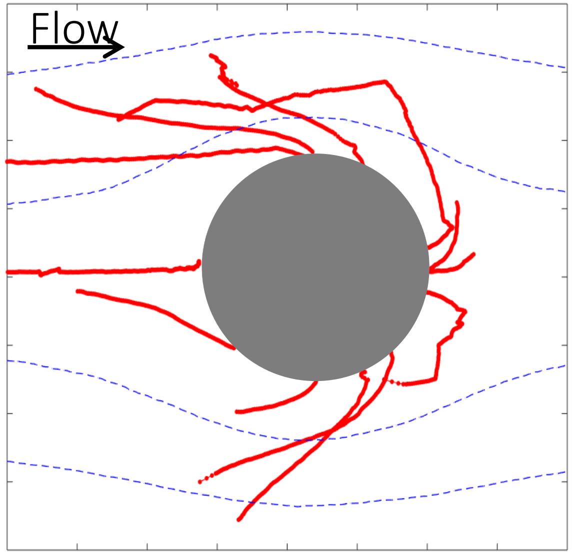


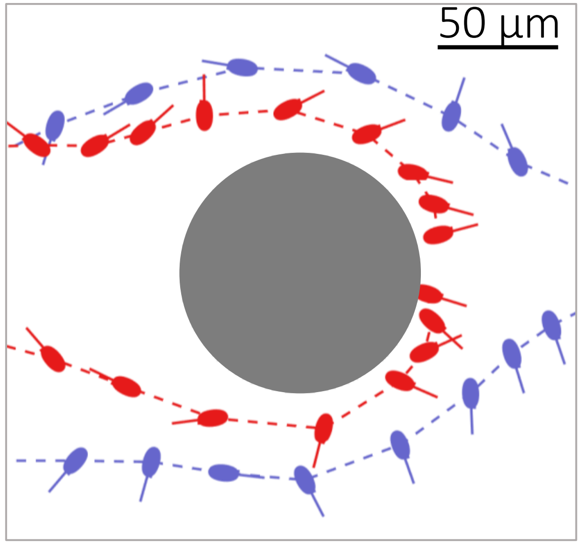


Motility and flow control bacterial transport and attachment around pillars

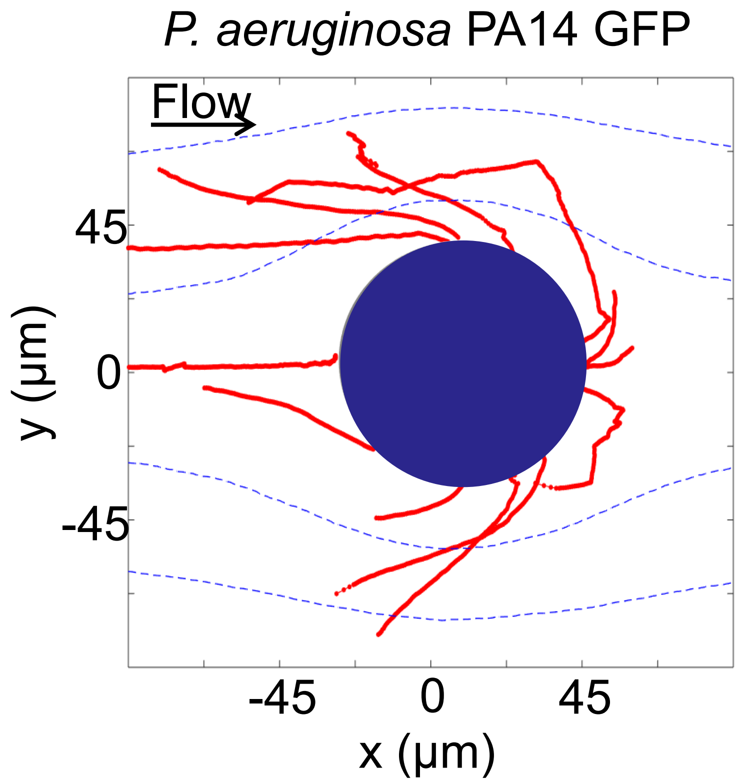
Pseudomonas aeruginosa PA14

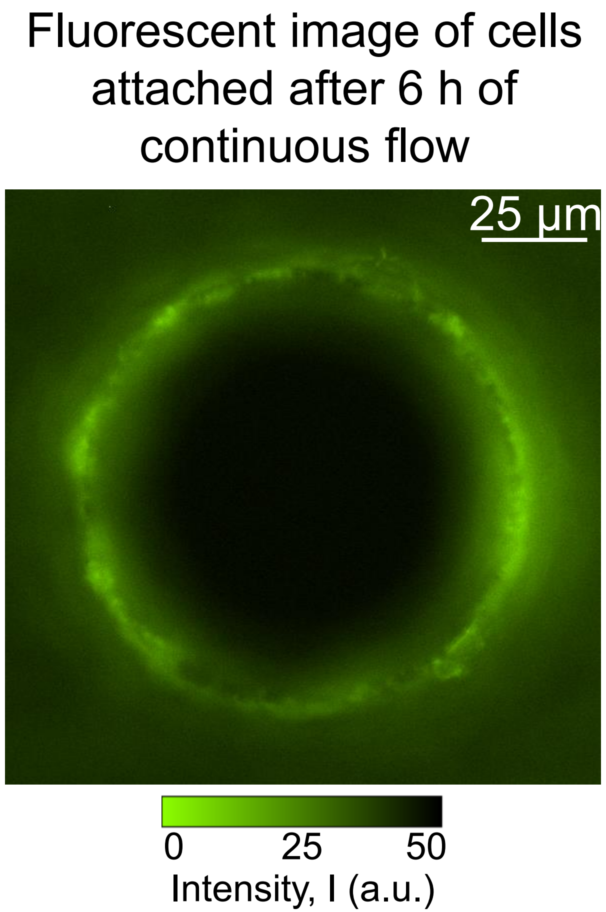


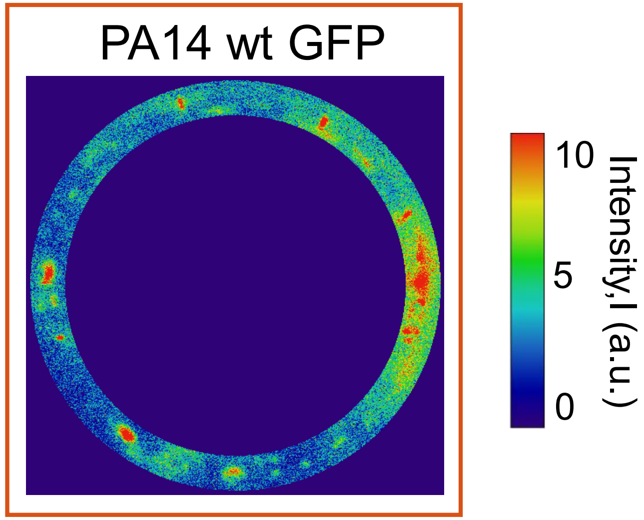


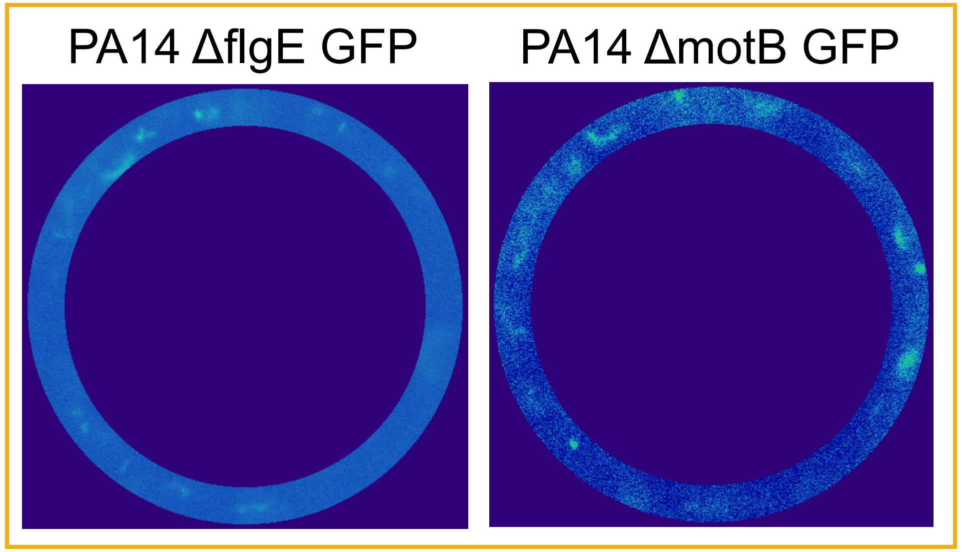


Motility and flow control bacterial transport and attachment around pillars





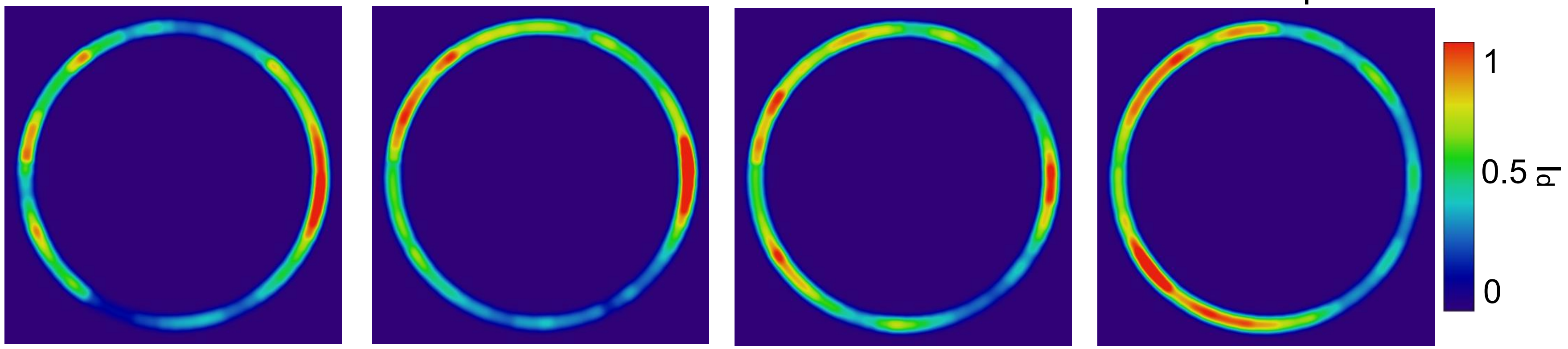




