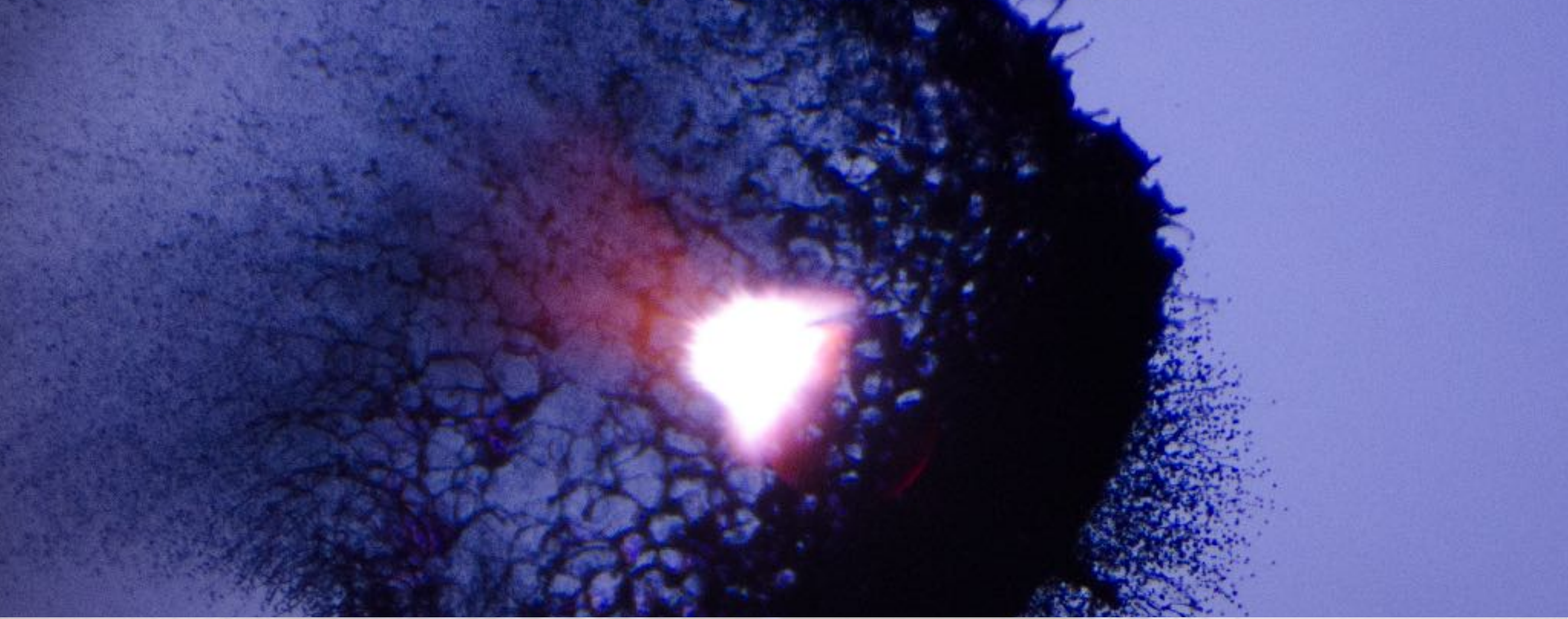


Drop impact phenomena in EUV lithography

Hanneke Gelderblom

EUV source workshop 05-11-2019

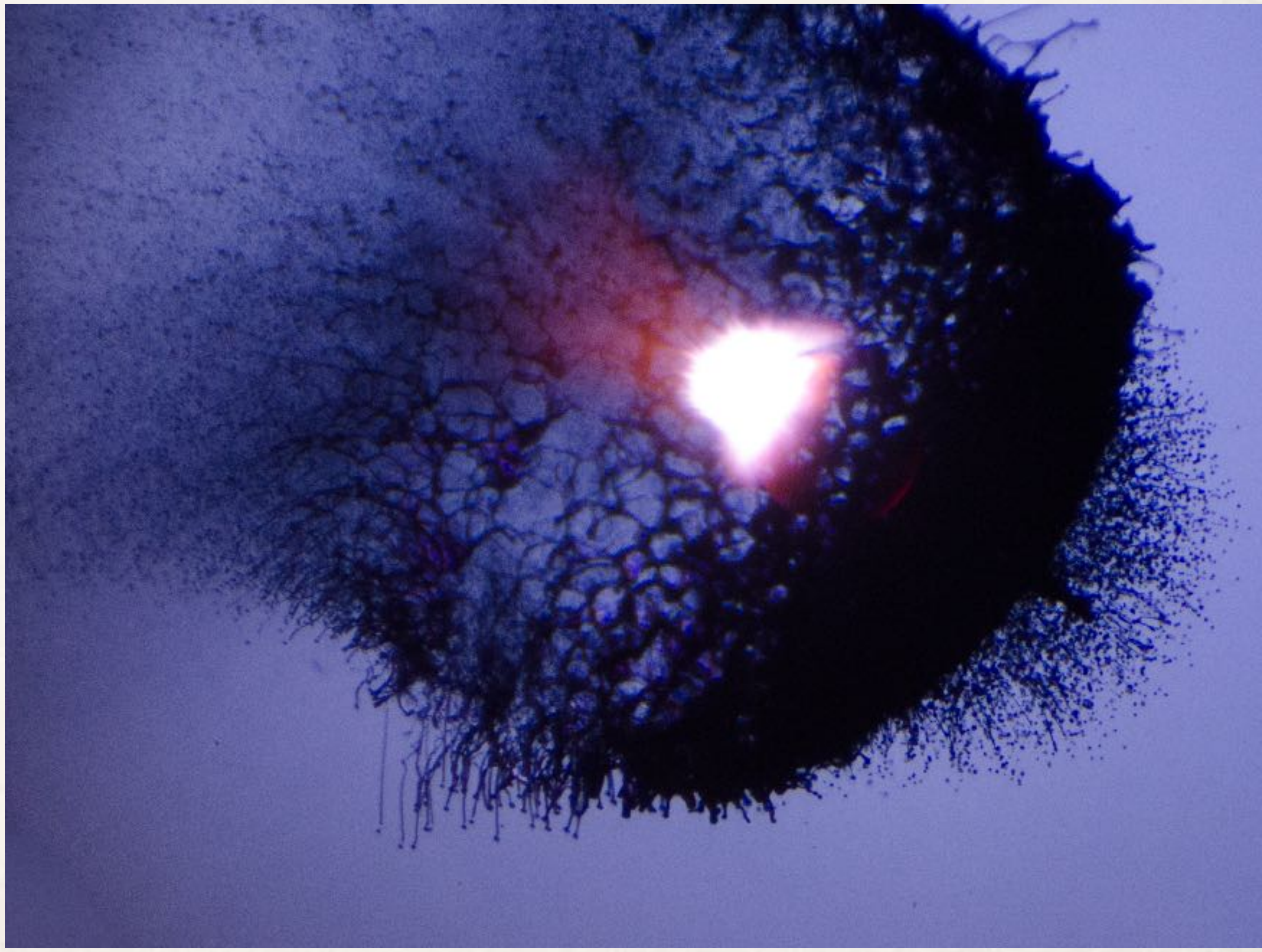
NWO Netherlands Organisation for Scientific Research
UNIVERSITY OF TWENTE.
TU/e
ASML
ARCNL ADVANCED RESEARCH CENTER FOR NANOLITHOGRAPHY

Drop dynamics challenges in the EUV source

- Optimal mass distribution for high CE
- Minimum debris

➡ How do drops deform?
➡ How do drops splash?

Parameter space:
prepulse energy, focus, beam profile, drop size, main pulse timing, wall temperature,..

