Collective behavior in active matter

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Active Matter

- Energy consumed at the level of each constitutent

S. Ramaswamy, S. Dhara

Kessler, Goldstein

Generic Collective properties

- Spontaneous flows
- Orientational defects
- Active (Motility induced) phase separation

Outline

1. *Spontaneous flows in active matter*
   - Hydrodynamic theory
   - Spontaneous flows of active matter
   - Active Turbulence

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   - Defects in tissues
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Hydrodynamic theory of active matter

Slow variables and hydrodynamic theory

- Study cooperative effects at long length scales and long time scales
- Liquid with polar and nematic order, polarisation **p**
- Slow variables : velocity field, orientational field, energy consumption (chemical energy $\Delta\mu$)
- Symmetries and conservation laws

Constitutive equations

$$
\begin{aligned}
2\eta v_{\alpha\beta} &= \tilde{\sigma}_{\alpha\beta} + \zeta \Delta\mu q_{\alpha\beta} - \frac{\nu}{2}(p_\alpha h_\beta + p_\beta h_\alpha) \ , \\
\frac{Dp_\alpha}{Dt} &= \frac{h_\alpha}{\gamma} - \nu v_{\alpha\beta} p_\beta \ , \\
r &= r_0 \Delta\mu + \zeta v_{\alpha\beta} q_{\alpha\beta} \ .
\end{aligned}
$$

- Hydrodynamics of nematic liquid crystals,
- Orientational field $h_\perp = K\nabla^2\phi$
- Active stress, Nematic tensor $q_{\alpha\beta} = p_\alpha p_\beta - \frac{1}{d}\delta_{\alpha\beta}$. Contractile if $\zeta < 0$.

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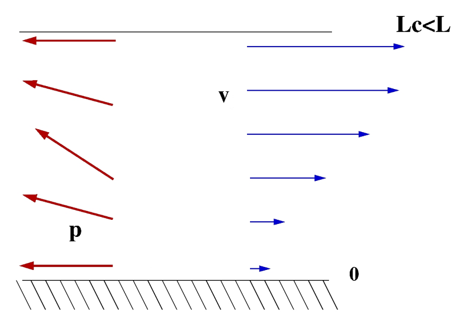
Stability of homogeneous state

- System oriented along x, contractile fluid, $\nu = 0$

$$\Omega(\vec{q}) = \left[\frac{\zeta \Delta\mu}{2\eta} \frac{q_x^2 - q_y^2}{q^2} - \left(\frac{1}{\gamma} + \frac{1}{4\eta} \right) K q^2 \right]$$

- Instability at zero wave vector in the direction perpendicular to orientation

Parallel anchoring conditions



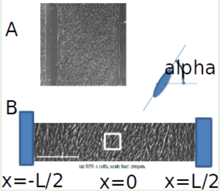
Flow bifurcation R.Voituriez

- Same anchoring condition on both surfaces
- Active stress equivalent to an external magnetic field along x axis
- Instability for a finite thickness

$$L_c = \left(- \frac{\pi^2 K (\frac{4\eta}{\gamma} + (\nu+1)^2)}{2\zeta\Delta\mu(\nu+1)} \right)^{1/2}$$

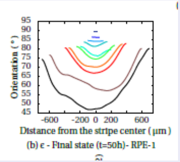
Spontaneous tissue flow G. Duclos, V. Yashunsky, P. Silberzan

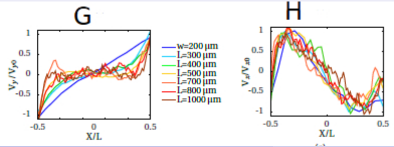
Experiment

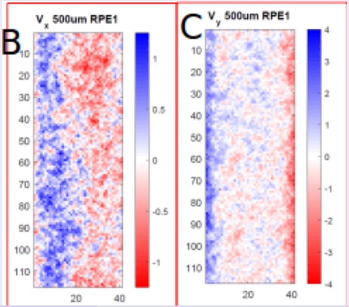


- Several cell types, nematic cells
- Stripe width 50μm to 800μm
- Cell orientation
- PIV

