The dynamics of Life

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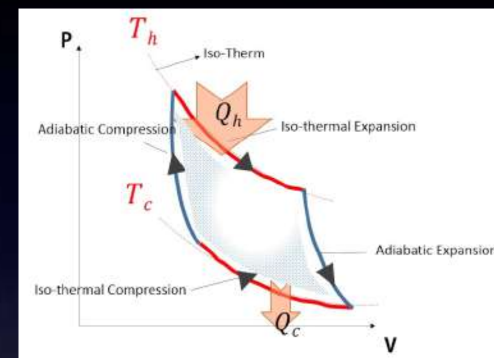
The dynamics of living beings is fascinating

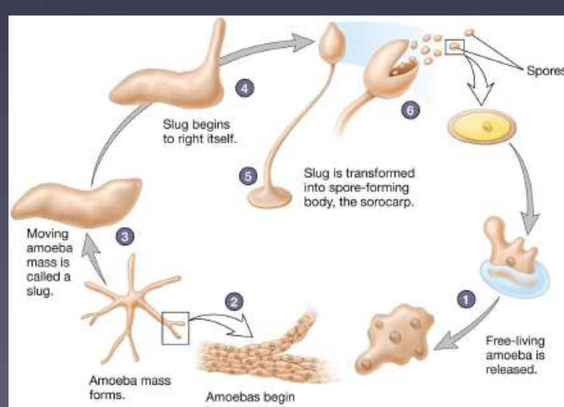
Developing zebrafish

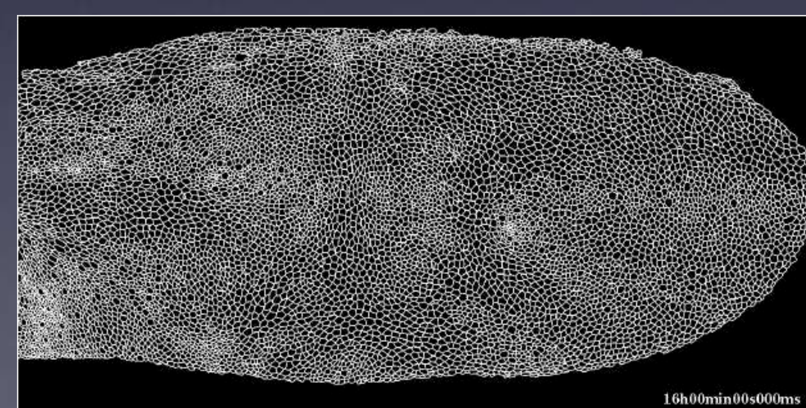
Karlstrom & Kane

Thermodynamics

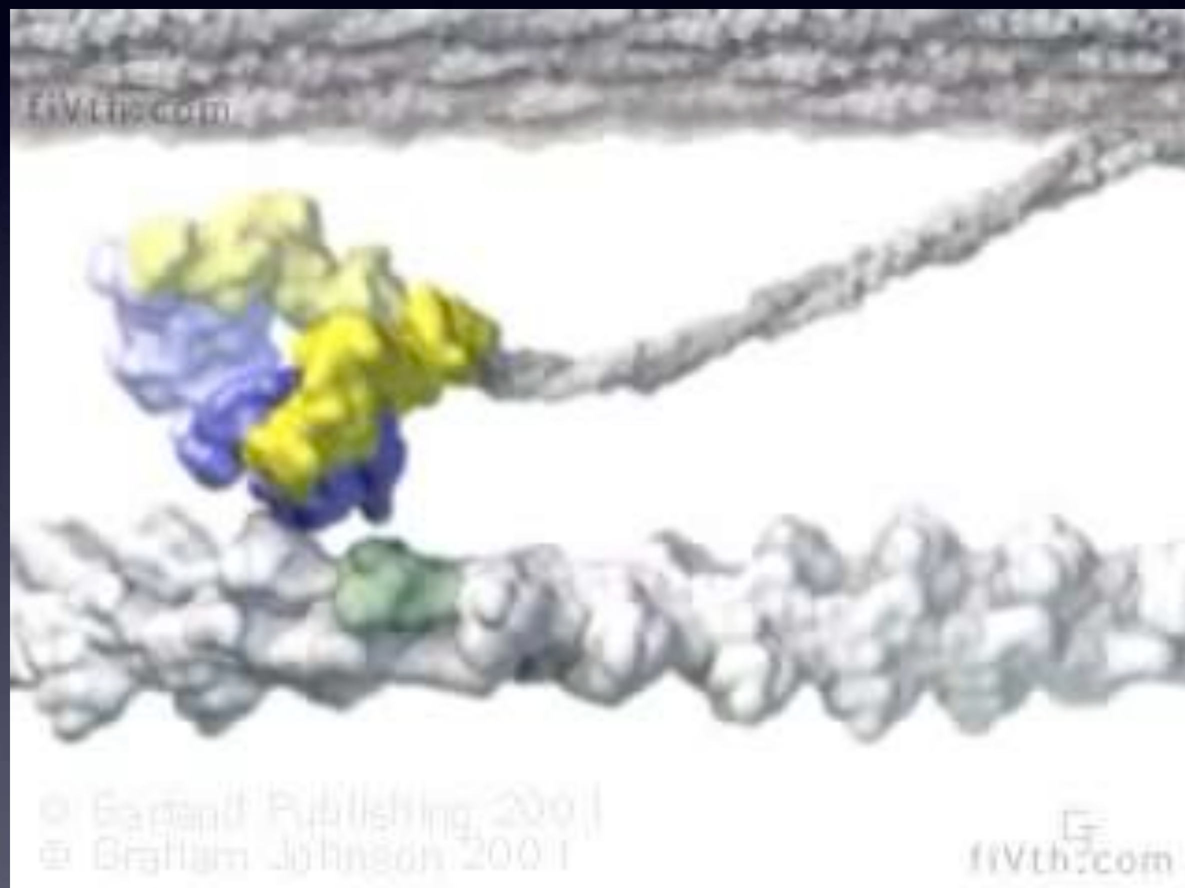


Vividynamics

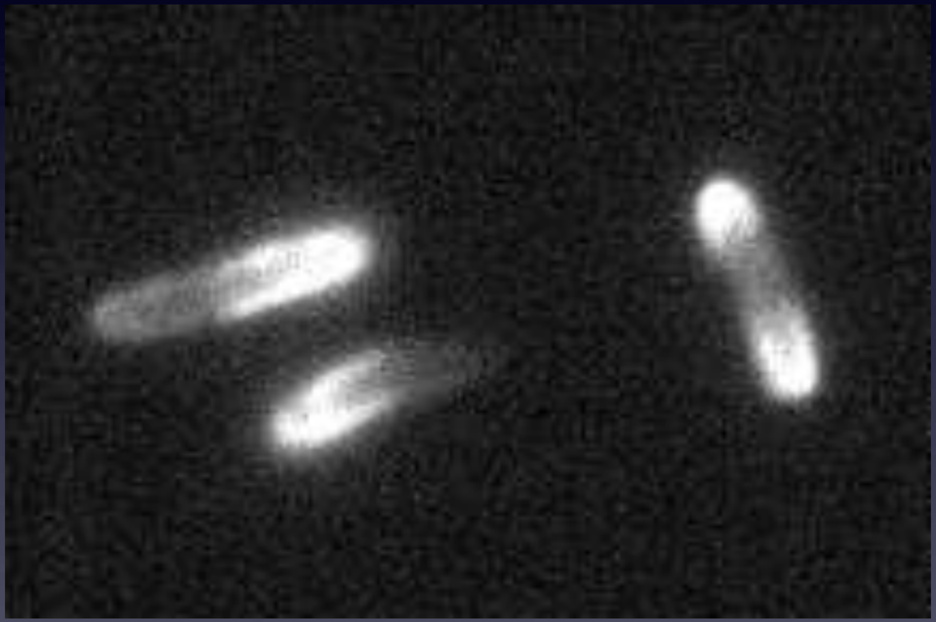




There are no living biomolecules

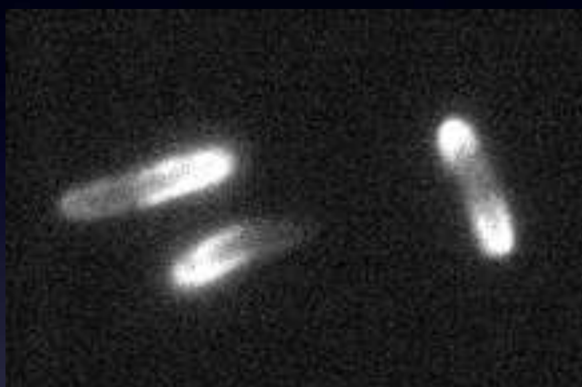


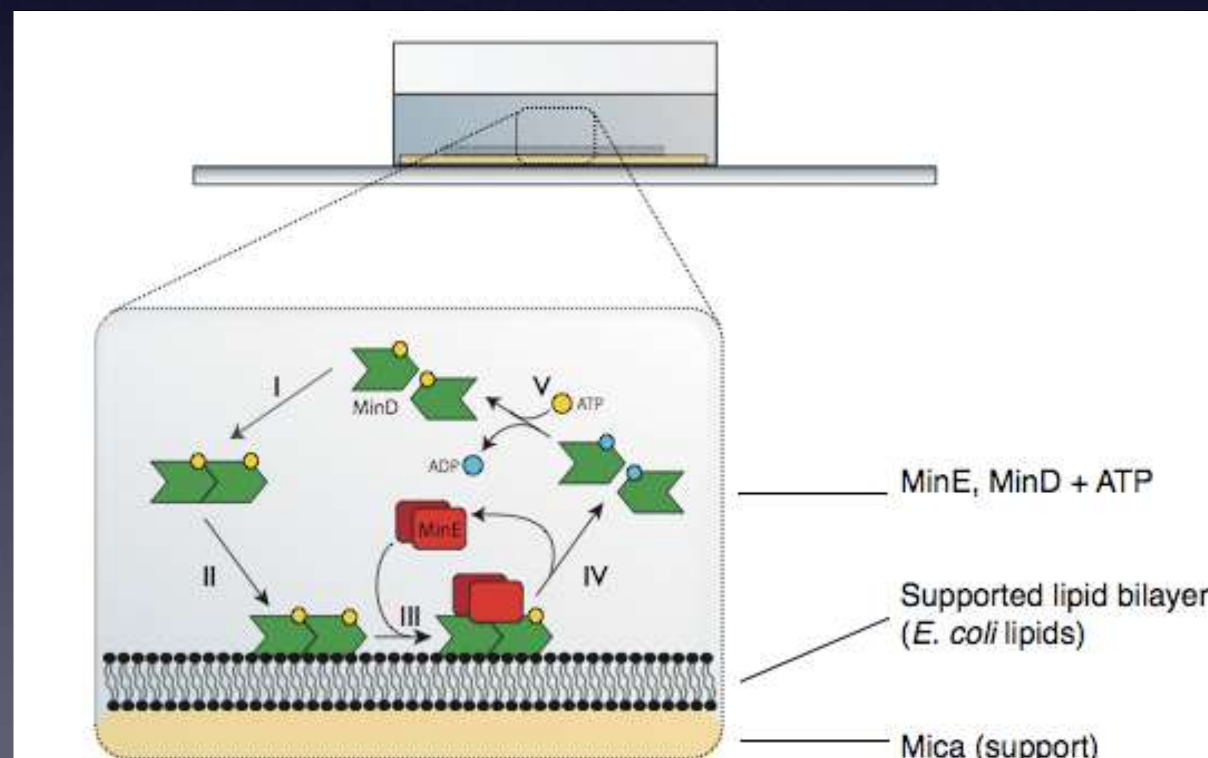
The Min-proteins form a standing wave in *Escherichia coli*



Raskin and de Boer, PNAS (1999)

