Active Nematics 2

Julia M Yeomans
University of Oxford

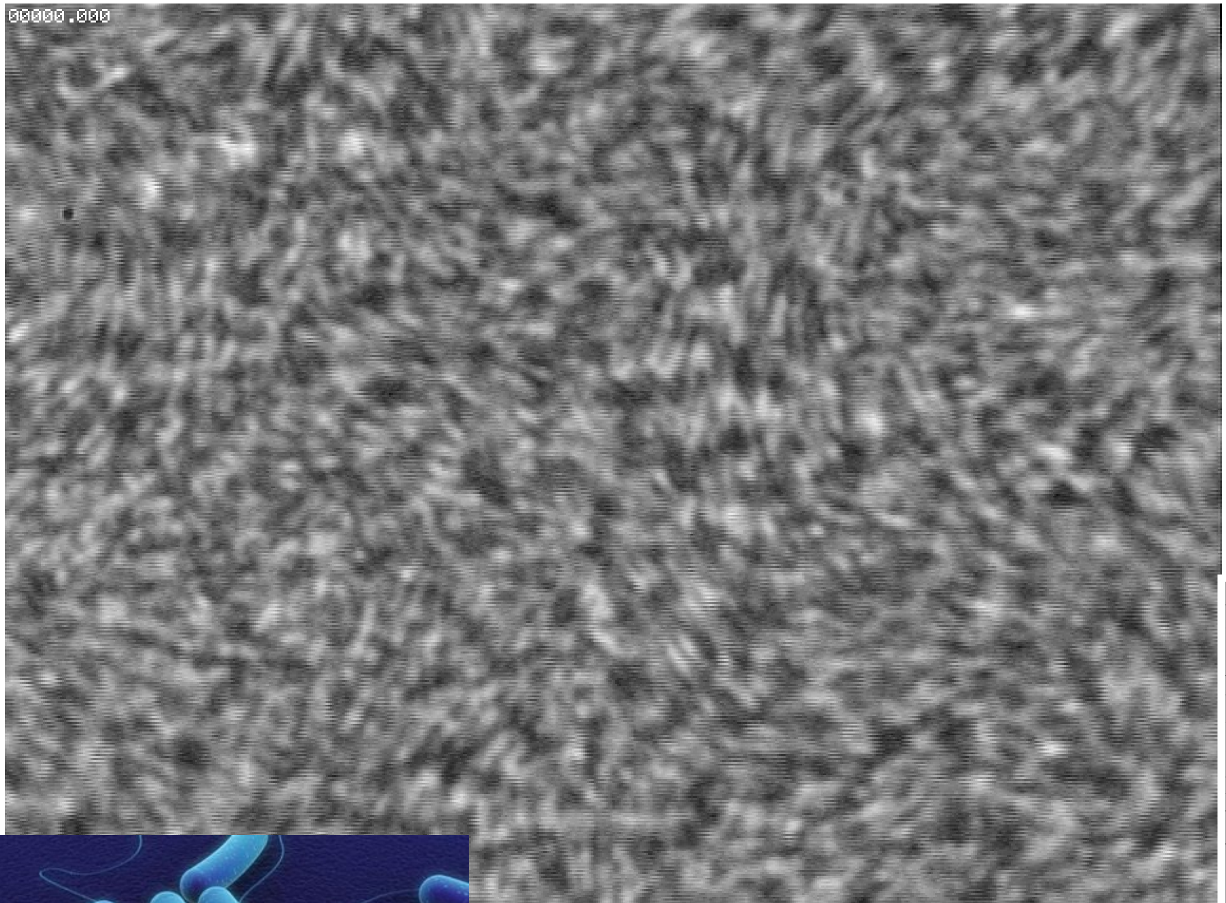
1. Introduction

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

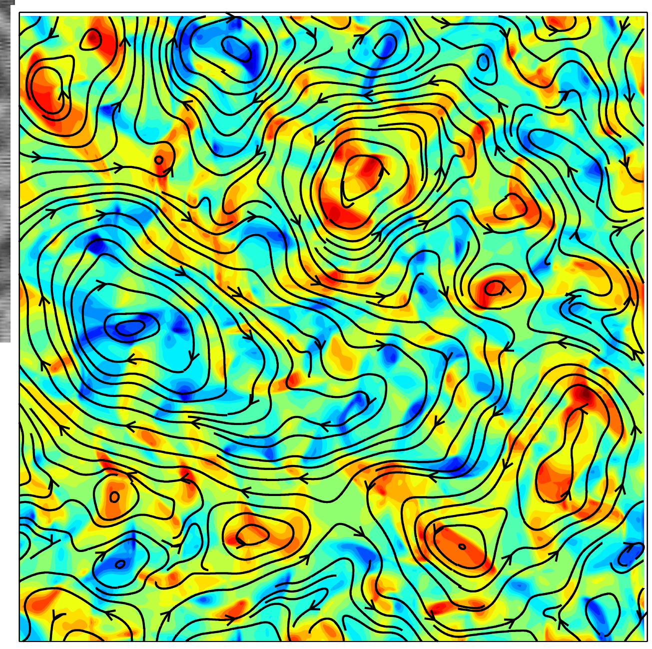
3. Confined systems 4. 3D 5. mechanobiology