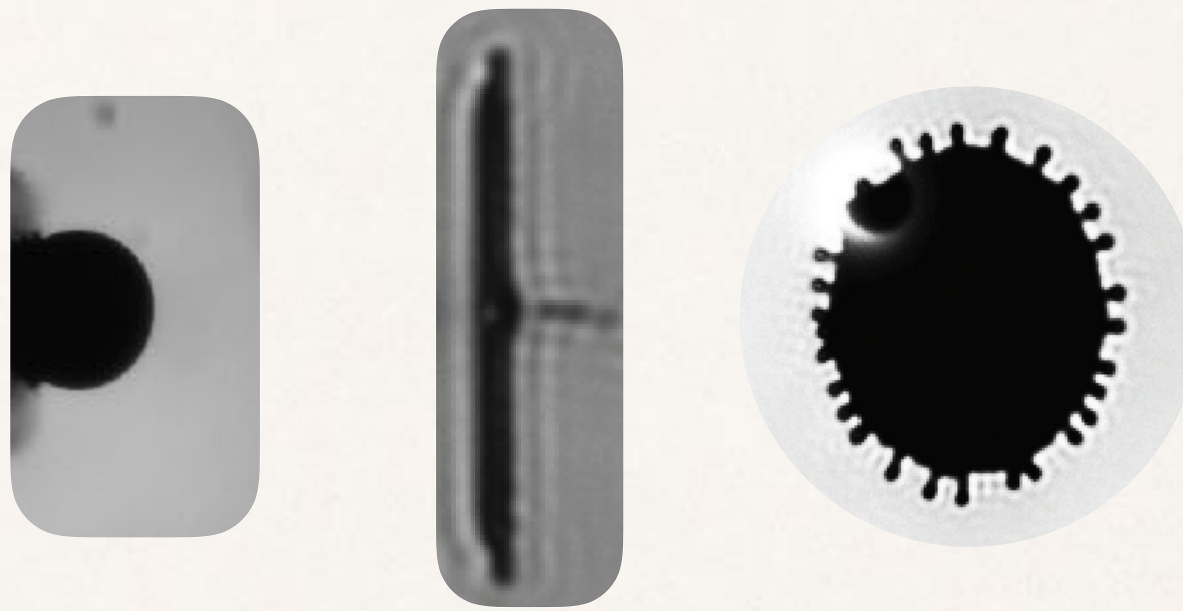


Required: understanding basic fluid dynamics

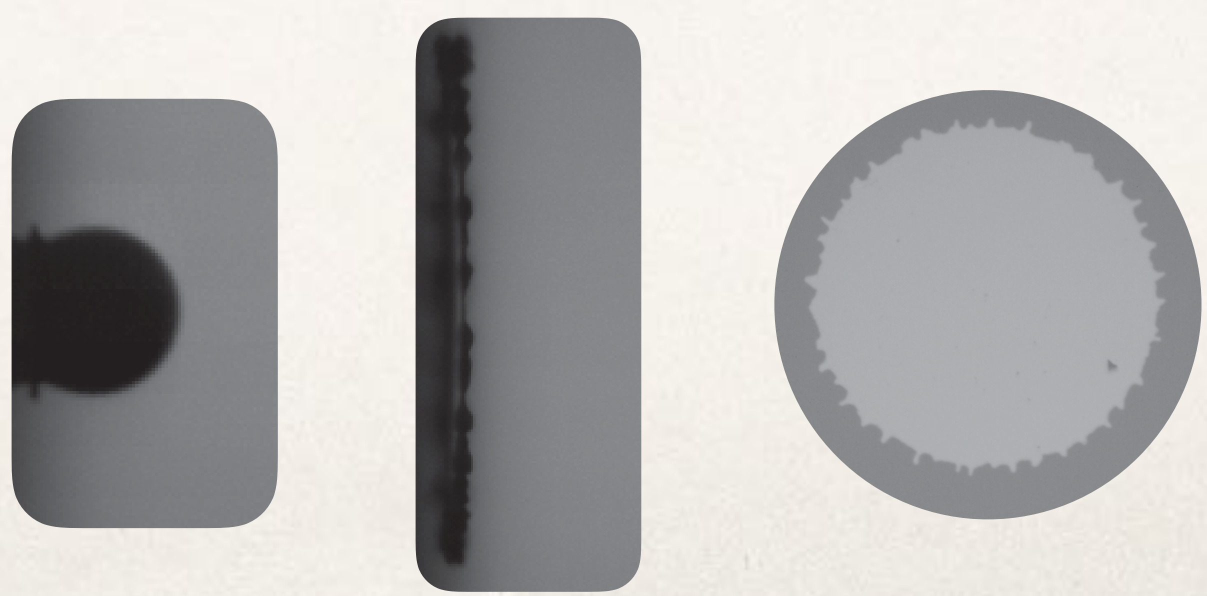
Drop impact in the EUV source

side view

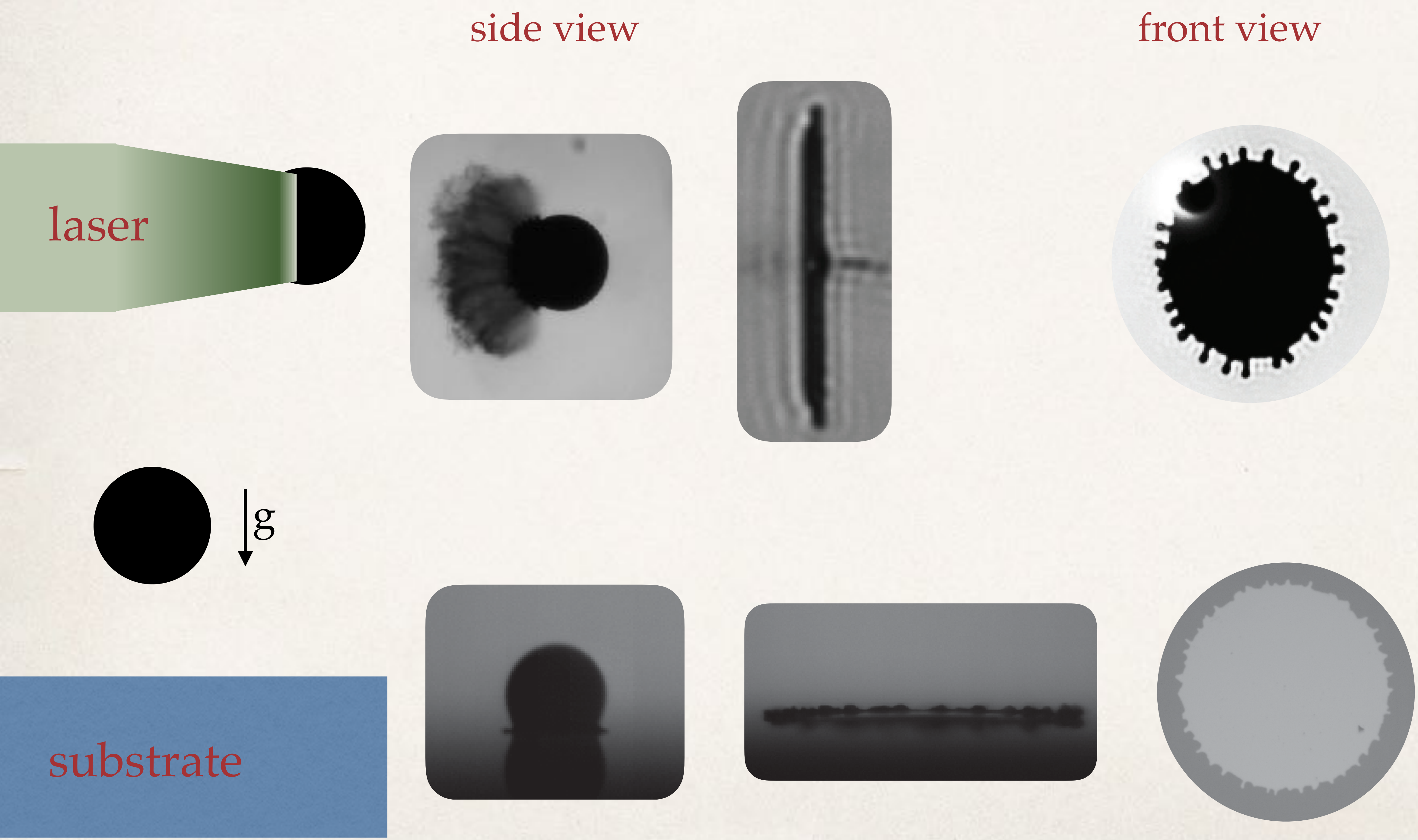
front view



What's the difference?

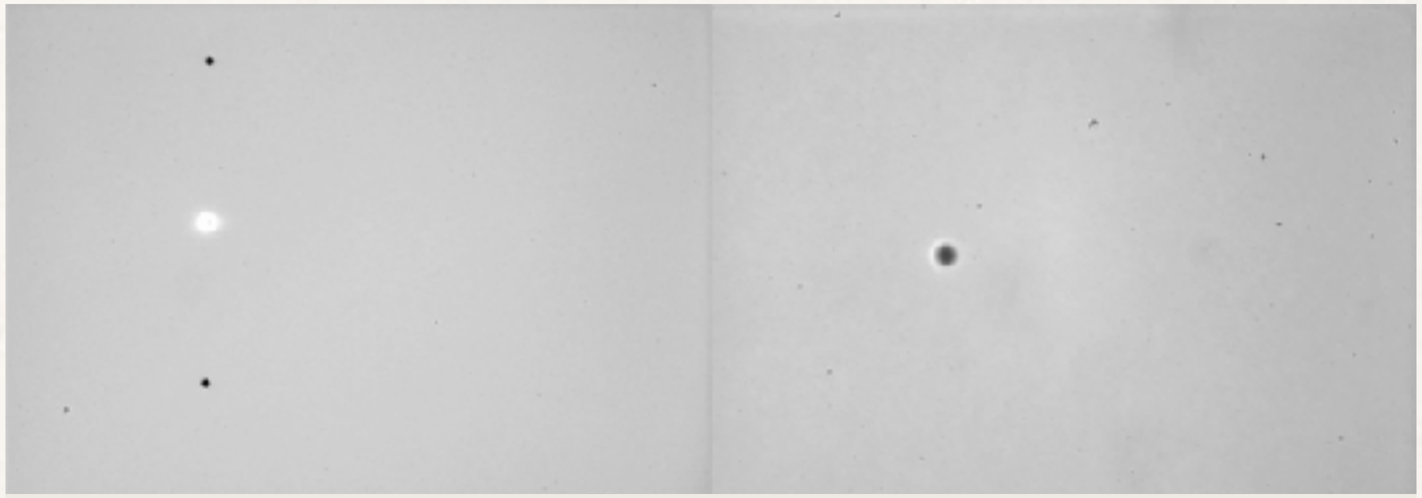


Drop impact in the EUV source



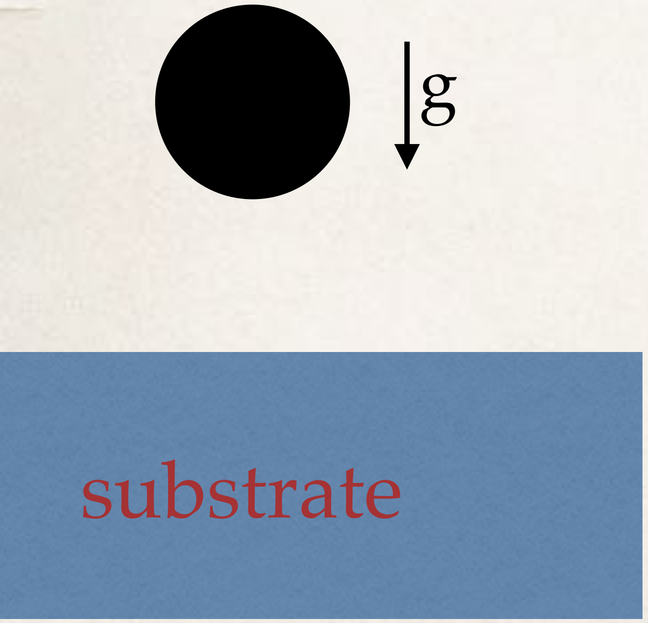
Drop impact in the EUV source

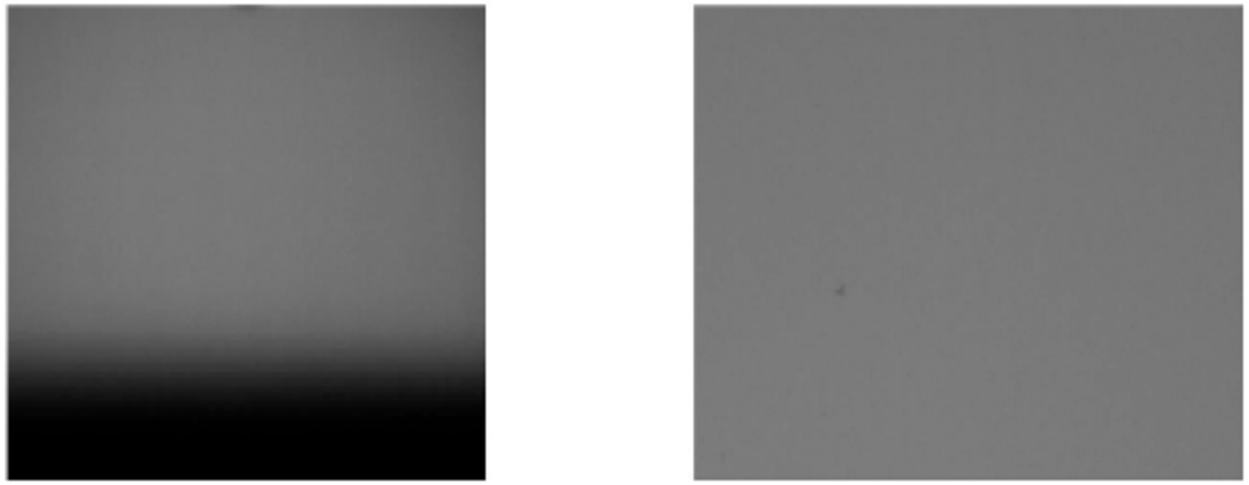
1. A 25-μm tin drop impacted by a 10 ns Nd:YAG laser



stroboscopic movie D. Kurilovich & O. Versolato (ARCNL)