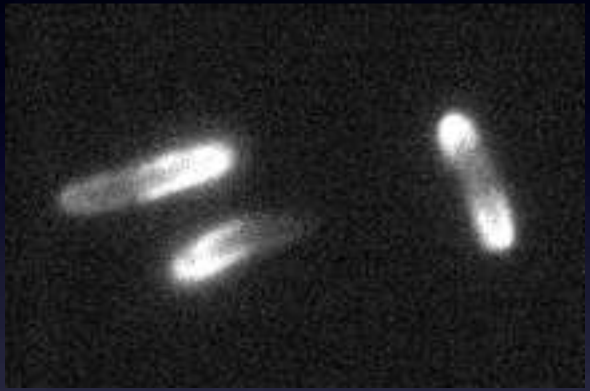
The Min-proteins dynamics can be reconstituted *in vitro*

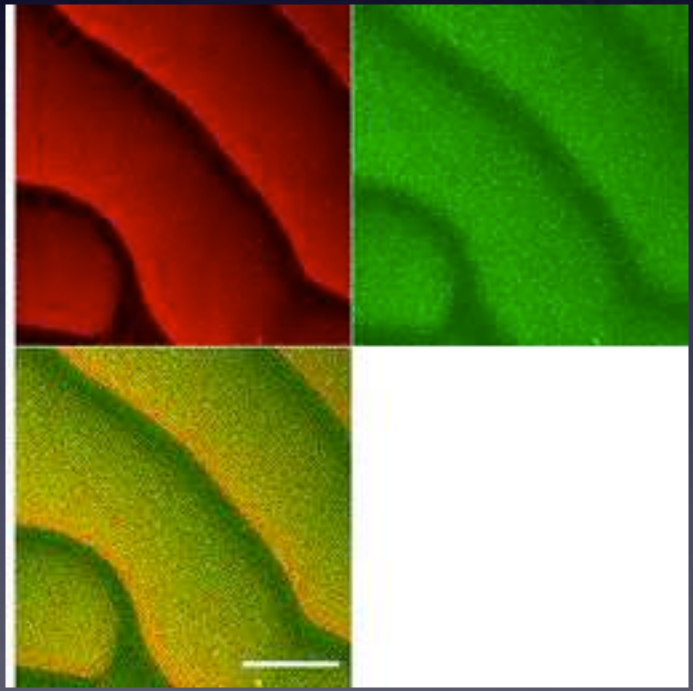




M. Loose, E. Fischer-Friedrich et al. Science (2008)

The Min-proteins dynamics can be reconstituted *in vitro*

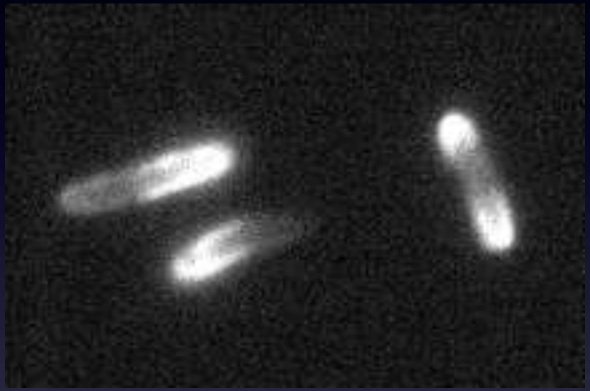


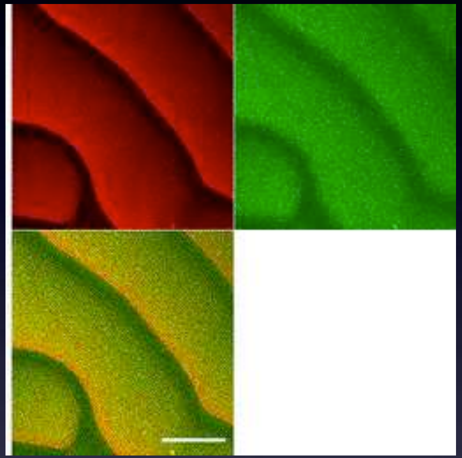


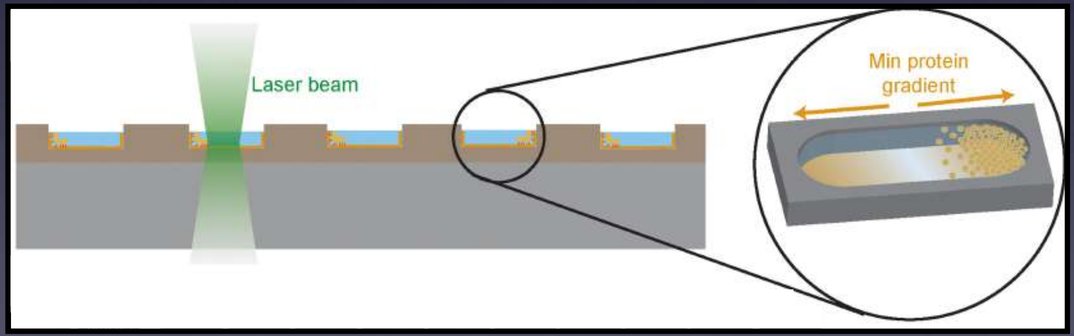
scale bar: 50μm
velocity: 0.5 μm/s

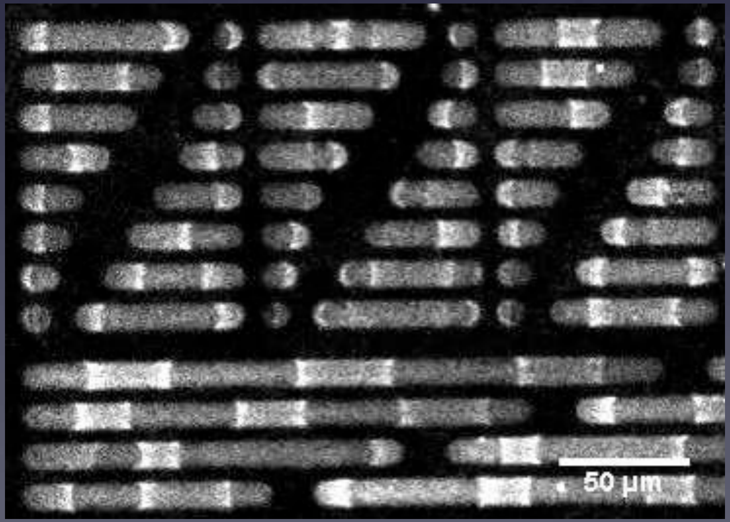
M. Loose, E. Fischer-Friedrich et al. Science (2008)

The Min-proteins dynamics can be reconstituted *in vitro*



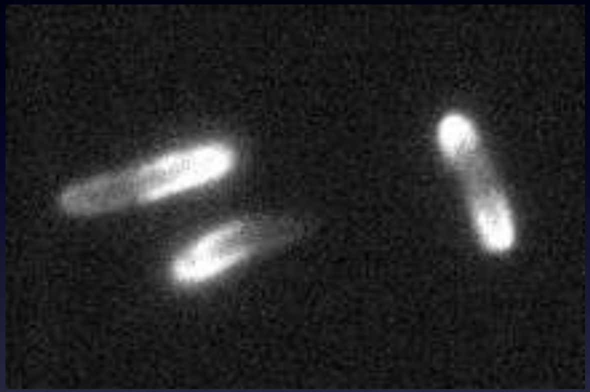


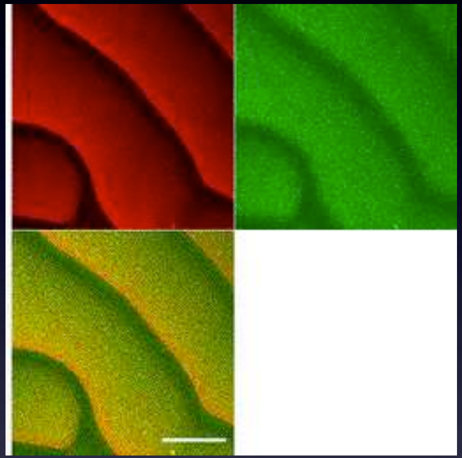


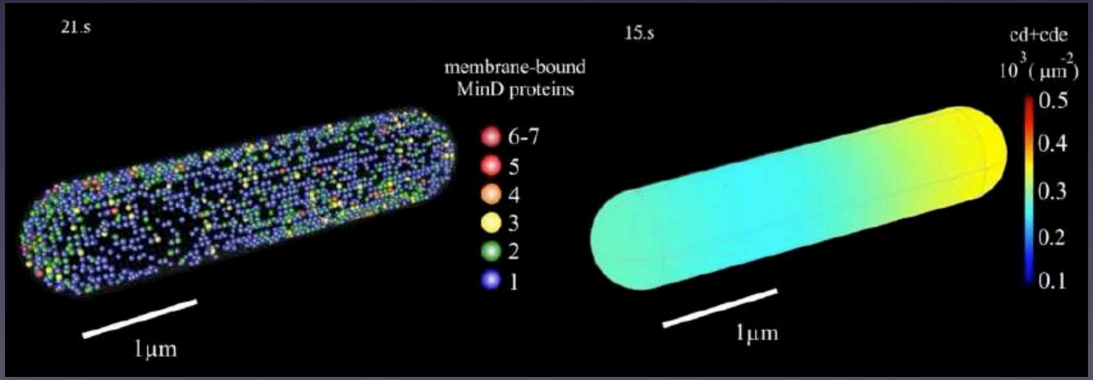


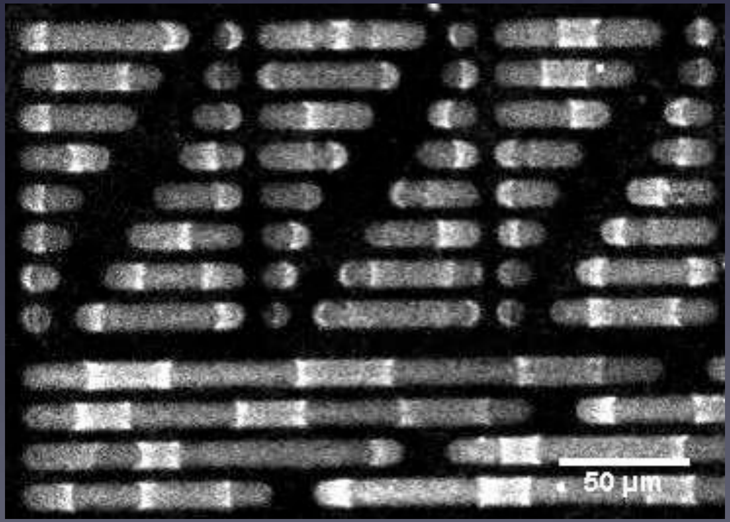
K. Zieske, P. Schwille, eLife (2014)

