Nearly-zero contact angle hysteresis on lubricated surfaces

Dan Daniel, IMRE, A*STAR

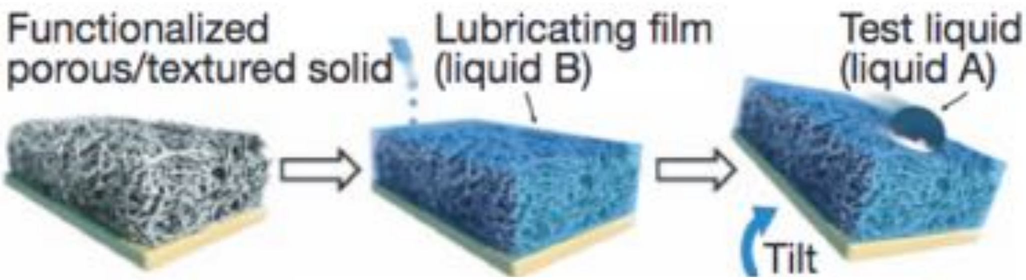
2011

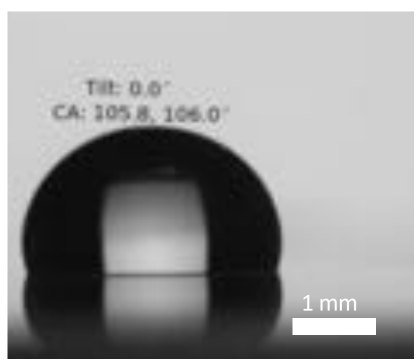
LETTER

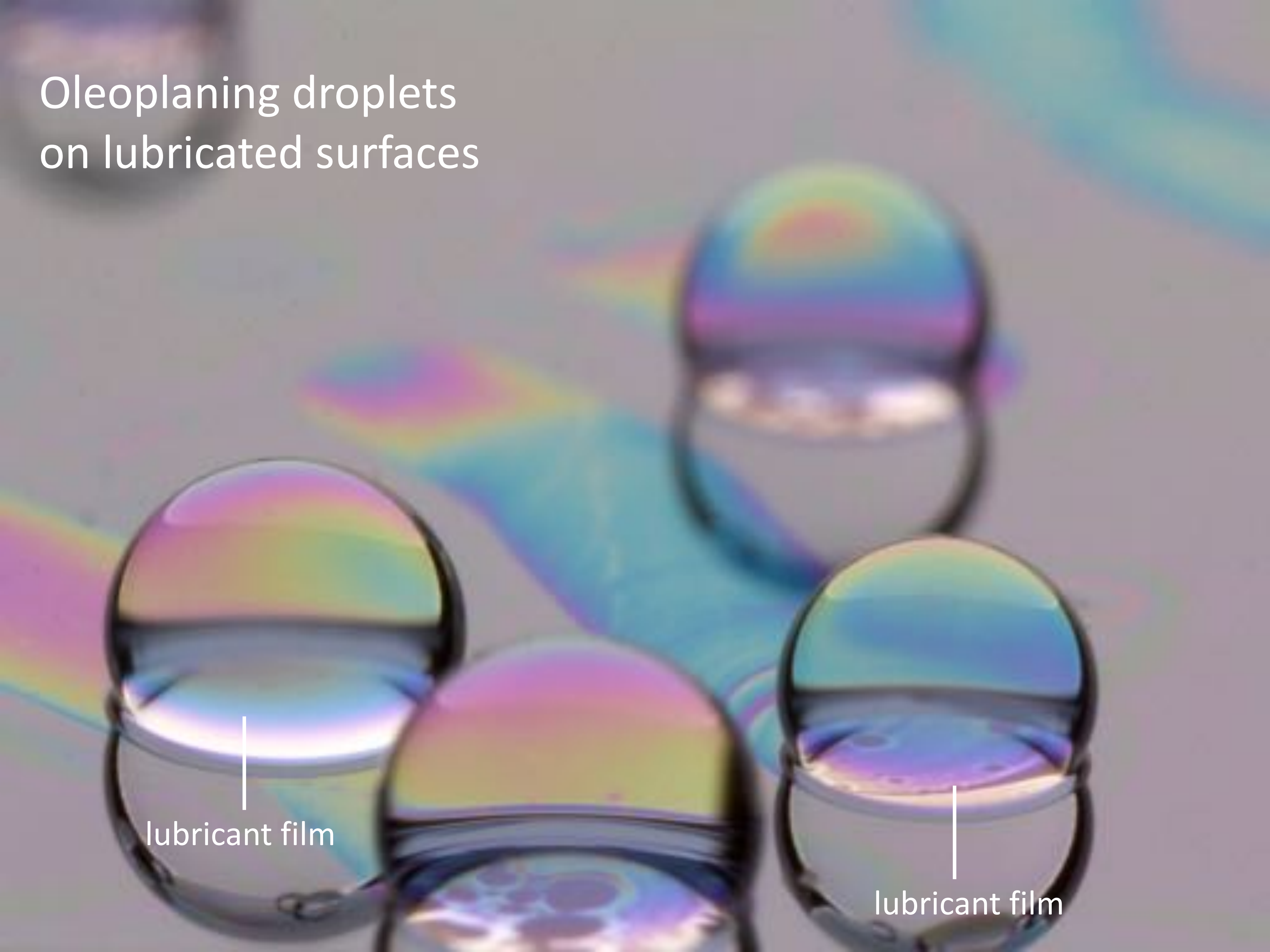
doi:10.1038/nature10447

Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity

Tak-Sing Wong[1], Sung Hoon Kang[1], Sindy K. Y. Tang[1], Elizabeth J. Smythe[2], Benjamin D. Hatton[1], Alison Grinthal[1] & Joanna Aizenberg[1]






Oleoplaning droplets
on lubricated surfaces
lubricant film
lubricant film

2011

LETTER

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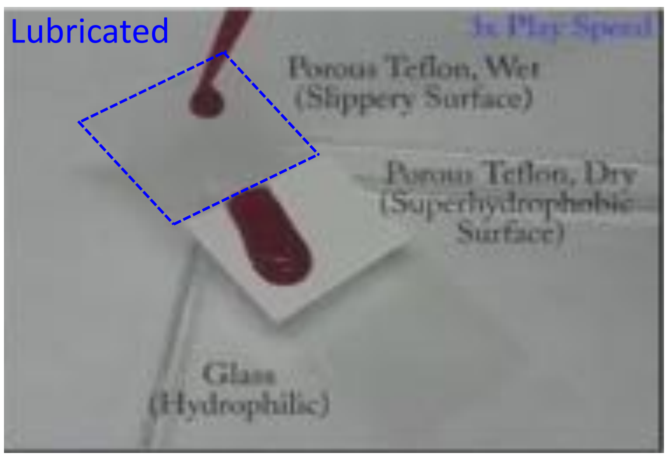
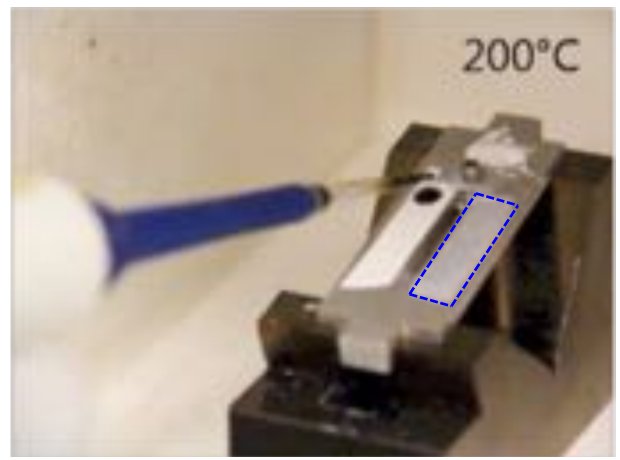


repels blood …



and crude oil

2005

INSTITUTE OF PHYSICS PUBLISHING REPORTS ON PROGRESS IN PHYSICS

Rep. Prog. Phys. **68** (2005) 2495–2532 doi:10.1088/0034-4885/68/11/R01

Non-sticking drops

David Quéré

"Slippery composite surface" that is "hemi-solid, hemi-liquid" with "non-measurable" contact angle-hysteresis.

2005

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Non-sticking drops

David Quéré

"Slippery composite surface" that is "hemi-solid, hemi-liquid" with "non-measurable" contact angle-hysteresis.

