Manipulating liquid surface tension: Two ways towards 3D mass microfabrication

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Microfluidics in a fluid mechanics lab

- The study of fluid flow on the Micron-scale
- Fluid mechanics at $Re \ll 1$ is simple (linear *Stokes* flow)

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  - Other physics (heat, surfactant, wetting, ...)
  - Chemistry (reaction-diffusion), biology/biophysics

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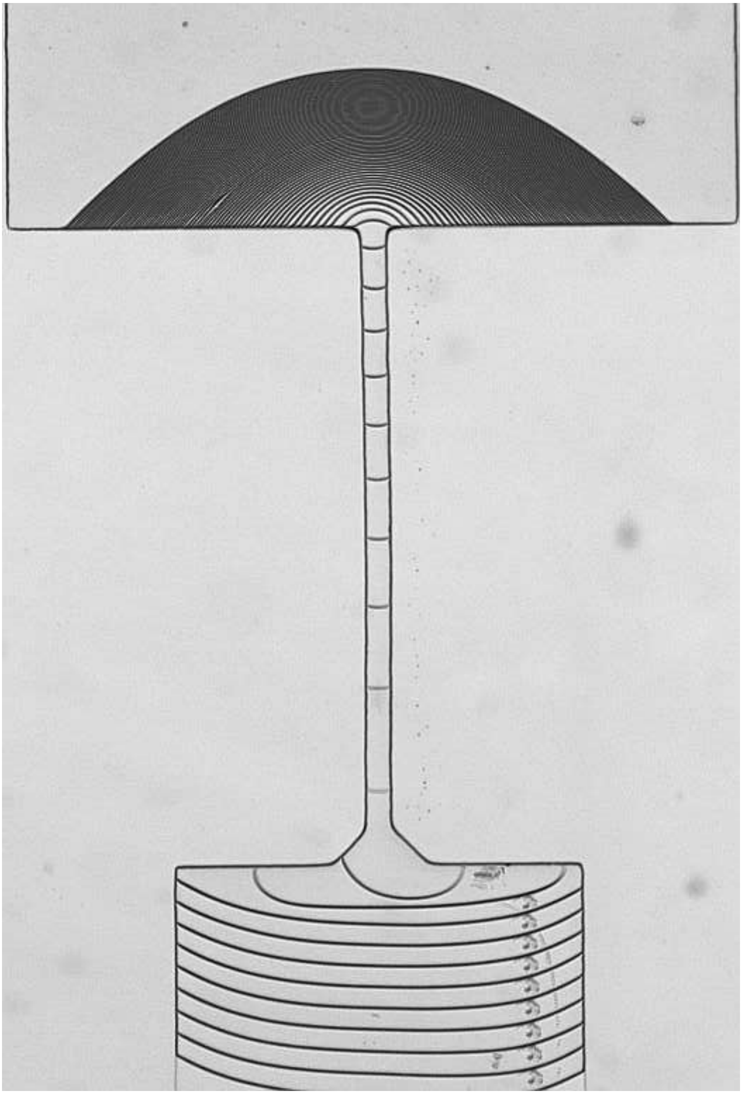
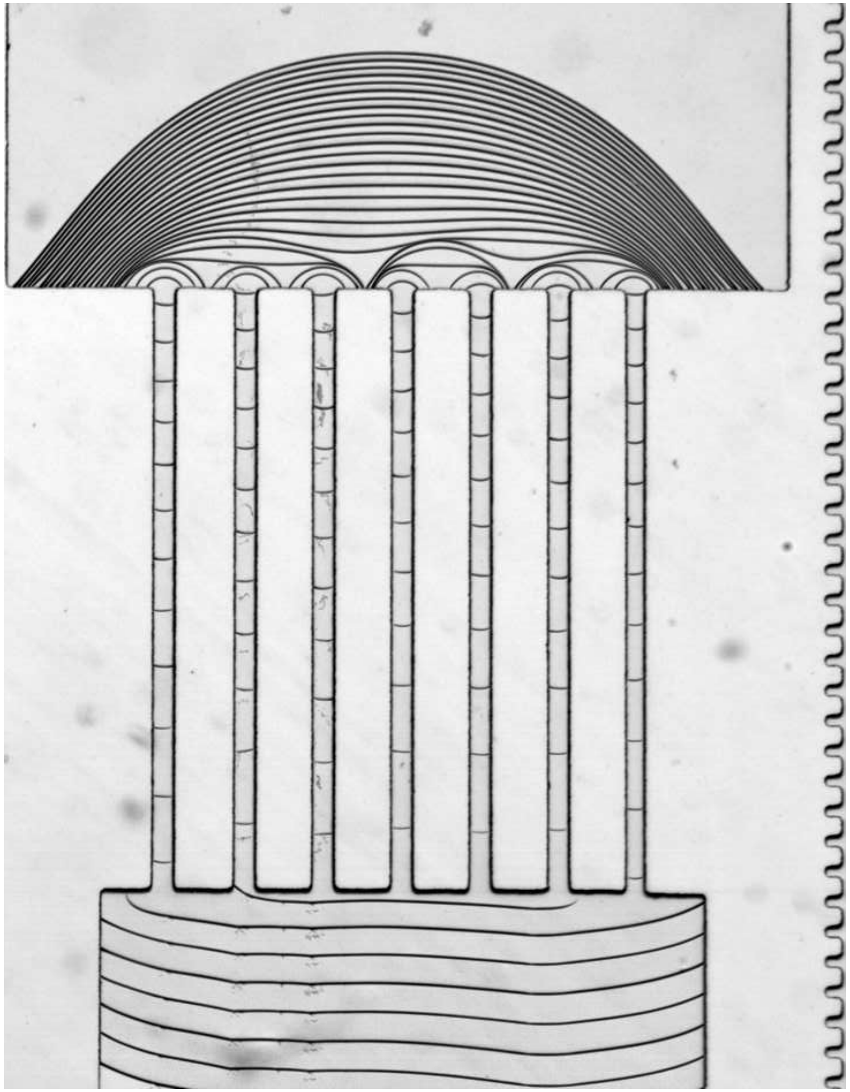
Surface tension: Dominant effect that should be tamed

Surface tension vs. viscosity

Collective effects of pores: complex geometries





Dynamic variations of surface tension

Formation of tiny little droplets

Part I: Surface tension vs. Elasticity

Self-assembly of 3D micro-structures

Surface tension vs. Elasticity

- Micro-fabrication of 3D structures is difficult
- Most methods rely on multiple layers of planar etching
- Recent approach: Fold planar structure into 3D shape (Origami)

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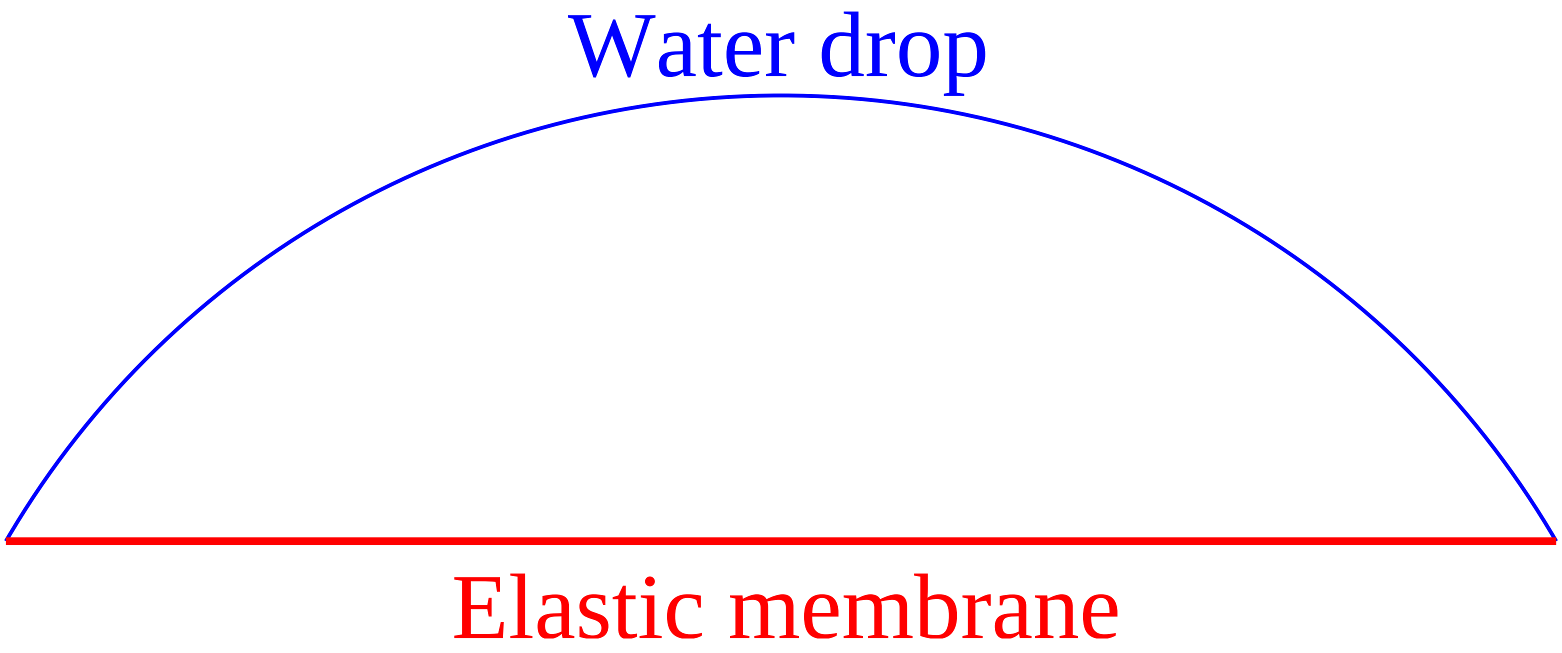
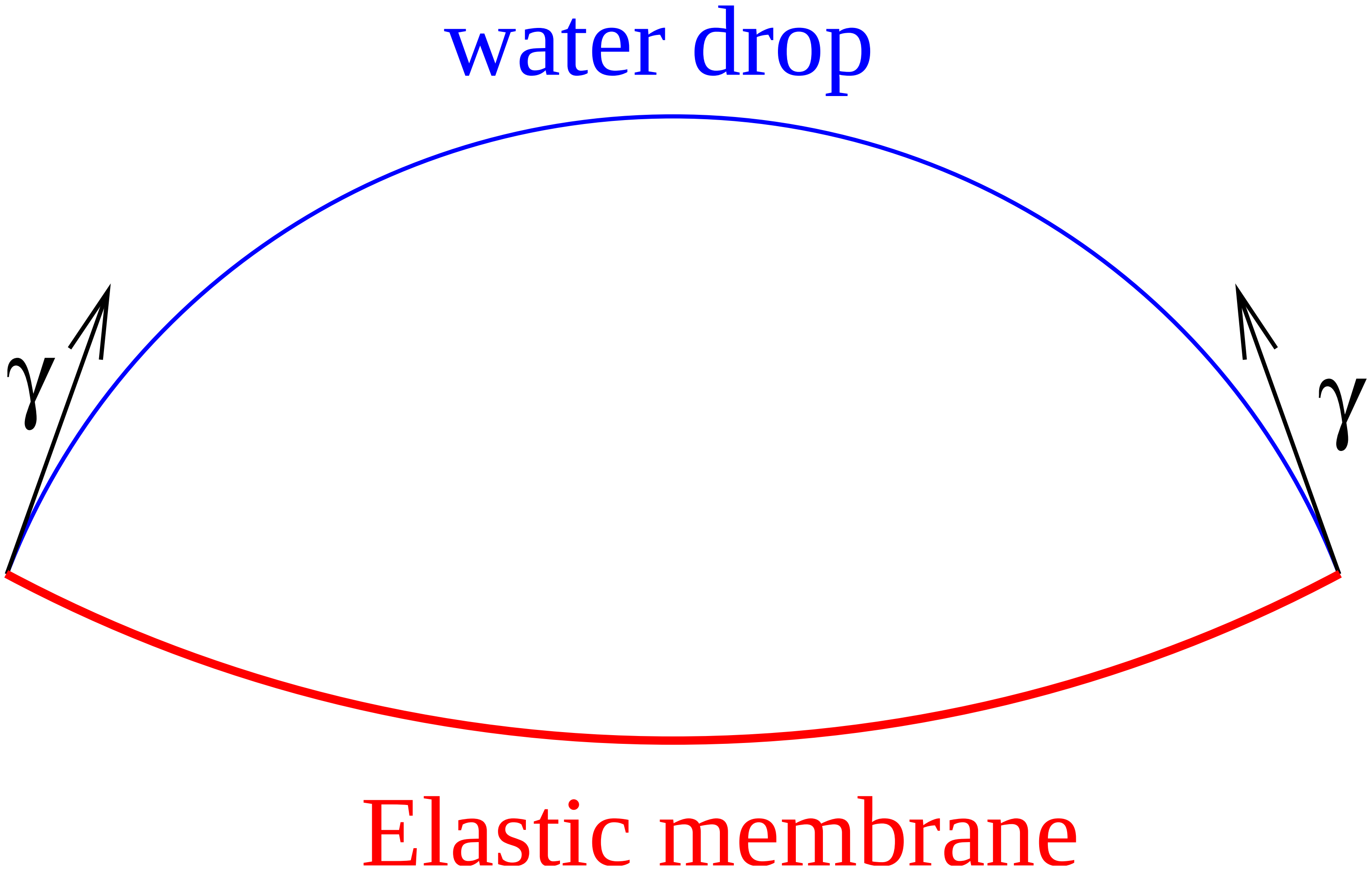
Capillary Origami: Place a water drop on a thin elastic membrane



Surface tension vs. Elasticity

Question 1: What is the equilibrium shape?



