Glissement aux parois et microfluidique

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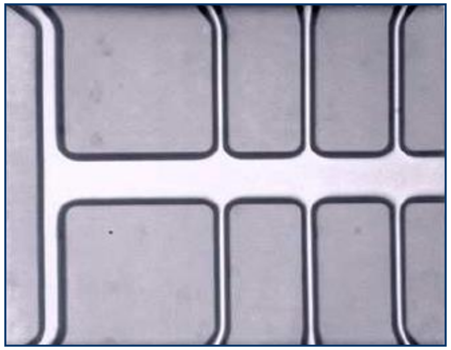
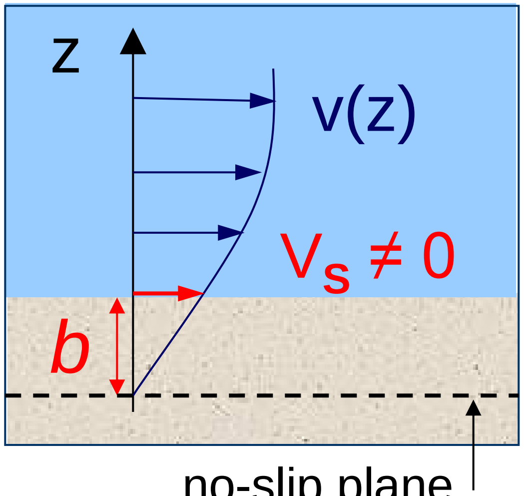
Introduction



- Micro- and nanofluidics:
  high surface to volume ratio
  - **importance of surface effects**

- Hydrodynamic boundary condition
  - **partial slip boundary condition**



$$\boxed{V_s = b \left.\frac{\partial V}{\partial z}\right|_{z=0}}$$

Navier (1823)

slip length

$$\boxed{b = \frac{\eta}{\lambda}}$$

liquid viscosity

liquid-solid friction coefficient

Why can slippage be important in microfluidics ?

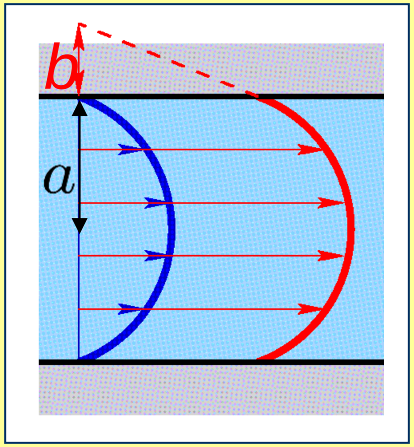
- Increasing the boundary slip ⟺ reducing the interfacial friction

  facilitates the flow

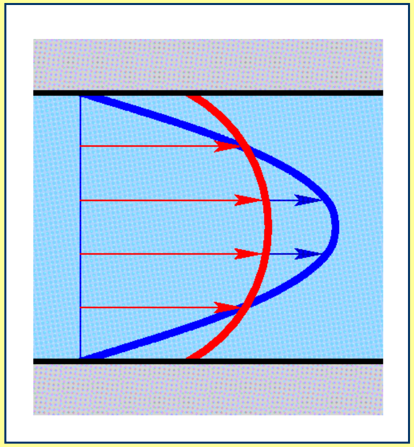
Illustration: Poiseuille flow in a capillary of radius a

mean velocity $$\boxed{U = -\frac{a^2}{8\eta}\left(1 + \frac{8b}{a}\right)\vec{\nabla}P}$$

- **higher mean velocity at a given pressure gradient**



- **lower pressure drop at a given mean velocity**



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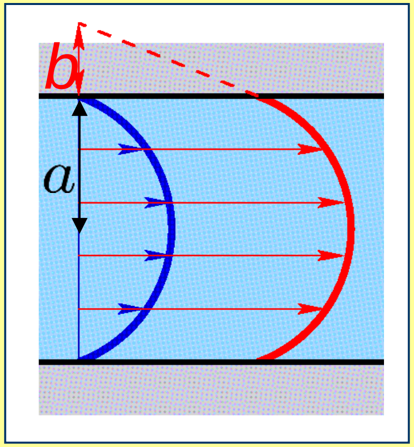
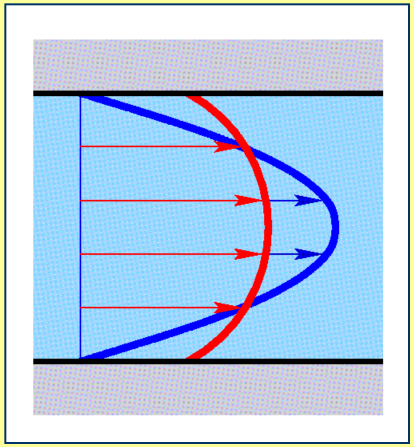


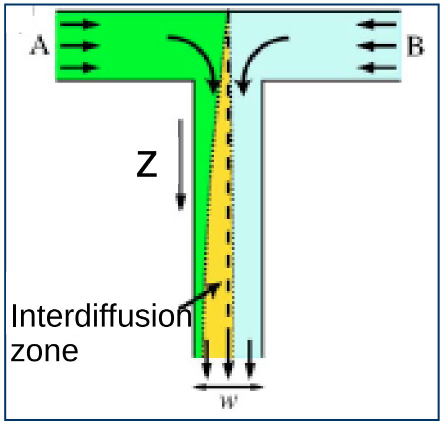
lower pressure drop at a given mean velocity

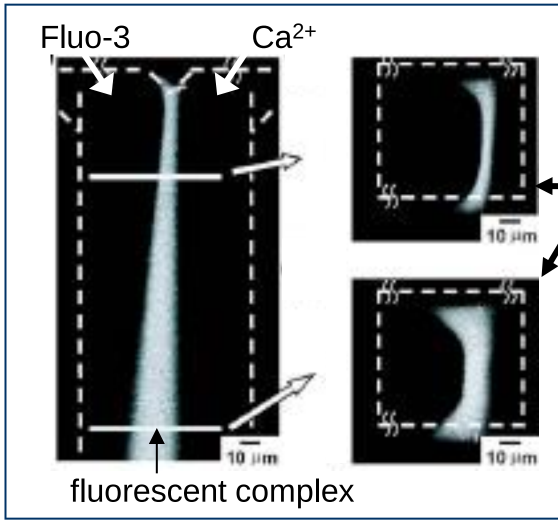


lower velocity gradients

Why can slippage be important in microfluidics ?

- Slippage can reduce velocity gradients that :
  - **complexify diffusion ⊥ to the flow**





confocal slices

- spreading in $z^{1/2}$ near the middle but in $z^{1/3}$ near the walls

Ismagilov et al.
Appl. Phys. Lett (2000)

Examples of applications:

- T-sensors to measure
  - diffusion coefficients
  - concentrations
  - reaction kinetics

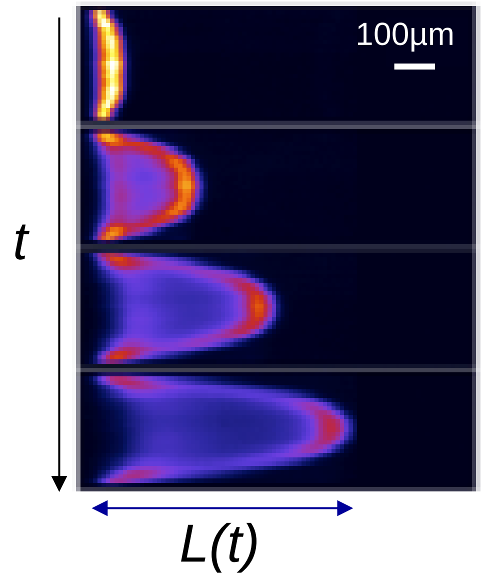
  Kamholz et al.
  Anal. Chem. (1999)

- creation of controlled concentration gradients

Why can slippage be important in microfluidics ?

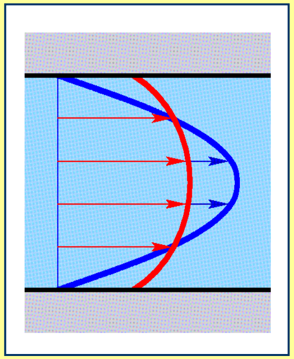
- Slippage can reduce velocity gradients that :
  - **are responsible for hydrodynamic dispersion // to the flow**

J.G. Santiago
Stanford Microfluidics Lab.



Reduction of hydrodynamic dispersion due to slippage:

Poiseuille flow
in a capillary of radius a
with identical mean velocity:



$$\frac{L_{slip,b}}{L_{noslip}} = \frac{1}{1+\frac{8b}{a}}$$

Summary

- Slippage improves transport of matter in microchannels

- Efficiency of slip effects $\sim \dfrac{b}{l}$ ← spatial range of velocity gradients

  ↳ ***b*** **must be at least** $\sim l$

For a Poiseuille flow in a capillary of radius a

$$\boxed{l = a}$$

Intrinsic slip on smooth homogeneous surfaces

- Theory + experiments
  - **no-slip on wetting substrates: b = 0 (<1 nm)**
  - **nanometric slippage on non-wetting substrates: b ~ 10 nm**

Bocquet and Barrat, Soft Matter (2007)

Vinogradova et al., Langmuir (2003)

Cottin-Bizonne et al., PRL (2005)

Joly et al., PRL (2006)

Craig et al, to appear

Huang and Breuer, Phys. Fluids (2007)

Honig and Ducker, PRL (2007)

Bouzigues et al., Phil. Trans. R. Soc. A (2008)

Maali et al., Appl. Phys. Lett. (2008)

