School of Modern Optics

10 May 2013, Puebla, Mexico

Lecture 5

Optomechanics of fluid interfaces

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www.loma.cnrs.fr/spip.php?rubrique331

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Per photon of a light beam

Energy

$$E = \hbar\omega$$

Linear momentum

$$\mathbf{p} = \hbar\mathbf{k}$$

Angular momentum

$$j_z = s_z + l_z$$

Mechanical principles

Forces

$$\frac{d\mathbf{P}}{dt} = \sum \mathbf{F}_{ext}$$

Torques

$$\frac{d\mathbf{J}}{dt} = \sum \mathbf{\Gamma}_{ext}$$

Mechanical consequence : light can rotate matter

Per photon of a light beam

$$\overbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}$$

Energy

$$E = \hbar\omega$$

Linear momentum

$$\mathbf{p} = \hbar\mathbf{k}$$

Angular momentum

$$j_z = s_z + l_z$$

Mechanical principles

$$\overbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad}$$

Forces

$$\frac{d\mathbf{P}}{dt} = \sum \mathbf{F}_{ext}$$

Torques

$$\frac{d\mathbf{J}}{dt} = \sum \boldsymbol{\Gamma}_{ext}$$

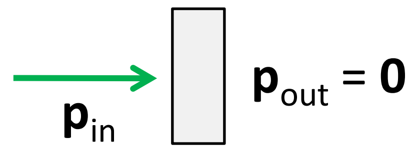
Mechanical consequence : light can displace matter

Introduction : optical forces

$$\boxed{\frac{d\mathbf{P}}{dt} = \sum \mathbf{F}_{ext}}$$

Transferred momentum per photon

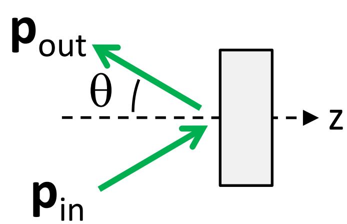
Absorption



$\hbar \mathbf{k}_{in}$

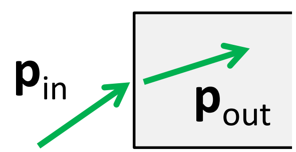
Redirection

Reflexion



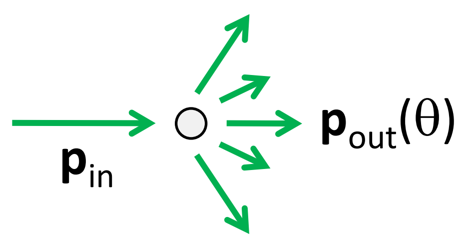
$2\hbar \cos\theta \, k_{in} \mathbf{z}$

Refraction



$\hbar(\mathbf{k}_{in} - \mathbf{k}_{out})$

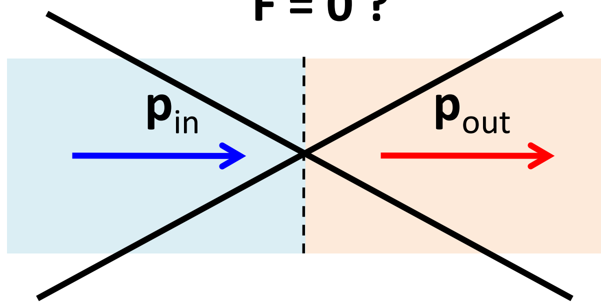
Scattering



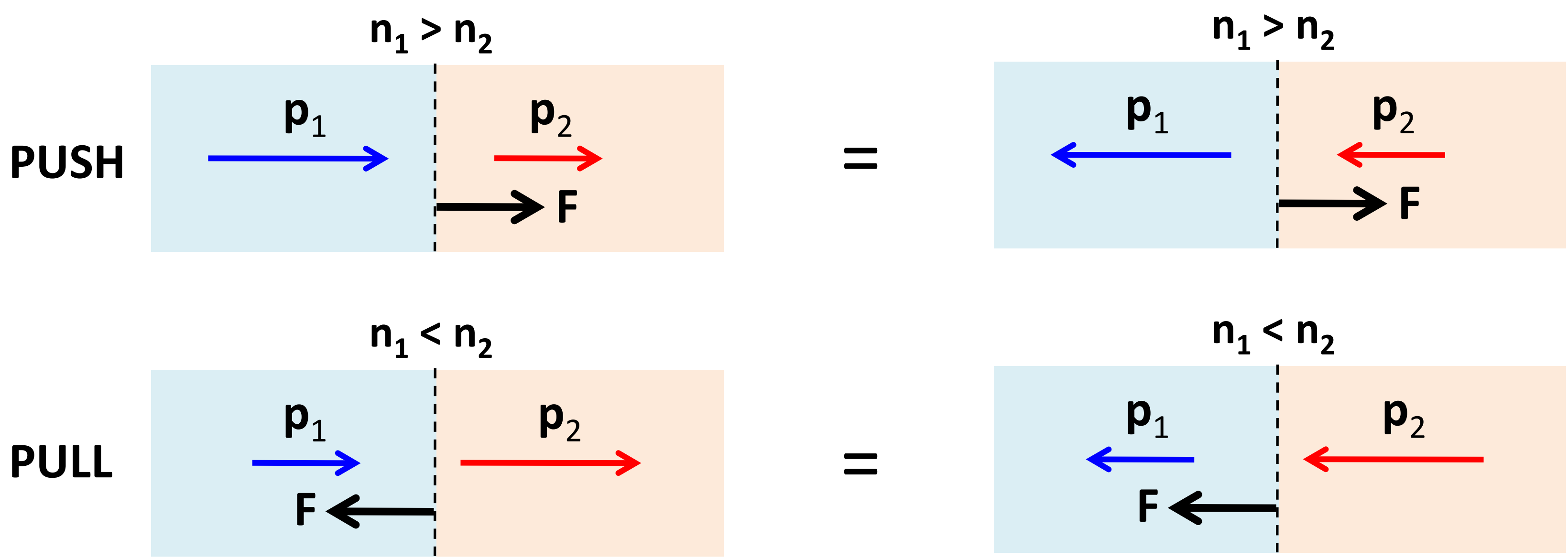
$\hbar \mathbf{k}_{in} - \hbar \int f(\theta) \, \mathbf{k}_{out}(\theta) d\theta$

Introduction : optical forces

F = 0 ?

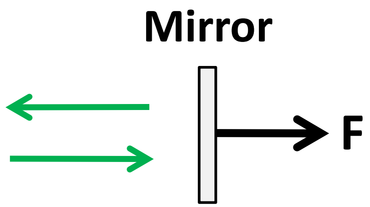


A photon in a dielectric medium : $\mathbf{p} = n\hbar\mathbf{k}$



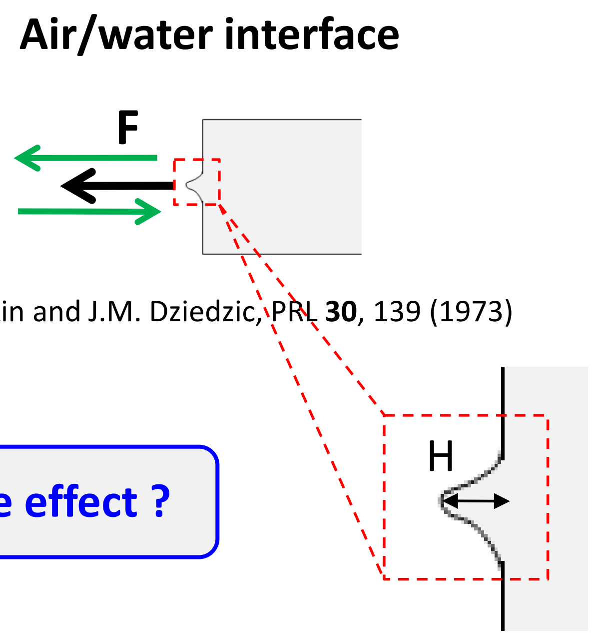
Optical force per unit surface : radiation pressure of light

Displacement



P. Lebedev, Ann. Phys. **6**, 433 (1901)
E.F. Nichols and G.F. Hull, Phys. Rev. **13**, 307 (1901)

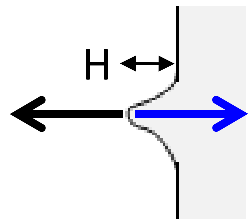
Deformation



A. Ashkin and J.M. Dziedzic, PRL **30**, 139 (1973)

How large is the effect ?

Equilibrium of the interface



$$\Pi_{\text{radiation}} = \Pi_{\text{Laplace}}$$

$$\Pi_{\text{radiation}} = F/S$$
$$= \Phi(n_1 - n_2)\hbar k$$
$$= \Phi(n_1 - n_2)\frac{\hbar\omega}{c}$$
$$= (n_1 - n_2)\frac{I}{c}$$

Number of photons per unit time and surface

$$\Pi_{\text{Laplace}} = \sigma\kappa$$
$$\approx \frac{\sigma H}{w^2}$$

Interface curvature

Surface tension

$$\boxed{H \approx (n_1 - n_2)\frac{Iw^2}{\sigma c} \approx (n_1 - n_2)\frac{P}{\sigma c}}$$

Soft interfaces are desirable

$P = 1\,\text{W}$, $\sigma = 10^{-3} - 10^{-2}\,\text{N/m} \Rightarrow \text{H} \approx 10 - 100\,\text{nm}$

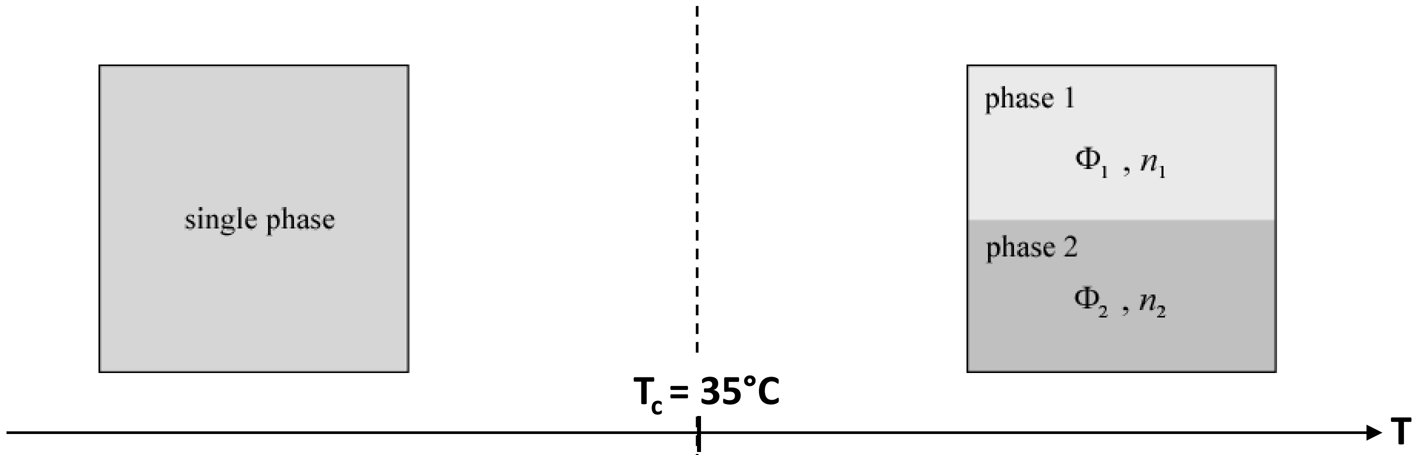
Outline

1. **Laser induced giant fluid interface deformations**
2. **Liquid-core liquid-cladding self-induced optical fibers**
3. **The optical micro-pipeline**
4. **Acoustic analogies**

A very soft interface in the lab

Quaternary liquid mixture

(toluene, butanol, water, surfactant)



Single phase below T_c

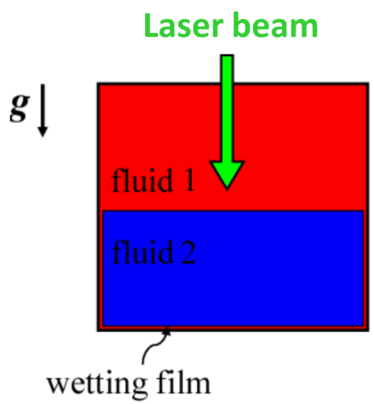
Two transparent water-in-oil micellar phases are formed above T_c

