The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
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SMR 1746 - 15

WORKSHOP ON DRIVEN STATES IN SOFT AND BIOLOGICAL MATTER
18 - 28 April 2006

Active Gels Under Stress in Cells and Biomimetic Systems

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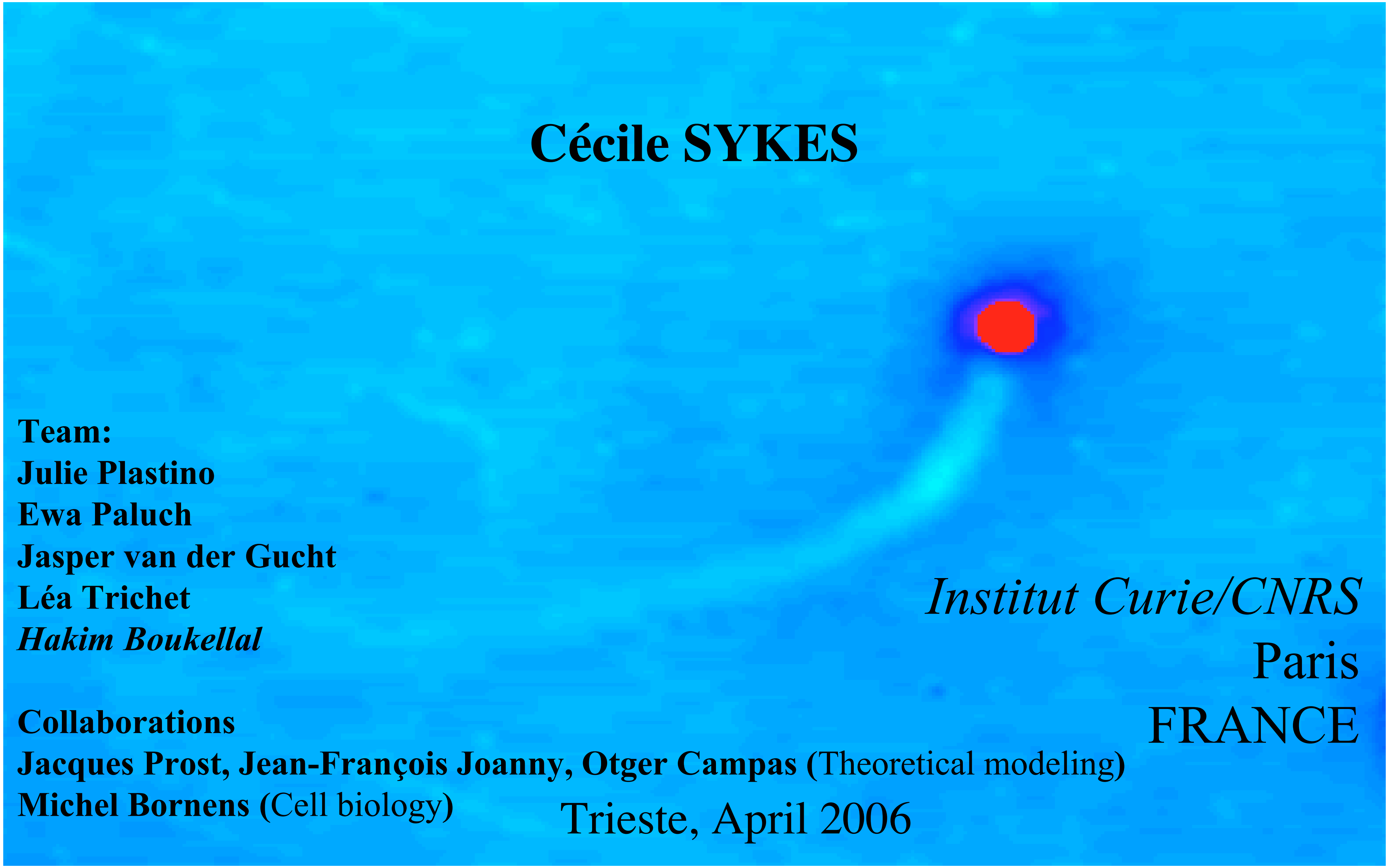
Active gels under stress in cells and biomimetic systems



Cécile SYKES

Team:
Julie Plastino
Ewa Paluch
Jasper van der Gucht
Léa Trichet
Hakim Boukellal

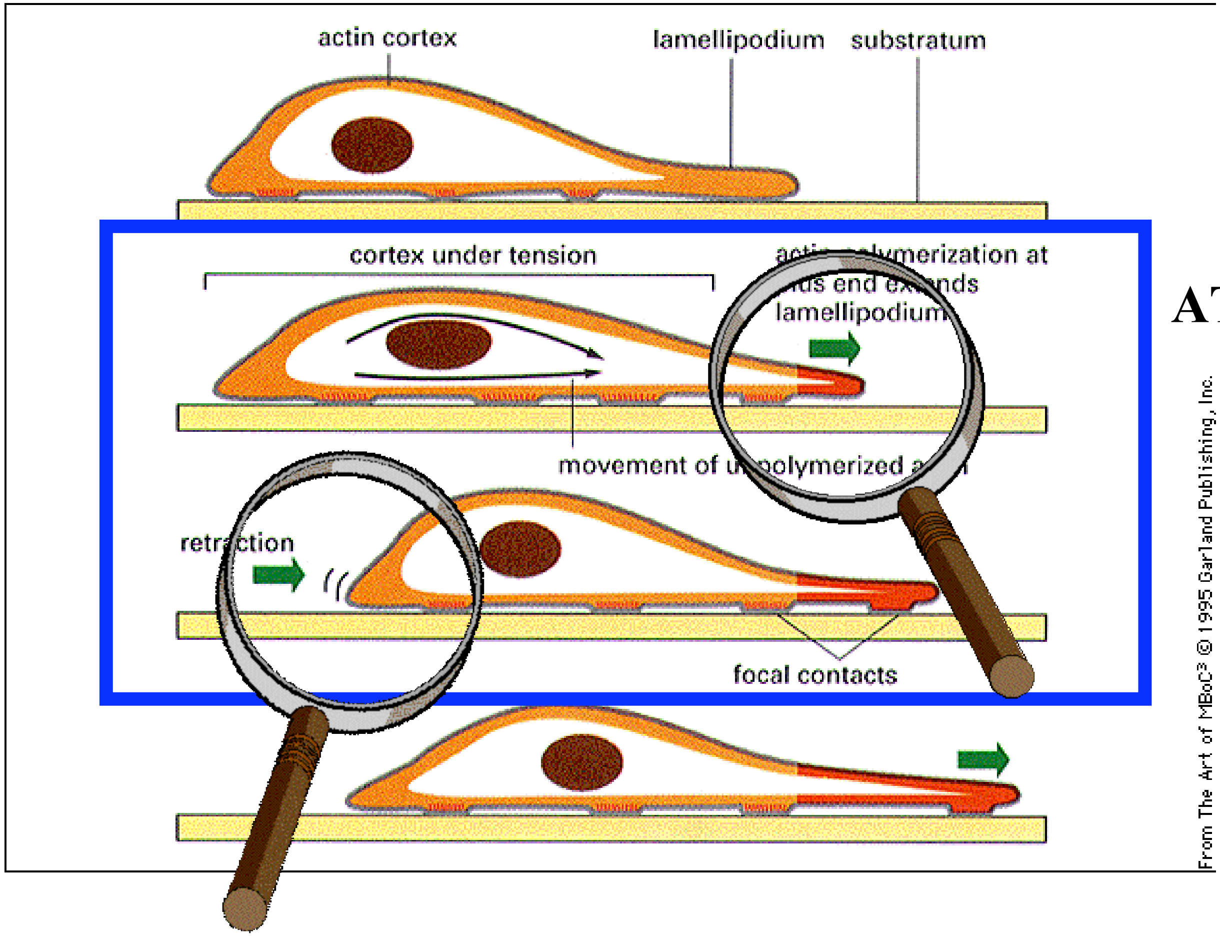
Collaborations
Jacques Prost, Jean-François Joanny, Otger Campas (Theoretical modeling**)**
Michel Bornens (Cell biology**)**

Institut Curie/CNRS
Paris
FRANCE

Trieste, April 2006

Cell motility

[M. Abercrombie *Proc. Royal Society London*, 1980]



ATP hydrolysis

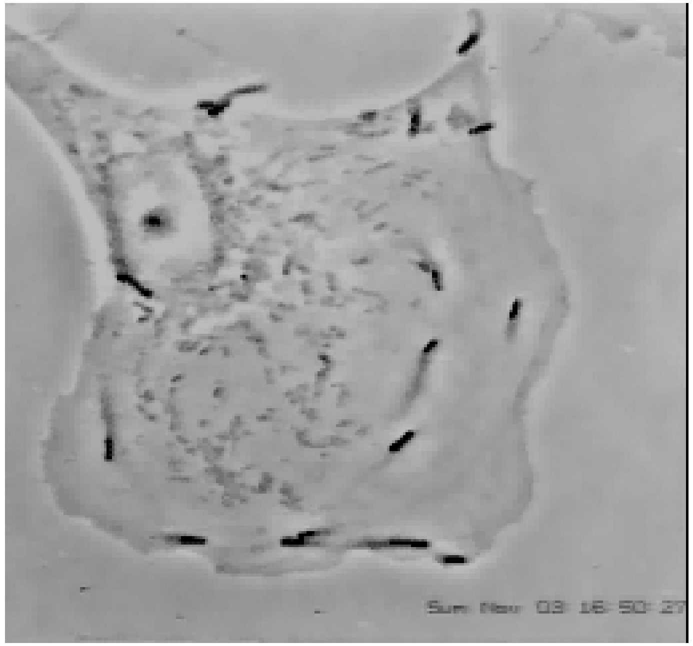
Force? Propulsion mechanism?

