

Snap-through induced by surface tension

A. Fargette ← PhD work

A. Antkowiak

S. Neukirch



CNRS / Univ. P. & M. Curie / ENS Paris

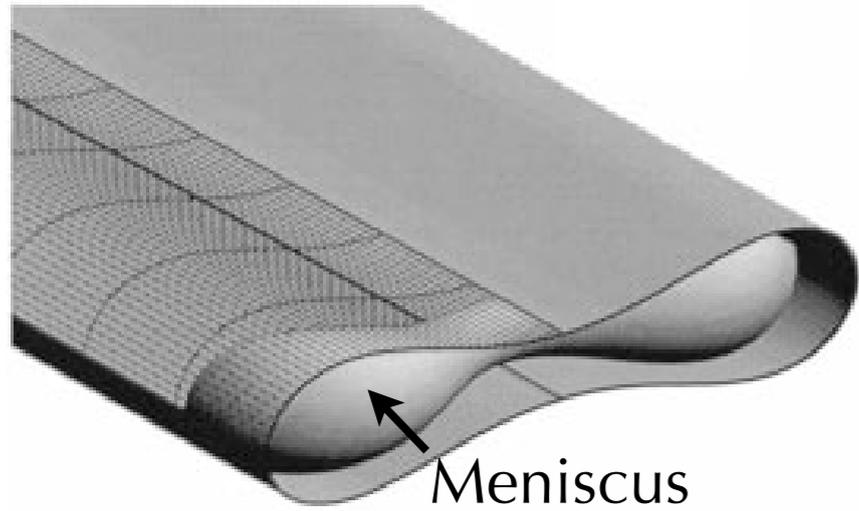
France

Elastocapillarity: (incomplete) state of the art

review article:

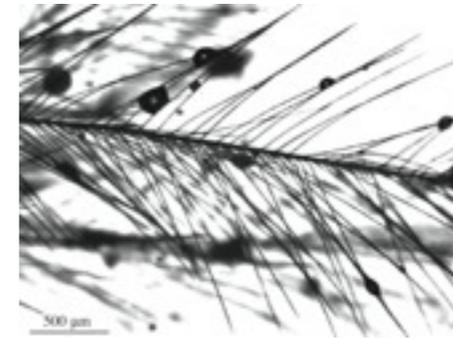
Roman + Bico (Journal of Physics: Condensed Matter) 2010

Elastocapillarity in Biology



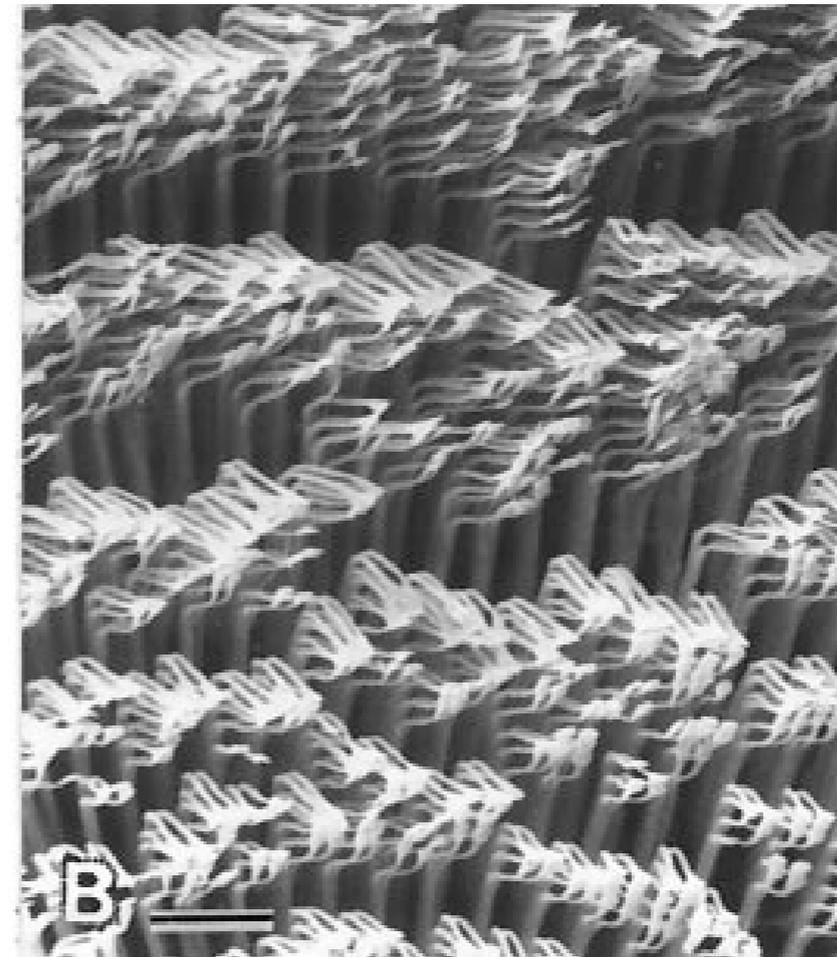
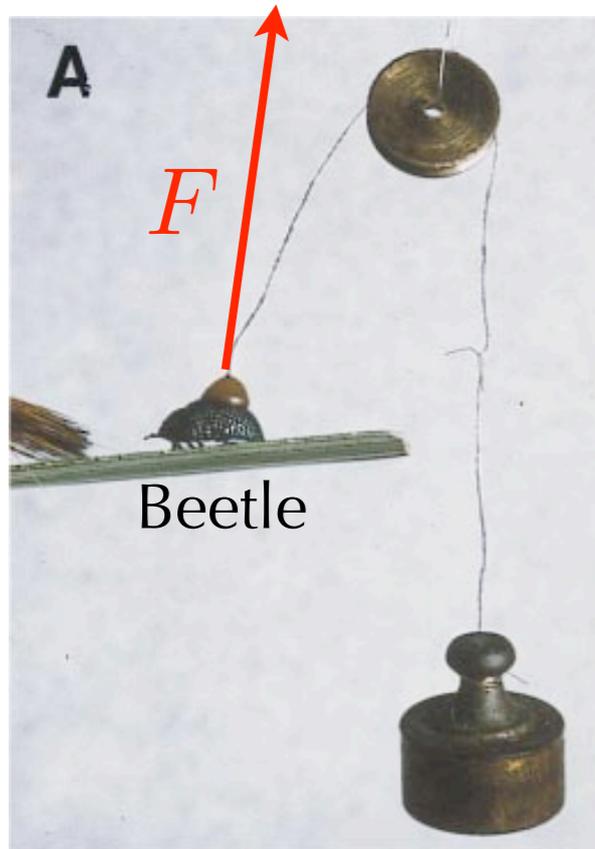
Lung's airway closure

e.g. Heil, J. Fluid Mech 380, 1999



Wet feathers

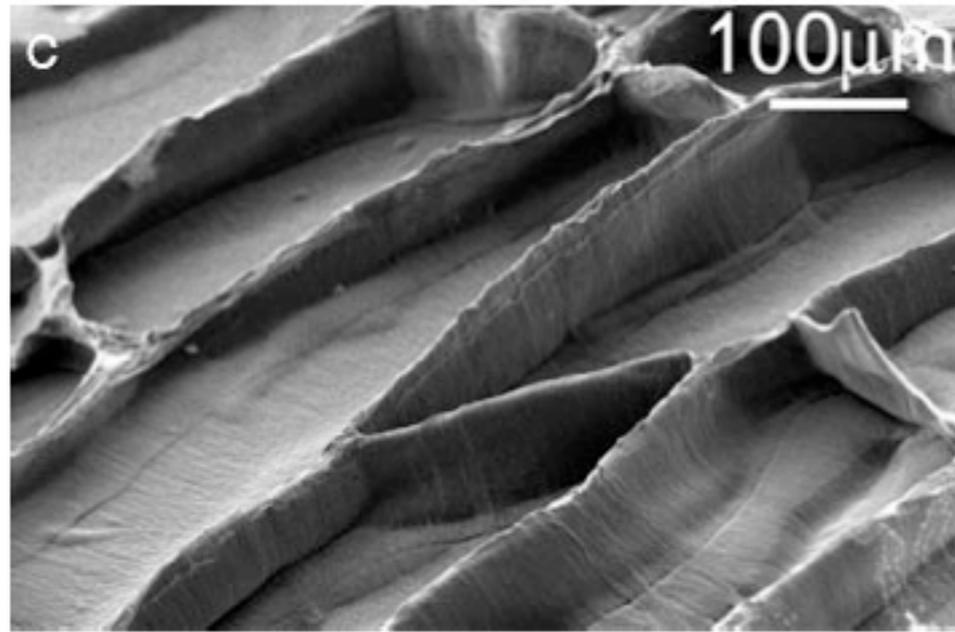
Duprat, Protière, Beebe and Stone, *Nature* (2012)



Insect adhesion

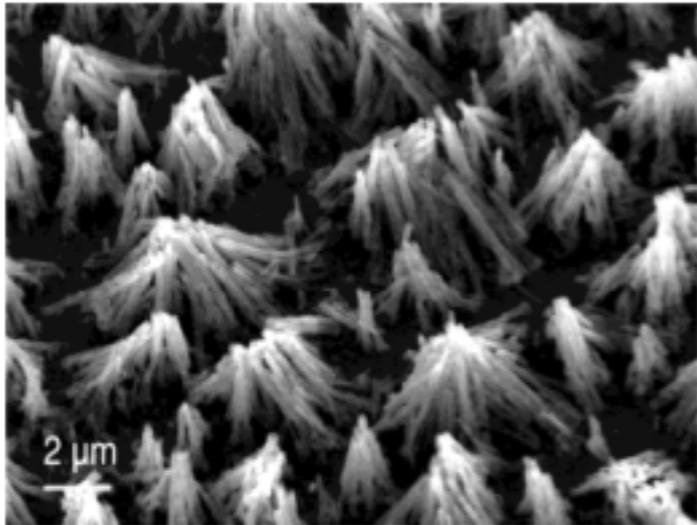
Eisner et al., PNAS, 2000

Elastocapillarity in Industry



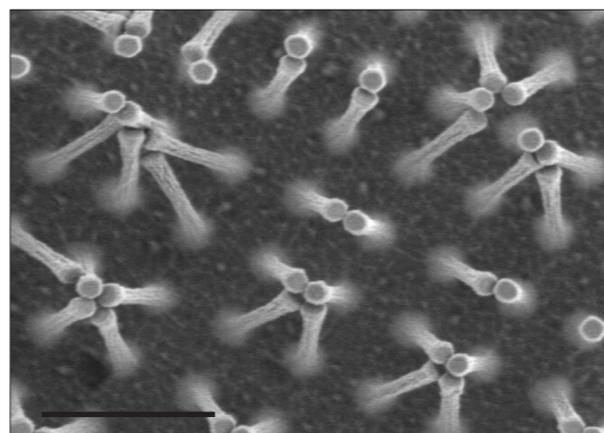
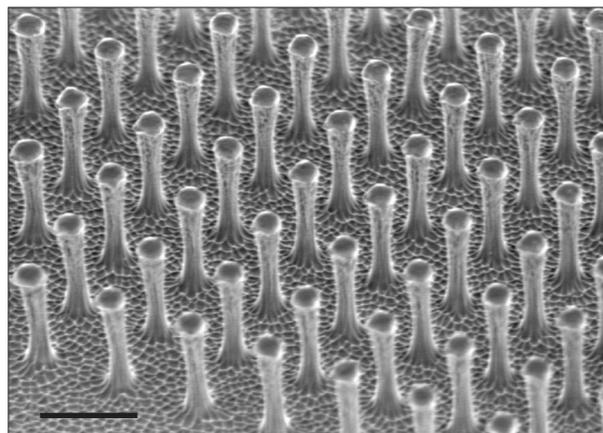
Cellular patterns

Chakrapani et al., PNAS, 2004



Teepee formation

Lau et al., Nano Lett., 2003



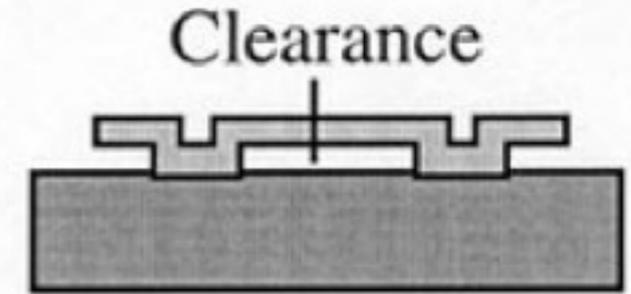
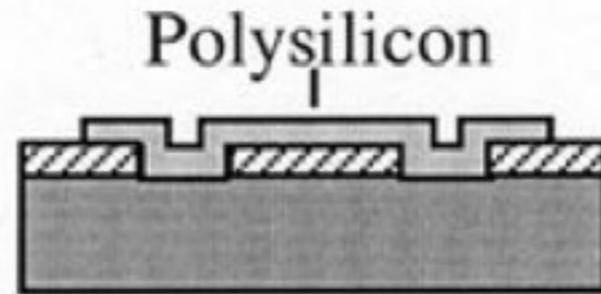
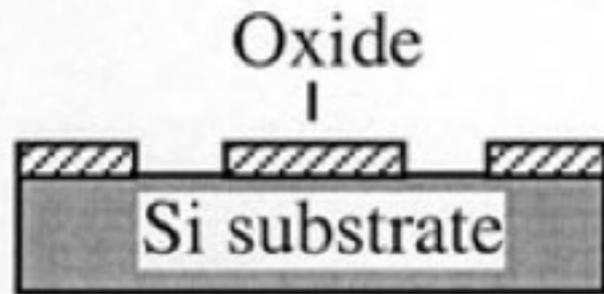
Bio-mimetism

Geim et al., Nature Mat., 2003

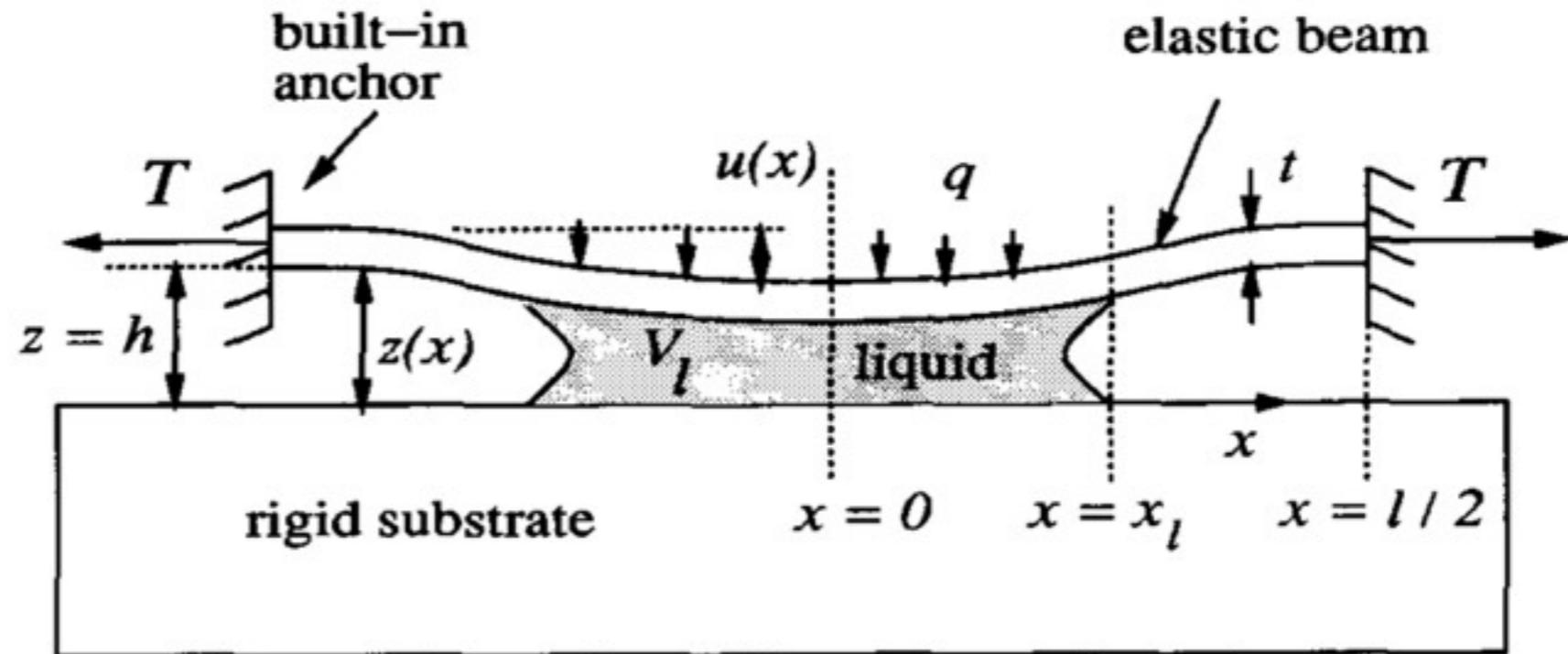
Elastocapillarity in Industry

suspended micromachined structures

Polysilicon micromachining



collapse during evaporation



surface tension forces are responsible for the collapse of microstructures during removal of sacrificial layers

Mastrangelo, Journal of MEMS (1993)

Elastocapillarity in Industry: Microfabrication

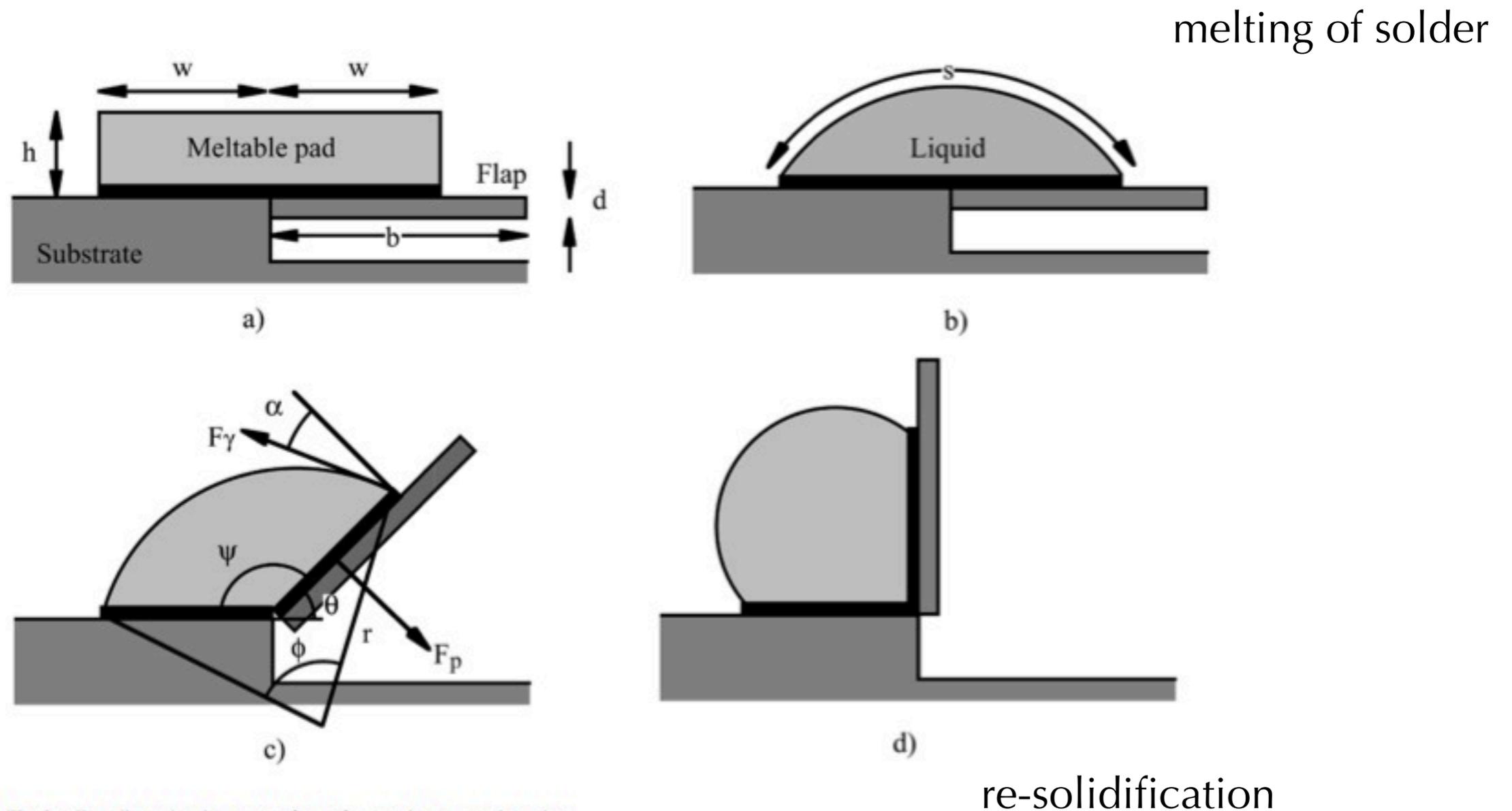
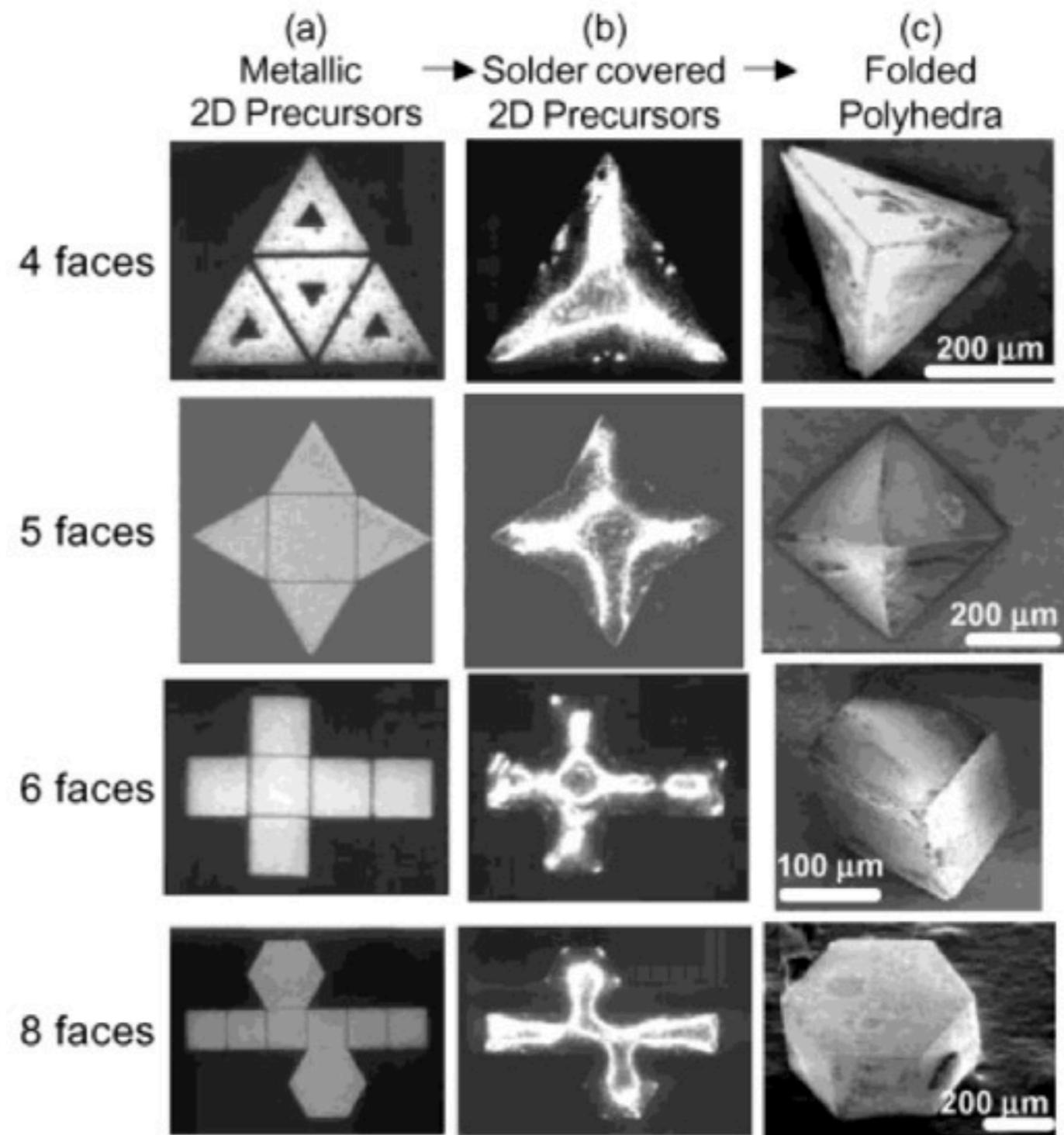
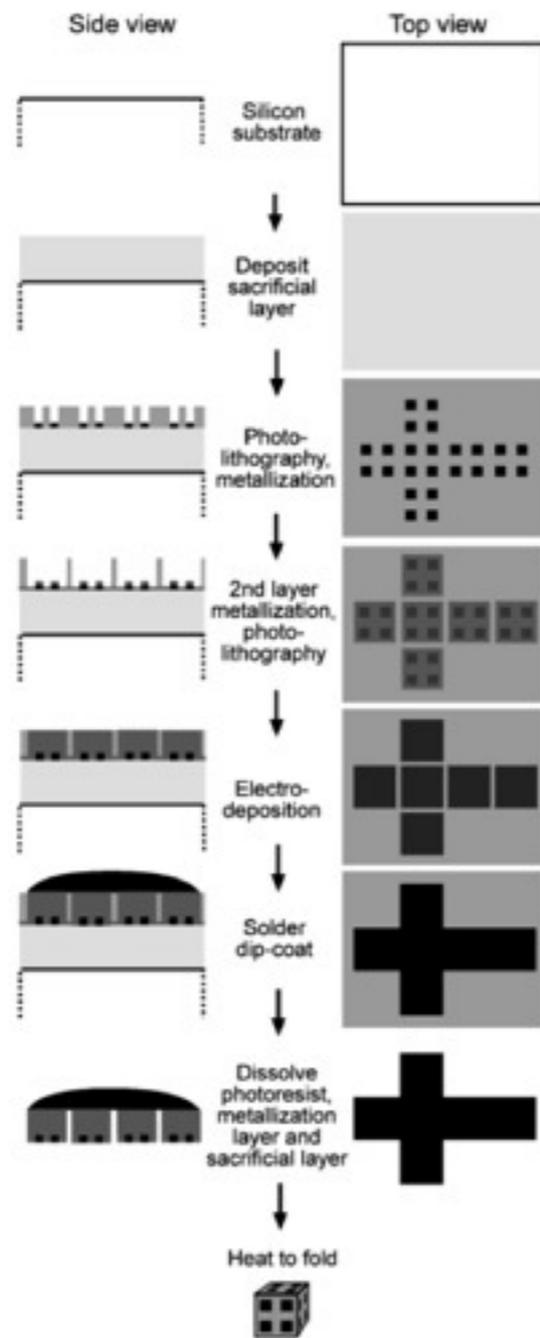


Fig. 3. Two-dimensional geometry for surface tension powered rotation.

