Stress and confinement in shaping lipid membranes

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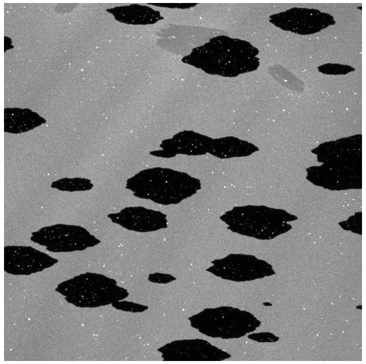
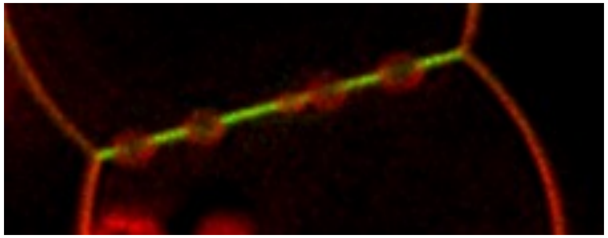
Content

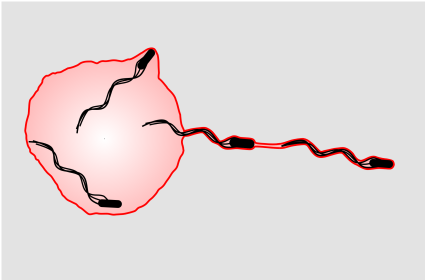
1. Friction dominated response of fluid supported membranes to lateral stretch



2. Hydraulic fracturing of membrane adhesion

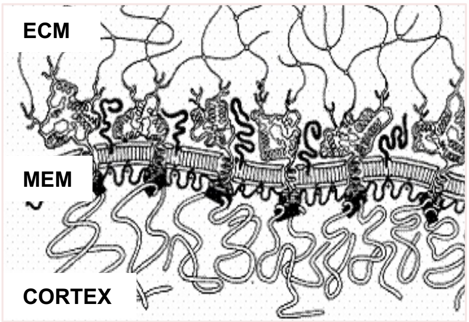


3. Propulsion of GUVs enclosing with active particles

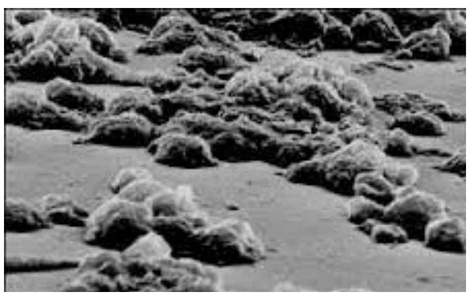


Membranes are coupled to dynamic structures

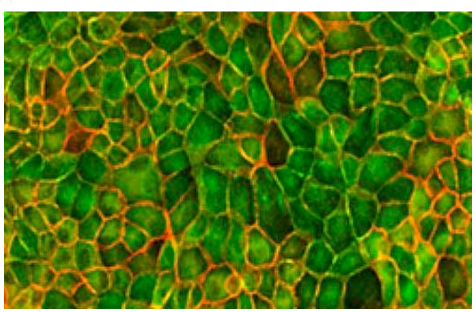
Sub-cellular



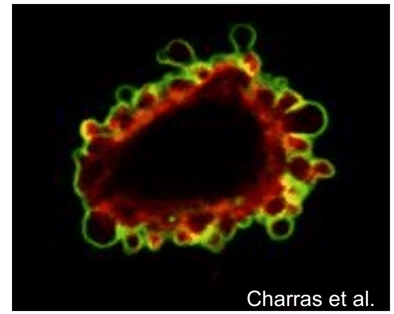
Cell-Substrate



Cell-cell

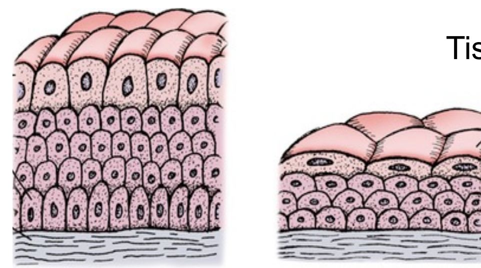


Ladoux's Lab



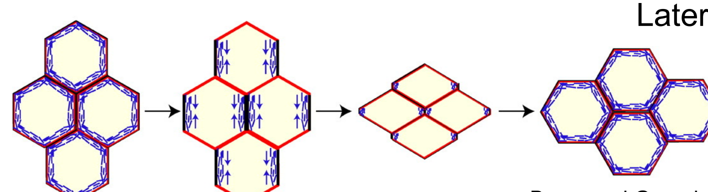
Charras et al.

Membrane blebs

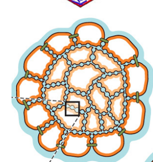


Tissue/organ deformations

Lateral remodeling

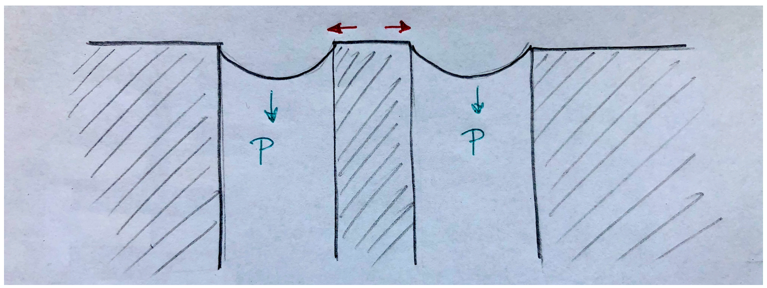


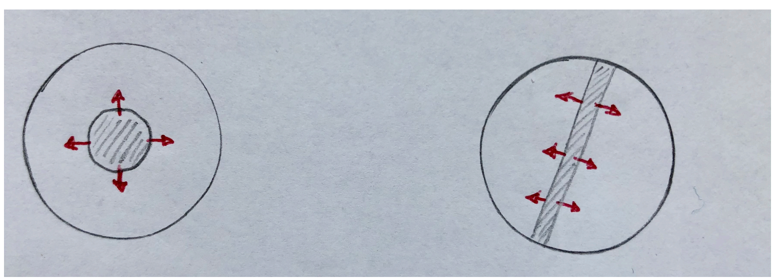
Baum and Georgiou, JCB 2011



Hydraulic pressure

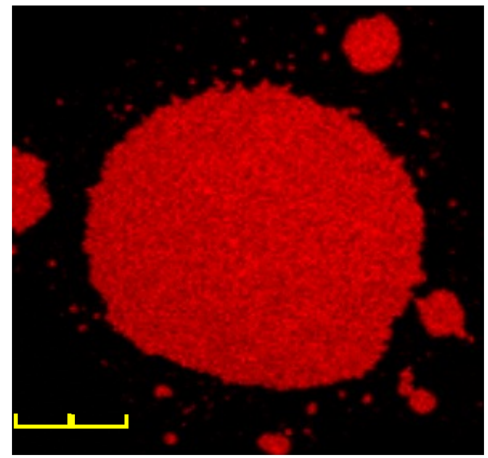
Stretching experiments

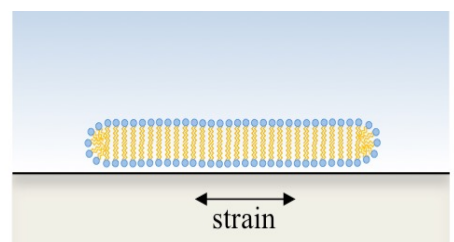




bi-axial

uni-axial



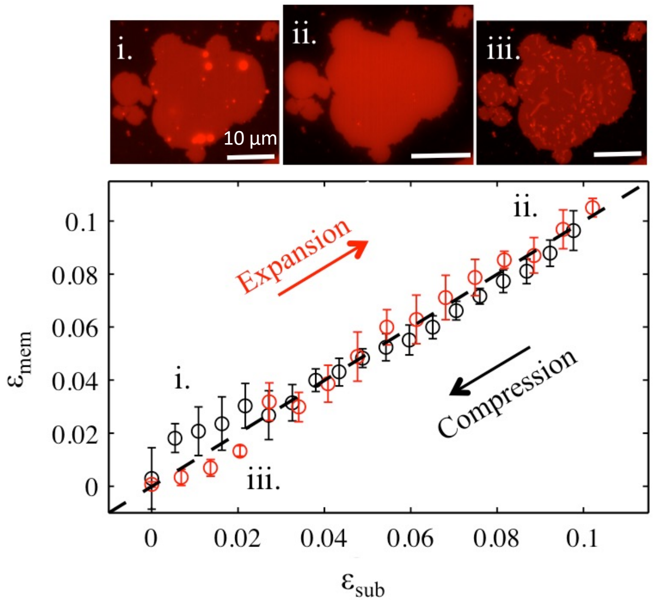


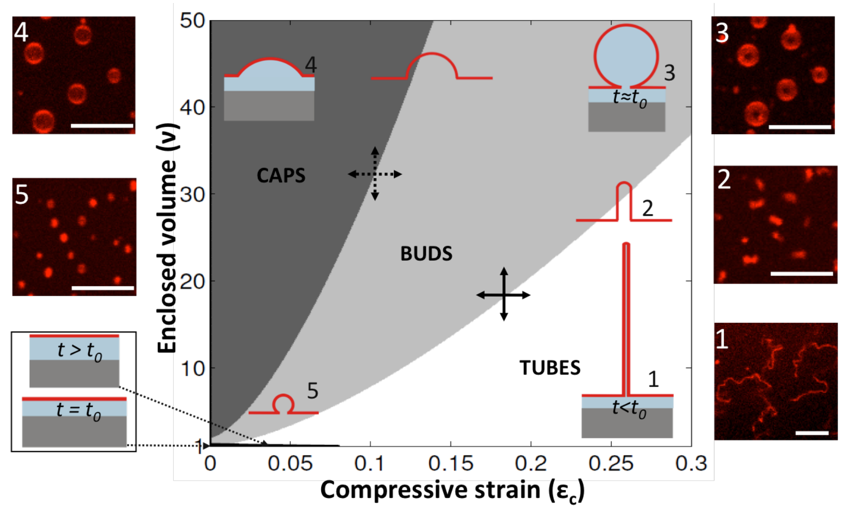
DOPC/
Rh-DPPE

Membrane buckling upon compression

(substrates with hydrophobic pinning points)

