Polar active liquid crystal emulsions

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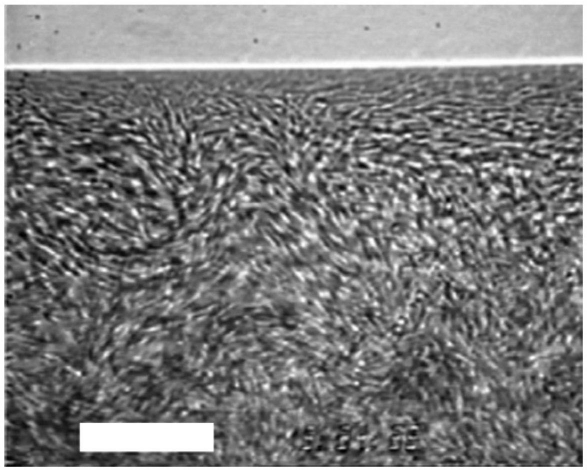
Xmas 2015, Bari - Italy

Active matter

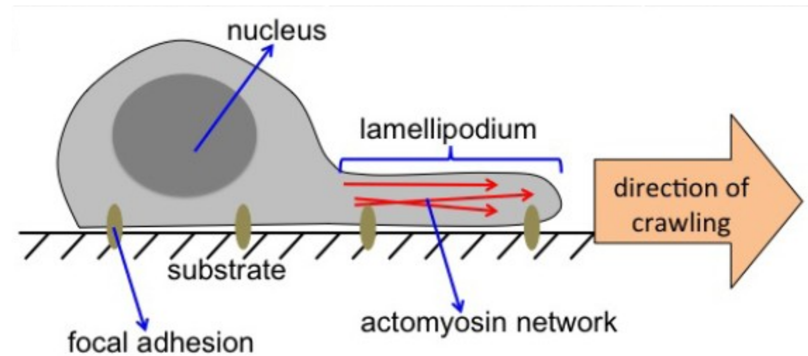
Inherent far from equilibrium system whose internal constituents continuously convert chemical energy into work (M.C. Marchetti et al., Rev. Mod. Phys. **85**, 1143 (2013))

Bacterial turbulence



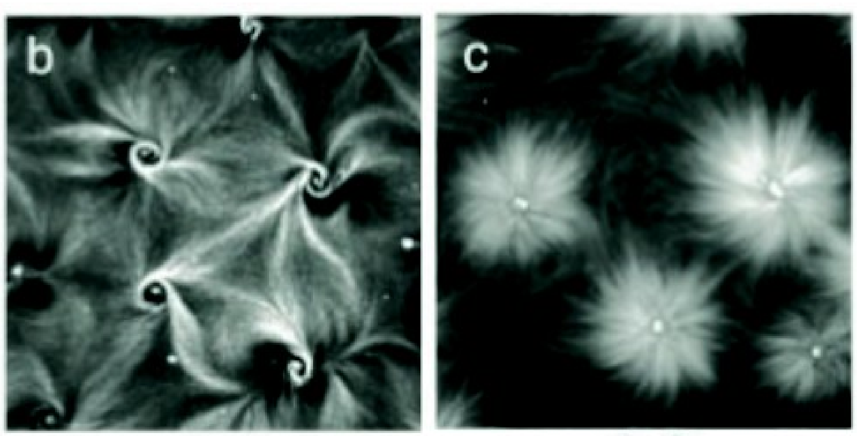
M.C. Marchetti et al, Rev. Mod. Phys., **85** (2013)

Crawling cell



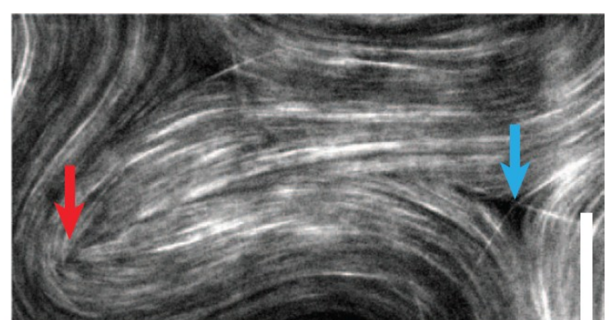
Tjhung et al., Nat. Comm. **6**, 5420 (2015)

Aster/spiral patterns

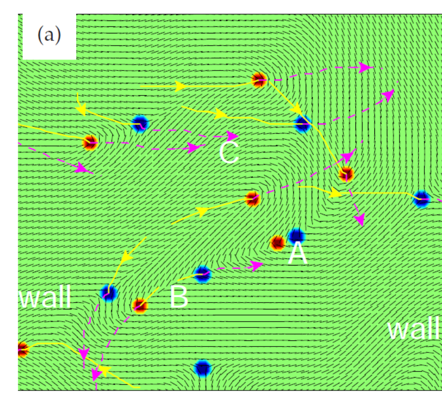


Surrey et al., Science **292**, 1167 (2001).

