Active matter under confinement

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P. Sartori, M. Pierno. P. Mistura

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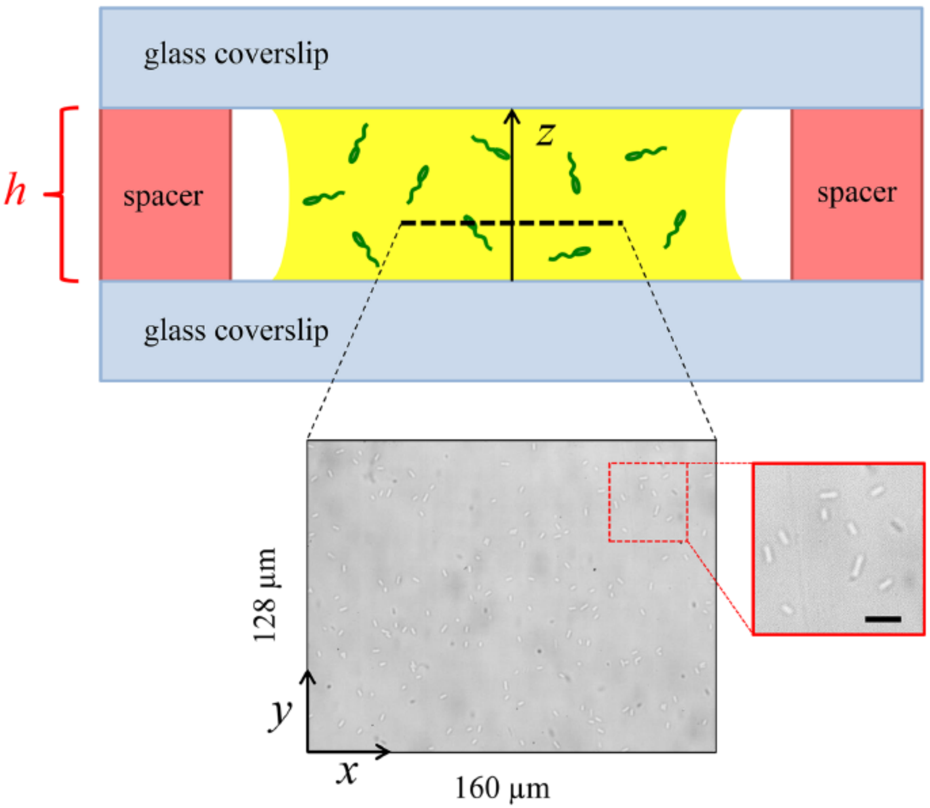
Active matter

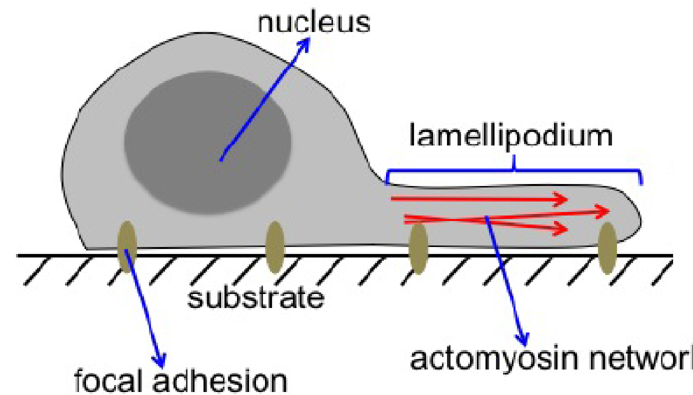
- Inherent far from equilibrium system whose internal constituents continuously convert chemical energy into work (M.C. Marchetti et al., Rev. Mod. Phys. **85**, 1143 (2013)).

