BGUM 2025

Numerical study of drop impact on concave surface: spread, jet, and splash

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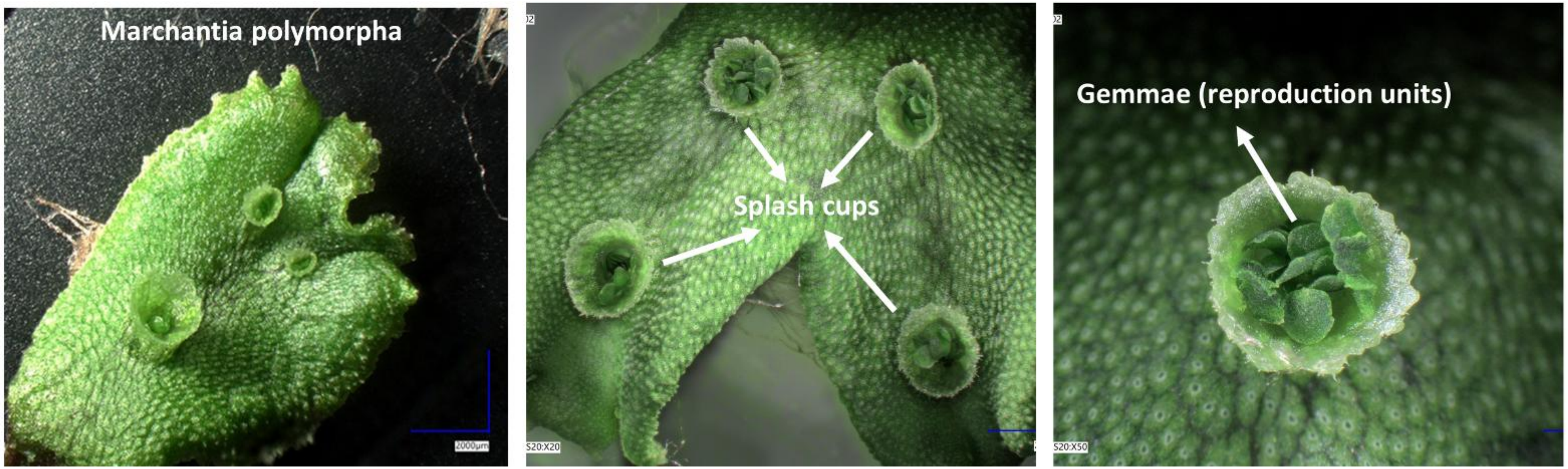
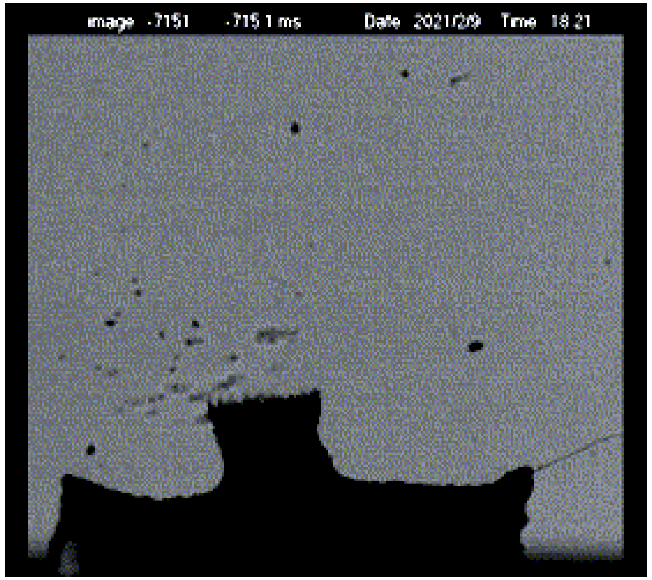
Motivation: reproduction mechanism of plants and fungi



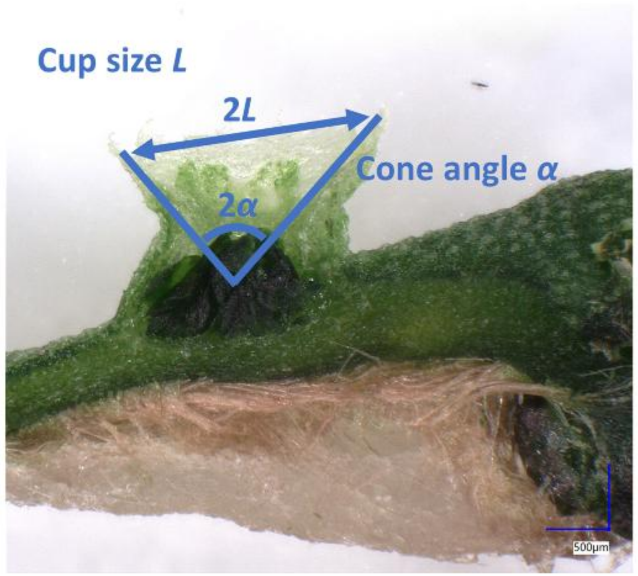
Courtesy of Ana-Maria Bratu & Stéphanie DREVENSEK, LadHyx

