Jet and film

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The problem

A thin liquid jet collides with a soap film. Depending on some appropriate parameters, the jet can either pass through the film, or flow into it creating interesting shapes. Explore and explain this interaction and the shapes being created.

Previous investigations

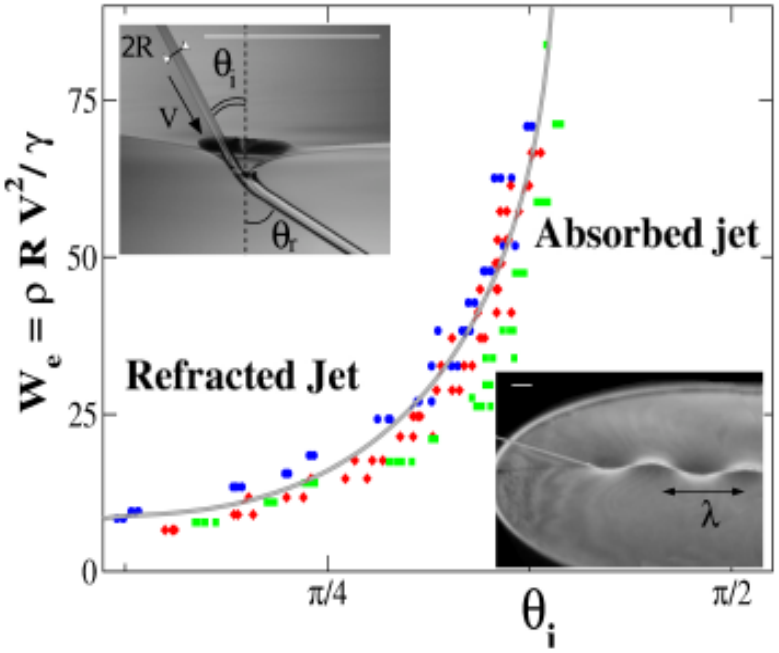


FIG. 1. Impact diagram displaying the refraction and absorption regions. Each point corresponds to the inset of the transition obtained for jet radii $R = 140$, 200 and 270 μm (circles, diamonds and squares respectively). The dashed line is a guide to the eyes. In the representative pictures, white scale bars have a length of 5 mm.

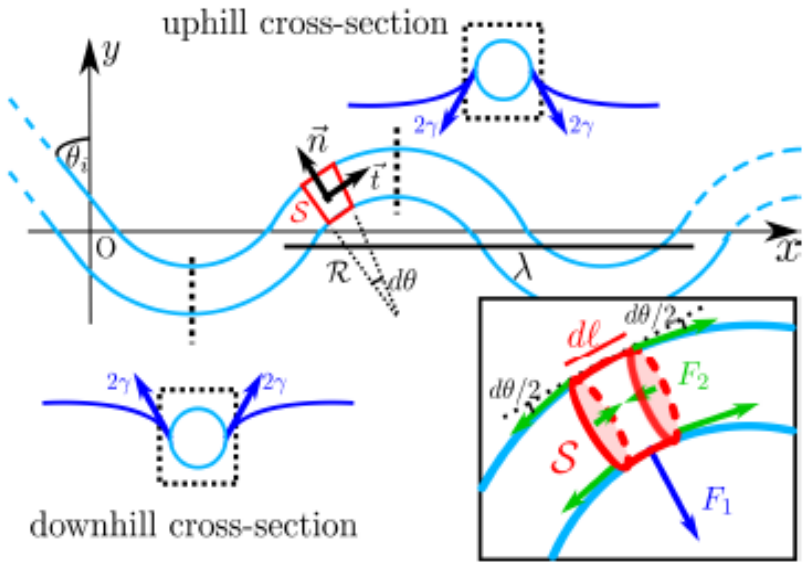
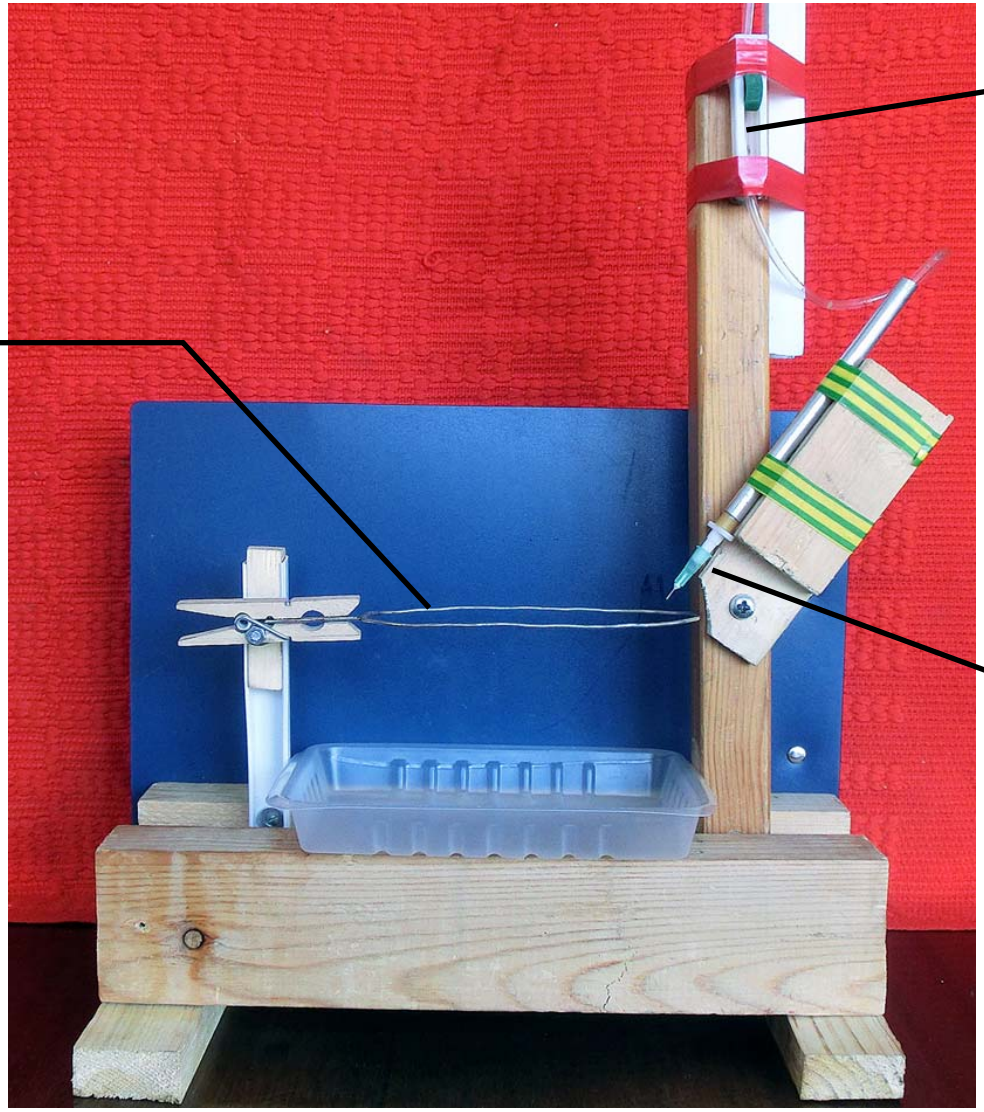


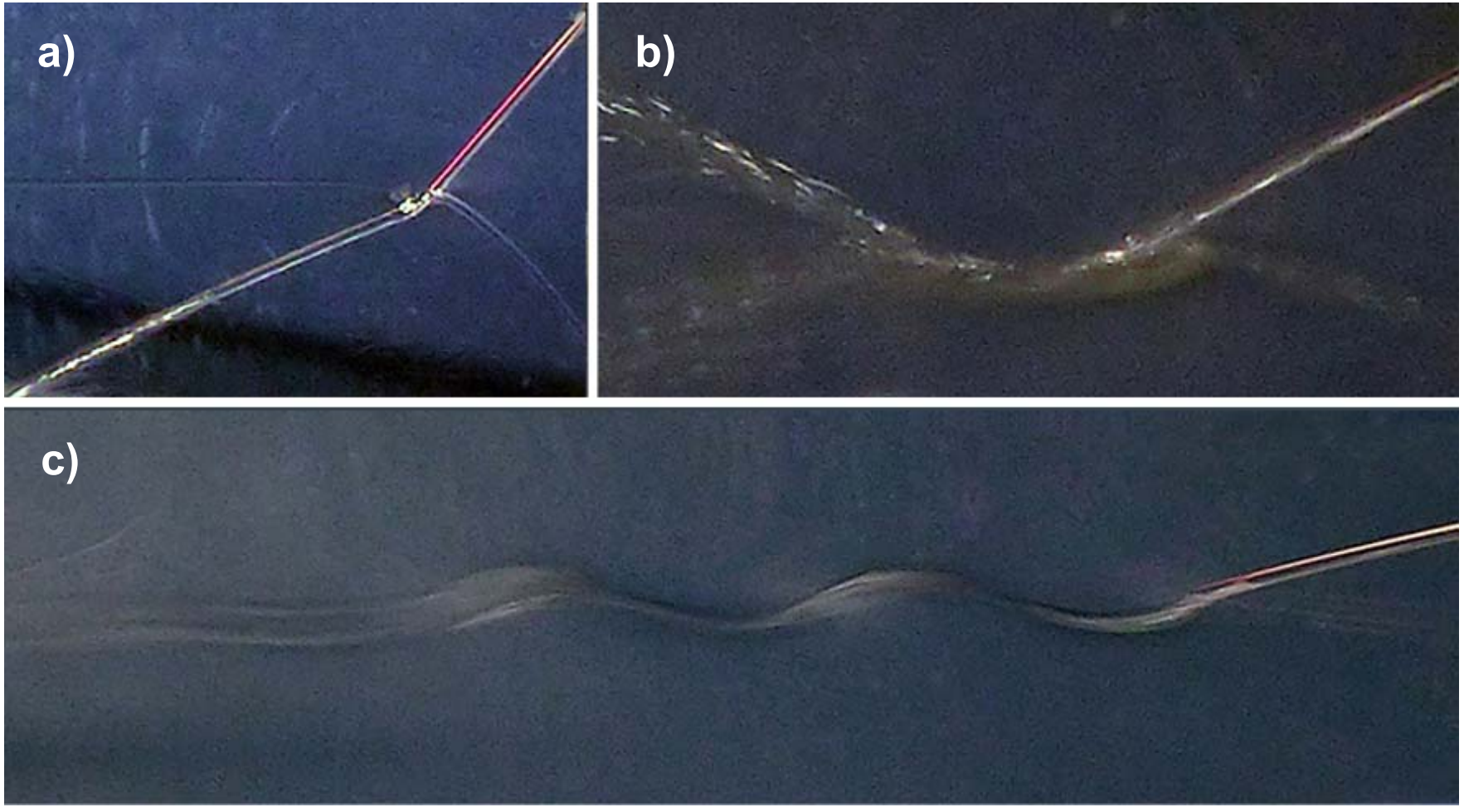
FIG. 4. Side view representation of the undulating jet (light blue) inside the film (dark blue). Two cross-sections are displayed showing a reasonable shape of the film-jet contact. Momentum balance equation is performed on a closed system $\mathcal{S}$. Insert: zoom over the system.