rotate hinged joints for the self-assembly of 3D microstructures

R. Syms, Journal of MEMS (1995)

Elastocapillarity in Industry: Microfabrication

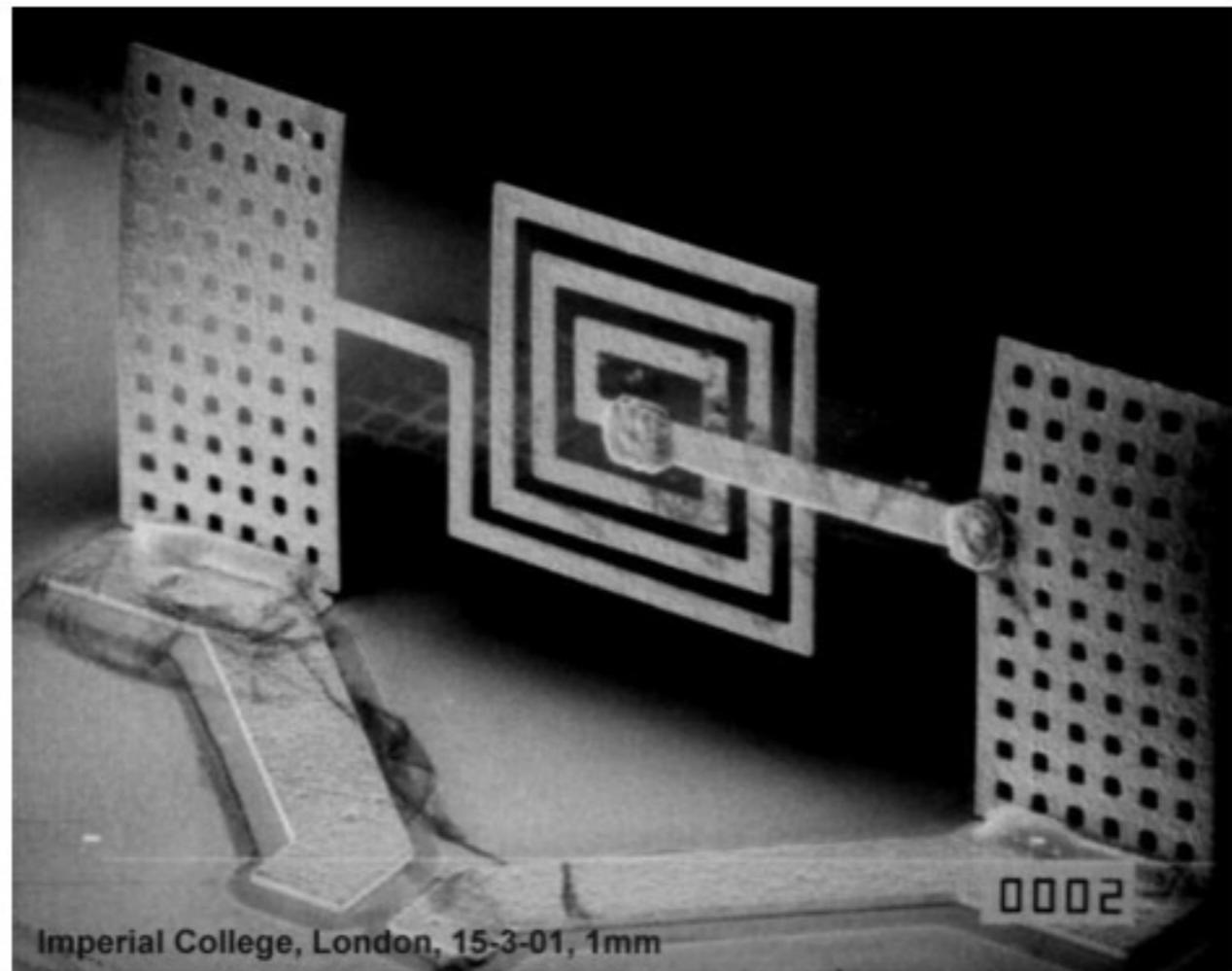


spontaneous folding of 2D structures under the influence of the surface tension of liquid solder

Gracias et al, Adv. Mat. (2002)

Elastocapillarity in Industry: Microfabrication

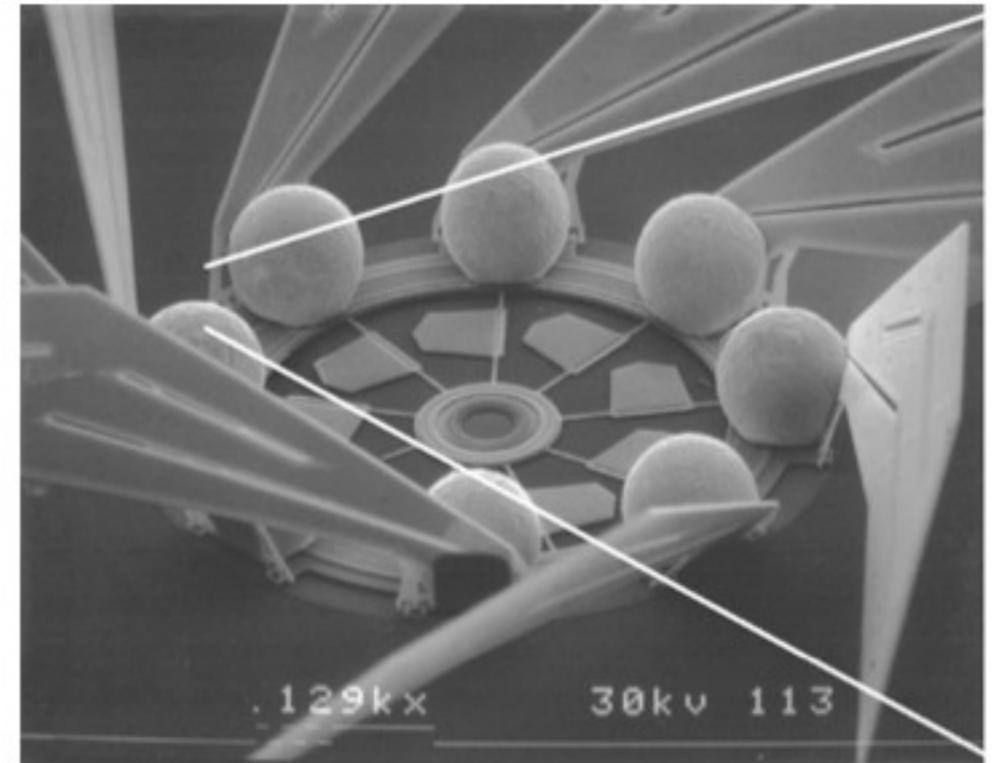
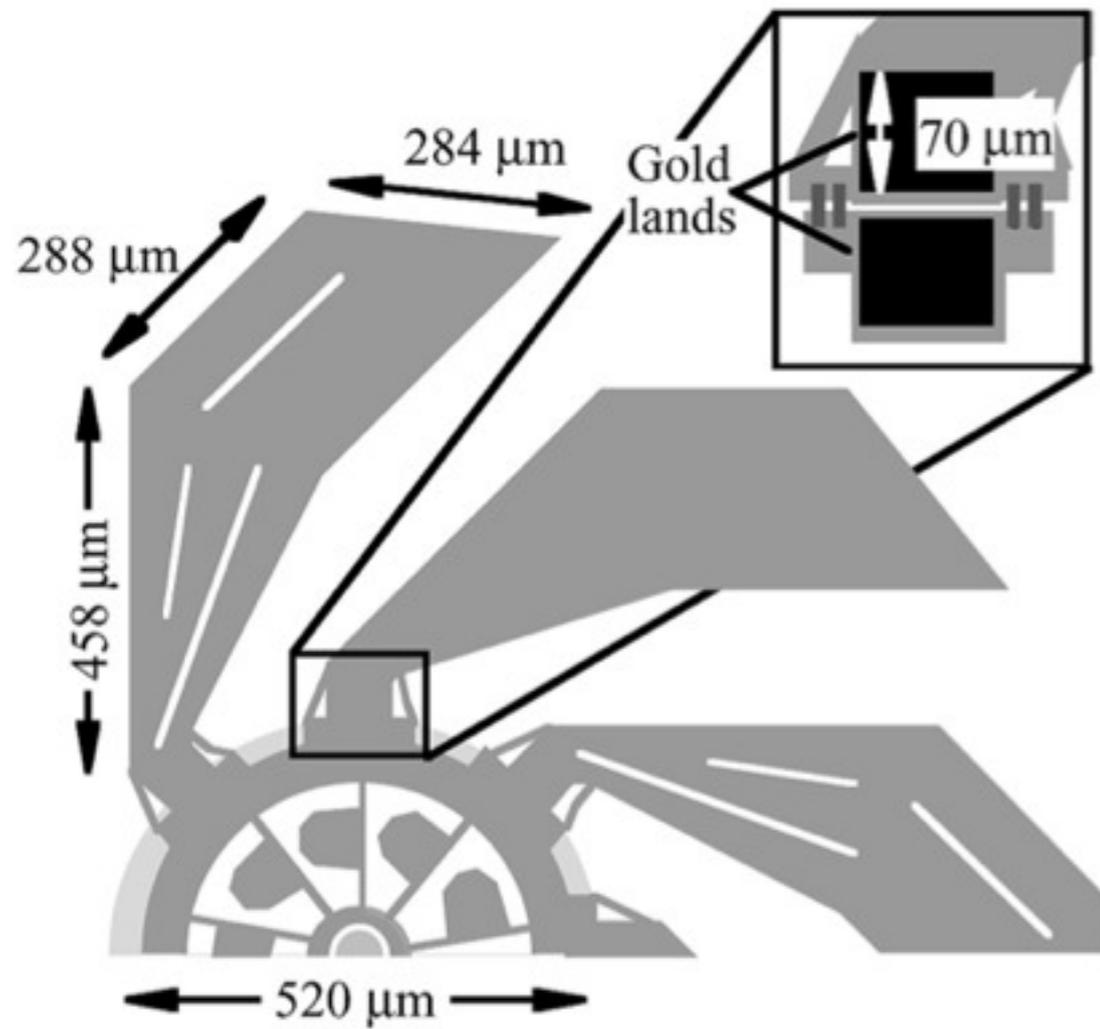
inductor has to be
away from (metallic) substrate to
prevent magnetic field loss



3D electrical components (here an inductor)
assembled by surface tension

Dahlmann, Electron Lett. (2000)

Elastocapillarity in Industry: Microfabrication



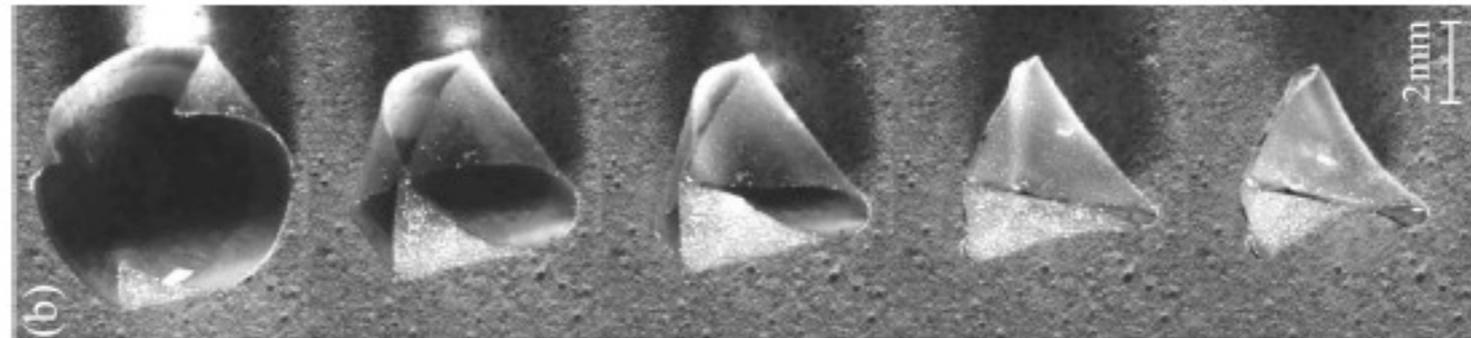
folding by surface tension of Pb:Sn solder spheres

microfan with polysilicon
180 rpm
micro-fluidic systems

Linderman et al, Sens. Actuators (2002)

Elastocapillarity in Industry: Microfabrication

Py et al
Capillary origami
Phys. Rev. Lett. 2007

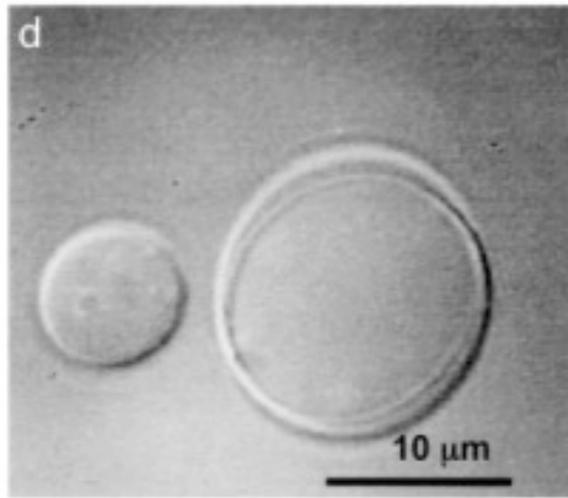


Guo et al., PNAS, 2009

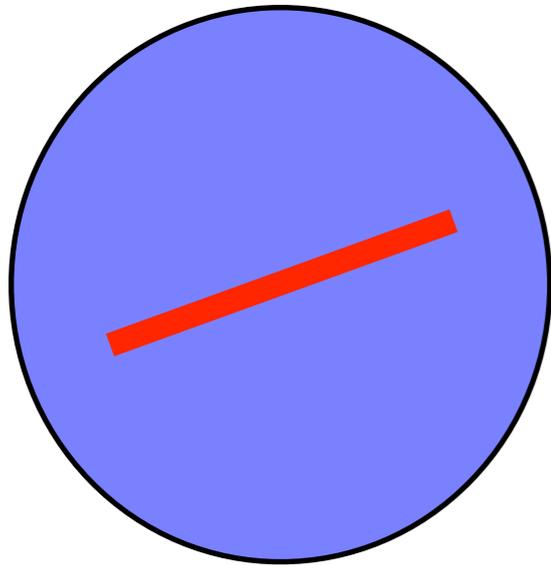
Applications: non-spherical lenses, 3D electronic circuits, curved micro solar panels, wrapping of active substances for targeted drug delivery...

The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

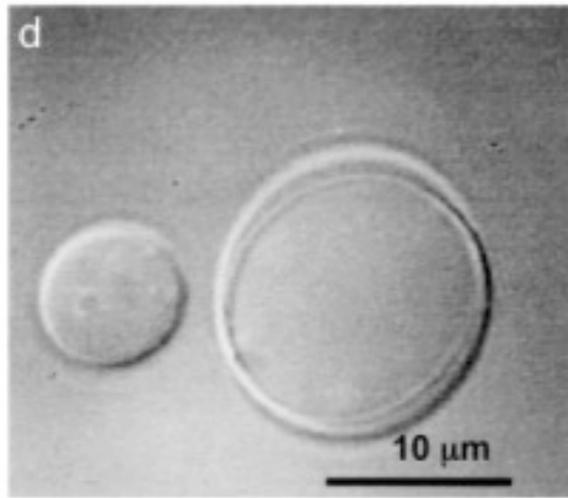


Cohen & Mahadevan, PNAS (2003)

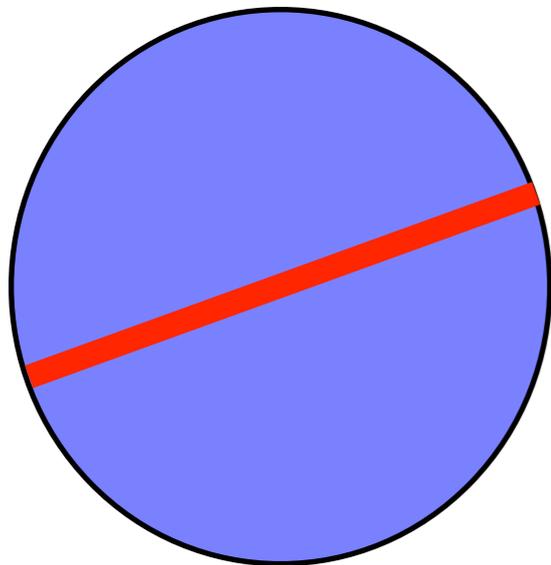


The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

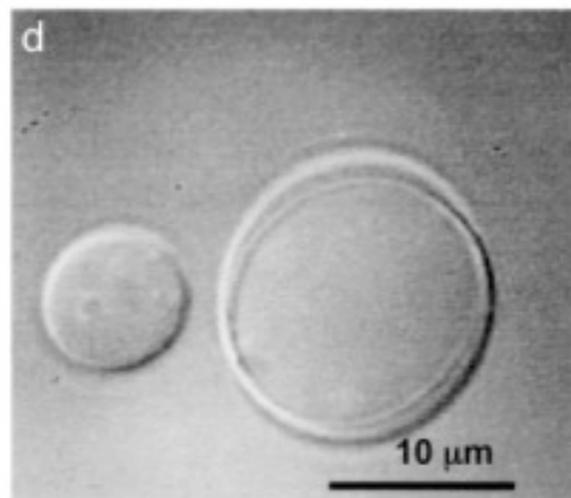


Cohen & Mahadevan, PNAS (2003)

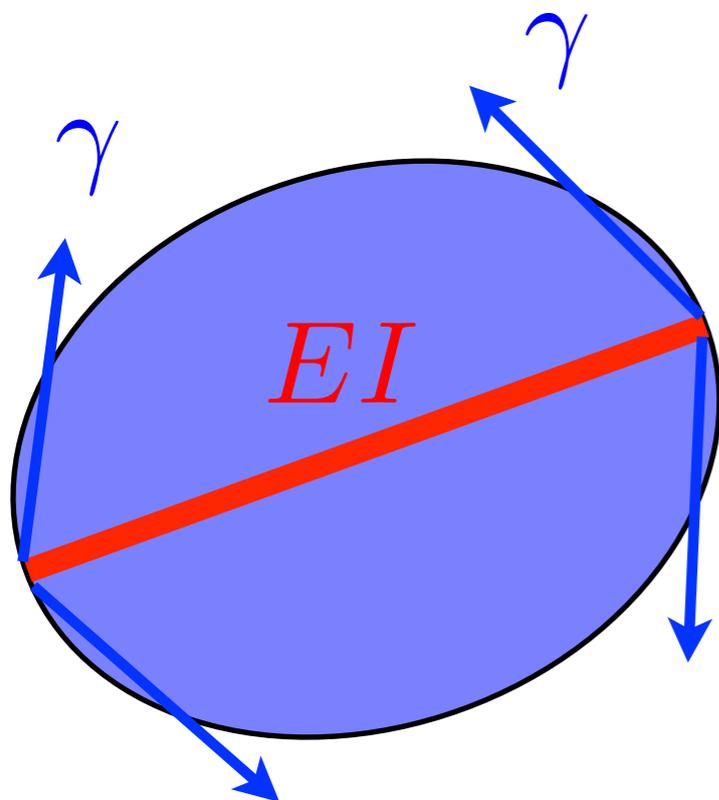


The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

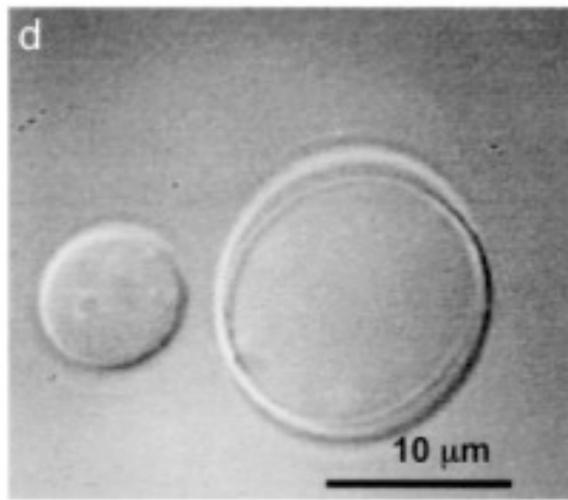


Cohen & Mahadevan, PNAS (2003)



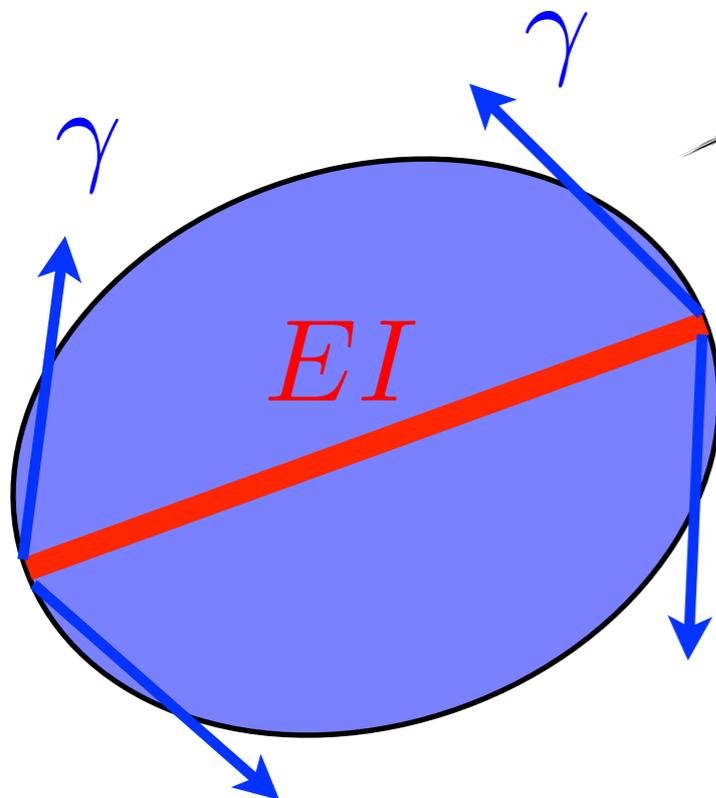
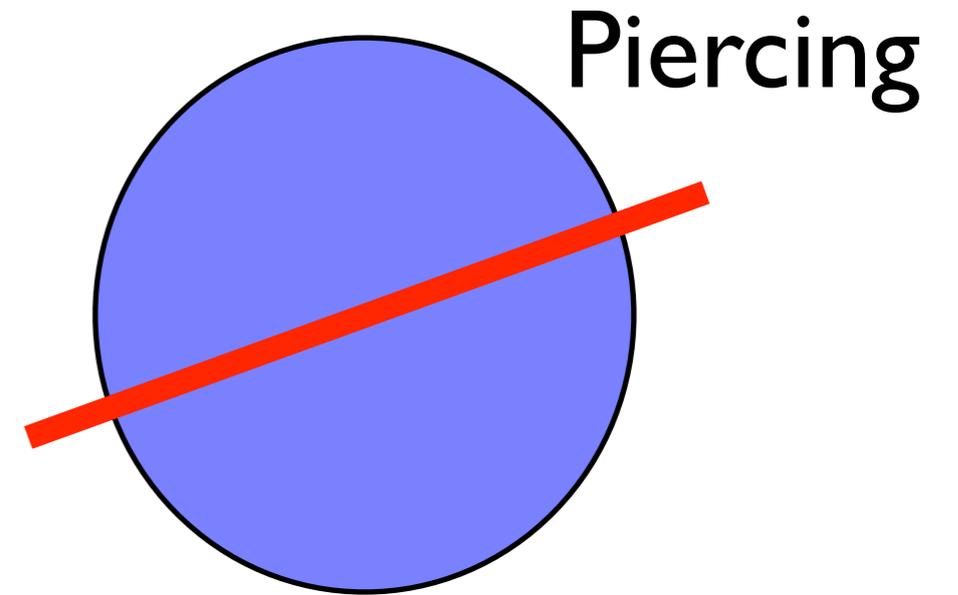
The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle



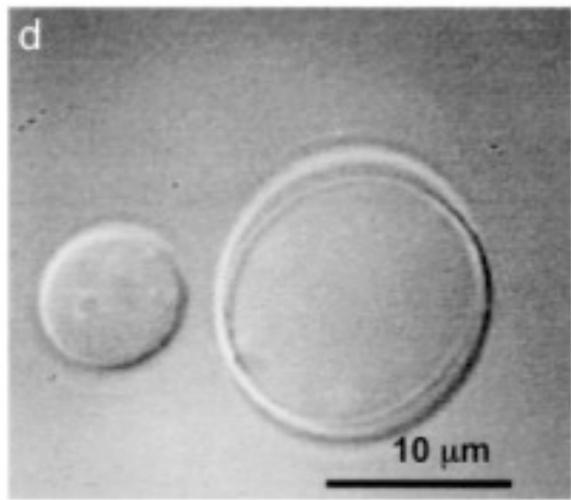
Cohen & Mahadevan, PNAS (2003)

$$\frac{EI}{L^2} \gg \gamma$$



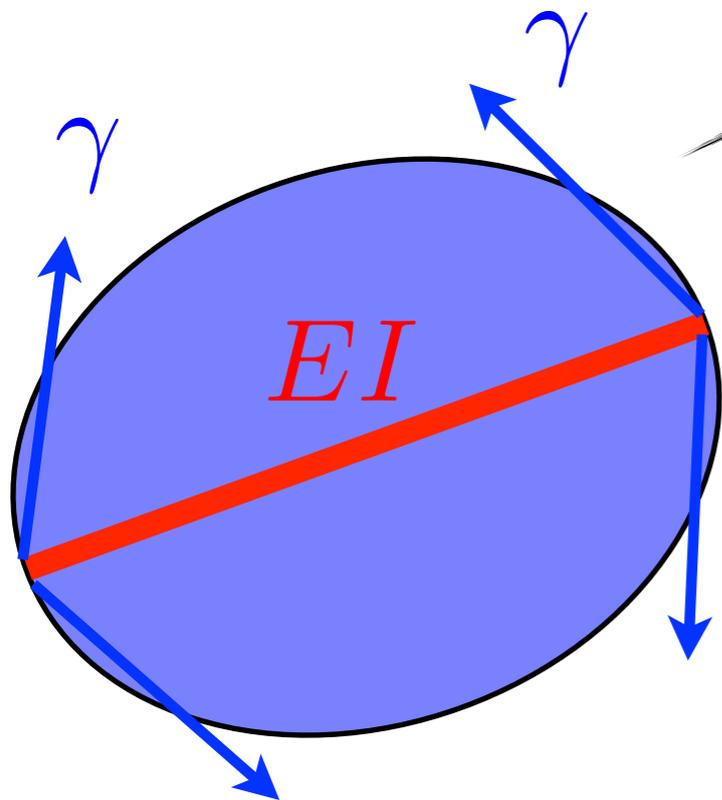
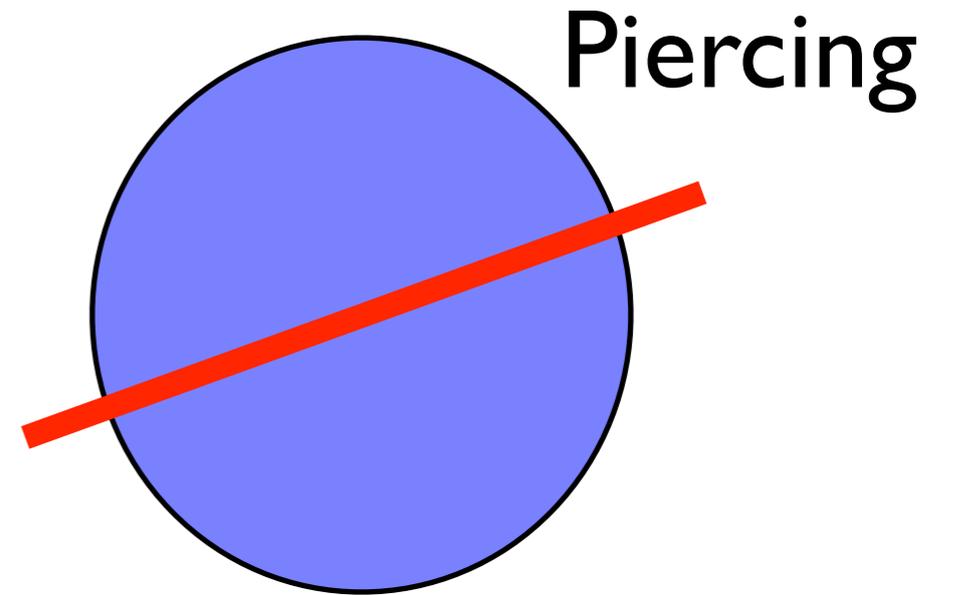
The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

