FONDATION PIERRE-GILLES DE GENNES POUR LA RECHERCHE

PARIS SCIENCES & LETTRES PSL QUARTIER LATIN

An Example of Active Matter: Active Gels

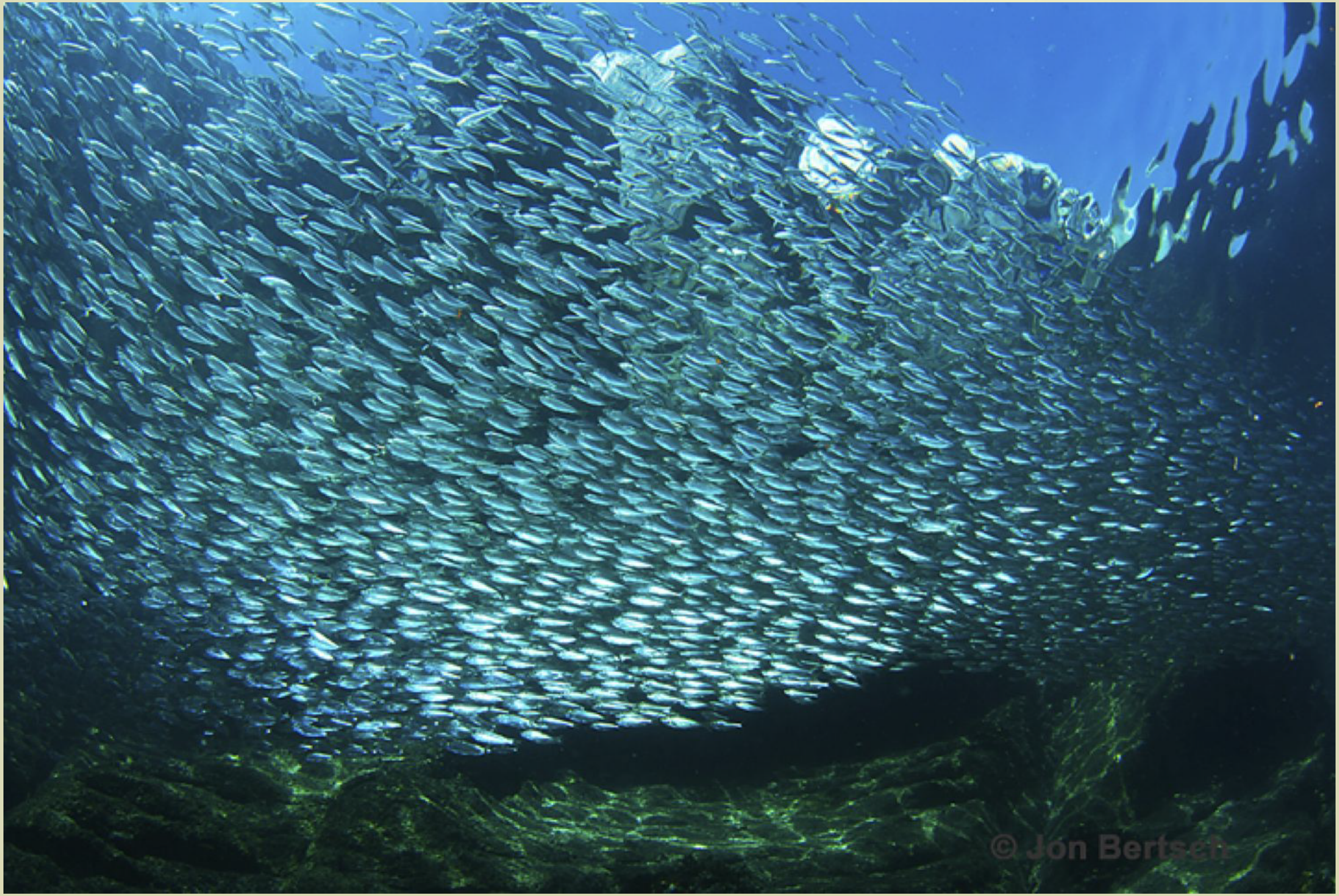
J.F. Joanny
K. Sekimoto
R. Voituriez

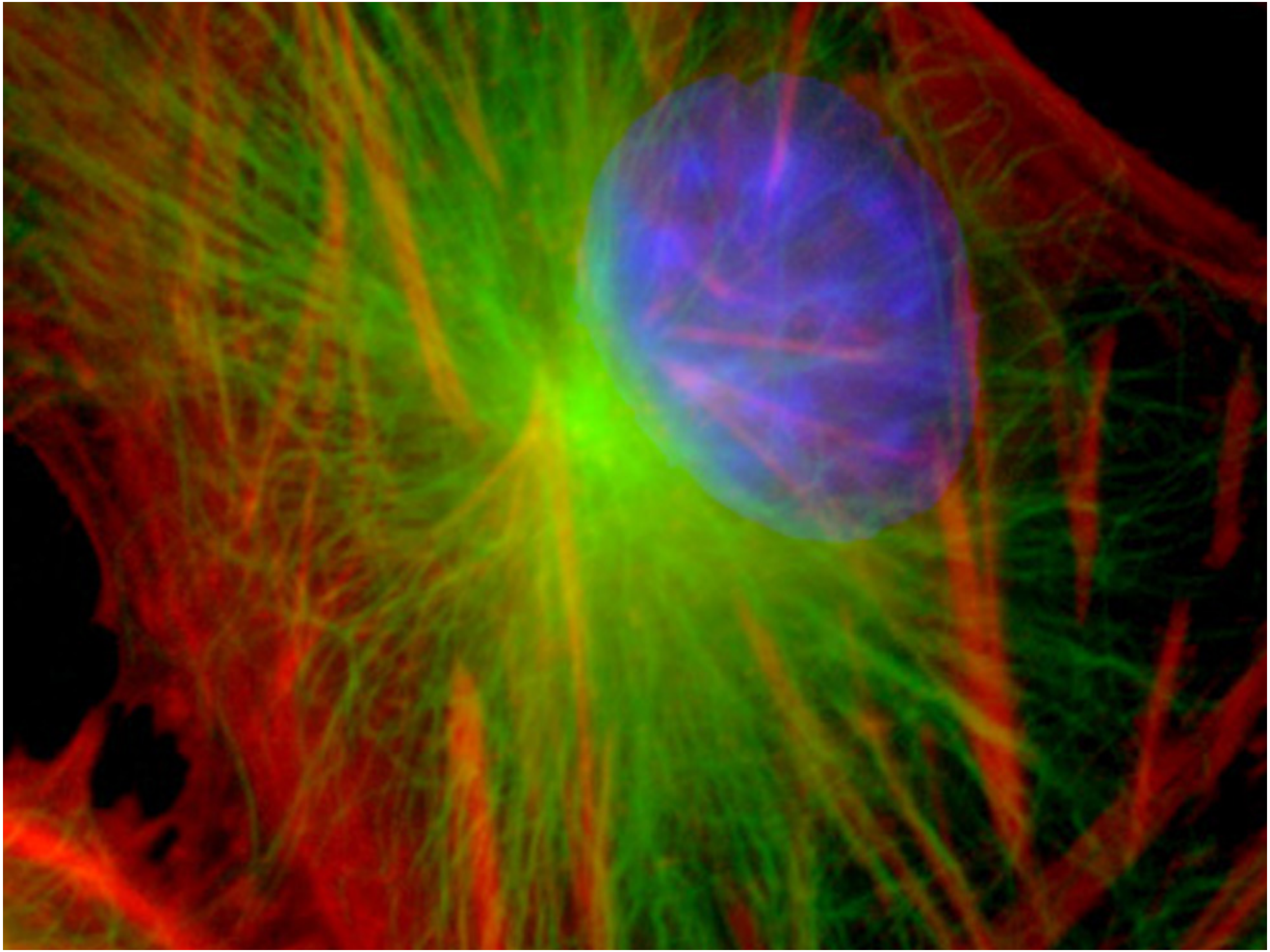
F. Julicher
K. Kruse

cnrs dépasser les frontières

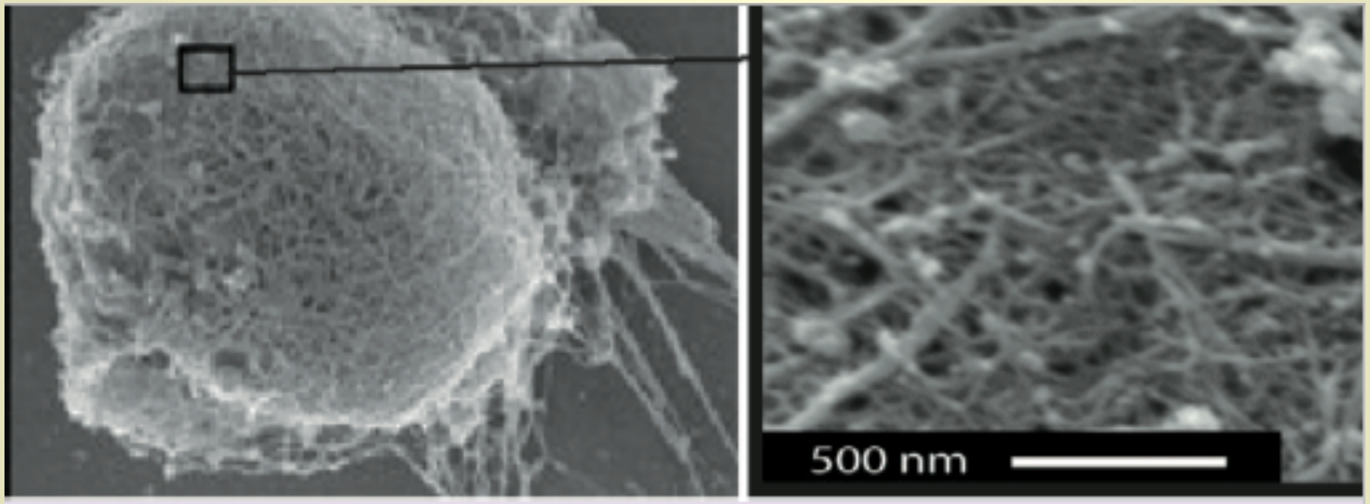
institut Curie

Active Matter

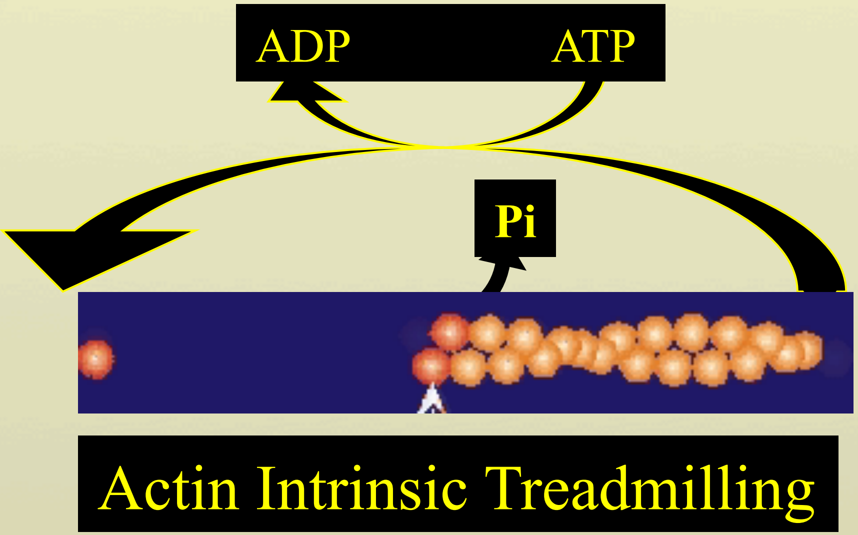


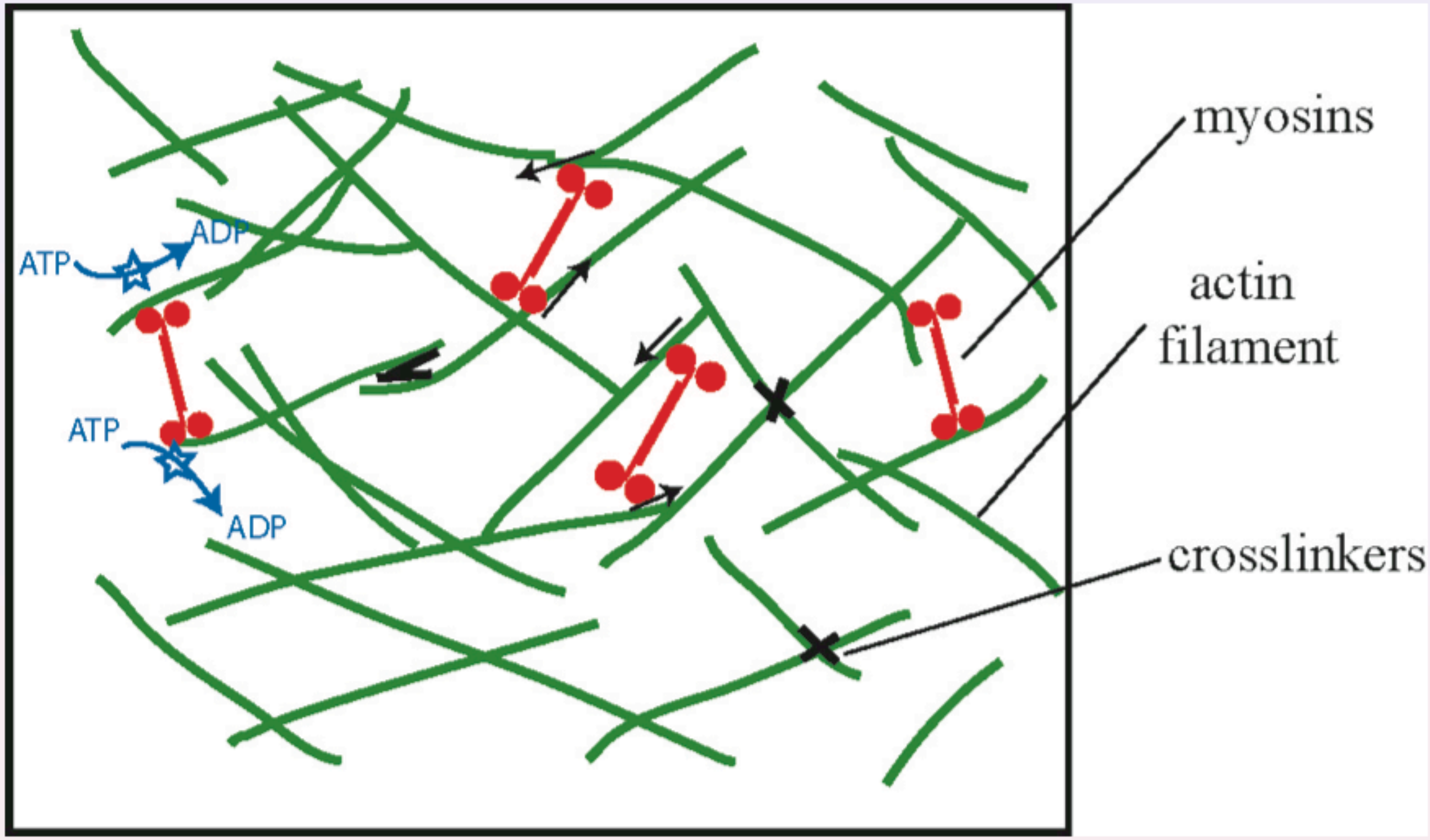


Actin-based dynamics



Hela cell, images Charras&al, JCB, 2006





Many microscopic mechanisms

Slow variables

Conserved quantities, Broken symmetries

Gradient expansion

(Toner,Tu 1995; Ramaswamy, Simha 2002 etc)

Generalized Hydrodynamics

P.C. Martin, O. Parodi, P. Pershan

Chaikin, Lubensky

- Actin (monomer+polymer)
- Myosin (bound, unbound)
- Momentum (force)
- Orientation-Polarization

