Bioinspired soft actuation

Joel Marthelot
CNRS
IUSTI, Aix-Marseille University

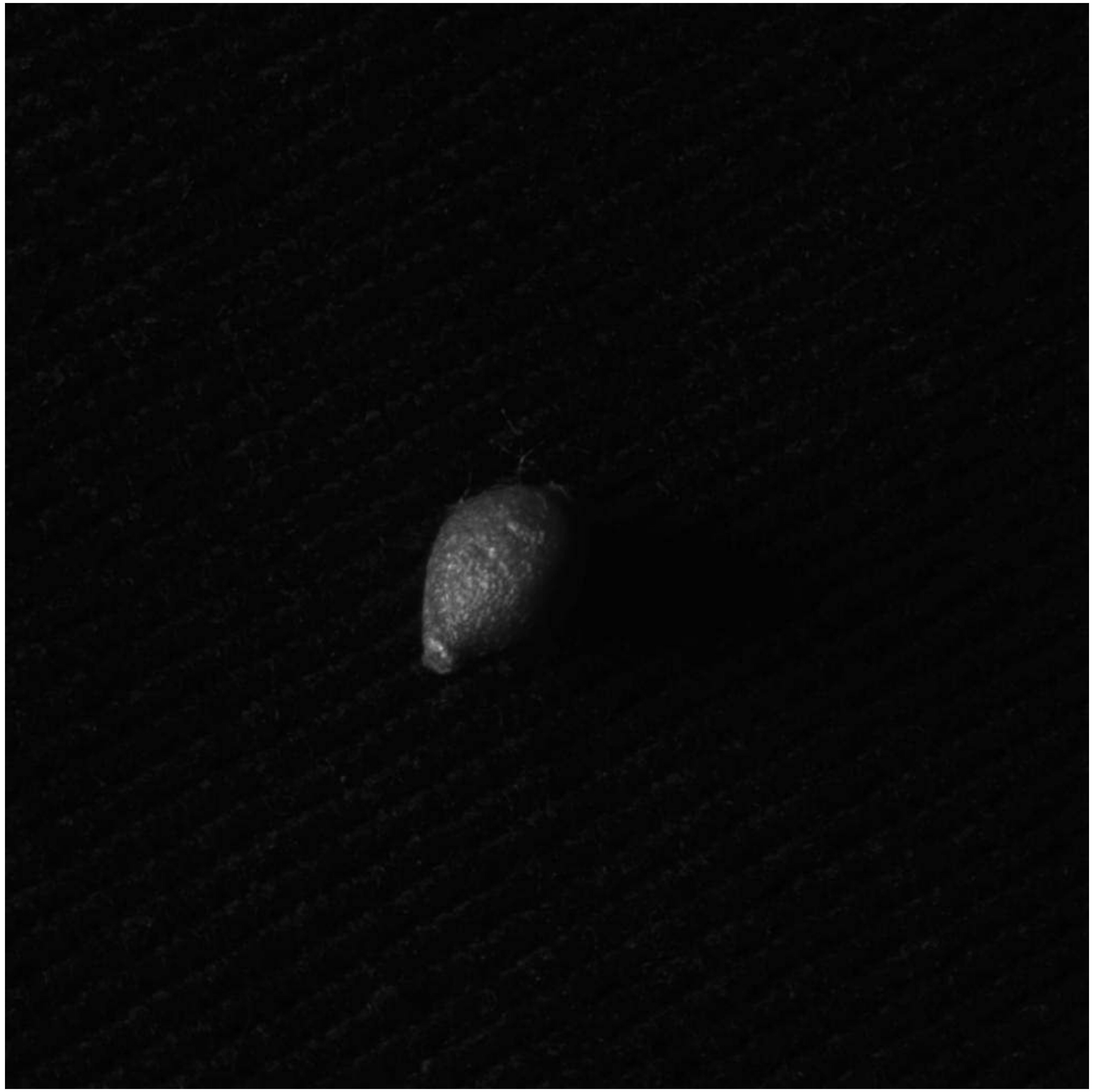
Bioinspiration: what can we learn?

Biological world is full of mechanical instability

Engineers hate instability

To disperse seeds

with Henri Lhuissier



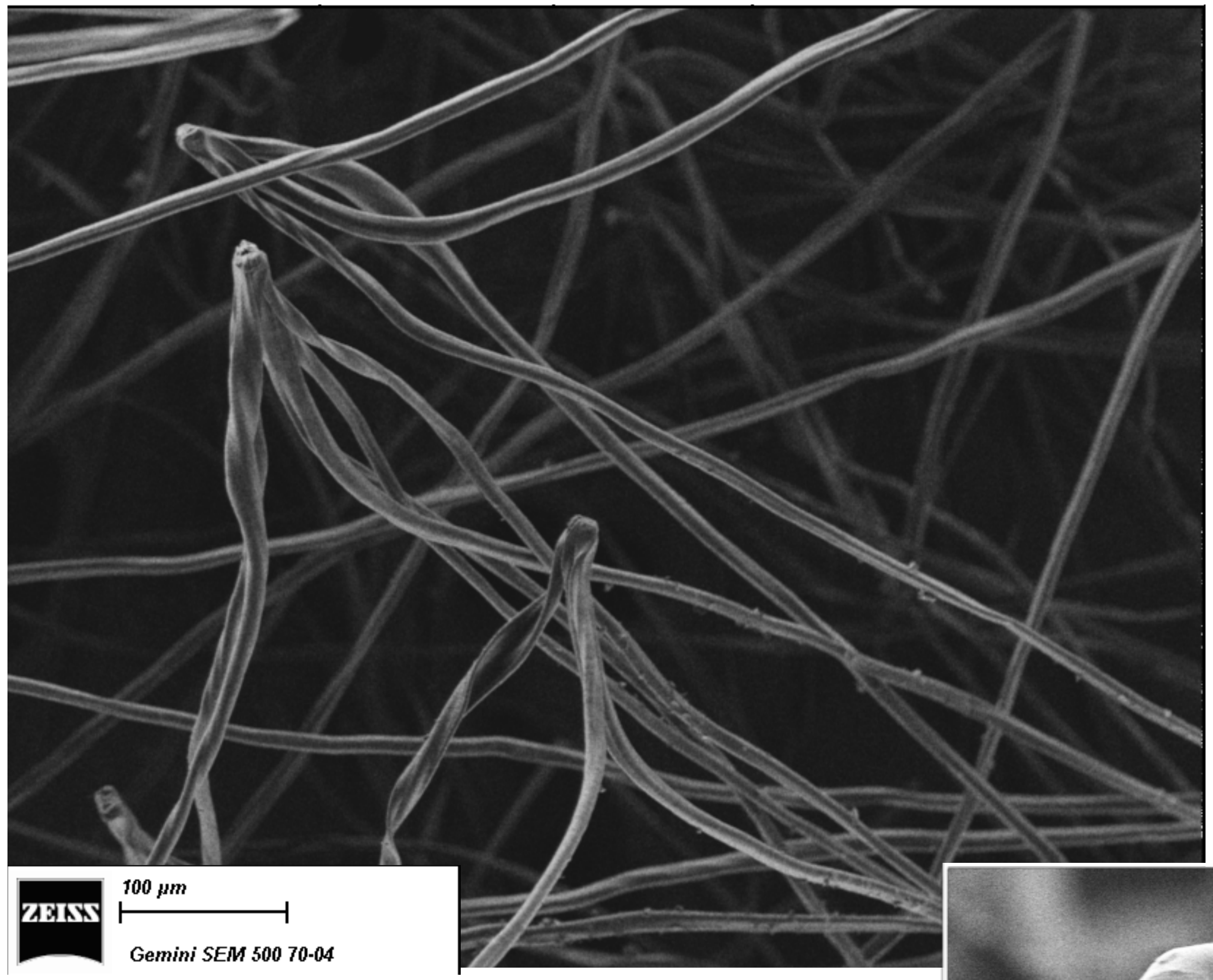
Bioinspiration: what can we learn?

Biological world is full of mechanical instability

To disperse seeds

with Henri Lhuissier

Engineers hate instability



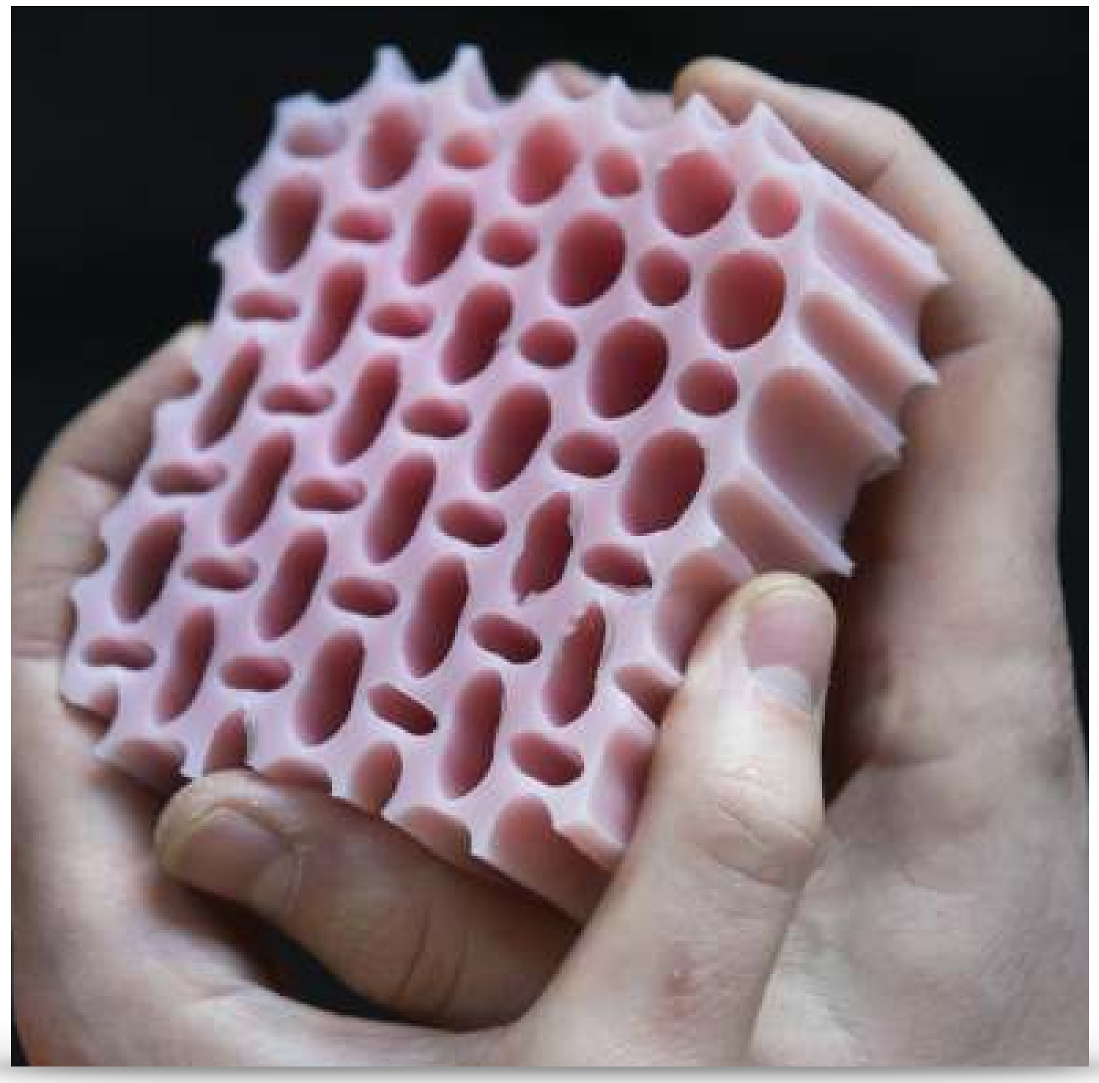
Slender structures:
Small strain
Large displacement

Interesting new physics:
Geometric nonlinearities
Universal mode of
deformations

Hygroscopic unfolding
of triplet fibers

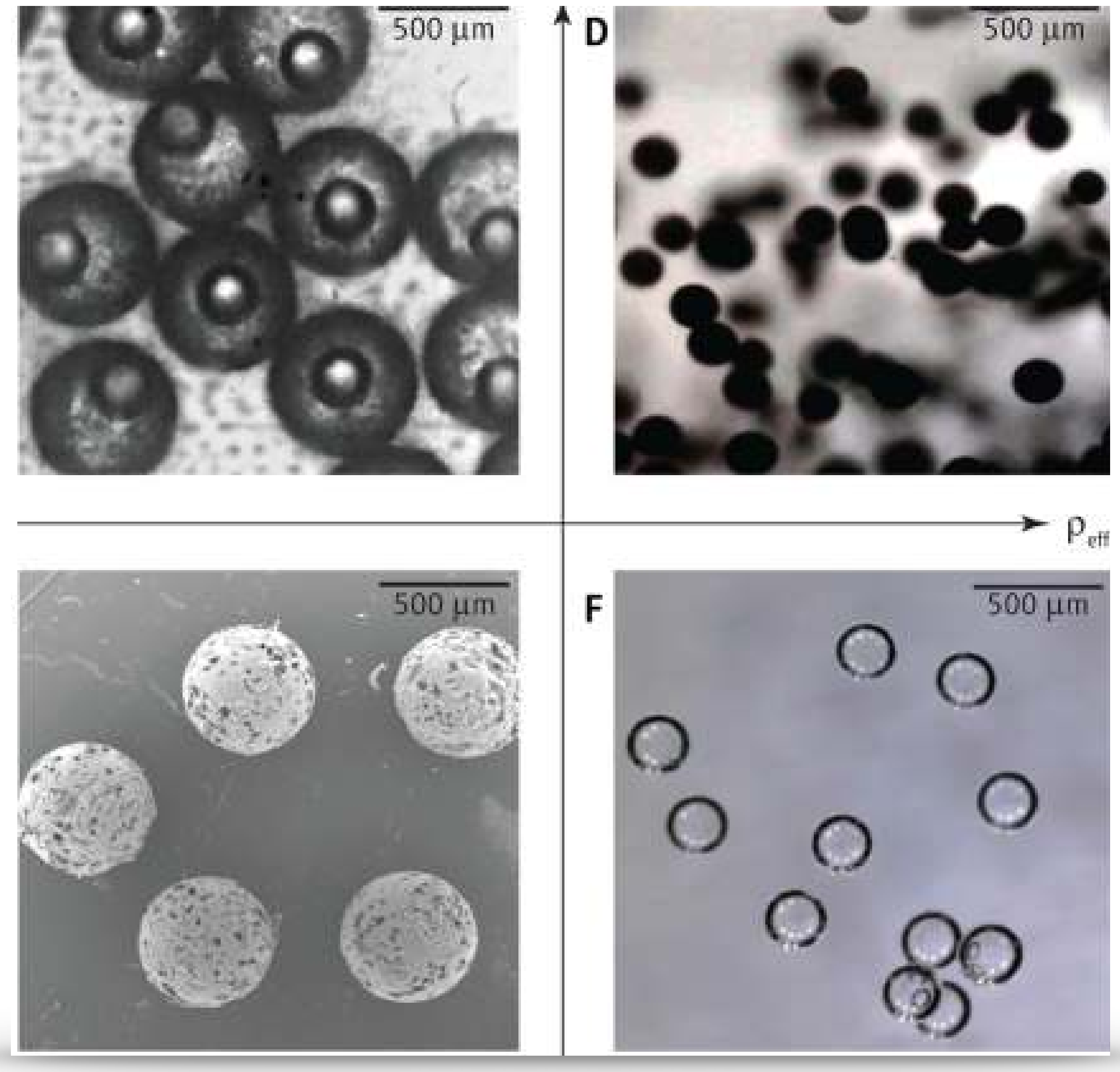
Geometry induced functionality

Mechanics



B. Florijn et al., Phys. Rev. Lett. (2014)

Acoustics

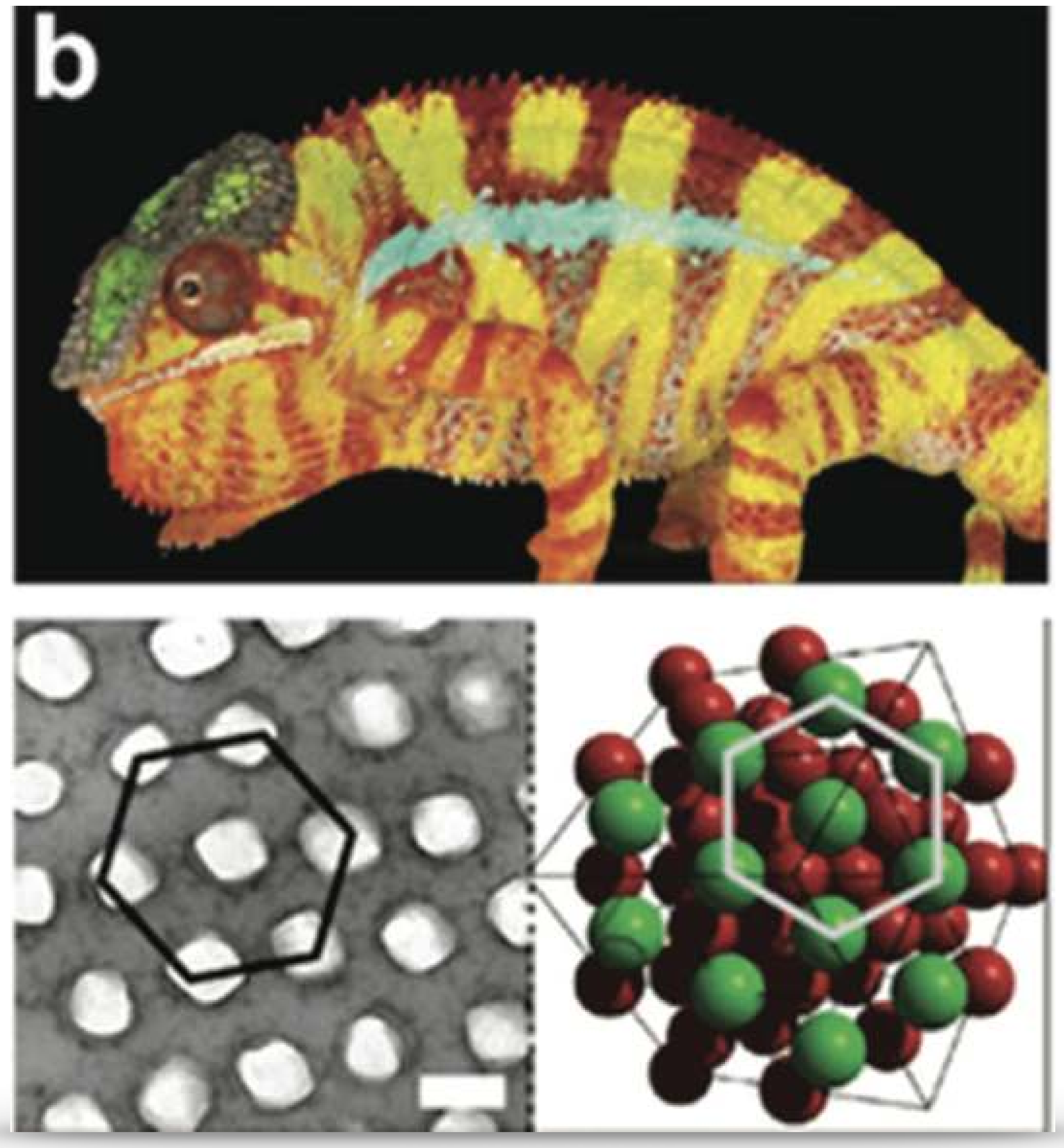


T Brunet et al. Science (2013)

Computer Graphics

C Konakovitch et al. ACM Trans. Graph.,(2016)

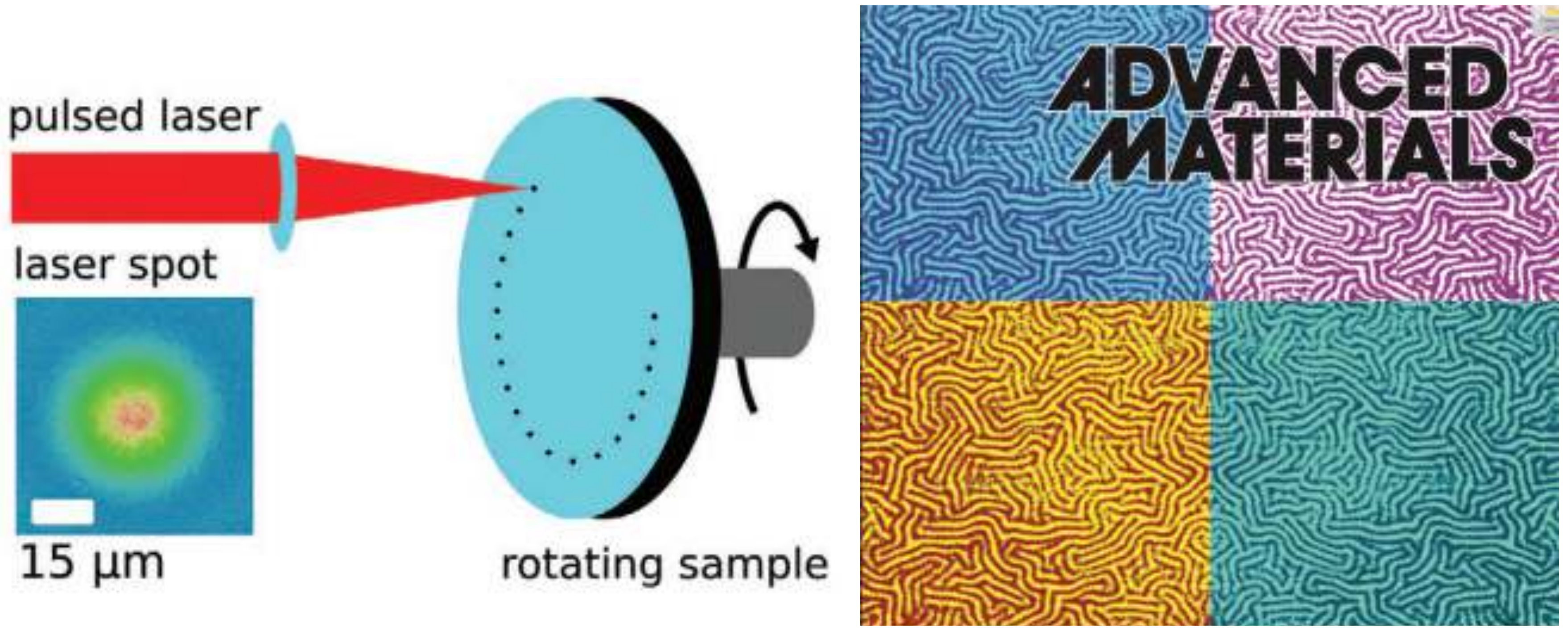
Optics



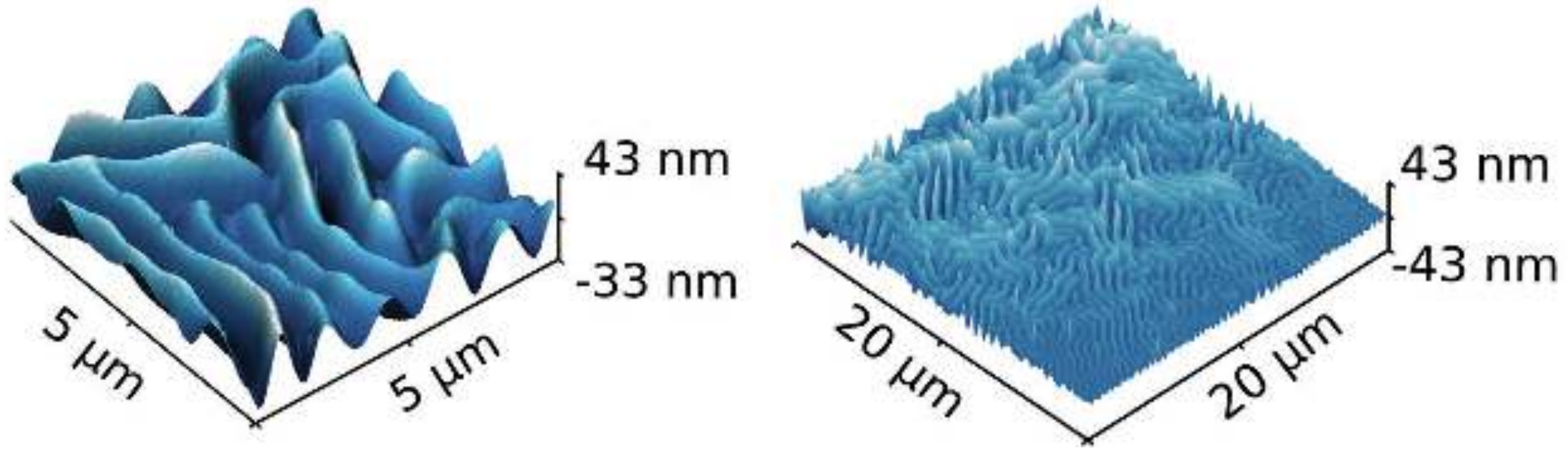
M Kolle et al. Adv. Mater., (2018)

Instabilities = spontaneous patterning

Wrinkles across scales

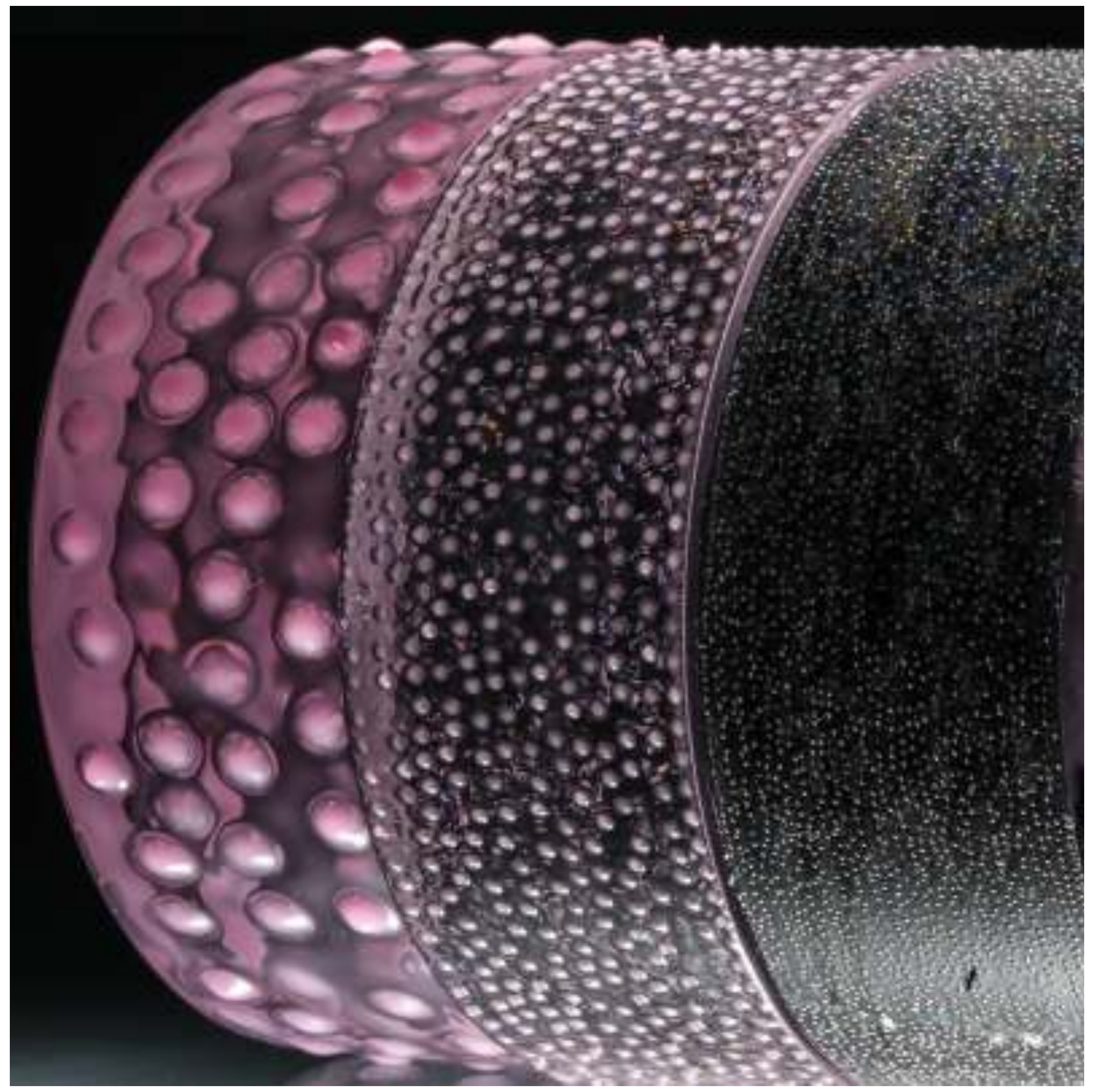


P. Martinez et al. Adv Mat (2020)



Morphing soft structures with instabilities

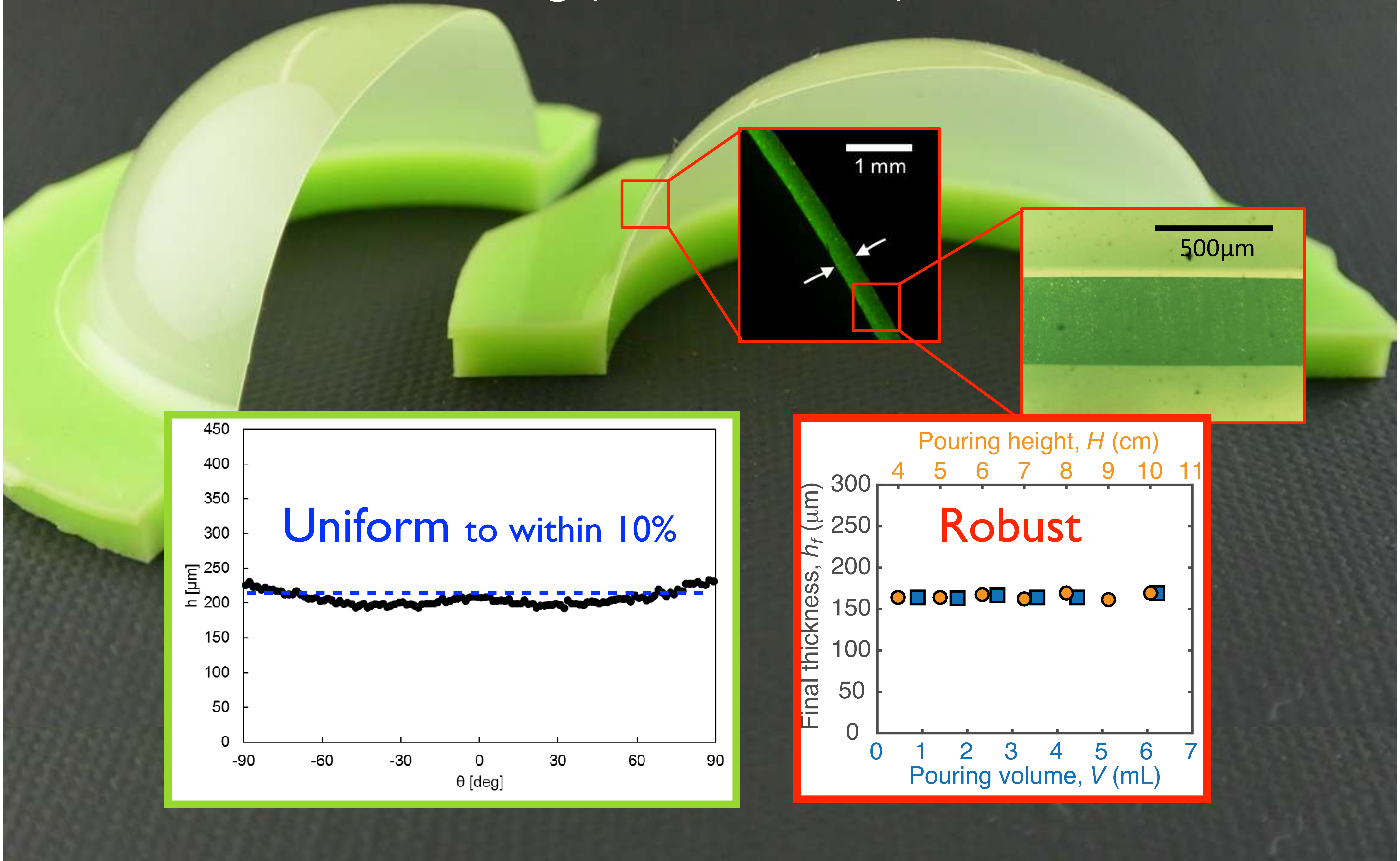





1. Chocolate egg problem/buckling
2. Rayleigh-Taylor instability
3. Rayleigh-Plateau instability
4. Bioinspired soft inflatable structures