The Min-protein patterns result form reactions and diffusion



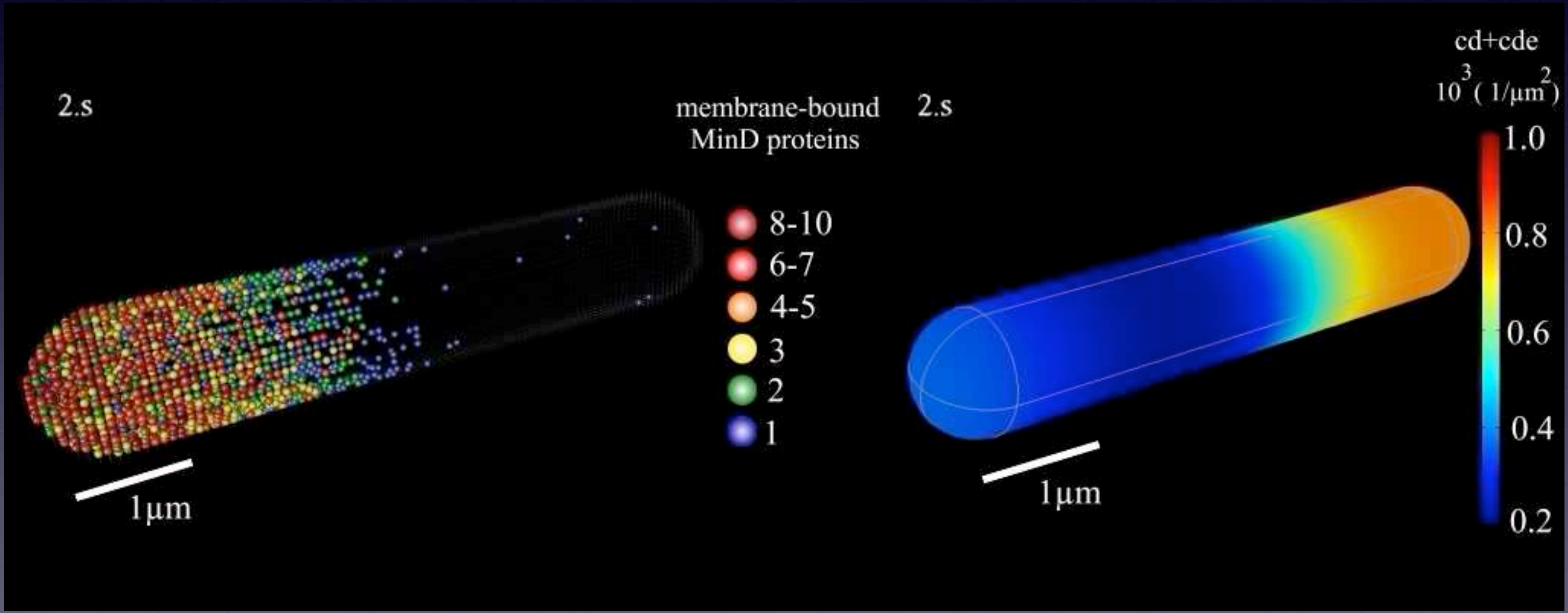






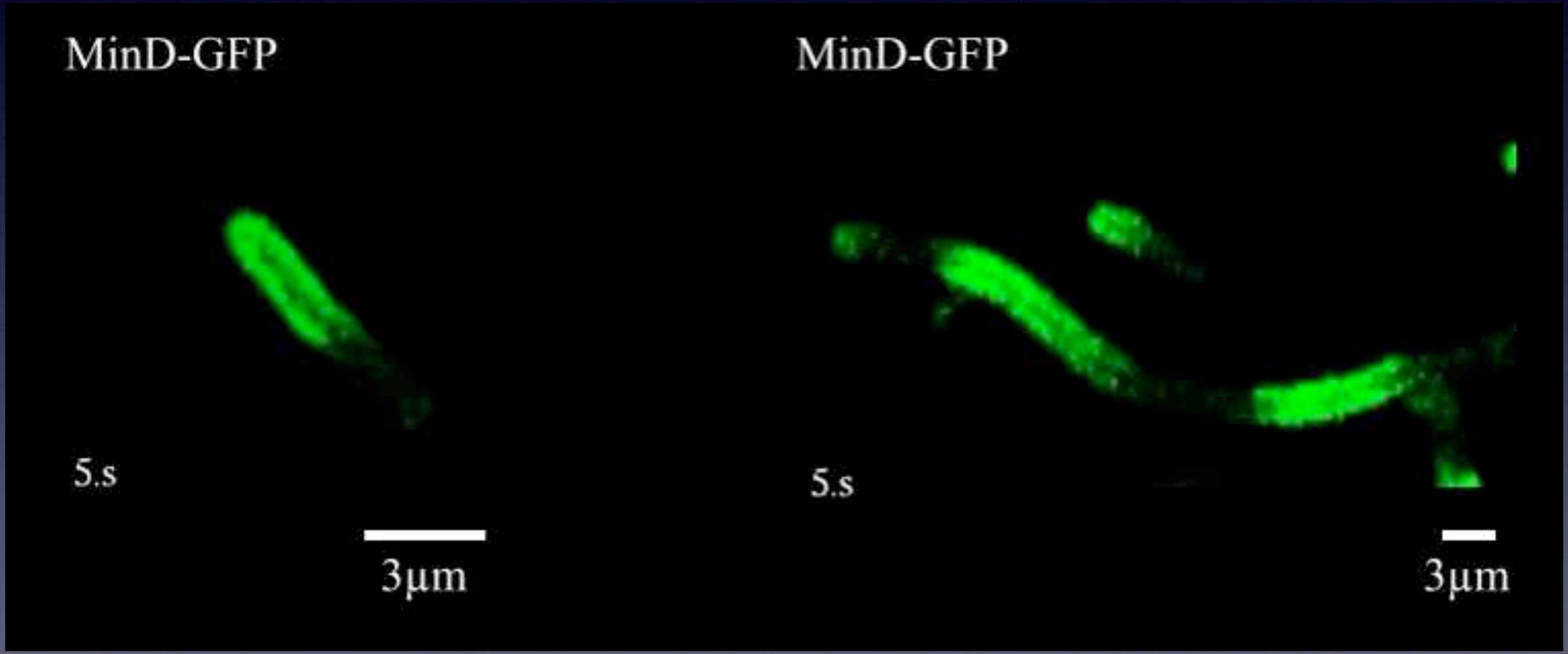
M. Bonny et al, PLoS Comp Biol (2013)

Computations predict traveling waves if MinD/E are over-expressed



M. Bonny et al, PLoS Comp Biol (2013)

Traveling waves can be observed in E. coli



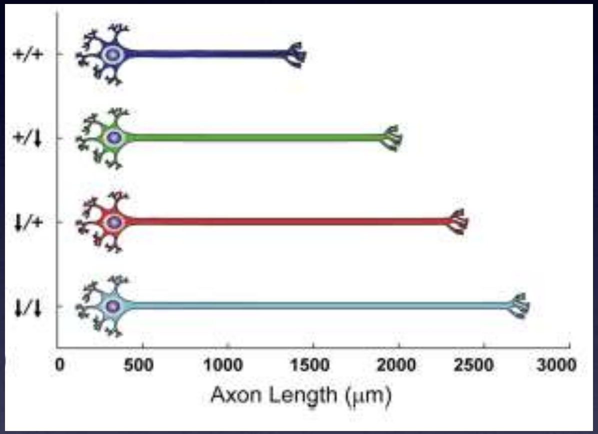
M. Bonny et al, PLoS Comp Biol (2013)

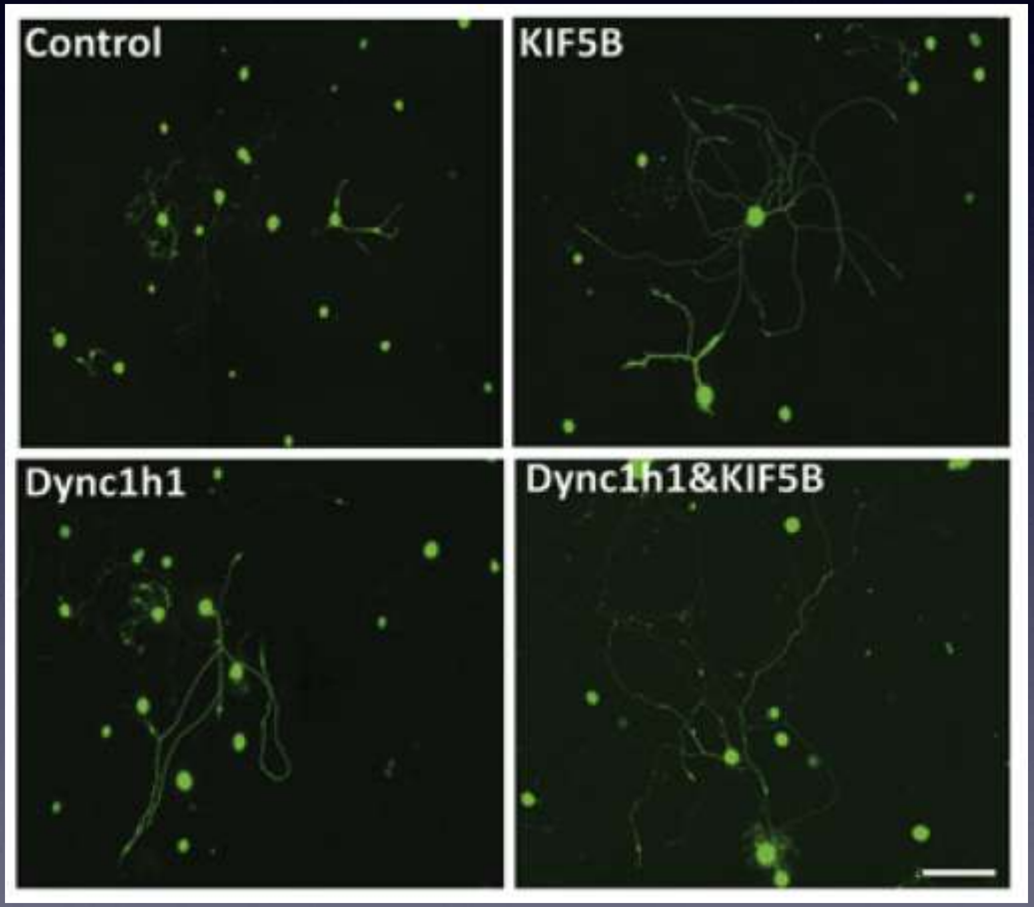
Neurons sense the length of their axons

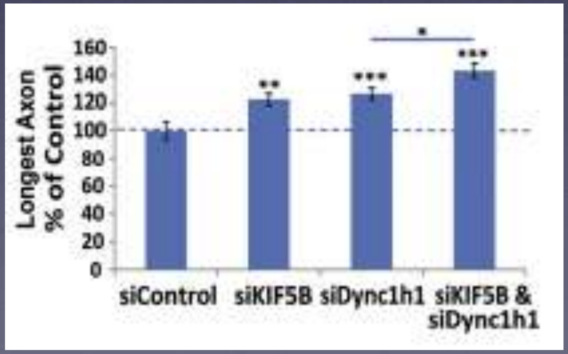
Kane Thomas

- Axons vary dramatically in length (μm to m)
- Neurons adapt (protein) metabolism to maintain homeostasis
- There is evidence for intrinsic length sensors
- Diffusion gradients only for lengths <100μm
- (Microtubule-based) rulers?
- There is evidence for intrinsic axonal length control (Albus et al, Trends Cell Biol **23**, 305 (2013)

Molecular motors are involved in length sensing and control

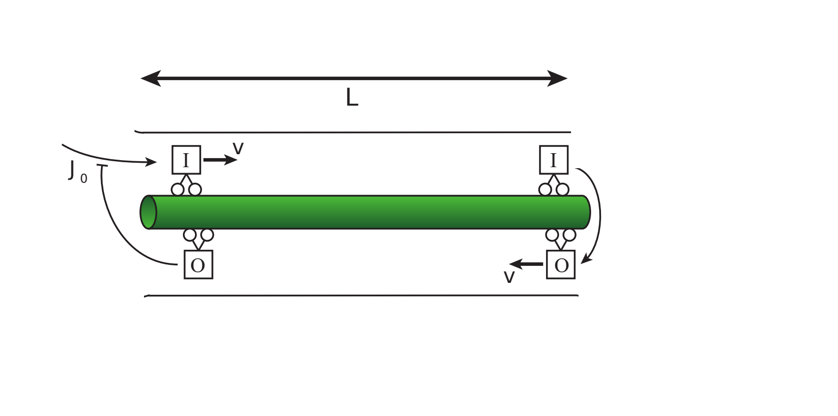






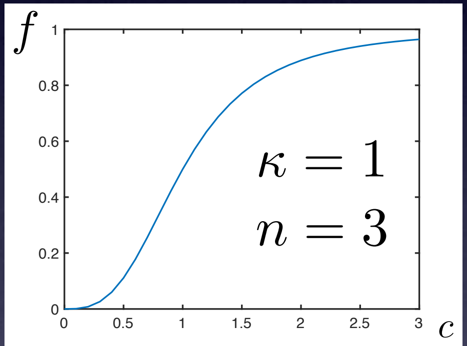
Rishal et al, Cell Reports **1**, 608 (2012)

