8

Jet and film

Michal Hledík

8. Jet and film

A thin liquid jet impacts on a soap film.

Depending on relevant parameters, the jet can either penetrate through the film or merge with it, producing interesting shapes.

Explain and investigate this interaction and the resulting shapes.

Existing work

Jet impact on a soap film

Geoffroy Kirstetter, Christophe Raufaste,[*] and Franck Celestini[†]
Laboratoire de Physique de la Matière Condensée, CNRS UMR 6622,
Université de Nice Sophia-Antipolis, 06108 Nice, France
(Dated: March 6, 2012)

imentally investigate the impact of a liquid jet on a soap film. We observe th
s the film and that two qualitatively different steady regimes may occur. The
on-like behavior obtained at small incidence angles when the jet crosses the f
the film-jet interaction. For larger incidence angles, the jet is absorbed by
to a new class of flow in which the jet undulates along the film with a cha
Besides its fundamental interest, this study presents a new way to guide a mi
id in the inertial regime and to probe foam stability submitted to violent pert
film scale.

Existing work

Jet impact on a soap film

3 modes of interaction:

1. The jet is reflected by the film
2. The jet penetrates the film
3. The jet undulates on the film

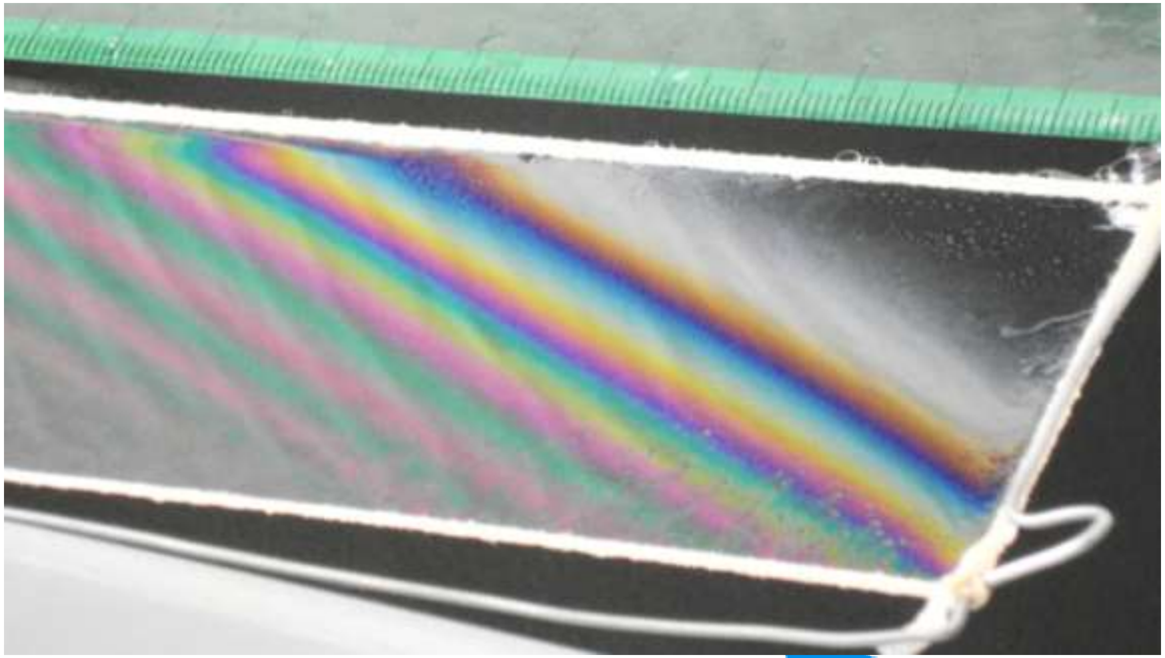
Our apparatus

- Soap : water 1:10 (both jet and film)

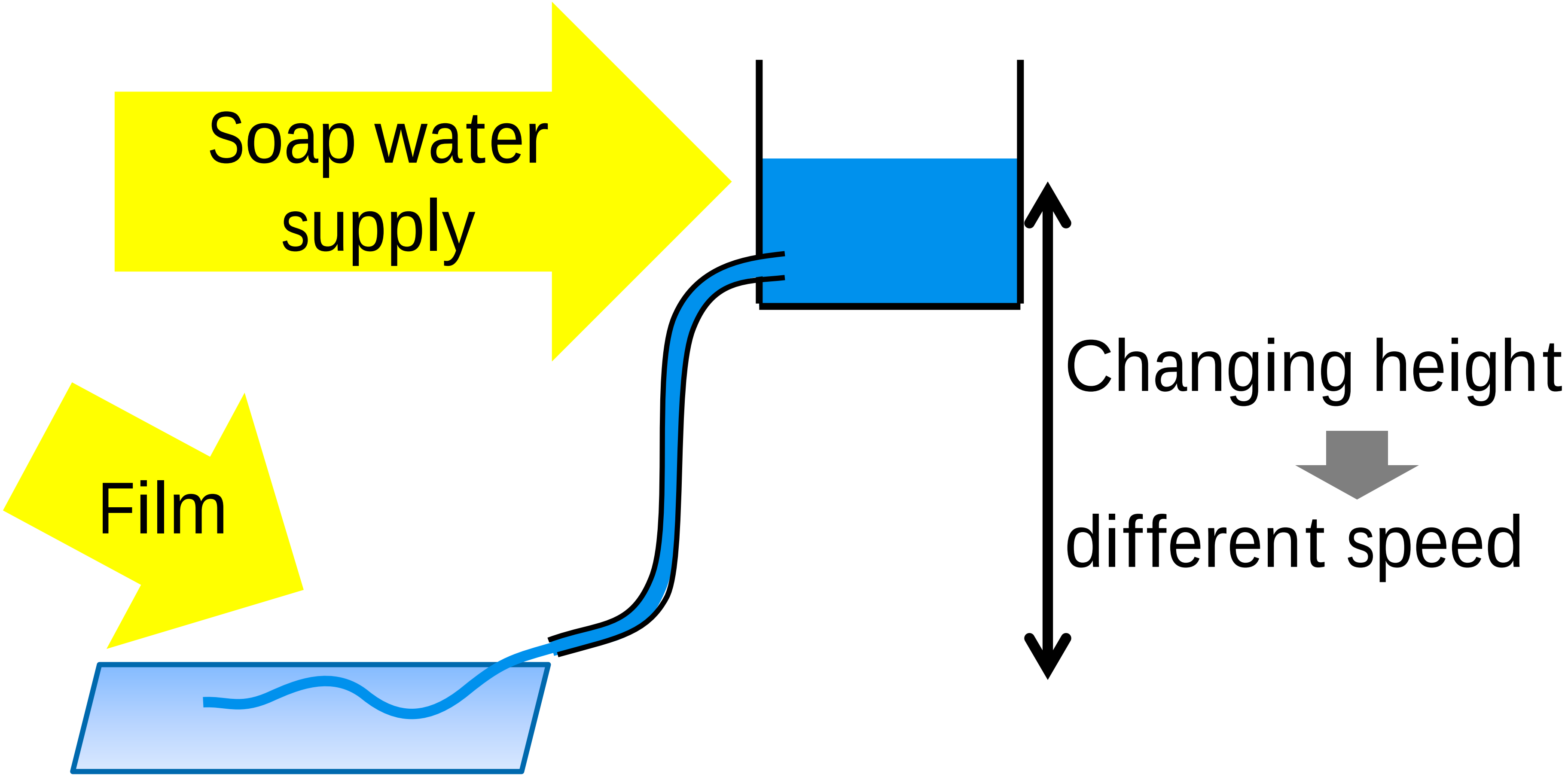
- Density $\rho = 1000 kg/m^3$
- Surface tension $\gamma = 0.025 kg/s^2$