Jet formation after the drop impact



Courtesy of Valentin LAPLAUD, LadHyx

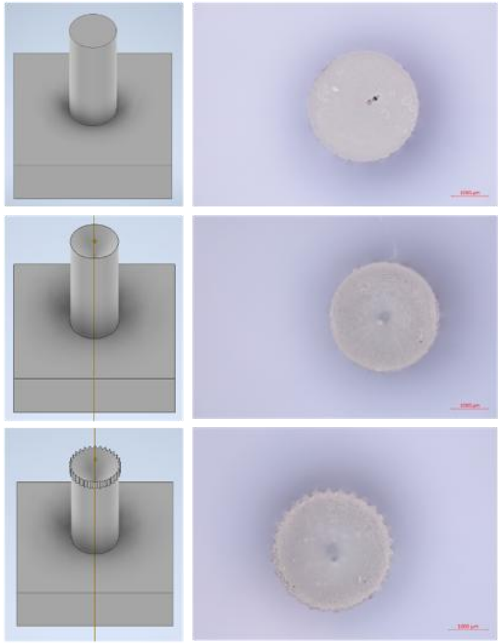
Cross-section of the splash cup



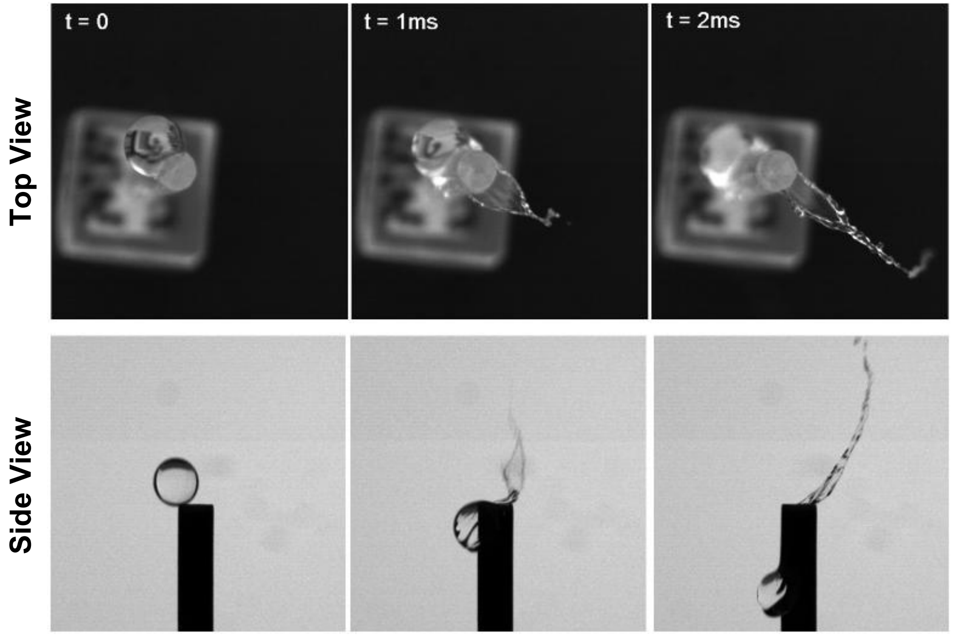
- Raindrops and splash cup diameters are only a few millimeters, yet the resulting jet can propel reproductive units several meters away.
- Hypothesis: concave surface is the key to the jet formation.

Bio mimical experiments and 2D simulations with Basilisk

3D print bio mimic splash cup



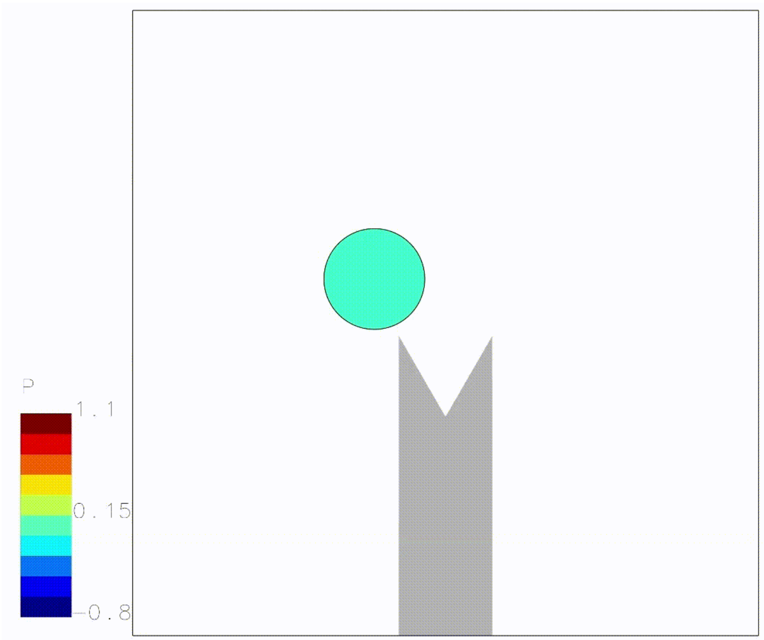
Experimental reproduction of jet formation formation



$$\mathrm{Re} = 1.22 \times 10^4, \mathrm{We} = 781$$

Courtesy of Ana-Maria Bratu, LadHyx

Pressure filed simulation



- The impact process mainly has two stages:

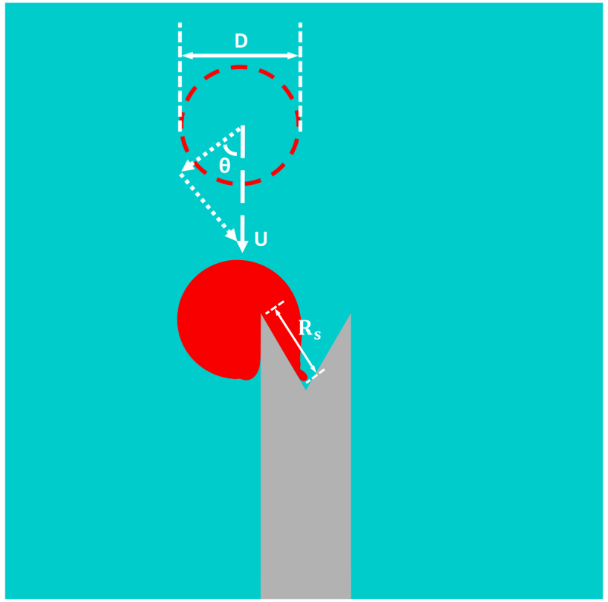
  Stage 1: Drop spreading alongside the solid, then the water converges in the bottom of the cup.

  Stage 2: Water is propelled, leading to the jet formation.

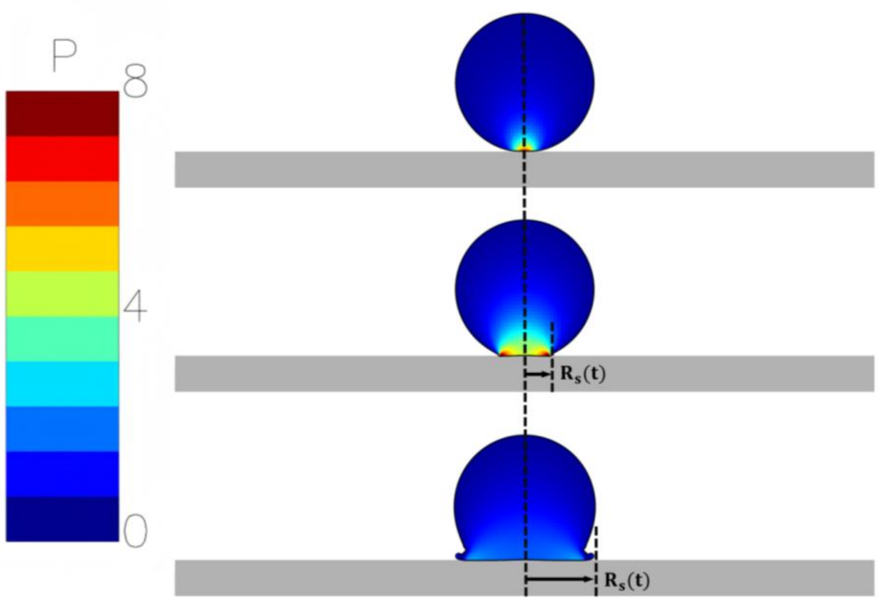
- **The liquid spreading in Stage 1 is important to the jet properties.**