[Alberts, Molecular Biology of the Cell, 2002]

- **I- Biomimicking Listeria propulsion**
  Symmetry breaking and movement

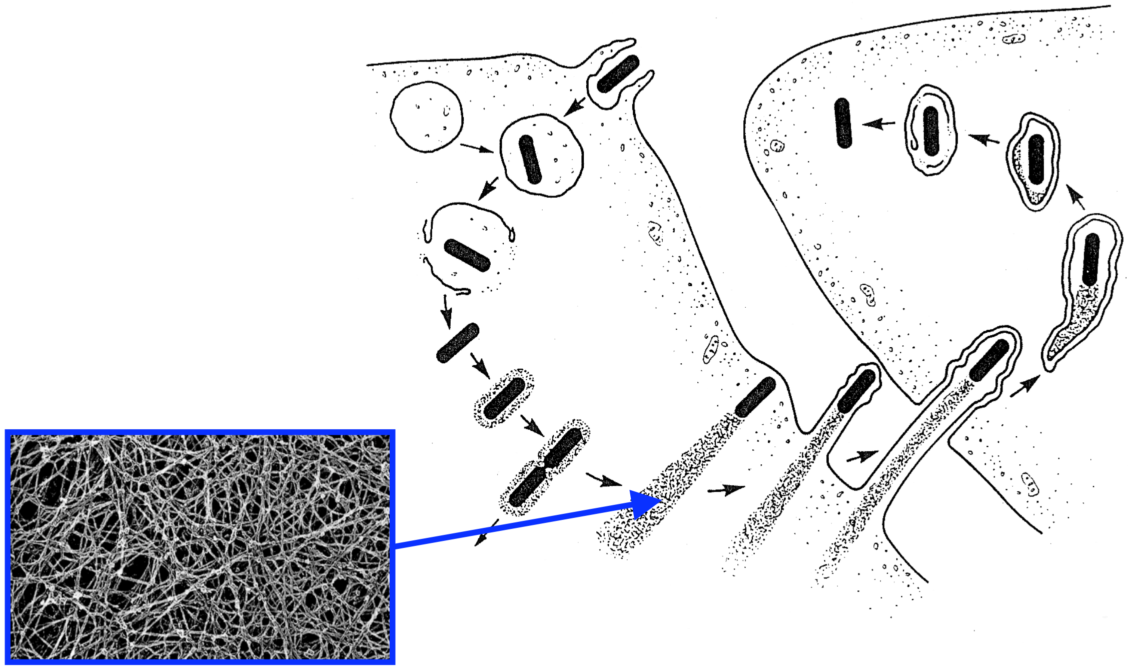
- **II- Spontaneous cortex breakage in cells (*in vivo*)**
  Oscillations

Listeria uses actin of host cell for motility



[Julie Theriot webpage]

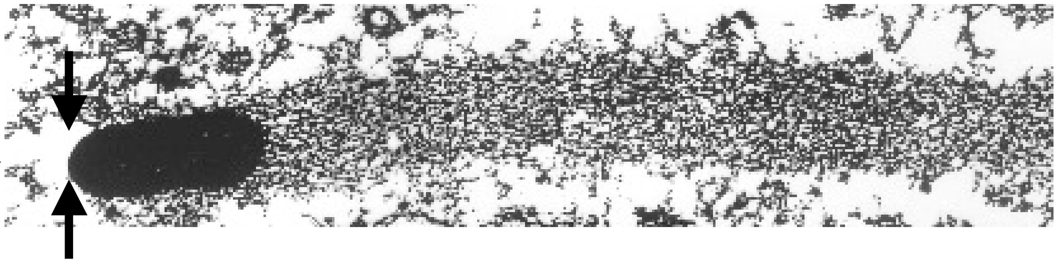
V= a few μm/min.



[Tilney,Portnoy,1989]

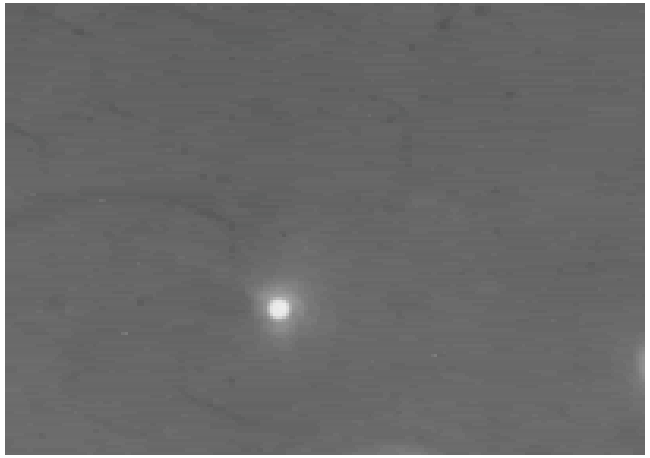
I- Biomimicking Listeria propulsion

0.5µm



Actin polymerization activator of Arp2/3

HeLa cell extracts
or
Purified proteins



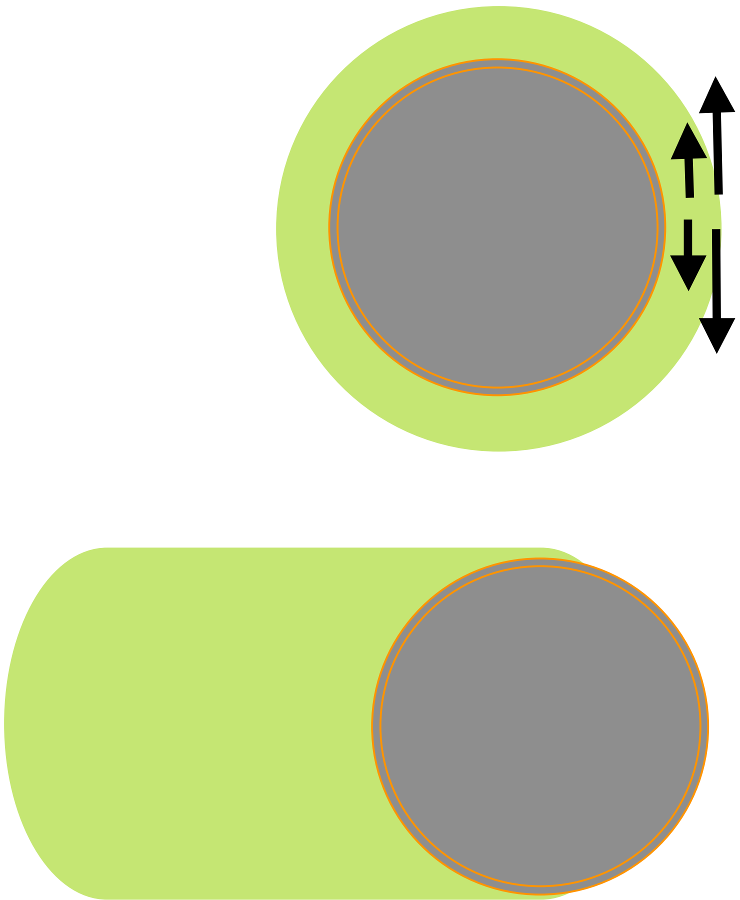
Φ=2µm

HeLa cell extracts

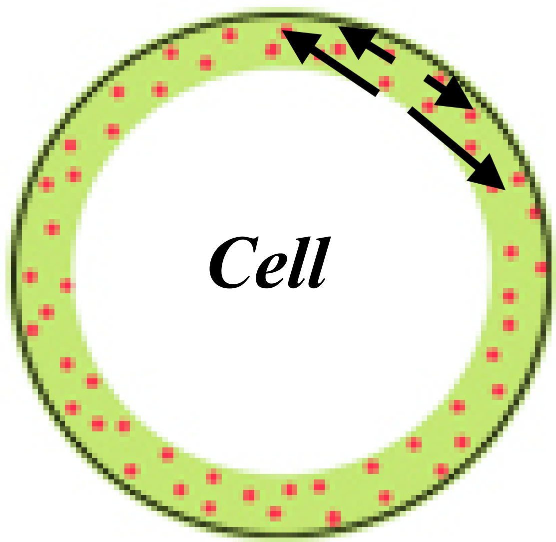
[A. Bernheim-Groswasser, 2002]

Symmetry breaking around actin-propelled beads

(II- Spontaneous cortex breakage in a cell)