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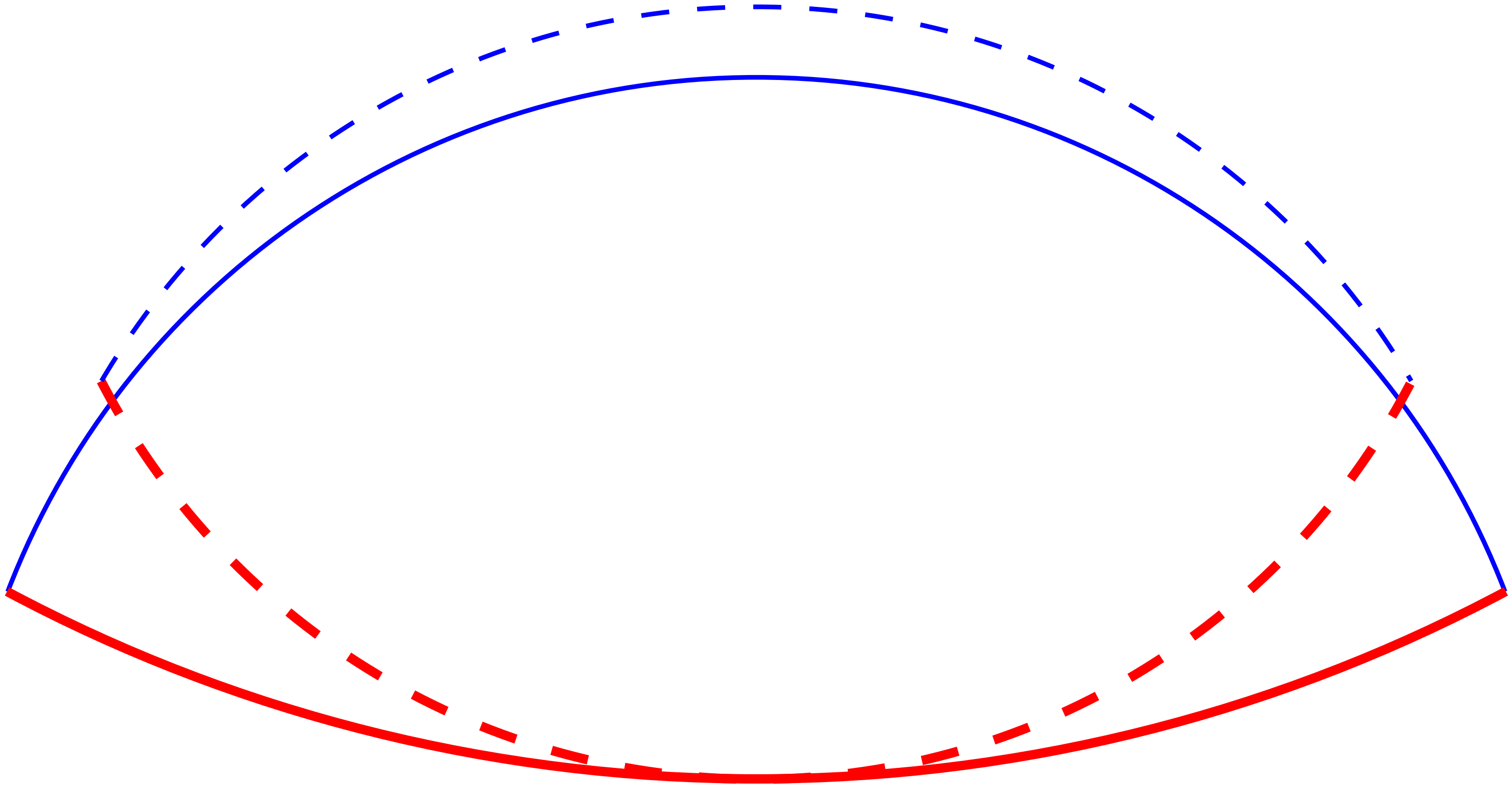

Minimize energy

Minimize total energy $E_{\mathtt{tot}} = E_{\mathtt{cap}} + E_{\mathtt{elast}}$

Capillary energy:

$$E_{\mathtt{cap}} \sim \gamma L^2$$

- γ: Surface tension
- L: Typical length scale

Elastic energy density:

$$\widehat{E}_{\mathtt{elast}} \sim \frac{Eh^3}{24(1-\nu^2)}\kappa^2$$

- κ: curvature
- h: membrane thickness
- E: Young's modulus
- ν: Poisson's ratio

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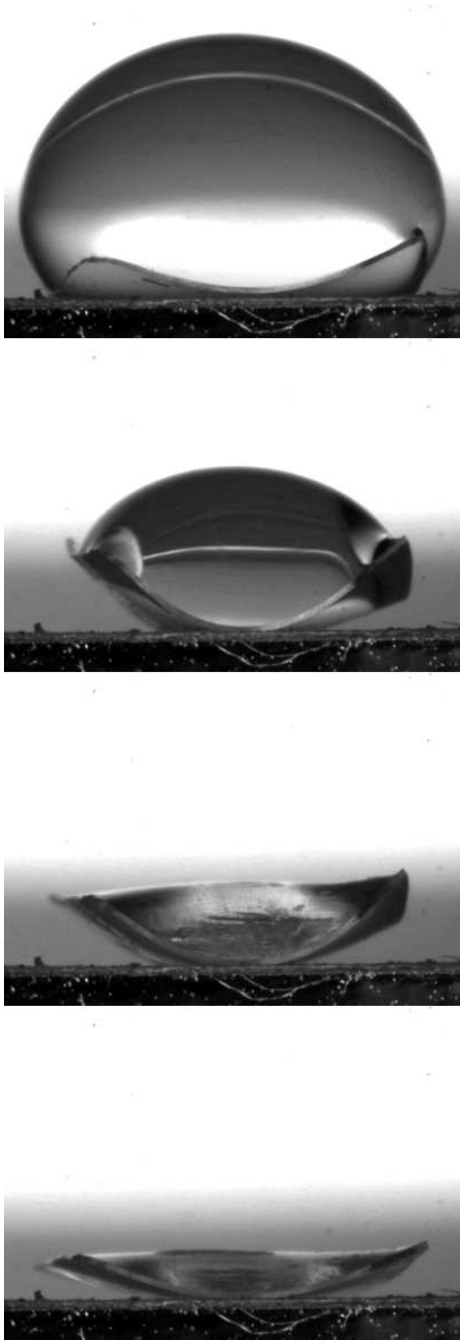
Define Elasto-Capillary length L_{EC}:

$$L_{EC} = \left(\frac{Eh^3/12(1-\nu^2)}{\gamma}\right)^{1/2}$$

Membrane Size, $L\ vs.\ L_{EC}$



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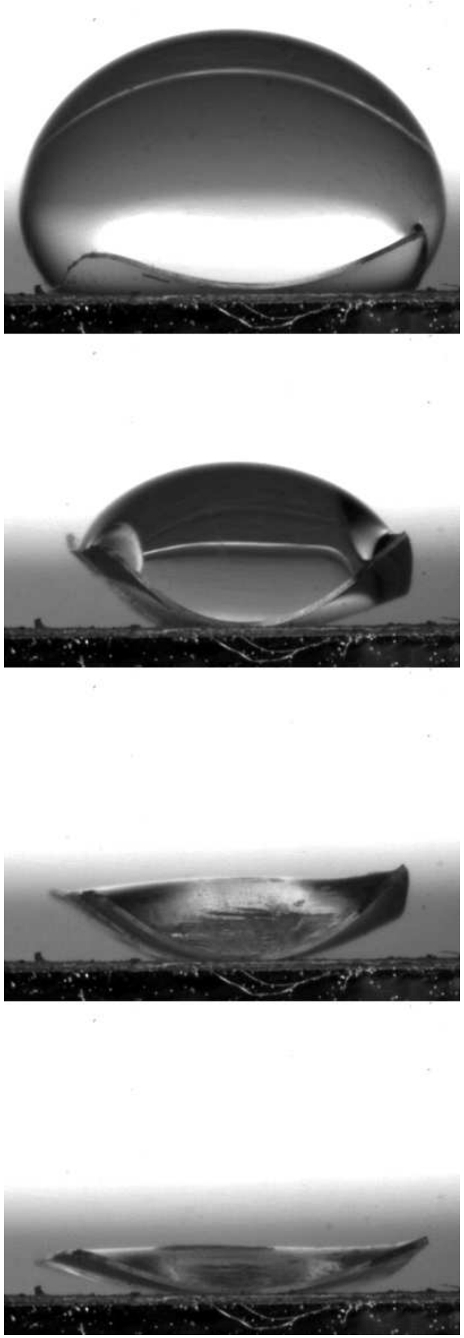
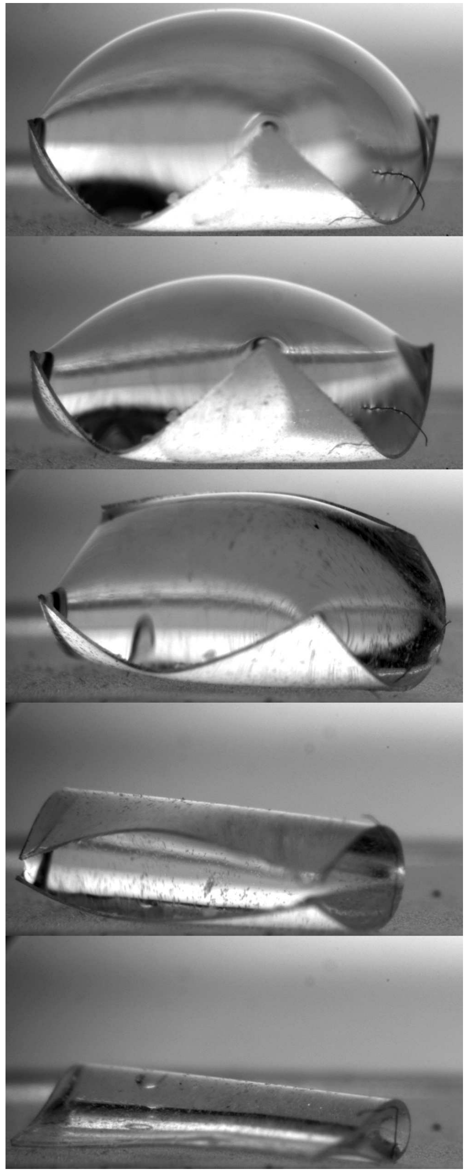
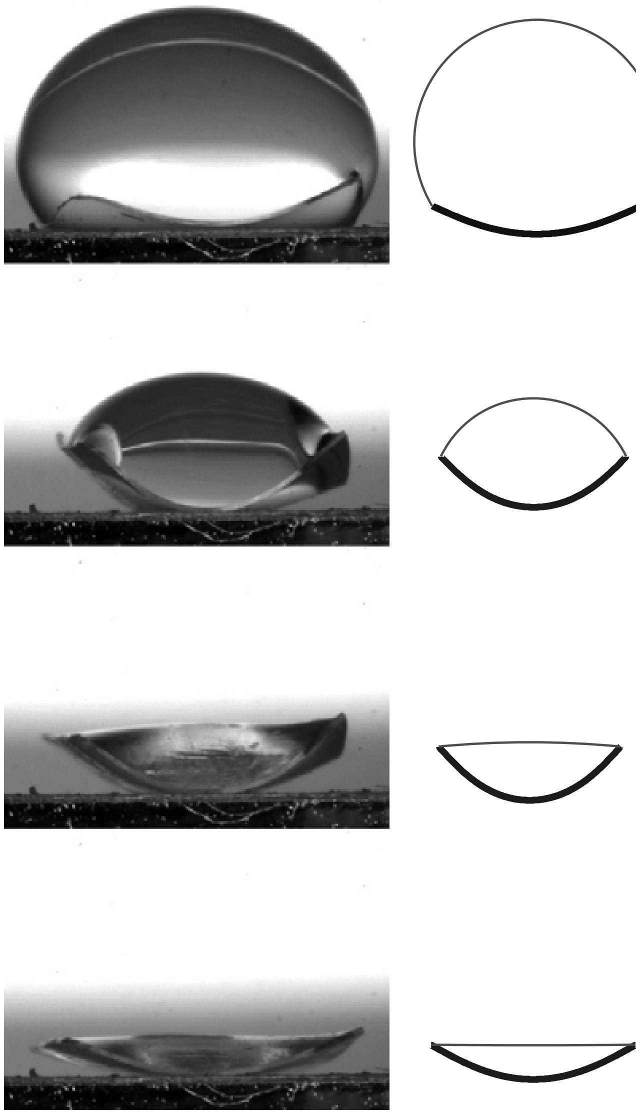




Membrane Size, L *vs.* L_{EC}

$L < L_{crit}$



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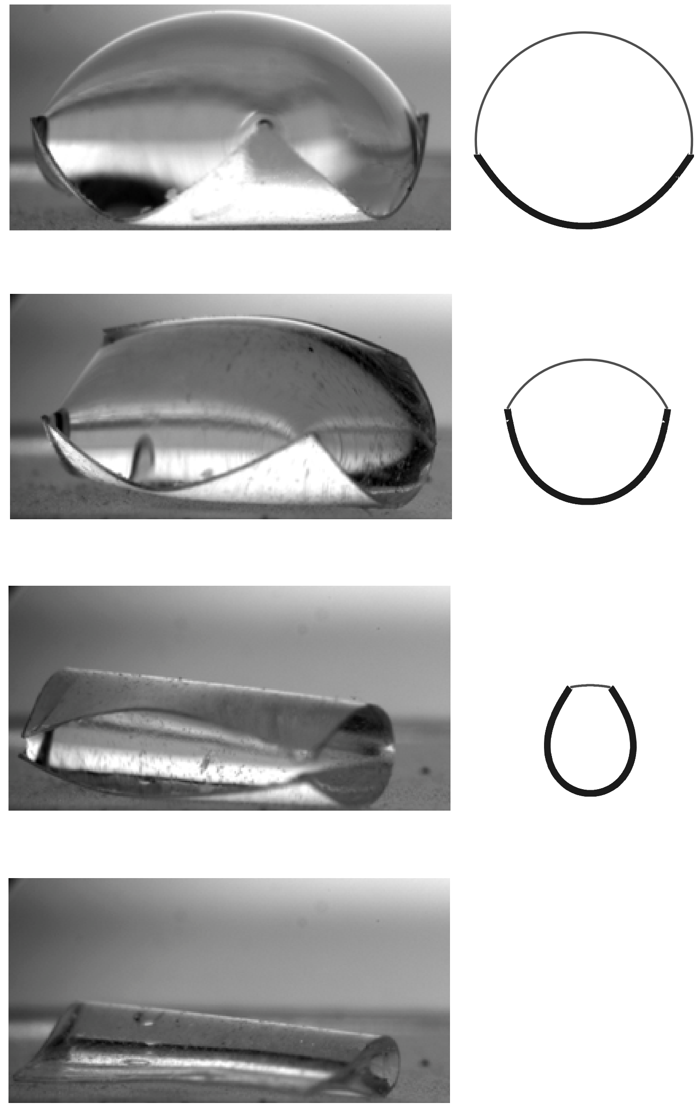
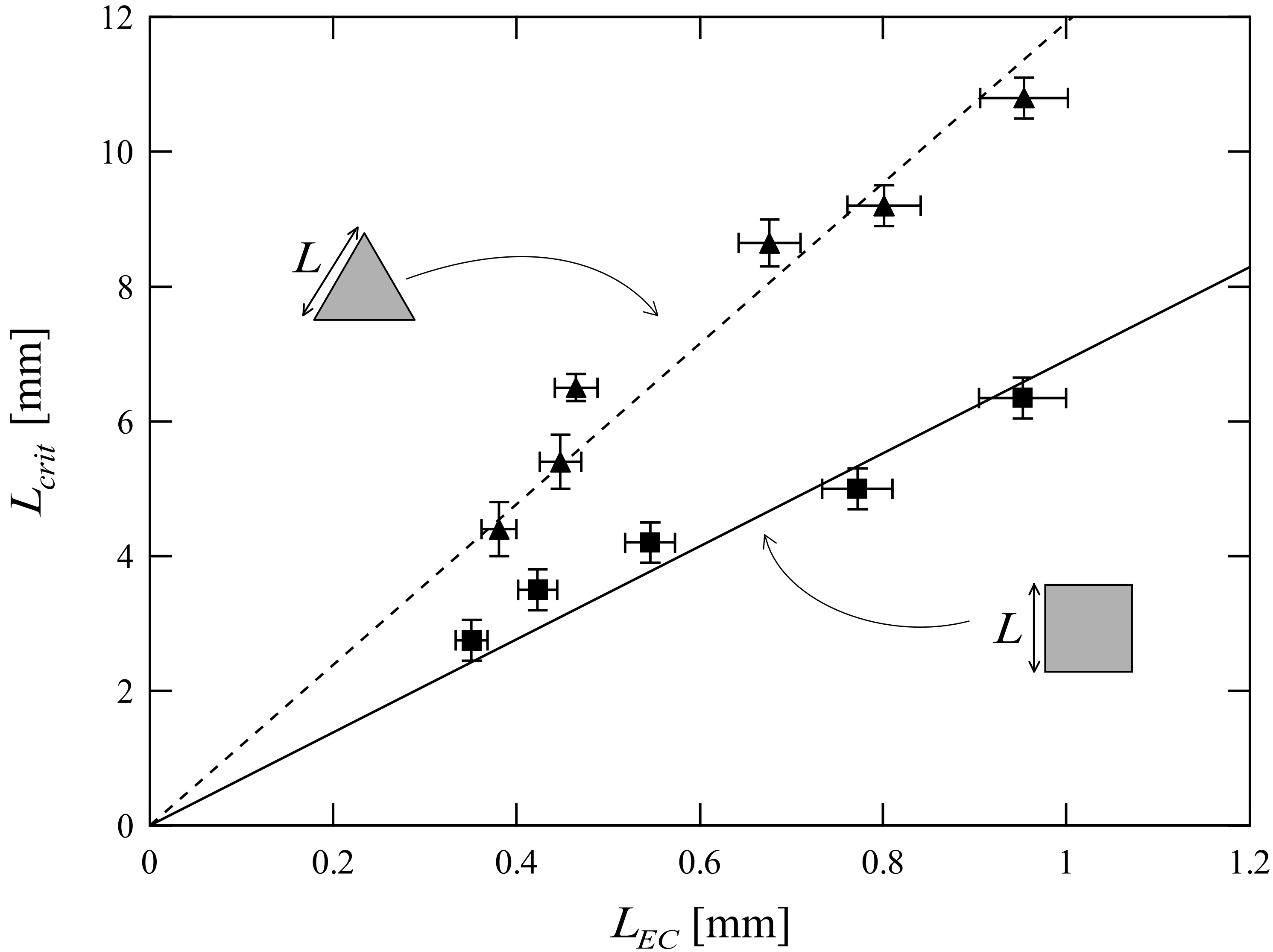