Oscillation with length-dependent period



Sigmoidal dose response

$$f_\kappa(c) = \frac{c^n}{\kappa^n + c^n}$$



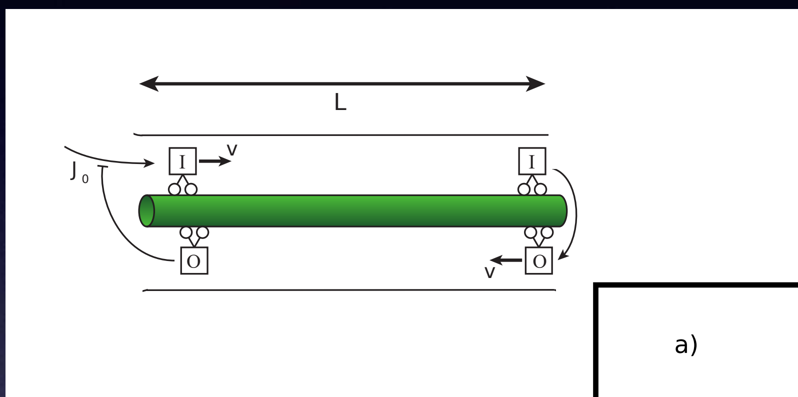
$$\dot{c}_I(t) = J_0 - J_I f_\kappa(c_O(t-\tau)) - \gamma_I c_I(t)$$

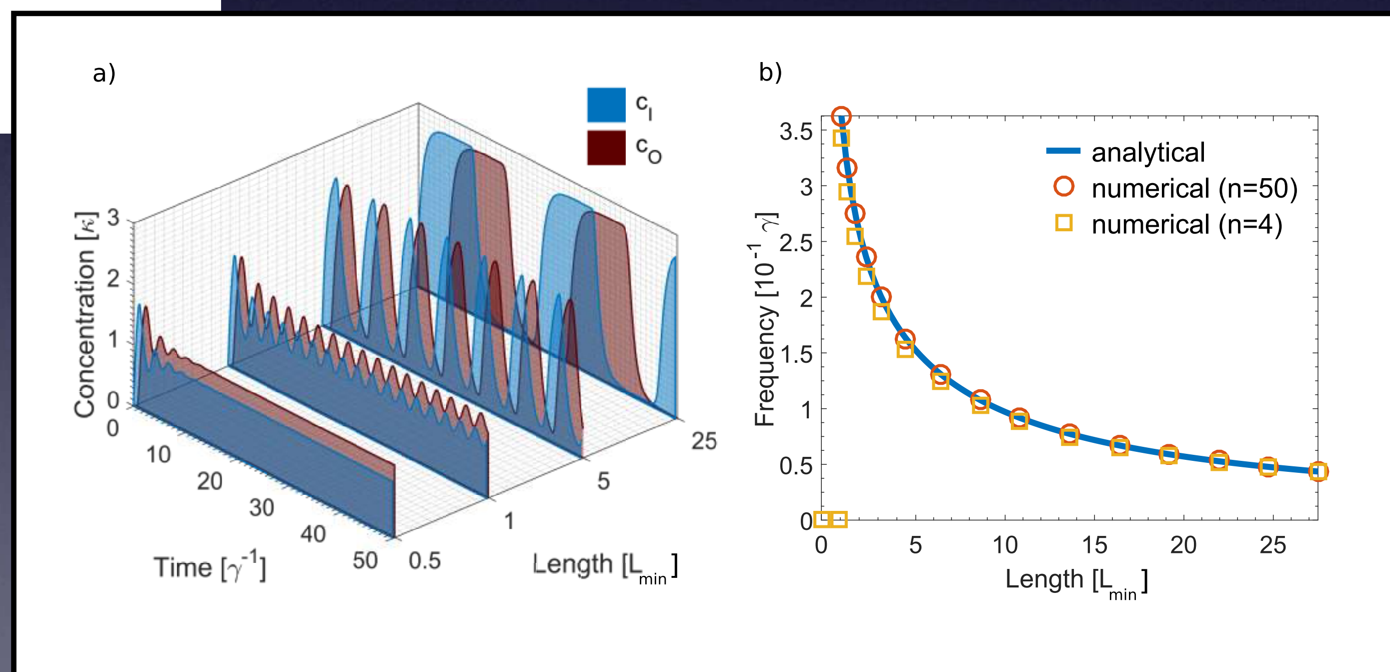
$$\dot{c}_O(t) = J_O f_\kappa(c_I(t-\tau)) - \gamma_O c_O(t)$$

$$\tau = L/v$$

Karamched and Bressloff, Biophys J **108**, 2408 (2015)

Oscillation with length-dependent period





Folz et al, Phys Rev E **99**, 050401(R) (2019)

How to read out length-dependent oscillations?

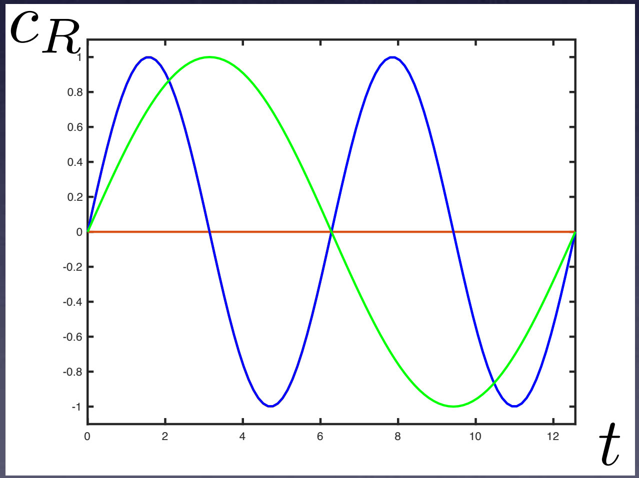
Incoming signal

$$c_I(t+T) = c_I(t)$$

Average signal

$$\langle c_I \rangle \equiv \frac{1}{T}\int_0^T c_I(t)\, dt$$

independent of T

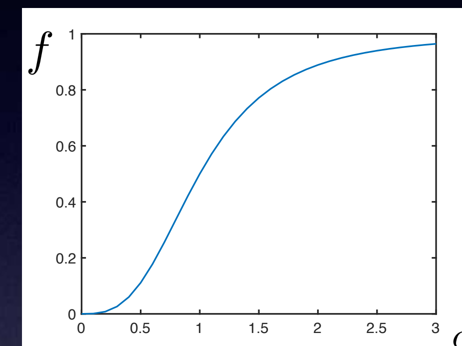


Folz et al, Phys Rev E **99**, 050401(R) (2019)

How to read out length-dependent oscillations?

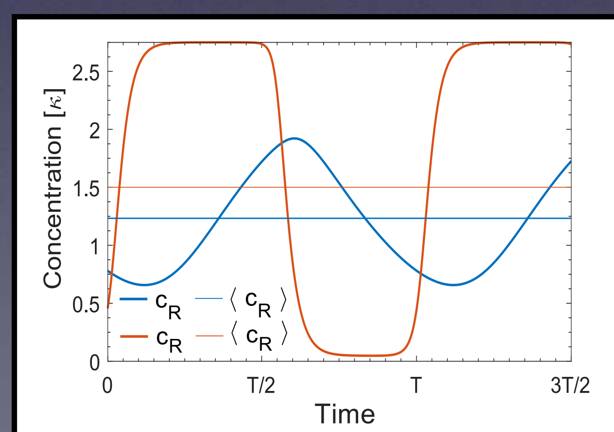
c_R

Response



$$\dot{c}_R = J_R(1 - f_\kappa(c_I)) - \gamma_R c_R$$

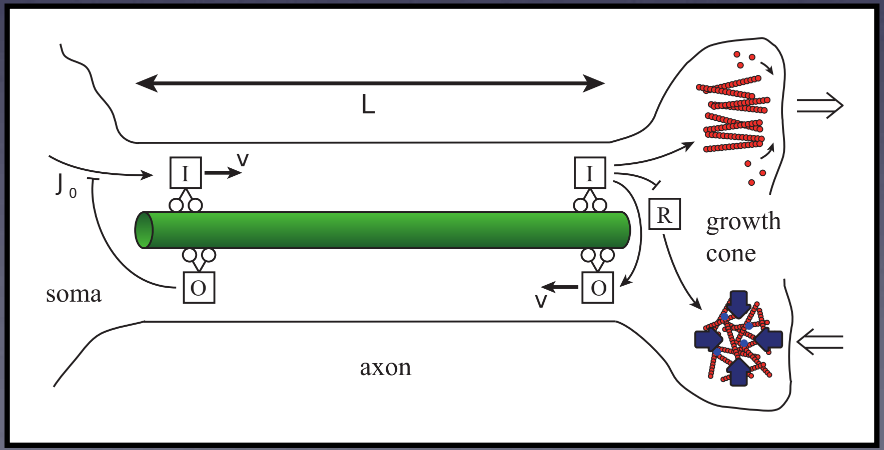
If the shape of c_R depends on T then so does $\langle c_R \rangle$



Folz et al, Phys Rev E **99**, 050401(R) (2019)

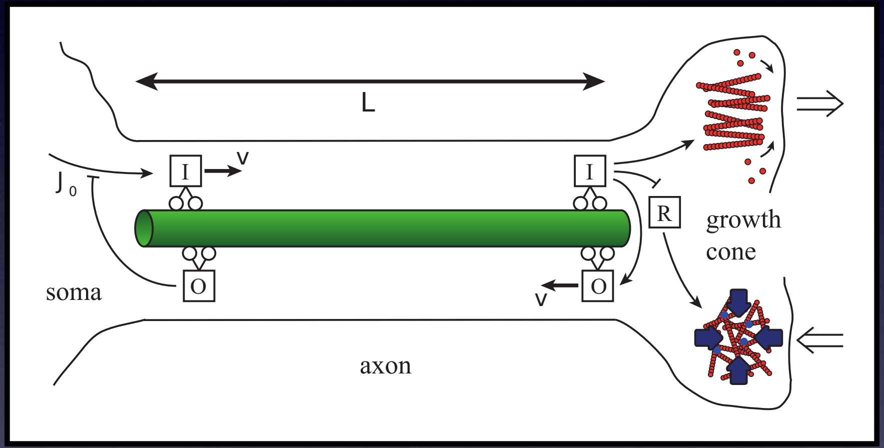
Mechanics is important for axonal growth

Bray, J Cell Sci **37**, 391 (1979)



Folz et al, Phys Rev E **99**, 050401(R) (2019)

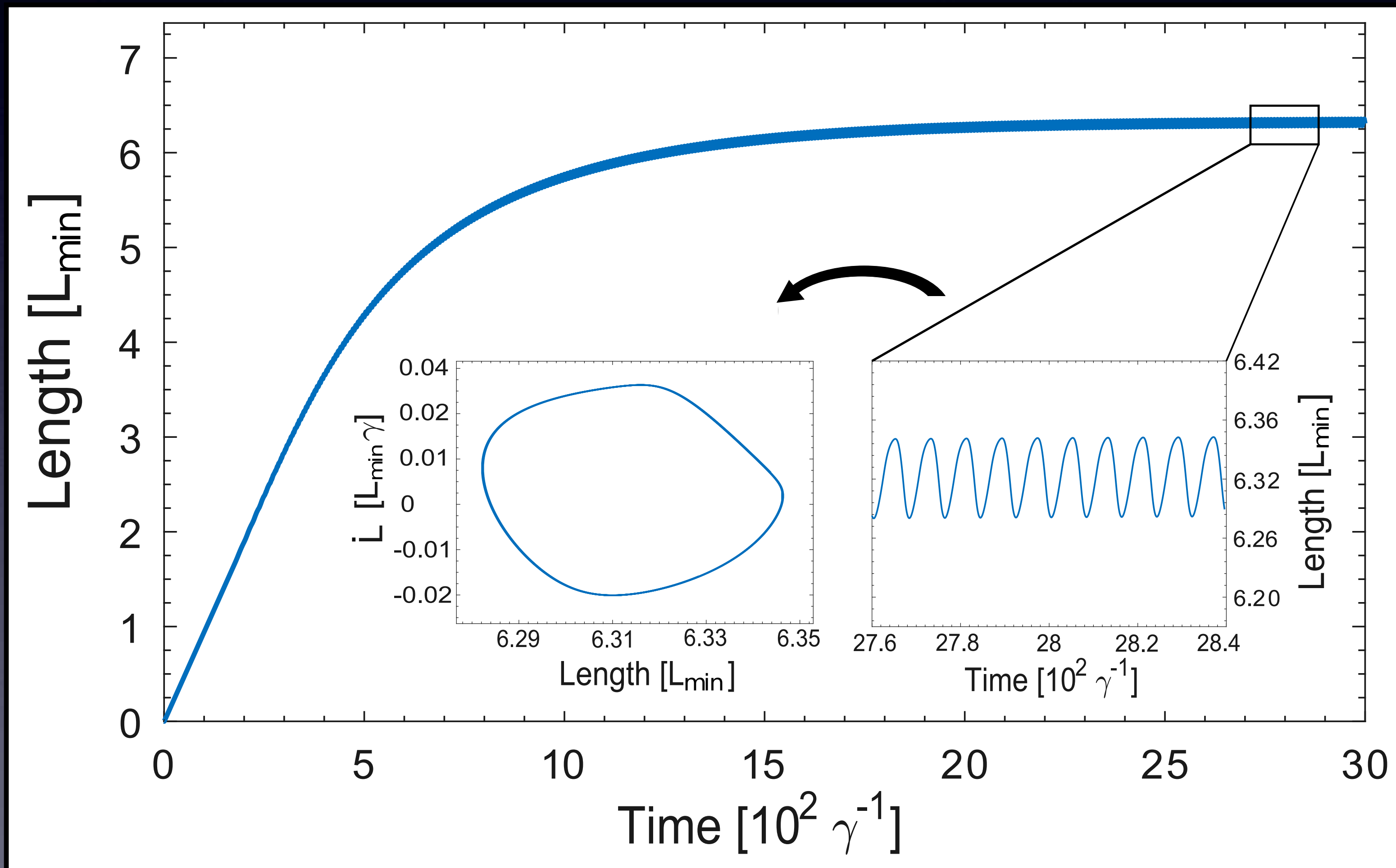
The signals regulate growth cone extension and retraction