Consequences

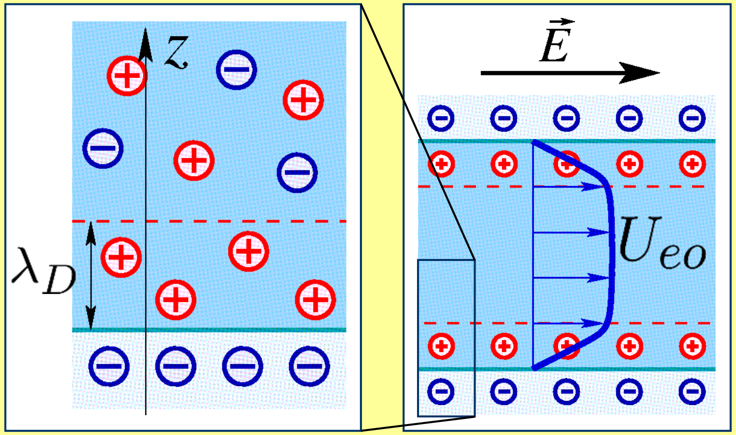
- To benefit from intrinsic slippage (b ~ 10 nm)
    - **use hydrophobic channels**
    - **slip effects in** $\frac{b}{l}$ ⇒ l **must be nanometric**

nanometric channels for Poiseuille flows

interfacially driven flows for wider channels

Important example:
electroosmose

Electroosmose



- Plug flow, $\boxed{l = \lambda_D}$

Debye length

water + monovalent salt, c = 10^{-2} M, λ_D ~ 3 nm

- Balance of electrical driving force and viscous stress

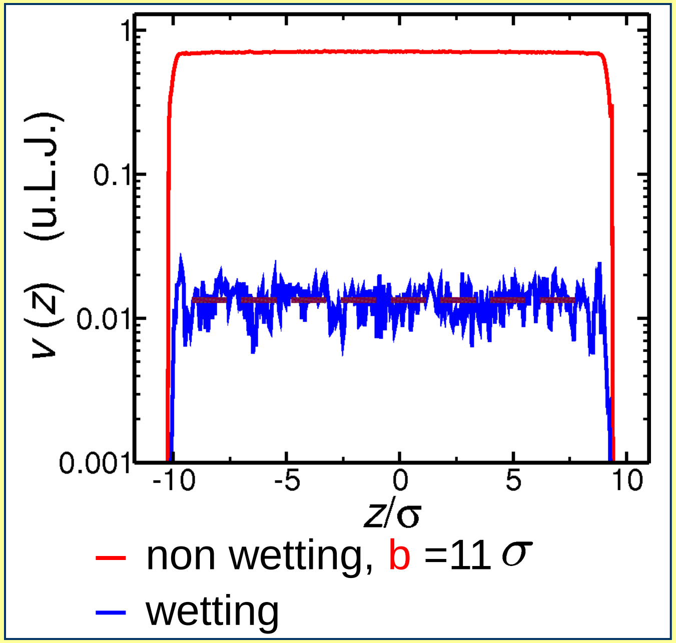
permittivity of the solvent surface potential

$$\boxed{\eta \frac{U_{eo}}{\lambda_D + b} = - \underbrace{\frac{\epsilon V_o}{\lambda_D}}_{\text{surface charge}} E}$$

↳ amplification factor $\boxed{1 + \frac{b}{\lambda_D}}$

large even for small b !

Lennard-Jones model, MD simulations



Joly et al., J. Chem. Phys. (2006)

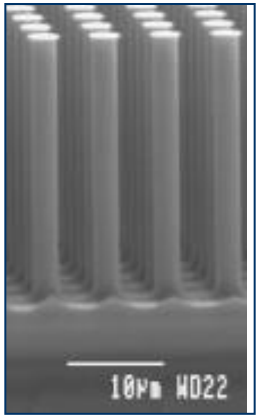
On the road toward giant slip lengths…

- To benefit from slippage effects for Poiseuille flows in micrometric channels
  - **the slip length must be micrometric**
  - **the effect must be robust**

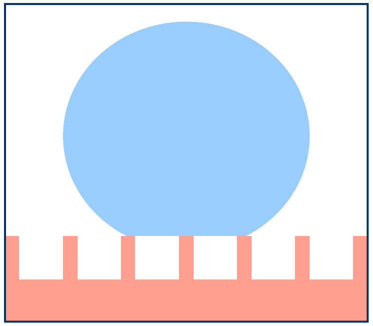
- How to obtain high and controlled slippage ?
  - **Idea: use superhydrophobic surfaces**

Superhydrophobic surfaces

- ❑ Wetting properties "fakir" effect

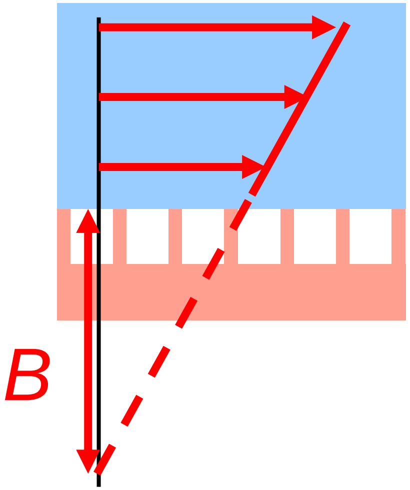


Callies *et al.* (2005)



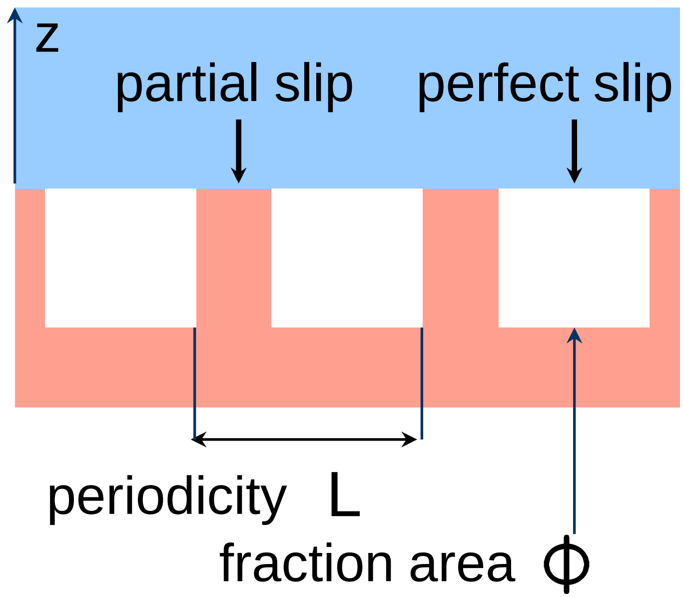
Cassie state

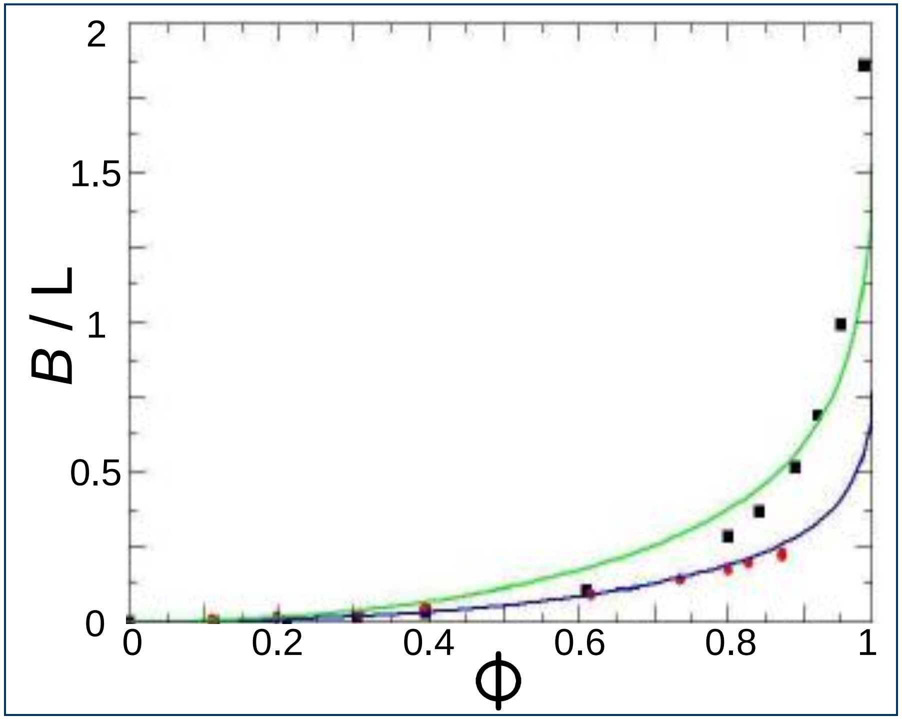
- ❑ Flow on superhydrophobic (SH) surfaces



- **Large *effective* slip length *B* due to reduced friction at the liquid-vapor interfaces ?**
- **Can we tailor surfaces to quantitatively control liquid slip ?**

Hydrodynamics on model SH surfaces





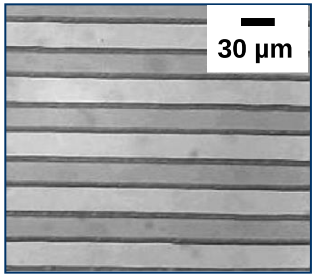
- stripes // flow
  Philip et al, Math. Phys. (1972)
- stripes ⊥ flow
  Lauga et al, J. F. Mech. (2003)
- square lattice of holes
  Cottin-Bizonne et al, EPJE (2004)
- square lattice of pillars
  Ybert et al, Phys. Fluids (2007)

- Flat composite interface

$$\boxed{\boldsymbol{B} = \mathbf{L}\, f(\Phi)}$$

Flow on SH surfaces: experiments

Stability of Cassie state:
in practice, L limited to ~ 1 μm



silanized silicon

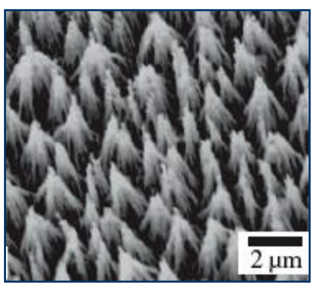
- Stripes // flow **Ou & Rothstein, Physics of Fluids (2005)**

  μ-PIV + pressure drop experiments

  ↳ **good agreement with theoretical predictions**

  B : 7 μm → 20 μm **Metastable state ?**

Diagonal stripes, $B_{//} = 2B_{\perp}$
➡ helical flow, **passive mixer**
Ou et al., PRE (2007)



carbon nanotubes
+ thiols

- Pillars **Joseph et al., PRL (2006)**

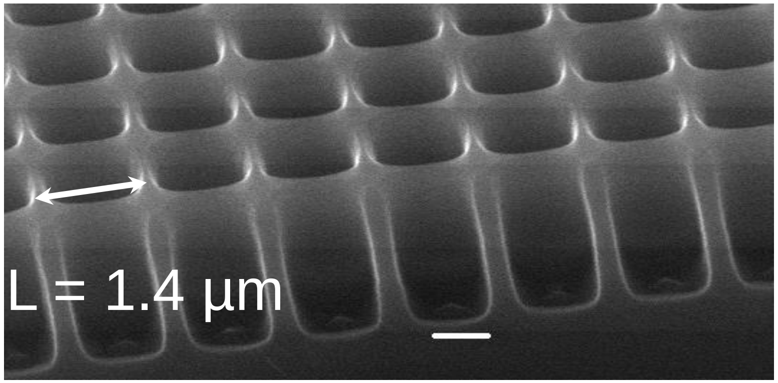
  μ-PIV experiments

  ↳ **good agreement with theoretical predictions**

  $B \propto L$; B : 0.5 μm → 1.5 μm

- Holes ?