Active defects

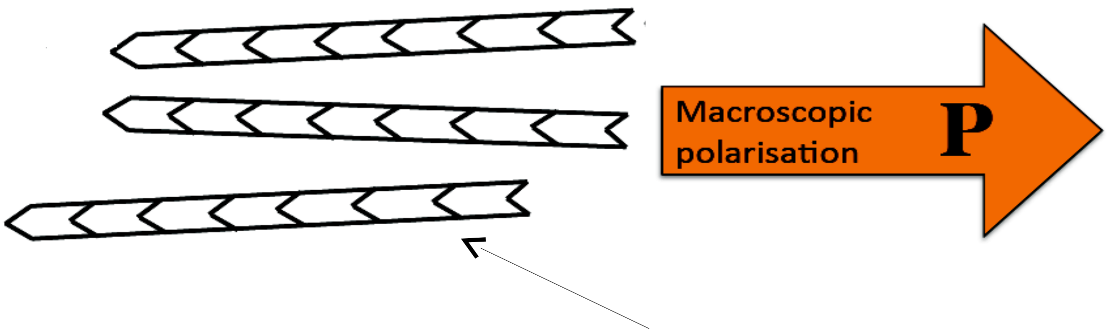


T. Sanchez et al., Nature, 491, 431 (2012)

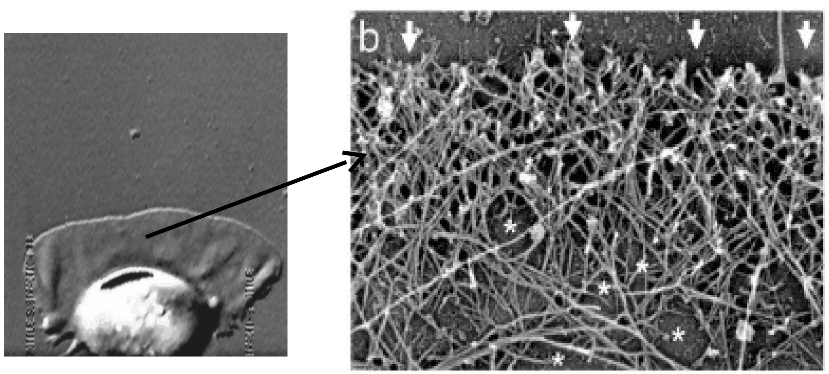


S.P. Thampi et al., Phil. Trans. A 372, 2029 (2014).

Polar active fluid



Actin filaments



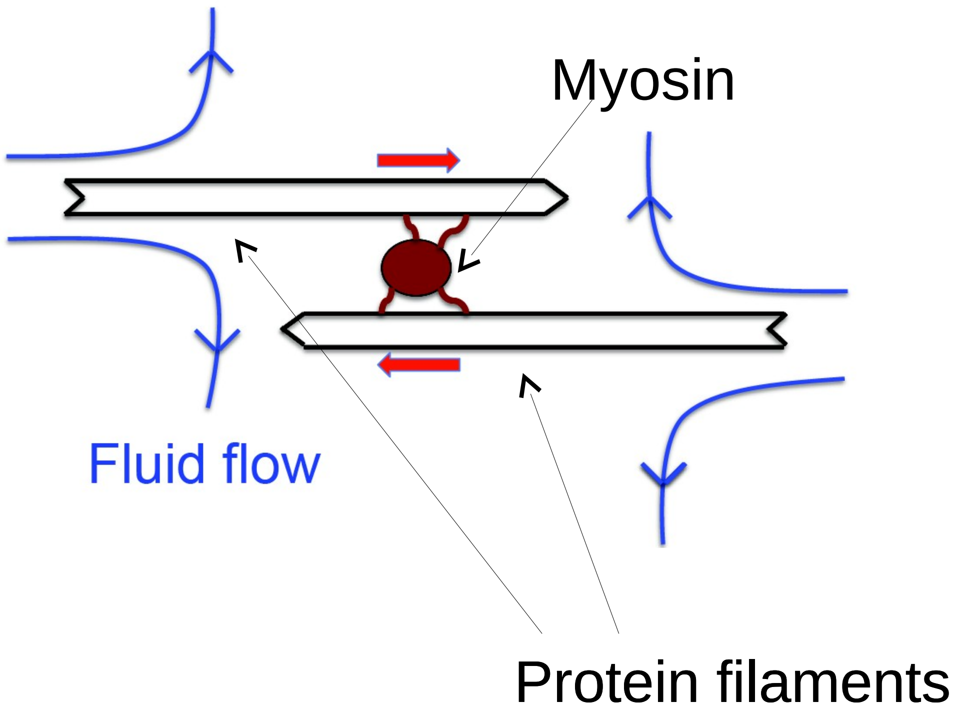
Contractile/puller swimmer

e.g actomyosin solution

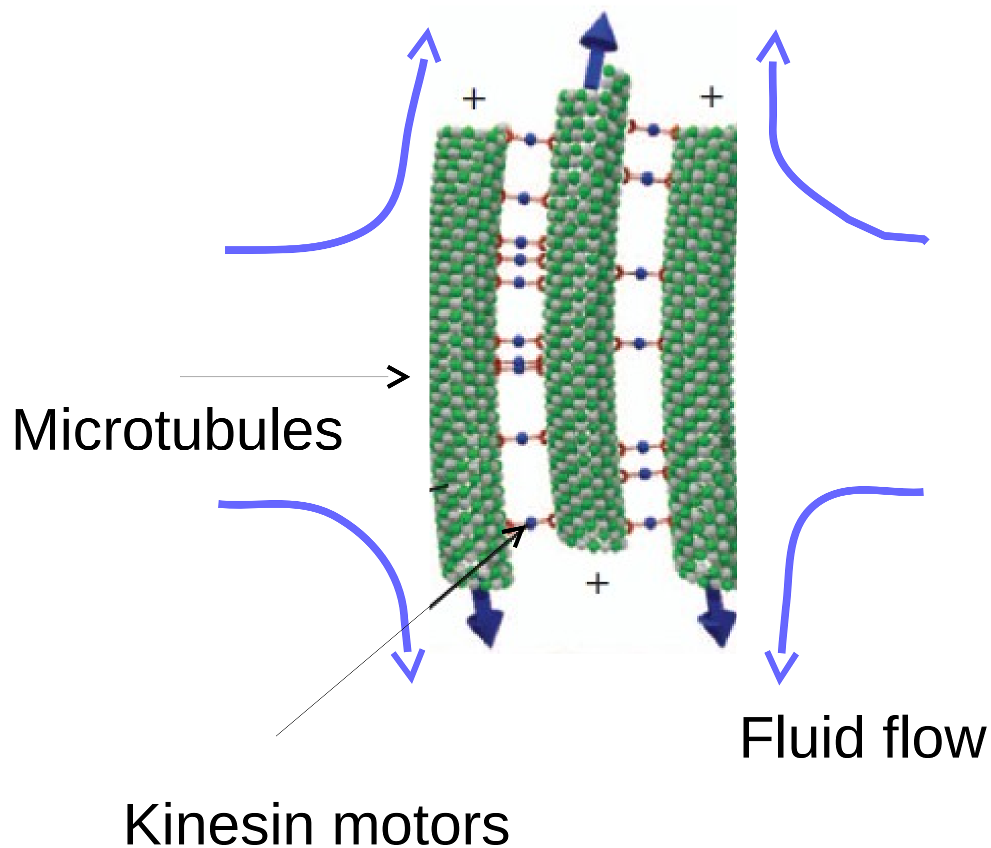
Macroscopic polarisation, average direction of the fibers