Lubricated surfaces, a rose by any other name …

SLIPS, LIS, Slippery pre-suffused surfaces, LubiSS

Outline

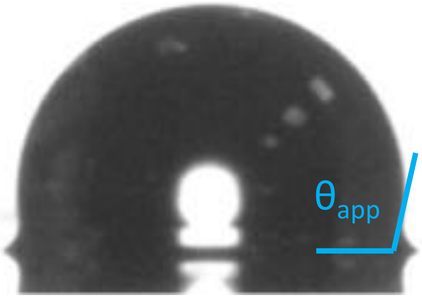
<u>Static</u>: droplet shape and geometry

<u>Dynamic</u>: oleoplaning droplet with nearly-zero hysteresis

Comparison with lotus-effect surface

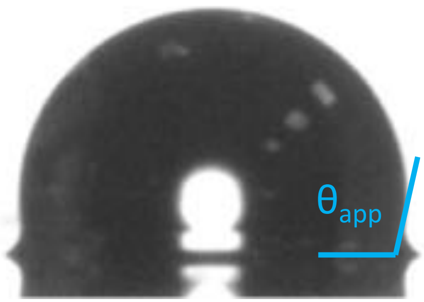
Thoughts/Open questions

Static droplet: contact angle



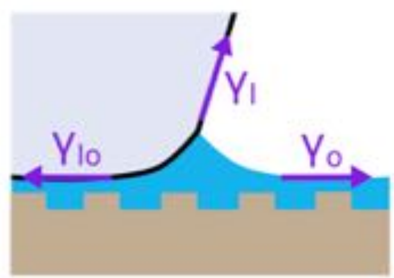
θ_{app} ~ 100^o
for water

Static droplet: contact angle



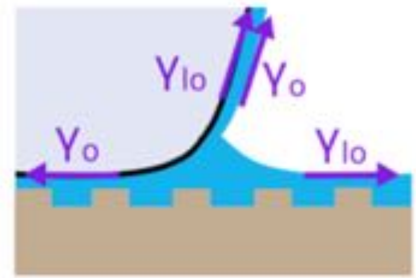
θ_{app} ~ 100^o
for water

<u>no cloaking</u>



$\gamma_l < \gamma_{lo} + \gamma_o$

<u>with cloaking</u>



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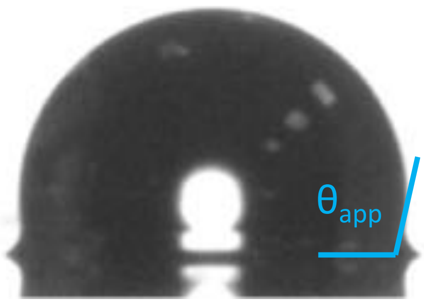
Static droplet: contact angle



θ_{app} ~ 100^o
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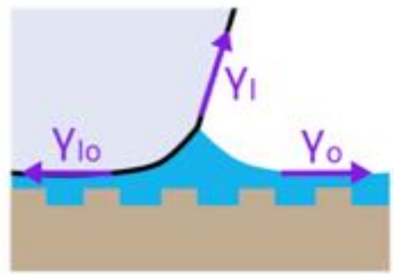
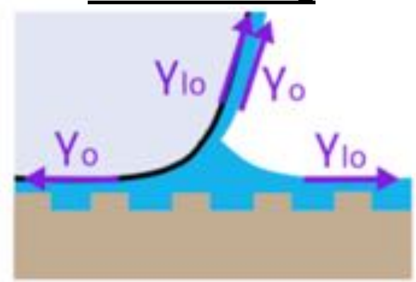


$\gamma_l < \gamma_{lo} + \gamma_o$

<u>with cloaking</u>



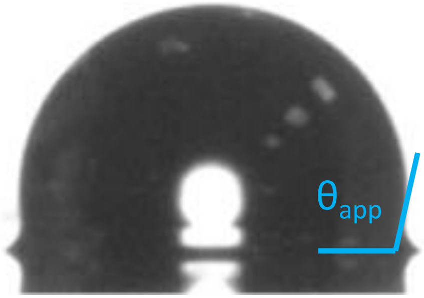
$\gamma_l > \gamma_{lo} + \gamma_o$

Modified Young's Equation

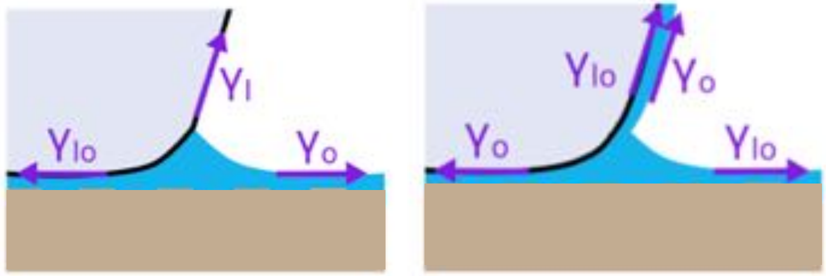
$\cos\theta_{app} = (\gamma_o - \gamma_{lo})/\ \gamma_{eff}$

$\gamma_{eff} = \gamma_l$ or $\gamma_{lo} + \gamma_o$
no/with cloaking

Static droplet: contact angle



θ_{app} ~ 100°
for water



$\gamma_l < \gamma_{lo} + \gamma_o$

$\gamma_l > \gamma_{lo} + \gamma_o$

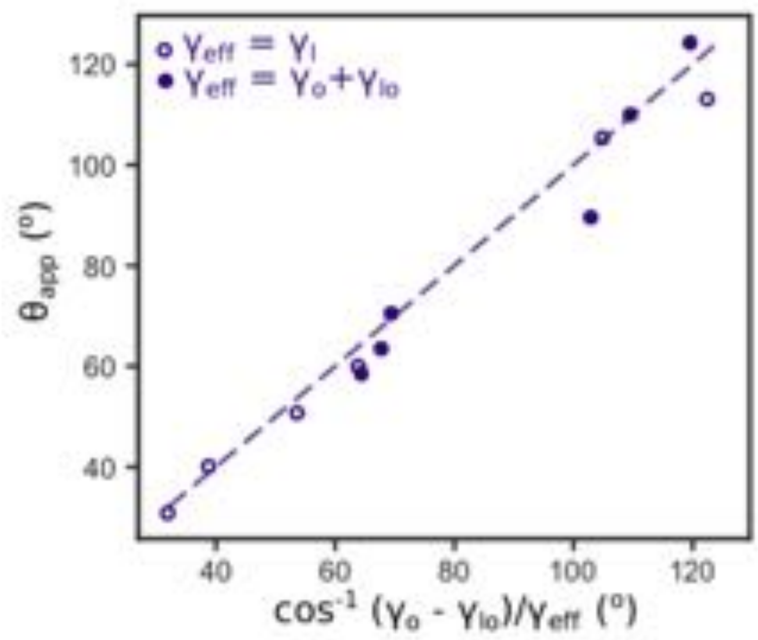
Modified Young's Equation

$\cos \theta_{app} = (\gamma_o - \gamma_{lo}) / \gamma_{eff}$

$\gamma_{eff} = \gamma_l$ or $\gamma_{lo} + \gamma_o$
no/with cloaking

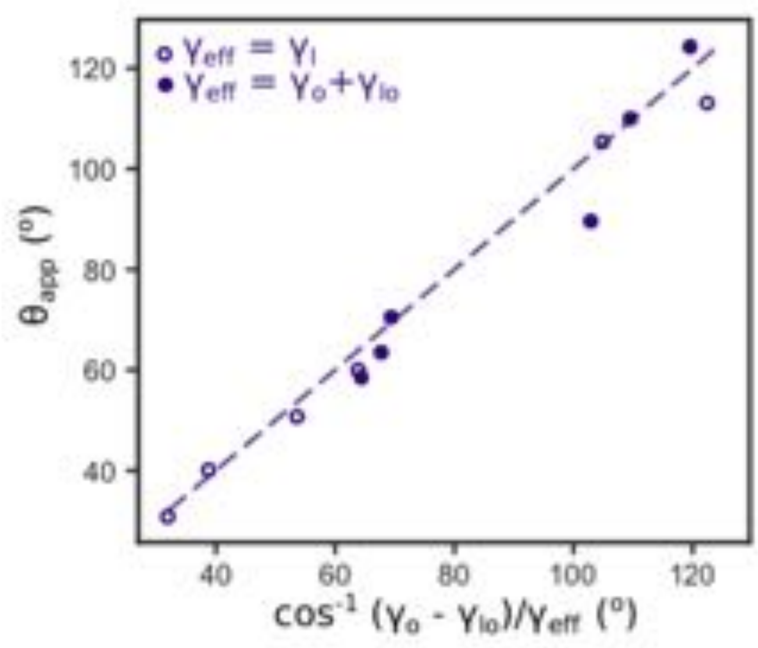
Independent of
micro-/nano-structures

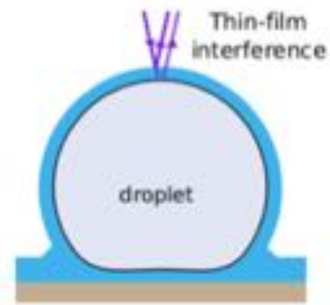
Static droplet: contact angle

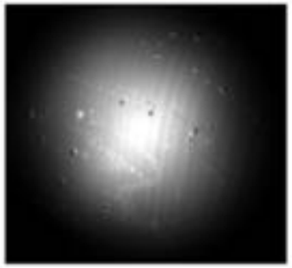


Data from
Wong *et al*, *Nature*, 2011
Schellenberger *et al*, *Soft Matter,* 2015

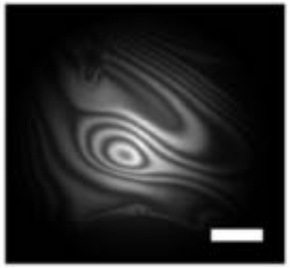
Static droplet: contact angle







no cloaking

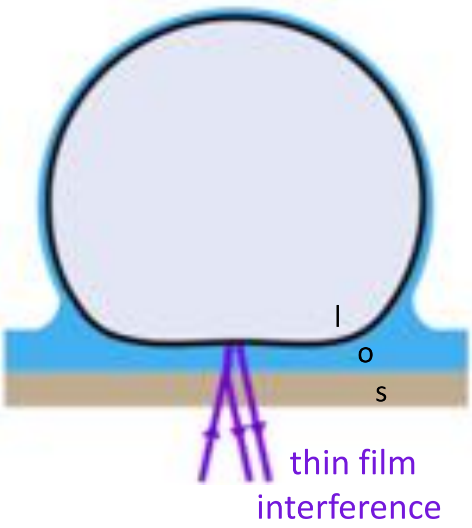


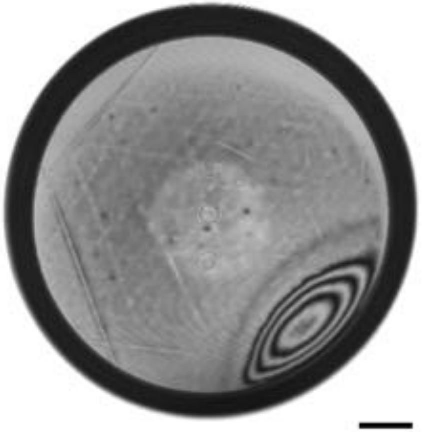
with cloaking

Data from
Wong *et al*, *Nature*, 2011
Schellenberger *et al*, *Soft Matter,* 2015

