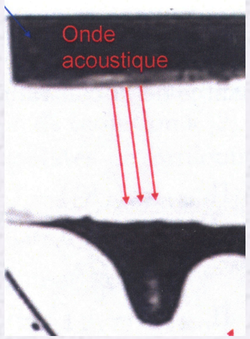
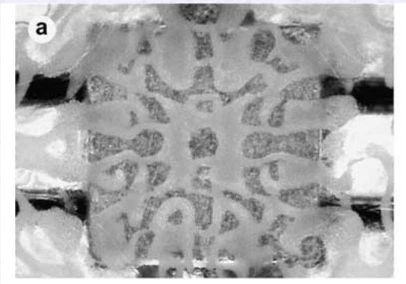
Acoustofluidics

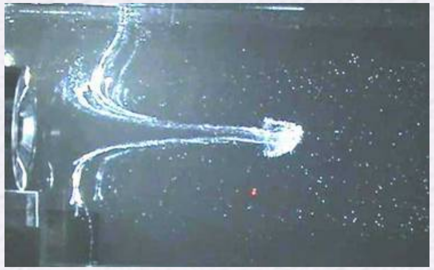
Philippe Marmottant
David Rabaud, Pierre Thibault, Q. Tran, Flore Mekki-Berrada, Thomas Combriat, Nicolas Bertin, Jean-François Louf, Maxime Harazi
Laboratoire Interdisciplinaire de Physique (LIPhy) Grenoble

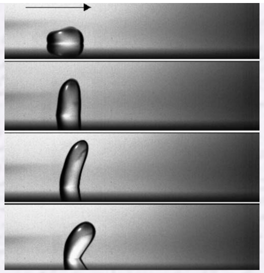
1) Using radiation pressure





2) Using acoustic streaming

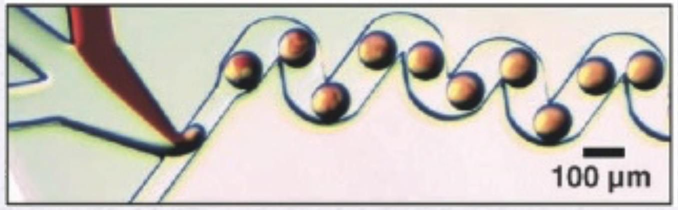




Microfluidics school Sète
October 13-18, 2019

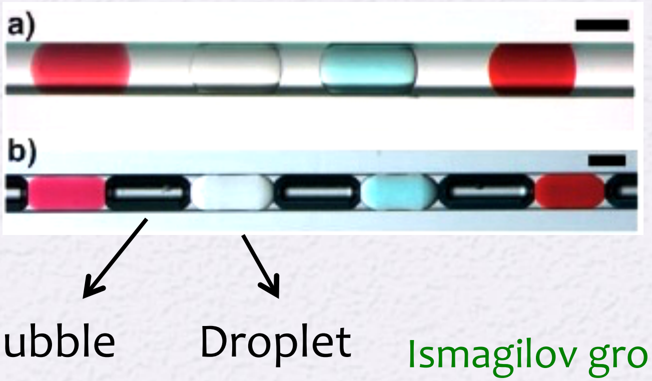
Context: digital microfluidics

Diluted droplets / bubbles follow the flow …



Ismagilov group 2003

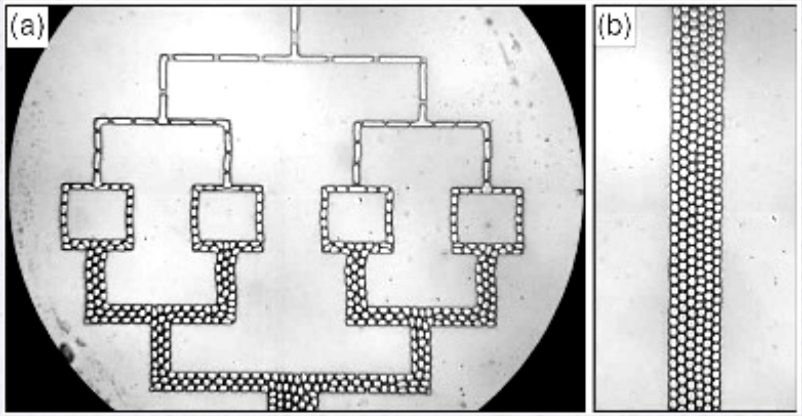
… or induce traffic jams



Bubble

Droplet

Ismagilov group 2005



Link 2004

How to use acoustic forces to control objects without contact?

Waves…

Acoustic wave definition: small disturbance around equilibrium of

- Pressure, $p=p_0+p_1(x,t)$
- Velocity, $\boldsymbol{v}=\boldsymbol{v}_0+\boldsymbol{v}_1(x,t)$

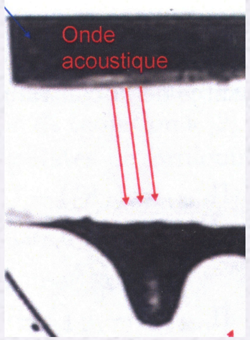
Propagating at speed of sound: $c=(K/\rho)^{1/2}$

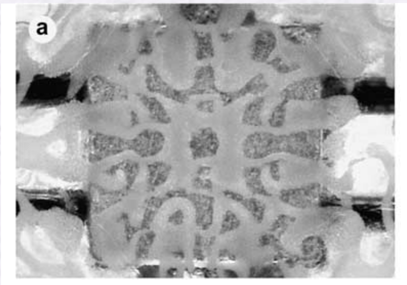
with fluid compressibility $K=\rho(\partial p/\partial\rho)_{S=cst}$

How can sound exert forces and motion?

Outline

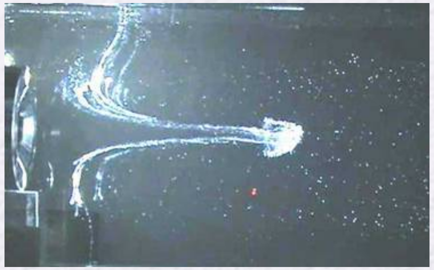
1) Radiation pressure

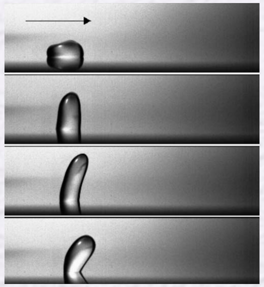




a) on interfaces
b) on particles, tweezers
c) on bubbles

2) Acoustic streaming



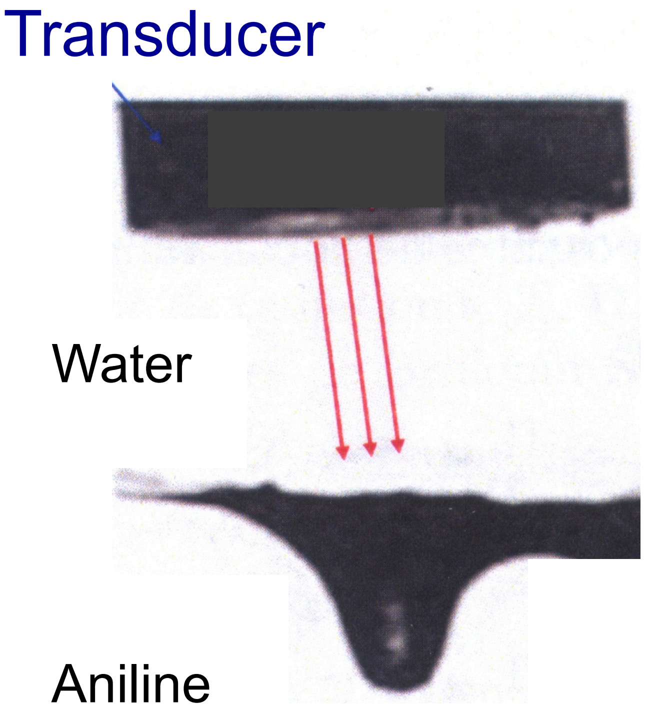


a) Quartz wind
b) near boundaries
c) near bubbles

1) Radiation pressure

- **Exists** in acoustics and in optics
  (laser forces, as in optical tweezers)
- **Peculiarity in acoustics**
  radiation pressure can be negative

a) On fluid interfaces

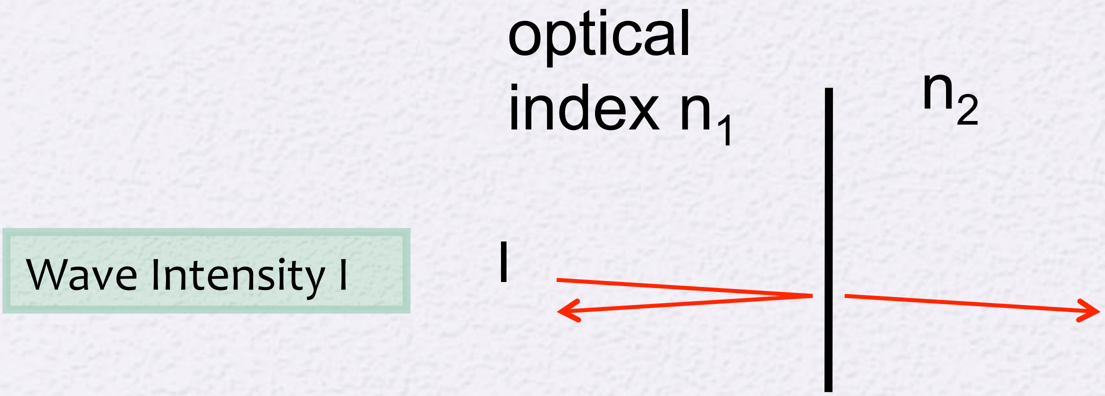


[redacted]

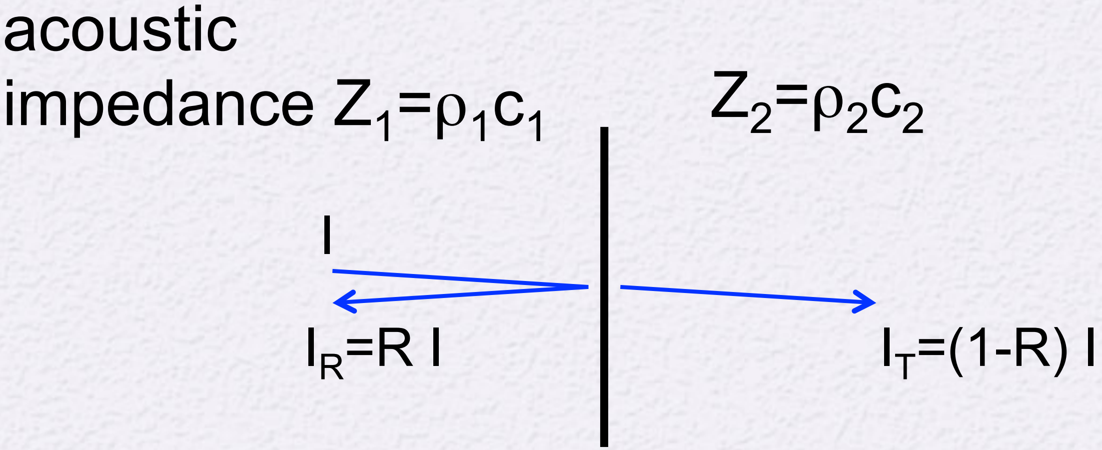
Hertz and Mende 1939

Origin: change of momentum at reflection

- Case of optics



- Acoustics



acoustic impedance $Z_1=\rho_1 c_1$

$Z_2=\rho_2 c_2$

I

$I_R=R\ I$

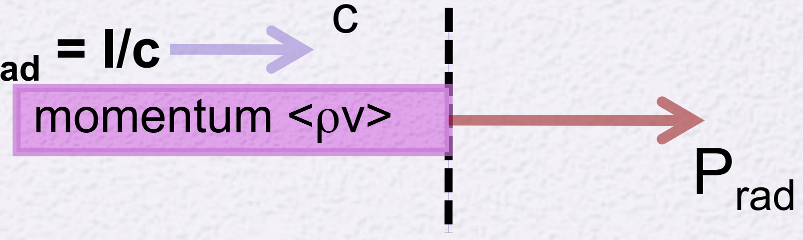
$I_T=(1-R)\ I$

Reflection $R=(Z_1-Z_2)^2/(Z_1+Z_2)^2$

Wave Intensity is $I=P_A{}^2/2Z$ (W/m²)
with peak acoustic pressure P_A

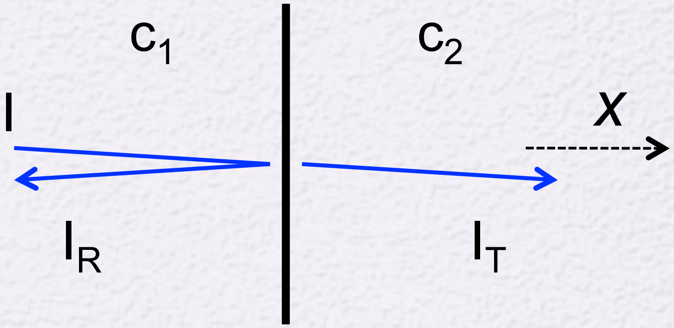
Wave momentum

Flux of momentum results in a pressure $\mathbf{P_{rad} = I/c}$



Reflection on an interface

- incident wave: $P_{rad}^{incident} = I/c_1$
- reflected wave: $P_{rad}^{reflected} = I_R/c_1$
- transmitted wave: $P_{rad}^{transmitted} = -I_T/c_2$

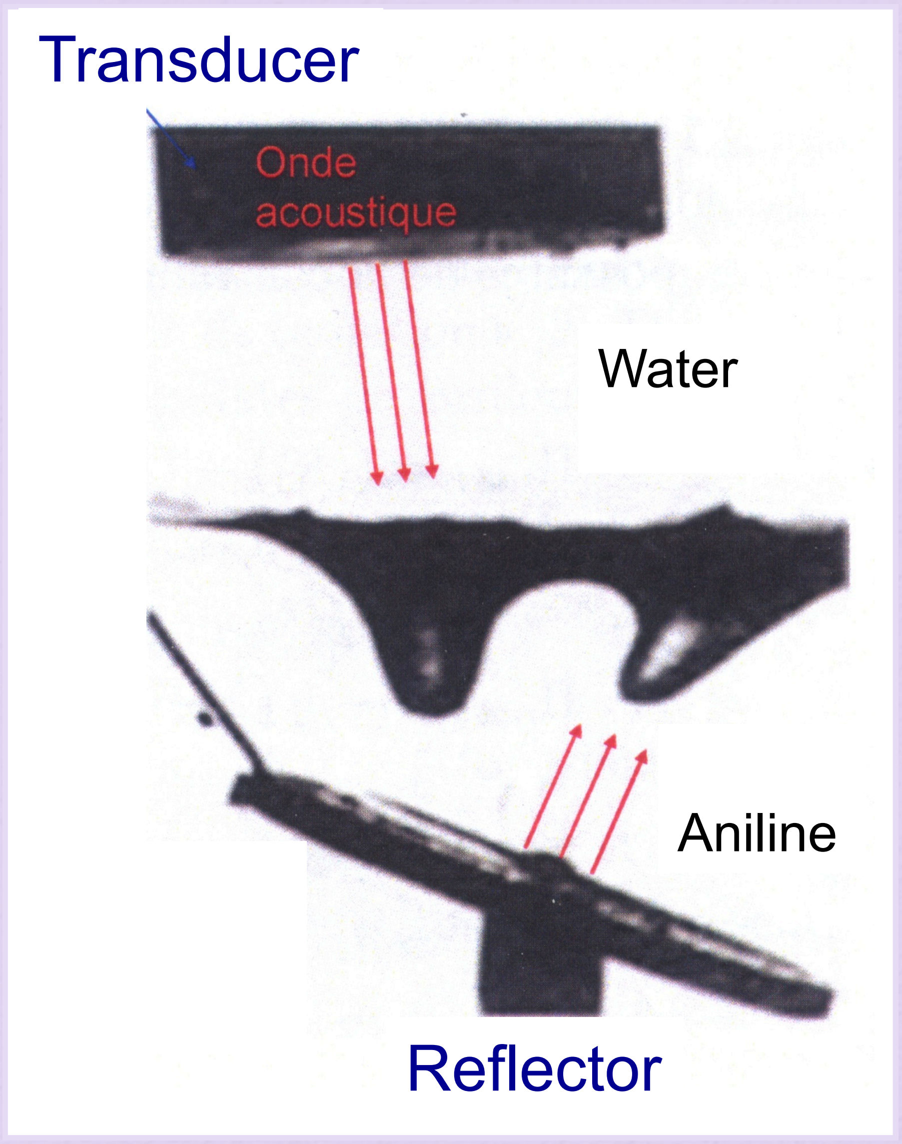


Total along +x

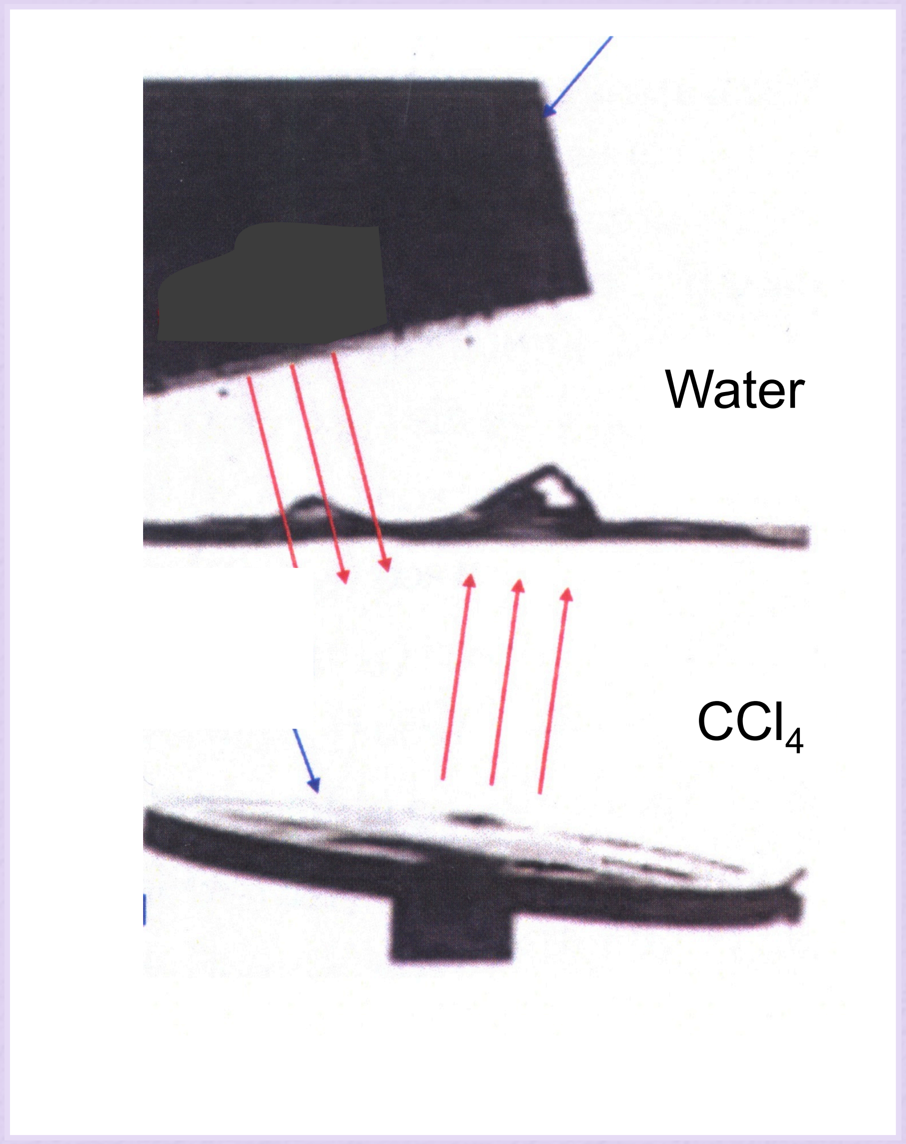
$$P_{rad} = I\left(\frac{1+R}{c_1} - \frac{1-R}{c_2}\right)$$

- P_{rad} can be negative (e.g. if $c_2 << c_1$)
- Can be independent of the direction of propagation

if exchanging $c_2 <-> c_1$
changes sign of P_{rad}

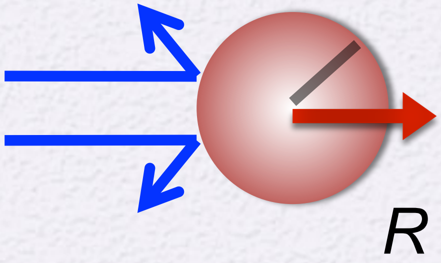


Hertz and Mende 1939


[redacted]

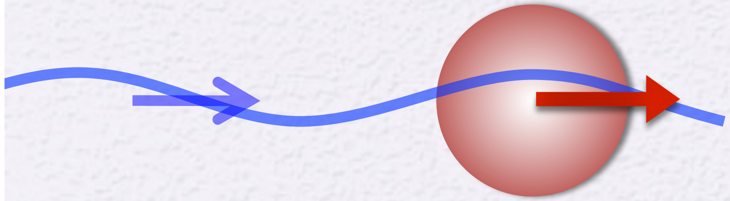
b) On solid particles: acousto-phoresis

- Mie regime, $R \gg \lambda$



$F_{rad} = S\ I/c$ with $S = \pi R^2$

- Rayleigh regime, $R \ll \lambda$ (microfluidics)



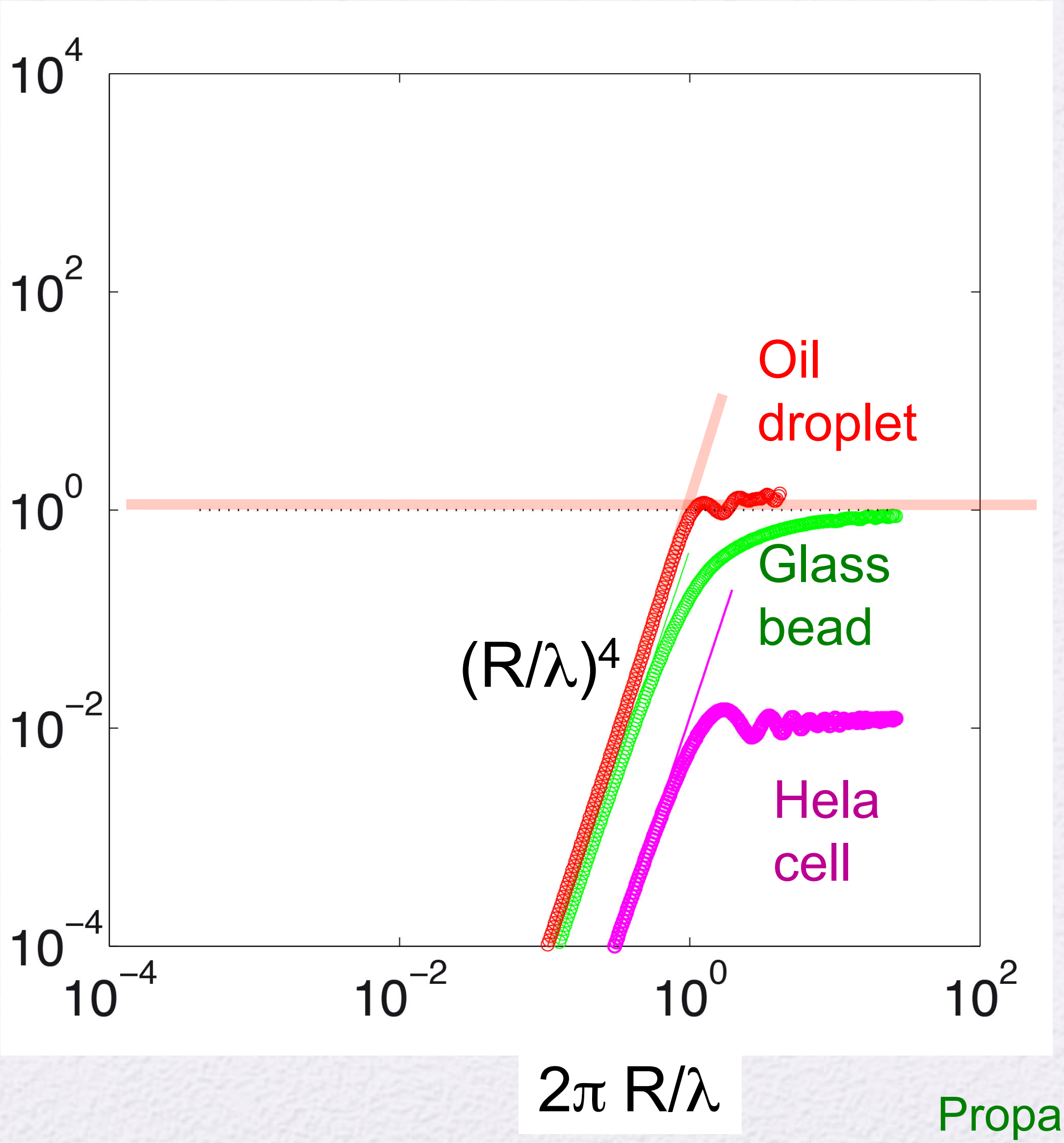
$F_{rad} = \Phi_{prop}\,(R/\lambda)^4\ S\ I/c$