Adaptation of Wagner's classical spreading model

Spreading in Stage 1



Pressure filed and liquid spreading of normal impact



Wagner's theory for early-stage radius of the wet area R_s in normal impact on a flat surface[1]:

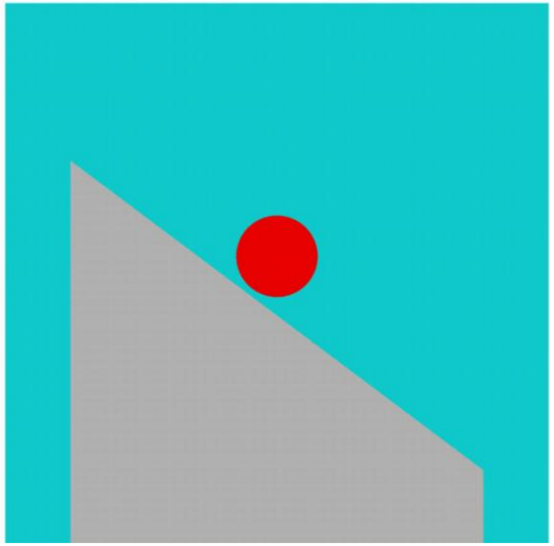
$$R_s^* = \frac{R_s}{D}, \qquad t^* = \frac{Ut}{D}$$

$$\text{for } Re \gg 1 \text{ and } t^* \ll 1, \; R_s^* \sim \sqrt{t^*}$$

[1] *Riboux, G., & Gordillo, J. M. (2014). Experiments of drops impacting a smooth solid surface: A model of the critical impact speed for drop splashing. Physical Review Letters, 113(2), 024507. https://doi.org/10.1103/PhysRevLett.113.024507*

Simplification:

Oblique impact



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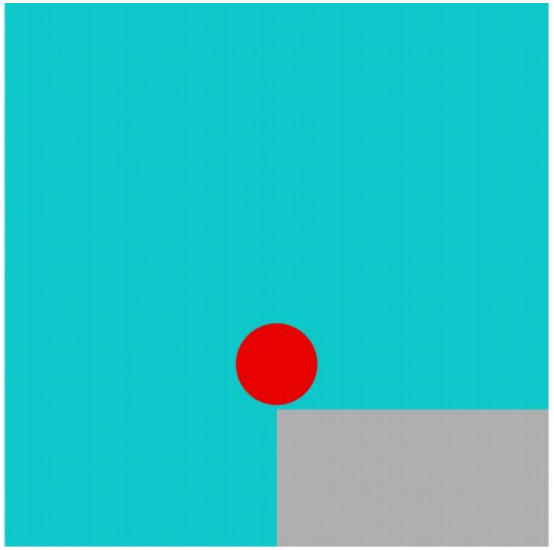
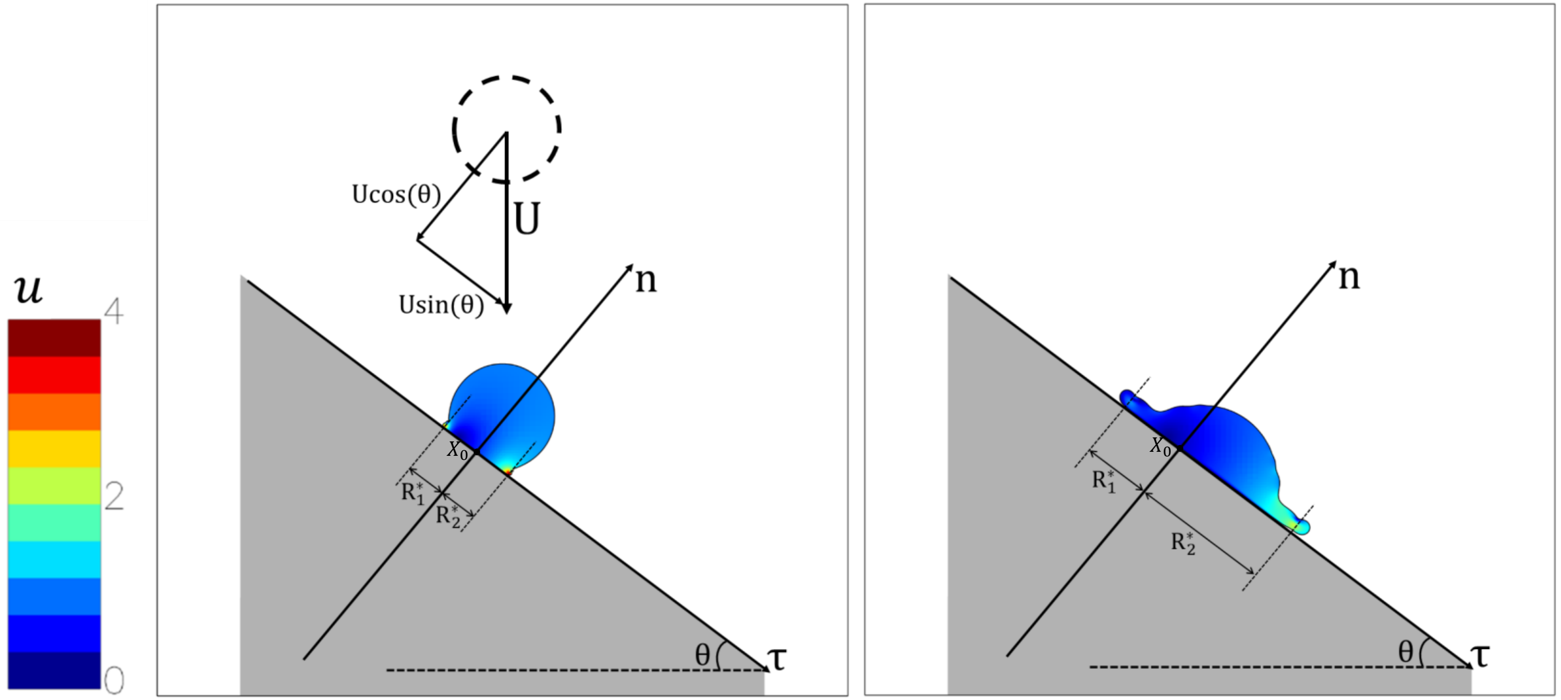
Corner impact



