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Lamellar ordering, droplet formation and phase inversion in exotic active emulsions

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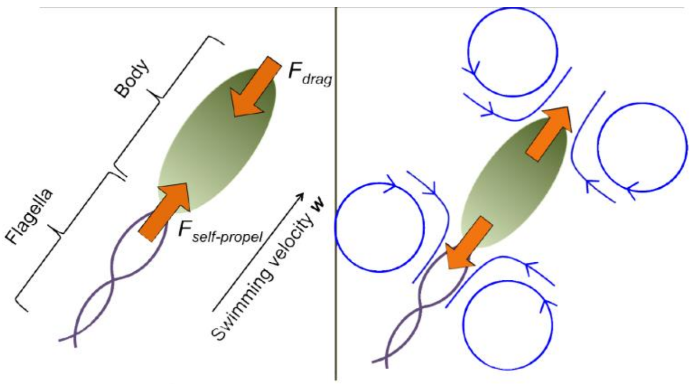
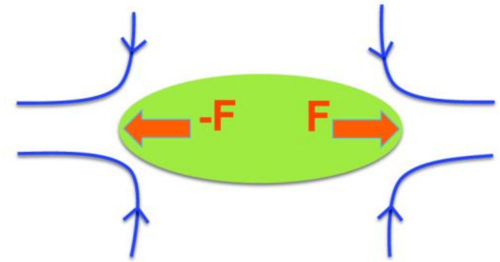
ACTIVE FLUIDS

Forces acting on a bacterium

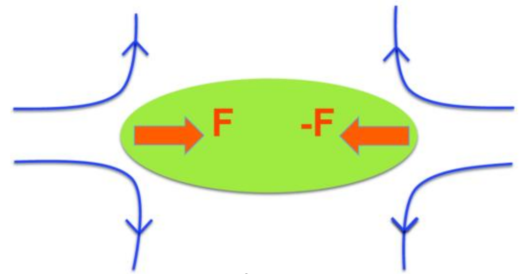
Forces acting on the surrounding fluid by the bacterium



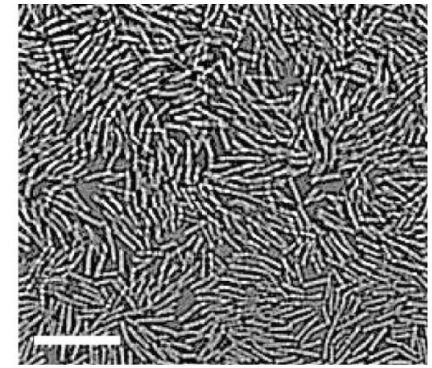
Schematic of a single bacterium suspended in a fluid solvent



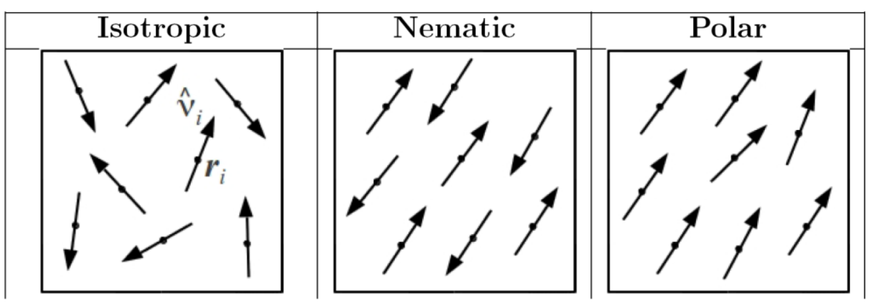
Extensile/pusher swimmer



Contractile/puller swimmer



Bacterial suspension;
Wensinka et al. PNAS, 4, 2012, 109, 36



Orientational order in a suspension of active particles

1. Elsen Tjhung, Phenomenology and Simulations of Active Fluids, PhD thesis, 2013

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

polar order in a sardine school

CONTINUUM MODEL

Three dynamical fields: velocity **u**, concentration of active component ϕ, polarization **P**

$$\begin{cases} \rho\left\{\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right\}\mathbf{u}=-\nabla P+\nabla\cdot\left(\underline{\underline{\sigma}}^{passive}+\underline{\underline{\sigma}}^{active}\right) \\ \frac{\partial\mathbf{P}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{P}=-\underline{\underline{\Omega}}\cdot\mathbf{P}+\xi\underline{\underline{D}}\cdot\mathbf{P}-\frac{1}{\Gamma}\frac{\delta F}{\delta\mathbf{P}} \\ \frac{\partial\phi}{\partial t}+\nabla\cdot(\phi\mathbf{u})=\nabla\left(M\nabla\frac{\delta F}{\delta\phi}\right) \end{cases}$$

Navier-Stokes equation

Leslie–Ericksen theory of nematic liquid crystals

Cahn–Hilliard equation

$$\underline{\underline{\sigma}}^{passive}=\underline{\underline{\sigma}}^{viscous}+\underline{\underline{\sigma}}^{elastic}$$

$\underline{\underline{\sigma}}^{active}=-\zeta\mathbf{PP}$ active stress. ζ distinguishes between active and contractile active fluids.