Interfacial surface tension vanishes at $T = T_c$

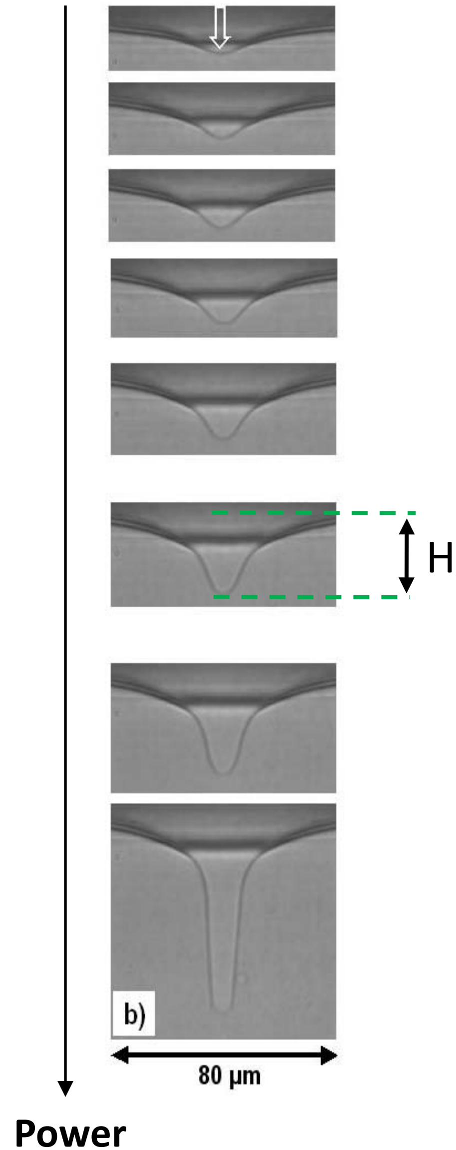
$$\sigma \rightarrow 0$$

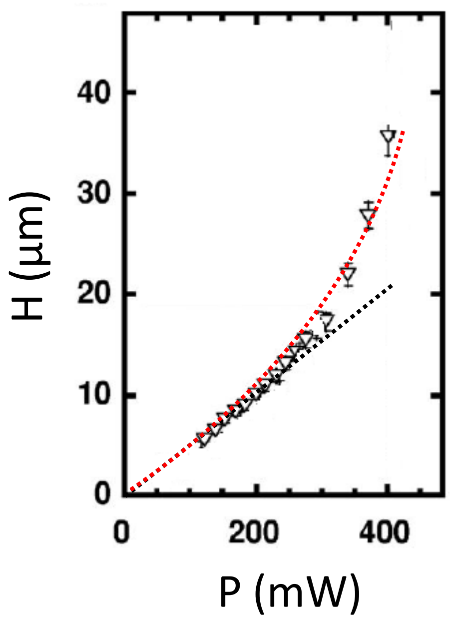
($\sigma \sim 10^{-7}$–10^{-6} N/m for $\Delta T = T - T_c \sim 2$ to 15K)

Giant fluid interface deformations by light



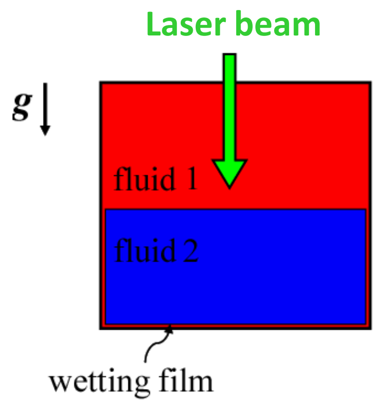
A. Casner and J.P. Delville, PRL **87**, 054503 (2001)



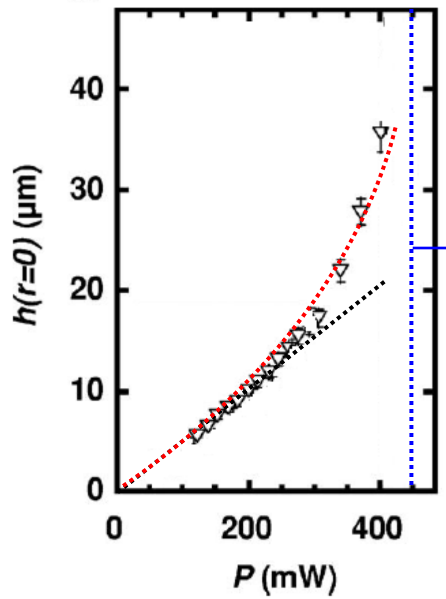


Nonlinear regime is observed

Fluid interface instability induced by light



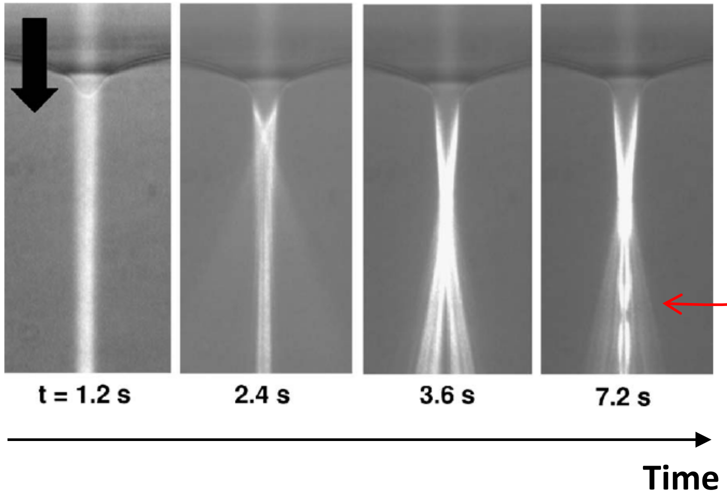
A. Casner and J.P. Delville, PRL **90**, 144503 (2003)



Jetting instability

Step-index optical fiber

Jetting transient dynamics



Total internal reflection

Outline

1. Laser induced giant fluid interface deformations

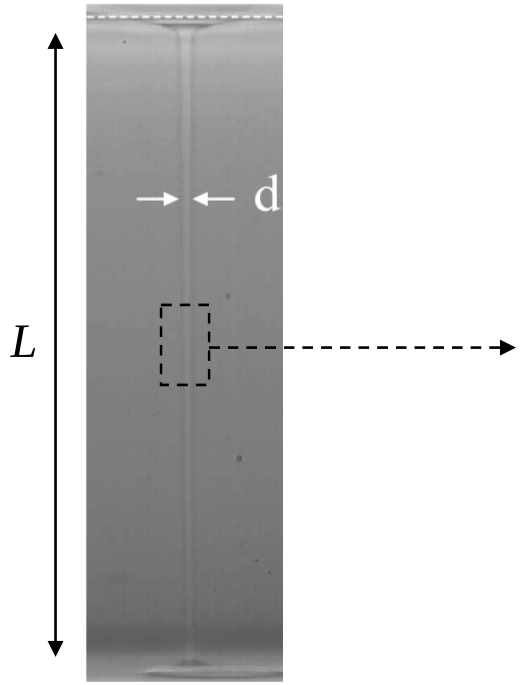
2. **Liquid-core liquid-cladding self-induced optical fibers**

3. The optical micro-pipeline

4. Acoustic analogies

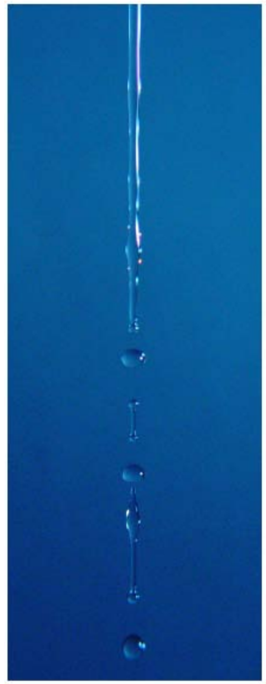
Existence of a liquid fiber : a surprising effect

In the lab



$n_1 > n_2$

In your kitchen



Why the liquid cylinder does not collapse (as usual) ?

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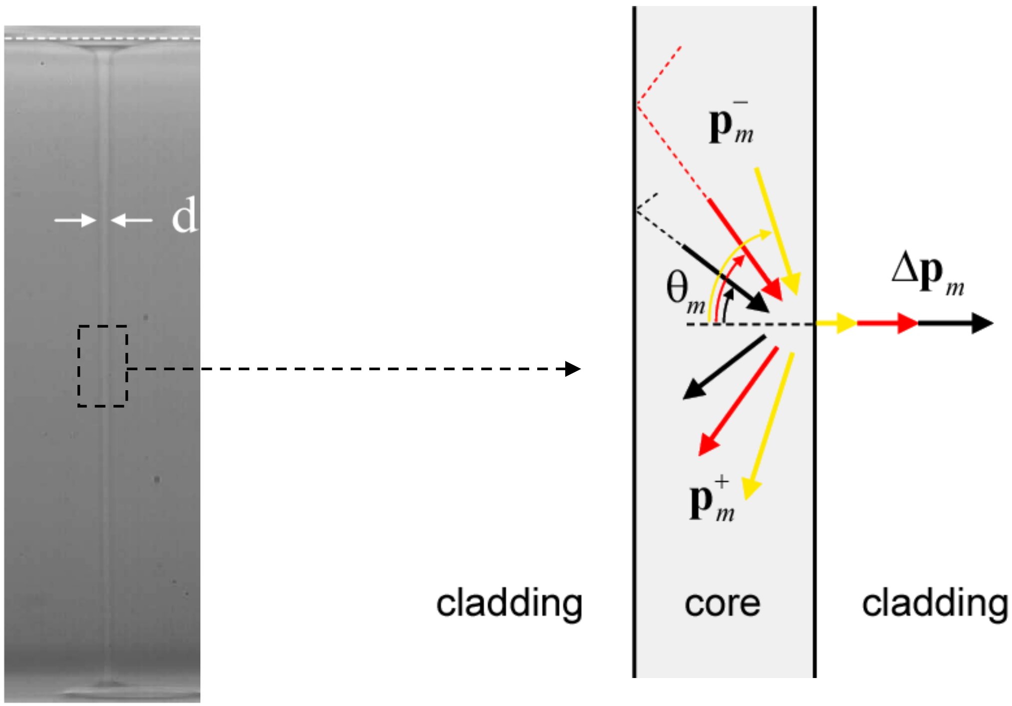
Capillary effects balanced by light !

$$\boxed{\Lambda = L / d > \pi}$$

Rayleigh-Plateau instability

A cylindrical liquid column with fixed ends and volume breaks into droplets when the aspect ratio is large enough.

