From vortex ratchets to rectification of self-propelled swimmers

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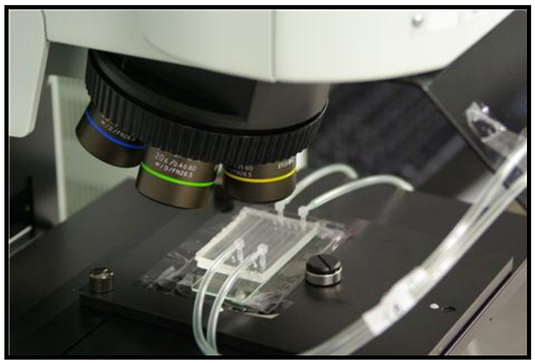
LABORATORY OF PHYSICS OF NANOSTRUCTURED MATERIALS

The 3M collaboration

MICROFLUIDIC CHIPS



Y. Jeyaram
V. V. Moshchalkov

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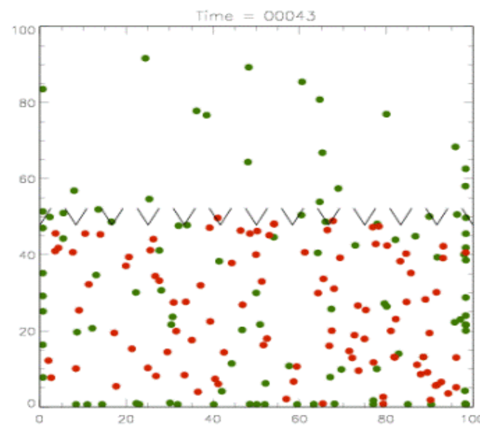
MD SIMULATIONS



V. Marconi
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University of Cordoba
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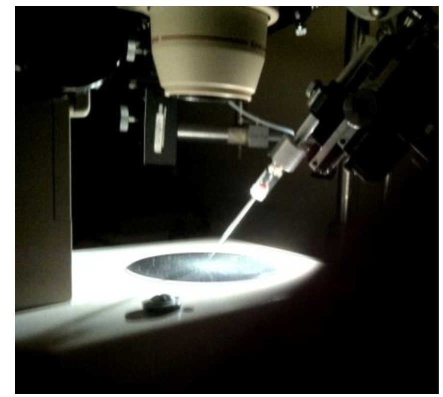
MICROSWIMMERS



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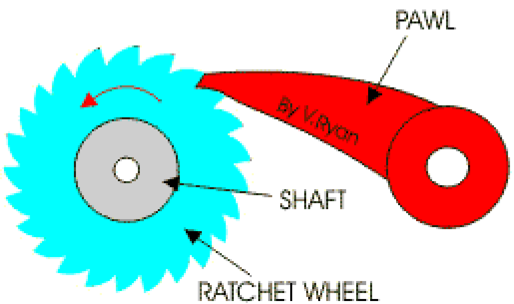
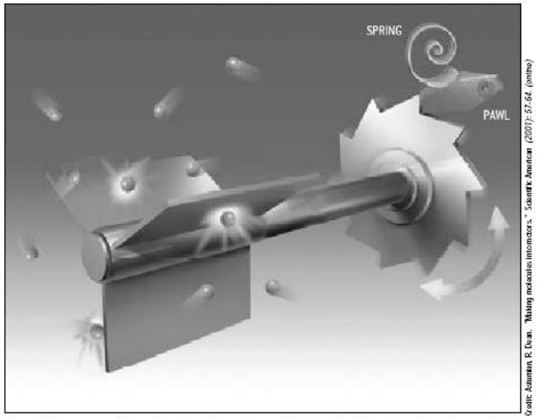
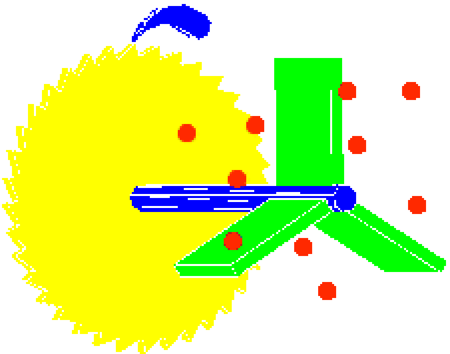
Brownian Ratchets





An artistic representation of a molecular ratchet mechanism that shows how Brownian motion is harnessed to spin the gear unidirectionally.

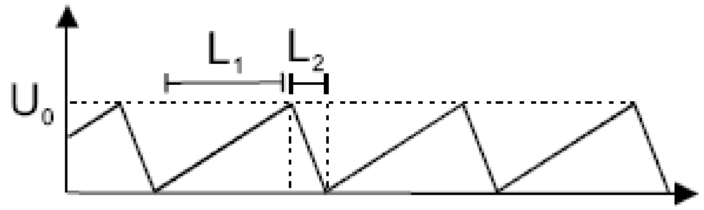


Directed transport in spatially periodic systems far from equilibrium under alternating excitation, without the need of a non-zero applied force and/or temperature gradients.

1900 Lippmann, 1912 Smoluckowski, Feynman

Rocking ratchets

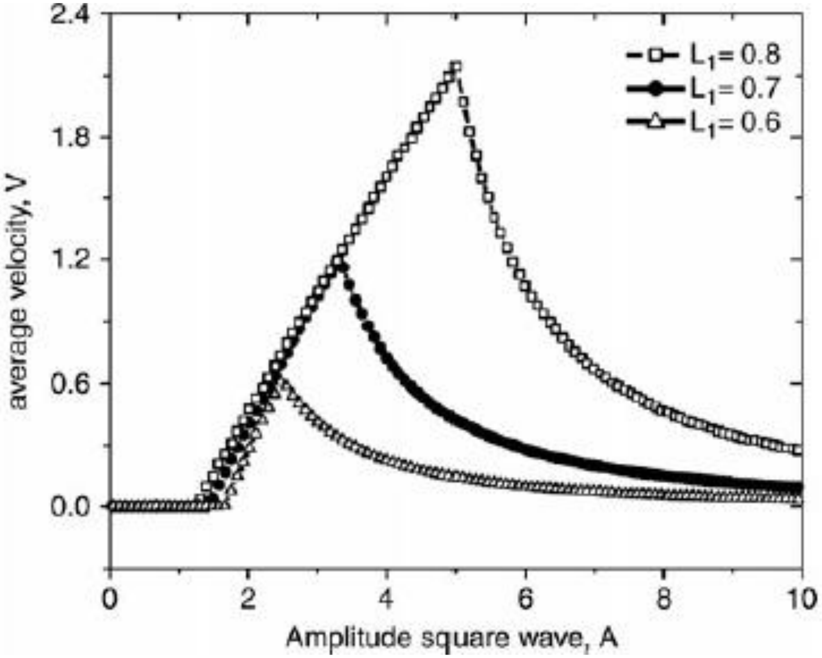
- breaking the inversion symmetry of the underlying periodic potential



- the system has to be driven out of equilibrium

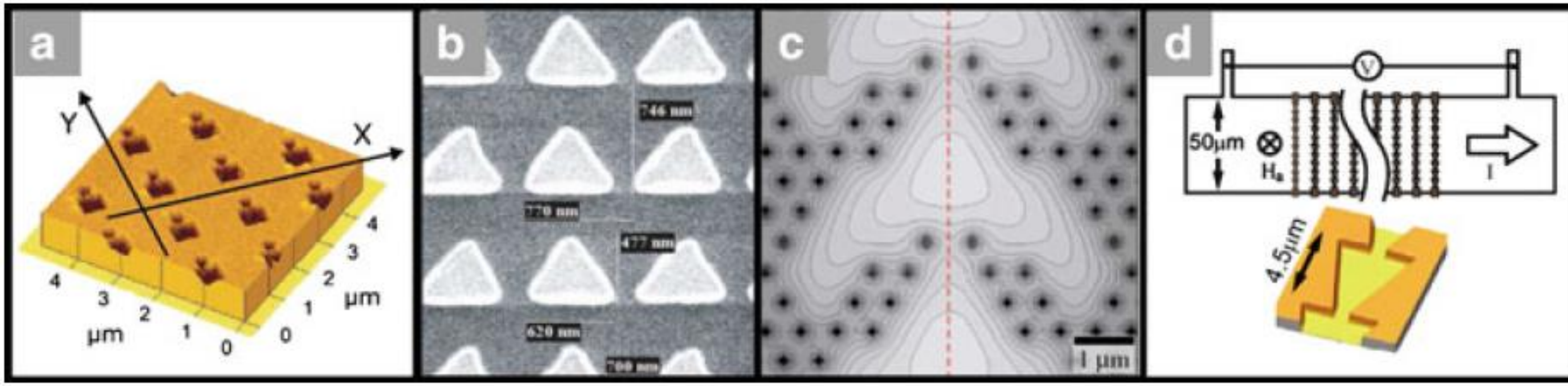
$$F_{ext} = A \sin \omega t$$

$$m\ddot{x} = -U'_p(x) - \eta\dot{x} + F_{ext} + \Gamma(t)$$



P. Reimann, Phys. Rep. 361, 57 (2002); P. Hanggi and F. Marchesoni, Rev. Mod. Phys. 81, 387 (2009)

Realization in Type-II superconductors



J. Van de Vondel *et al.*, Phys. Rev. Lett. **94**, 057003 (2005)

J. E. Villegas *et al.*, Science **302** 1188 (2003)

Y. Togawa *et al.*, Phys. Rev. Lett. **95**, 087002(2005)

K. Yu *et al.*, Phys. Rev. B **76** 220507(R) (2007)

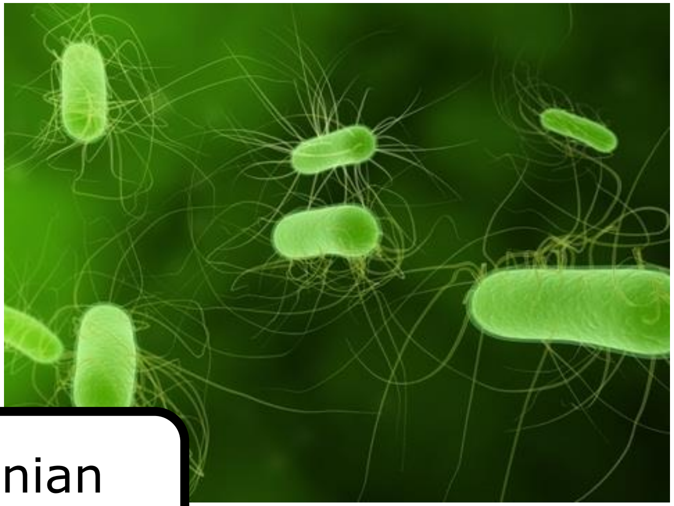
- simi-rigid objects
- size of ~ 0.1 to 1 μm
- no-inertia
- guided by physical boundaries
- Repulsive interactions
- very homogeneous population
- externally excited

