Active Matter Models of Mechanobiology

Julia Yeomans
University of Oxford

1. Introduction

2. Active turbulence: the basics

- Background 1: Swimming at low Re
- Background 2: nematic liquid crystals
- Active stress and active instabilities
- Active topological defects
- 3D
- P. Mirabilis spreading

3. Active turbulence: details (other instabilities, confinement)

4. Mechanobiology

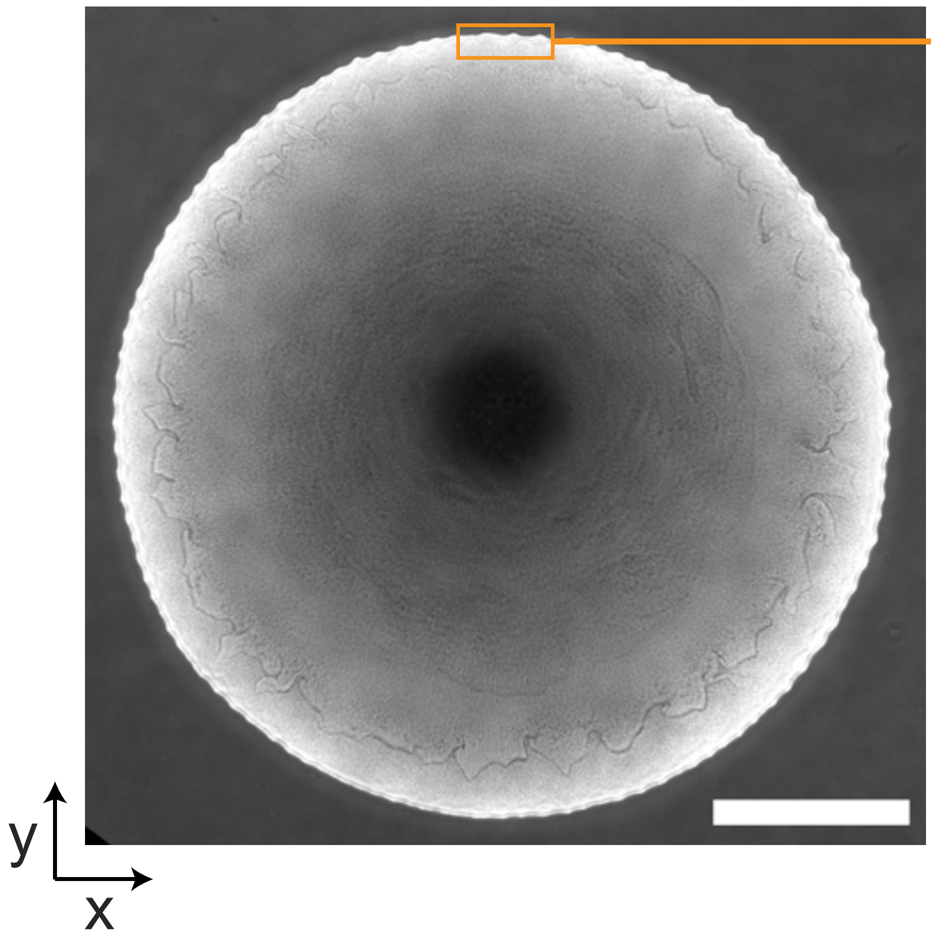
Mehrana Nejad

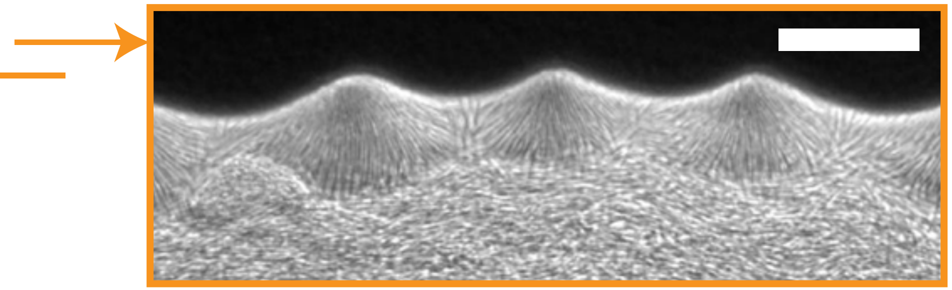
Experiment:s

Haoran Xu
Yilin Wu

The Chinese University of
Hong Kong

Xu, Nejad, Yeomans, Wu, PNAS 2023

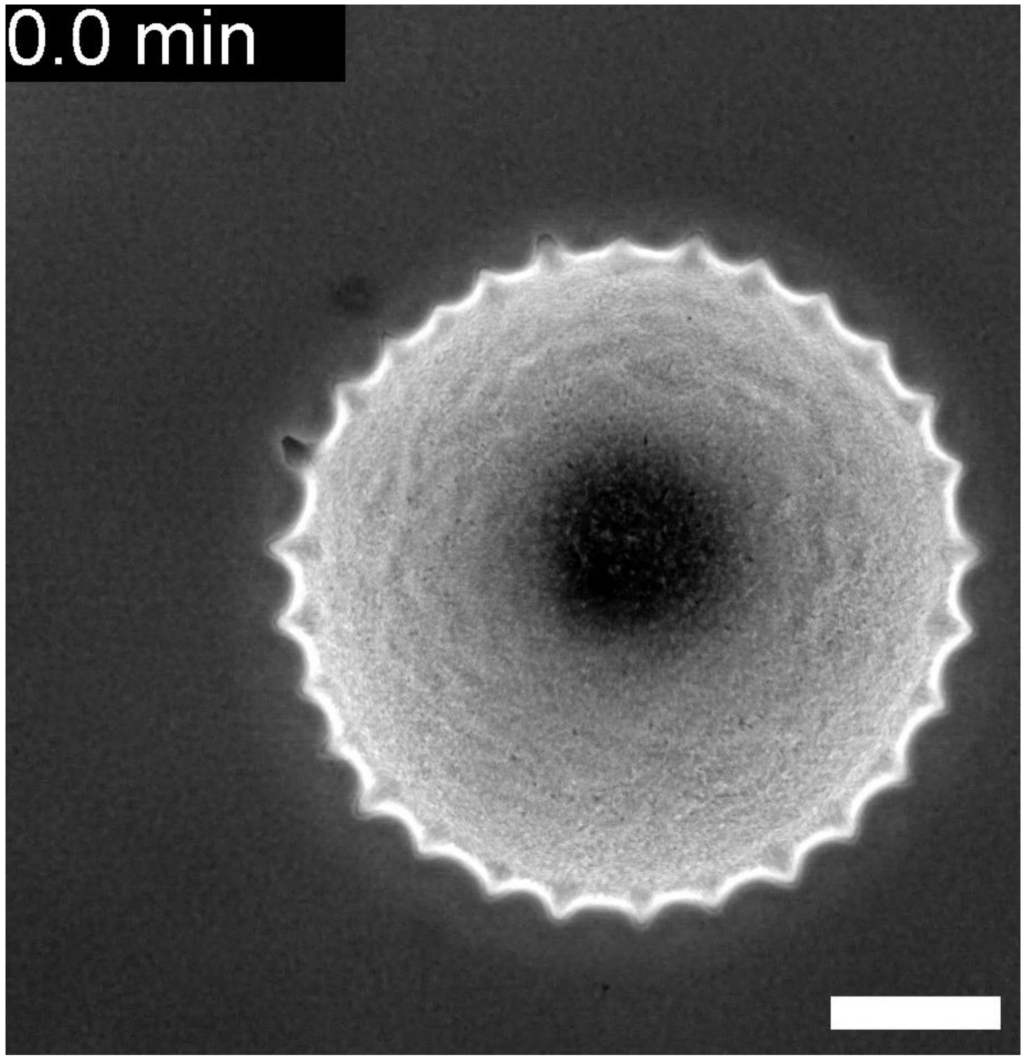


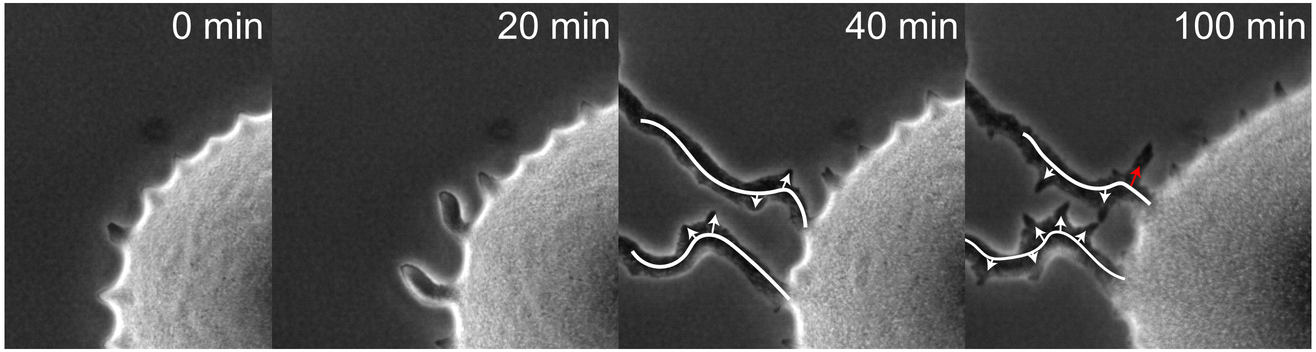


Scale bar 50 microns

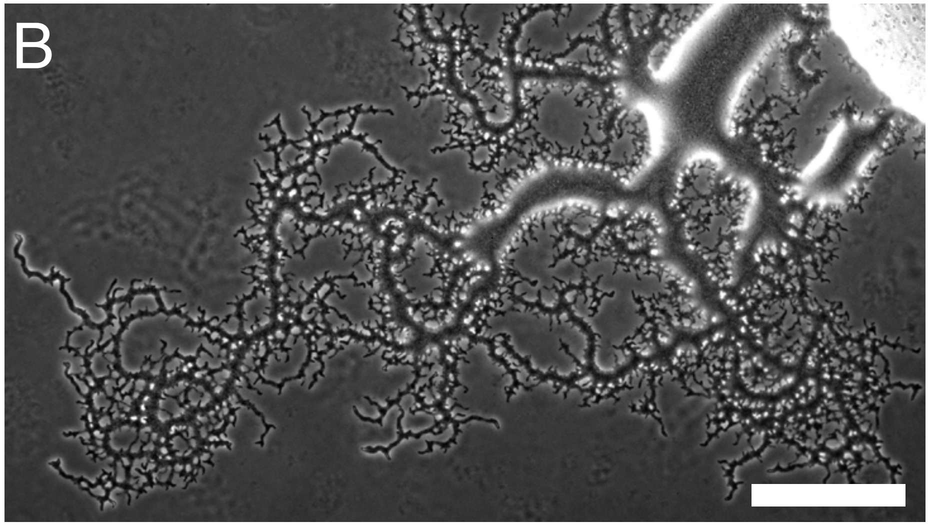
P. Mirabilis on agar
Scale bar 500 microns