PNAS 108 (2011);
PRL 110 (2013);
Soft matter 32 (2017)



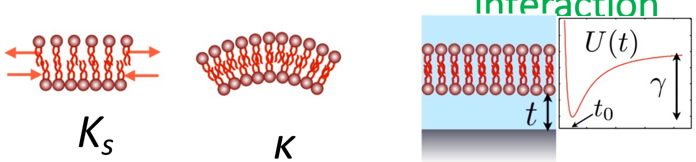


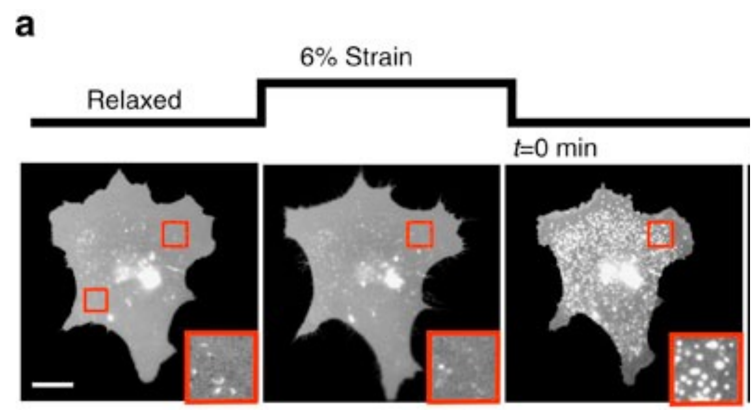
$$f = \frac{K_s}{2}\left(\phi^{+2} + \phi^{-2}\right) + \frac{\kappa}{2}H^2 + U(t)$$

Elastic

Bending

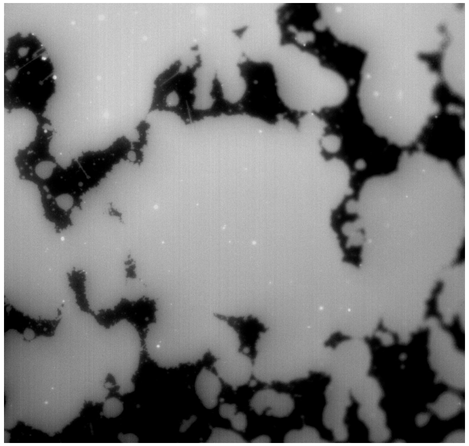
Bilayer-substrate interaction

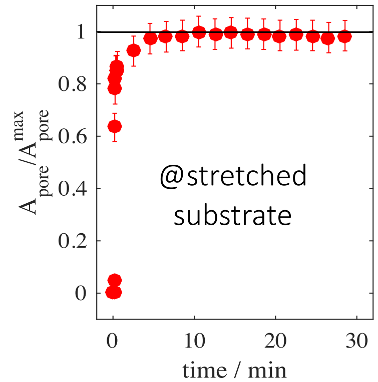


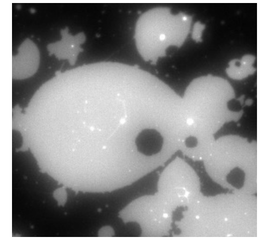


Kosmalska et al., Nat Comm 2015

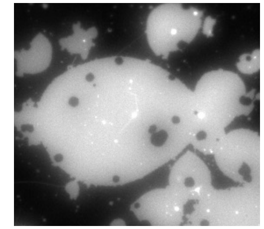
Pores upon *bi-axial* stretch (hydrophilic substrates)





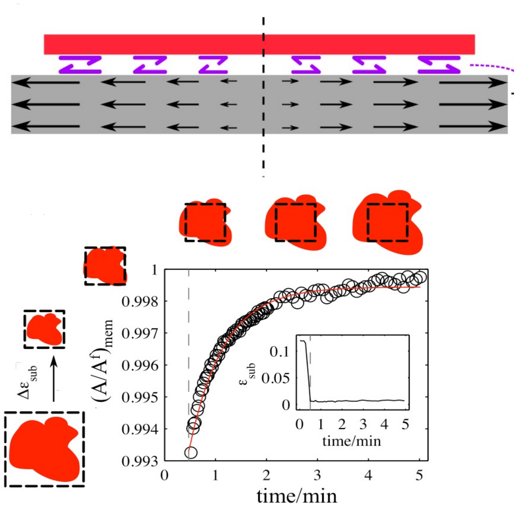


$\dot{\varepsilon} \sim 0.05\ \%\ s^{-1}$



$\dot{\varepsilon} \sim 0.4\ \%\ s^{-1}$

Characteristic length-scales



Characteristic length over which tension propagates:

$$L_c = \sqrt{\frac{K_s}{b\dot{\varepsilon}}}$$

Stretching modulus
$K_s = 0.1\ Nm^{-1}$
b- friction coefficient

When $R_{patch} > L_c$ multiple pores open

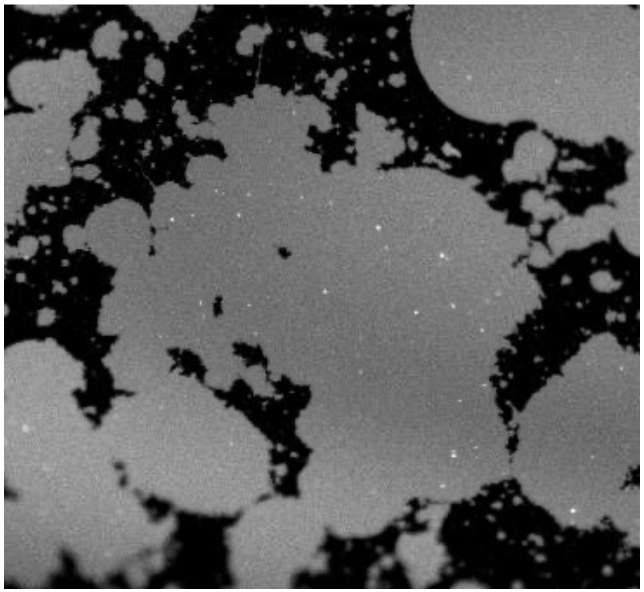
$$\tau = \frac{b R_{pore}^3 e}{\gamma}$$

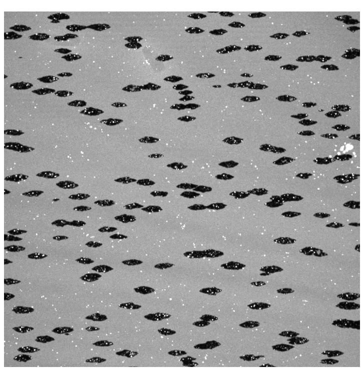
Edge tension
$\boldsymbol{\gamma}$ = 10 pN

Takes tens of hours to reseal the pores

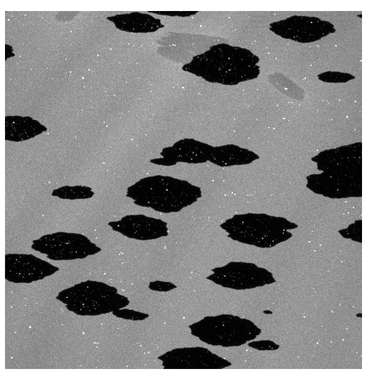
Sliding is opposed to dynamic friction

Elliptic pores upon *uni-axial* stretch.
Mechanism?

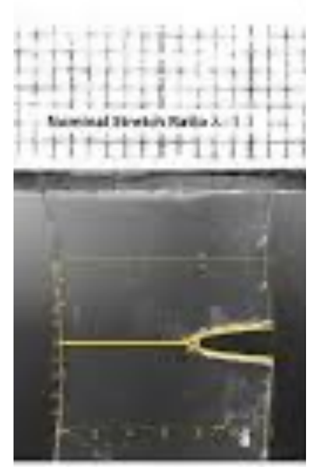




$\dot{\varepsilon} \sim 0.3\ \%\ s^{-1}$



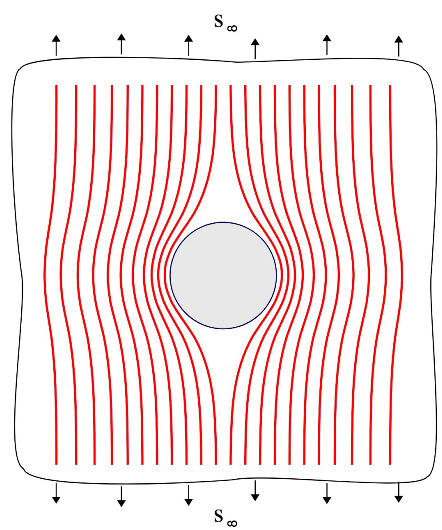
$\dot{\varepsilon} \sim 0.01\ \%\ s^{-1}$



(a)