Static droplet: nm lubricant film

$\gamma_{sl} > \gamma_{so} + \gamma_{lo}$ and
repulsive $A > 0$





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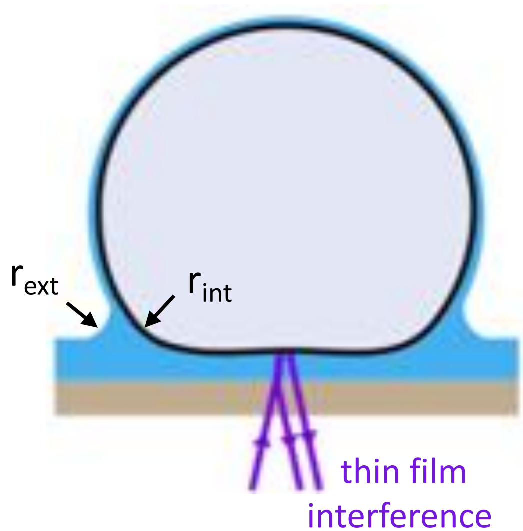
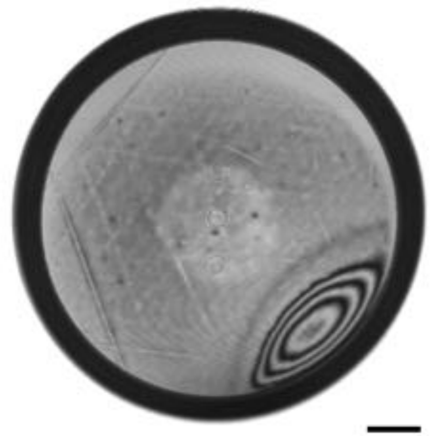