King 1934

Φ_{prop} depends on the particle properties

Yosioka 1955

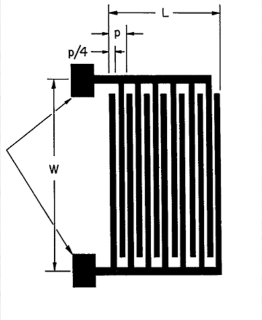
Radiation force
$F_{rad} / (\pi R^2 I/c)$



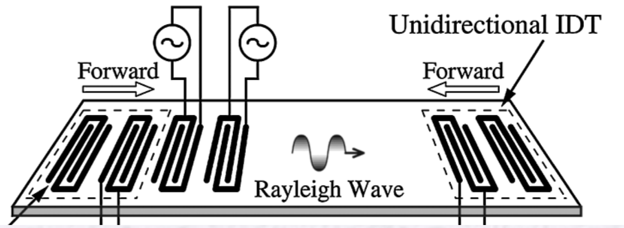
Propagating waves
Yosioka 1955

In practice:

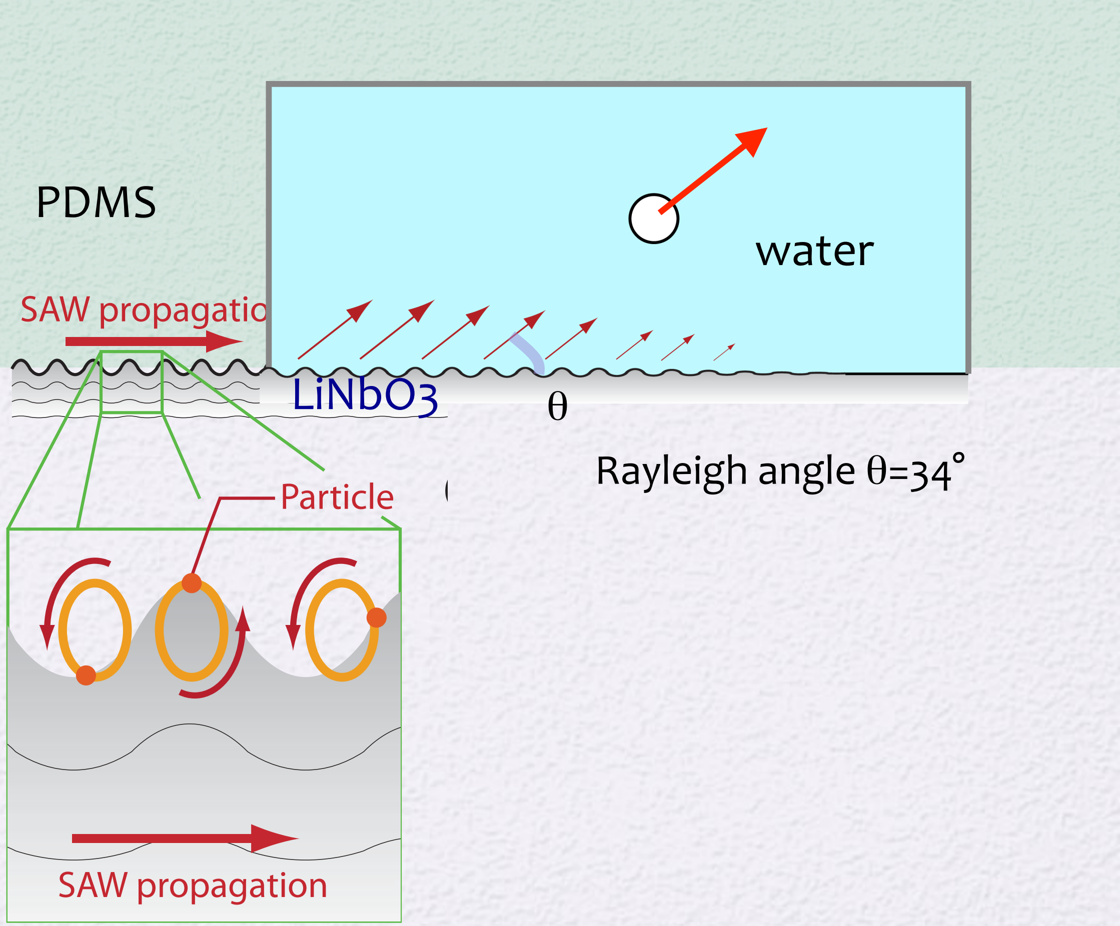
inject sound in a microsystem with surface acoustic waves



Interdigitated
electrodes (IDT)



LiNbO3
piezo-electric crystal
transparent

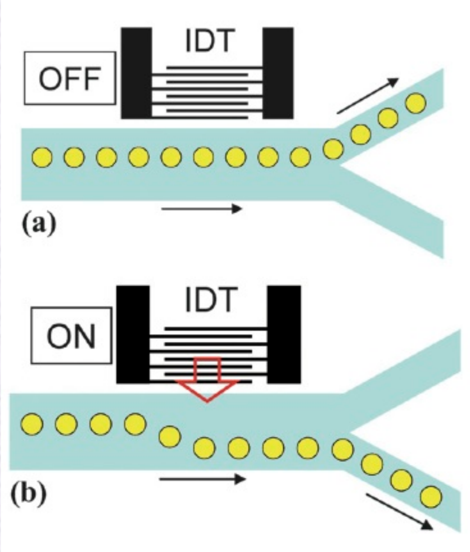


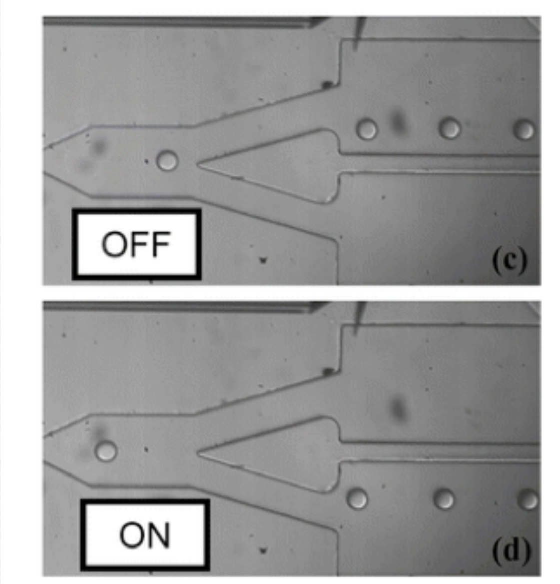
Rayleigh angle θ=34°

See review by *Friend and Yeo 2011*

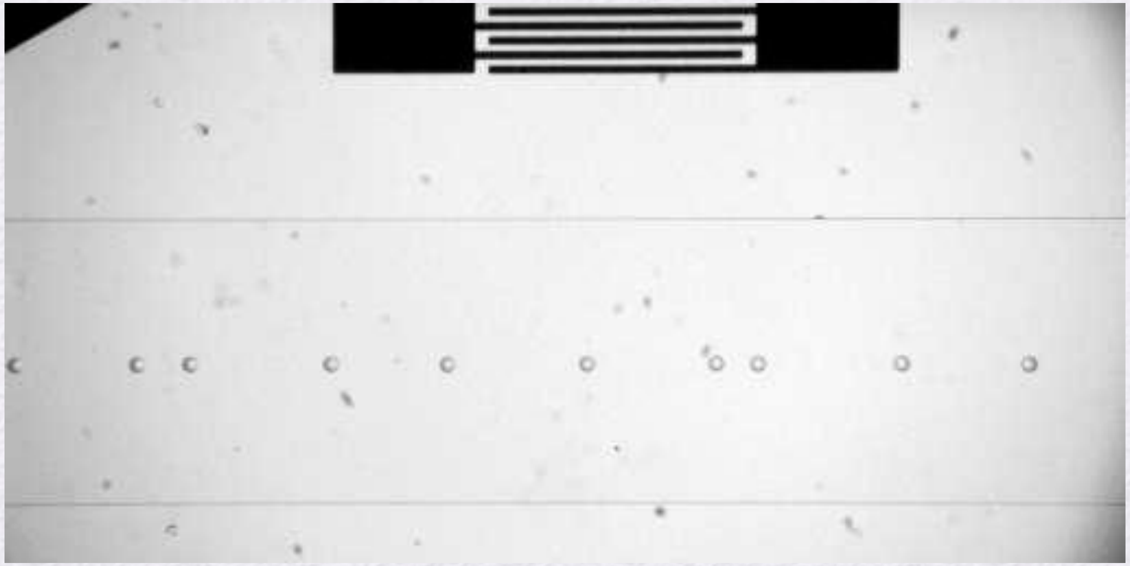
(SAW or Rayleigh waves)

a tool to push particles/droplets





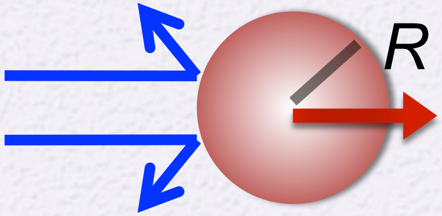
Franke 2009
Lab on a Chip



our lab
unpublished

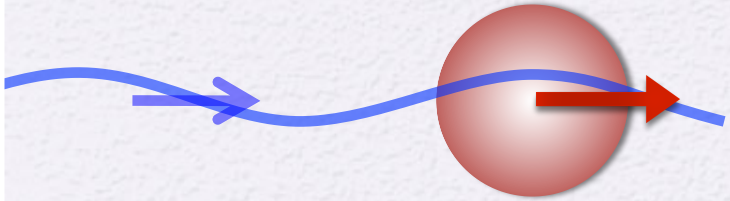
standing waves/propagating waves

- Mie regime, $R >> \lambda$

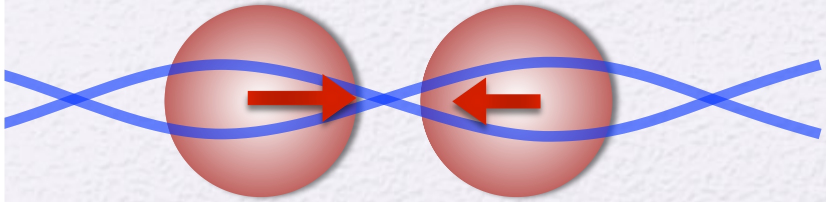


Propagative: $F_{rad} = S\ I/c$

- Rayleigh regime, $R << \lambda$ (microfluidics)

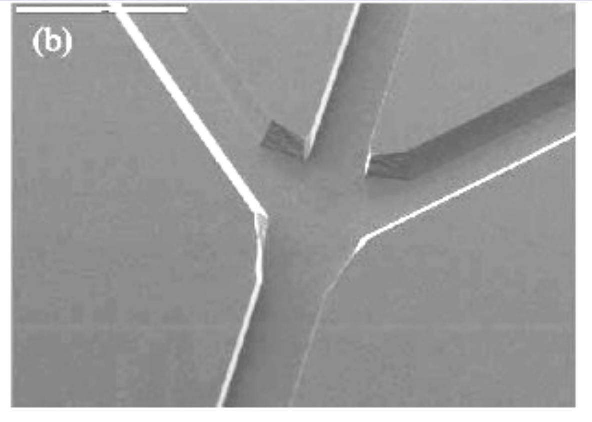


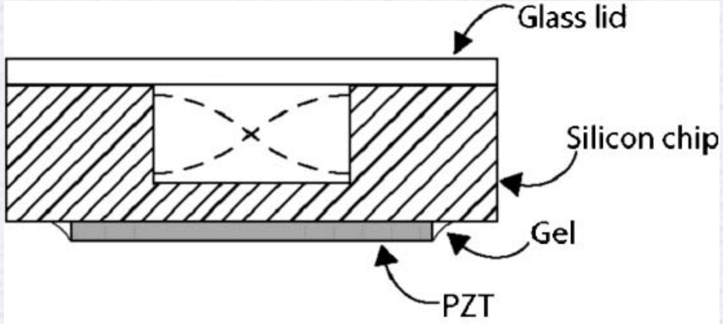
Propagative: $F_{rad} \sim (R/\lambda)^4\ S\ I/c$



Stationary: $F_{rad} \sim (R/\lambda)^1\ S\ I/c$

standing waves, examples

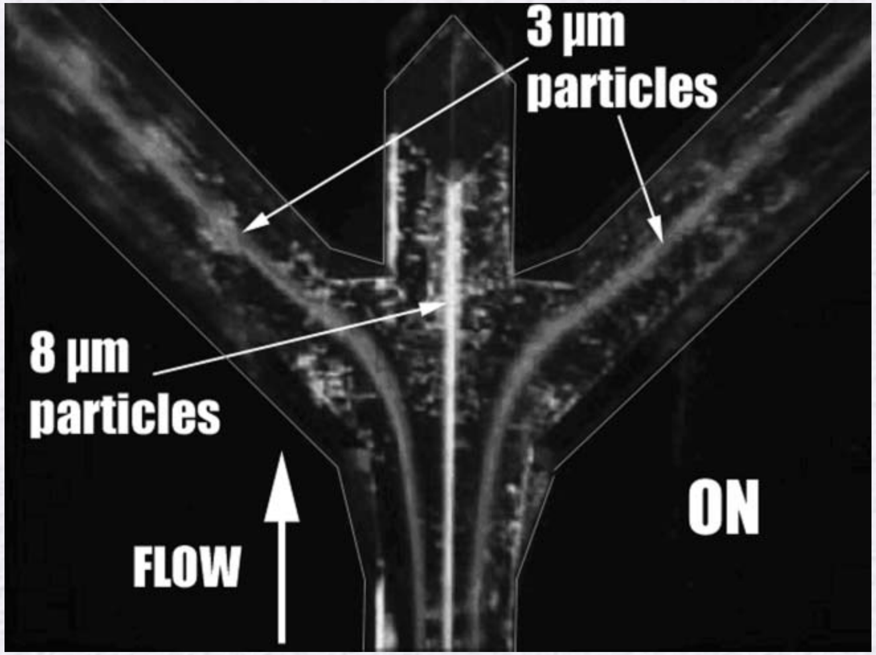




$F_{rad} \sim (R/\lambda)^1 \, S \, I/c \quad \sim R^3$

$F_{drag} = 6\pi\eta R v \quad \sim R^1$

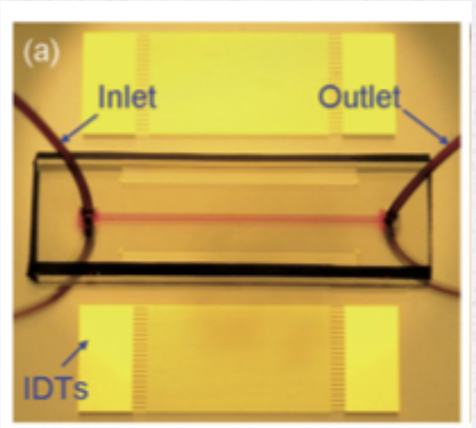
stronger effect on large particles



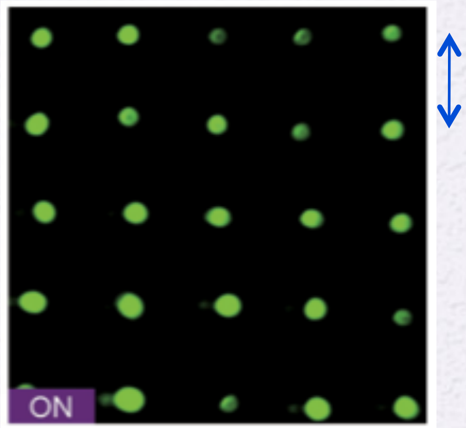
Petersonn 2007

1D - patterning

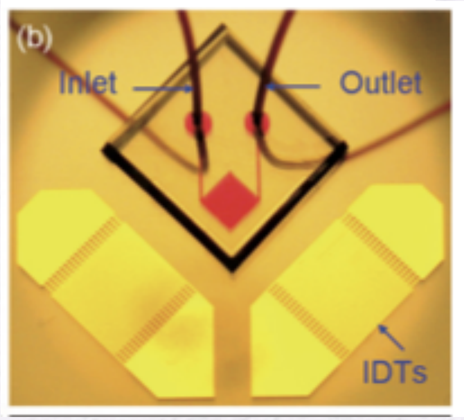
λ/2 = 50 µm



2D - patterning



λ/2 = 100 µm



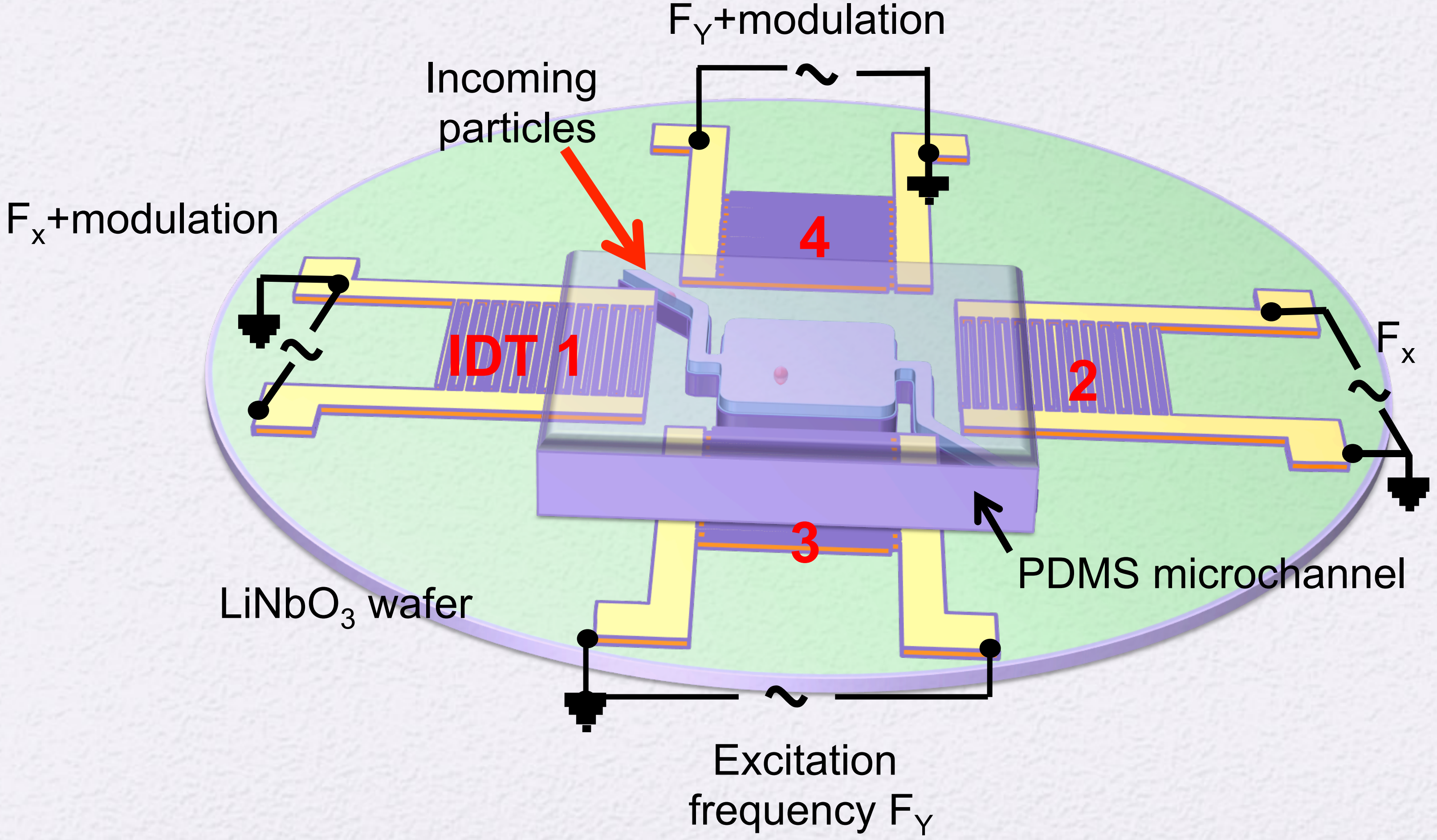
Shi 2009

Acoustic sorting
ESPCI startup

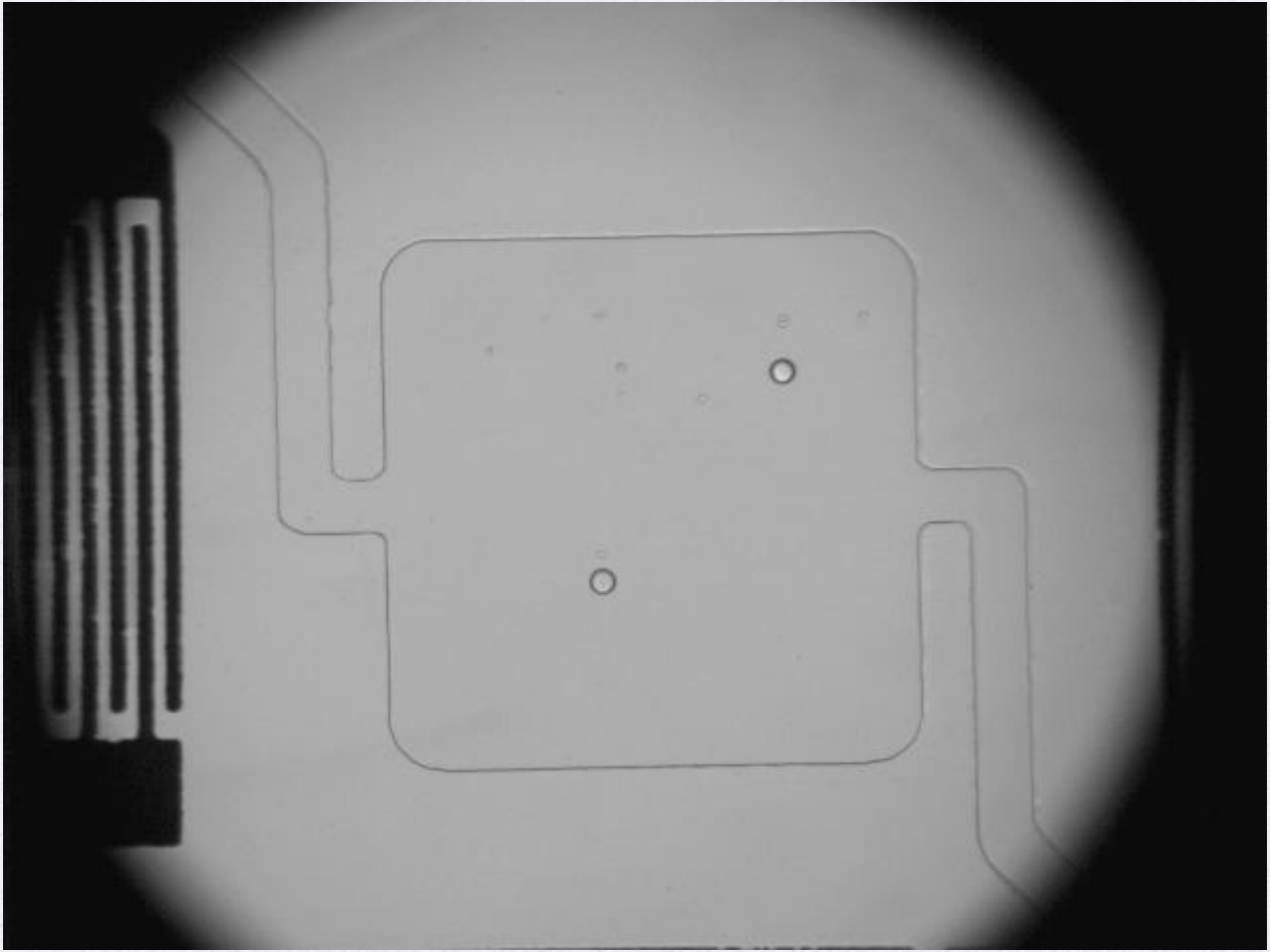
ænitis
TECHNOLOGIES

acoustic tweezers:

