Emergent order and structure of growing biofilms

Philip Pearce

Harvard Medical School

[soon: University College London]

Acknowledgements

- **Microfluidic experiments (MPI Marburg)**
  - Raimo Hartmann
  - Praveen Singh
  - Hannah Jeckel
  - Knut Drescher

- **Theory and simulations (MIT)**
  - Rachel Mok
  - Boya Song
  - Dominic Skinner
  - Jeffrey Oishi (MIT/Bates College)
  - Jörn Dunkel

Hartmann, *et al. Nat. Phys.* 15 (2019)
Pearce, *et al. PRL* 123 (2019)

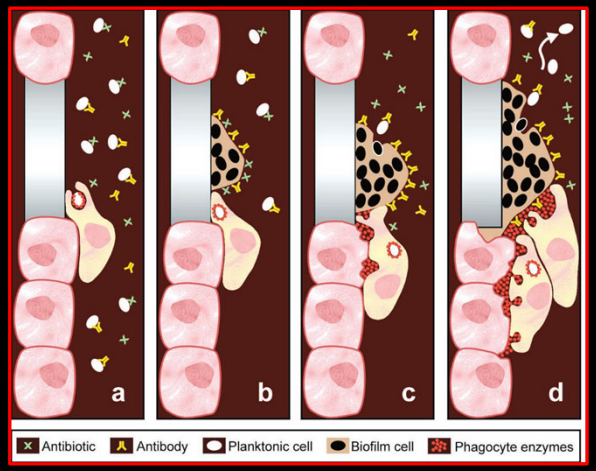
Why model bacterial biofilms?

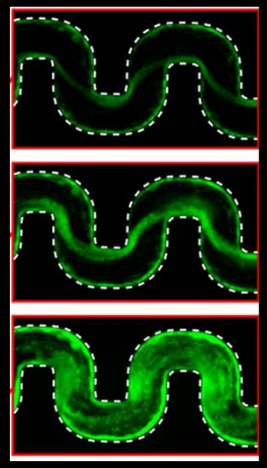
Why are bacterial biofilms interesting?

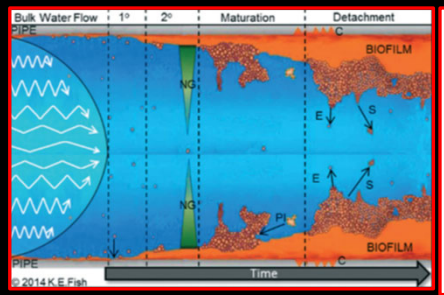
- Active complex materials in which energy is injected (e.g. swimming or growth) and chemicals created/consumed by cells
- Antibiotic resistance thought to cause 700,000 deaths per year globally

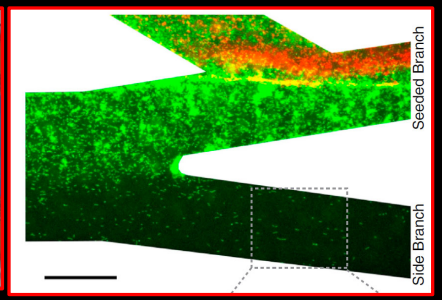
Why is fluid flow interesting?

- It affects mechanics and transport at the cell and population levels
- It is ubiquitous in bacterial habitats (e.g. lungs, gut, nasal passage, medical devices, industrial pipes, …)







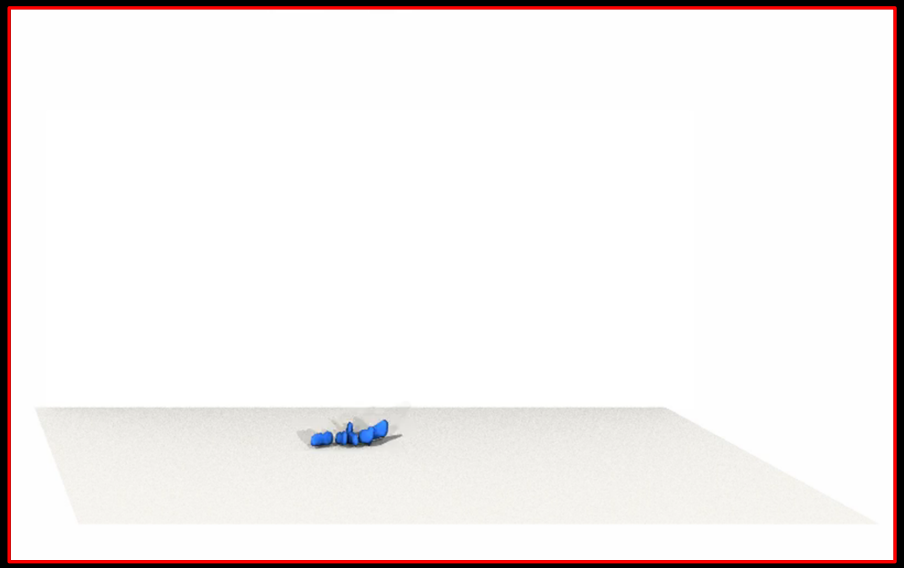


Tackling antimicrobial resistance 2019 - 2024 – The UK's five-year national action plan (2019)

Costerton *et al. Science* (1999)
Fish *et al. Environ. Sci.* (2013)

Drescher *et al. PNAS* (2013)
Siryaporn *et al. Curr. Biol.* (2015)