Velocity and cell orientation

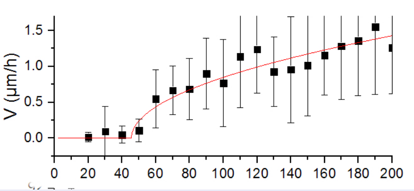






Spontaneous flow

- Fredericks transition



Theoretical developments

- Substrate friction: screening length $\lambda = \left(\frac{4\eta+\gamma(\nu+1)^2}{\xi}\right)^{1/2}$

$$\frac{1}{L_c^2} = \frac{1}{L_c^2}(\xi = 0) - \frac{1}{\lambda^2}$$

- Transverse flow related to cell division
- Chiral effects

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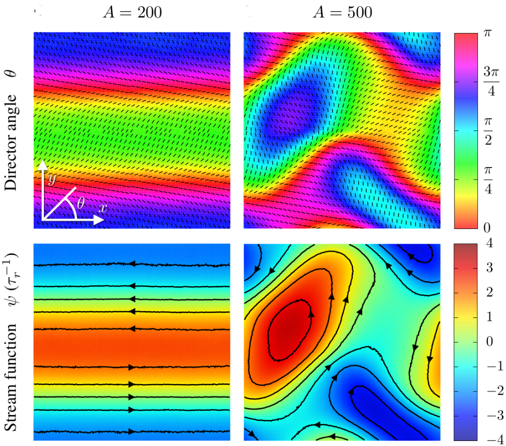
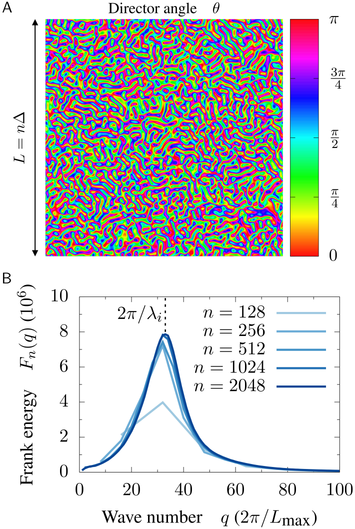
- Activity parameter $A = (L/L_c)^2$, flow alignment parameter $\nu = 0$, 2 dimensions.
- Instability beyond a critical activity number



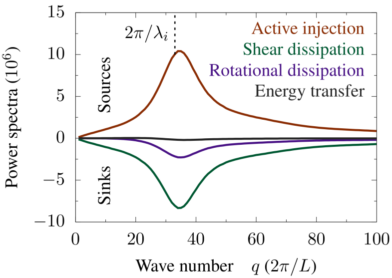

A
Director angle θ
L = nΔ
π
3π/4
π/2
π/4
0
B
Frank energy $F_n(q)$ (10^6)
2π/λ_i
n = 128
n = 256
n = 512
n = 1024
n = 2048
0
2
4
6
8
10
0
20
40
60
80
100
Wave number q (2π/L_max)

Energy and power spectra

- Global energy balance

$$-\frac{dF_n}{dt} = \int_{\mathcal{A}} \left[2\eta\, v_{\alpha\beta} v_{\alpha\beta} + \frac{1}{\gamma} h_\alpha h_\alpha - \zeta\, q_{\alpha\beta} v_{\alpha\beta} \right] d^2\vec{r}$$

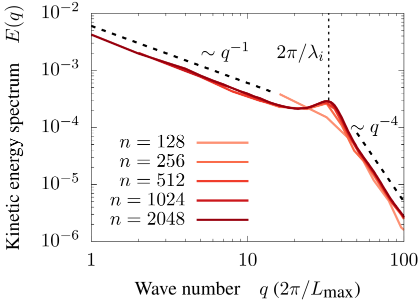
- Power spectra $\dot{F}_n(q) = -D_s(q) - D_r(q) + I(q) + T(q) = 0$

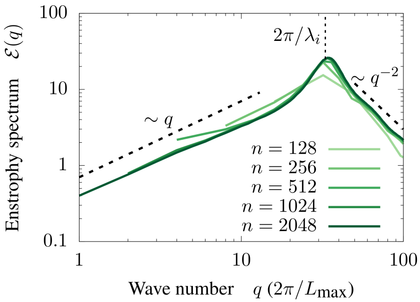


- No energy transfer between scales (but $\nu = 0$).
- Energy dissipated at the scale where it is produced