Membrane Size, $L \; vs. \; L_{EC}$



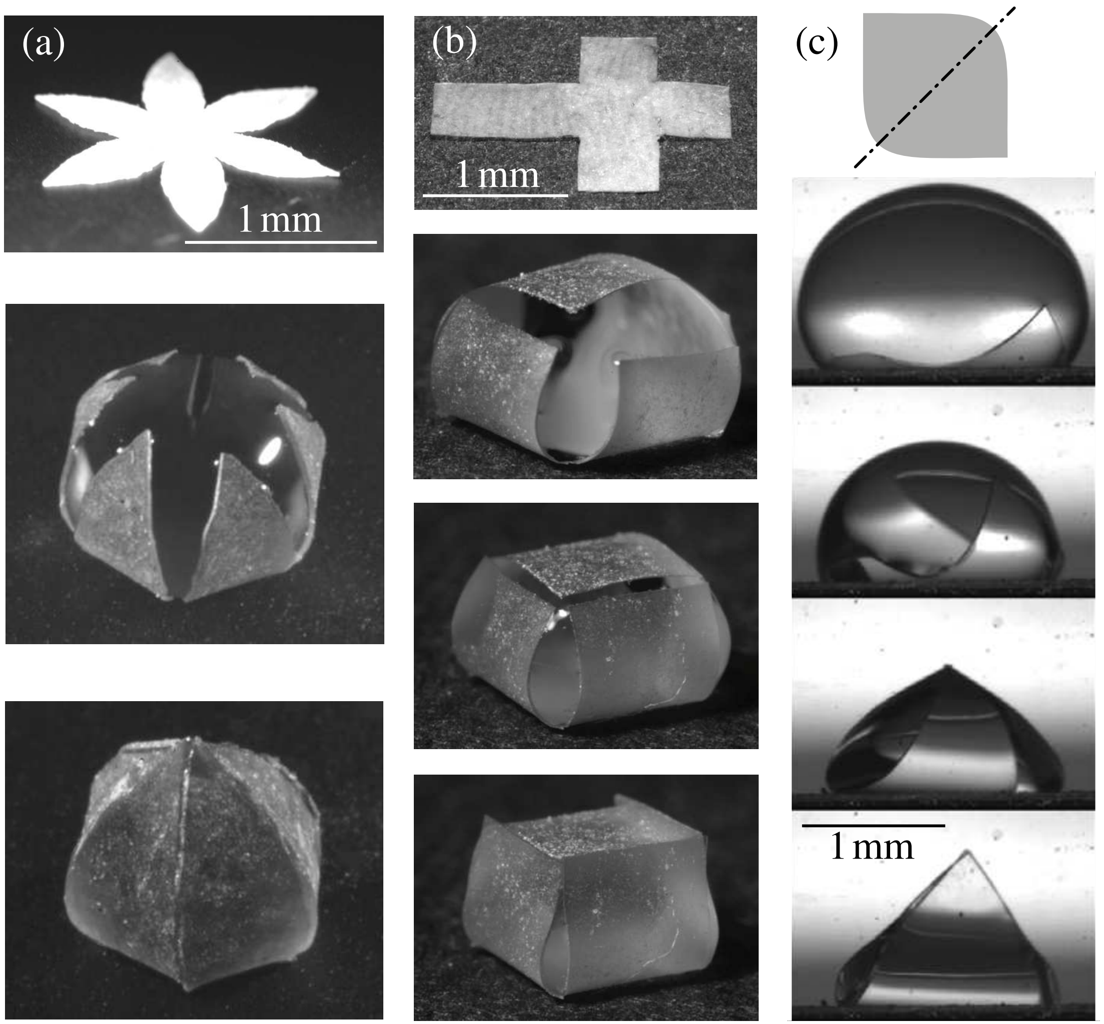
Three-dimensional effects

Triangle $\rightarrow$ Pyramid

Three-dimensional effects

Rounded corners $\rightarrow$ Triangle

Folding through surface tension



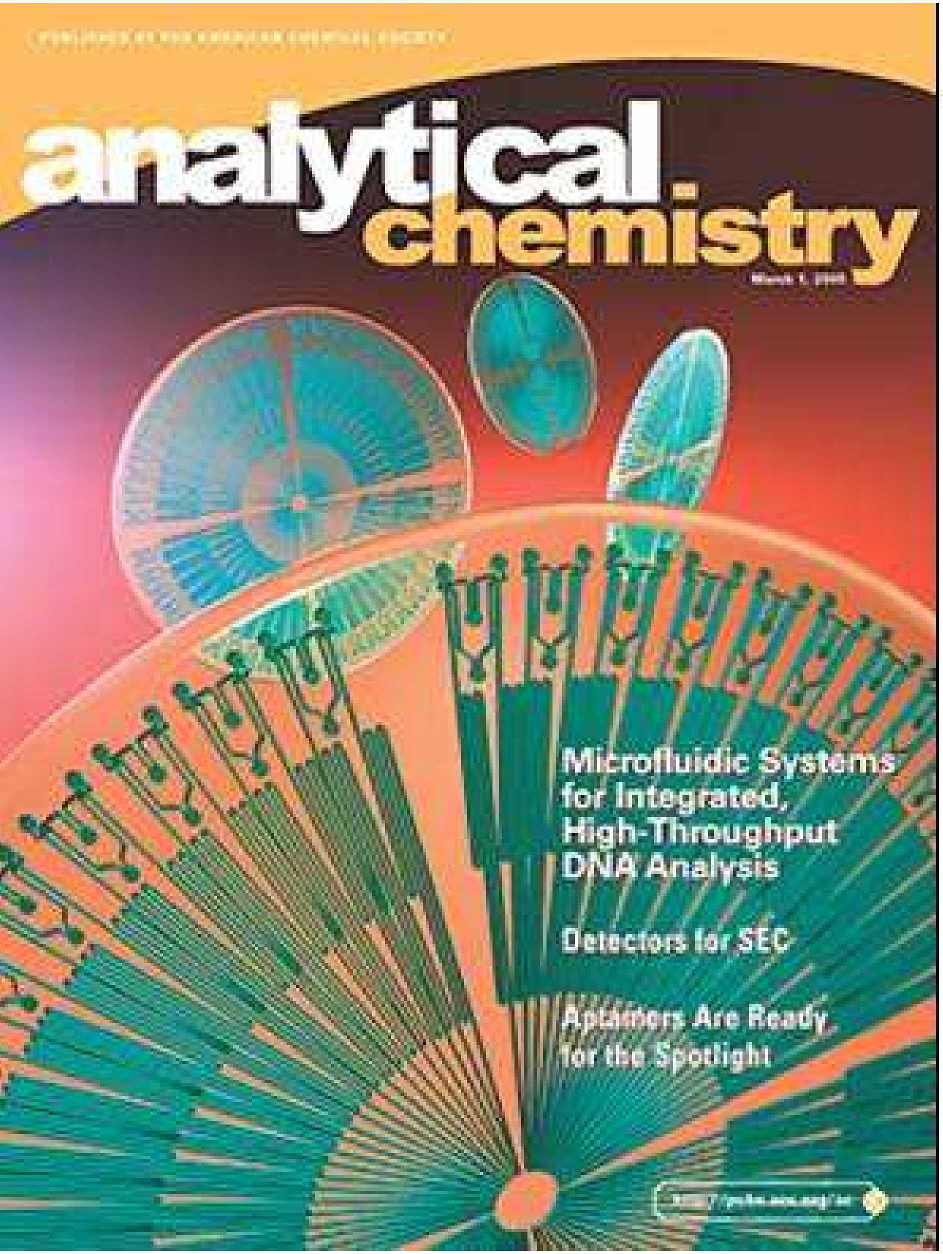
<u>See:</u> Py, Reverdy, et al. “Capillary Origami: Spontaneous Wrapping of a Droplet with an Elastic Sheet”. *Phys. Rev. Lett.* 2007

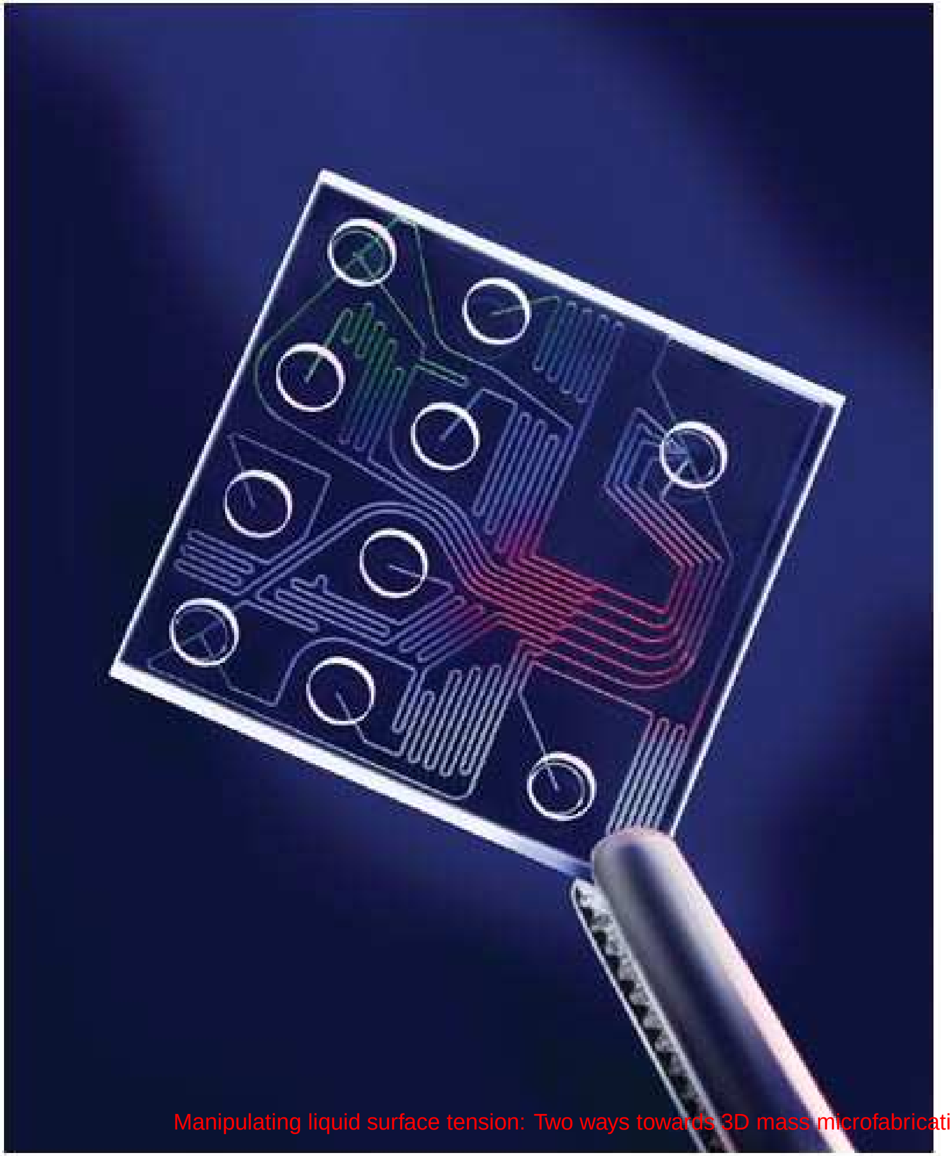
Part II: Dynamic Surface tension

Manipulations inside microchannels

Lab on a chip

- Microfluidics: A field driven by applications





Doplets in microchannels

In a lab-on-a-chip: Use a drop as a microreactor.

- No dispersion / no contamination
- Controlled reaction start (fusion)
- Well calibrated quantities
- Follow sample in time

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Small volumes:

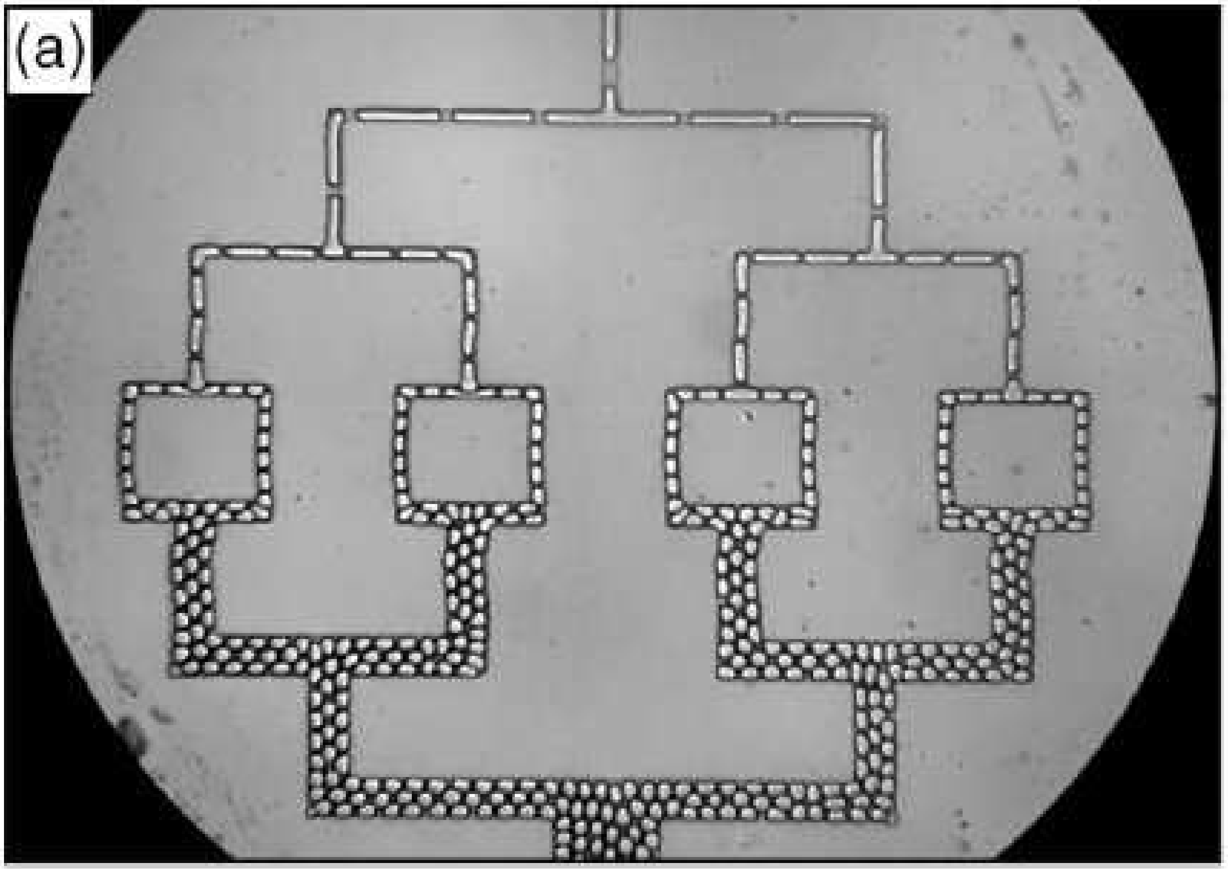
- $100 \times 100 \times 100$ μm = 10^{-12} m^3=1 nL.
- A "small drop" = 1 μL.

