Active Nematics 3

Julia Yeomans University of Oxford

Amin Doostmohammadi

Tyler Shendruk

Sumesh Thampi

Kristian Thijssen

Roman Muller

Guanming Zhang

Mehrana Nejad

Liam Ruske

Thuan Ben Saw

Benoit Ladoux

Oli Meacock

William Durham

Lakshmi Balasubramanian

Frances Sagues

Jordi Ignes-Mullol

1. Introduction

2. Active turbulence and active topological defects

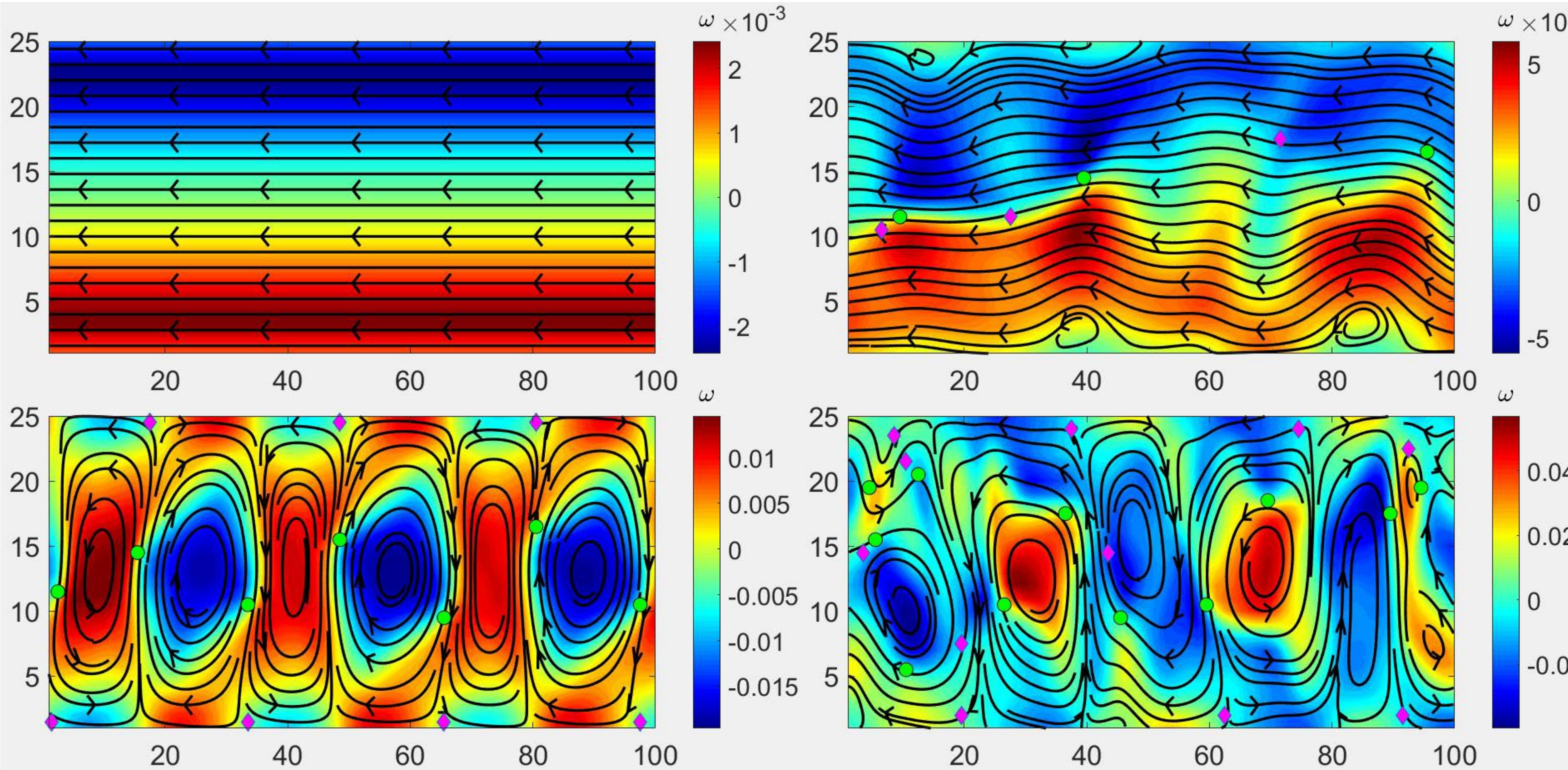
3. Confining active systems

- The sequence of dynamical states
- Topological defects and the dancing state
- Transition to active turbulence in a channel

4. Mechanobiology

- 3D active matter and gastrulation
- confluent cell layers: active turbulence again

States of an Active Nematic in a Channel



States of an Active Nematic in a Channel

No flow

⇩

Laminar flow

⇩

Oscillatory flow

⇩

Dancing state

⇩

Active turbulence

Control parameter

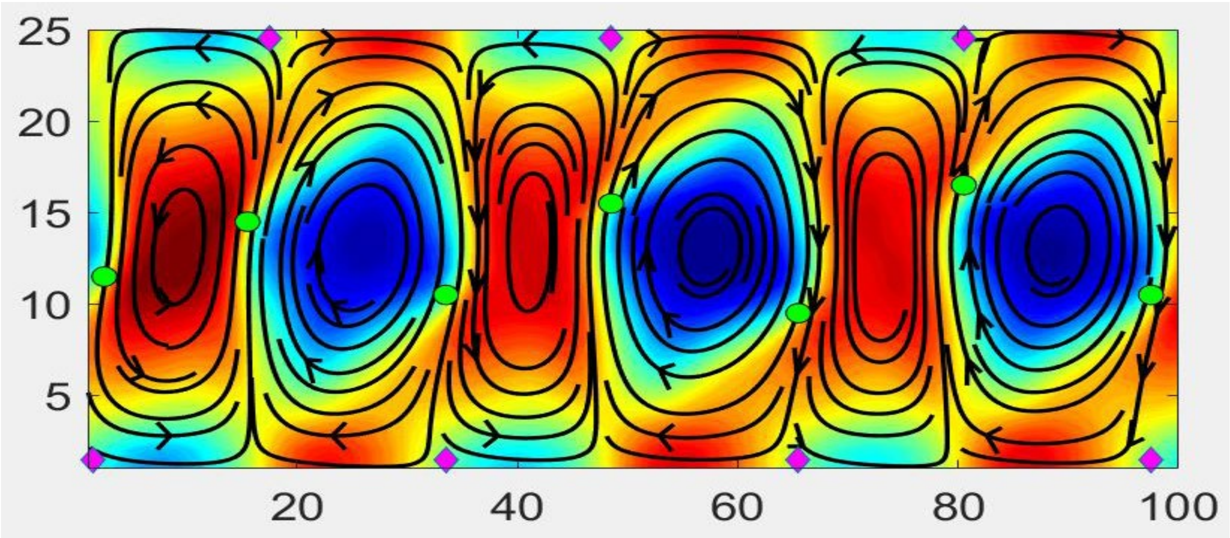
Activity number A=

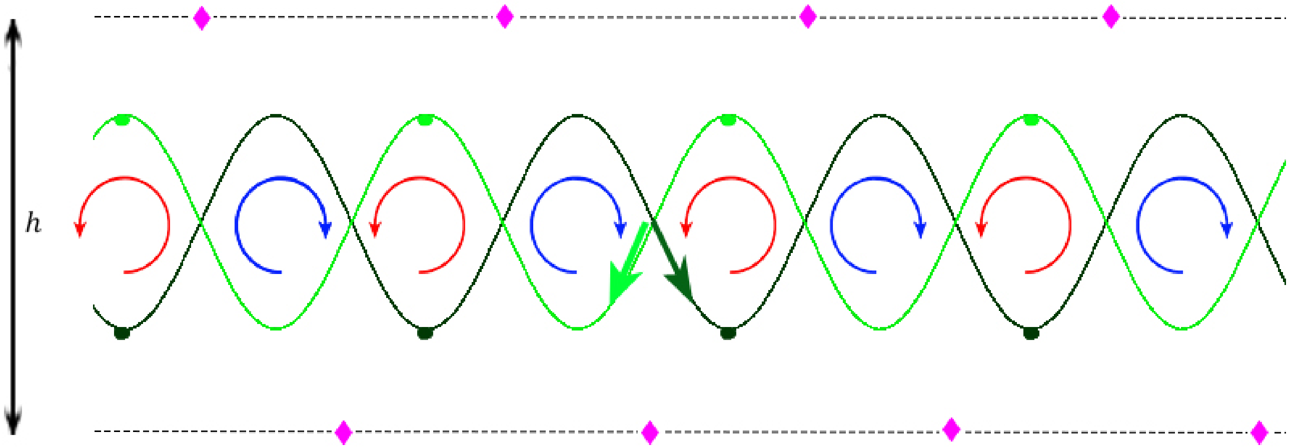
$$\sqrt{z h^2 / K}$$

Channel height

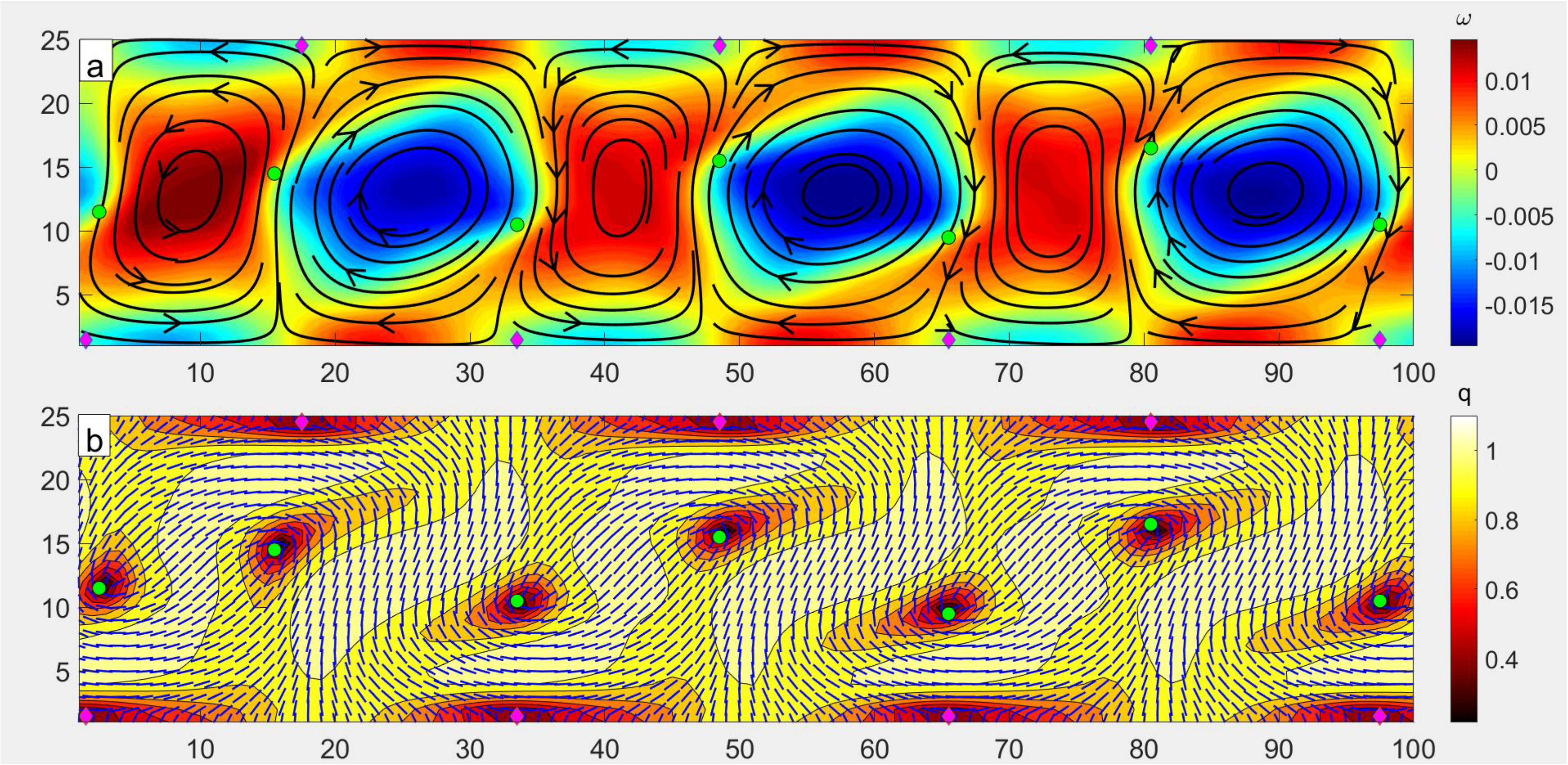
Vortex size

Ceilidh Dance



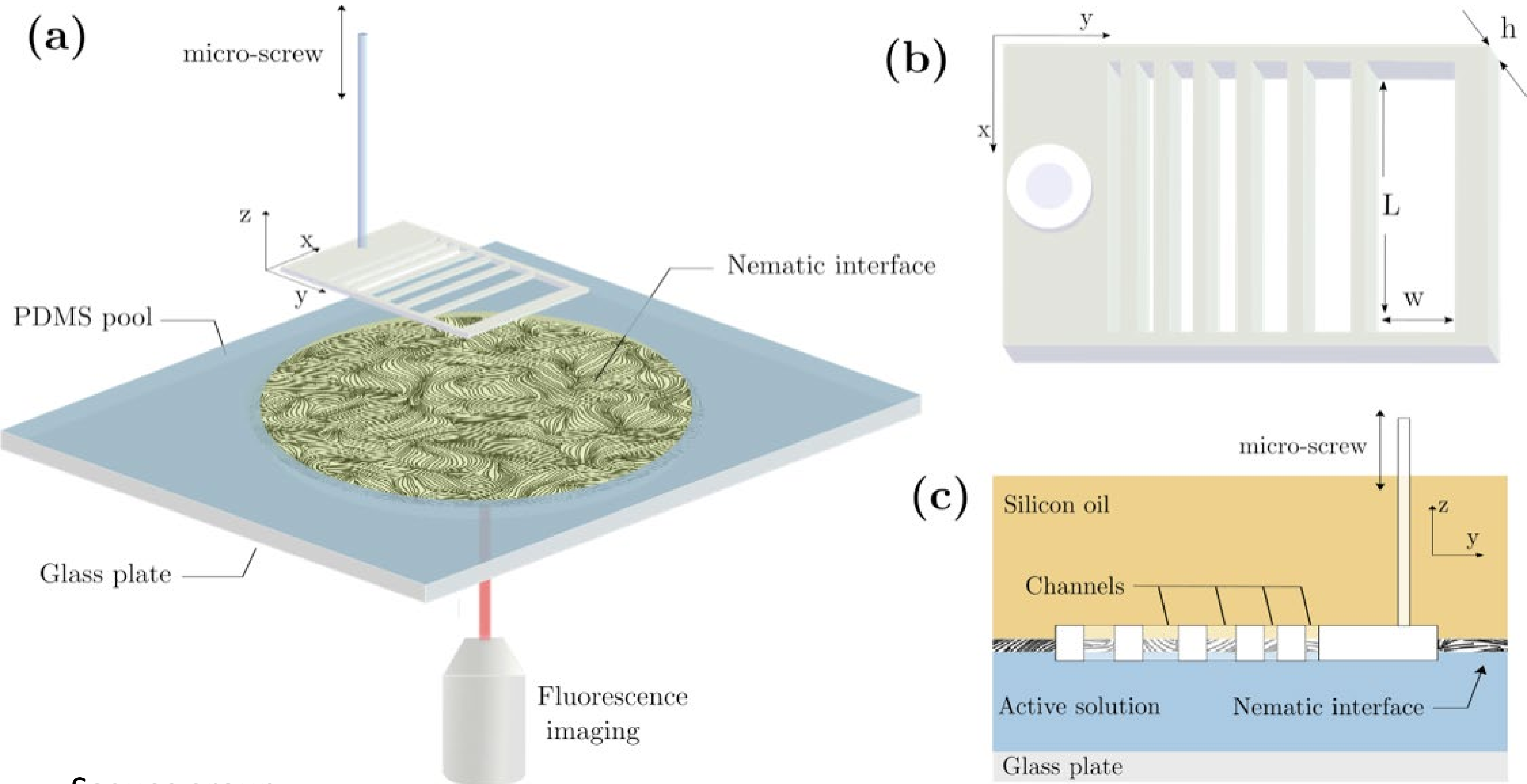


Vortex lattice and active topological microfluidics



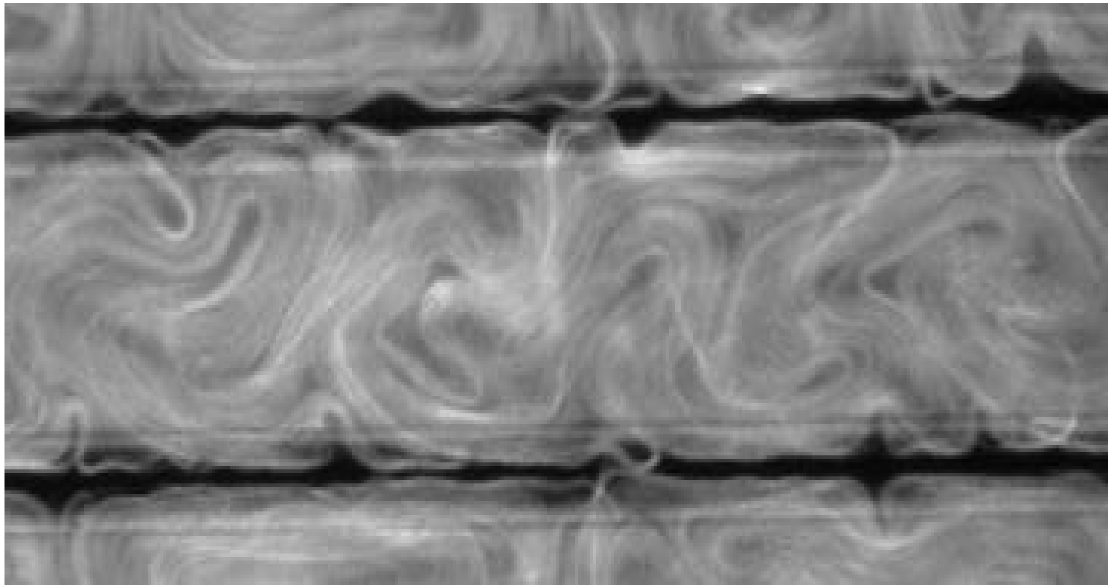
Microtubules and kinesin motors in channels

Widths 30 – 400 microns



Sagues group

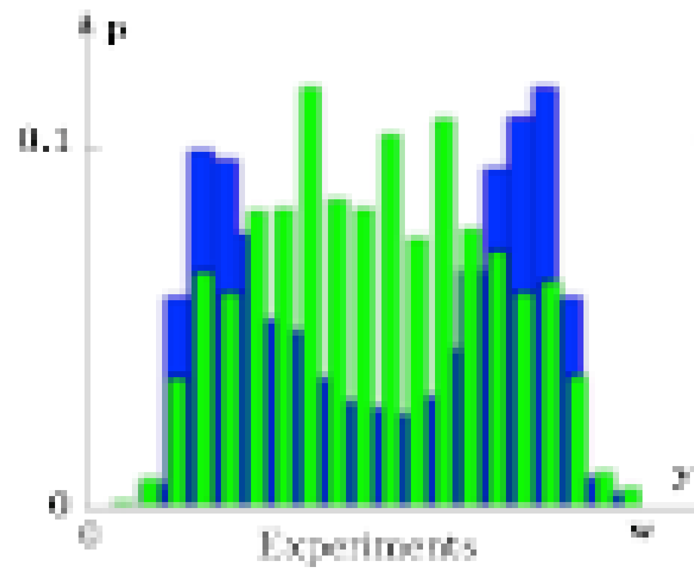
The dancing state in confined microtubule – kinesin mixtures



