Floating on air

Physics of Fluids
University of Twente

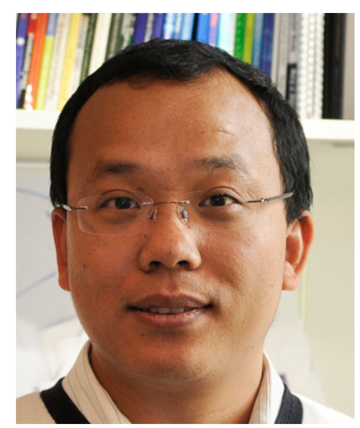
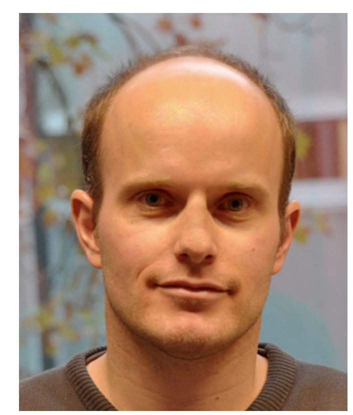
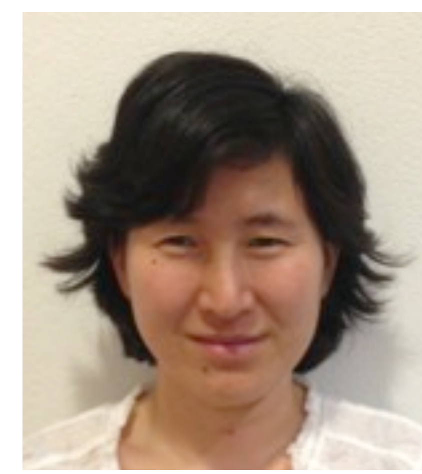
Detlef Lohse
Physics of Fluids
University of Twente

Coworkers

Bram Borkent
Wilco Bouwhuis
Nicolas Bremond
Henri Lhuissier
Hanneke Gelderblom
Stefan Gekle
Alvaro Marin
Devaraj van der Meer
Ivo Peters
Andrea Prosperetti
David Rivas
Jacco Snoeijer
ErikJan Staat
Chao Sun
Peichun Amy Tsai
Tuan Tran
Roeland van der Veen
Koen Winkels
Xuehua Zhang

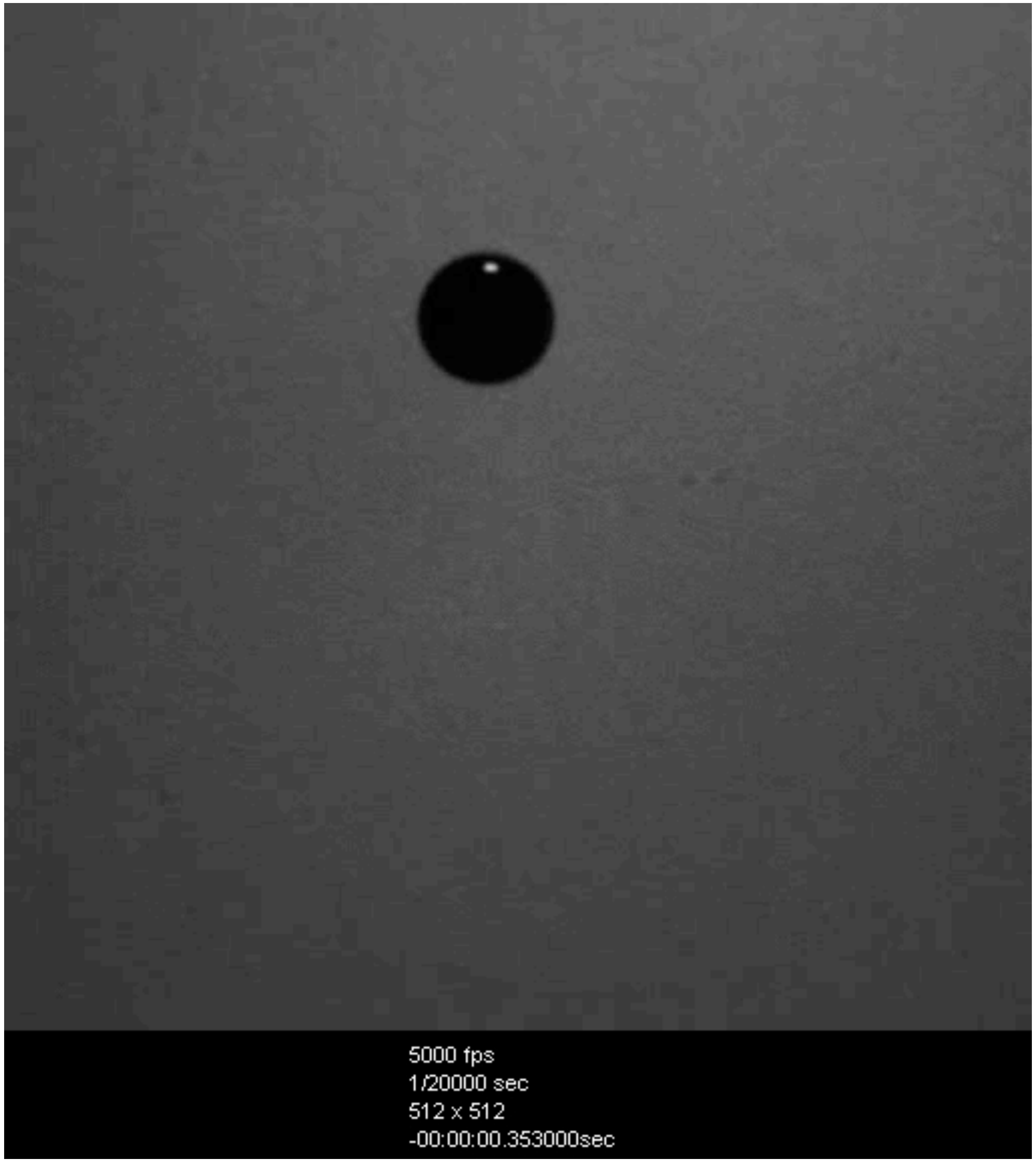




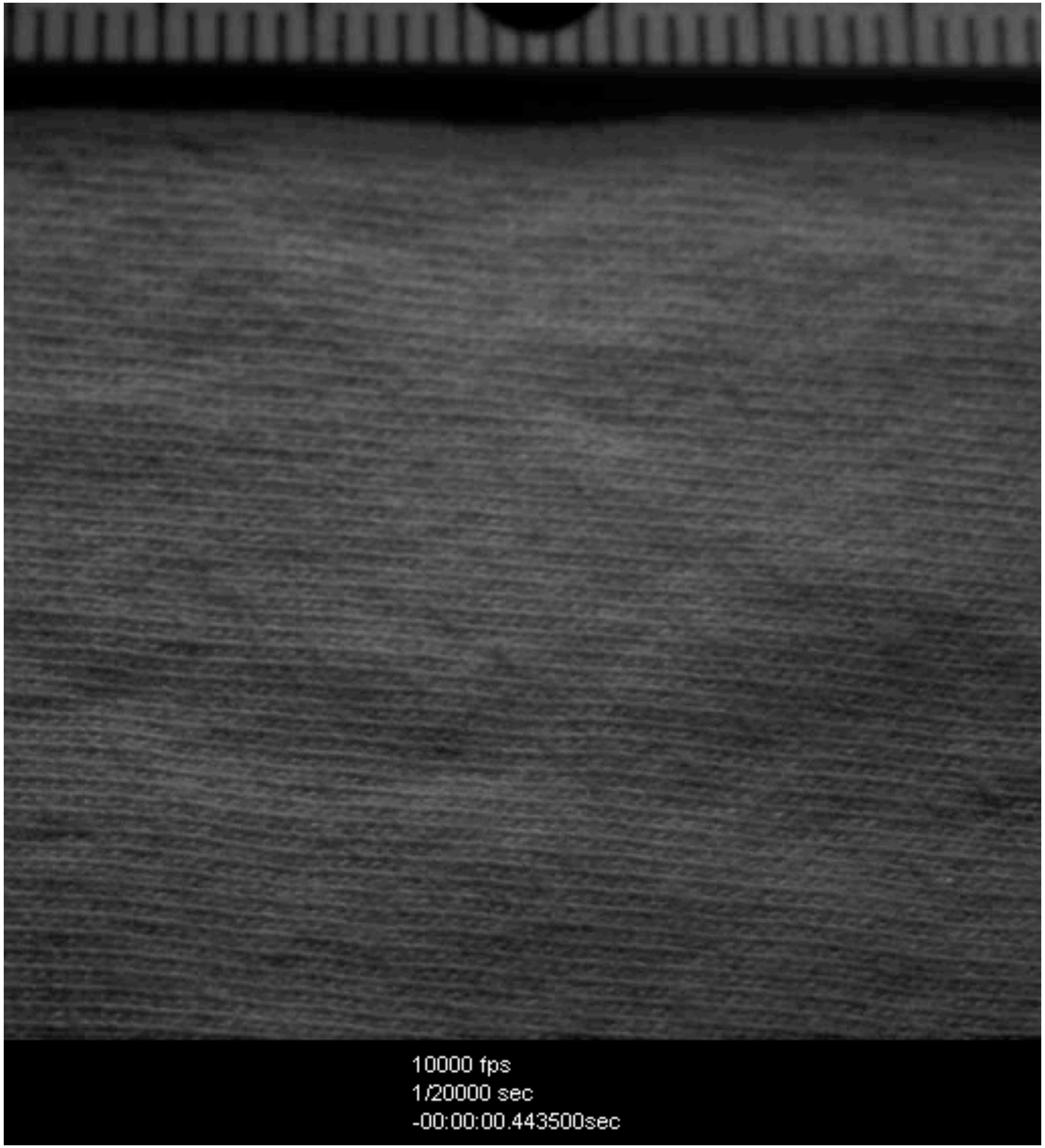


Droplet impact



… on paper

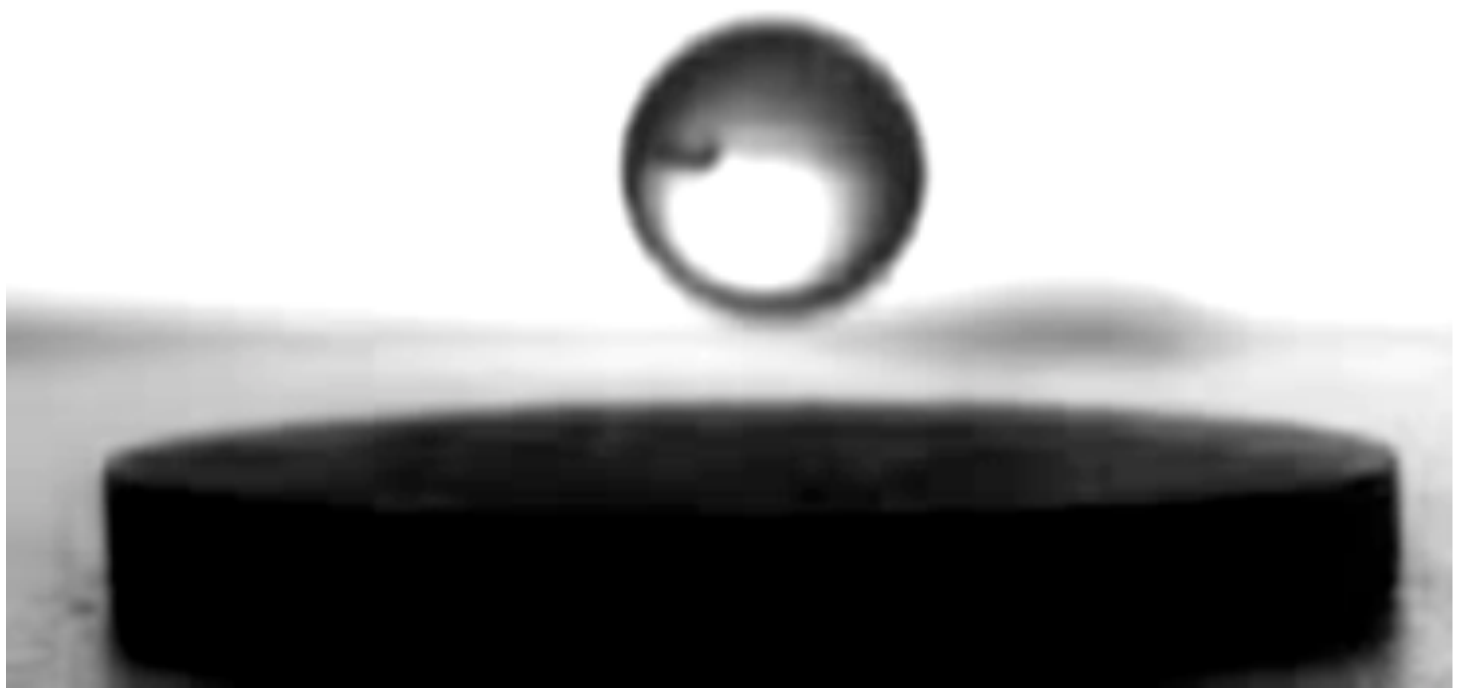
Strong dependence on type of surface



… on cotton

Liquid: blood
Nederlands Forensisch Institute

Impact on hydrophobic surface

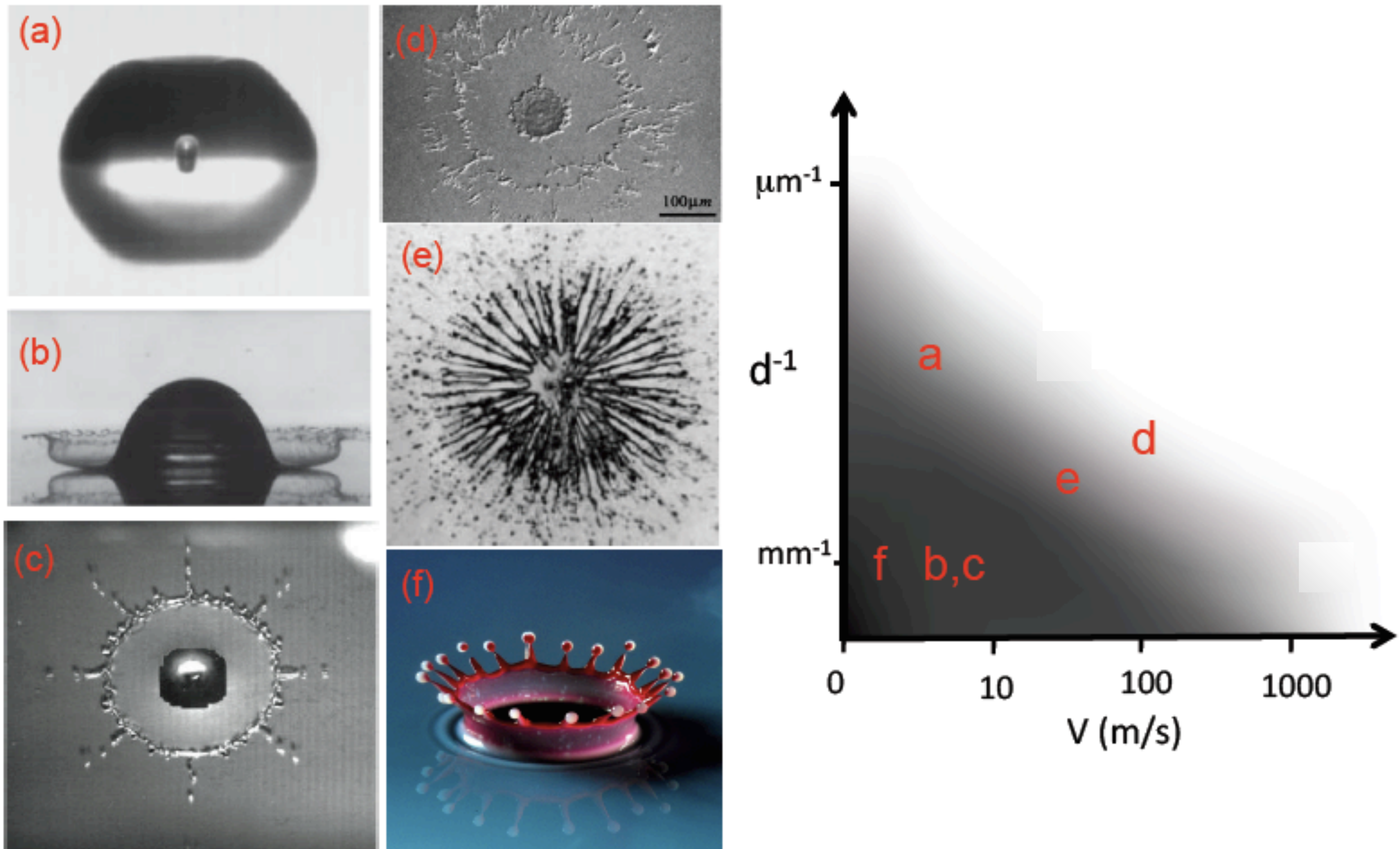


low
velocity

Impact on hydrophobic surface

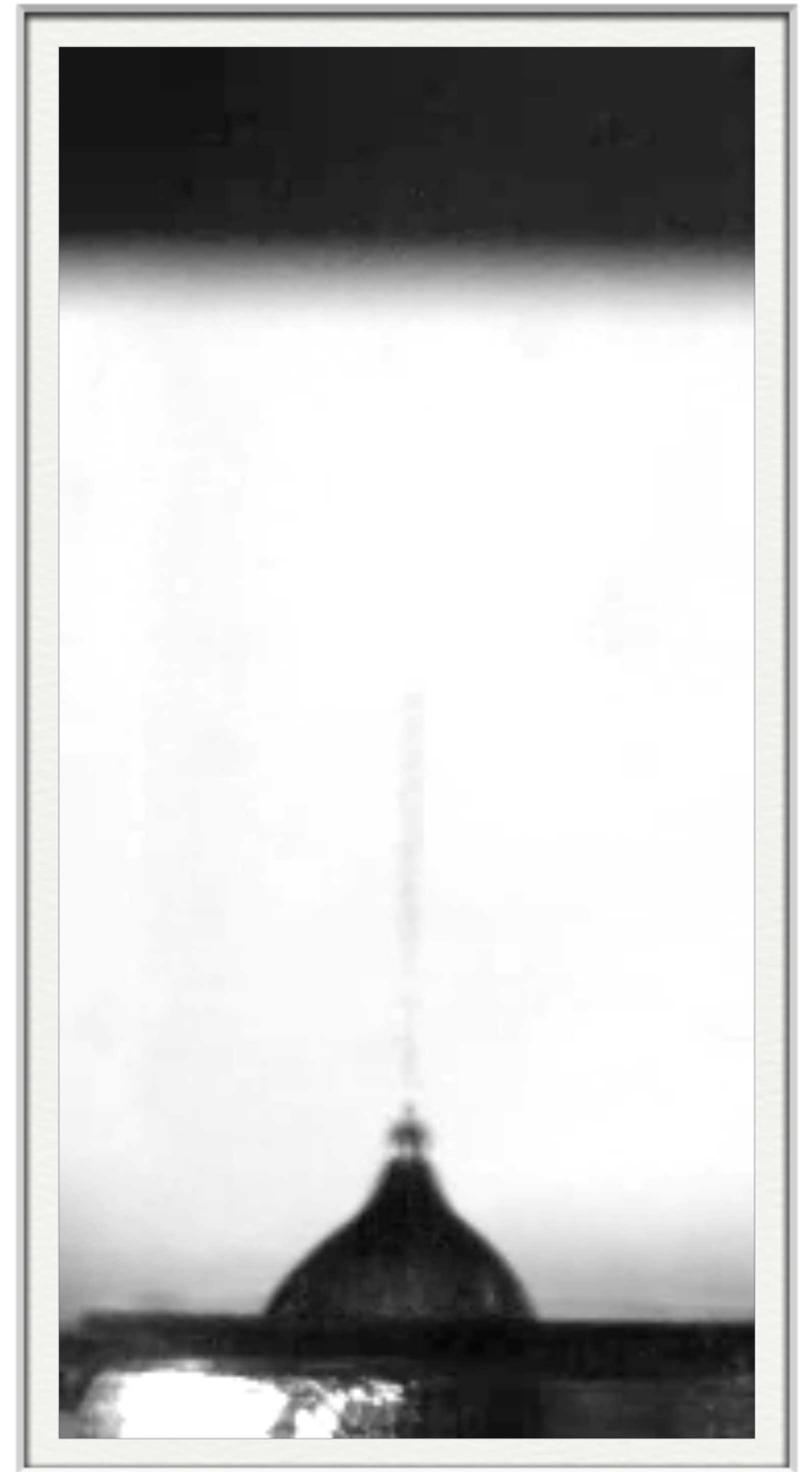
high velocity

Phase space of impact



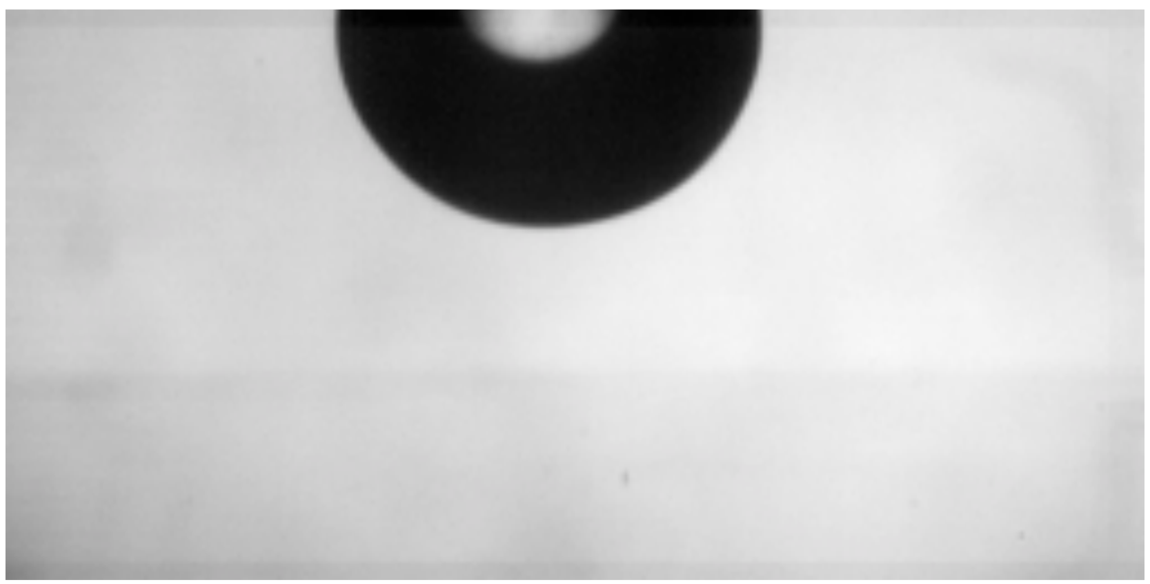
Phase space of impact

- Velocity
- Diameter
- Viscosity
- Surface tension
- Roughness of surface
- Temperatures
- Air pressure
- ...

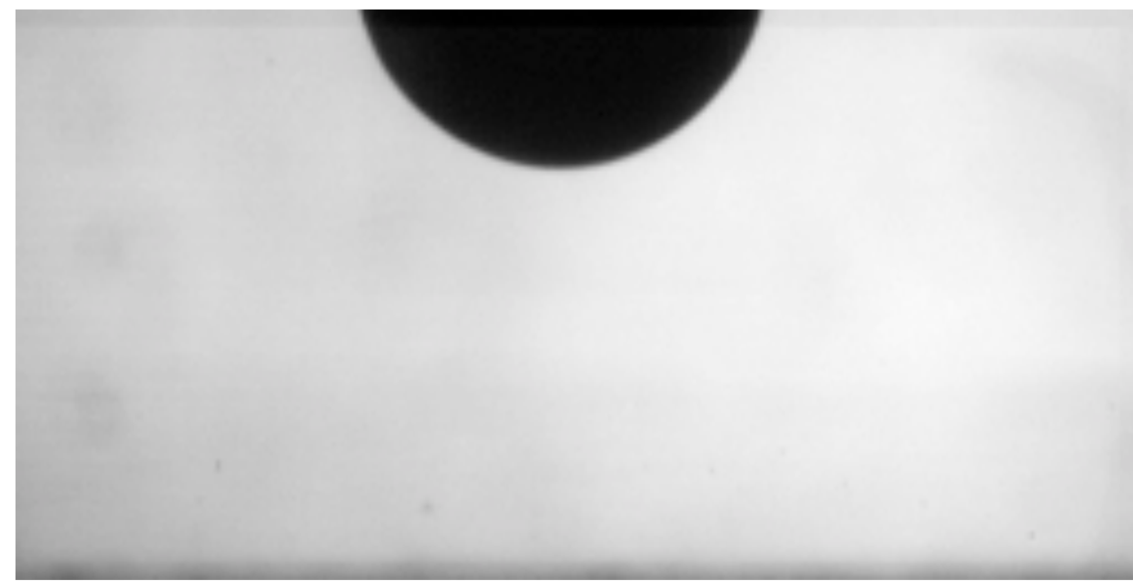


Influence of air pressure on impact event

1 atm



0.2 atm

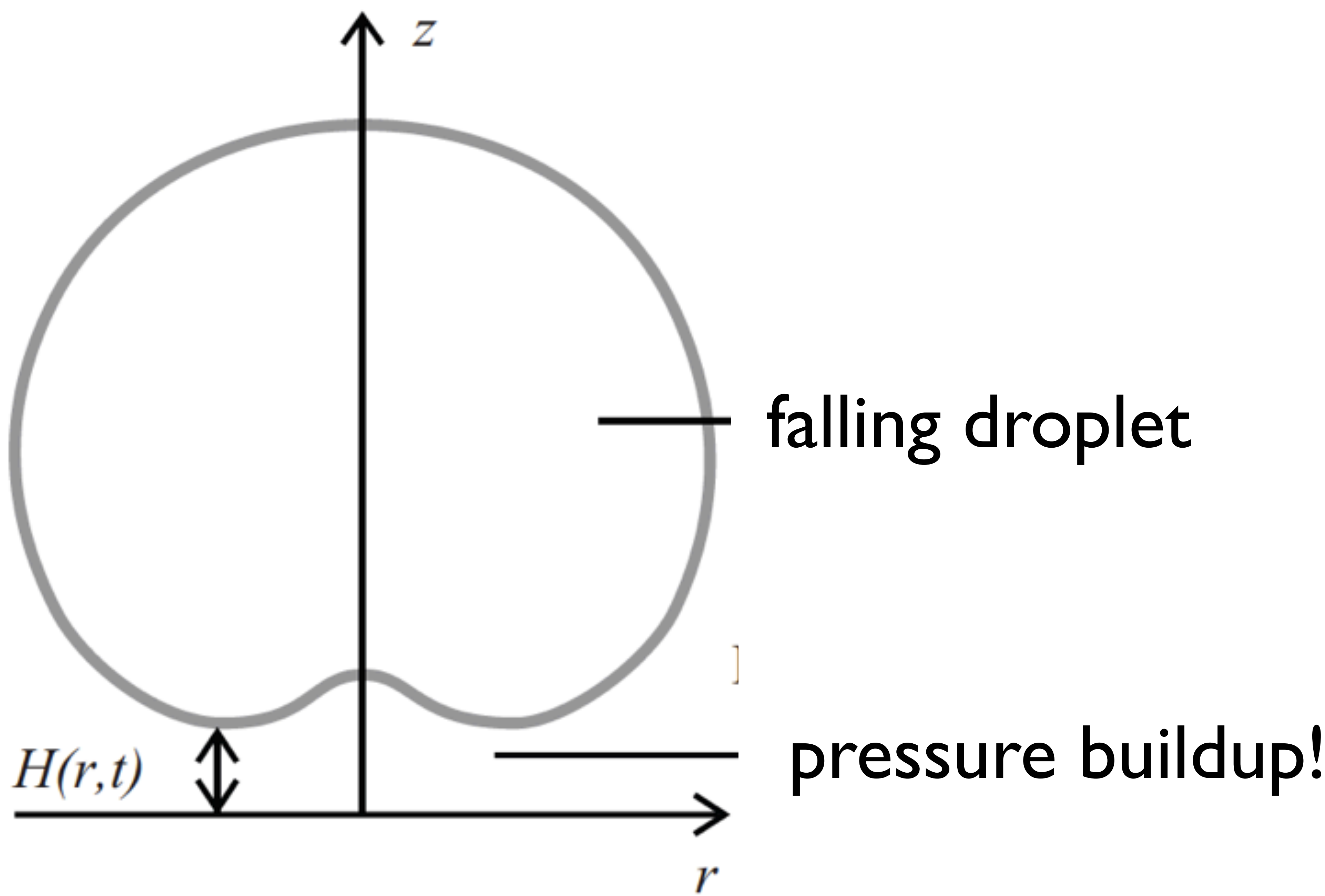


no splash!

Xu, Zhang, Nagel, Phys. Rev. Lett. 94, 184505 (2005)

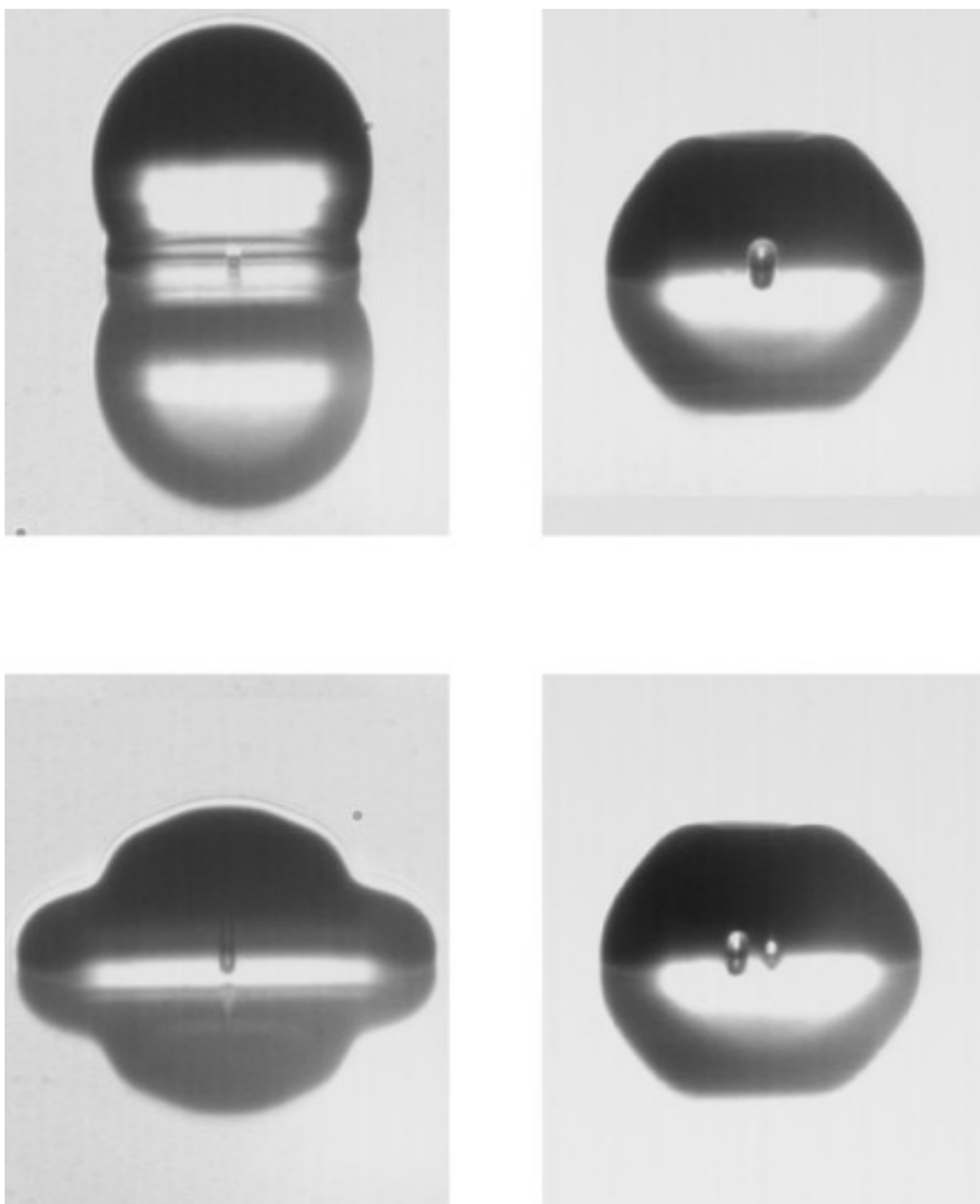
How come?

Sketch of impacting drop



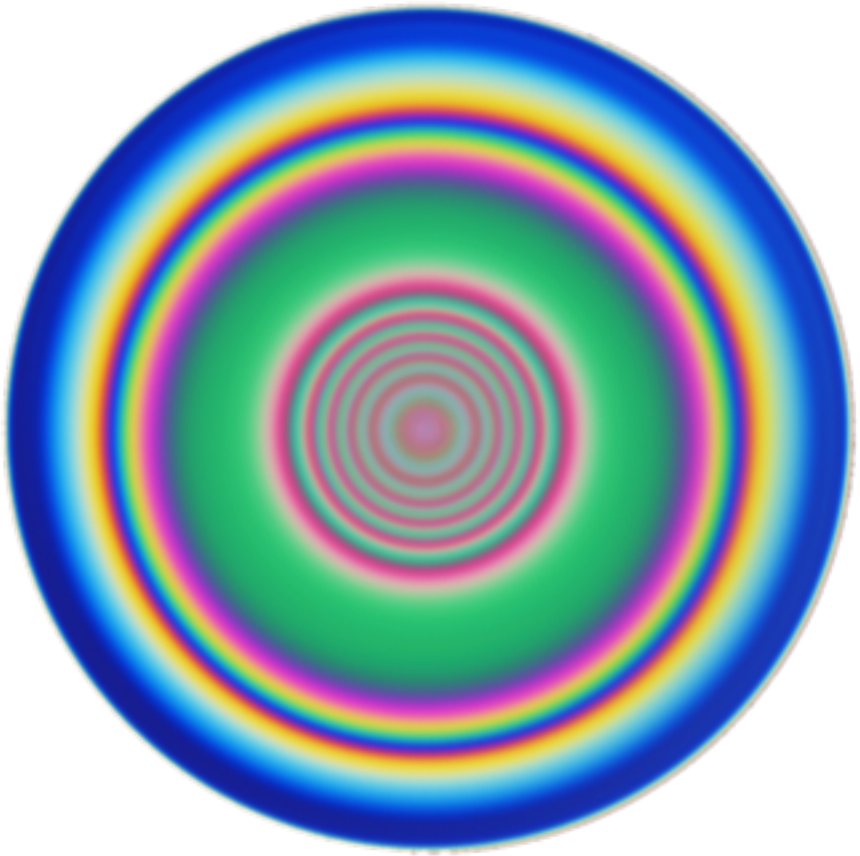
Dimple-formation!

Consequence: entrained bubble under droplet!



Van Dam, Le Clerc, Phys. Fluids 16, 3403 (2004)

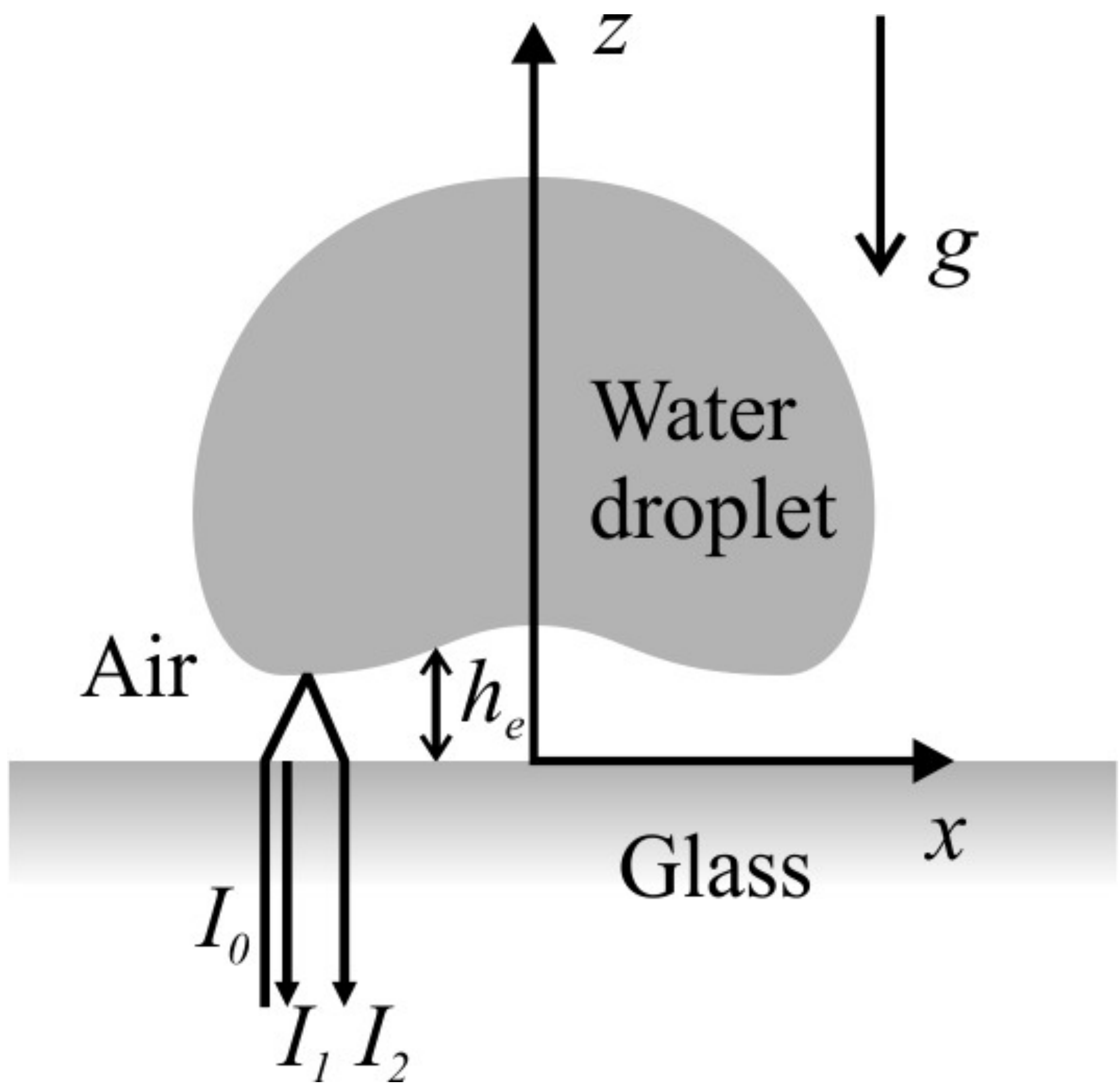
Ultra-high-speed color interferometry



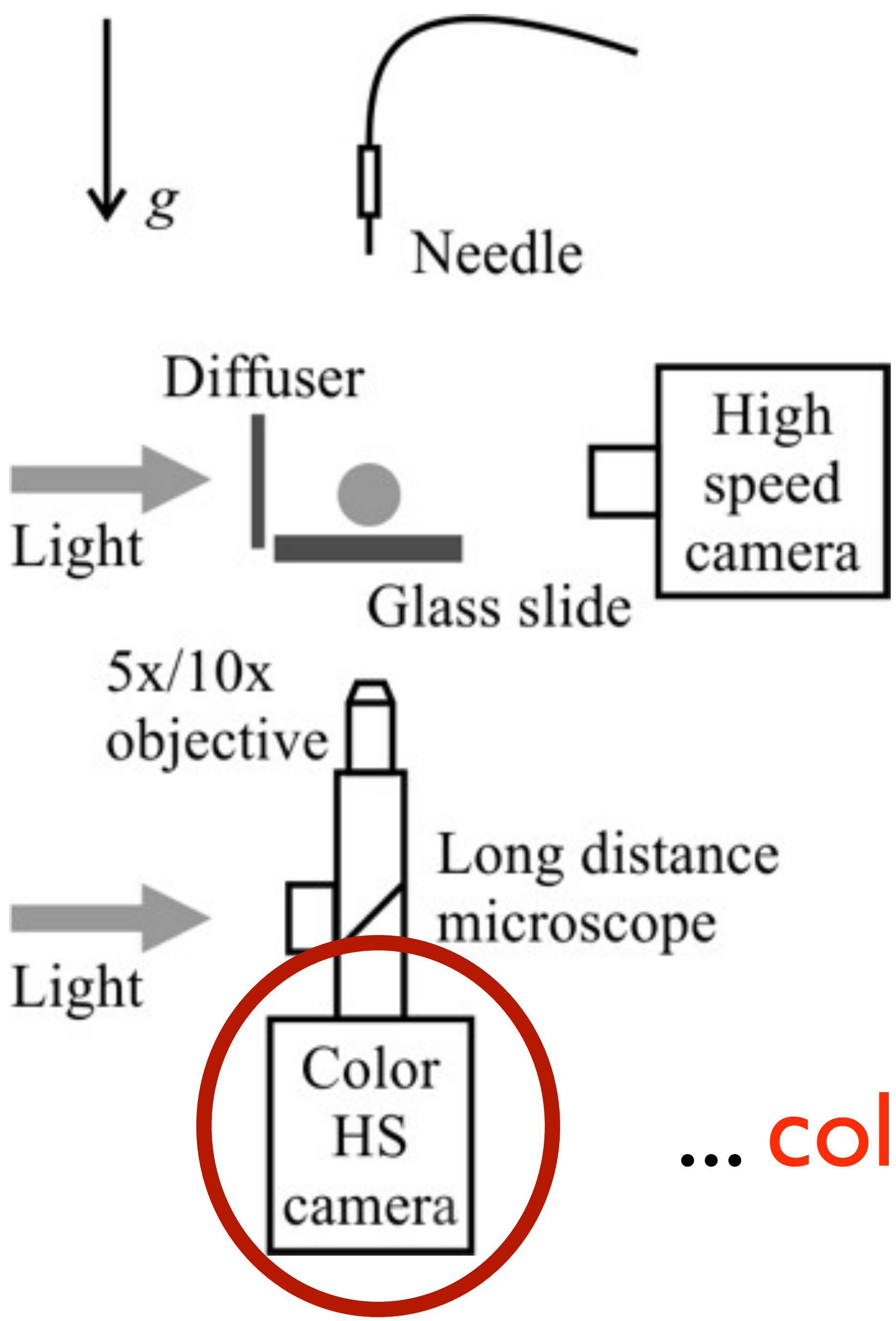
Direct measurements of air layer profiles under impacting droplets

van der Veen, Tran, Lohse, Sun, Phys. Rev. E 85, 026315 (2012);
Bouwhuis et al., Phys. Rev. Lett. 109, 264501 (2012)

Interferometry for falling droplets

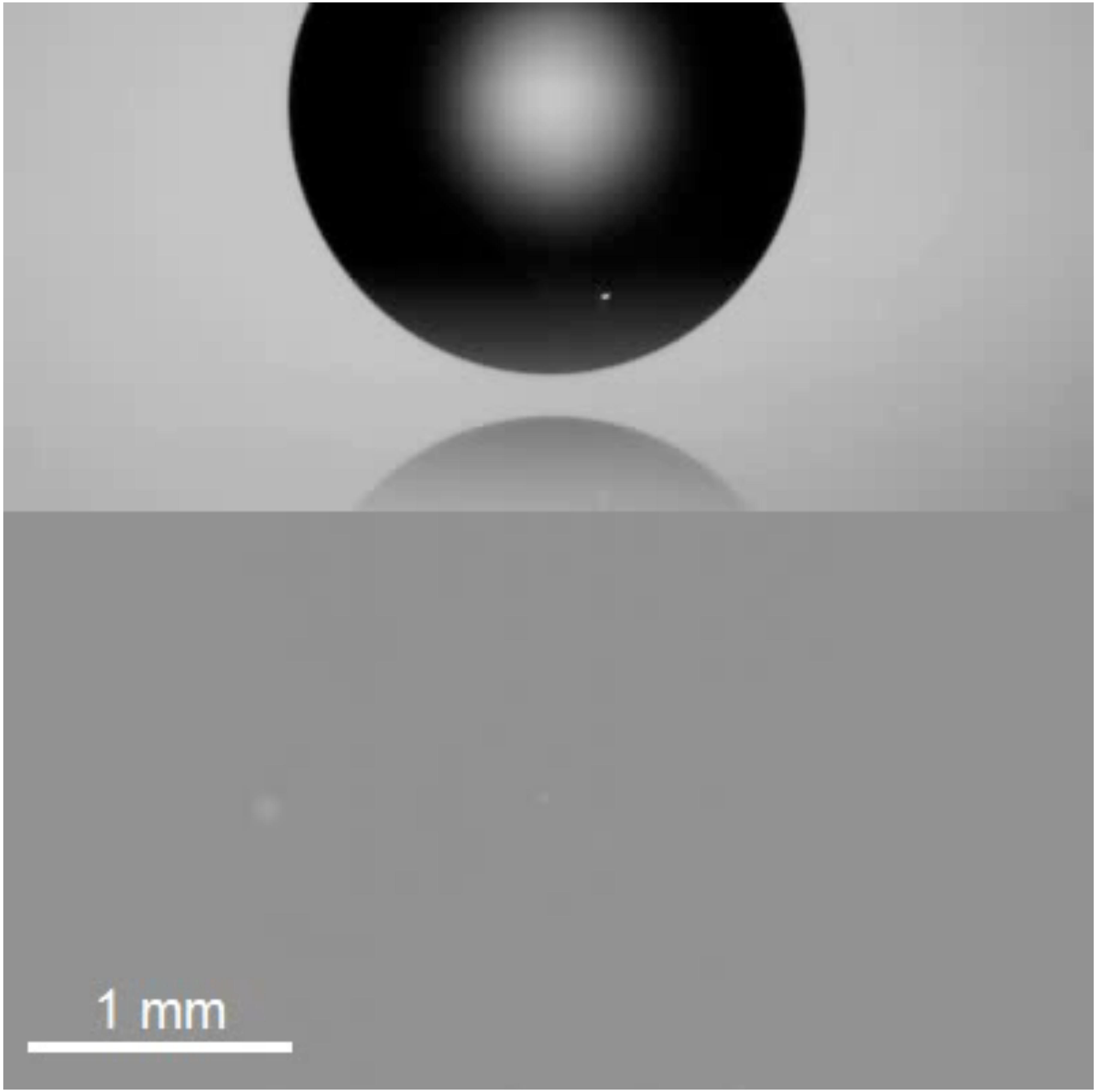


Experimental setup



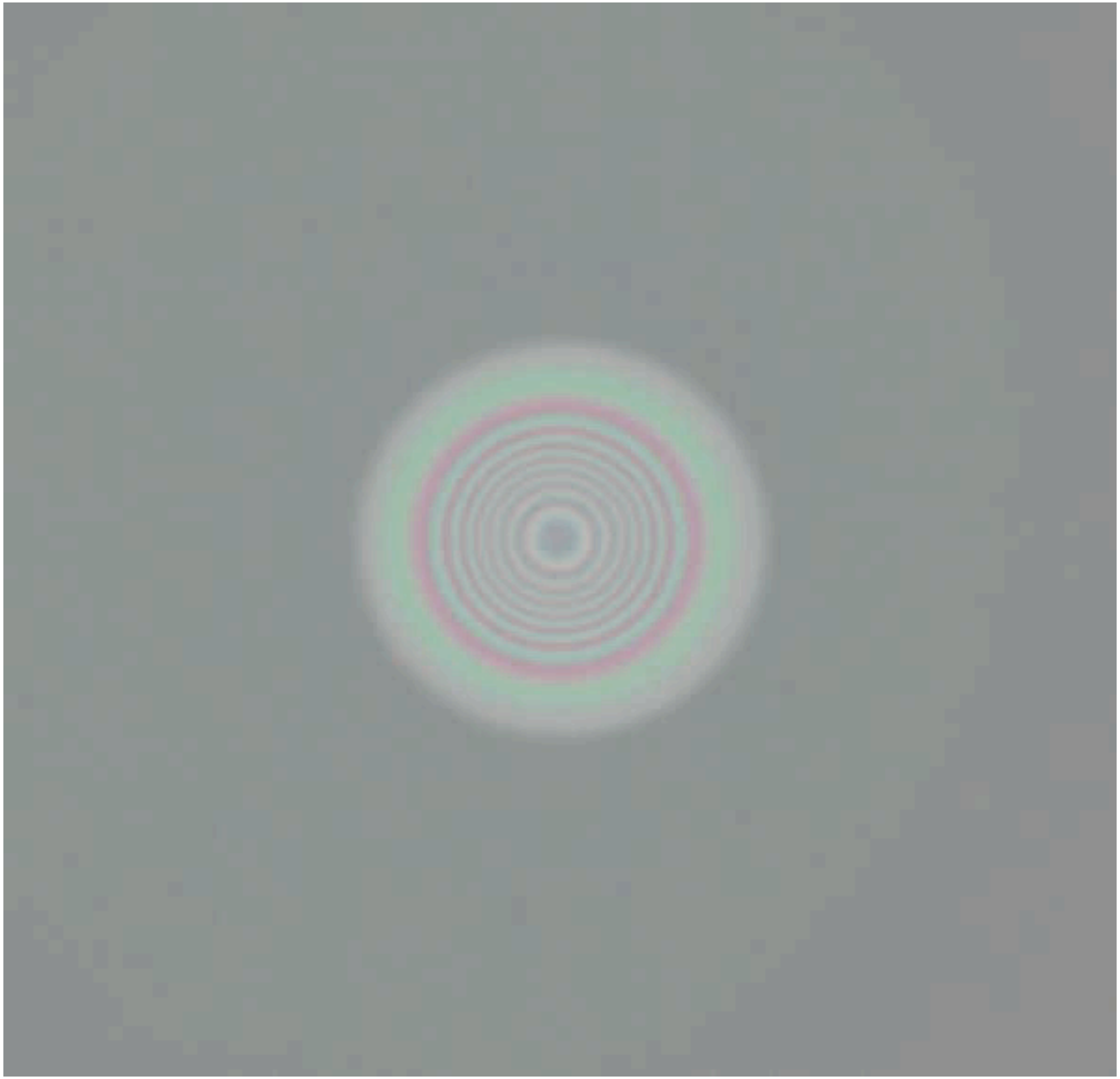
side view and...