$\Rightarrow$ run <u>1000</u> tests on <u>one</u> droplet.

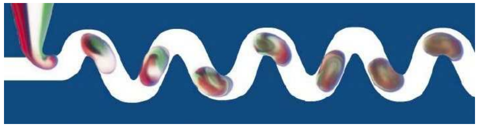
Doplet microfluidics – until recently

Use geometry to act on drops

Forming an emulsion



Link et al., 04



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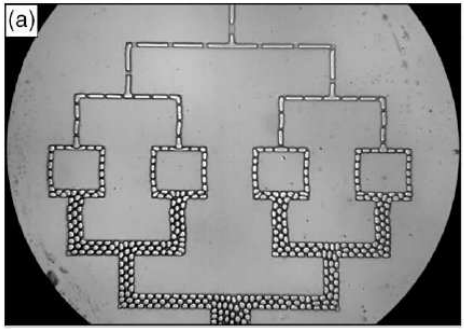
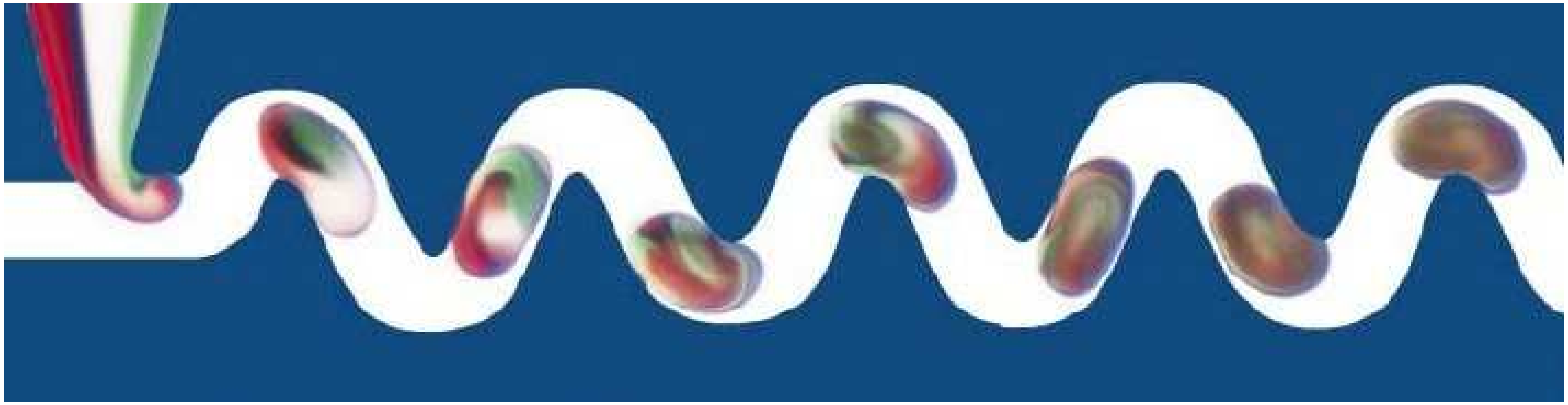


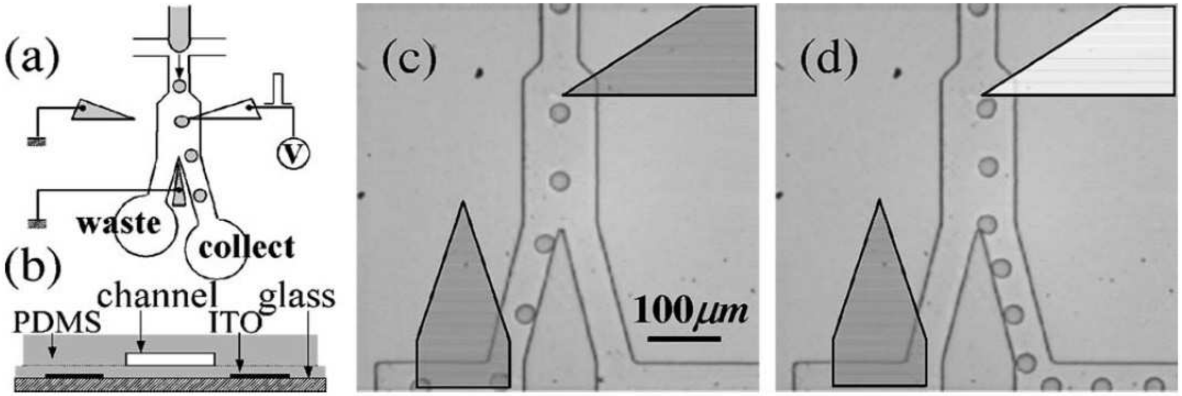
Mixing drop contents



Song et al 2003

Active control in a microchannel?

Very recently: Dielectrophoresis to sort droplets in a microchannel. (Ahn et al. 2006)



Strong points:

- Fast response time
- Can “push” and “merge” drops (also Priest et al., 2006)
- Integrated with PDMS channels

Disadvantages:

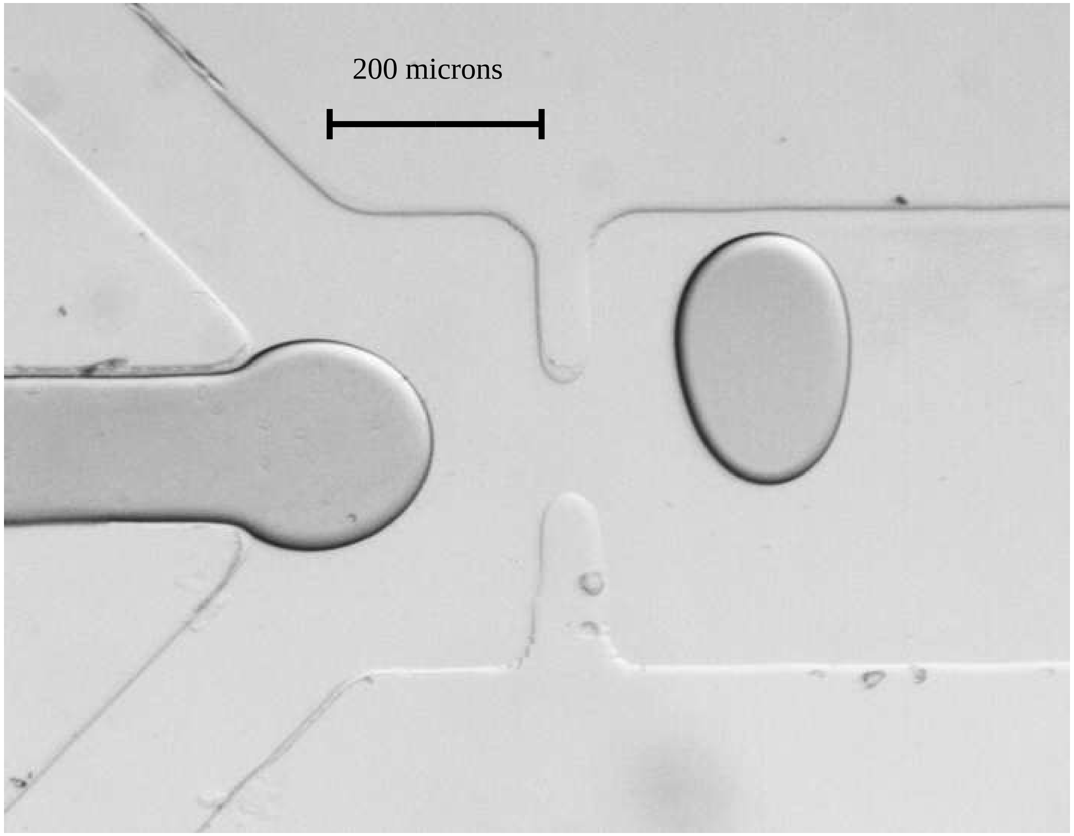
- Body force $\Rightarrow$ Scales as R^3
- Forces around 10 nN
- Requires specific microfabrication
- Not portable (high V)
- Leak currents

Can we do better?

Laser control of drops in microchannels

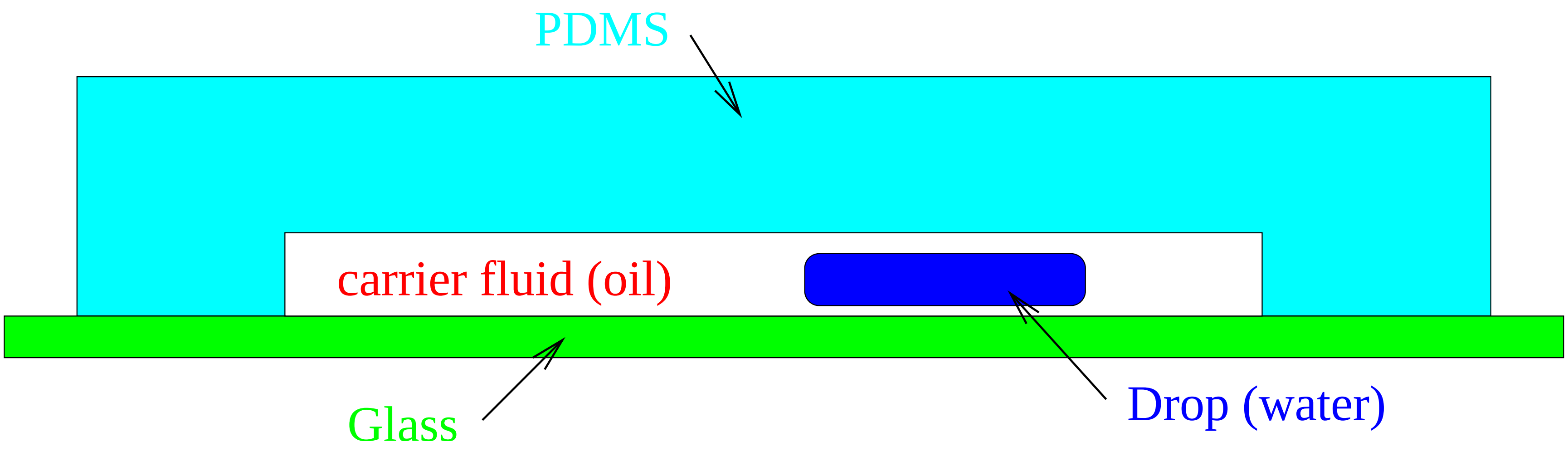
Microchannels

- Polymer channels
- Simple fabrication
- Transparent
- Typical sizes:
  1. width $\sim 100 - 500\ \mu$m.
  2. height $\sim 20 - 50\ \mu$m.



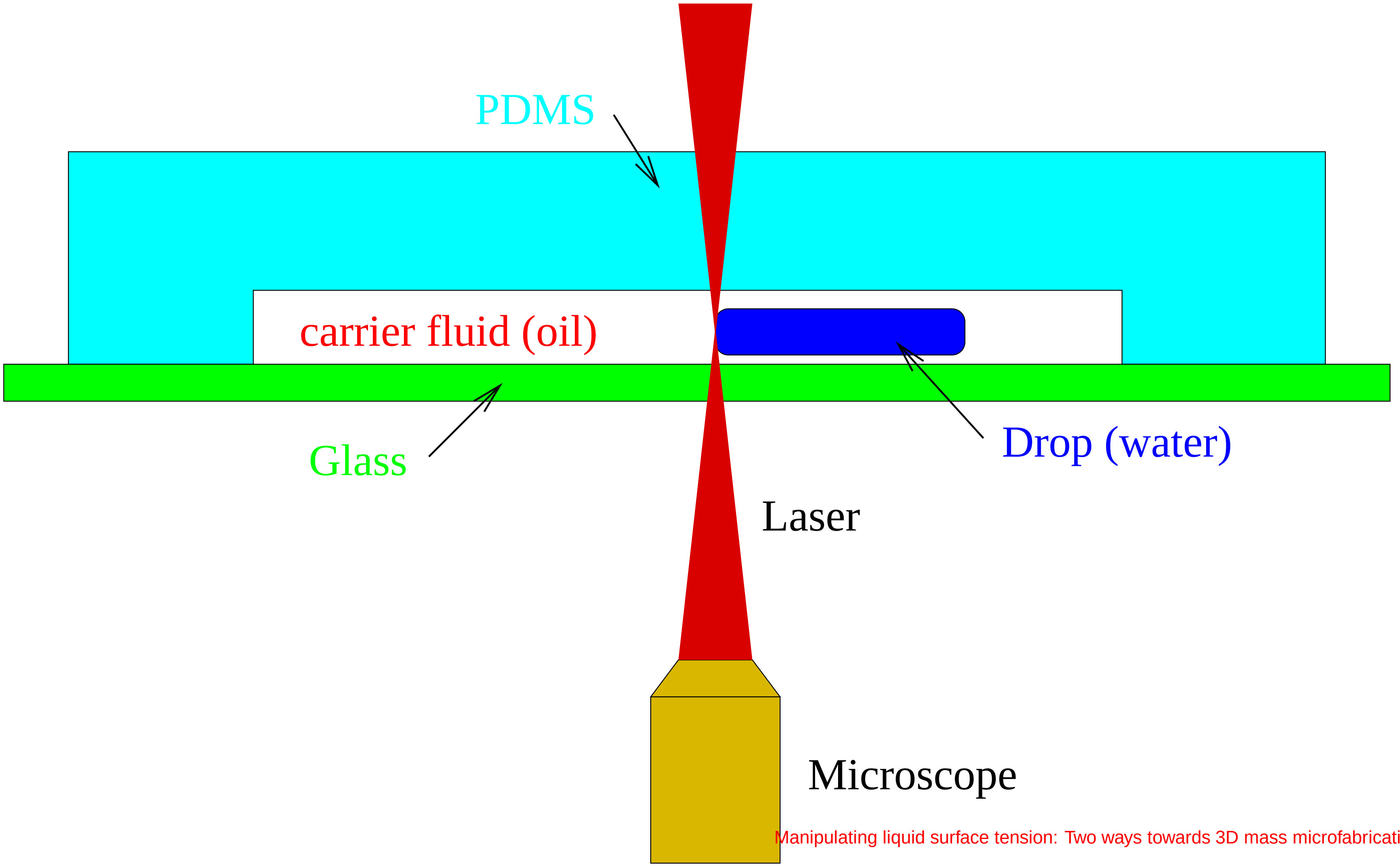
Cross-section

Drops are water in oil “pancakes”

