

Mécanobiologie

Physique/mécanique et fonctions biologiques

Journée UFR 25/6/2019

Un processus emblématique:

Le développement

Développement des organismes vivants

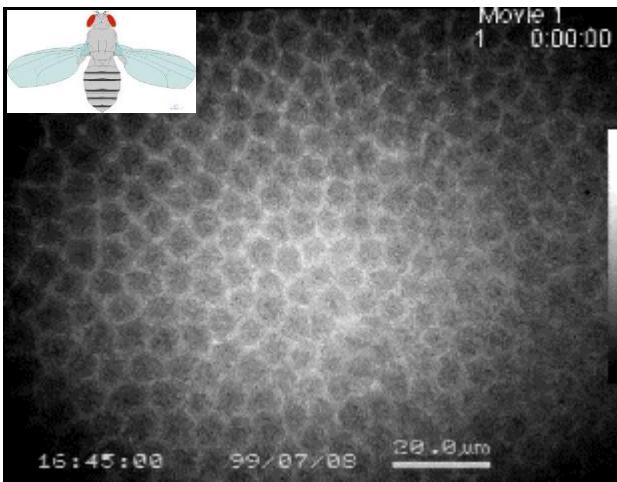
Morphogénèse

=

Contraintes mécaniques



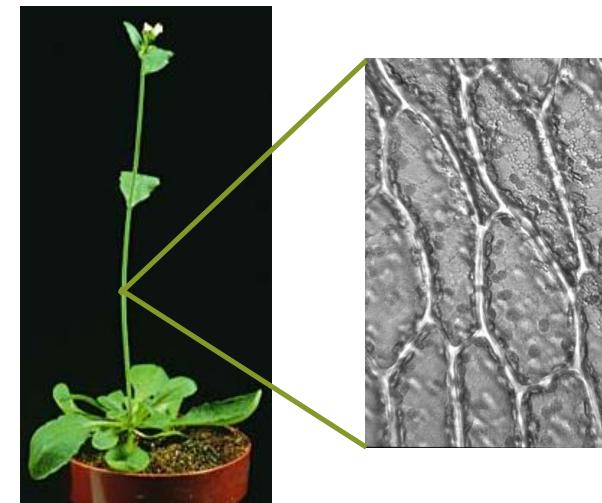
Gastrulation de l'embryon de drosophile



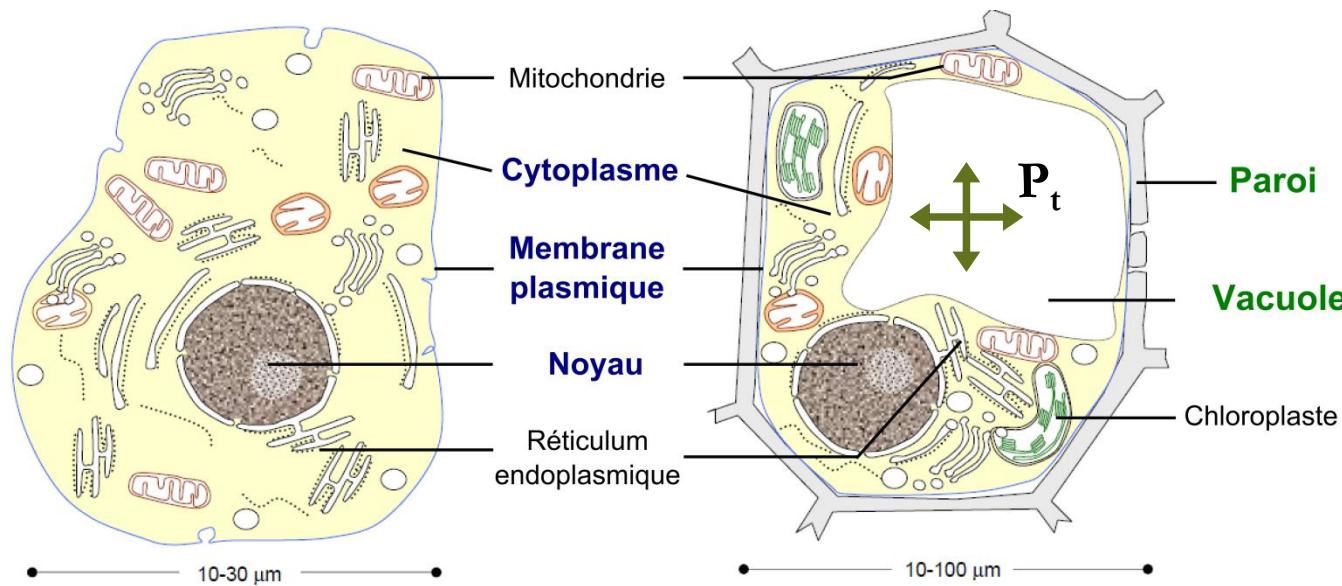
Oda and Tsukita, 2001



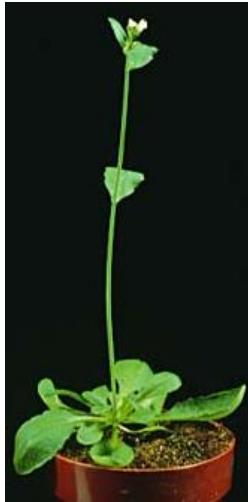
Croissance orientée des plantes



Structure des cellules animales et végétales



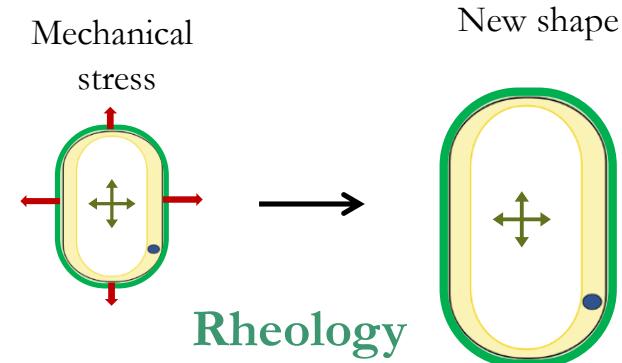
Croissance orientée (anisotrope) des plantes



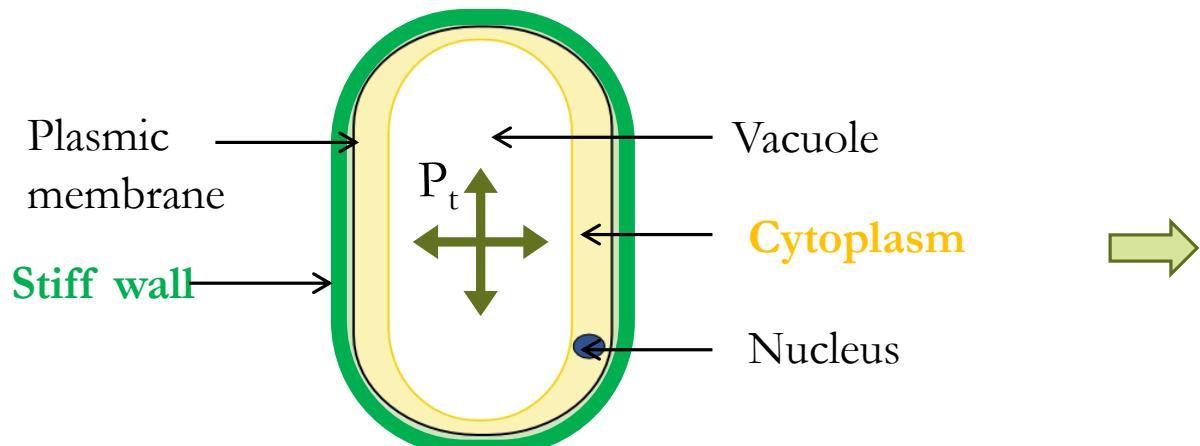
Anisotropy

Directed growth

Deformation of cells



...Mais pression isotrope !