Free energy functional:

$$F[\phi,\mathbf{P}]=\int dr^3\left\{\frac{a}{4\phi_{cr}^4}\phi^2(\phi-\phi_0)^2+\frac{k}{2}|\nabla\phi|^2+\frac{c}{2}\left(\nabla^2\phi\right)^2-\frac{\alpha}{2}\frac{(\phi-\phi_{cr})}{\phi_{cr}}|\mathbf{P}|^2+\frac{\alpha}{4}|\mathbf{P}|^4+\frac{\kappa}{2}(\nabla\mathbf{P})^2+\beta\mathbf{P}\cdot\nabla\phi\right\}$$

$\mathbf{h}=-\frac{\delta F}{\delta\mathbf{P}},\ \mu=\frac{\delta F}{\delta\phi}$ Molecular field and chemical potential favouring relaxation towards the free energy minimum

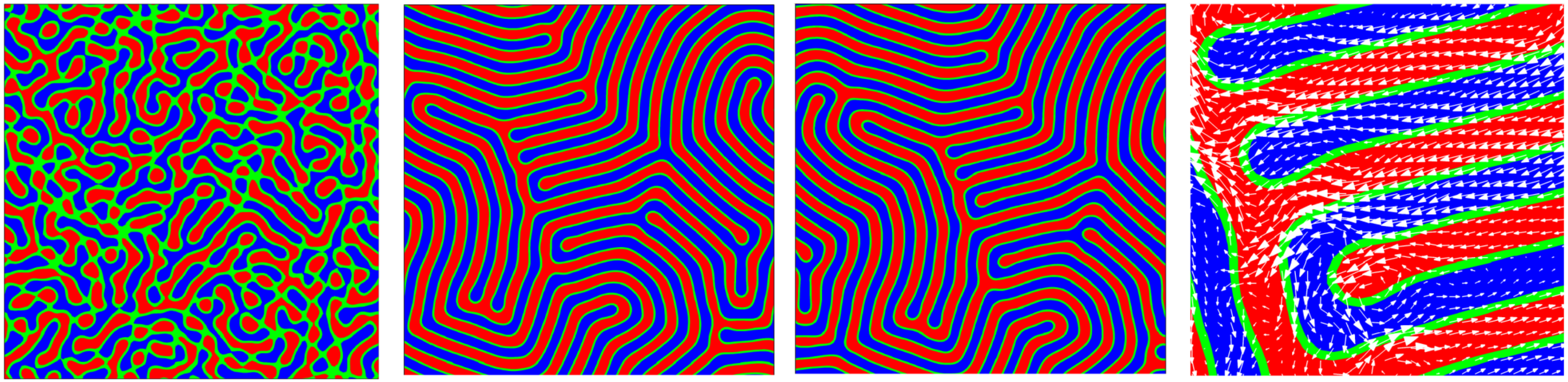
$\underline{\underline{D}}$ and $\underline{\underline{\Omega}}$ are the symmetric and anti-symmetric part of the velocity gradient tensor, Γ is a relaxational constant related to the rotational viscosity of the liquid crystalline fluid and ξ is related to the geometry of the swimmers, i.e. $\xi>0$ for rod-like molecules and $\xi<0$ for oblate molecules

2.P. G. de Gennes and J. Prost. The Physics of Liquid Crystals. Clarendon Press,1993.