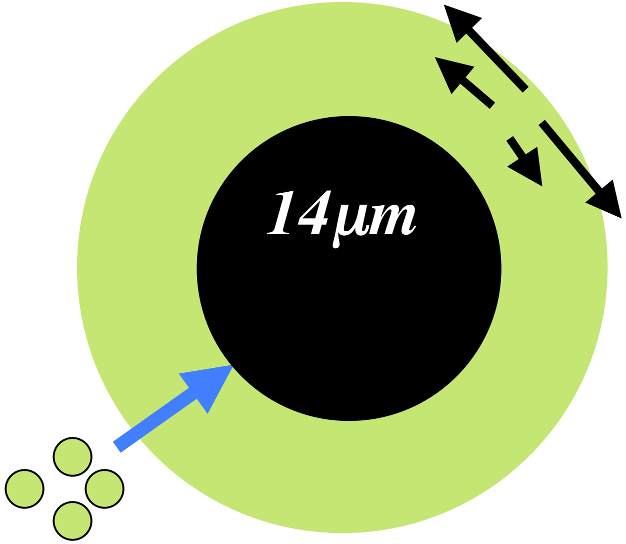


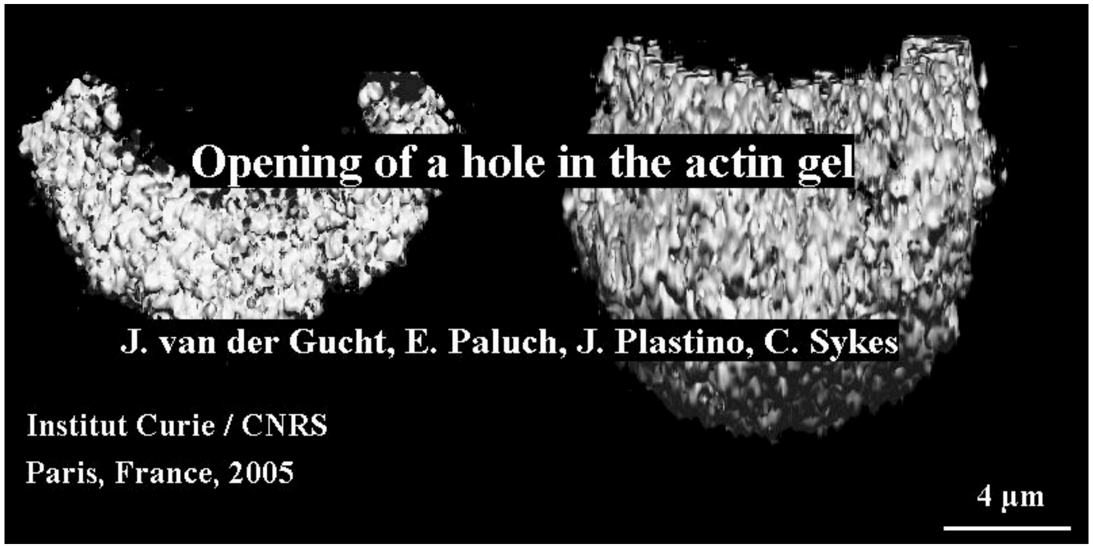
actin + myosin = contractility

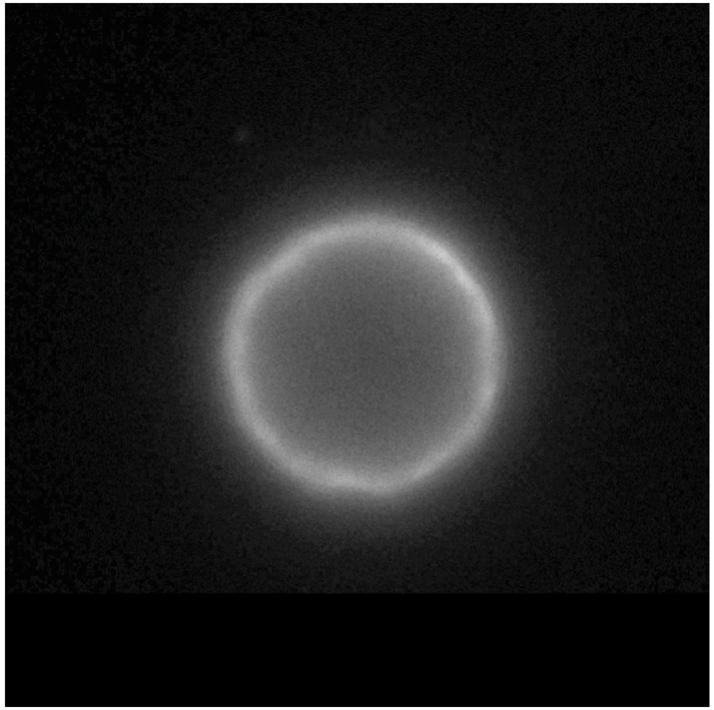


Suspension cell

Symmetry breaking in actin gels under tension (*in vitro*)



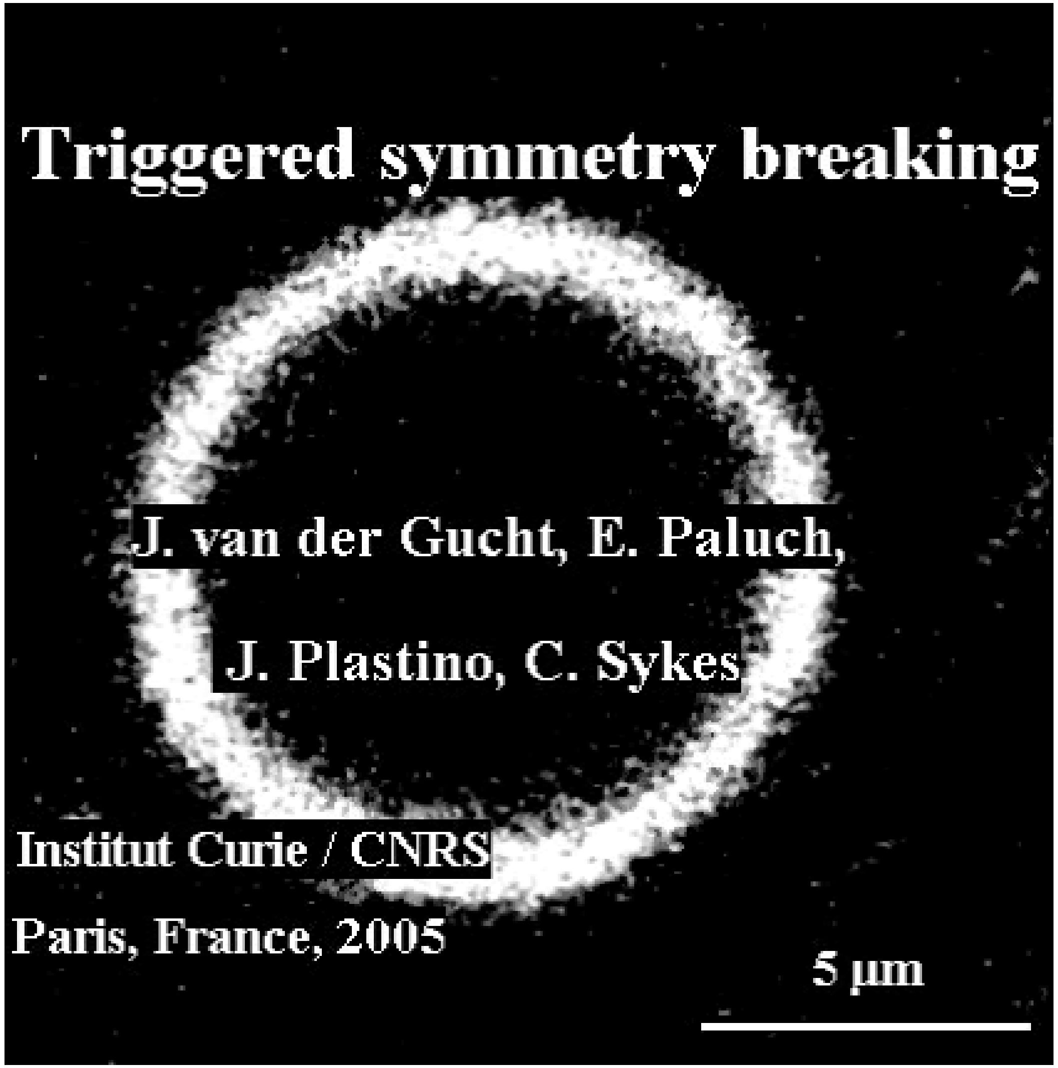




Total: 10 min.

[J. van der Gucht, *PNAS* 2005]

Symmetry breaking can be triggered by local photo-damage

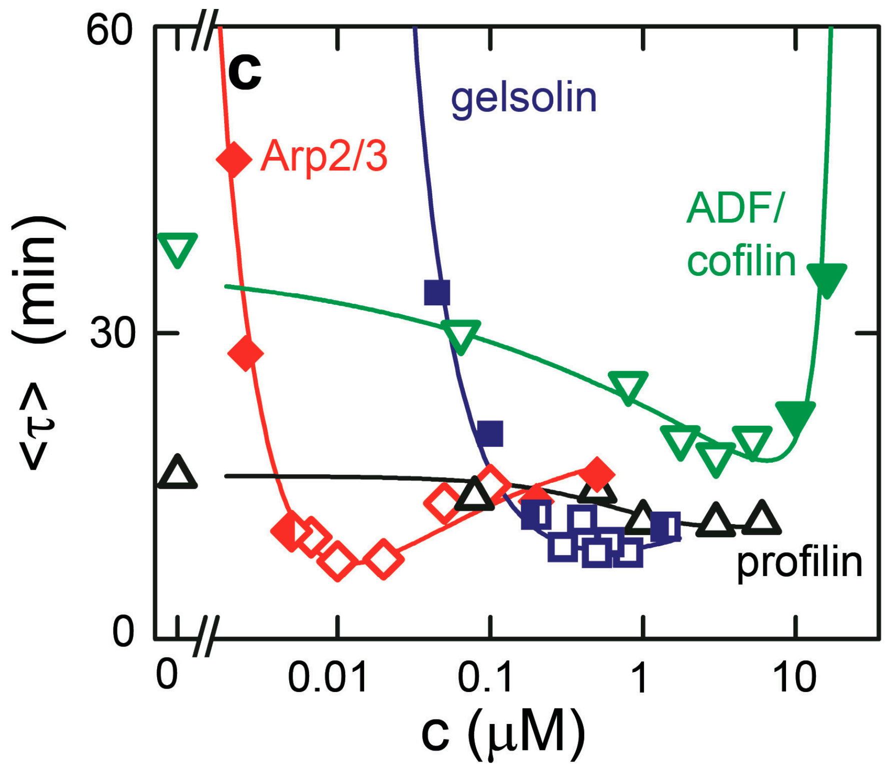


[J. van der Gucht, *PNAS* 2005]

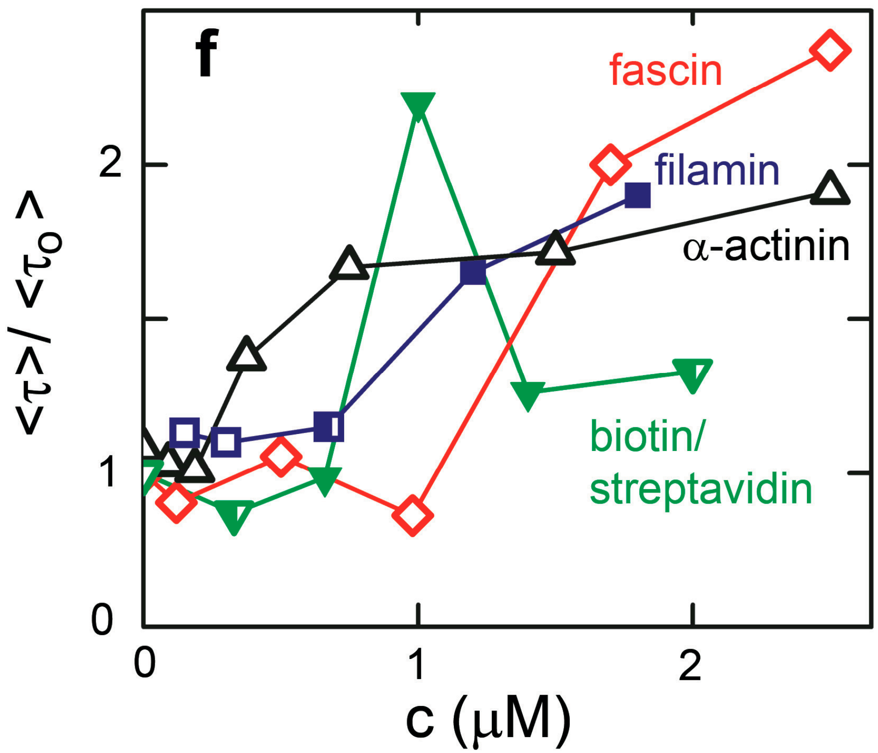
Effect of actin-binding proteins

Needed for gel growth: ARP2/3
Nedded for symmetry breaking and movement: ARP2/3 + gelsolin

