Liquid wires

Fiber coiling inside a droplet provides highly compressible device

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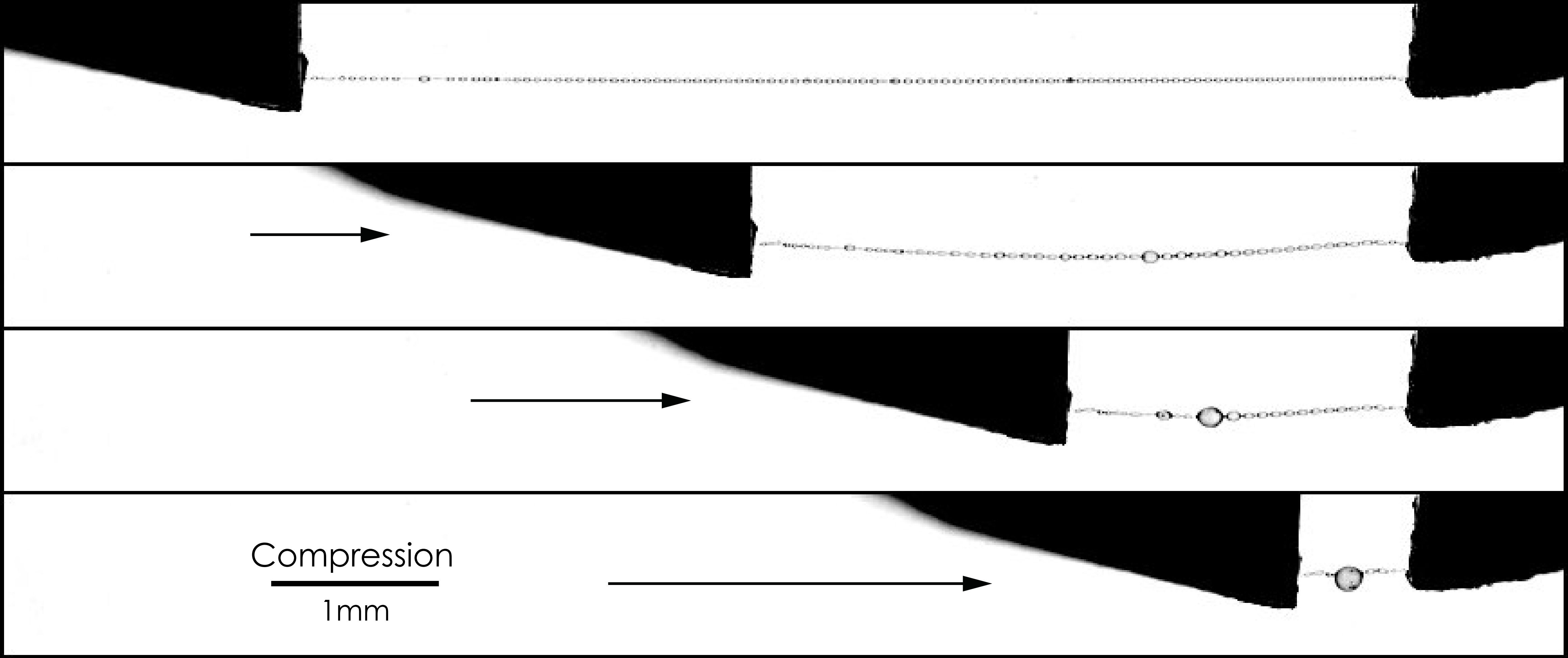
Biological inspiration

Nephila
golden orb weaver

Interesting properties
of its capture silk

Nephila capture silk

Its highly compressible property

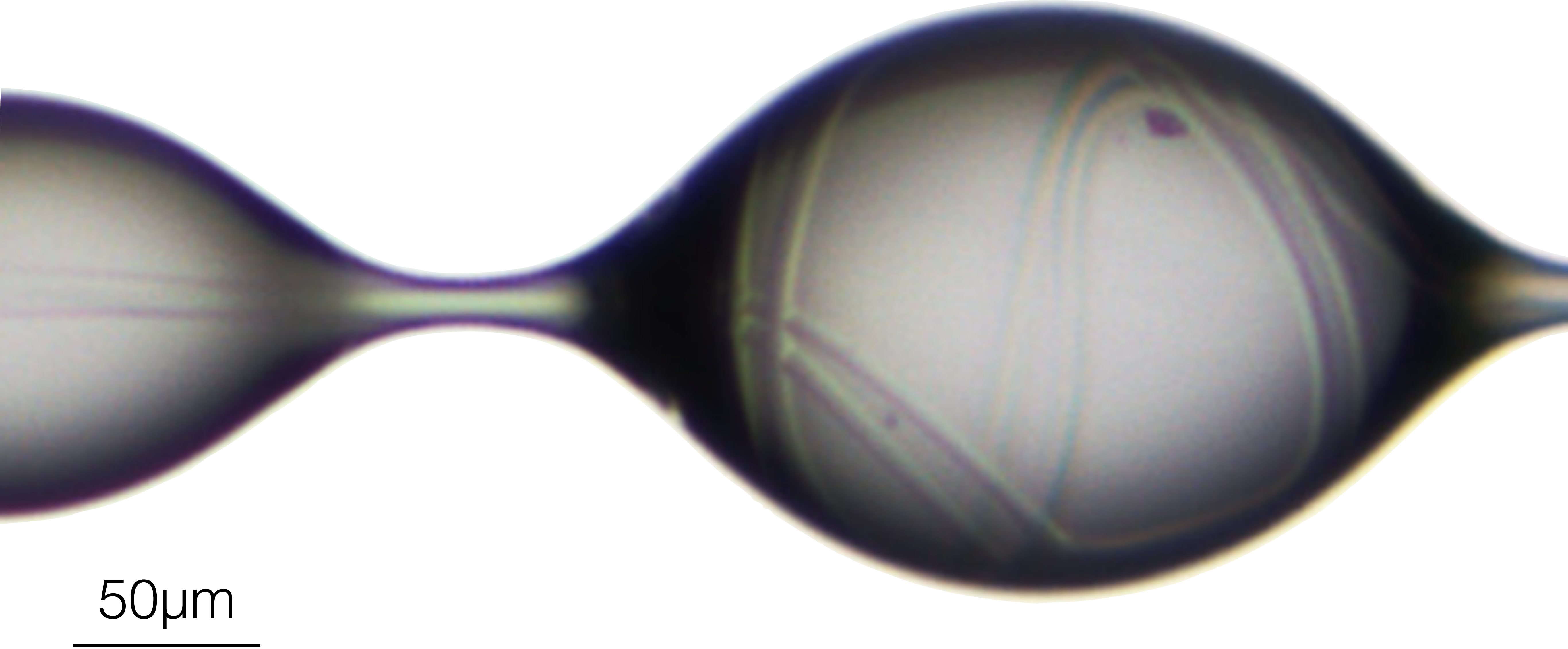


Nephila spider capture silk **thread** coated with small water **droplets**.
Throughout the **compression**, the fiber **does not sag**,
it remains under **tension**.

Video credit: Hervé Elettro

Nephila capture silk

A closer look inside the droplets



During the **compression**,
the thread **spools** inside the water **droplets**.

Droplet on a hair

The disappointing reality of a rainy day

Silicone oil **droplet** on a strand of my very own **hair**.
Note the significant absence of anything noteworthy happening.