Kirstetter G., Raufaste C., Celestini F. (**2012**) "Jet impact on a soap film". *Phys. Rev. E*, **86**, 036303.

Experimental setup

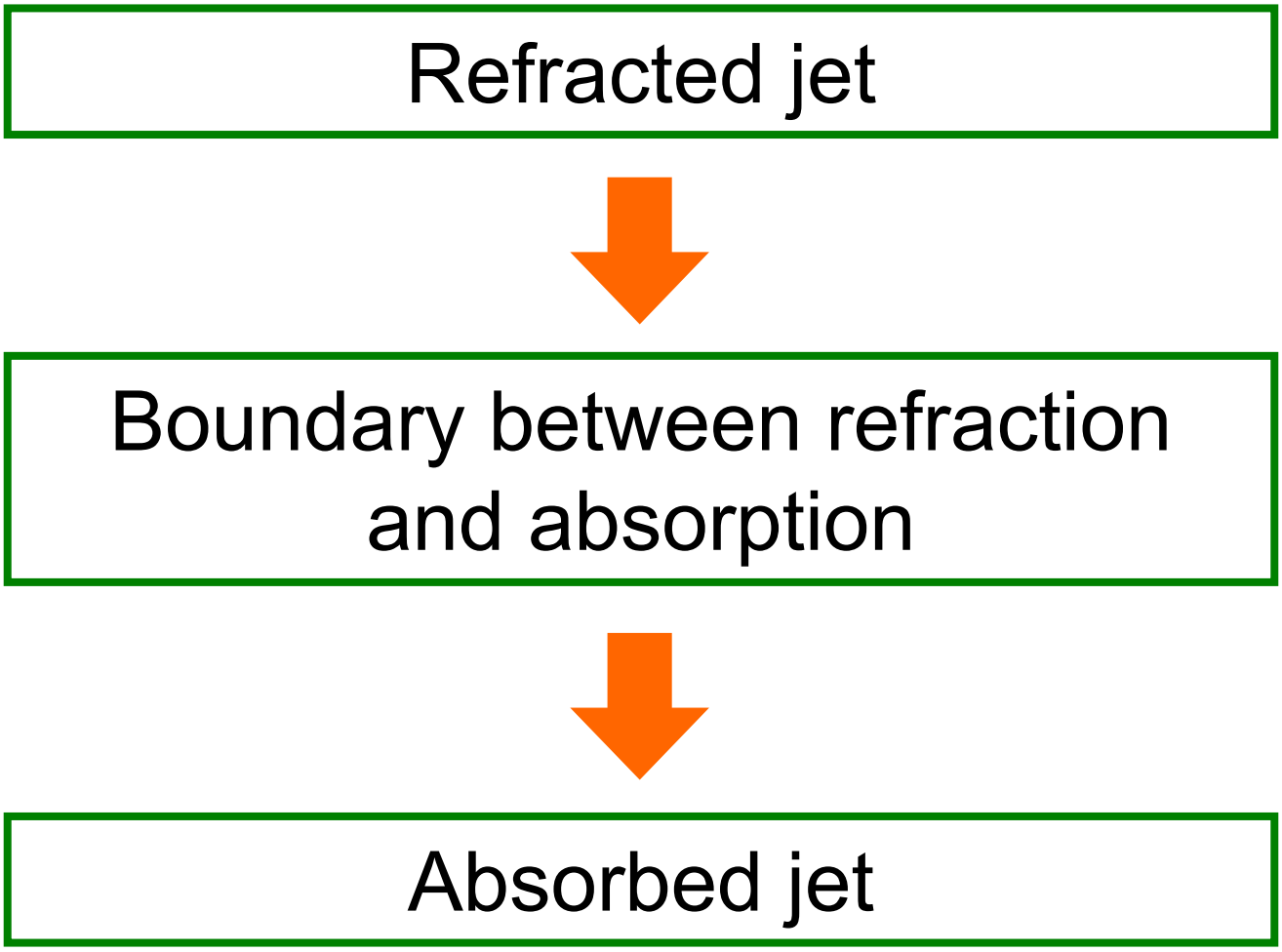


Three regimes of jet-film interaction

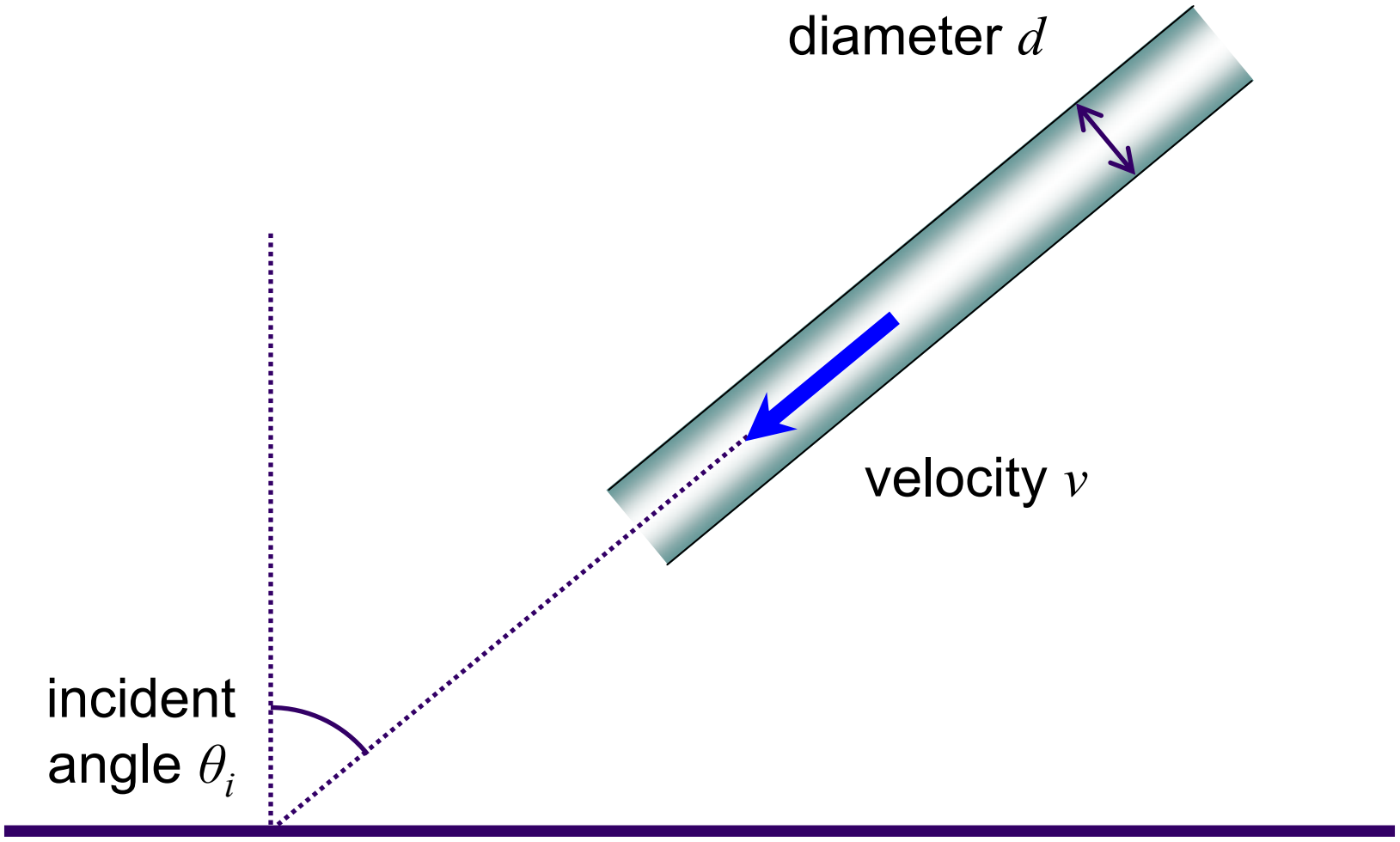


(a) refraction; (b) reflection; (c) absorption.