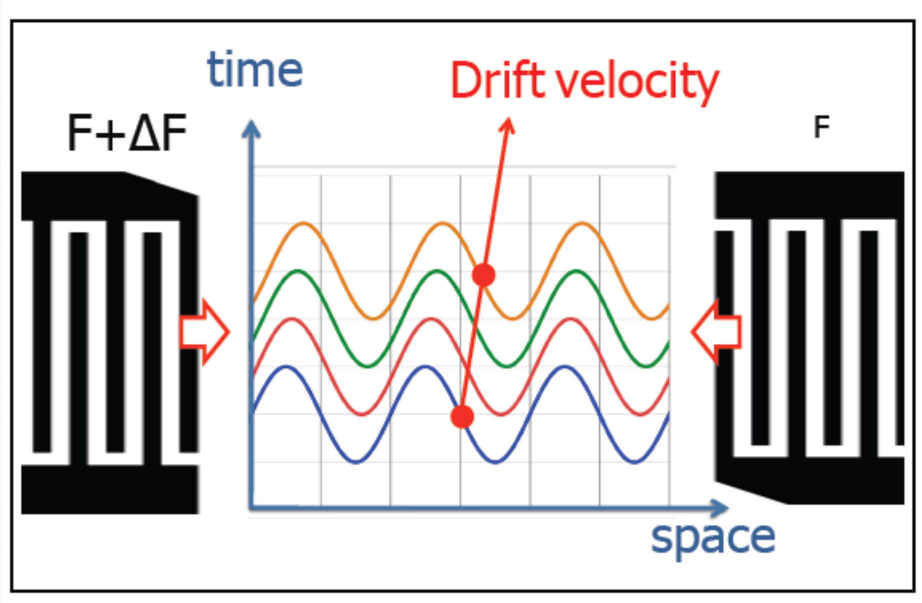
with "mobile" standing waves



Tran, Marmottant and Thibault   Appl. Phys. Lett. 2012



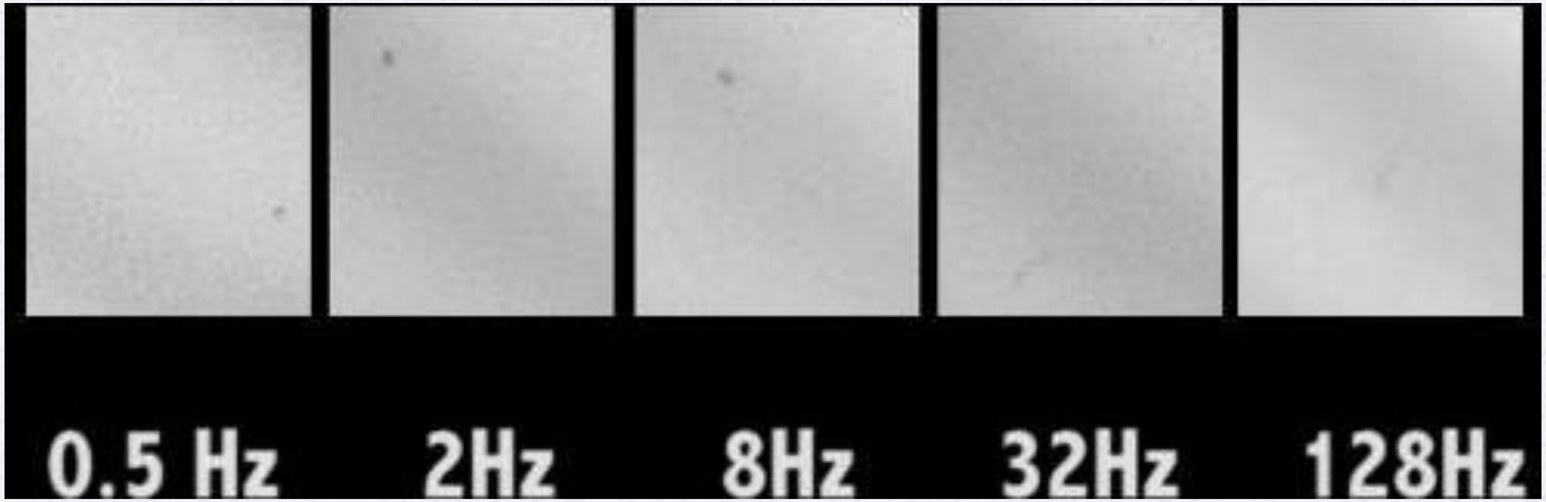
Principle: phase shift on one electrode

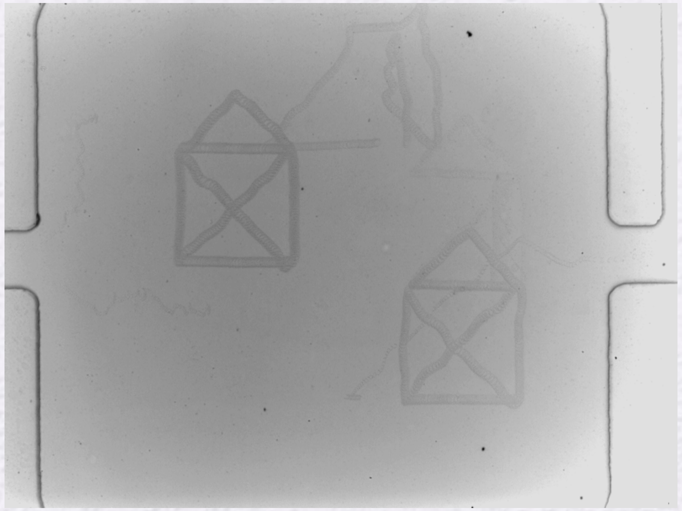


Standing wave that drifts because the left electrode emits

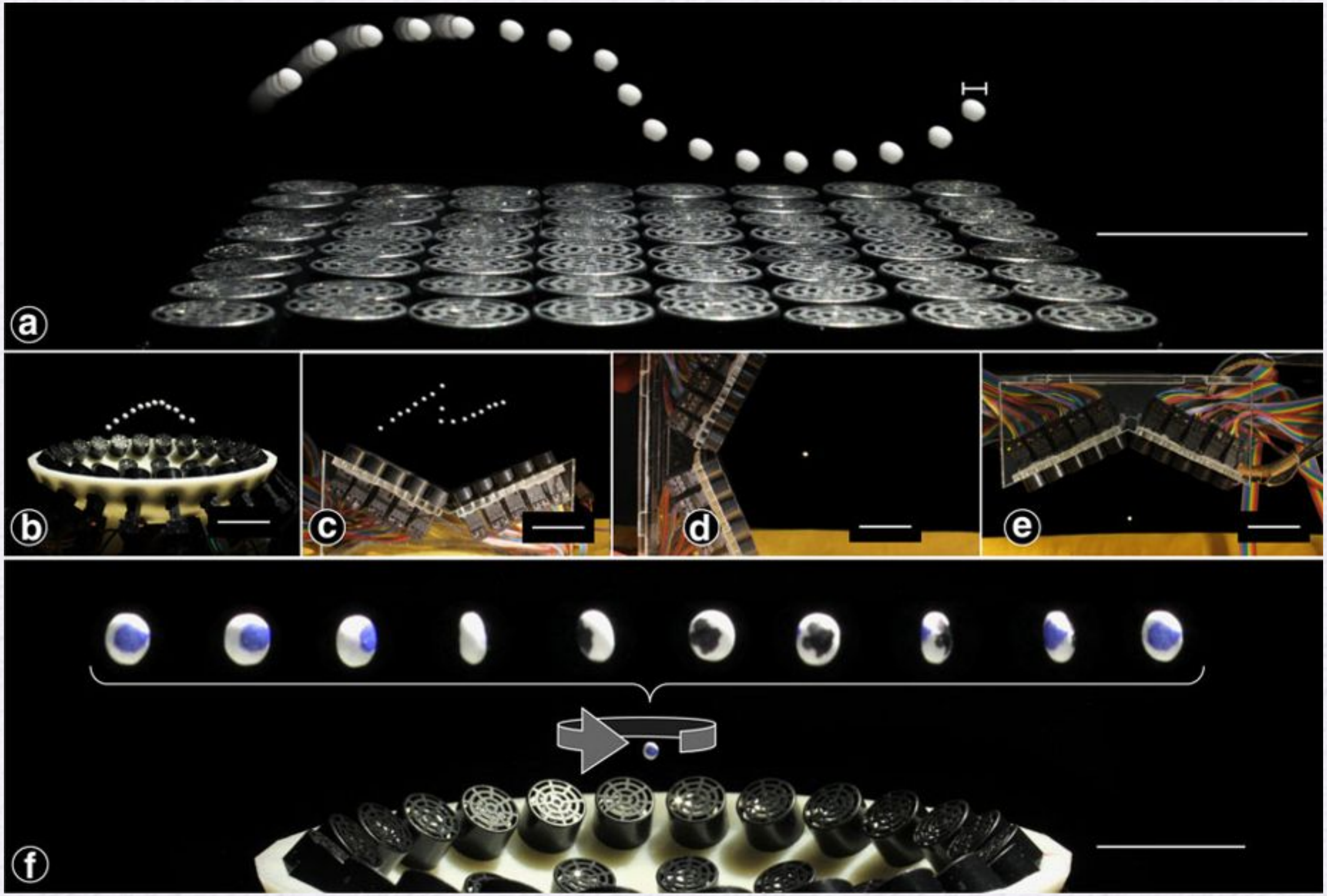
$$\cos\left(2\pi F t + \int_0^t 2\pi \Delta F(\tau)\, d\tau\right)$$

controled phase shift


0.5 Hz
2Hz
8Hz
32Hz
128Hz

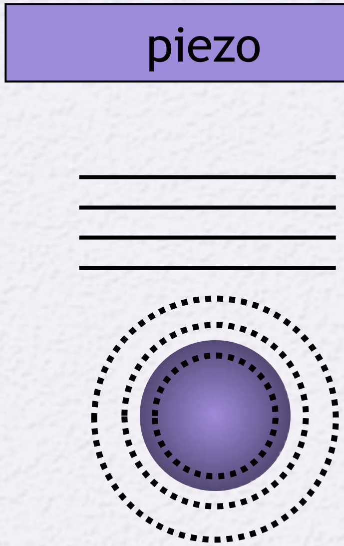


Holographic tweezers

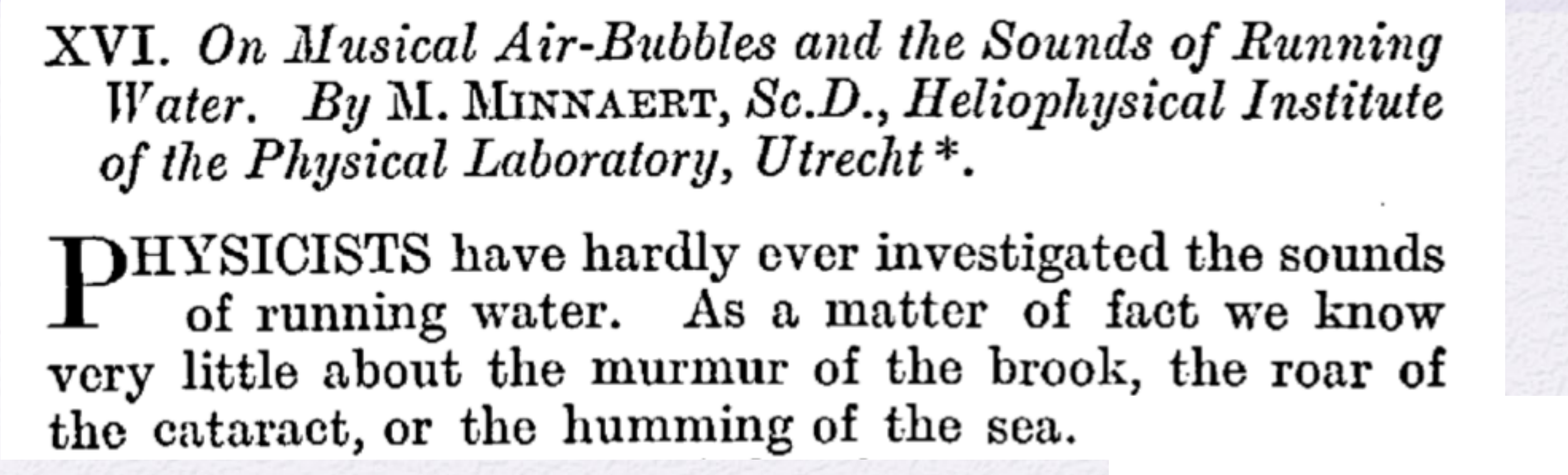


Marzo Nature Comm 2015

c) On compressible bubbles: resonance and Bjernes forces


piezo

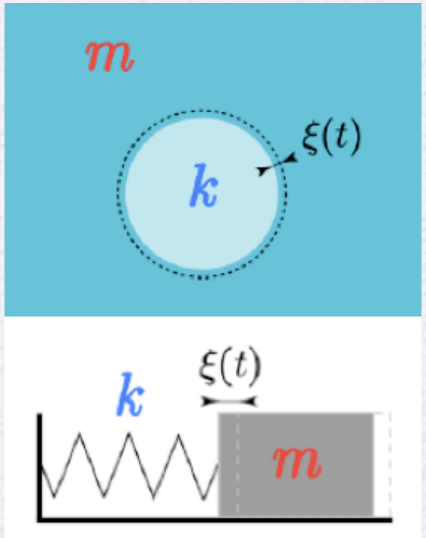
Resonance of bubbles



XVI. *On Musical Air-Bubbles and the Sounds of Running Water. By* M. MINNAERT, *Sc.D., Heliophysical Institute of the Physical Laboratory, Utrecht *.*

PHYSICISTS have hardly ever investigated the sounds of running water. As a matter of fact we know very little about the murmur of the brook, the roar of the cataract, or the humming of the sea.

(*Philosophical Magazine*, 1933)



Illustrations: Olivier Vincent

bubble = harmonic oscillator

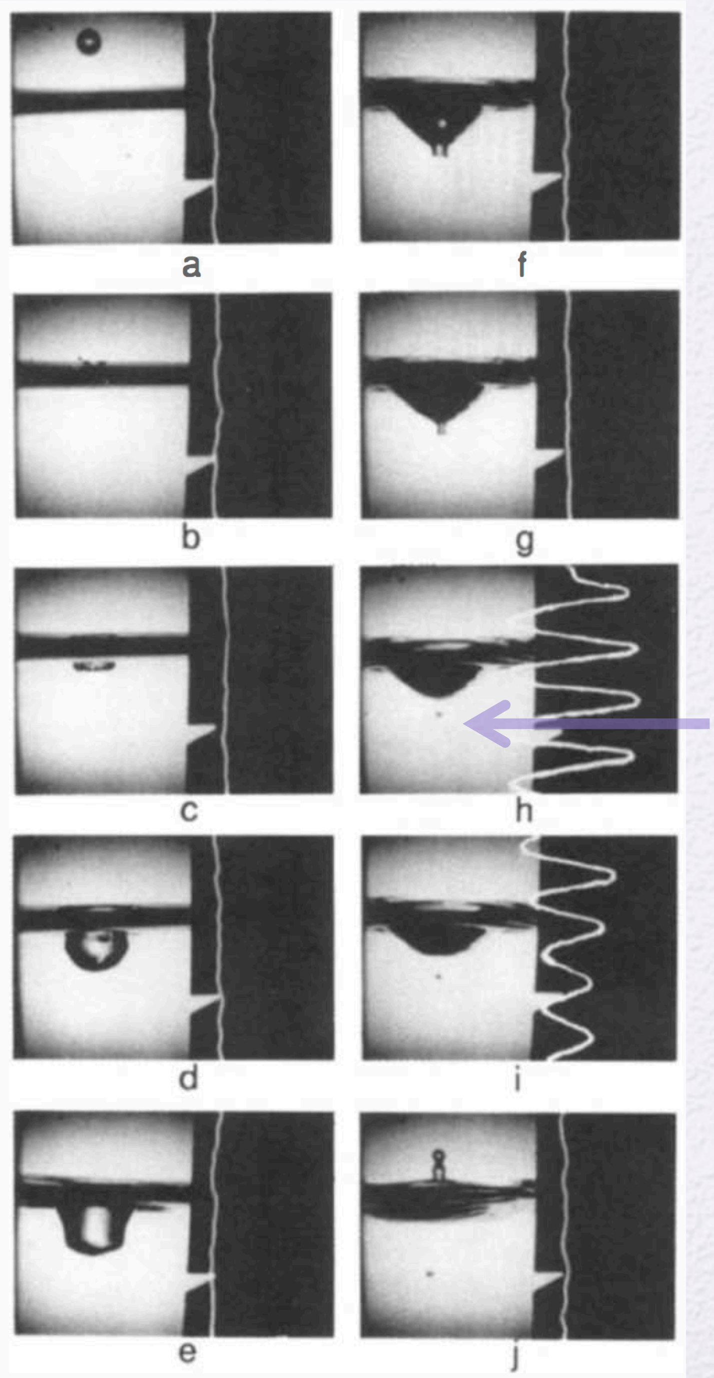
mass : dispaced liquid
stiffness : gas compressiility

Minnaert formula

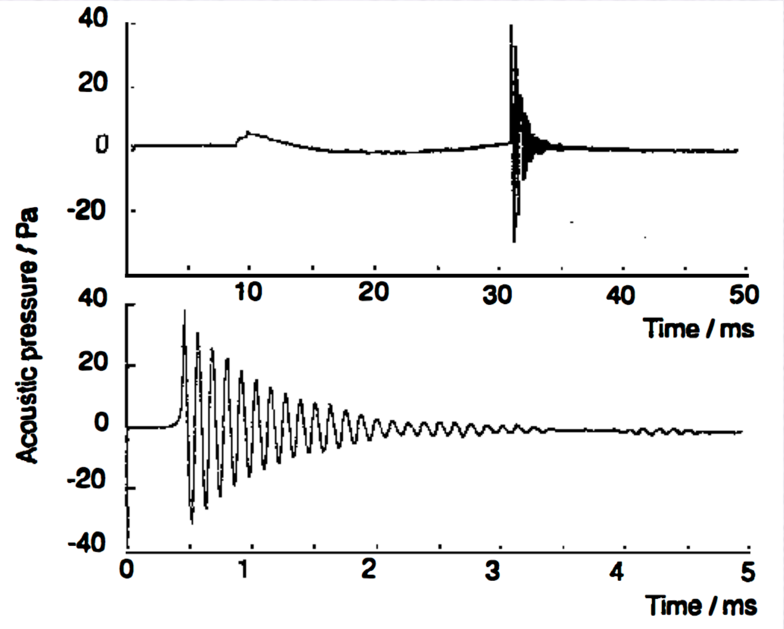
$$\boxed{f \times R \simeq 3\,\mathrm{m/s}}$$

3 kHz for 1 mm bubbles

Sound of rain droplet: due to a bubble!



bubble



Pumphrey 1989

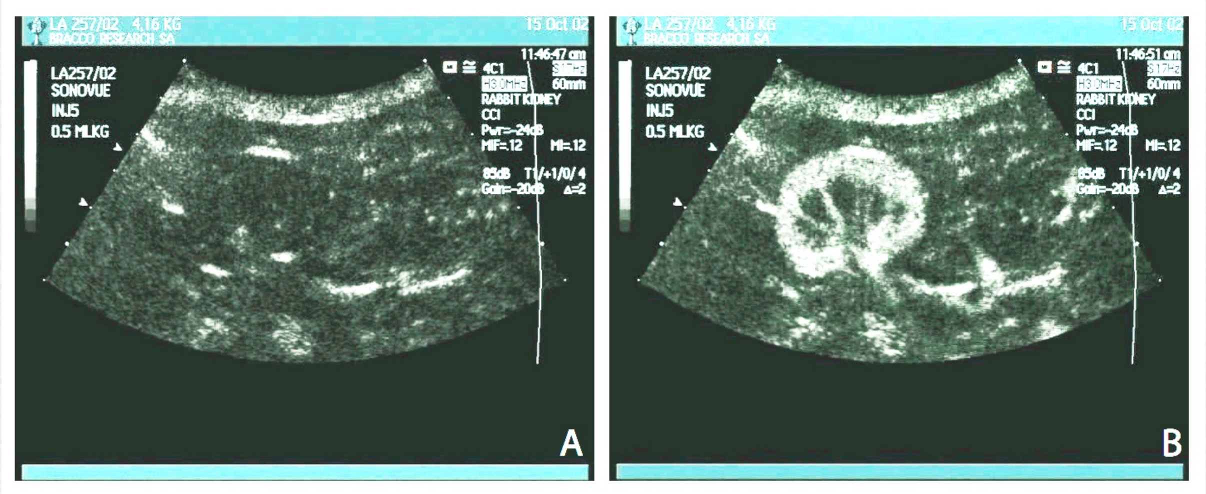
The bubble piano

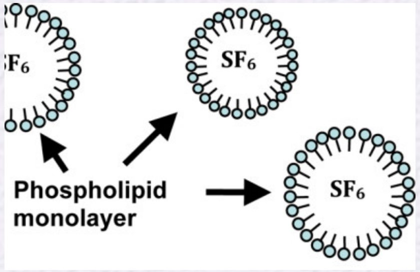
Valentin Leroy, MSC, Paris 7

Playing "Ode to Joy" with the bubble piano

Biomedical applications

- **Contrast agents for ultrasound echography**





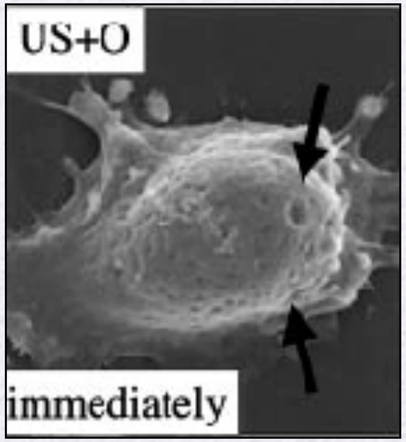
Sonovue® bubbles d~ 3 μm
Driven at ~1 MHz