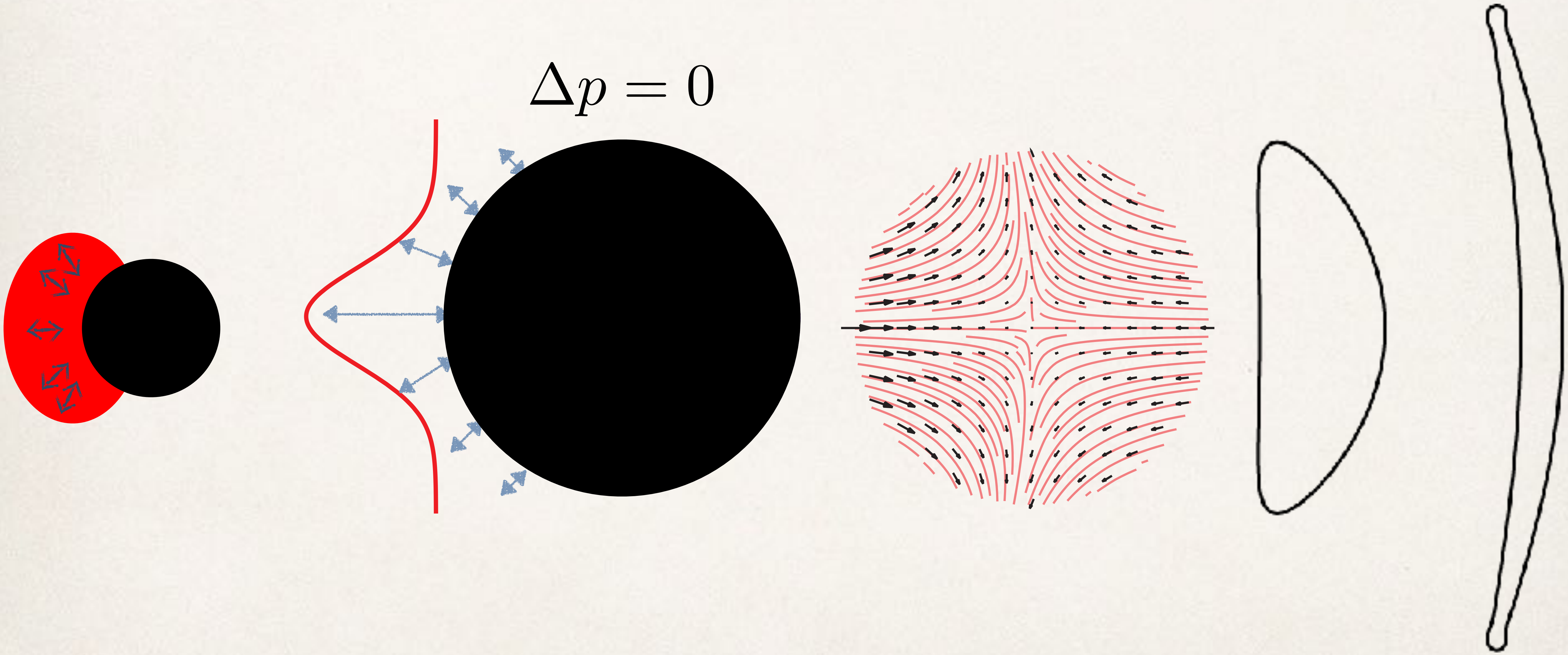
2. A 1.6-mm tin drop impacting a sapphire substrate





high-speed movie (30 kFPS)

Laser impact on a liquid drop:
Pushing on a liquid sphere



Gelderblom et al. *J. Fluid Mech.* 794 (2016)

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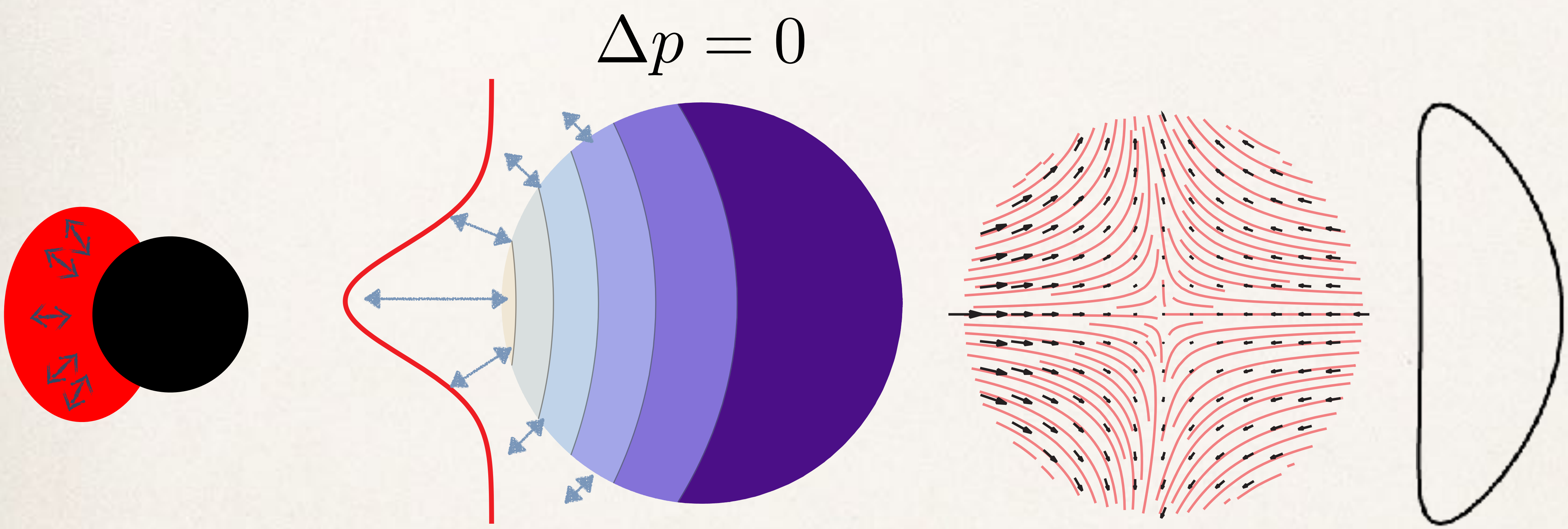
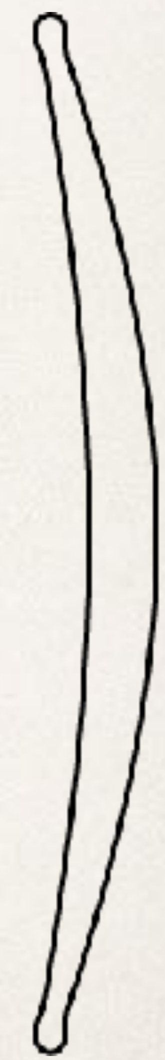




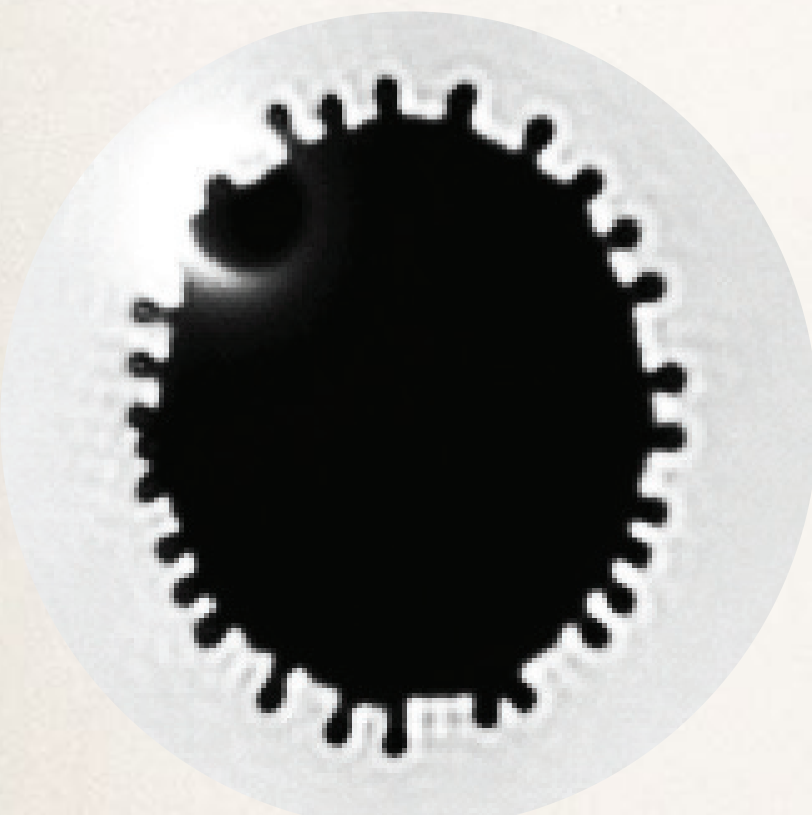
Consequences:

1. *Other 'pushing mechanisms' give similar fluid dynamic response*
2. *Pressure profile predicts direction of motion, shape & breakup*

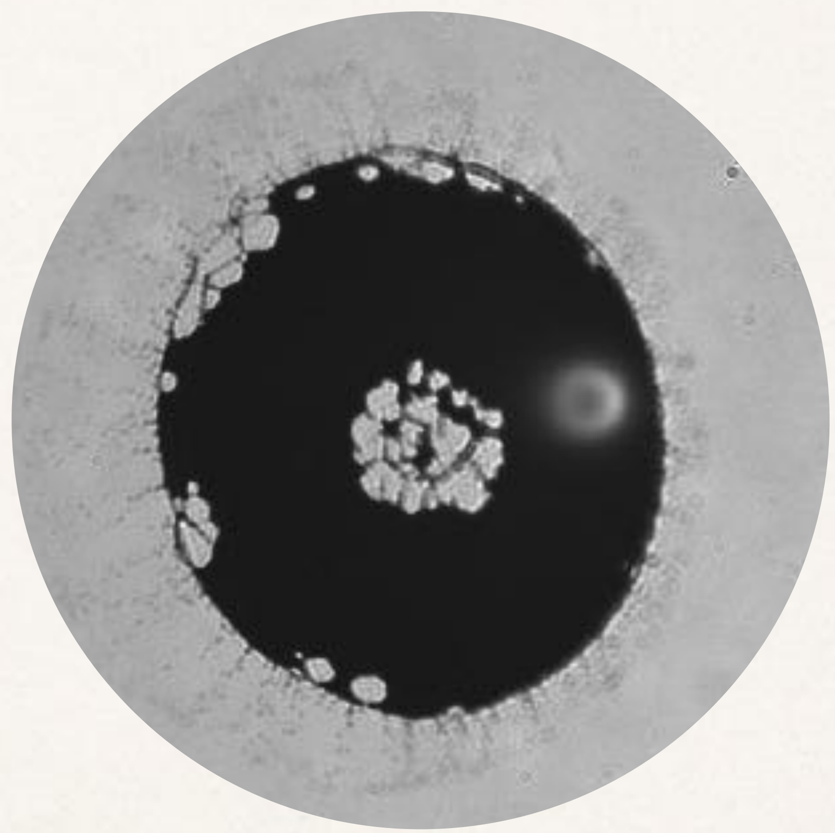
Gelderblom et al. J. Fluid Mech. 794 (2016)   Kurilovich et al. Phys. Rev. Applied 6 (2016)