Active fluid

Contractile/puller swimmer



Extensile/pusher swimmer

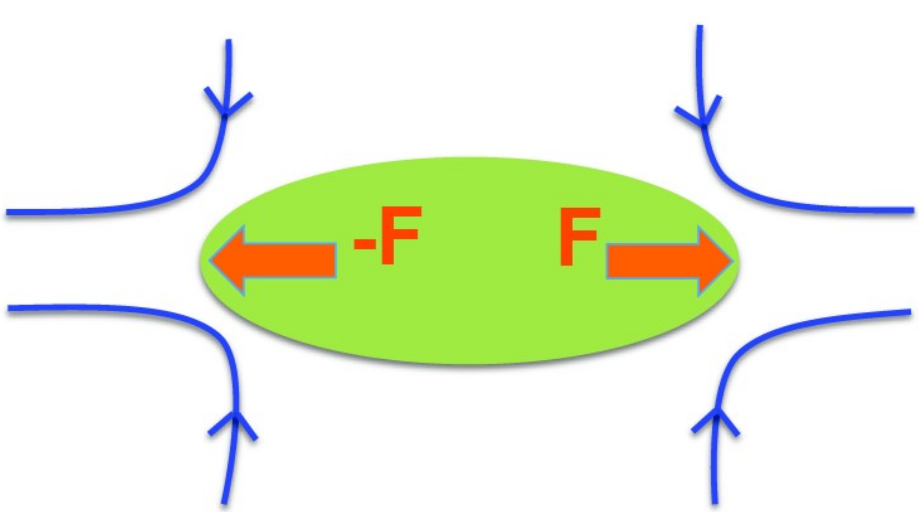


Tjhung et al., PNAS (2012)

Dogic et al., Nature (2013)

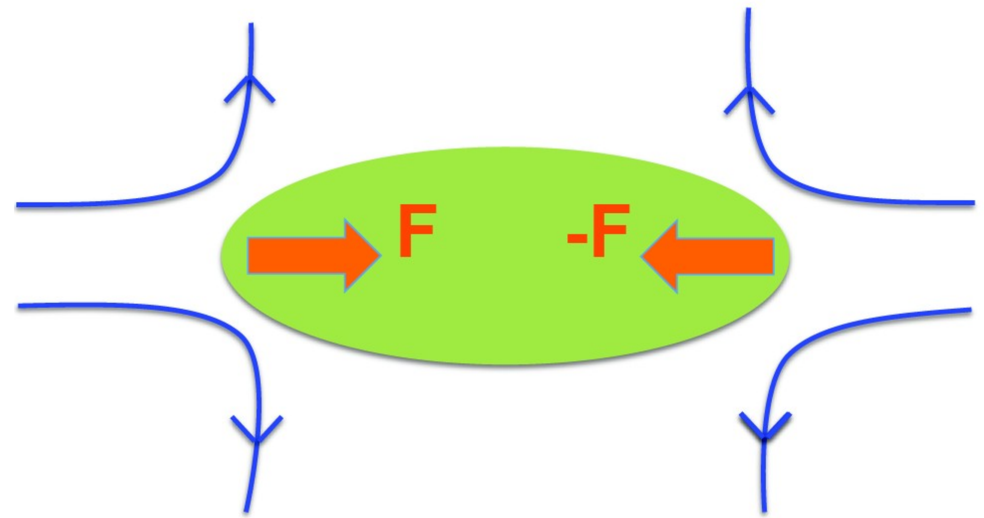
Active fluid

Force dipole approximation



Extensile/pusher swimmer

e.g. bacterial suspension, microtubules and kinesin



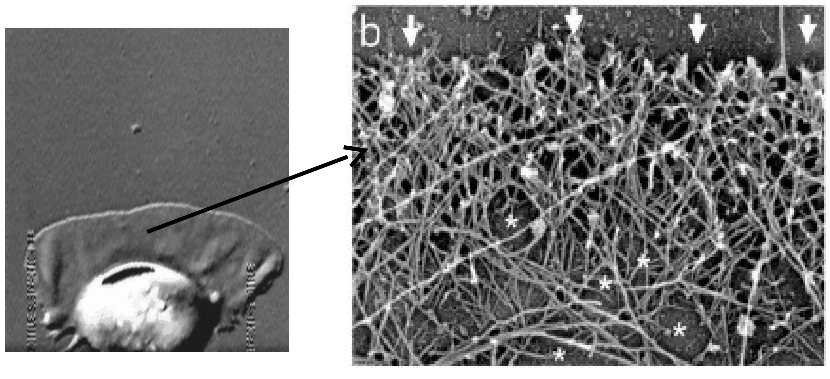
Contractile/puller swimmer

e.g. actomyosin solution

Active stress

$$\sigma^{a}_{\alpha\beta} = -\zeta\left(P_\alpha P_\beta - \frac{1}{3}P^2\delta_{\alpha\beta}\right)$$

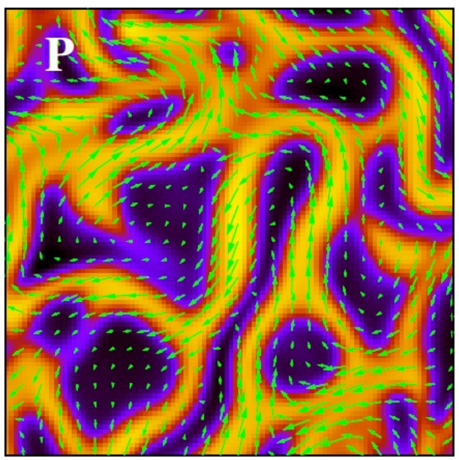
(Ramaswamy *et. al.* PRL (2004))