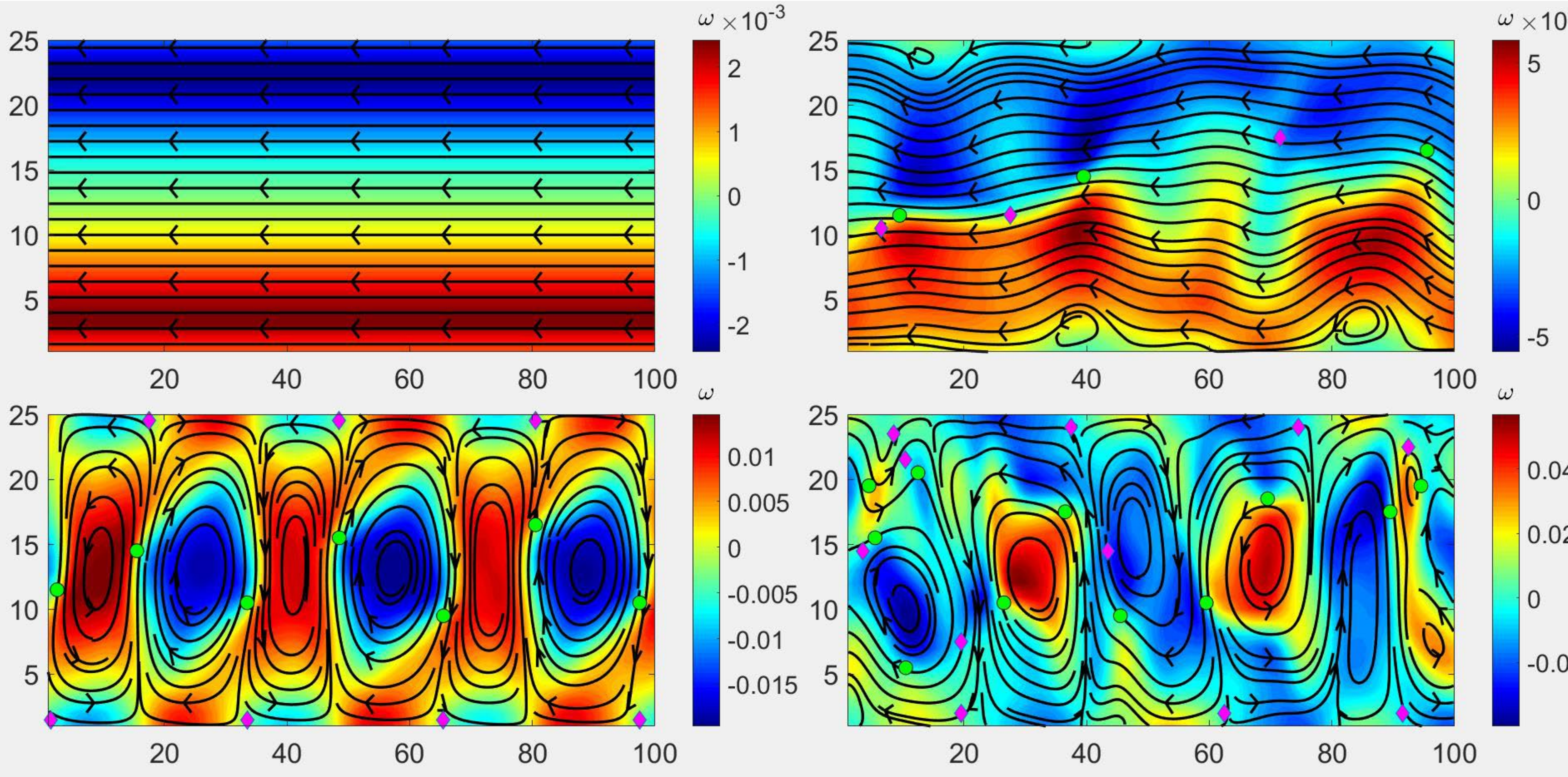
Distribution of defects across
 the channel:

Blue -1/2

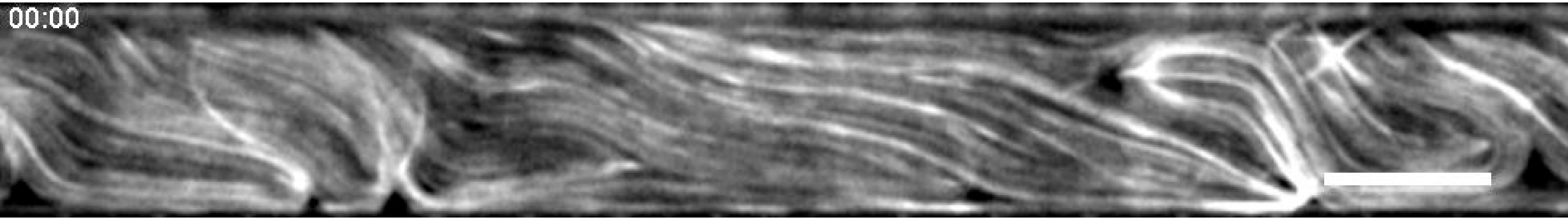
Green +1/2



States of an Active Nematic in a Channel

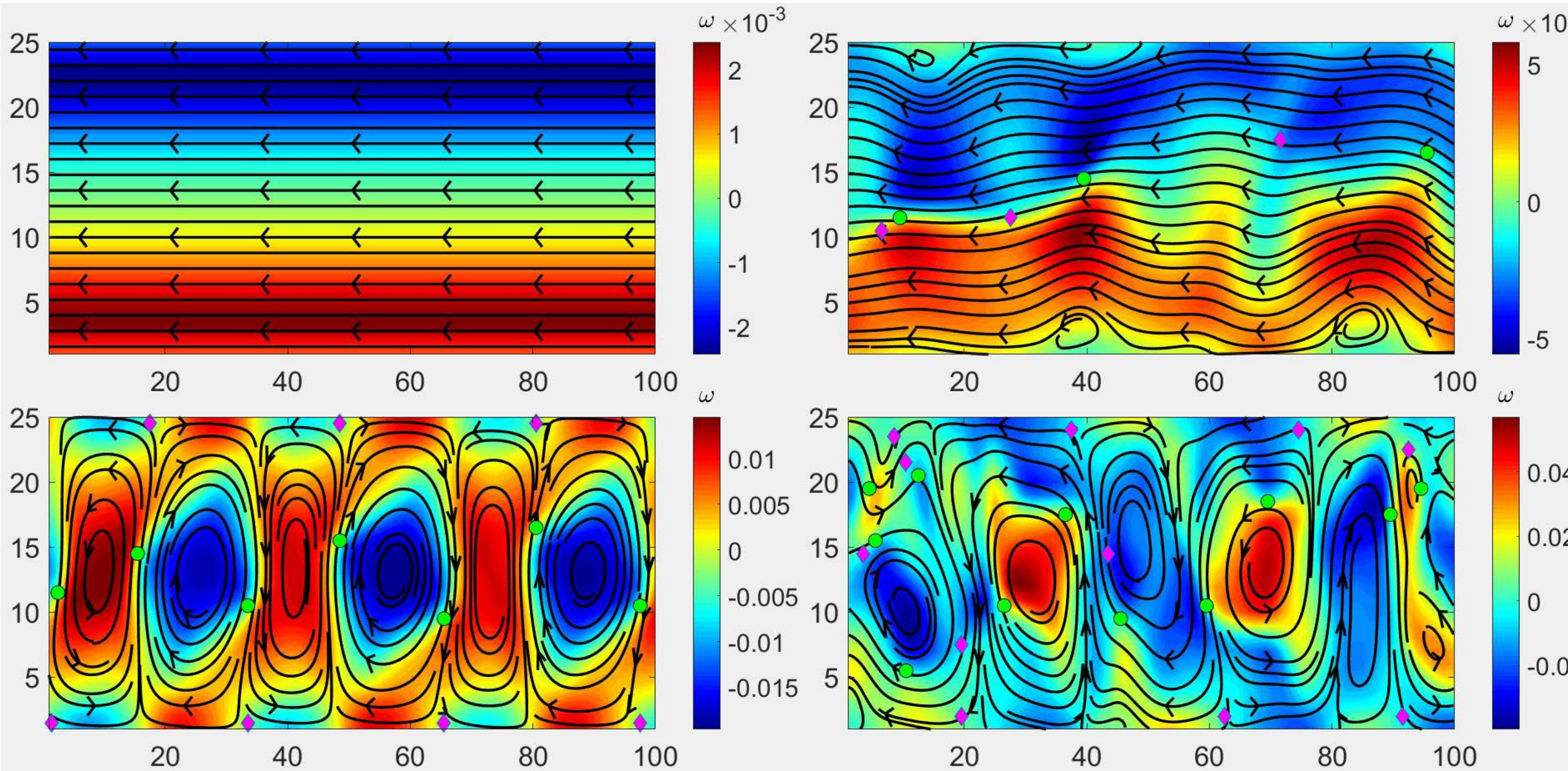


Shear + periodic bursts of defects

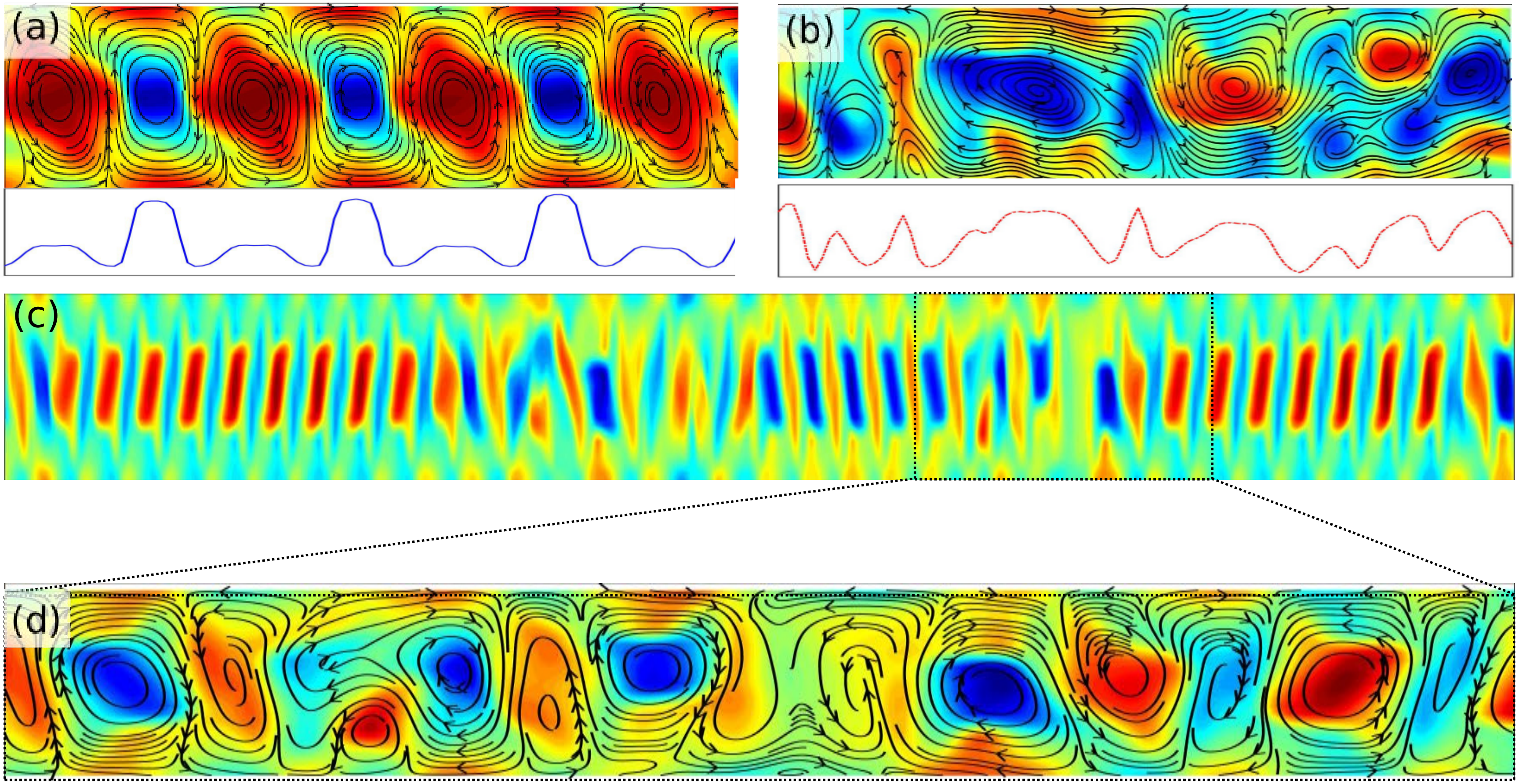


Distance between defects is set by the channel width

States of an Active Nematic in a Channel

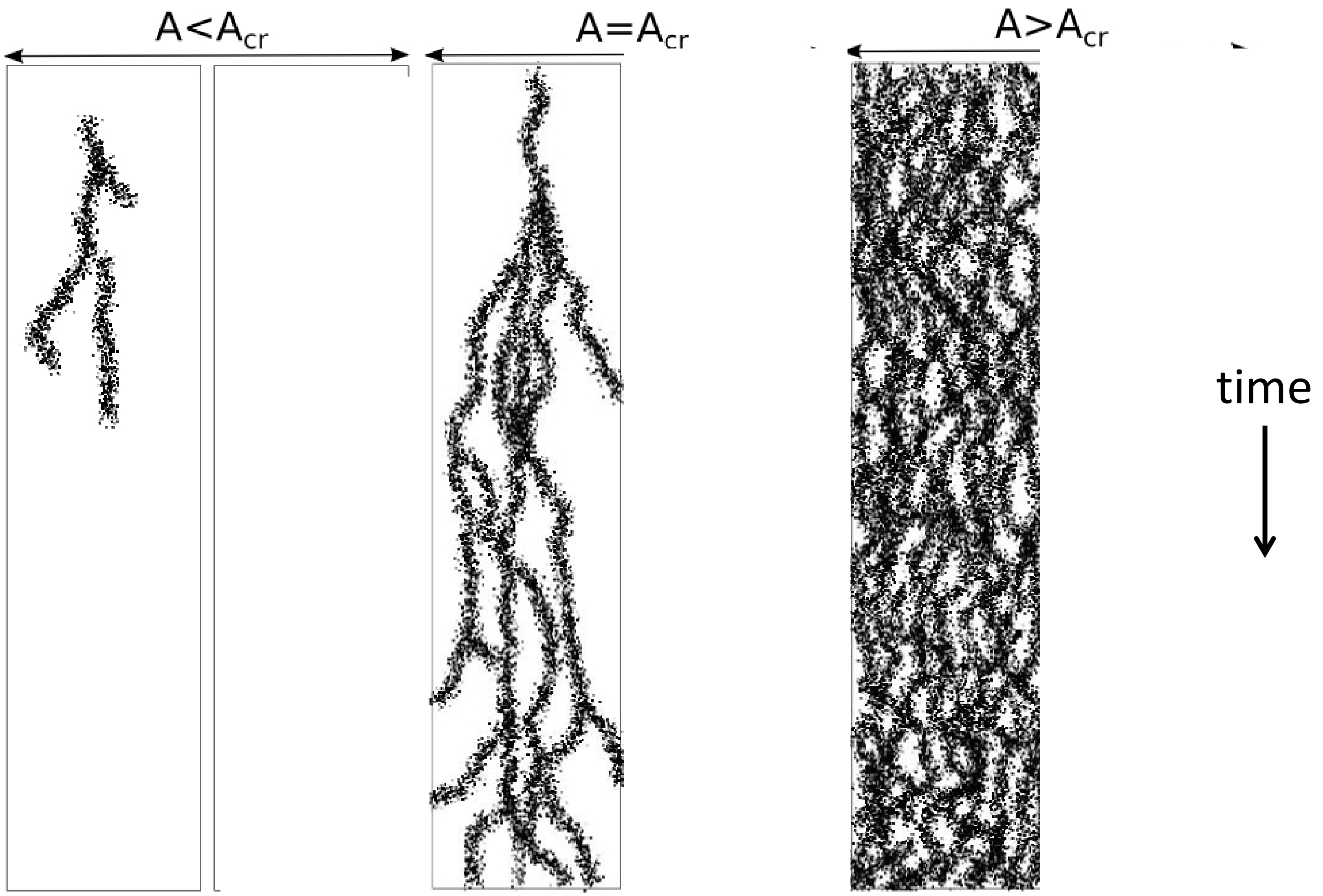


Vorticity distribution



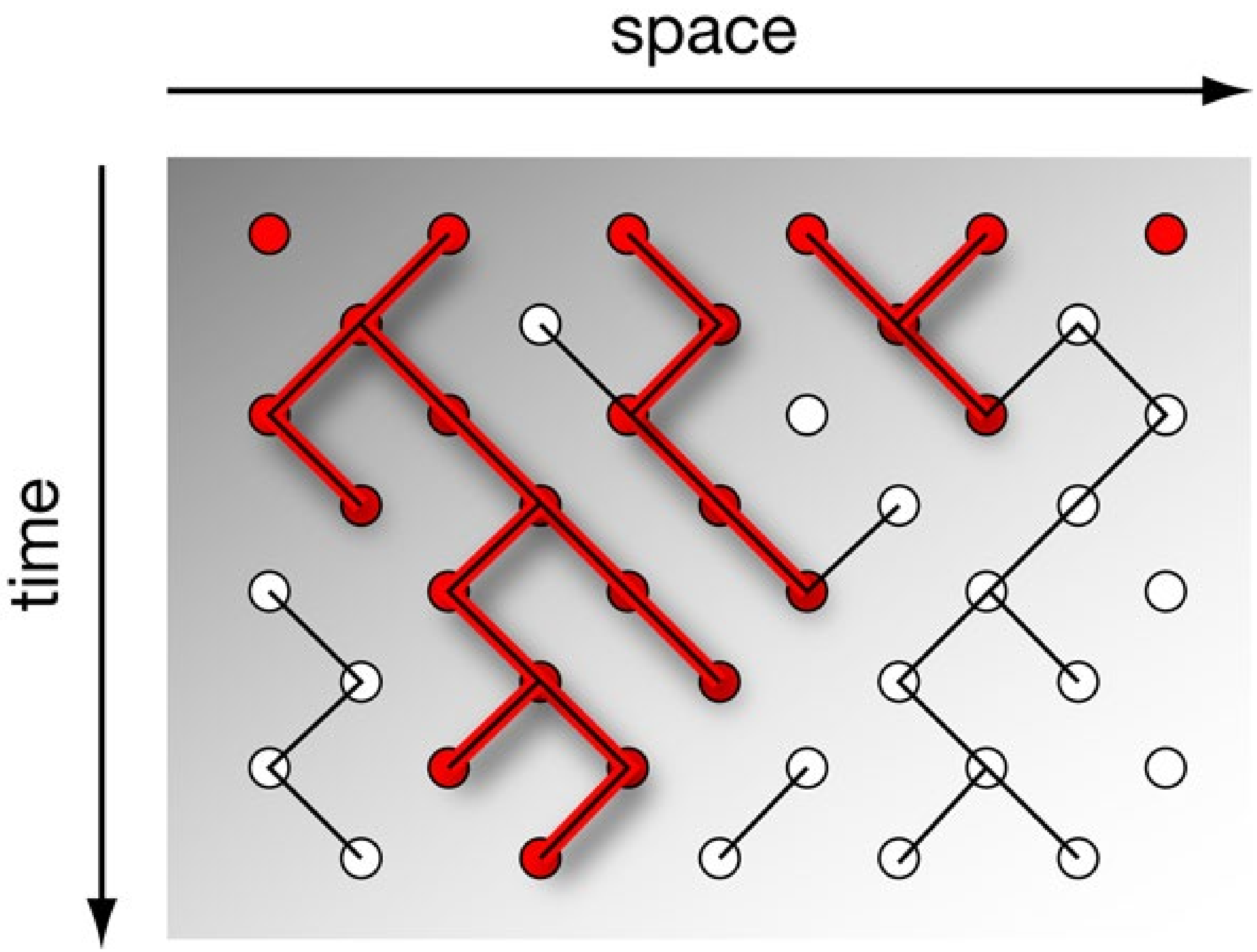
Measure the enstrophy – $|\text{vorticity}|^2$

