Sommaire

- microorganismes nageurs
  - bactéries
    - la nage d'E. Coli, motorisation
    - autres bactéries
  - eukaryotes
    - organismes unicellulaires mono et biflagellés
    - tapis de cils
    - structure et motorisation des cils et flagelles
- hydrodynamique à Re=0
  - les contraintes de l'absence d'inertie
  - hydrodynamique des cils et flagelles
- interactions
  - interactions entre cils, synchronisation
  - interactions avec une paroi, pompes biologiques microscopiques
  - interactions entre nageurs, comportements collectifs
- systèmes artificiels
  - viscosité et élasticité
  - micronageurs magnétiques

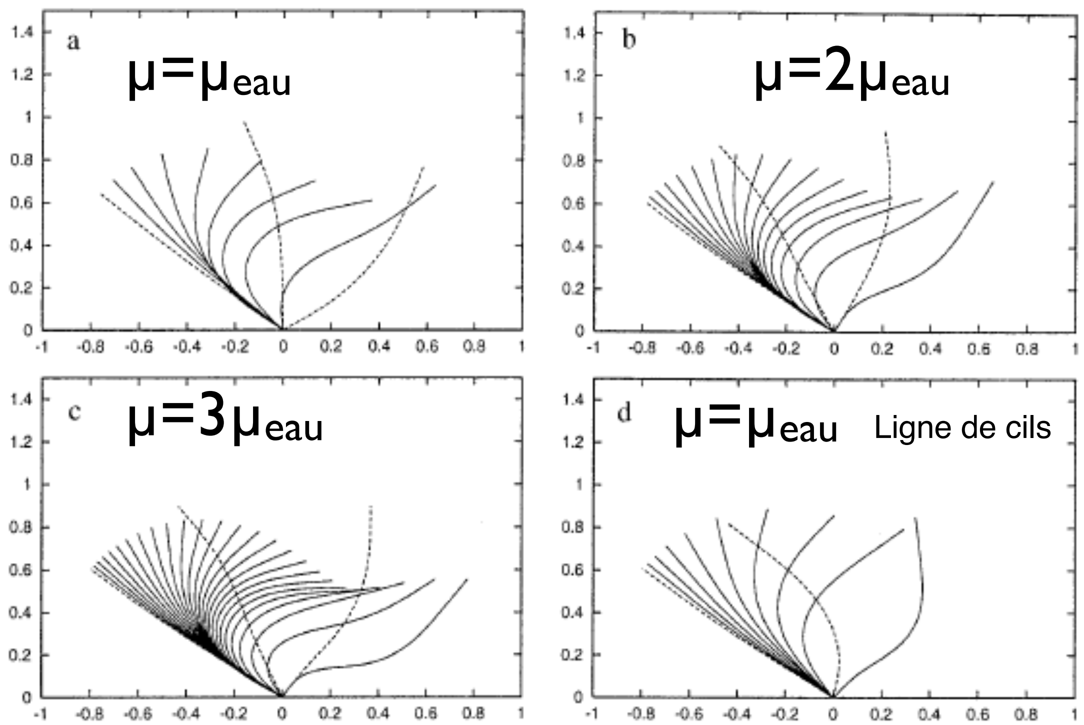
Théorème de la coquille St Jacques : pour nager il faut briser la symétrie +t/-t

Absence d'inertie = somme des forces et des couples = 0

L'anisotropie de mobilité est essentielle

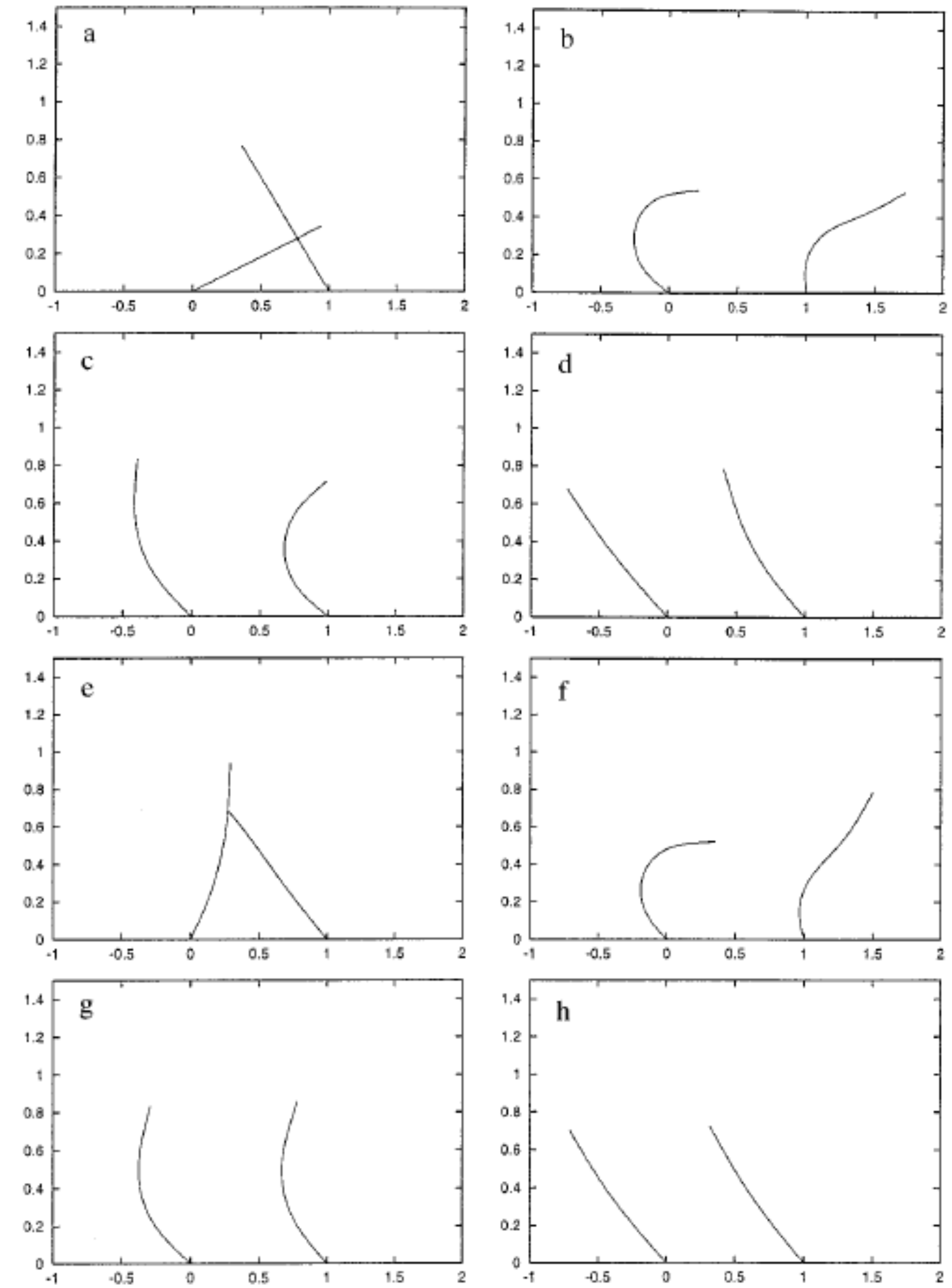
Pour un objet très allongé $$\zeta_\perp \approx 2\zeta_{||}$$

coordination des cils



Paramètres de modèle ajustés sur l'observation de cils de paramécie

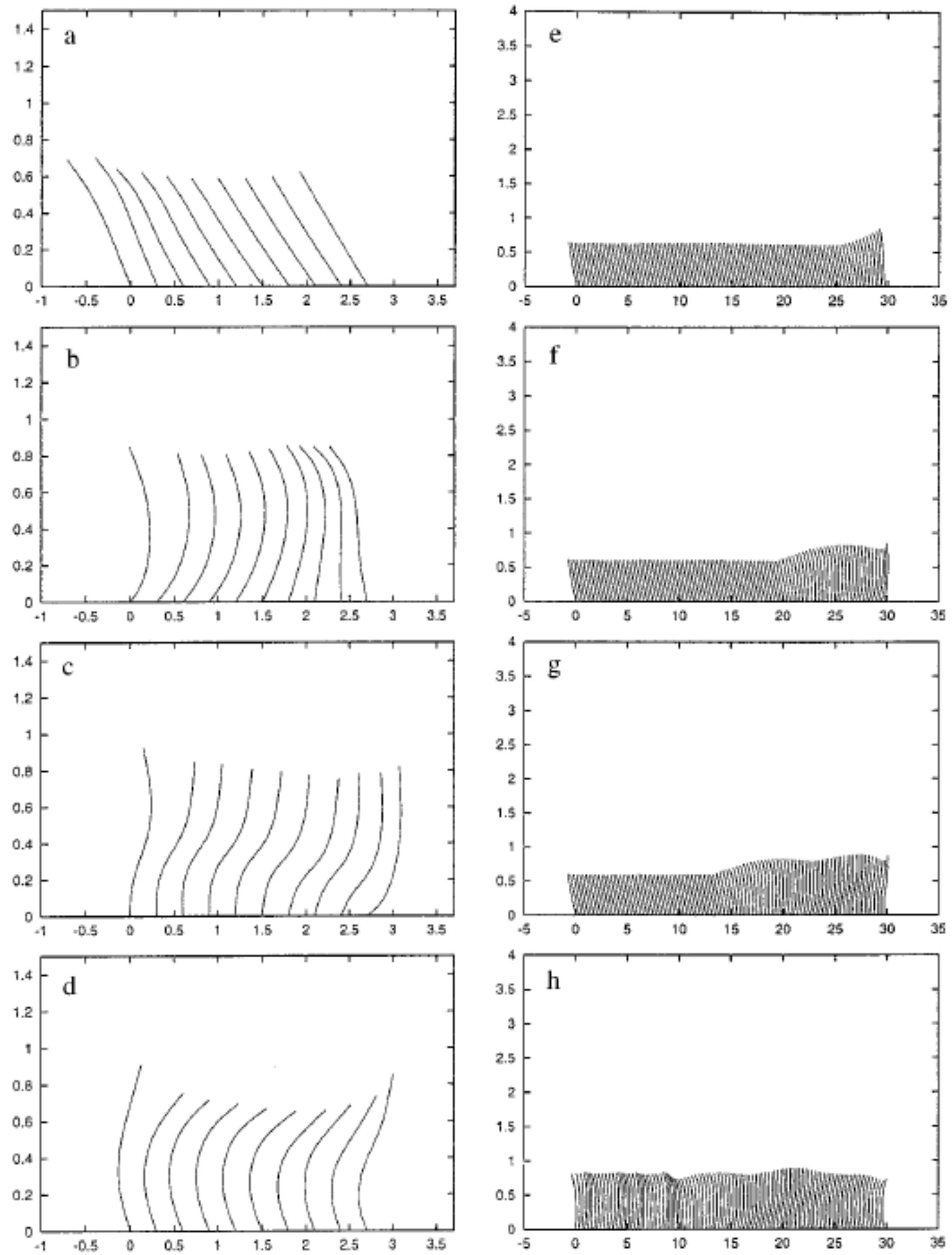
Loi de rétroaction des efforts hydrodynamiques sur les moteurs