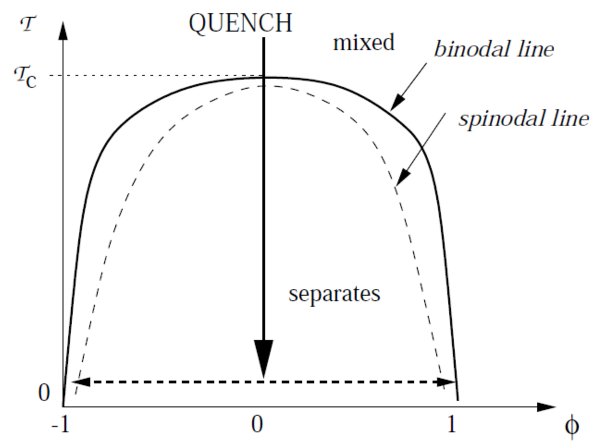


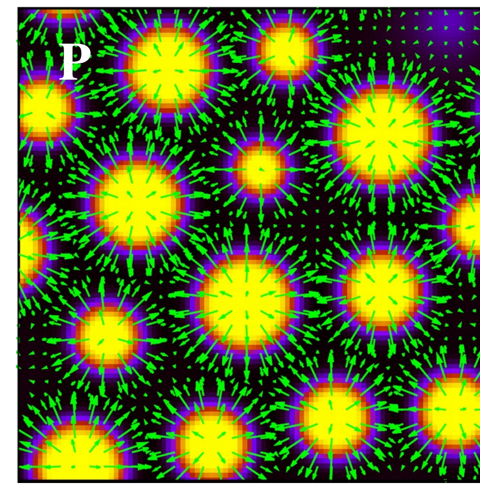
Phase separation in a polar active fluid

Active material can coexist with an isotropic fluid:

- active droplets (Tjhung et al., PNAS 2012, Nat. Comm 2015, M Blow et al.,PRL 2014)
- inverted emulsion in an active host (Demagistris et al., Soft Matter 2014)
- bacterial colonies (Boyer at al., Phys. Biol. 2011)







$$L(T) = 2\pi \frac{\int S(k,T)\,\mathrm{d}k}{\int k S(k,T)\,\mathrm{d}k}$$

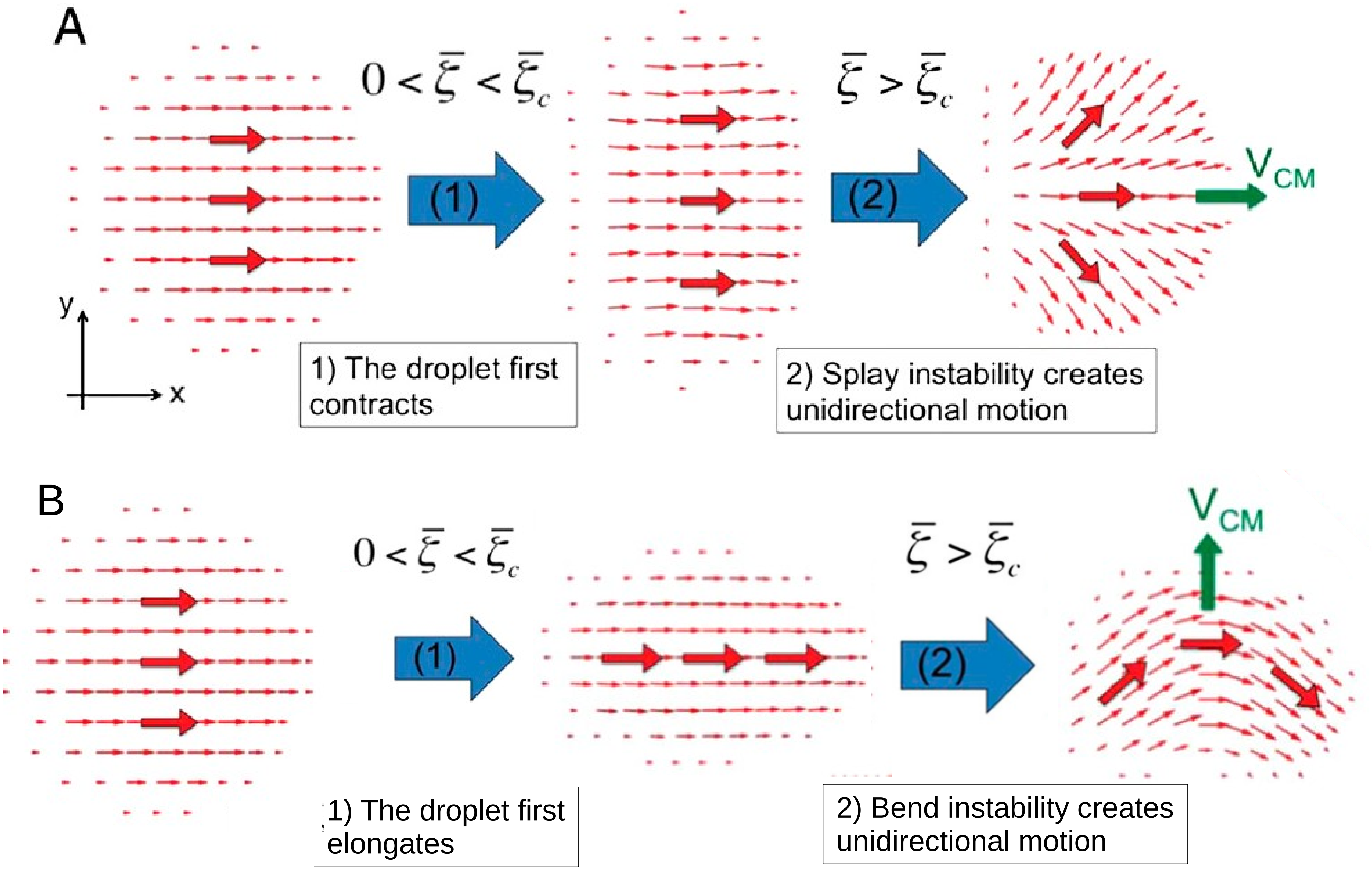
$$S(k,T) \equiv \langle \phi(\mathbf{k},T)\phi(-\mathbf{k},T)\rangle$$

$L(T) \sim T^{1/3}$	Diffusive regime
$L(T) \sim T^{2/3}$	Inertial regime
$L(T) \sim T$	Viscous regime

- Polarization and velocity fields when active?
- Can emulsions acquire motion?
- What about the coarsening dynamics?