Akin to elastic fracture of solid materials (hydrogels)

Guo et al., JMPC '18



Stress concentration around holes in solid materials

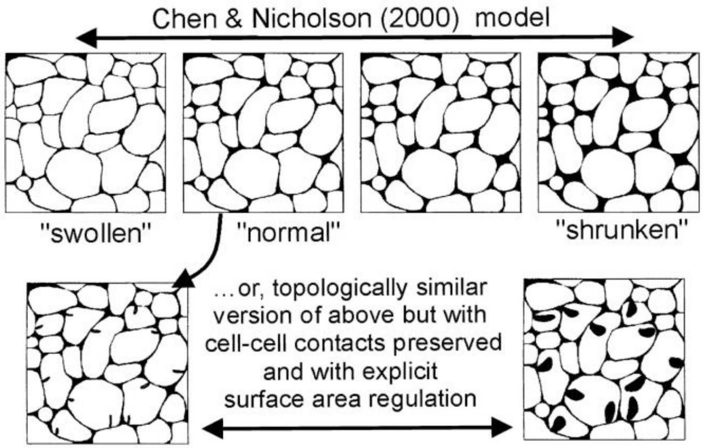
Marino Arroyo

Céline Dinet

Alejandro Torres-Sánchez

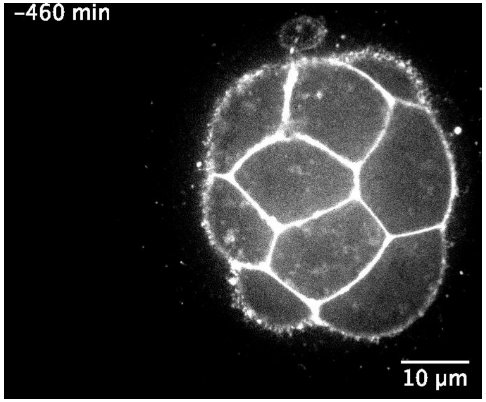
Hydraulic Fracturing at Membrane interfaces

Brain tissue tortuosity?



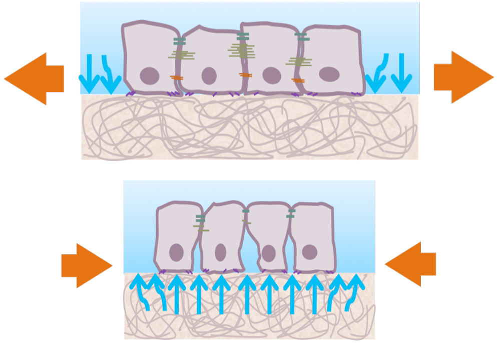
Morris et al.,
Biophys J 1999

Formation of embryo lumen



Dumortier et al.,
Science 2019

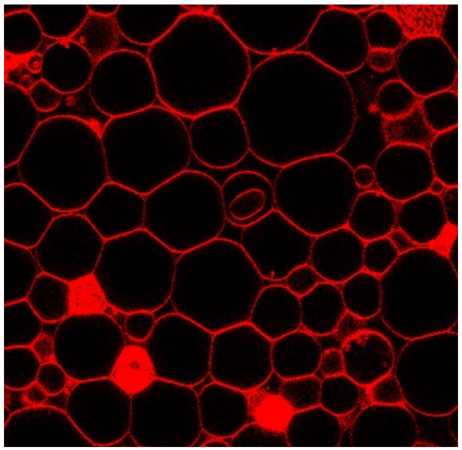
Fracking in epithelial sheets



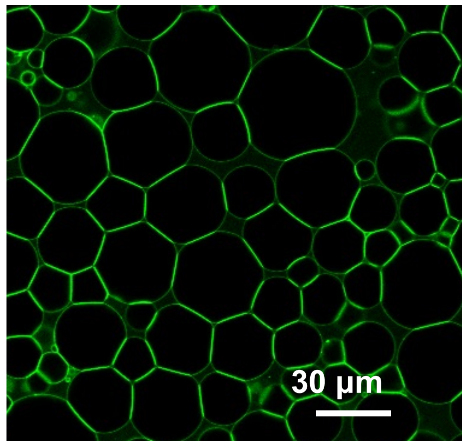
Casares et al,
Nat Mat 2015

Experimental system

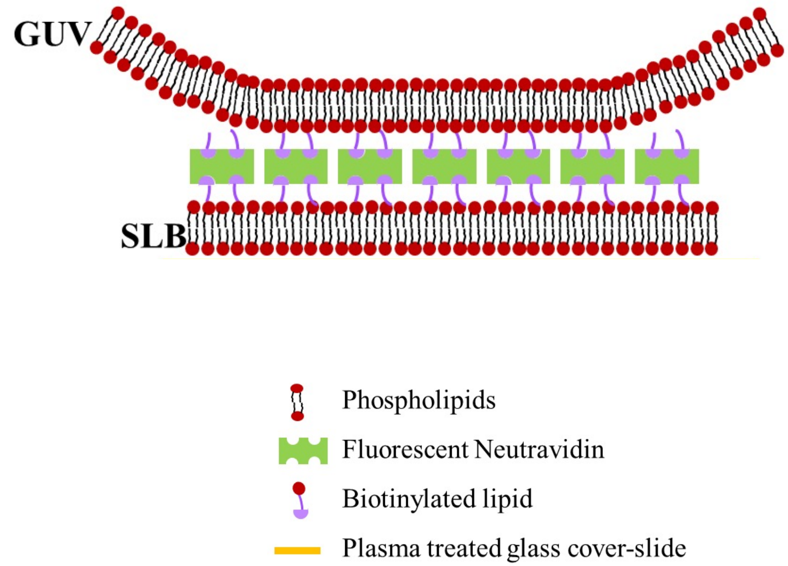
Artificial tissue made of vesicles

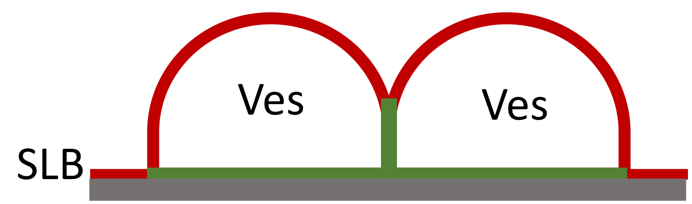


Membrane channel
(Rhodamine)



Protein linker channel
(Neutravidin-Dy488)





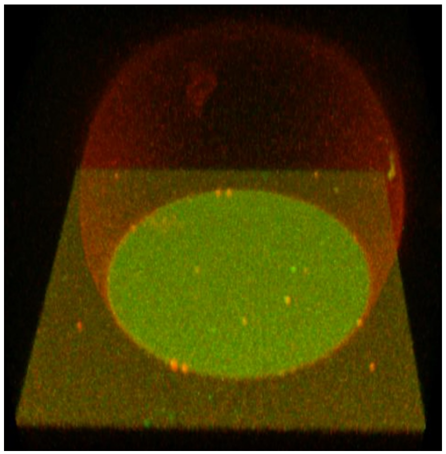
We vary:

- Magnitude of the osmotic shock: (25-100mM)
- Linker density: 0.2 - 4mol %
- Linker type: NaV, DNA, E-cadherins

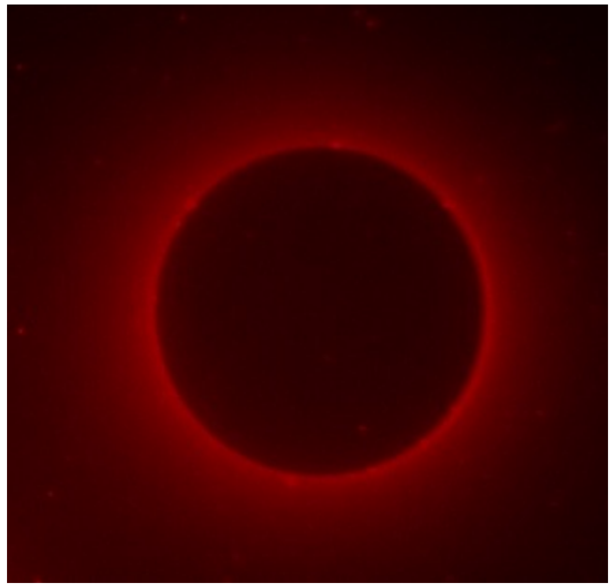
We image:

- Vesicle-SLBplane
- Vesicle-Vesicle plane

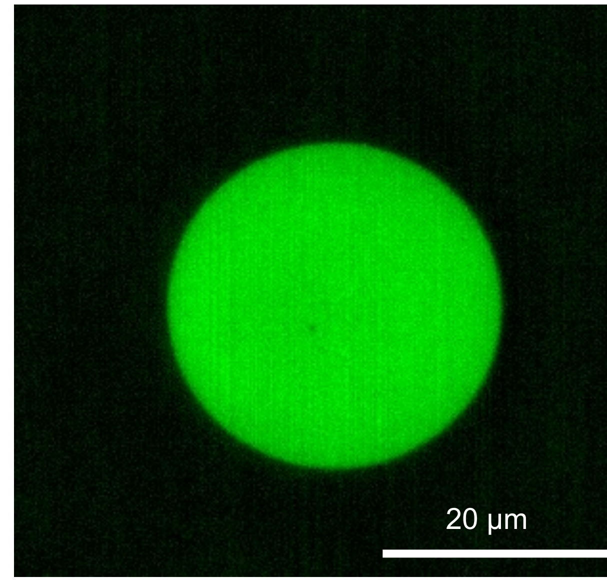
Hydraulic fractures at membrane adhesion contacts