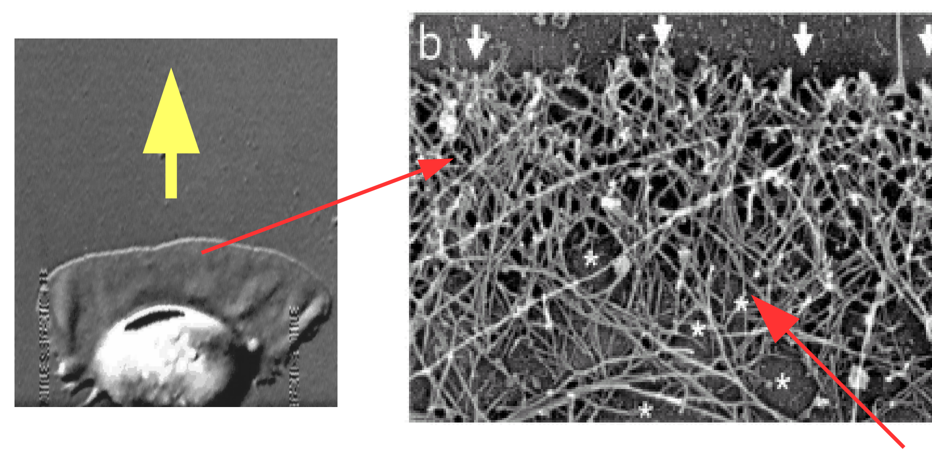
Bacteria under slit confinement



P. Sartori et al., sub. to PRF

Crawling cell

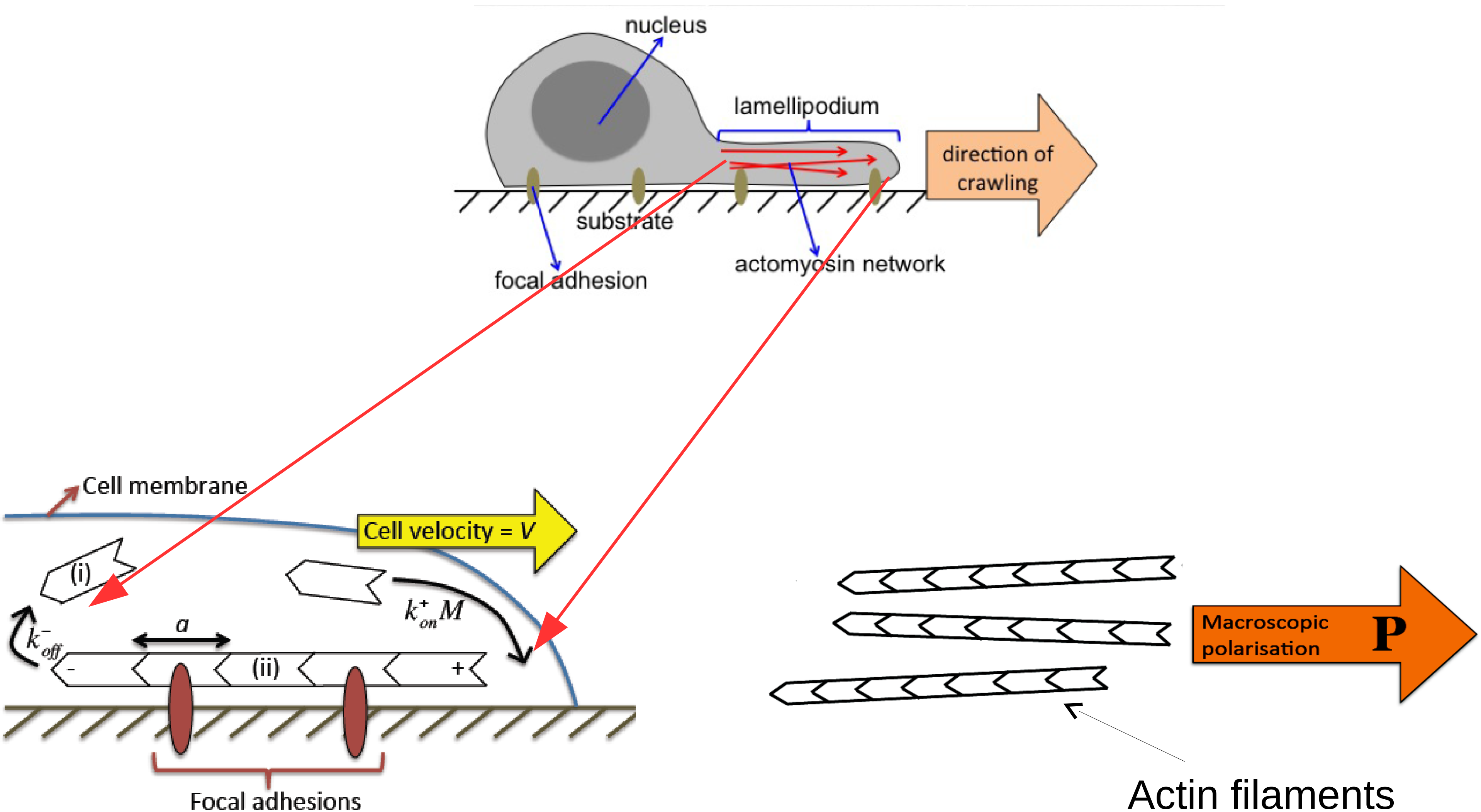




Actin filaments

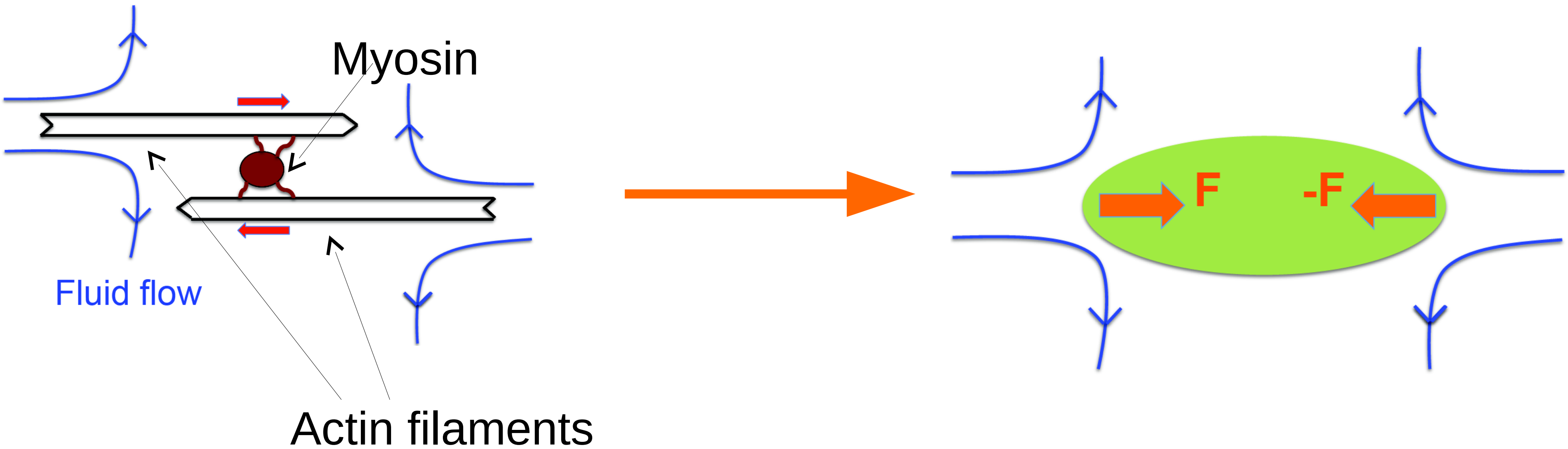
