Dynamics of living liquid crystals: Bacteria in Lyotropic Chromonic Liquid Crystals

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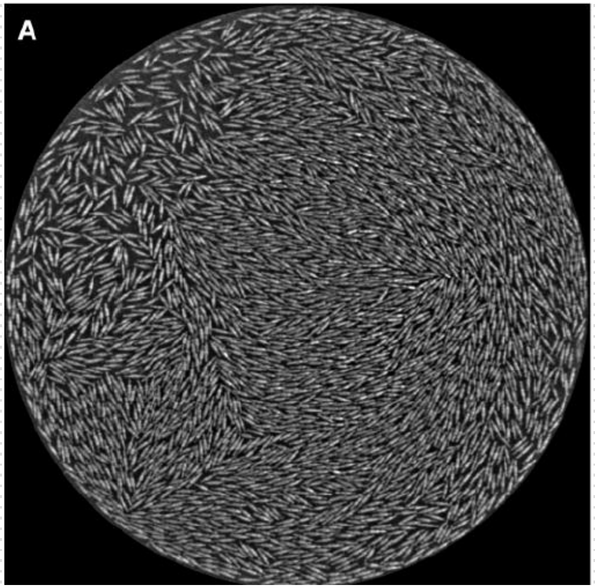
Support: NSF DMR

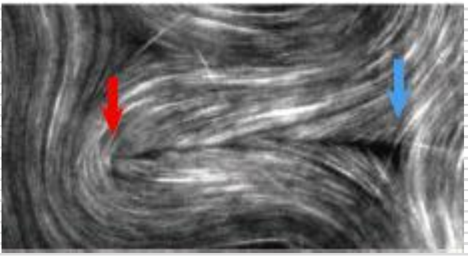
Active Processes in Living and Nonliving Matter, Feb 10-14, 2014

Examples of active fluids



Narayan, Ramaswamy, Menon, *Science* (2007): Active granular rods with disclinations and giant number fluctuations

Sanchez, Dogic et al,
Nature (2012): Active microtubules with flows and disclinations



Review: Marchetti et al RMP (2013)

This work: Living Liquid Crystal (LLC), dispersion of rod-like self-propelling bacteria in lyotropic (water-based) chromonic liquid crystal

Motivation: The system allows one to control orientational order and activity separately

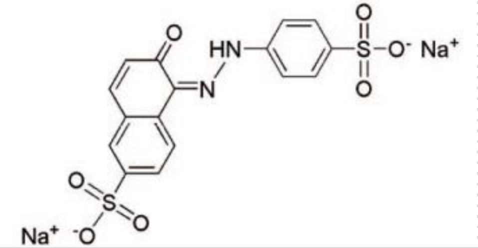
- Orientational order modifies bacterial behavior
- Bacterial activity modifies orientational order

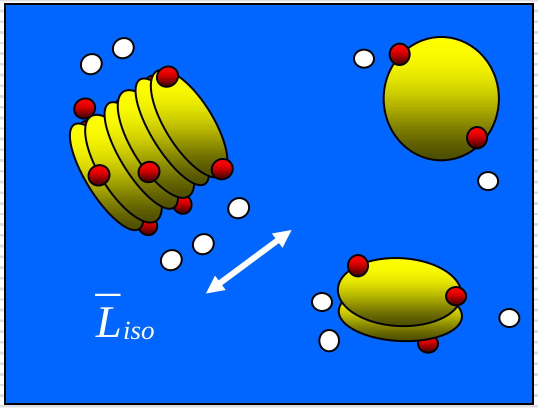
Living Liquid Crystals: Content

- Chromonics (inactive): Basic properties
  - Phase diagram
  - Viscoelasticity
- Living liquid crystals=*Chromonics*+*B. Subtilis*
  - Behavior of individual bacteria in a chromonic
  - Collective effects: activity-controlled transition from equilibrium uniformity to topological turbulence

Chromonics

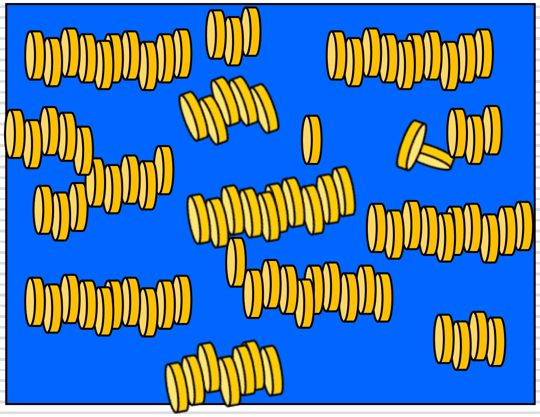
- Chromonics are formed by rigid polyaromatic molecules that assemble face-to-face into elongated aggregates in water





- As the concentration increases, the aggregates form a nematic
- Similar to the Onsager mechanism, but not exactly, since the system is also “thermal”: The aggregates are kept together by weak non-covalent interactions $E \sim 10\, k_B T$, which makes their length strongly temperature dependent and concentration dependent:

$$\bar{L}_{iso} \approx L_0 \sqrt{\phi}\, \exp\left(\frac{E}{2k_B T}\right)$$



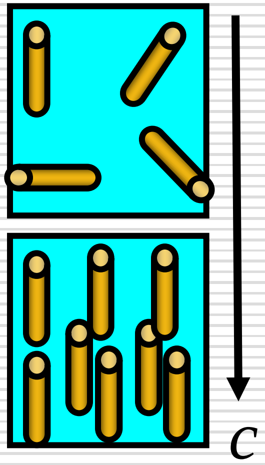
HS Park, ODL in Liquid crystals beyond displays, Editor Q. Li (2012)

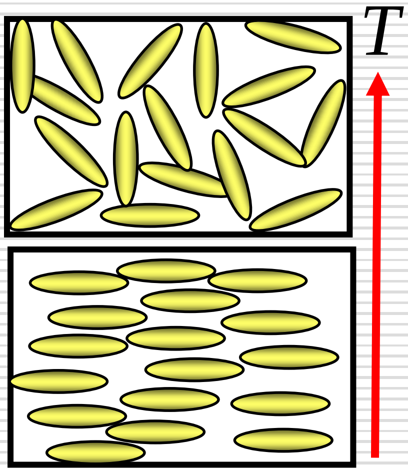
Inactive chromonics as “living polymers”

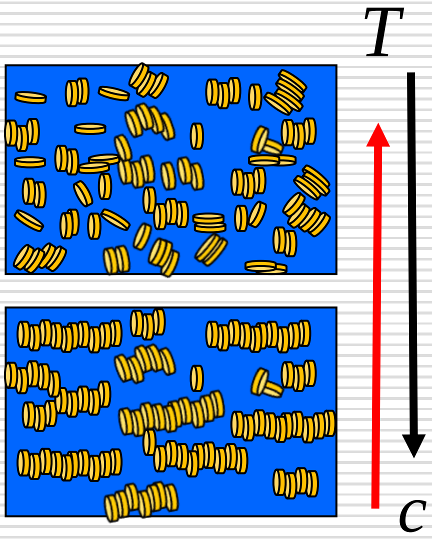
Onsager systems (TMV):
The same rods,
athermal,
aligned at high *c*