Kendon et al., J. Fluid. Mech. **440**, 147 (2001)

Motility of an active emulsion



E. Tjhung, D. Marenduzzo, M. E. Cates, PNAS **109**, 12381 (2013).

Equations of motion

Hydrodynamics fields

- Concentration of active material $\phi(\boldsymbol{r}, t)$

- Velocity of the fluid $\boldsymbol{v}(\boldsymbol{r}, t)$

- Polarisation field $\boldsymbol{P}(\boldsymbol{r}, t)$

The fluid is assumed incompressible: $\nabla \cdot \boldsymbol{v} = 0$

Equations of motion

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \mathbf{v}) = \nabla \left(M \nabla \frac{\delta F}{\delta \phi} \right)$$

$$\frac{\partial \mathbf{P}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{P} = -\underline{\underline{\Omega}} \cdot \mathbf{P} + \xi \underline{\underline{D}} \cdot \mathbf{P} - \frac{1}{\Gamma} \frac{\delta F}{\delta \mathbf{P}}$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = -\nabla P + \nabla \cdot \left(\underline{\underline{\sigma}}^{\text{act}} + \underline{\underline{\sigma}}^{\text{pass}} \right)$$

Passive stress

$$\sigma^{\text{visc}}_{\alpha\beta} = \eta(\partial_\alpha v_\beta + \partial_\beta v_\alpha),$$

$$\sigma^{\text{elas}}_{\alpha\beta} = \frac{1}{2}(P_\alpha h_\beta - P_\beta h_\alpha) - \frac{\xi}{2}(P_\alpha h_\beta + P_\beta h_\alpha) - \kappa \partial_\alpha P_\gamma \partial_\beta P_\gamma,$$

$$\sigma^{\text{inter}}_{\alpha\beta} = \left(f - \phi \frac{\delta F}{\delta \phi} \right) \delta_{\alpha\beta} - \frac{\partial f}{\partial(\partial_\beta \phi)} \partial_\alpha \phi.$$

Active stress

$$\sigma^a_{\alpha\beta} = -\zeta \varphi \left(P_\alpha P_\beta - \frac{1}{3} P^2 \delta_{\alpha\beta} \right)$$

E. Tjhung, D. Marenduzzo, M. Cates, PNAS (2013); E. Tjhung, A.T., D. Marenduzzo, M. Cates., Nat. Comm. (2015)

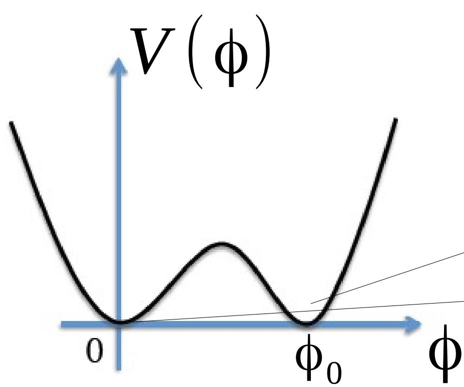
Equations of motion

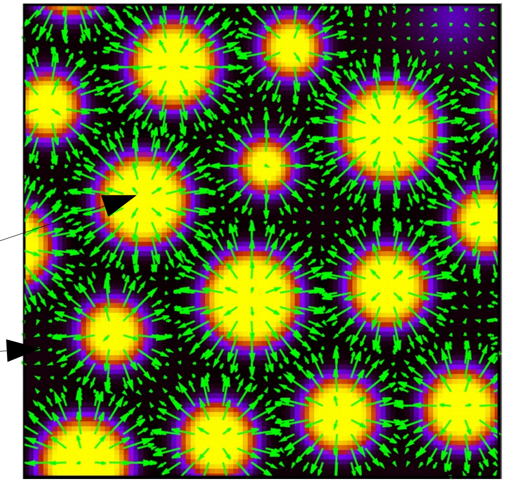
Binary fluid

$$F[\phi, \mathbf{P}] = \int d^3r \left\{ \frac{a}{4\phi_{\mathrm{cr}}{}^4}\phi^2(\phi-\phi_0)^2 + \frac{k}{2}|\nabla\phi|^2 - \frac{\alpha}{2}\frac{(\phi-\phi_{\mathrm{cr}})}{\phi_{\mathrm{cr}}}|\mathbf{P}|^2 + \frac{\alpha}{4}|\mathbf{P}|^4 + \frac{\kappa}{2}(\nabla\mathbf{P})^2 + \beta_1 \mathbf{P}\cdot\nabla\phi + \beta_2(\mathbf{P}\cdot\nabla\phi)^2 \right\}.$$