$$\dot{L} = v_g c_I - v_s c_R$$

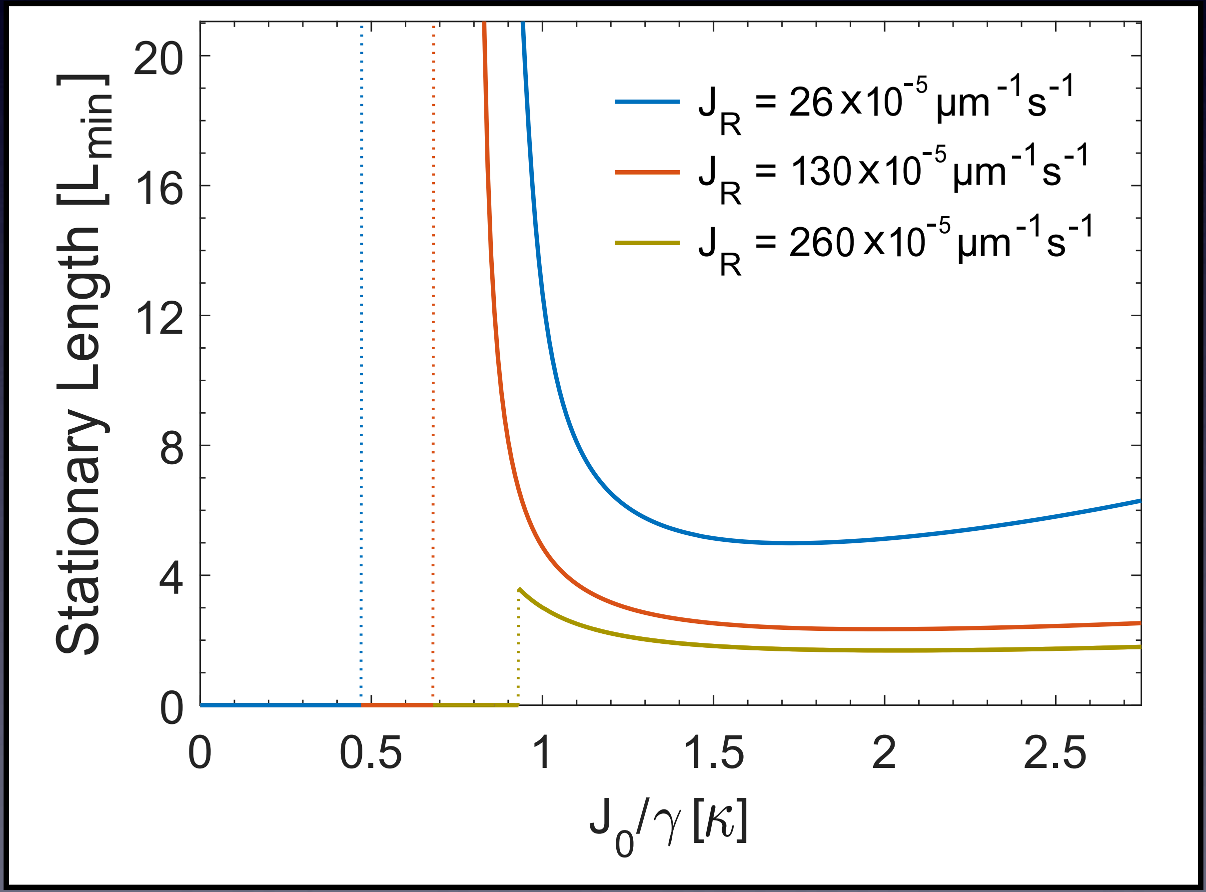
Folz et al, Phys Rev E **99**, 050401(R) (2019)

The oscillatory signal can set the axon length



Folz et al, Phys Rev E **99**, 050401(R) (2019)

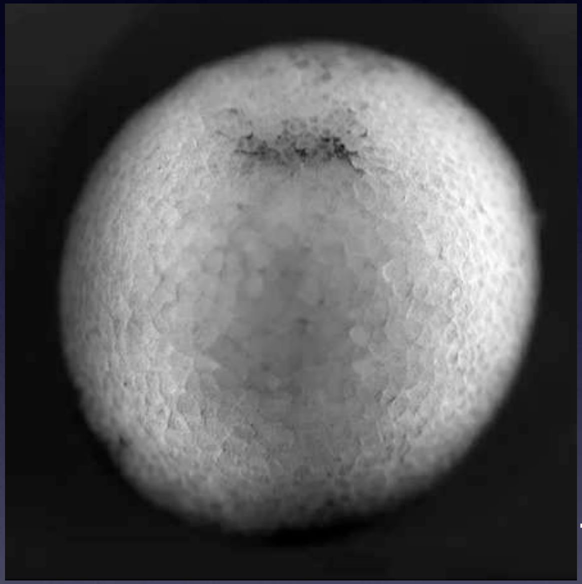
Length can increase with decreasing motor concentration



Folz et al, Phys Rev E **99**, 050401(R) (2019)

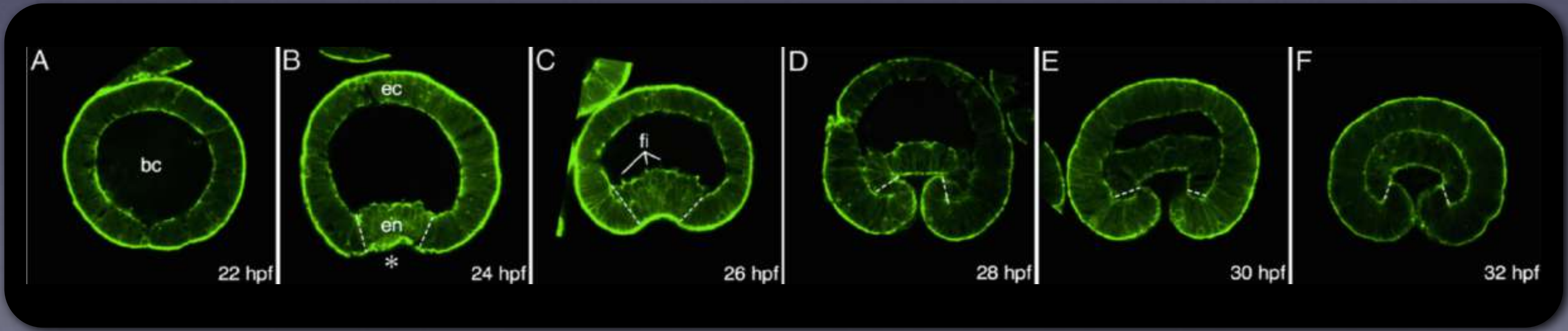
A single-cell layer invaginates during gastrulation

Xenopus laevis



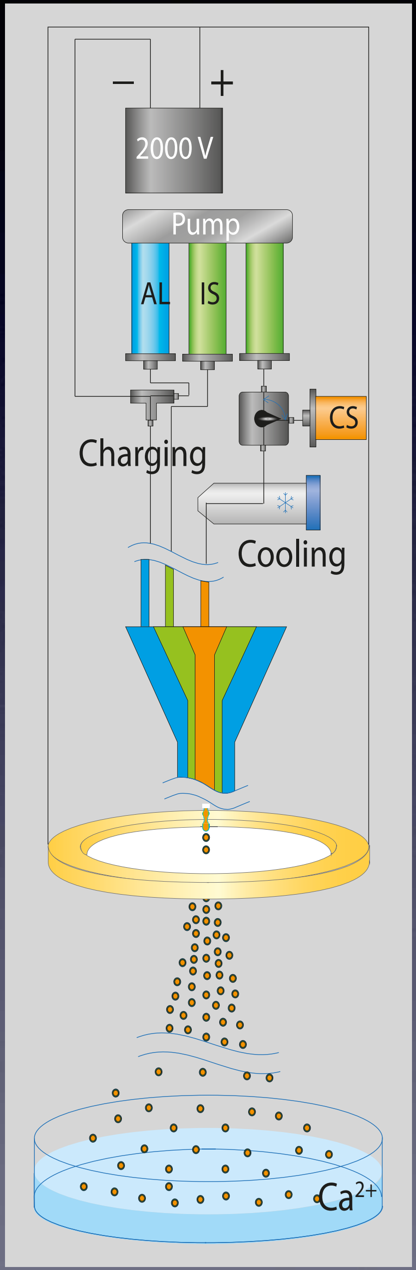
Total time: 15 hours

D. Shook from: Gastrulation: From Cells to Embryo, CSHL Press (2004)



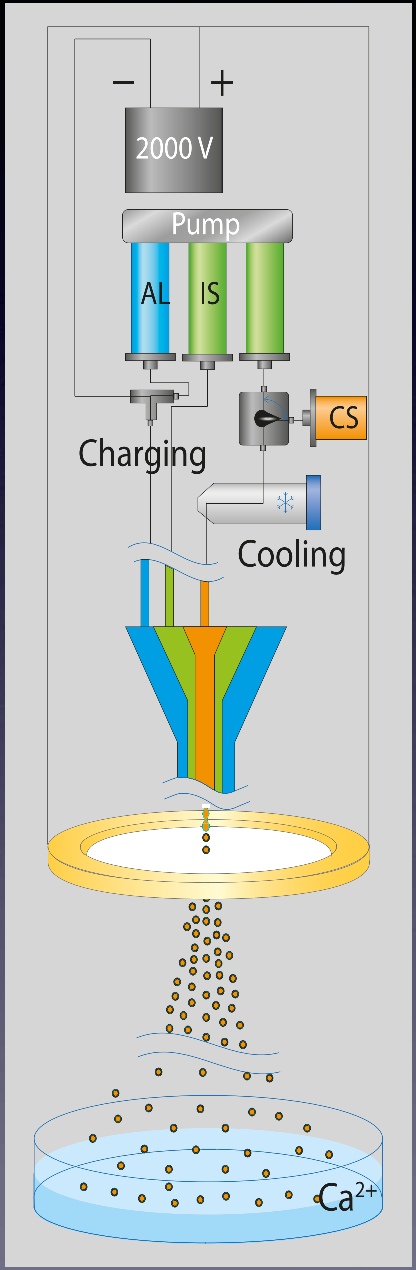
Tamulonis et al, Dev Biol (2011)