Liquid-core liquid-cladding optical fiber sustained by light radiation pressure



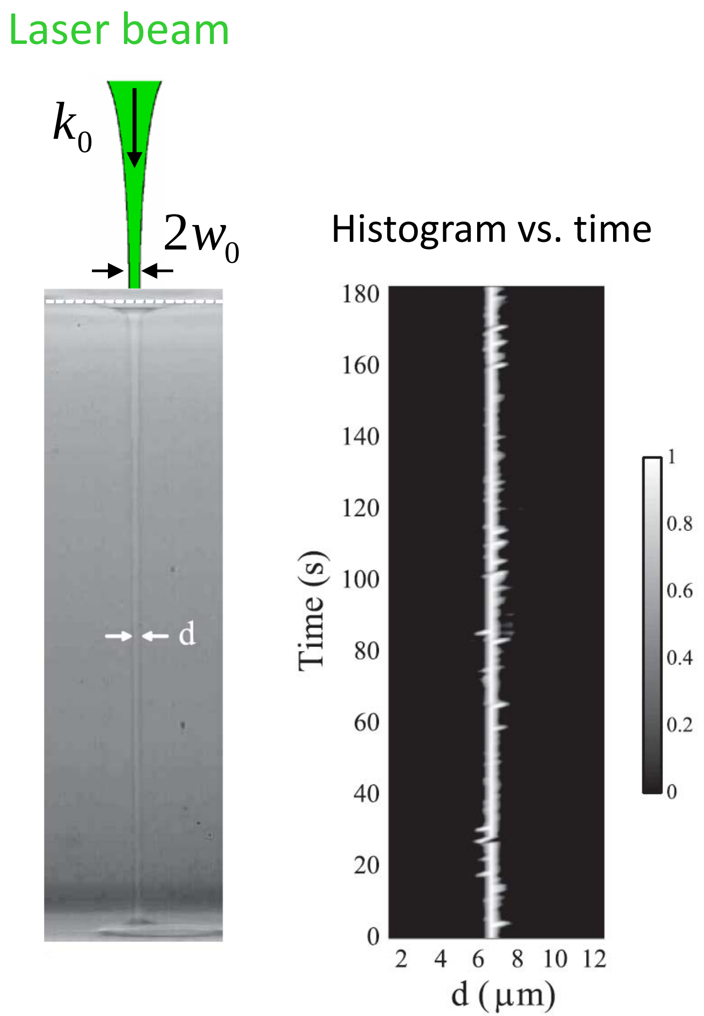
$n_{in} > n_{out}$

Many modes may contribute to radiation pressure

$$\Pi_{\text{radiation}} = \sum_m \Phi_m \Delta\mathbf{p}_m \cdot \mathbf{u}_r$$

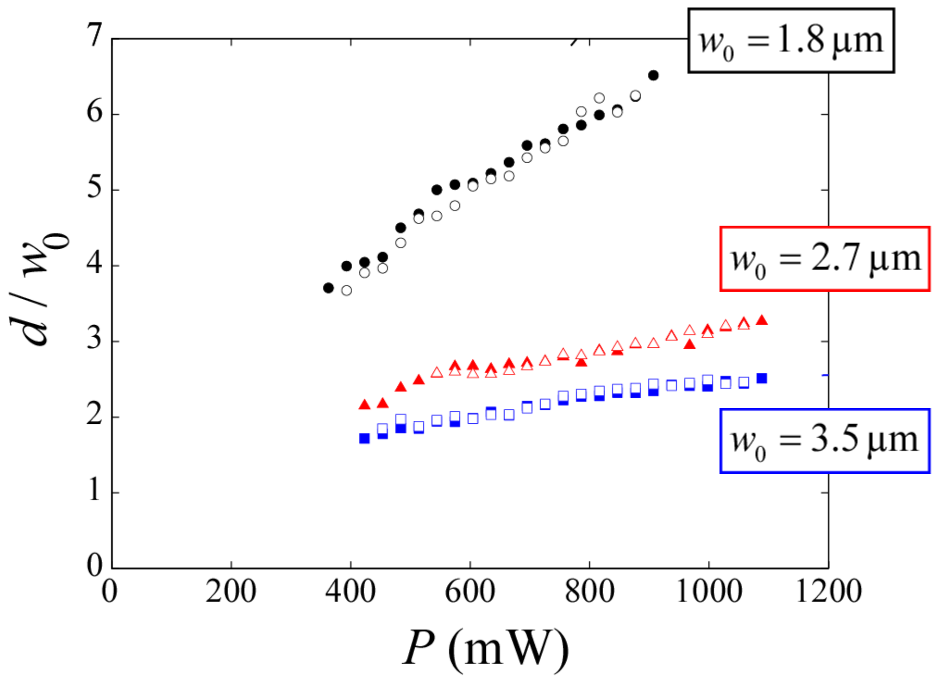
Ray optics approach

Step-index liquid fiber : experiment



Single-valued and stationary diameter distribution

Dependence on incident power and waist



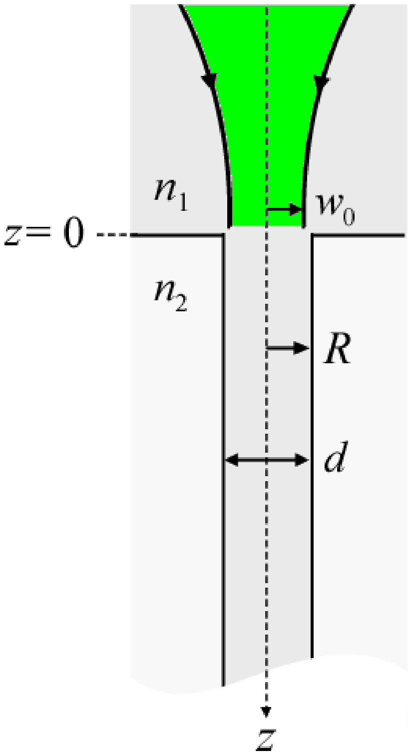
Self-adapted liquid optical fiber

E. Brasselet *et al*, PRL **101**, 014501 (2008)

Step-index liquid fiber : model

Equilibrium equation

$$\Pi_{\text{Laplace}} = \Pi_{\text{radiation}} \qquad \begin{cases} \Pi_{\text{Laplace}} = \dfrac{\sigma}{R} \\ \Pi_{\text{radiation}} = \epsilon_0 \dfrac{n_1^2 - n_2^2}{4} \left(|\mathbf{E}_{\text{t},1}|^2 + \dfrac{n_1^2}{n_2^2} |\mathbf{E}_{\text{n},1}|^2 \right)_{r=R} \end{cases}$$



Weakly guiding fiber approximation

$$\mathbf{E}^{(m)} = E_0^{(m)} \mathcal{R}_m(r) e^{i\beta_m z} \mathbf{u}_x$$

$$\Downarrow$$

$$\Pi_{\text{radiation}} = \frac{1}{2} \epsilon_0 n (n_1 - n_2) \sum_m \underline{|E_0^{(m)}|^2}$$

Depends on power transmitted to mode m (LP_{0m})

$$P_m = T_m P$$

$$T_m = \frac{\left| \int_0^\infty \mathbf{E}^{(m)} \cdot \mathbf{E}^{(\text{inc})} r \, dr \right|^2}{\int_0^\infty |\mathbf{E}^{(m)}|^2 r dr \int_0^\infty |\mathbf{E}^{(\text{inc})}|^2 r \, dr}$$

Equilibrium equation

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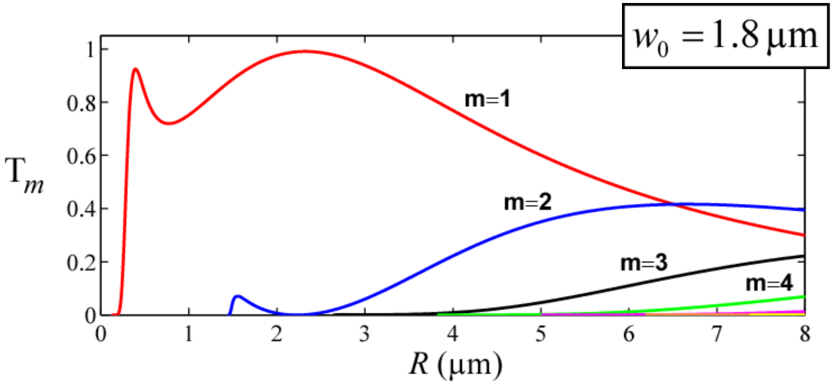
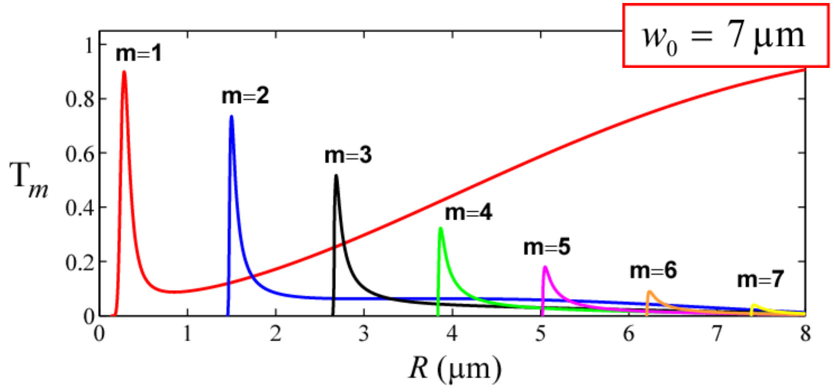
Modal tranmissions





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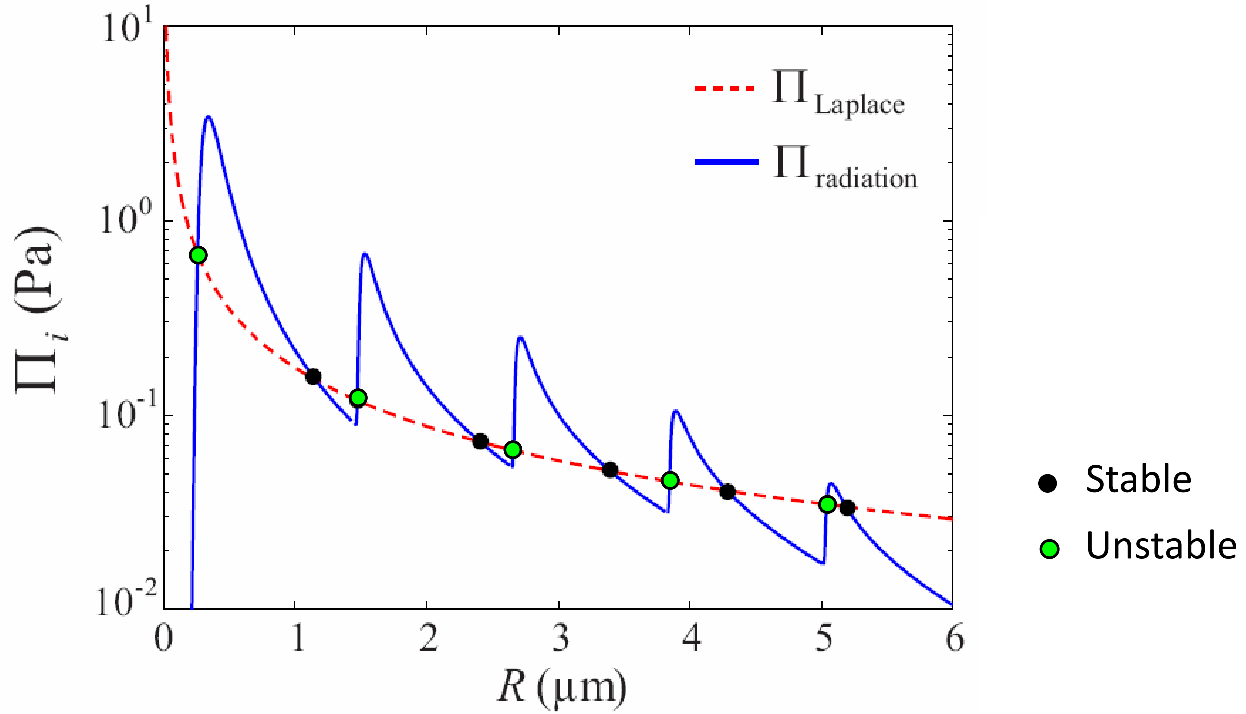
$w_0 = 7\mu m$
$P = 500 mW$
$\Delta T = 2K$