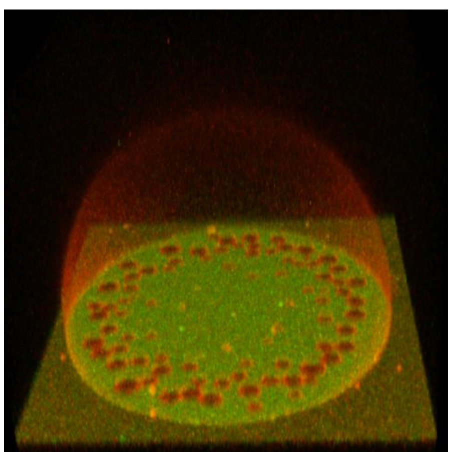


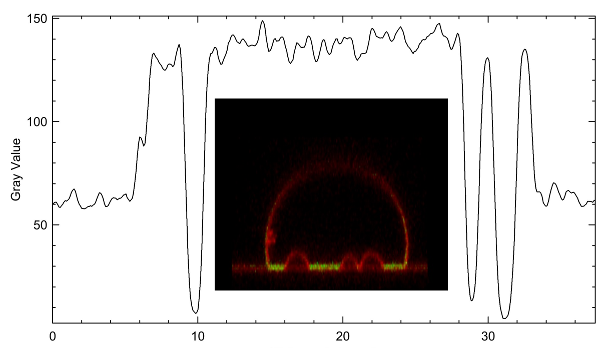
Lipid Membrane

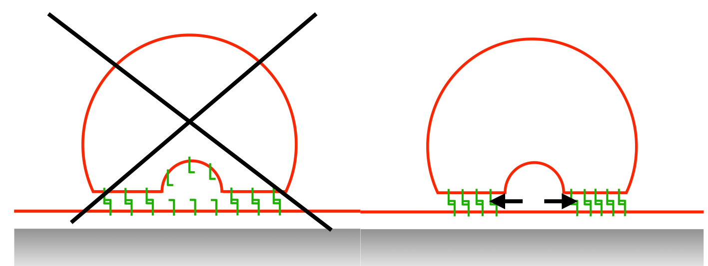


Neutravidin

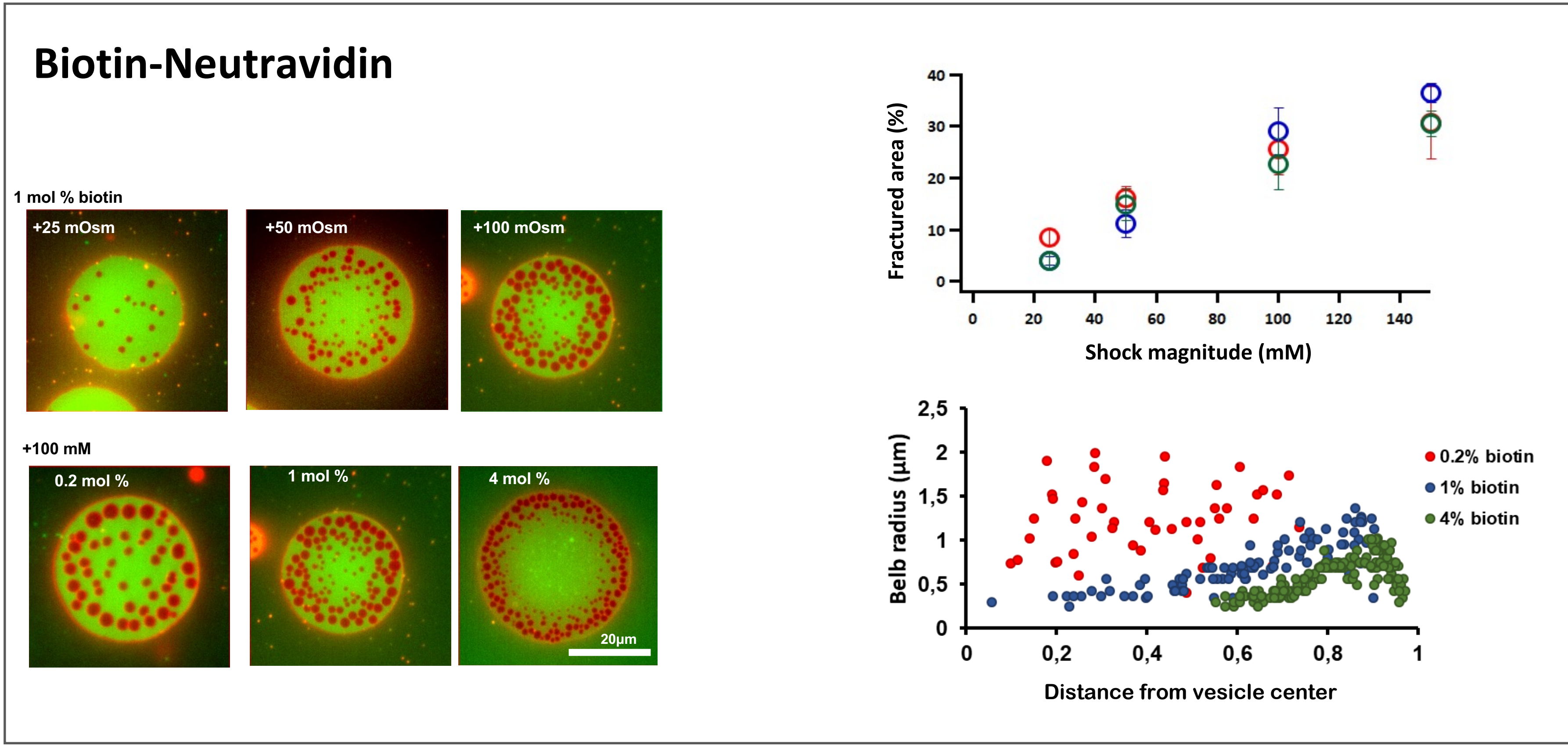




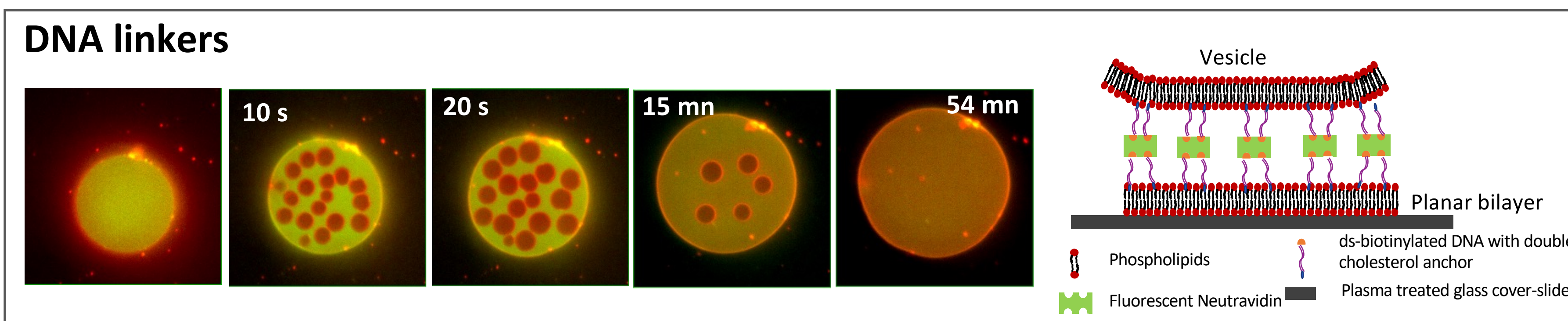




Belbs- by fast redistribution of linkers



Biotin-Neutravidin
1 mol % biotin
+25 mOsm
+50 mOsm
+100 mOsm
+100 mM
0.2 mol %
1 mol %
4 mol %
20µm
Fractured area (%)
40
30
20
10
0
0
20
40
60
80
100
120
140
Shock magnitude (mM)
Belb radius (µm)
2,5
2
1,5
1
0,5
0
0
0,2
0,4
0,6
0,8
1
Distance from vesicle center
0.2% biotin
1% biotin
4% biotin



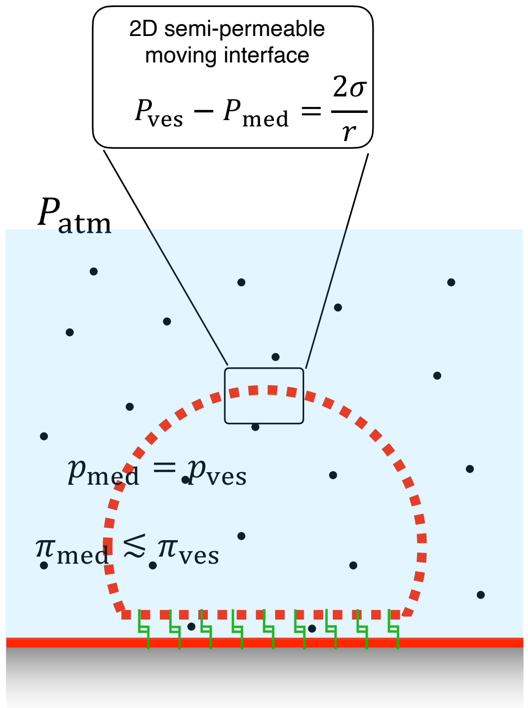
DNA linkers
10 s
20 s
15 mn
54 mn
Vesicle
Planar bilayer
Phospholipids
ds-biotinylated DNA with double cholesterol anchor
Fluorescent Neutravidin
Plasma treated glass cover-slide