Bracco Research

- **Sonoporation**

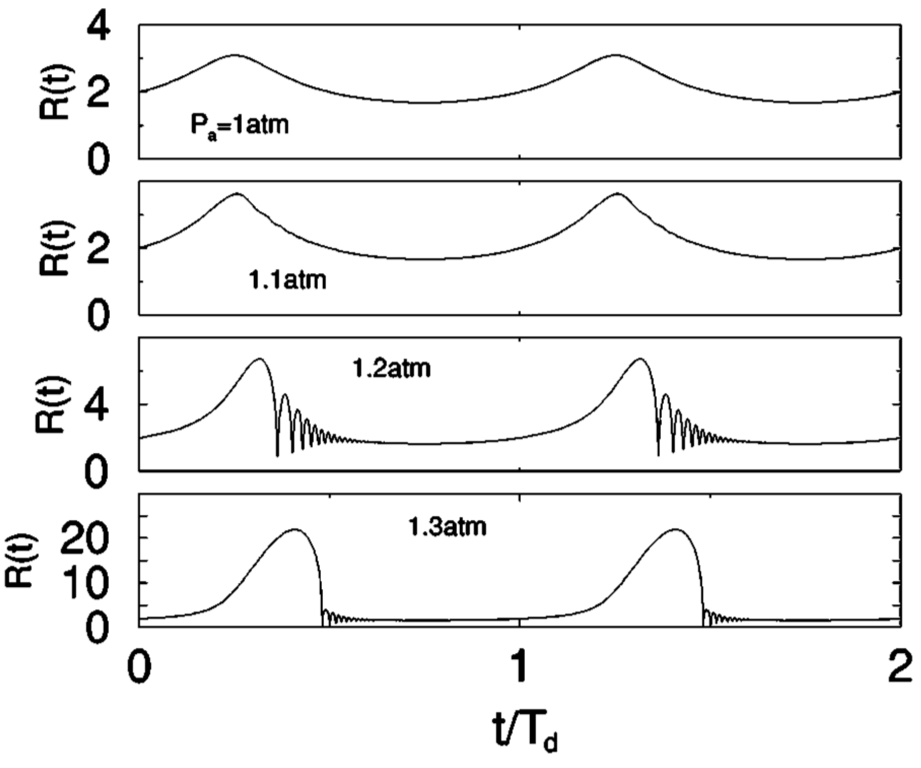
Near membranes enhanced permeabilisation

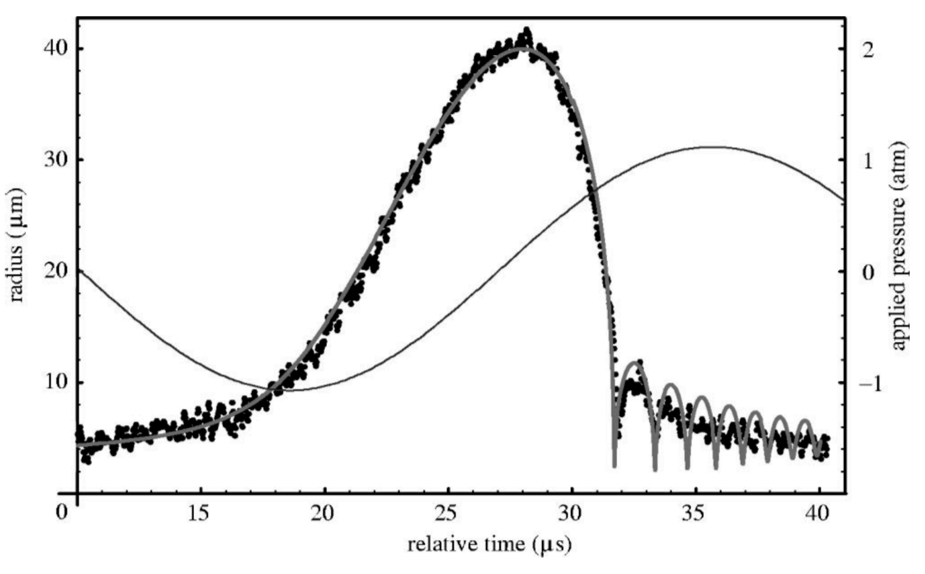
Targeted delivery



Taniyama et al Circulation 105 (2002)

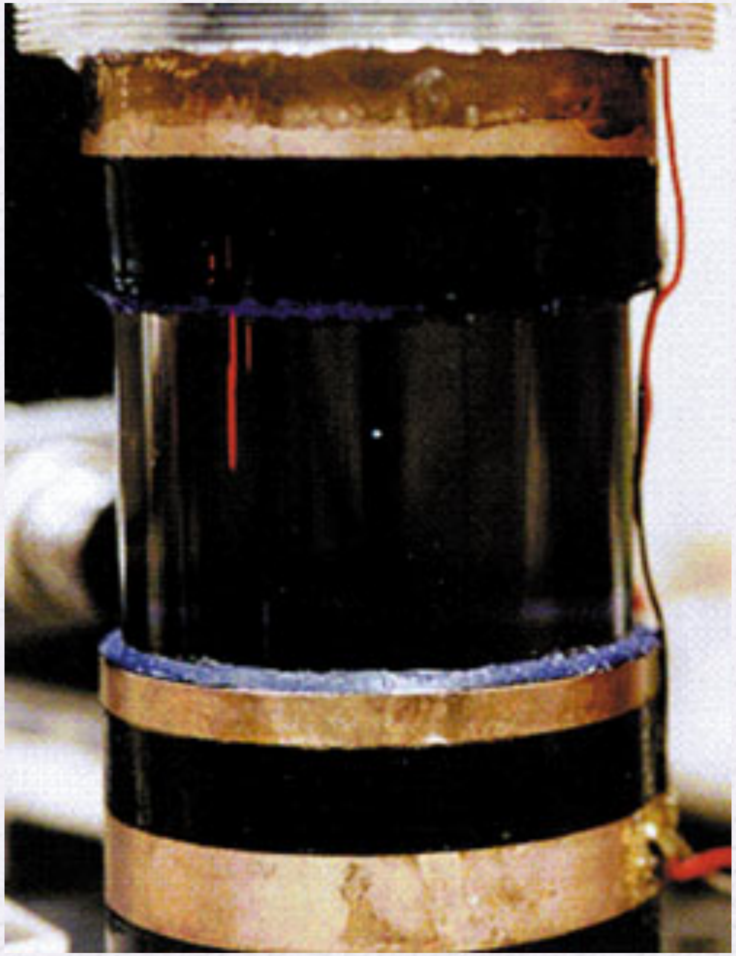
Excitation at large amplitude, $f \ll f_{res}$



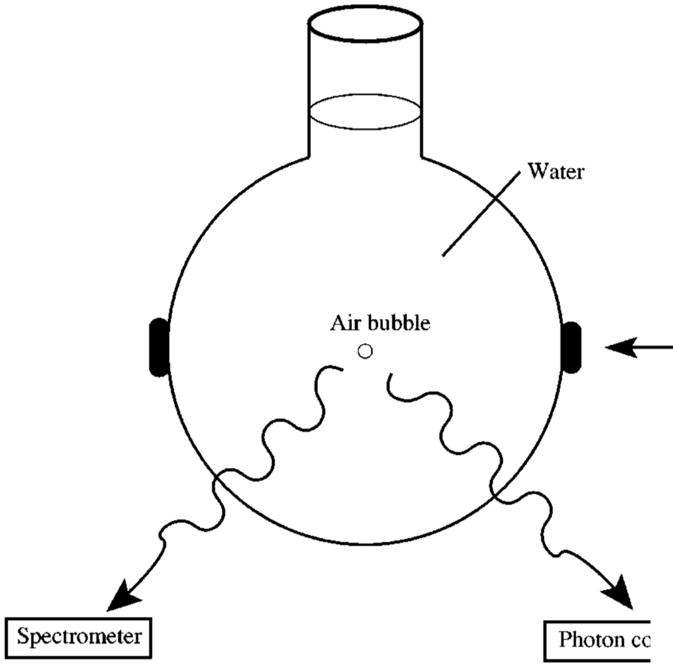


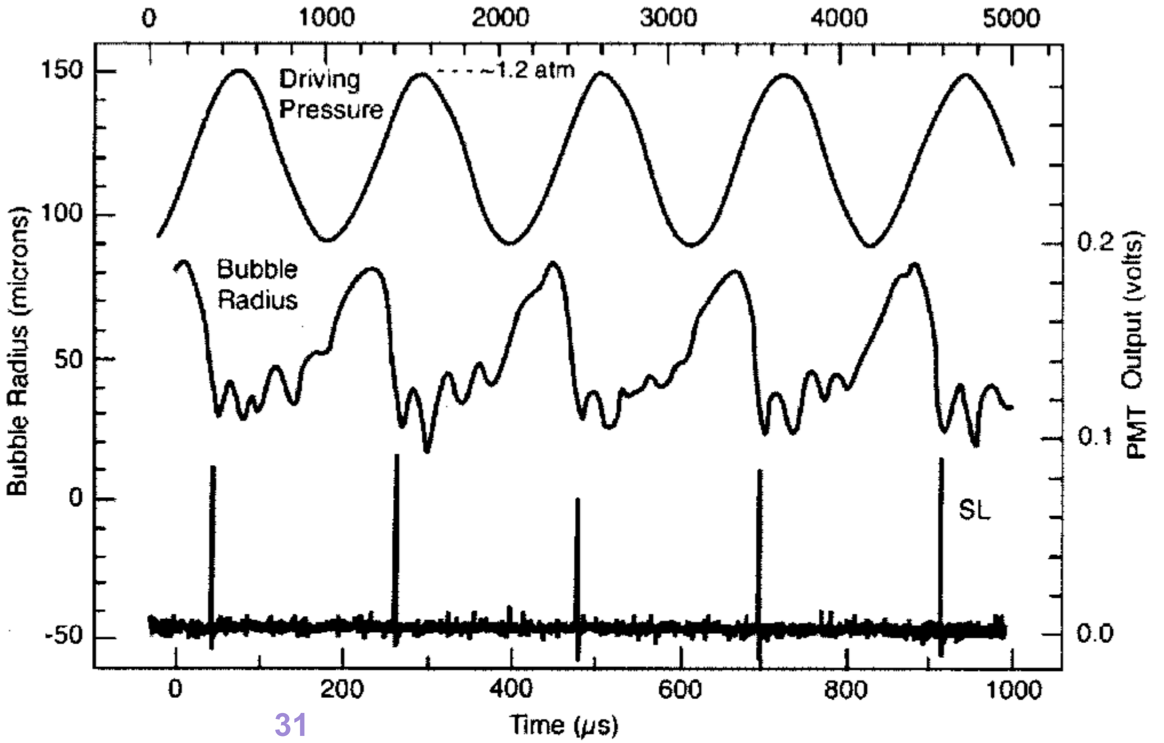
Brenner 2002

Sonoluminescence



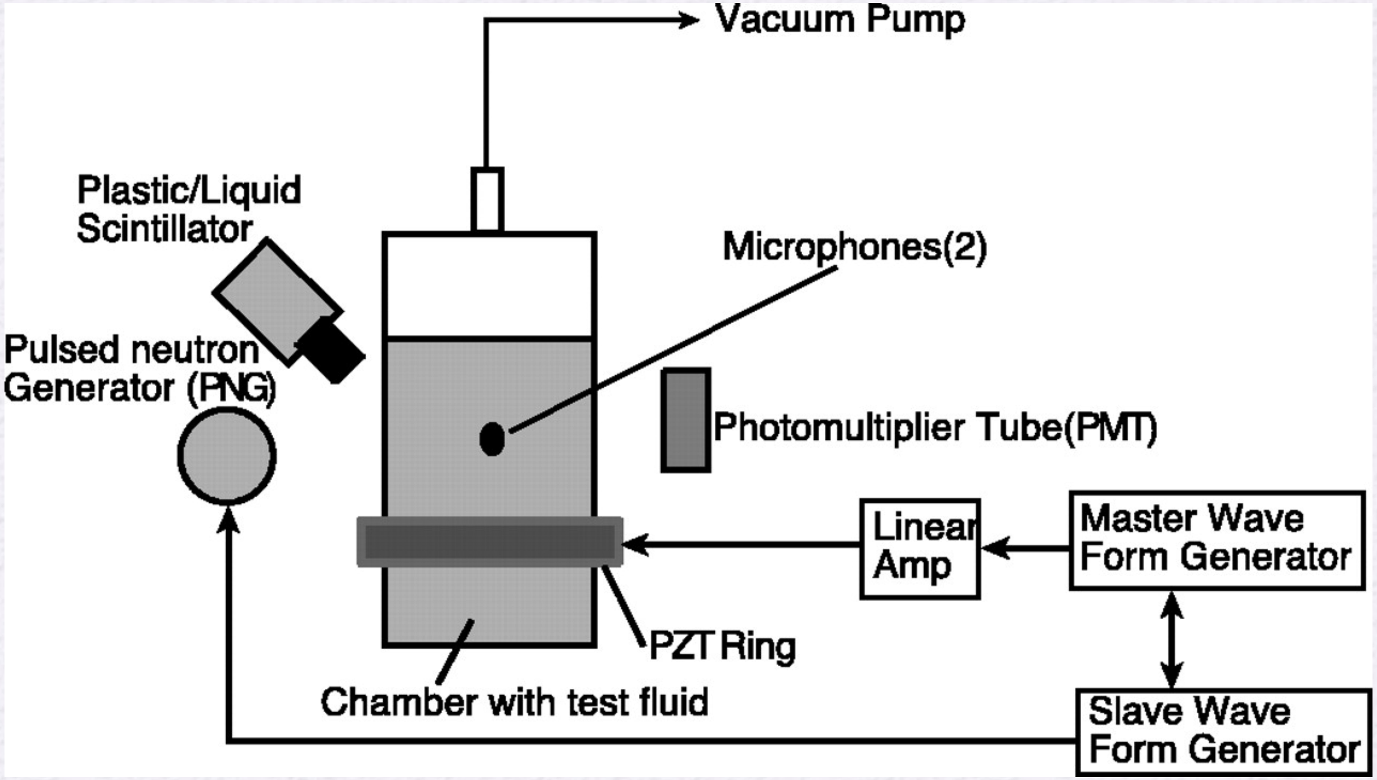
Crum 1994


Water
Air bubble
Piezos
Spectrometer
Photon co


0
1000
2000
3000
4000
5000
Driving
Pressure
~1.2 atm
Bubble
Radius
SL
Bubble Radius (microns)
150
100
50
0
-50
PMT Output (volts)
0.2
0.1
0.0
0
200
400
600
800
1000
Time (μs)

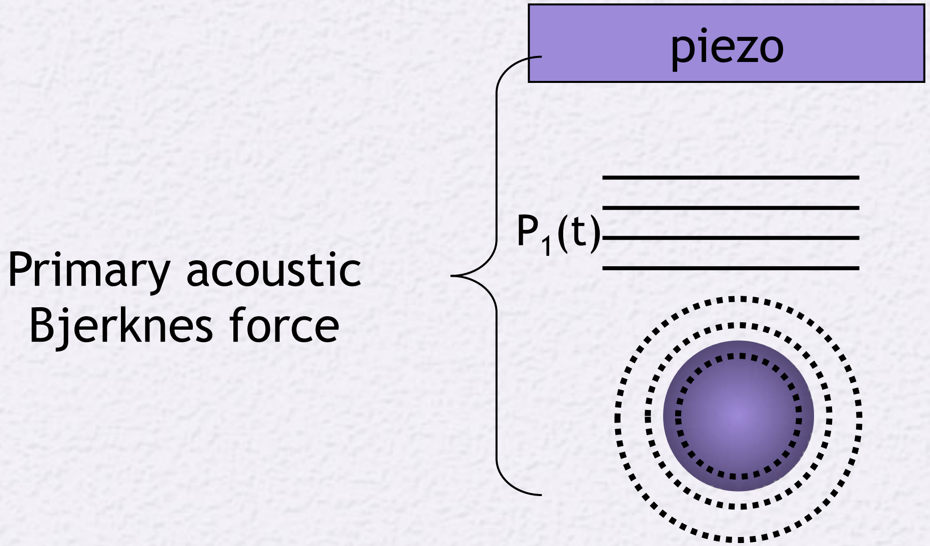
Crum 1994

Sonofusion?



Taleyarkhan 2002

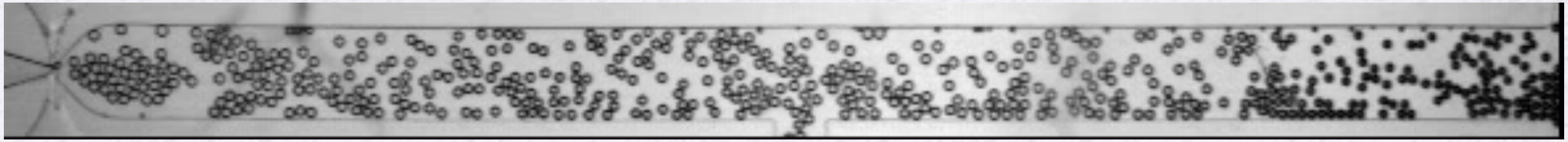
c) On compressible bubbles: resonance and Bjernes forces



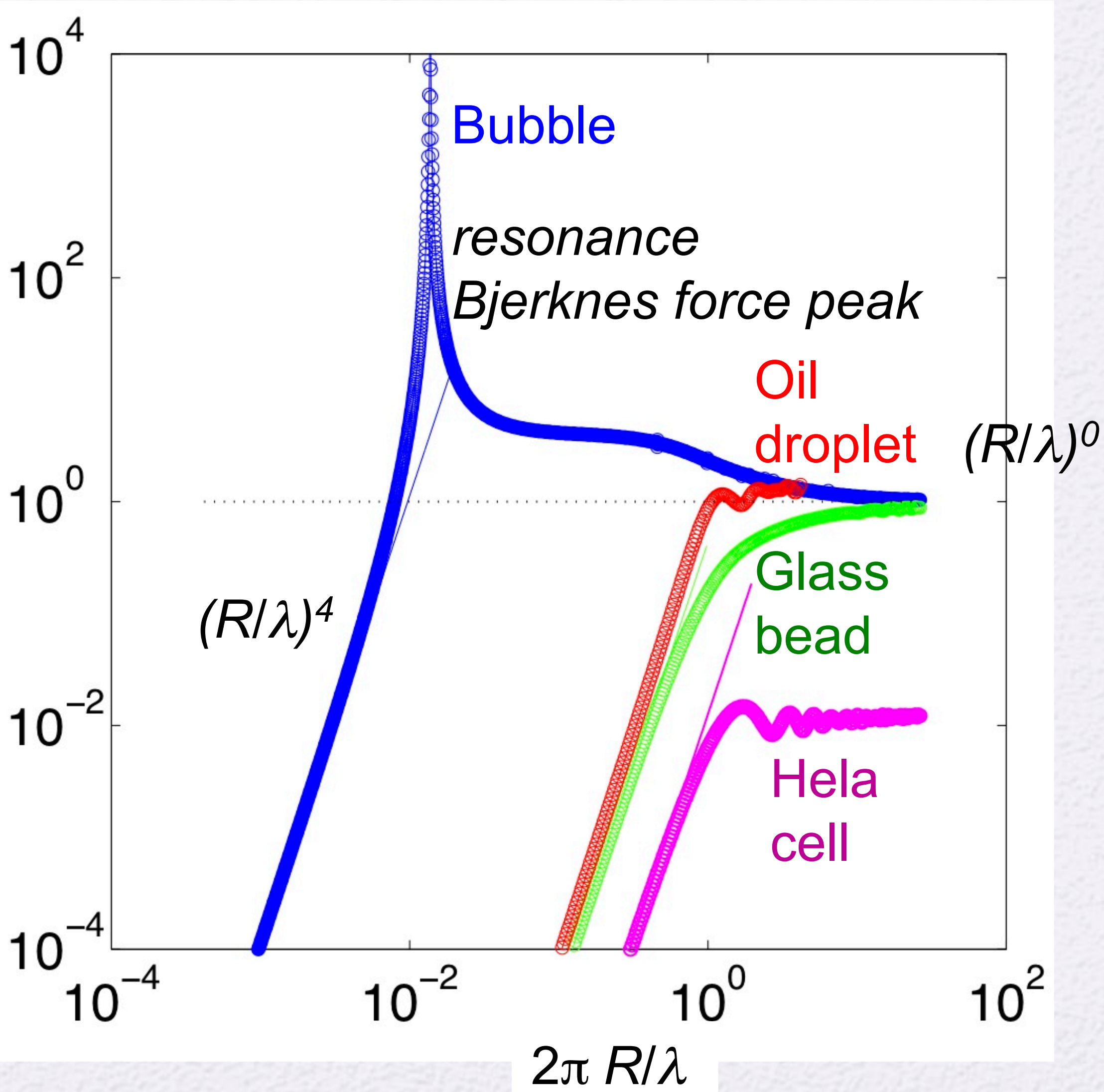
piezo

$P_1(t)$

Primary acoustic
Bjerknes force



Radiation force
F_{rad}
in units of
$\pi R^2 I/c$



Propagating waves
Yosioka 1955

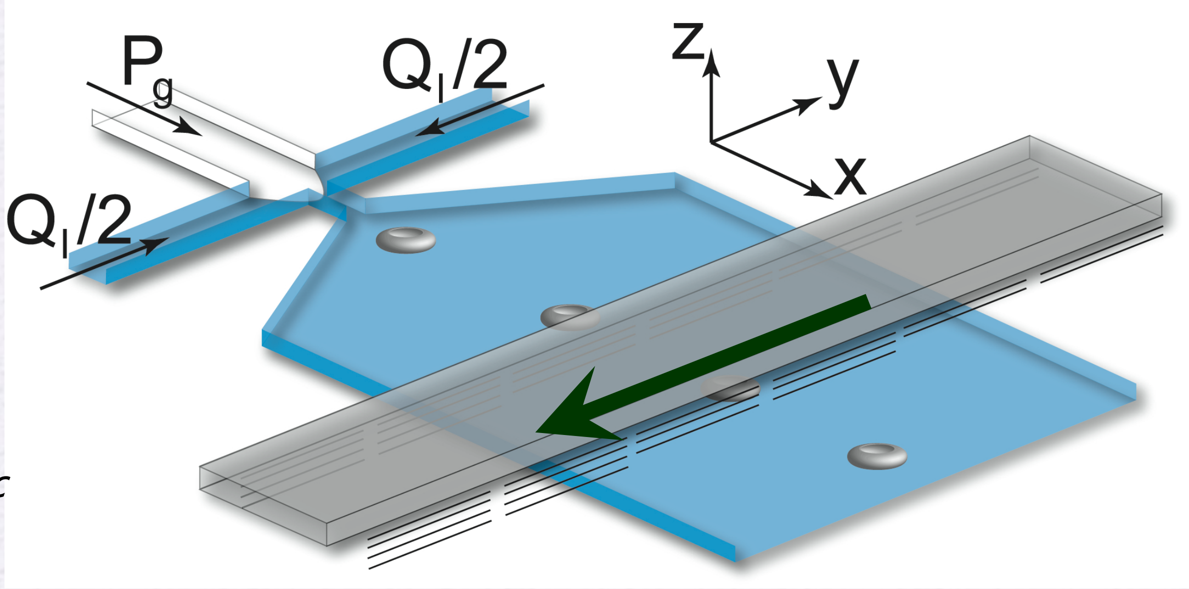
The Bjerknes force

- Bjerknes force:
  due to large **volume oscillation** at resonance,
  in a pressure gradient

$$
\begin{aligned}
F_{\text{Bjerknes}} &= \left\langle -V(t)\ \nabla P_{\text{Acoustic}}(t) \right\rangle \\
&= \left\langle -\left[V_0 + \delta V \cos(\omega t + \varphi) \right] \left[\nabla P_A \cos(\omega t) \right] \right\rangle \\
&= -\delta V\ \nabla P_A \cos\varphi
\end{aligned}
$$

