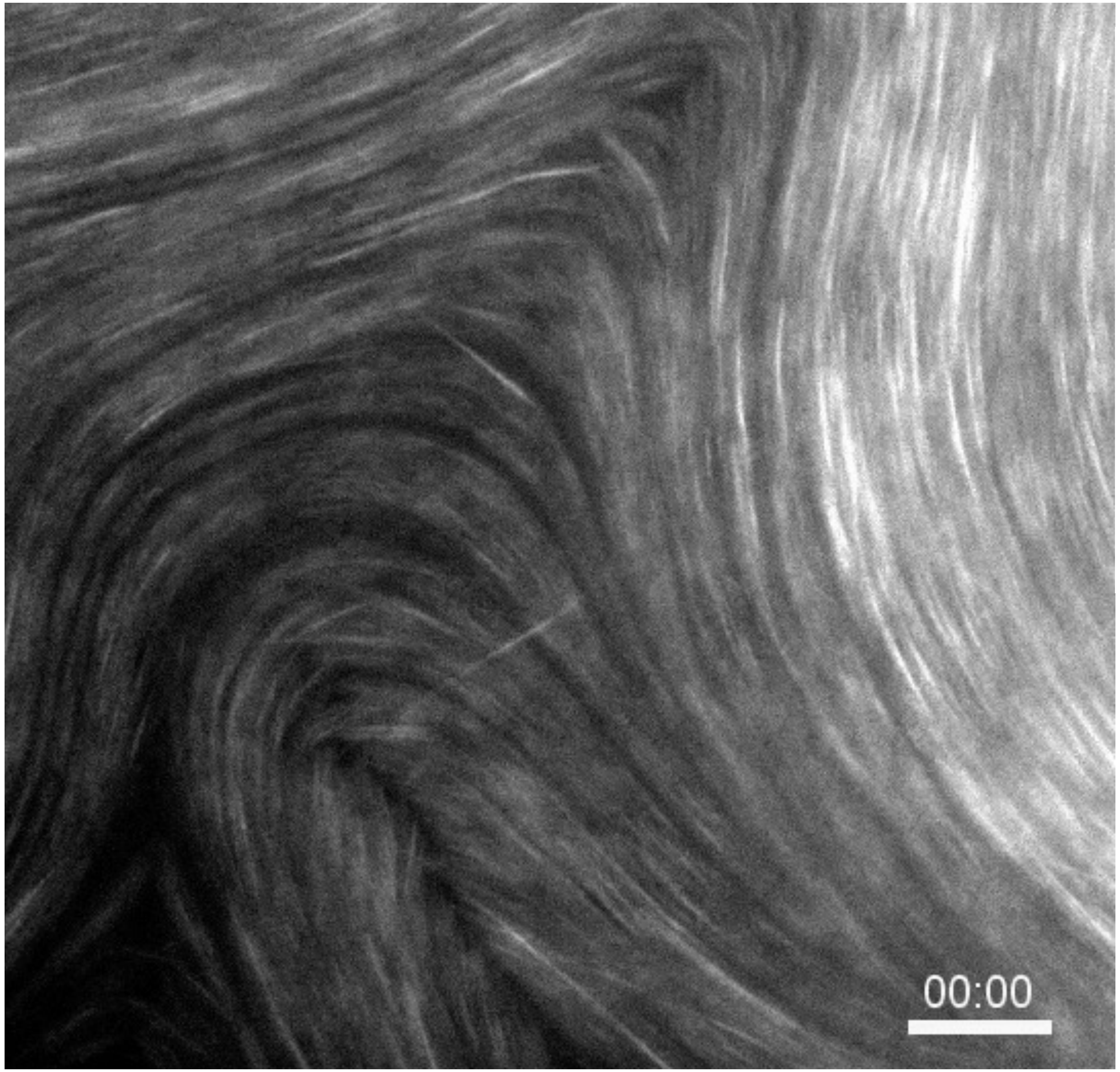
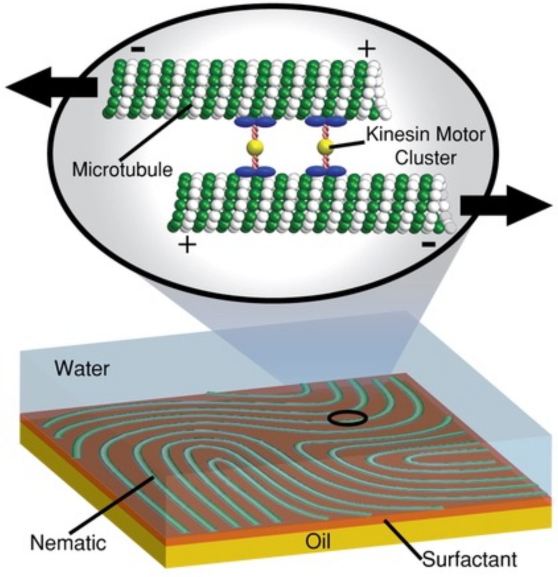
Active nematic liquid crystal: spatiotemporal chaotic flows and topological defects

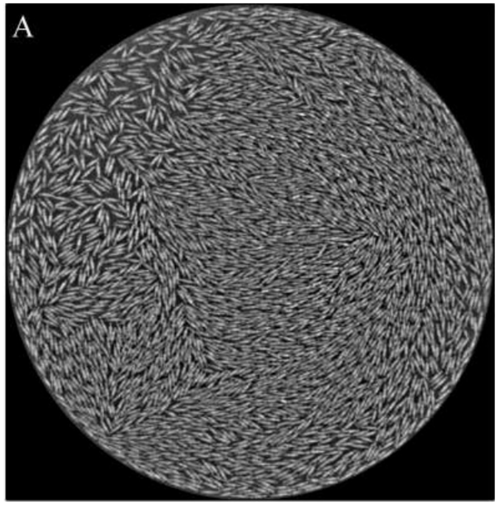


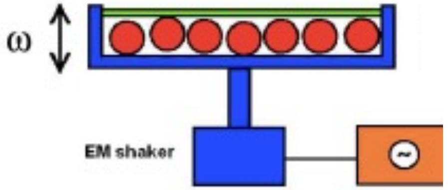


Tim Sanchez *et al.*
Nature 2012

Nematic Order Ubiquitous in Active Systems

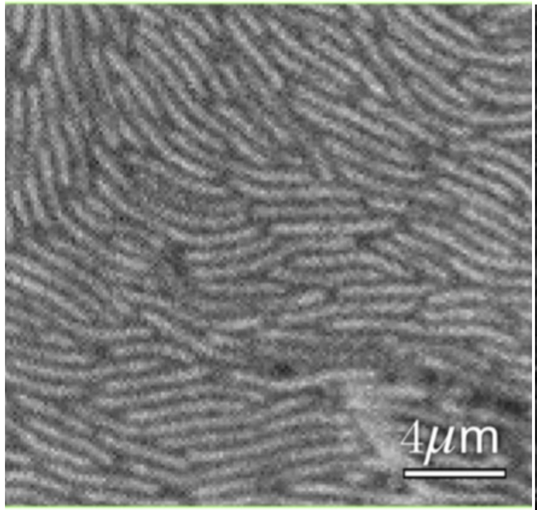
Vibrated rods





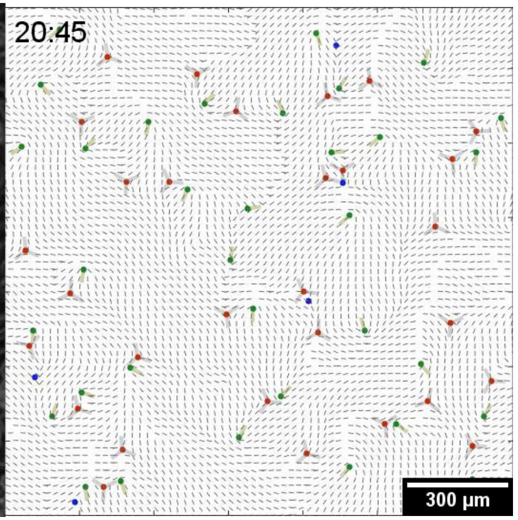
Narayan *et al.*
Science 2007

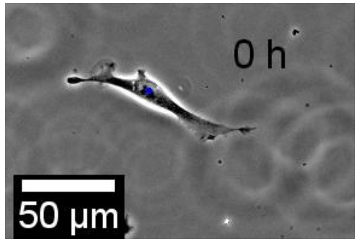
Myxococcus Xanthus



Copehangen *et al.*
Nat Phys 2020

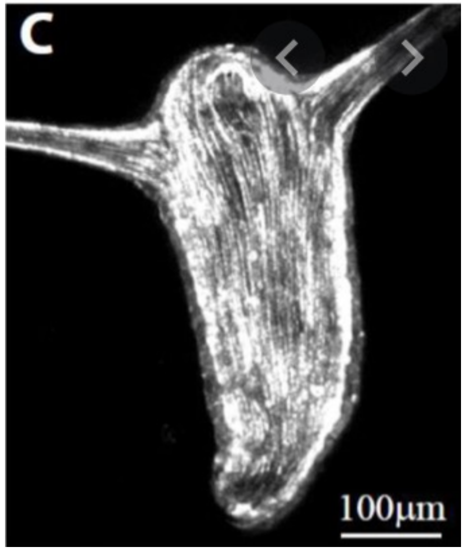
Cell sheets





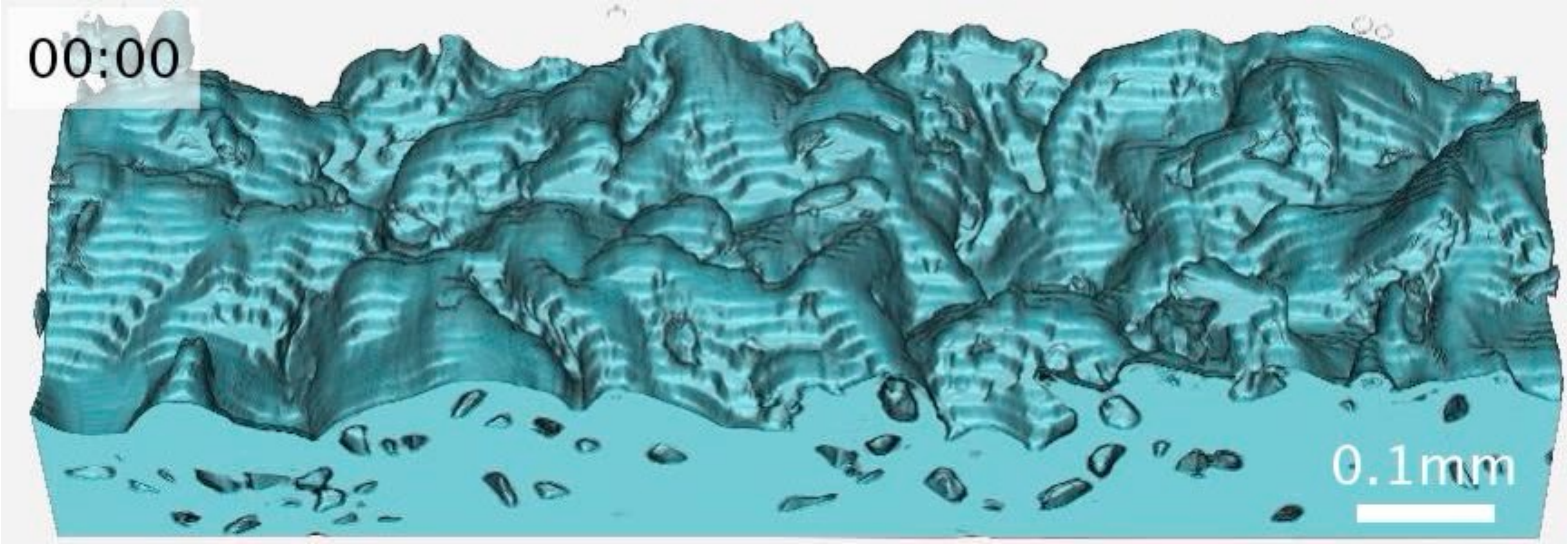
Blanch-Mercader *et al.*
PRL 2018

Hydra



Maroudas-Sacks *et al.*
Nat Phys 2020

3D realization



Liang Zhao, UCSB

- Nematic liquid crystals
- Quantifying order: Q-tensor
- Landau-de Gennes free energy
- Excitation and Topological defects
- Nematic Hydrodynamics

} Passive nematics

- Active stresses and Active nematic hydrodynamics
- Motile topological defects
- Some directions of current research

Orientational Order in Active Matter

Active units are often elongated and can align due to a variety of interactions, organizing in states with orientational order.