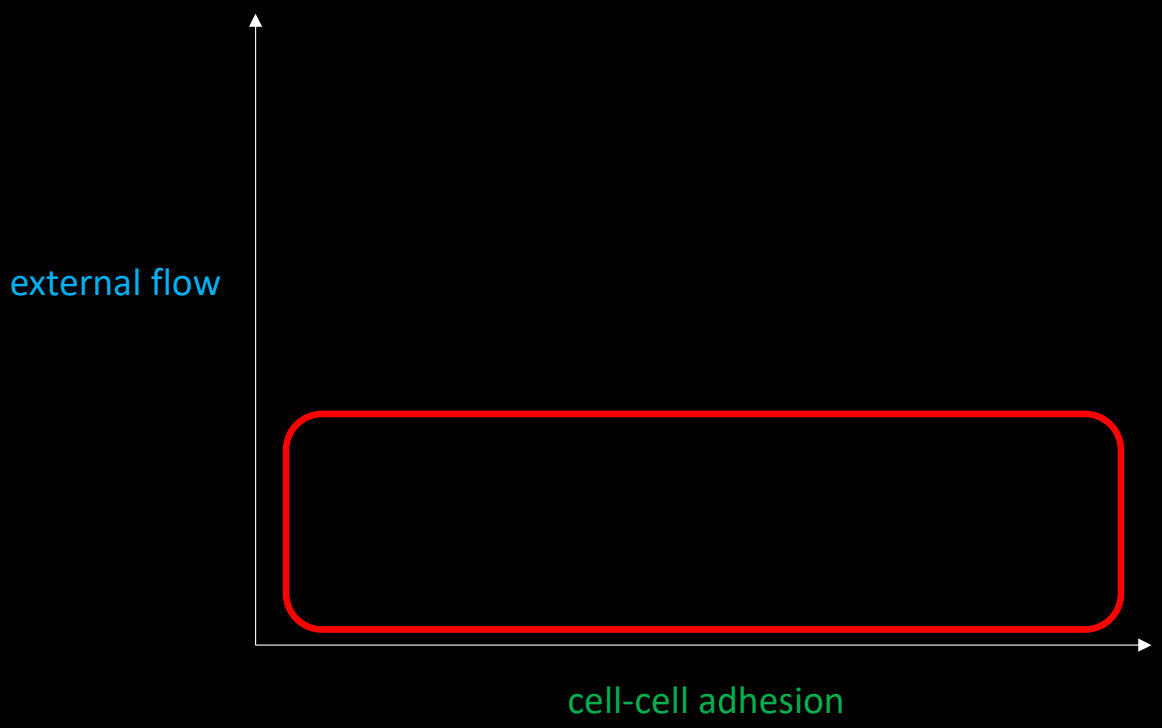
Biofilm growth



Key physics during biofilm growth

activity (growth, division)
cell-surface interactions

cell-cell interactions
cell-flow interactions



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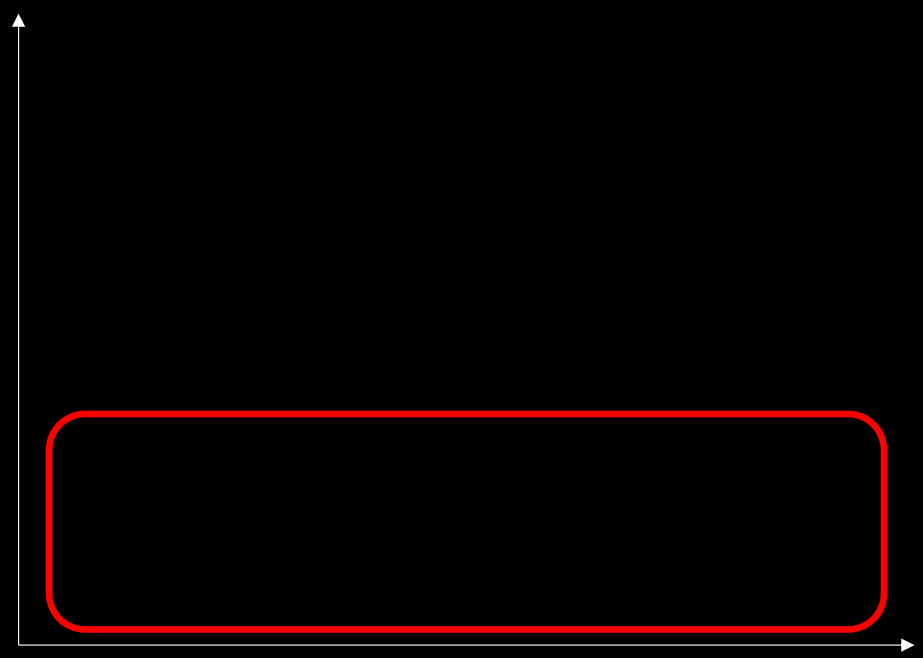
external flow

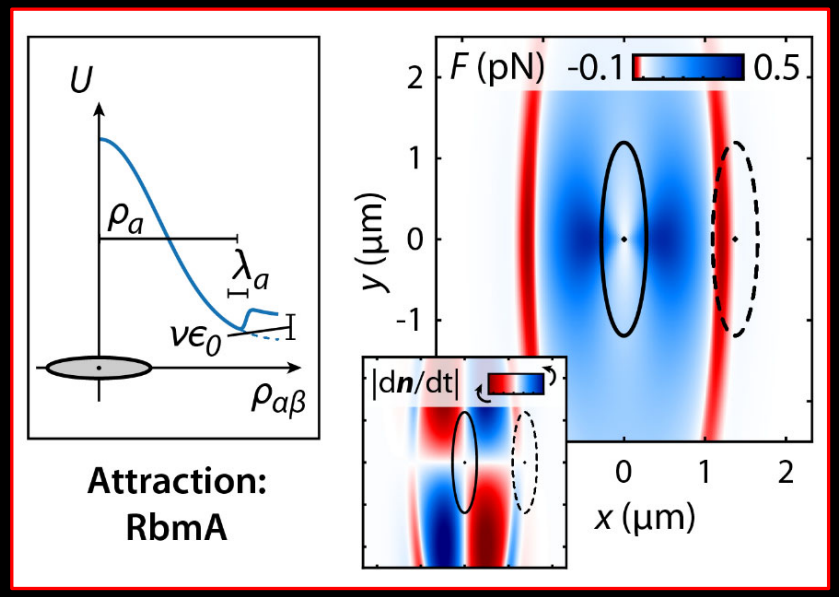


cell-cell adhesion

cell-cell interactions

$$U = \epsilon_0 \epsilon_1 \left(e^{-\frac{\rho^2}{\lambda_r^2}} + \frac{\nu}{1 + e^{\left(\frac{\rho_a - \rho}{\lambda_a}\right)}} \right)$$

repulsion attraction



Hartmann, *et al. Nat. Phys.* 15 (2019)

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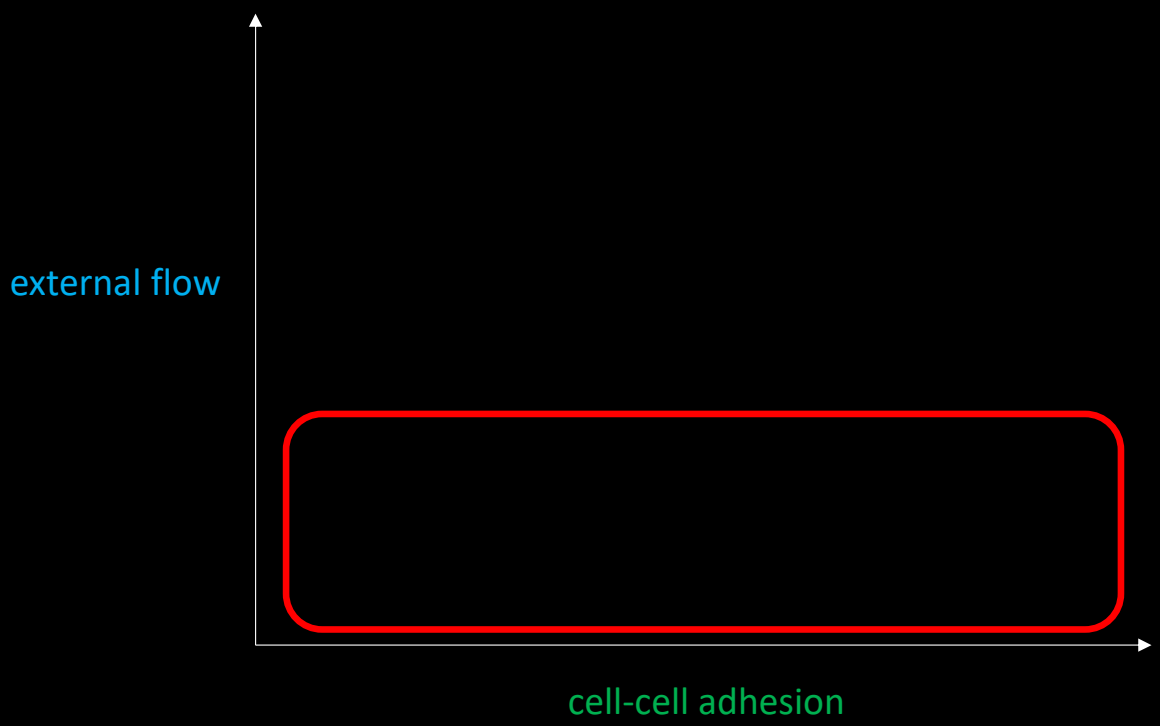