- **Goal: Investigate whether the early-stage spreading of oblique impact and corner impact follows Wagner's theory with appropriate modifications.**

Adaptation of Wagner's spreading model in oblique impact

Estimation of R_s^* based on peak tangential velocity locations



Assumption: Adding a uniform tangential velocity component has negligible effect on the impact dynamics.

$$R_1^* - X_0 \sim -\sqrt{\cos(\theta)\, t^*} + \sin(\theta)\, t^*$$

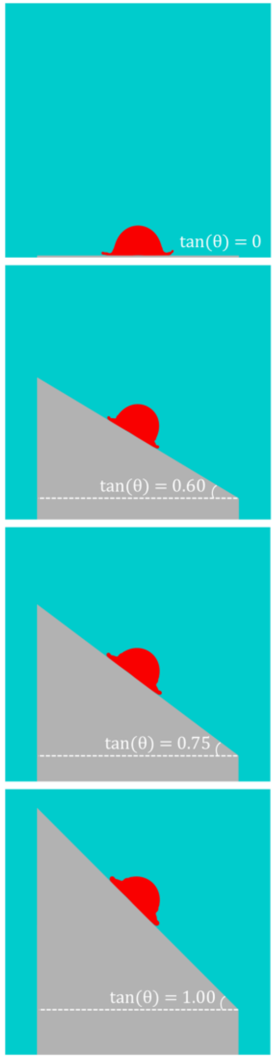
$$R_2^* - X_0 \sim \sqrt{\cos(\theta)\, t^*} + \sin(\theta)\, t^*$$

$$\Longrightarrow$$

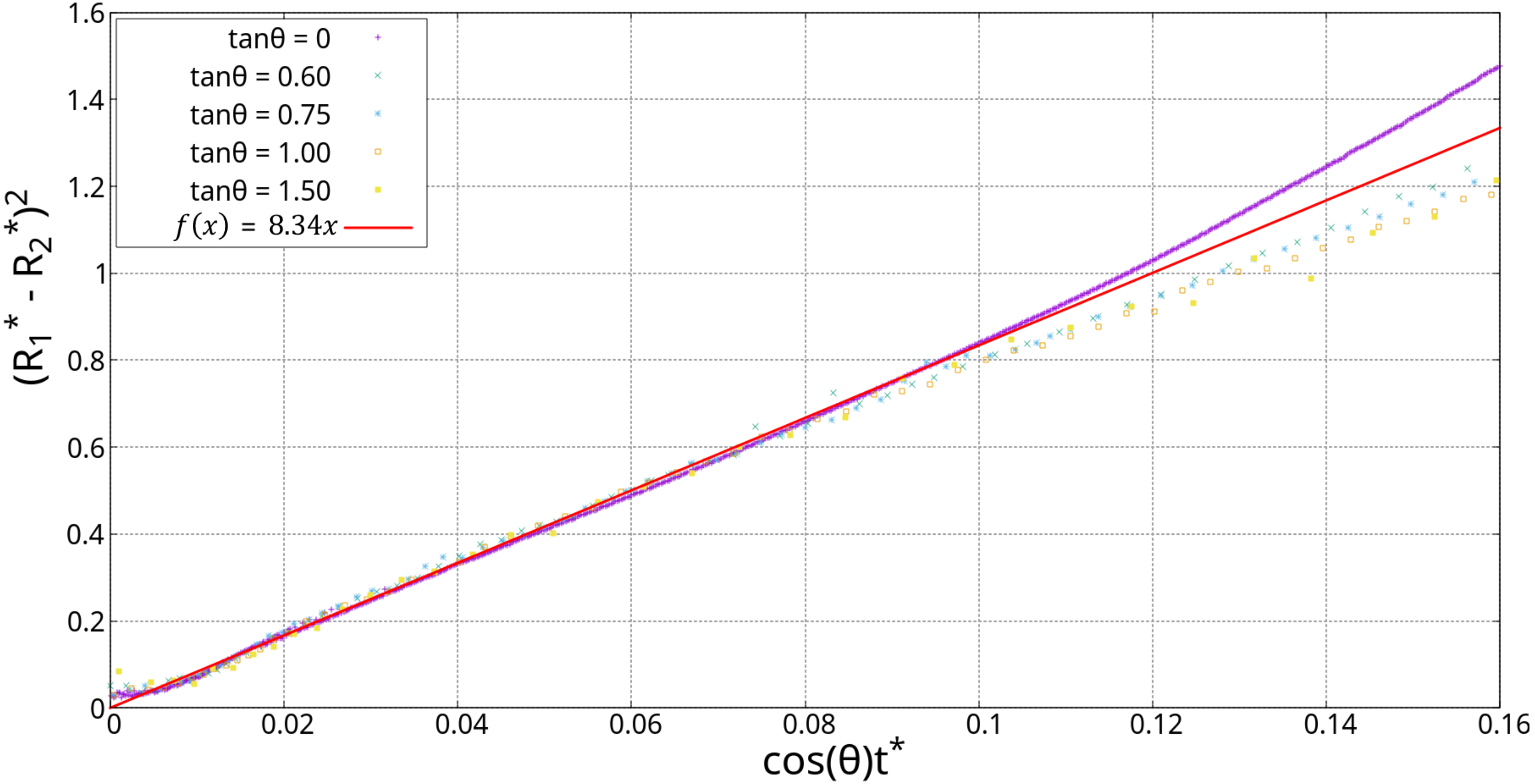
$$(R_1^* - R_2^*)^2 \sim \cos(\theta)\, t^*$$