Actin-regulating proteins



Crosslinking proteins



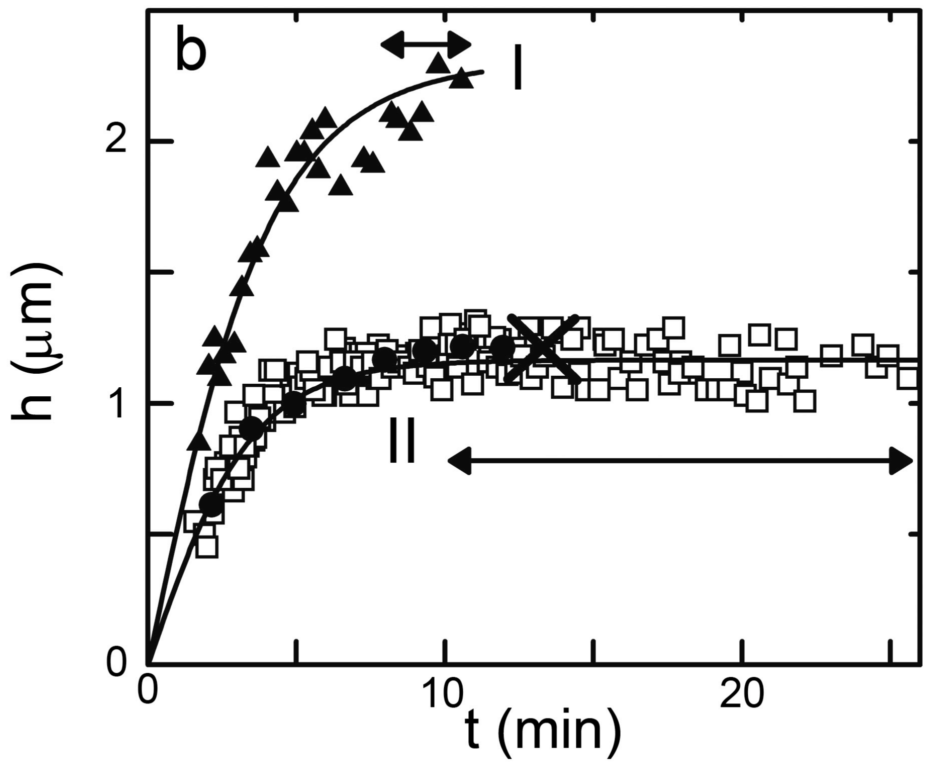
(crosslinkers slow down symmetry breaking)

Two scenarios

Steady-state thickness: Critical thickness:

$$h^{s} \cong R\left(\frac{\Delta\mu}{E\xi^{2}a}\right)^{1/2} \qquad h^{f} \cong R\left(\frac{\Gamma}{Ed}\right)^{1/2}$$

$\Delta\mu$, chemical energy of polymerization, ξ, mesh size of actin gel, Γ, fracture energy per unit surface, *d*, pre-existing crack size



Case I :

→ no plateau

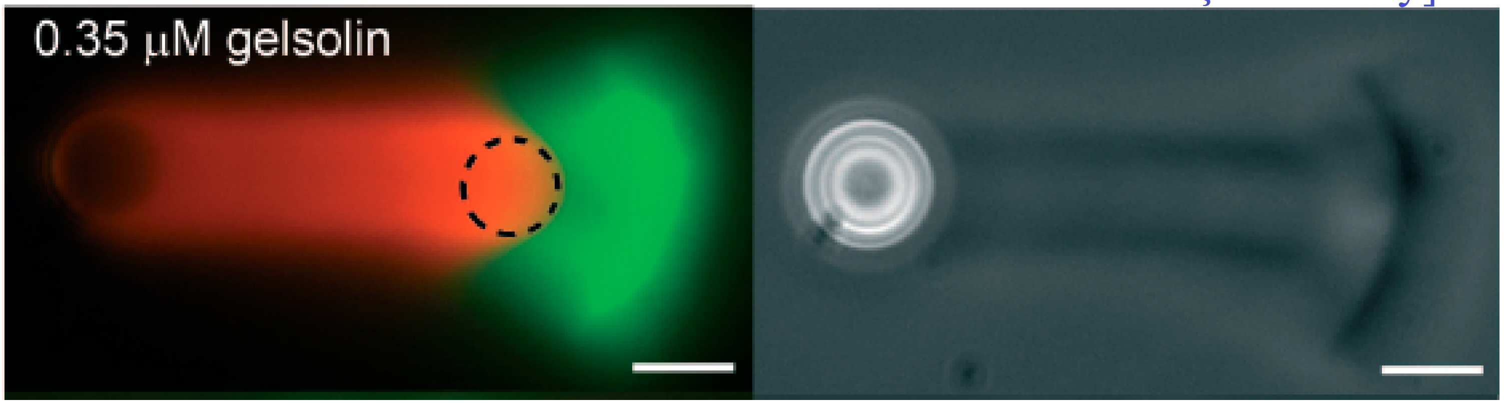
Case II :

→ plateau

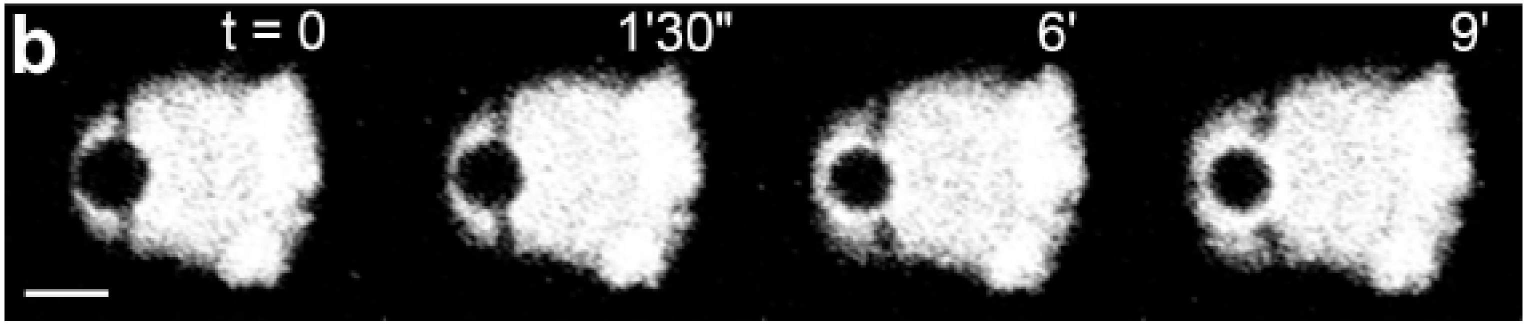
[J. van der Gucht, *PNAS* 2005]

How is elasticity involved in the movement?

[Ewa Paluch, Jasper van der Gucht Jean-François Joanny]



5μm

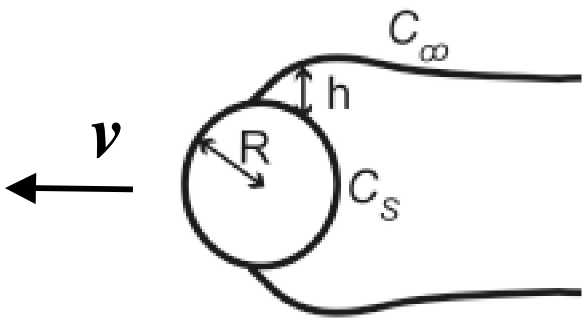


5μm

Or is monomer diffusion involved?

[Richard Dickinson]

Effect of diffusion on bead motility?



D: diffusion coefficient
k: polymerization rate
ξ: distance between activators

Diffusive flux of monomers

$$J_D \simeq D(C_\infty - C_S)/R,$$

Monomer consumption per unit area

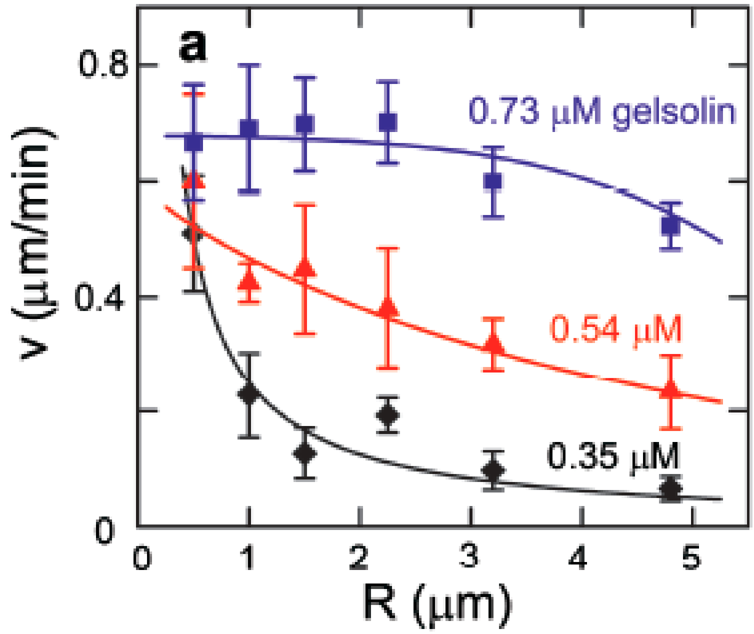
$$J_P = kC_S/\xi^2$$

$$J_D = J_P$$ gives $$C_S \simeq \frac{C_\infty D}{kR/\xi^2 + D}$$

Diffusion is limiting if $D \ll kR/\xi^2$

In that case $$v \simeq \frac{C_\infty D \xi^2 a}{R}$$

Bead velocity as a function of its radius



$\xi \nearrow$ $D \ll kR/\xi^2$

$D \ll kR/\xi^2$

Diffusion-limited regime ($v \propto 1/R$)

Stress-limited regime (v independent of R)

[J. Prost]

