Thickness profile of a stretched semi-transparent sheet of liquid metal formed by laser-prepulse impact

Bo Liu
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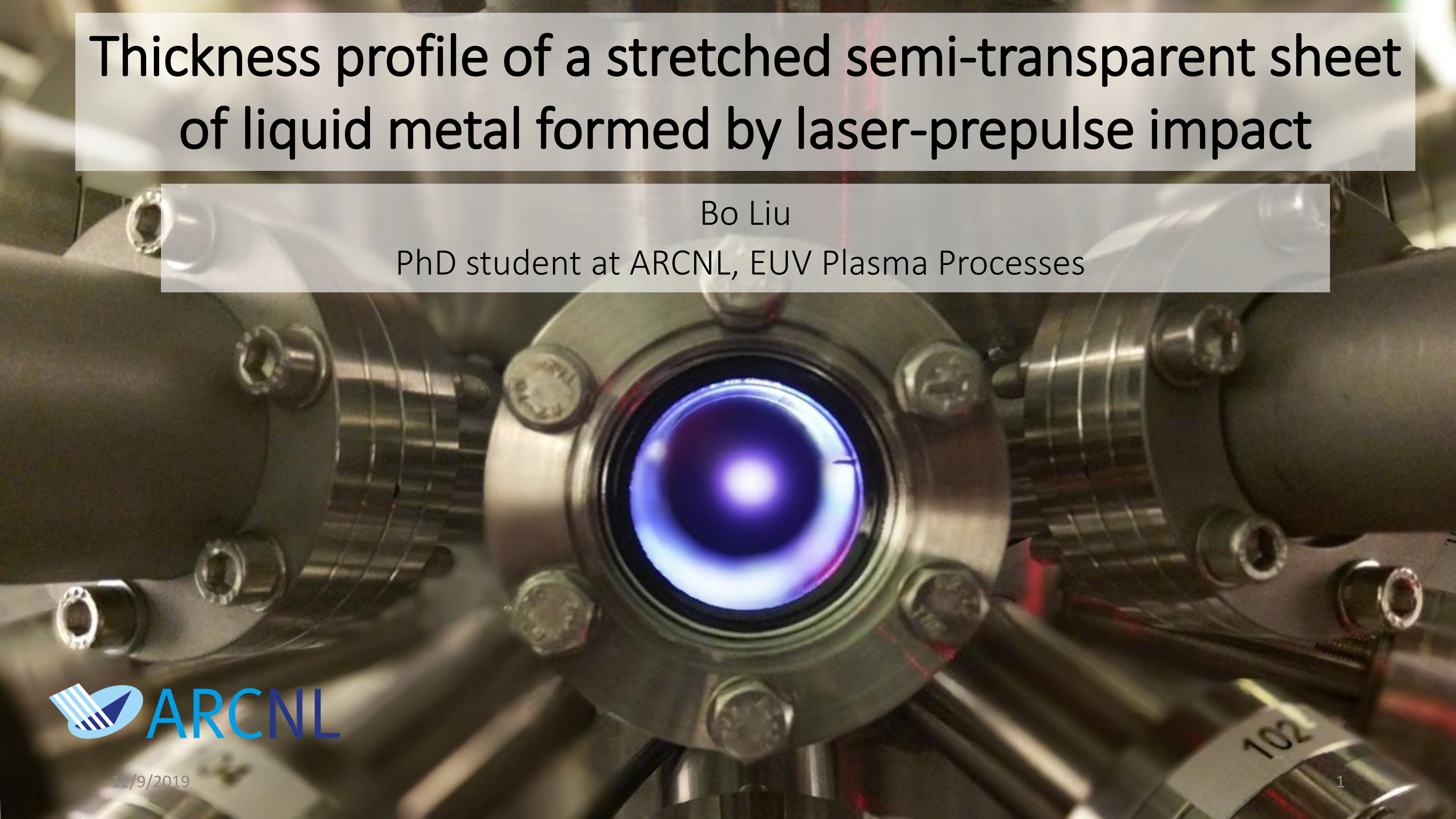

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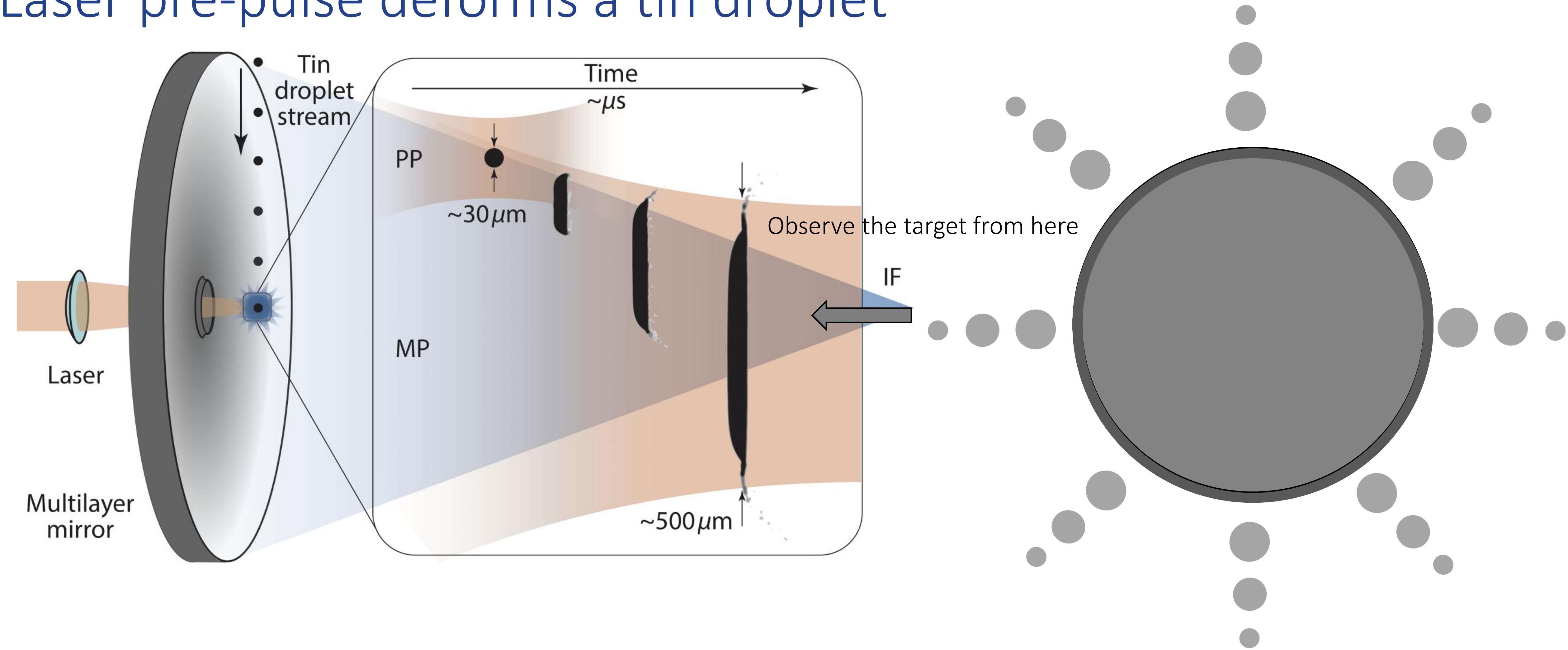
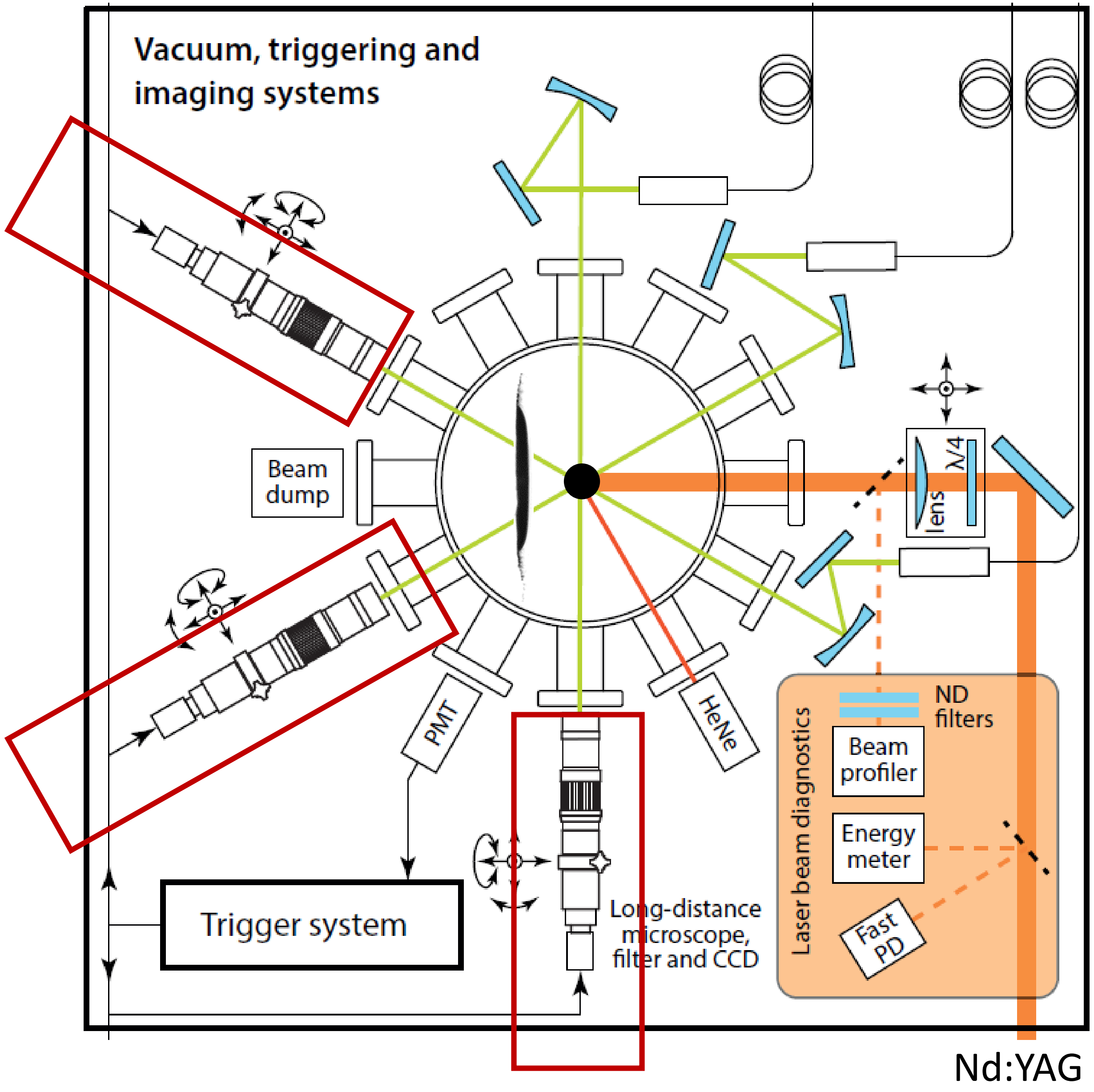
Laser pre-pulse deforms a tin droplet

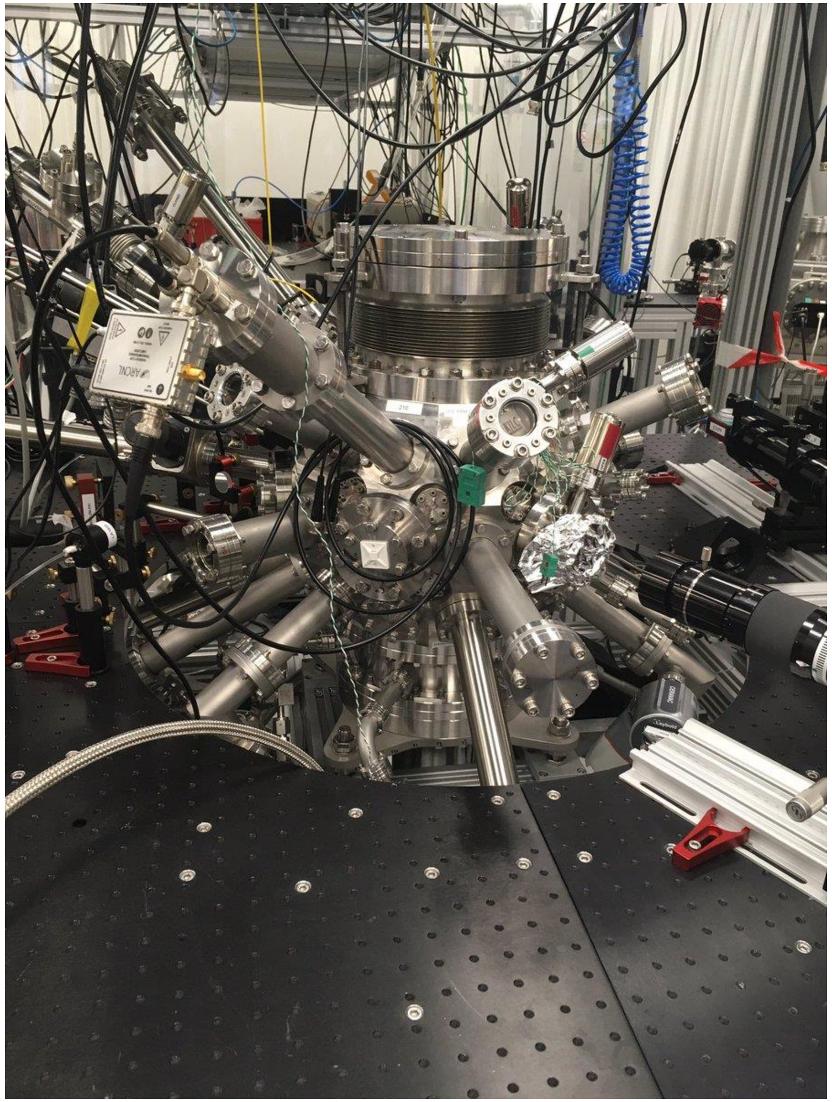


- Morphology of the target: volume of sheet? of rim? of fragmentation?