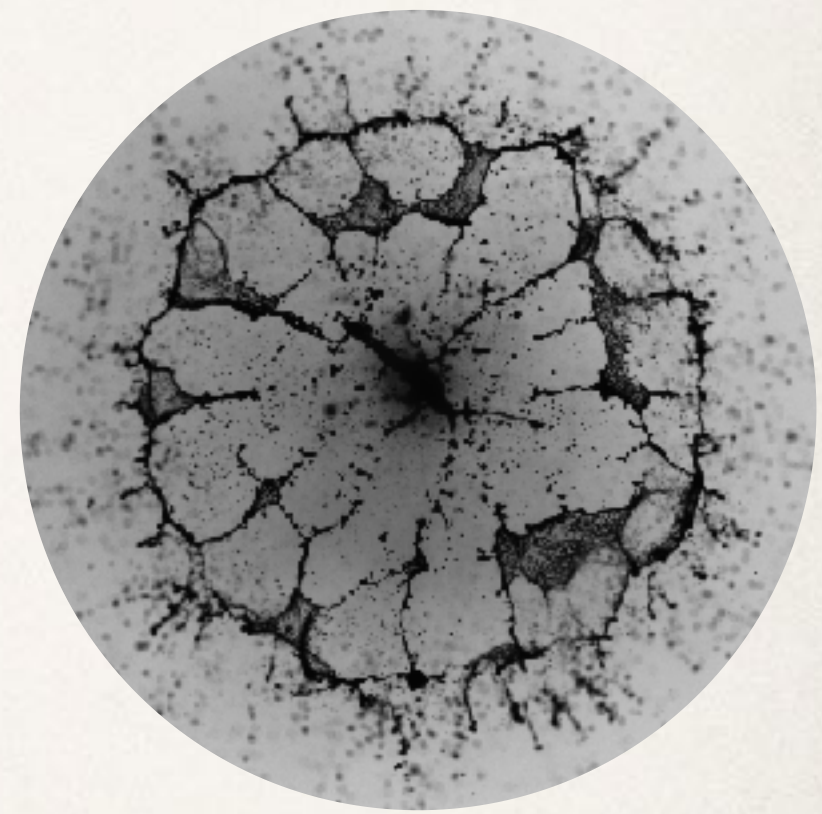
Drop breakup scenarios

rim breakup



hole nucleation





key parameter governing drop deformation & fragmentation

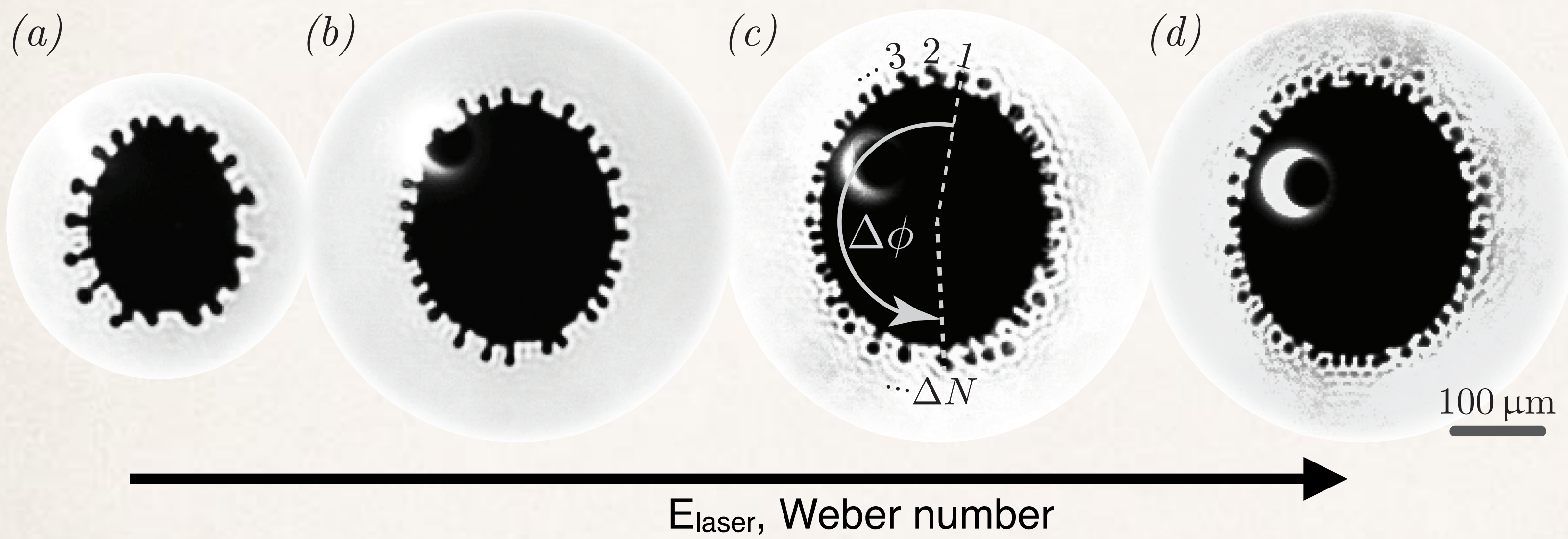
$$\textbf{Weber number} = \frac{\text{kinetic energy}}{\text{surface energy}} = \frac{\rho R_0 U^2}{\gamma}$$

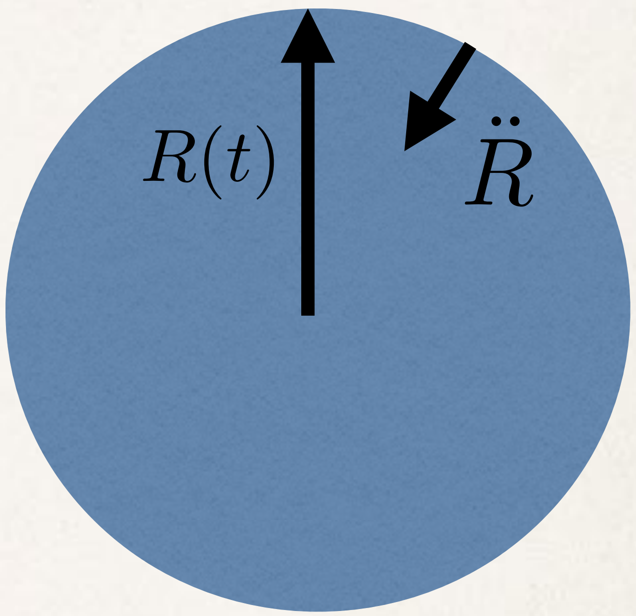
Gelderblom et al. J. Fluid Mech. 794 (2016)
Klein et al. submitted (2019) arXiv:1910.02522

Link speed U to laser pulse energy: Kurilovich et al. Phys. Rev. Applied 6 (2016)

Rim breakup

Rayleigh-Taylor & Rayleigh-Plateau instabilities





Predictions:

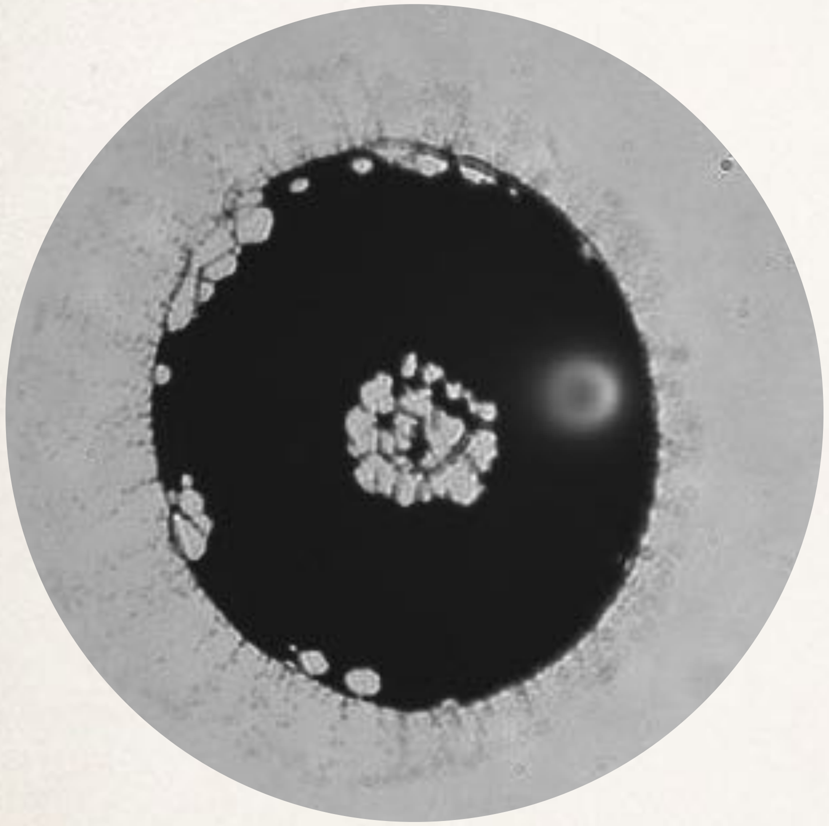
$$\omega \sim \left(\frac{\rho \ddot{R}^3}{\gamma}\right)^{1/4}$$

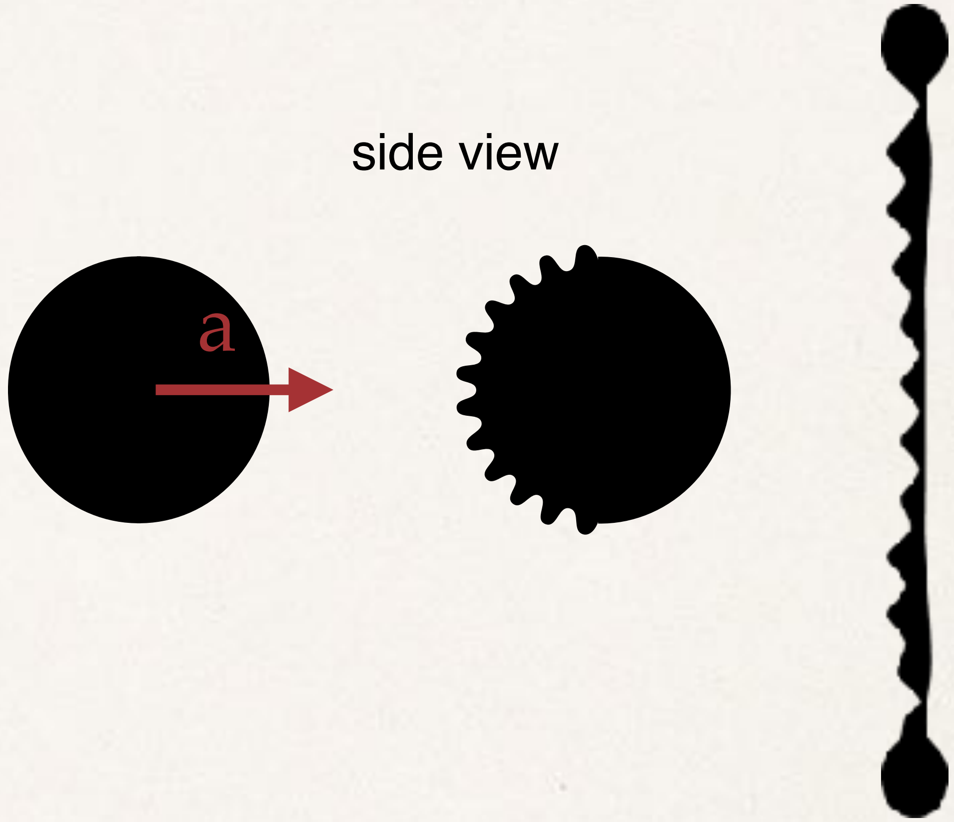
$$\lambda \sim \left(\frac{\gamma}{\rho \ddot{R}}\right)^{1/2}$$

