

# Snap-through induced by surface tension

*A. Fargette* ← PhD work

*A. Antkowiak*

*S. Neukirch*



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

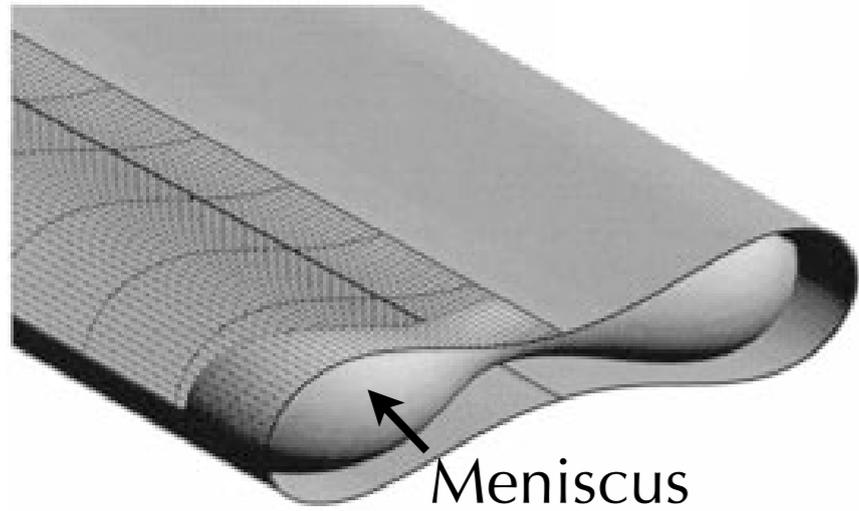
France

# Elastocapillarity: (incomplete) state of the art

*review article:*

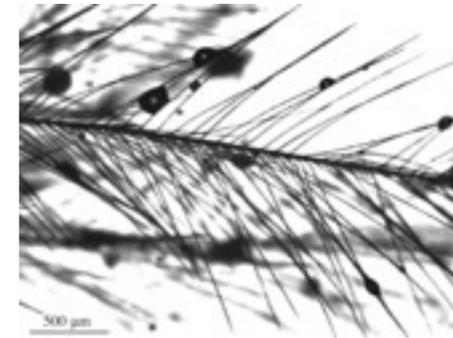
Roman + Bico (Journal of Physics: Condensed Matter) 2010

# Elastocapillarity in Biology



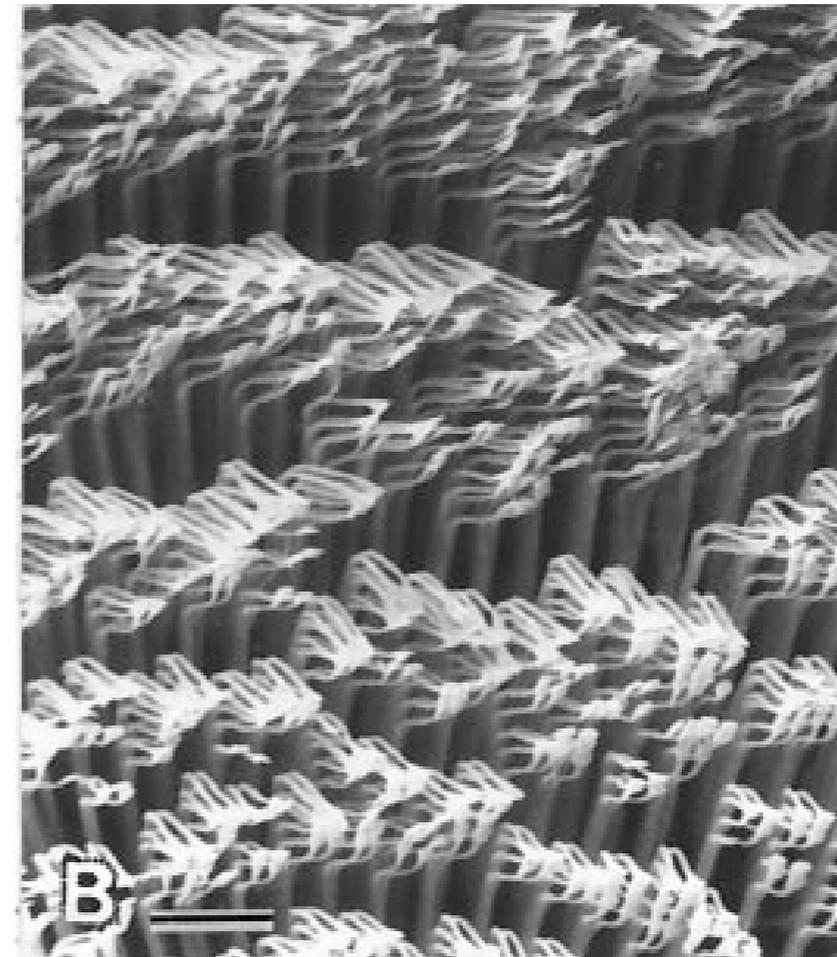
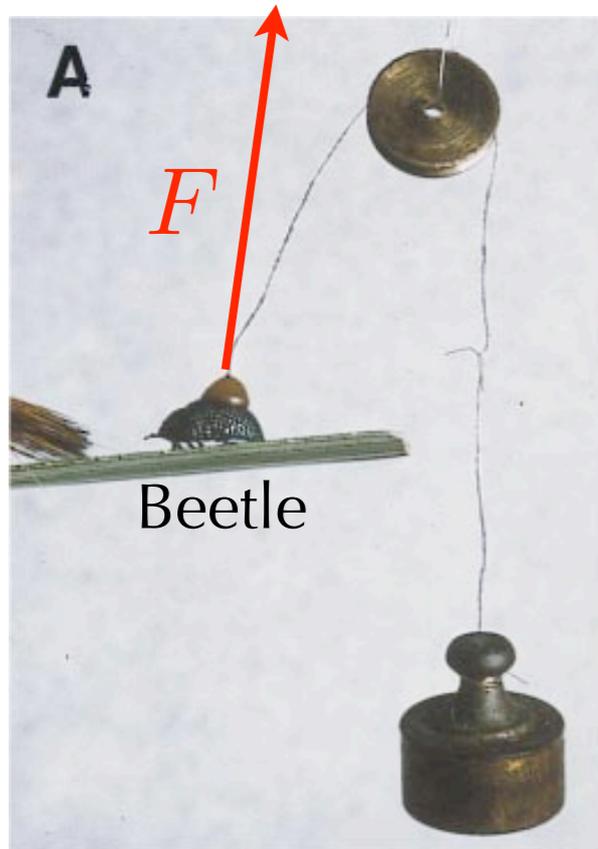
Lung's airway closure

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



Wet feathers

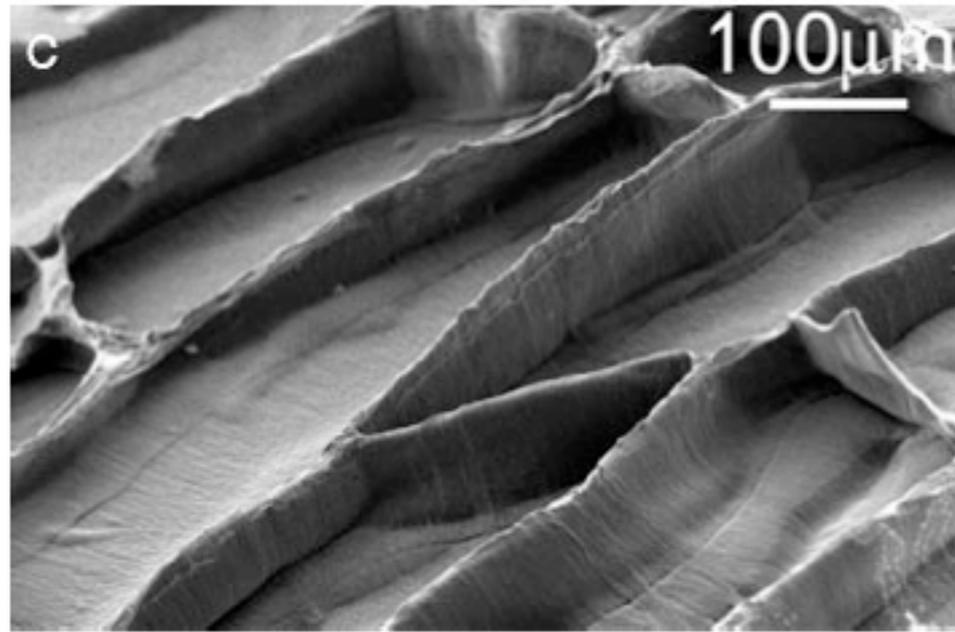
Duprat, Protière, Beebe and Stone, *Nature* (2012)



Insect adhesion

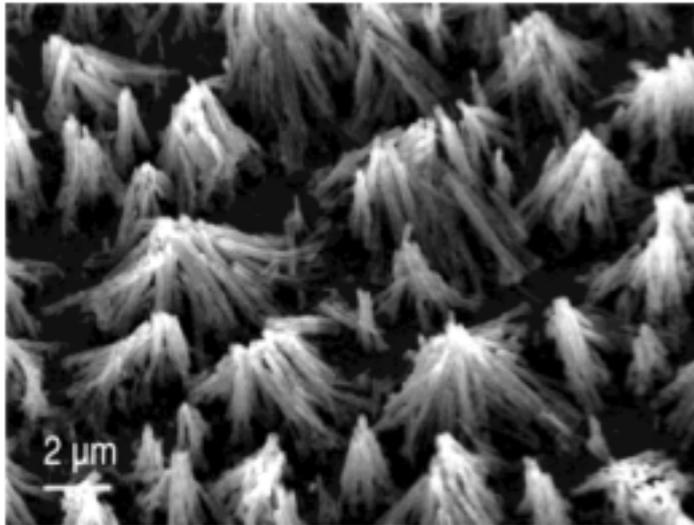
Eisner et al., PNAS, 2000

# Elastocapillarity in Industry



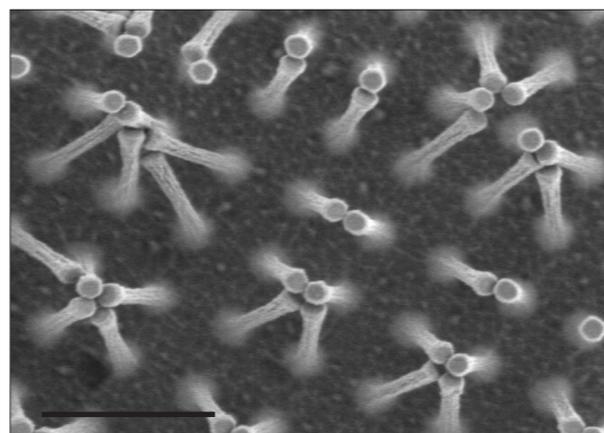
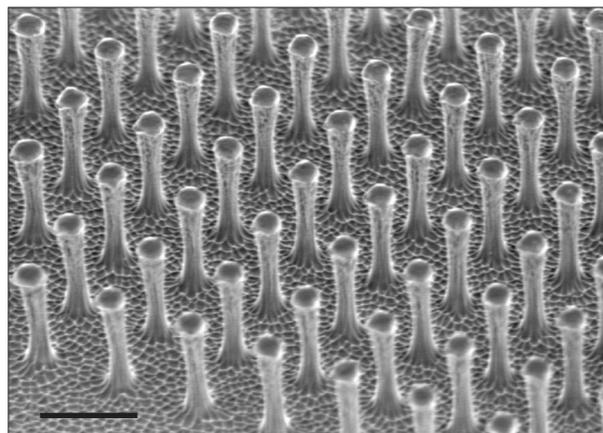
## Cellular patterns

Chakrapani et al., PNAS, 2004



## Teepee formation

Lau et al., Nano Lett., 2003



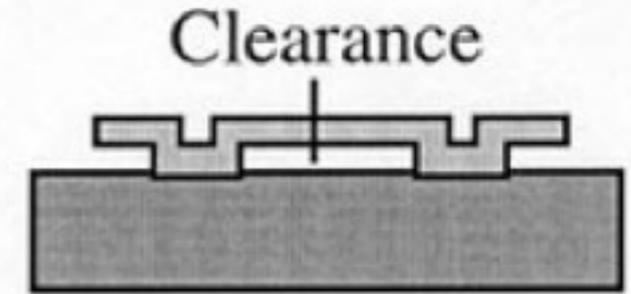
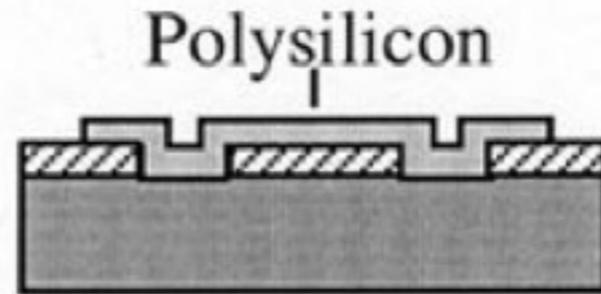
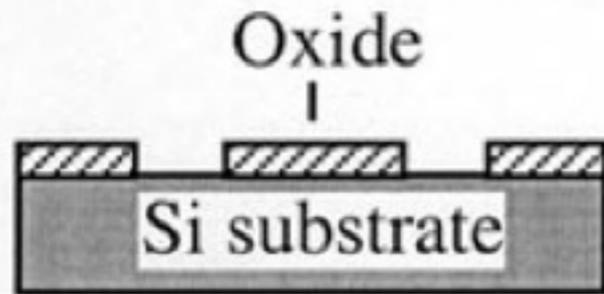
## Bio-mimetism

Geim et al., Nature Mat., 2003

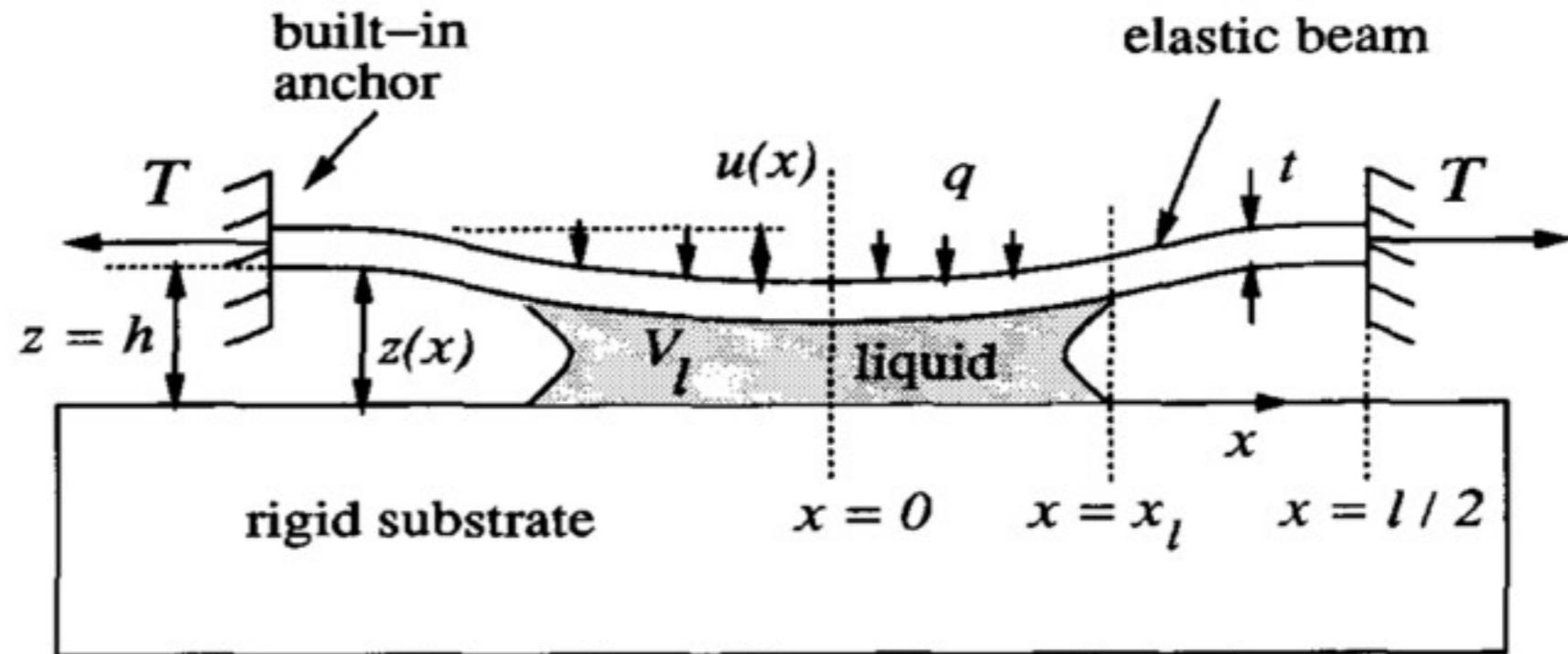
# Elastocapillarity in Industry

suspended micromachined structures

*Polysilicon micromachining*



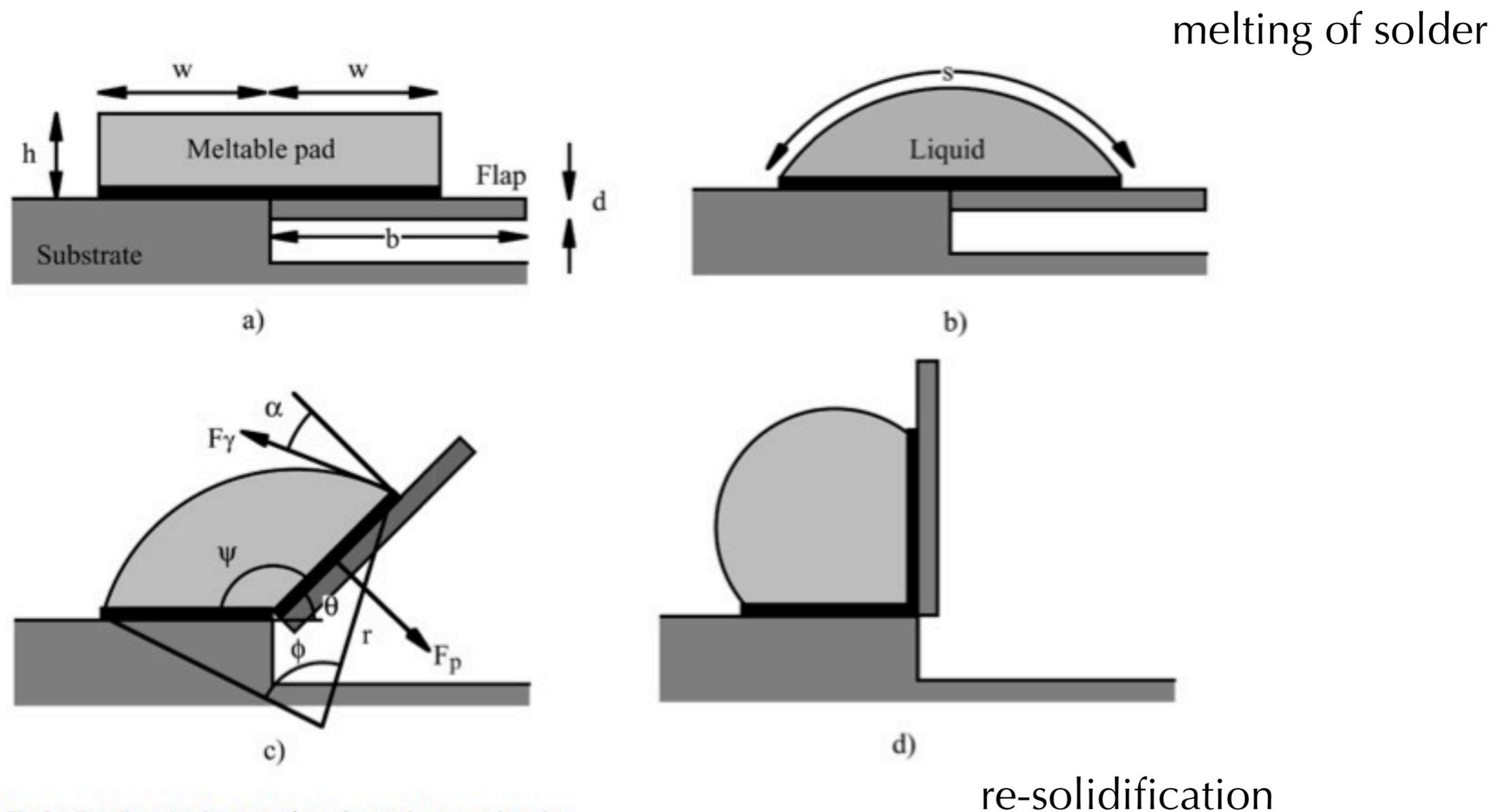
collapse during evaporation



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

Mastrangelo, Journal of MEMS (1993)

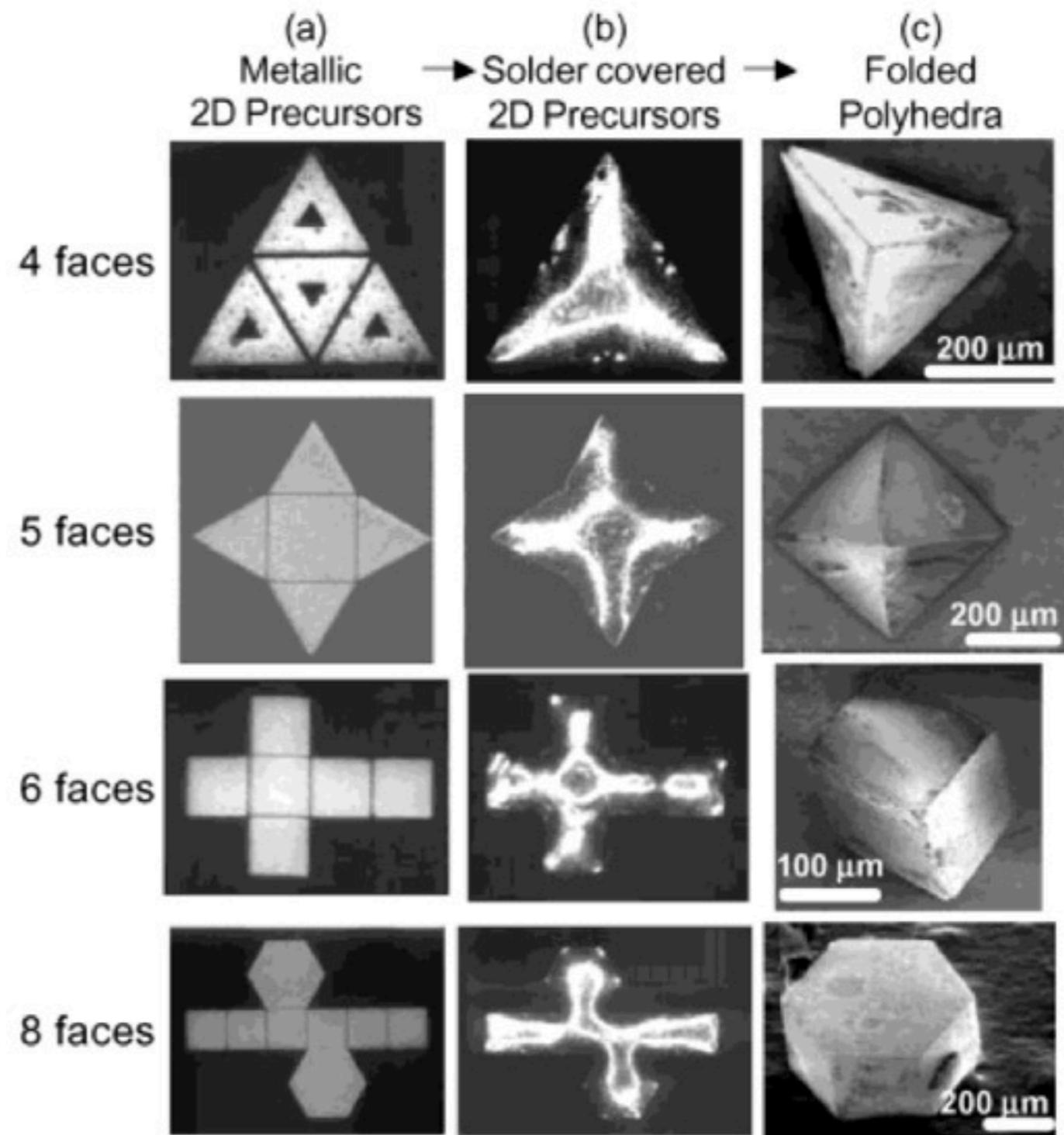
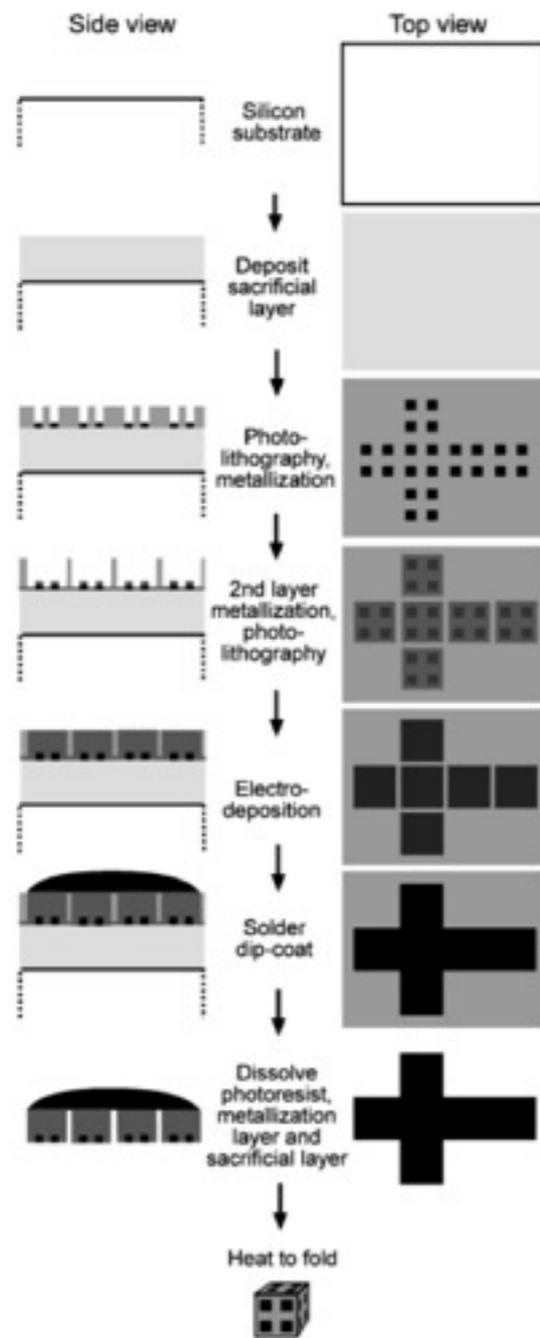
# Elastocapillarity in Industry: Microfabrication