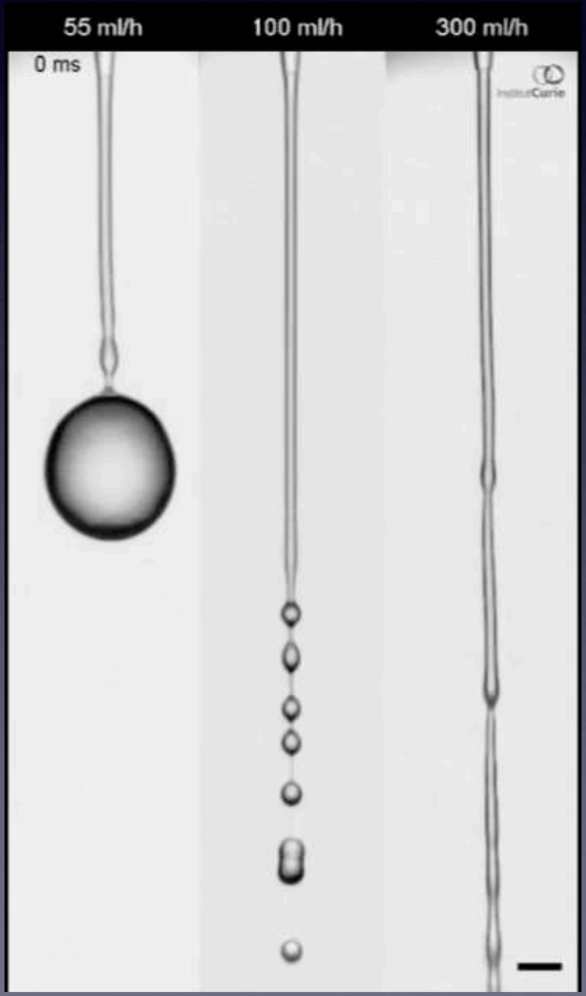
Epithelial cells can be confined in alginate capsules



Alessandri et al, Lab on Chip (2016)

Epithelial cells can be confined in alginate capsules

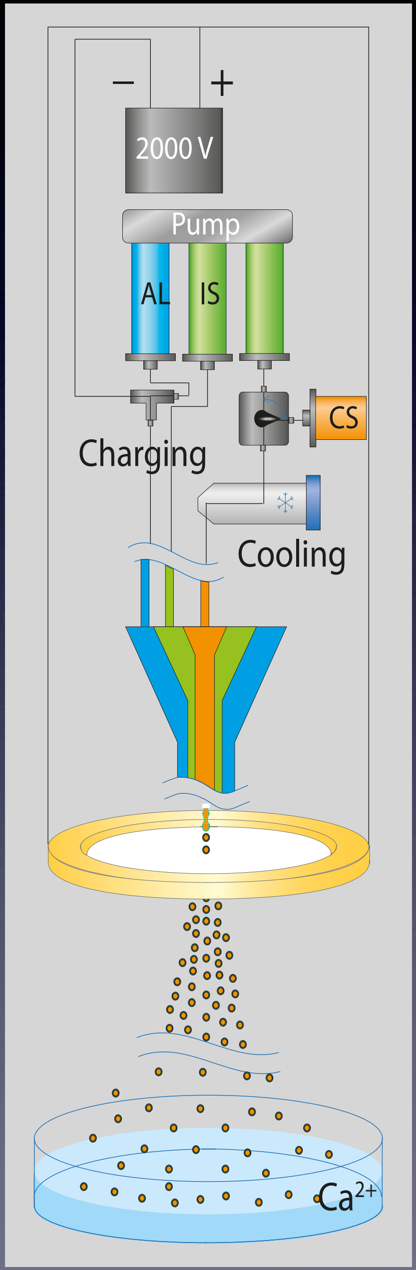




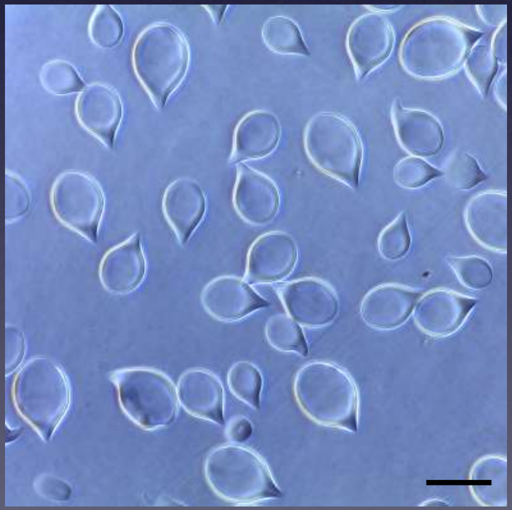
Drop radius:
~100-200 μm

Alessandri et al, Lab on Chip (2016)

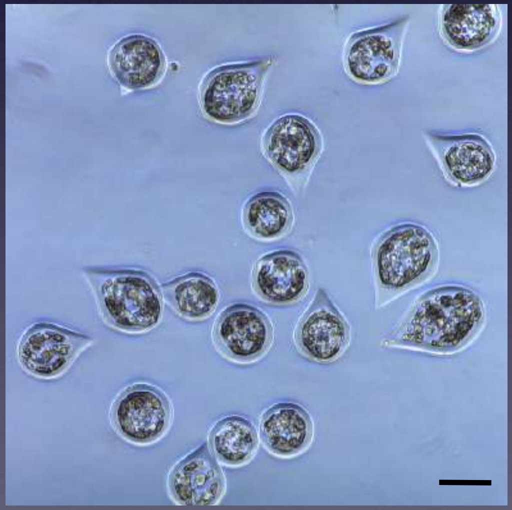
Epithelial cells can be confined in alginate capsules



w/o cells

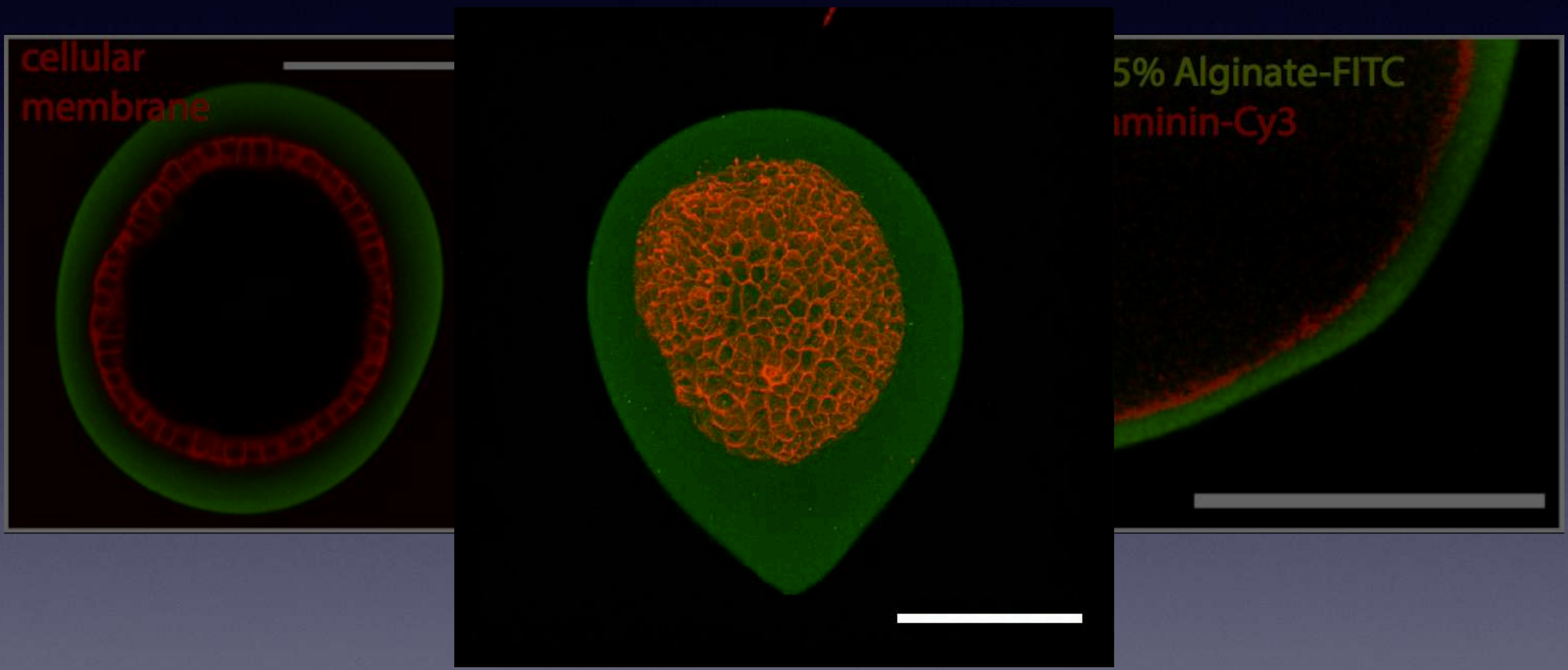


with cells



Alessandri et al, Lab on Chip (2016)