... colored bottom view



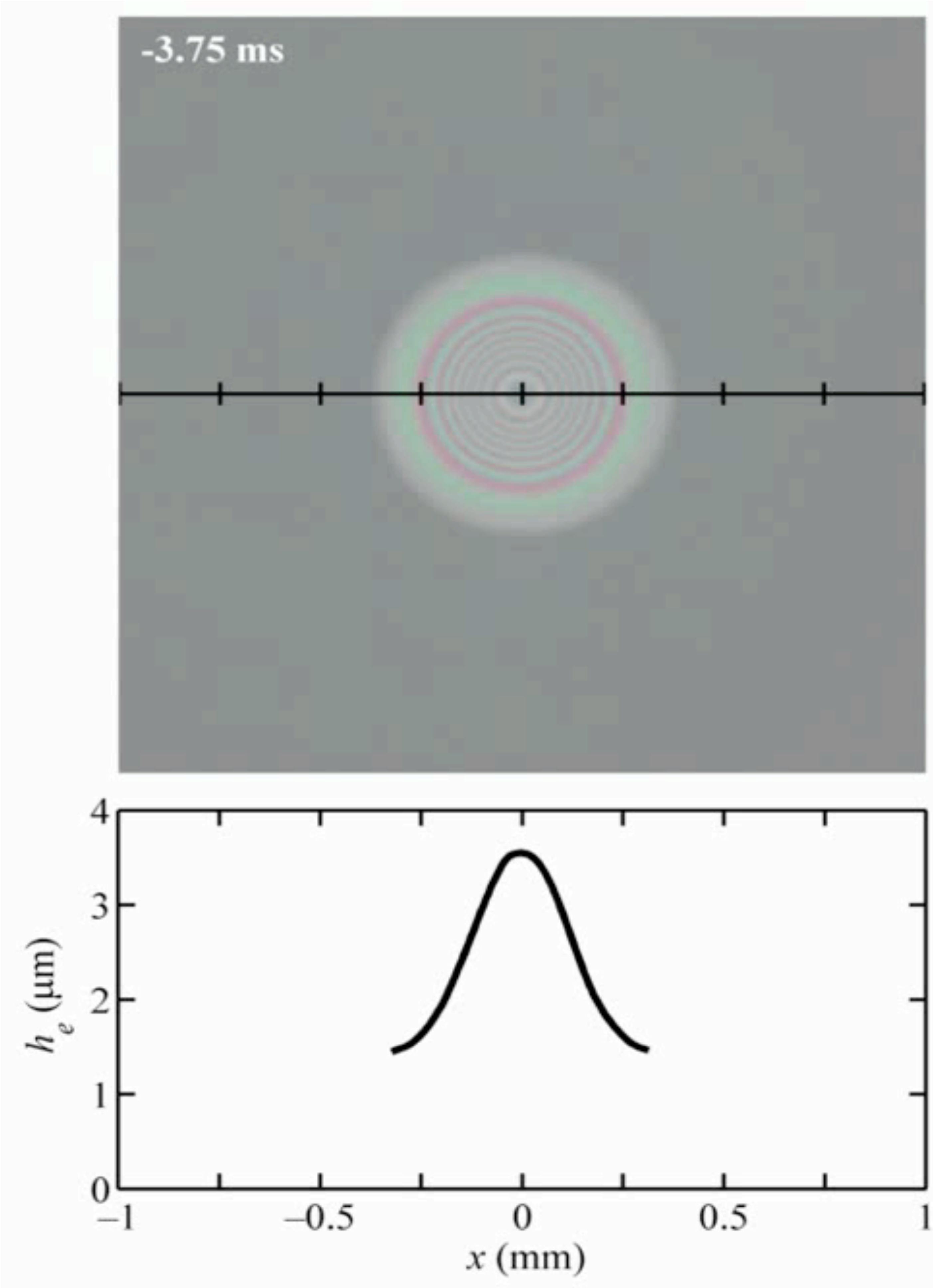
Water
D = 2.0 mm
U = 0.19 m/s
We = 1.0

20000 fps



Water
D = 2.0 mm
V = 0.22 m/s
We = 1.3

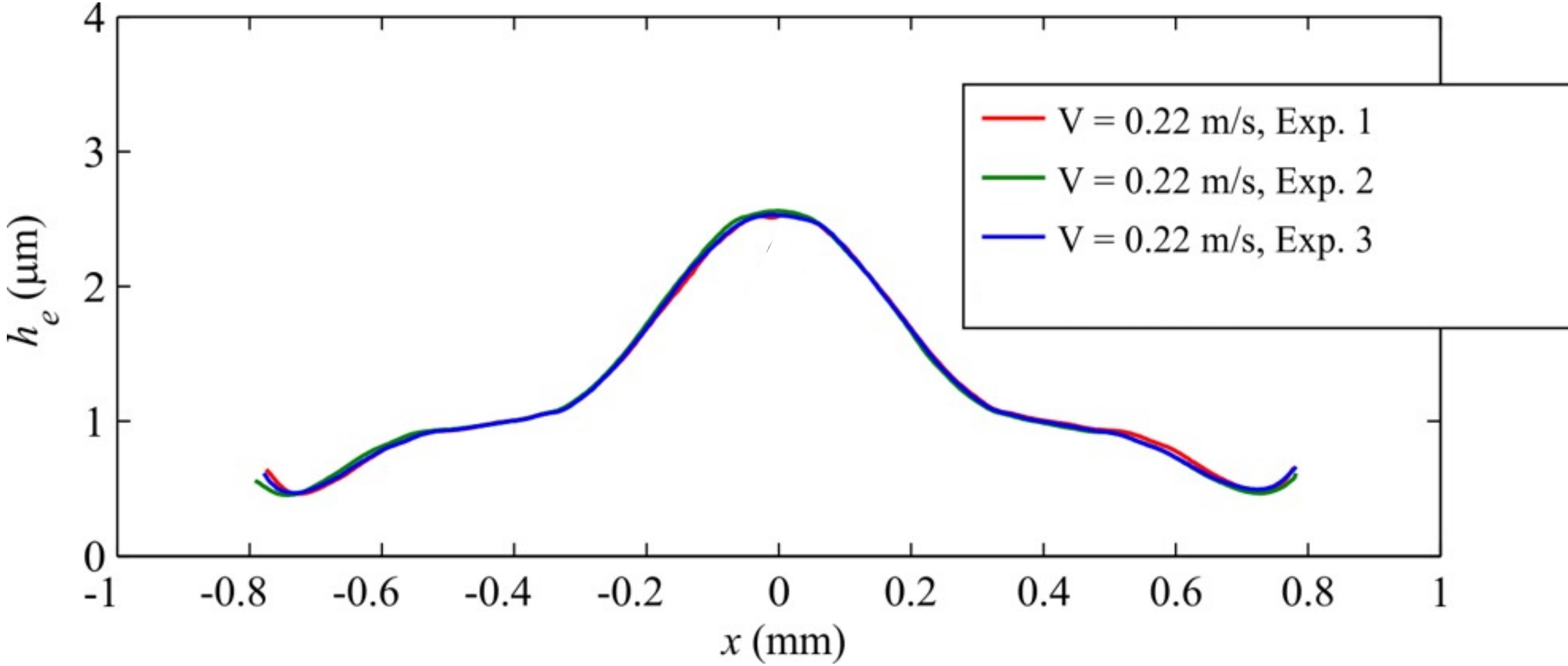
4800 fps



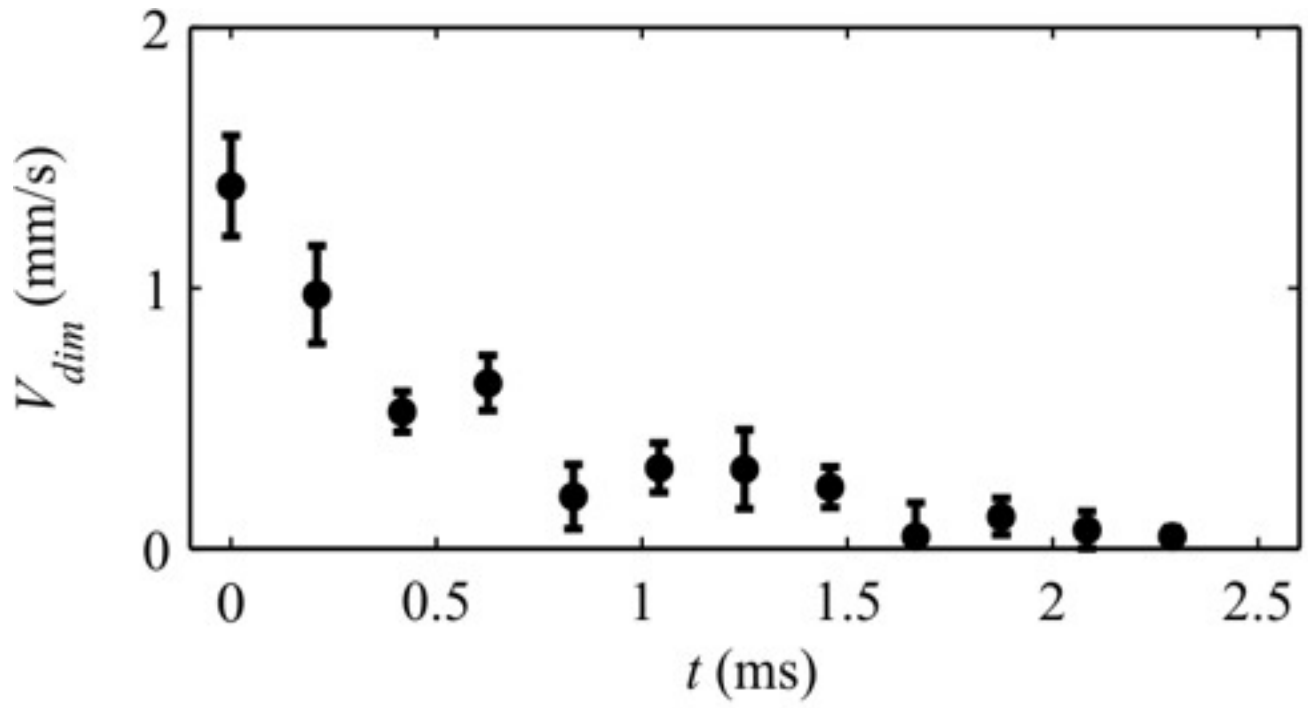
Water
D = 2.0 mm
V = 0.22 m/s
We = 1.3

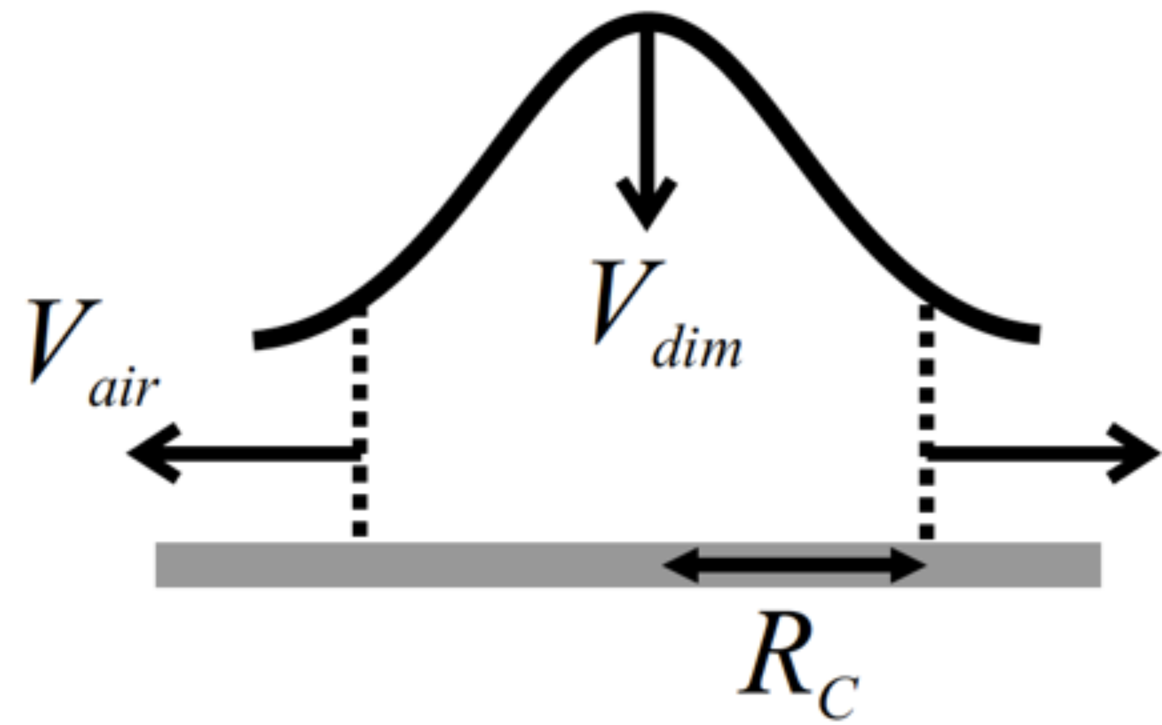
4800 fps

Reproducibility perfect!



Profile dynamics & dimple velocity allows to calculate velocity of outwards air flow

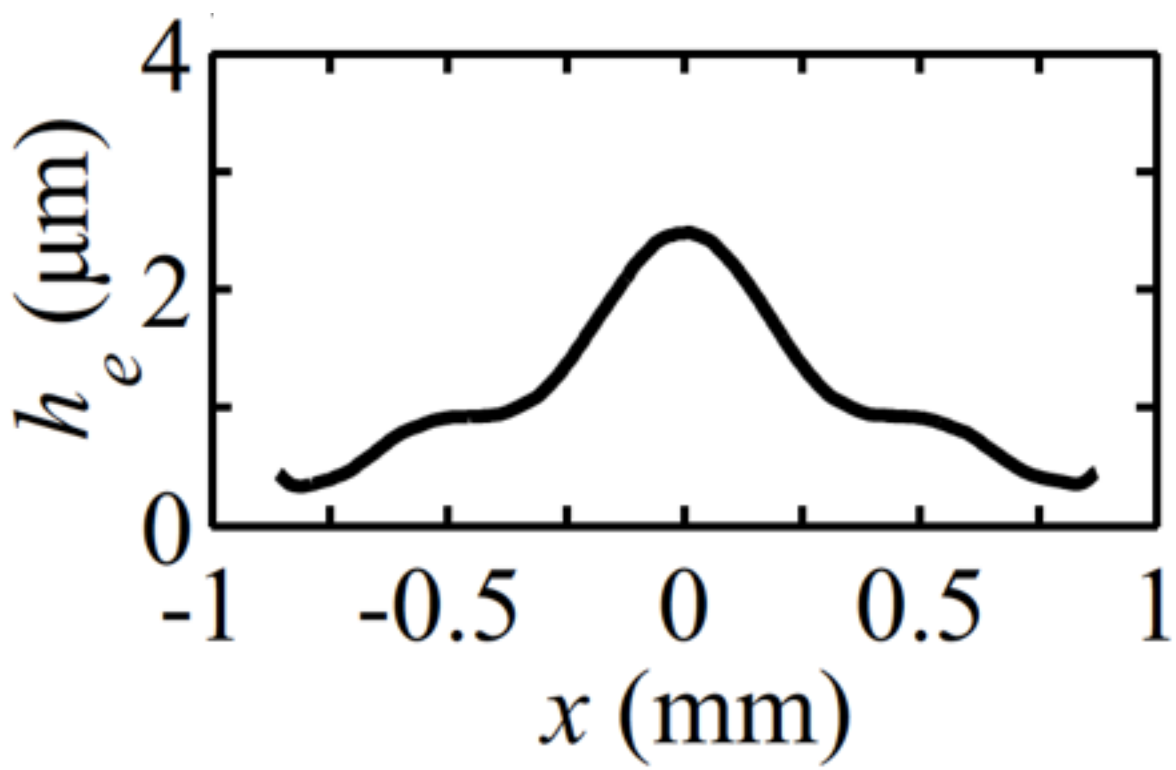




assume incompressibility

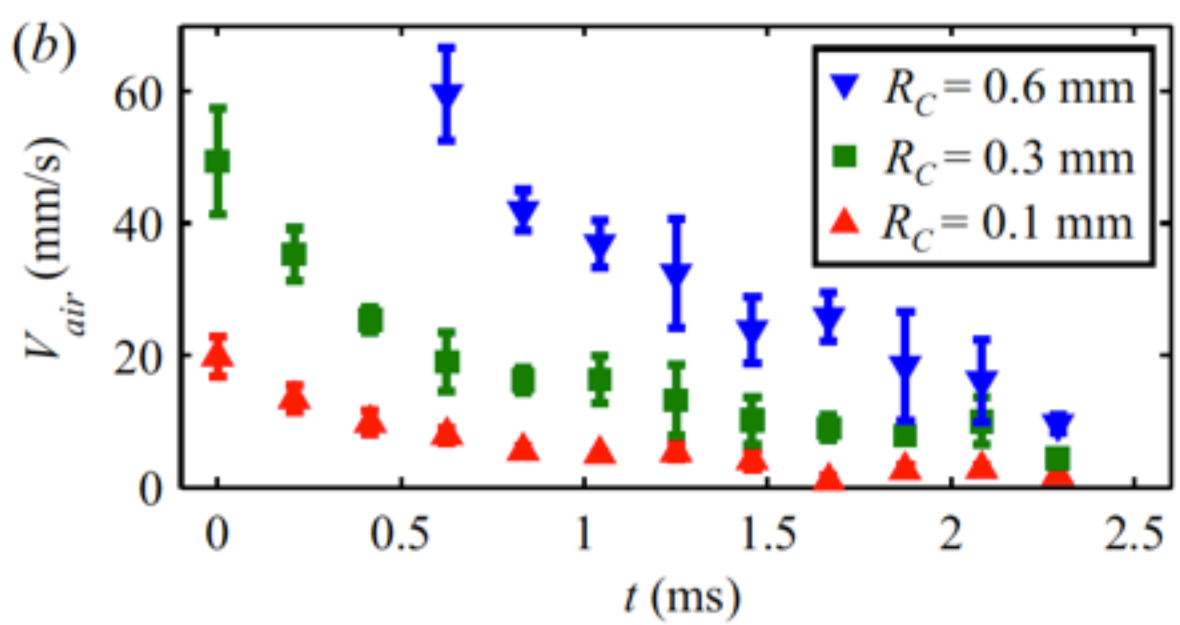
60 x higher air flow velocities!

Note the numbers...



$$Re \sim \frac{V_{air}\, h_e}{\nu_{air}}$$

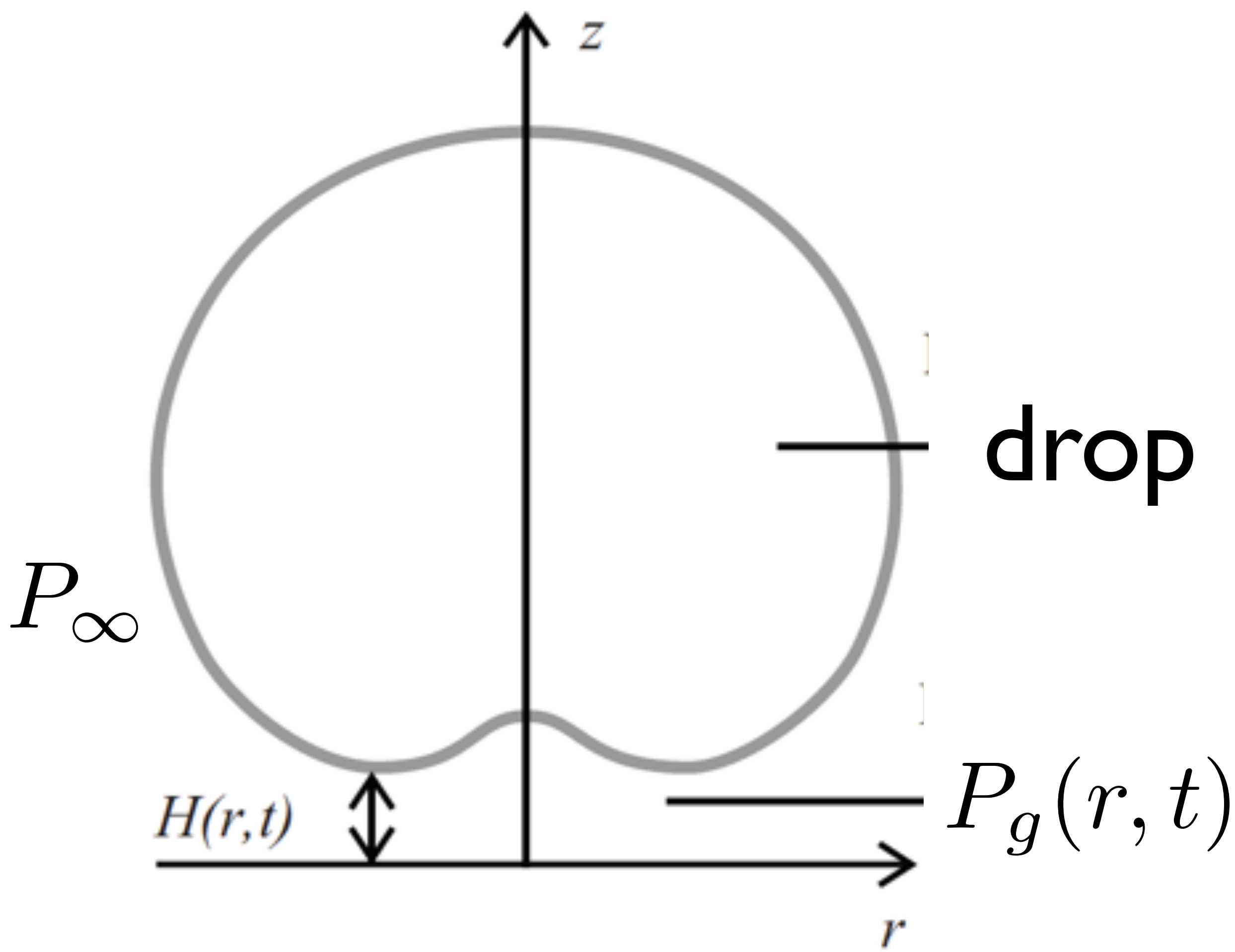
$$\sim 0.01$$



Air-flow under the drop is viscous flow!

Numerics & theory

Compare to BI calculations



Laplace equation:

$$\nabla^2 \phi = 0$$

Solve for

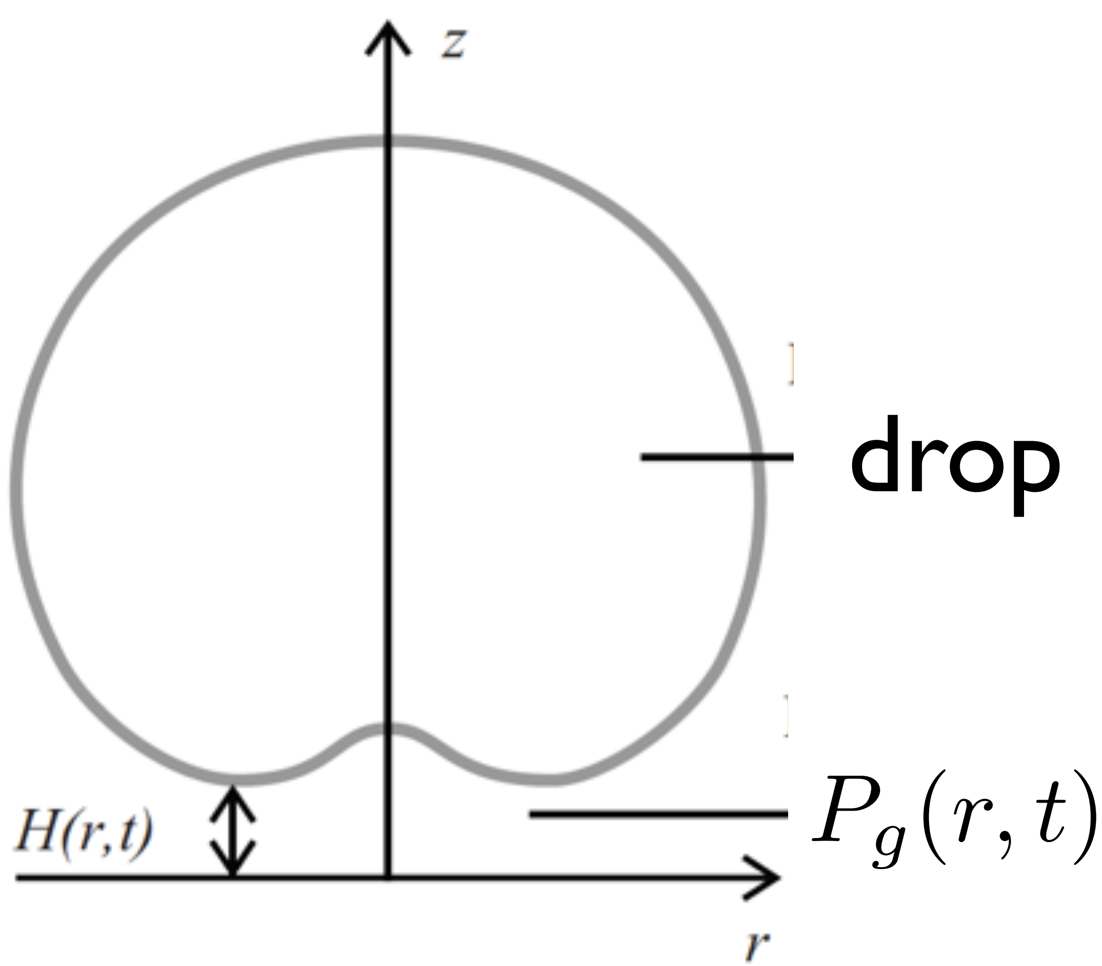
$H(r,t)$ & $P_g(r,t)$

Unsteady Bernoulli equation for liquid:

$$\partial_t \phi + 1/2 |\nabla \phi|^2 = -gz - \frac{\gamma}{\rho_l}\kappa(H(r,t)) - \frac{1}{\rho_l}(P_g(r,t) - P_\infty)$$

Obtain pressure from Stokes equation for gas (viscous!) in lubrication approximation

$$\partial_t H(r,t) - \frac{1}{r}\frac{\partial}{\partial_r}\left(\frac{r(H(r,t))^3}{12\eta_g}\partial_r P_g(r,t)\right) = 0$$



Solve the two coupled PDEs for

$H(r,t)$ & $P_g(r,t)$

Dimensionless numbers

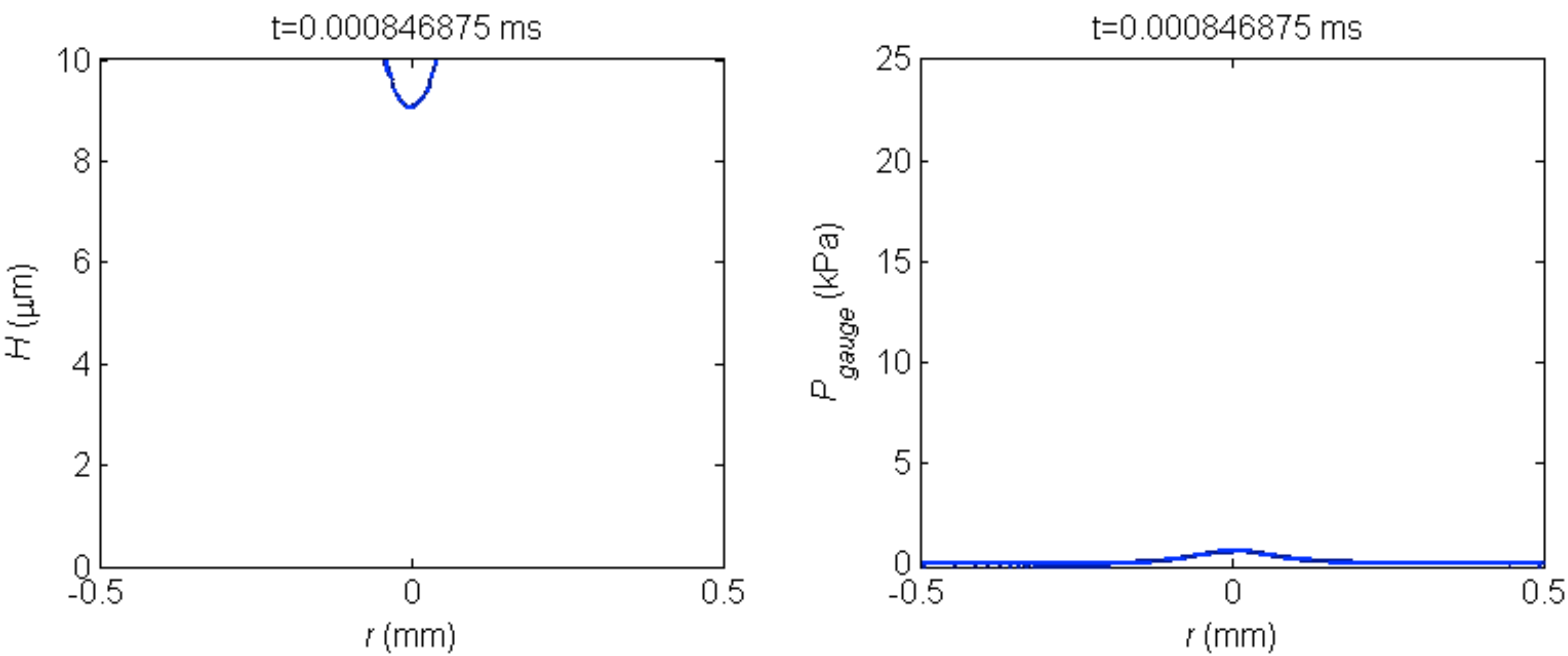
Weber number: $$We = \frac{\rho_l R U^2}{\gamma}$$

Bond number: $$Bo = \frac{\rho_l g R^2}{\gamma}$$

Gas flow relevant:
(inverse) Stokes number: $$St = \frac{\eta_g}{\rho_l U R}$$

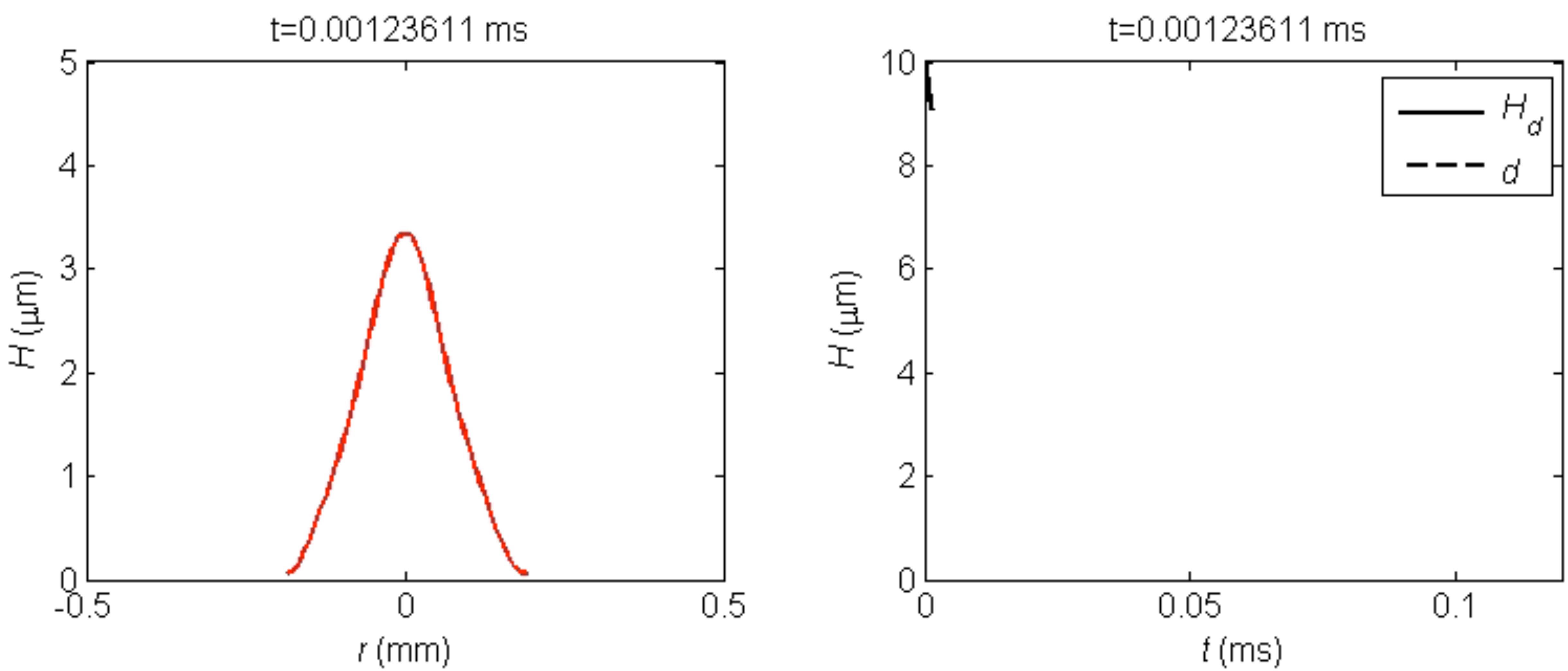
Capillary number: $$Ca = \frac{\eta_g U}{\gamma} = St \cdot We$$

Profile & pressure



ethanol, U=1.12m/s, D=1.8mm, We=40

Profile dynamics in inertial regime: comparison with experiment



U=1.12m/s,   We=40

no free parameter!

Under what conditions is the entrained bubble maximal?

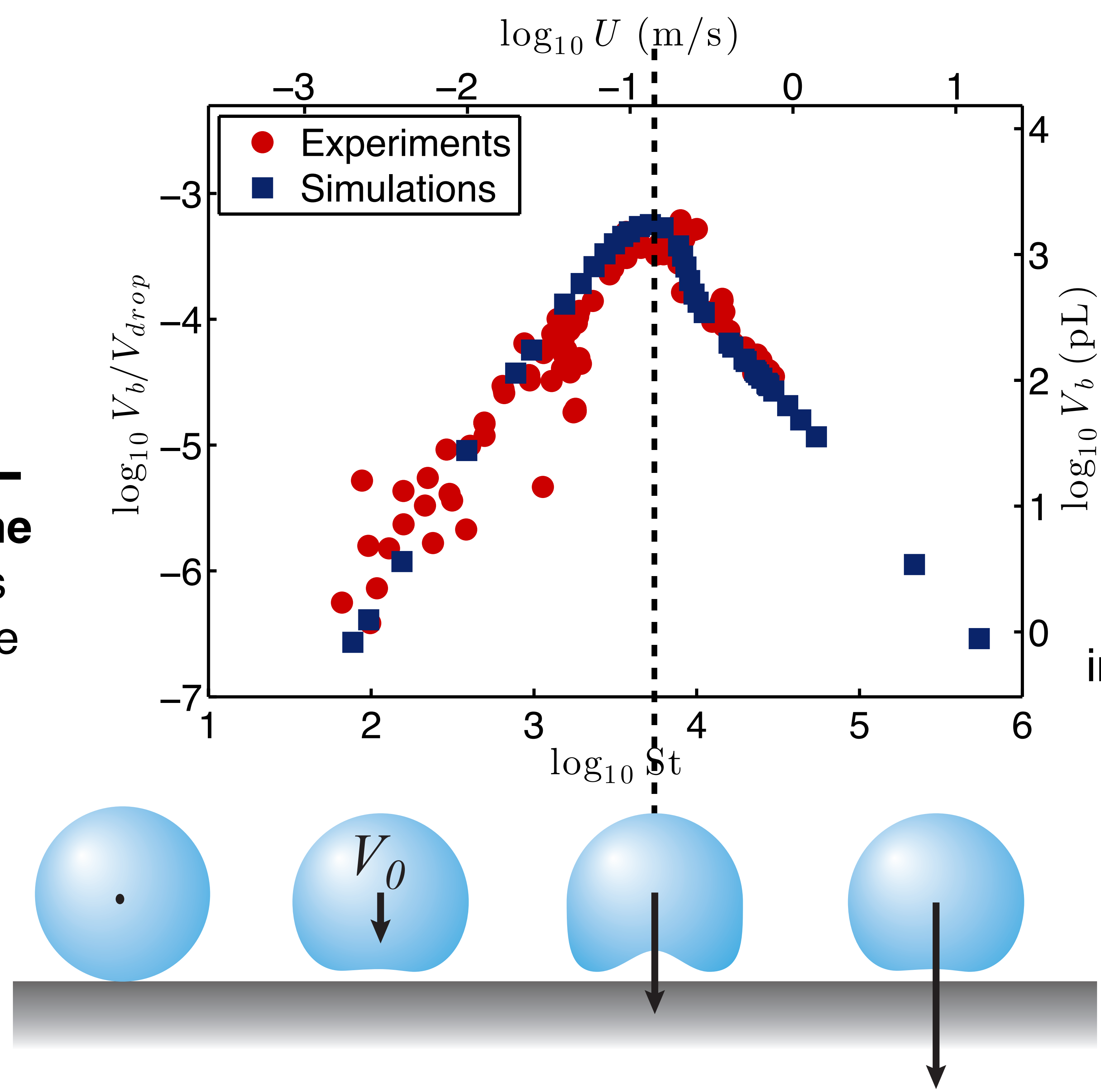
large U (and/or larger R):

inertia of impact makes smaller dimples

small U (and/or smaller R):

capillary forces make smaller dimples

Entrapped bubble size at impact

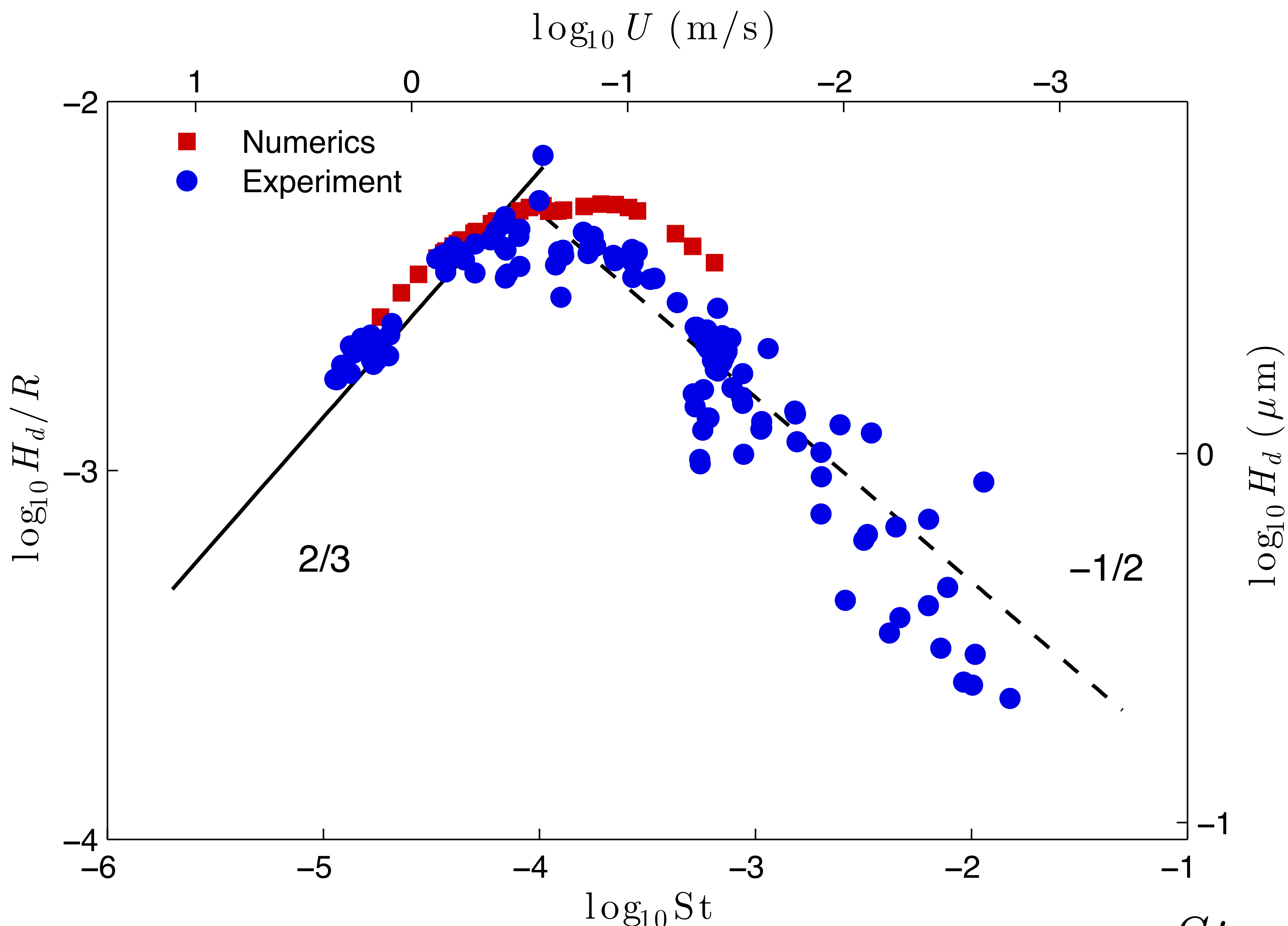


Capillary regime
capillary forces
minimize bubble

Inertial regime
inertia flattens bubble

Bouwhuis et al.,
PRL 109, 264501 (2012)

Experimental & numerical data: dimple height



Bouwhuis et al., Phys. Rev. Lett. 109, 264501 (2012)

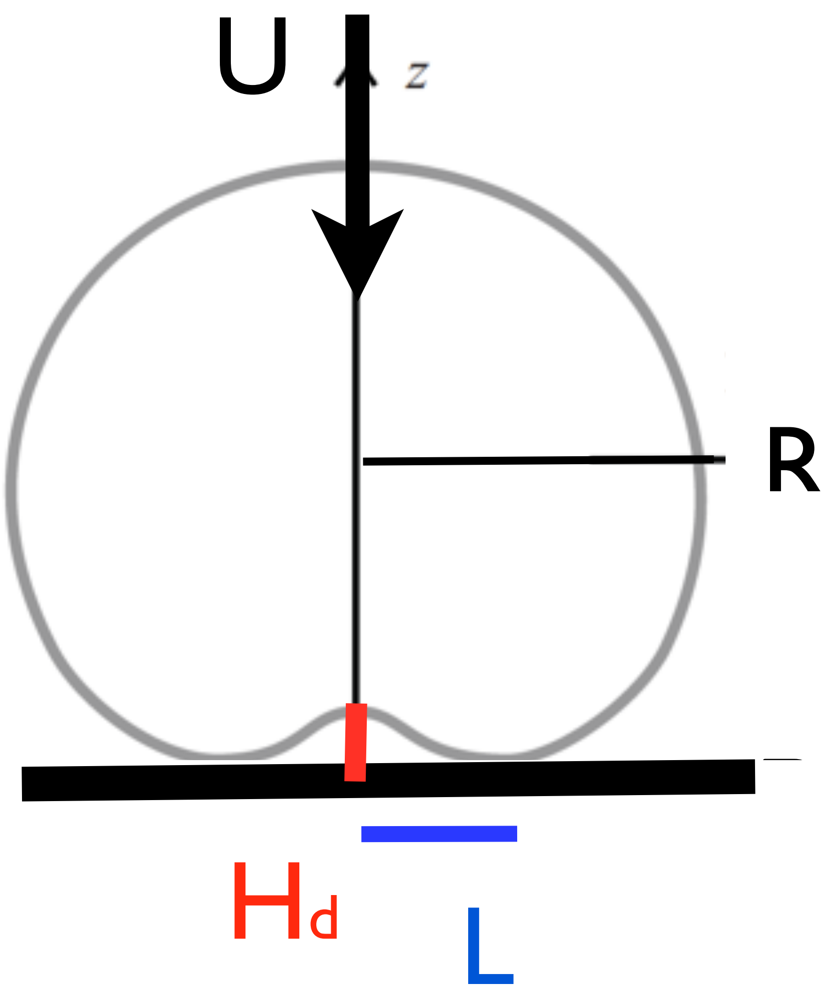
$$St = \frac{\eta_g}{\rho_\ell U R}$$

Indeed two regimes:

- inertial regime
- capillary regime

Analytical derivation of scaling laws in the two regimes

Inertial regime:
Derivation of 4/3-scaling



horizontal lengthscale:

$$L \sim \sqrt{RH_d}$$

horizontal velocity:

$$u_x \sim LU/H_d$$

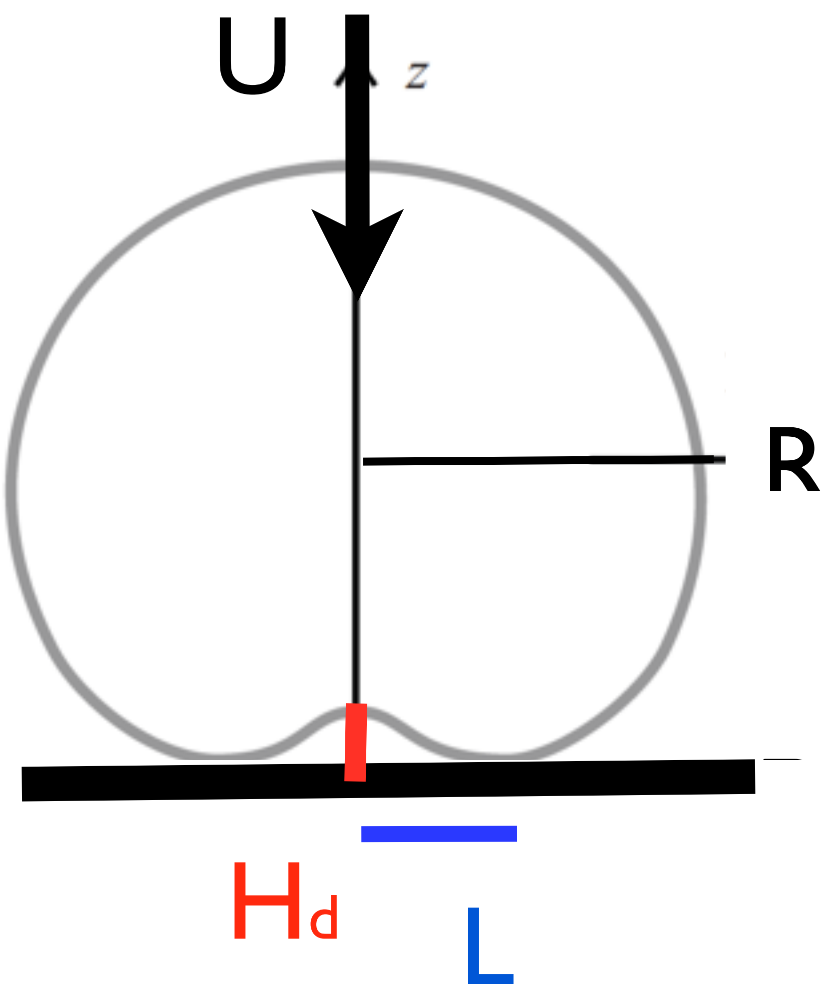
gas pressure: Stokes equation:

$$\partial_x p \sim \eta_g \partial_y^2 u_x$$

$$\frac{P_g}{L} \sim \eta_g \frac{u_x}{H_d^2}$$

(Mani, Mandre, Brenner, JFM 2010)

Inertial regime: Derivation of 4/3-scaling



liquid pressure from unsteady Bernoulli eq.:

$$\partial_t \phi \sim P_l / \rho_l$$

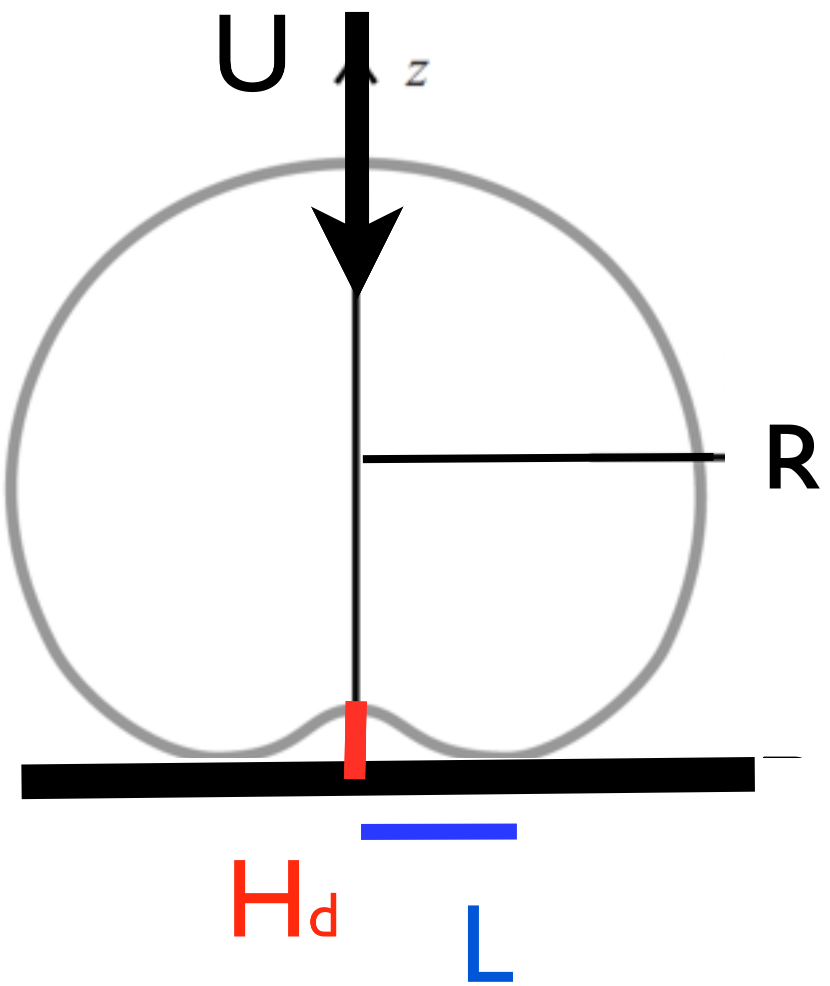
dimensional analysis:

$$\phi \sim UL \qquad \partial_t \sim U / H_d$$

liquid pressure:

$$P_l \sim \rho_l U^2 L / H_d$$

Inertial regime: Derivation of 4/3-scaling



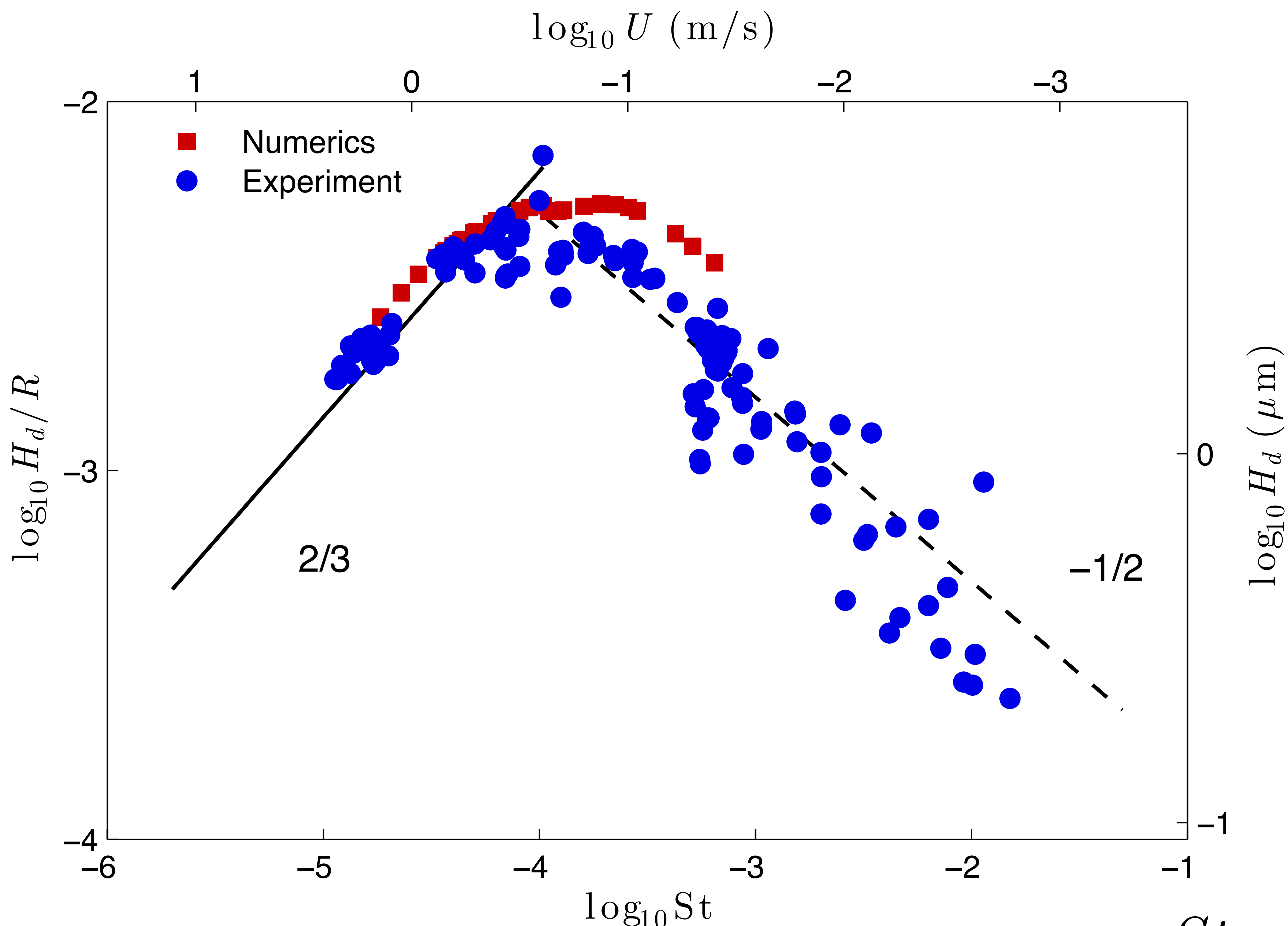
Droplet deforms once:

$$P_g \sim P_l$$

$$H_d \sim R\ St^{2/3}$$

$$V_b \sim L^2 H_d \sim R^3\ St^{4/3}$$

Experimental & numerical data: dimple height



Bouwhuis et al., Phys. Rev. Lett. 109, 264501 (2012)

$$St = \frac{\eta_g}{\rho_\ell U R}$$

Scaling in capillary regime

balance capillary and viscous forces:

$$\partial_x(\gamma\kappa(H(x)) \sim \eta_g \partial_z^2 u_x$$

$$\frac{H_d}{R} \sim \sqrt{Ca} \sim \sqrt{St\ We} \sim \frac{\eta_g}{\sqrt{\gamma\rho_l R}} St^{-1/2}$$