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

R. Syms, Journal of MEMS (1995)

# Elastocapillarity in Industry: Microfabrication

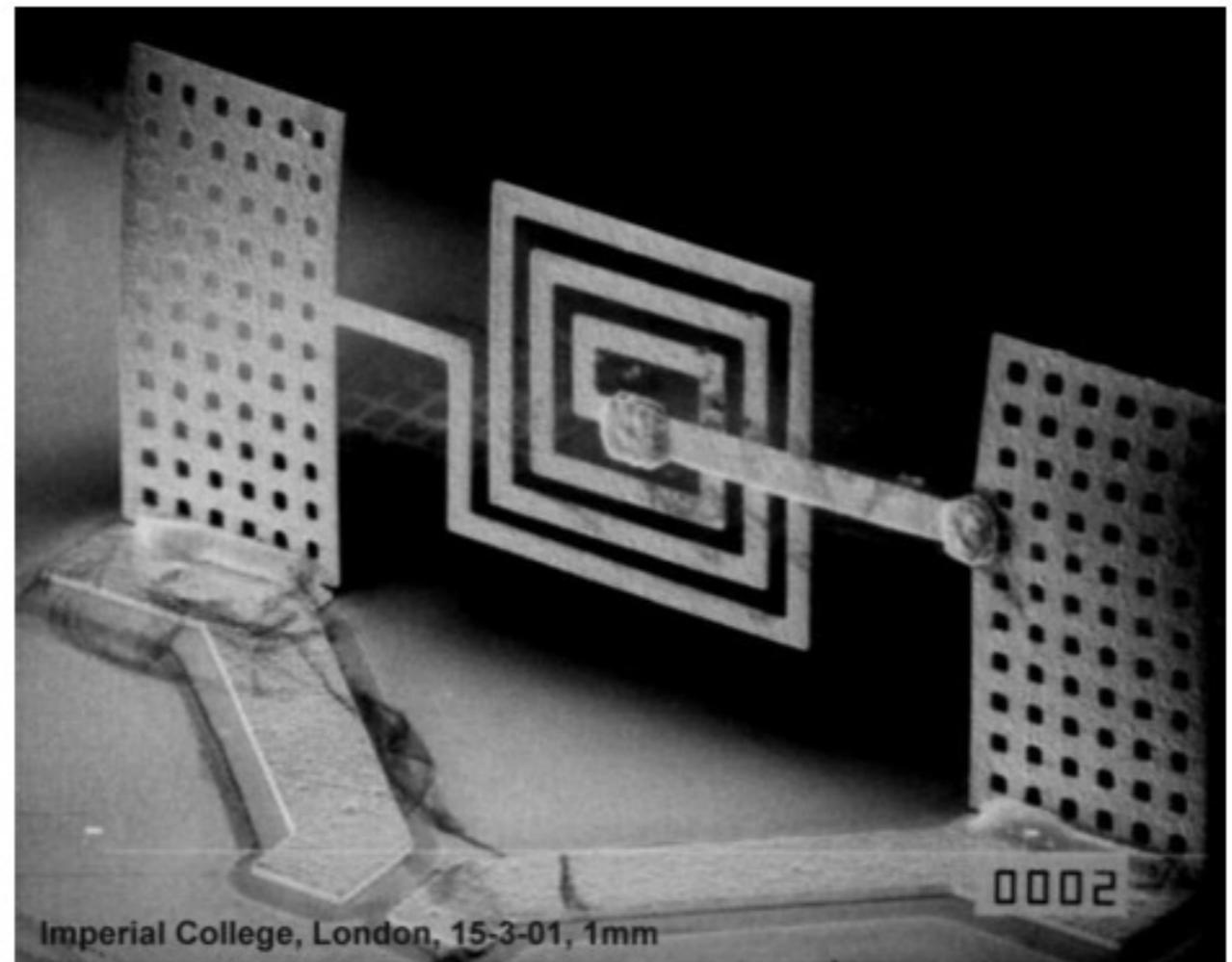


spontaneous folding of 2D structures under the influence of the surface tension of liquid solder

Gracias et al, Adv. Mat. (2002)

# Elastocapillarity in Industry: Microfabrication

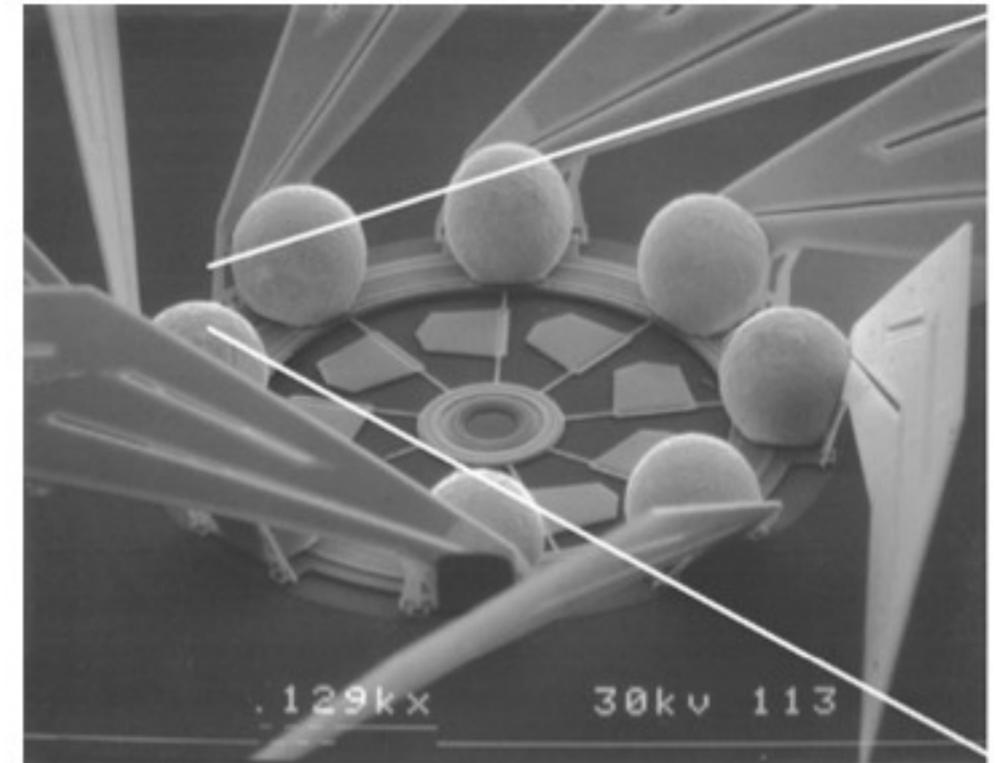
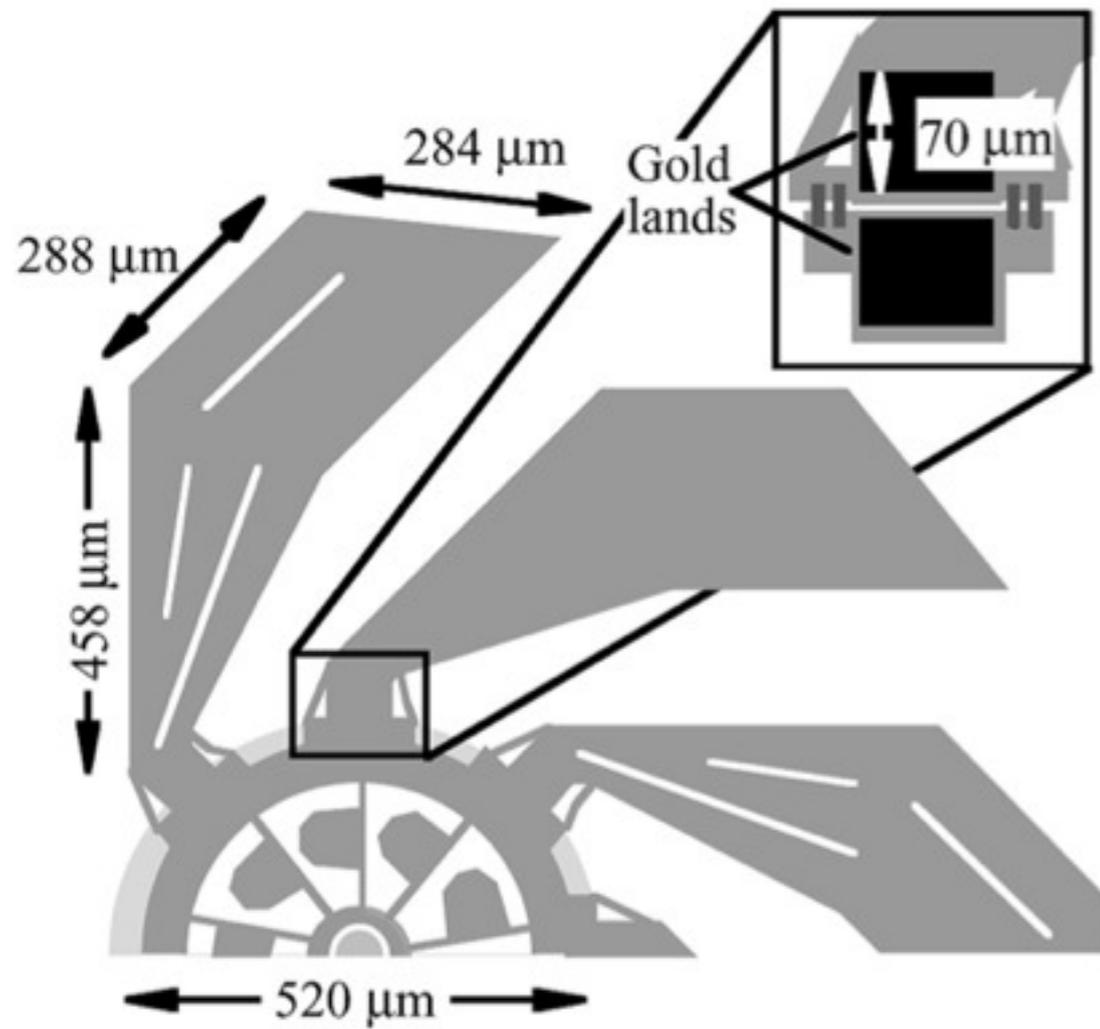
inductor has to be  
away from (metallic) substrate to  
prevent magnetic field loss



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

Dahlmann, Electron Lett. (2000)

# Elastocapillarity in Industry: Microfabrication



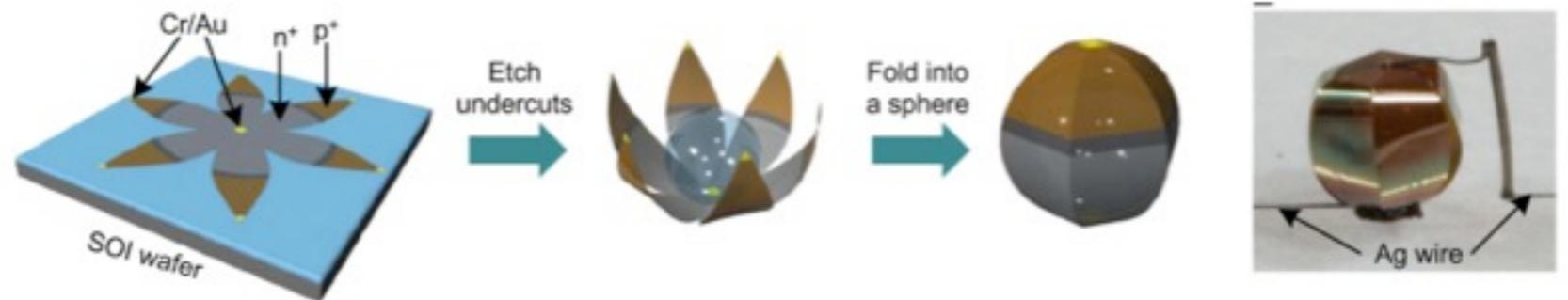
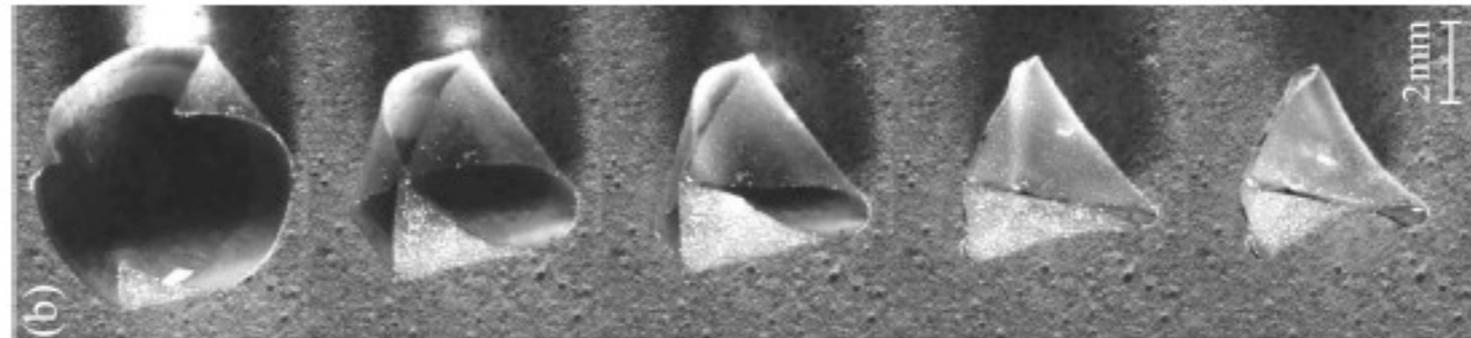
folding by surface tension of Pb:Sn solder spheres

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

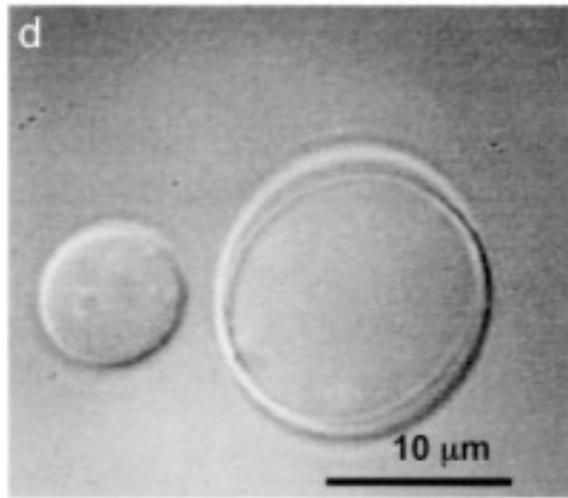


Guo et al., PNAS, 2009

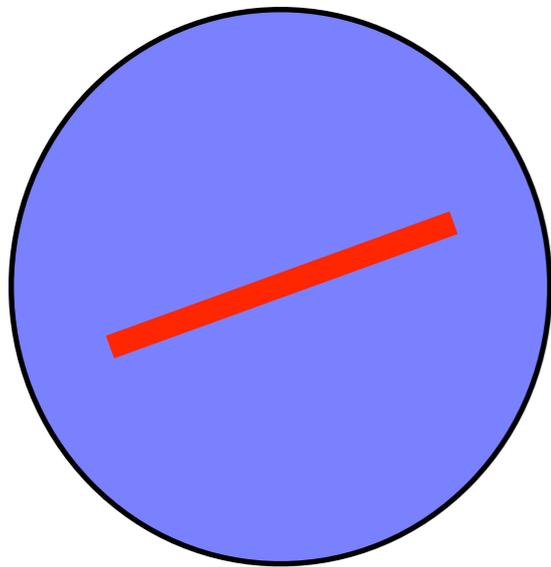
Applications: non-spherical lenses, 3D electronic circuits, curved micro solar panels, wrapping of active substances for targeted drug delivery...

# The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

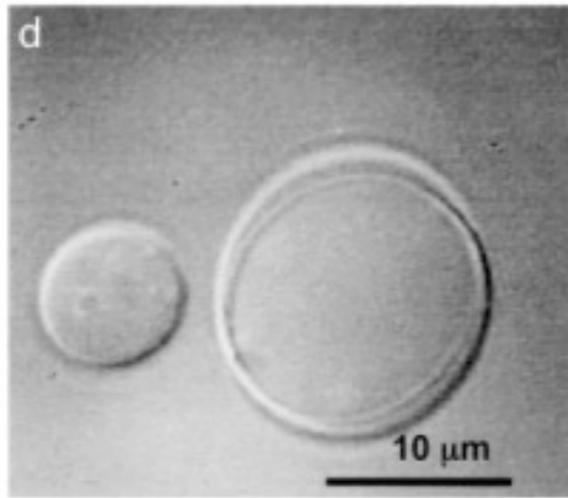


Cohen & Mahadevan, PNAS (2003)

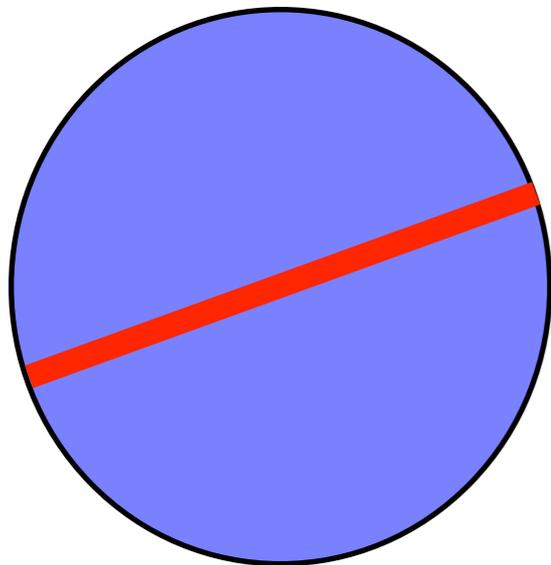


# The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

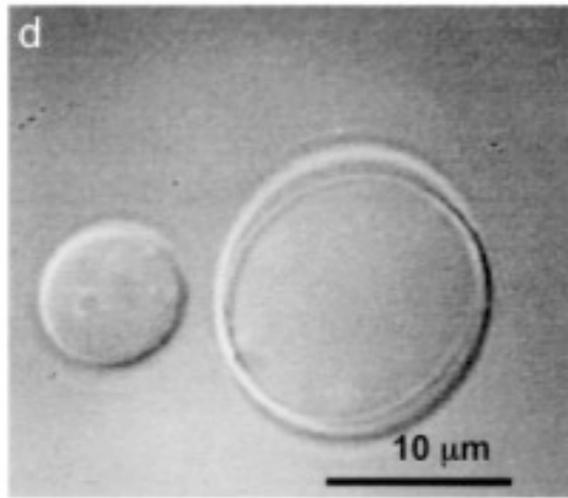


Cohen & Mahadevan, PNAS (2003)

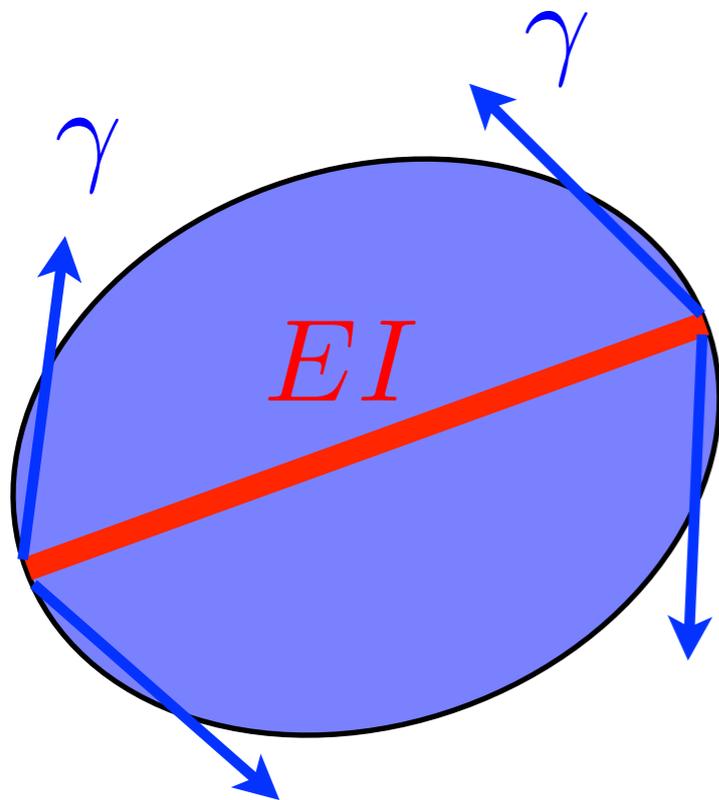


# The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

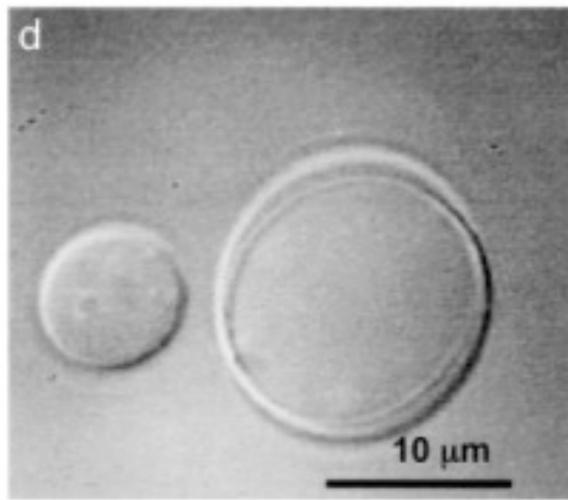


Cohen & Mahadevan, PNAS (2003)



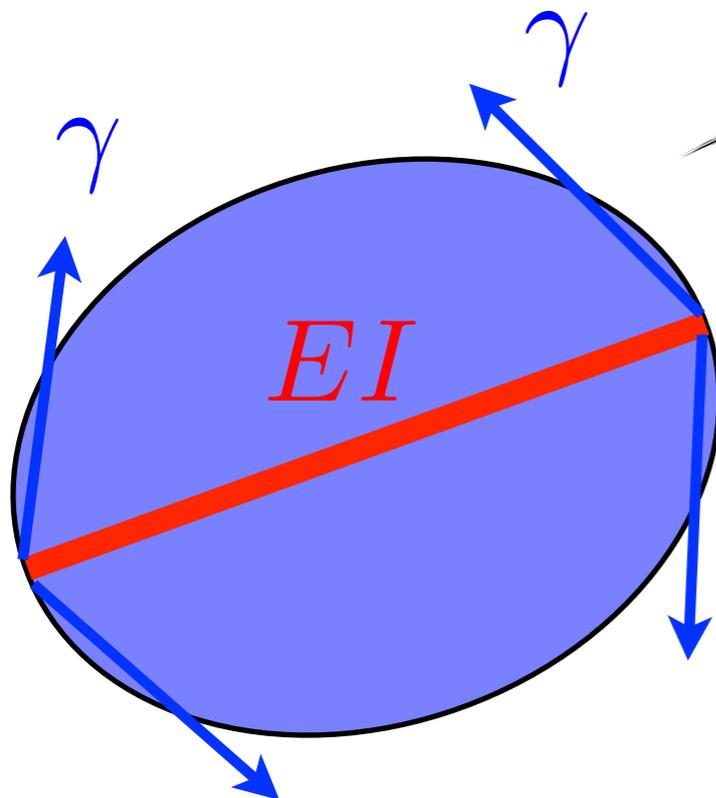
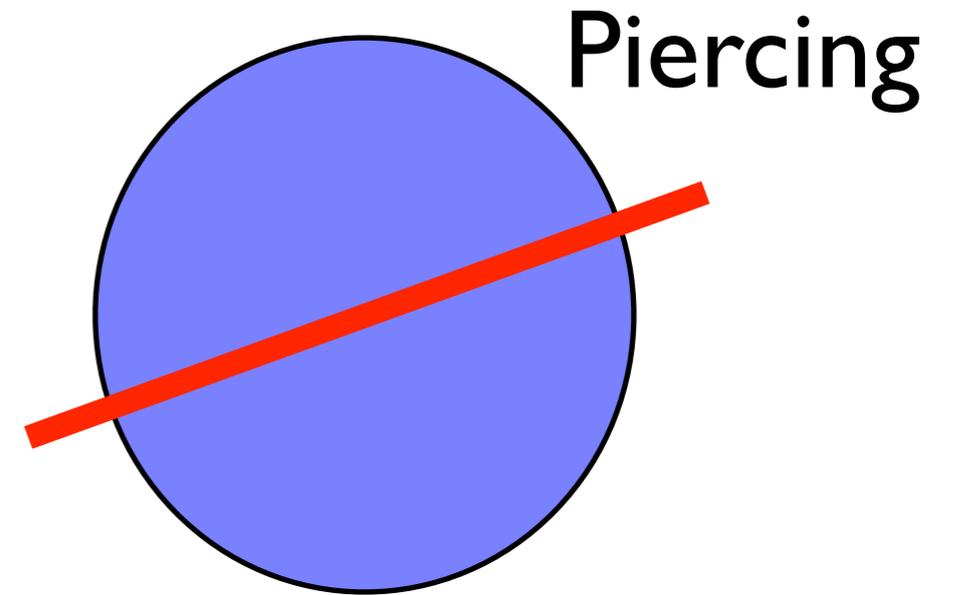
# The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle



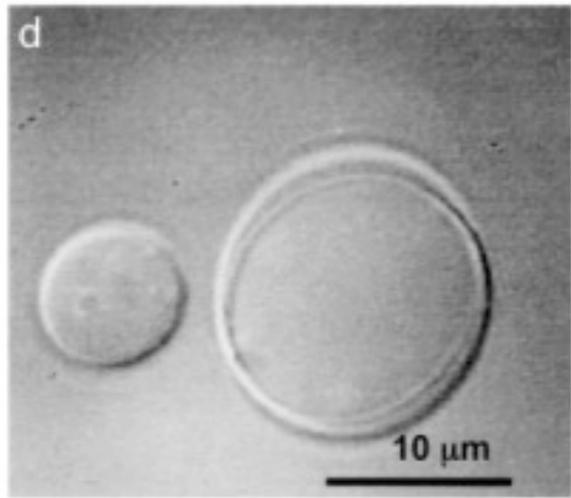
Cohen & Mahadevan, PNAS (2003)

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



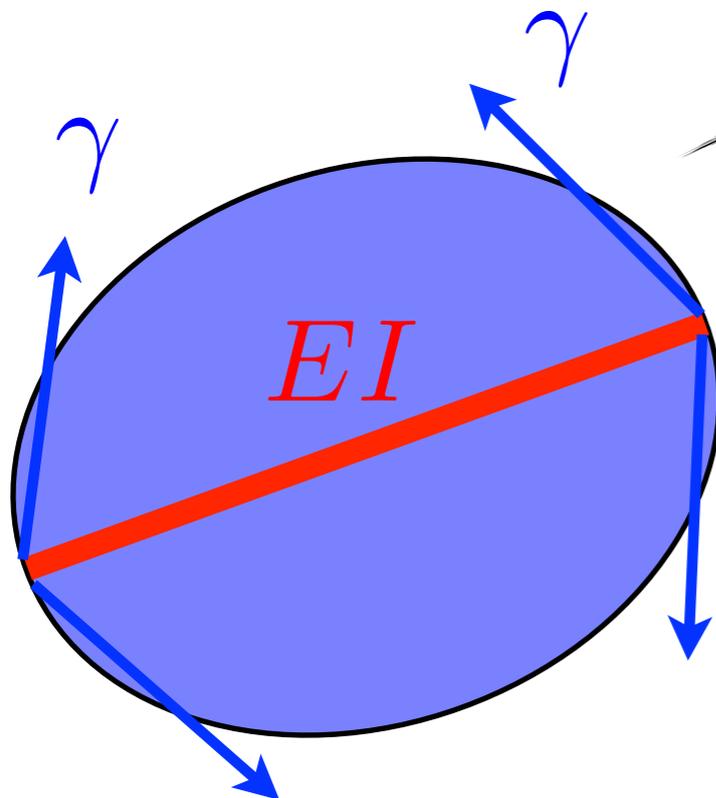
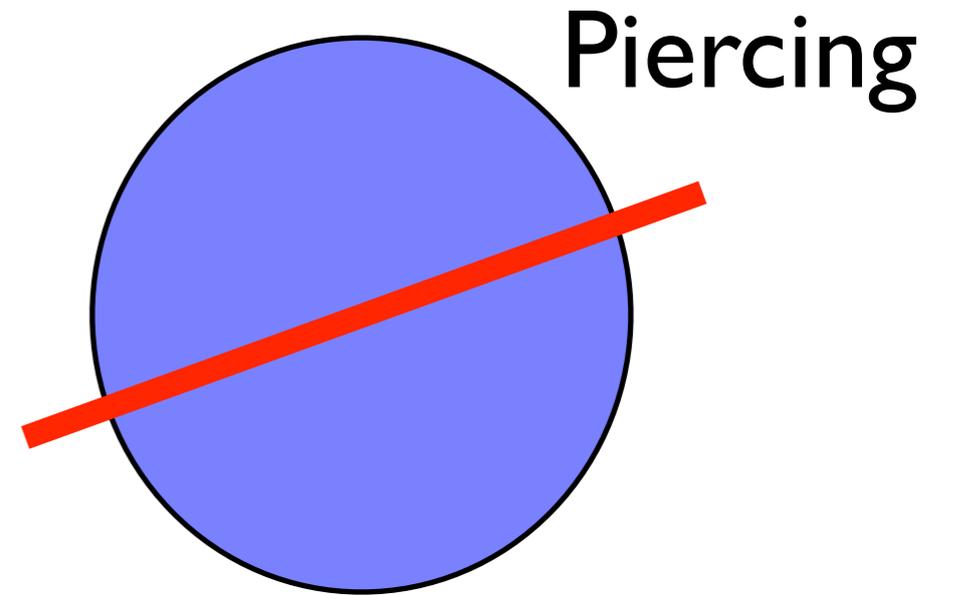
# The Elastocapillary lengthscale