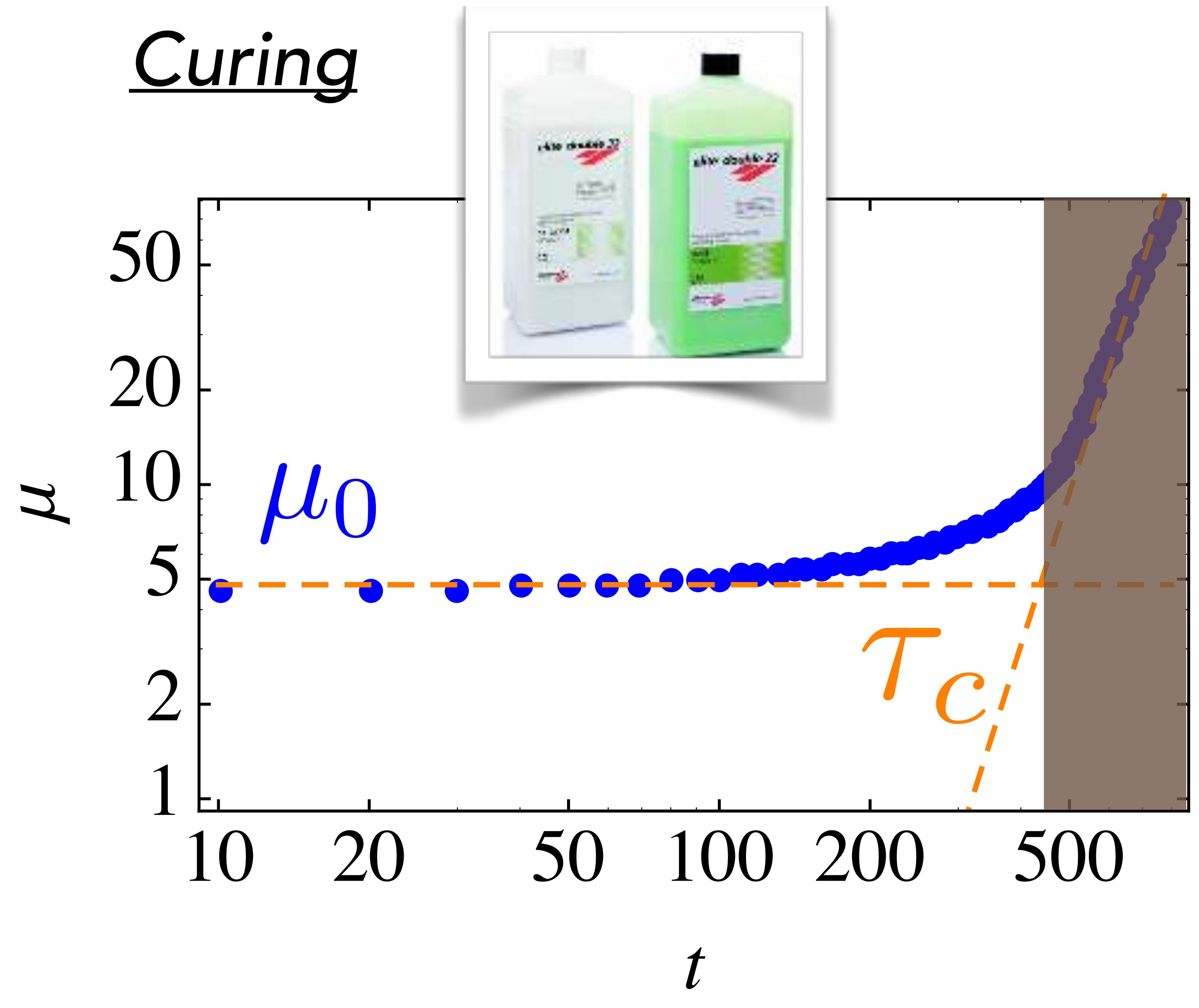

elite double 32
elite double 32

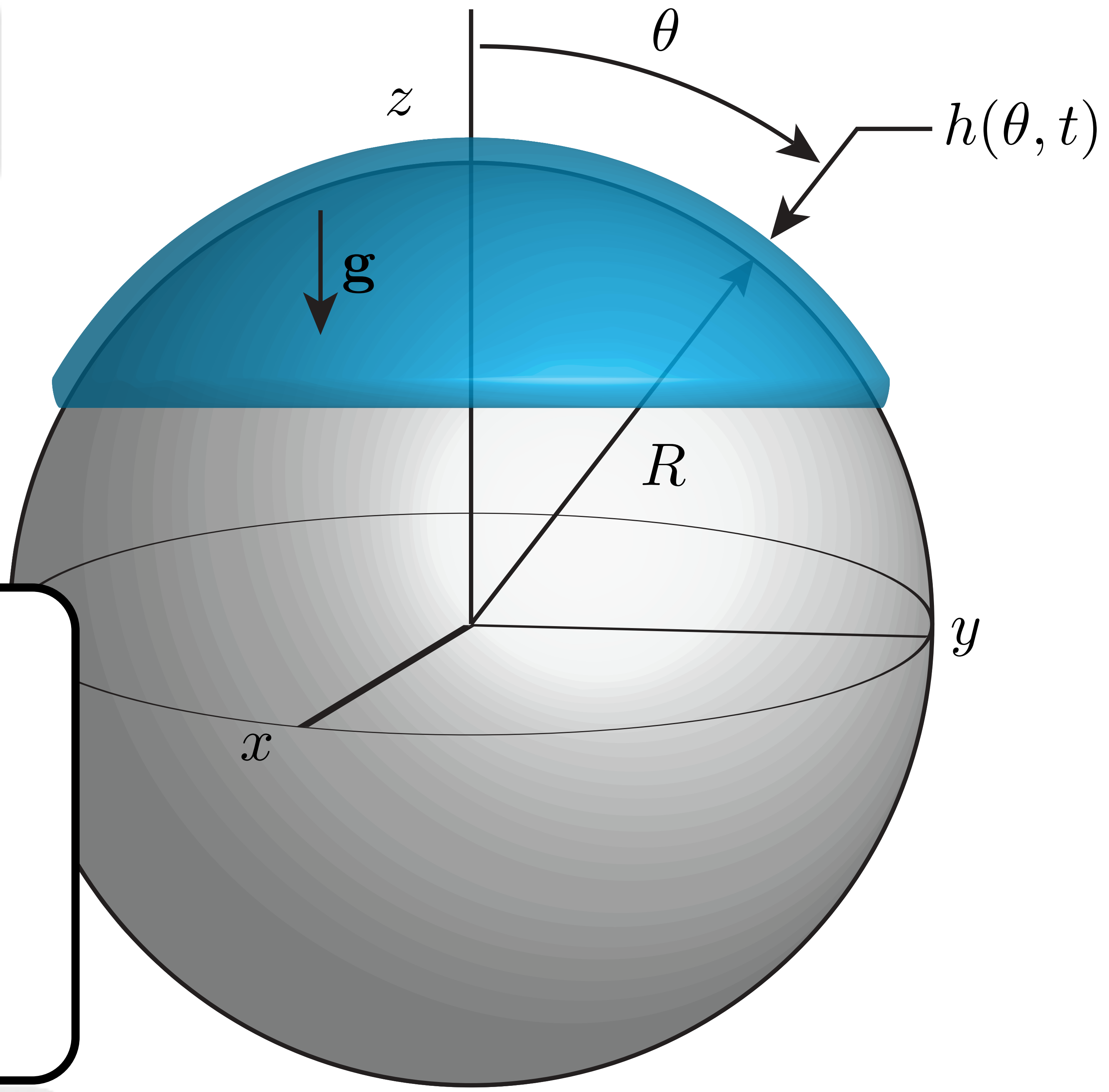
The coating problem: experiments



A hand-wavy model

Curing





$$h_f \sim \sqrt{\frac{\mu_0 R}{\rho g \tau_c}}$$

Scales

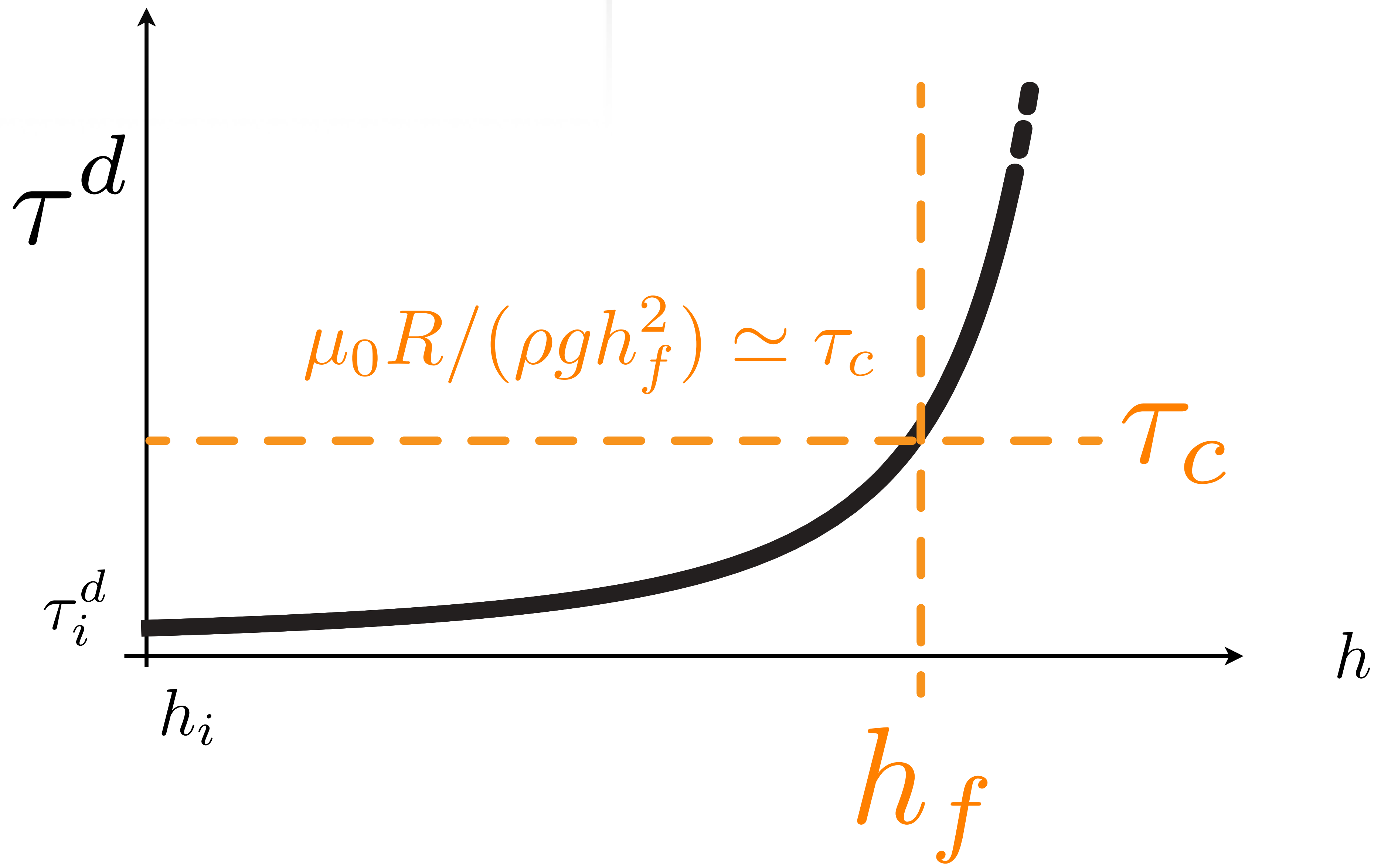
Initial Thickness h_i

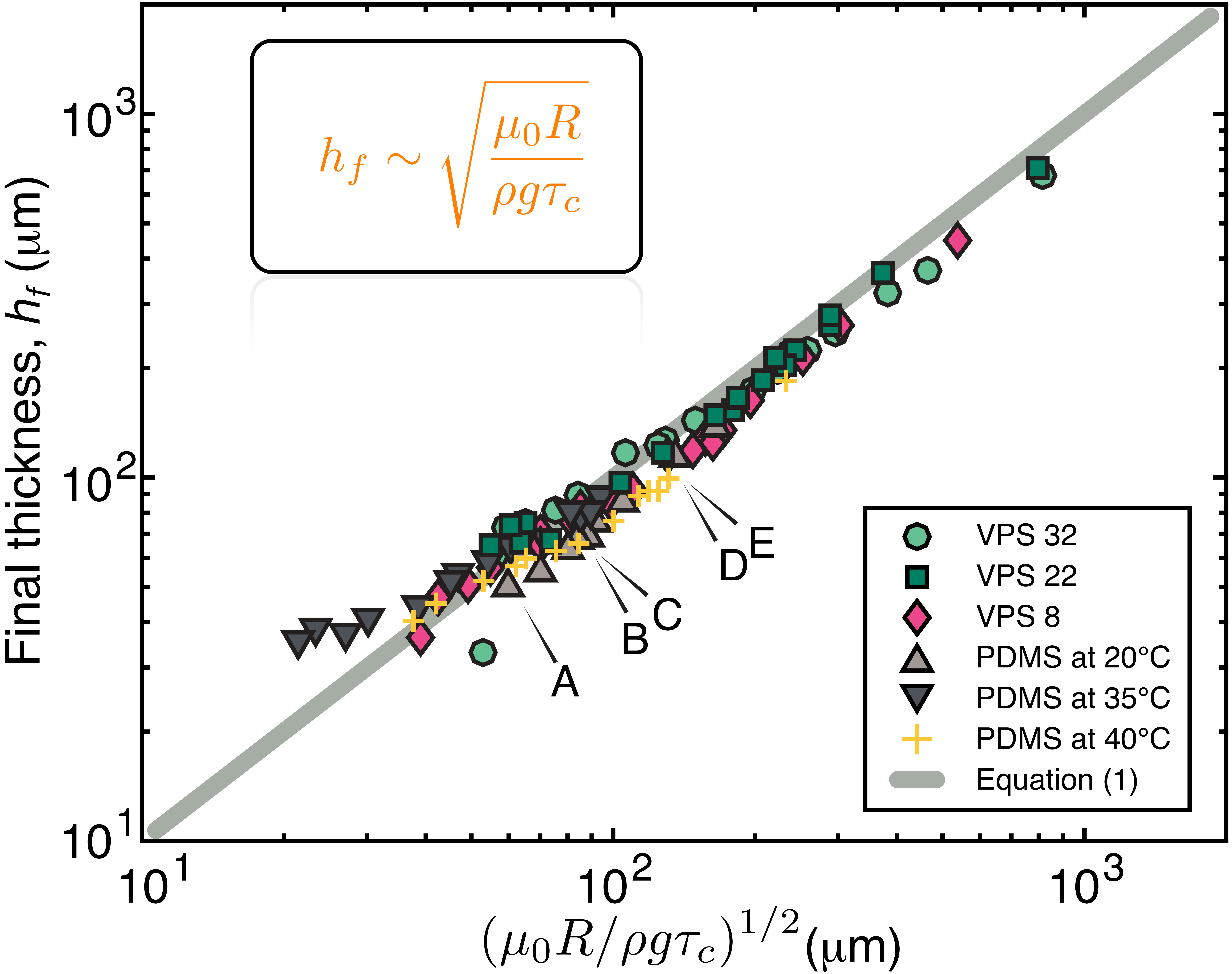
Time $\tau_i^d = \mu R/(\rho g h_i^2)$

Scales II

Thickness $h < h_i$

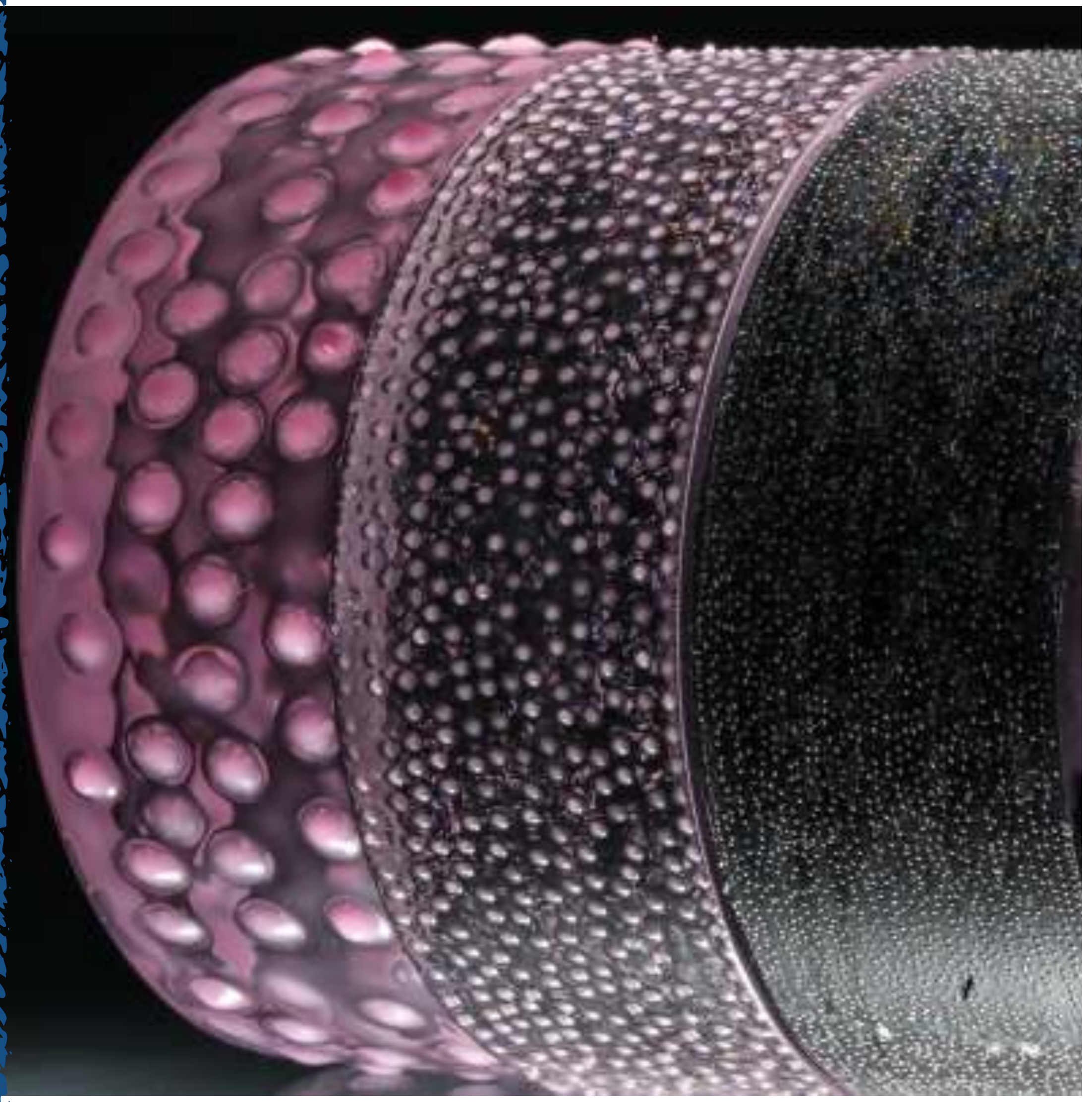
Time $\tau^d = \mu R/(\rho g h)^2 > \tau_i^d$





$h_f \sim \sqrt{\frac{\mu_0 R}{\rho g \tau_c}}$
Final thickness, h_f (μm)
$(\mu_0 R/\rho g \tau_c)^{1/2}$ (μm)
10^1
10^2
10^3
A
B
C
D
E
VPS 32
VPS 22
VPS 8
PDMS at 20°C
PDMS at 35°C
PDMS at 40°C
Equation (1)

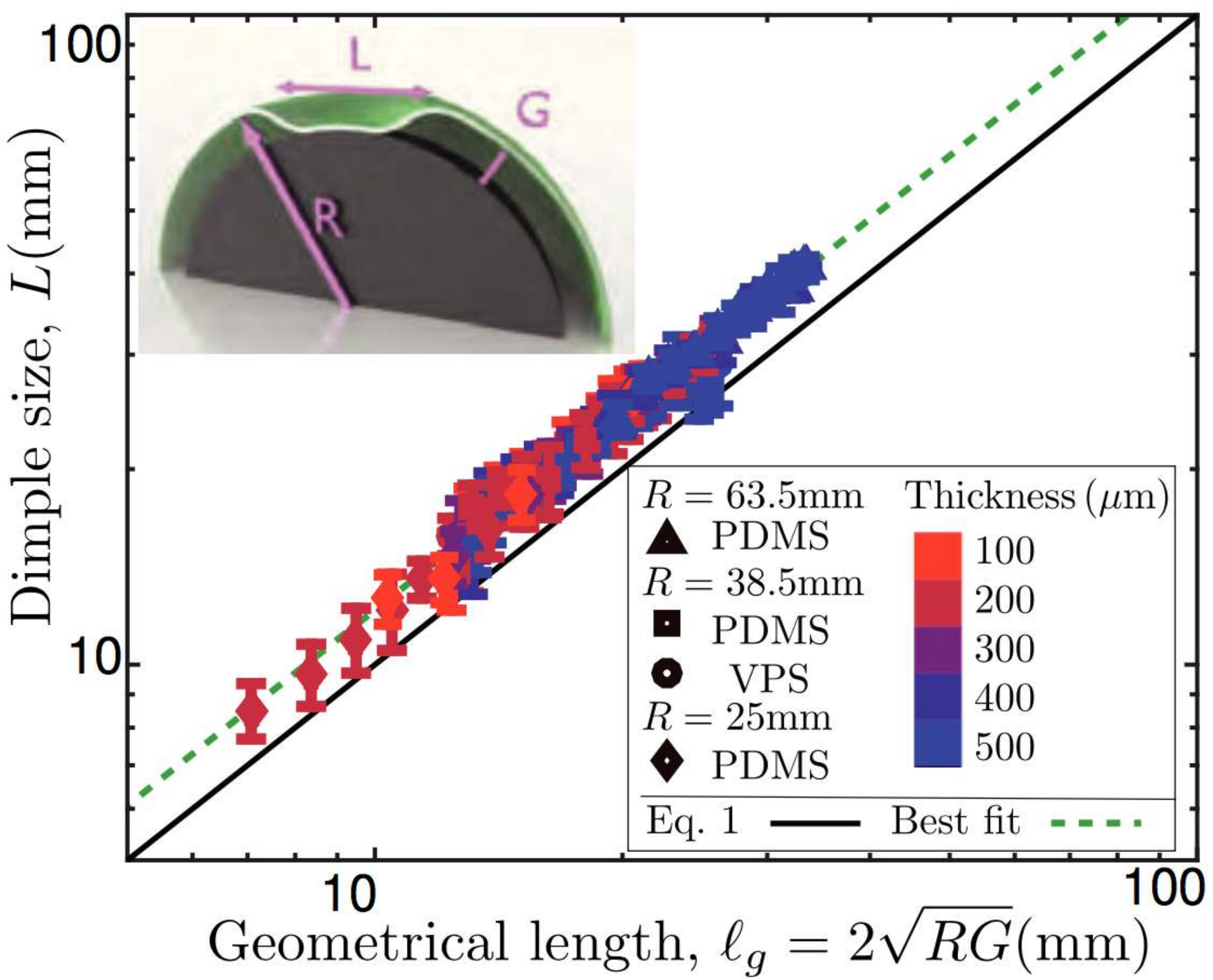
Morphing soft structures with instabilities



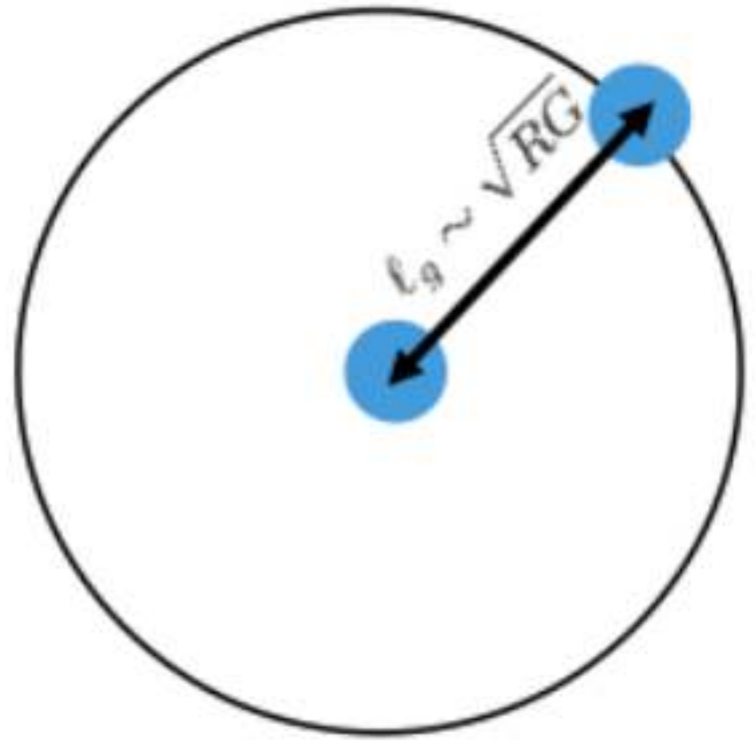
1. Chocolate egg problem/buckling
2. Rayleigh-Taylor instability
3. Rayleigh-Plateau instability
4. Bioinspired soft inflatable structures

with PT Brun, F Lopez Jimenez, PM Reis (MIT)
JW Hutchinson (Harvard)

Length scale



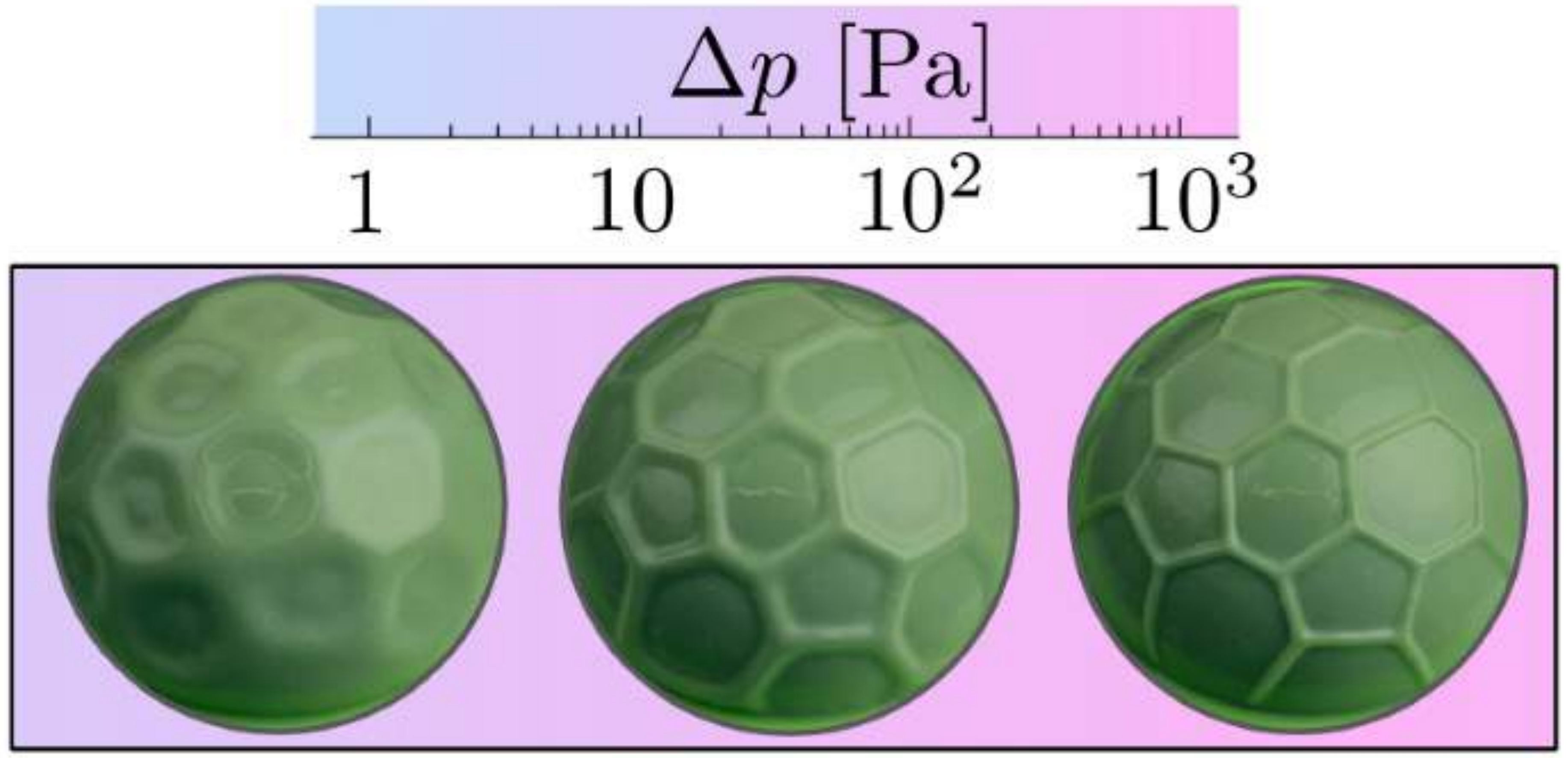
Progression of the buckling front

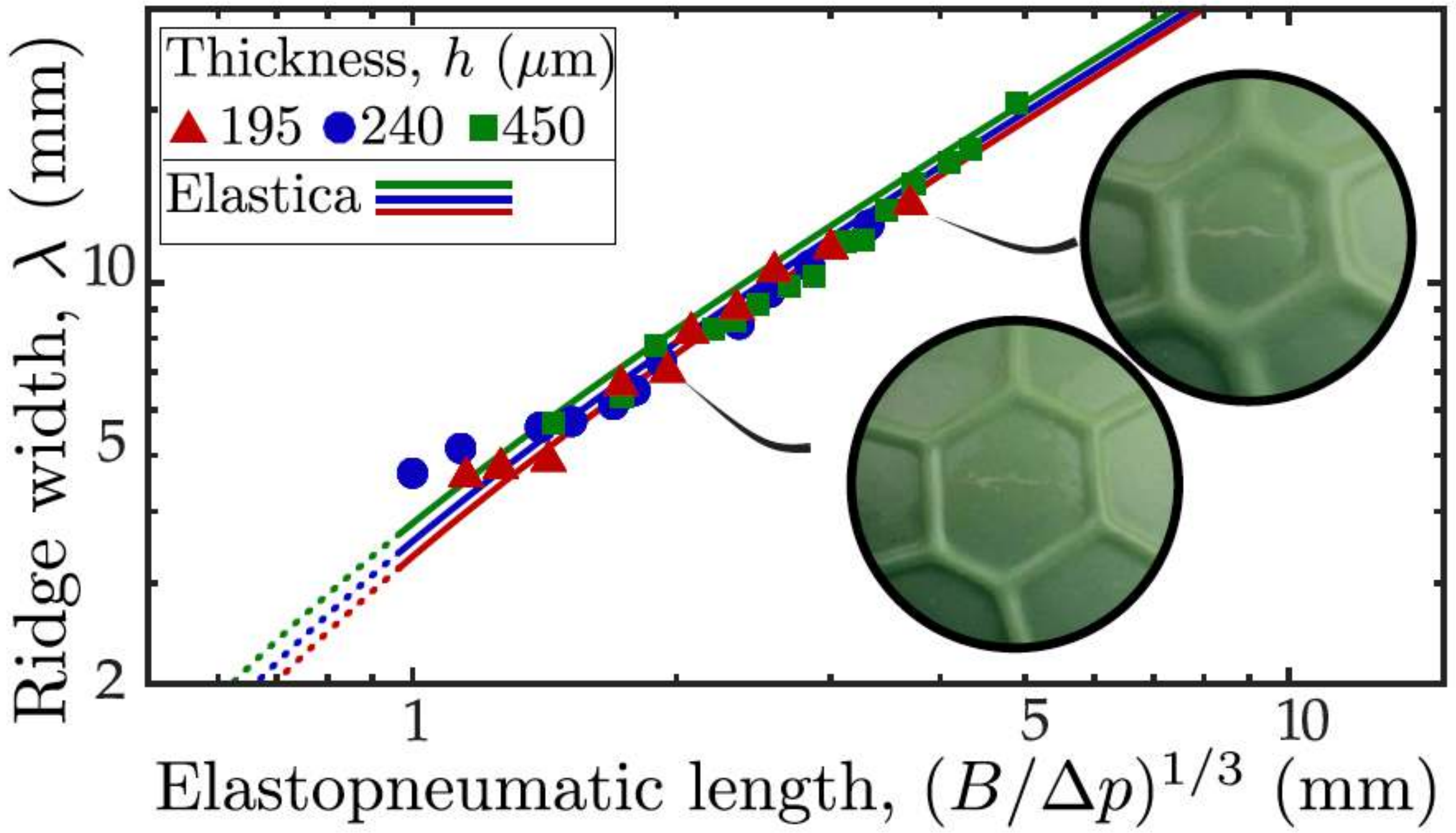


Position set by the previous dimples

Topological defects on the hemisphere

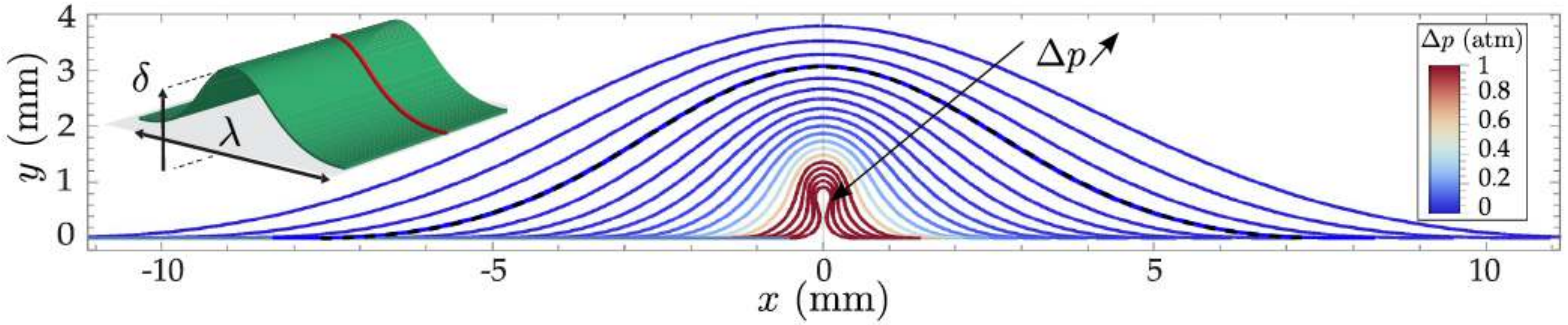
Control of the sharpness of the ridges



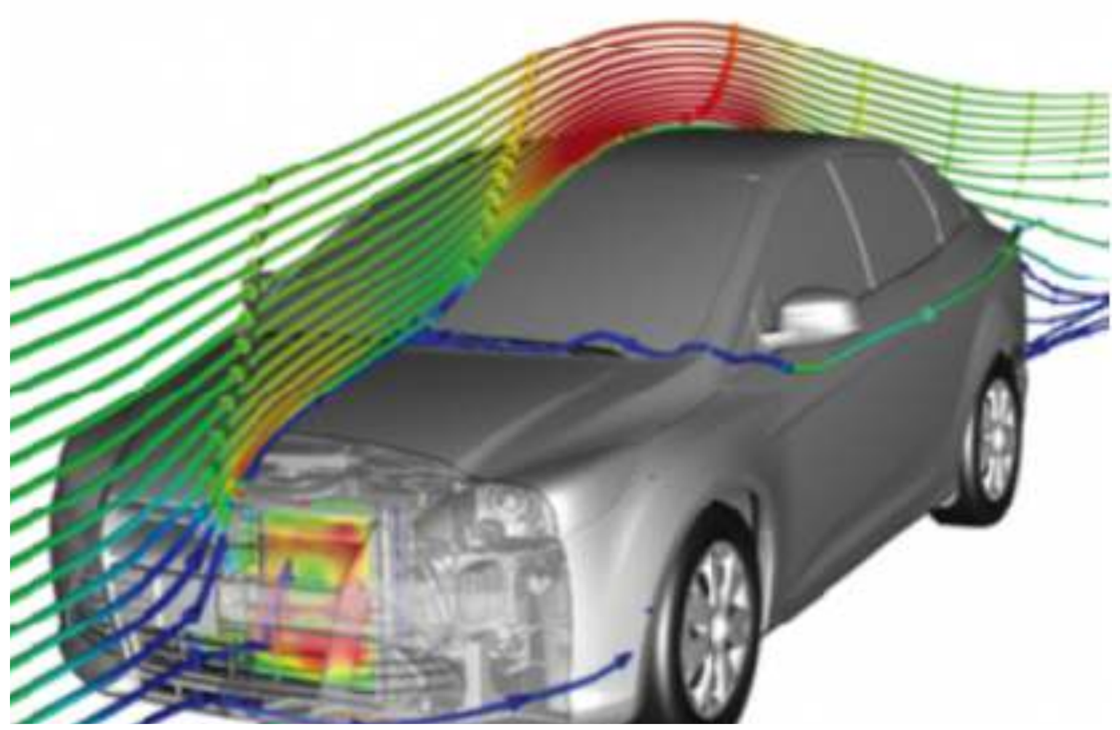


Elastopneumatic length:
Set by the interplay between elasticity and pressure
where $B = Eh^3/12(1-\nu^2)$

Elastica with pressure

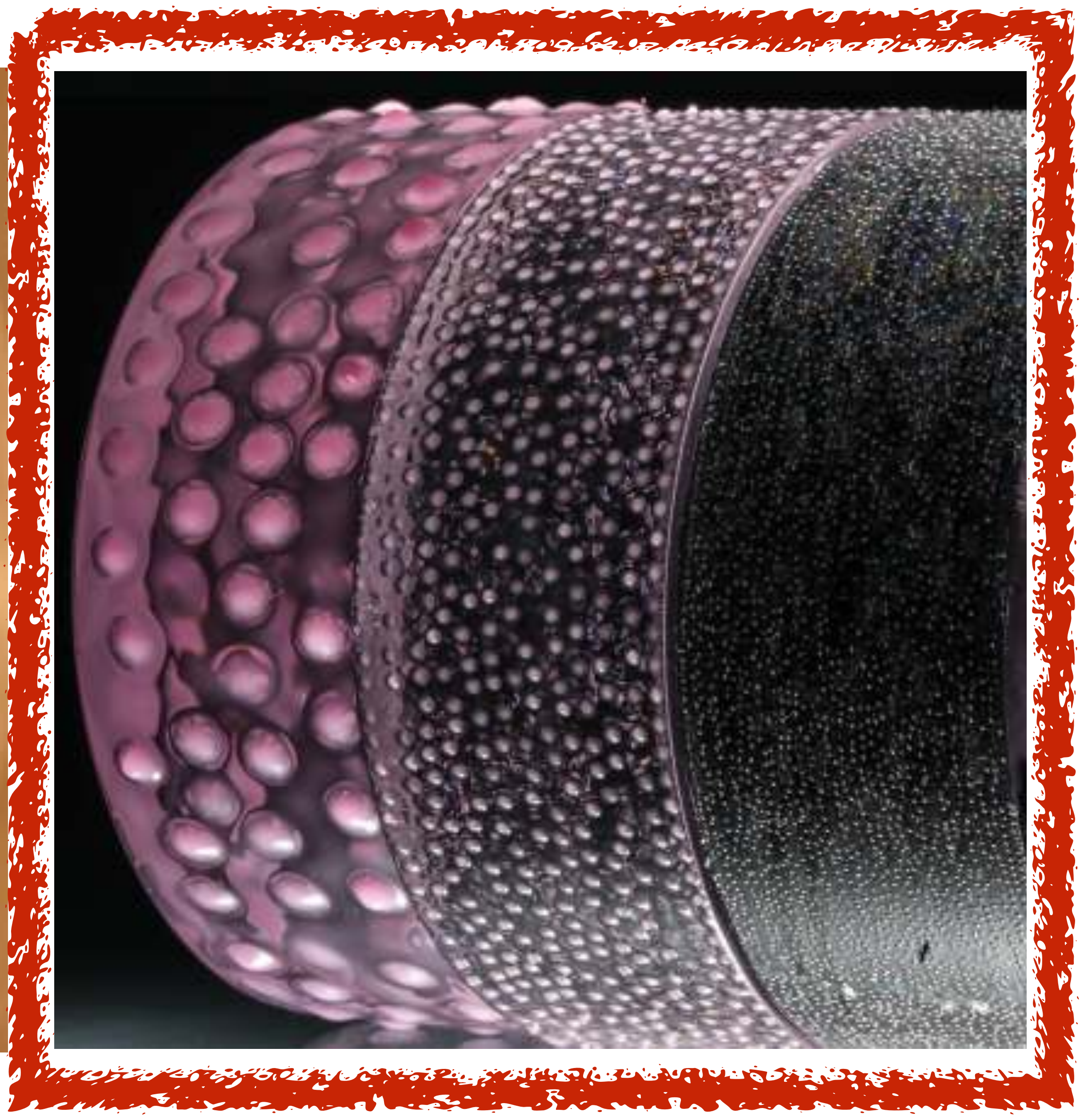


Control roughness: aerodynamic drag reduction



[Phys Rev Mat, 2017]