Two types ~~direction ≠ orientation~~ {direction $\neq$ orientation}

1) <u>polar/ferromagnetic</u> $\nearrow \nearrow \nearrow \vec{p}$ unit vector identifying molecular ~~orientation~~ ~~and~~ direction

order of polar particles

Order parameter is a vector field

I could represent the probability distribution of molecular direction w/ a function of $\vec{p}$, $\Psi(\vec{p})$

$\vec{p}$ lies on the surface of a sphere

$\int d\vec{p}\, \Psi(\vec{p}) = 1$ isotropic state $\Psi = \frac{1}{2\pi}$ 2d

First moment $\int d\vec{p}\, \vec{p}\, \Psi(\vec{p}) = \vec{m}$ order parameter

vanishes in isotropic state

2) apolar / still use a unit vector $\vec{p}$ to identify orientation, by $\vec{p} = -\vec{p}$

$\Psi(\vec{p})$ must satisfy $\Psi(\vec{p}) = \Psi(-\vec{p})$

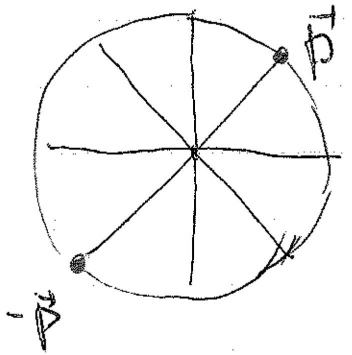
The first moment that will be $\neq 0$ is

$M_{ij} = \int d\vec{p}\, p_i p_j\, \Psi(\vec{p})$ isotropic state $M_{ij} = \frac{1}{d} \delta_{ij}$

$Q_{ij} = \int d\vec{p} \left(p_i p_j - \frac{1}{d} \delta_{ij} \right) \Psi$ de Gennes Q-tensor

More geometrically:

in 2d the space of orientations are lines through the origin – but points separated by π must be identified (of length 1)

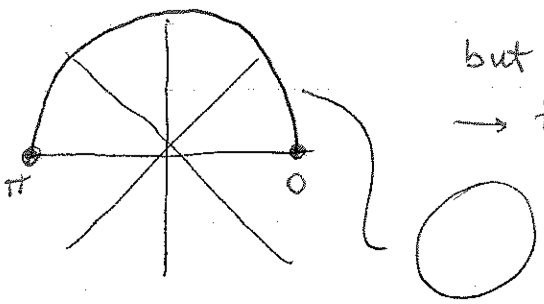


Need a quantity quadratic in $\vec{p}$ invariant for $\vec{p}, -\vec{p}$

$\vec{p} \otimes \vec{p}$ a matrix

($\vec{p} \cdot \vec{p}$ is invariant but does not identify orientation)

The space of possible $\vec{p}$ values is $\frac{1}{2}$ circle



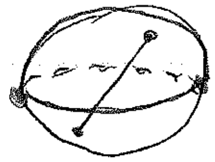
but the two red points are the same → topology of a circle

S^1 / Z_2

S^1 circle

$Z_2 = (+1, -1)$ inversion

3d antipodis identified



but all opposite point on equator are the same

S^2 / Z_2

{ACTIVE NEMATIC LIQUID CRYSTALS}

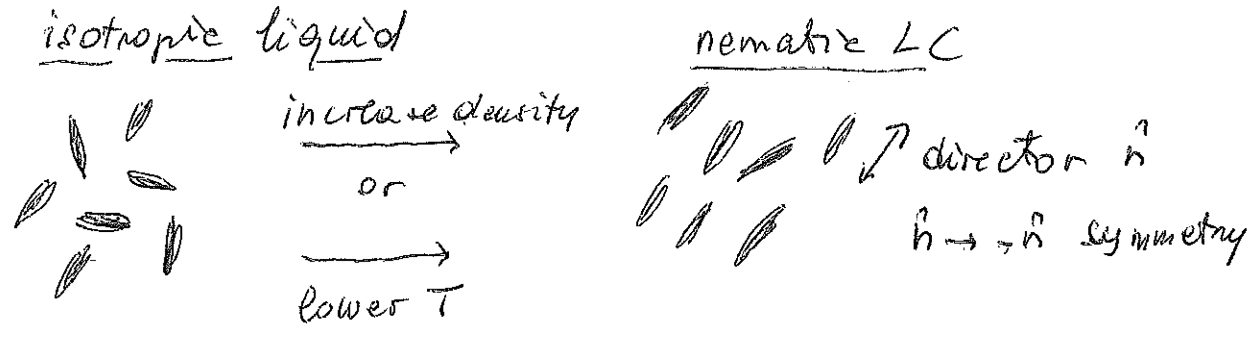
ACTIVE NEMATIC LIQUID CRYSTALS

Nematic order is seen in many biological systems, from chromosome territories to cell monolayers (epithelia, stem cells) to entire organisms.

First a brief introduction to the physics and dynamics of nematic liquid crystals, then move on to active systems.

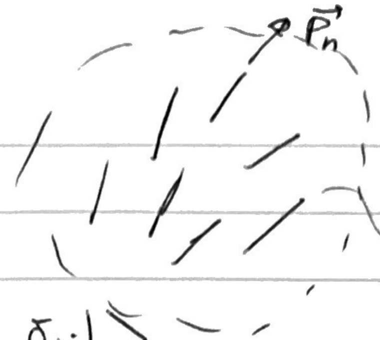
For reviews w/experimental references
- MCM et al RMP (2013) 85, 1143
- A Doostmohammadi et al Nat Comm 9, 3246 (2018)
- Bowick et al PRX 12, 010501 (2022)
- Shankar et al Nat Phys Reviews 4, 380 (2022)

Crystals have both translational (T) and orientational (O) order (long-ranged in 3d)
Liquids have neither
LIQUID CRYSTALS are fluid of rod-like molecules that can exist in states with O order, but no T order



The transition occurs in systems of purely repulsive hard rod - Onsager 1949   steric effects vs entropy

Coarse-graining



$$Q_{ij} = \left\langle \frac{1}{V} \sum_n \left(P_{ni} P_{nj} - \frac{1}{2}\delta_{ij} \right) \right\rangle$$

↑
symmetric traceless

uniaxial liquid crystal $Q_{ij}(\vec{r}) = S(r)\left(n_i n_j - \frac{1}{2}\delta_{ij}\right)$

$$Q = \frac{S}{2}\begin{pmatrix} \cos 2\vartheta & \sin 2\vartheta \\ \sin 2\vartheta & -\cos 2\vartheta \end{pmatrix}$$

S = magnitude of nematic order

$Q \to S e^{2i\vartheta}$

$\vec{n}(\vec{r})$ director $|\vec{n}| = 1$

Onsager 1949 isotropic-nematic transition
in hard thin repulsive rods.

Gain entropy and lower free energy by aligning

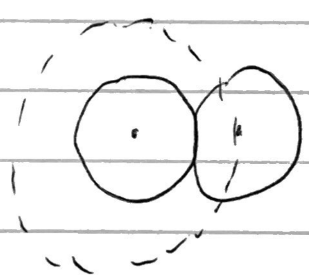
$S = k_B \ln(\#\text{states})$

ideal gas $S \sim k_B \ln V^N$

excluded volume $S \sim k_B \ln (V - N_{ex})^N$

S increases as N_{ex} decreases

aligned rods have smaller N_{ex}



Continuum level:

Order Parameter field of a uniaxial nematic is a symmetric, traceless, rank-2 tensor

$$Q_{ij}(\vec{r},t) = S(\vec{r},t)\left[n_i(\vec{r},t)\, n_j(\vec{r},t) - \frac{1}{d}\delta_{ij}\right]$$

S → magnitude of order

$S = 0$ disordered

$S = 1$ ordered

$\vec{n}(\vec{r},t)$ director

$|\vec{n}| = 1$

direction of spontaneously broken symmetry

Energy and dynamics must respect $\vec{n} \to -\vec{n}$ symmetry

→ Landau - de Gennes free energy

Landau - de Gennes free energy

describes ground states and excitations

invariants $\mathrm{Tr}\,Q^2 \sim S^2$, $\mathrm{Tr}\,Q^3 \sim S^3$, $(\mathrm{Tr}\,Q^2)^2 \sim S^4$

2d $\quad \mathrm{Tr}\,Q^3 = 0$

$$F_{GL} = \int d\vec{r} \left\{ \frac{A(\rho)}{2} \mathrm{Tr}\,Q^2 + \frac{B}{4} (\mathrm{Tr}\,Q^2)^2 + \frac{K}{2} (\partial_i Q_{jk})^2 \right\}$$

↑ different elastic constants

$A(\rho) < 0$ ordered state

$S^2 = -A/B \to 1$

$\vec{n} = (\cos\vartheta, \sin\vartheta)$ spontaneously broken symmetry

We will work deep in the nematic state where $S \sim \mathrm{const} = 1$

Free energy of director distortions (Frank)

$$F = \frac{1}{2} \int d\vec{r}\; K (\nabla n)^2$$

3d

bend

K_3

splay

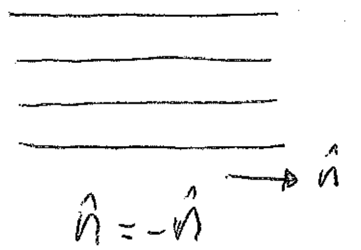
K_1

twist

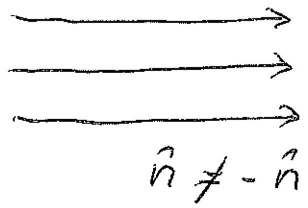
K_2

Topology describes properties that are conserved under continuous deformations of shape

Ground state



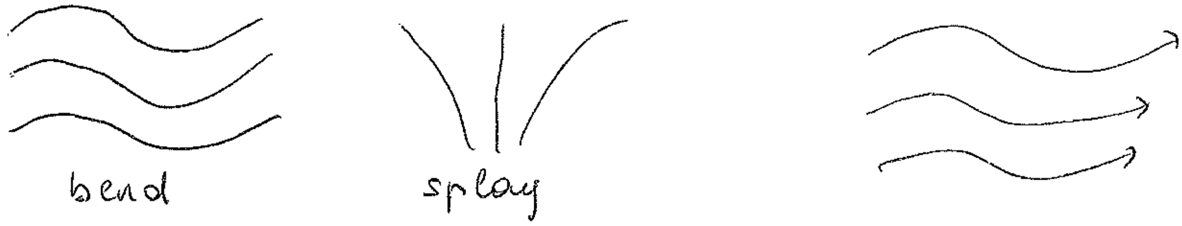
Compare to ferromagnetic / polar g.s



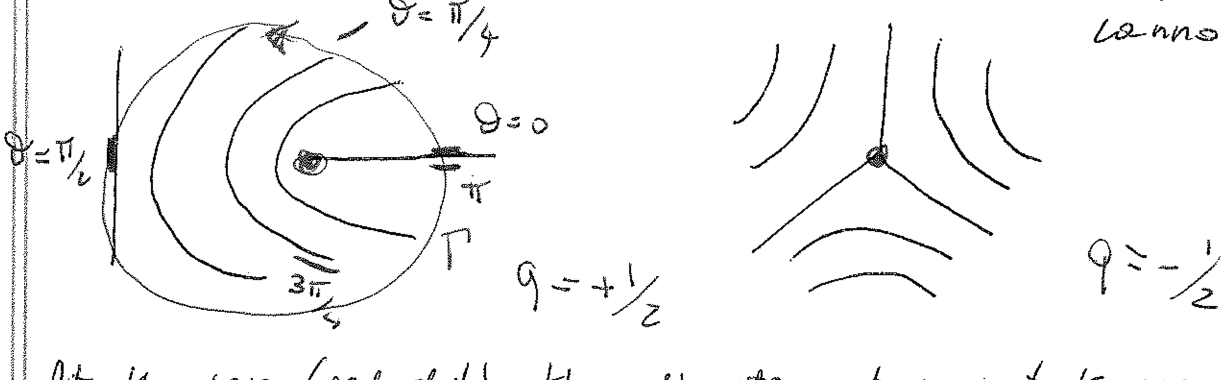
We will work deep in the ordered state where $S=1$ and only consider deformations of the director field. This is just to simplify our life and work with vectors instead of tensors.

Also for simplicity we consider 2 dim

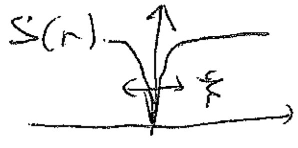
<u>Smooth deformations</u> "spin waves"



<u>Singular distortions</u> : topological defects – a tear in the OP field that cannot be patched



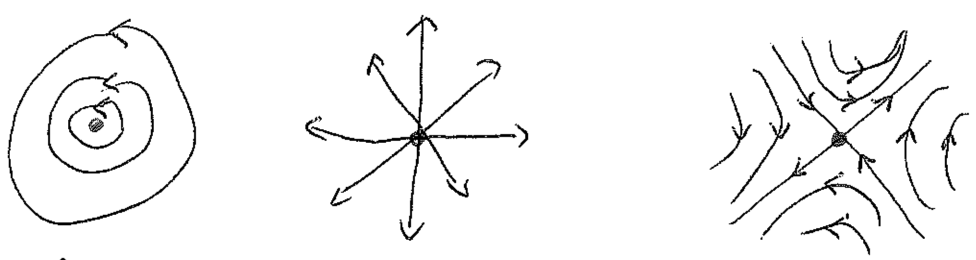
At the core (red dot) the director does not know where to point (and $S \to 0$)



charge or winding number $q = \frac{1}{2\pi} \oint_\Gamma d\vartheta$ — net angle through which the OP rotates as one circles the defect

$q = \pm 1/2$ defects → disclinations

<u>Vector field</u> - let us compare. cannot have $\pm 1/2$ defects



$q = +1$ $q = +1$ $q = -1$

A nematic can have charge $q = \pm 1$ defects
But the energy cost for creating a defect $\sim q^2$
Hence ± 1 defects cost 4 time more energy - a $+1$ will decay in 2 $+1/2$.