Synchronisation de deux cils

S. Gueron et al., PNAS **94** 6001 (1997)

génération d'ondes métachronales

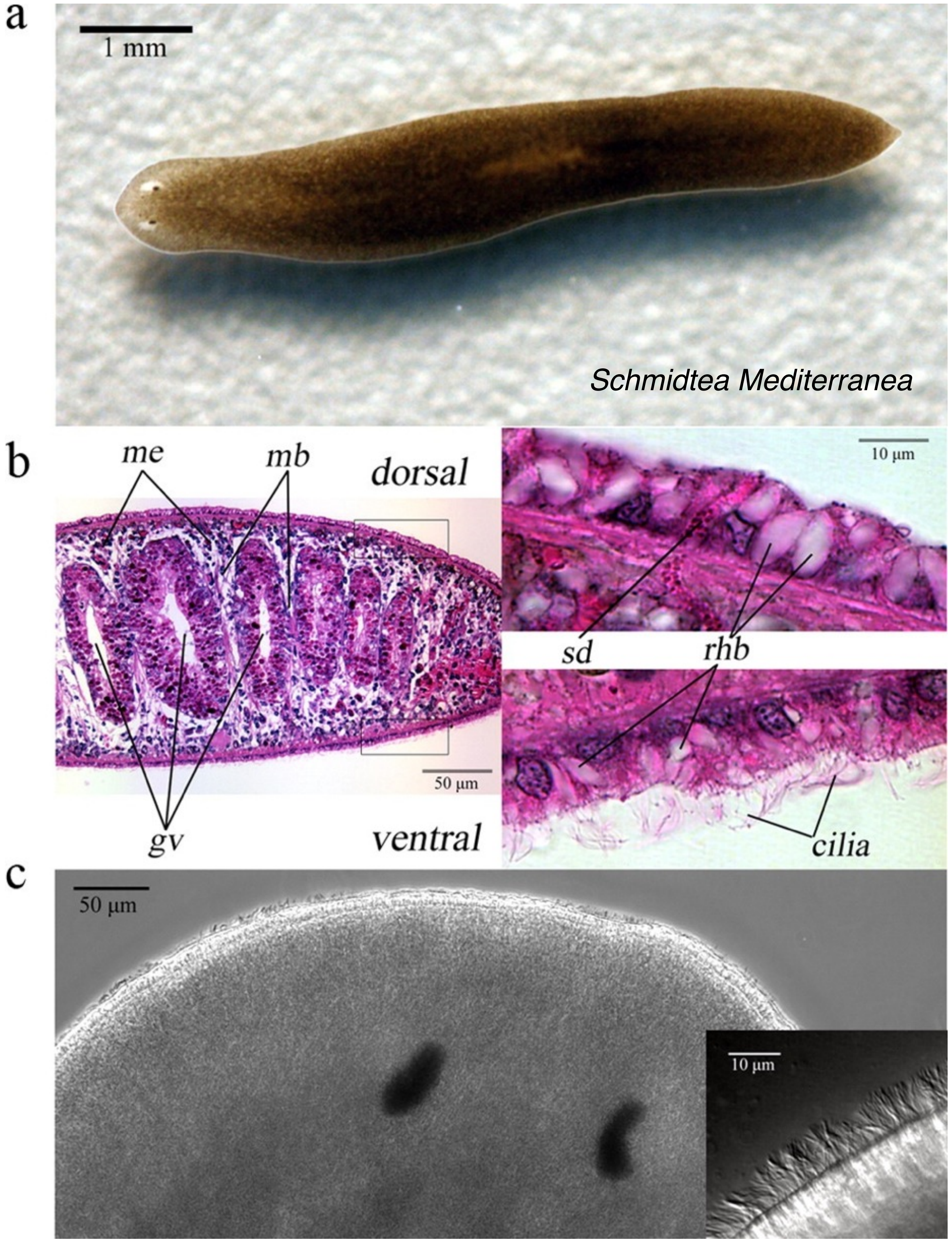


10 cils

100 cils

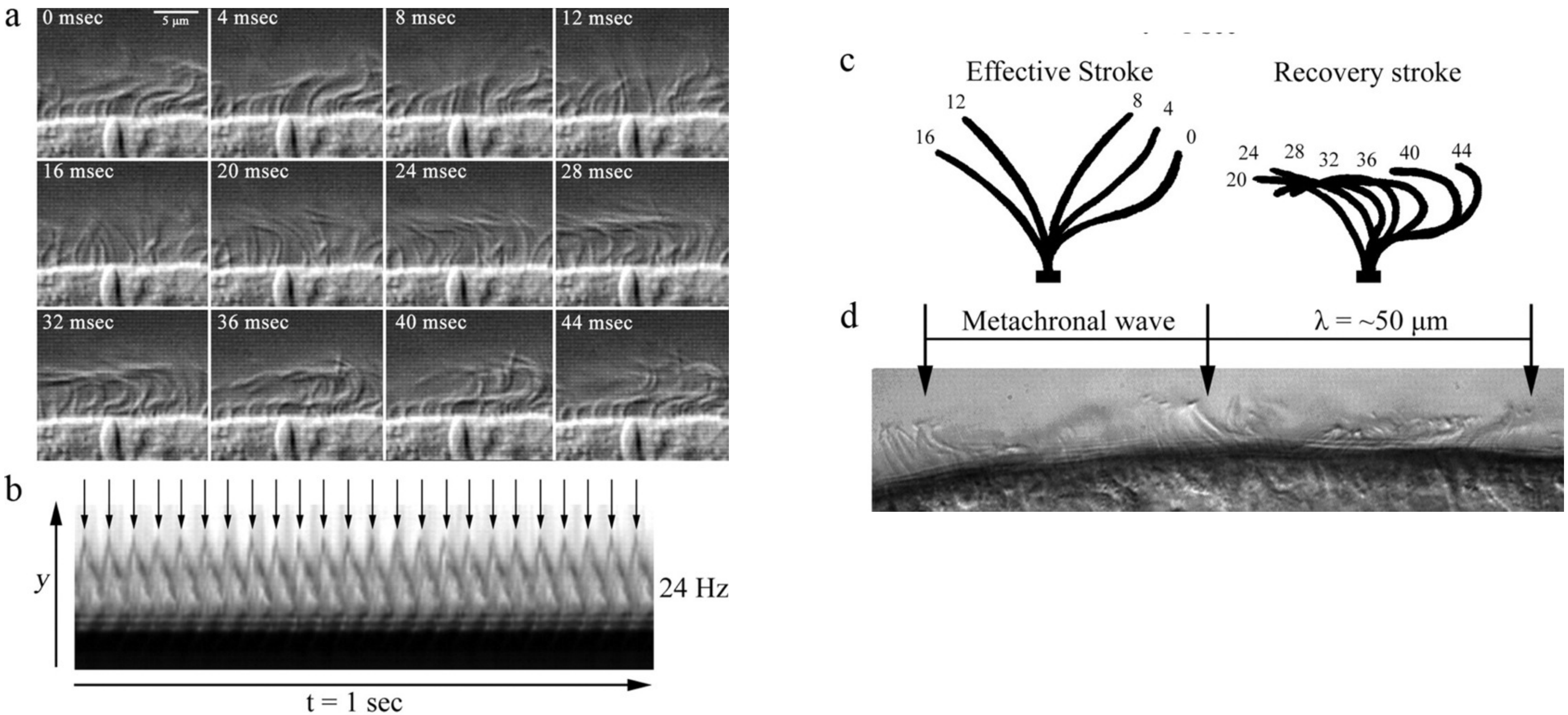
S. Gueron et al., PNAS **94** 6001 (1997)

Cils des planaires



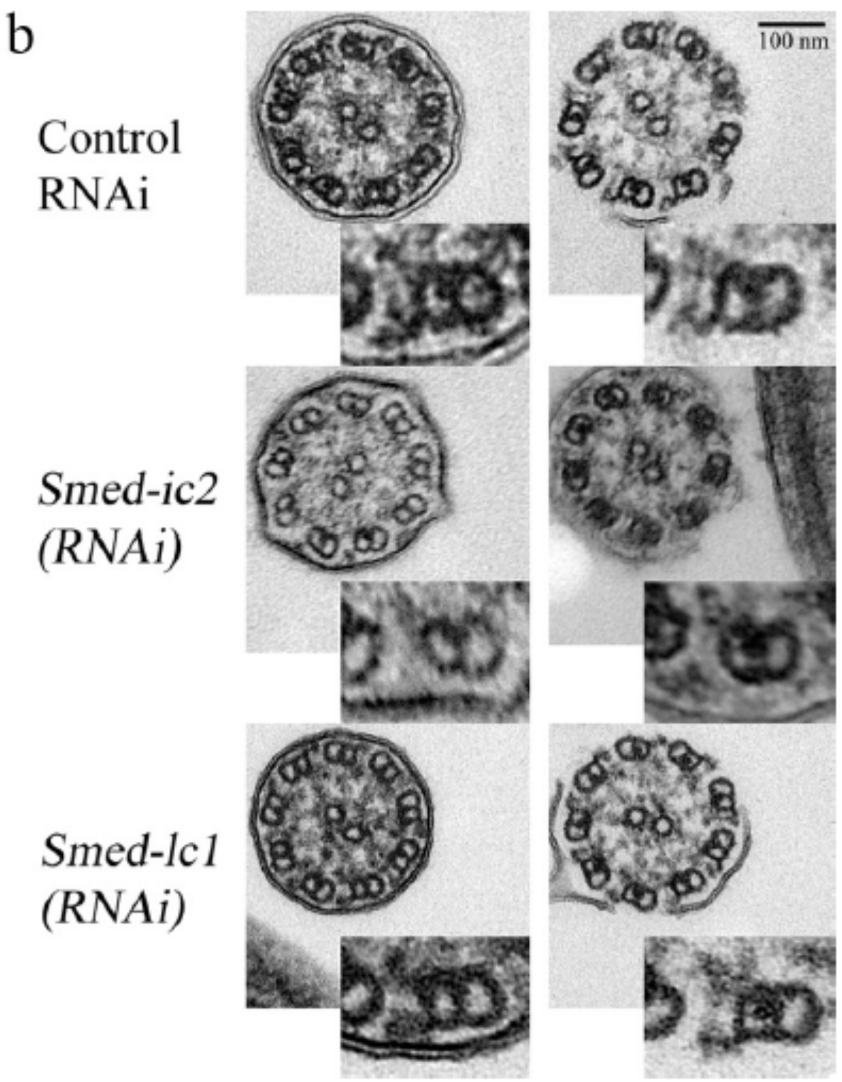
P. Rompolas, R. S. Patel-King, and S. M. King Mol. Biol. Cell **21** 3669 2010

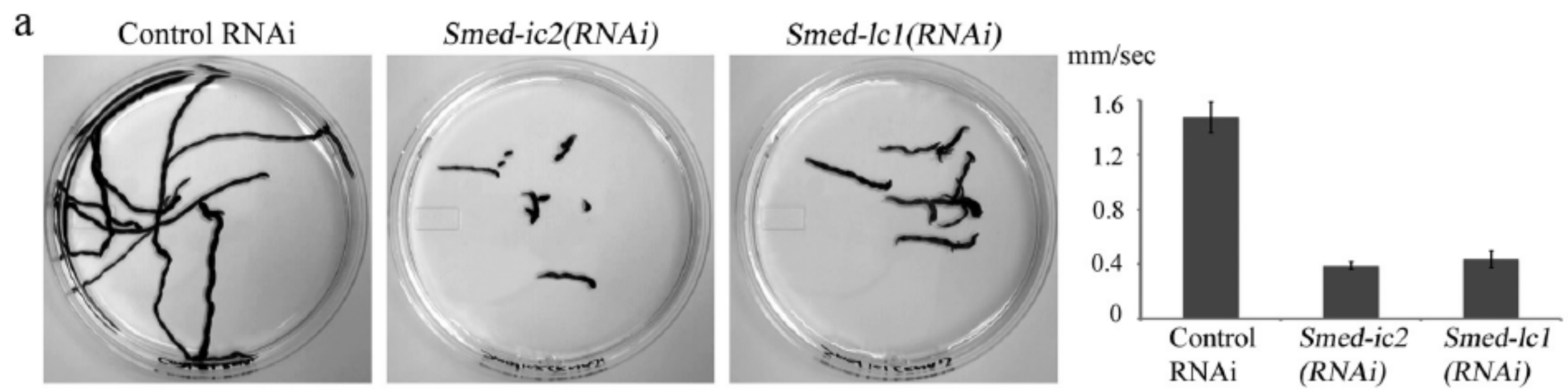
Cils des planaires

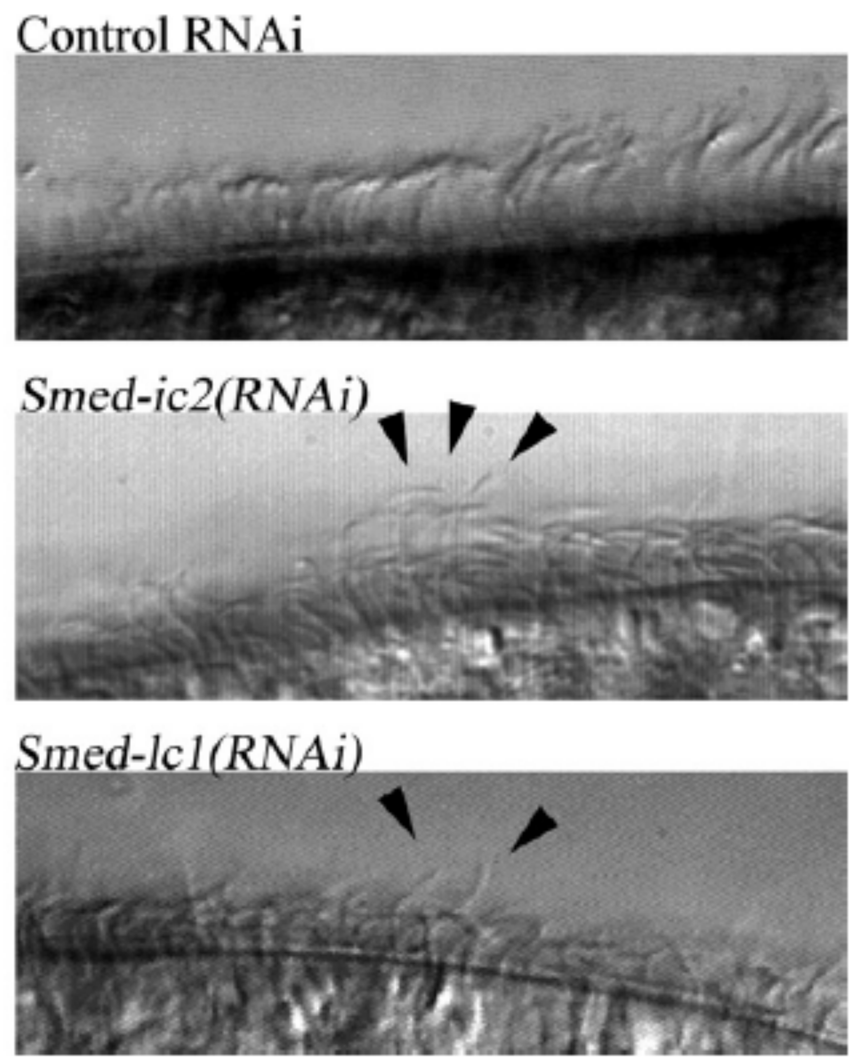


P. Rompolas, R. S. Patel-King, and S. M. King Mol. Biol. Cell **21** 3669 2010

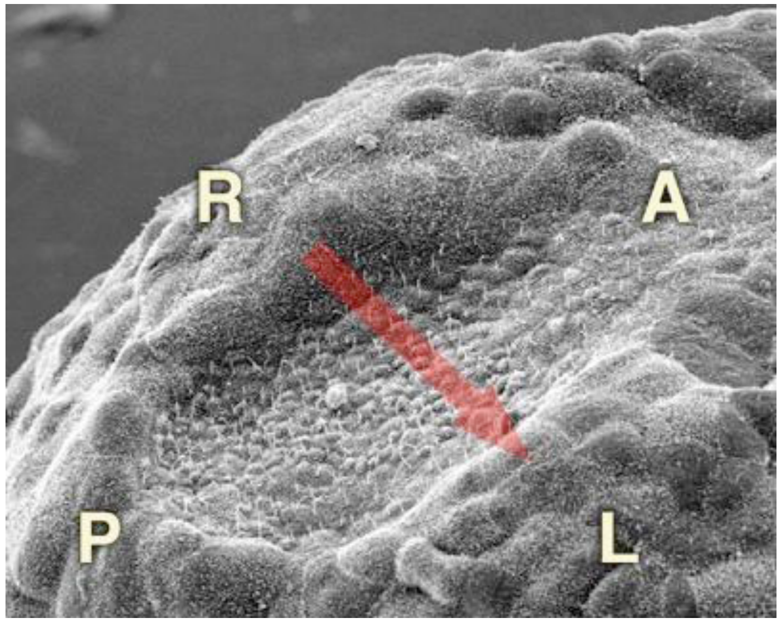
Modifications des battements et d ela synchronisation.