Patterned surface

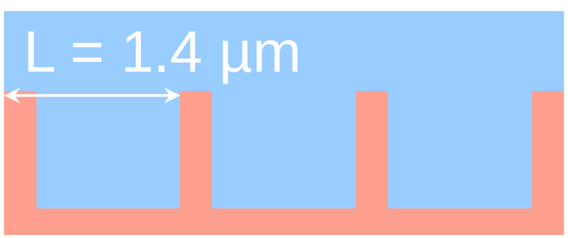


P. Kleimann (INL, Lyon)

- square lattice of holes in silicon
  obtained by **photolithography**

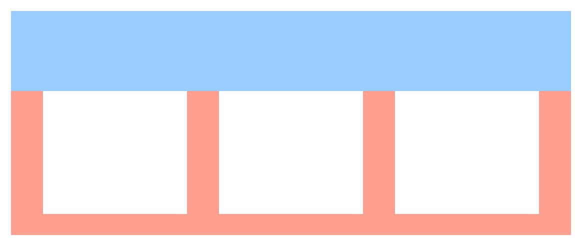
fraction area of holes: ϕ = (68 +/- 6)%
holes radius: a = (0.65 +/- 0.03) µm
holes depth = 3.5 µm

bare silicon
hydrophilic



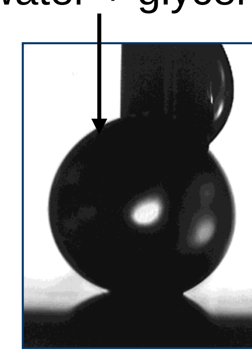
Wenzel regime

OTS-coated silicon
superhydrophobic



Cassie regime

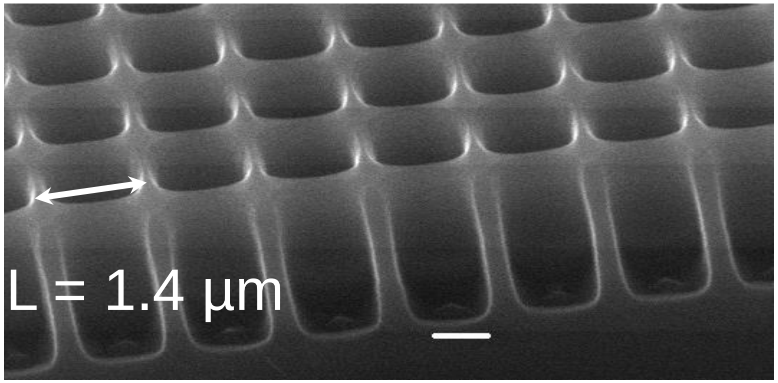
water + glycerol



$\Theta_a = 148°$

$\Theta_r = 139°$

Patterned surface



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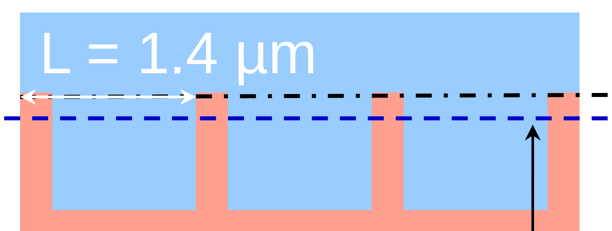
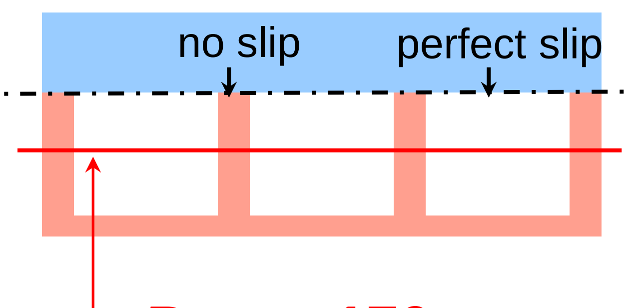


$\boldsymbol{B_{num}}$ **= 55 nm**

Calculation of B.C.
model surface
a = 0.65 µm

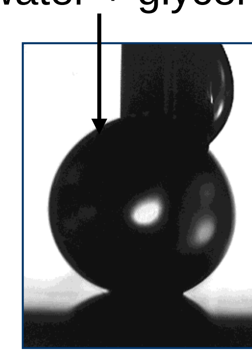
effective no-slip plane

OTS-coated silicon
superhydrophobic



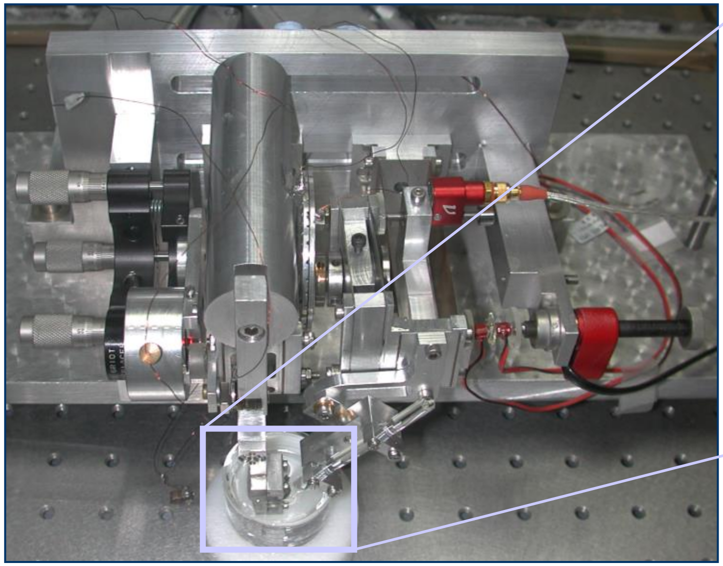
$\boldsymbol{B_{num}}$ **= 170 nm**

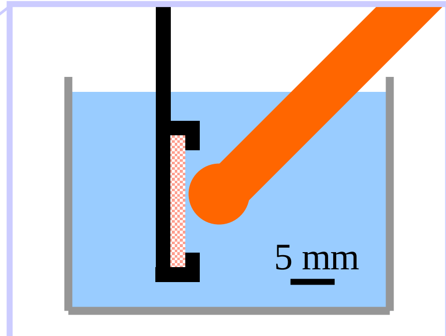
water + glycerol

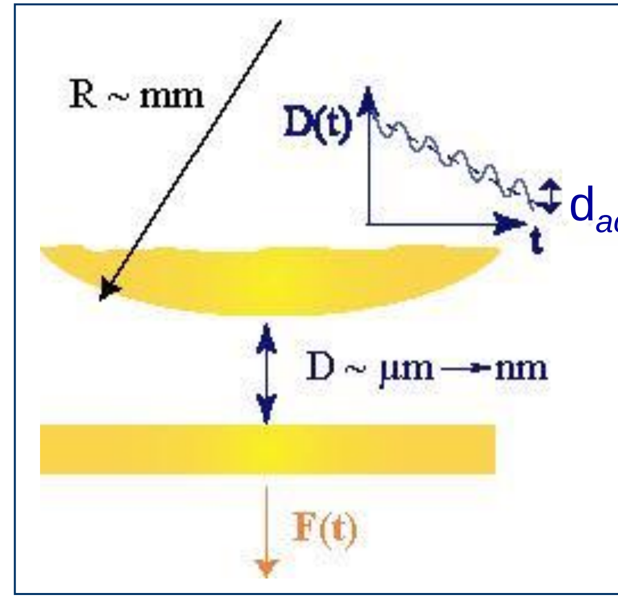


Θ_a = 148°
Θ_r = 139°

Nanorheology experiments in dSFA







- Dynamic force response to a small sinusoidal displacement

$$\boxed{G_\omega(D) = \frac{F_{ac}}{d_{ac}} = G'_\omega(D) + iG''_\omega(D)}$$

$d_{ac} \sim 1$ nm

$10\text{ Hz} < \omega/2\pi < 100\text{ Hz}$

$dD/dt \sim 5$ Å/s

stiffness

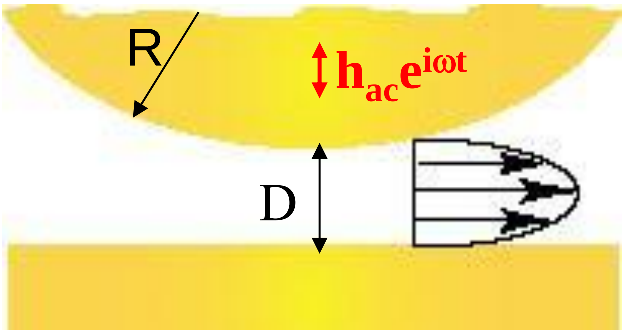
viscous damping

newtonian and incompressible liquid

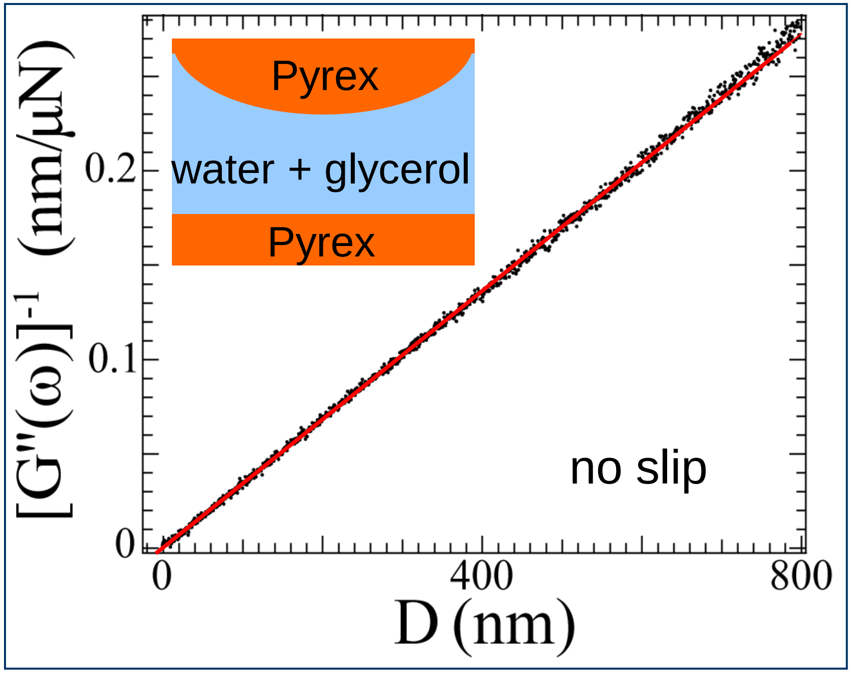
➡ **surface elasticity**

➡ **slip length**

No slip h.b.c.