A tubulin rod growing inside a lipid vesicle

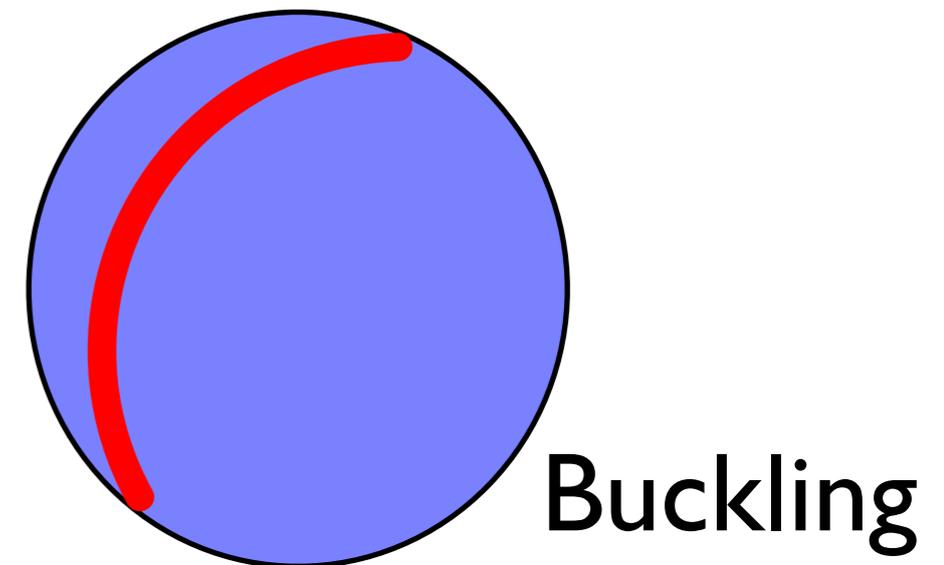


Cohen & Mahadevan, PNAS (2003)

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

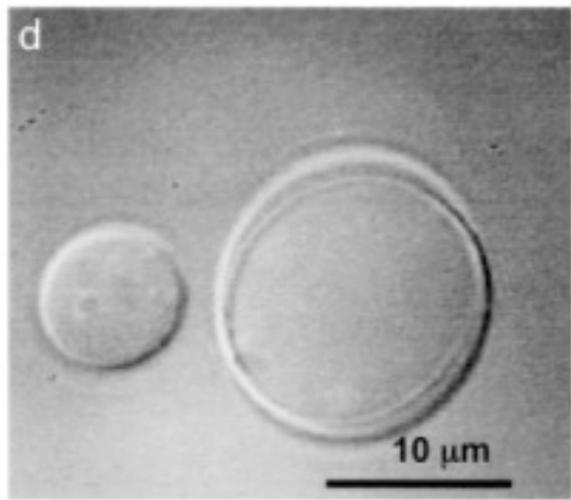


$$\frac{EI}{L^2} \ll \gamma$$



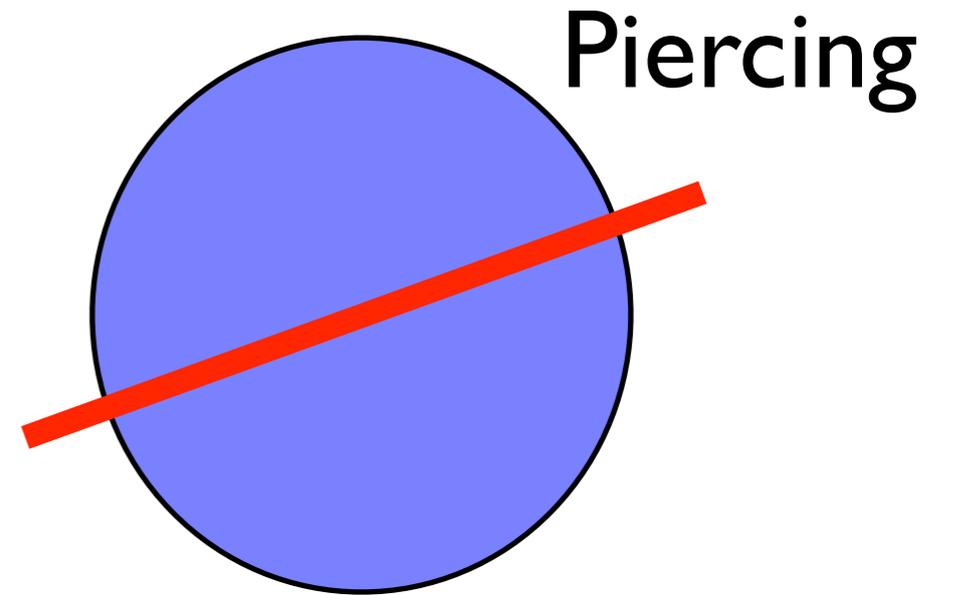
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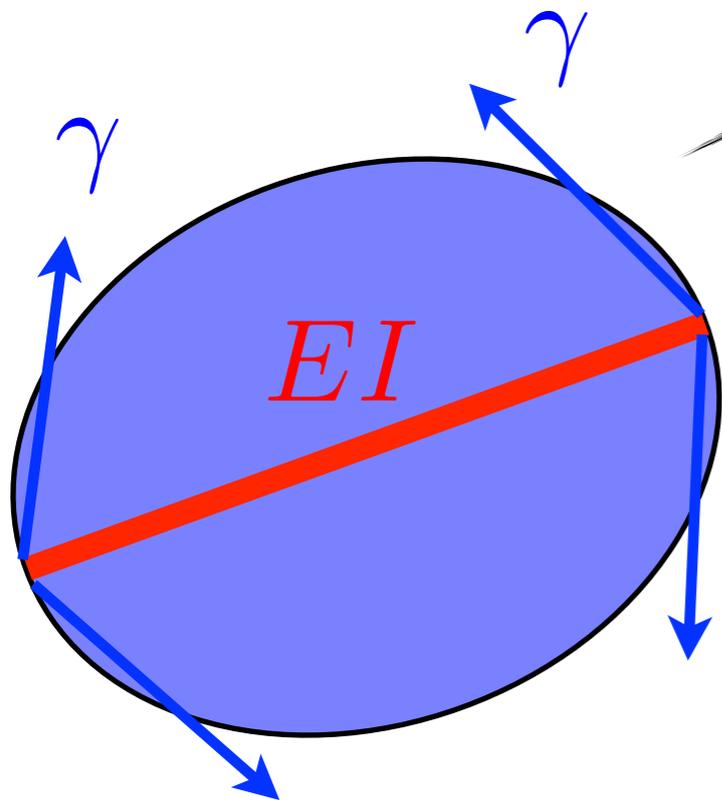
Cohen & Mahadevan, PNAS (2003)

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

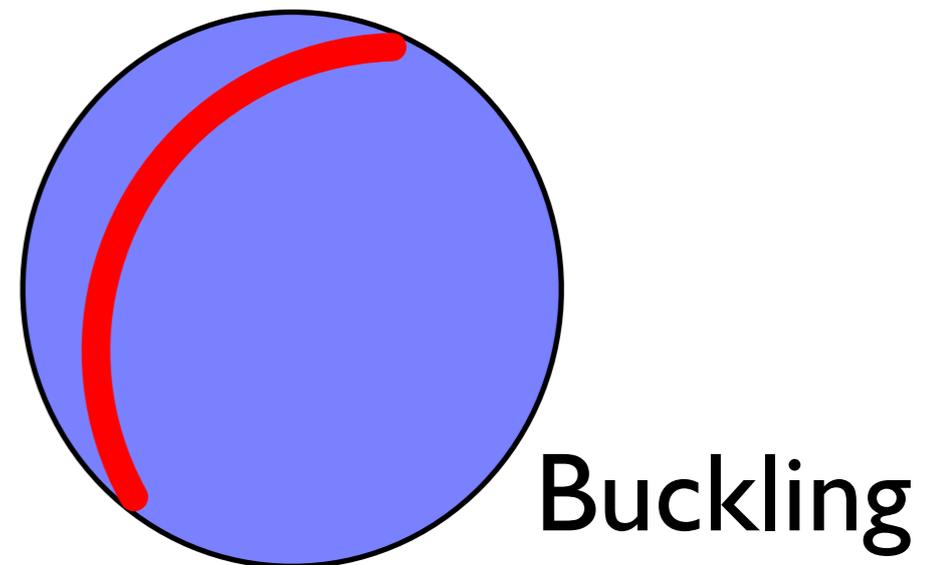


$$\frac{EI}{L^2} \sim \gamma$$

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

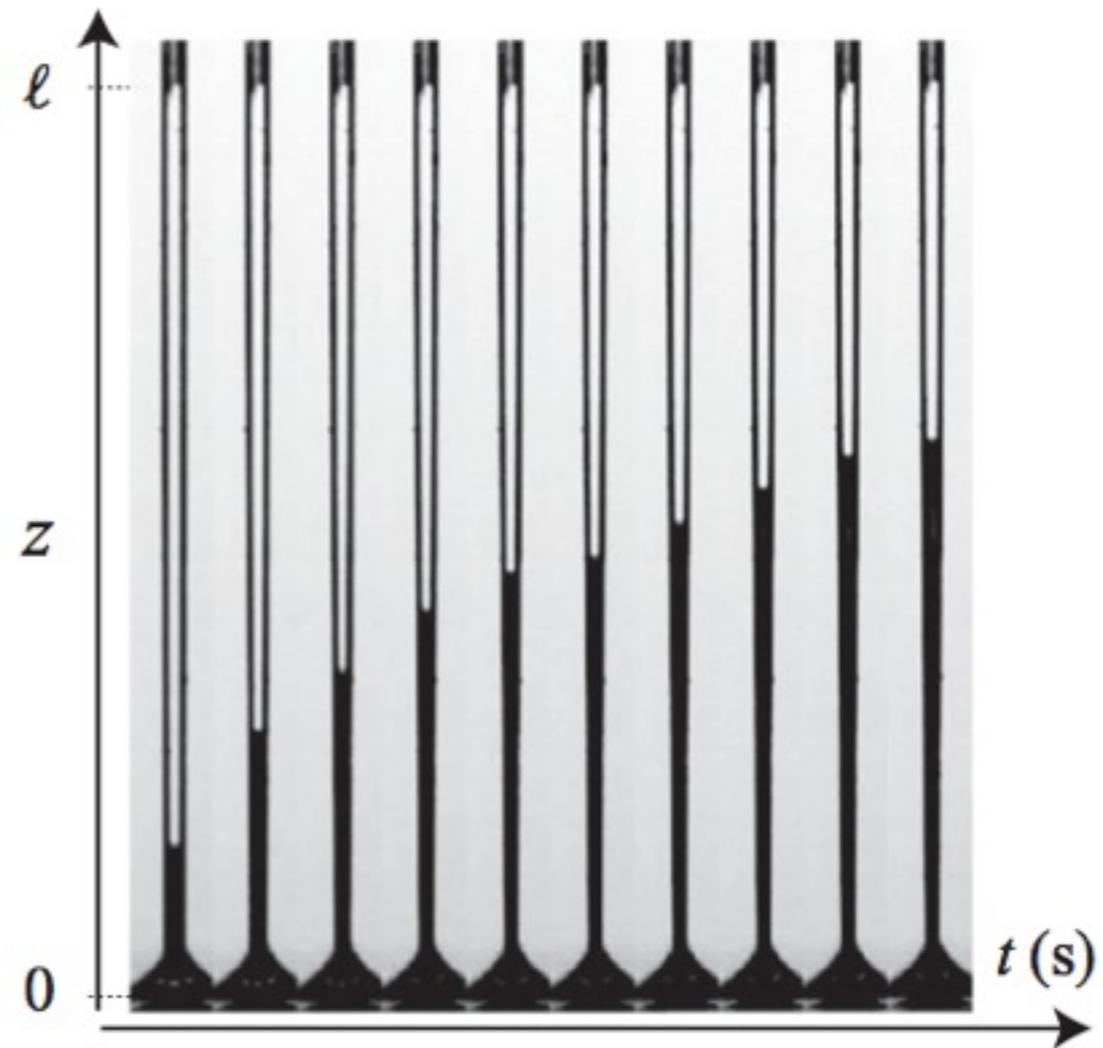


$$\frac{EI}{L^2} \ll \gamma$$



# Mechanisms: Aggregation

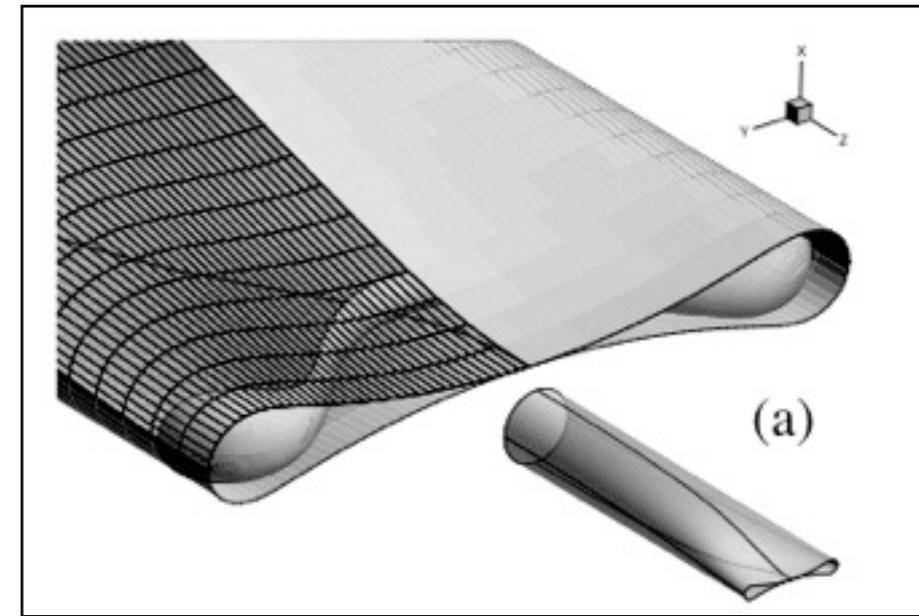
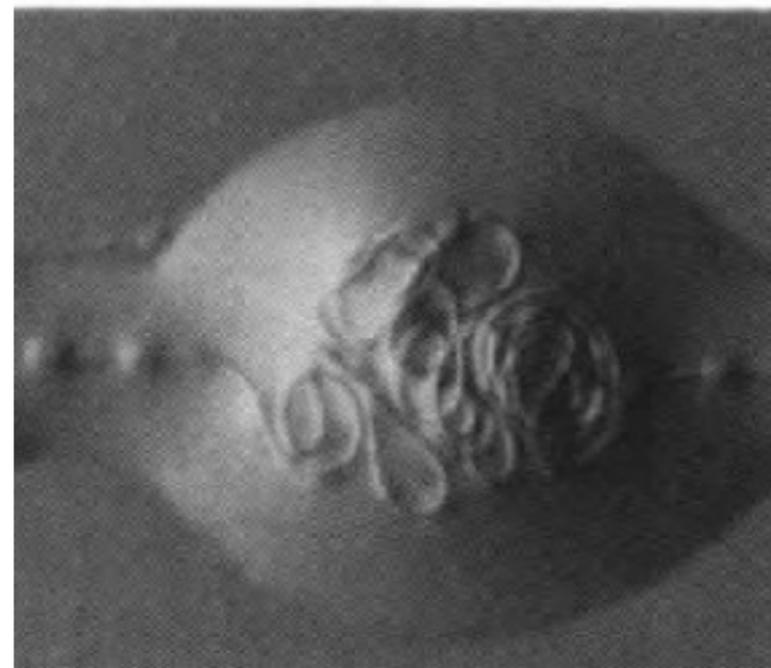
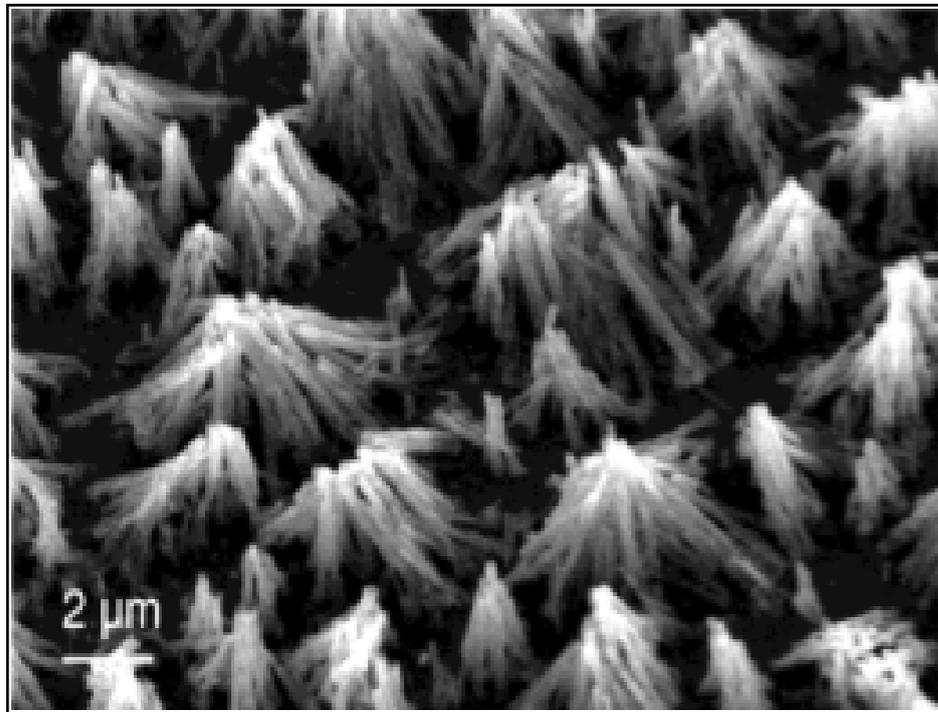
Wet hairs: elastic Jurin's law and aggregation



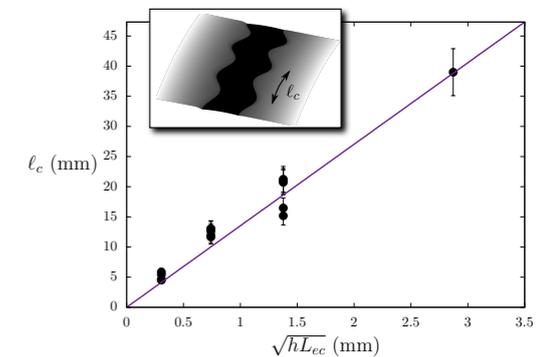
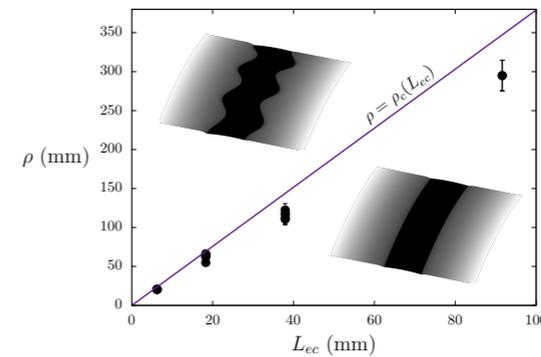
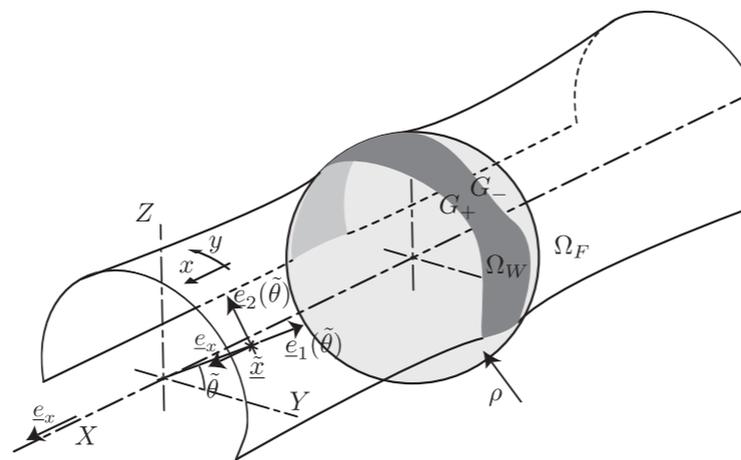
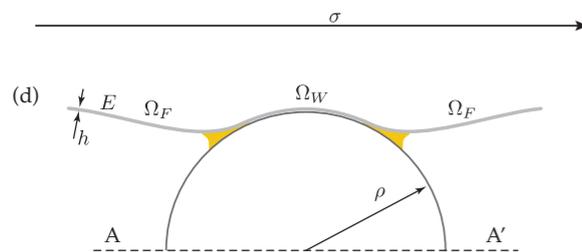
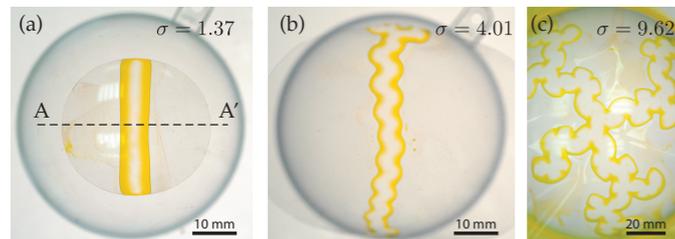
Bico et al., Nature (2004),  
Kim & Mahadevan, JFM (2006),  
Duprat et al., JFM (2011),  
Cambeau et al., EPL (2011)

# Mechanisms: Buckling

## Capillary buckling

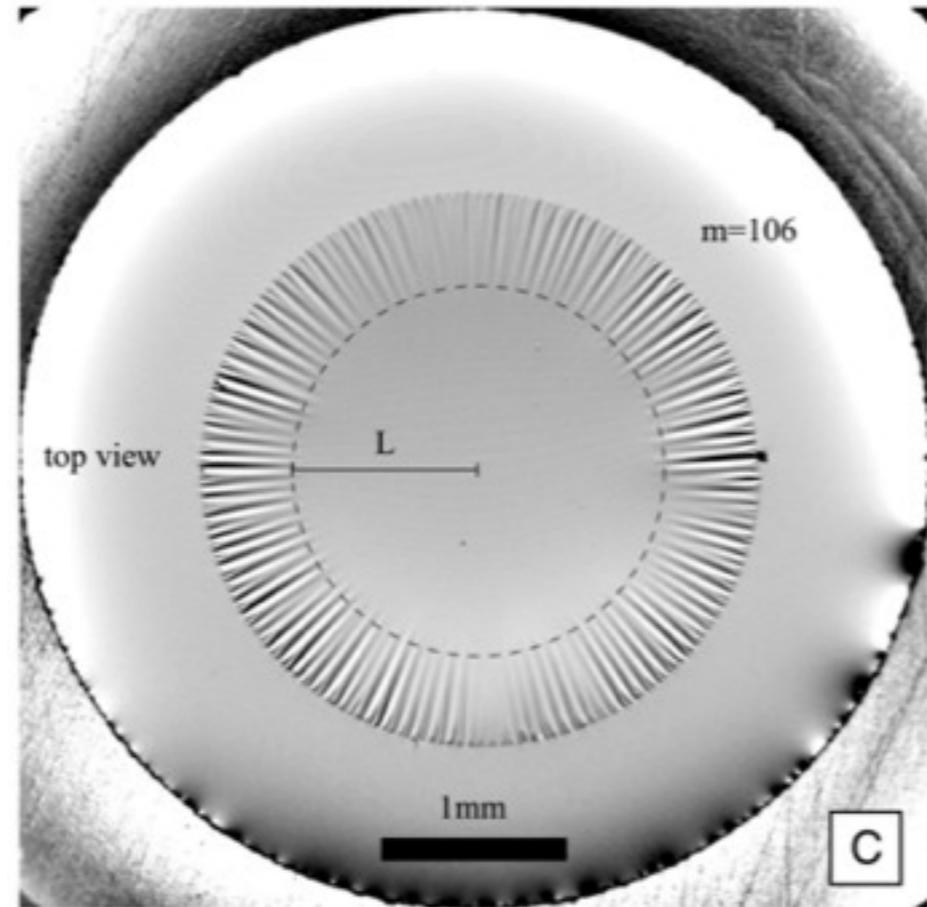
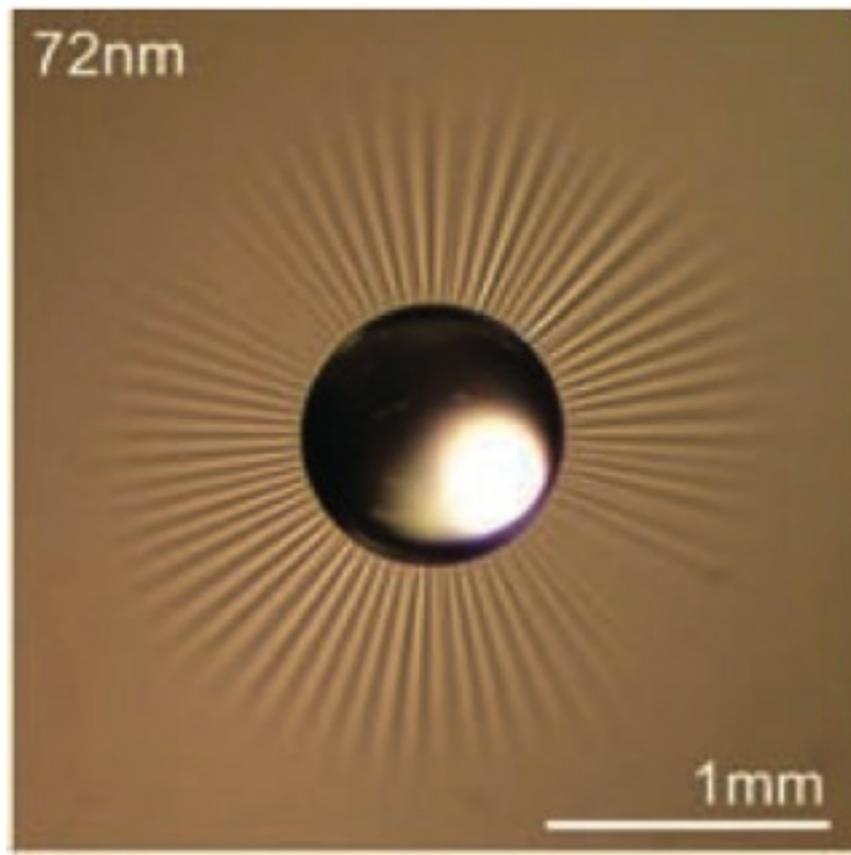


Vollrath & Edmonds, *Nature* (1989),  
 Heil, *JFM* (1999),  
 Lau et al., *Nano Lett.* (2003),  
 Neukirch et al., *JMPS* (2007)