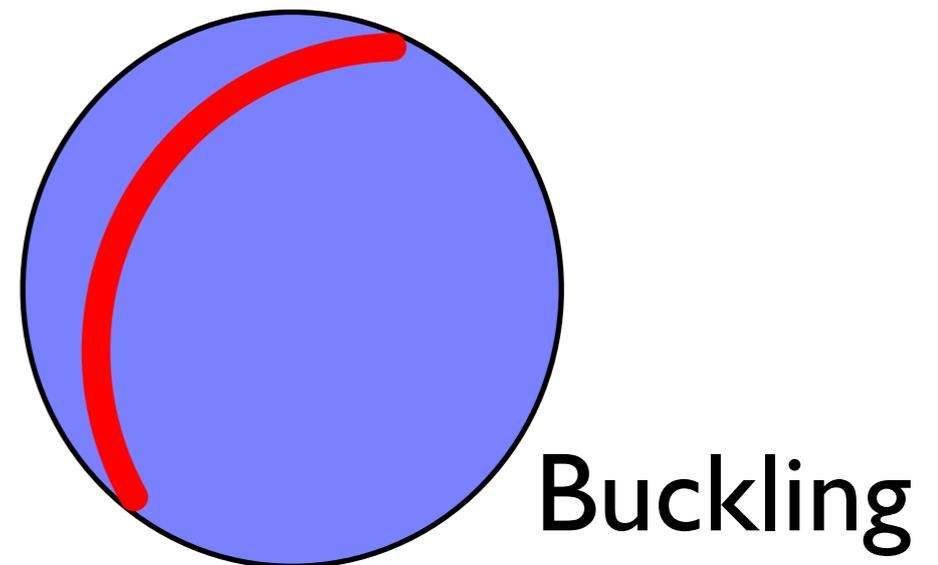


Cohen & Mahadevan, PNAS (2003)

$$\frac{EI}{L^2} \gg \gamma$$

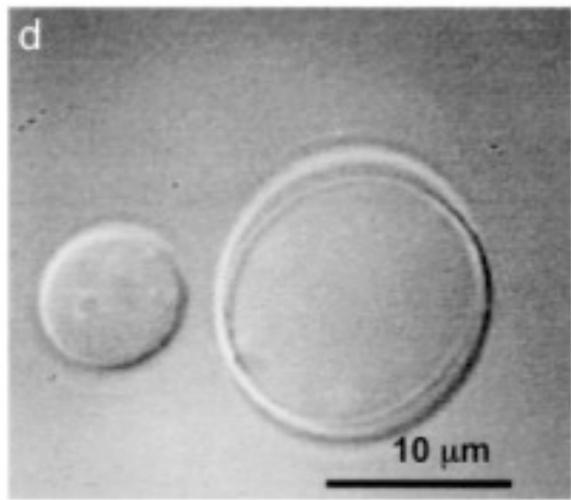


$$\frac{EI}{L^2} \ll \gamma$$



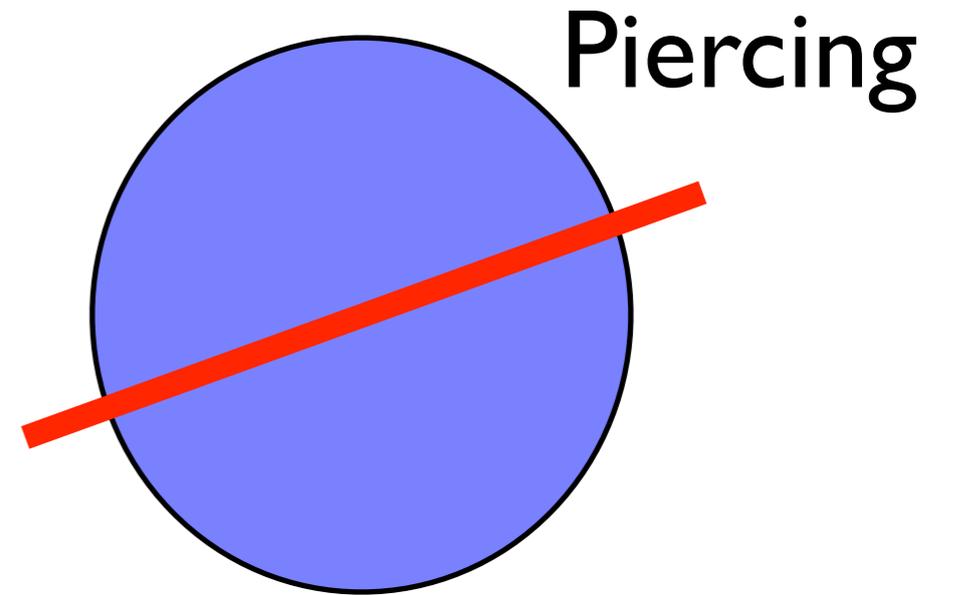
The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle



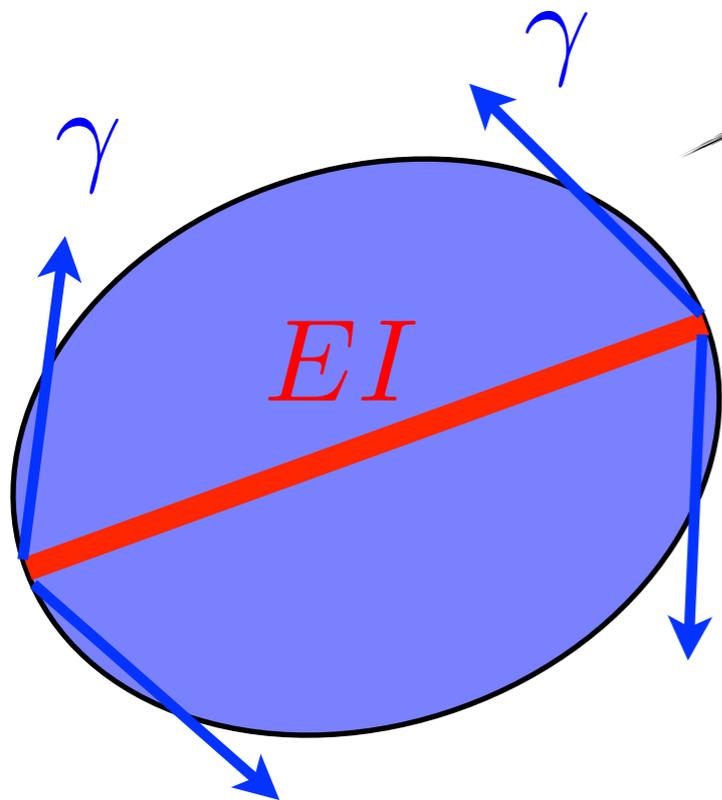
Cohen & Mahadevan, PNAS (2003)

$$\frac{EI}{L^2} \gg \gamma$$

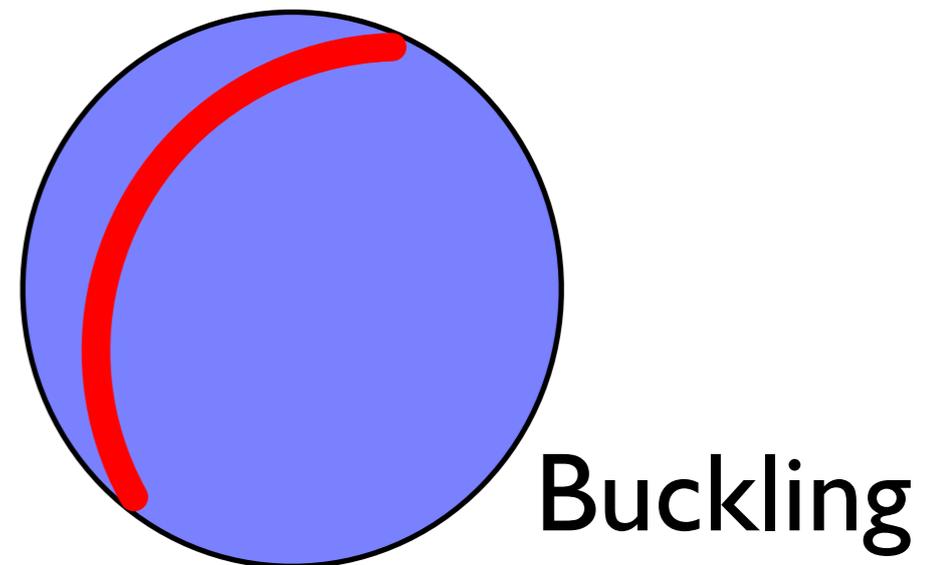


$$\frac{EI}{L^2} \sim \gamma$$

$$L_{\text{EC}} = \sqrt{\frac{EI}{\gamma}}$$

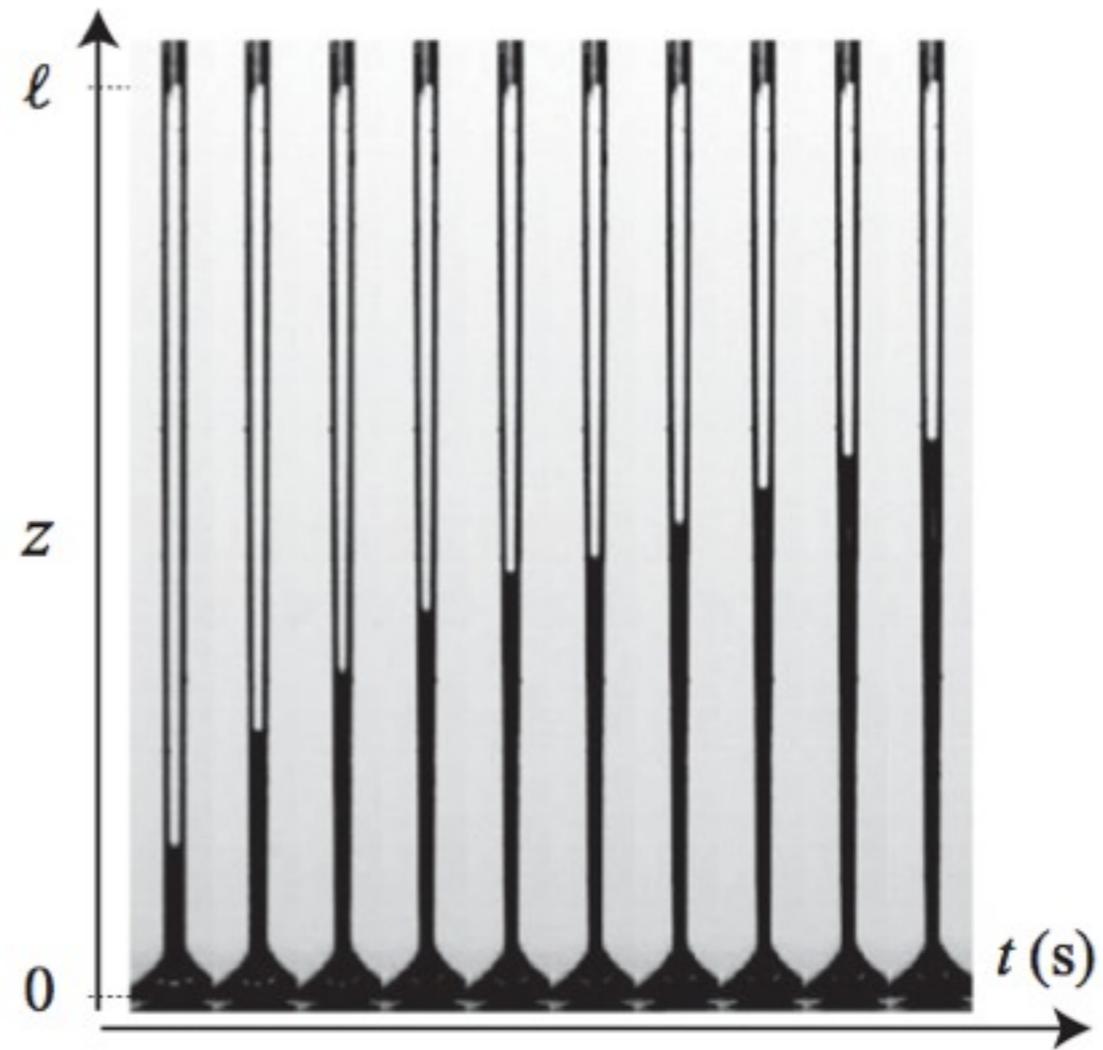


$$\frac{EI}{L^2} \ll \gamma$$



Mechanisms: Aggregation

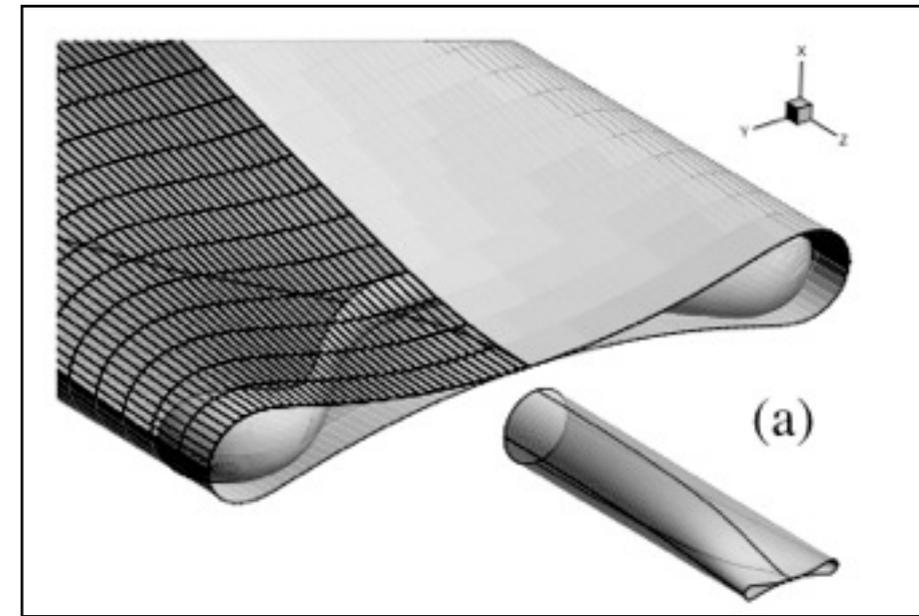
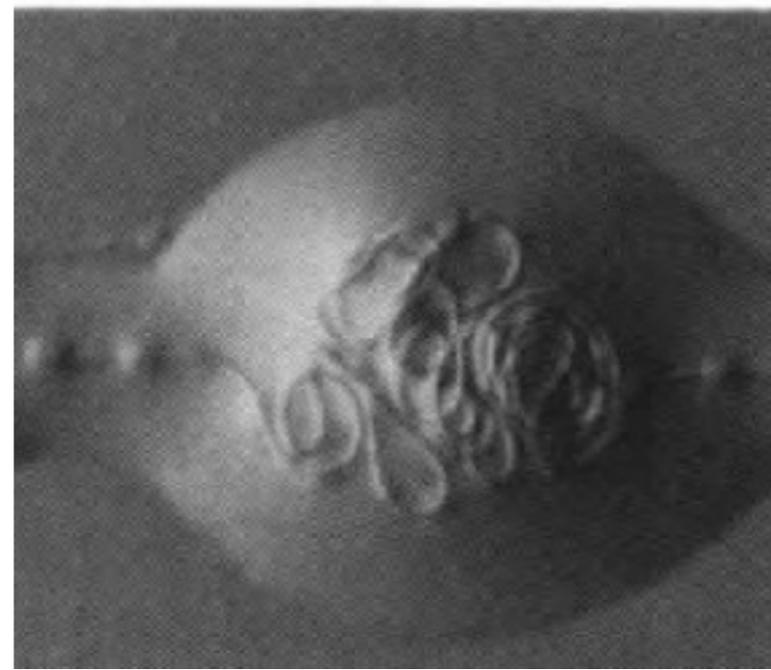
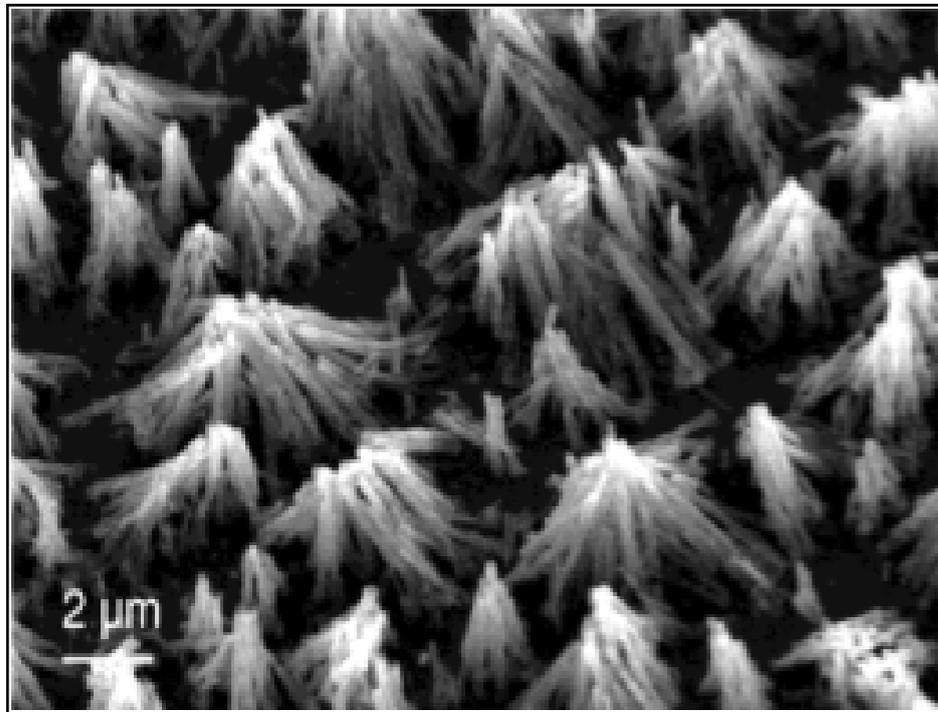
Wet hairs: elastic Jurin's law and aggregation



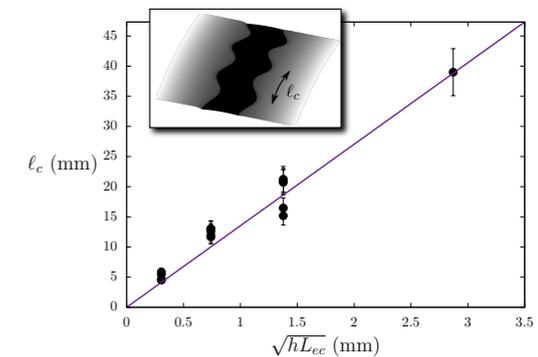
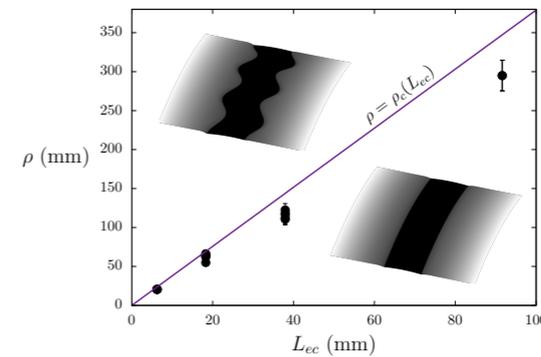
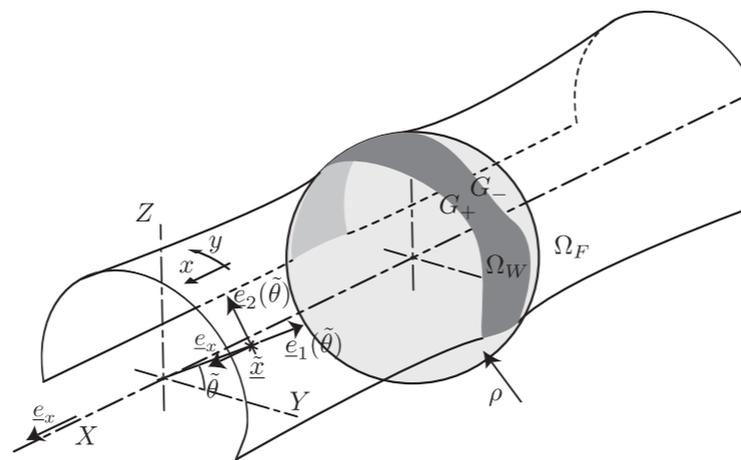
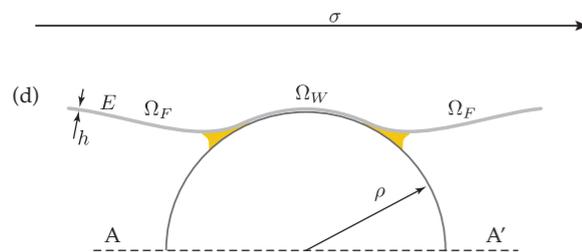
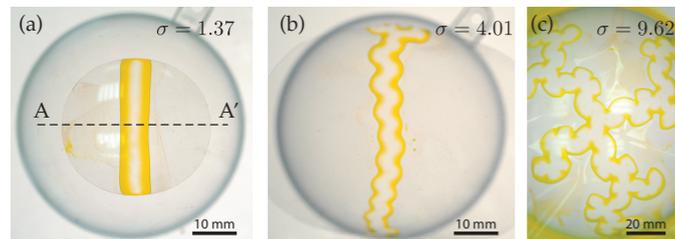
Bico et al., Nature (2004),
Kim & Mahadevan, JFM (2006),
Duprat et al., JFM (2011),
Cambeau et al., EPL (2011)

Mechanisms: Buckling

Capillary buckling

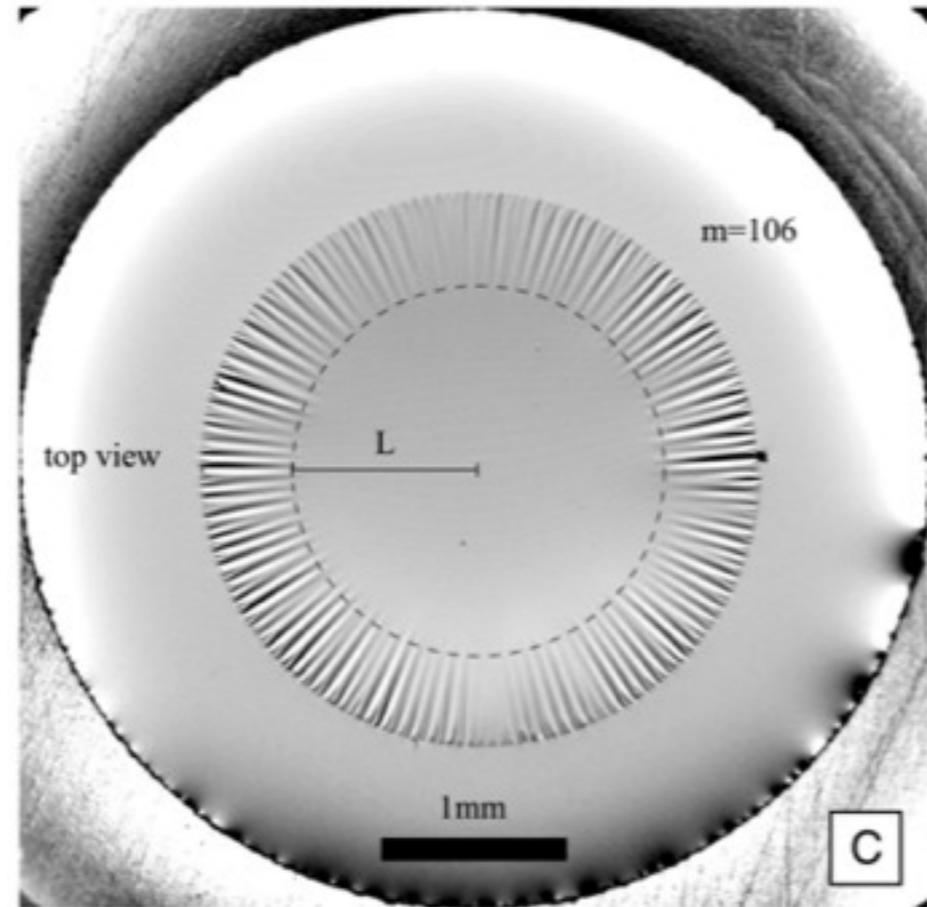
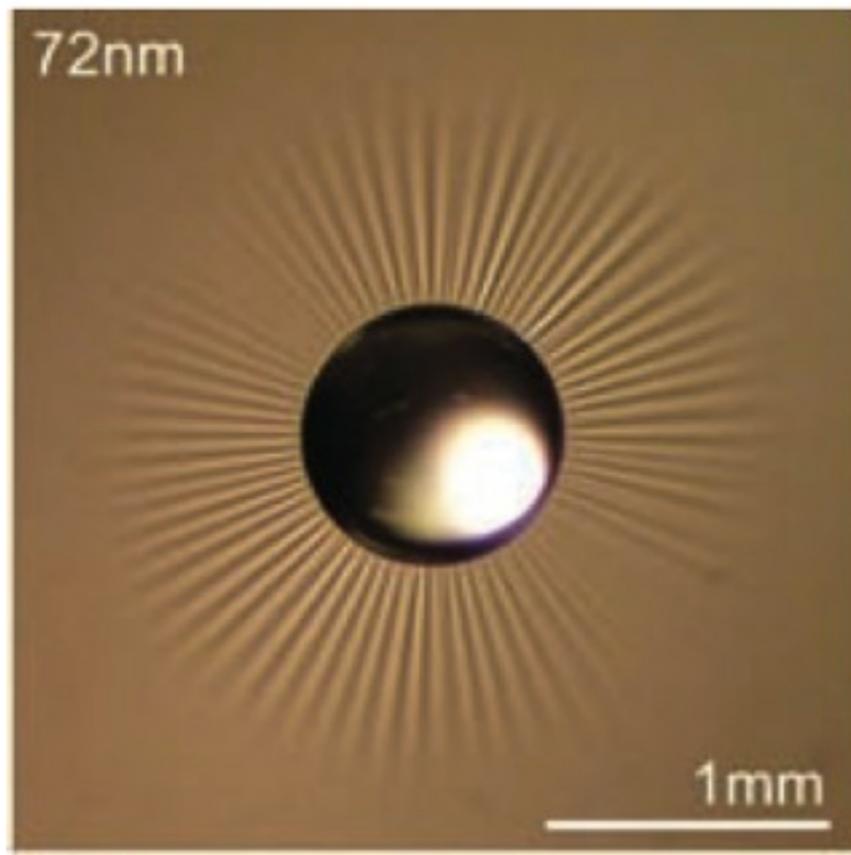


Vollrath & Edmonds, *Nature* (1989),
 Heil, *JFM* (1999),
 Lau et al., *Nano Lett.* (2003),
 Neukirch et al., *JMPS* (2007)