- Inertia dominated
- 30 < We < 400
  (Weber number)

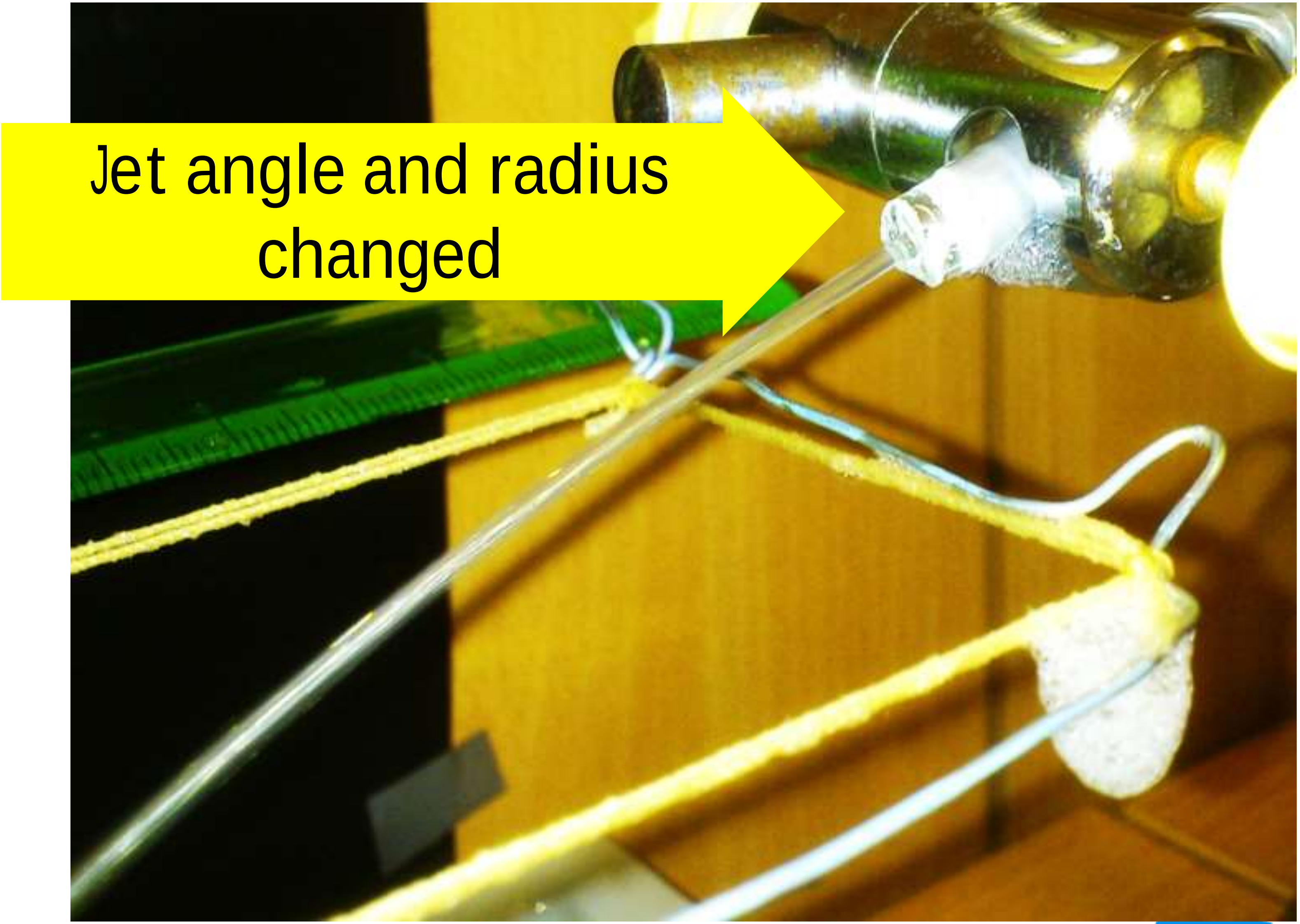
- Film thickness
  $\approx \lambda_{VISIBLE\ LIGHT}$