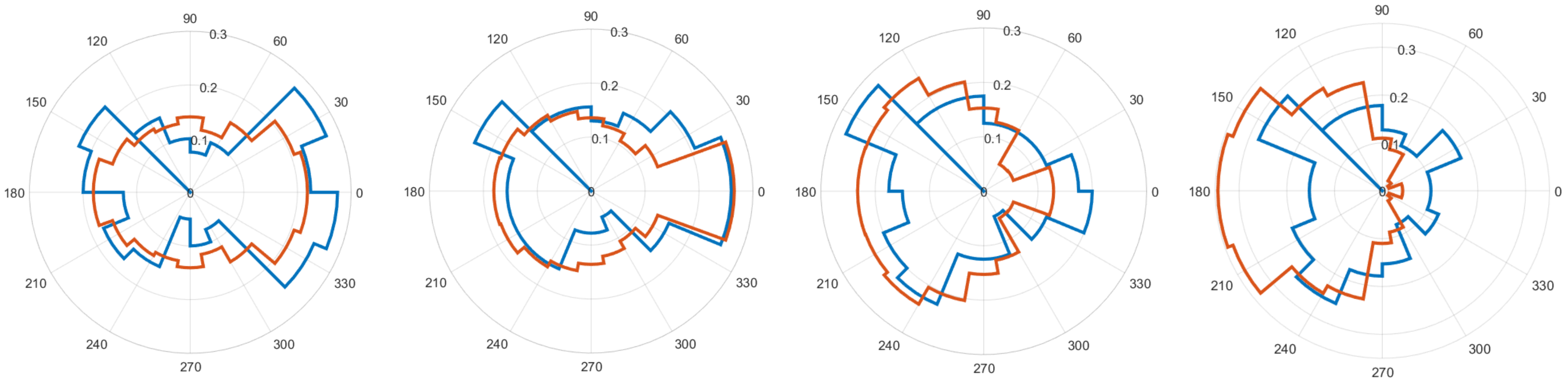
Motility and flow control bacterial transport and attachment around pillars

Normalized intensity distribution

U= 150 μm/s　U= 300 μm/s　U= 600 μm/s　U= 1000 μm/s



Polar distribution



Flow

Simulations, Experiments

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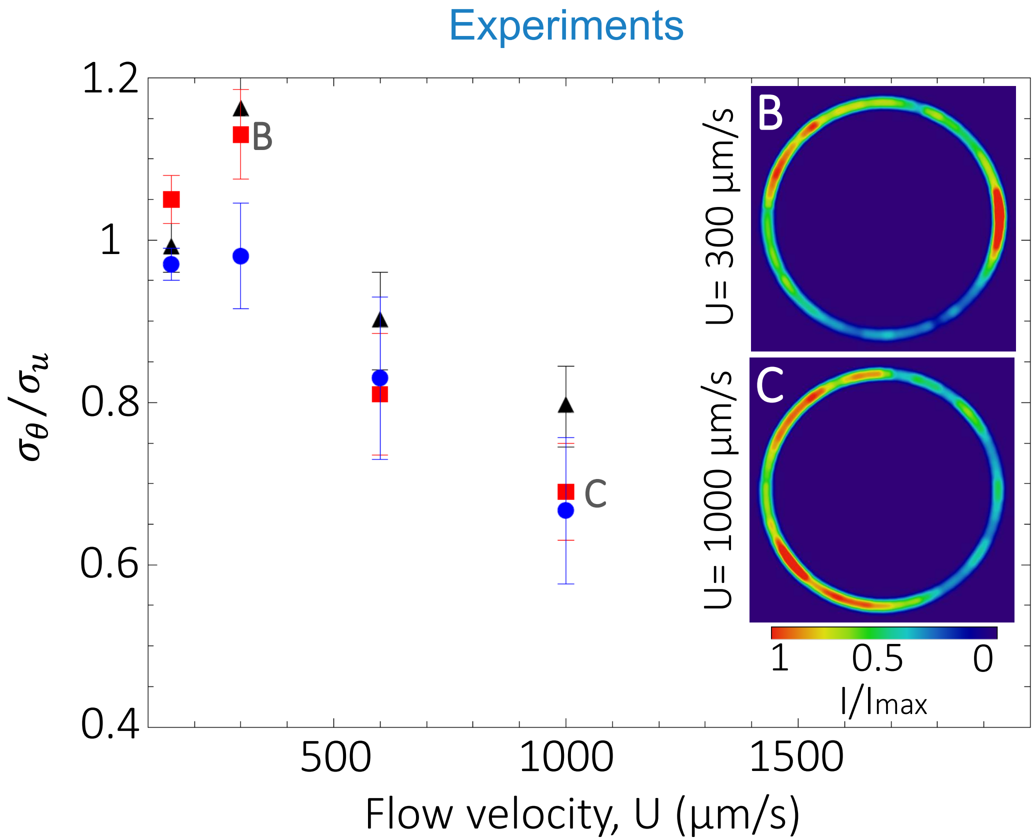
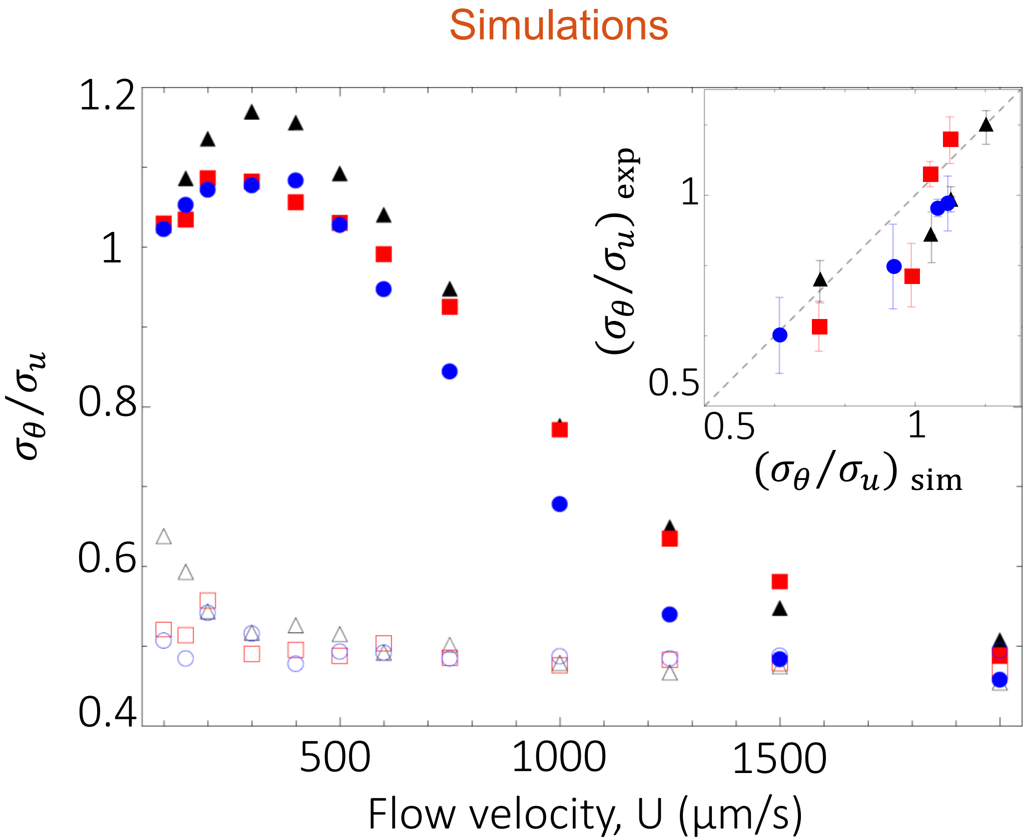
Motility and flow control bacterial transport and attachment around pillars