- Hypothesis :
  - Newtonian fluid, viscosity η
  - Perfectly rigid surfaces
  - Lubrication approximation
  - No-slip boundary condition

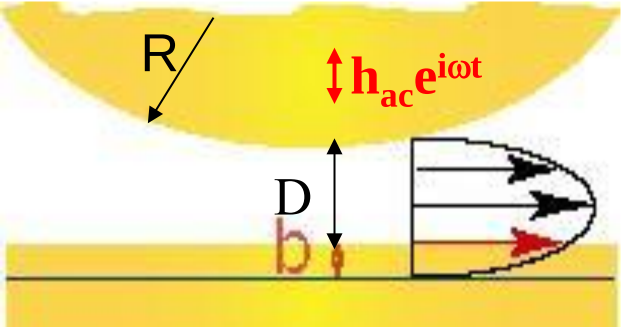


➡ No stiffness: $G'(\omega) = 0$

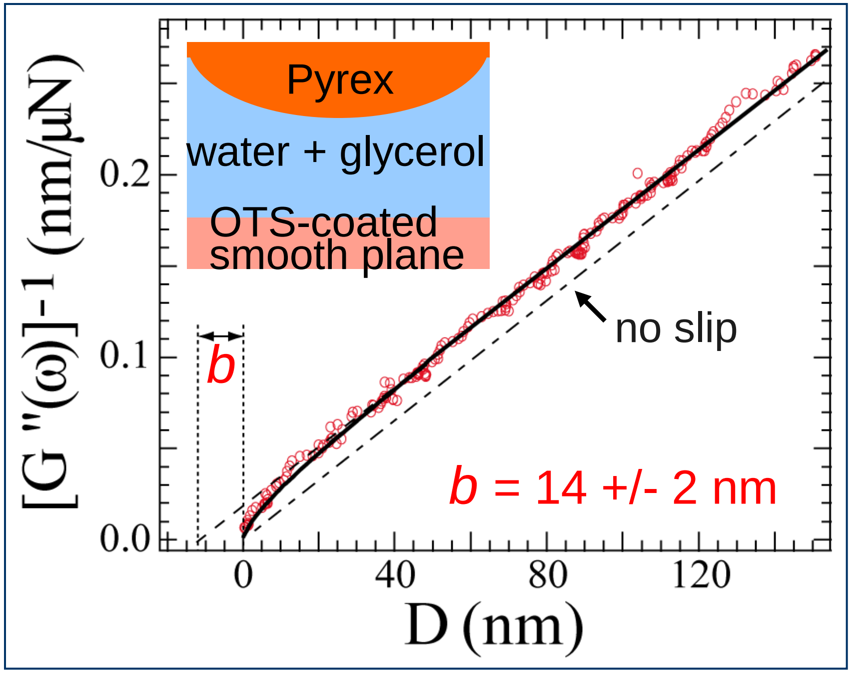
➡ The viscous damping is given by the Reynolds force

$$G''(\omega)^{-1} = \frac{D}{6\pi\eta\omega R^2}$$

Partial slip on the plane



- Hypothesis :
  - **Newtonian fluid, viscosity** η
  - **Perfectly rigid surfaces**
  - **Lubrication approximation**
  - **Partial slip on the plane, *b***



No stiffness: $G'(\omega) = 0$

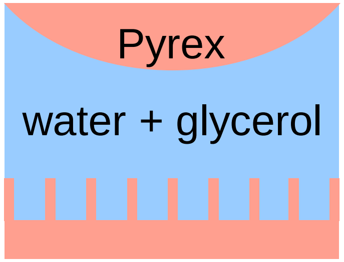
Modified viscous damping

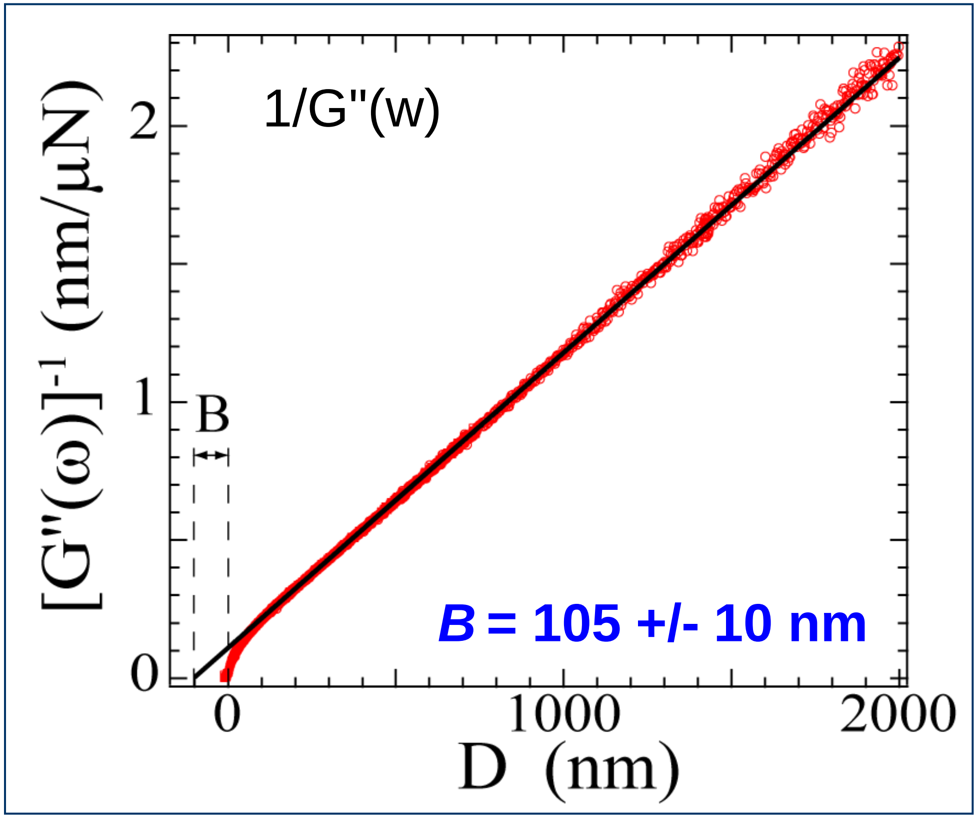
O. Vinogradova, Langmuir (1995)