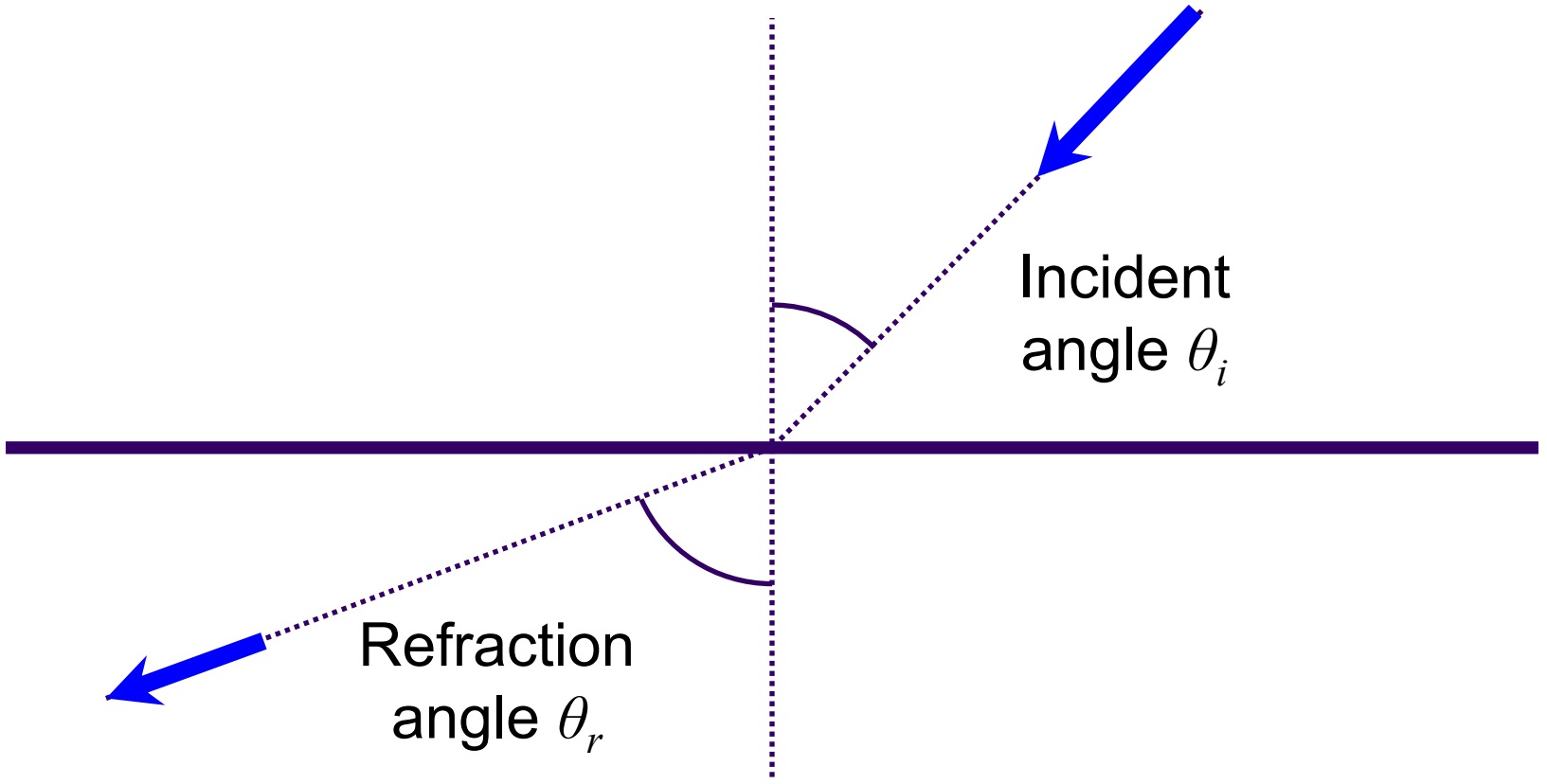
Program to investigate



Incident jet



Incident and refraction angles



Weber number

Weber number

- characteristic inertial force:

$$F_{in} = \rho r^2 v^2$$

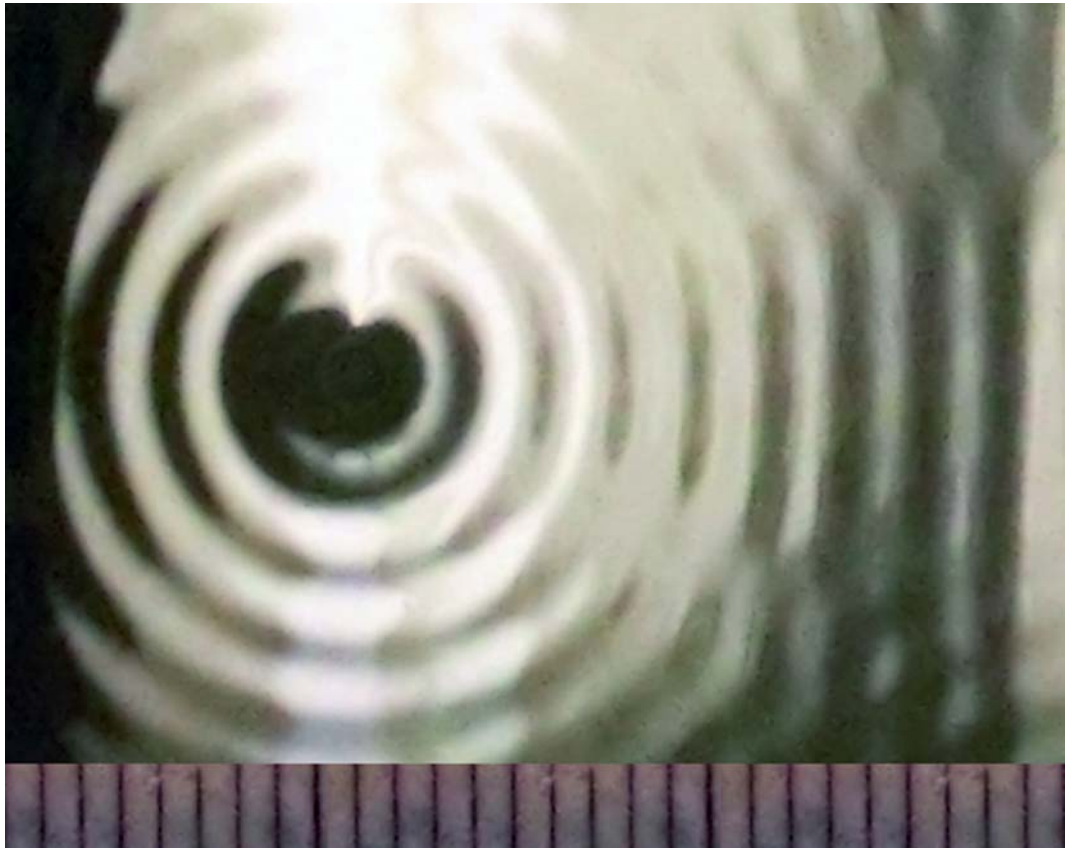
- characteristic capillary force:

$$F_{ca} = \sigma r$$

- ratio of two forces:

$$W = \frac{F_{in}}{F_{ca}} = \frac{\rho r v^2}{\sigma}$$

Measuring of the surface tension

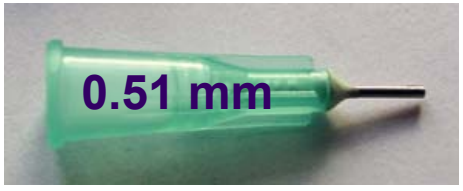


Surface tension is measured with a help of capillary waves.

$$\nu = 130 \text{ Hz}$$
$$\lambda = 2.0 \text{ mm}$$

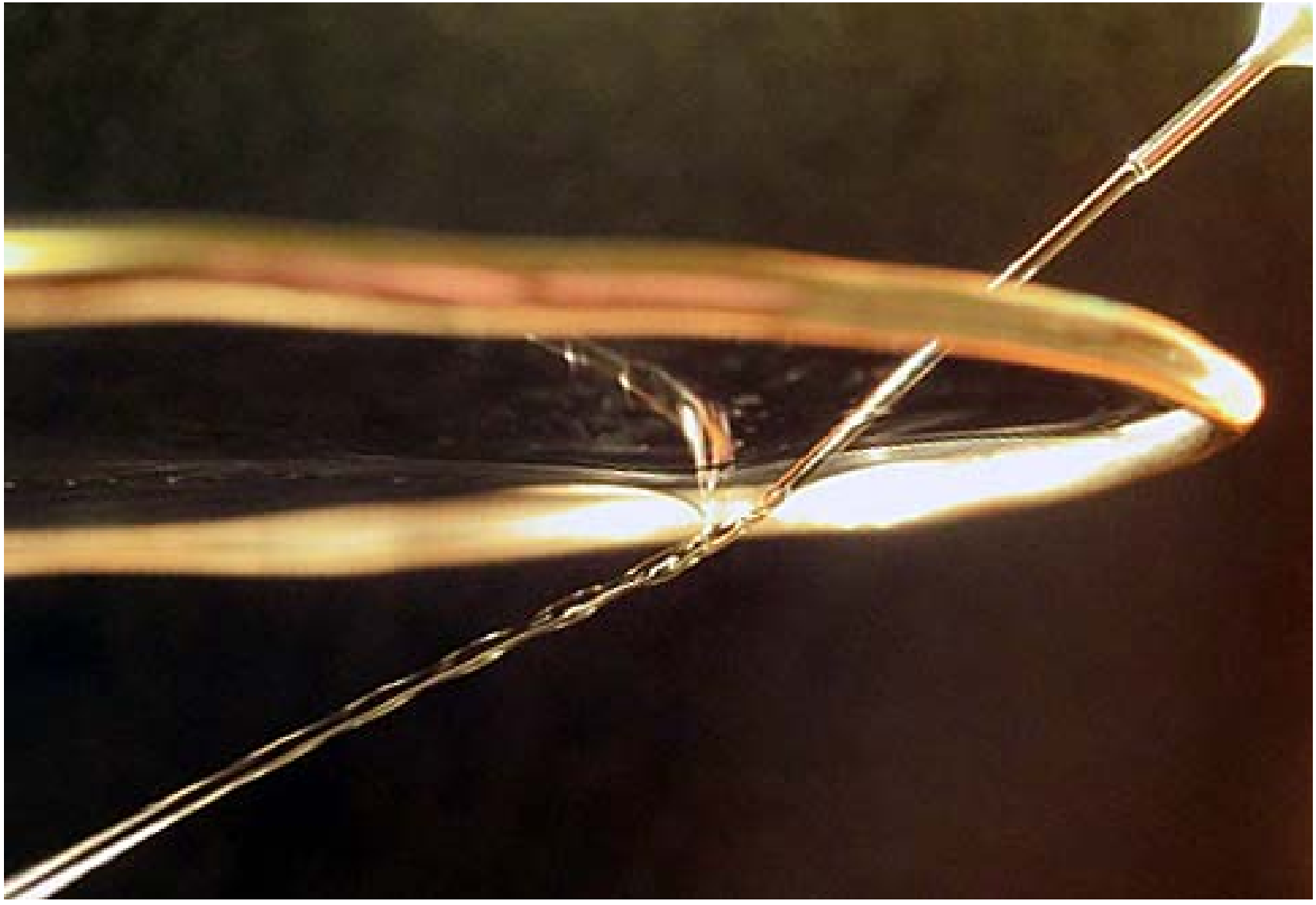
$$\sigma = \frac{\rho \nu^2 \lambda^3}{2\pi} =$$
$$= (2.2 \pm 0.1) \cdot 10^{-2} \text{ N/m}$$