F. Nedelec et al 1997; K. Kruse, F. Jülicher, 2000; T. Liverpool, C. Marchetti 2002; I. ; H. Chaté 2002; Aranson2005, B. Mulder et al 2005; T. Liverpool, C. Marchetti, J.F. Joanny, J.P. 2009.

Conservation laws

$$\frac{\partial \rho}{\partial t} + \nabla(\mathbf{v}\rho) = -k_d\rho + k_p\delta_S.$$

Actin

$$\frac{\partial \rho^{(a)}}{\partial t} + \nabla \mathbf{j}^{(a)} = k_d\rho - k_p\delta_S$$

$$\frac{\partial c^{(m)}}{\partial t} + \nabla \mathbf{j}^{(m)} = k_{\mathrm{off}} c^{(b)} - k_{\mathrm{on}}\rho(c^{(m)})^n$$

Myosin

$$\frac{\partial c^{(b)}}{\partial t} + \nabla \mathbf{j}^{(b)} = -k_{\mathrm{off}} c^{(b)} + k_{\mathrm{on}}\rho(c^{(m)})^n.$$

$$\partial_\alpha(\sigma^{\mathrm{tot}}_{\alpha\beta} - \Pi\delta_{\alpha\beta}) + f^{\mathrm{ext}}_\beta = 0$$

Momentum

Entropy production