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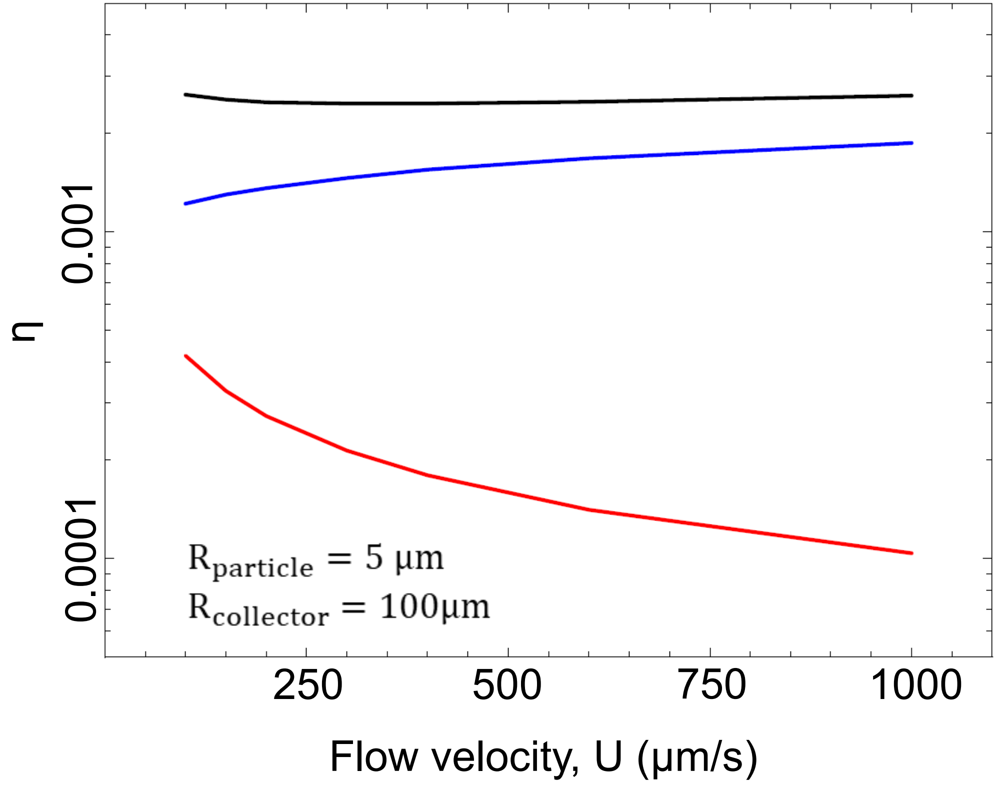
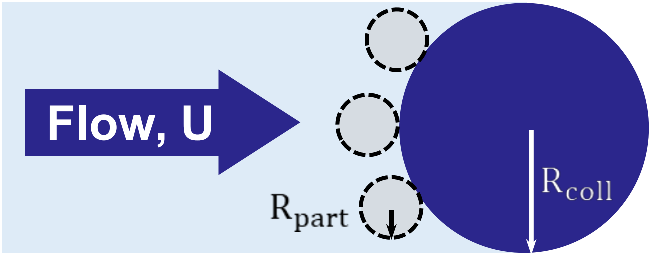
Motility and flow control bacterial transport and attachment around pillars

Capture efficiency

$$\eta = \frac{\text{Particles captured by the collector}}{\text{Particles in the volume of liquid passing through the projected area of the collector}}$$





- **Direct interception** (Fuchs, 1964)

$$\eta = 2A\left[(1+r_p)\ln(1+r_p) - \frac{r_p(2+r_p)}{2(1+r_p)}\right]$$

- **Diffusional deposition** (Natanson, 1957)

$$\eta = 3.64\, Pe^{-2/3} A^{1/3}$$

- **Direct interception and diffusional deposition** (Friedlander, 1957)