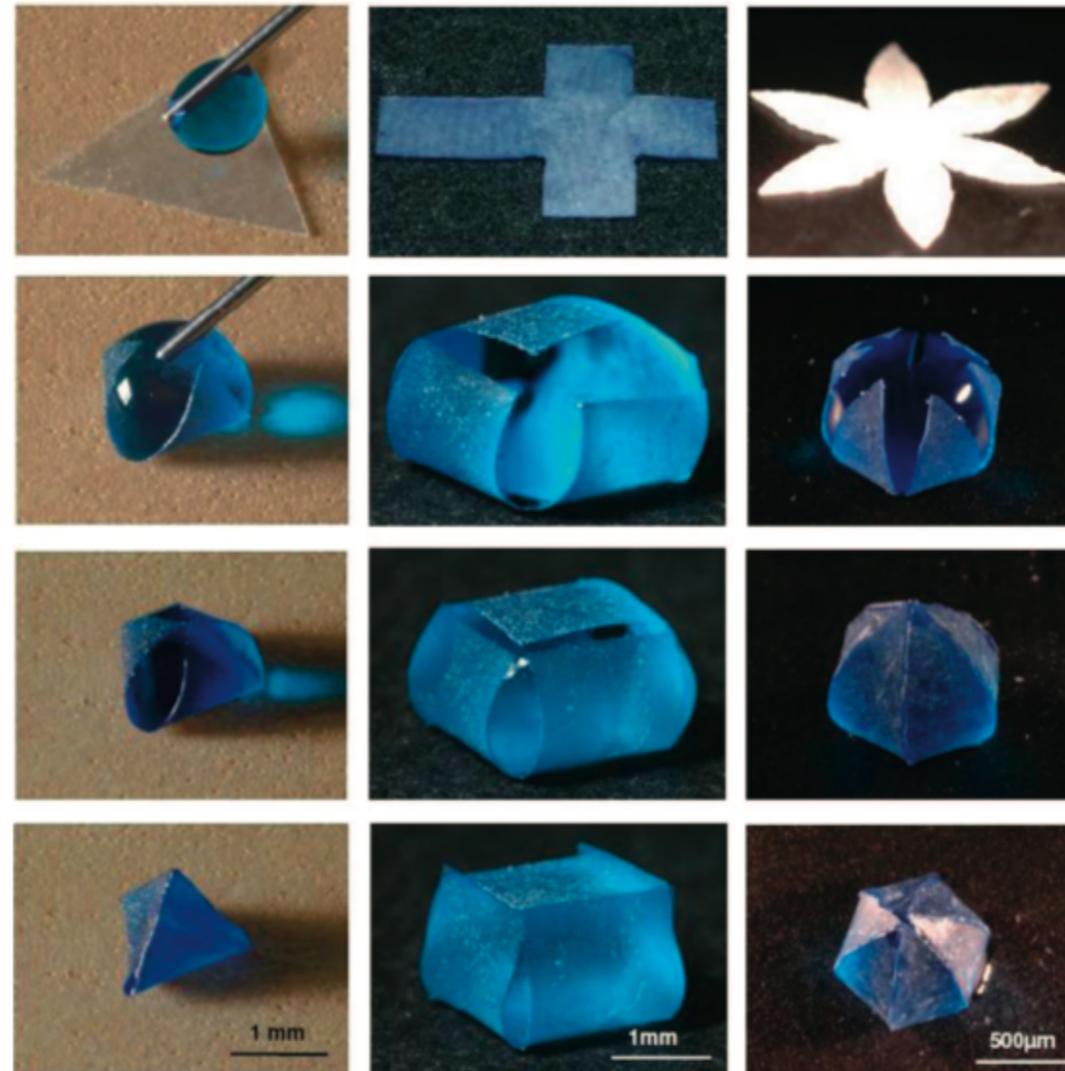
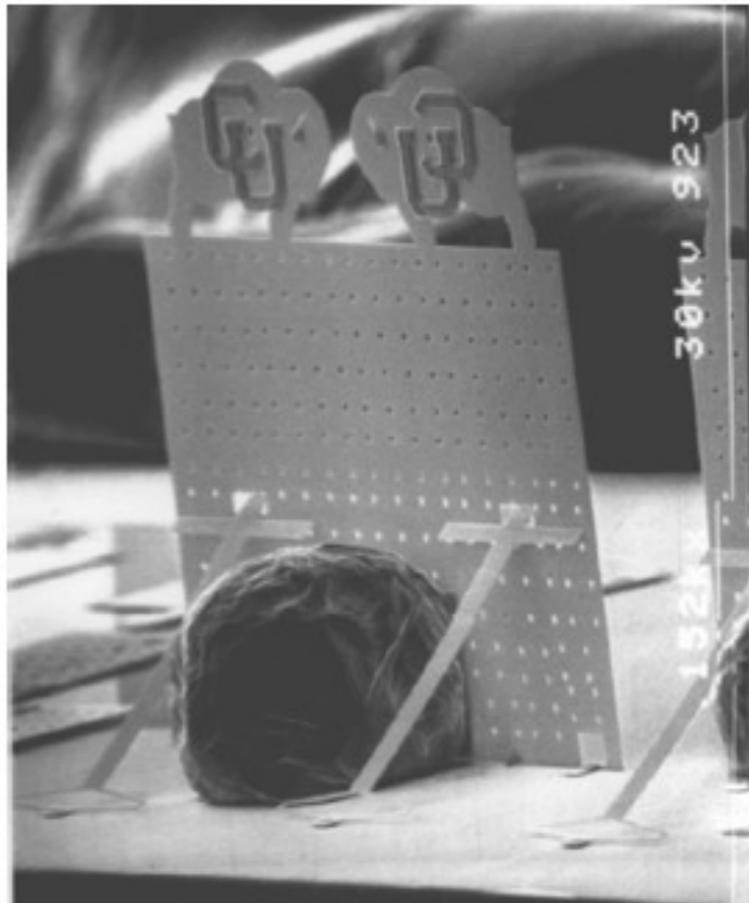
Hure & Audoly, *JMPS* (2012)

Mechanisms: Wrinkling



Huang et al., Science (2007), Pocivavsek et al., Science (2008), Hunt et al., Soft Matter (2012)

Mechanisms: Wrapping & Folding

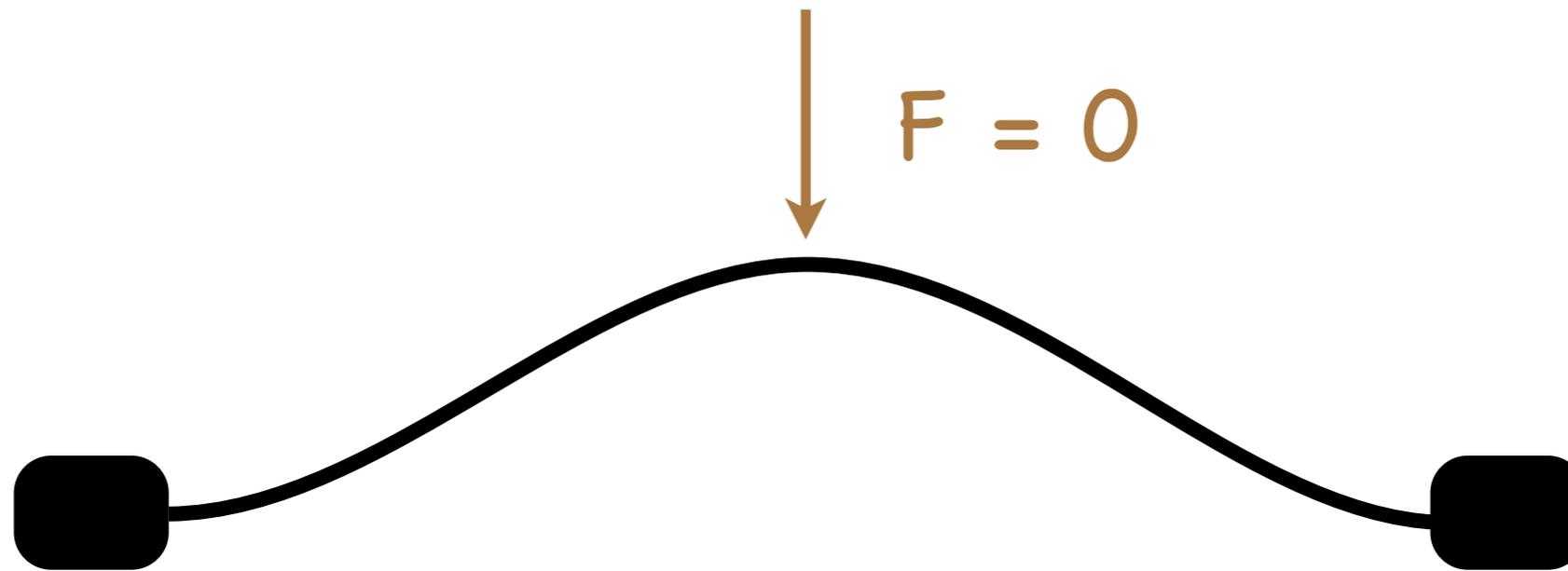


Syms et al., J. of MEMS (2003),
Py et al., PRL (2007),
Reis et al., Soft Matter (2010)

Here :

snap-through of an elastic beam
induced by a drop

Classical snap-through



Timoshenko, Philosophical Magazine (1922)

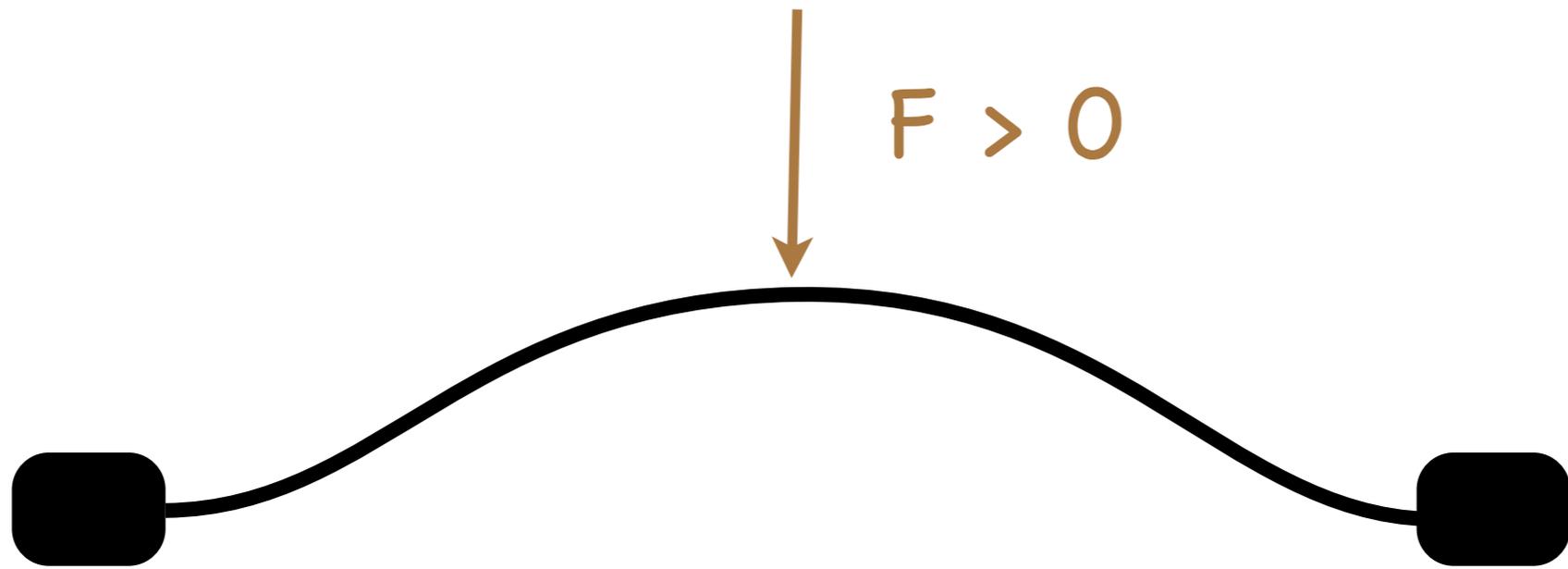
Timoshenko, J. Appl. Mech. (1935)

....

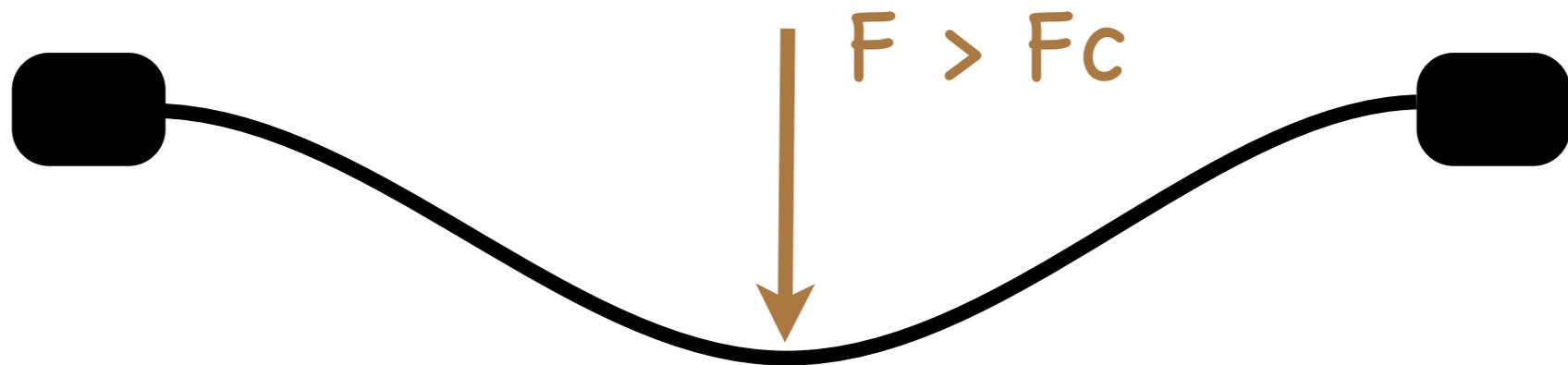
Chen + Hung, European Journal of Mechanics - A/Solids (2011).

Pandey et al (2013)

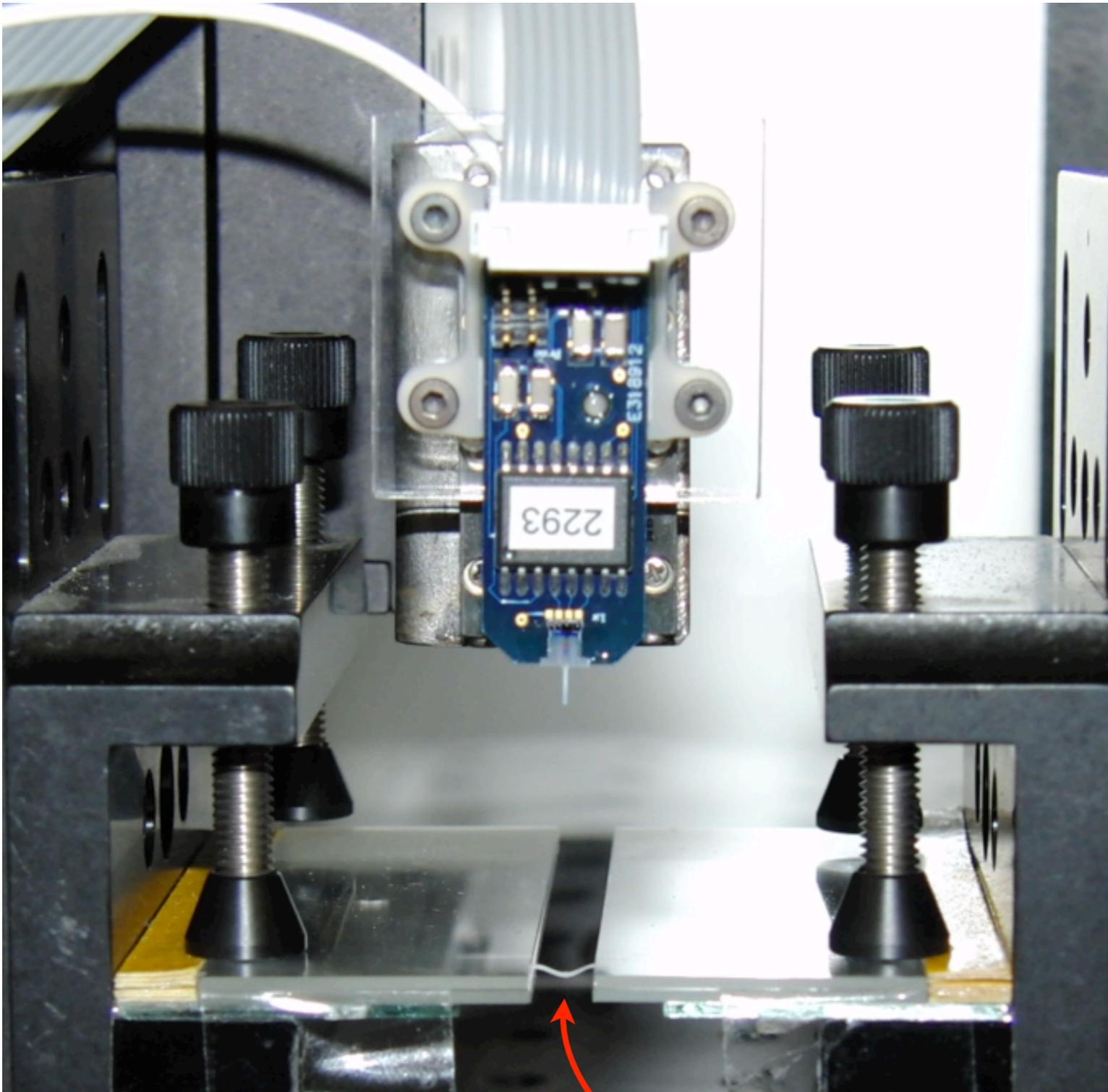
Classical snap-through



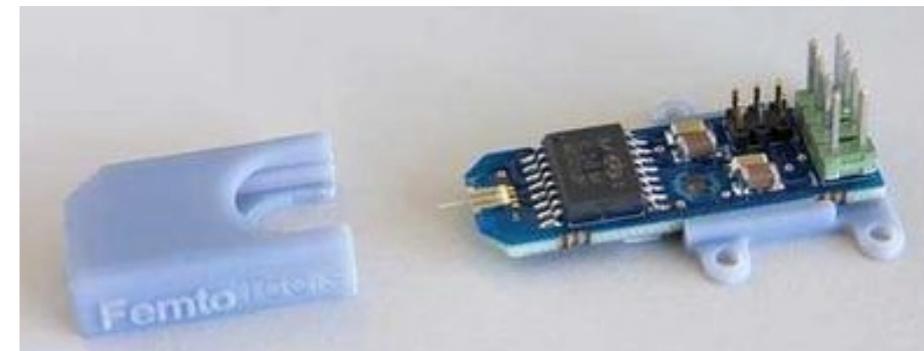
Classical snap-through



Force transducer / positioning system



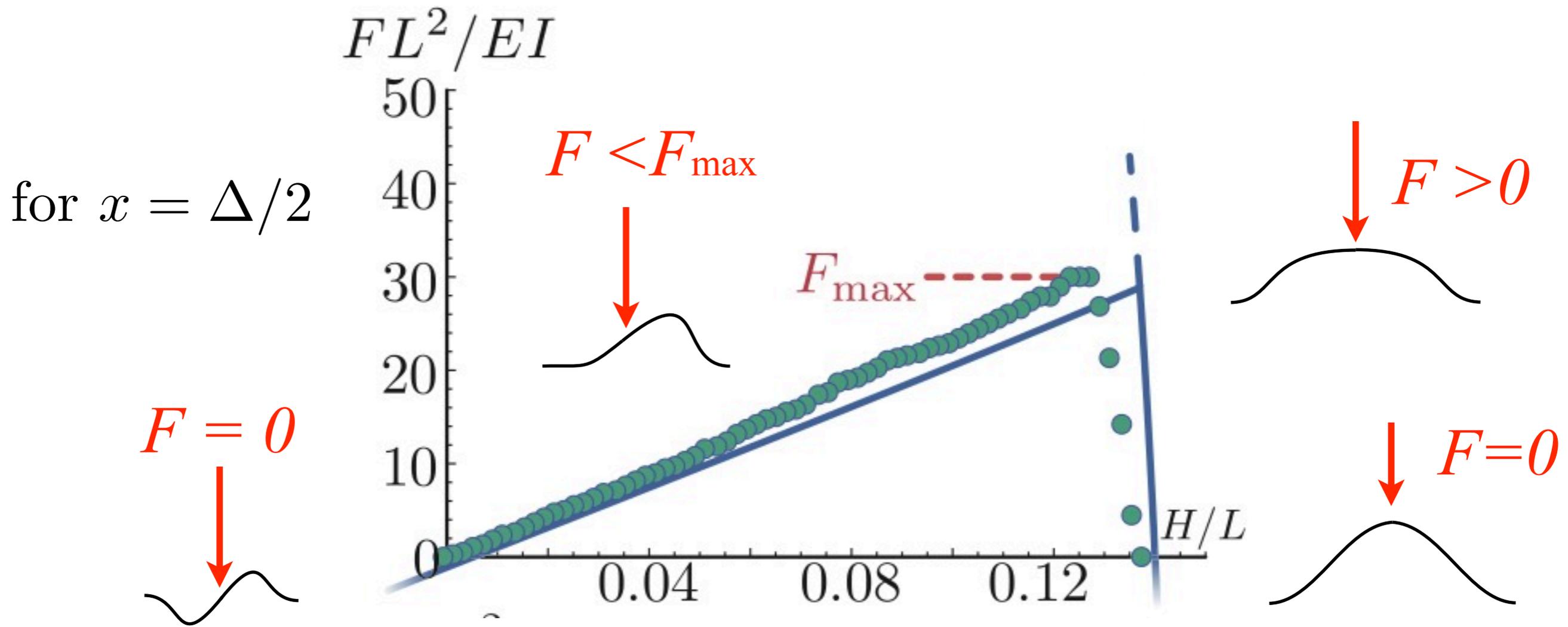
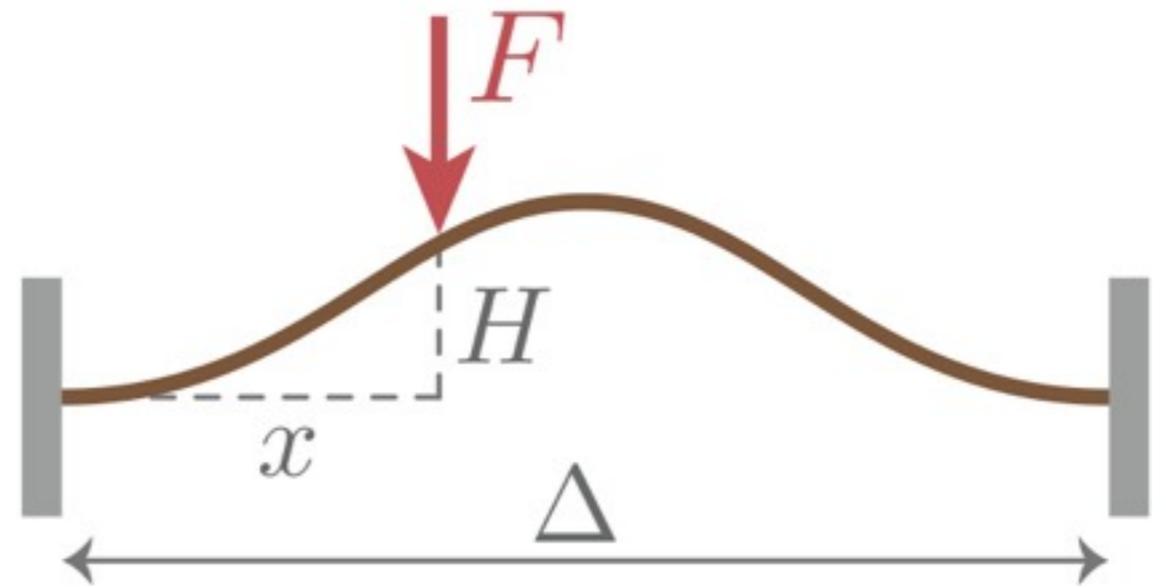
Femttools FT-S270