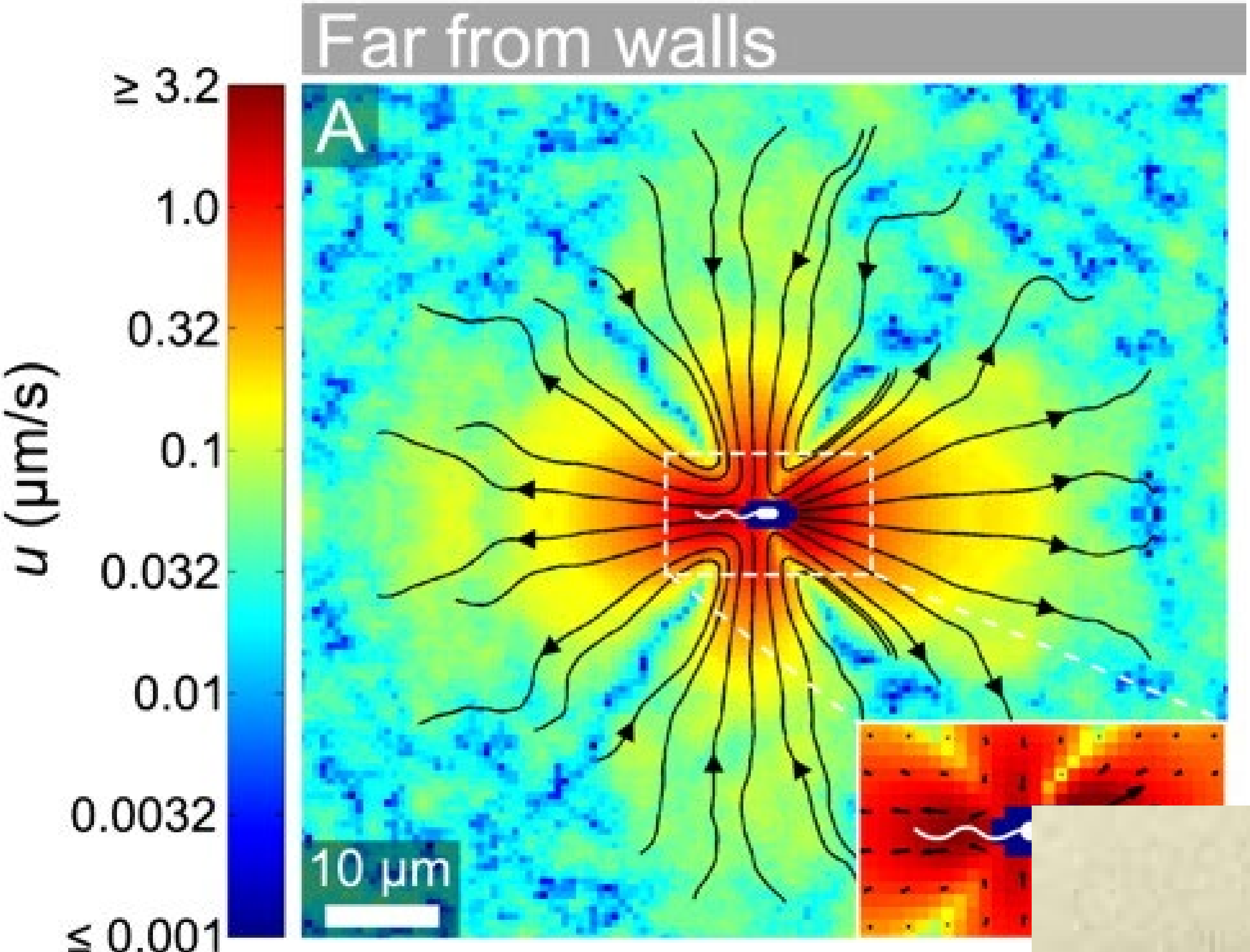
Active turbulence



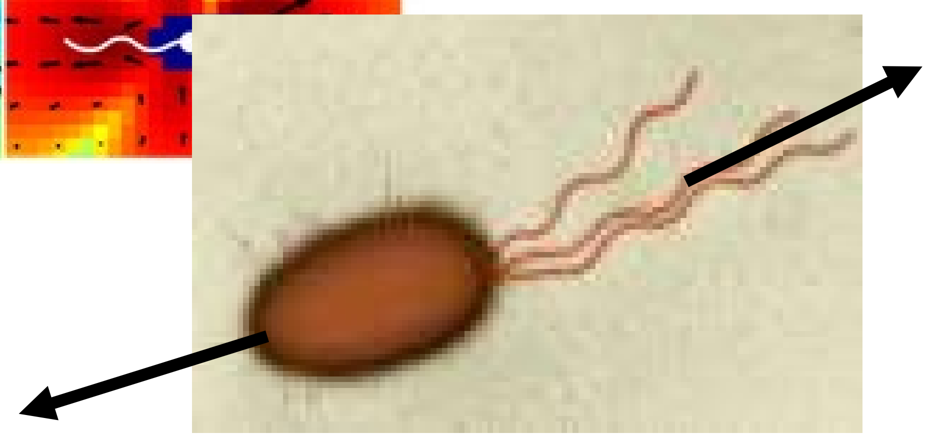
Dense suspension of microswimmers

Vorticity field





NB nematic symmetry



E-coli

Goldstein group, Cambridge

Continuum equations of liquid crystal hydrodynamics

$$(\partial_t + u_k\partial_k)Q_{ij} - S_{ij} = \Gamma H_{ij}$$

couples nematic order and shear flows

relaxation to minimum of Landau-de Gennes free energy

$$\rho(\partial_t + u_k\partial_k)u_i = \partial_j\Pi_{ij}$$

viscous + passive

Continuum equations of active liquid crystal hydrodynamics

$$(\partial_t + u_k \partial_k) Q_{ij} - S_{ij} = \Gamma H_{ij}$$

couples nematic order and shear flows

relaxation to minimum of Landau-de Gennes free energy

$$\rho(\partial_t + u_k \partial_k) u_i = \partial_j \Pi_{ij}$$

viscous + passive + active stress

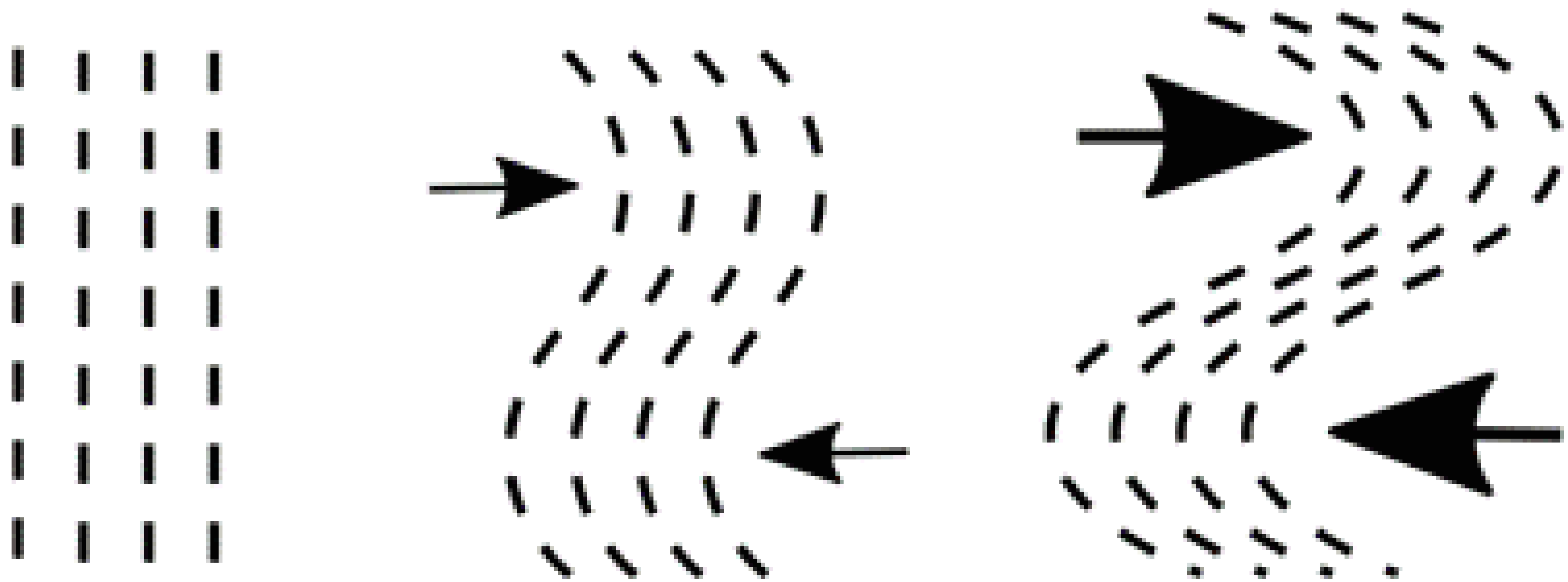
$$\Pi_{ij}^{active} = -\zeta Q_{ij}$$

Active stress => active turbulence

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

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

Hatwalne, Ramaswamy, Rao, Simha, PRL 2004 nematic ordering is unstable to flow



Active stress => active turbulence

Active contribution to the stress $-\zeta Q$

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

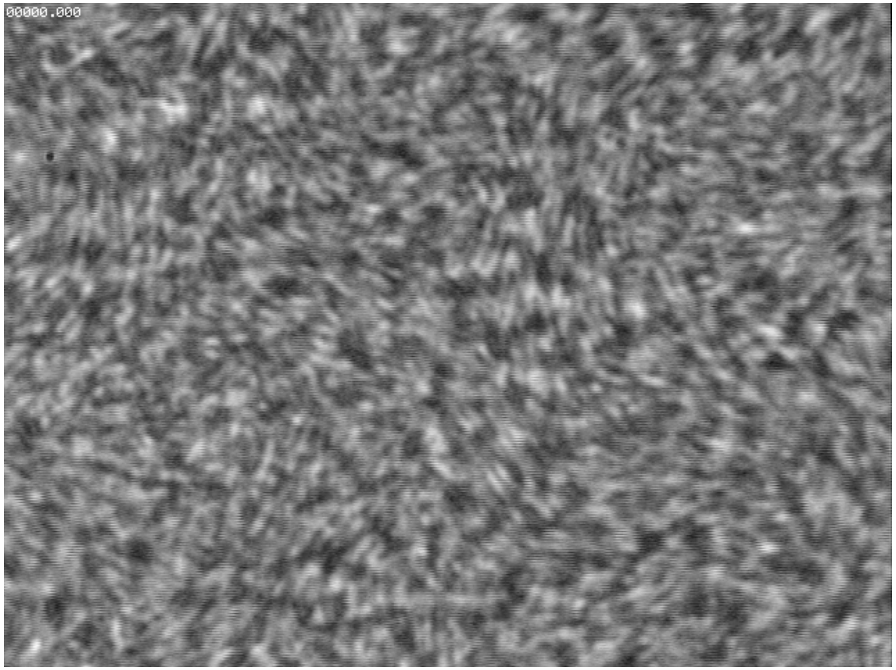
⇒

Linear stability analysis =>
nematic state is unstable to vortical flows

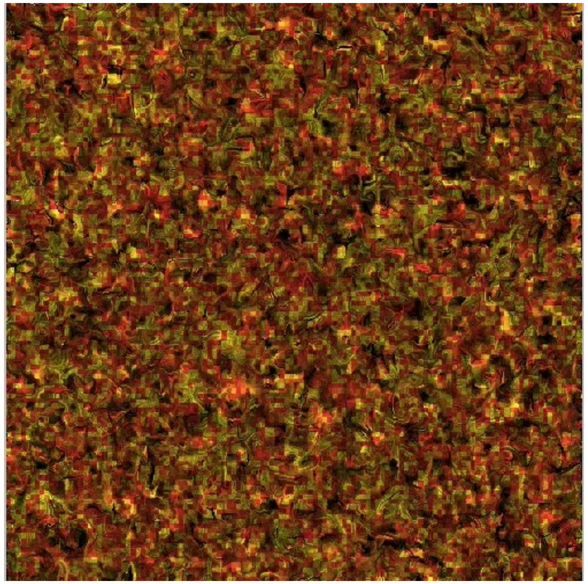
What happens instead is active turbulence