Elastocapillarity

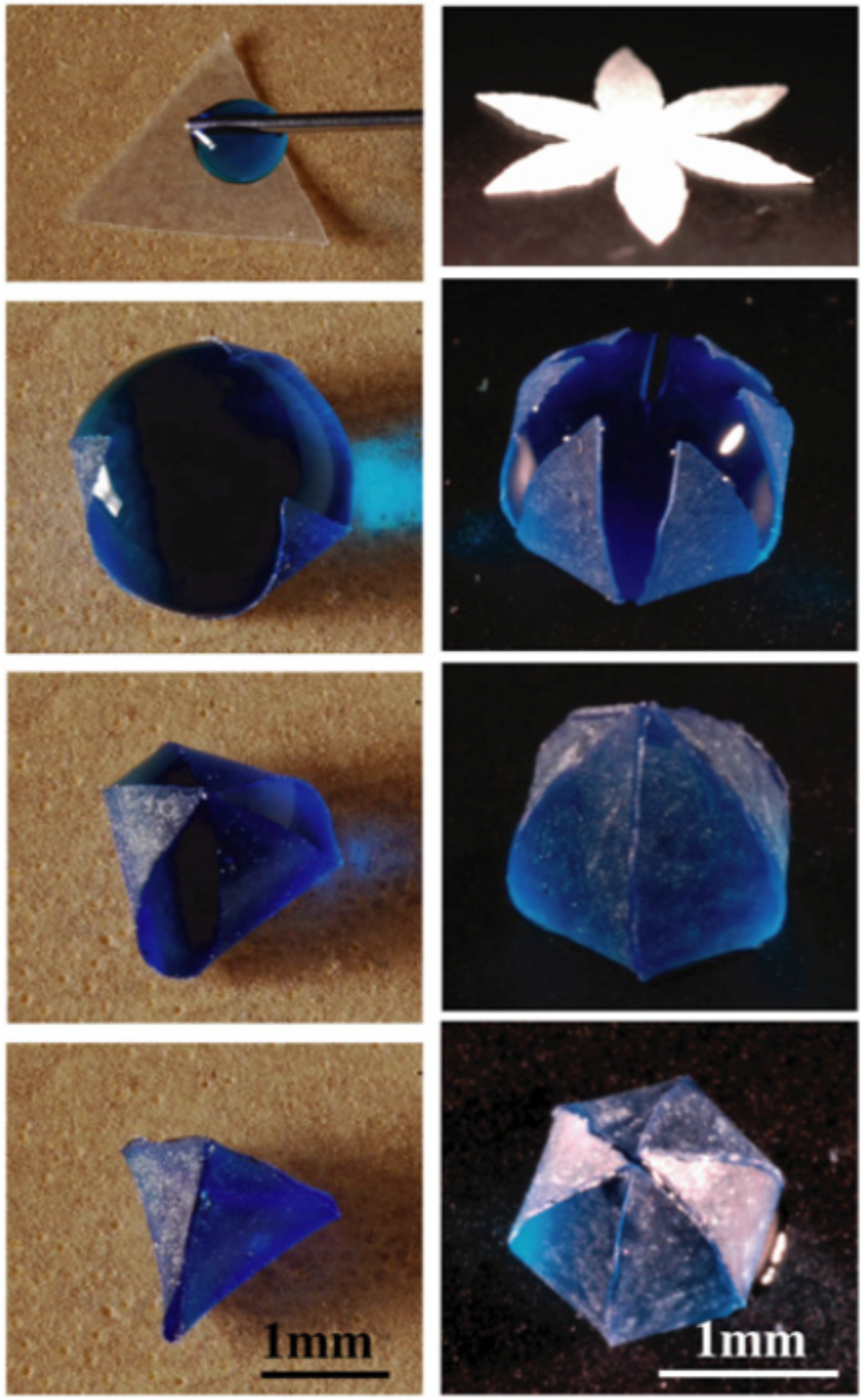
When liquids deform elastic structures

Review article :