Thermotropic LC (in your displays):
The same molecules,
c=const, aligned at low *T*

Chromonics (close to “living polymers” and “worm-like micelles”): phase diagram is controlled by both *c* and *T*

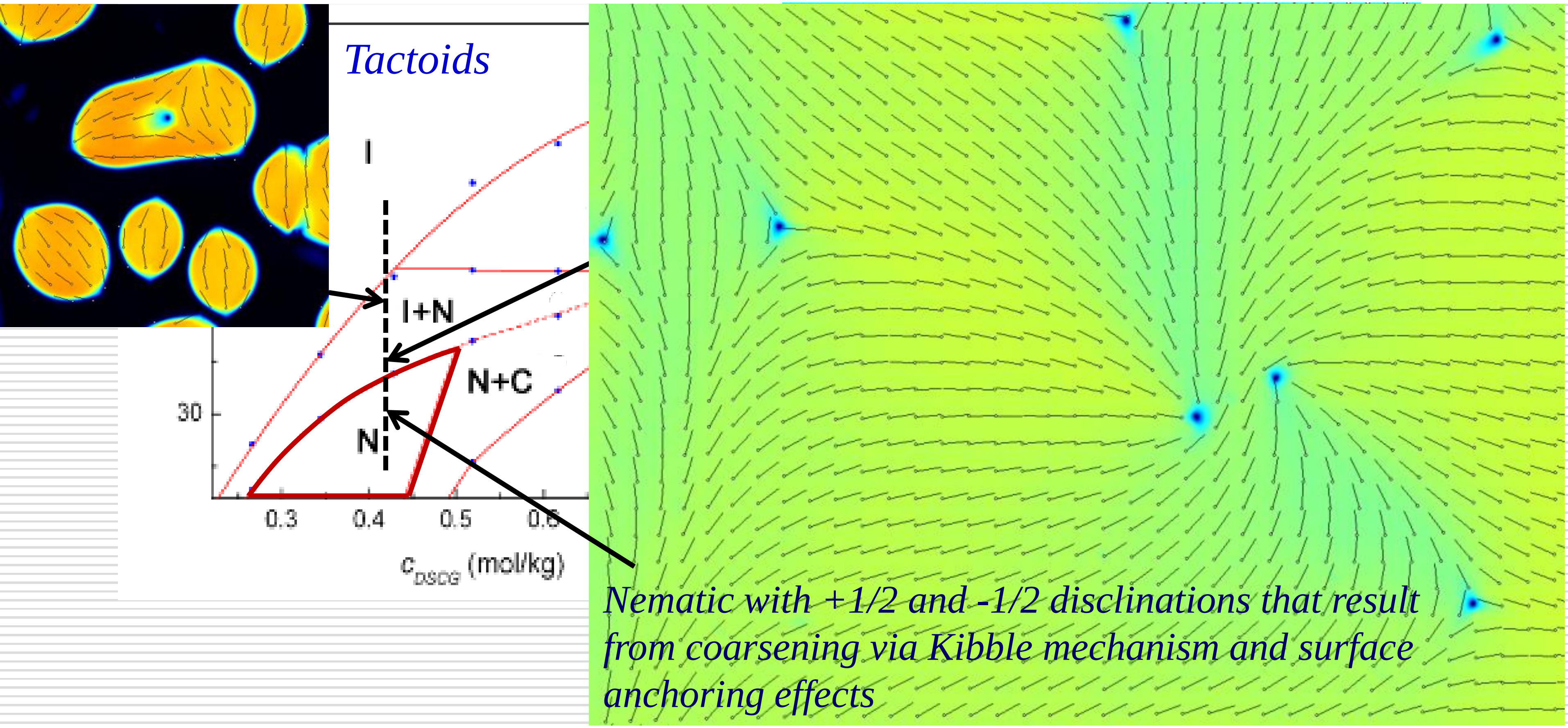






HS Park, ODL in Liquid crystals beyond displays, Editor Q. Li (2012)

Chromonics: *c* and *T* dependent phases



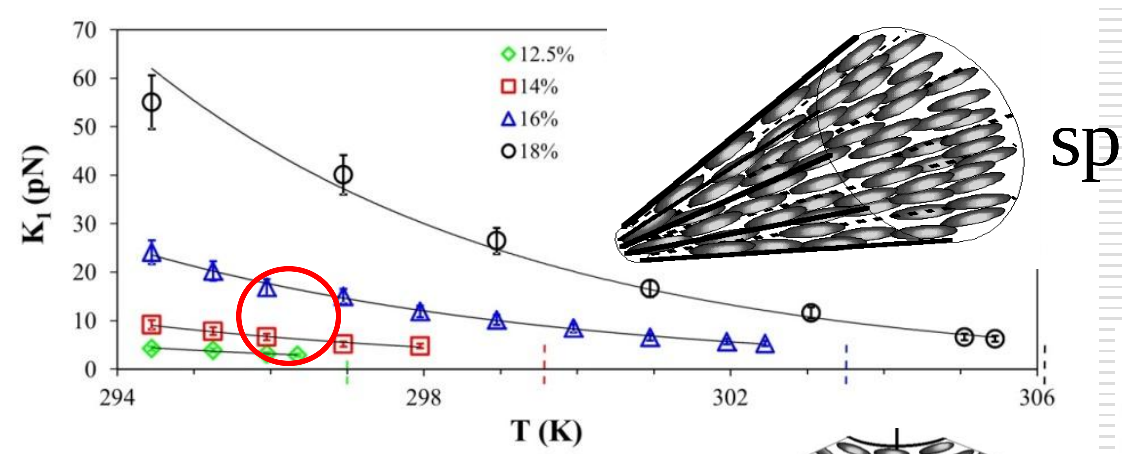
Tactoids

Nematic with +1/2 and -1/2 disclinations that result from coarsening via Kibble mechanism and surface anchoring effects

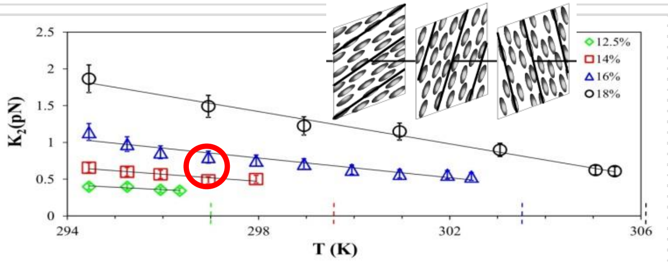
Director field of real samples, reconstructed by LC PolScope (no simulations)