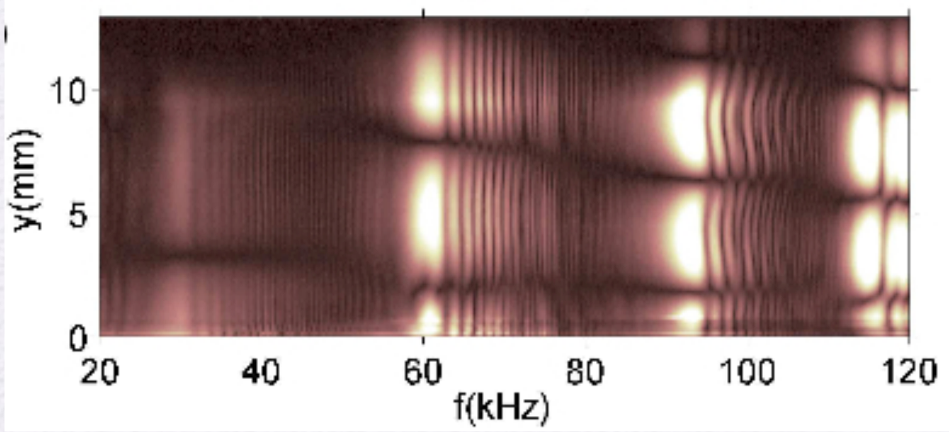
Bjerknes 1906

Set-up to induce Bjerknes forces



$\vec{\nabla} P_{Acoustic}$

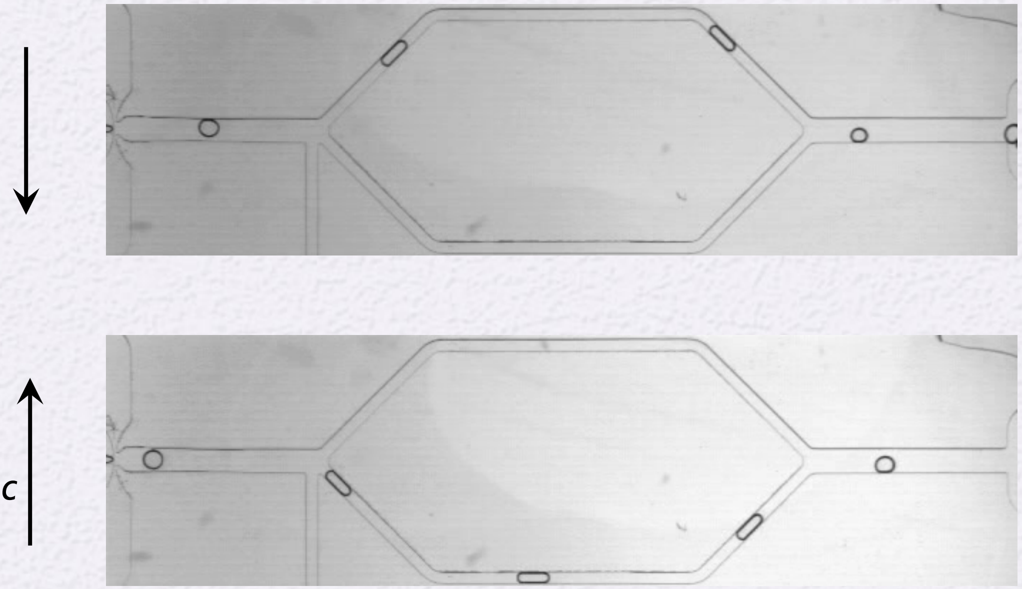
vibrating glass rod



stand wave
rod vibration

deviations

With a change of the standing wave pattern



$\vec{\nabla} P_{Acoustic}$

f = 147 kHz

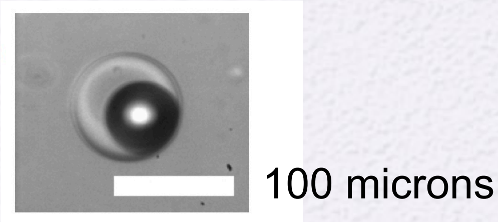
$\vec{\nabla} P_{Acoustic}$

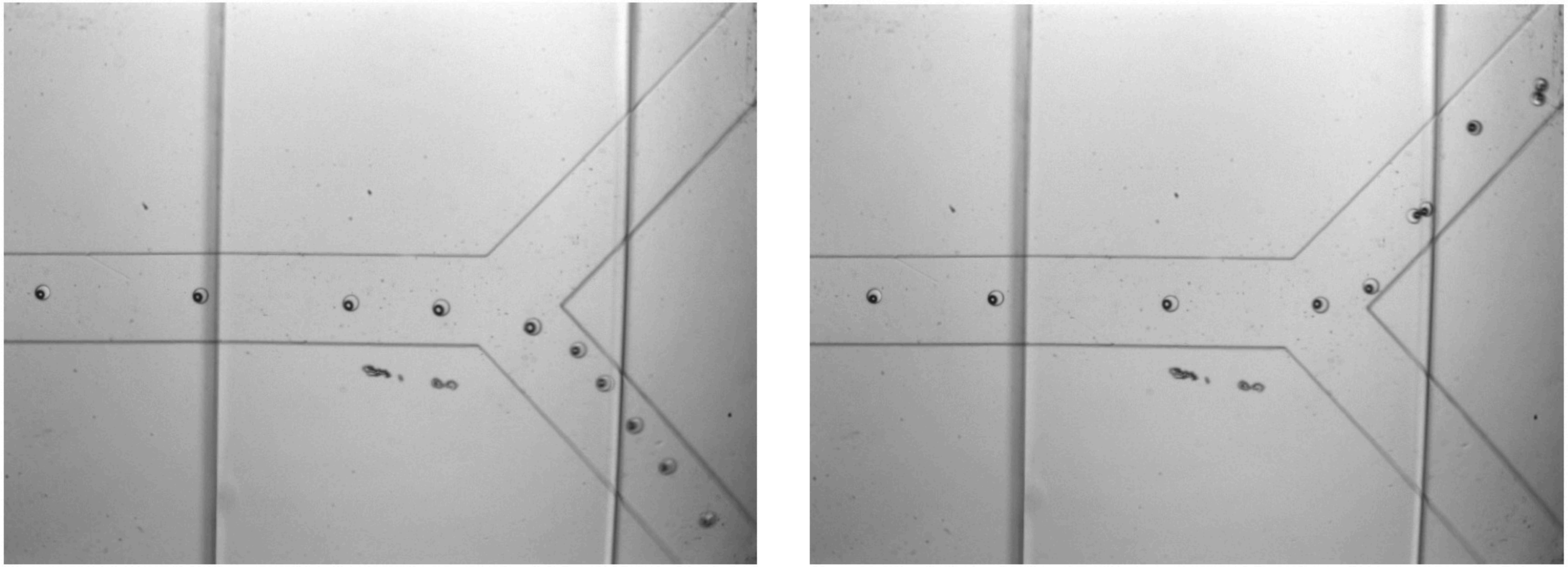
f = 151 kHz

Rabaud, Thibault, Raven, Hugon,
Lacot and Marmottant
Phys. Fluids 2011

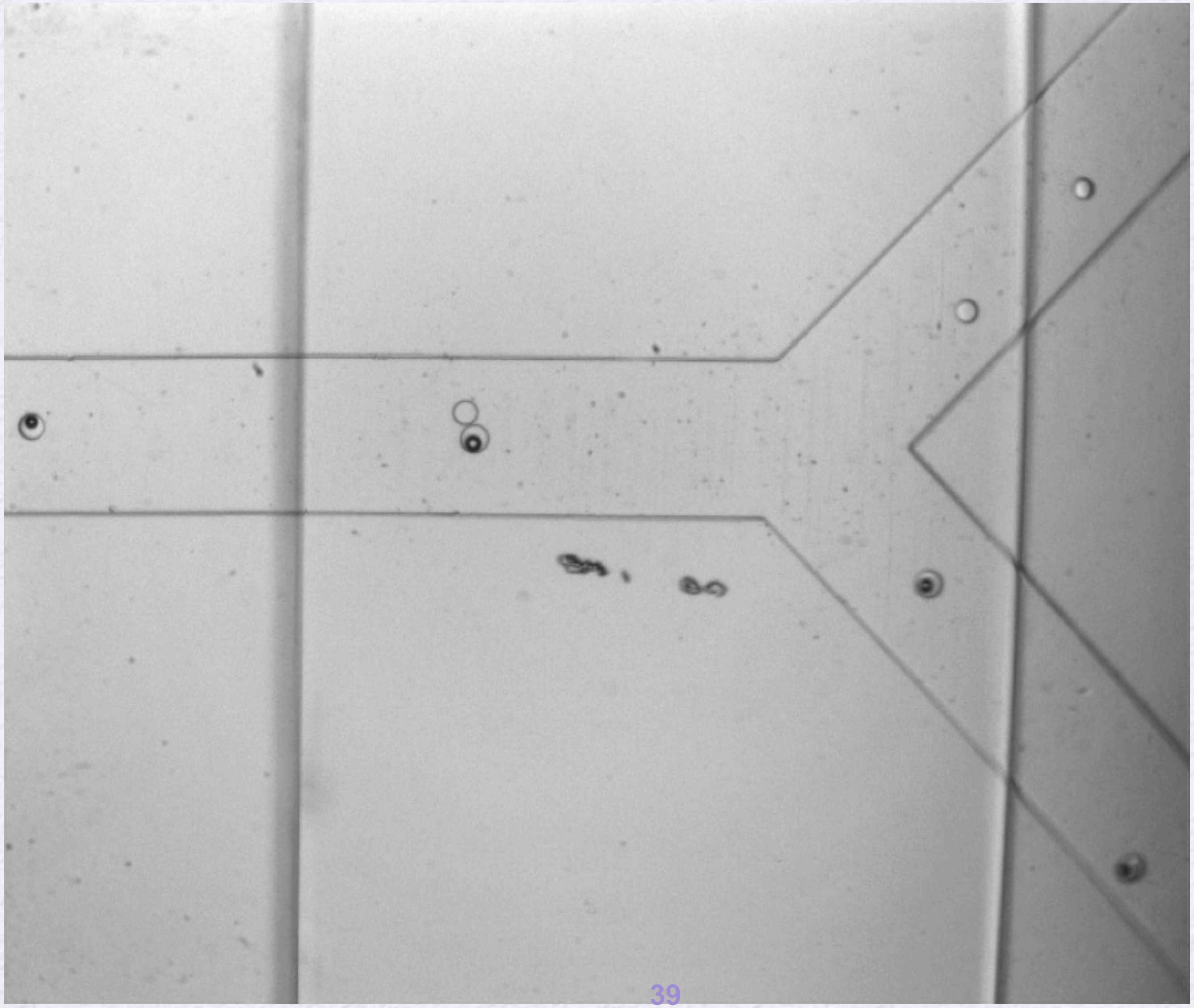
Example of applications of Bjerknes forces

- Switch droplets containing a bubble

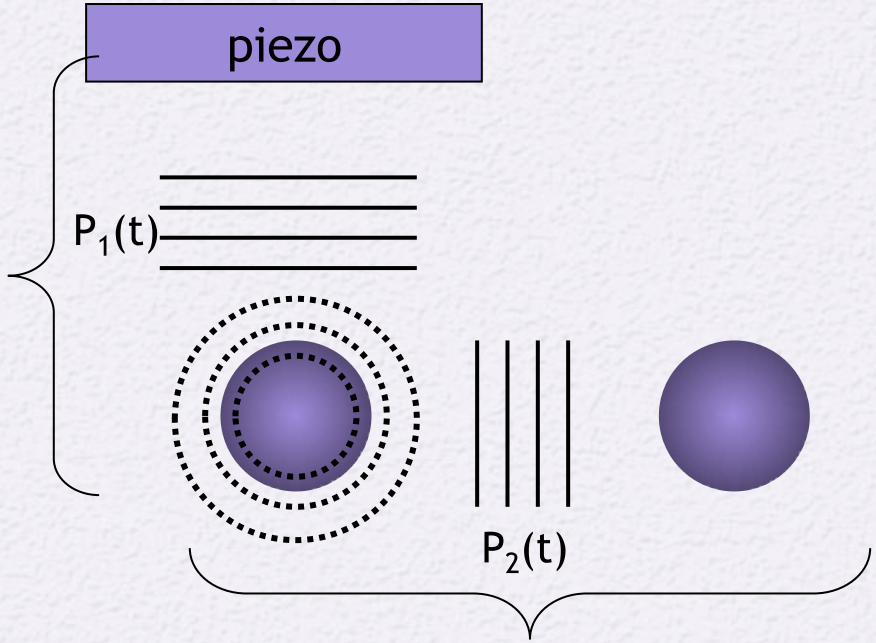




- Sort droplets



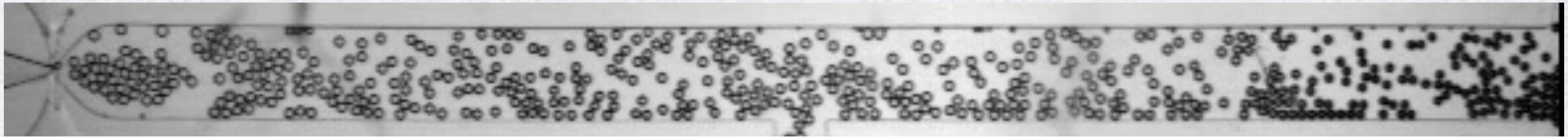
Many bubbles: Self-organisation



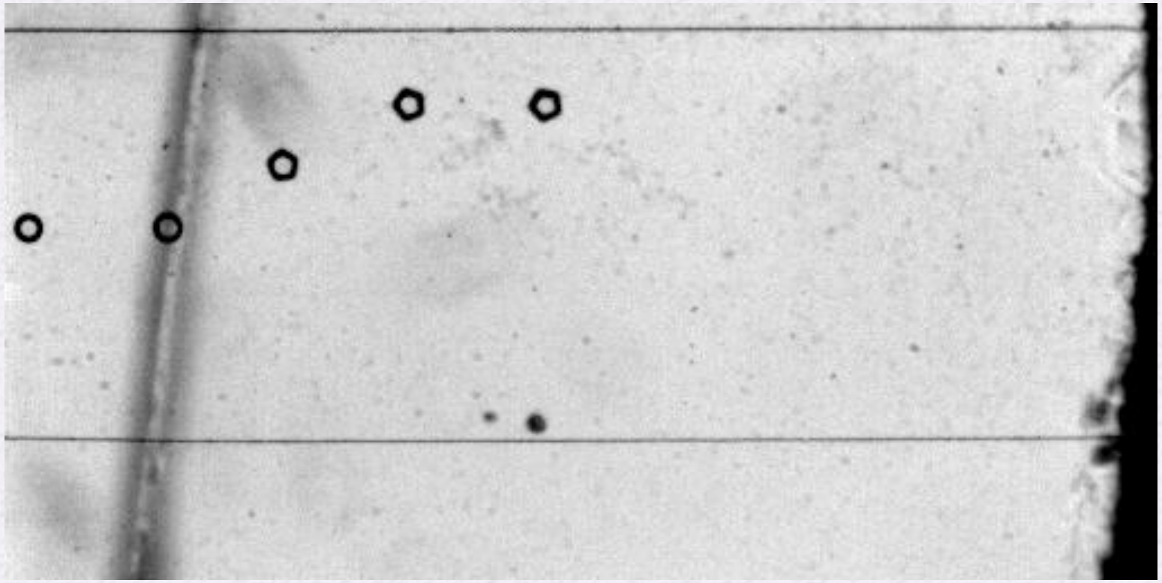
Primary acoustic Bjerknes force

Secondary acoustic force

attractive at small amplitude *Crum 1975*

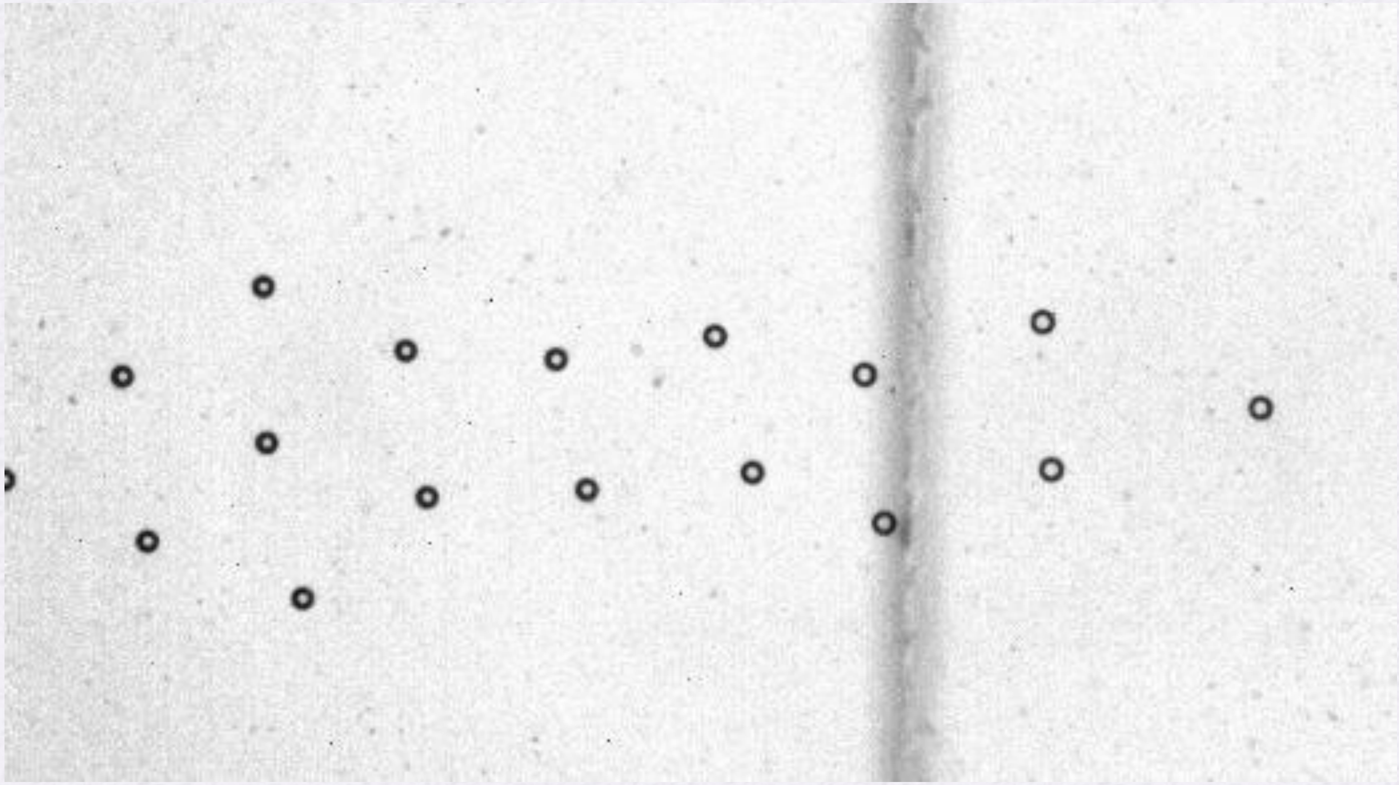


Ultrasonic "ballet" at larger amplitudes.



Bubbles keep their distance…

acoustically-bound crystals

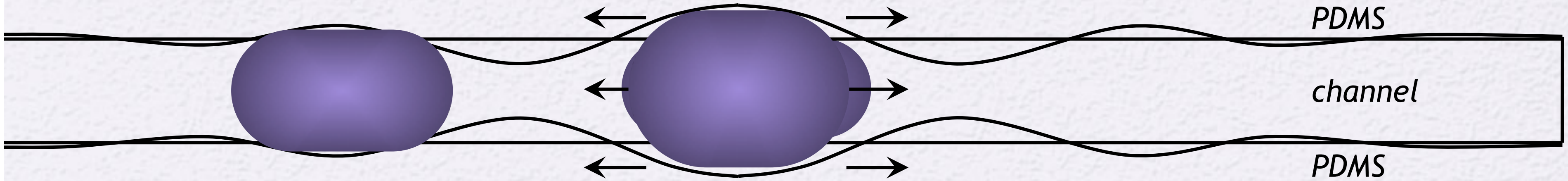


…and **acoustically-bound crystals** are formed.

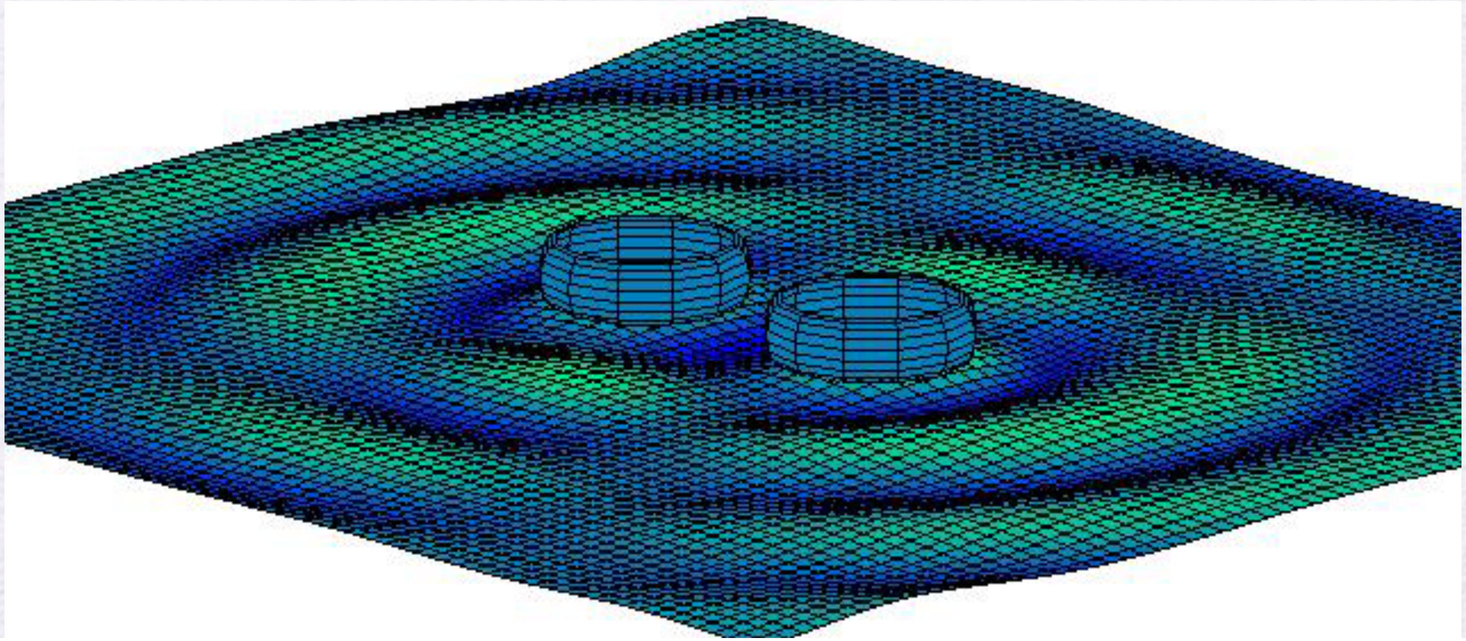
Rabaud, Thibault, Mathieu and
Marmottant *Phys. Rev. Lett*. 2011

Interaction through surface acoustic waves, on PDMS!