B. Roman, J. Bico
Journal of Physics: Condensed Matter 2010

Elastocapillarity

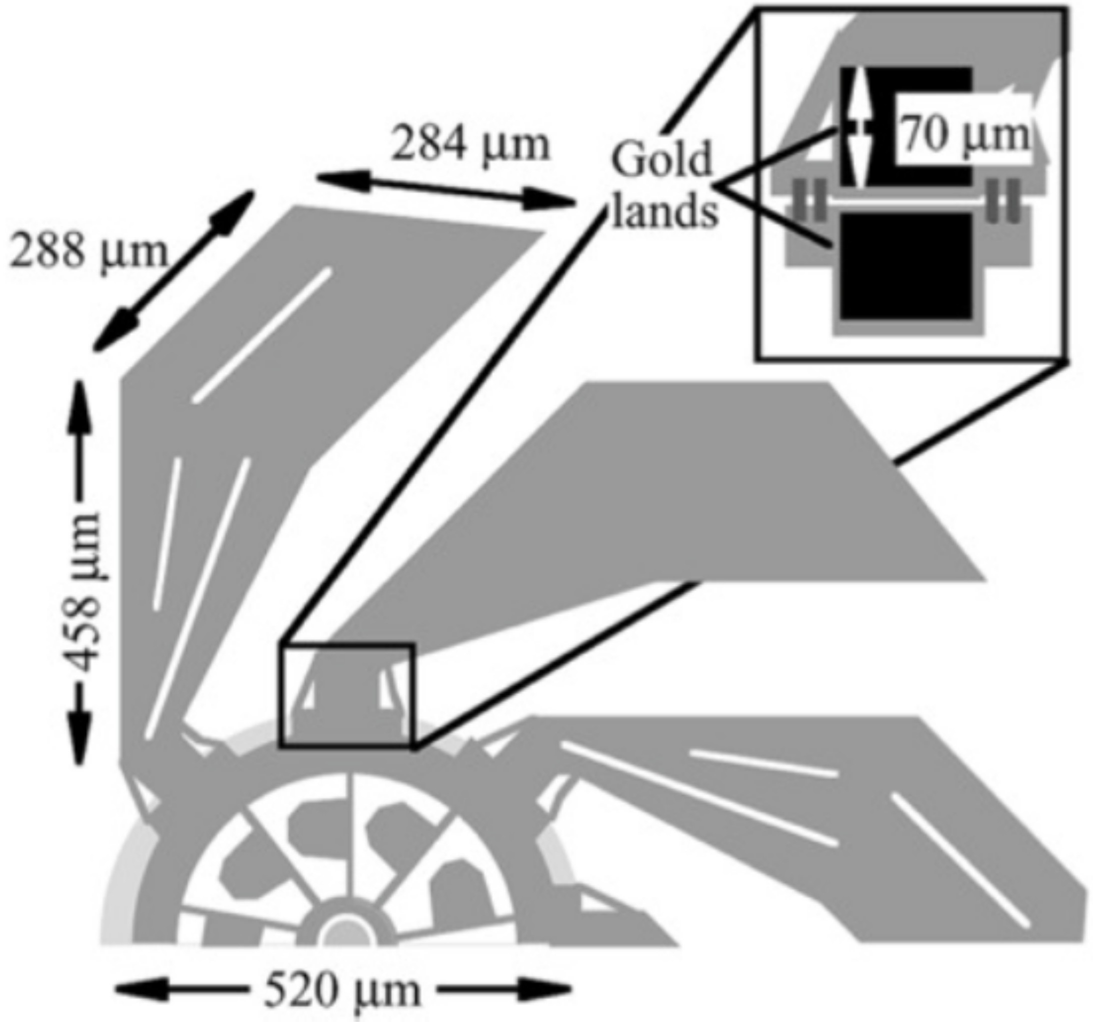
Capillary Origami



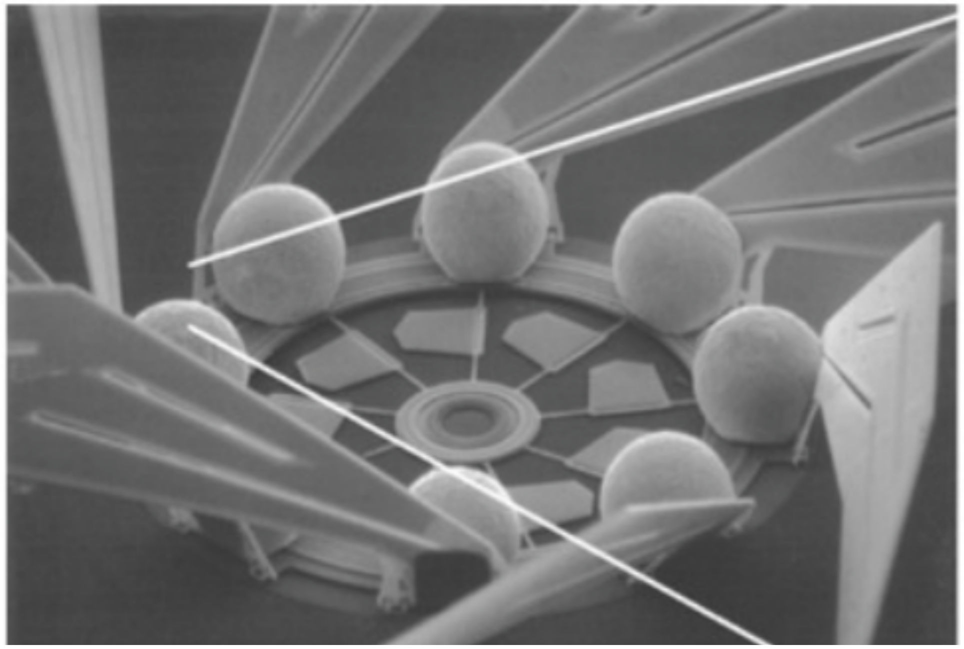
C. Py *et al.* 2007
Capillary origami: spontaneous wrapping of a droplet with an elastic sheet.
Phys. Rev. Lett. 98 156103

Elastocapillarity

Industrial micro-fabrication



Microfan with polysilicone 180 rpm
micro-fluidic system

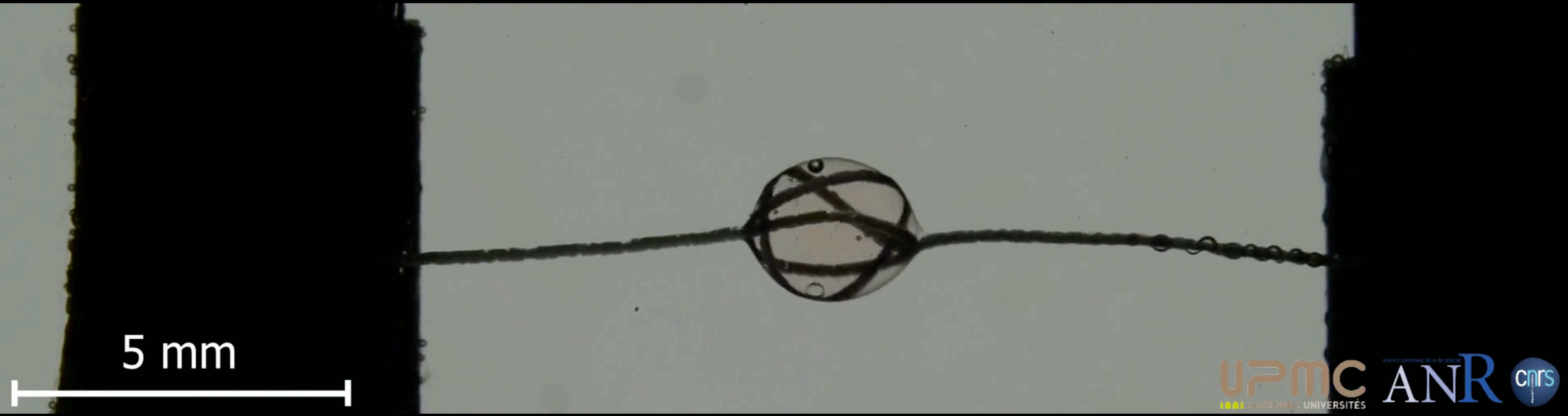


Folding by surface tension of
Pb:Sn solder spheres

Linderman *et al*, **Development of the micro rotary fan**
Sens. Actuators (2002)

Elastocapillary in-drop spooling

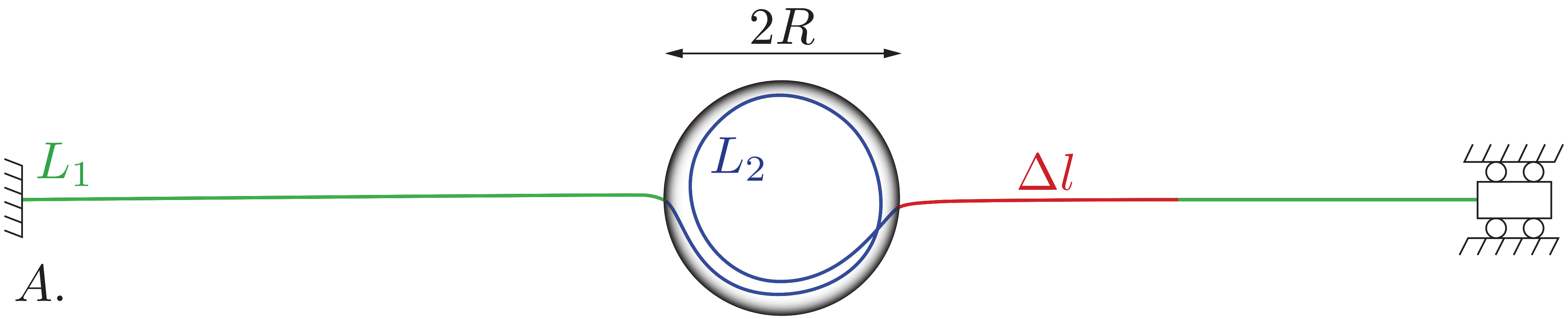
The movie



Silicone oil **droplet** on a RTV (silicone polymer) fiber.
The system is **immersed** in a water bath.
Fiber: radius $a\approx35$ μm, Young's modulus $E\approx1$ Mpa.
Droplet : radius $R=1.5$ mm, $\Delta\gamma\approx40$ mN/m.