Tjhung et al., Nat. Comm. **6**, 5420 (2015)

Crawling cell

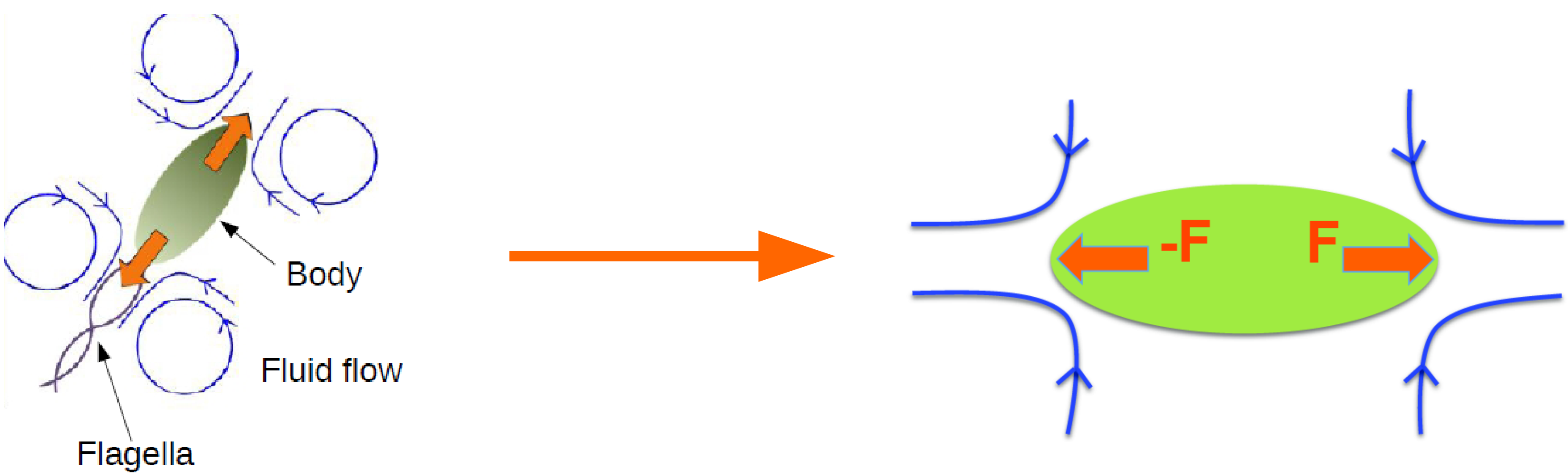


Tjhung et al., Nat. Comm. **6**, 5420 (2015)

Crawling cell



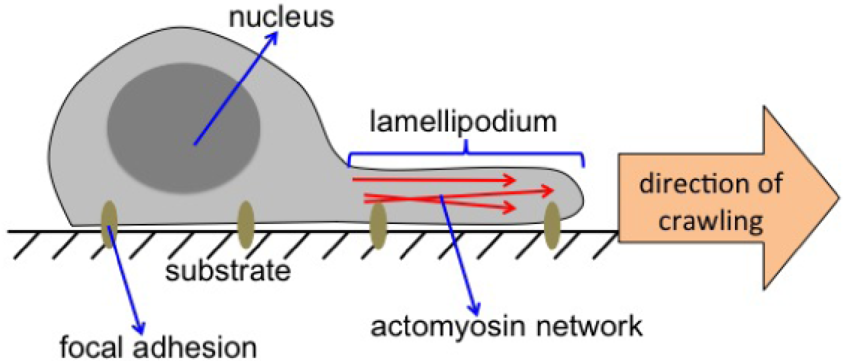
OSS.