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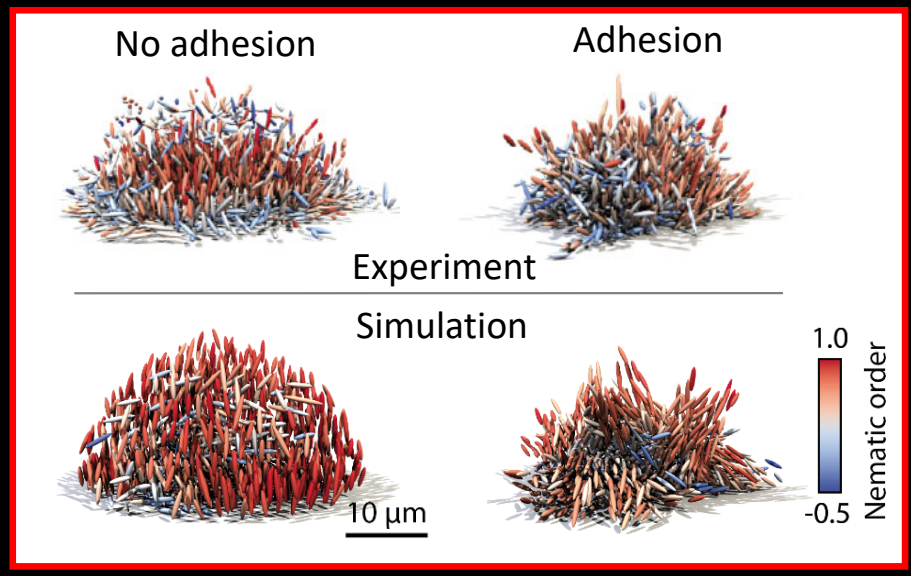

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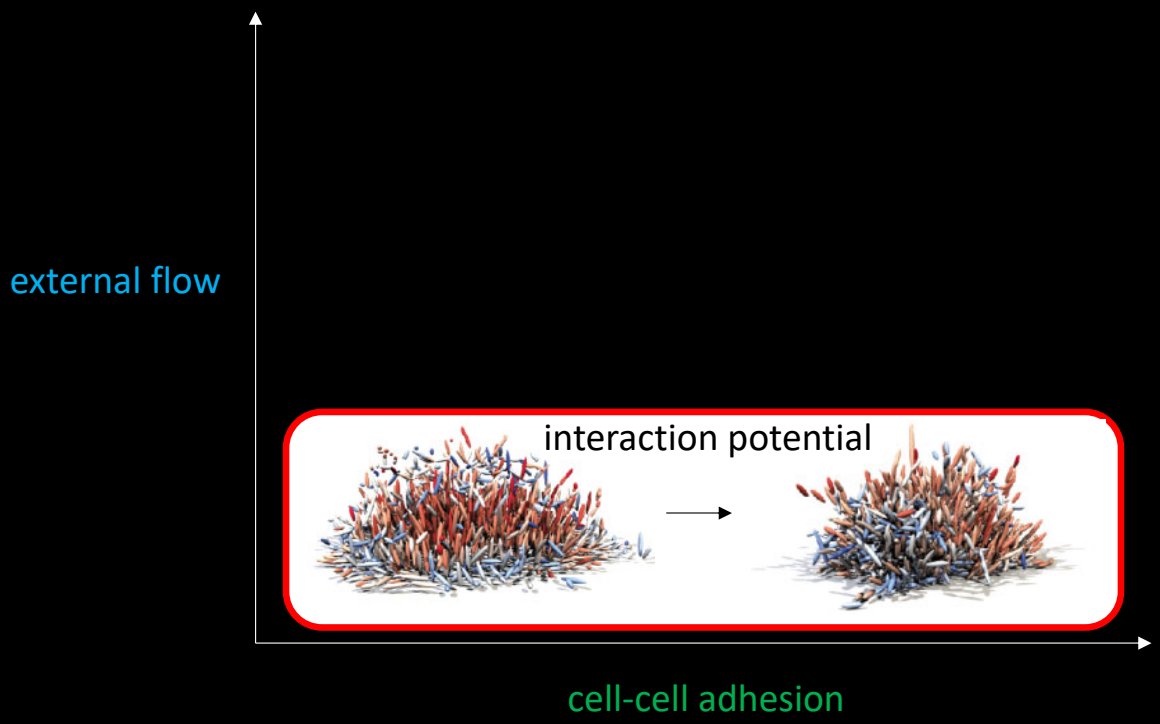

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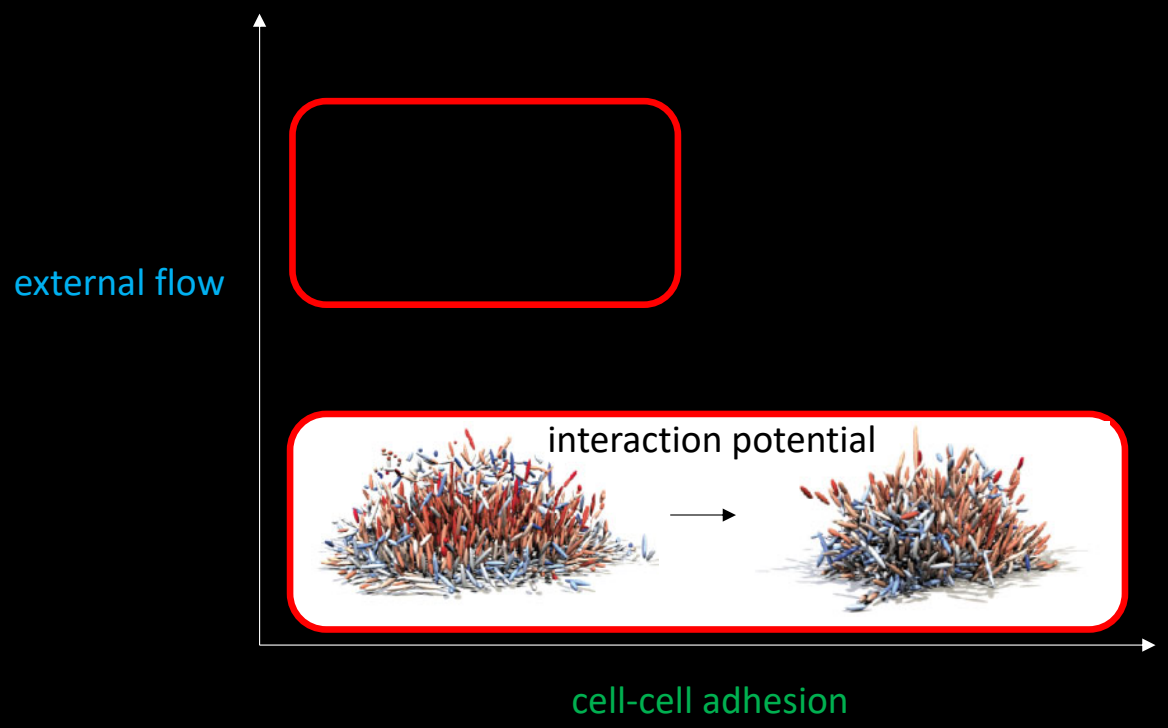