Hatwalne, Ramaswamy,
Rao, Simha, PRL 2004

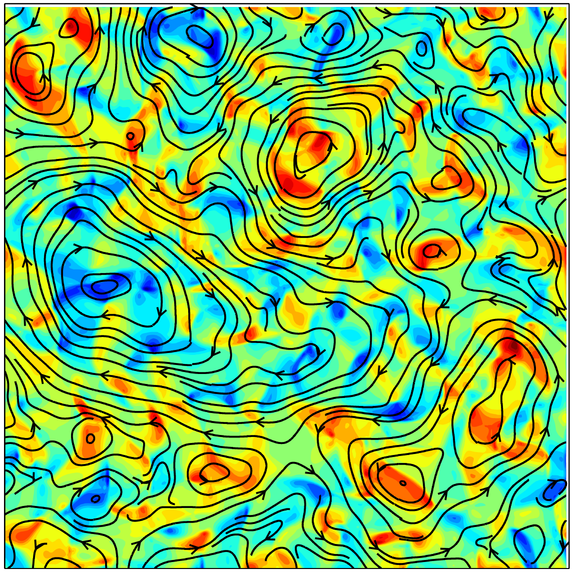
Active turbulence



Flow field

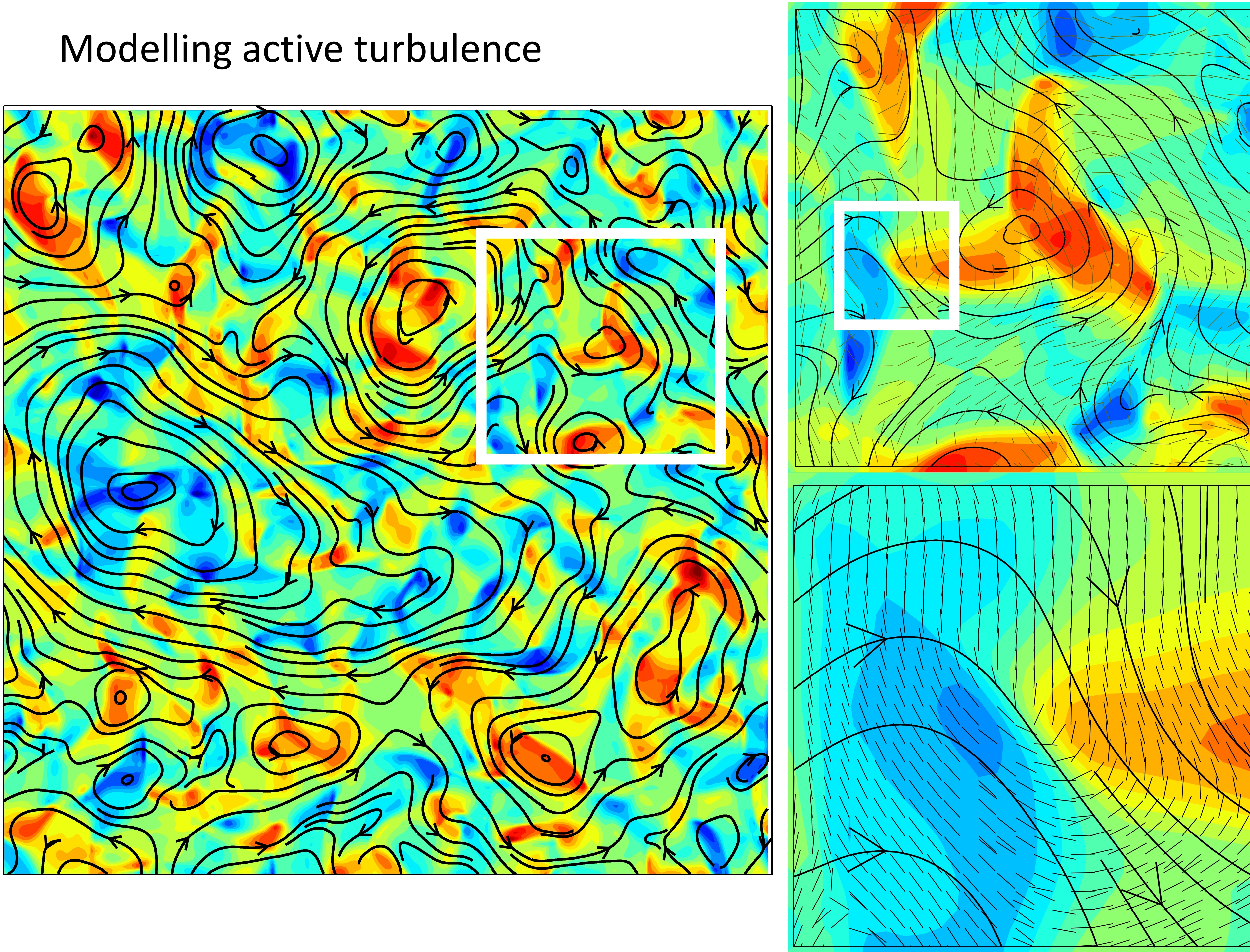


Dense suspension of microswimmers

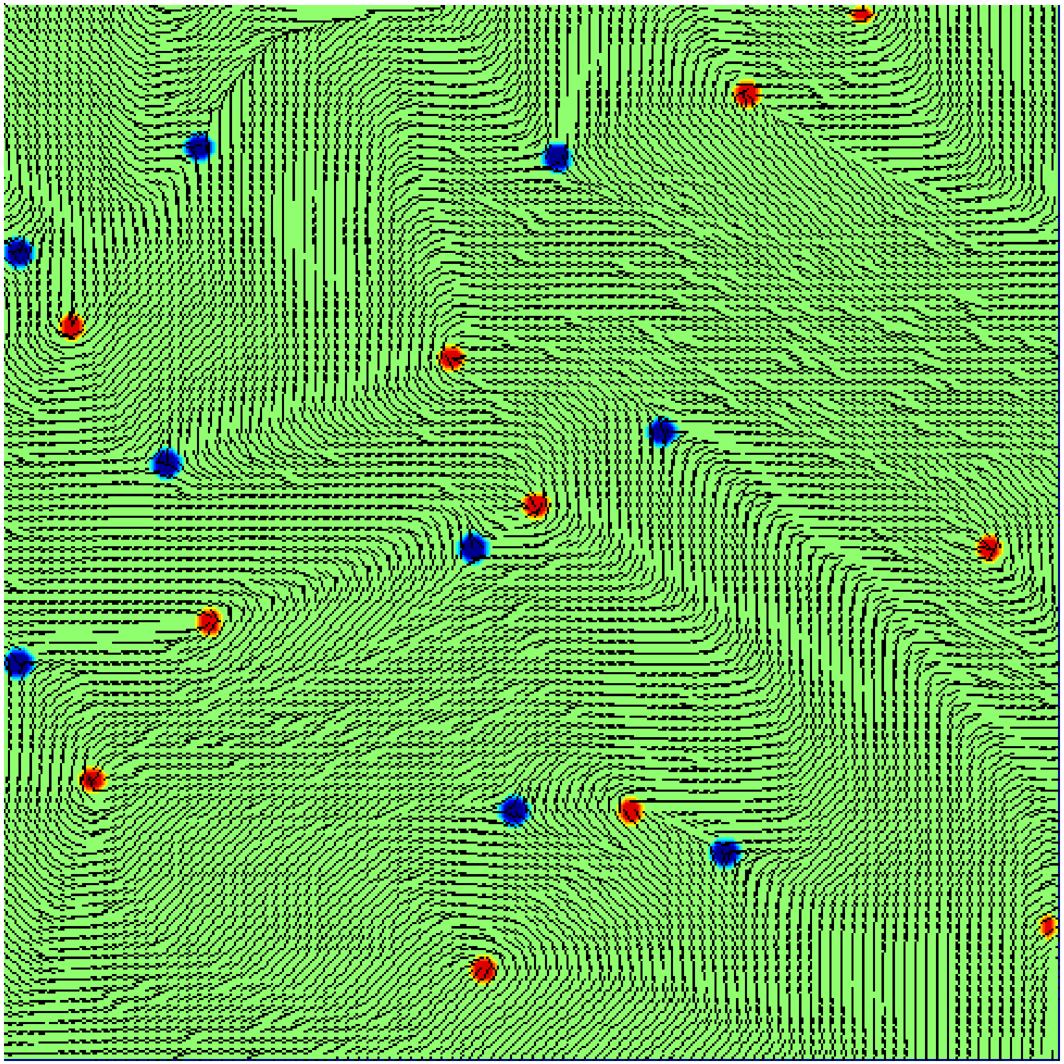


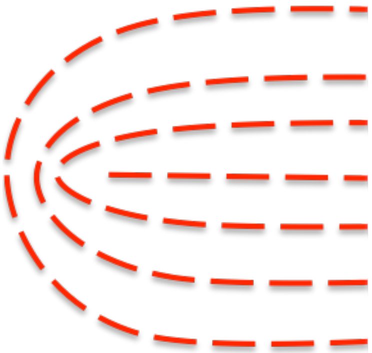
Vorticity field

Modelling active turbulence

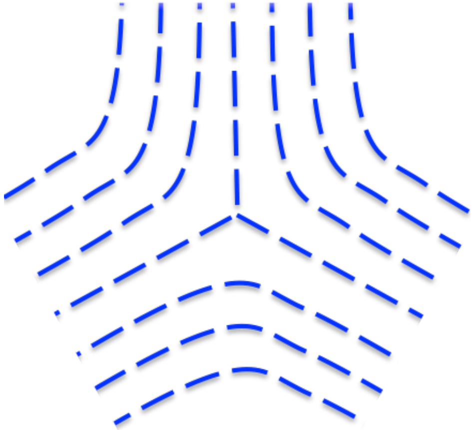


Active turbulence: topological defects are created and destroyed





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



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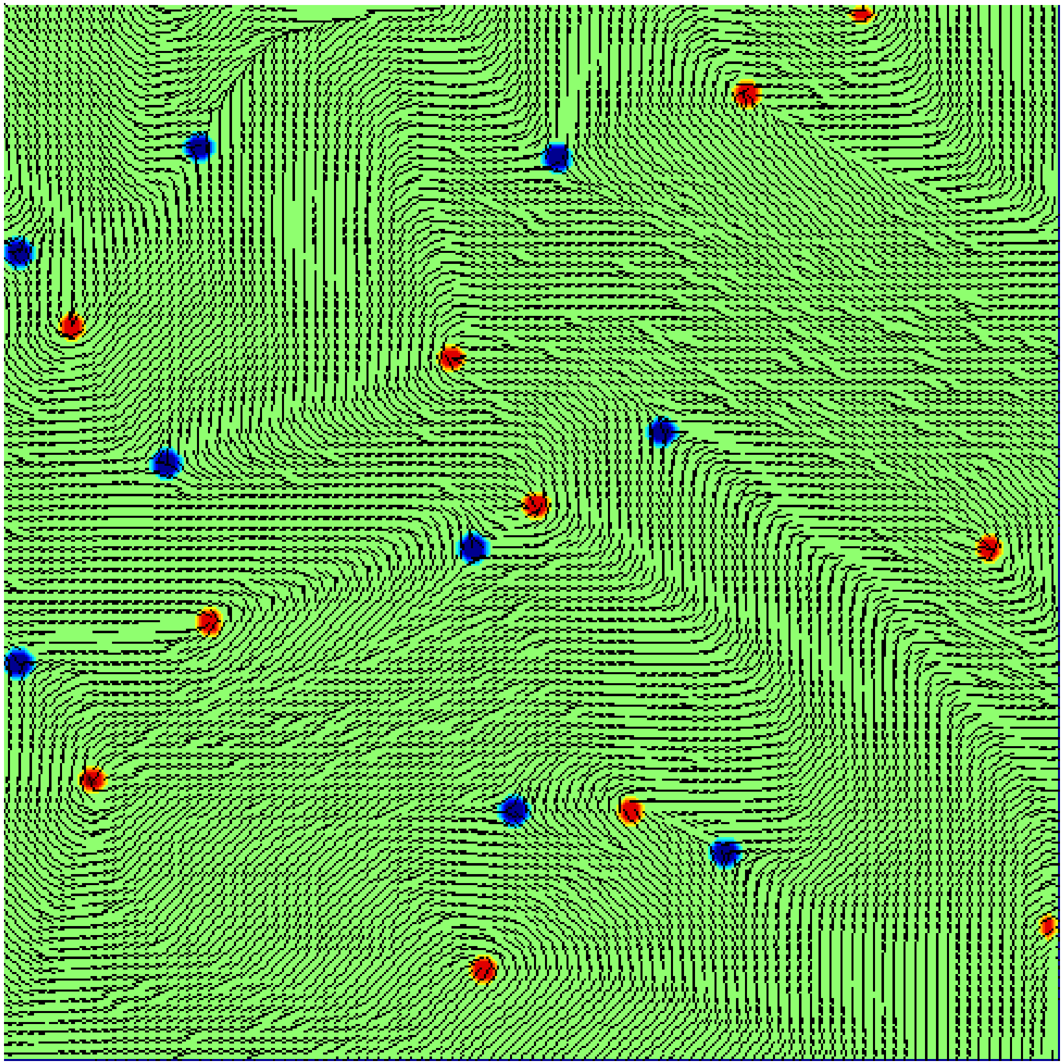
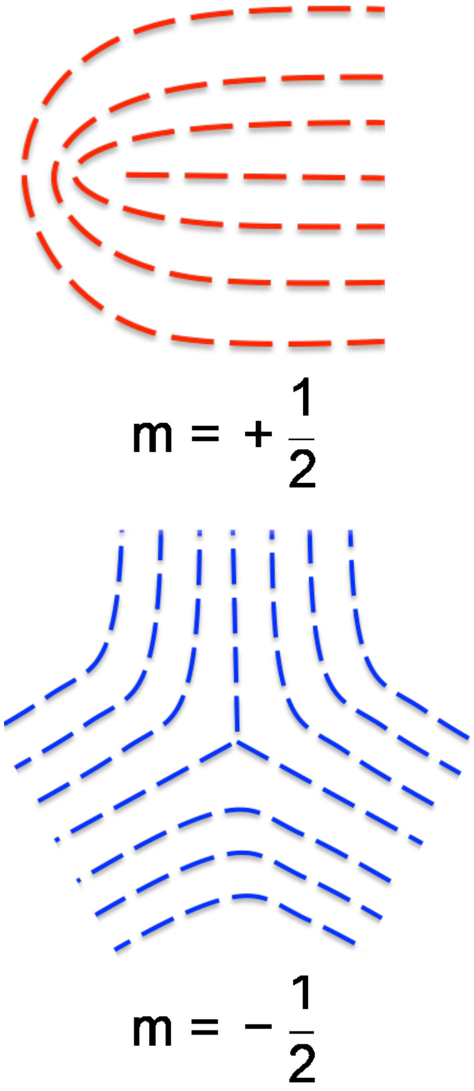
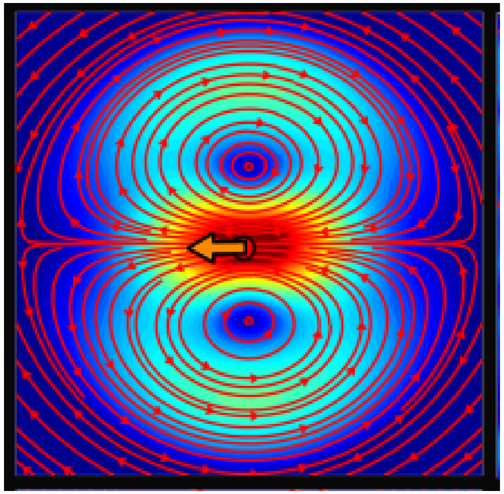
Active turbulence: topological defects are created and destroyed