- Topological charge is conserved
- ~~Planar~~ Net topological charge is zero in the plane, $+2$ on a sphere, $+1$ in a disc
- In 3d defects are lines and loop.

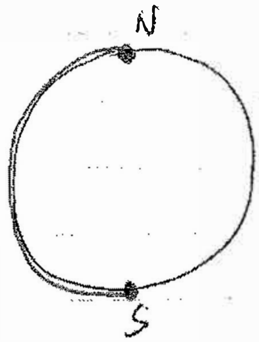
- global excitations
- quasiparticles : in 2d the stat phys of defects can be mapped out that of Coulomb charges

$$V(r) = 2\pi K q_i q_j \ln\left(\frac{|r_{ij}|}{a}\right)$$ like repel, unlike attract

- fingerprint of broken symmetry

Topological defects are noncontractable ~~paths~~ ~~that~~ windings of the order parameter in the OP space

On a sphere a closed loop from the N to the S pole is contractable



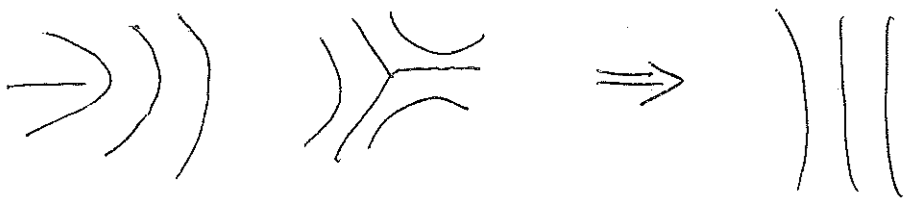
but in a nematic N and South are the same point So the red path is a closed loop but it is not contractable

It cannot be shrunk to zero without by a continuous deformation → must cut

Due to inversion symmetry the basic defects in 2d nematics are 180° windings → defined as charge ½

topological invariant
handles ⟷ topological defects

2d order/disorder transitions as defect unbinding
BKT



Well established description of passive LC in terms of Landau - de Gennes free energy.

To describe active LC we need dynamics.
First dynamics of passive liquid crystals.

Fluid dynamics → Hydrodynamics (more general)
ρ density field $\quad \partial_t \rho + \vec{\nabla} \cdot \rho \vec{v} = 0$
$\vec{v}$ flow velocity → NS equation
[ε energy density] will not consider
incompressible flows $\rho = \text{const}$, $\vec{\nabla} \cdot \vec{v} = 0$

Navier-Stokes equation (essentially $m \frac{d\vec{v}}{dt} = \vec{F}$)

$$\rho\left(\partial_t \vec{v} + \vec{v} \cdot \vec{\nabla}\right) \vec{v} = \underbrace{-\vec{\nabla} p + \eta \nabla^2 \vec{v}}_{\text{Force density on fluid element}}$$

When inertia is negligible* → just force balance

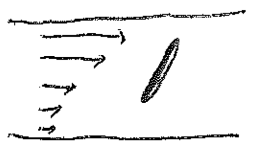
$$0 = -\vec{\nabla} p + \eta \nabla^2 \vec{v} \qquad \text{Stokes equation}$$

---

* low Re number $\quad Re \sim \frac{\text{inertia}}{\text{viscous dissipation}} \sim \frac{v^2 \rho / L}{\eta v / L^2}$

$$Re \sim v L \rho / \eta$$

LC HYDRODYNAMICS



shear and vortical flows rotate LC molecules
→ deform director

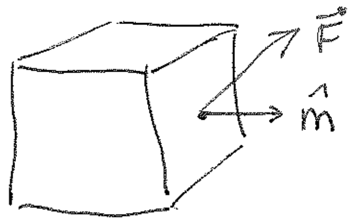
coupling of orientation and flow

coupled dynamics of $\vec{v}$ and $\hat{n}$

$$\rho\,\partial_t \vec{v} = \eta \nabla^2 \vec{v} - \vec{\nabla} p + \vec{\nabla}\cdot \overleftrightarrow{\sigma}^{el}$$

↑ elastic stress associated with energy cost of deforming order

stress tensor = force/area
but it is a tensor



$\hat{m}$ unit vector denotes direction of surface area

σ_{ij} i-th component of force on an area ⊥ m_j

$\sigma^{el}_{ij} \sim n_i K \nabla^2 n_j$ we will neglect it below

$$* \quad \partial_t n_i + \vec{v}\cdot\vec{\nabla} n_i \ddagger + \omega_{ij} n_j = \lambda u_{ij} n_j + \frac{K}{\gamma} \nabla^2 n_i$$

‡ should enforce $|\hat{n}|=1$ w/ Lagrange multiplier

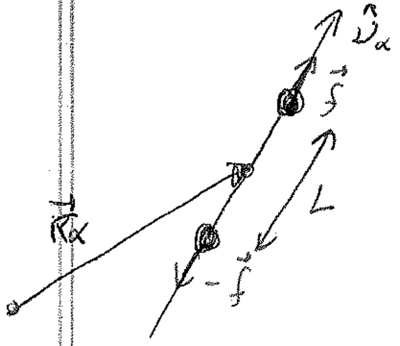
$$\omega_{ij} = \frac{1}{2}\left(\partial_i v_j - \partial_j v_i\right) \rightarrow \vec{\nabla}\times\vec{v} \quad \text{Vorticity}$$

$$u_{ij} = \frac{1}{2}\left(\partial_i v_j + \partial_j v_i\right) \quad \text{strain rate}$$

λ microscopic parameter that depends on molecular shape

K stiffness K_1 splay $\neq K_3$ bend ($+ K_2$ twist in 3d)

Active forces → ACTIVE STRESS



force on surrounding fluids

$$F_i = \sum_\alpha \left[f \hat{\nu}_{\alpha i}\, \delta\!\left(\vec r - \vec R_\alpha - \frac{L}{2}\nu_\alpha\right) - f \hat{\nu}_{\alpha i}\, \delta\!\left(\vec r - \vec R_\alpha + \frac{L}{2}\hat{\nu}_\alpha\right) \right]$$

lenght scales >> L

$$F_i \simeq \sum_\alpha f \nu_{\alpha i} \left(-\frac{L}{2}\nu_{\alpha j}\partial_j \delta(\vec r - \vec R_\alpha) - \frac{L}{2}\nu_{\alpha j} \frac{\partial}{\partial r_j} \delta(\vec r - \vec R_\alpha) \right)$$

$$= - f L \partial_j \sum_\alpha \nu_{\alpha i} \nu_{\alpha j}\, \delta(\vec r - \vec R_\alpha)$$

$$= - f L \partial_j \sum_\alpha \left(\nu_{\alpha i}\nu_{\alpha j} - \frac{1}{d}\delta_{ij} \right) \delta(\vec r - \vec R_\alpha) - f L \partial_j \sum_\alpha \delta(\vec r - \vec R_\alpha)$$

$F_i(\vec r) = + \partial_j\, \alpha\, Q_{ij}(r)$ + active pressure gradient

Active stress $\quad \sigma^a_{ij} = \alpha Q_{ij} \sim \alpha n_i n_j \qquad S \simeq 1$

α dimensions of stress - activity

$\alpha < 0$ extensile

$\alpha > 0$ contractile

Active LC hydrodynamics

$$\rho \partial_t \vec v = - \vec\nabla p + \eta \nabla^2 \vec v + \vec\nabla \cdot \left(\overleftrightarrow{\sigma}^a + \overleftrightarrow{\sigma}^{el} \right)$$

(neglect $\overleftrightarrow{\sigma}^{el}$)

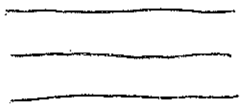
$$\vec\nabla \cdot \vec v = 0$$

Stokes limit

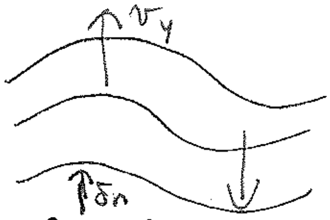
irrotational part of $\vec{v}$ $\qquad \eta \nabla^2 \vec{v} + \vec{\nabla} \cdot \overleftrightarrow{\sigma}^a = 0$

↑ active stress as a source of flow

ACTIVE NEMATICS ARE UNSTABLE



$\hat{n} = \hat{x}$



$\hat{n} = \hat{x} + \hat{y}\, \delta n(x)$

bend deformation

$$\left.\begin{aligned} \eta\, \partial_x^2 v_y &= \alpha\, \partial_x \delta n_y \\ \partial_t \delta n_y &= \frac{\lambda + 1}{2}\, \partial_x v_y \end{aligned}\right\}$$

Fourier modes

$$v_y = \frac{\alpha}{2} \frac{iq}{q^2} \delta n_y$$

$$\partial_t \delta n_y = \frac{\lambda+1}{2} iq v_y = -\frac{\alpha}{2} \delta n_y$$

$|\alpha|/\eta$ rate of energy injection

unstable growth for $\alpha < 0$ extensile any $|\alpha|$

contractile systems are unstable to splay

inclusion of elasticity reveals a length scale for most unstable modes

$$\frac{K}{\ell^2} \sim |\alpha| \Rightarrow \ell_\alpha = \sqrt{\frac{K}{|\alpha|}} \sim 100\,\mu m$$

in MT nematics

Can be stabilized below α_c by

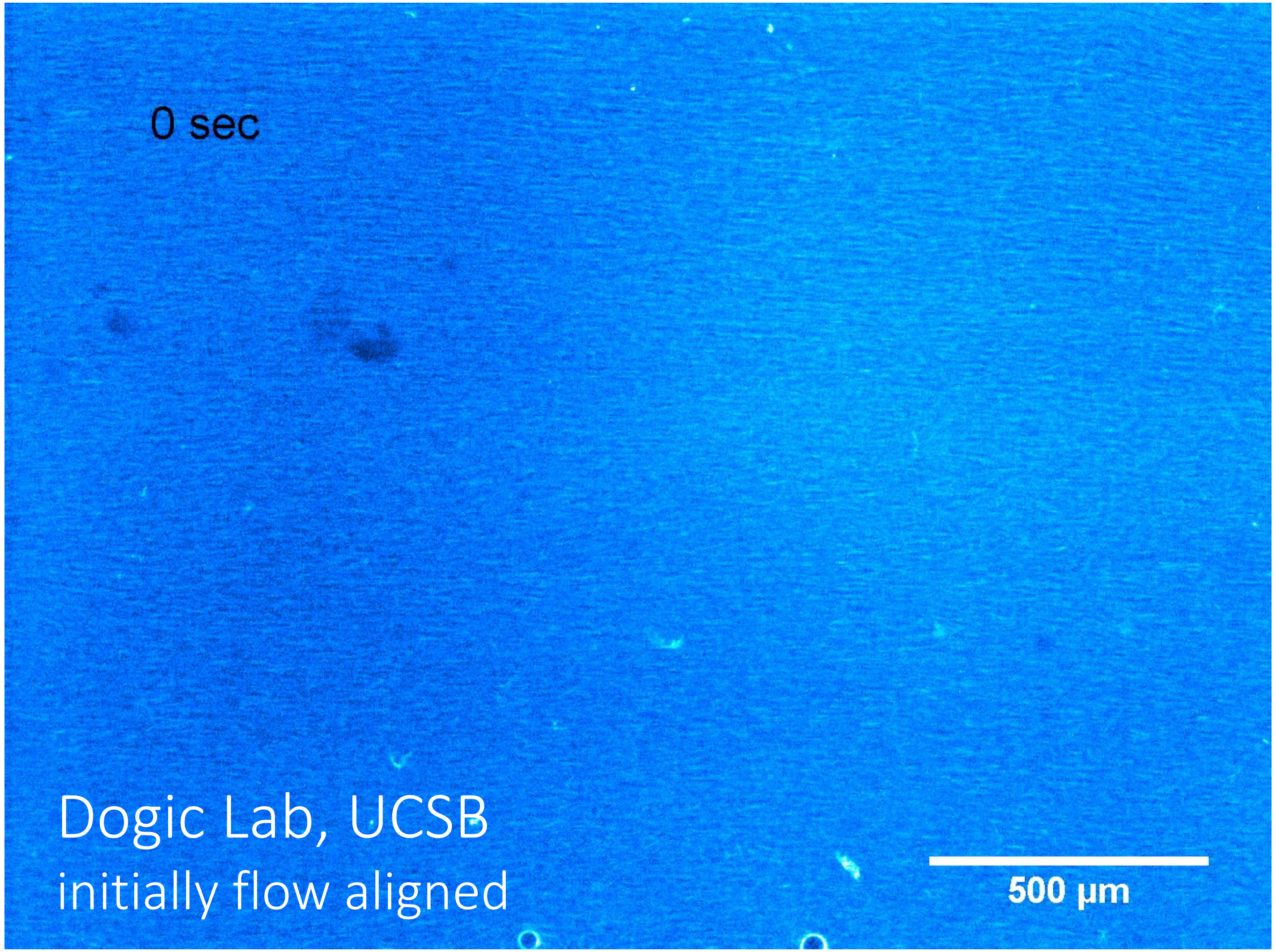
- substrate
- confinement
- viscoelasticity