High turgor pressure (~ 10 atm)

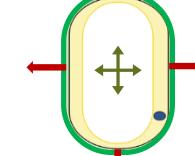
Isotropic force that drives cell growth



Directed growth

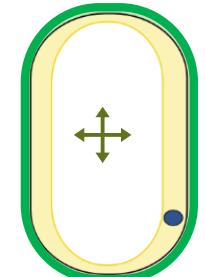
Cell wall anisotropy

Mechanical stress



Rheology

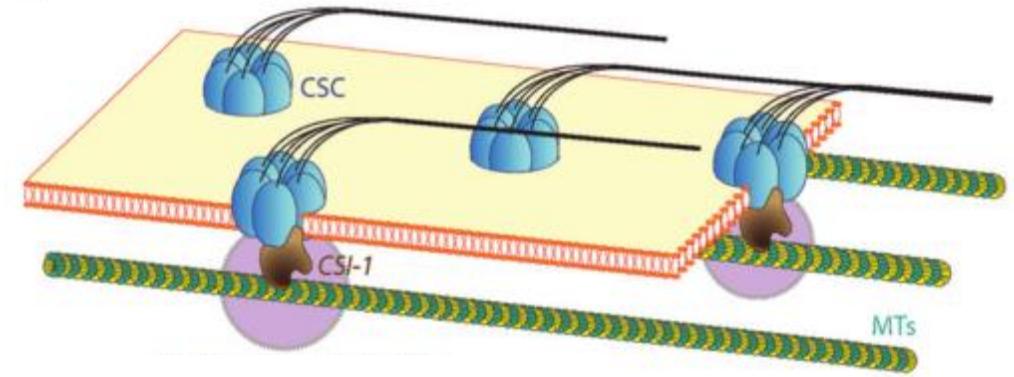
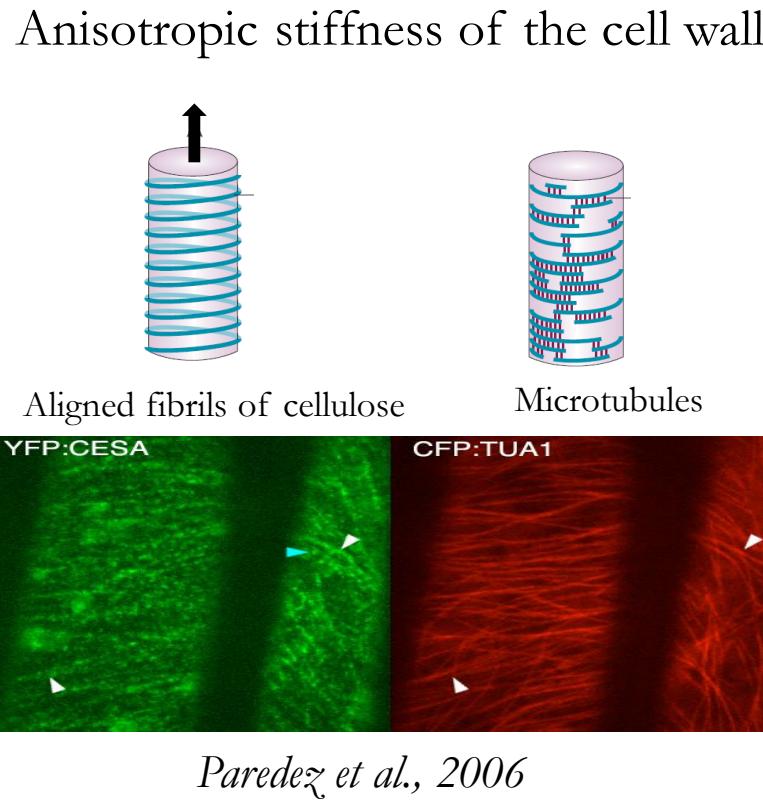
New shape



Deformation of cells

Synthèse orientée des fibres de la paroi

Mecano-sensing at the single plant cell scale



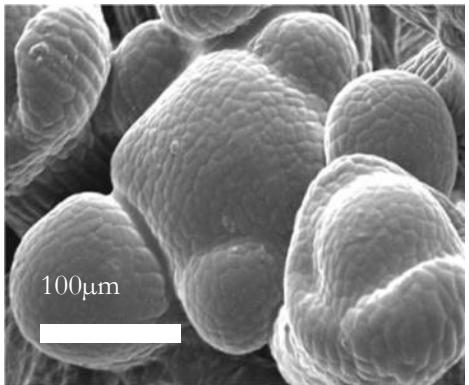
Emons et al., 2006
Landrein et al., 2013

How microtubules get this specific orientation?

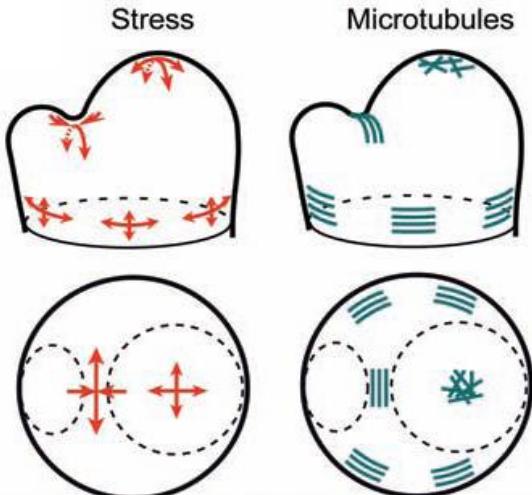
Mécano-sensibilité des microtubules

Microtubules are aligned along main axis of mechanical stress.

O. Hamant *et al.*, 2008, *Science*



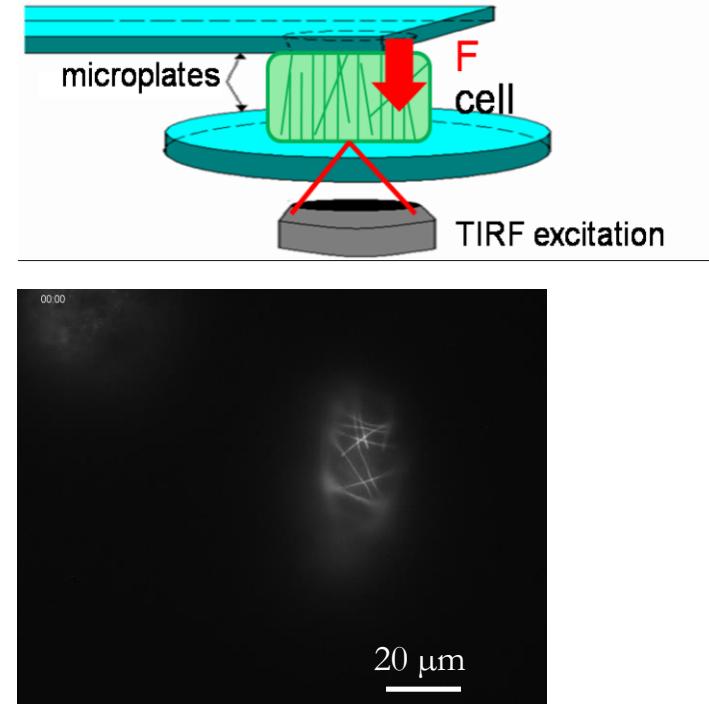
Meristem of a plant



Modelling :
getting stress distribution from shape and pressure drop

Y. Couder, A. Peaucelle

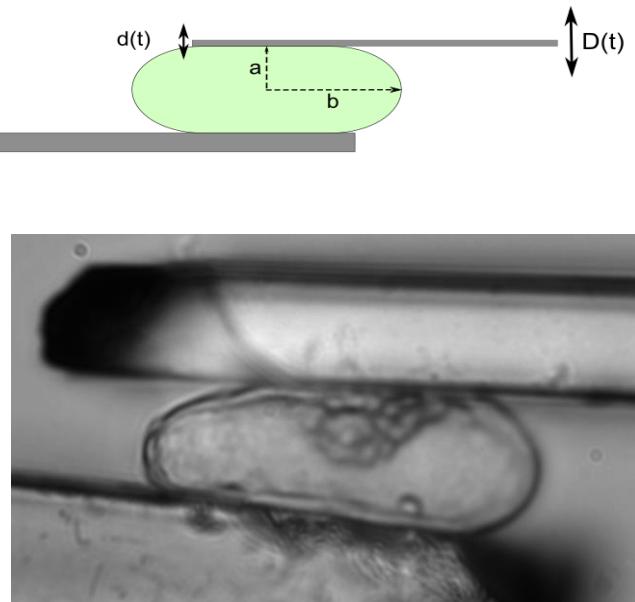
Microtubules dynamics of a cell submitted to a calibrated force:



P. Durand-Smet, A. Asnacios

Régulation de la pression de turgescence

Mesure du module complexe



$D(t)$ imposé, $d(t)$ mesuré

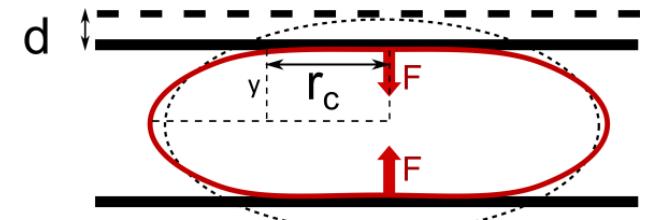
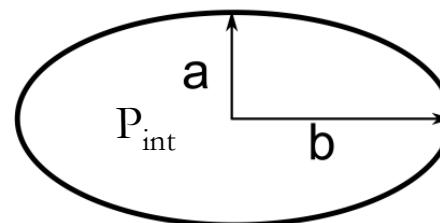
$$\sigma(t) = \frac{D - d}{S} k$$
$$\varepsilon(t) = \frac{d}{2a}$$