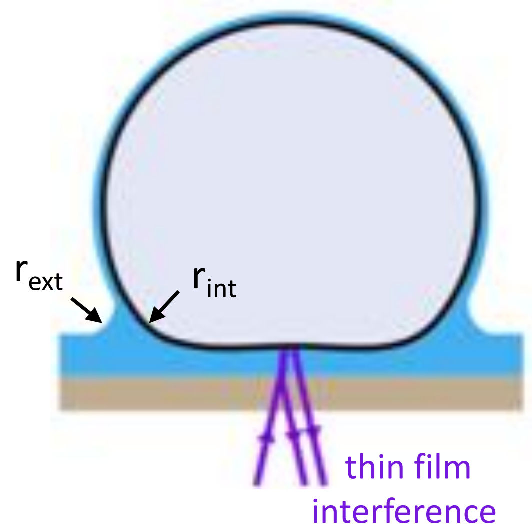


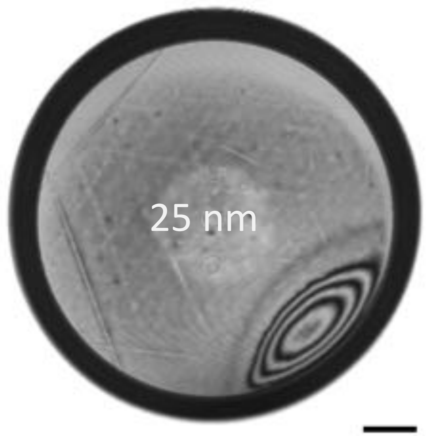
low pressure
in ridge

$$|\Delta P| \approx \gamma_o / r_{ext}$$
$$\approx \gamma_{lo} / r_{int}$$

Static droplet: nm lubricant film

$\gamma_{sl} > \gamma_{so} + \gamma_{lo}$ and
repulsive $A > 0$





low pressure in ridge

$|\Delta P| \approx \gamma_o / r_{ext}$
$\approx \gamma_{lo} / r_{int}$

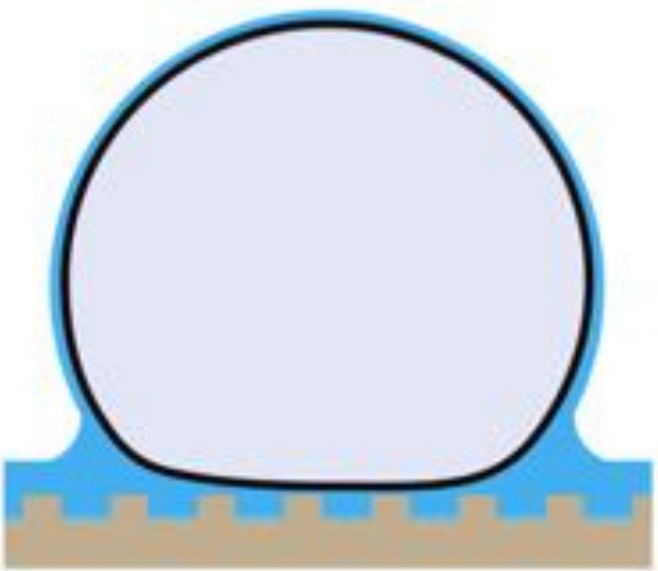
balanced by

$\Pi \approx A/6\pi h^3$

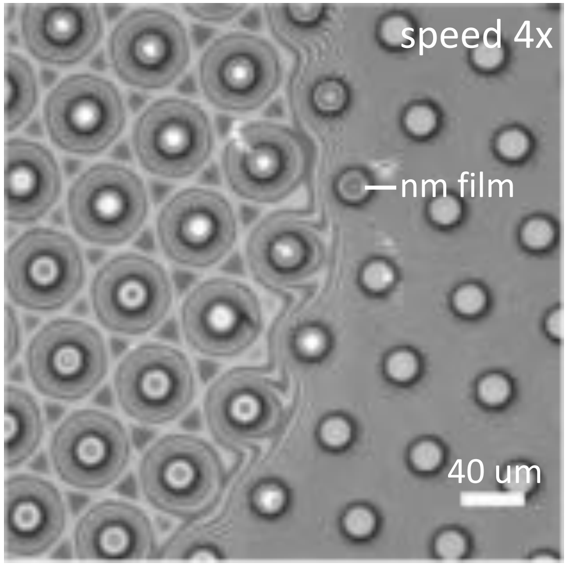
Disjoining pressure

$\mathbf{h \sim (r\,A/\,\gamma)^{1/3}}$
tens of nm

Static droplet: nm lubricant film on top of posts

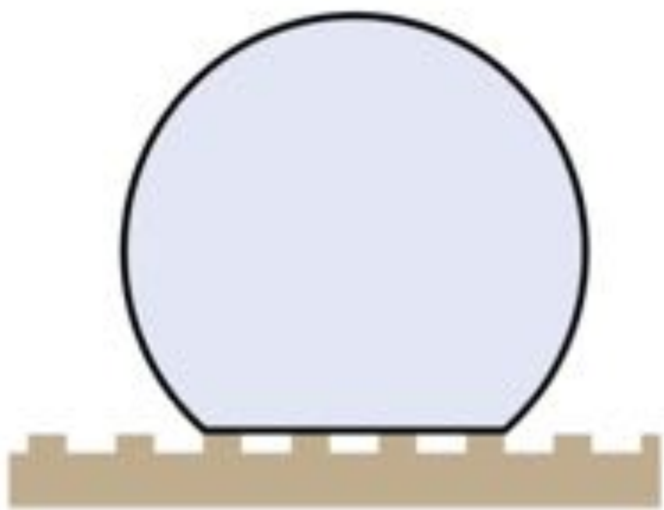


film thickness set by
post heights

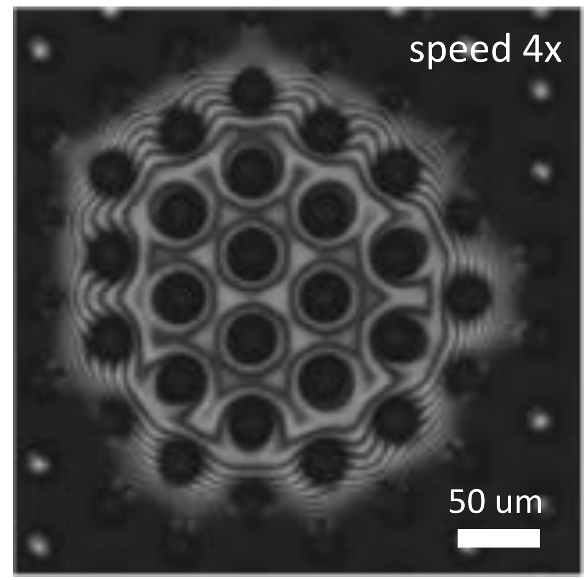


no contact line
pinning

Comparison with
lotus-effect surfaces

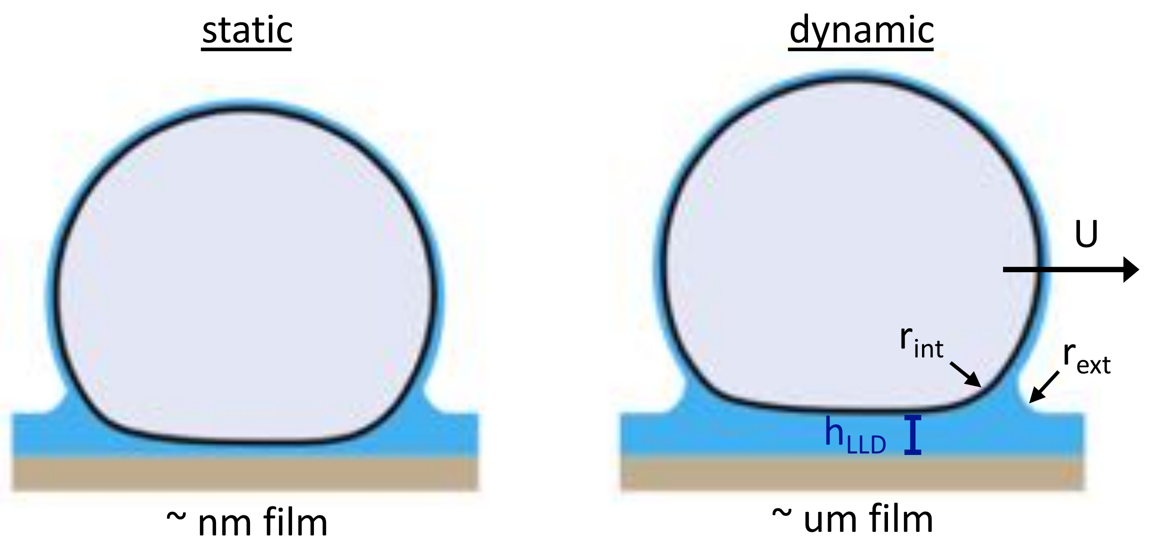


air film instead
of lubricant film



with contact line
pinning

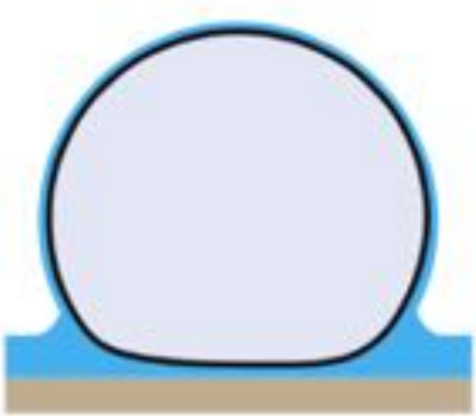
Droplet oleoplanes with Landau-Levich film



$$h_{LLD} \sim r_{int}\,(\eta U/\gamma_{lo})^{2/3}$$
$$= r_{int}\,Ca^{2/3}$$

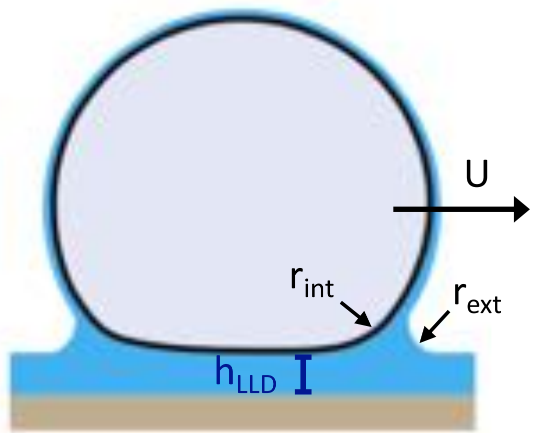
Droplet oleoplanes with Landau-Levich film

static



~ nm film

dynamic



~ um film

$$h_{LLD} \sim r_{int}\,(\eta U/\gamma_{lo})^{2/3}$$
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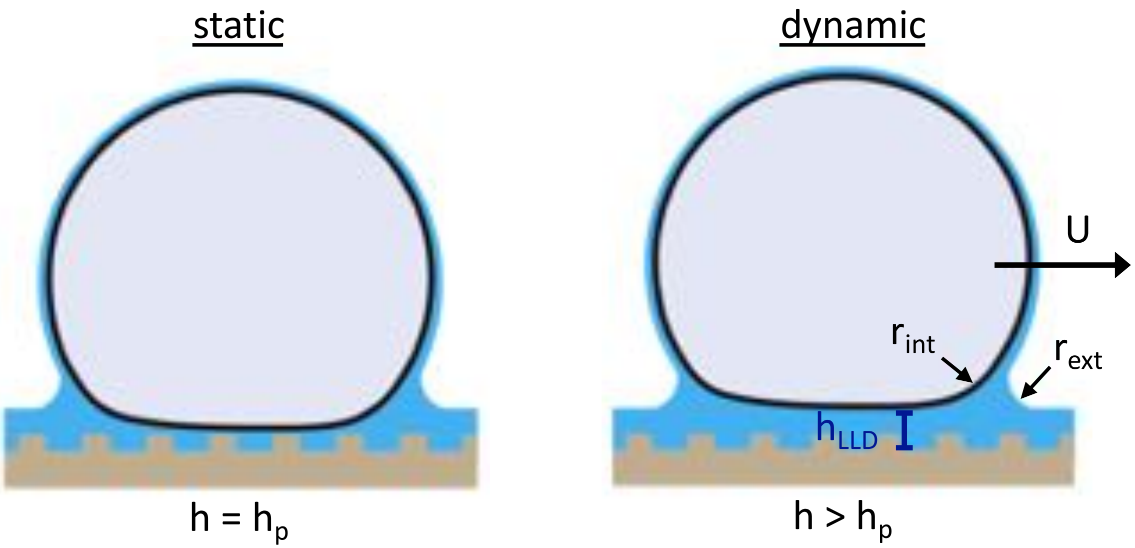
$$= (\gamma_{lo} / \gamma_o)\; r_{ext}\,Ca^{2/3}$$

Droplet oleoplanes
with Landau-Levich film



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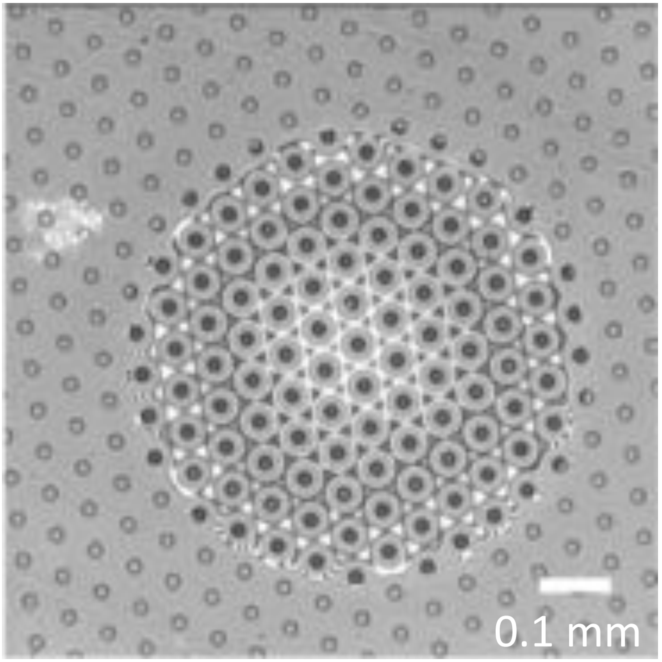
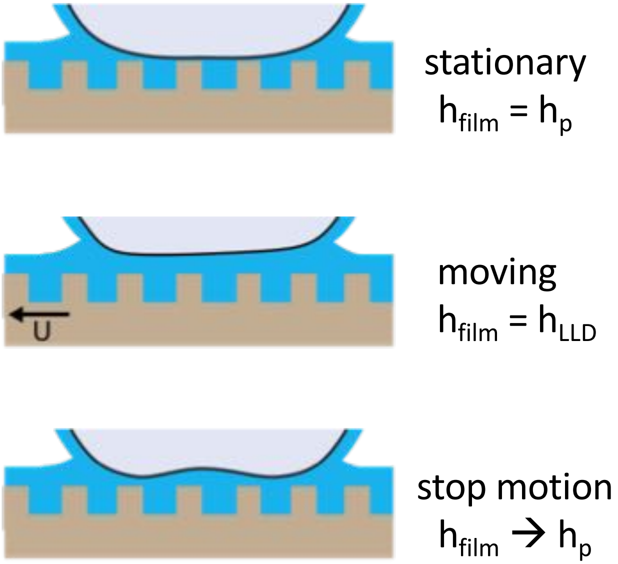
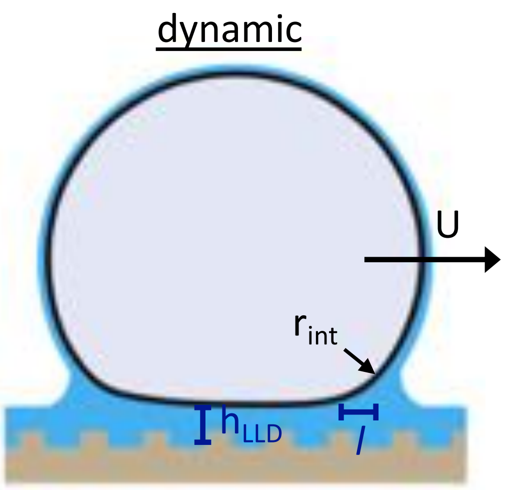
Droplet oleoplanes
with Landau-Levich film