Crossover, when: $St \sim Ca^{3/4}$

Maximum in dimple height

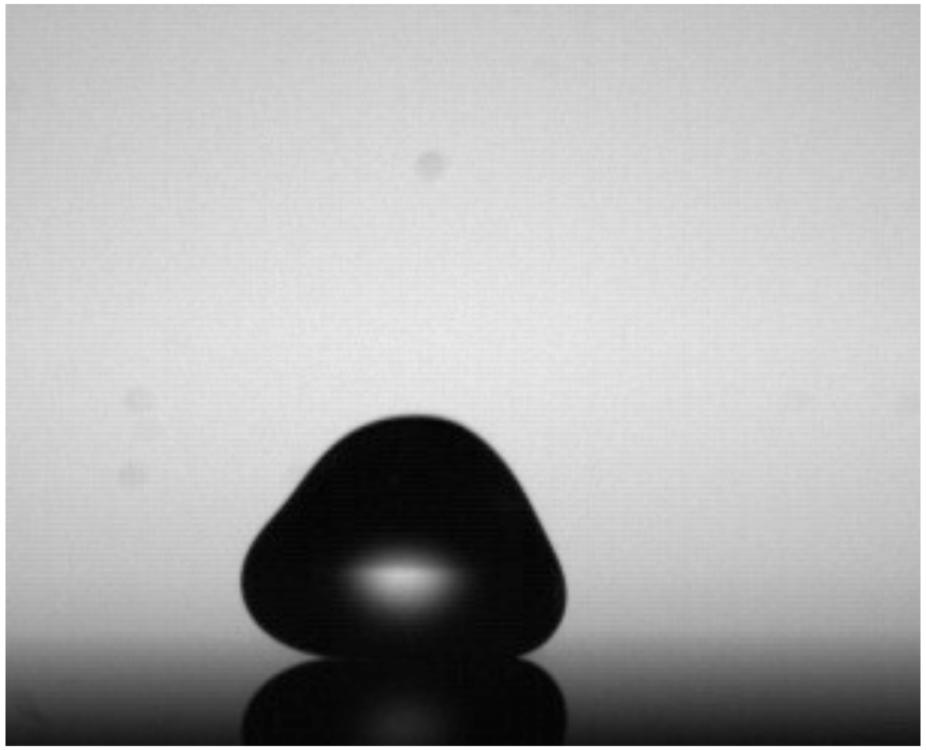
at:

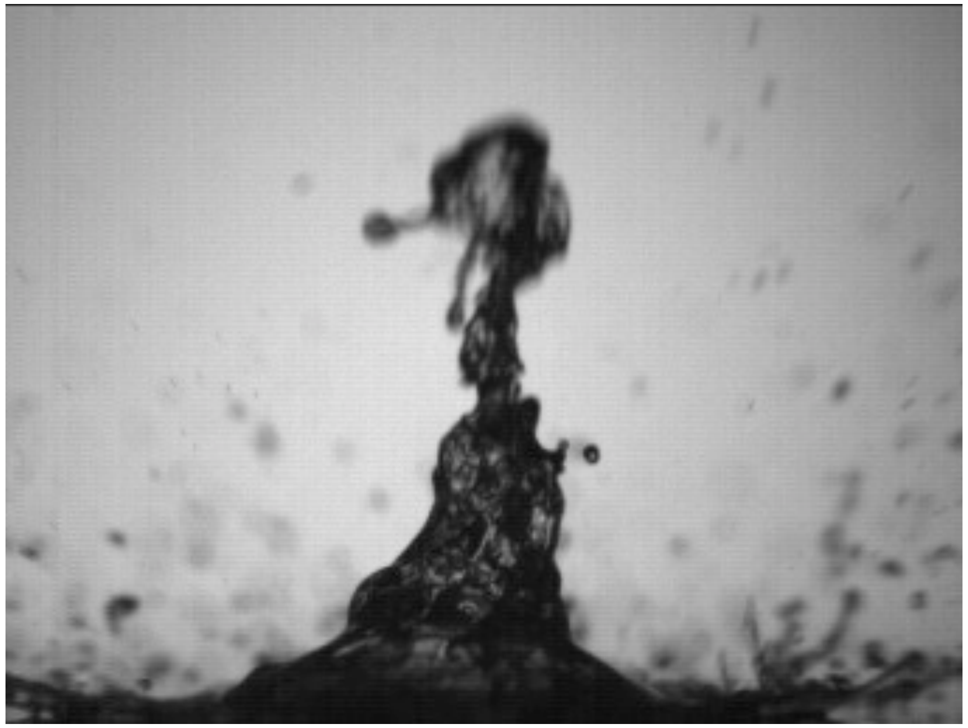
$$St \sim Ca^{3/4} \sim \frac{\eta_g^{6/7}}{(\gamma \rho_l R)^{3/7}}$$

smaller St = larger U (and/or larger R):
inertia of impact makes smaller dimples

larger St = smaller U (and/or smaller R):
capillary forces make smaller dimples

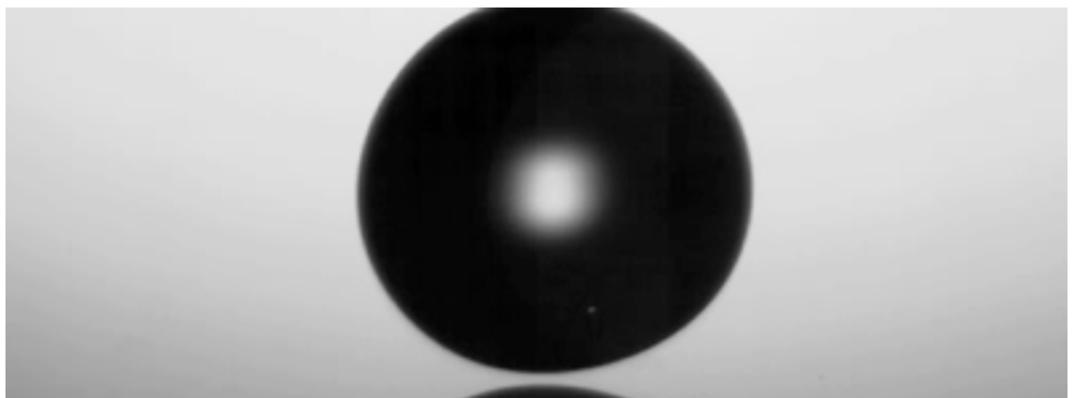
Impact on superheated surfaces

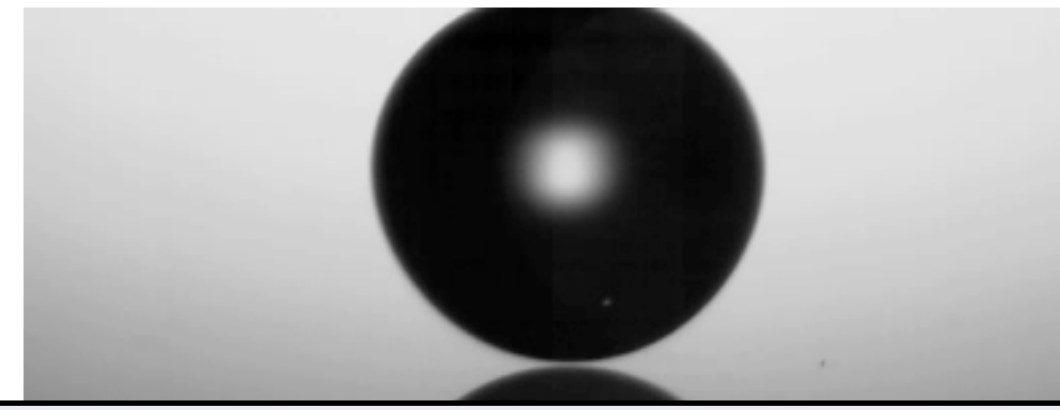




Tran, Staat, Prosperetti, Sun, Lohse, PRL 108, 036101 (2012)

Influence of surface temperature



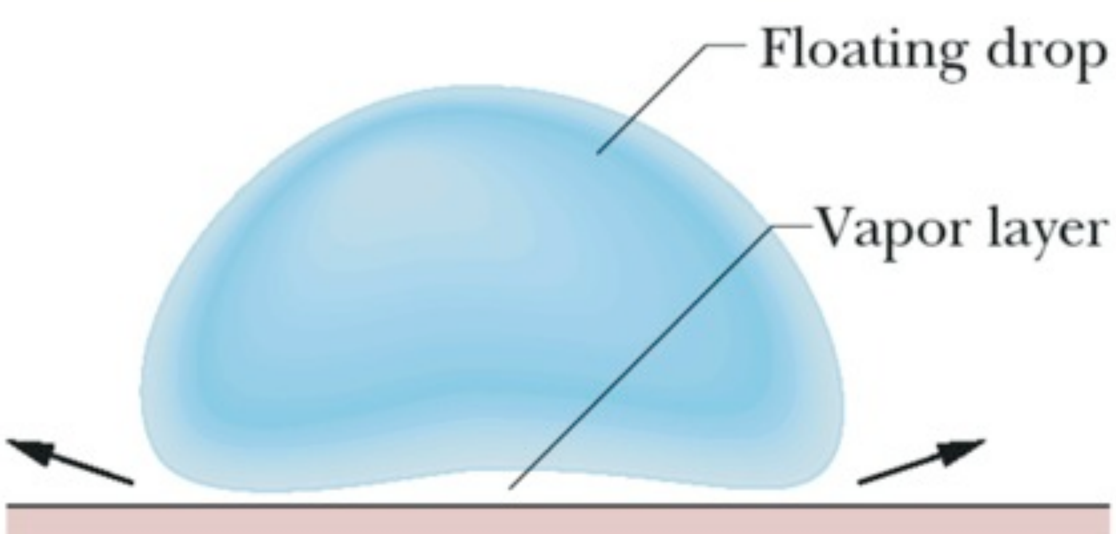


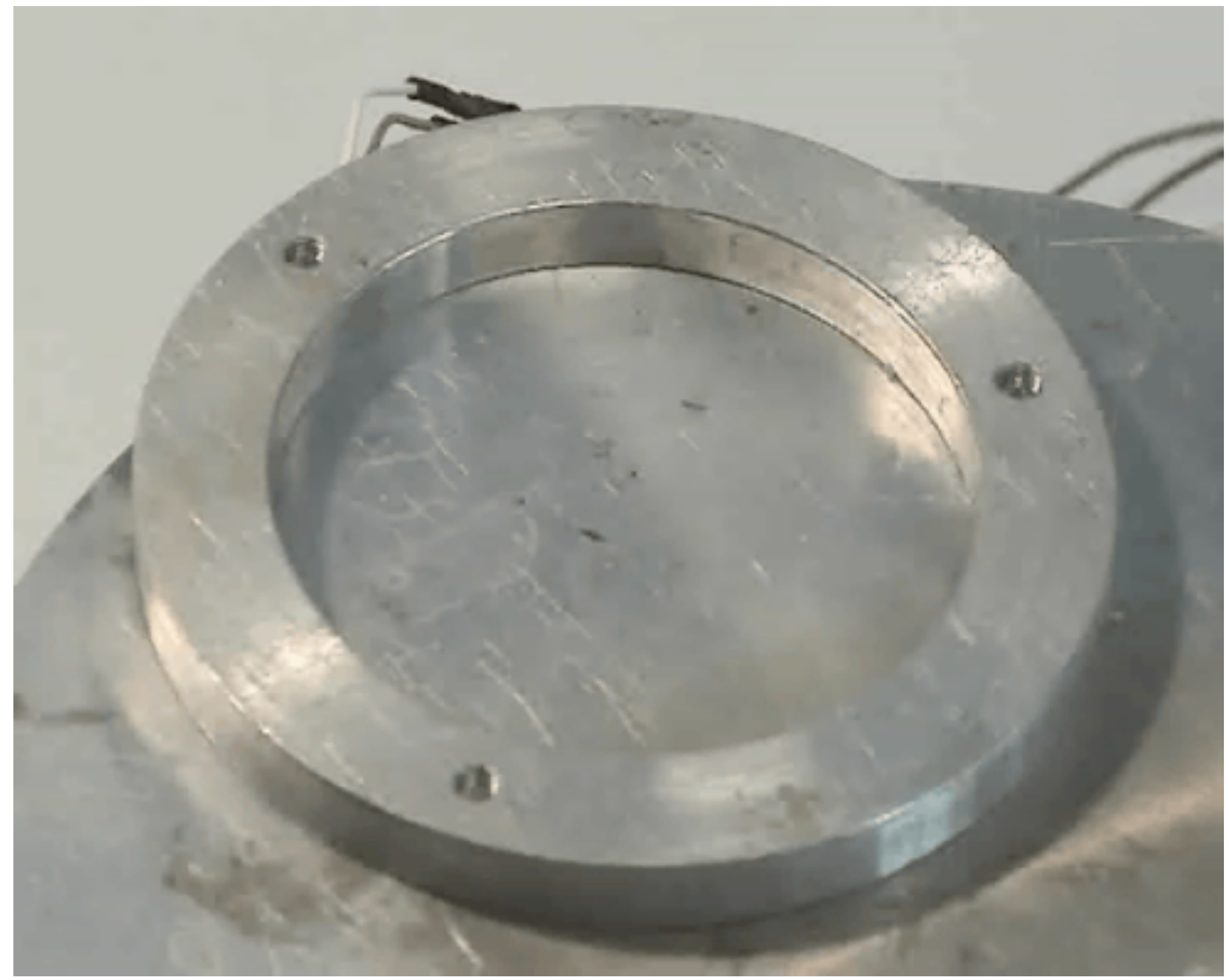
T = 200°C

T = 300°C

$$T_{Leidenfrost} = 180^o C$$ (static)

Static Leidenfrost effect

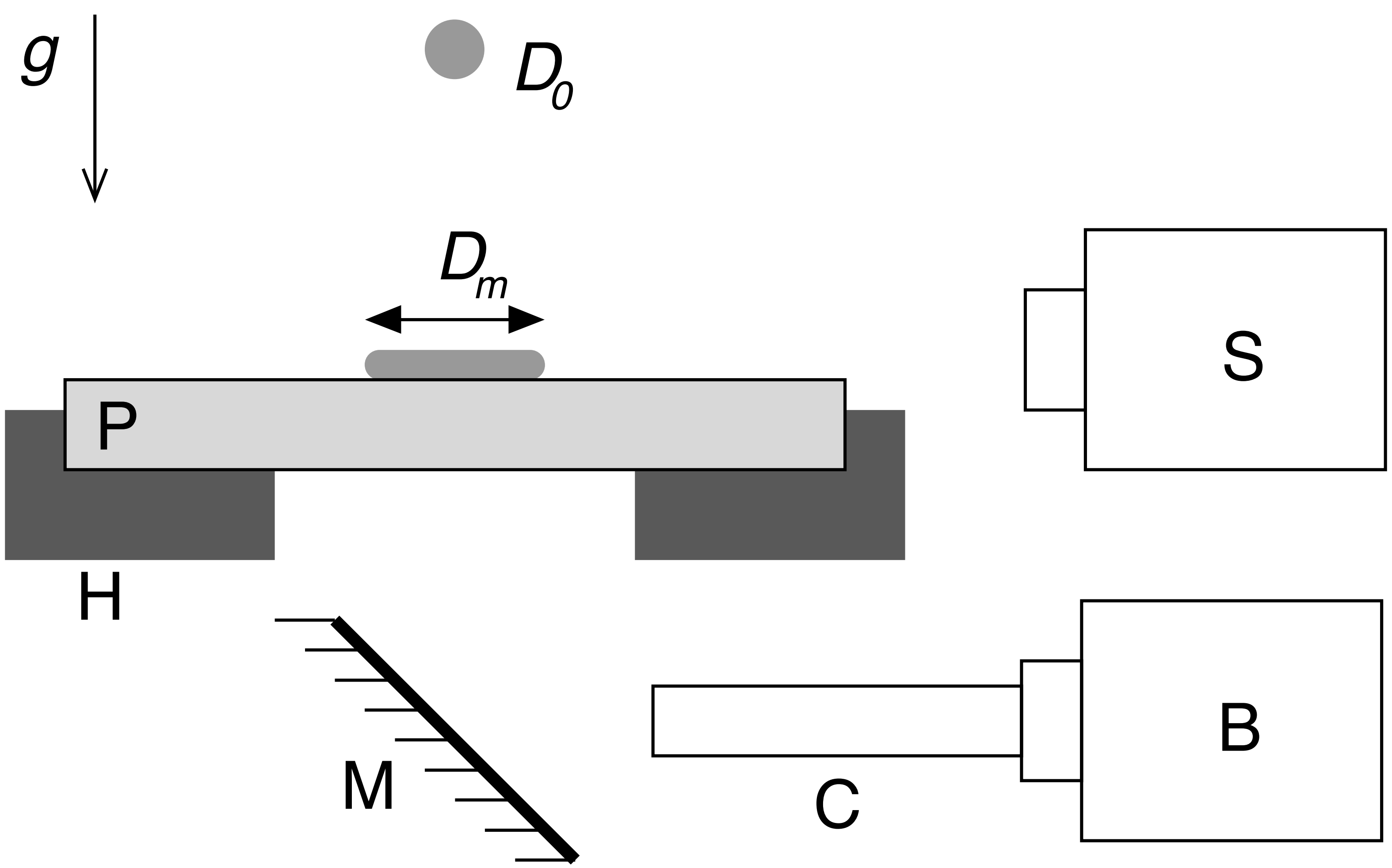




Johann Gottlob Leidenfrost (1756)

Towards the dynamic Leidenfrost effect

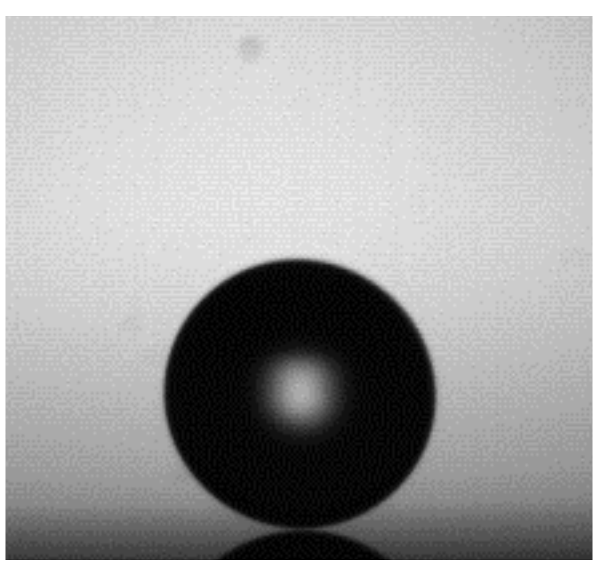
Experimental setup

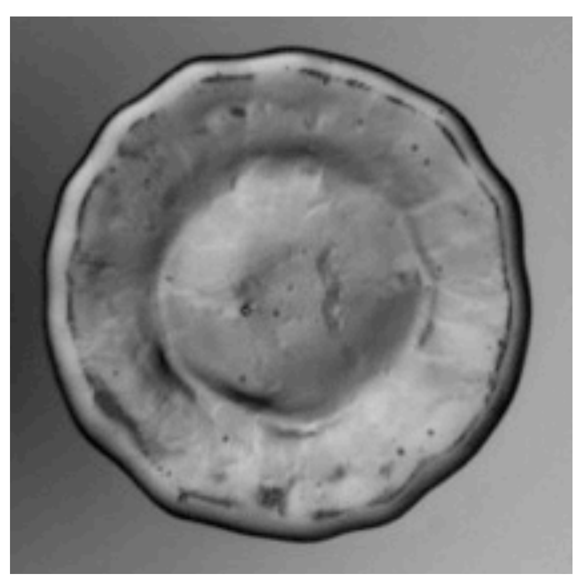


- Liquids: water & FC-72
- Surfaces: polished silicon, structured silicon, **sapphire** & carbon nano fibers
- Control parameters:

$$200^oC \leq T \leq 600^oC$$

$$0.5 \leq \mathrm{We} = \frac{\rho D_0 V^2}{\sigma} \leq 500$$

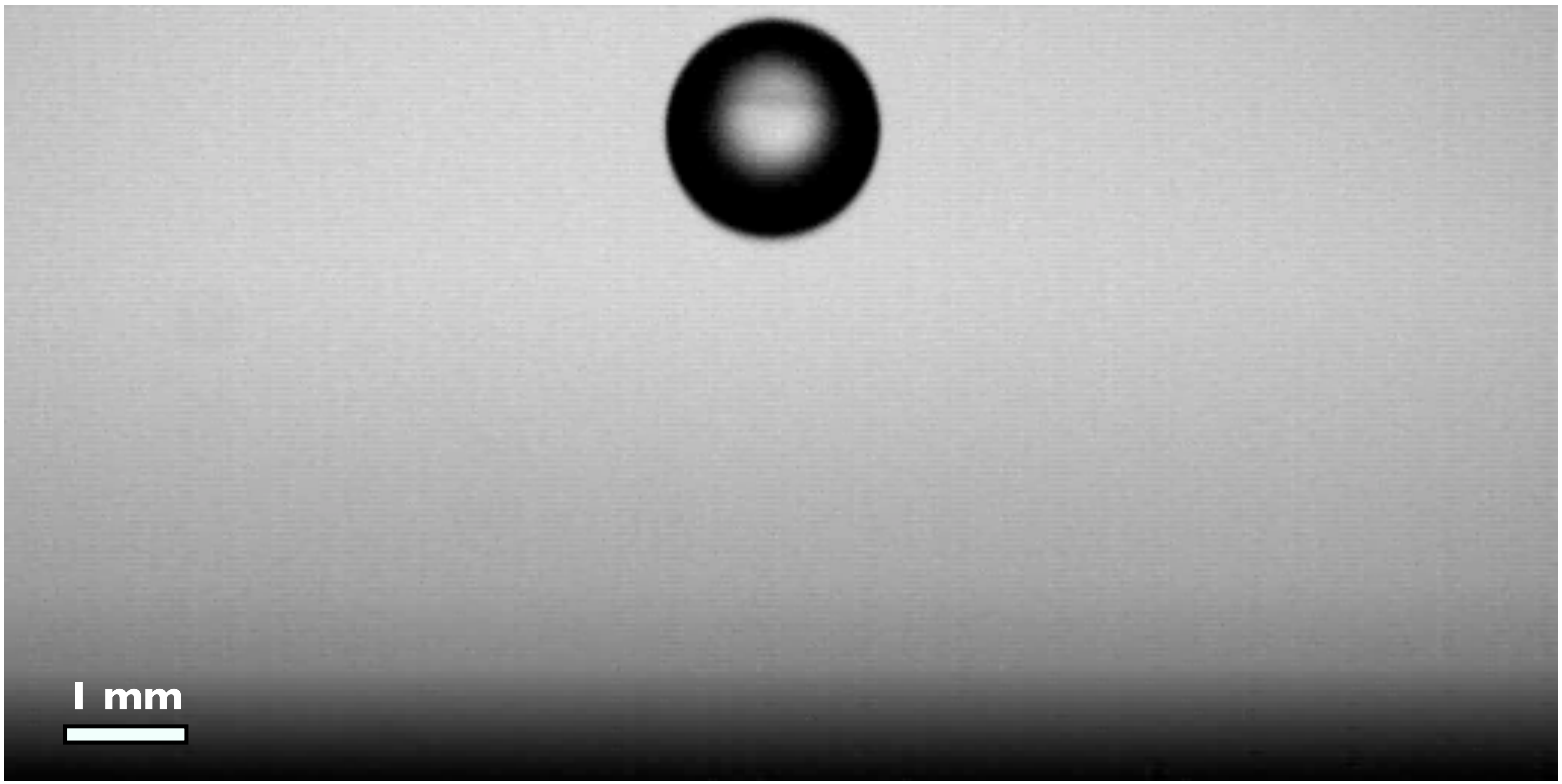




Different boiling regimes:

1. Contact boiling

Side view recording

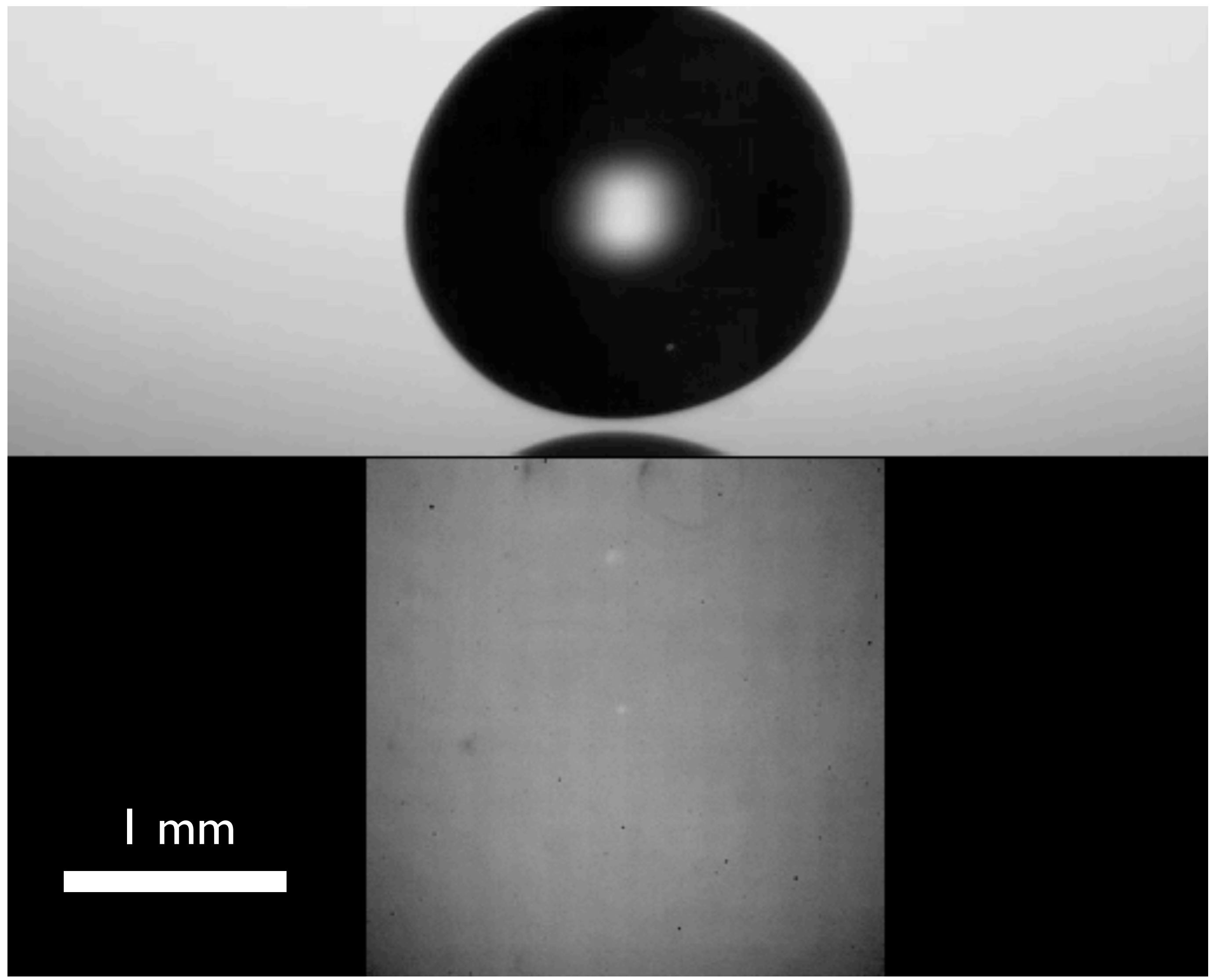


T = 400 °C

We = 67.7

1. Contact boiling

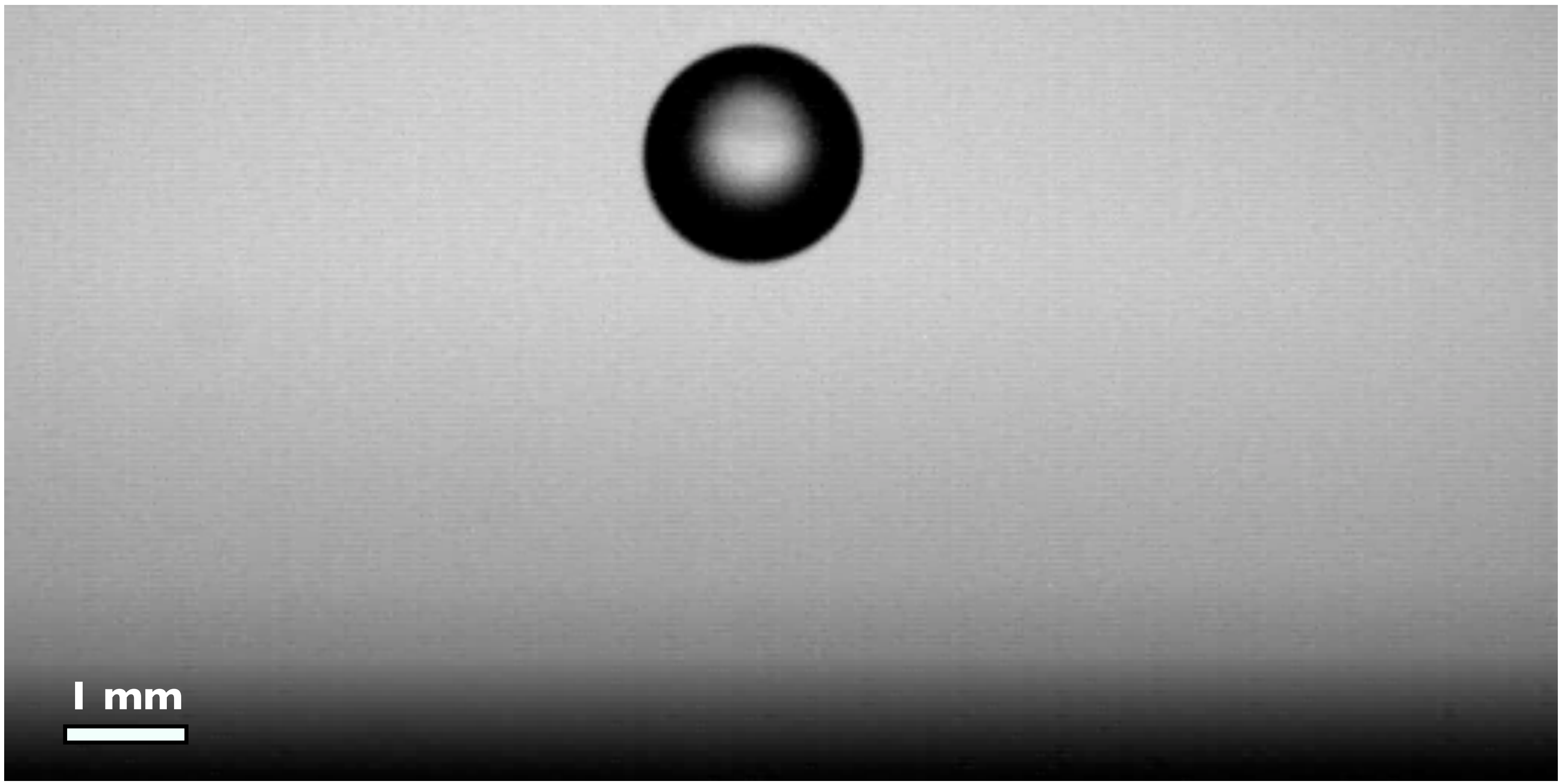
Bottom interferometric view



Liquid makes contact with the surface

2. Gentle film boiling

Side view recording

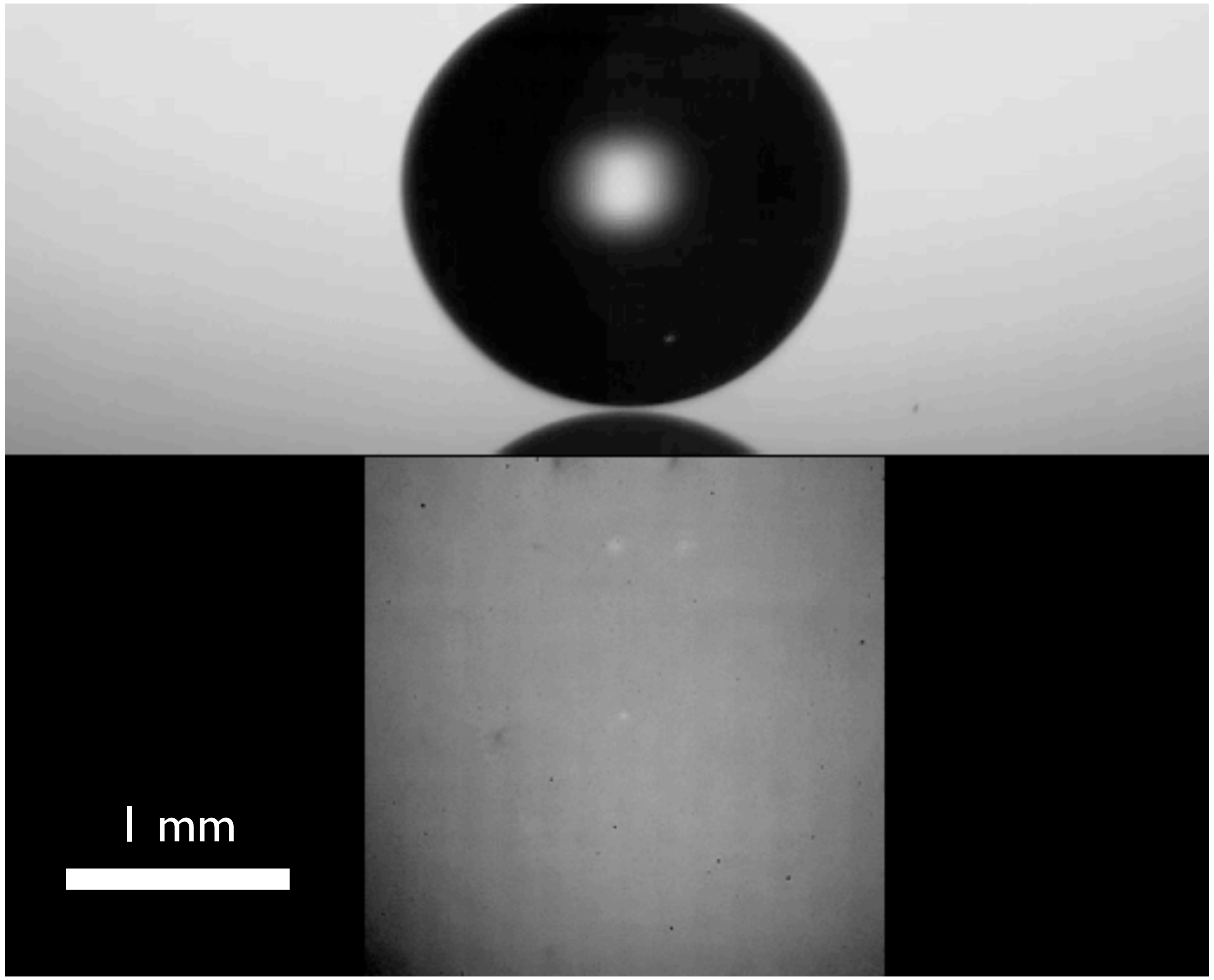


T = 460 °C

We = 66.7

2. Gentle film boiling

Bottom interferometric view

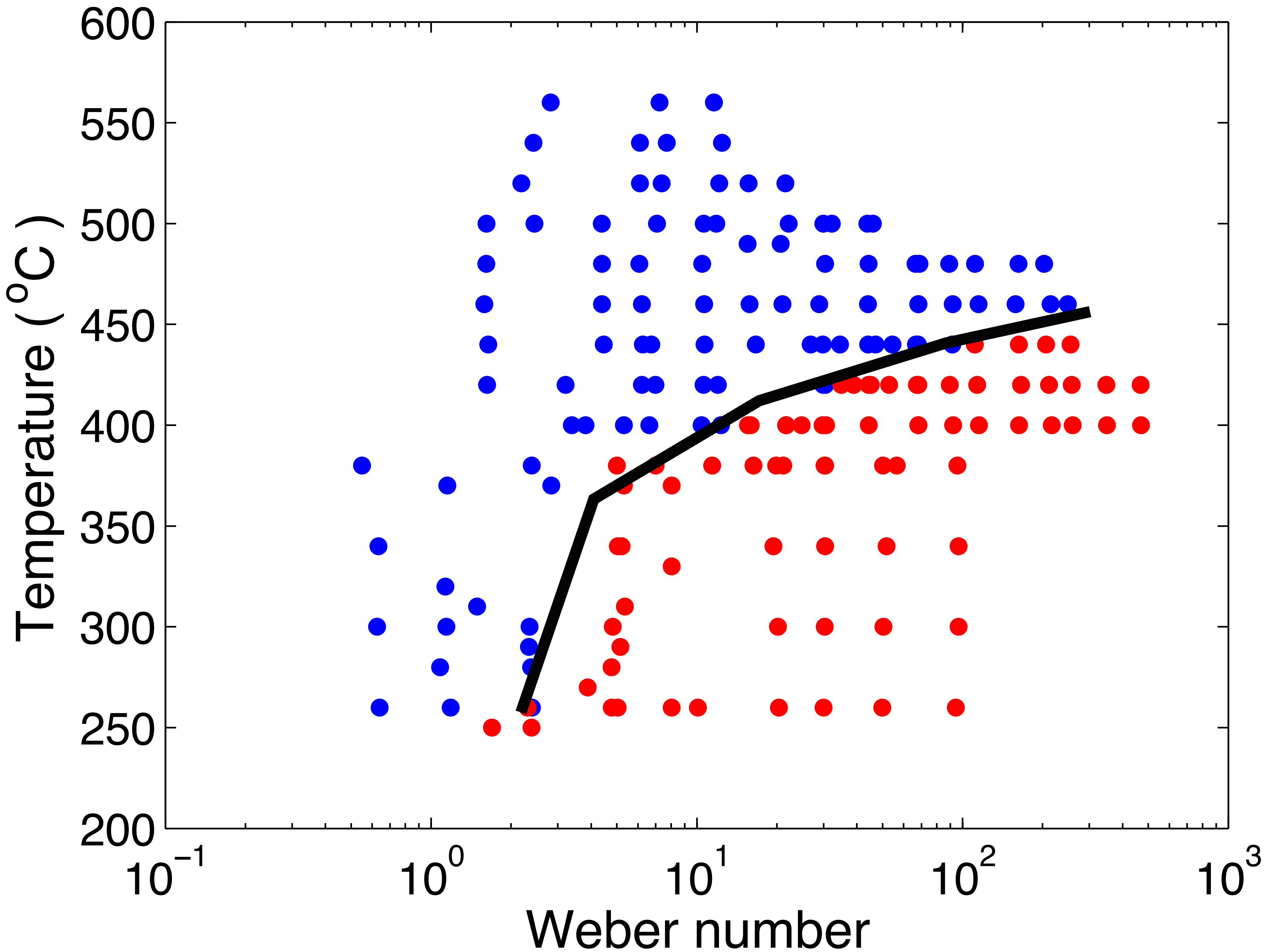


Liquid makes **no contact** with the surface:
(dynamic) Leidenfrost state

Phase diagram water on smooth silicon

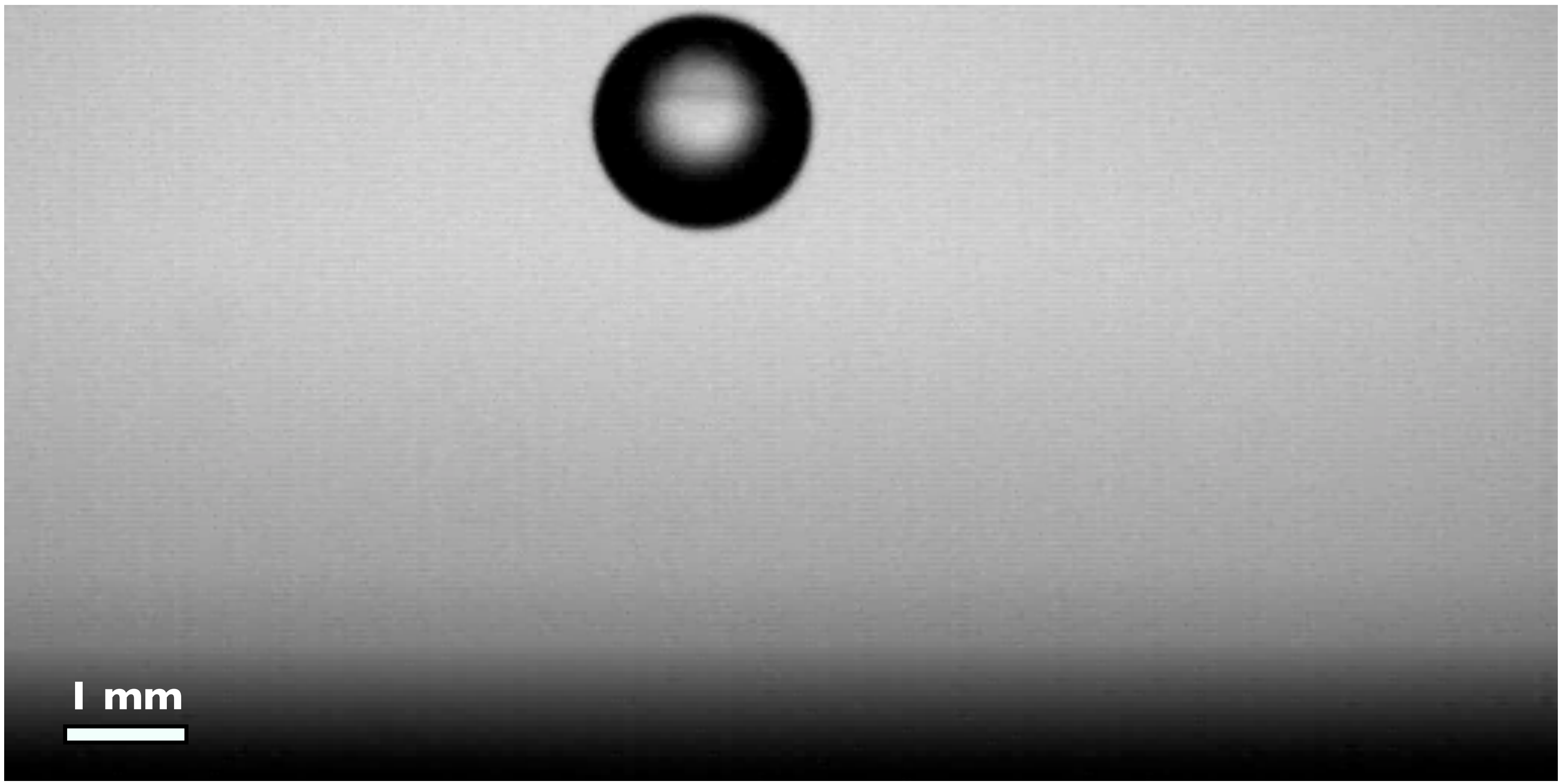
Contact boiling

Gentle film boiling



3. Spraying film boiling

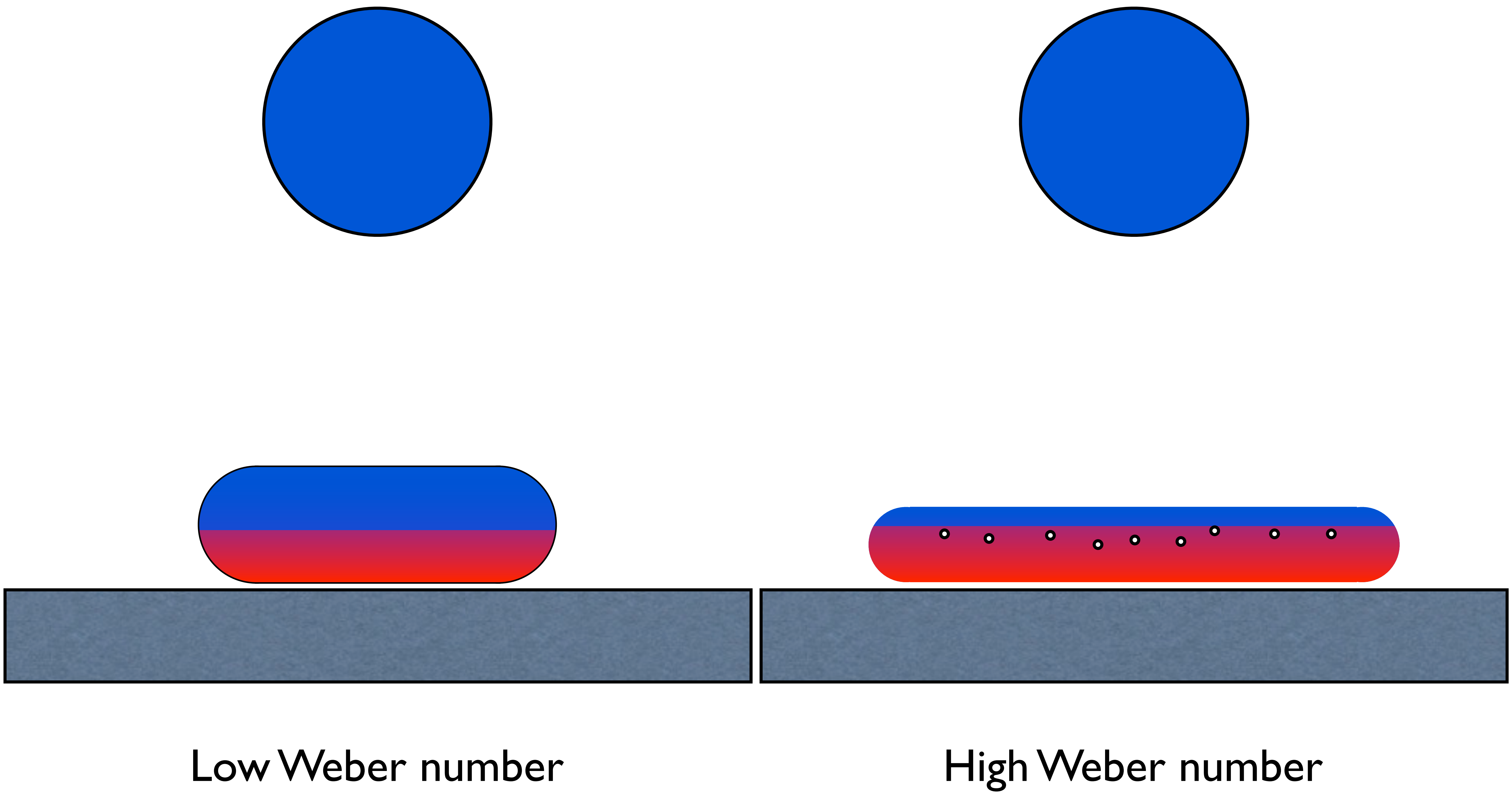
Side view recording



T = 520 °C

We = 65.4

Mechanism of spraying film boiling

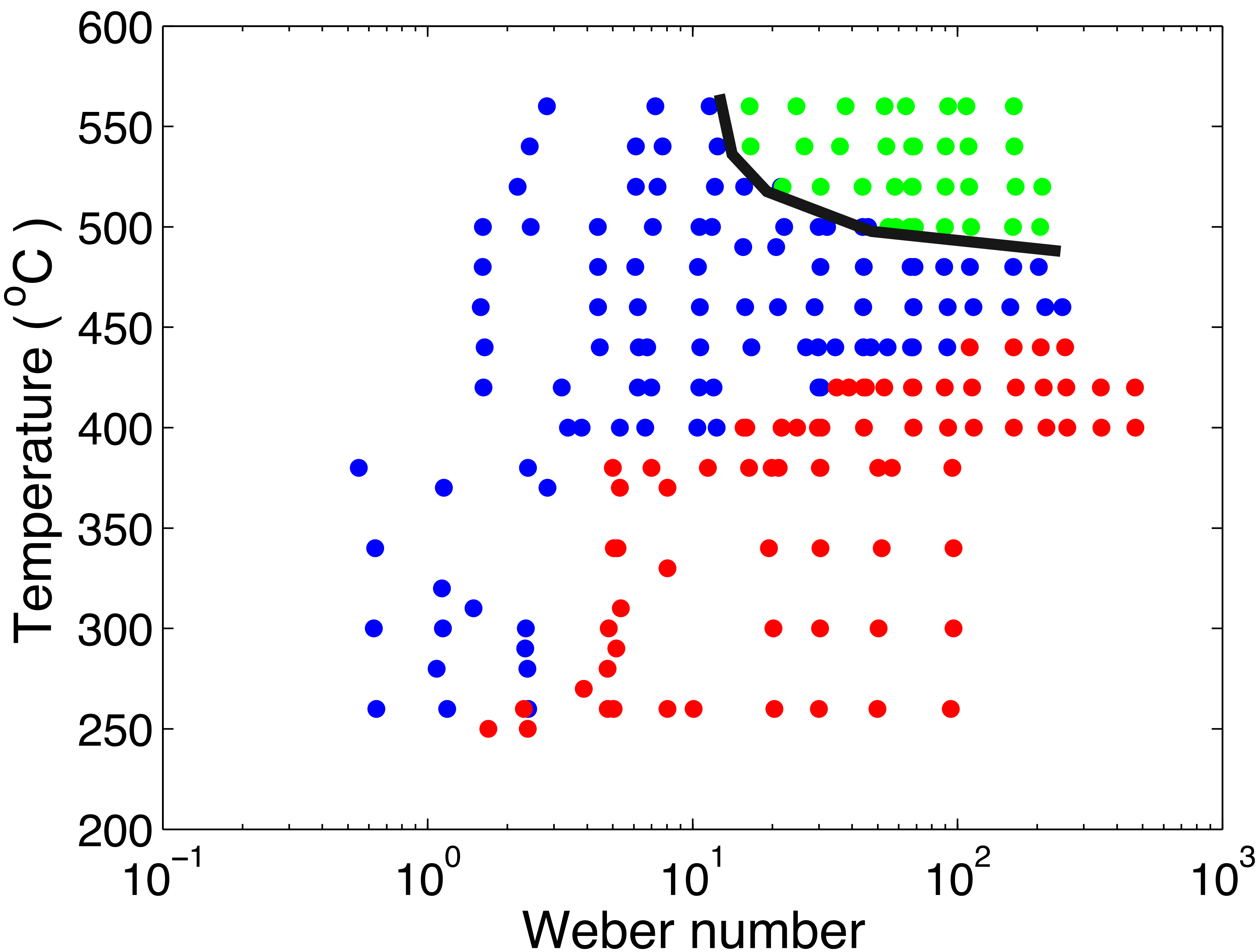


Phase diagram water on smooth silicon

Contact boiling

Gentle film boiling

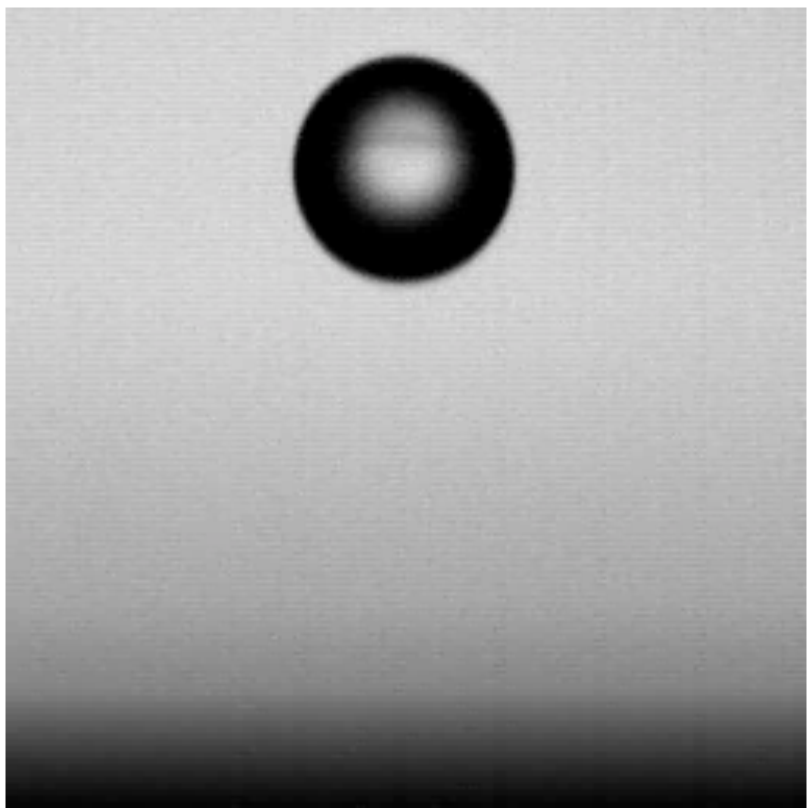
Spraying film boiling



Contains >1000 individual experiments

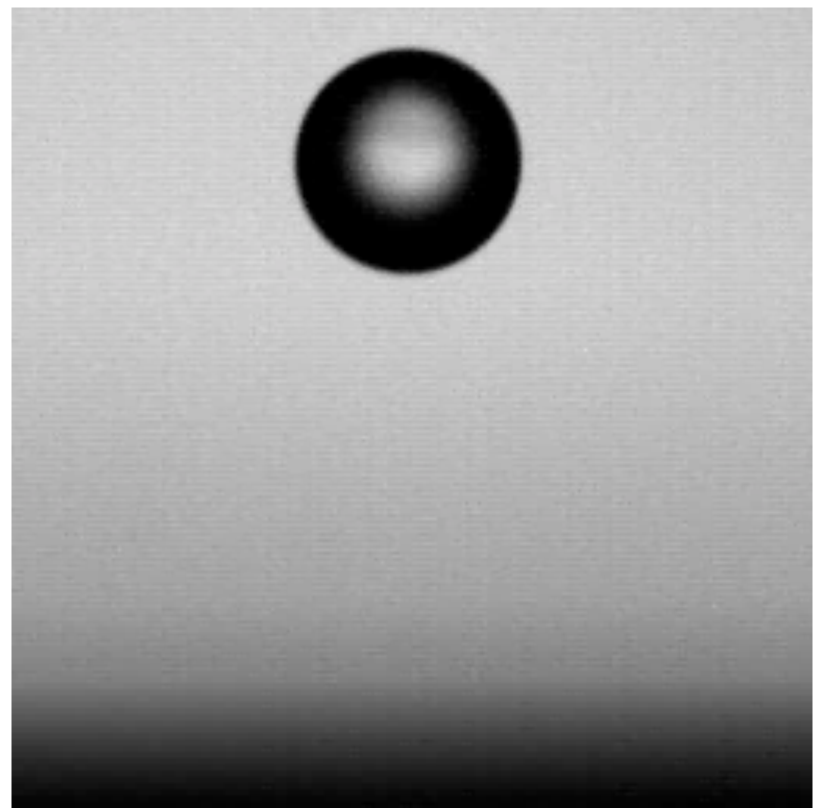
The three scenarios in comparison

Contact boiling



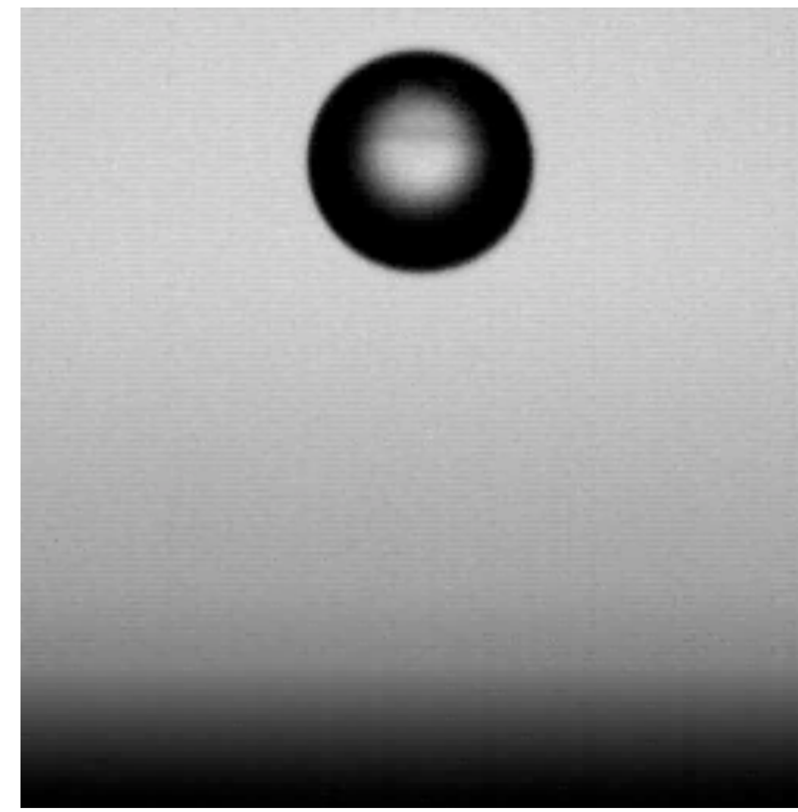
T = 400 °C

Gentle film boiling



T = 460 °C

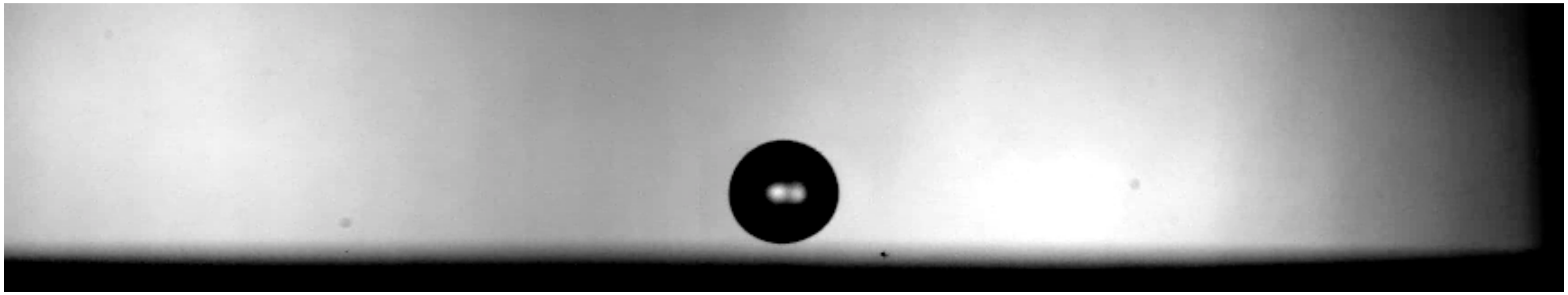
Spraying film boiling

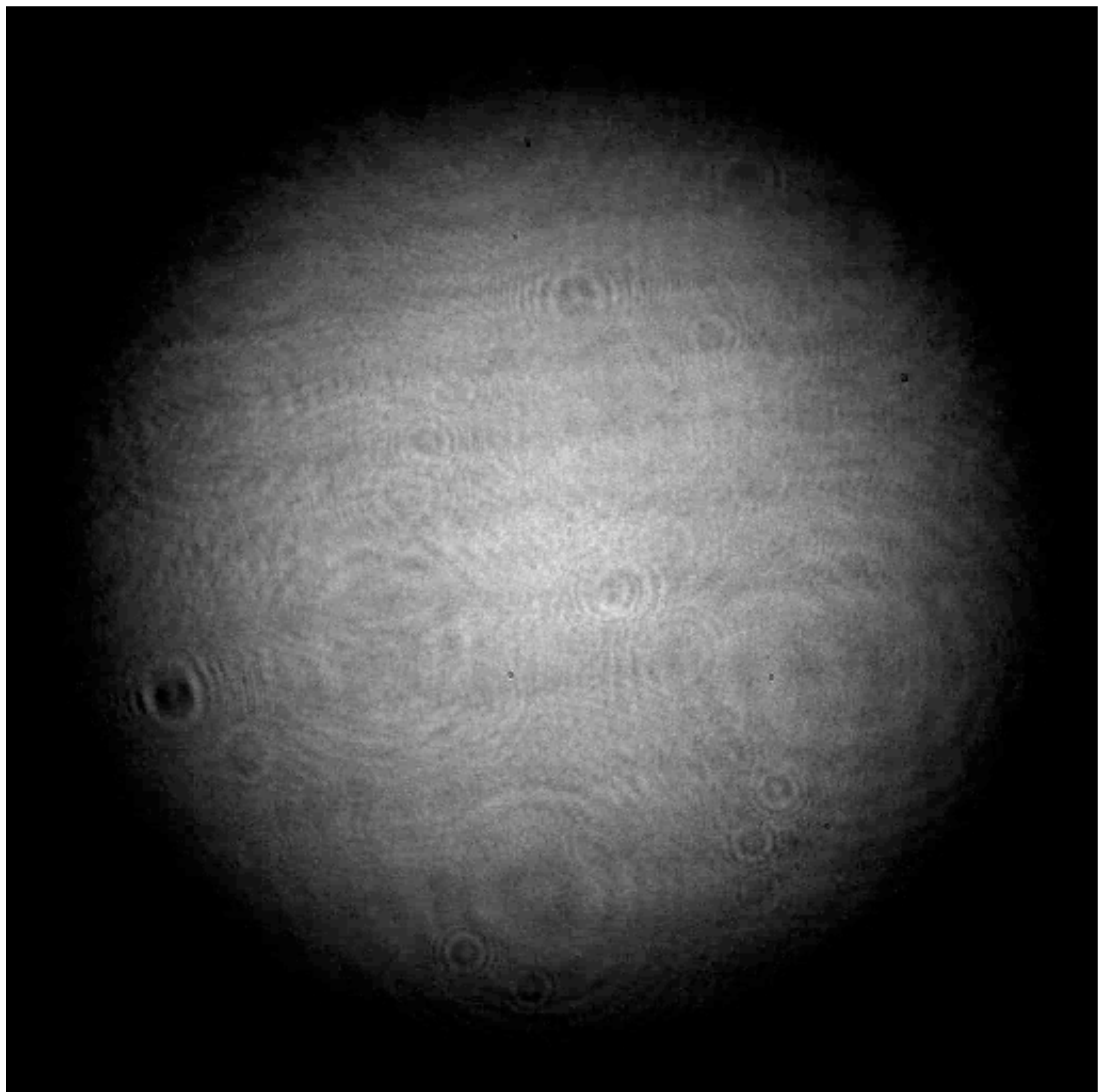


T = 520 °C

Is splashing possible in the Leidenfrost regime? (no contact!)

Film boiling splash

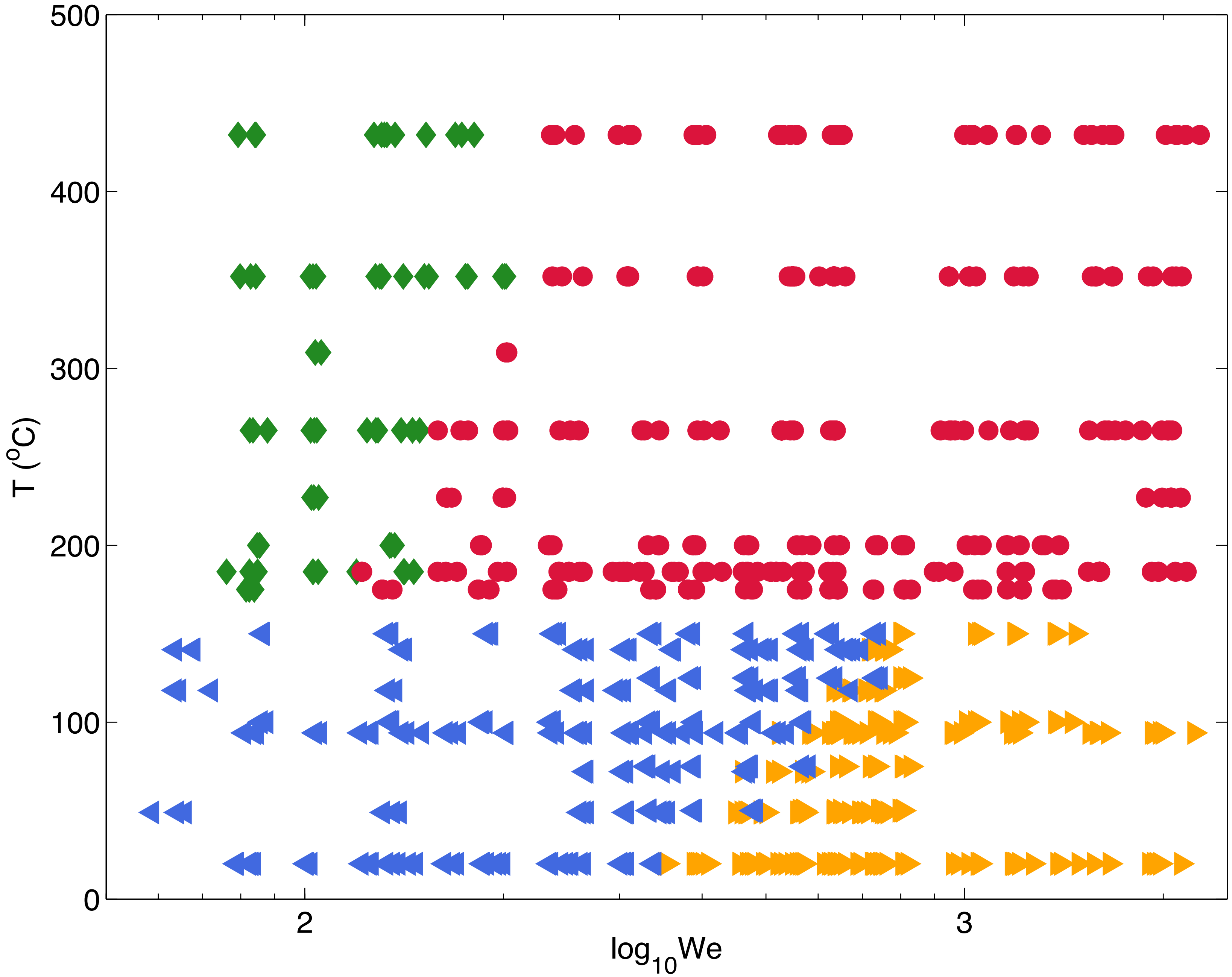




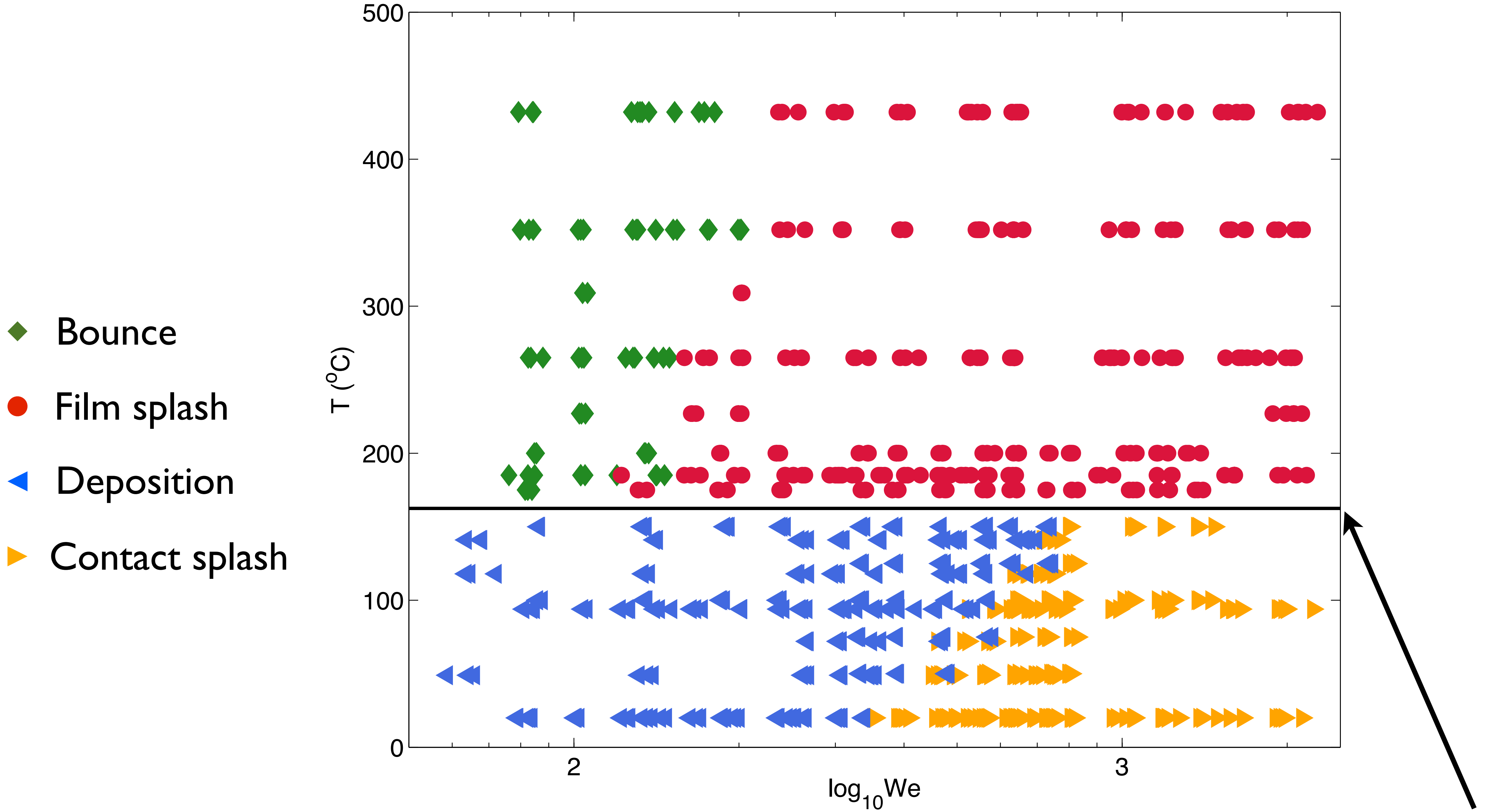
T = 200 ºC
D = 2.5mm
We = 1390
ethanol

Full phase space of boiling & splashing behavior

- Bounce
- Film splash
- Deposition
- Contact splash



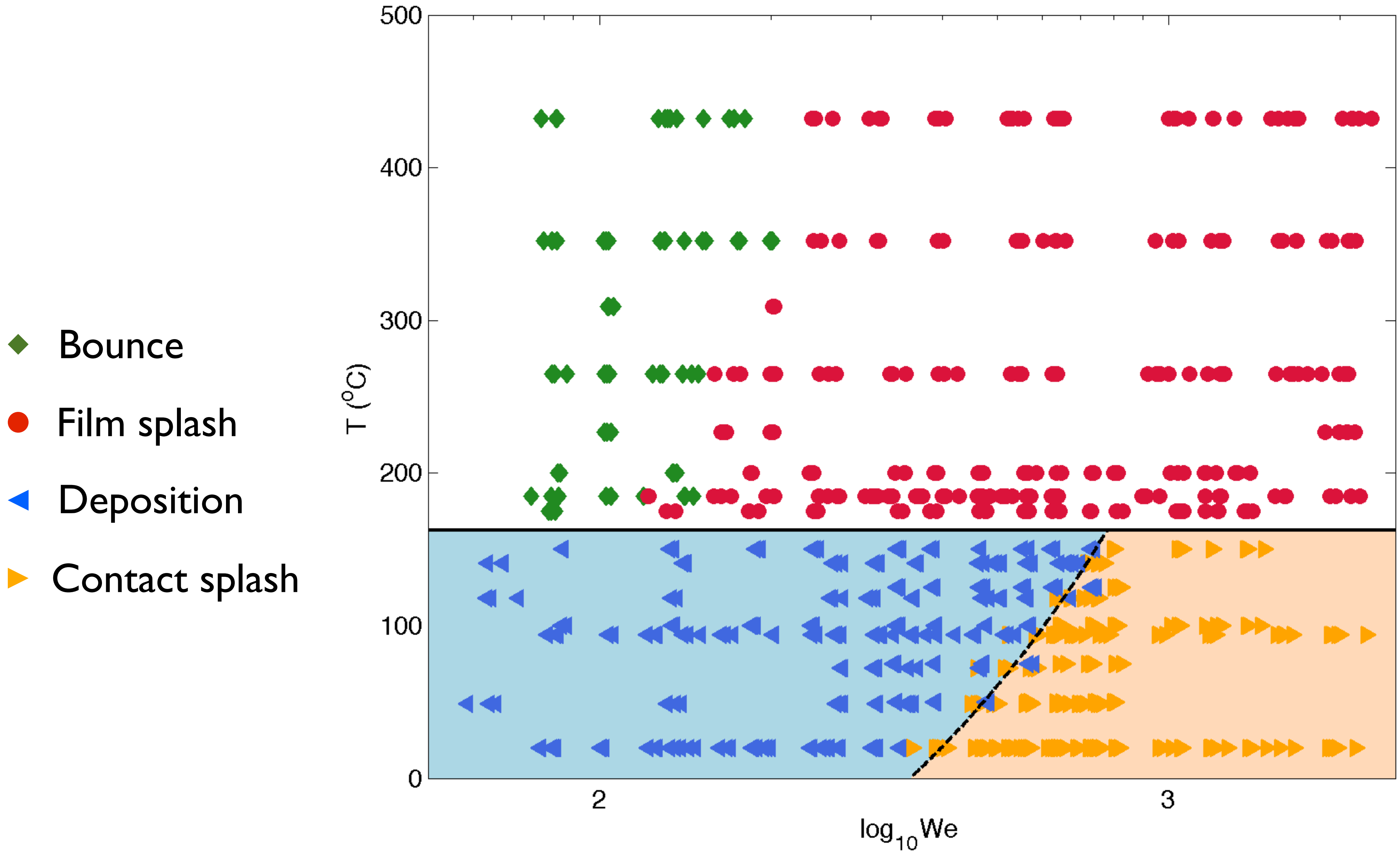
Transition to film boiling



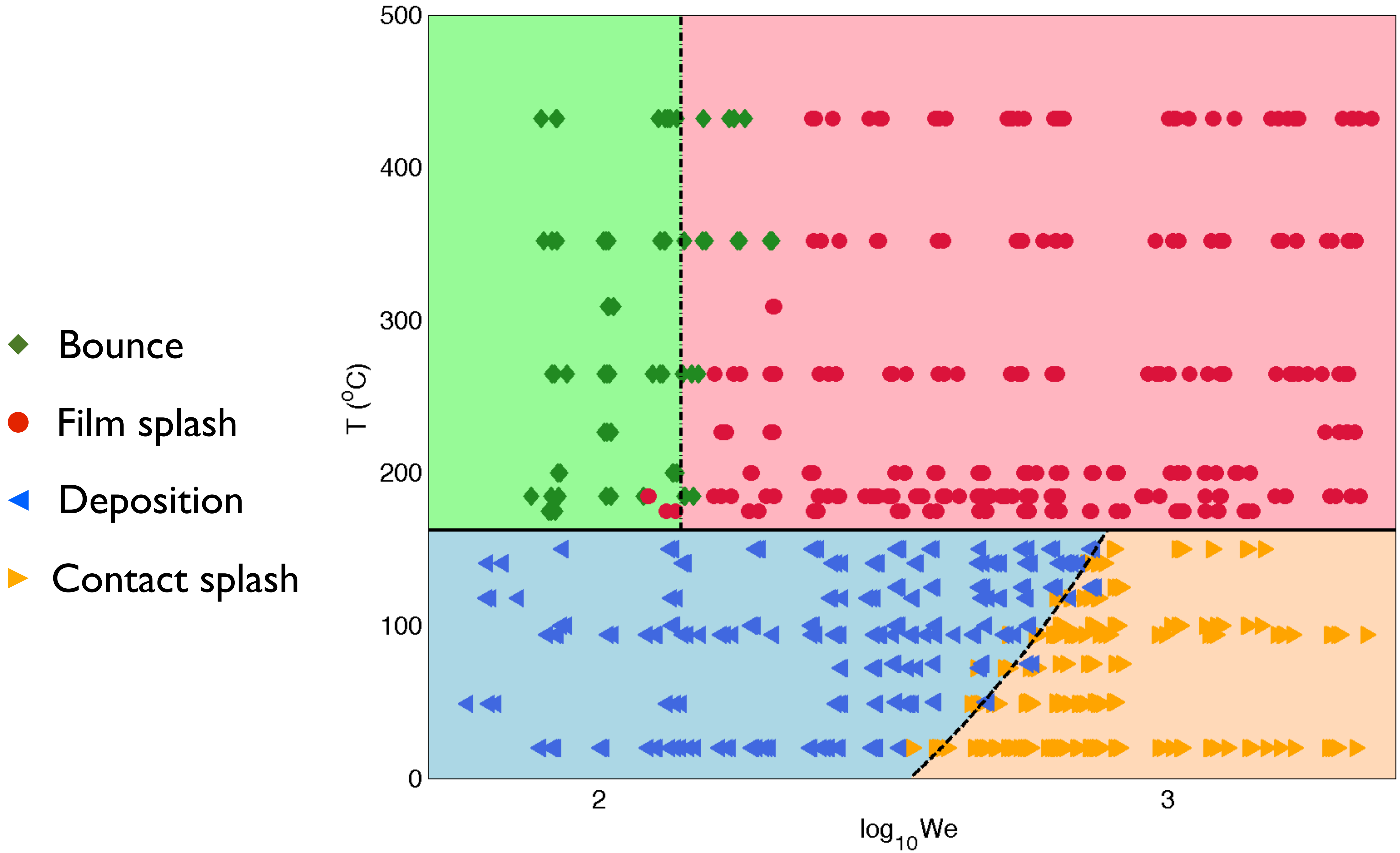
Transition temperature to film boiling regime: T_L = 162 °C

Tran, Staat, Prosperetti, Sun, Lohse, Phys. Rev. Lett. 108, 036101 (2012)

below T_L: increasing temperature suppresses splashes!



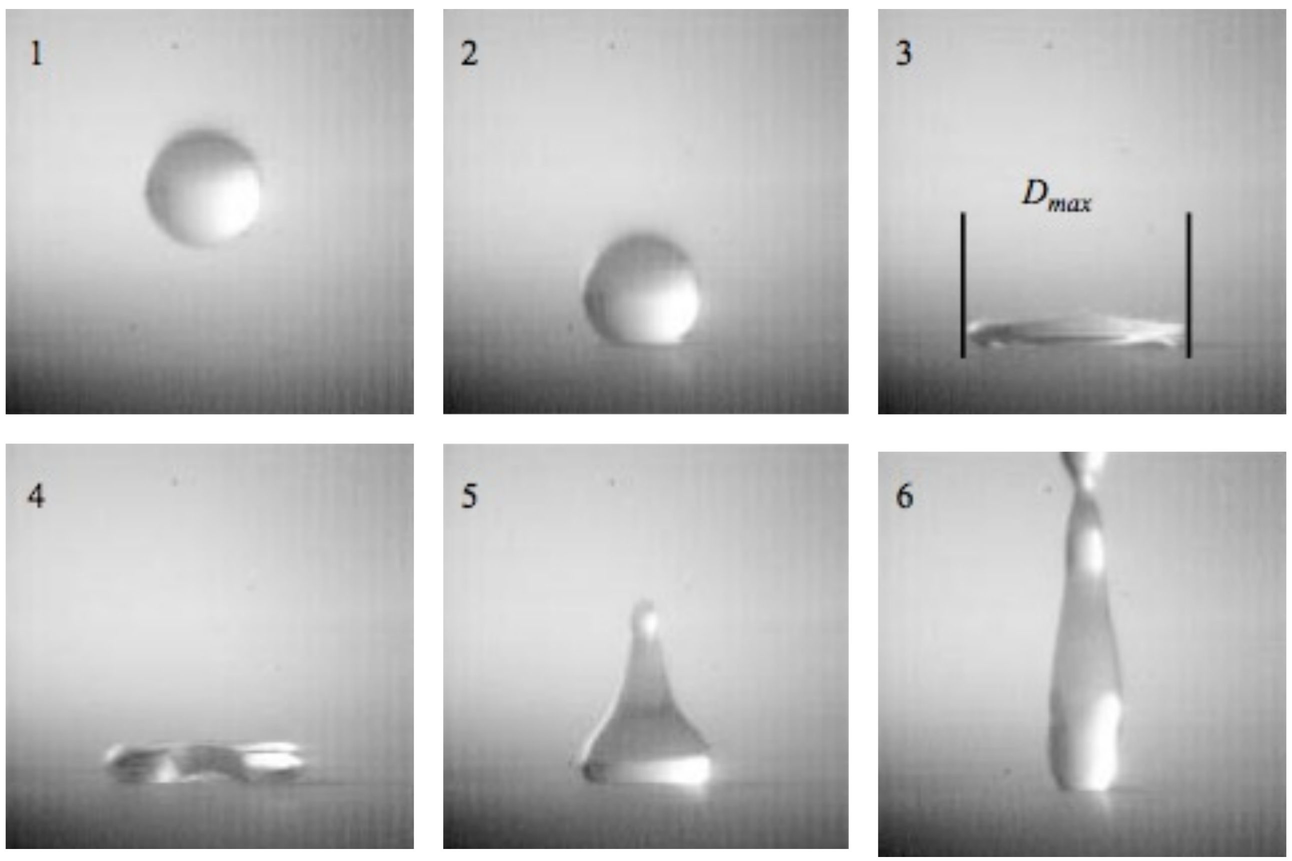
above T_L: much lower We-threshold for splashing !!



How much do droplets spread?

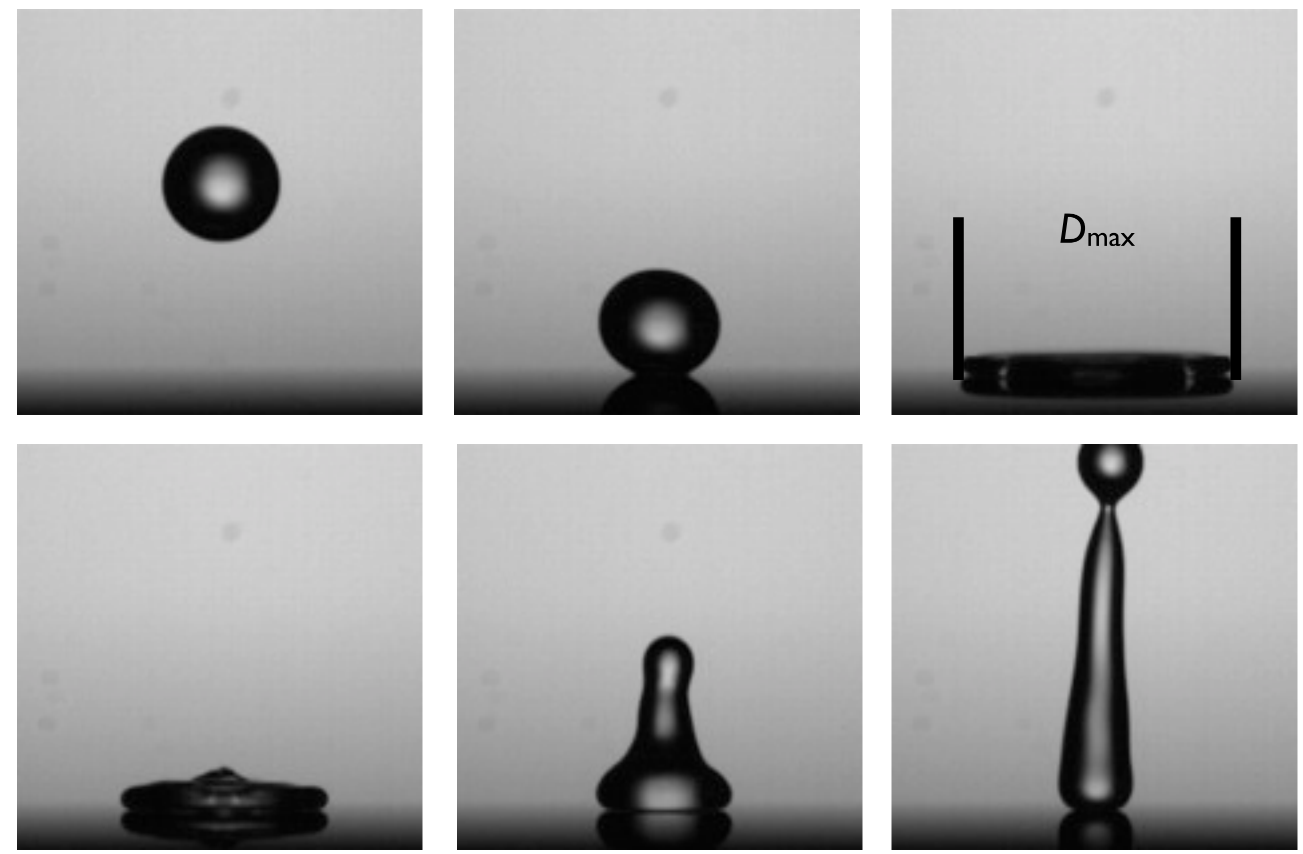
Spreading of impacting droplets

Impact on (non-heated) **superhydrophobic** surface



We = 24

Impact on **superheated** surface in film boiling regimes



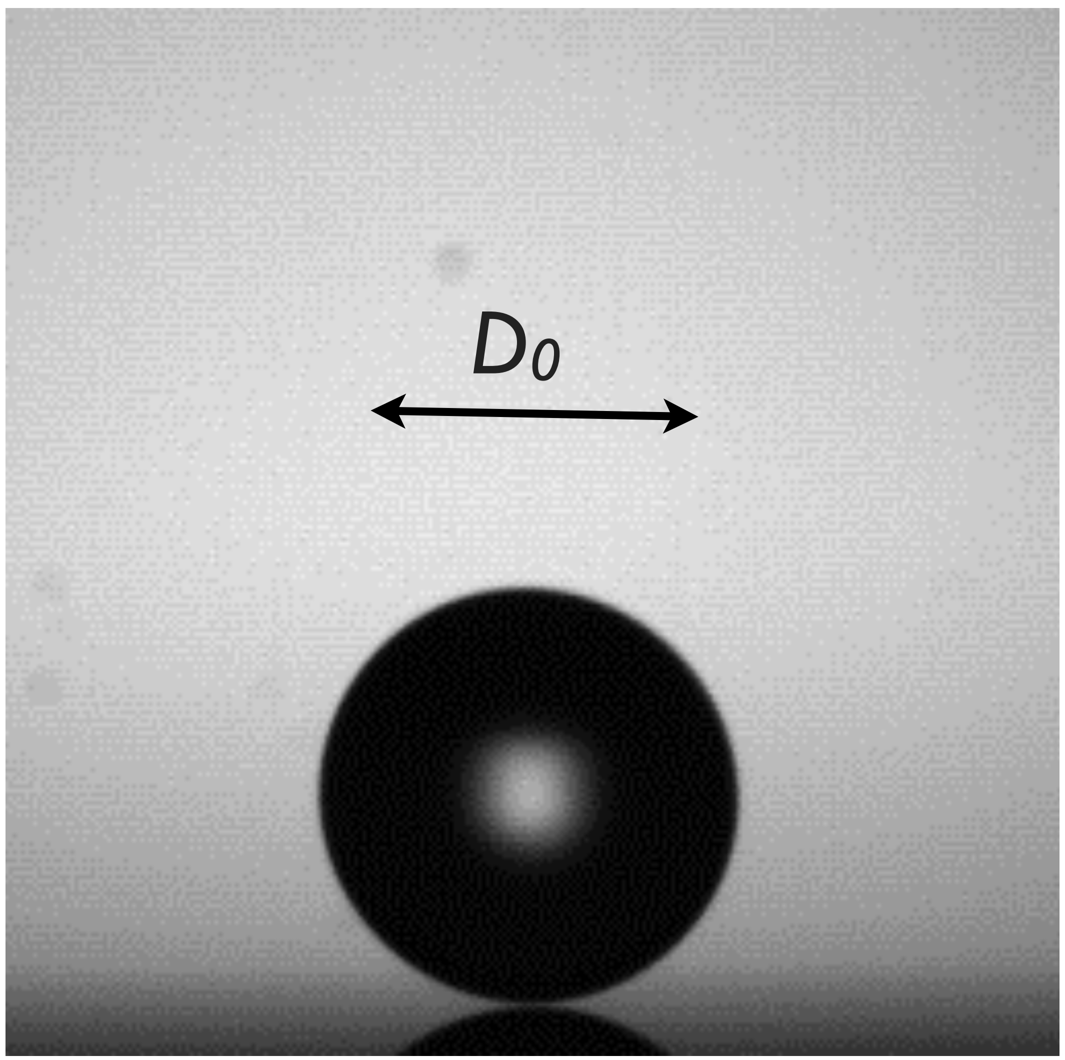
We = 32

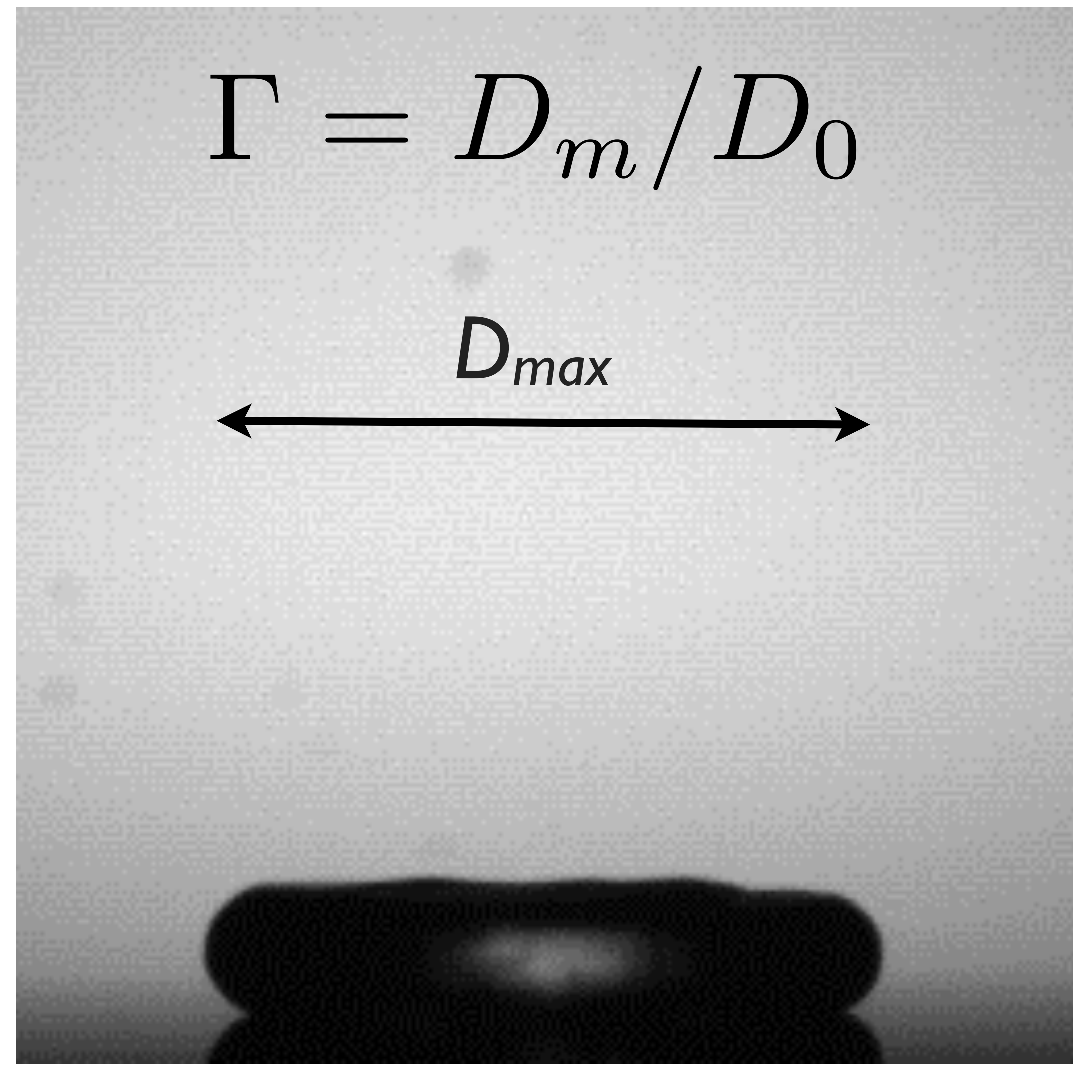
Clanet *et al.*, J Fluid Mech. 517, 199 (2004)

Looks identical!

What is the spreading of impacting droplets on standard and on superheated surfaces?

Maximal deformation of droplets at impact

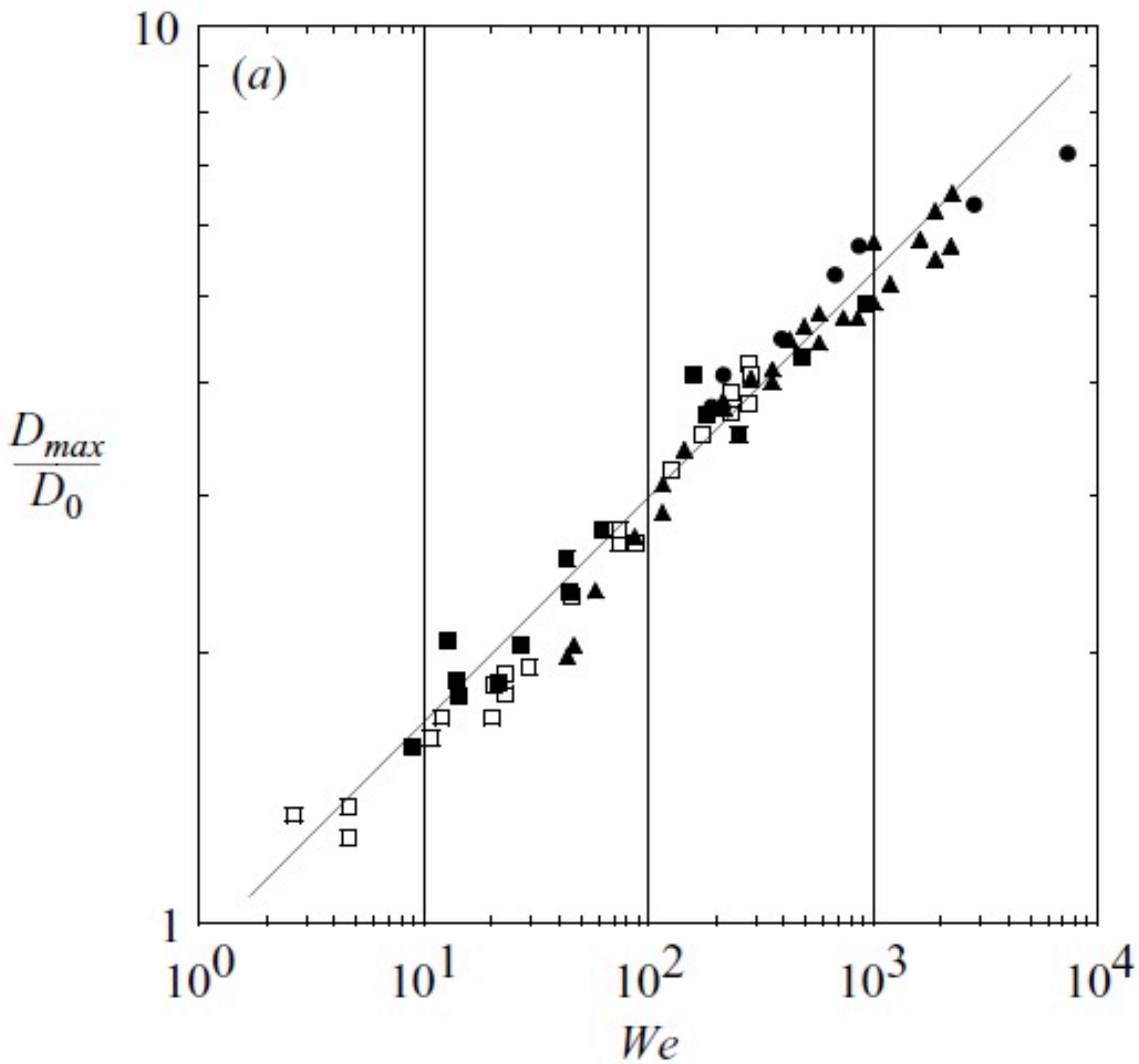




h

$$D_0^3 \sim hD_{max}^2$$

$$D_{max}/D_0 \sim We^{1/4}$$

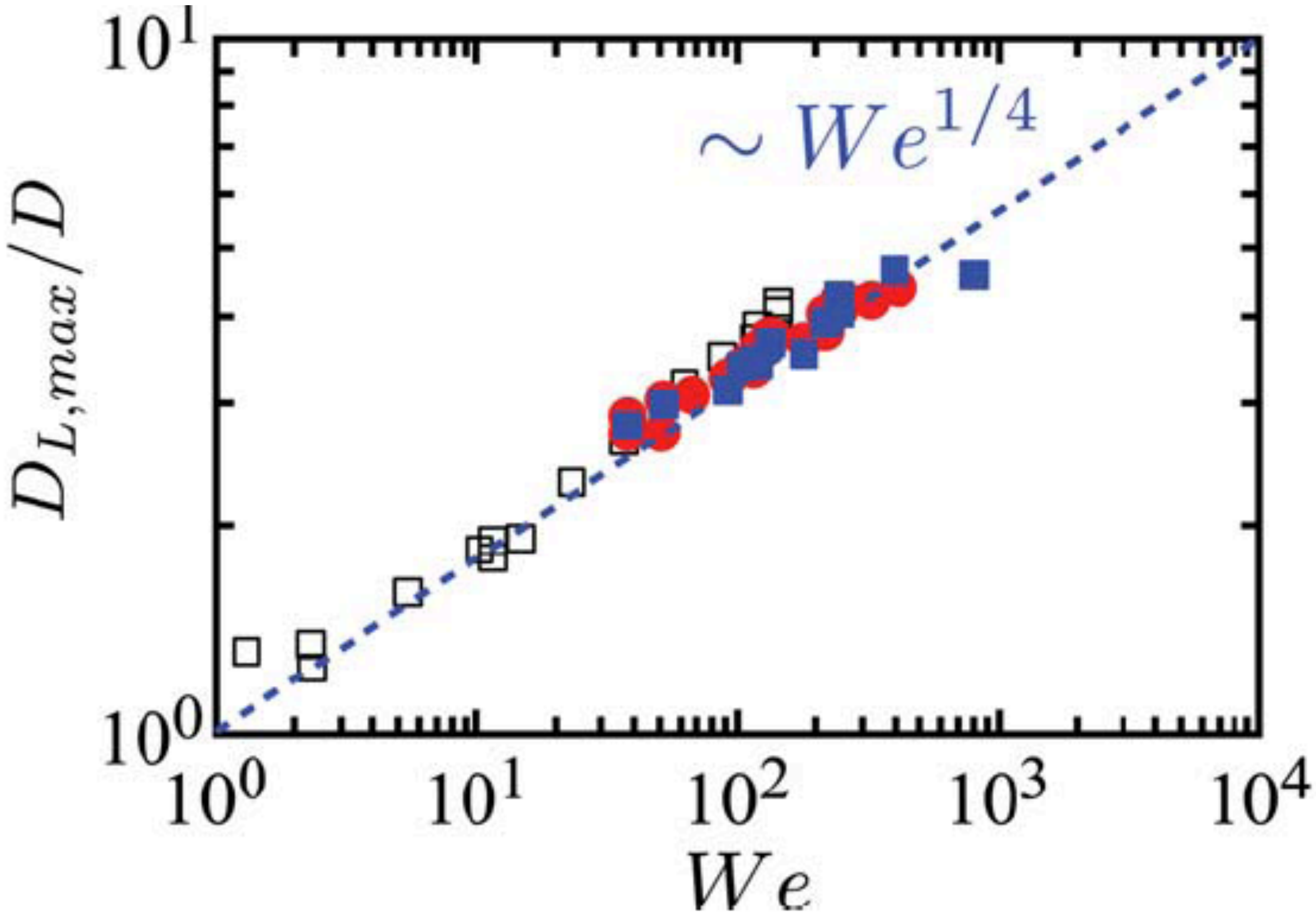


$$F_{cap} \sim F_{inertial}$$

$$We = \frac{\rho D_o U^2}{\gamma}$$

Clanet, Beguin, Richard, Quere, J. Fluid Mech. 517, 199 (2004)

1/4-scaling extremely robust

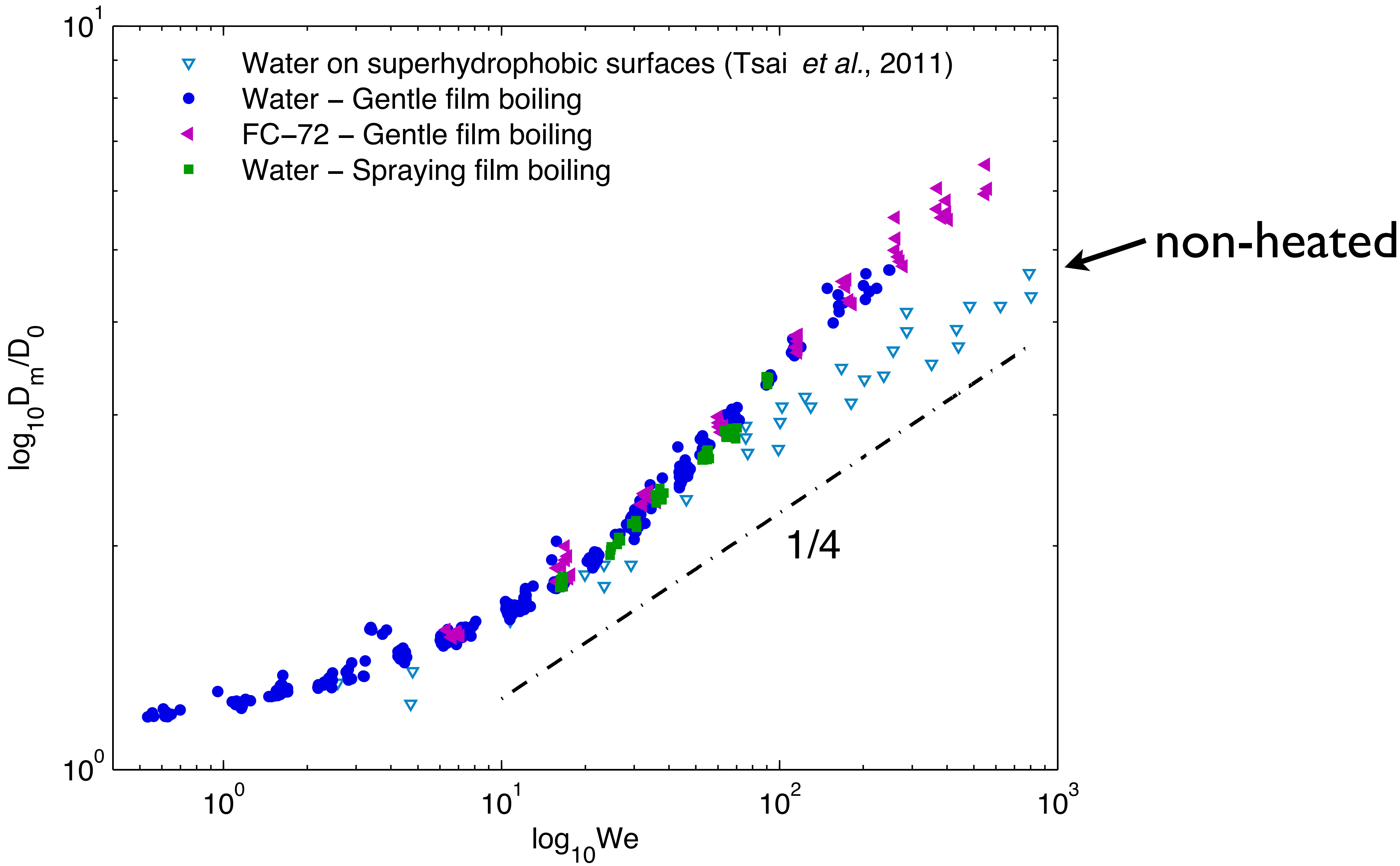


Impact on micro-structured surfaces

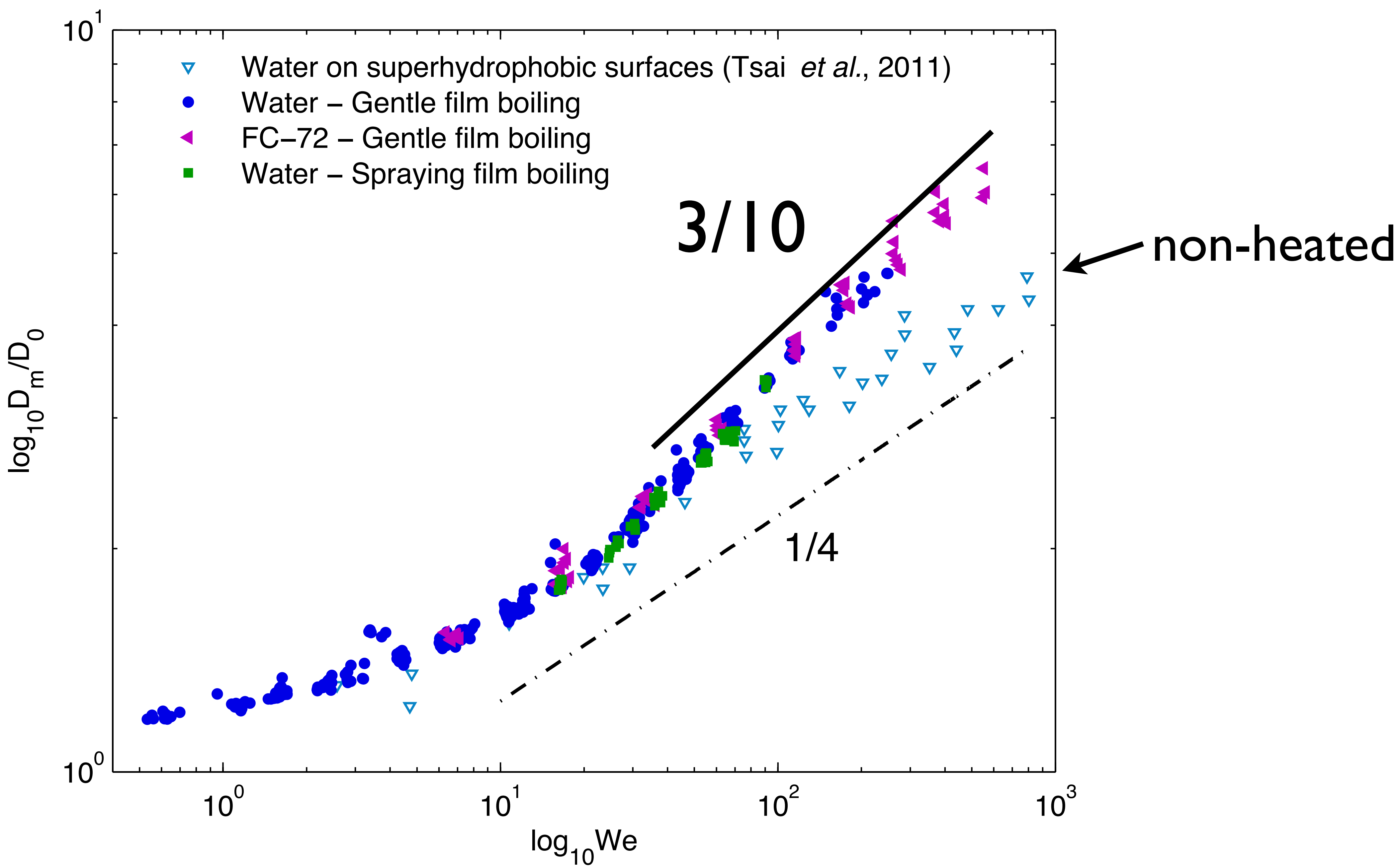
Scaling also independent of contact angle ➜ gas layer!