Experiment setup

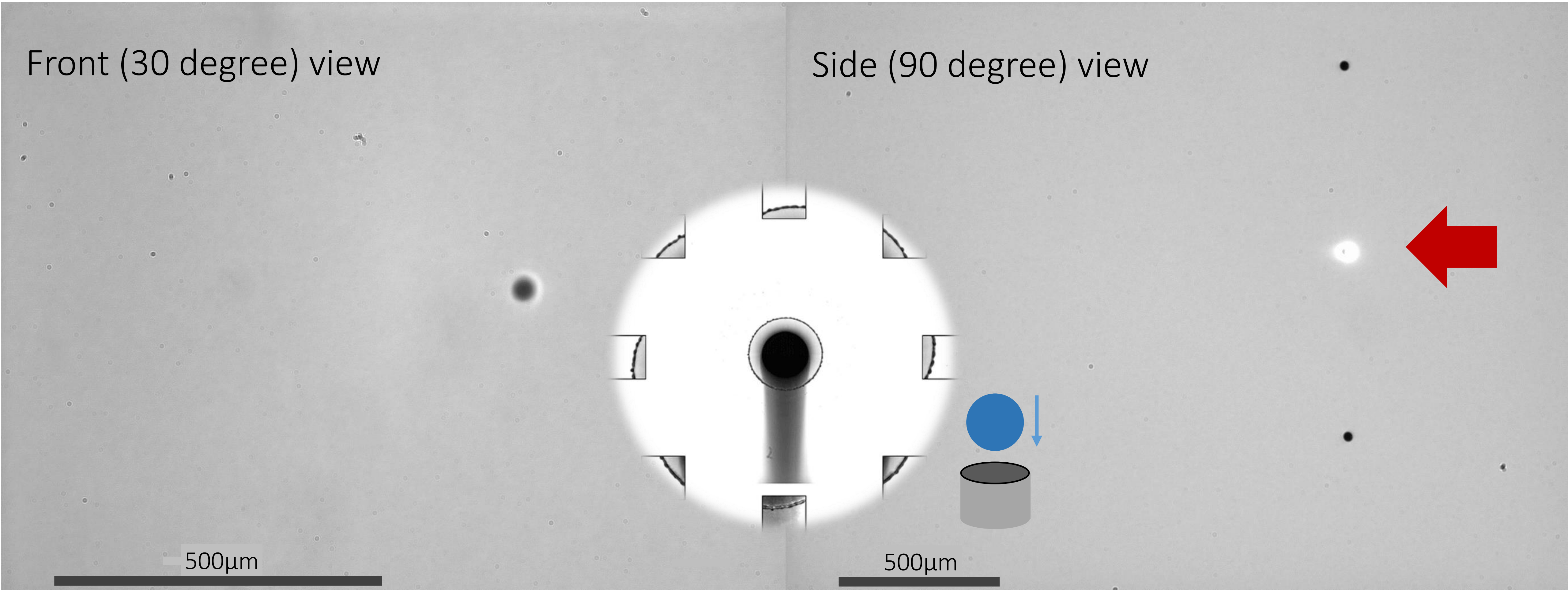
High-quality stroboscopic multi-angle shadowgraphy





Experimental observation on droplet expansion

Shadowgraphy diagnostic tech. visualizes the droplet responding to the laser

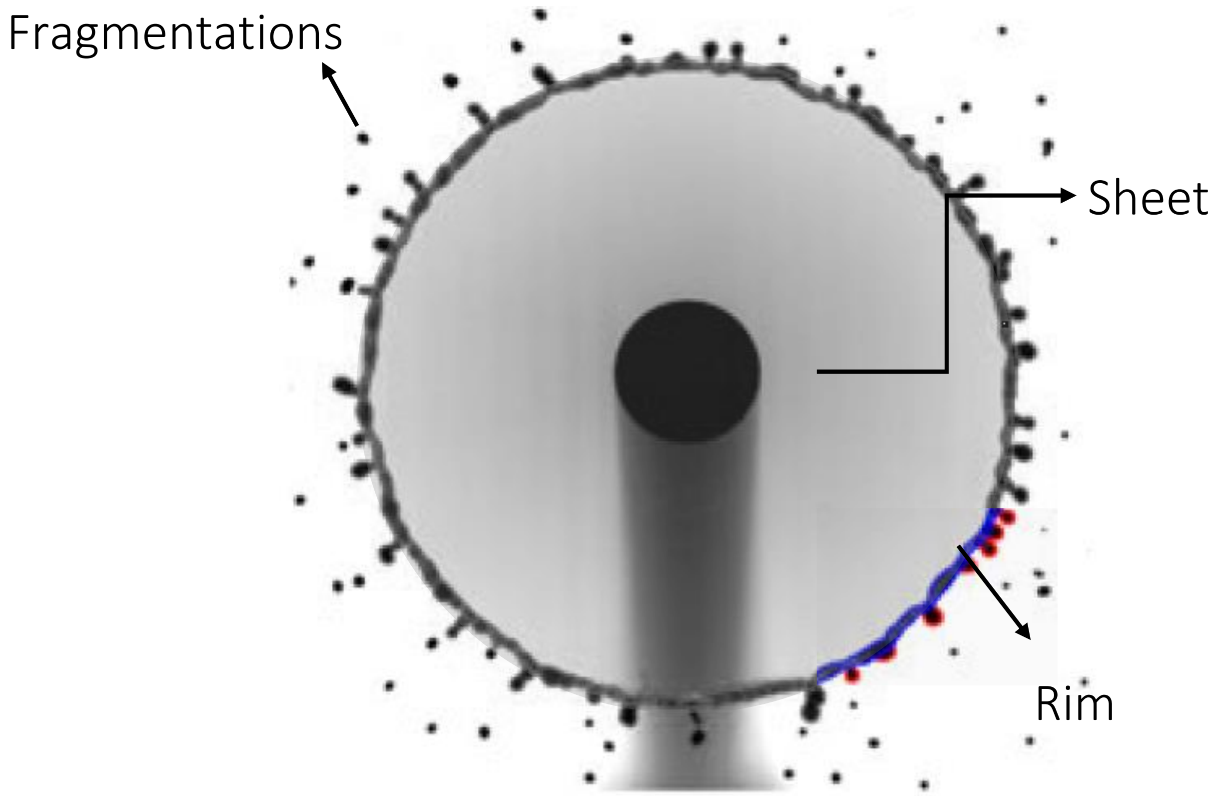


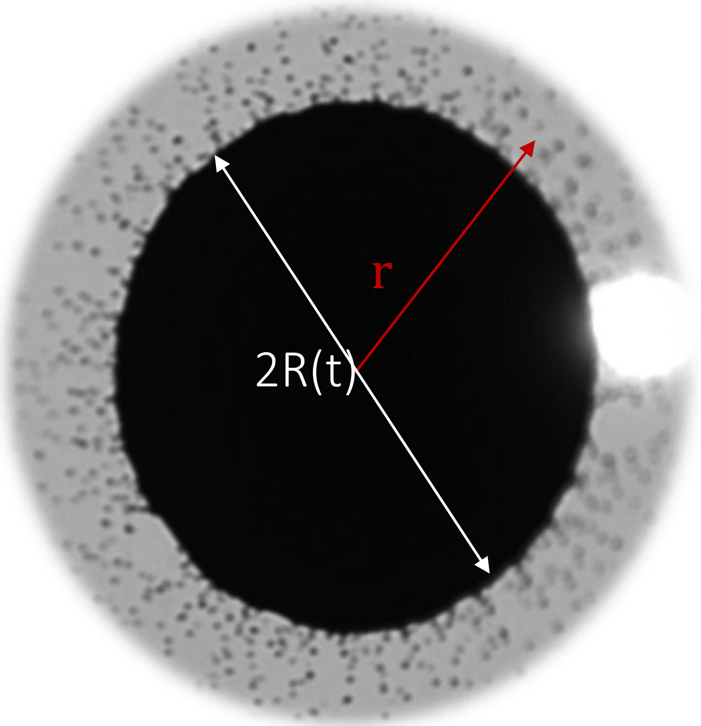
- The expansion is similar to water-pillar impact*.

*Y. Wang, R. Dandekar, N. Bustos, S. Poulain, and L. BourouibaPhys.Rev. Lett. 120, 204503 (2018).

Comparison with water-pillar impact

Similar in mass distribution



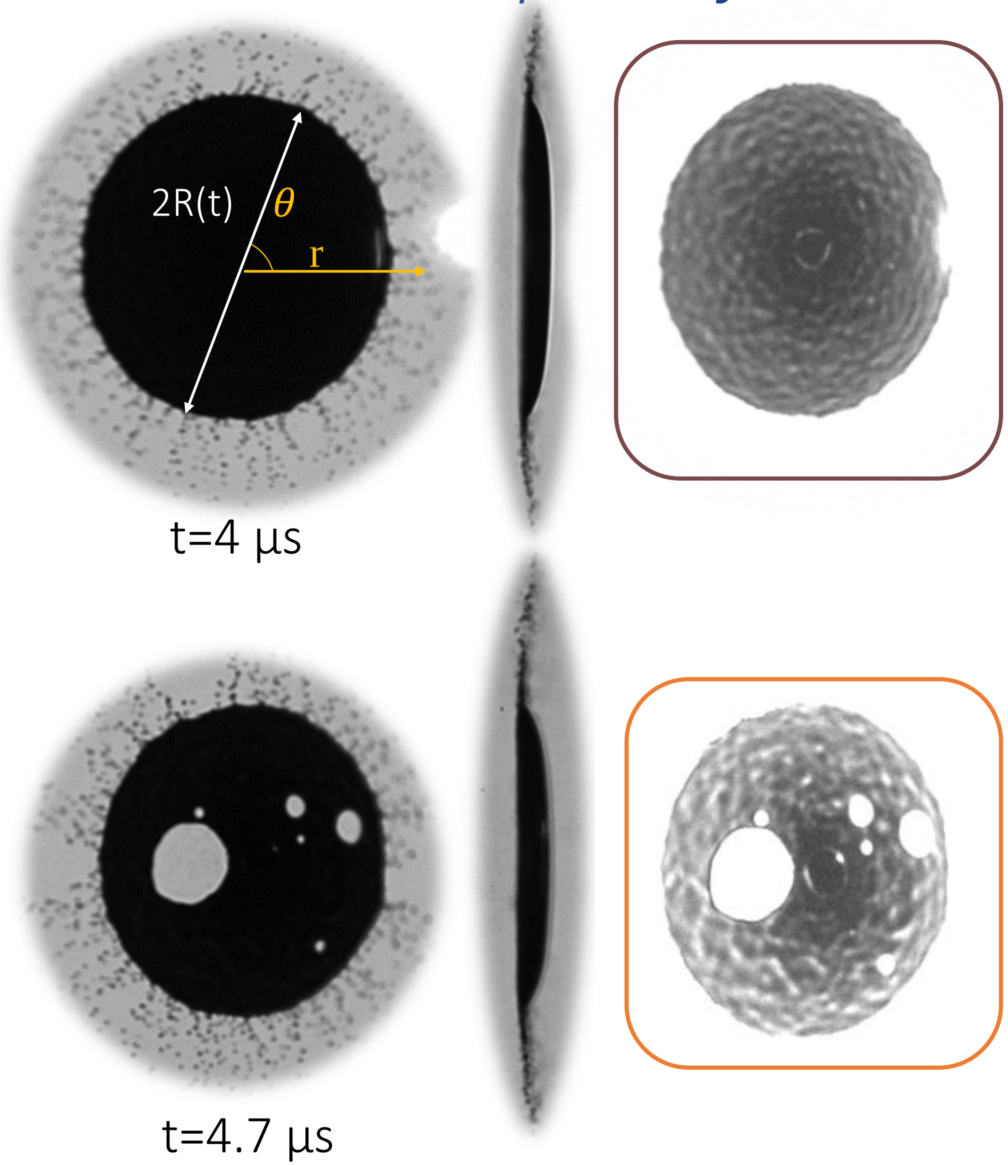


- Mass distribution of the initial droplet: $V_0 = V_{sheet} + V_{fragmentation} + V_{rim}$
- Axisymmetric expansion→ thickness profile is necessary to get V_{sheet}

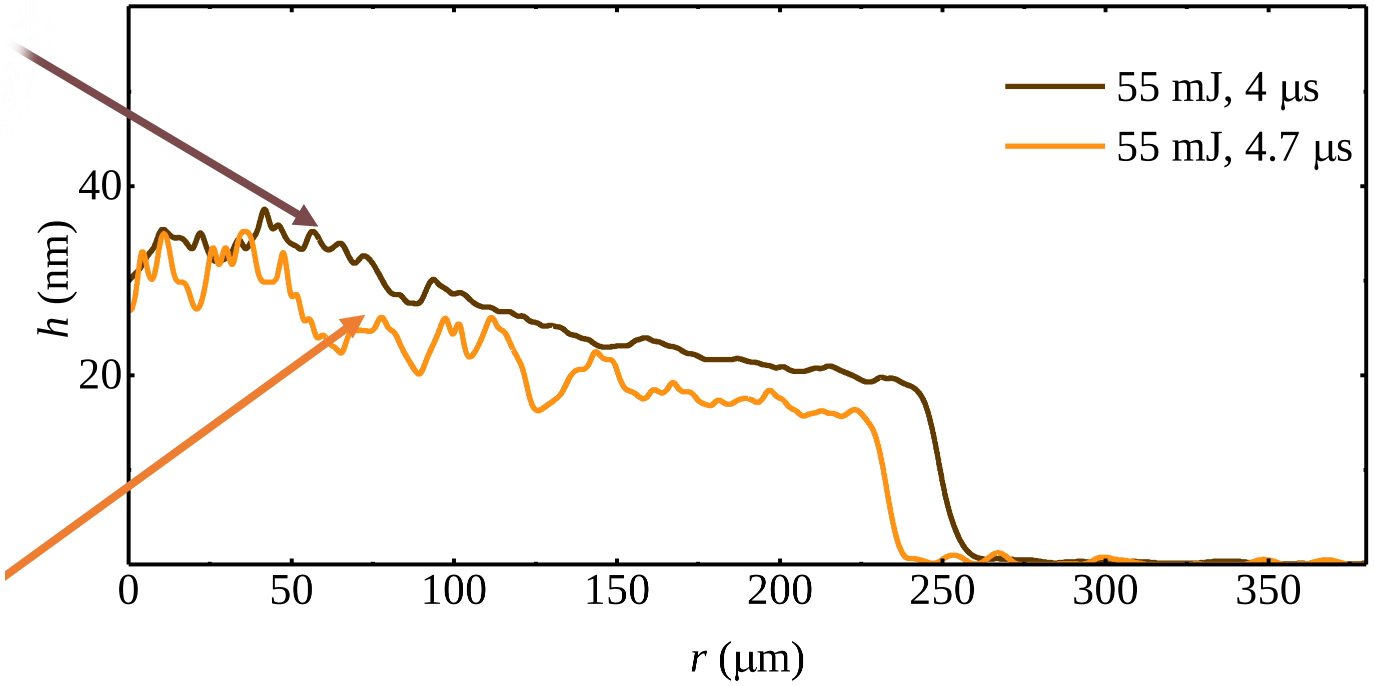
Y. Wang, R. Dandekar, N. Bustos, S. Poulain, and L. BourouibaPhys.Rev. Lett. 120, 204503 (2018).