Deterministic ratchet

From fluxon ratchets to rectification of self-propelled objects

BACTERIA

- semi-rigid objects
- size of ~ 1 μm
- no-inertia ?
- Repulsive interactions ?
- guided by physical boundaries ?
- heterogeneous population
- driven by internal motor

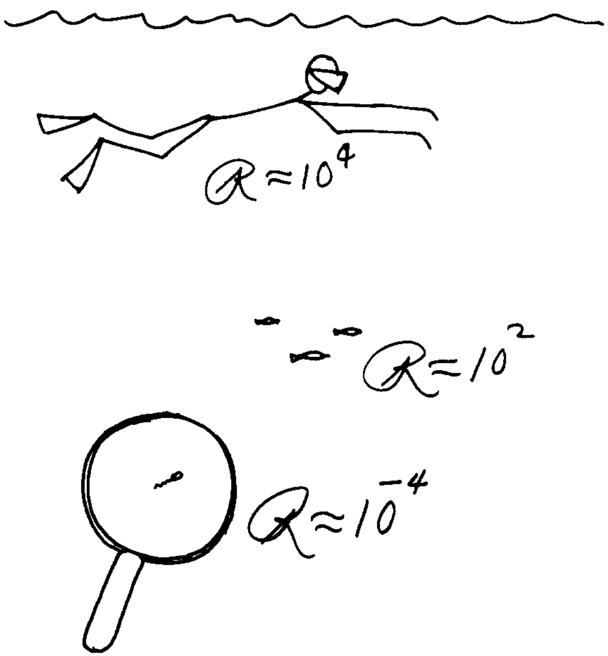


Brownian ratchet

Life without inertia

~~Navier~~-Stokes:

$$-\nabla p + \eta \nabla^2 \vec{v} = \cancel{\rho \frac{\partial \vec{v}}{\partial t}} + \cancel{\rho (\vec{v} \cdot \nabla) \vec{v}}$$



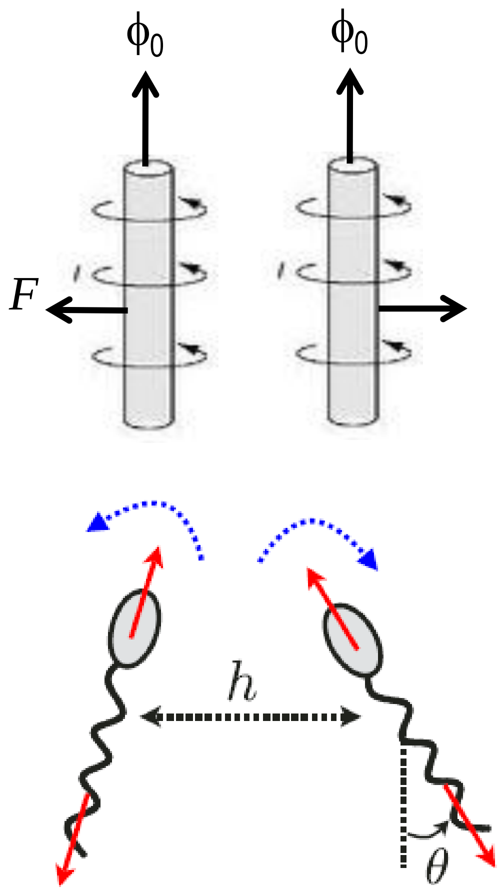
$$\mathrm{Re} = \frac{inertial \quad term}{viscous \quad term} \approx \frac{\rho L v}{\eta}$$

HOW FAR AN E-COLI WILL COAST IF SUDDENLY STOPS SWIMMING ?

~ 0.1 Å IN ABOUT 1 μs

E.M. Purcell, *Am. J. Phys.* **45**, 3 (1977)

swimmer-swimmer interaction



$$-\nabla p+\eta\nabla^2\boldsymbol{u}=0,\qquad \nabla\cdot\boldsymbol{u}=0$$

$$\boldsymbol{u}(\boldsymbol{r})=\frac{p}{8\pi\eta r^3}\left[3\cos^2\theta-1\right]\boldsymbol{r}$$

$$|p|\sim\eta U L^2$$

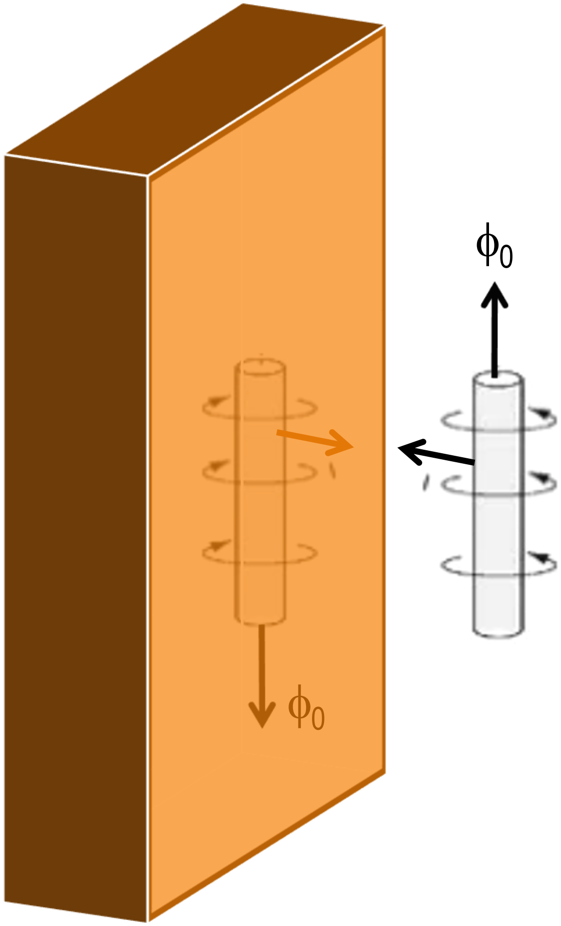
TWO SIDE BY SIDE ($\theta=\pi/2$) E-COLI ATTRACT EACH OTHER

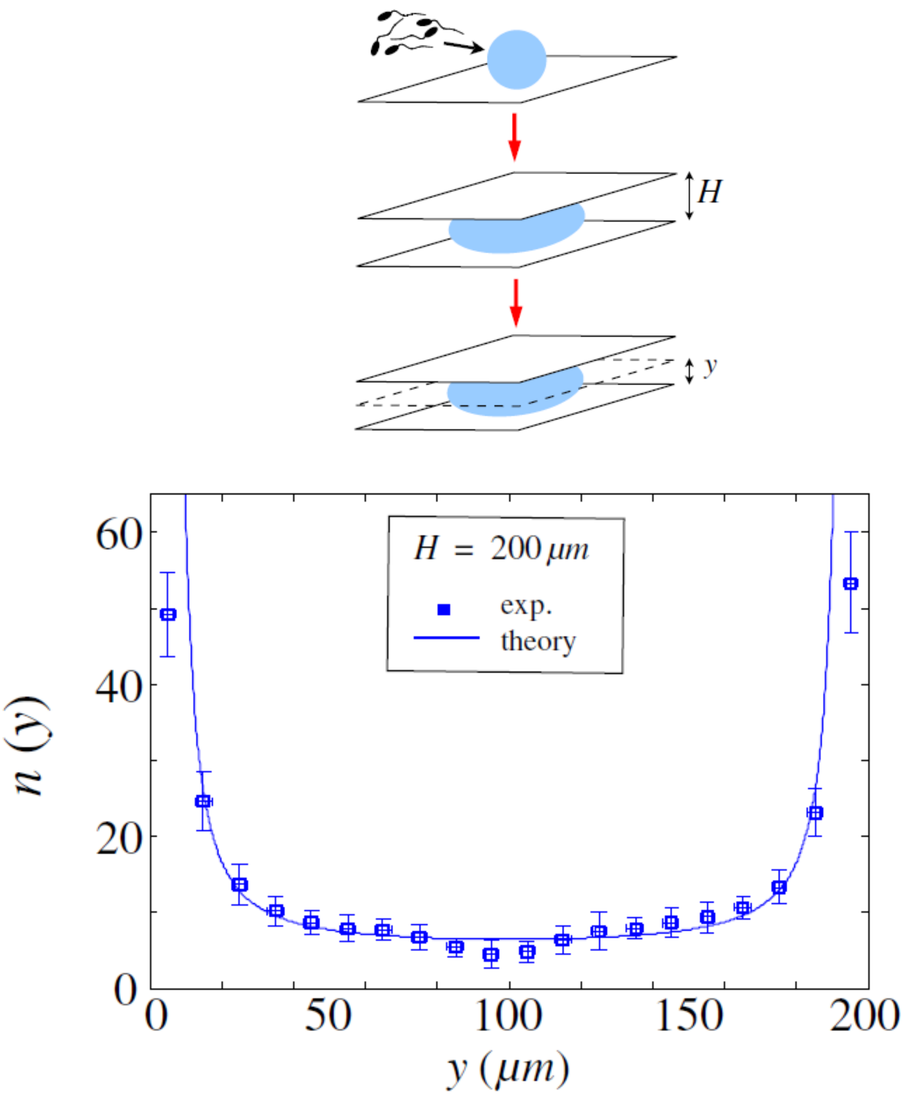
TWO SWIMMERS ALIGNED ($\theta=0$) REPEL EACH OTHER