Elastocapillary in-drop spooling

The energetic approach



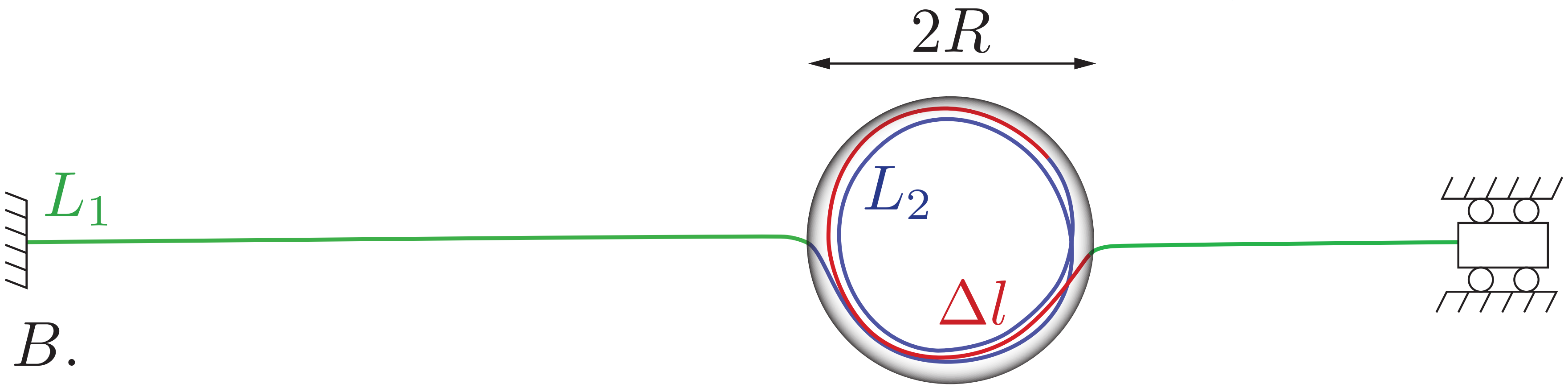
Solid-vapor interface energy

Solid-liquid interface energy

Bending energy

Solid-vapor interface energy

$$V_A = PL_1\gamma_{\mathrm{sv}} + PL_2\gamma_{\mathrm{sl}} + L_2\frac{1}{2}\frac{EI}{R^2} + P\Delta l\gamma_{\mathrm{sv}}$$



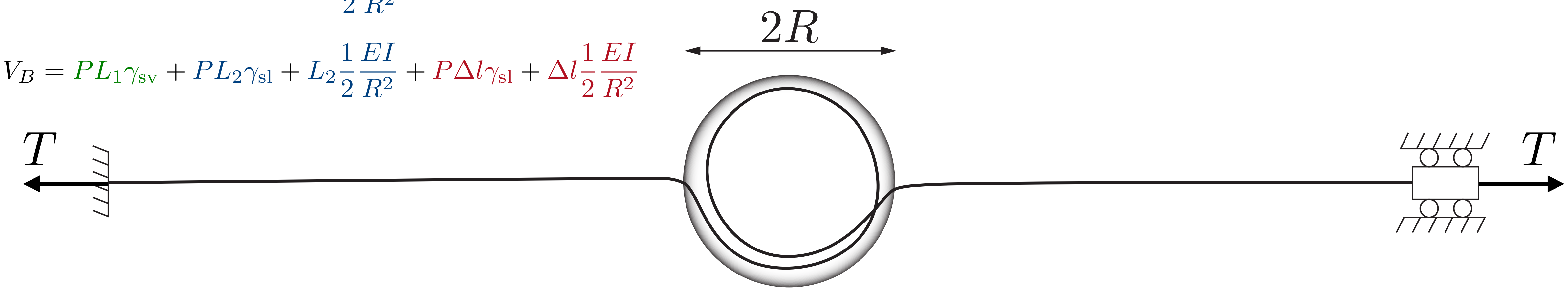
$$V_B = PL_1\gamma_{\mathrm{sv}} + PL_2\gamma_{\mathrm{sl}} + L_2\frac{1}{2}\frac{EI}{R^2} + P\Delta l\gamma_{\mathrm{sl}} + \Delta l\frac{1}{2}\frac{EI}{R^2}$$

Elastocapillary in-drop spooling

The energetic approach

$$V_A = PL_1\gamma_{\mathrm{sv}} + PL_2\gamma_{\mathrm{sl}} + L_2\frac{1}{2}\frac{EI}{R^2} + P\Delta l\gamma_{\mathrm{sv}}$$

$$V_B = PL_1\gamma_{\mathrm{sv}} + PL_2\gamma_{\mathrm{sl}} + L_2\frac{1}{2}\frac{EI}{R^2} + P\Delta l\gamma_{\mathrm{sl}} + \Delta l\frac{1}{2}\frac{EI}{R^2}$$



$$\Delta V = \Delta l\left(\frac{1}{2}\frac{EI}{R^2} - P\Delta\gamma\right)$$

$$T = -\frac{\Delta V}{\Delta l} = \left(P\Delta\gamma - \frac{1}{2}\frac{EI}{R^2}\right)$$

$$T > 0\,?$$

$$a < \sqrt[3]{\frac{16R^2\Delta\gamma}{E}} \sim 10\,\mu\mathrm{m}$$

Circular cross section fiber of radius a:

$$P = 2\pi a$$

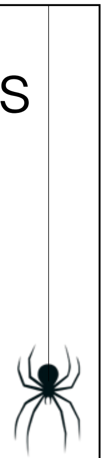
$$I = \frac{\pi a^4}{4}$$

Typical values (spider silk):