Tjhung et al., PNAS (2012)

Dogic et al., Nature (2013)

Equations of motion



$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi(\mathbf{v} + w_0 \mathbf{P})) = \nabla \left(M \nabla \frac{\delta F}{\delta \phi} \right)$$

$$\frac{\partial \mathbf{P}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{P} = -\underline{\underline{\Omega}} \cdot \mathbf{P} + \xi \underline{\underline{D}} \cdot \mathbf{P} - \frac{1}{\Gamma} \frac{\delta F}{\delta \mathbf{P}}$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = -\nabla P + \nabla \cdot \left(\underline{\underline{\sigma}}^{\mathrm{act}} + \underline{\underline{\sigma}}^{\mathrm{pass}} \right)$$

$$\nabla \cdot \boldsymbol{v} = 0$$

Active stress $\sigma^a_{\alpha\beta} = -\zeta \varphi \left(P_\alpha P_\beta - \frac{1}{3} P^2 \delta_{\alpha\beta} \right)$

$\zeta < 0$ Contractile

$\zeta > 0$ Extensile

E. Tjhung, D. Marenduzzo, M. Cates, PNAS (2013); E. Tjhung, A.T., D. Marenduzzo, M. Cates., Nat. Comm. (2015)

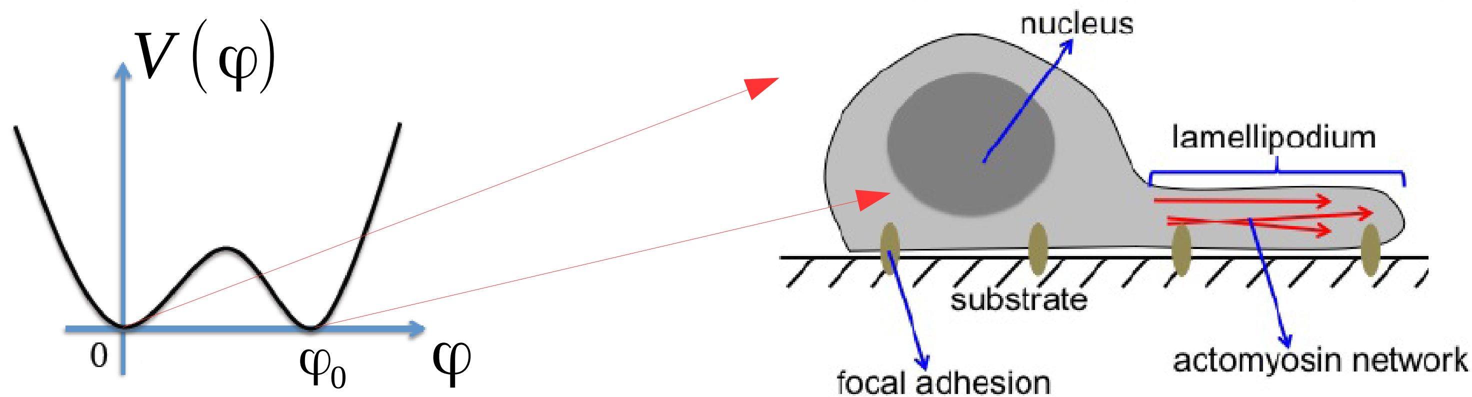
Equations of motion

Binary fluid

$$F[\phi,\mathbf{P}] = \int d^3r \left\{ \frac{a}{4{\phi_{\mathrm{cr}}}^4}\phi^2(\phi-\phi_0)^2 + \frac{k}{2}|\nabla\phi|^2 - \frac{\alpha}{2}\frac{(\phi-\phi_{\mathrm{cr}})}{\phi_{\mathrm{cr}}}|\mathbf{P}|^2 + \frac{\alpha}{4}|\mathbf{P}|^4 + \frac{\kappa}{2}(\nabla\mathbf{P})^2 + \beta_1 \mathbf{P}\cdot\nabla\phi \right\}$$

Polar liquid crystal

Anchoring



E. Tjhung, D. Marenduzzo, M. Cates, PNAS (2013); E. Tjhung, A.T., D. Marenduzzo, M. Cates., Nat. Comm. (2015)

Crawling cell

Fried-egg shape

P.T. Yam et al., J. Cell. Biol. **178**, 1207-1221 (2007).