$$|R_1^* + R_2^*| \sim \sin(\theta)\, t^*$$

Validation of the assumption for oblique impact: effect of geometry

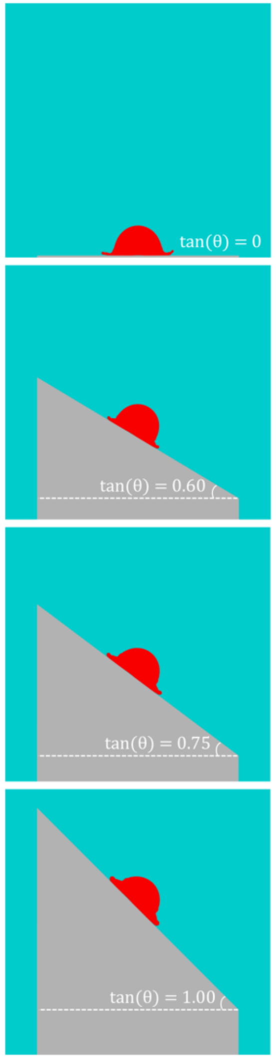


$(R_1^* - R_2^*)^2$ as a function of $\cos(\theta)\, t^*$

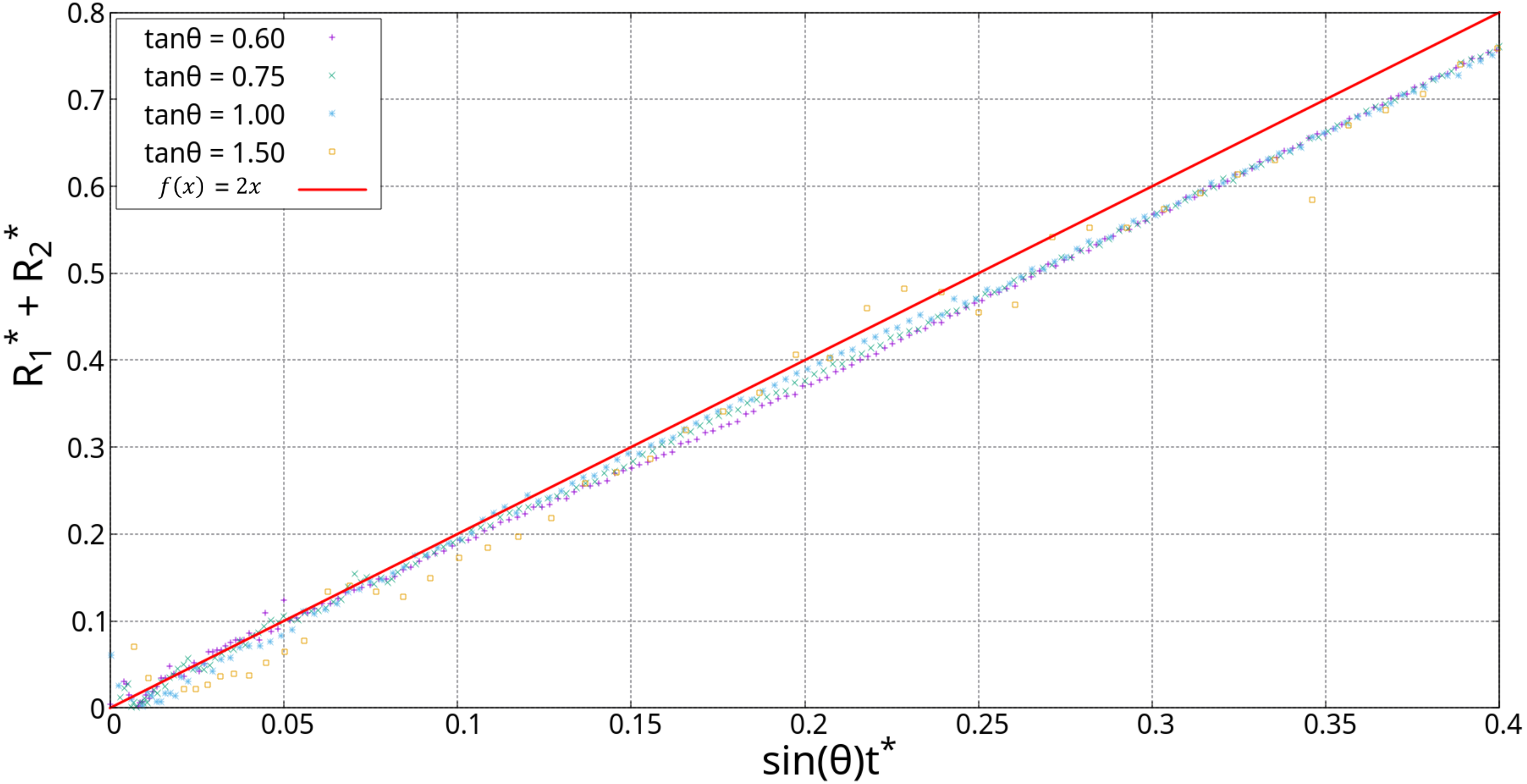


- $(R_1^* - R_2^*)^2$ **is proportional to** $\cos(\theta)\, t^*$ when $t^* \ll 1$.
- Curves collapse for varying surface slopes.

Validation of the assumption for oblique impact: effect of geometry



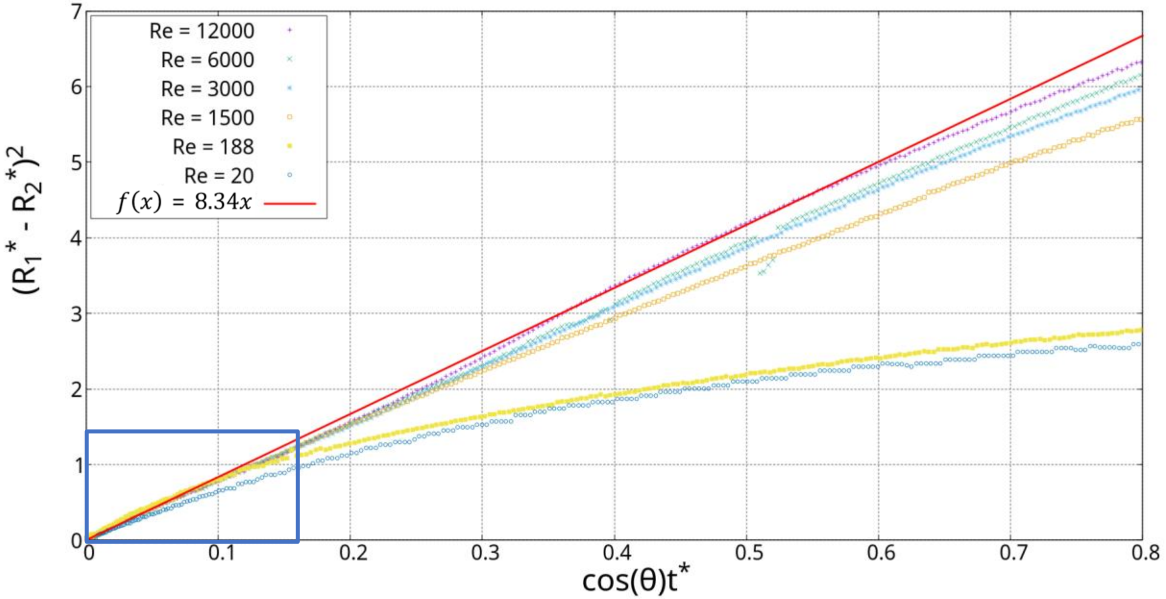
$|R_1^* + R_2^*|$ as a function of $\sin(\theta)\, t^*$