Droplet oleoplanes with Landau-Levich film

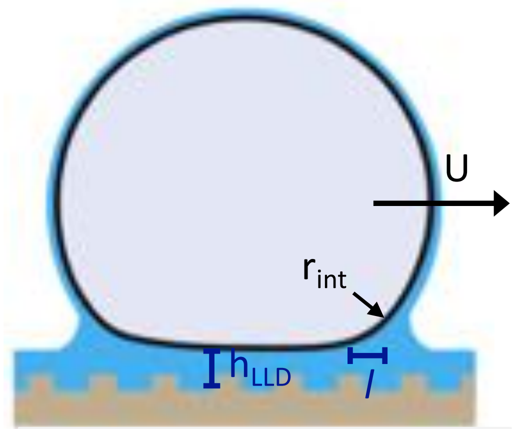


Viscous dissipation in transition region $l \sim r_{int}\,Ca^{1/3}$

$$F \sim \eta_o U/h_{LLD}\,(2a\,l) = 2a\gamma_{lo}\,Ca^{2/3}$$

Droplet oleoplanes with Landau-Levich film

<u>dynamic</u>



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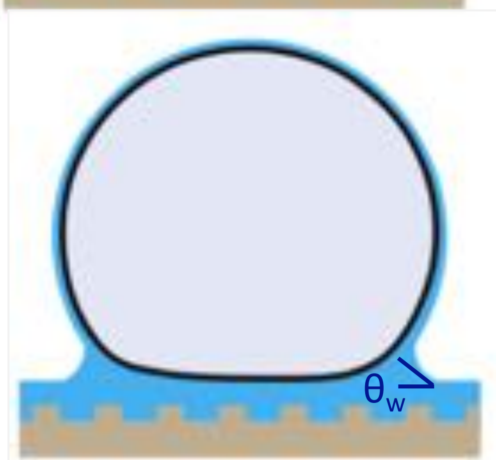


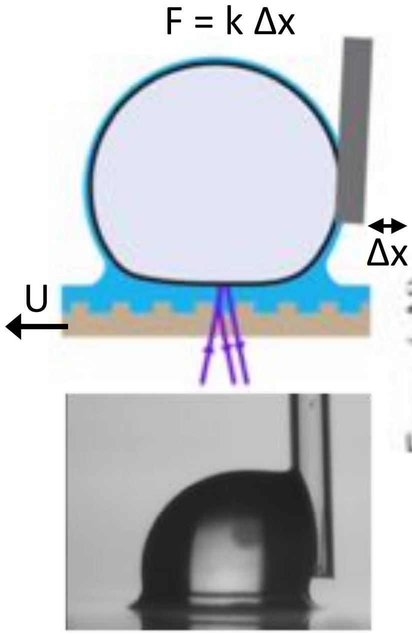
Viscous dissipation in wetting ridge (Tanner's law)

$$\theta_w \sim Ca^{1/3}$$

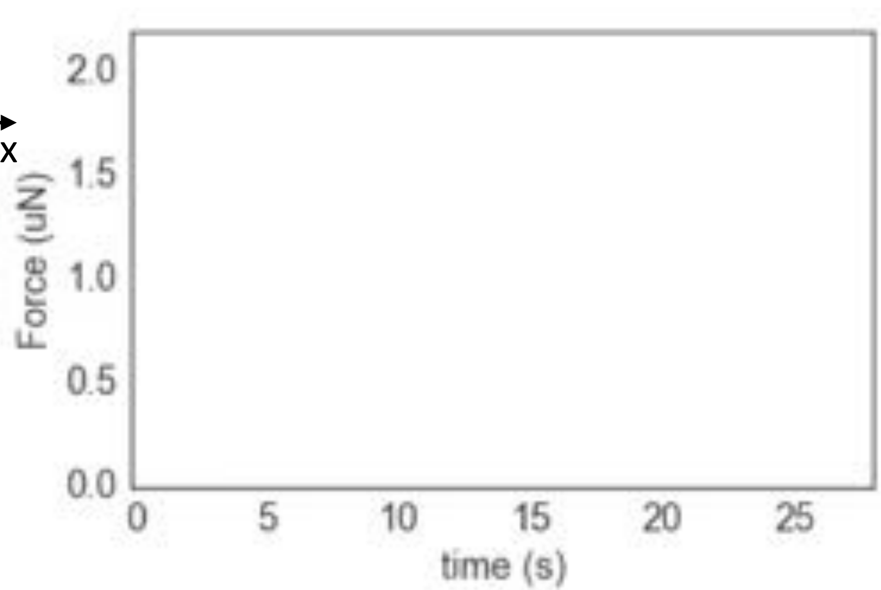
$$\mathbf{F \sim (\eta_o U / \theta_w)\, 2a}$$
$$\mathbf{= 2a\gamma_o\, Ca^{2/3}}$$

Keiser *et al*, *Soft Matter*, 2017

Custom-built force sensor to measure dissipation force

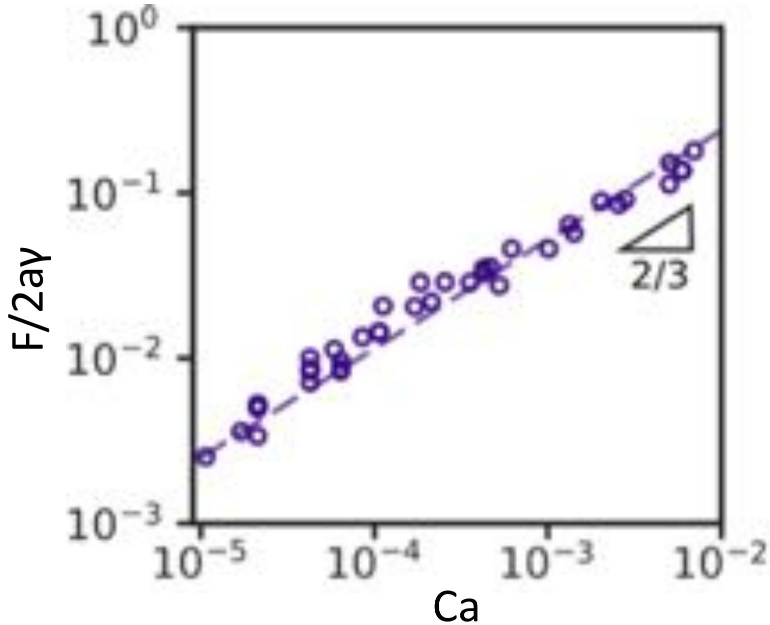


2 µl droplet, U = 0.3 mm/s



Contact angle hysteresis

$\Delta\cos\theta \sim Ca^{2/3}$



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$= 2a\gamma_{lo}\,Ca^{2/3}$

Contact angle hysteresis

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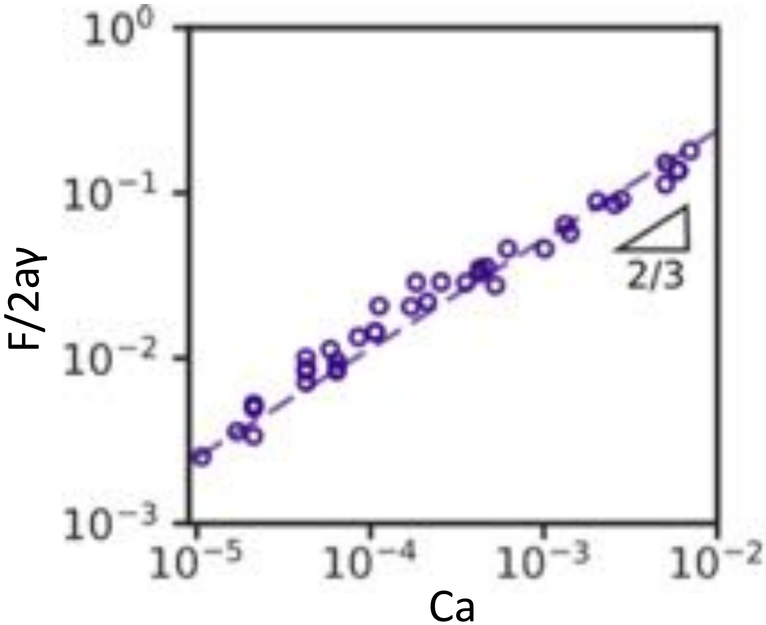

$F \sim \eta_o U/h_{LLD}\,(2a\,l\,)$
$= 2a\gamma_{lo}\, Ca^{2/3}$

$\Delta\cos\theta = F/\,2a\gamma_l$
$= (\gamma_{lo}\,/\,\gamma_l)\, F/\,2a\gamma_{lo}$
$\sim Ca^{2/3}$

Contact angle hysteresis

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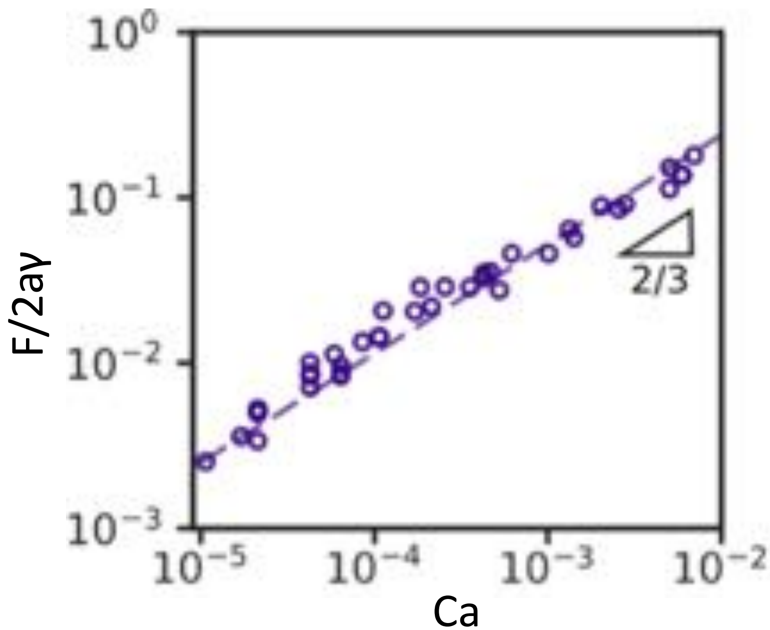