$$\eta = 1.25A\left[r_p + \frac{1.69}{(APe)^{0.367}}\right]^{1.82}$$

with $r_p = \frac{R_{particle}}{R_{collector}}$ and $A = \frac{1}{2(2-\ln(Re))}$

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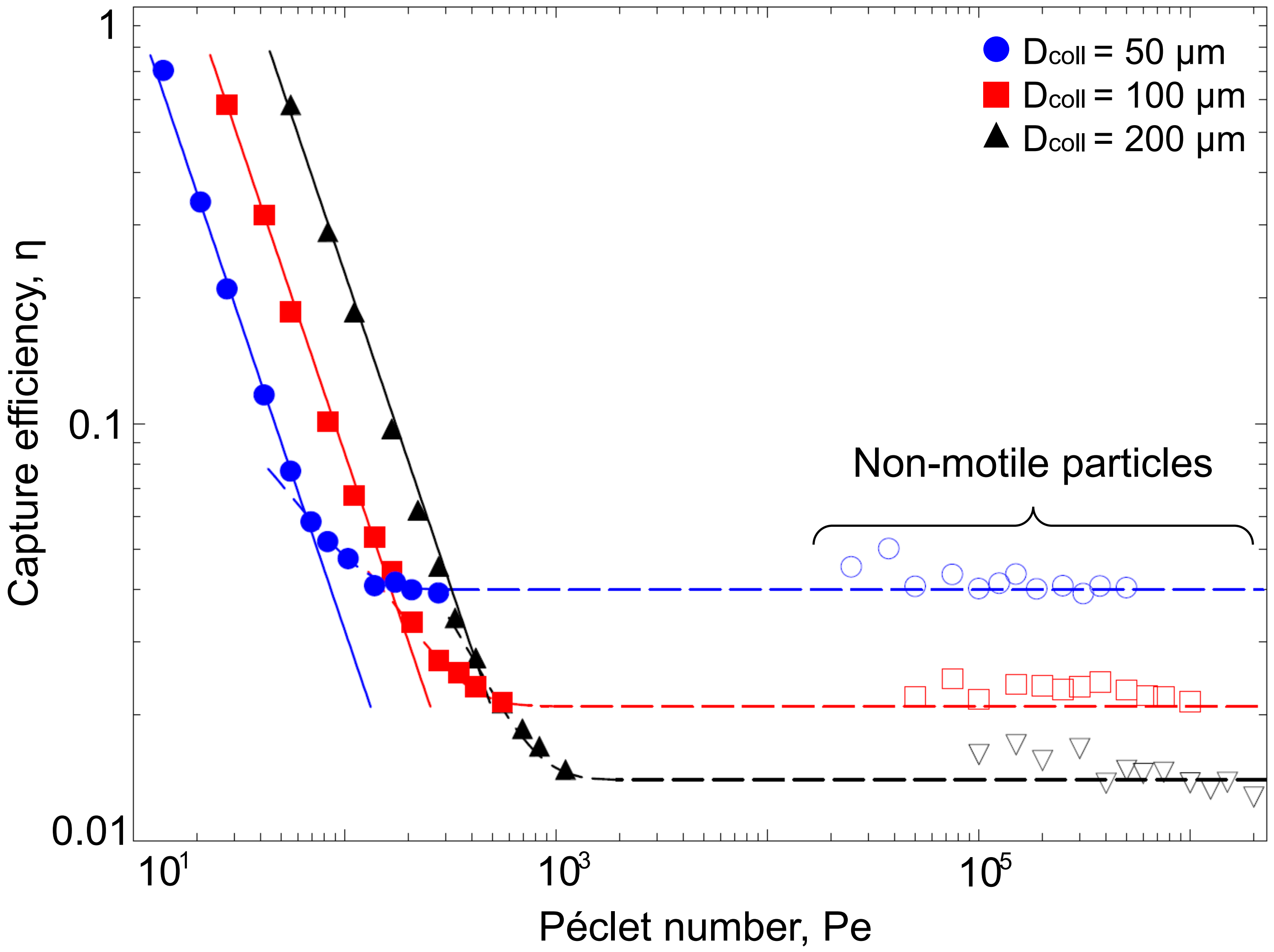
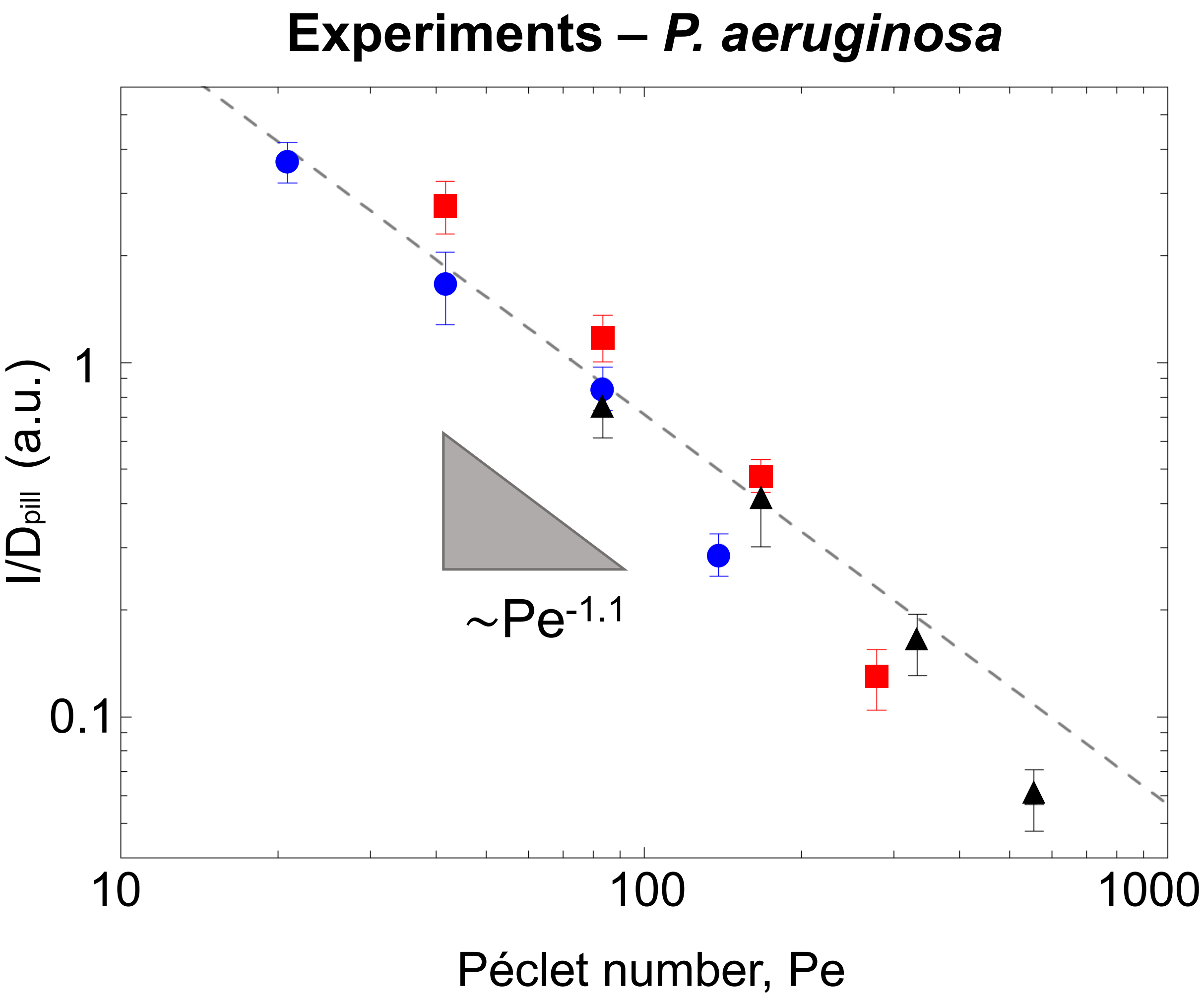
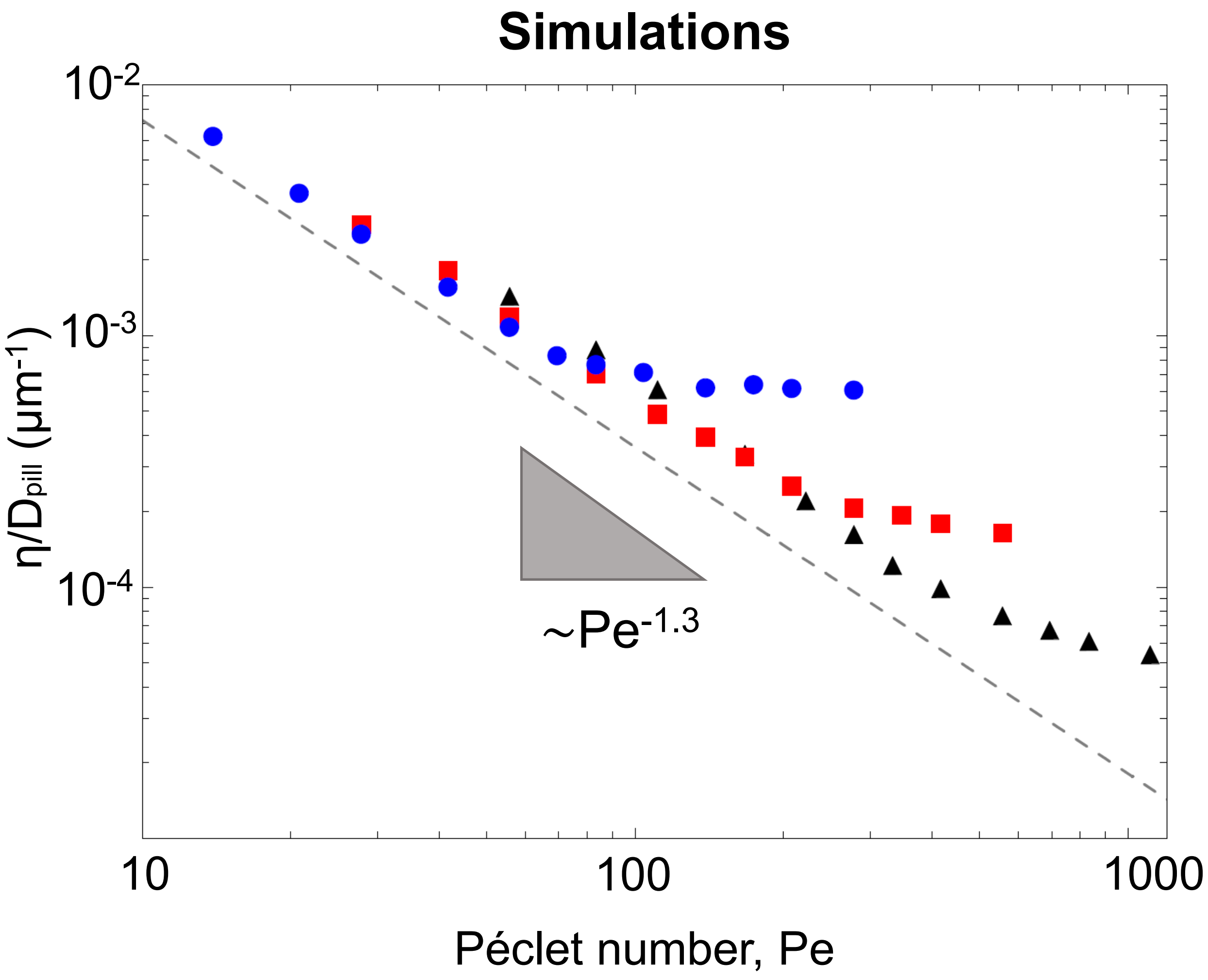
Motility and flow control bacterial transport and attachment around pillars