Apparatus



Apparatus – nozzle

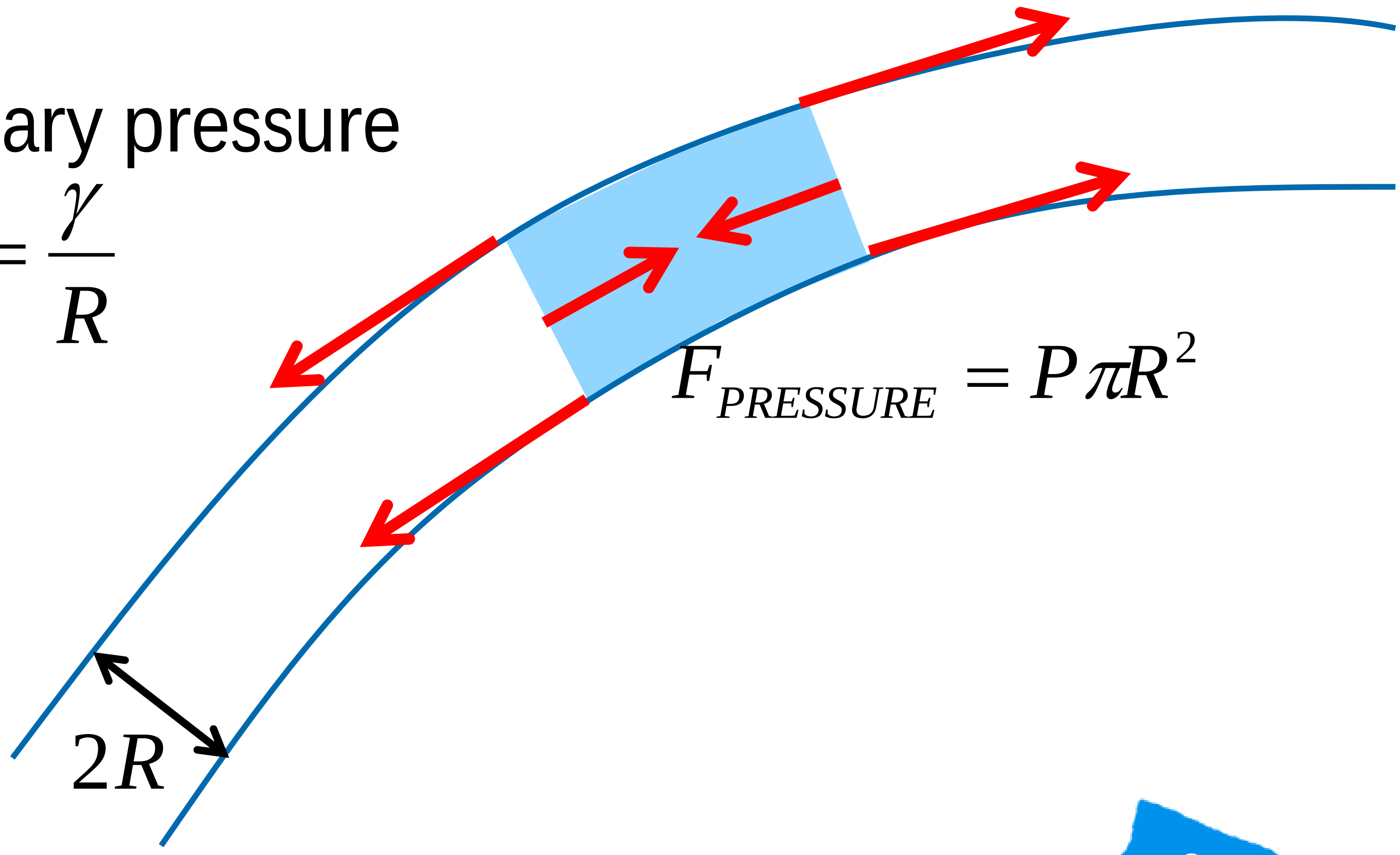


Basic forces in a jet

- Surface tension
- Capillary pressure

$$P = \frac{\gamma}{R}$$

$$F_{SURFACE\ TENSION} = 2\pi R\gamma$$

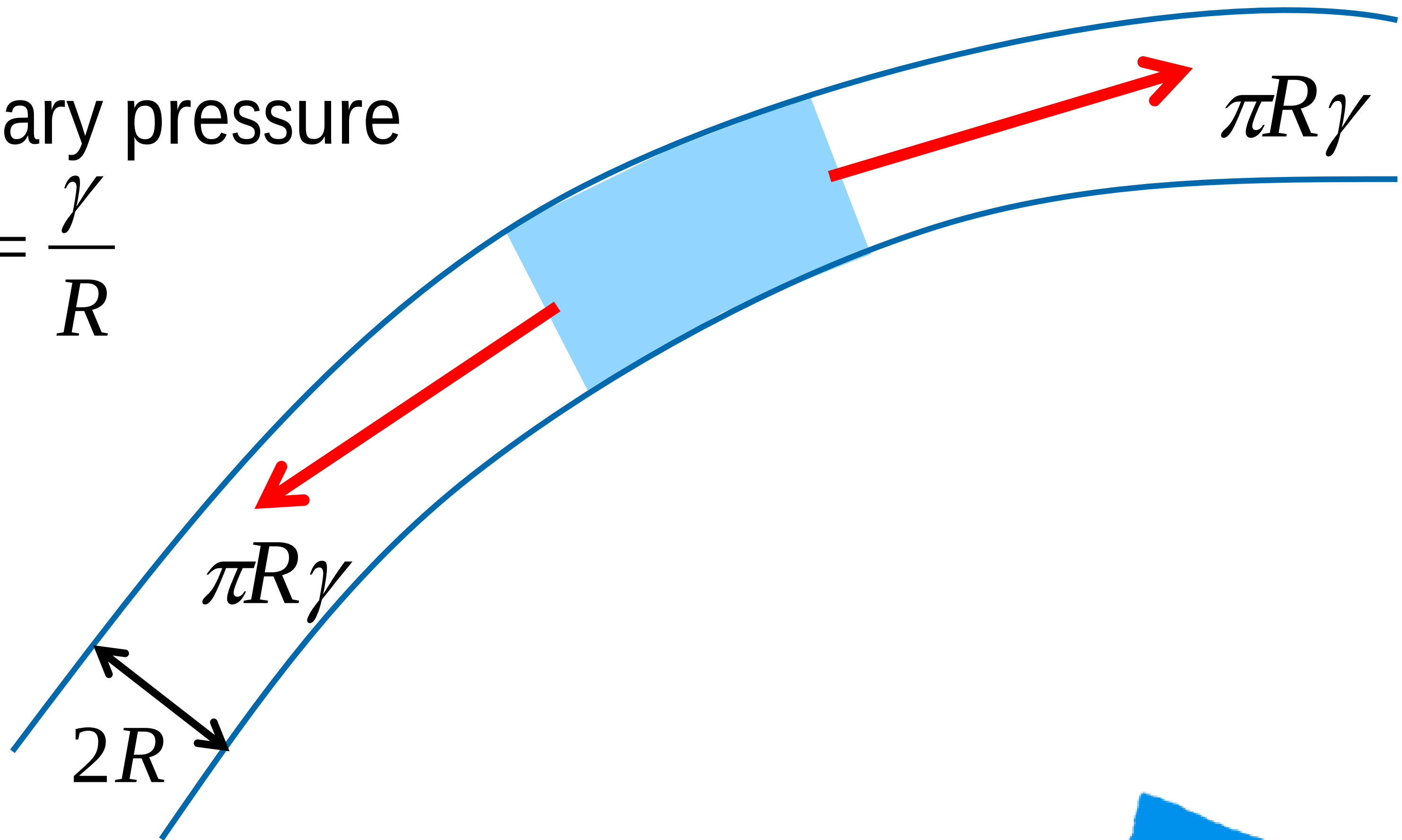


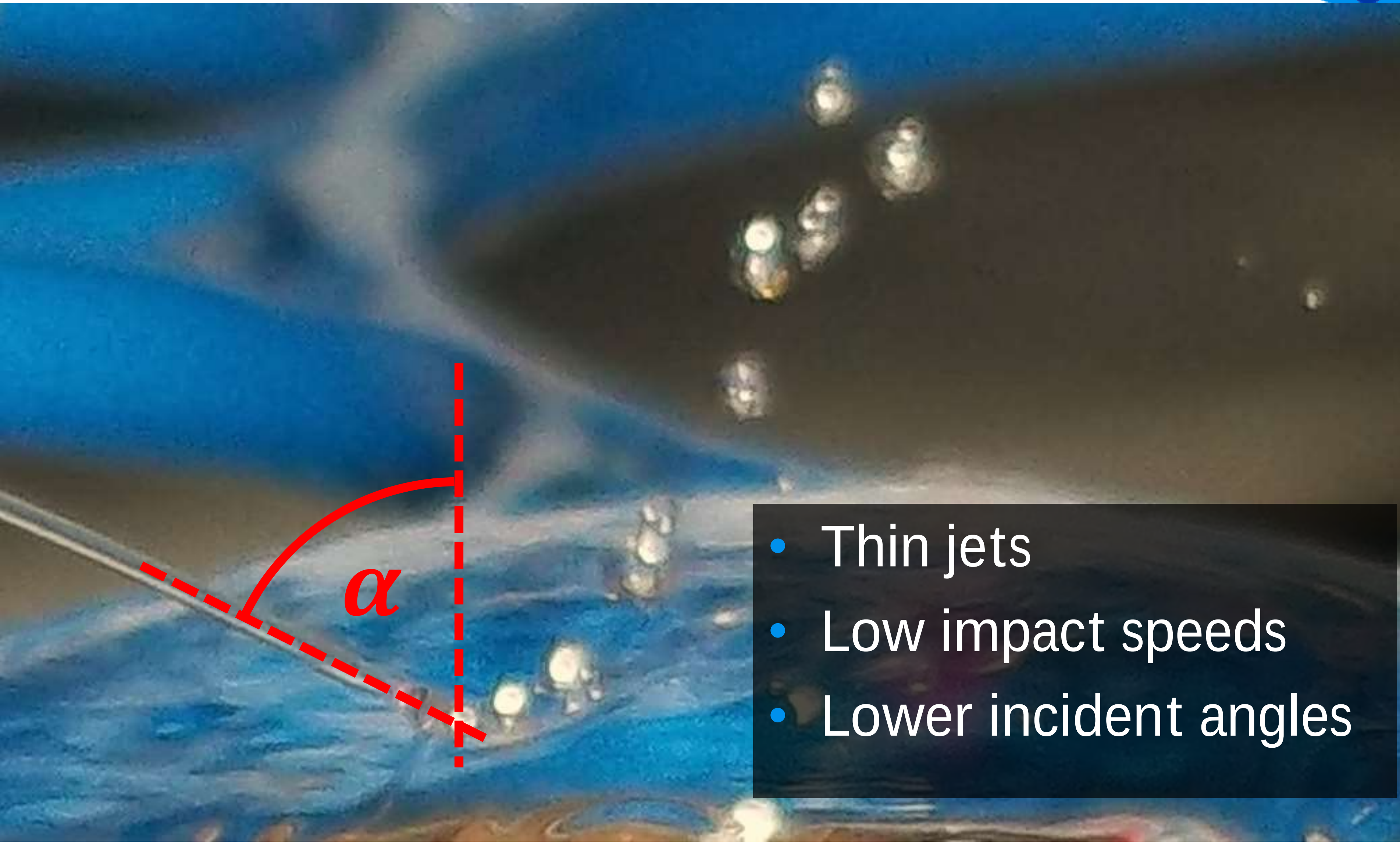
$$F_{PRESSURE} = P\pi R^2$$

Basic forces in a jet

- Surface tension
- Capillary pressure

$$P = \frac{\gamma}{R}$$





- Thin jets
- Low impact speeds
- Lower incident angles

Reflection Penetration Undulation

Reflection

- Thin jets → drops
  (Plateau-Rayleigh instability)