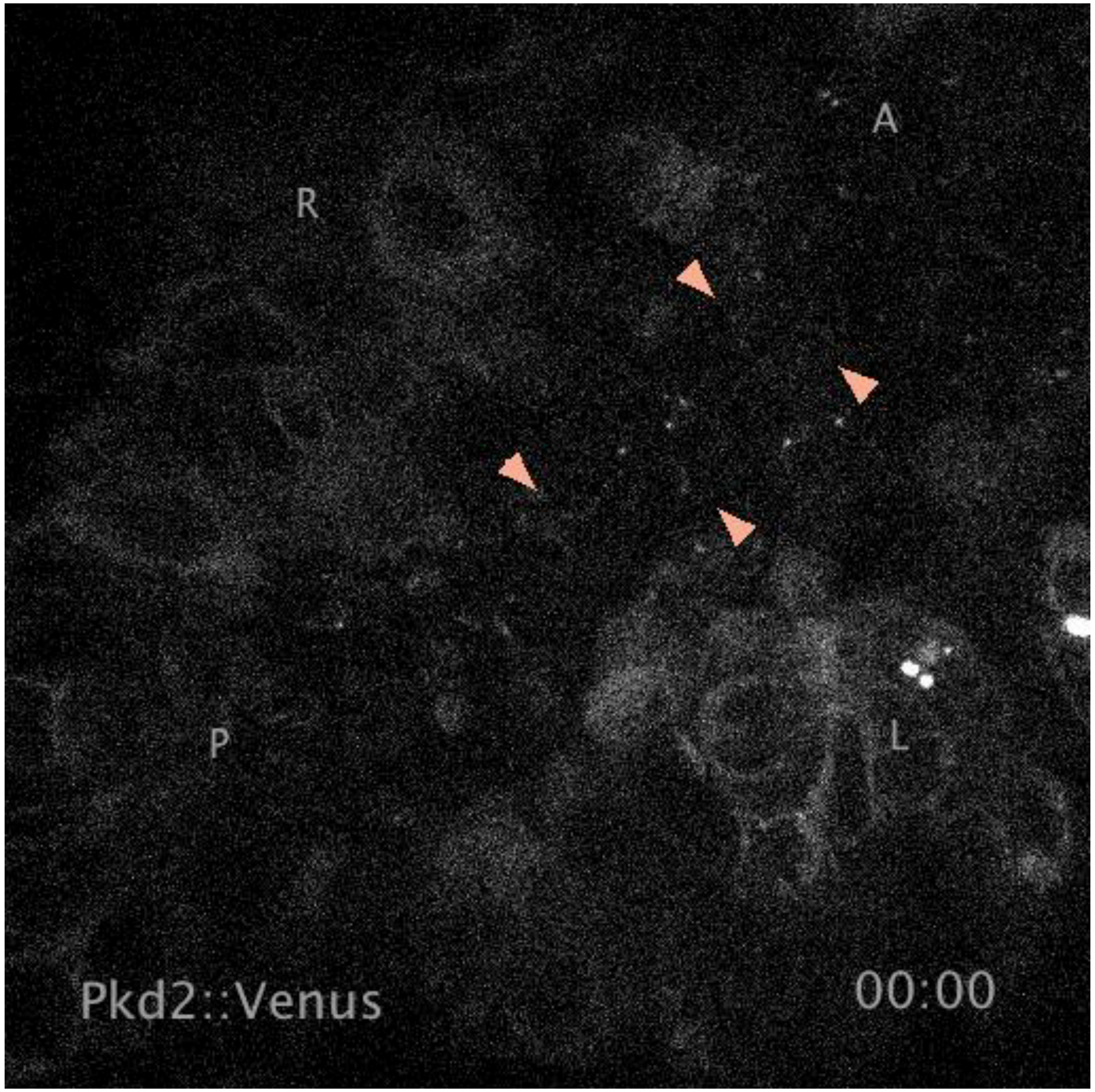




Cils nodaux et différentiation droite-gauche des embryons

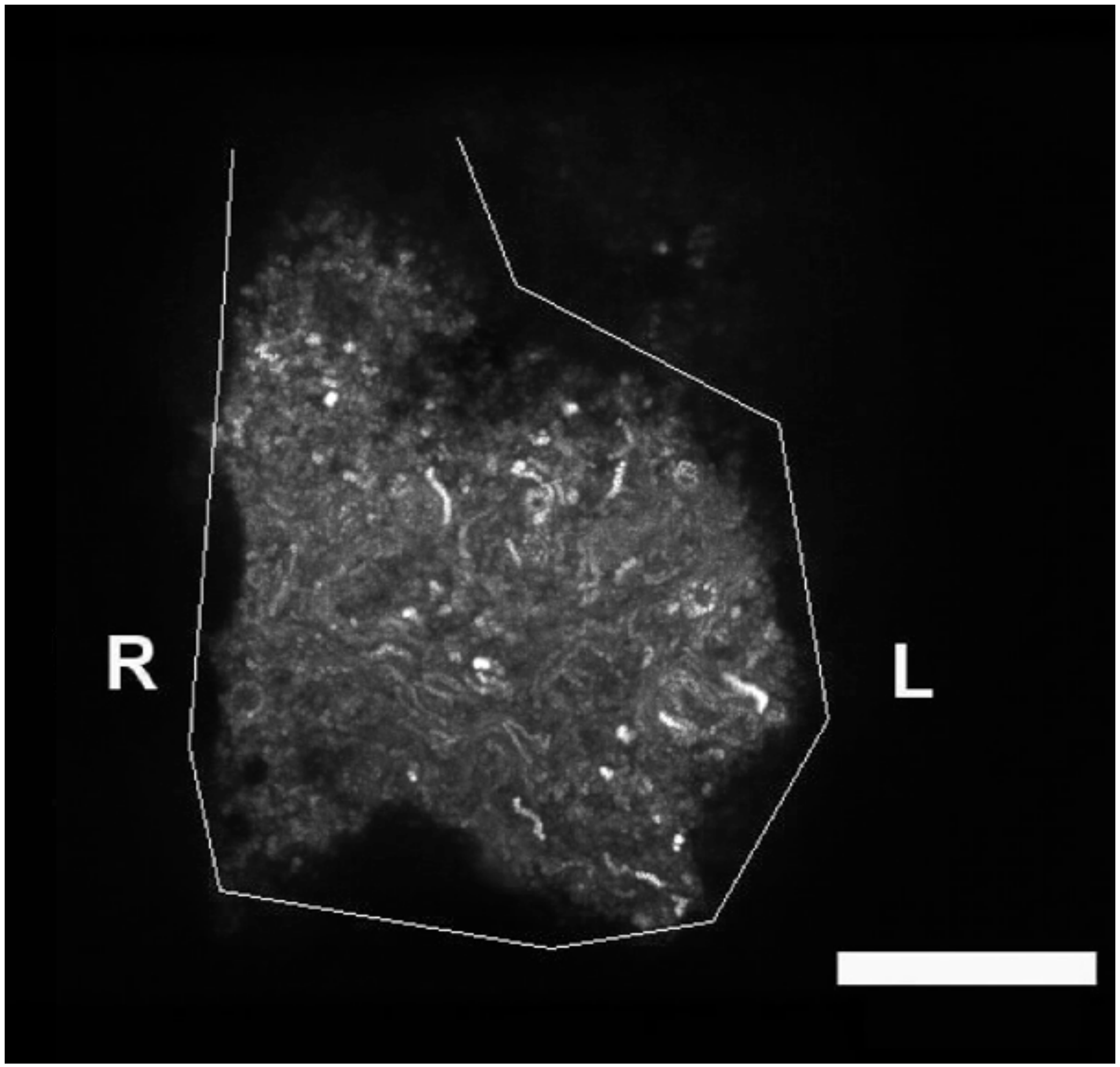


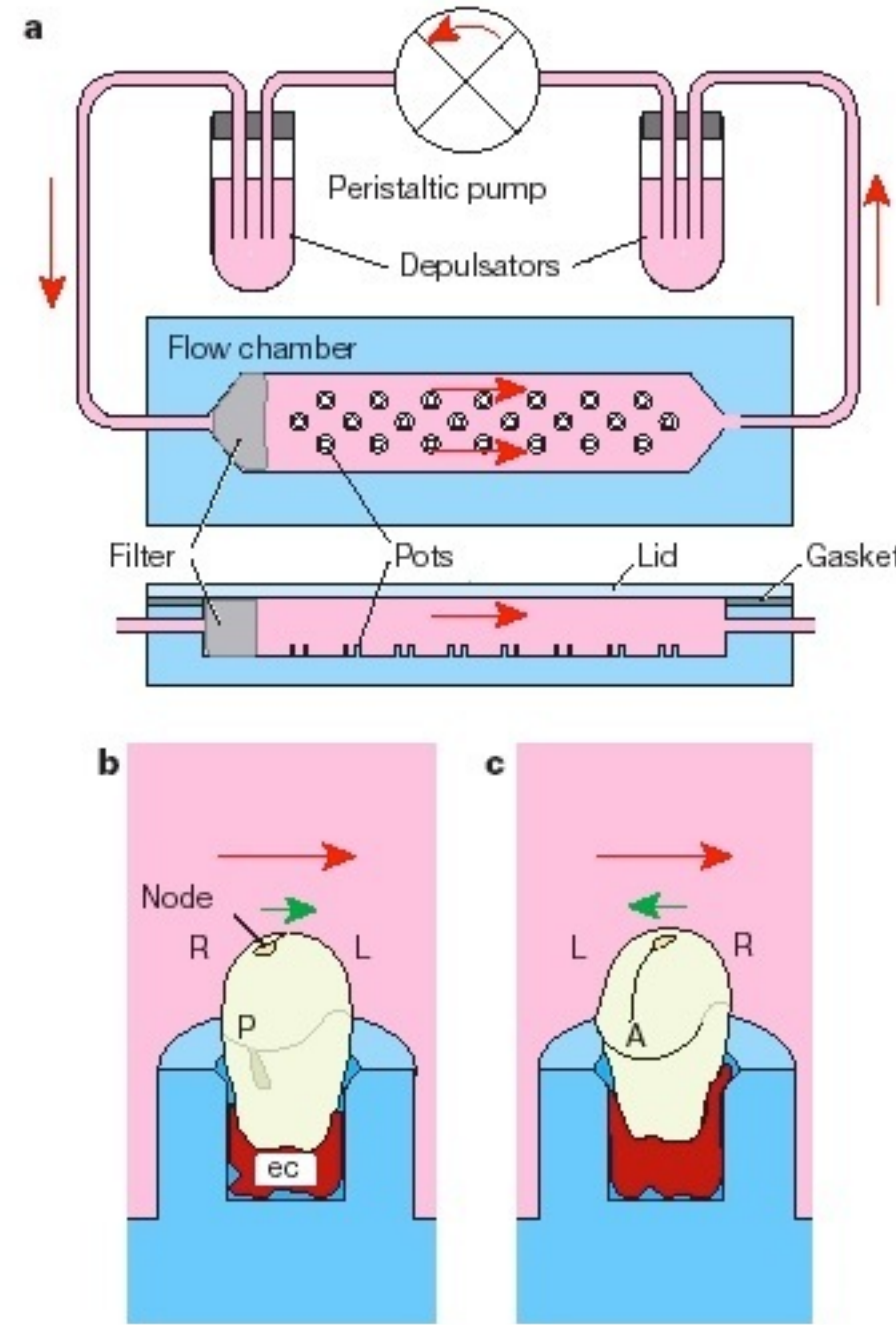
S.S. Plotkin website



S. Yoshiba et al., *Science*, 2012

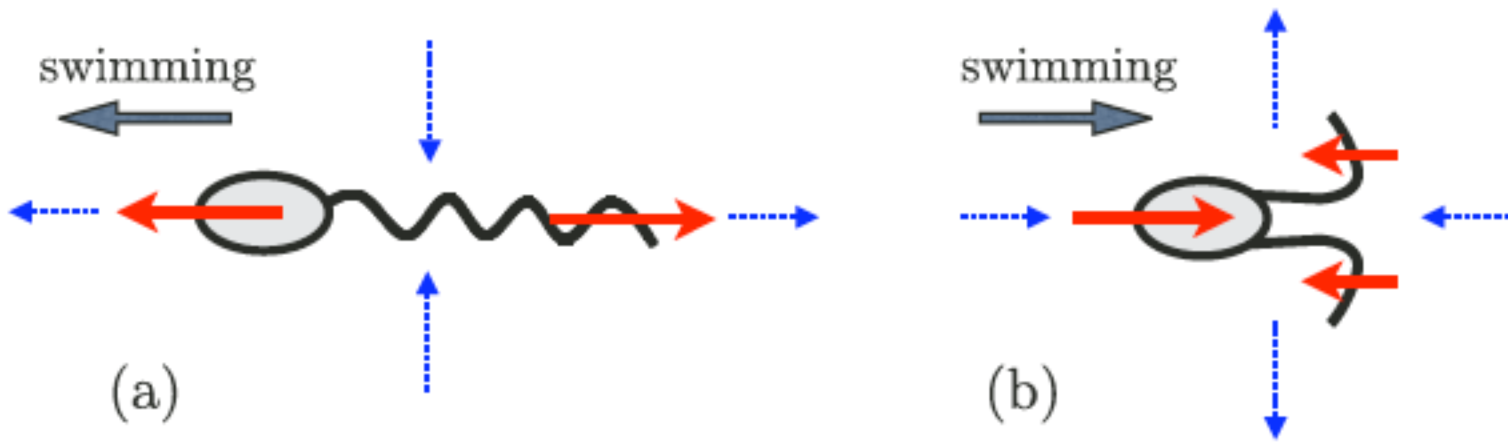
Cils nodaux et différentiation droite-gauche des embryons