Simulations

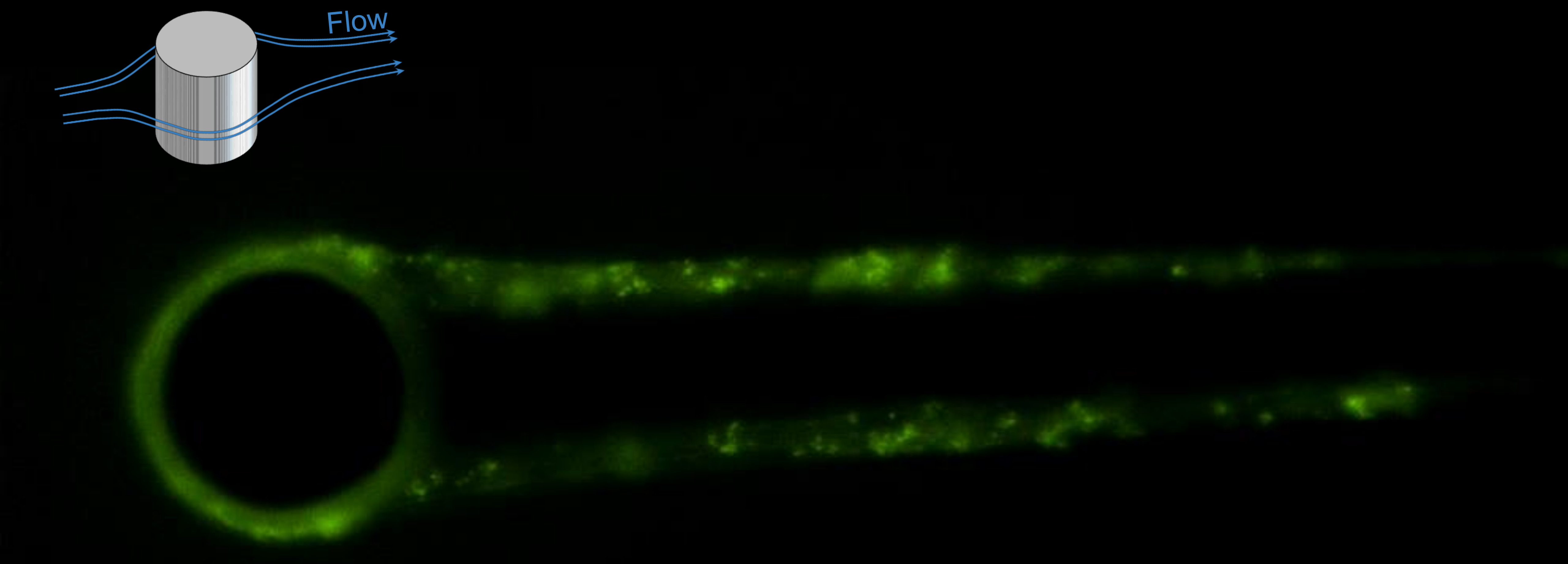


Motility and flow control bacterial transport and attachment around pillars



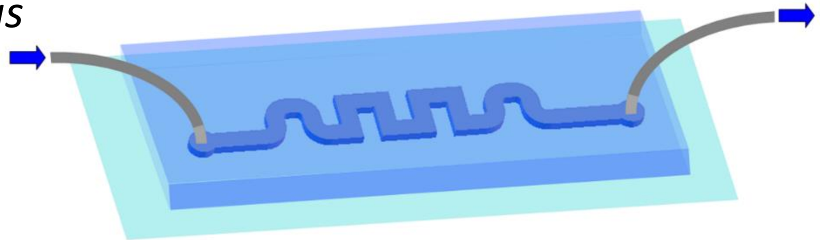


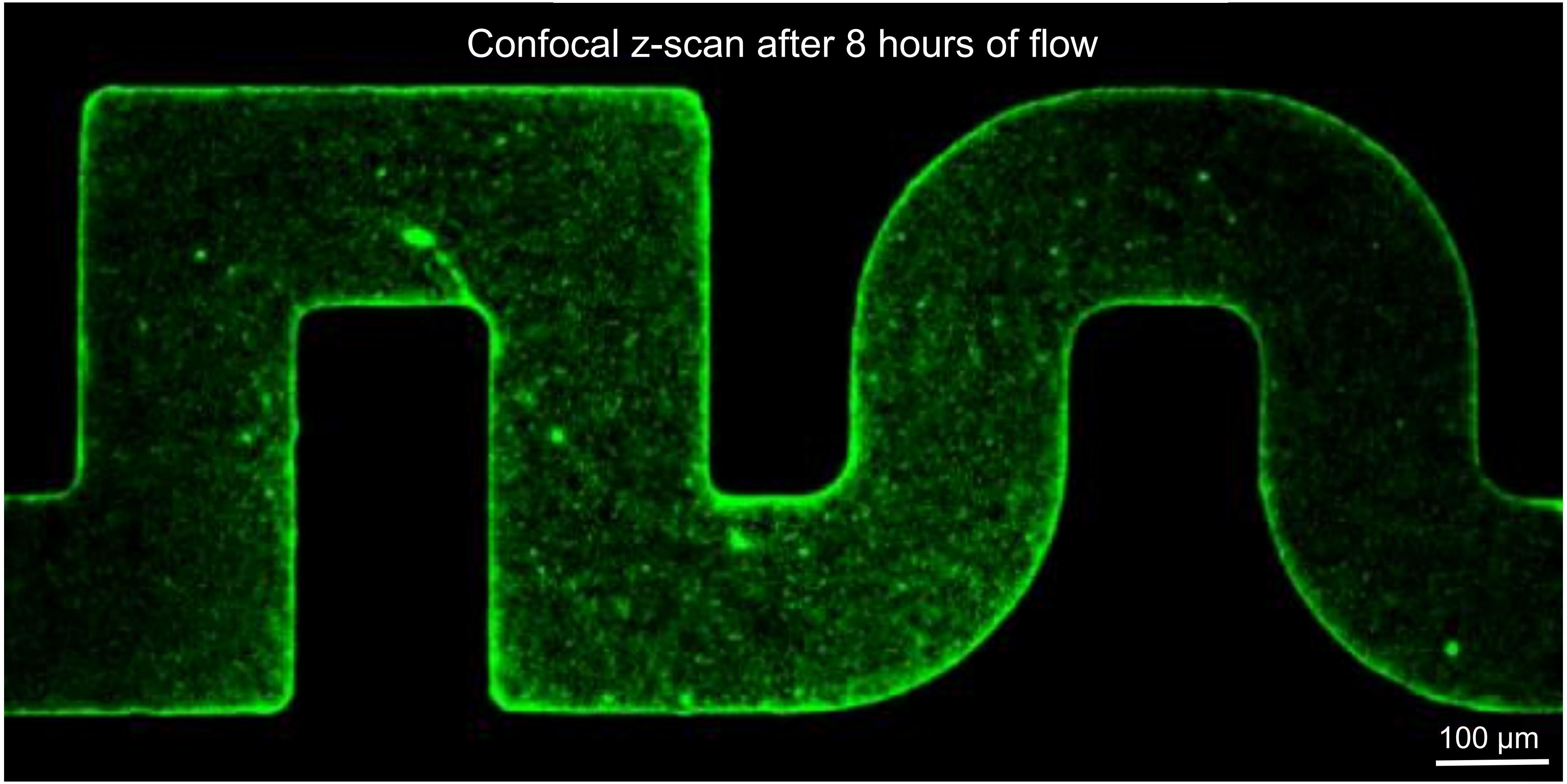
Motility and flow control bacterial transport and attachment around pillars