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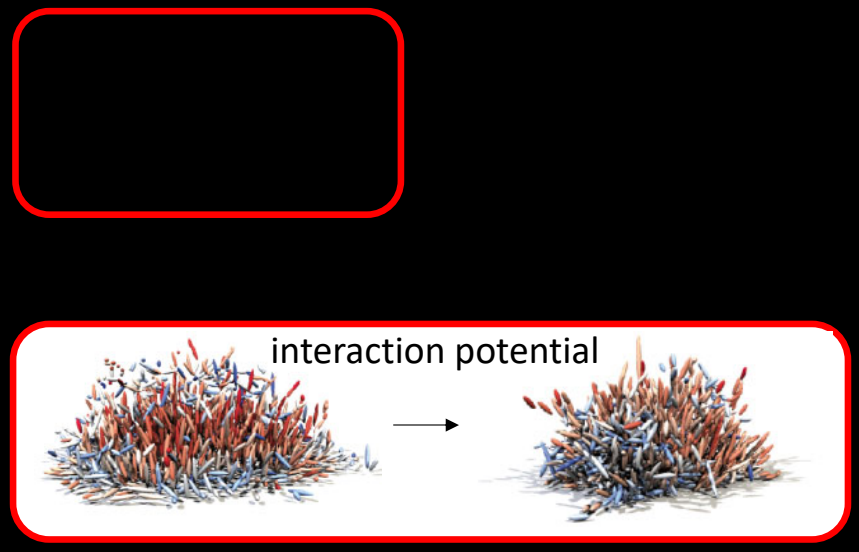

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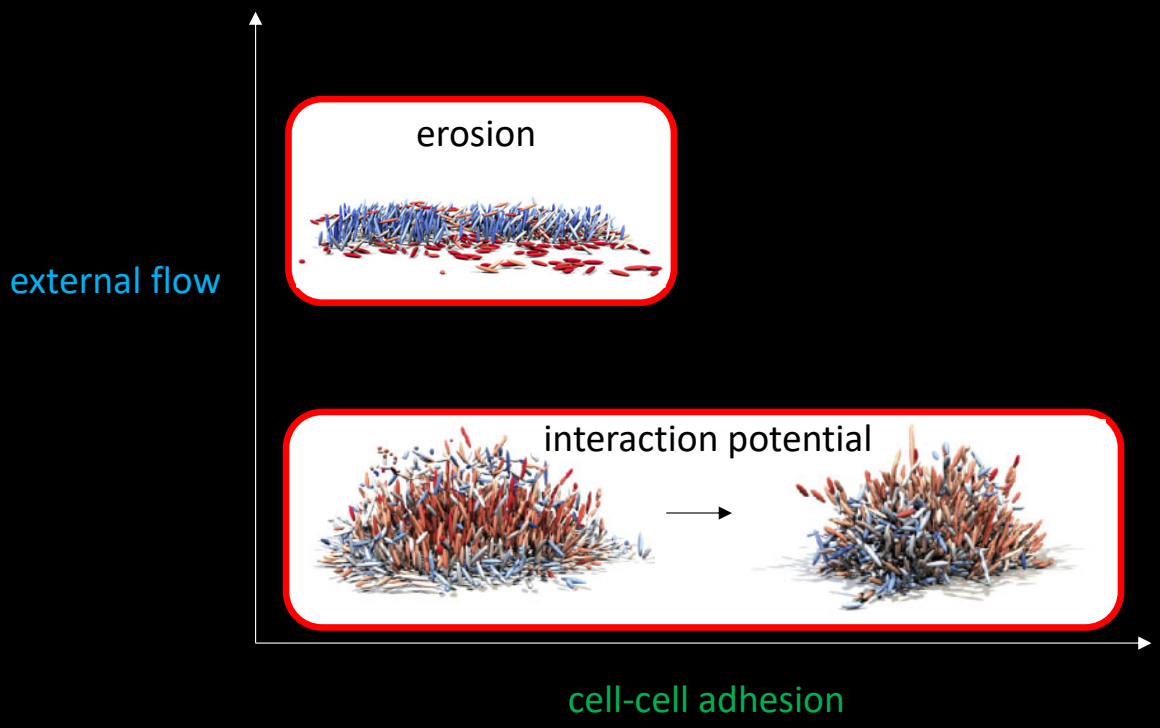