Enstrophy kymograph



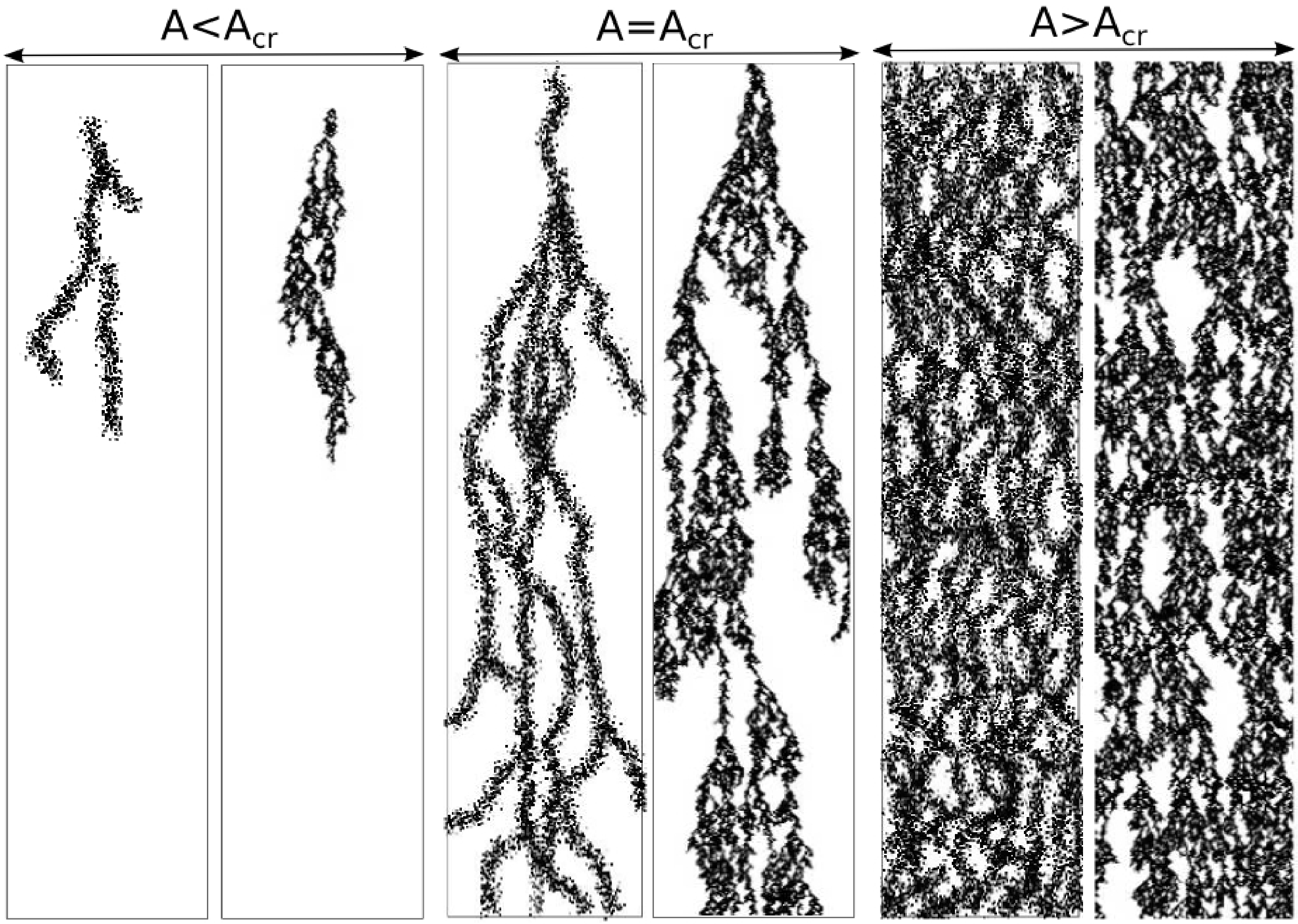
left hand panels: active nematic

Directed percolation



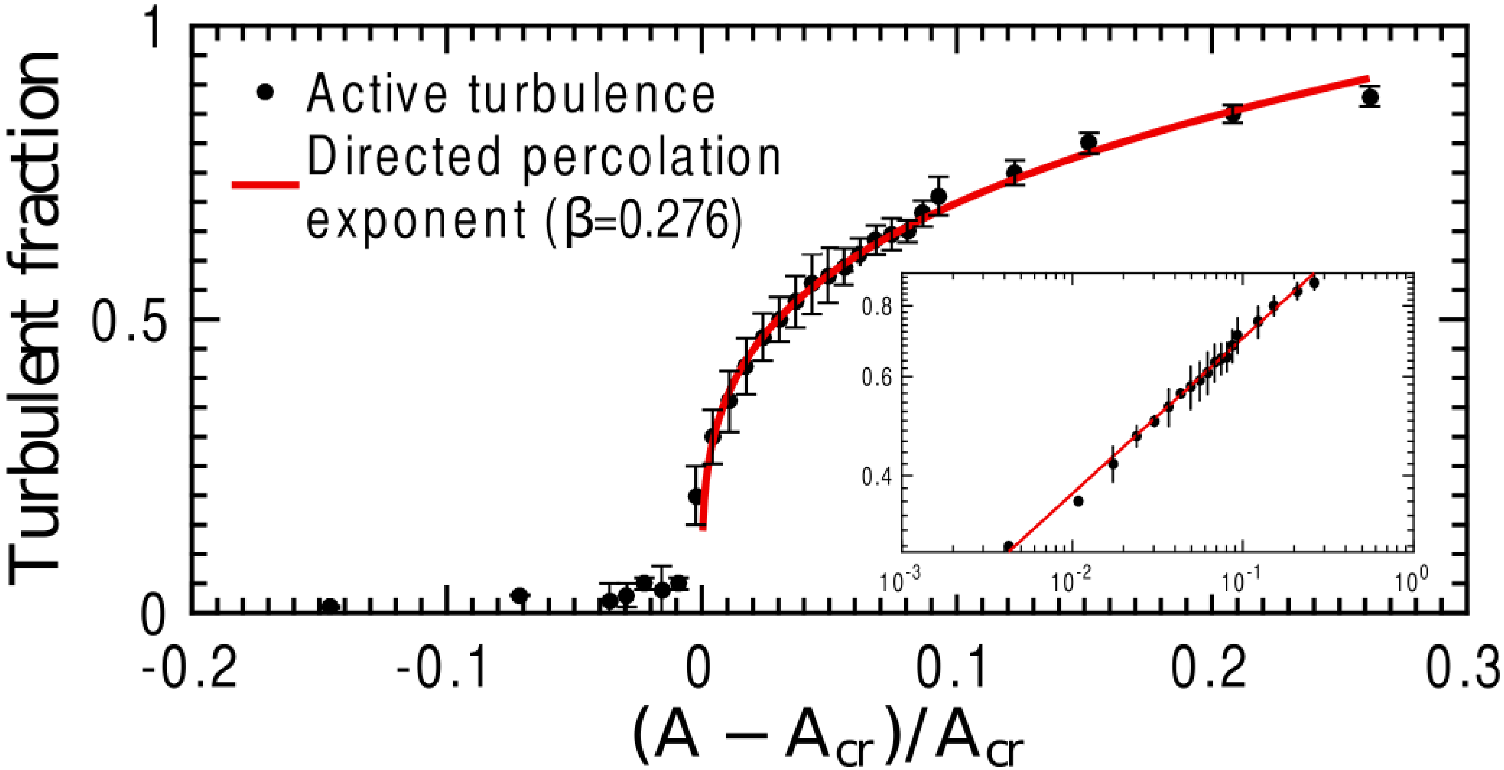
probability p that a site is occupied

Enstrophy kymograph



left hand panels: active nematic
right hand panels: directed percolation

Turbulent fraction as a function of activity



Critical exponents	β
Active turbulence at zero-Reynolds number	0.275±0.043
Couette experiments for inertial turbulence (*12*)	0.28±0.03
$(1+1)$ directed percolation (*28*)	0.276

1. Introduction

2. Active turbulence and active topological defects

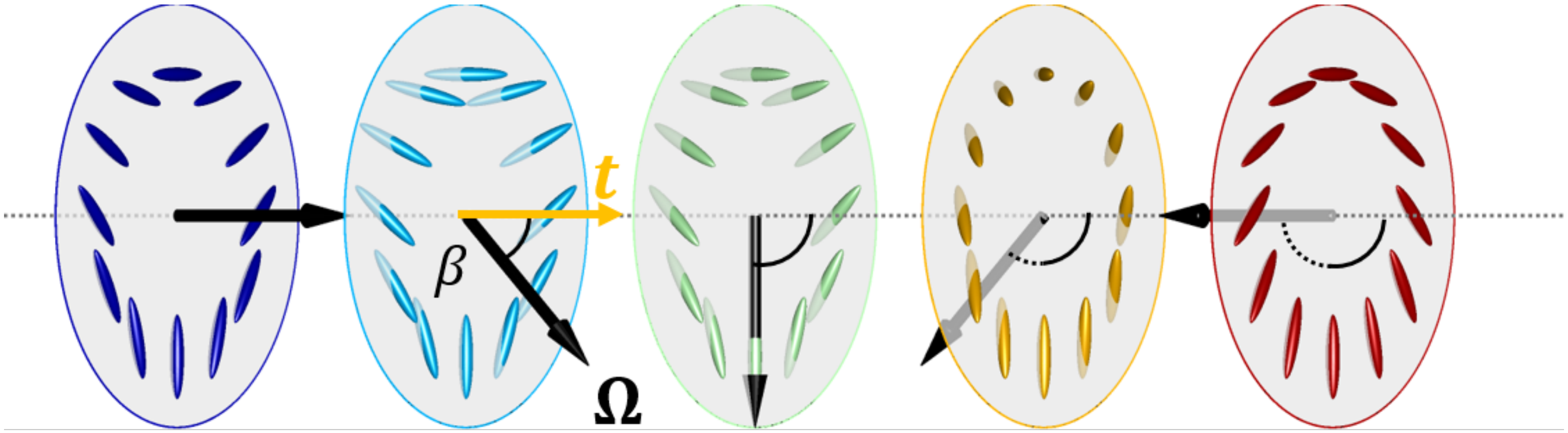
3. Confining active systems

4. Mechanobiology

- 3D active matter and gastrulation
- confluent cell layers: active turbulence again

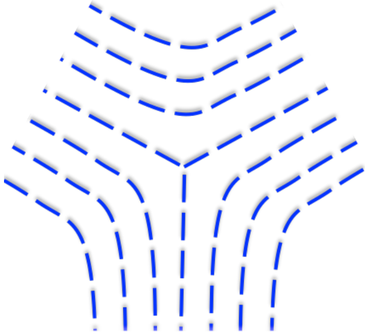
3D: Disclination Lines

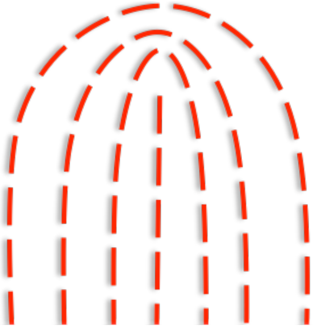
cross section of disclination lines



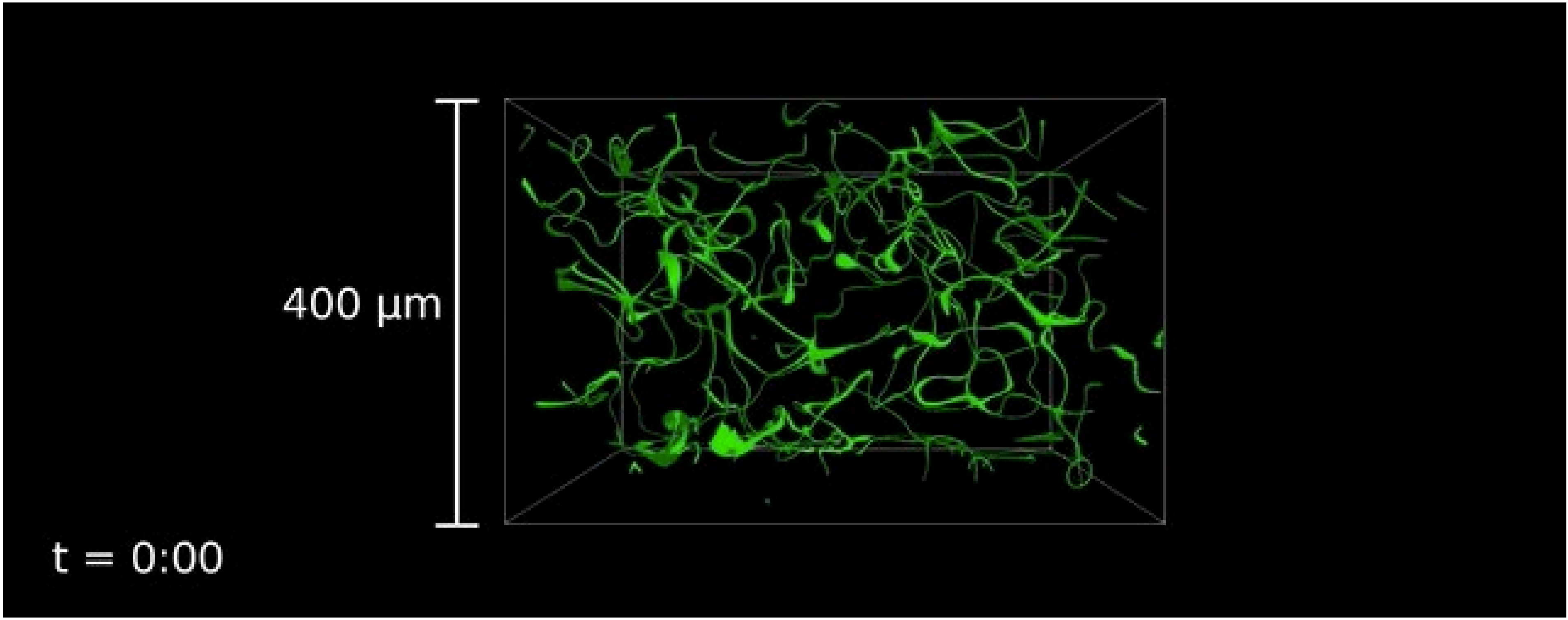
−1/2 Wedge　　　　　Twist　　　　　+1/2 Wedge

Twist angle: 0　　　　　$\pi/2$　　　　　π



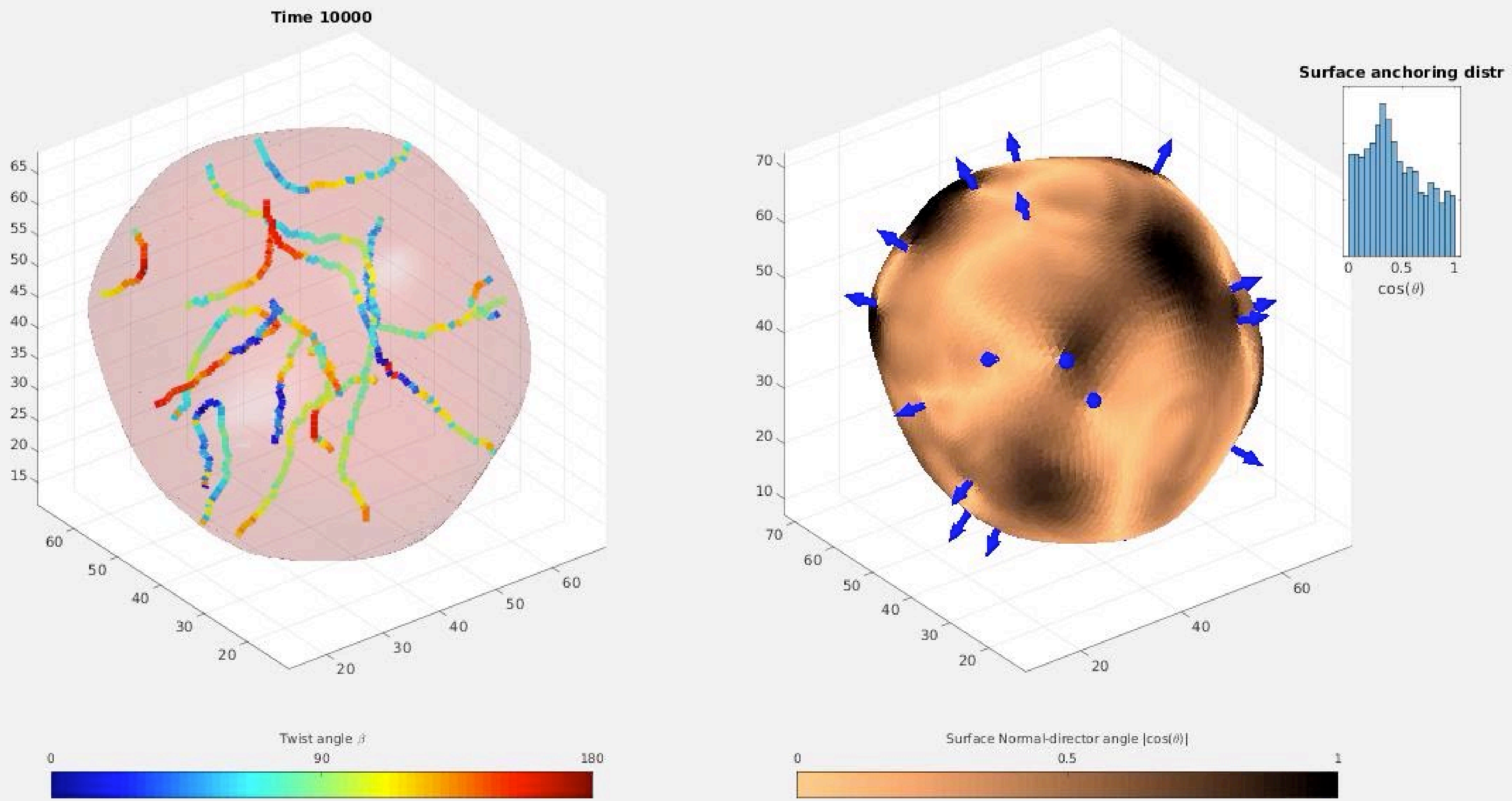


active microtubule bundles in a background of nematic colloids



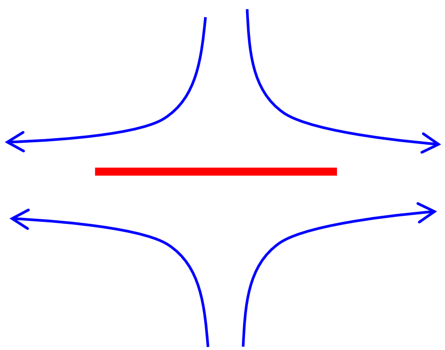
Duclos et al Science 2020

Disclination lines in an active droplet



Extensile and Contractile

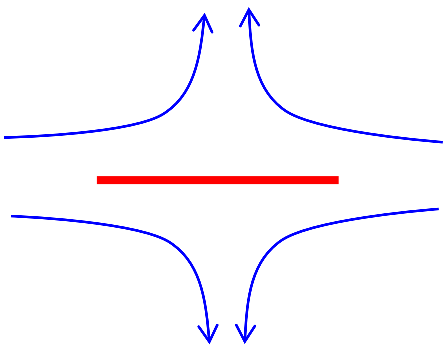
$\zeta > 0$



Extensile

Pusher

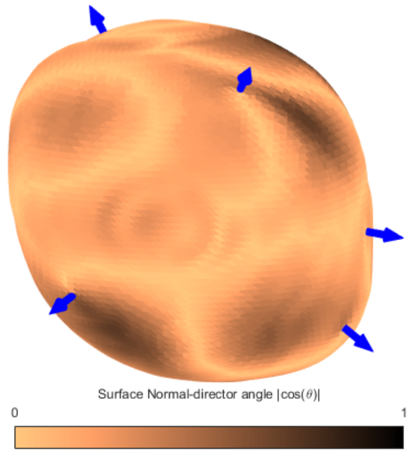
$\zeta < 0$



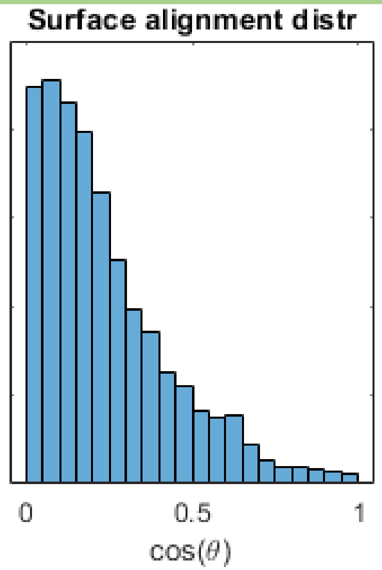
Contractile

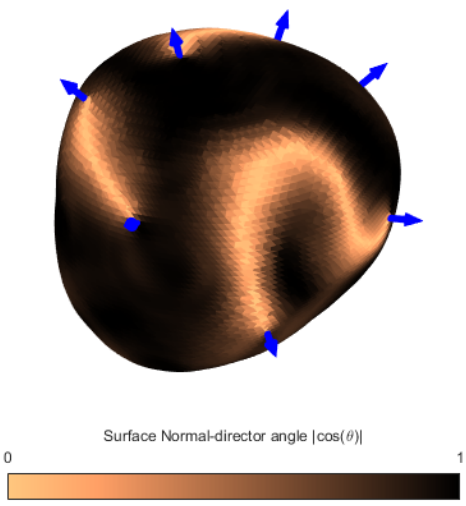
Puller

Active anchoring

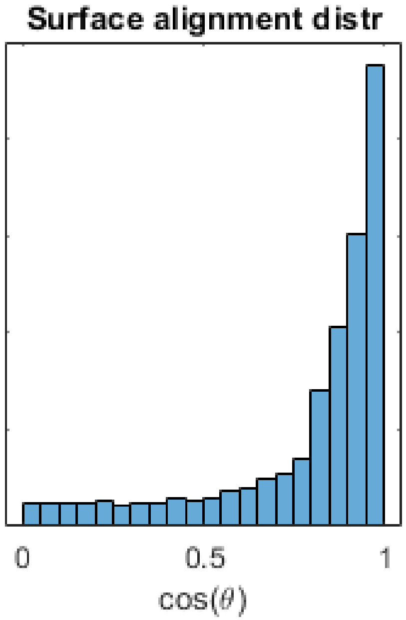


extensile flows =>
In-plane surface
anchoring
(light brown)