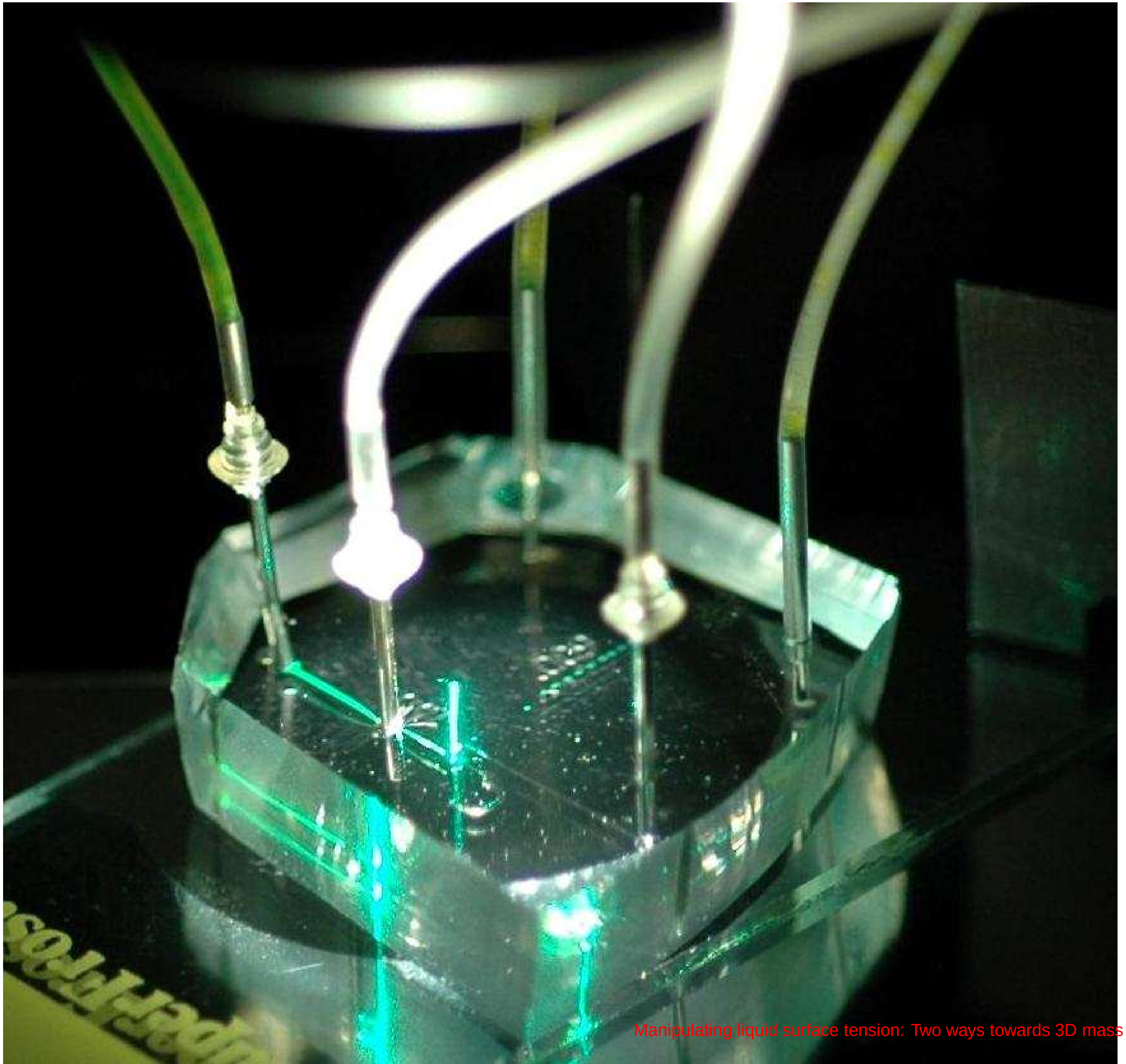


Cross-section

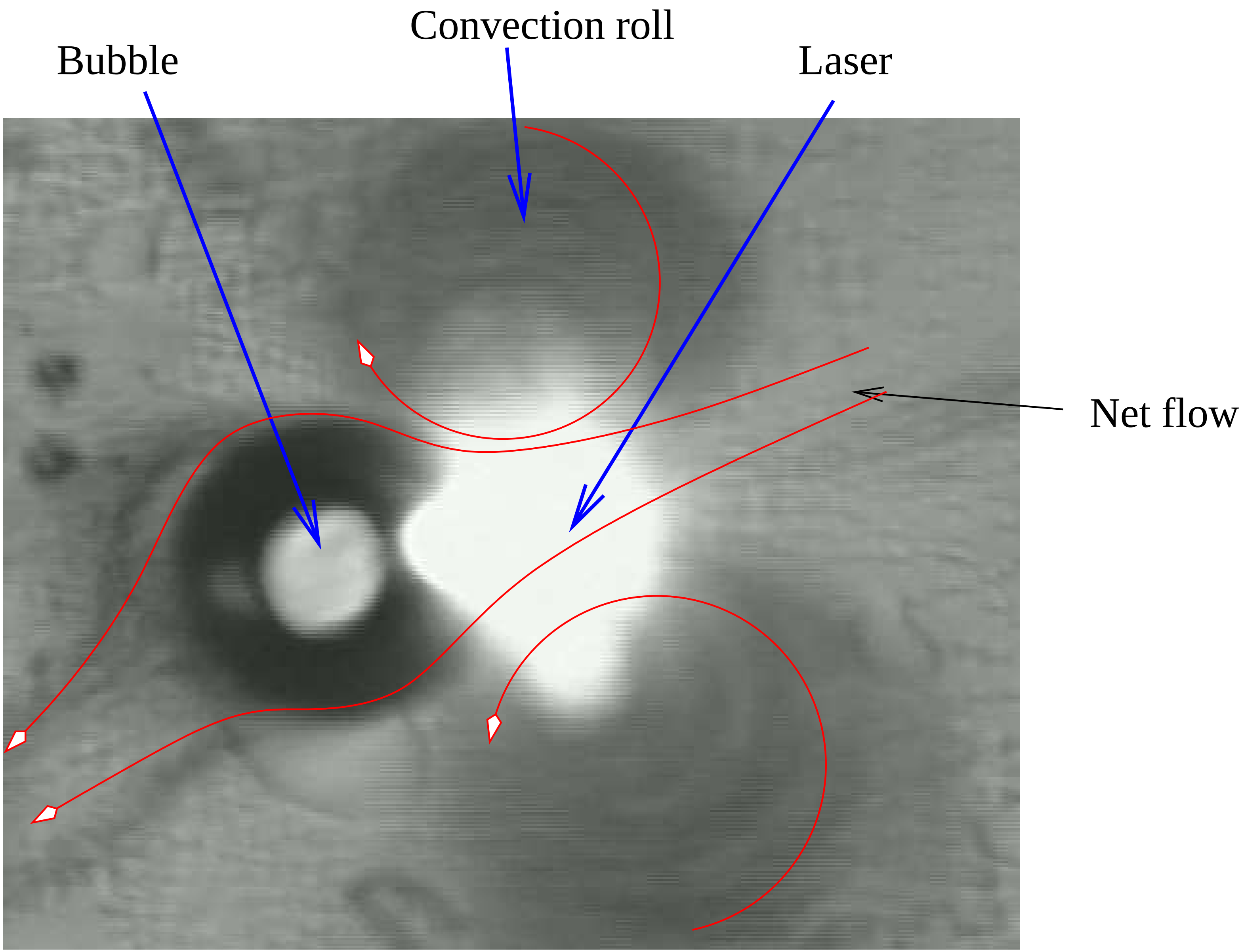
Laser beam is almost cylindrical at intersection



What it looks like



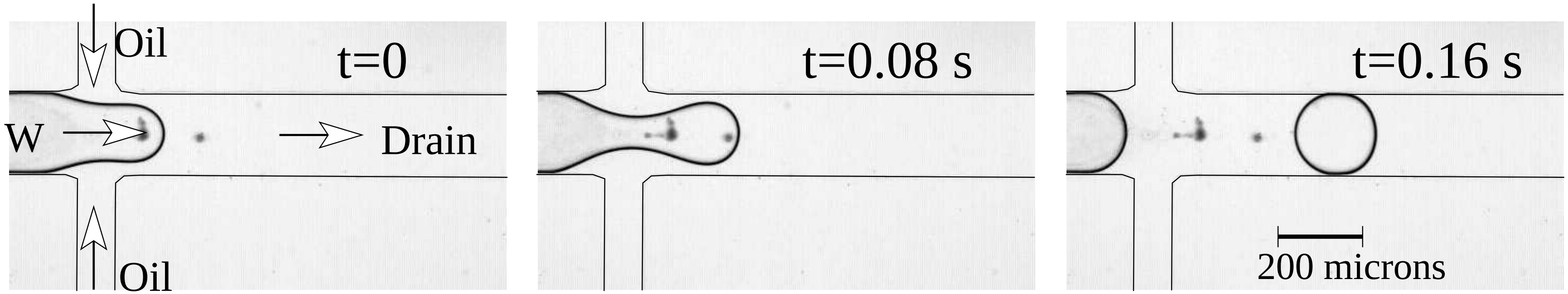
Optically-induced Marangoni flows



Optical forcing – in a microchannel

- Use a carrier fluid to form drops
- Use laser to individually control them

The beginning of the story.



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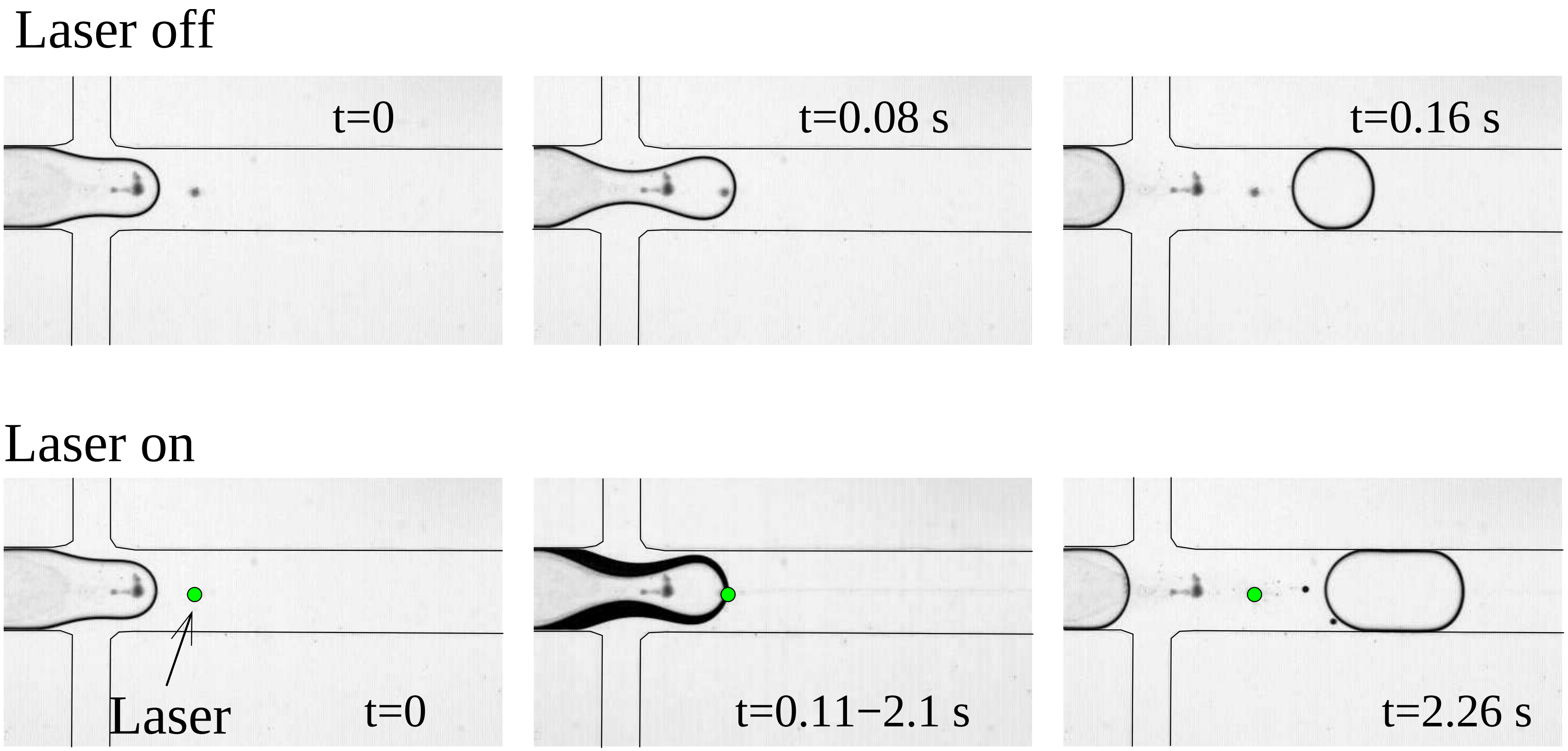
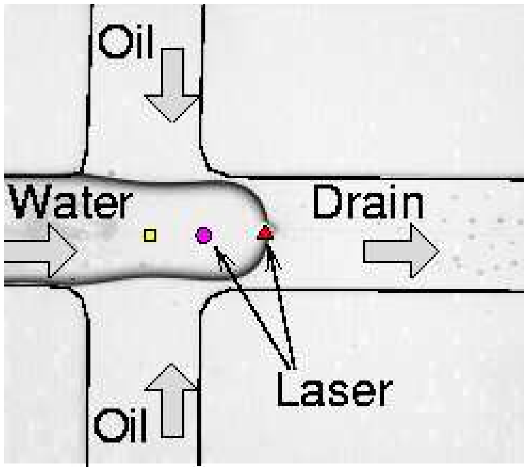
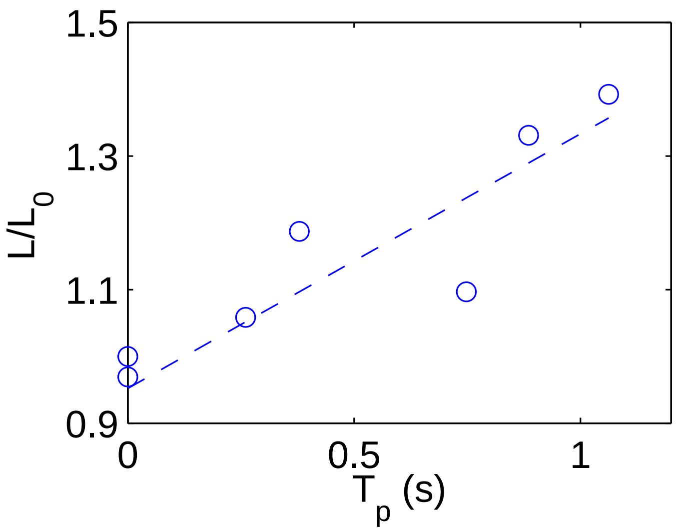
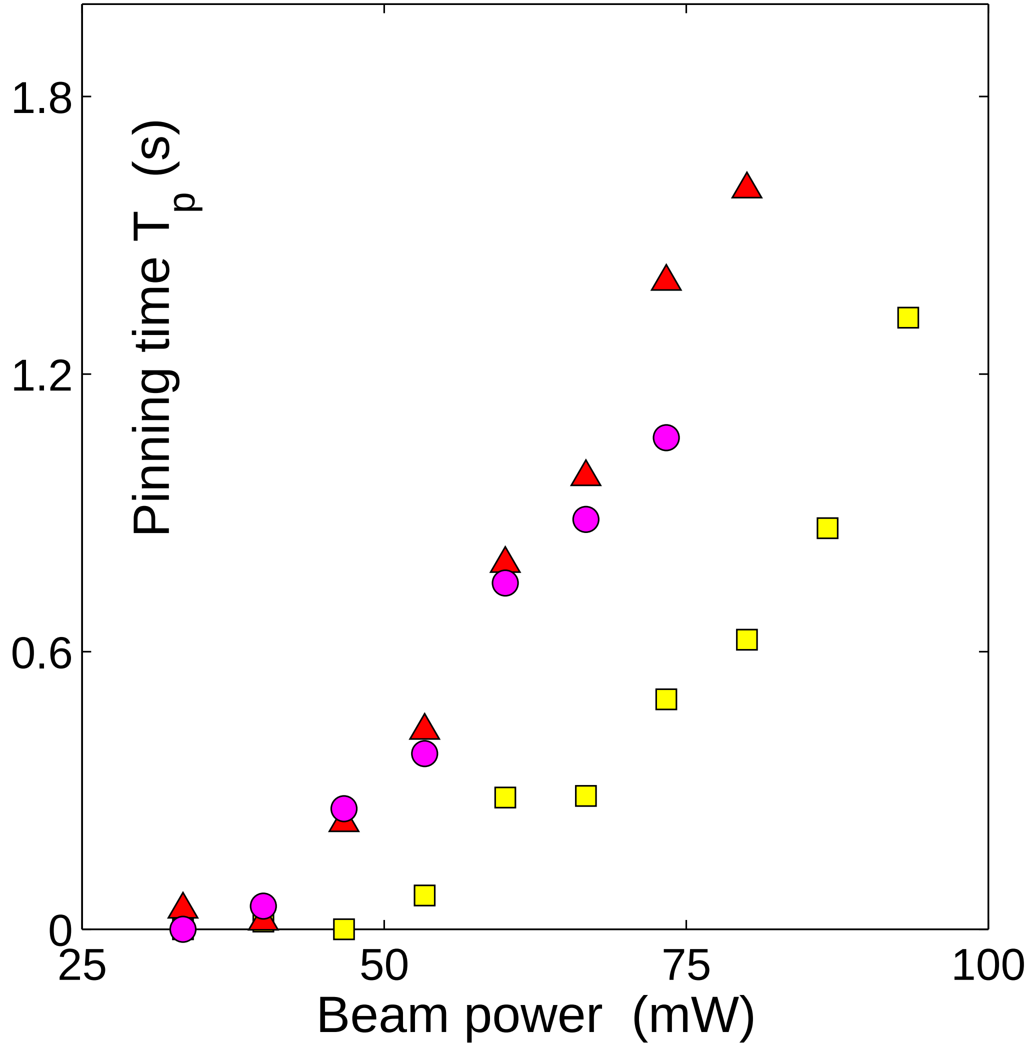