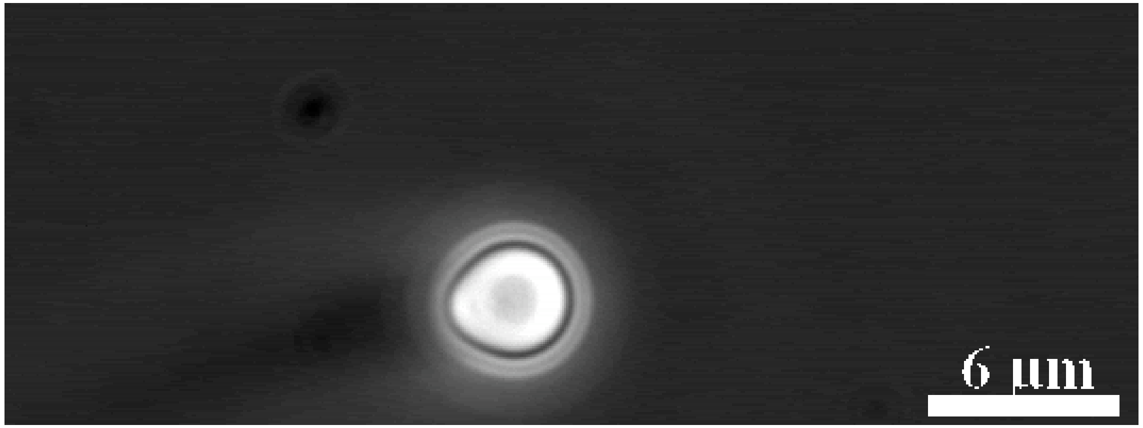
$$F_{\mathrm{el}} \sim Eh^3/R$$

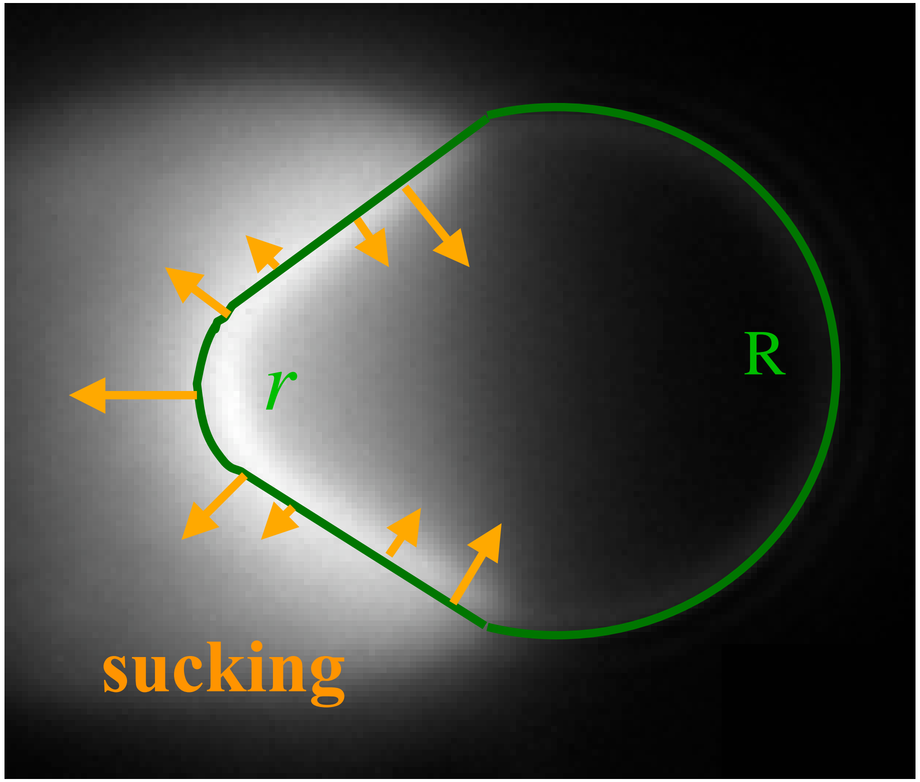
$$F_{\mathrm{fr}} \sim \gamma v R^2$$

$$h \alpha R$$

v is independent of R

Squeezing





Laplace equation

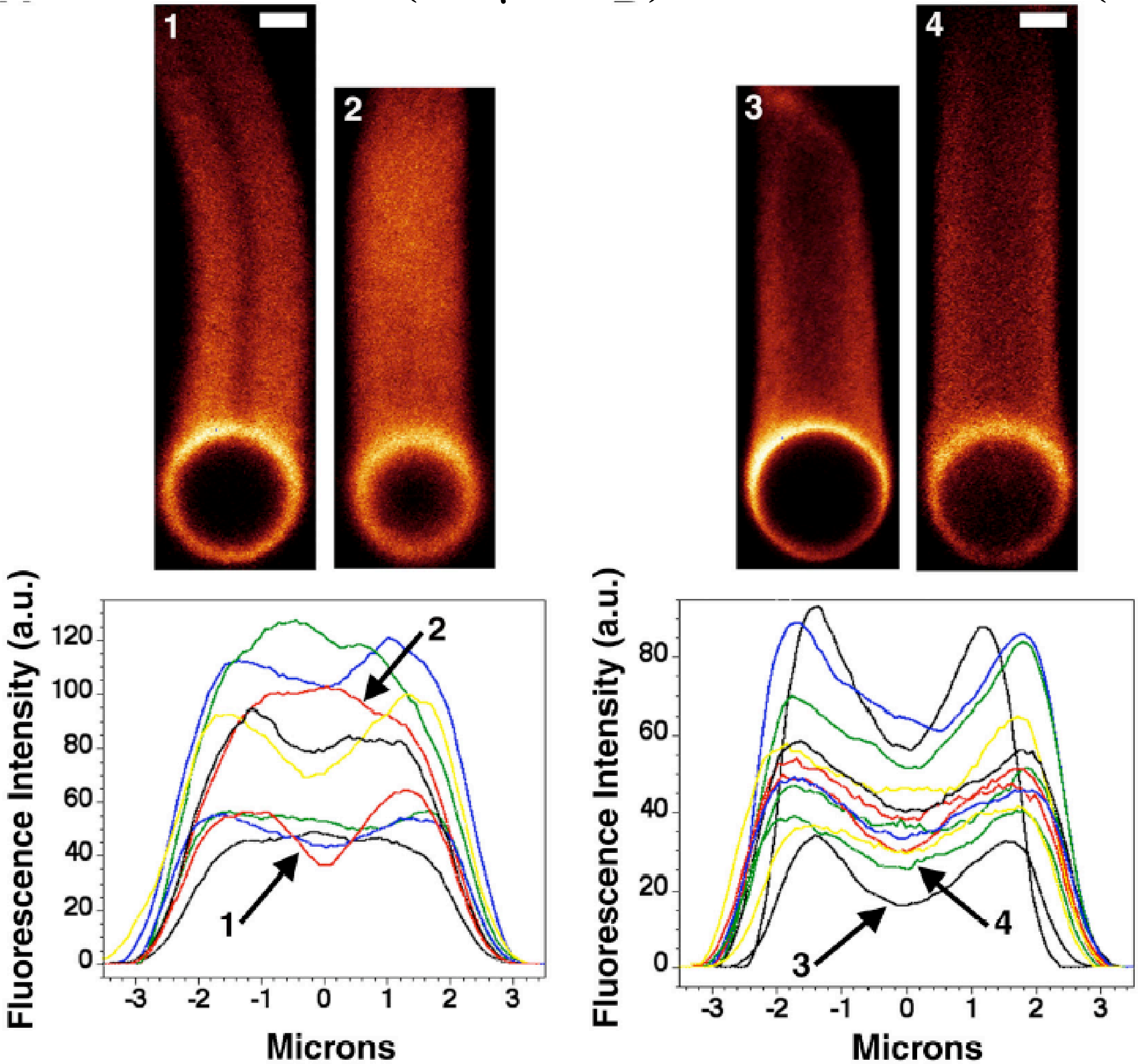
$$\Delta P = \frac{\gamma(\textit{surface tension})}{r\ (\textit{radius of curvature})} + \sigma$$

σ: normal stress exerted on the droplet by the actin gel

[H. Boukellal, *Physical Review E* 2004]

Enhancing filament detachment creates hollow comets

2.1% mole PRO (V=3μm/min). **12.5% mole PRO (V=10μm/min)**



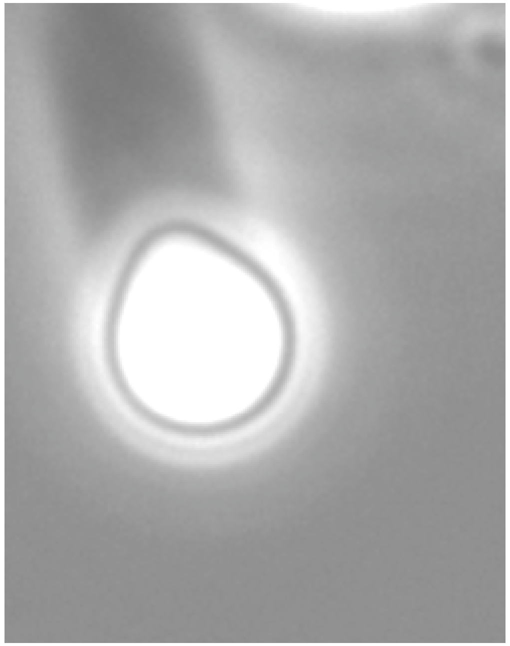
[J. Plastino, S. Olivier, C. Sykes, *Current Biology* 2004]

Hollow comets on soft beads

(cell extracts)

[Léa Trichet, Julie Plastino]