regular interfacial protrusions



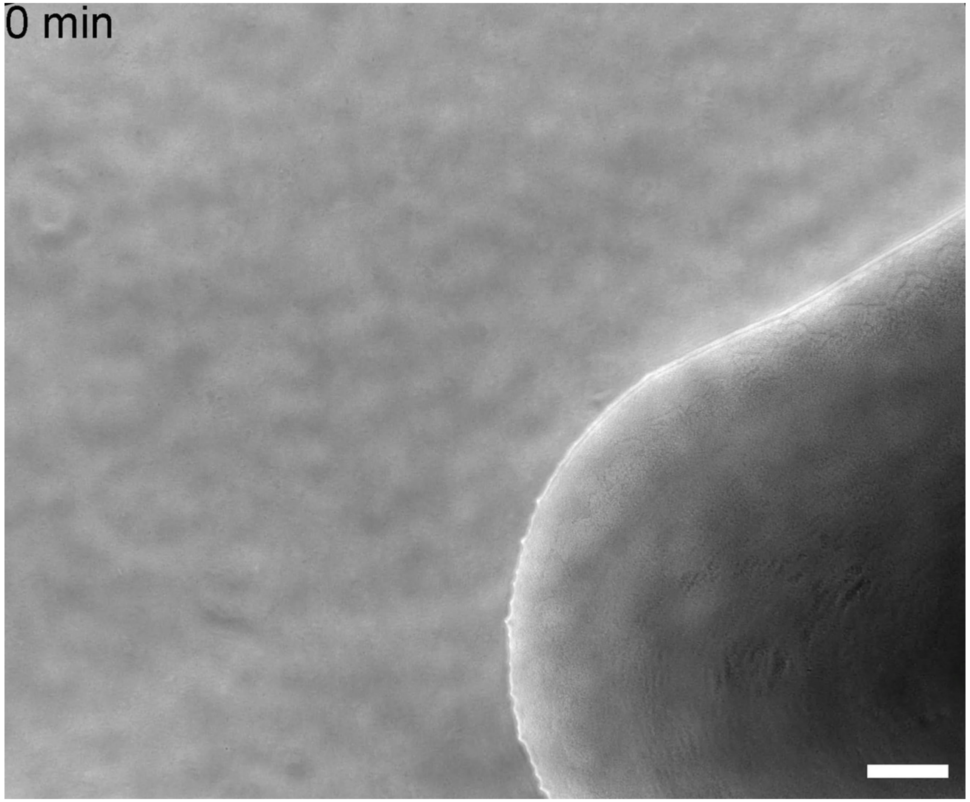


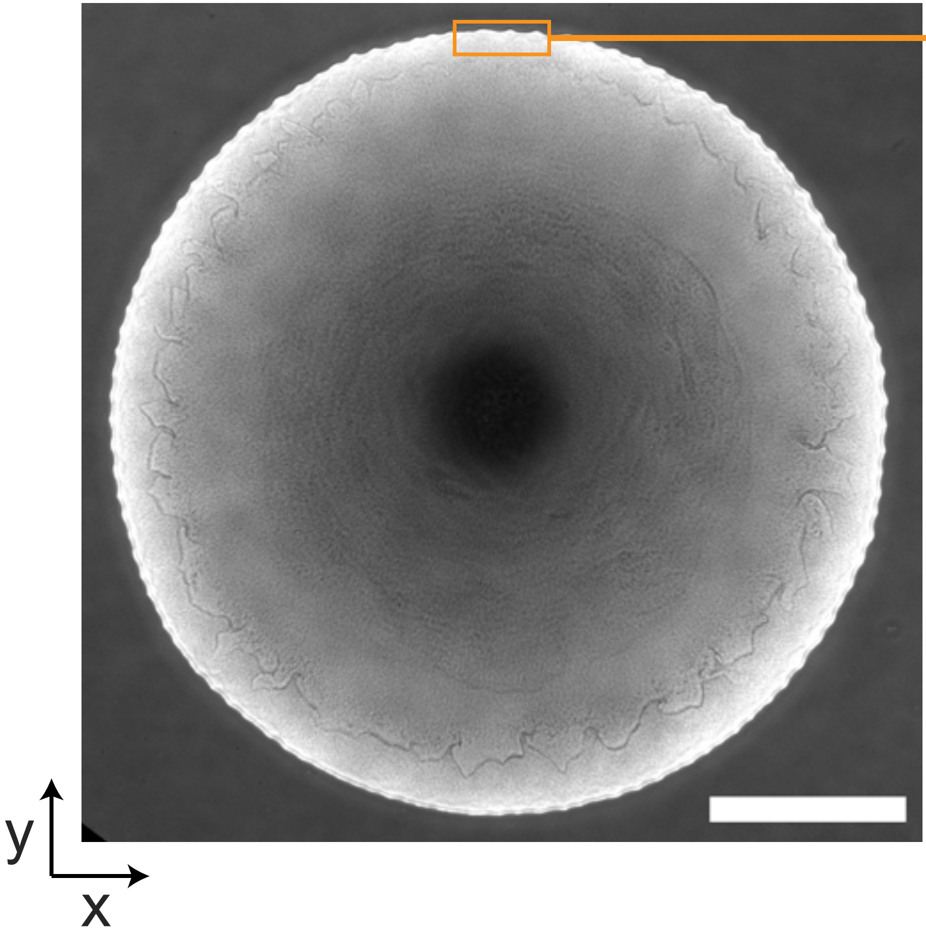
creeping branches

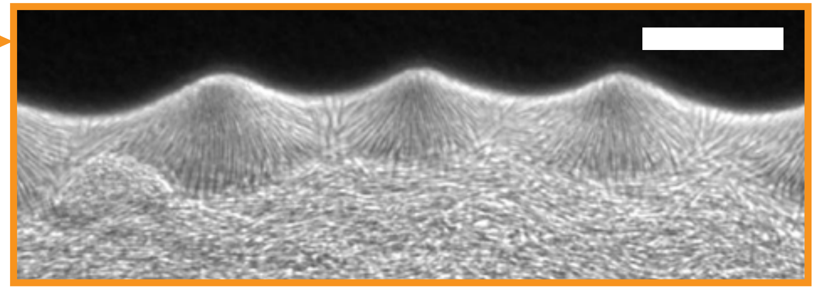


Scale bar 500 microns

Scale bar 50 microns

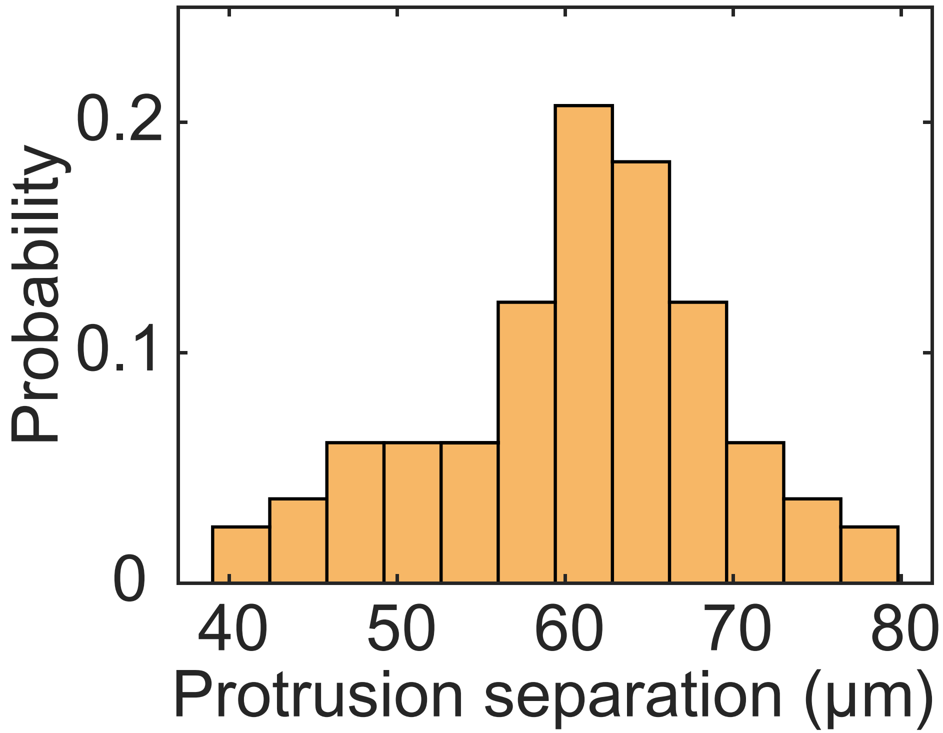






Scale bar 50 microns

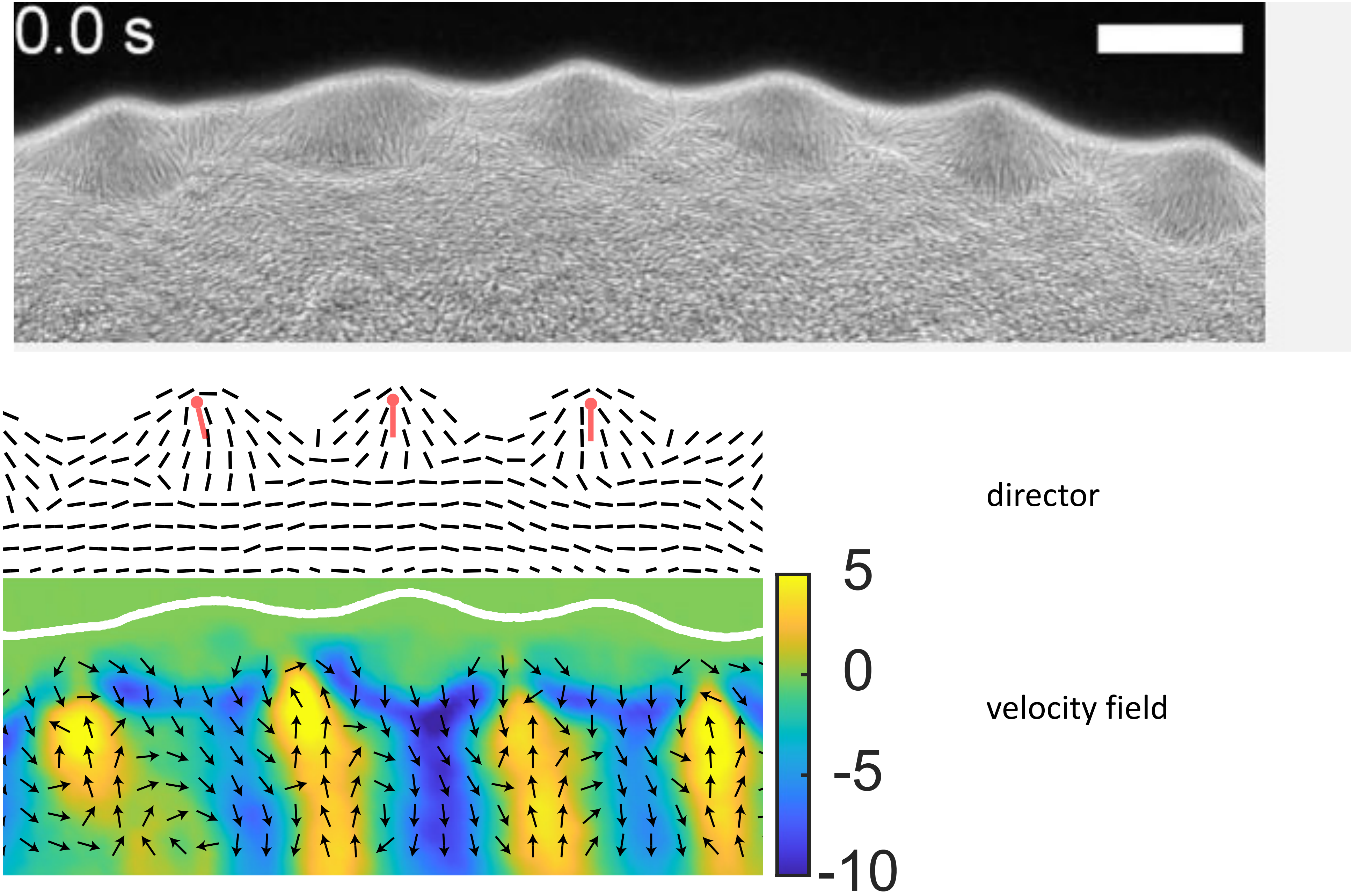
P. mirabilis
Scale bar 500 microns



regular interfacial protrusions

regular interfacial protrusions

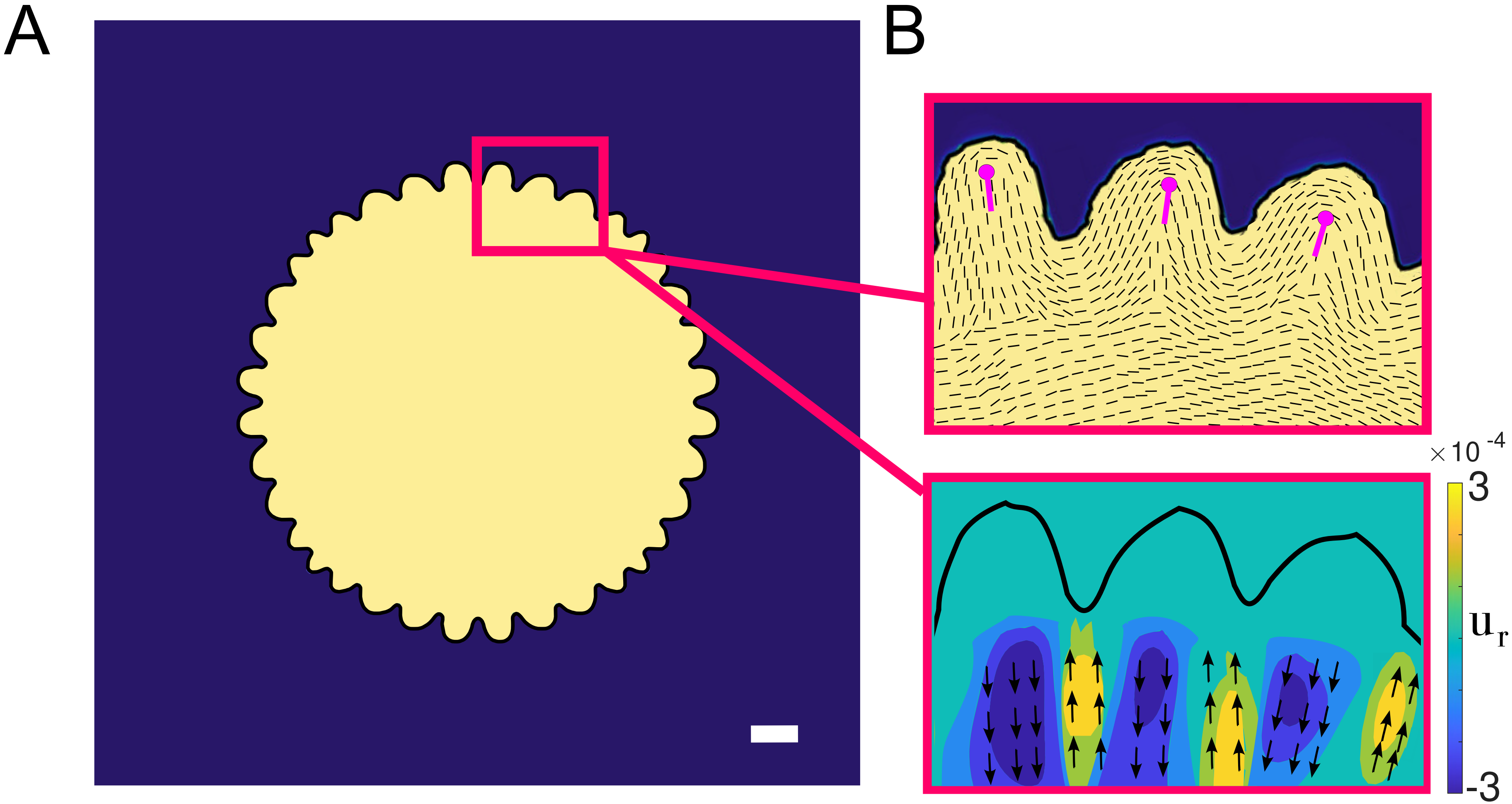
Scale bar 50 microns



Simulations: technical comments

- Active nematohydrodynamic equations of motion, extensile activity
- Interface modelled by a phase field, +1 inside the drop, -1 outside, moves in response to the active velocity
- Initial conditions: director field parallel to the interface with an imposed noise and zero velocity field
- the strength of nematic order was taken to decay from the edge to the center of the drop