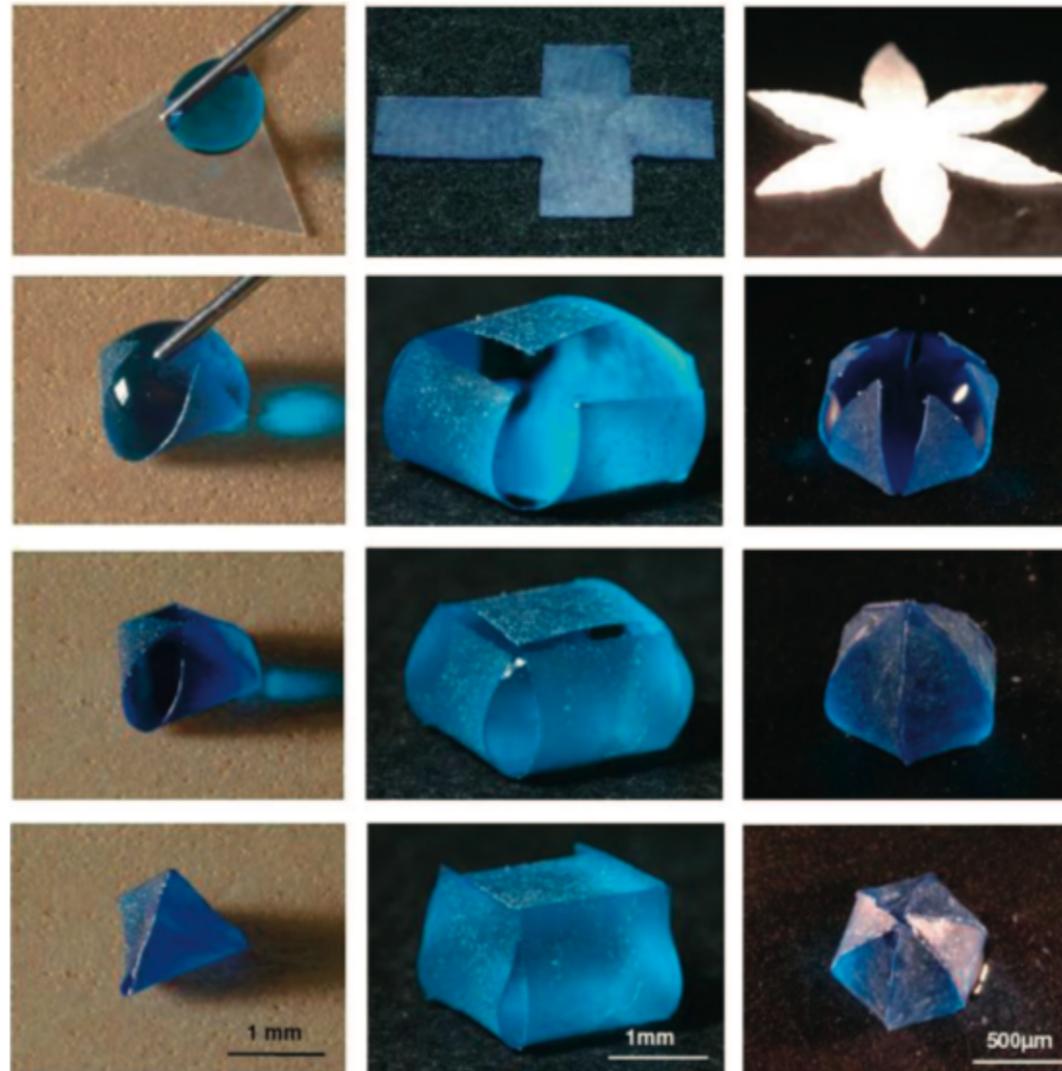
Hure & Audoly, *JMPS* (2012)

# Mechanisms: Wrinkling



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

# Mechanisms: Wrapping & Folding

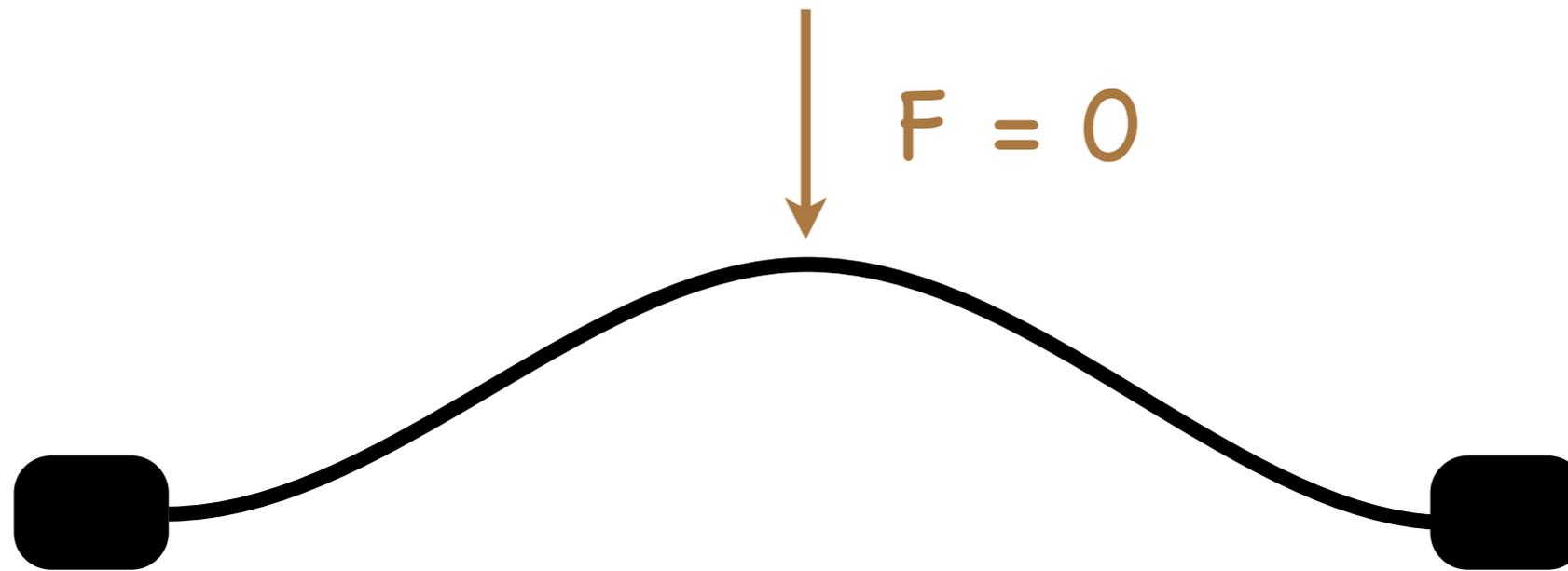


Syms et al., J. of MEMS (2003),  
Py et al., PRL (2007),  
Reis et al., Soft Matter (2010)

Here :

snap-through of an elastic beam  
induced by a drop

# Classical snap-through



Timoshenko, Philosophical Magazine (1922)

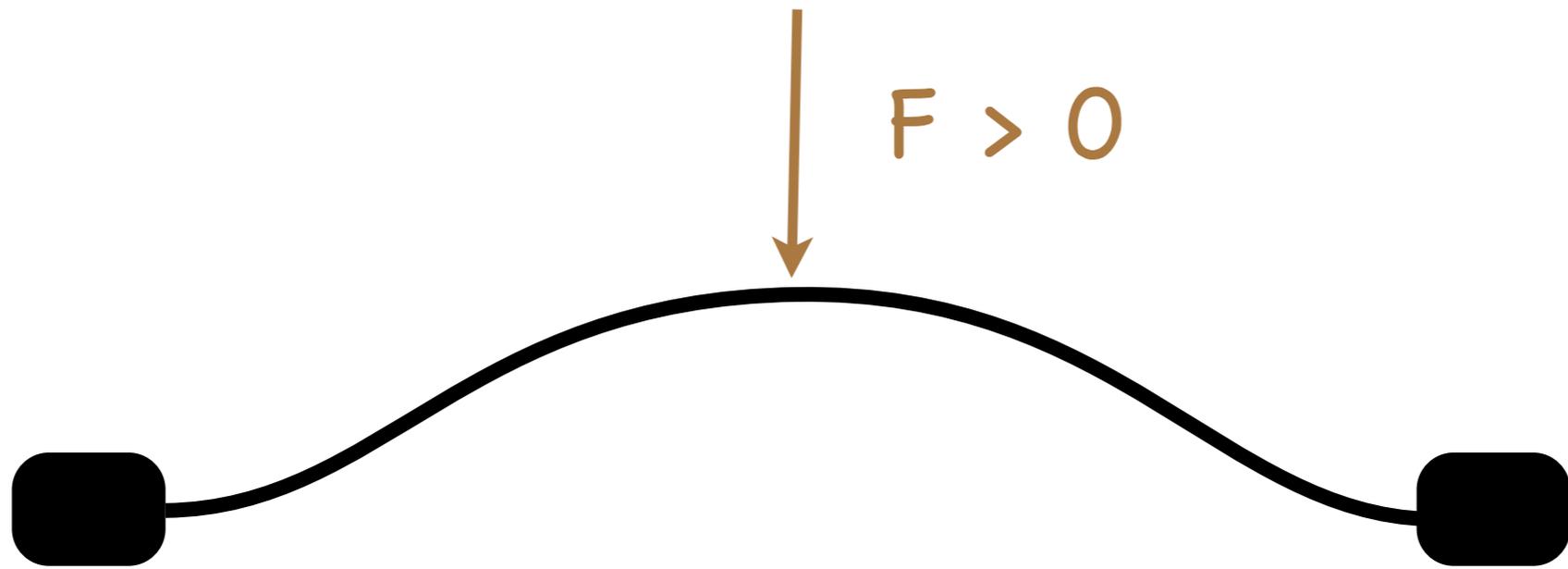
Timoshenko, J. Appl. Mech. (1935)

....

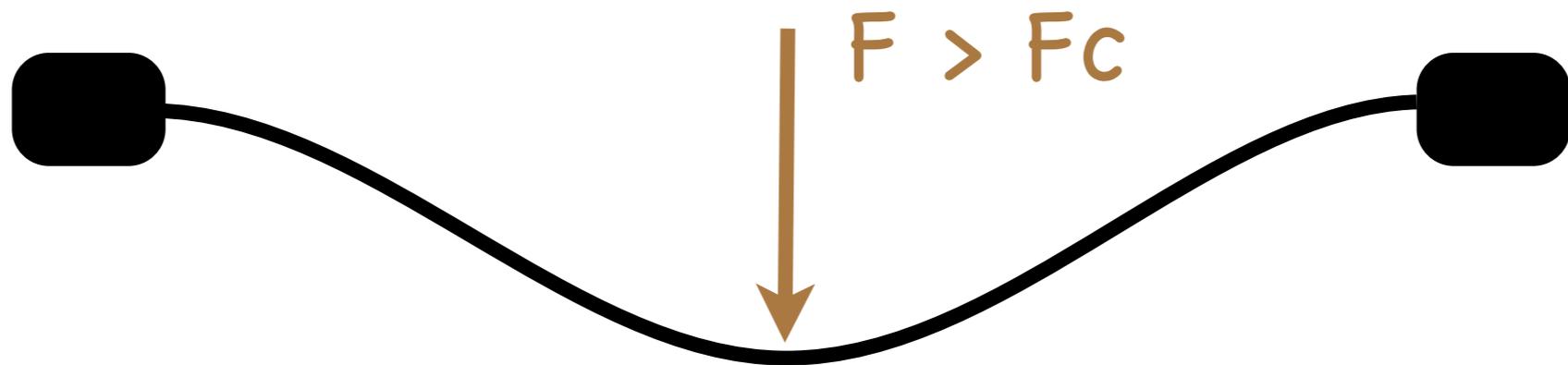
Chen + Hung, European Journal of Mechanics - A/Solids (2011).

Pandey et al (2013)

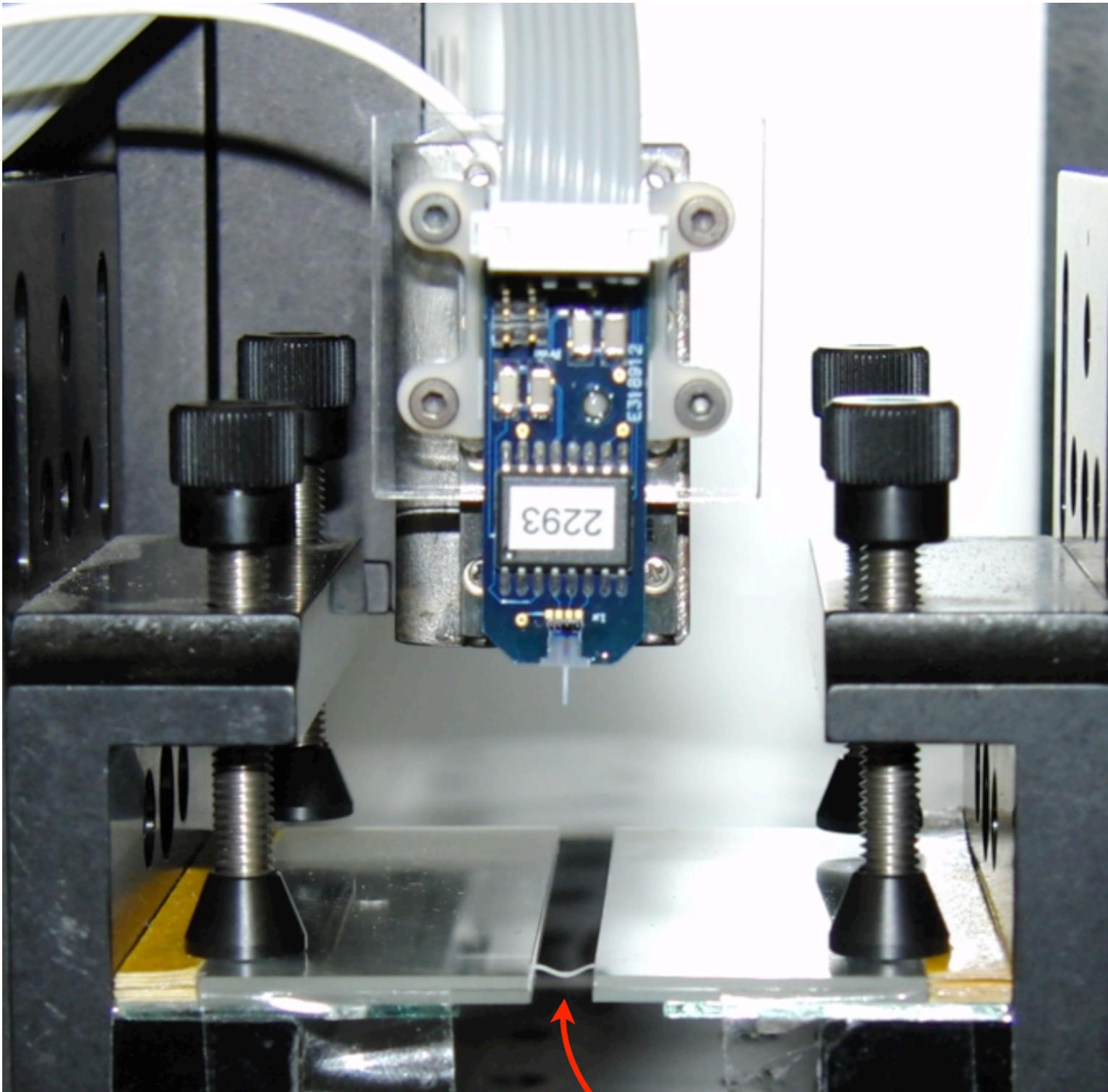
# Classical snap-through



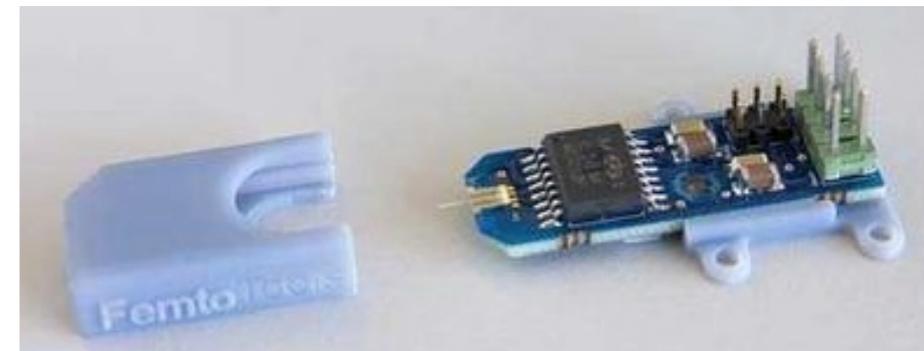
# Classical snap-through



# Force transducer / positioning system



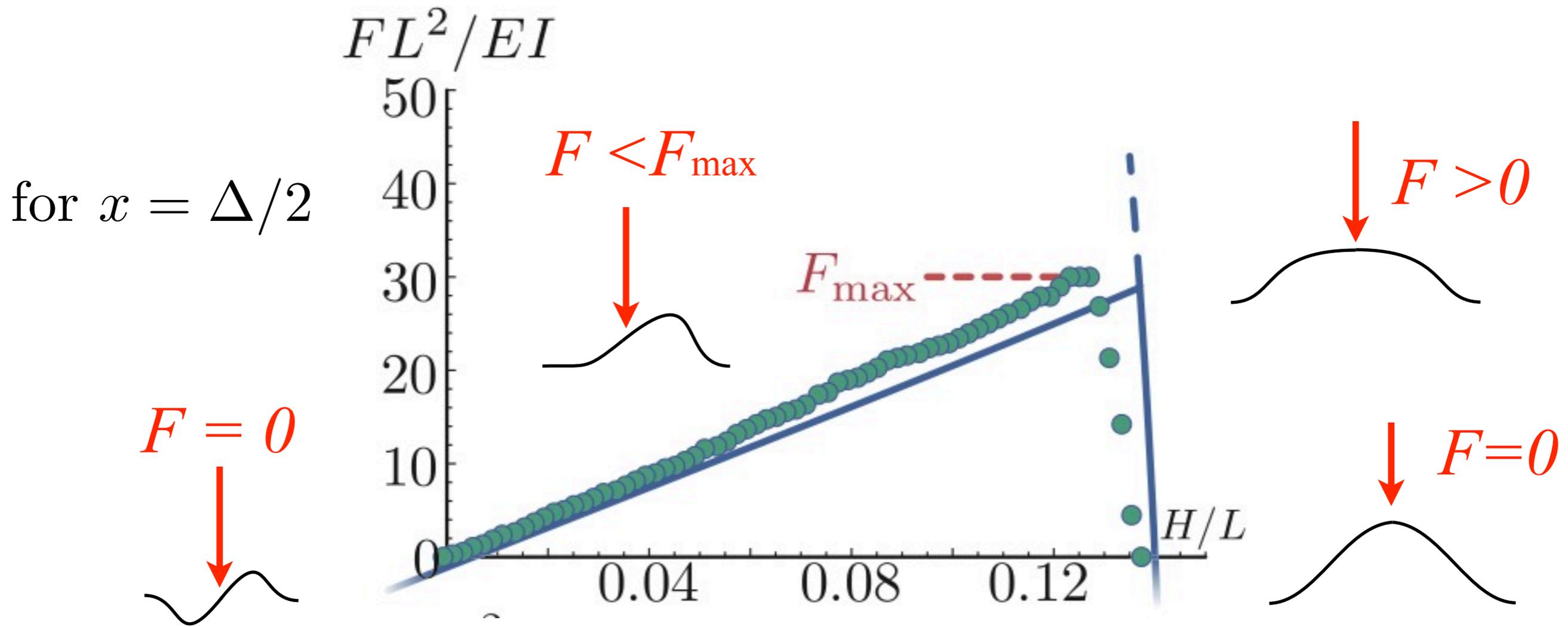
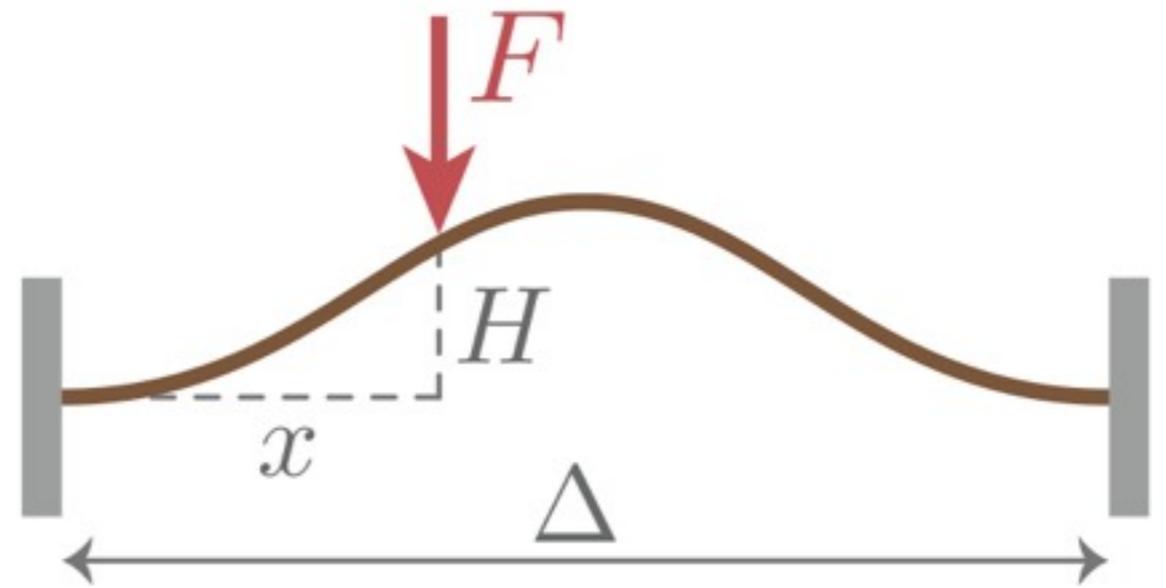
Femttools FT-S270



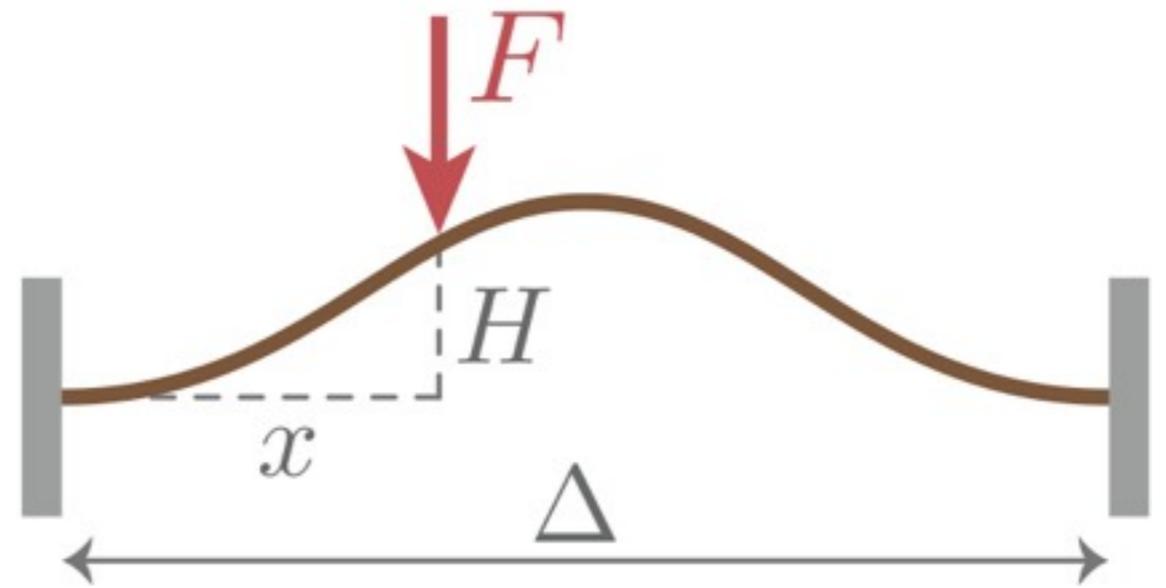
<http://www.femttools.com/>

**3 mm PDMS elastic strip**

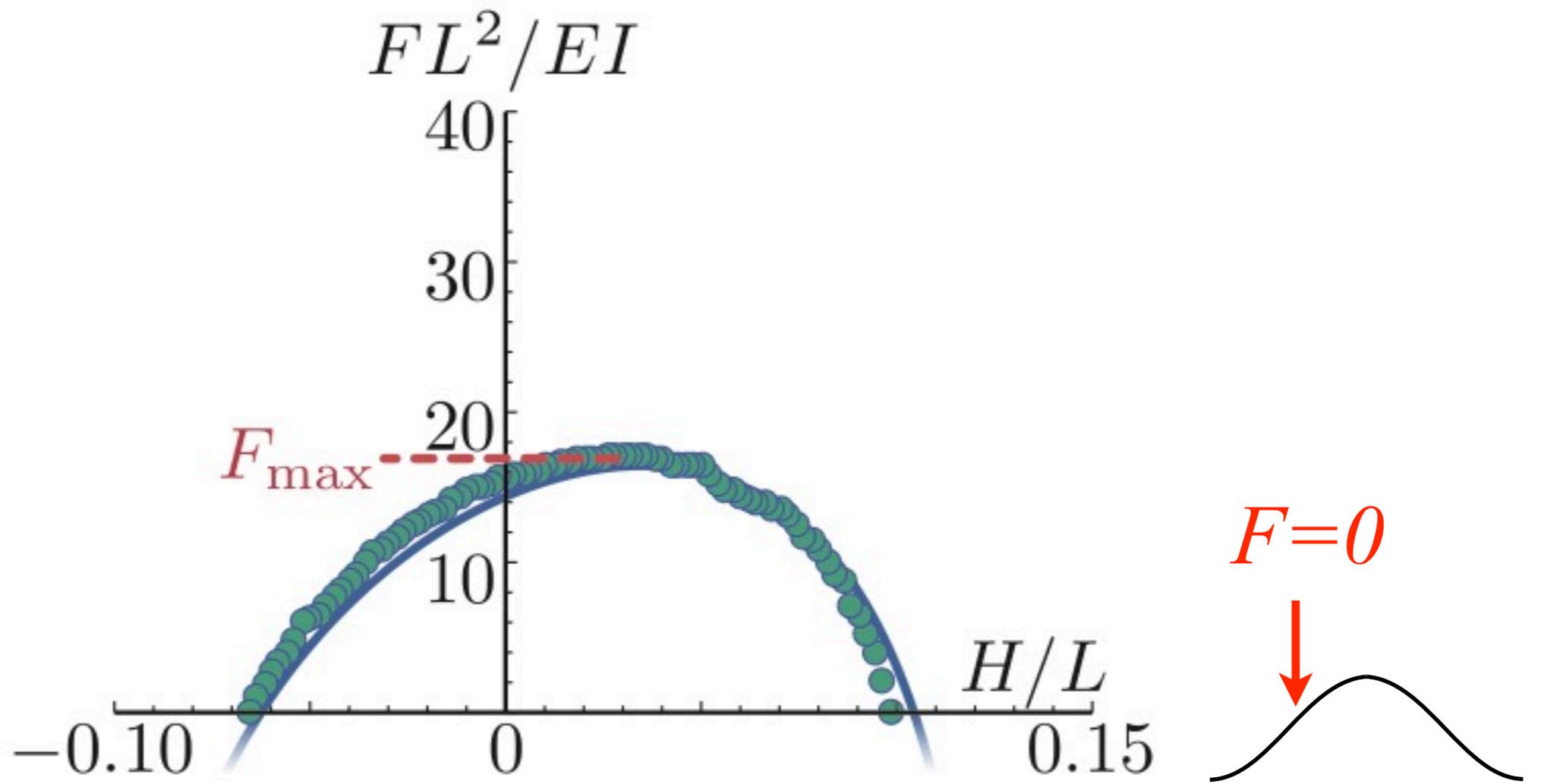
# Classical snap-through



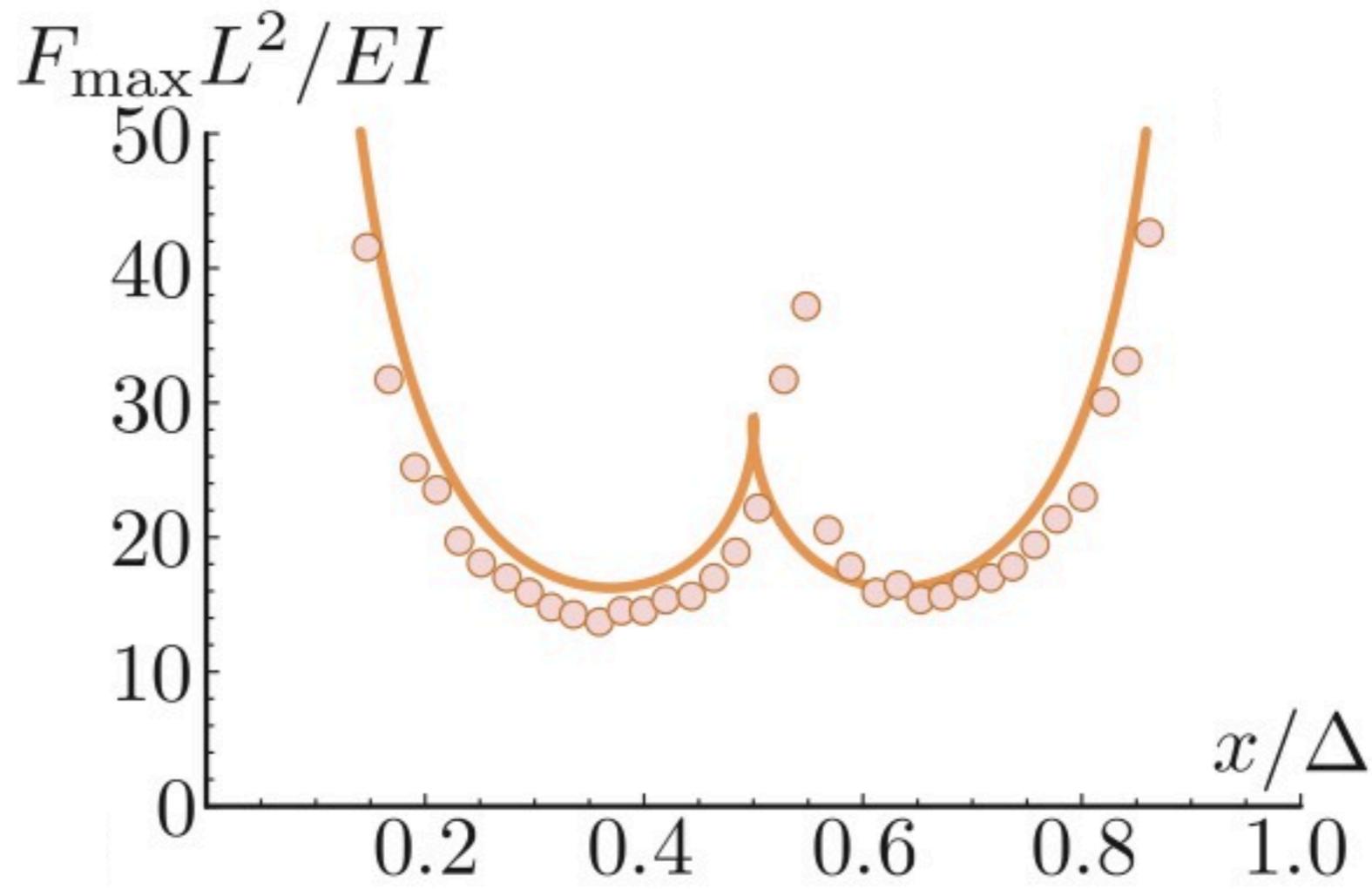
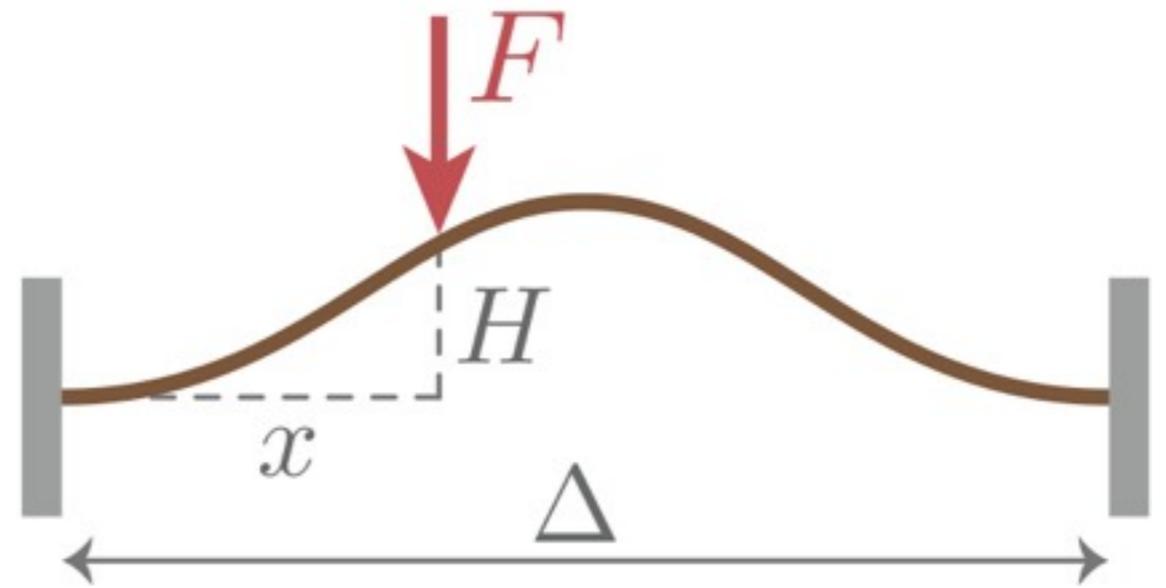
# Classical snap-through