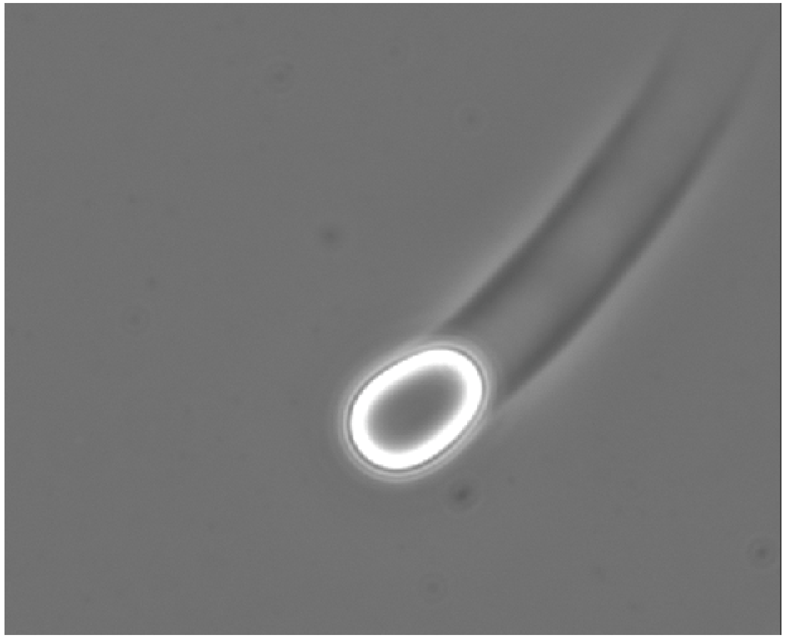
Arp2/3



1.5 µm

PEARS

Arp2/3 + VASP



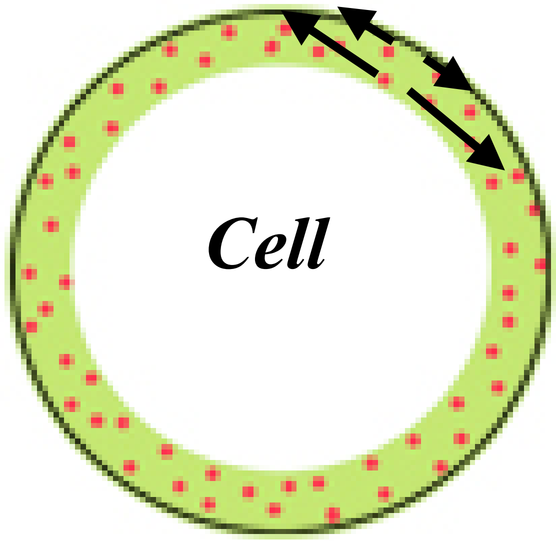
5 µm

KIWIS

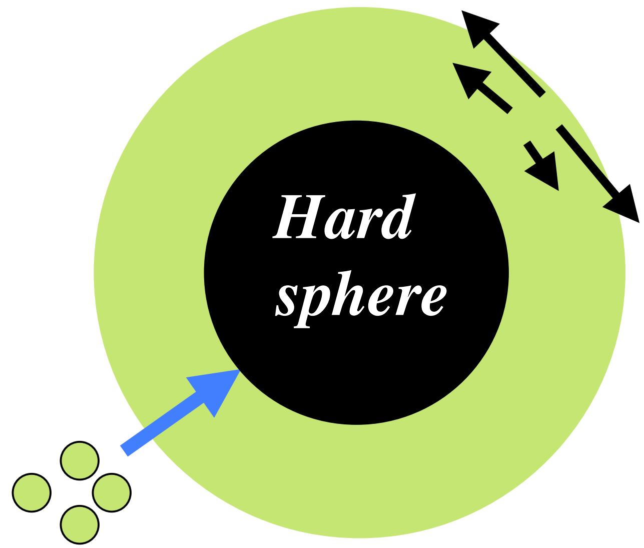
II- Actin gels under stress in cells

(I- Symmetry breaking around actin-propelled beads)