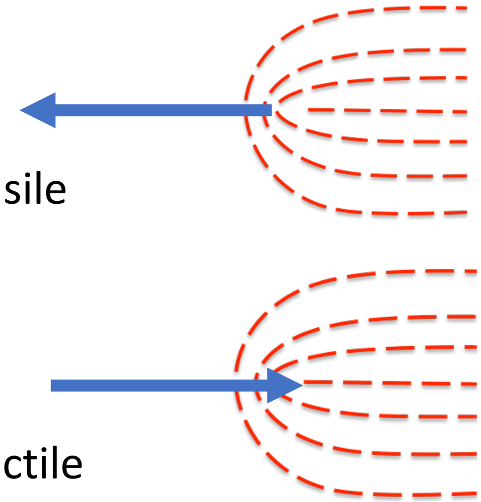


Topological defects are self motile



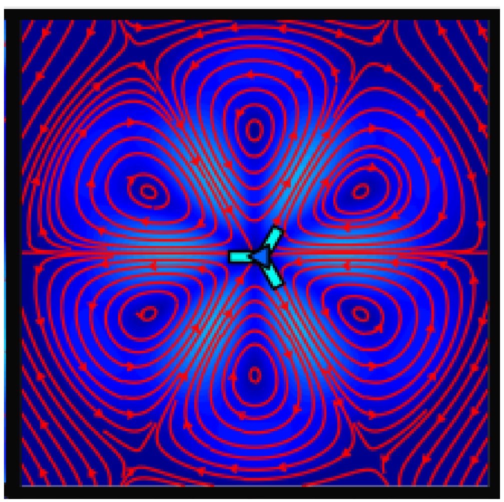
Flow fields around defects

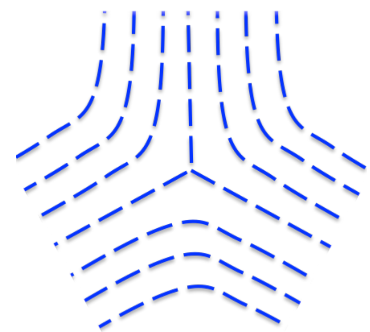




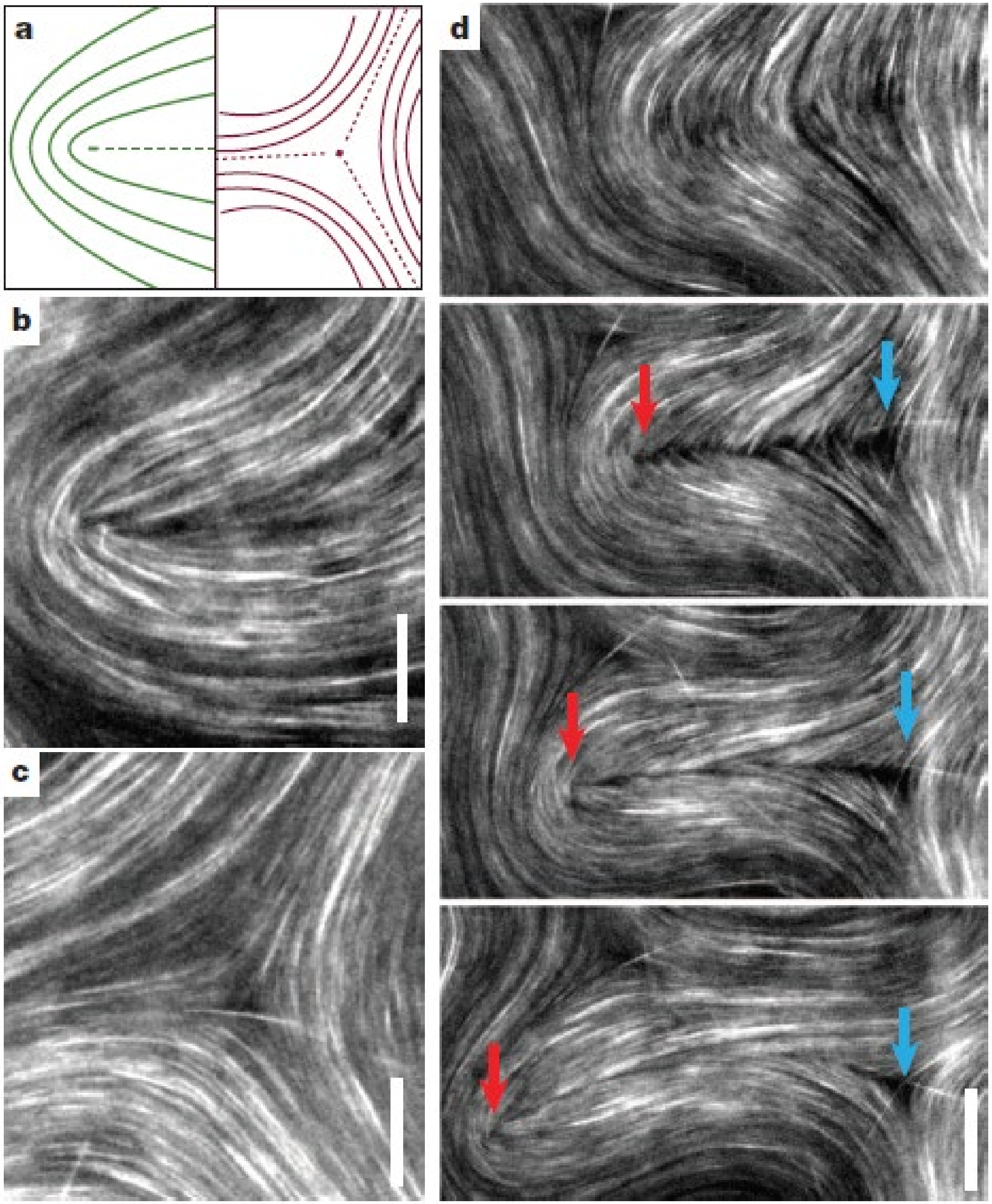
extensile

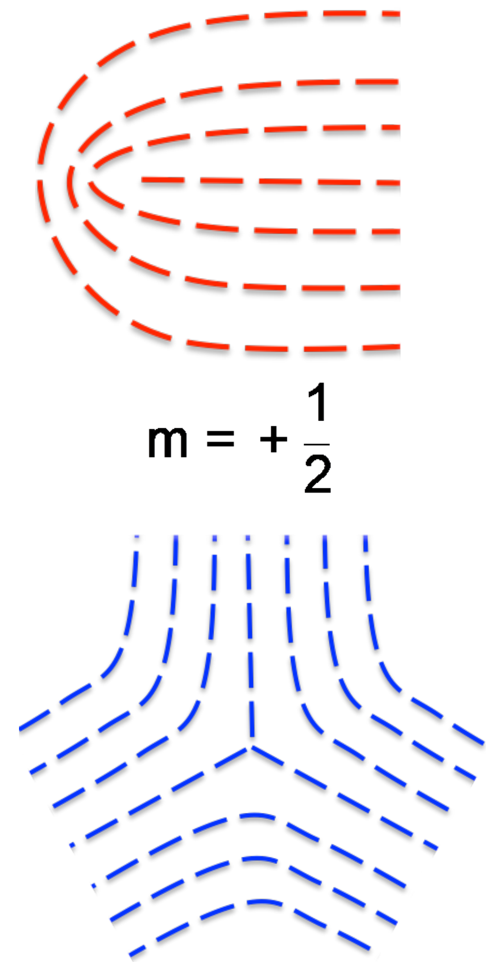
contractile





L. Giomi



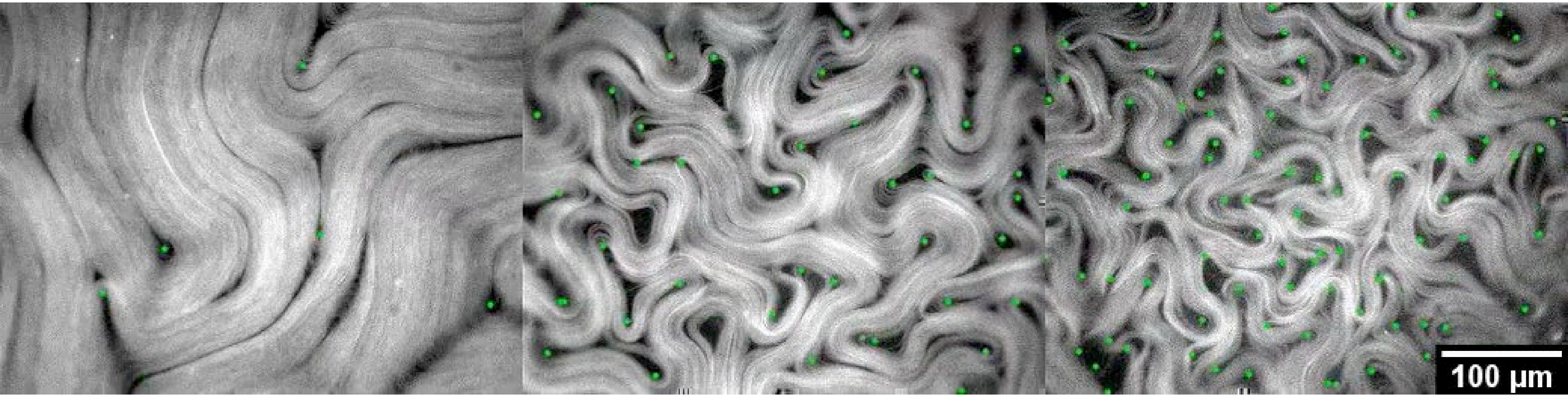


$m = +\frac{1}{2}$

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

Sanchez, Chen, DeCamp, Heymann, Dogic, Nature 2012

L. Giomi, M.J. Bowick, Ma Xu, M.C. Marchetti, PRL 110, 228101

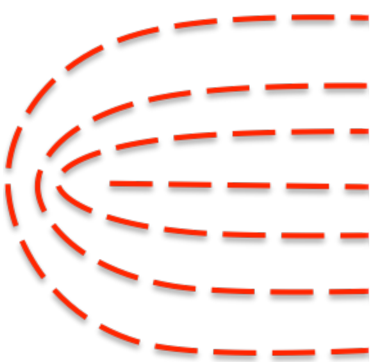


F Sagues lab

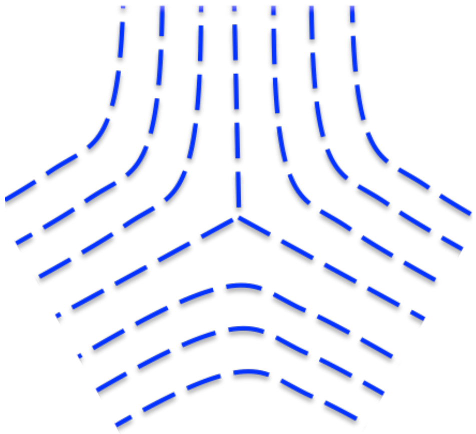
Active nematics:

Gradients in the order parameter => stresses => flows

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



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



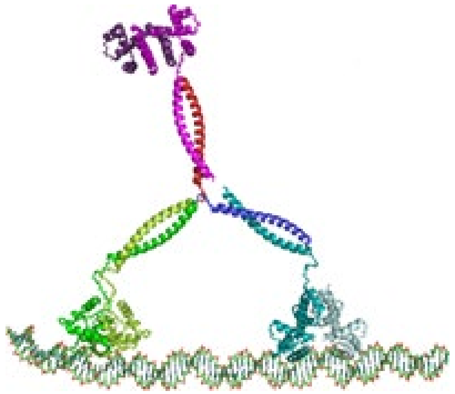
$m = -\frac{1}{2}$

Active nematics review:

A. Doostmohammadi et al. Nature Comms. 9 3246 (2018)

The 2020 motile active matter roadmap

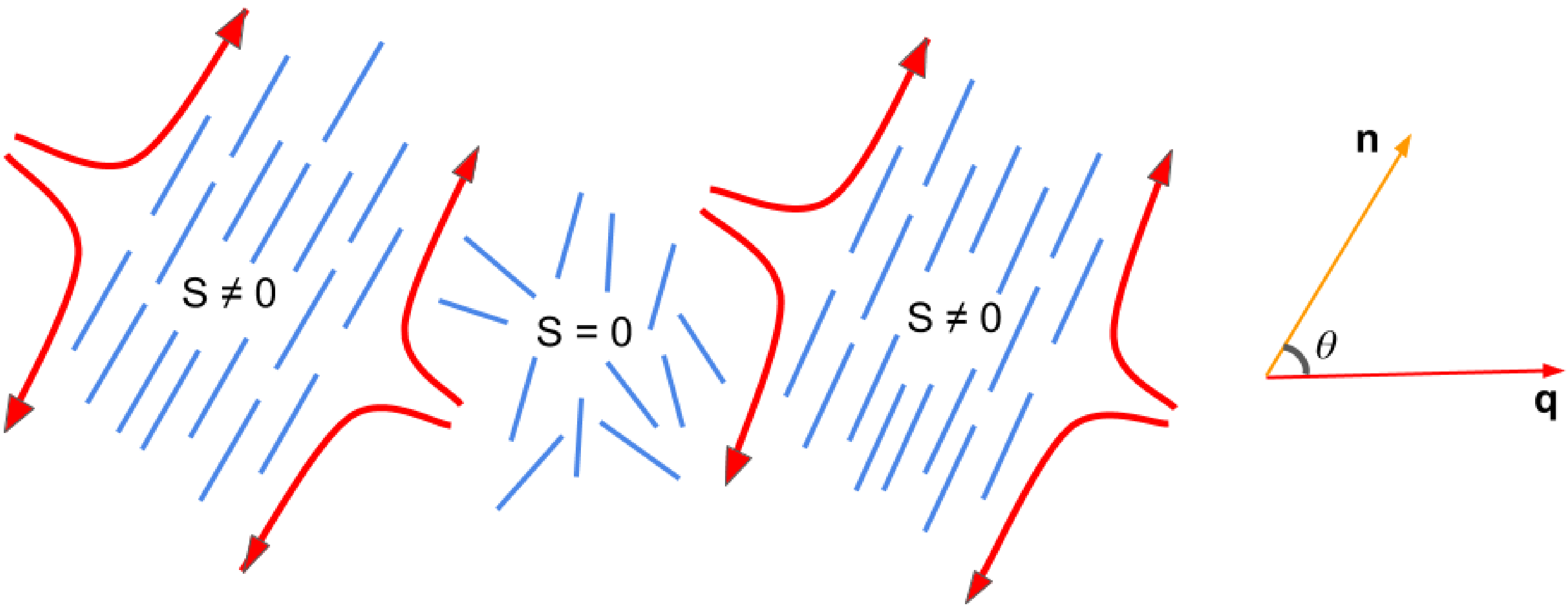
G. Gompper et al 2020 J. Phys.: Condens. Matter 32 193001



BUT

No real reason for thermodynamic ordering in many active systems

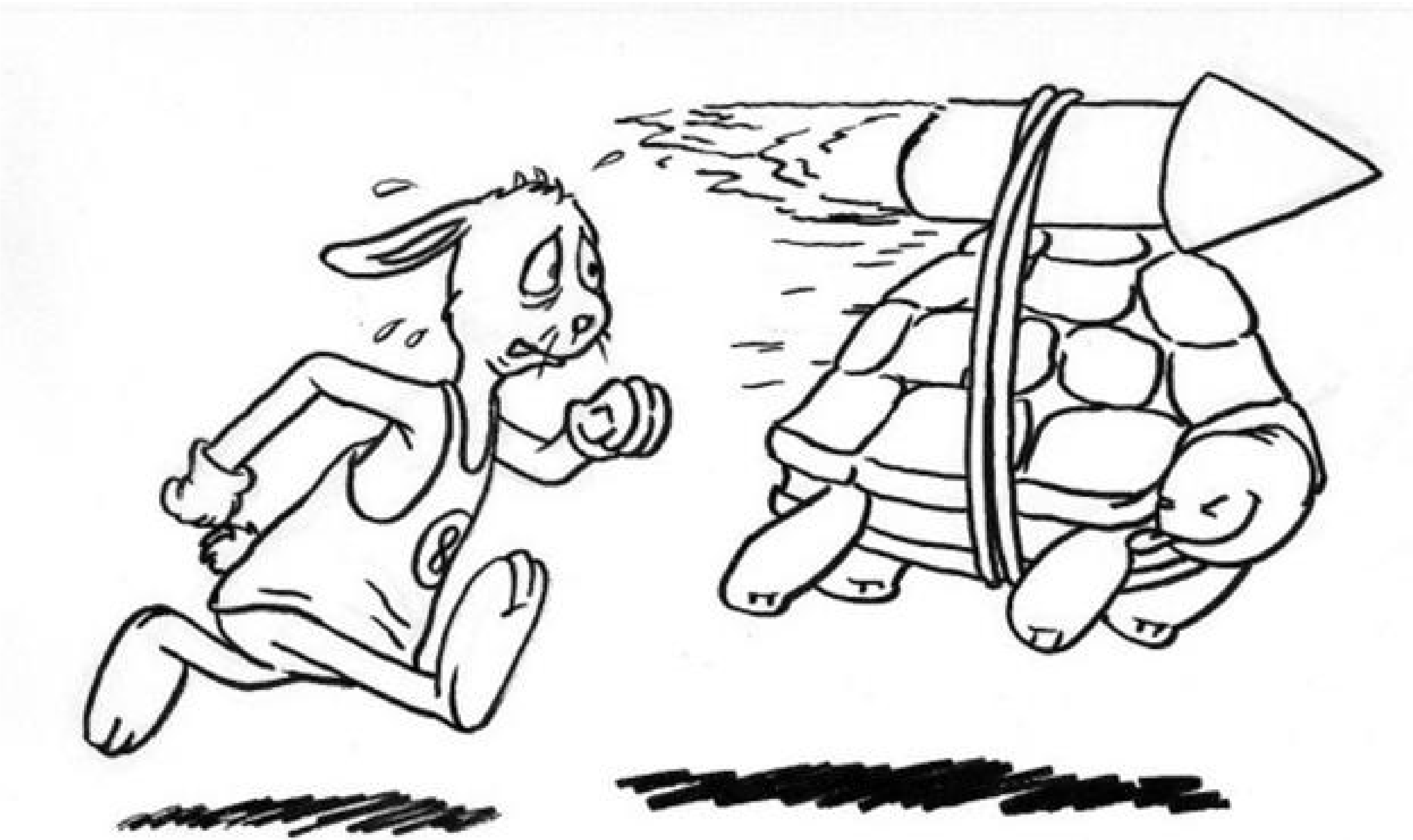
Instability 2: isotropic state is unstable to nematic order



Even if the passive system is isotropic, can still get active turbulence
(for extensile rod-like particles or contractile disc-shaped particles)