$$F = \int d^3x\,(f(c^{(i)}) + \frac{1}{2}\rho v^2 + \frac{K_1}{2}(\vec{\nabla}.\vec{p})^2 + \frac{K_3}{2}((\vec{p}.\vec{\nabla})\vec{p})^2 + \frac{K_2}{2}((\vec{p}\times\vec{\nabla})\vec{p})^2)$$

$$T\dot{S} = \dot{F} = -\int d^3\mathbf{r}\left\{\sigma^S_{\alpha\beta}u_{\alpha\beta} + h_\alpha P_\alpha + \Delta\mu r - j^{(i)}_\alpha \partial_c \tilde{\mu}^{(i)}\right\}$$

$$c^{(i)}\partial_\alpha \mu_i = \partial_\alpha P + \frac{\partial f}{\partial(\partial_\beta p_\gamma)}\partial_\alpha(\partial_\beta p_\gamma)$$

$$\tilde{\mu}_i = (\frac{\mu_i}{m_i} - \frac{\mu_s}{m_s})$$

$$h_\alpha = -\frac{\delta F}{\delta p_\alpha}$$

$$\omega_{\alpha\beta} = \tfrac{1}{2}(\partial_\alpha v_\beta - \partial_\beta v_\alpha)$$

$$u_{\alpha\beta} = \tfrac{1}{2}(\partial_\alpha v_\beta + \partial_\beta v_\alpha)$$

$$P_\alpha = \frac{D}{Dt}p_\alpha = \frac{\partial p_\alpha}{\partial t} + (v_\gamma \partial_\gamma)p_\alpha + \omega_{\alpha\beta}p_\beta$$