Module complexe

$$G^* = \frac{\sigma(t)}{\varepsilon(t)} = G' + iG''$$

Modèle de Hertz

Calcul de la pression interne des cellules végétales



- Elasticité de la coque négligeable
- $d \ll a$
- $P_{int} \sim \text{cte}$

$$\Delta P = \Pi_{int} - \Pi_{ext}$$

$$\left\{ \begin{array}{l} \Delta P = \frac{d}{a} G_0 \\ \Pi_{int} = \Pi_{ext} + \frac{d}{a} G_0 \end{array} \right.$$

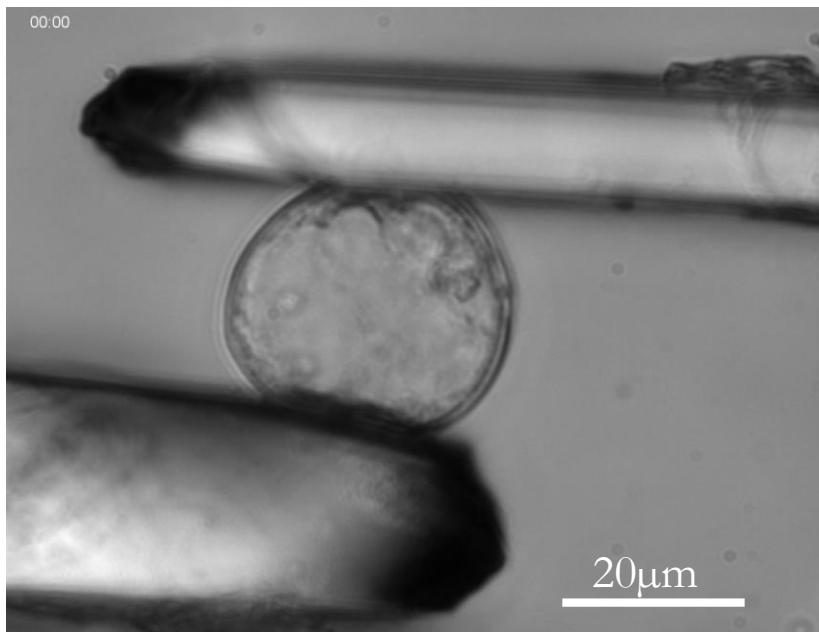
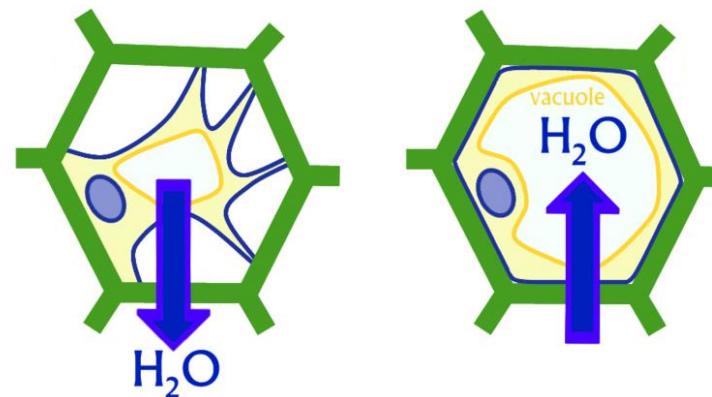
Régulation de la pression de turgescence

1M mannitol

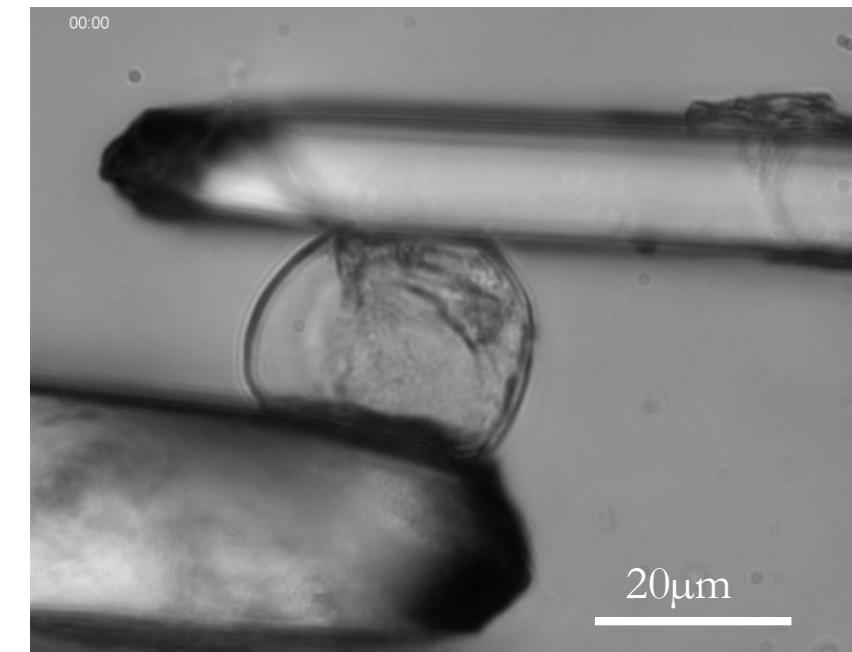
External osmolarity

Pure water

Plasmolyzed cell



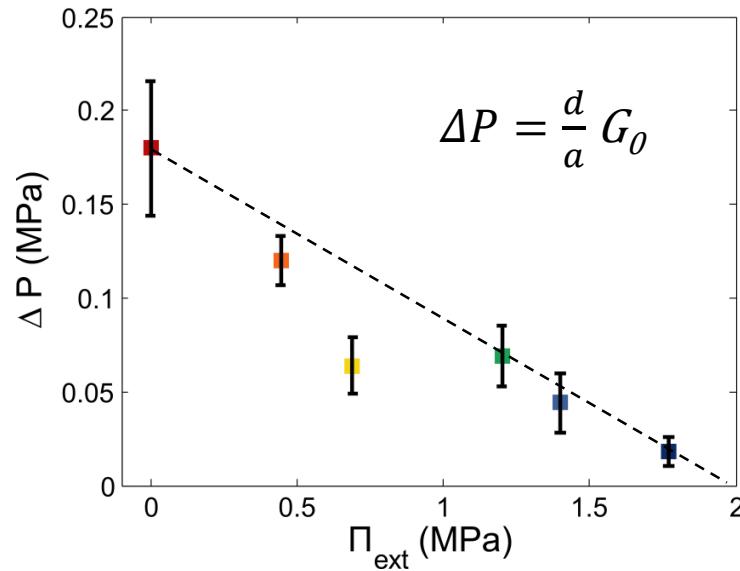
Turgid cell
 $P_t \sim 1 \text{ MPa}$



20µm

20µm

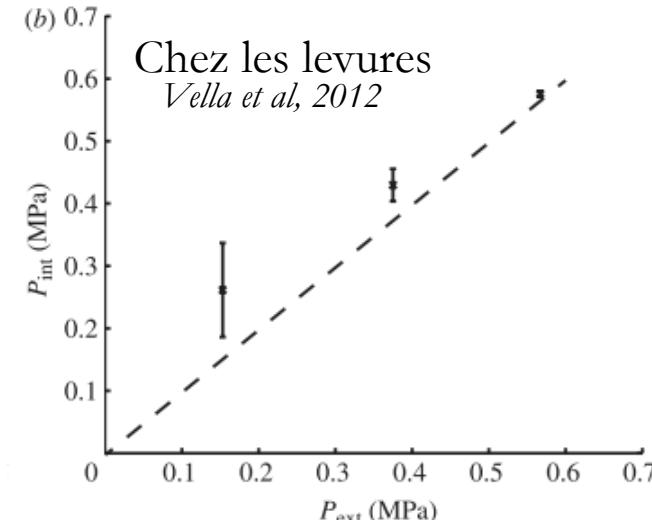
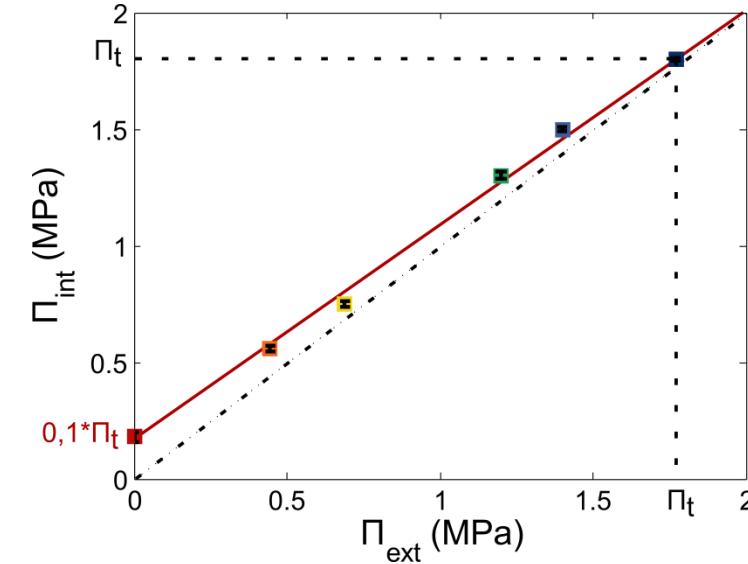
Régulation de la pression de turgescence