Santhosh et al J Stat Phys 2020

Topological defects in a bacterial colony



Thank You

Amin Doostmohammadi
Oxford, soon to be
Neils Bohr Institute

William Durham
University of Sheffield

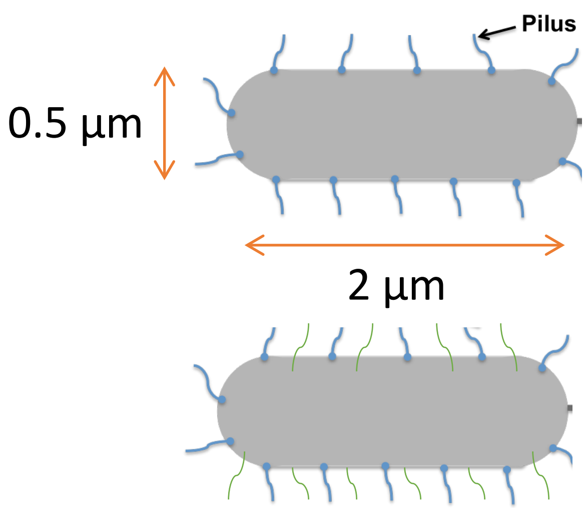
Kevin Foster
Oxford Zoology

Oliver Meacock
Oxford Zoology

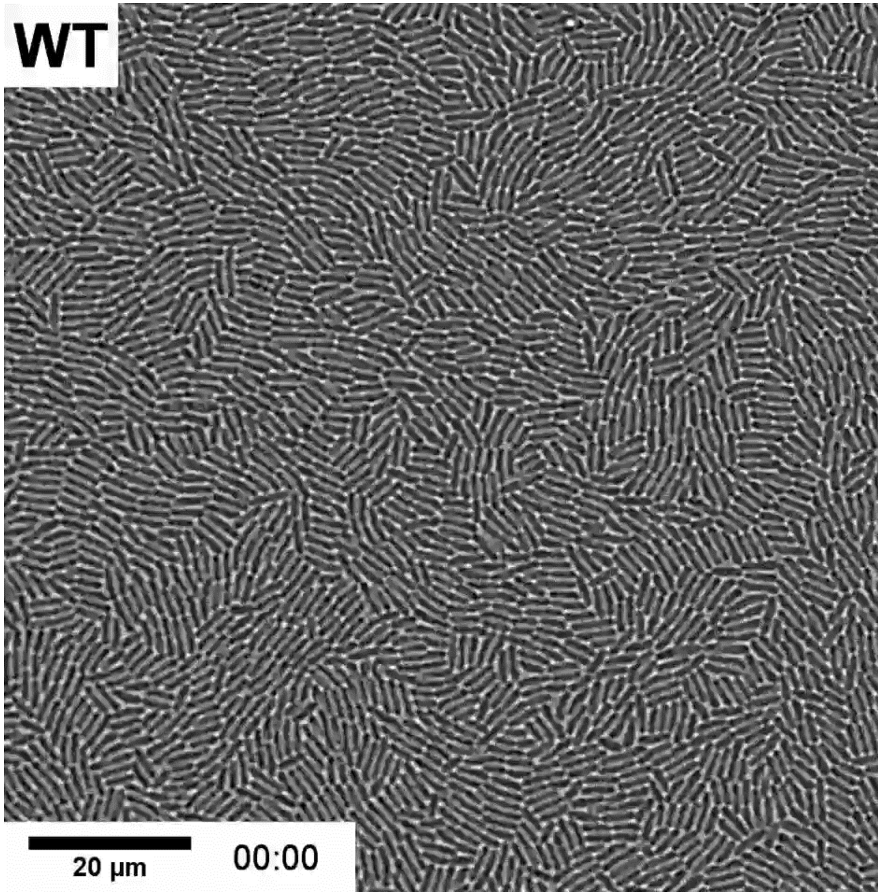
Pseudomonas aeuriginosa

twitching motility using Type IV Pili

reversals



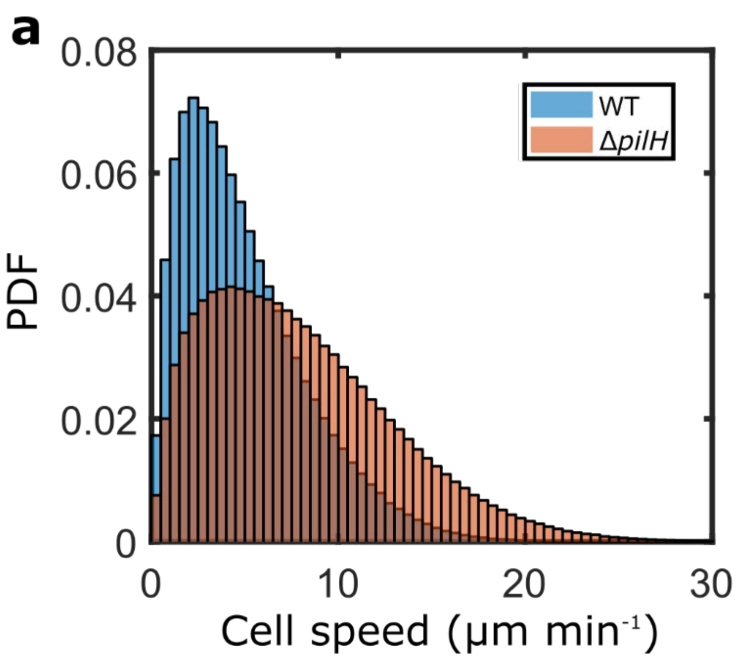
Hyper-pilated
~ 2 faster

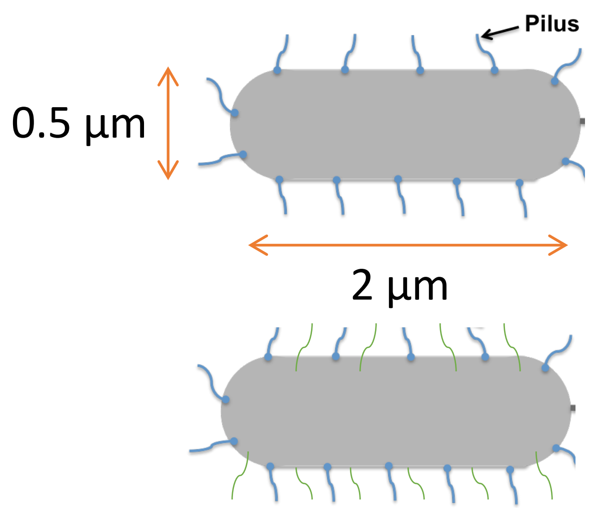


Two competing cell types

Wild Type (slower)

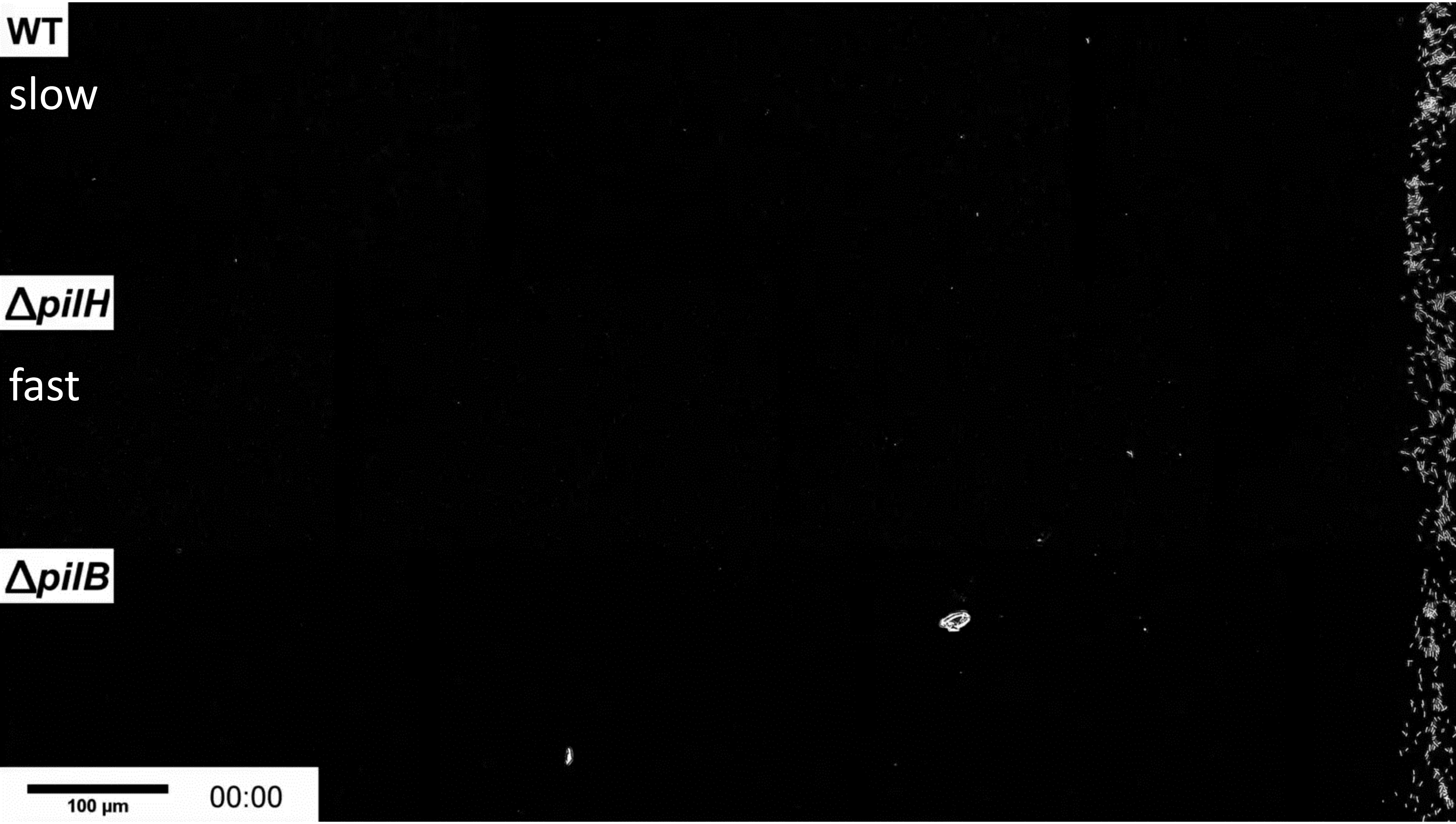
Δ*pilH* – hyperpilated, individual cells move 1.6 x faster (faster)



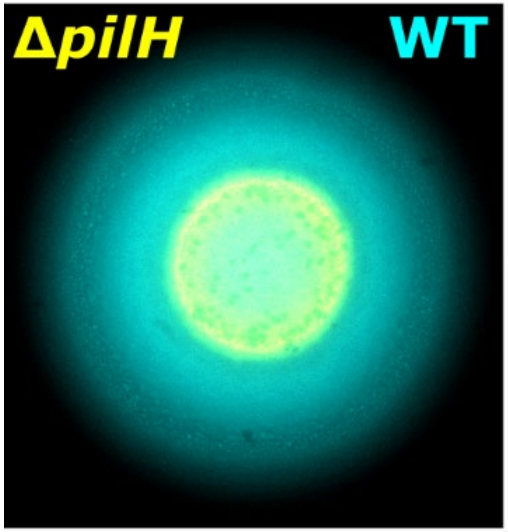


Hyper-pilated
faster ~2

Colony growth

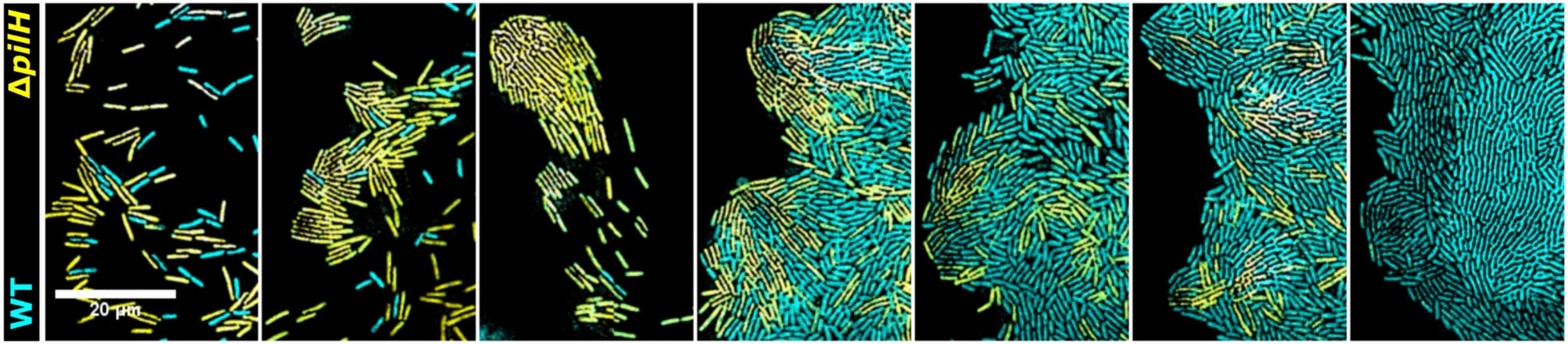


Colony expansion: two competing cell types



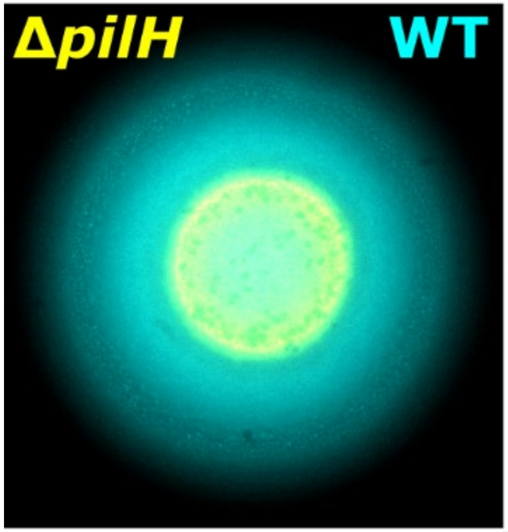
Individual WT slower, but they dominate the colony growth