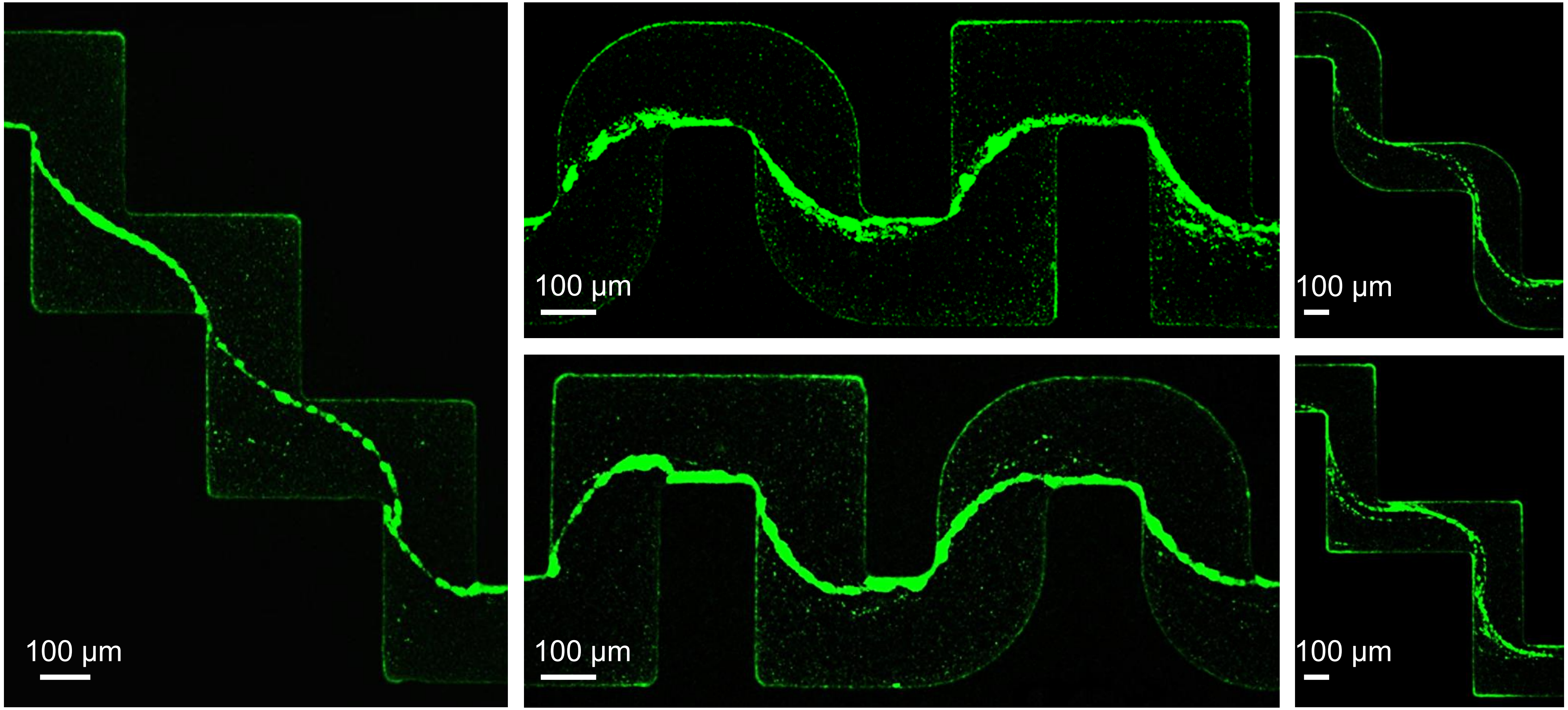
Flow around corners triggers the formation of streamers

Pseudomonas aeruginosa suspension





Flow around corners triggers the formation of streamers



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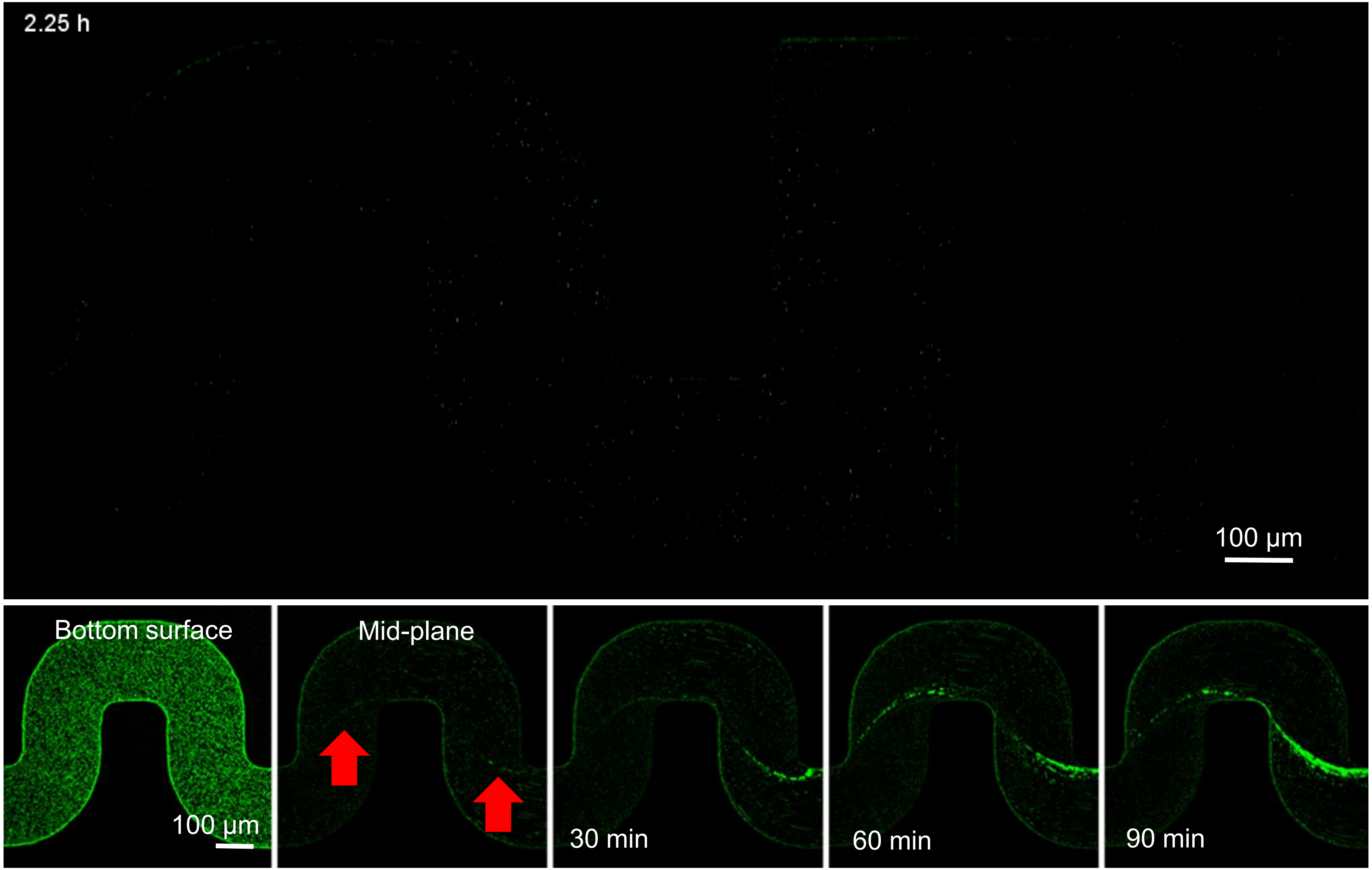
Flow around corners triggers the formation of streamers



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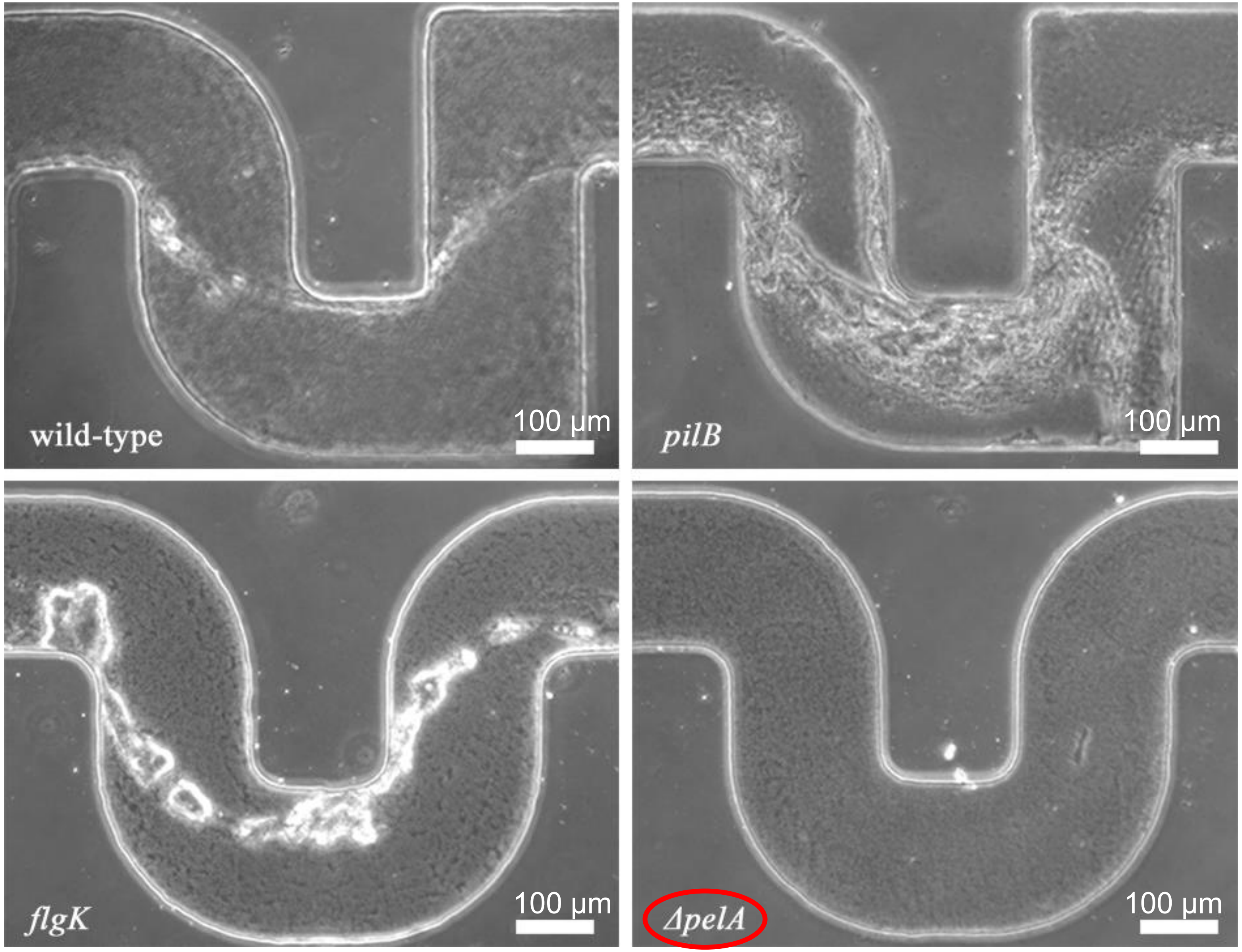
Streamer formation is independent of bacterial motility