Weber numbers for different nozzles

Level (cm)	70	85	100	115	130
	29	40	48	57	73
	18	25	30	36	43
	10	16	21	26	33

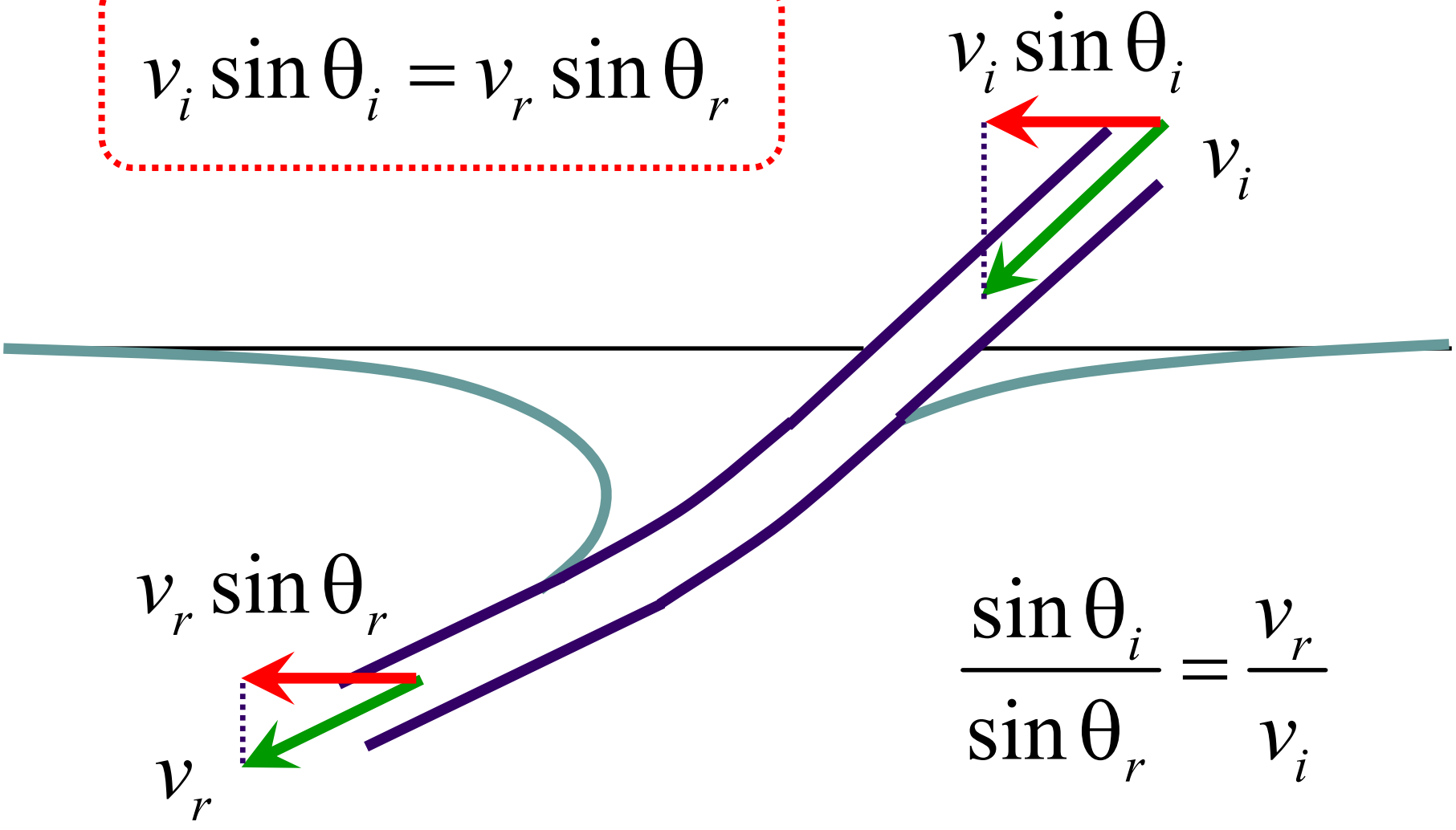
Refracted jet

Meniscus shape



Conservation of a horizontal momentum

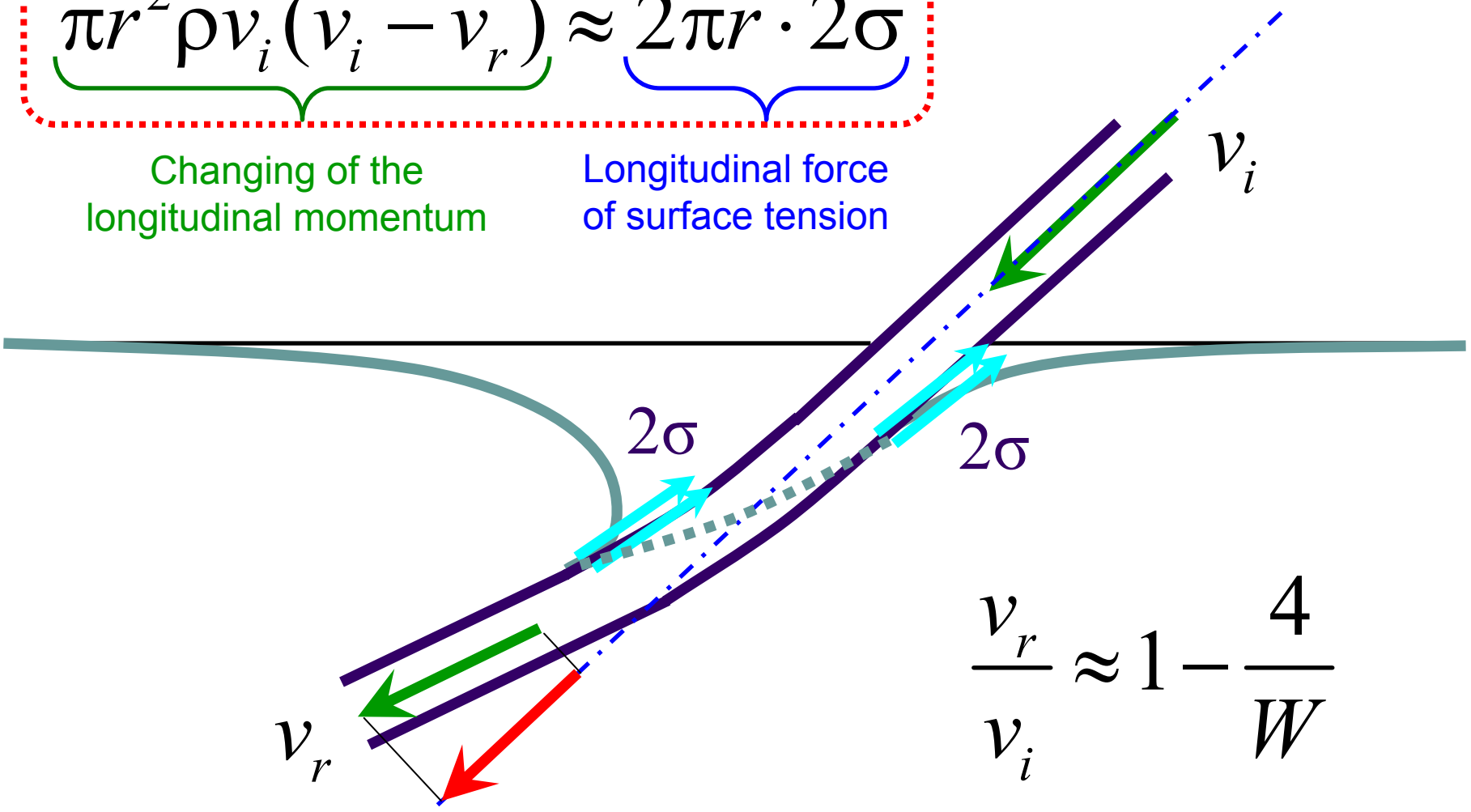
$$v_i \sin\theta_i = v_r \sin\theta_r$$



$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{v_r}{v_i}$$

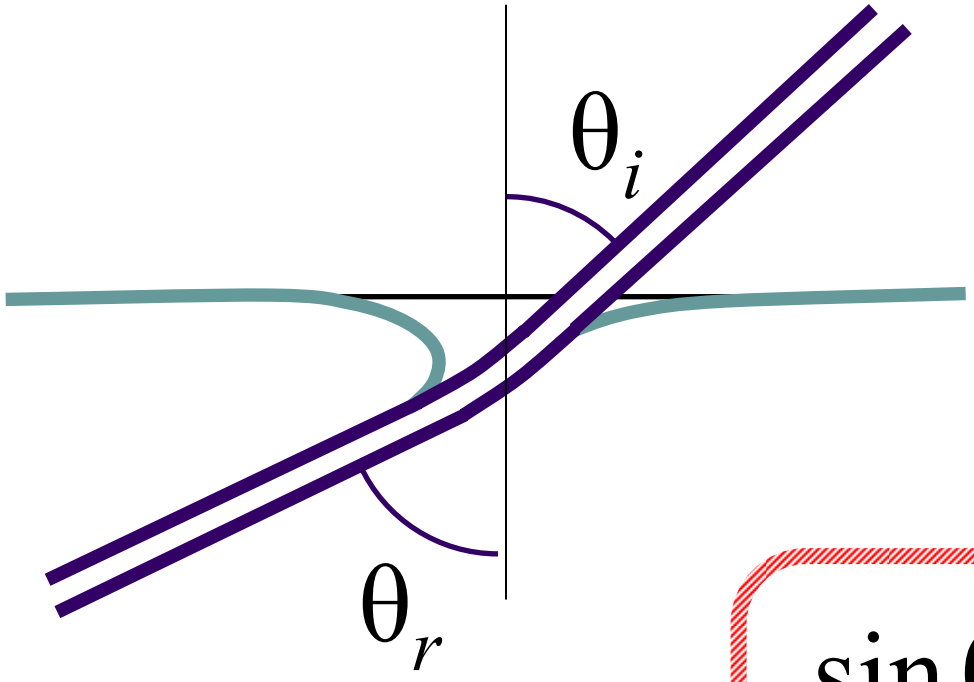
Balance of longitudinal momentum

$$\underbrace{\pi r^2 \rho v_i (v_i - v_r)}_{\text{Changing of the longitudinal momentum}} \approx \underbrace{2\pi r \cdot 2\sigma}_{\text{Longitudinal force of surface tension}}$$