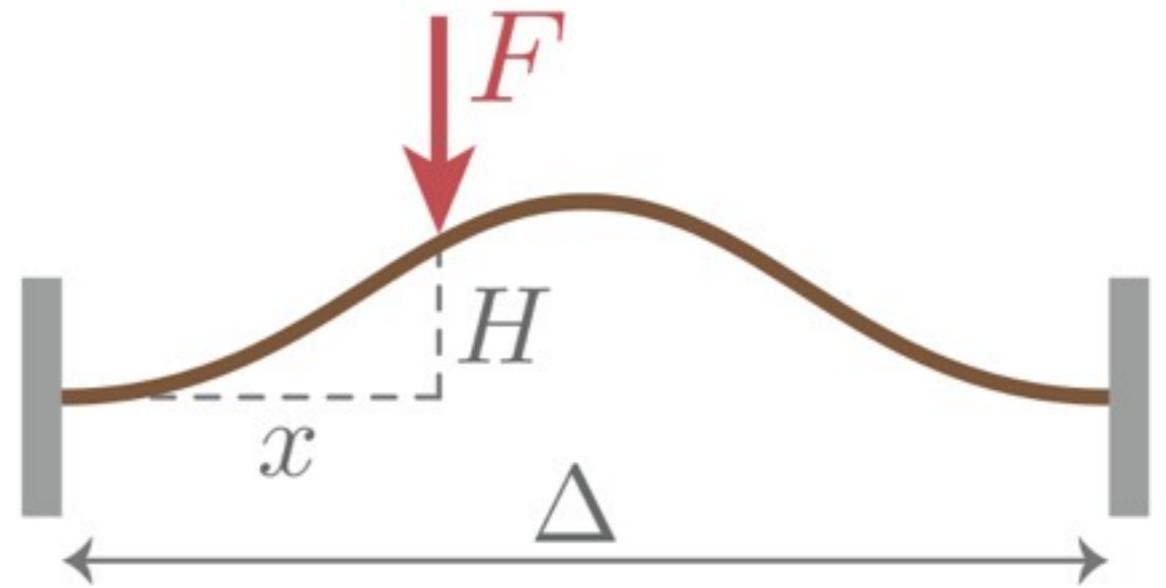
<http://www.femttools.com/>

3 mm PDMS elastic strip

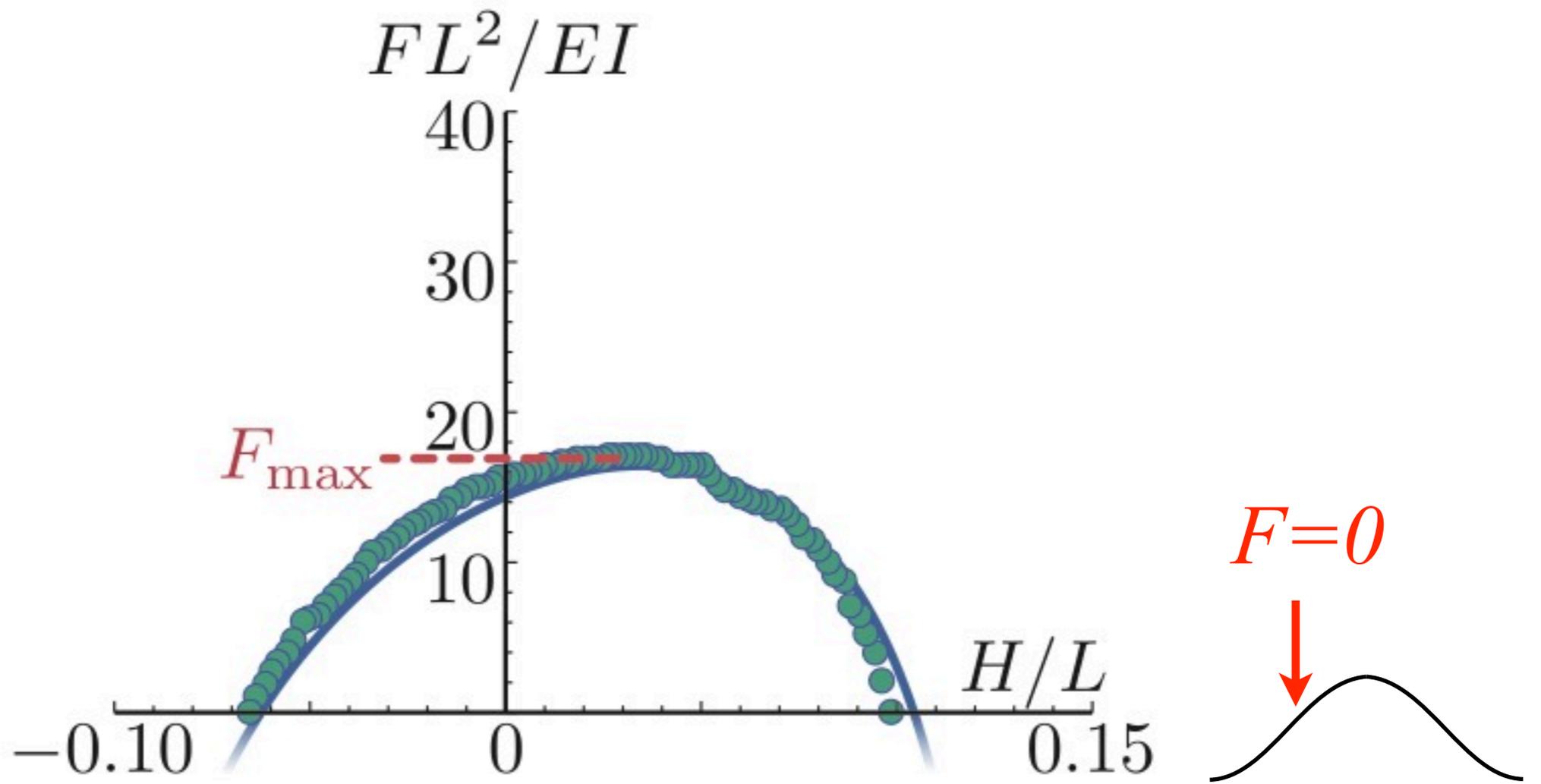
Classical snap-through



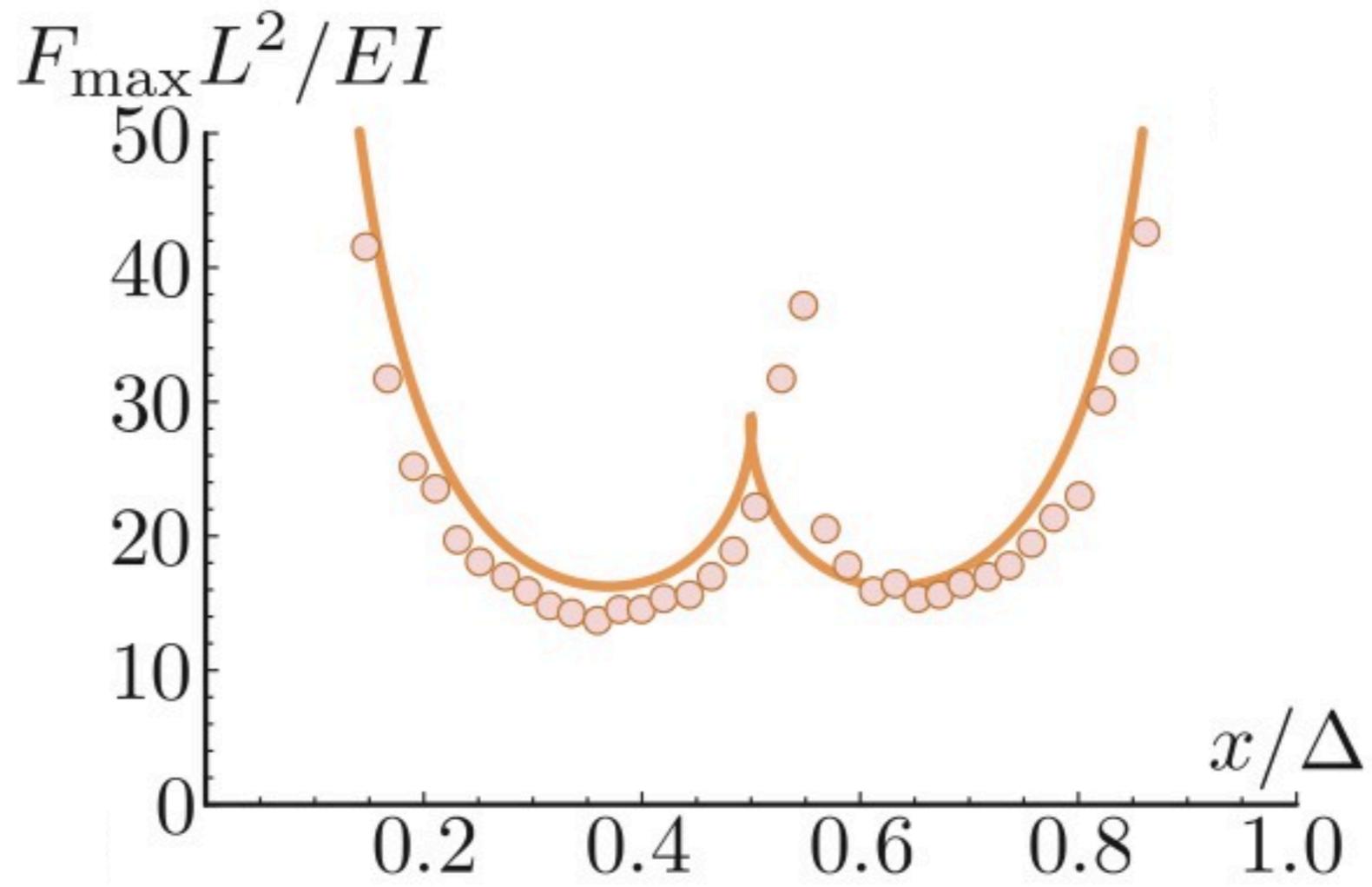
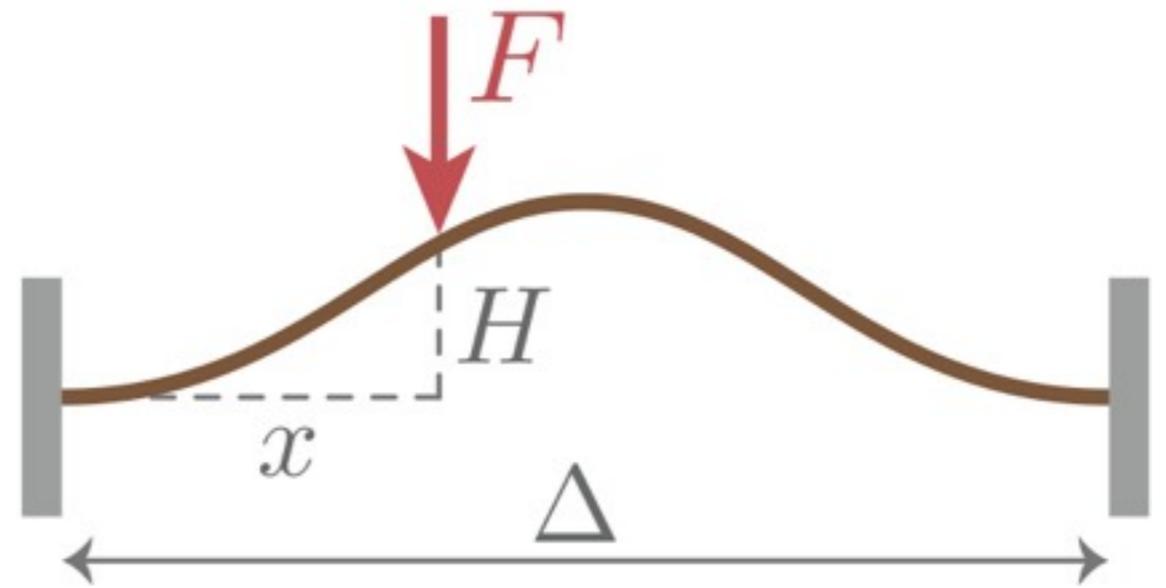
Classical snap-through



for $x = \Delta/3$

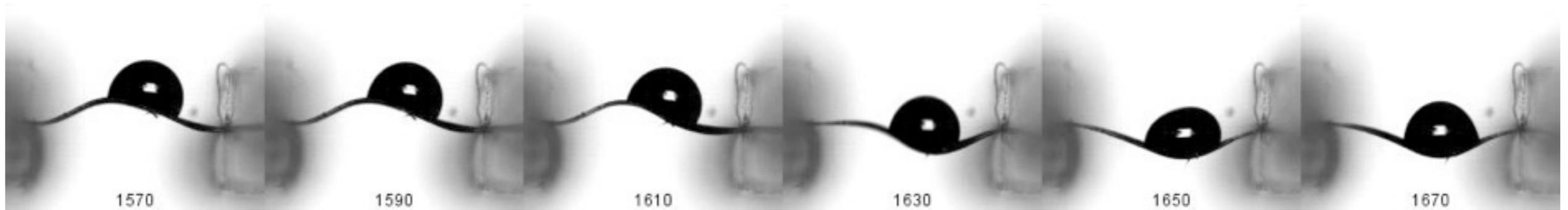
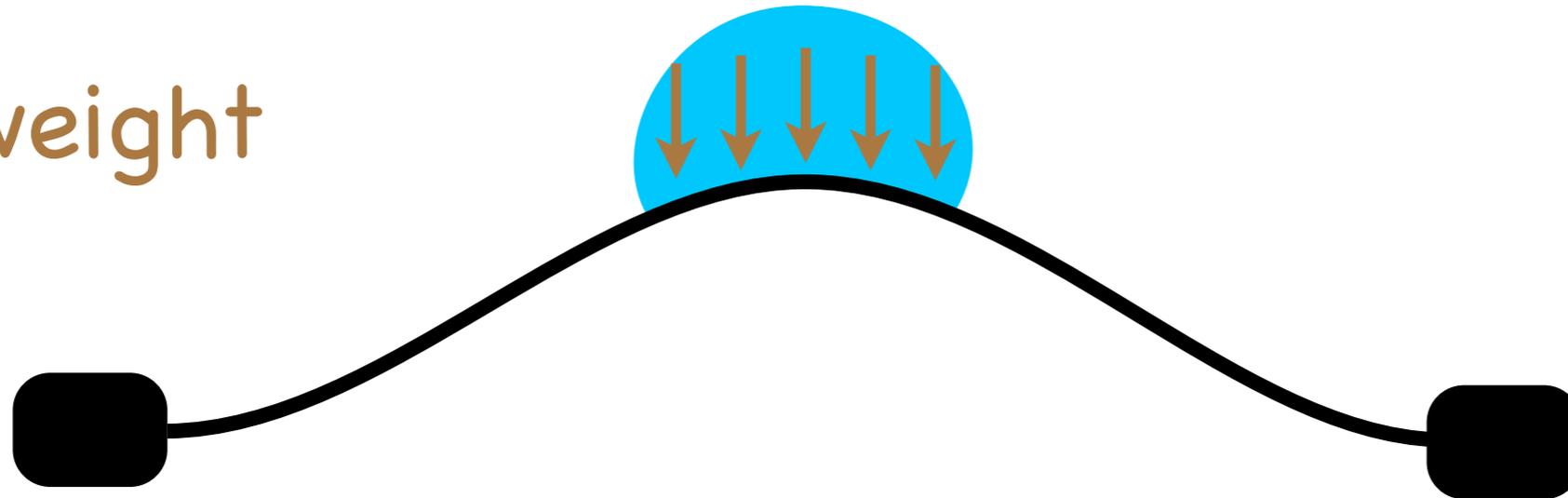