$$\sigma^{\mathrm{s}}_{\alpha\beta} = \sigma_{\alpha\beta} + \rho v_\alpha v_\beta - \sigma^{\mathrm{a}}_{\alpha\beta} - \sigma^{\mathrm{e,s}}_{\alpha\beta},$$

$$\sigma^{\mathrm{a}}_{\alpha\beta} = \left(p_\alpha h_\beta - p_\beta h_\alpha\right)/2.$$

$$\begin{aligned} \text{flux} &\leftrightarrow \text{force} \\ \sigma_{\alpha\beta} &\leftrightarrow u_{\alpha\beta} \\ P_\alpha &\leftrightarrow h_\alpha \\ r &\leftrightarrow \Delta\mu \\ j_\alpha^{(i)} &\leftrightarrow \partial_\alpha \mu^{(i)}. \end{aligned}$$

$$\begin{aligned} \sigma_{\alpha\beta} &= \sigma_{\alpha\beta}^r + \sigma_{\alpha\beta}^d \\ P_\alpha &= P_\alpha^r + P_\alpha^d \\ r &= r^r + r^d. \end{aligned}$$

$$\int_0^T dt(r^r \Delta\mu + P_\alpha^r h_\alpha + \sigma_{\alpha\beta}^r u_{\alpha\beta}) = 0.$$

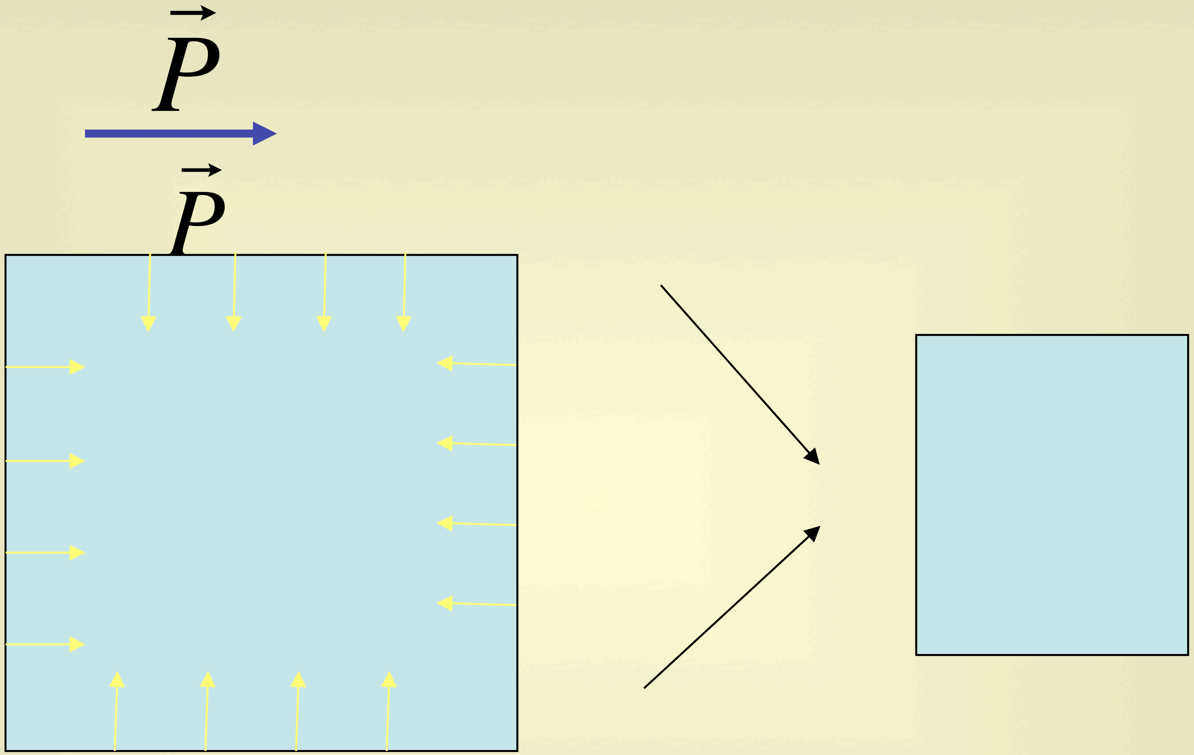
ONE COMPONENT
+ *Maxwell+incompressible*

$$\left(1 + \tau\frac{D}{Dt}\right)\left\{\tilde{\sigma}_{\alpha\beta} + \zeta\Delta\mu\, q_{\alpha\beta} - \frac{\nu_1}{2}\left(p_\alpha h_\beta + p_\beta h_\alpha - \frac{2}{3}p_\gamma h_\gamma \delta_{\alpha\beta}\right)\right\} = 2\eta\tilde{v}_{\alpha\beta}$$

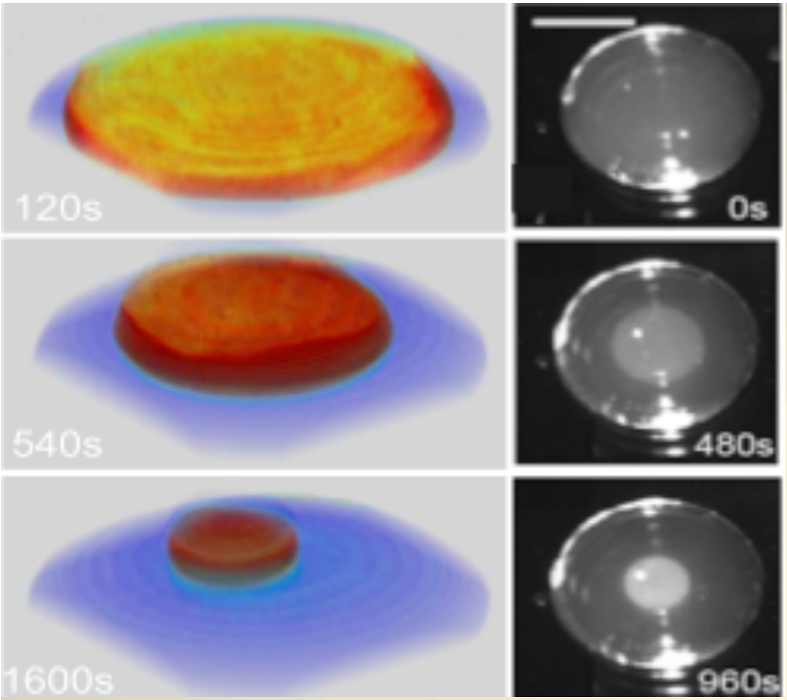
$$\frac{D}{Dt}p_\alpha = \left(1 + \tau\frac{D}{Dt}\right)\frac{1}{\gamma_1}h_\alpha + \lambda_1 p_\alpha \Delta\mu - \nu_1 p_\beta v_{\alpha\beta}$$

$$r = \lambda_1 p_\alpha h_\alpha + \Lambda\Delta\mu + \zeta q_{\alpha\beta}\tilde{v}_{\alpha\beta}$$