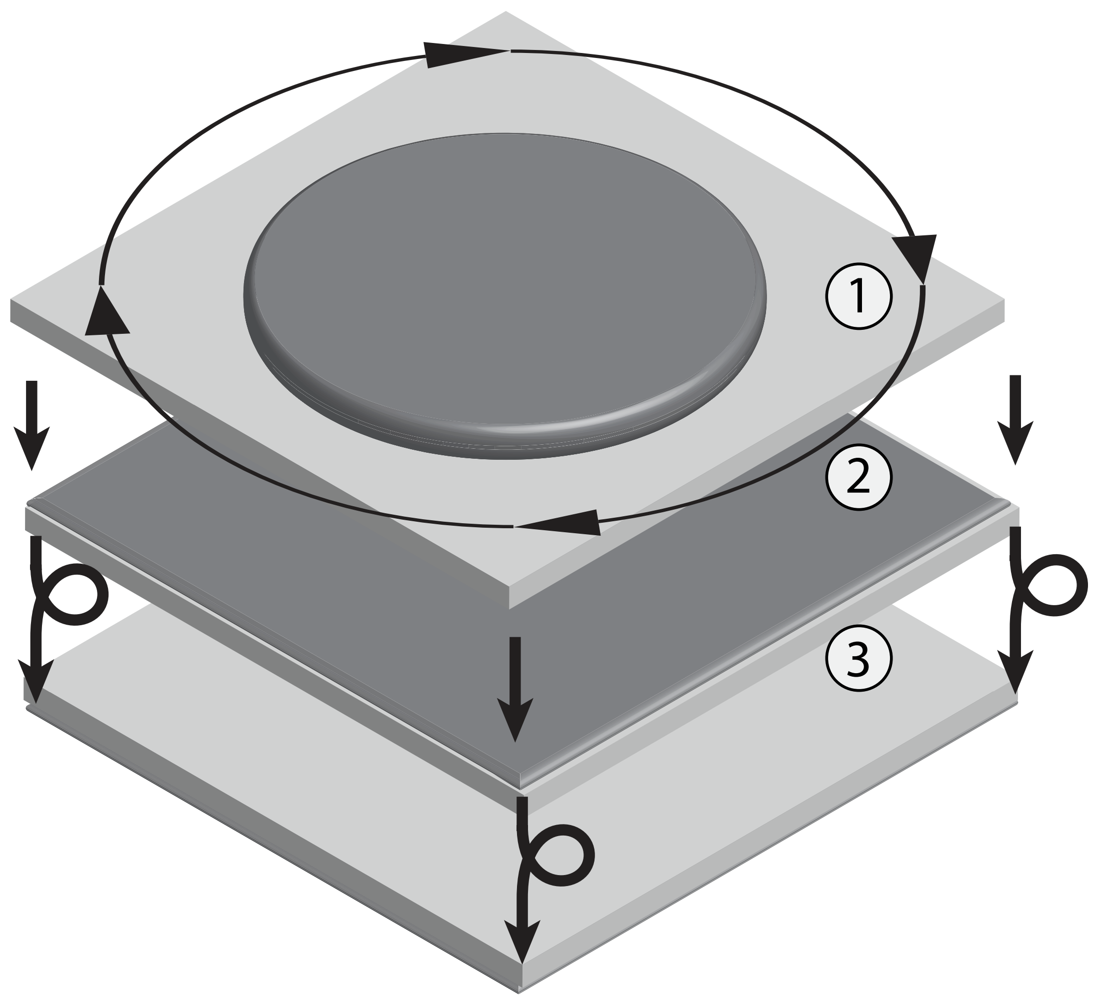
Morphing soft structures with instabilities



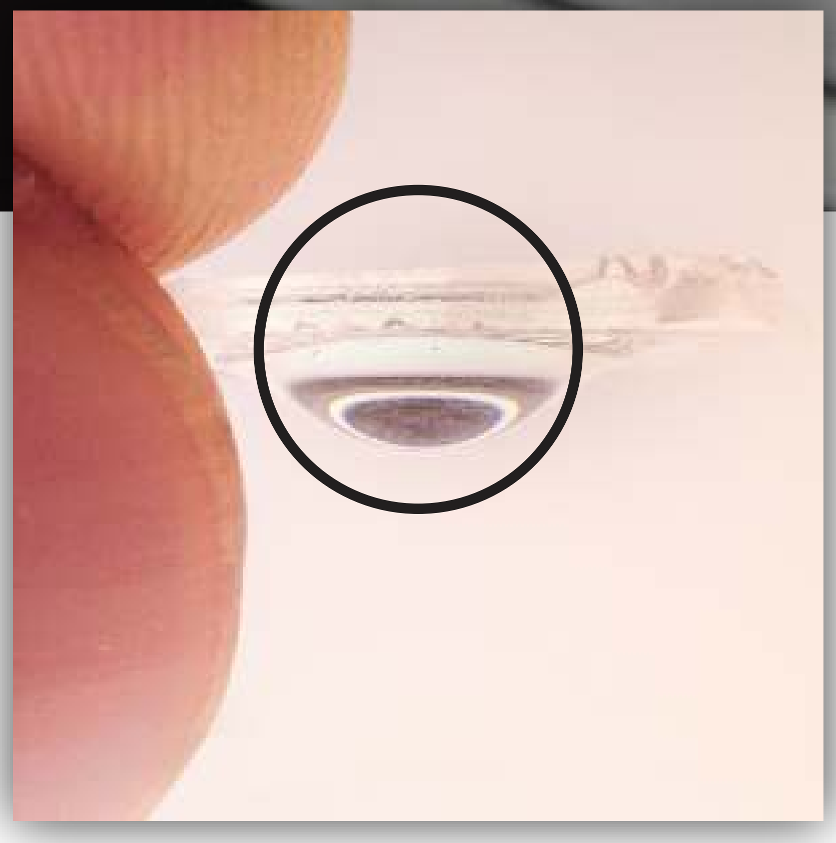
1. Chocolate egg problem/buckling
2. Rayleigh-Taylor instability
3. Rayleigh-Plateau instability
4. Bioinspired soft inflatable structures

with PT Brun (Princeton)

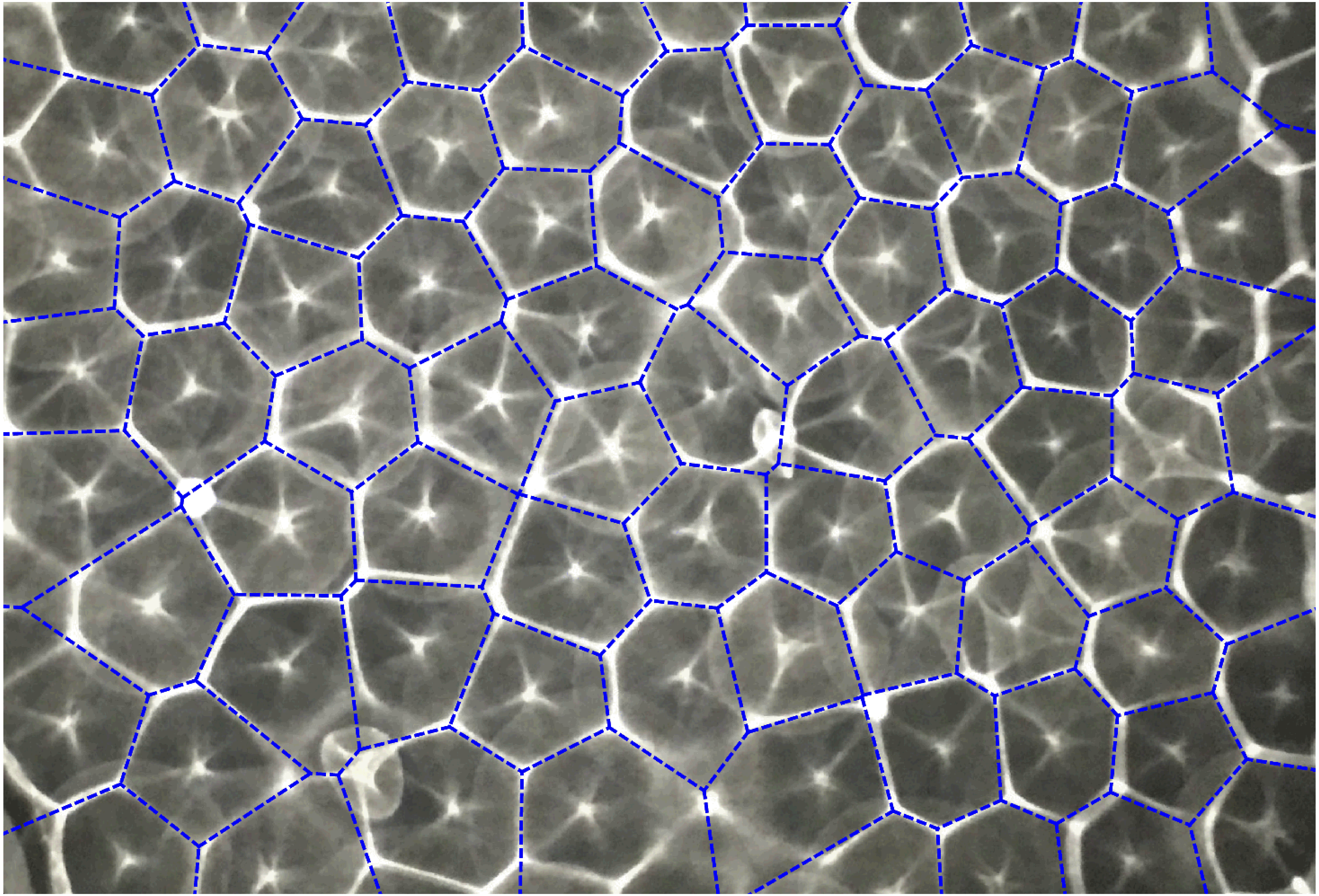
Elastic structures mediated by RTI



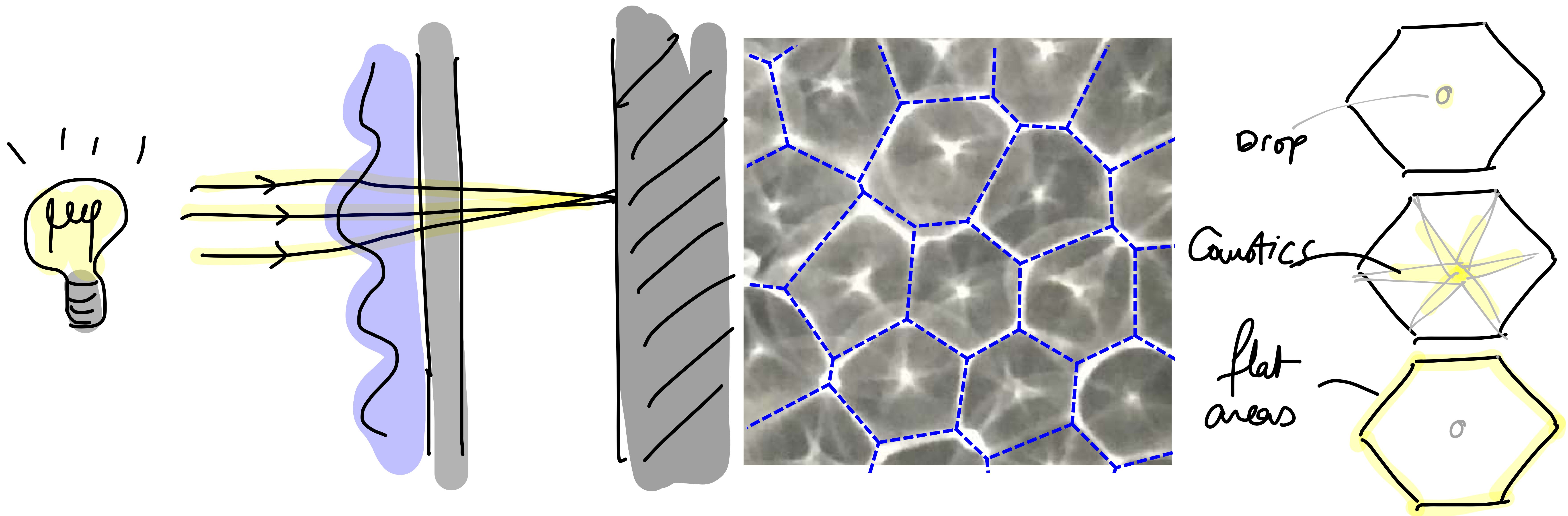
1. Drop lattice
2. Shape
3. Size

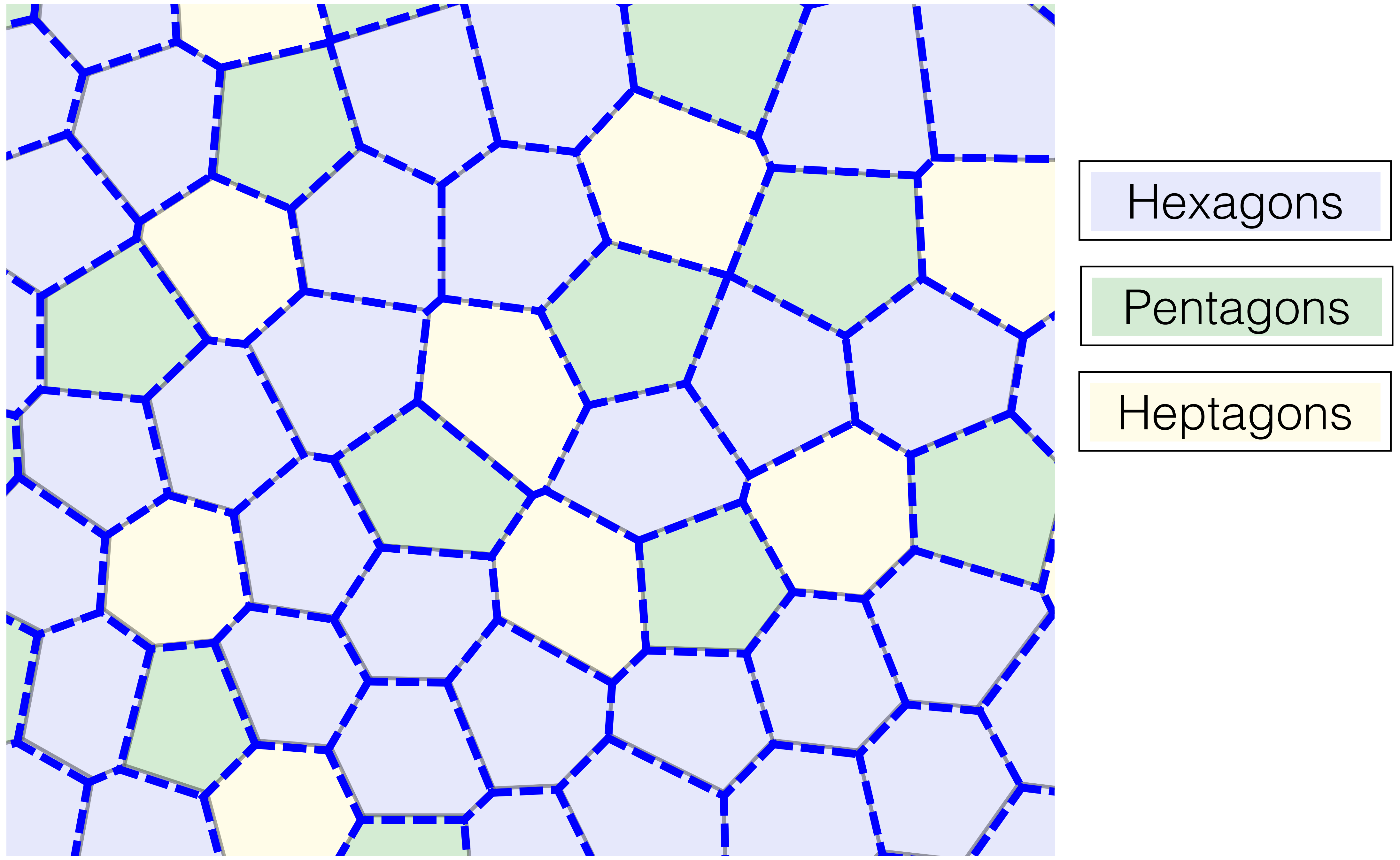


Drop arrangement

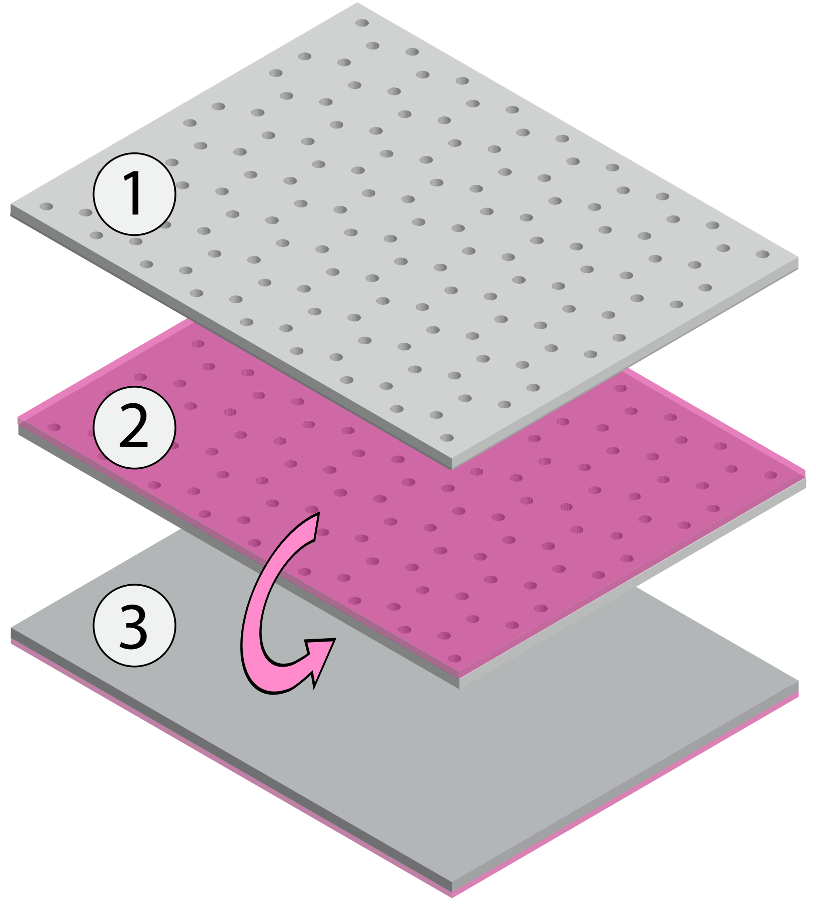


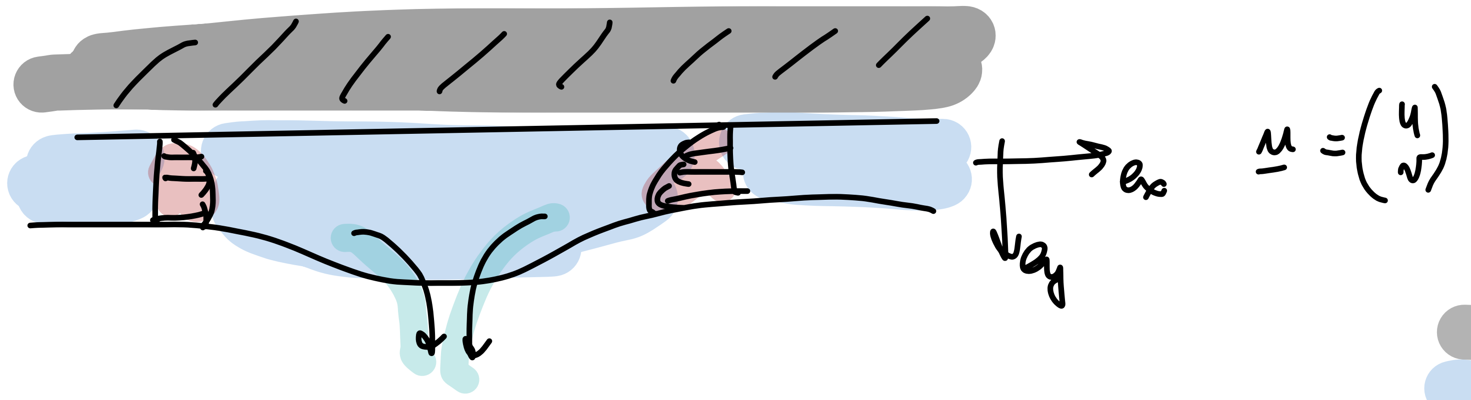
Drop arrangement

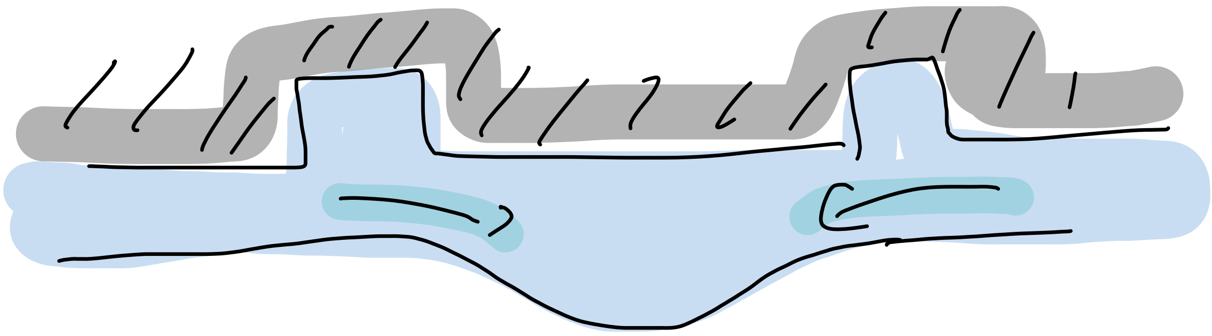




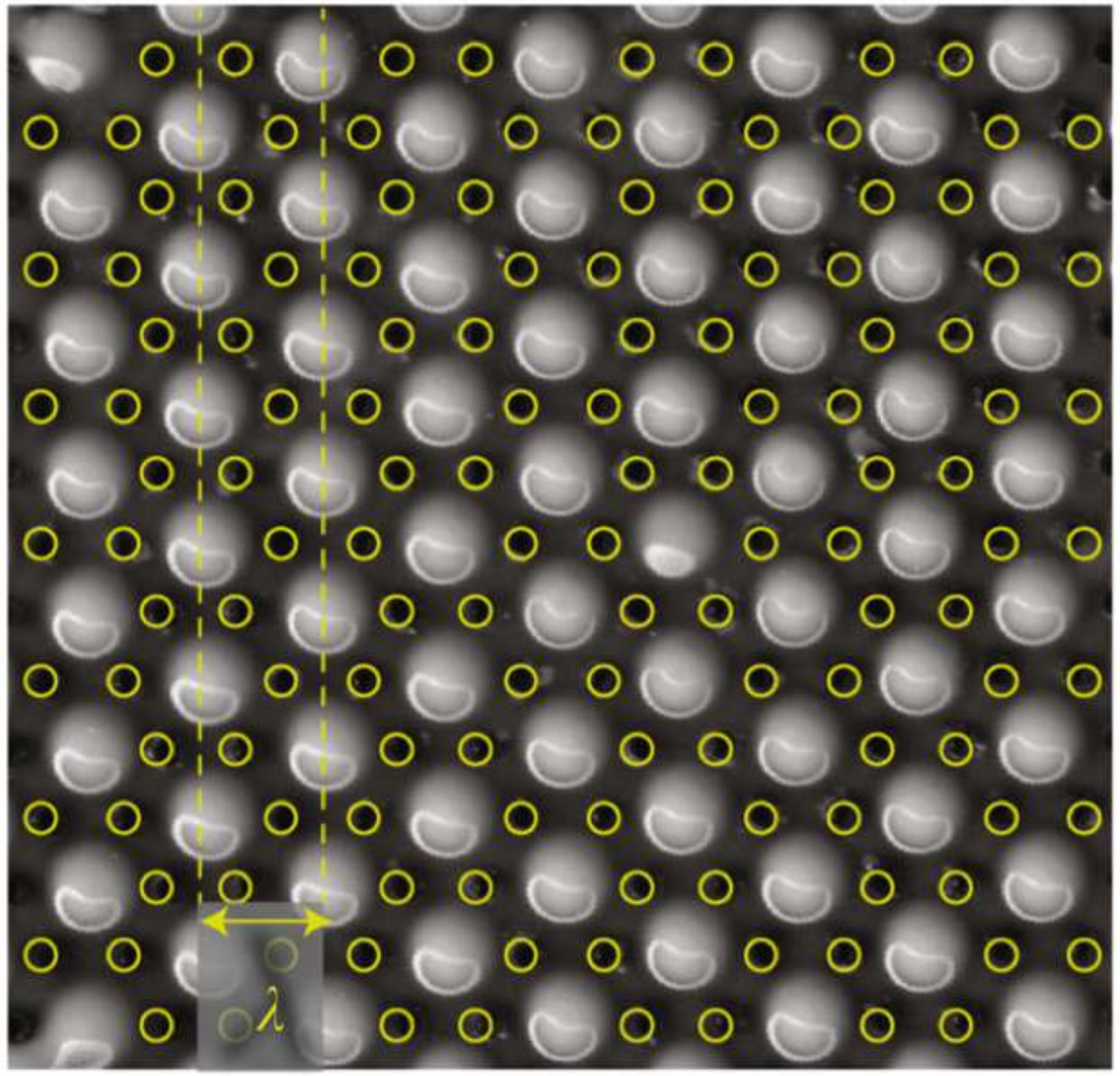
Control of the drop lattice

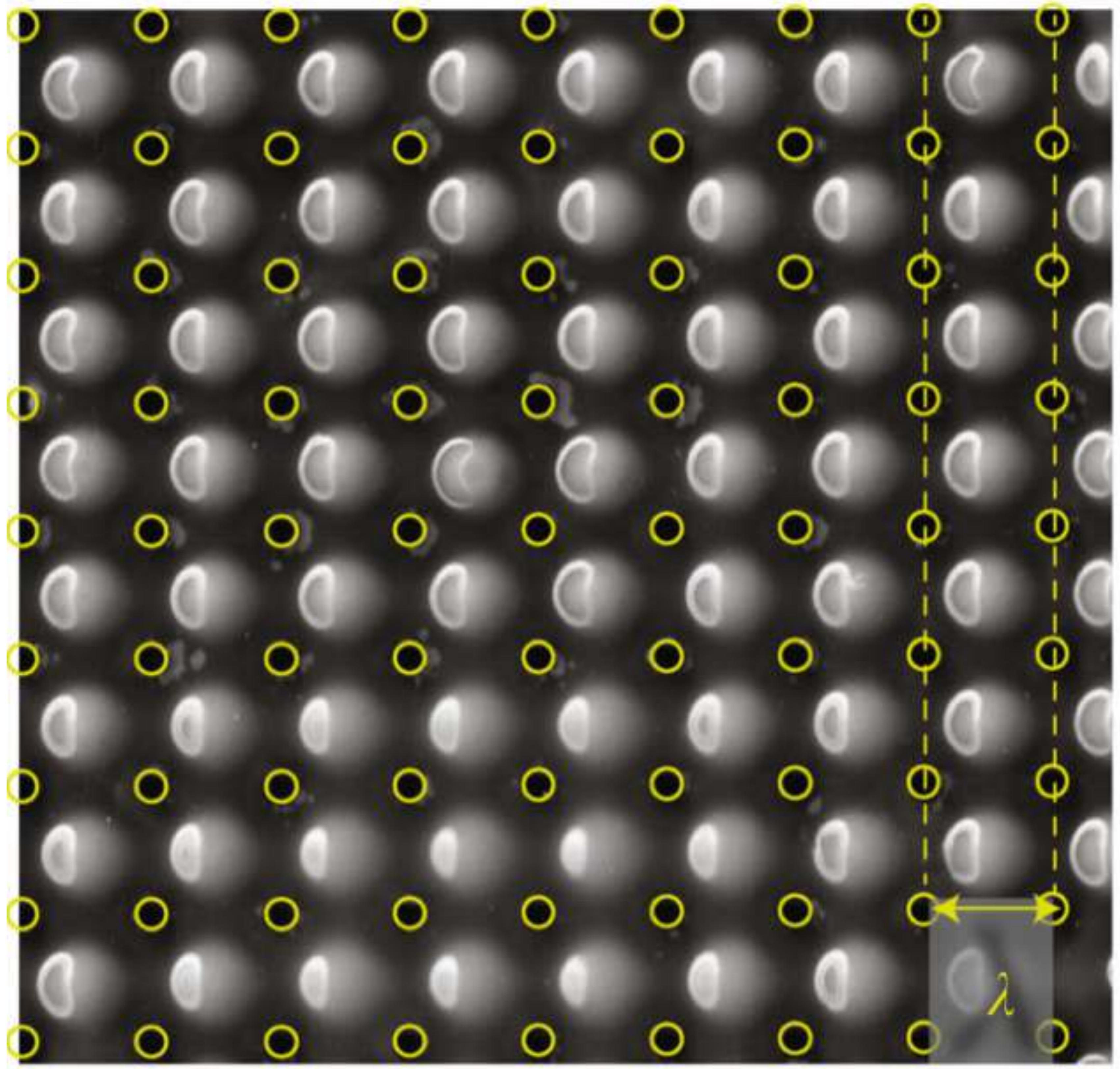






$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad \frac{u}{\lambda} \sim \frac{v}{h} \qquad \Rightarrow v = \frac{h}{\lambda} u \ll u$$

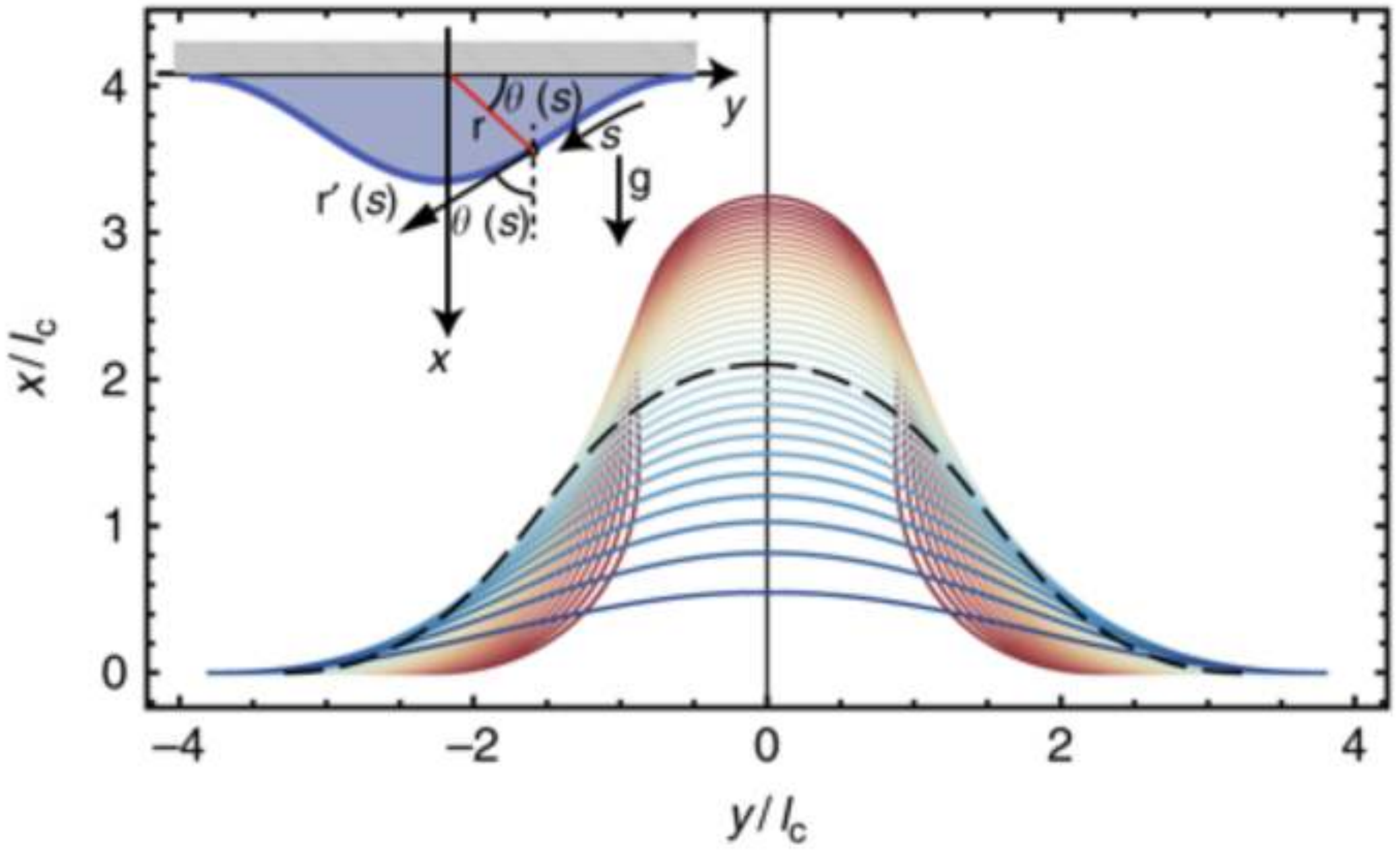


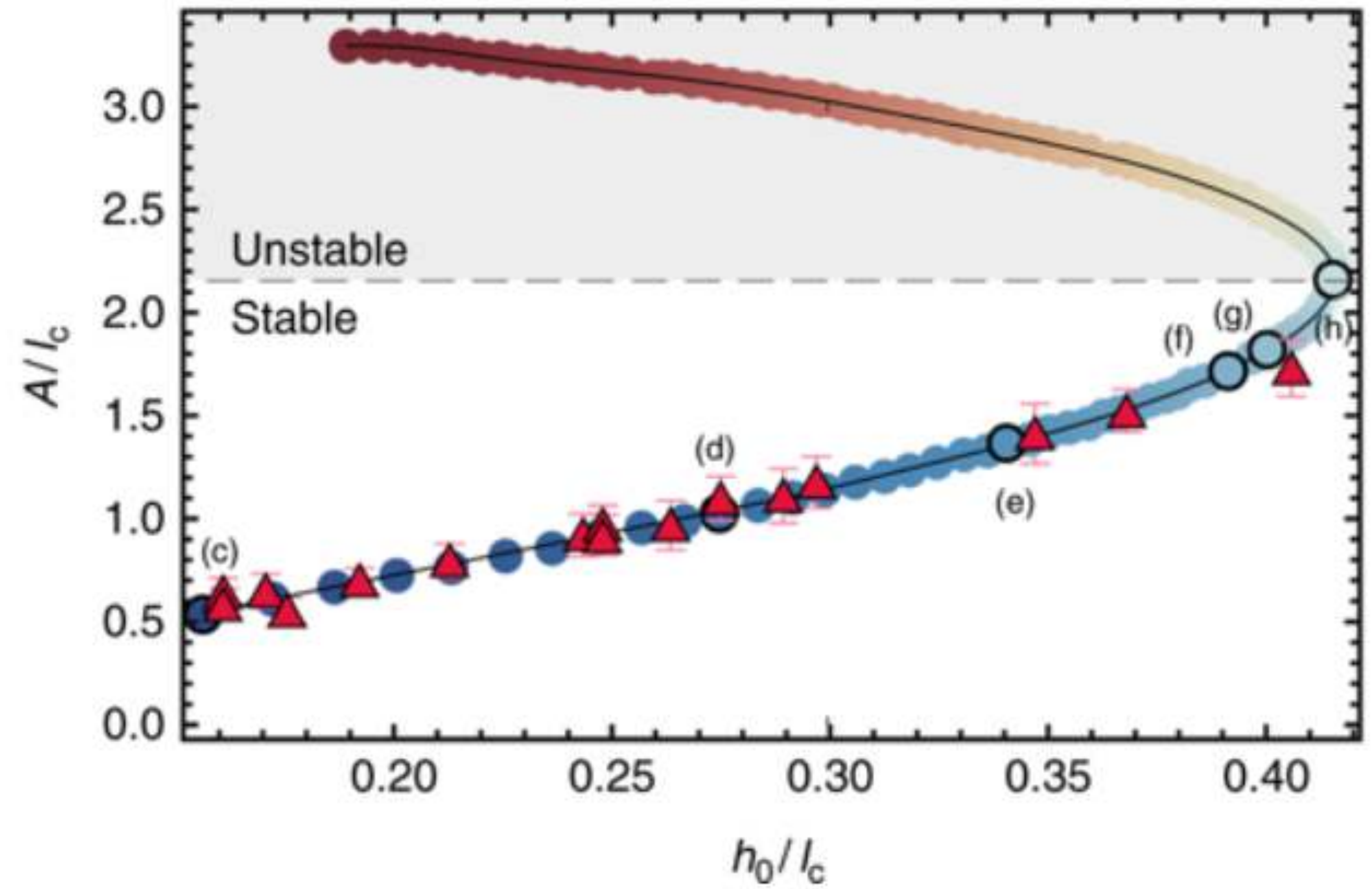


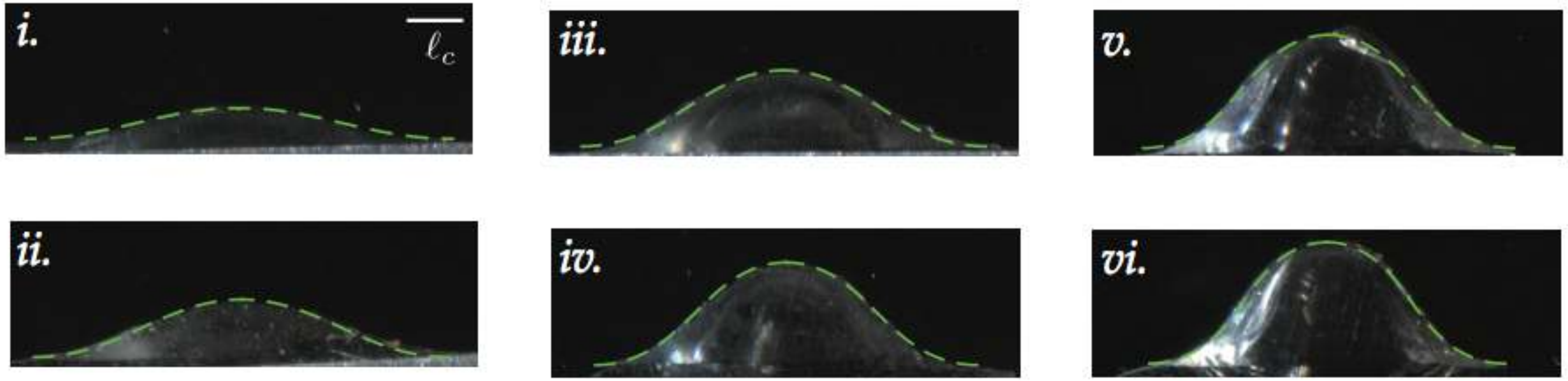
<u>*Control of the shapes*</u>

<u>*Separation of timescales*</u> $\tau_i << \tau_c$

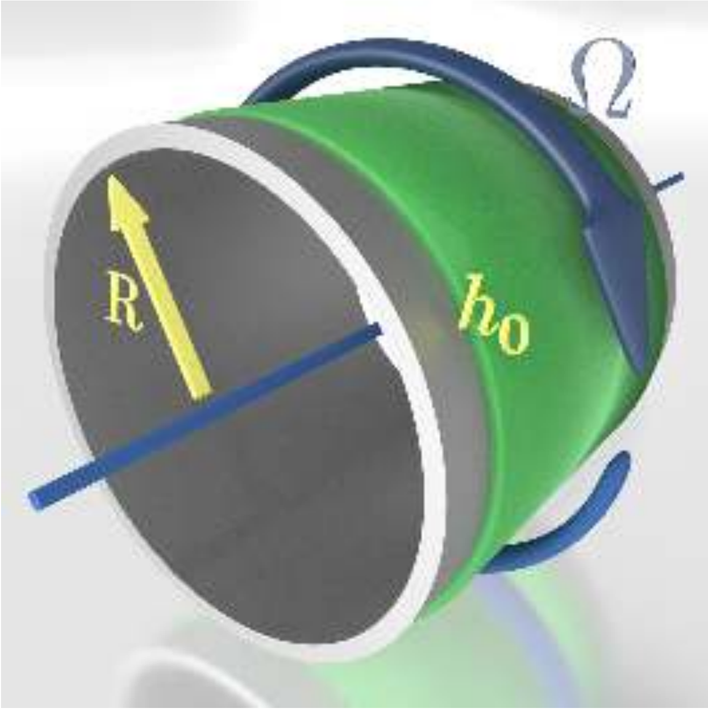
$$\theta''(s) = -\ell_c^{-2}\cos\theta(s) + \left(\frac{\cos\theta(s)}{y(s)}\right)'$$