Classical snap-through

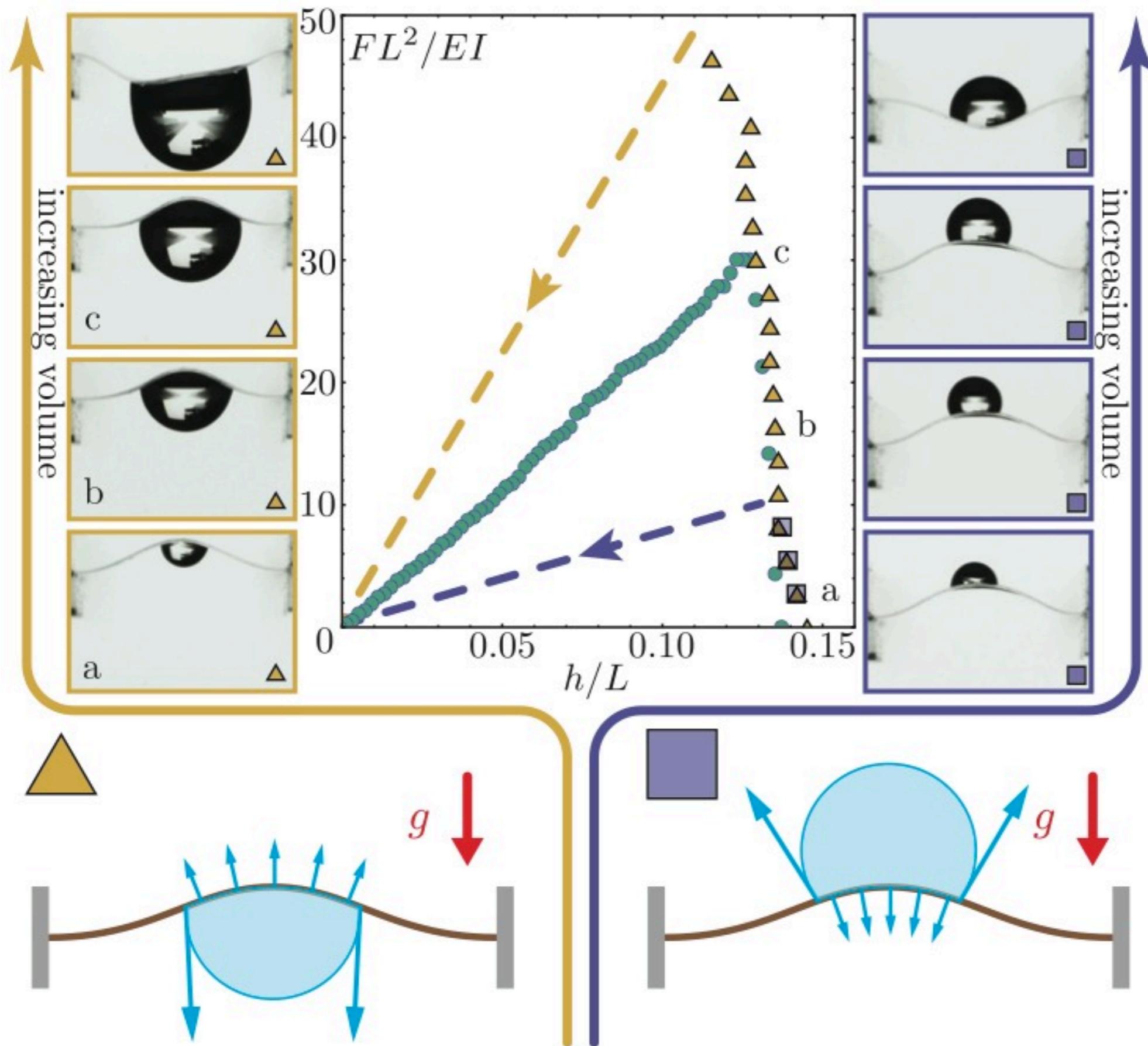


Capillary induced snap-through

weight

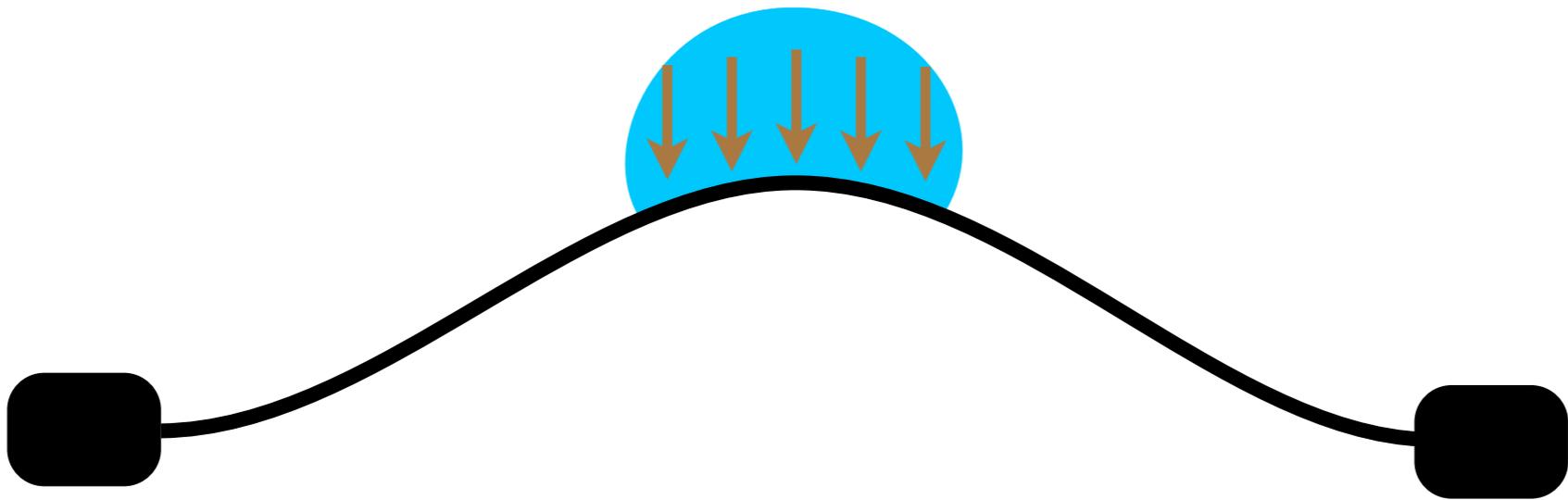


Capillary induced snap-through

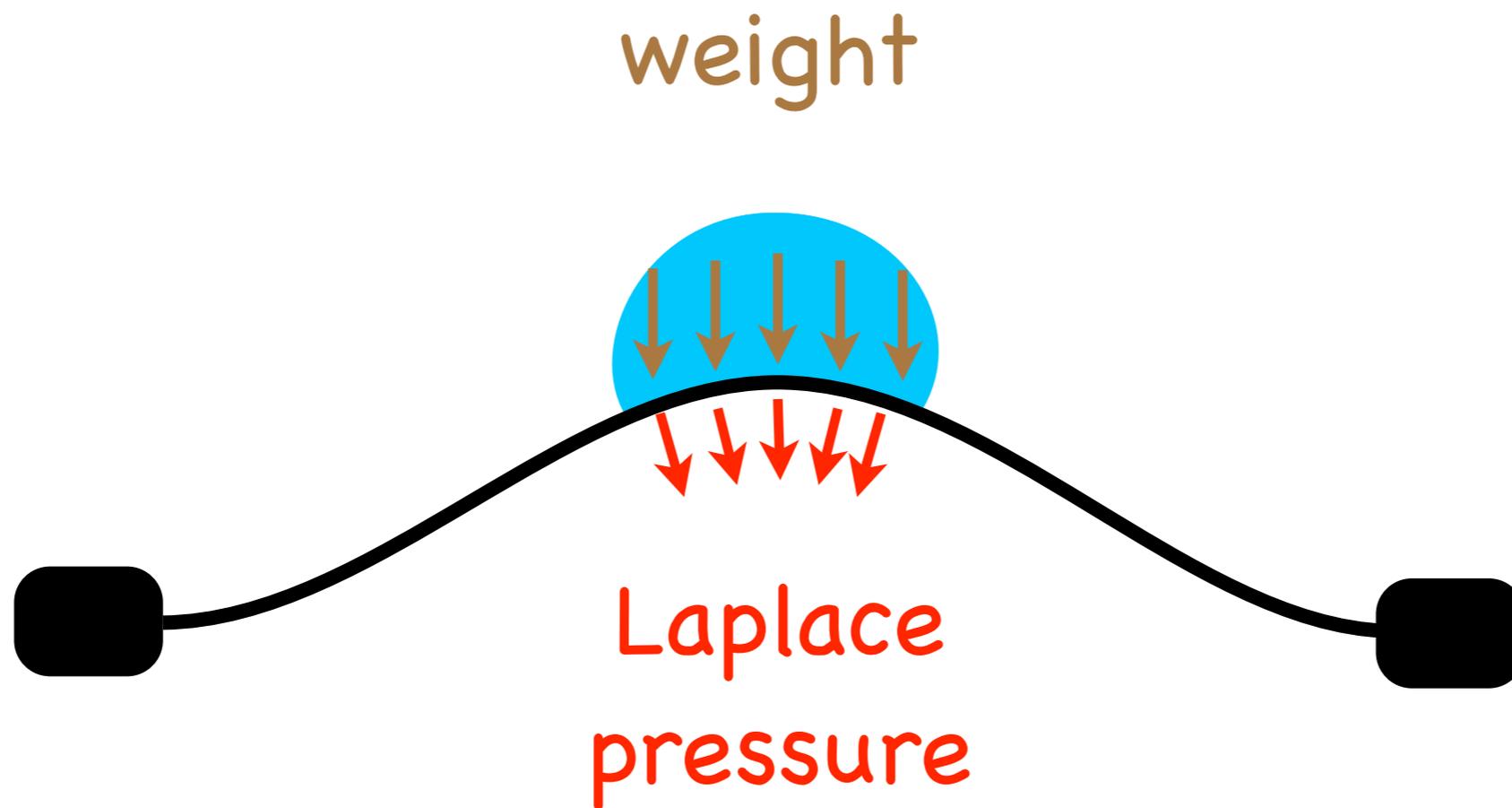


Capillary induced snap-through

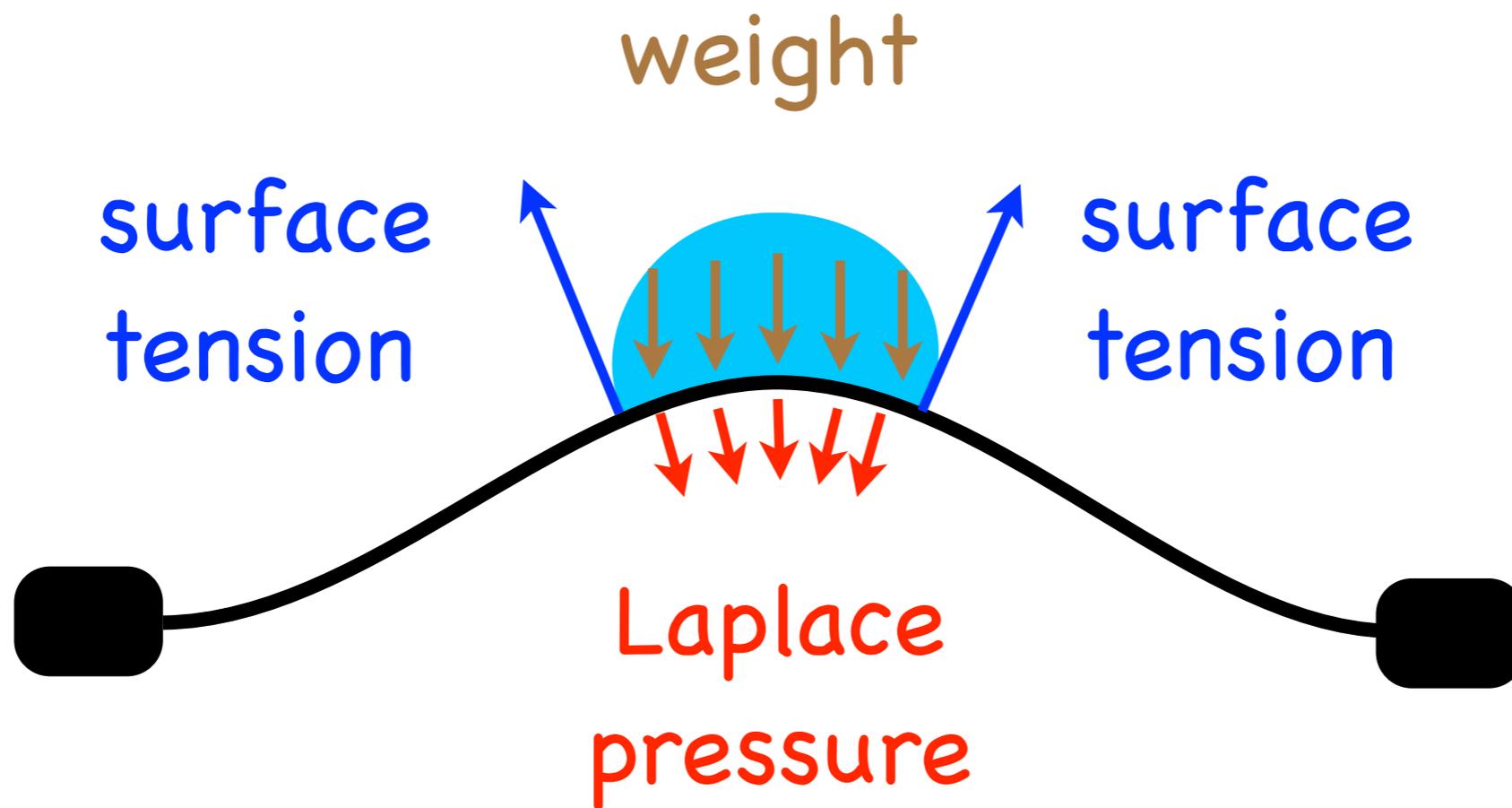
weight



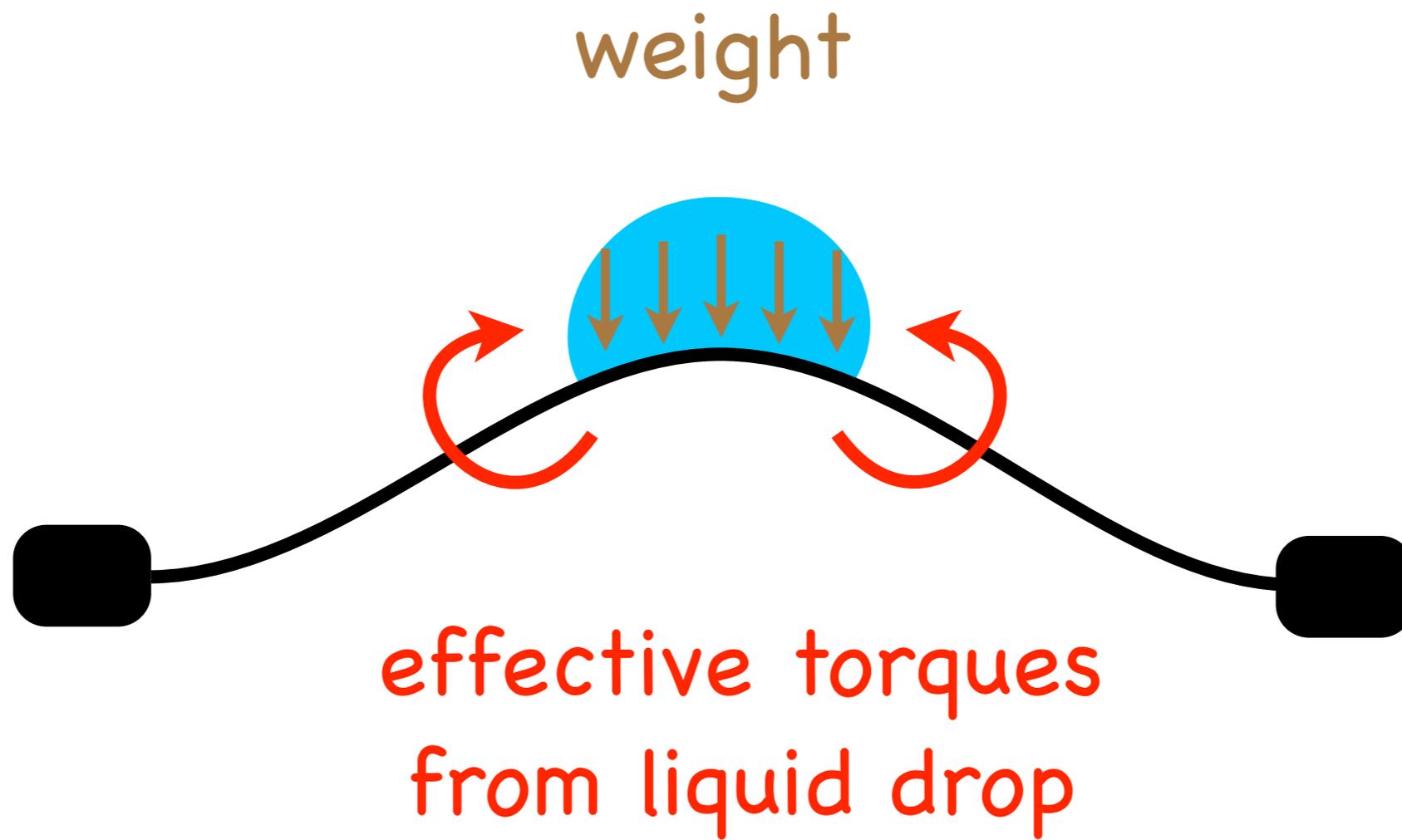
Capillary induced snap-through



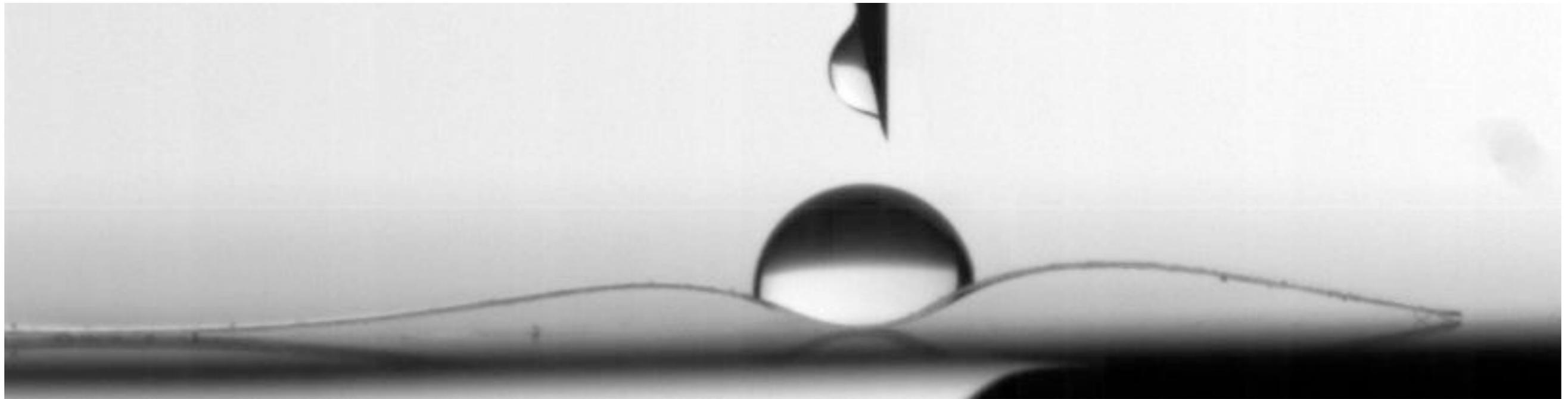
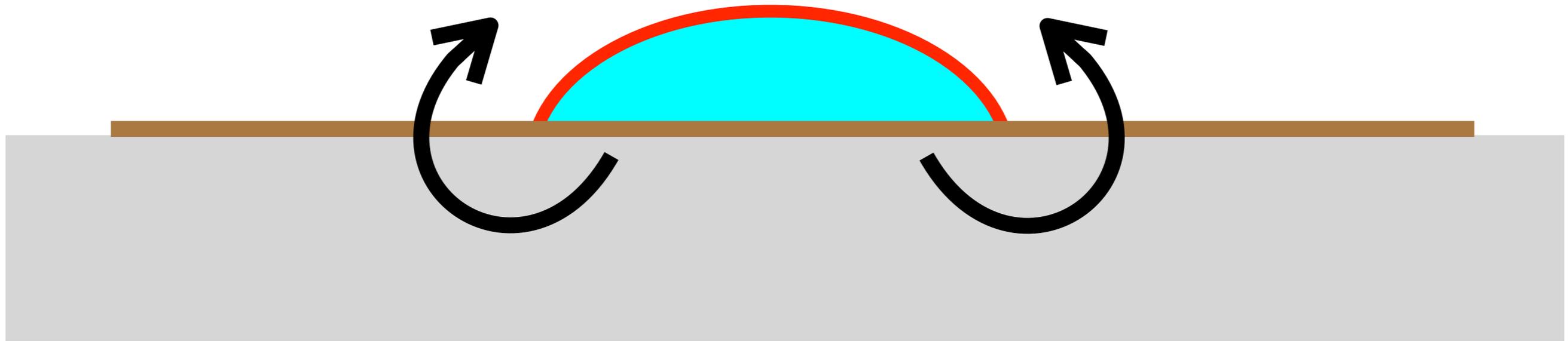
Capillary induced snap-through



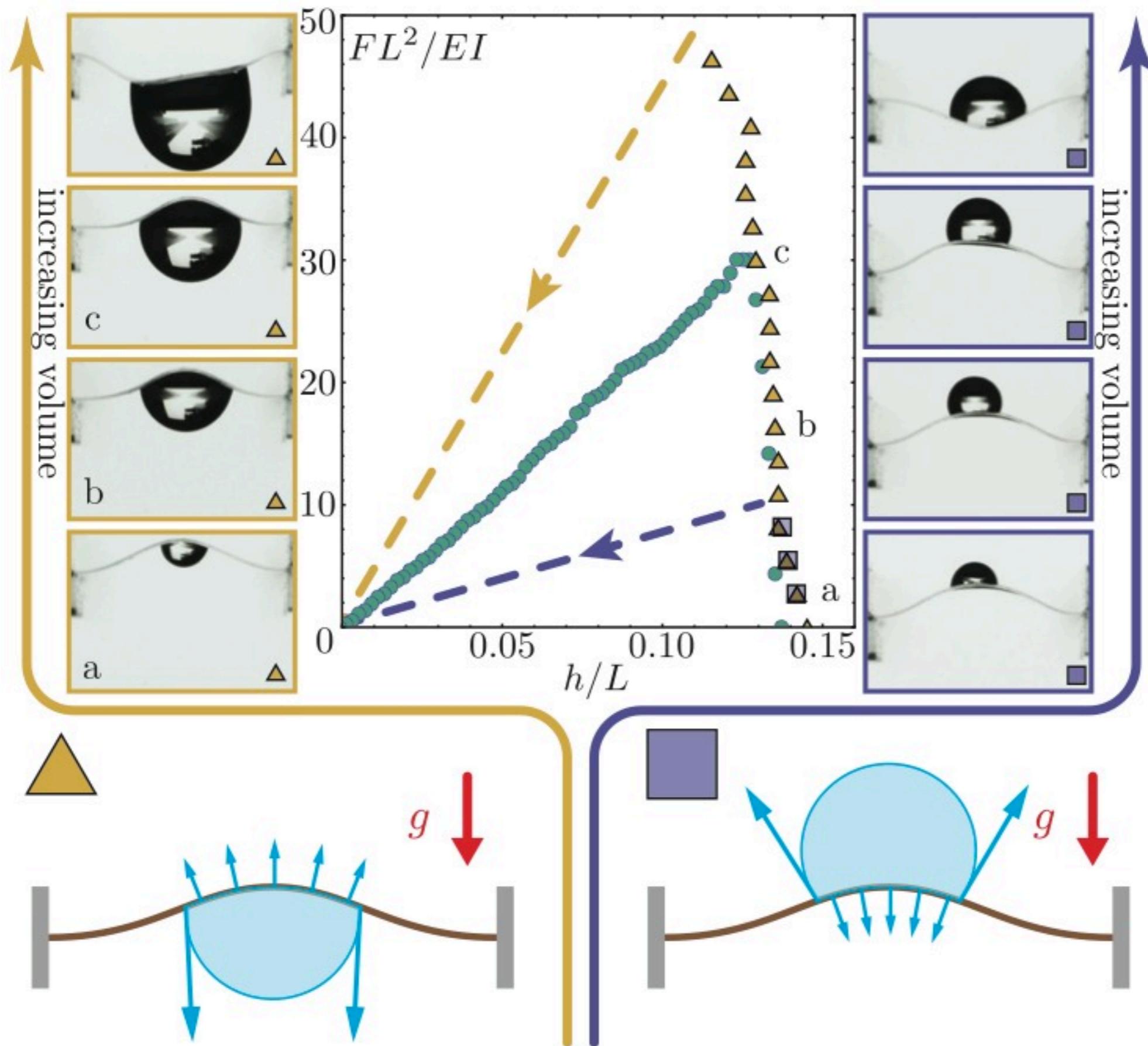
Capillary induced snap-through



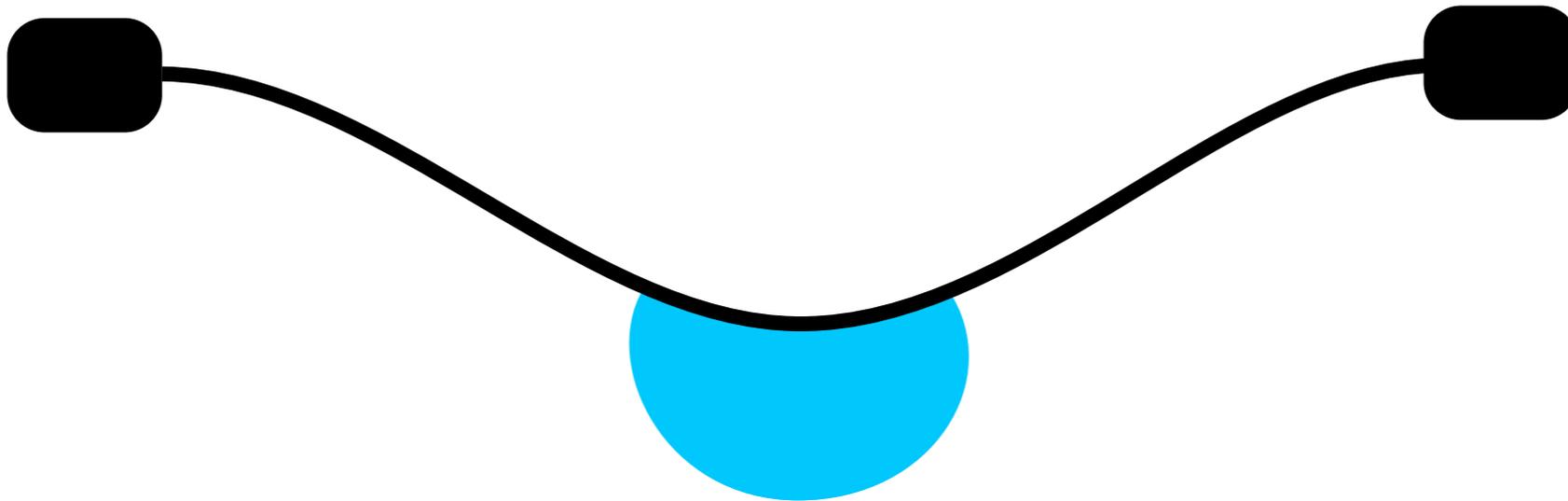
effective bending moments



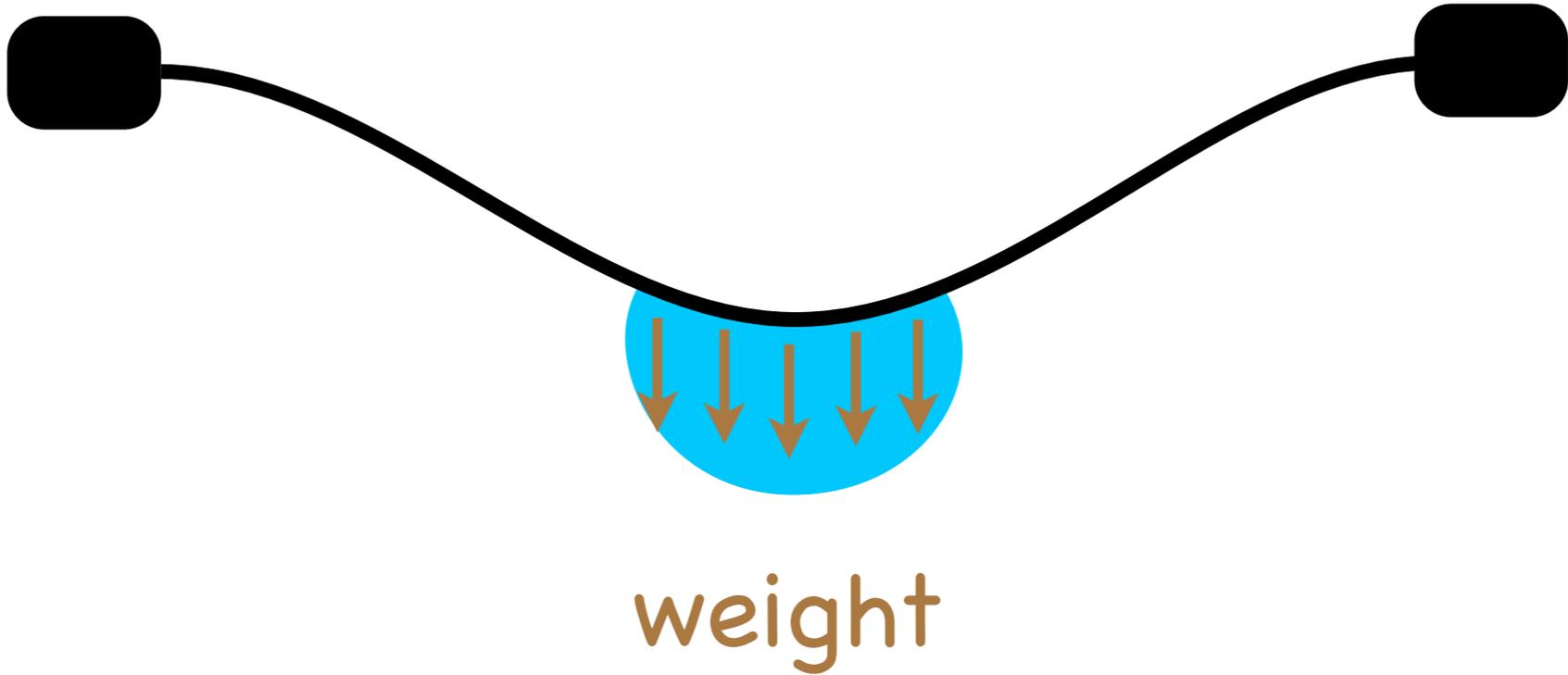
Capillary induced snap-through



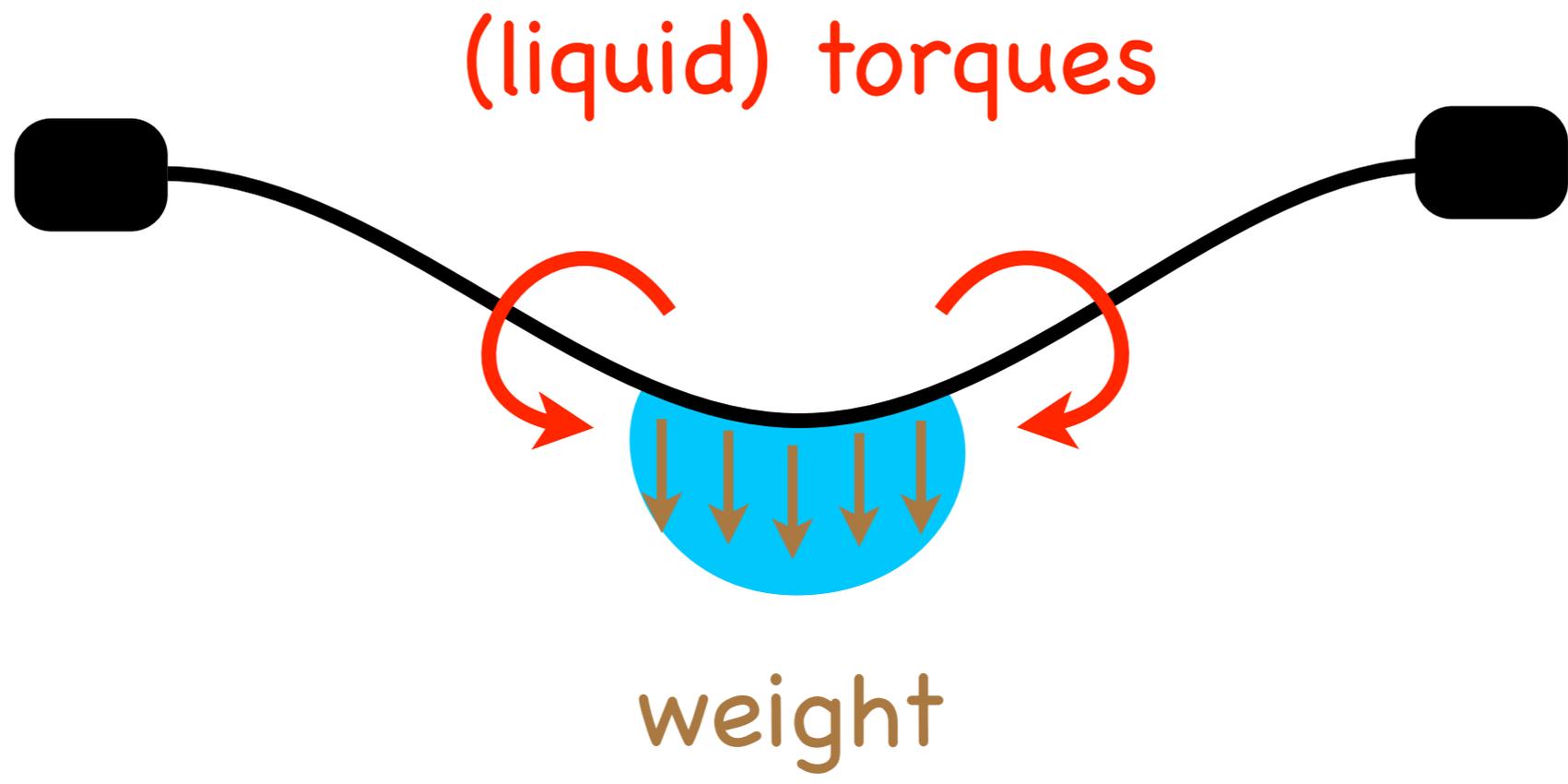
Capillary induced snap-through



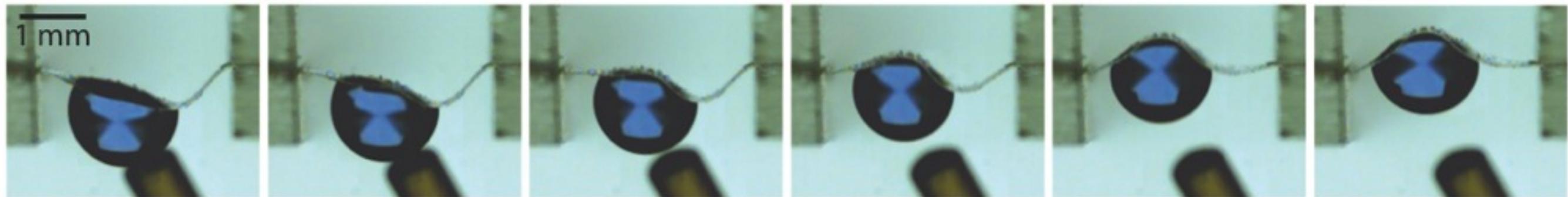
Capillary induced snap-through



Capillary induced snap-through



Capillary induced snap-through



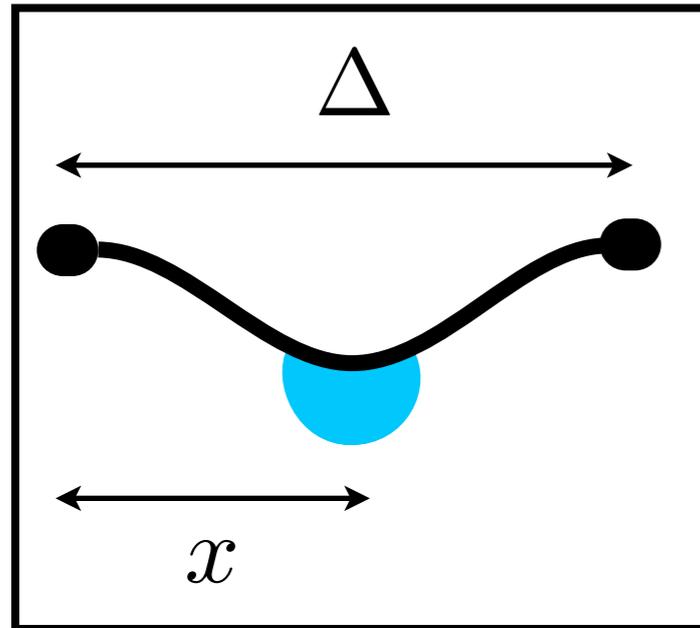
PDMS strip

dimensions: 34 microns by 1 mm by 3.5 mm

time interval between frames: 5 ms

Capillary induced snap-through

start

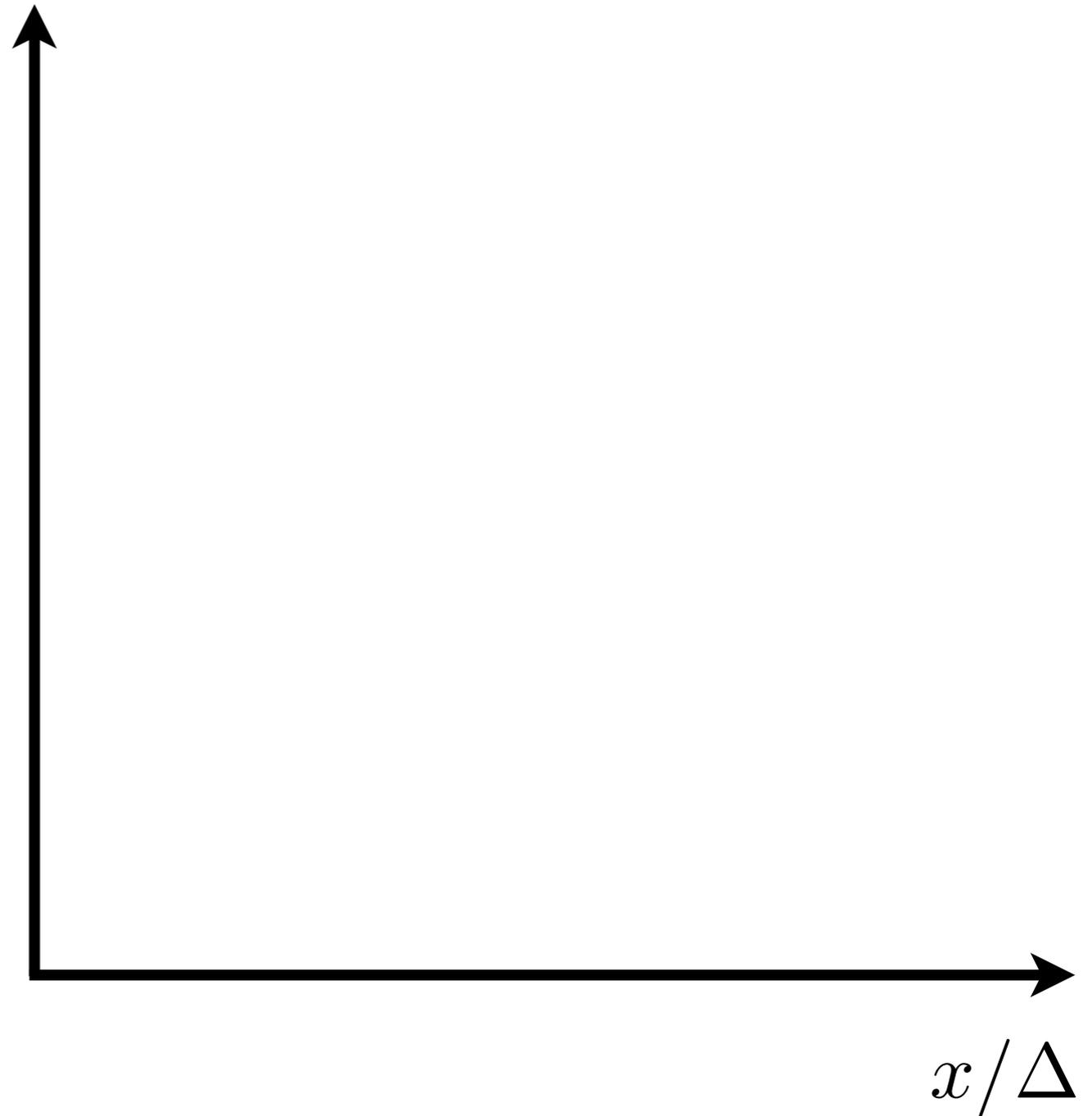
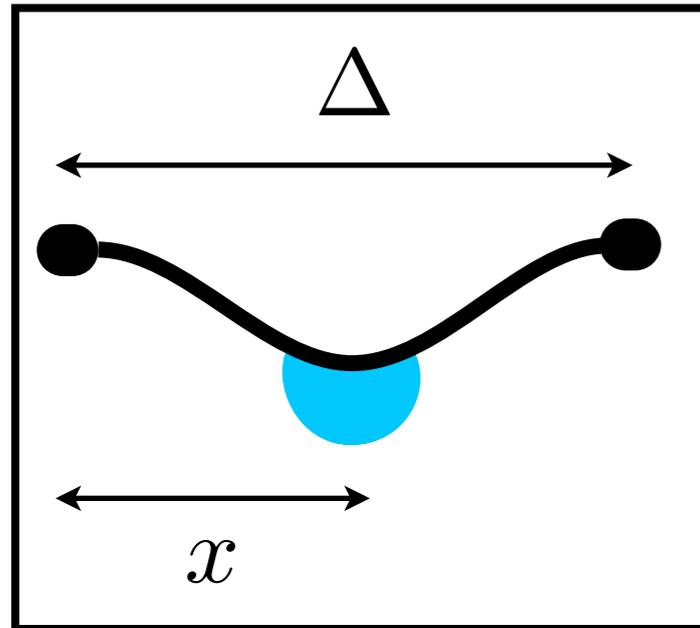