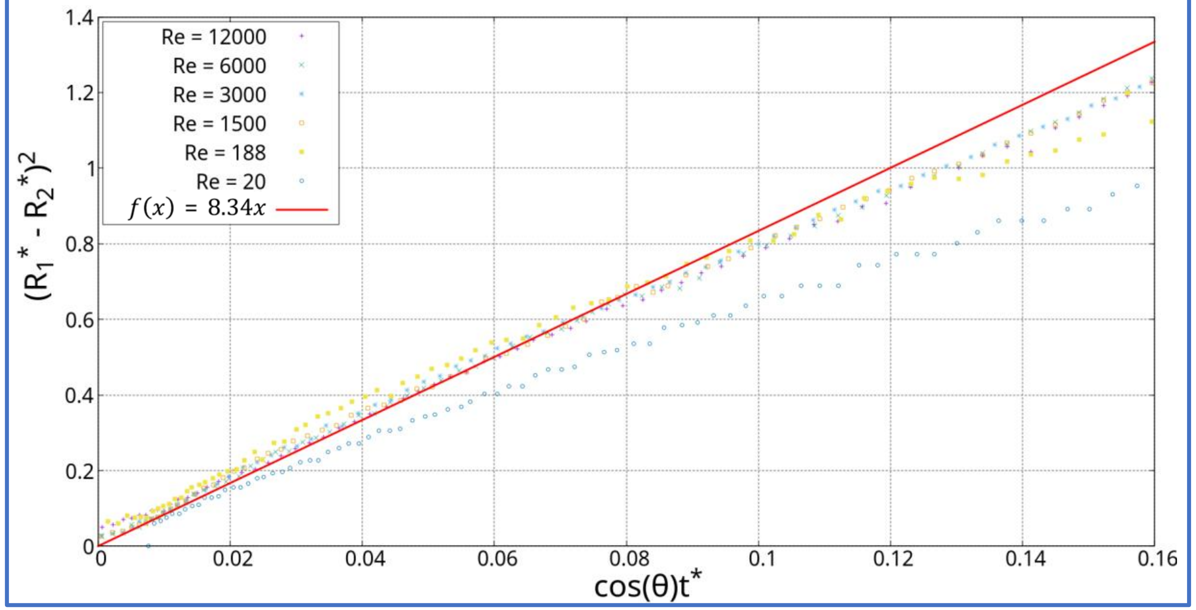
- $|R_1^* + R_2^*|$ **is proportional to** $\sin(\theta)\, t^*$ **for a sustained time interval**.
- Curves collapse for varying surface slopes.

Validation of the assumption for oblique impact: effect of Re

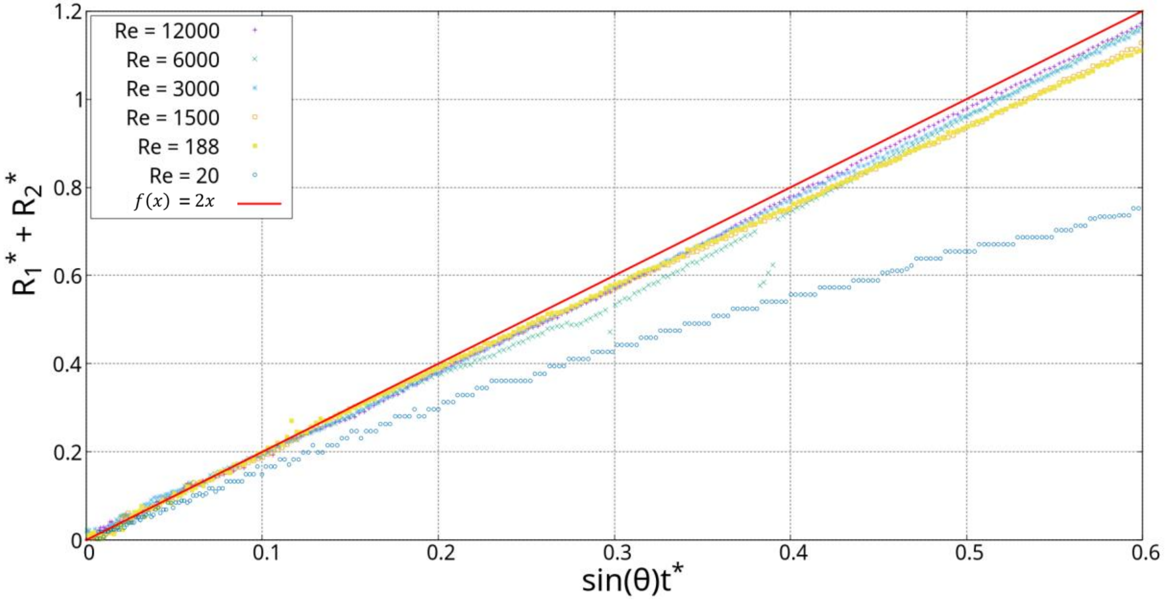
$(R_1^* - R_2^*)^2$ as a function of $\cos(\theta)\,t^*, \tan(\theta) = 0.75$