$F \sim \eta_o U/h_{LLD}\,(2a\,l\,)$

$\quad = 2a\gamma_{lo}\,Ca^{2/3}$

$\Delta\cos\theta = F/\,2a\gamma_l$

$\quad = (\gamma_{lo}\,/\,\gamma_l)\,F/\,2a\gamma_{lo}$

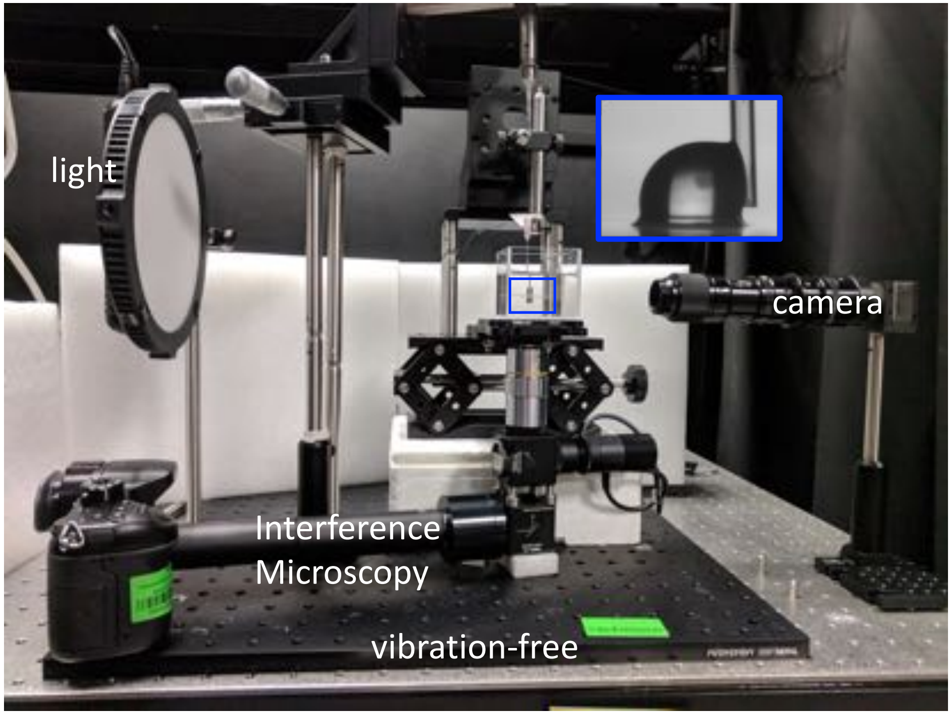
$\quad \sim Ca^{2/3}$

$\Delta\cos\theta \rightarrow 0$, $Ca \rightarrow 0$

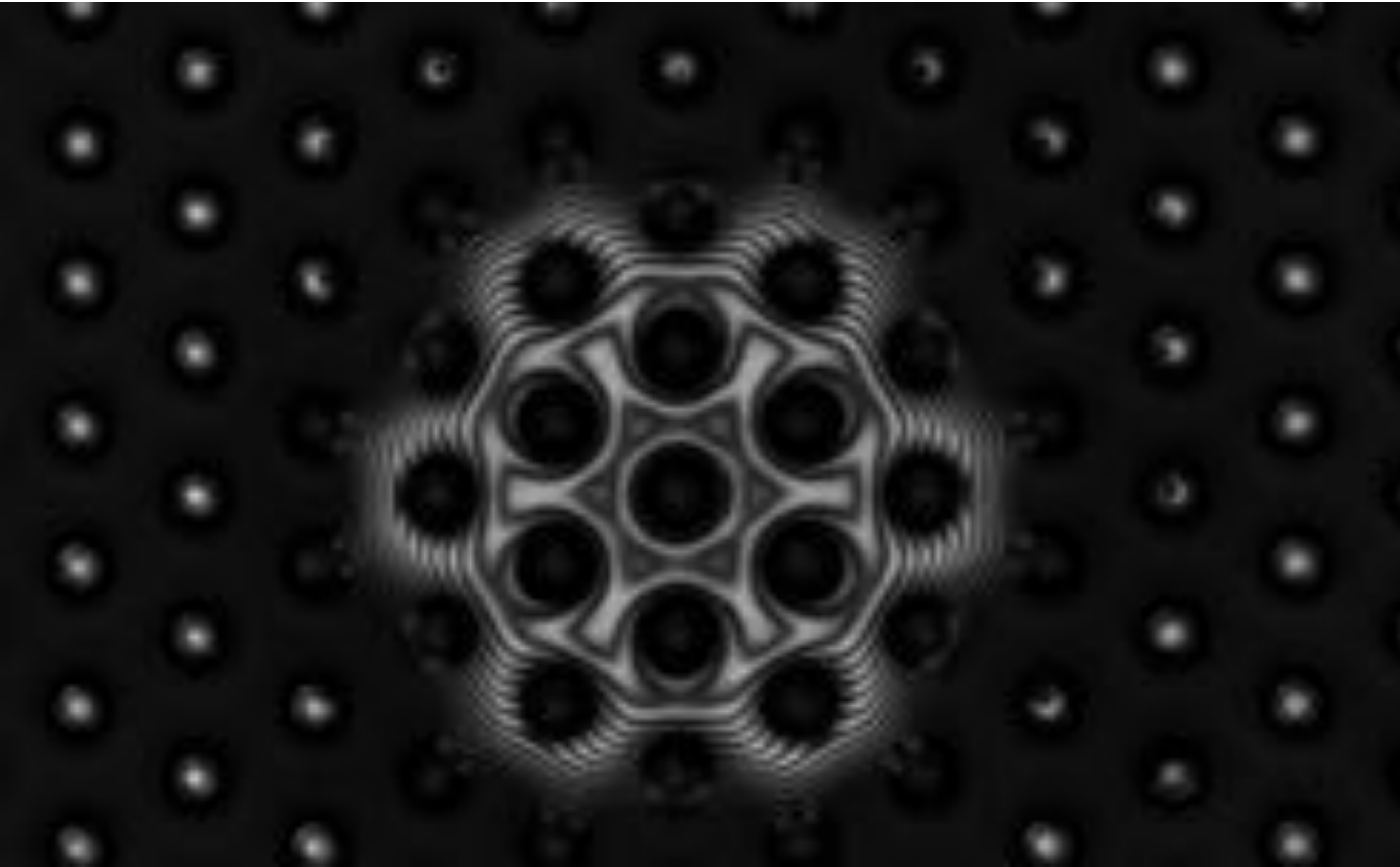
Nearly zero hysteresis

No contact line pinning

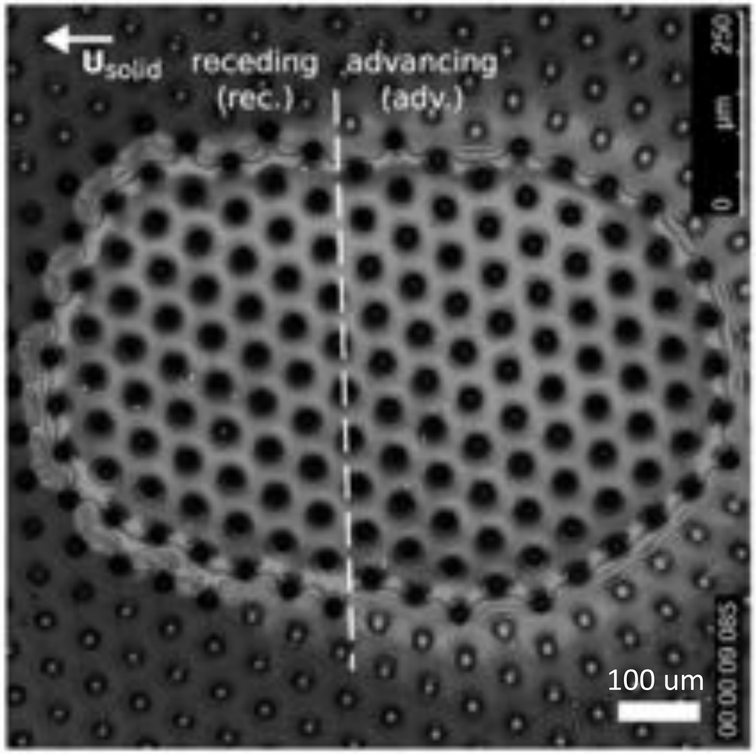
Custom-built force sensor currently at IMRE, A*STAR