Capillary induced snap-through

liquid weight

$$FL^2/EI$$

start

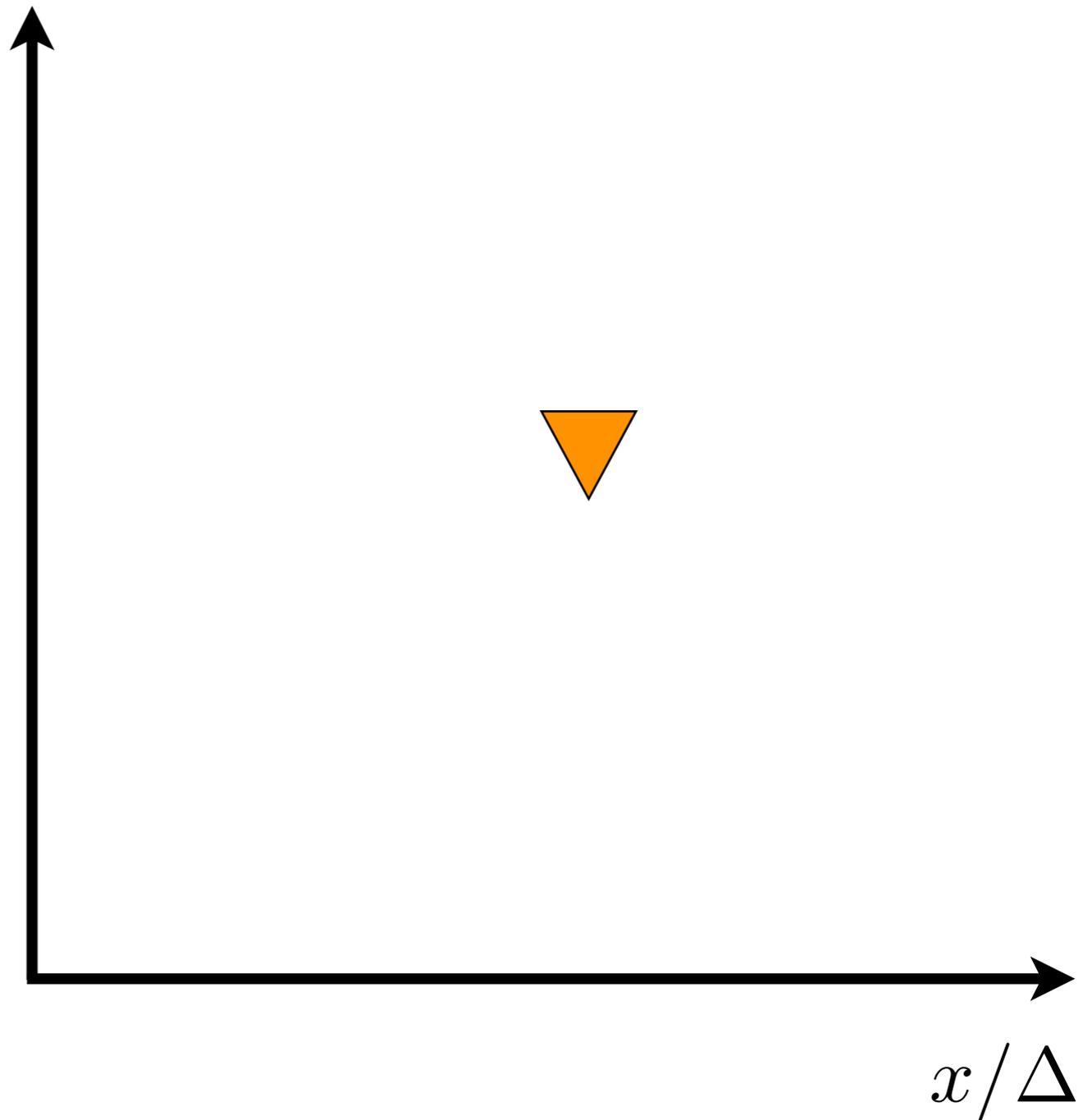
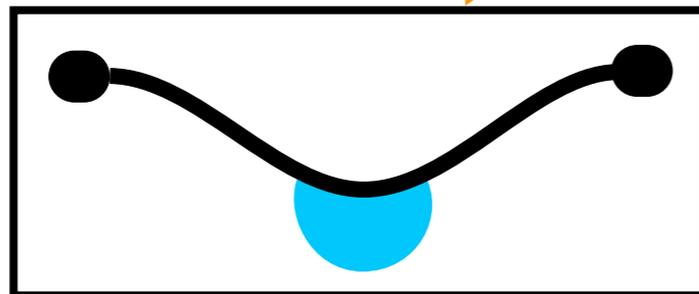
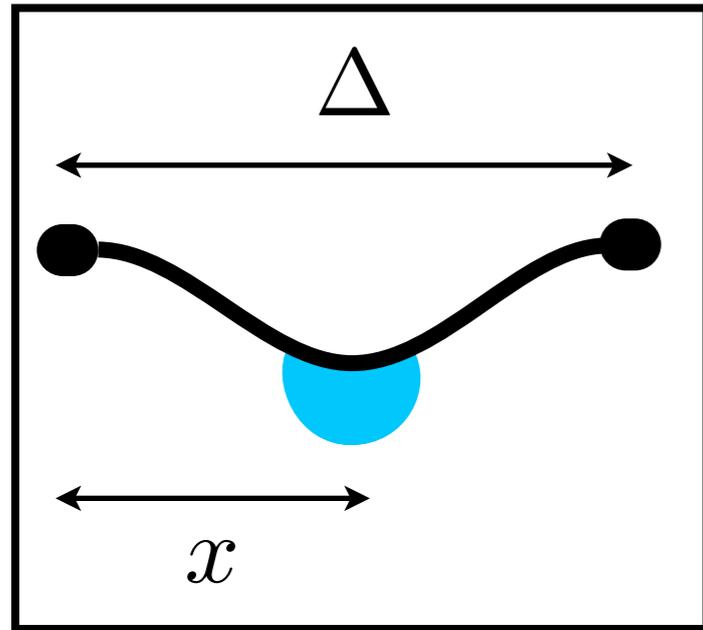


Capillary induced snap-through

liquid weight

$$FL^2/EI$$

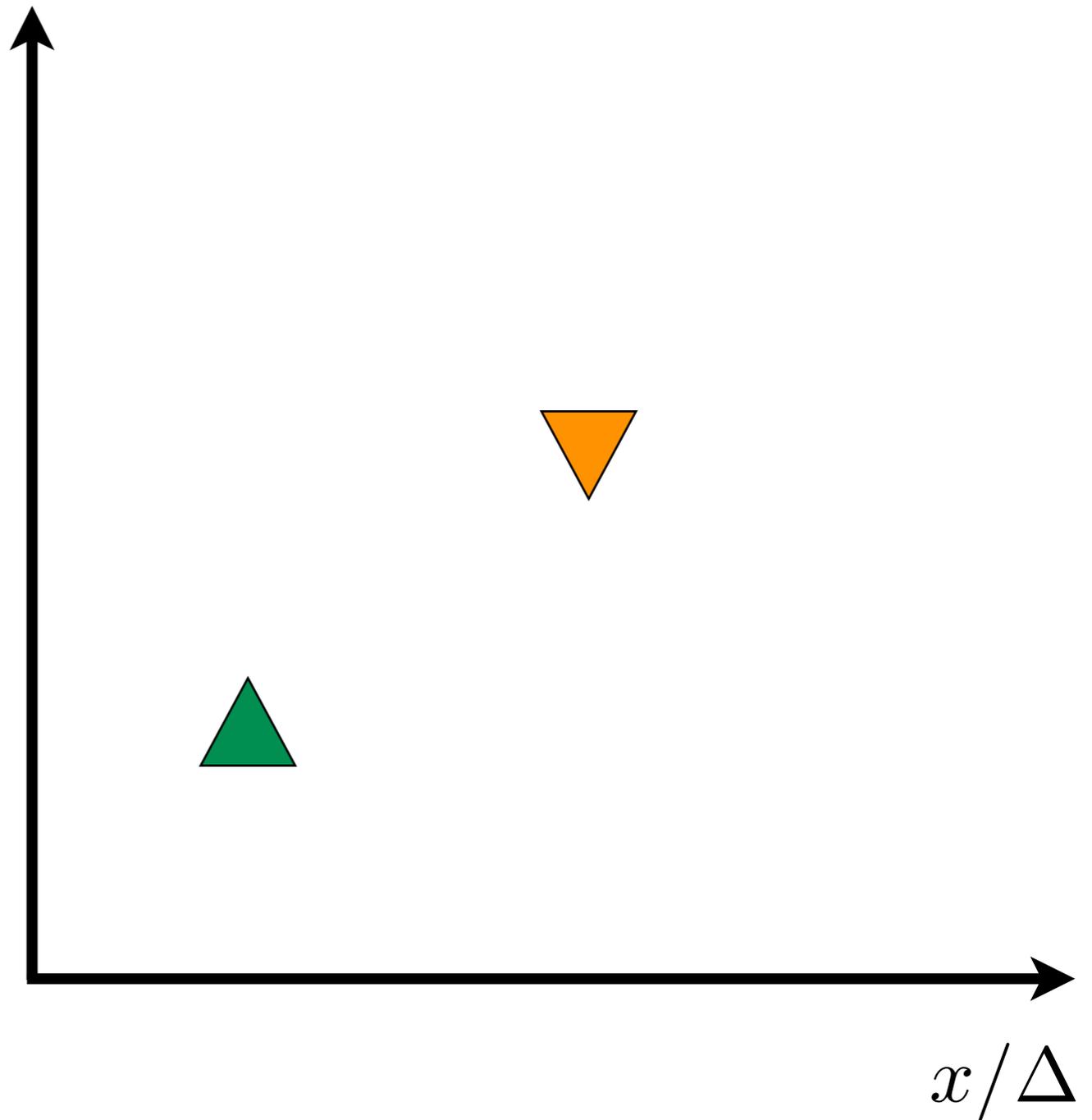
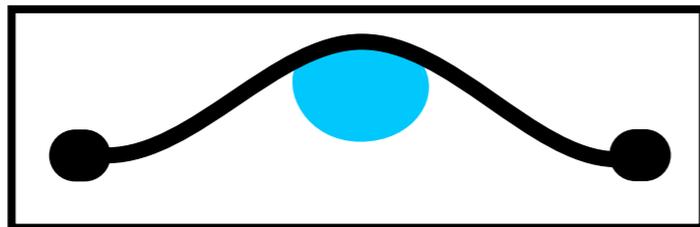
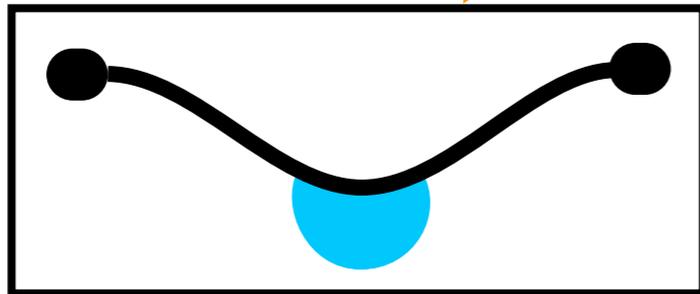
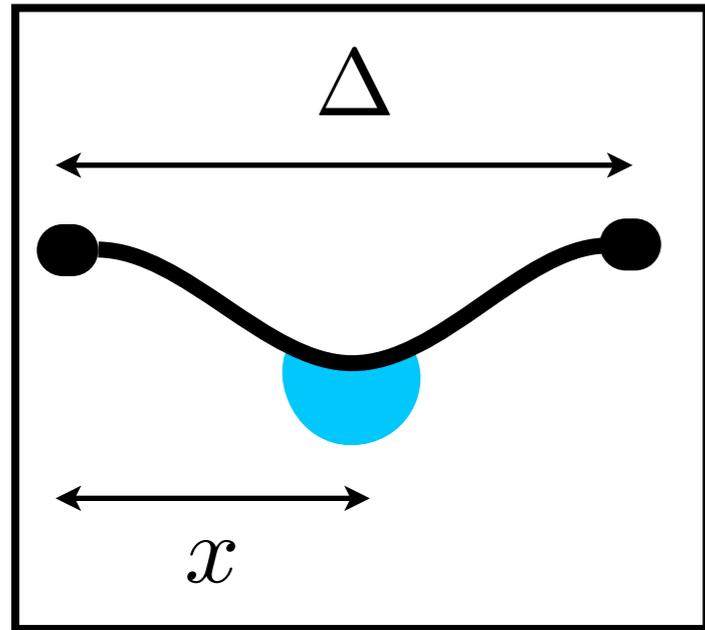
start



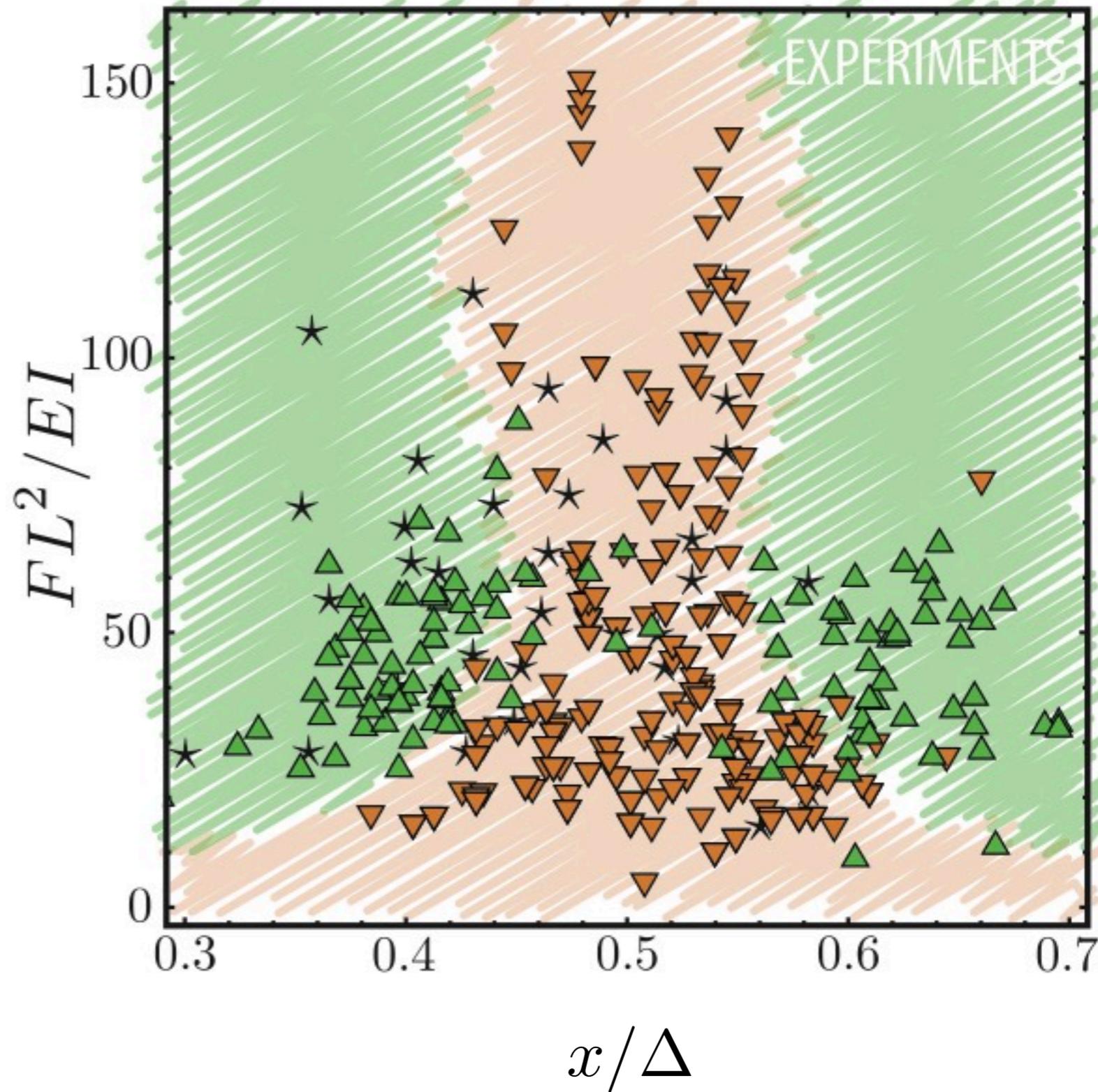
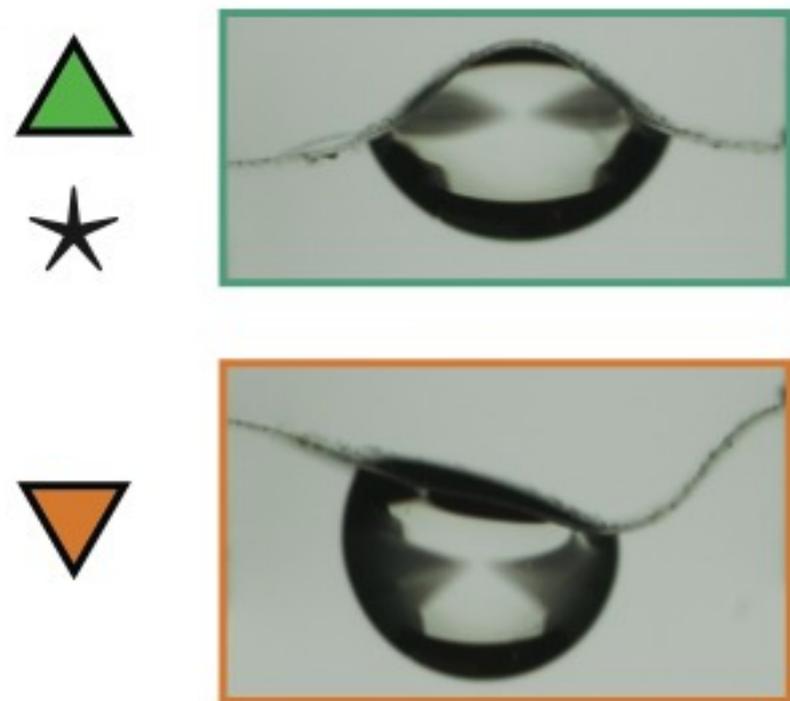
Capillary induced snap-through