→ Local force on the fluid

E. Lauga and T.R. Powers, *Rep. Prog. Phys.* **72**, 096601 (2009)

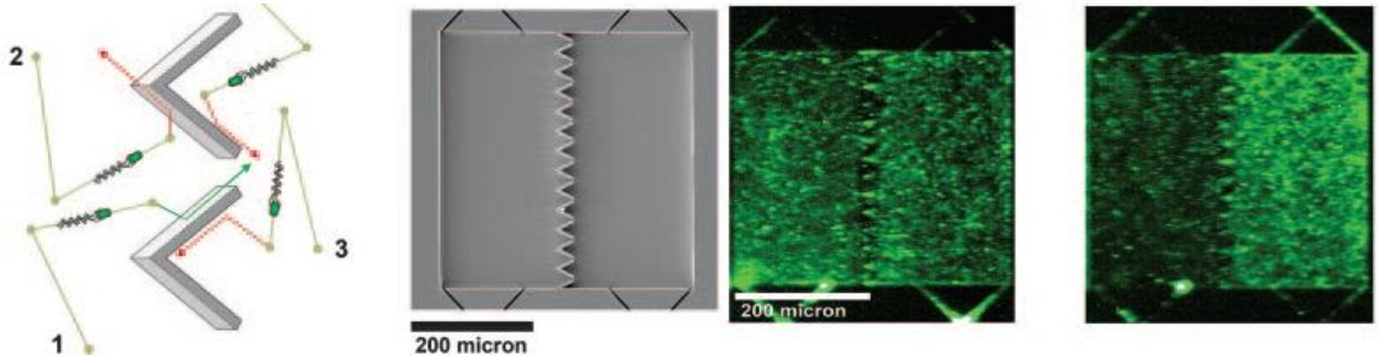
Swimmer-wall interactions



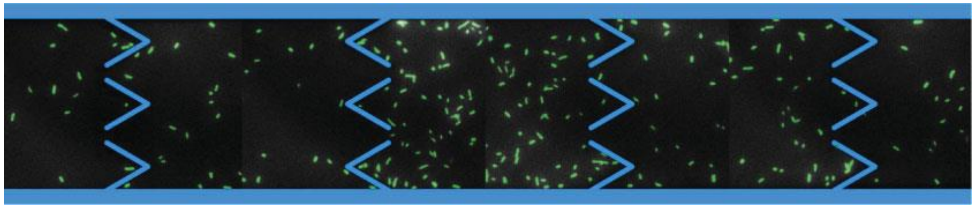


L. Rothschild, Nature 198, 1221 (1963); Berke et al., Phys.Rev.Lett. 101, 038102 (2008)

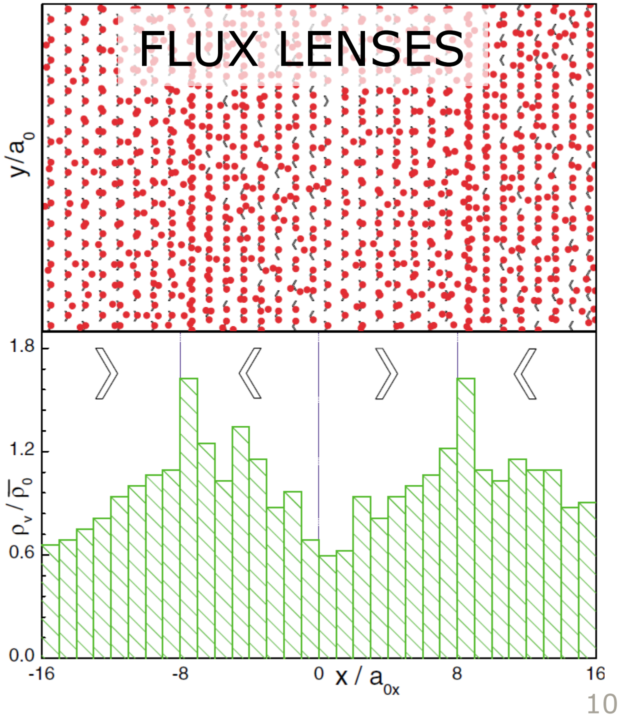
Ratchet of self-propelled swimmers



Galajda *et al., J. Bacteriol.* **189**, 8704 (2007)



Hulme *et al., Lab on a chip* (2008)
Mahmud *et al., Nature Physics* **5**, 606 (2009)
Lambert *et al., Phys. Rev. Lett.* **104**, 168102 (2010)



Zhu, Marchesoni, Nori, *Phys. Rev. Lett.* **92**, 180602 (2004)

Now we know that ratchets work for self-propelled microorganisms, what next?

- Does the swimming strategy play a role in the rectification efficiency ?

- Assuming heterogeneity in a swimmer population, say different “smartness”, can we separate them?

Life without inertia

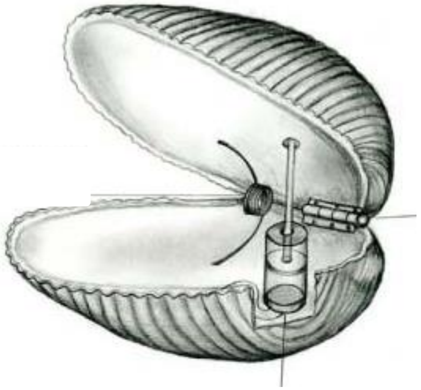
~~Navier~~ - Stokes:

$$-\nabla p + \eta \nabla^2 \vec{v} = \cancel{\rho \frac{\partial \vec{v}}{\partial t}} + \cancel{\rho (\vec{v} \cdot \nabla) \vec{v}}$$

LINEAR AND TIME INDEPENDENT !

AT LOW Re THE RESPONSE IS DETERMINED BY THE FORCES EXERTED AT THAT MOMENT AND BY NOTHING IN THE PAST

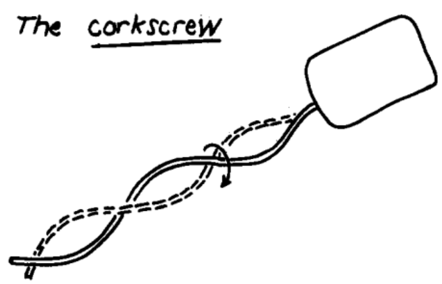
THE SCALOP CANNOT SWIM AT LOW Re

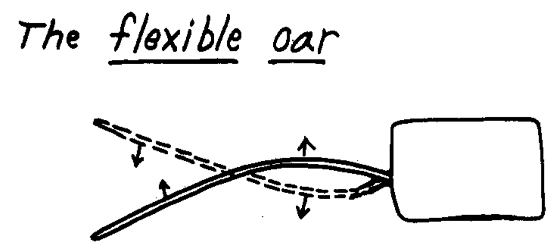


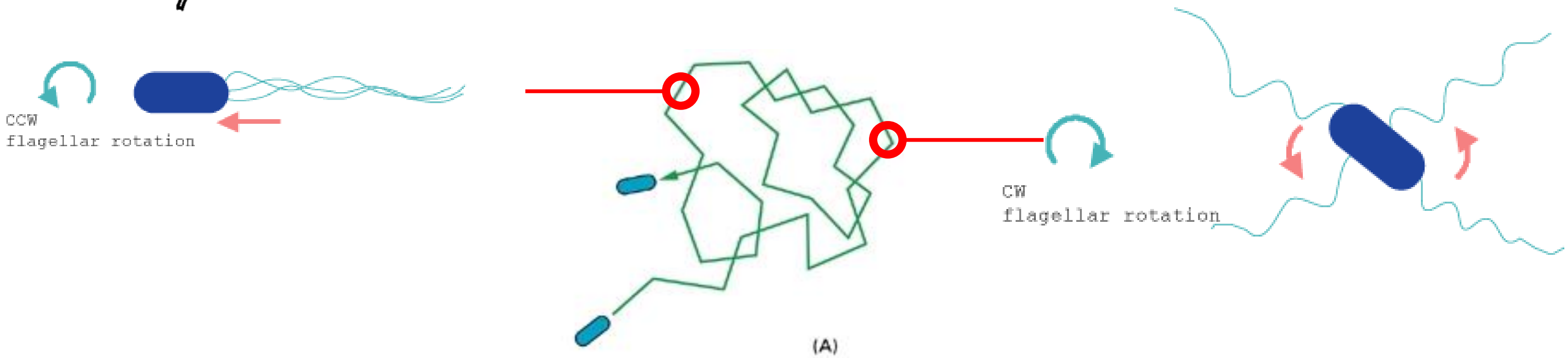
E.M. Purcell, *Am. J. Phys.* **45**, 3 (1977)

Avoiding the scalop theorem

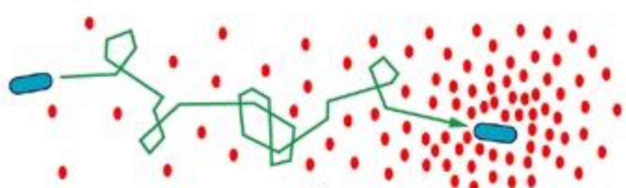
WE NEED NON RECIPROCAL BODY KINEMATICS







(A)