$$R \sim 100\,\mu\mathrm{m}$$

$$E \sim 10\ \mathrm{MPa}$$

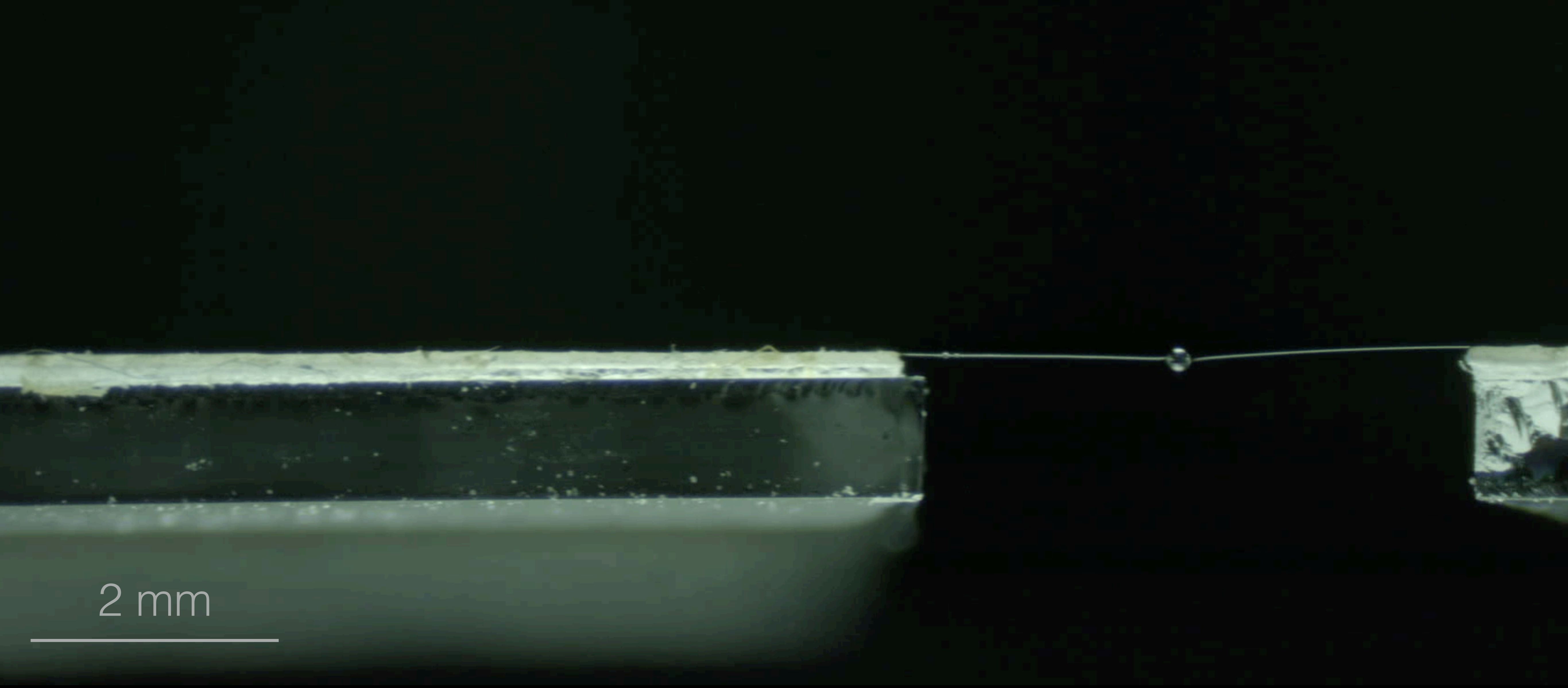
$$\Delta\gamma \sim 50\ \mathrm{mN/m}$$



If it is **thin** and **elastic** enough, a thread can coil inside a droplet!

Elastocapillary in-drop spooling

The movie II

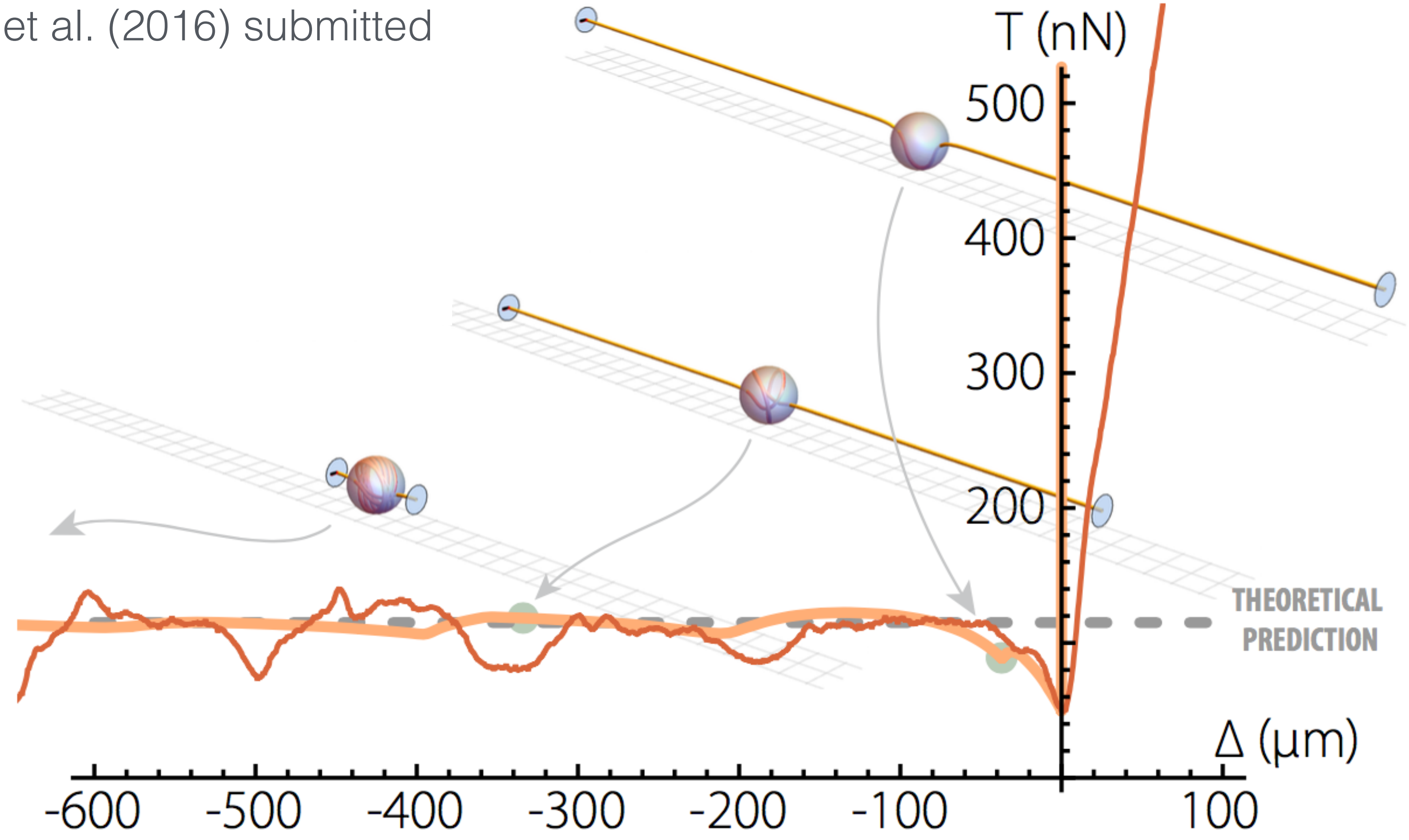


Silicone oil **droplet** on a thermoplastic polyurethane **microfiber**.
An artificial ultra **compressible/extensible** device.
Fiber: radius a=3.4 µm, Young's modulus E=17 Mpa.
Droplet : radius R=106 µm, $\Delta\gamma \approx 20$ mN/m.

Elastocapillary in-drop spooling

The mechanical response

Figure: Elettro et al. (2016) submitted



Silicone oil **droplet** on a thermoplastic polyurethane **microfiber**.
Mechanical behaviour under **extension**.
Fiber: radius *a*=1 μm, Young's modulus E=17 Mpa.
Droplet : radius *R*=31 μm, $\Delta\gamma$ = 20 mN/m.

With great power comes great stiffness

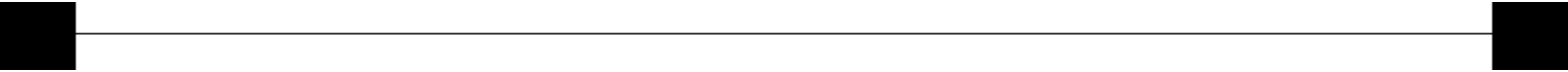
Electrically conducting materials usually have high Young's moduli
E ~ 1-10 GPa for conducting polymers
E ~10 -100 GPa for metals

$$a < \sqrt[3]{\frac{16R^2\Delta\gamma}{E}} \sim 0.1 - 1\,\mu\mathrm{m}$$

To spool conducting fibers, we need **sub-micronic** fibers.

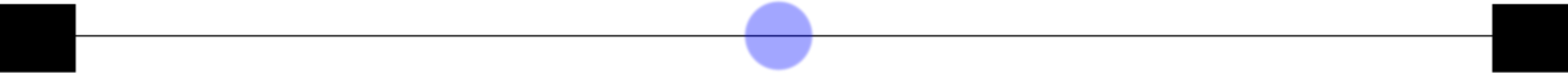
Difficult to manufacture!