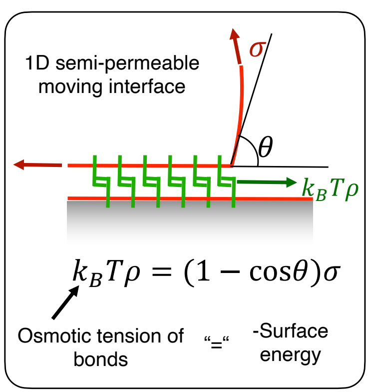
Mechanism

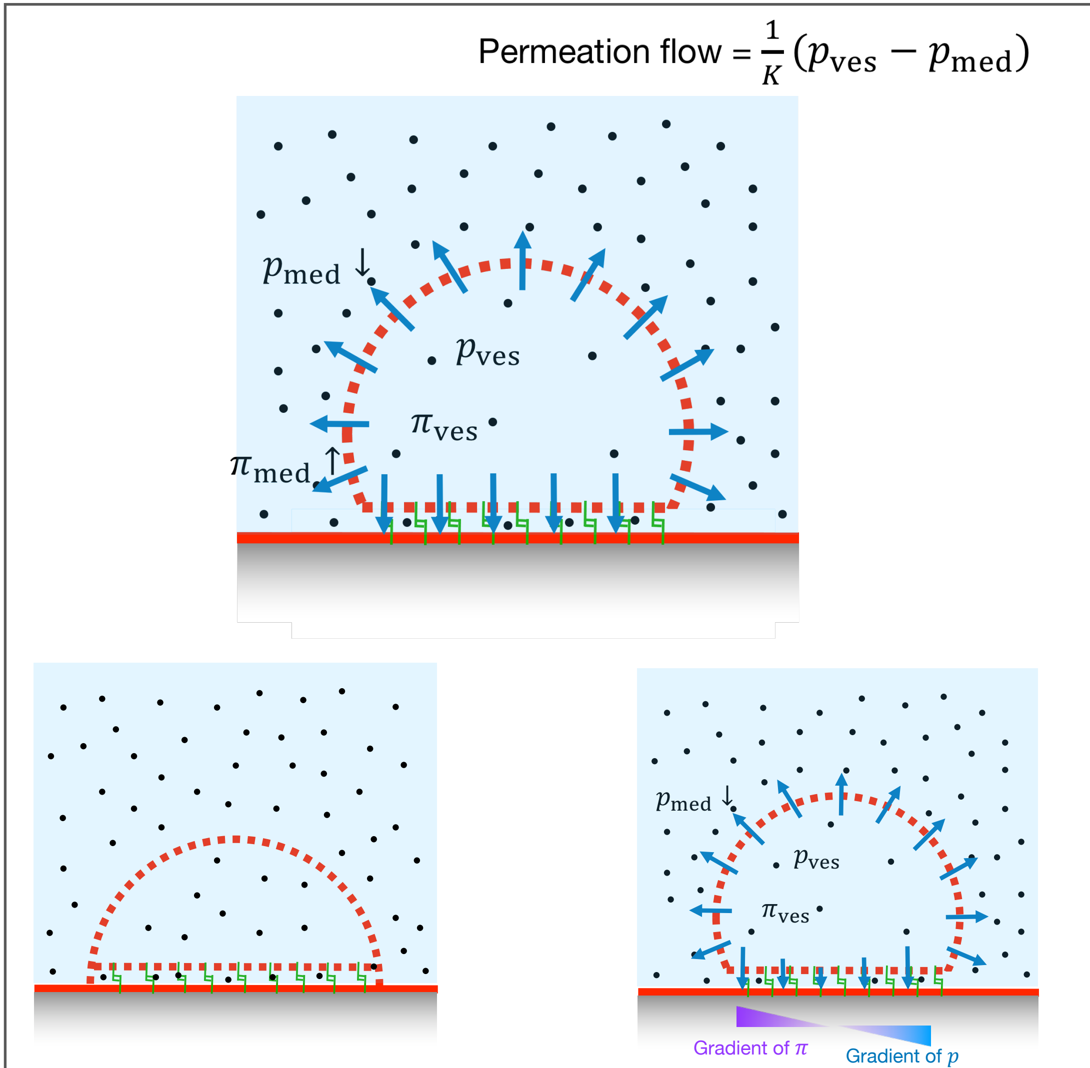
Water partial pressure p

Osmotic pressure π

Mechanical pressure $P = p + \pi$



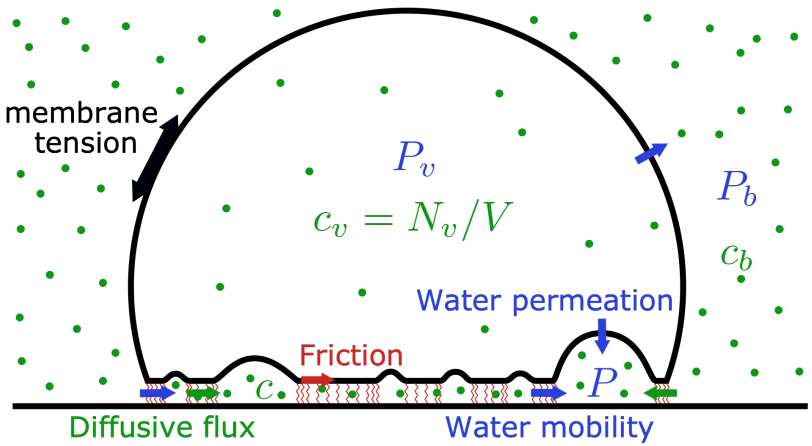




Fast osmolyte diffusion
No hydraulic confinement

Finate osmolyte diffusion
Some hydraulic confinement

Model



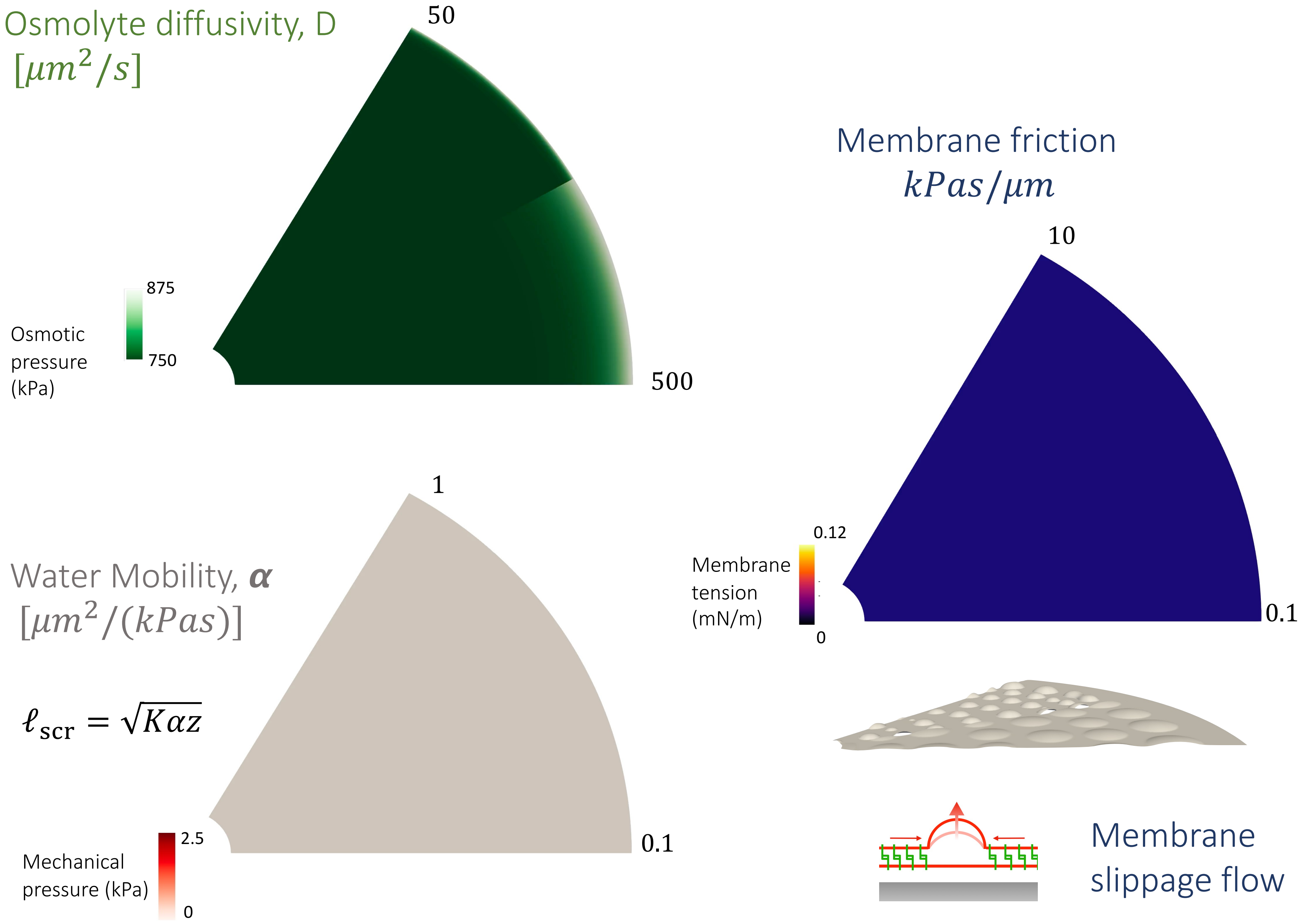
Ingredients:

- Mechanics of fluid membrane in/out-of-plane.
- Water transport
- Osmolyte transport
- Adhesion molecule dynamics (advection, reaction, diffusion)

- Size of vesicle/patch ☑
- Number of linkers ☑
- Osmolarity and magnitude of shock ☑

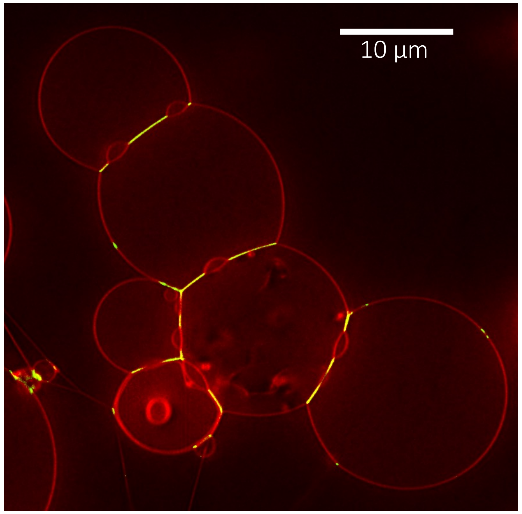
- Membrane viscosity ☑
- Membrane permeability ☑
- Length of bonds ☑
- Stiffness of bonds ☑

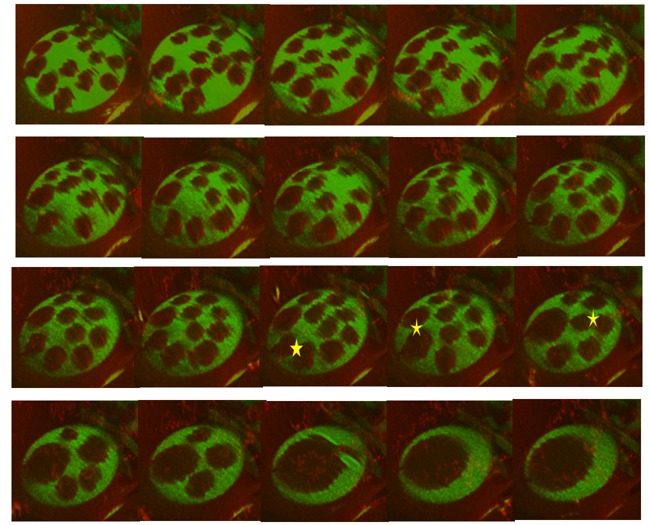
- Membrane friction
- Darcy permeability of interstitial space
- Diffusivity of osmolytes in interstitial space



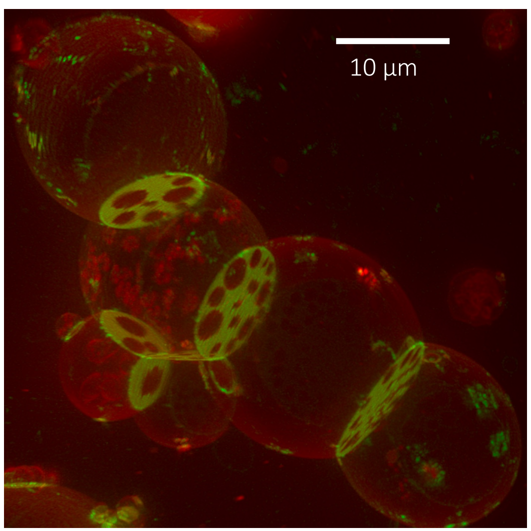
Osmolyte diffusivity, D
$[\mu m^2/s]$
50
500
875
750
Osmotic pressure (kPa)
Membrane friction
$kPas/\mu m$
10
0.1
0.12
0
Membrane tension (mN/m)
1
0.1
Water Mobility, $\boldsymbol{\alpha}$
$[\mu m^2/(kPas)]$
$\ell_{\mathrm{scr}} = \sqrt{K\alpha z}$
2.5
0
Mechanical pressure (kPa)
Membrane slippage flow

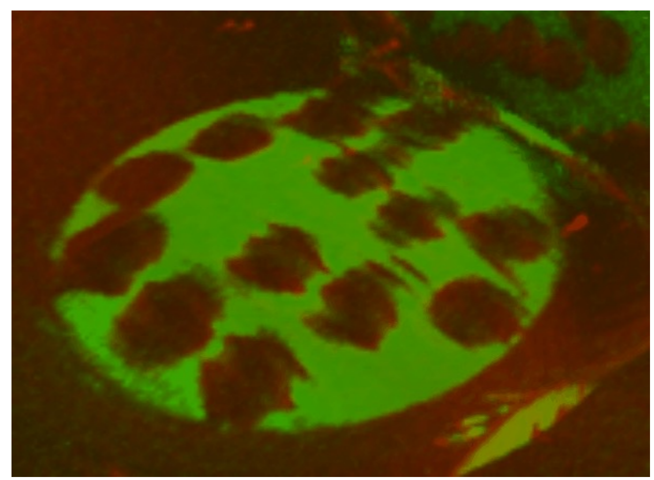
Fast dynamics at membrane-membrane interface





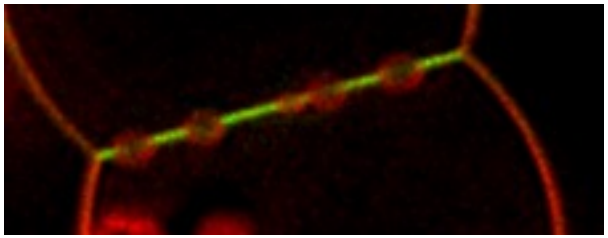
Time lapse: 20s

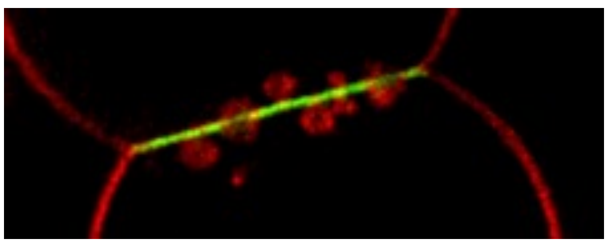


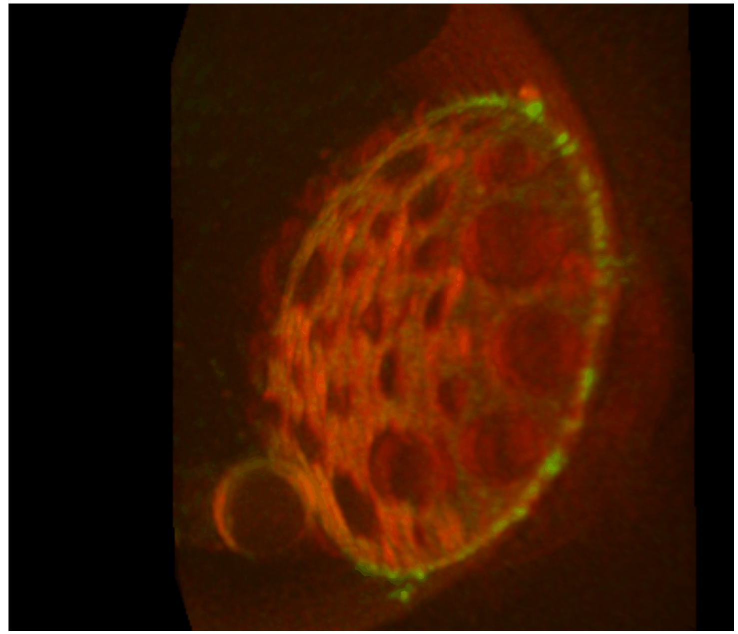


‘Endocytosis’

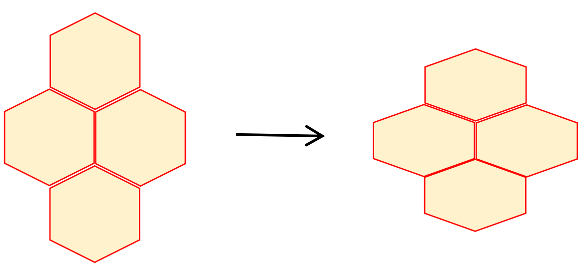
Higher linker density
Pulling apart the two vesicles



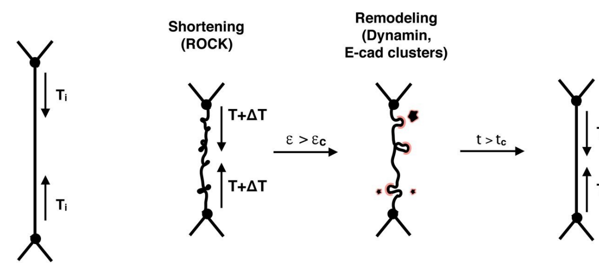




? Passive mechanism for shortening of cell contacts



.. a relevant mechanism for the reduction of junctional membrane area during tissue elongation