Villermaux & Bossa J. Fluid Mech. 668 (2011)
Klein et al. submitted (2019) arXiv:1910.02522

Hole nucleation

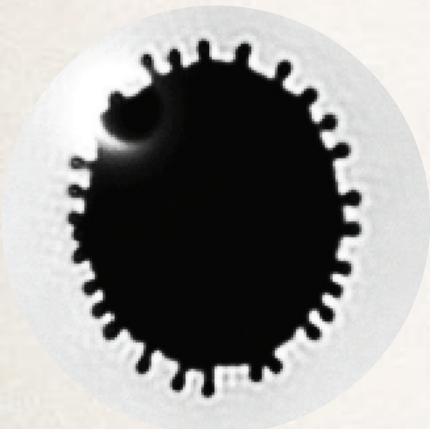
RT instability caused by impulsive acceleration





Klein et al. submitted (2019) arXiv:1910.02522

Prediction of breakup time

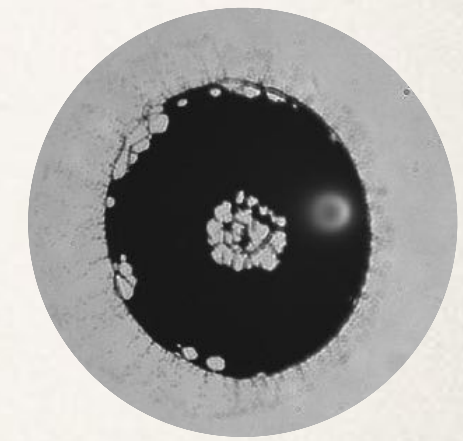


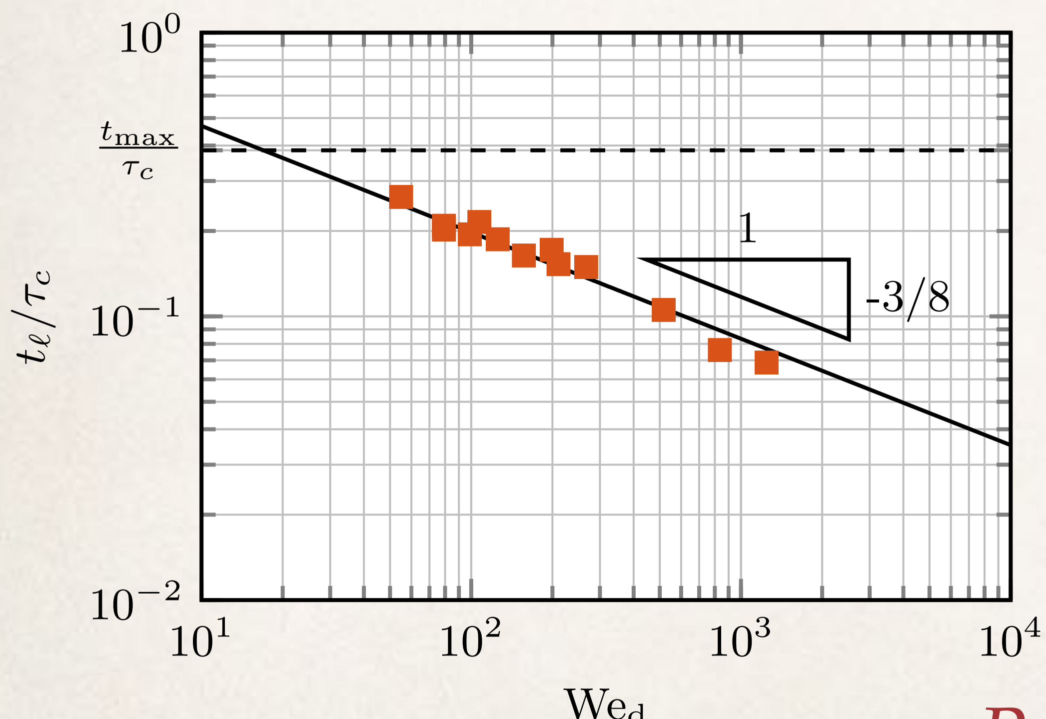
rim breakup

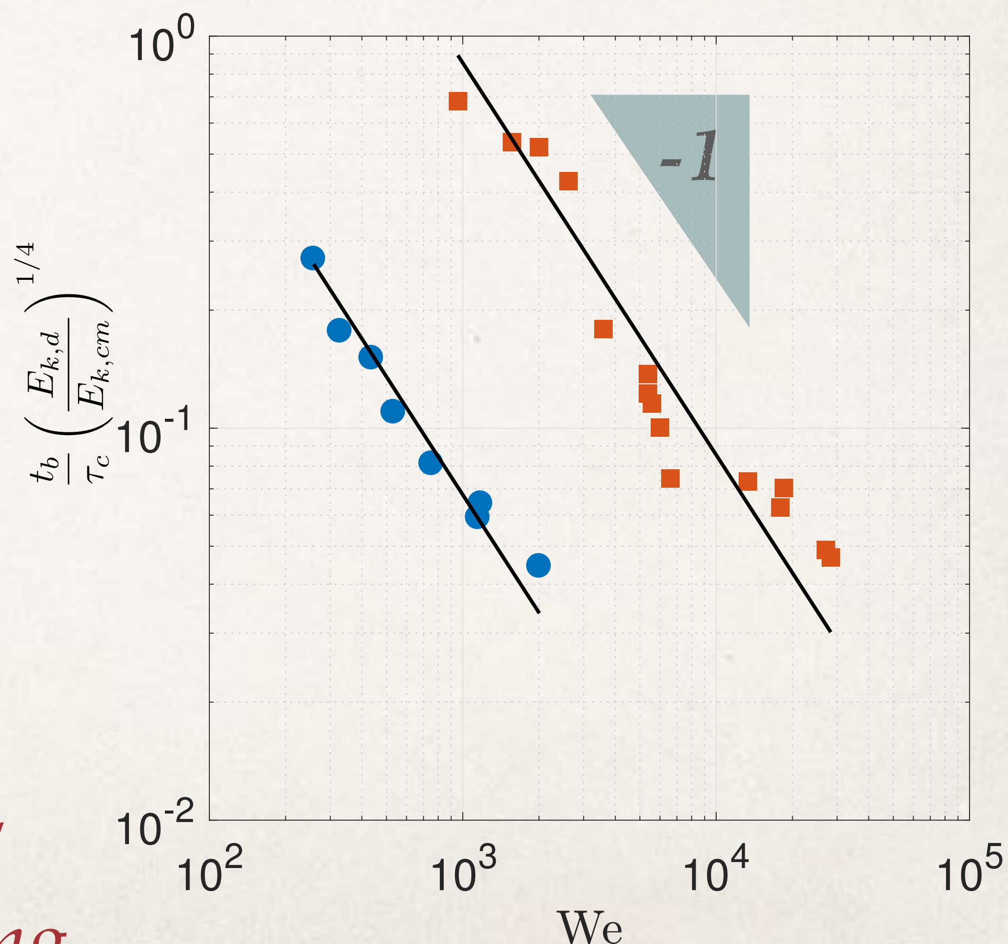
$$t_\ell/\tau_c \sim We^{-3/8}$$

hole nucleation

$$t_b/\tau_c \sim We^{-1}$$







- *Pre-pulse energy*
- *Main pulse timing*

Klein et al. submitted (2019) arXiv:1910.02522