D >> *B* : $$\boxed{G''(\omega)^{-1} = \frac{D+b}{6\pi\eta\omega R^2}}$$

D → 0 : $$\boxed{G''(\omega)^{-1} \rightarrow 0}$$

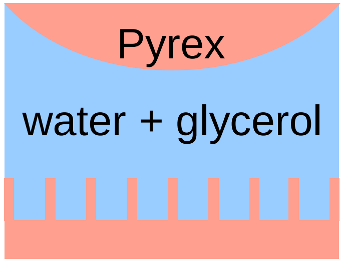
Viscous damping : Wenzel regime

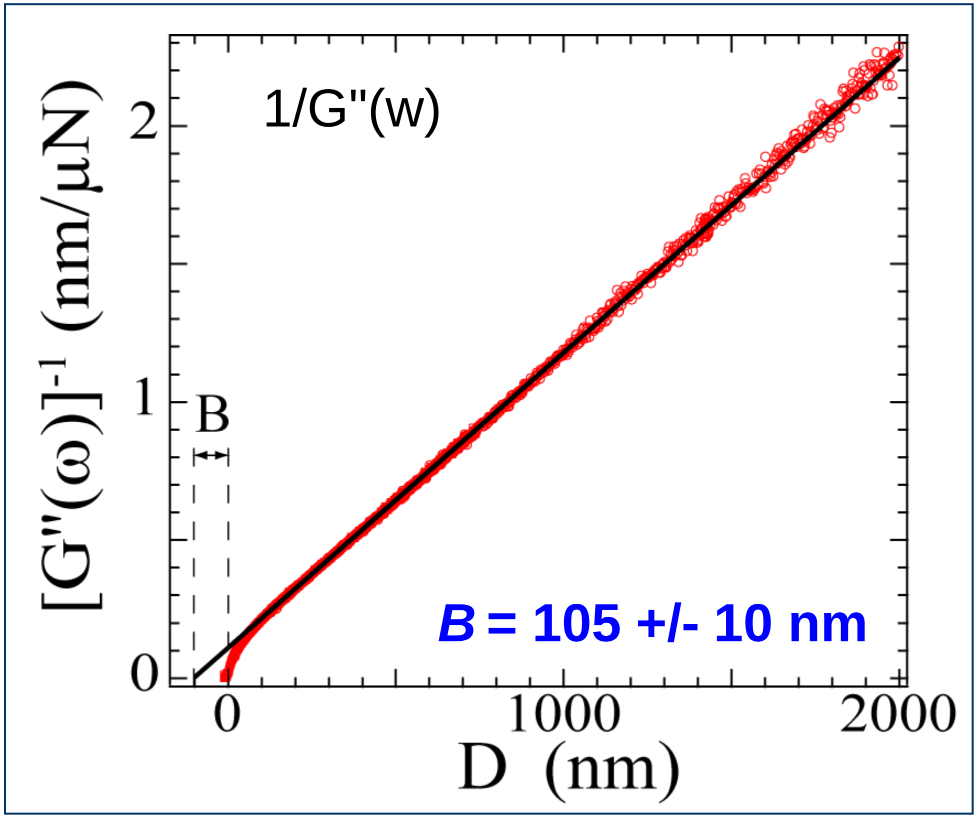




B_{num} = 55 nm

Viscous damping : Wenzel regime





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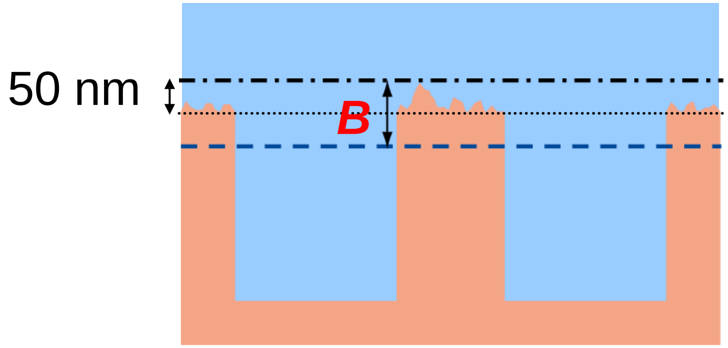
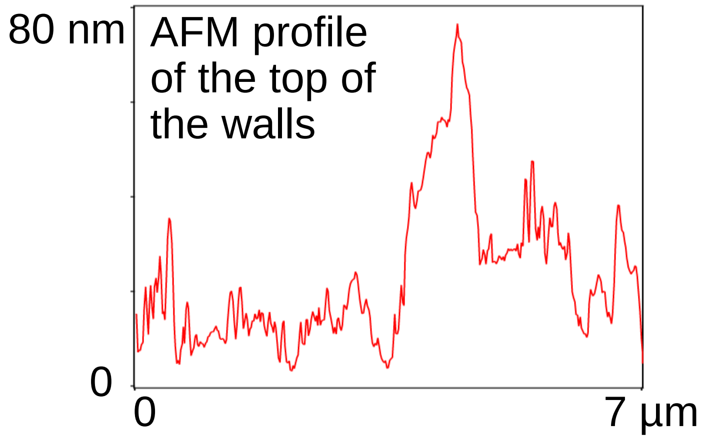
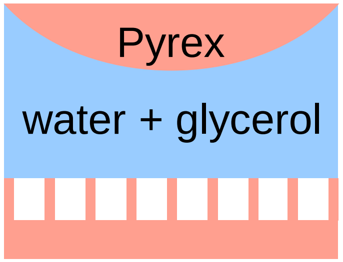
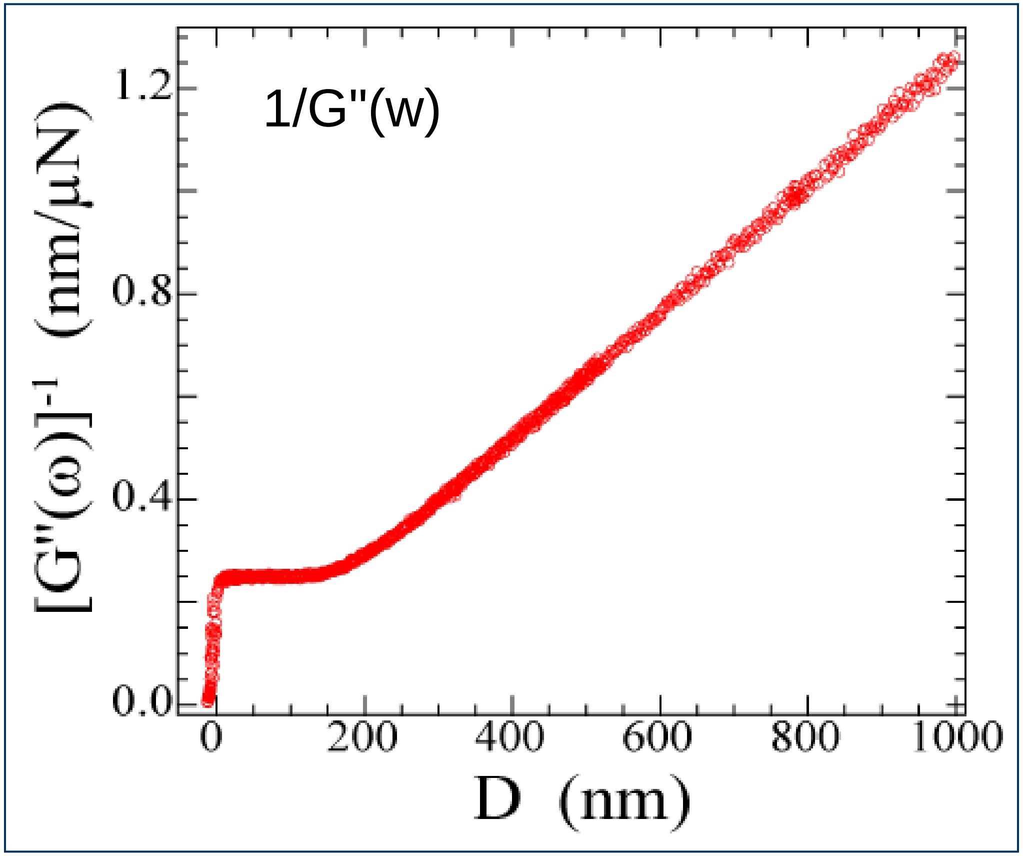




Viscous damping : Cassie regime

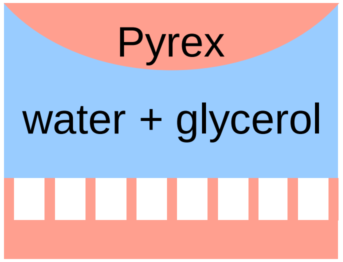


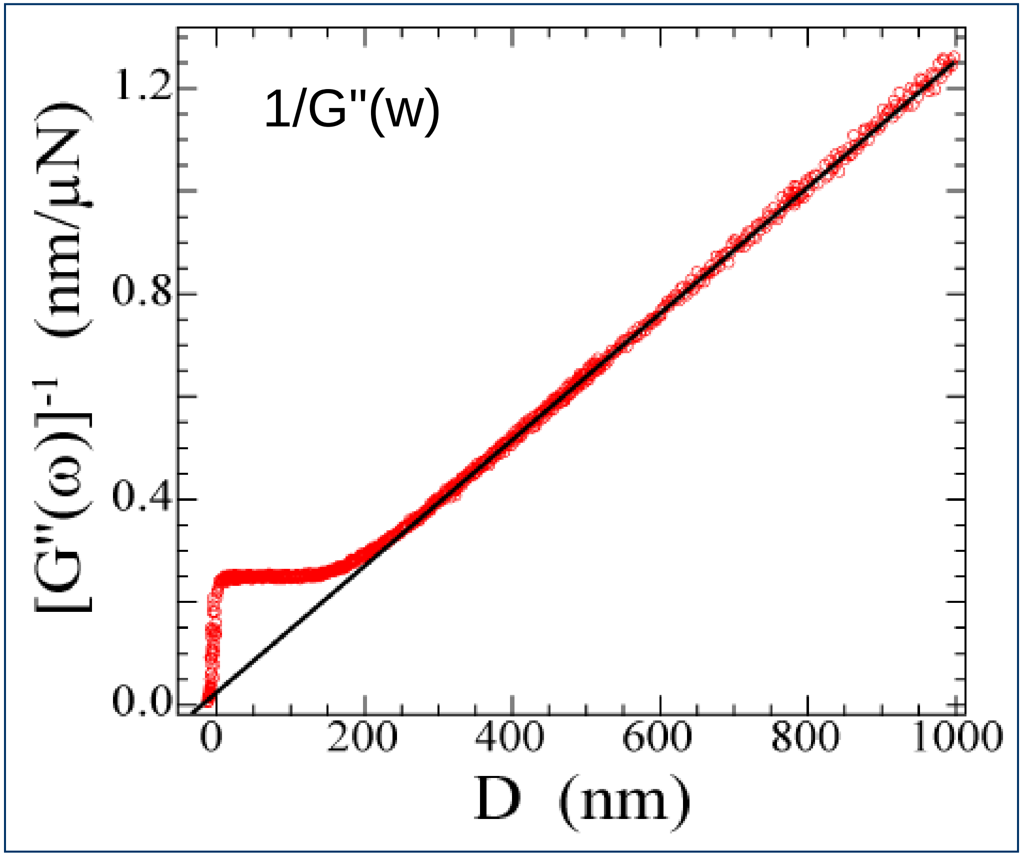


B_{num} = 170 nm

↳ **Saturation**

Viscous damping : Cassie regime



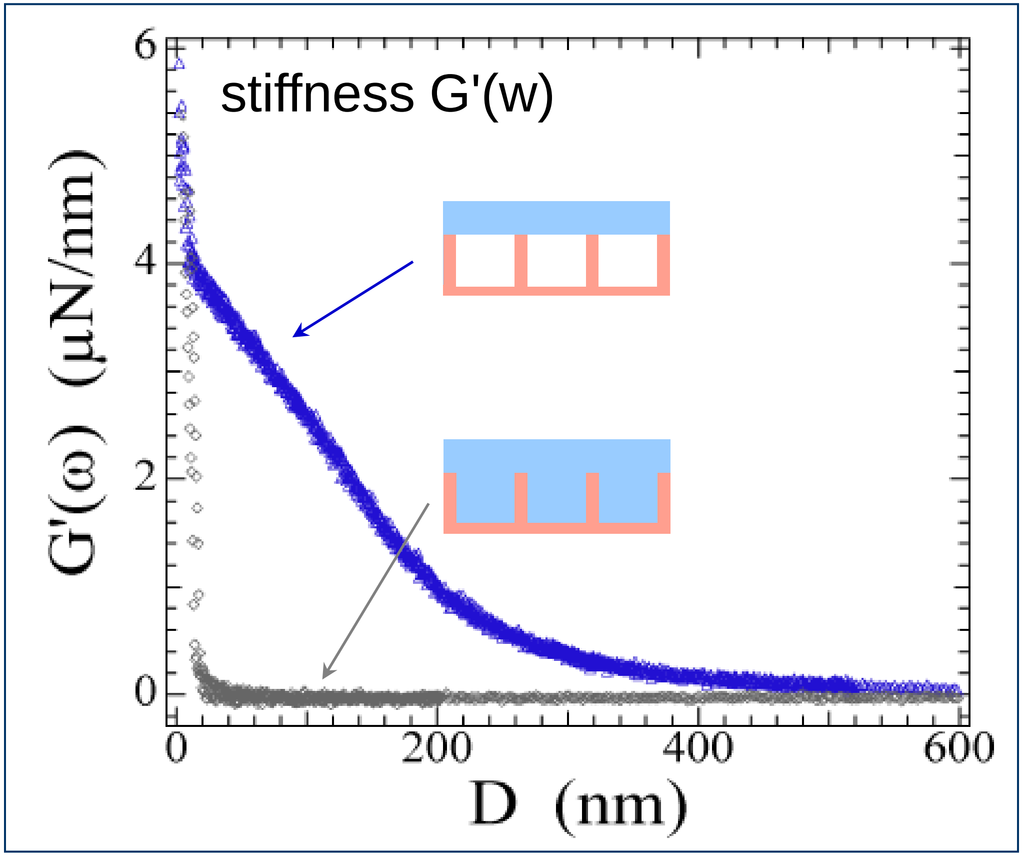


***B_{num}* = 170 nm**

- **Saturation**
- **Asymptotic behaviour :** ***B* = 20 +/- 10 nm**

Effective slip smaller than in the Wenzel regime !!!