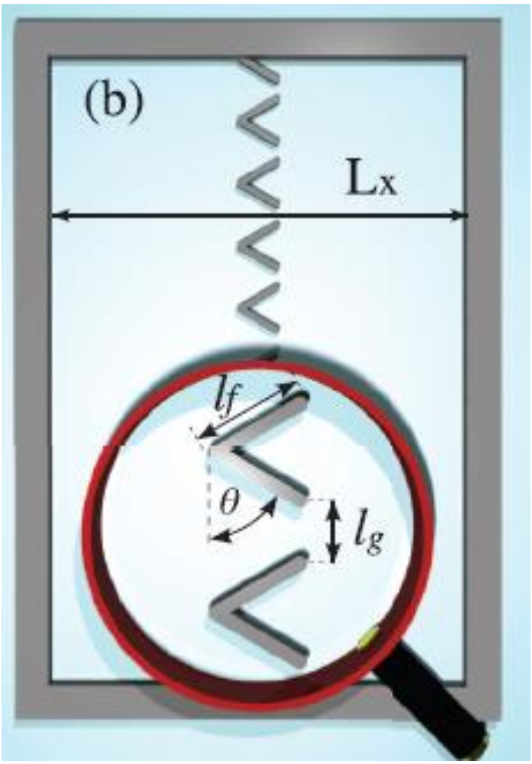


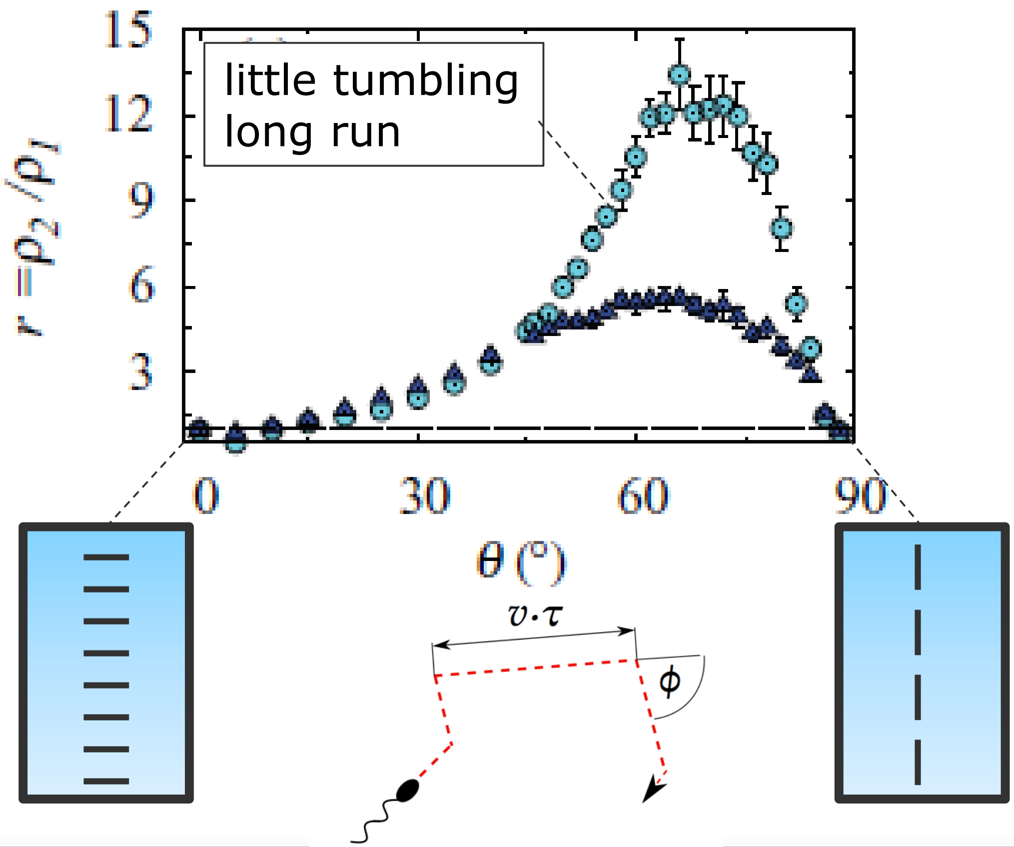
(B)

E.M. Purcell, *Am. J. Phys.* **45**, 3 (1977)

Optimization of the ratchet geometry

$$\gamma \frac{d\mathbf{r}_i}{dt} = \mathbf{F}_i^m + \mathbf{F}_i^{sw} + \mathbf{F}_i^s,$$

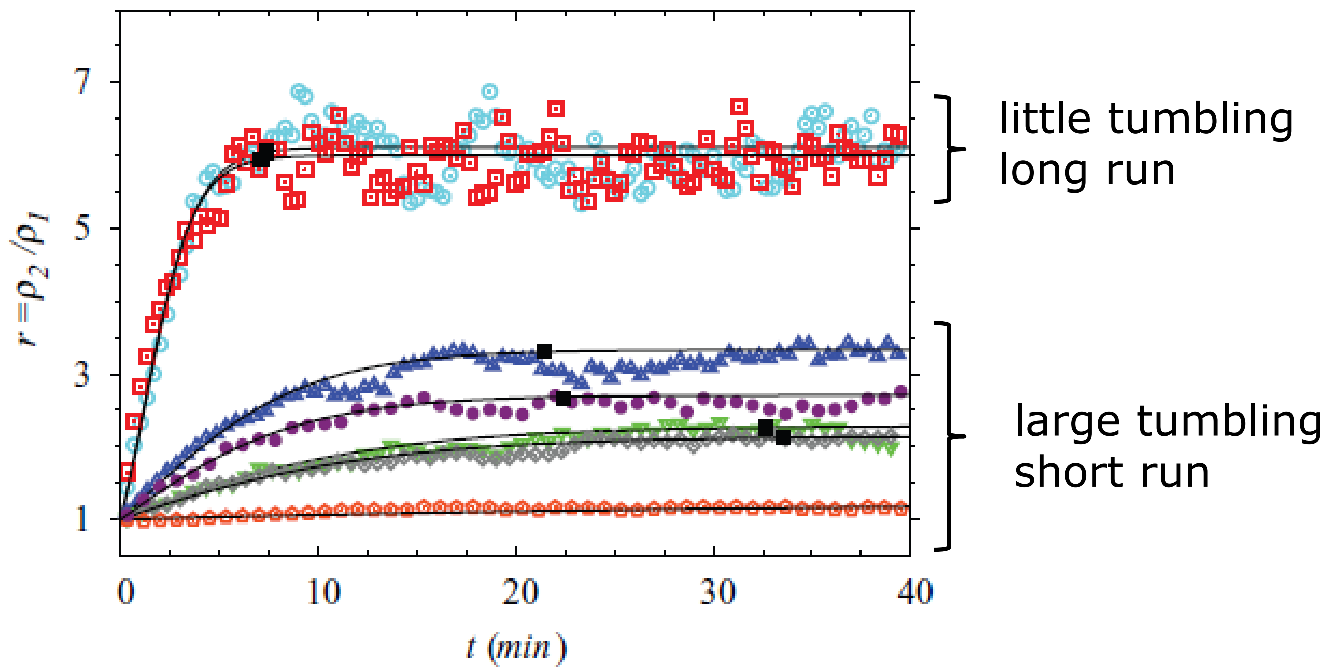




Berdakin et al., *Phys. Rev. E* **87**, 052702 (2013)

Little tumbling improves the rectification

	Mean direction change, $\bar{\phi}$ (°)	Mean run duration, τ (s)	Mean speed, $\bar{v}$ (μm/s)	D (μm^2/s)	Rectification time (min)
s_1	33 ± 15	6.3	20 ± 4.9	1788	7.1
s_2	0 ± 36	100	14.2 ± 3.4	1293	7.4
s_3	68 ± 36	0.86	14.2 ± 3.4	128	21.4
s_4	74 ± 33	0.42	14.4 ± 3.9	48	32.7
s_5	180 ± 36	0.86	14.2 ± 3.4	51	33.5
s_6	68 ± 36	0.01	14.2 ± 3.4	1.6	95.9
s_7	90(srw)	0.86	14.2 ± 3.4	87	22.4

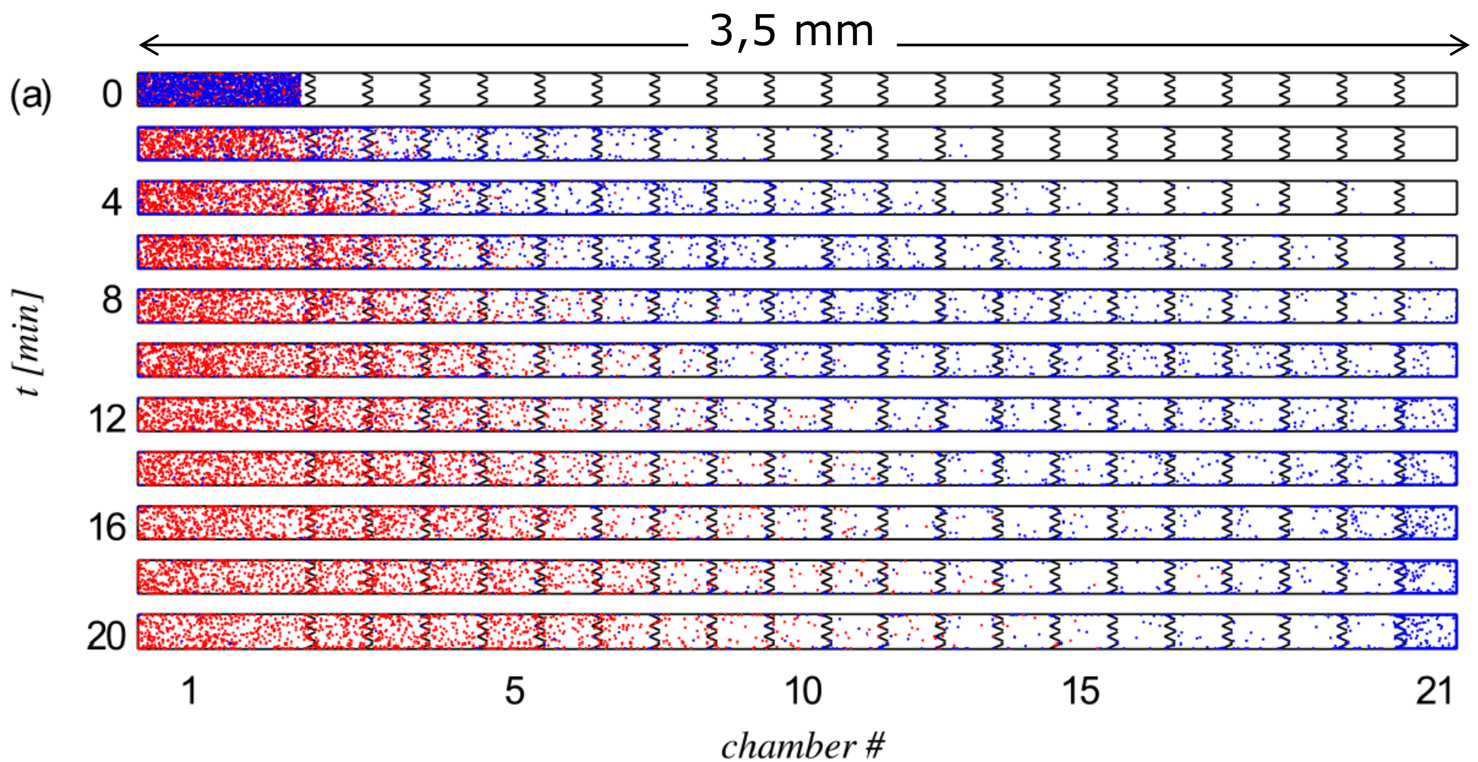


Berdakin et al., *Phys. Rev. E* **87**, 052702 (2013)