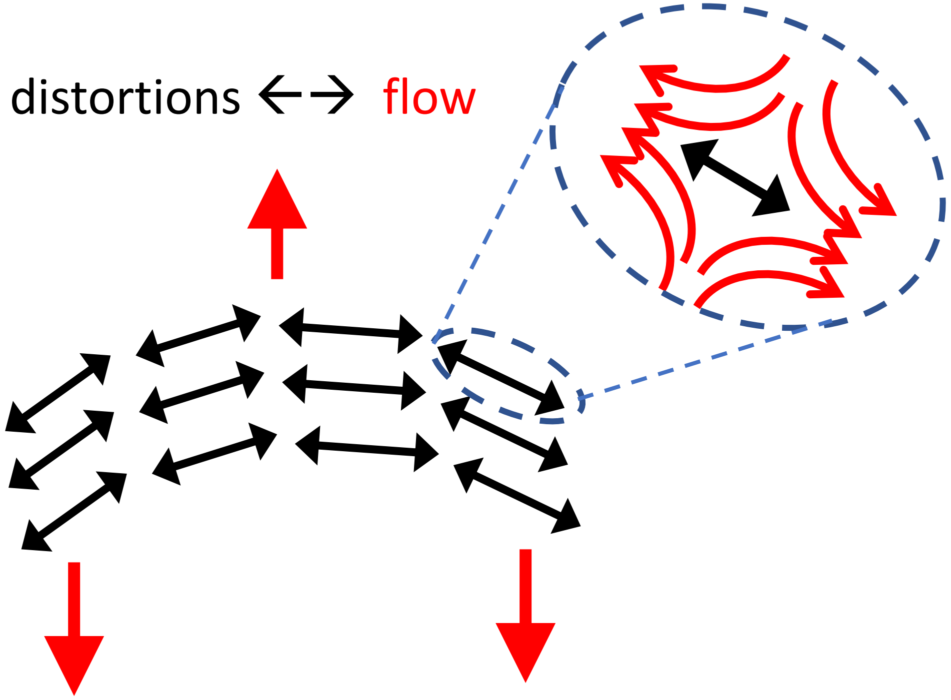
} any mechanism that screens flows

$$\Gamma \vec{v} = \eta \nabla^2 \vec{v} + \nabla \cdot \sigma^a \qquad \ell_\eta = \sqrt{\eta/\Gamma}$$

Active hydrodynamics predicts linear instability

predicted theoretically Simha & Ramaswamy 2002





elastic stress K/ℓ^2 $\sim$ active stress α

$$\ell = \sqrt{\frac{K}{\alpha}}$$

Active Nematics flow spontaneously

No external forces needed

$$\sigma_{xy} = 0 = \eta\, \partial_y v_x + \alpha\, n_x n_y$$

L vs l_α

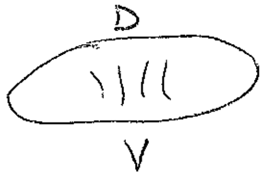
$L < l_\alpha$	$L > l_\alpha$	$L \gg l_\alpha$
anchoring and elasticity win → no flow	spontaneous laminar flow	chaotic flow "active turbulence" + topological defects

seen in MT nematic, cell monolayers } quantitative comparison

Active stress as source of flow in Drosophila embryo during gastrulation.

Independently measure pattern of myosin → nematic tensor and cellular flows

Streichan Elife 2019 anisotropic myosin stresses with nematic alignment dorso-ventral



drives flows during gastrulation (from 1 layer of cells to many)

Back to the defects.

Nematic order in fibroblasts : TR Elsdale 1968 (Edinburgh)

"patchwork of aligned groups of parallel cells with narrow interstices between them that we will term <u>frontiers</u>"

Now nematic order in many active systems interrupted by topological defects

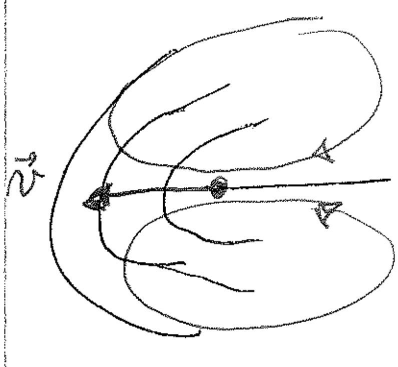
- defects are often motile
- opposite signs may "repel"
- biological function of defects : cell extrusion/death
  - morphogenesis
  - fruiting body

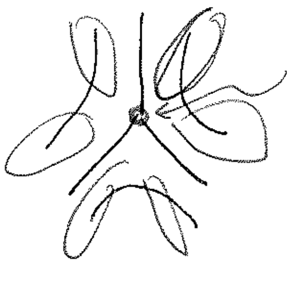
<u>Why are active defects motile?</u>

we saw that distortions of orientation generate flows

$$\eta \nabla^2 \vec{v} = -\alpha \vec{\nabla} \cdot \hat{n}\hat{n}$$

insert defect texture and calculate resulting flow





$v \sim \alpha/2$

Motility of +1/2 defects

- Order parameter deformations generate flow
- TRS-breaking active stresses + geometric polarity of +1/2 defect → autonomous motility

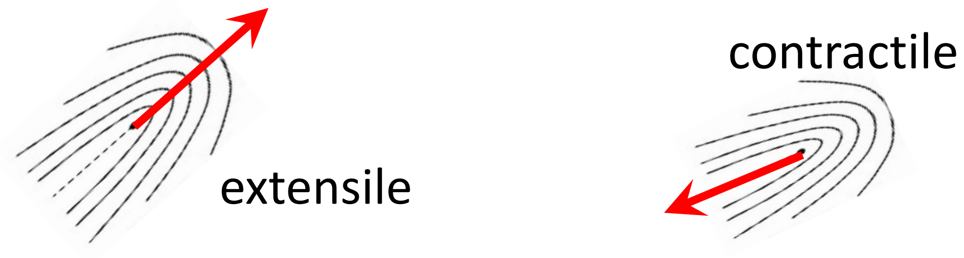
Motility from active flows:

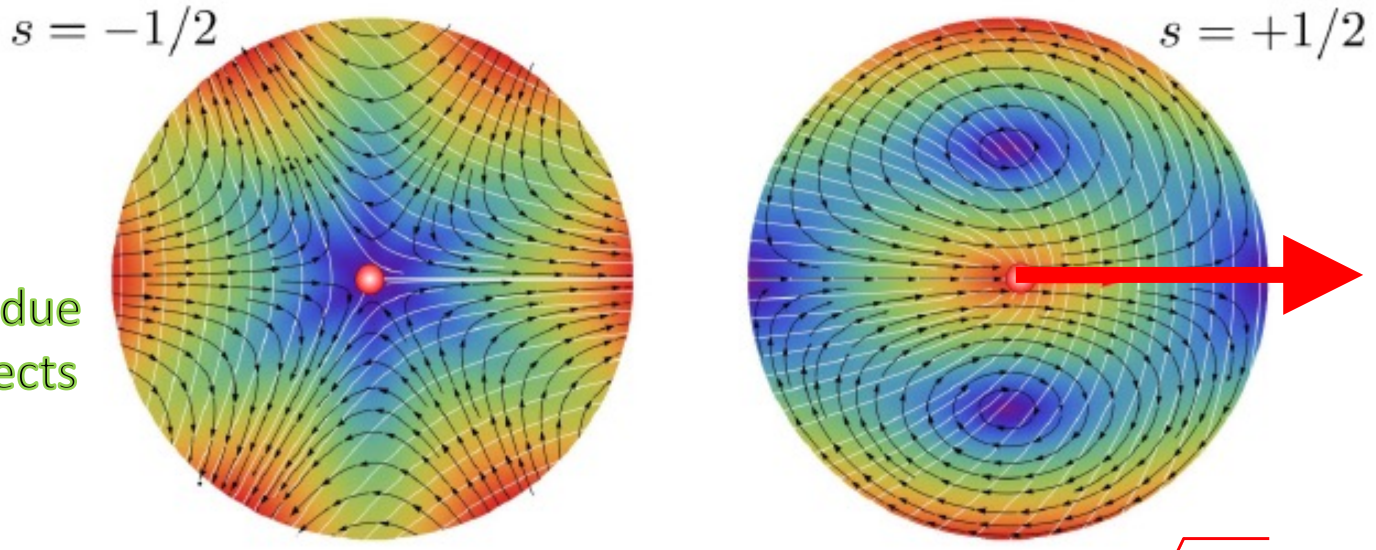
$$\Gamma \mathbf{u} - \eta \nabla^2 \mathbf{u} = \alpha \nabla \cdot \mathbf{Q}$$

Defect rides with self-generated flow

$$\zeta \left[\partial_t \mathbf{r} - \mathbf{u}(\mathbf{r}) \right] = \mathbf{F}(\mathbf{r})$$

Elastic force due to other defects





$$v_{core} = 0$$

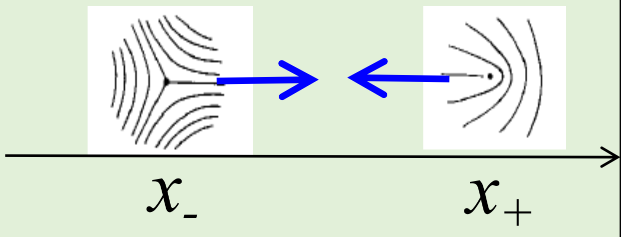
$$v_{core} = |\alpha| / \sqrt{\eta \Gamma}$$

Direction of motion of +1/2 reveals the nature of active stress

Giomi, Ma, Bowick, MCM, PRL 2013; Pismen, PRE 2013
J Rønning, MCM, MJ Bowick, L Angheluta, Proc R Soc A 2022

Active Defects as ``Self-Propelled'' Particles

In equilibrium defects can be described as ``charged'' particles with known interactions. Opposite-sign defects attract and annihilate



Pair dynamics and annihilation controlled by balance of *friction* and ***attraction***

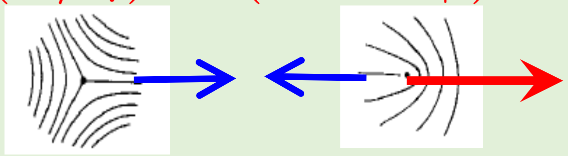
$$x = x_+ - x_- \qquad \gamma \dot{x} = -\nabla \left[K \ln(x/a) \right]$$

In active systems defects ride with the active backflow and behave as self-propelled particles.