$(R_1^* - R_2^*)^2$ as a function of $\cos(\theta)\,t^*, \tan(\theta) = 0.75$



$|R_1^* + R_2^*|$ as a function of $\sin(\theta)\,t^*, \tan(\theta) = 0.75$

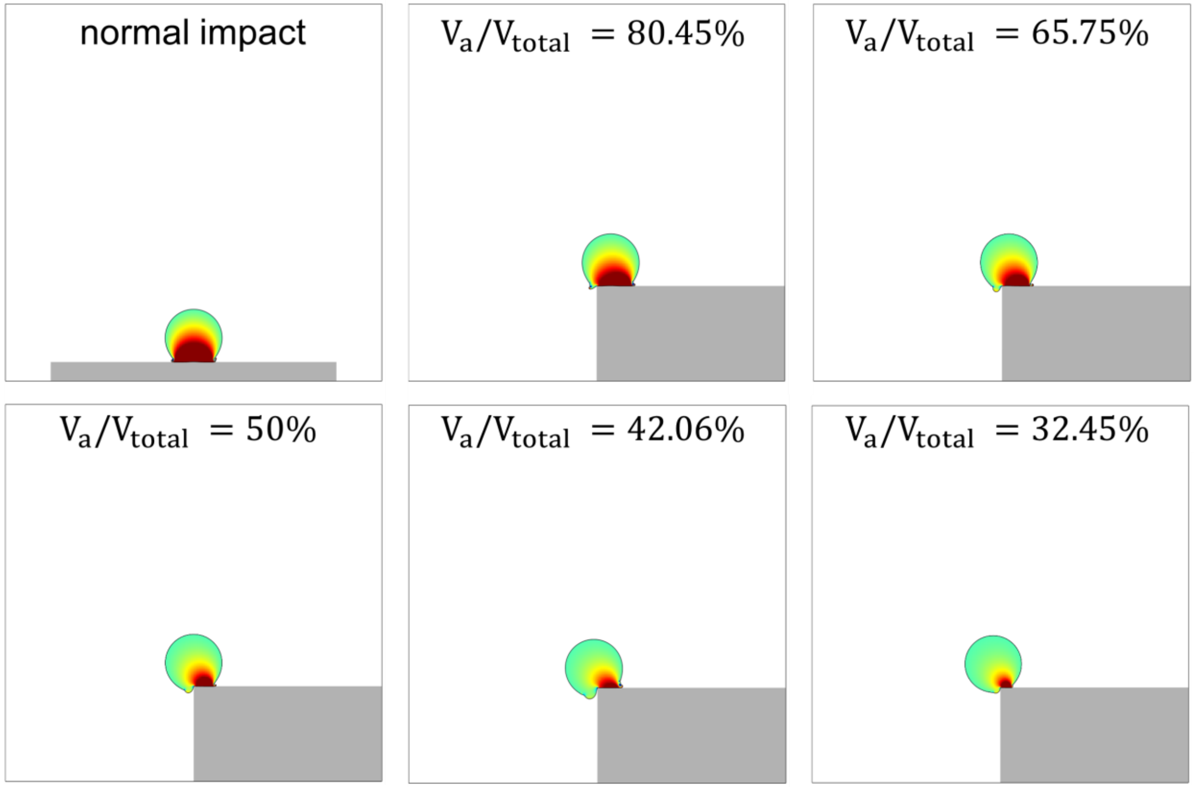


- Consistent with theoretical expectations, in high Re regime $(R_1^* - R_2^*)^2 \sim \cos(\theta)\,t^*$, $|R_1^* + R_2^*| \sim \sin(\theta)\,t^*$.

- **Wagner's spreading theory can be extended to oblique impact.**

Adaptation of Wagner's spreading model in corner impact

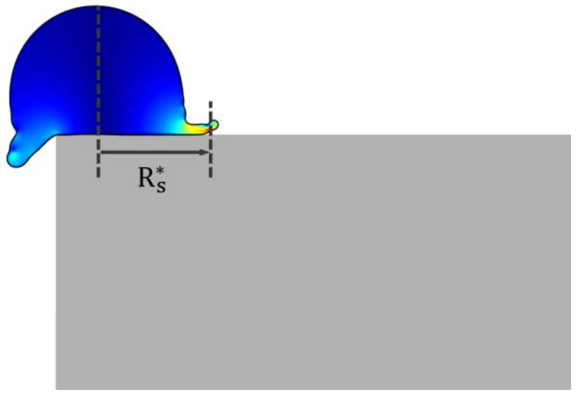
Pressure field for different initial liquid volume above the solid V_a, $t^* = 0.13$



- The length scale of the self-similar pressure field is on the order of R_s [2], and It decreases as V_a/V_{total} decreases.

[2] Gordillo, L., Sun, T.-P., & Cheng, X. (2018). Dynamics of drop impact on solid surfaces: evolution of impact force and self-similar spreading. *Journal of Fluid Mechanics*, 840, 190–214. doi:10.1017/jfm.2017.90

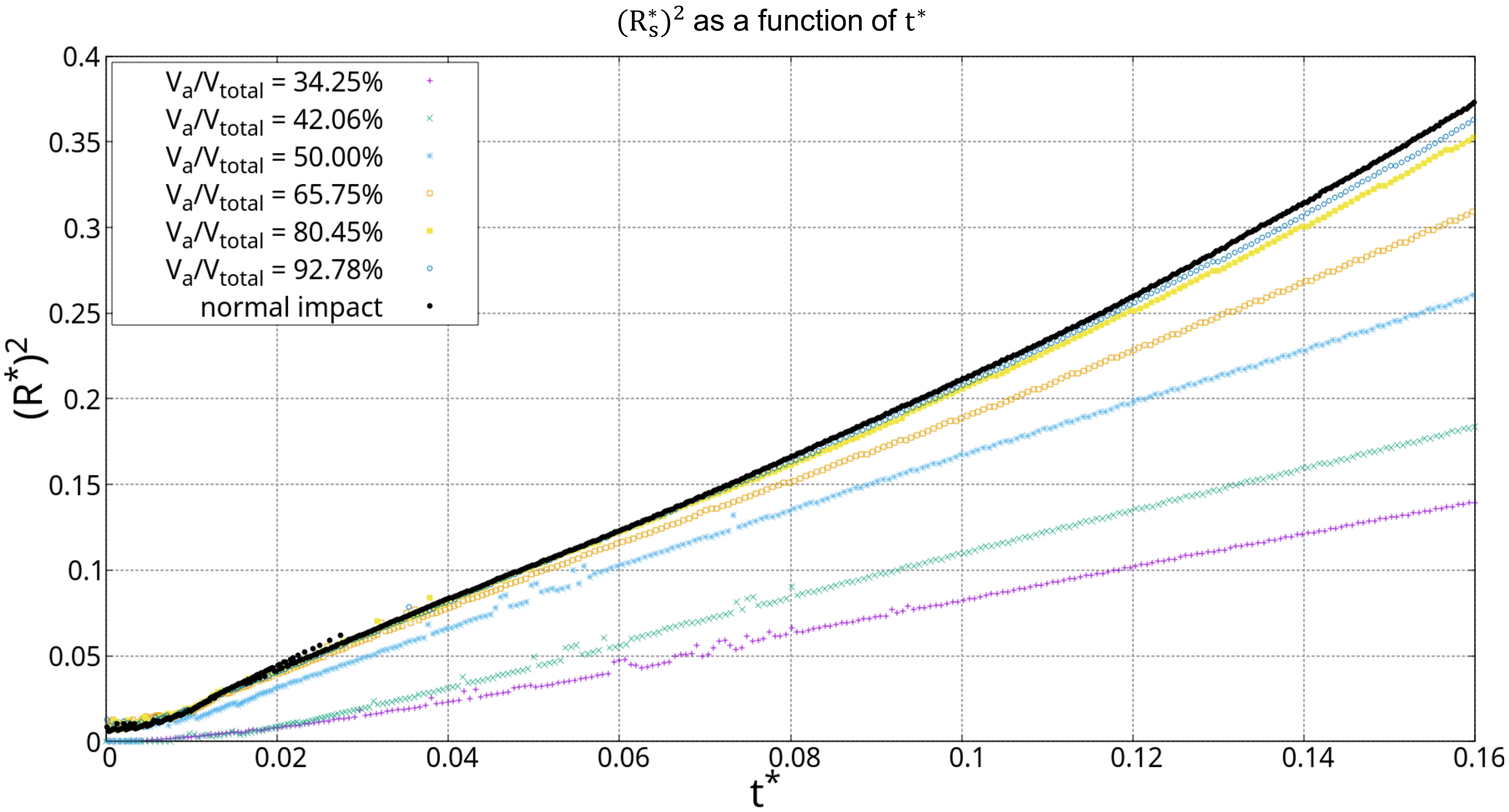
Estimation of R_s^* based on peak horizontal velocity locations