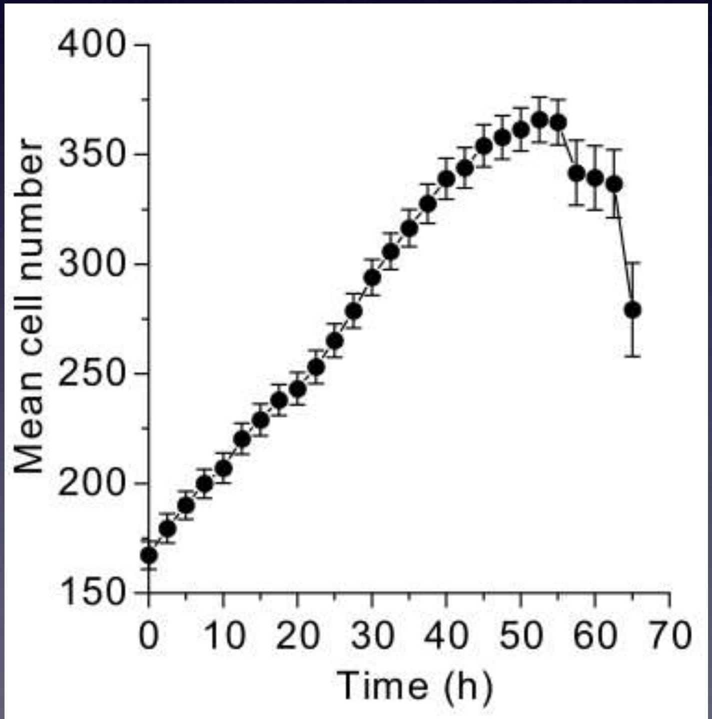
Cells form a monolayer in the capsule

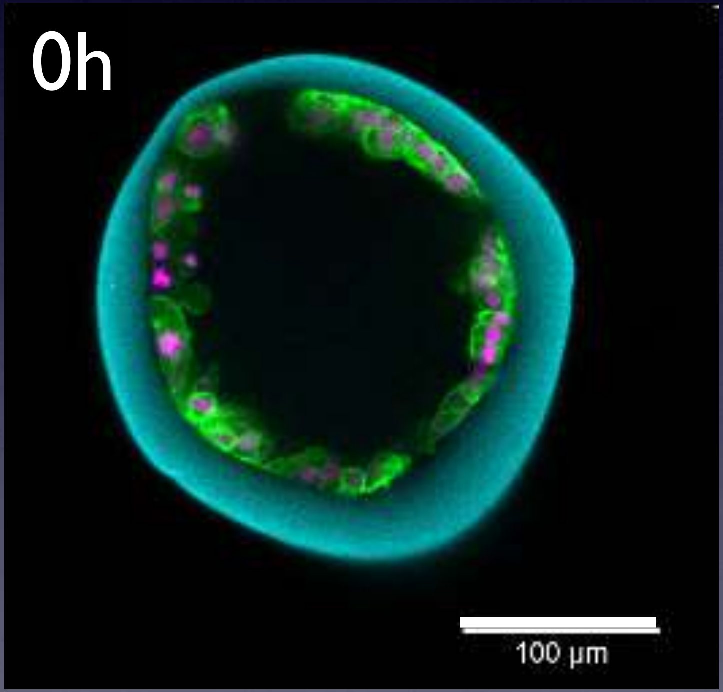


A. Trushko et al, Dev Cell (2020)

Scale bars: 100 μm

Cell number increases by proliferation

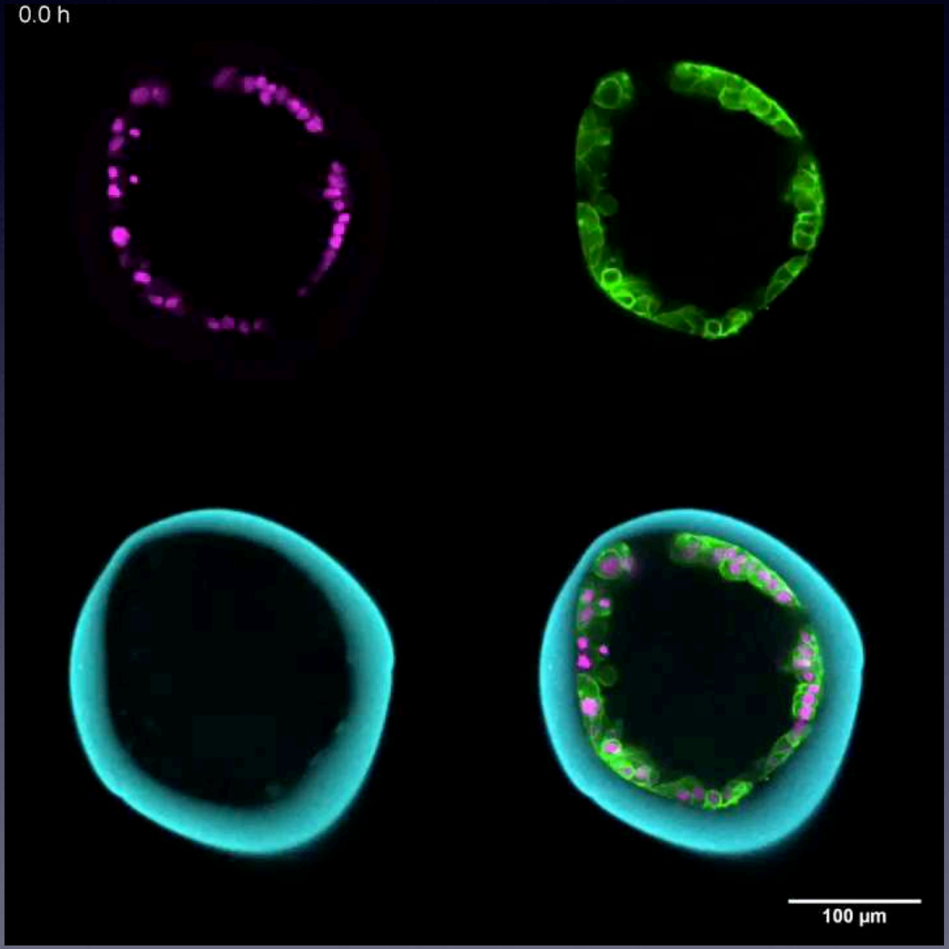




100 μm

A. Trushko et al, Dev Cell (2020)

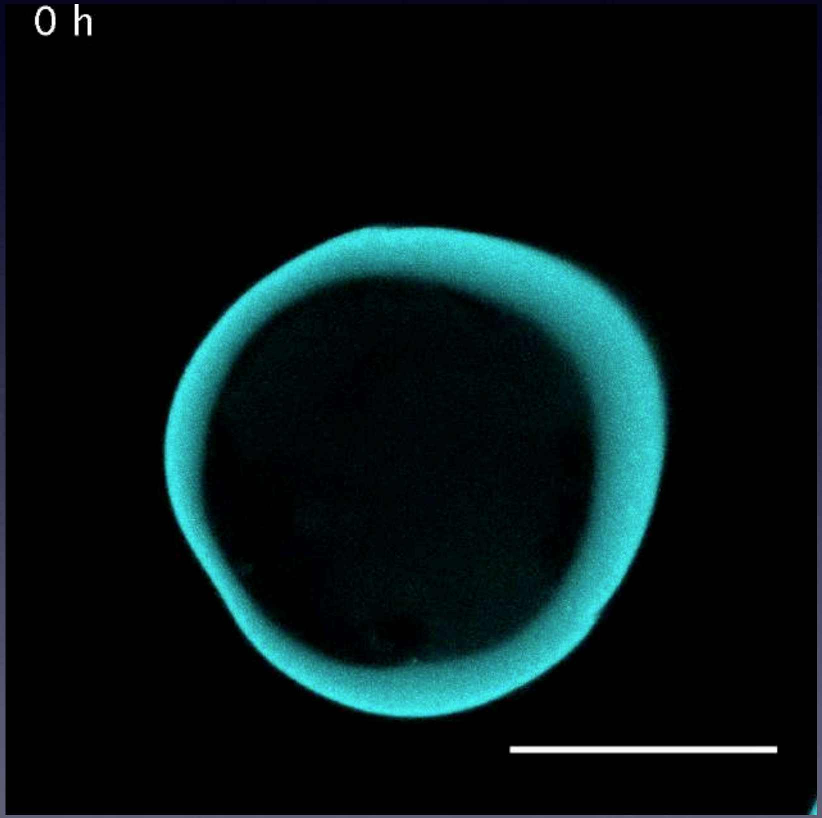
Cell layers growing in capsules can fold



100 μm

A. Trushko et al, Dev Cell (2020)

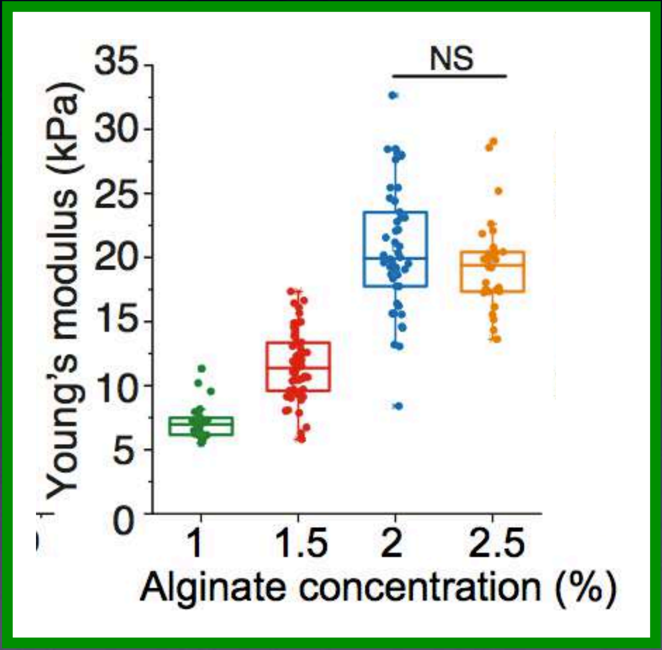
Capsule thickness changes with time

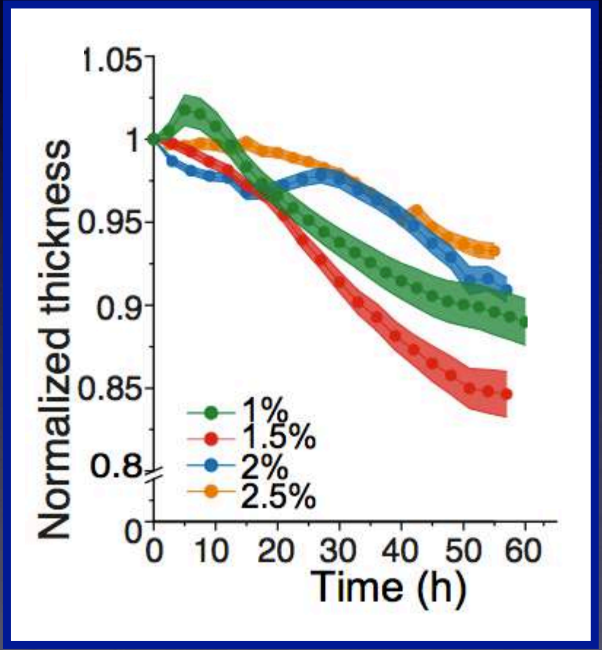


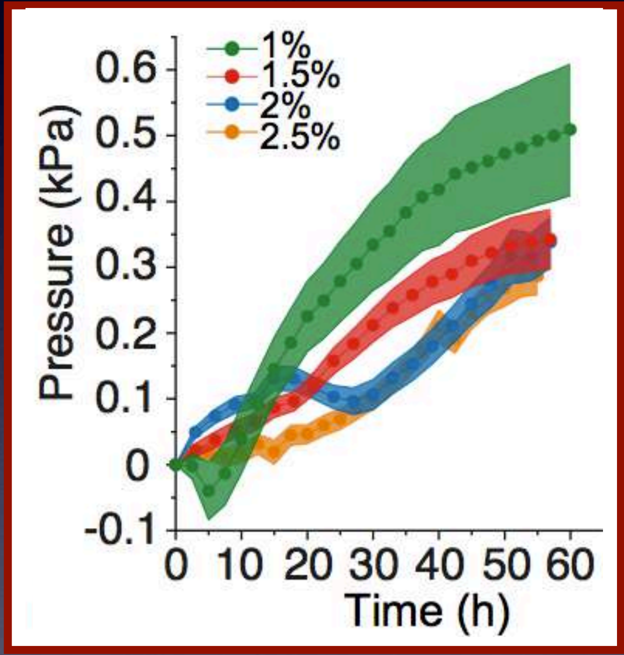
100 μm

A. Trushko et al, Dev Cell (2020)

Capsule deformations allow to measure pressure







$$\frac{2E}{1-\nu}\frac{h(0)h(t)}{R^2} = P$$

A. Trushko et al, Dev Cell (2020)

We describe the monolayer as an elastic material

$$\mathcal{E} = \boxed{K}\int_L \kappa^2 \mathrm{d}s + \boxed{\lambda}\int_{L_0} \epsilon^2 \mathrm{d}s_0 + \boxed{k}\int_L (r(s) - R)^2 \, \mathrm{d}s$$

Bending rigidity **Compressibility modulus** **Capsule stiffness**

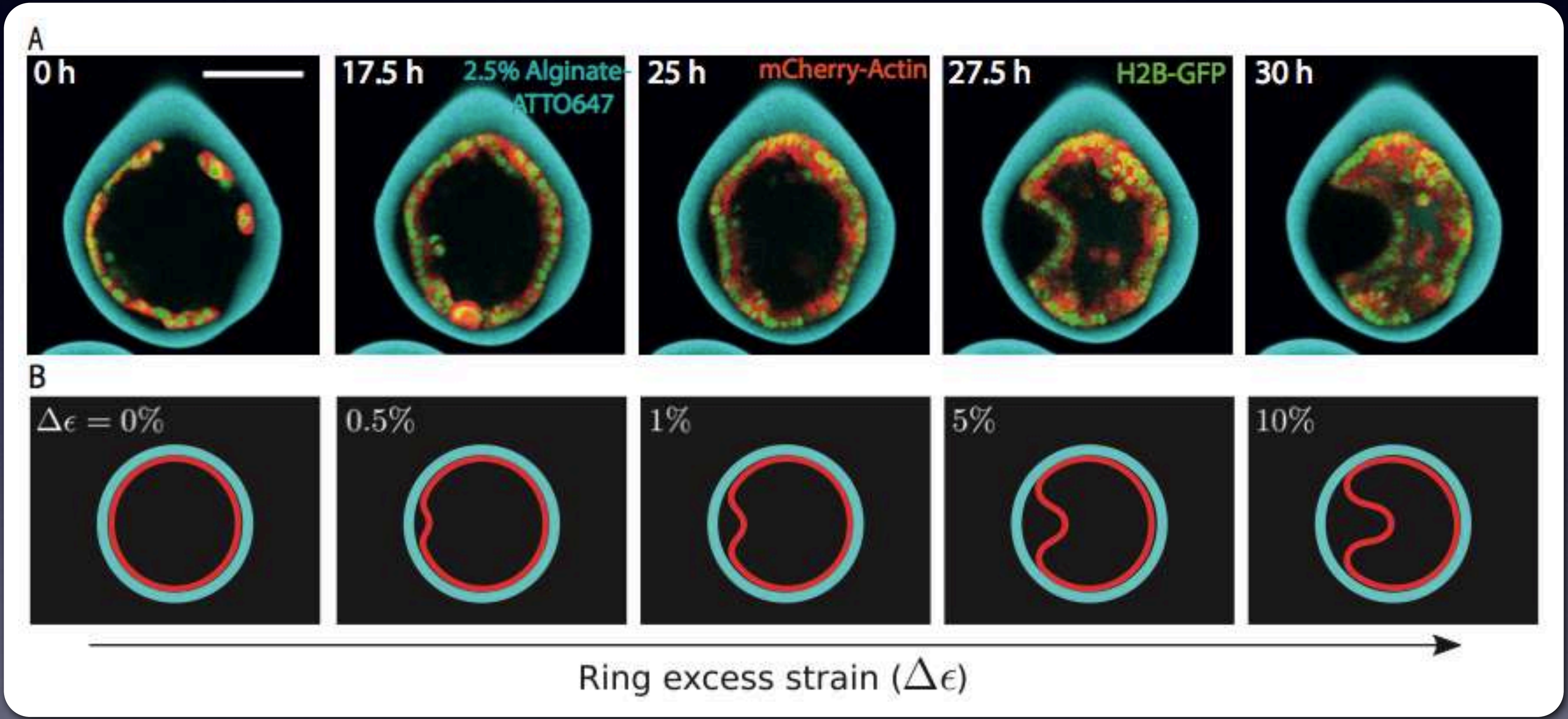
Dimensionless parameters:

$$\frac{\lambda R^2}{K} \qquad \frac{\lambda}{kR^2} \ll 1 \qquad \Delta\epsilon = \frac{L - 2\pi R}{2\pi R}$$