liquid weight
 FL^2/EI

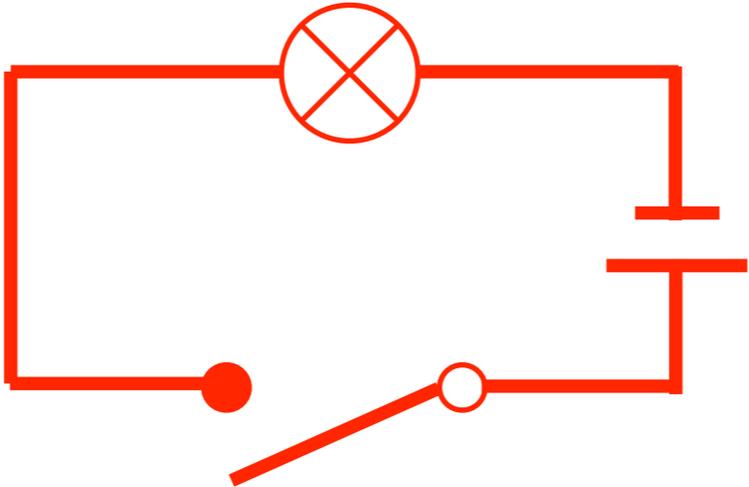
start



Capillary induced snap-through

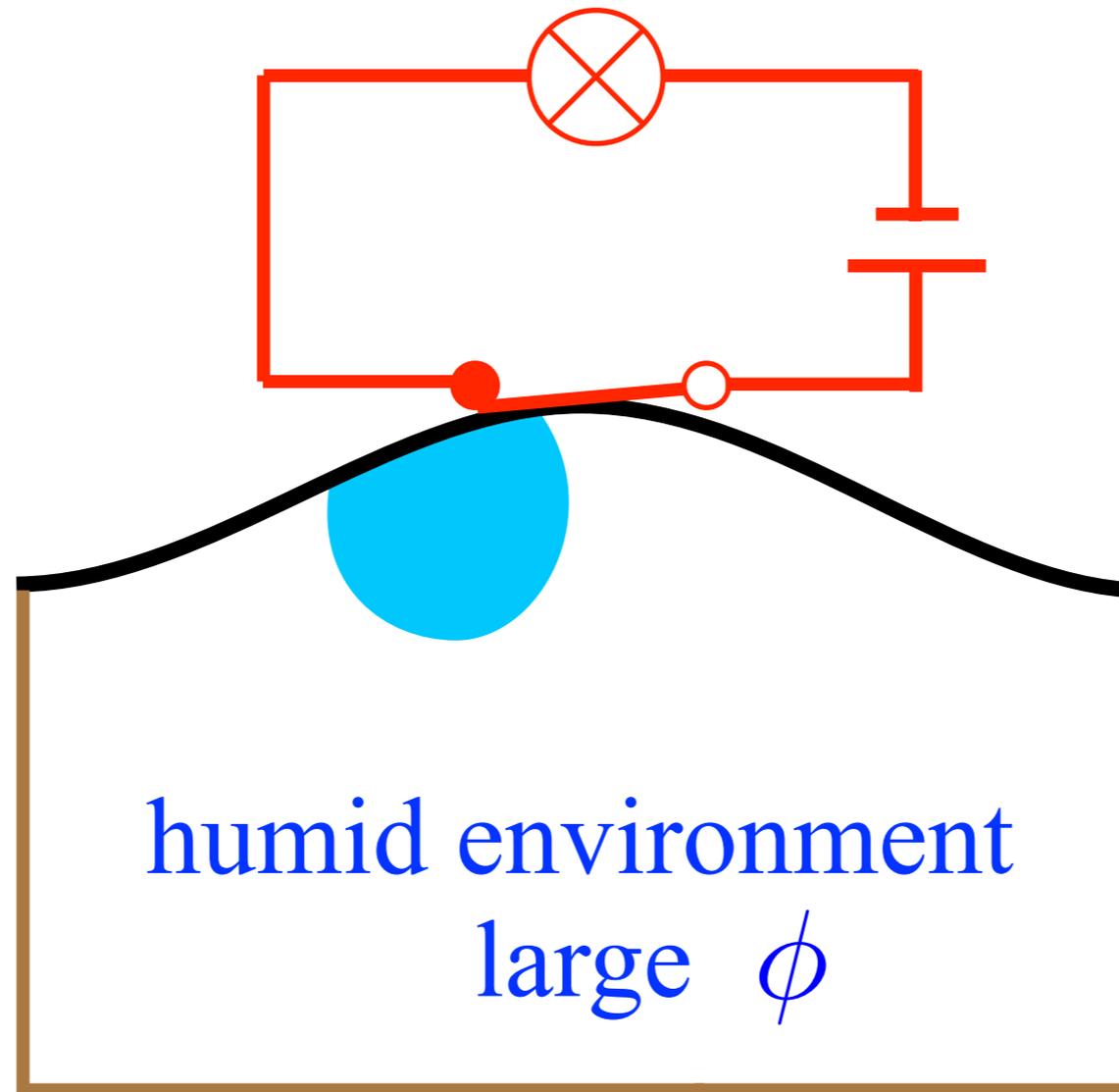


Condensation induced snap-through



1 mm

Condensation induced snap-through

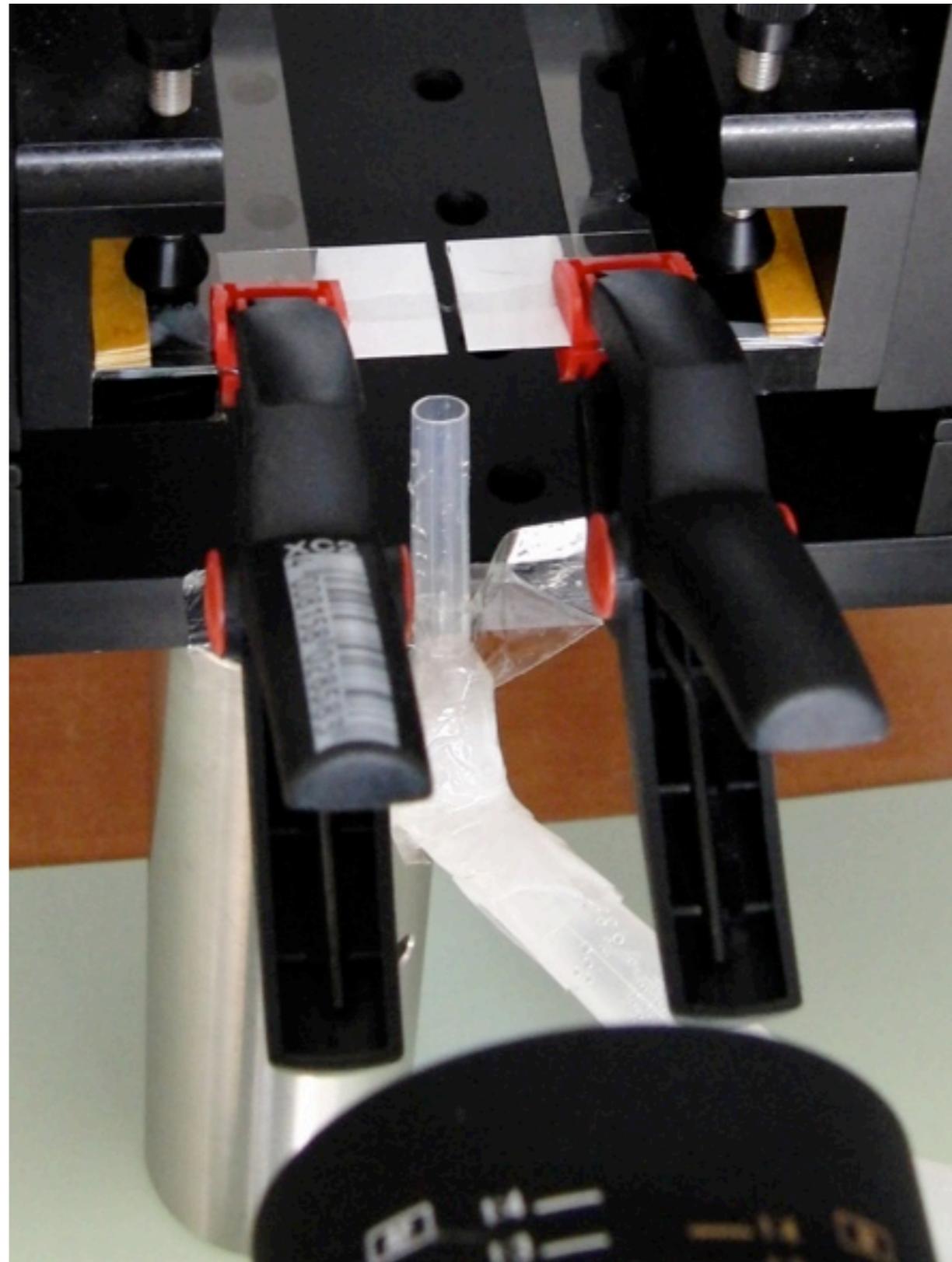


1 mm

Condensation induced snap-through



Condensation induced snap-through



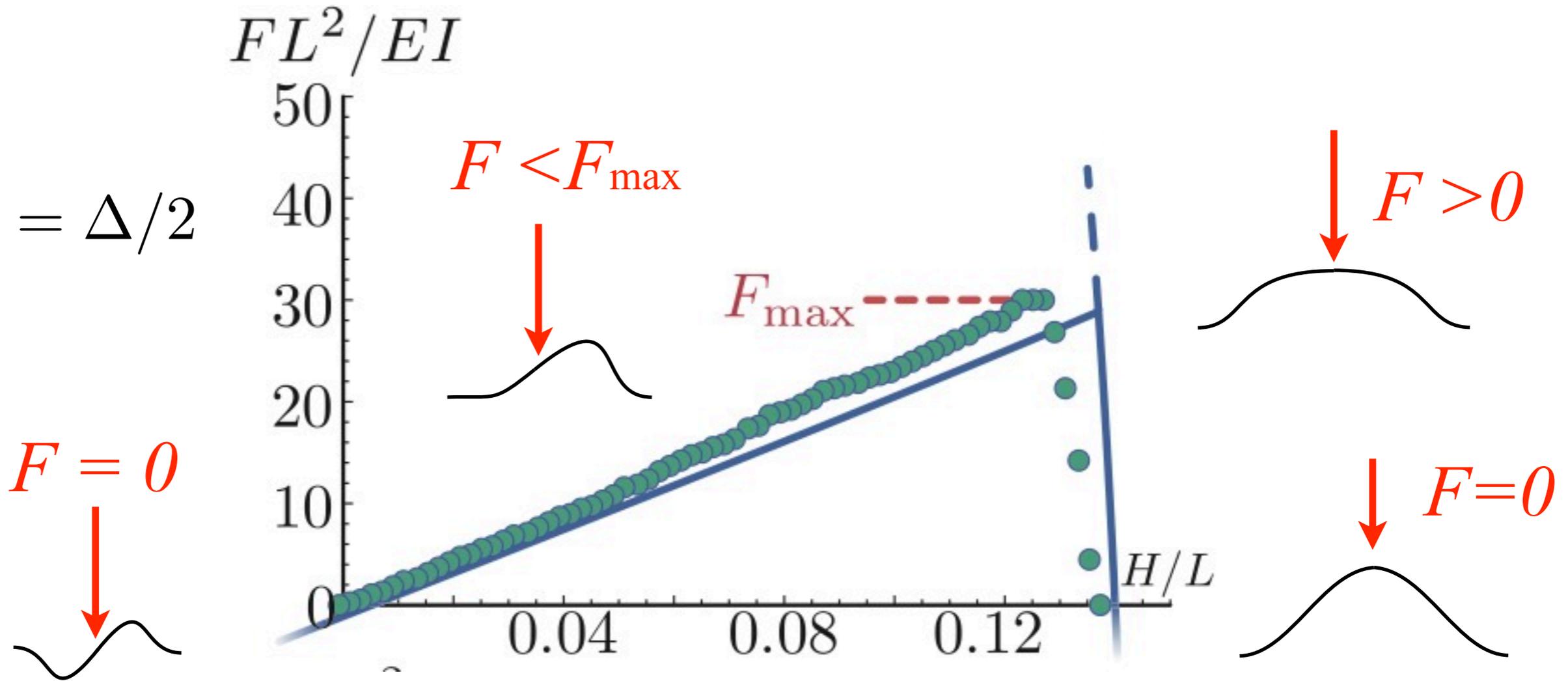
Condensation induced snap-through



PDMS strip
made hydrophilic on lower face
experiment lasts ~ 3 min

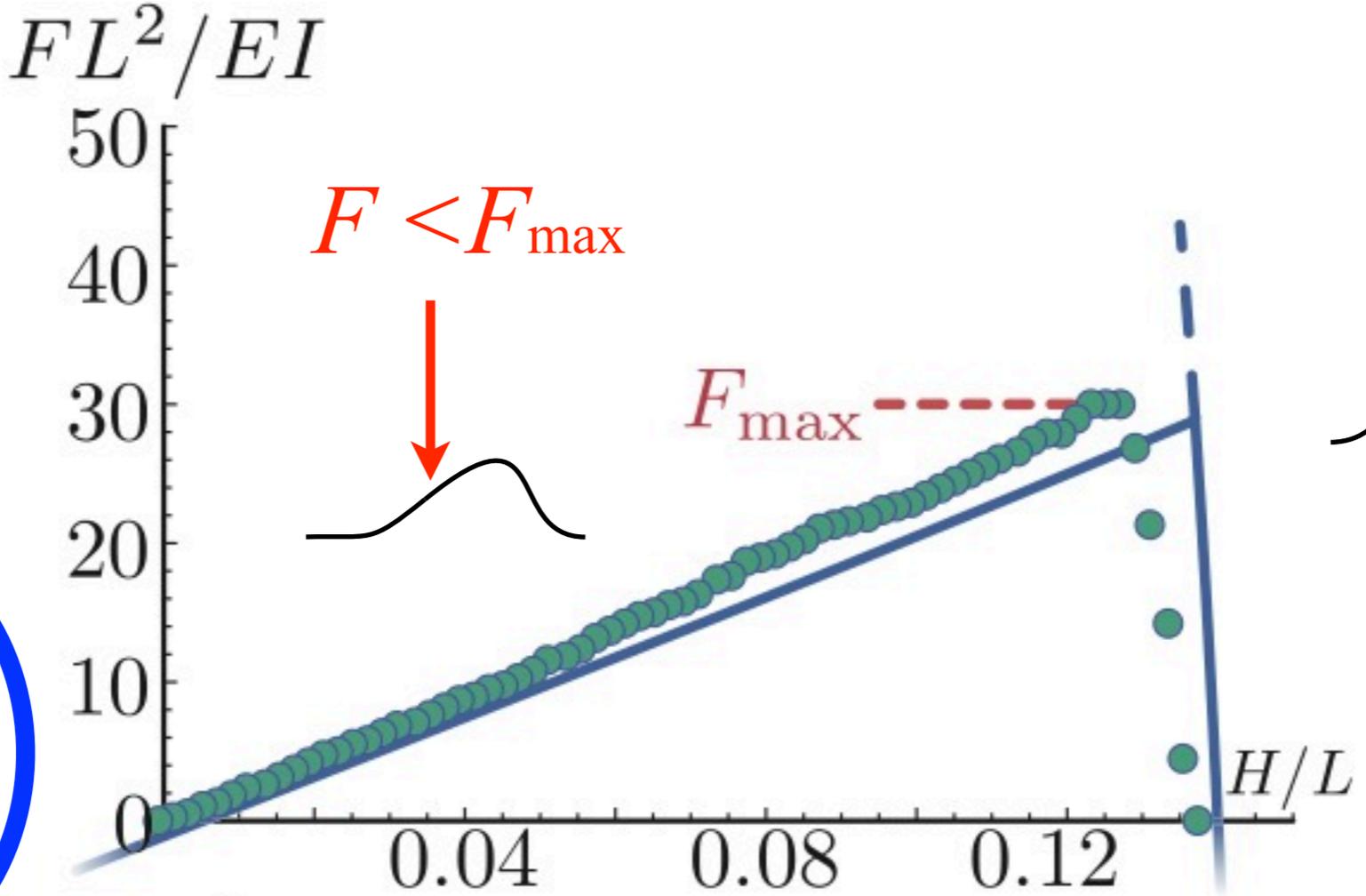
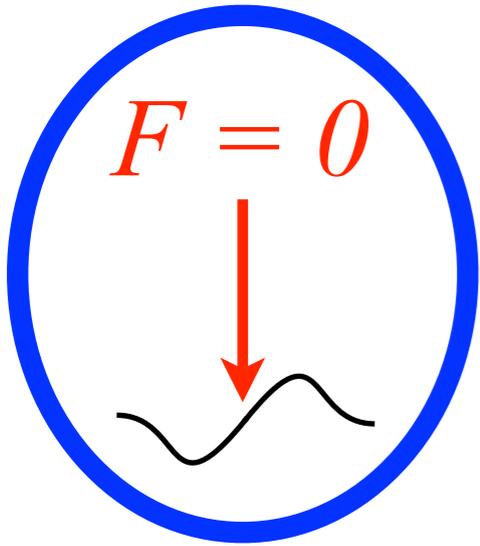
Snap-through dynamics: the dry case

for $x = \Delta/2$

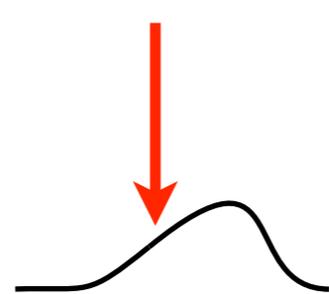


Snap-through dynamics: the dry case

for $x = \Delta/2$

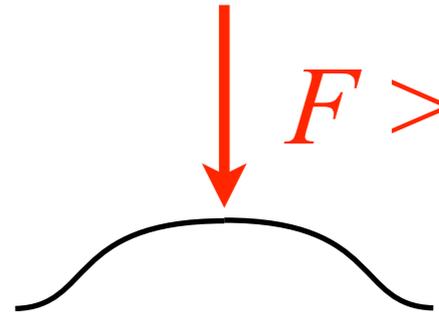


$F < F_{max}$

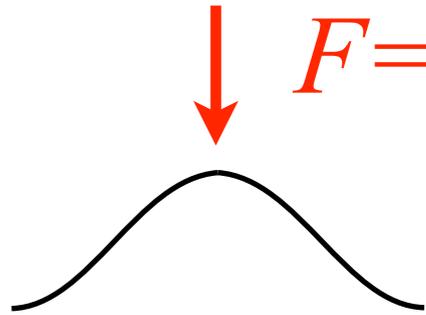


F_{max}

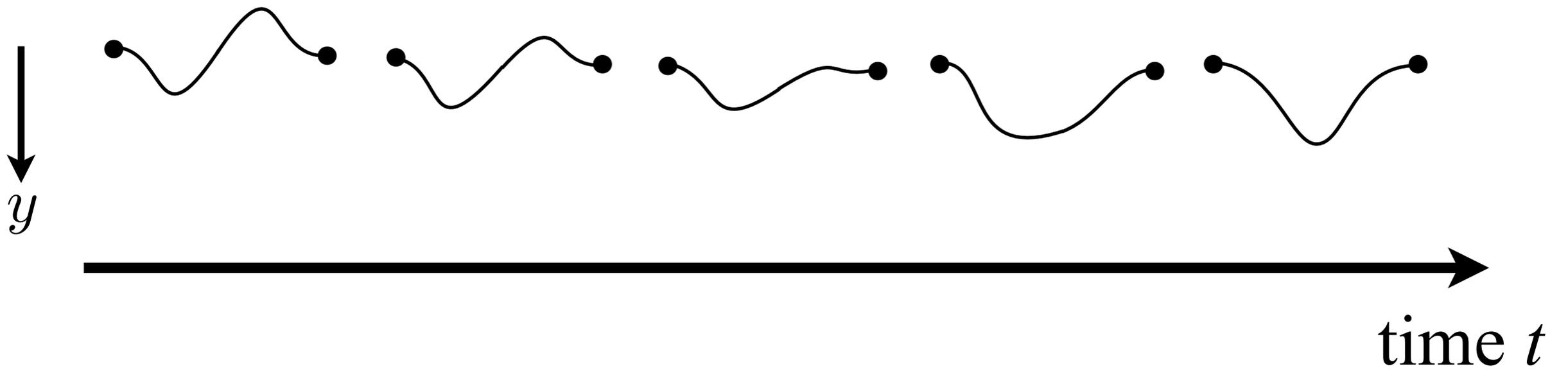
$F > 0$

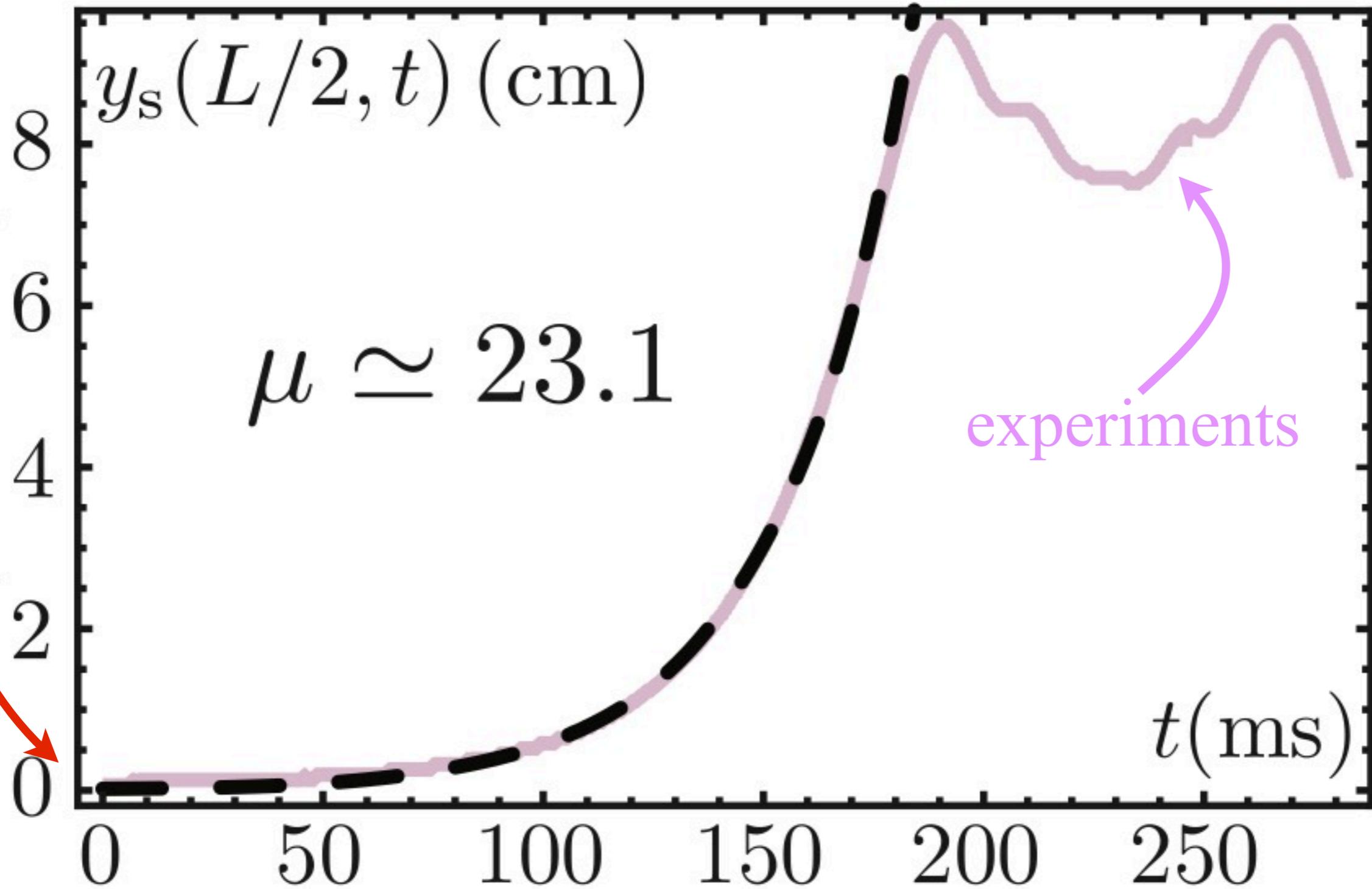
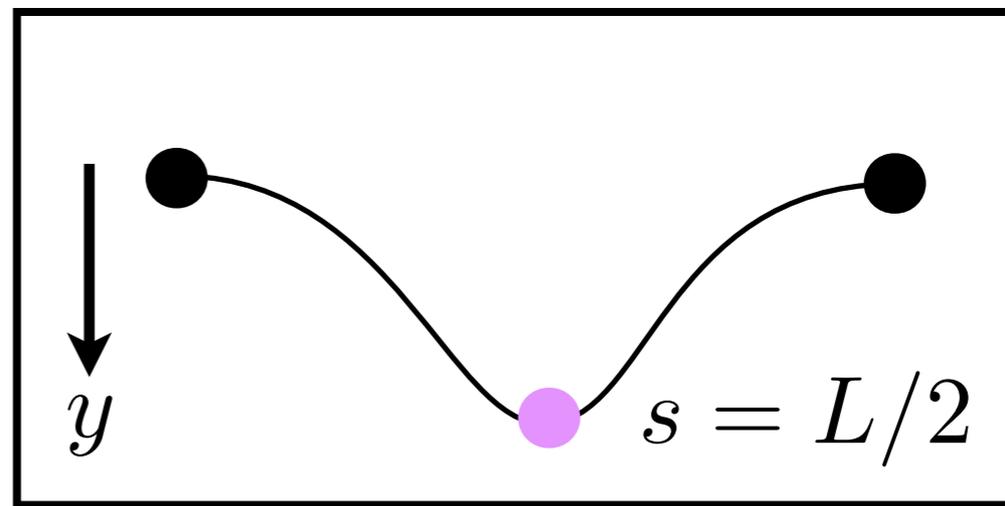
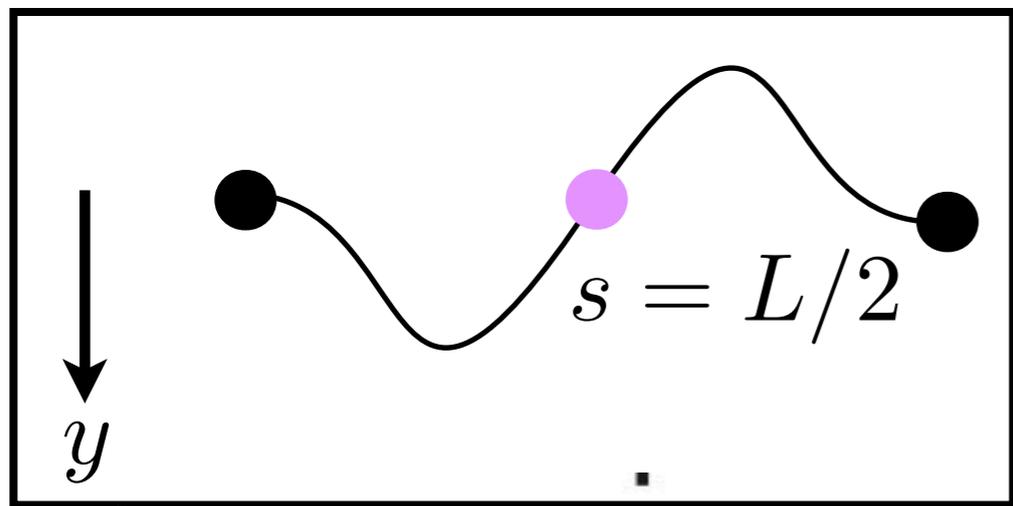


$F = 0$



Snap-through dynamics: the dry case





Snap-through dynamics: the dry case

Experiments:

near the unstable solution

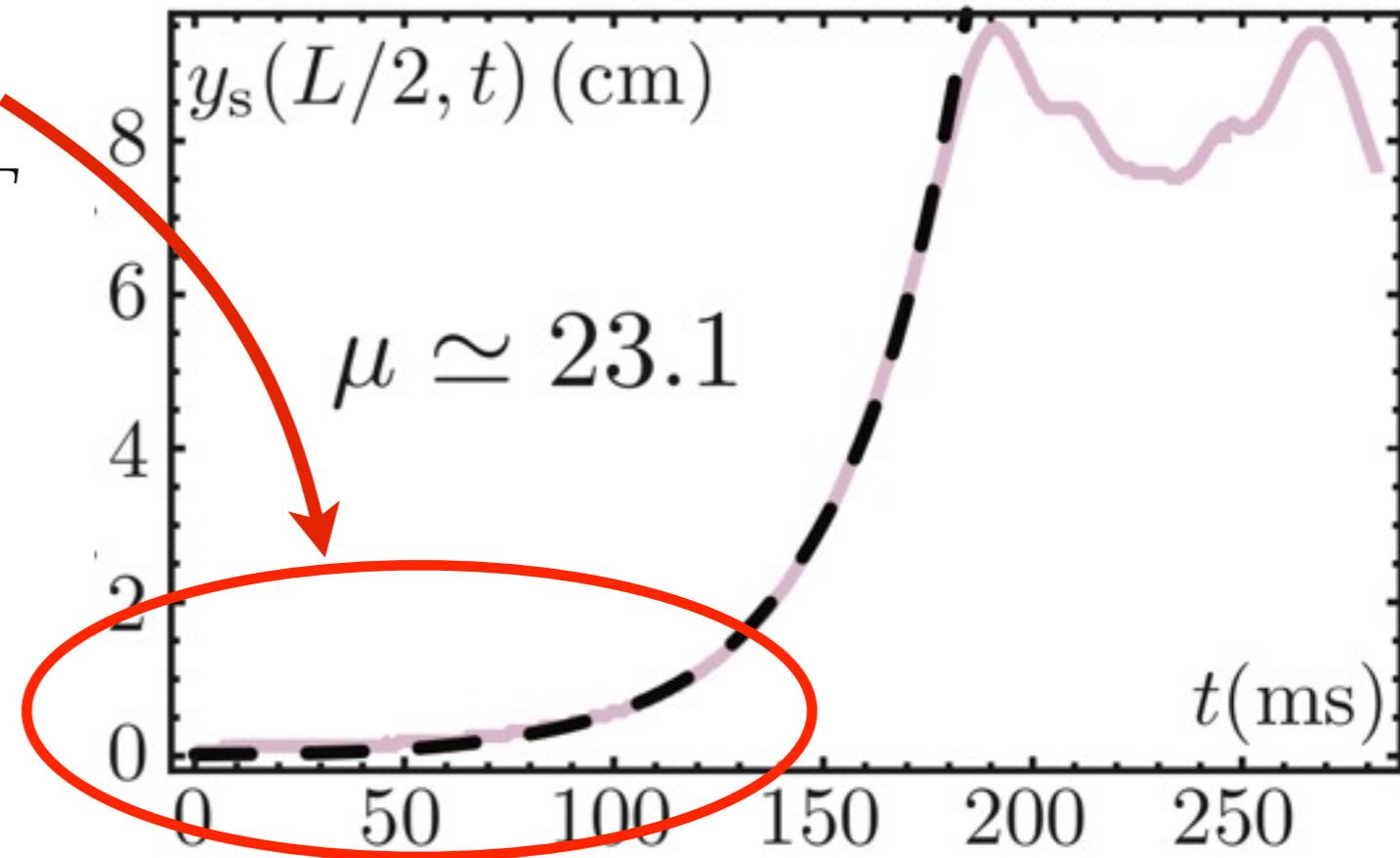
$$y(s, t) = y_{EQ}(s) + \bar{y}(s) e^{\mu t/T}$$

with scaling time:

$$T = L^2 \sqrt{\lambda/(EI)}$$

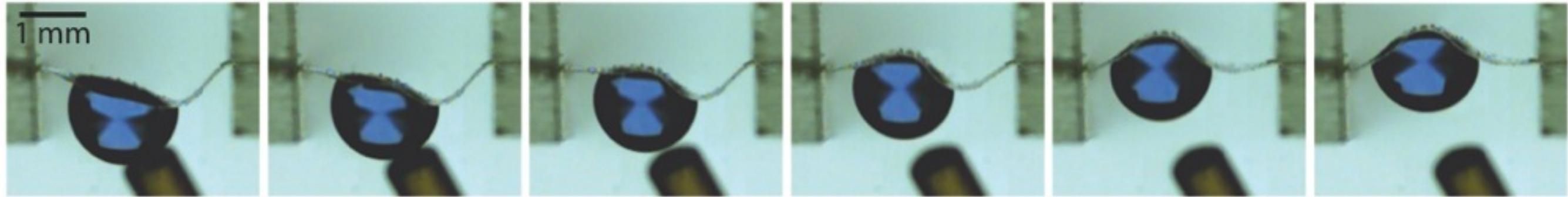
we fit and find

$$\mu \simeq 23.1$$



Theory says:
 $\mu = 24.3$

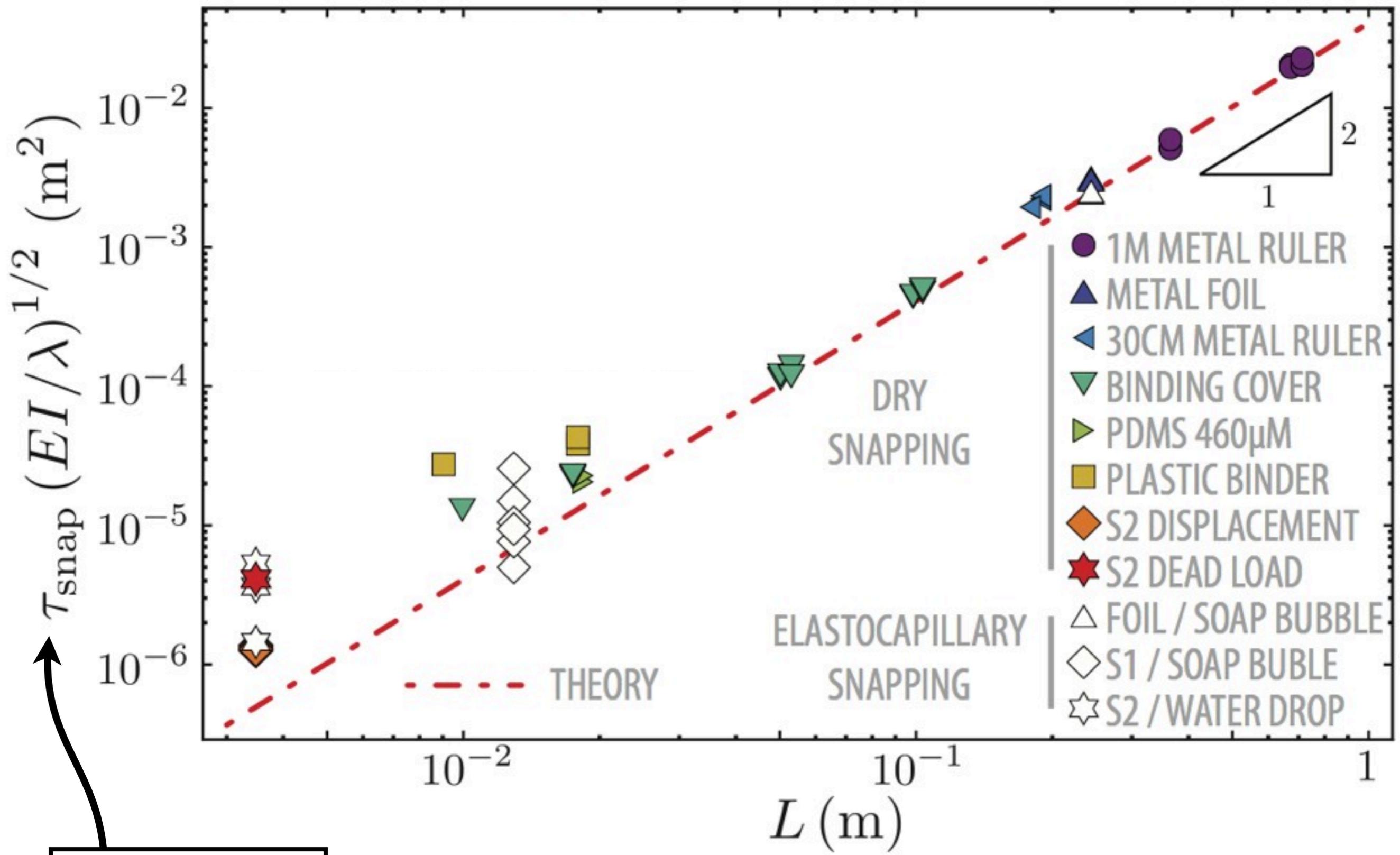
Snap-through dynamics: the wet case



Is the dynamics ruled by:

- inertia of drop (m) ?
- gravity (g) ?
- other effects (e.g. viscous) ?
- or just beam bending dynamics ?

Snap-through dynamics



$$\tau_{\text{snap}} = 1/\mu$$

Thank you

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- CNRS
- ANR
- Ville de Paris