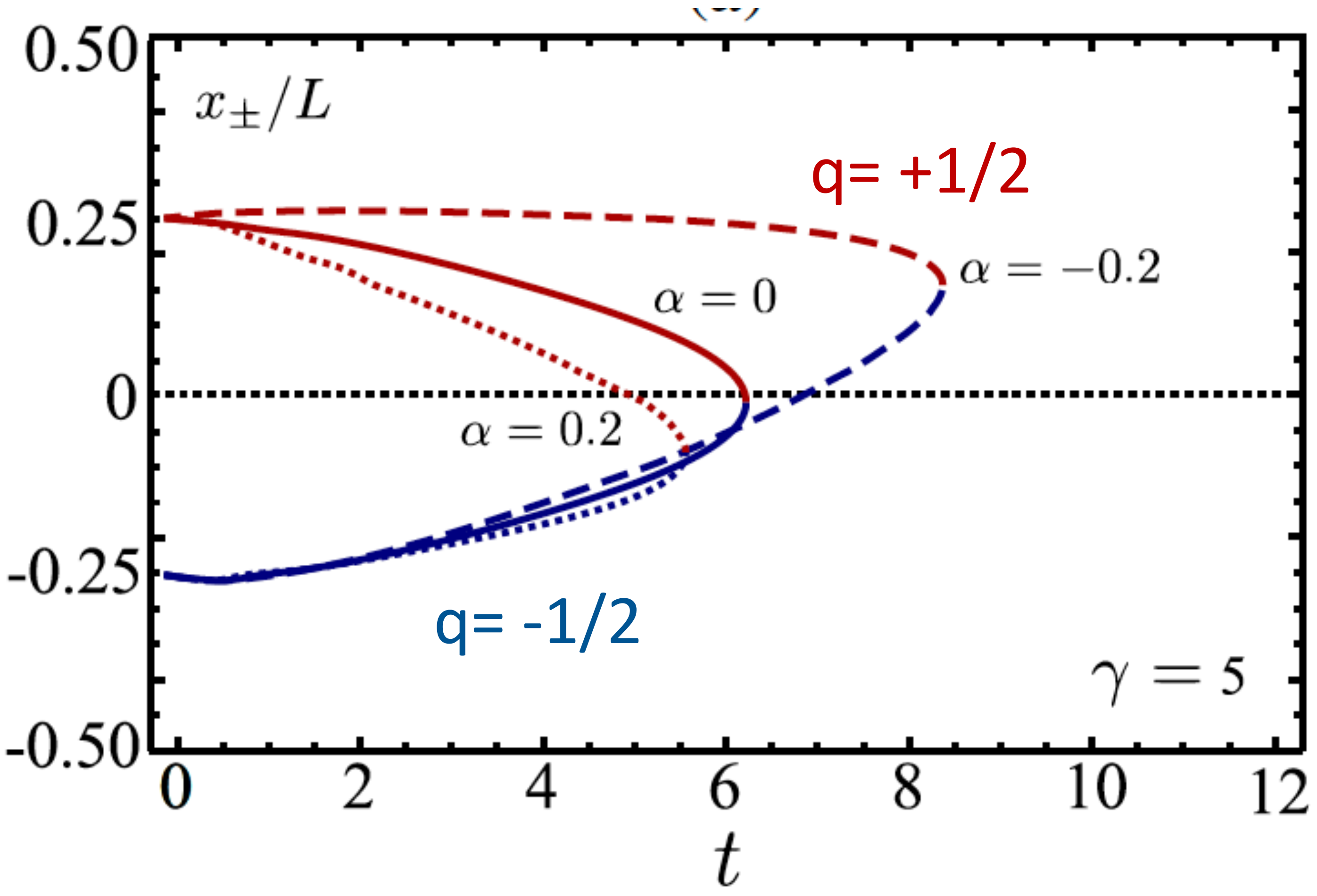
$$\gamma \left[\dot{x}_\pm - v_b(x) \right] = -\nabla \left[K \ln(x/a) \right]$$

$$v_b(x) \simeq -(\alpha/\eta) R \delta(x - x_+)$$

Activity may overcome attraction



Defect Trajectories



Giomi, Ma, Bowick, MCM, PRL 2013

Three directions of current research on active nematics

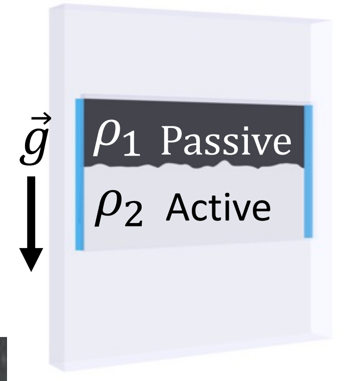
- Activity as a handle for tuning interfacial properties: large fluctuations, wetting, active emulsions (with Zvonimir Dogic)

- Tuning activity in space and time to control flows in active fluids and deformations and shape in active gels

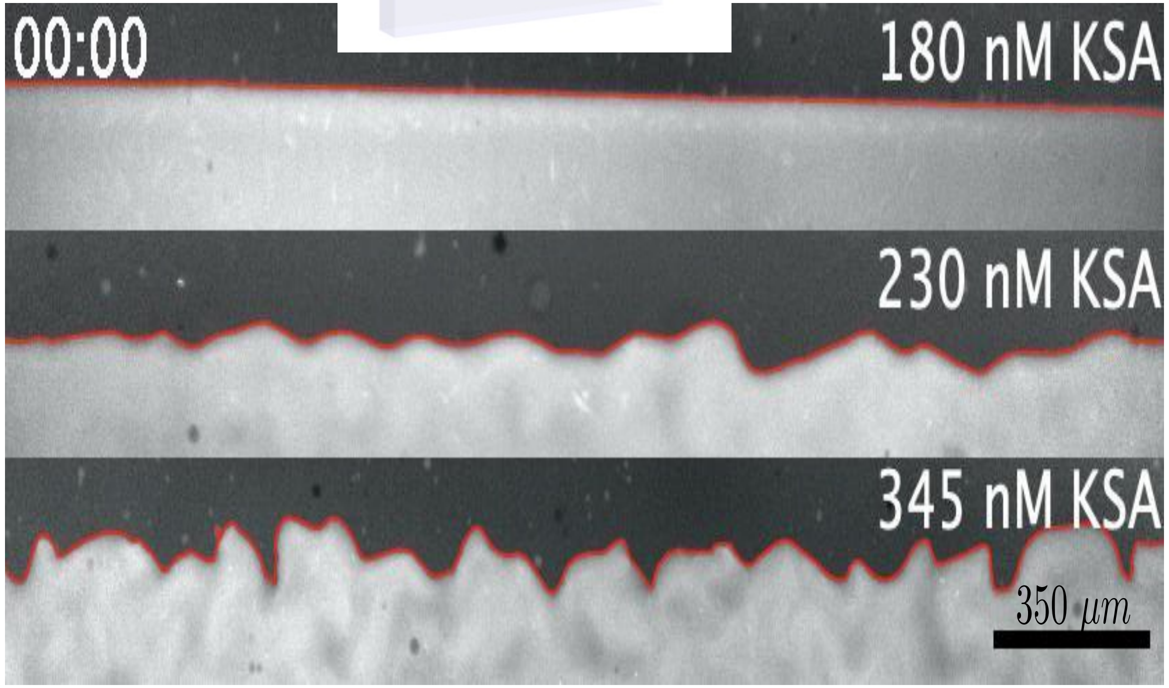
- Active nematic *solids*: defects as centers of stress focusing → *Hydra* development

Giant fluctuations & traveling waves at active/passive interfaces

R Adkins *et al.*, *Science* Aug. 2022; F Caballero, MCM, PRL 2022
AM Tayar *et al.* Nat Mat 2023; L Zhao *et al.* , *arXiv 2024*
P Gulati *et al. arXiv 2024*