- Drops do not merge with the film, they bounce and roll

- No full theory exists yet

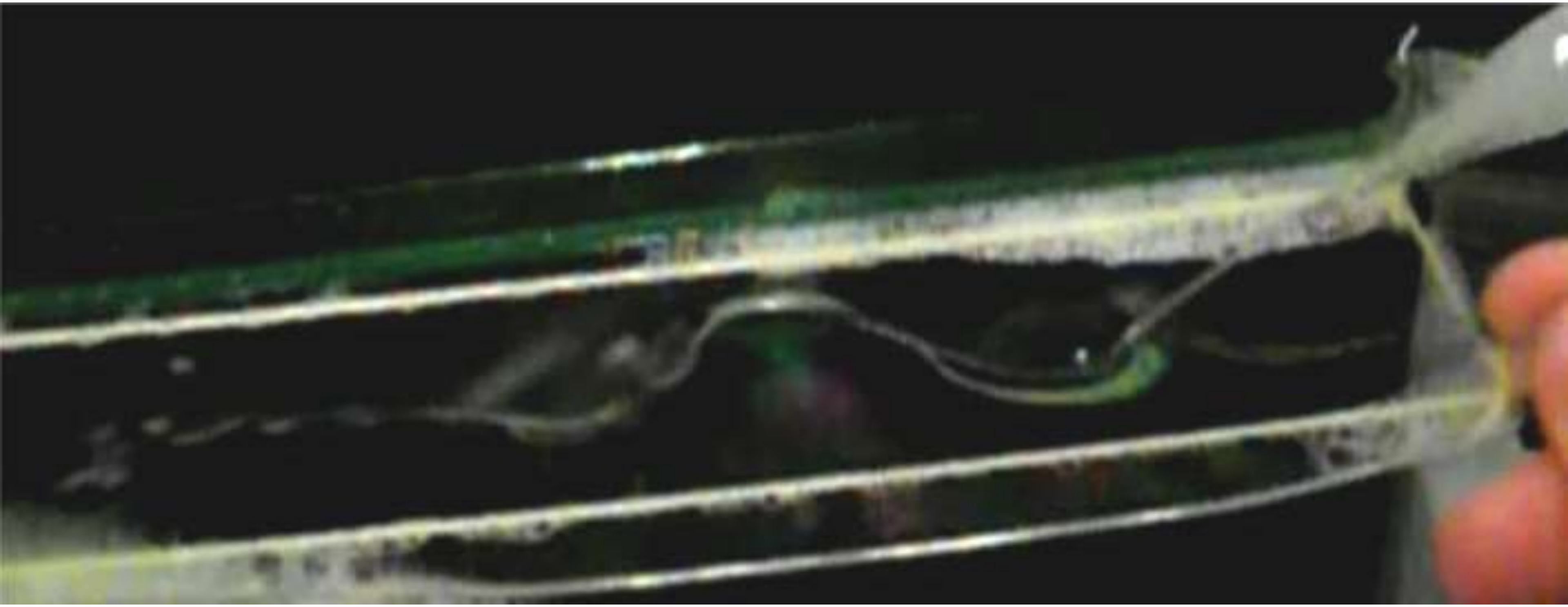
Reflection – drops

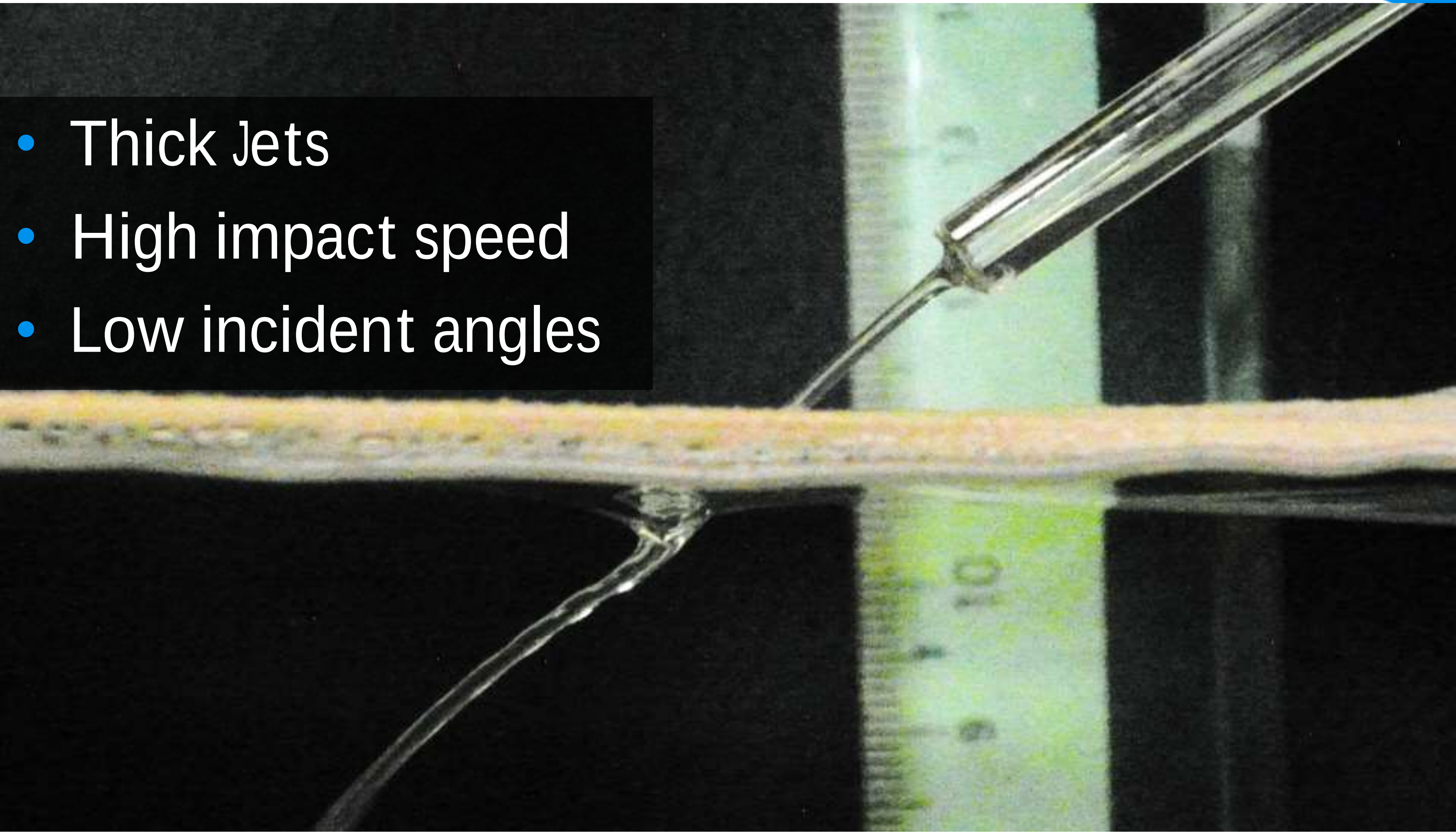
Reflection on a bubble

Spherical shape of the film
– the jet keeps some of its momentum, “escapes”