Side view of a pulsating bubble

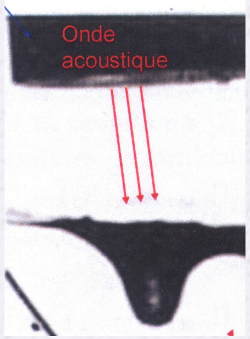


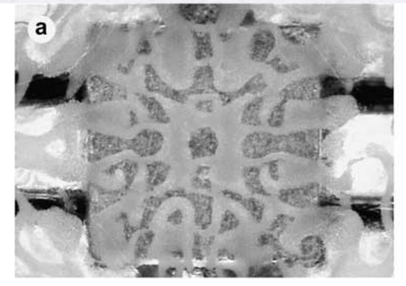
Surface acoustic waves (Rayleigh waves) on the PDMS walls



Outline

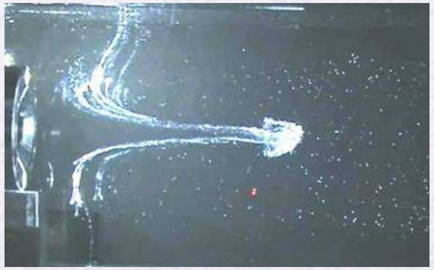
1) Radiation pressure

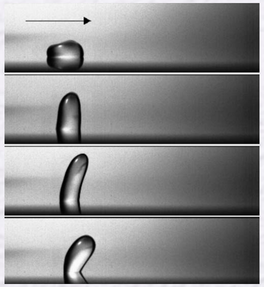




a) on interfaces
b) on particles, tweezers
c) on bubbles

2) Acoustic streaming





a) Quartz wind
b) near boundaries
c) near bubbles

2) Acoustic streaming

Navier-Stokes equation

$$\rho \frac{\partial \mathbf{v}}{\partial t} = -\nabla p + \eta \nabla^2 \mathbf{v} - \rho\left(\mathbf{v}.\nabla\right)\mathbf{v}$$

Inertia

Consequences of inertia

1) non-reversibility of fluid (ex: flamme)
2) turbulence
3) non-linear, steady forcing on average:

Navier-Stokes averaged over time

$$\mathbf{0} = -\nabla\left\langle p\right\rangle + \eta\nabla^2\left\langle \mathbf{v}\right\rangle - \left\langle \rho\left(\mathbf{v}.\nabla\right)\mathbf{v}\right\rangle$$

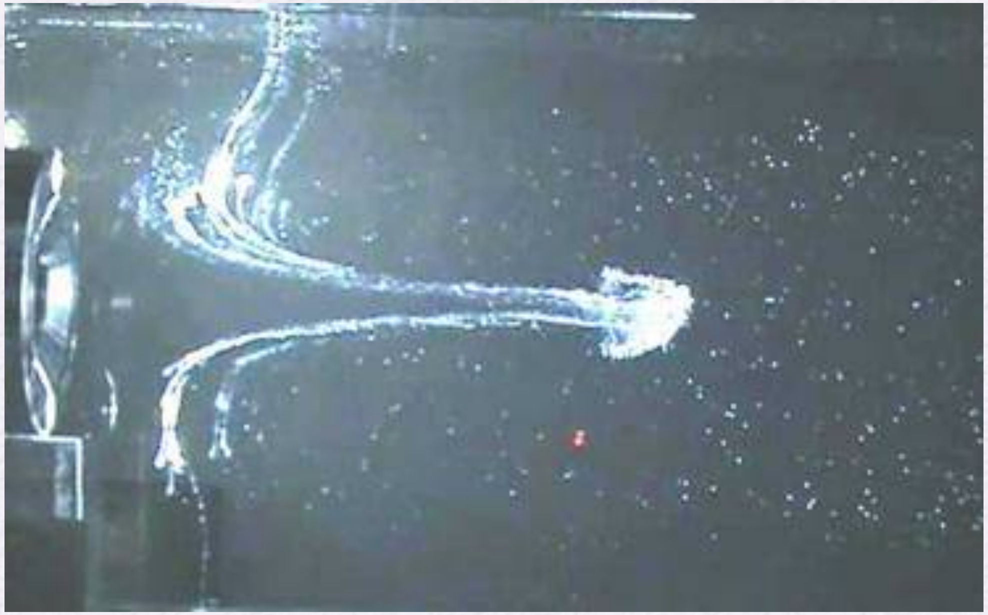
steady streaming

Reynolds stress

$$\mathbf{f}_{\text{Reynolds}} = \left\langle -\rho\left(\mathbf{v}.\nabla\right)\mathbf{v}\right\rangle$$

quadratic

a) Quartz wind



Attenuated wave $\mathbf{v} = \mathbf{v}_{\mathrm{A}} \exp(-\alpha x) \cos(\omega t - kx)$

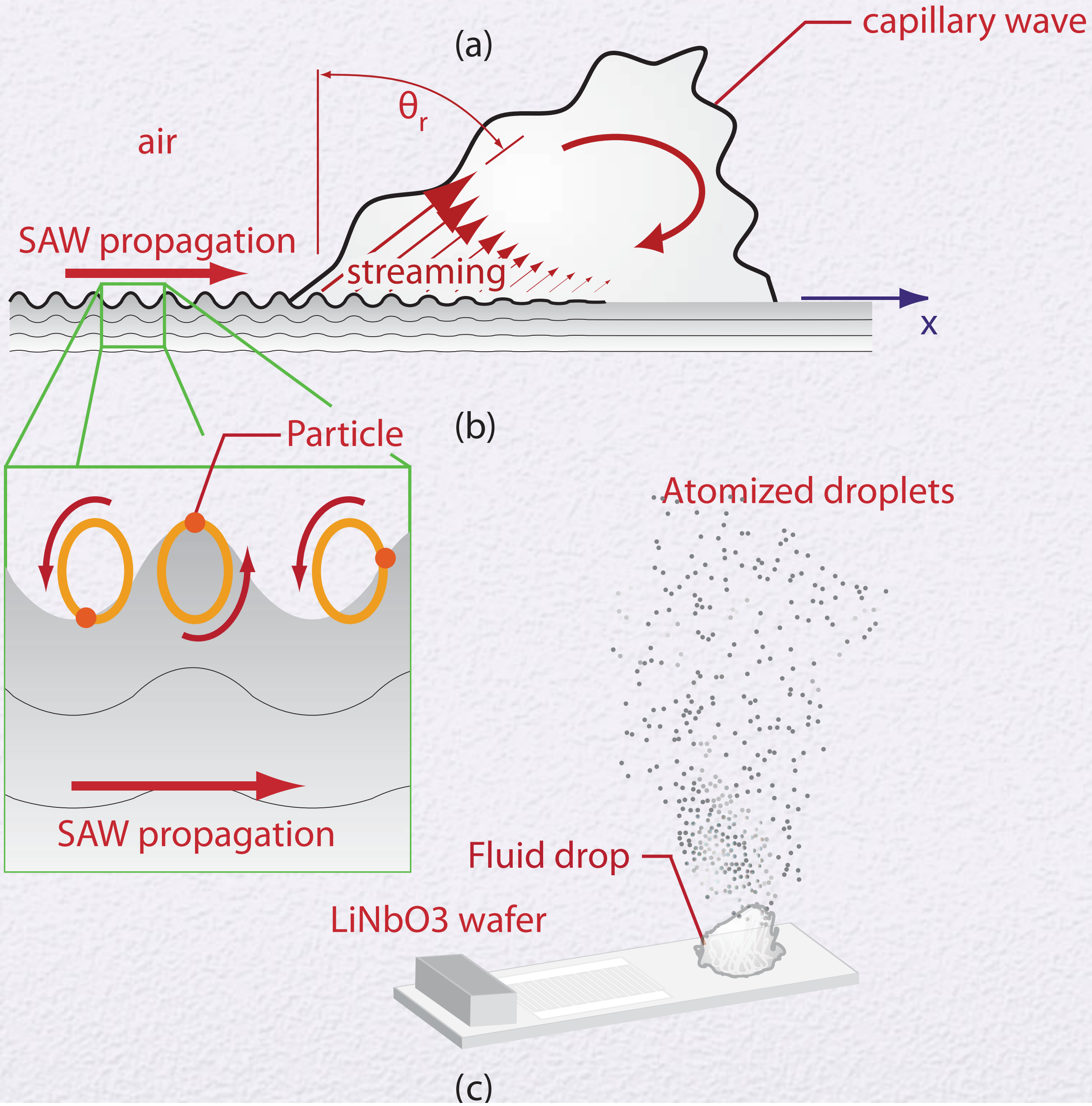
$$\mathbf{f}_{\mathrm{Reynolds}} = \frac{1}{2} \rho \alpha v_{\mathrm{A}}^{2} \exp(-2\alpha x) \mathbf{e}_{x}$$

Attenuation length in water $\alpha^{-1} = 50\,\mathrm{m.MHz}^2 / f^2$

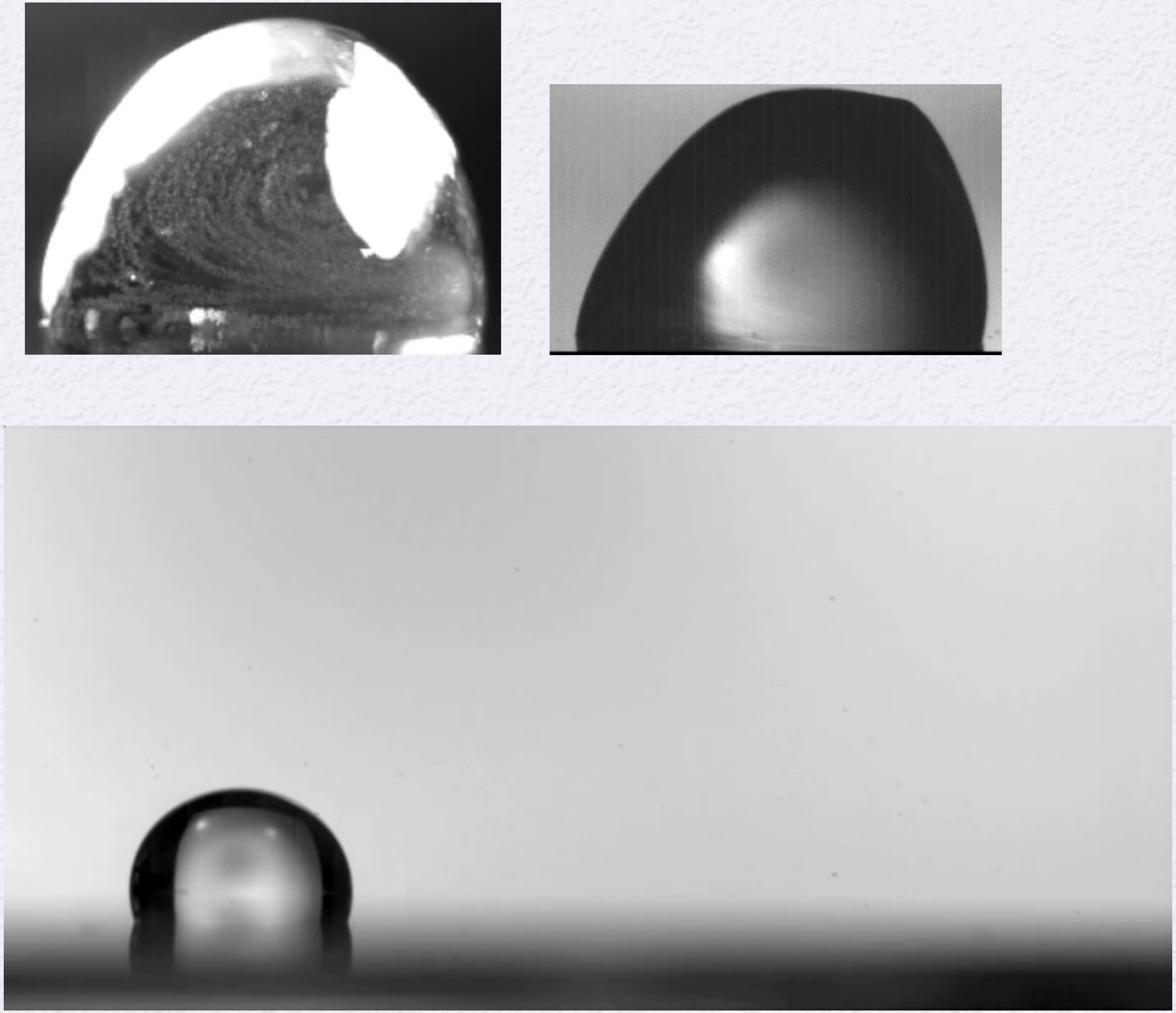
In air $\alpha^{-1} = 1\,\mathrm{m.MHz}^2 / f^2$

Botton

In a droplet



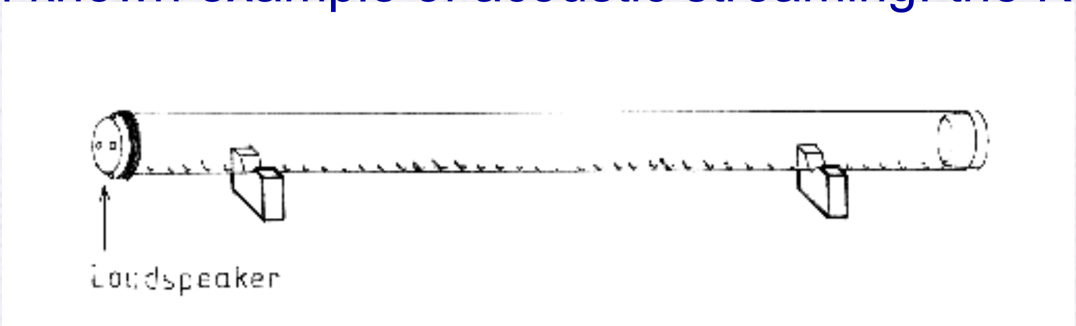
Qi 2008

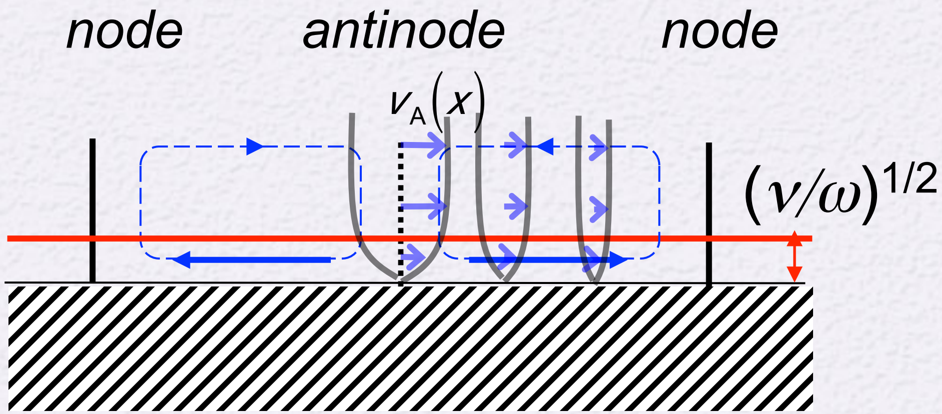


Brunet 2010

b) near a wall

A very well known example of acoustic streaming: the Kundt tube (1866)

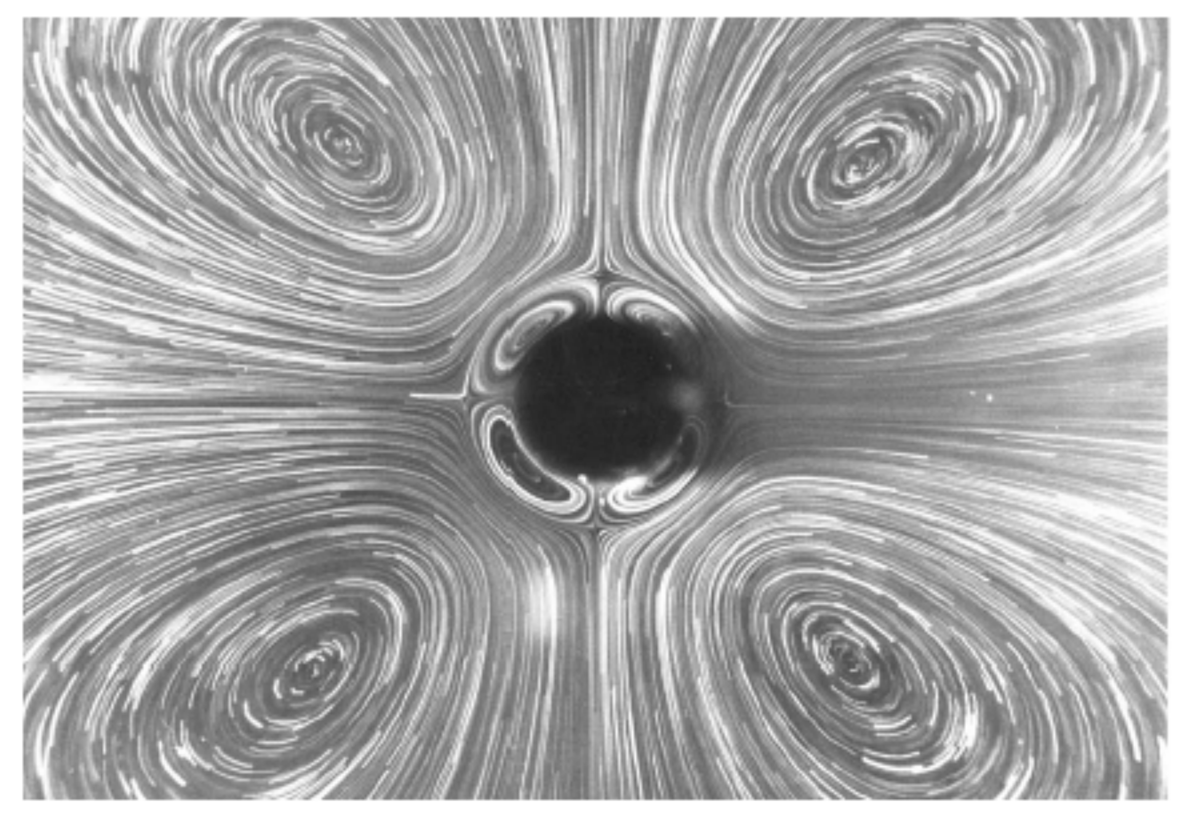




Reynolds stresses are important in the Stokes oscillatory boundary layer

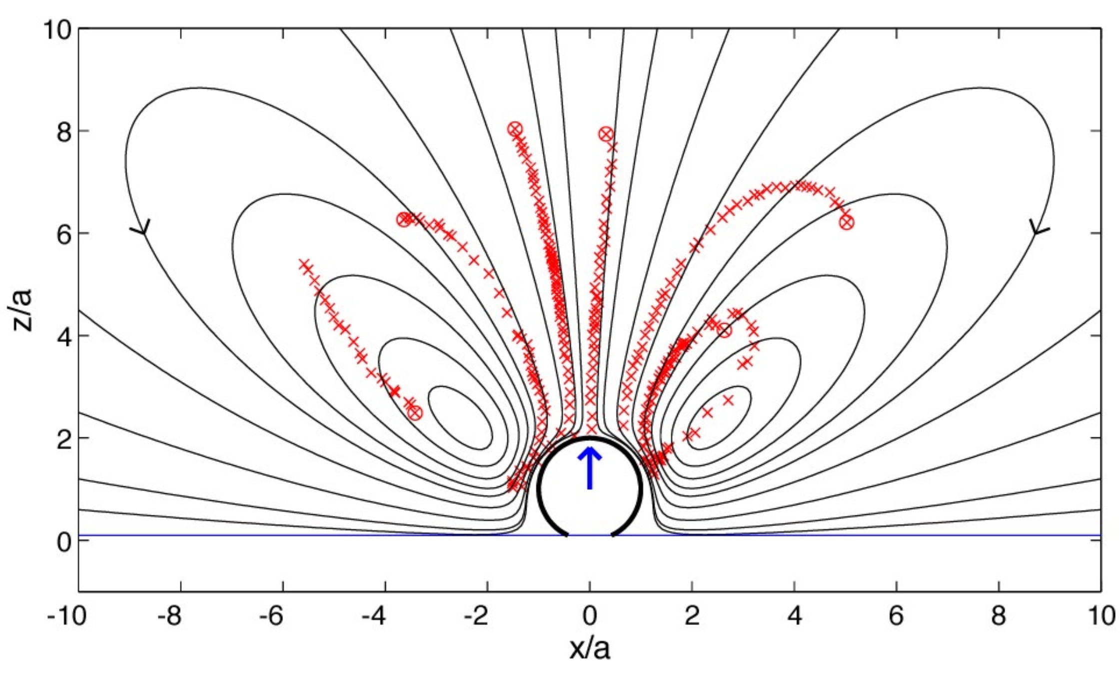
$$\mathbf{f}_{\text{Reynolds}} = \left\langle -\rho\left(\nabla.\mathbf{v}\right)\mathbf{v}\right\rangle \sim -\rho v_A \frac{\partial v_A}{\partial x}\mathbf{e}_x$$

b) near a wall: vibrating cylinder



Tatsuno 1980

c) Near bubbles

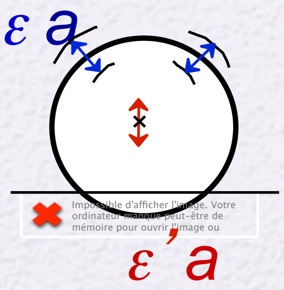


Gentilles oscillations de la bulle $\varepsilon << 1$

- rayon $r = \varepsilon a \cos(\omega t)$
- centre $z = \varepsilon' a \cos(\omega t - \phi)$