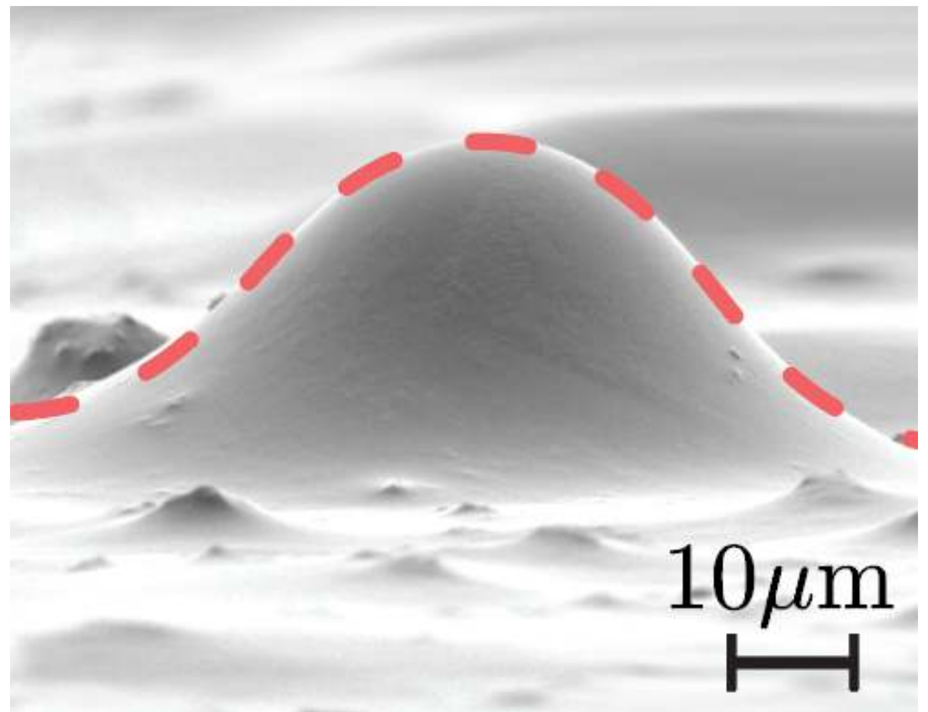


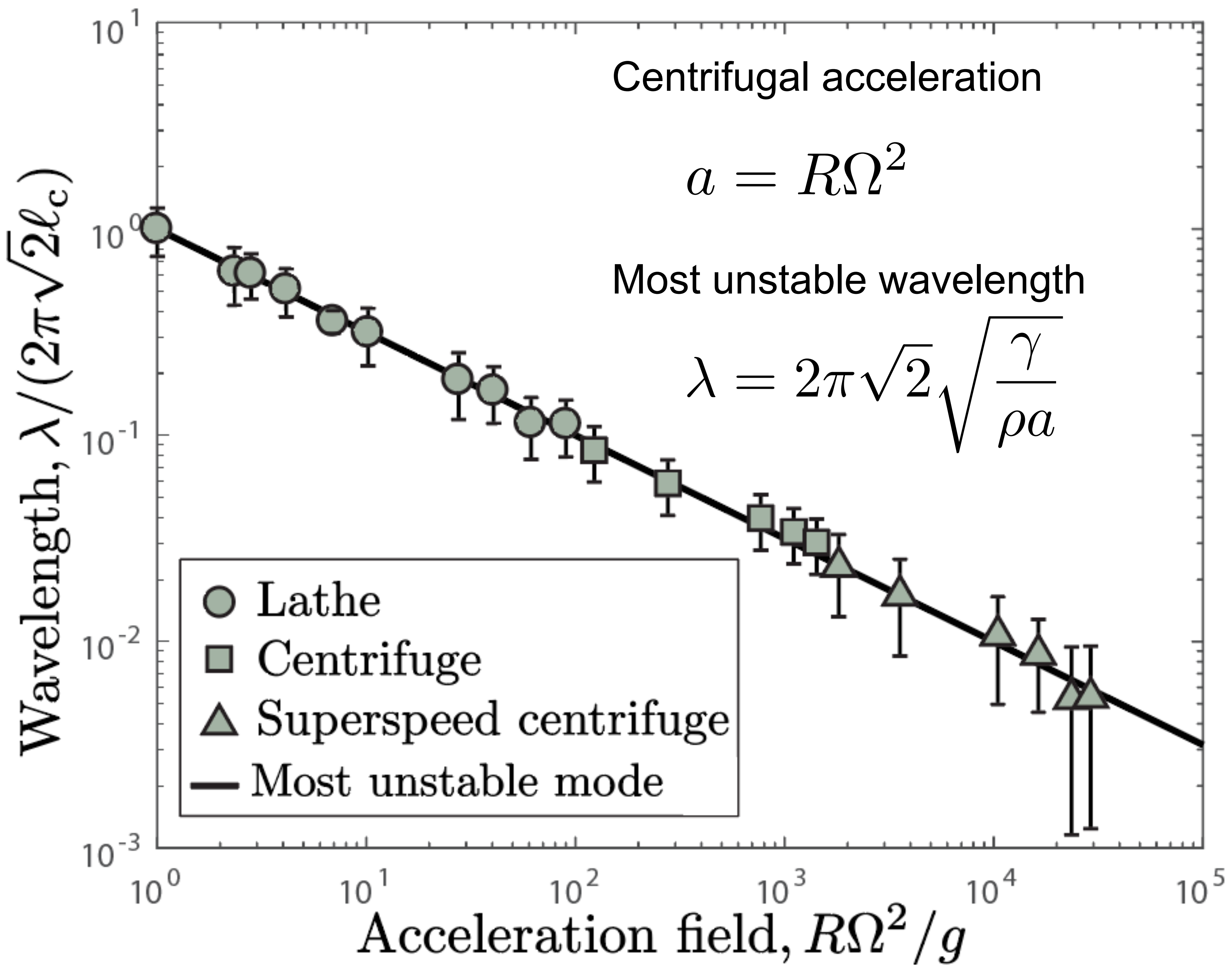


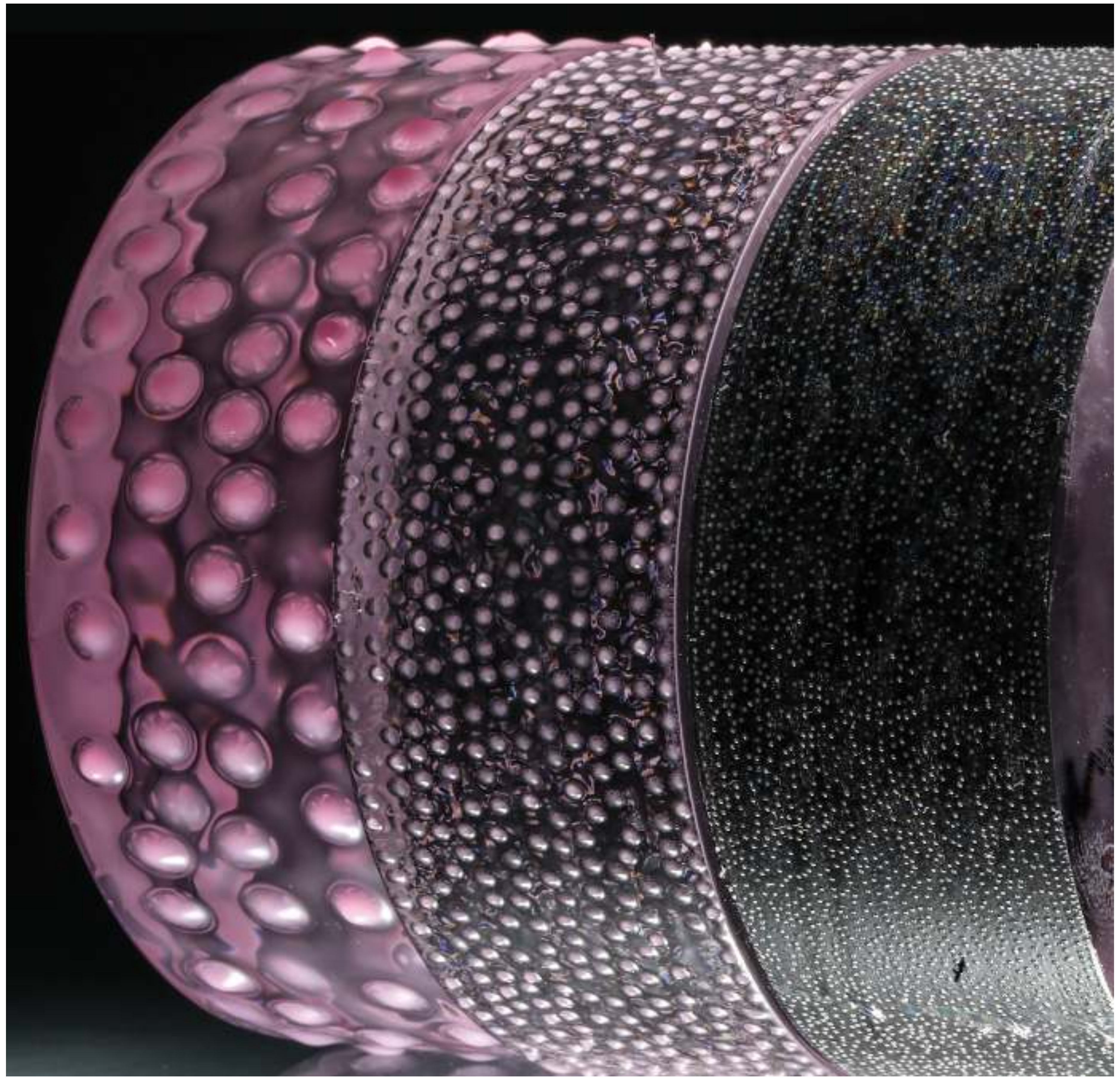


Control of the sizes

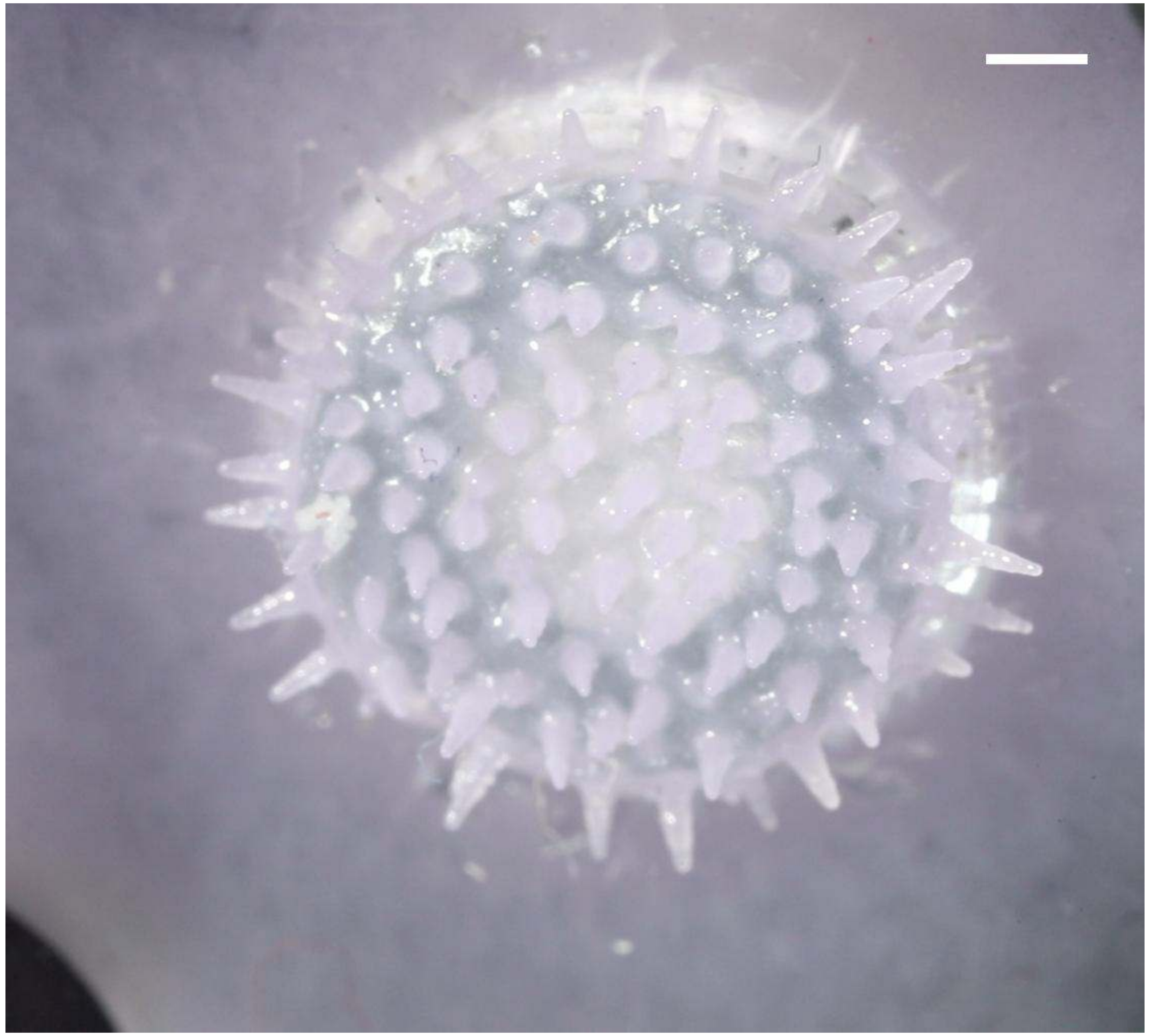




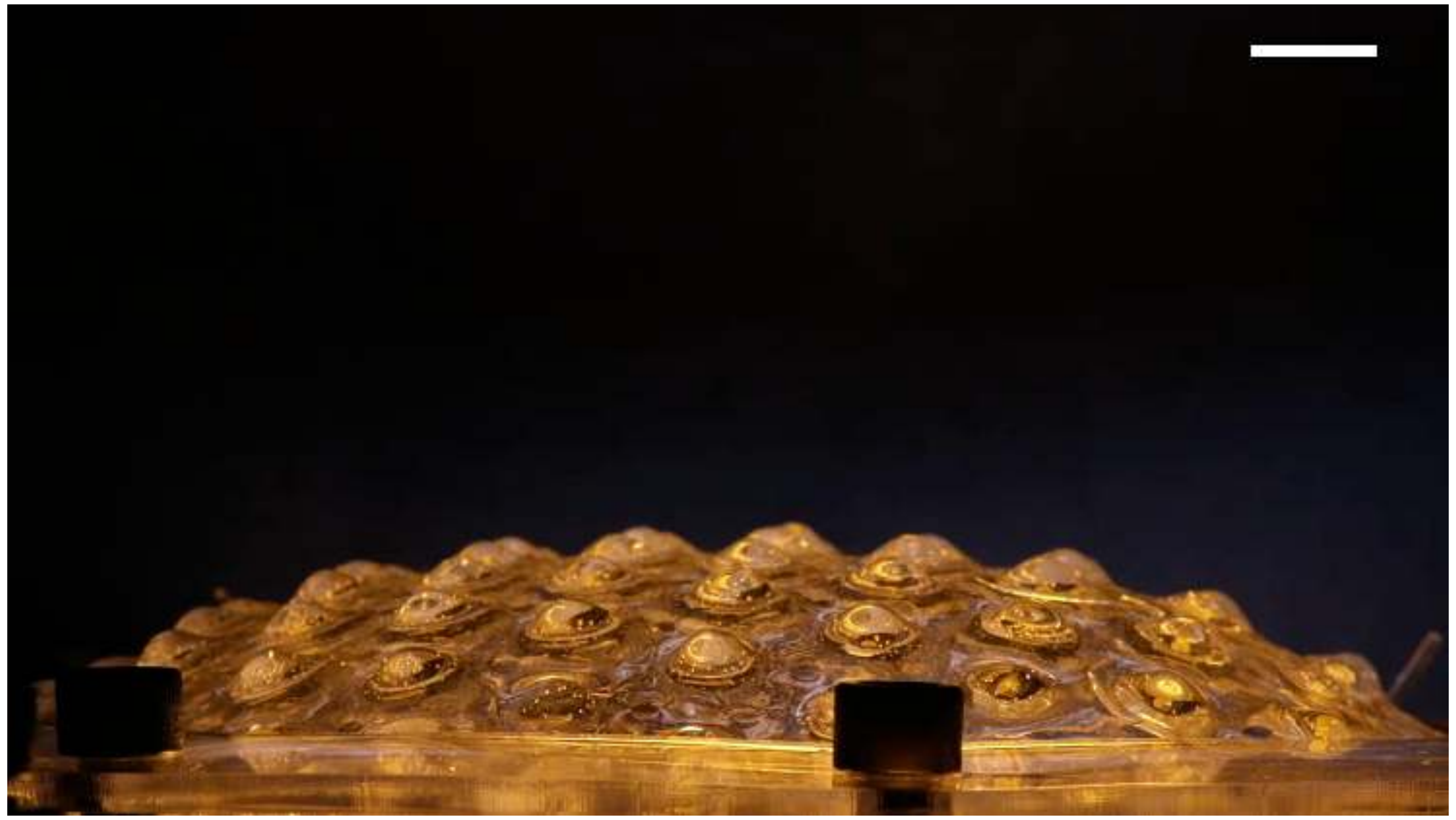




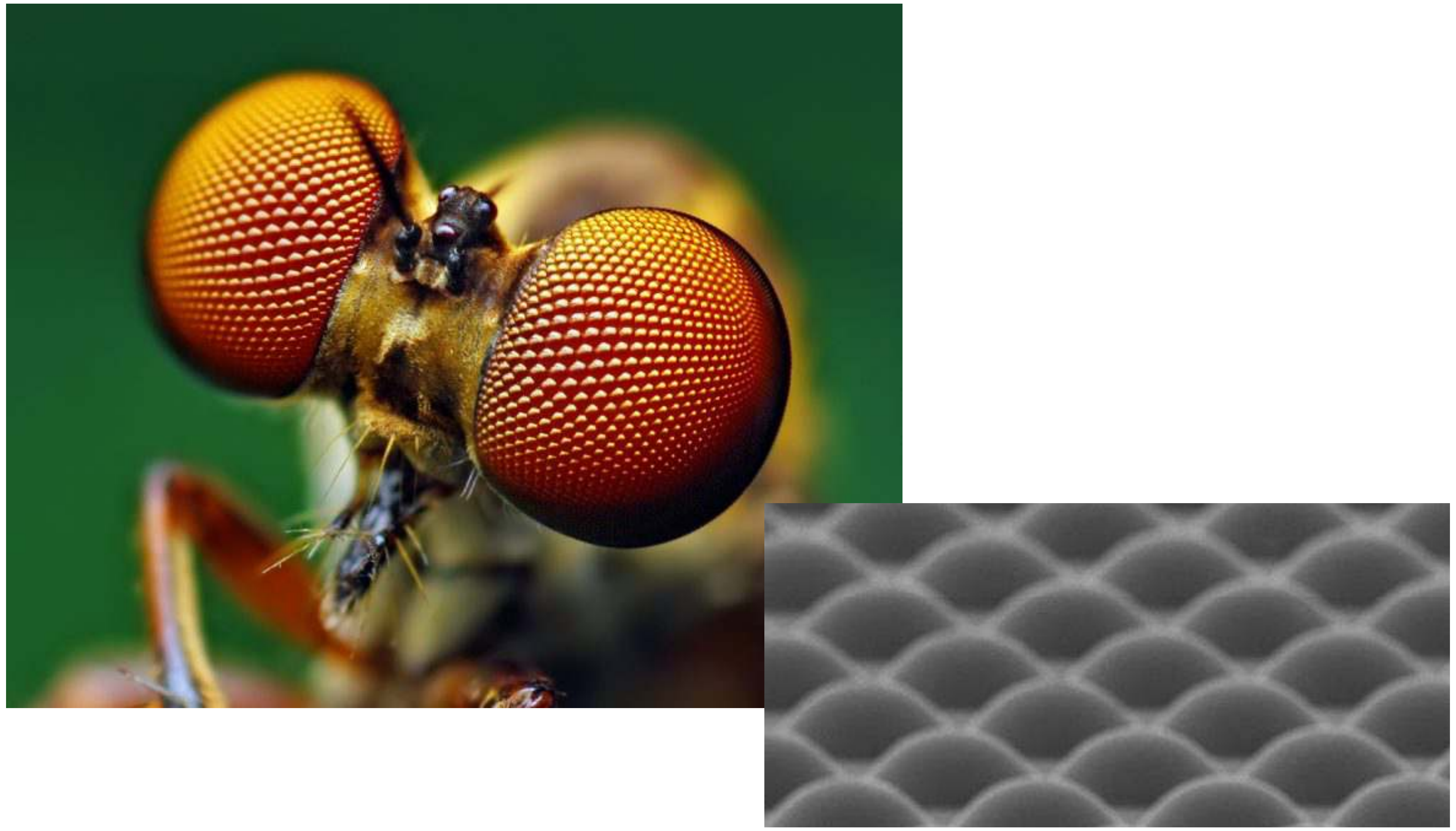
Reversible actuation of the elastic structures



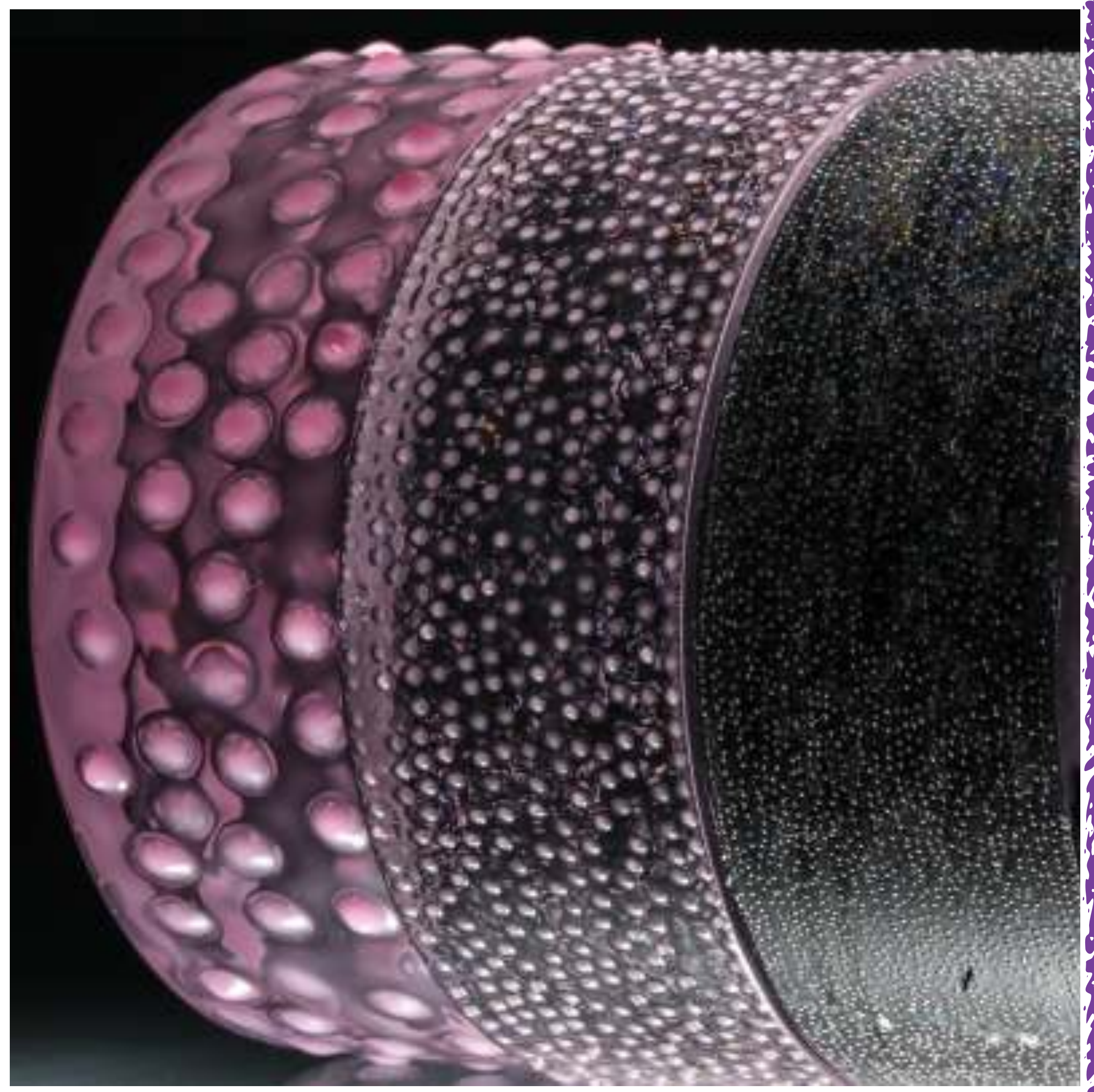
[Nature Com 2018]

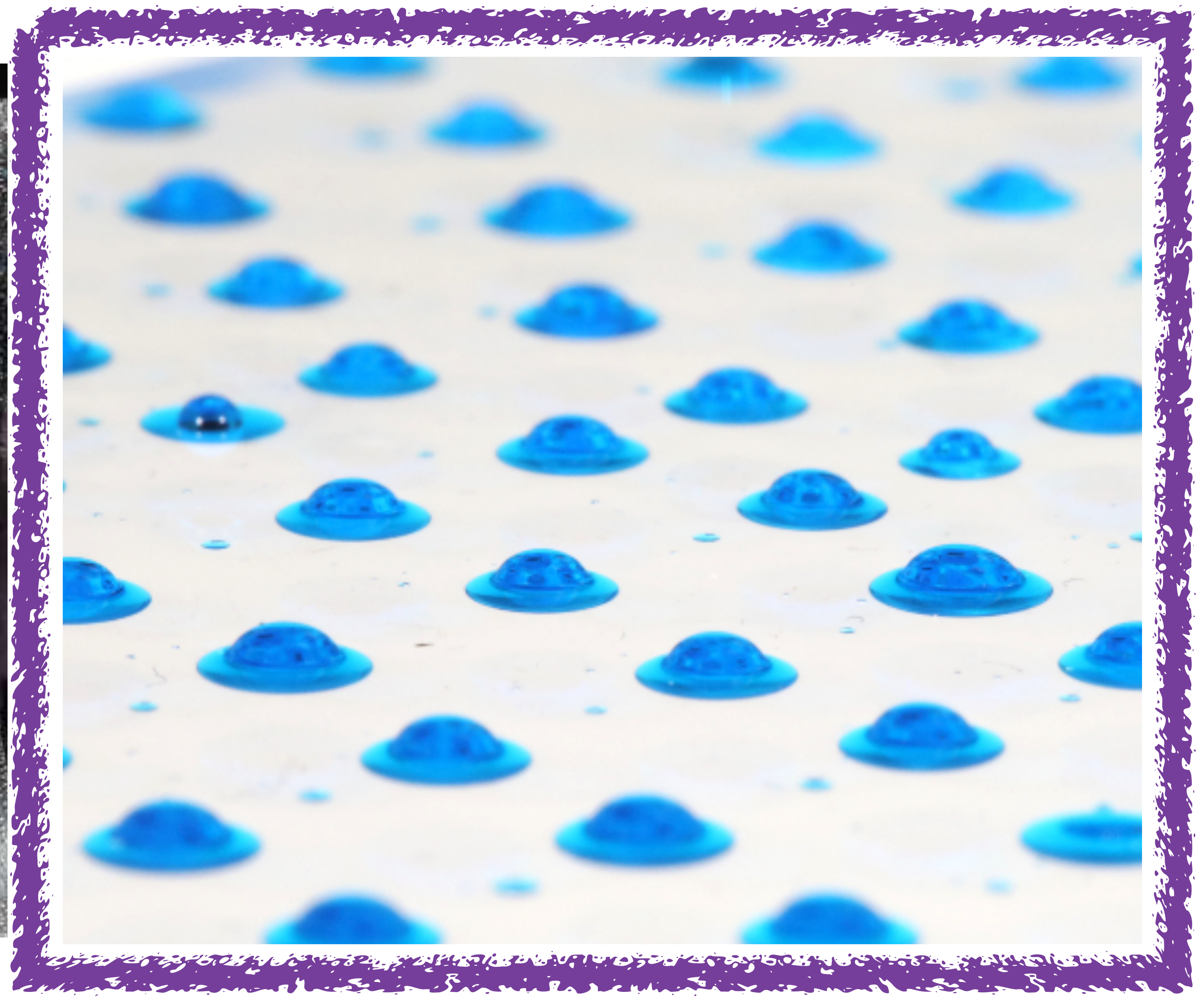


Towards the mass production of micro lenses array



Morphing soft structures with instabilities



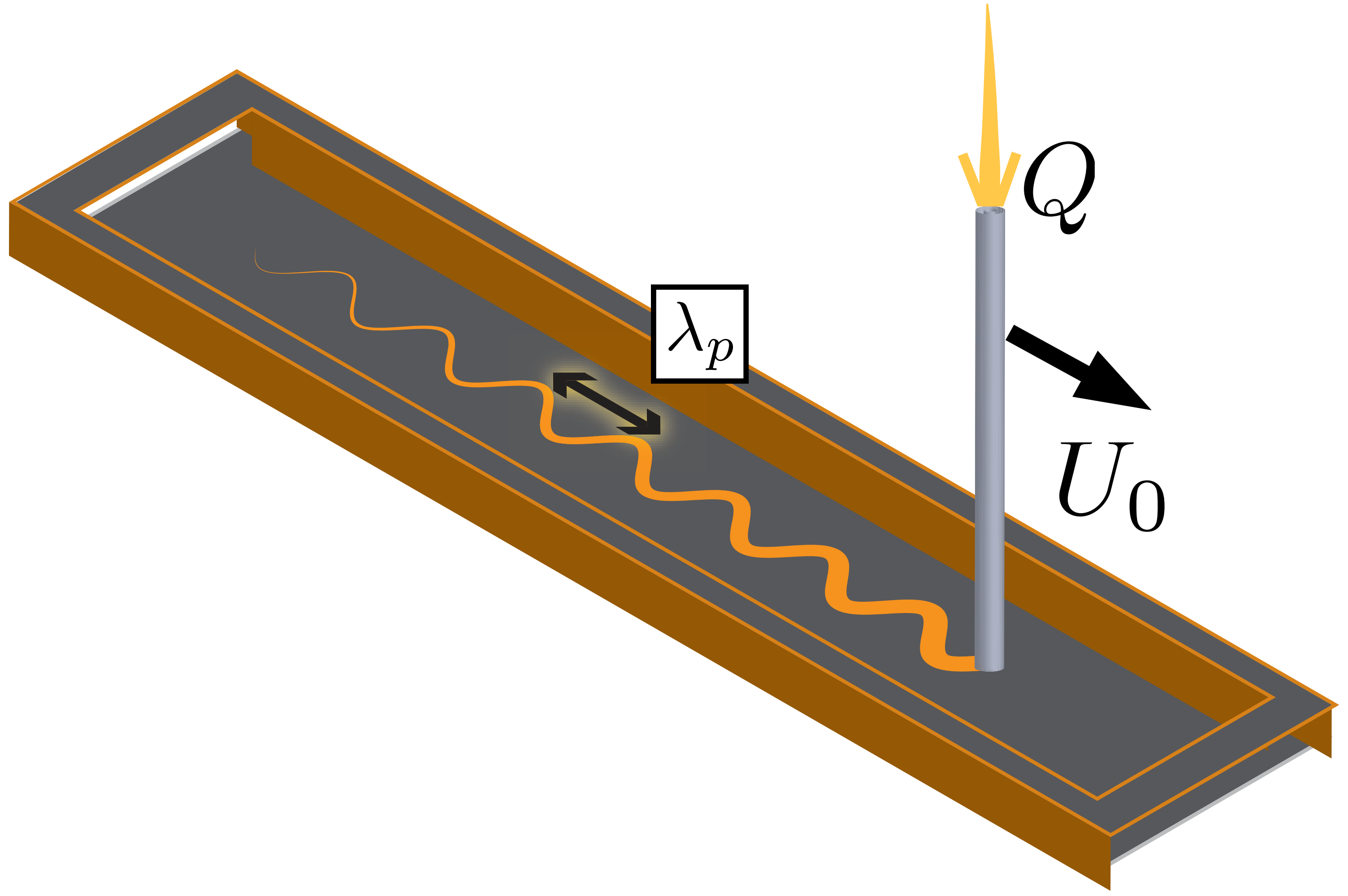


1. Chocolate egg problem/buckling
2. Rayleigh-Taylor instability
3. Rayleigh-Plateau instability
4. Bioinspired soft inflatable structures