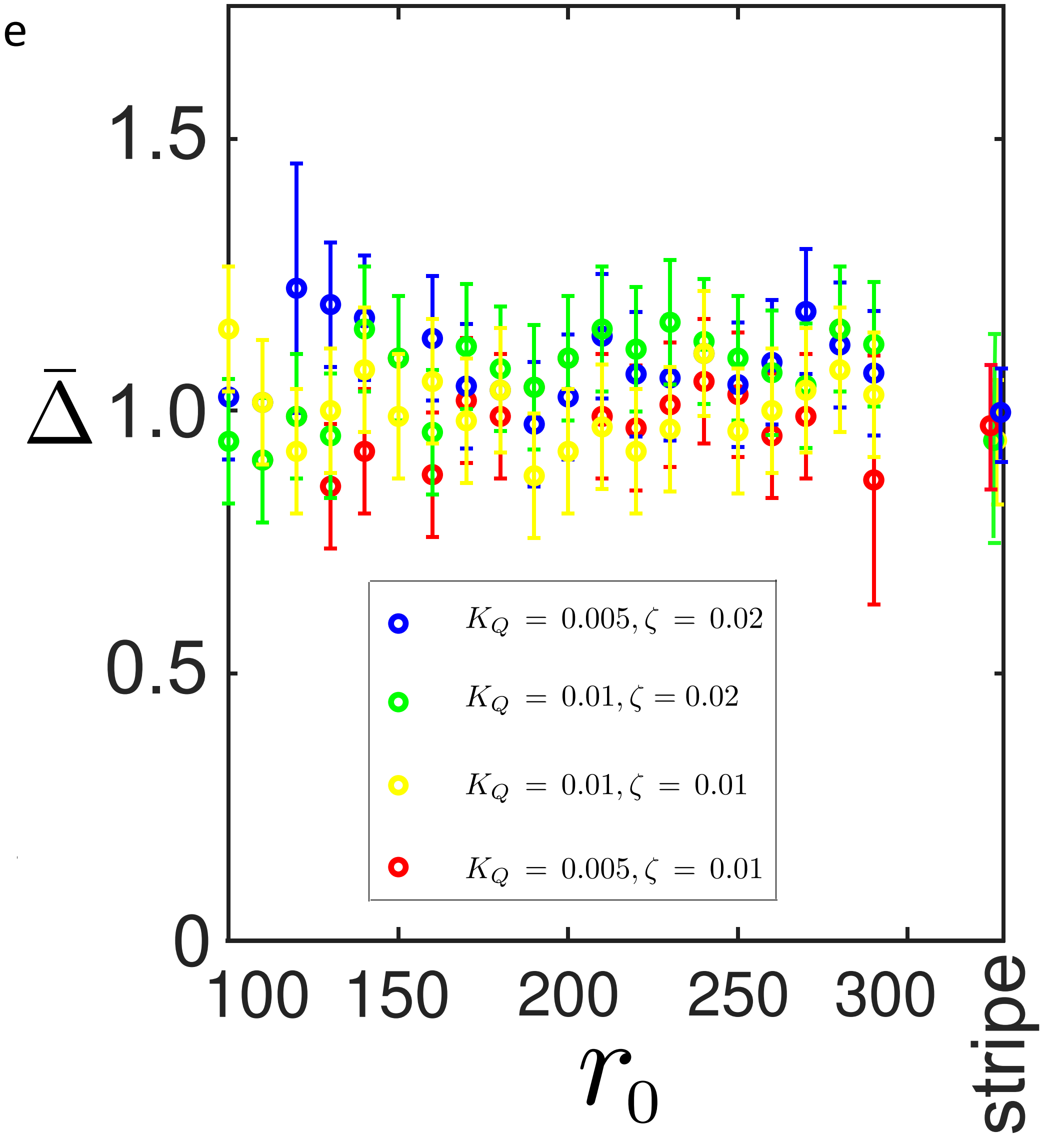
Simulations: results



distance between
protrusions scaled
with active length scale

$c_0\sqrt{K_Q / \zeta}$

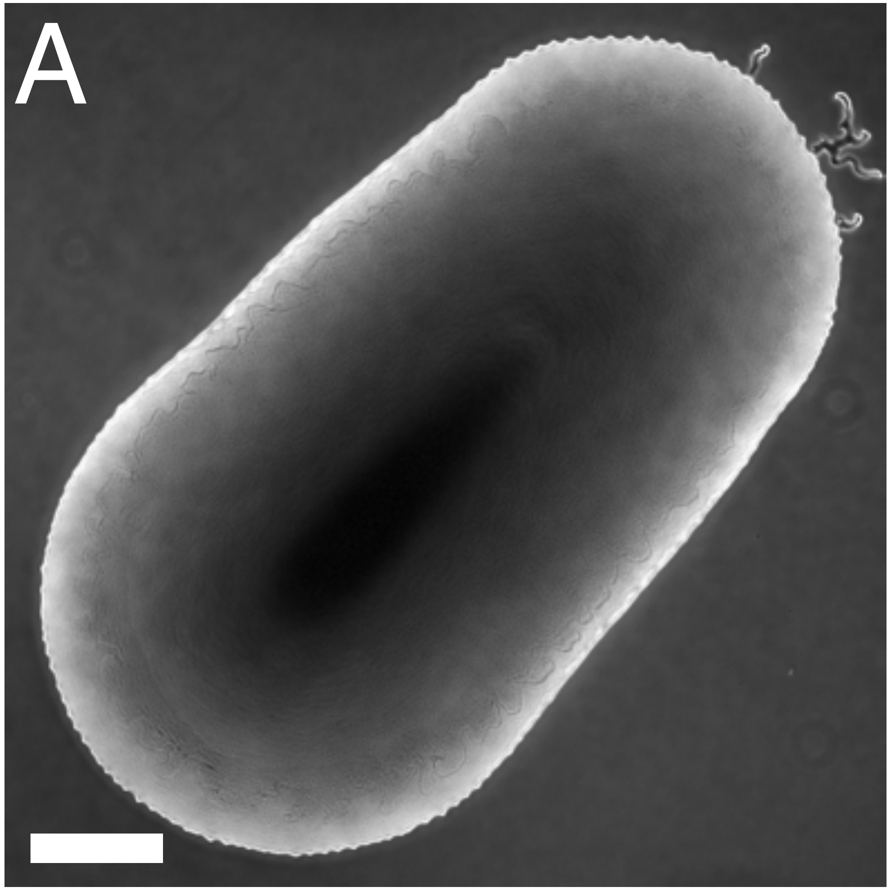
colours: different
active length scales

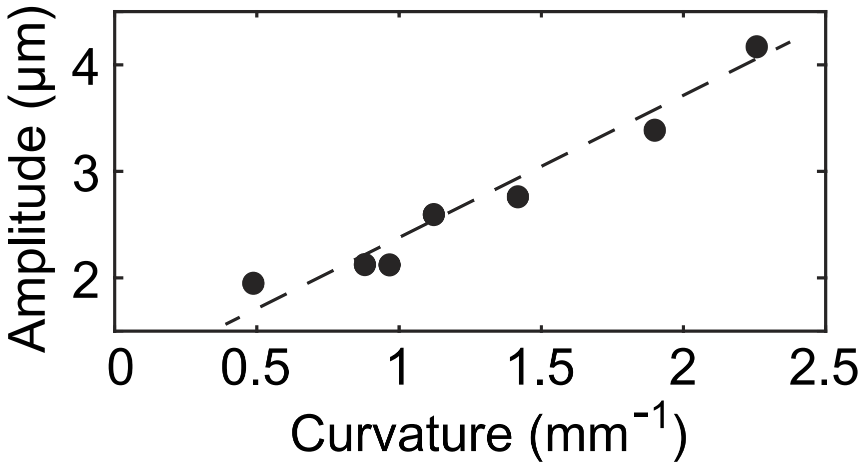


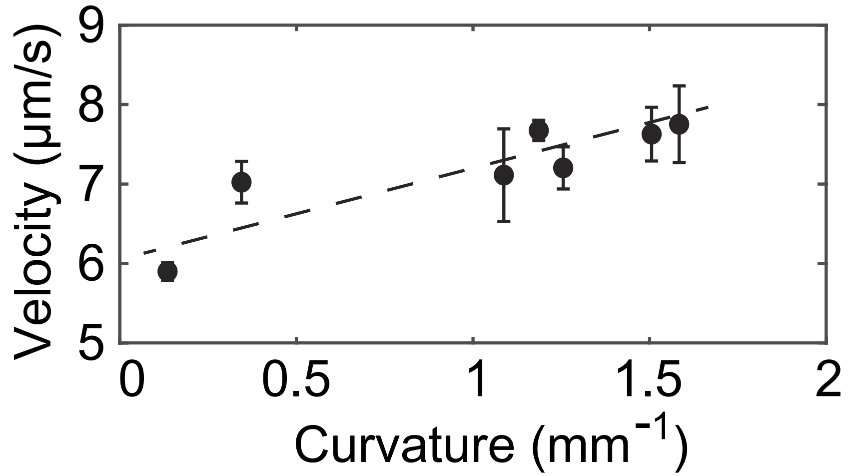
drop radius

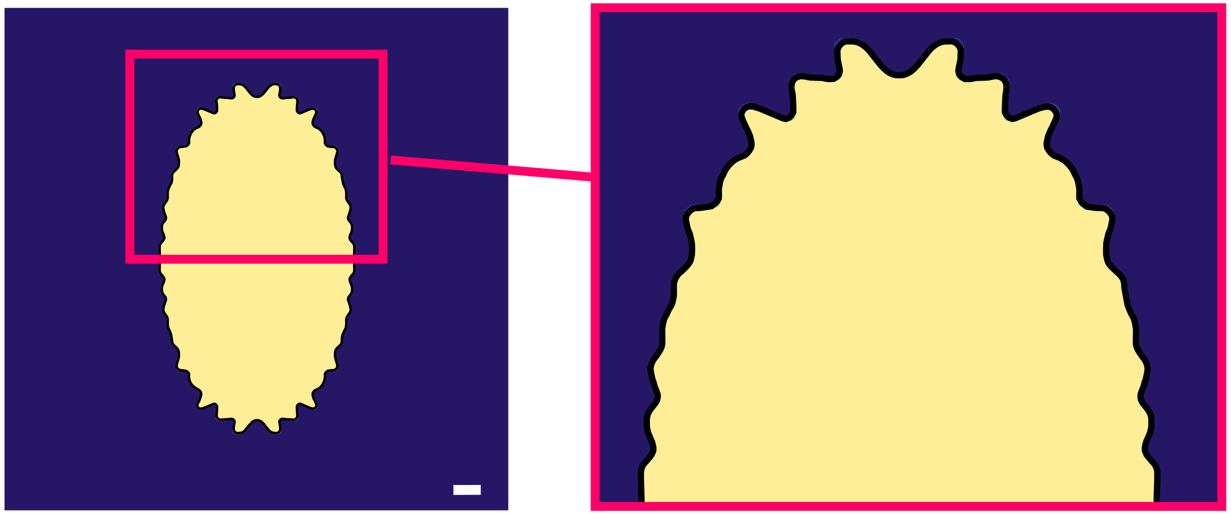
Distance between
protrusions independent
of drop radius

Curvature

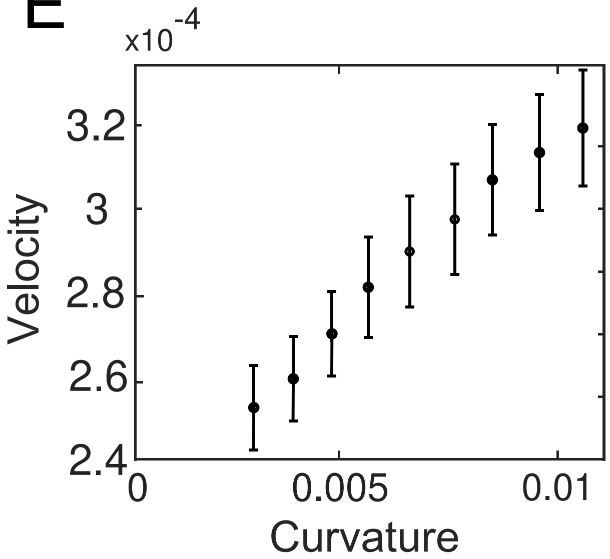

A


Amplitude (μm)
Curvature (mm^{-1})
0
0.5
1
1.5
2
2.5
2
3
4

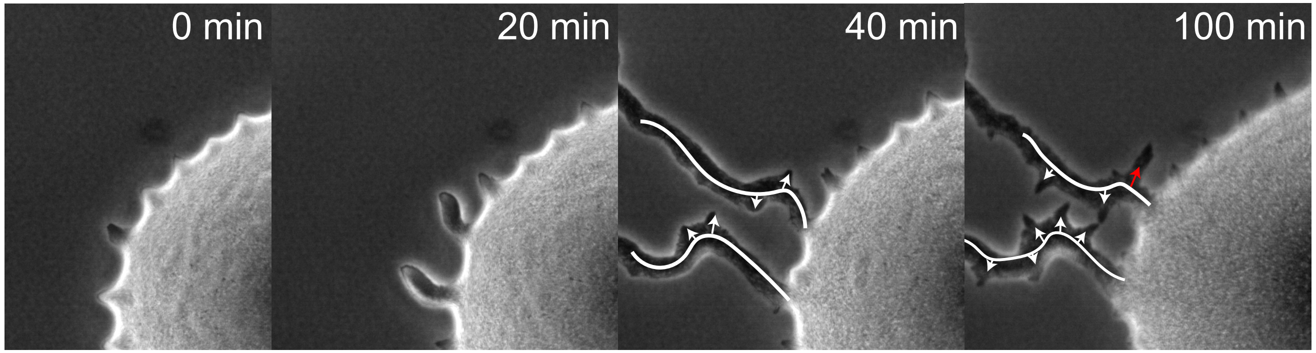

Velocity (μm/s)
Curvature (mm^{-1})
0
0.5
1
1.5
2
5
6
7
8
9



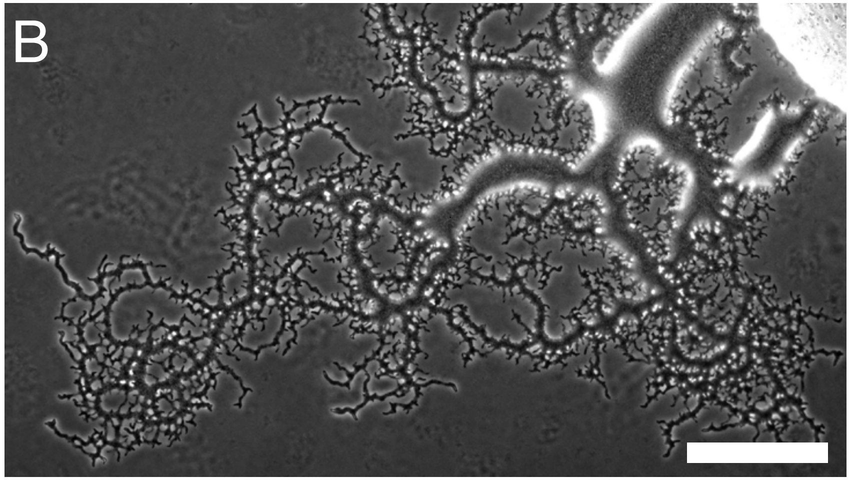
E

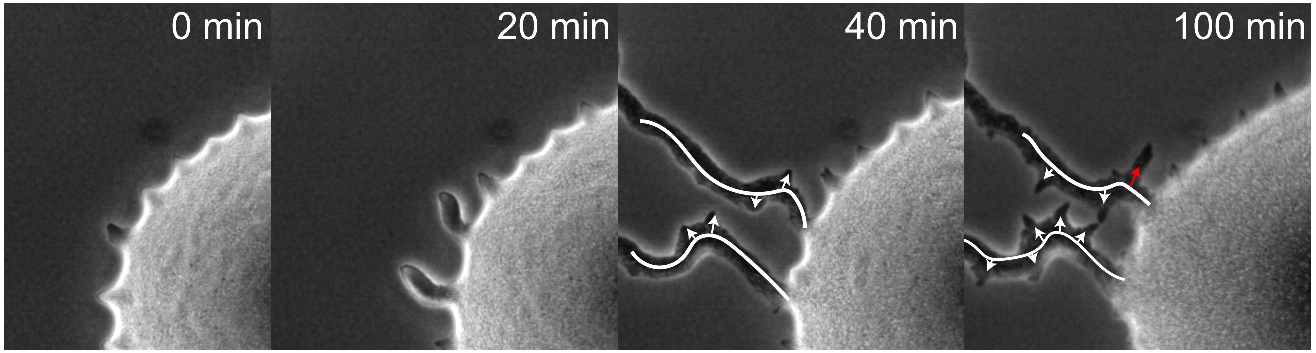


Usual extensile active nematic instability.
can form more easily near a curved interface.
=> higher active velocities