Coiling the uncoilable



Rigid thin fiber E_1, P_1, I_1

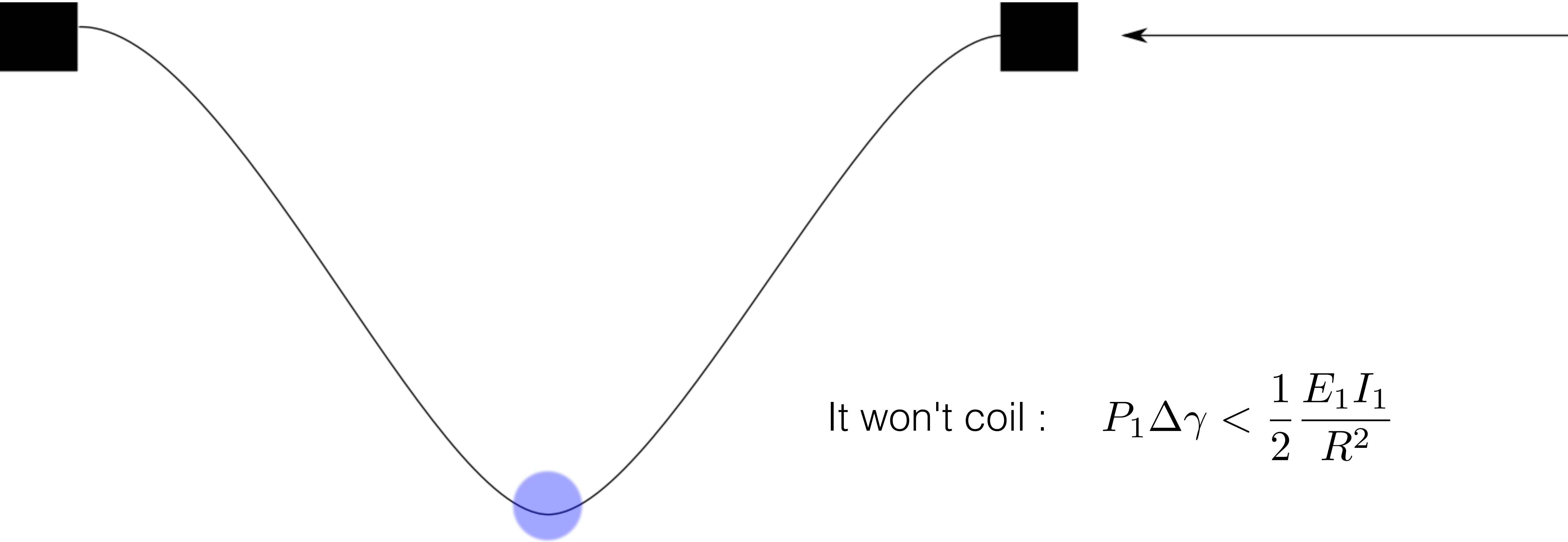
Coiling the uncoilable



Rigid thin fiber (E_1, P_1, I_1) + Droplet $(\Delta\gamma, R)$

Coiling the uncoilable

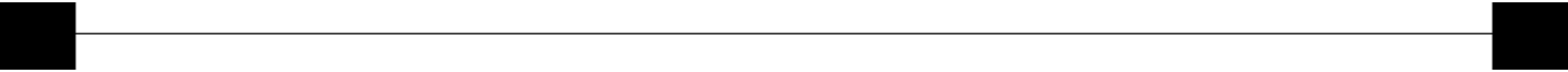
Rigid thin fiber (E_1, P_1, I_1) + Droplet $(\Delta\gamma, R)$



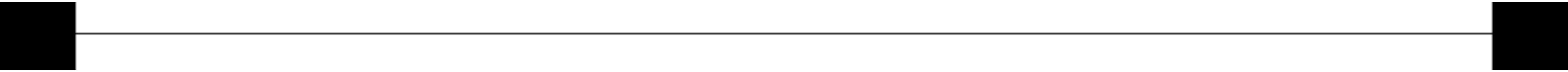
It won't coil : $P_1 \Delta\gamma < \frac{1}{2} \frac{E_1 I_1}{R^2}$

Coiling the uncoilable

Rigid thin fiber (E_1, P_1, I_1) + Droplet $(\Delta\gamma, R)$



Coiling the uncoilable



Rigid thin fiber (E_1, P_1, I_1)

Coiling the uncoilable

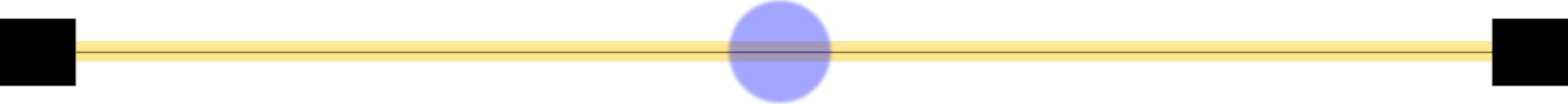
Rigid thin fiber (E_1, P_1, I_1)

+ Soft big fiber (E_2, P_2, I_2)

Coiling the uncoilable

the soft tutor

Rigid thin fiber (E_1, P_1, I_1) + Droplet $(\Delta\gamma, R)$



+ Soft big fiber (E_2, P_2, I_2)