Polar liquid crystal

Anchoring



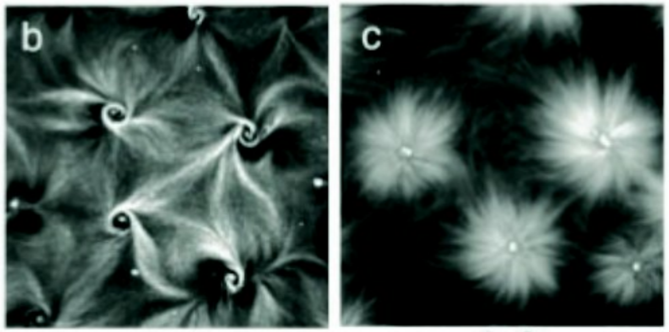


E. Tjhung, D. Marenduzzo, M. Cates, PNAS (2013); E. Tjhung, A.T., D. Marenduzzo, M. Cates., Nat. Comm. (2015)

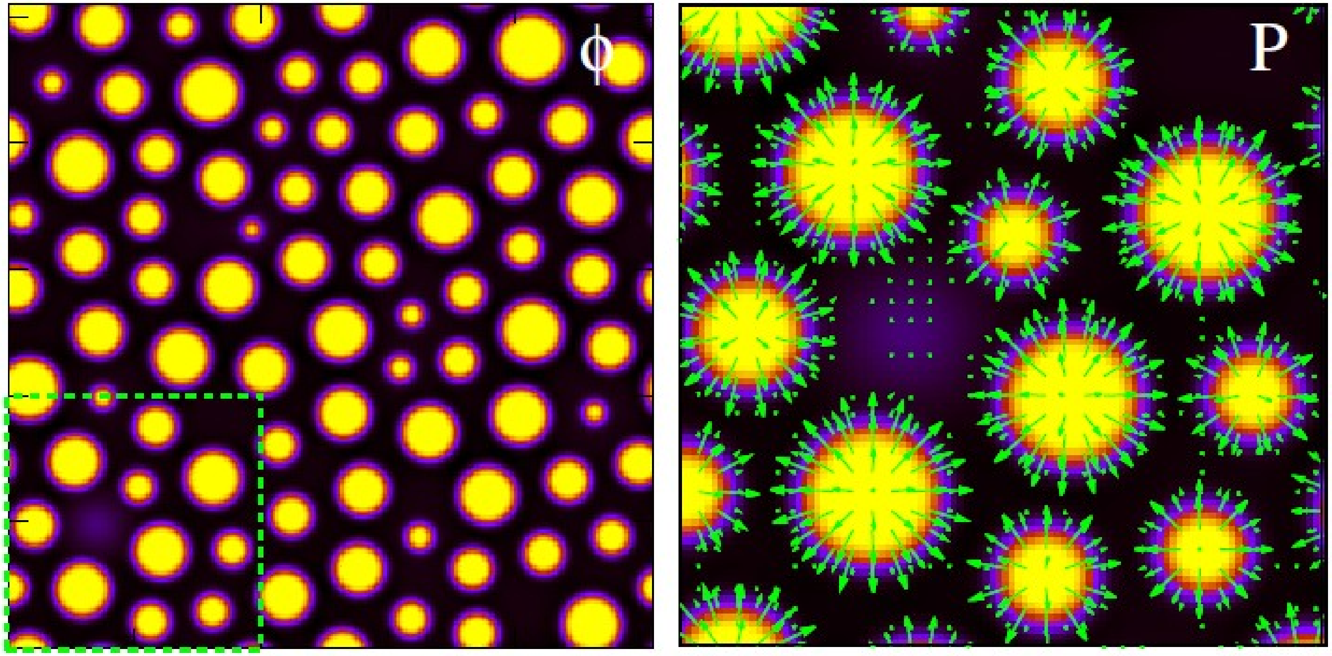
The droplet phase

Polar extensile – isotropic passive mixture

$$\zeta \sim 0 \qquad \beta_1 \neq 0$$



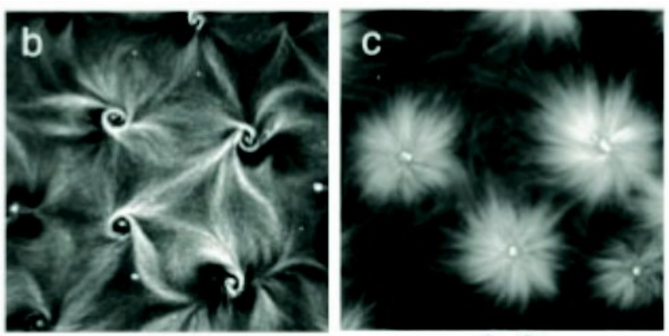
Surrey et al., Science **292**, 1167 (2001).



The droplet phase

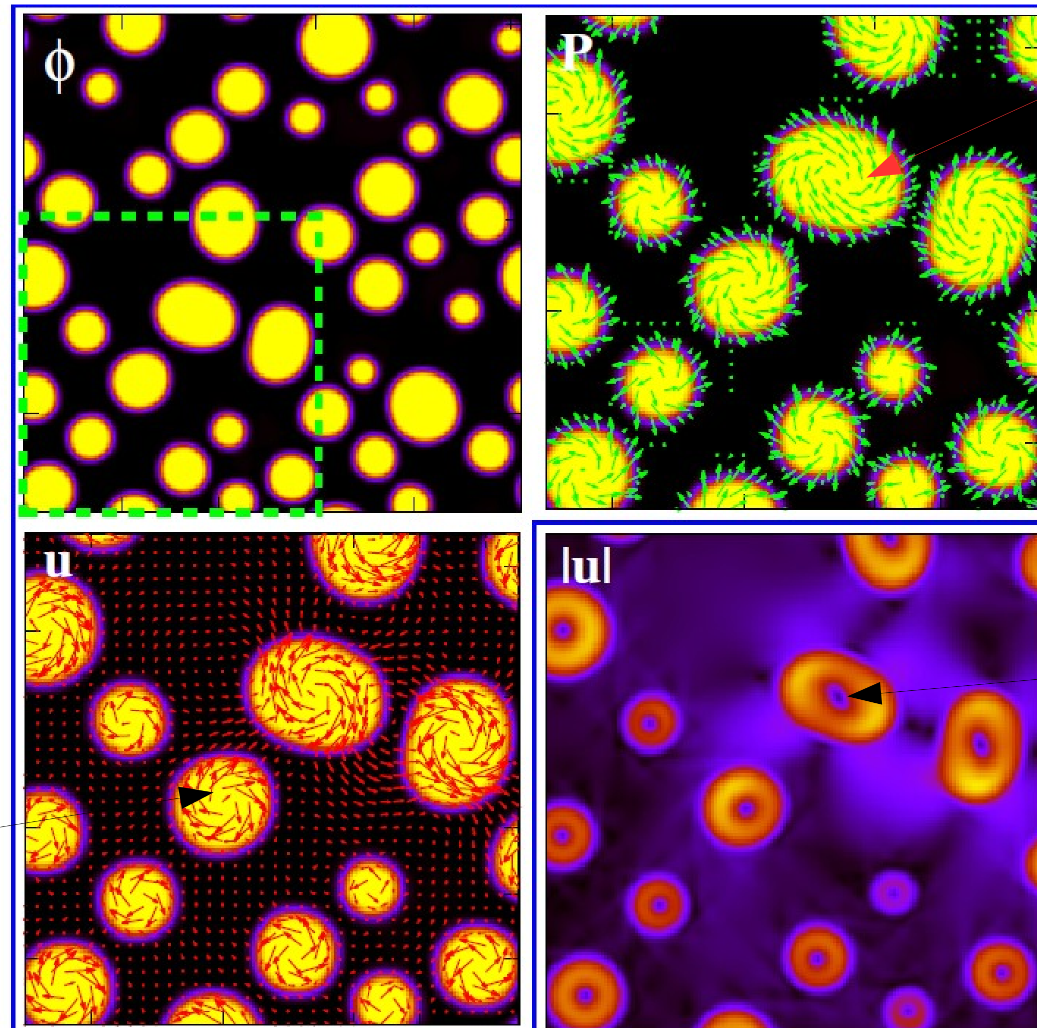
Polar extensile – isotropic passive mixture