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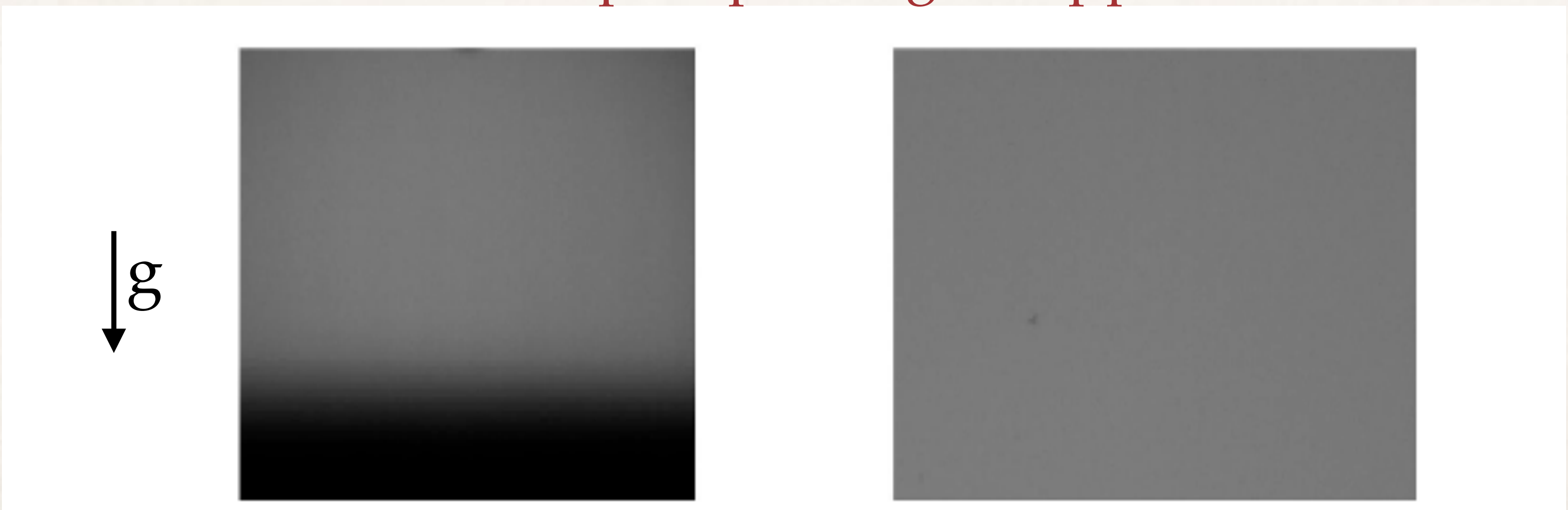
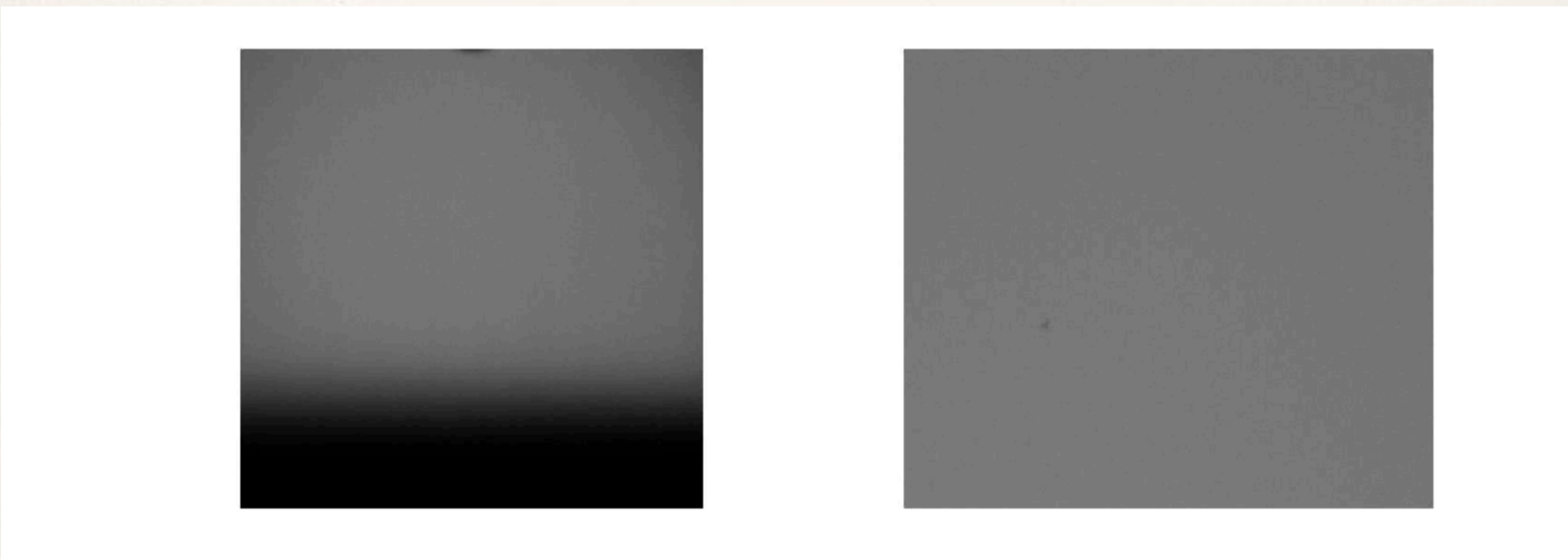


high-speed movie (30 kFPS)

Isothermal impact of tin on sapphire

We= 310, U = 3.9 m/s
T_s = 250 °C

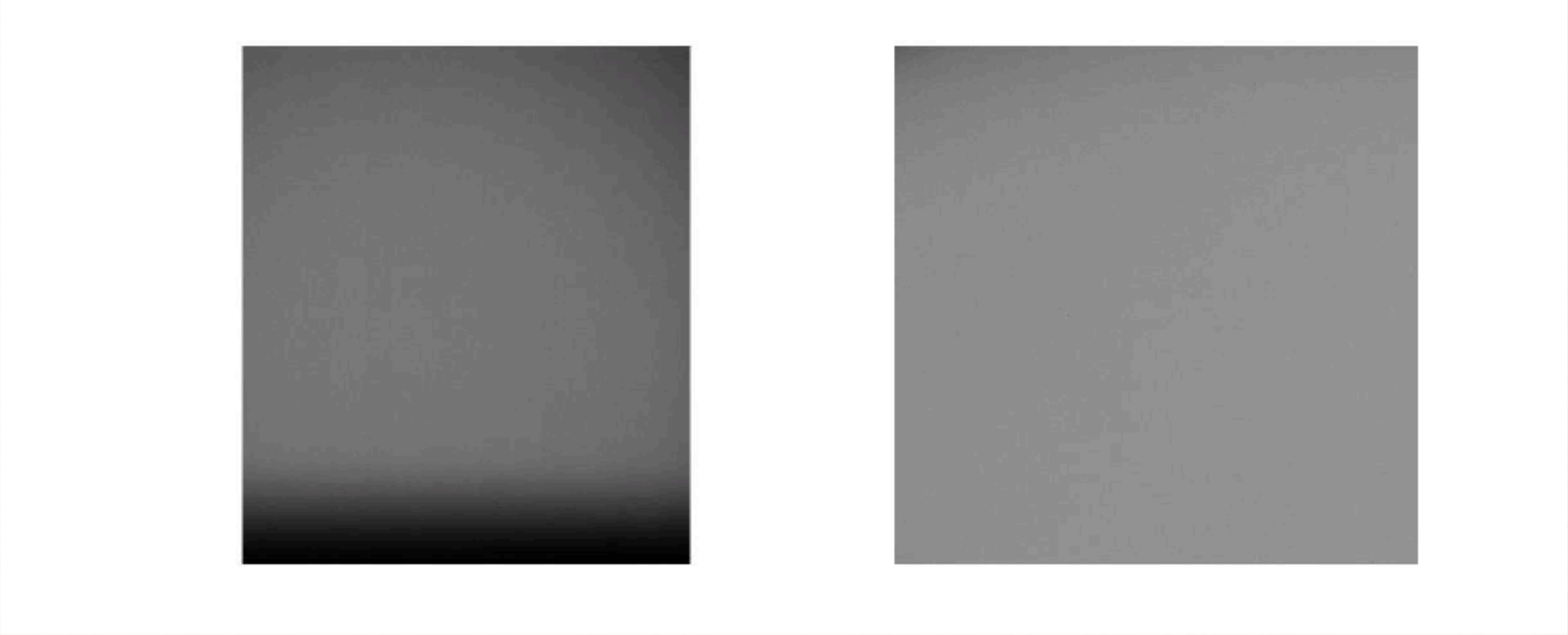
How does freezing affect impact dynamics?



M.V. Gielen, R. de Ruiter, R. Koldeweij, J.H. Snoeijer, D. Lohse and H. Gelderblom, J. Fluid Mech. 2019 (accepted)

Tin drop impact on cold sapphire

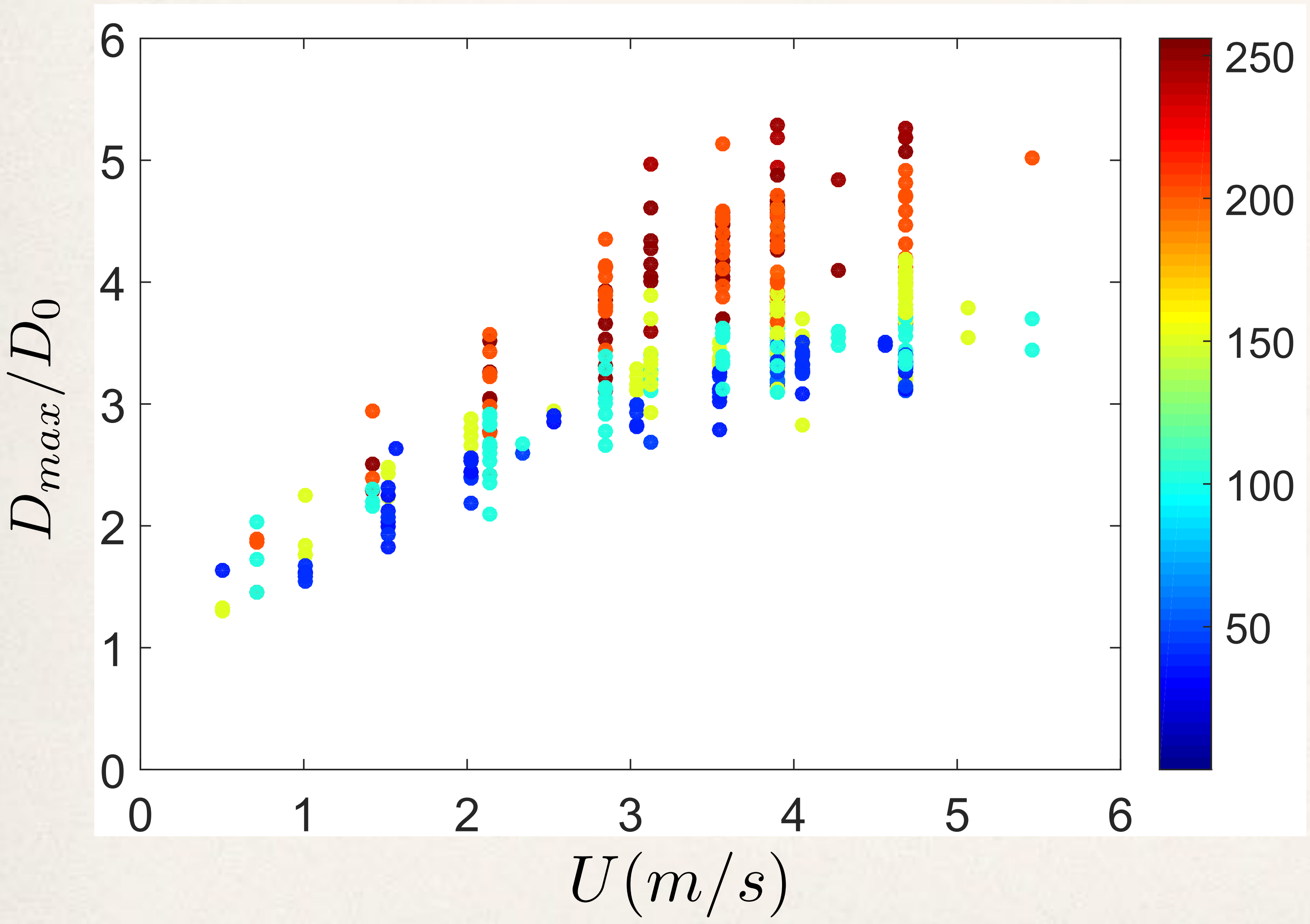
We= 267, U = 3.5 m/s
T_s = 150 °C

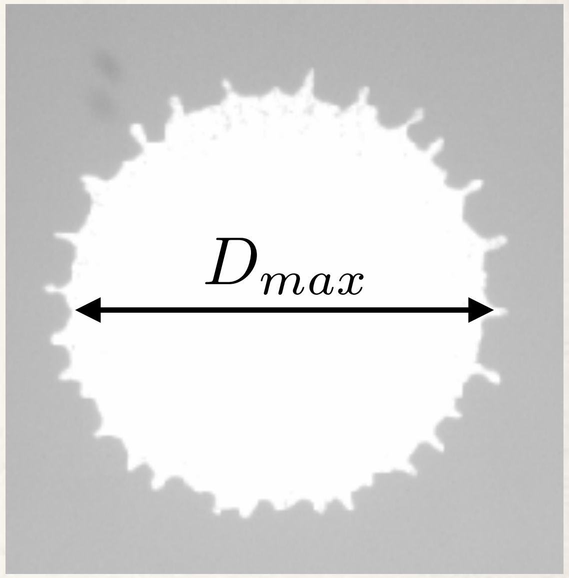


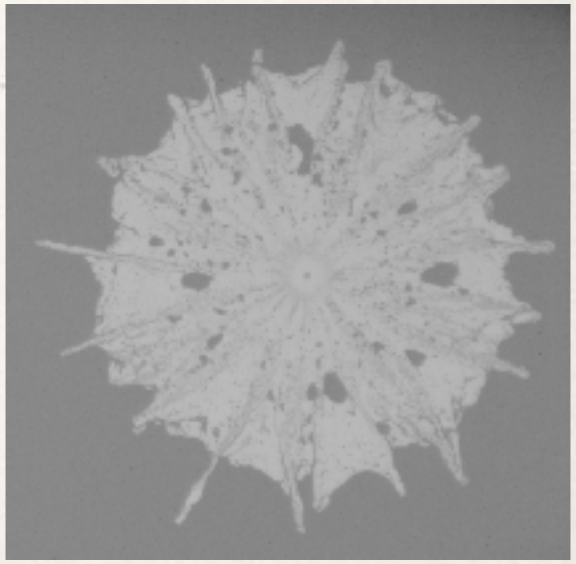
No bounce, no splash, spreading & fingering reduced