c

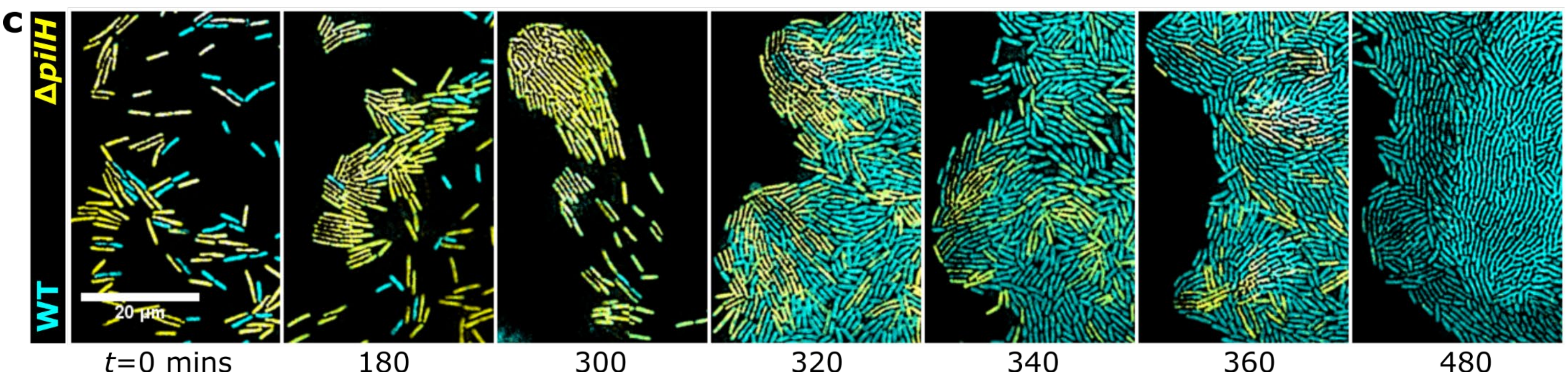


t=0 mins 180 300 320 340 360 480

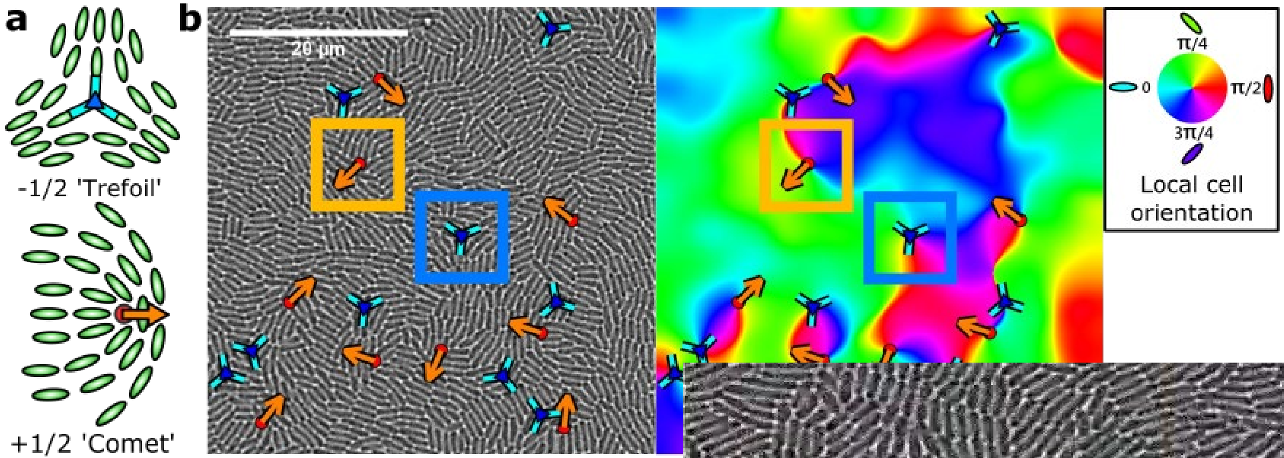
Two competing cell types

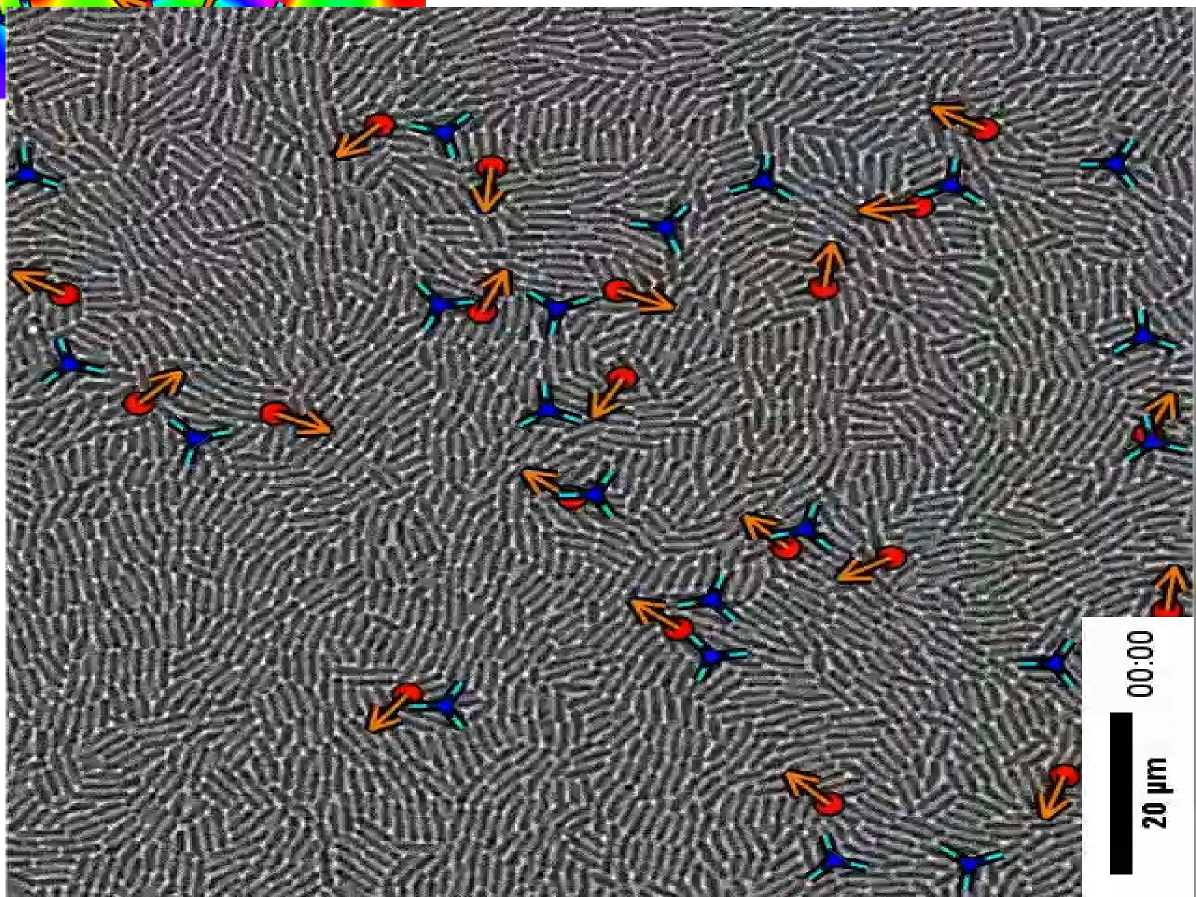


- At leading edge proportion of *ΔpilH* drops from 0.92 at 200 minutes to 0.11 at 400 minutes
- Colony expansion rate changes from *ΔpilH* to WT value (ie speeds up)
- Density of leading edge increases
- Not due to a growth defect



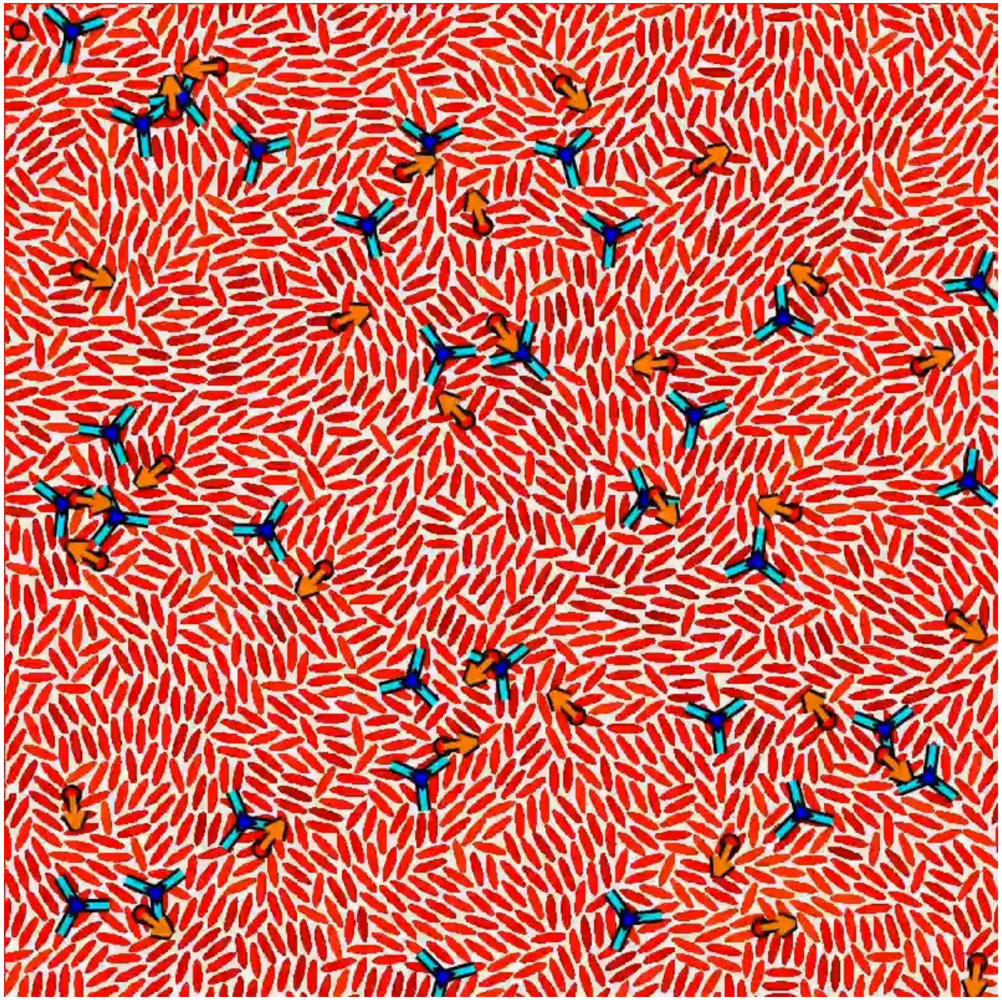
Topological defects





Model 1: driven rods

2. Self-propelled rods

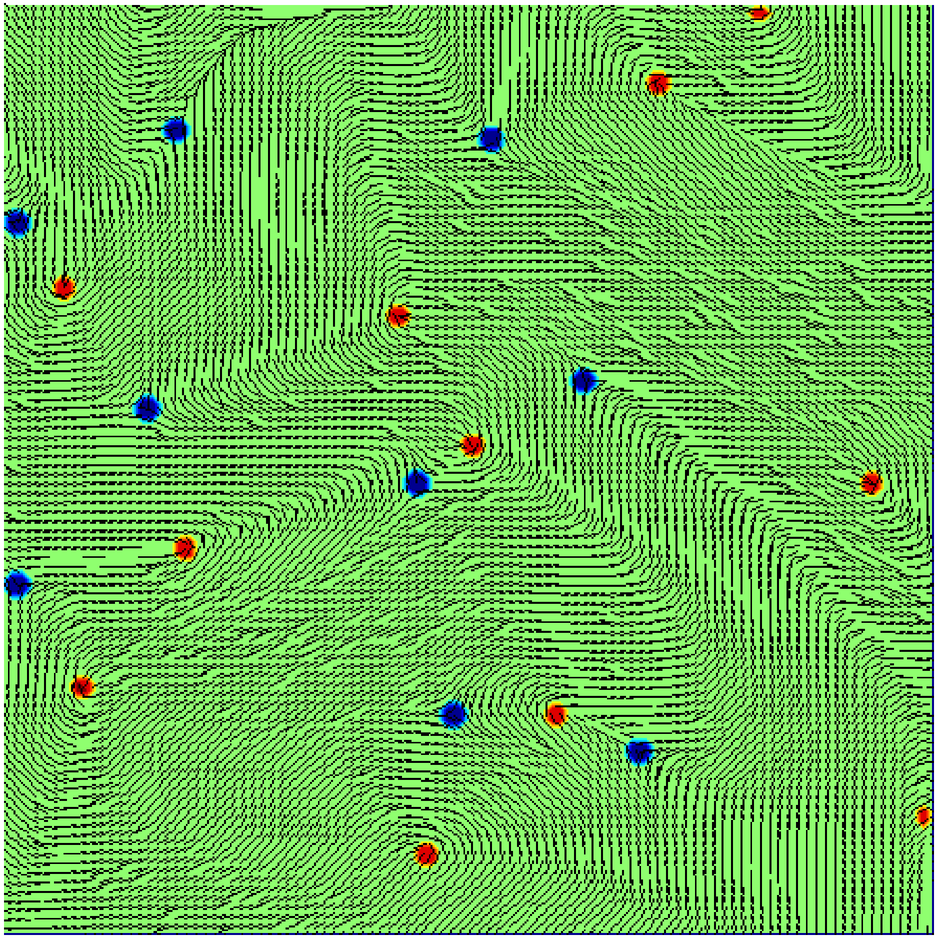


Hard rods (Yukawa potentials)

Each rod subject to a constant driving force

Model 2: continuum equations of motion

Continuum model of active nematohydrodynamics



$$(\partial_t + u_k \partial_k) Q_{ij} - S_{ij} = \Gamma H_{ij}$$

couples nematic order and shear flows

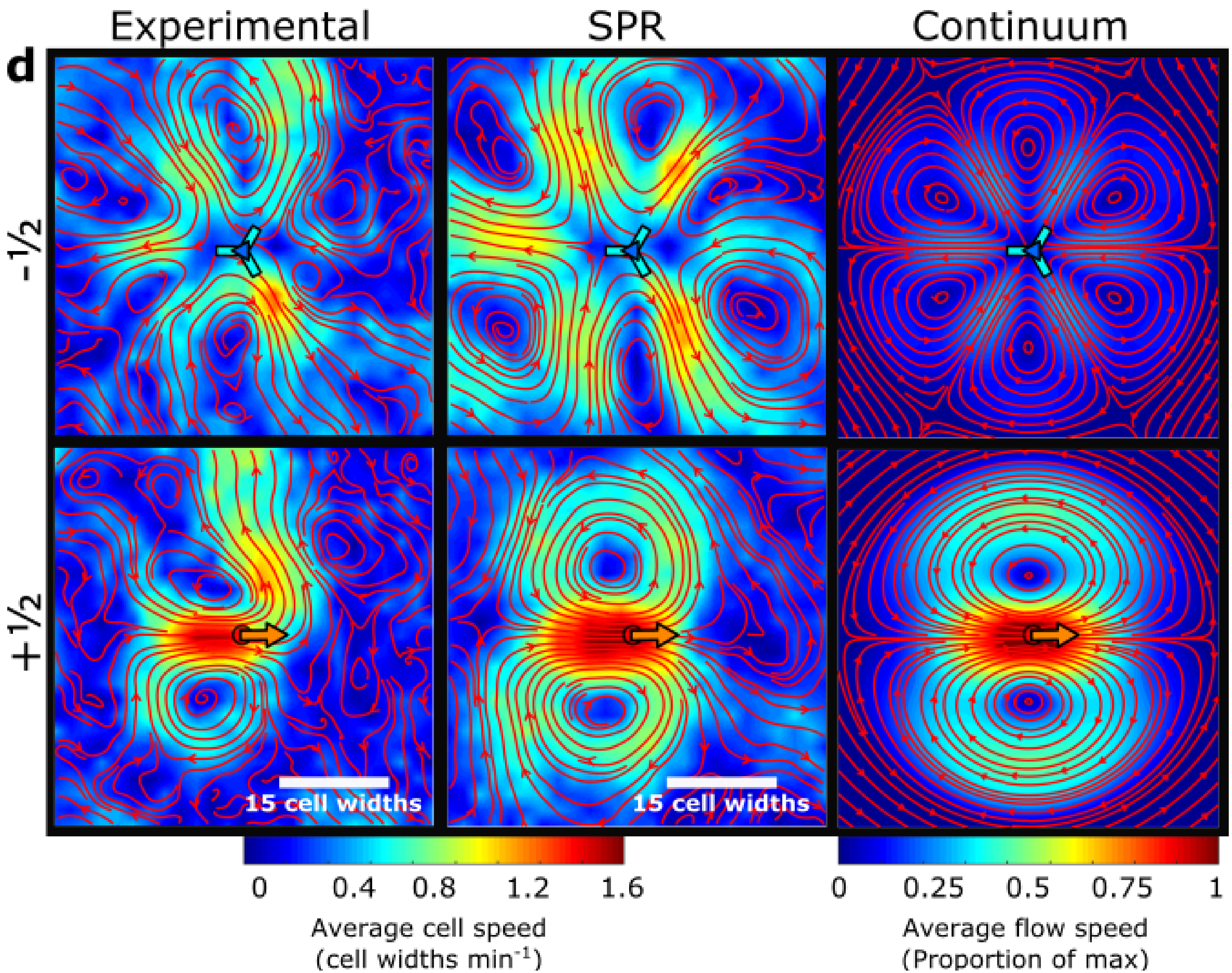
relaxation to minimum of Landau-de Gennes free energy