Y.K. Kim, S. Shiyanovskii, ODL, J. Phys. Cond. Matt. (2013)

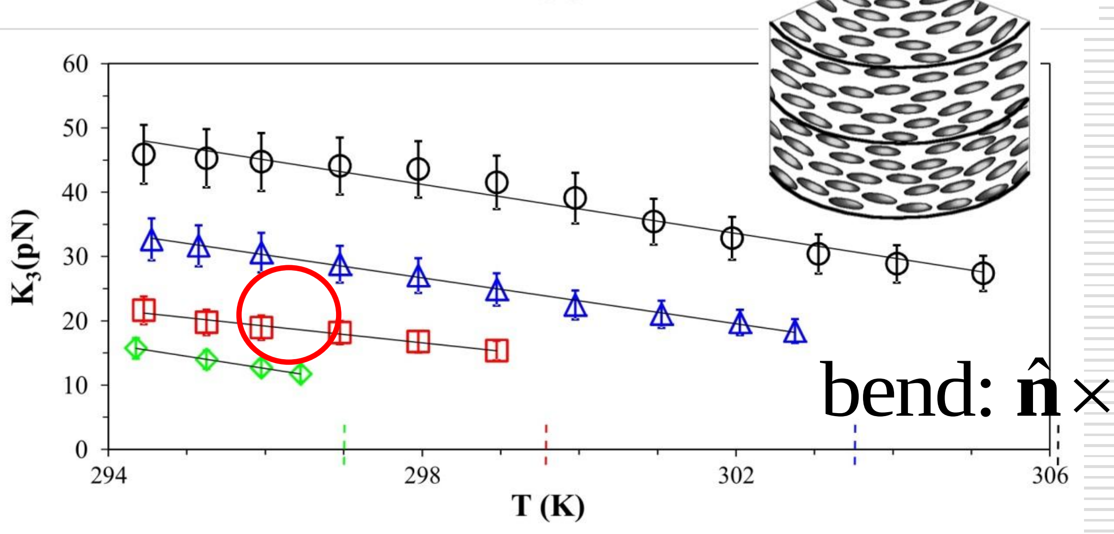
T, *c* dependent elastic constants



splay: $\operatorname{div}\hat{\mathbf{n}} \neq 0$



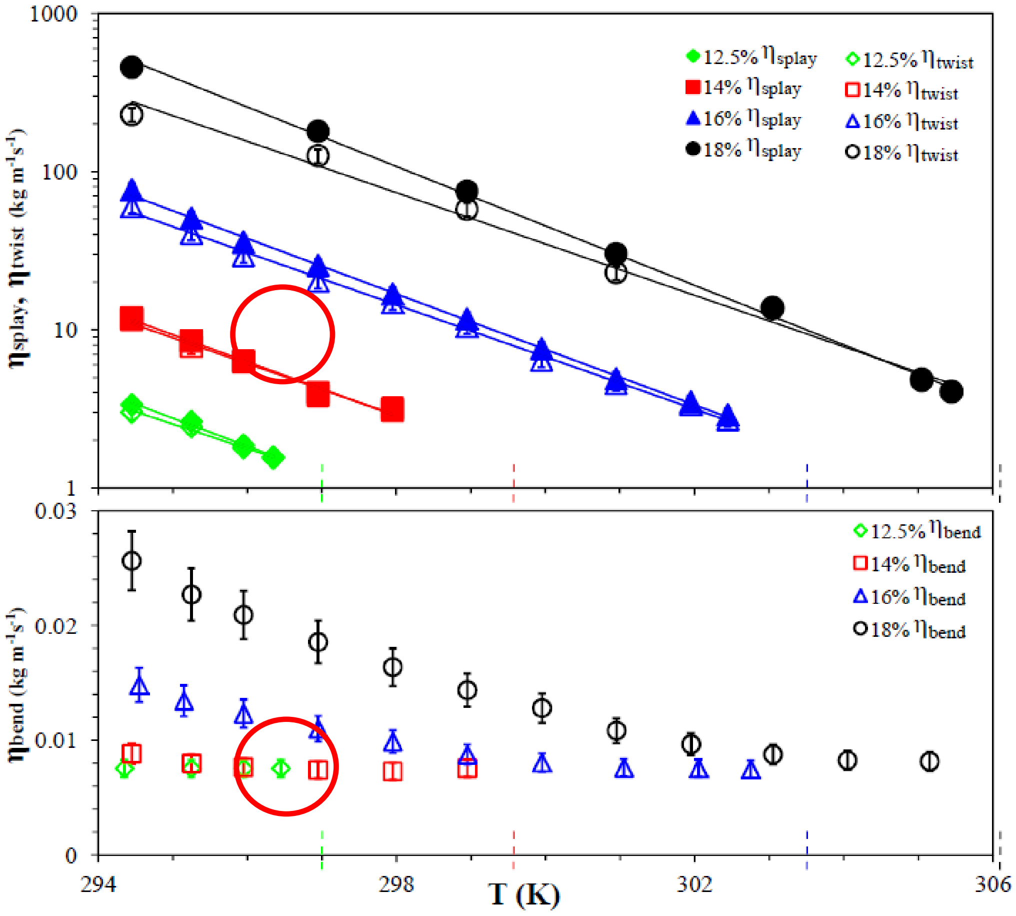
twist: $\hat{\mathbf{n}} \cdot \operatorname{curl}\hat{\mathbf{n}} \neq 0$



bend: $\hat{\mathbf{n}} \times \operatorname{curl}\hat{\mathbf{n}} \neq 0$

S. Zhou et al., PRL (2012): Magnetic field reorientation;
Dynamic light scattering, in preparation

T, *c* dependent viscosities

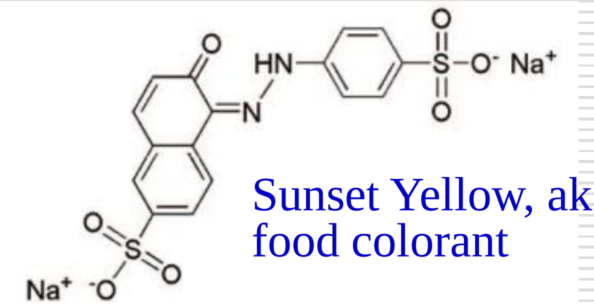


S. Zhou et al., Dynamic light scattering, in preparation

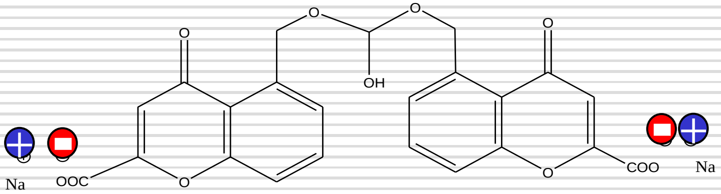
LCI KENT STATE UNIVERSITY

Chemistry and biocompatibility of chromonics

- ☐ Chromonics are different from the surfactant based lyotropics: molecules have no aliphatic tails, thus chromonics are friendly to biological systems