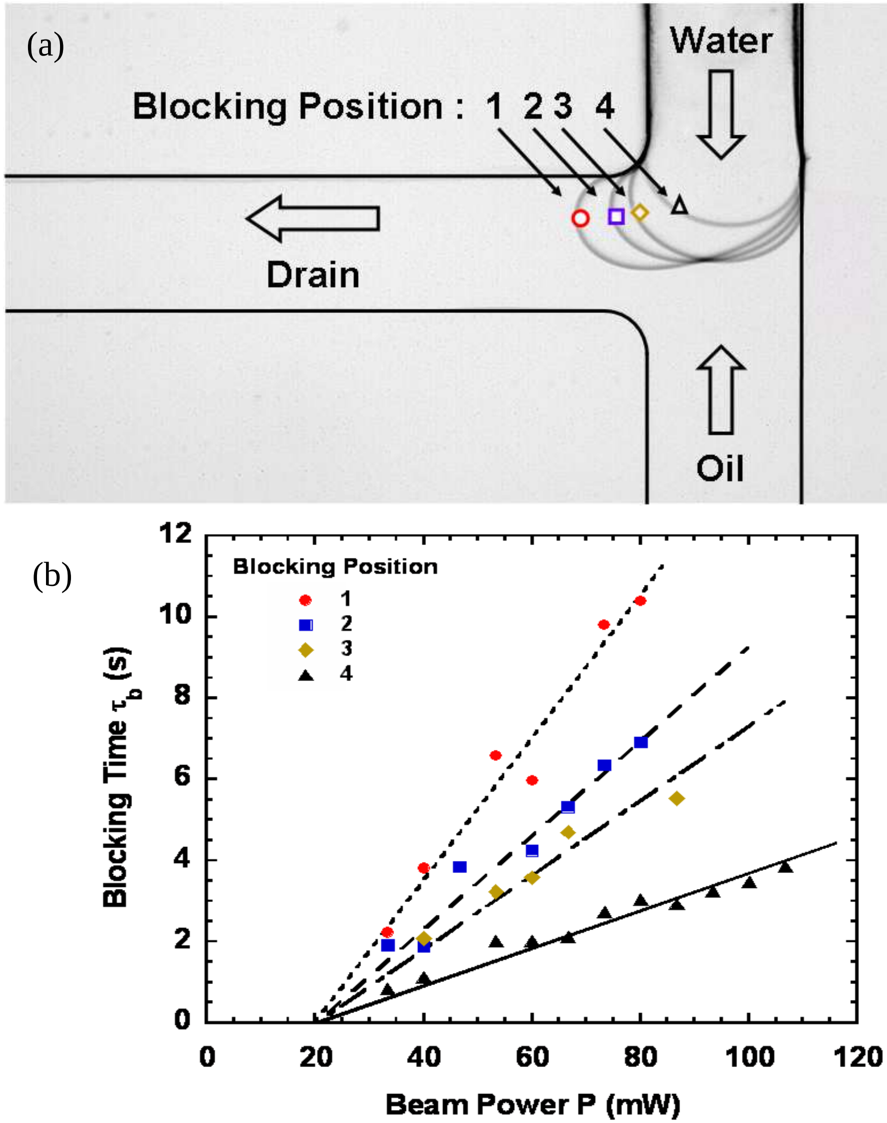
Optical valve







Another example



- Works equally well for isolated drops or in other geometries.
- Look for a force generating mechanism

How does it work?

Anomalous Marangoni flow

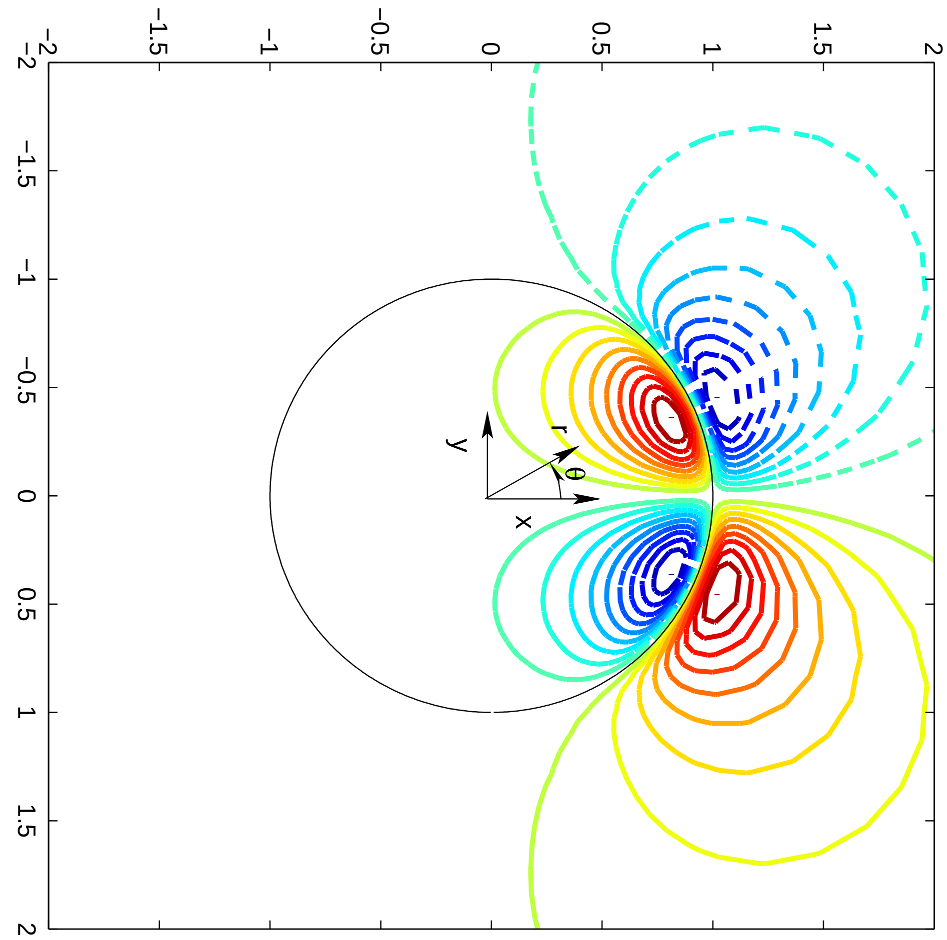
Visualize flow with tracer particles:

Flow directed towards hot side along the interface

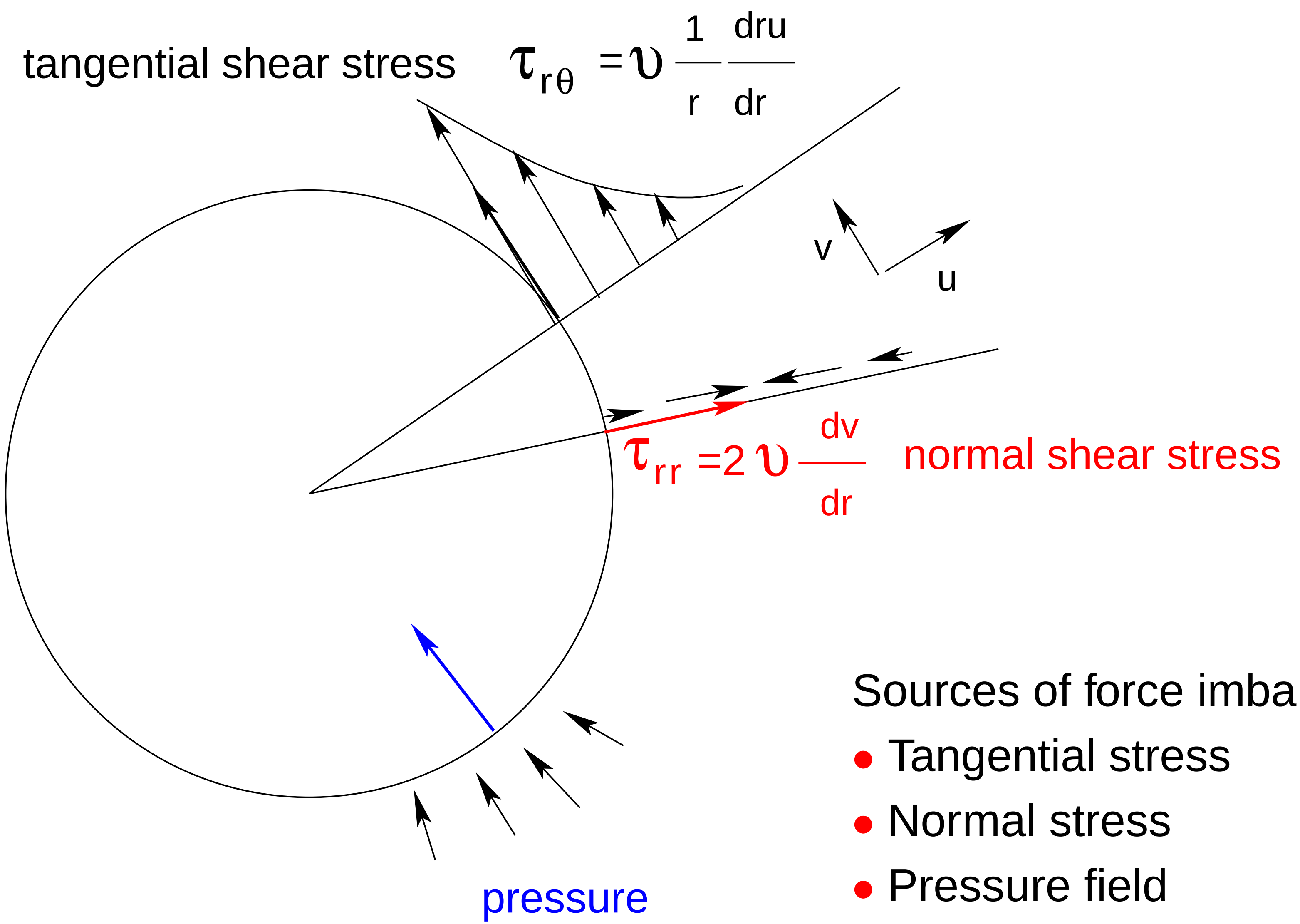
Numerical simulations

Simulation conditions:

- Assume circular drop
- Local or global heating.
- “pseudo” Hele-Shaw
- Measure stress distributions



What to measure?