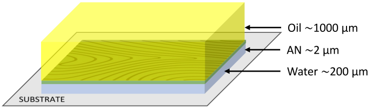
Vorticity

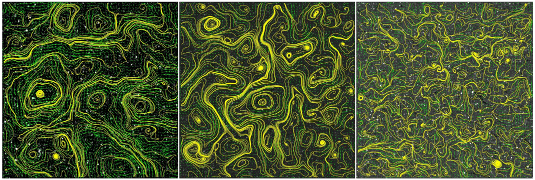
- Finite range of orientation correlations L_c
- Vorticity equation $\nabla^2\omega = \frac{\zeta\Delta\mu}{\eta}\left[\frac{1}{2}\left[\partial_x^2 - \partial_y^2\right]\sin 2\phi - \partial_{xy}^2\cos 2\phi\right]$
- Exponential distribution of vortex sizes L. Giomi





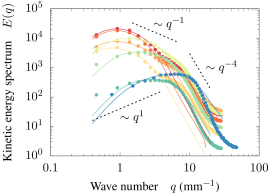
Substrate friction *B. Martinez Prat, F. Sagues, R. Alert, F.Meng...*





Energy spectrum

- Kinesin-microtubule layer on an oil substrate
- Energy spectrum $E(q) \sim (\frac{\zeta\Delta\mu}{\eta})^2 \frac{q^3}{\left(q^2+(q\eta_b/\eta)\coth qH\right)^2}$



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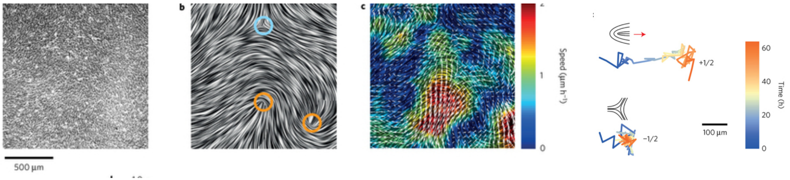
Defect motion *Giomi et al, Pismen*

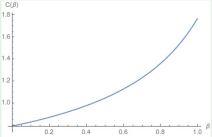


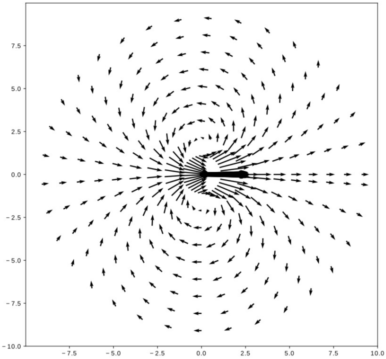
Spontaneous motion of +1/2 defects, L. Brézin, T. Risler

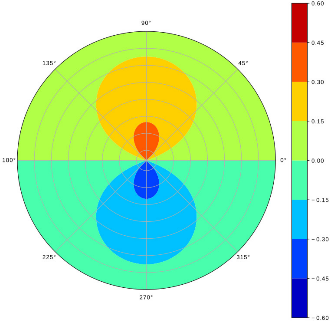
- Infinite 2d system, friction ξ, hydrodynamic screening length $L_h = (\eta/\xi)^{1/2}$
- First order perturbation in active stress
- Limit of vanishing rotational viscosity : $h_\perp = 0, \phi = \theta/2$
- Finite defect velocity $v_0 = -\frac{\pi}{8}\frac{\zeta\Delta\mu}{(\xi\eta)^{1/2}}$

Finite rotational viscosity, flow alignment parameter $\nu = 0$

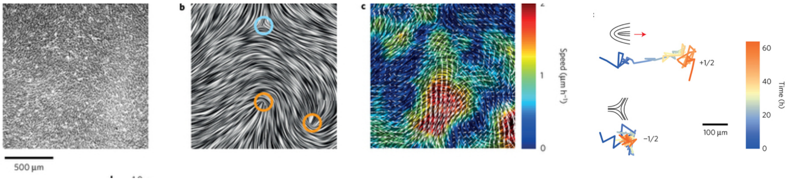
- Orientation perturbed by the flow
  $h_\perp = \frac{\gamma}{2}[\omega - v_\theta/r]$
- Defect velocity
  $v_0 = -\frac{\zeta\Delta\mu}{2[\xi(\eta+\gamma/4)]^{1/2}} C(\beta), \quad \beta = \frac{\gamma}{\gamma+4\eta}$







- Velocity field around a contractile defect
- Vorticity heatmap around a contractile defect