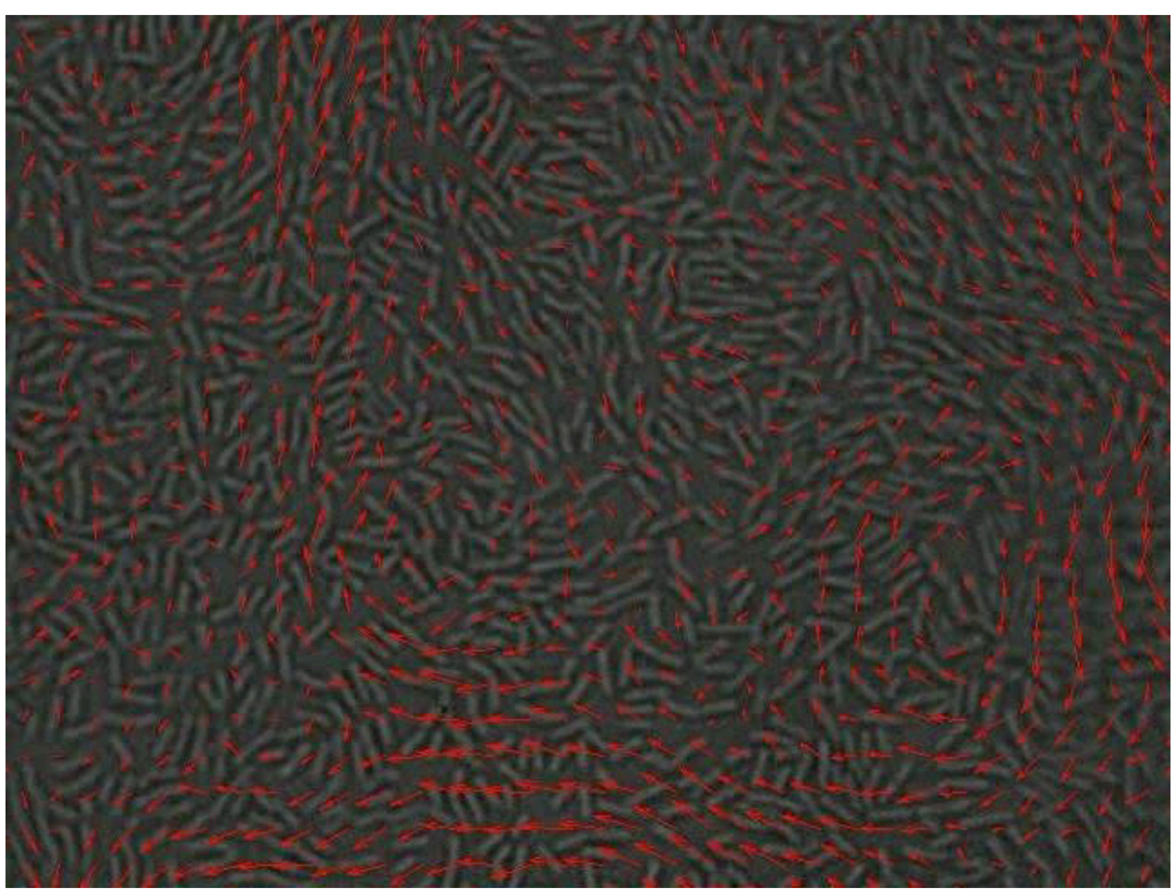
Nonaka, S., Shiratori, H., Saijoh, Y. & Hamada, H. Nature **418**, 96–99 (2002).