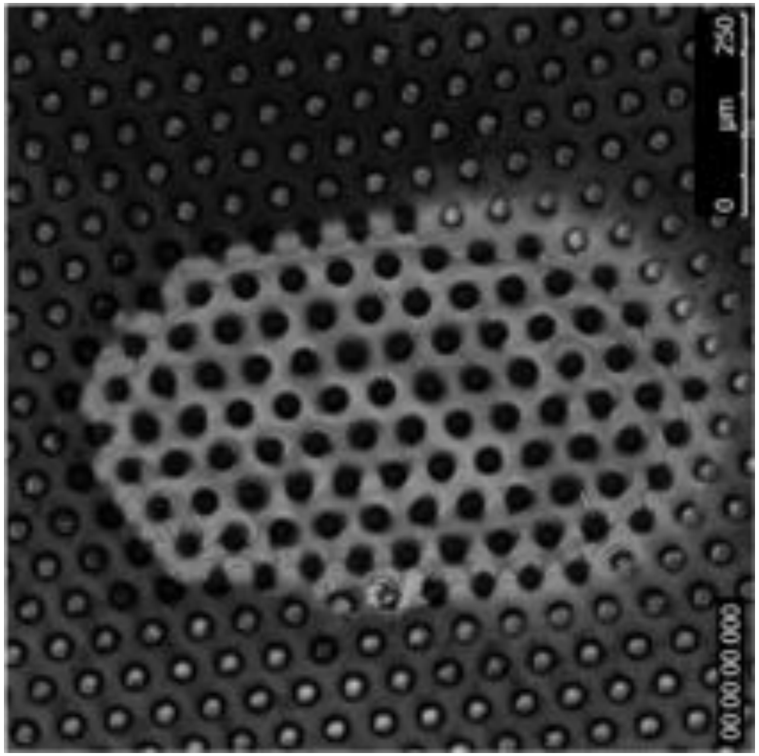
Comparison with lotus-effect surfaces



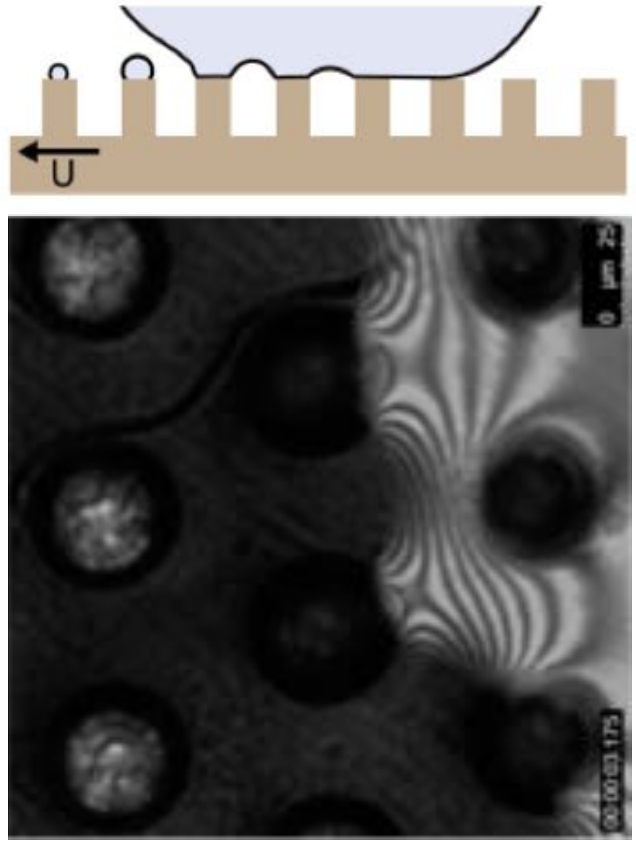
Contact line pinning on lotus-effect surface



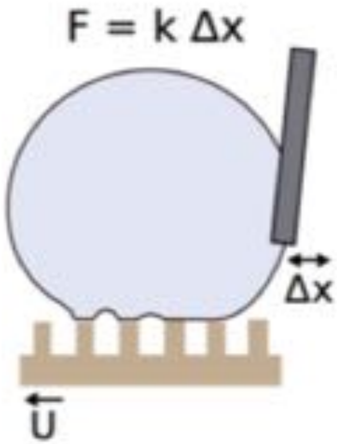
Contact line pinning on lotus-effect surface

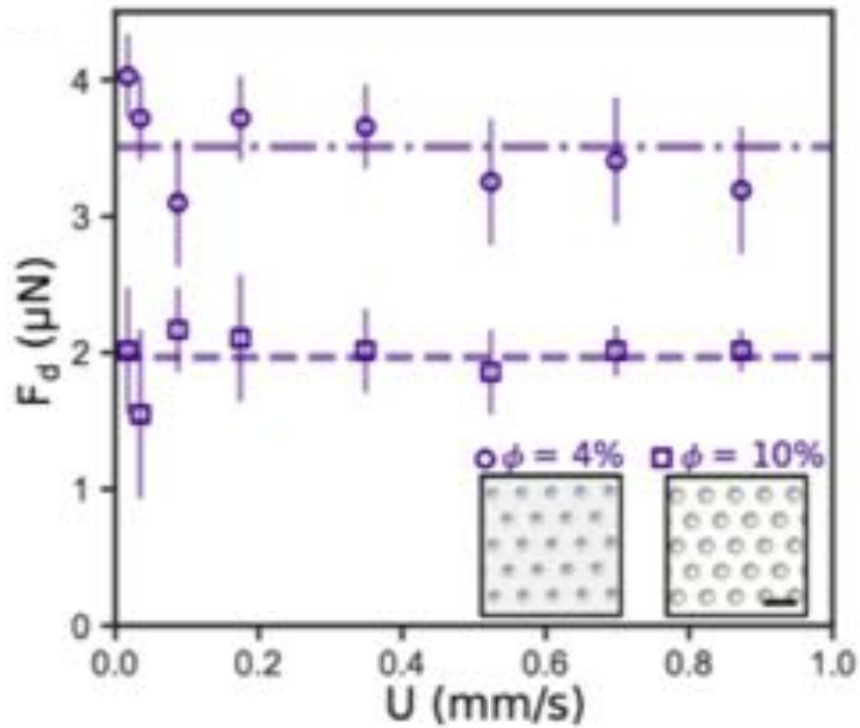


Micro-droplets after
breakup of capillary bridges



F independent of U
for lotus-effect surfaces





F independent of U
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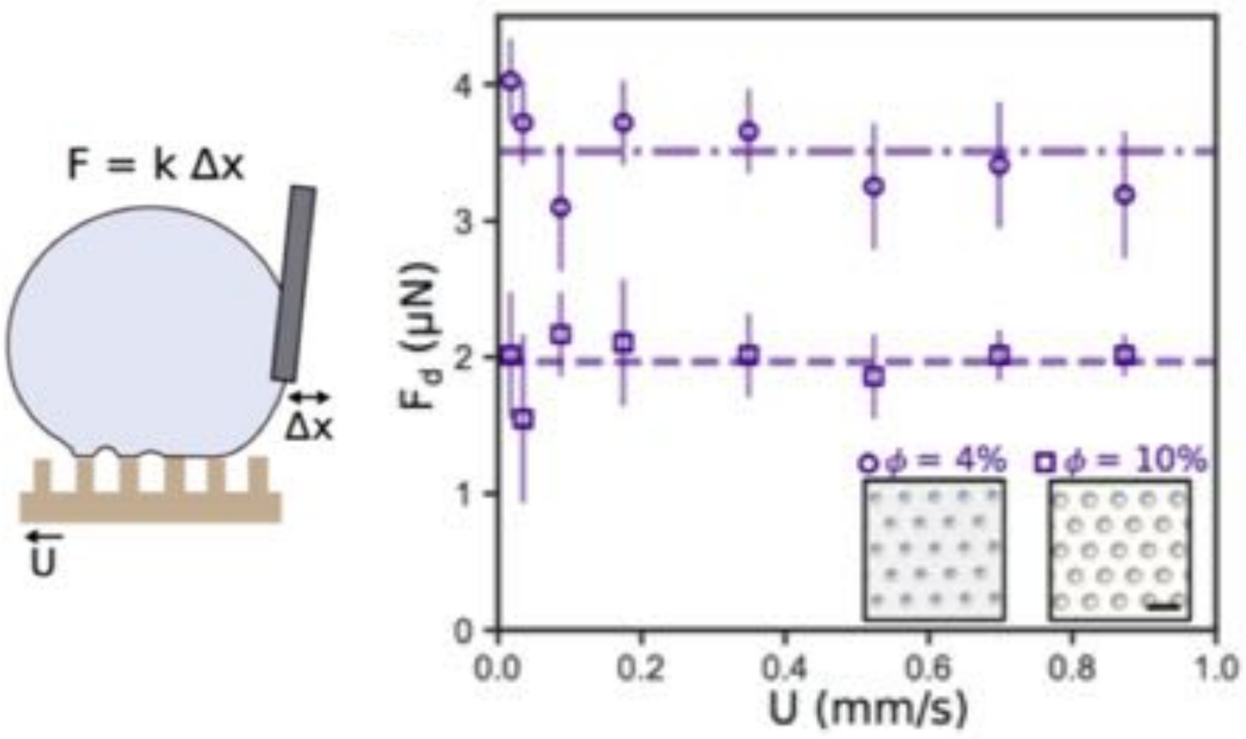


$\Delta \cos\theta > 0$, $Ca \rightarrow 0$

finite hysteresis

Results presented
can be found in

D. Daniel, J.V.I Timonen, R. Li, S.J. Velling and J. Aizenberg
"Oleoplaning droplets on lubricated surfaces"
Nat. Phys. 2017

D. Daniel[+], J.V.I Timonen, R. Li, S.J. Velling, M.J. Kreder, A. Tetreault and J. Aizenberg[+]
"Origins of extreme liquid repellency on structured, flat, and lubricated surfaces"
in revision to *Phys. Rev. Lett.* (and ArXiv)
[+]*co-corresponding authors*

M.J. Kreder*, D. Daniel*, A. Tetreault , Z. Cao, B. Lemaire, J.V.I Timonen and J. Aizenberg
"Film dynamics and lubricant depletion by droplets moving on lubricated surfaces"
in revision to *Phys. Rev. X*
co-first authors

Useful literature

A. Keiser, L. Keiser, C. Clanet and D. Quere
"Drop friction on liquid infused surfaces"
Soft Matter 2017

M. Tress, S. Karpitschka, P. Papadopoulos, J. H. Snoeijer, D. Vollmer and H.-J. Butt
"Shape of a sessile drop on a flat surface covered with a liquid film"
Soft Matter 2017