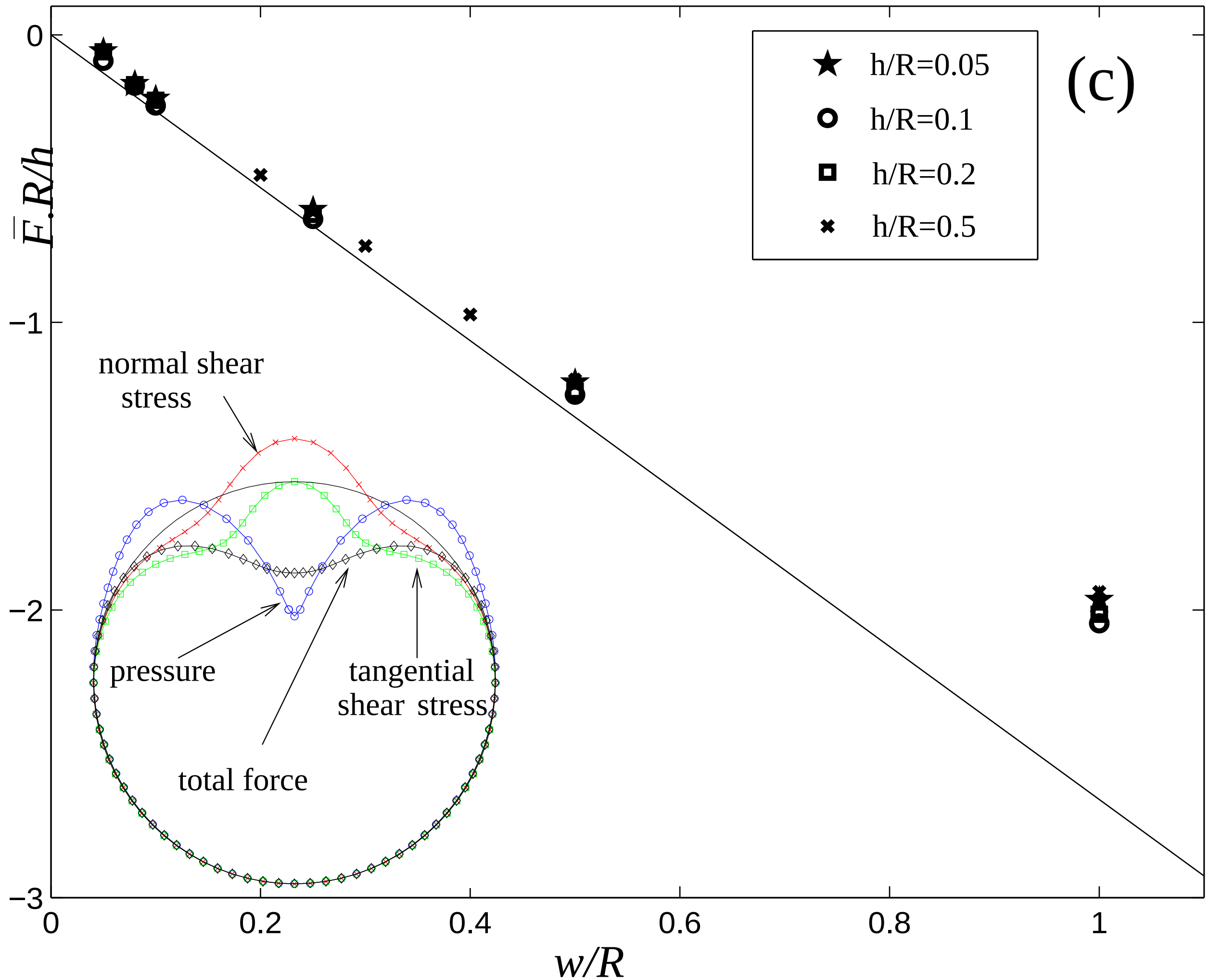


Sources of force imbalance:

- Tangential stress
- Normal stress
- Pressure field

Force scaling

Analytical derivation: $$F = \frac{\mu_2}{\mu_1+\mu_2}\frac{\partial\gamma}{\partial T}\Delta T\frac{hw}{R}$$



Summary

Conclusions:

- Force due to Marangoni flow
- Force increases as local radius of curvature decreases.
- About $1\ \mu$N for a drop of $100\ \mu$m.

See: Baroud, Delville, Gallaire, Wunenburger. “Thermocapillary valve for droplet production and sorting”. *Phys. Rev. E* 2007

Summary

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Open Questions:

- Origin of the reverse Marangoni flow?
- Role of surfactant?
- How much heat is necessary?
- What is the fastest response time?

See: Baroud, Delville, Gallaire, Wunenburger. “Thermocapillary valve for droplet production and sorting”. *Phys. Rev. E* 2007

What can you do with it?

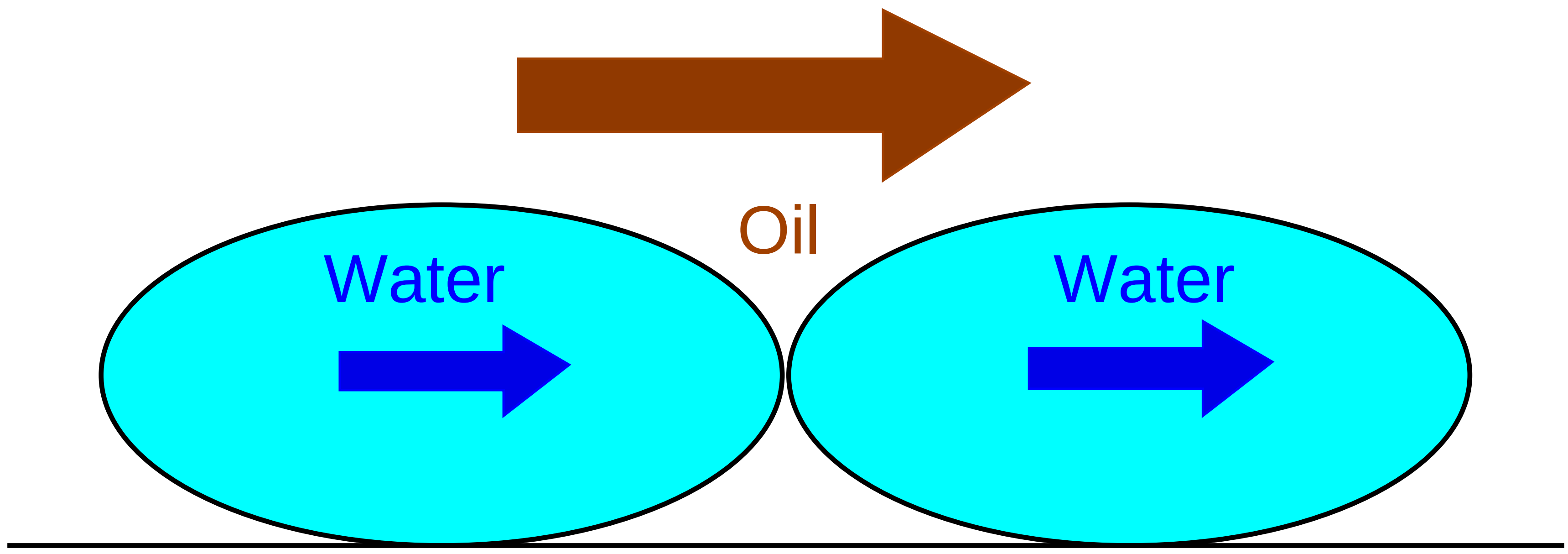
Applications

Apply technique to microfluidic operations.

- Recall steps:
  - Produce drops – Control size and timing
  - Divide drops – control relative sizes
  - Sort drops – run intelligent tests
  - Merge drops
  - Mix drop contents

Fusion

Marangoni flow for fusing drops



Fusion

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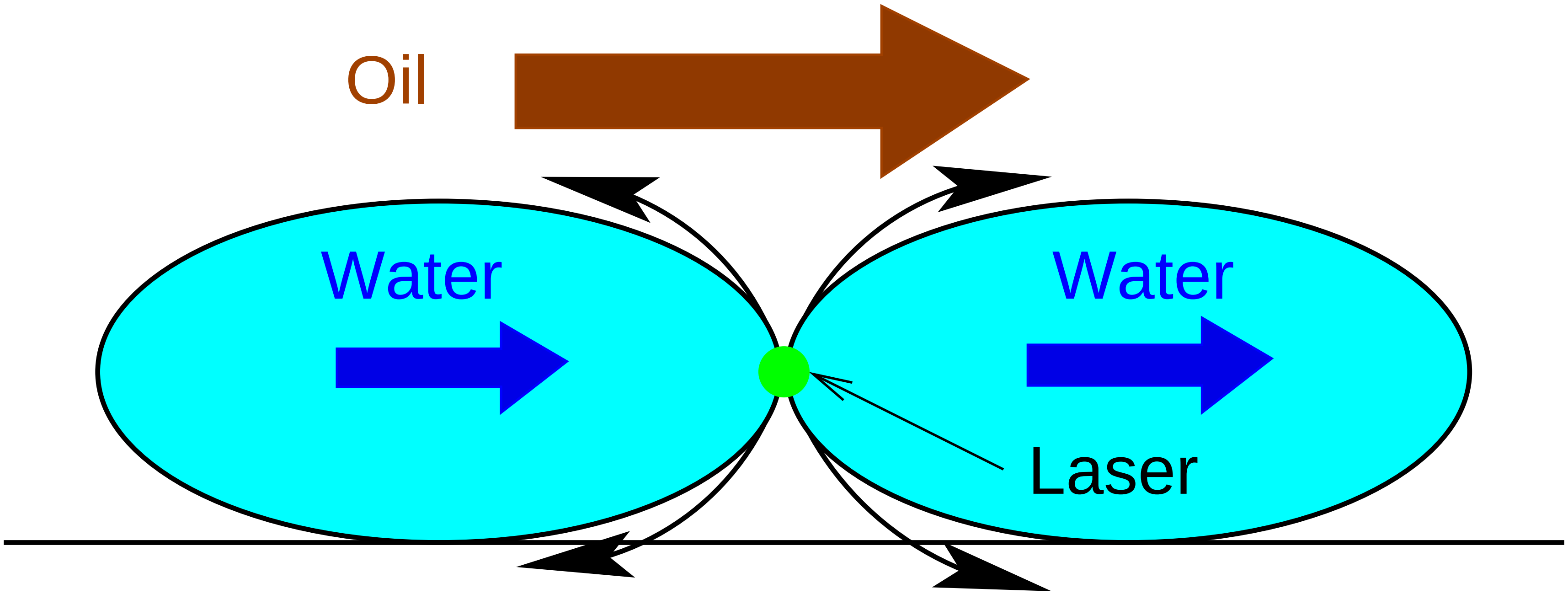

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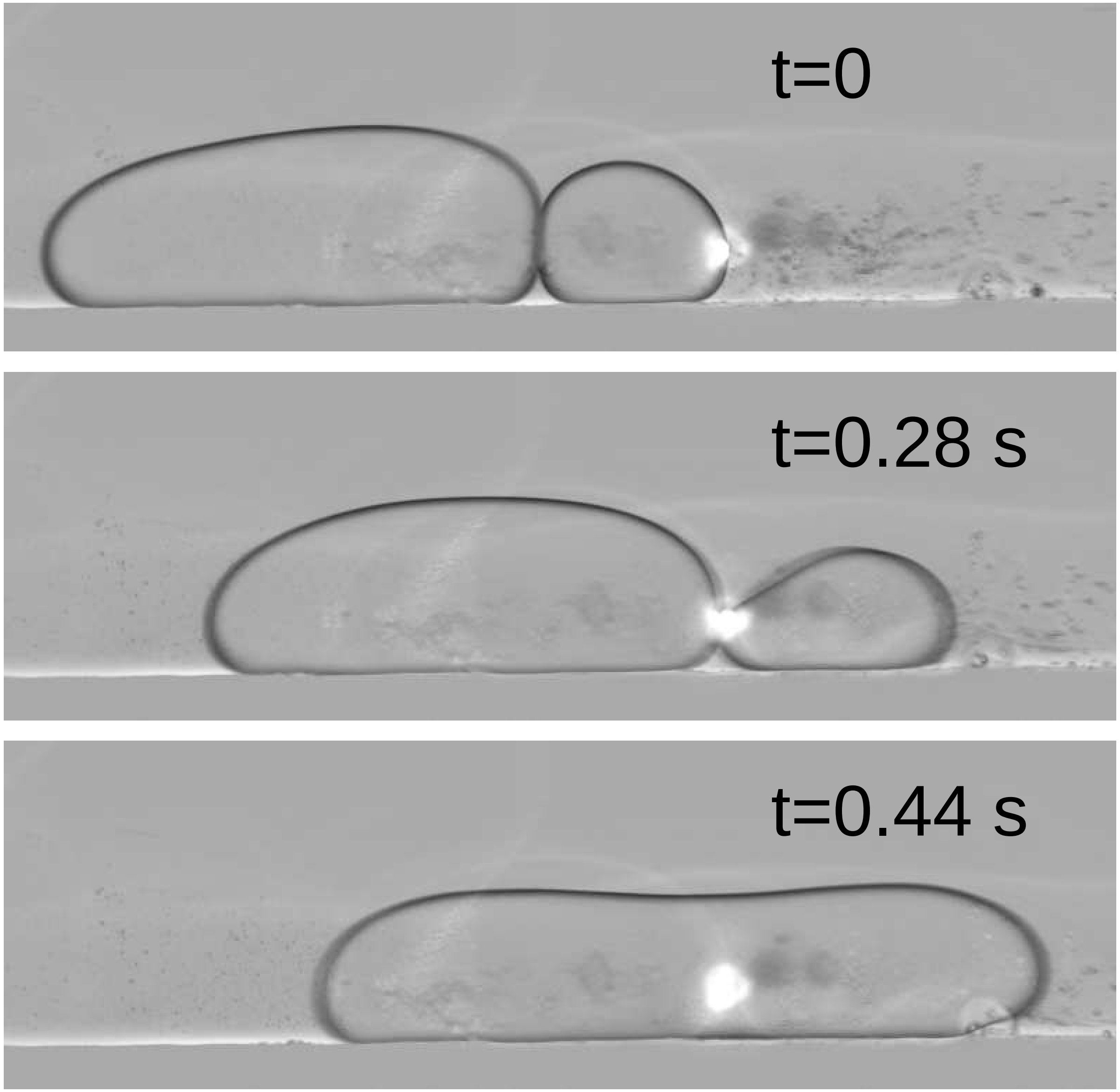


Fusion of large drops?

Fusion at formation

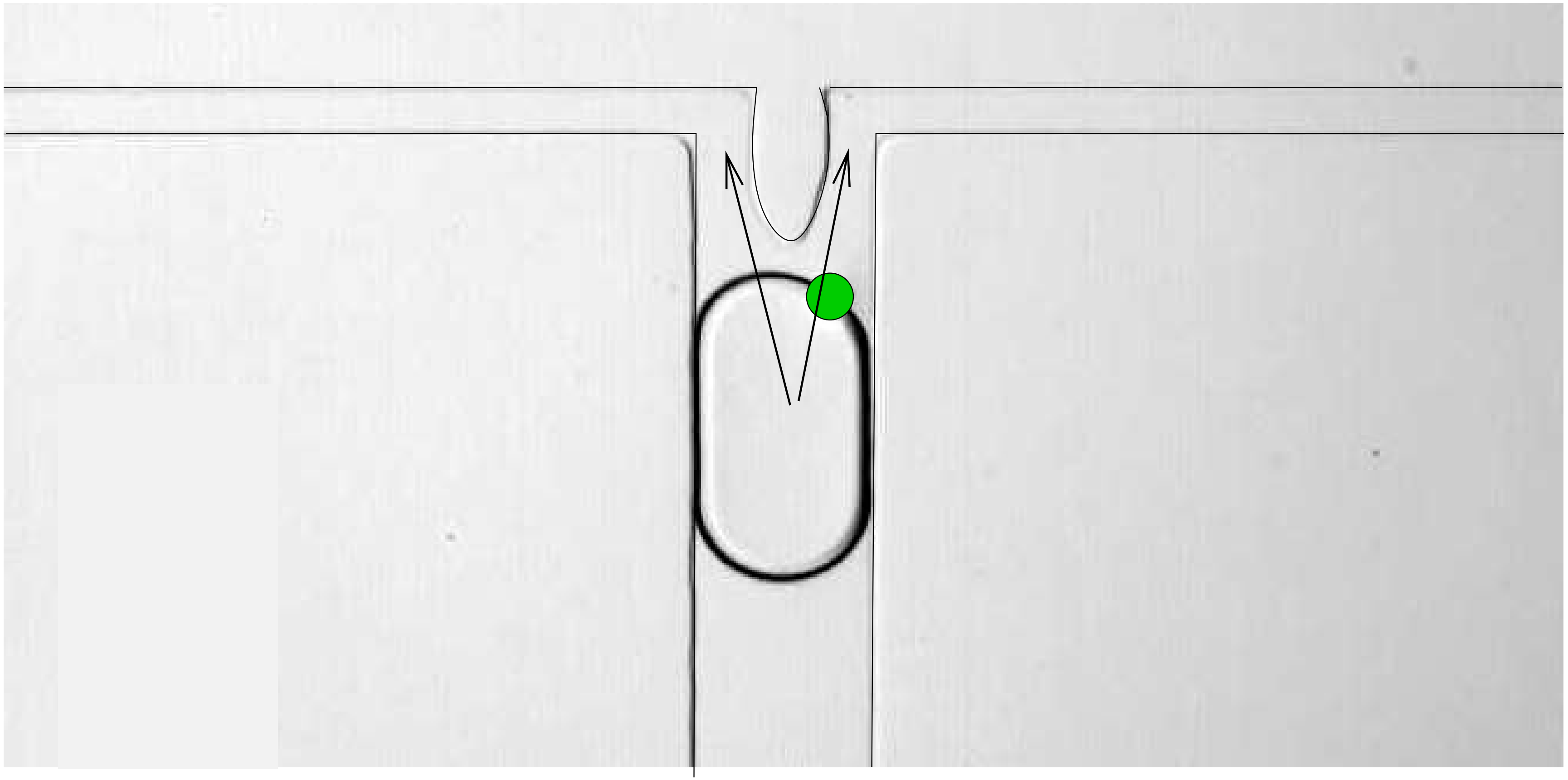
- No laser: Cannot synchronize drops and cannot merge them.