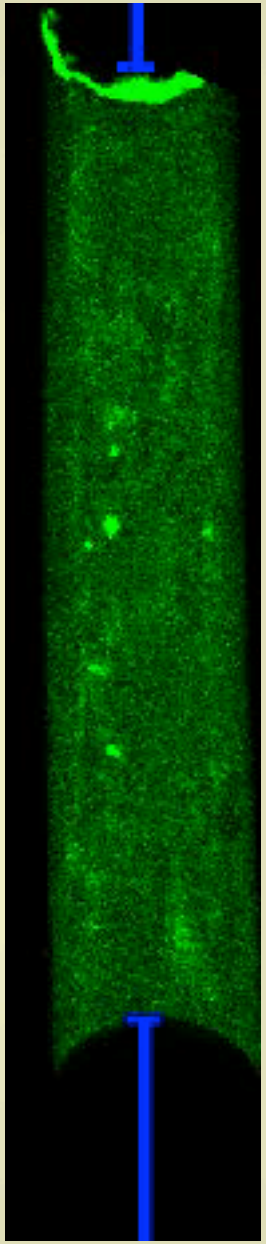
$$q_{\alpha\beta} = p_\alpha p_\beta - \frac{1}{3}\delta_{\alpha\beta}$$



K. Takiguchi,1991
P.M. Bendix et al 2006

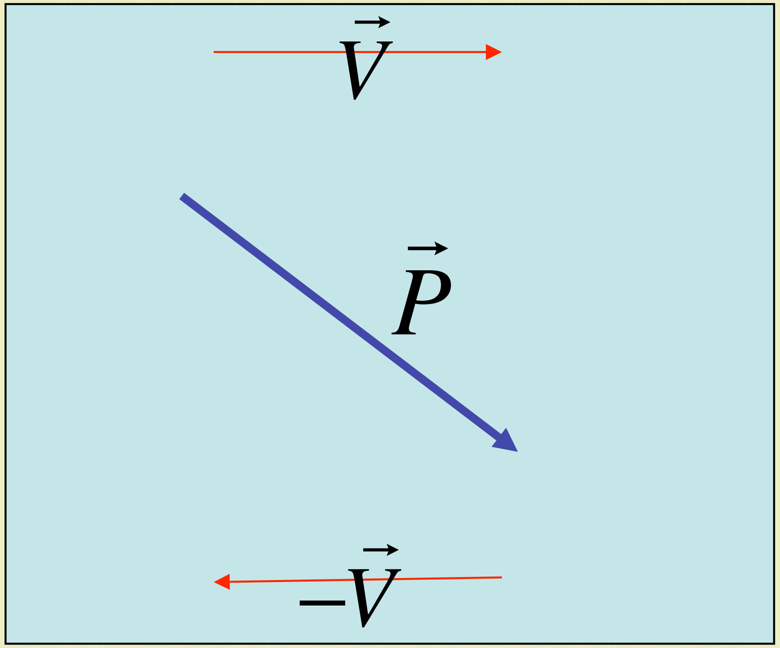


P.M. Bendix et al



Contractility measured in units of Pascal
(*like a pressure or an elastic modulus*)

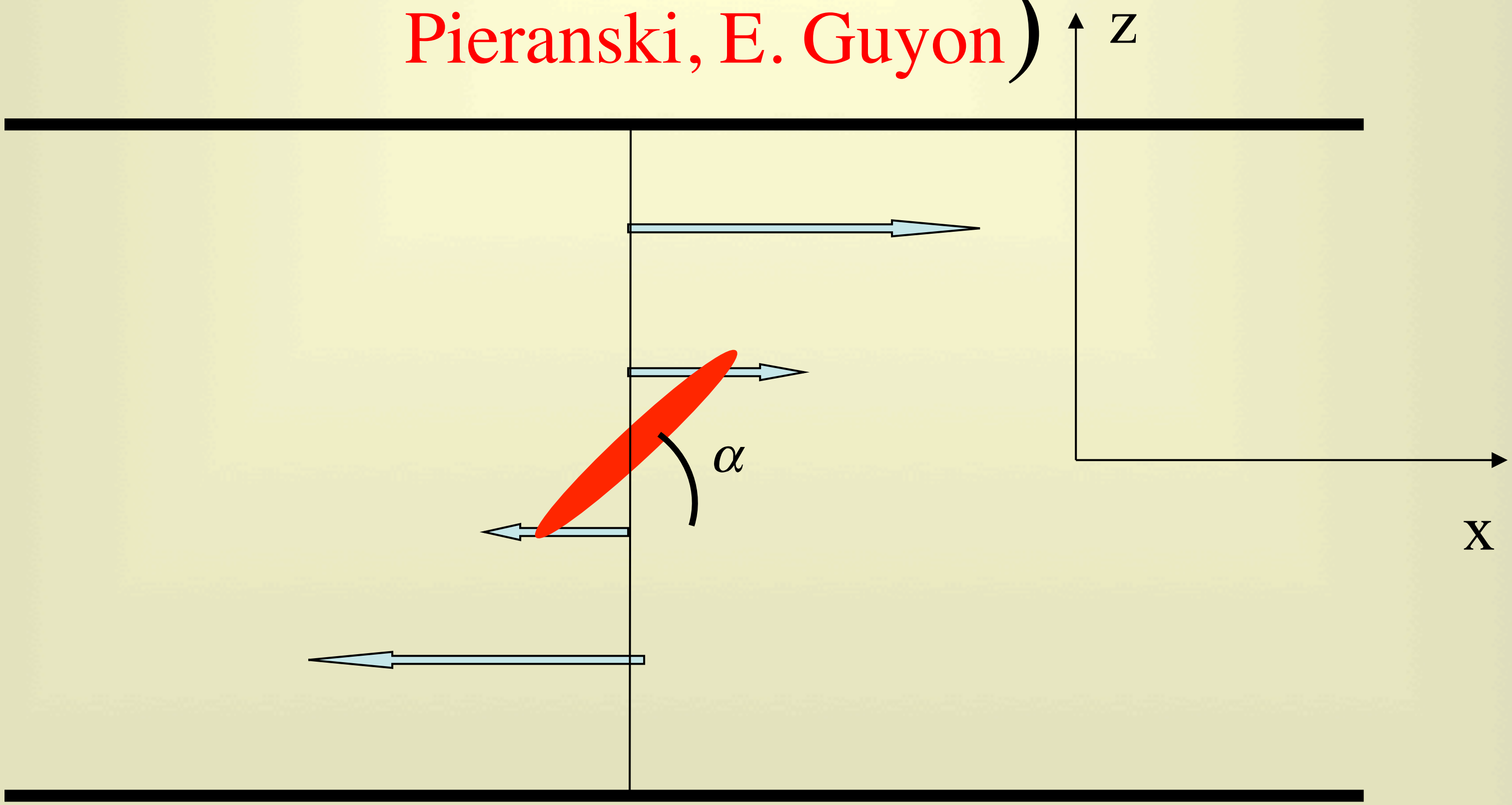
$$\zeta \; \nabla\mu \cong 10^3 \;\; Pascal$$