for  $x = \Delta/3$

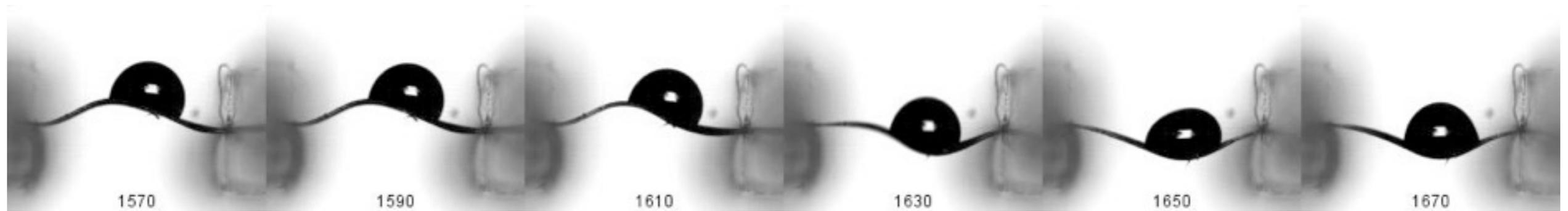
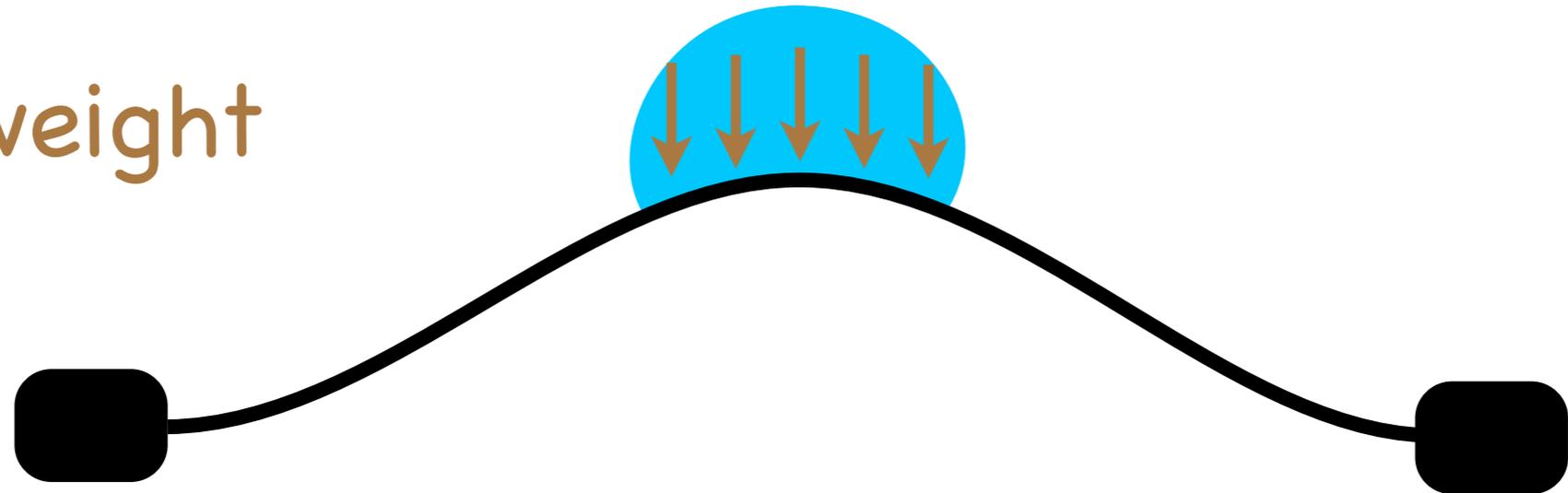


# Classical snap-through

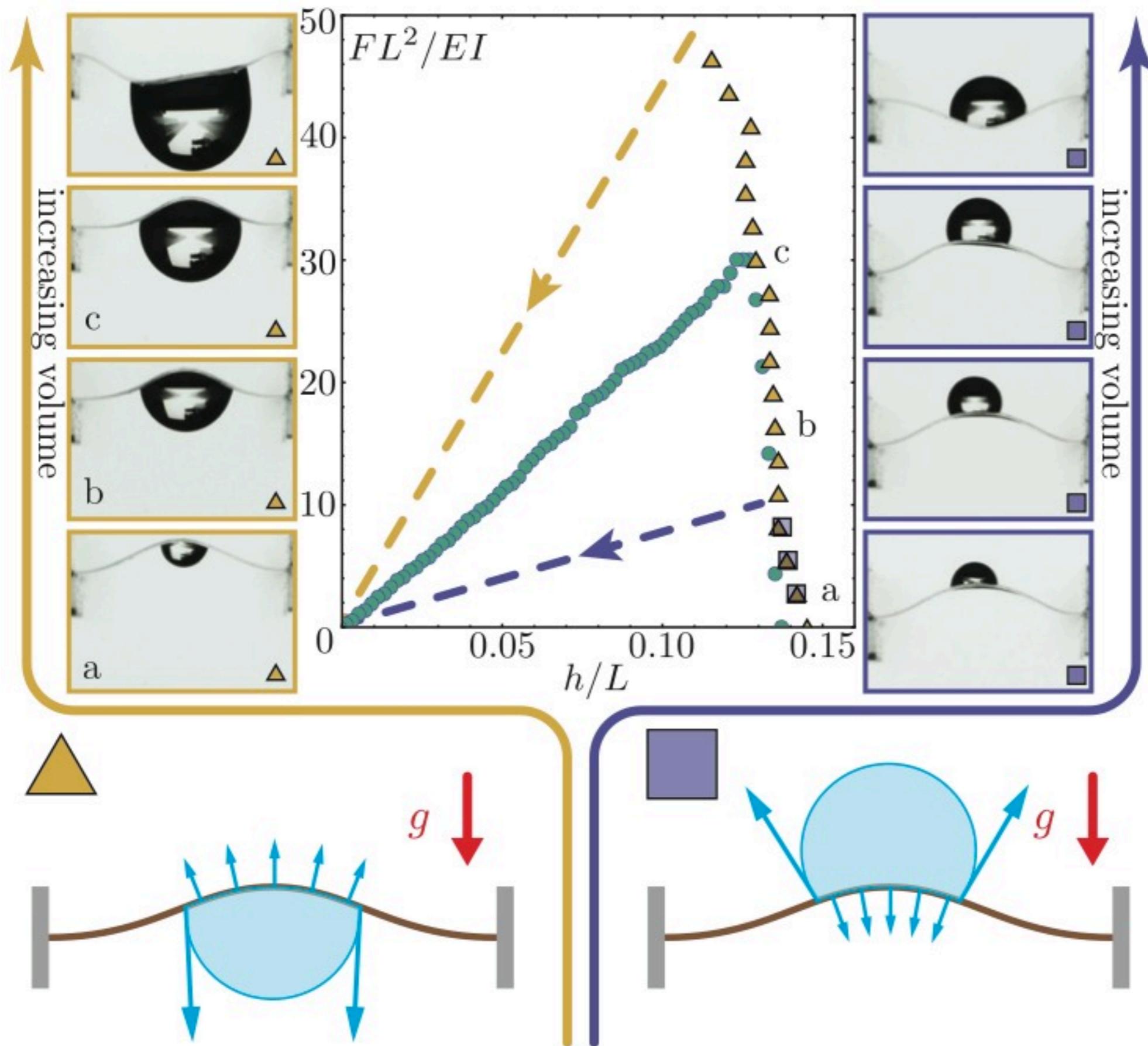


# Capillary induced snap-through

weight

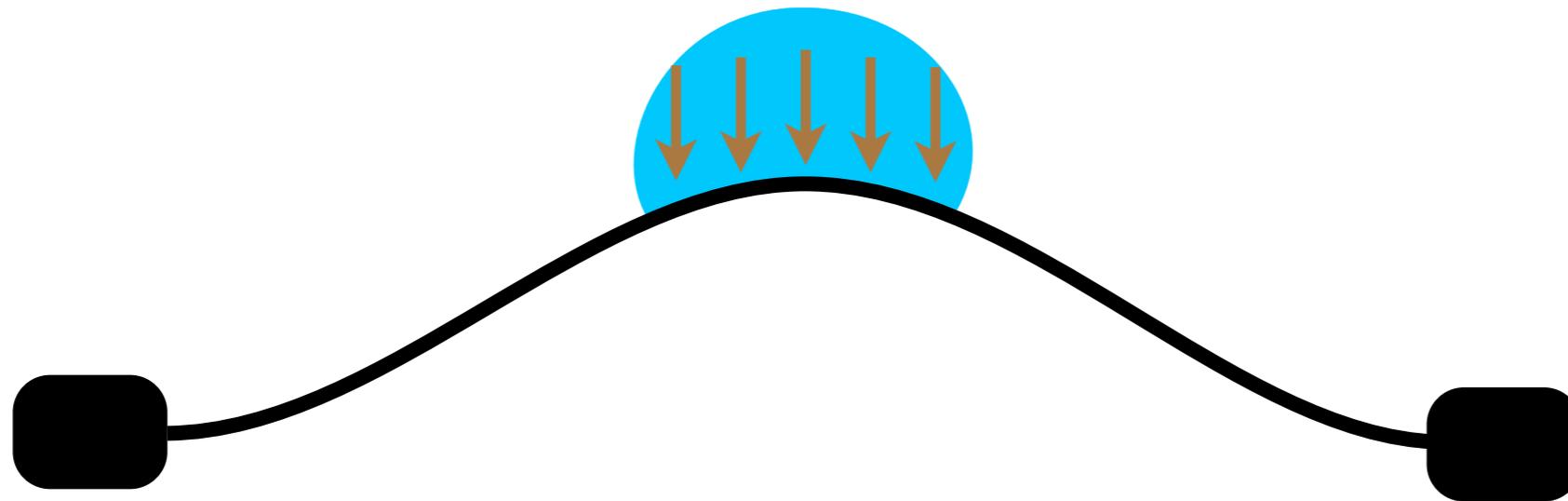


# Capillary induced snap-through

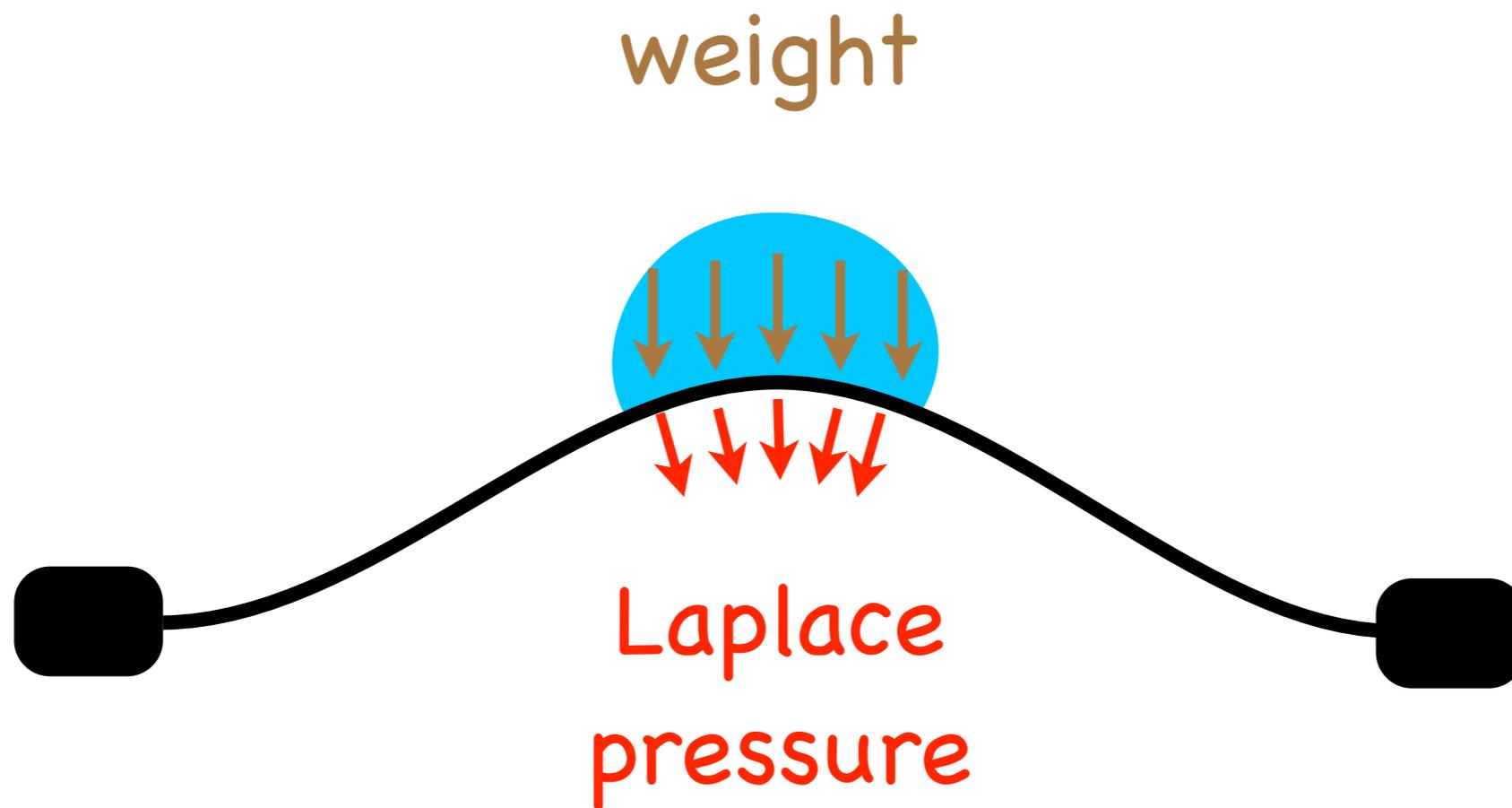


# Capillary induced snap-through

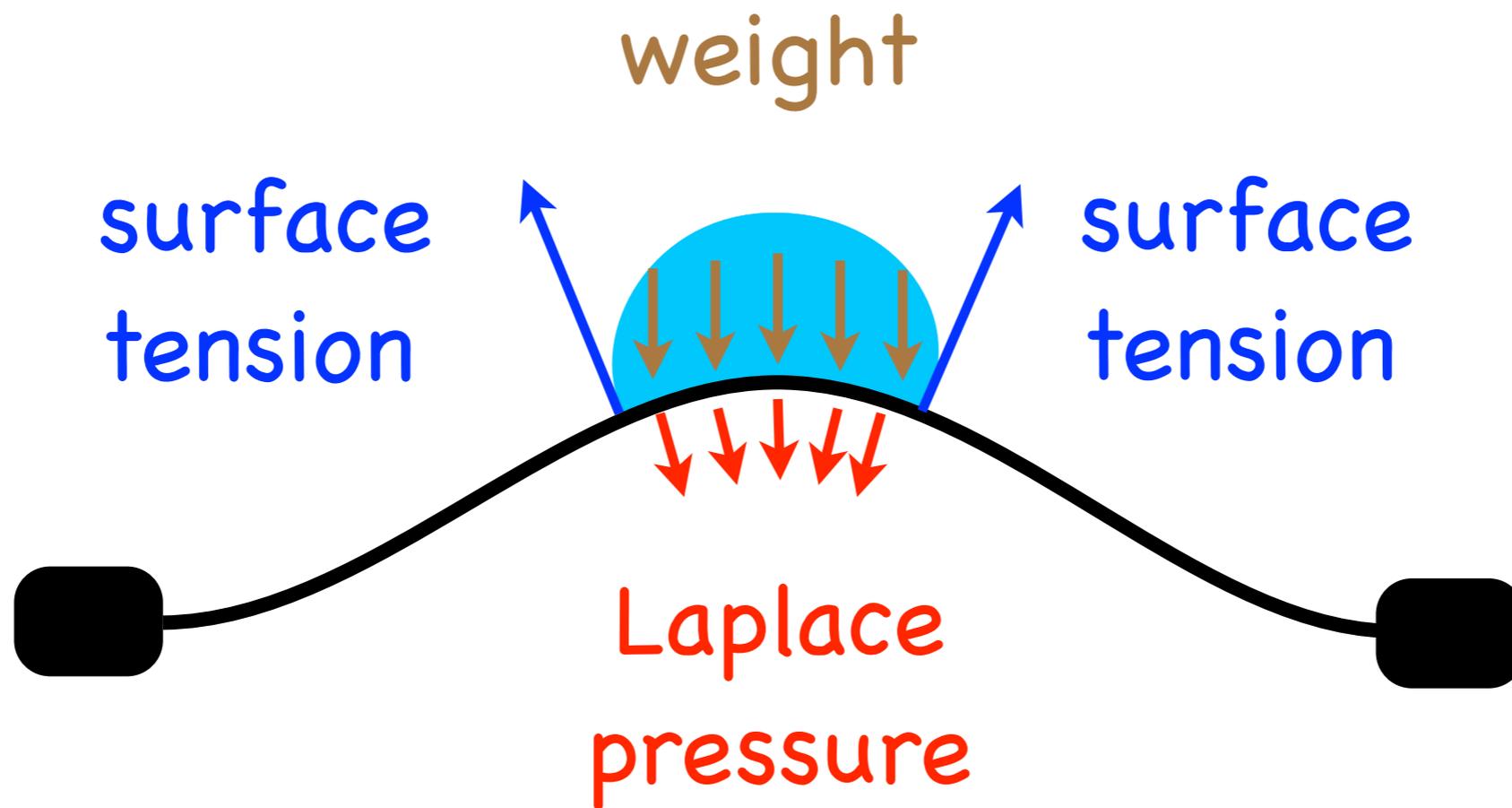
weight



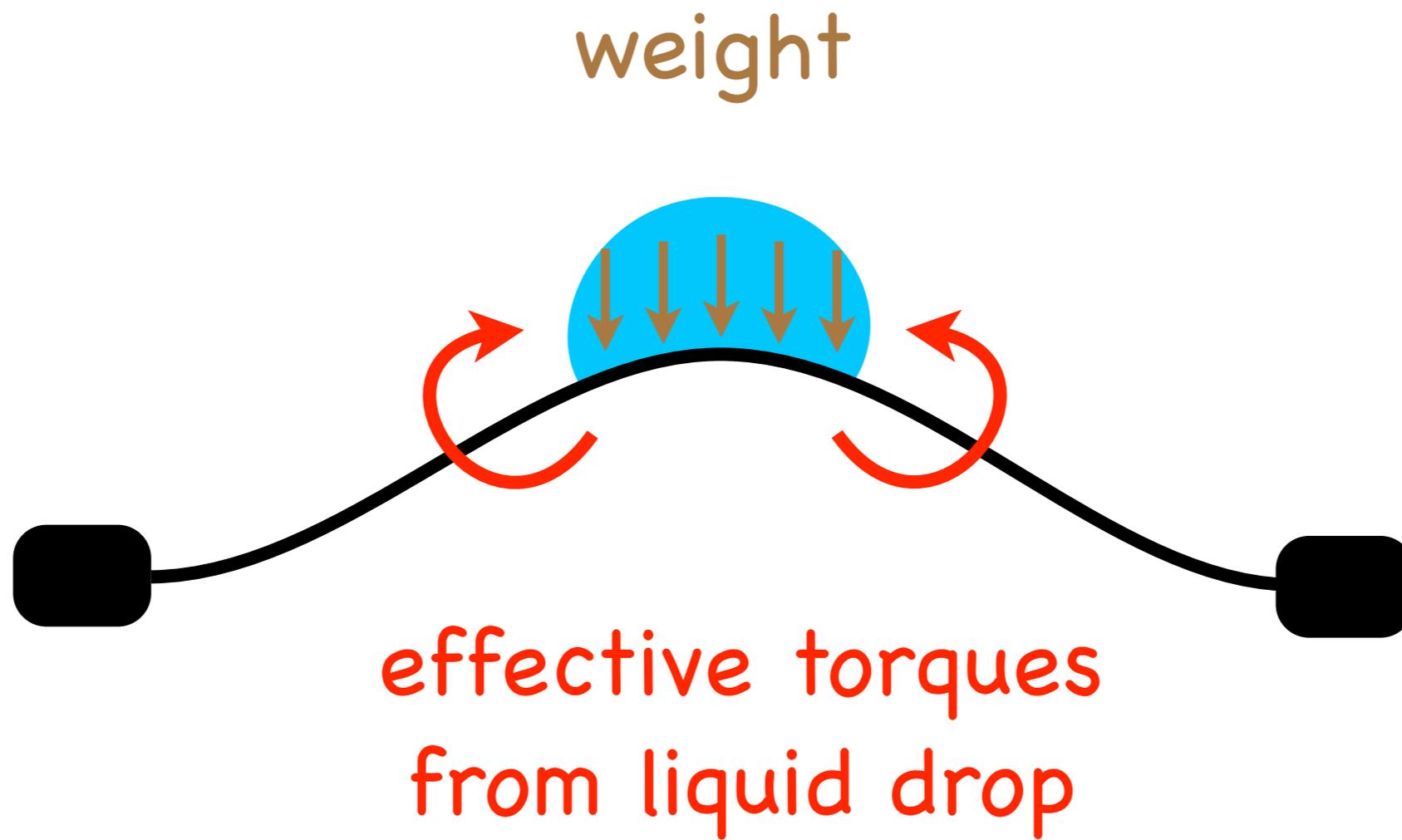
# Capillary induced snap-through



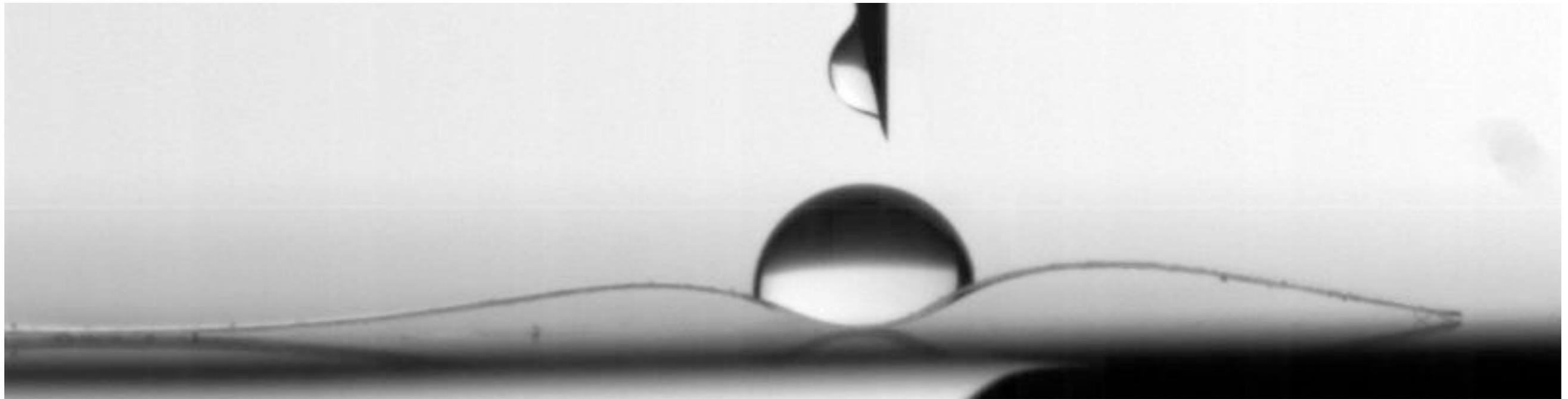
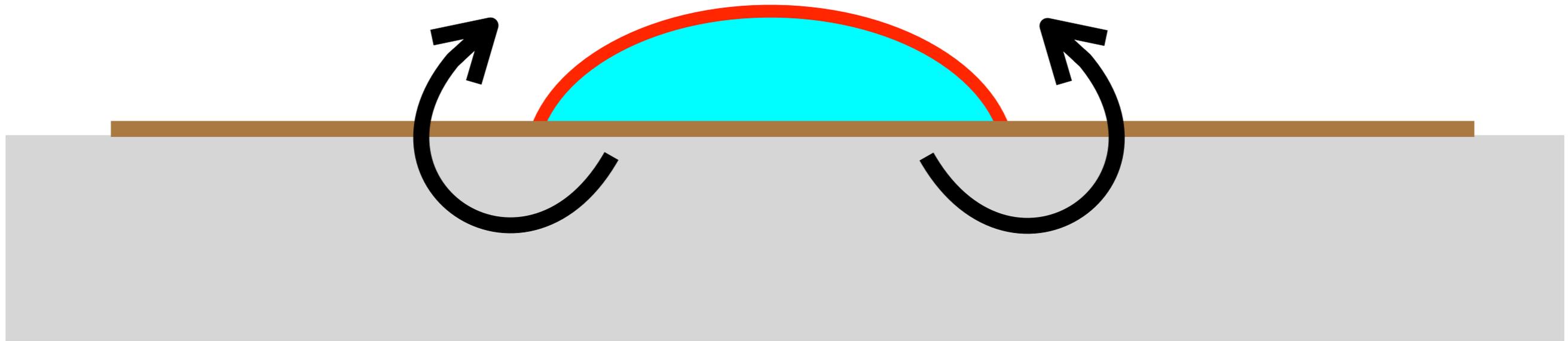
# Capillary induced snap-through