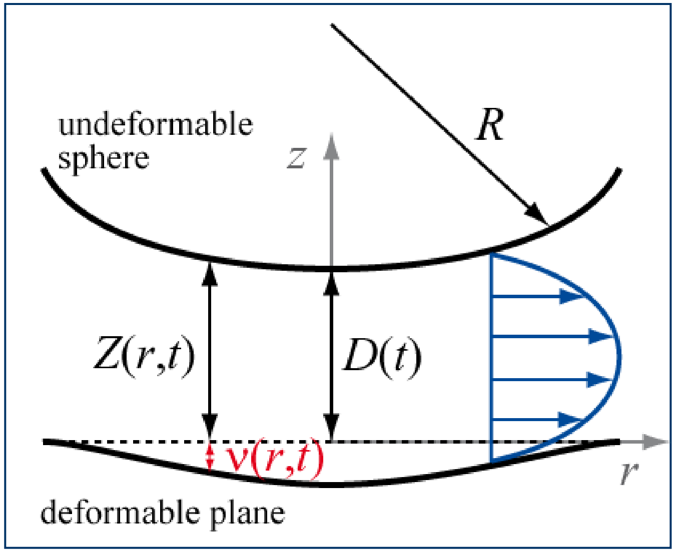
Elasticity



Non-zero elastic response on superhydrophobic surface

↳ **dynamic signature of the entrapped bubbles**

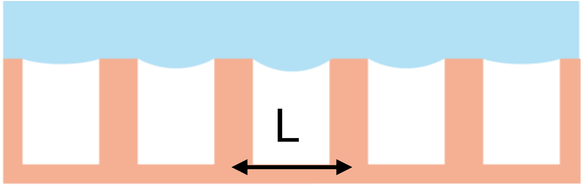
Elastohydrodynamic model

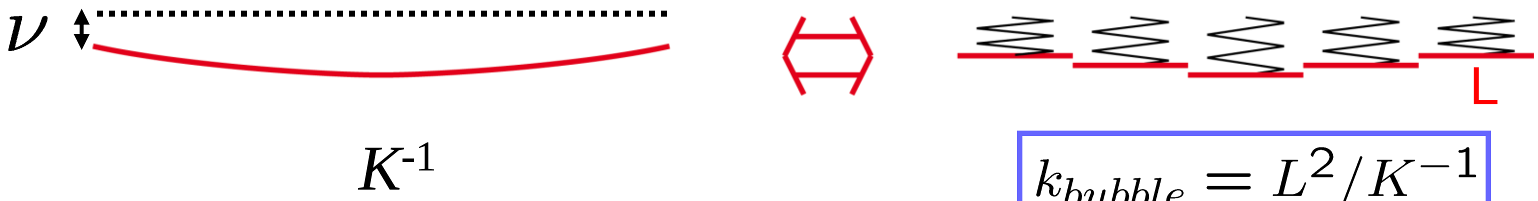


- **Newtonian and incompressible fluid,** η
- **Rigid sphere with no slip h.b.c.**
- **Uniform, deformable plane, *B***
- **Local surface compliance**

$$\boxed{\nu(r,t) = K^{-1} P(r,t)}$$

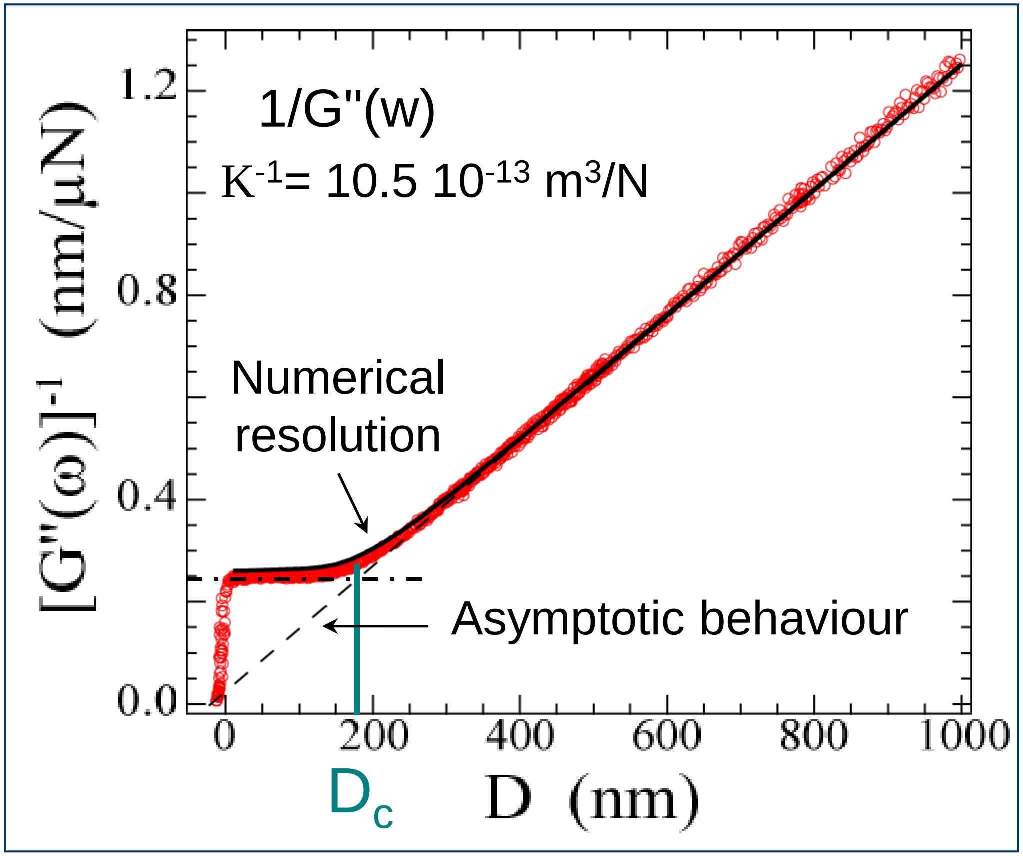
surface compliance [m³/N]





$$\boxed{k_{bubble} = L^2 / K^{-1}}$$

Results: viscous damping



- **Far field flow** **D >> *B***
  D > D_c

$$G''(\omega)^{-1} = \frac{D+B}{6\pi\eta R^2\omega}$$

not modified

- **Near field flow** **D < D_c**

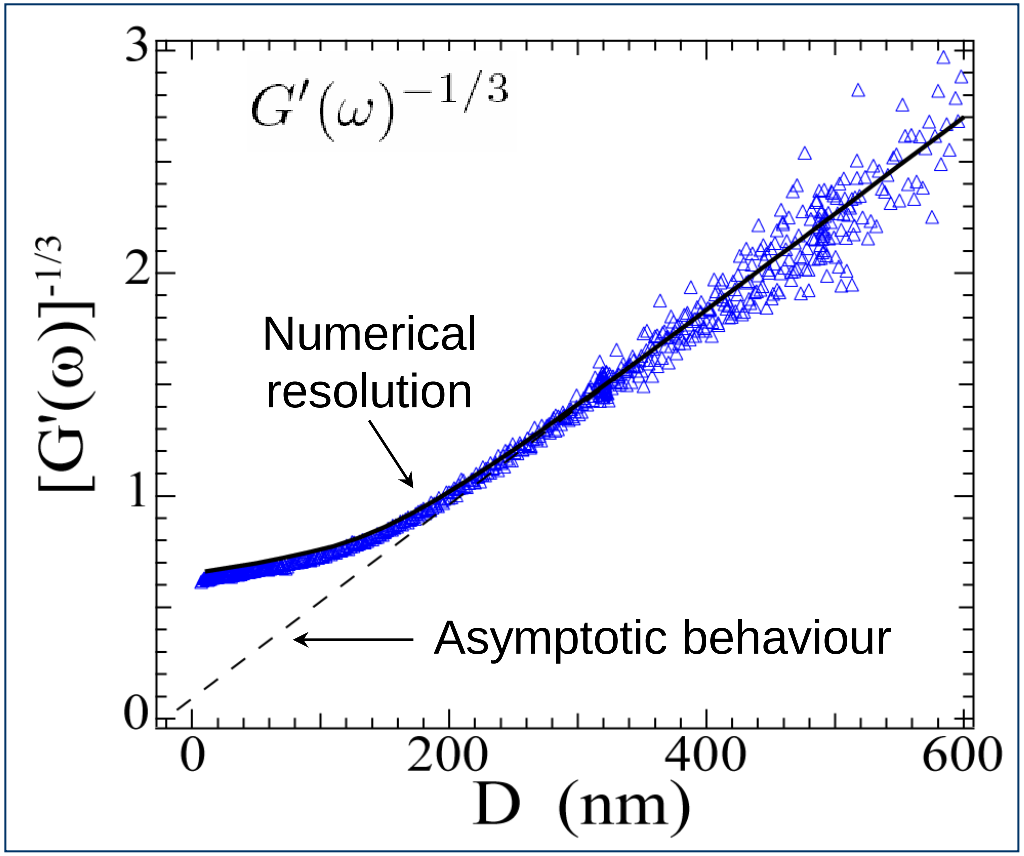
saturation

D_c : cross-over

$$\boxed{D_c \sim \sqrt{\eta R \omega K^{-1}}}$$

$$\boxed{G''(\omega)^{-1}\Big|_{plateau} \sim \sqrt{\frac{K^{-1}}{\eta R^3 \omega}}}$$