Sunset Yellow, aka Yellow #6, food colorant



This work: DSCG, a.k.a. cromolyn, anti-asthma drug, concentration 14-17 wt%

Approved by FDA for intake by humans:

Living Liquid Crystals

- ☐ Chromonics (inactive): Basic properties
  - Phase diagram
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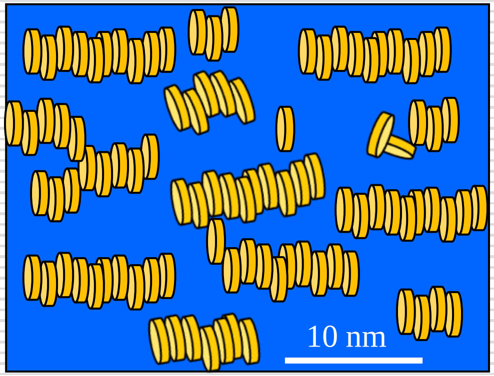

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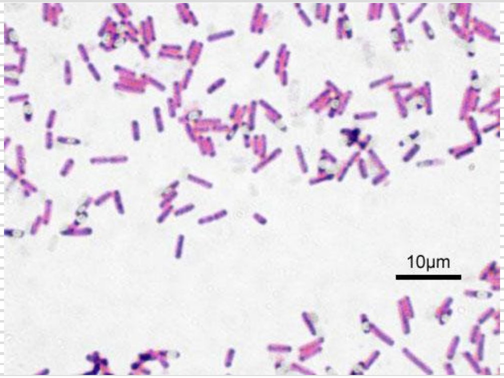
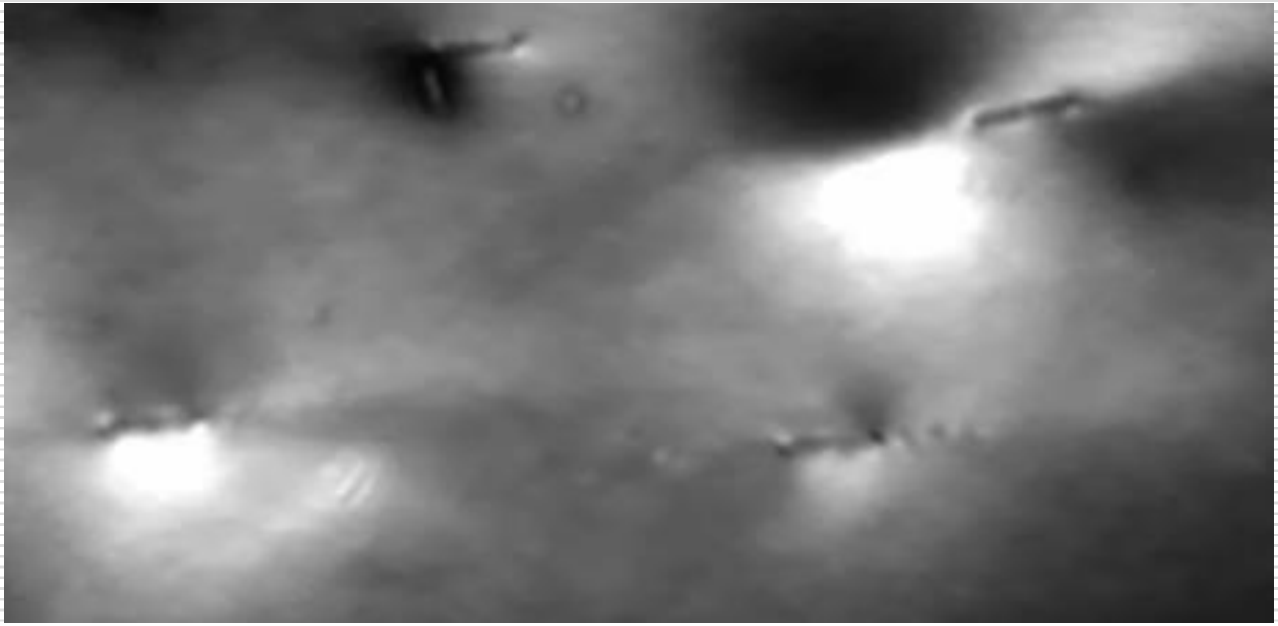


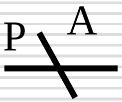
Chromonics

Bacillus subtilis

Living LC: Individual bacteria follow $\hat{\mathbf{n}} = const$

Low concentration of bacteria ($c<10^8$ /cm^3)