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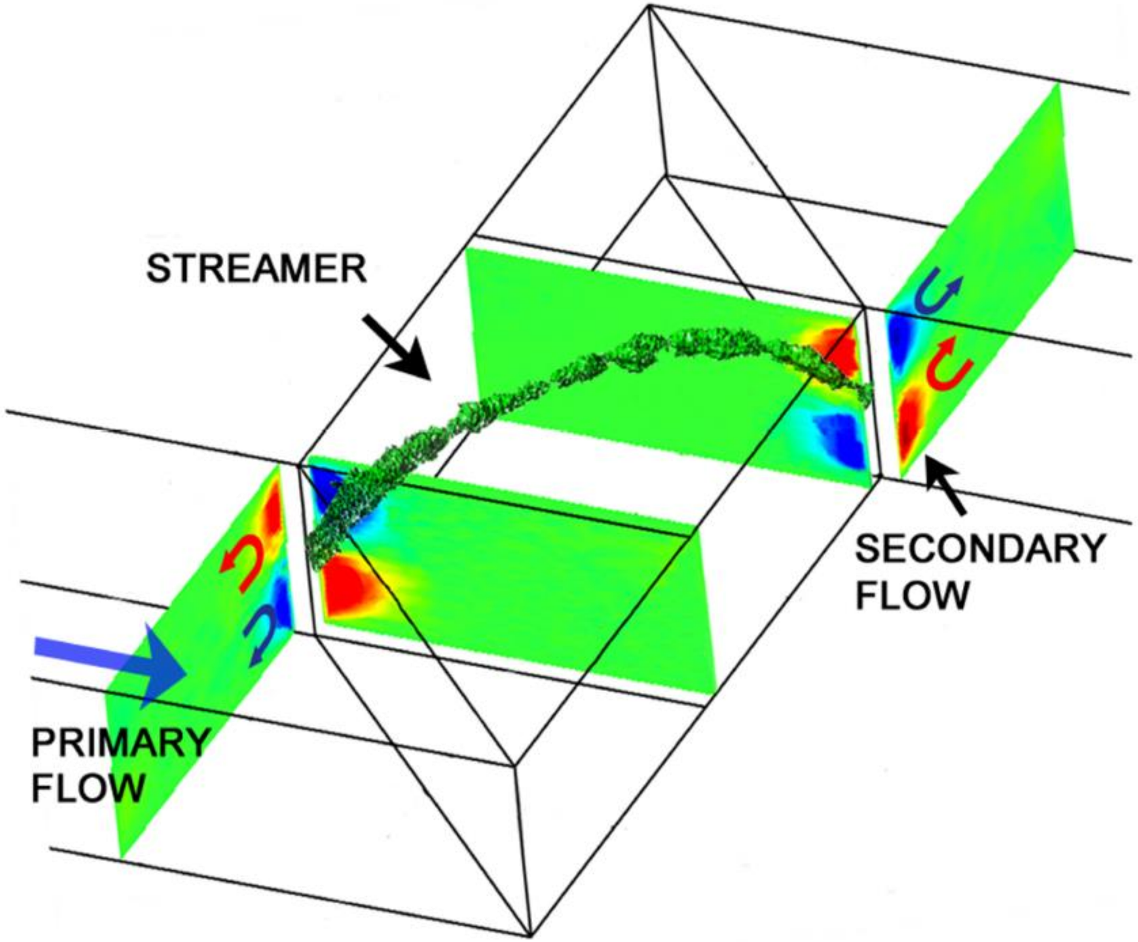
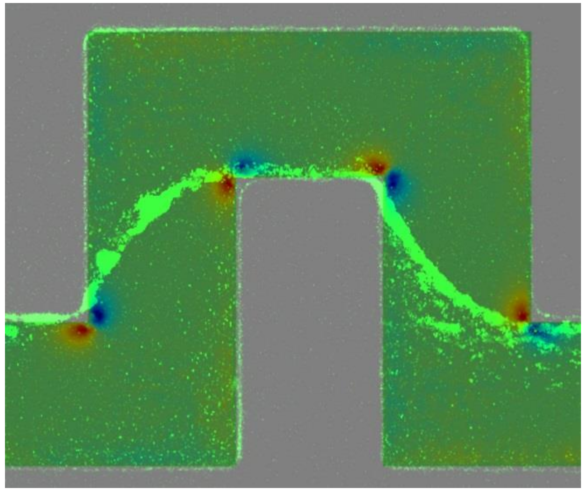
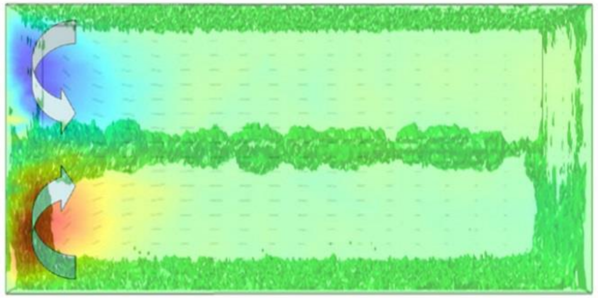
Secondary flow drives streamer formation