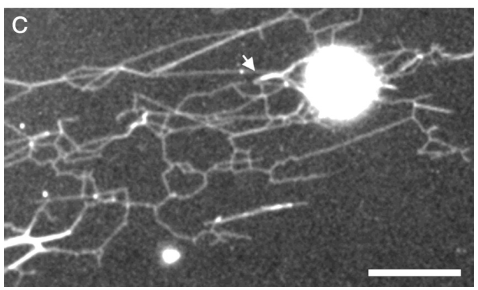


Cavanaugh et al’20

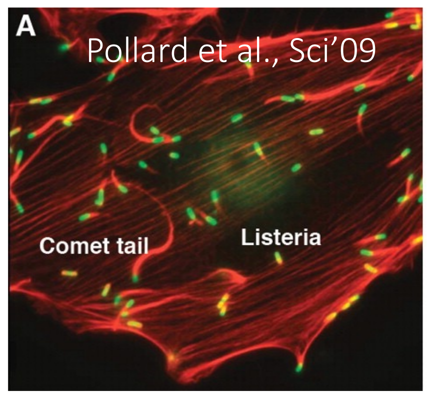
Lucas le Nagard

Wilson Poon

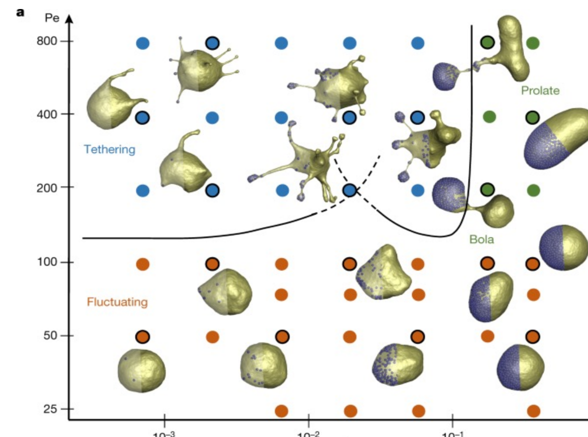
Swimming vesicles powered by bacteria



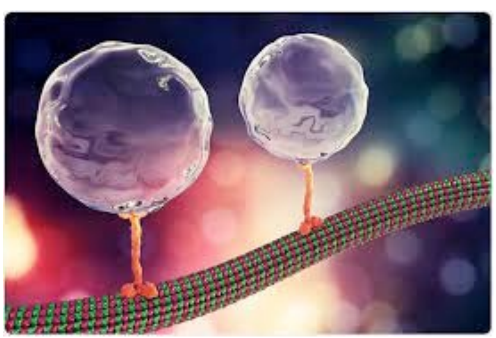
Koester, PNAS'03

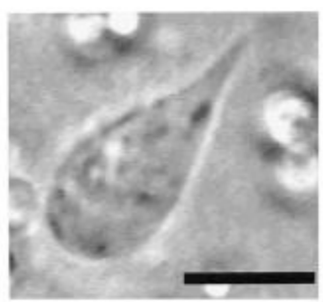


Pollard et al., Sci'09

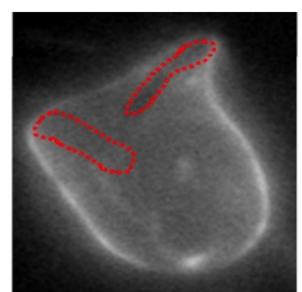


Vutukuri et al., Nature'20





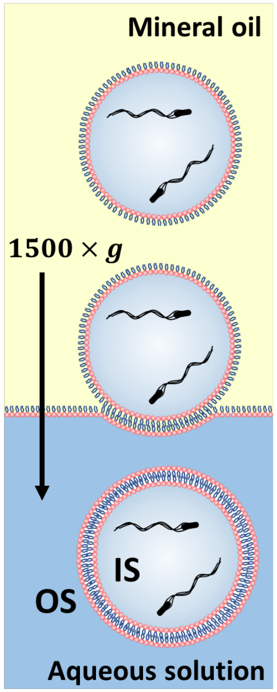
Miyata et al., PNAS'99

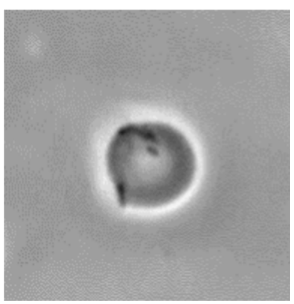


Takatori et al., PRL'20

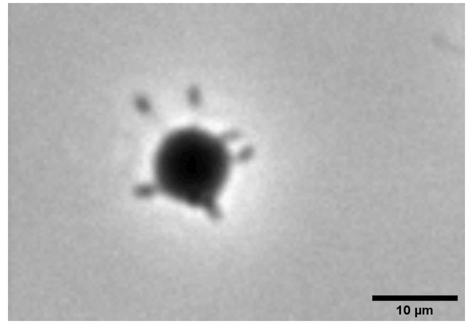
Bacteria push lipid tubes

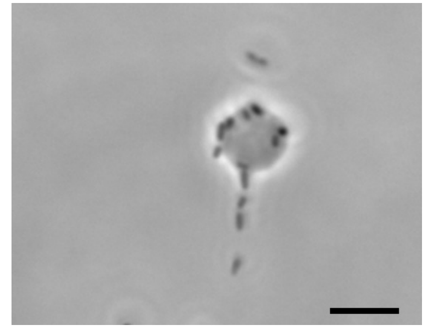
E. coli in POPC GUVs



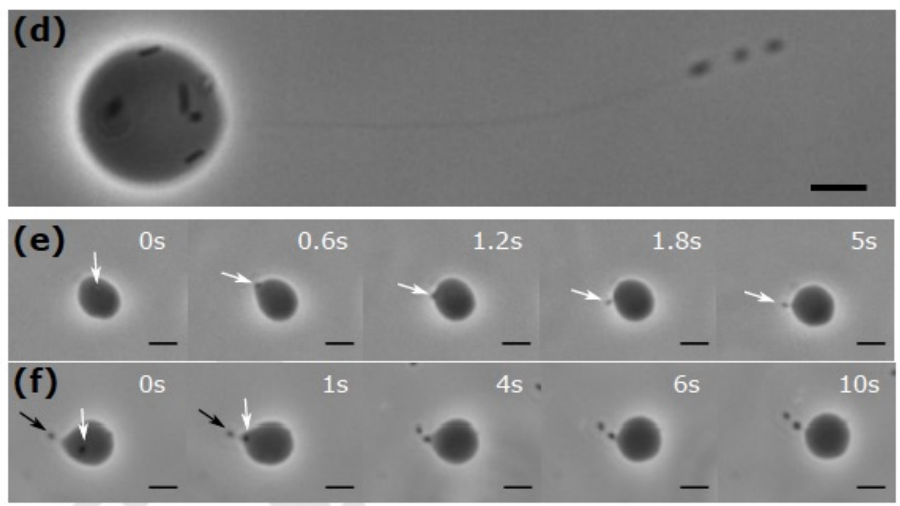


Tense vesicles

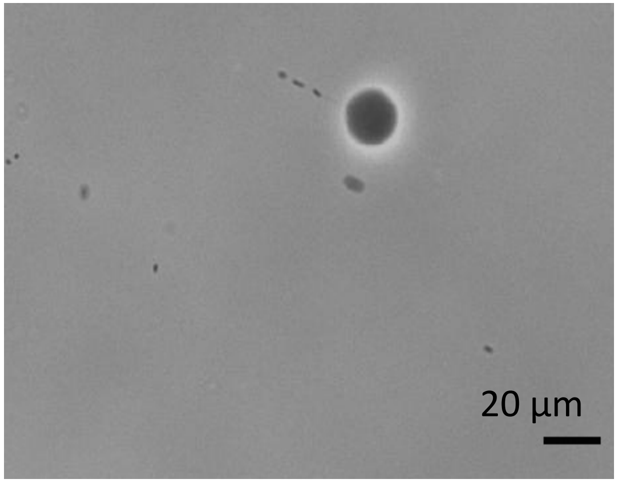


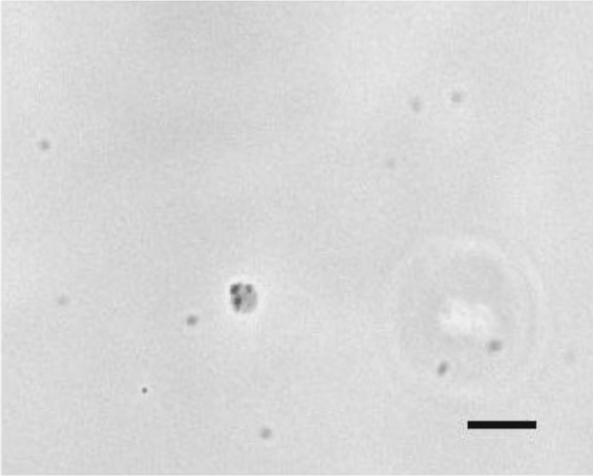


Low membrane tension allows bacteria to extrude tubes

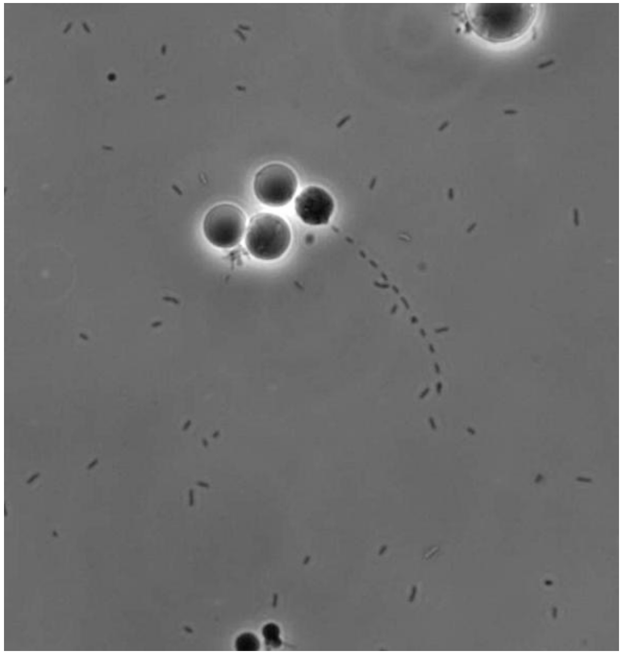


Vesicles propelled by bacteria





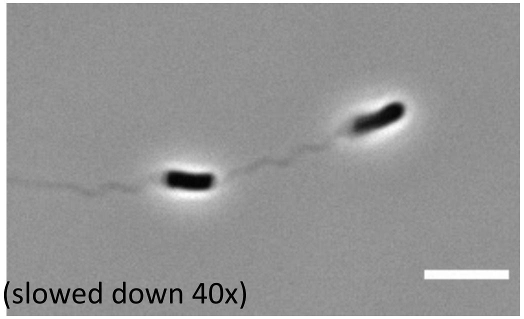
(accelerated 10x)