Tsai, Hendrix, Dijkstra, Shui, Lohse, Soft Matter 7, 11325 (2011)

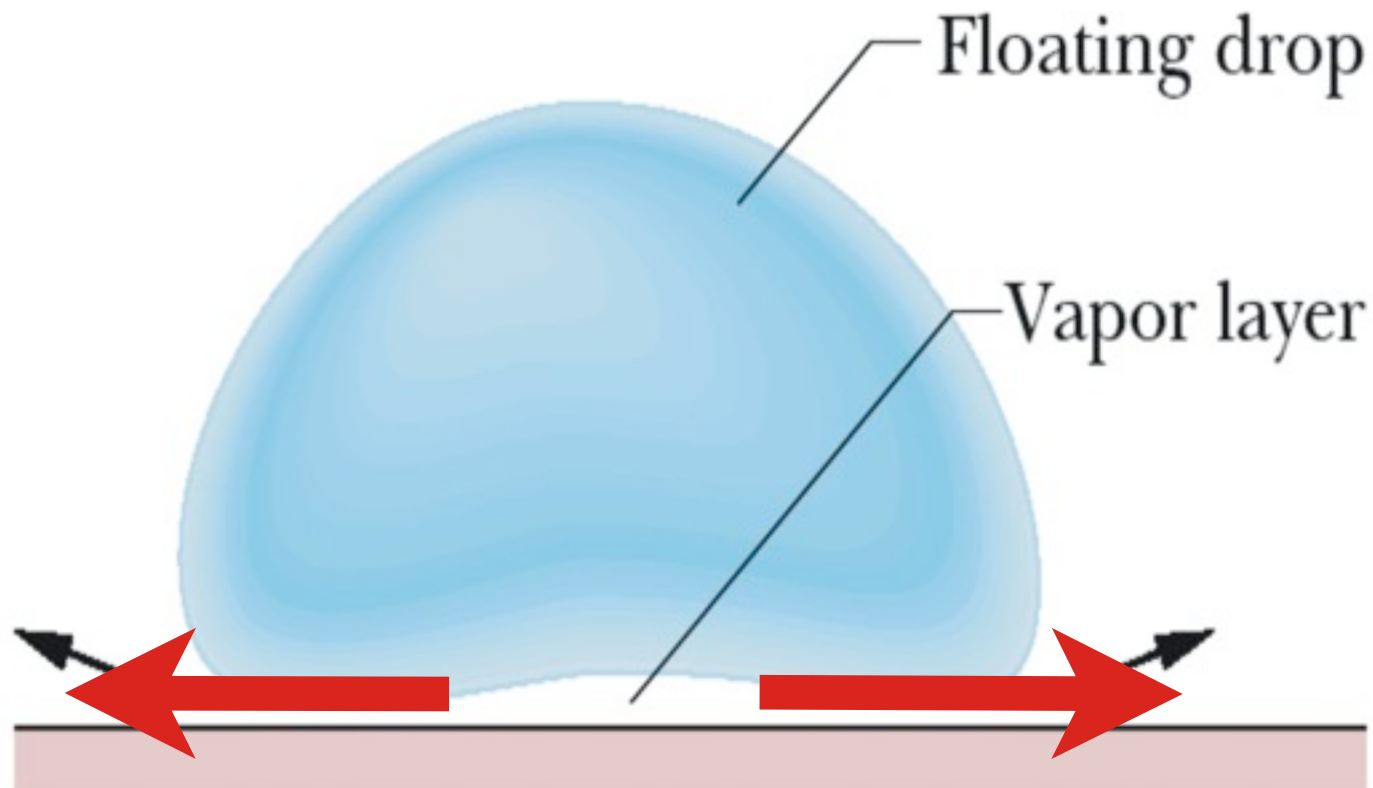
Maximum spreading in film boiling regime



Maximum spreading in gentle & spraying film boiling regimes

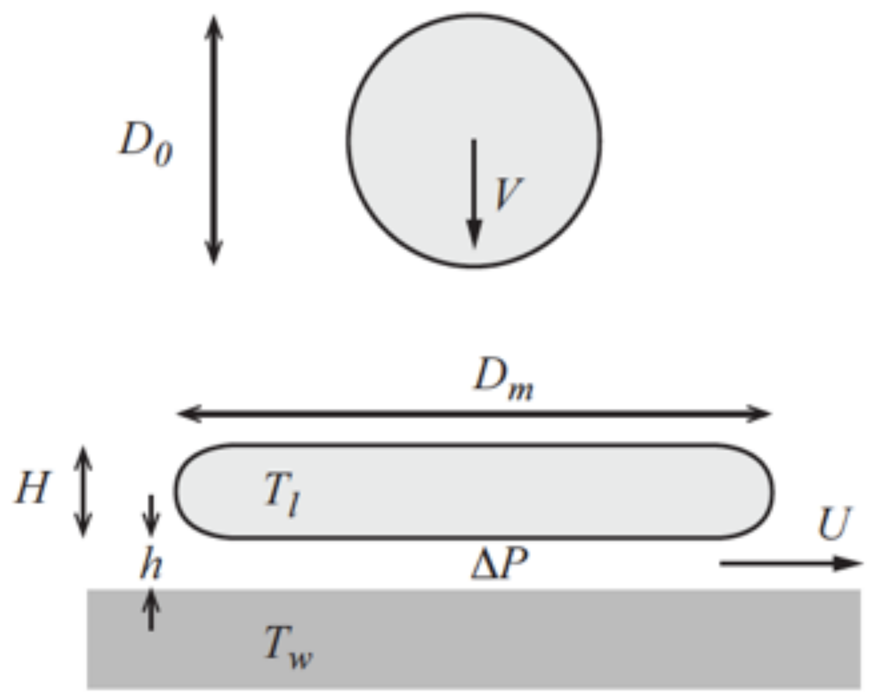


Physical mechanism of enhanced spreading



- Vapor shoots out and drags liquid along!
- The more, the larger U, as then more liquid evaporates

Derivation of the 3/10 scaling law for impact on superheated surfaces



$$\Delta P \sim \rho V^2$$

1. viscous driving force vs capillarity

$$\frac{\gamma}{H} \sim \mu_v \frac{U}{h}$$

2. Pressure buildup drives viscous vapor flow

$$\frac{\Delta P}{D_m} \sim \mu_v \frac{U}{h^2}$$

3. mass evaporation rate ~ flow rate

$$\frac{k\Delta T}{Lh} D_m^2 \sim \frac{\rho_v}{\mu_v} h^3 \Delta P.$$

Non-dimensionalize

$$\Gamma = D_m / D_0$$

$$We = \frac{\rho_l D_0 V^2}{\gamma}$$

$$\tilde{U} = U/V$$

$$\tilde{h} = h/D_0$$

$$St = \frac{\rho_l D_0 V}{\mu_v}$$

$$Pe = \frac{V D_0 L \rho_v}{k \Delta T}$$

Resulting scaling laws

$$\Gamma \sim \frac{We^{2/5}}{St^{1/10} Pe^{1/10}}$$

$$\Gamma \sim We^{3/10}$$

$$\tilde{h} \sim \frac{We^{1/5}}{St^{3/10} Pe^{3/10}}$$

$$\tilde{h} \sim We^{-1/10}$$

Predictions!

$$\tilde{U} \sim \frac{St^{1/2}}{Pe^{1/2}}$$

$$\tilde{U} \sim We^{0}$$

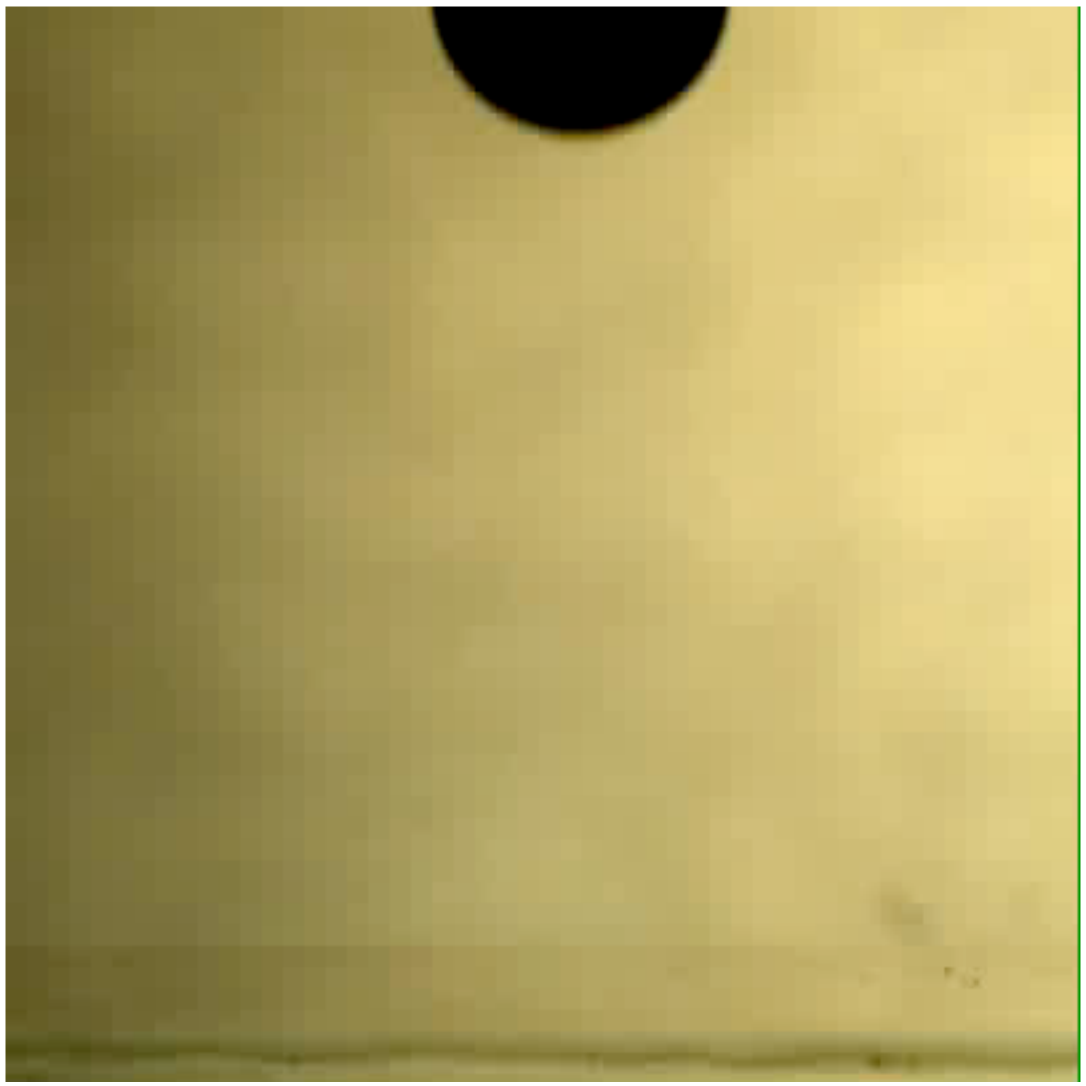
... and when all velocity dependences are put into We:

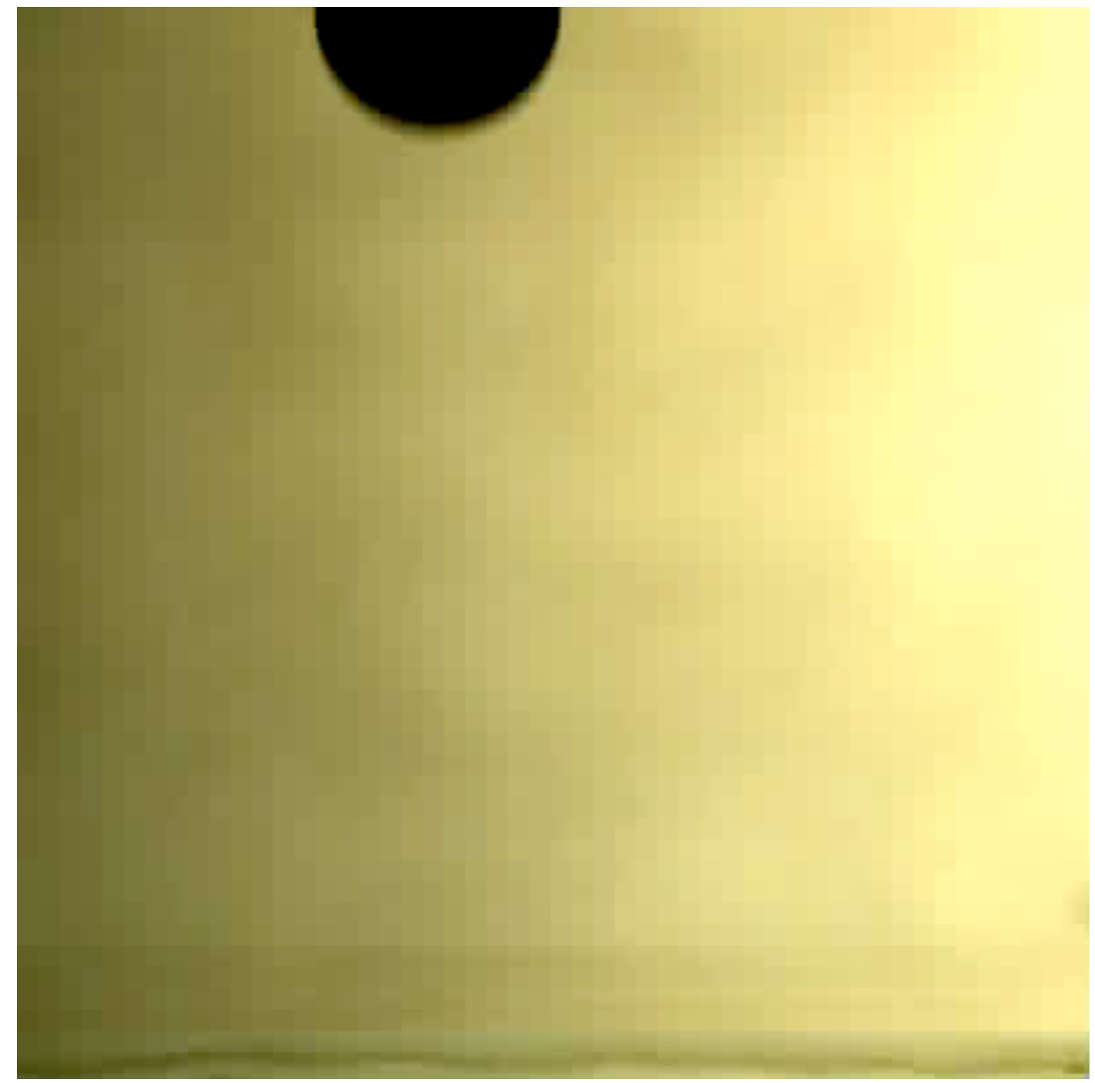
Impact of suspension droplets

e.g.: paint (pigments!)

Boyer, Dijksman, Snoeijer, Lohse (2012)

Impact of 39%-suspension droplet

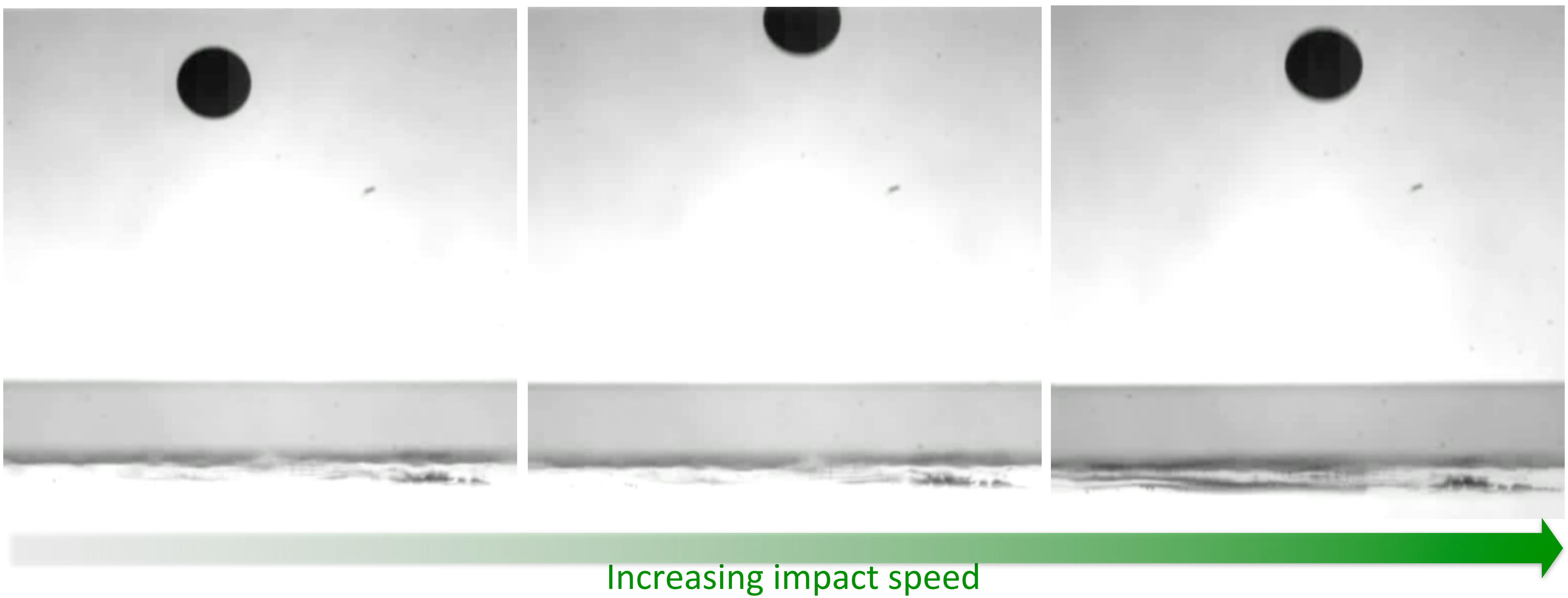




shear-thickening

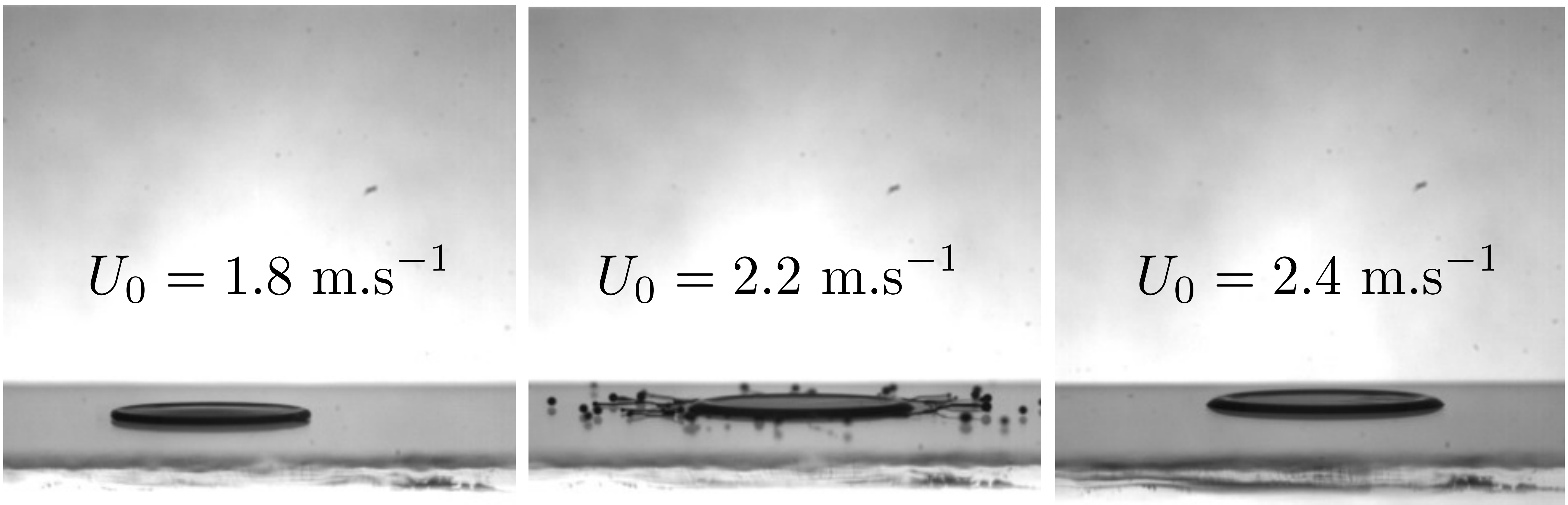
Is there a splash at impact?

From spreading.... to splashing... **and spreading again!**



Is there a splash at impact?

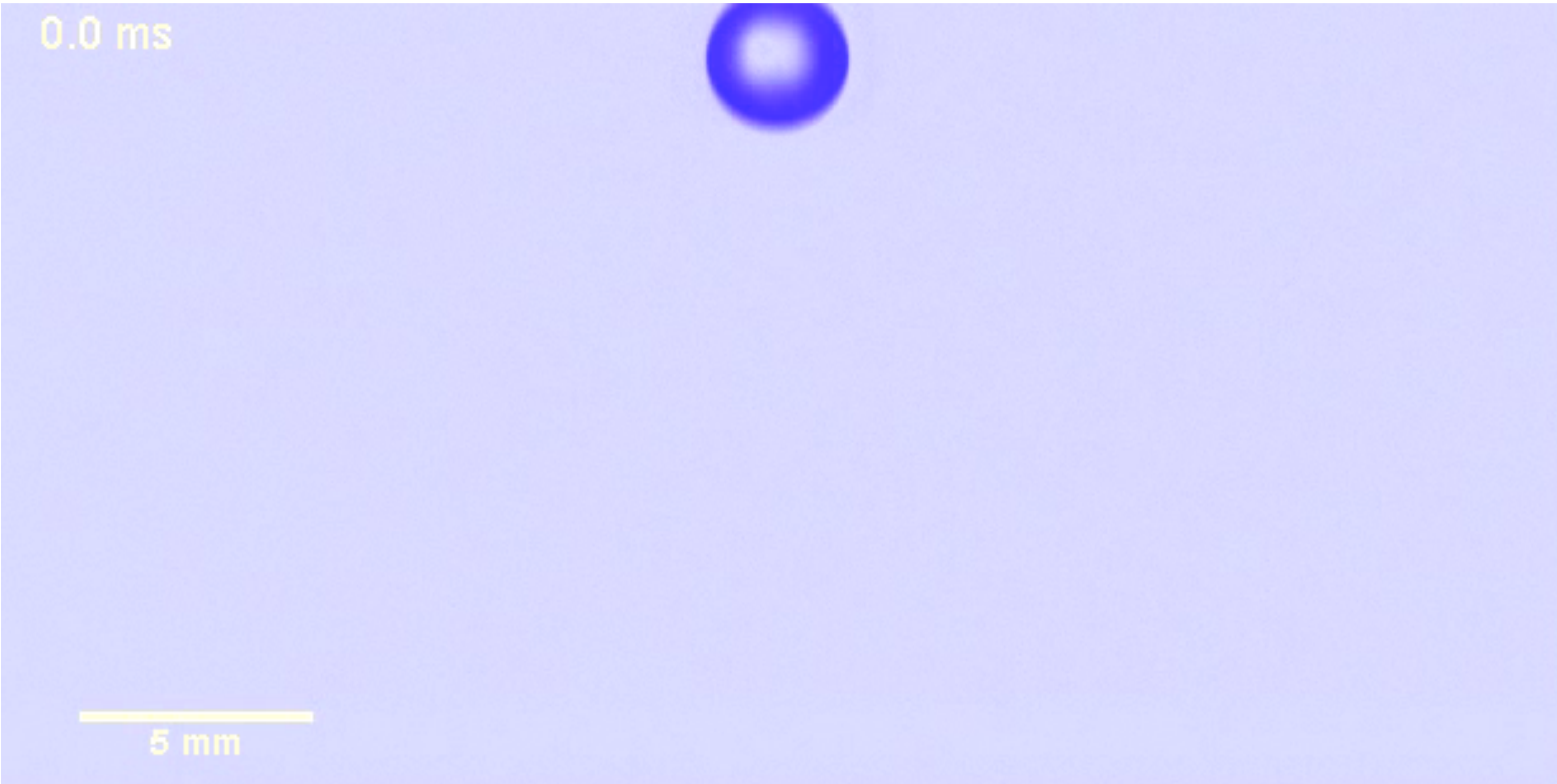
spreading | splashing | **spreading**



Increasing impact speed

shear-thickening!

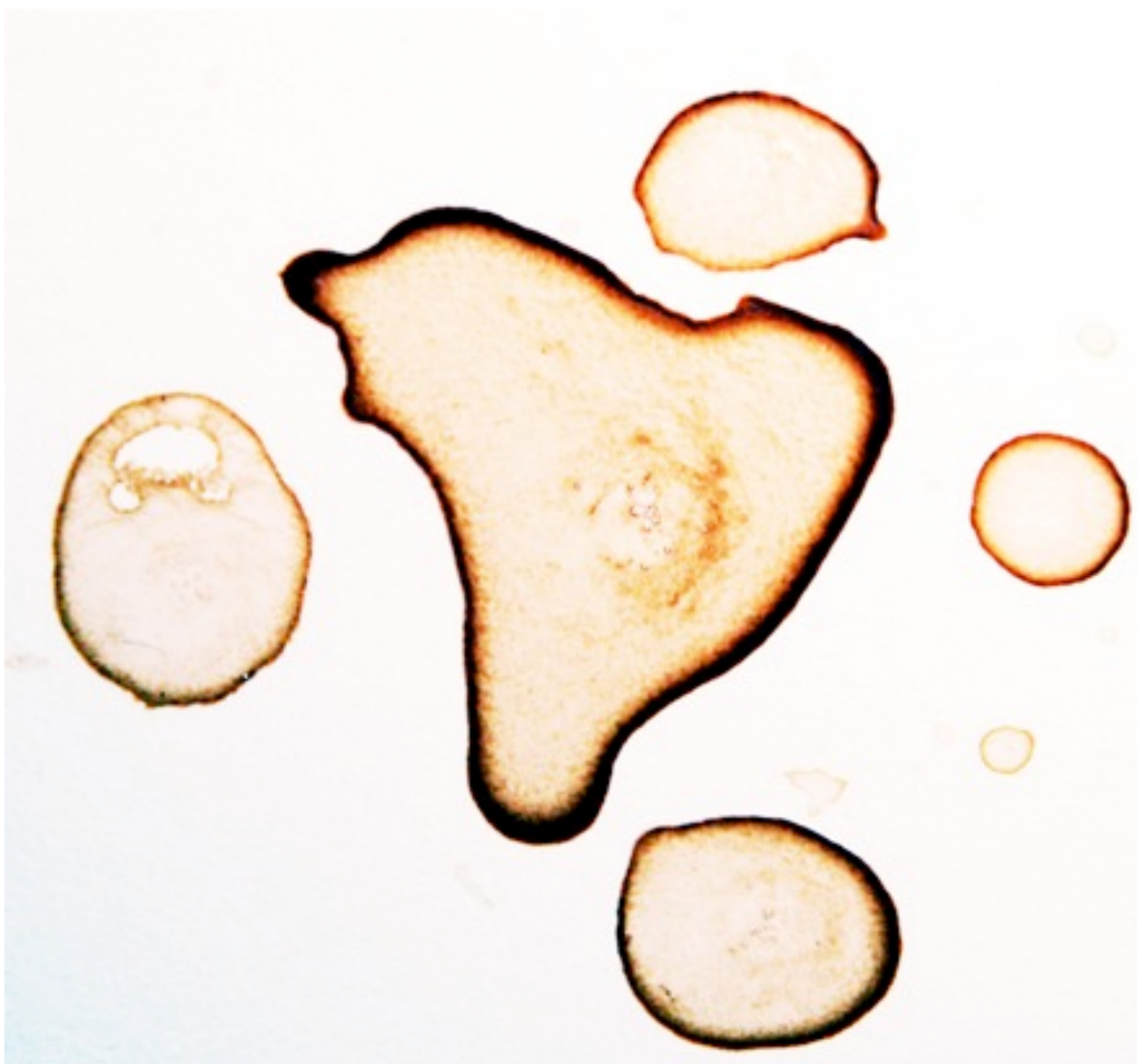
Impact of shear-thinning liquid



How do suspension droplets dry?

Marin, Gelderblom, Lohse, Snoeijer, Phys. Rev. Lett. 107, 085502 (2011)

How do such droplets dry?

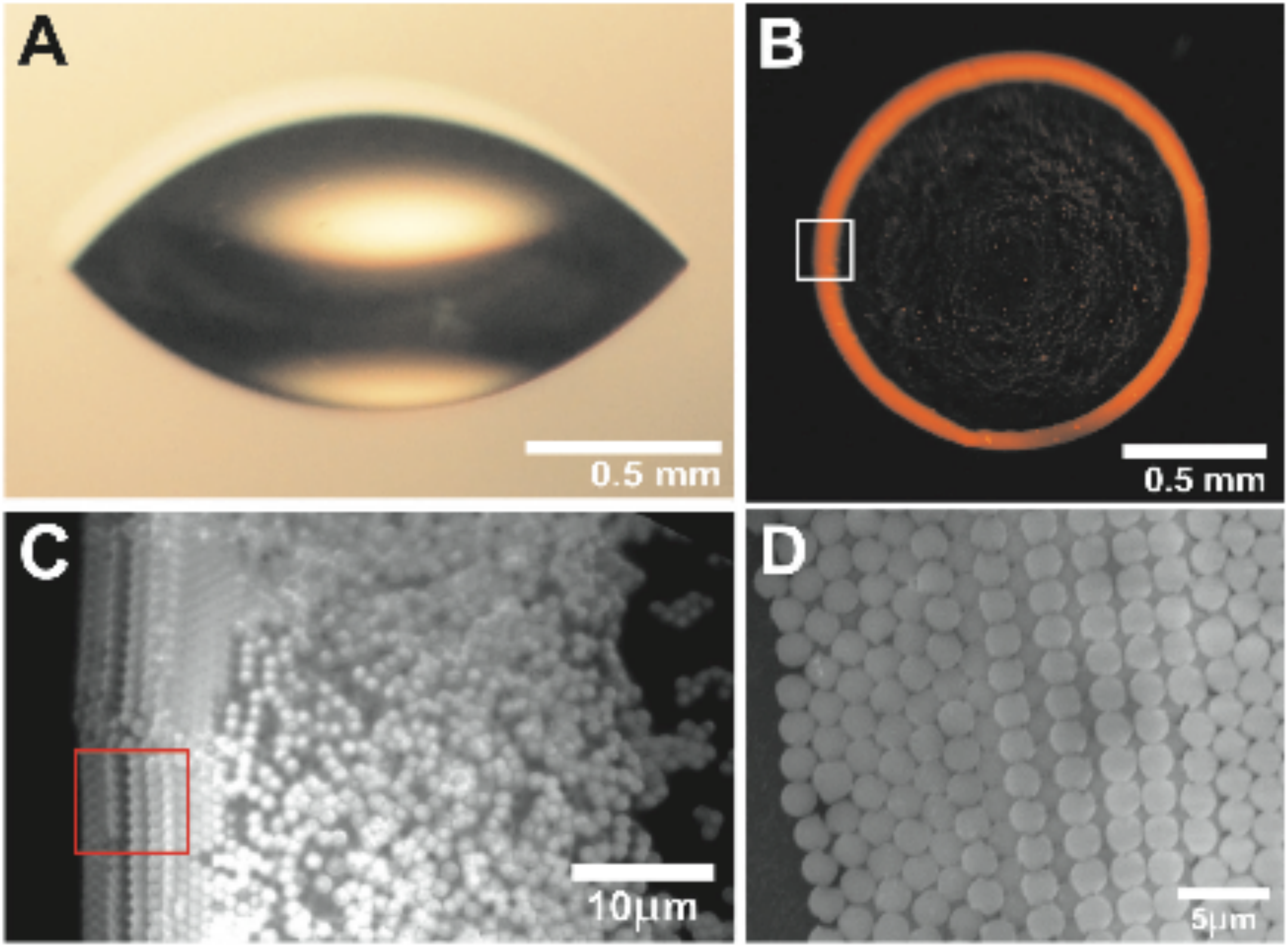


"coffee-stain problem"

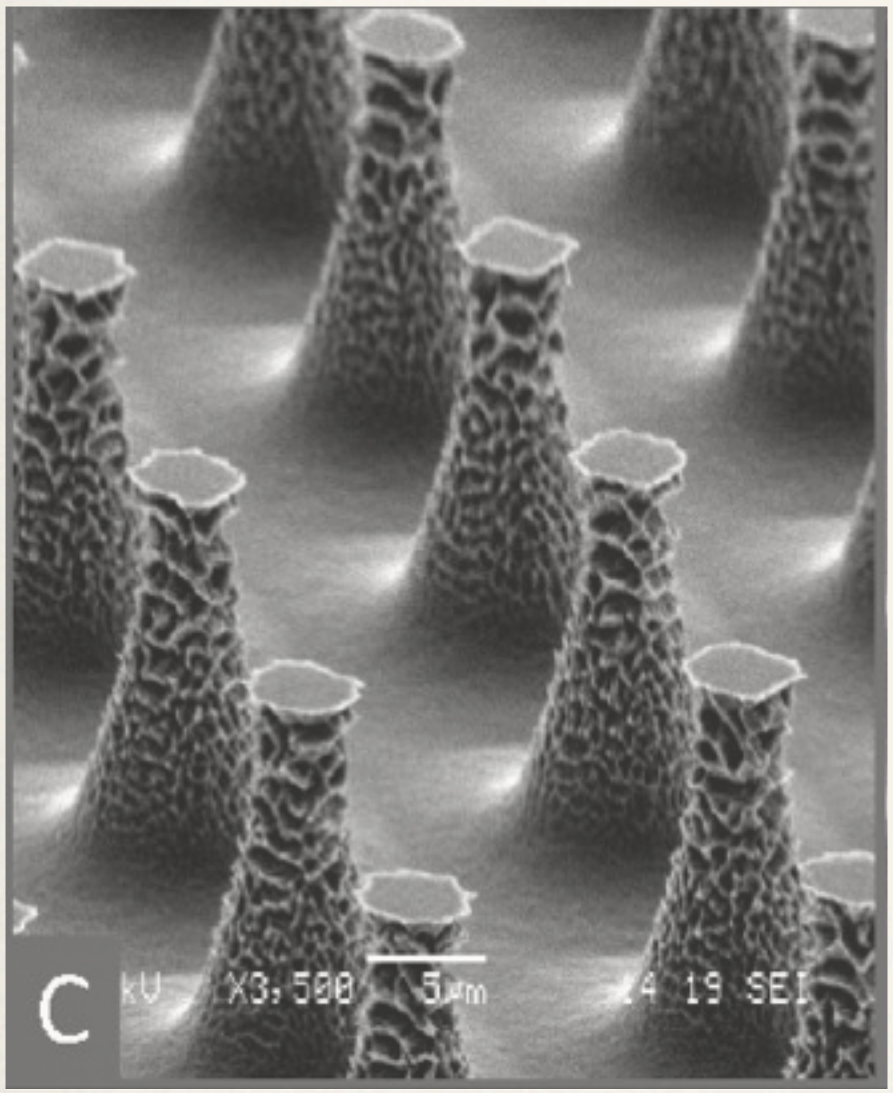
Marin, Gelderblom, Lohse, Snoeijer, Phys. Rev. Lett. 107, 085502 (2011)

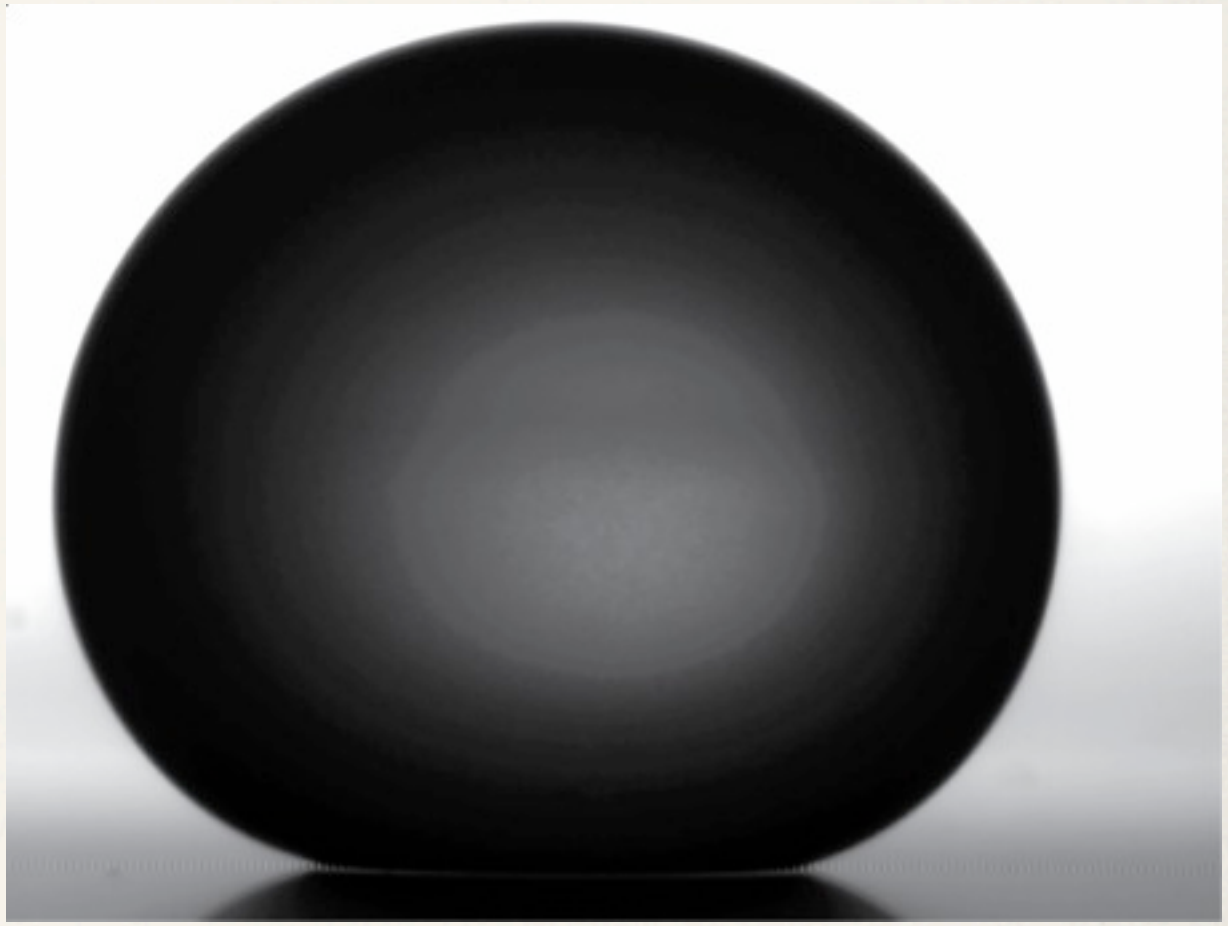
Avalanche of Particles in Evaporating Drops

A. G. Marin, H. Gelderblom,
J. Snoeijer, D. Lohse
Physics of Fluids, Univ. Twente


A
0.5 mm
B
0.5 mm
C
10μm
D
5μm

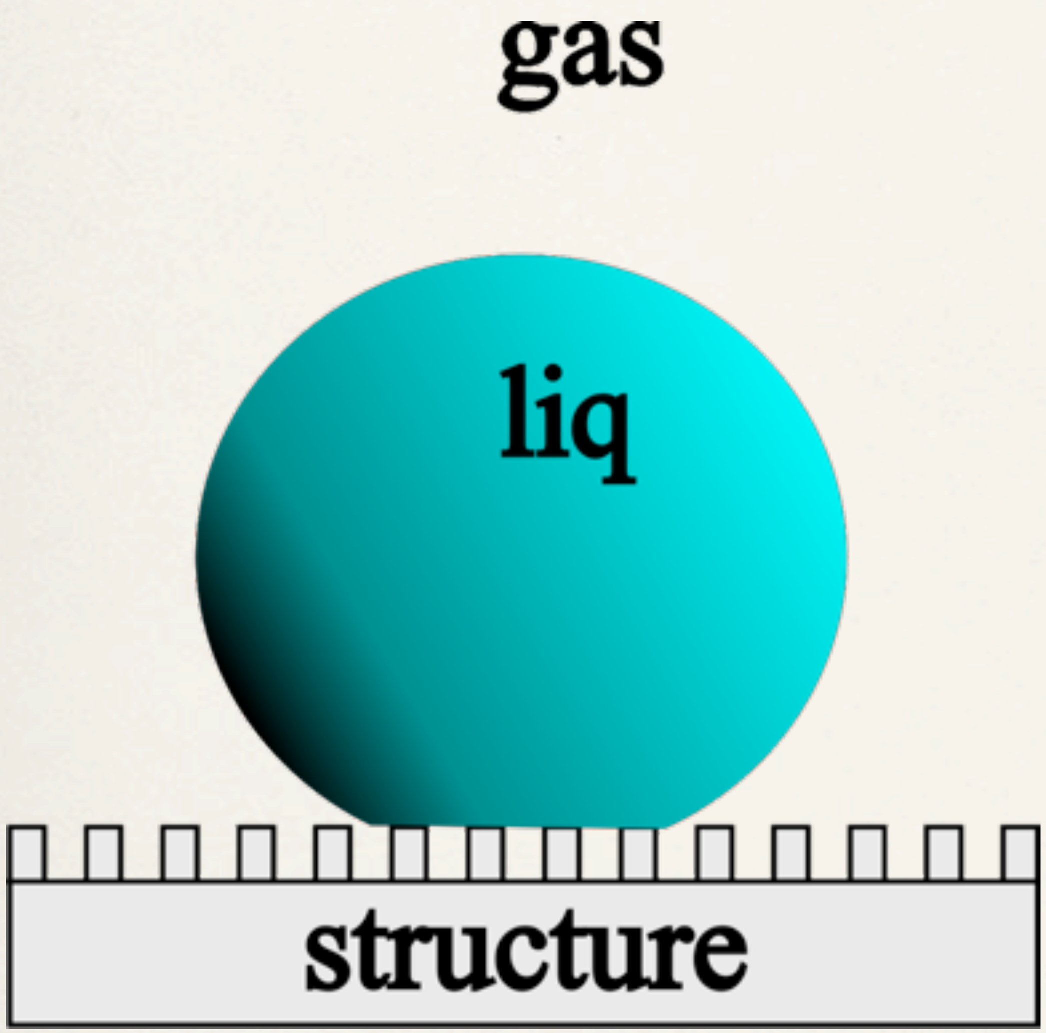
Microstructured substrates



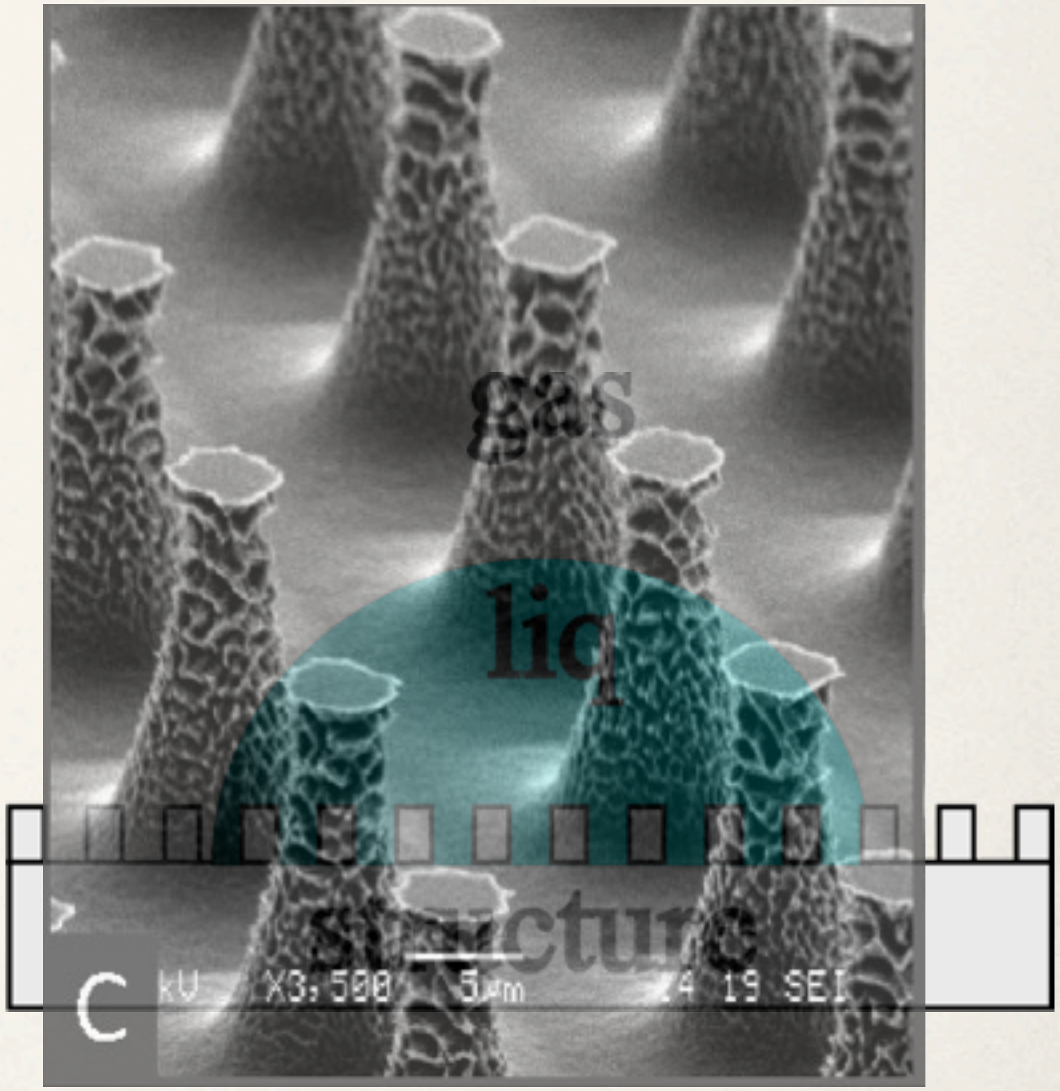


Absence of an evaporation-driven wetting transition on omniphobic surfaces,
Susarrey-Arce, Marín, Nair, Lefferts, Gardeniers, Lohse, van Houselt, Soft Matter 8 (2012)
Susarrey-Arce et al. J. Micromech. Microeng. 23 (2013)