M.V. Gielen et al. *J. Fluid Mech.* 2019 (accepted)

Maximum spreading

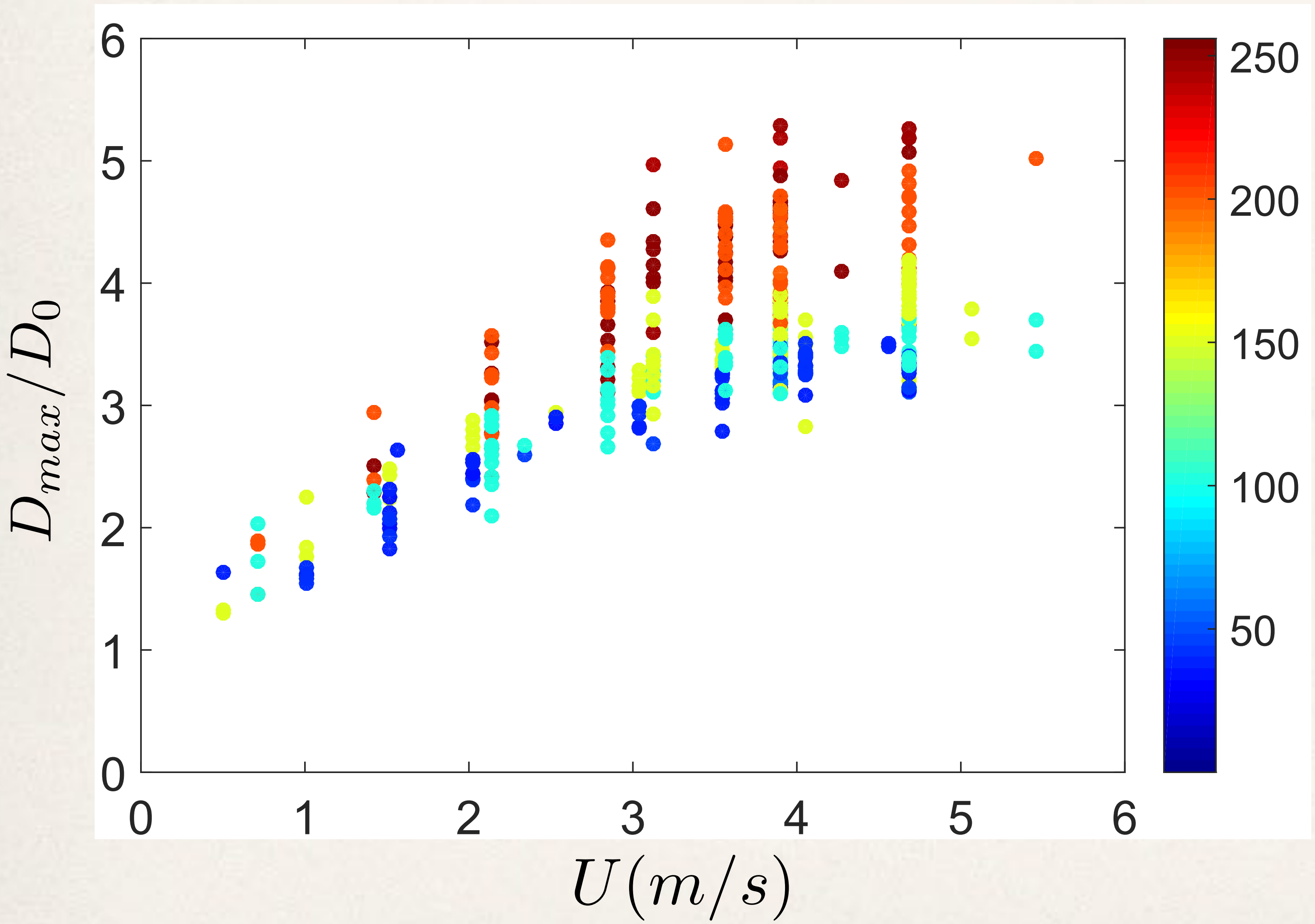






M.V. Gielen et al. J. Fluid Mech. 2019 (accepted)

Maximum spreading



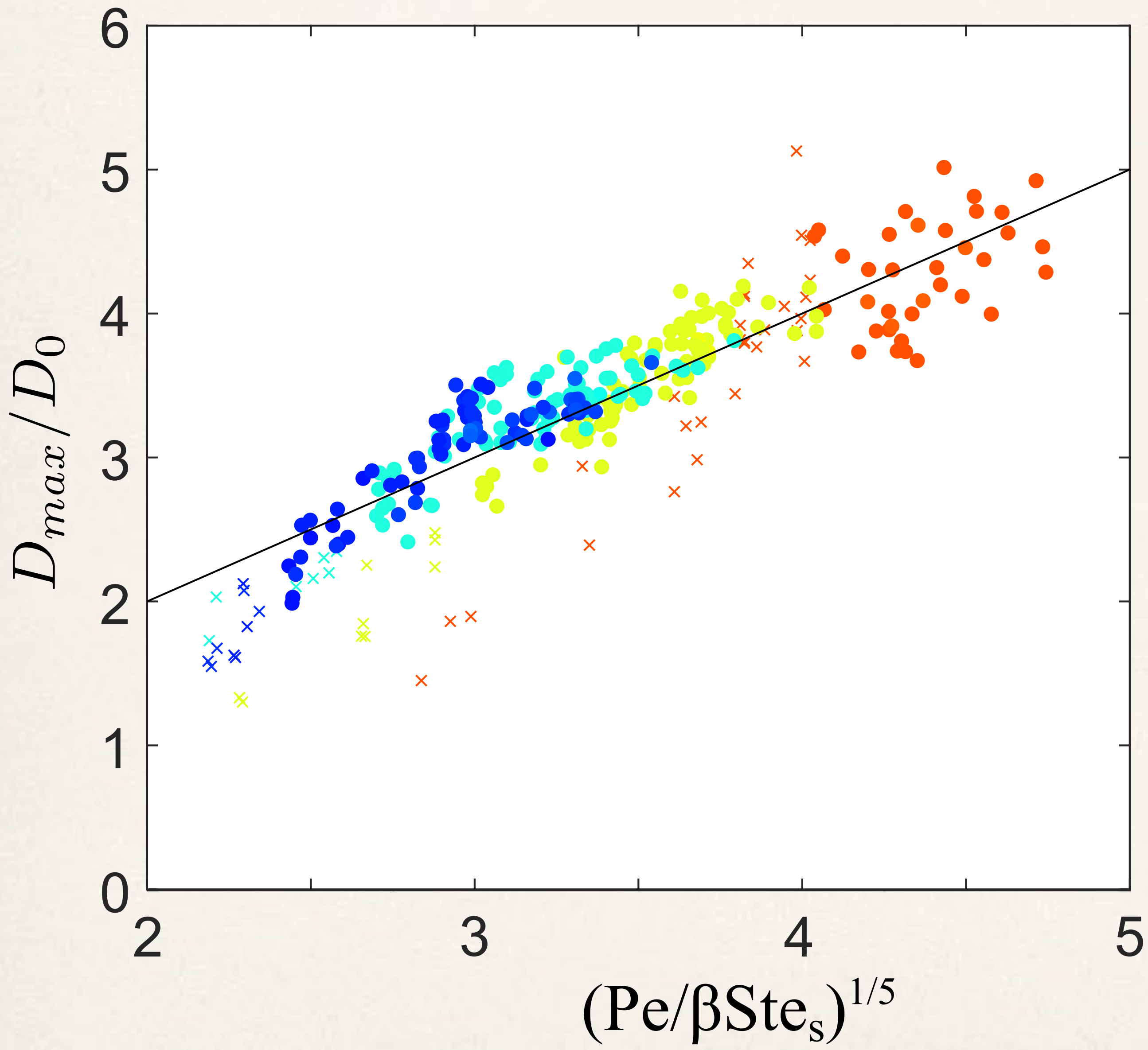
$$\frac{D_{max}}{D_0} \sim \left(\frac{\mathrm{Pe}}{\beta \mathrm{Ste}_s}\right)^{1/5}$$

$$\mathrm{Pe} = \frac{D_0 U}{\alpha}$$

$$\mathrm{Ste} = \frac{c_p(T_m - T_s)}{L}$$

M.V. Gielen et al. J. Fluid Mech. 2019 (accepted)