$$\zeta = 3.5x10^{-3} \qquad \beta_1 \neq 0$$



Surrey et al., Science **292**, 1167 (2001).

Emulsions rotate.
Velocity field induced by active stress and bend (backflow).



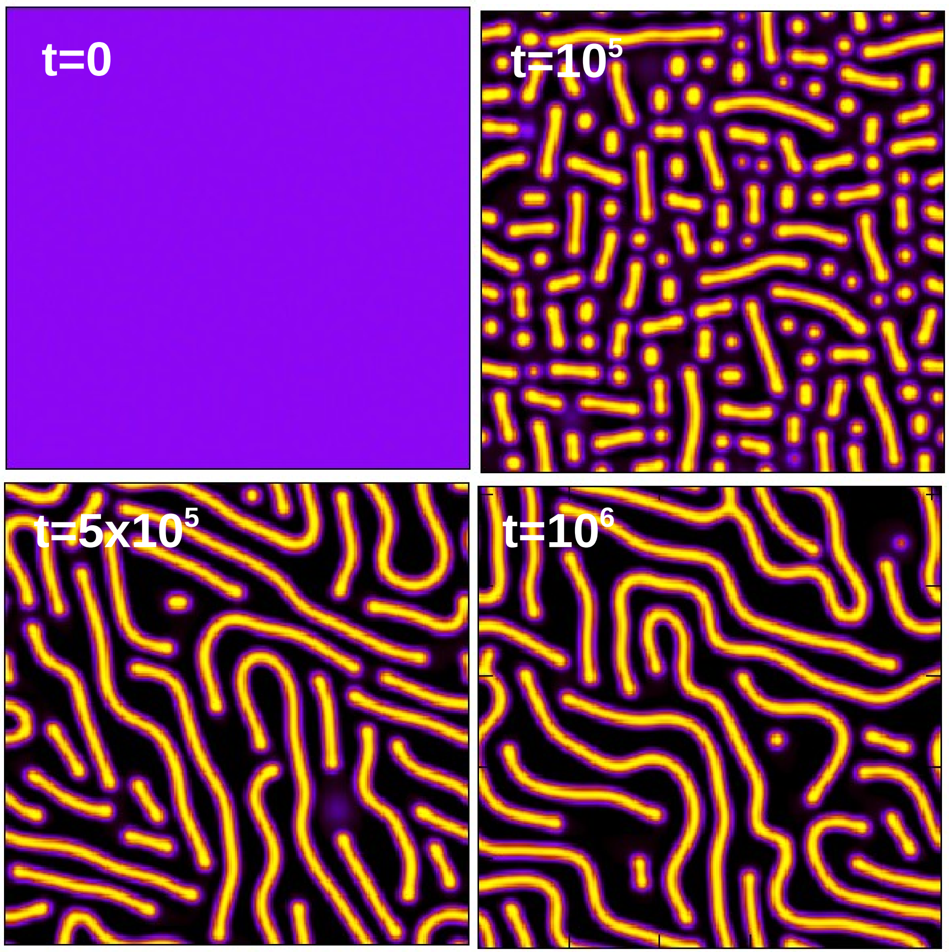
Bend distortions induced by the activity

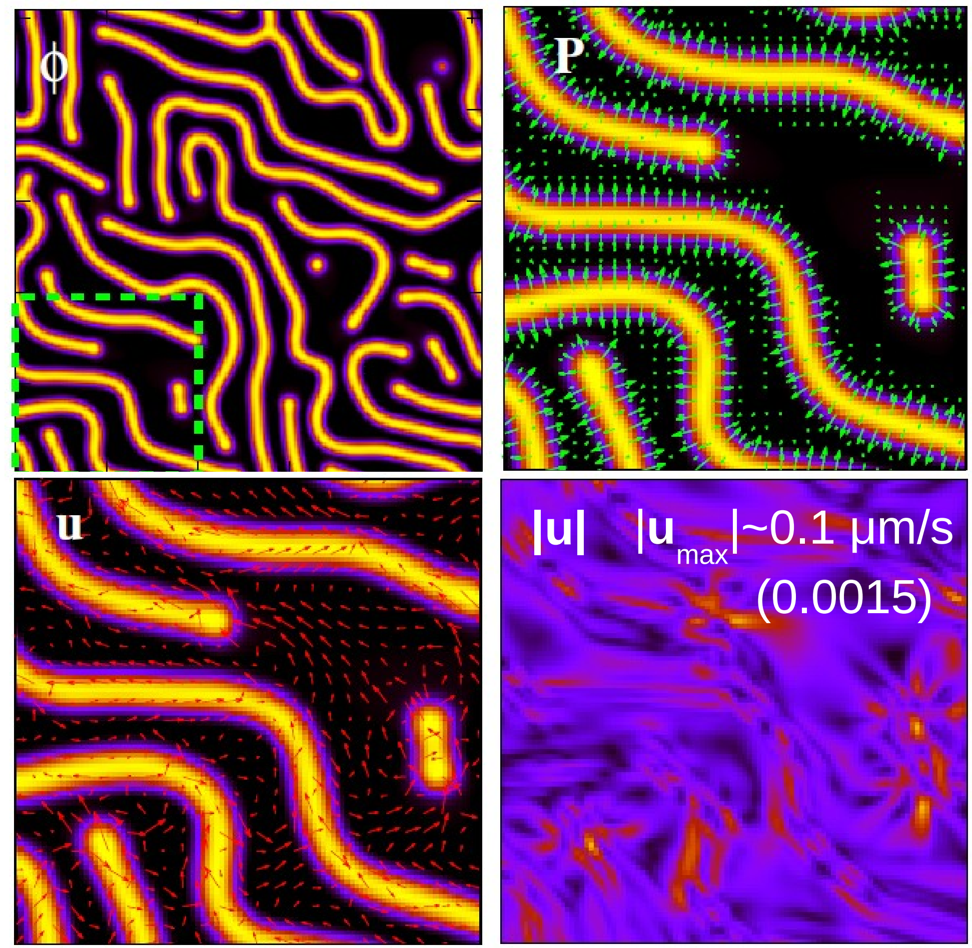
$|u_{max}|$~1 μm/s
(0.015)