actin + myosin = contractility

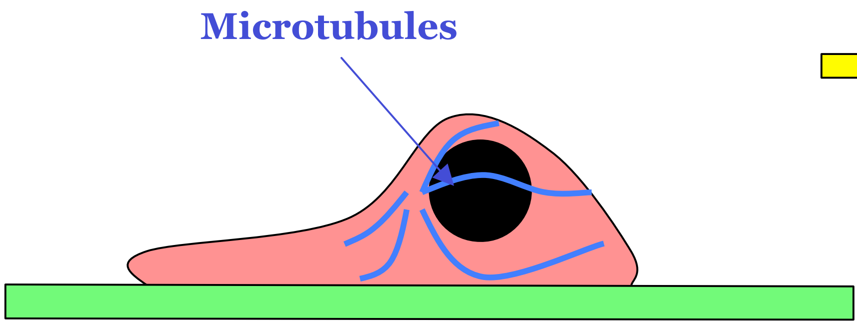


Suspension cell

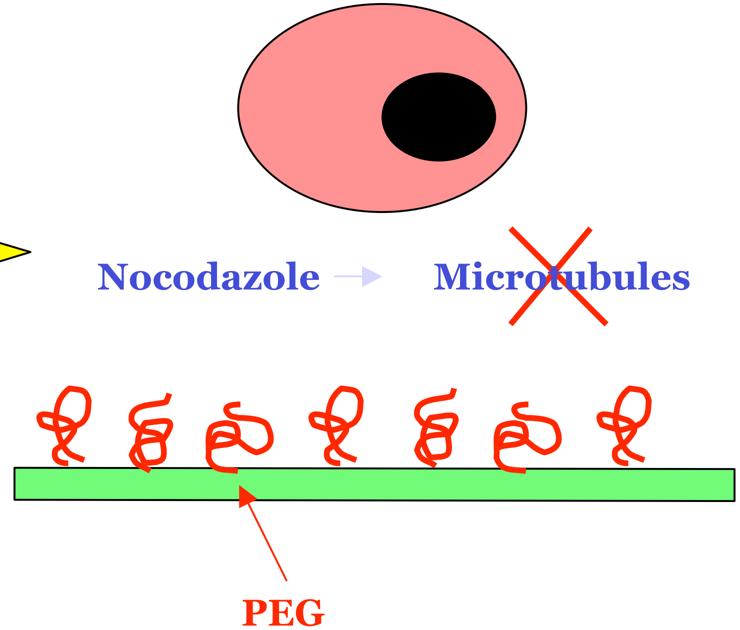


Spherical actin growth

Acto-myosin system *in vivo*



L929 Fibroblasts



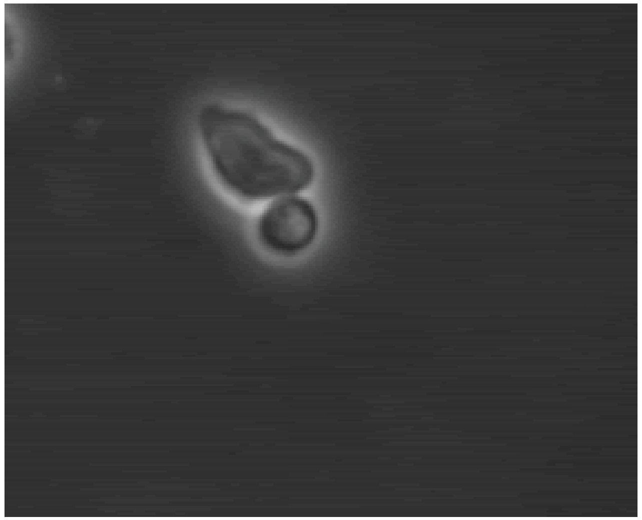
~~MT~~

↓

Rho pathway

↓

contractility

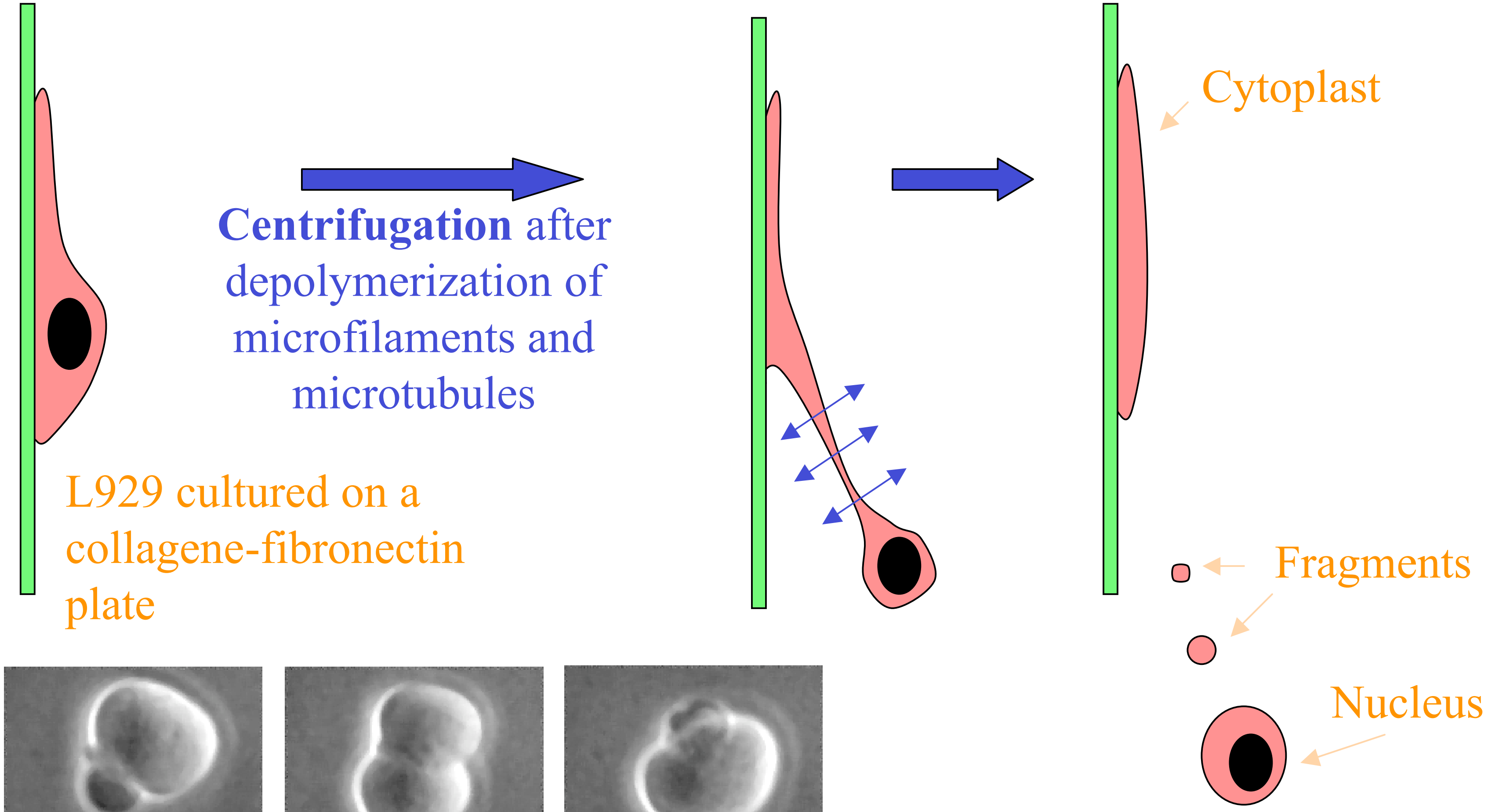


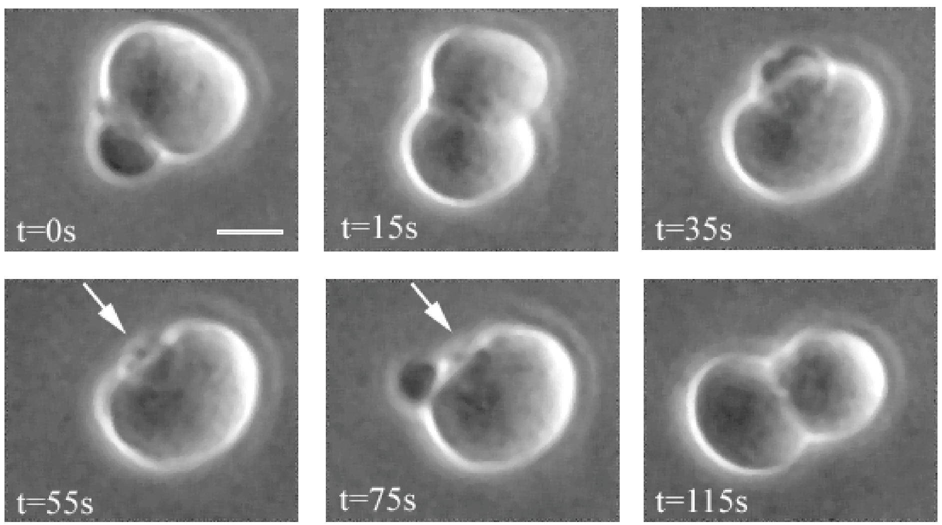
T≅ 8 minutes

[Bornens et al, *JCB* 1989
Pletjushkina et al, *CMC* 2001]

[E. Paluch, *Biophys. J.* 2005]

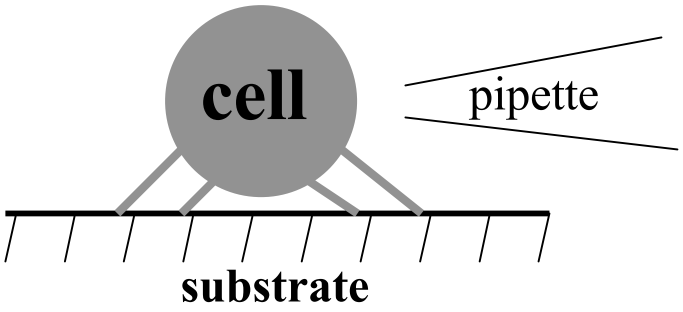
Cell fragments oscillate

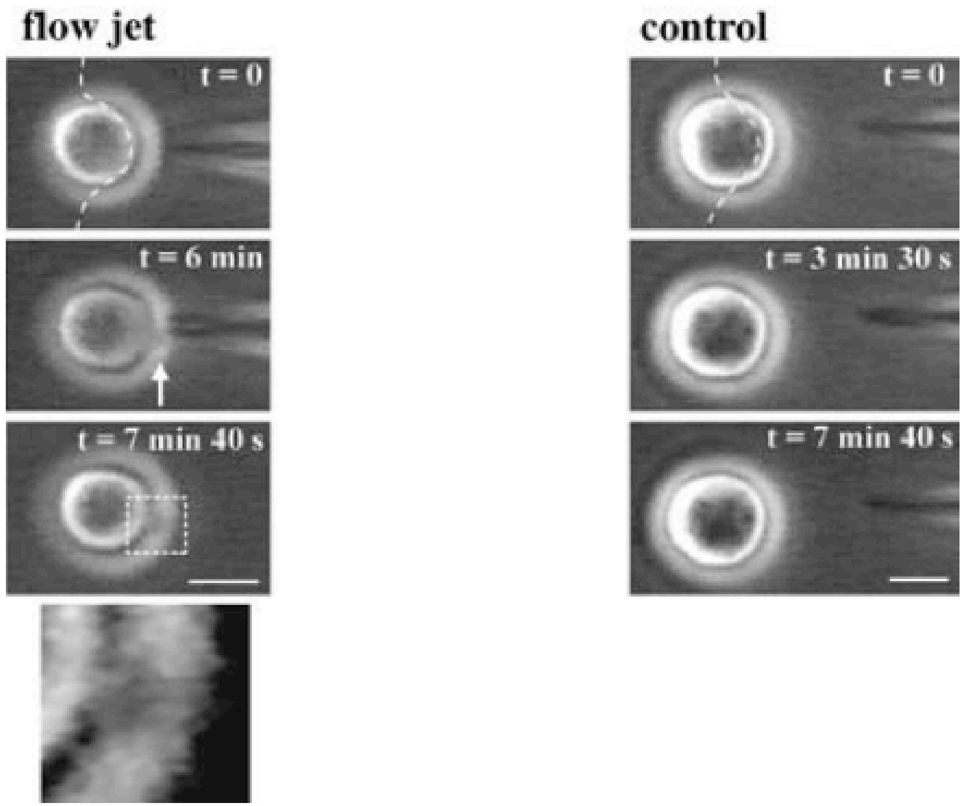




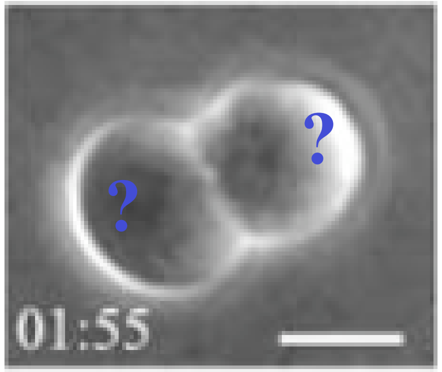
Cell fragment
T≅ 1 minute

The membrane bulge can be triggered locally

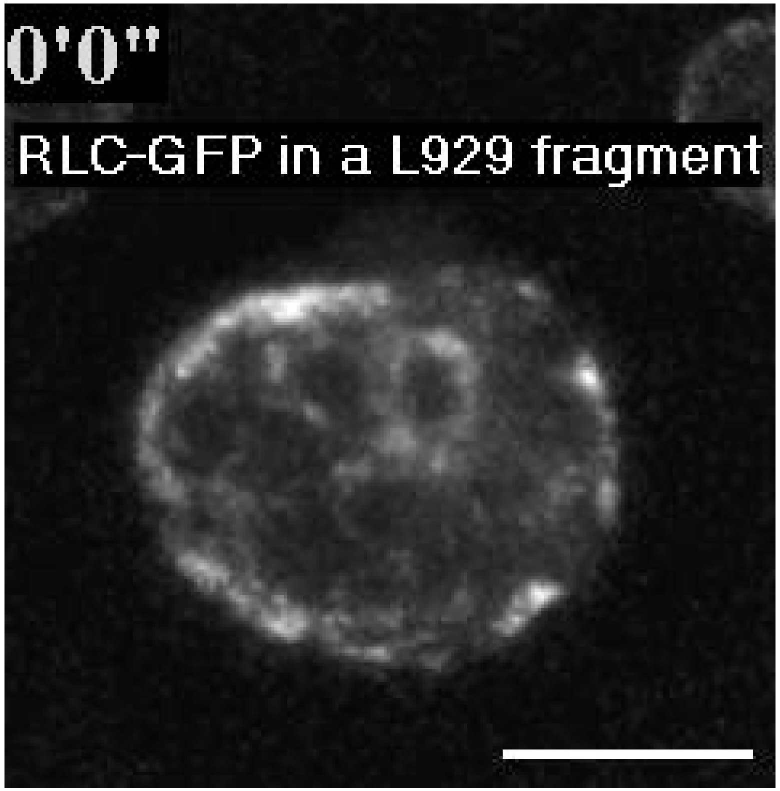




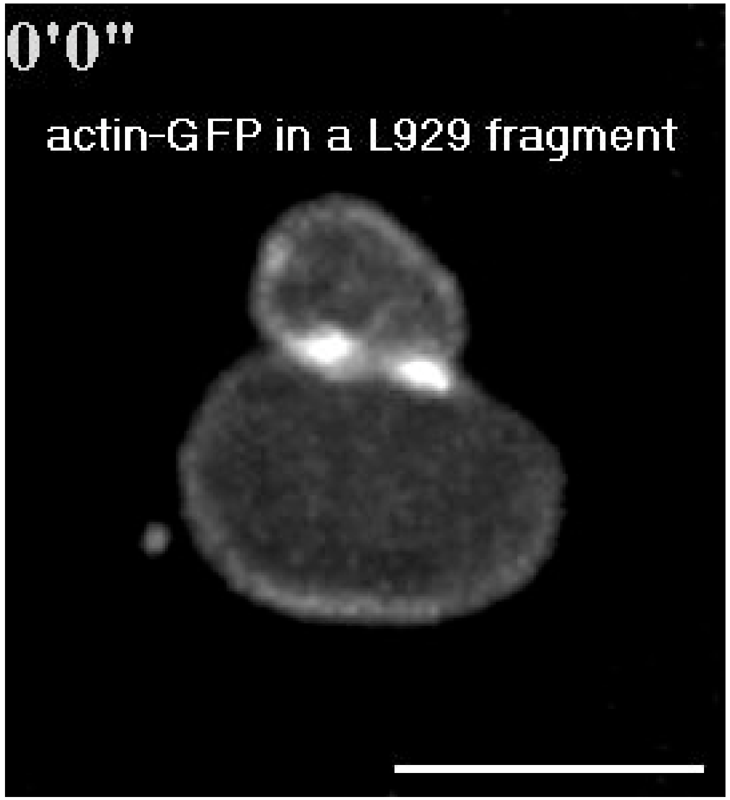
[E. Paluch, M. Piel, M. Bornens, J. Prost, C. Sykes, *Biophys*. *J*. 2005] myosin