creeping branches





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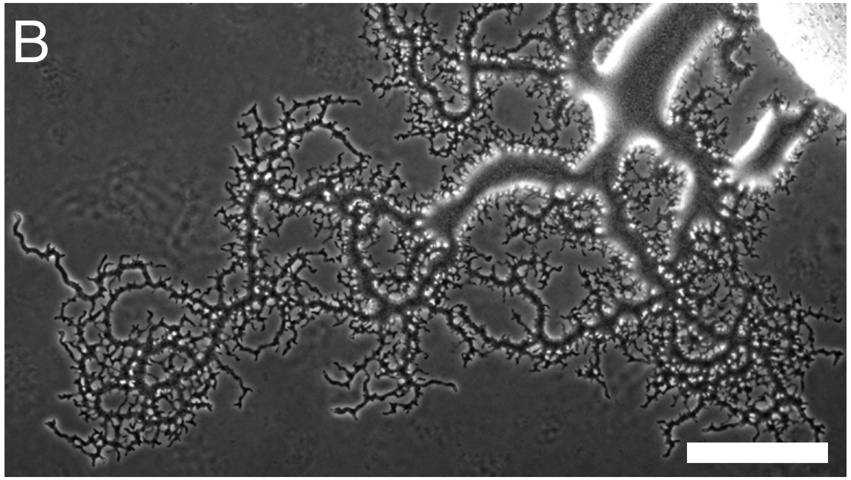
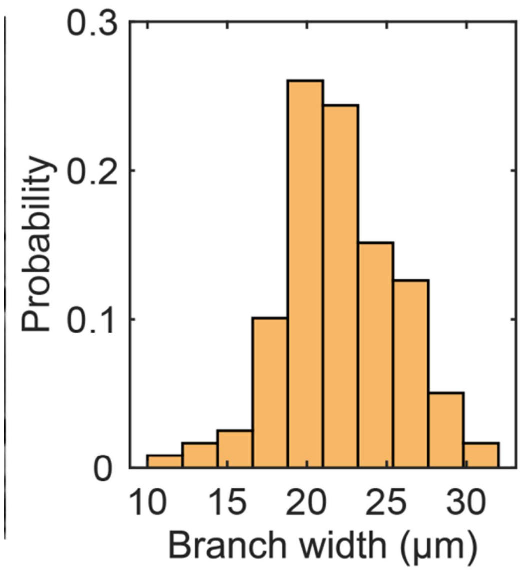
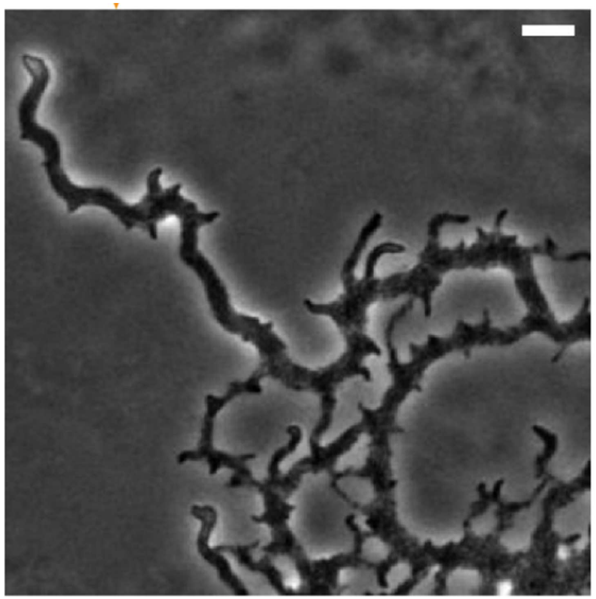
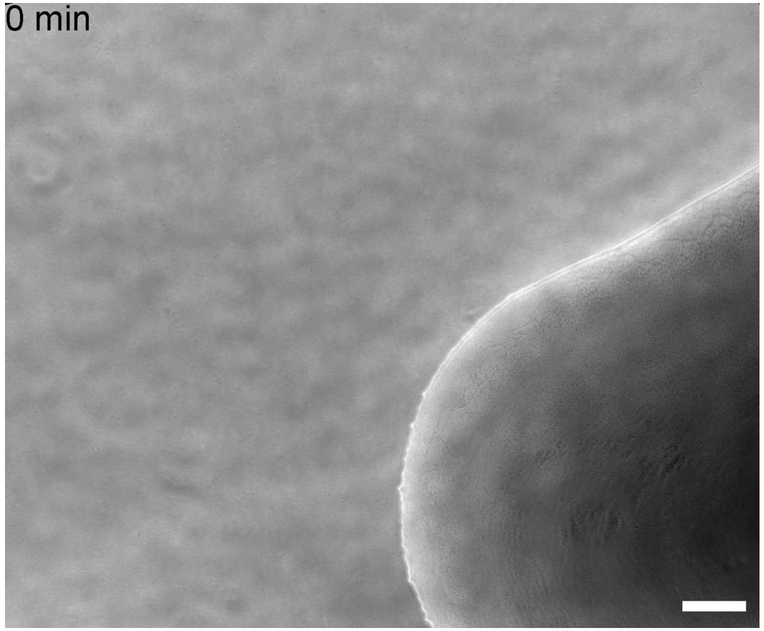




Initial width approx.
same for all branches

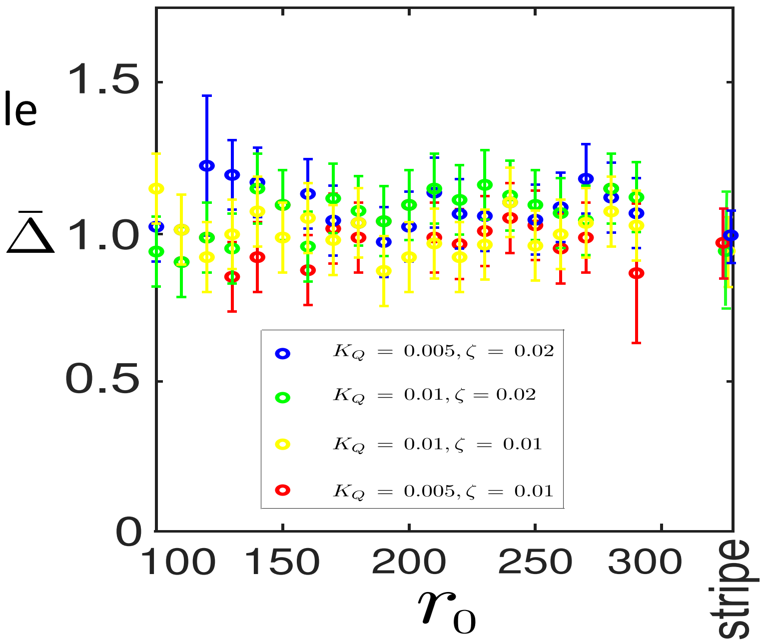




distance between protrusions scaled with active length scale

$c_0\sqrt{K_Q/\zeta}$

colours: different active length scales



drop radius

branches also formed by active nematic instability

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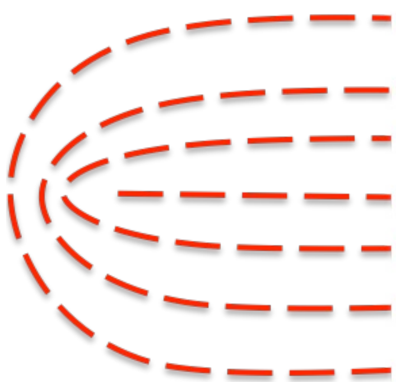
3. Active turbulence: details (other instabilities, confinement)

4. Mechanobiology

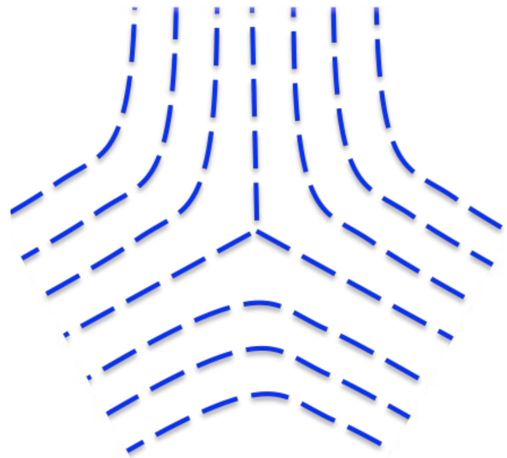
Active nematics:

Gradients in the order parameter => stresses => flows

Active topological defects: the +1/2 defects are self-propelled



$m = +\frac{1}{2}$



$m = -\frac{1}{2}$

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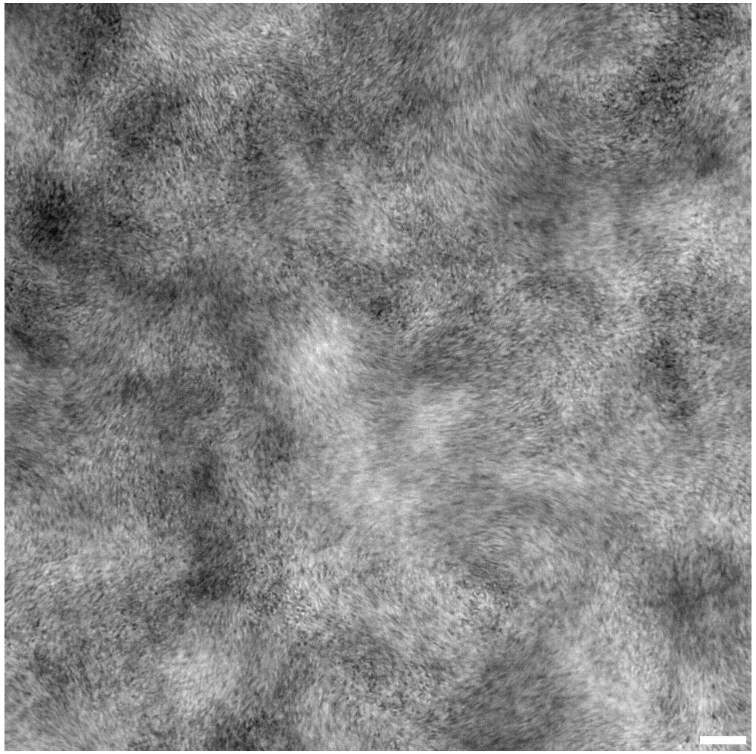
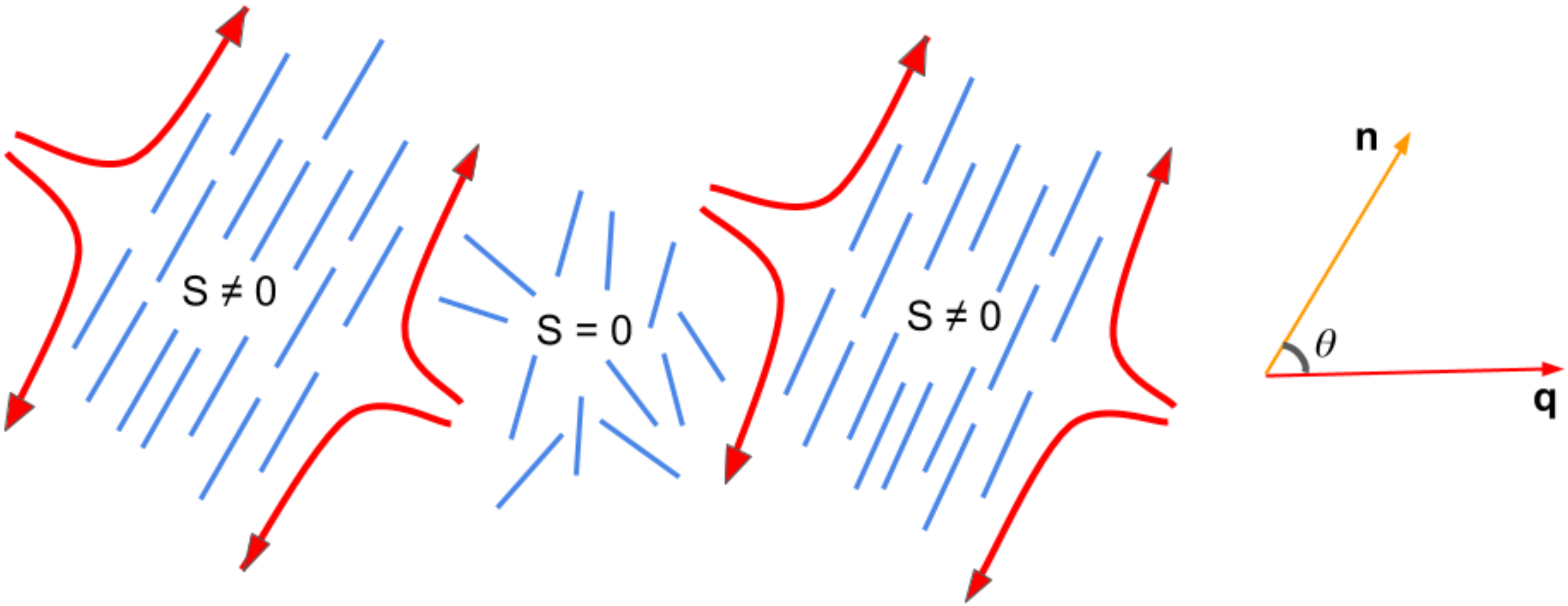
- Instability 2 (activity-induced nematic ordering)
- Instability 3 (squishy nematogens)
- Confinement
- Active anchoring and cell sorting

4. Mechanobiology

Can we get active turbulence if the passive state is isotropic?



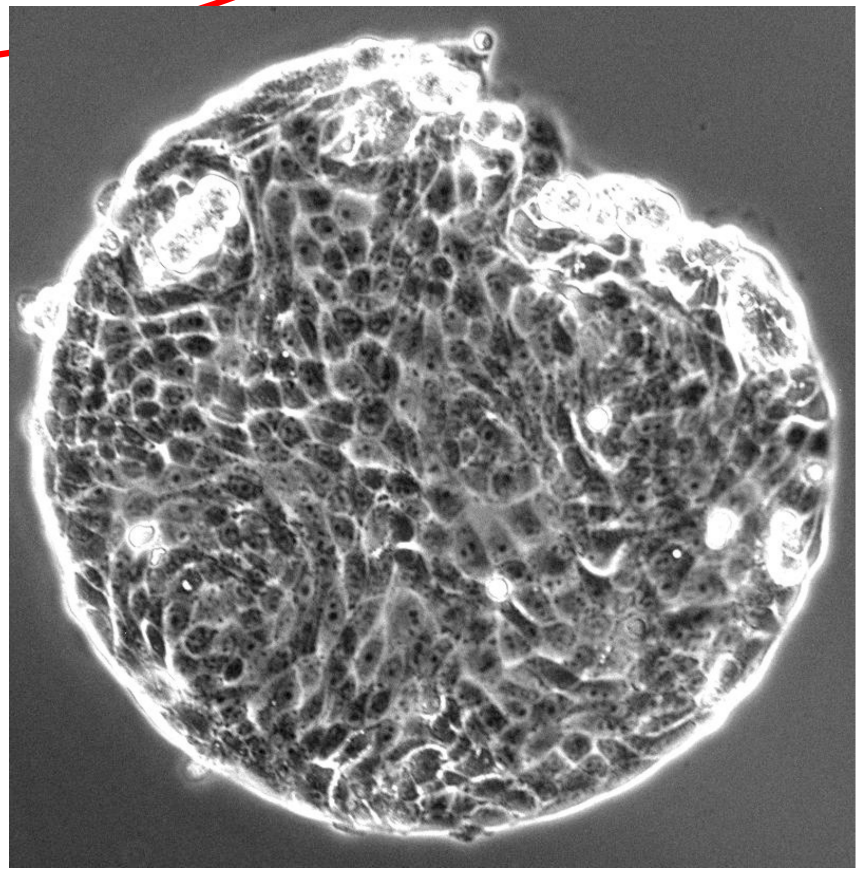
Instability 2: isotropic nematogens are unstable to nematic order



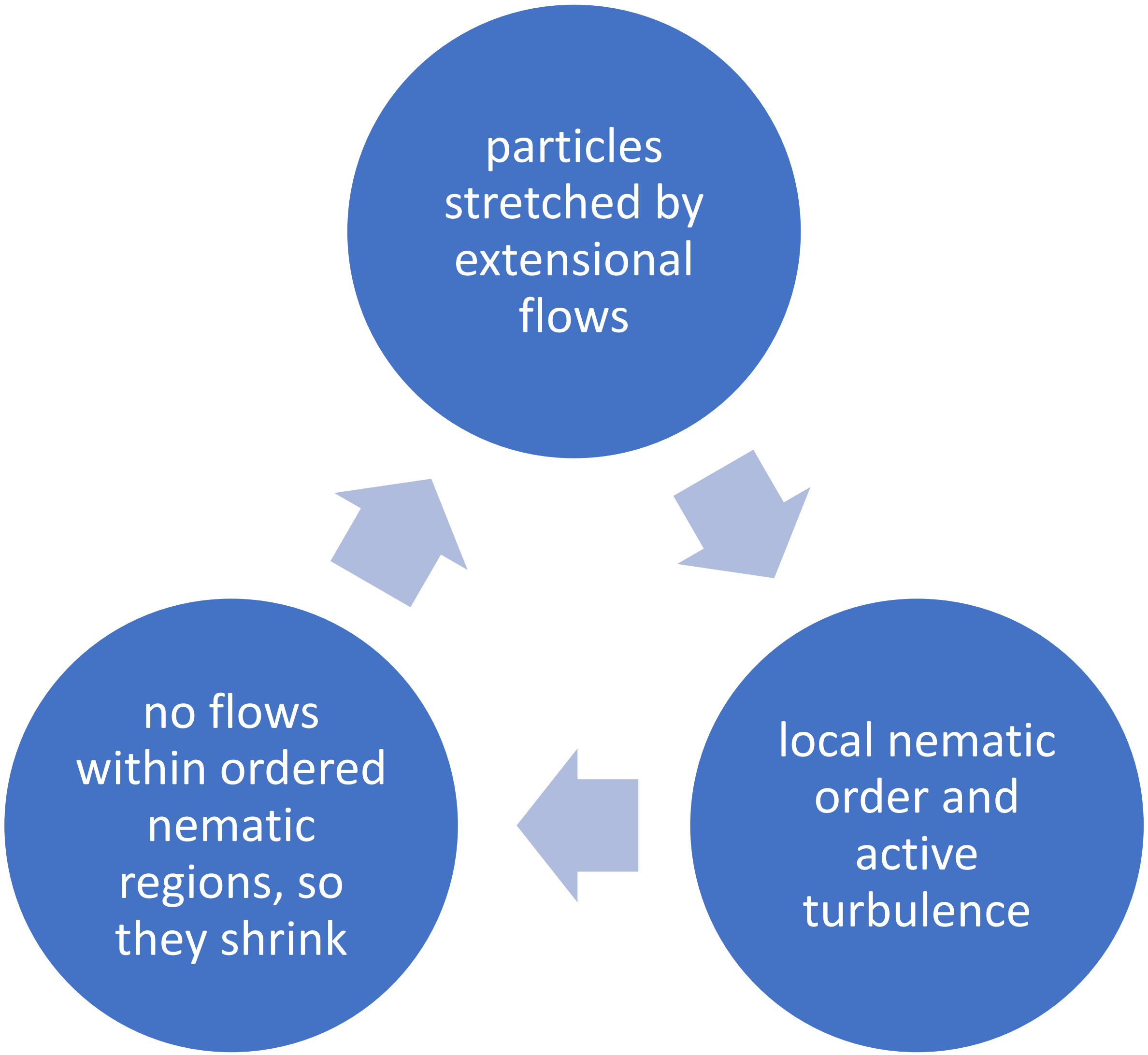
even if the passive system is isotropic, can still get active turbulence –

BUT need flow aligning parameter x activity > 0

Can we get active turbulence if the individual nematogens are isotropic?