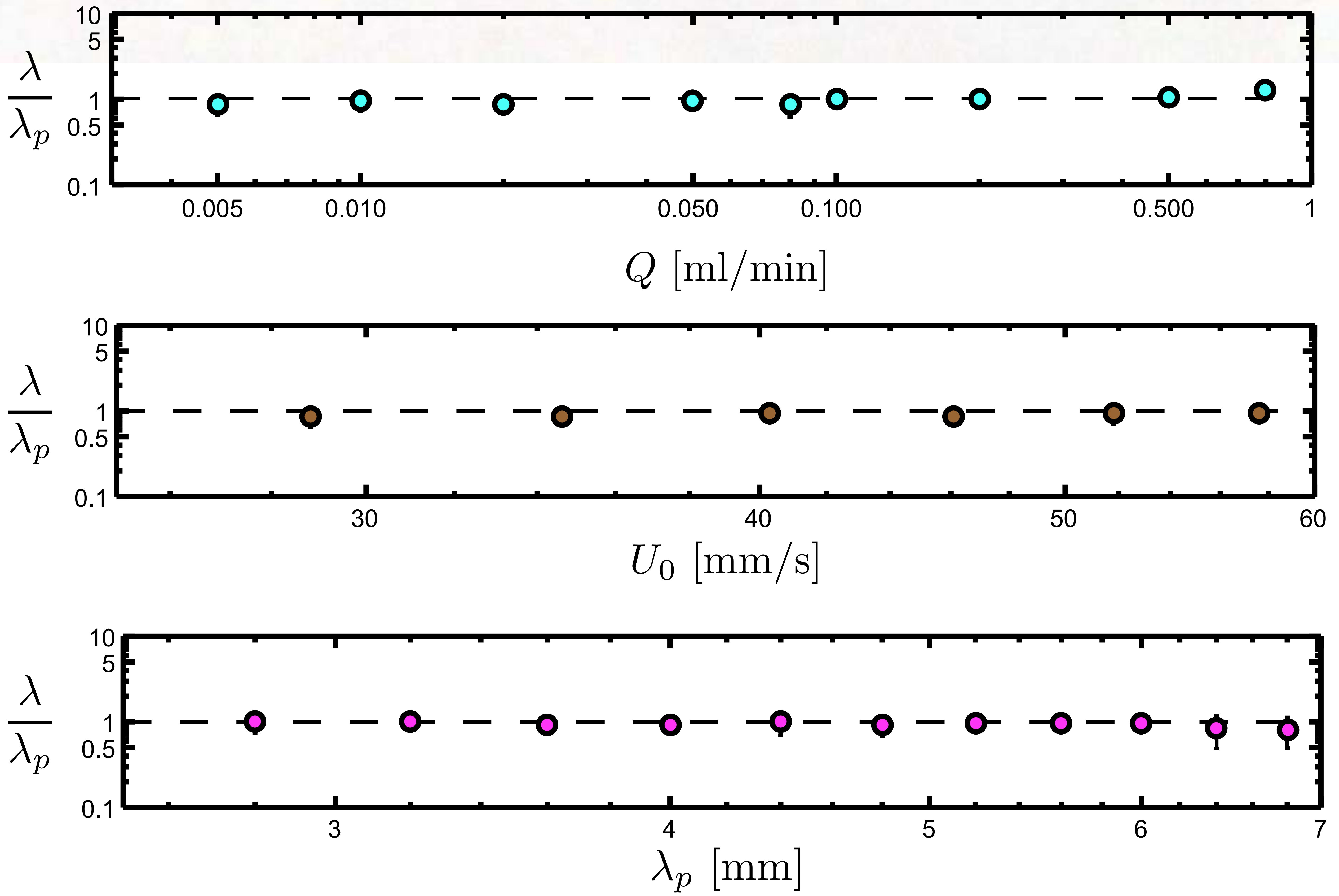
with Lingzhi Cai, PT Brun (Princeton)


Translational stage
Glycerol
Nozzle
Polymer melt (PDMS)

Sine waves

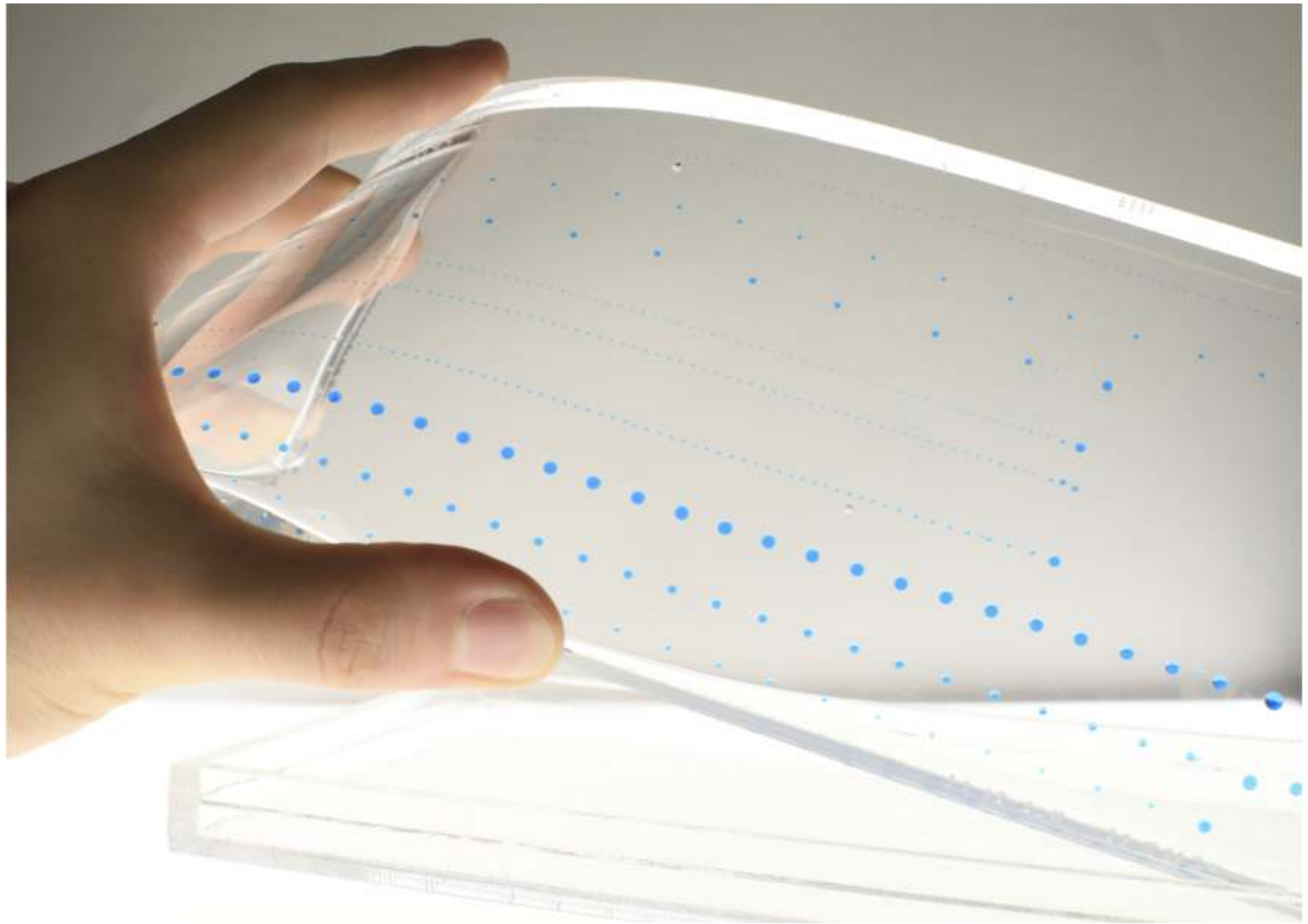


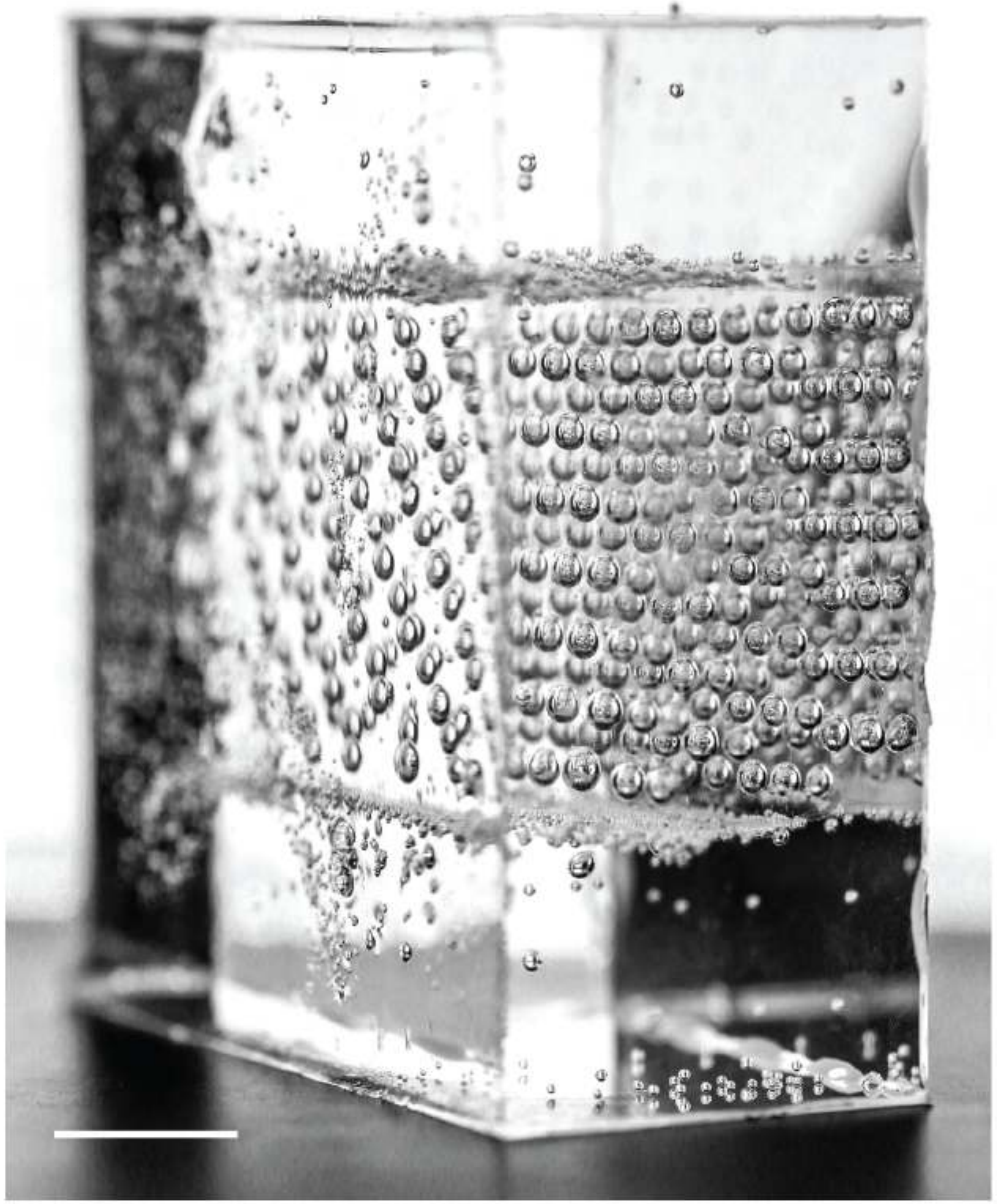
Q
λ_p
U_0



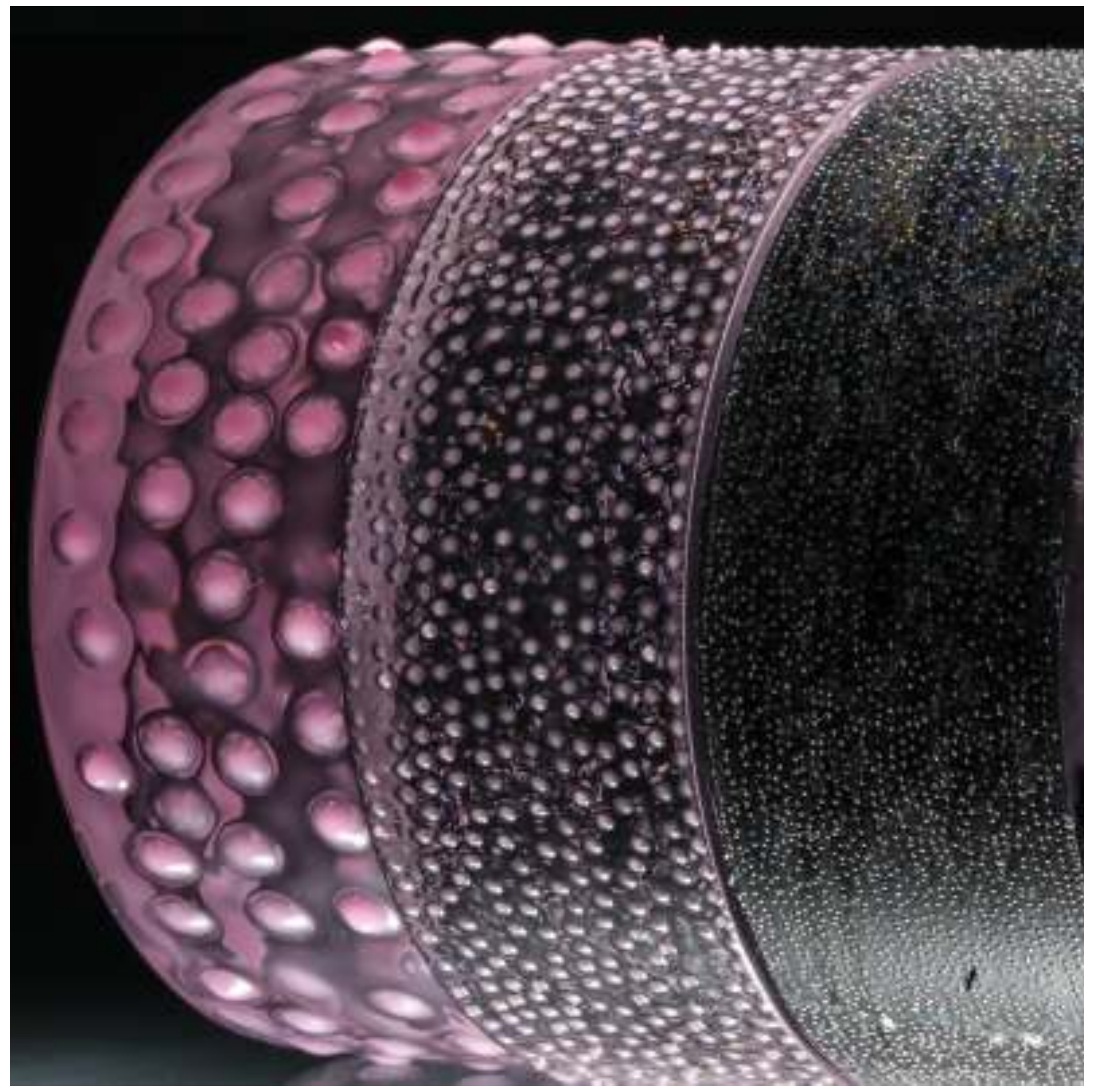
$\frac{\lambda}{\lambda_p}$
10
5
1
0.5
0.1
0.005
0.010
0.050
0.100
0.500
1
Q [ml/min]
U_0 [mm/s]
30
40
50
60
λ_p [mm]
3
4
5
6
7

Curing





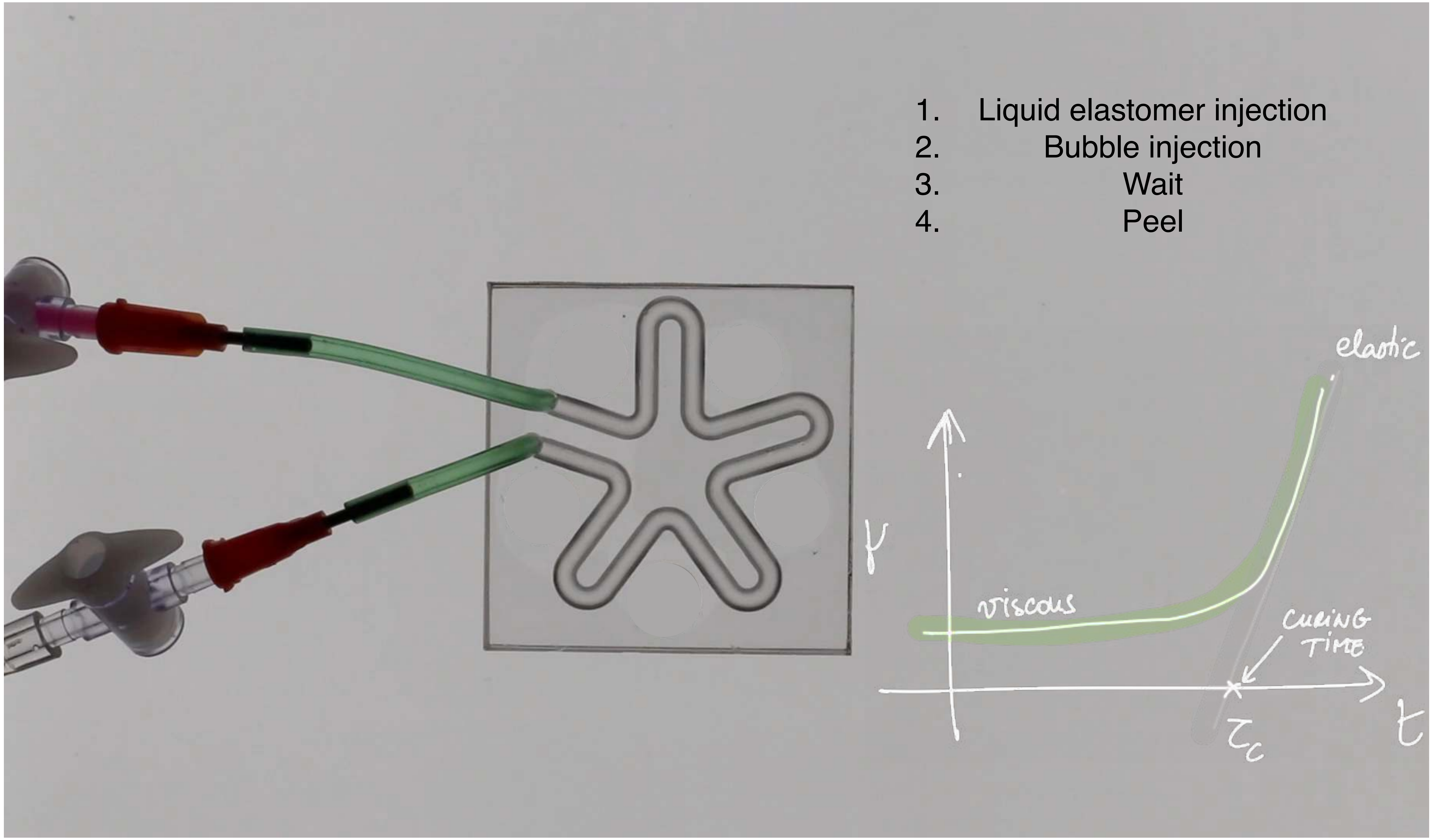
Morphing soft structures with instabilities



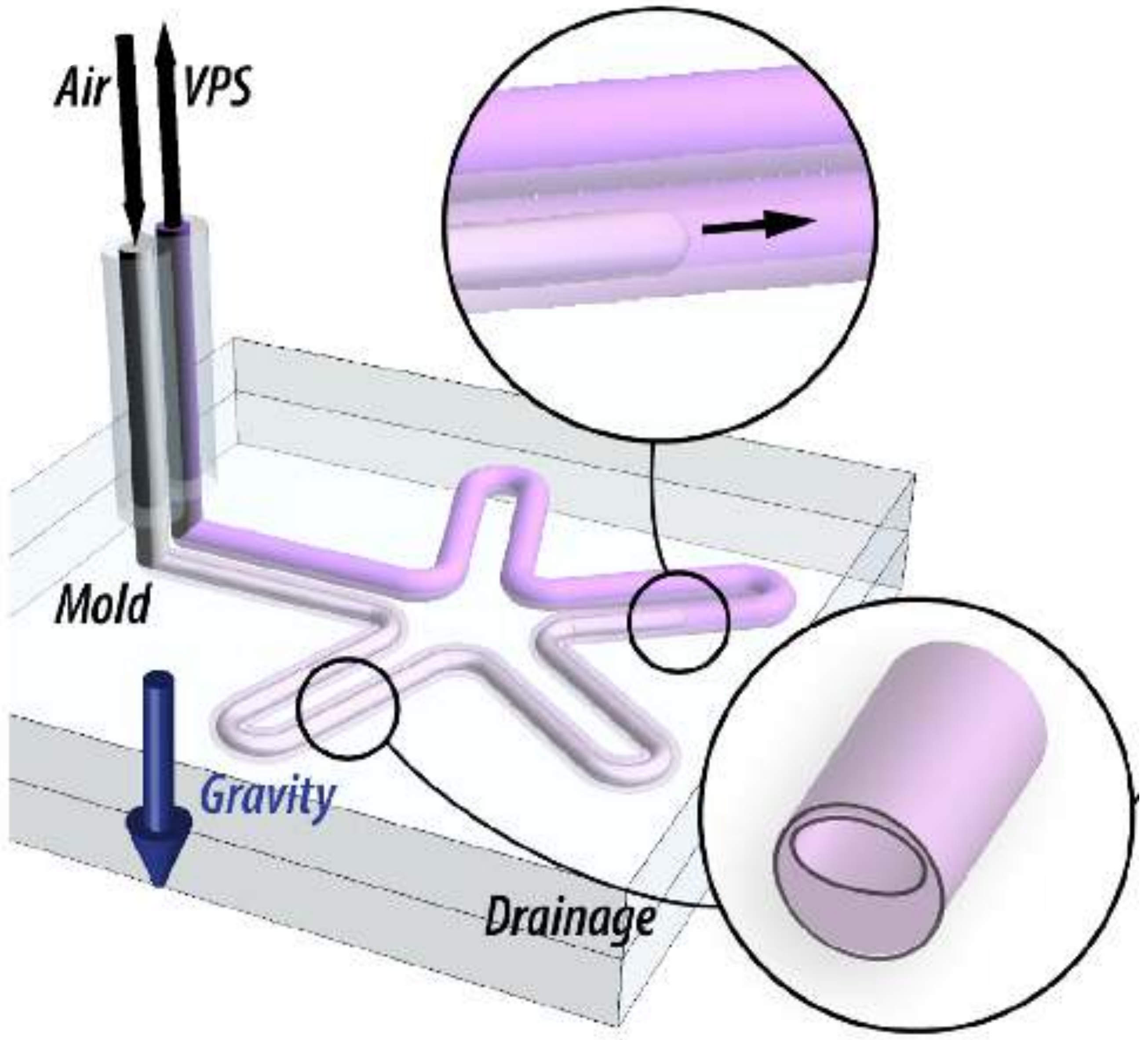
1. Chocolate egg problem/buckling
2. Rayleigh-Taylor instability
3. Rayleigh-Plateau instability
4. Bioinspired soft inflatable structures

with T.J. Jones, E Jambon Puillet, PT Brun (Princeton)

Building asymmetric tubes



Shape of the cross-section



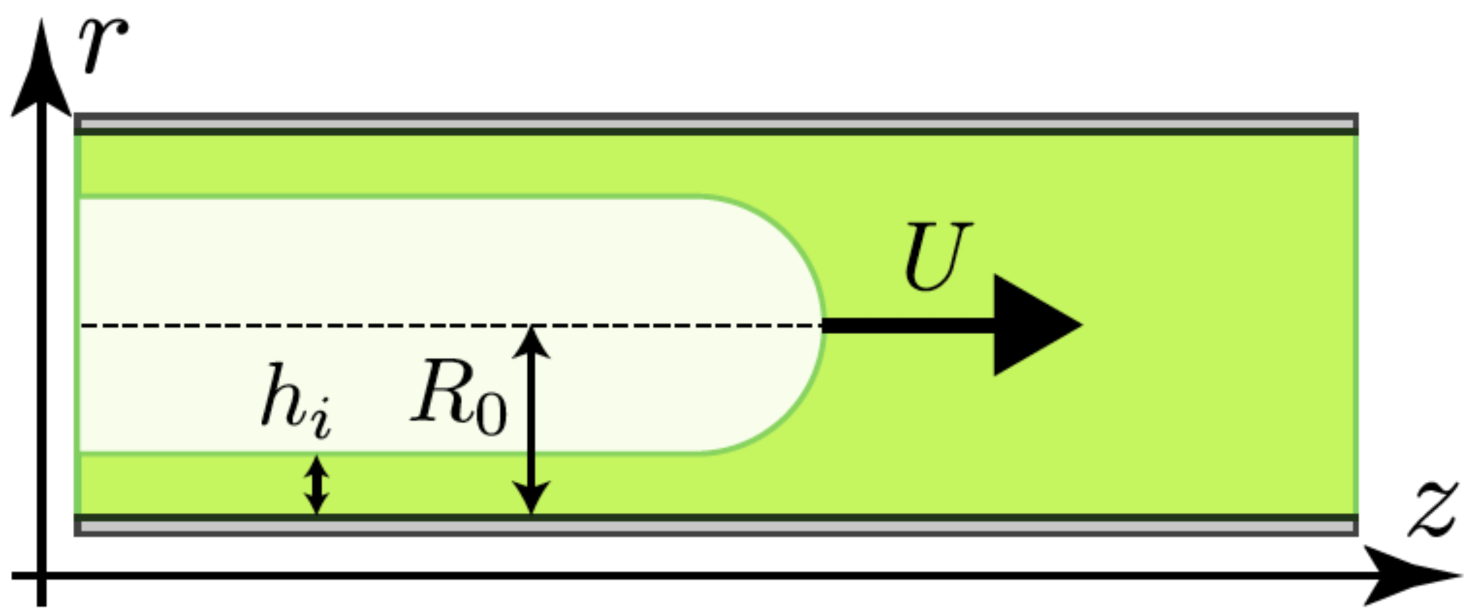
viscous effects $\sim$ capillary effects

$$\frac{\mu U}{h_i^2} \sim \frac{\gamma}{R\ell}$$

Matching static and dynamic meniscus

$$-\frac{\gamma}{R} - \frac{\gamma h_i}{\ell^2} \sim -\frac{2\gamma}{R}$$

Bretherton: initial thickness of the coating



Iso-pressure interface:

$$\rho g \cos\theta - \gamma\theta'' = 0$$

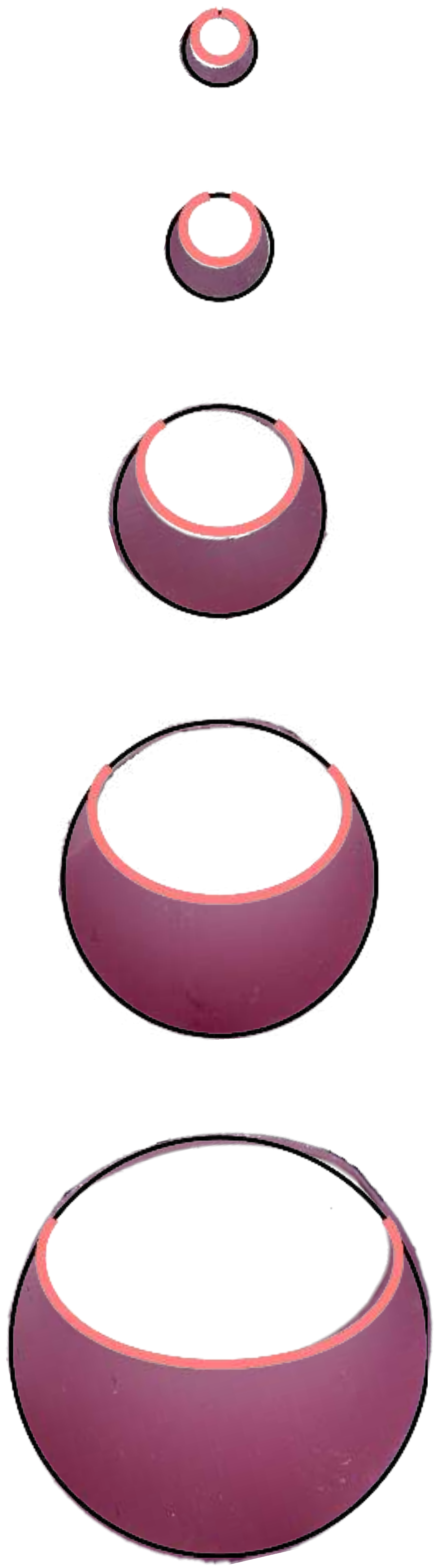
Boundary conditions:

Wetting

$$\theta(0) \parallel \text{Cylinder}$$

Symmetry

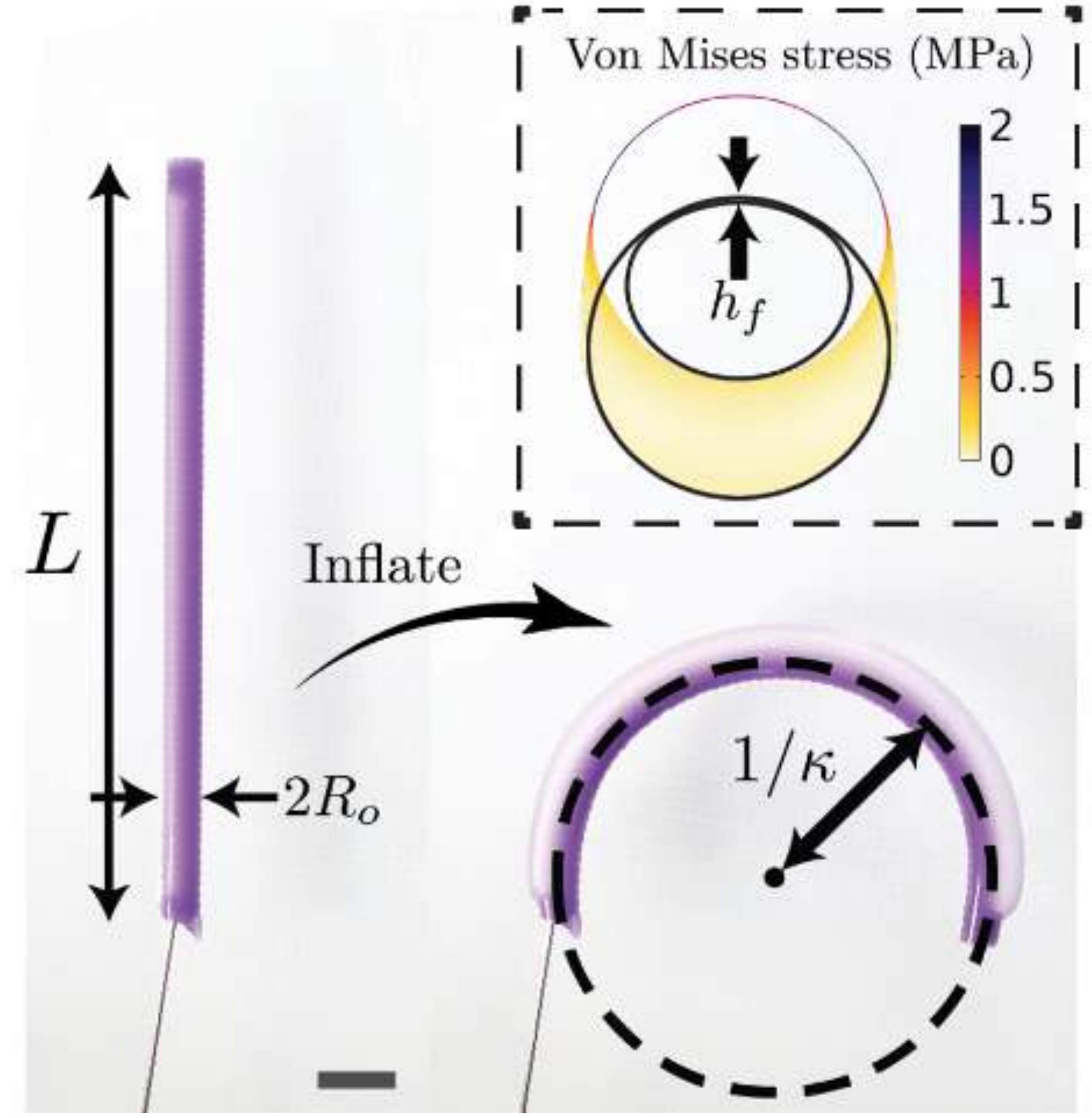
$$\theta(L/2) \perp \text{gravity}$$

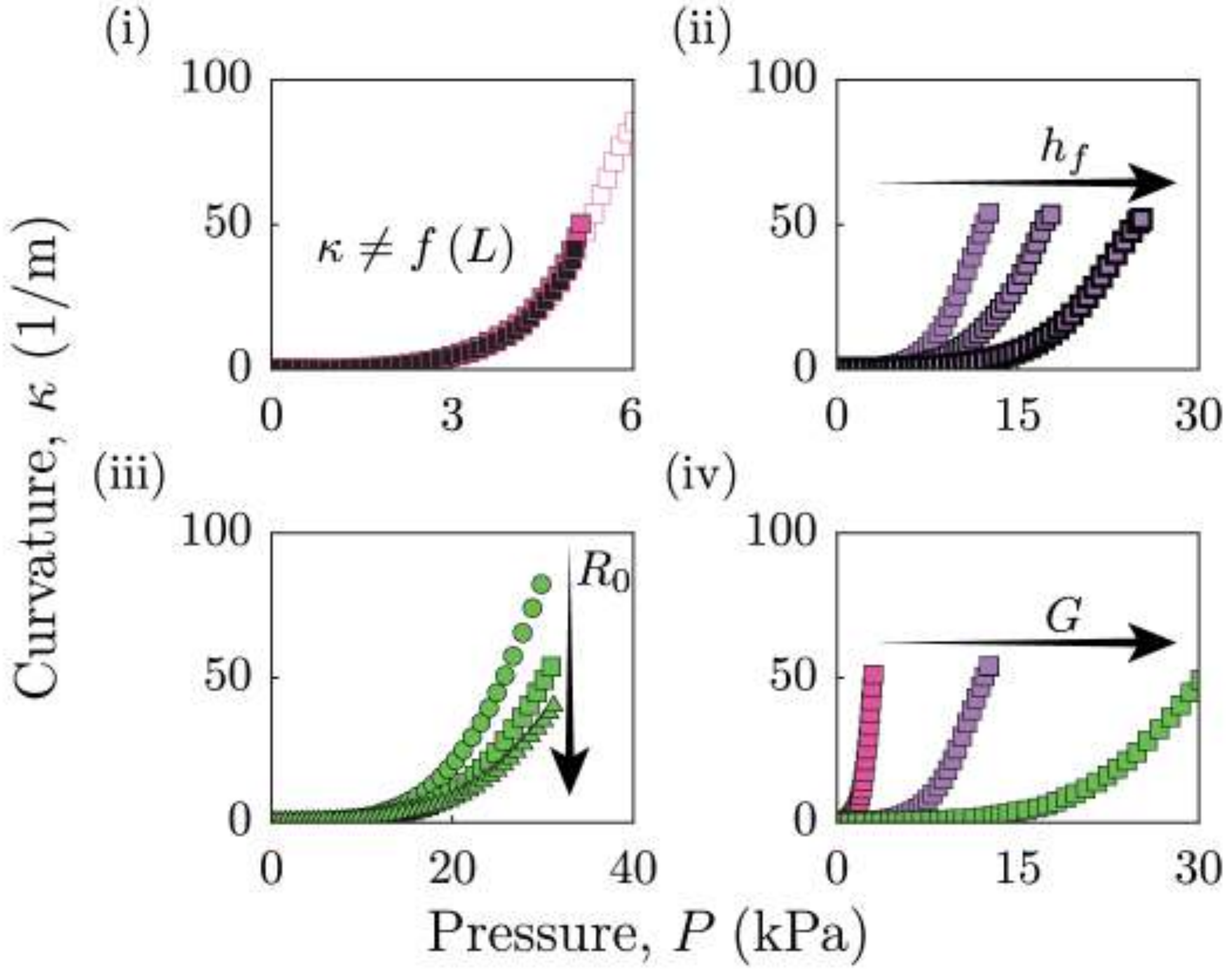


Actuation of the asymmetric tube

Experiments at the interface of a water bath

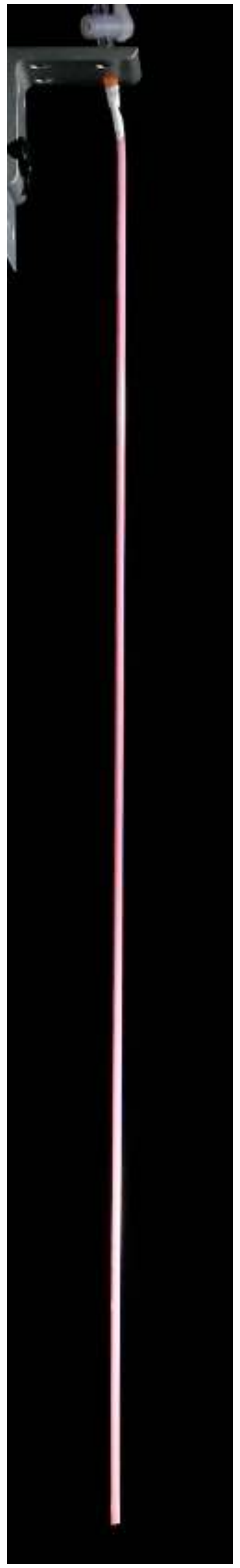
Thin membrane expands → Uniform bending

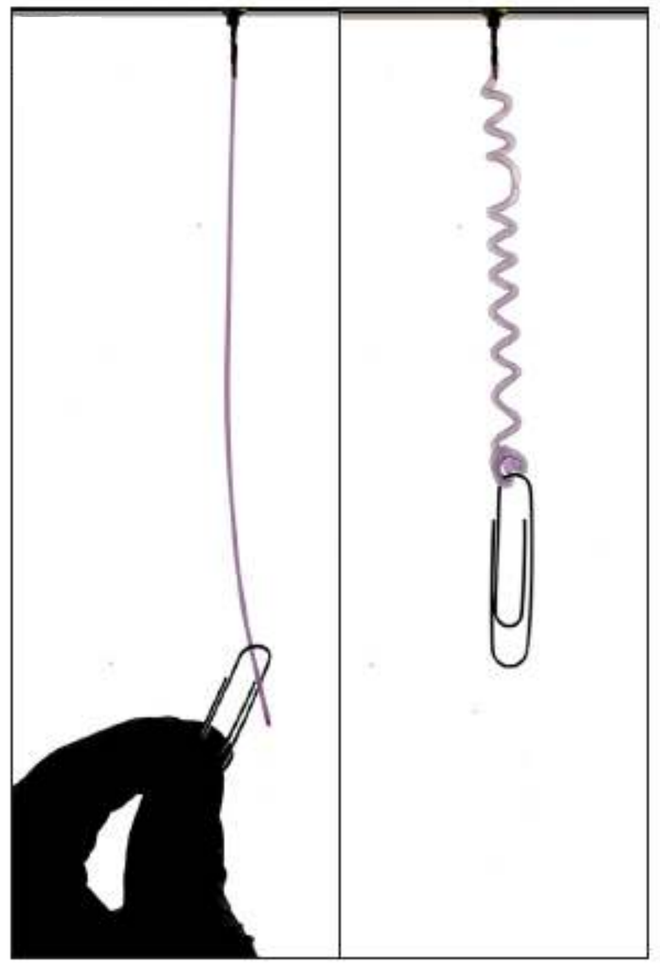


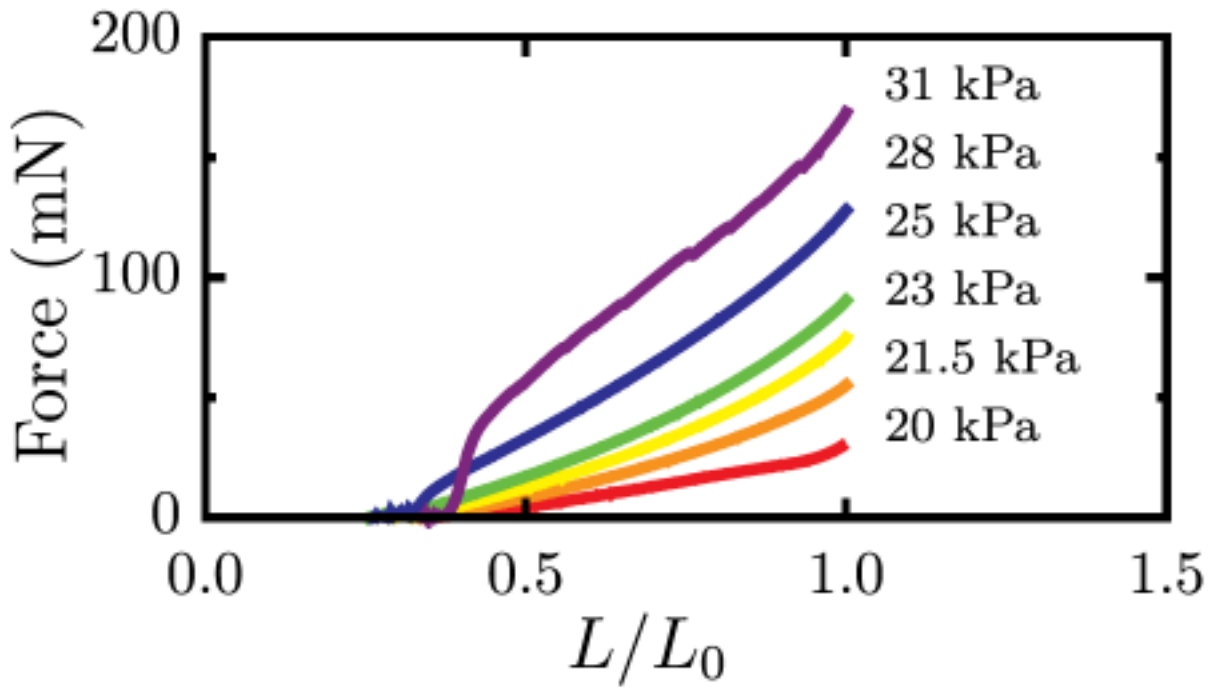


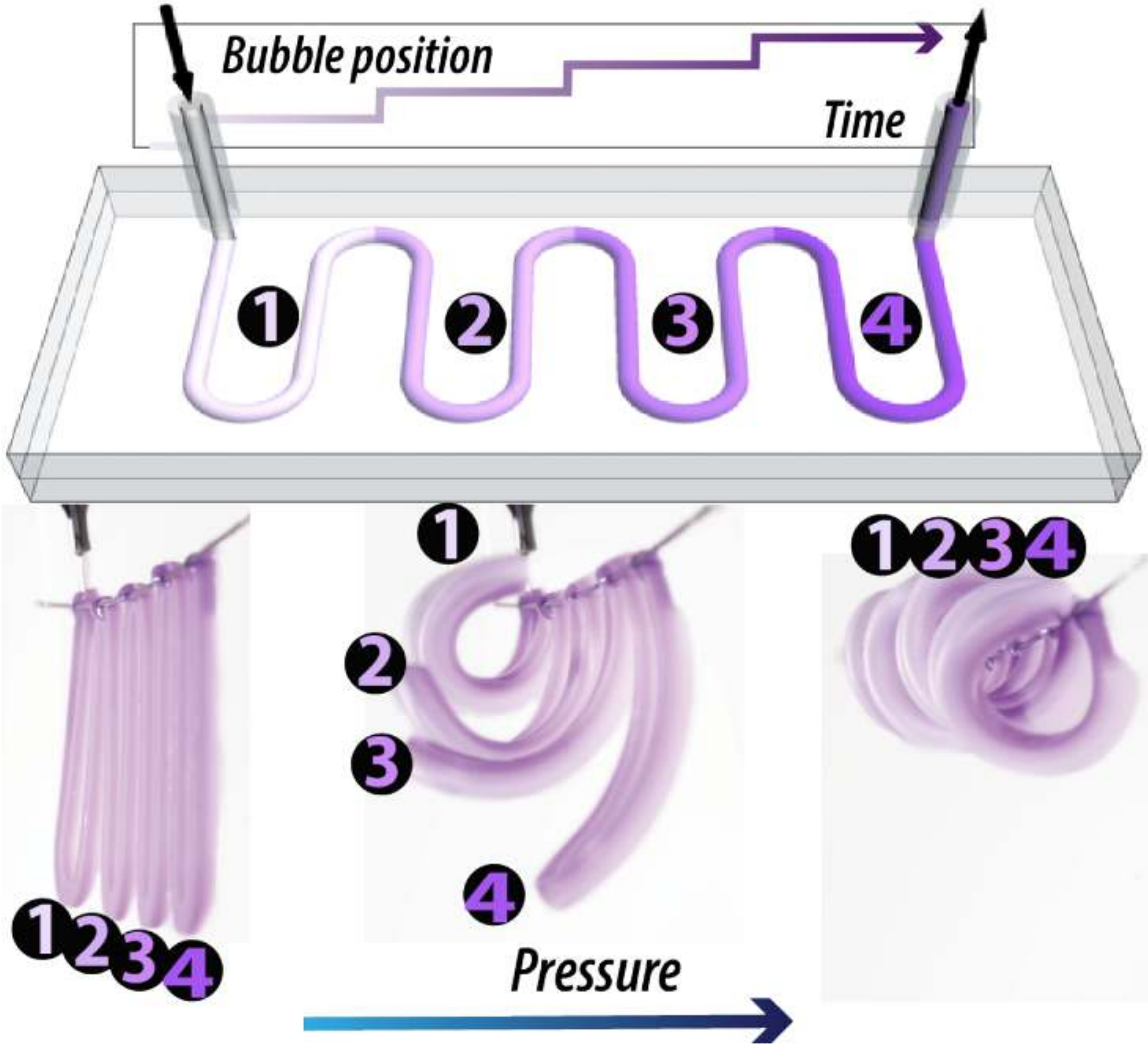
Towards more complicated actuation

Coupling with nonlinearities from the tube: muscles





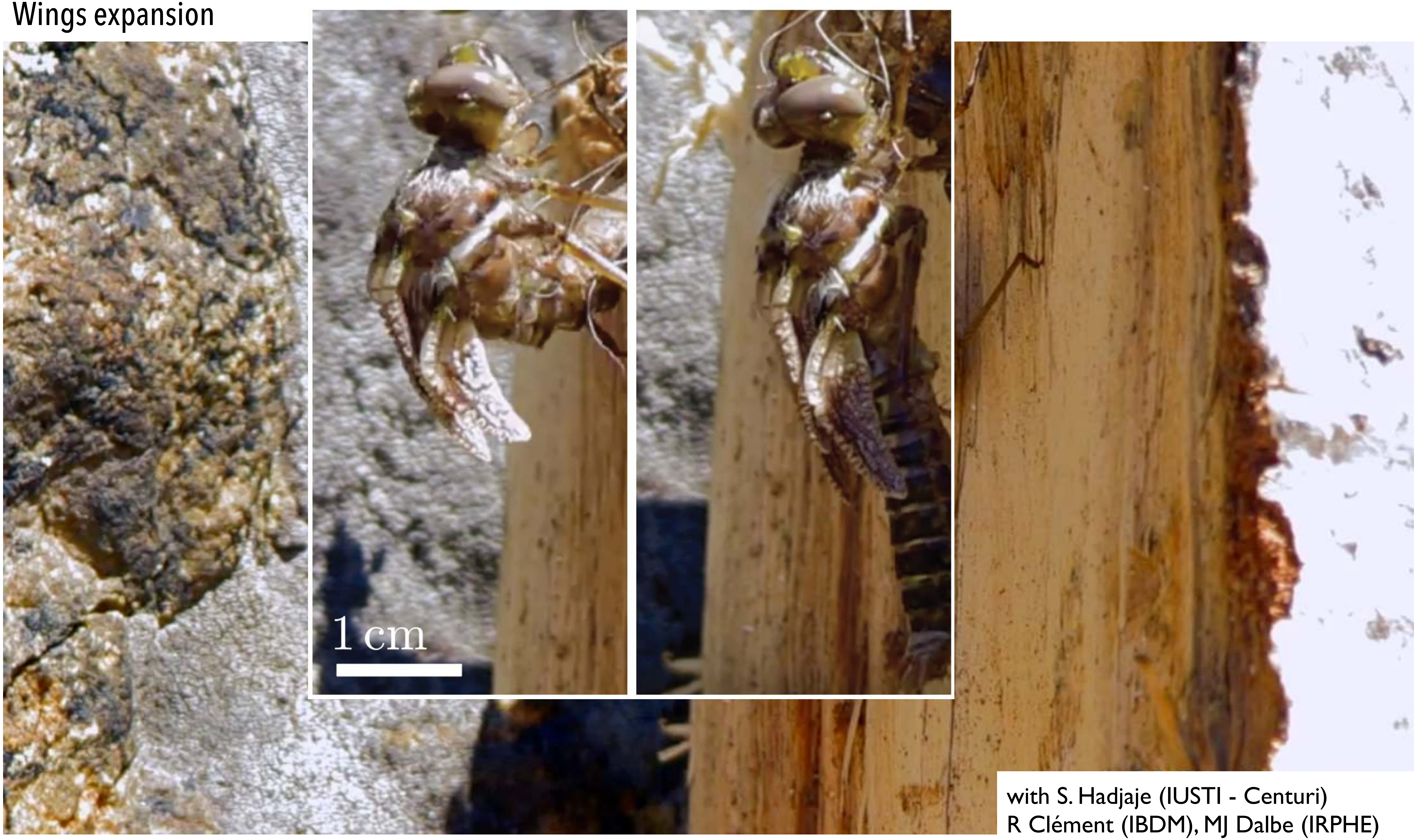




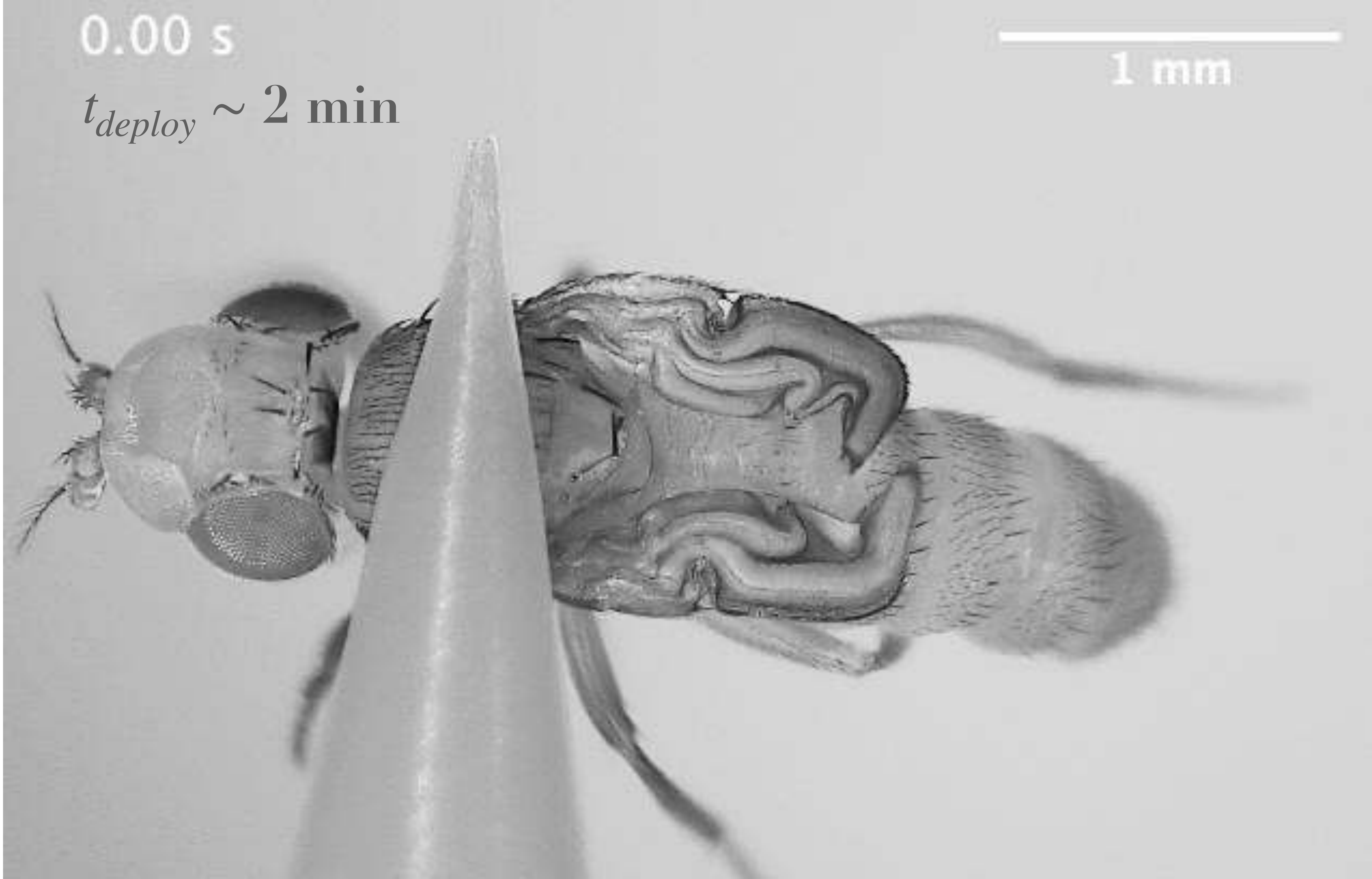
with T.J. Jones, E Jambon Puillet, PT Brun (Princeton)

1. Chocolate egg problem/buckling
2. Rayleigh-Taylor instability
3. Rayleigh-Plateau instability
4. Bioinspired soft inflatable structures

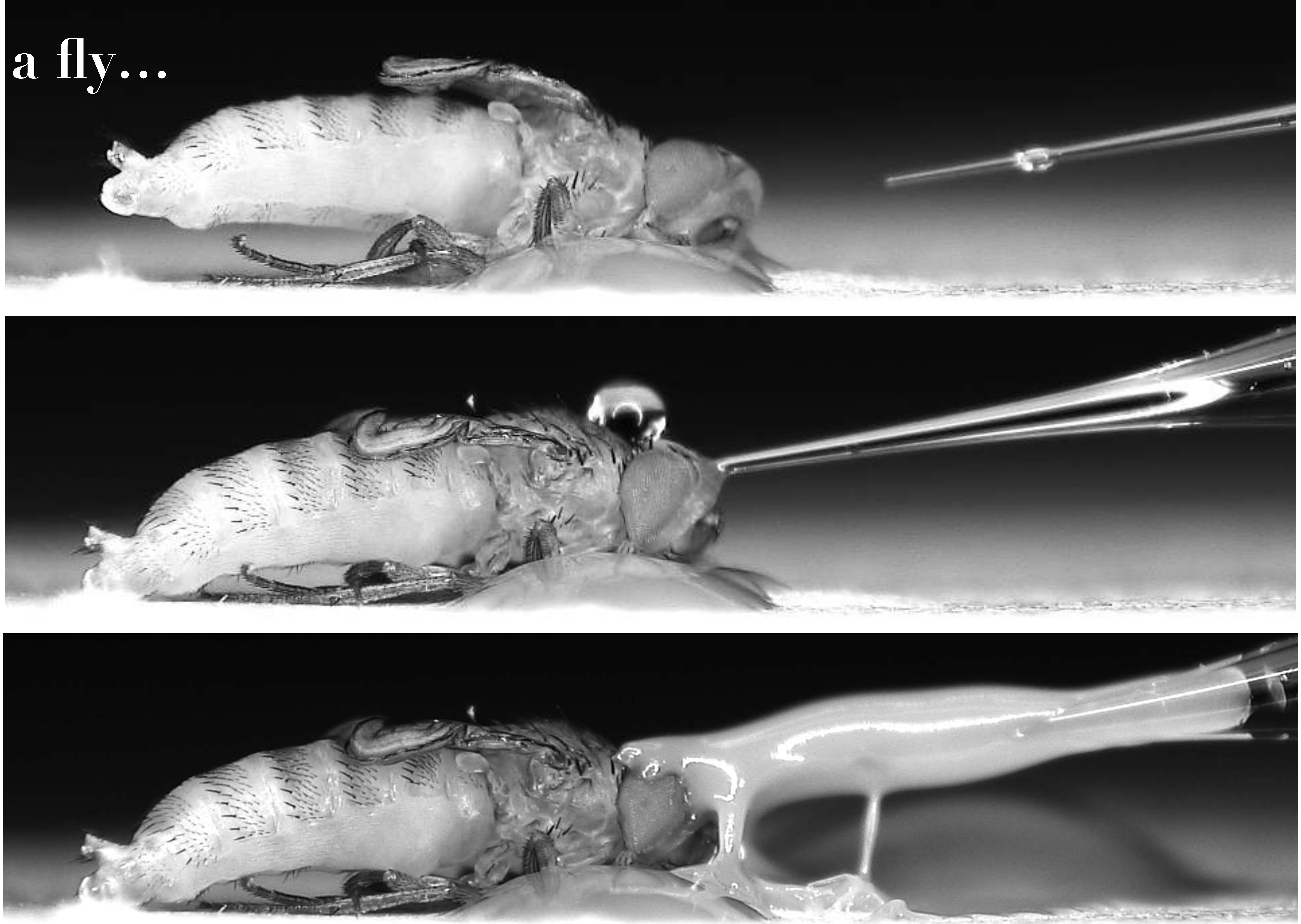
Wings expansion



with S. Hadjaje (IUSTI - Centuri)
R Clément (IBDM), MJ Dalbe (IRPHE)


0.00 s
1 mm
$t_{deploy} \sim 2$ min

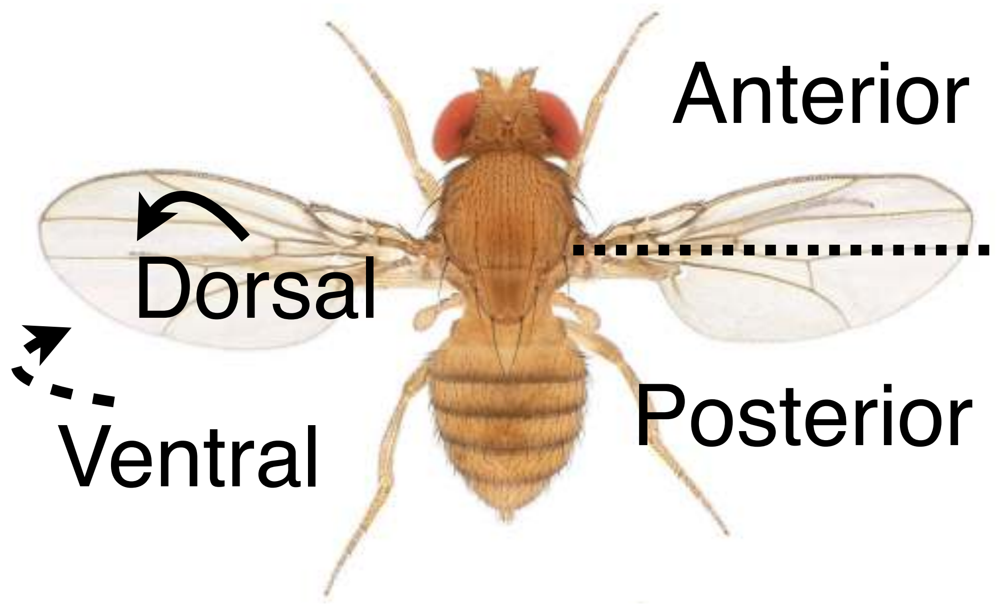
Poking a fly…



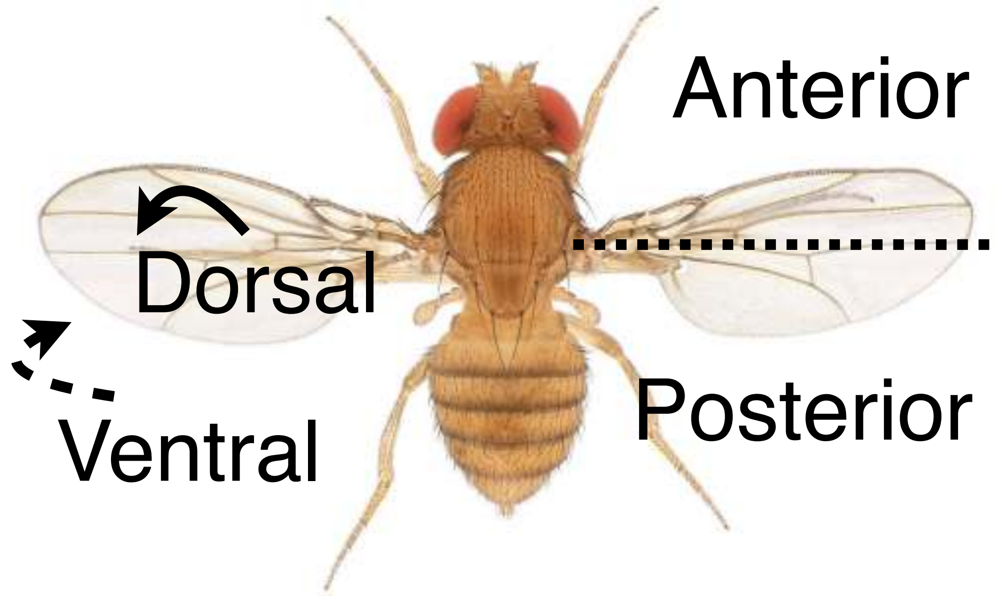
… to inflate it

Large scale structure : folds

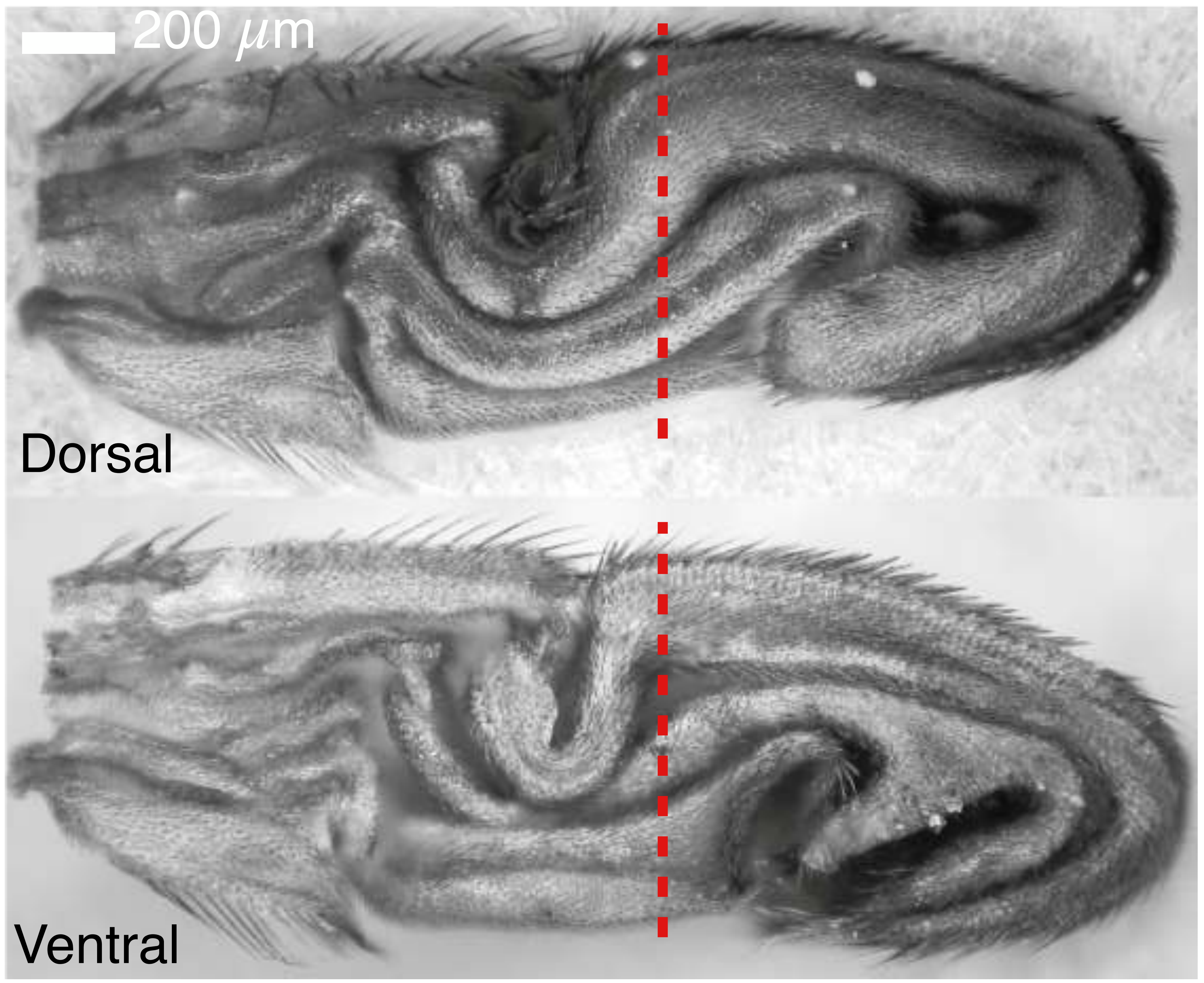
The initial wing folds follow the vein network