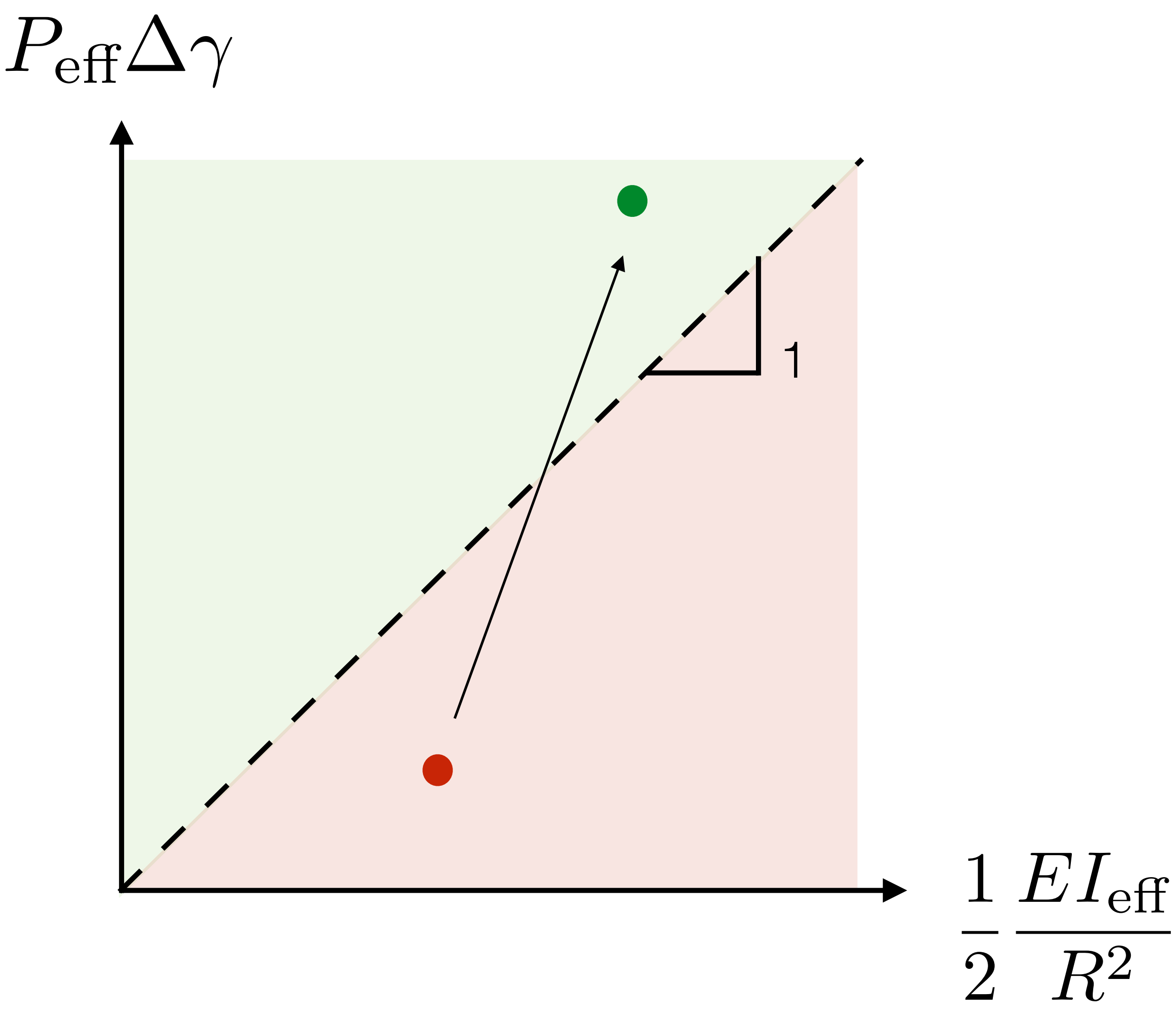
Coiling the uncoilable

The soft tutor

Rigid thin fiber (E_1, P_1, I_1) + Droplet $(\Delta\gamma, R)$

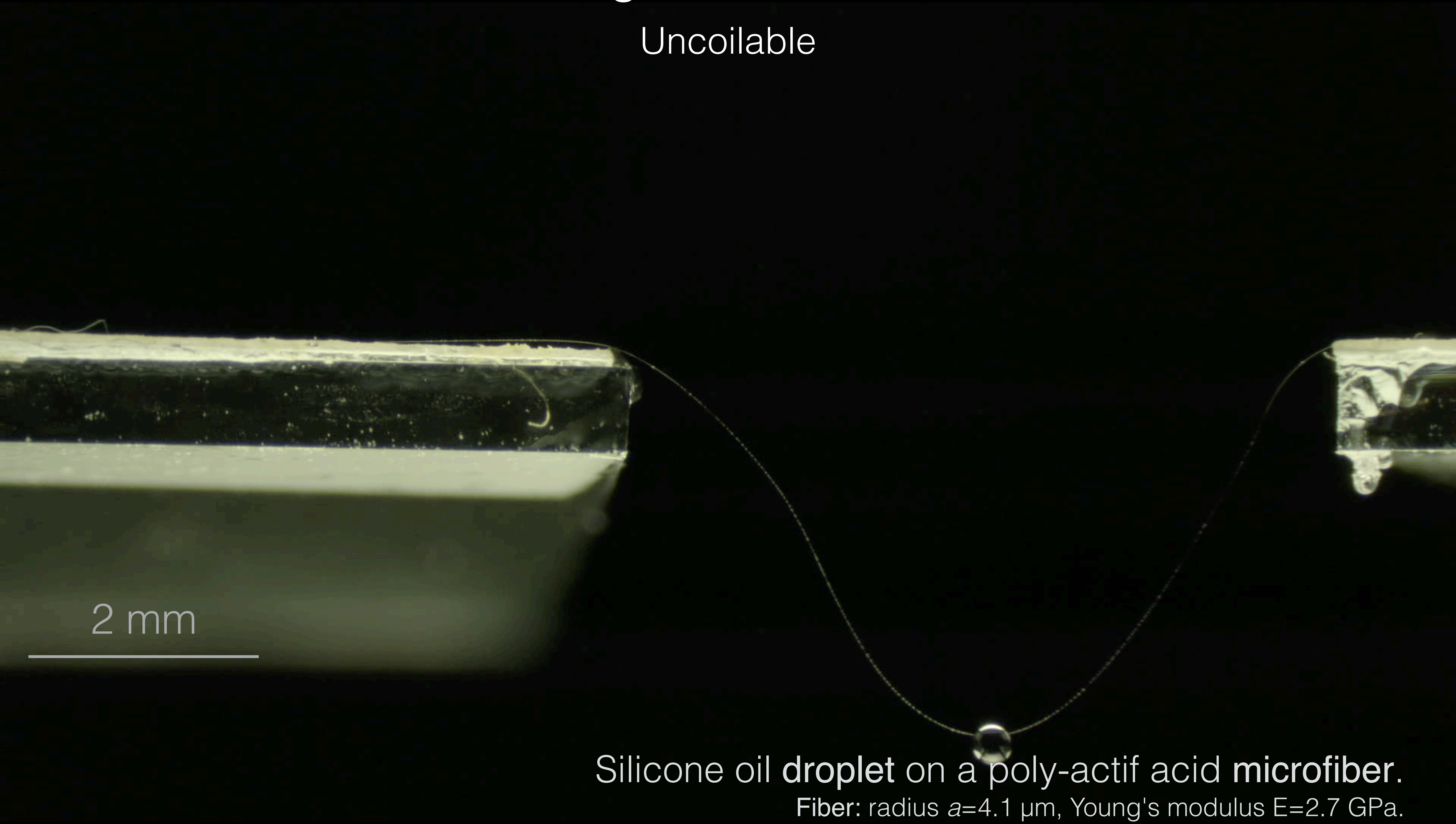
+ Soft big fiber (E_2, P_2, I_2)

It coils: $(P_1 + P_2)\,\Delta\gamma > \dfrac{1}{2}\dfrac{E_1 I_1 + E_2 I_2}{R^2}$