$$\rho(\partial_t + u_k \partial_k) u_i = \partial_j \Pi_{ij}$$

viscous + passive + active stress

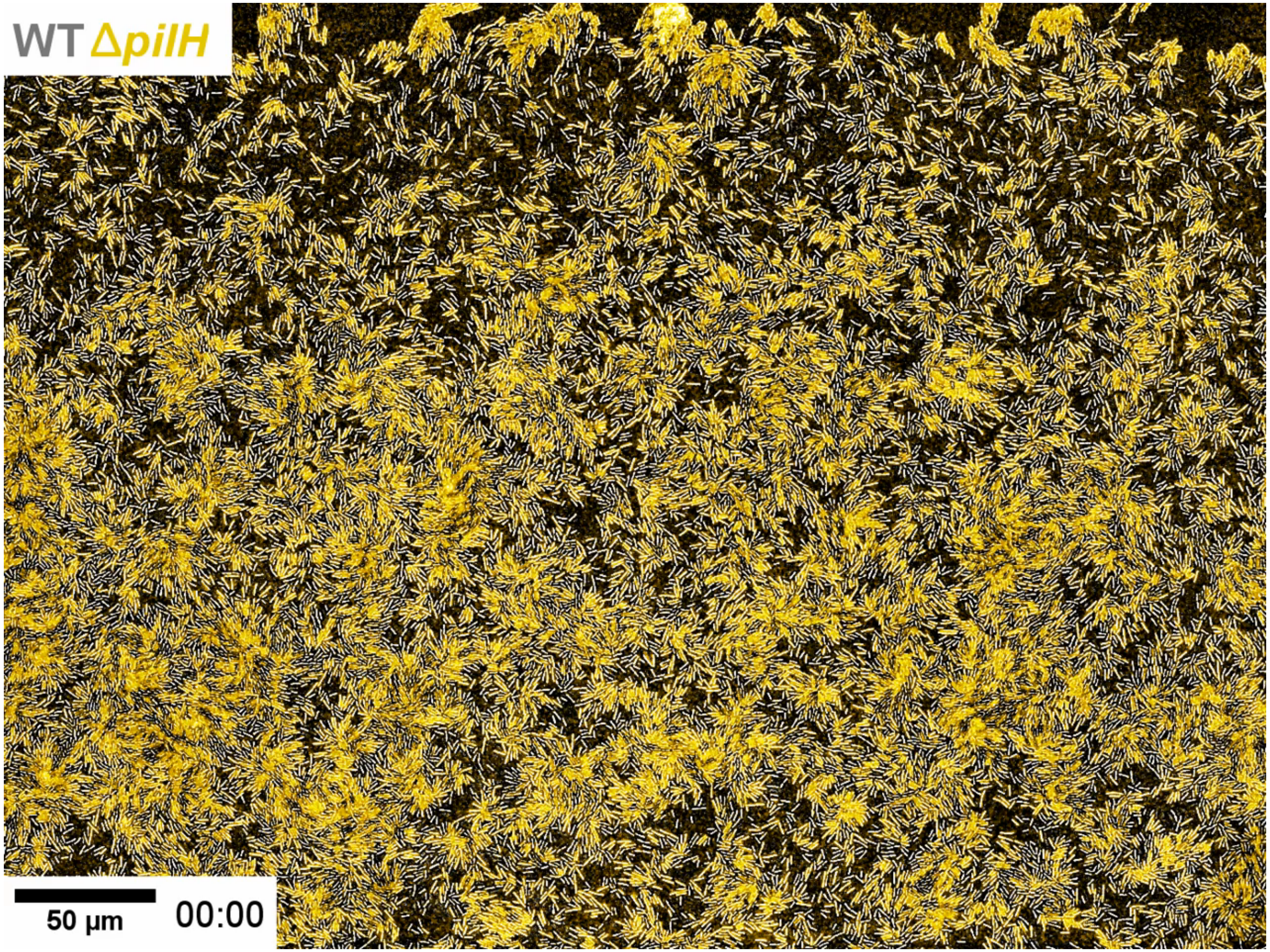
$$\Pi_{ij}^{active} = -\zeta Q_{ij}$$

Comparing velocity fields around topological defects



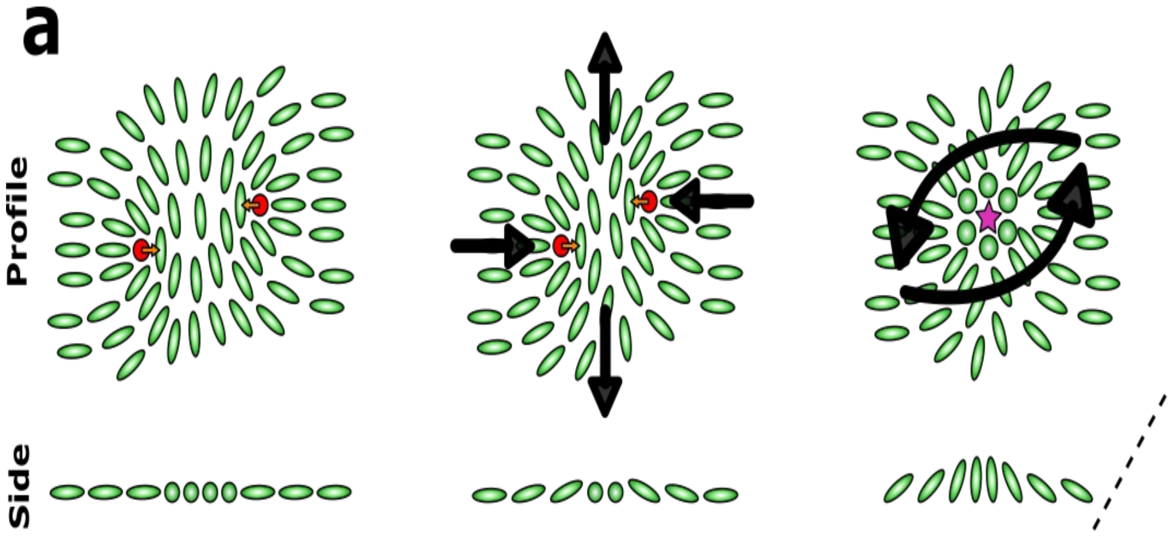
Rosettes

static accumulations of Δ*pilH* cells form in high density regions -- removing them from the pool of cells that is able to expand

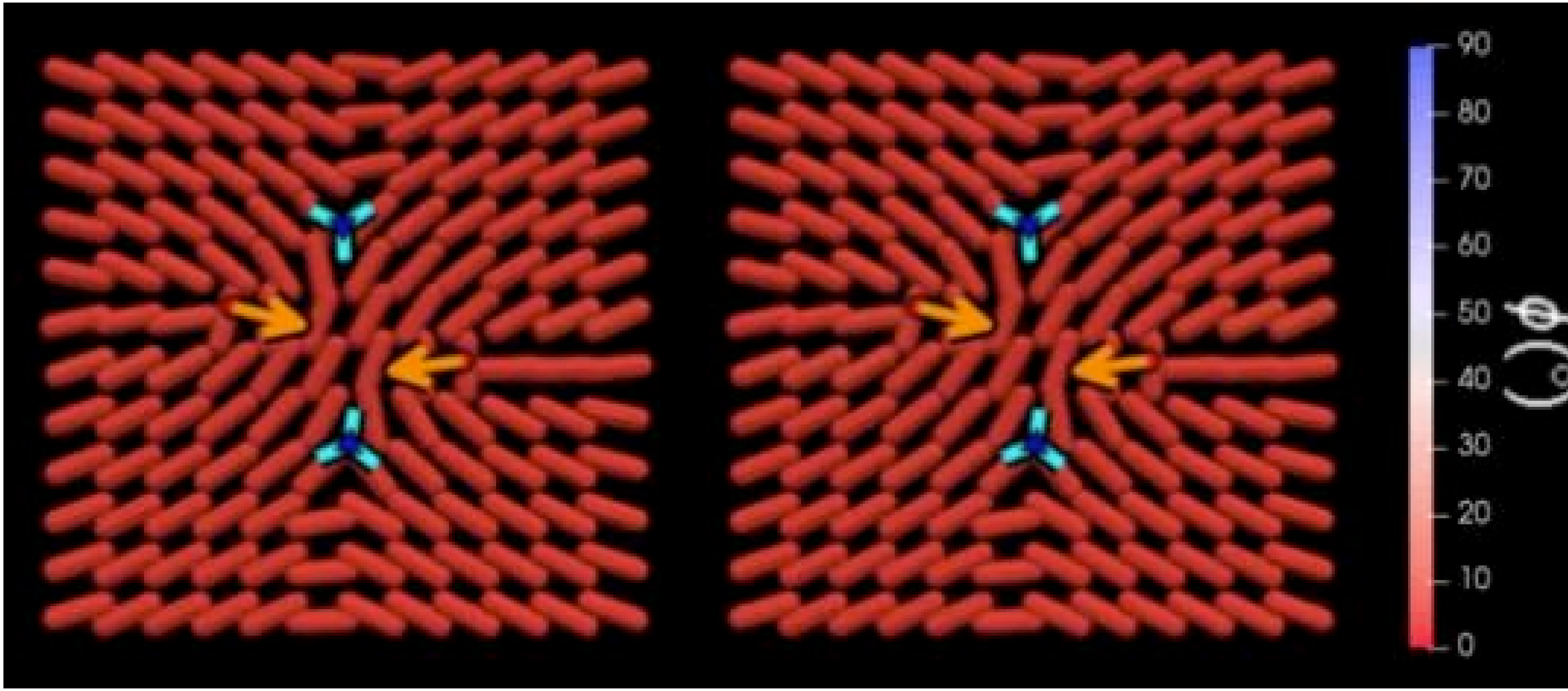


Rosettes

these are initiated at places where two +1/2 defects approach each other => rosette formation