Pression de turgescence: $P_t = \Delta P$
dans l'eau ~ 0.2 MPa

- canaux mécano-sensibles ?
- aquaporines ?
- synthèse d'amidon ?

$$\Pi_{int} = \Pi_{ext} + \frac{d}{a} G_0$$

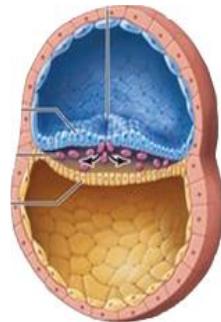
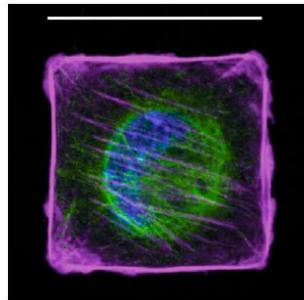
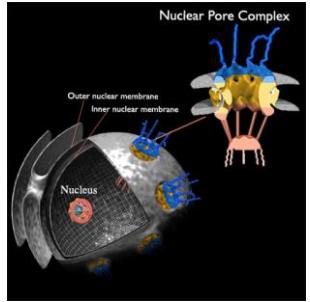


Chez les levures
Vella et al, 2012

La mécano-biologie à...

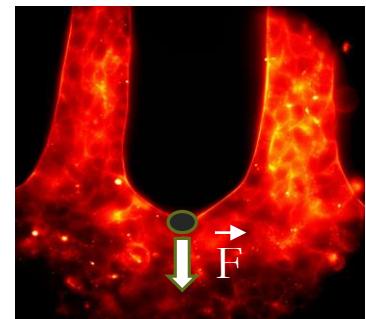
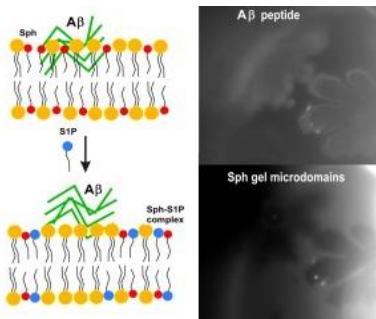
MSC

Des pores nucléaires à l'organisme



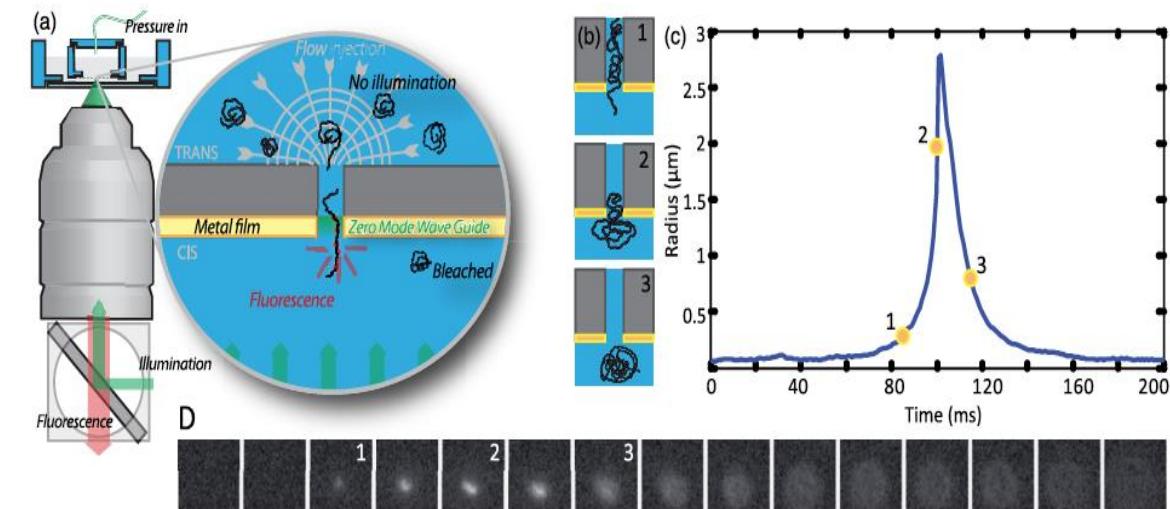
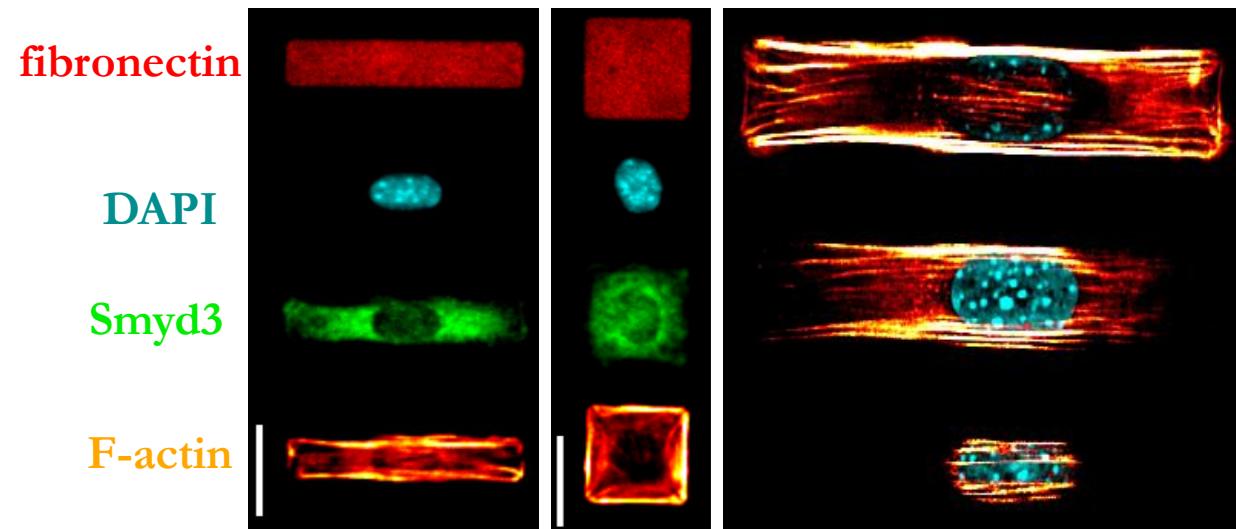
nm

m



Translocation de polymères au travers de nanopores

- Géométrie cellulaire et translocation de facteurs épigénétiques
- Translocation de polymères au travers de nanopores