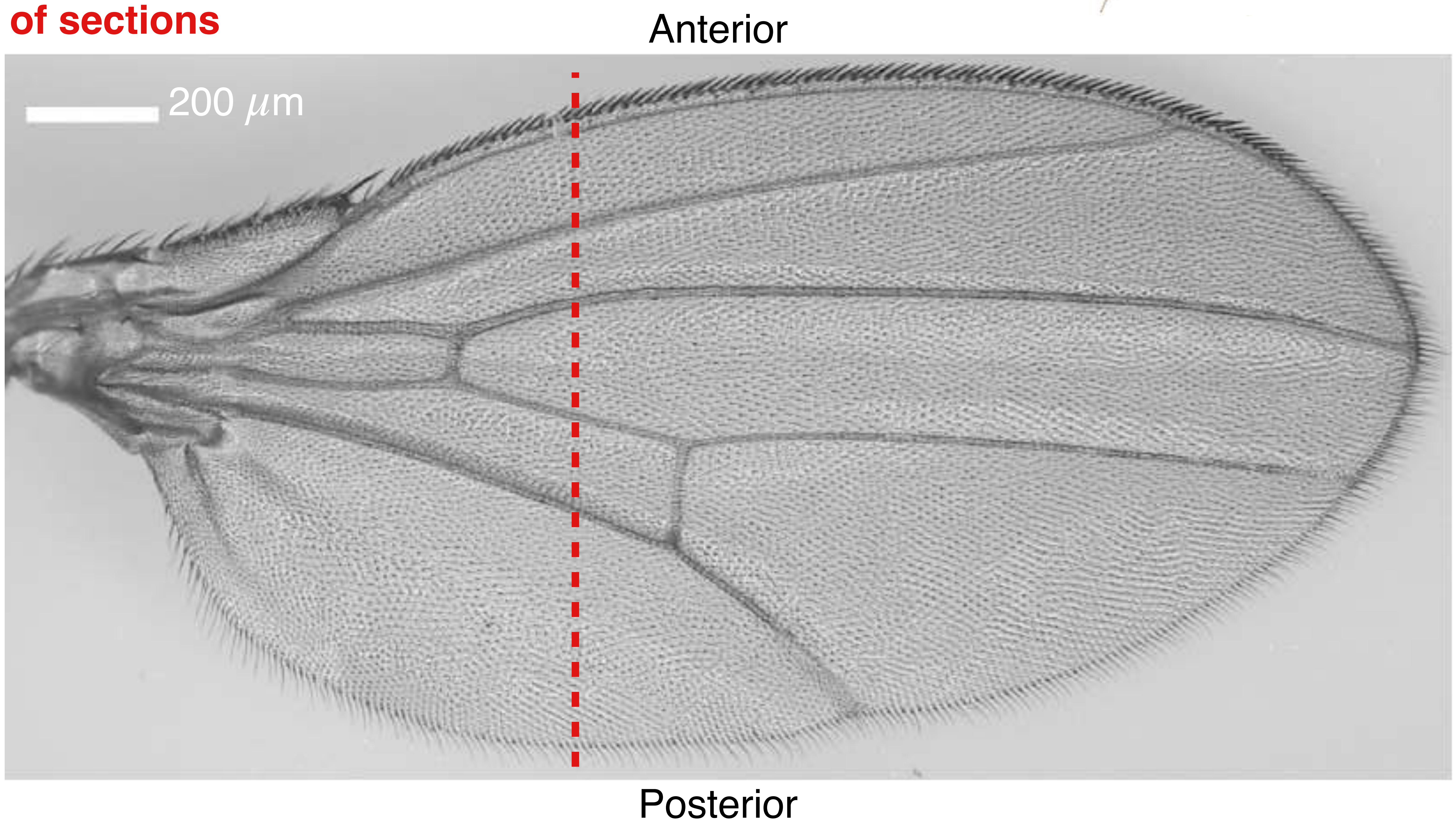


Large scale structure : folds



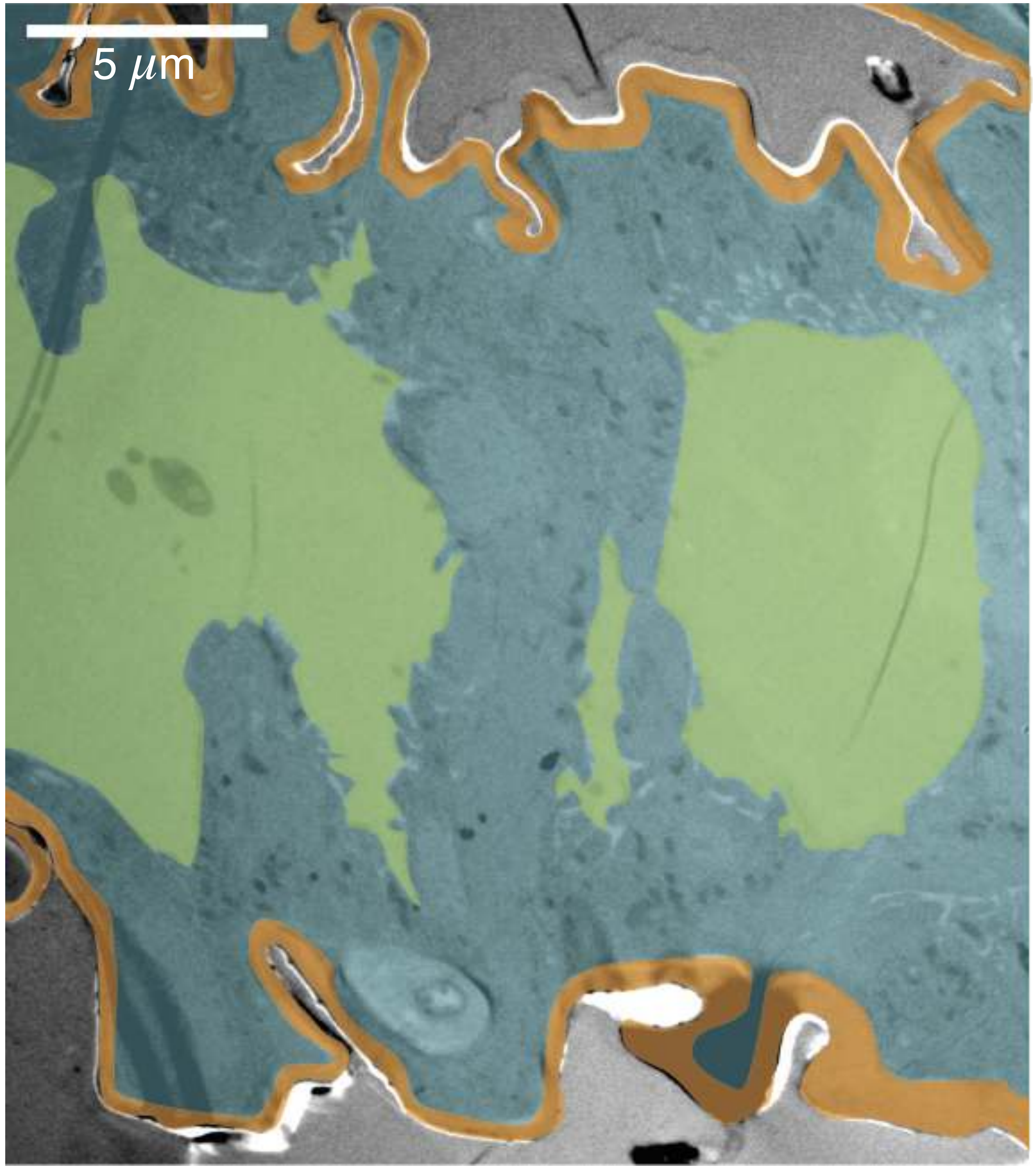
Micrographs of sections

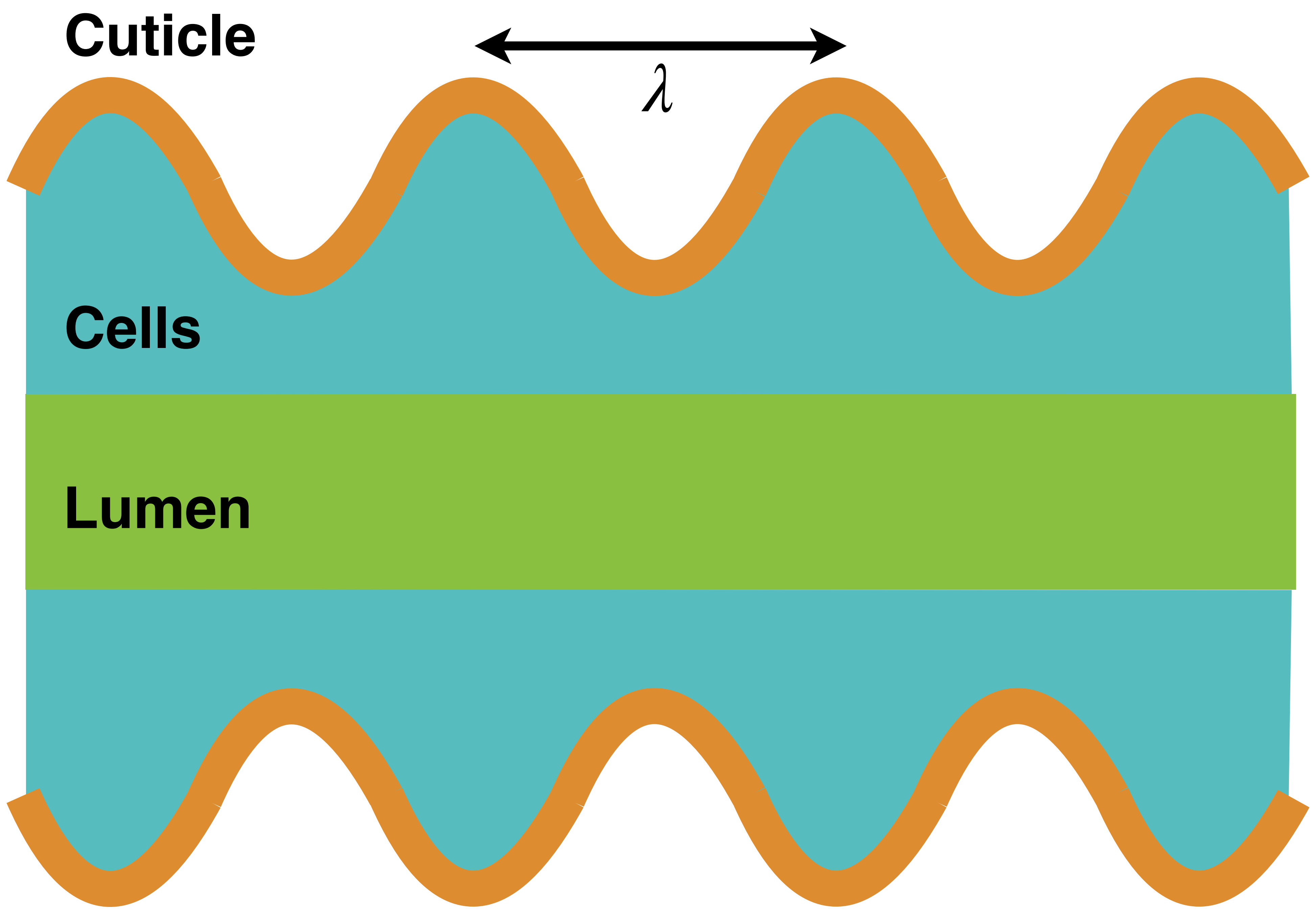




Small scale structure : wrinkles

Wing lamellae are made of cuticle, cells and lumen

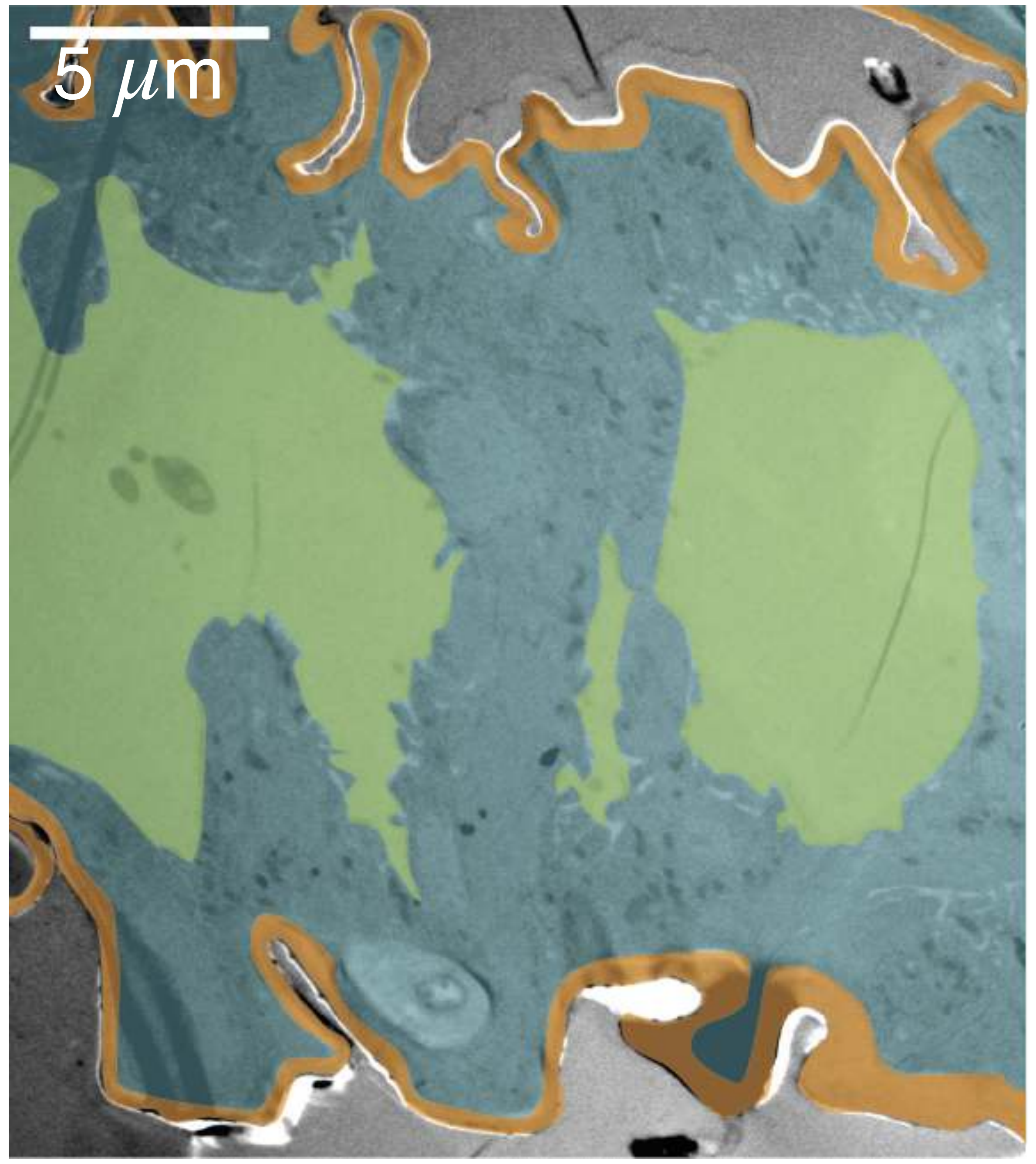


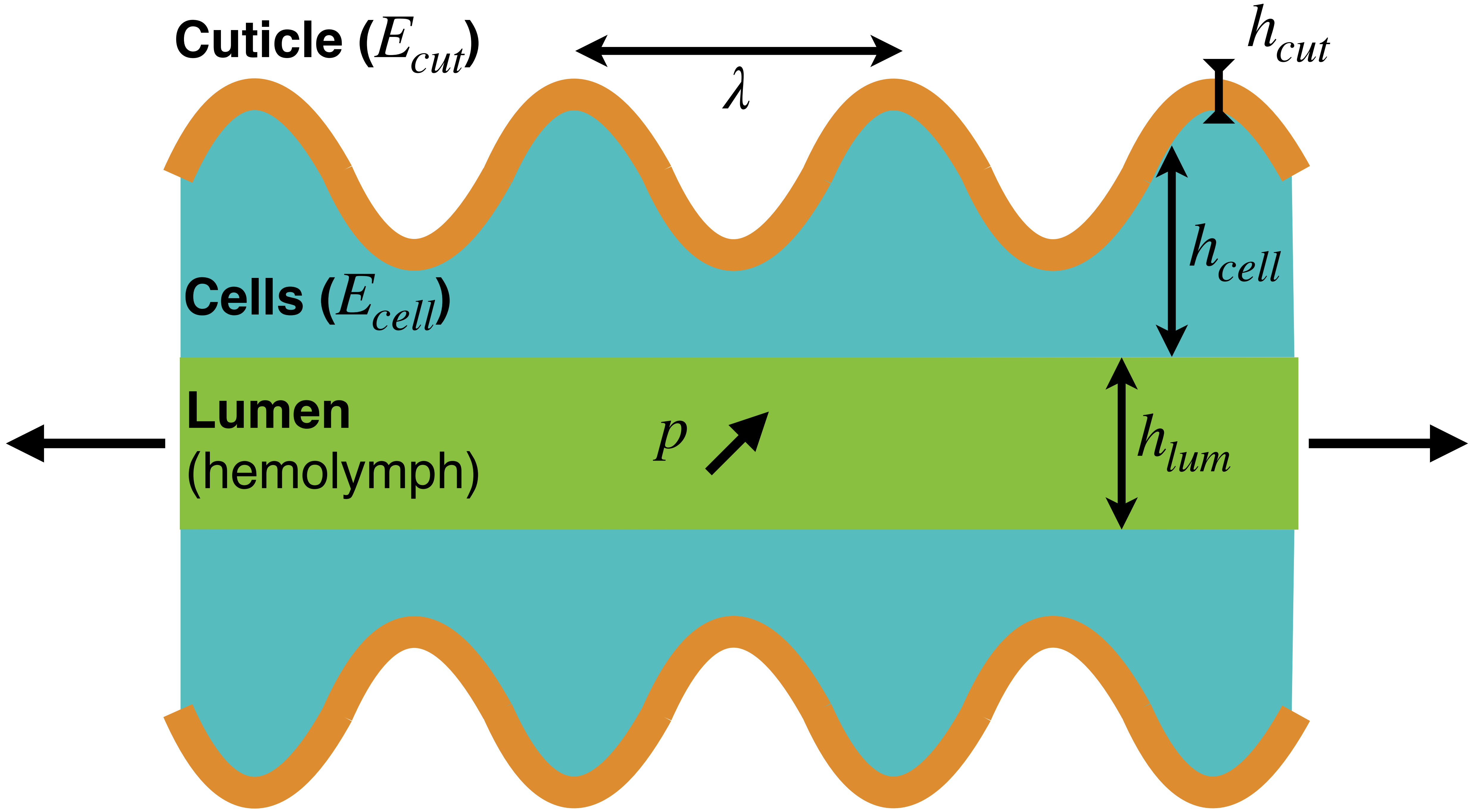


Stretching the structure

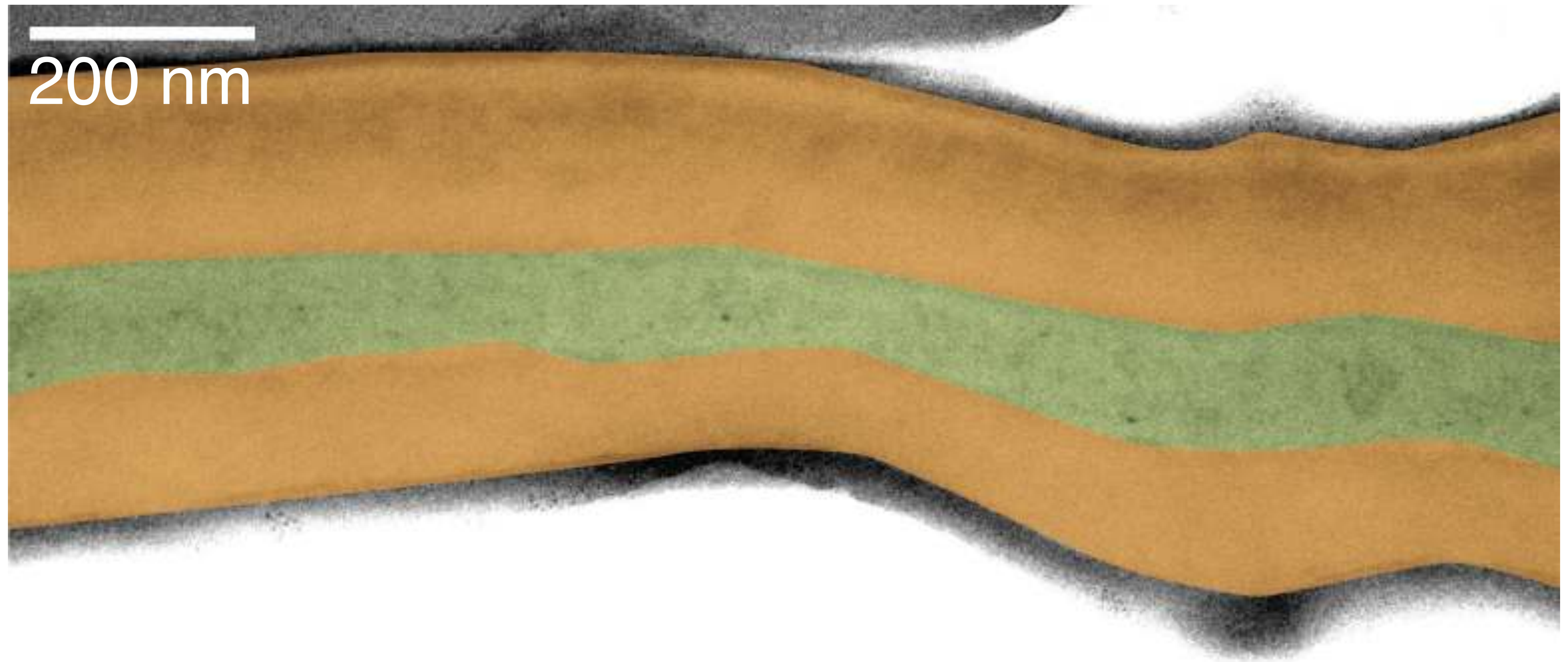
The cuticle unfolds

Folded



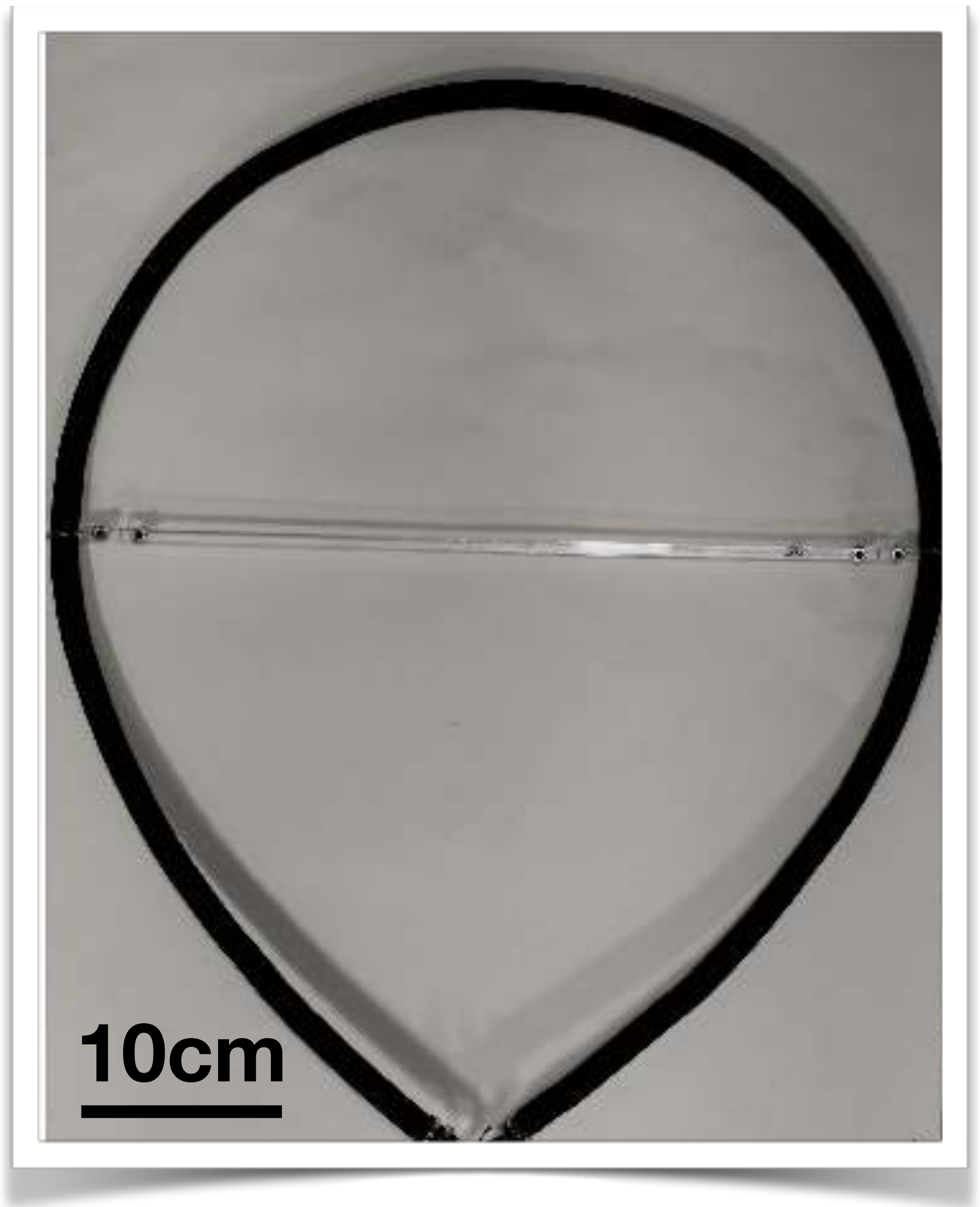


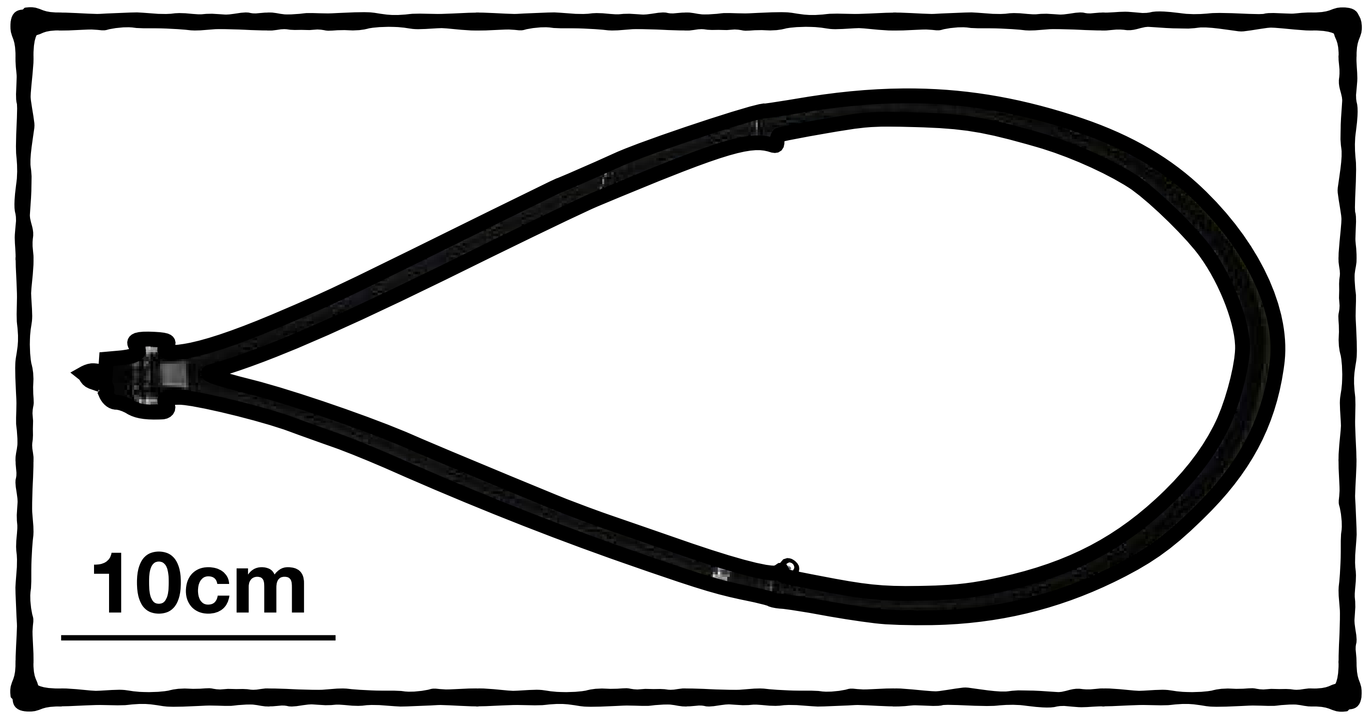
4h after
deployment

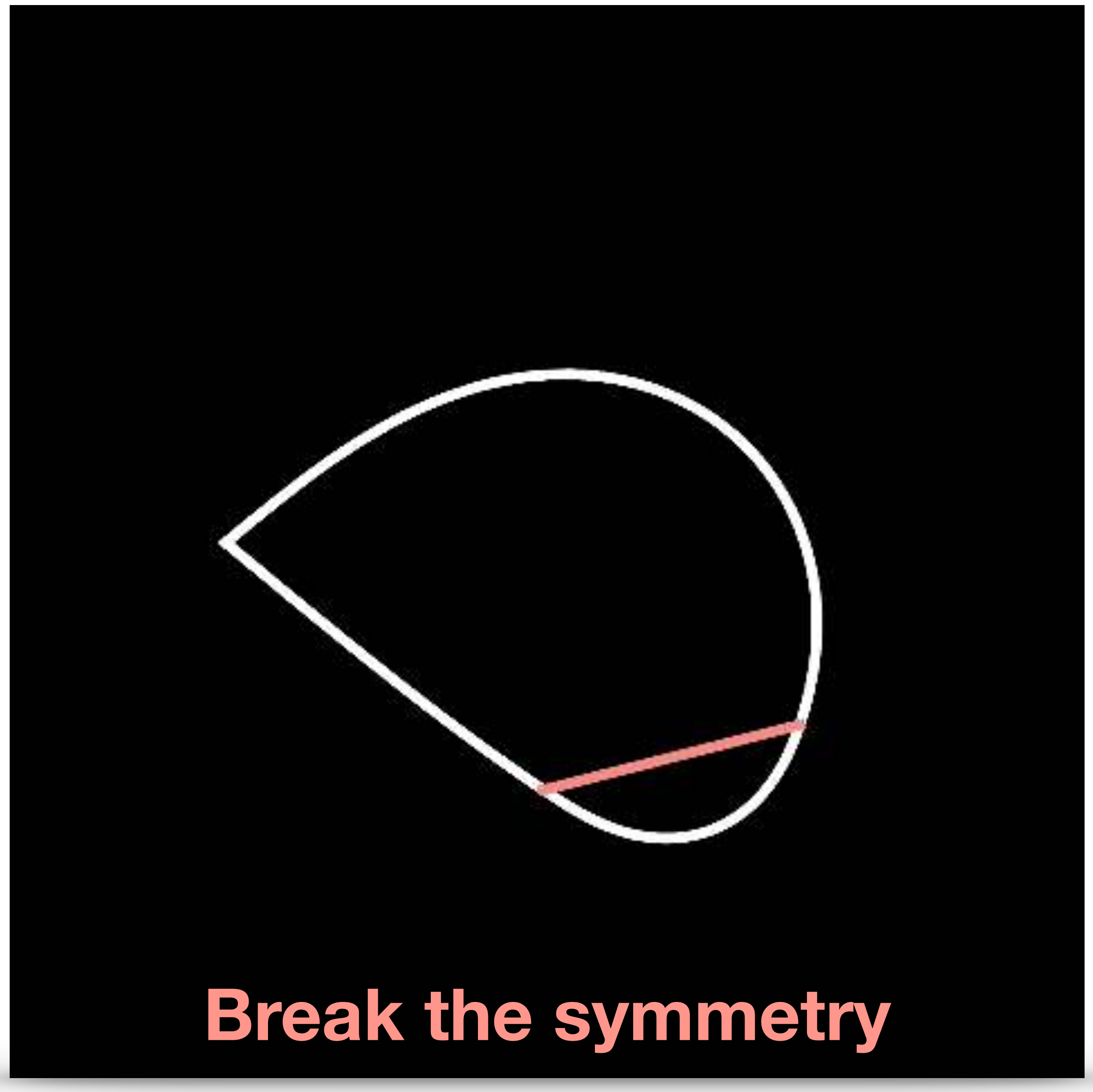


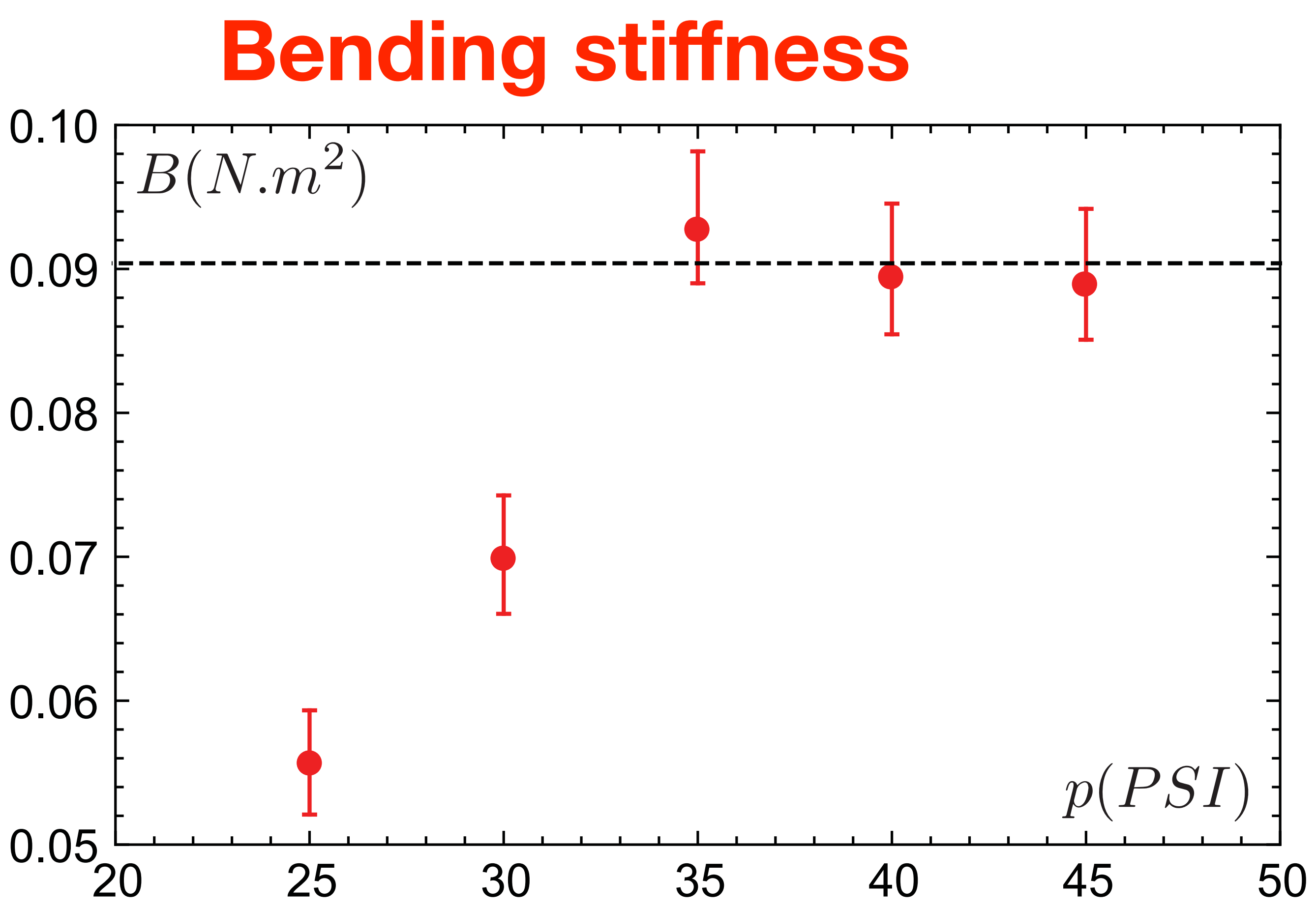
Minimal artificial vein

Behaves as an elastic rod



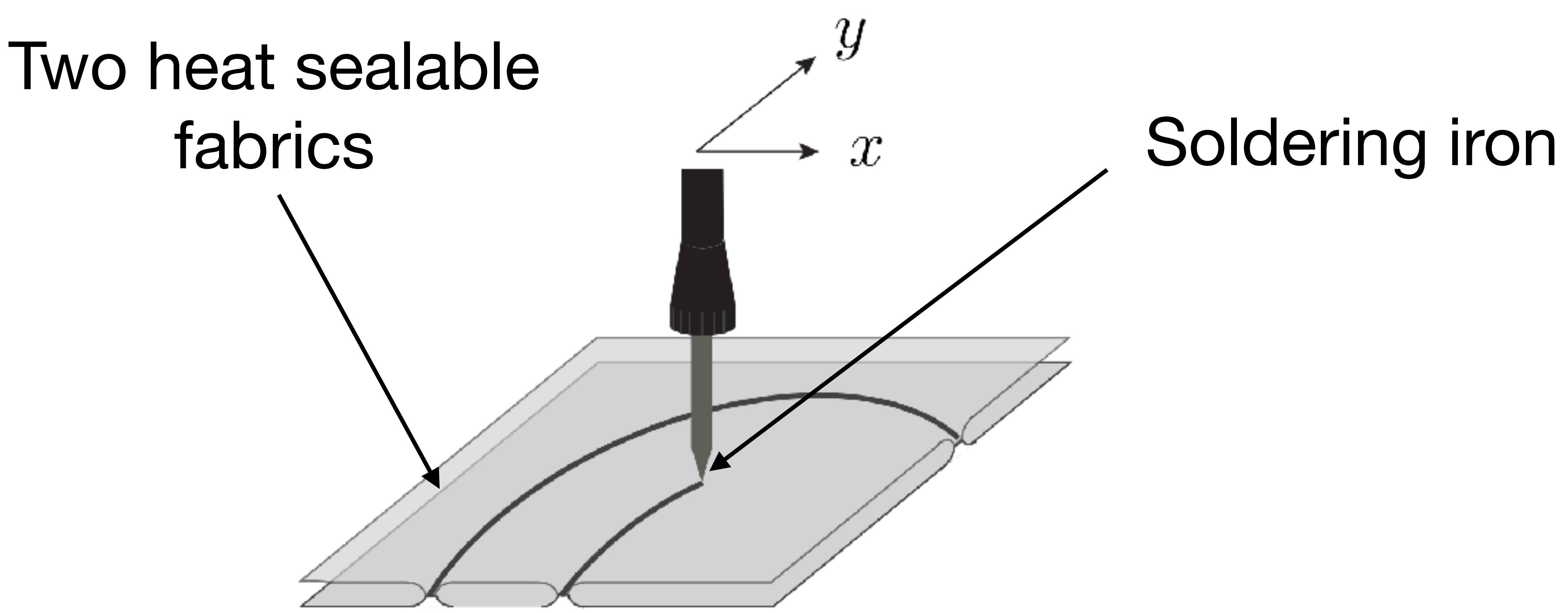




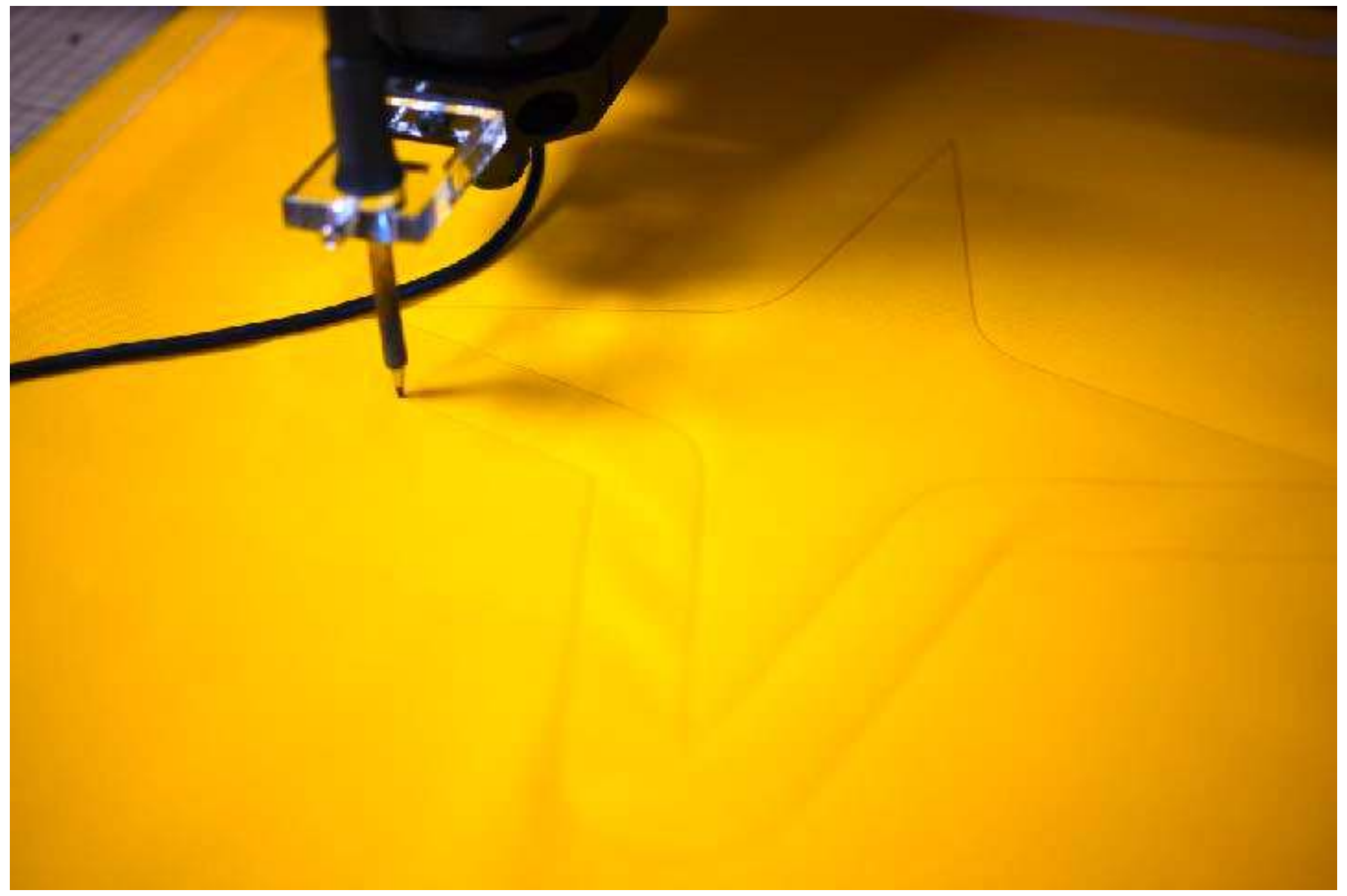


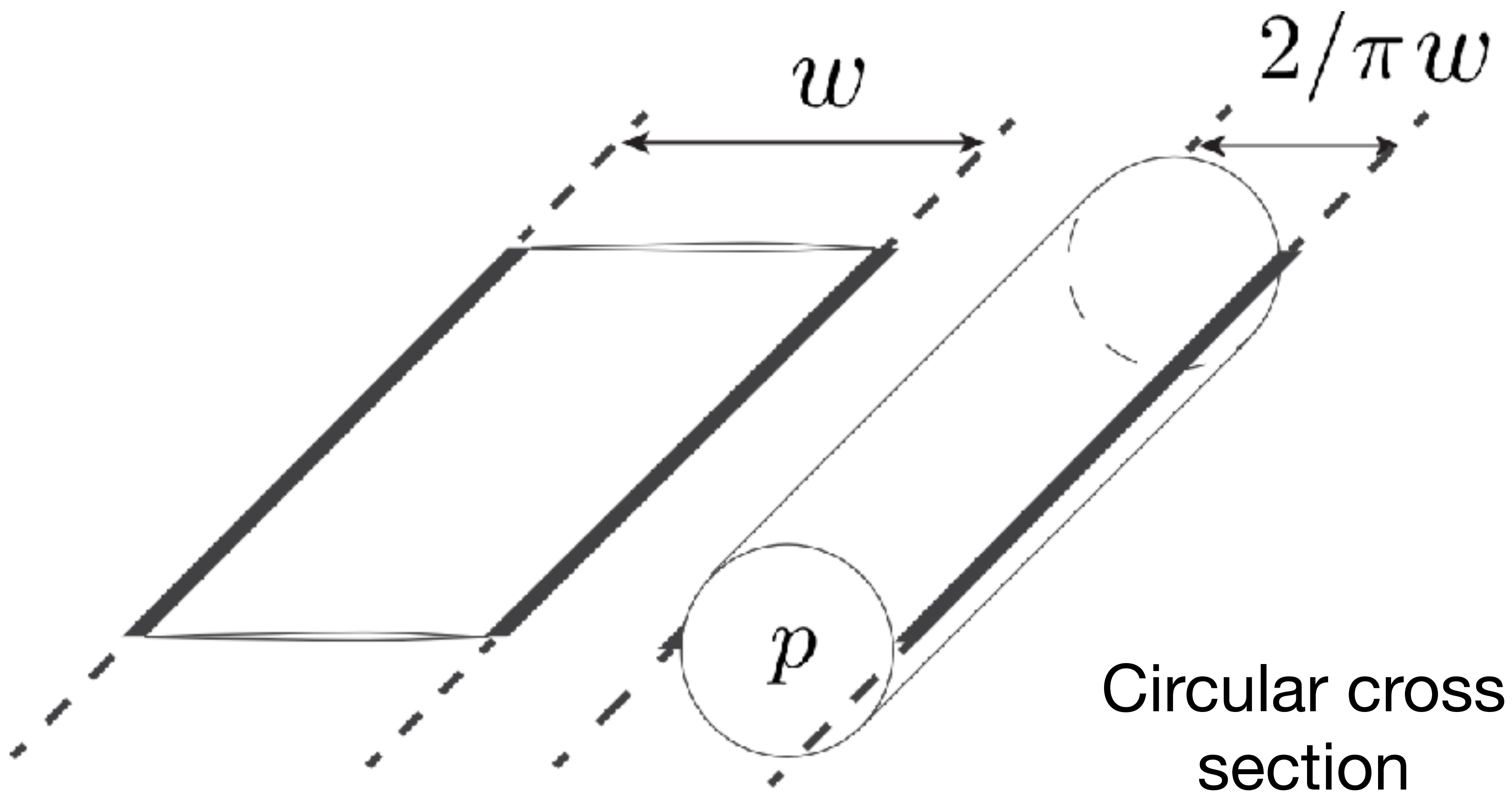
<u>*Towards complex network*</u>

Fabric-based tubes



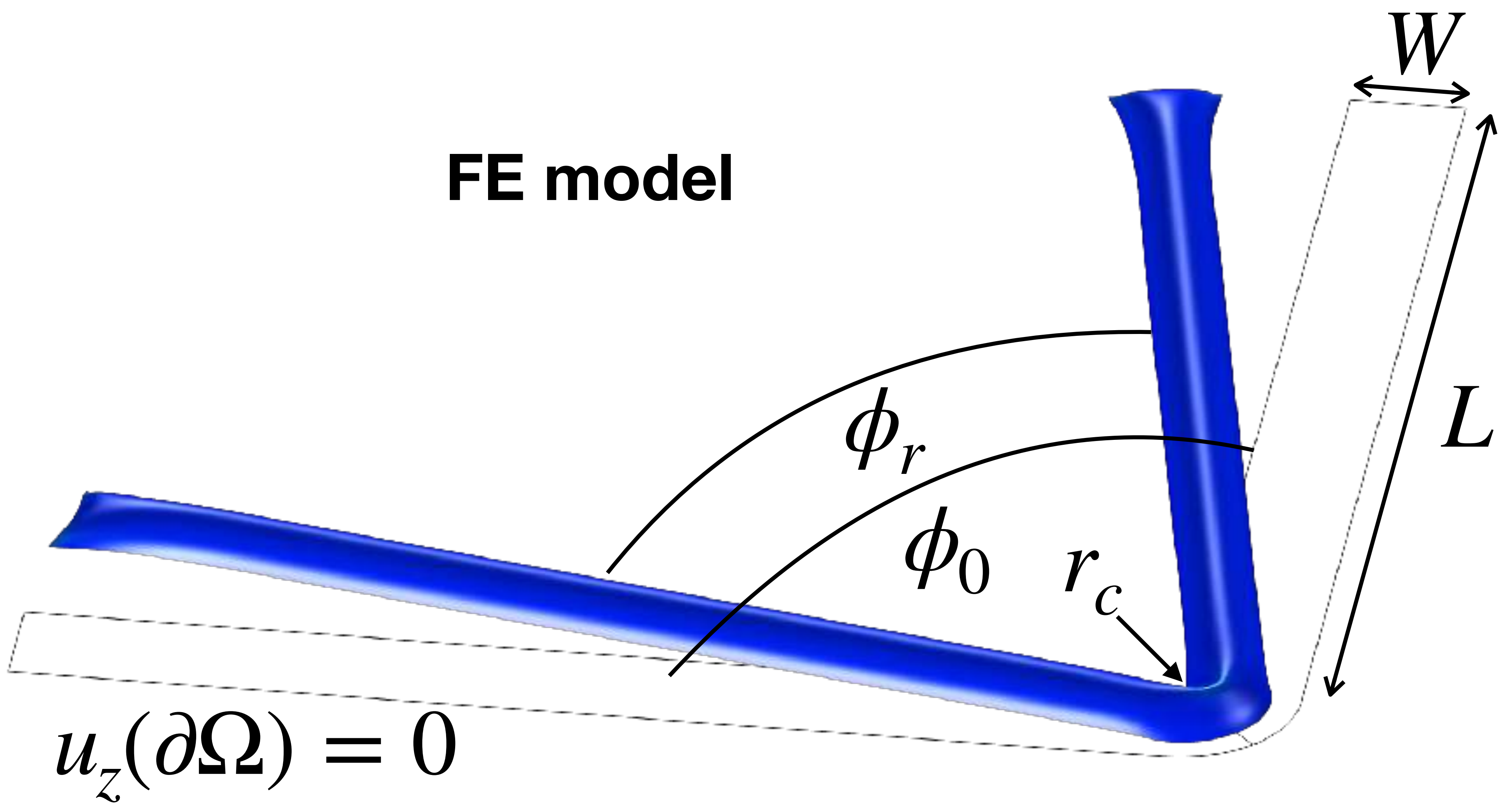
We “print” our design in a X-Y plotter



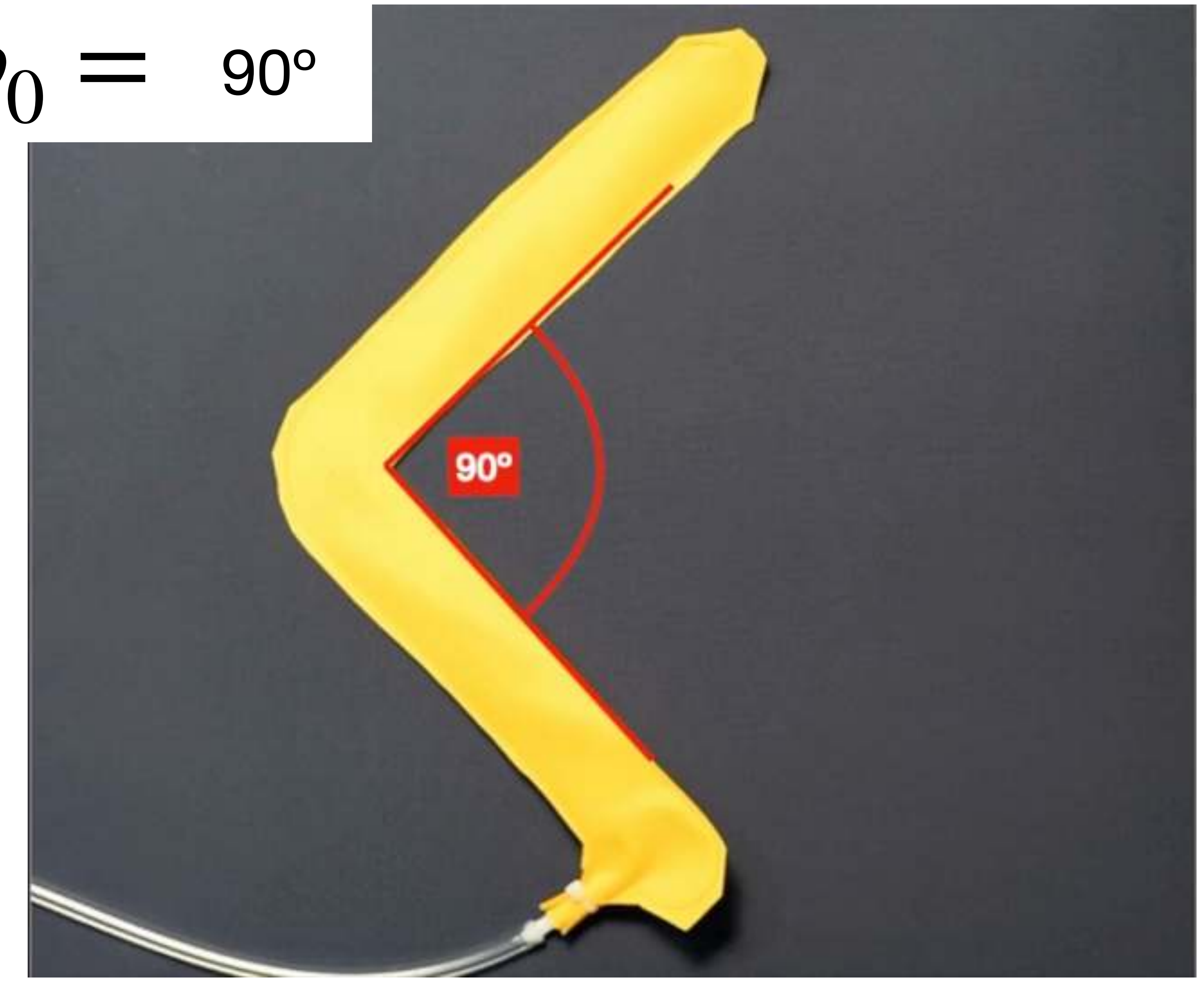