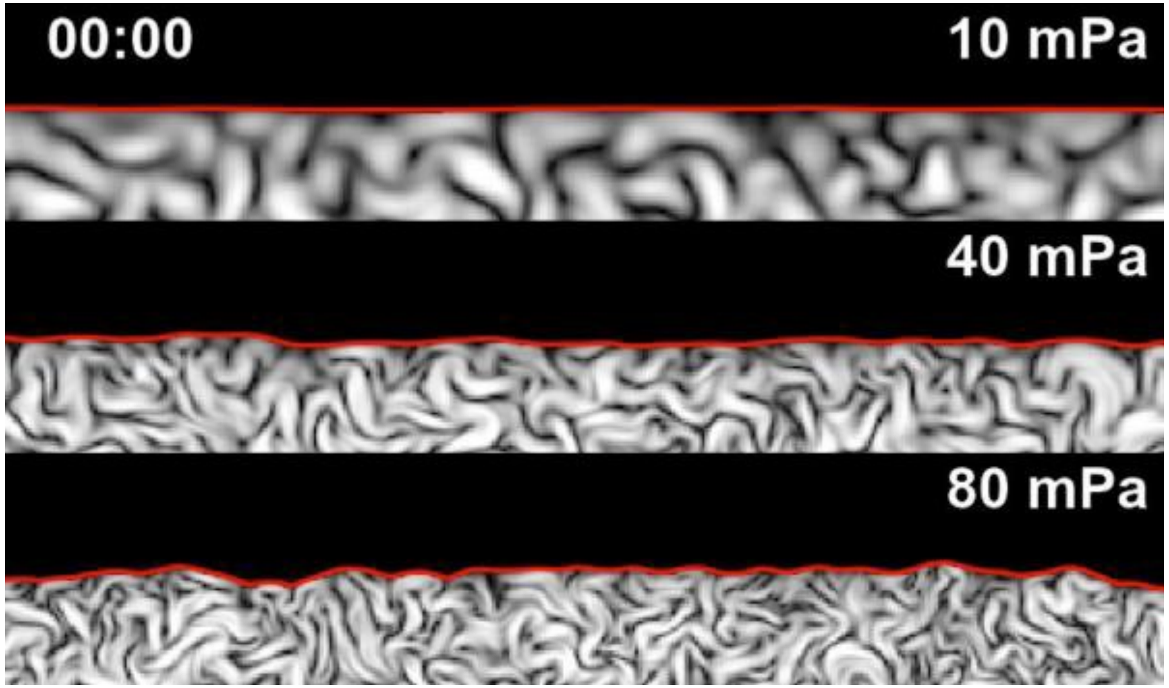


Increasing kinesin concentration



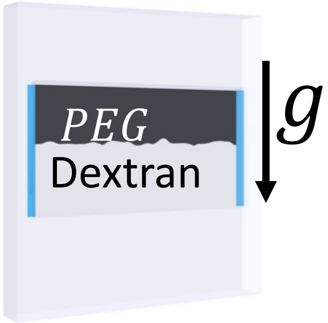
experiments

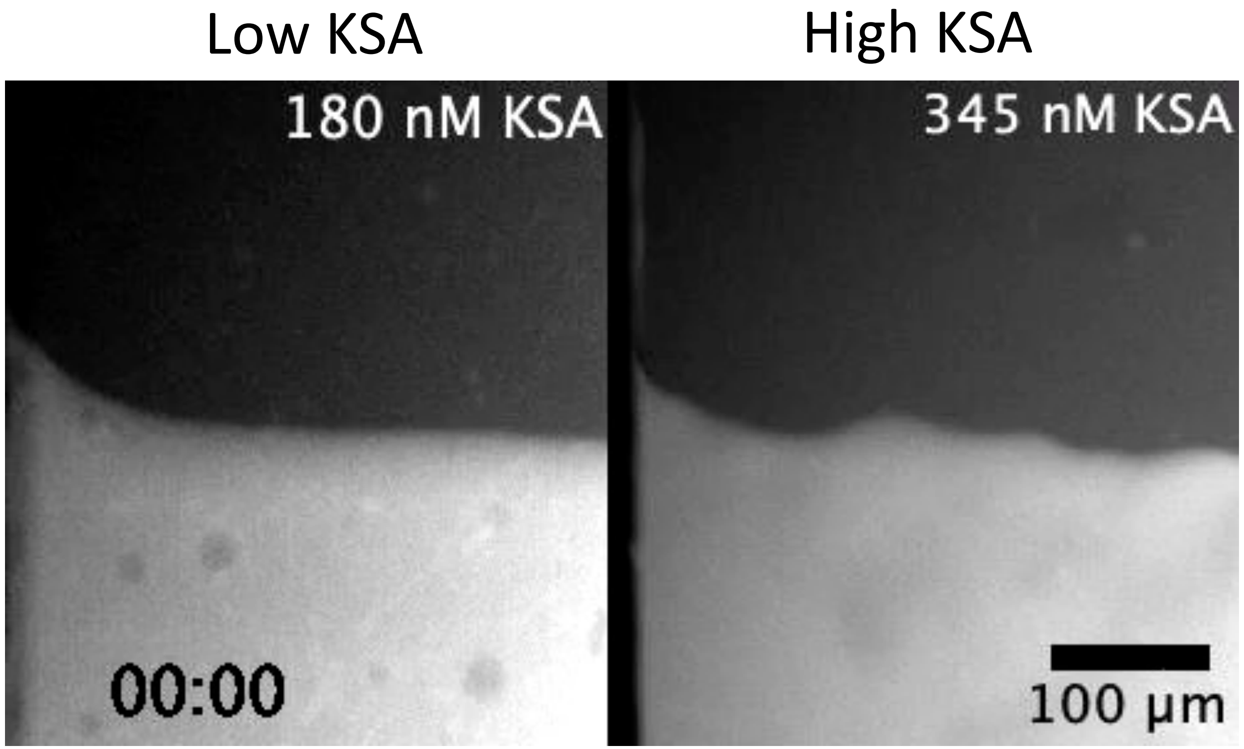
Increasing activity $|\alpha|$



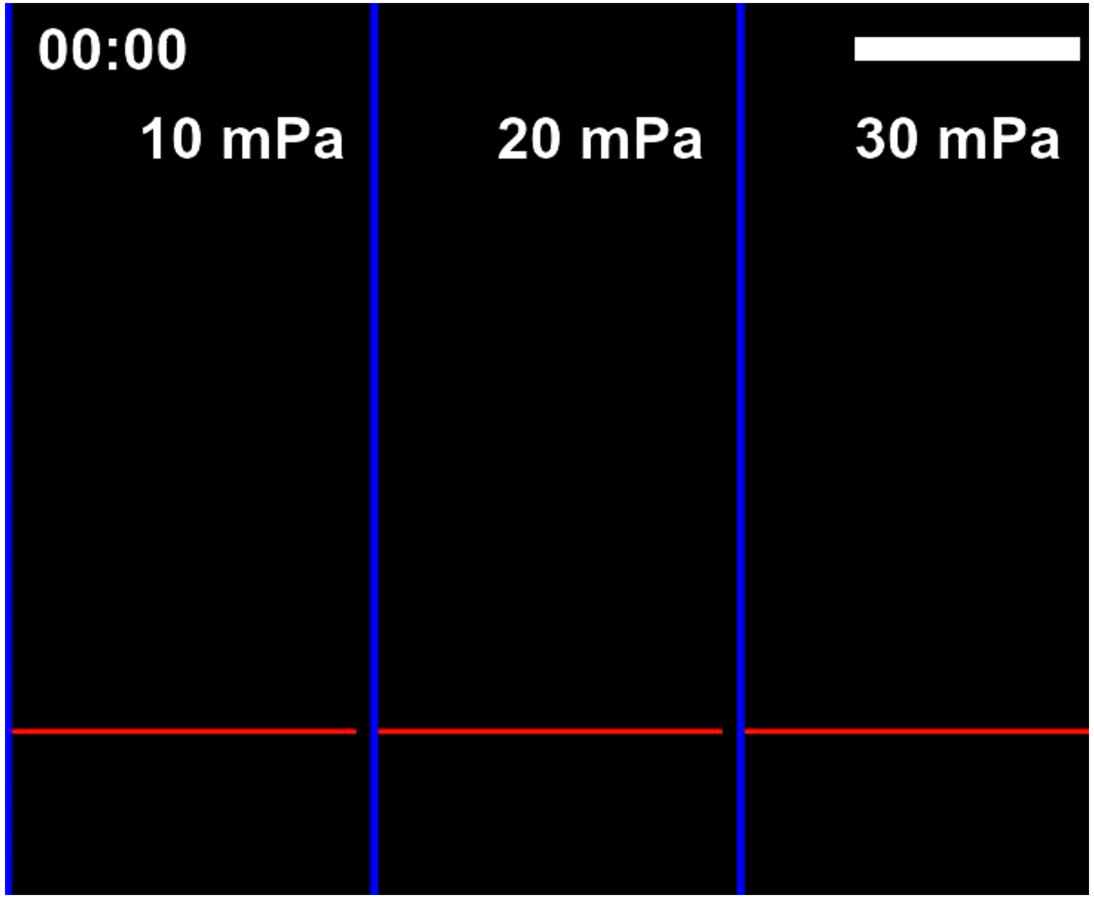
simulations

Active Wetting



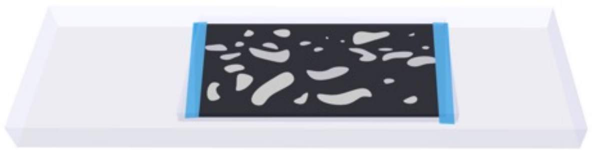


experiments



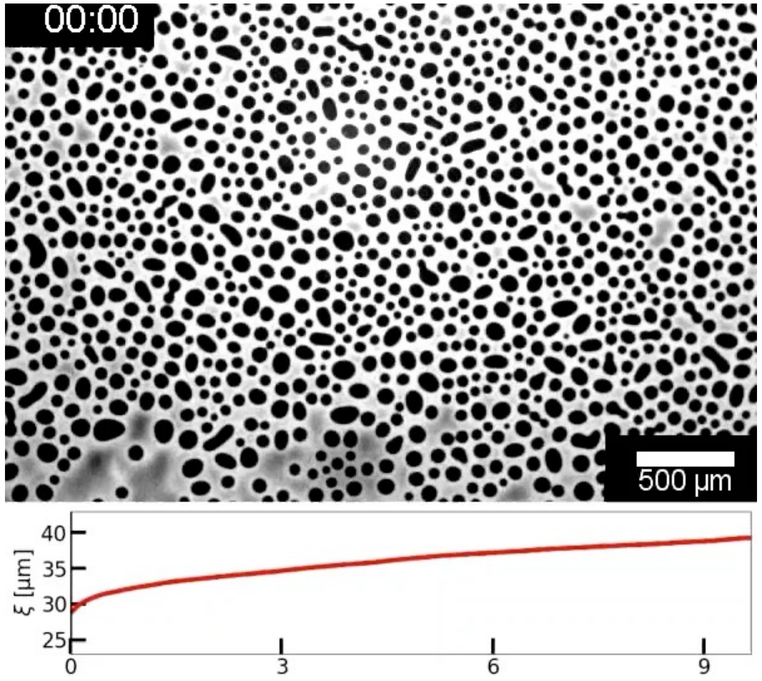
simulations

Active Emulsions: activity speeds up then arrests coarsening

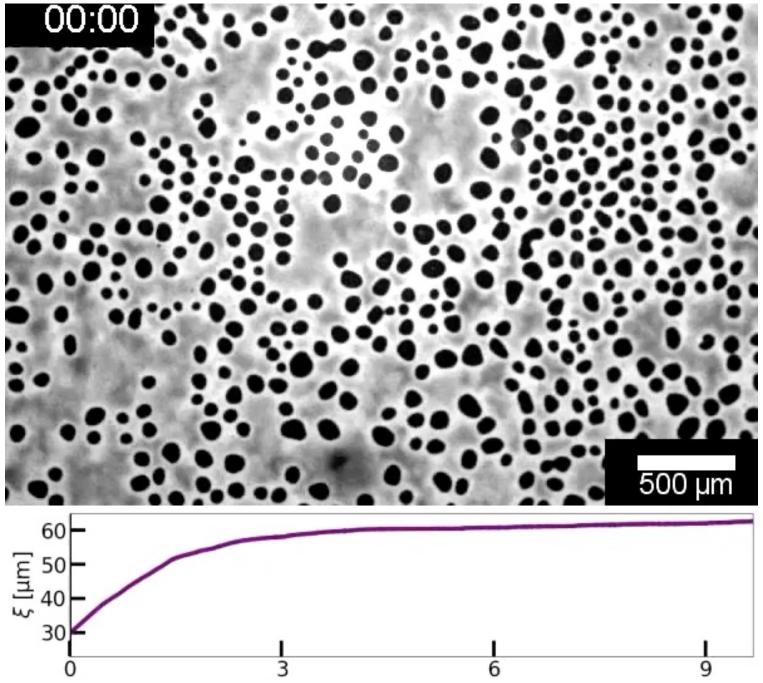


activity

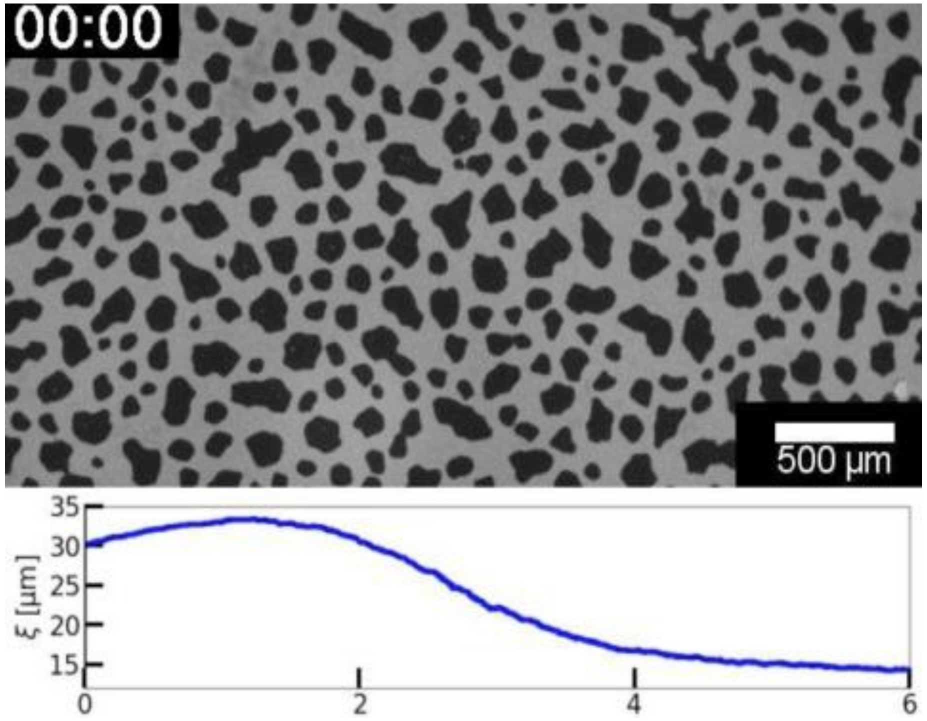
Steady state is an active emulsion



KSA 0 nM

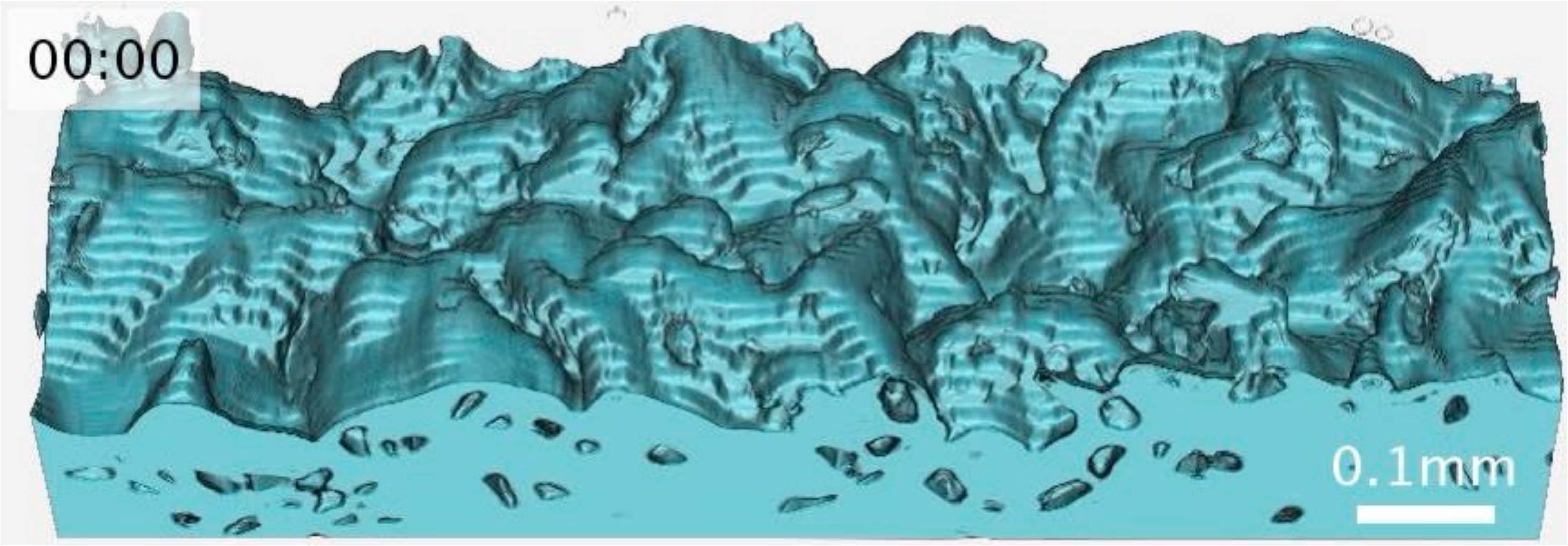


KSA 135 nM



KSA 230 nM

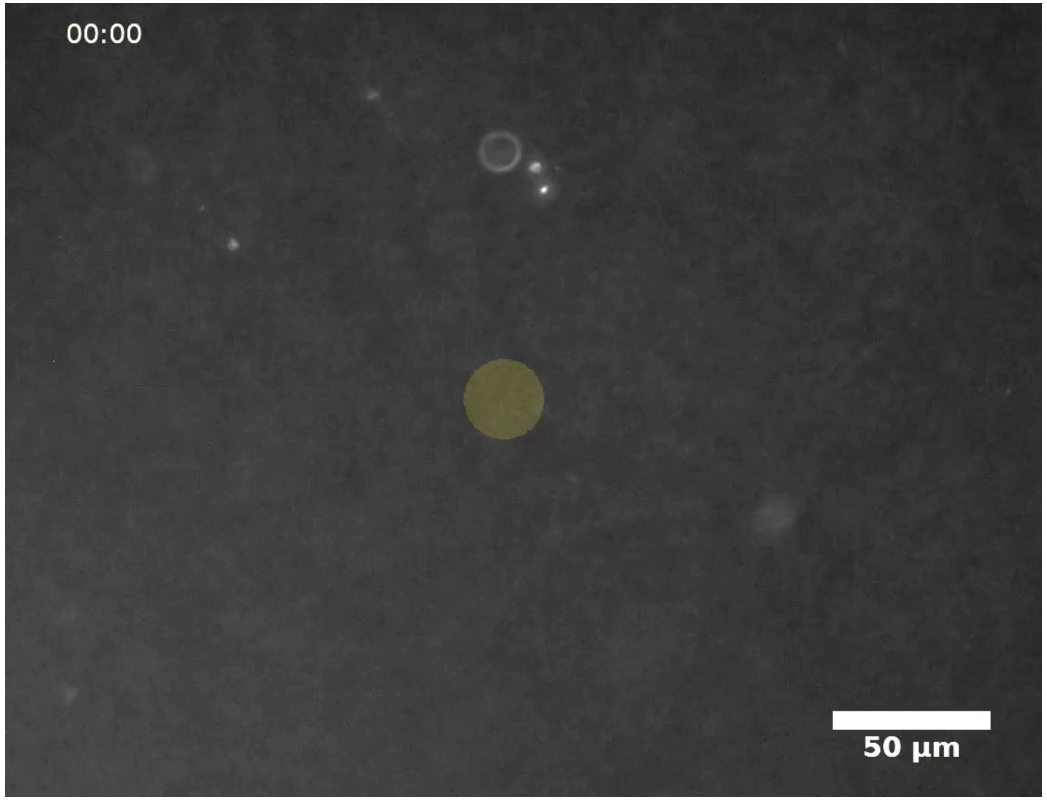
And 2D active interfaces



Liang Zhao, UCSB

Patterning activity to control defects in space & time

Optogenetically modified motor proteins allow spatiotemporal control of activity in cytoskeletal suspensions