Lamellipodium

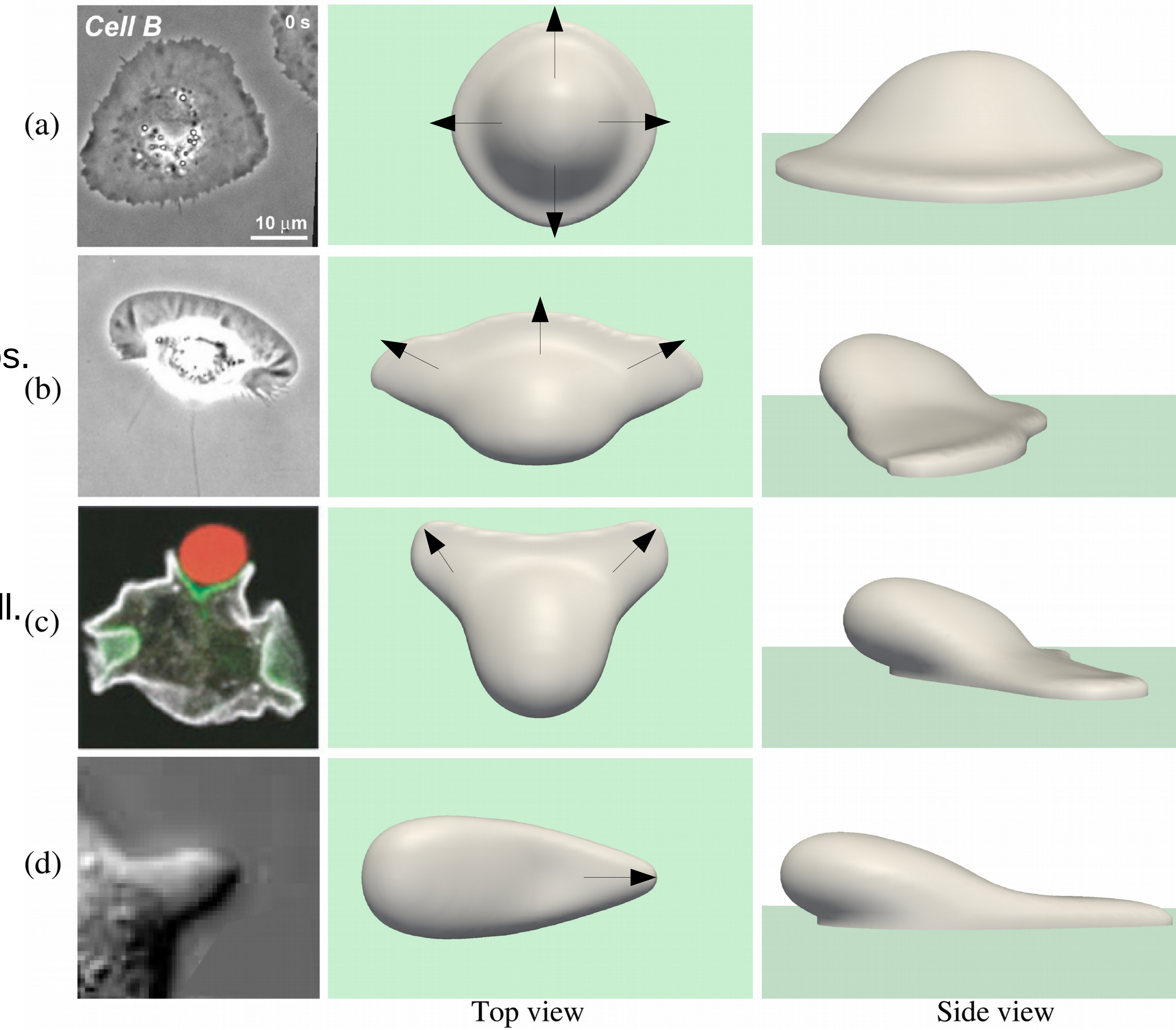
Barnhart E. L. et al., Plos. Biol. **178**, e1001059 (2011).

Phagocytic cup

Mercanti V. et al., J. Cell. Biol., **119**, 4079 (2006).

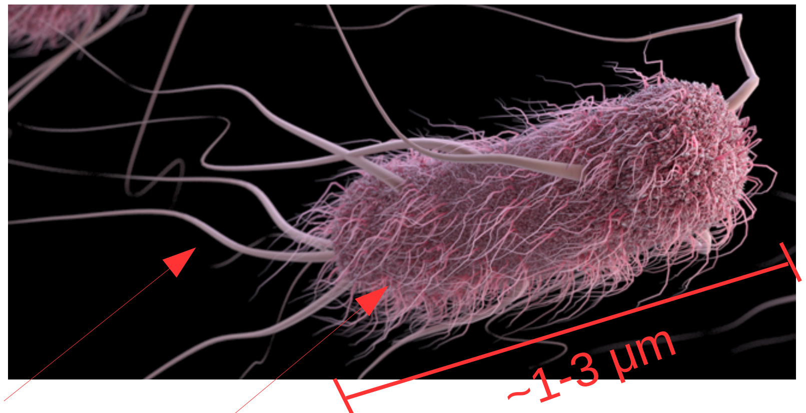
Pseudopodium

Zhang H. et al., J. Cell. Sci., **115**, 1733 (2002).