Results: stiffness



- **Far field flow D >> *B***
  D > D_c

scaling law

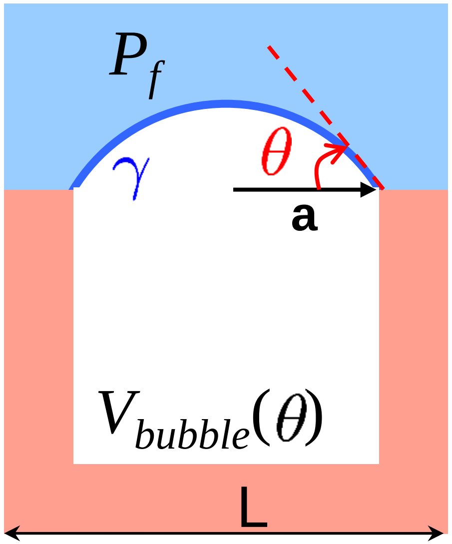
$$[G'(\omega)]^{-\frac{1}{3}} = \frac{D+B}{(6\pi\eta^2\omega^2R^3K^{-1})^{\frac{1}{3}}}$$

Non-contact measurement of surface compliance K^{-1}

K^{-1}= (10.5 +/- 1.0) 10^{-13} m^3/N

k_{bubble} = 1.9 +/- 0.2 N/m

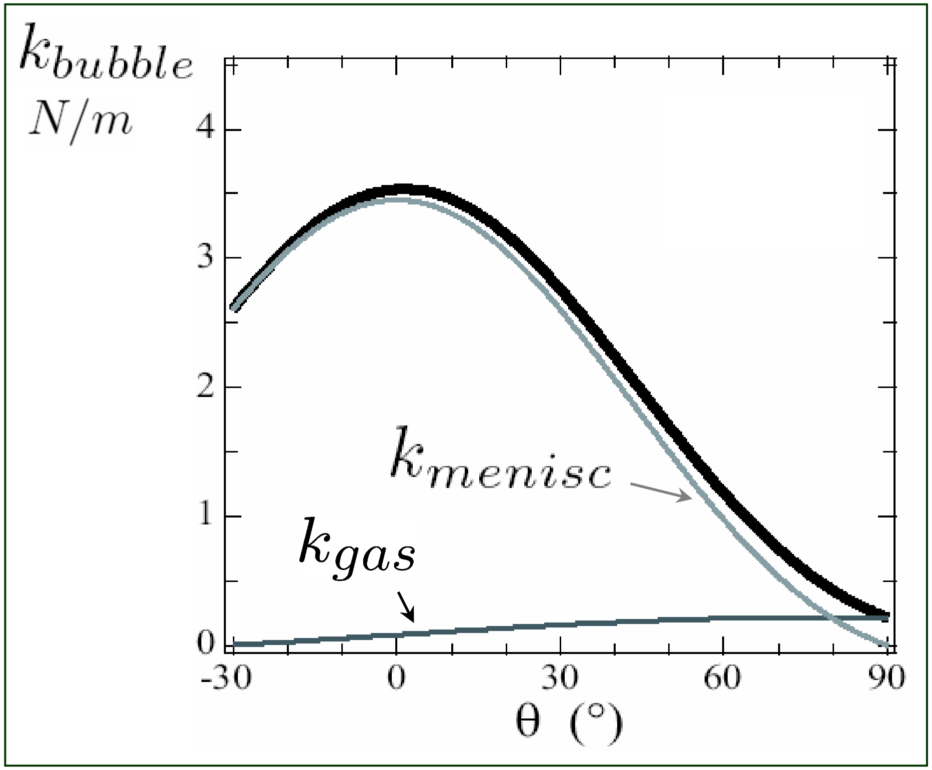
Stiffness of one trapped bubble



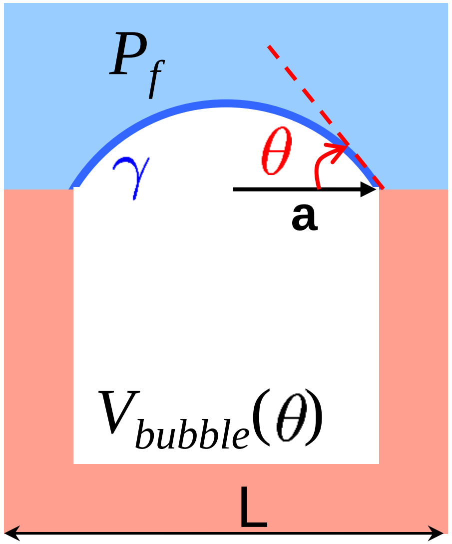
$$\boxed{k_{bubble} = k_{menisc} + k_{gas}}$$

$$k_{menisc} = \frac{\gamma L^4}{a^4}\frac{2}{\pi}\cos\theta(1+\cos\theta)$$

$$k_{gas} = L^4 \frac{P_f + \frac{2\gamma\sin\theta}{a}}{V_{bubble}(\theta)}$$



Stiffness of one trapped bubble



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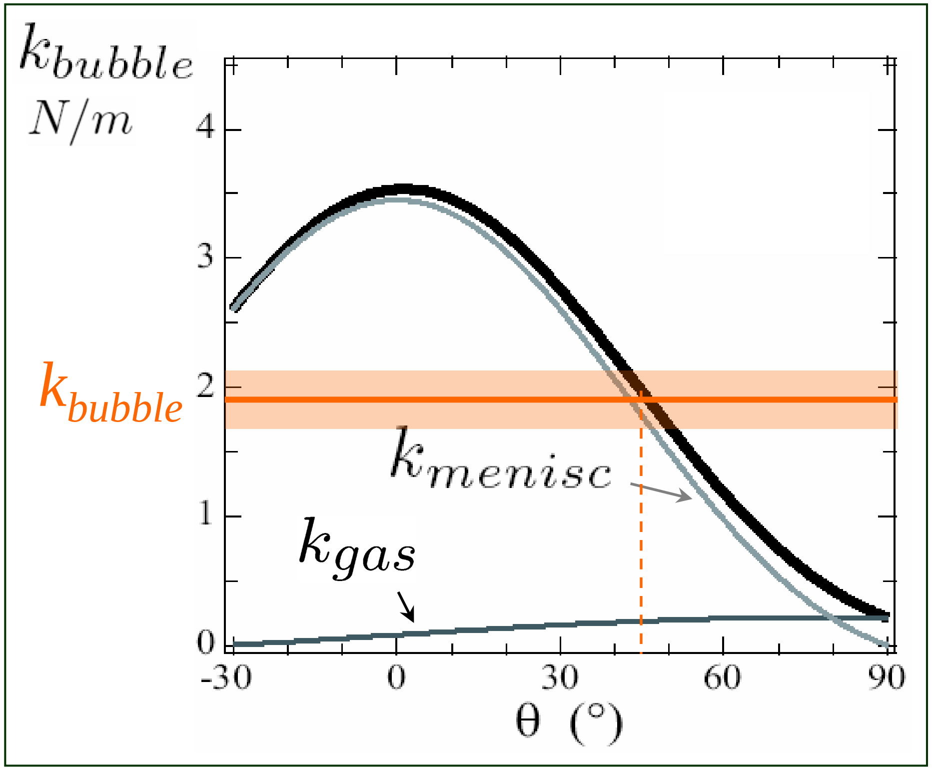