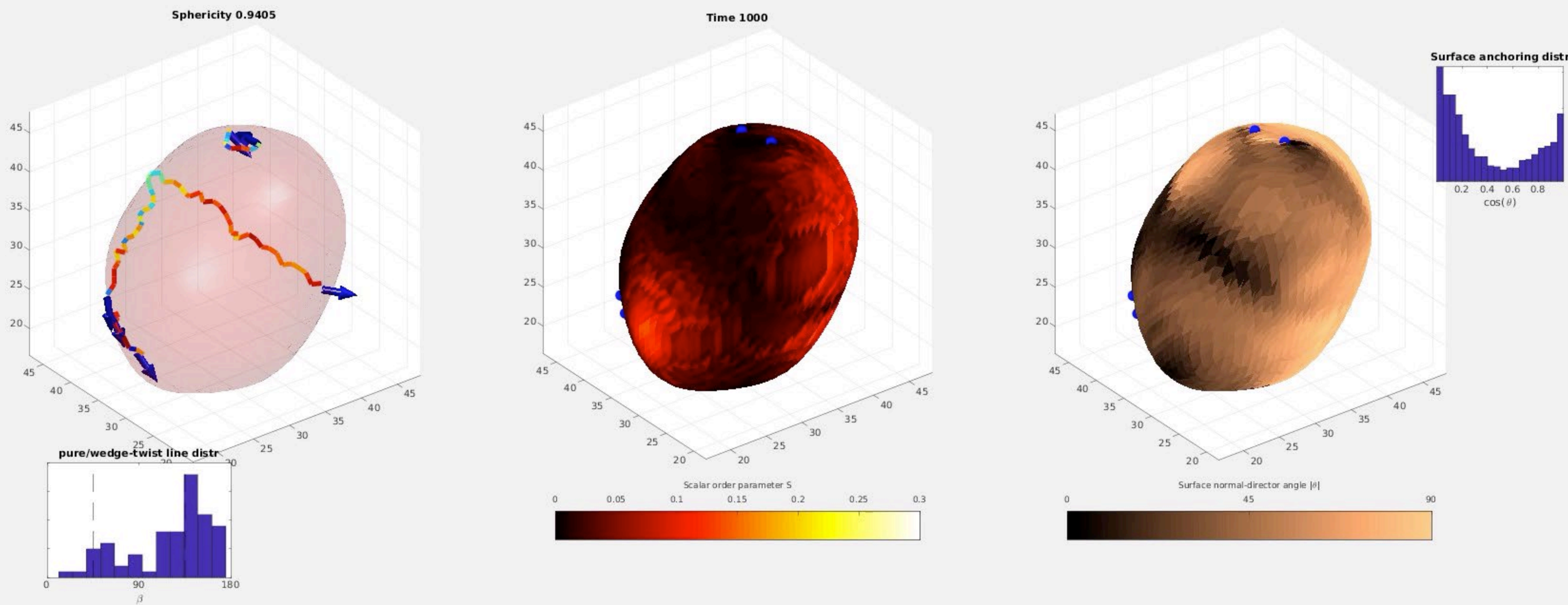




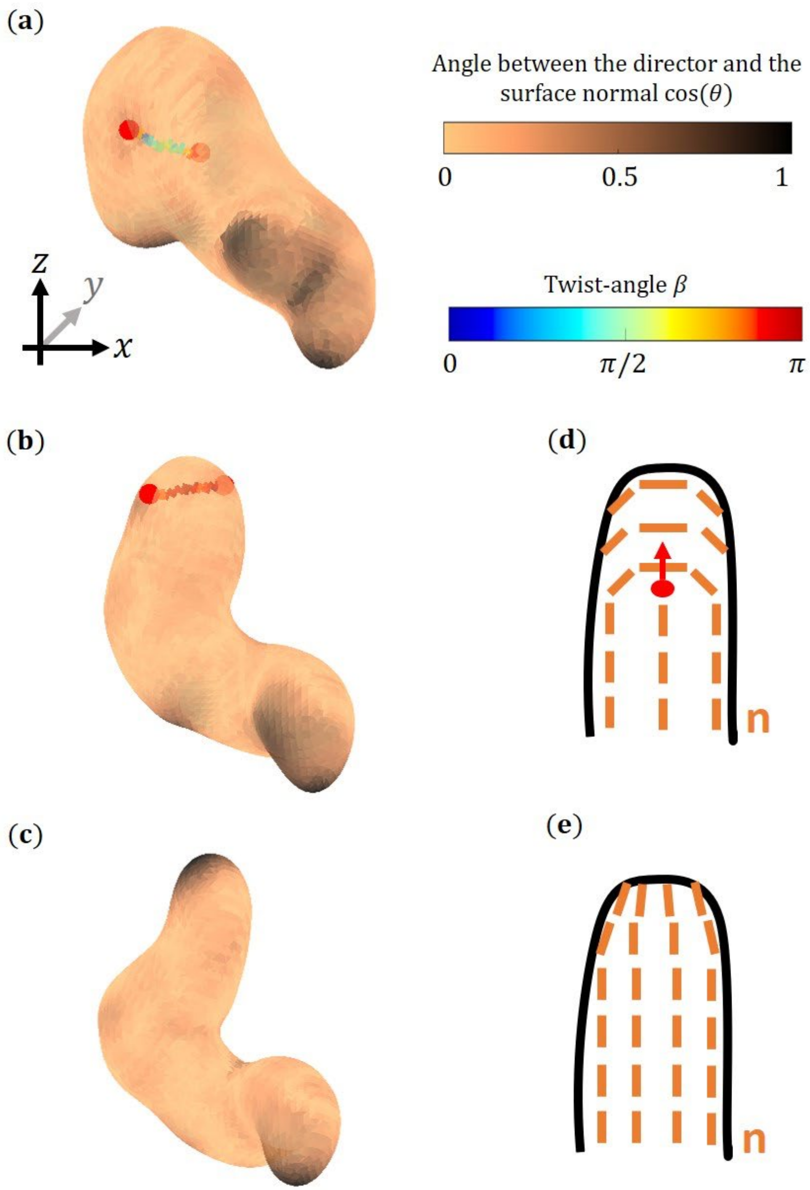
contractile flows =>
normal surface
anchoring
(dark brown)



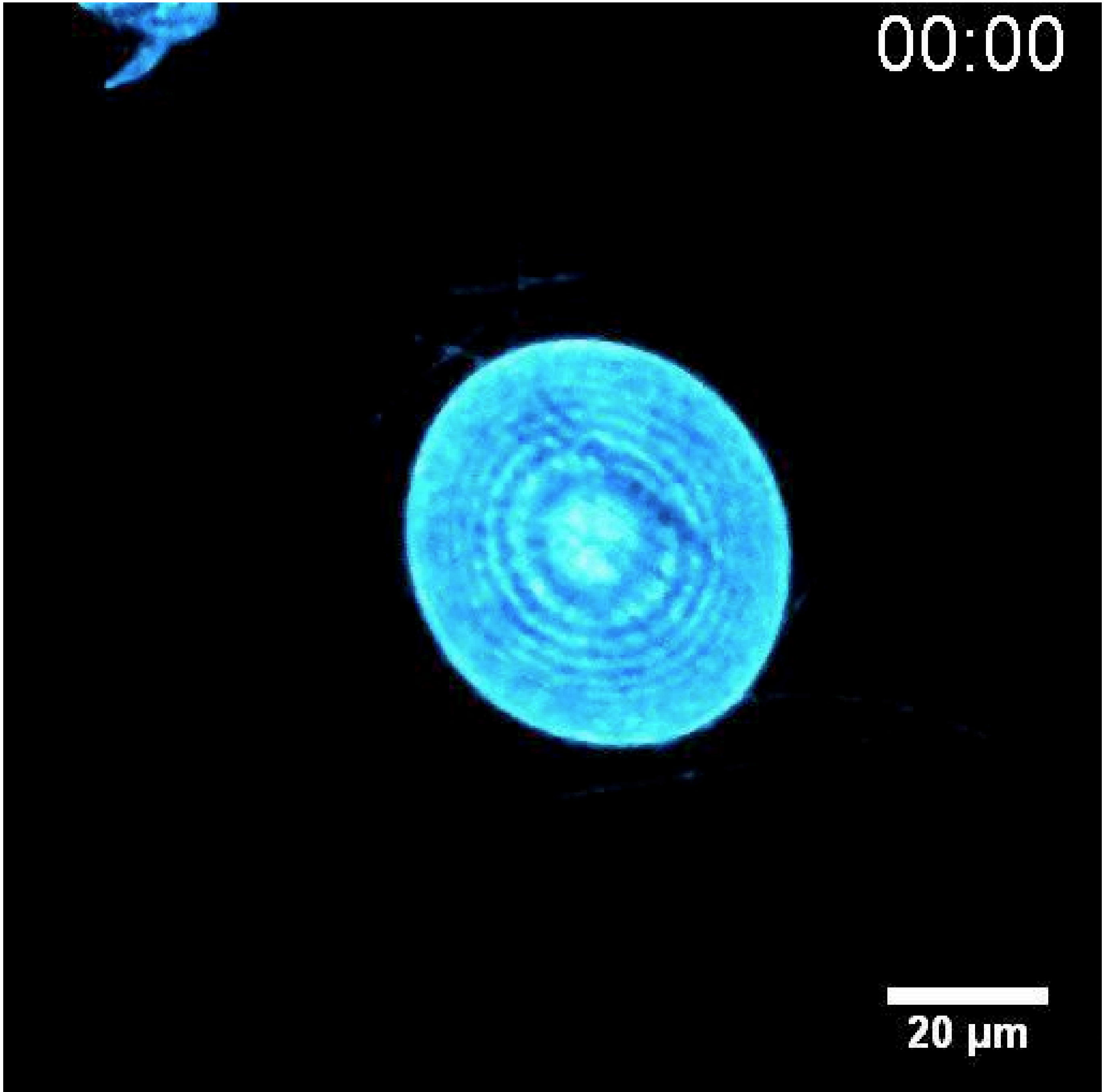
1. Extensile: in-plane anchoring



1. Extensile: protrusions form where disclination lines meet the surface

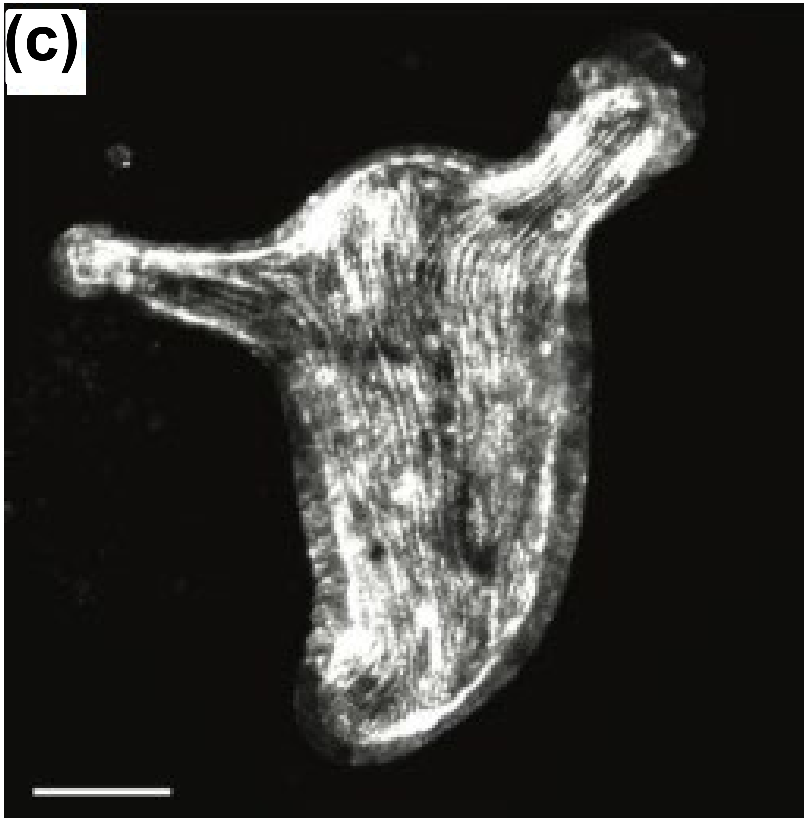


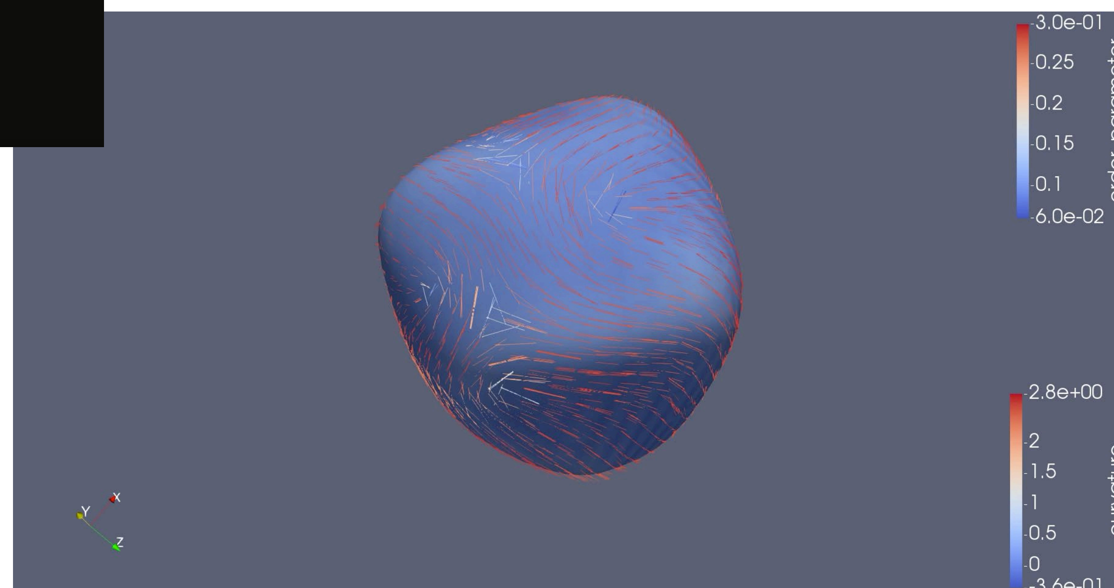
disclination lines tend to line up across protrusions



Keber et al
Science 2014

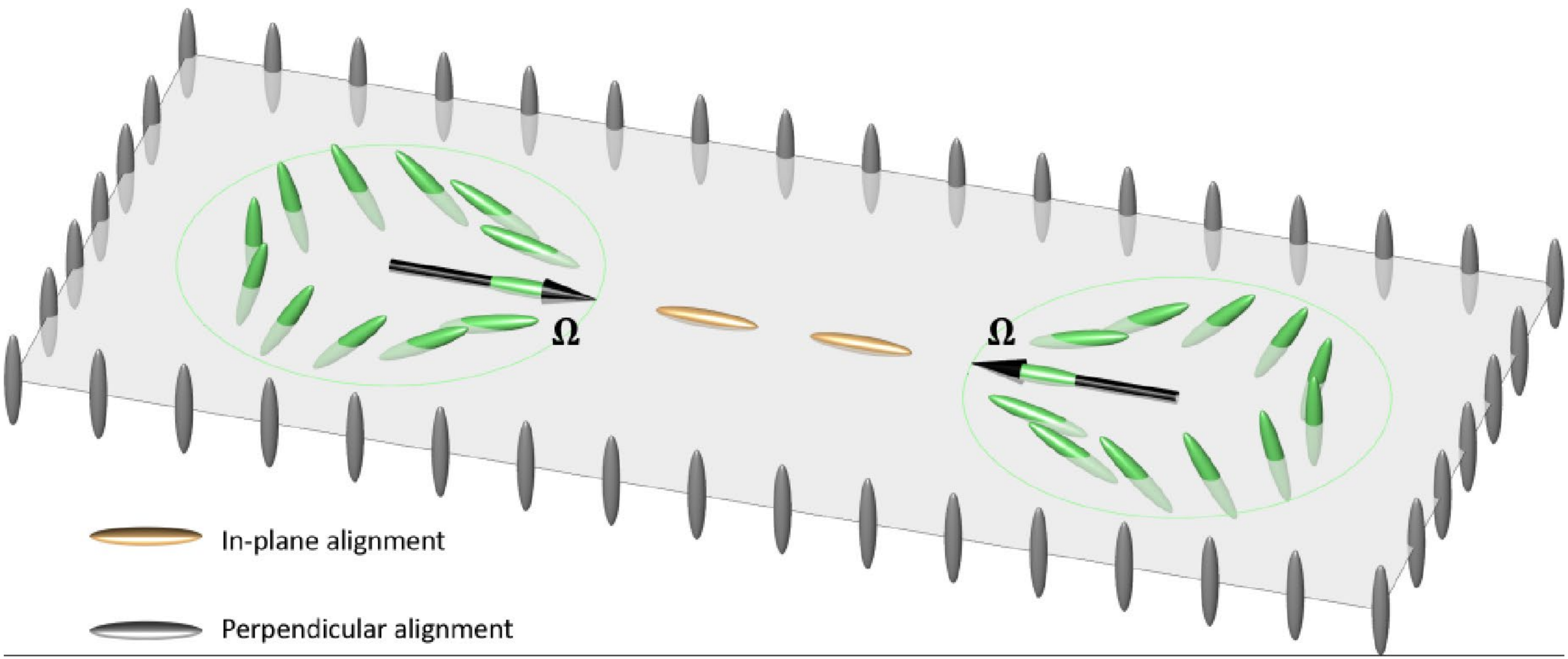
Hydra





Maroudas-Sacks et al
Nature Physics 17, 251 (2021)

2. Contractile: lines of in-plane alignment at surface



Movie 4:

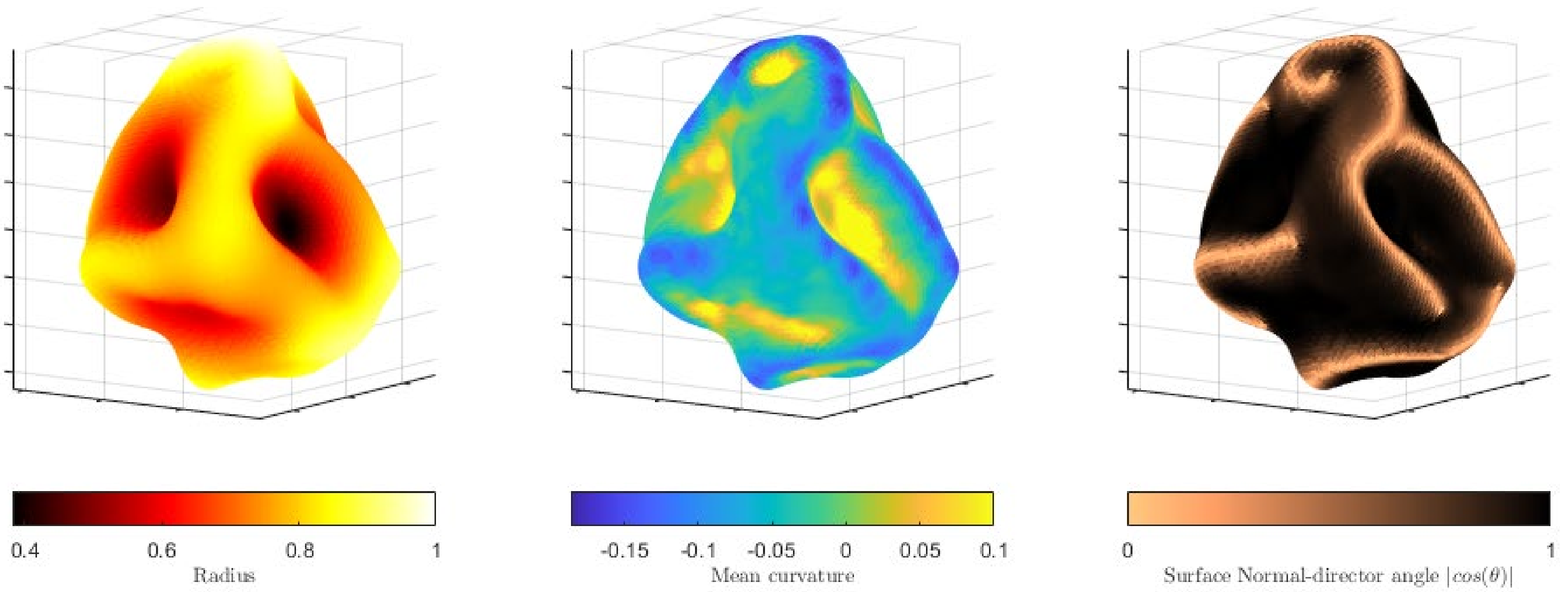
Active wrinkling and dimples in contractile drop