Pousseurs et tireurs



Pousseur Tireur

1 nageur autonome = 1 dipôle de forces



Bacillus Subtilis

A. Sokolov et al., PRL 98, 158102 (2007)

Micronageurs et micropompes artificiels

Source d'énergie

systèmes hybrides avec moteurs biologiques

systèmes catalytiques

nageurs magnétiques

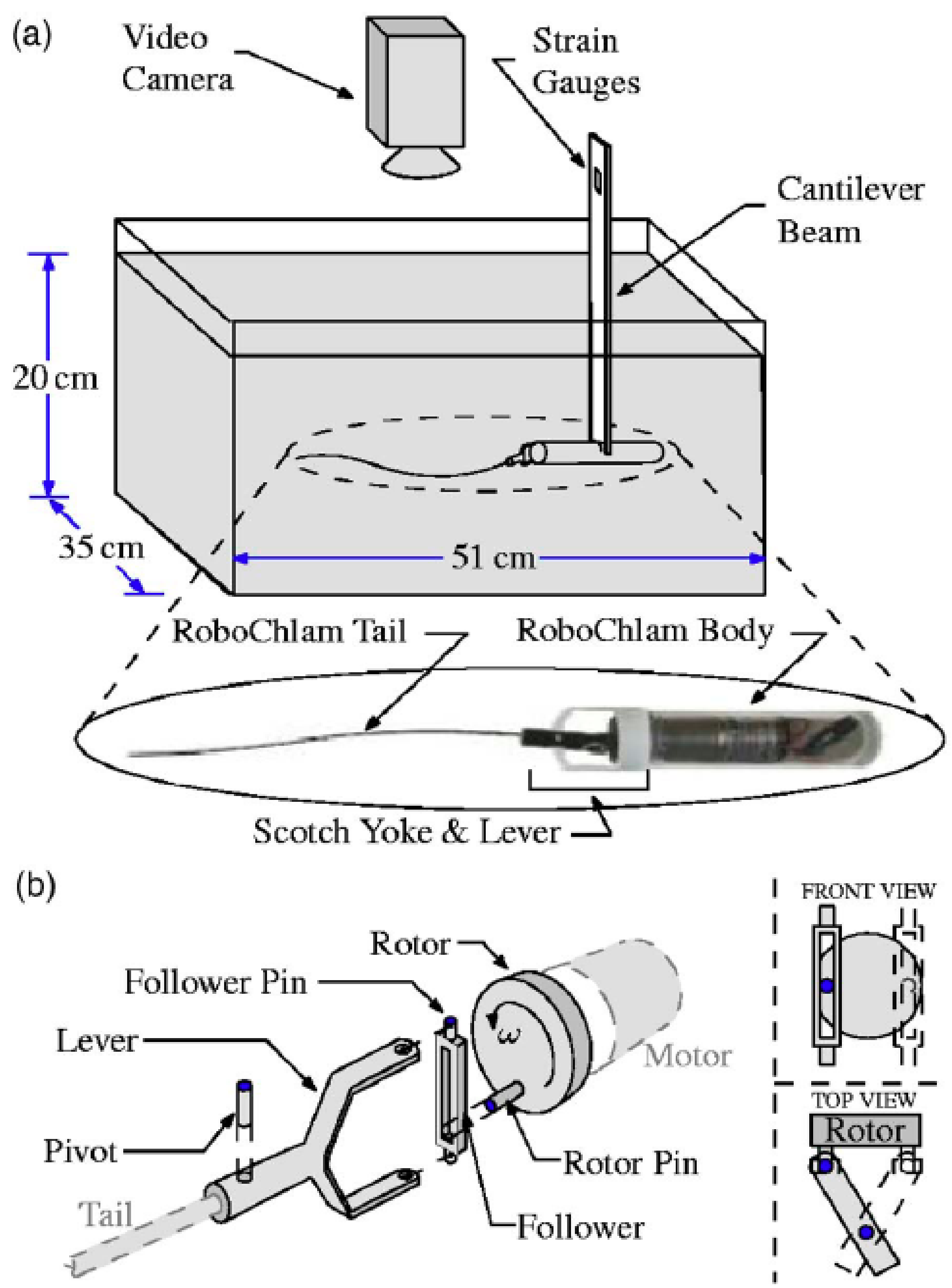
Mouvements non réciproques

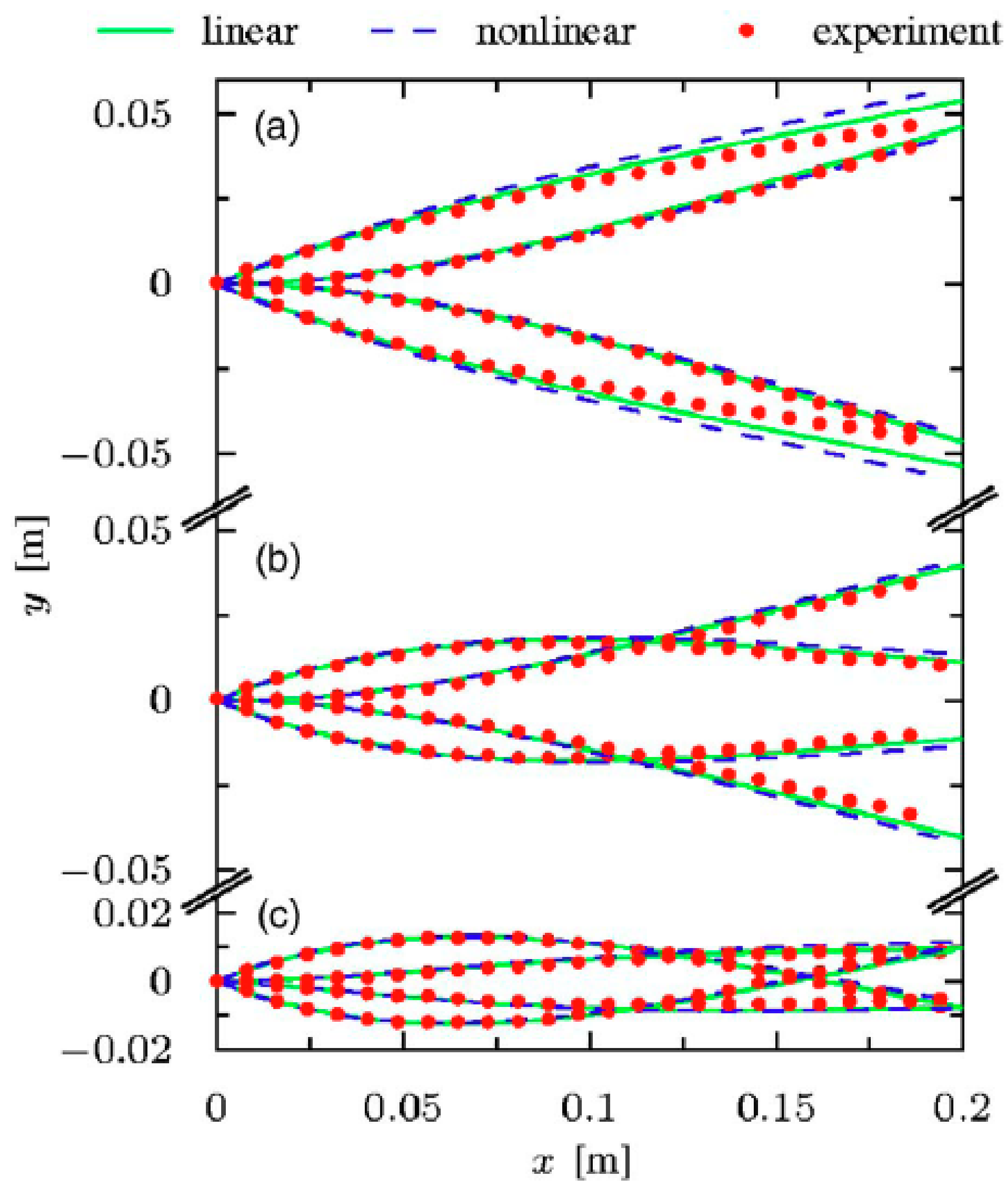
Compétition viscosité élasticité

Compétition couple moteur/résistance visqueuse

Couplage rotation/translation

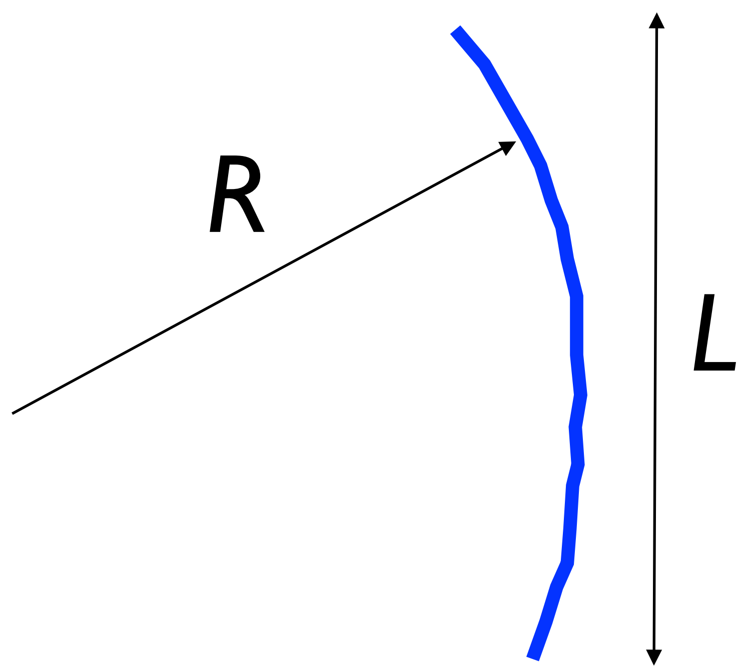
Modèles physiques de propulsion ciliée





T. S. Yu, E. Lauga and A. E. Hosoi, Phys. Fluids, **18**, 091701, 2006

Une analyse en loi d'échelle



Energie élastique

$$U_{el}/L \sim \frac{\kappa_b}{R^2}$$

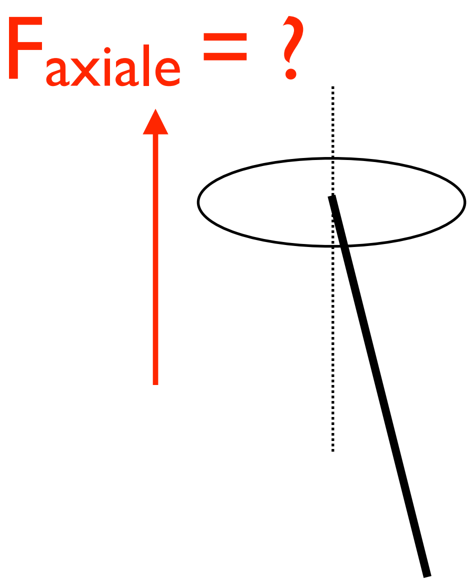
Couple visqueux

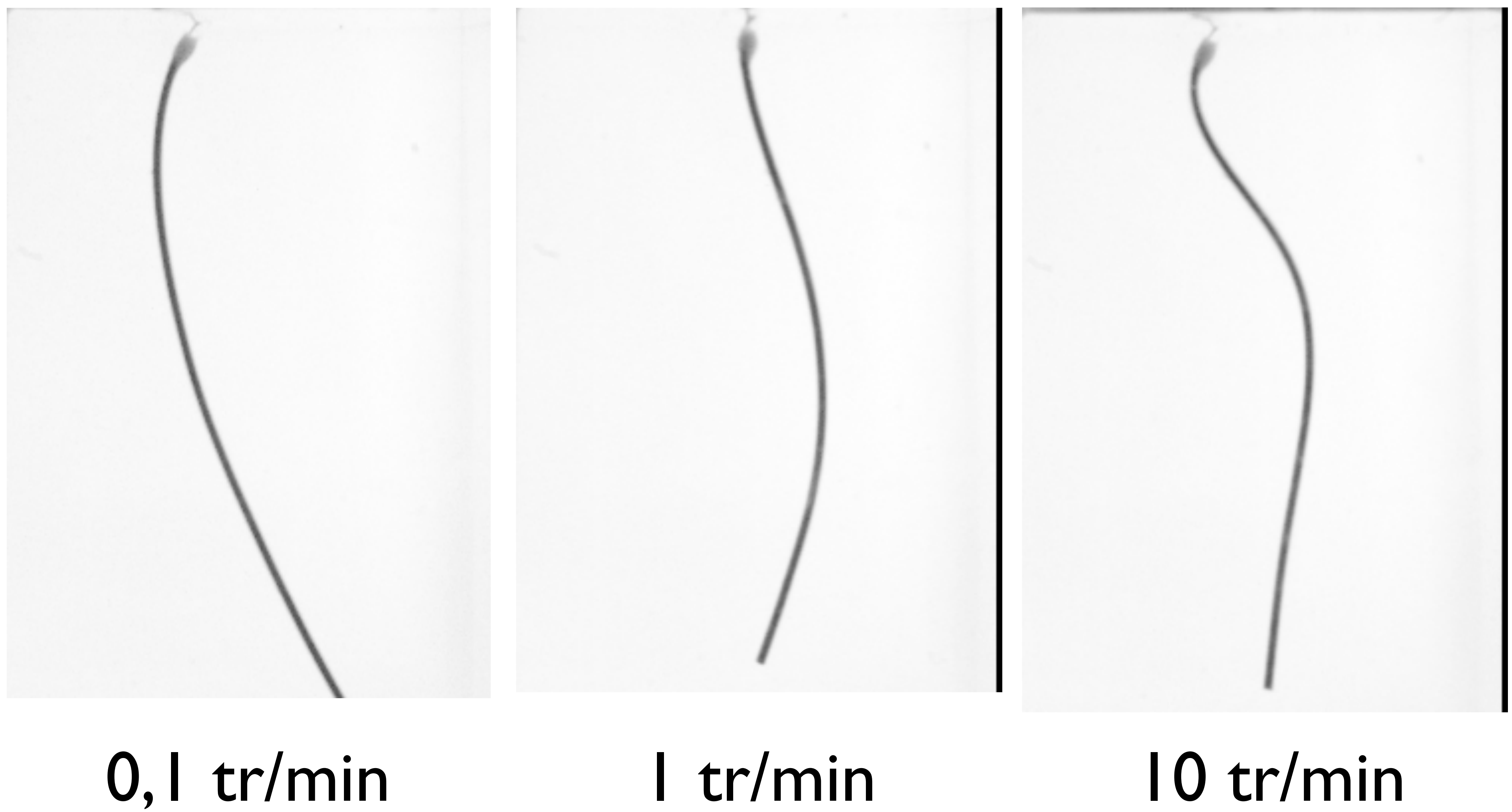
$$U_{el} \sim \frac{\kappa_b}{L} \sim \eta\omega L^3$$