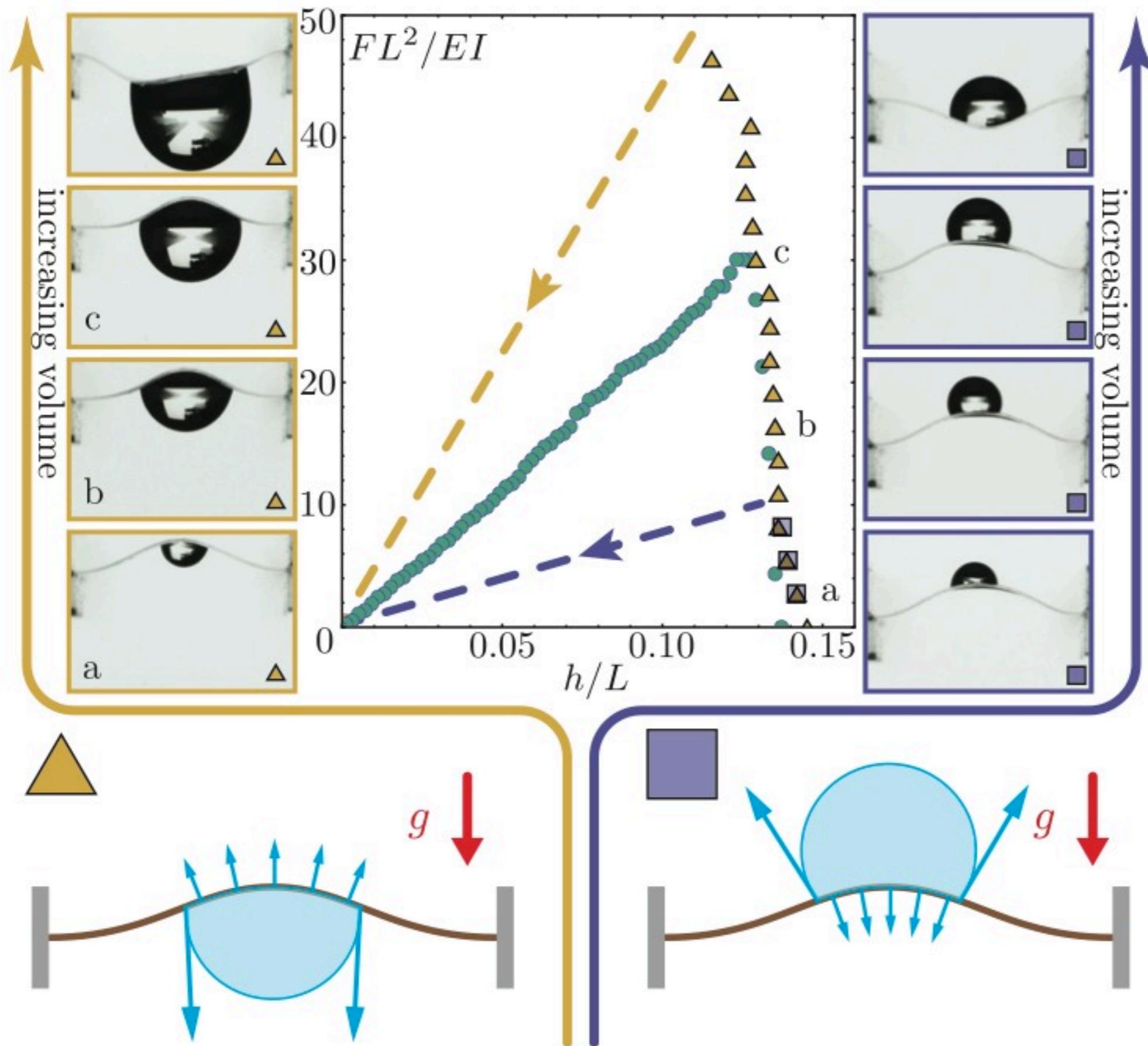
# Capillary induced snap-through



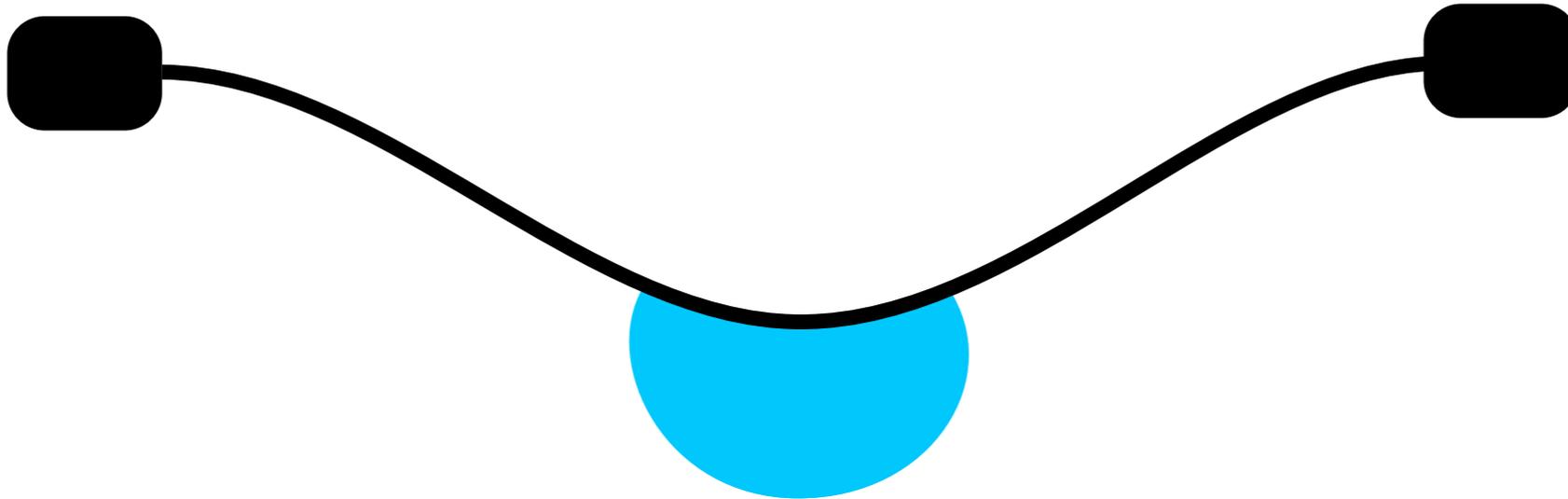
# effective bending moments



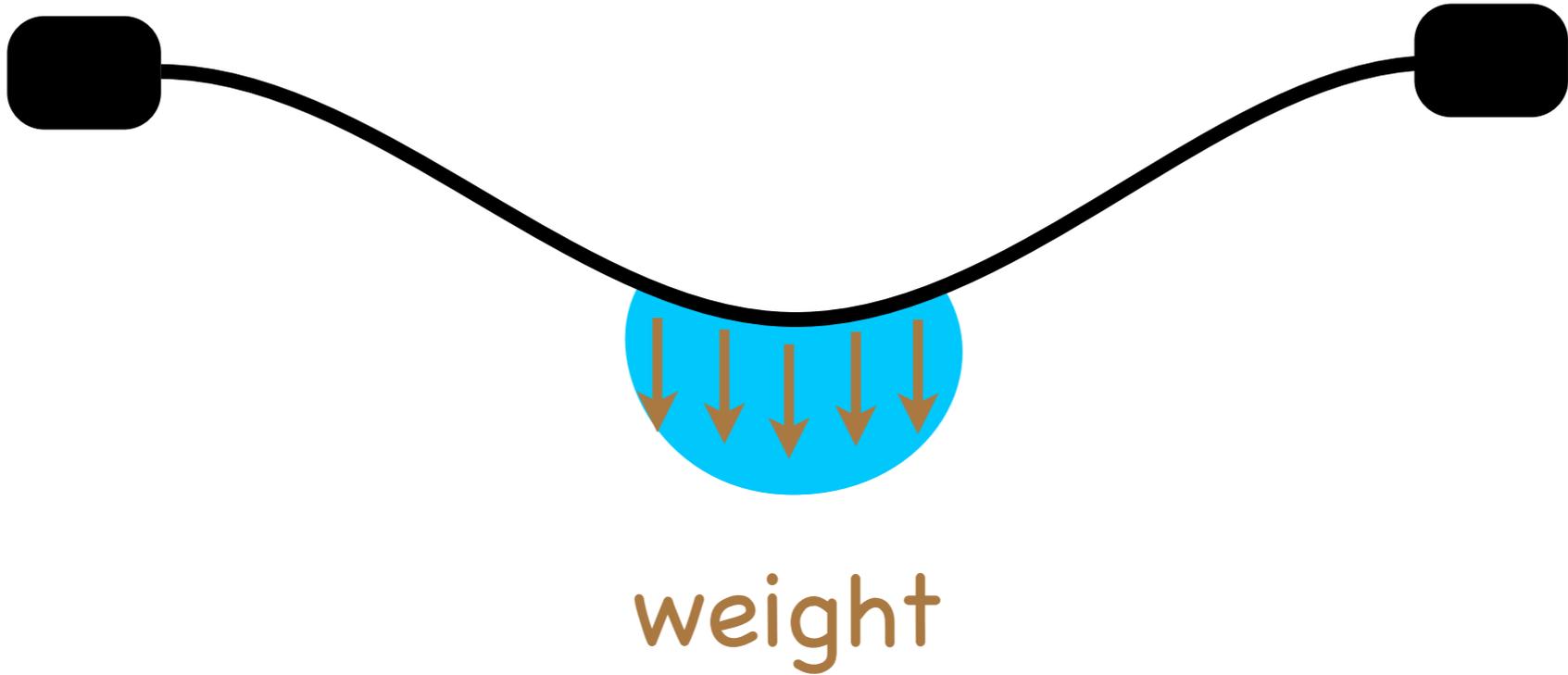
# Capillary induced snap-through



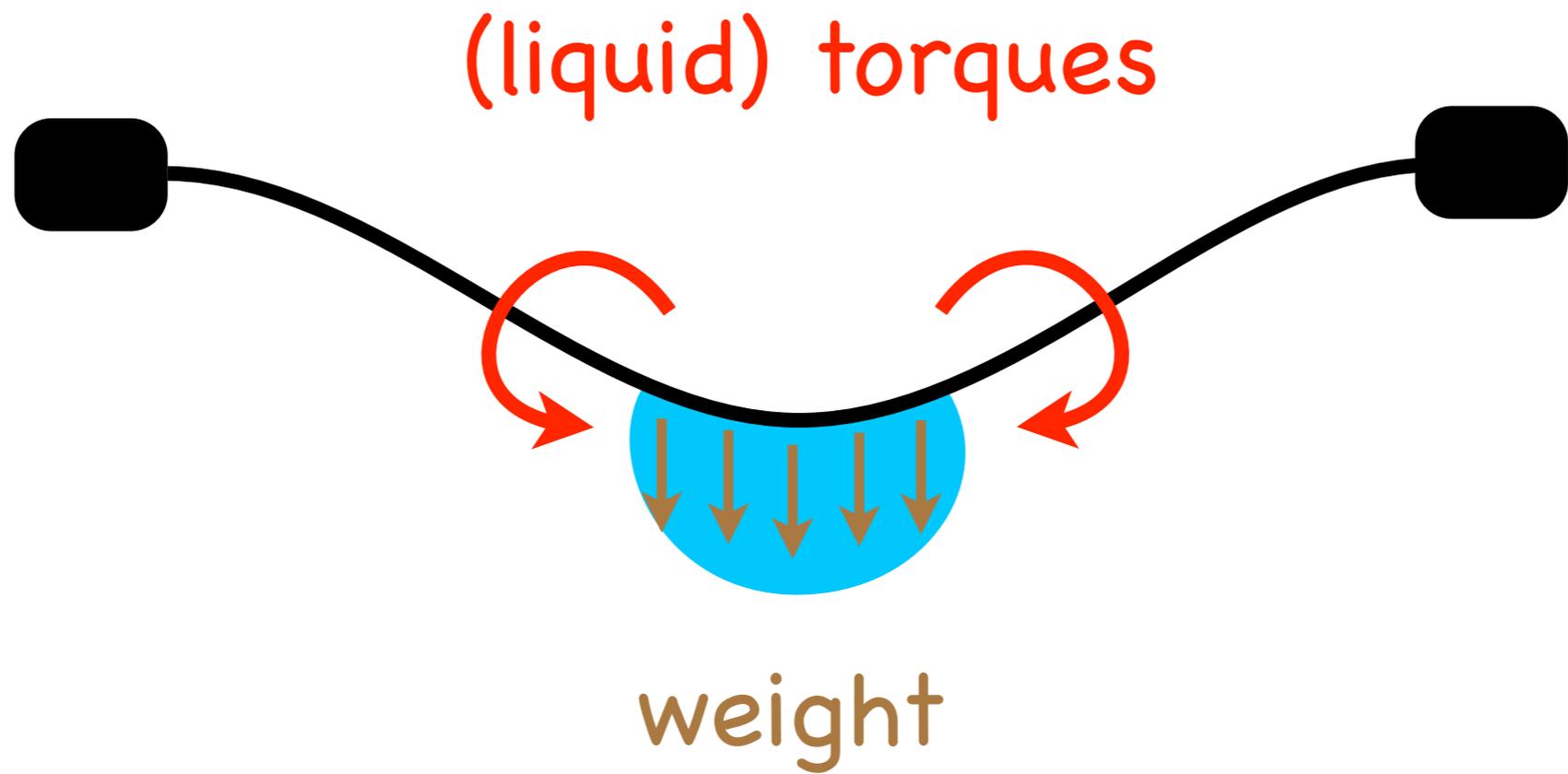
# Capillary induced snap-through



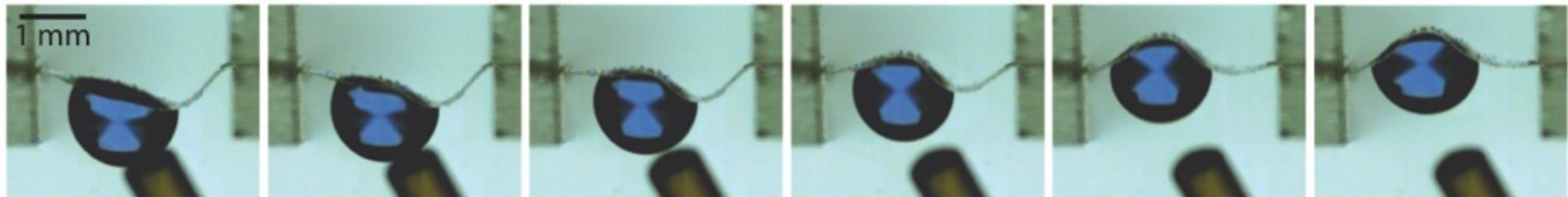
# Capillary induced snap-through



# Capillary induced snap-through



# Capillary induced snap-through



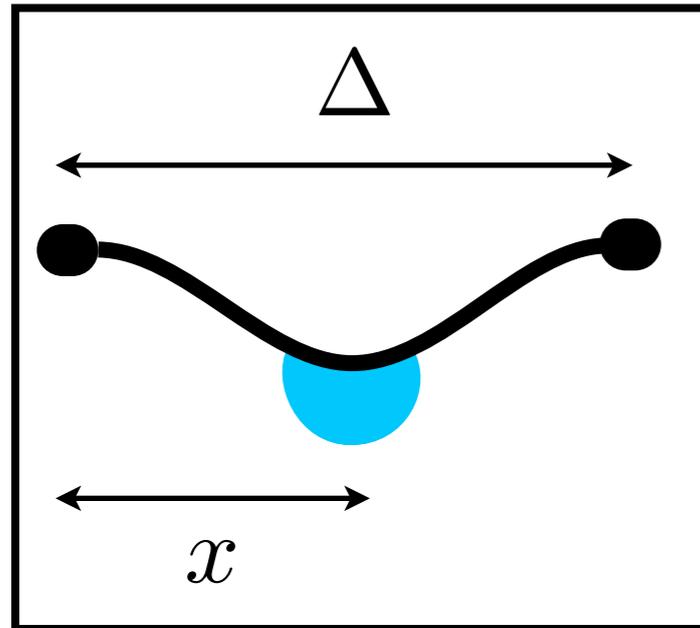
PDMS strip

dimensions: 34 microns by 1 mm by 3.5 mm

time interval between frames: 5 ms

# Capillary induced snap-through

start

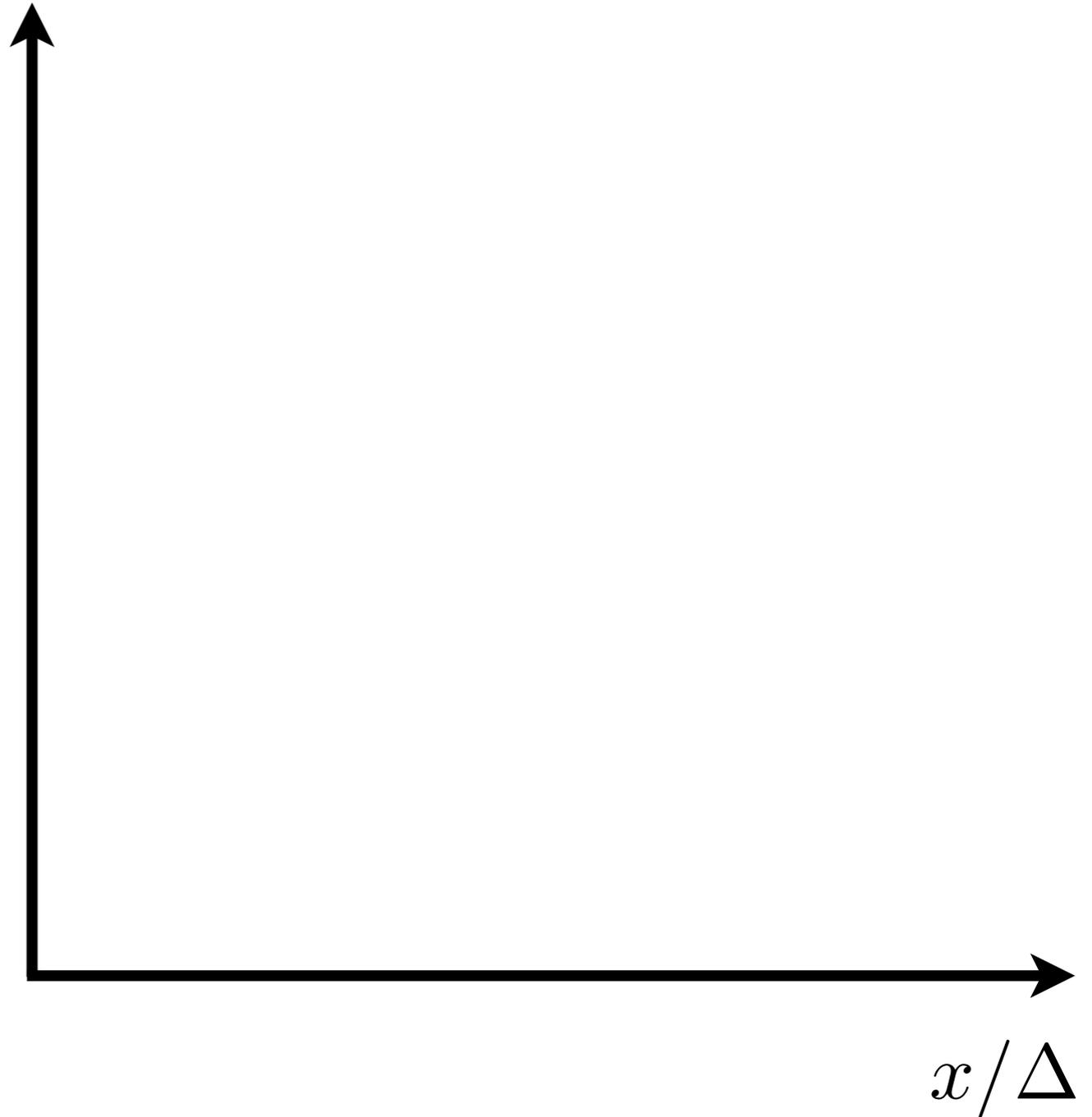
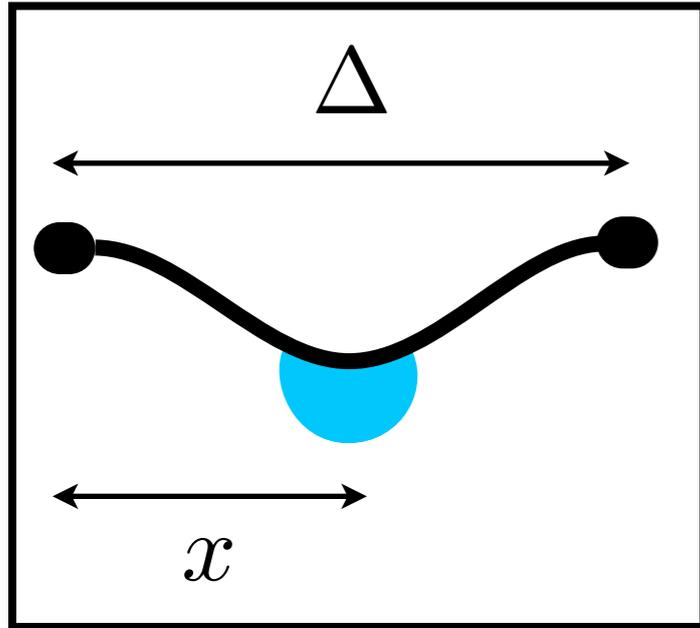


# Capillary induced snap-through

liquid weight

$$FL^2/EI$$

start

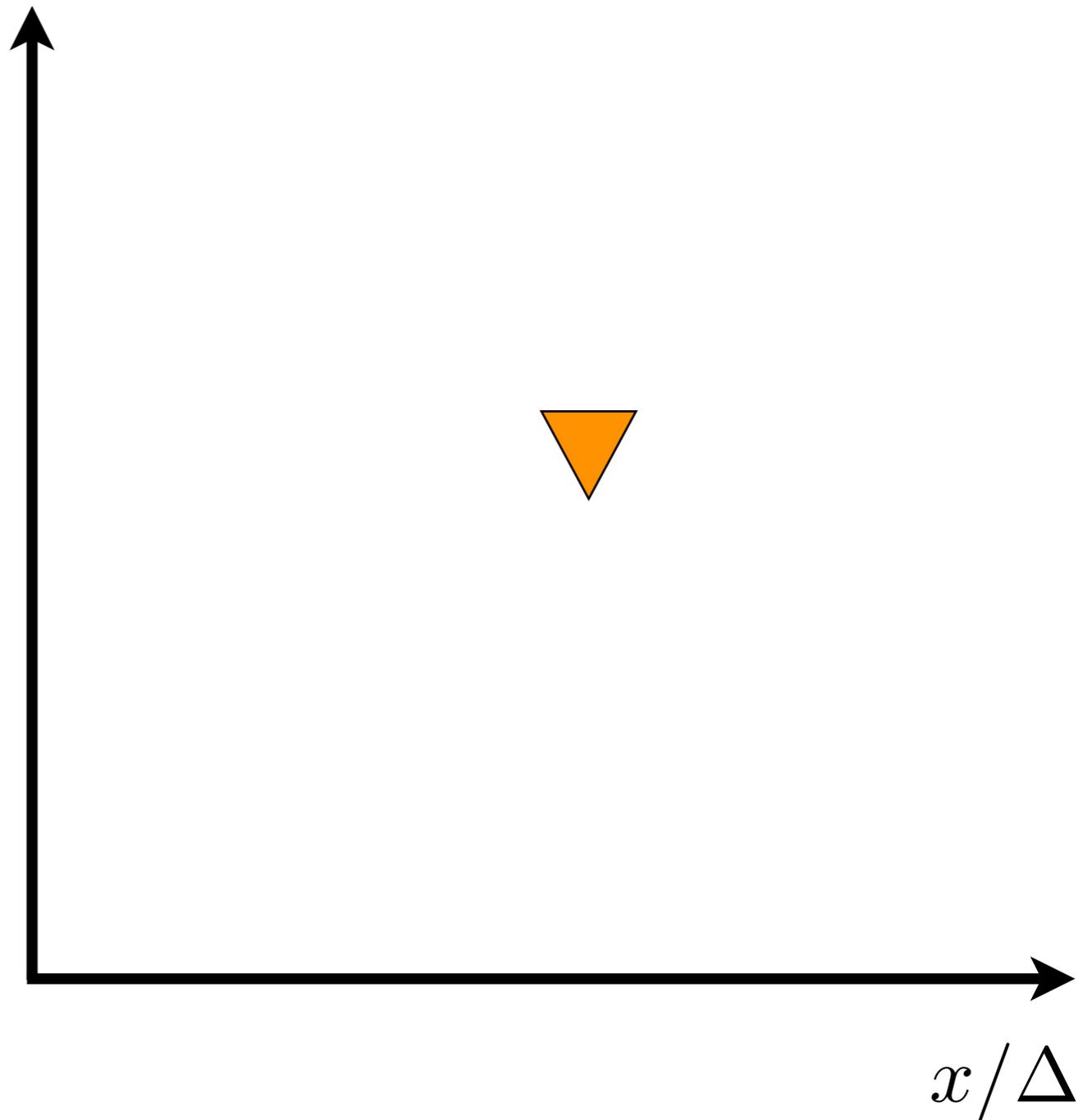
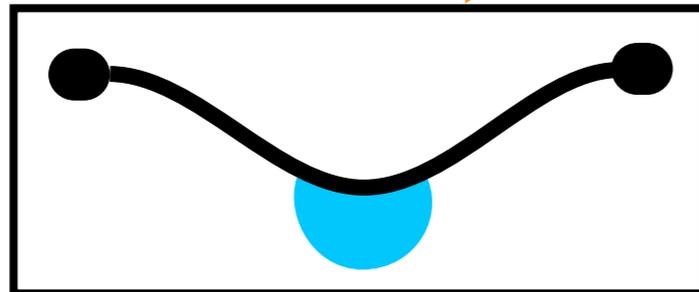
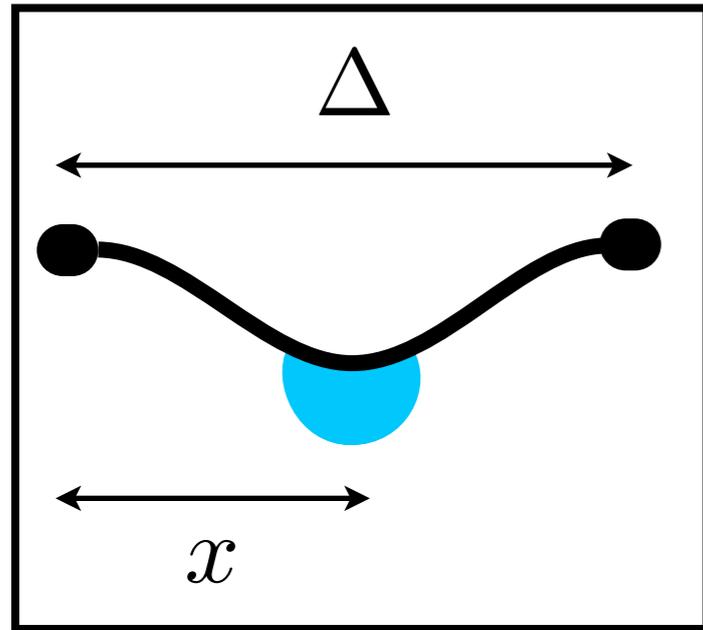