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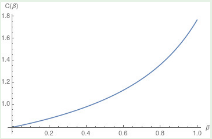
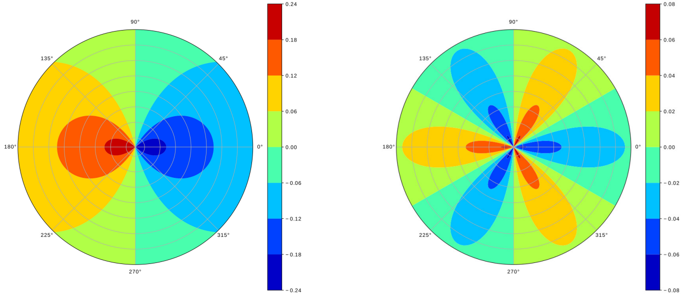


Tissue Hydrodynamics

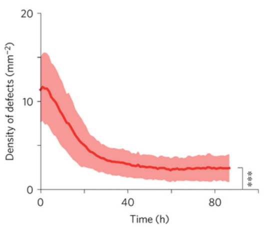
- Incompressible tissue. Pressure dependent growth rate $\nabla \mathbf{v} = k_d(P) - k_a(P) = -\frac{1}{\bar{\eta}}(P - P_h)$
- Bulk viscosity $\bar{\eta}$ of the tissue. Calculation with $\gamma = 0$.
- Cells extruded from the tissue in regions where $\nabla \mathbf{v} < 0$
- $+\frac{1}{2}$ defects act as nucleation centers for multilayering

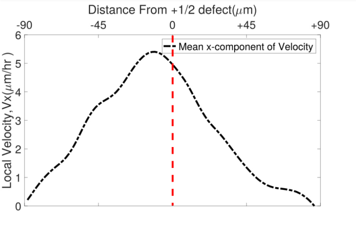


Experimental Velocity profiles T. Sarkar, P. Silberzan

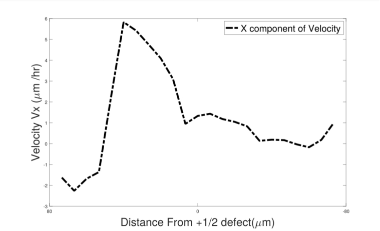
Motile and non motile $+\frac{1}{2}$ defects

- Motile defects
  - Move at expected velocity
  - Annihilate with $-\frac{1}{2}$ defects
  - Do not promote multilayering
- Non-Motile defects
  - Do not annihilate
  - Act as nucleation centers for multilayering





Motile



Non motile

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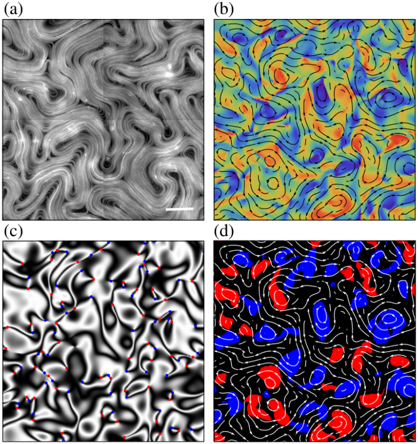
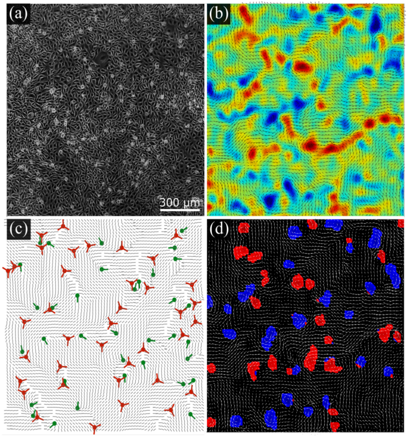


L. Giomi



C. Blanch-Mercader, V. Yashunsky

Summary

- Spontaneous flows and Frederiks transition
  - Chiral fluids Fuerthauer, Vitelli, Maitra
  - Cell extrusion and layering
- Active turbulence
  - Route to turbulence
  - Finite flow alignment parameter
  - 3 dimensional turbulence
  - Active polar fluids
- Active defects
  - Coupling between defects and flow
  - Interactions between defects Bowick, Marchetti, Ramaswamy
- Active Phase transitions Tailleur, Cates
  - Analogy with equilibrium phase transitions
  - Bubble phases (membraneless compartments?)
- Biological systems as active matter
  - Tissues, cancer and development. Active plastic materials
  - Cytoskeleton. Non homogeneous activity