Left panel:	Disclination lines with colour code indicating twist angle
Middle panel:	Mean curvature of droplet surface
Right panel:	Angle between director and surface normal $\cos(\theta)$

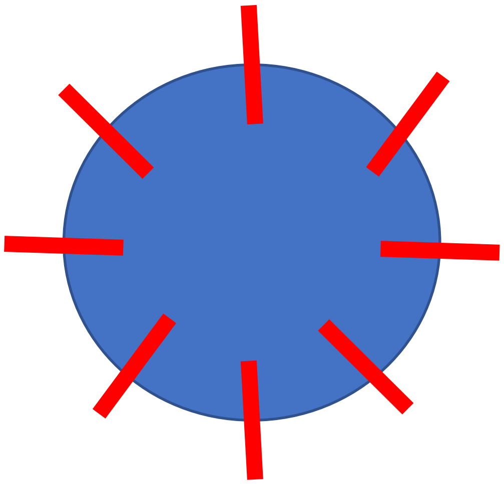
Simulation parameter (in LB-units):

$$K_{LC} = 0.2, K_{\varphi} = 0.2, A_{LC} = 1.5, \zeta = -0.02, R = 30$$

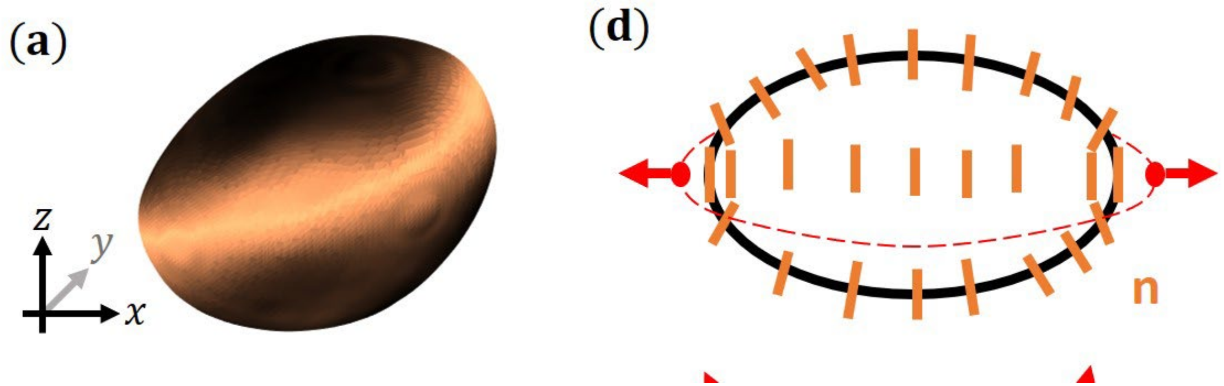
Contractile: surface wrinkles

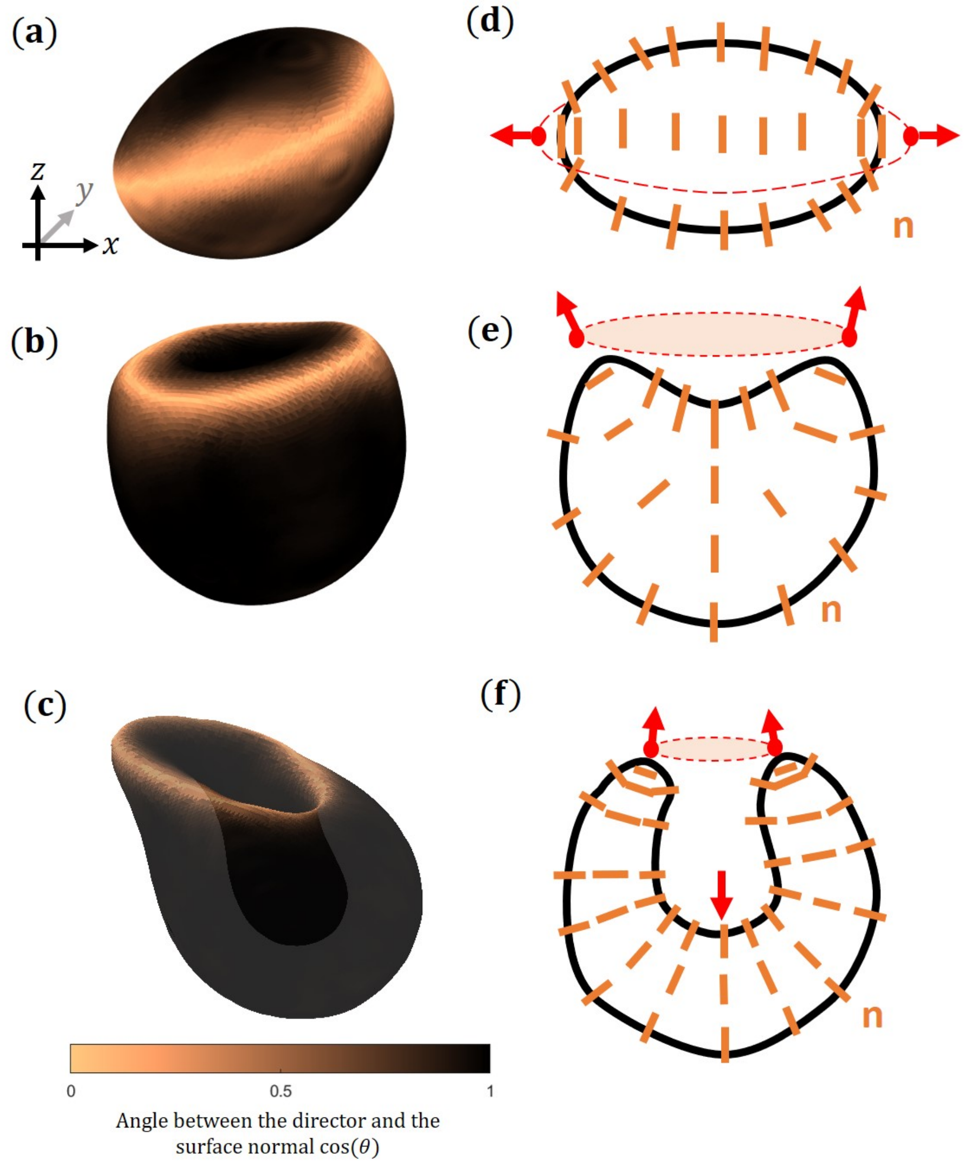


3. Contractile (small droplets):invagination



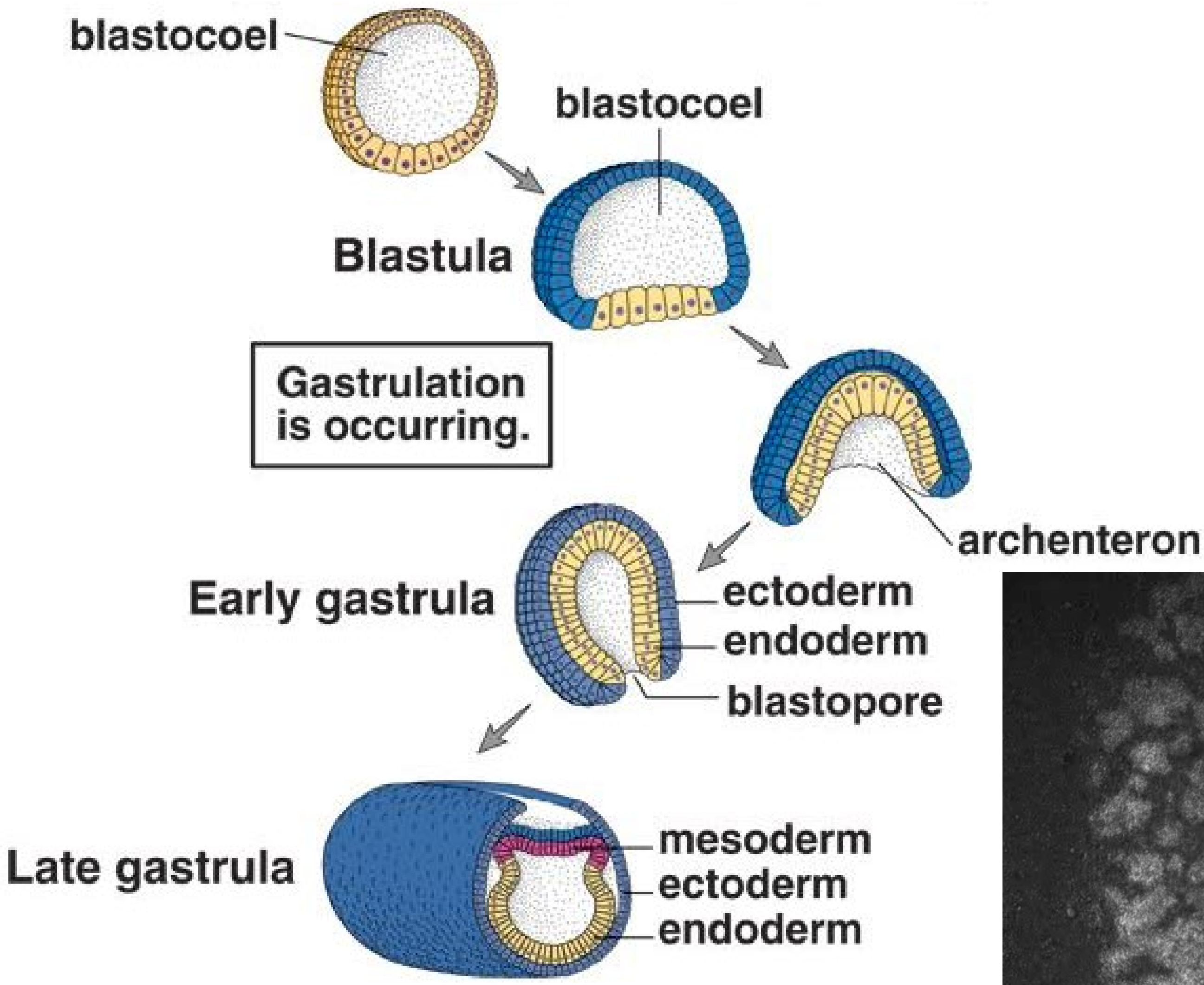
10



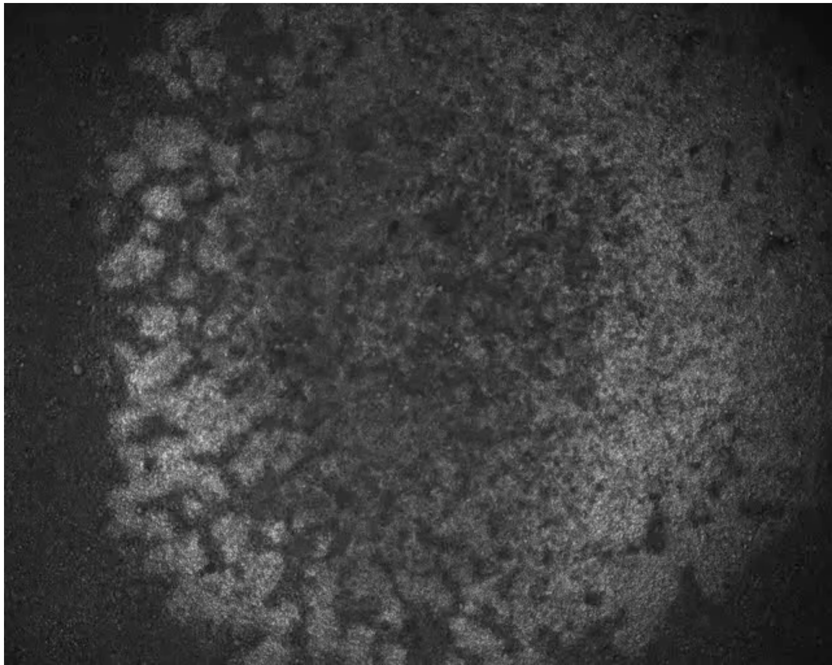


(a)
(b)
(c)
(d)
(e)
(f)
z
y
x
n
n
n
0
0.5
1
Angle between the director and the surface normal cos(θ)

Shape changes in early embryogenesis



C.J. Weijer, Developmental Biology 2005



1. Introduction

2. Active turbulence and active topological defects

3. Confining active systems

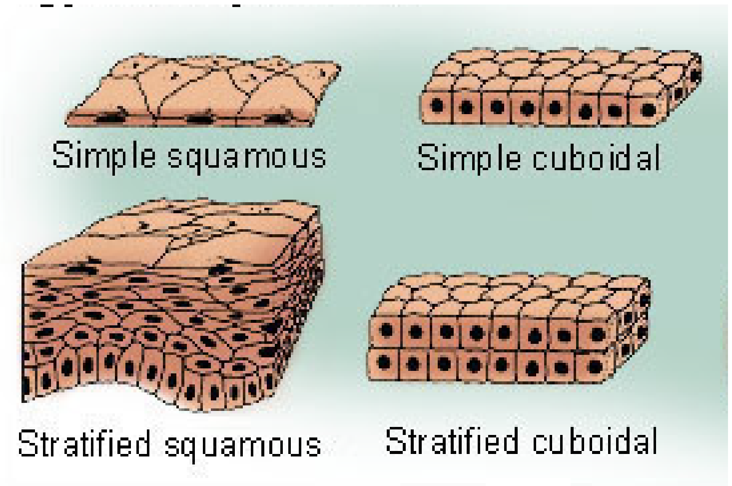
4. Mechanobiology

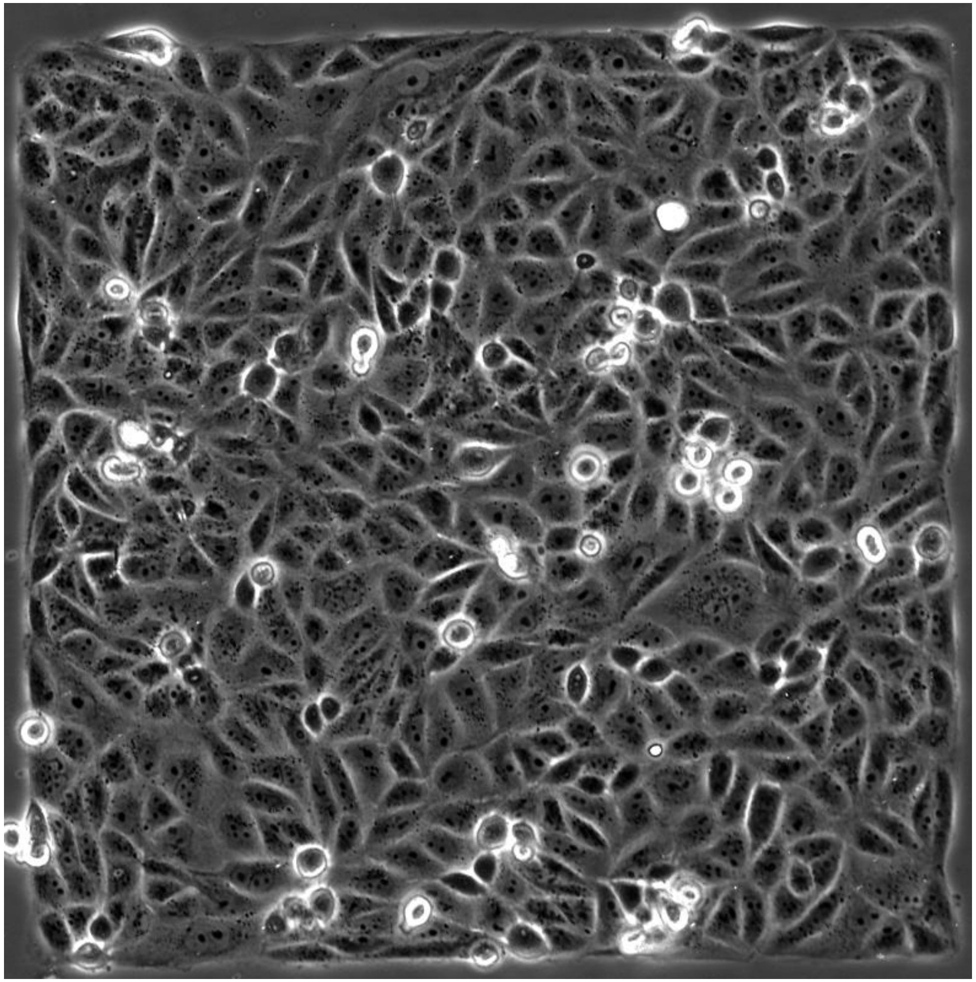
- 3D active matter and gastrulation

- confluent cell layers: active turbulence again

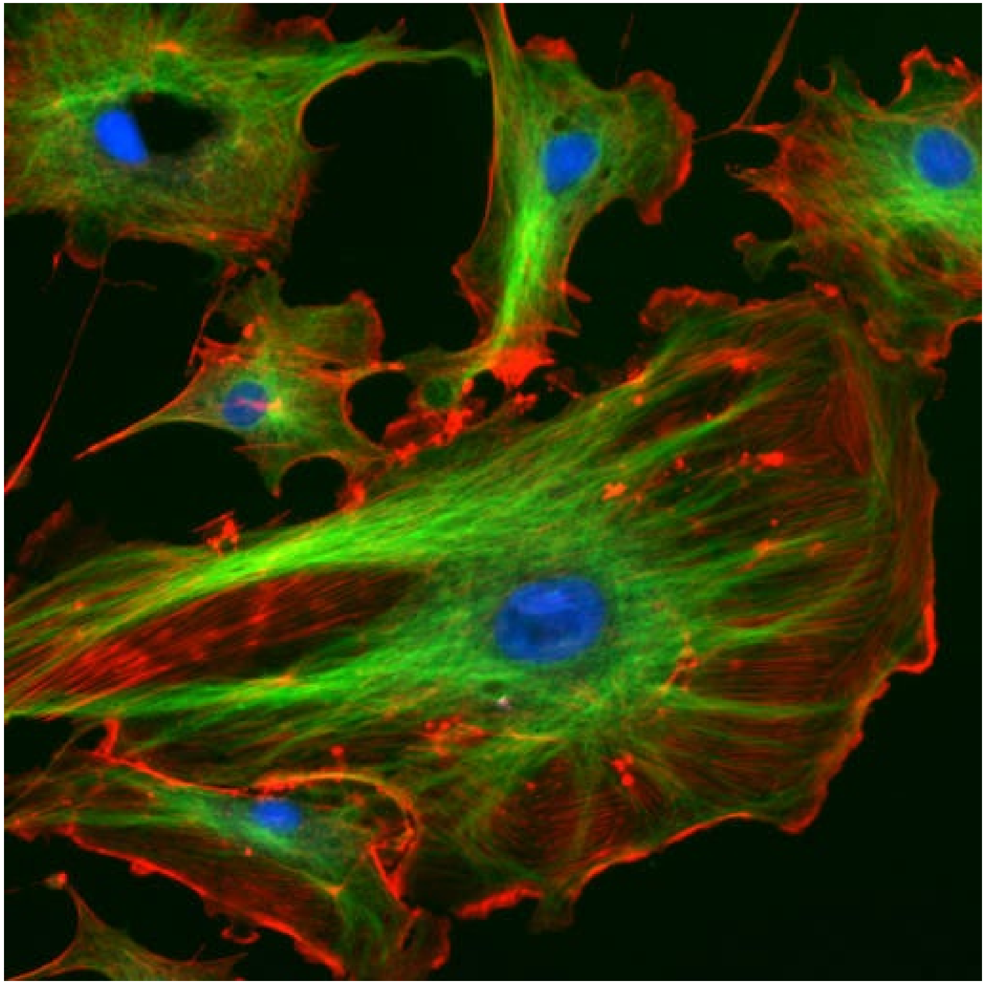
How do layers of cells move?