Intermediate state

Unstable waves, oscillate, small drops are splashed away





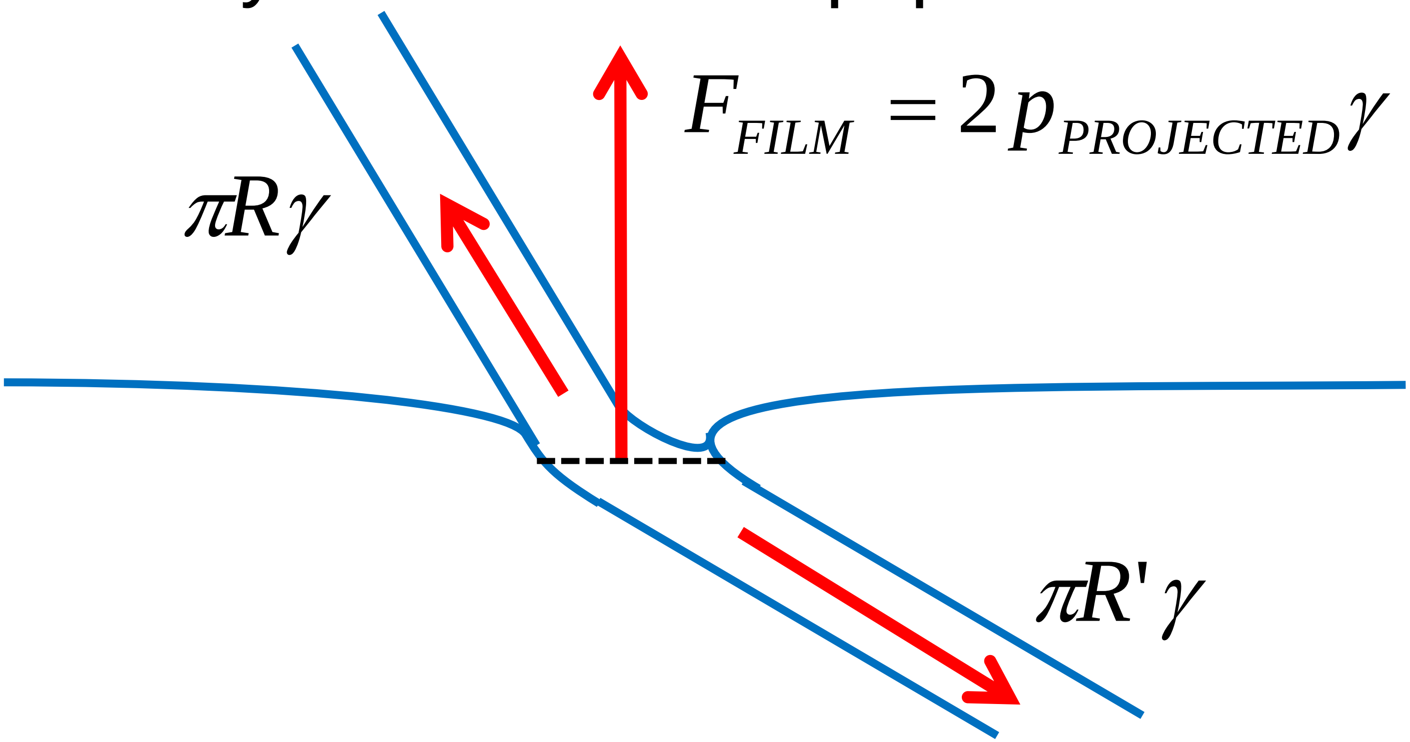
- Thick Jets
- High impact speed
- Low incident angles

Reflection **Penetration** Undulation

Penetrating the film

Penetrating the film

- Theory from the cited paper



$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = Q\rho\left(\mathbf{v}_{AFTER} - \mathbf{v}_{BEFORE}\right) \qquad Q_{AFTER} = Q_{BEFORE}$$