Bacteria under slit confinement

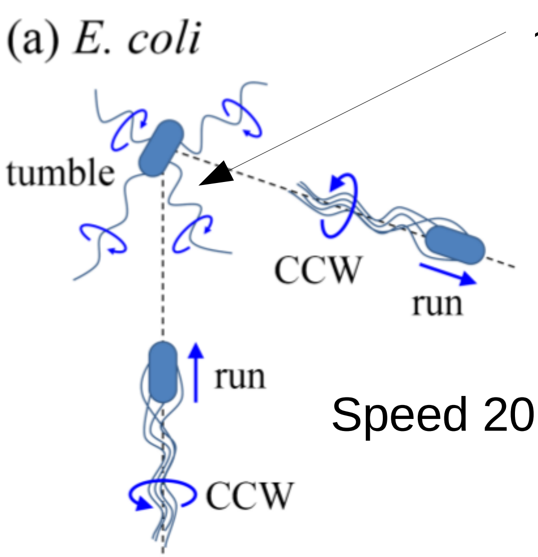
Escherichia Coli



Flagellum

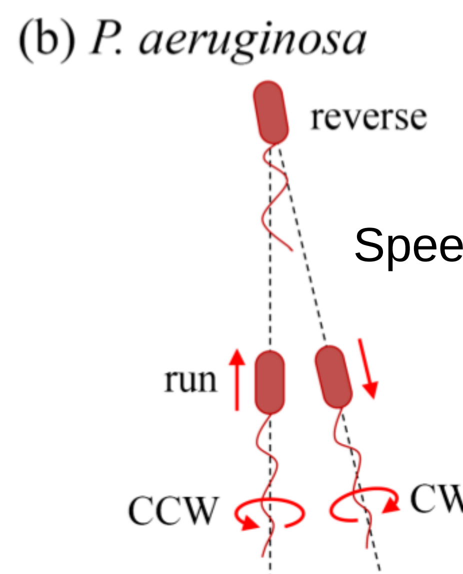
Body

Pseudomonas Aeruginosa



~70°

Speed 20 – 40 µm/s

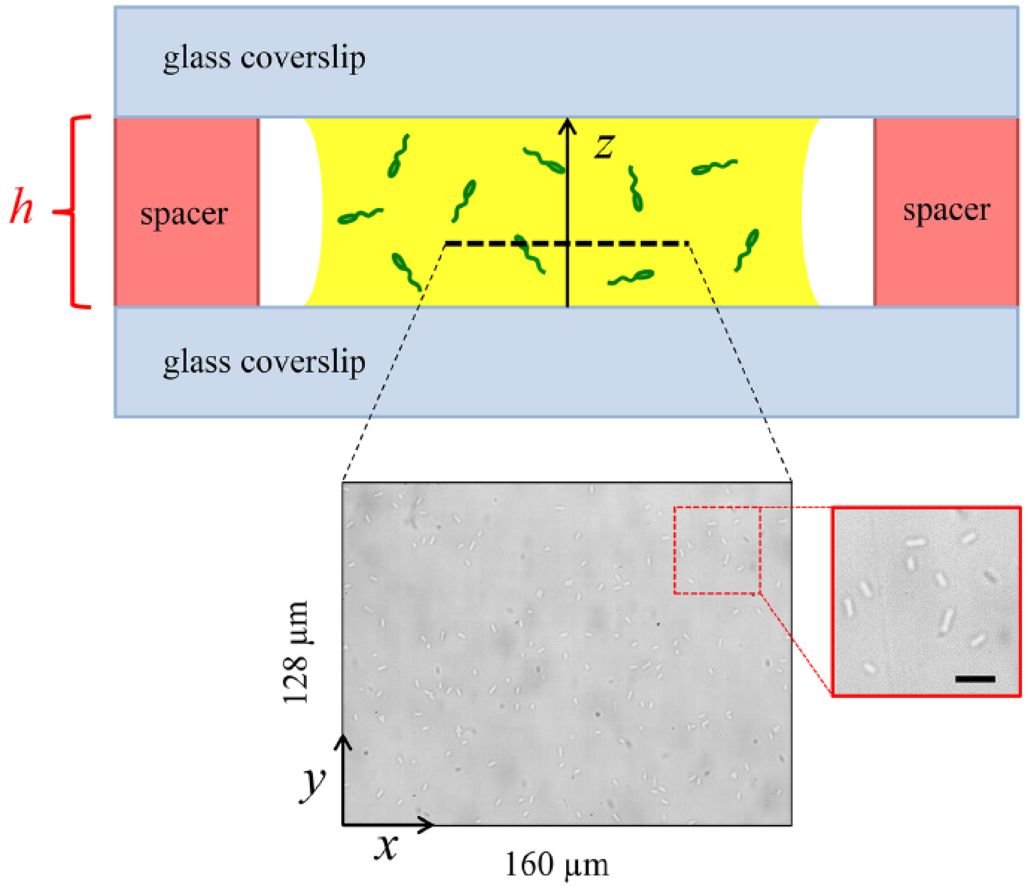


Speed 40 – 50 µm/s

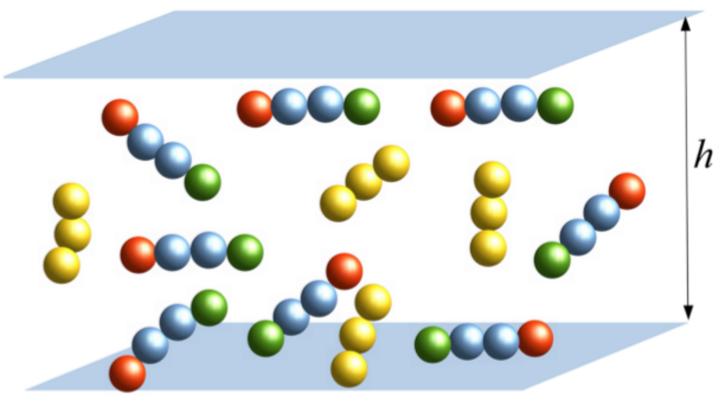
M.C. Marchetti et al., Rev. Mod. Phys. **85**, 1143 (2013); E. M. Purcell, Am. Journ. Phys **45**, 3 (1977)

Bacteria under slit confinement

Experiment



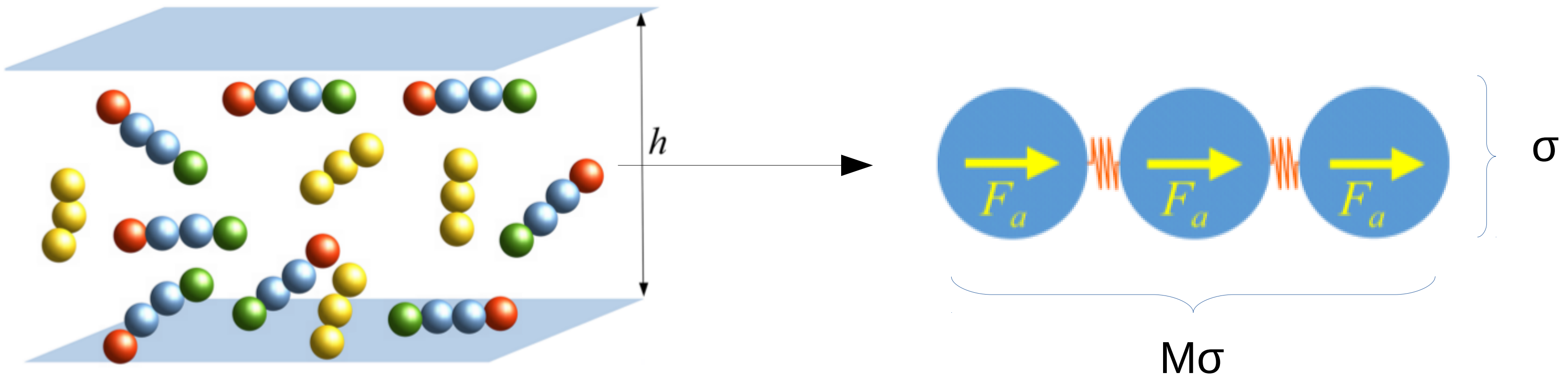
Simulation



- Anisotropy can be controlled
- Active and passive bodies can be distinguished
- Active force applied on each bead
- Hydrodynamic interactions are neglected

A. P. Berke et al., PRL **101**, 038102 (2008), G. Li et al., PRL **103**, 078101 (2009), M. Molaei et al, PRL **113**, 068103 (2014) P. Sartori et al., sub. to PRF

Bacteria under slit confinement



$$m_i \frac{d^2\mathbf{r}_i}{dt^2} = -\gamma \frac{d\mathbf{r}_i}{dt} - \nabla_i U + \boldsymbol{F}_a + \sqrt{2k_B T \gamma_i}\boldsymbol{\xi}_i(t)$$

$$U_{KP} = \sum_{i=2}^{M-1} K \left(1 - \frac{\mathbf{r}_{i-1} \cdot \mathbf{r}_i}{|\mathbf{r}_{i-1}|\,|\mathbf{r}_i|}\right)$$

$$U_{i,j}^{LJ}(r) = \left\{4\epsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] - V_{LJ}(r = r_c)\right\}\theta(r - r_c)$$