Assumption: An effective impact diameter D_e positively correlated with V_a/V_{total} is introduced such that the following equation holds.

$$D_e \leq D, \qquad R_s^* \sim \sqrt{\frac{D_e}{D} t^*} \leq R^*_{s,\,normal} \;\Rightarrow\; (R_s^*)^2 \sim t^*$$

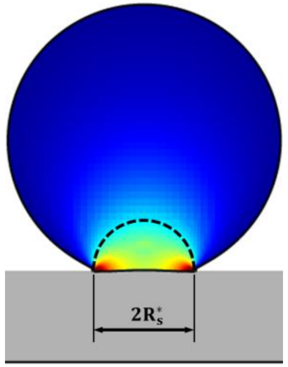
Validation of the assumption for corner impact



- $(R_s^*)^2$ **is proportional to** t^* when $t^* \ll 1$.
- For large V_a/V_{total}, R_s^* closely follows the normal impact case, the corner effect is negligible when $t^* \ll 1$.
- R_s^* grows more slowly over time in cases with lower V_a/V_{total}.

Liquid pressure near the self-similar region

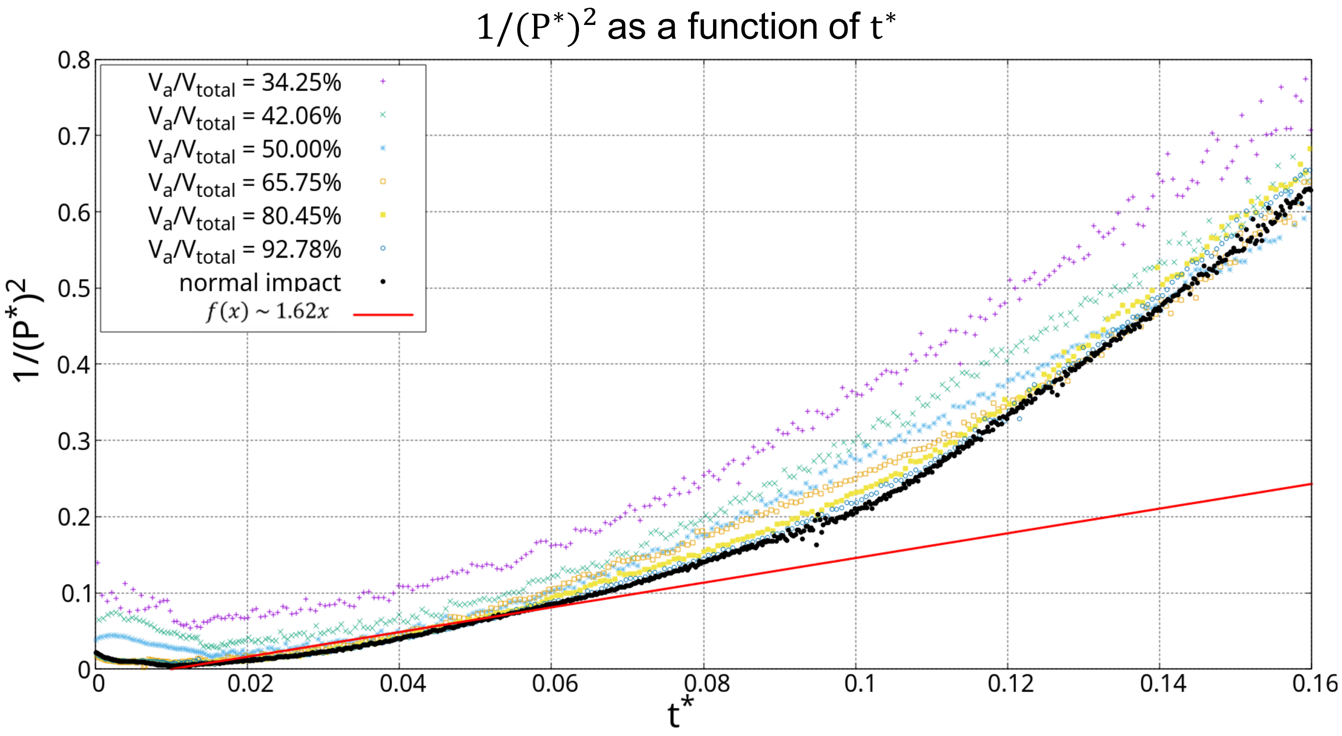
Balancing the pressure force with the momentum entering the self-similar region.



$$P^* \cdot \pi(R_S^*)^2 = \frac{d}{dt^*}\frac{2}{3}\pi(R_S^*)^3$$

$$P^* = 2\frac{dR_S^*}{dt^*} \sim \sqrt{\frac{D_e/D}{t^*}} \Rightarrow \frac{1}{(P^*)^2} \sim \frac{D}{D_e}t^*$$

when $t^* \ll 1$



- At the very early stage ($t^* \ll 1$) of impact, $(P^*)^2$ **is proportional to** t^* for most cases.
- A smaller V_a/V_{total} leads to a lower pressure.
- When V_a/V_{total} is small enough ,the hydrodynamic influence outside the impacted region becomes non-negligible.
- **Wagner's spreading theory can be extended to corner impacts. But the pre-factor D_e requires further quantitative analysis.**

Conclusions

- Generalization of Wagner's theory to oblique and corner impact.

- Oblique impacts with different surface slopes follow the same spreading mechanism. After rescaling time with cos/sin, $\mathrm{R_s^*}$ approximately collapse onto a single curve.

- For corner impacts, reducing $\mathrm{V_a}$ has a similar effect to using a smaller droplet, resulting in decreased $\mathrm{R_s^*}$ and lower pressure in the impact zone.

Outlooks

- Comprehensive scaling and quantitative analysis of $\mathrm{D_e}$.
- Simulate the fluid forces acting on the wet area and compare the results with Wagner's solution.
- Initiate the study of oblique impacts on solids with corners.

Thank you very much for your listening and suggestions.