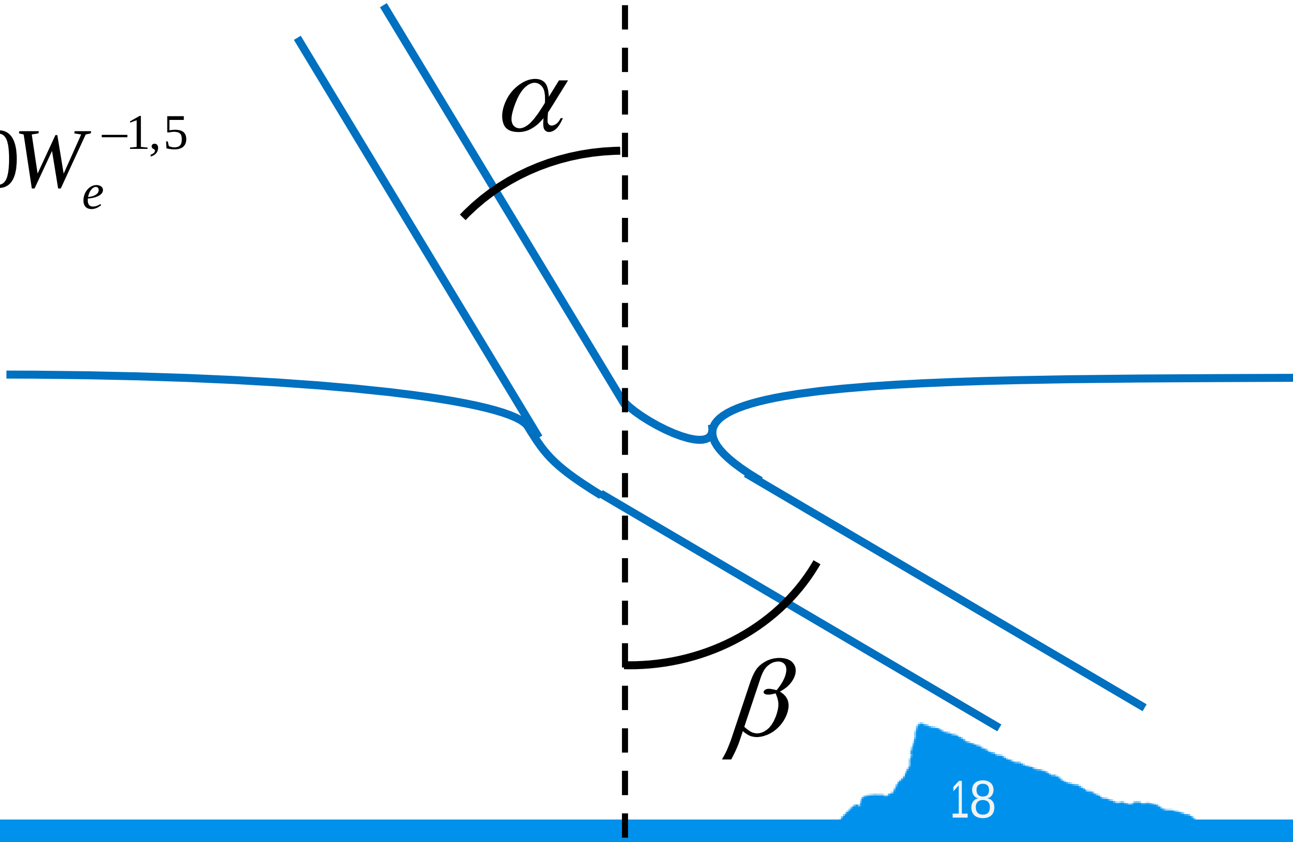
"Refraction" of the jet

- Numerical solution

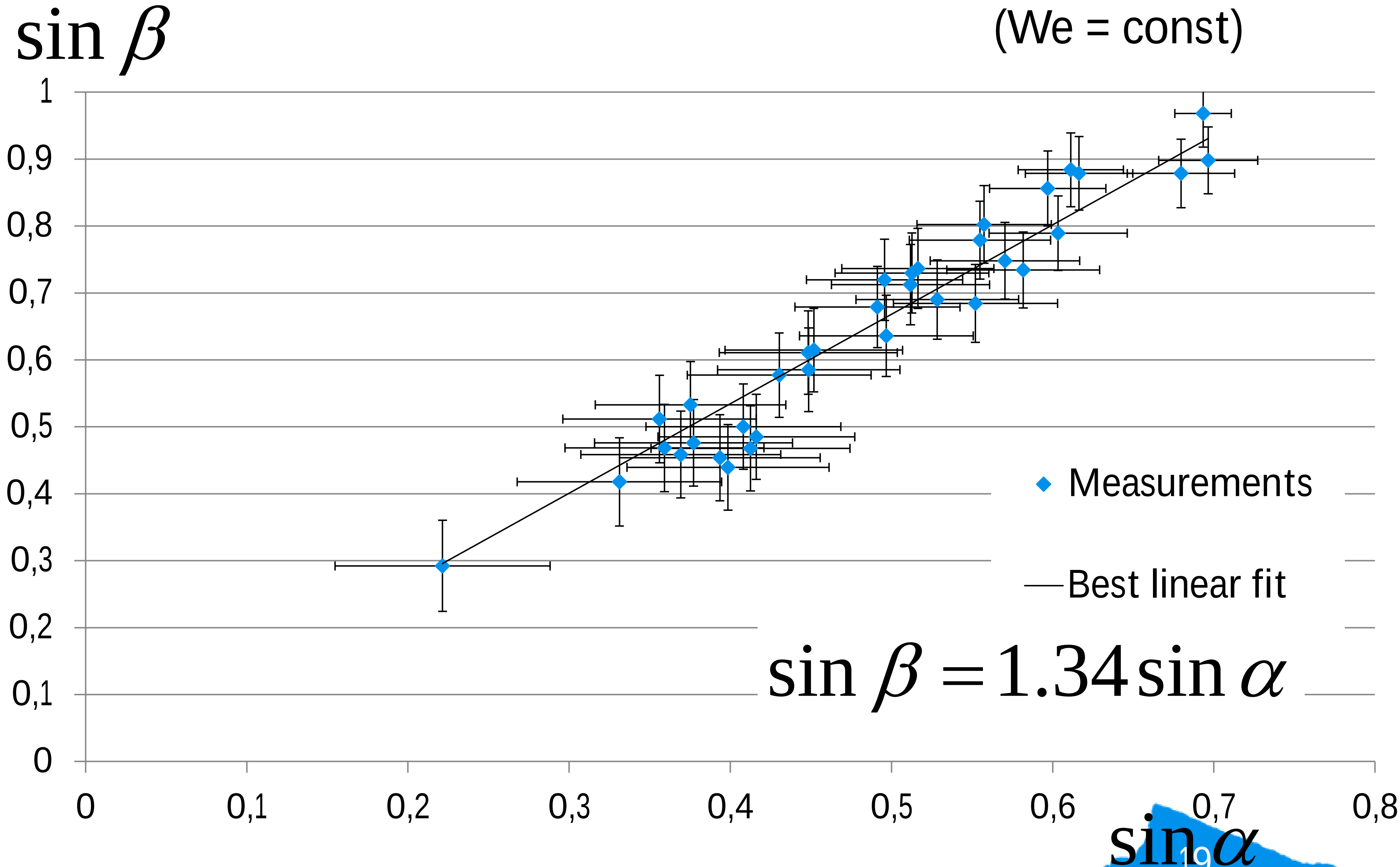
- **Analogy to Snell's law of refraction**