Diehard superhydrophobic substrates

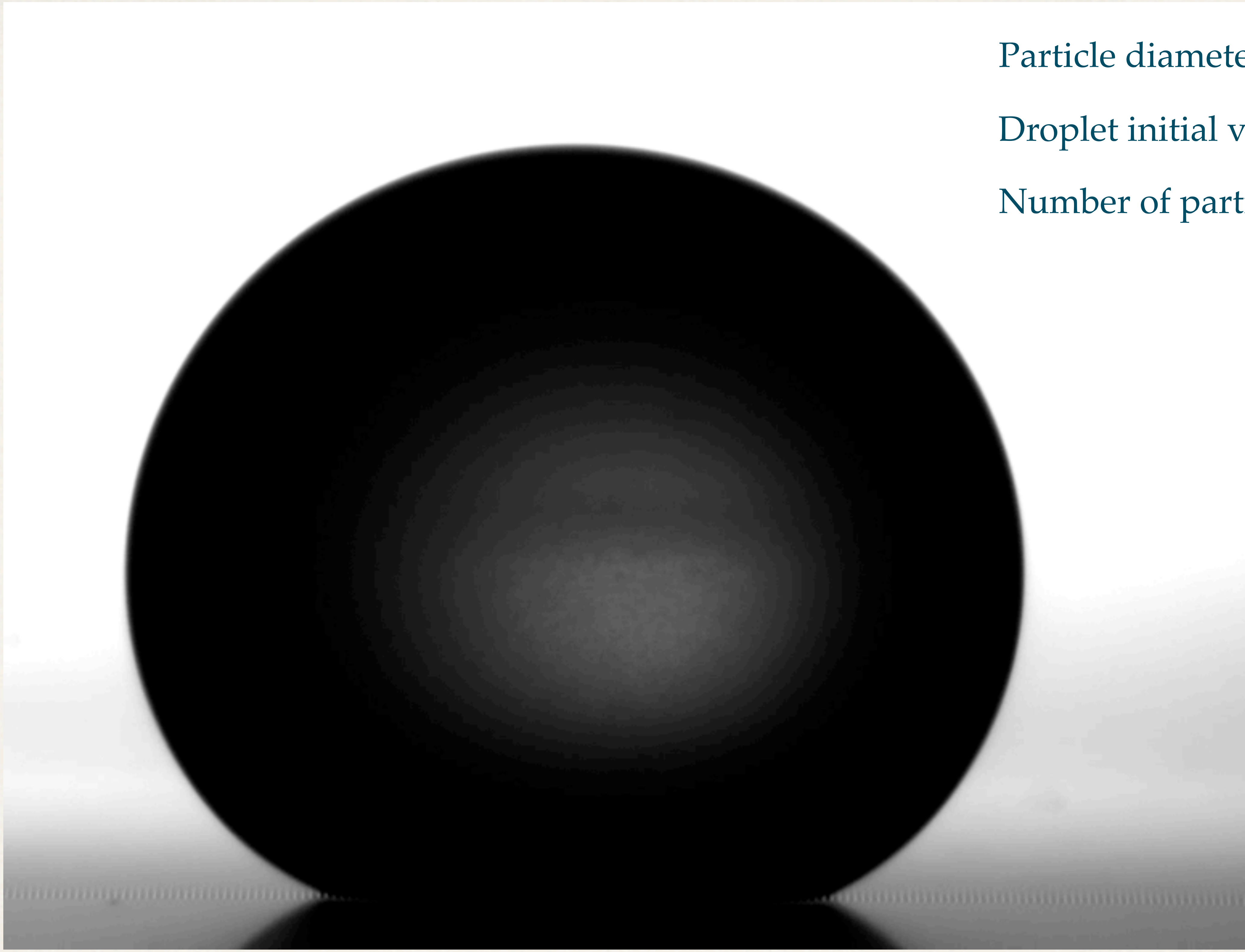


Cassie-Baxter or "fakir" state



Wenzel or "impaled" state

Drying a colloidal suspension on a die-hard surface



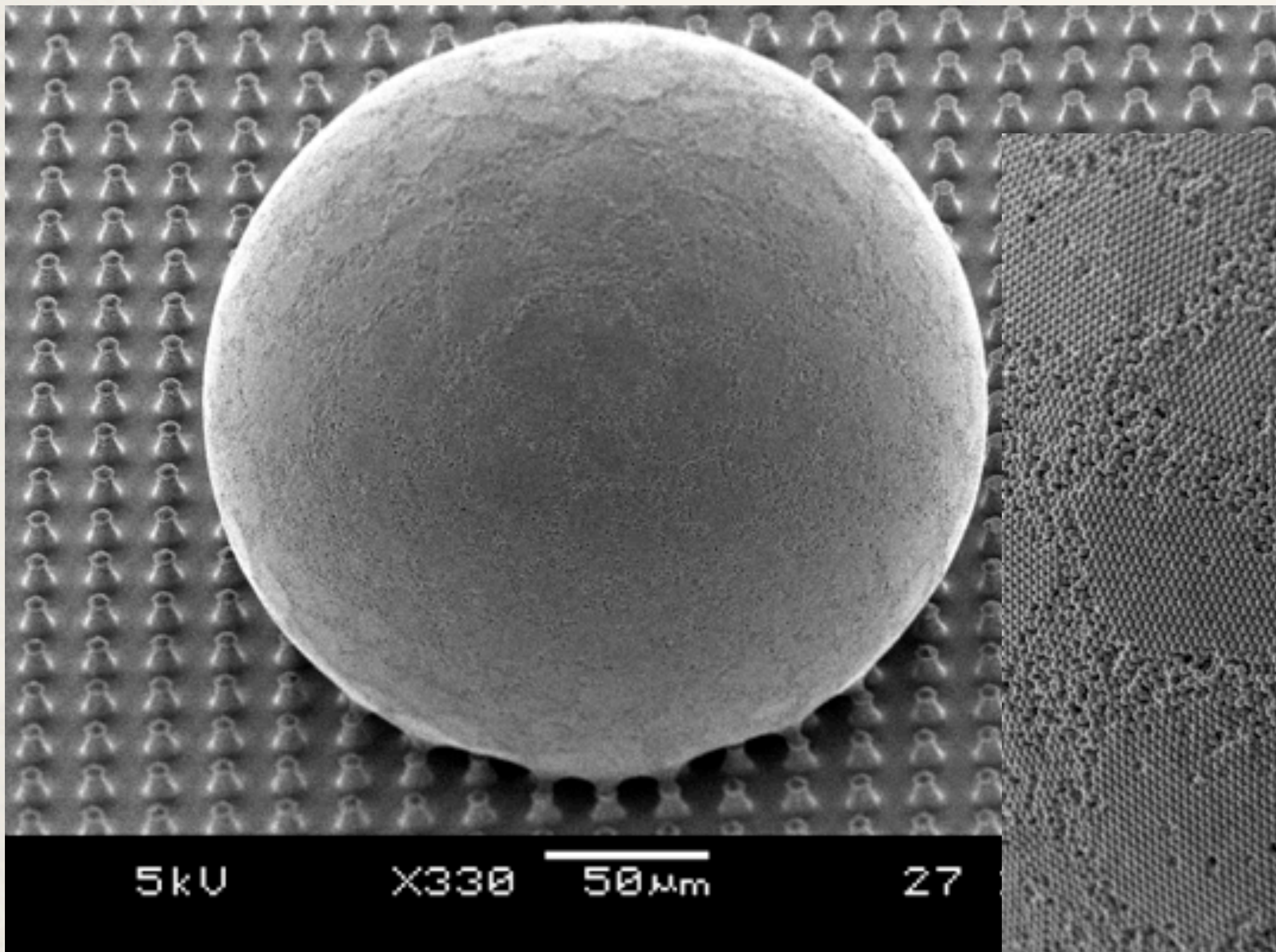
Particle diameter 1μm

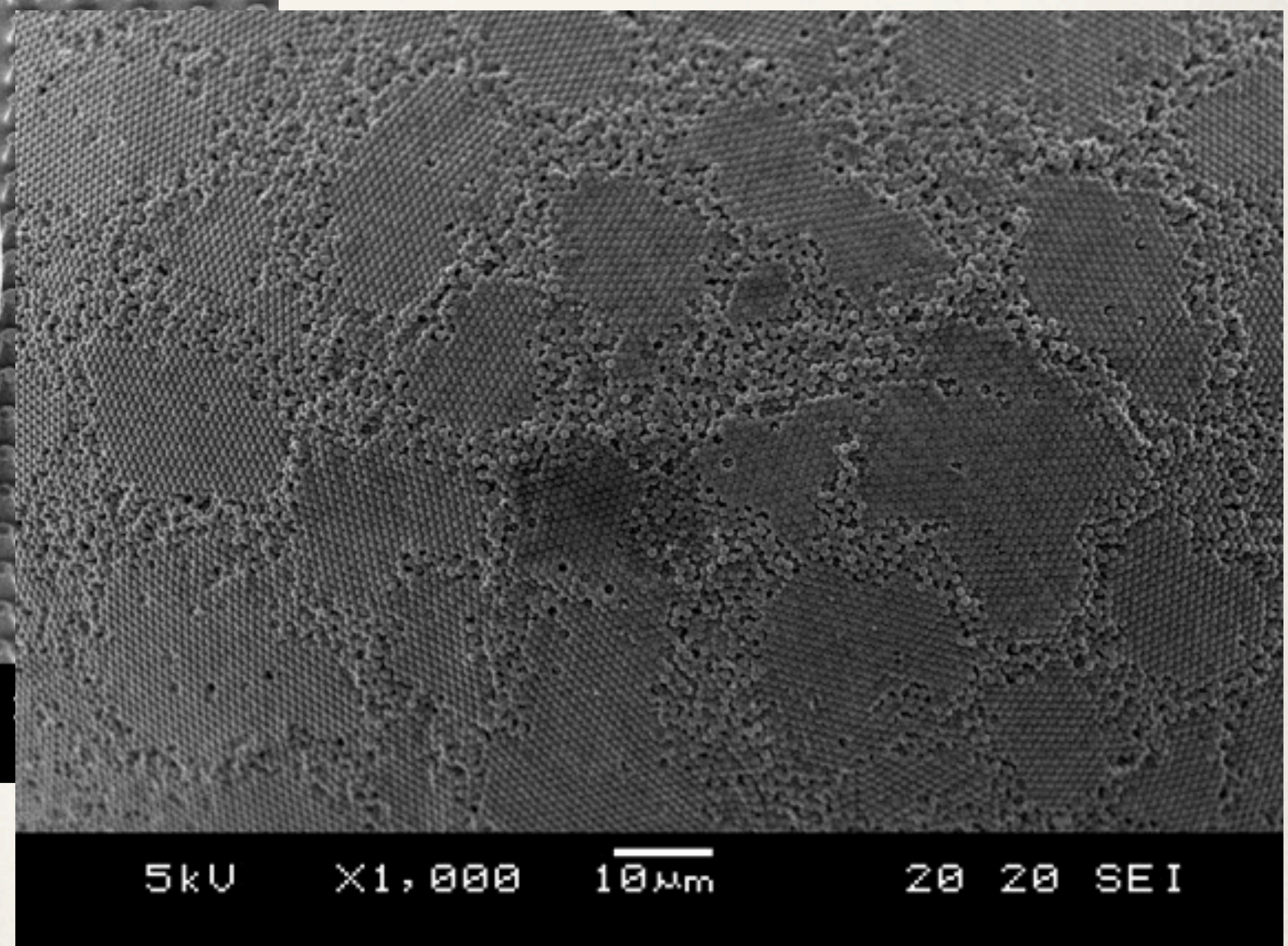
Droplet initial volume: 10μl

Number of particles ~ 10^7

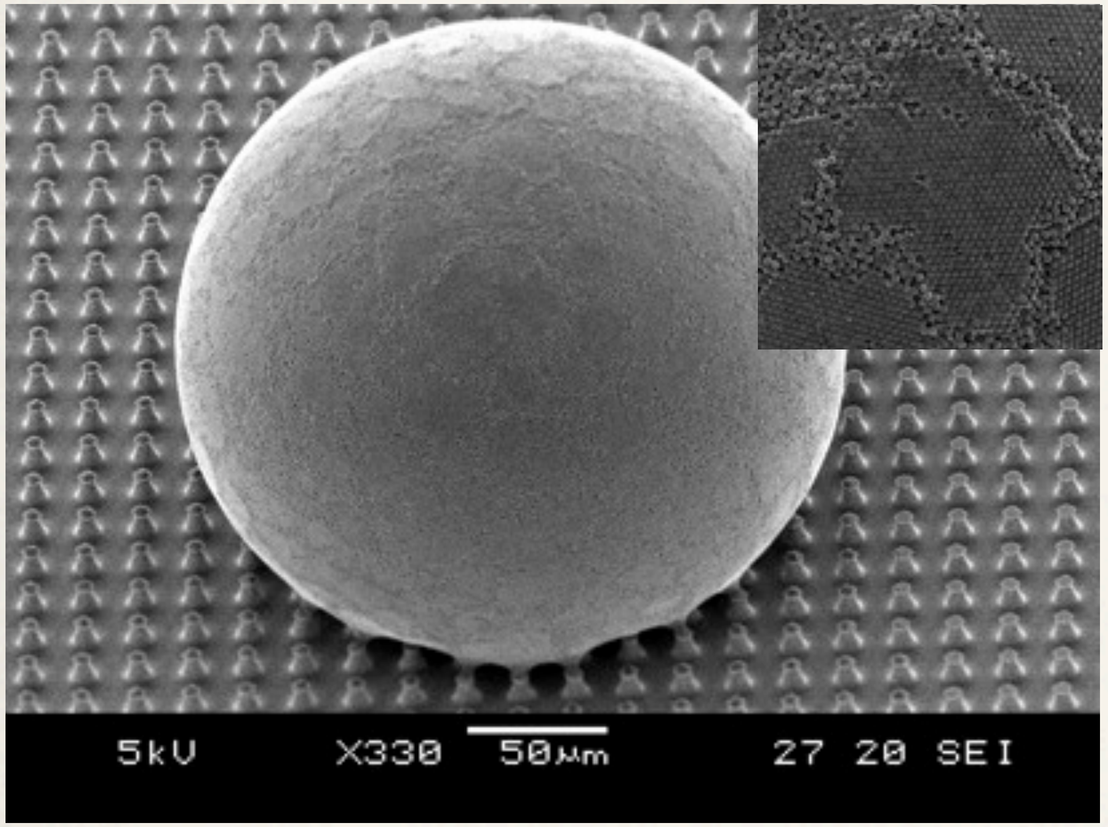
Marin *et al*., PNAS 109, 16455 (2012)

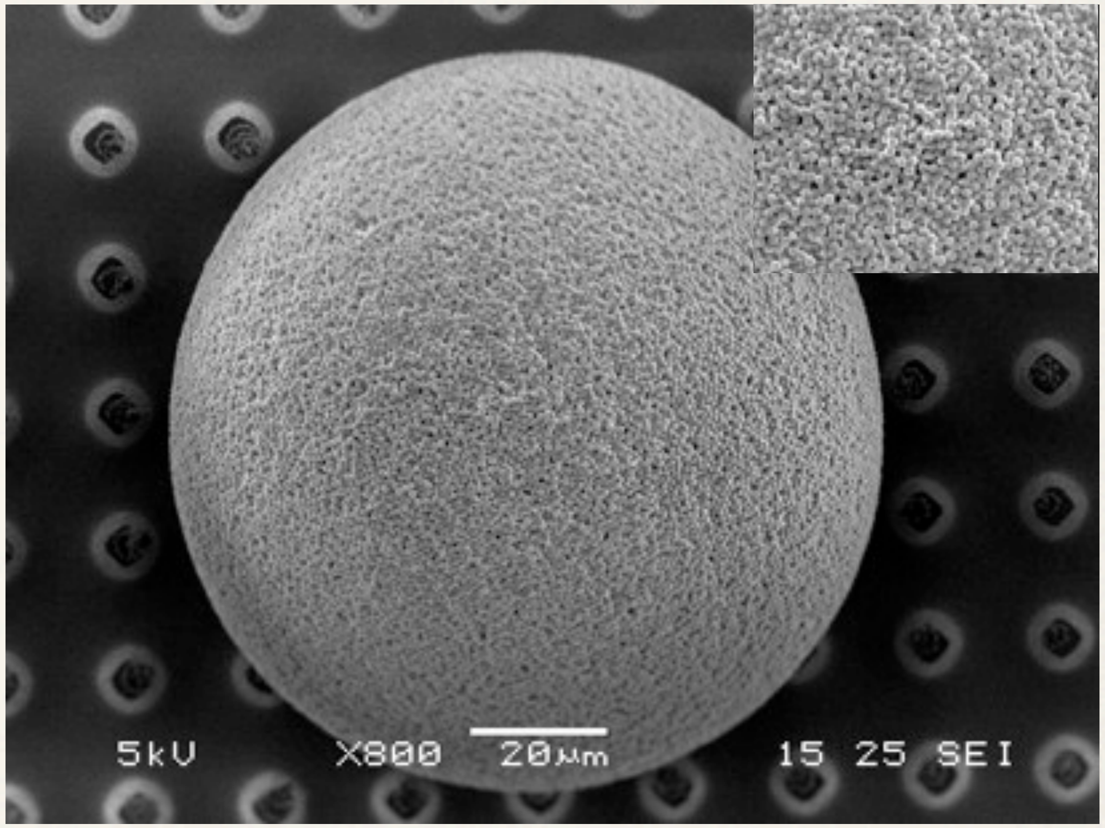
Microscopic soccer balls!

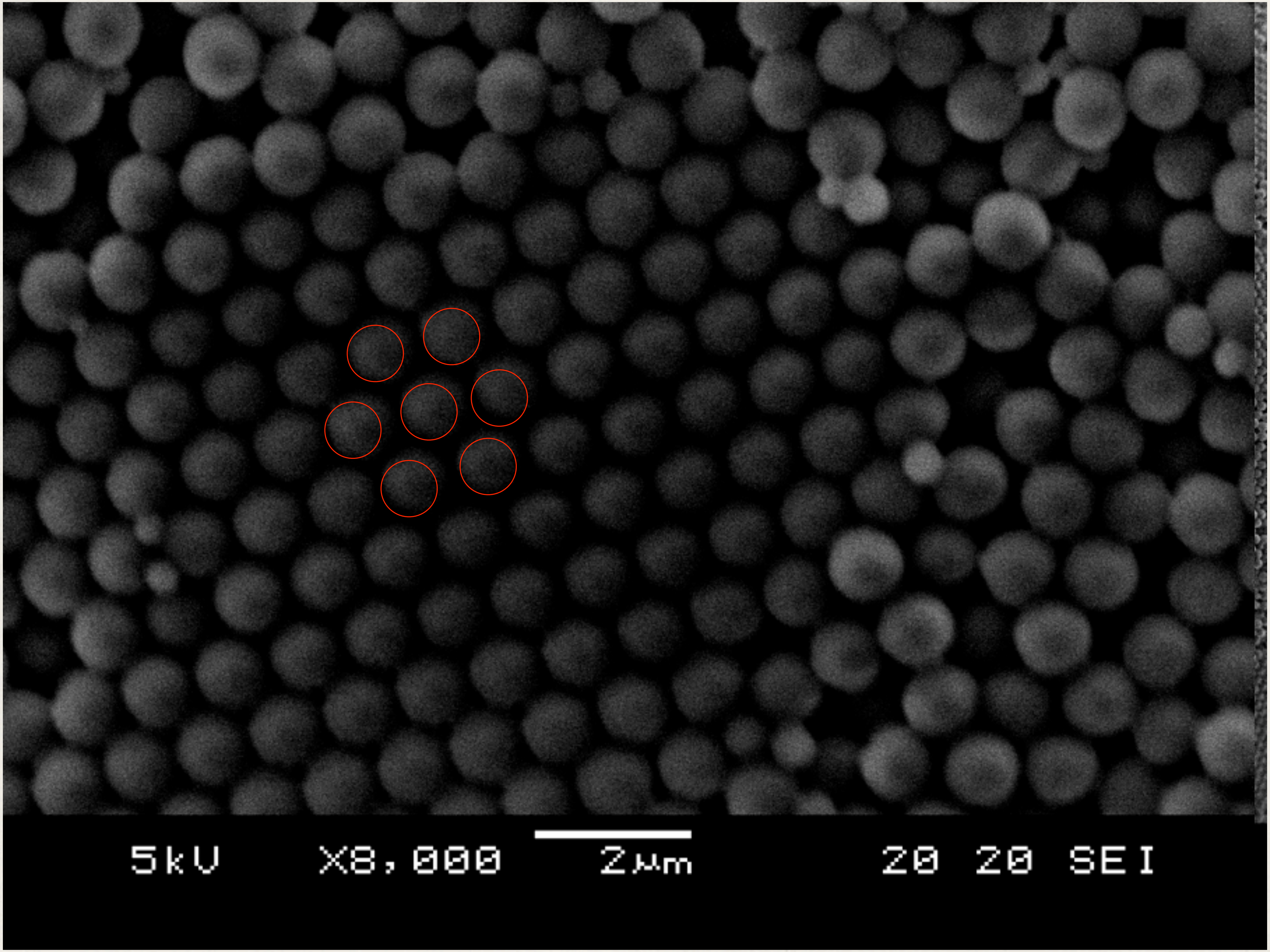




Different structures?

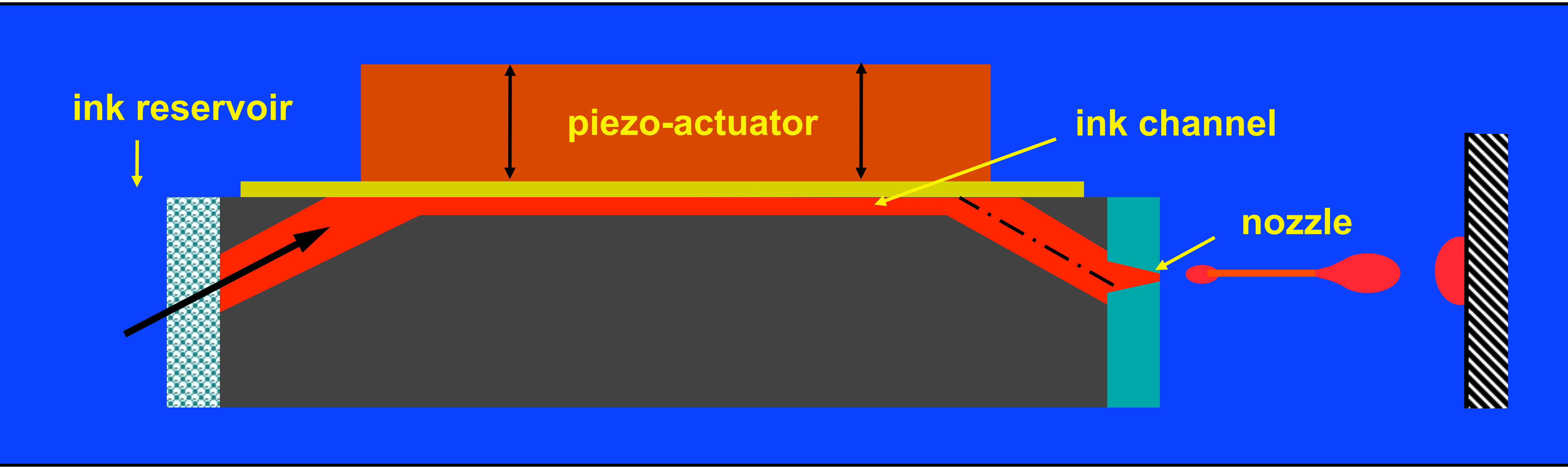


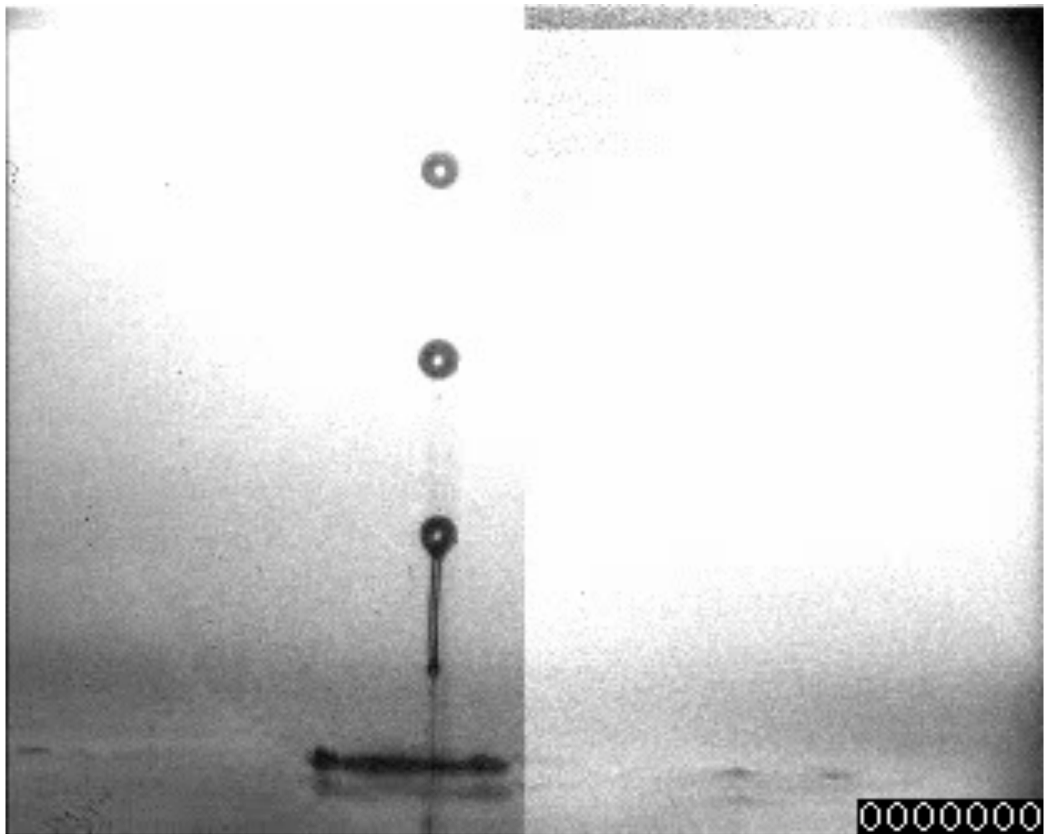



5kV X8,000 2μm 20 20 SEI

Making of extremely controlled droplets: inkjet printing

Piezoacoustic inkjet printing

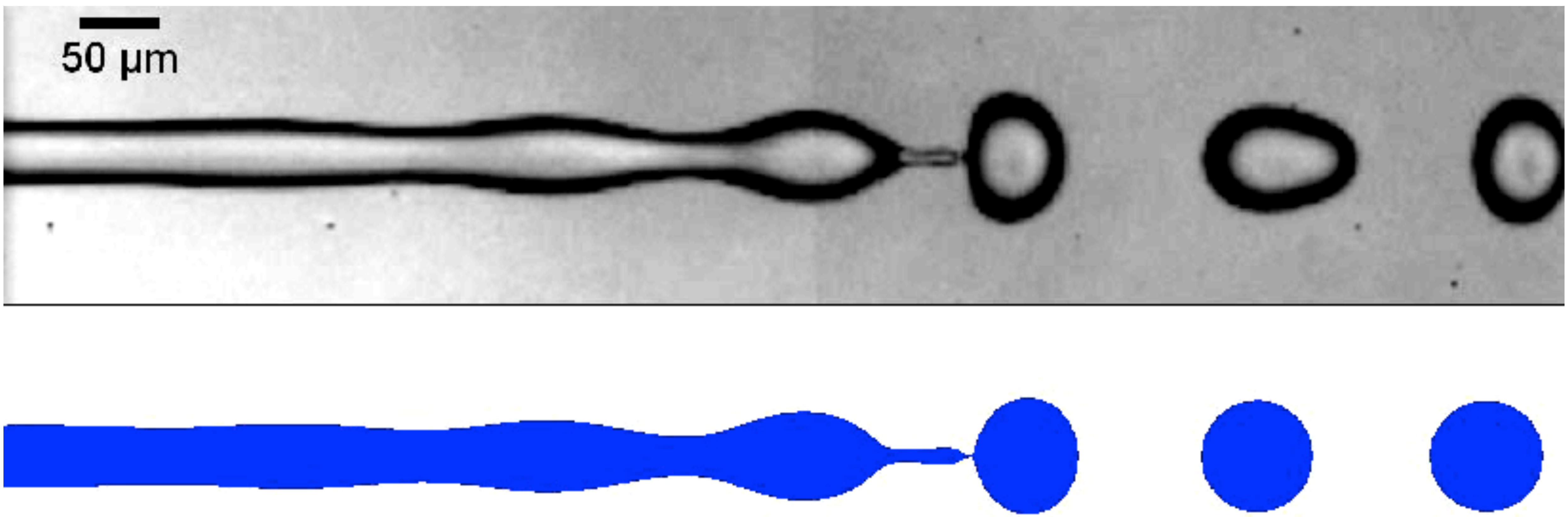




... or even MEMS-based ...

High speed imaging:
1MHz

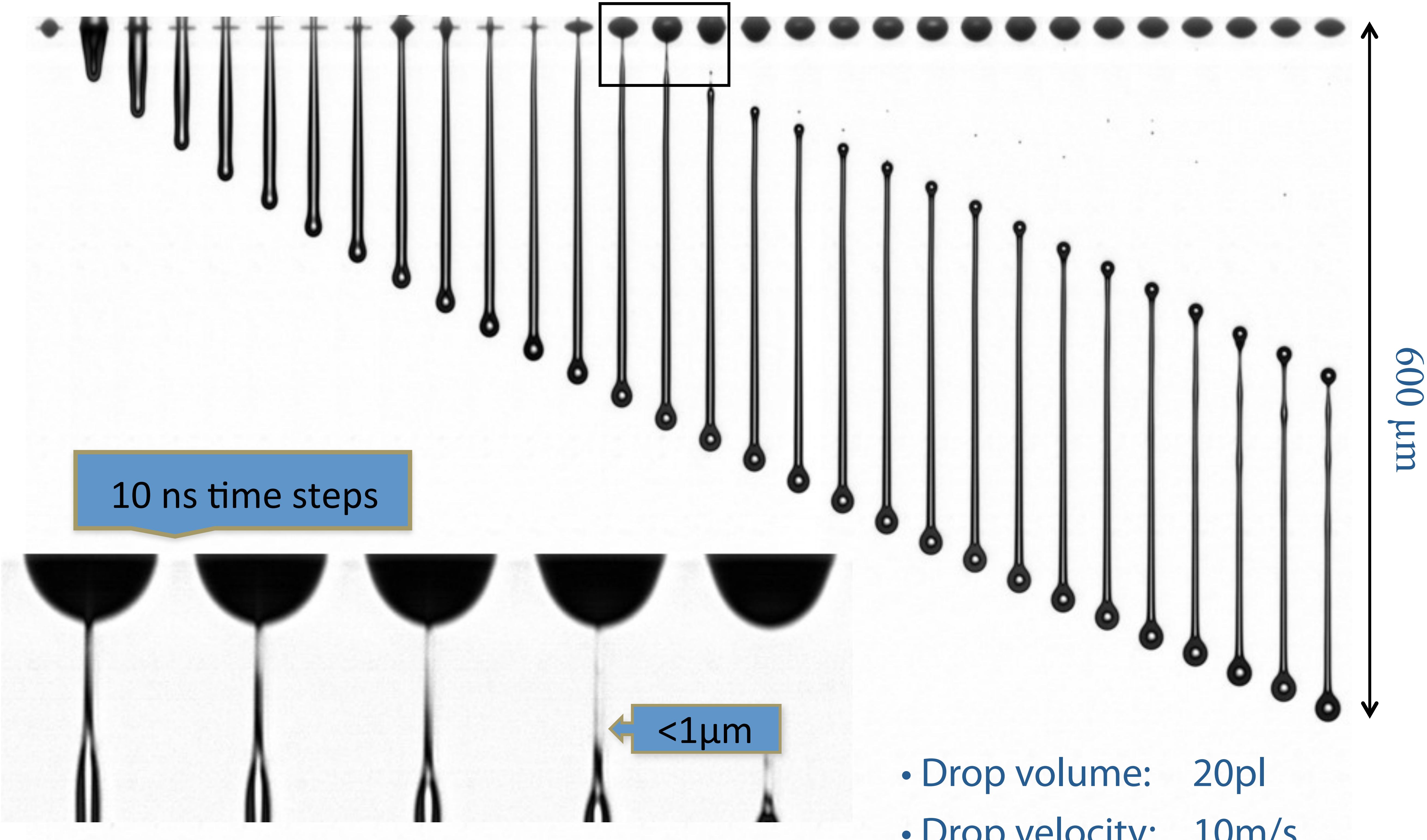
Comparison experiment vs lubrication model



Satellite droplets

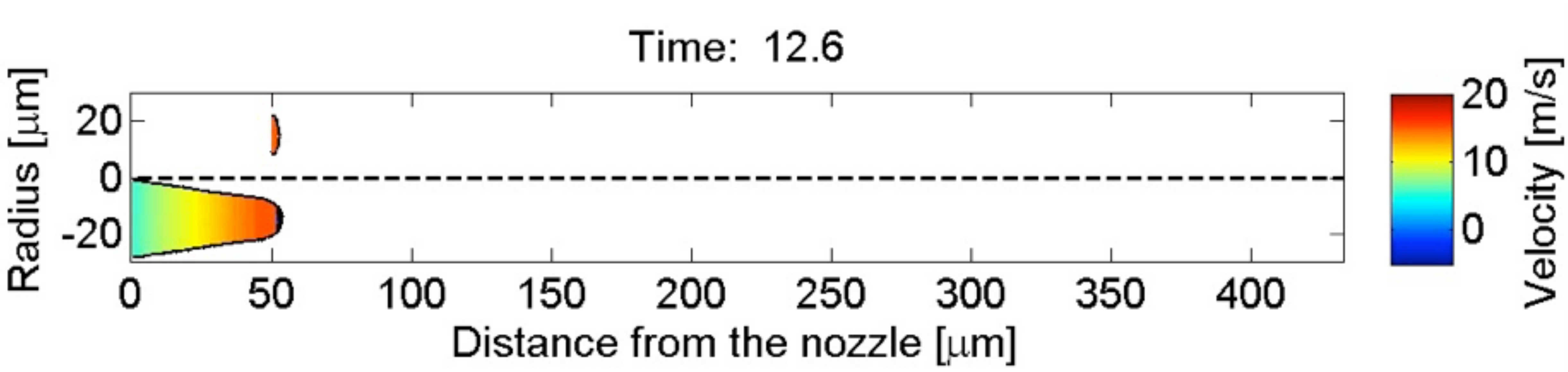
van Hoeve, Gekle, Snoeijer, Versluis, Brenner, Lohse, Phys. Fluids 22, 122003 (2010)

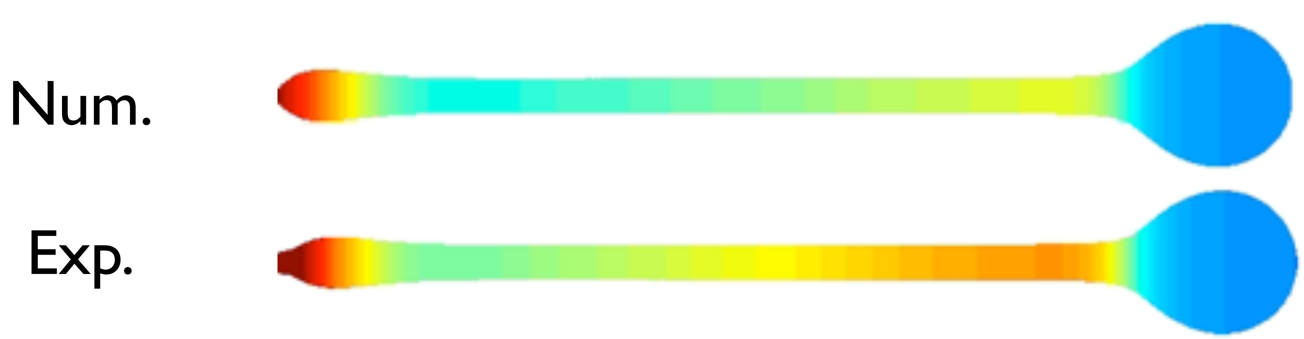
Stroboscopic imaging: iLIF



- Drop volume: 20pl
- Drop velocity: 10m/s

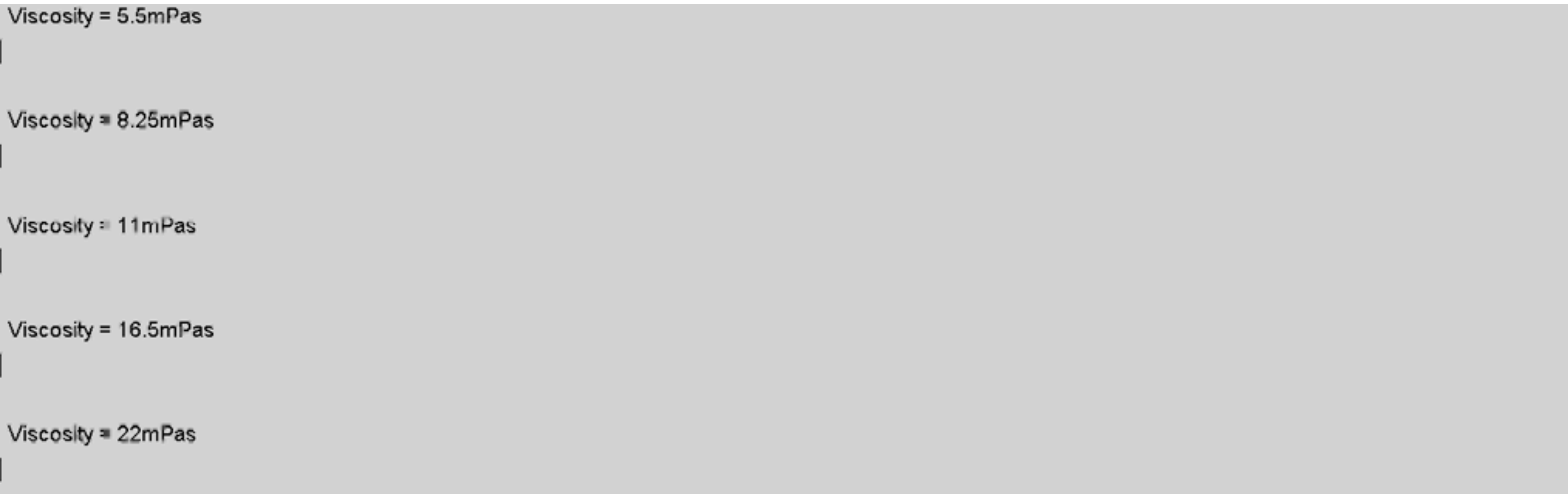
Comparison with lubrication model



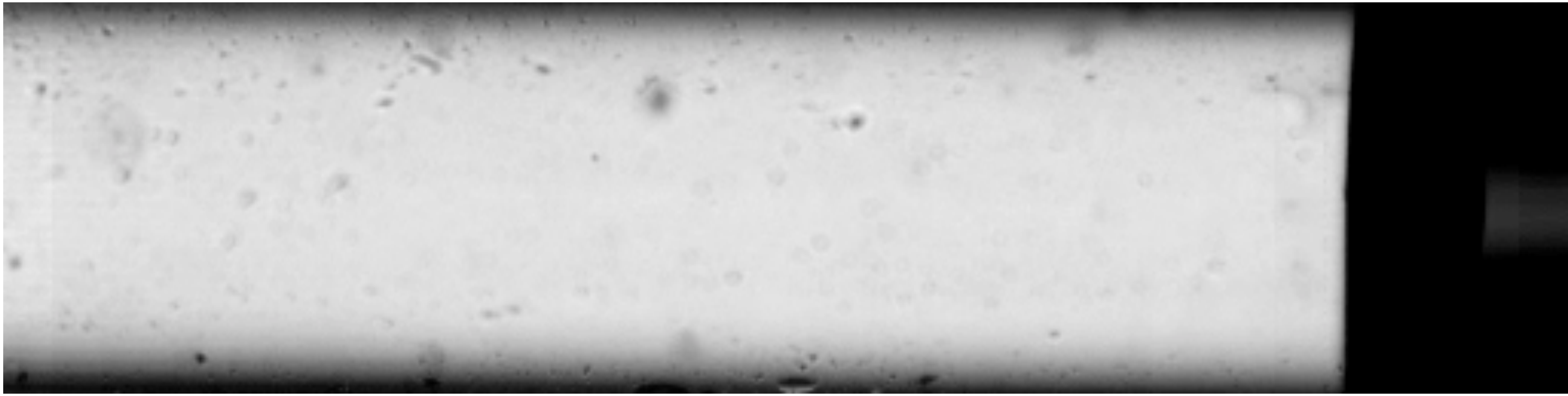


Difference due to air friction!

Predictions from lubrication model for inks with different viscosity



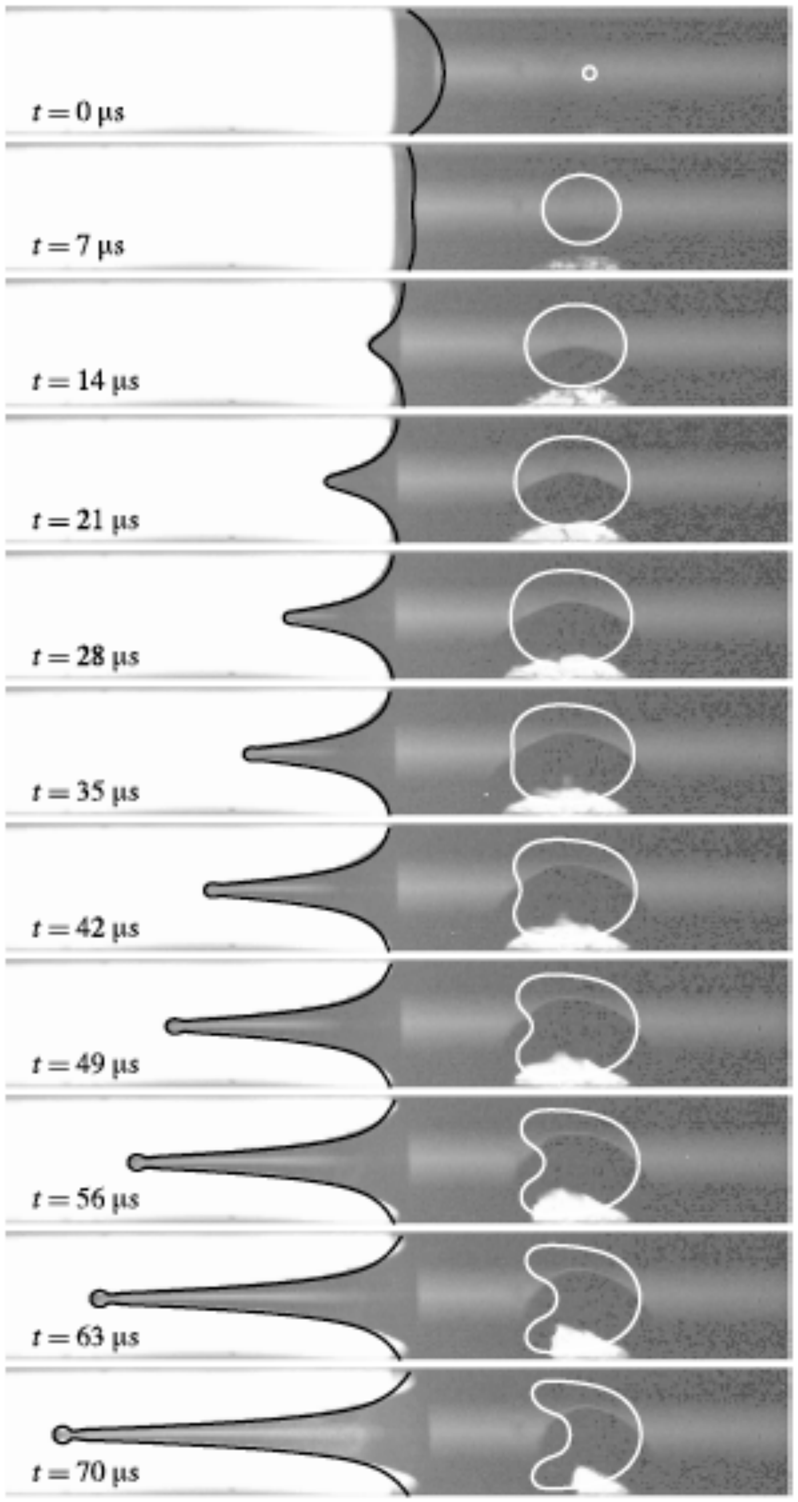
Supersonic microjets through flow focusing!

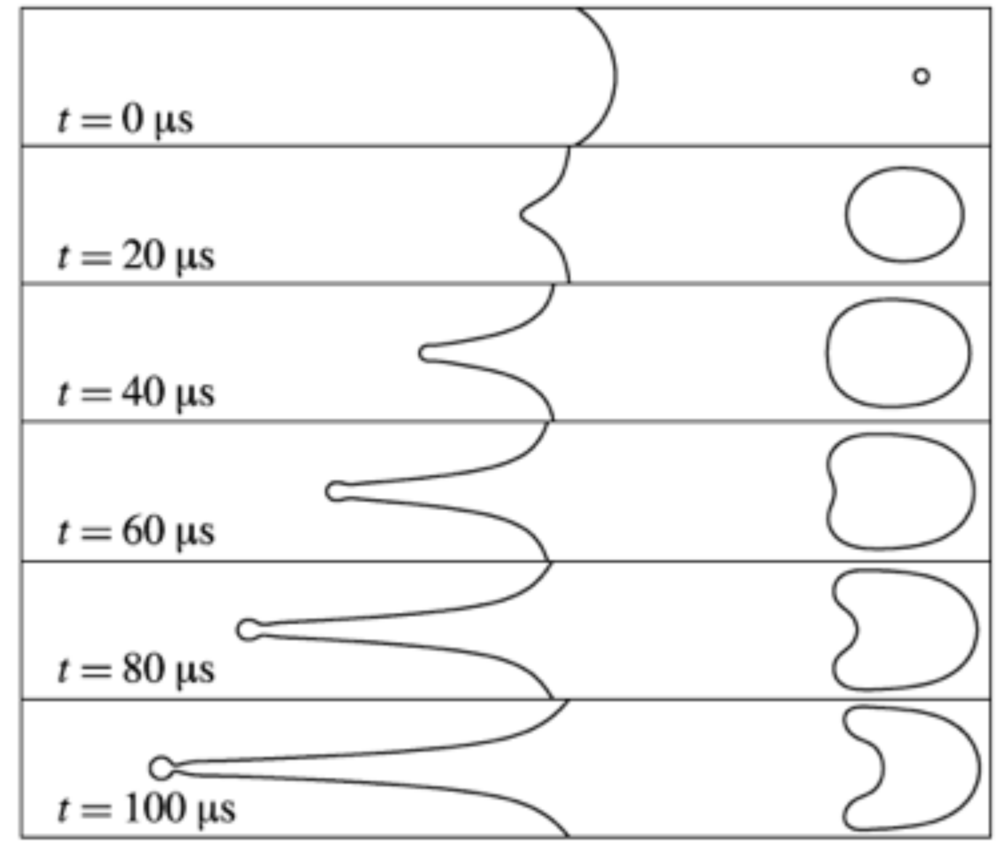


v ~ 1000 m/s D ~ 10 μm

I. R. Peters *et al.*, JFM 719, 587 (2013)

Mechanism: flow focusing





boundary integral

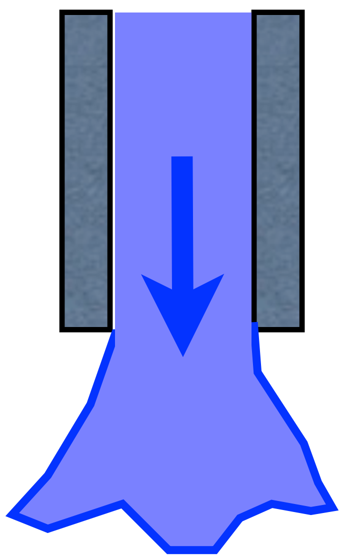
experiment

I. R. Peters *et al.*, JFM 719, 587 (2013)

Application: Needle-free injection

Existing methods

Piston-syringe system



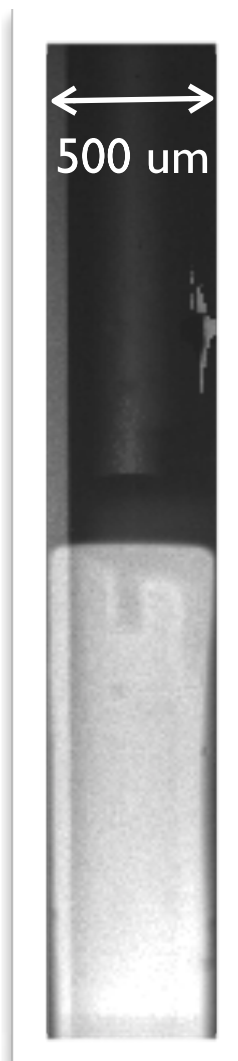
Diffusive jets

- Severe deceleration
- Scattered pattern

➡ Causes pain
➡ Insufficient penetration
➡ Little volume control

Novel method

Highly-focused supersonic microjets

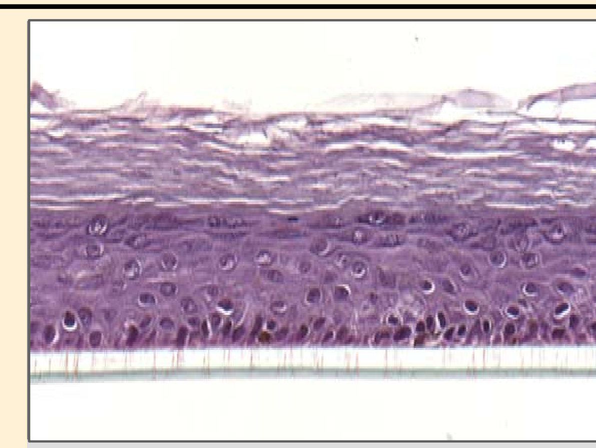


Tagawa et al., PRX 2, 031002 (2012)

- **Highly-focused** shape
- **Ultra-high speed** (up to *850* m/s)
- Good controllability

Target materials

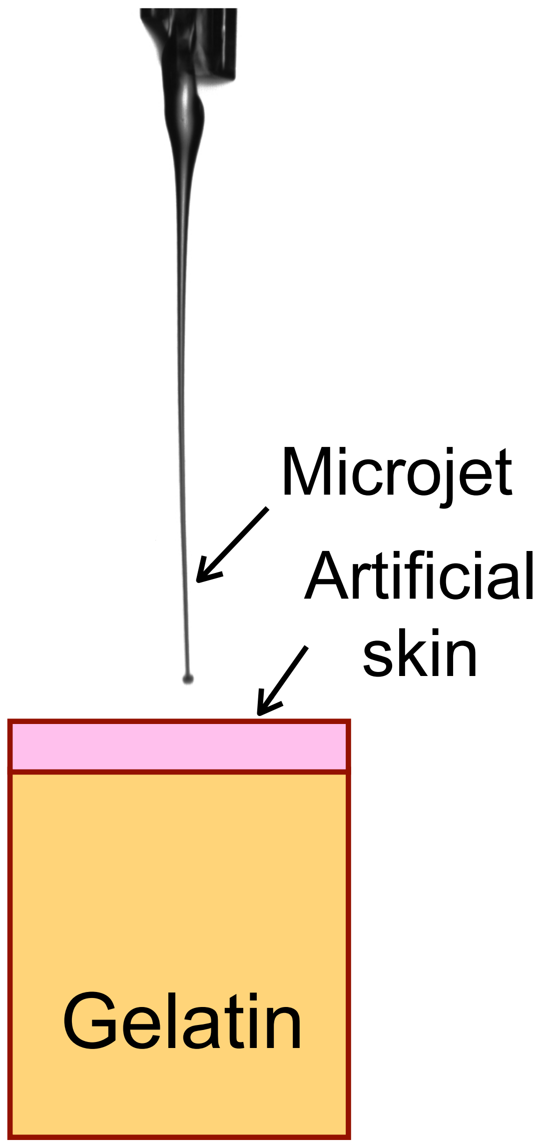
✦ Artificial human skin



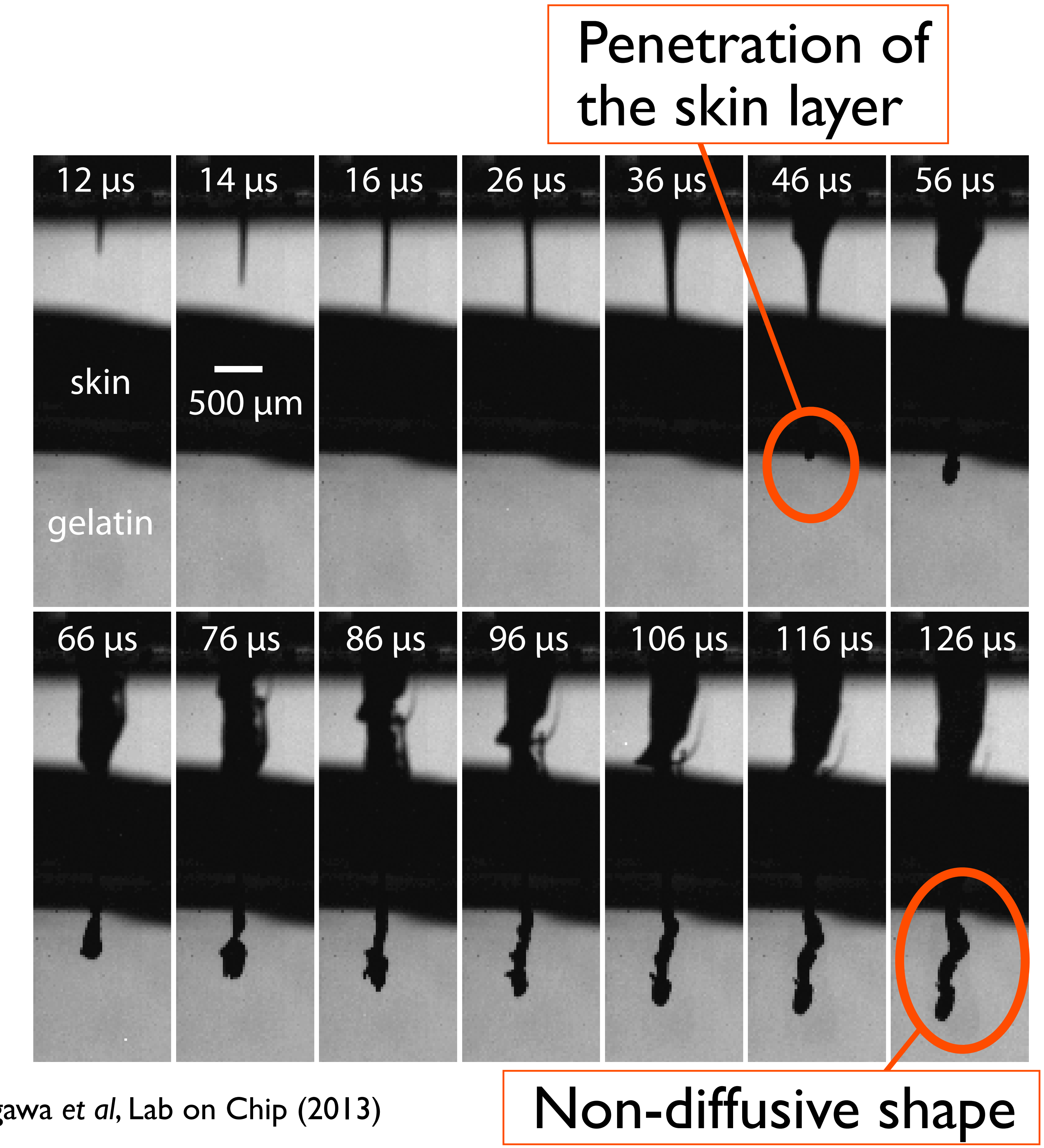
Leiden epidermal skin model

✦ Gelatin 5wt%
(Human soft tissue equivalent)