The droplet phase

Polar contractile – isotropic passive mixture

$$\zeta \sim -5\text{x}10^{-3} \qquad \beta_1 \neq 0$$

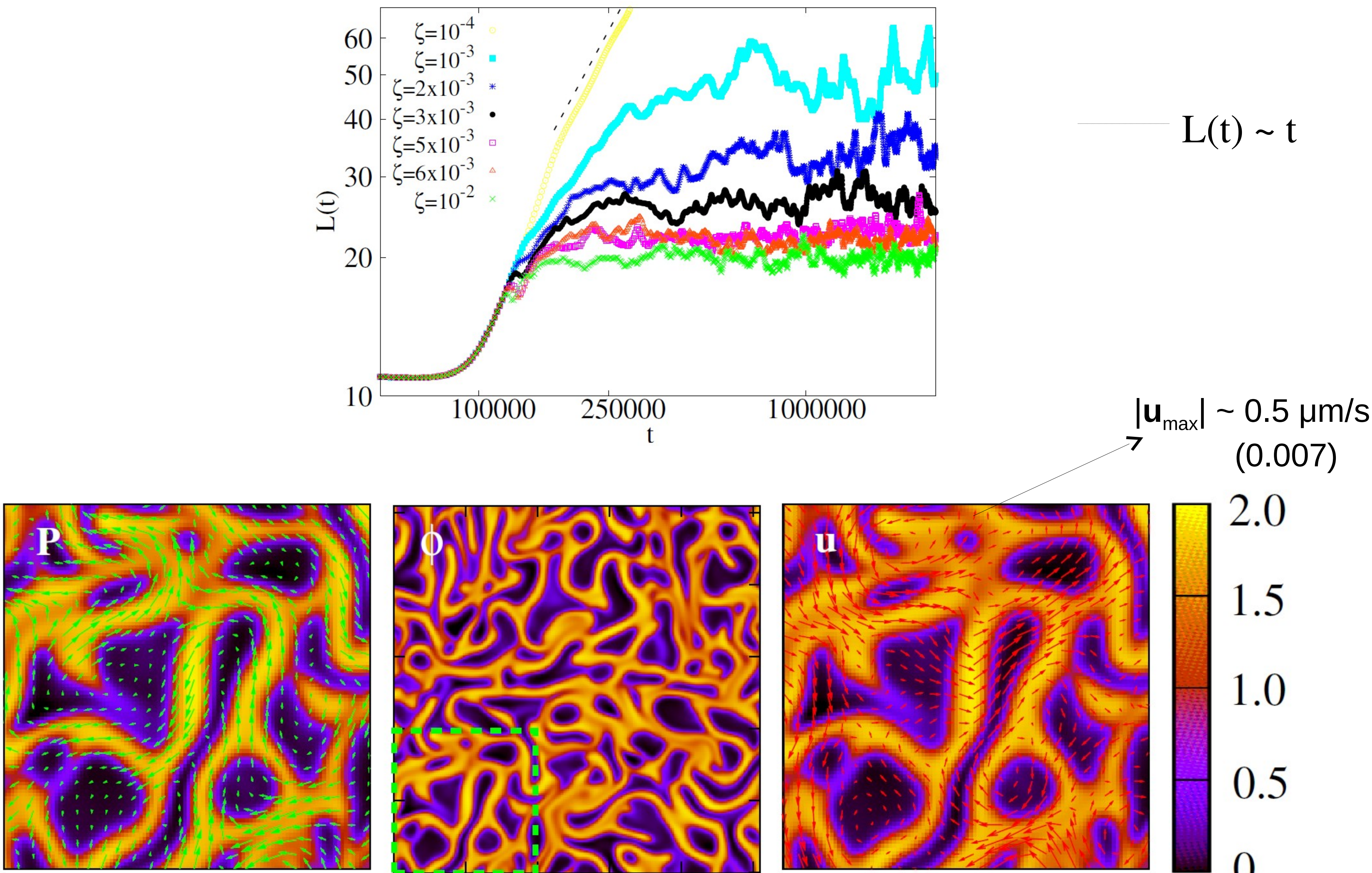




Dynamics of the concentration of the mixture

Splay distortions induced by the activity. Emulsions elongate and arrange into a lamellar-like pattern.

Polar extensile – isotropic passive mixture



Conclusions

- Extensile emulsions grow with time (mainly through coalescence and Ostwald ripening, as in the passive case) and acquire rotation for high enough activity.

- Contractile emulsions elongate and arrange in lamellar-like patterns. Possible route towards active soft channels.

- Symmetric mixtures (either pushers or pullers) show arrested phase separation for high enough activity.