Instability 3: deformable, isotropic particles can give nematic order



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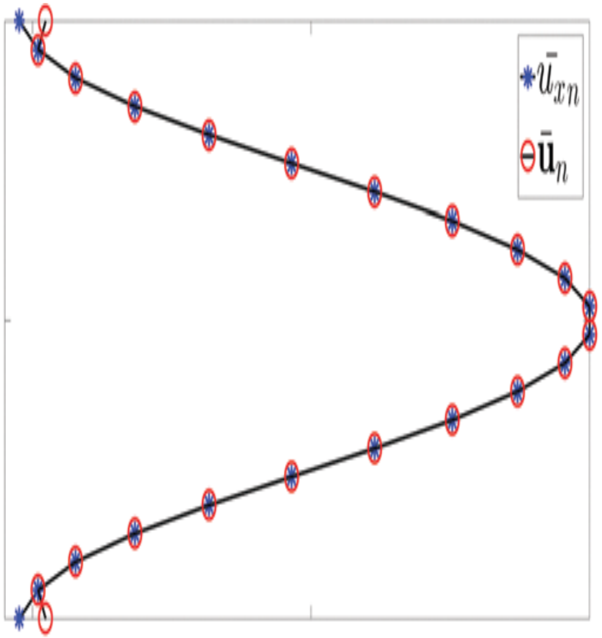
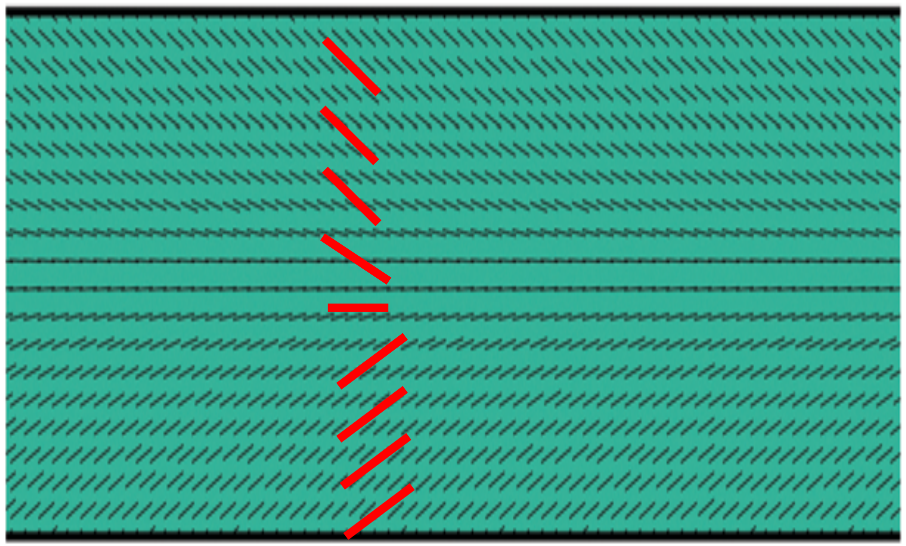
no slip at walls and
weak parallel anchoring

flow



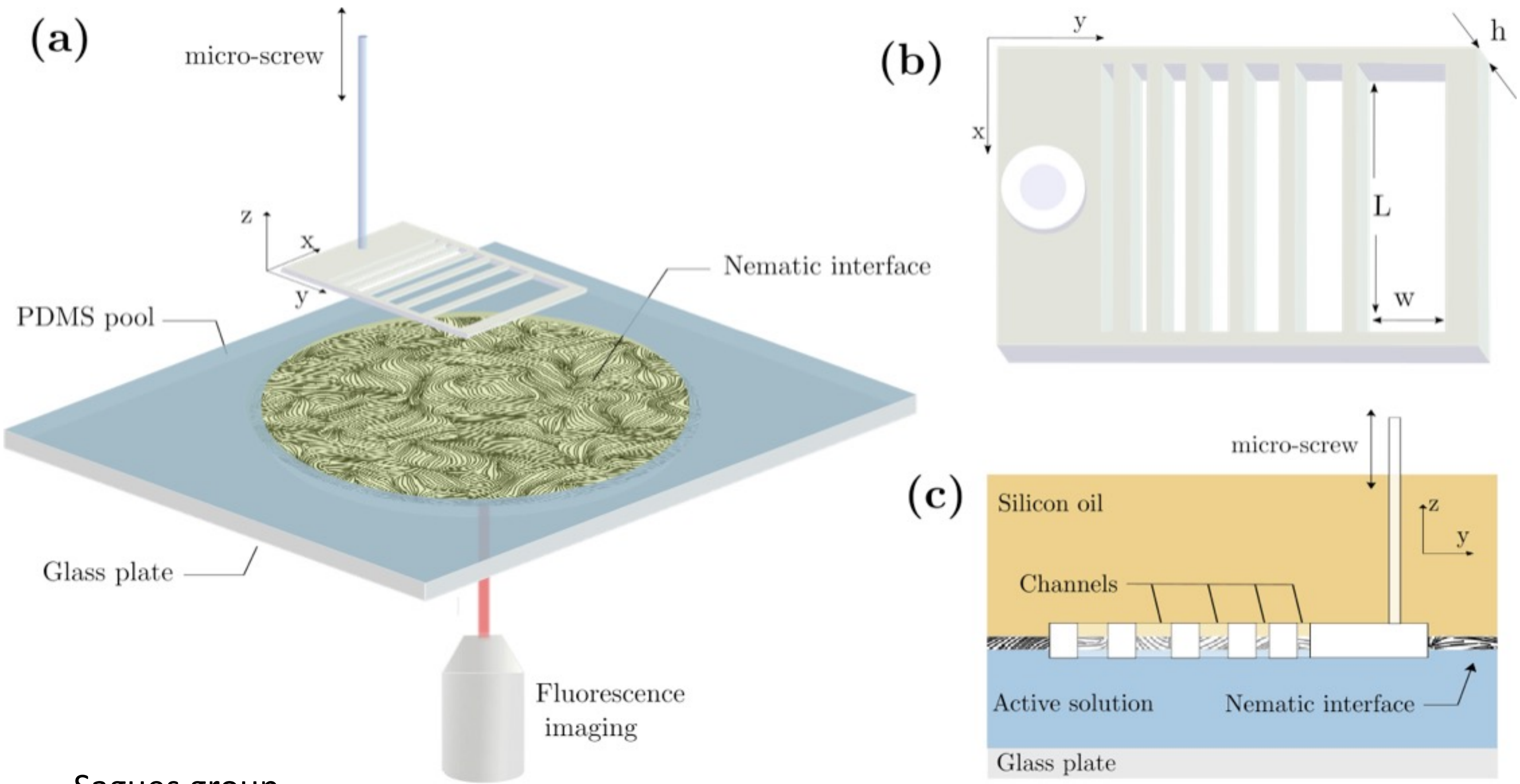
director field



Voituriez et al, EPL 2005

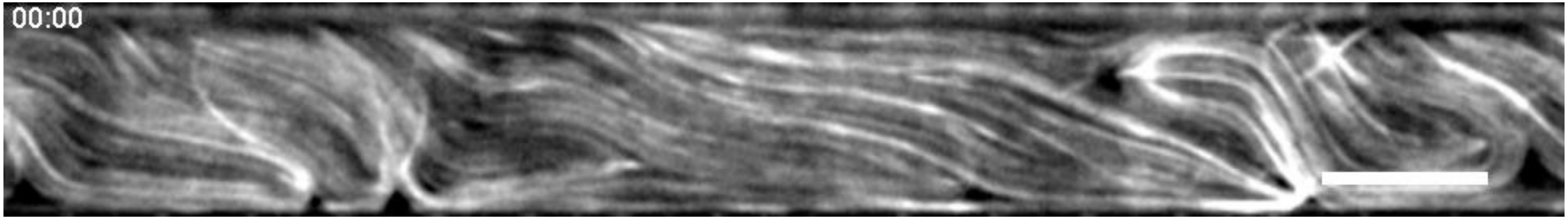
Microtubules and kinesin motors in channels