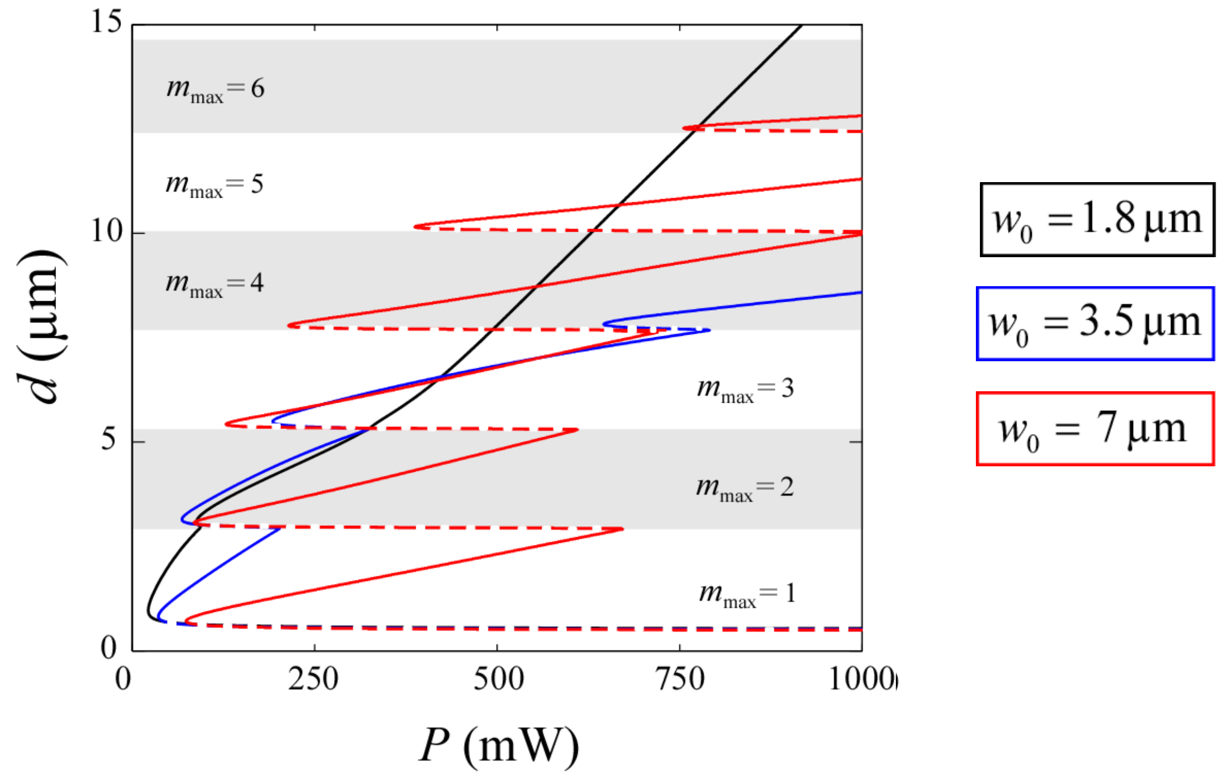
Equilibrium states

$$\Pi_{\text{Laplace}} = \Pi_{\text{radiation}}$$

Stability criterion

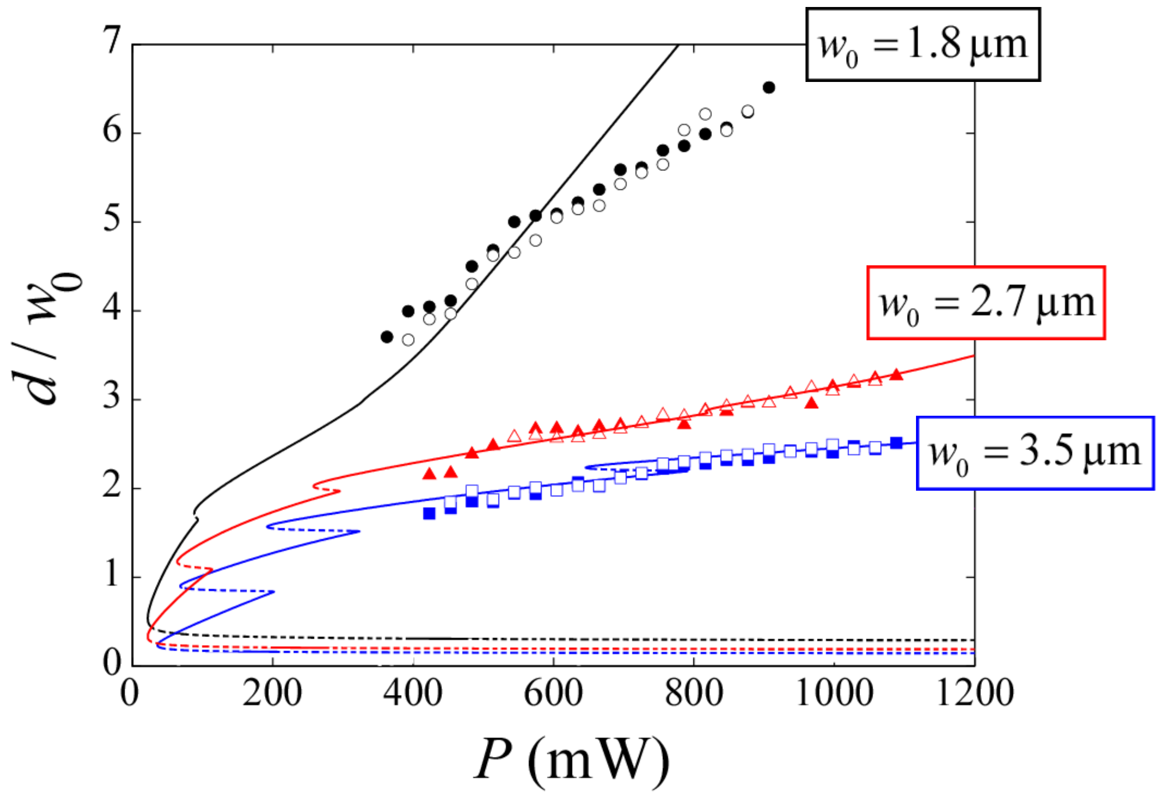
$$\left.\frac{\partial \Pi_{\text{radiation}}}{\partial R}\right|_{R=R_{\text{eq}}^{(n)}} < \left.\frac{\partial \Pi_{\text{Laplace}}}{\partial R}\right|_{R=R_{\text{eq}}^{(n)}}$$

Step-index liquid fiber : model



The core diameter can be either single or multivalued and sustained by one or several guided modes

Step-index liquid fiber : experiment / model



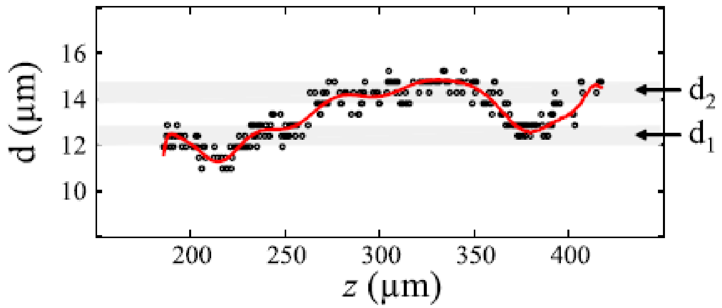
Satisfying agreement at lower beam waists

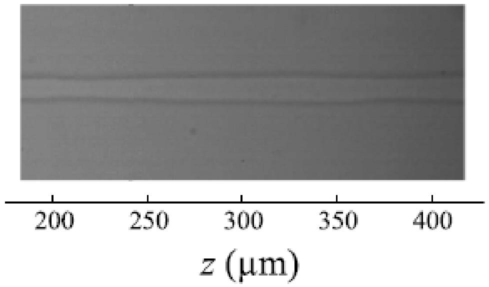
Step-index liquid fiber : qualitative multistable core behavior

Signature of multistability at larger beam waists at a fixed time

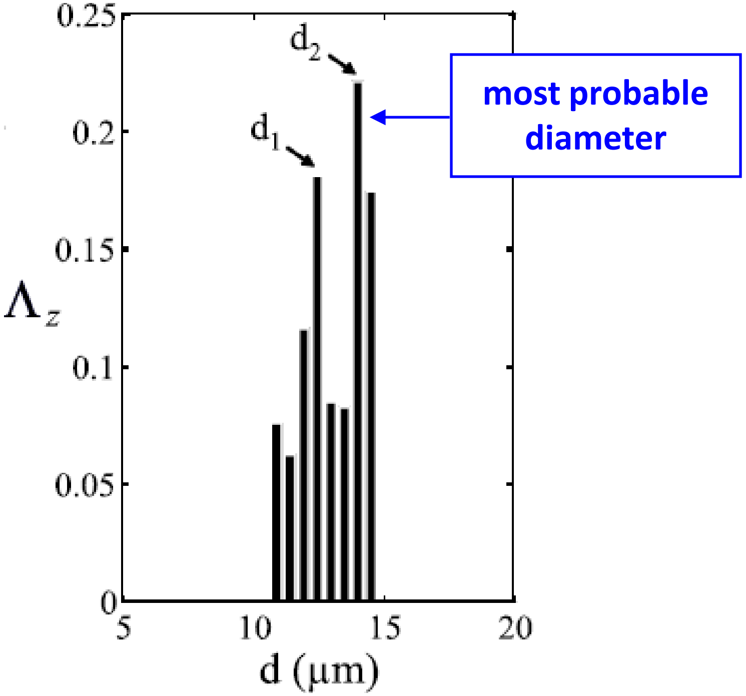
$$w_0 = 7.0 \ \mu\text{m}$$

$$P = 575 \text{ mW}$$





Diameter probability distribution



Outline

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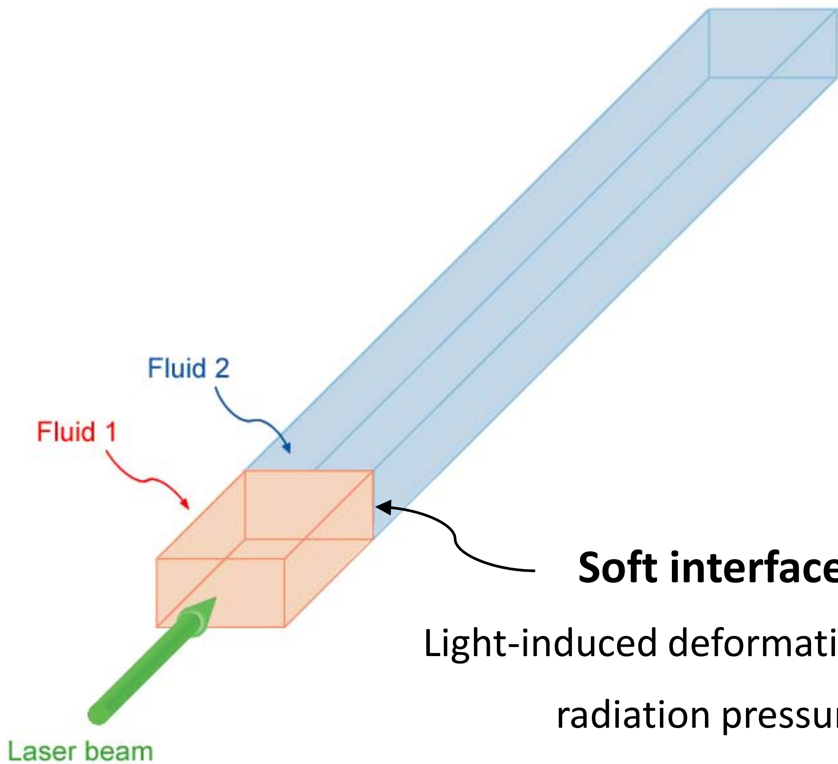
2. Liquid-core liquid-cladding self-induced optical fibers
3. **The optical micro-pipeline**
4. Acoustic analogies

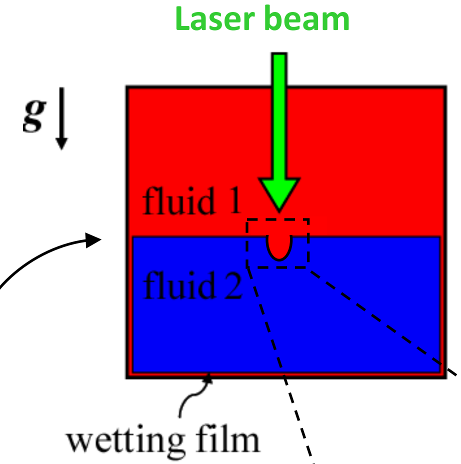
All-liquid micro-optical pipeline concept



Soft interface

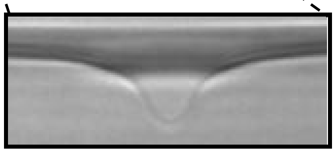
Light-induced deformations using radiation pressure

The experiment



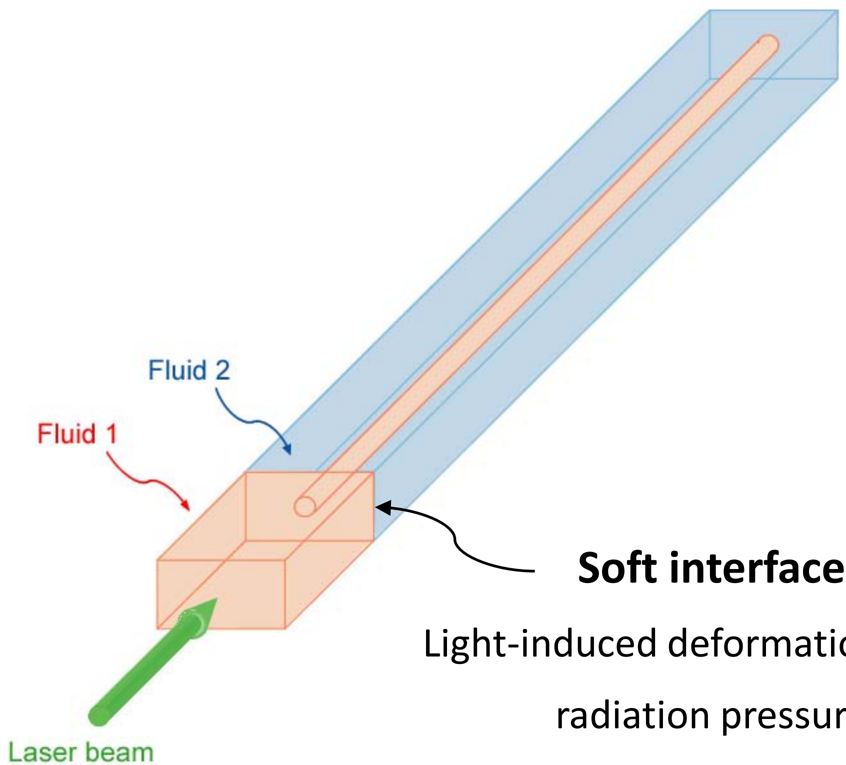
$$\mathbf{p}_i = n_i \hbar \mathbf{k}_i$$

$$n_1 > n_2$$



Low power

All-liquid micro-optical pipeline concept



Soft interface

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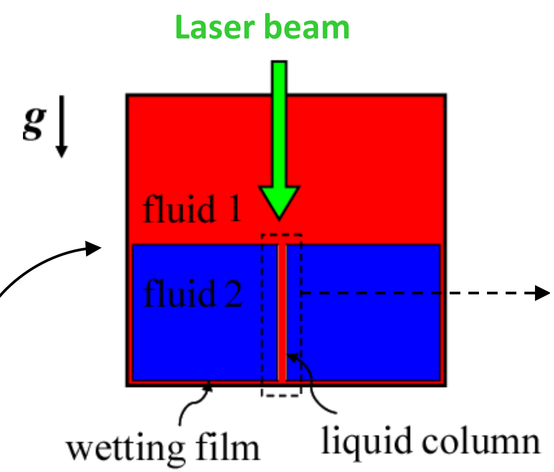