Thickness measurement from transmission

32 um diameter droplet deforms into a sheet with thickness of several 10 nm



- Local thickness profile now understood using:
  - Transmissivity information of thin tin sheets (n,k)

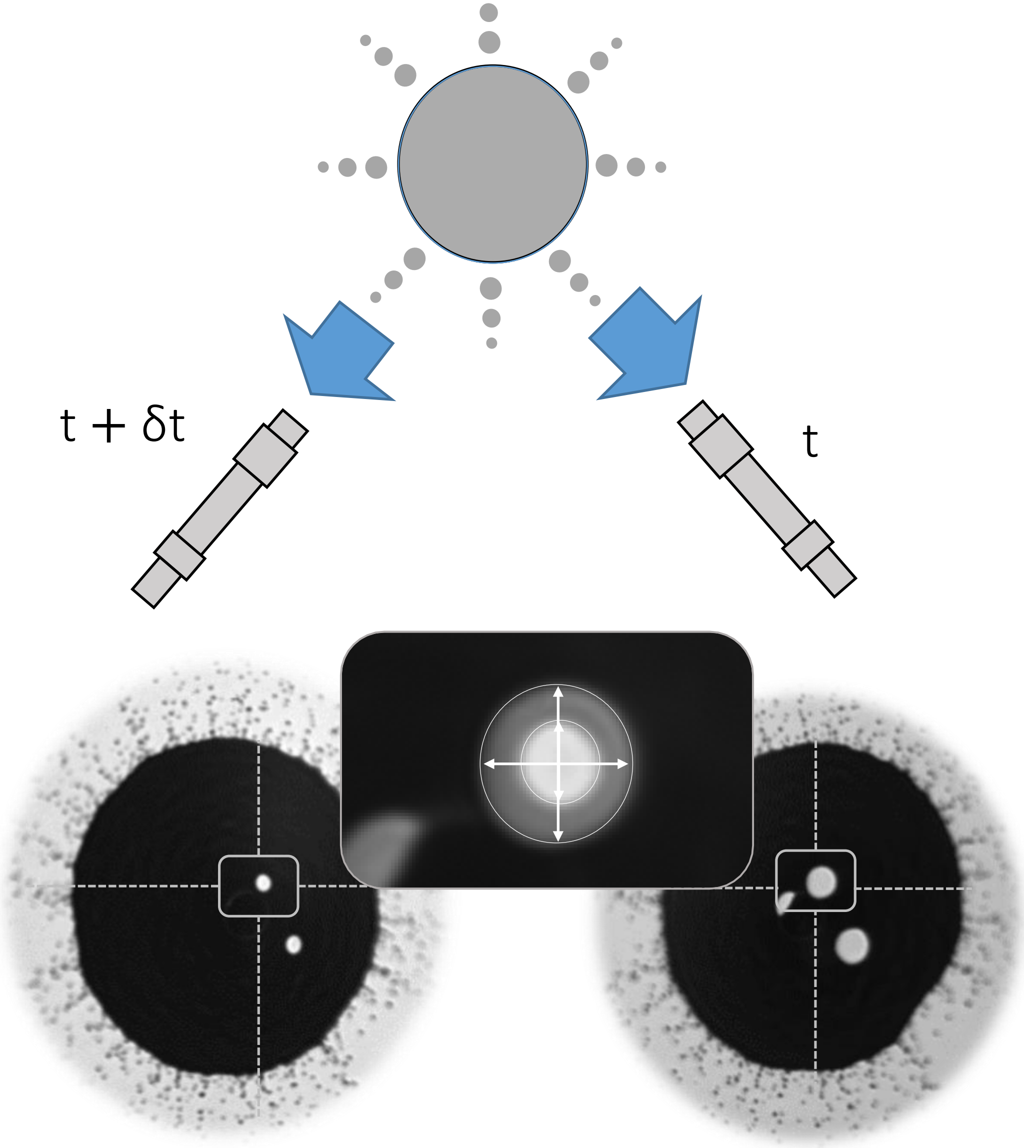


- h ~ several 10 nm
- h(r)↓, h(t) ↓

B. Liu, D. Kurilovich, H. Gelderblom and O.O. Versolato, submitted

Thickness measurement from hole opening (Taylor-Culick speed)

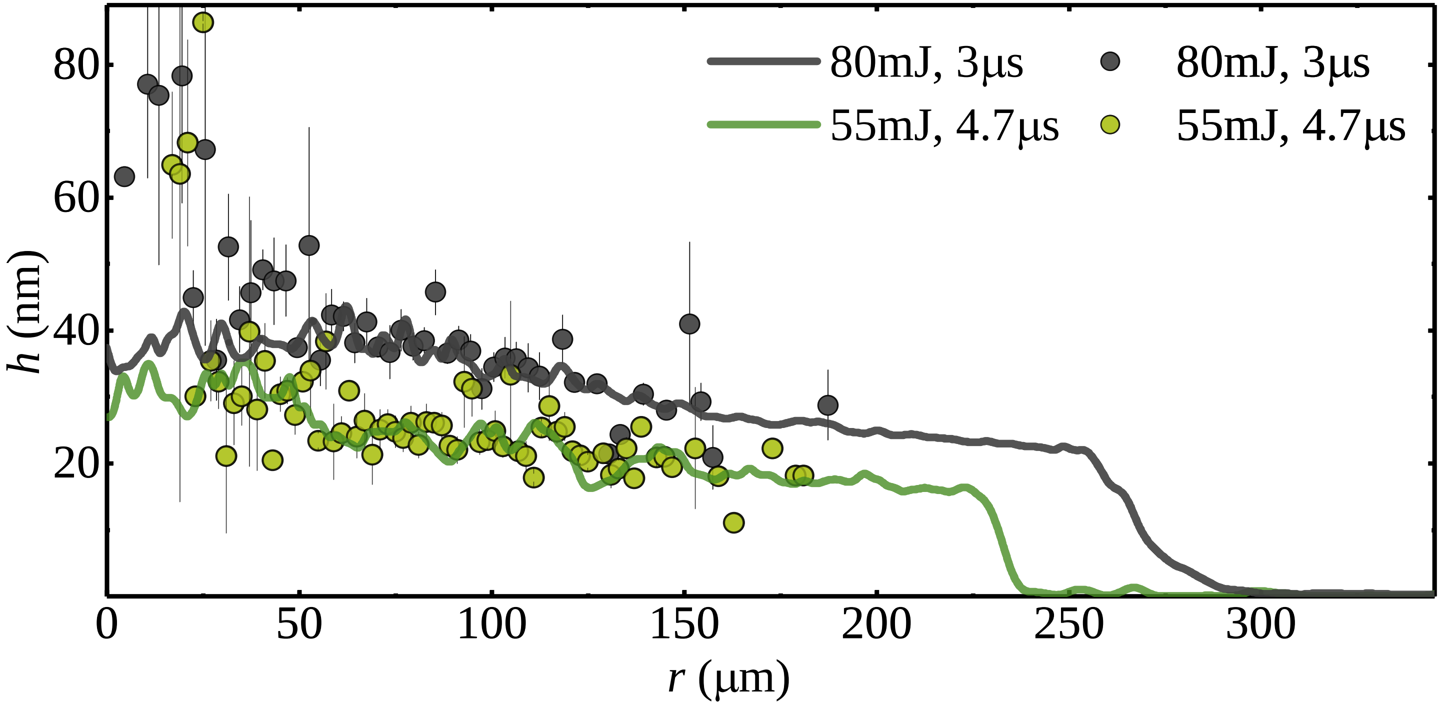
32 um diameter droplet deforms into a sheet with thickness of several 10 nm



t = 4.8 μs

t = 4.8 μs + 150 ns

- Double-pulse shadowgraphy to determine the velocity with which holes are formed (ρ,σ).
- Agreement between two methods.



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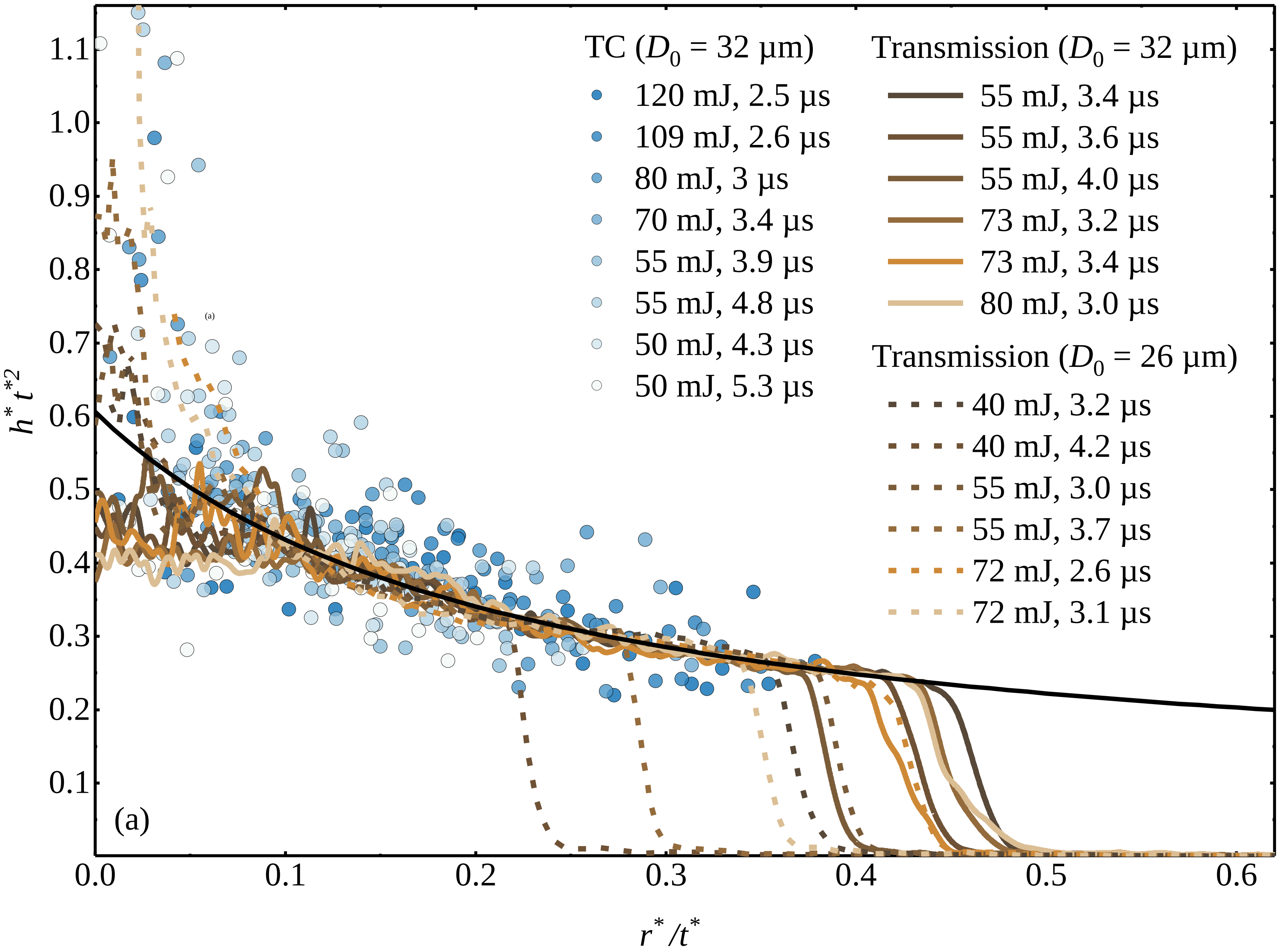
Self-similar behavior of the thickness evolution

- $\frac{h}{D_0} = h^*$, $\frac{r}{D_0} = r^*$, $\frac{tU_0}{D_0} = t^*$
- $h^* t^{*2} = f\left(\frac{r^*}{t^*}\right)$
- $f(x) = \frac{1}{a_0 + a_1 x + a_2 x^2}$