Quantification of the sorting efficiency

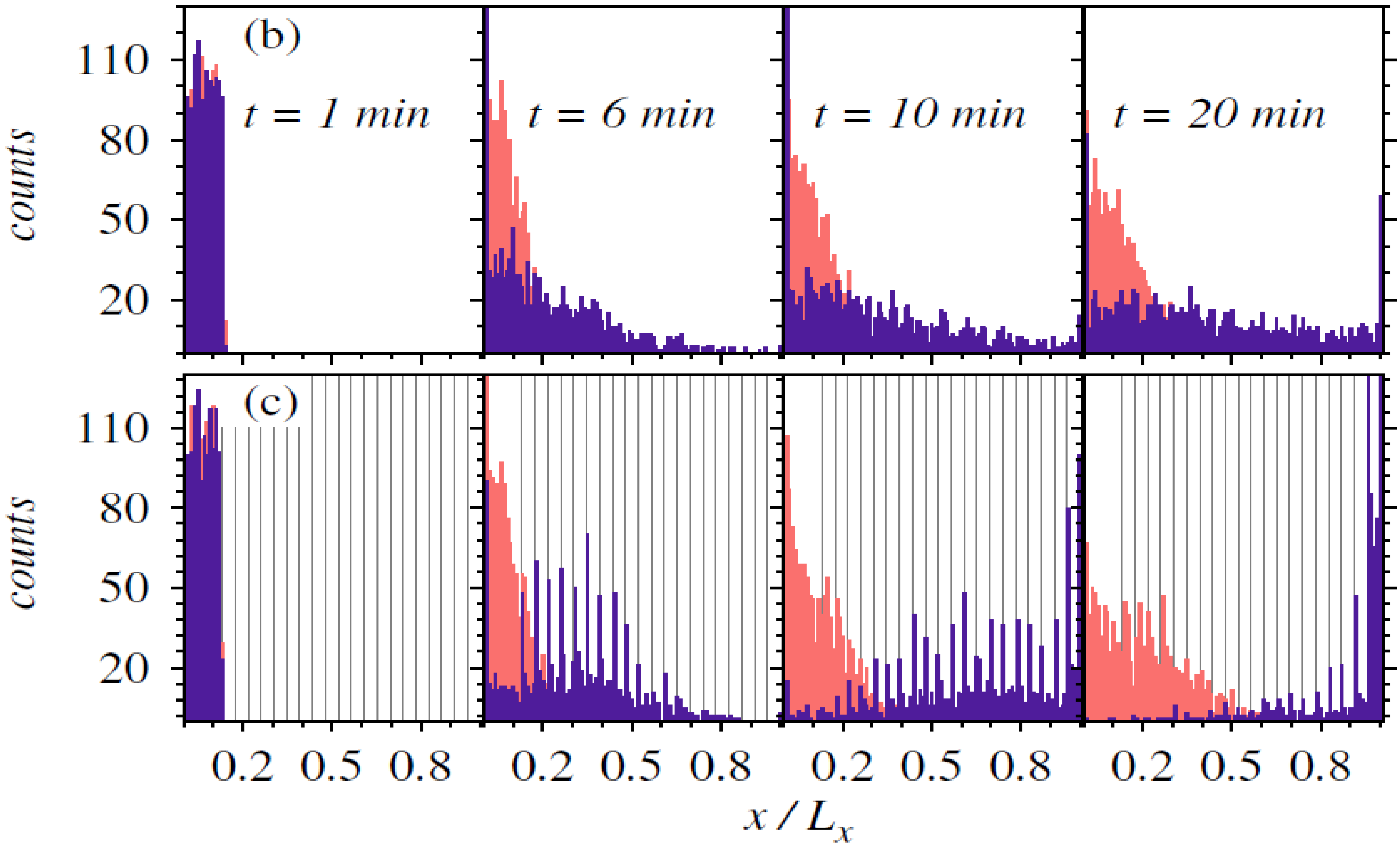
Table 1. Motility parameters of two different *E. coli* strains: s_1 corresponds to AW405 and s_2 to CheC497 in Ref. [31].

Swimmer	$\bar{v}$[μm/s]	σ_v[μm/s]	$\bar{\phi}$[°]	σ_ϕ[°]	τ[s]	D_R[rad^2/s]
s_1 (wild type)	14.2	3.4	68	36	0.86	0.18
s_2 (mutant)	20.0	4.9	33	15	6.30	0.06



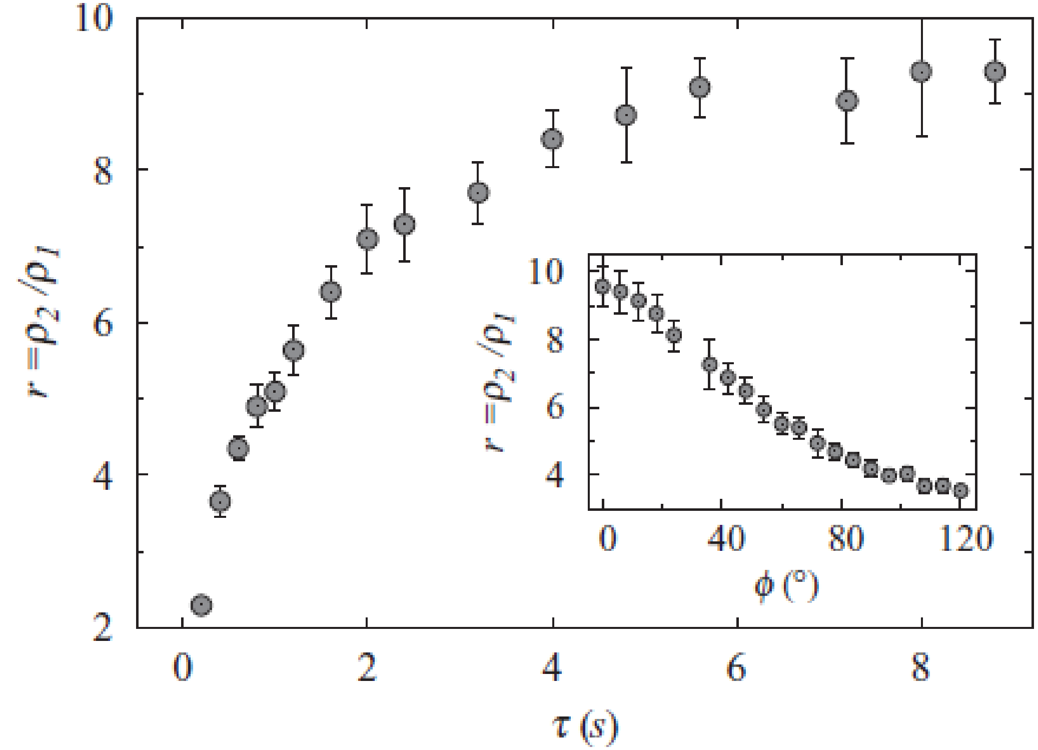
Berdakin et al., Cent. Eur. J. Phys. **11**, 1653 (2013)

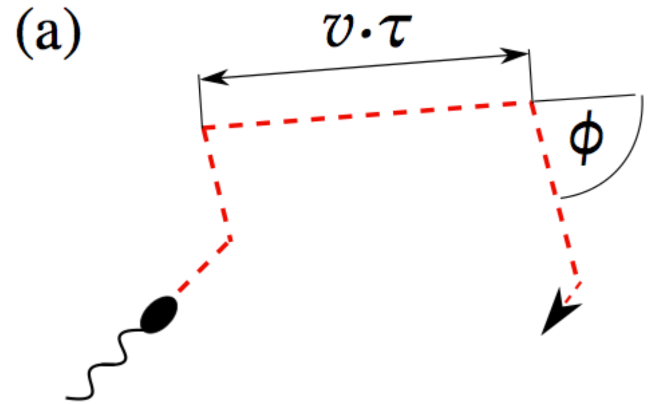
Ratchet enhanced diffusion

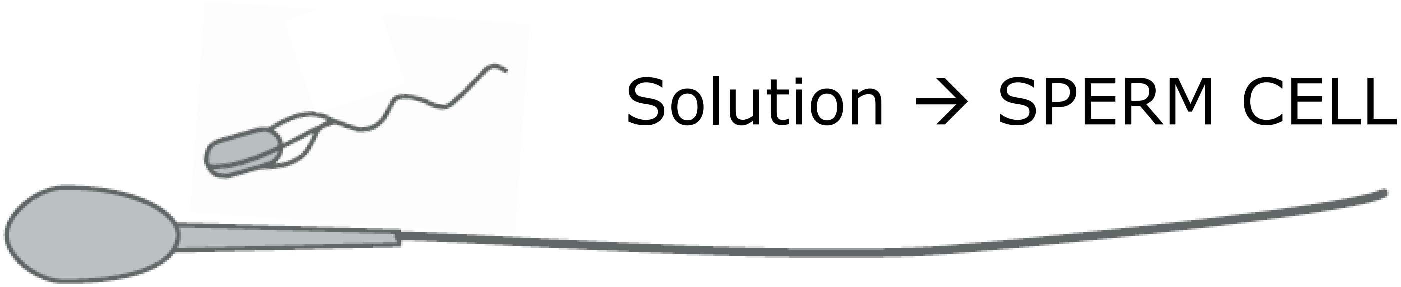


Berdakin et al., Cent. Eur. J. Phys. **11**, 1653 (2013)