$$2\eta \; u_{\alpha\beta} = \ldots\ldots + \zeta\Delta\mu \;\; p_\alpha p_\beta + \ldots$$

Nematic Hydrodynamics

(F.M. Leslie, F. Brochard, P.G. de Gennes, P. Pieranski, E. Guyon)

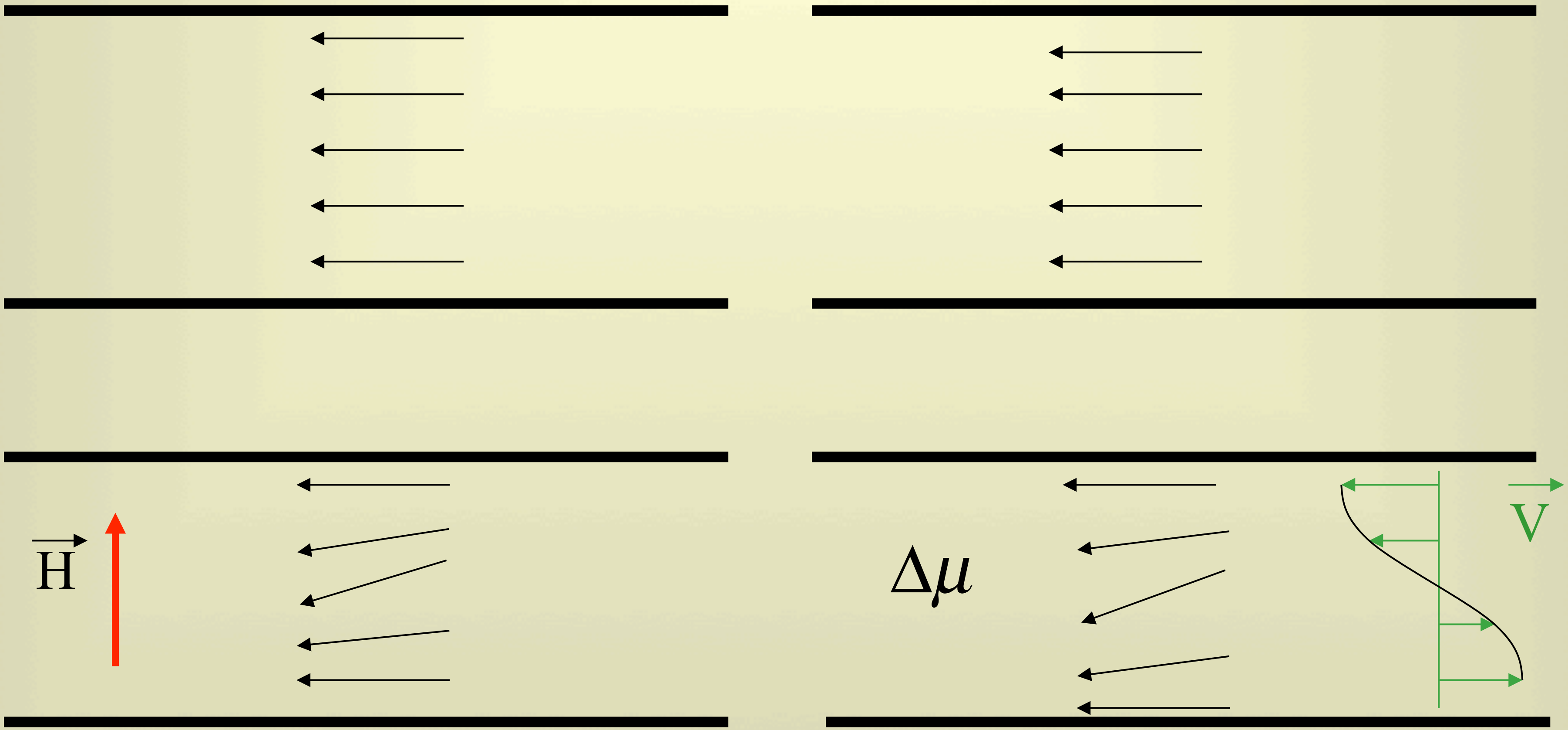


$$\frac{Dp_\alpha}{Dt} = \ldots\ldots\ldots + \omega_{\alpha\beta} p_\beta + \ldots\ldots = \ldots\ldots + \nu_1 u_{\alpha\beta} p_\beta + \ldots\ldots$$

$$\cos(2\alpha) = -1/\nu_1$$

Spontaneous Frederiks transition

R. Voituriez et al



Active :