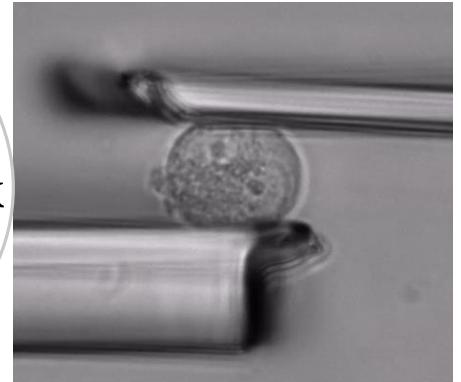
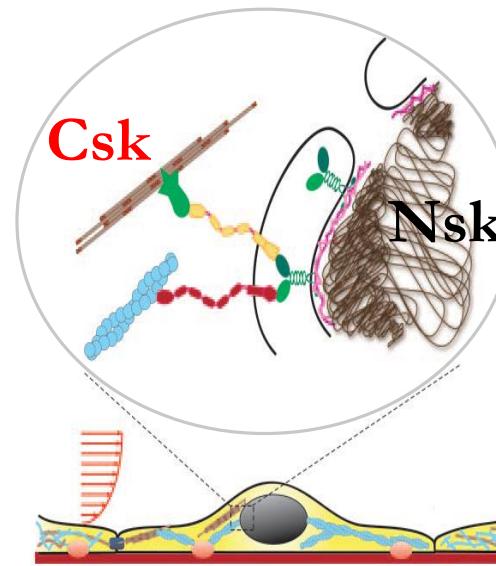
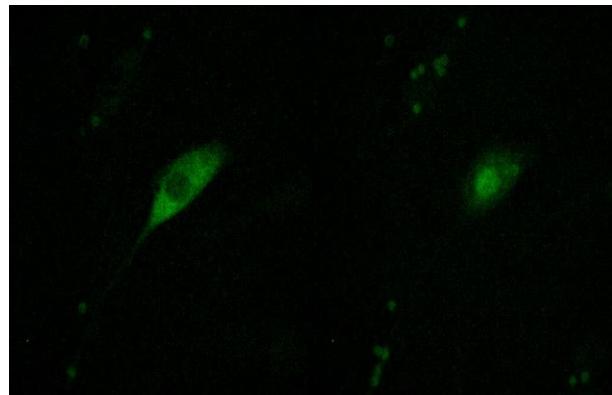
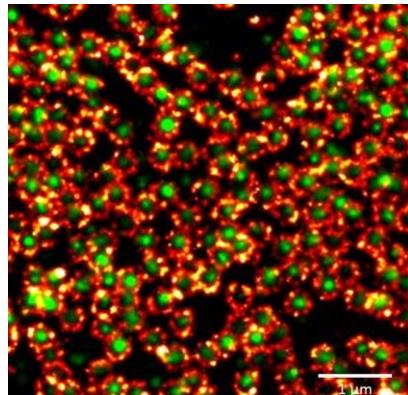
Chercheurs impliqués : S. Hénon, A. Richert - L. Auvray, G. Charron, J.-M. Di Meglio, F. Montel.

Non permanents : L. Montel, D. Pereira - T. Auger.

Collaborations : A. Sotiropoulos (I. Cochin), J. Weitzman (UFR de Biologie, P7) - J. Mathé (U. Évry), V. Viasnoff (N. U. Singapore), O. Faklaris, M. Penrad-Mobayed (IJM), C. Dargemont (Hôpital Saint Louis), T. Talisman (City of Hope, USA, CA), P. Guégan (P6), J.-C. Lacroix (P7), J. Gierak (C2N, Marcoussis).

Signalisation à la paroi nucléaire

- Translocation des polymères au travers des pores nucléaires
- Translocation mécano-sensible dans la cellule musculaire
- Mécano-transduction à l'interface Csk-Nsk chez les plantes

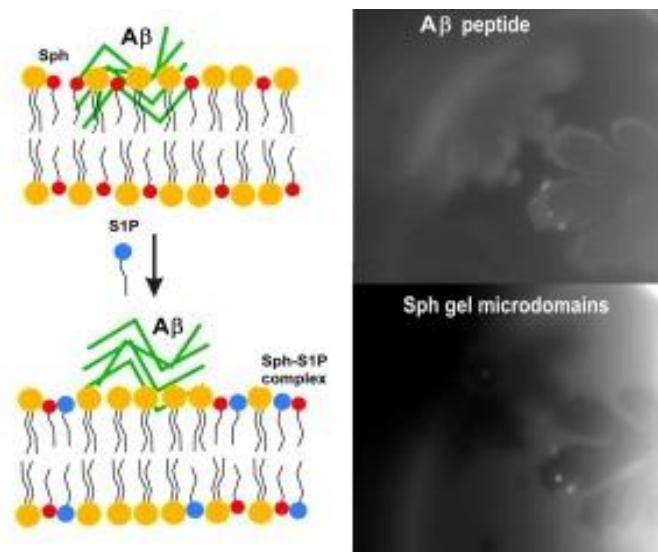
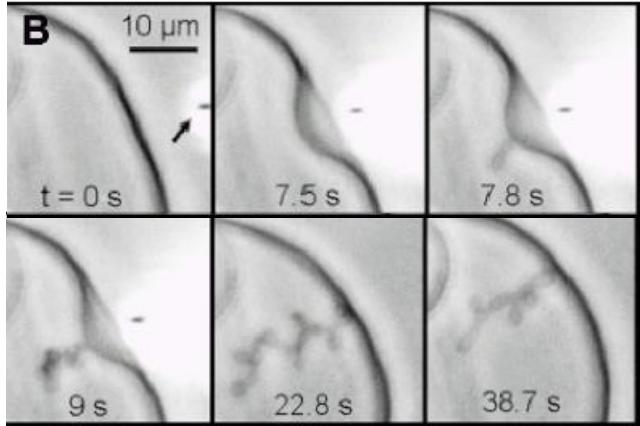


Chercheurs impliqués : A. Asnacios, J.-M. Di Meglio, F. Gallet, S. Hénon,

Collaborations : F. Montel (ENS Lyon) - Delphine Delacour (IJM) - M.-E. Chabouté (IBMP, Strasbourg), O. Hamant (ENS Lyon).

Des radeaux lipidiques à la maladie d'Alzheimer

- Rafts, déformation de vésicules géantes et structure des mitochondries
- Peptides membranaires et maladie d'Alzheimer



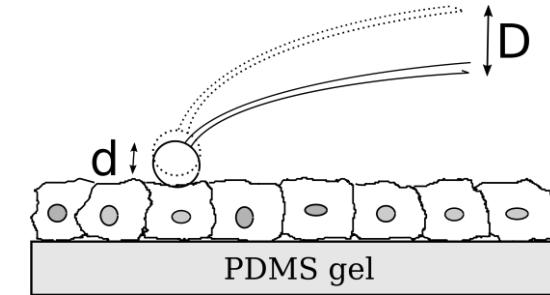
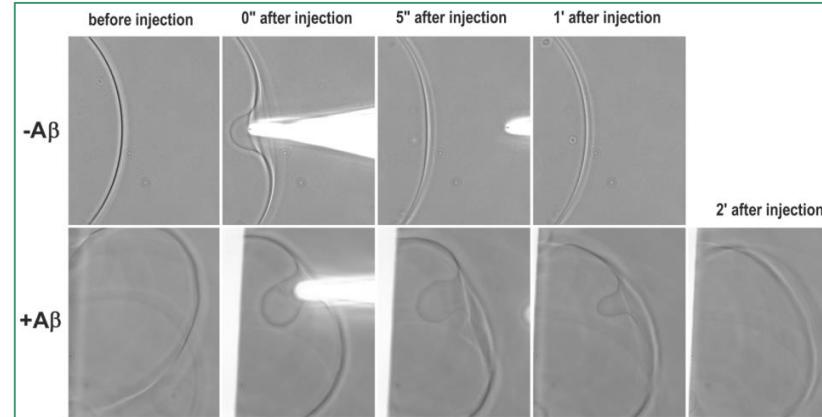
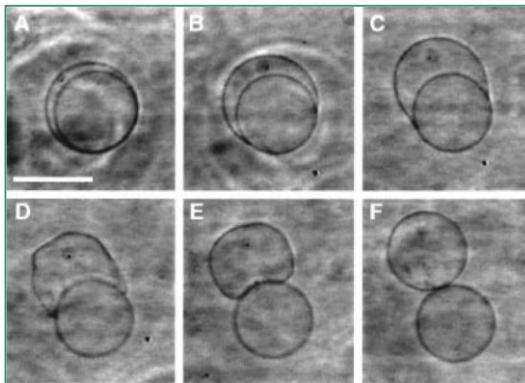
Chercheurs impliqués : M. Angelova, J.-B. Fournier, P. Galatola, N. Puff, M. Seigneuret.

Non permanents : A.-F. Bitbol, N. Khalifat, C. Watanabe .

Collaborations : G. Staneva (IBBE, Sofia), M. Arroyo (U. Barcelone), M. Imai (Tohoku U., Sendai), R. Jockers (I. Cochin), D. Tareste (IJM).