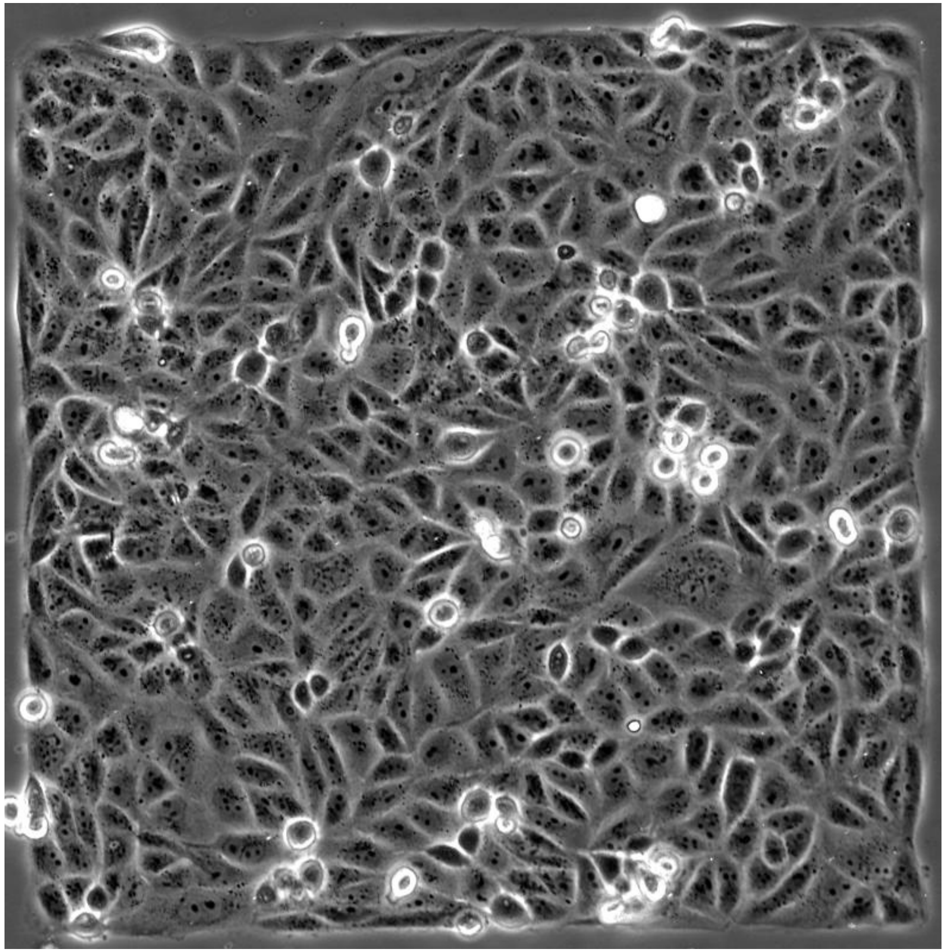
Widths 30 – 400 microns

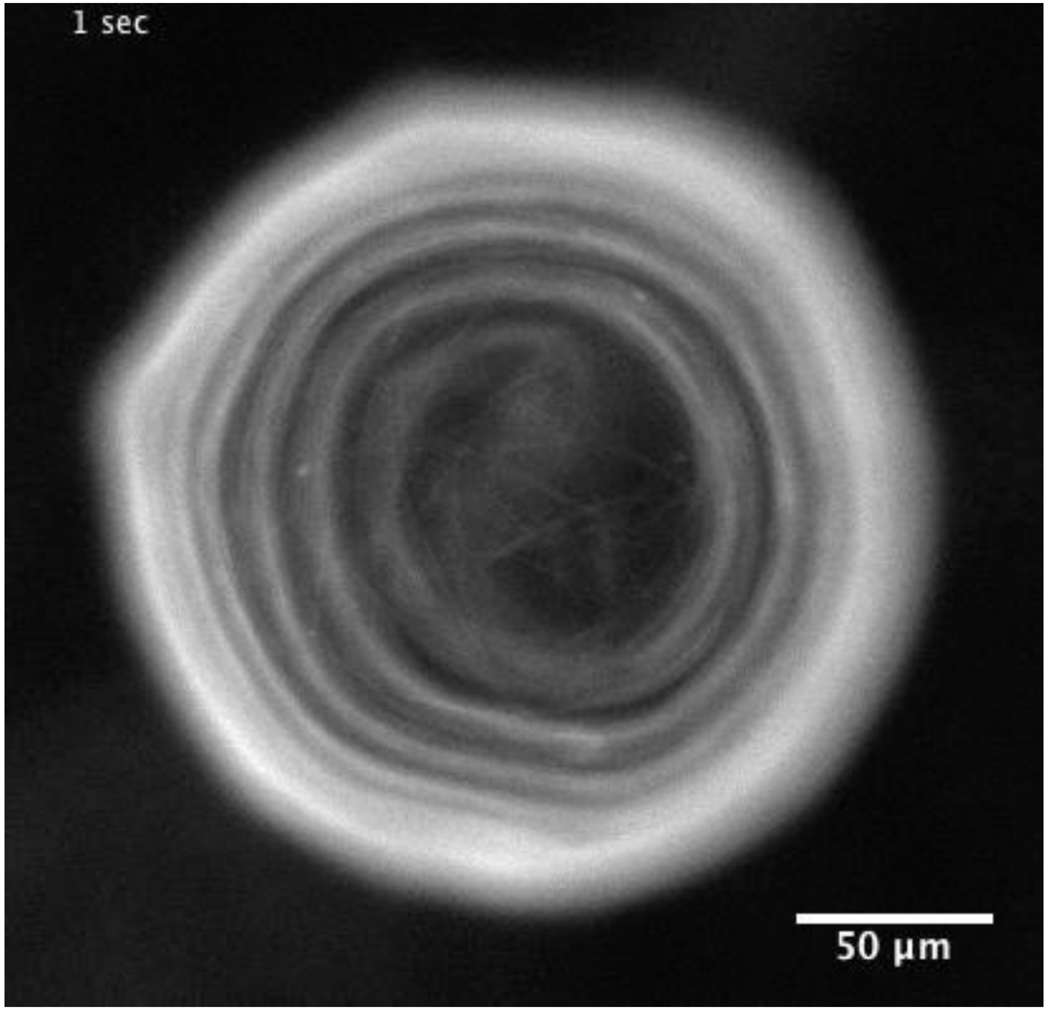


Sagues group

Shear + periodic bursts of defects

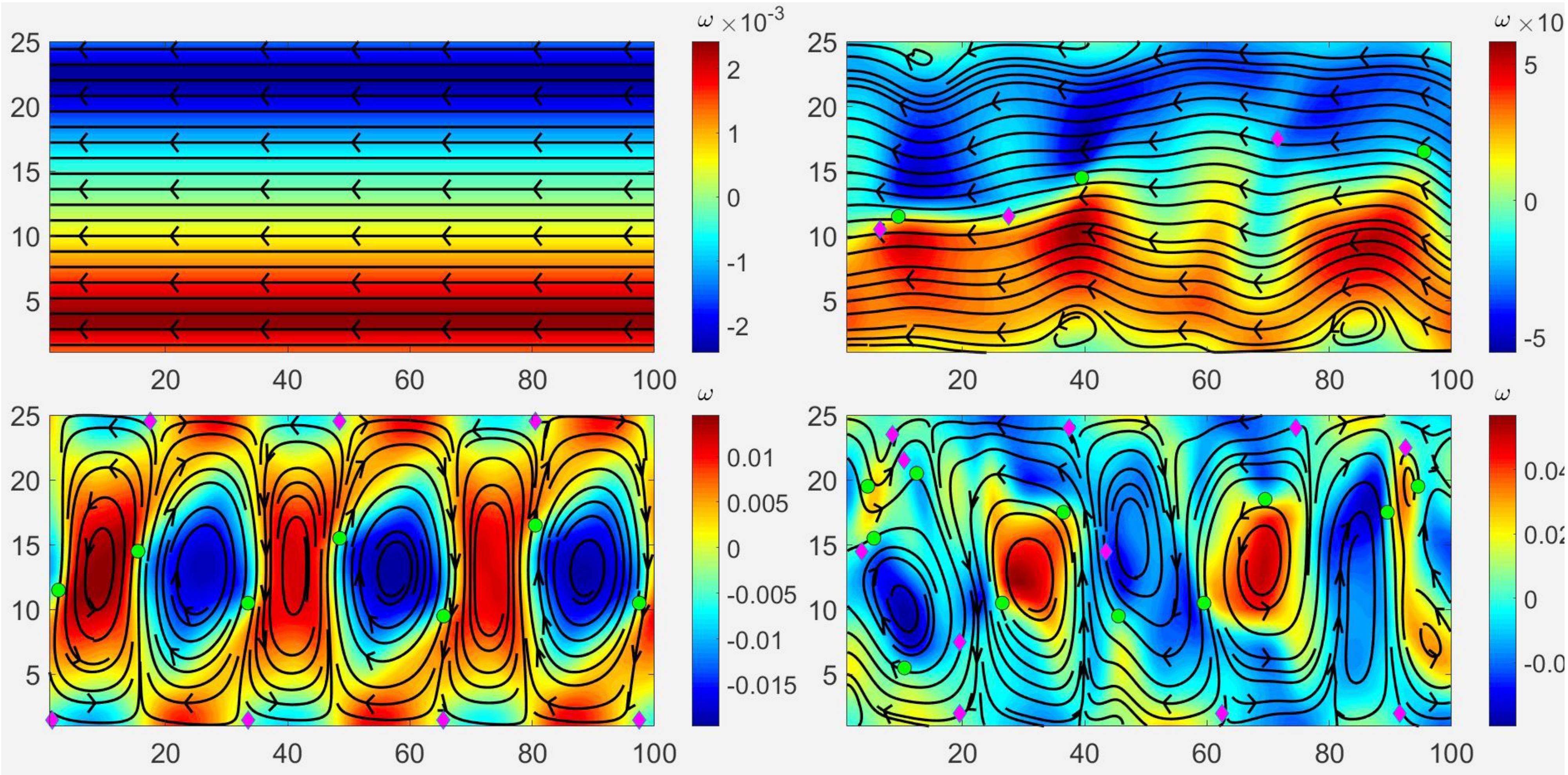






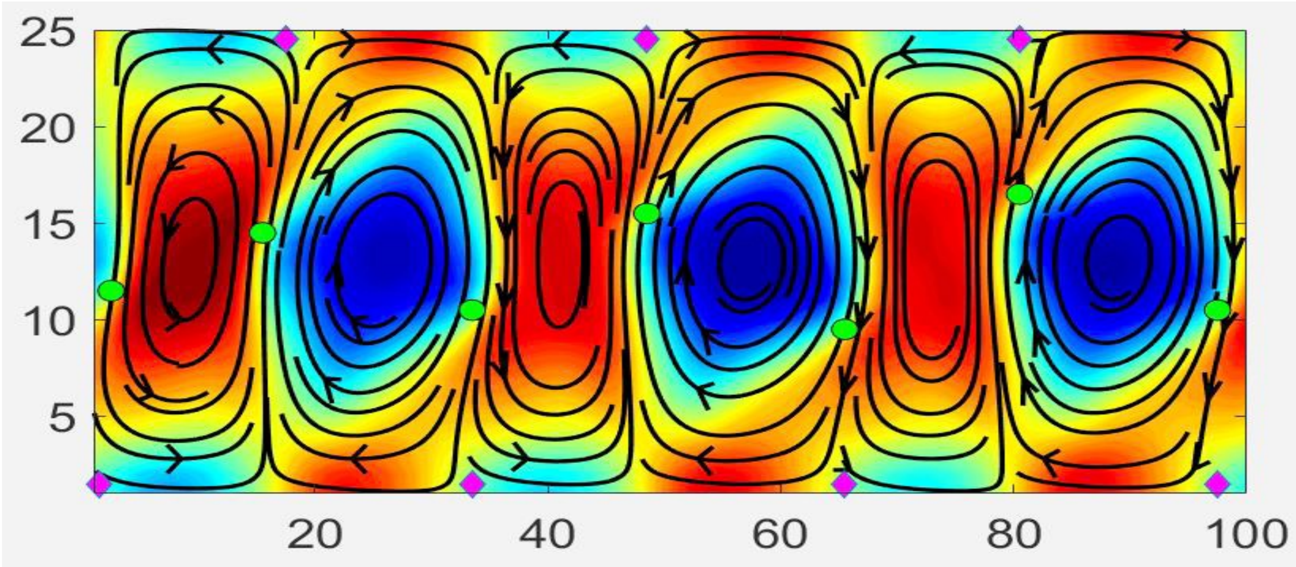
Opathalage et al PNAS 116, 4788 (2019)

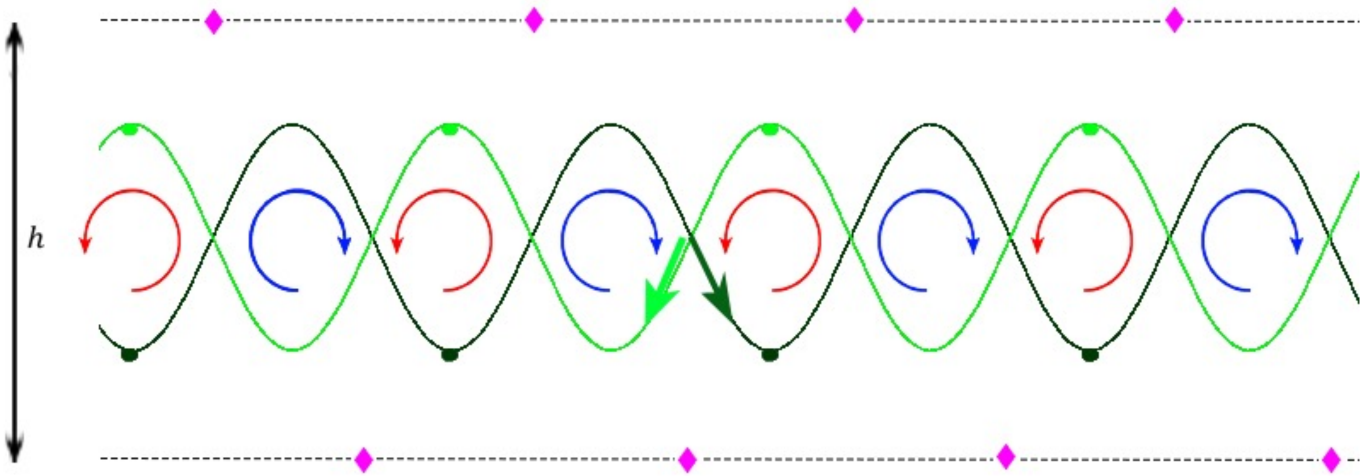
States of an Active Nematic in a Channel



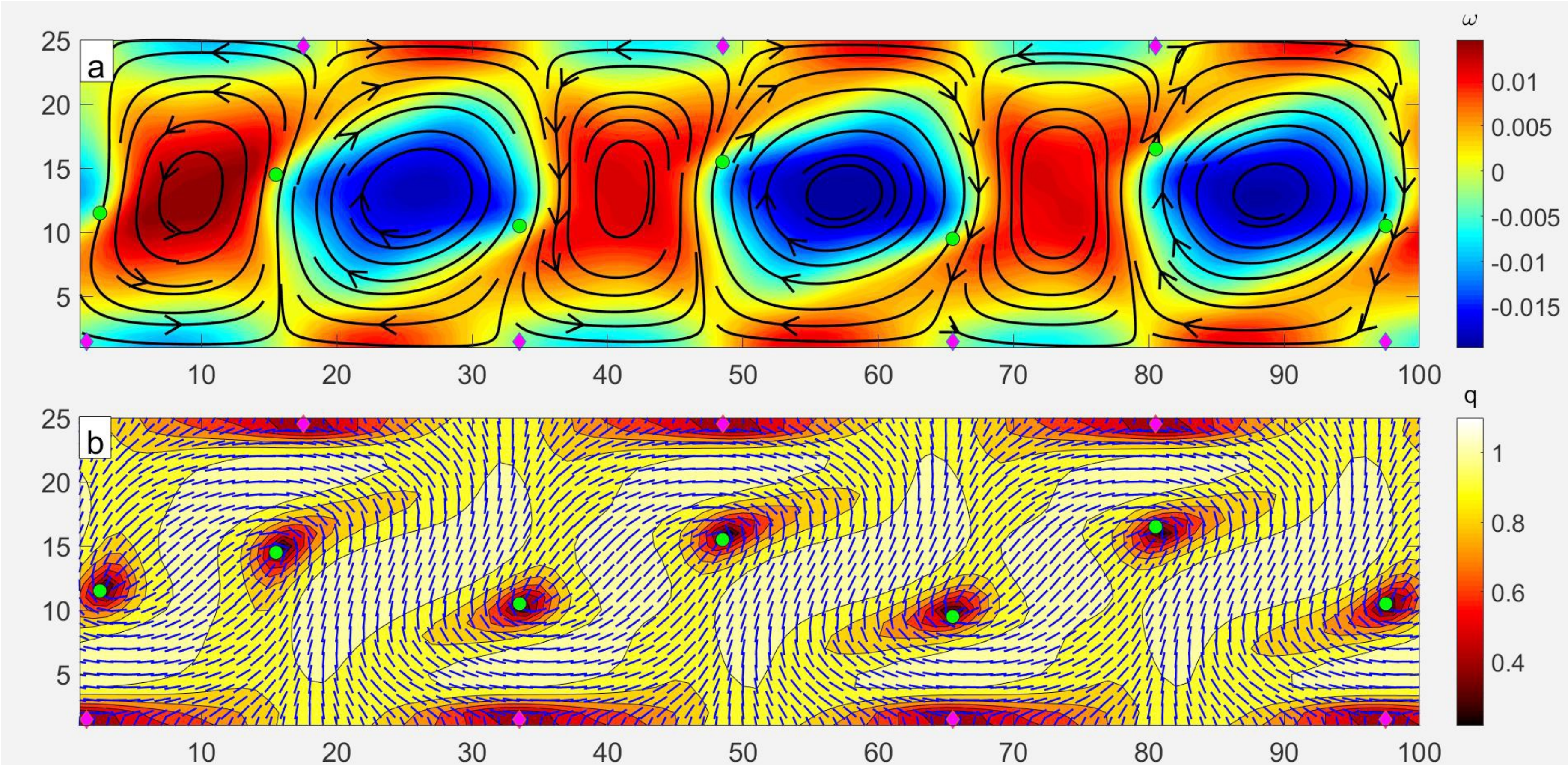
simulations by Kristain Thijssen

Ceilidh Dance

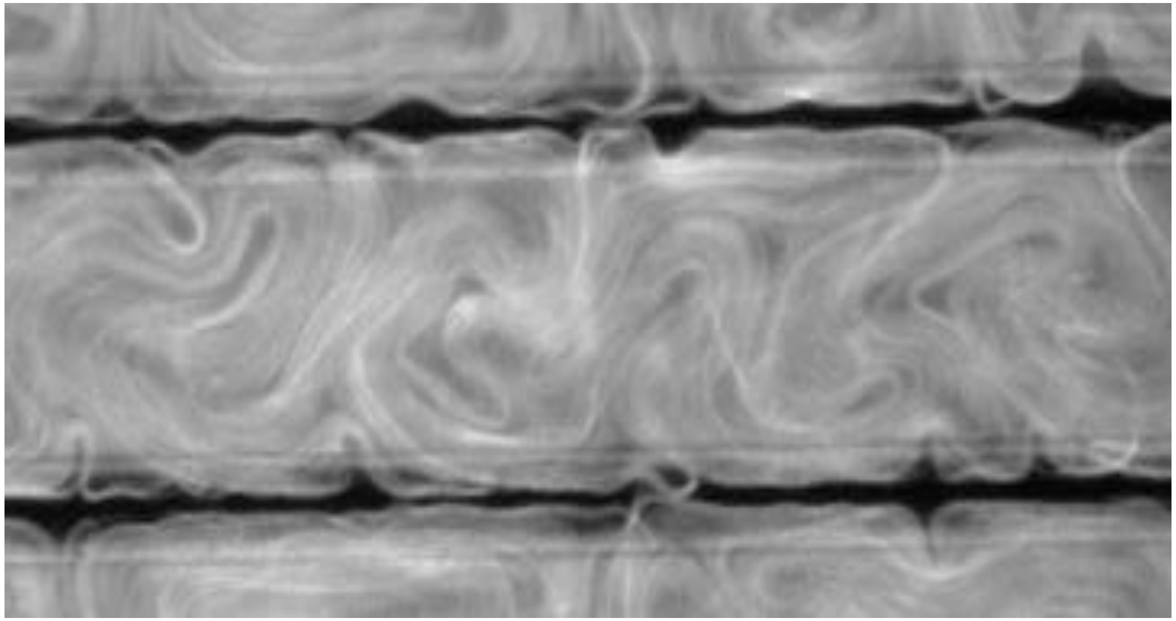




Vortex lattice and active topological microfluidics



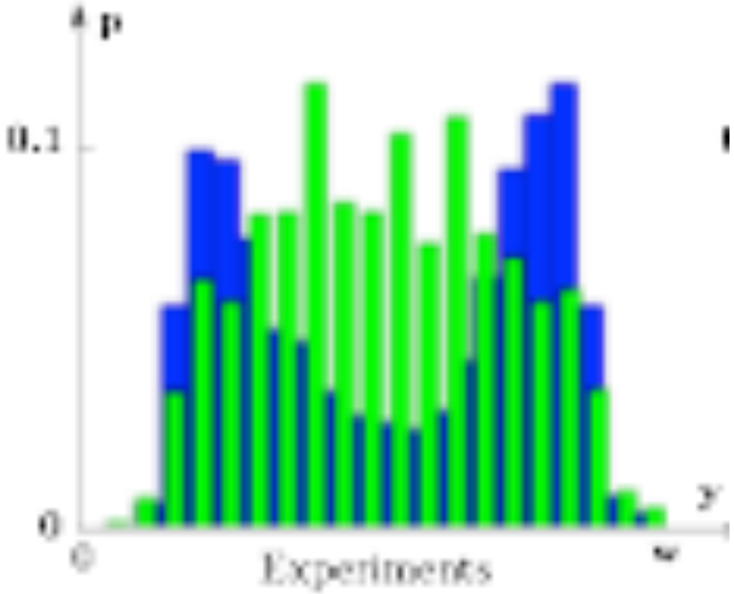
The dancing state in confined microtubule – kinesin mixtures