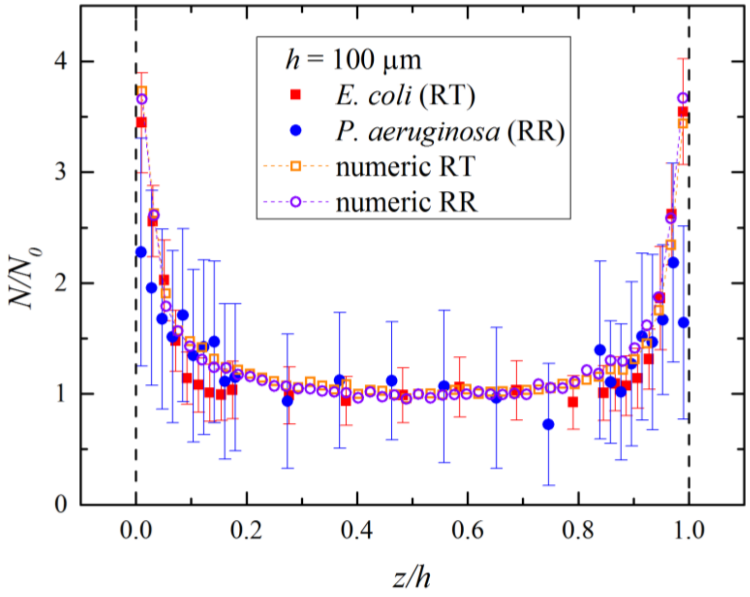
$\boldsymbol{\xi}_i(t)$ Gaussian noise

γ Viscous friction

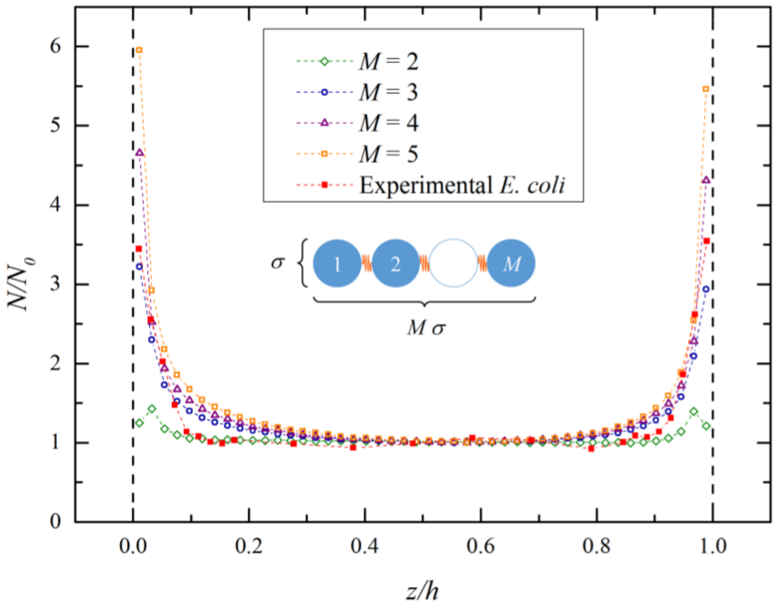
$\boldsymbol{F}_a$ Active force applied on each bead

K Bending rigidity

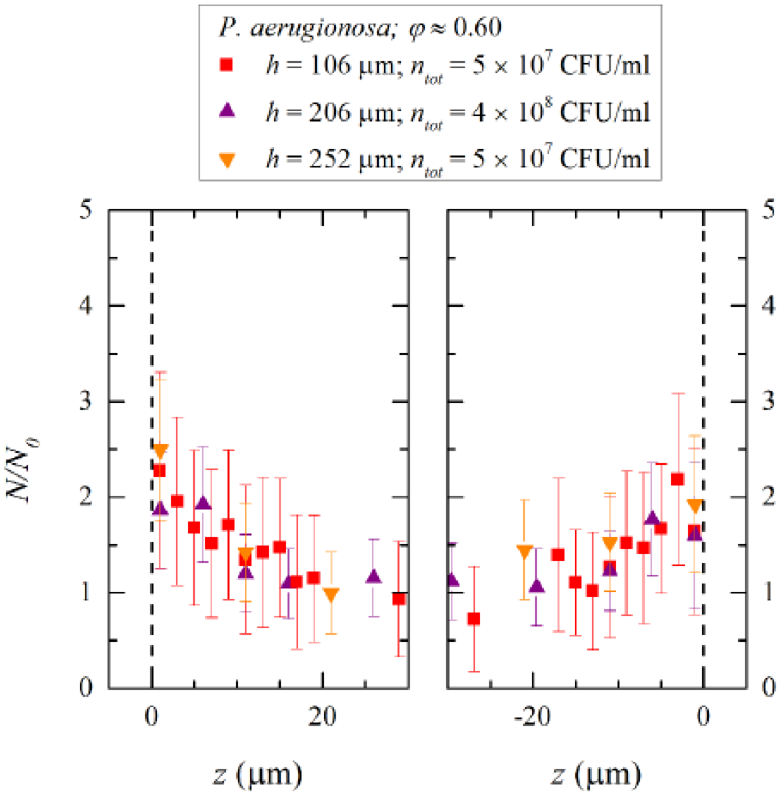
Bacteria under slit confinement



- φ~0.75
- n=5x10^{8} CFU/ml



Aspect ratio



Height of the slit

Conclusions

- A minimal continuum model with a few physical ingredients (such as treadmilling, contractility and anchoring) captures many of the observed features of motile and spreading cells

- Numerical simulations of self-propelling particles reproduce wall accumulation of (low-density) bacteria in good agreement with experimental results. Microscopic dynamics has negligible effects on the accumulation.