C. Blanch Mercader

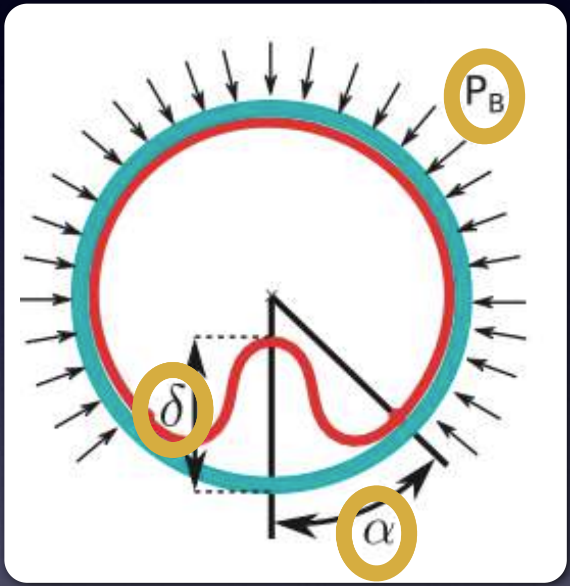
A. Trushko et al, Dev Cell (2020)

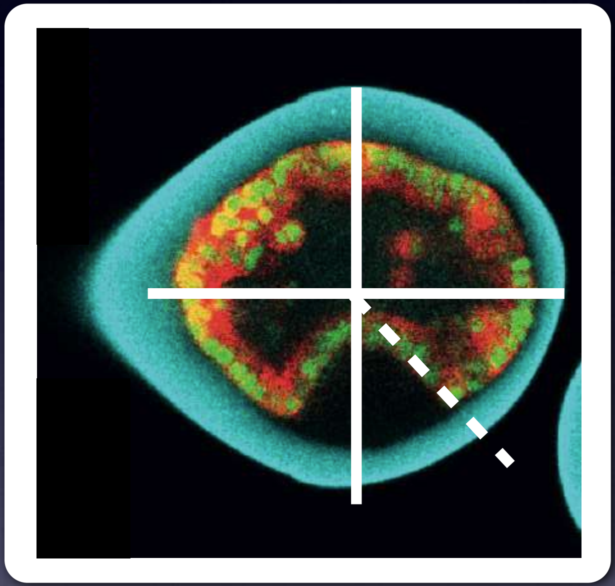
The folded shapes of elastic rings and monolayers are similar

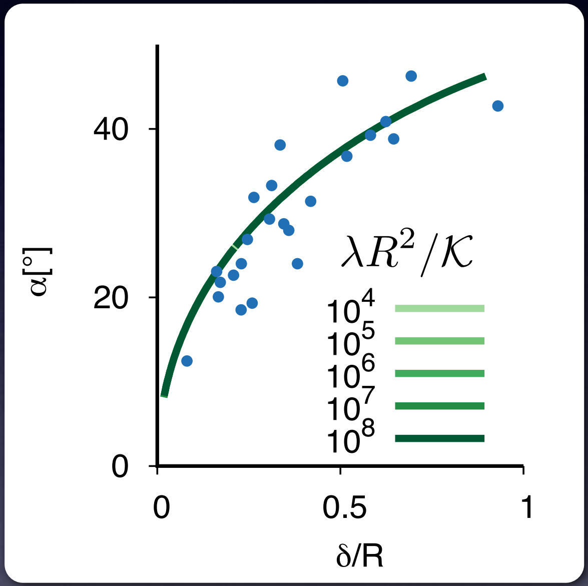


A. Trushko et al, Dev Cell (2020)

The similarity can be quantified







α: opening angle

δ : invagination depth

A. Trushko et al, Dev Cell (2020)

Our parameter values are consistent with the measured capsule stiffness

Parameter values

$$\lambda \approx 0.1 \frac{\mu\mathrm{N}}{\mu\mathrm{m}}$$

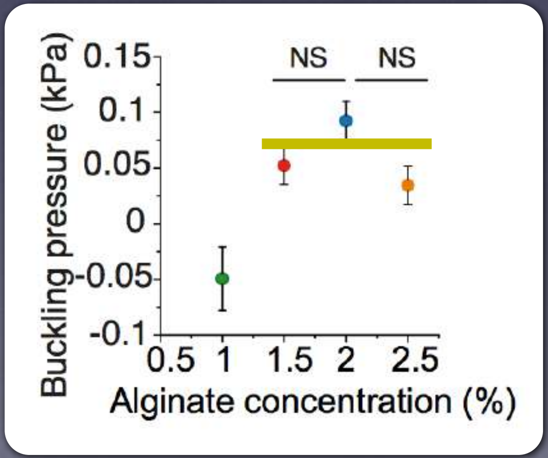
$$K \approx 1\mu\mathrm{N}\,\mu\mathrm{m}$$

$$R \approx 100\mu\mathrm{m}$$

Pressure at buckling

$$P_{\mathrm{buck}} \sim \frac{\lambda^{2/5} K^{3/5}}{R^{11/5}}$$

$$\approx 0.1\ \mathrm{kPa}$$



A. Trushko et al, Dev Cell (2020)

Das Leben ist tot.

Das Leben ist tot.
Und wir haben es getötet.

Das Leben ist tot.

Und wir haben es getötet.

Life is dead.

And we have killed it.

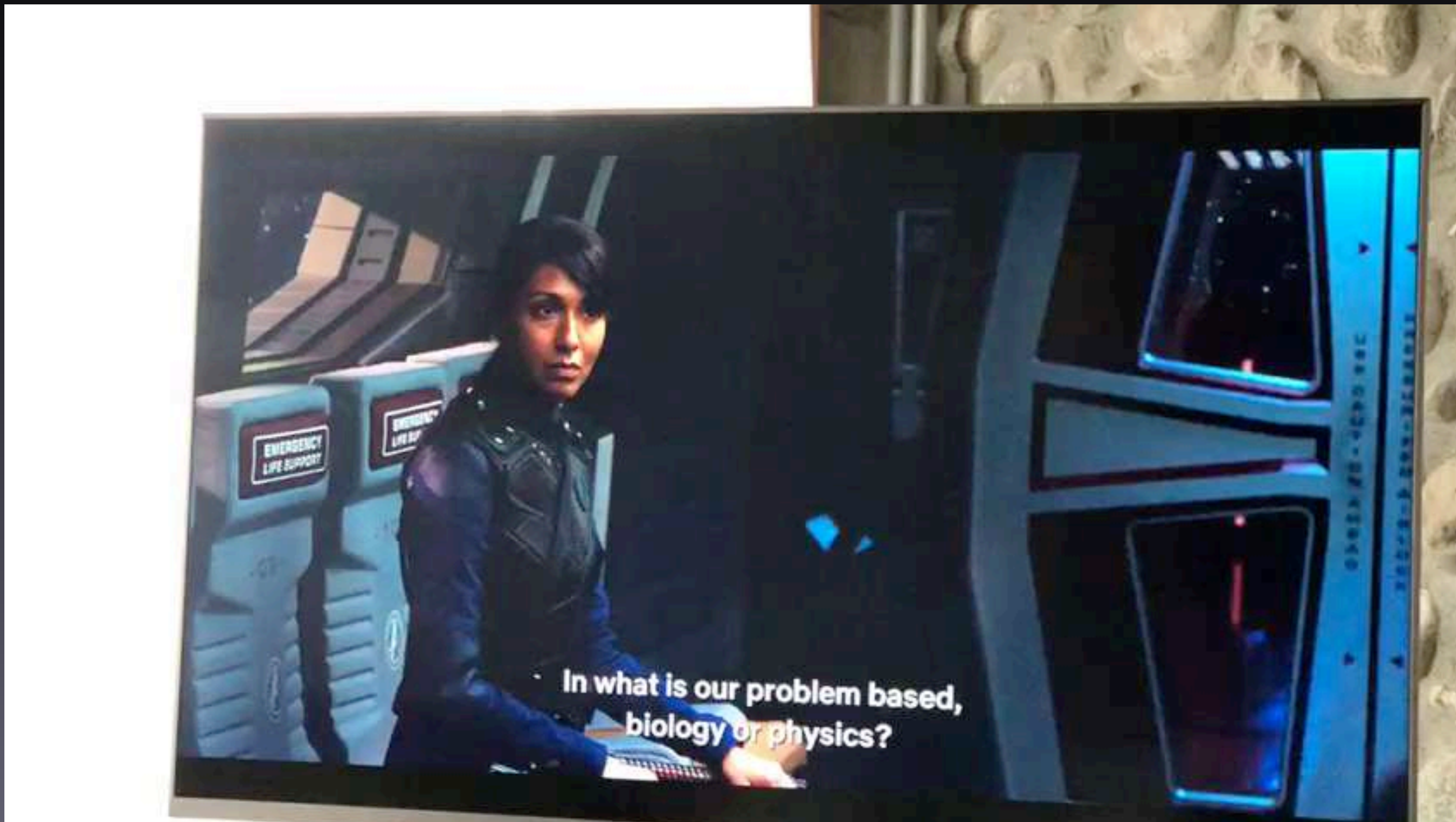
Alors on peut bien parier que la vie s’effacerait, comme à la limite de la mer un visage de sable.

Alors on peut bien parier que la vie s’effacerait, comme à la limite de la mer un visage de sable.

So we can surely bet that Life would erase itself, like a face in the sand at the border of the sea.

At the quantum level, there is no difference between physics and biology. No difference at all. (…) Physics and biology? No; physics as biology.

Paul Stamets, Astromycologist, 2256



Paul Stamets, astromycologist, 2256

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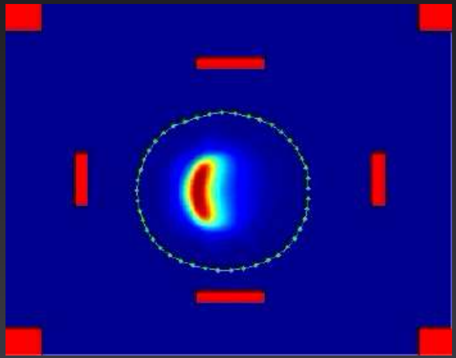
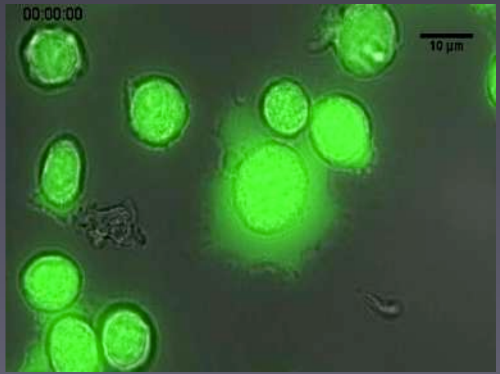
- M. Hoth (medical school)





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