Membranes biomimétiques, mécanique cellulaire et Alzheimer

- Cellule minimale par couplage de vésicules lipidiques et stimuli chimiques
- Toxicité mécanique et maladie d'Alzheimer

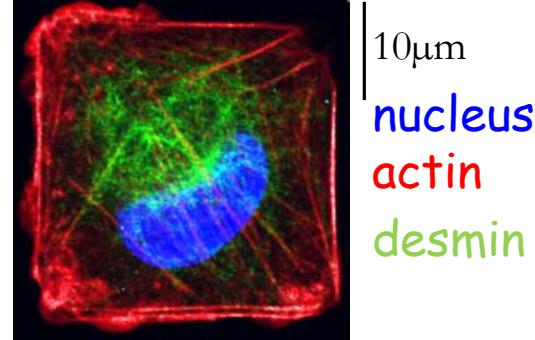


Chercheurs impliqués : M. I. Angelova, N. Puff, M. Seigneuret, A. Asnacios; J.-B. Fournier, P. Galatola.

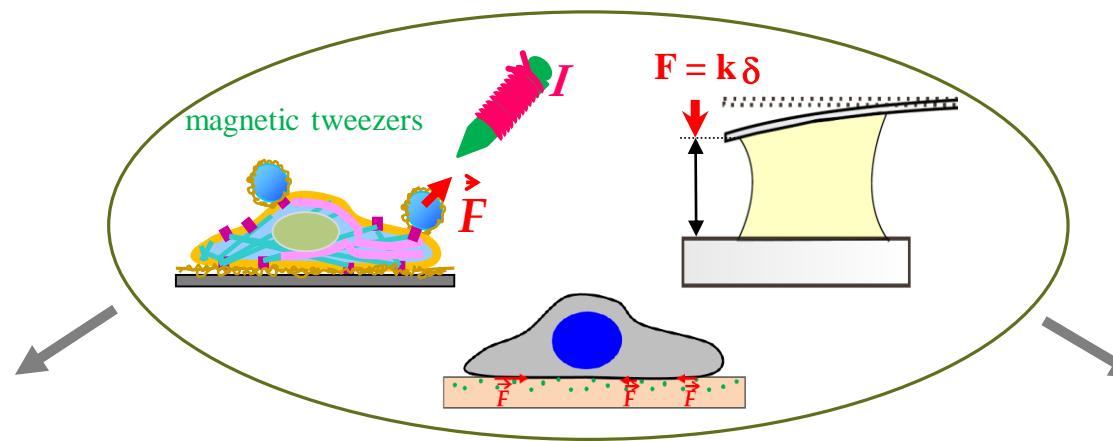
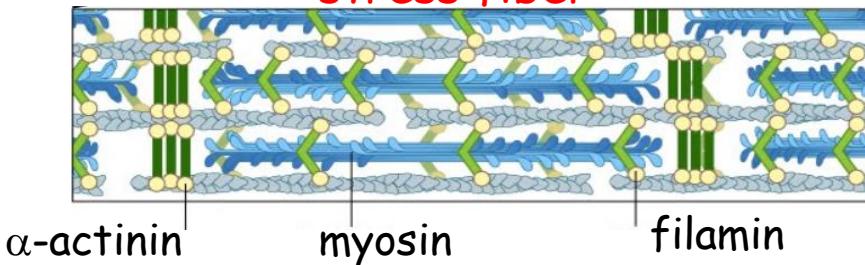
Collaborations : A. Yamada (ENS, Dpt. Chimie), G. Staneva (IBBE, Sofia), M. Imai, Y. Sakuma (Tohoku U., Sendai) & S.Komura (Tokyo Metropolitan U., Japan).

Mécanique, fonctions cellulaires et pathologies

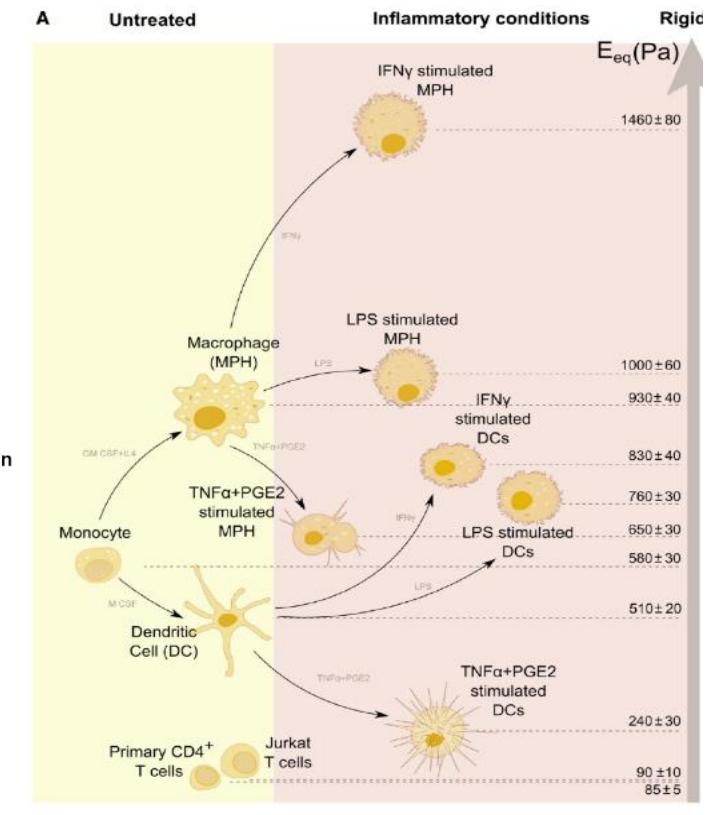
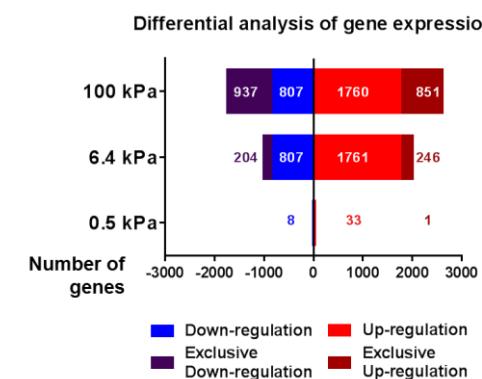
- Relation structure/force et desminopathies



stress fiber



- Inflammation et rigidité cellulaire



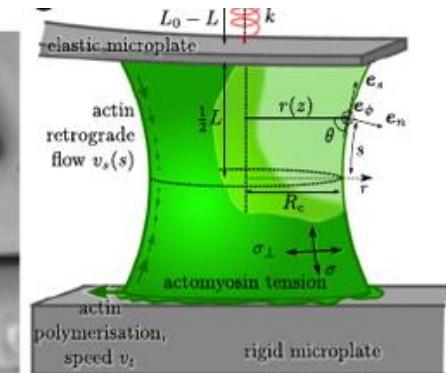
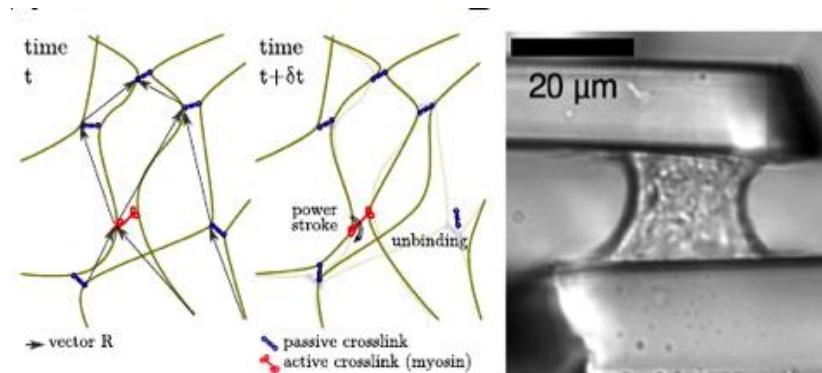
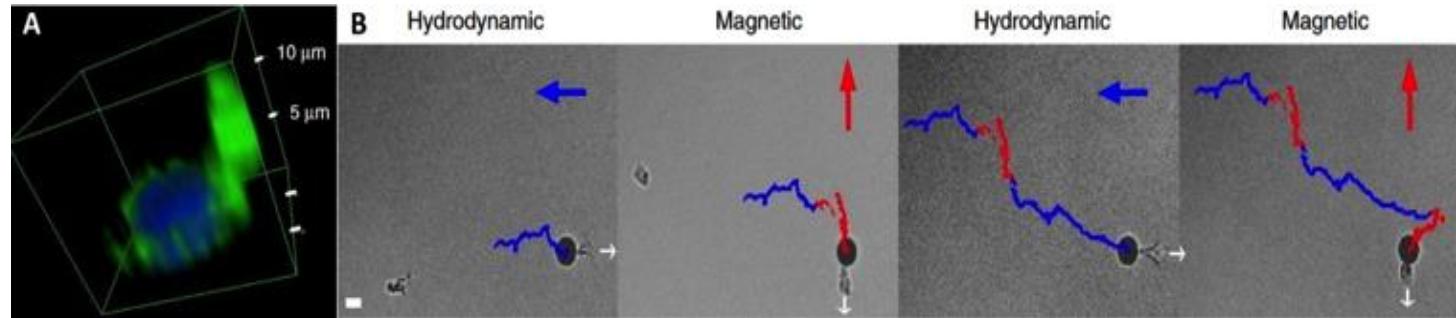
Chercheurs impliqués : A. Asnacios, F. Gallet, S. Hénon, A. Richert.