Combined operations

- With laser: Combine valve and merger

Controlling division

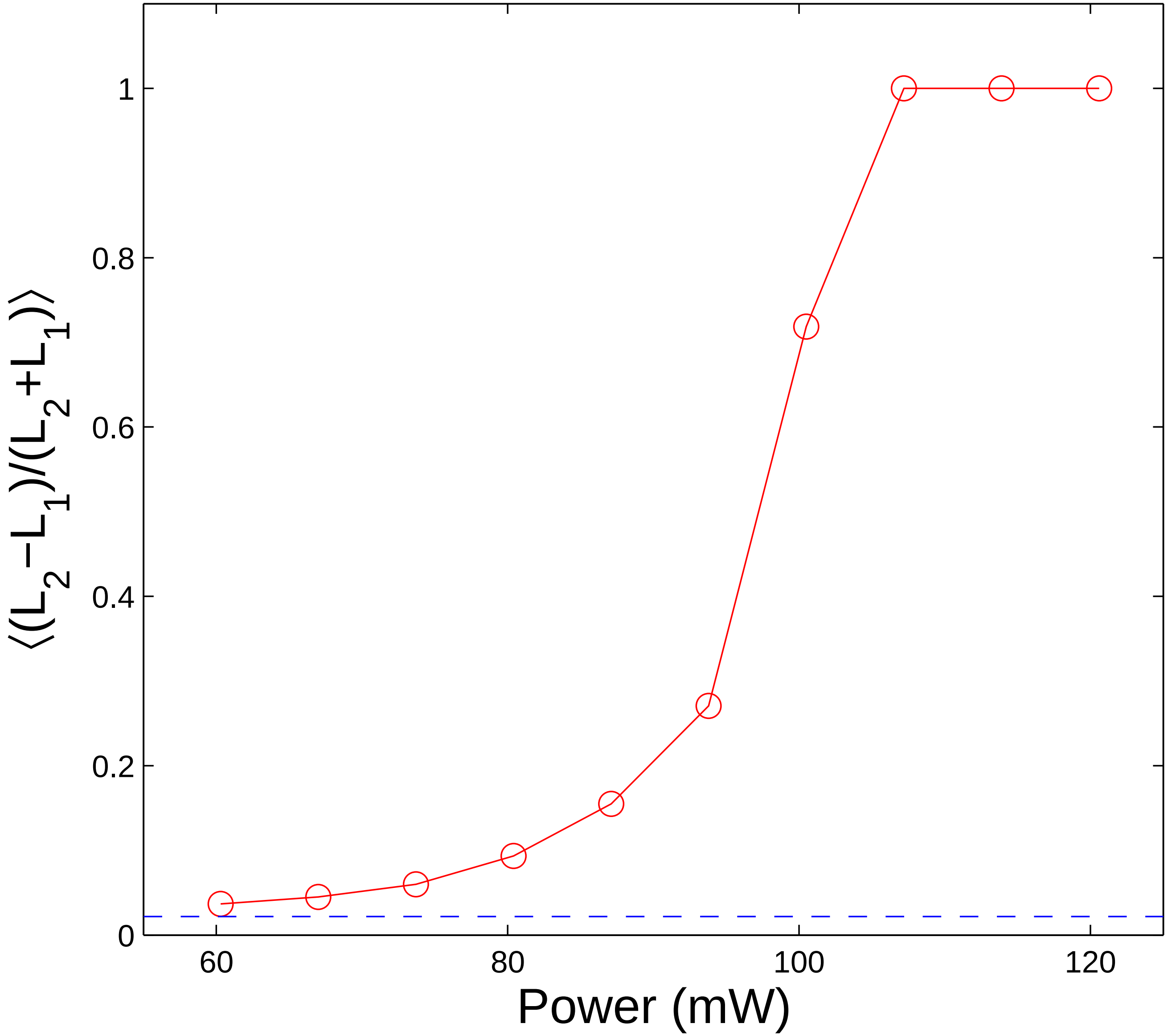
Asymmetric pinning in diverging streamlines



Dividing asymmetrically

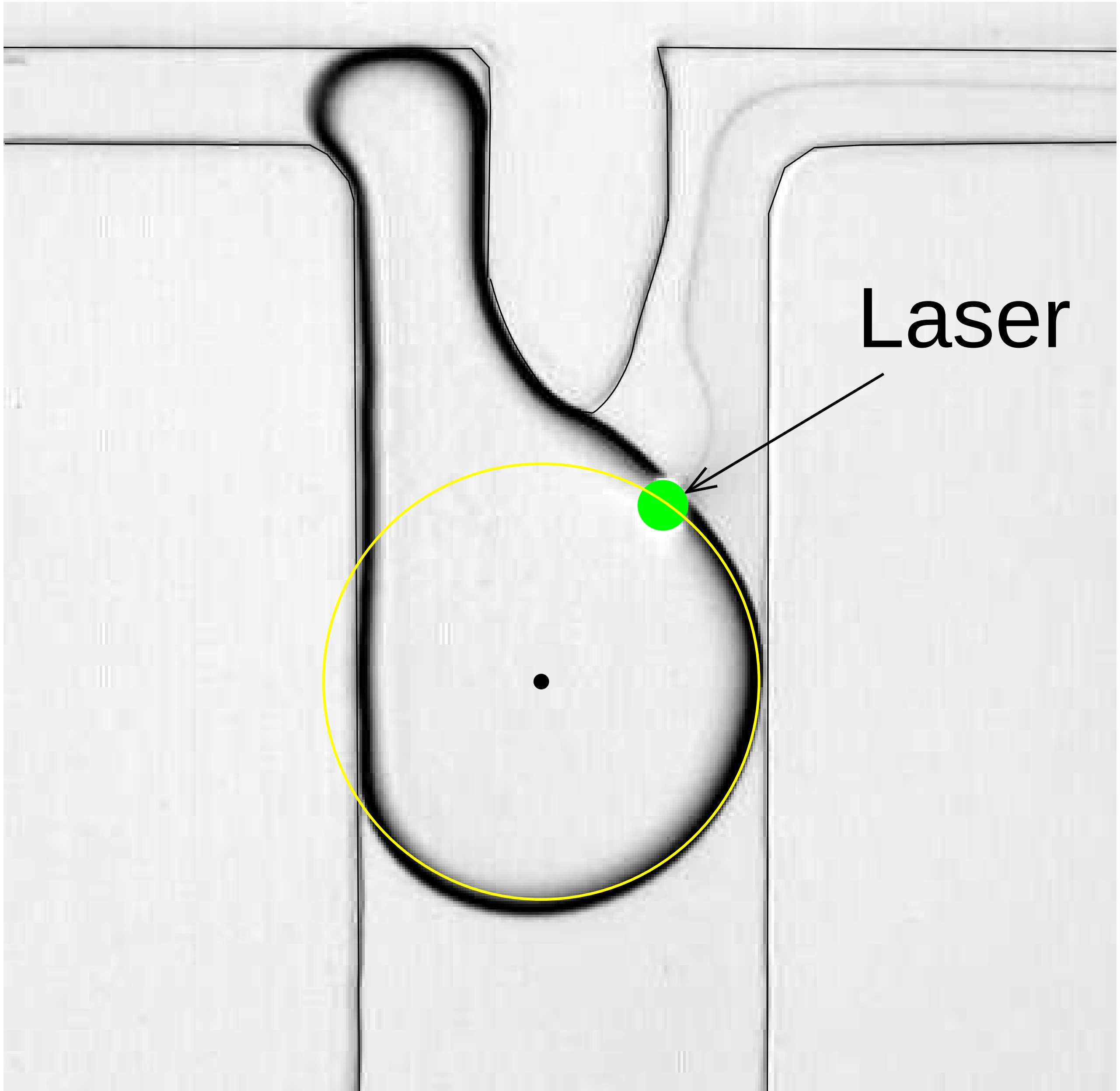
Controllability

Variation with laser power:



Sorting

Sorting



Summary

New microfluidic forcing technique

- Use favorable scaling laws
- Combine geometry and local forcing
- Implement fundamental operations
  (Production, sorting, division, fusion...)

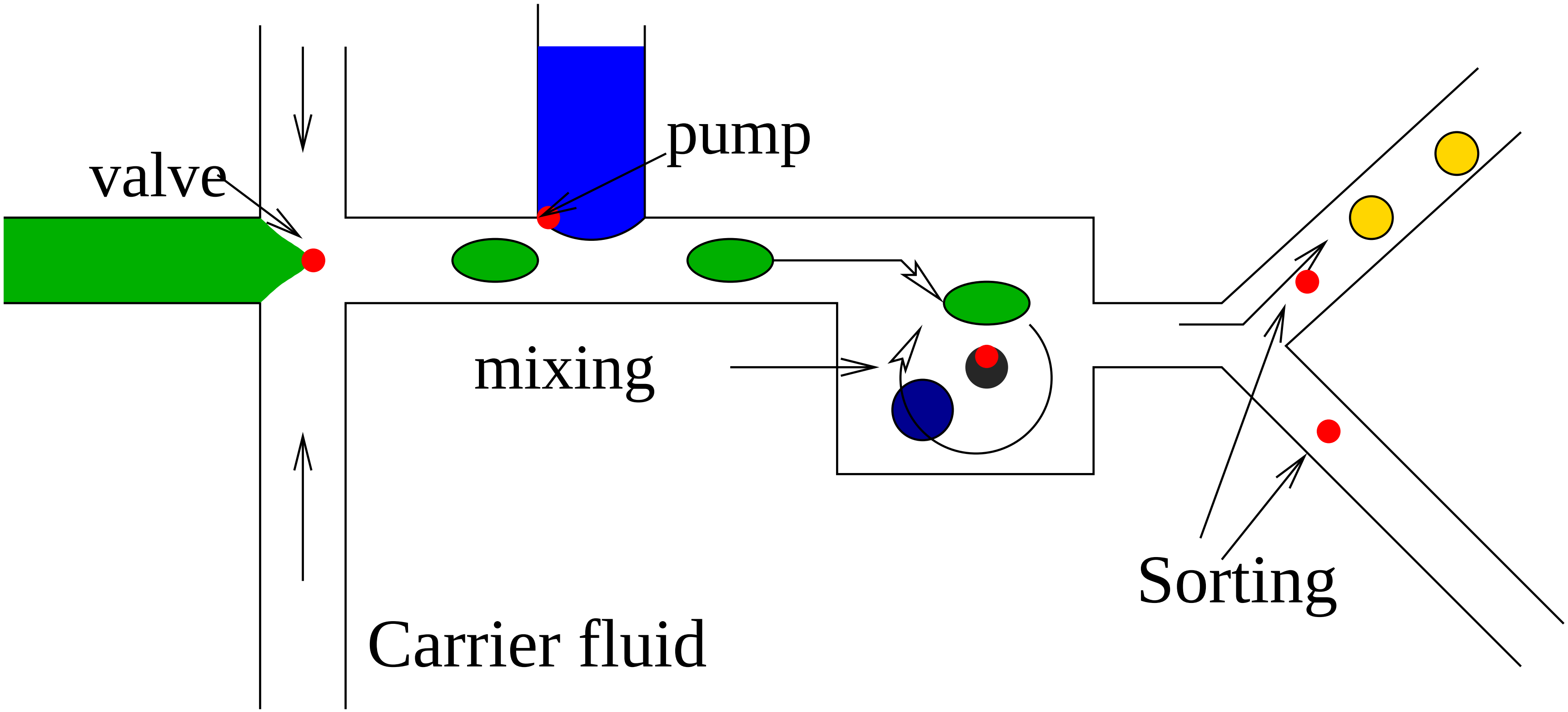
Main technical advantages

- No mechanical contact/special fabrication
- fast
- Scalable: One laser for many concurrent operations
- Generalizable: Independent of fluid type

See: Baroud, Robert de Saint Venant, Delville. “An optical toolbox for total control of droplet microfluidics”. *Lab on a chip* 2007

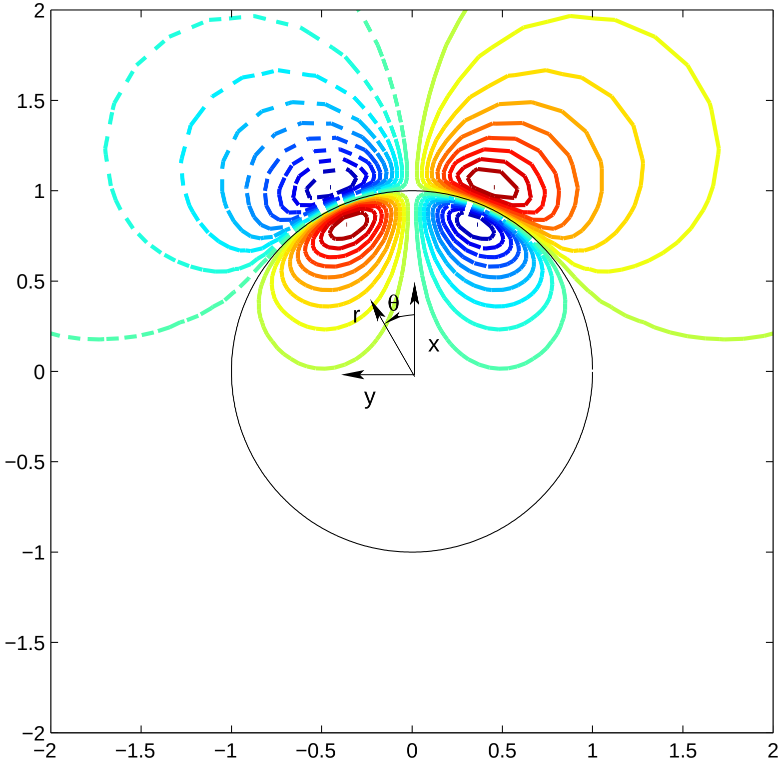
Future work

Do something useful with it



Applications in single-cell studies

Understanding the scaling



1. Separation of scales:
   - $\vec{r}$ scale given by depth h
   - $\vec{\theta}$ scale by Gaussian width w
2. Velocity scale given by Marangoni effect (Eq. 3)

$$U \sim \frac{\Delta T \gamma'}{\mu_1 + \mu_2} \frac{h}{w}.$$

3. Force due to the tangential shear is obtained by multiplying $\sigma_{r\theta} \sim \mu_2 U/h$ by $\sin\theta \simeq w/R$ and integrating on the portion $w \times h$ of the interface:

$$F \sim \mu_2 \frac{U}{h} \frac{w}{R} wh \qquad (0)$$