# Capillary induced snap-through

liquid weight

$$FL^2/EI$$

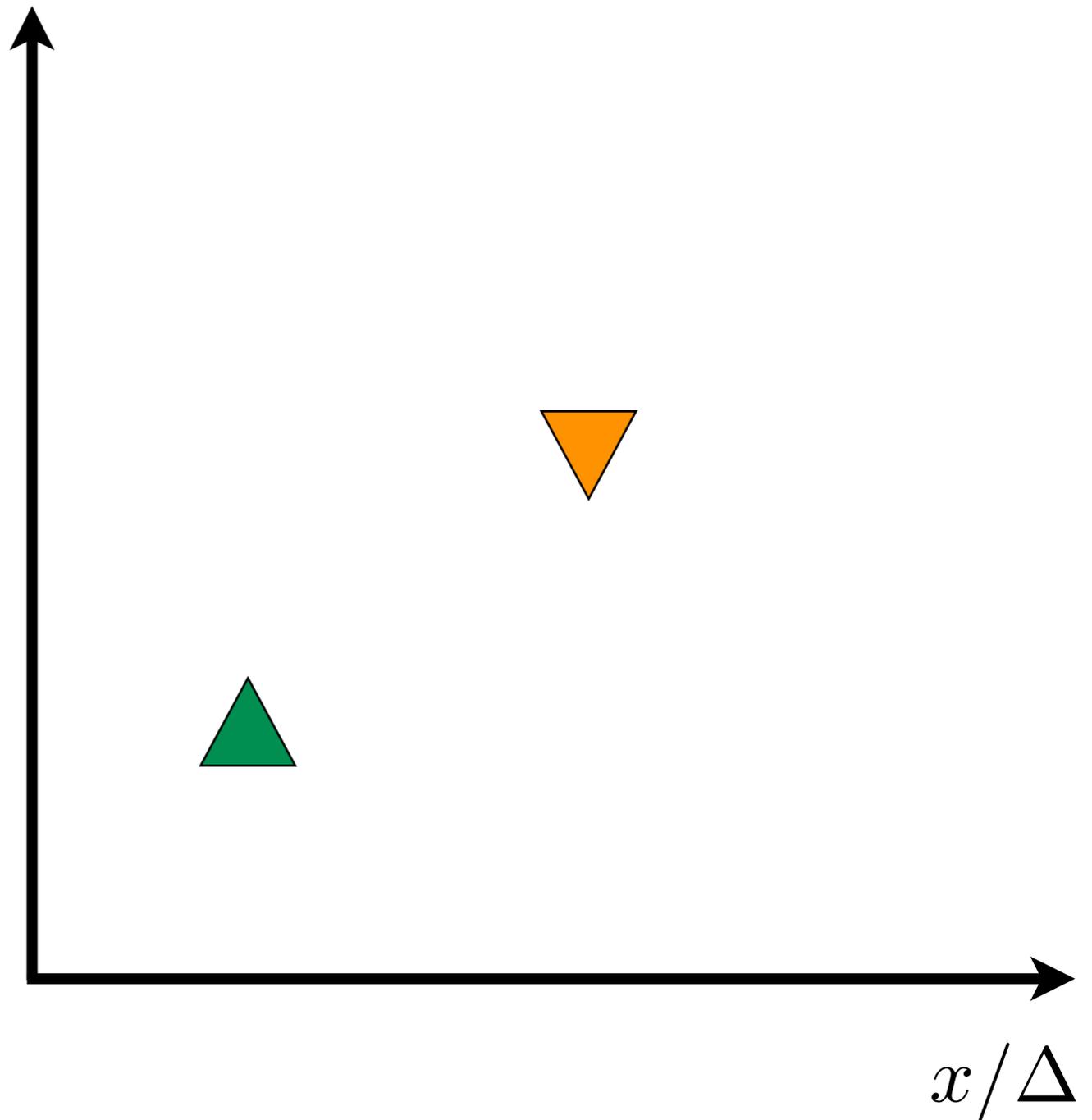
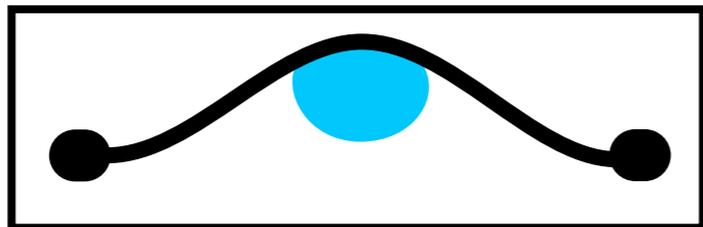
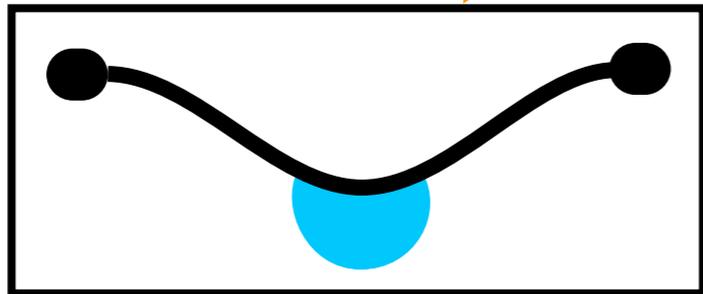
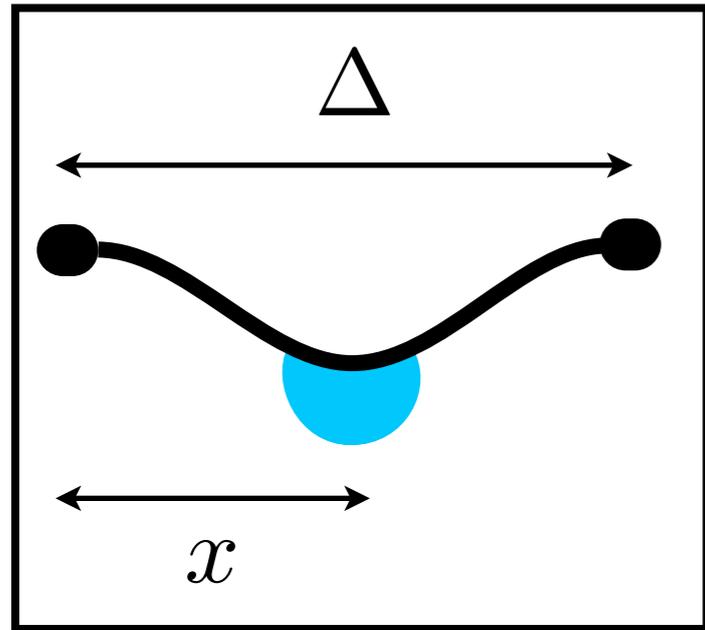
start



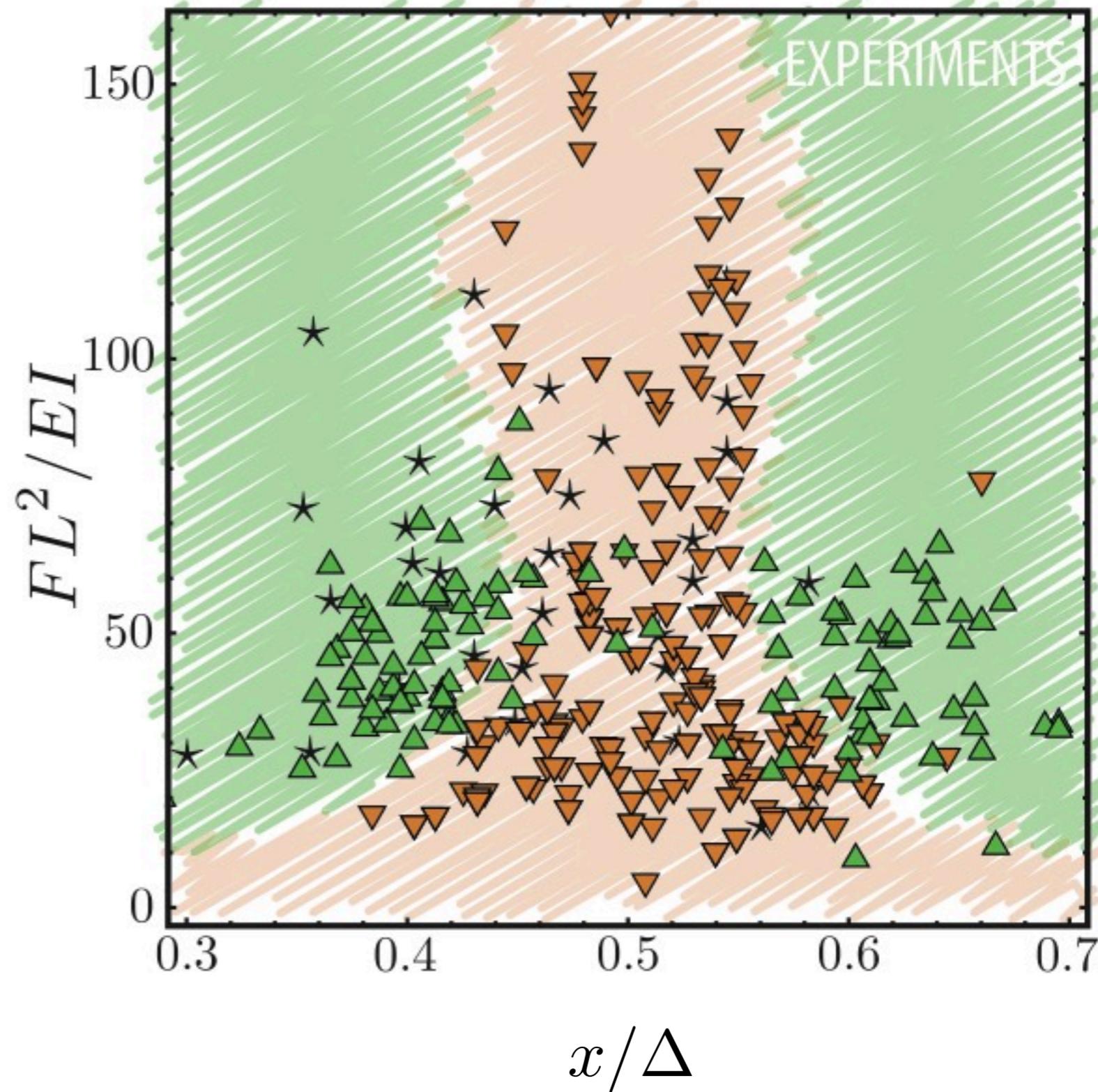
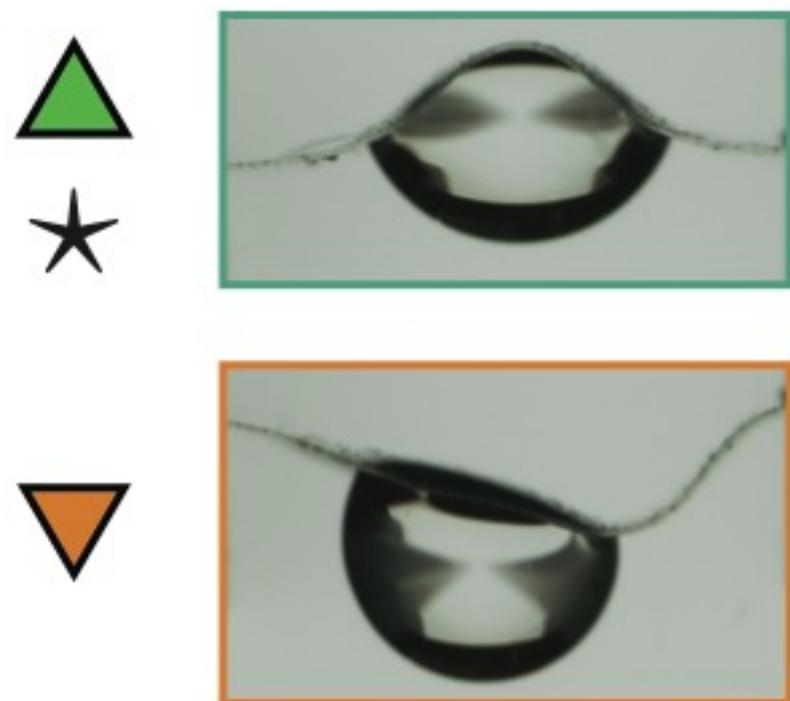
# Capillary induced snap-through

liquid weight  
 $FL^2/EI$

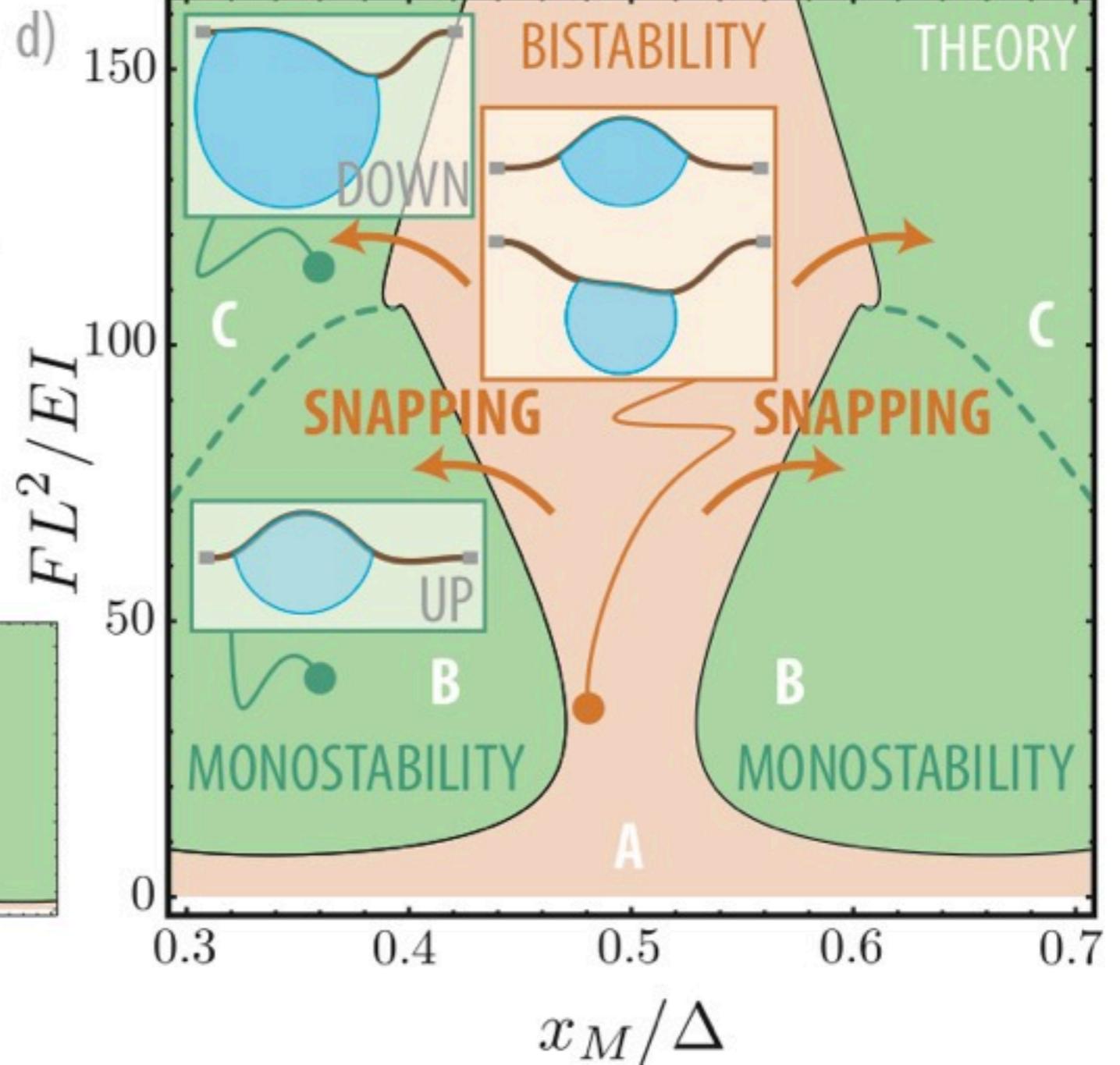
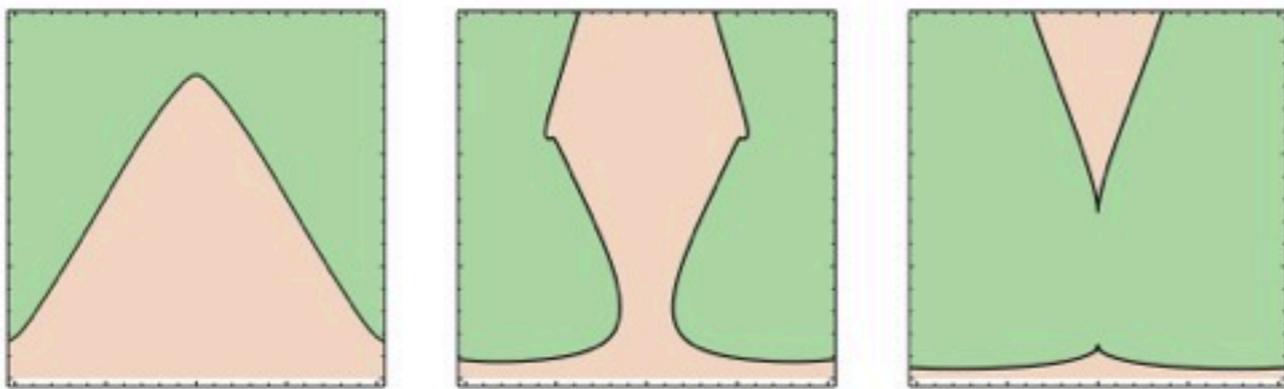
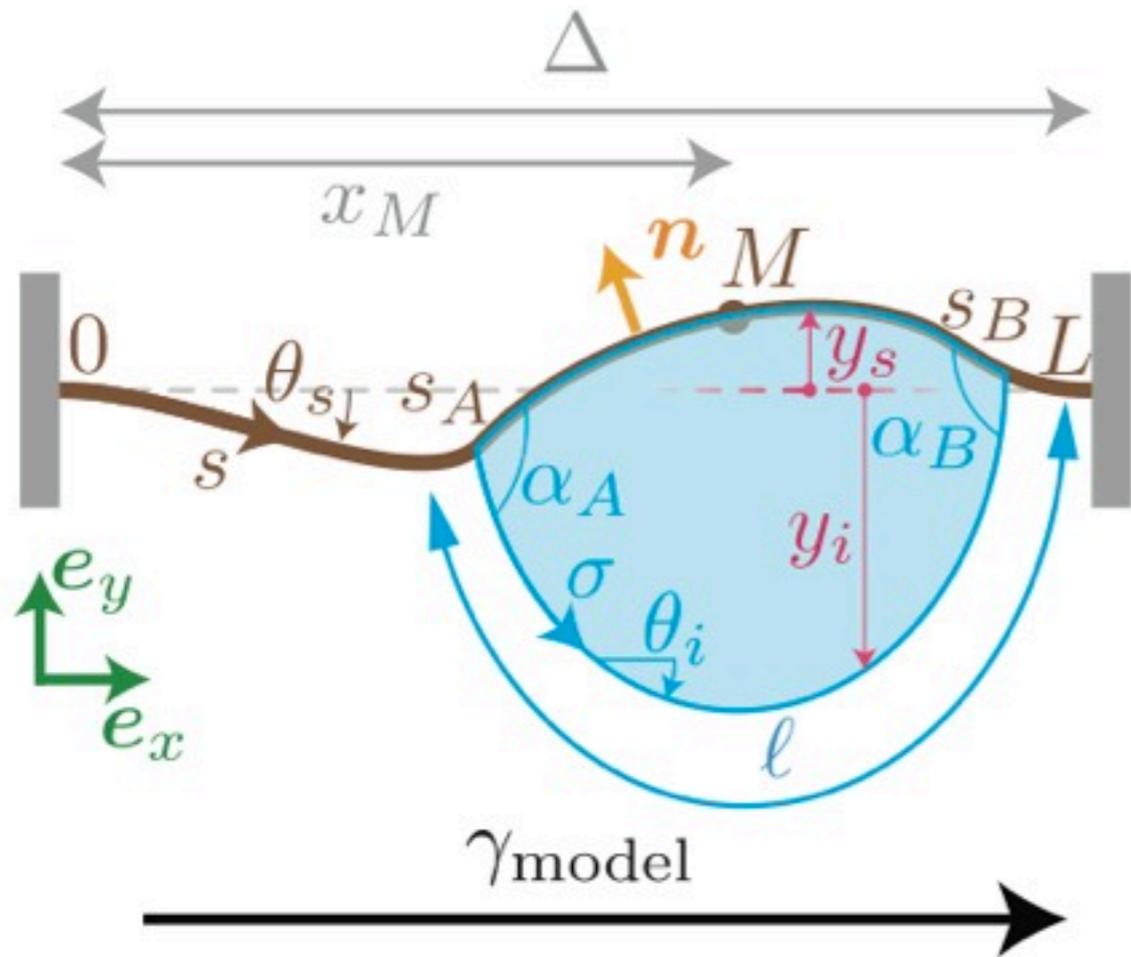
start



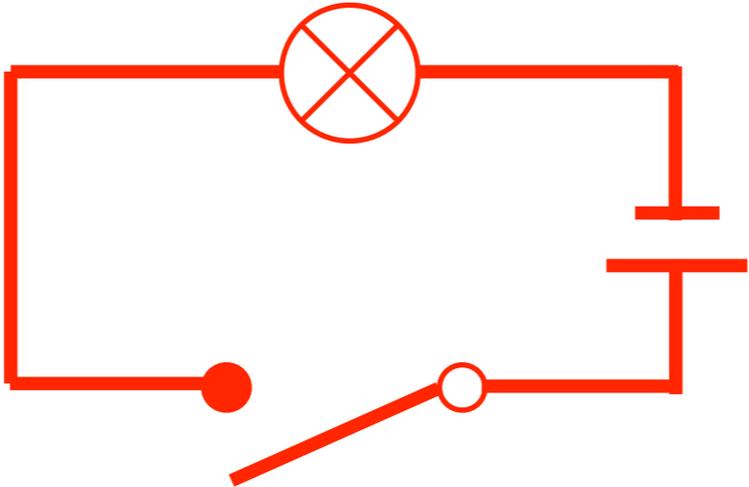
# Capillary induced snap-through



# Capillary induced snap-through



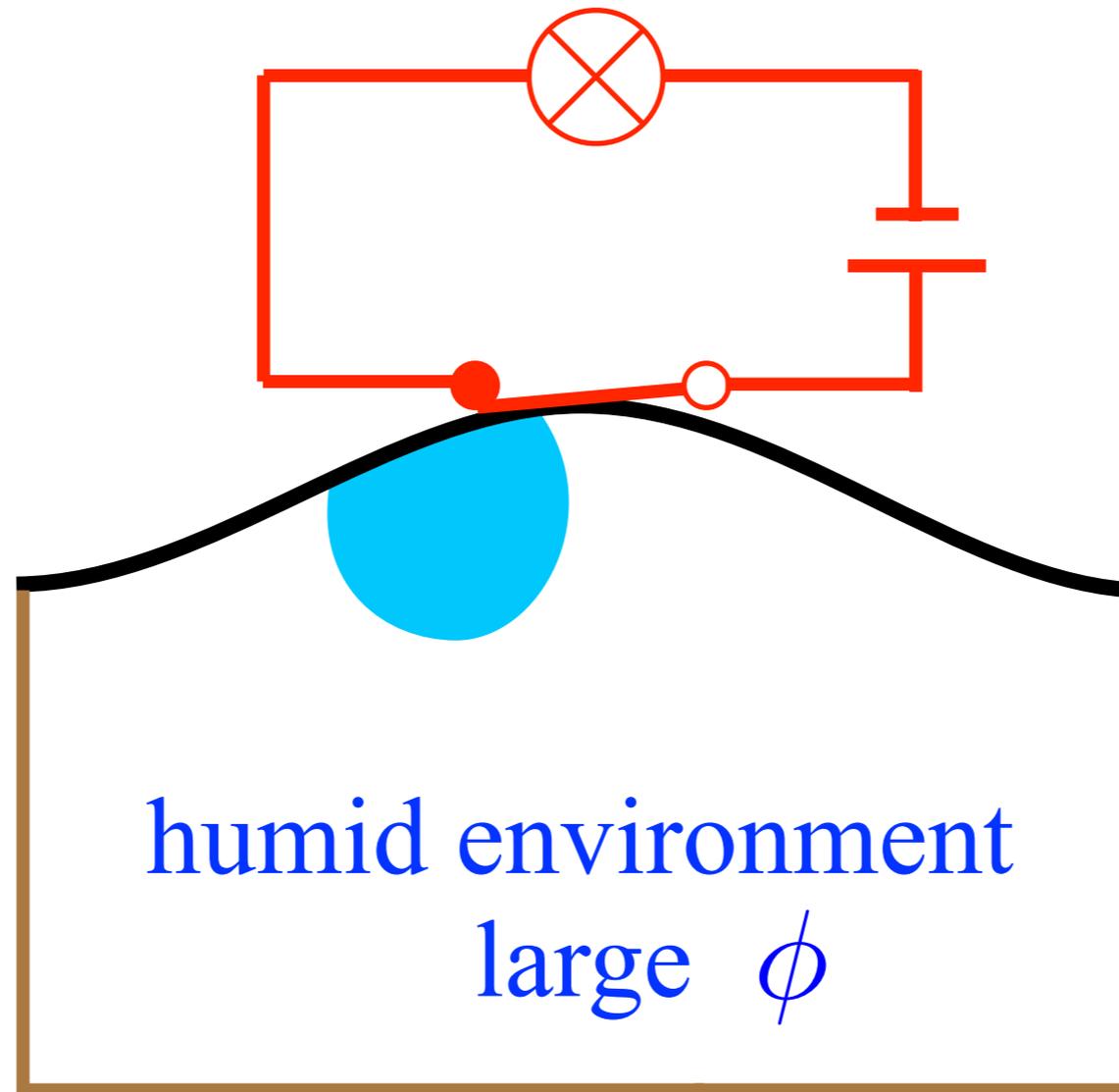
# Condensation induced snap-through



1 mm  

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# Condensation induced snap-through