Coiling the uncoilable

Uncoilable



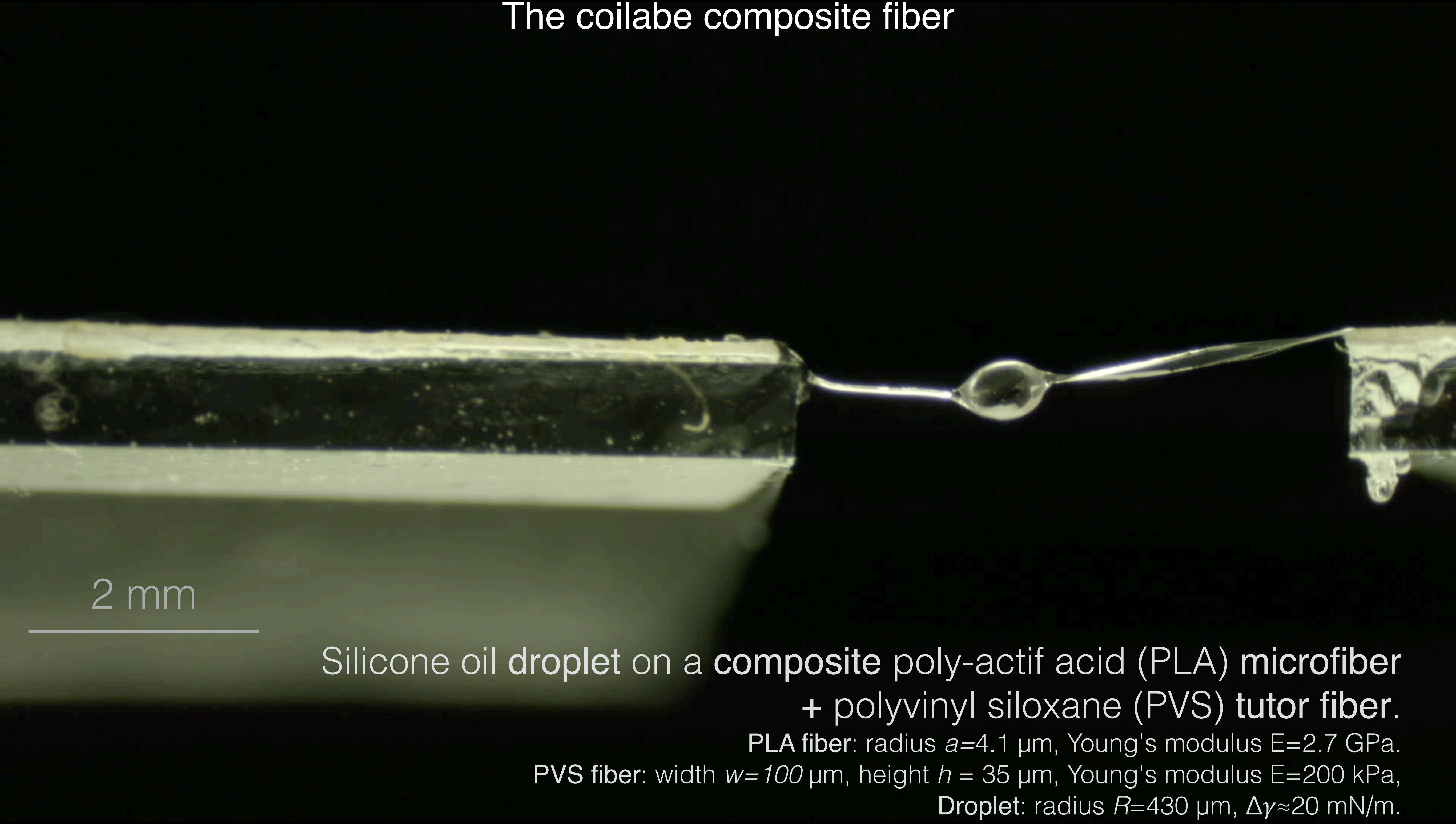
Silicone oil **droplet** on a poly-actif acid **microfiber**.

Fiber: radius a=4.1 μm, Young's modulus E=2.7 GPa.

Droplet : radius R=256 μm, $\Delta\gamma\approx$20 mN/m.

Coiling the uncoilable

The coilabe composite fiber

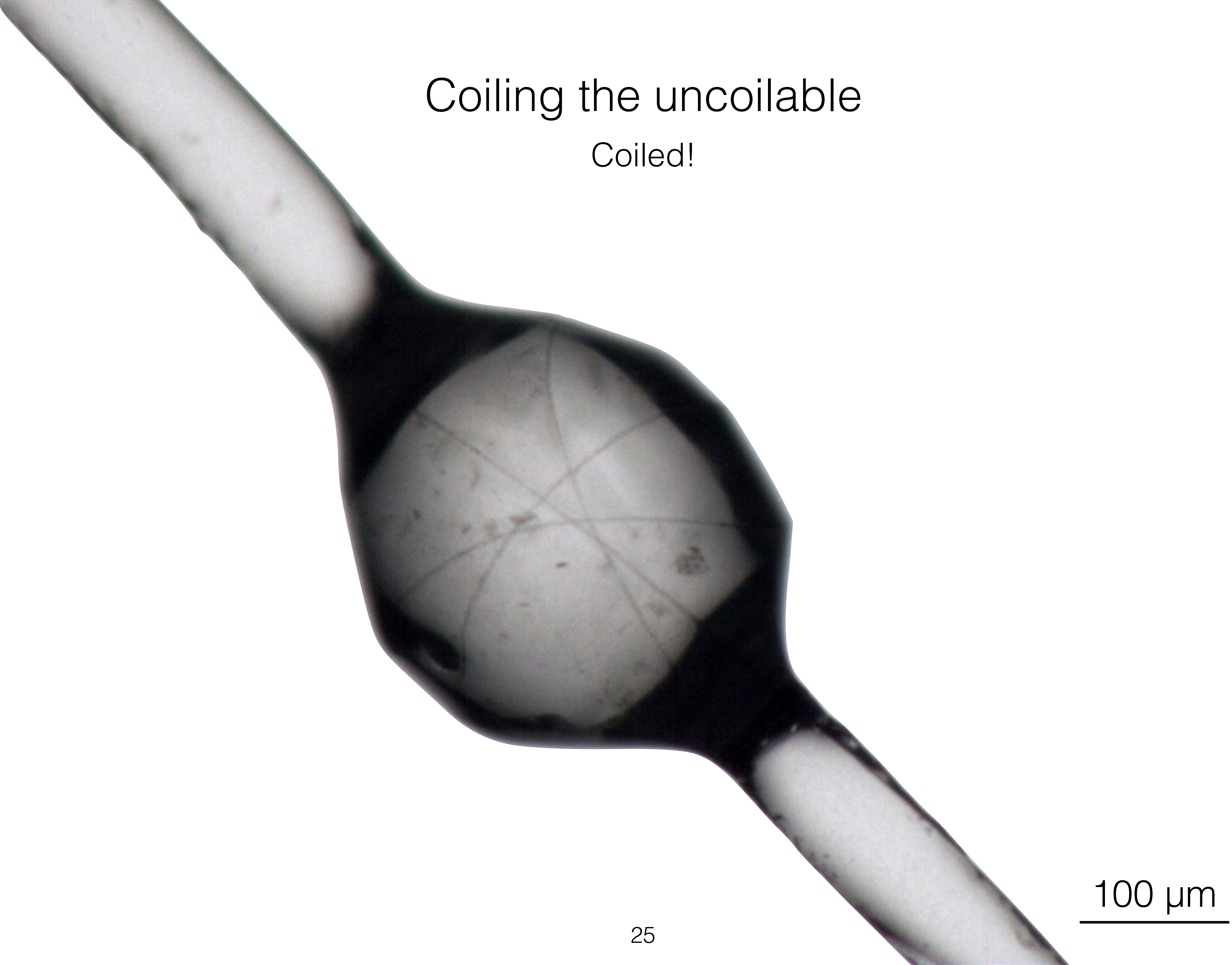


Silicone oil **droplet** on a **composite** poly-actif acid (PLA) **microfiber**
\+ polyvinyl siloxane (PVS) **tutor fiber**.

PLA fiber: radius a=4.1 μm, Young's modulus E=2.7 GPa.
PVS fiber: width w=*100* μm, height h = 35 μm, Young's modulus E=200 kPa,
Droplet: radius R=430 μm, $\Delta\gamma\approx$20 mN/m.

Coiling the uncoilable

Coiled!



Thank you!