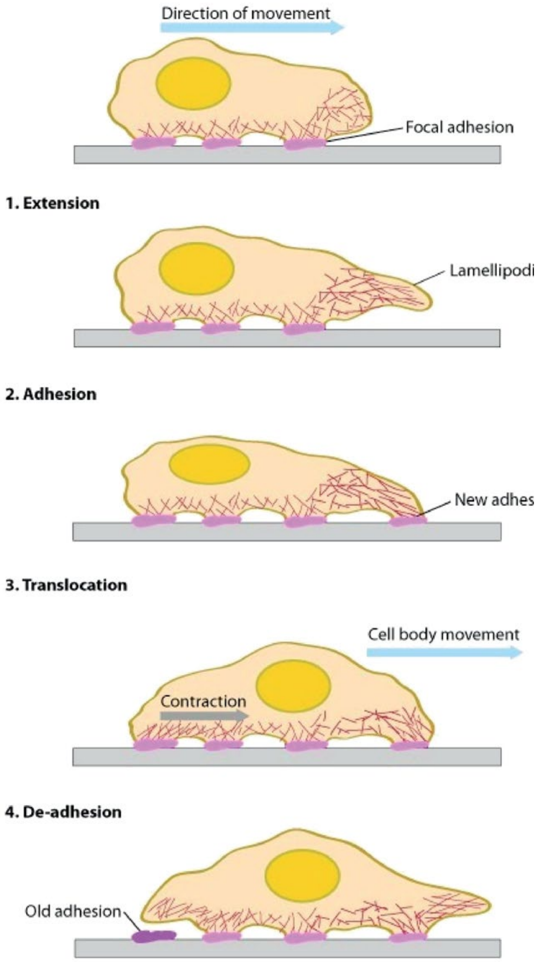
epithelial cells





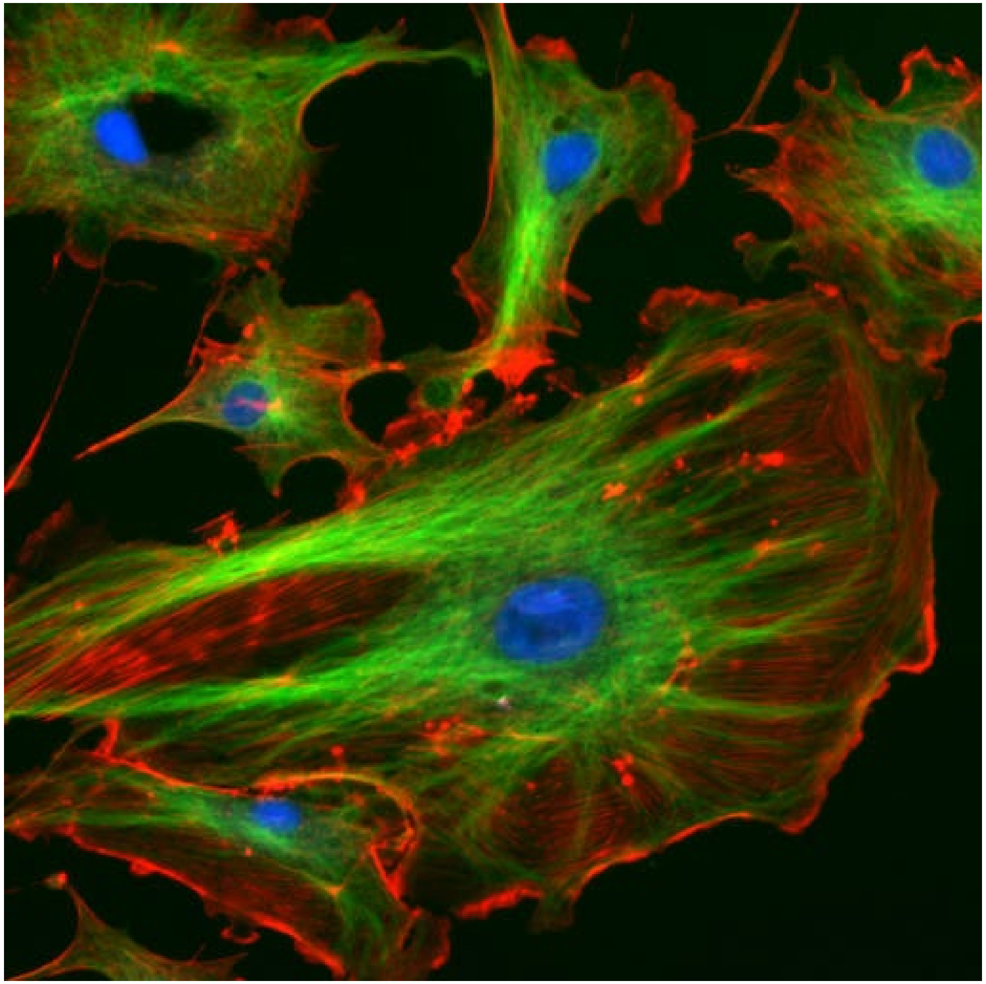
How do individual cells move?

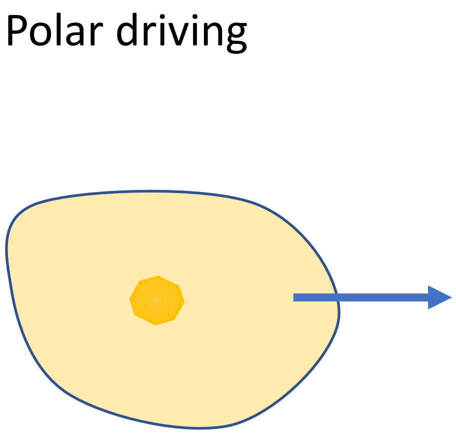


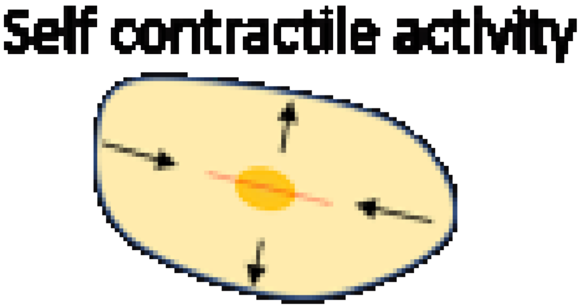


Ladoux and Nicholas Rep Prog Phys 2012

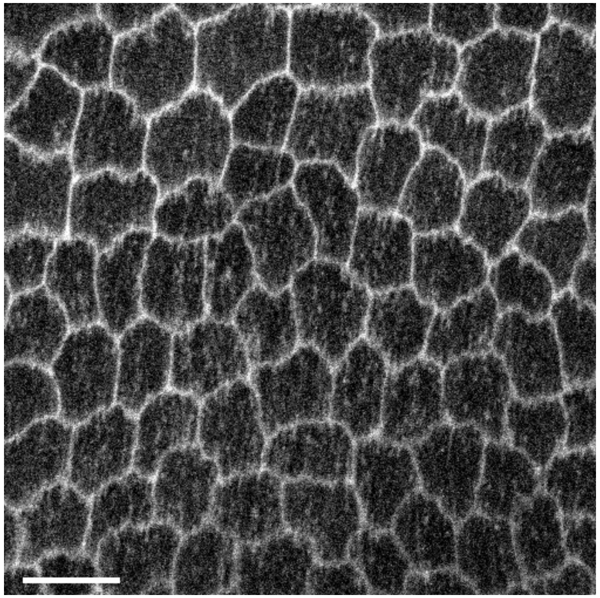
How do individual cells move?

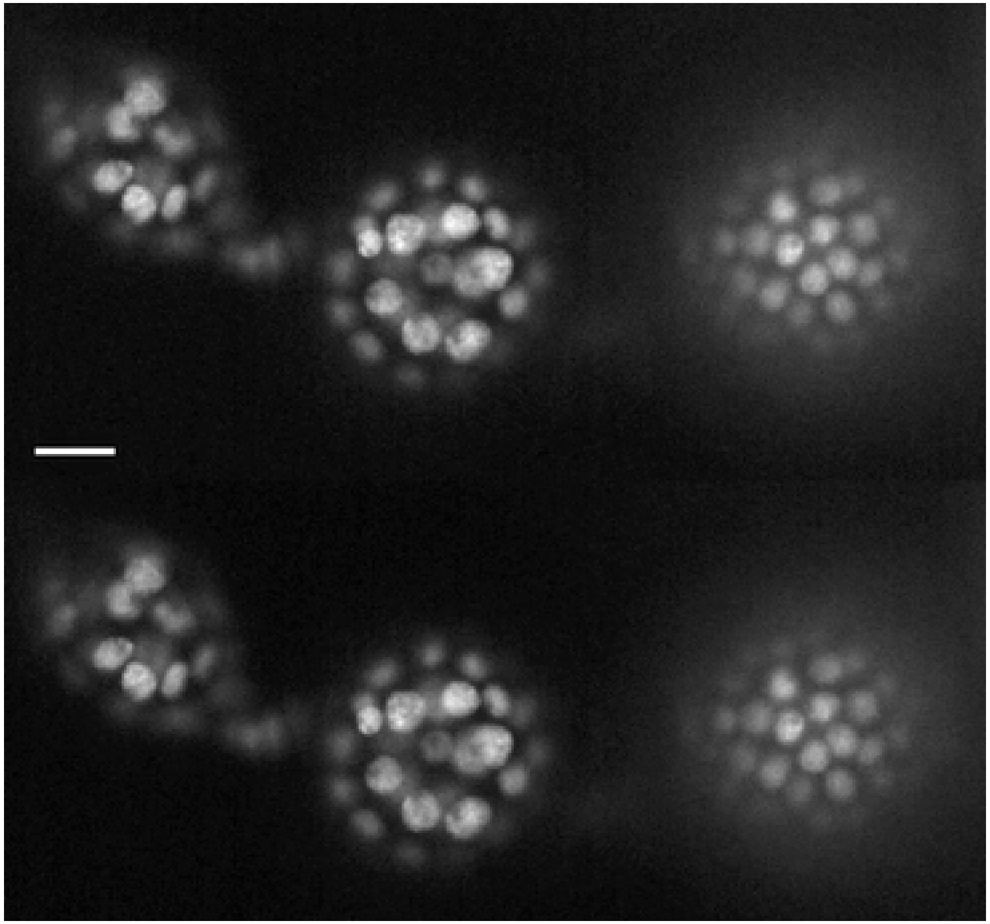






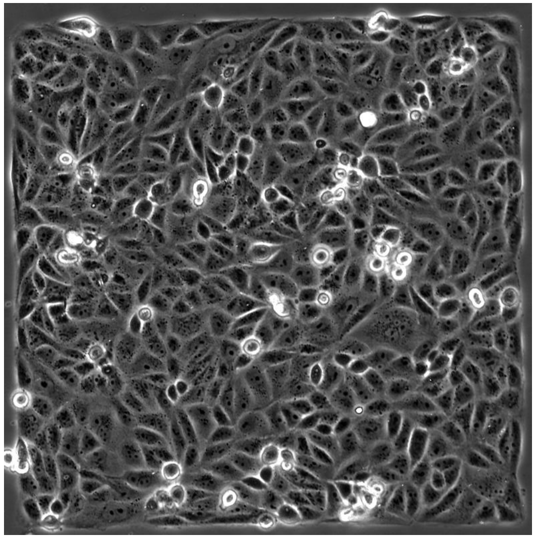
How do layers of cells move? Flocking

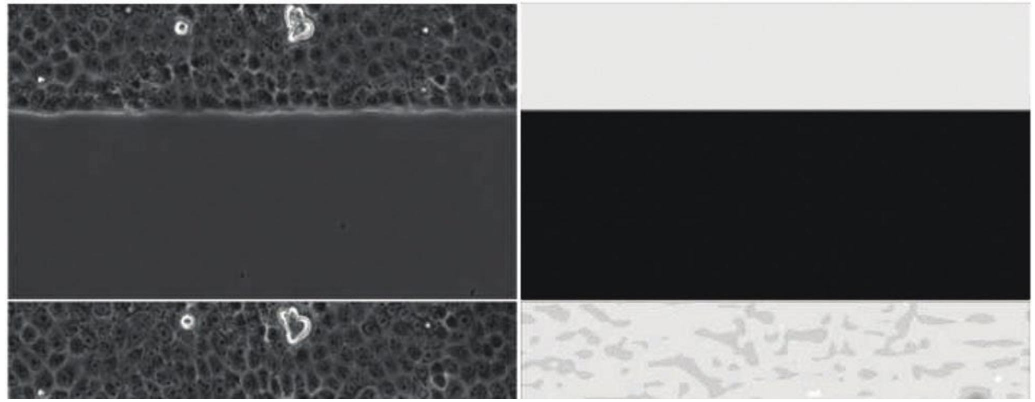




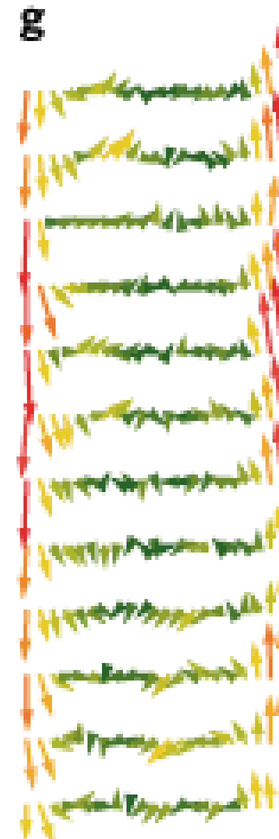
Cetera et al. Nature Comms. 5, 5511 (2014)

How do layers of cells move? Active turbulence?

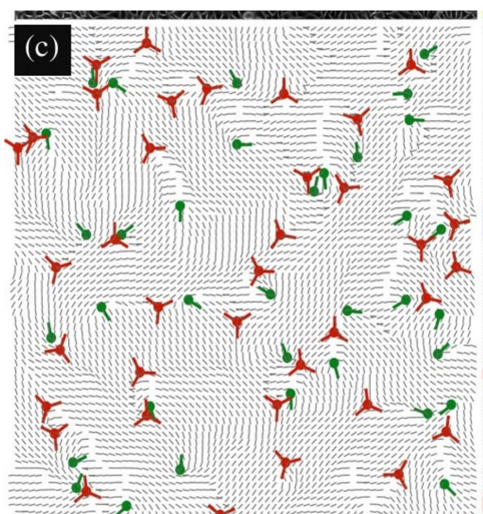




velocity fields reminiscent
of active turbulence

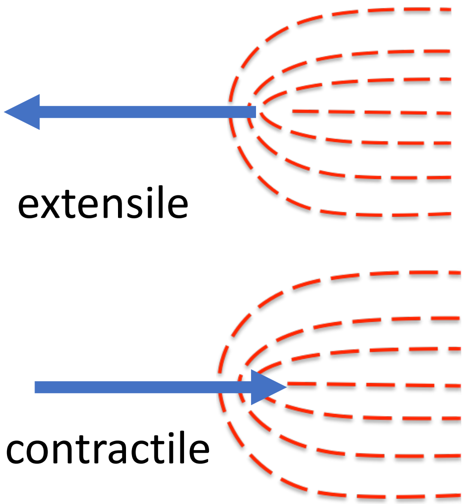


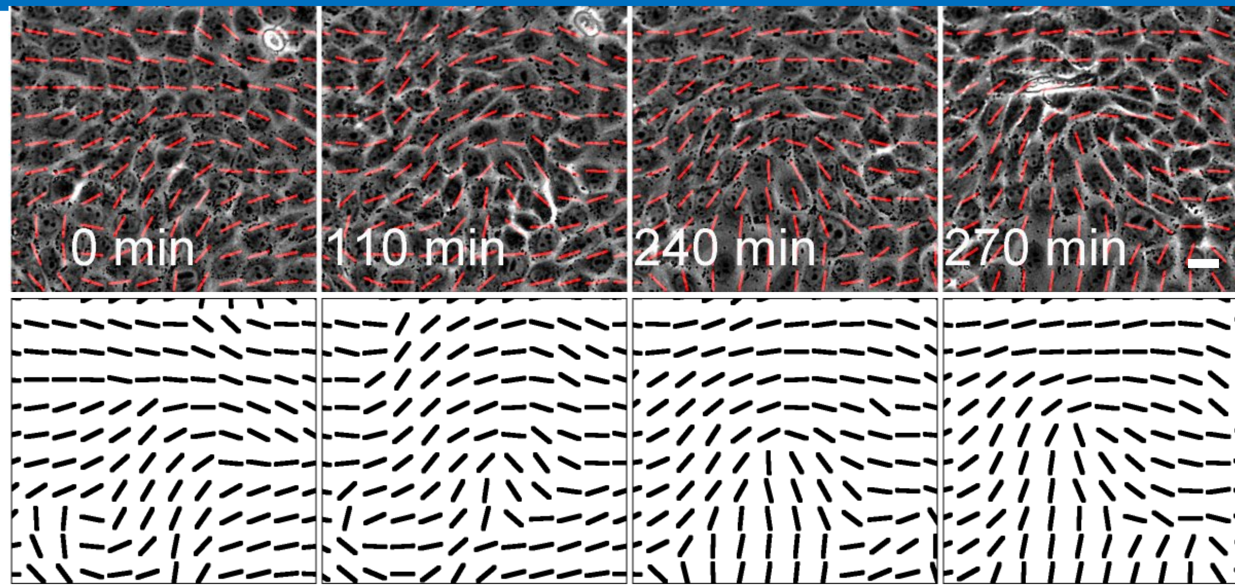
shear flow in
confined channels
(Duclos et al Nat Phys 2018)



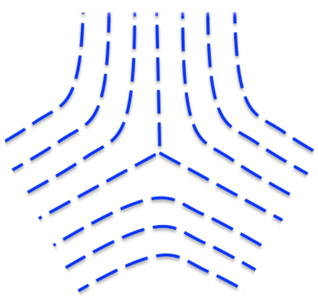
topological defects in human
bronchial epithelial cells
Blanch-Mercader et al PRL 2018

Active defects



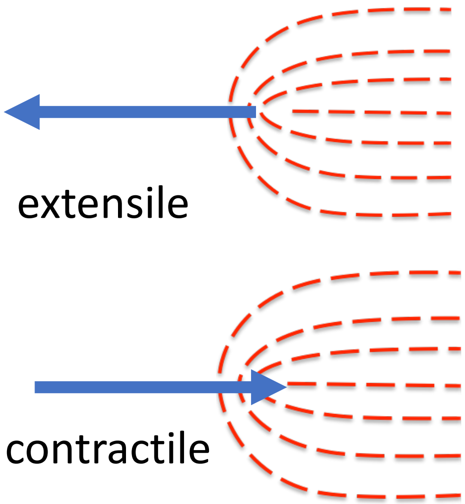


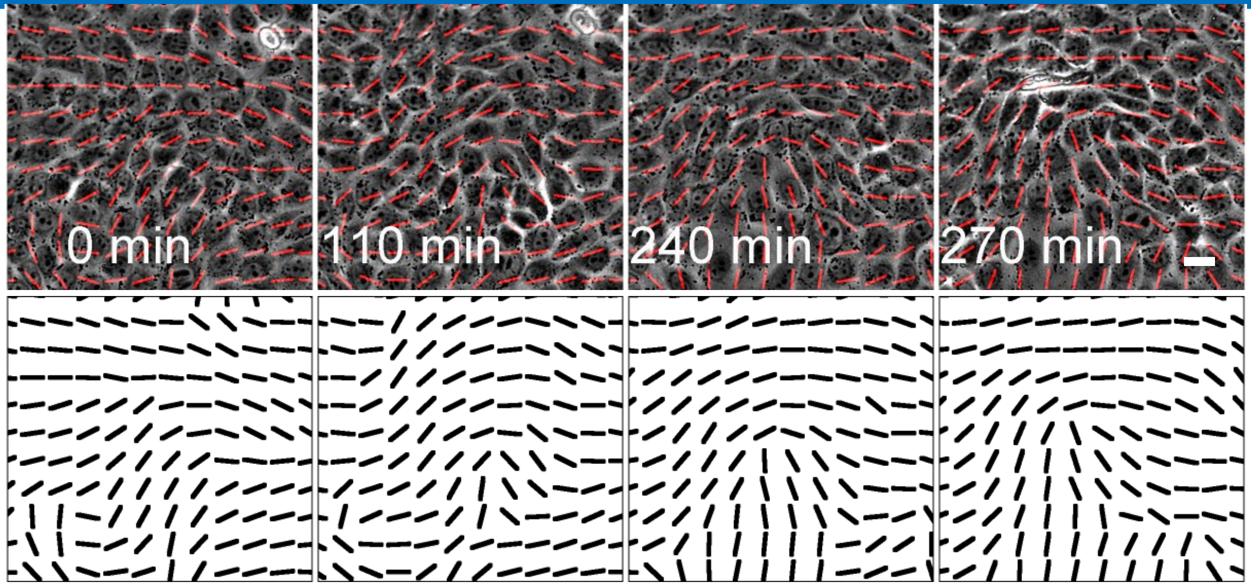
+1/2



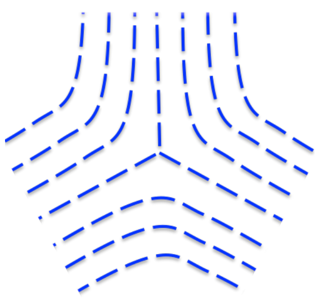
-1/2

Active defects



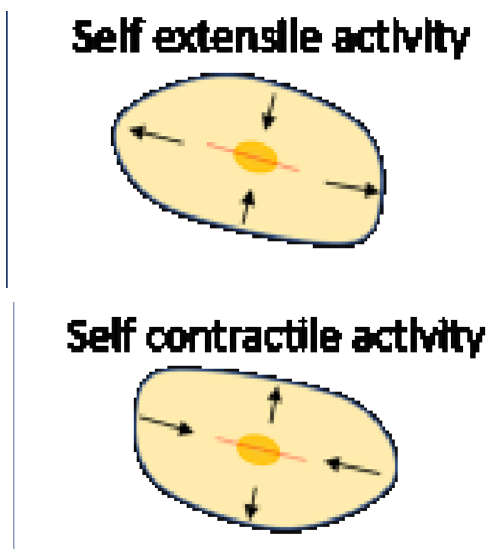


+1/2



-1/2

Need elongated cells ??