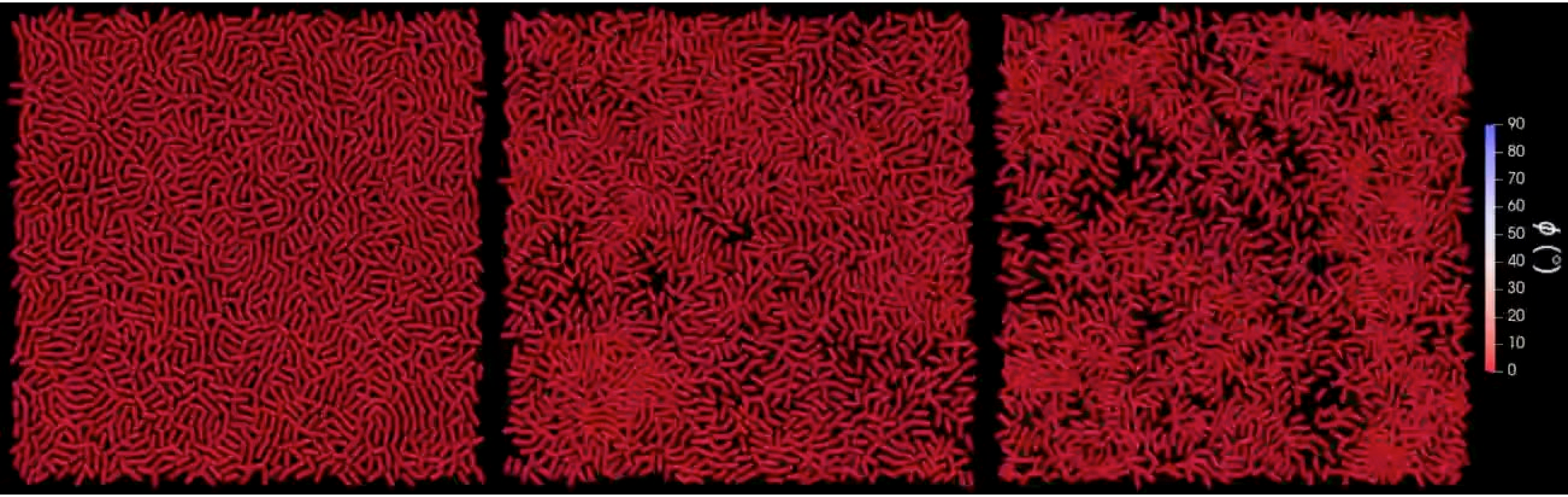
Rosette formation I



slow fast

Additions to model: 3D Yukawa potential + noise + elastic resistance

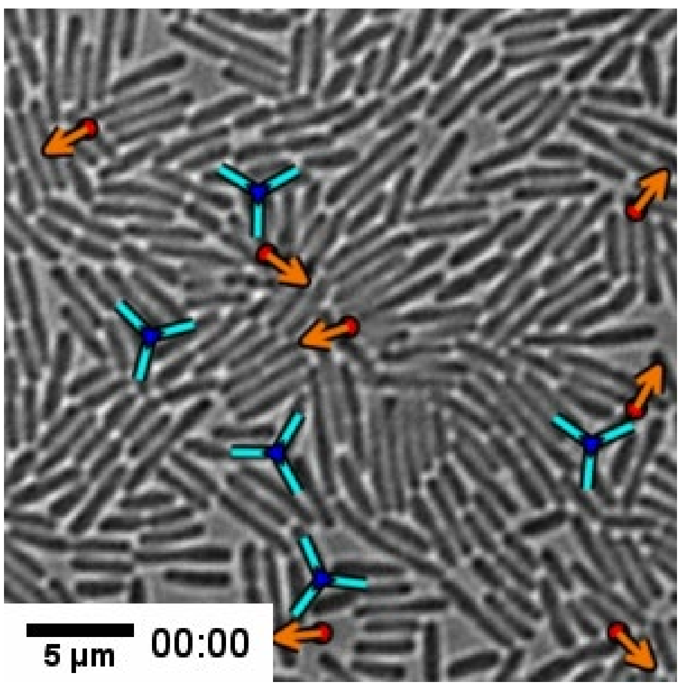
Rosette formation II

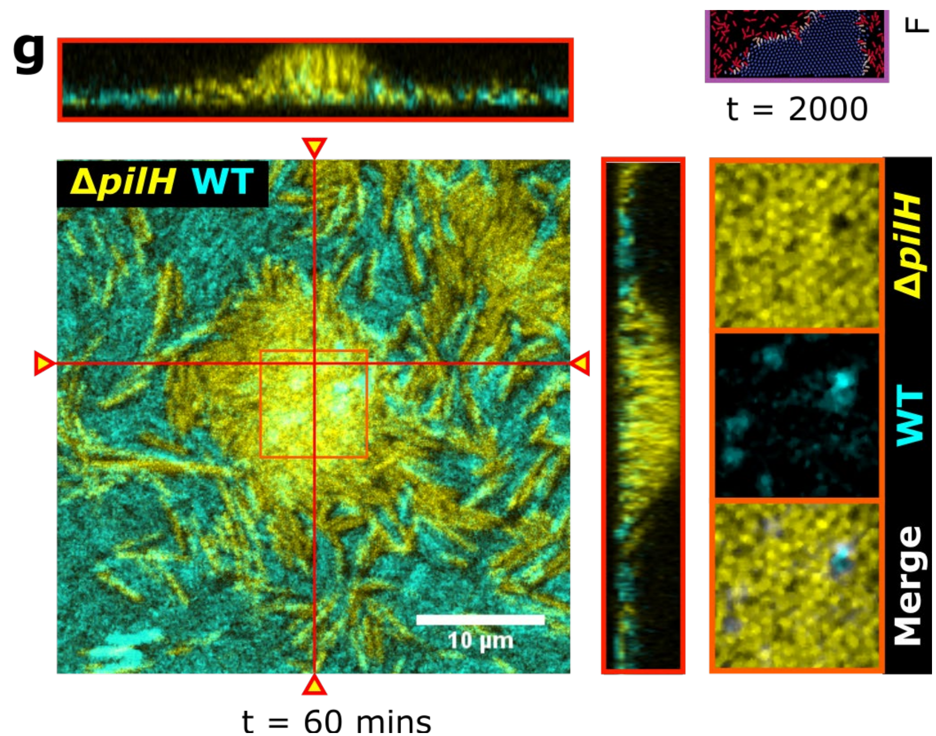


Increasing bacterial speed -----------→

Rosette formation: experiments

these are initiated at places where two +1/2 defects approach each other => rosette formation

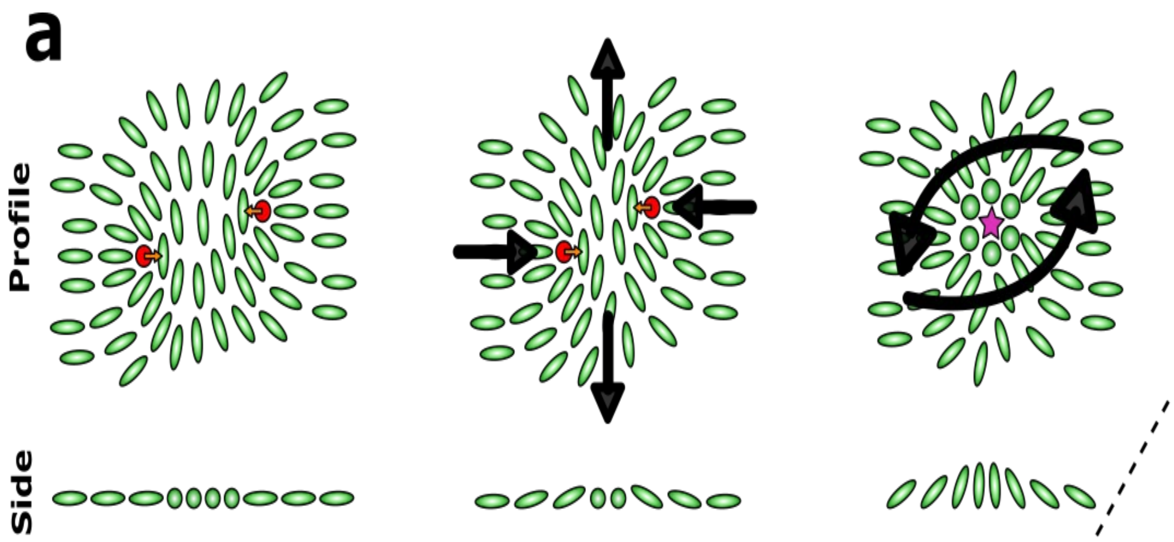




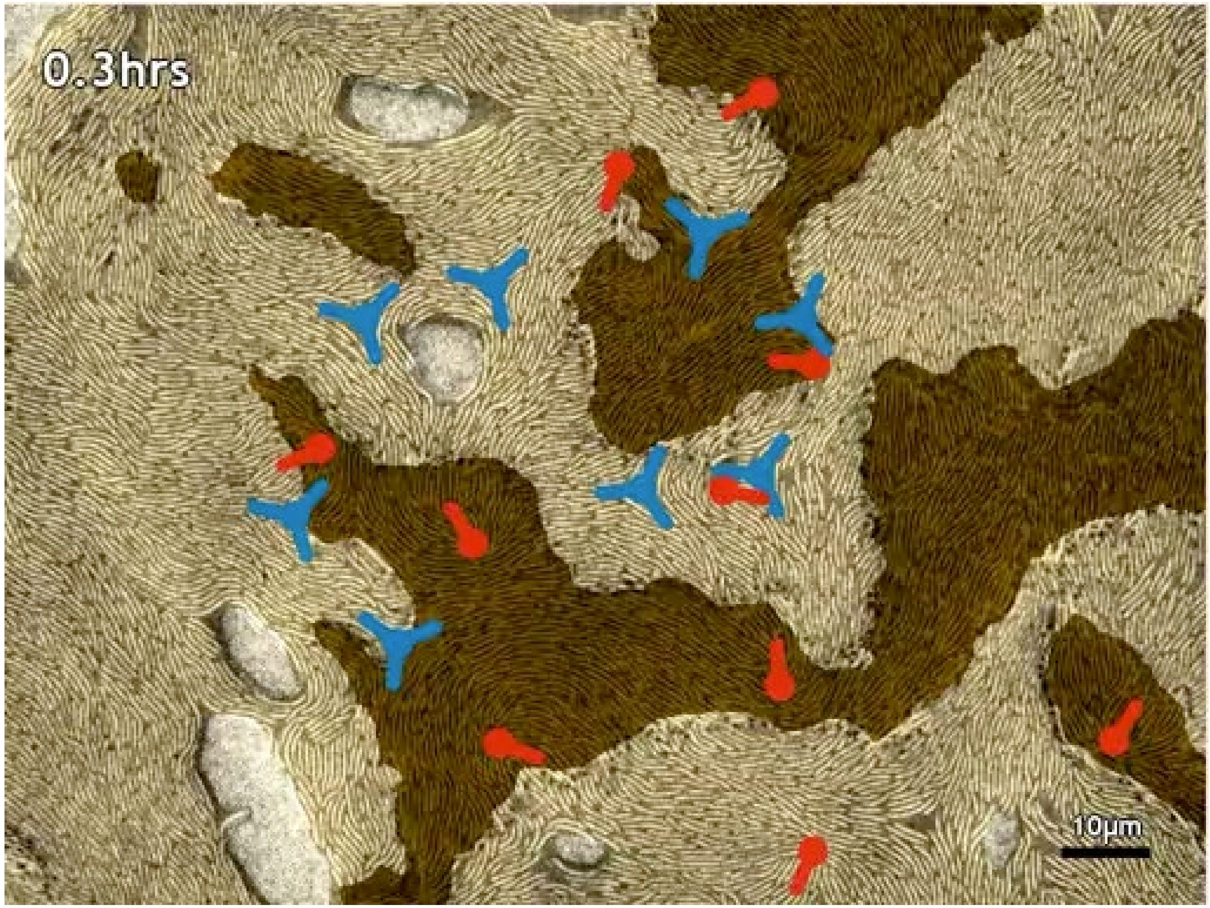
Bacteria which are individually slower can expand faster when in colonies

… because the faster bacteria can form virtual +1 topological defects

This drives them to point vertically, which nucleates growing immotile clusters



Layers form at positions of +1/2 defects, holes at -1/2 defects

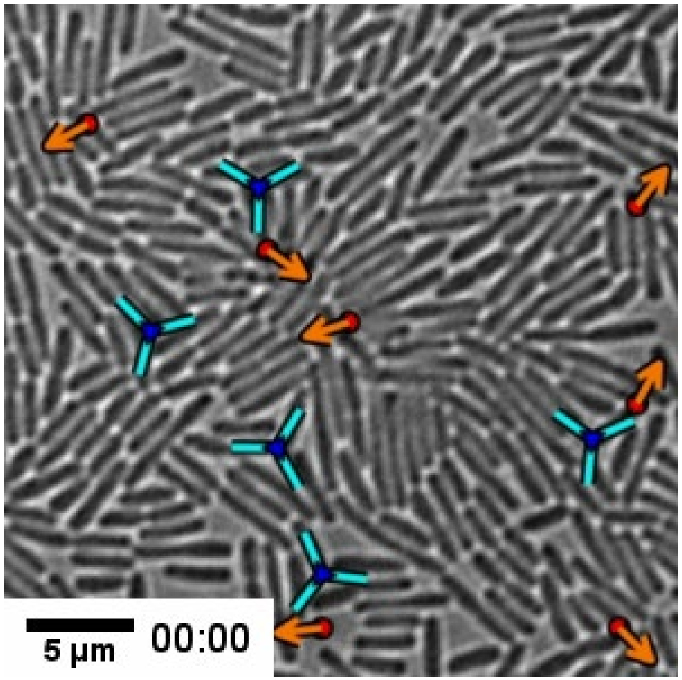


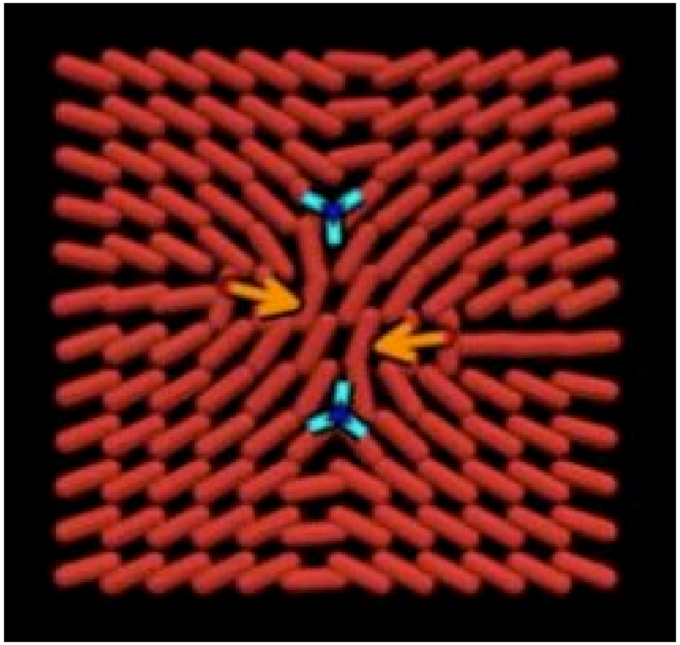
Copenhagen et al, Nature Physics **17** 211 (2021)

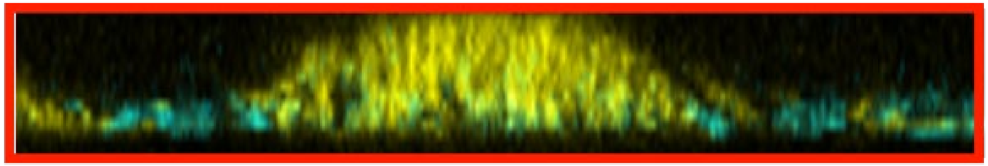
Myxococcus xanthus

Cells pushed vertical by flow around defects

two +1/2 defects approach each other and create flows that push cells out-of-plane (*pseudomonas*)







Meacock et al, Nature Physics **17** 205 (2021)

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- The hare and the tortoise

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