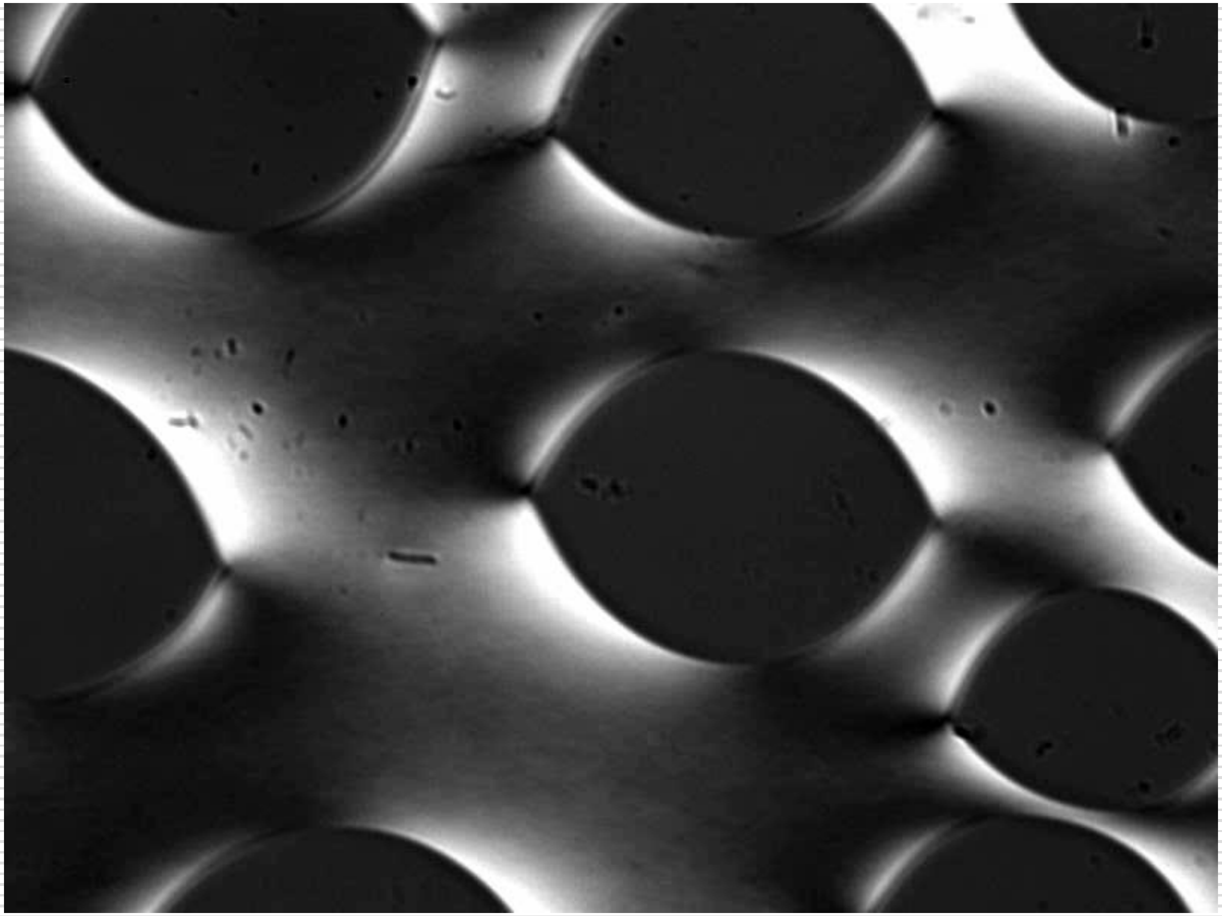
Rate ¼

Isolated bacteria follow the uniform director, similar to observations by T. Galstian et al, Mol. Cryst. Liq. Cryst (2013) and N. Abbott et al, Soft Matter (2014)

Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

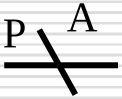
Living LC: Individual bacteria follow $\hat{\mathbf{n}}(\hat{\mathbf{r}})$

…bacteria follow distorted director of the chromonic around isotropic tactoids



Isotropic tactoids

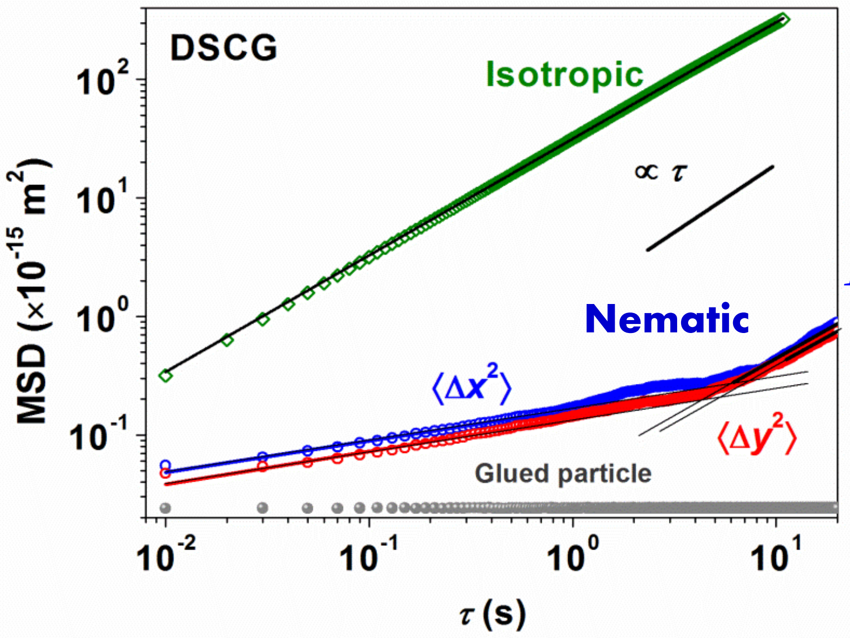
Rate ¼



Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

Living LC: Individual bacteria follow $\hat{\mathbf{n}}(\hat{\mathbf{r}})$

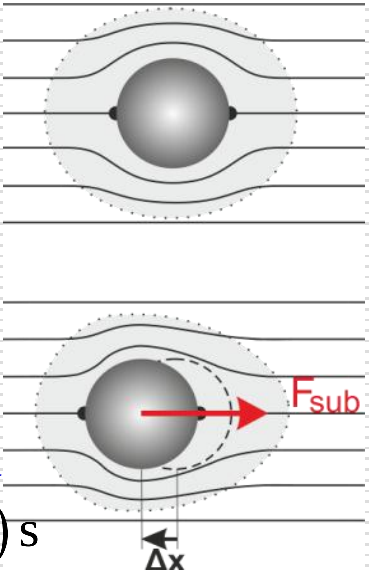
Both elastic and viscous effects favor swimming along the director lines



Diffusion of a 5 μm sphere is easier parallel to the director as compared to perpendicular direction

$$D_{\parallel} = 6.8\times10^{-17}\ \mathrm{m^2 s^{-1}}$$

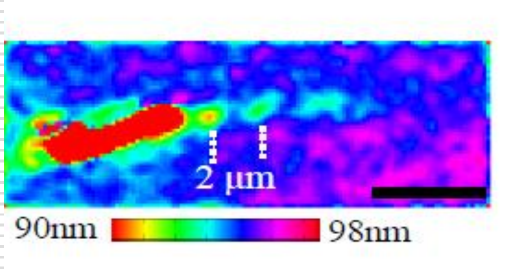
$$D_{\perp} = 4.5\times10^{-17}\ \mathrm{m^2 s^{-1}}$$

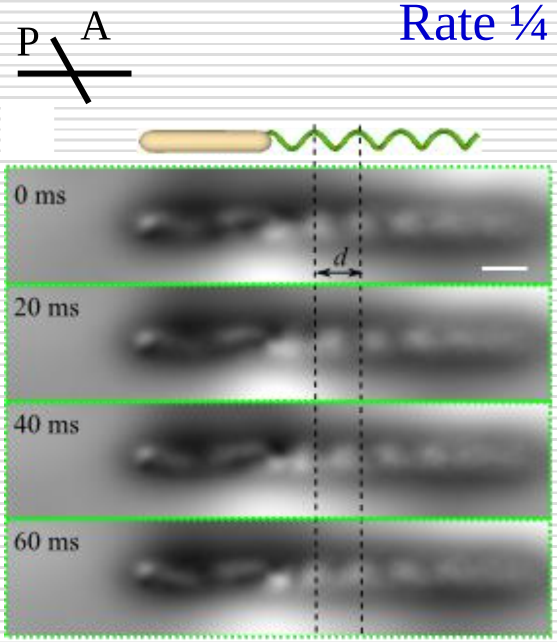


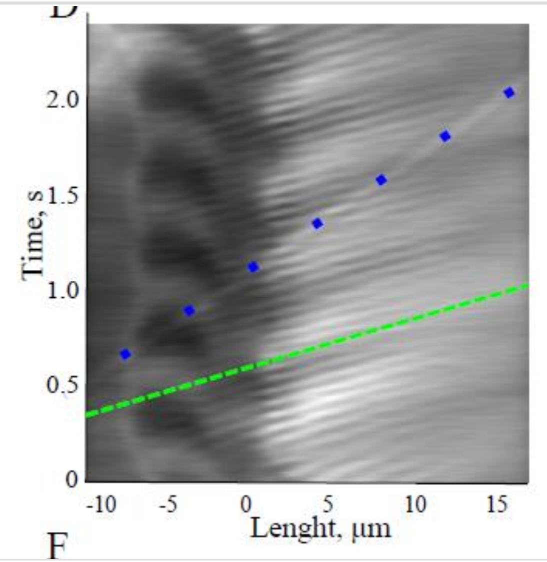
Note sub-diffusive regime at short times: An intrinsic memory associated with the director relaxation $\tau_d :\ \eta d^2 / K \sim (1-10)\ \mathrm{s}$