$$Sp \sim \left(\frac{\eta\omega L^4}{\kappa_b}\right)$$

$$l_{ev} \sim \left(\frac{\kappa_b}{\eta}\right)^{1/4} \omega^{-1/4}$$

Nageurs macroscopiques artificiels

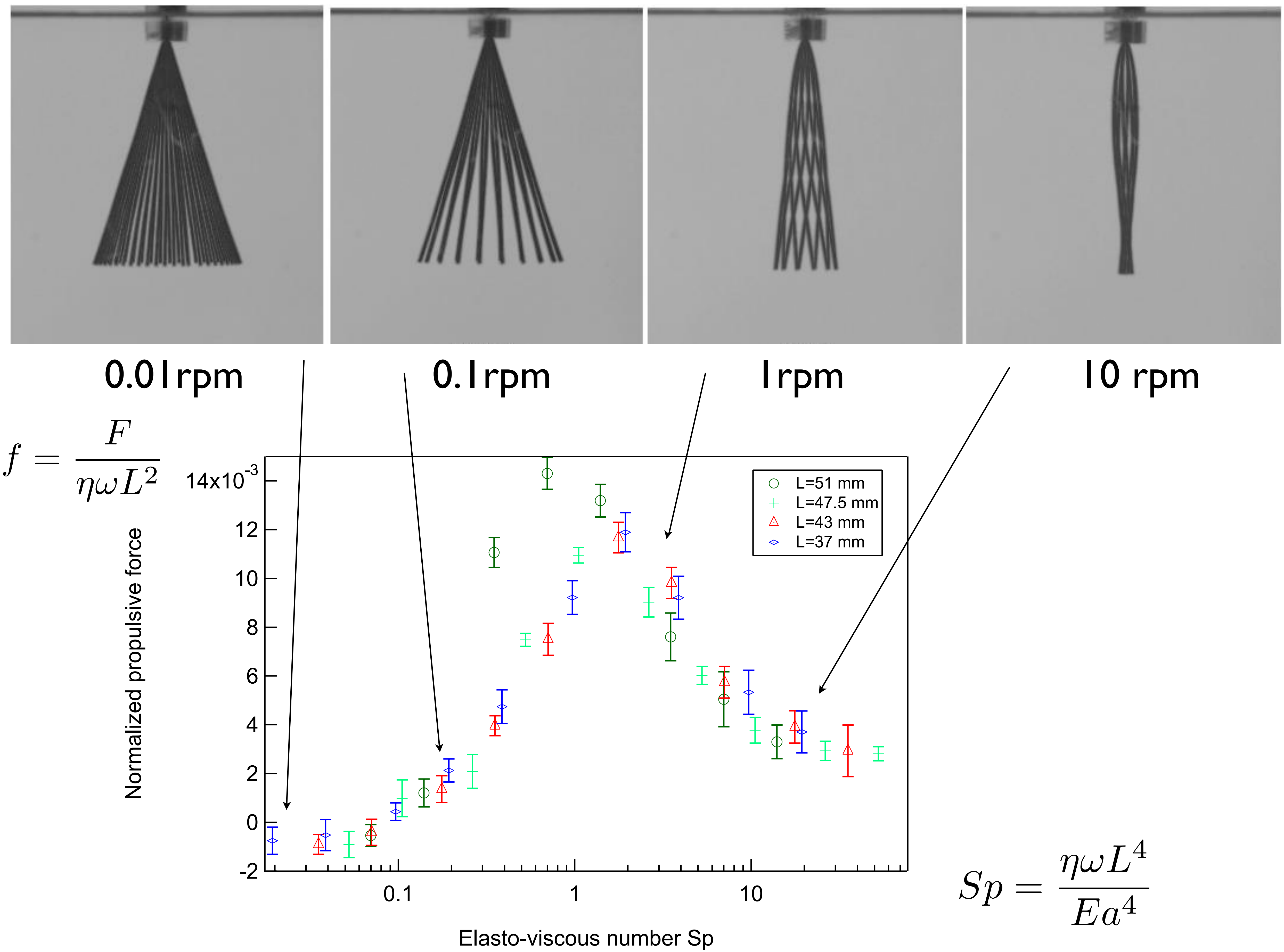




filament élastique dans un bain de glycérine

N. Coq, O. du Roure, J. Marthelot, D. Bartolo & M. Fermigier, Phys. Fluids **20**, 051703 (2008)

$$f = \frac{F}{\eta \omega L^2}$$

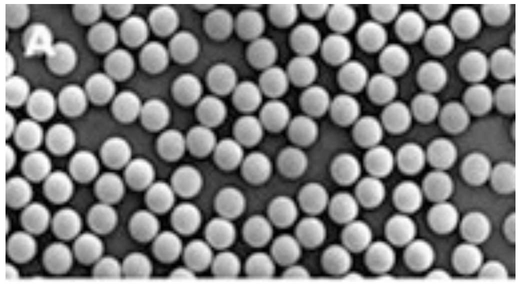


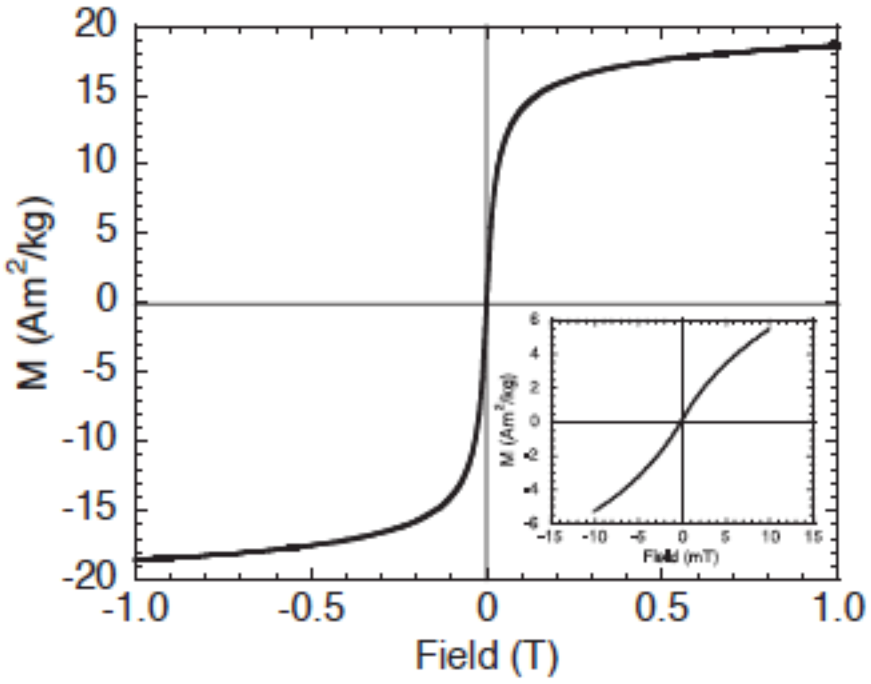
$$Sp = \frac{\eta \omega L^4}{E a^4}$$

Auto-assemblage unidimensionnel

- Particules colloidales superparamagnetiques

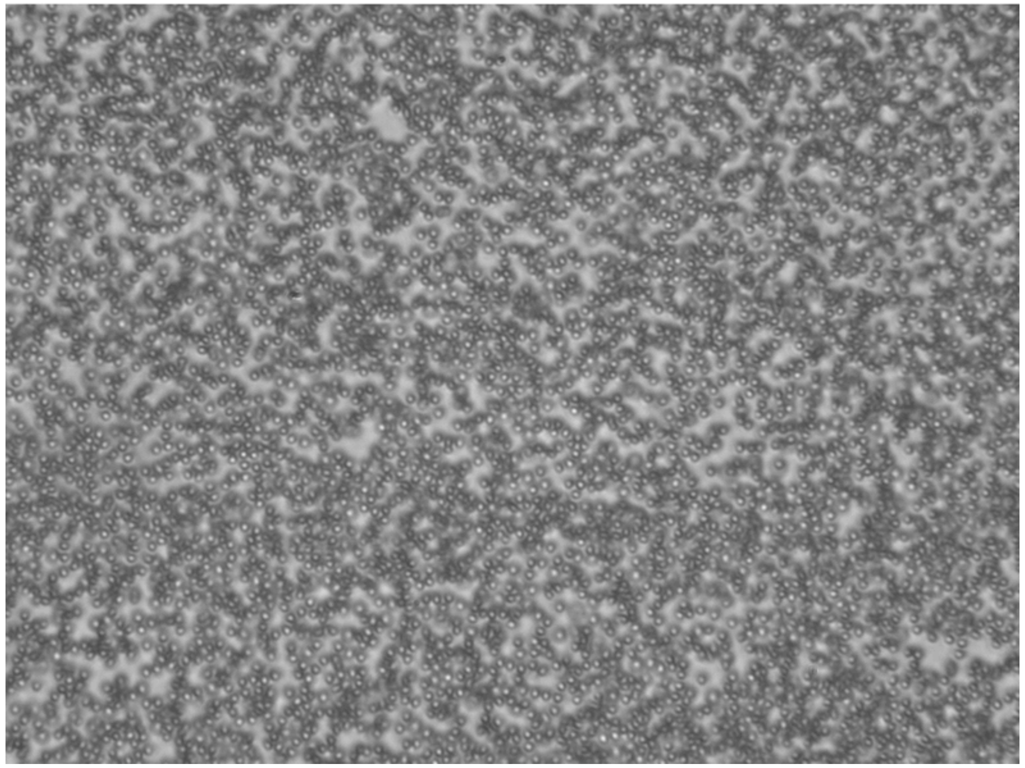
  rayon 0.1 à 2 microns

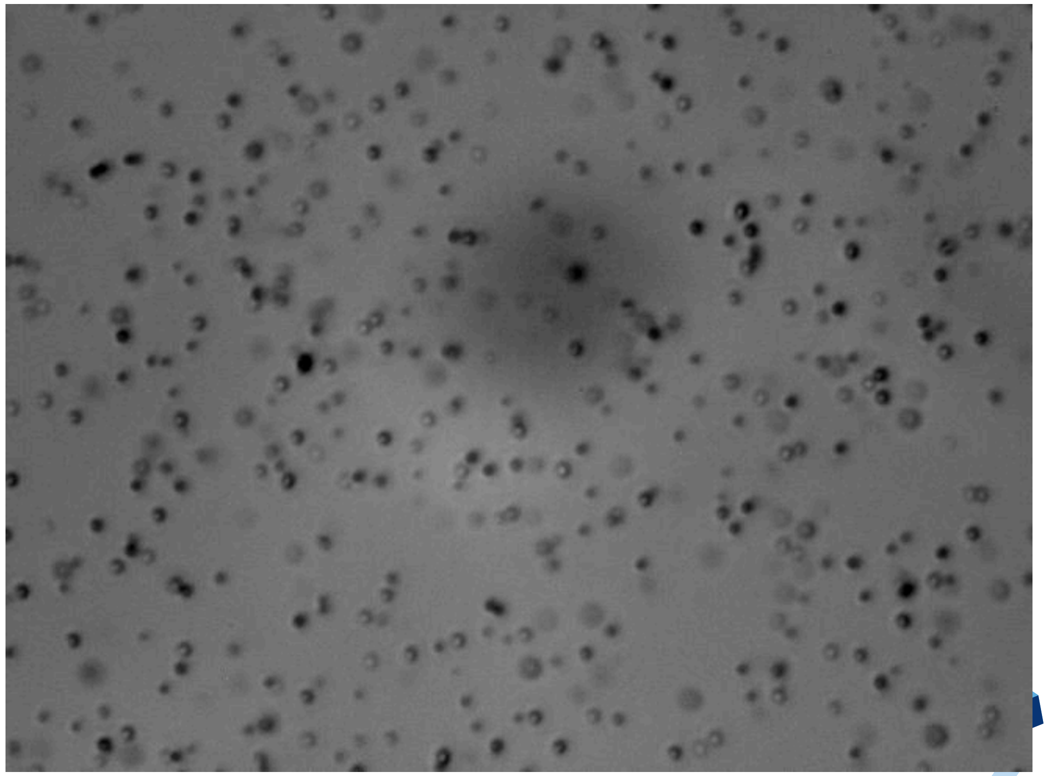




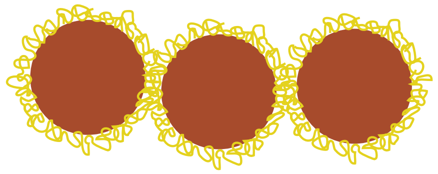
Typical magnetization curve (Dynabeads M450)

- auto-assemblage dipolaire

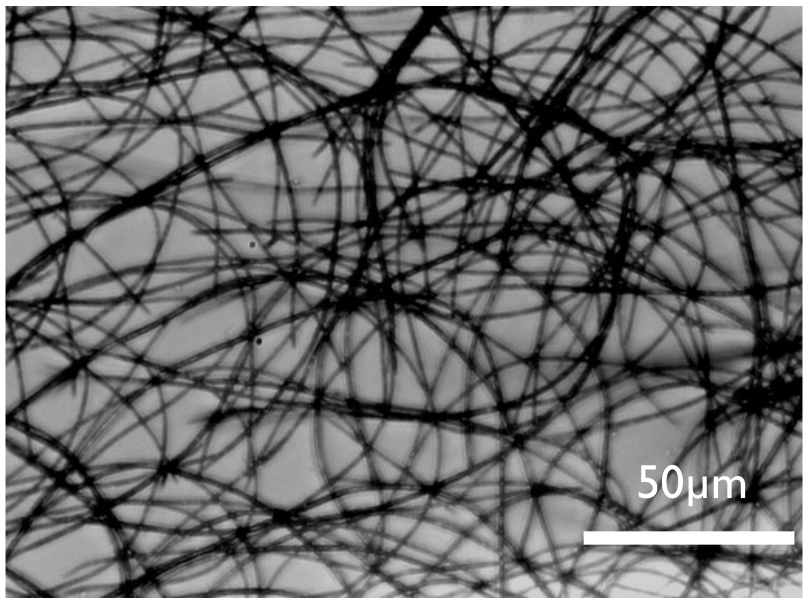


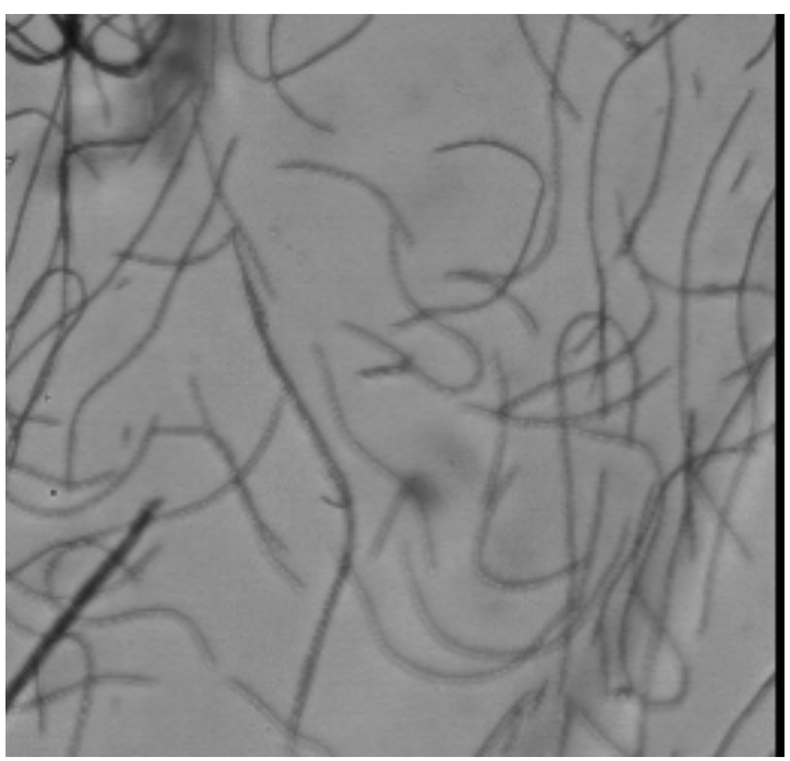


glued or not

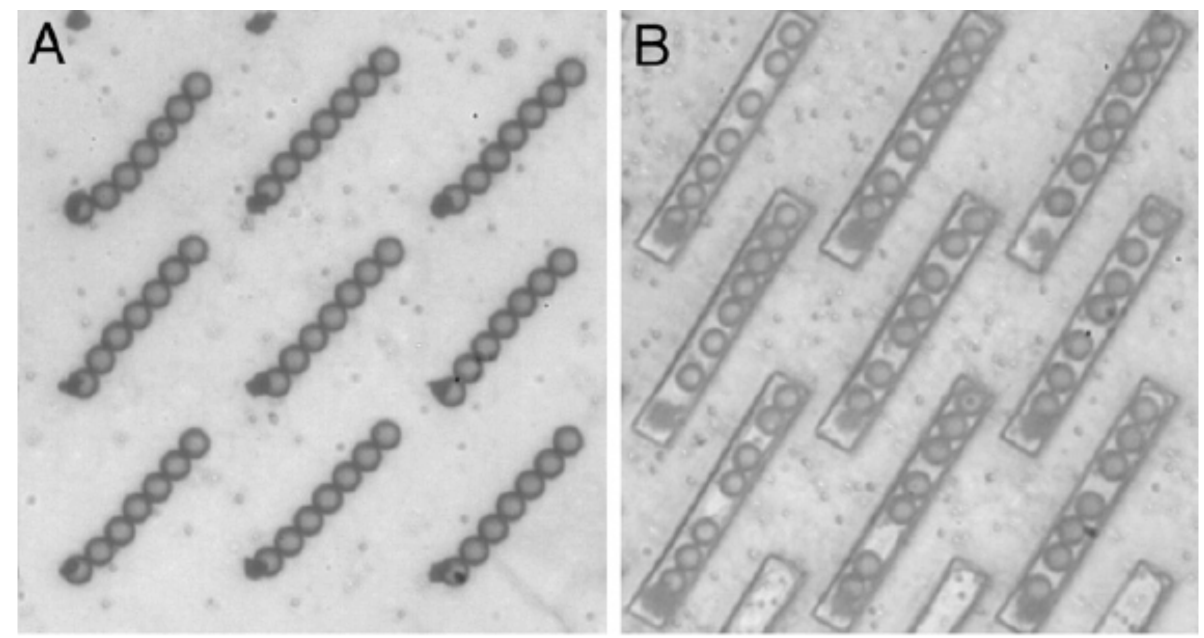
Cross linking 

- non specific adsorbtion (PAA)
- specific binding





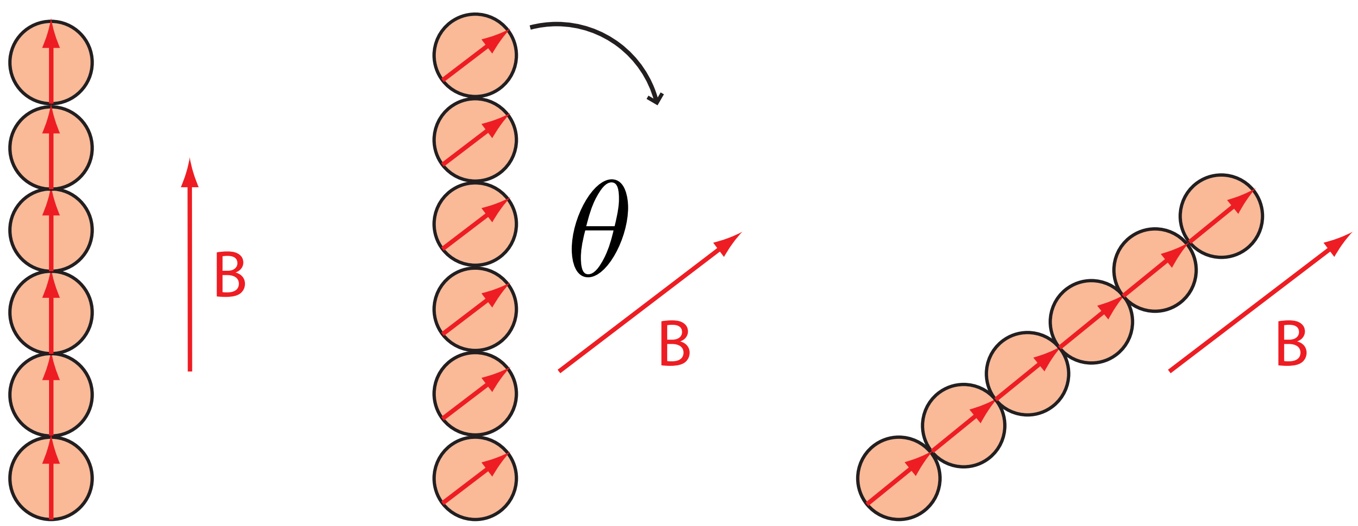
Non cross-linked particles anchored on nickel dots



*Vilfan et al. PNAS, **107**, 1844 (2010)*

bending coefficient
$K \sim 8 \times 10^{-26}$ J.m
persistence length $l_p = K/k_B T$
$l_p \sim 20$ microns