Siéfert, E., et al. PNAS (2019)

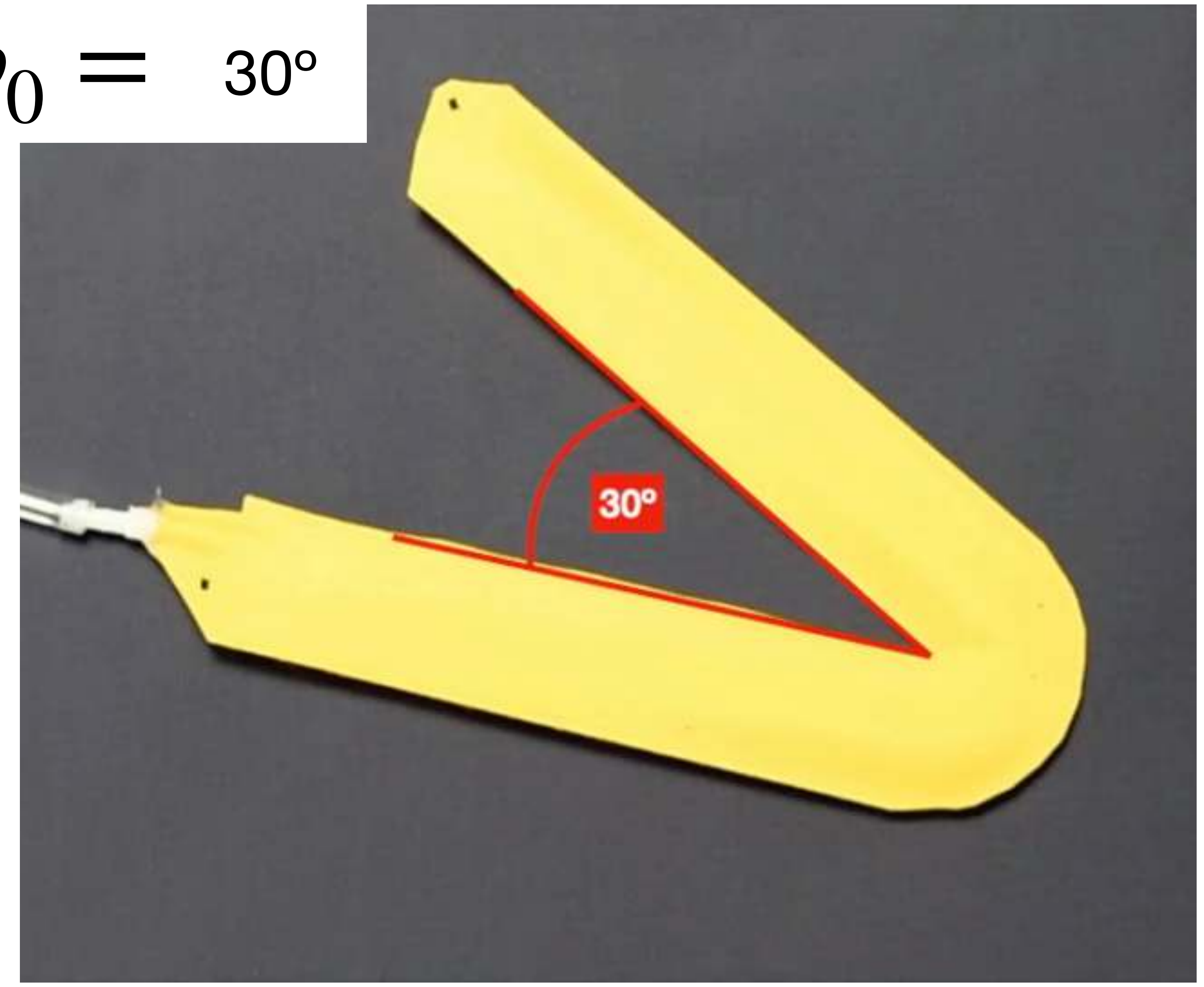
Elbow geometry



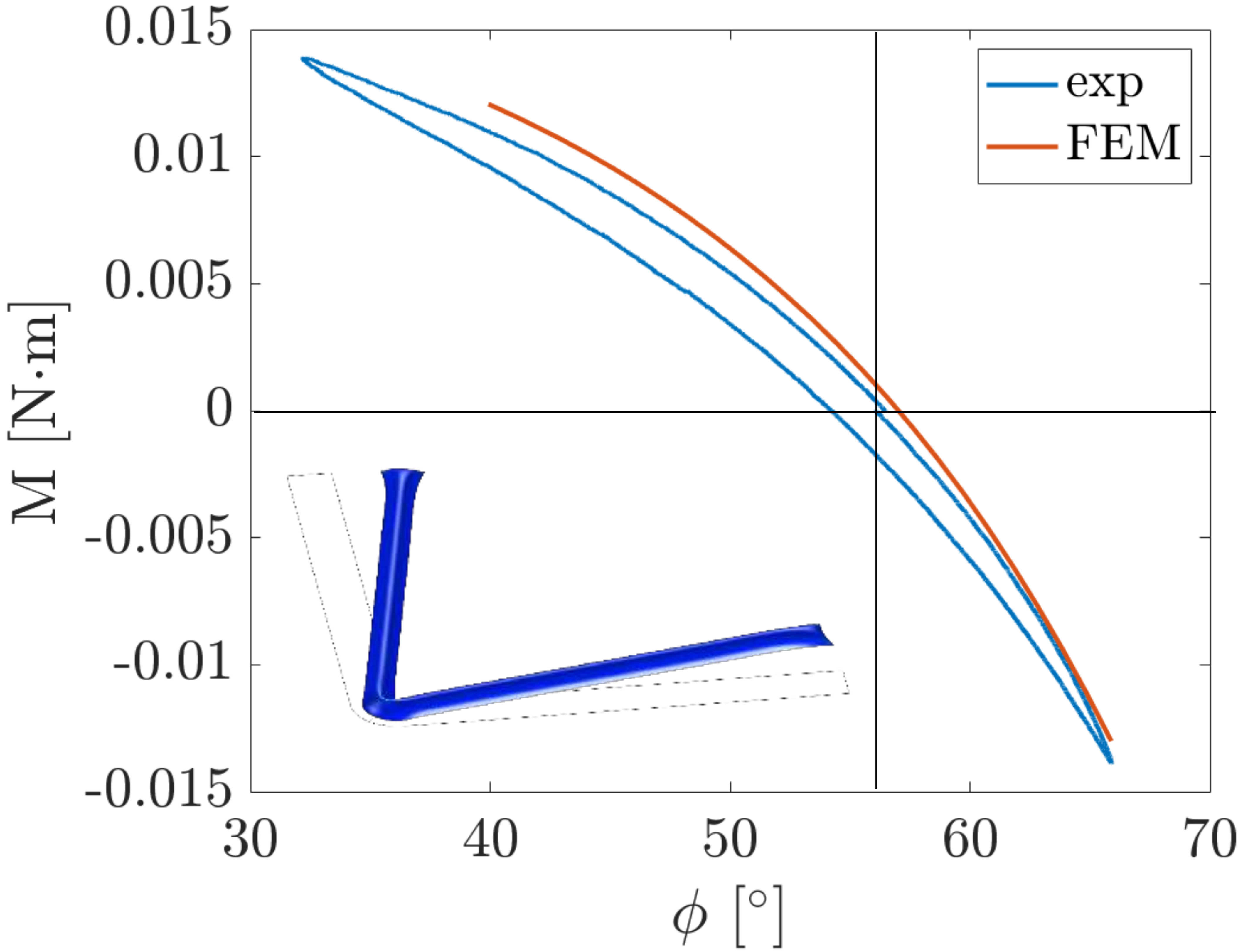
$\phi_0 =$ 90°



$\phi_0 =$ 30°

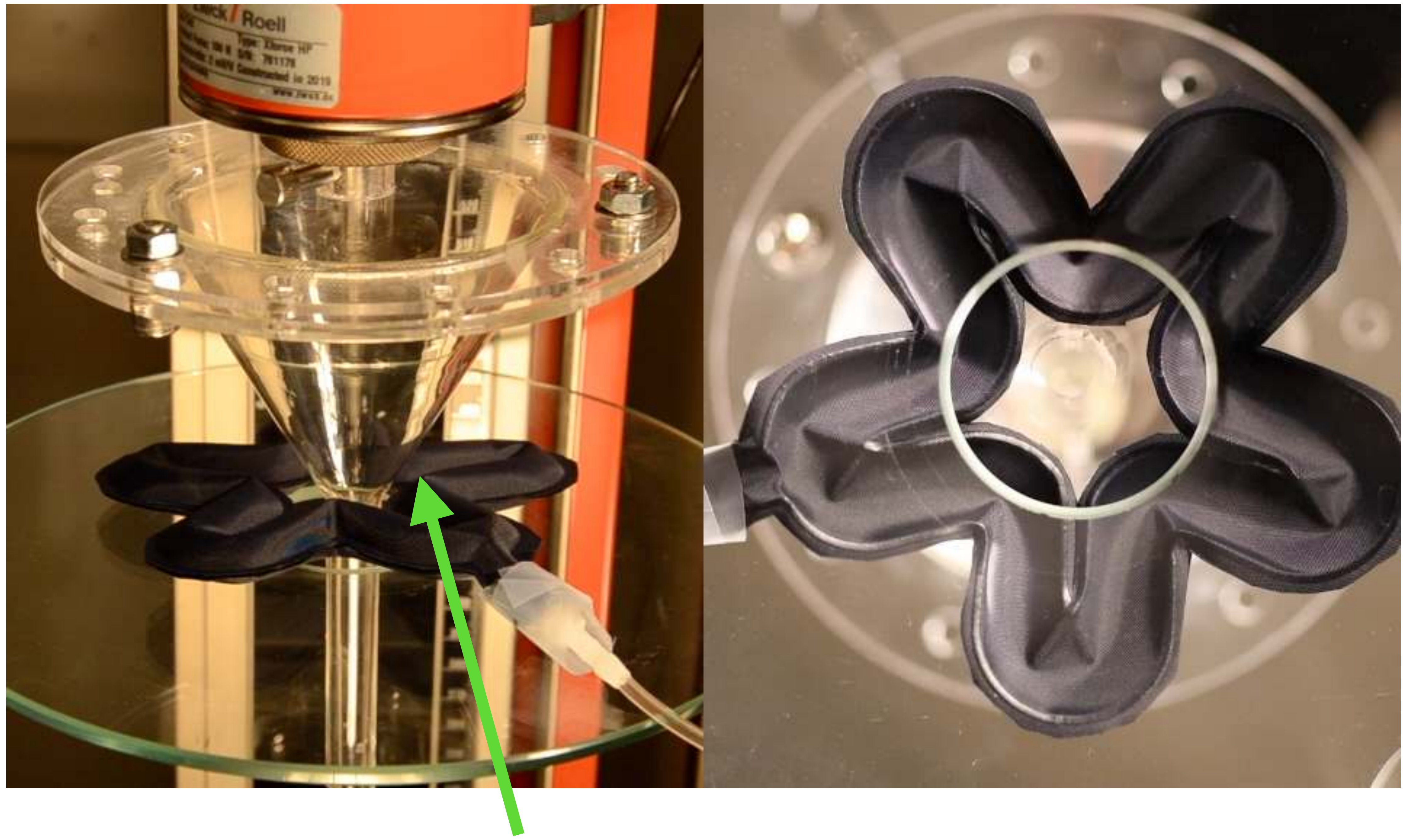


Hinge like mechanism

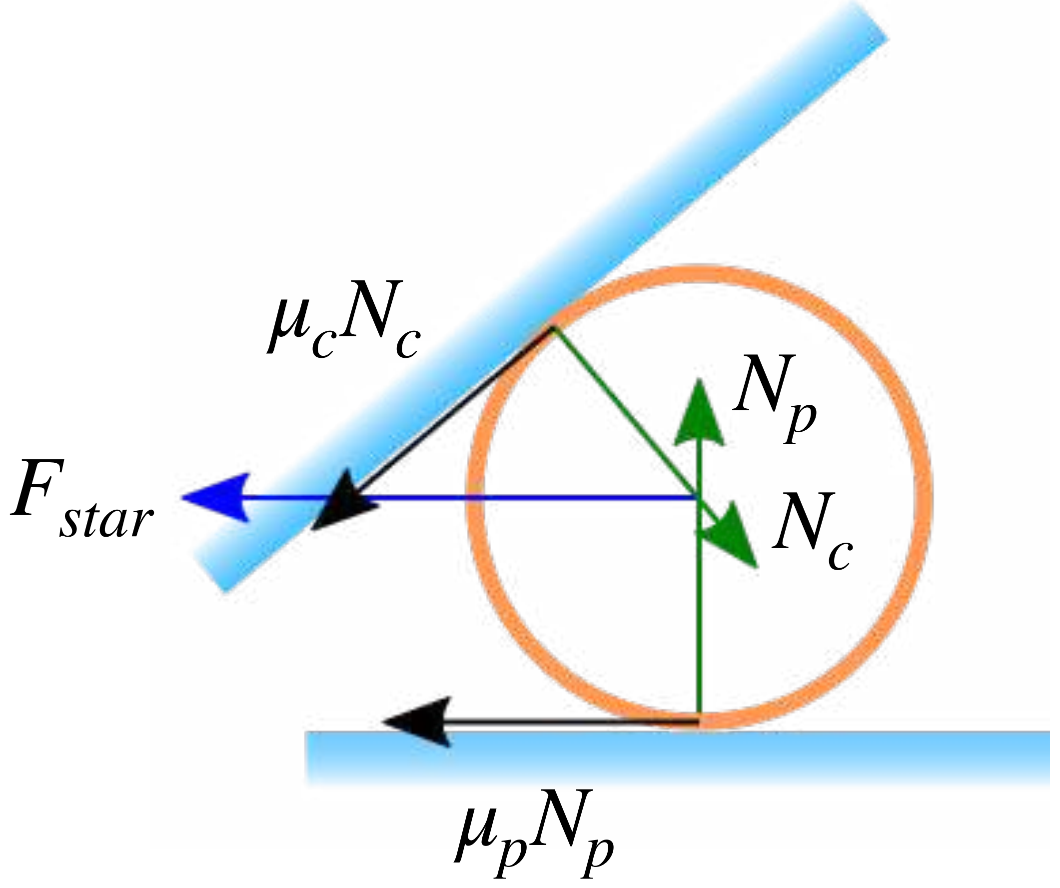


Use the hinge in a network

Gripping force

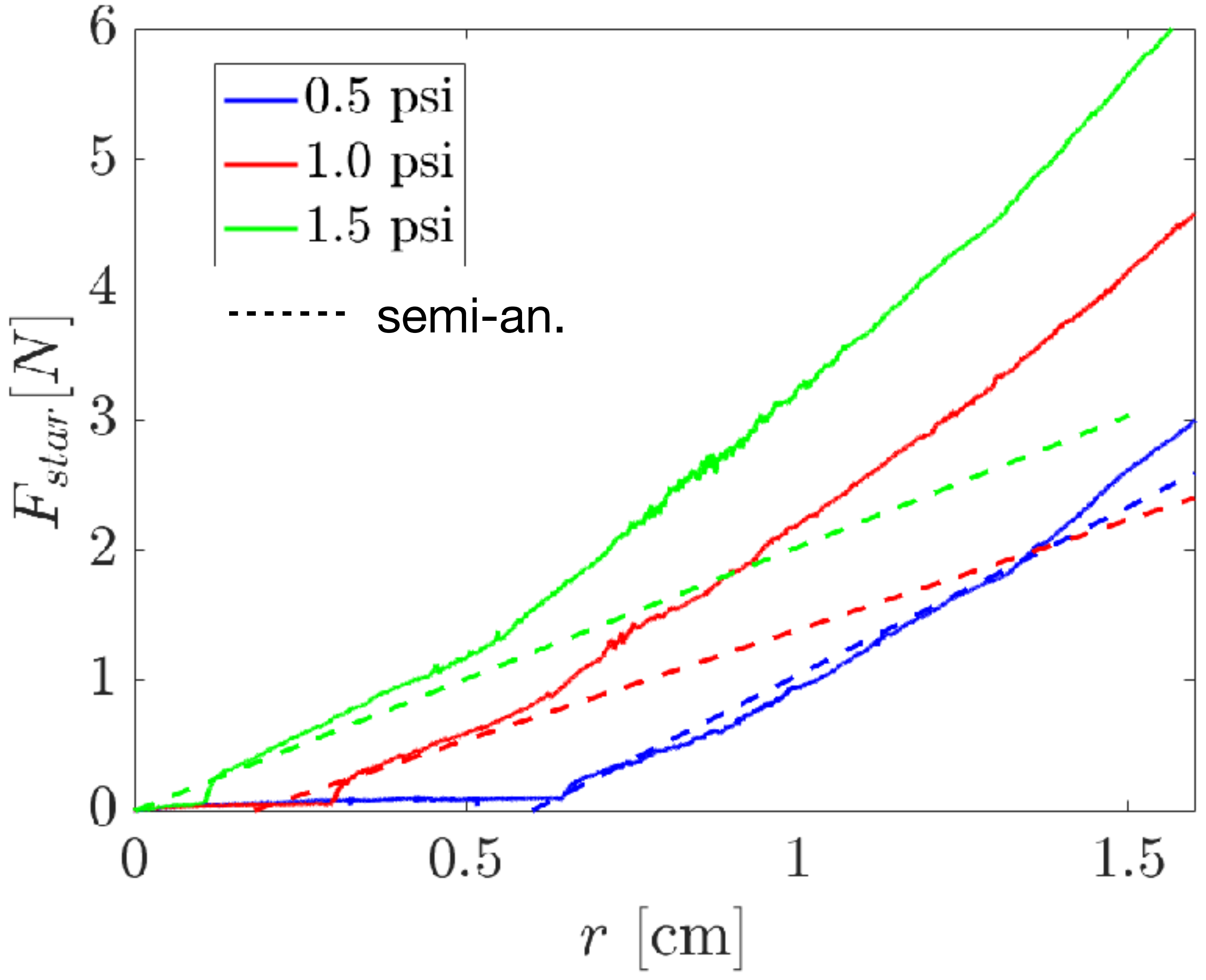


Cone



$$F_{star} = \frac{dE_{star}}{dr} \approx \frac{4n(C_i + C_e)\ \sin(\pi/n)^2}{l^2\ \cos^2(\phi_i^{eq}/2)}(r - r_{eq})$$

Gripping employs the <u>opening</u> (stiffer) mode!

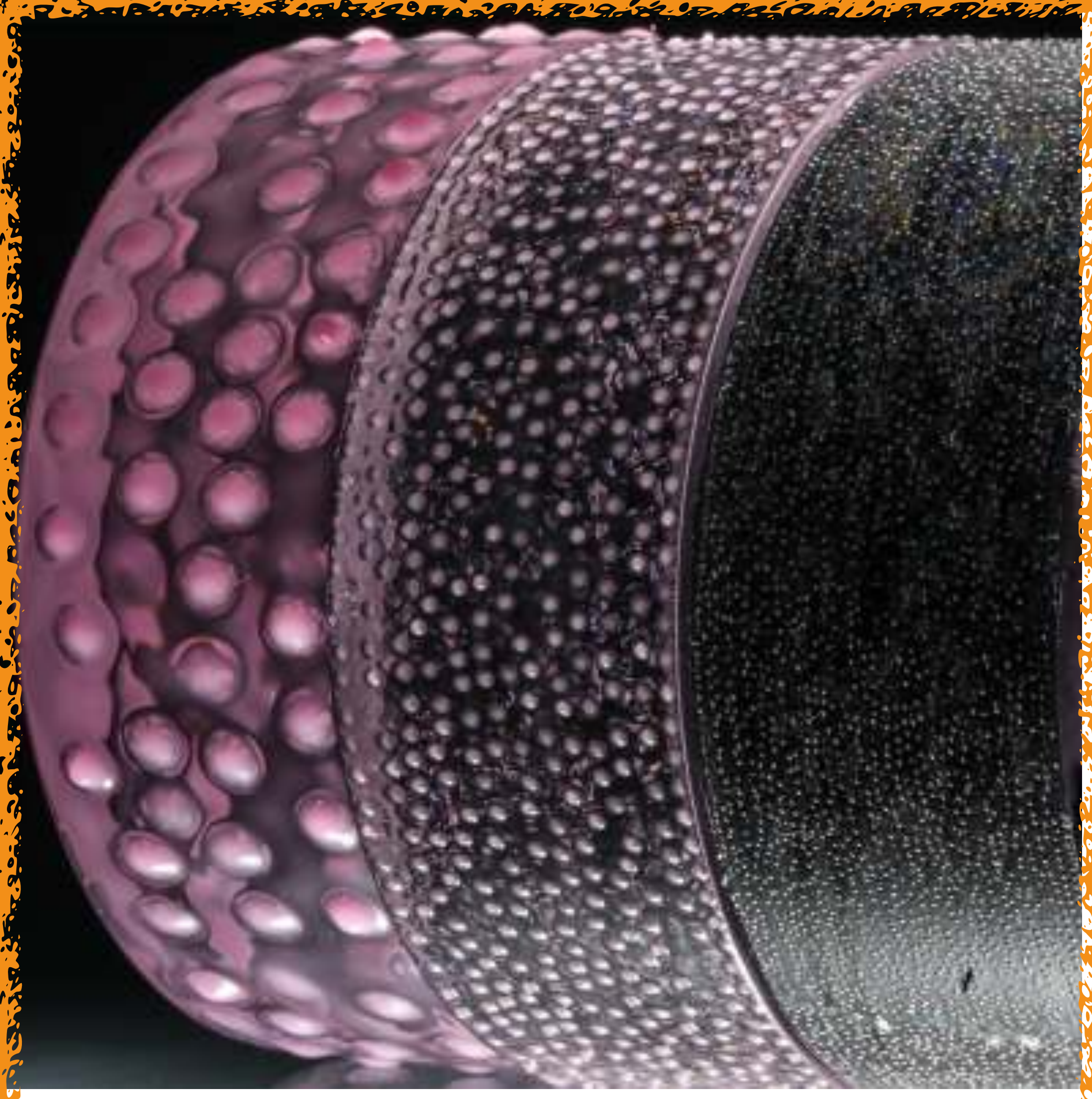


Soft gripper

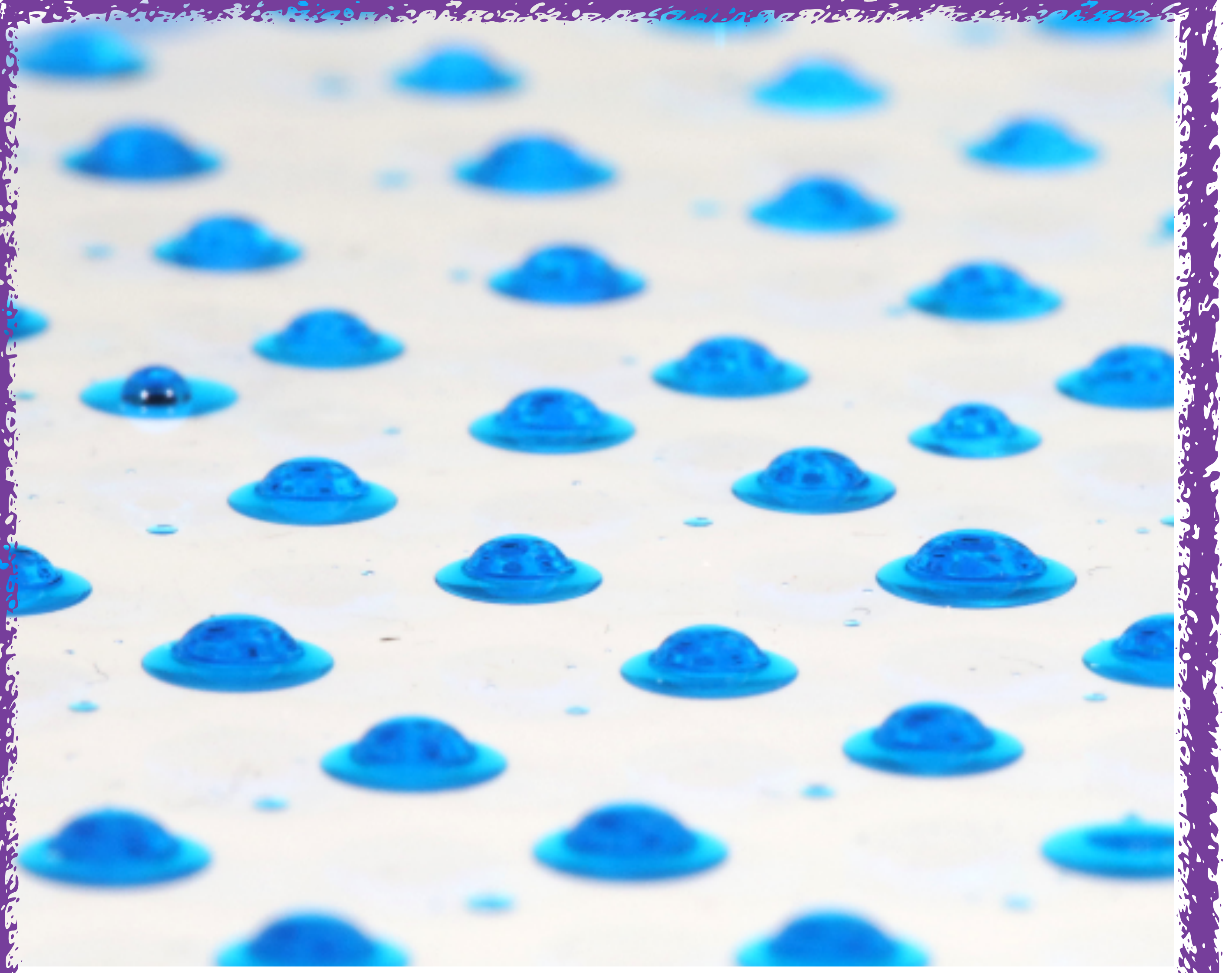
Conclusion

[Nature Communications, 2016]
[Phys Rev Mat 2017]

[Nature 2021]



[Nature Communications, 2018]
[Phys Rev Fluid, 2018]



[PNAS, 2019]
[Advanced Mat, 2020] [Soft Matter, 2020]

PT Brun
Princeton University

Pedro Reis
MIT

Lingzhi Cai
Princeton University

Victor Charpentier
AMU

Ignacio Andrade
AMU

Simon Hadjaje
AMU