$h \rightarrow V_{sheet}$



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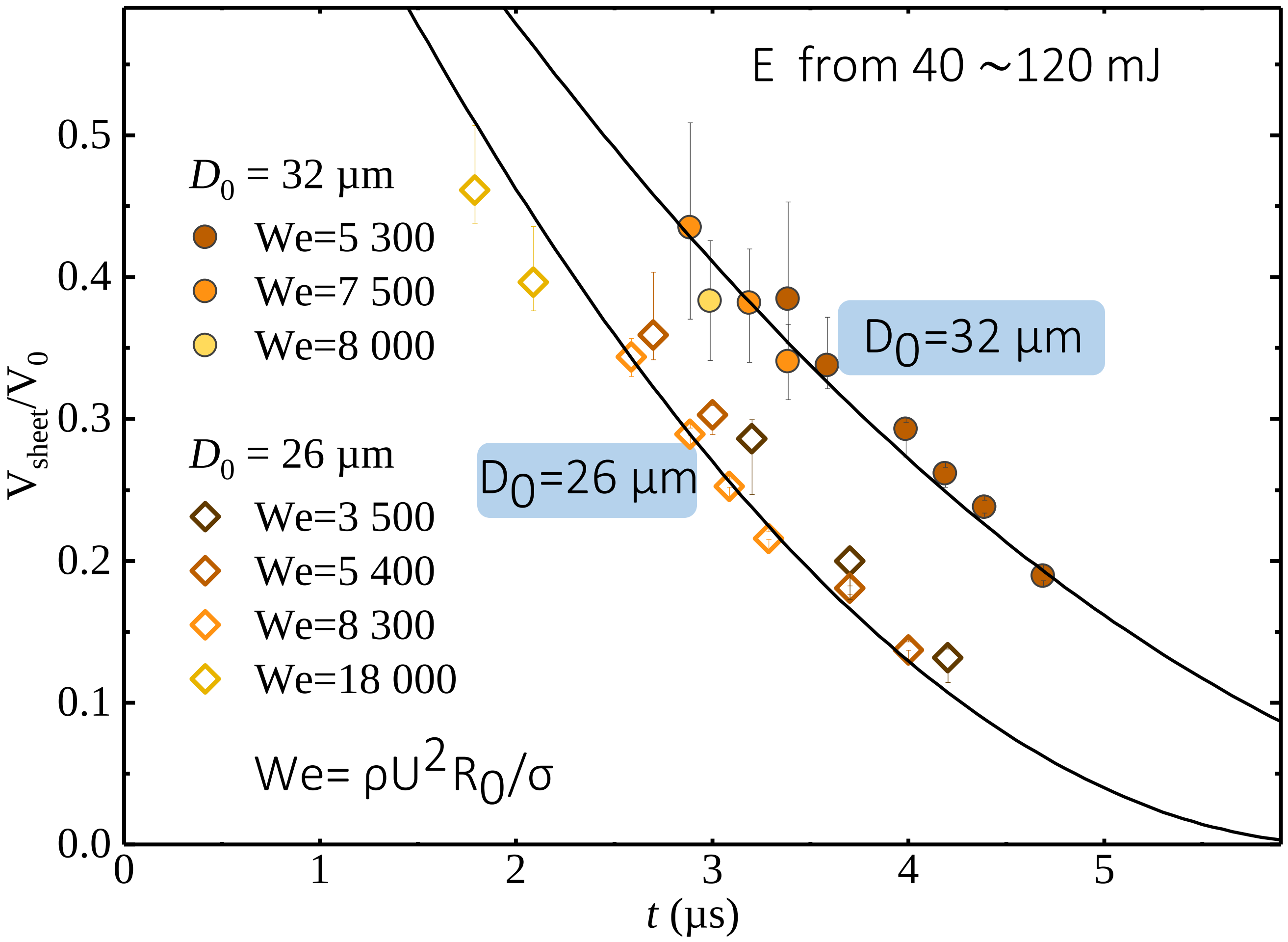
Sheet volume

Local thickness profile enables volume determination



- Over **50%** of tin is **NOT** in the sheet shortly after the impact!
- $V_{sheet}(t)\downarrow$, V_{sheet}(independent on E)
- Data agrees with a zero-fitting parameter model* for water-pillar impact;

B. Liu, D. Kurilovich, H. Gelderblom and O.O. Versolato, submitted.
*E. Villermaux and B. Bossa, J. Fluid Mech. (2011), vol.668, pp. 412–435.

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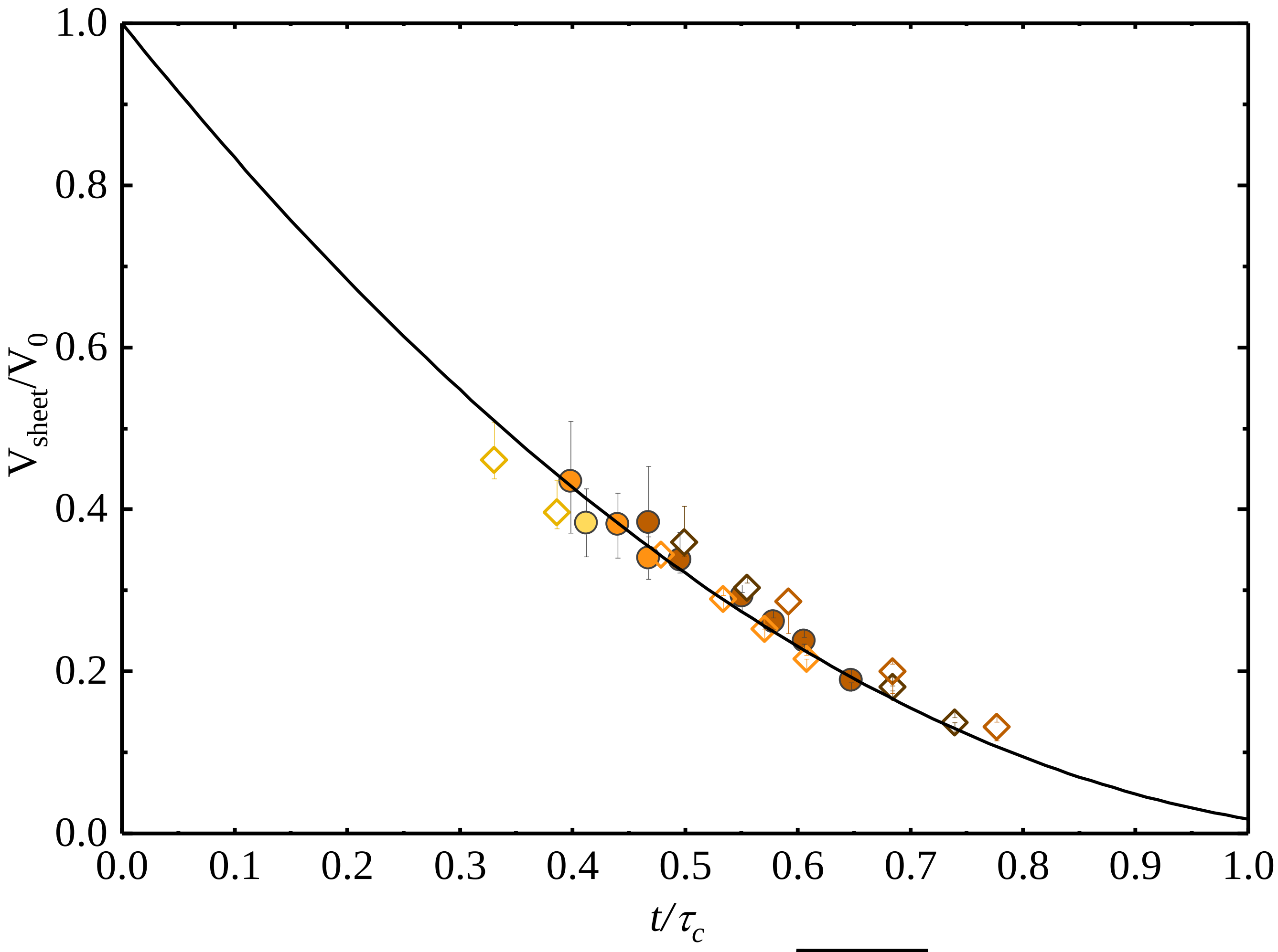


$\tau_C = \sqrt{\rho R_0^3/\sigma}$

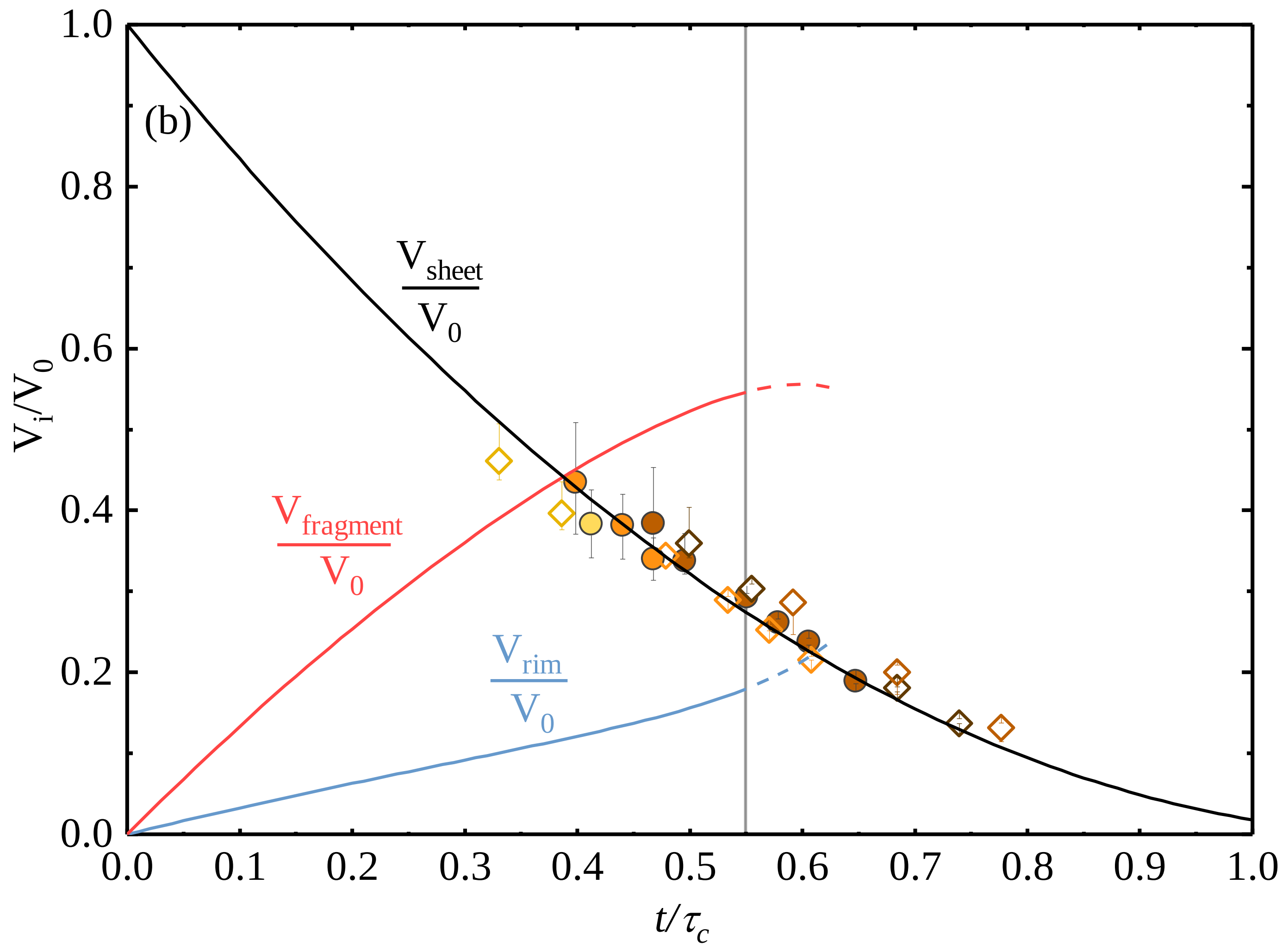
- Over **50%** of tin is **NOT** in the sheet shortly after the impact!
- $V_{sheet}(t)\downarrow$, V_{sheet}(independent on E)
- Data agrees with a zero-fitting parameter model* for water-pillar impact;
- Sheet volume is parameterized by t/τ_C → given R_0, sheet volume at a time is accessible.

B. Liu, D. Kurilovich, H. Gelderblom and O.O. Versolato, submitted.
E. Villermaux and B. Bossa, J. Fluid Mech. (2011), vol.668, pp. 412–435.

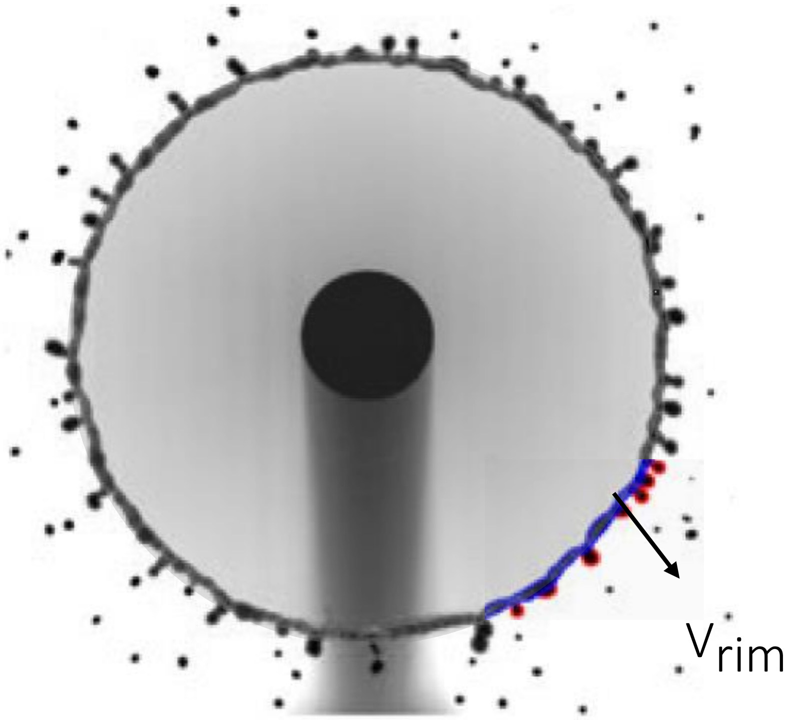
Volume of the rim

Existing analytical model enables an estimation on the rim volume

$V_0 = V_{sheet} + V_{rim} + V_{Fragmentation}$



- ➢ An existing, analytical model** on the rim volume (universally) applied to a fragmenting sheet.