Summary

How do confluent cell layers move?

Flocking

Liquid with active nematic turbulence-like dynamics

Jamming

Questions

How do we model this?

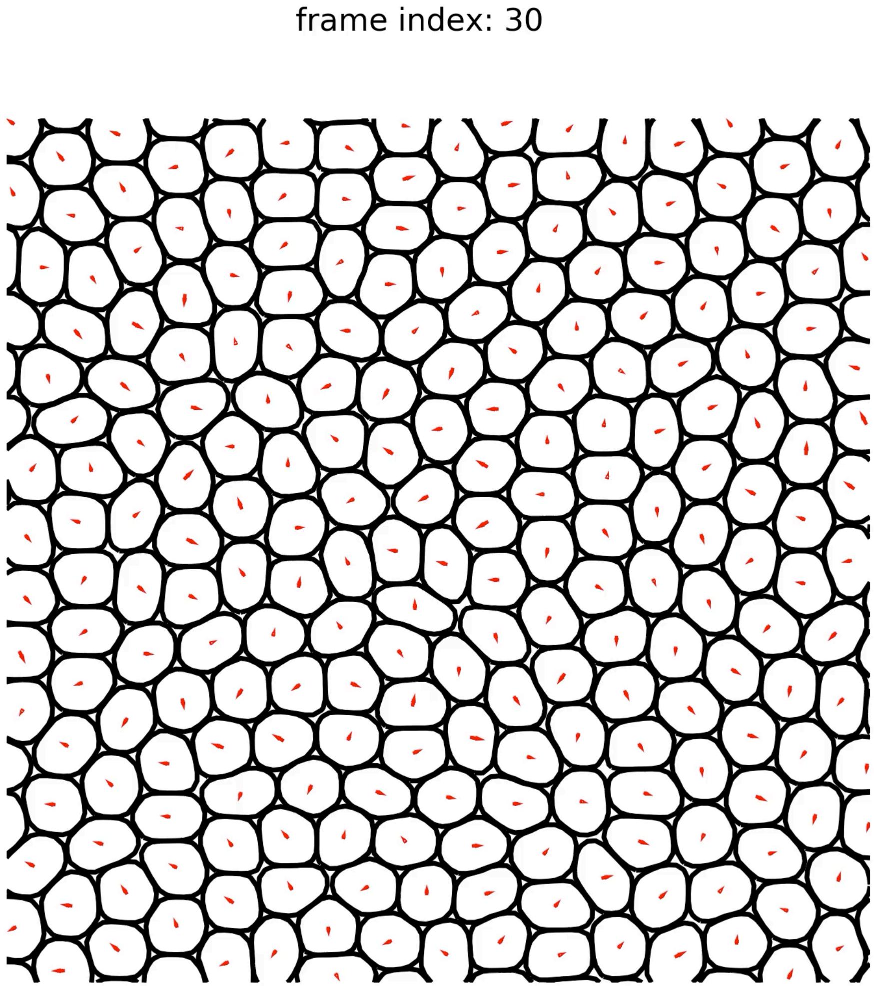
What are the physical interactions behind the dynamics of confluent cell layers?

What drives the crossover between the different states?

Are cell layers extensile or contractile … or both?

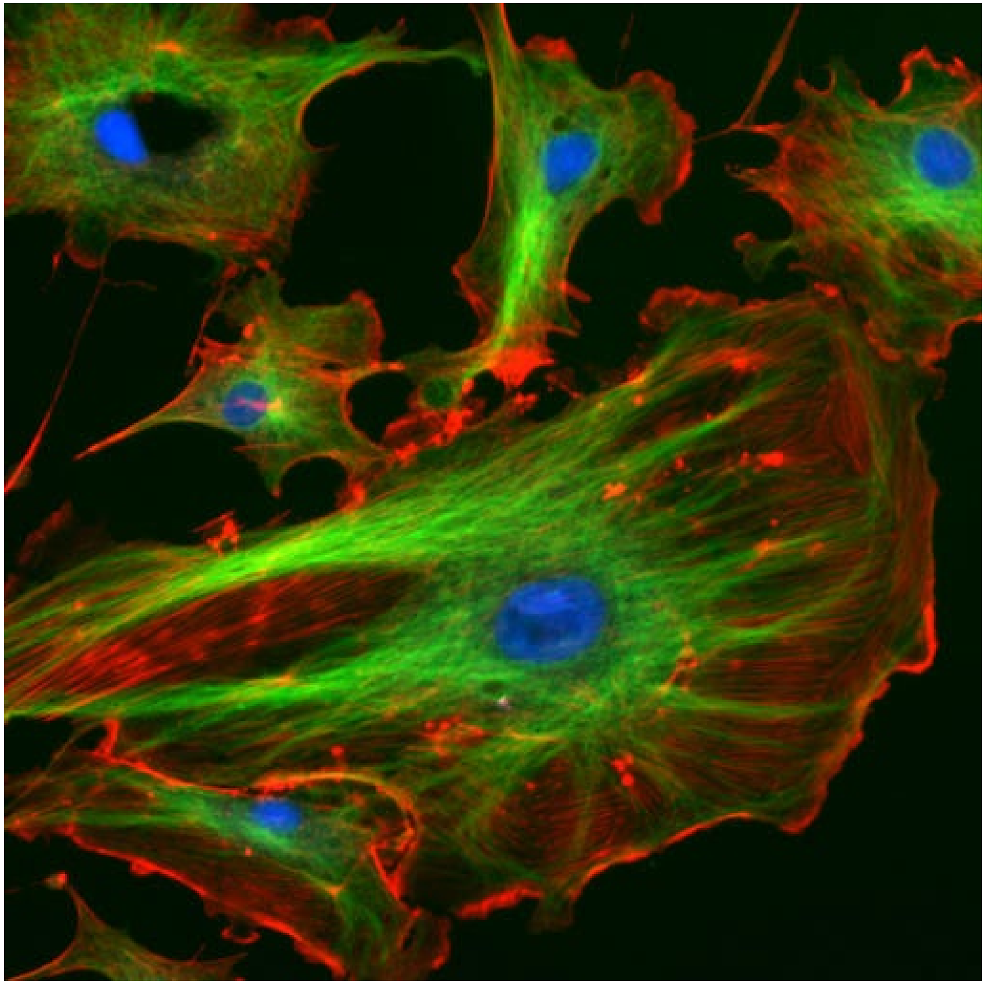
What is the difference between deformable active nematics and those comprised of rods?

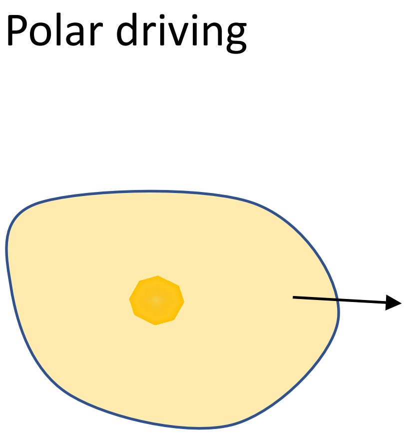
Phase field model

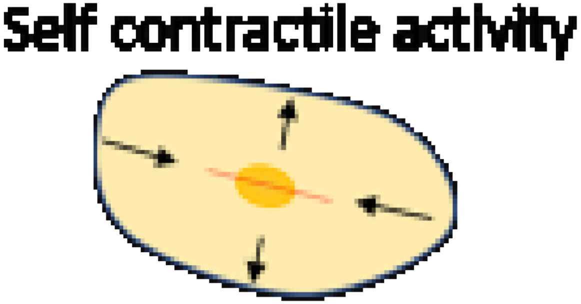


Grant, Aranson

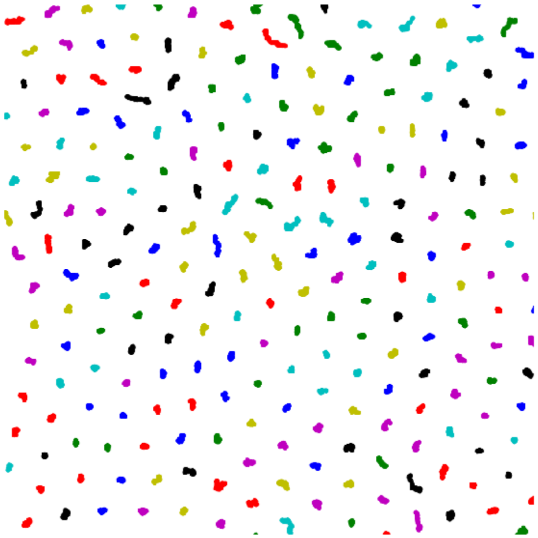
How do individual cells move?



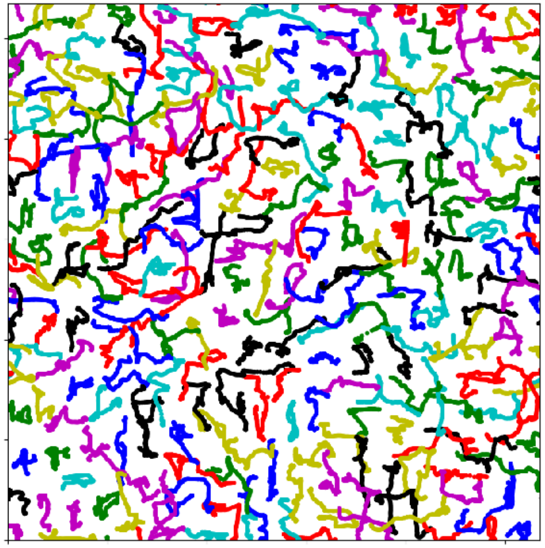




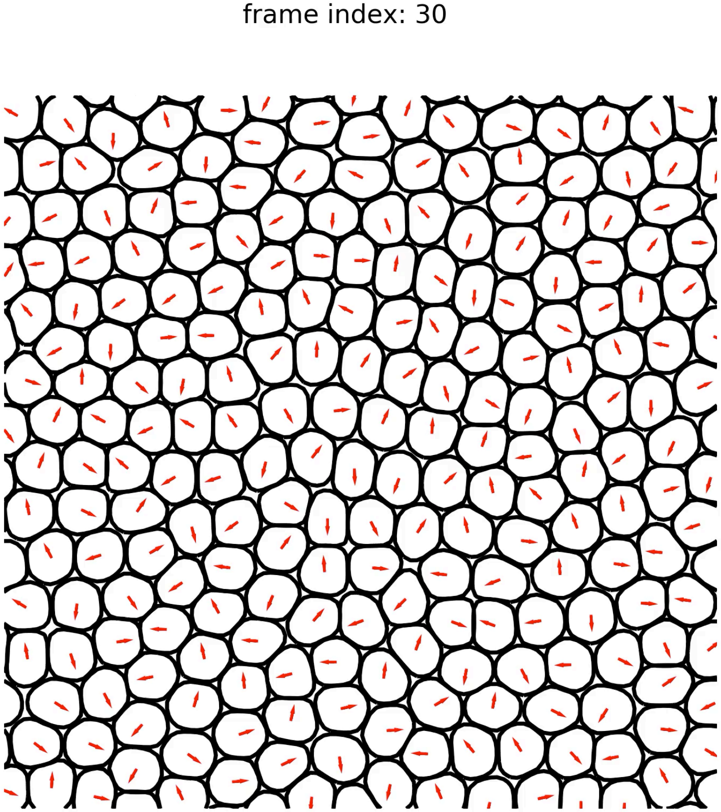
Polar forcing: results



jammed state



liquid



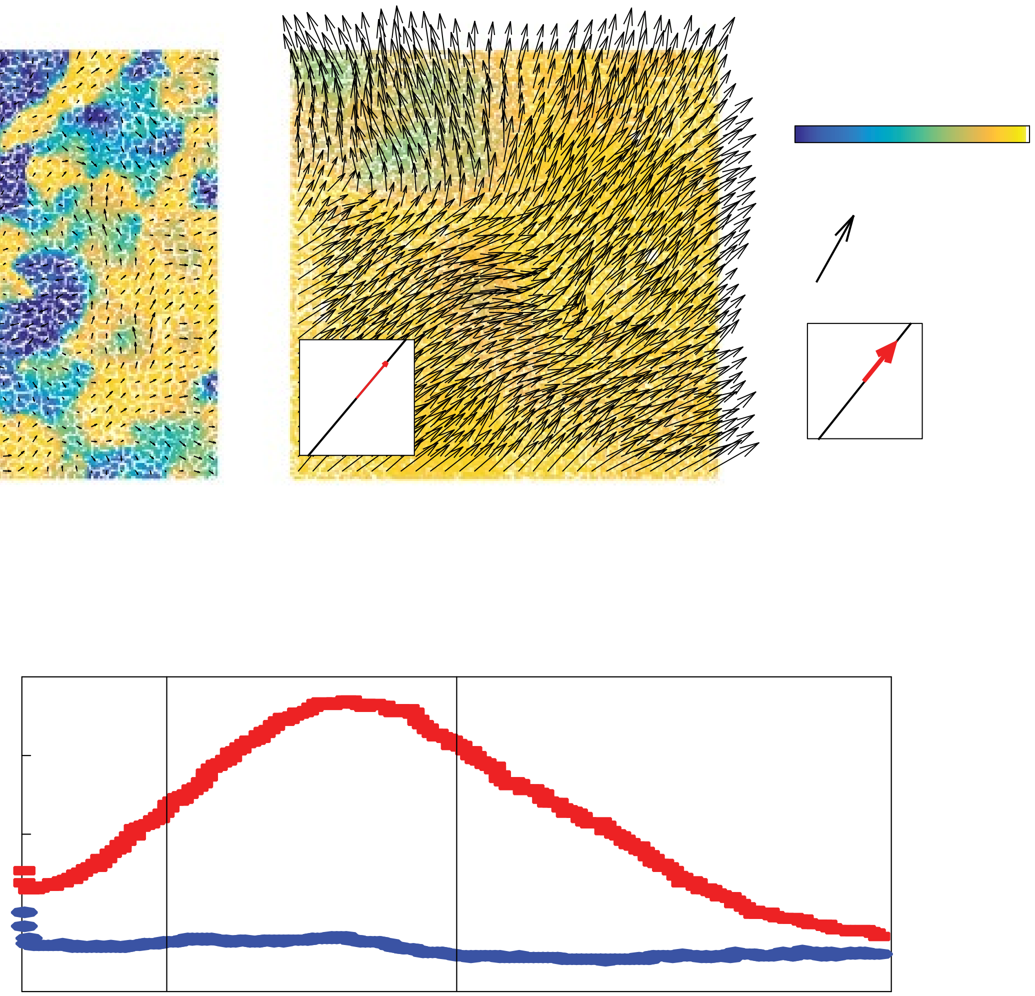
flocking if the polarisation aligns with the velocity

Contact inhibition of locomotion (Abercrombie, 1953)

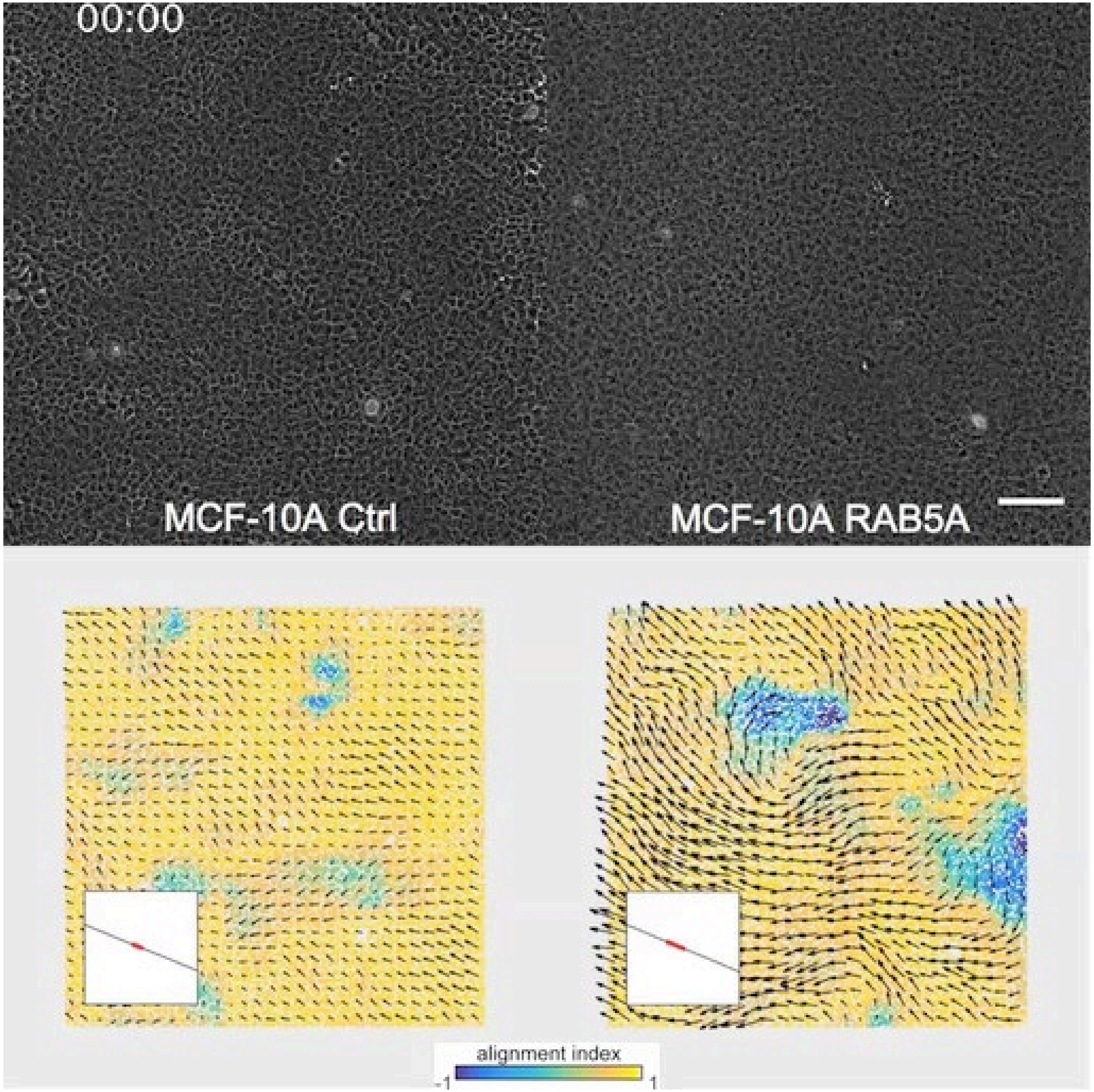
Cells within a colony are much less likely to form lamellopodia

Strength of the polarization decreases with increasing cell-cell overlap

Malinverno et al Nature Materials 16 (2017)



Malinverno et al Nature Materials 16 (2017)