Non permanents : N. Buñi, E. Charrier, L. Montel, M. Saitakis.

Collaborations : S. Batonnet-Pichon, P. Vicart (BFA, Paris 7), M. Balland (LiPhy, Grenoble), C. Hivroz (I. Curie).

Aspects physiques de la mécano-sensibilité cellulaire

- Cellule qui remonte le courant par effet gouvernail
- Réponse à la rigidité reproduite par le comportement d'un gel de polymères semi-flexibles à liens actifs.
- Angle de contact contrôle la croissance des adhésions focales



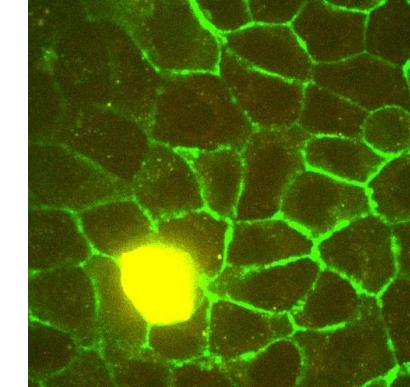
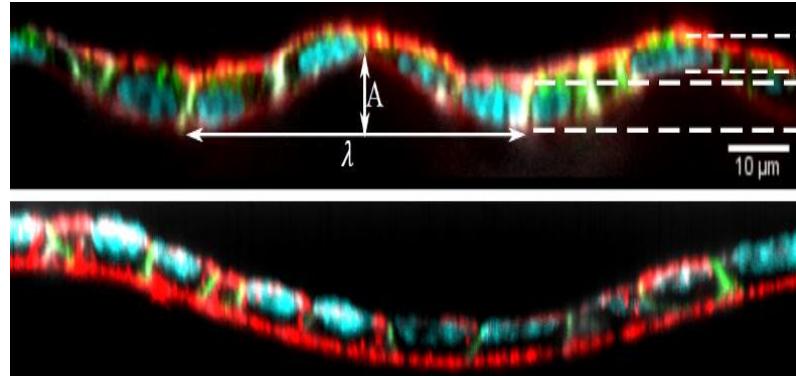
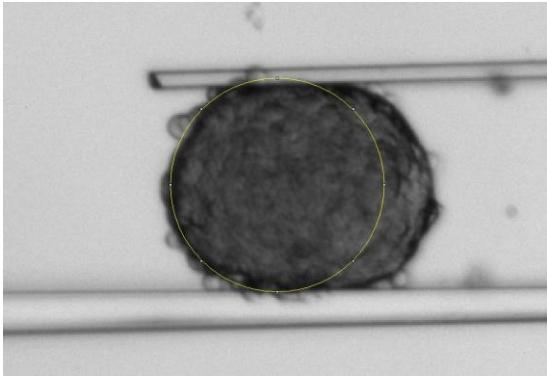
Chercheurs impliqués : A. Asnacios, O. Cardoso, F. Gallet, S. Hénon, A. Richert.

Non permanents : A. Proag, J. Fouchard, N. Buñi, P. Durand.

Collaborations : O. Theodoly et M.-P. Valignat (LAI, Marseille), J. Etienne (LiPhy, Grenoble).

Mécanique des tissus

- Mécanique des agrégats cellulaires : propriétés émergentes, cancer
- Organisation des épithéliums, Cartographie des contraintes dans un tissu vivant, et développement



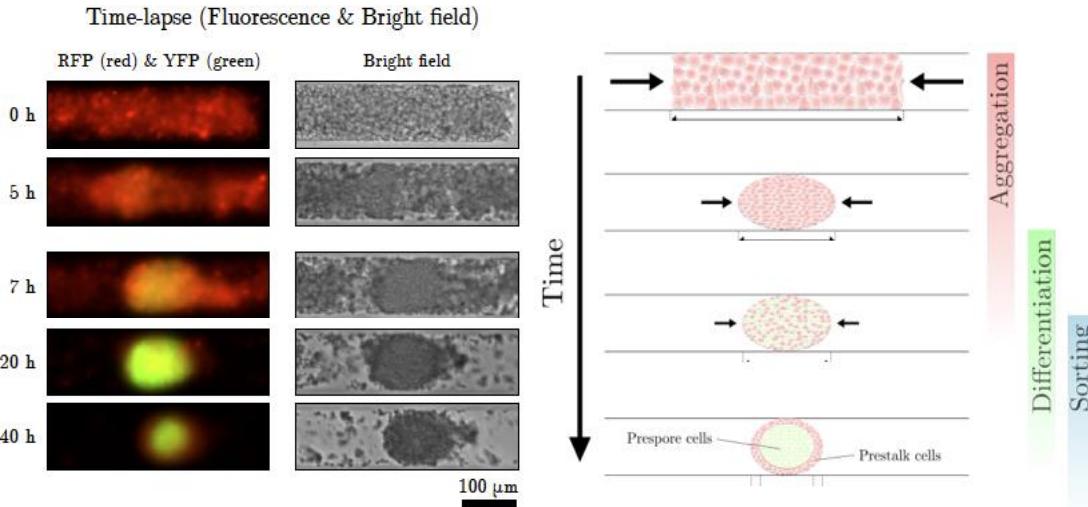
Chercheurs impliqués : A. Asnacios, F. Gallet, S. Hénon, C. Wilhelm, F. Gazeau, F. Graner, A. Cornelissen, C. Gay.

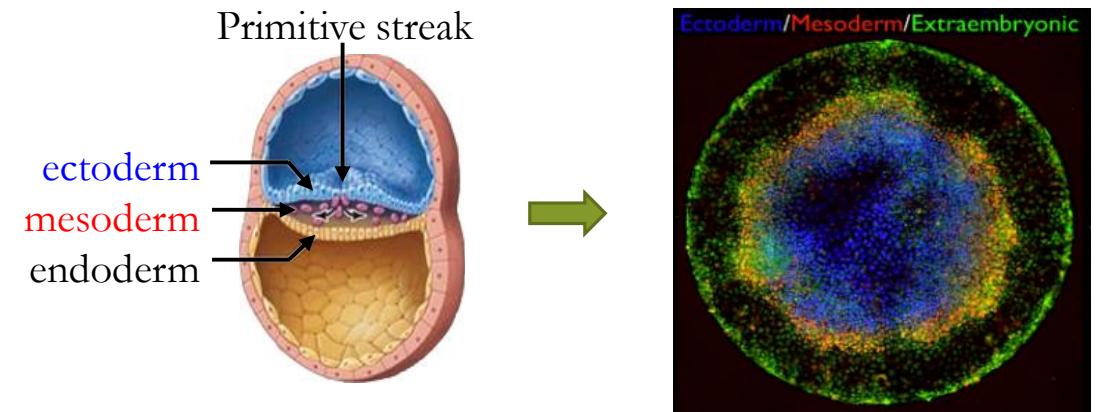
Non permanents : N. Harmand, A. Souchaud,

Collaborations : P. Nassoy (U. Bordeaux), D. Vignjevic (institut Curie), Delphine Delacour (IJM).