No tumbling at all improves the rectification



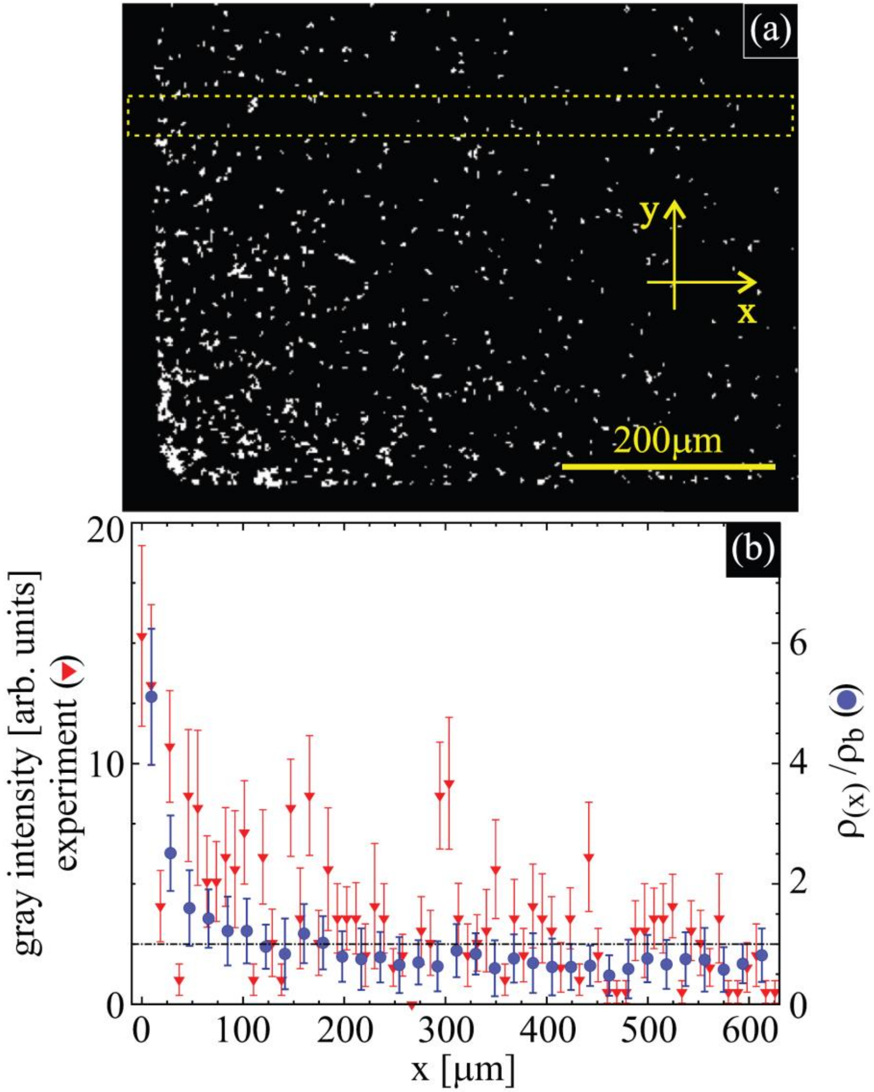




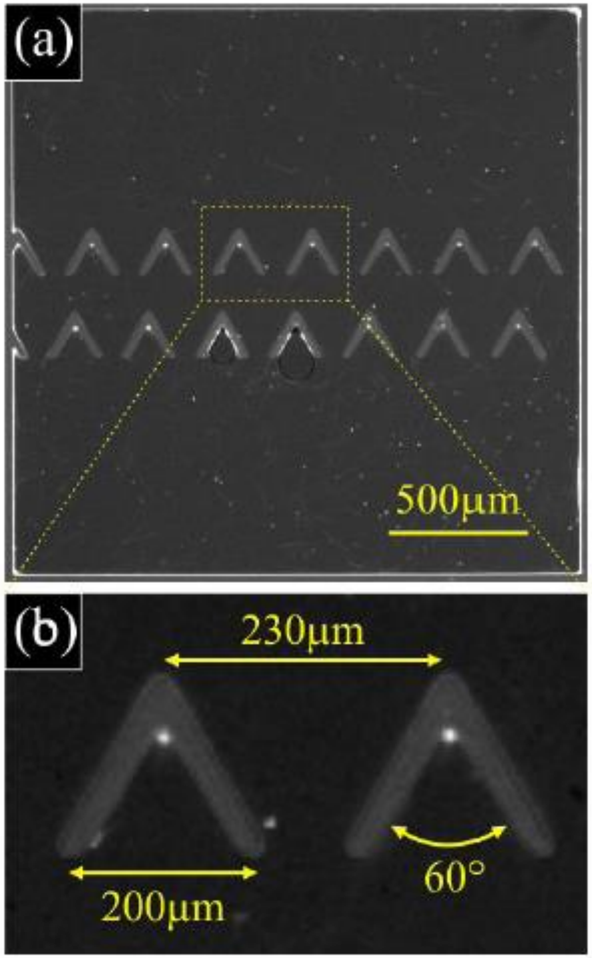
Solution → SPERM CELLS

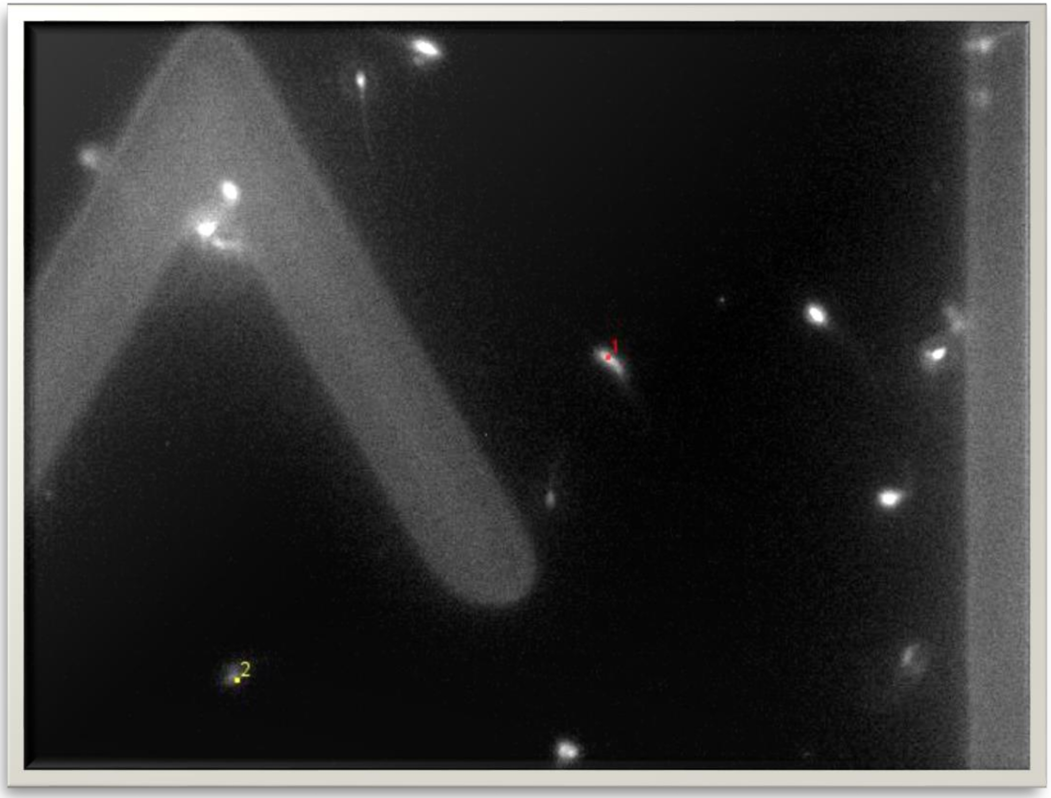
Berdakin et al., *Phys. Rev. E* **87**, 052702 (2013)

Wall accumulation



No separation but trapping



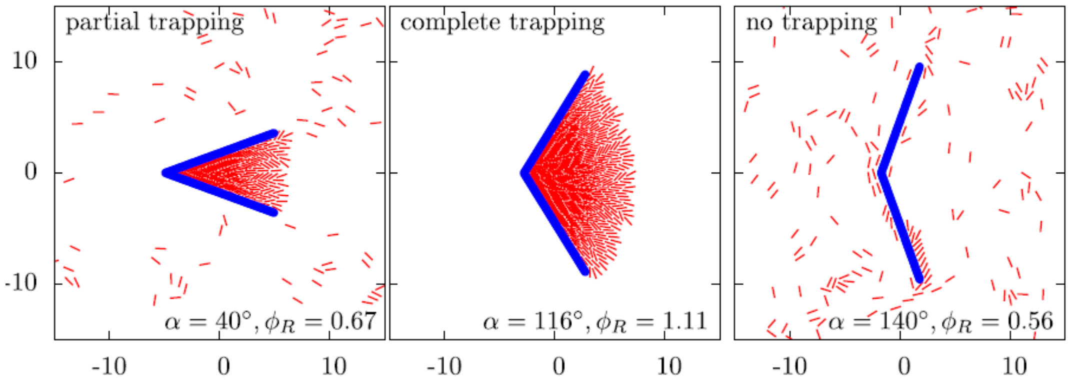


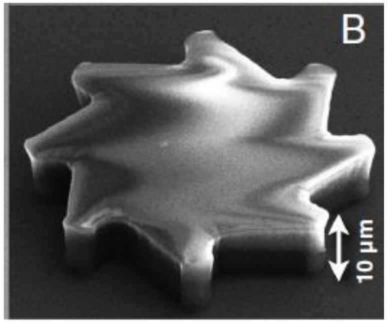
Guidobaldi *et al.*, *Phys. Rev. E* 89, 032720 (2014)

PRL **108,** 268307 (2012) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2012