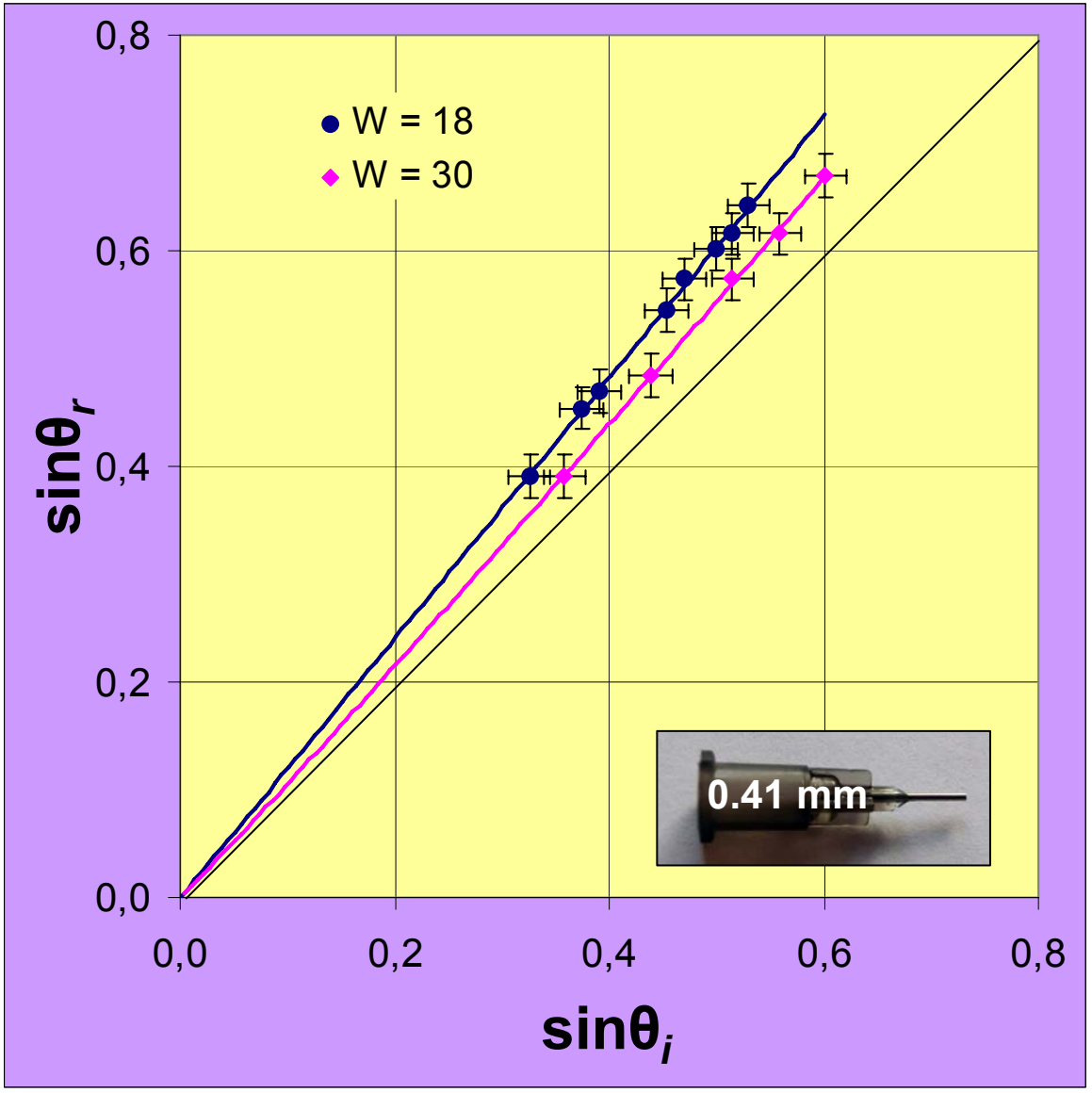
$$\frac{v_r}{v_i} \approx 1 - \frac{4}{W}$$

Law of refraction



$$\frac{\sin\theta_i}{\sin\theta_r} \approx 1 - \frac{4}{W}$$

Experimental results



Theory

$$\frac{\sin\theta_i}{\sin\theta_r} = 1 - \frac{4}{W}$$

Experiment

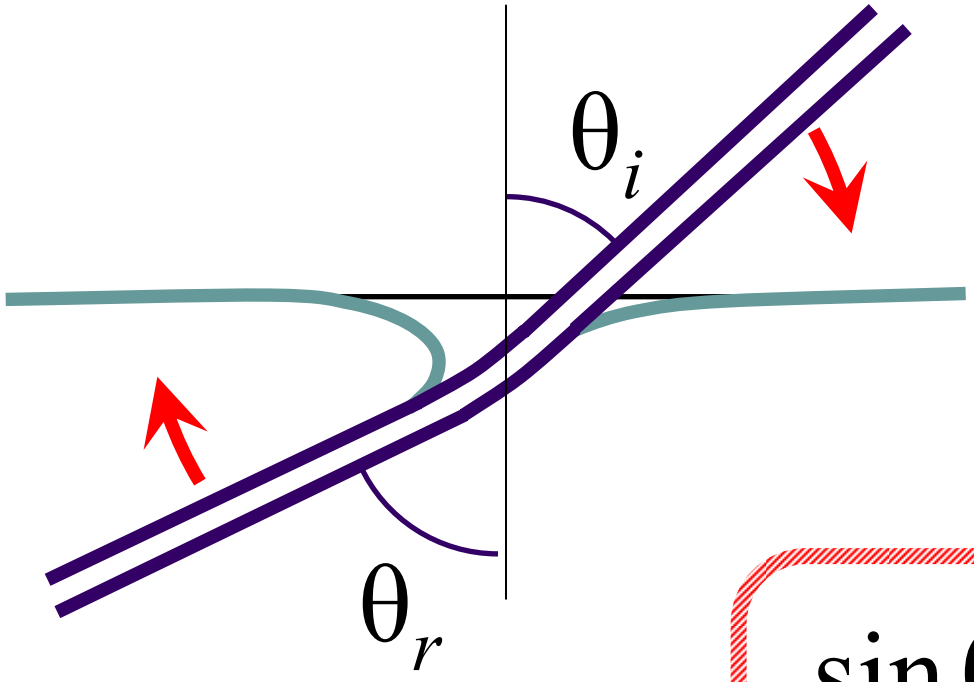
$$\frac{\sin\theta_i}{\sin\theta_r} = 1 - \frac{3}{W}$$

A = 3.0 ± 0.2

Transition from refraction to absorption

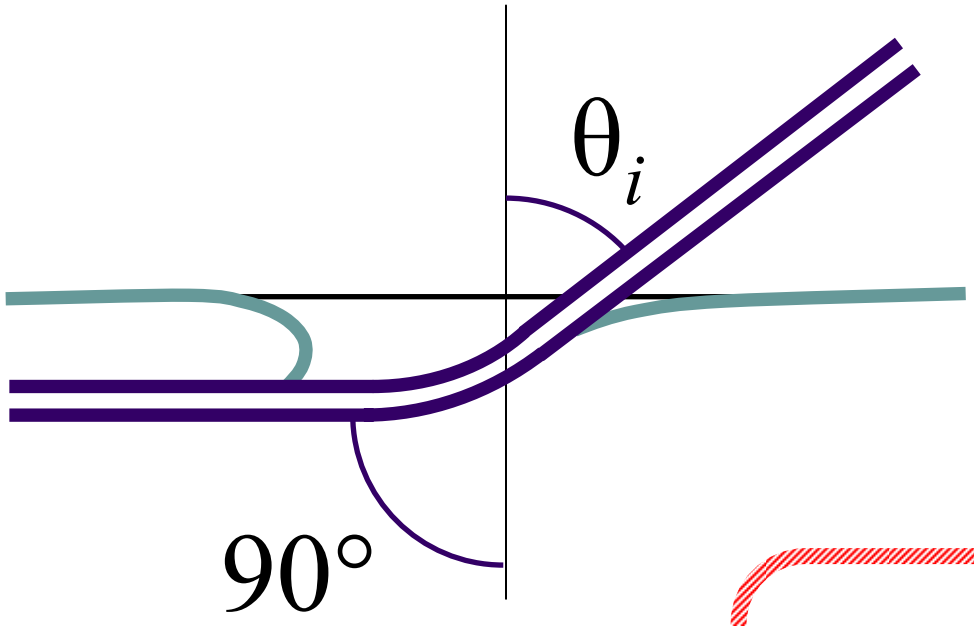
Experimental procedure (video)