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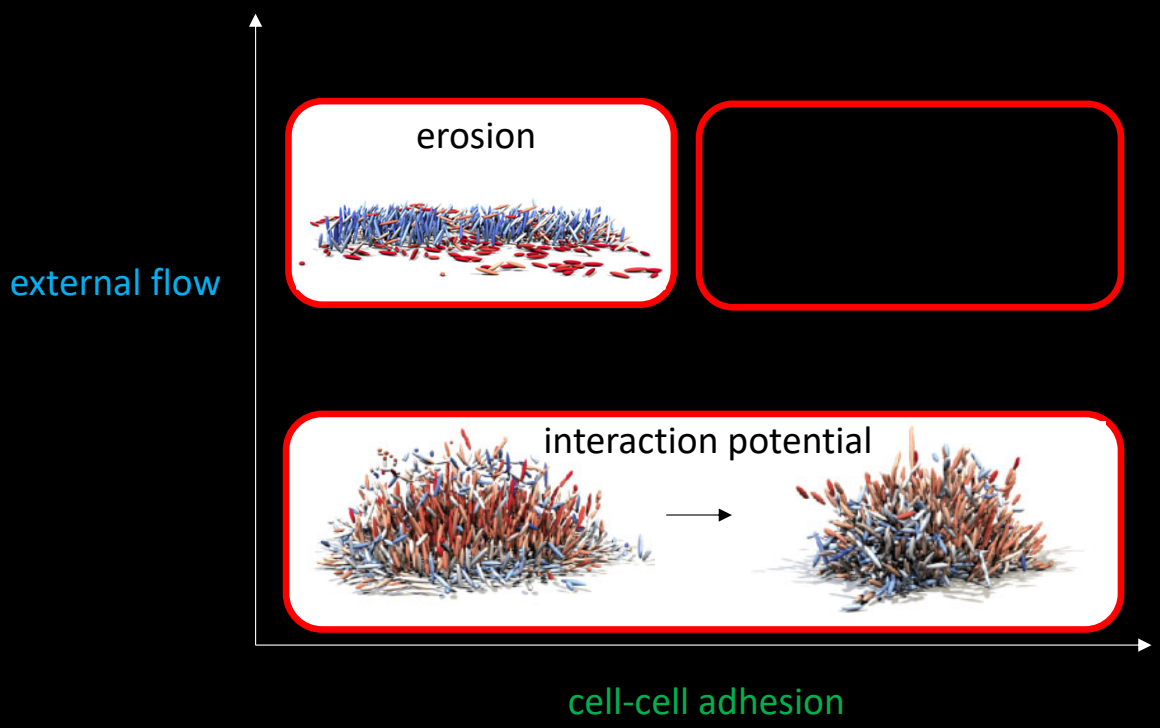

Pearce, *et al. PRL* 123 (2019)

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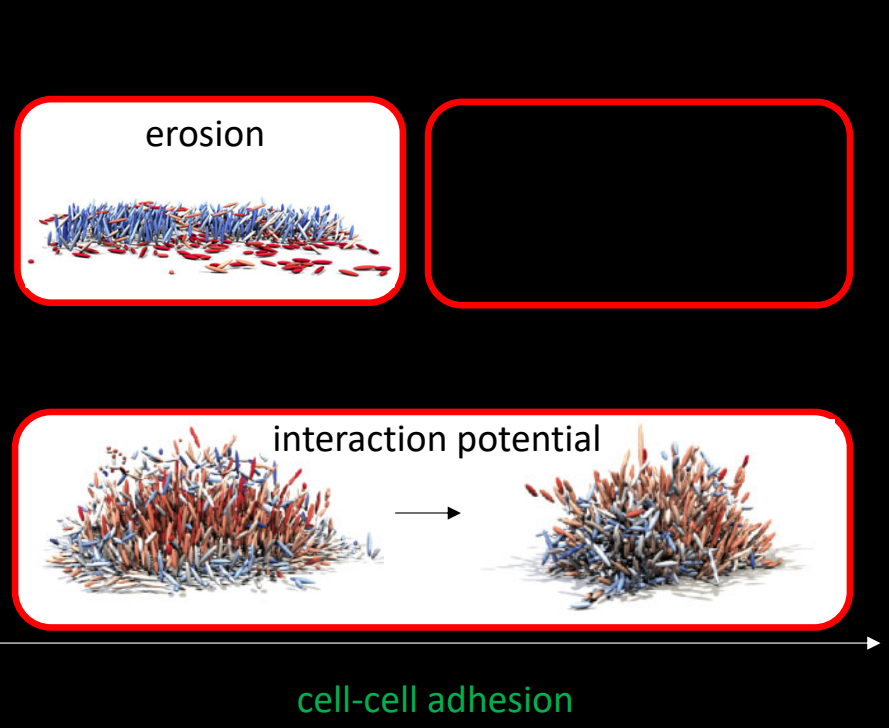
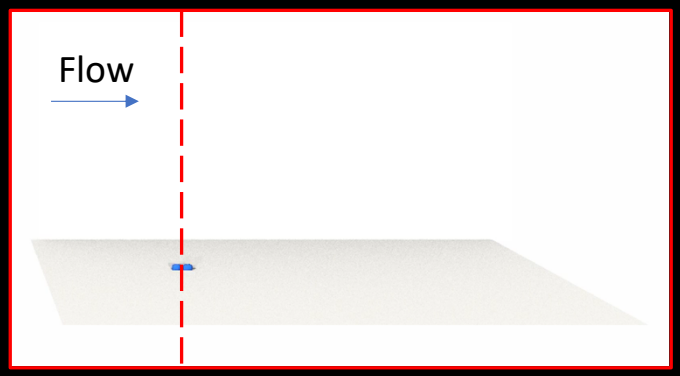
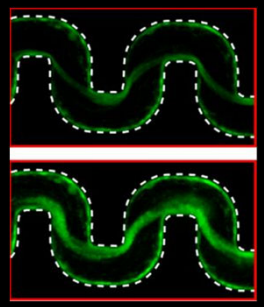




- Initially: asymmetric growth



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Pearce, *et al. PRL* 123 (2019)

Drescher *et al. PNAS* (2013)

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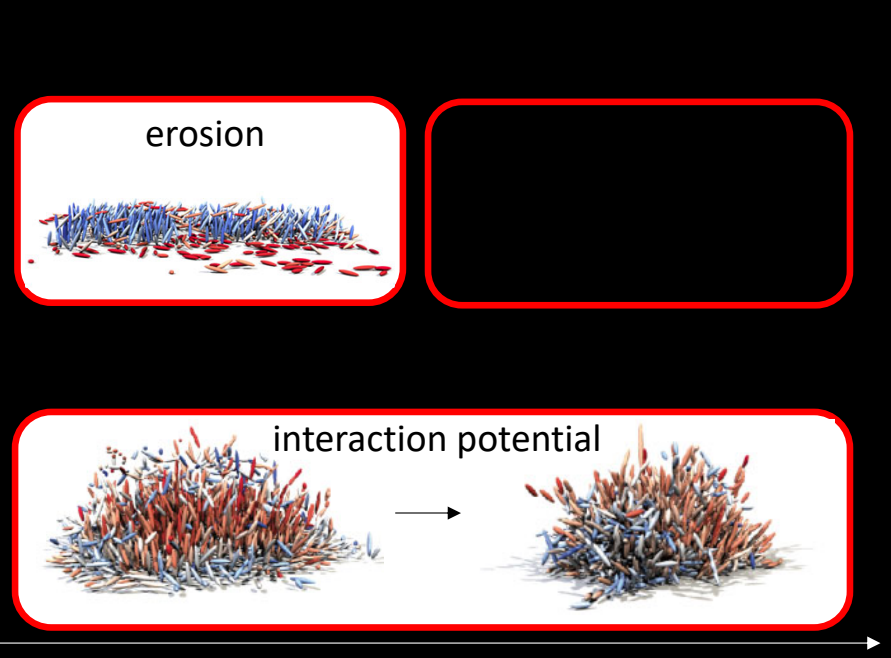
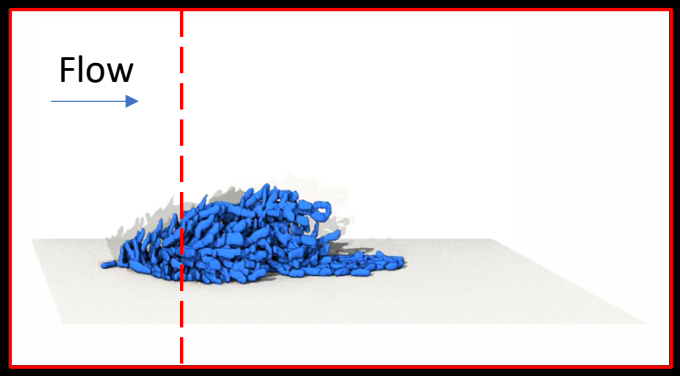