T Ross *et al*. Nature 2019

Light-sensitive kinesins and microtubules

Asters track the light pattern up to 200 nm/s

Also: R Zhang, Nat Mat 2021, …

Constructing spatiotemporal profiles of active stresses to achieve a target configuration of active defects and flow

Suraj Shankar

Luca Scharrer

Linearity of Stokes dynamics allows us to construct a symmetry-based additive approach

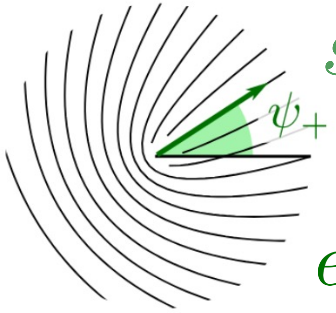
$$\ell_\eta^2 \nabla^2 \mathbf{u} - \mathbf{u} + \Gamma^{-1}\nabla \cdot \alpha(\mathbf{r},t)\mathbf{Q} - \Gamma^{-1}\nabla p = 0 \qquad \nabla \cdot \mathbf{u} = 0$$

Flow structure dictated by combined symmetry of defect texture ***Q*** and activity field α

defect velocities
$$\begin{cases} \mathbf{v}_0 = \lim_{r\to a} \int_0^{2\pi} d\phi \; \mathbf{u}(r,\phi) \\ \boldsymbol{\omega}_0 = \lim_{r\to a} \int_0^{2\pi} d\phi \; \boldsymbol{\nabla} \times \mathbf{u}(r,\phi) \end{cases}$$

Defect symmetry number $s = 2|1-q|$

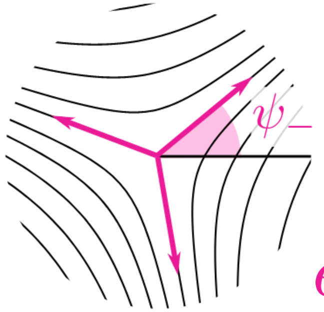
$q = +1/2$



$s = 1$

$e^{i\psi_+}$

$q = -1/2$



$s = 3$

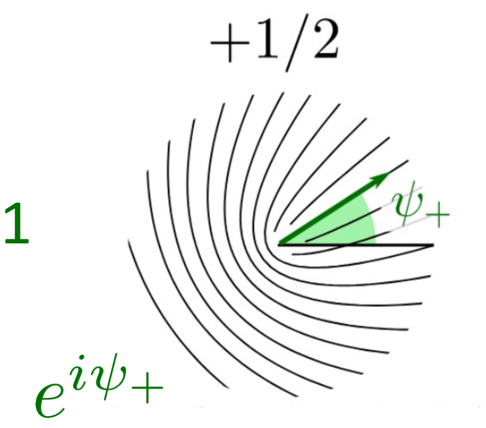
$e^{3i\psi_-}$

Activity profile decomposed in polar components of defined rotational symmetry:

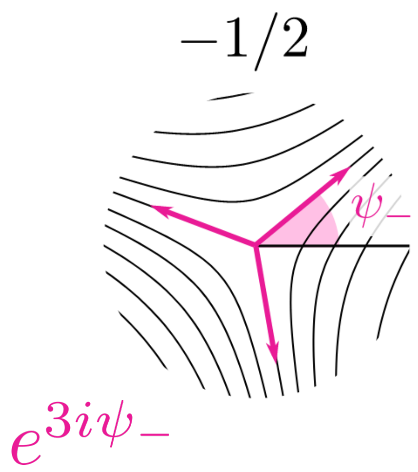
$$\alpha(\mathbf{r},t) = \sum_k \alpha_k(r,t) e^{ik\phi}$$

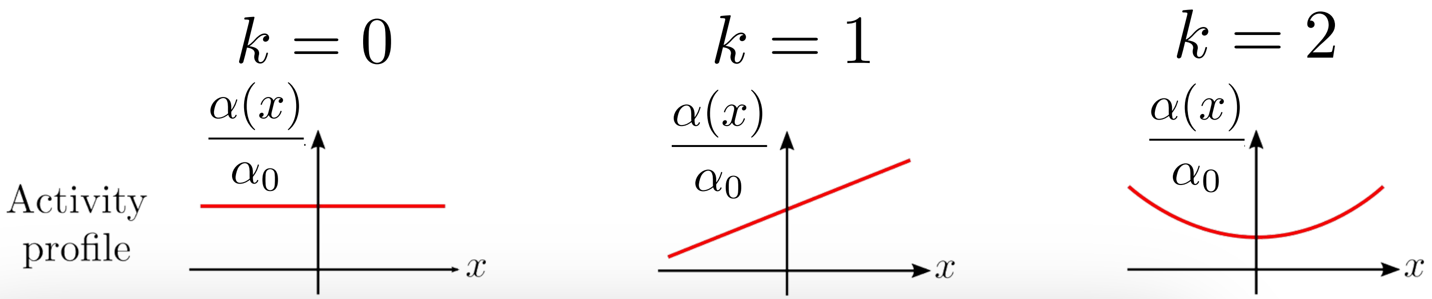
A simple rule for additive control of defects

$s_d = 1$



$s_d = 3$





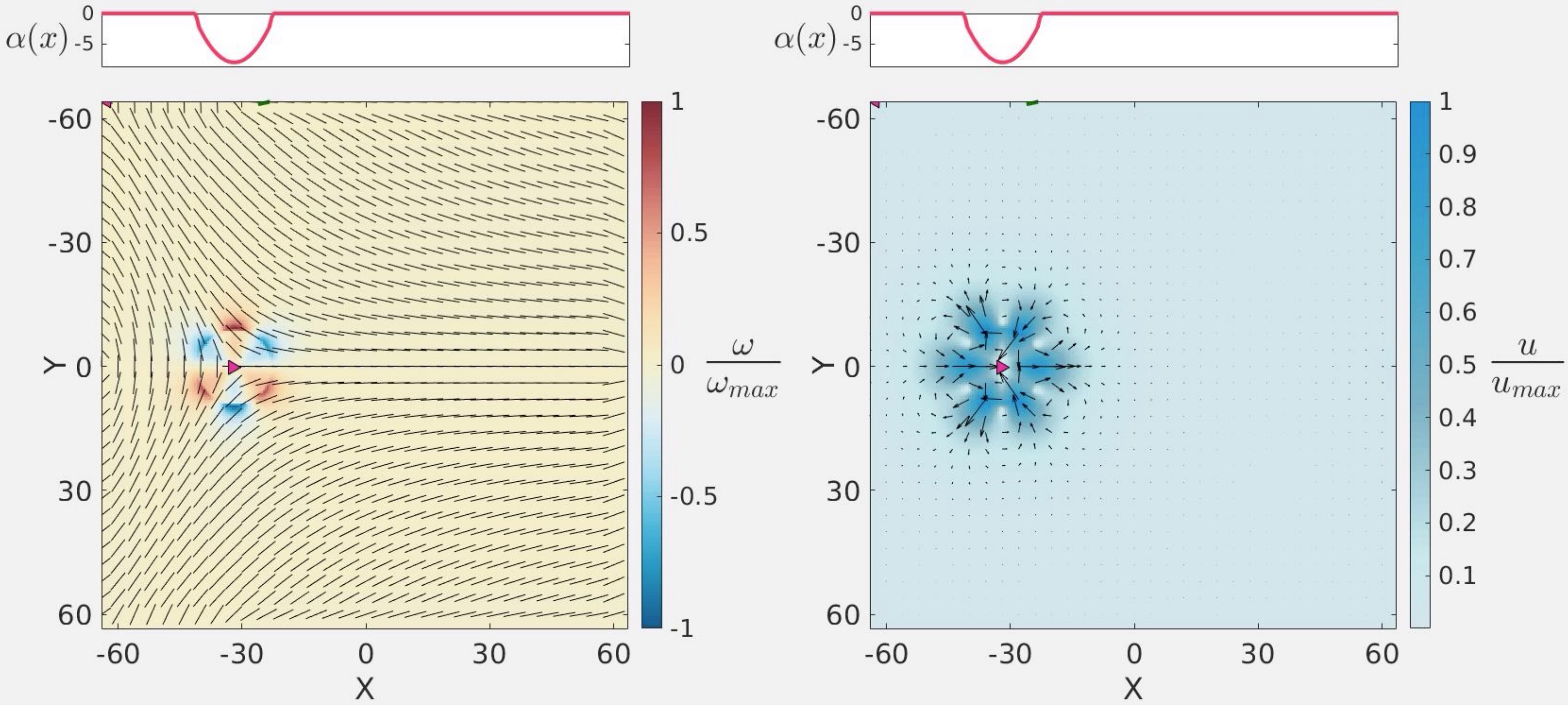
$$\Delta s = s - k$$

$|\Delta s| = 1$ - Nonzero defect velocity

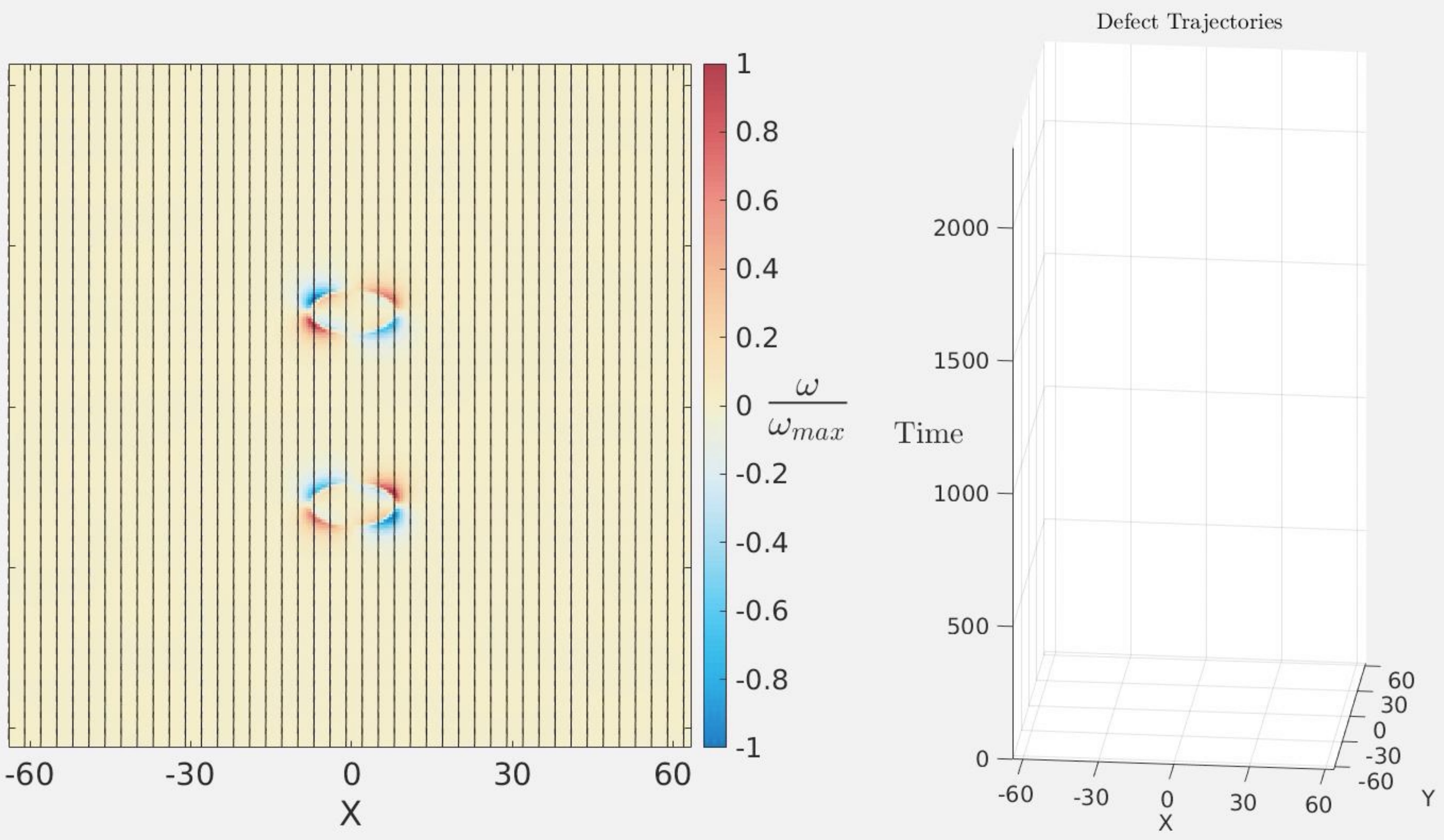
$|\Delta s| = 0$ - Nonzero defect vorticity