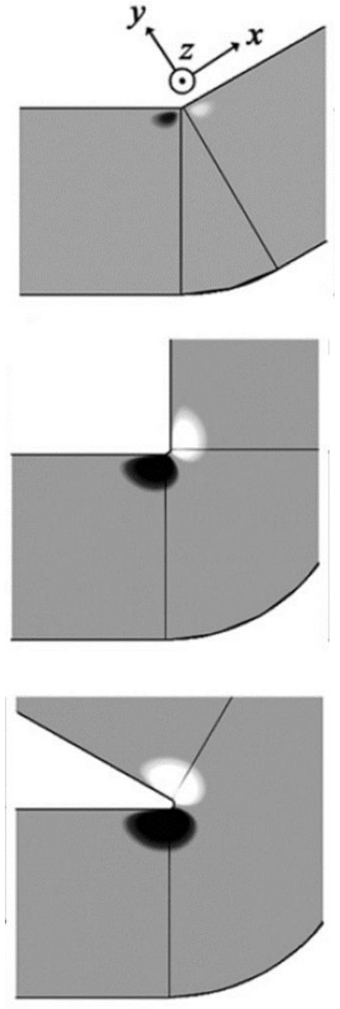




Rusconi et al. *J. R. Soc. Interface* 2010

Secondary flow drives streamer formation

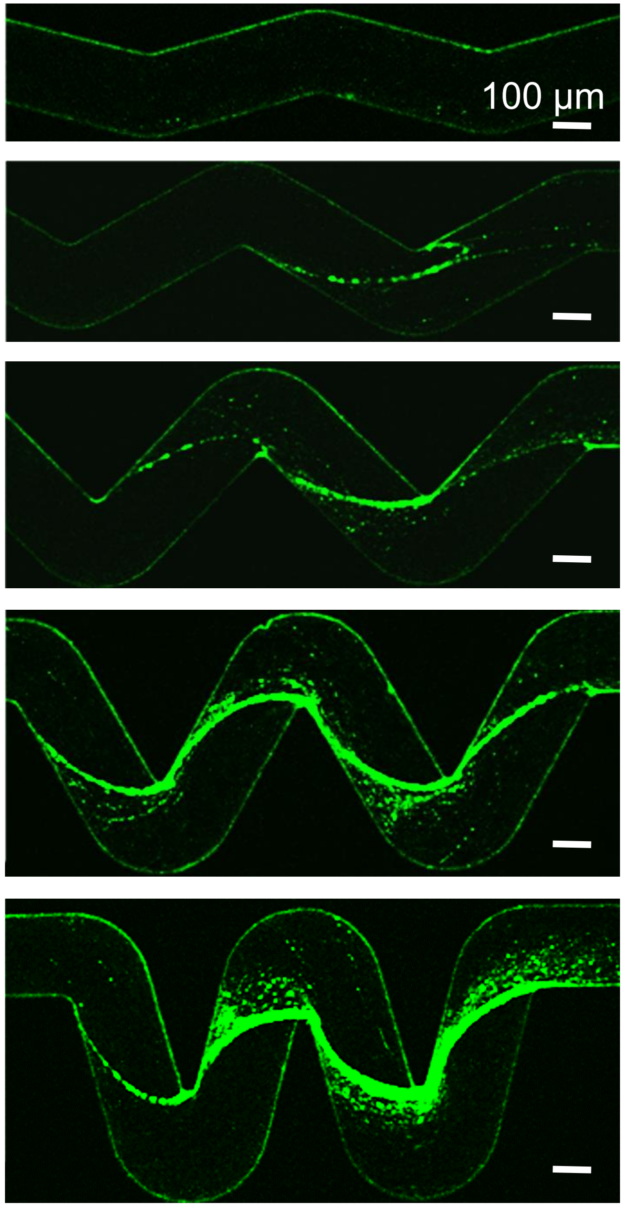
Numerical simulations



Rusconi et al. *Biophys. J.* 2011

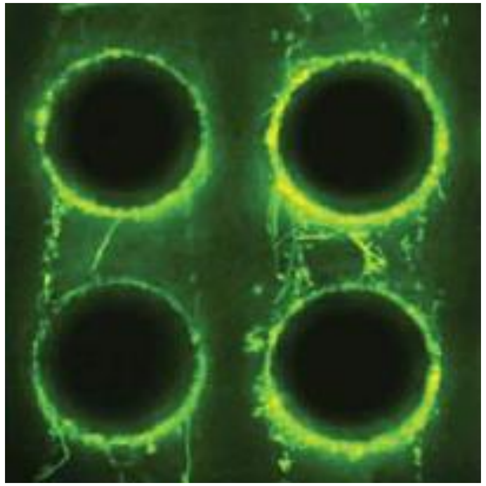
Sharper turns

More streamers



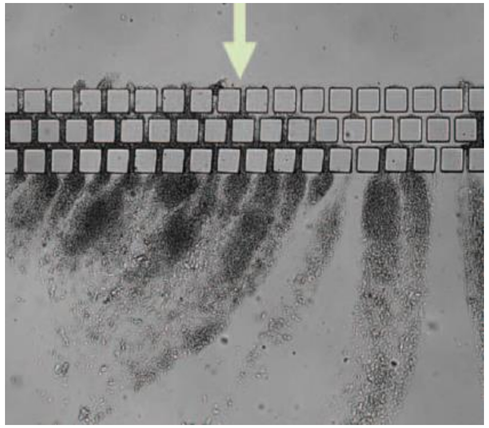
Streamers are frequent in natural and artificial systems

Porous media



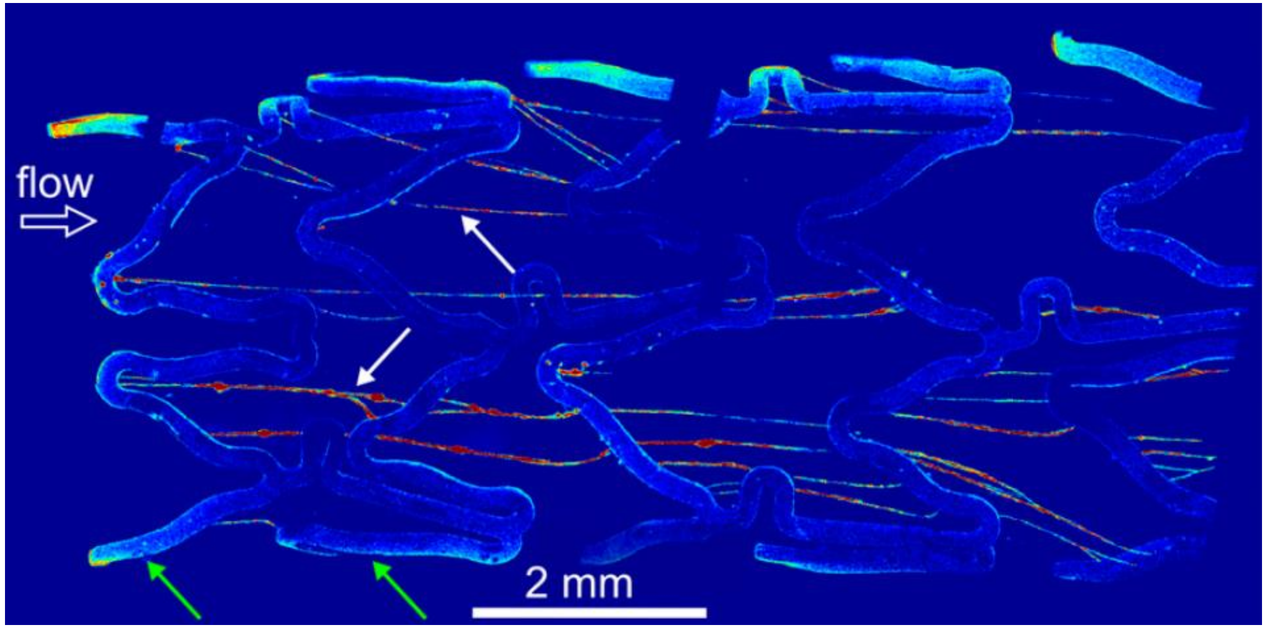
Valiei et al. *Lab Chip* 2012

Filtration systems



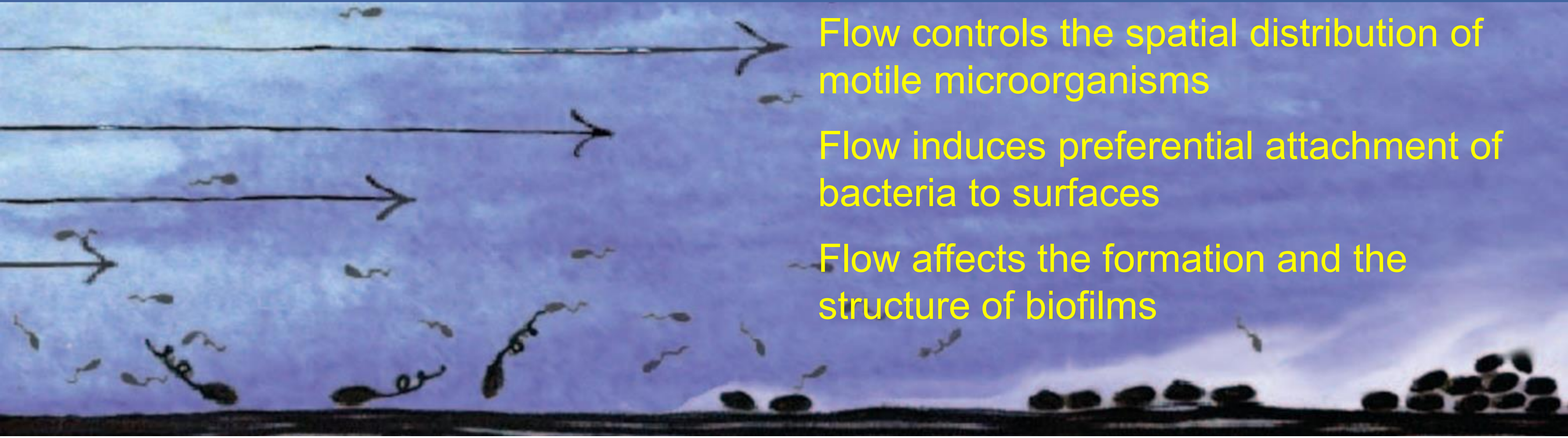
Marty et al. *Biofouling* 2012

Medical stents



Drescher et al. *PNAS* 2013

Summary and acknowledgments



Flow controls the spatial distribution of motile microorganisms

Flow induces preferential attachment of bacteria to surfaces

Flow affects the formation and the structure of biofilms

Roman Stocker (ETH)

Jeff Guasto (Tufts)

Howard Stone (Princeton)

Sigolene Lecuyer (Lyon)

Eleonora Secchi (ETH)

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