Refraction angle grows…



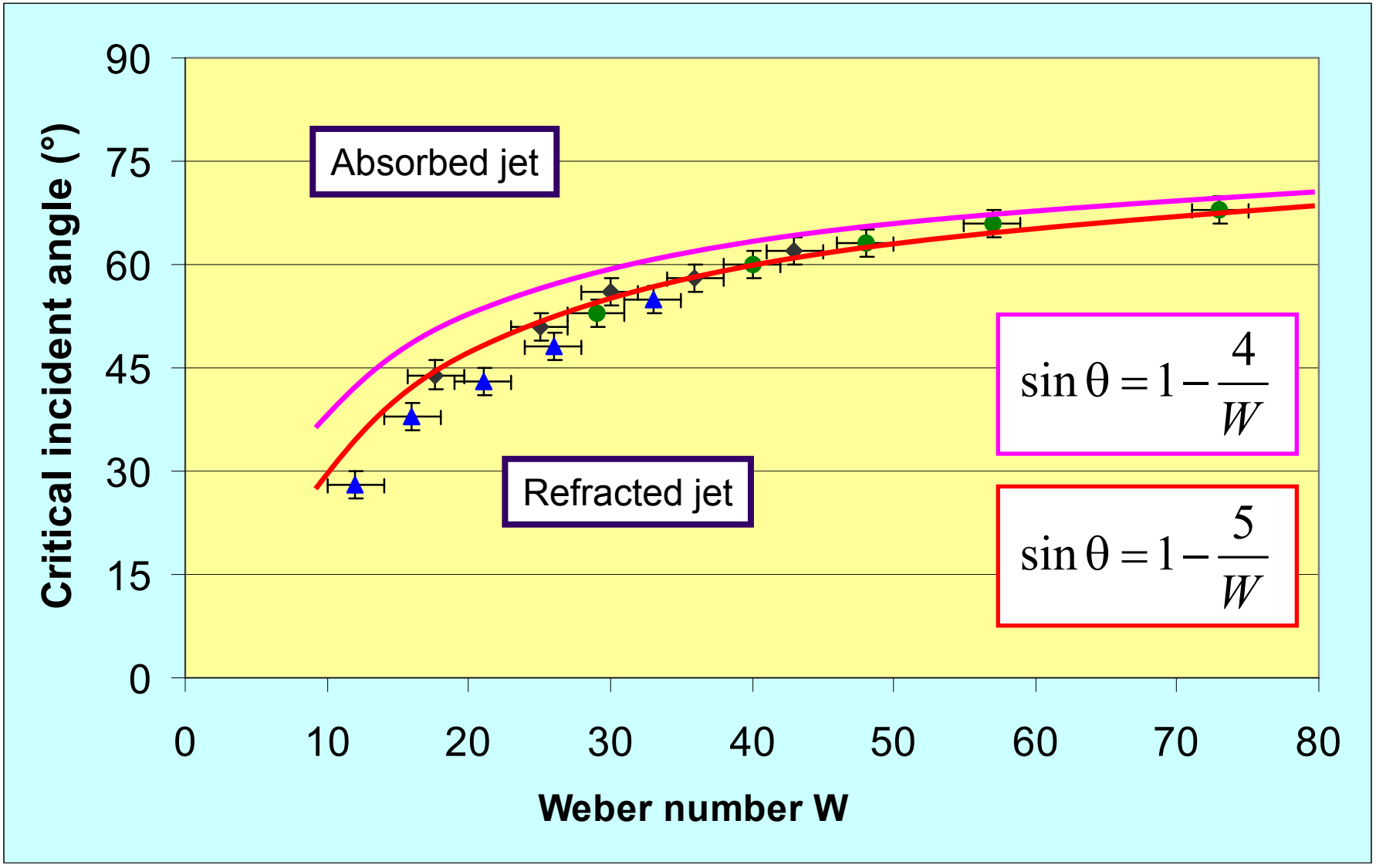
$$\frac{\sin\theta_i}{\sin\theta_r} \approx 1 - \frac{4}{W}$$