Application: Needle-free injection



Equivalent to human body

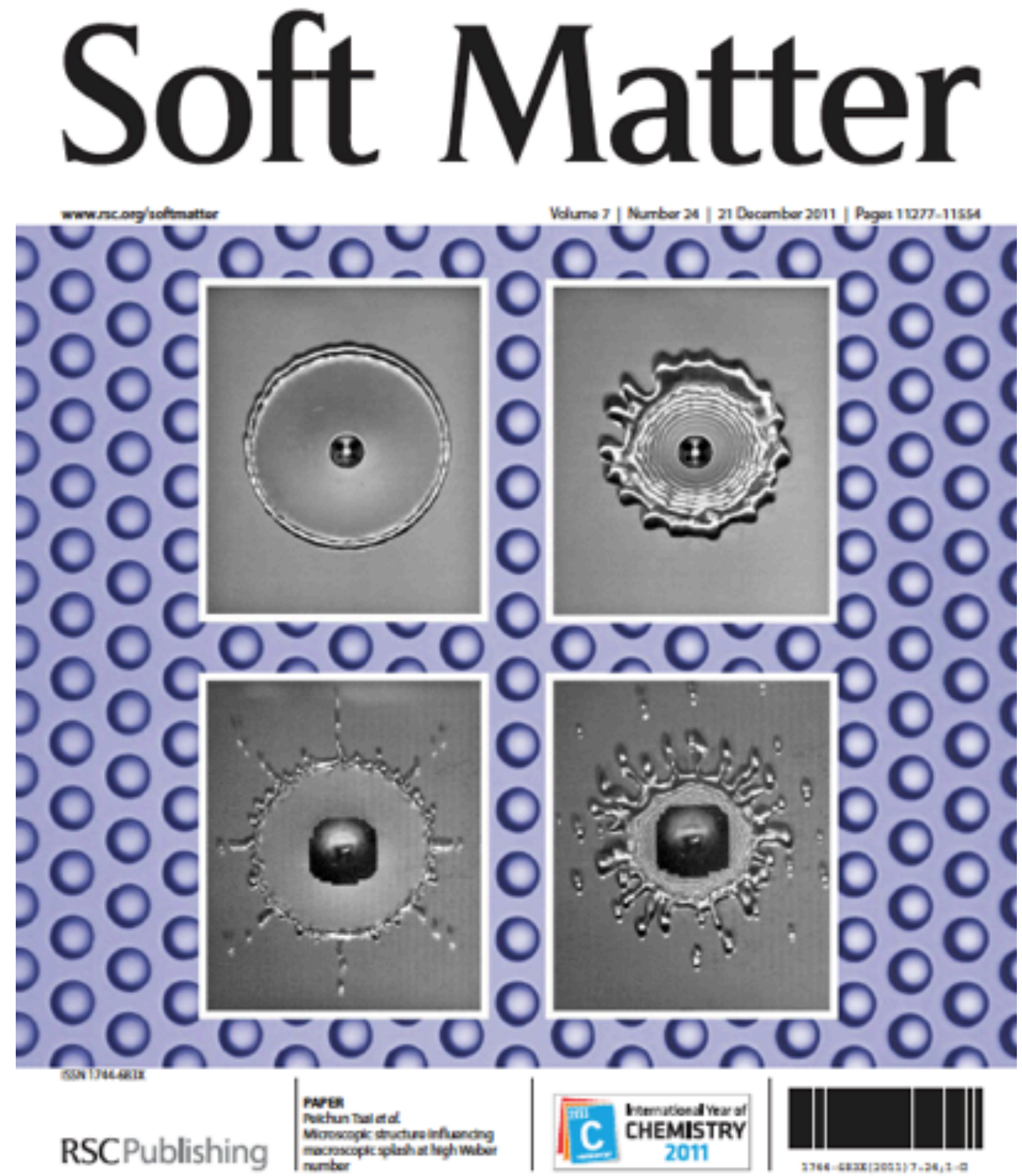


Tagawa *et al*, Lab on Chip (2013)

Impact on structured surfaces

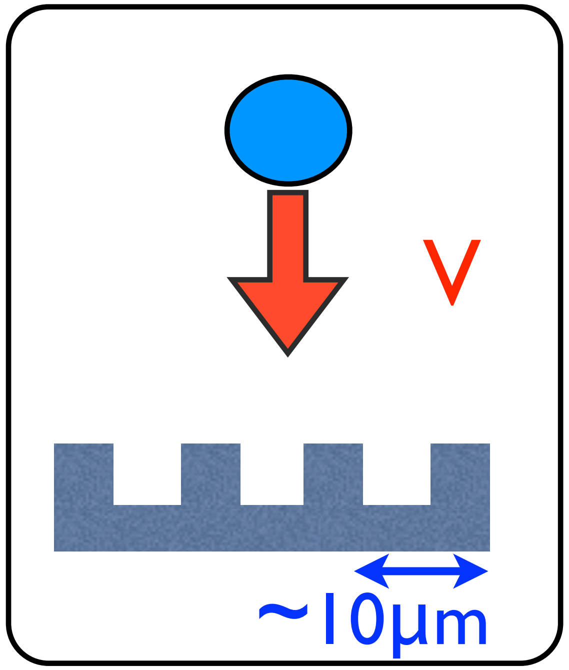
Tsai, van der Veen, van der Raa, Lohse, Langmuir 26, 9640 (2010)

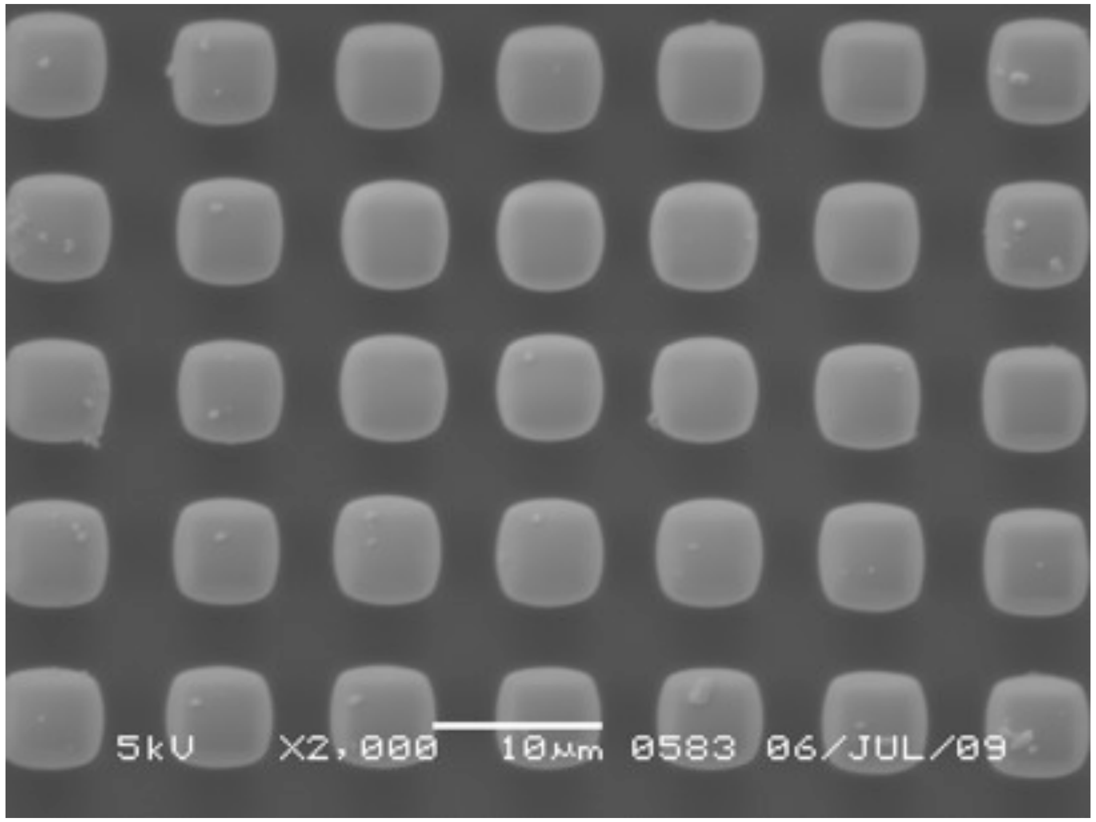
P. Tsai, S. Pacheco, C. Pirat, L. Lefferts, & D. Lohse,
Drop impact upon micro- and nanostructured superhydrophobic surfaces,
Langmuir **25**, 12293 (2009).



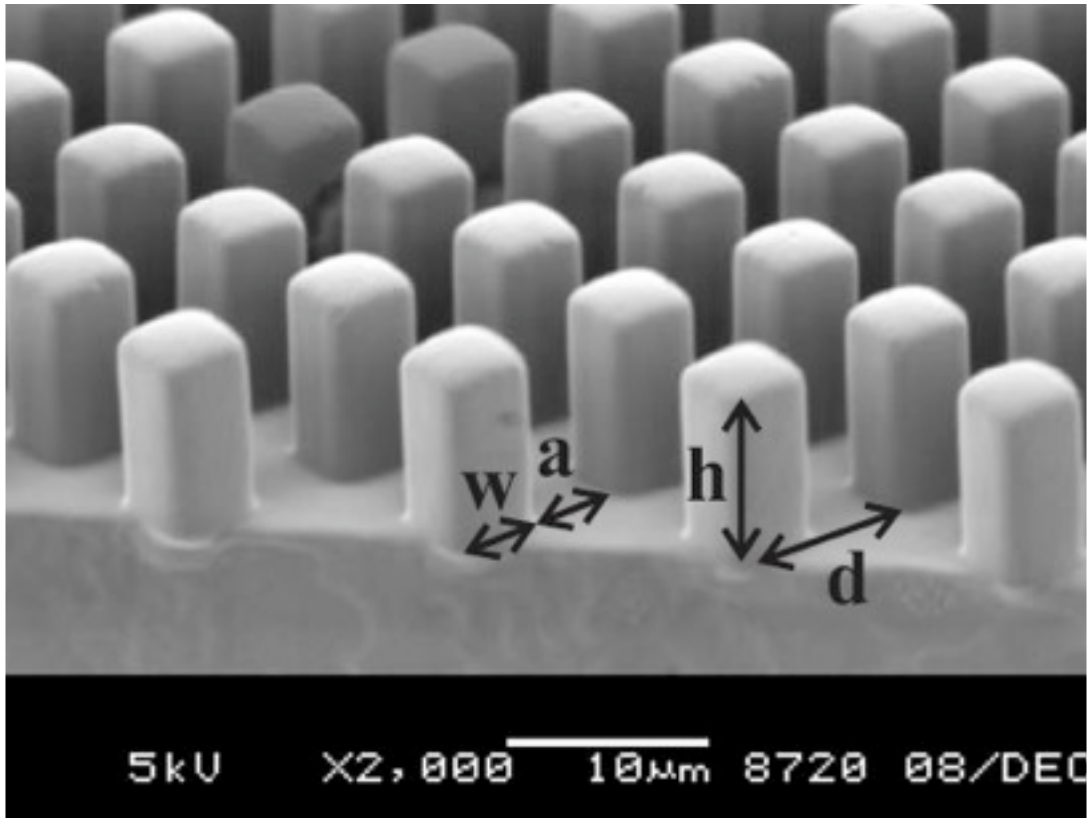
P. Tsai, M. Hendrix, R. Dijkstra, L. Shui & D. Lohse,
Microscopic structure influences macroscopic splash at large We,
Soft Matter **7**, 11325 (2011).

Structure of the surfaces



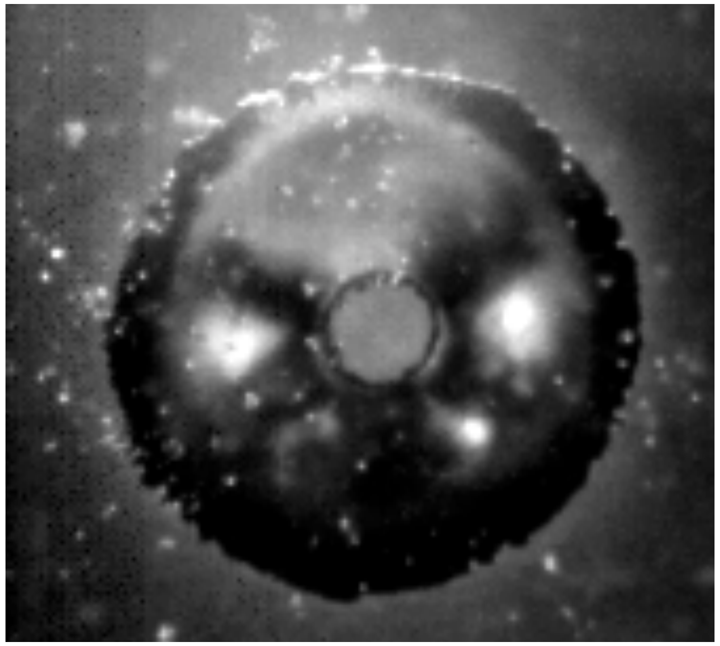


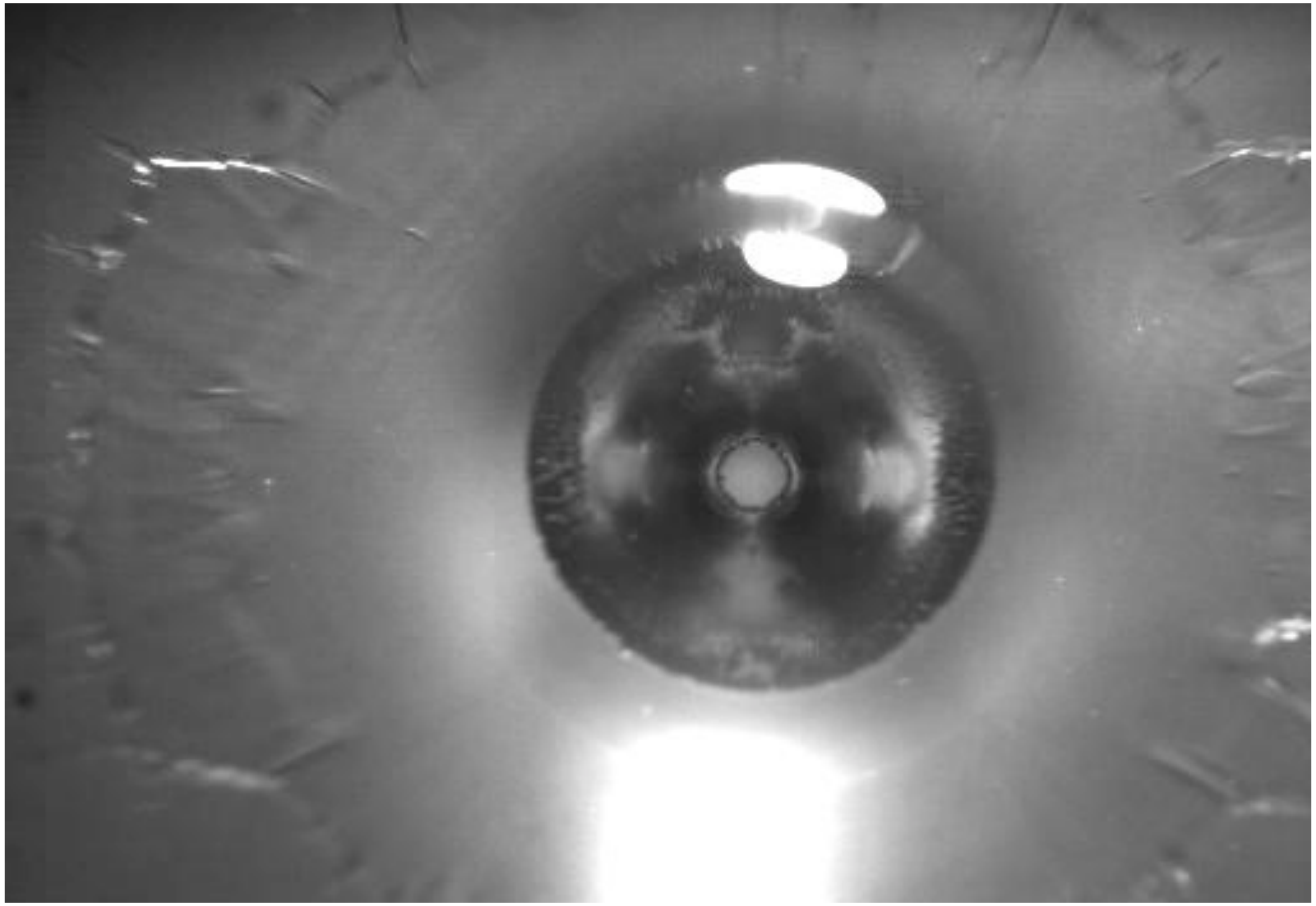
Transparent PDMS
(polydimethylsiloxane)



h = 6 μm
w = 5 μm

Entrapped air bubbles & wetted central region

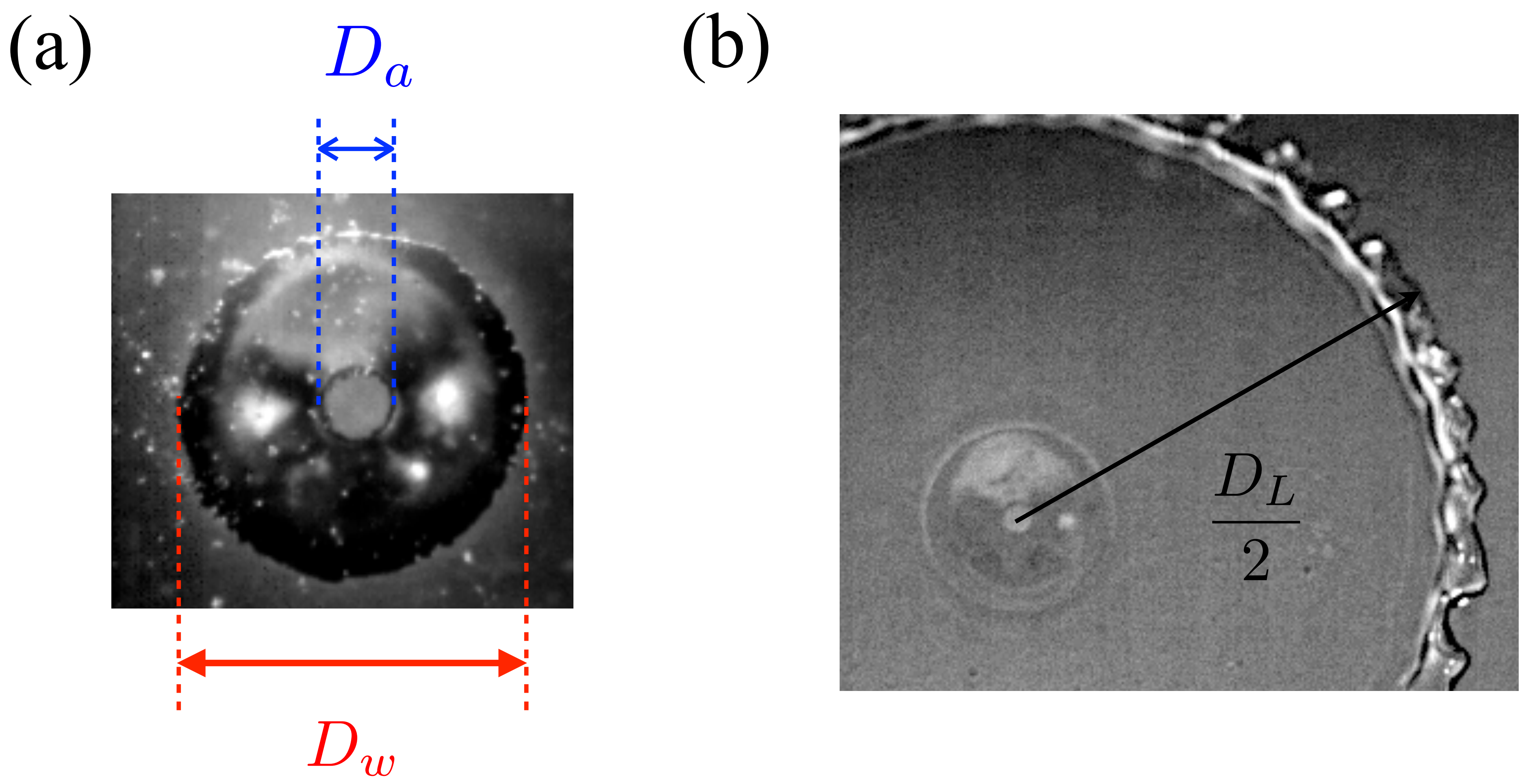




D_a = diameter of entrapped air disk

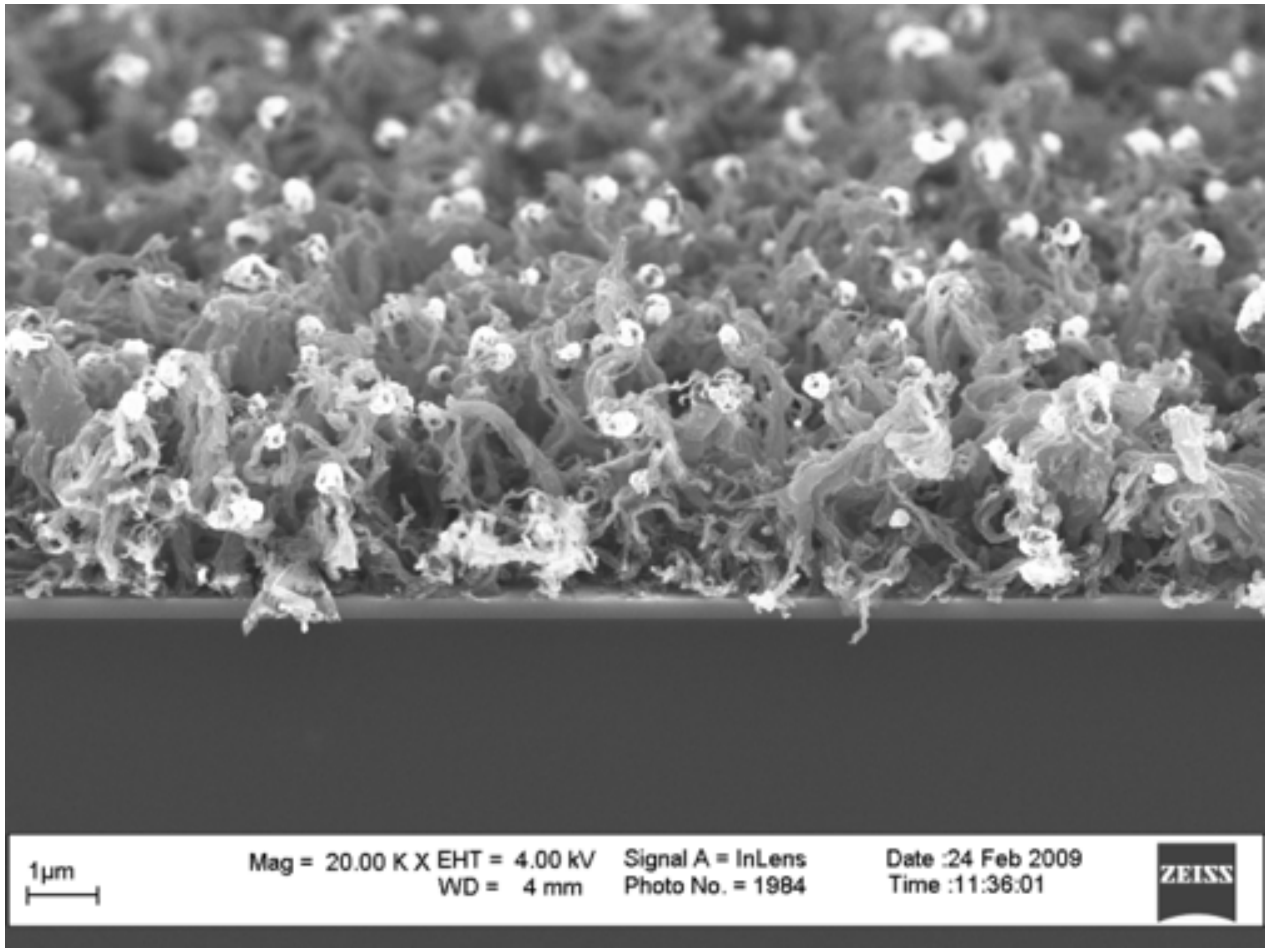
D_w = diameter of wetted area

D_L = diameter of max. spreading lamella



$$w = 5\mu m, h = 6\mu m, d = 10\mu m$$

Impact on superheated carbon nanofiber jungle surface



H ~ 4 μm;
d_{CNF} ~ (80-200) nm

D ~ 2.27 mm
U ~ 0.4 m/s

SEM


Photron
FASTCAM SA2 mode... 10000 fps
1/30000 sec
512 x 416
frame : -2635
-00:00:00.2635
Date : 2011/11/15
Time : 14:28

T=350°C

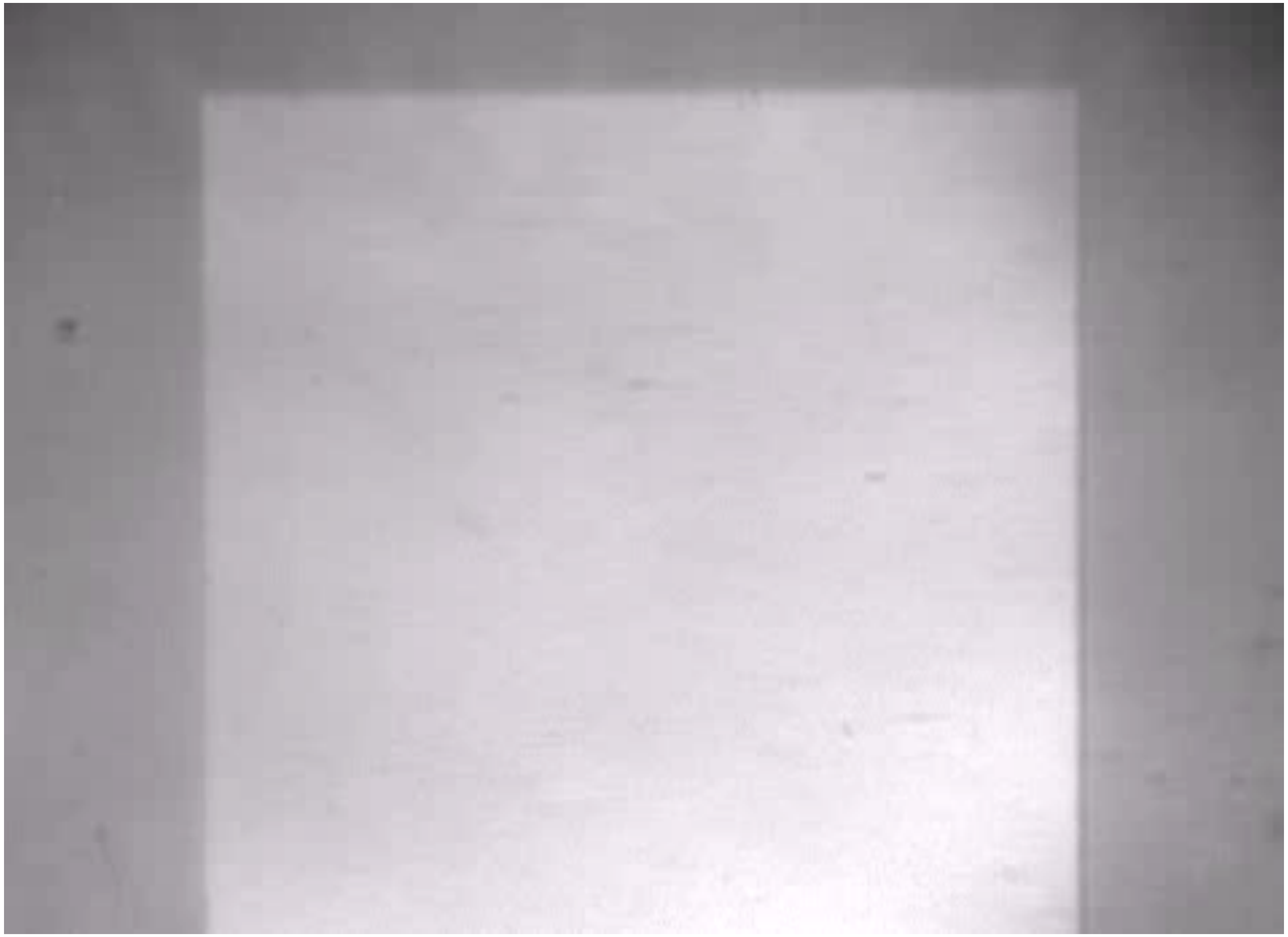

Photron
FASTCAM SA2 mode... 10000 fps
1/30000 sec
512 x 416
frame : -3224
-00:00:00.3224
Date : 2011/11/15
Time : 15:12

T=440°C

Surface manipulation and controlled cavitation

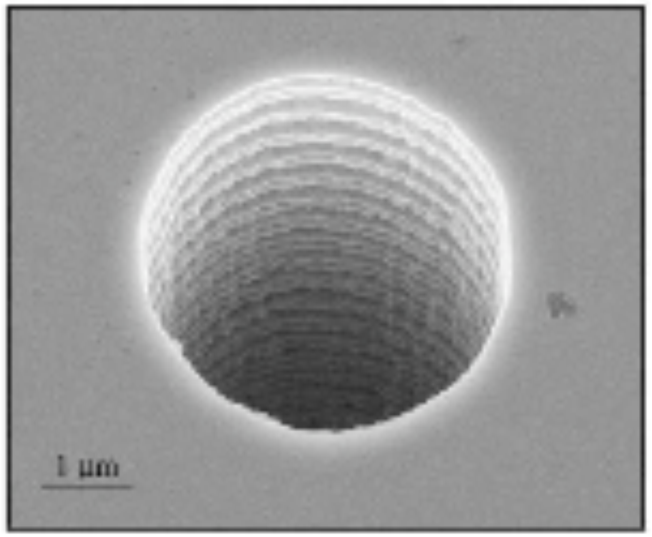
Bremond, Arora, Ohl, Lohse, Phys. Rev. Lett. 96, 224501 (2006);
Borkent, Gekle, Prosperetti, Lohse, Phys. Fluids 21, 102003 (2009)

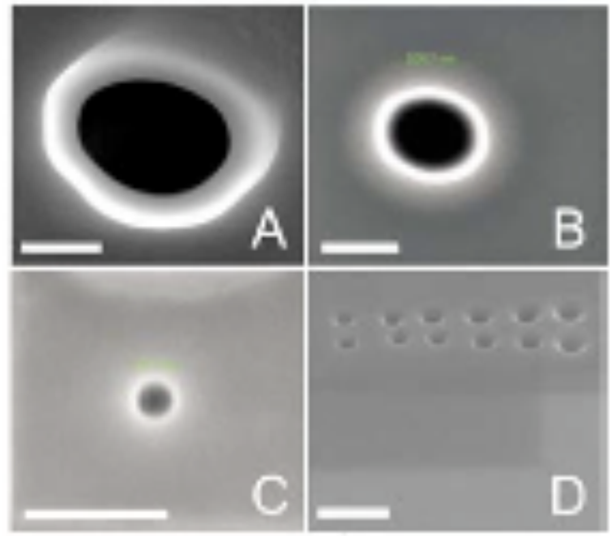
Massive pressure reduction:
Uncontrolled cavitation & bubble nucleation



1 Mfps movie, Si surface, nucleation at natural crevices

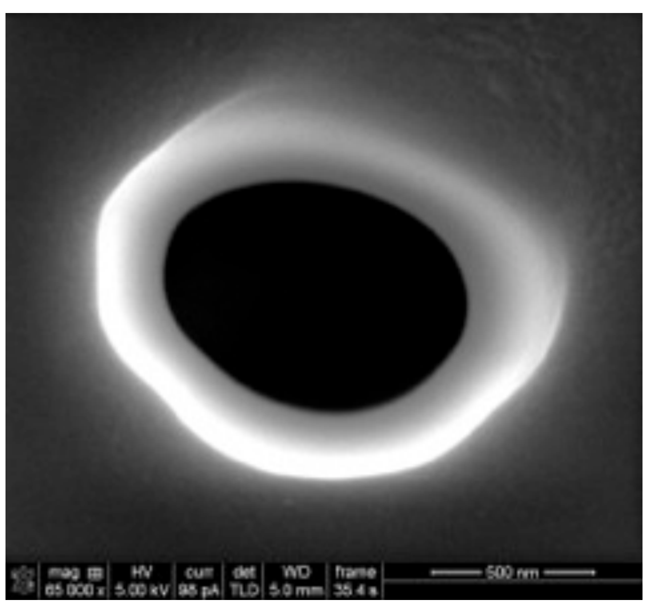
Offer system weak spots through micro- & nano-machined “artifical crevices”



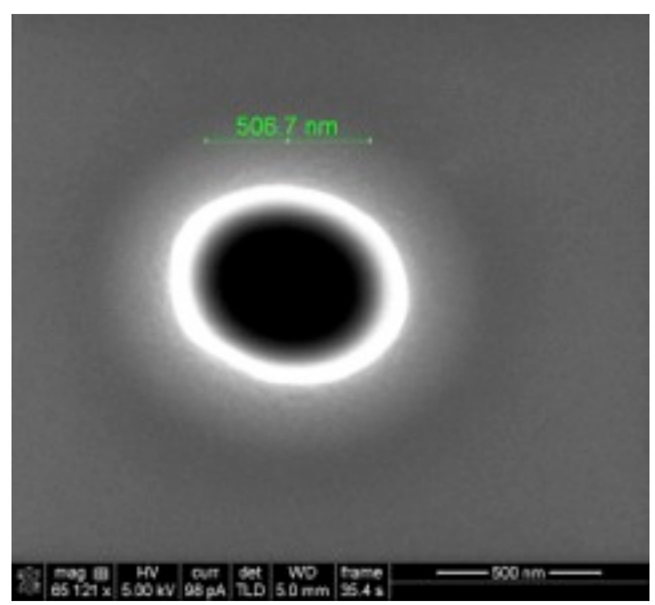


made by focused ion-beam

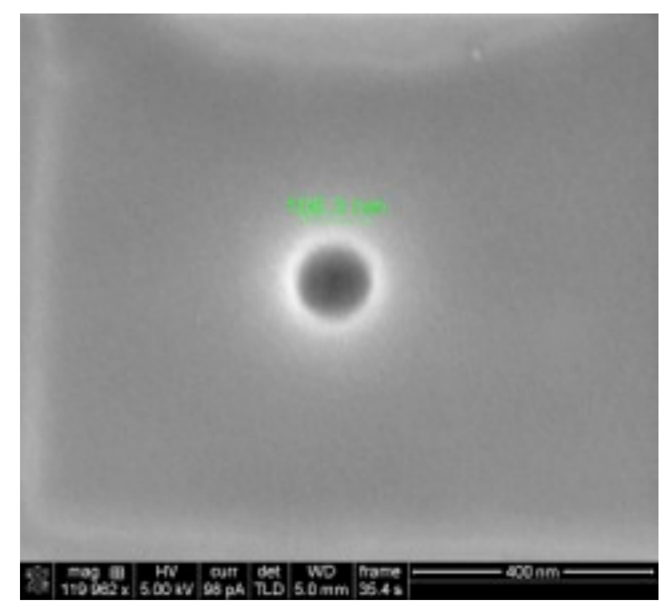
2000nm



900nm

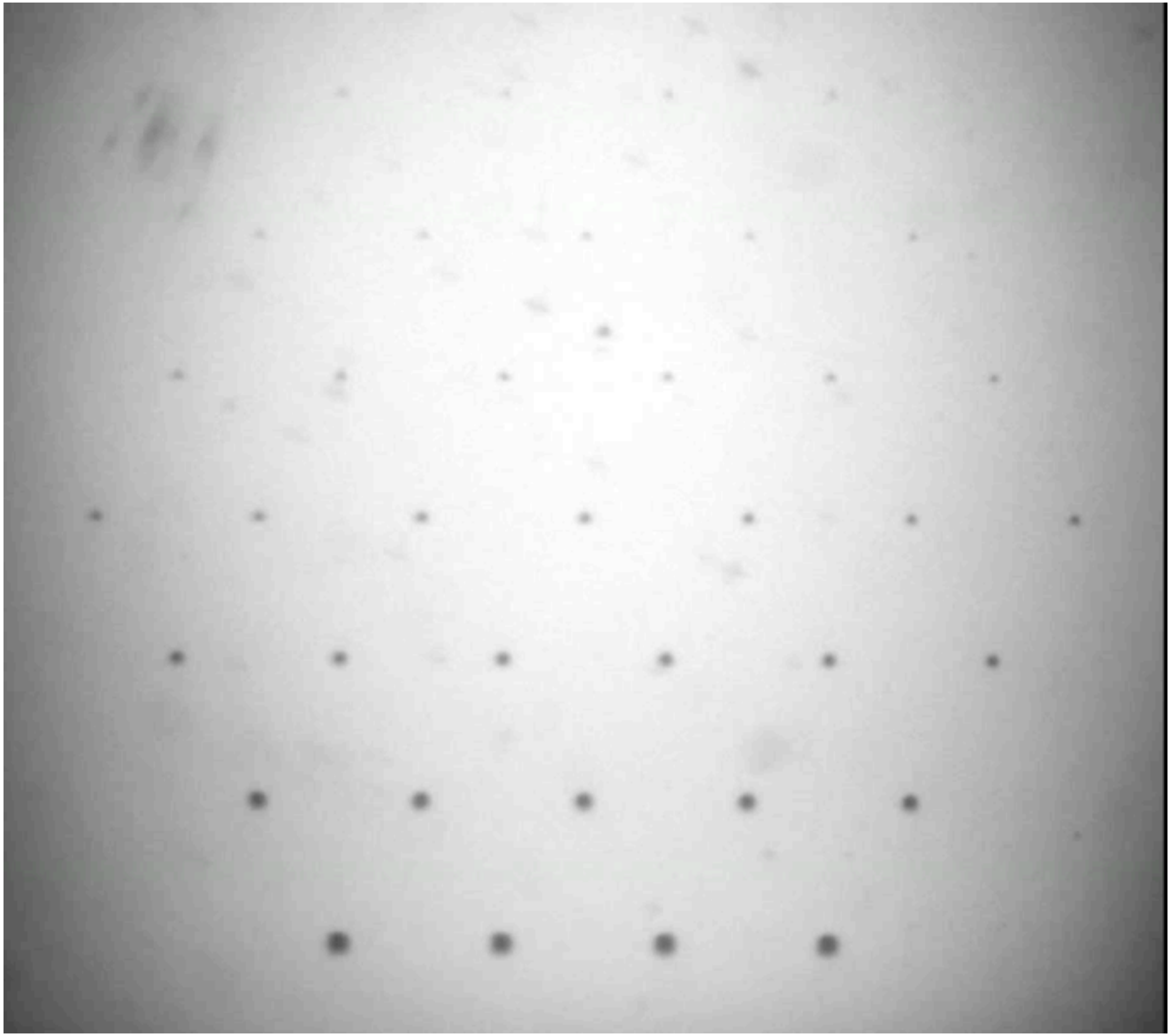


500nm

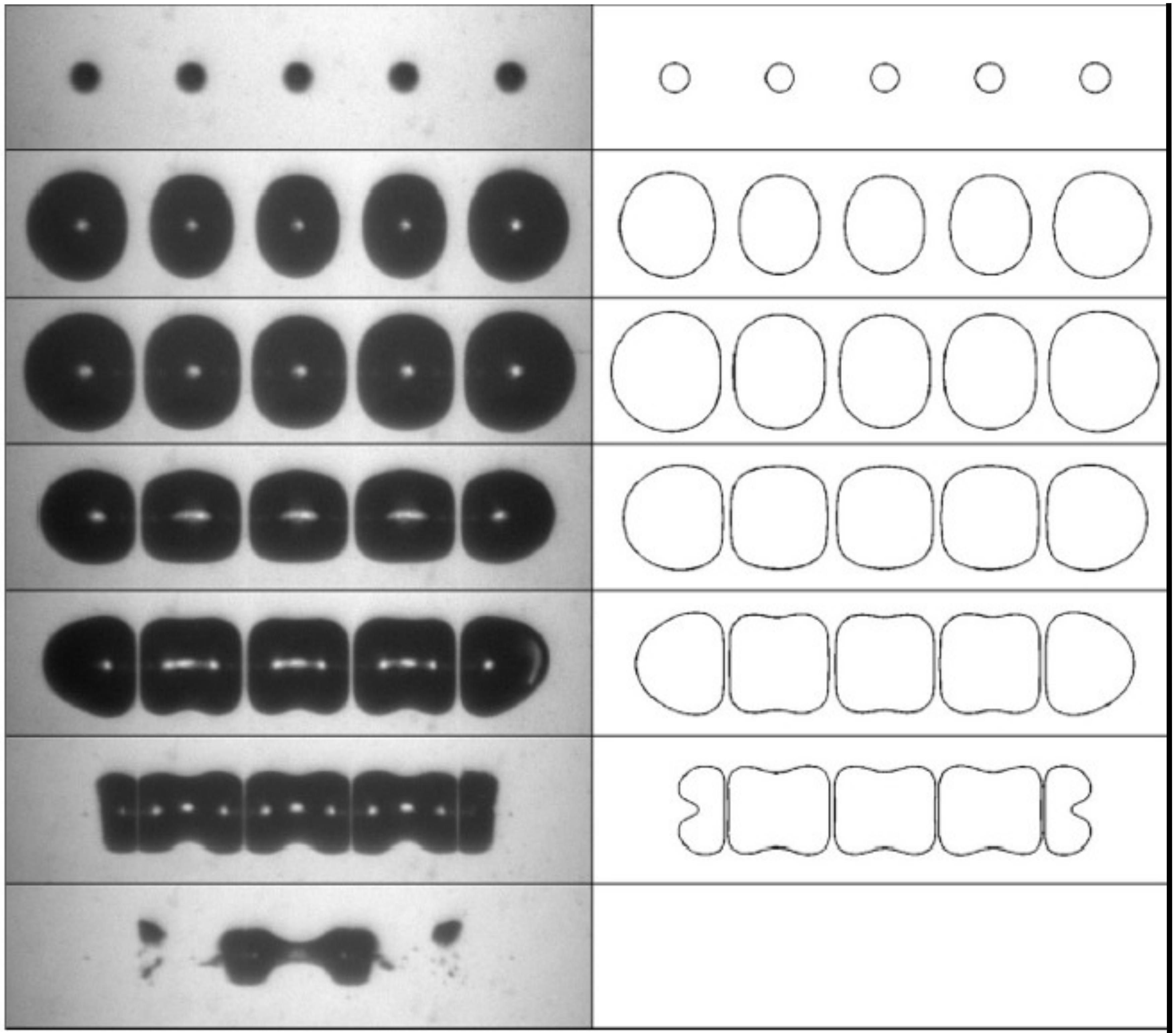


100nm

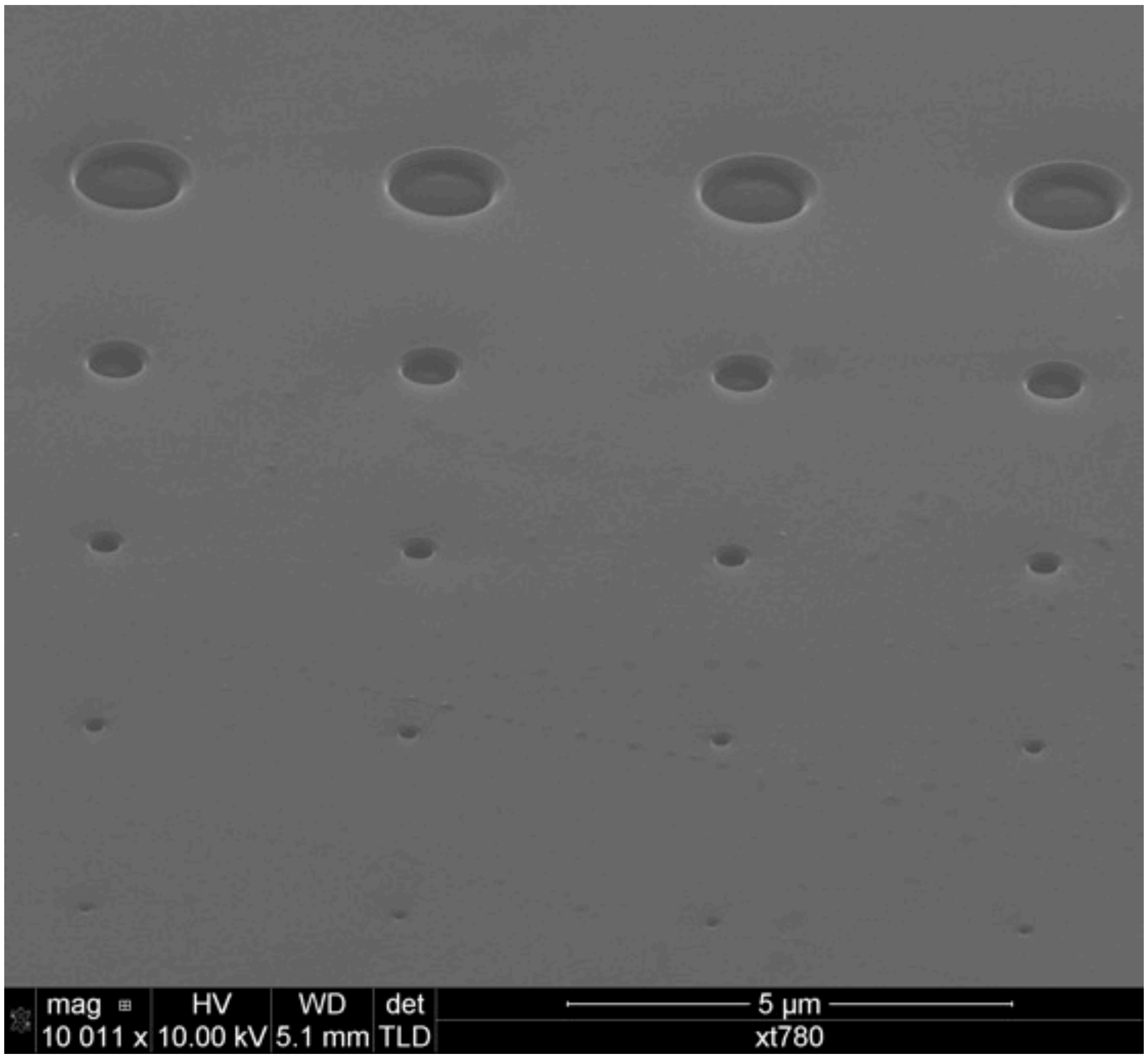
Pattern of bubbles



Shielding effect of bubbles: experiment vs theory



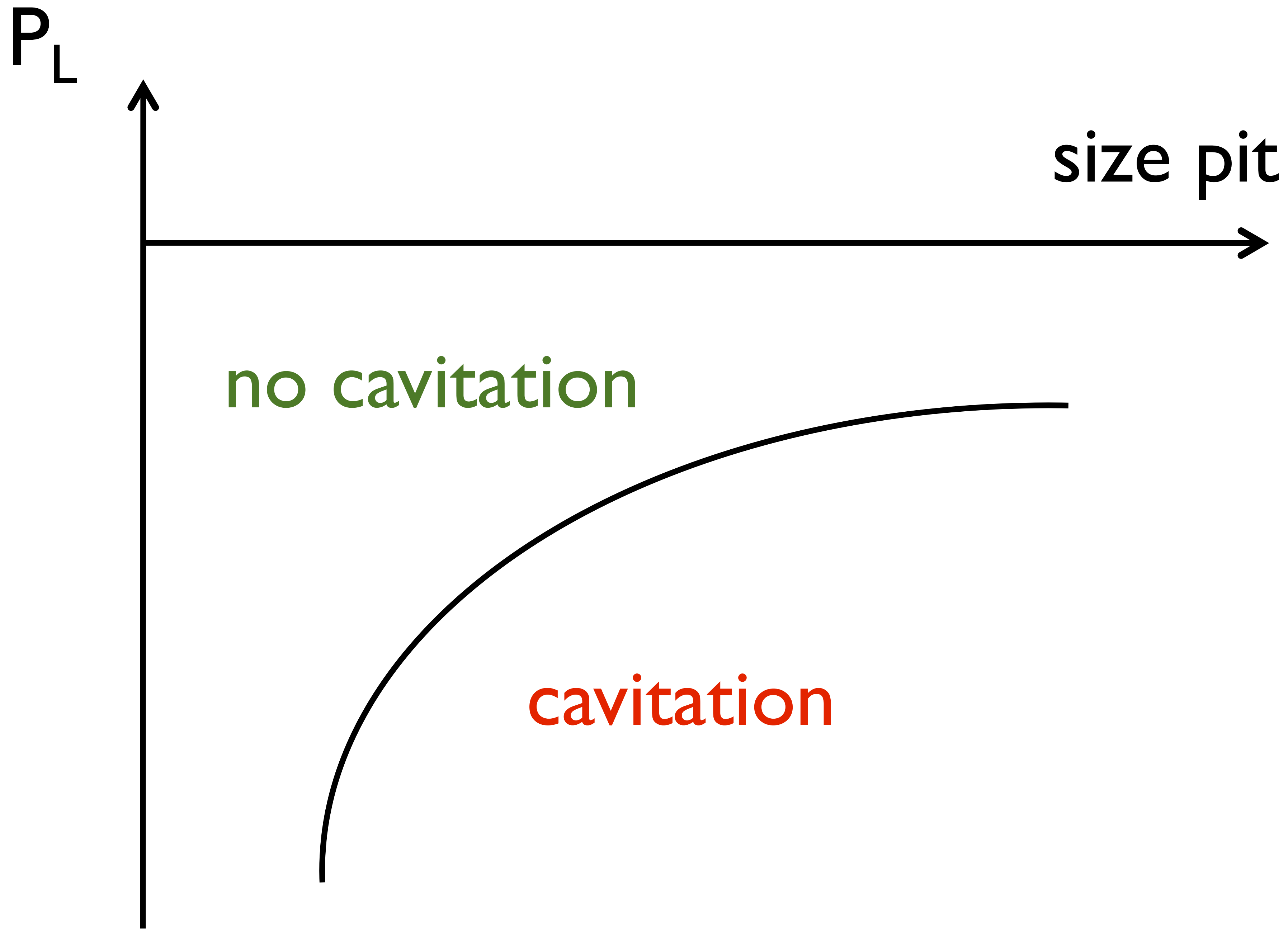
Cavitation from nanopits?
How small can we go?