Distribution of defects across
 the channel:

Blue -1/2

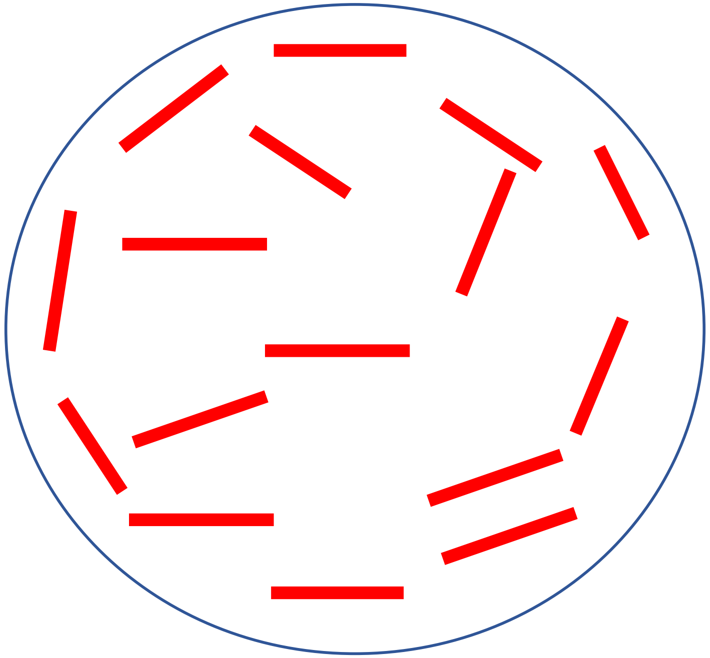
Green +1/2



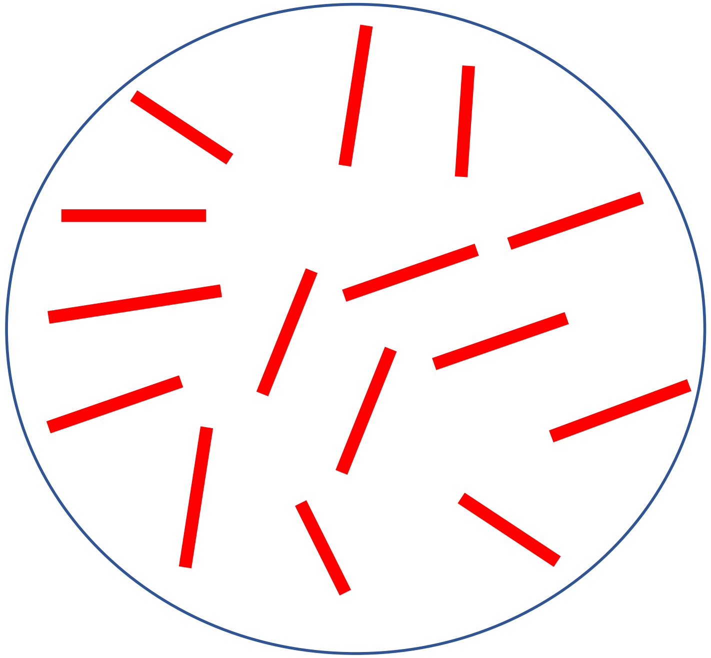
Active anchoring

Nematogens tend lie along (or perpendicular to) a surface
(aligned by flows along the surface)

Gradients in the magnitude or direction
of the nematic order induce flow.



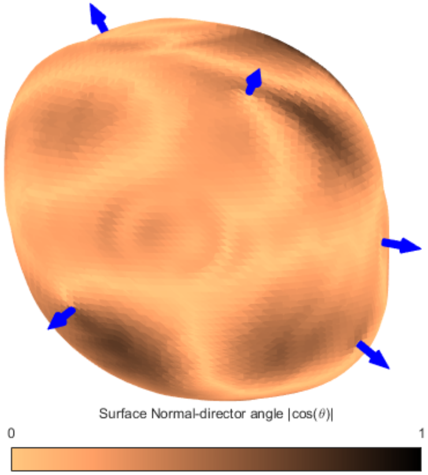
Extensile – align along surface



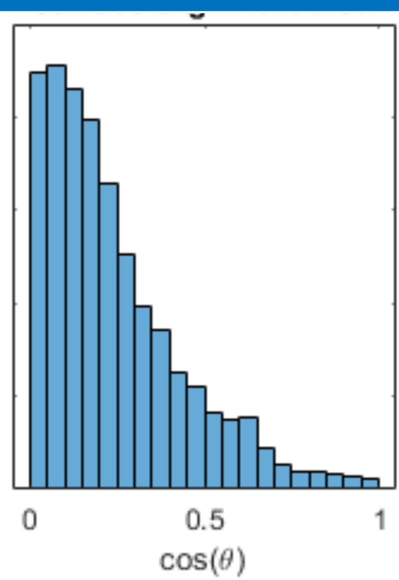
Contractile – align perpendicular to surface

Active anchoring

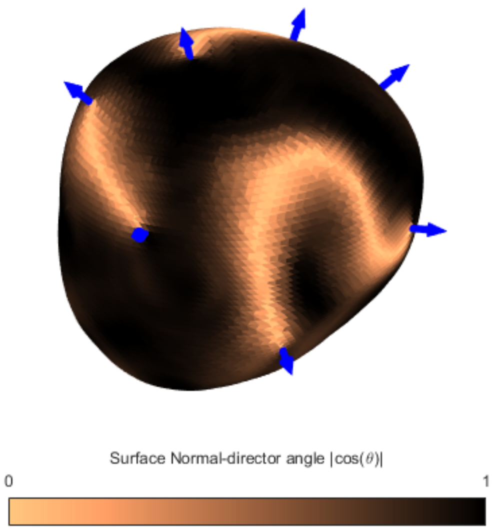
$\zeta > 0$



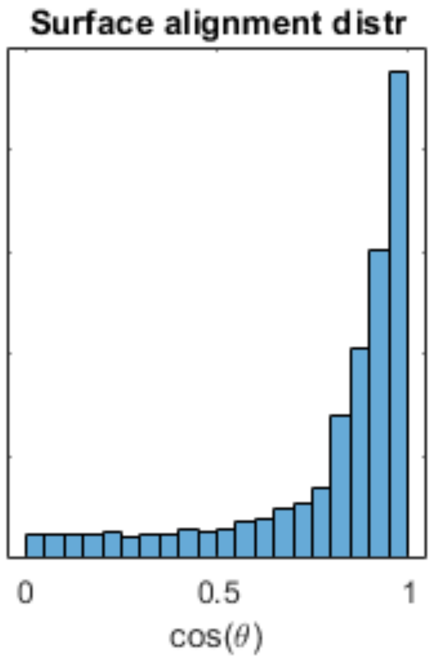
extensile flows =>
in-plane anchoring
(light brown)



$\zeta < 0$



contractile flows =>
normal anchoring
(dark brown)



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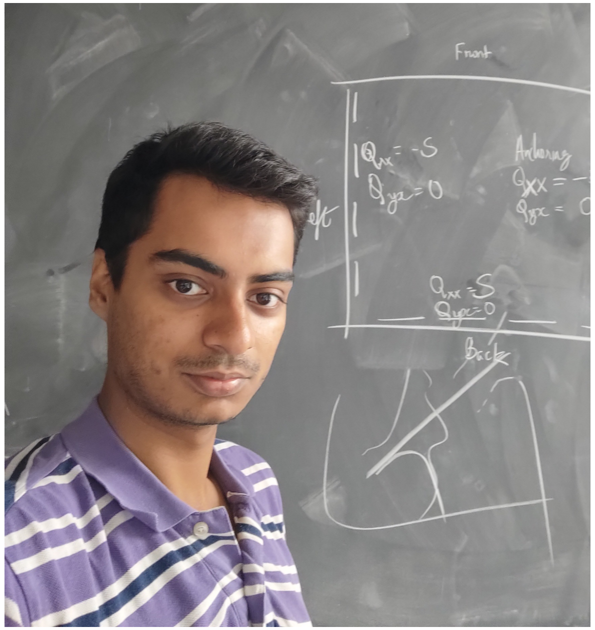
Active anchoring and cell sorting

How do confluent cell layers move?

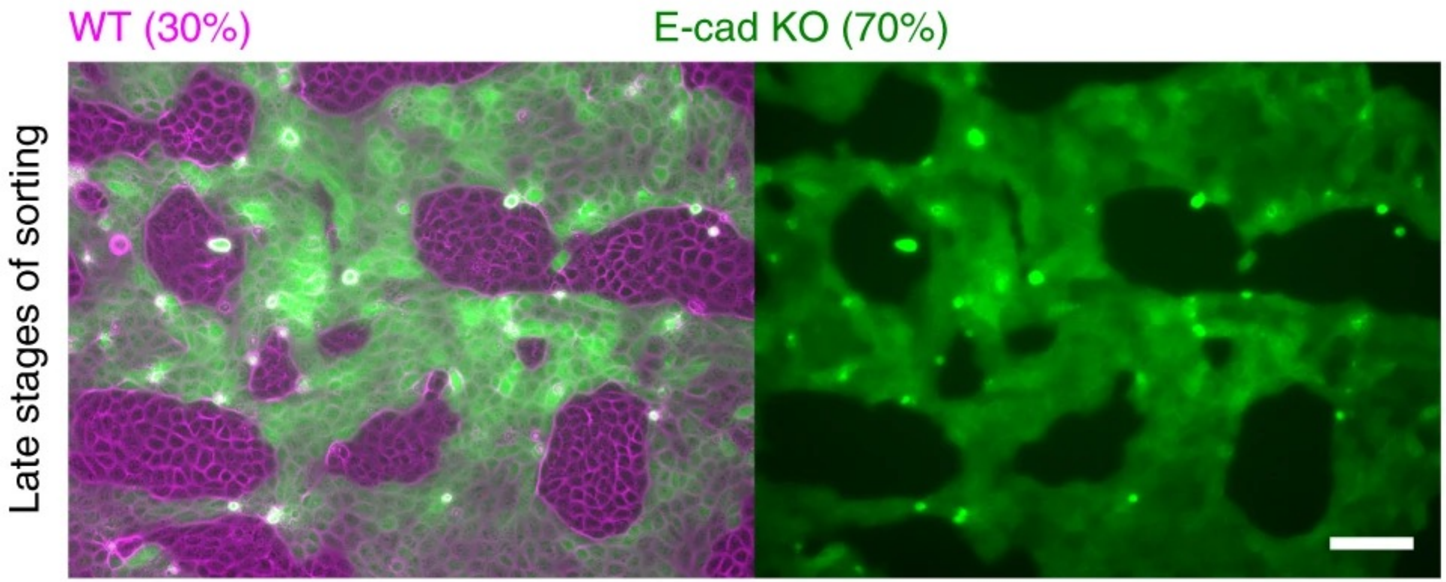
Are cells extensile or contractile?

Cell sorting



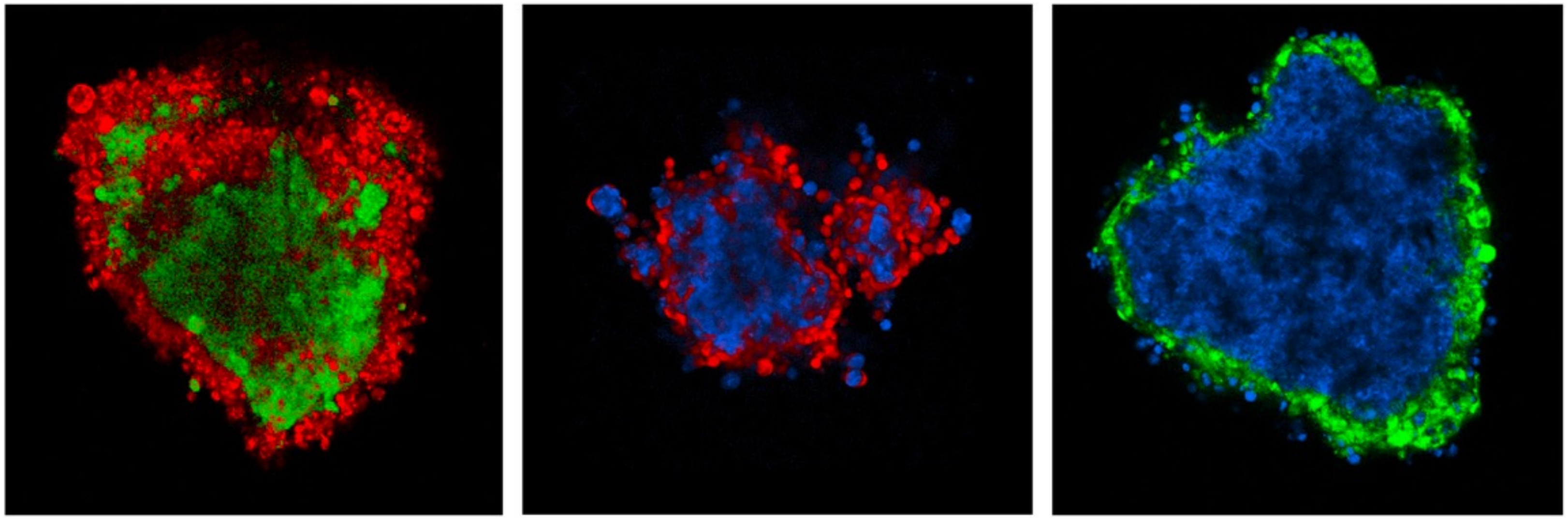
Saraswat Bhattacharyya

Sorting in cell monolayers



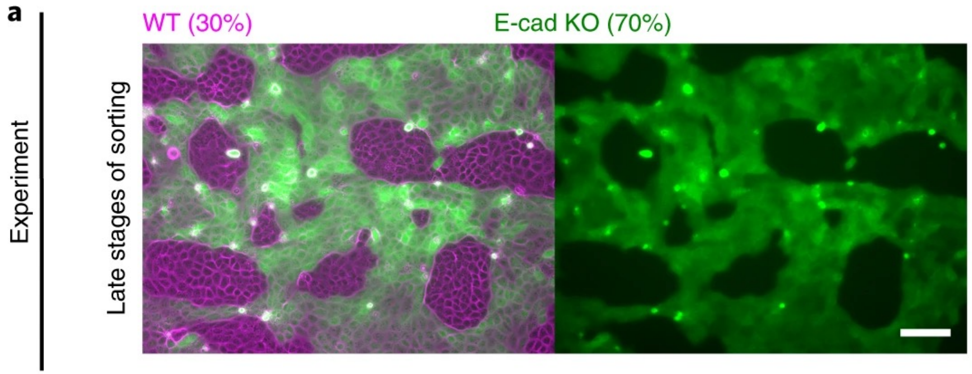
Balasubramanian et al Nature Materials **20** 1156 (2021)