Other *Δ*s values leave defects unaffected

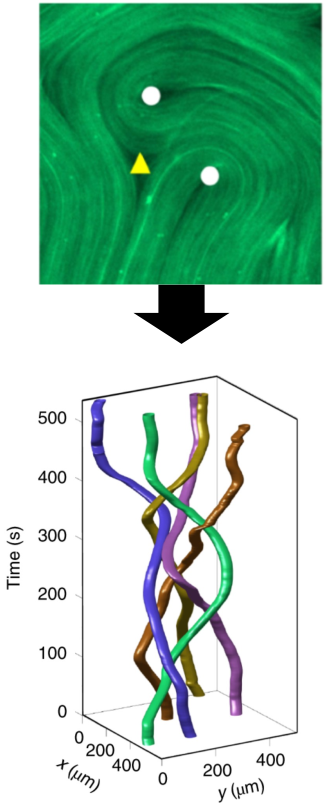
Parabolic activity trap moves -1/2 defect



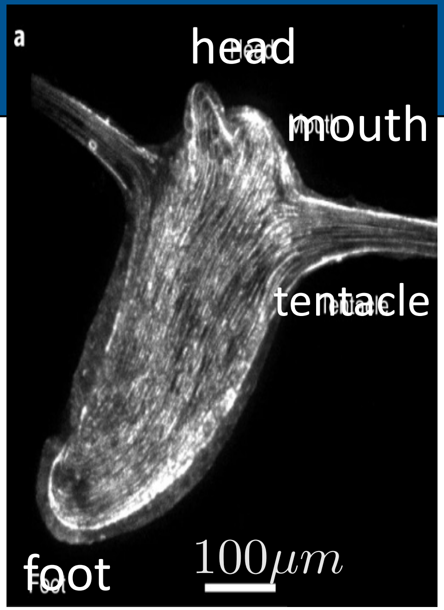
Defect braiding with active topological tweezers



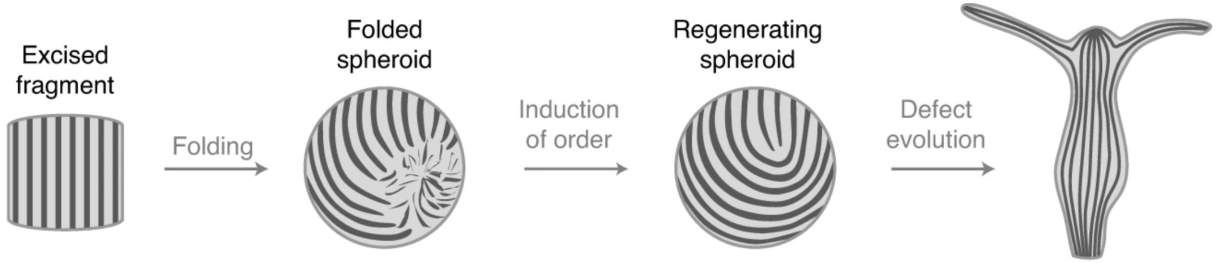
Defect trajectory braiding in chaotic state provides a quantitative measure of fluid mixing → topological entropy Tan *et al.* Nat Phys 2019



Hydra: defects as organizing centers of morphogenesis

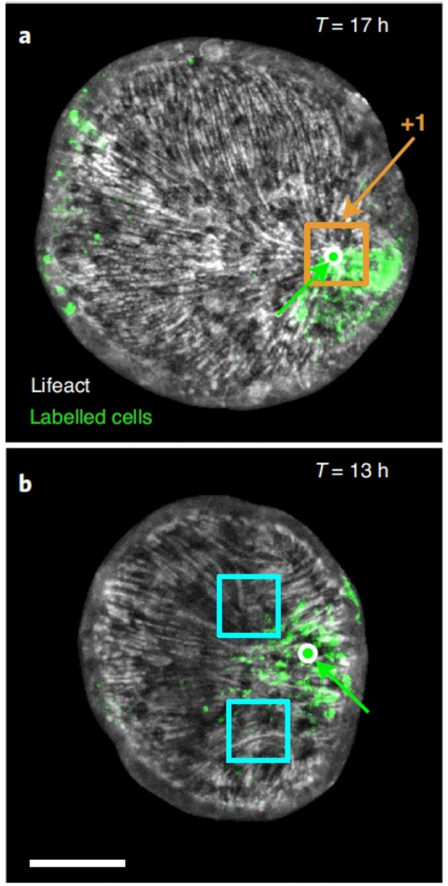


Hydra budding and regeneration Maroudas-Sacks *et al*. Nat Phys 2020



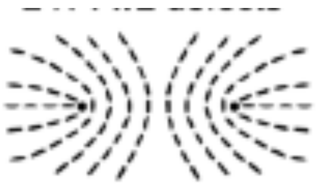
Nematic organization of supracellular actin controls morphogenetic processes

Specific defects as organizers of head, foot, tentacles



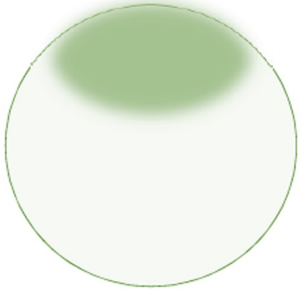
Future head coincides with +1 defect

Future foot coincides with two -1/2 defects



Interplay of mechanics, geometry and biochemical signaling:

- sphere elongates into ellipsoid → coupling between geometry and orientational order
- Strain promotes expression of head morphogen (Wnt)
  Ferenc et al. Sci Adv 2021



Defect motility in active nematic solids

Coupling nematic texture to strain $\epsilon_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i)$ $\epsilon_{kk} \simeq -\delta\rho/\rho_0$

$$\partial_t \mathbf{Q} = (1 + b\epsilon_{kk} - Tr[\mathbf{Q}^2])\mathbf{Q} + K\nabla^2\mathbf{Q} + \chi\tilde{\epsilon}$$

b>0 → compressional strains $(\epsilon_{kk} < 0)$ ``melt'' the nematic

aligns

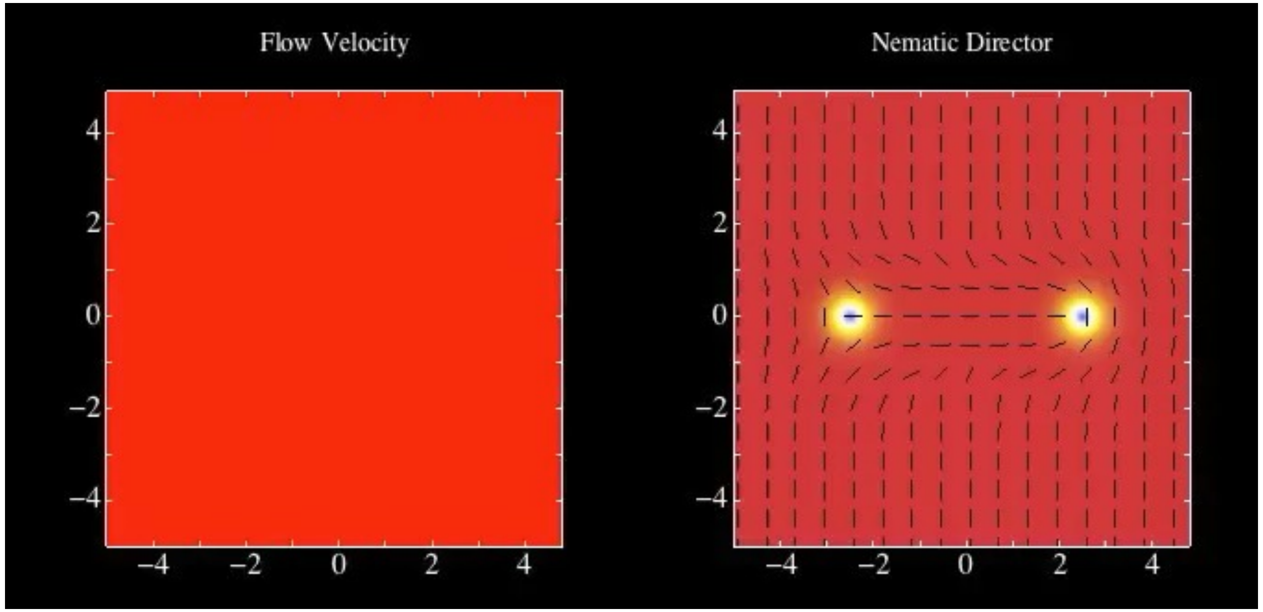
Force balance $$\partial_j[2\mu\epsilon_{ij} + (B+\mu)\delta_{ij}\epsilon_{kk}] + \partial_j[(\alpha_B - b)Tr[\mathbf{Q}]^2\delta_{ij} + (\alpha - \chi)Q_{ij}] = 0$$

elastic forces

Active stresses can tune and even suppress instabilities

Nematic fluid

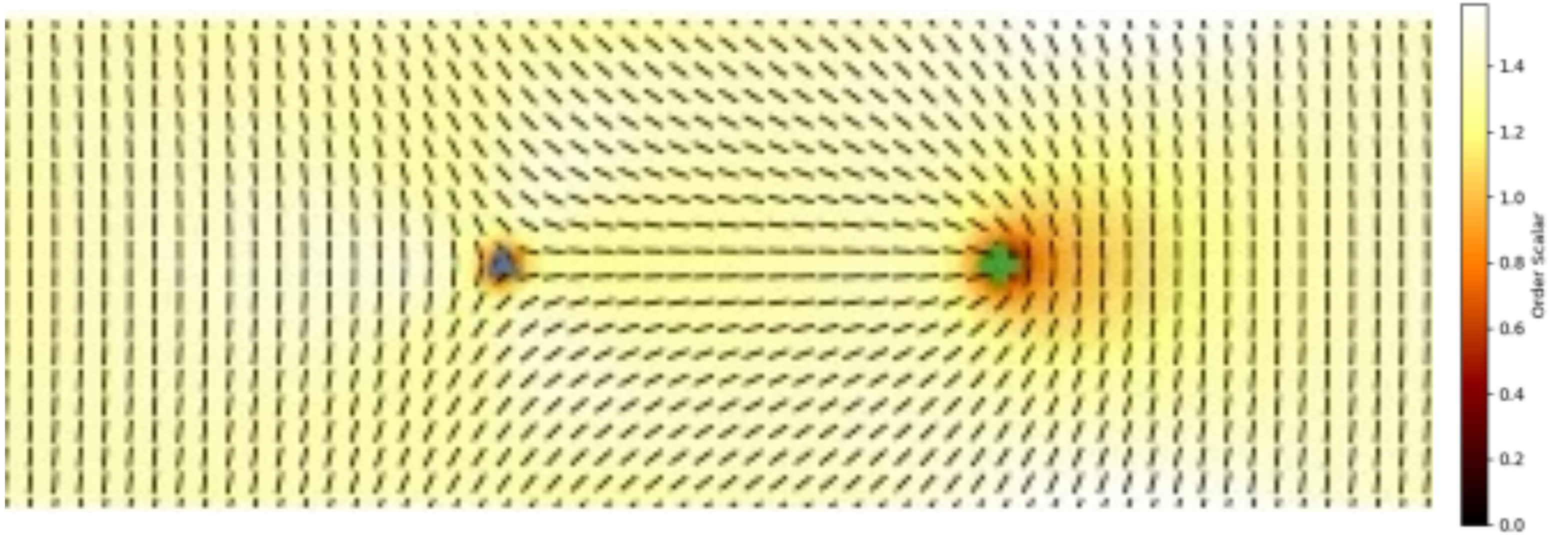
L Giomi, MJ Bowick, X Ma, MCM, PRL 2013



Defects move advected by local flow

Nematic solid

M O'Leary, F Brauns, MJ Bowick, MCM 2024



Defects move relative to elastic material as nematic texture remodels

The elasto-nematic coupling can give rise to stable +1 defects that form by merging of two self-propelled +1/2 defects.