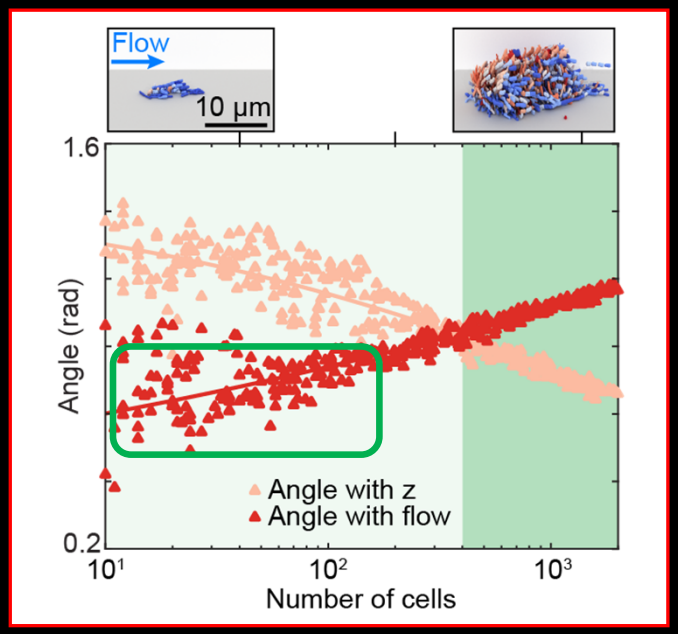


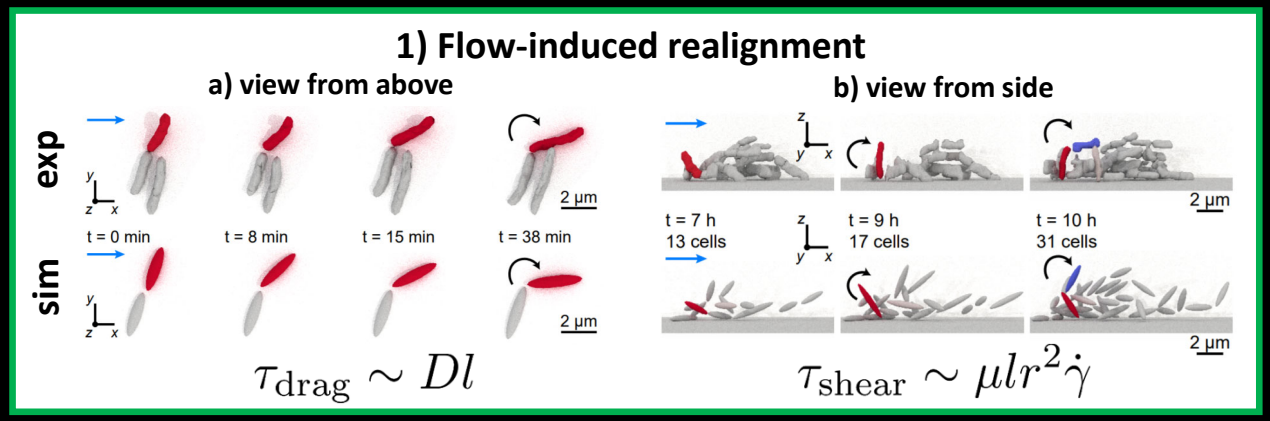
- Initially: asymmetric growth
- Later: symmetric growth

Pearce, *et al. PRL* 123 (2019)

Biofilm growth in fluid flow

- Initially: flow-aligned
- Later: vertical





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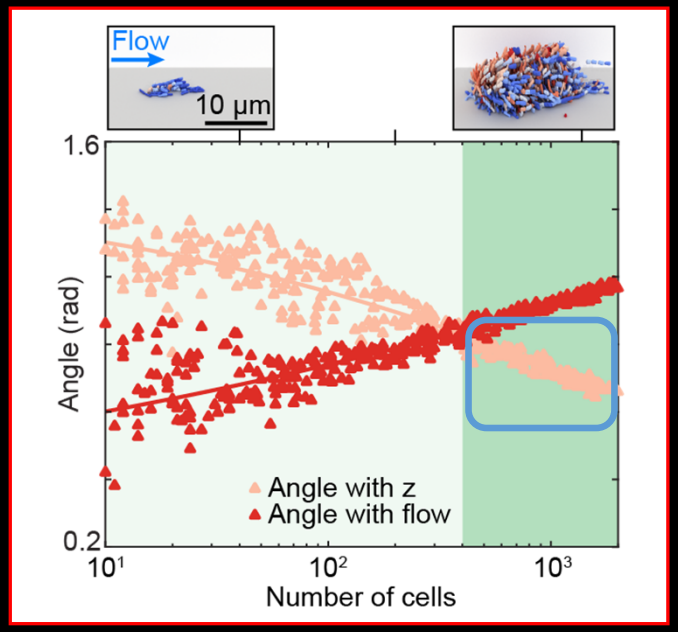