Sorting in cell spheroids



Pawlizak et al New Journal of Physics 2015

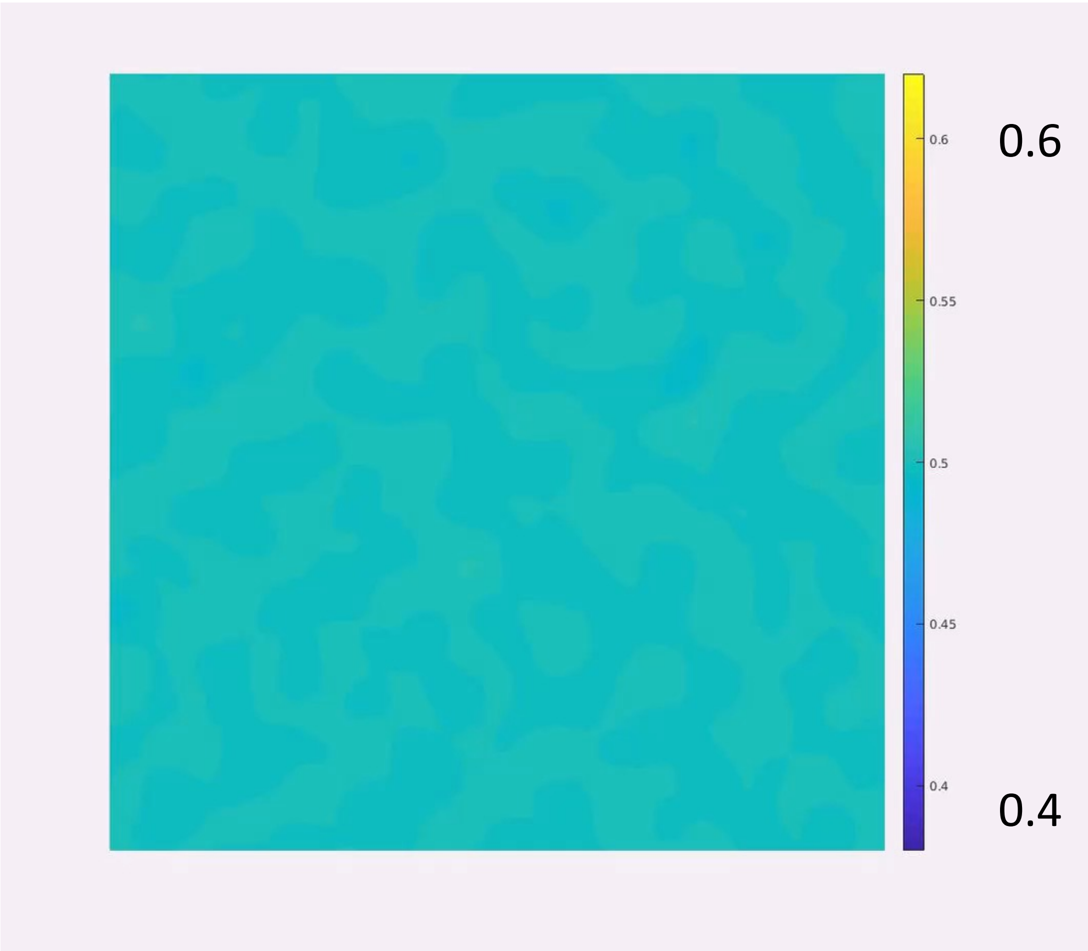
Can mixtures of cells with different activities phase separate?



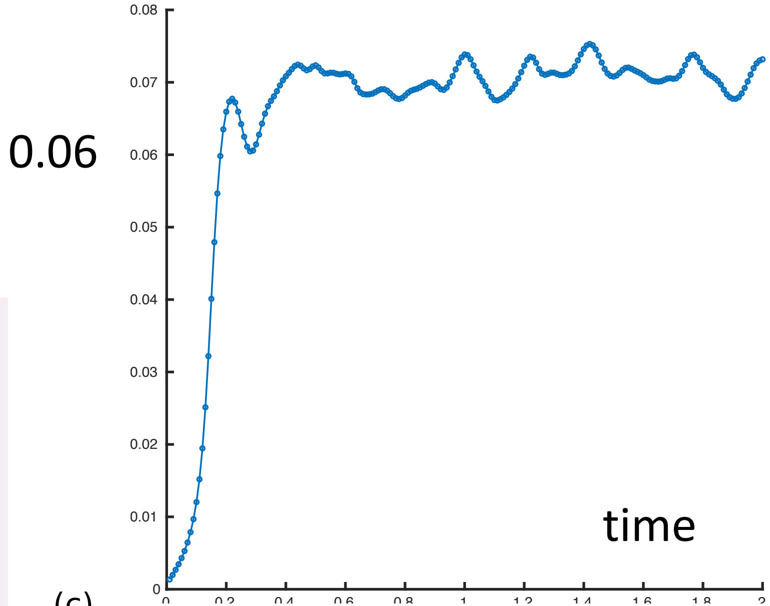
- An active two-fluid model with compressible components
- Centre-of-mass fluid behaves like an incompressible fluid
- Relative flows allow concentration field to change
- Viscous drag between component fluids keeps relative flows small

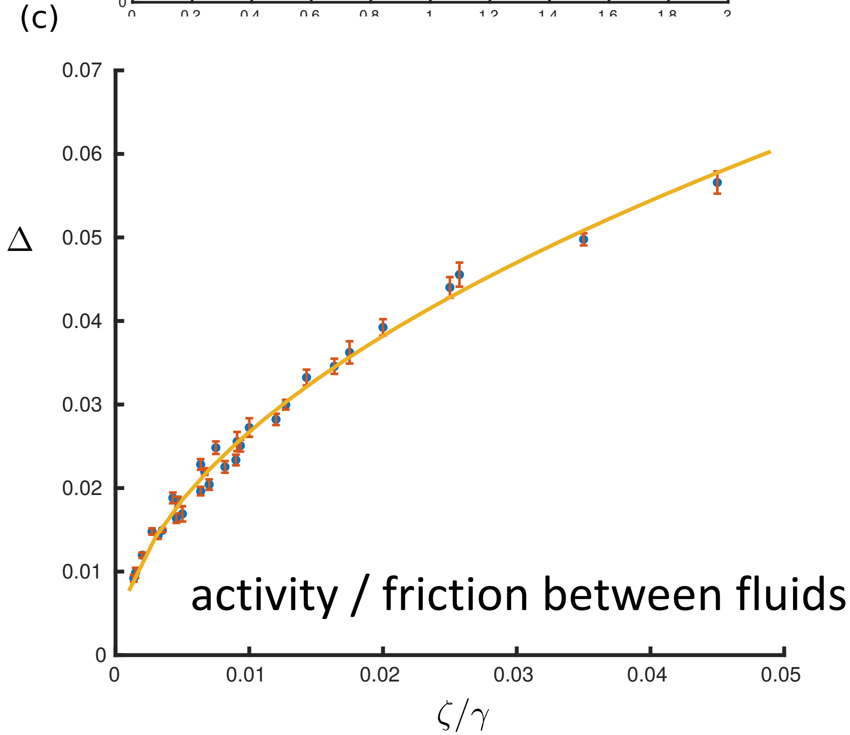
active + passive
no thermodynamic ordering

concentration difference

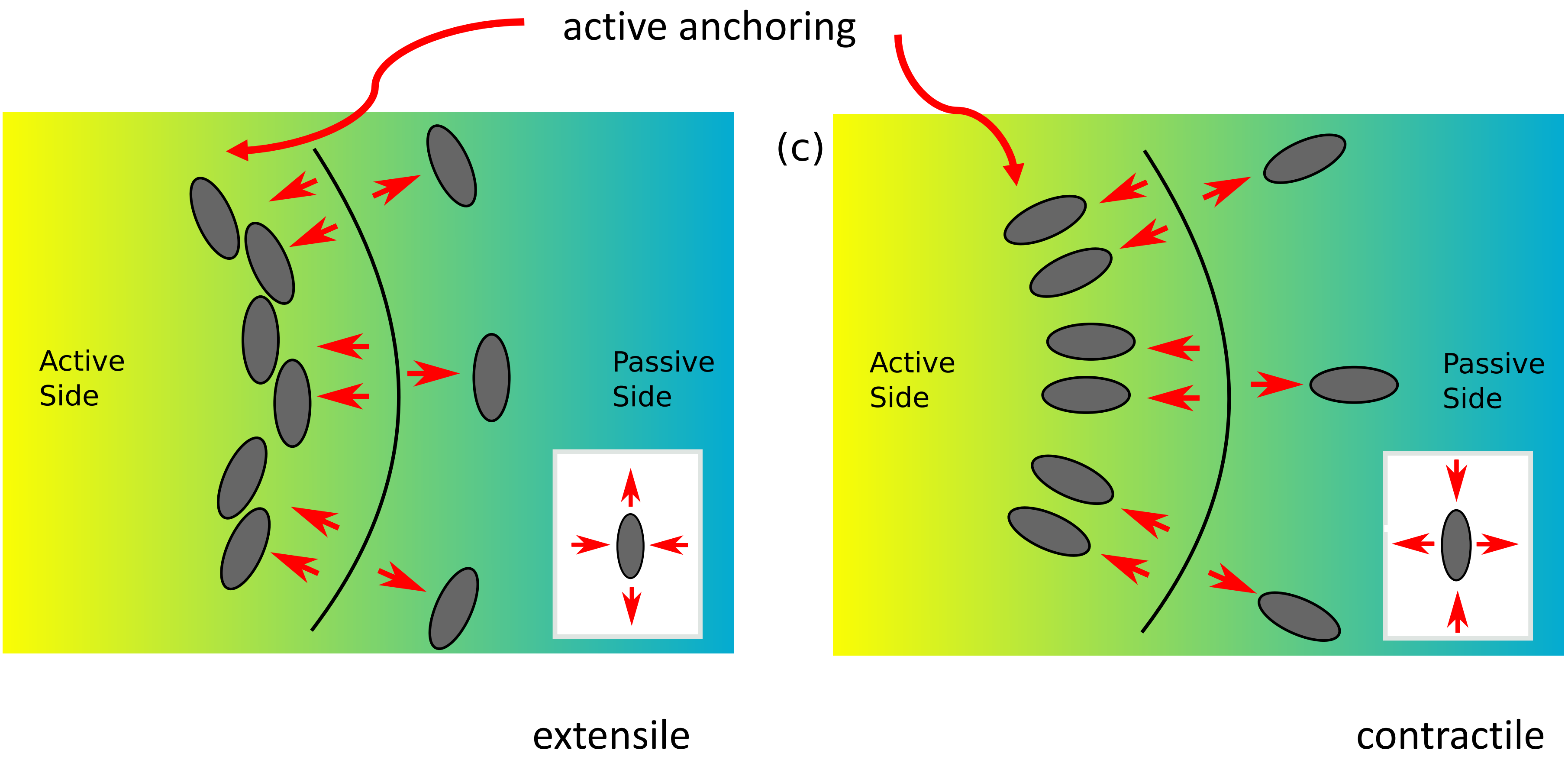


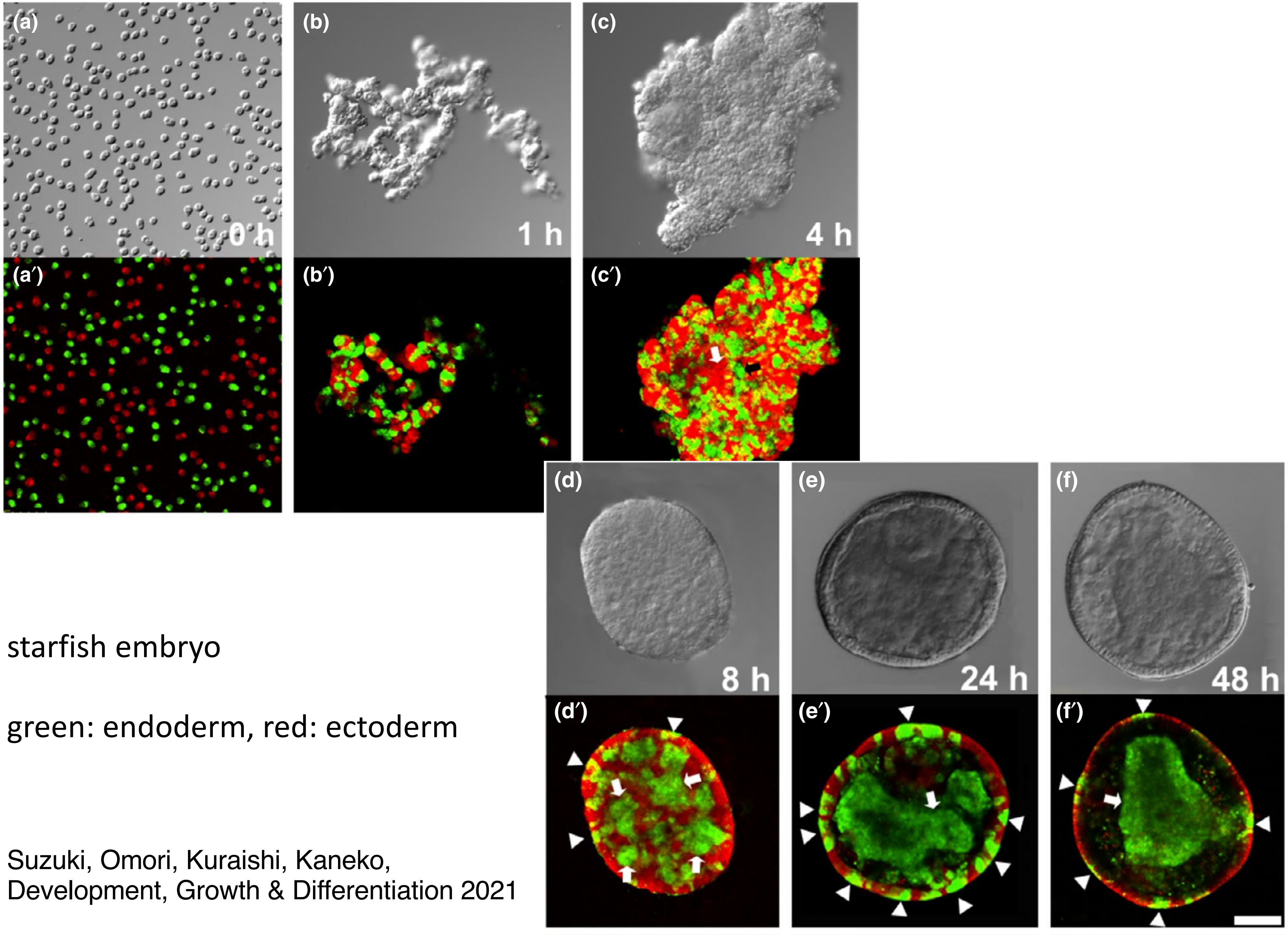
concentration
difference





Mechanism: flows + active anchoring





starfish embryo

green: endoderm, red: ectoderm

Suzuki, Omori, Kuraishi, Kaneko,
Development, Growth & Differentiation 2021