High power

The micro-optical pipeline : how it looks in the lab

Bulk opto-mechanical effects

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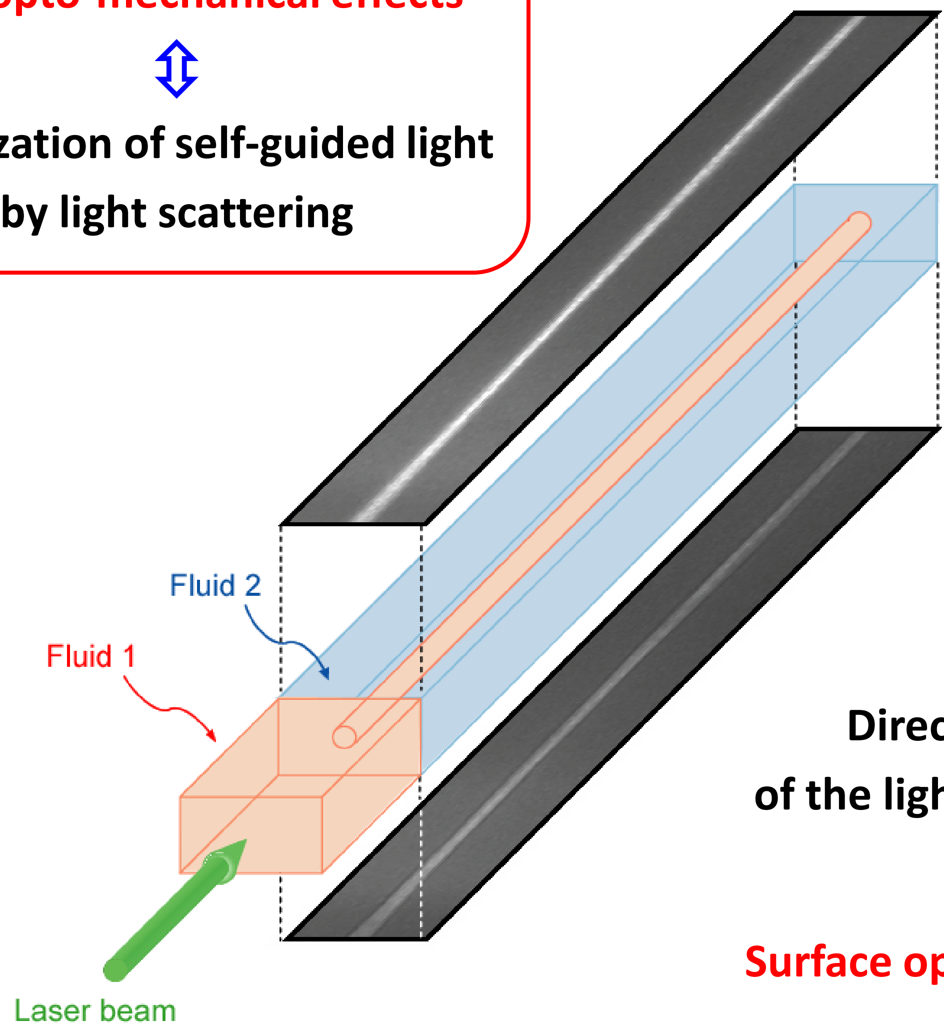
Visualization of self-guided light by light scattering



Direct optical imaging of the light-induced liquid fiber

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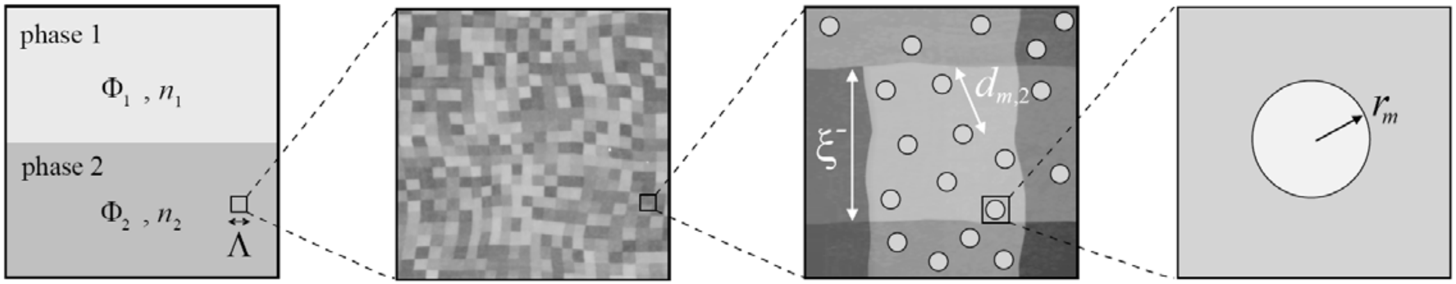
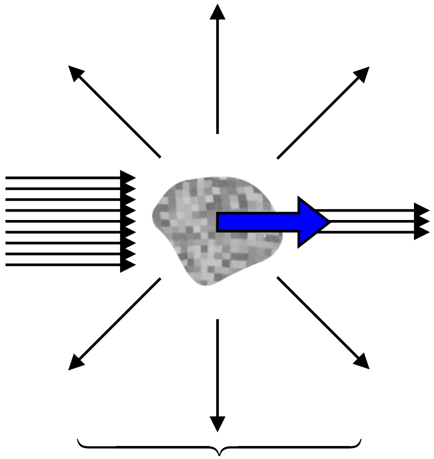
Surface opto-mechanical effects

Bulk contribution of the optical force density : light scattering

Micellar phases scatter light



Input momentum density flux



Output momentum density flux

Scattered light

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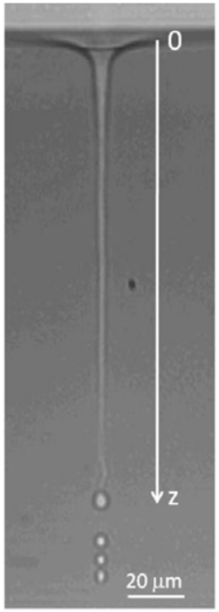
Longitudinal scattering force density

⇨ FLUID FLOW

Dripping jet



Light-induced bulk flow in the lab

Scattering force

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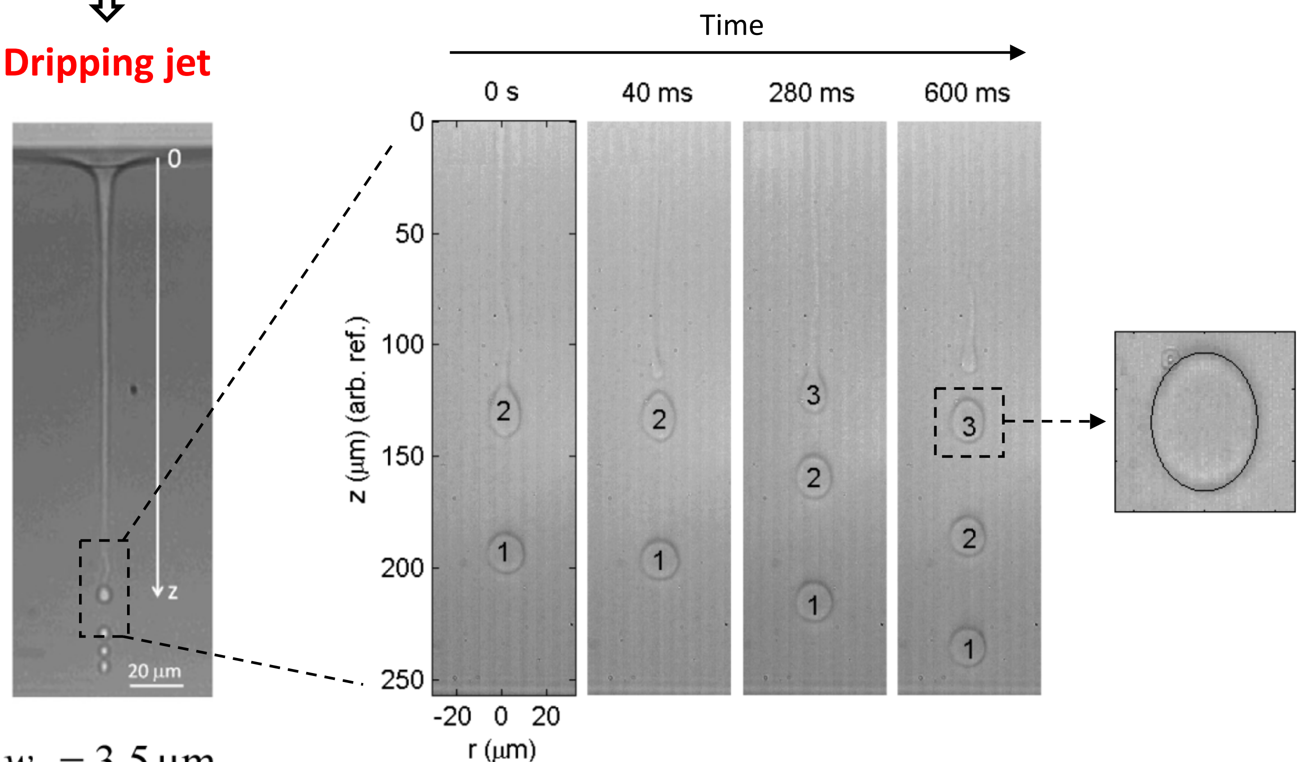
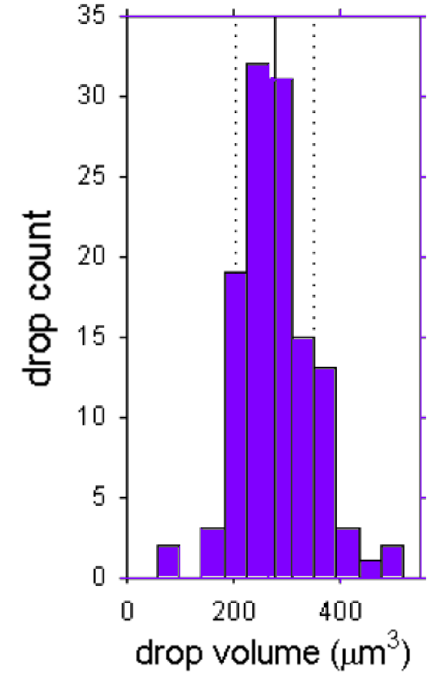
Dripping jet