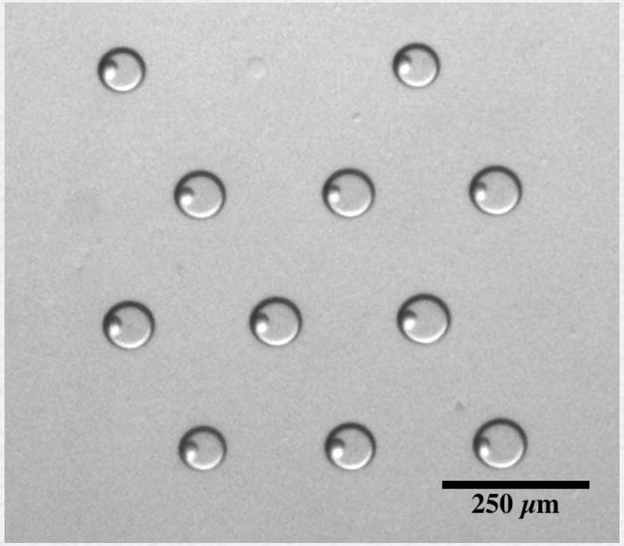
Streaming

$\langle u_2 \rangle$ $\sim \varepsilon\varepsilon' a\omega \sin\phi$



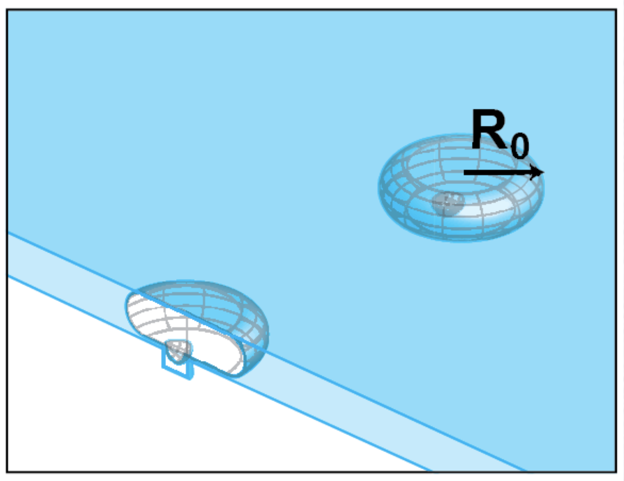
Marmottant 2003

Microfluidic set-up: flattened and anchored bubbles

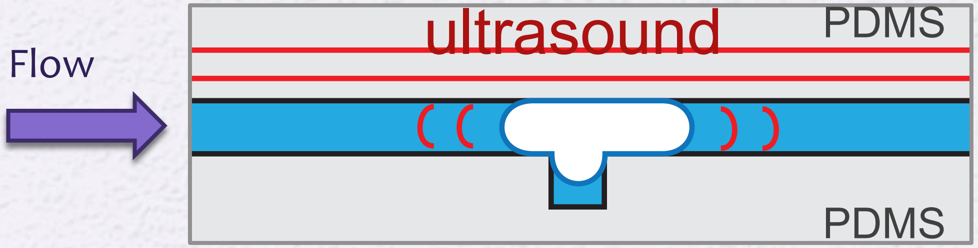


Top view

Perspective



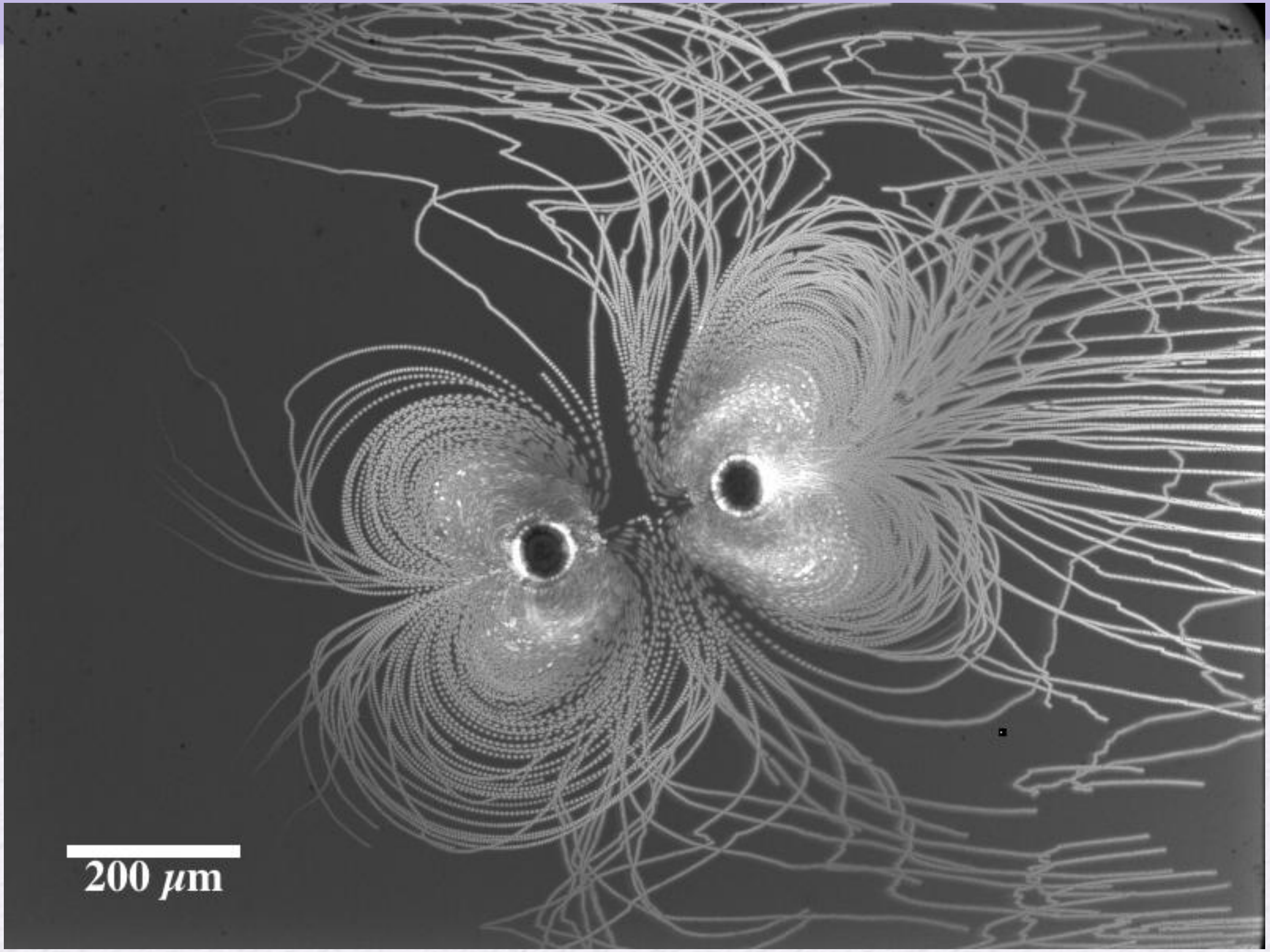
Cross-section



anchors: micropits

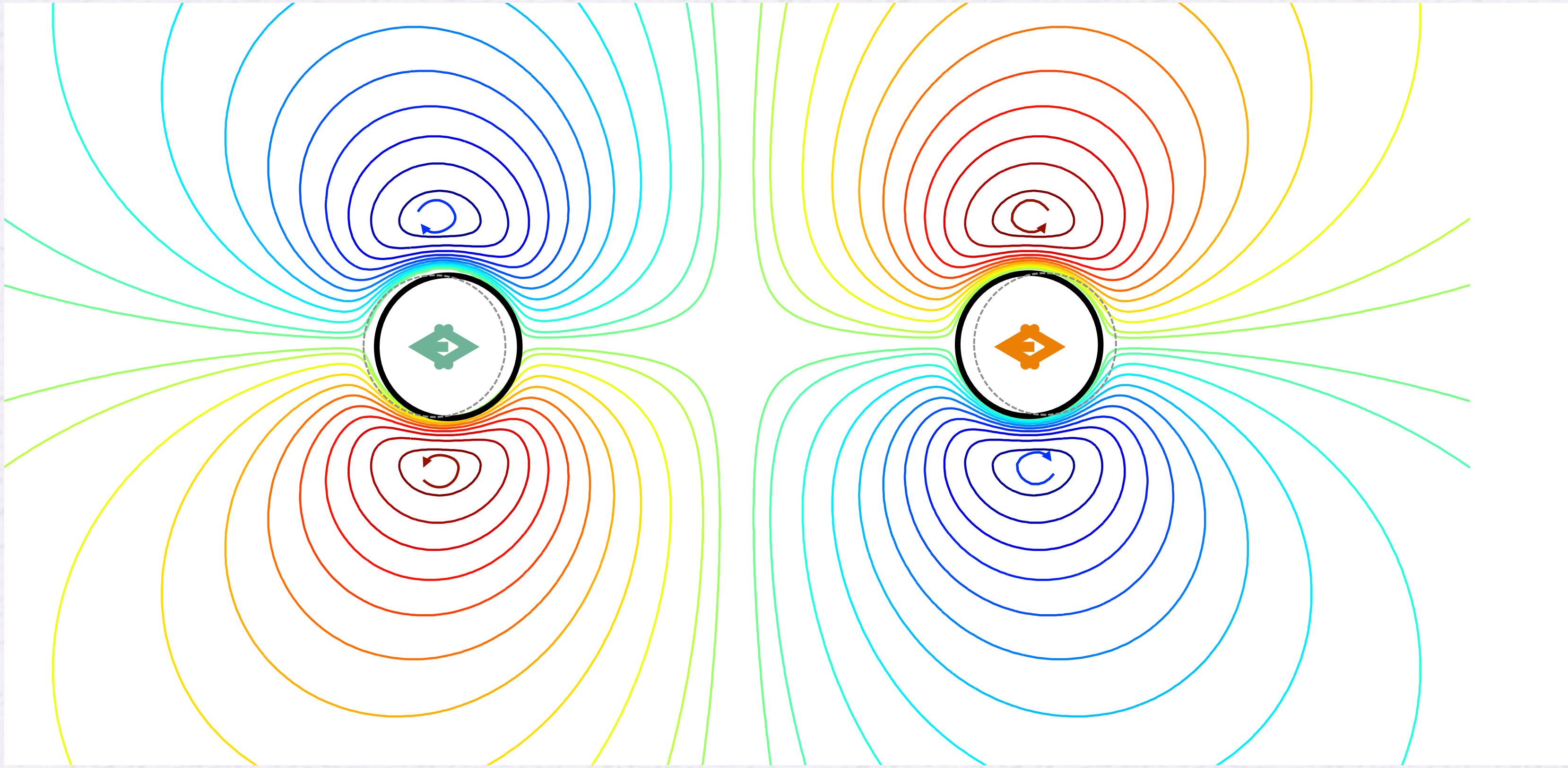
Pit method by Dangla et al 2011

Two bubbles vibrating: passionate streaming!



Acoustic streaming:

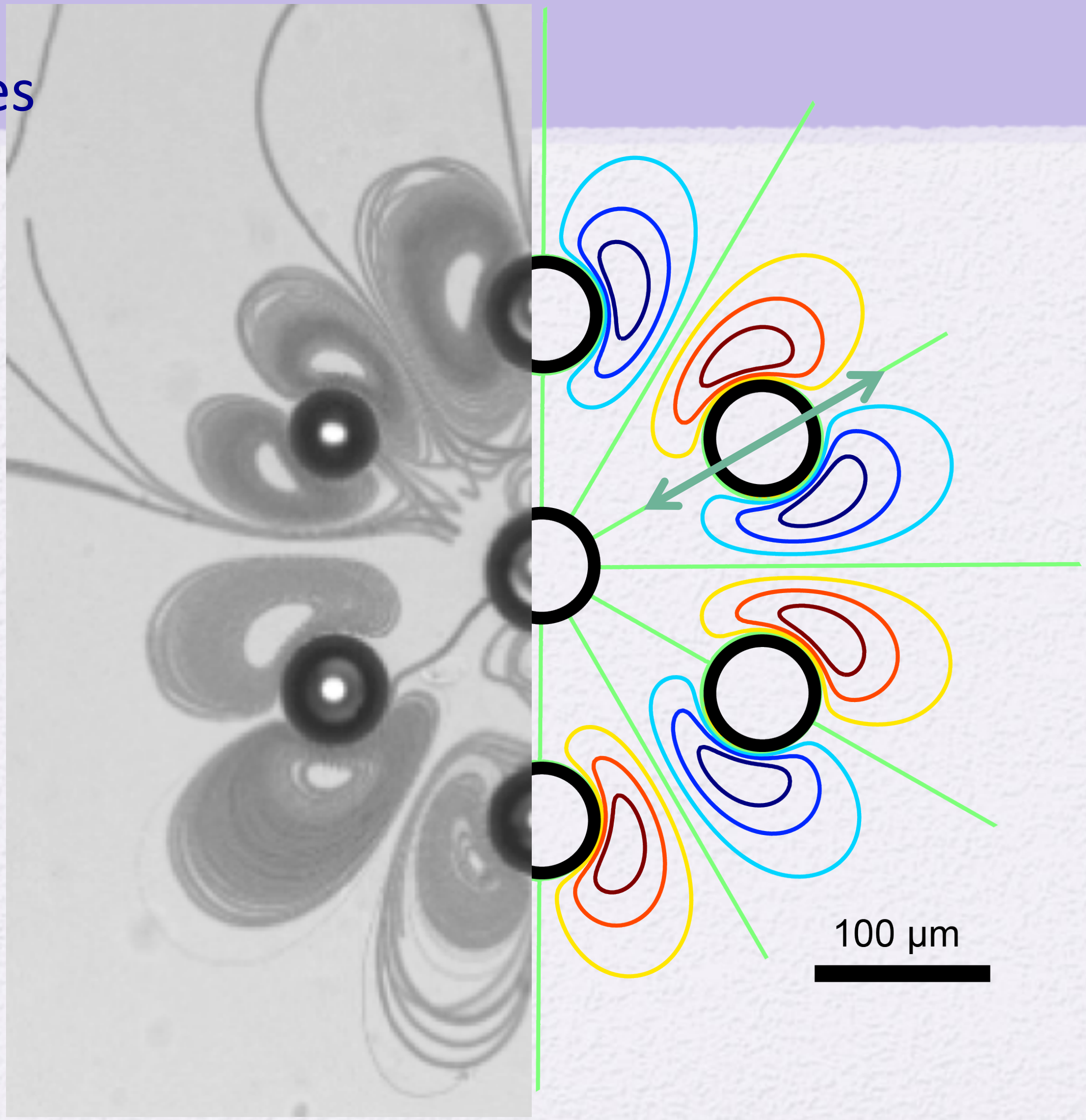
predictions from translation+oscillation vibrations

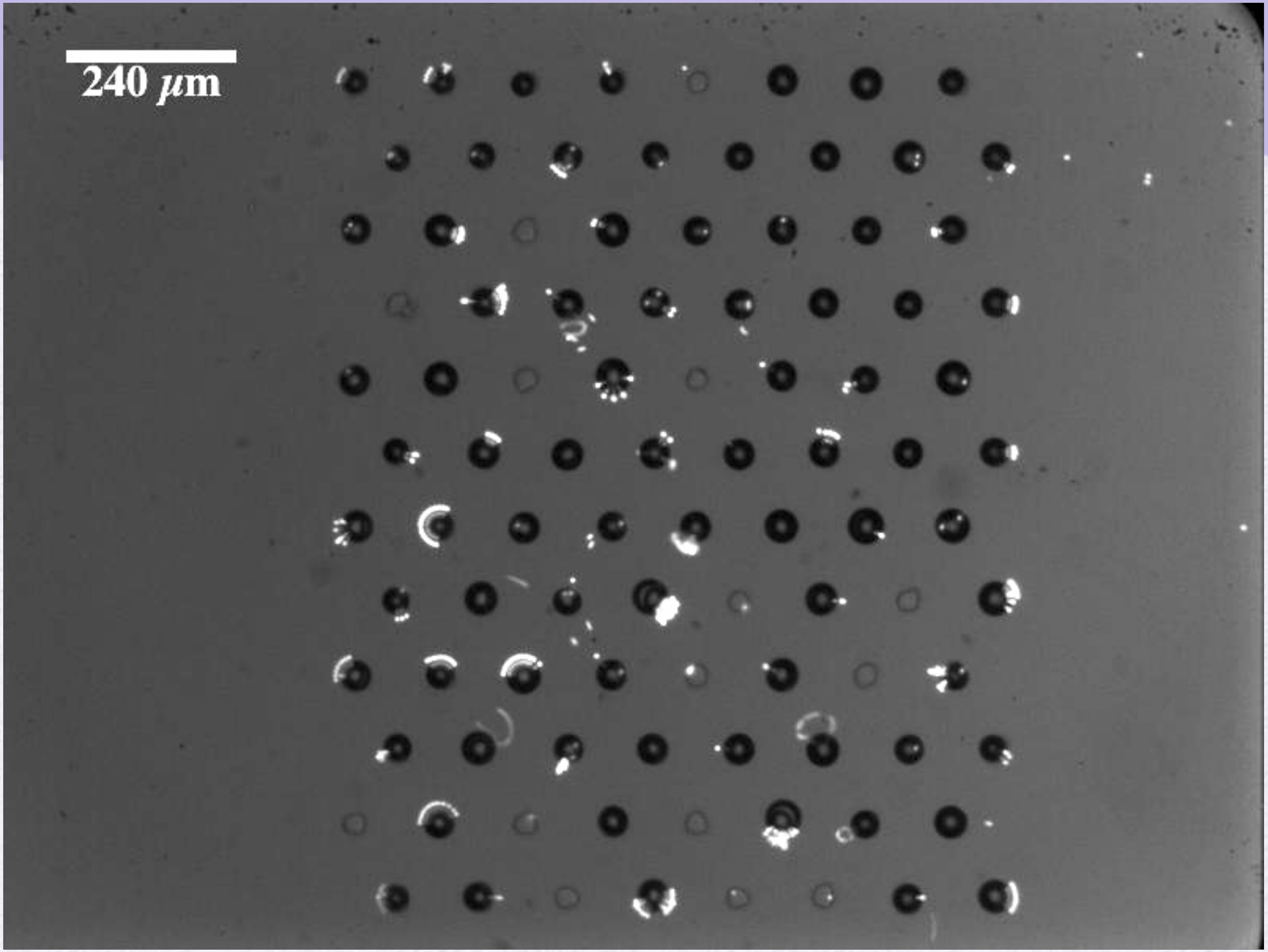


$$\Psi_L = \Psi_L^{\text{bubble 1}} + \Psi_L^{\text{bubble 2}}$$

- Seven bubbles

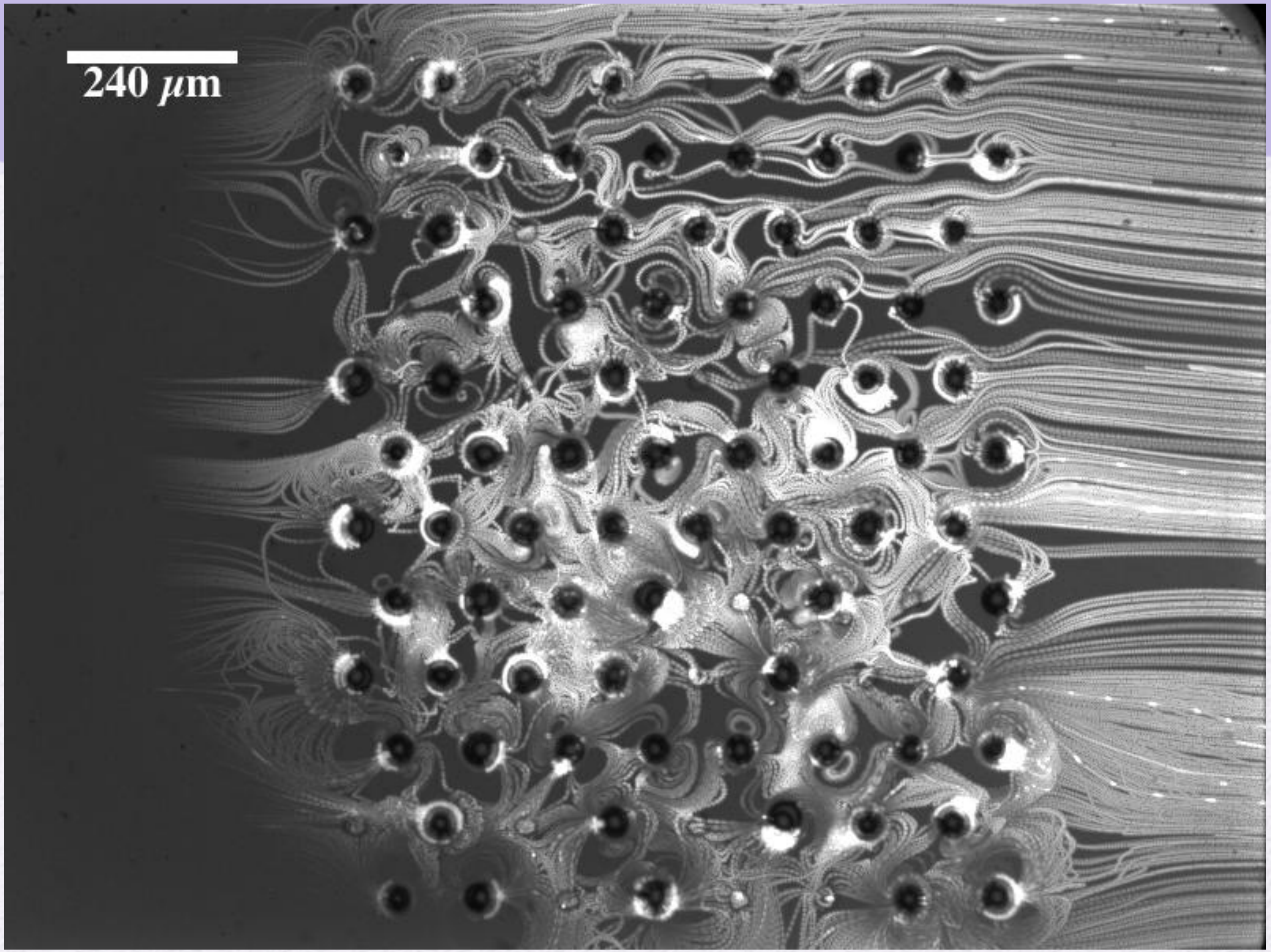
- Seven bubbles





- Microfluidic "pinball"

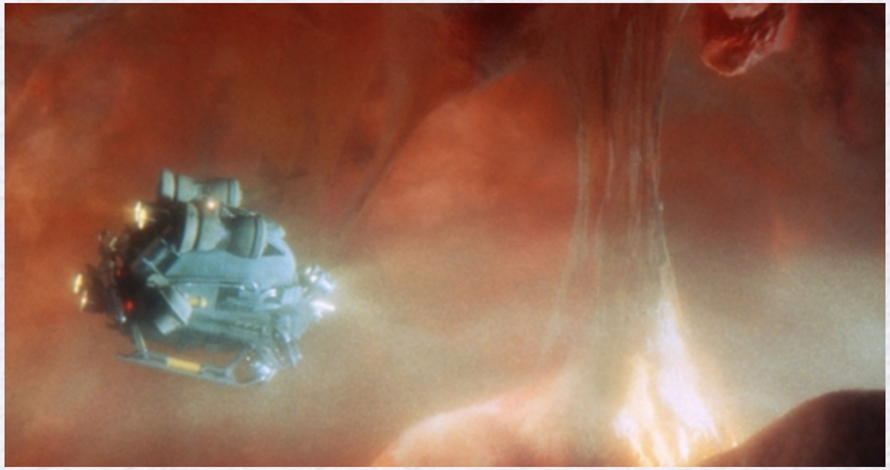
f = 110 kHz



- Microfluidic "pinball"

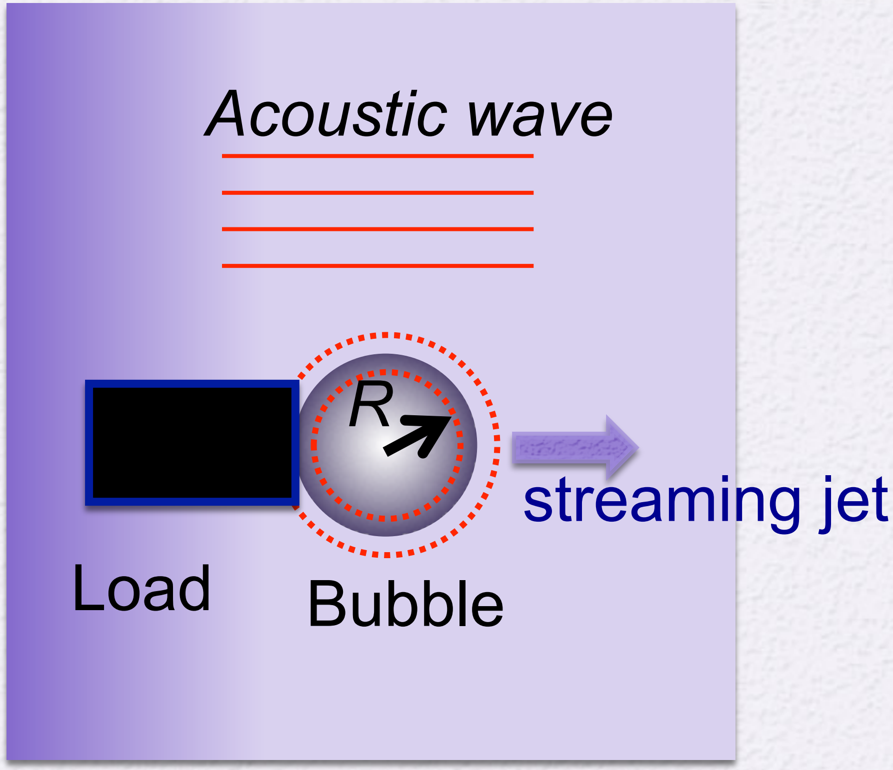
Artificial microswimmers

Applications
- *Drug delivery in capillary vessels*
- *Micromixing*



Innerspace, 1987

Idea: use a resonant bubble as a motor



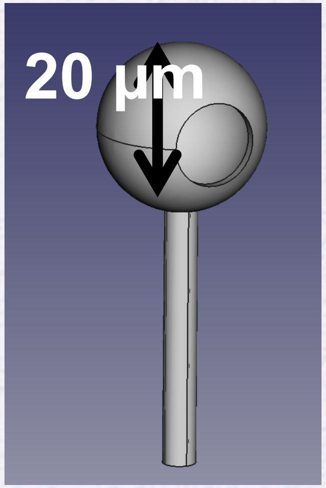
Resonance frequency
given by the Minnaert formula:

$$f \times R \simeq 3\,\mathrm{m/s}$$

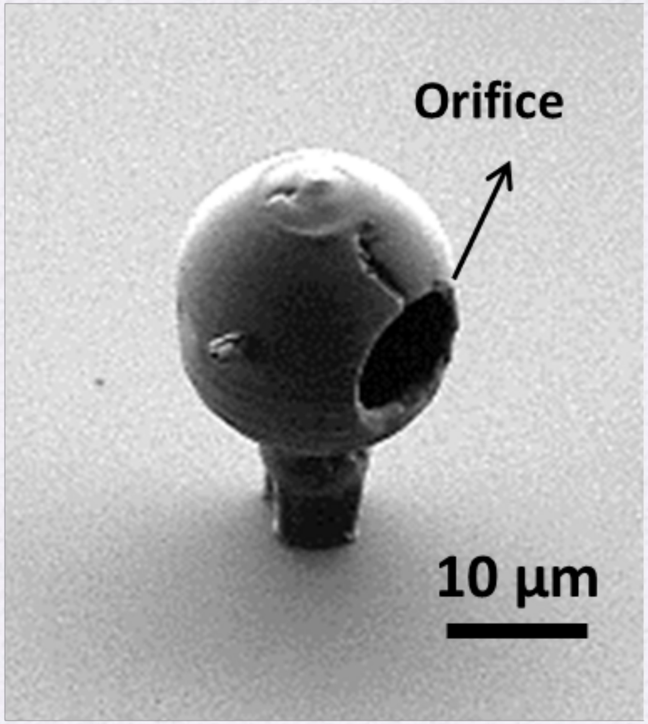
- Strong amplitude of vibration at resonance
- Issue: dissolution of the gas, especially at small scales!