… and became equal 90°

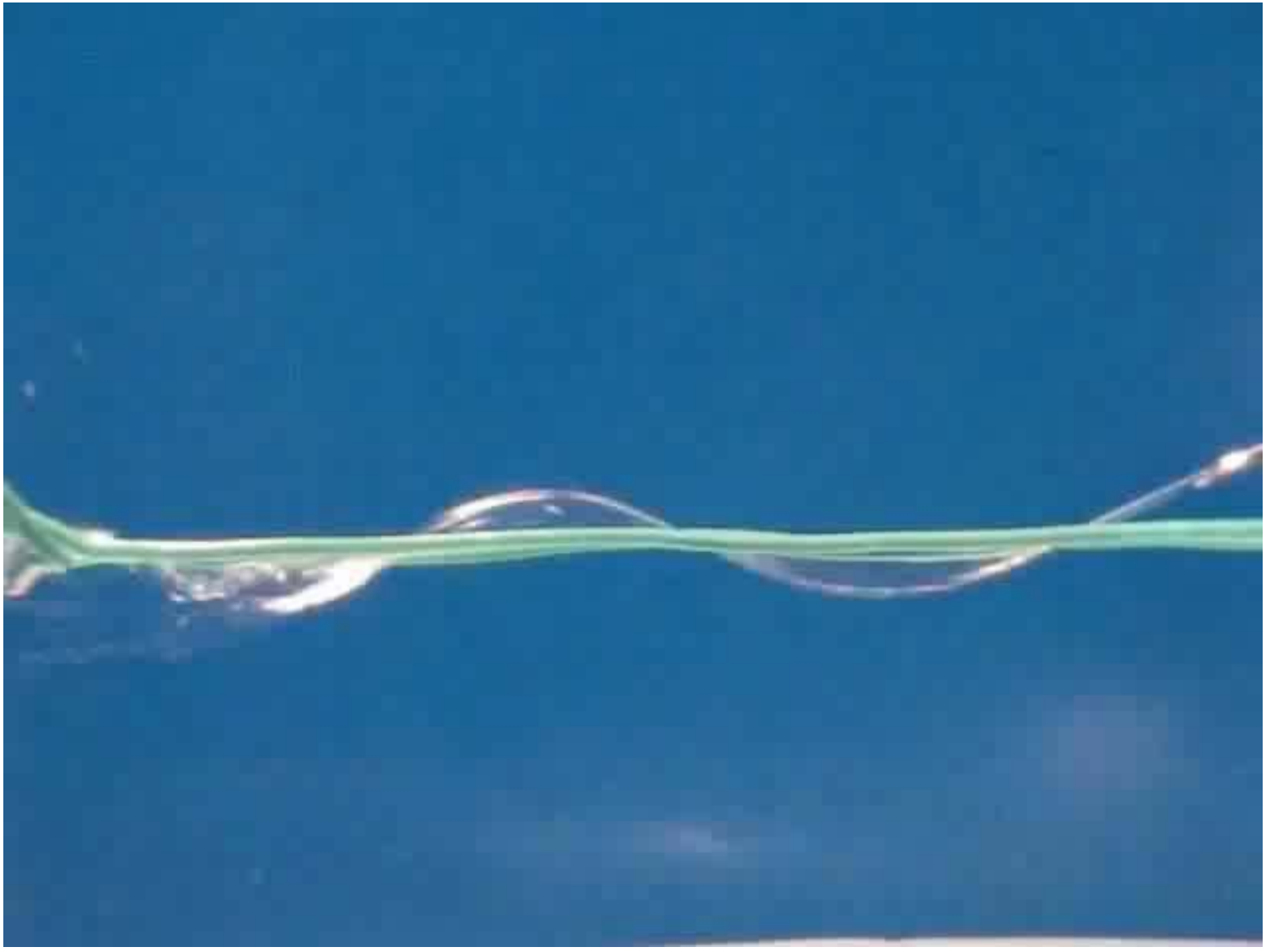


$$\sin\theta_i \approx 1 - \frac{4}{W}$$

Boundary between two regimes

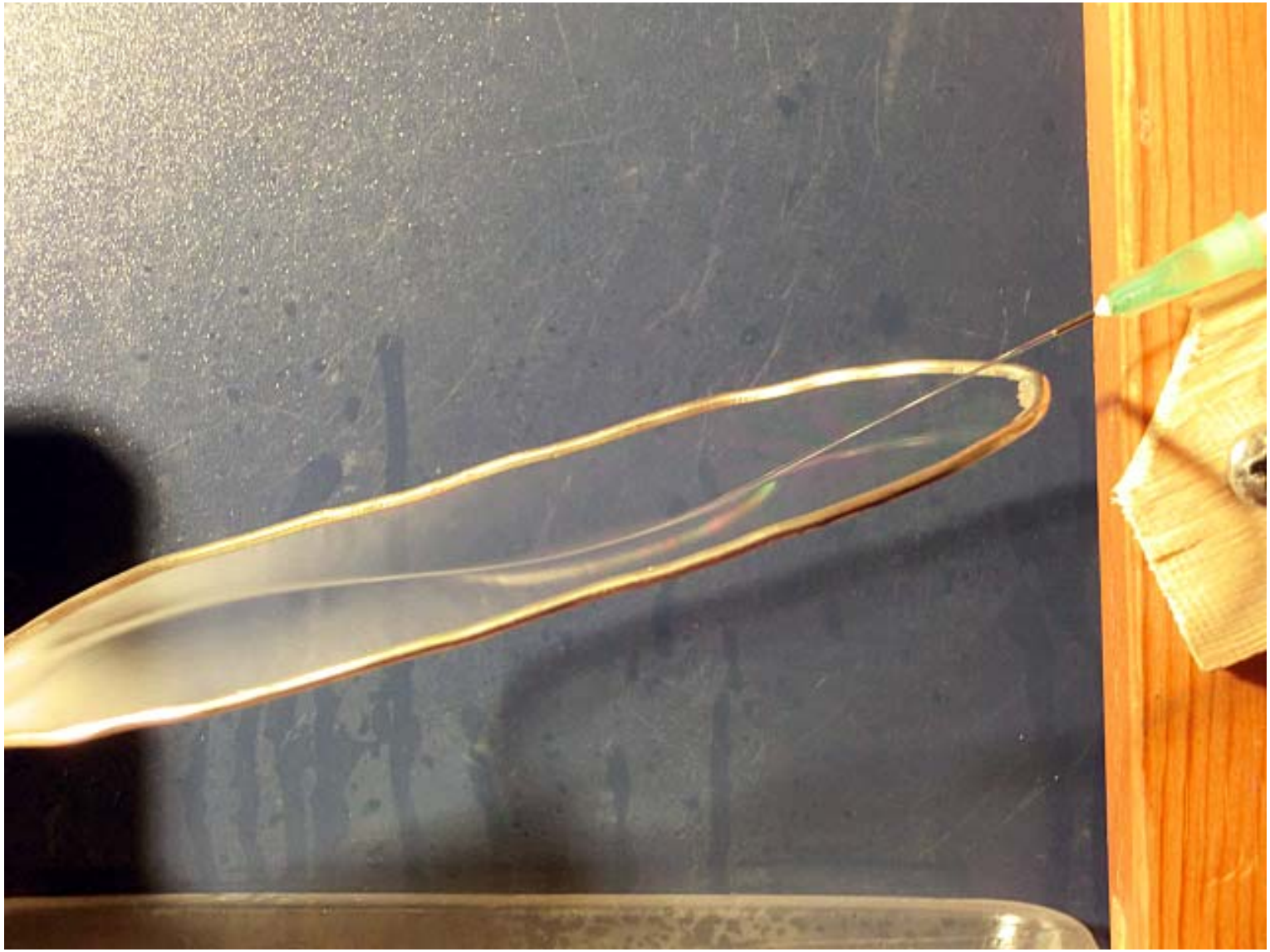


Regime of reflection (240 fps)