How to Capture Active Particles

A. Kaiser,[1] H. H. Wensink,[1,2,*] and H. Löwen[1]

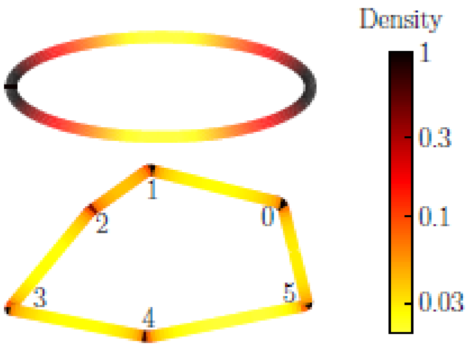




Di Leonardo *et al., PNAS.* **107**, 9541 (2010)

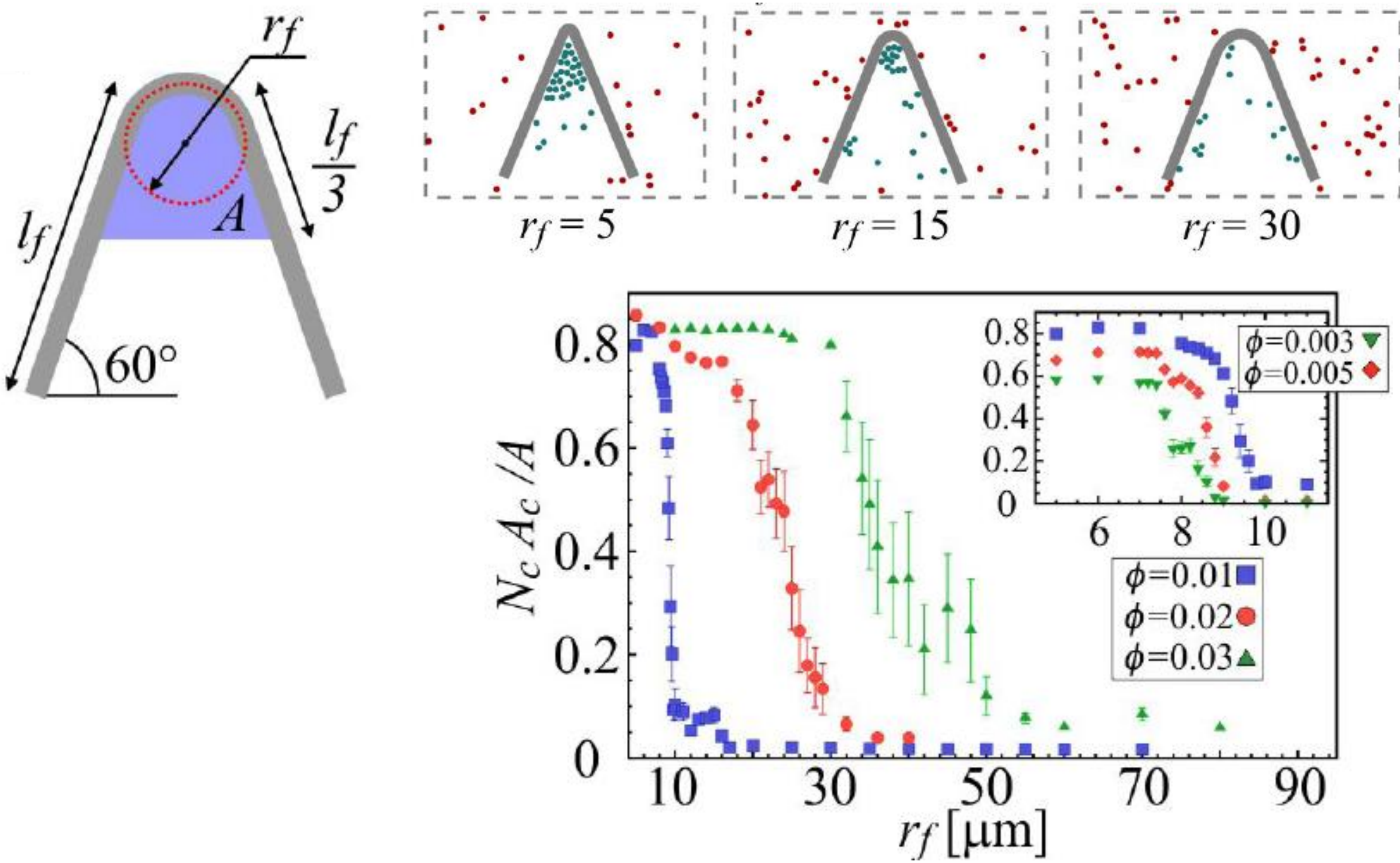
Dynamics of Self-Propelled Particles Under Strong Confinement

Yaouen Fily, Aparna Baskaran, Michael F. Hagan
Martin Fisher School of Physics, Brandeis University, Waltham, MA 02453, USA
(Dated: February 25, 2014)



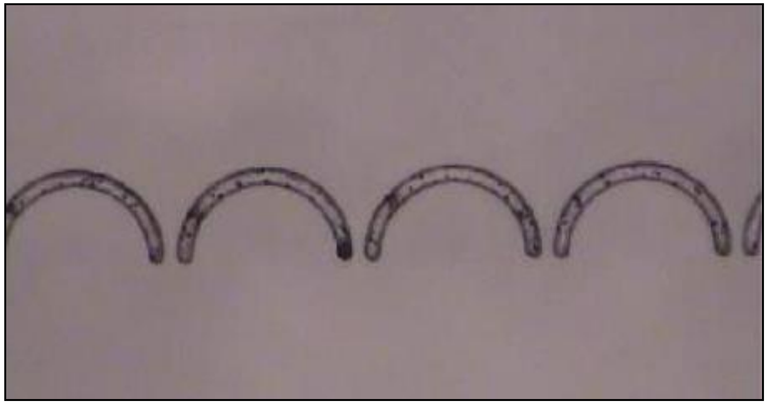
The steady-state distribution of particles at the boundary is proportional to the local curvature

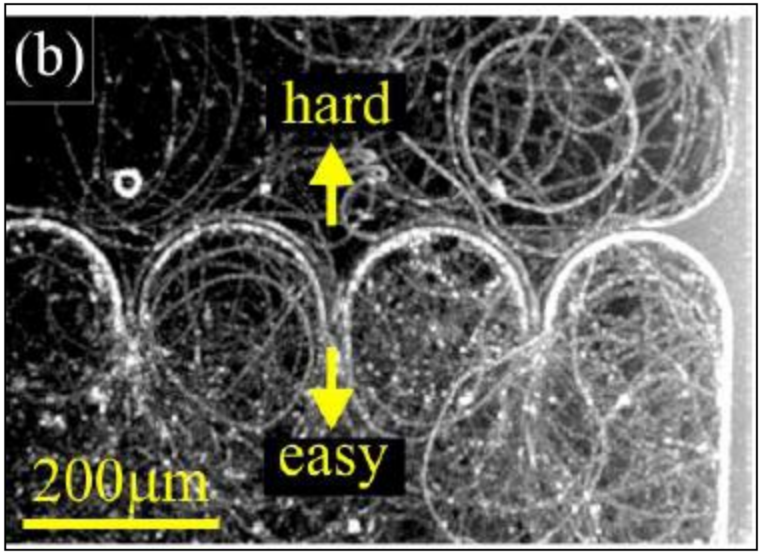
U-shape instead of V-shape

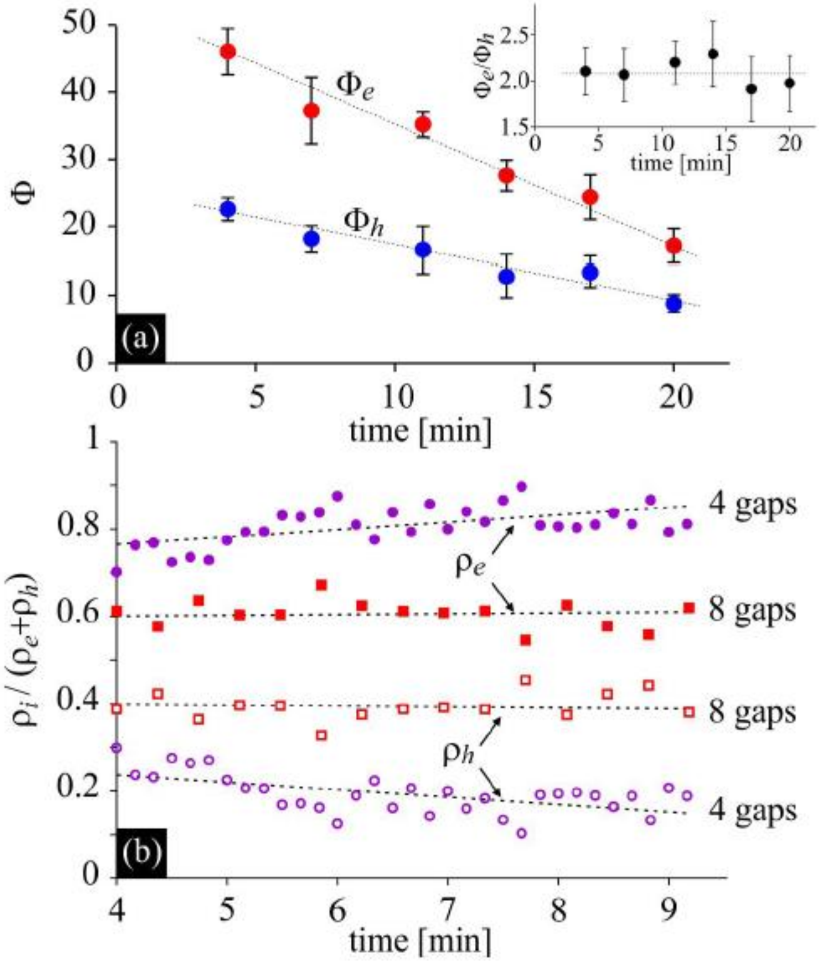


Guidobaldi *et al., Phys. Rev. E* 89, 032720 (2014)