B. Liu, D. Kurilovich, H. Gelderblom and O.O. Versolato, submitted.
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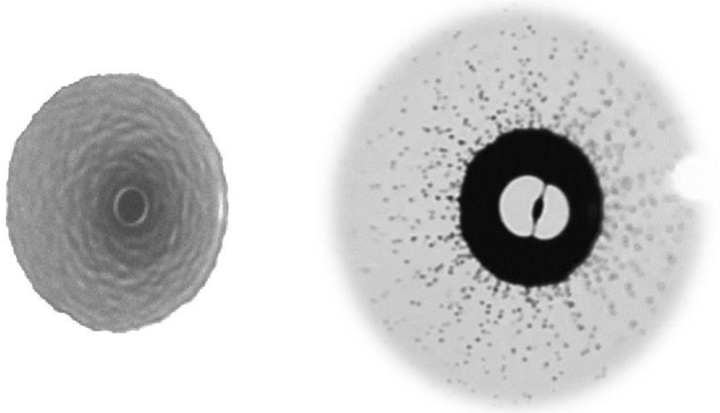
**Y. Wang, R. Dandekar, N. Bustos, S. Poulain, and L. BourouibaPhys.Rev. Lett. 120, 204503 (2018).

Conclusion

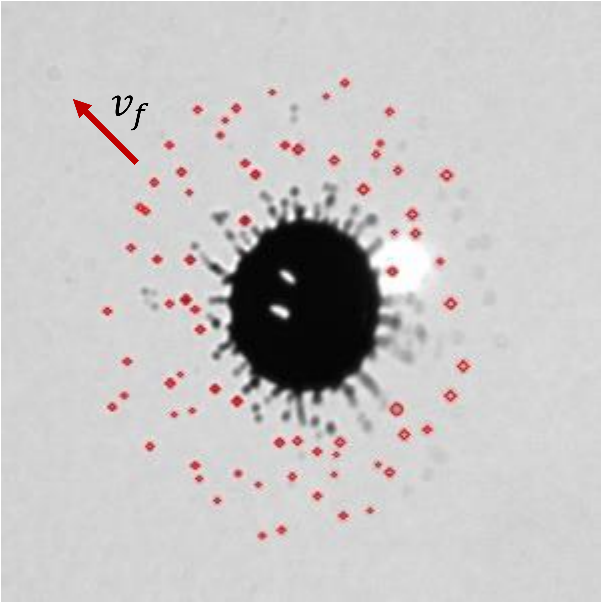
- Sheet with thickness of several 10 nm is formed after the laser pulse.
- Self-similar behavior of the thickness evolution gives a model for the prediction on h(r, t).
- We determine the mass in the target sheet: less than half of tin resides in the sheet.
- Rim and fragmentations account for 10% and 40% amount of the initial tin, respectively.

Outlook

- What happens in the sheet center? (difference between plasma and pillar?)



- Fragmentation (size? velocity?)



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Lars Benhke (PhD)
Lucas Poirier (PhD)
John Sheil (postdoc)
Laurens van Buuren (technician)
Ronnie Hoekstra (group leader)
Wim Ubachs (group leader)
Oscar Versolato (group leader)

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Zeudi Mazzotta (PD)
Stefan Witte (group leader)
Kjeld Eikema (group leader)

Academic collaborators:

H. Gelderblom (TU/e)
A. Klein (UT, ASML)

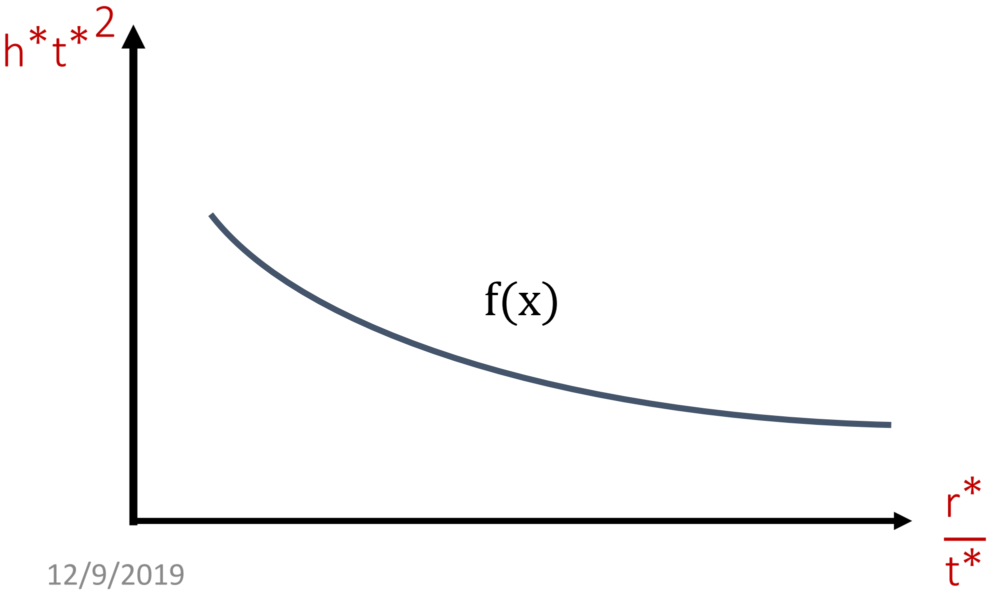
Thanks for your attention!

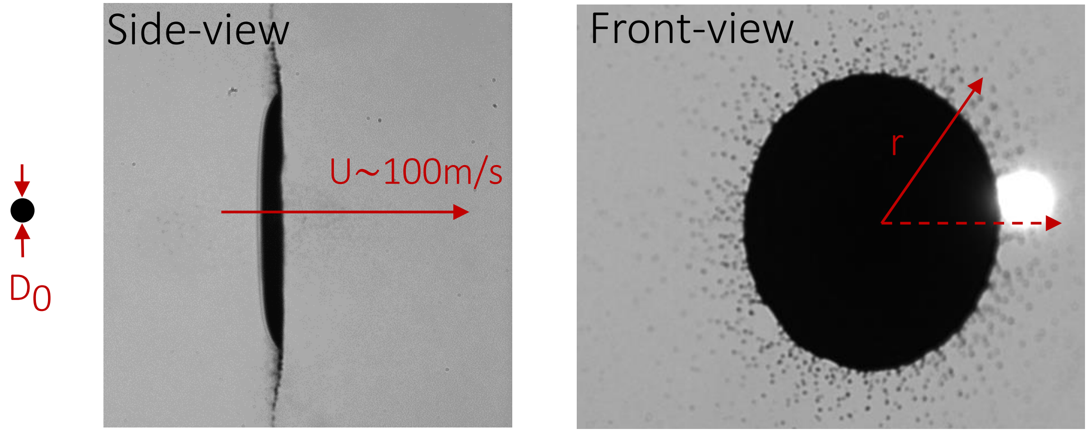
Questions?

Self-similar behavior of the thickness evolution

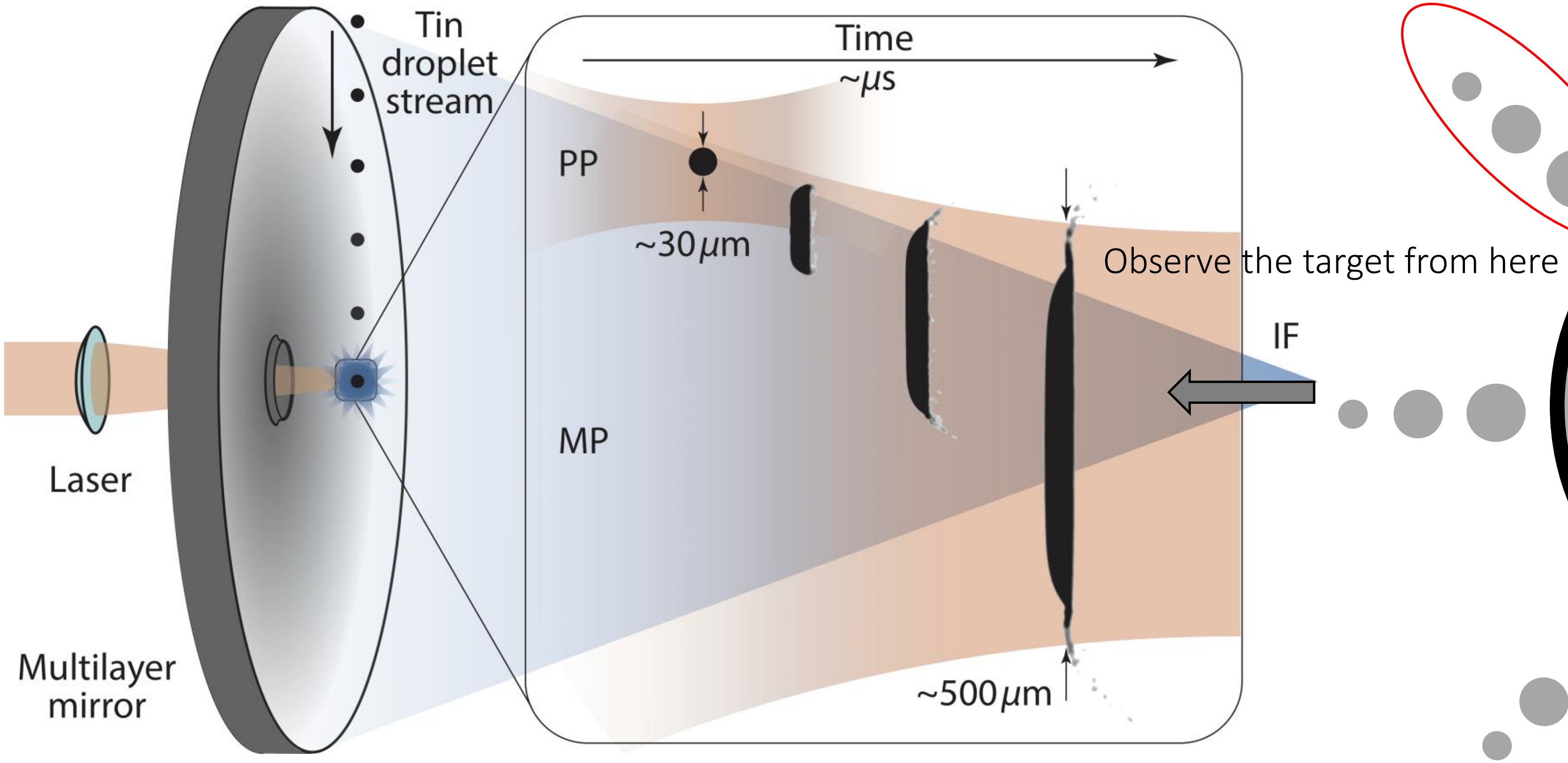
based on an existing model for the droplet-pillar impact

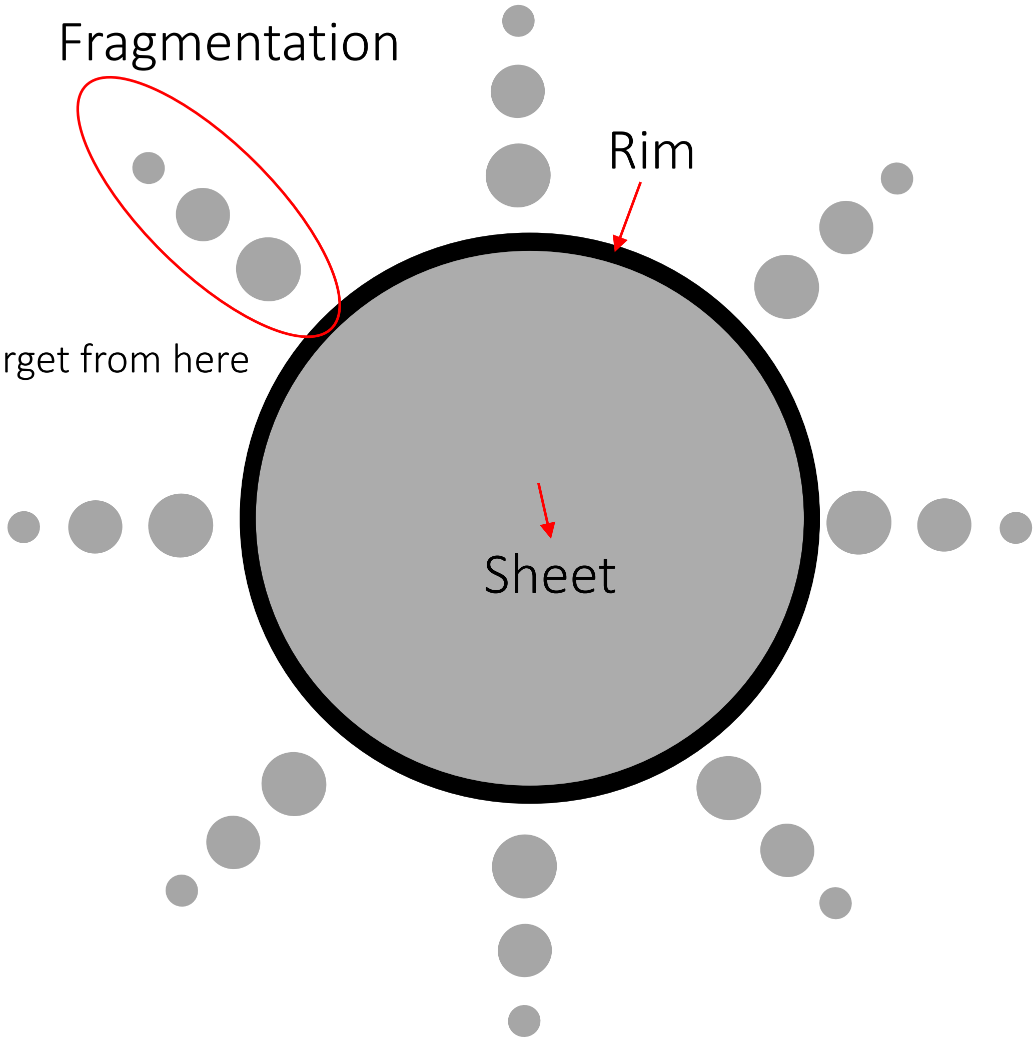
- Similar shape for the thickness.
- *h, u* are determined from momentum & mass conservation; $F(D_0, U, r, t, h) = 0$;
- 5 physical variables, 2 physical units; $F(\pi_1, \pi_2, \pi_3) = 0$; $[\pi_i]=1$;
- $\pi_1=\frac{h}{D_0}=h^*$, $\pi_2=\frac{r}{D_0}=r^*$, $\pi_3=\frac{tU_0}{D_0}=t^*$
- $h^* {t^*}^2 = f\left(\frac{r^*}{t^*}\right)$