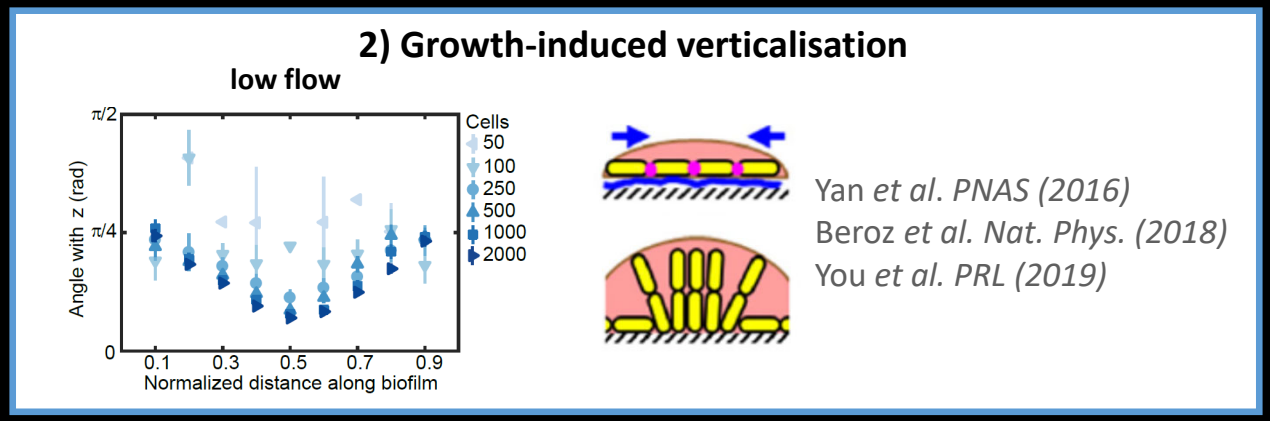

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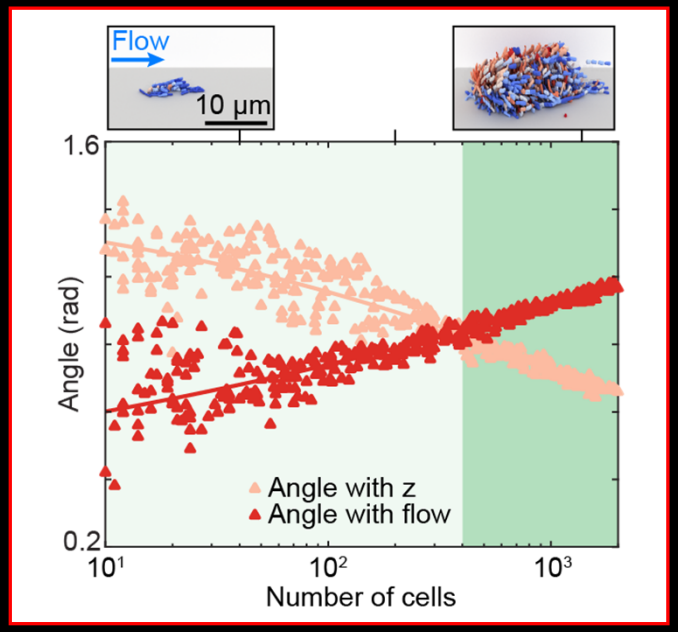
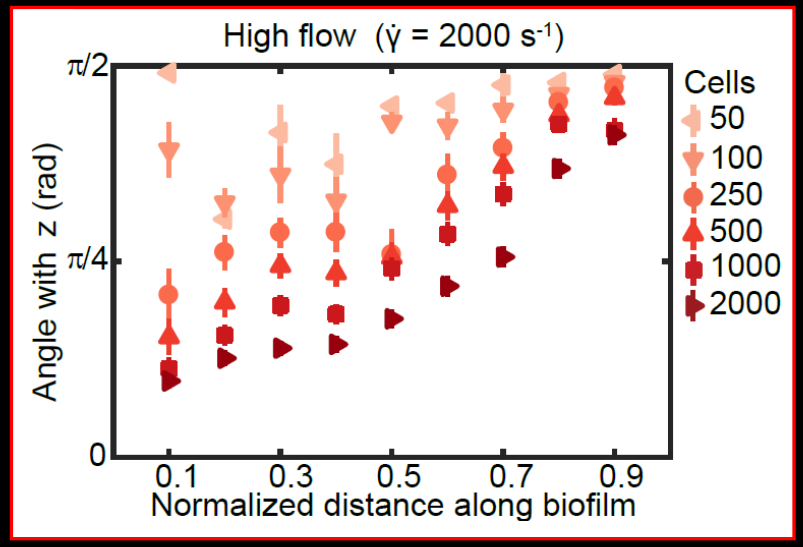
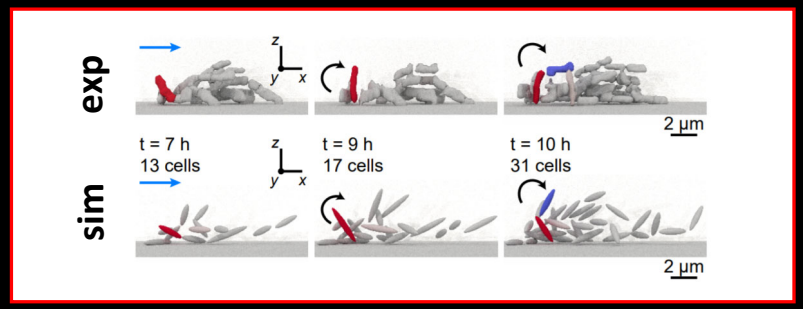






Pearce, *et al. PRL* 123 (2019)

Biofilm growth in fluid flow

Continuum model

Stokes equations

$$\nabla \cdot \mathbf{v} = g$$ ← growth

$$\nabla \cdot \sigma = \nabla p$$

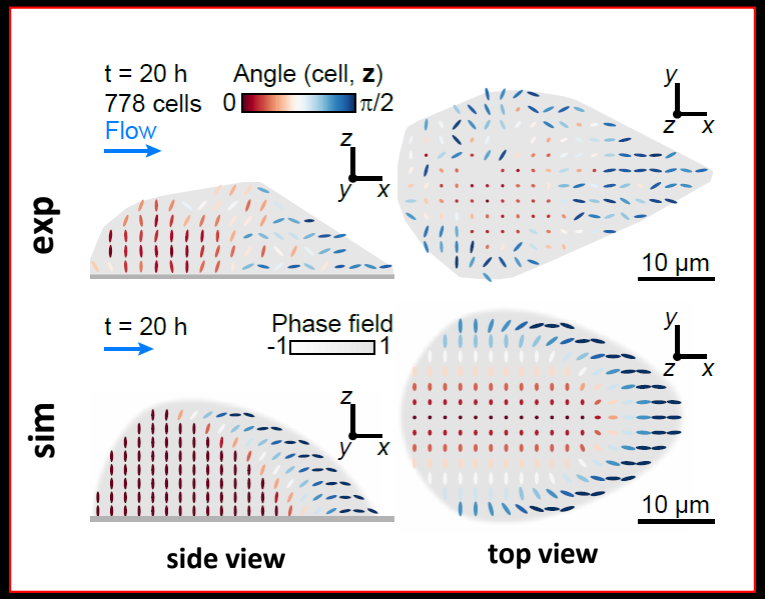
Stress tensor

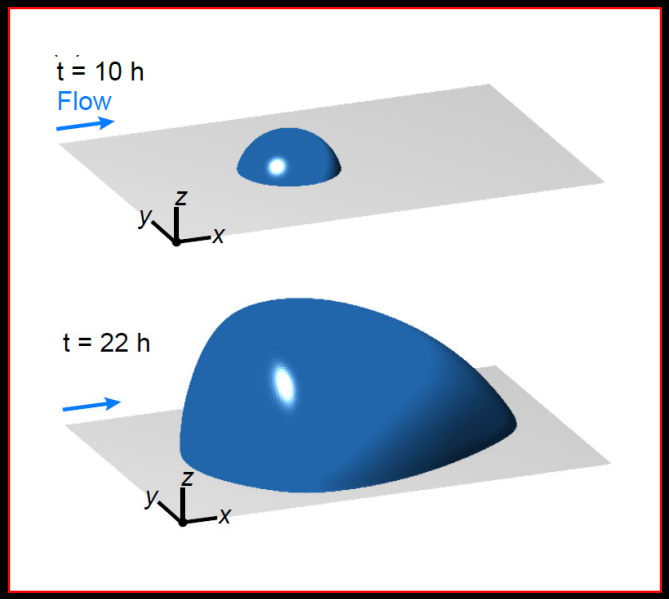
$$\sigma = 2\mu \mathbf{D} - 2\mu g \mathbf{Q}$$

$$\mathbf{D} = \frac{1}{2}(\nabla \mathbf{v} + \nabla \mathbf{v}^T)$$

$$\mathbf{Q} = \langle \mathbf{nn} \rangle - \mathbf{I}/3$$

(tracked with phase-field variable)