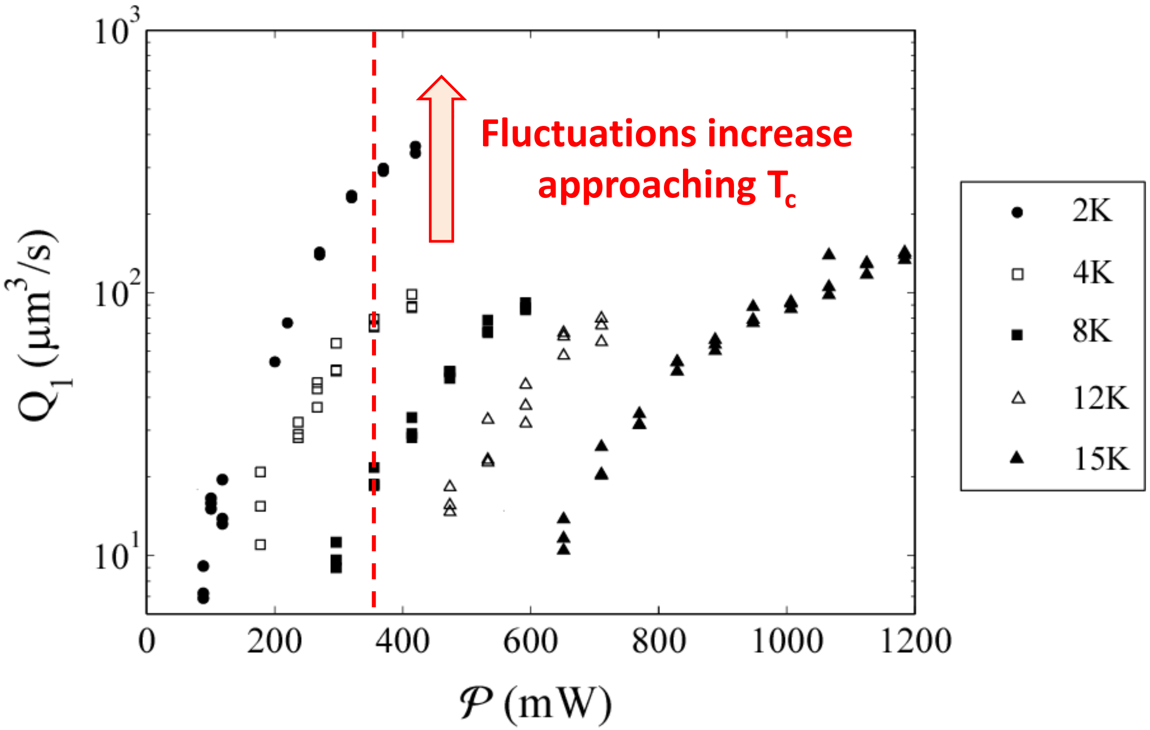
$w_0 = 3.5\ \mu\mathrm{m}$

Flow rate statistics



R. Wunenburger *et al*, J. Fluid Mech. **666**, 273 (2011)

Average flow rate as a function of temperature and incident power



Light scattering is temperature dependent
via the size of refractive index fluctuations

Hydrodynamic model for light-induced flow

Bulk force balance

$$\mathbf{0} = \mathbf{f}_i^{\text{hydro}} + \mathbf{f}_i^{\text{em}} + \mathbf{f}_i^{\text{scatt}}, \quad i = 1, 2$$

$$\mathbf{f}_i^{\text{hydro}} = \boldsymbol{\nabla}.T_i^{\text{hydro}}$$

$$T_i^{\text{hydro}} = -p_i I + \eta_i \left(\boldsymbol{\nabla}\mathbf{v} + {}^t\,\boldsymbol{\nabla}\mathbf{v}\right)$$

$$\mathbf{f}_i^{\text{em}} = \boldsymbol{\nabla}.T_i^{\text{em}}$$

$$T_i^{\text{em}} = \tfrac{1}{2}\varepsilon_0\rho_i \left.\frac{\partial\varepsilon_i}{\partial\rho_i}\right|_T \mathbf{E}^2 I - \tfrac{1}{2}\varepsilon_0\varepsilon_i\mathbf{E}^2 I + \varepsilon_0\varepsilon_i\mathbf{E}\,{}^t\mathbf{E}$$

Individual spherical scatterer

$$\mathbf{F}^{\text{scatt}} = \sigma n S/c$$

Micellar phases

$$\mathbf{f}_i^{\text{scatt}} = N\mathbf{F}_i^{\text{scatt}} = \tau_i n_i \mathbf{S}_i/c$$

$$\tau_i = \int\!\!\int \frac{1}{I_i}\frac{d^2 I_i}{d\Omega dz}(\Omega)\, d\Omega$$

Surface force balance

$$\left(T_2^{\text{hydro}} - T_1^{\text{hydro}}\right)\mathbf{n}_{1\to2} + \left(T_2^{\text{em}} - T_1^{\text{em}}\right)\mathbf{n}_{1\to2} - \sigma\kappa\mathbf{n}_{1\to2} = \mathbf{0}$$

Hydrodynamic model for light-induced flow

Translational invariance along beam propagation

$$\mathbf{E}_i = \mathbf{E}_i(r)$$
$$\mathbf{f}_i^{\text{scatt}} = f_i^{\text{scatt}}(r)\hat{\mathbf{z}}$$
$$\mathbf{v}_i = v_i(r)\hat{\mathbf{z}}$$

⇙ ⇘

Surface force balance

$$\eta_1 \frac{dv_{z,1}}{dr} \underset{r=R}{=} \eta_2 \frac{dv_{z,2}}{dr}$$ (axial contribution)

$$\Pi_{\text{Laplace}} = \Pi_{\text{radiation}}$$ (radial contribution)

Bulk force balance

$$\eta_i \Delta \mathbf{v}_i + \mathbf{f}_i^{\text{scatt}} = K$$

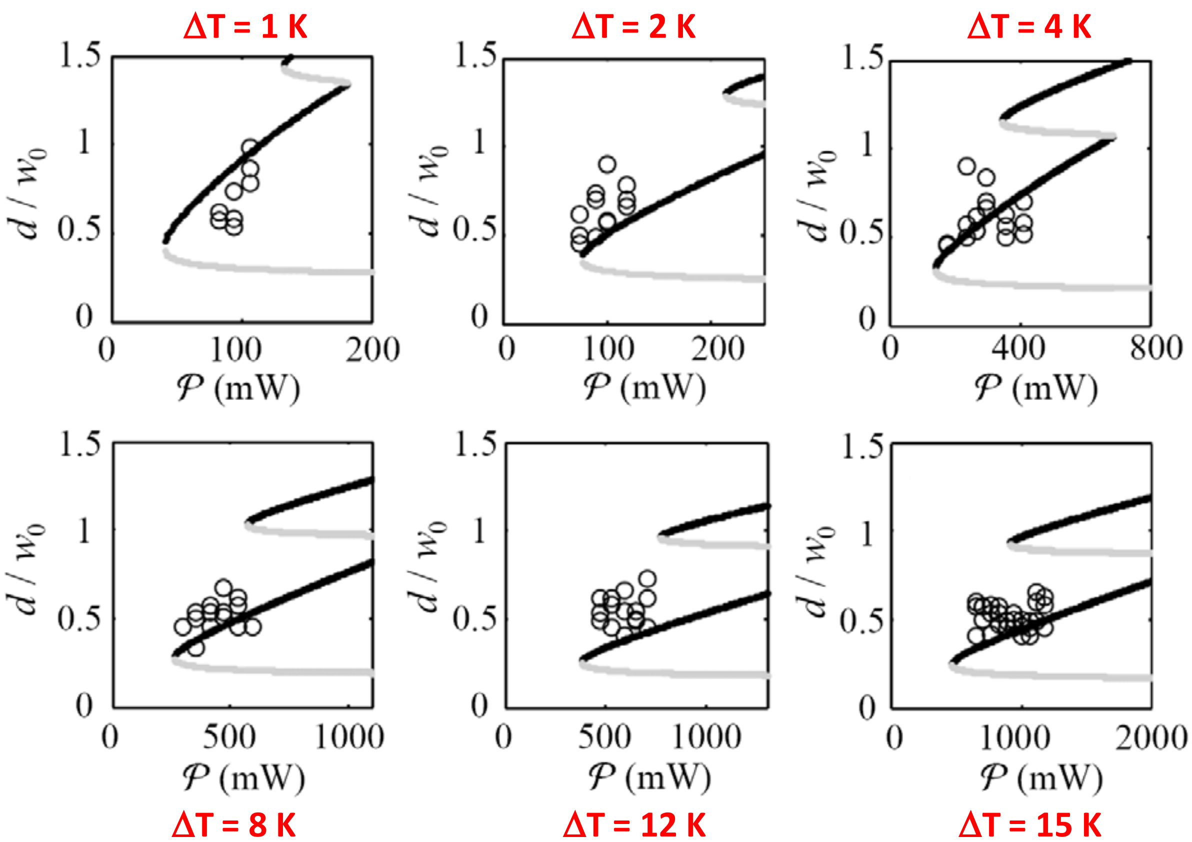
Fluid flow and light propagation inside micro-pipeline are decoupled