3. Y. Hatwalne, S. Ramaswamy, M. Rao and R. A. Simha, Phys. Rev. Lett., 2004, 92, 118101.

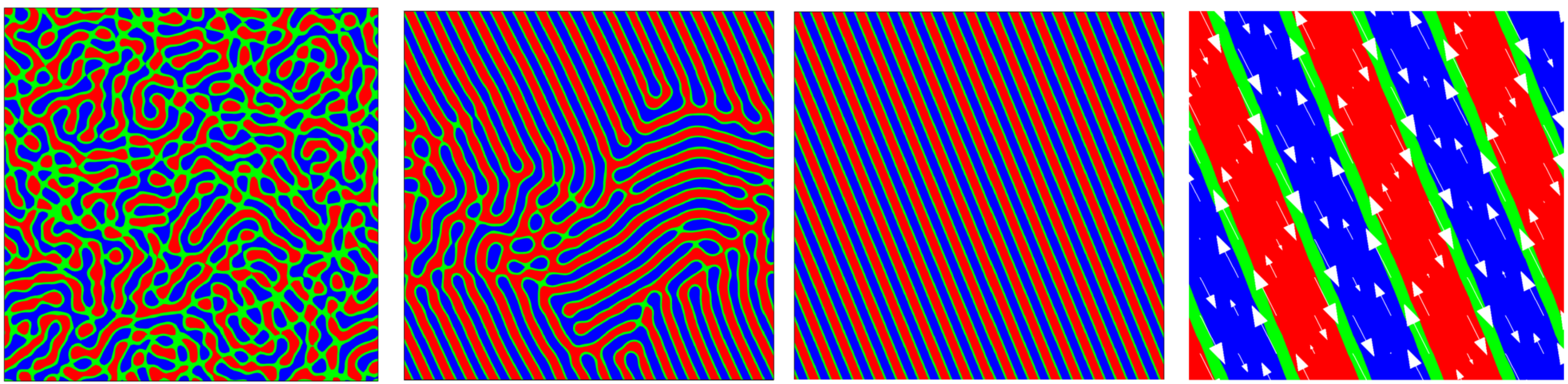
Contractile active component

$\beta = 0.01 \; \zeta = -0.002$



$t = 7000$ $t = 5 \cdot 10^6$ $t = 10^7$ $t = 10^7$

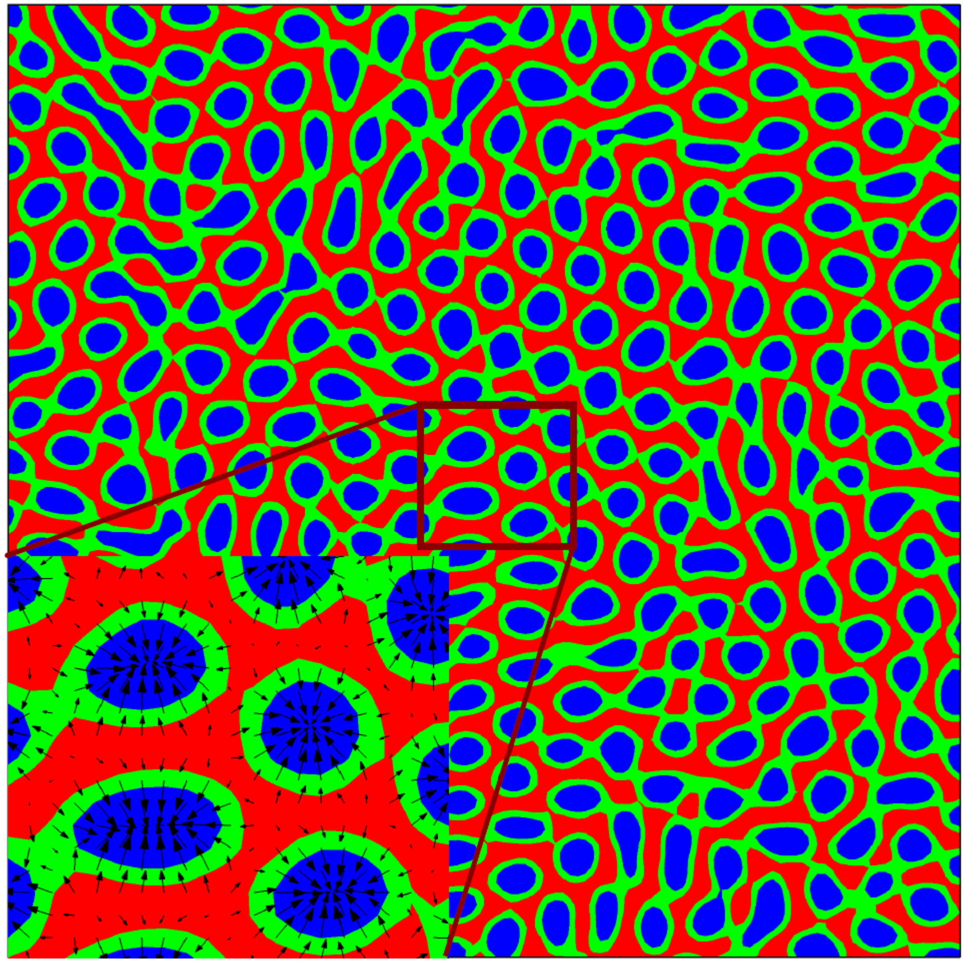
$\beta = 0.01 \; \zeta = -0.006$



$t = 7000$ $t = 1.4 \cdot 10^6$ $t = 4 \cdot 10^6$ $t = 4 \cdot 10^6$

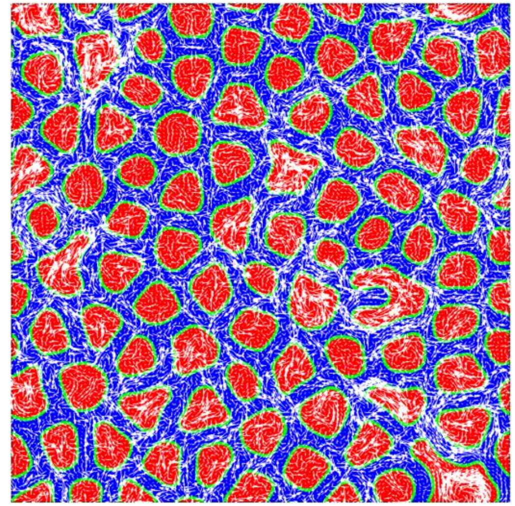
Strong contractile, extensile and not symmetric mixtures

Strong Contractile

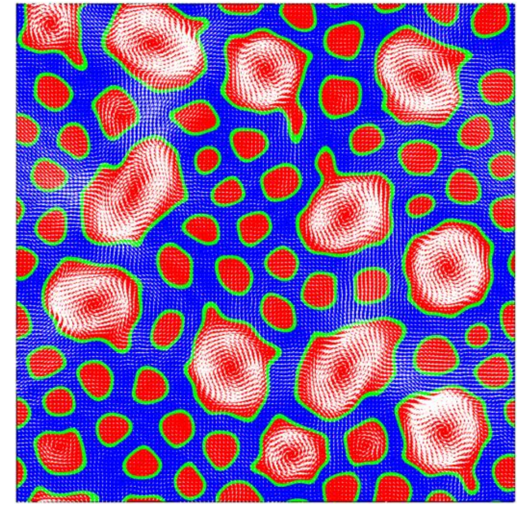


$\zeta = -0.02$

Extensile active component

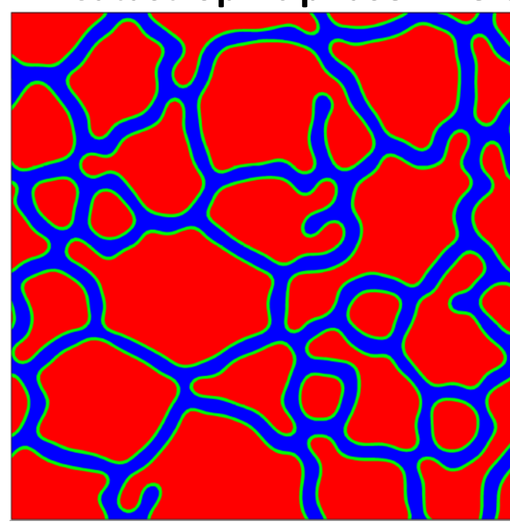