Auto-organisation et morphogénèse

- Auto-organisation de colonies de *Dictyostelium*
- Auto-organisation des colonies Cellules souche embryonnaires humaines (hESC)





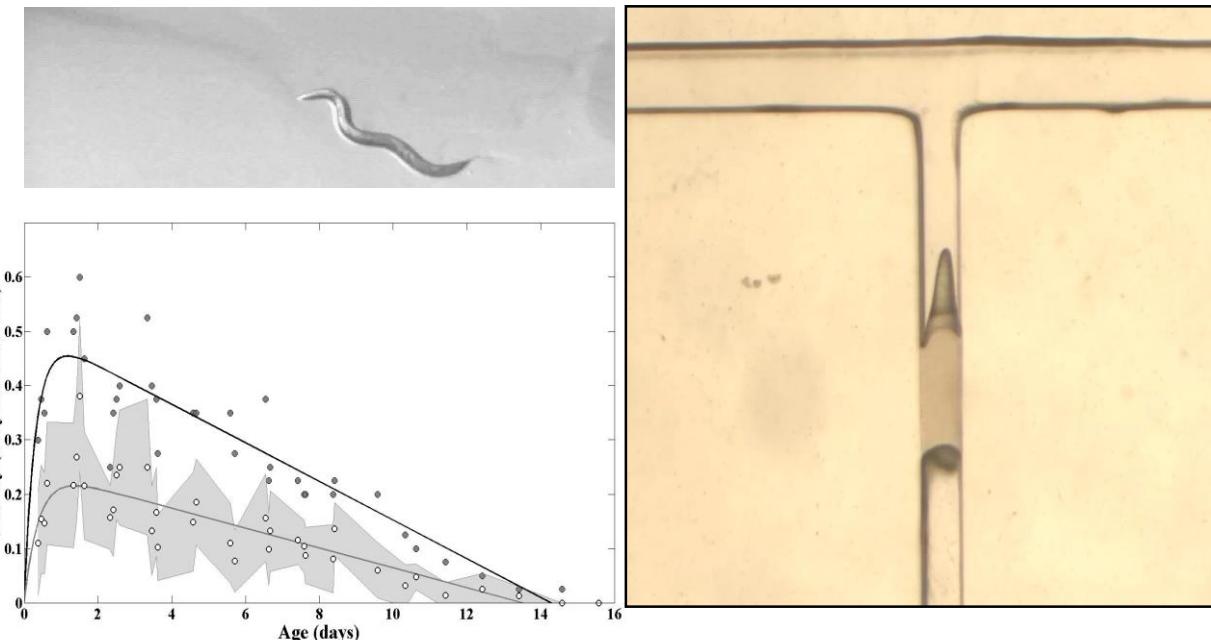
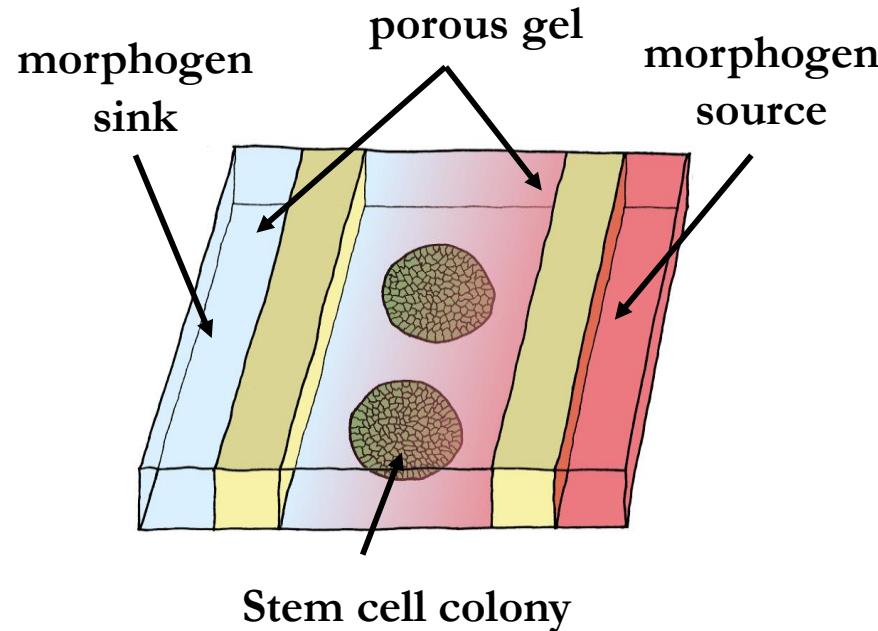
Chercheurs impliqués : Benoit Sorre, Jean-Marc Di Meglio, Pascal Hersen.

Non permanents : Sara Bonavia, Jean Louis Plouhinec, Tom Wyatt.

Collaborations : Jérôme Collignon (IJM), Alexandre Kabla (U. Cambridge), Clément Nizak (ESPCI).

Environnements contrôlés : auto-organisation, mouvements collectifs et prise de décision

- colonies de cellules souches embryonnaires humaines : physique + biochimie
- Vieillissement, locomotion, prise de décision



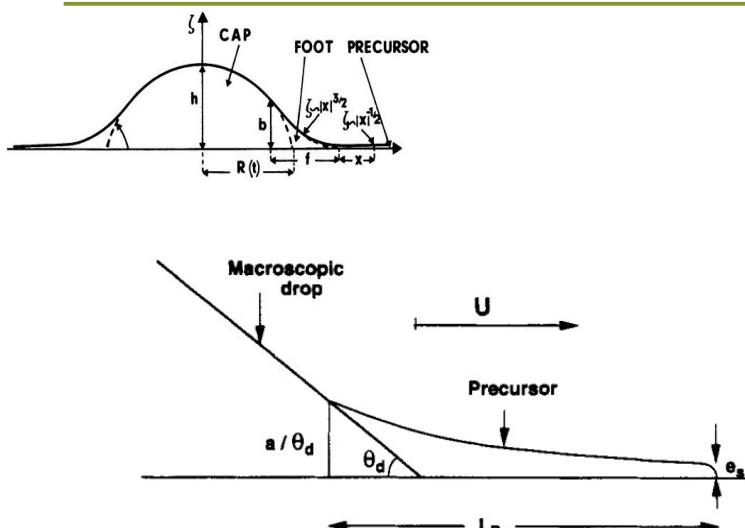
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Collaborations : Jérôme Collignon (IJM), Alexandre Kabla (U. Cambridge), Clément Nizak (ESPCI) - Pierre-Paul Vidal (P 5).

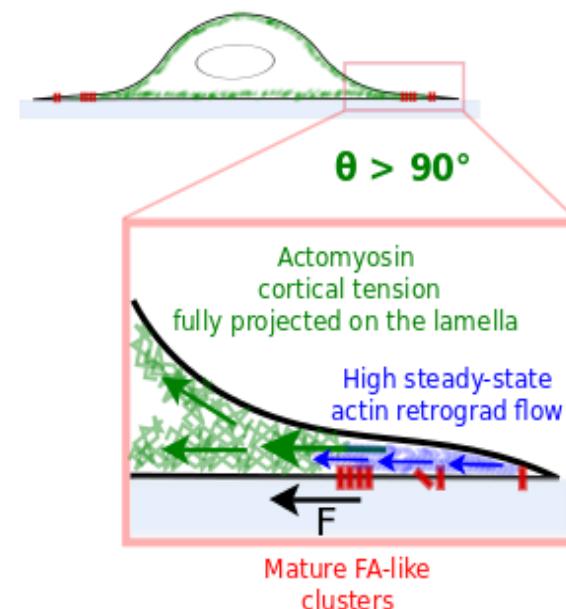
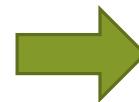
Feedback vers les systèmes
complexes et les origines de la vie !

Des similitudes remarquables

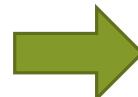
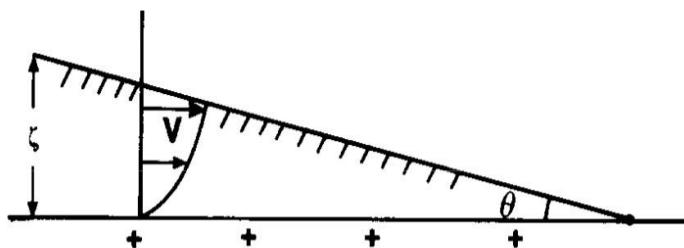


F. B. and P.G. de G., *J. Phys. Lett.*, 1984

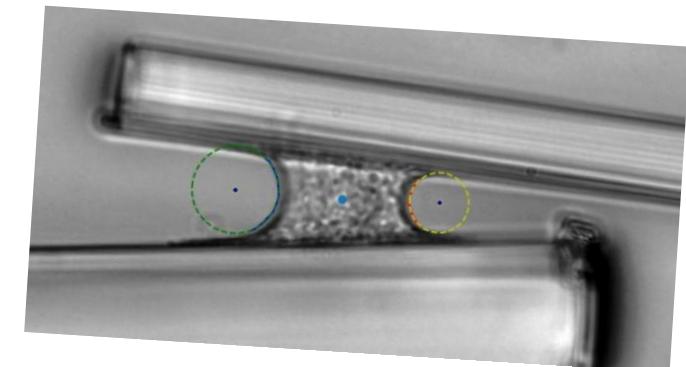
F. B-W et al., *Langmuir*, 1994



J. Fouchard et al., *PNAS*, 2014



F. B-W and P.G. de G.,
Adv. In Colloid and Interface Science, 1992



J. Vermeil, *in progress*

Merci !