Geometry ⇔ waveguiding properties

Flow rate ⇔ scattering force density

Optical micro-pipeline shape : experiment

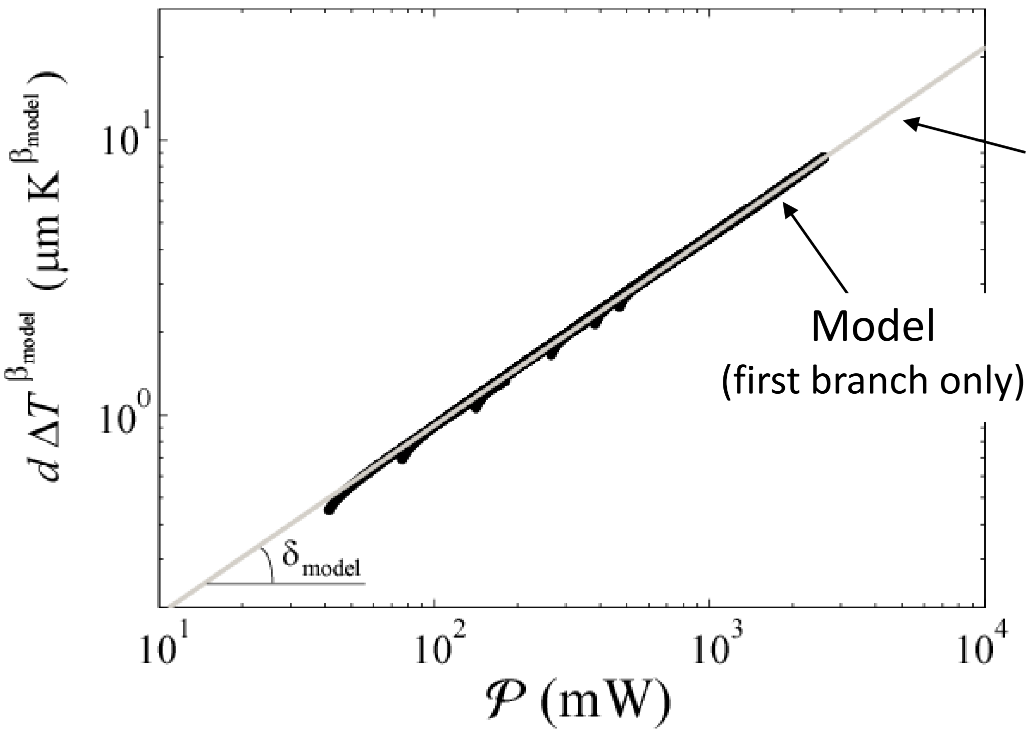
$\Delta T = T - T_c$



Only the first stable branch is explored for w_0 = 3.5µm

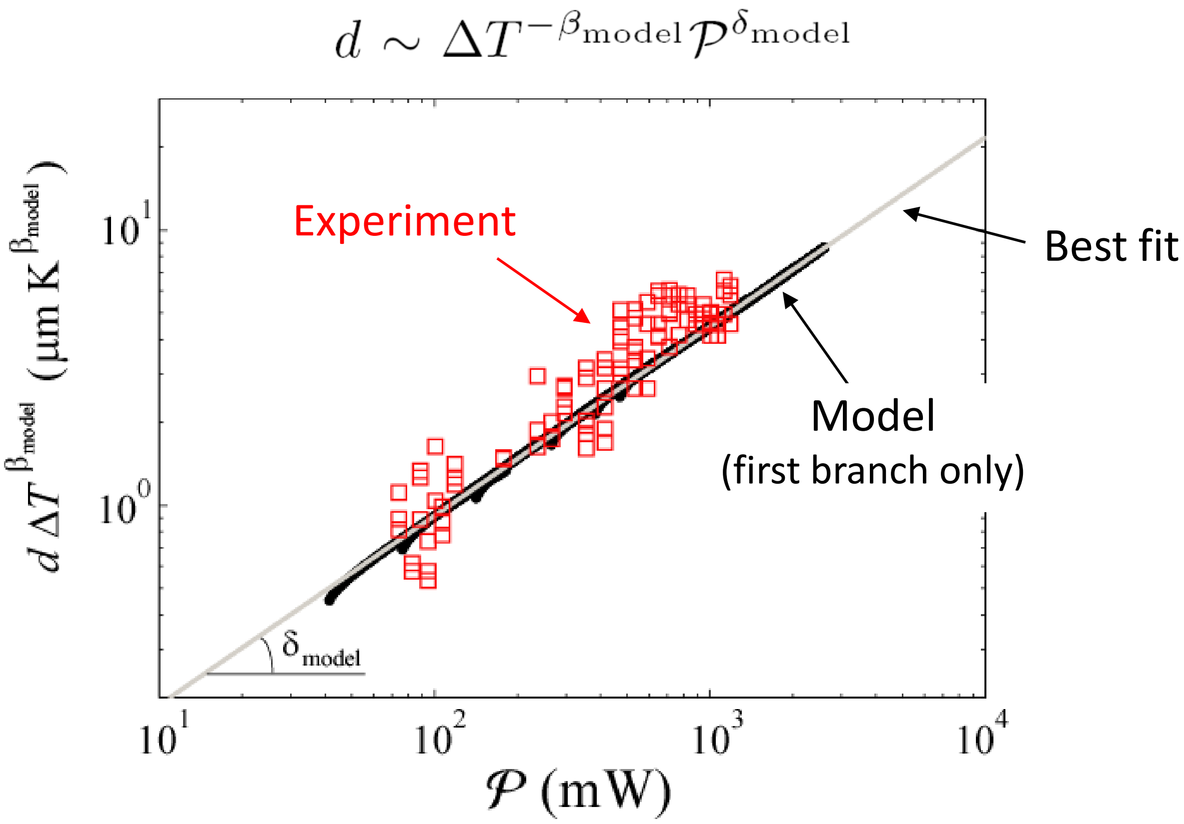
Optical micro-pipeline shape : model

$$d \sim \Delta T^{-\beta_{\mathrm{model}}} \mathcal{P}^{\delta_{\mathrm{model}}}$$



Overall behavior is well-described by an empirical power law fit

Optical micro-pipeline shape : experiment / model



Satisfying agreement is obtained

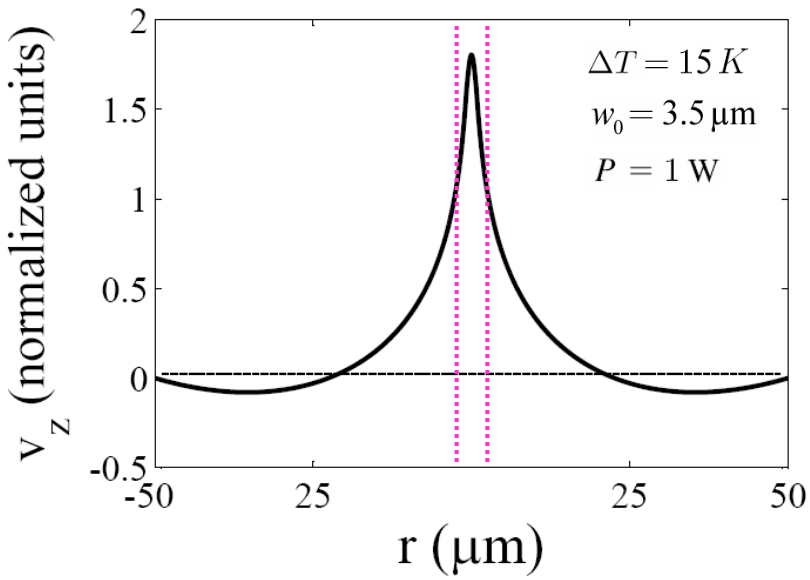
Bulk force balance

$$\eta_i \Delta \mathbf{v}_i + \mathbf{f}_i^{\text{scatt}} = K$$

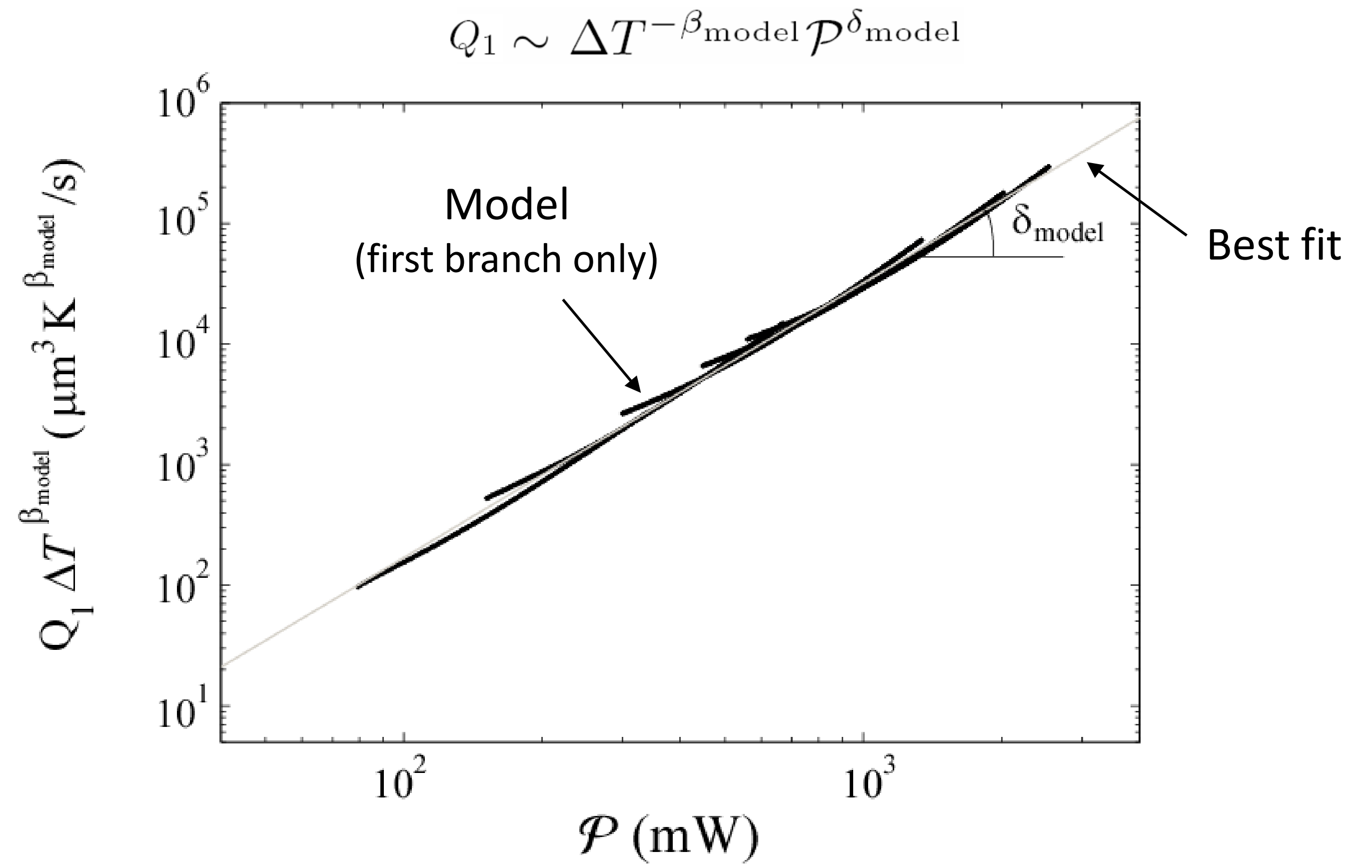
⇨ **4 boundary conditions**

$$\begin{cases} v_{z,1} \underset{r=R}{=} v_{z,2} \\ \eta_1 \dfrac{dv_{z,1}}{dr} \underset{r=R}{=} \eta_2 \dfrac{dv_{z,2}}{dr} \\ v_{z,2} \underset{r=R_{\text{box}}}{=} 0 \\ Q_2 = \displaystyle\int_R^{R_{\text{box}}} 2\pi r v_{z,2}(r)\ \mathrm{dr} = 0 \end{cases}$$

Calculated velocity profile

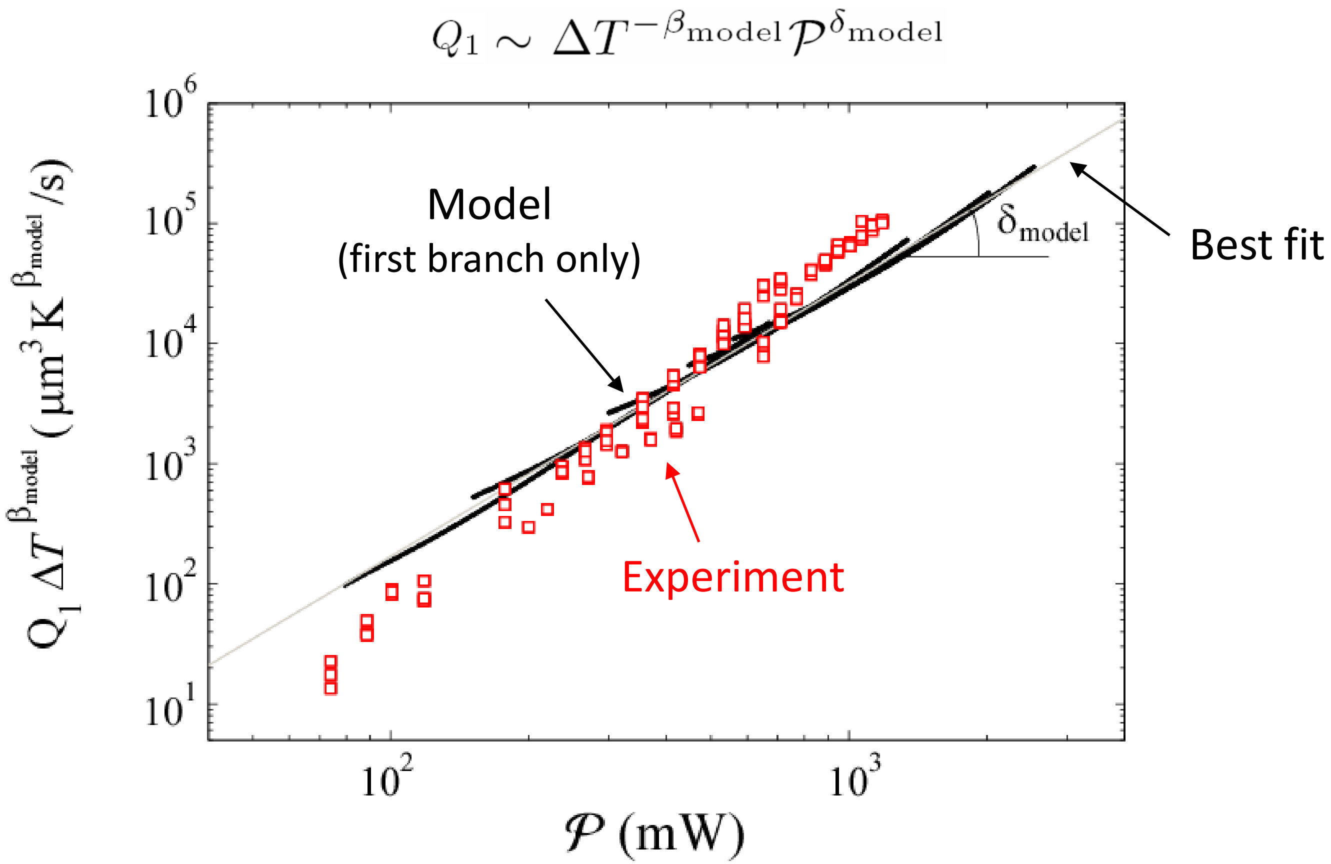


Optical micro-pipeline shape : experiment / model



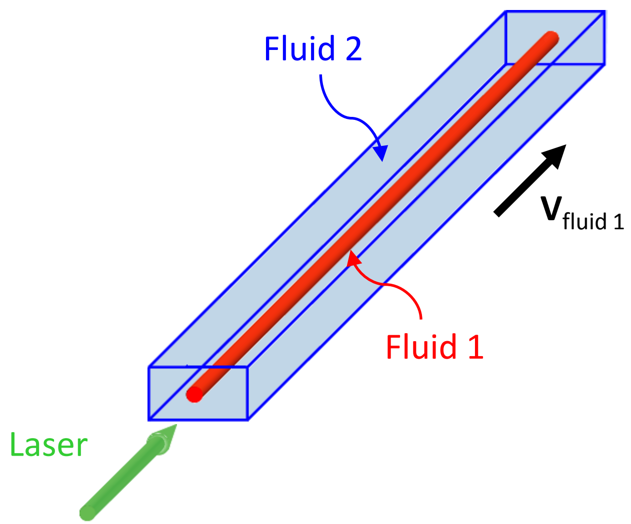
Overall behavior is well-described by an empirical power law fit

Optical micro-pipeline shape : experiment / model



Satisfying agreement is obtained

All-optical micro-pipeline / Fluid-mediated optical interconnect



Geometry

Light radiation pressure from propagating waveguided modes

Fluid flow

Light scattering force density

Experimental realization and quantitative theoretical description

E. Brasselet *et al.*, PRL **101**, 014501 (2008)
E. Brasselet *et al.*, PRA **78**, 013835 (2008)
R. Wunenburger *et al.*, J. Fluid Mech. **666**, 273 (2011)

Outline

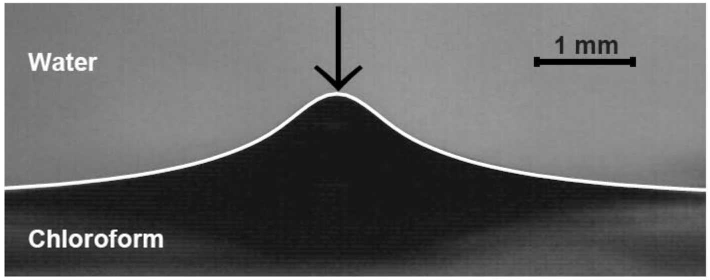
1. Laser induced giant fluid interface deformations
2. Liquid-core liquid-cladding self-induced optical fibers
3. The optical micro-pipeline
4. **Acoustic analogies**

Mechanical effects of waves are not restricted to light !