How to protect a bubble from dissolving?

partial encapsulation in 3D microfabricated shells

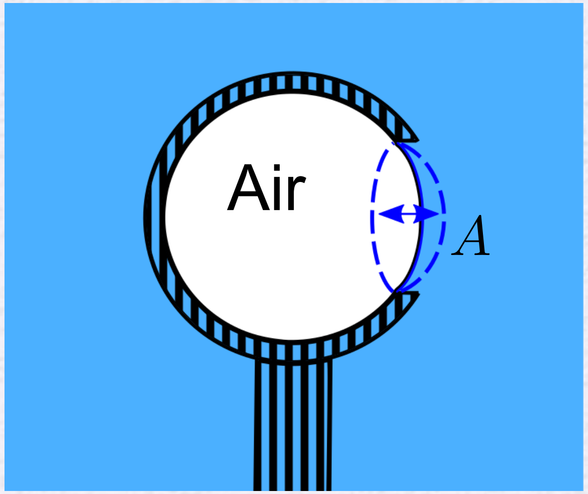


FreeCAD



Microfabrication

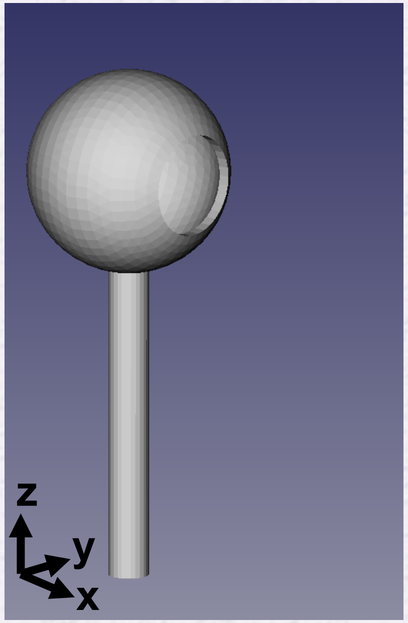
2 photon polymerisation
0.5 µm in resolution

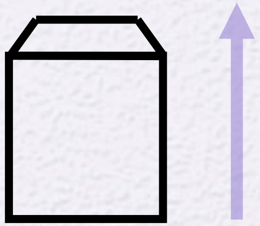


In water

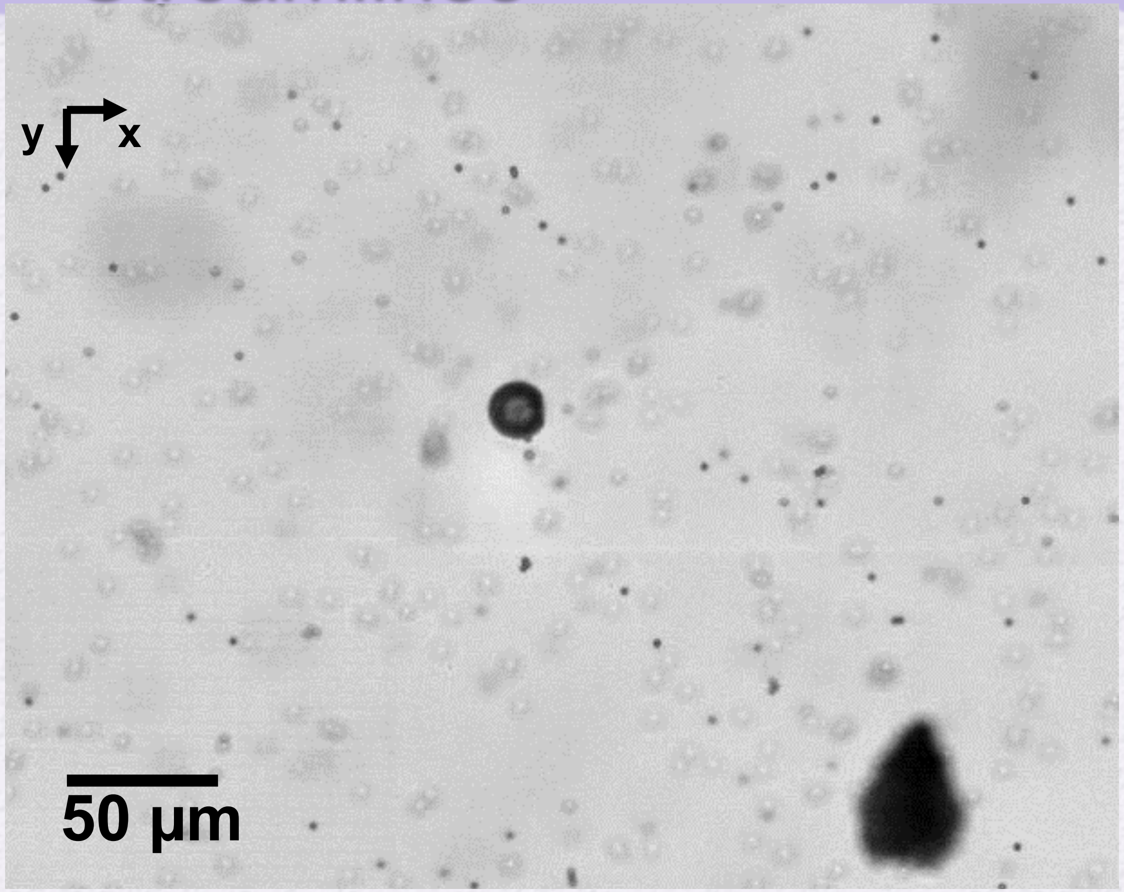
- Interface is pinned: dissolution is prevented (but not condensation)
- Large amplitudes of vibration!

Streamlines





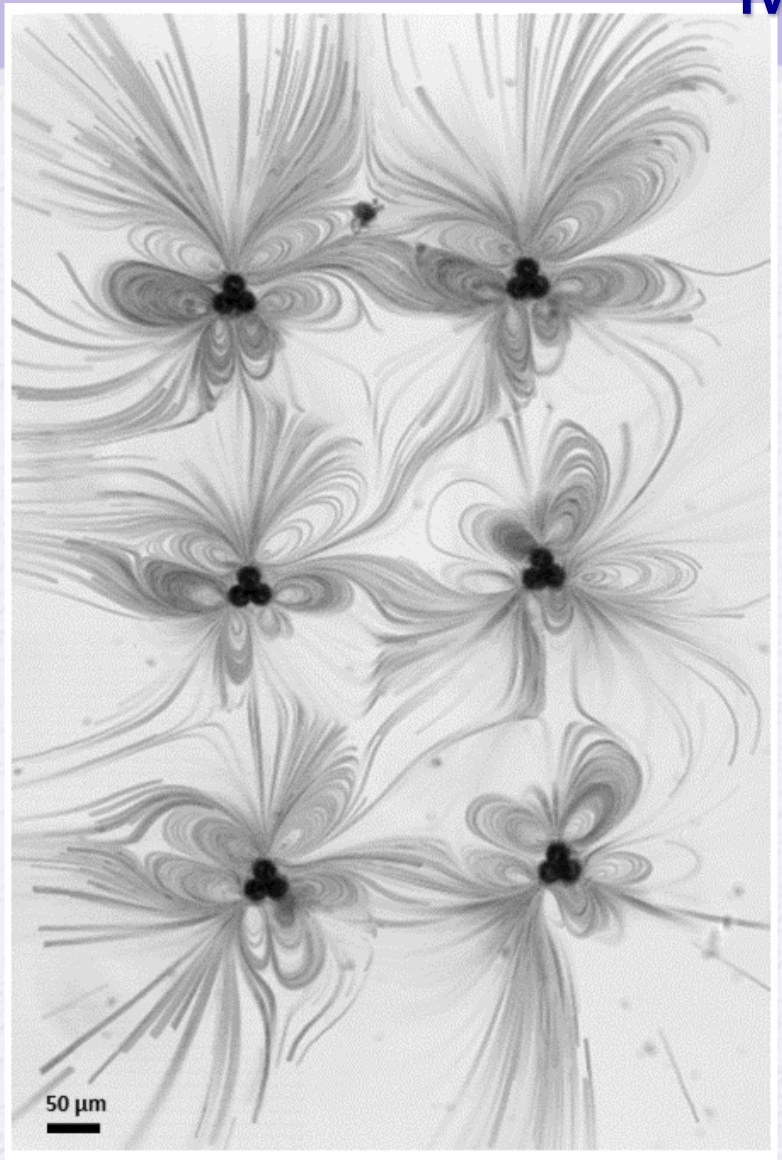
Observation

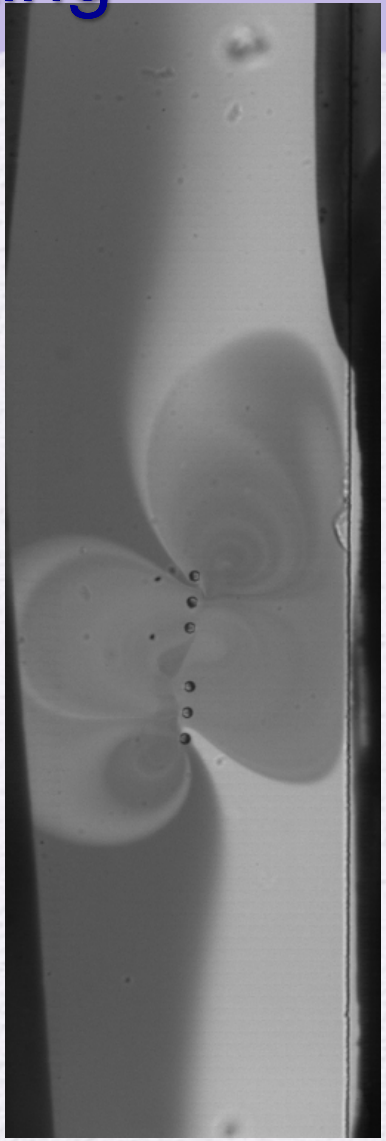


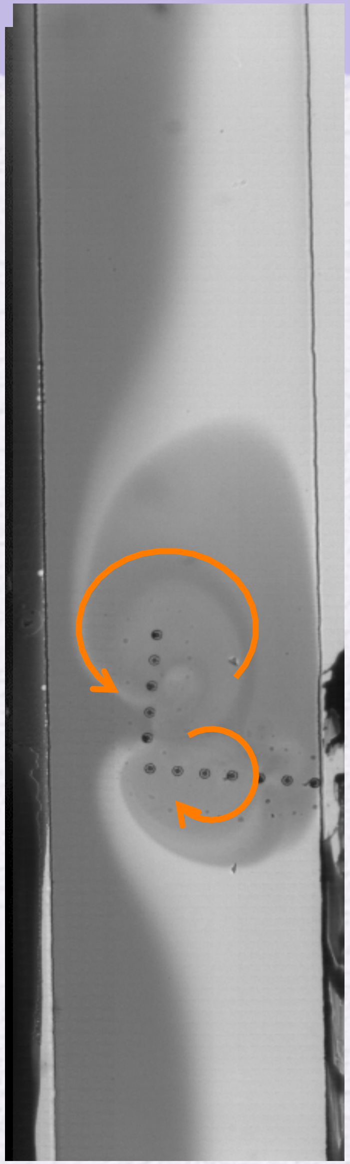
f_{transd} = 320 kHz, P_{ac} = 9.2 kPa, slowed down 32x

Bertin 2015

Mixing

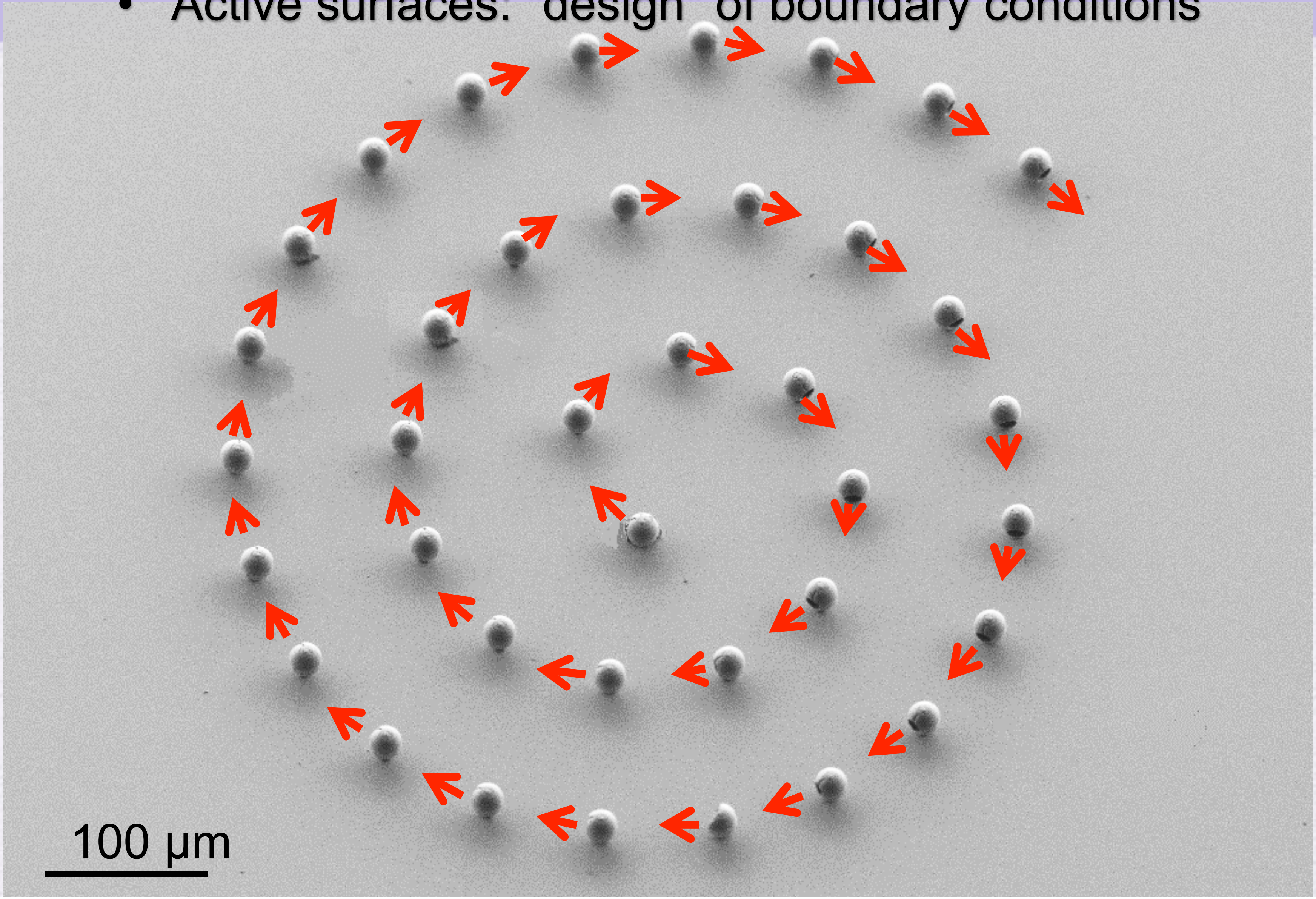




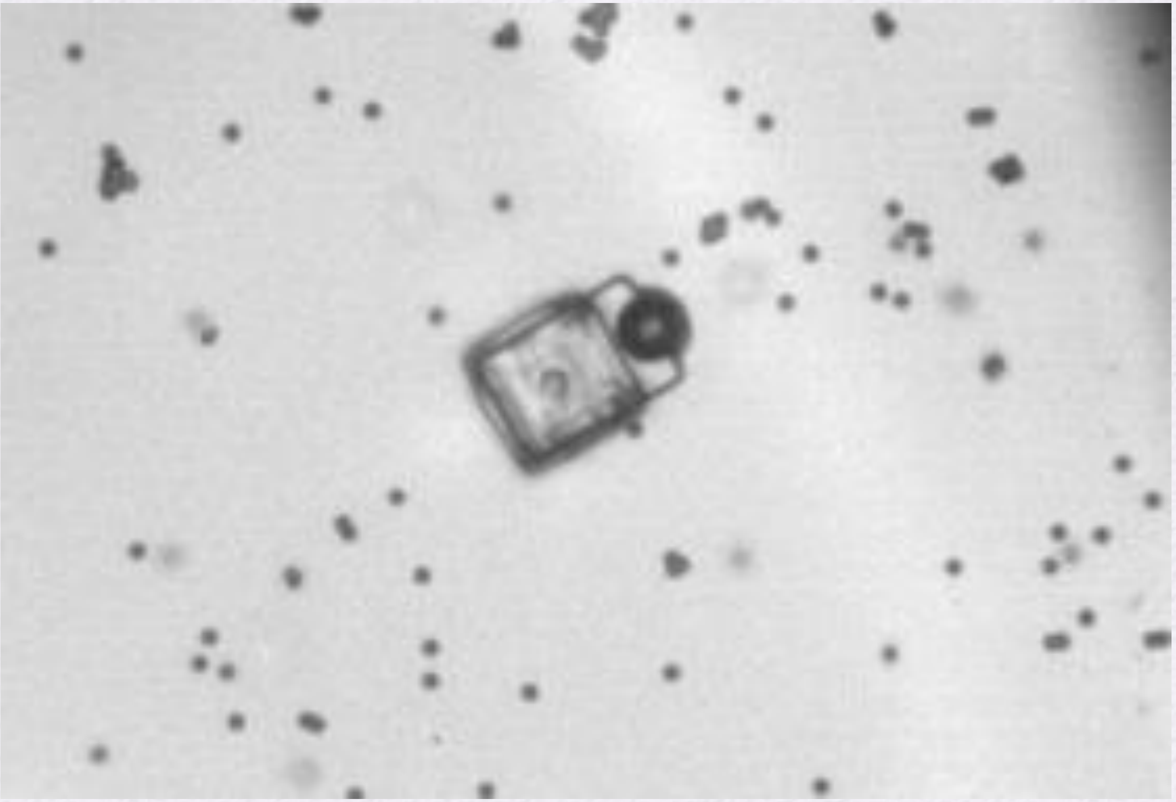


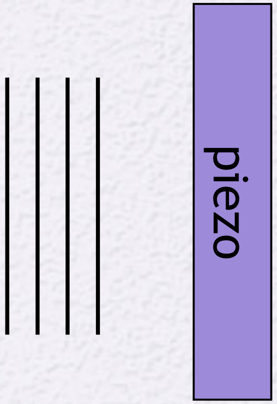
Bertin 2017

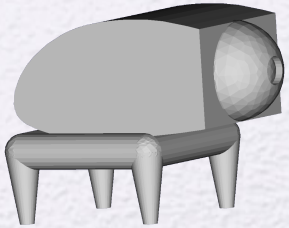
- Active surfaces: "design" of boundary conditions



Swimmer!

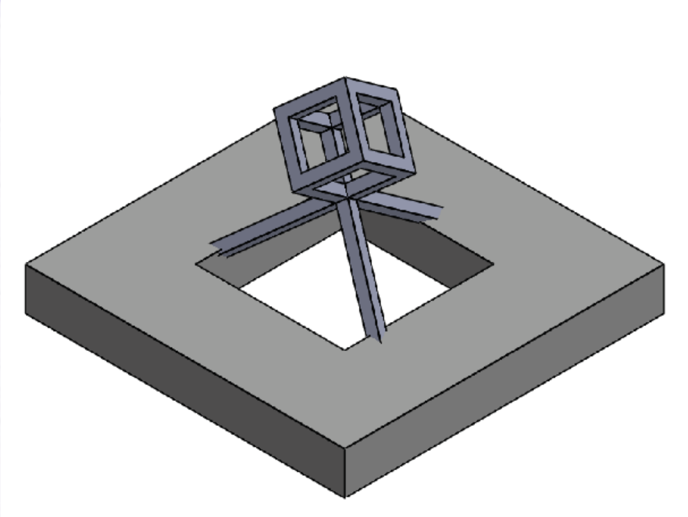




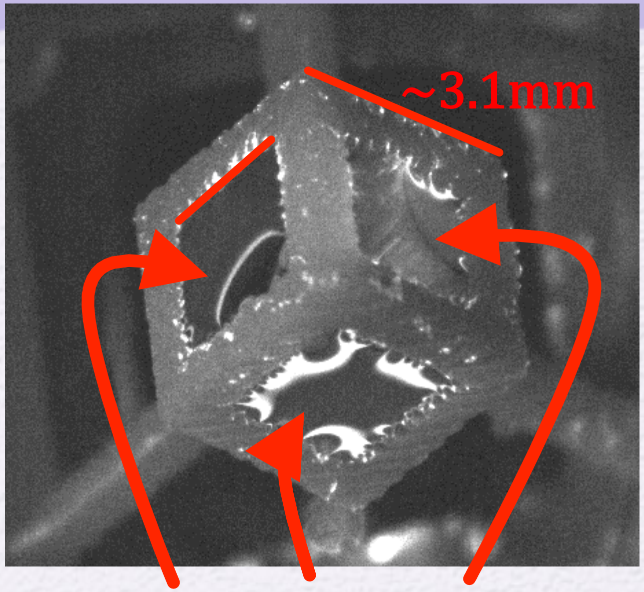


Video Jean-François Louf, f=340 kHz

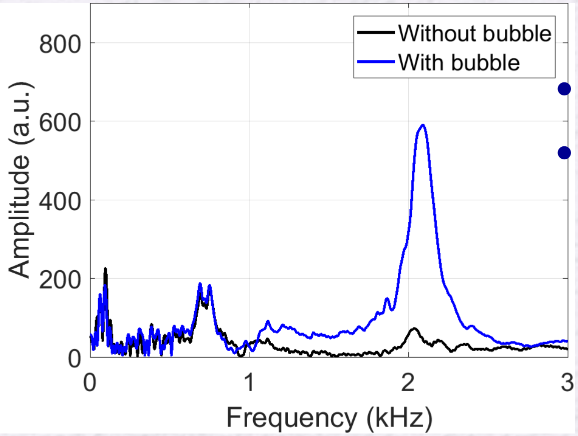
Cubic bubbles



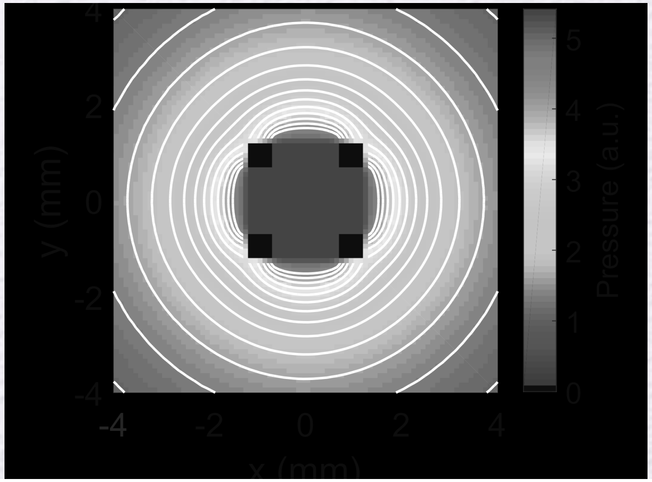
3D fabrication (SLA)



Water-air interfaces



- Stable
- Good resonator!



Conclusion

- Acoustics: **easy to implement**

- Strong radiation forces on objects:
  I/c when larger than λ
  I/c $(R/\lambda)^4$ for objects smaller
  I/c $(R/\lambda)^1$ for standing waves

- Forces on water itself: acoustic streaming

- Care has to be taken to **focus the energy**
  (use of high frequency, resonances, bubbles