T. Turiv et al, *Science* (2013)

Living LC: Individual bacteria distort $\hat{\mathbf{n}}(\hat{\mathbf{r}})$







Flagella rotation:16 Hz

Body rotation: f=2.5 Hz

The rotation is fast enough to make the Ericksen number larger than 1

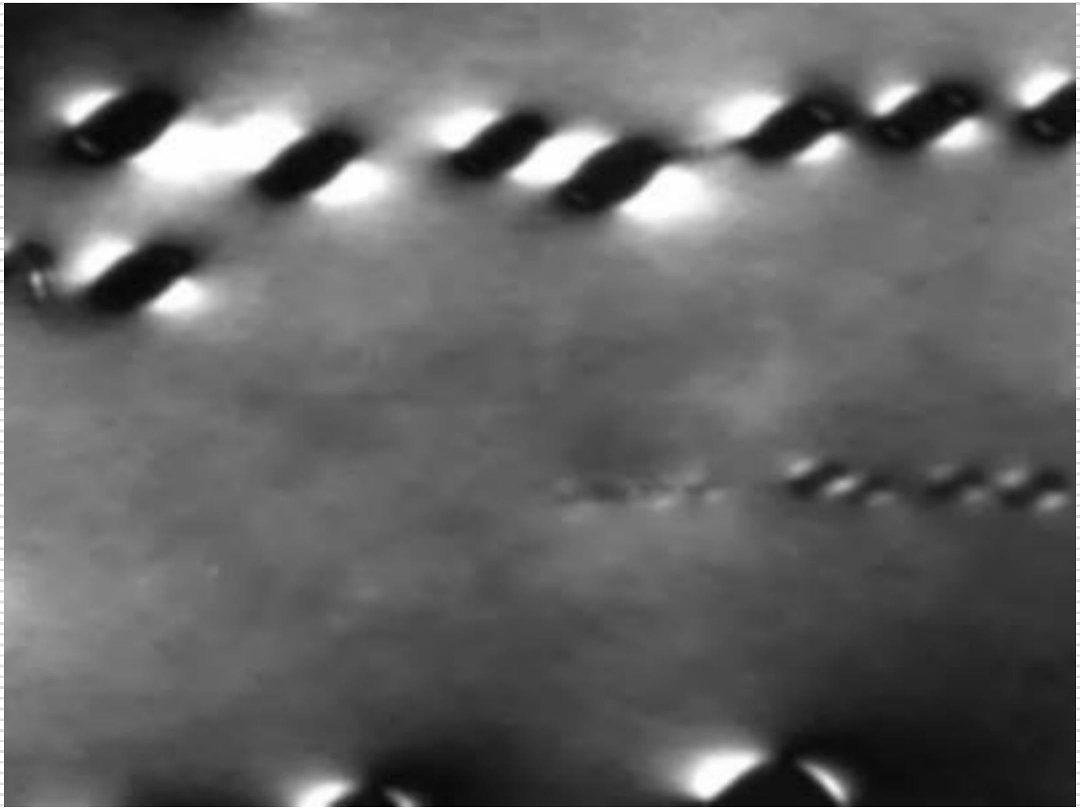
$$Er = \eta_{eff} frh / K \sim 10$$

implying that the director is distorted by moving flagella

Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

Living LC: Individual bacteria melt LC

Moving bacterium can also change the scalar order parameter, melting the material and forming isotropic droplets-tactoids in its wake (“Wilson chamber”)



Rate ½

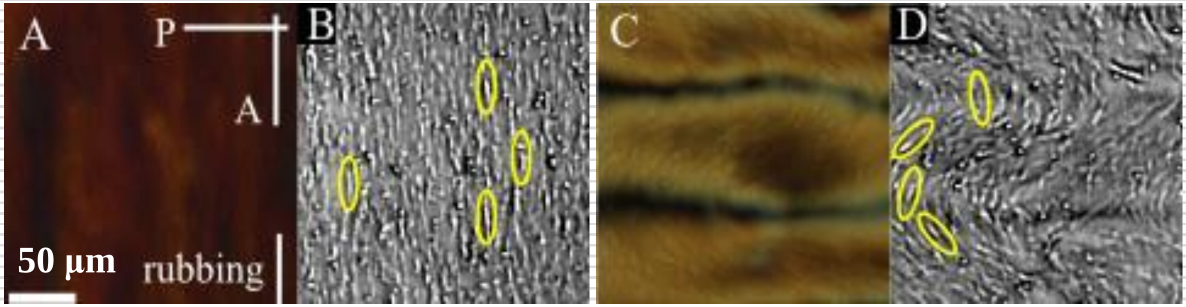
Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

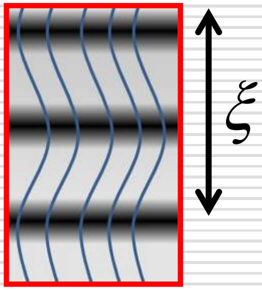
Living LC: Collective effects, Bend stripes

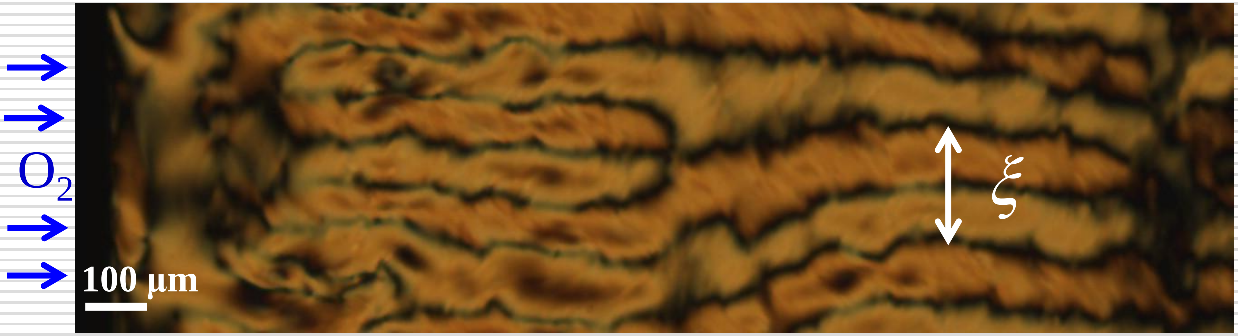
No oxygen; equilibrium state of uniform director