Acoustic radiation pressure

$$\Pi \sim I / c$$

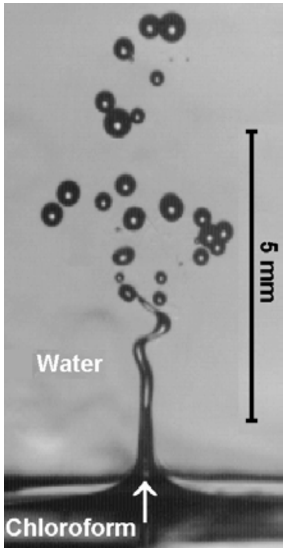
Acoustic fields are more efficient than light fields (~10^5)



B. Issenmann *et al.*, Europhys. Lett. **83**, 34002 (2008)

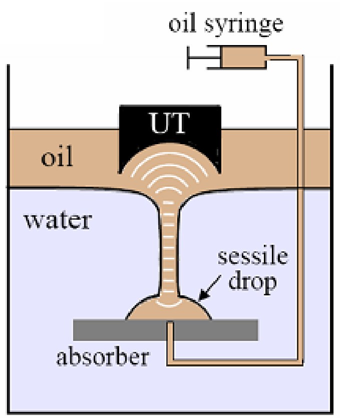
Acoustic radiation force density

Acoustic-matter interaction is dissipative while it is conservative for light (in our case)

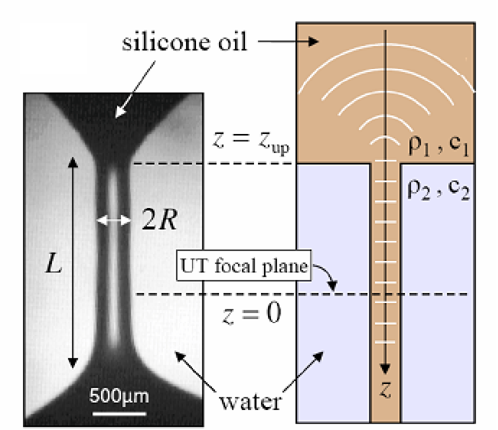


The acoustic milli-pipeline

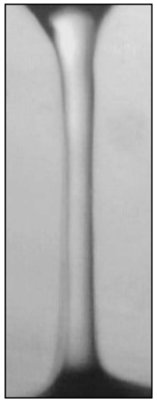
The experiment



The model



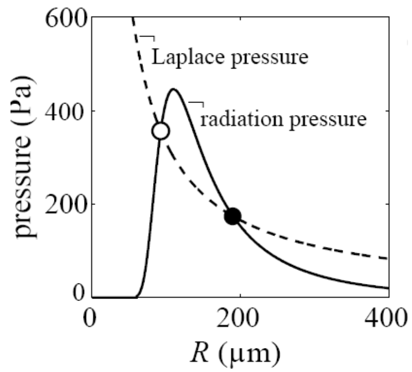
$\Lambda \sim 10$

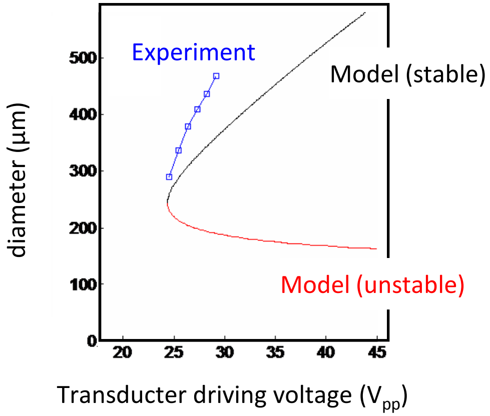


N. Bertin *et al.*, PRL **105**, 164501 (2010)

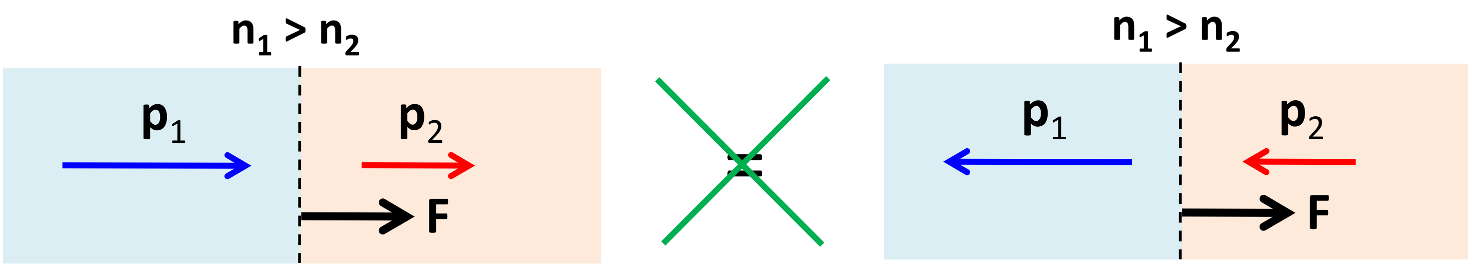
Acoustic waveguiding

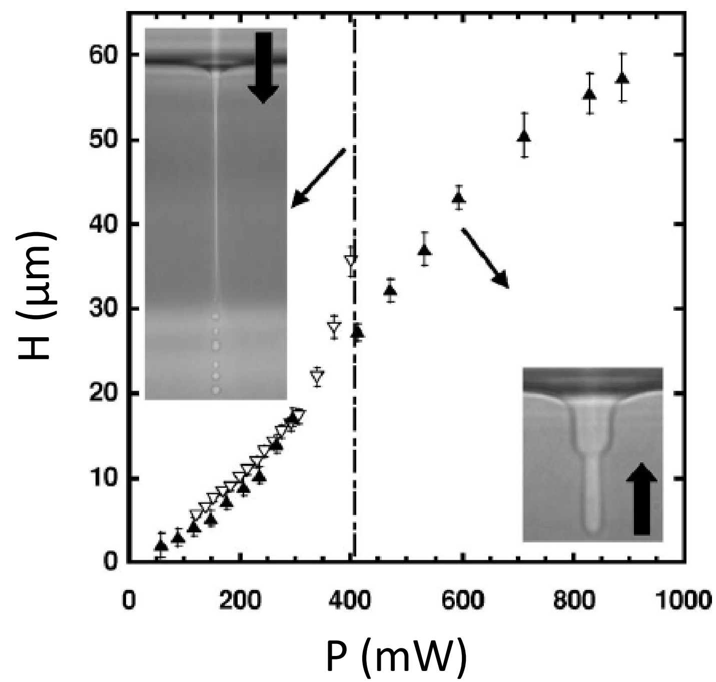
$$c_1 = 998 \text{ m.s}^{-1} < c_2 = 1488 \text{ m.s}^{-1}$$





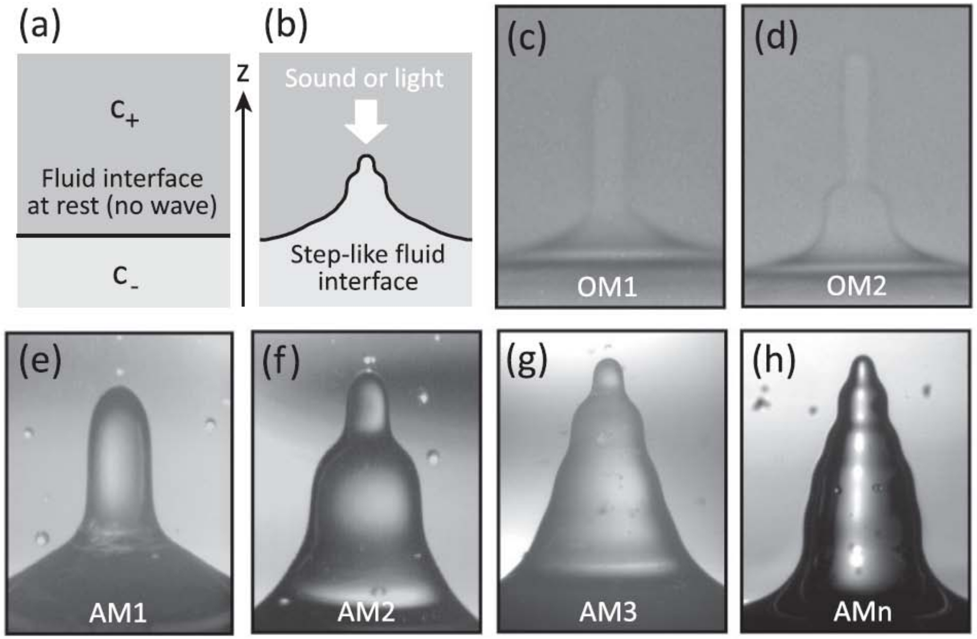
A closer look to up/ down symmetry





R. Wunenburger *et al.*, PRE **73**, 036314 (2006)

Analogy between optics and acoustics remains

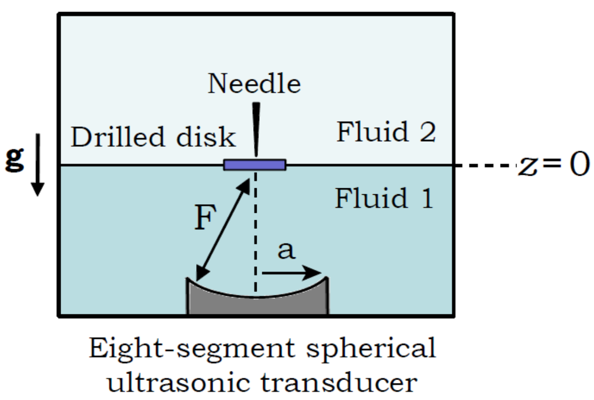


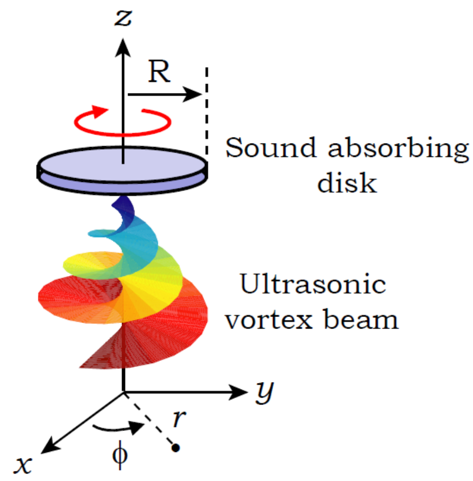
Universal morphologies of fluid interfaces deformed by the radiation pressure of acoustic or electromagnetic waves

N. Bertin *et al.*, PRL **109**, 244304 (2012)

Sound can also carry orbital angular momentum !

Rotational acousto-mechanics





A. Anhauser *et al.*, PRL **109**, 034301 (2012)