U-shape instead of V-shape

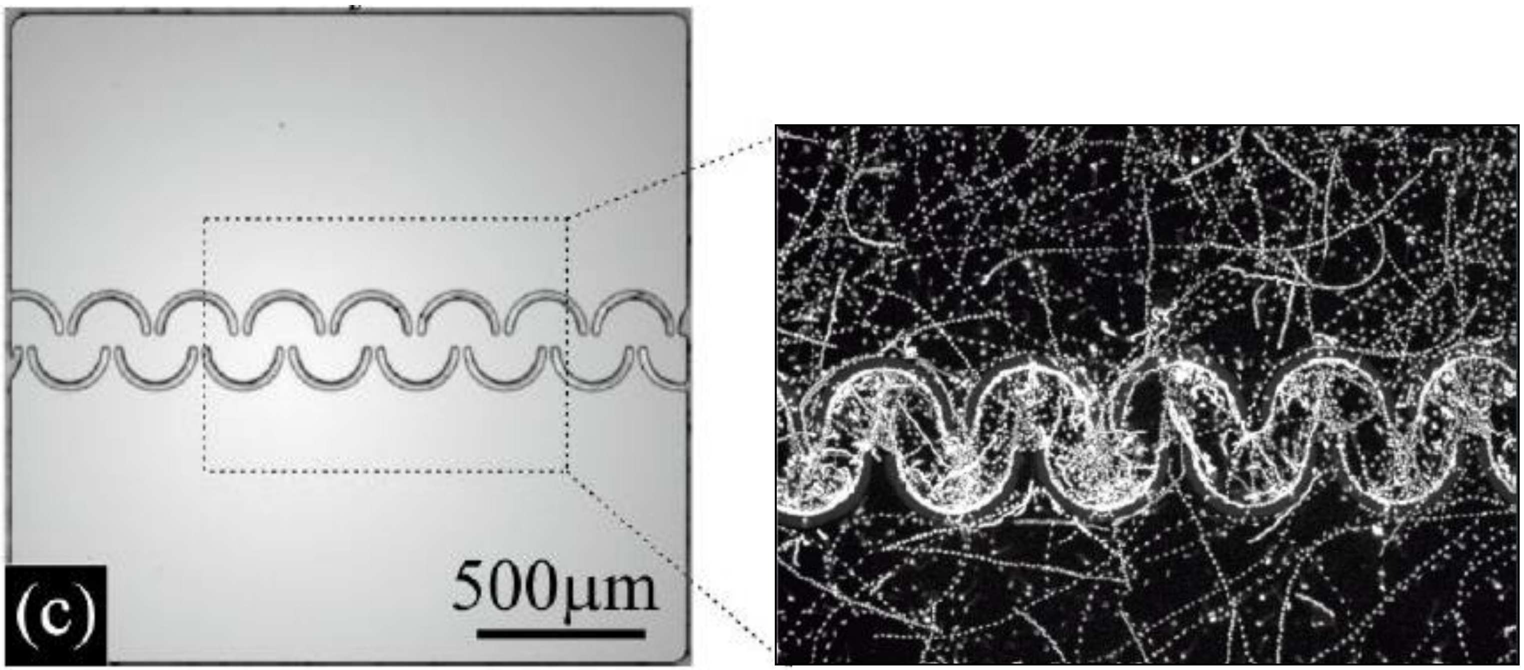






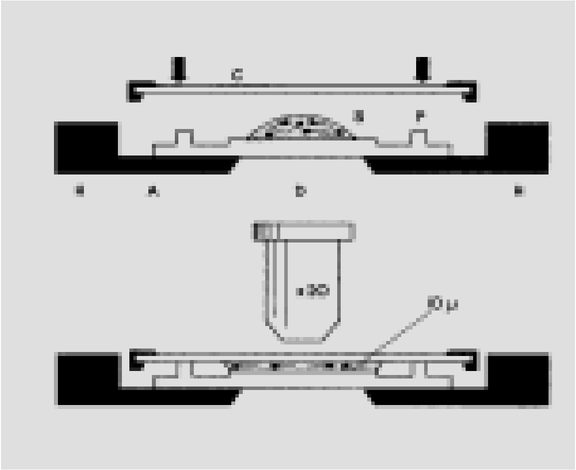
Guidobaldi *et al., Phys. Rev. E* 89, 032720 (2014)

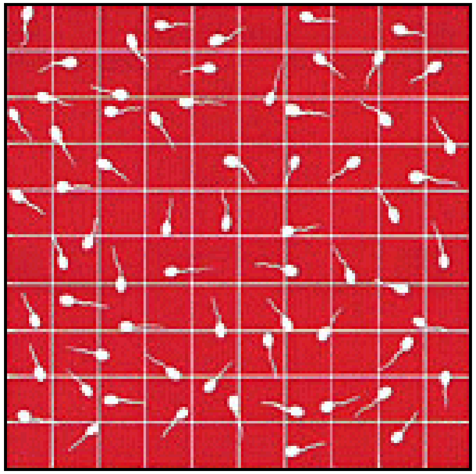
Sperm concentrator

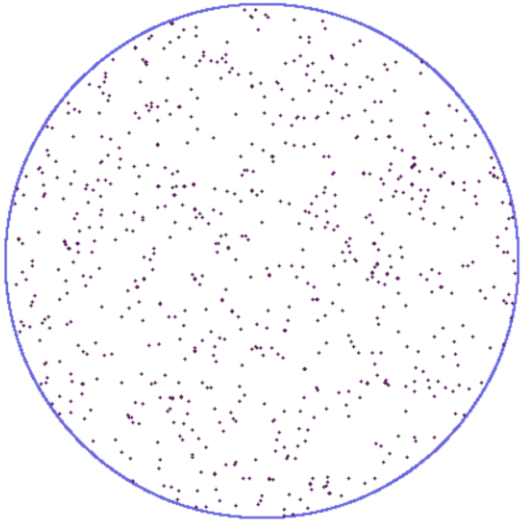


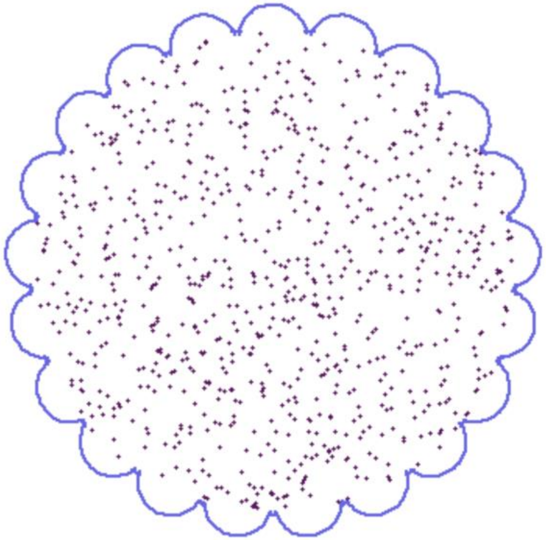
Guidobaldi *et al.*, *Phys. Rev. E* 89, 032720 (2014)

Where are we heading to ?

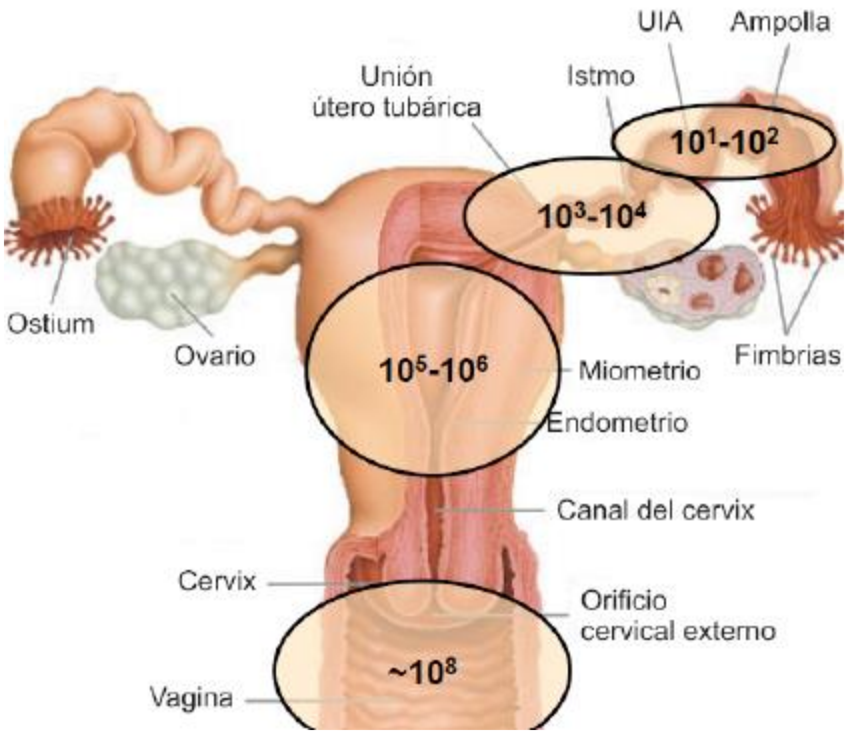








What for ?



From millions
only 10-100 arrive!

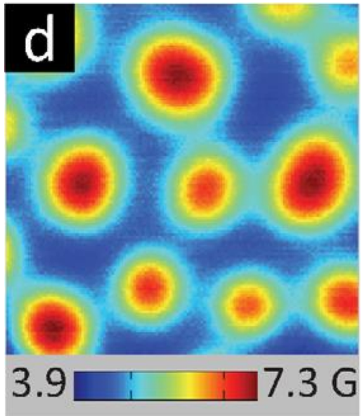
ONLY selected and
capacitated
spermatozoa will be
useful..

HOW TO DIRECT AND
SELECT the smarter
IN VITRO?

Odds of winning the lottery are about 18 million to 1
The likelihood you’ll be killed by lightning is roughly 2,650,000 to 1
Odds of becoming a saint: 1 in 20 million

Conclusion

• Mapping of dissimilar problems: control of micro-objects via surface patterning



• Reversal due to swimmers interactions?

• Ratchets in type I superconductors?

• Geometrical ratchet may help to eliminate cellular stress and damage assocoated with centrifugation

• A sizable fraction of swimmers can be 100% purified even if the original mixture are dynamically sligthly different

• Hyperactivation may prevet sperm from becoming trapped with the convoluted ephitelial folds of the fallopian tubes

Thank you

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