Added oxygen; director undulations

Higher concentration of bacteria ($c_B \sim 10^9$ /cm^3)







Oxygen supplied from the left hand side

Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

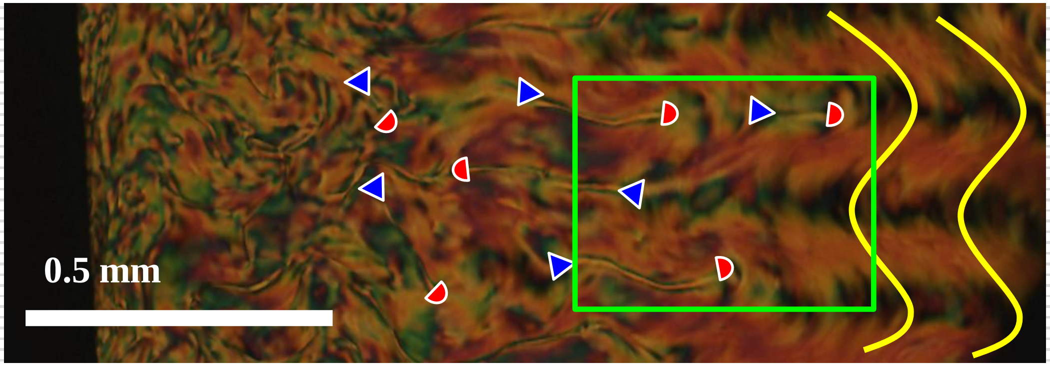
Living LC: Collective effects, Bend stripes

High concentration of bacteria, addition of oxygen: periodic undulations with a characteristic spatial scale that depends on c_B, amount of oxygen, etc.

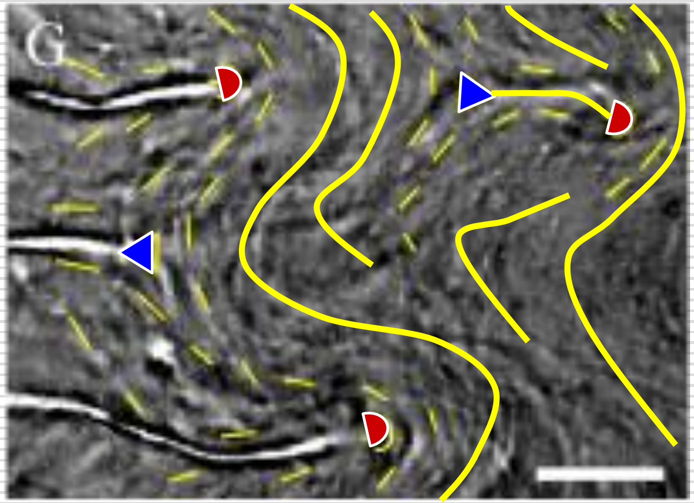
Oxygen supplied from the left hand side, rate 100

Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

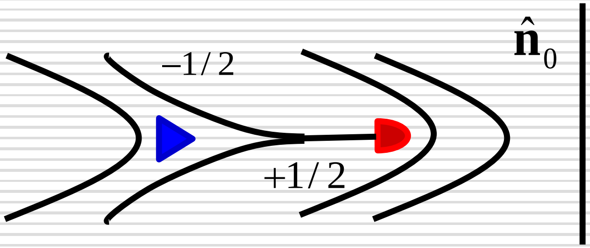
Higher activity: Bend stripes replaced by disclination pairs



Nucleation of disclination pairs

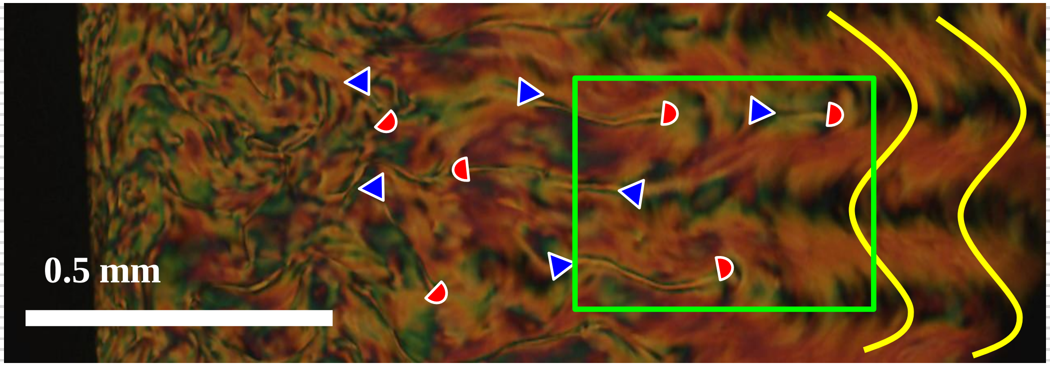


Director within the pair realigned by 90^o w.r.t. the original director



Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

Bending vs disclination pairs: Elasticity and surface anchoring



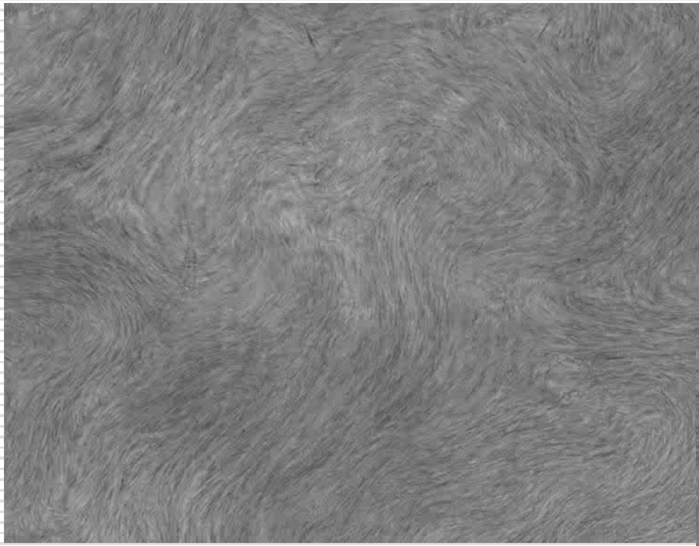
As activity increases, the uniform state (1) undergoes transition into periodic bend stripes, then
(2) into the sea of nucleating and annihilating disclination pairs
Similar 2 stage scenario is seen in numerical simulations:
Thampi, Golestanyan, Yeomans, EPL (2014); poster at BIOACTER;
M. Shelley et al, http://arxiv.org/pdf/1401.8059v1.pdf
See also Shi, Ma, Nature Comm (2013)

Why the walls are replaced by disclination pairs?