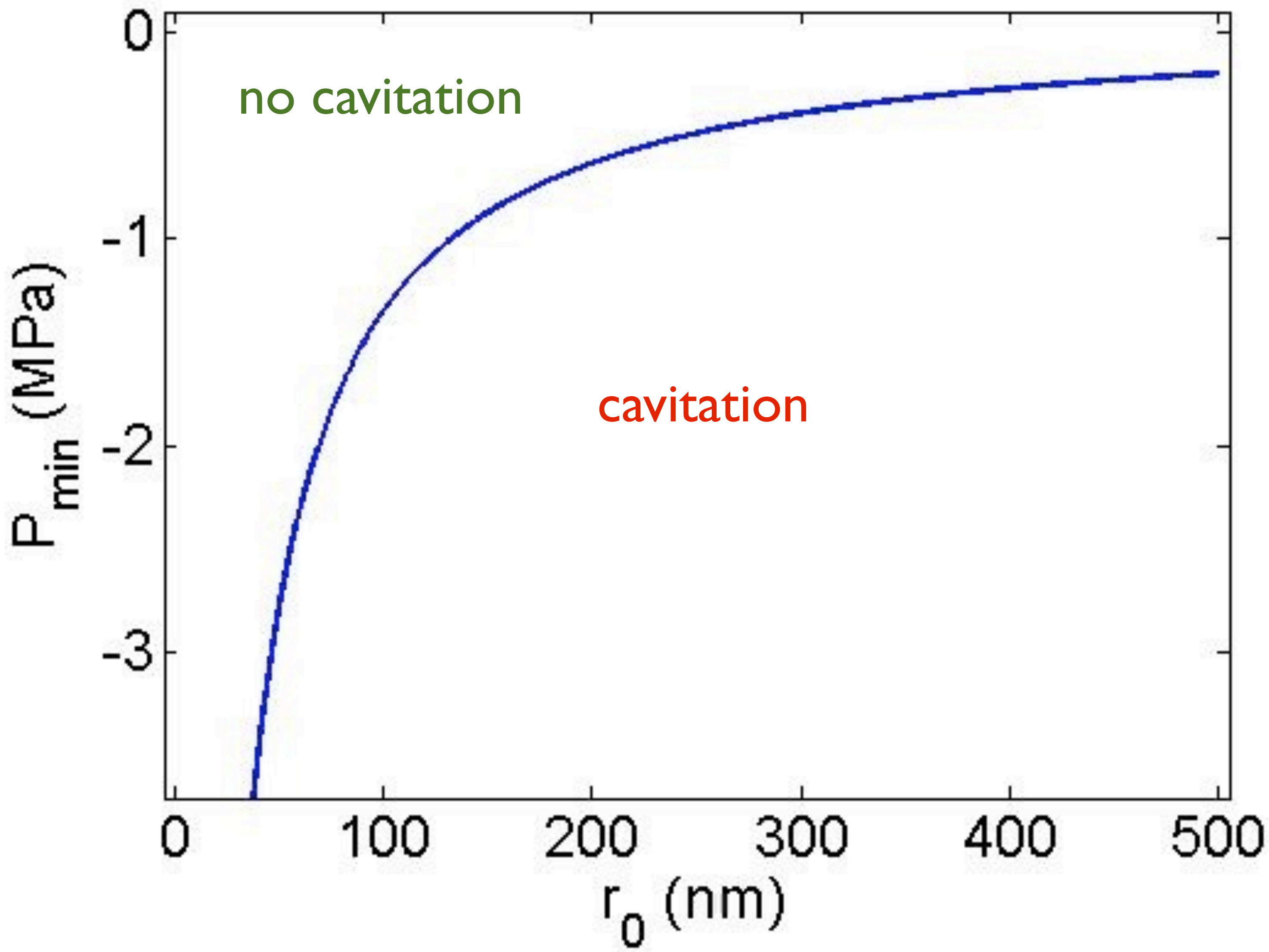
900nm

100nm

Calculate & measure phase diagram of bubble nucleation

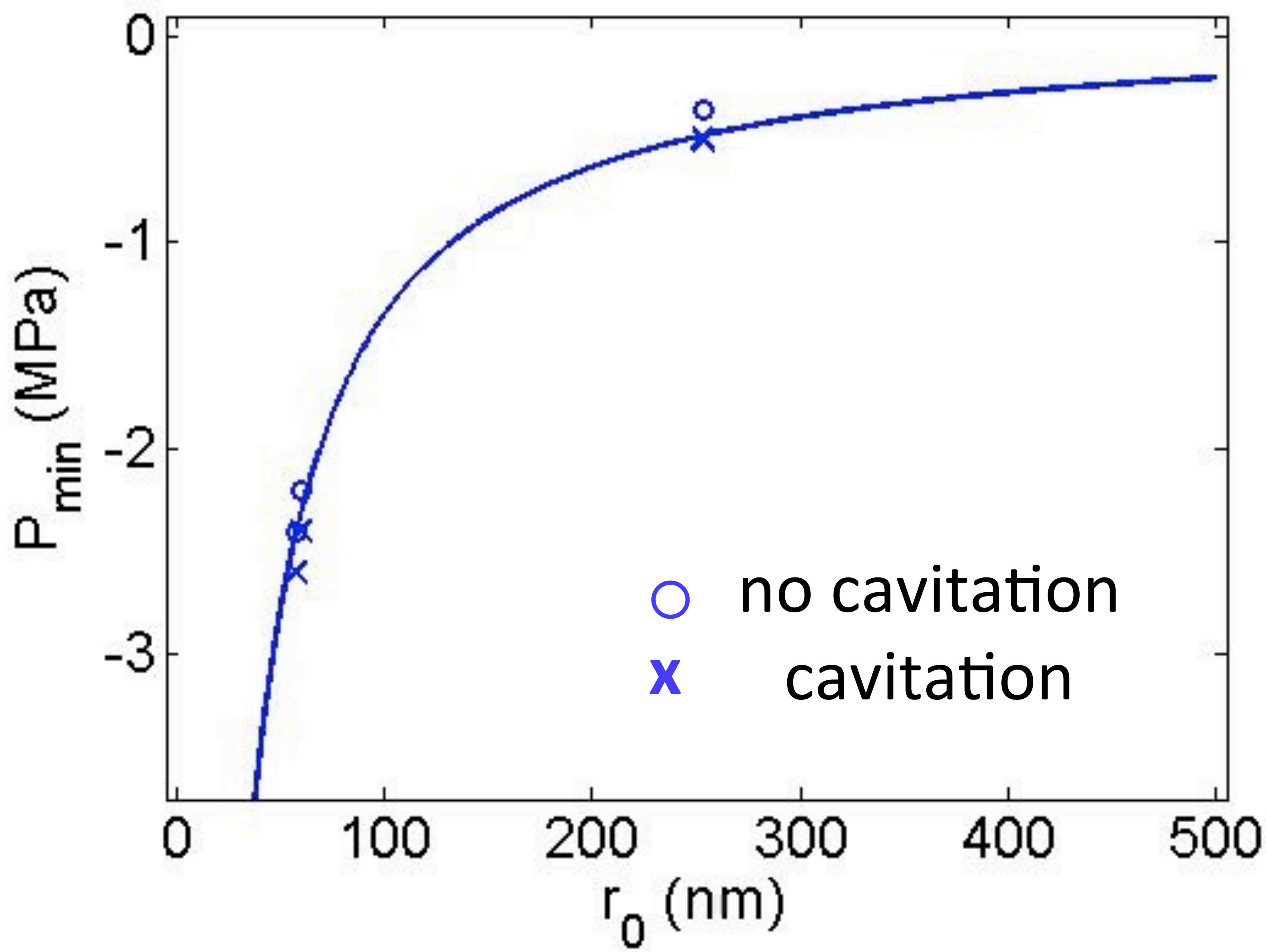


Theoretical prediction



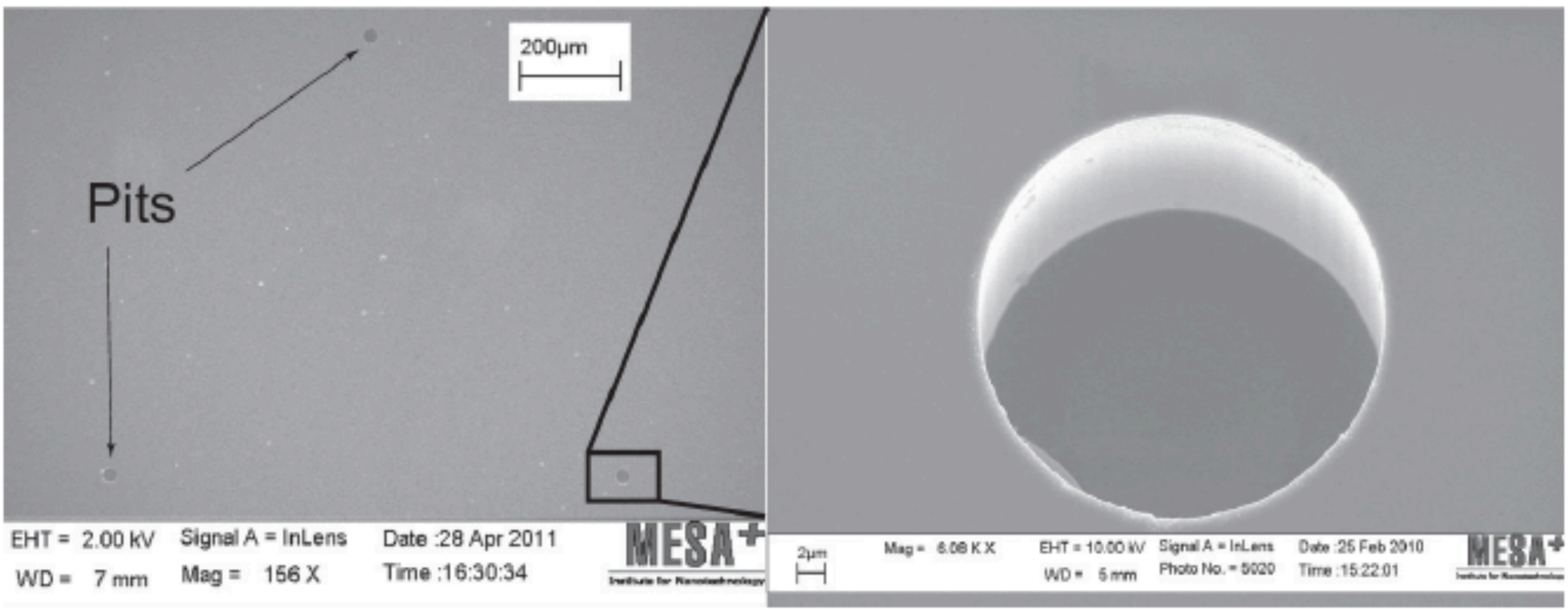
$$p_L = p_v + \frac{3p_{g,0}}{3 + r_0/d_0 f(\theta)} - \frac{2\sigma}{r_0}$$

Perfect agreement theory vs experiment



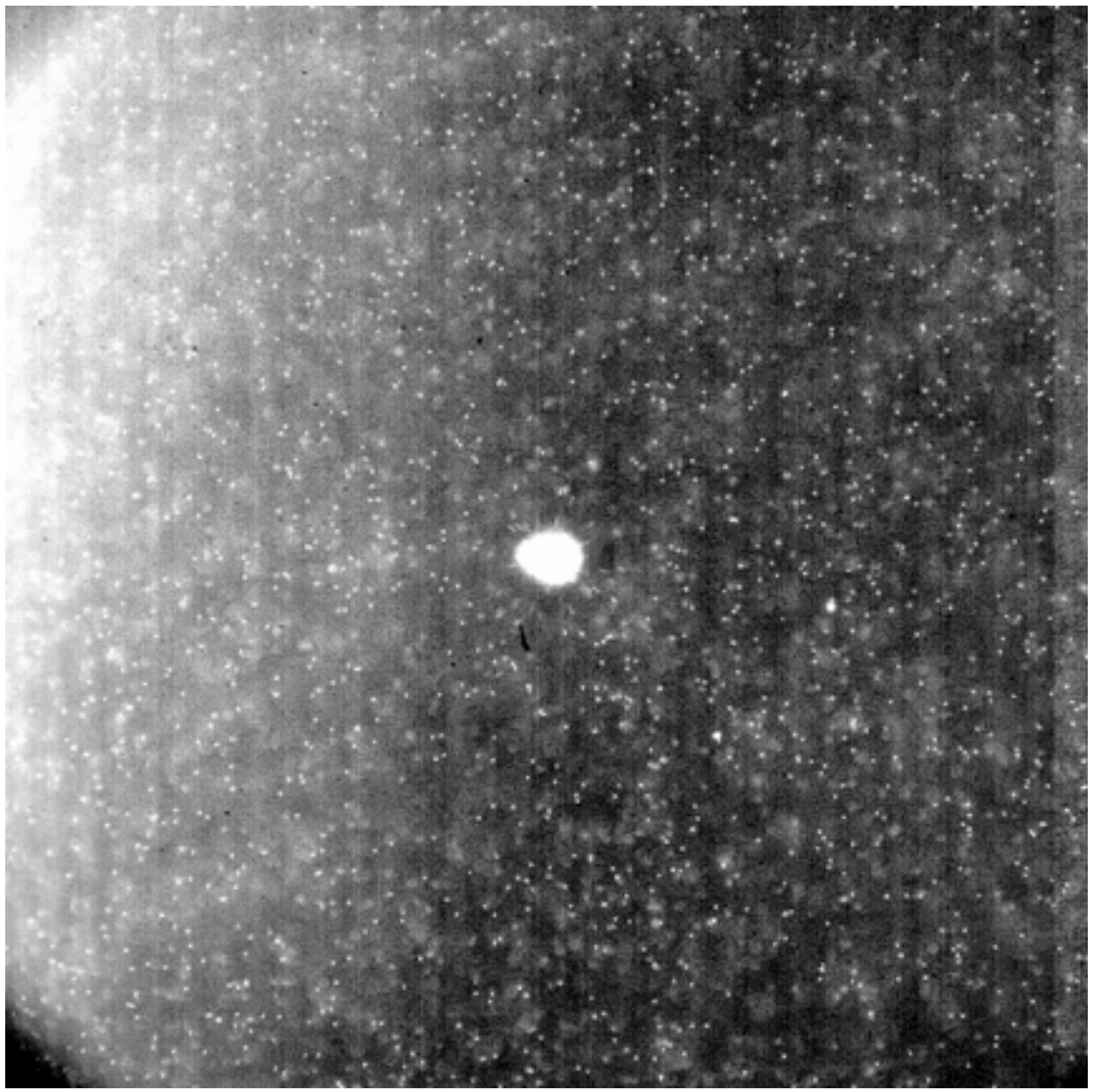
No free parameter!

Use micropits to stimulate bubble production and thus to enhance chemical activity

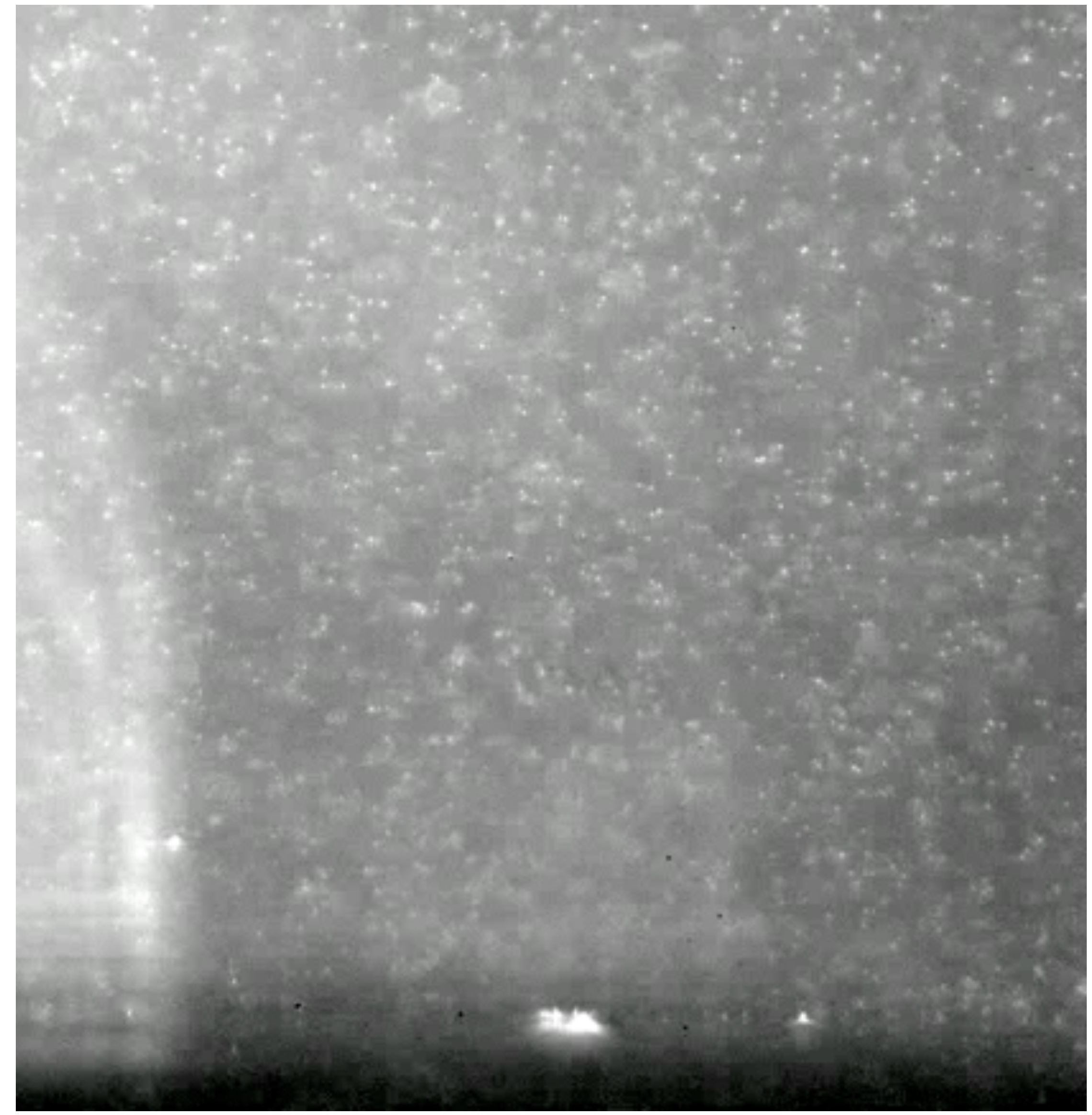


Rivas, Prosperetti, Zijlstra, Lohse, Gardeniers, Angw. Chem. Int. Ed. 49, 9699 (2010);
Rivas, Stricker, Zijlstra, Gardeniers, Lohse, Prosperetti, Ultrason. Sonochem. 20, 510 (2013).

Acoustic streaming around weakly driven meniscus



top view



side view

Stronger driving:
Bubble pinch-off out of pit

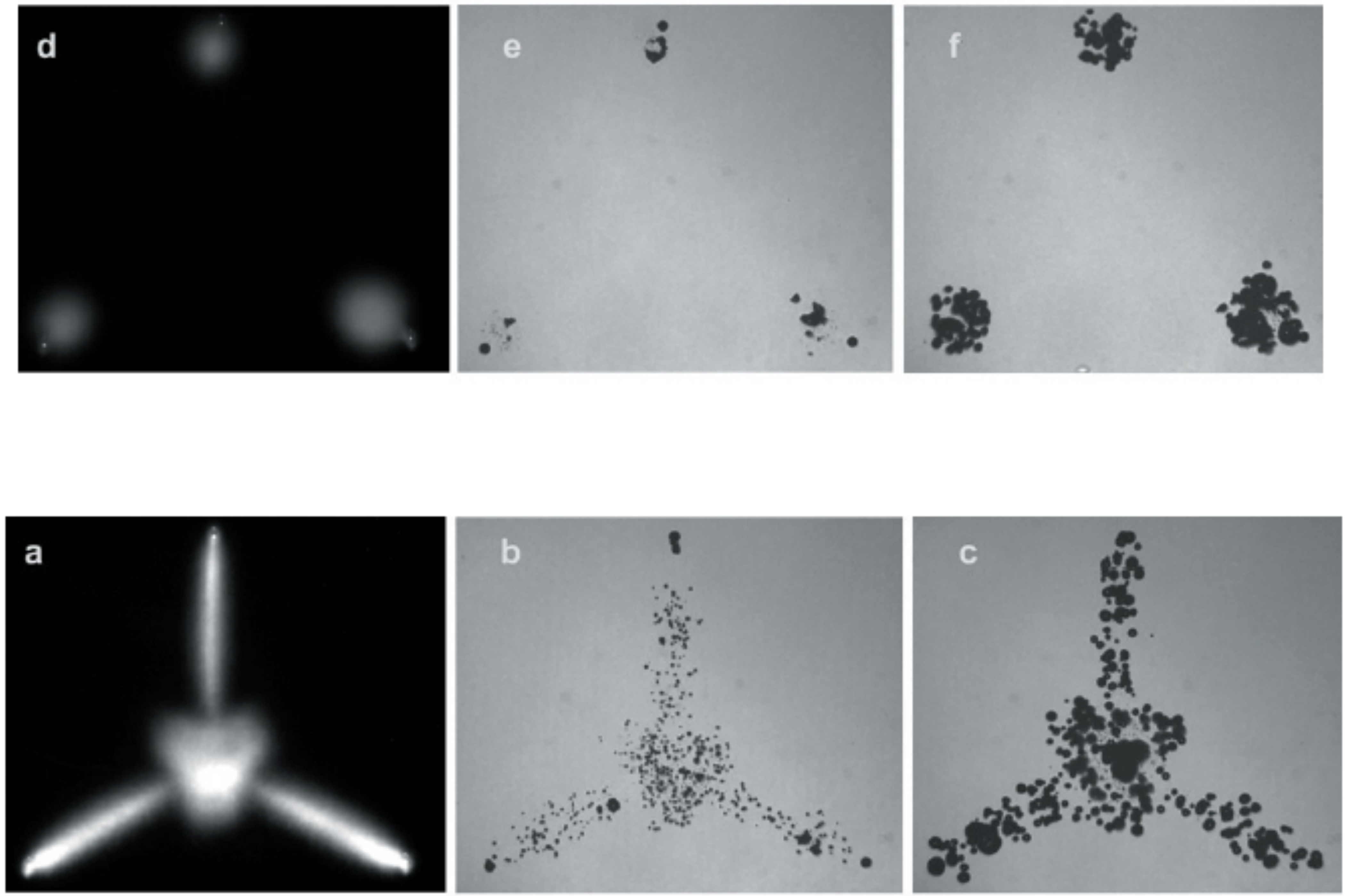
f = 80.8 kHz 500,000 fps (0.16 acoustic cycles/frame)

Average pinch-off rate: 13.4 kHz (1 per 6 acoustic cycles)

Three-pit geometry

low power

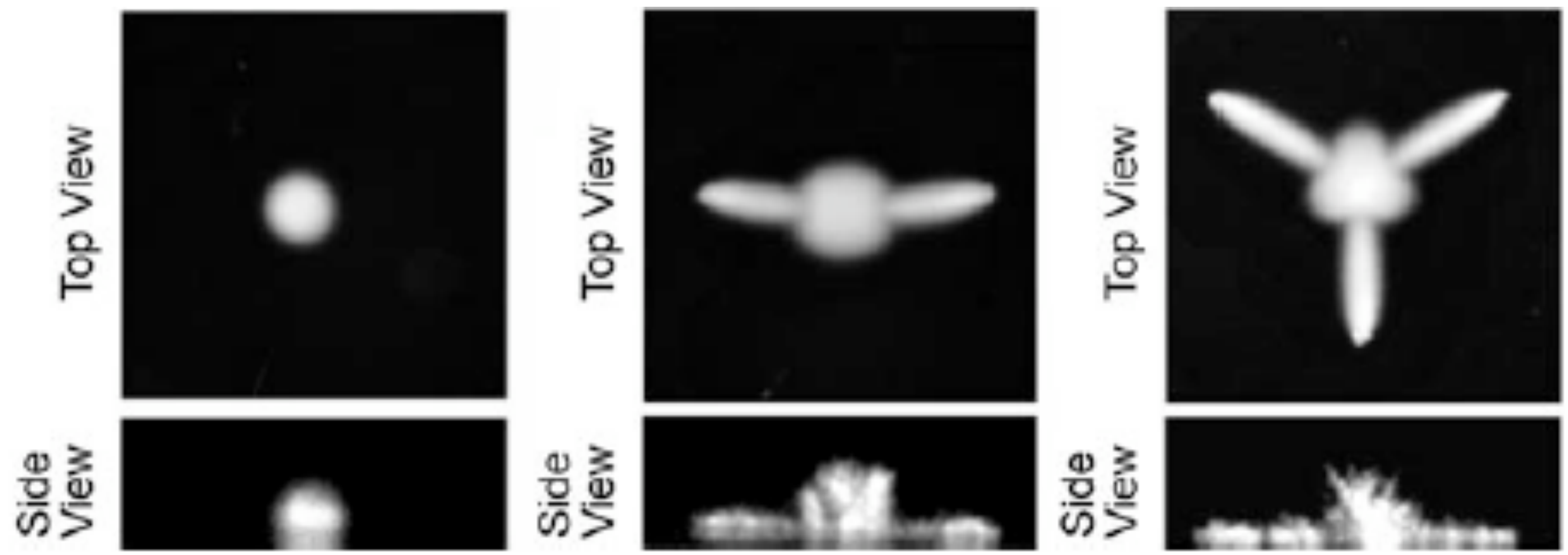
high power



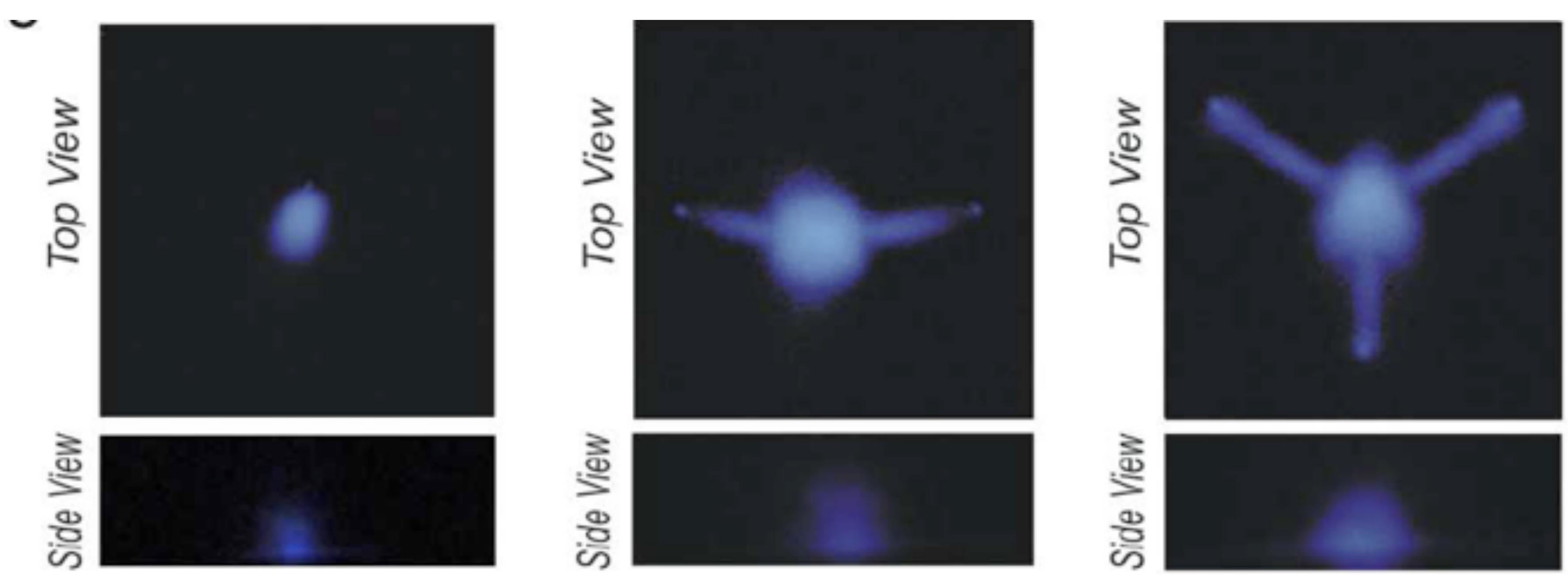
Switching between low and high intensity

Correlate light reflection & chemical activity of microbubbles emitted from micropits

Light reflection



Chemical activity



Rivas, Prosperetti, Zijlstra, Lohse, Gardeniers, Angw. Chem. Int. Ed. 49, 9699 (2010)

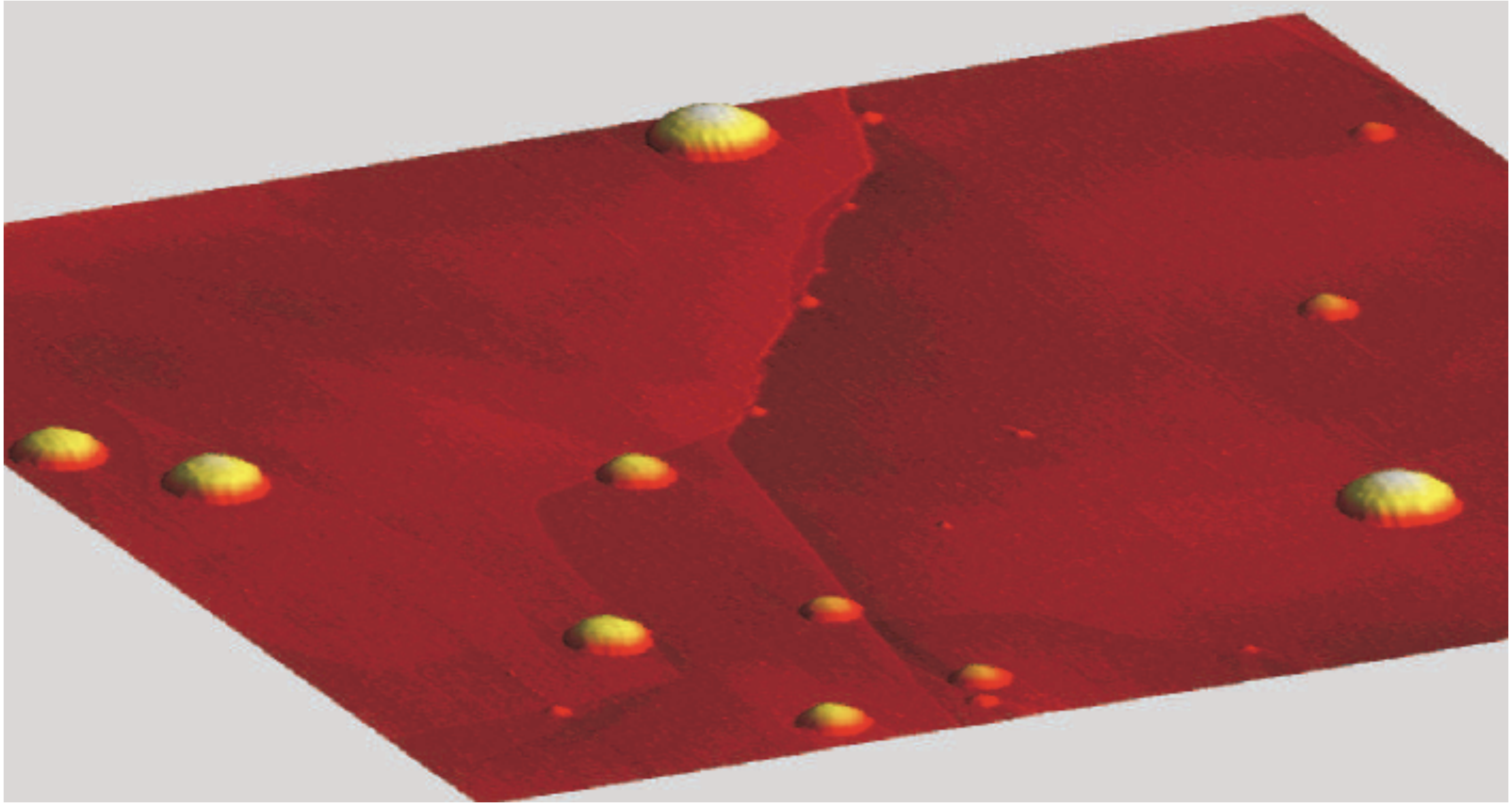
Strongly driven multiple micropits

Micro-pit dimensions
R=9.6 µm
H=20 µm

f = 221 kHz
f_r = 210 kHz

Surface nanobubbles and controlled nucleation of droplets

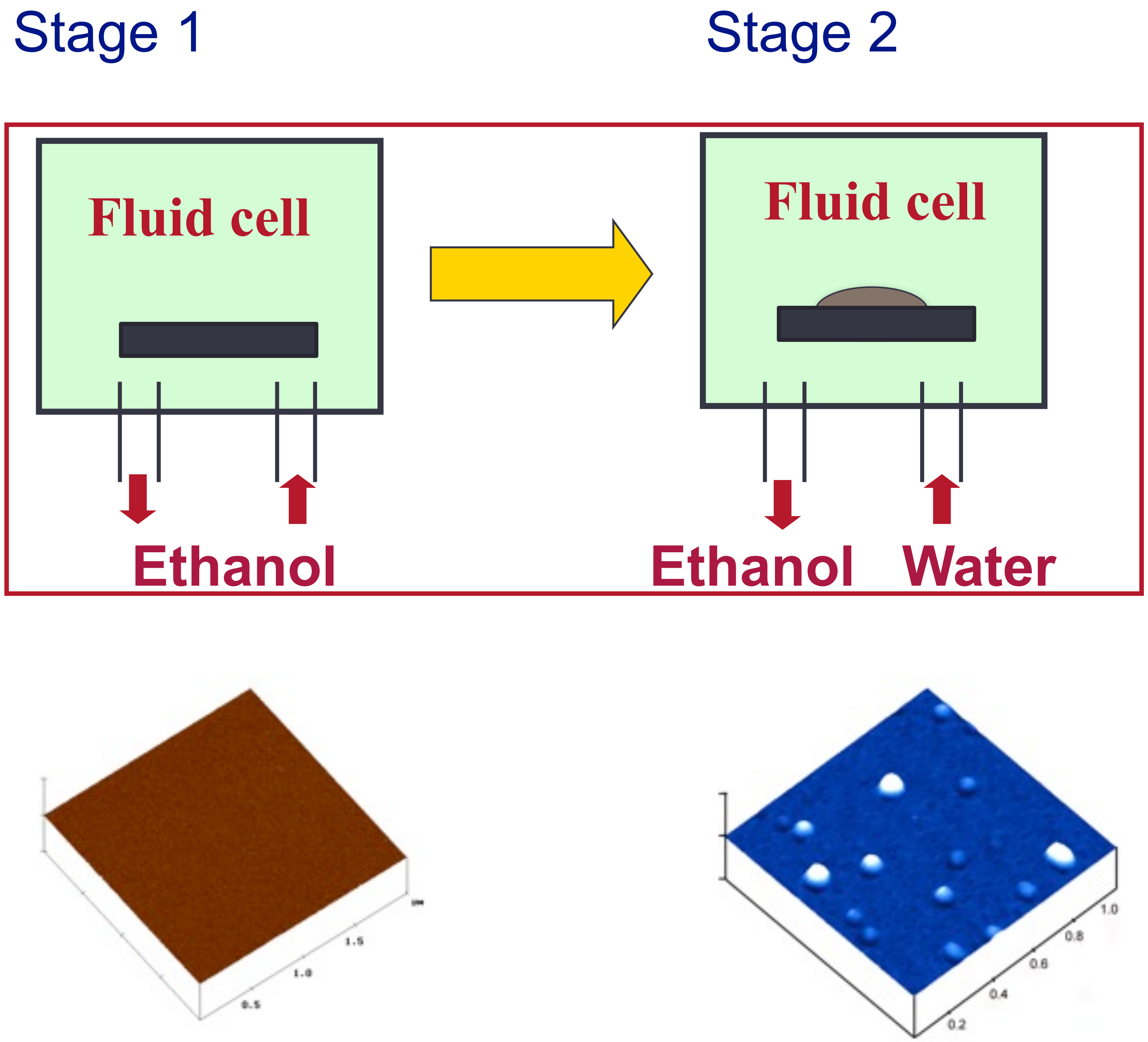
Surface nanobubbles



Why don't nanobubbles dissolve?

AFM

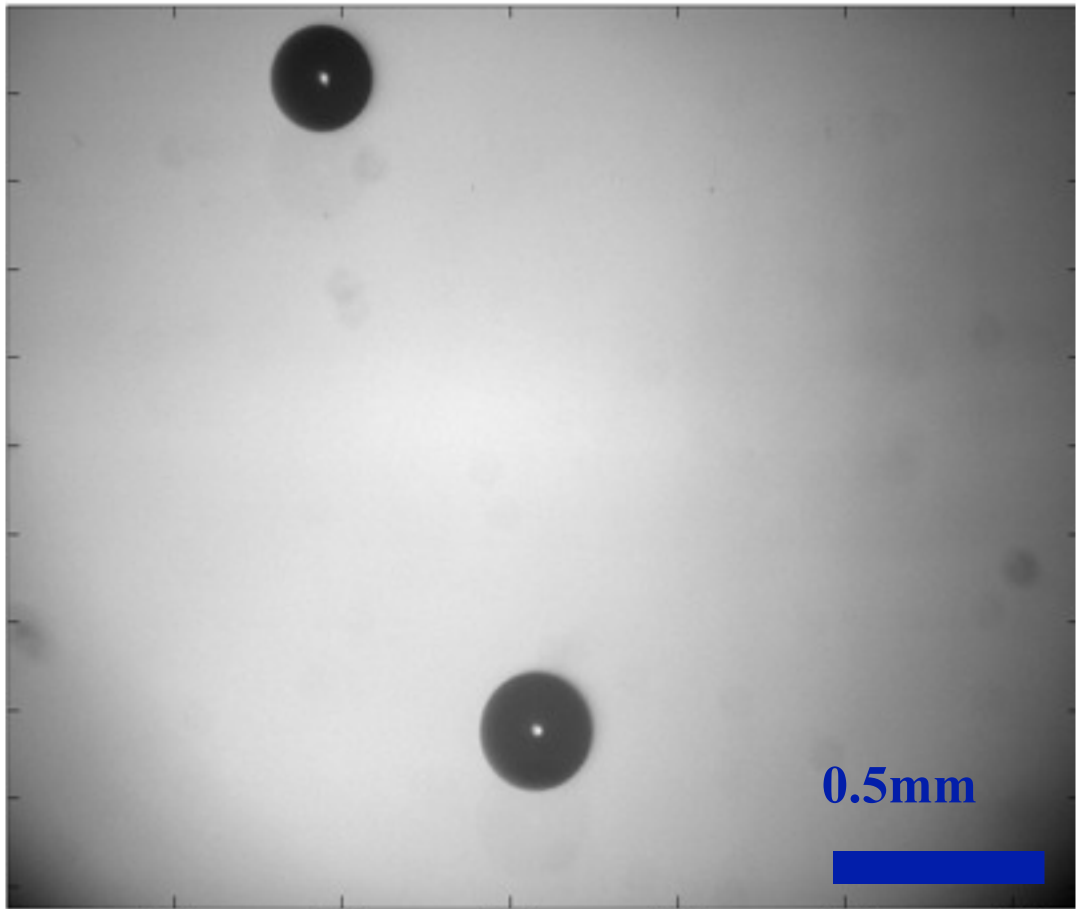
How to easily produce surface nanobubbles?



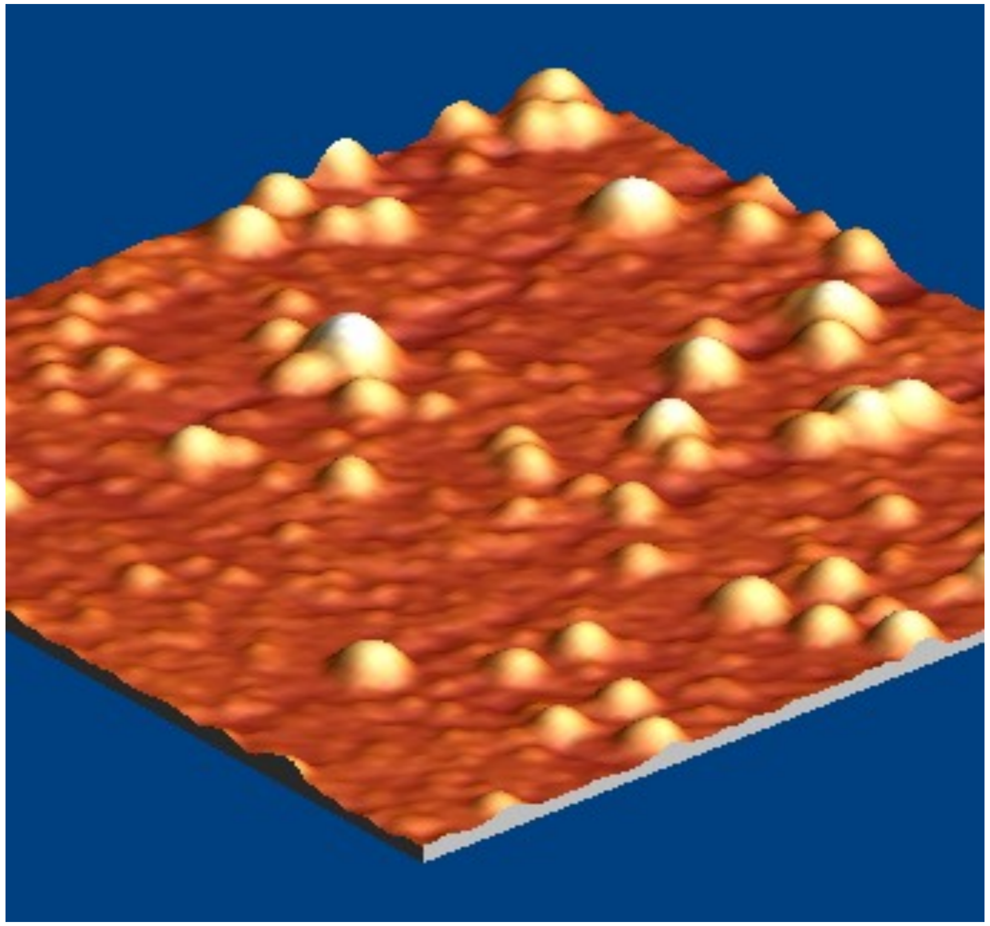
"Ethanol-water exchange"

S. T. Lou et al., J. Vac. Sci. Tech.-B 18, 2573 (2001)

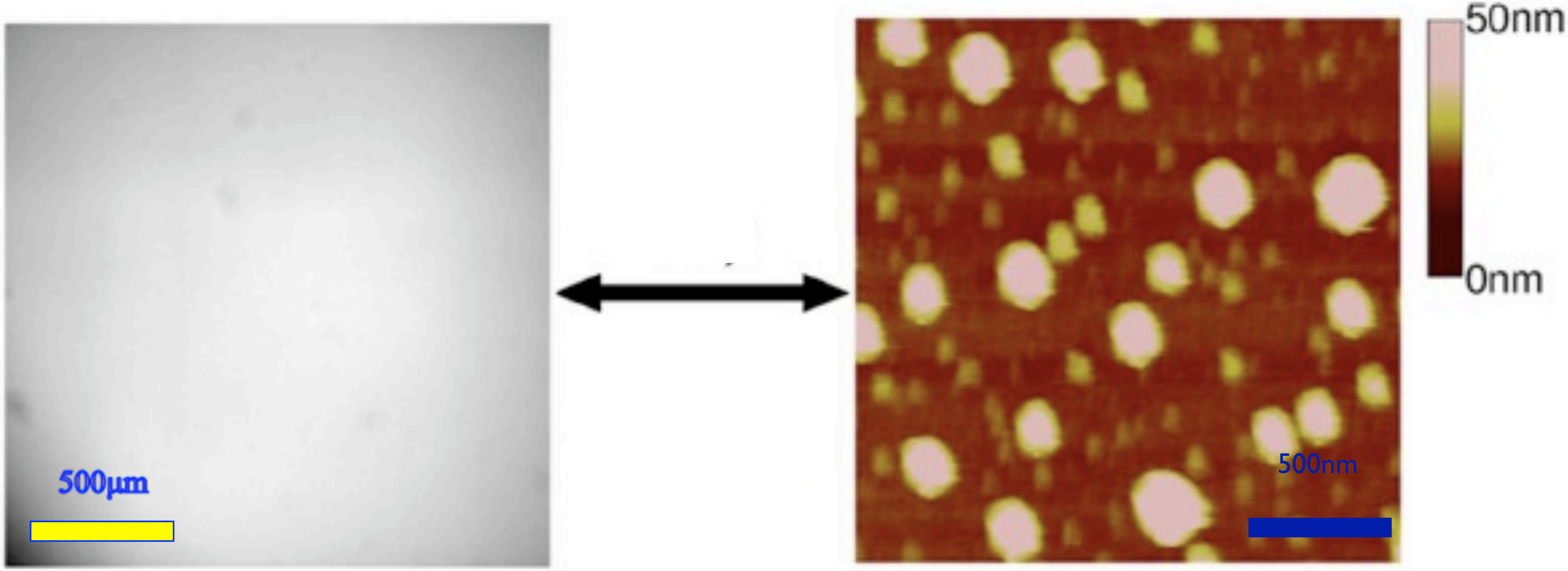
Do they cavitate?



? ⇔



There is no correlation between nanobubbles and nucleated bubbles: Superstability of surface nanobubbles



(Lack of) cavitation activity

Nanobubbles in AFM

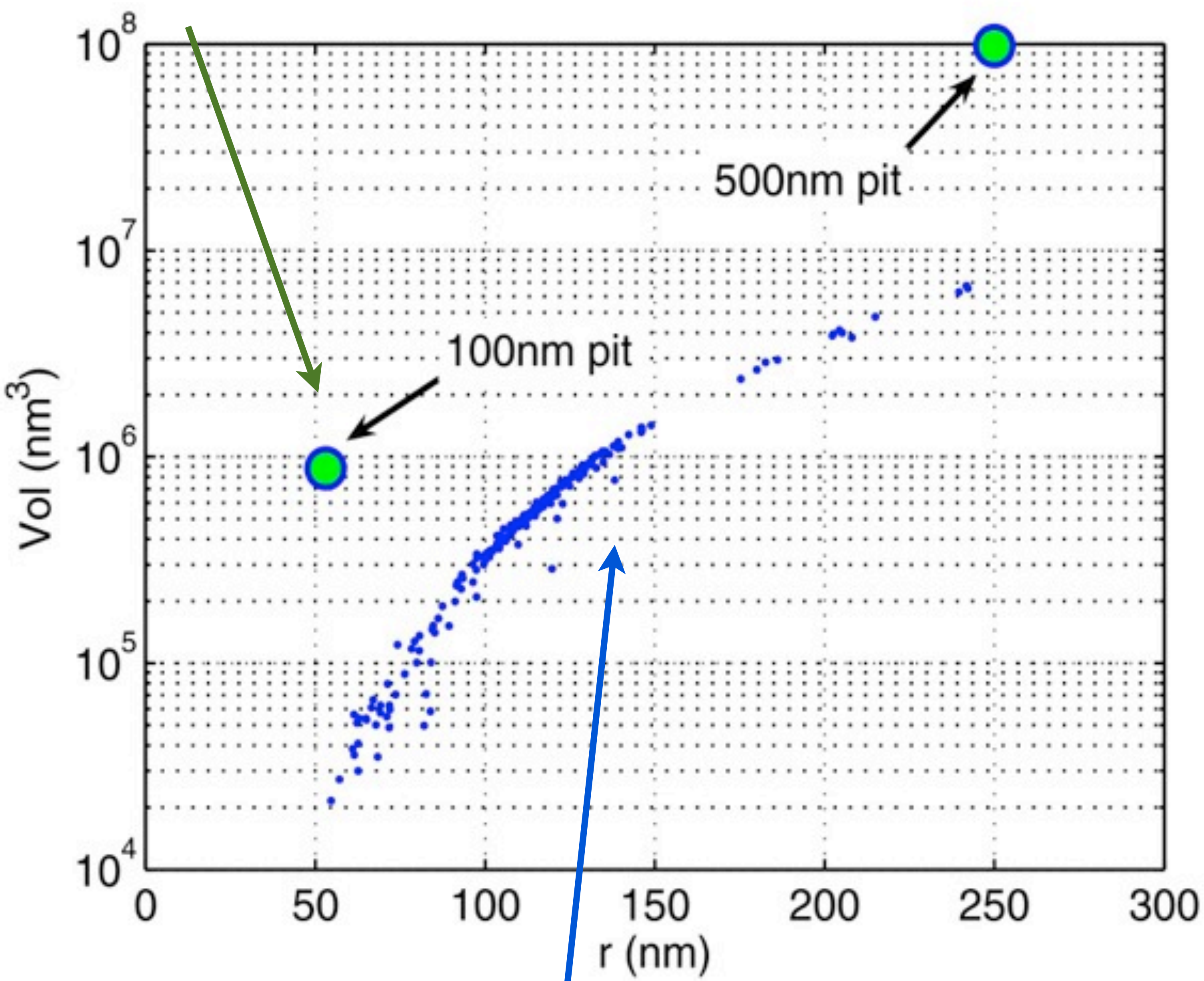
Borkent, Dammer, Schönherr, Vancso and Lohse, Phys. Rev. Lett. **98**, 204502 (2007)

There is no such correlation!

Nanobubbles even “survive” pressure reductions down to –60 bar!

“Superstability”!

Nanopits do nucleate bubbles

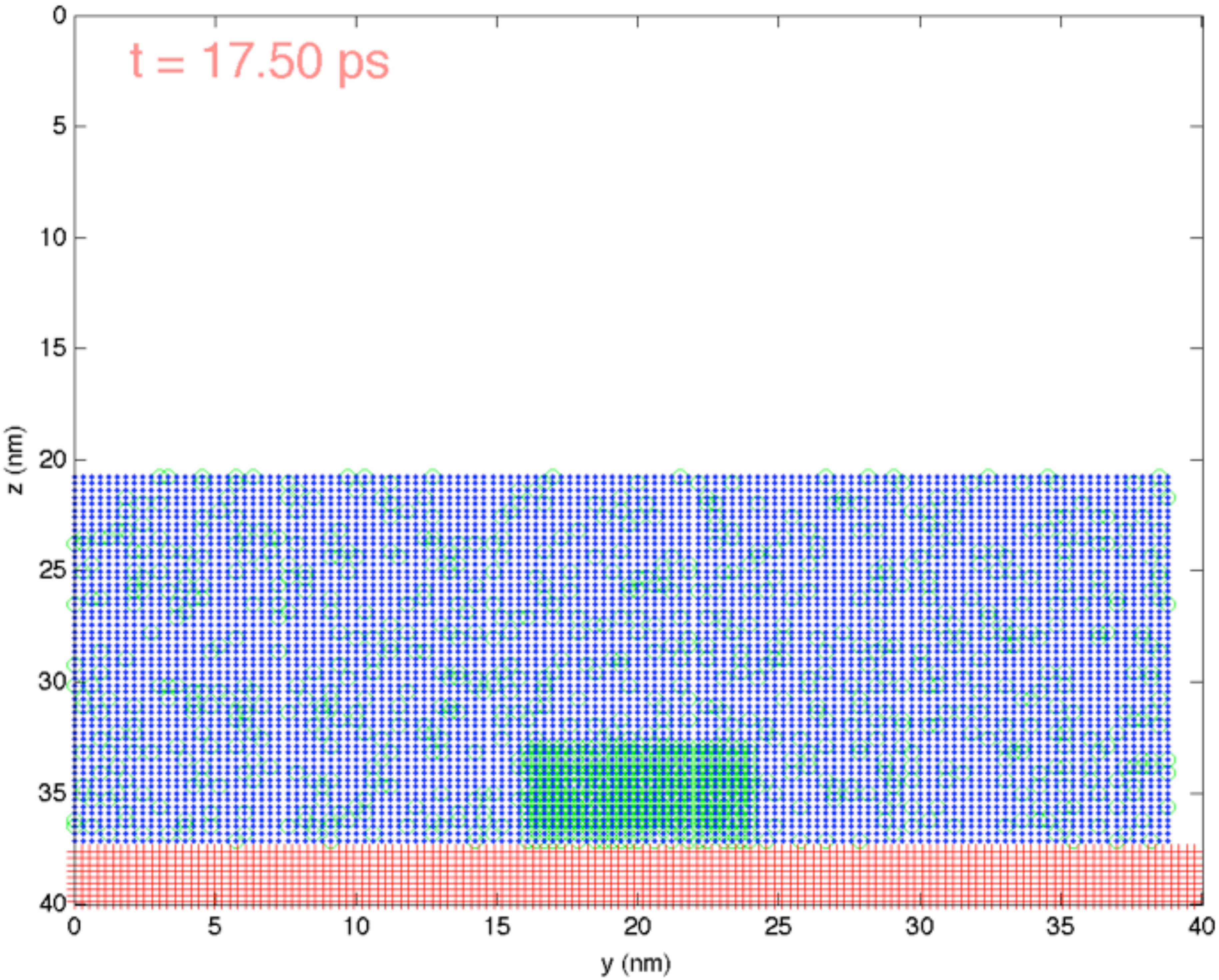


Nanobubbles (of same size/volume) do NOT nucleate bubbles

Coworkers & funding

Bram Borkent
Wilco Bouwhuis
Nicolas Bremond
Henri Lhuissier
Hanneke Gelderblom
Stefan Gekle
Alvaro Marin
Devaraj van der Meer
Ivo Peters
Andrea Prosperetti
David Rivas
Jacco Snoeijer
ErikJan Staat
Chao Sun
Peichun Amy Tsai
Tuan Tran
Roeland van der Veen
Koen Winkels
Xuehua Zhang

Nanobubbles in MD simulations



Nanobubbles pin receding surface contact line and cause deposits on surface