Passive under ac electric field

$$\frac{\partial\alpha}{\partial t}=\frac{K}{\gamma_1}\frac{\partial^2\alpha}{\partial z^2}-(1+\nu_1)u_{zx}$$

$$\frac{\partial\alpha}{\partial t}=\frac{1}{\gamma_1}(K\frac{\partial^2\alpha}{\partial z^2}-\frac{\Delta\varepsilon E^2}{2}\sin(2\alpha))-(1+\nu_1)u_{zx}$$

$$2\eta u_{zx}\approx\sigma_{zx}+\frac{\zeta\Delta\mu}{2}\sin(2\alpha)-\nu_1 K\frac{\partial^2\alpha}{\partial z^2}$$

$$2\eta u_{zx}\approx\sigma_{zx}-\nu_1(K\frac{\partial^2\alpha}{\partial z^2}-\frac{\Delta\varepsilon E^2}{2}\sin(2\alpha))$$

$$free\,boundary:\sigma_{zx}=0$$

$$\frac{\partial\alpha}{\partial t}=\frac{K}{\tilde{\gamma}_1}\frac{\partial^2\alpha}{\partial z^2}-\frac{\tilde{\zeta}\Delta\mu}{2\eta}\sin(2\alpha)$$

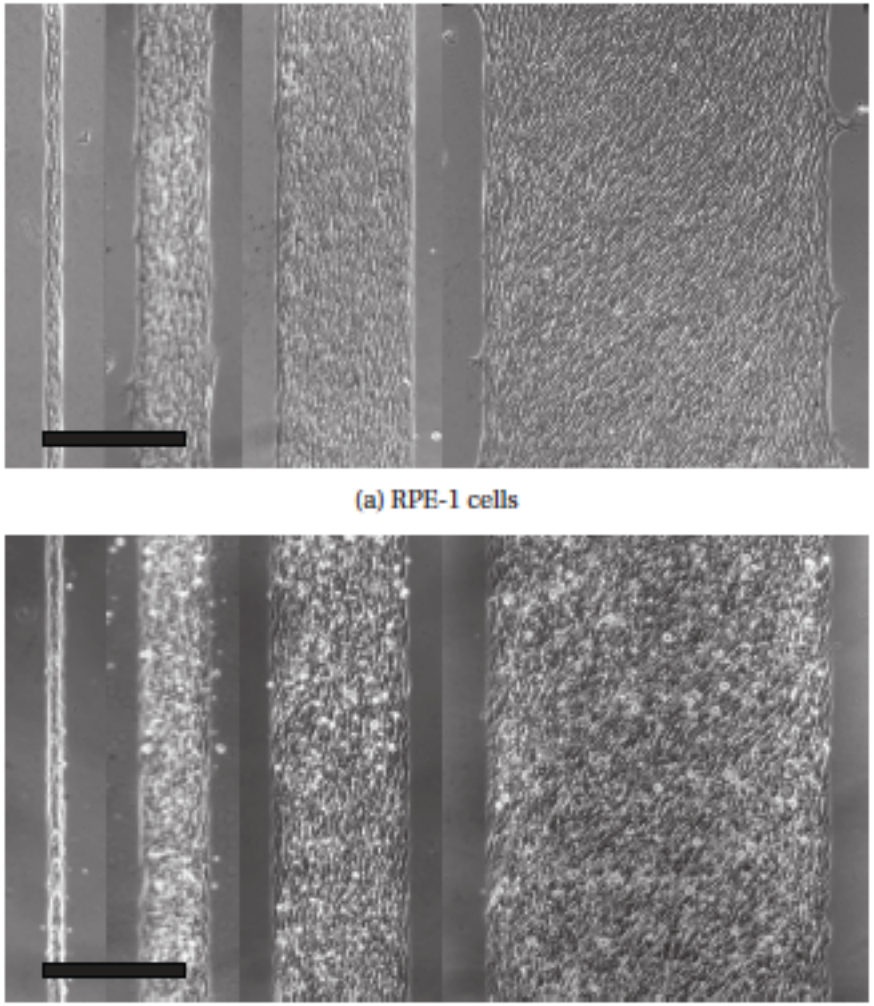
$$\frac{\partial\alpha}{\partial t}=\frac{1}{\tilde{\gamma}_1}(K\frac{\partial^2\alpha}{\partial z^2}-\frac{\Delta\varepsilon E^2}{2}\sin(2\alpha))$$

$$\alpha\cong\alpha_m\sin(\frac{\pi}{D}z)$$

$$(\tilde{\zeta}\Delta\mu)_c=\frac{\tilde{\eta}}{\tilde{\gamma}_1}K(\frac{\pi}{D})^2$$

$$(\Delta\varepsilon E^2)_c=K(\frac{\pi}{D})^2$$

Nematic Tissues?