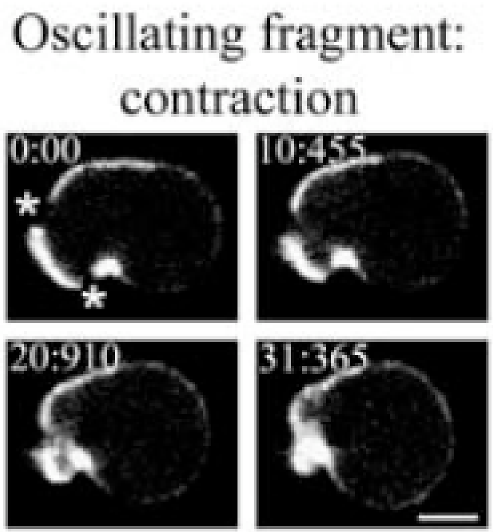
actin

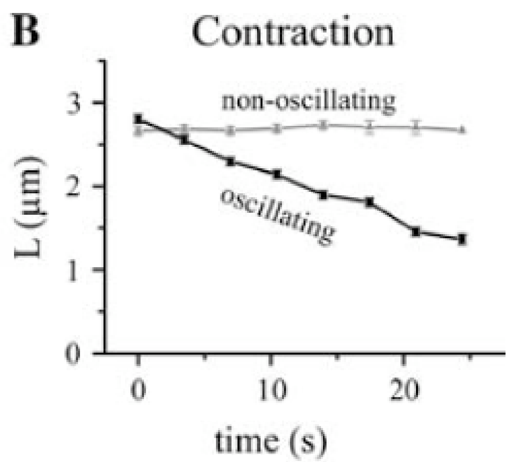


For T/2 = 100s, delay = 50s



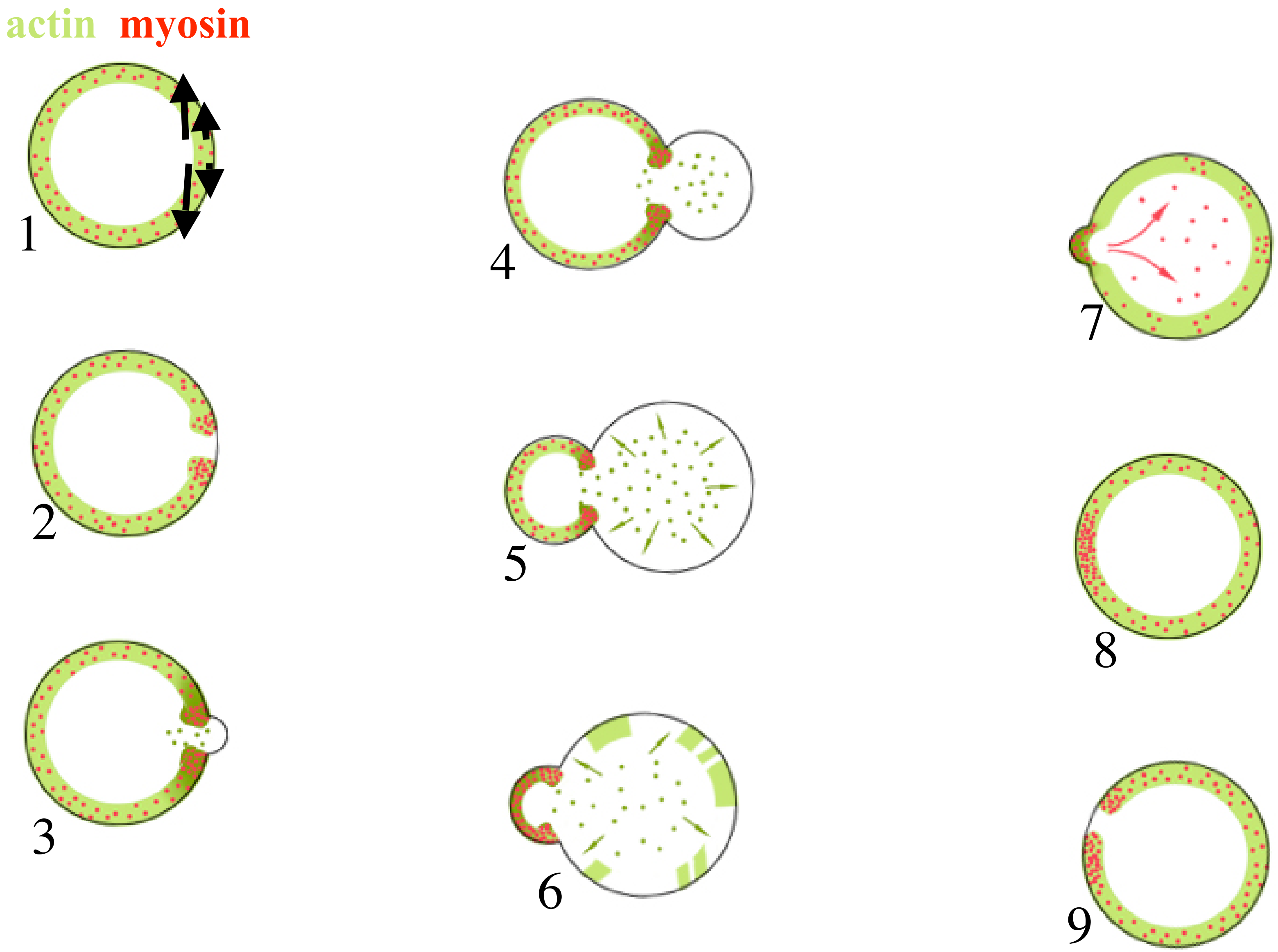
Contraction of an oscillating fragment





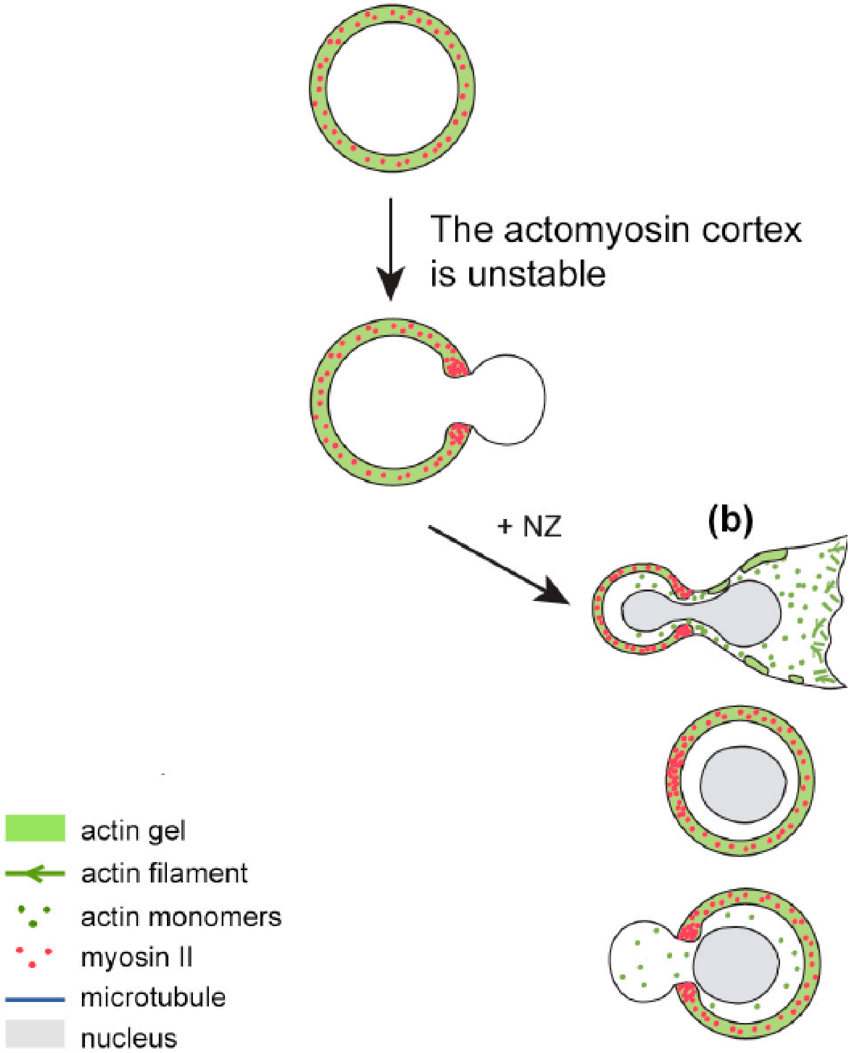
V=1 - 9 µm/min [Munro et al, *Dev Cell* 2004]

A model for the oscillation of cells

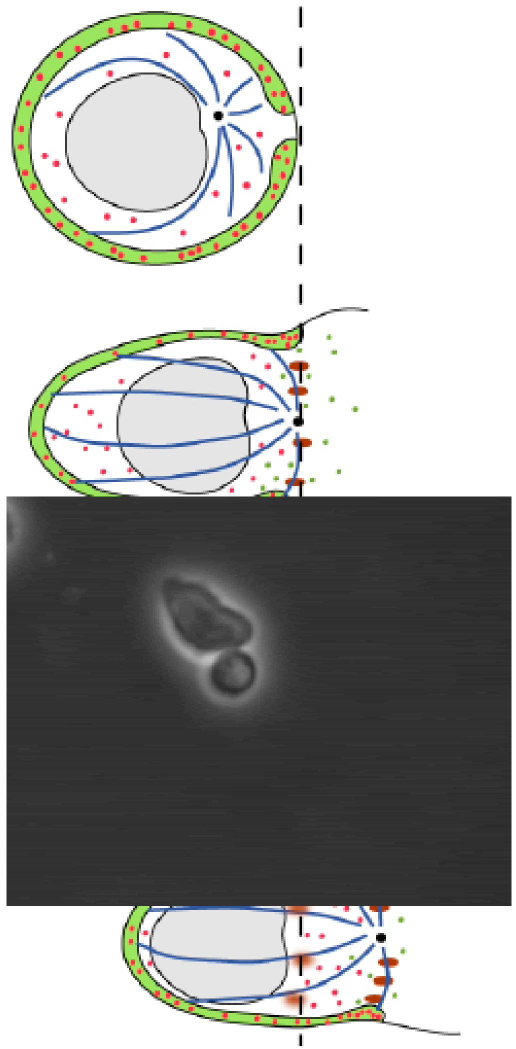


[E. Paluch, *Biophys*. *J*. 2005]

How could cells use this oscillation?



motility



Conclusion

- Cell shape changes result from active gel dynamics

- Simplified biomimetic systems are great tools for understanding cell shape changes