Laser pre-pulse deforms a tin droplet

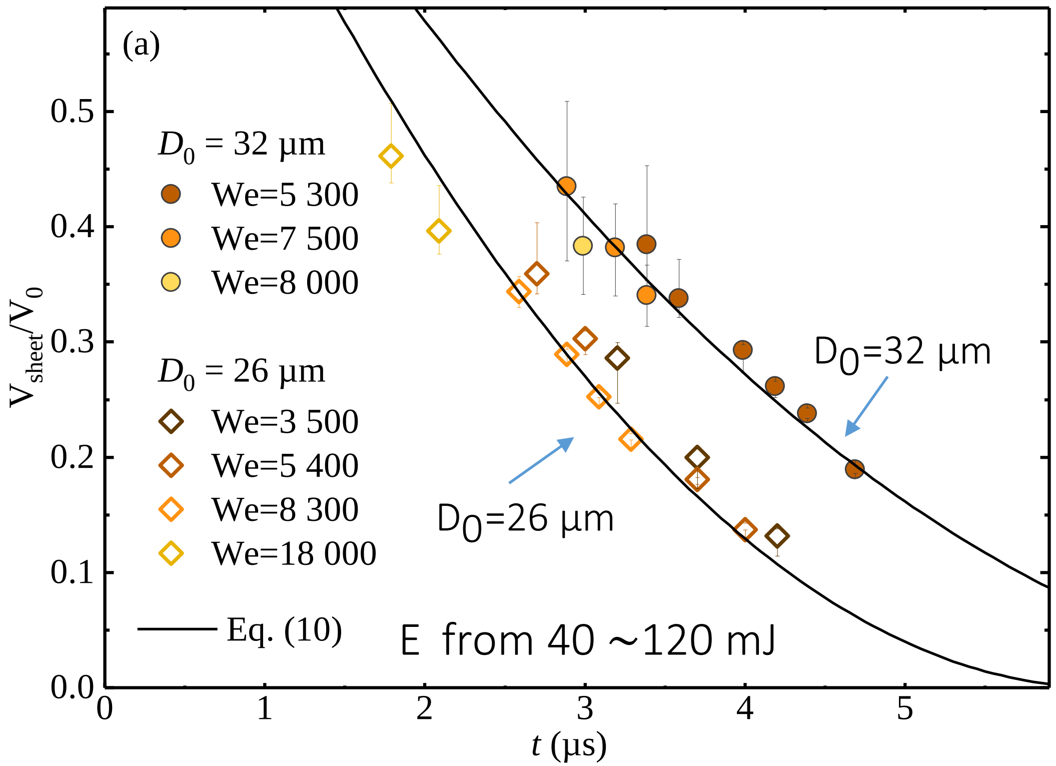




- Morphology of the sheet: volume of sheet? of rim? of fragmentation?

Results of sheet volume

Local thickness profile enables volume determination



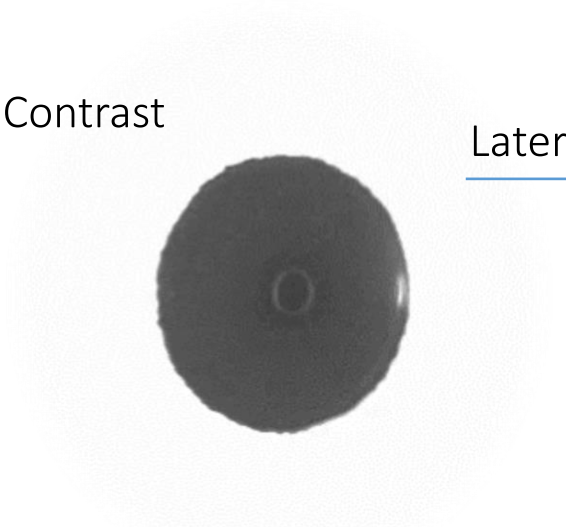
- Over **50%** of tin is **NOT** in the sheet shortly after the impact!
- More loss when waiting longer.
- Volume in the sheet depends on the droplet size.
- Volume in the sheet has weak dependency on the PP energy (in the range of energy measured)
- Data agrees with a zero-fitting parameter model for water-pillar impact.

B. Liu, D. Kurilovich, H. Gelderblom and O.O. Versolato, submitted to Phys. Rev. Applied, 2019.
E. Villermaux and B. Bossa, J. Fluid Mech. (2011), vol.668, pp. 412–435.

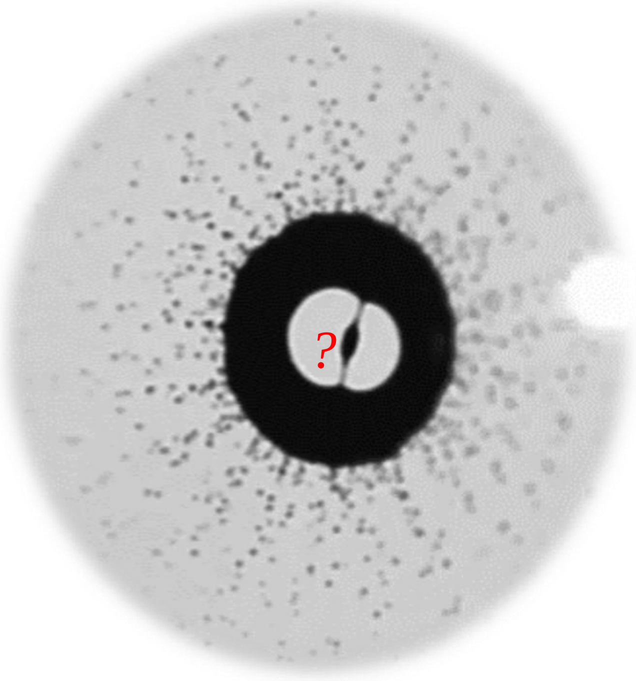
Outlook

- What happens in the sheet center?

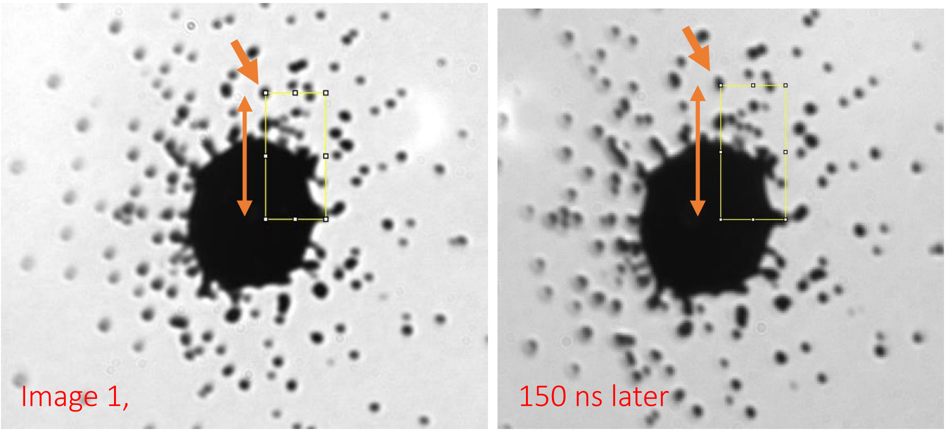
Enhanced Contrast

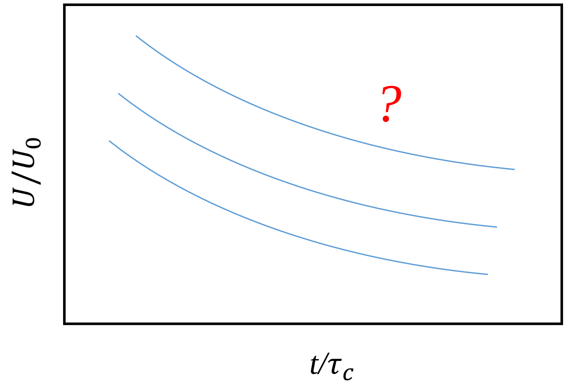


Later time



- Fragmentation & splash (how much? how fast?)

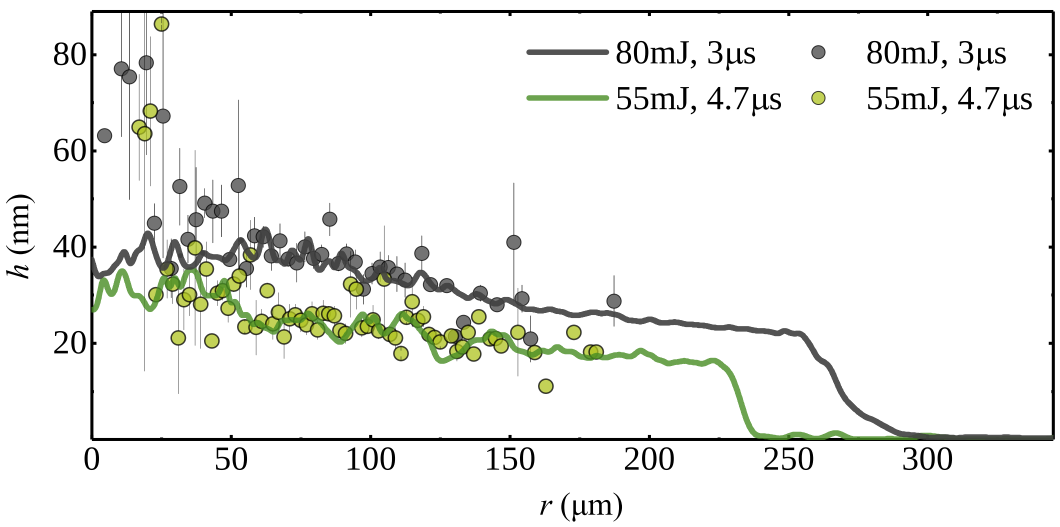


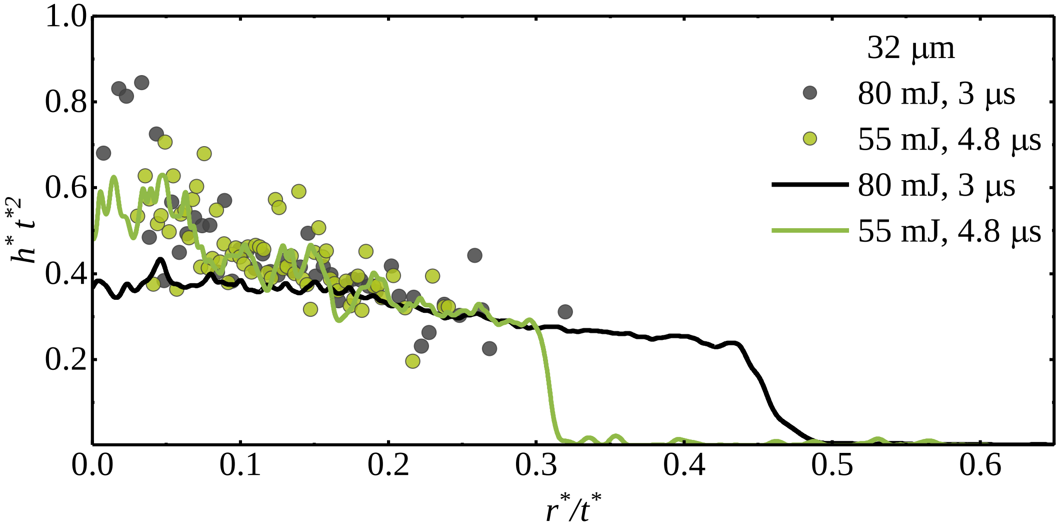


A double shutter model camera will be beneficial (~100 ns interframing)

Self-similar behavior of the thickness evolution

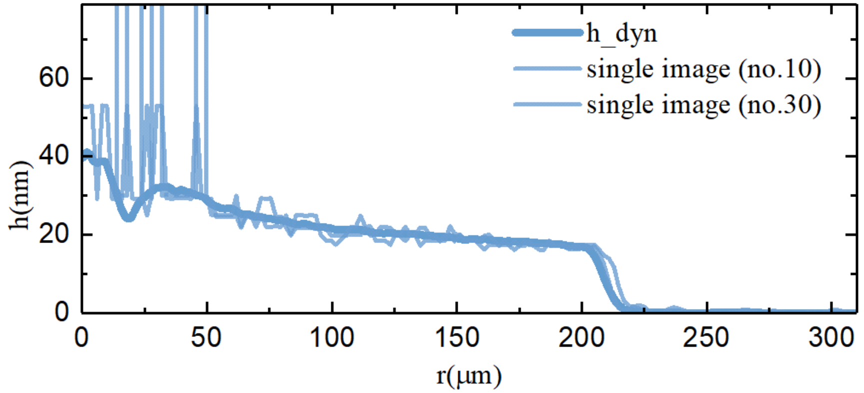
based on an existing model for the droplet-pillar impact