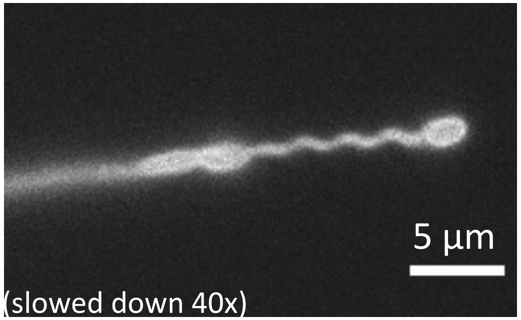


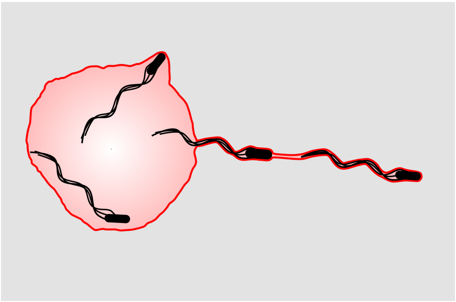
(accelerated 50 x)

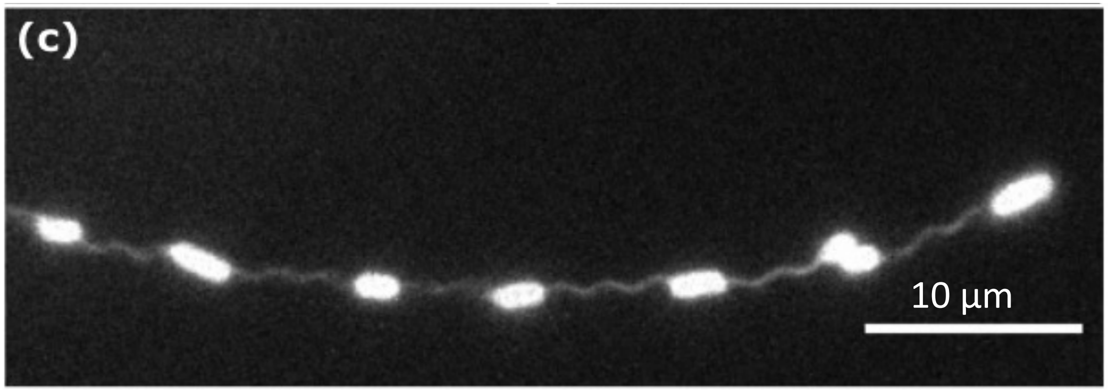
Typical speed of a GUV propelled by one bacteria : 1 $\mu m.s^{-1}$

Tube act as a flagellum







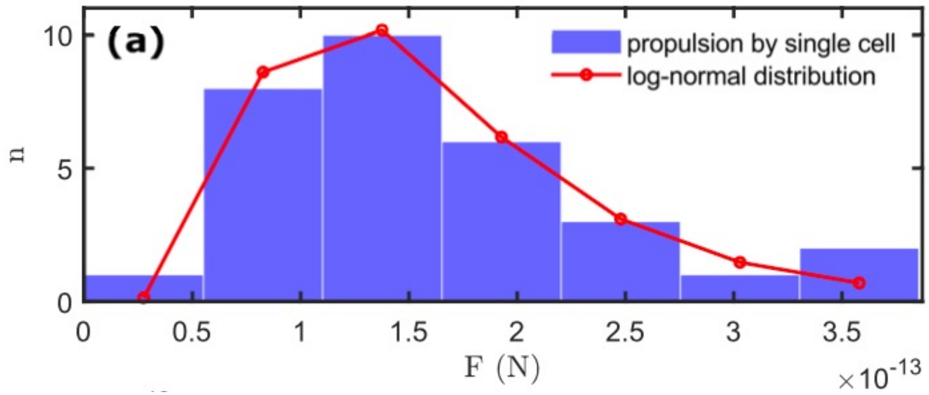


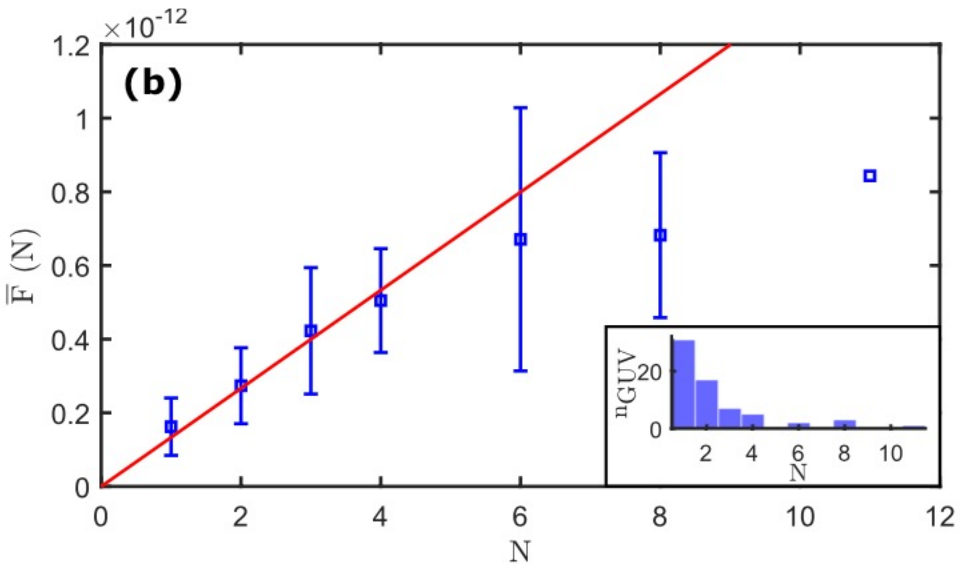
Lipid tube act as a flagellum for the propulsion of vesicle

Tube characteristics correspond to those of the flagella bundle:

- Rotation speed $\sim 60 - 100$ Hz
- Helix pitch ~ 2.3 µm
- Diameter ~ 0.4 µm

Propulsive force





Force-free swimmer at low Reynolds number: propulsive force F exactly balanced by drag force on the swimmer.

$$F = (\xi_{GUV} + N_b \xi_b)v$$

$N_b = 1, n = 31$

$\langle F \rangle = (1.6 \pm 0.5) \times 10^{-13}$N

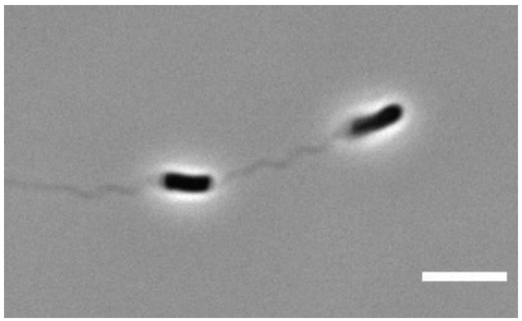
3x smaller than thrust force in bulk

$$\bar{F} = 1.3 \times 10^{-13} N_b\, N$$

Each additional cell in the tube contributes to increasing the resulting force

Questions

1. Why are tubes so thin?



Symmetric membrane, no spontaneous curvature

$$f = 2\pi\sqrt{2\kappa\sigma}$$

$$R = \sqrt{\frac{\kappa}{2\sigma}}$$

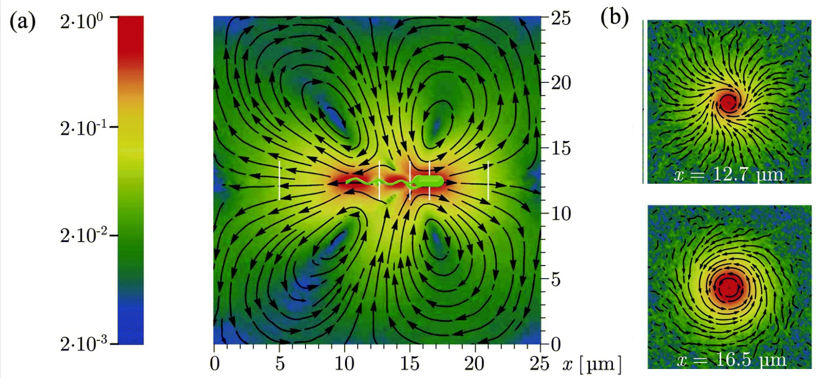
$f \sim 4.5^{-13}$ N — Bacteria thrust force

$\kappa \sim 10^{-19}$ J — Bending rigidity of POPC membrane

$R_{min} \sim 1.4\ \mu m$

2. Stability of tubes with large in plane shear?

Hu et al., Soft Matter'15



@ flagellum

@ body

Parallel to swimming plane

Perpendicular to swimming plane

3. Swimming of bacteria in membrane confinement?

- Vibrio species with membrane sheath
- Intracellular pathogens, such as Salmonella, deforming cell membranes