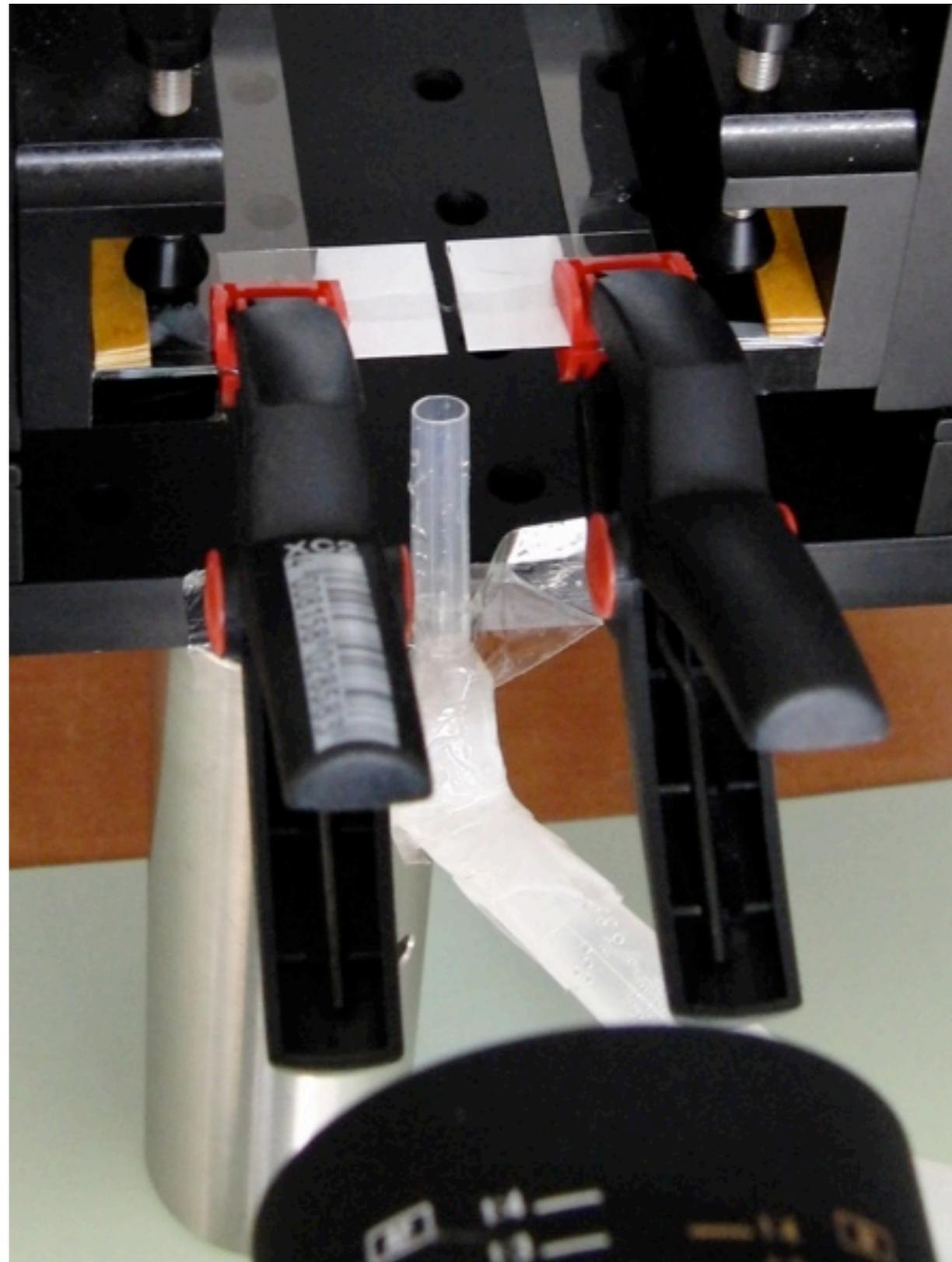
1 mm

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# Condensation induced snap-through



# Condensation induced snap-through



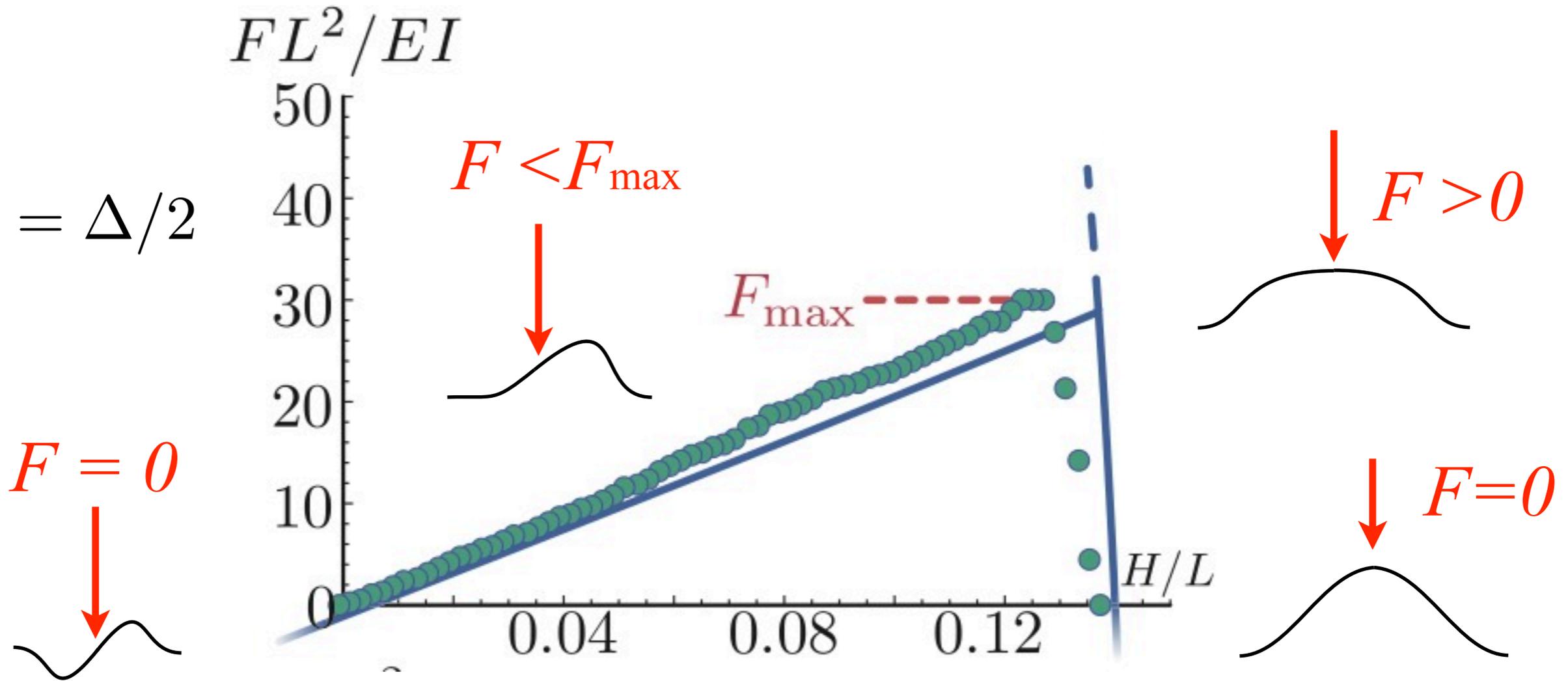
# Condensation induced snap-through



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

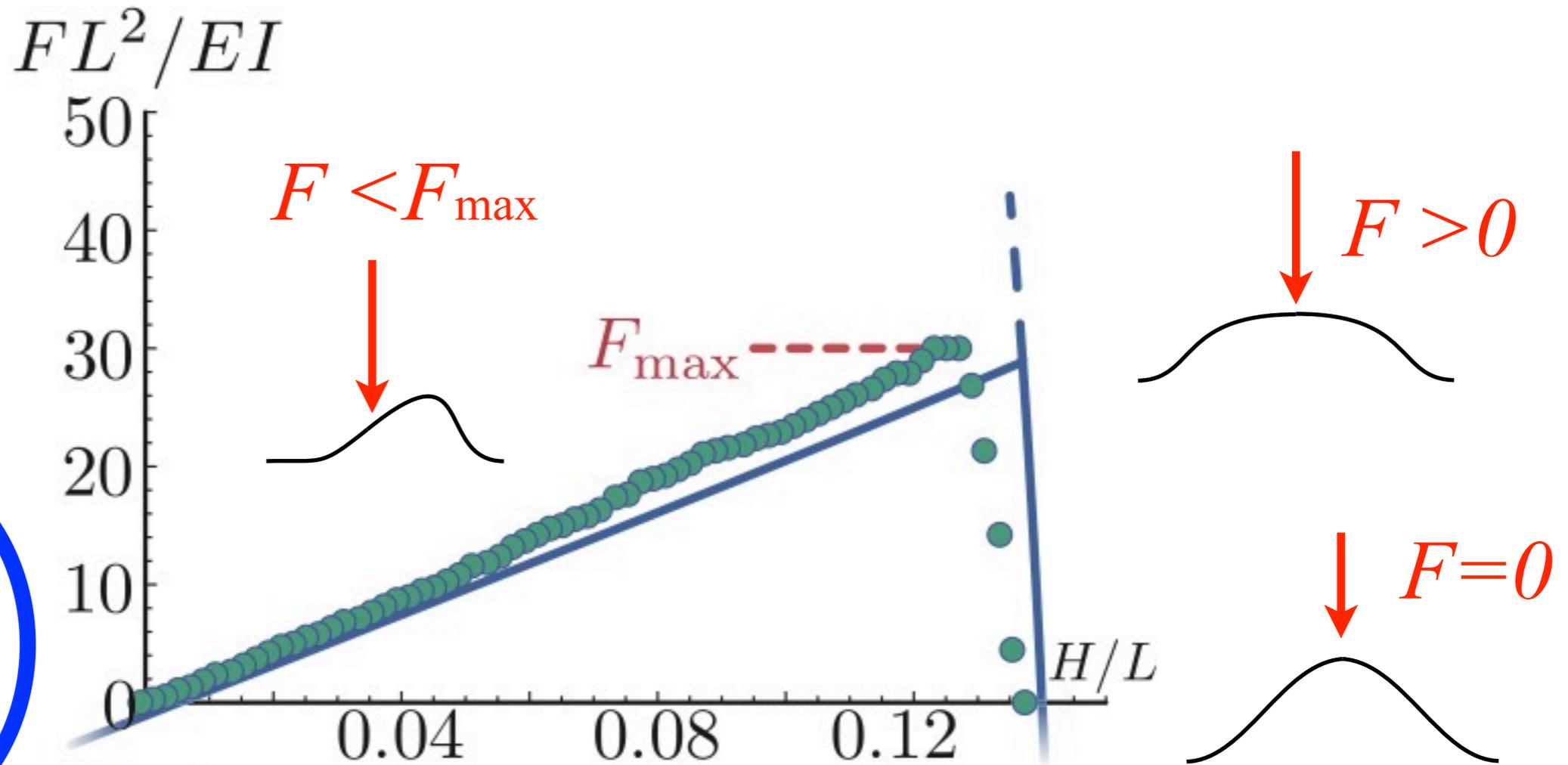
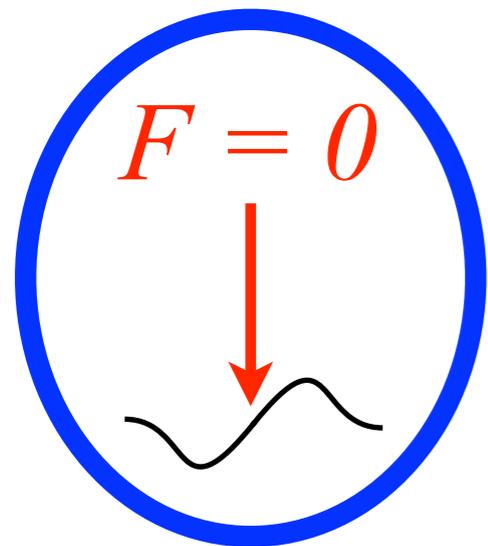
# Snap-through dynamics: the dry case

for  $x = \Delta/2$

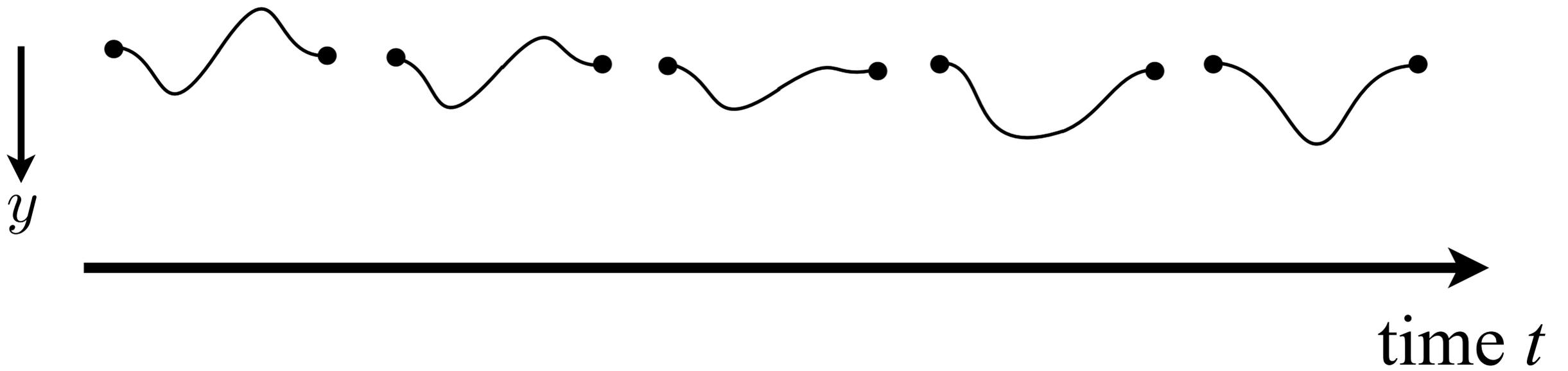


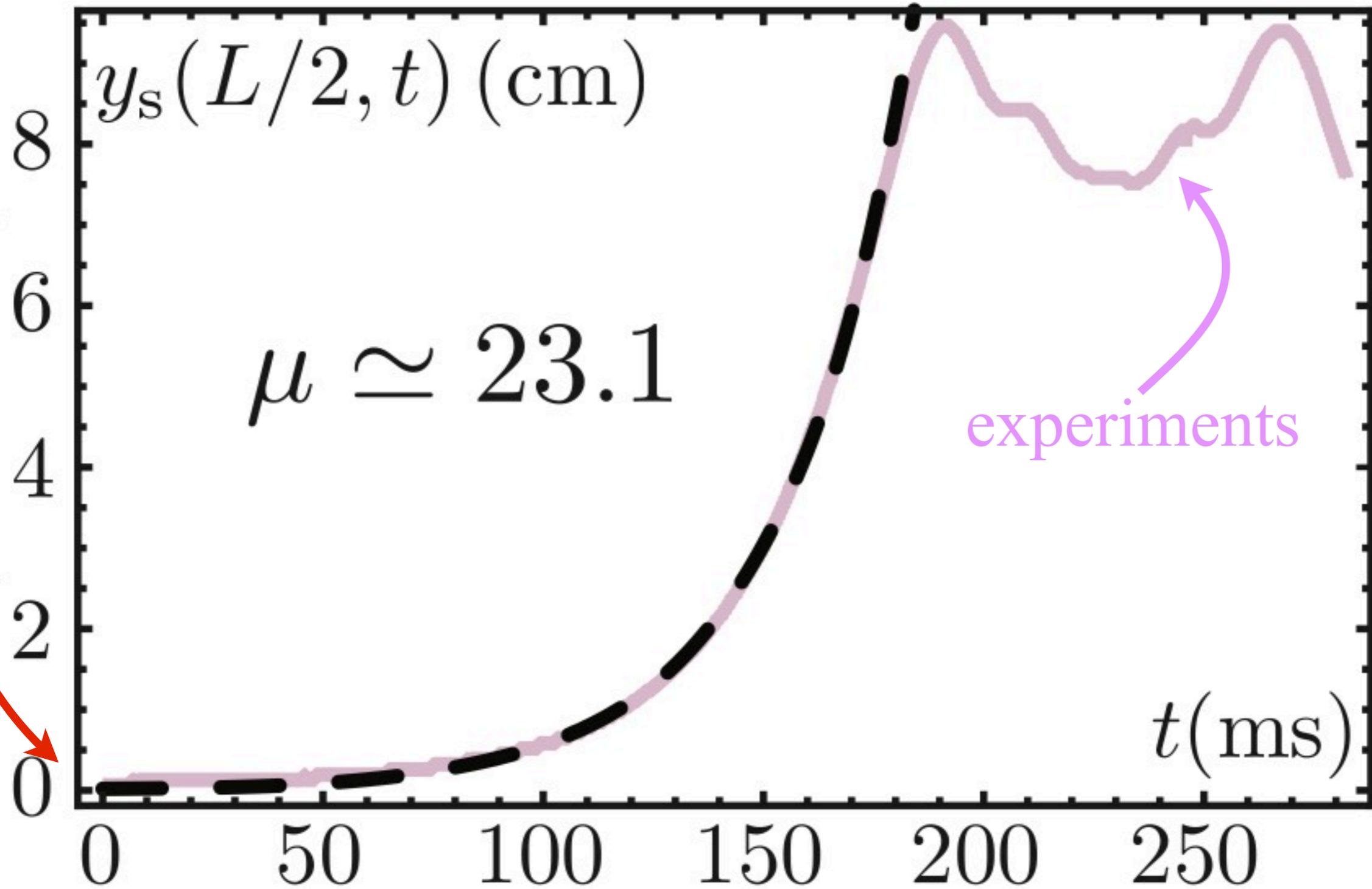
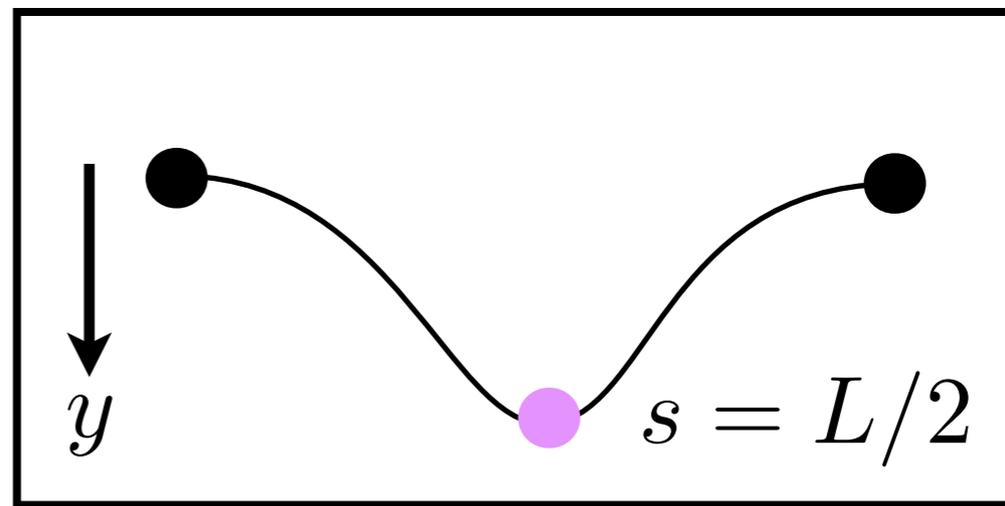
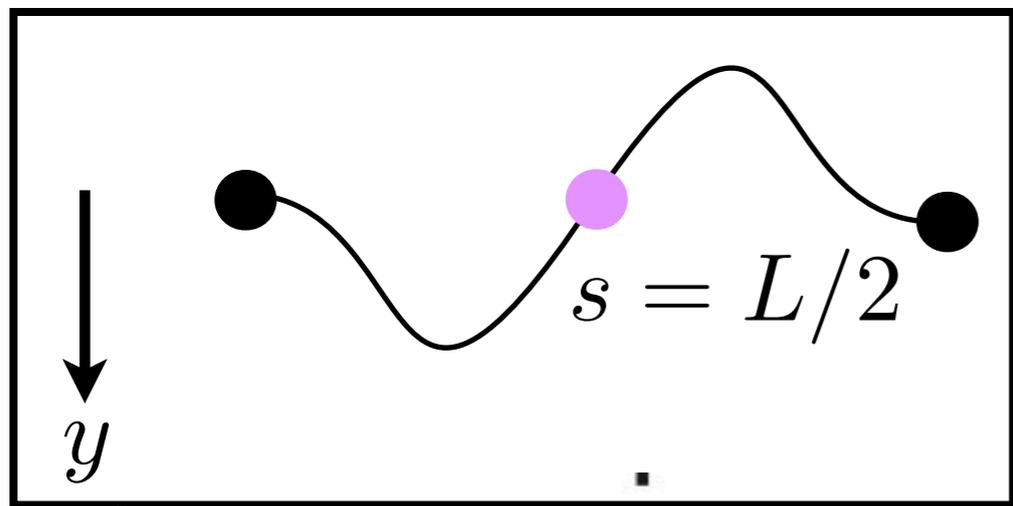
# Snap-through dynamics: the dry case

for  $x = \Delta/2$



# Snap-through dynamics: the dry case





# Snap-through dynamics: the dry case

Experiments:

near the unstable solution

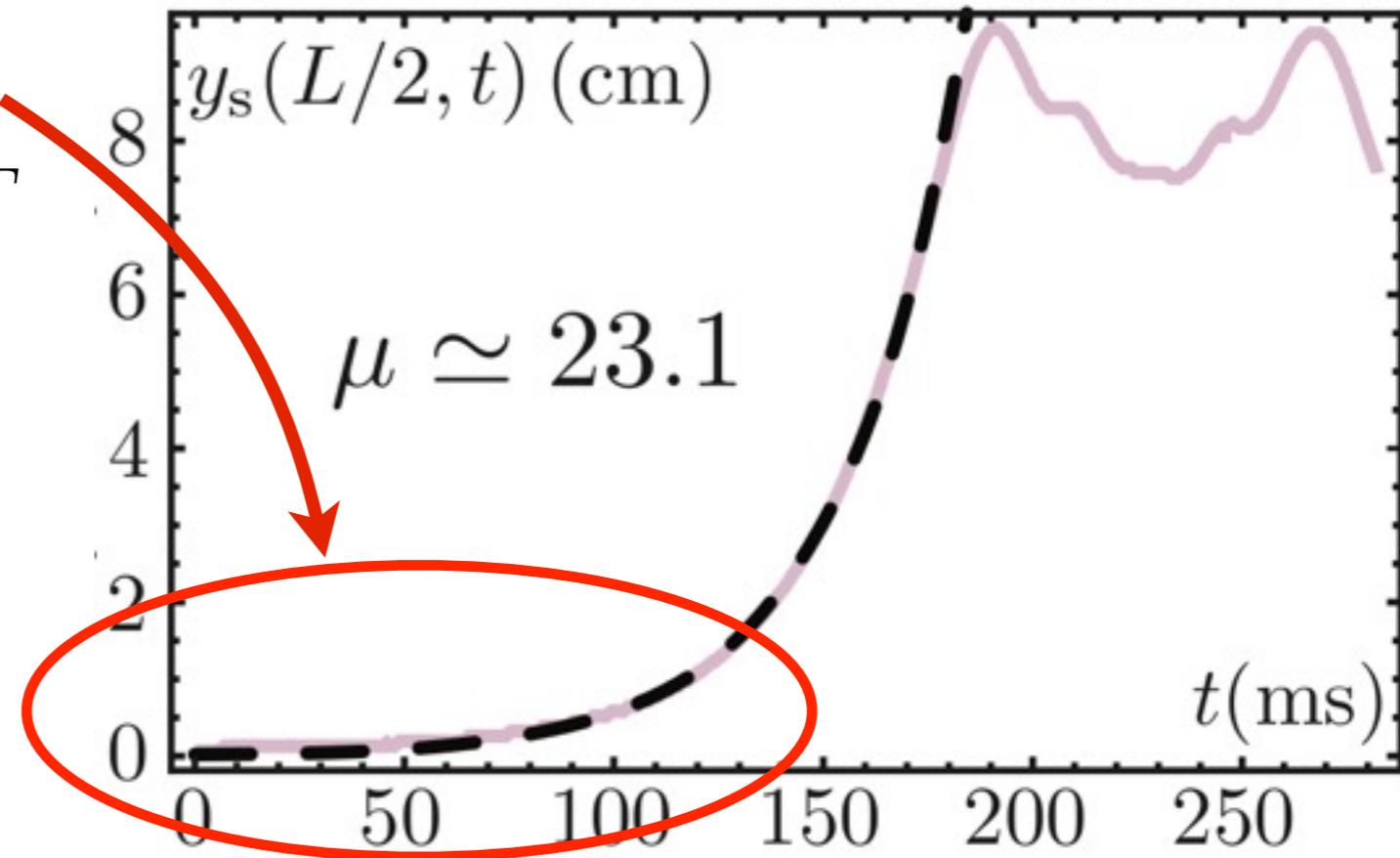
$$y(s, t) = y_{EQ}(s) + \bar{y}(s) e^{\mu t/T}$$

with scaling time:

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

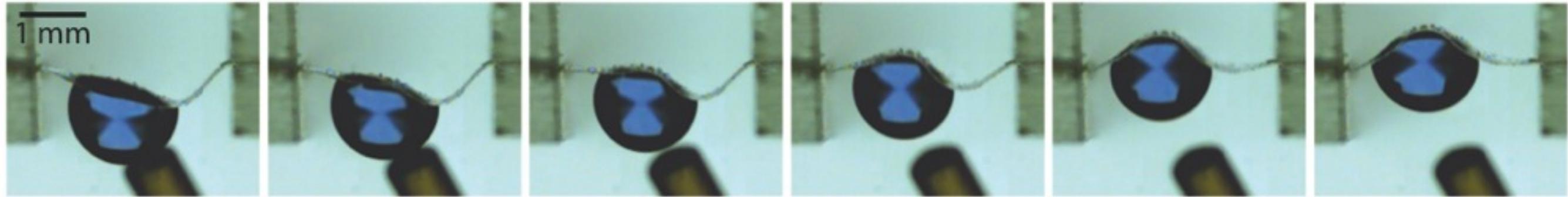
we fit and find

$$\mu \simeq 23.1$$



Theory says:  
 $\mu = 24.3$

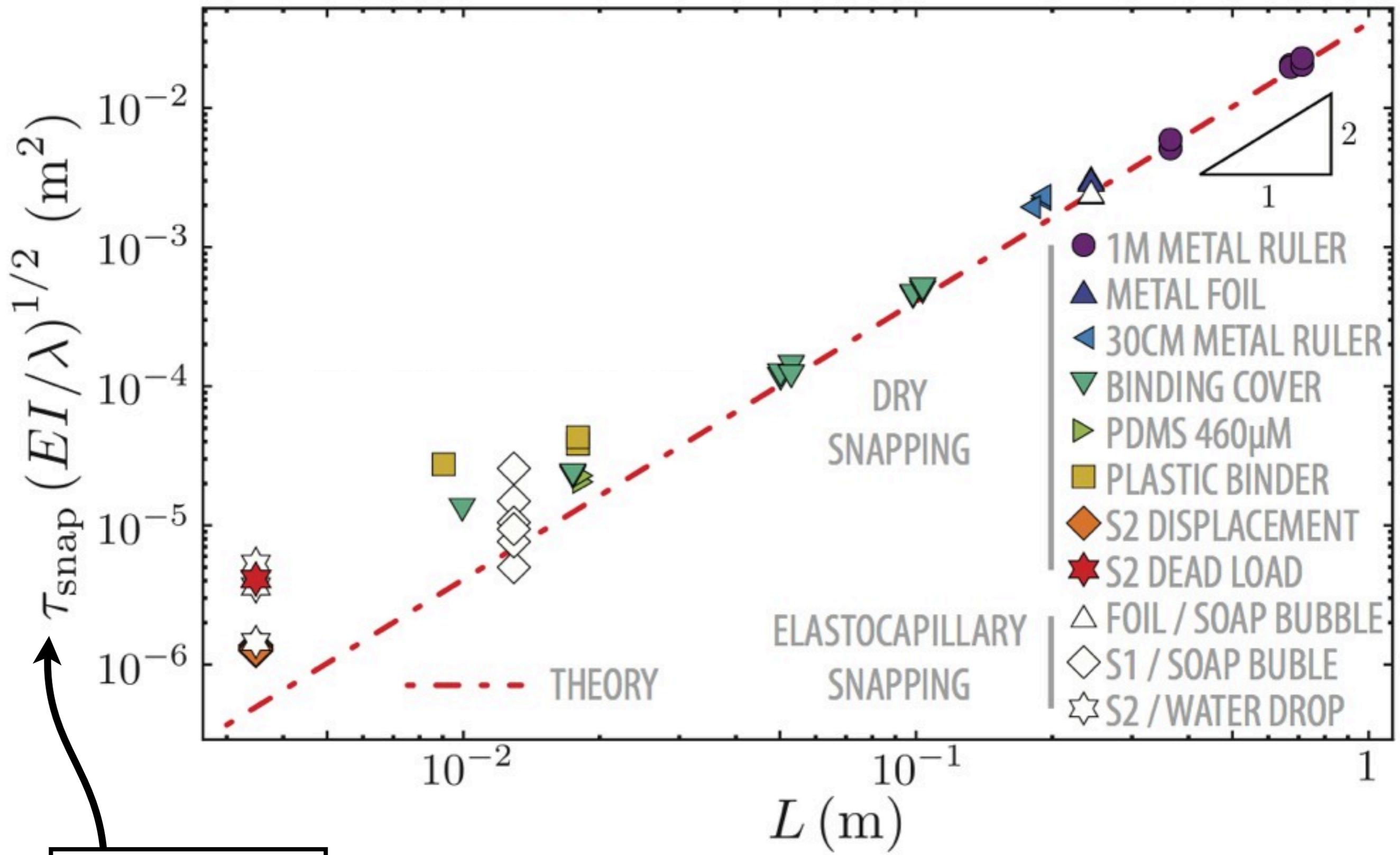
# Snap-through dynamics: the wet case



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