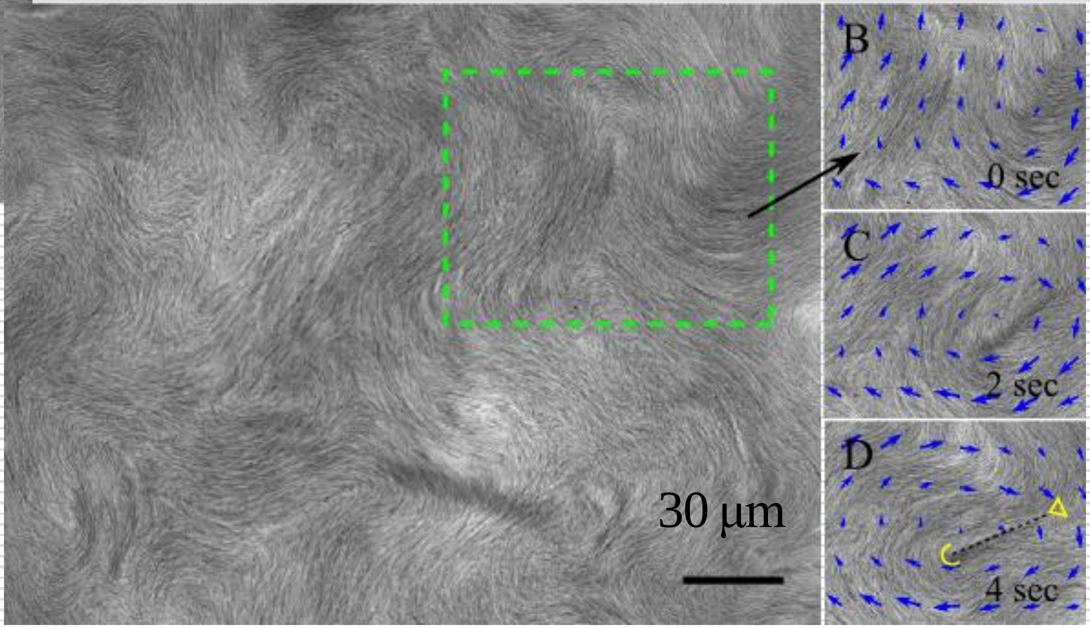
$$\text{Walls: } F_w \propto \frac{K}{\xi^2} \qquad \text{Pairs: } F_w \propto \frac{K}{\xi_d^2} \ln \xi_d / r_c$$

Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

High activity: Topological turbulence



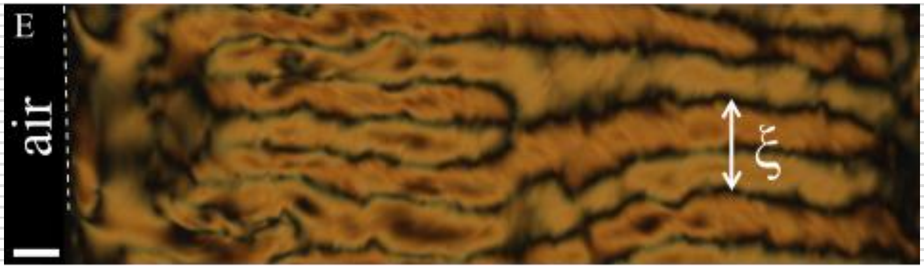
Blue arrows: LLC flow velocity field

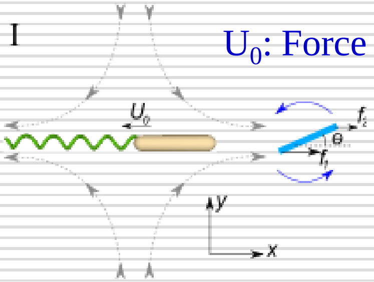


Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

Bending: Activity vs Elasticity

Spatial scale: balances viscous shear (bacterial) and elastic (LC) torques





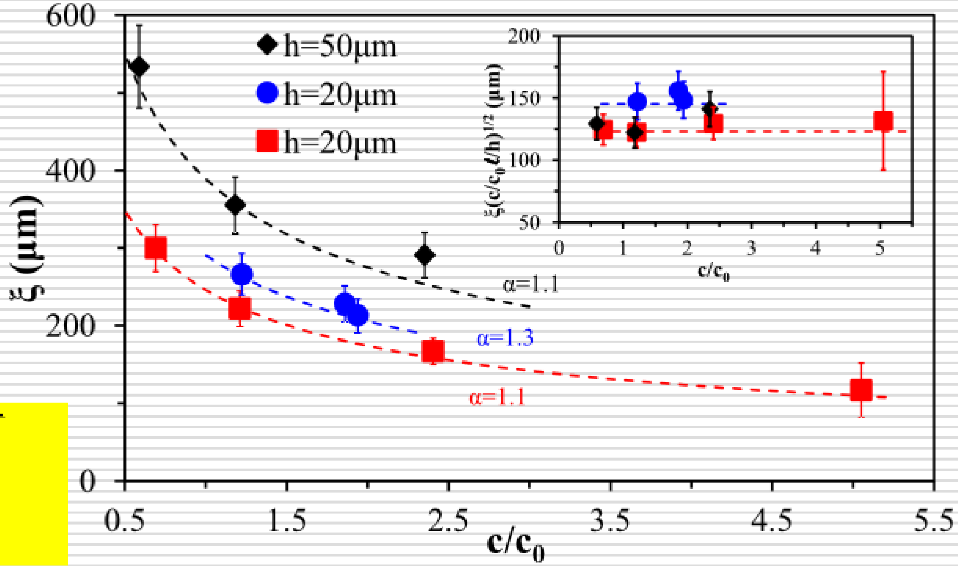
U_0: Force dipole ~ 1 pN μm

$$\left.\begin{array}{l}\Gamma_{shear}\sim \alpha c U_0 \theta \\ \Gamma_{elastic}\sim K\dfrac{\partial^2\theta}{\partial r^2}\end{array}\right\}\Rightarrow \xi=\sqrt{\frac{K}{\alpha c U_0}}$$

Similar to Ramaswamy Ann. Rev. CMP (2010)

Cell thickness correction (mass conservation) $\alpha \rightarrow \alpha_0 l/h \Rightarrow$

$$\xi=\sqrt{\frac{Kh}{\alpha_0 l c U_0}}$$



Zhou, Sokolov, ODL, Aranson, PNAS doi/10.1073/pnas.1321926111

Living Liquid Crystals: Summary

- Non-uniform director guides nonlinear trajectories of bacteria
- Birefringence-enhanced visualization of microflows generated by nanometers-thick flagella
- Bacteria produce local melting of chromonic LC
- Activity increase drives a transition from a uniformly ordered state to the topological turbulent state through two steps:
  - Formation of periodic bend, period $\xi = \sqrt{K / \alpha c U_0}$
  - Nucleation and proliferation of disclination pairs