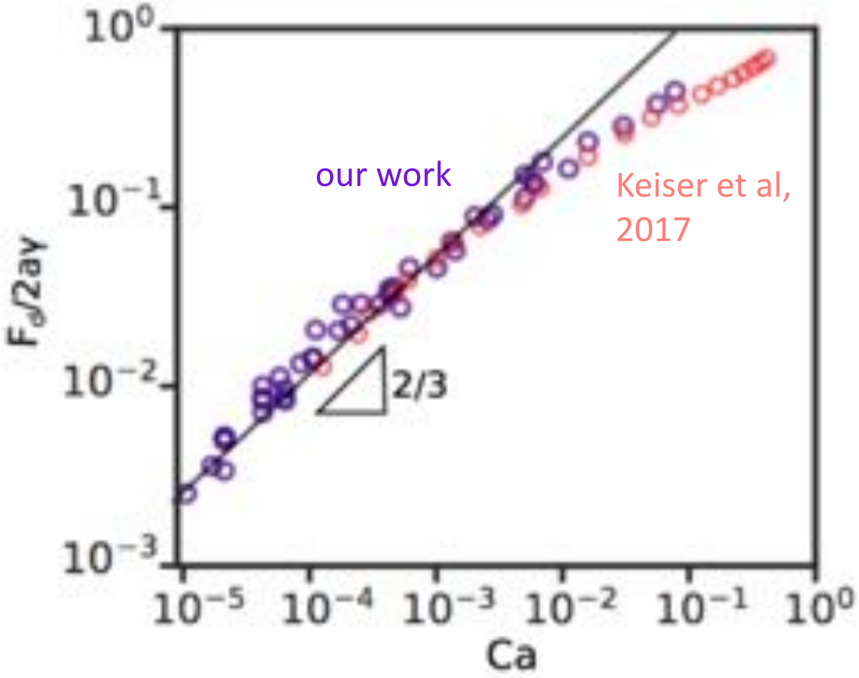
F. Schellenberger *et al*
"Direct observation of drops on slippery lubricant-infused surfaces "
Soft Matter 2015

J. D. Smith *et al*
"Droplet mobility on lubricant-impregnated surfaces "
Soft Matter 2013

A. Lafuma and D. Quere
"Slippery pre-suffused surfaces."
Euro. Phys. Lett. 2011

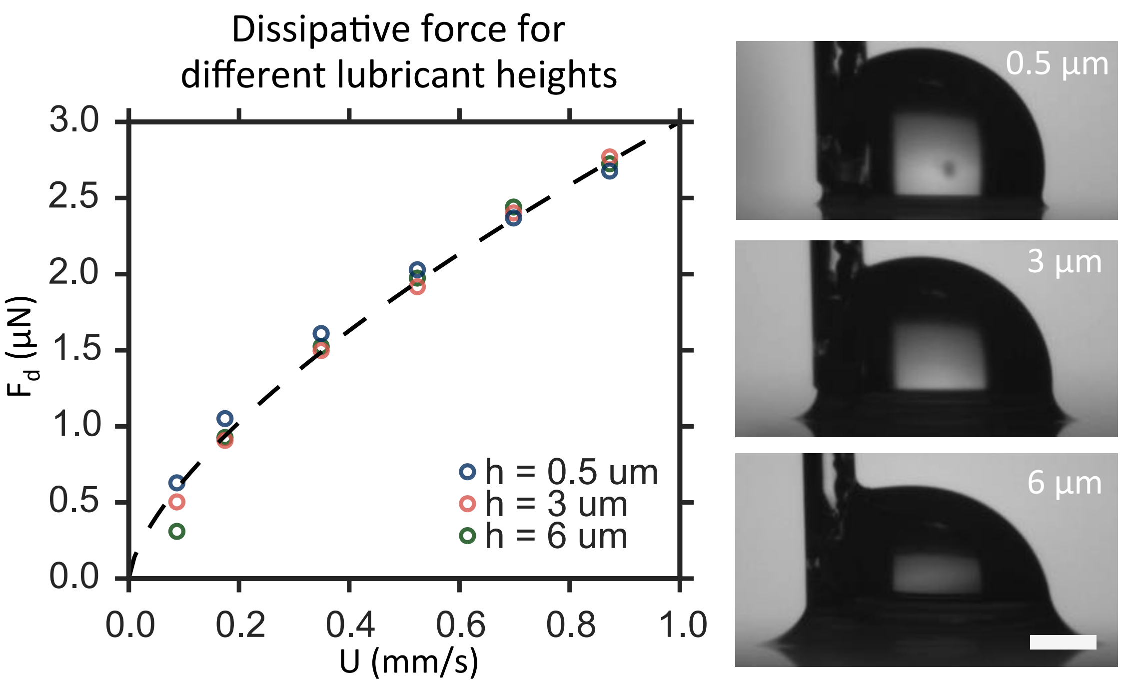
Thoughts and open questions

Contact angle hysteresis
for high Ca



Keiser *et al*, *Soft Matter*, 2017

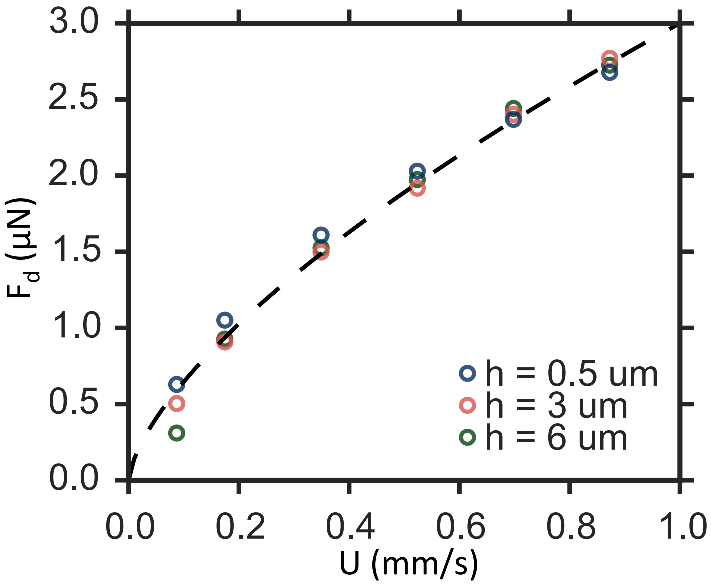
Contact angle hysteresis
for different initial film thicknesses

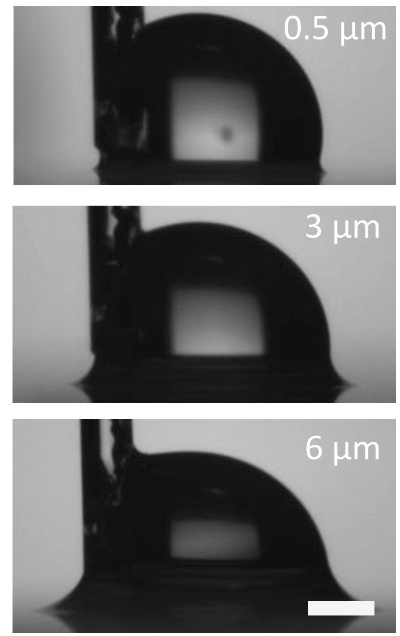


Δcos θ ~ Ca$^{2/3}$ independent of initial *h*
for thick micron-film

Contact angle hysteresis
for different initial film thicknesses

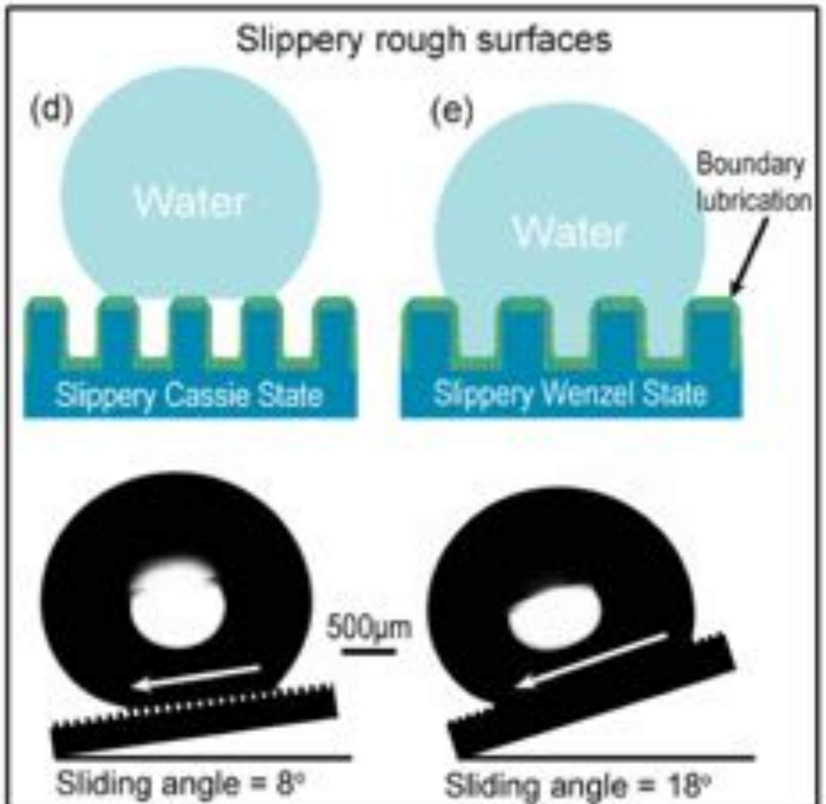
Dissipative force for
different lubricant heights





$\Delta\cos\theta$ ~ $Ca^{2/3}$ independent of initial *h*
for thin nano-film ?

Contact angle hysteresis
for structured surfaces with thin nano-film ?



Dai *et al*, *ACS Nano*, 2015
Slippery Wenzel State

Thanks to …

HARVARD
John A. Paulson
School of Engineering
and Applied Sciences

Aalto University


Prof. J. Aizenberg


M. J. Aizenberg


Prof. J. V. I. Timonen


Prof. Bob. E Cohen


Prof. Paul V. Braun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