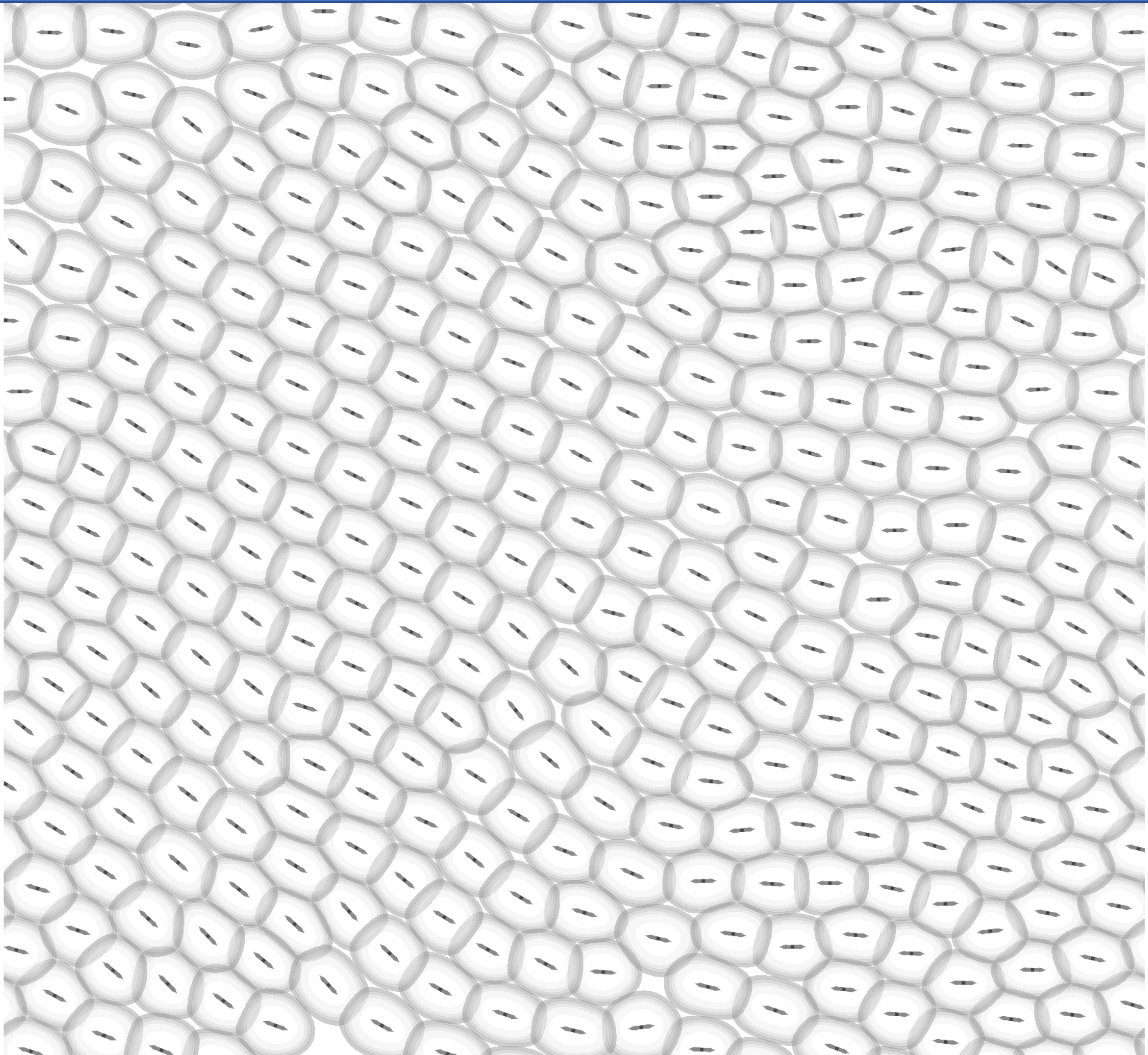
Contact inhibition of locomotion turns off polar forces …

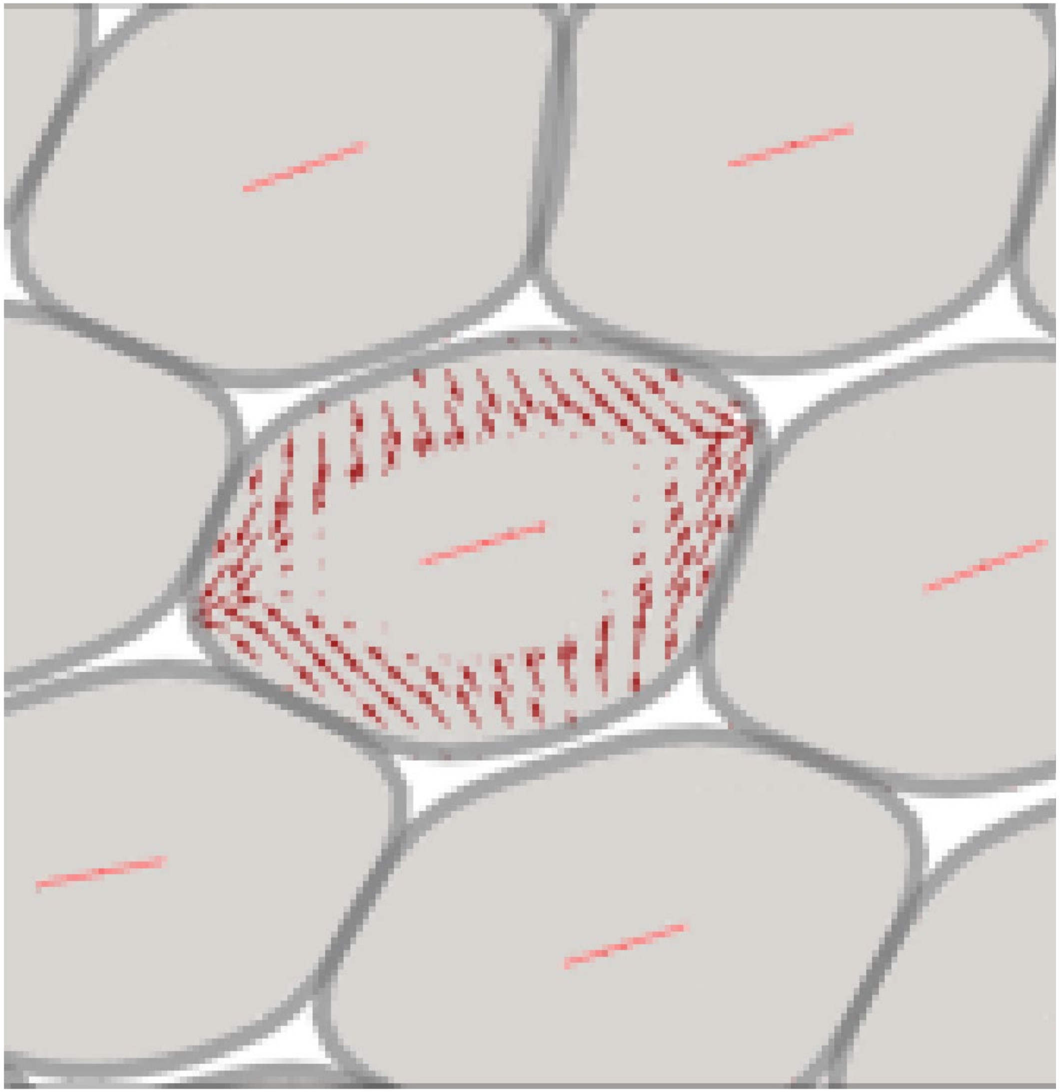
so to model the dynamics of a cell layer we need:

active, contractile inter-cellular interactions

$$\boxed{\Pi_{ij}^{active} = -\zeta Q_{ij}}$$

Active, contractile, intercellular forces => active turbulence



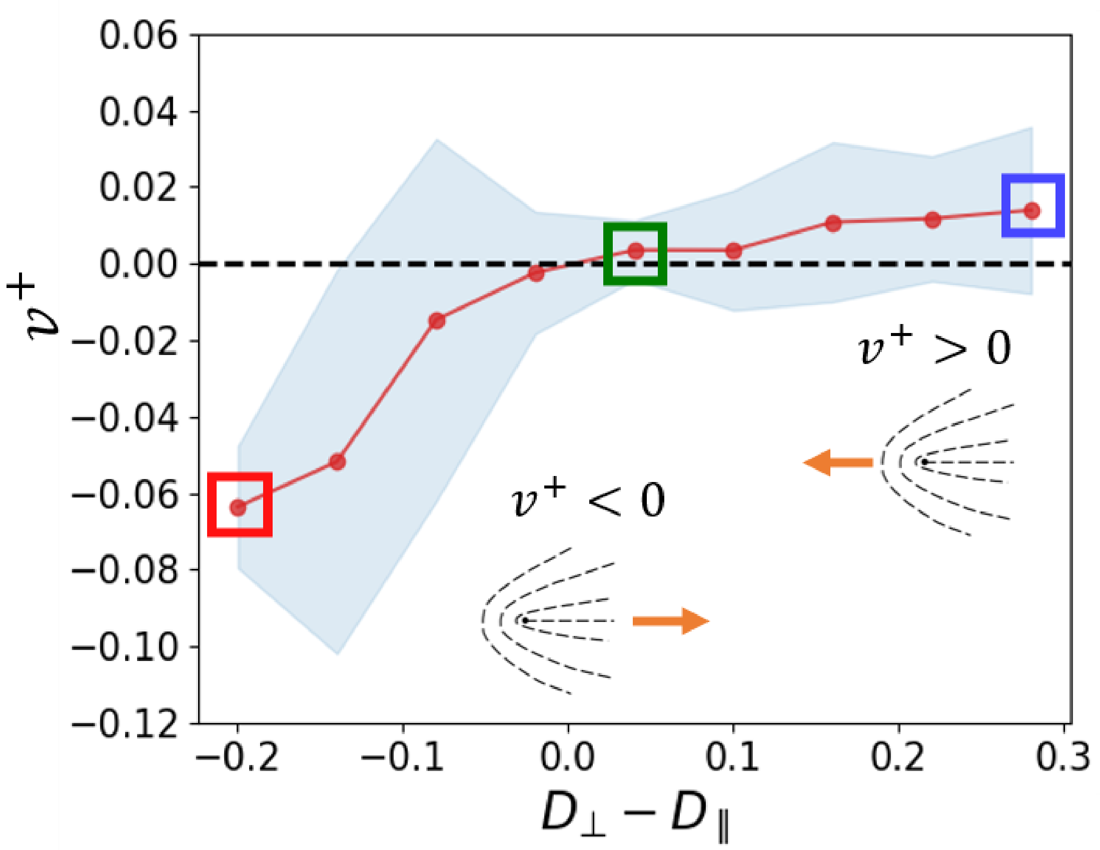


cell extended by contractile forces from its neighbours

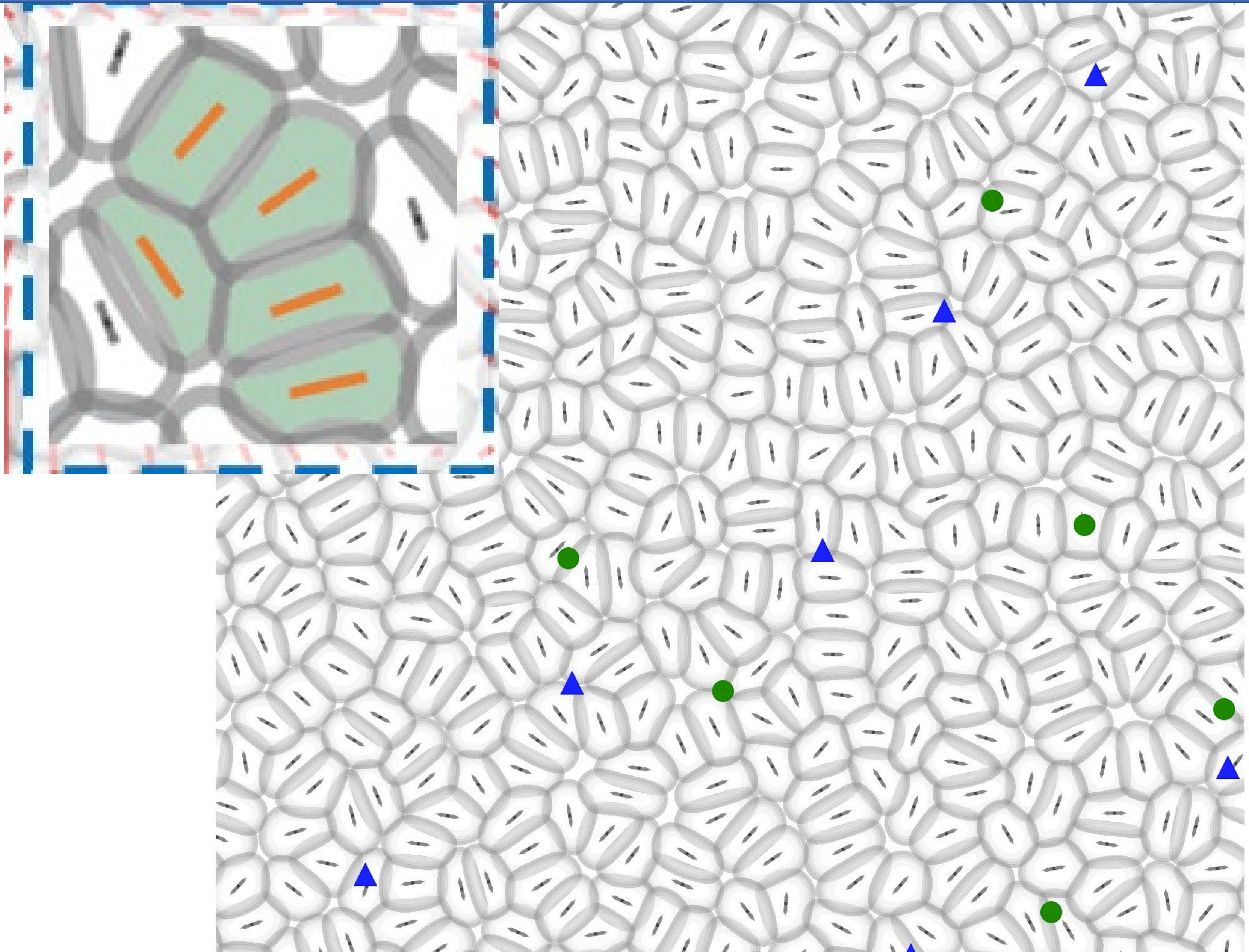
Fluctuations: change forces from contractile to extensile

Anisotropic shape fluctuations – spontaneous noise that changes the cell shape

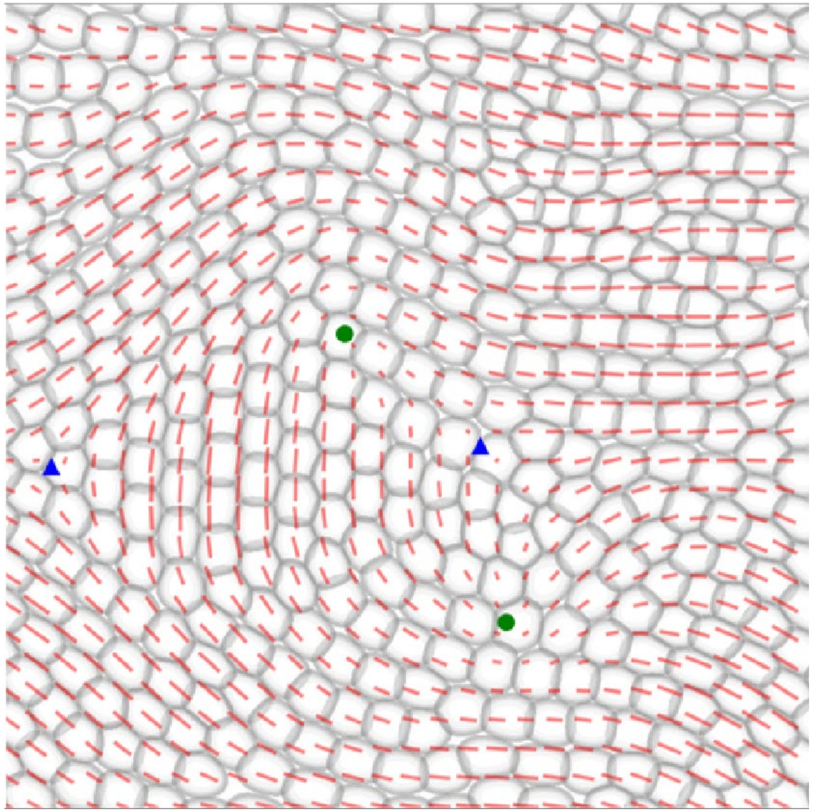
Different in magnitude along the long and short cell axes



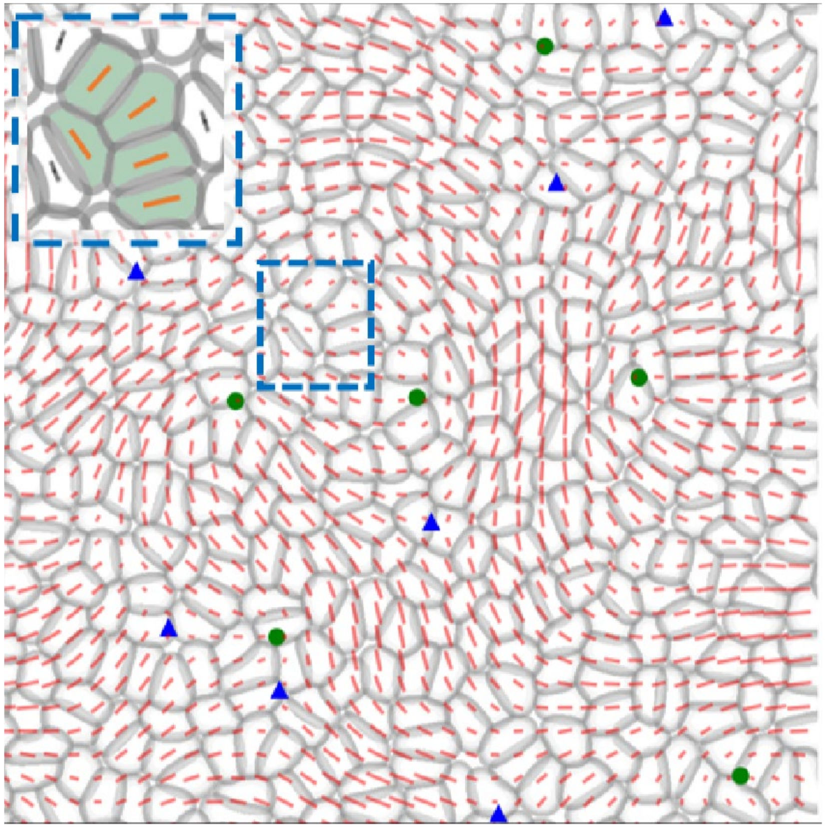
Active, extensile, intercellular forces



Active, extensile, intercellular forces



contractile



extensile

How can we construct a minimal model of a confluent cell layer?

Active, contractile, inter-cellular interactions

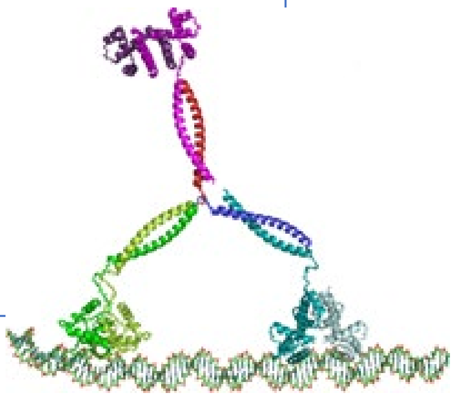
+

Shape fluctuations

lead to the active nematic behaviour seen in many monolayers – active turbulence + motile defects

Next step: experiments

[Zhang, Yeomans arXiv:2111.14401]()



1. Introduction

2. Active turbulence and active topological defects

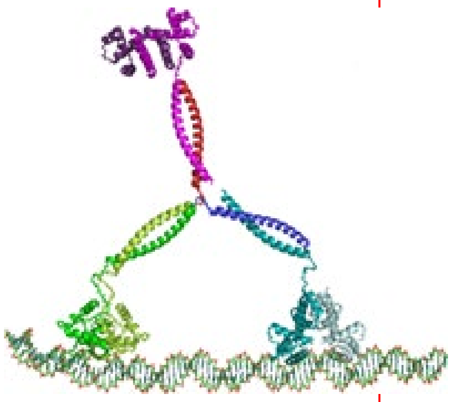
- Background 1: Swimming at low Re
- Background 2: nematic liquid crystals
- Active stress
- Active topological defects
- The hare and the tortoise

3. Confining active systems

- The sequence of dynamical states
- Topological defects and the dancing state
- Transition to active turbulence in a channel

4. Mechanobiology

- 3D active matter and gastrulation
- confluent cell layers: active turbulence again



Active turbulence and motile topological defects

- Active turbulence
- Self propelled topological defects

review: Doostmohammadi et al Nature Comms. **9** 3246 (2018)

Shape changes, and into 3D

- from 2D to 3D
- the morphologies of active droplets

Ruske and Yeomans, PRX **11** 021001 (2021)
Nejad and Yeomans, PRL **128**, 048001 (2022)

Modelling confluent cell monolayers

- active, inter-cellular interactions

Zhang and Yeomans, arXiv:2111.14401