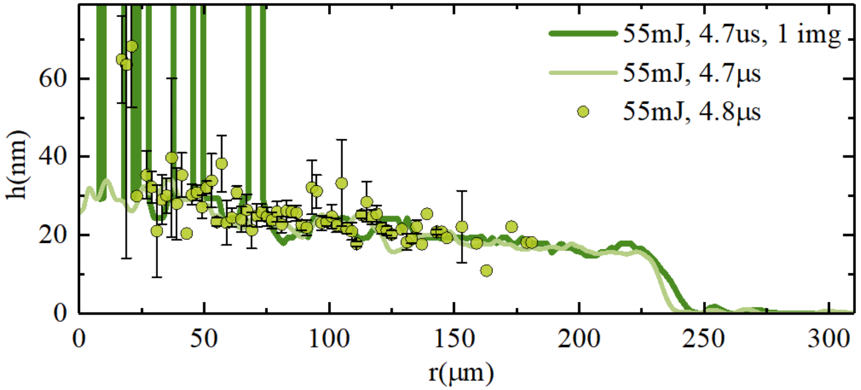


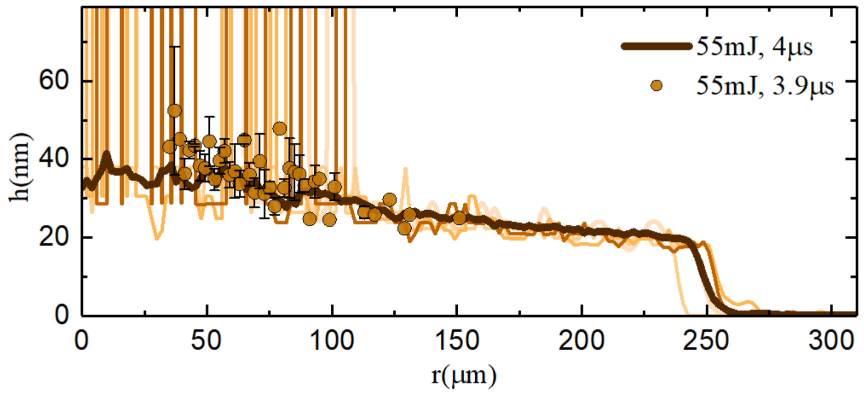


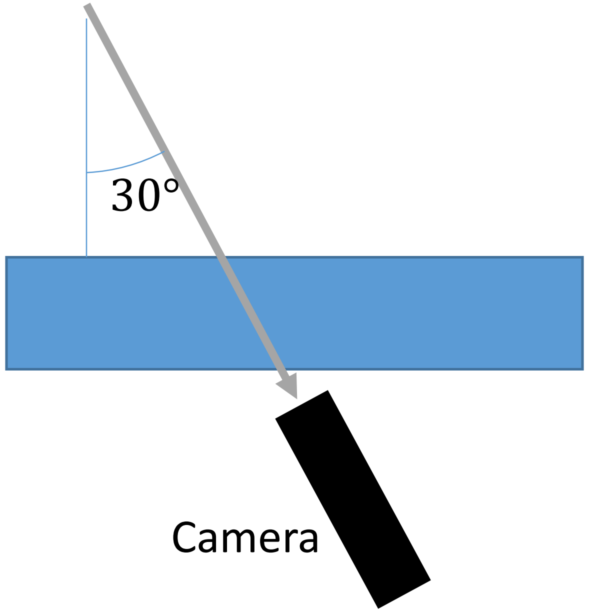
B. Liu, D. Kurilovich, H. Gelderblom and O.O. Versolato, Phys. Rev. Applied, 2019, submitted.

Average of the images for the transmission measurement



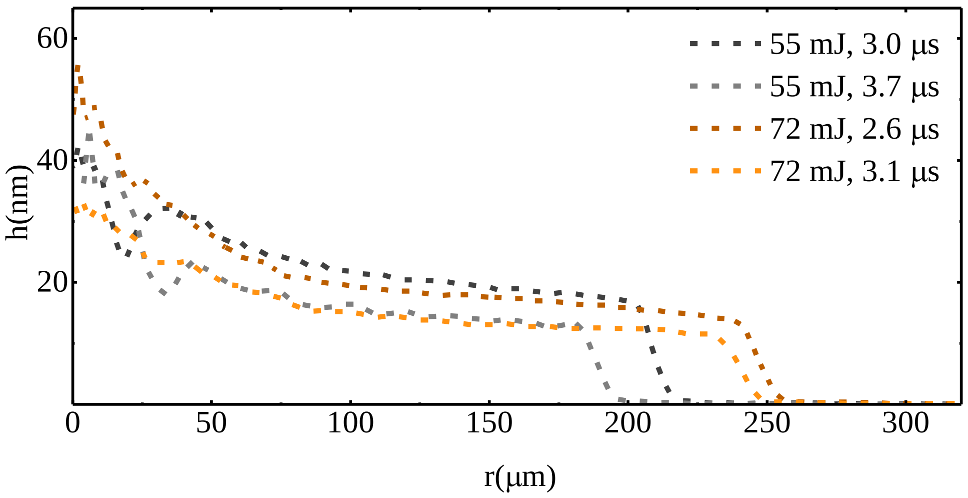


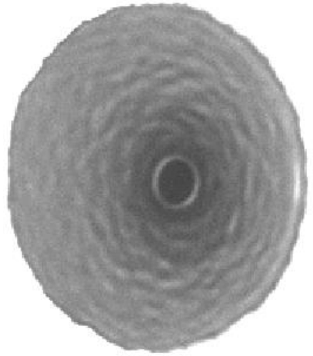


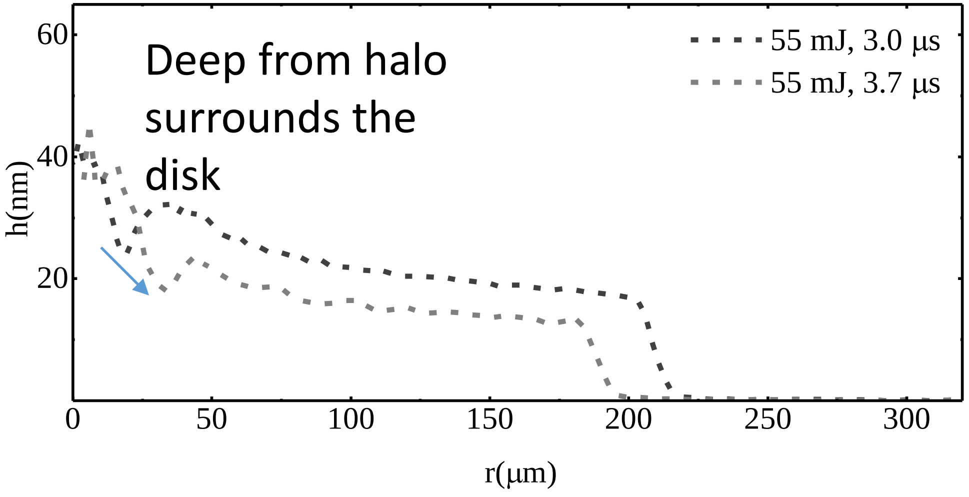


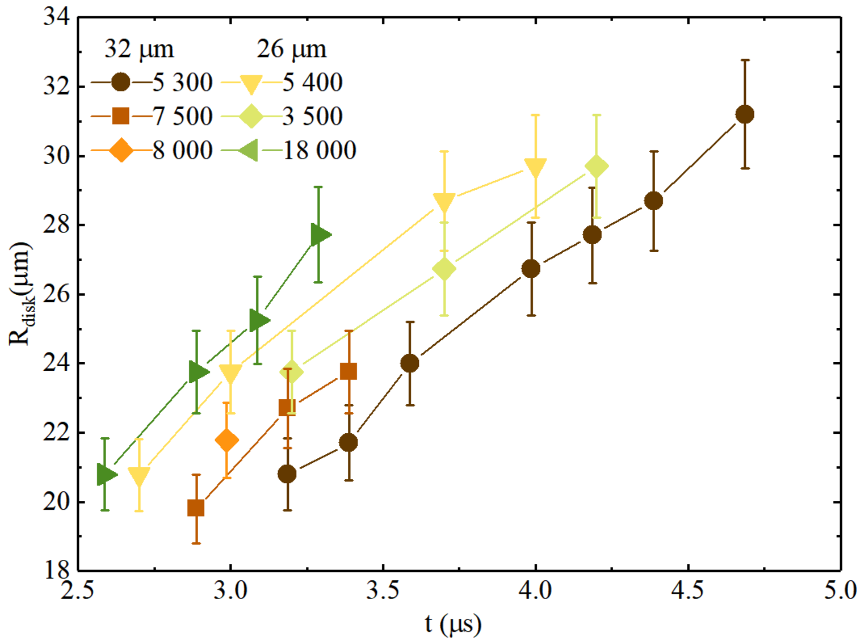
Smaller droplet, transmission measurement

Thinner sheet than the bigger droplet, and disk feature is captured.



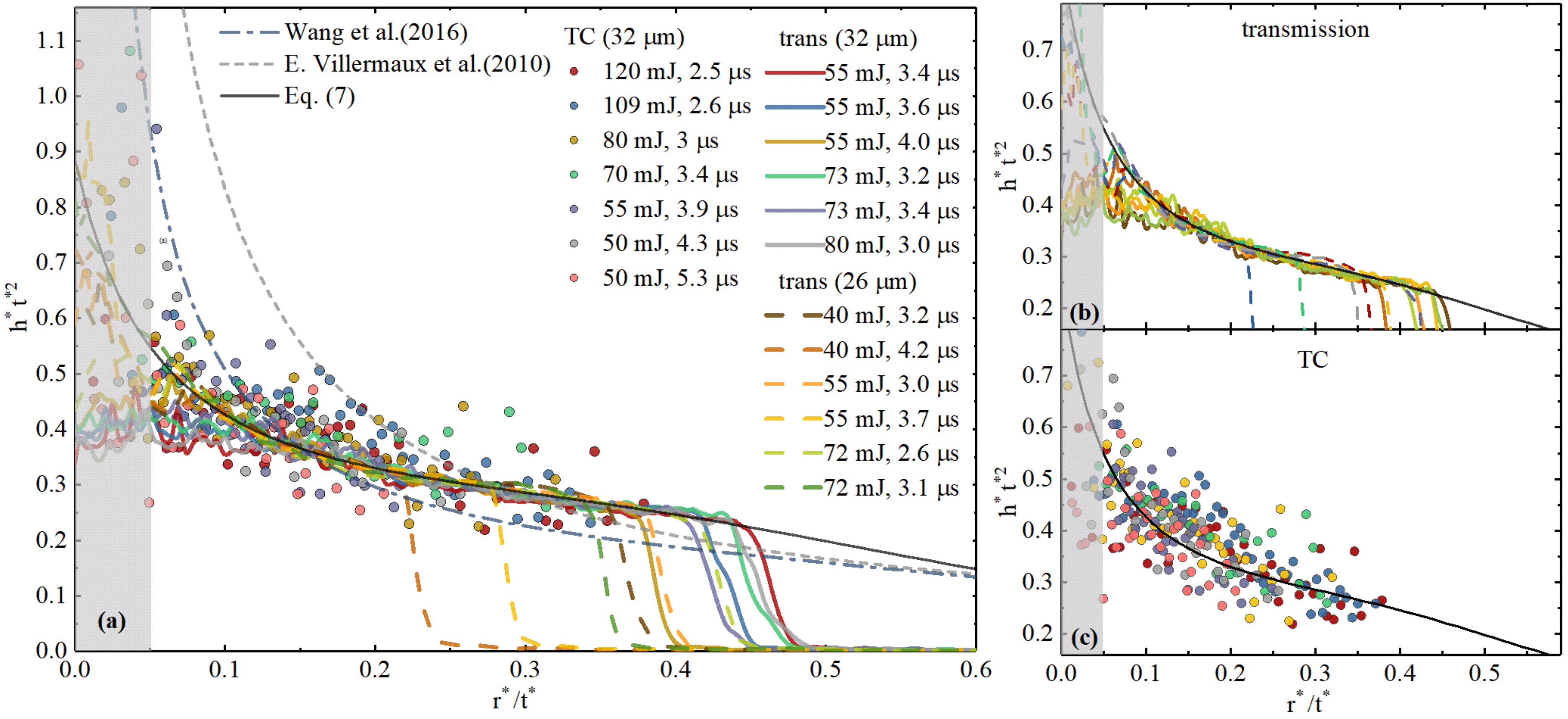




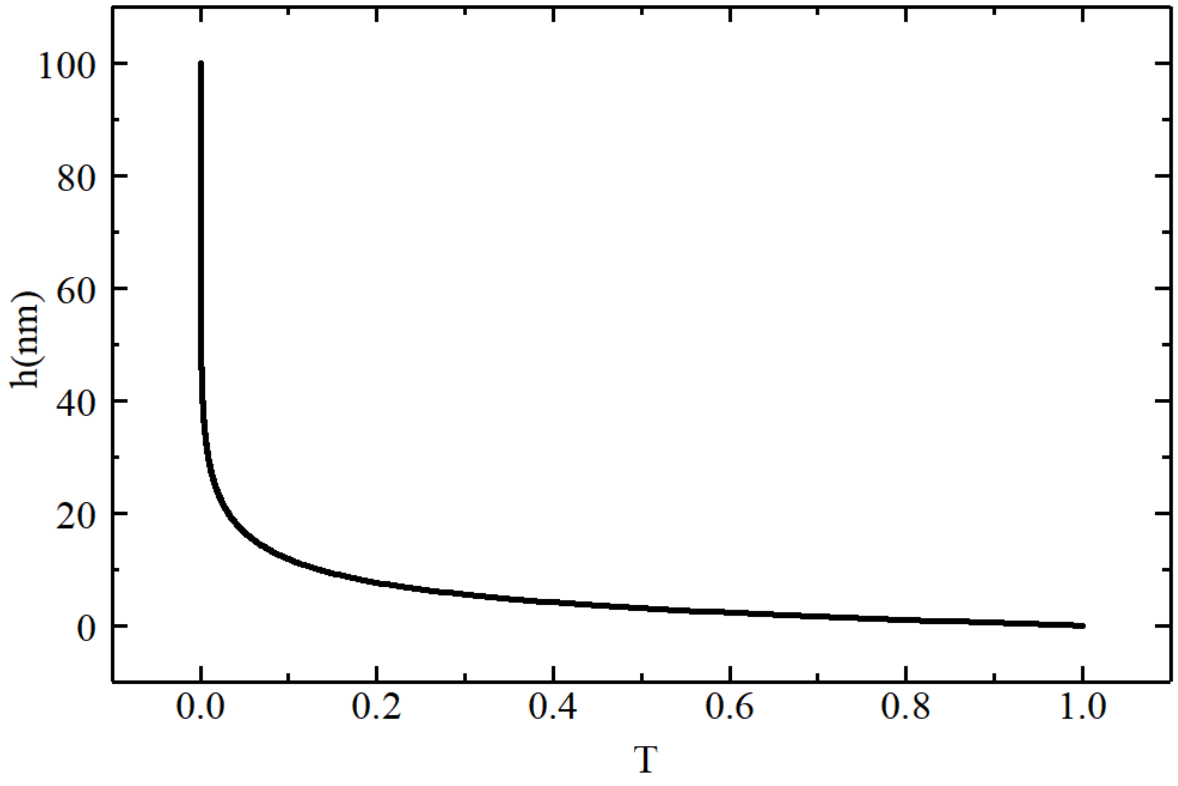


Comparison of thickness profile with water-pillar

The water-pillar case shows difference with laser impact.