(a) RPE-1 cells

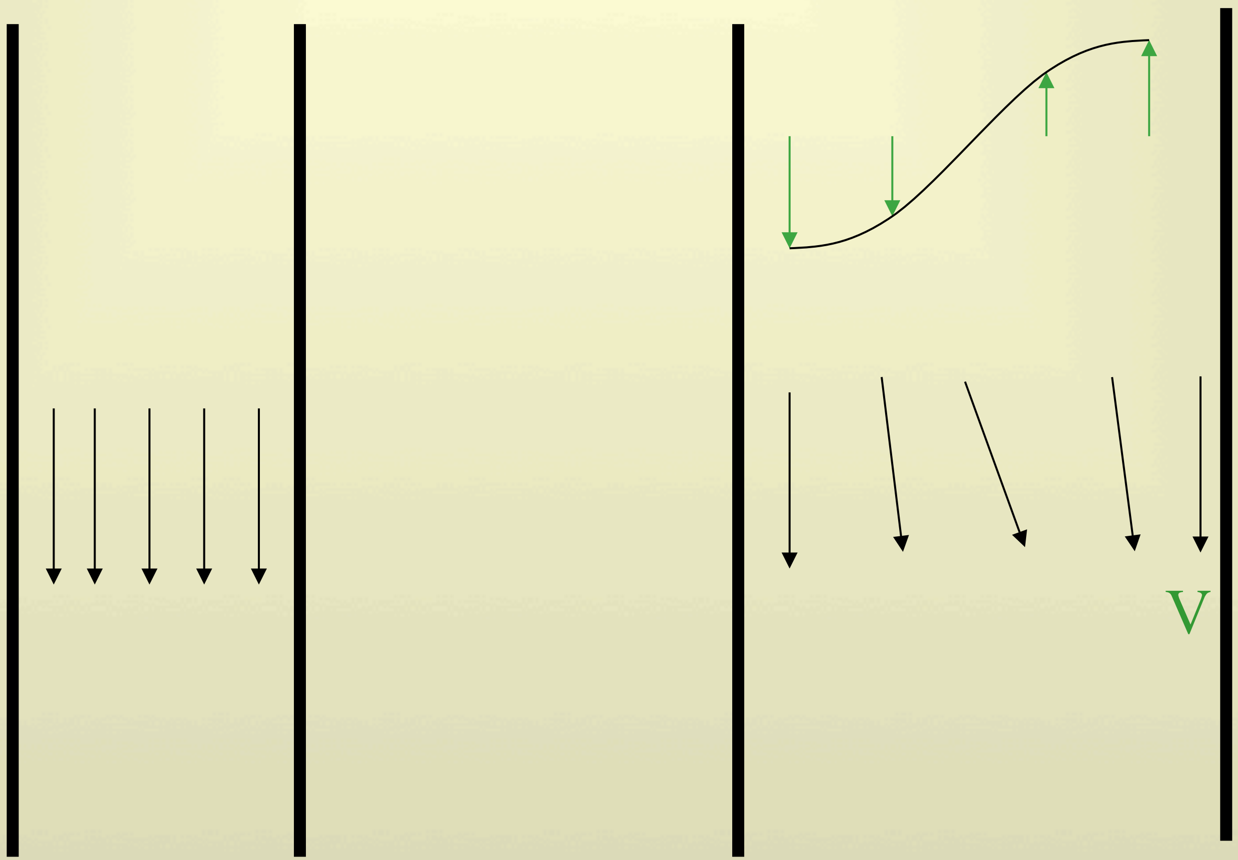
(b) C2C12 cells

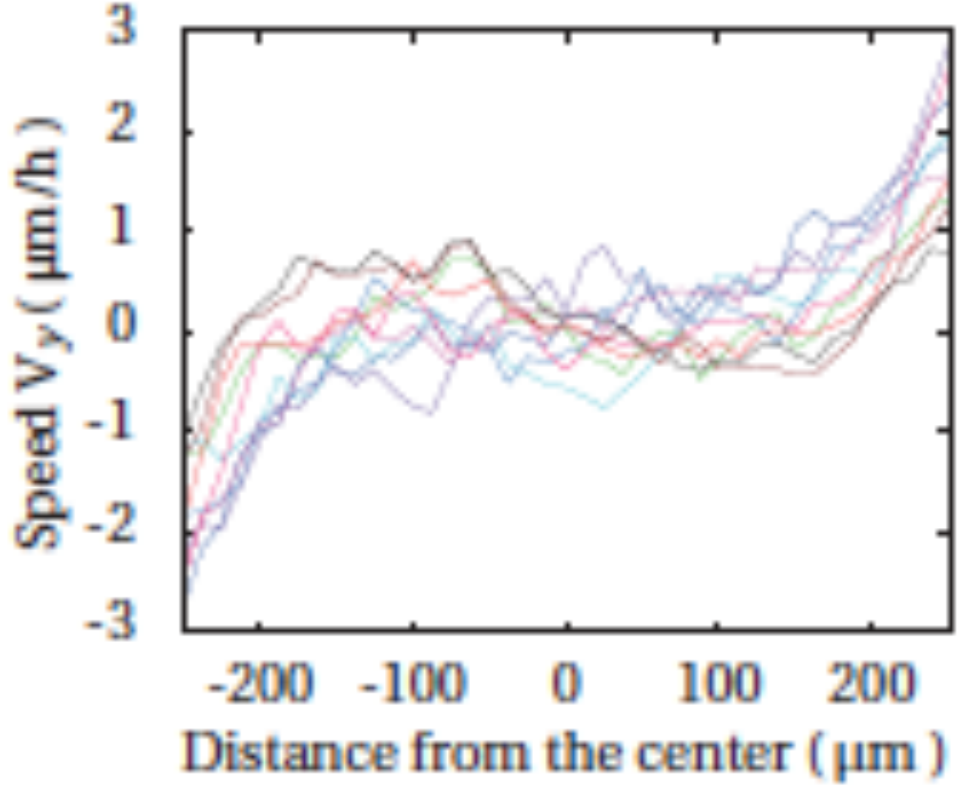
Guillaume Duclos, Pascal Silberzan

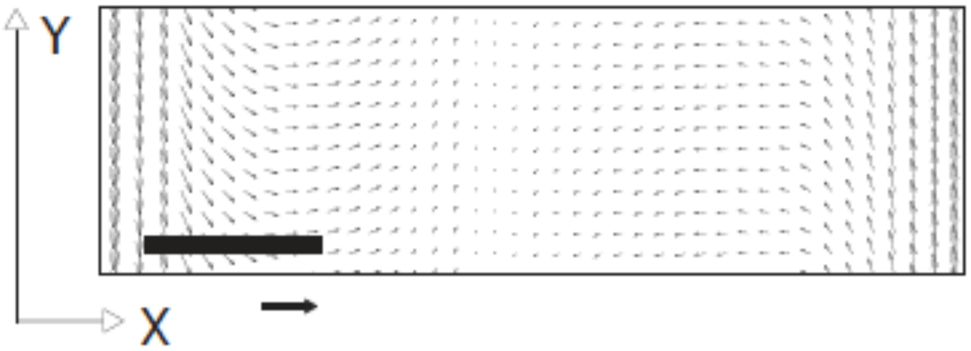
P Friedl

Spontaneous Frederiks transition

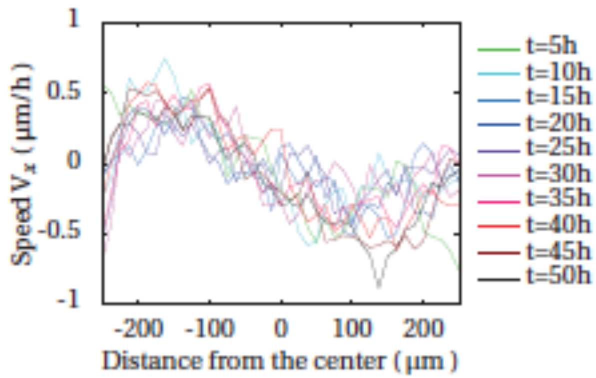
R. Voituriez et al 2005




3
2
1
0
-1
-2
-3
Speed V_y (μm/h)
-200
-100
0
100
200
Distance from the center (μm)



(a) RPE-1 cells, scale bar: 100 µm, scale arrow: 2 µm/h.



(c)

C B Mercader, J F Joanny, J P