$\zeta = 0.002$

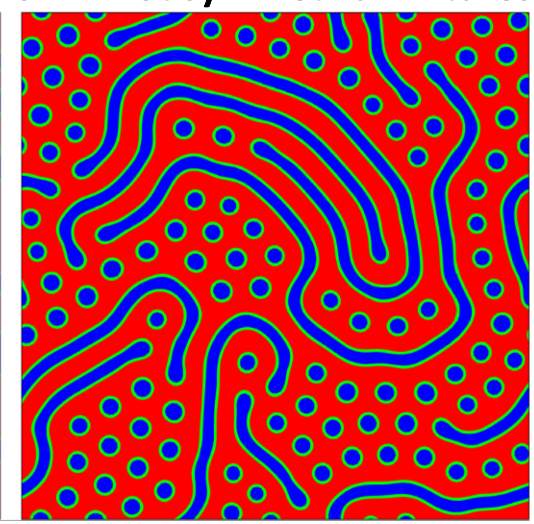


$\zeta = 0.004$

Catastrophic phase inversion in not symmetric mixtures



$\zeta = 0.002$



$\zeta = 0.004$

SUMMARY

Mixtures of passive and polar active fluids with surfactant exhibit extremely rich phase behavior when activity is varied:

Symmetric mixtures:

- Lamellar order for moderate contractile activity
- Passive droplets in an active bi-continuous self-stirring matrix for strong contractiles
- Poly-disperse droplets of extensile active fluid in passive background

Majority of active component:

- High internal phase emulsion
- Phase inversion when activity is switched off