Conversion from transmission to the thickness

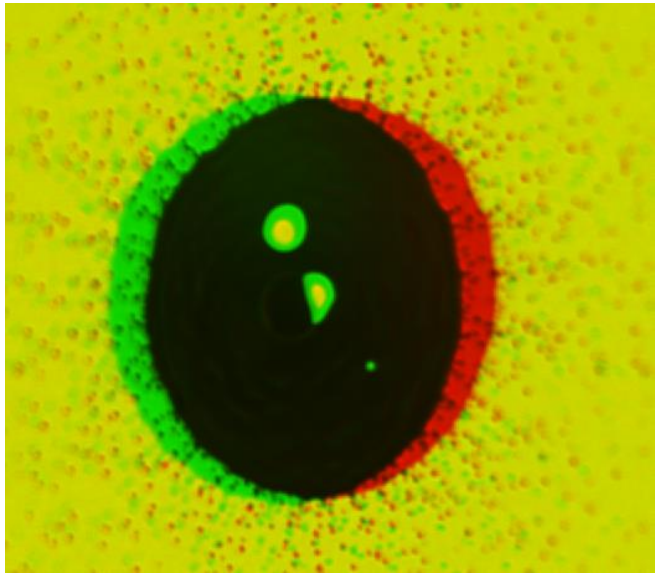


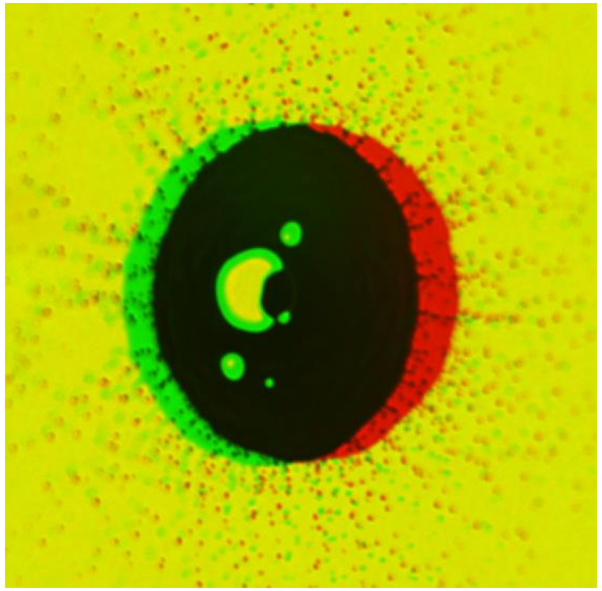
$$T(h_m) = \frac{[(1-R)^2 + 4R\sin^2\delta]e^{-2\beta h_m}}{(1-e^{-2\beta h_m}R)^2 + 4e^{-2\beta h_m}R\sin^2(\delta+\alpha h_m)}, \quad (1)$$

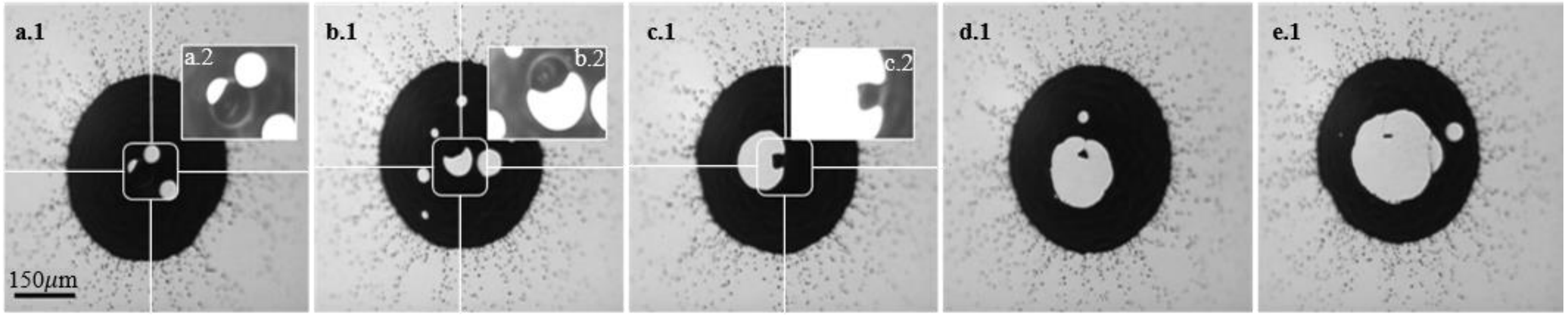
where $R = \left\| \frac{\underline{n}_0 \cos\theta_i - \underline{n}_m \cos\theta_i}{\underline{n}_0 \cos\theta_i + \underline{n}_m \cos\theta_i} \right\|^2$ is reflectance with $\underline{n}_0$ and θ_i presenting the vacuum refractive index and the incident angle, respectively. The wavevector inside the material are given by $\alpha = \mathrm{Re}[k_0\underline{n}_m]$ and $\beta = \mathrm{Im}[k_0\underline{n}_m]$.

Center measurement from hole opening

Hole opening speed is affected by the center disk

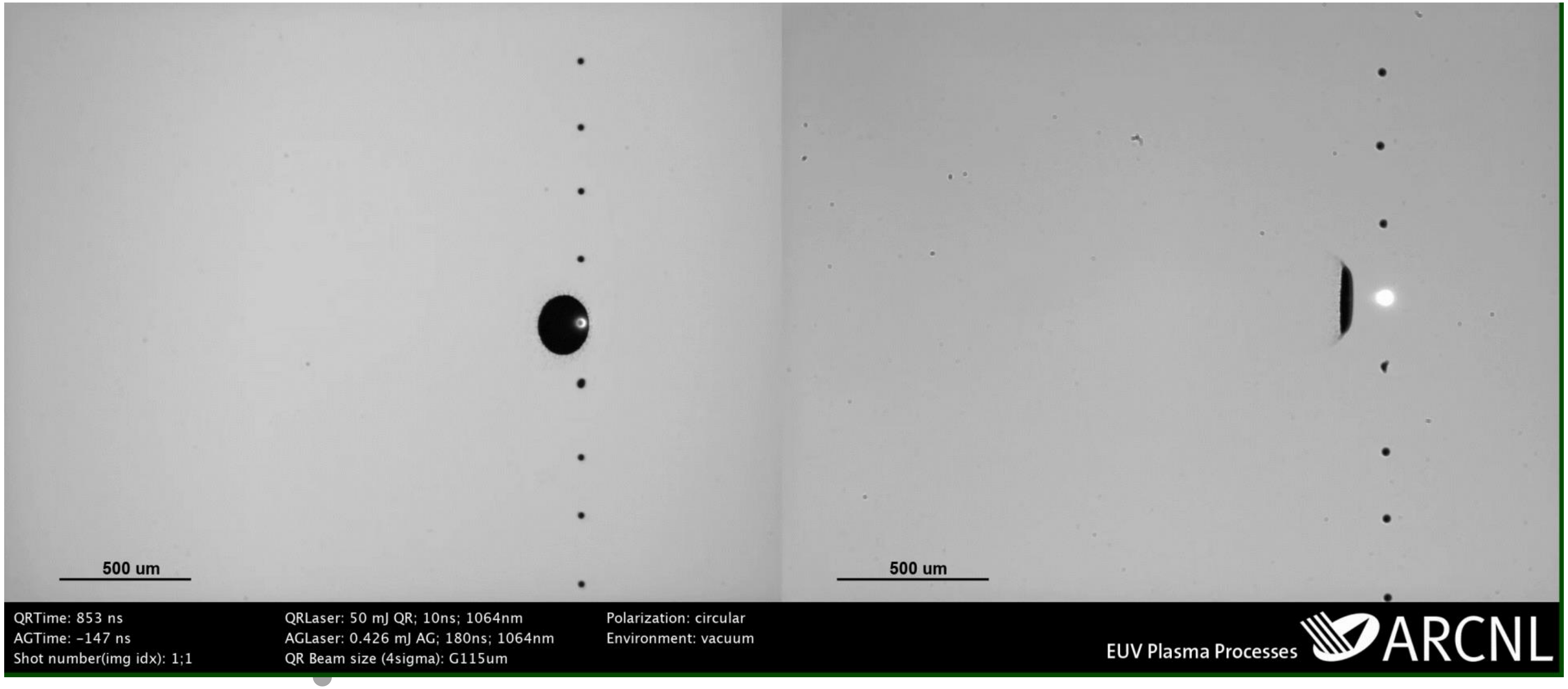




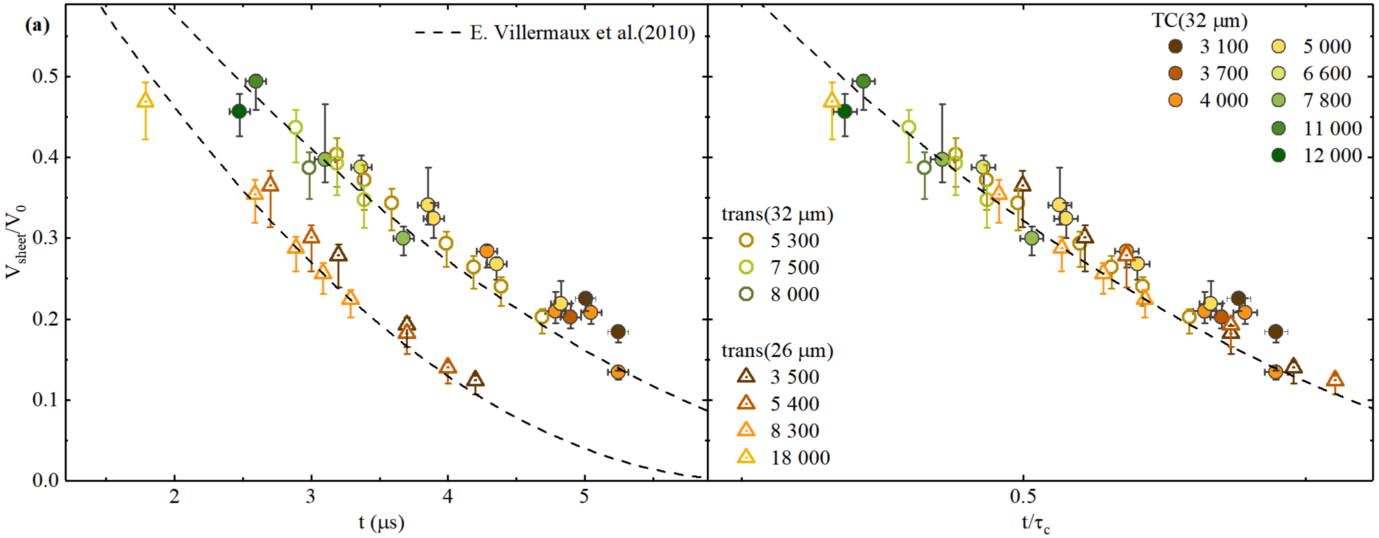


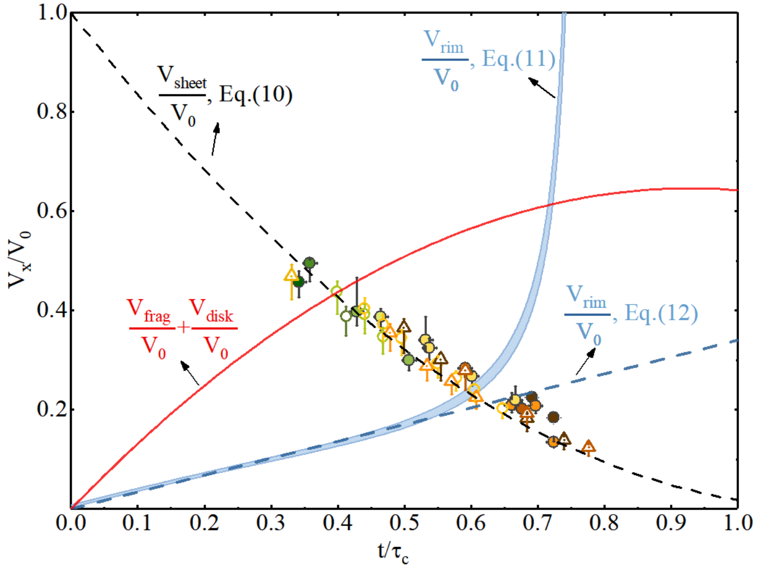
Two-pulses series to the droplet

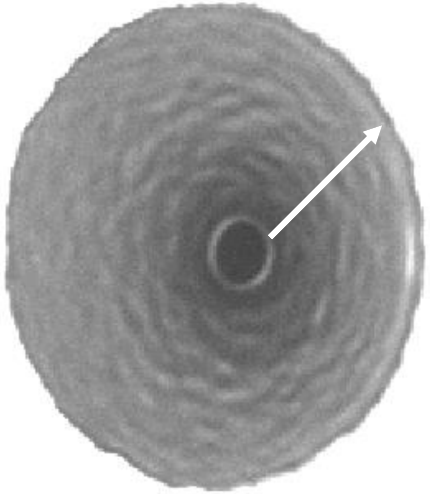
A recent experiments shows the existence of bounding rim and center 'disk'



Collapse of volume ratio for different size droplet







$$V_{sheet} = \int_{R_{disk}}^{R(t)} 2\pi r\, h(r,t)\, dr$$