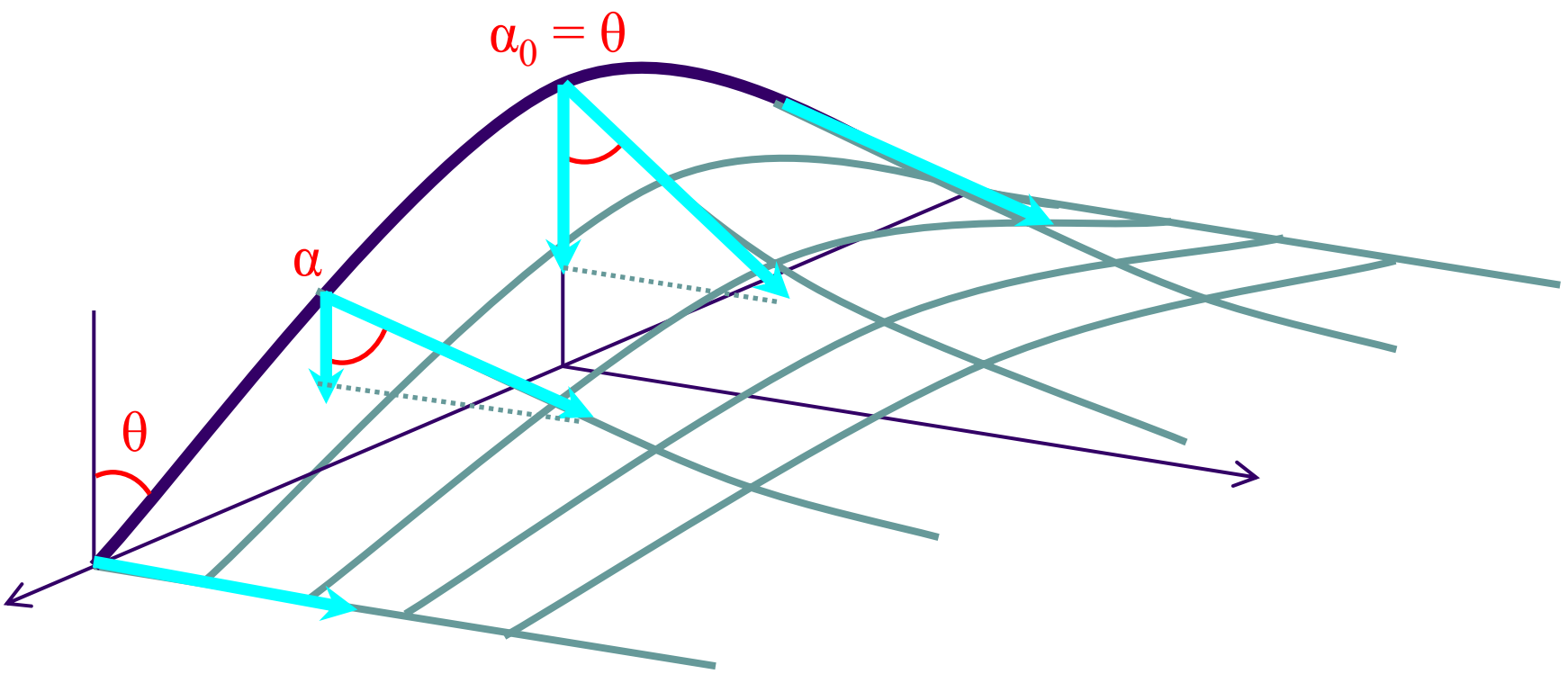


Absorbed jet

Shape of a wave

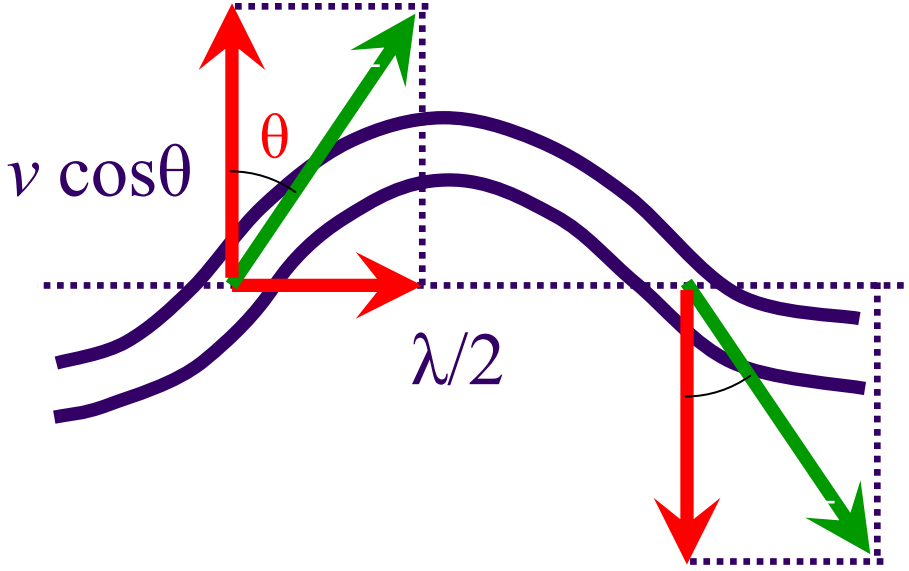


Average slope angle

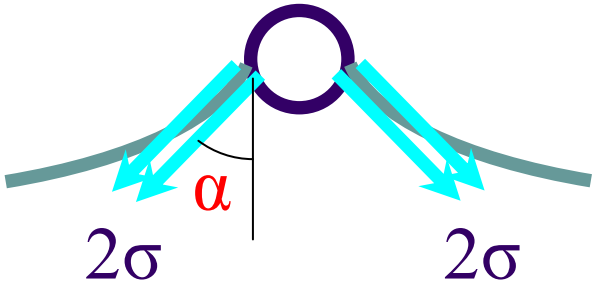


$$\langle \cos(\alpha) \rangle = \frac{2}{\pi} \cos(\theta)$$

Momentum balance

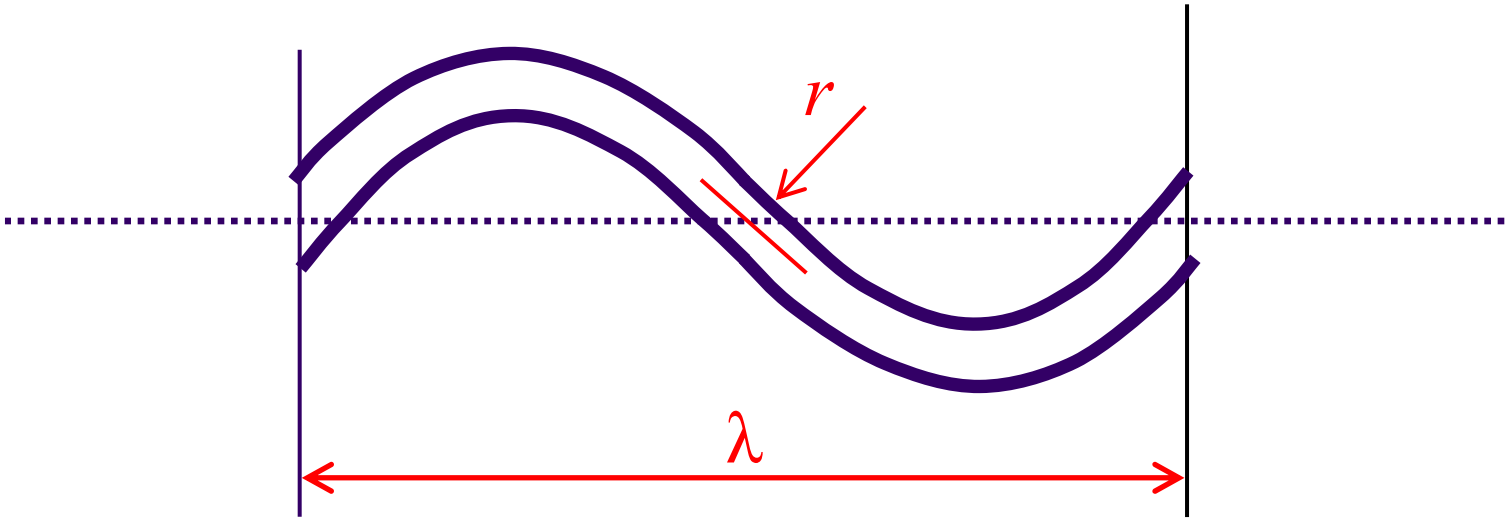


Uphill cross-section



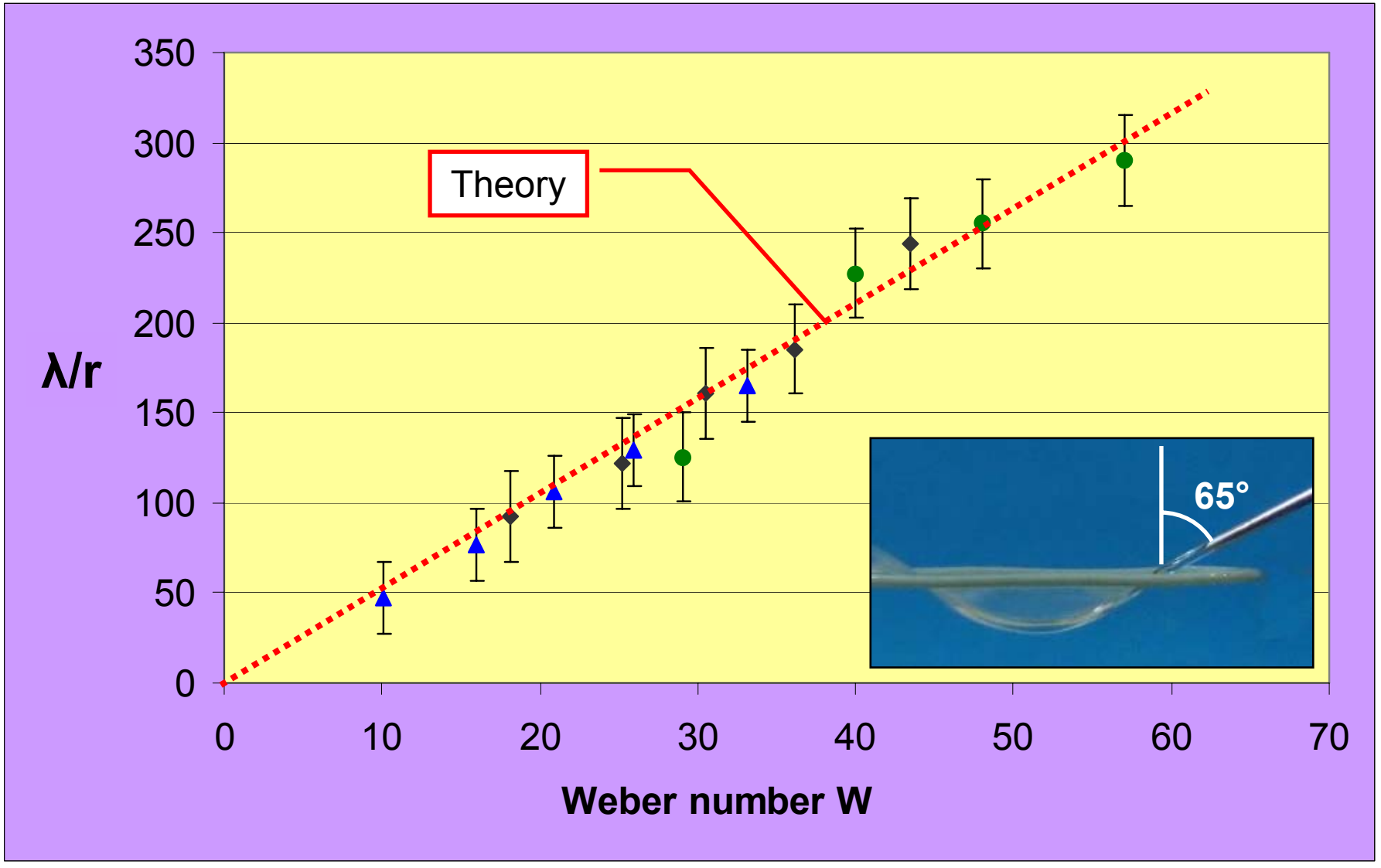
$$\frac{\Delta p}{\Delta t} = F \quad \Rightarrow \quad \underbrace{\pi r^2 \rho v \cdot 2v\cos\theta}_{\text{Changing of the vertical momentum}} = \underbrace{\frac{\lambda}{2} \cdot 4\sigma \cdot \langle \cos\alpha \rangle}_{\text{Vertical force of surface tension}}$$

Theoretical prediction

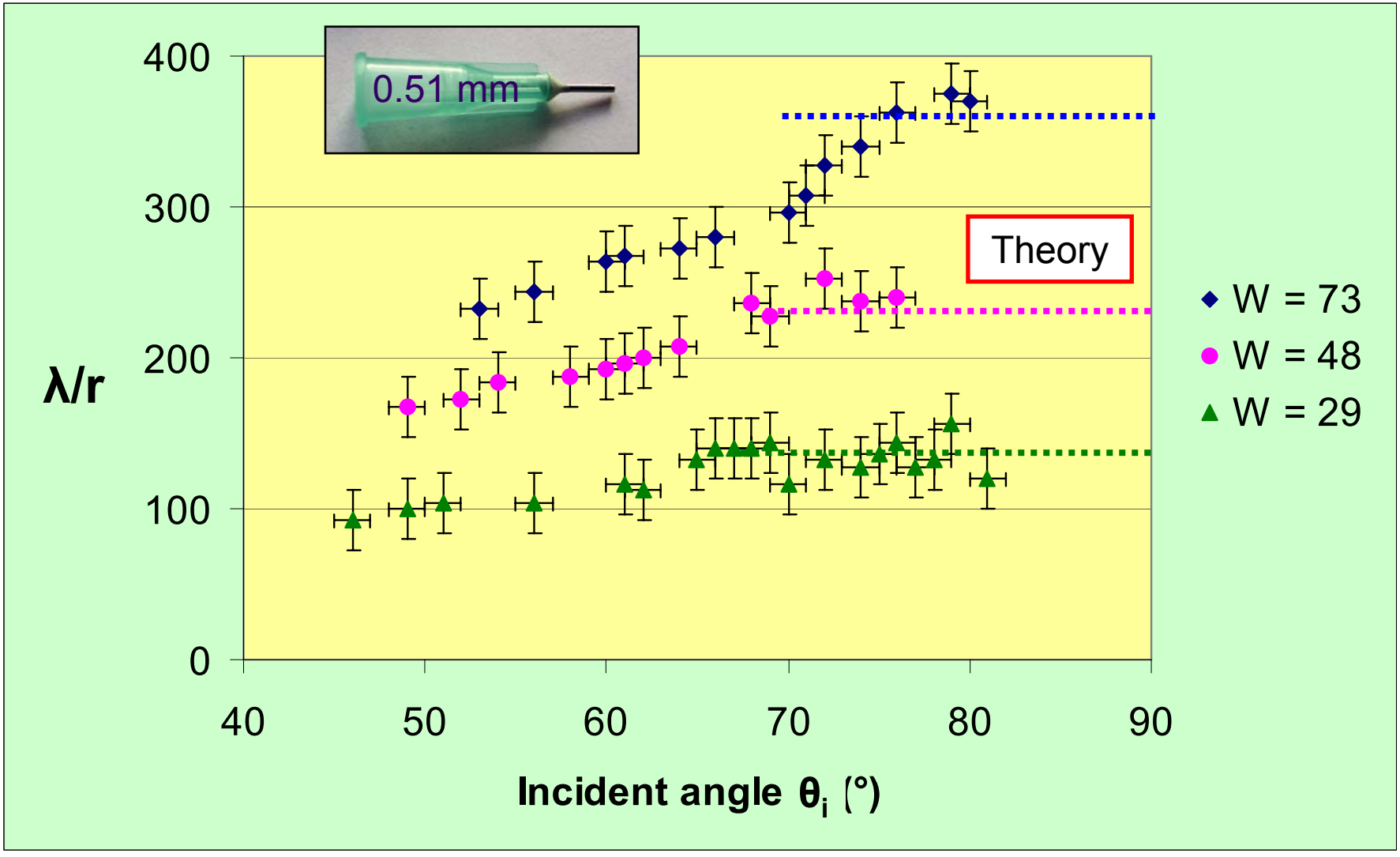


$$\frac{\lambda}{r} = \frac{\pi^2}{2} \cdot W \approx 4.9 \cdot W$$

Wavelength vs. Weber number



Wavelength vs. incident angle



Summary

Conclusions

- The nature of jet-film interaction is determined by two parameters: jet incident angle and Weber number (ratio of inertial forces to capillary forces).
- **Absorption regime** occurs for large incident angles and low Weber numbers. **Refraction regime** occurs for small incident angles and high Weber numbers. **Reflection regime** is transient between the two previous.

References

- Kirstetter G., Raufaste C., Celestini F. (2012) “Jet impact on a soap film”. *Phys. Rev. E*, **86**, 036303.
- Raufaste C., Kirstetter G., Celestini F. (2012) “Deformation of a free surface pierced by a tilted cylinder”. *Europhys. Lett*, **99**, 24001.

Thank you for your attention!