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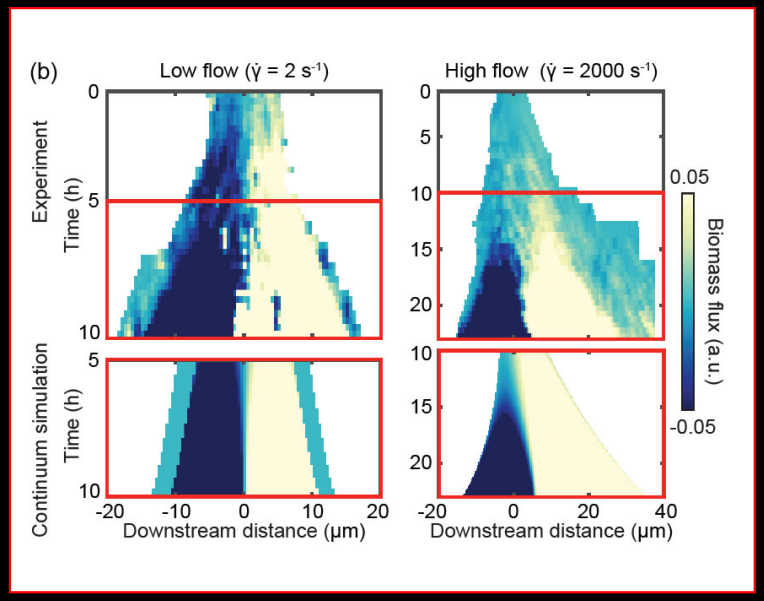

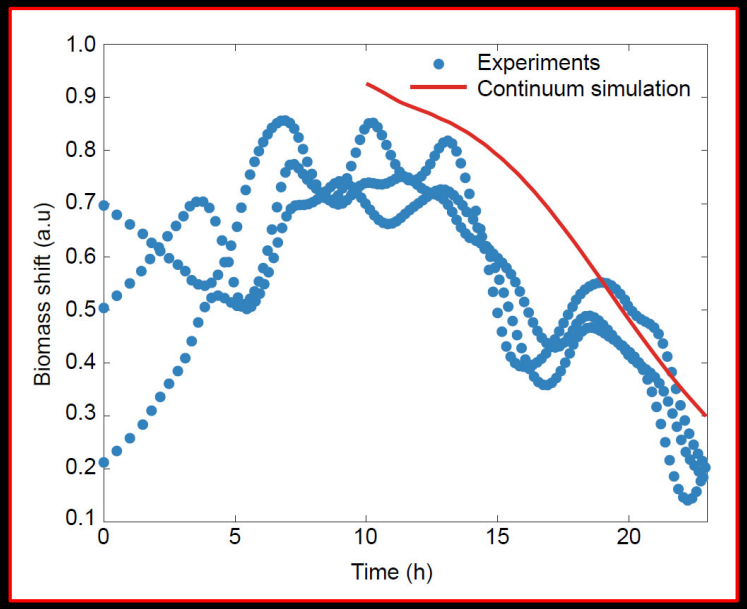

Shift from asymmetric to symmetric growth

Pearce, *et al. PRL* 123 (2019)

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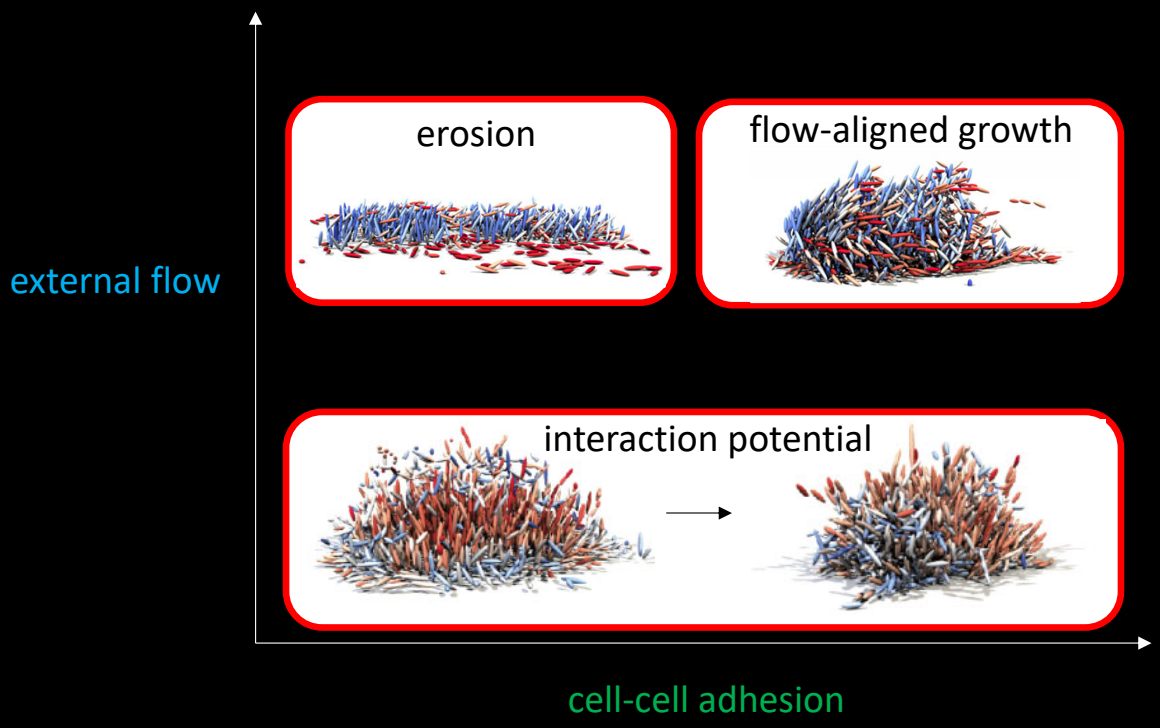

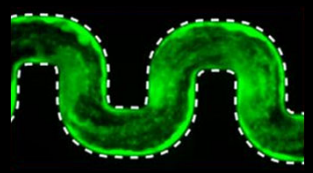

Precursor to streamers – but only if verticalisation does not overcome flow alignment?

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Thanks for listening!