Actuation des cils superparamagnetiques



interaction dipole-dipole
entre deux colloïdes

$$E_m = \frac{\mu_o m^2}{4\pi}\left[\frac{1 - 3\cos^2\theta}{r^3}\right]$$

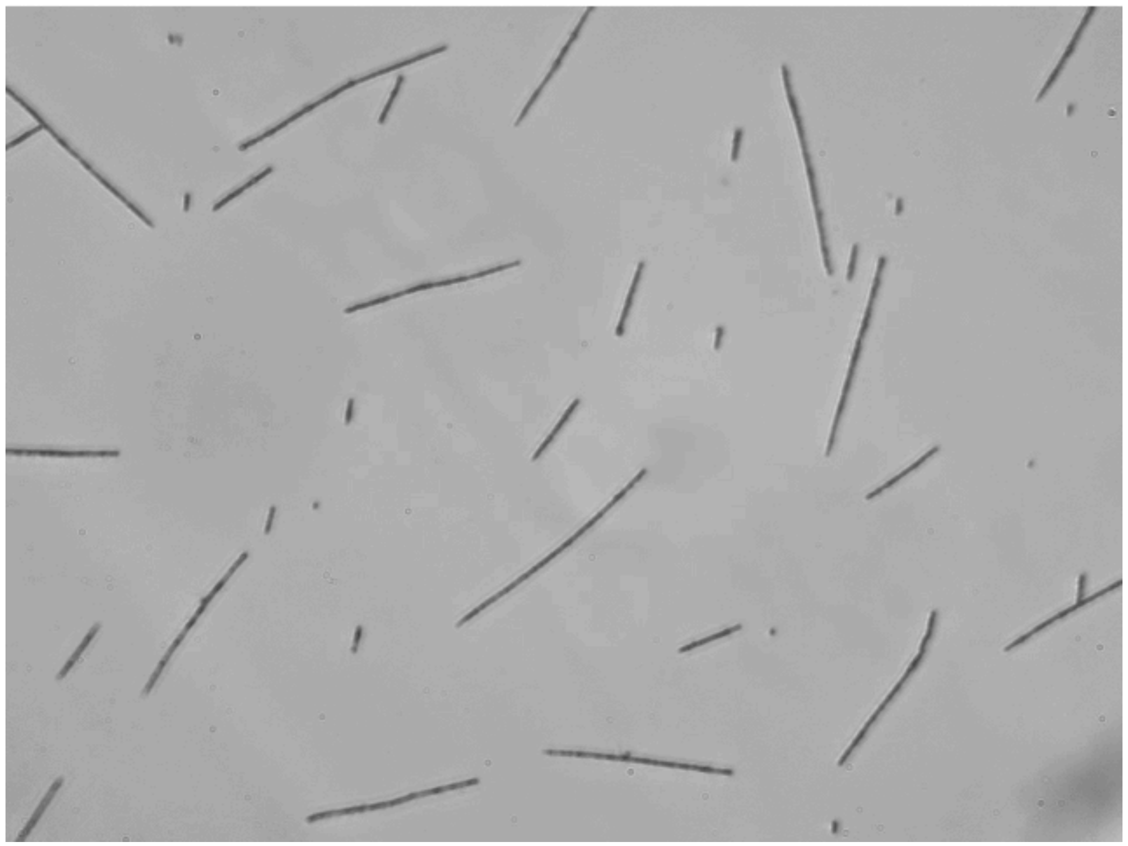
à r=a

$$E_m \propto \frac{\chi_e^2 B^2 a^3 (1 - 3\cos^2\theta)}{\mu_0}$$

couple magnétique

$$\Gamma_m = \frac{\partial E_m}{\partial \theta} \propto \frac{\chi_e^2 B^2 a^3 \sin 2\theta}{\mu_0}$$

Compétition effets visqueux/effets magnétiques



Couple visqueux :

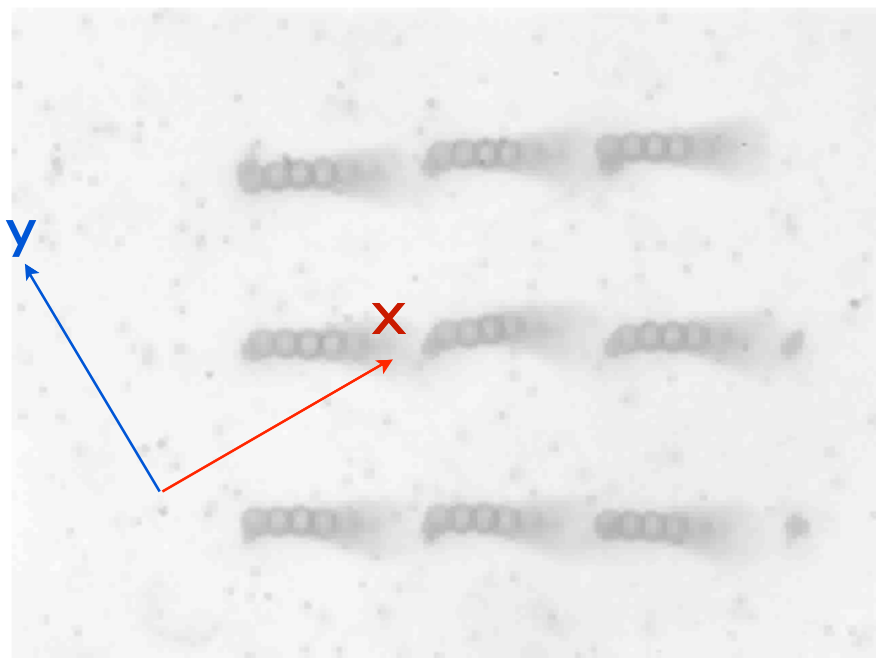
$$\Gamma_{visc} \sim \eta \omega L^3$$

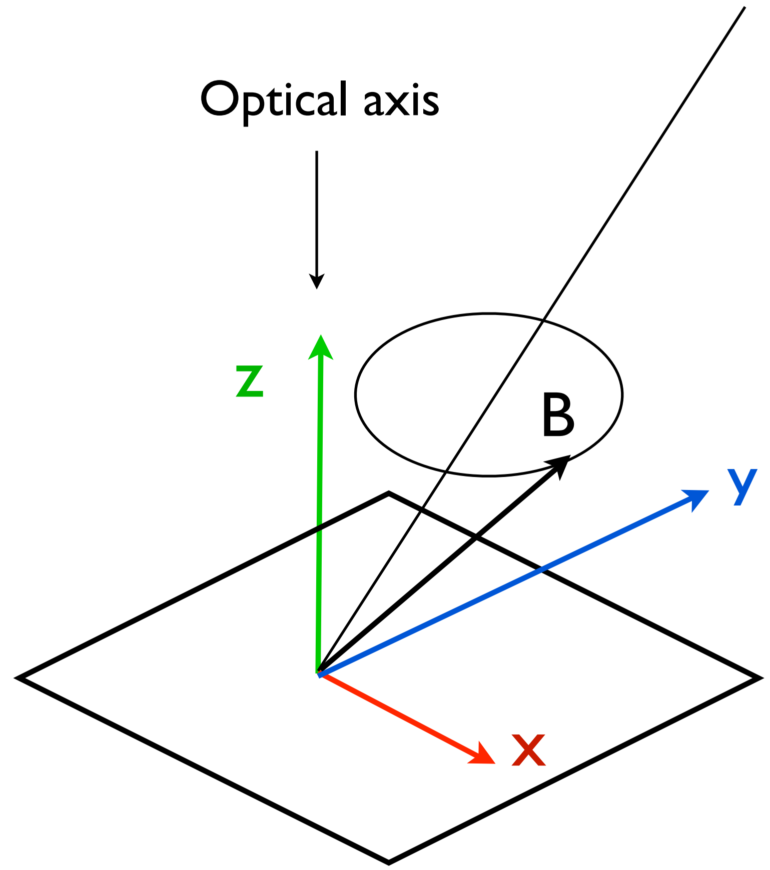
Couple magnétique :

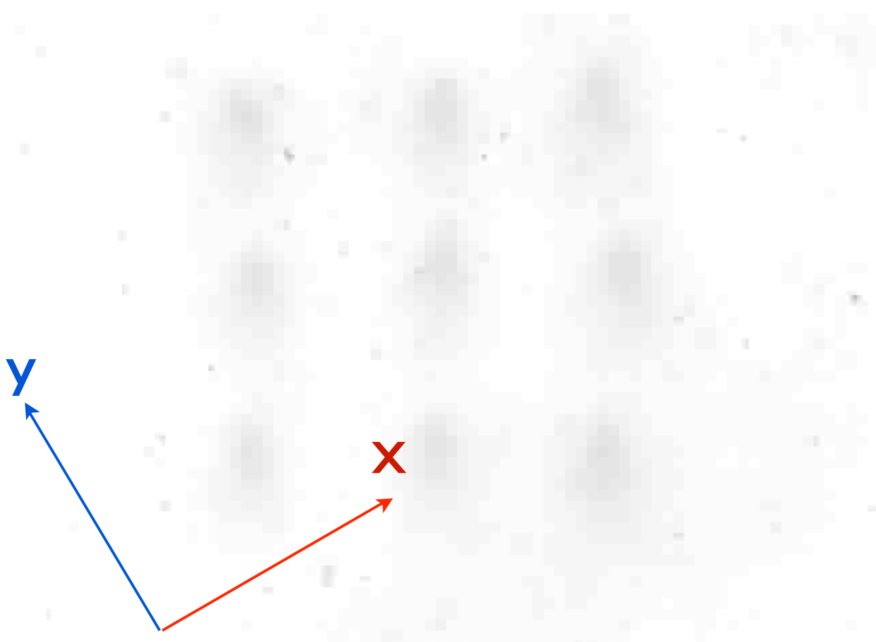
$$\Gamma_m = \frac{\partial U_{mag}}{\partial \theta} \sim \lambda k_B T \frac{L}{2a} \sin 2\theta$$