Experiment

30° < θ < 60°

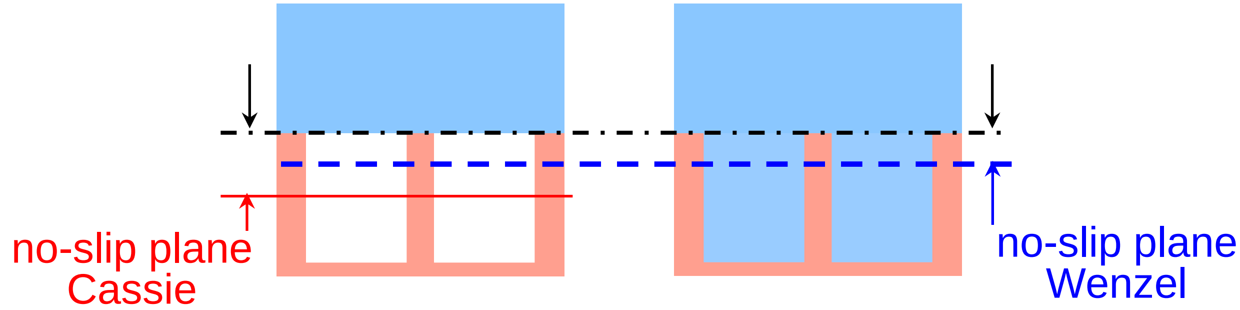
a = (0.65 +/- 0.03) µm

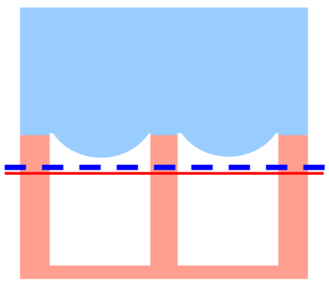
γ= (63 +/- 3) mN/m

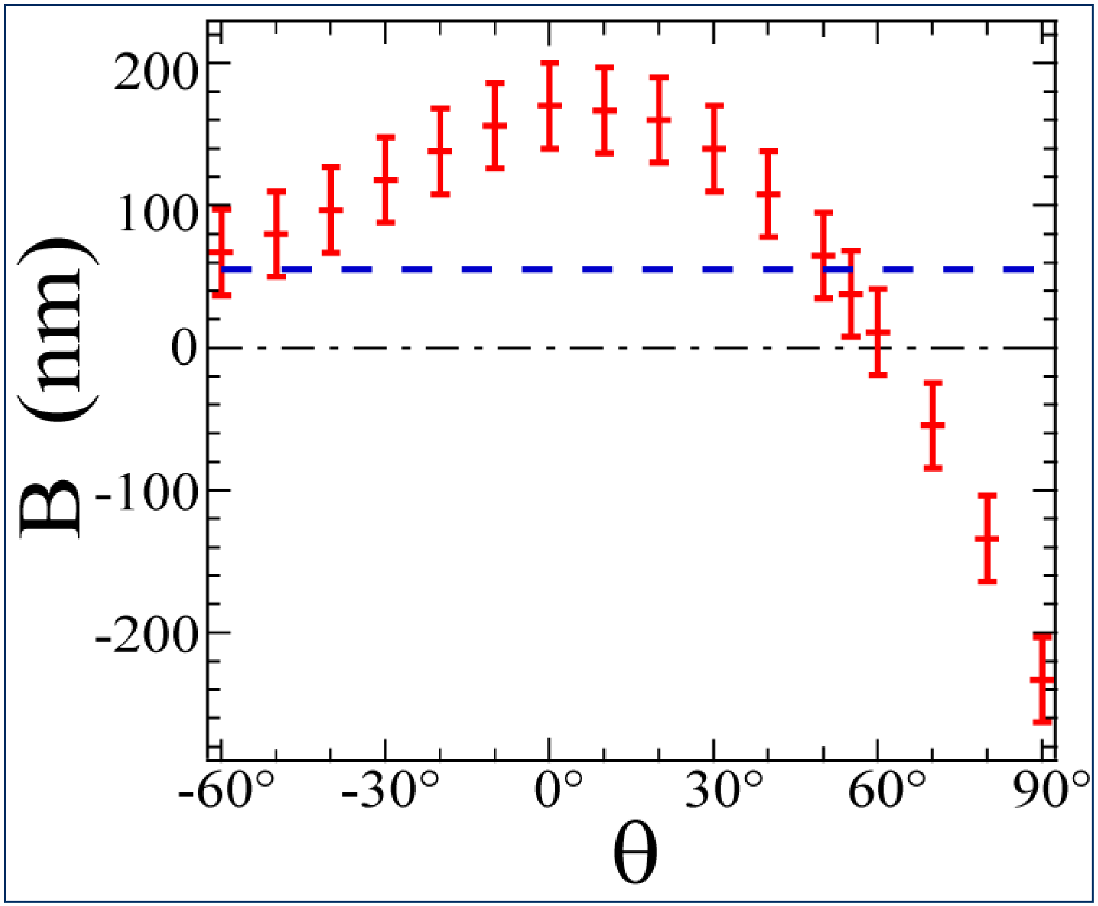
allows to probe meniscus shape of L/V interface

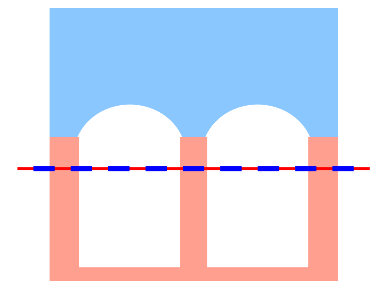
Finite elements calculation of effective slip

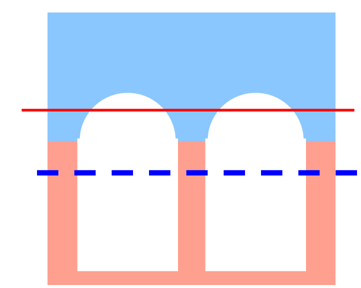
a = (0.65 +/- 0.03) µm







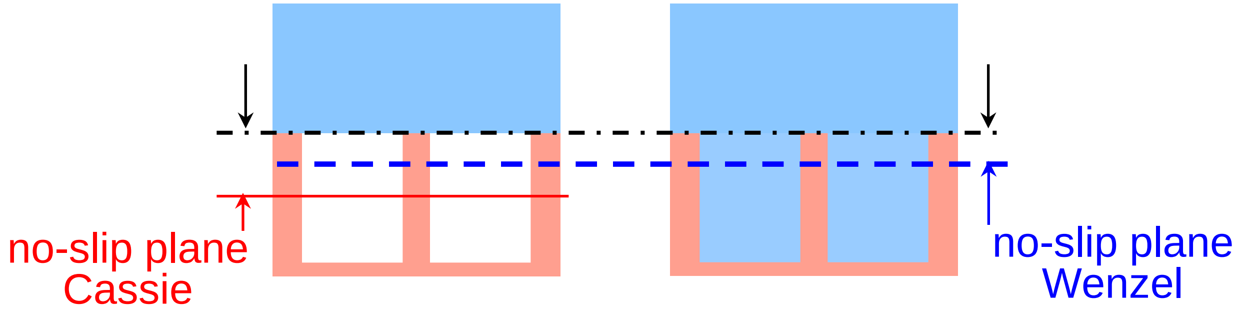


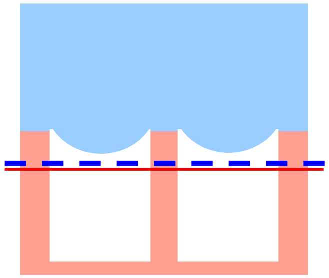


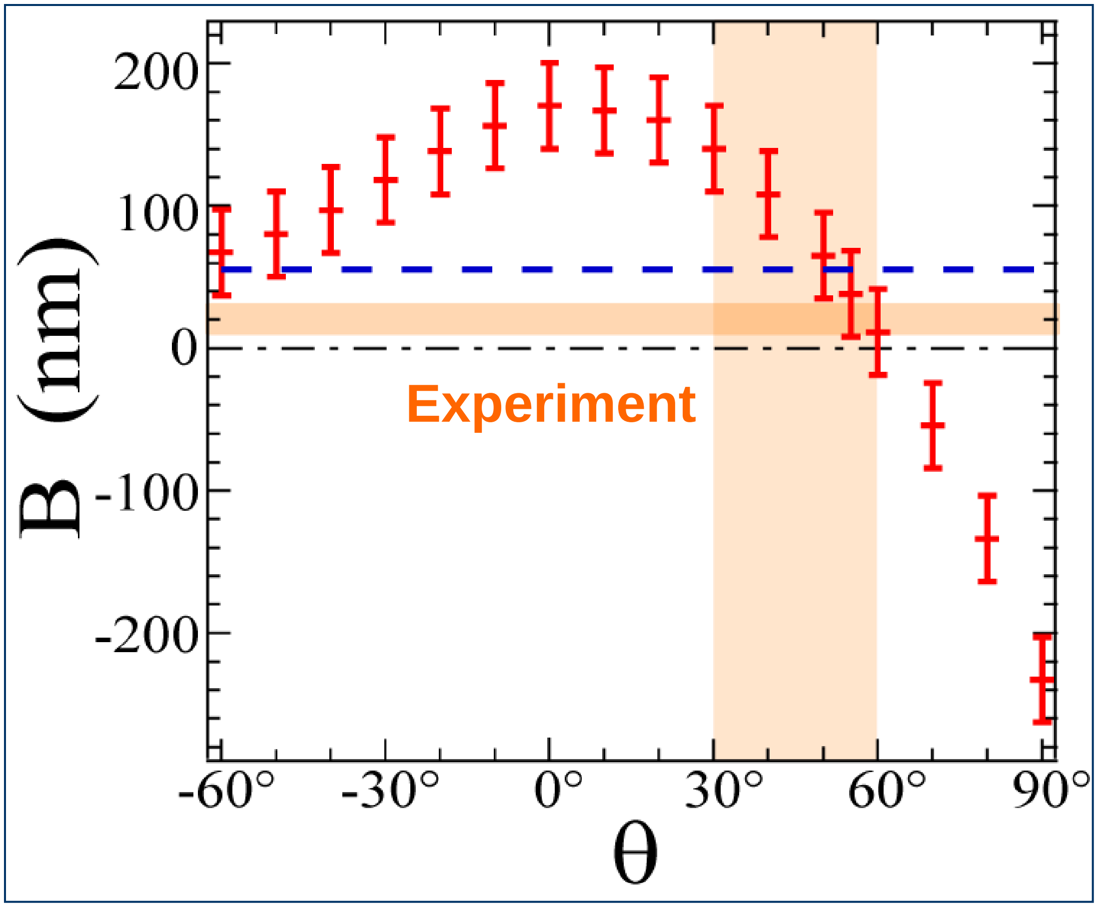
SH surfaces can promote high friction flow

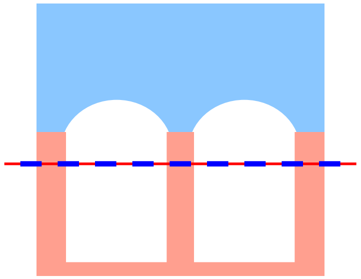
Finite elements calculation of effective slip

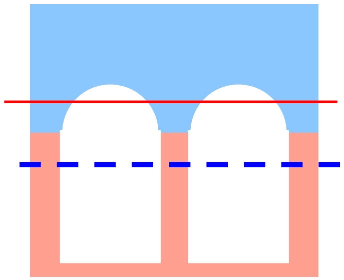
a = (0.65 +/- 0.03) µm











SH surfaces can promote high friction flow

Summary

- Gaz trapped at L/S interface does not always favor slippage. It can also promote high friction.

  - **meniscus shape is important for b.c.**

  - **has to be (almost) flat to obtain high slippage with SH surfaces**

Steinberger et al, Nature Materials (2007)

Steinberger et al, PRL (2008)

Control of pressure of gas phase

- tunable meniscus shape

tunable effective slippage

Conclusion and outlook

- To benefit from slippage in micrometric channels

intrinsic slippage
+ interfacial effects

superhydrophobic surfaces
for high effective slippage

Electrokinetic effects in polarized hydrophobic microchannels?

Schasfoort et al., Science (1999)

Surface engineering is crucial !

- high stability of Cassie state
  L ~ 1 µm, height ~ 10 µm
- low fraction of solid surface
- **flat** liquid-gas interfaces
  Best geometry: **pillars**
- **cost ?**

Conclusion and outlook

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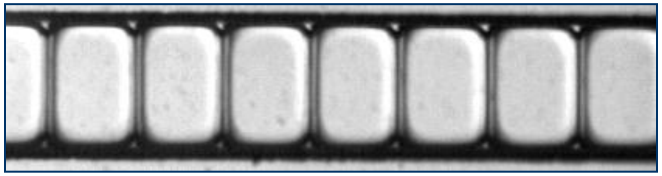
- Other solution to avoid hydrodynamic dispersion :



discrete microfluidics

foams, emulsions

Thanks !

Cecile Cottin-Bizonne

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Marie Charlotte Audry

Catherine Barentin

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