Maximum spreading



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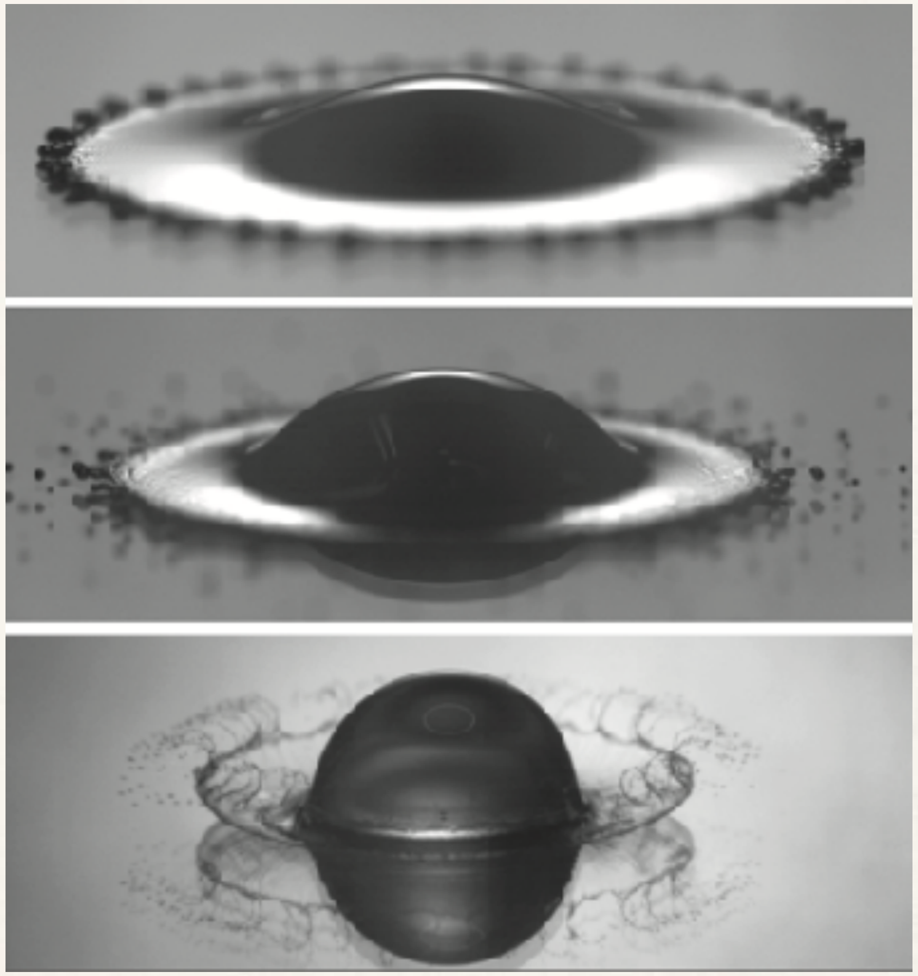
$$\mathrm{Ste} = \frac{c_p(T_m - T_s)}{L}$$

- *Debris control & inspection*

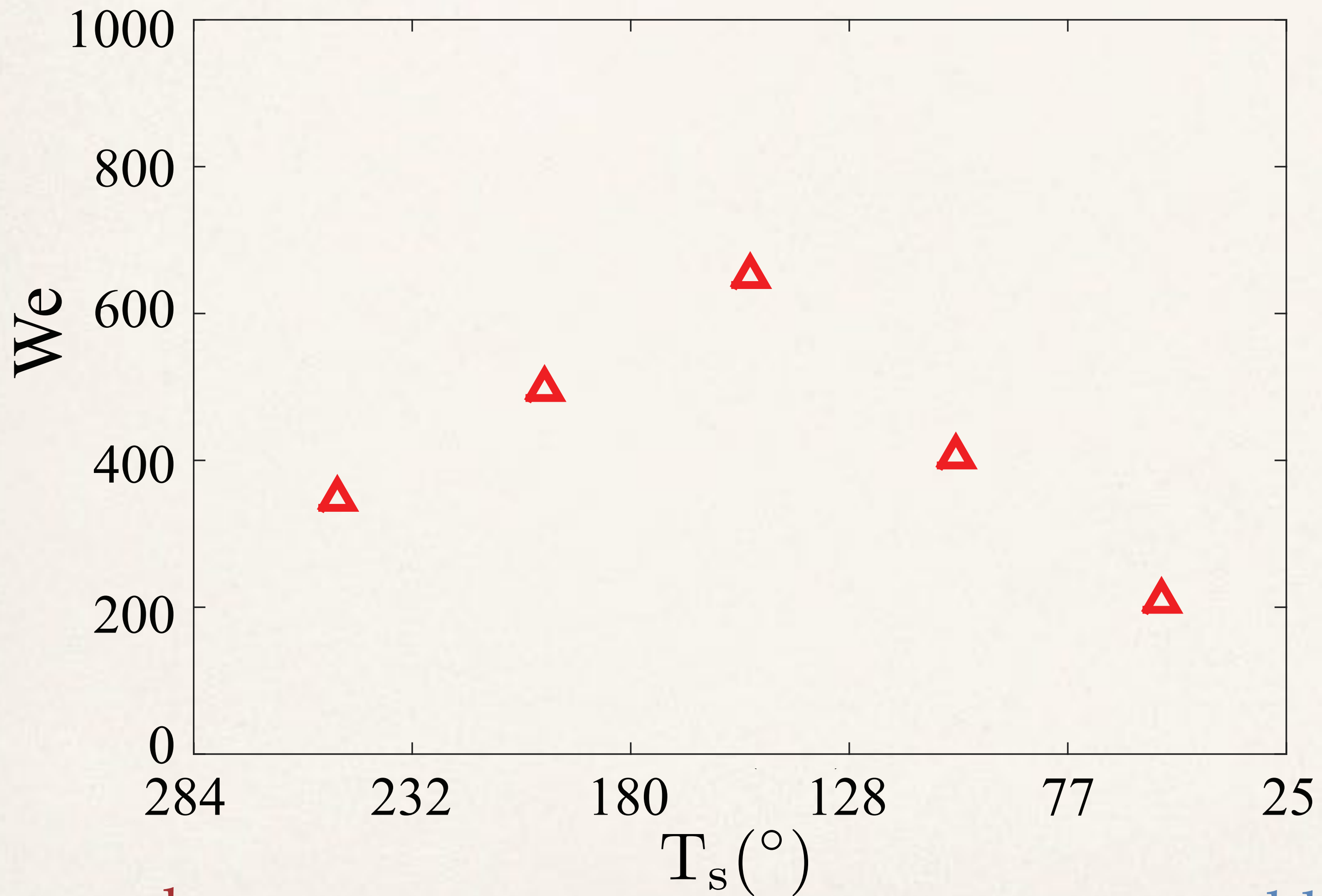
M.V. Gielen et al. J. Fluid Mech. 2019 (accepted)

Splashing threshold



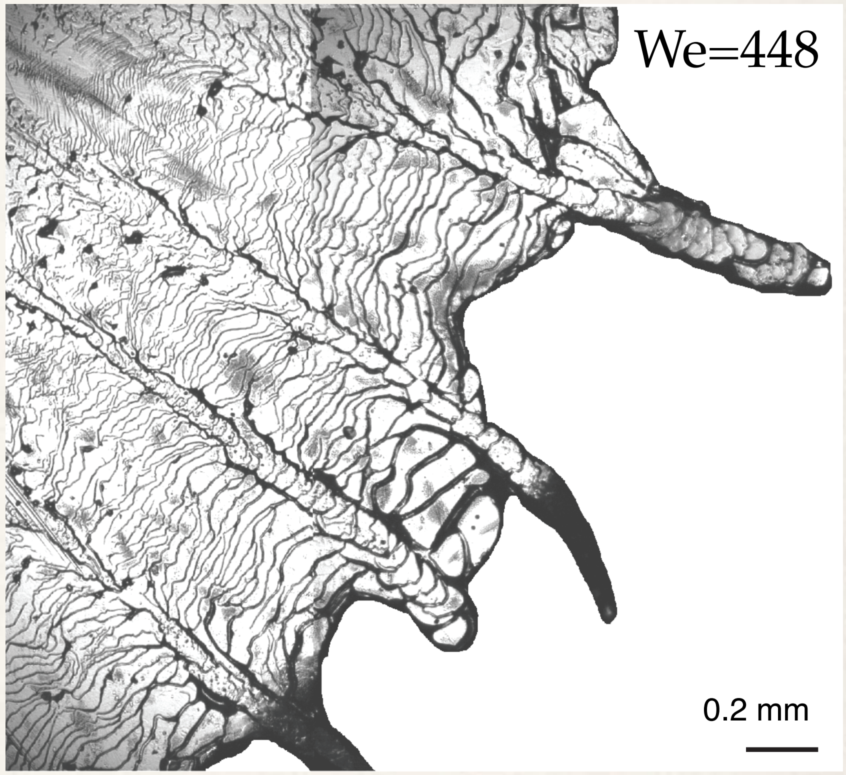
Josserand & Thoroddsen Ann. Rev. Fluid Mech. 48 (2016)

Splashing threshold



hot

cold

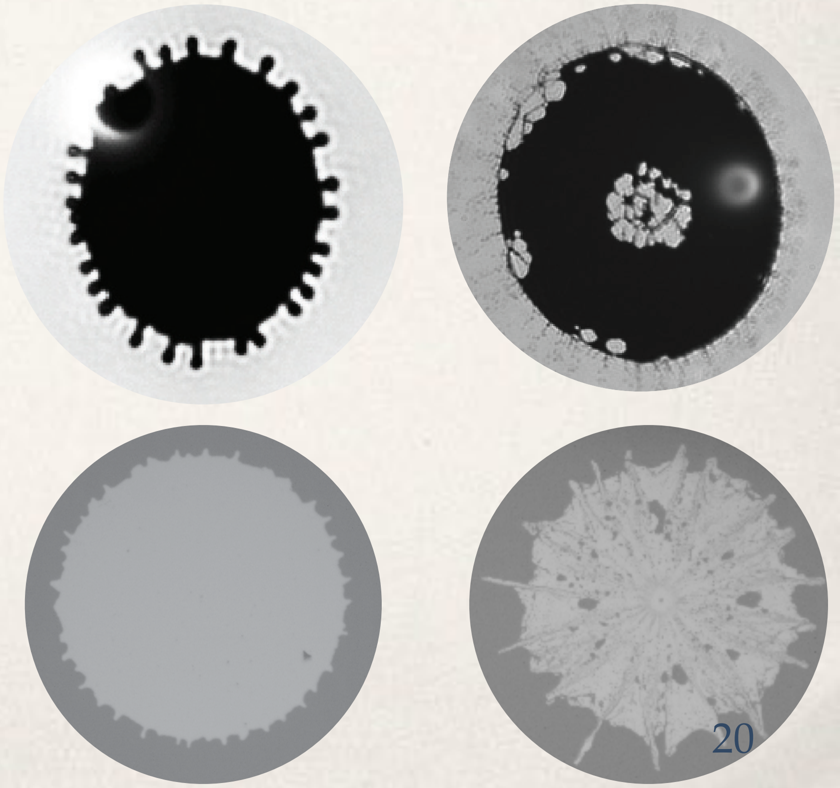


- *Vessel wall temperature*

M.V. Gielen et al. J. Fluid Mech. 2019 (accepted)

Conclusion

- Impacts by laser pulse & onto a substrate show similar features
- Fluid dynamic instabilities cause drop breakup
- Solidification (cold substrate)
  - Reduces spreading
  - Reduces or enhances splashing



Thank you for your attention!

More information*:

De Ruiter et al. Phys Rev. Fluids 2 (2017)
Gelderblom et al. J. Fluid Mech. 794 (2016)
Gielen et al. Phys. Rev. Fluids 2 (2017)
Gielen et al. J. Fluid Mech. (2019, to appear)
Klein et al. Phys. Rev. Applied 3 (2015)
Klein et al. Phys. Fluids 27 (2015)
Klein et al. Rev. Sci. Instrum. 88 (2017)
Klein et al. arXiv:1910.02522 (2019)
Kurilovich et al. Phys. Rev. Applied 6 (2016)
Reijers et al. J. Fluid Mech. 828 (2017)
Reijers et al. J. Appl. Phys. 124 (2018)
Reijers et al. arXiv: 1903.08978 (2019)

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