$$\text{Ł}_{mv} \sim \left(\frac{\lambda k_B T}{a \eta \omega} \right)^{1/2}$$

pumping efficiency of rotation on a tilted cone

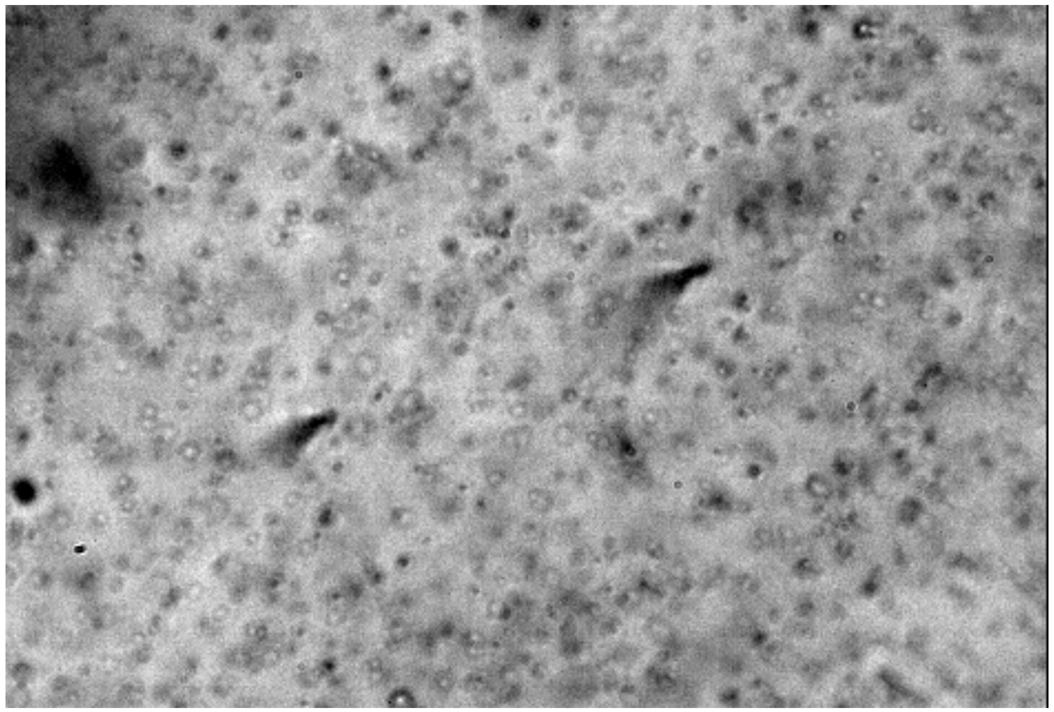


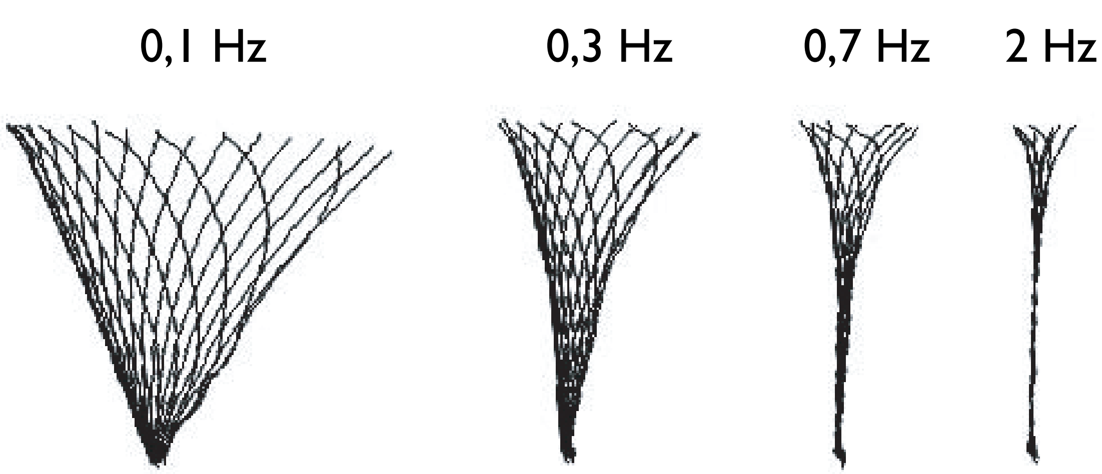


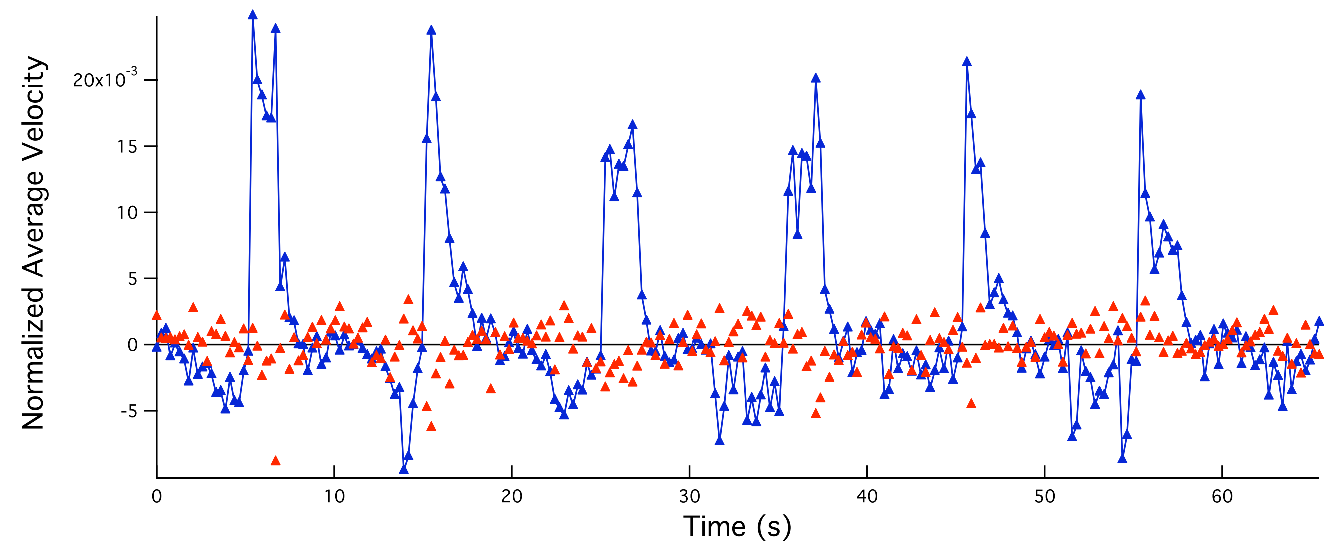


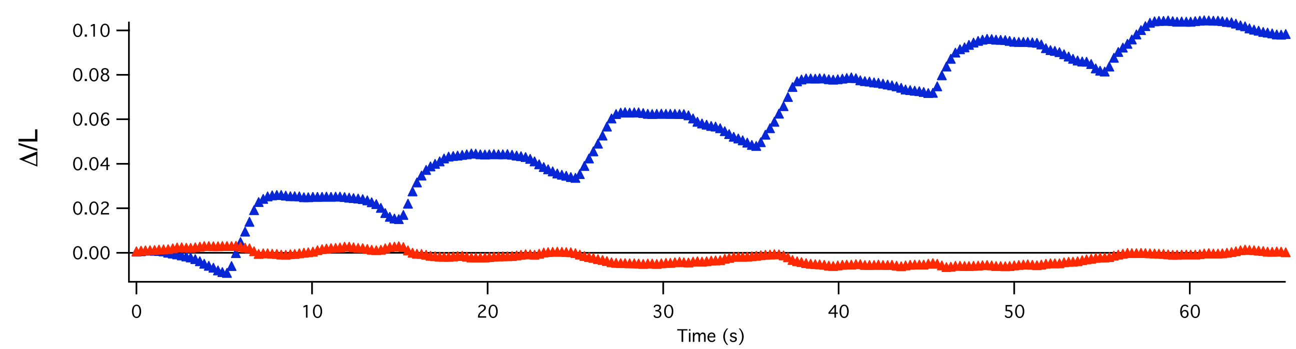
*Vilfan et al. PNAS, **107**, 1844 (2010)*

Ecoulement induit par les cils magnétiques





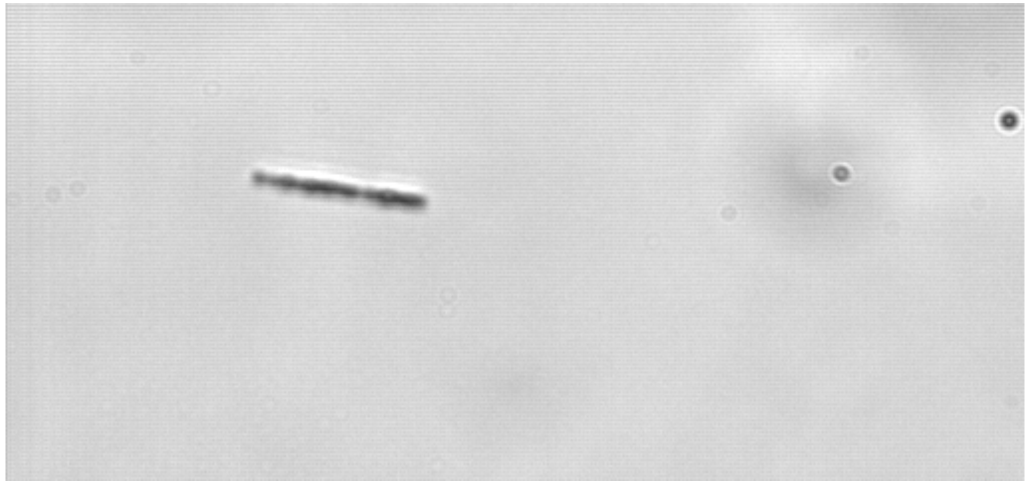


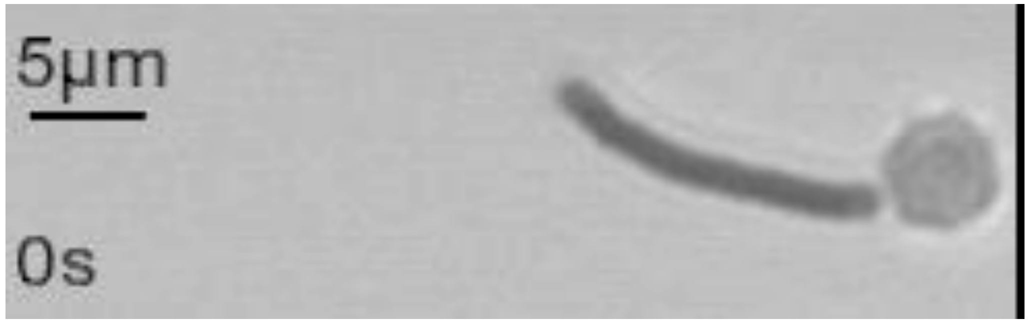


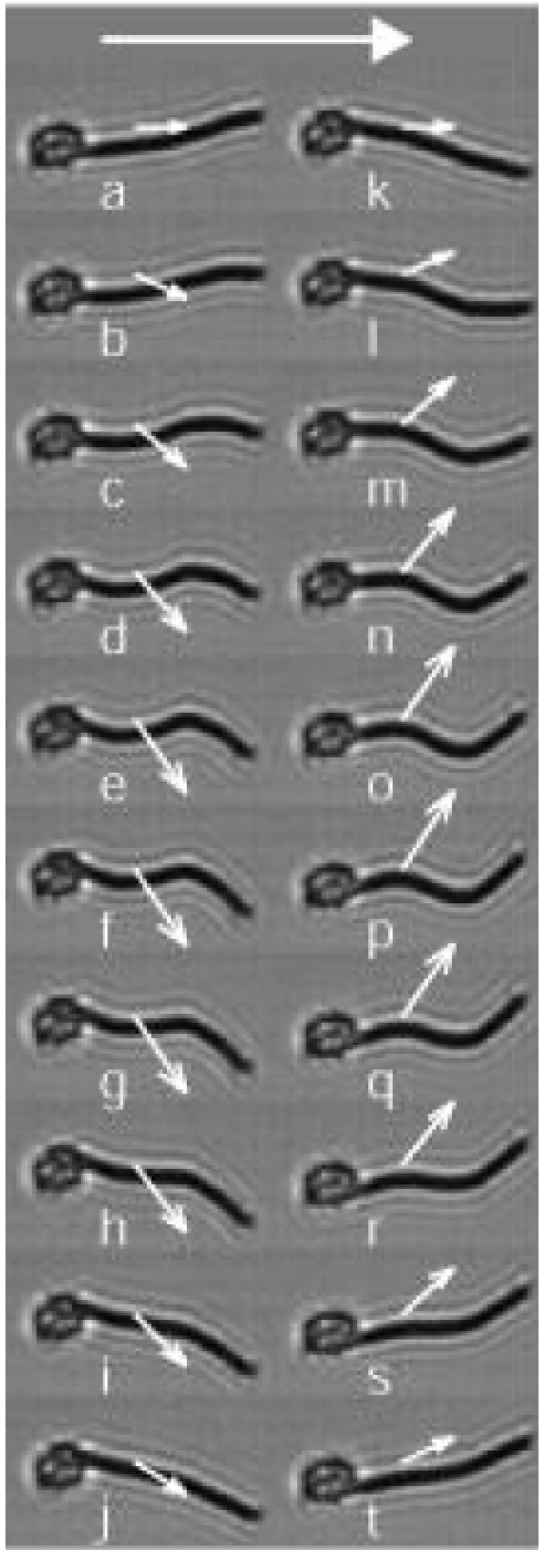
Battement asymétrique,
f+/f- = 10

A. Babataheri, M. Roper, M. Fermigier & O. du Roure, J. Fluid Mech. **678** 5 (2011)

Nageurs magnétiques

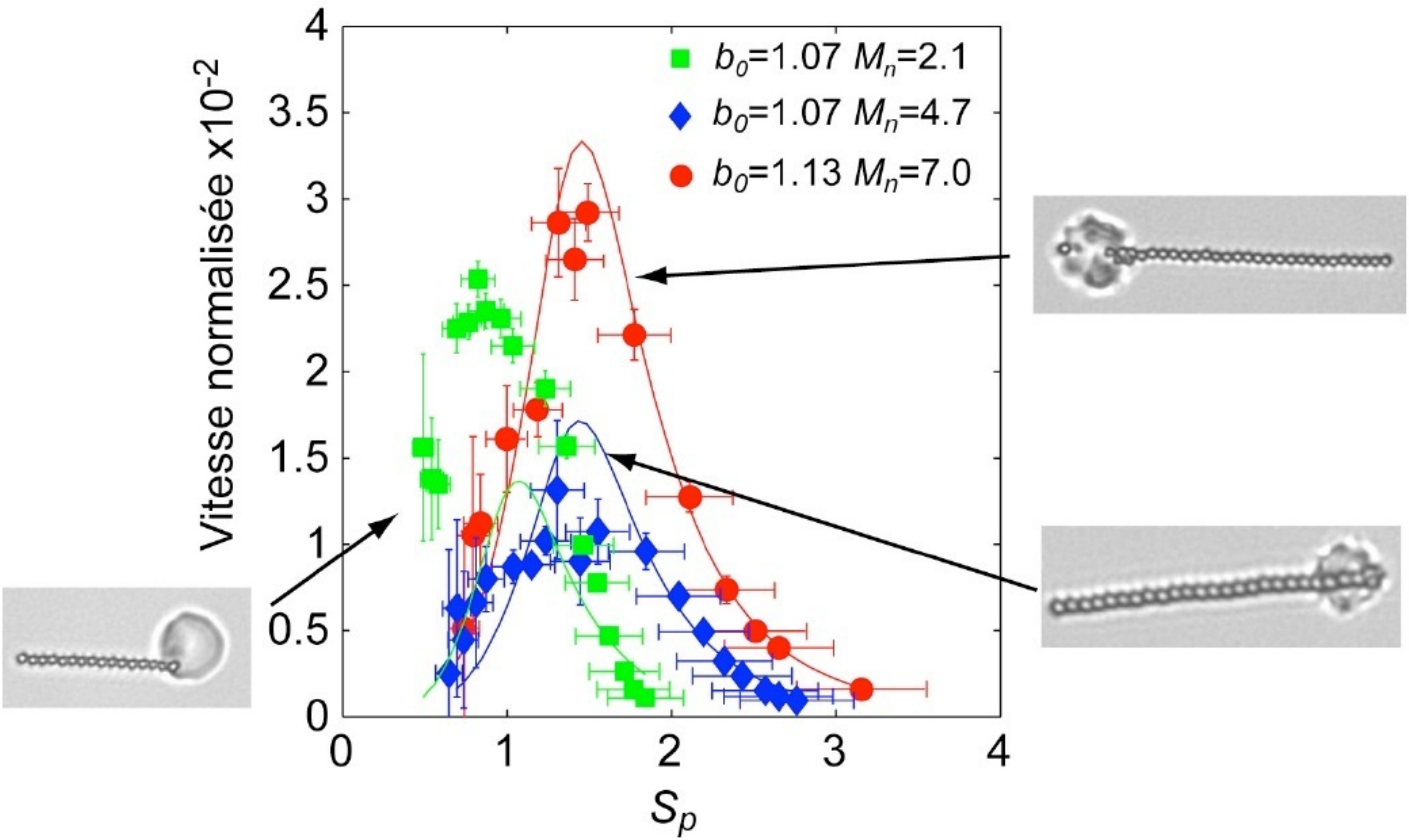


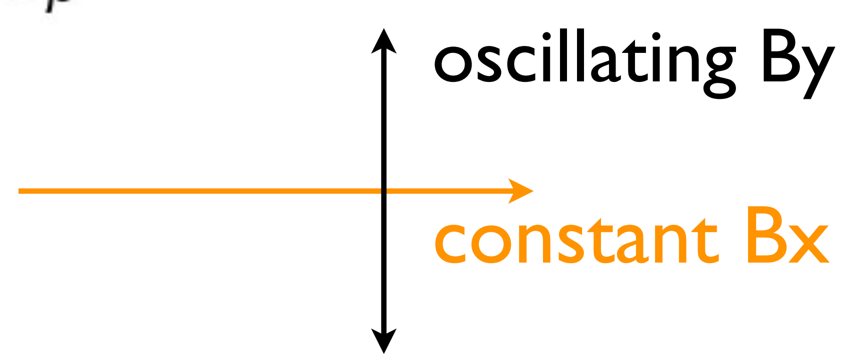




R. Dreyfus et al., Nature **437**, 862 (2005)

Efficacité de propulsion





$b_0 = |By|/|Bx|$

R. Dreyfus et al., Nature **437**, 862 (2005)