$$\frac{\sin\beta}{\sin\alpha} \approx 1 + 30 W_e^{-1,5}$$

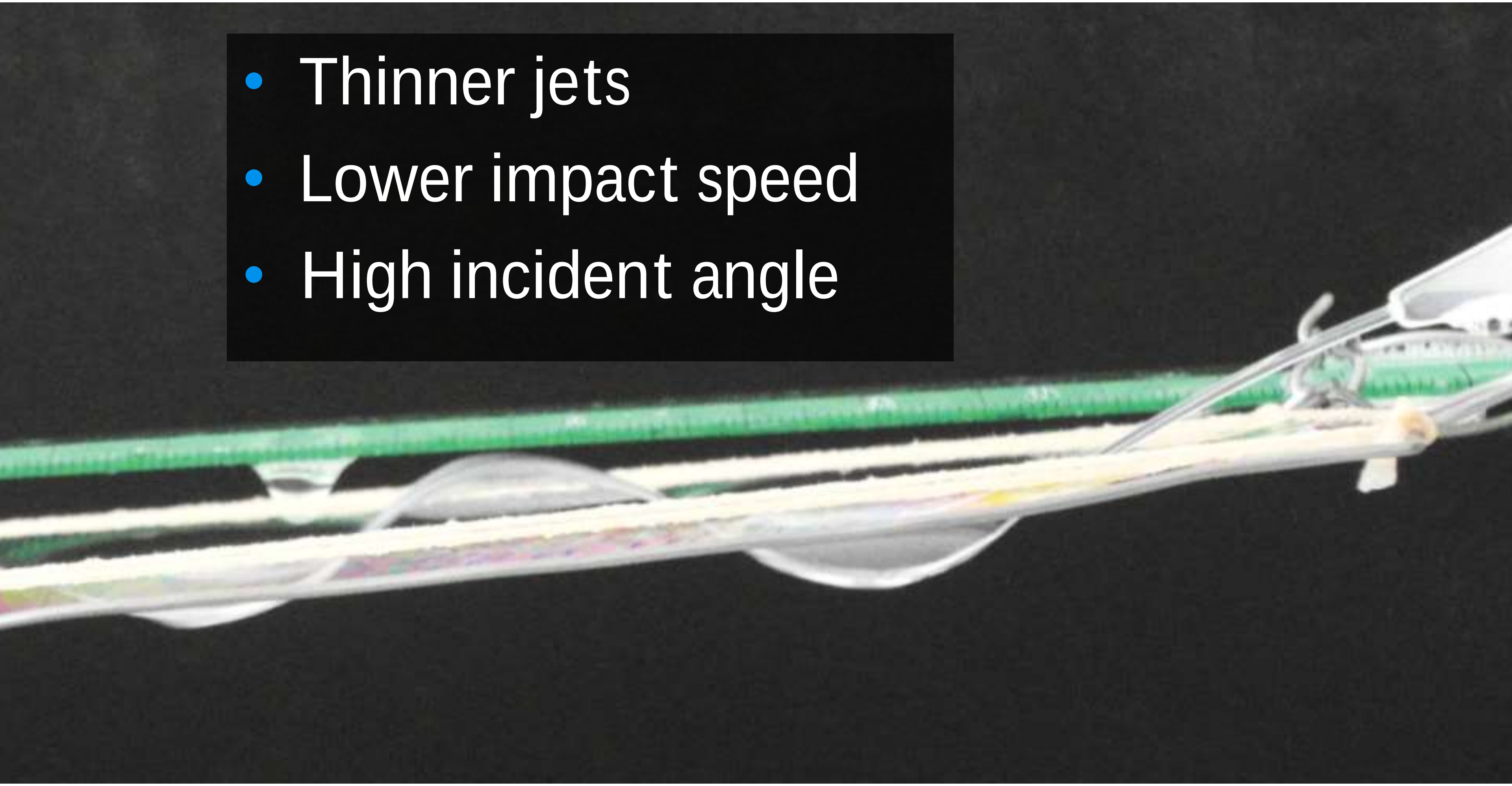
$$W_e = \frac{\rho v^2 R}{\sigma}$$



"Refraction" of the jet



$$\sin\beta = 1.34 \sin\alpha$$

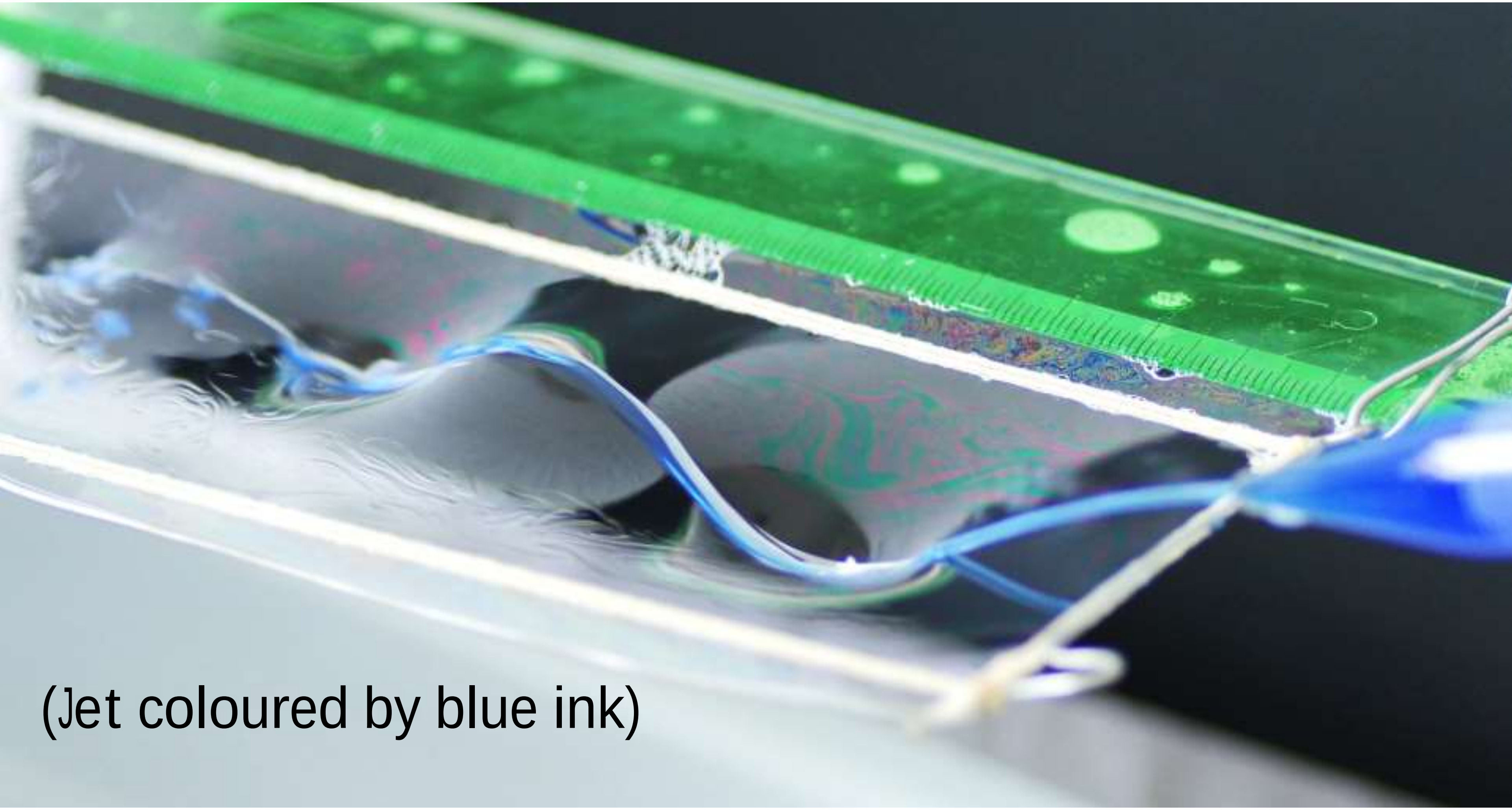


- Thinner jets
- Lower impact speed
- High incident angle

Reflection Penetration **Undulation**

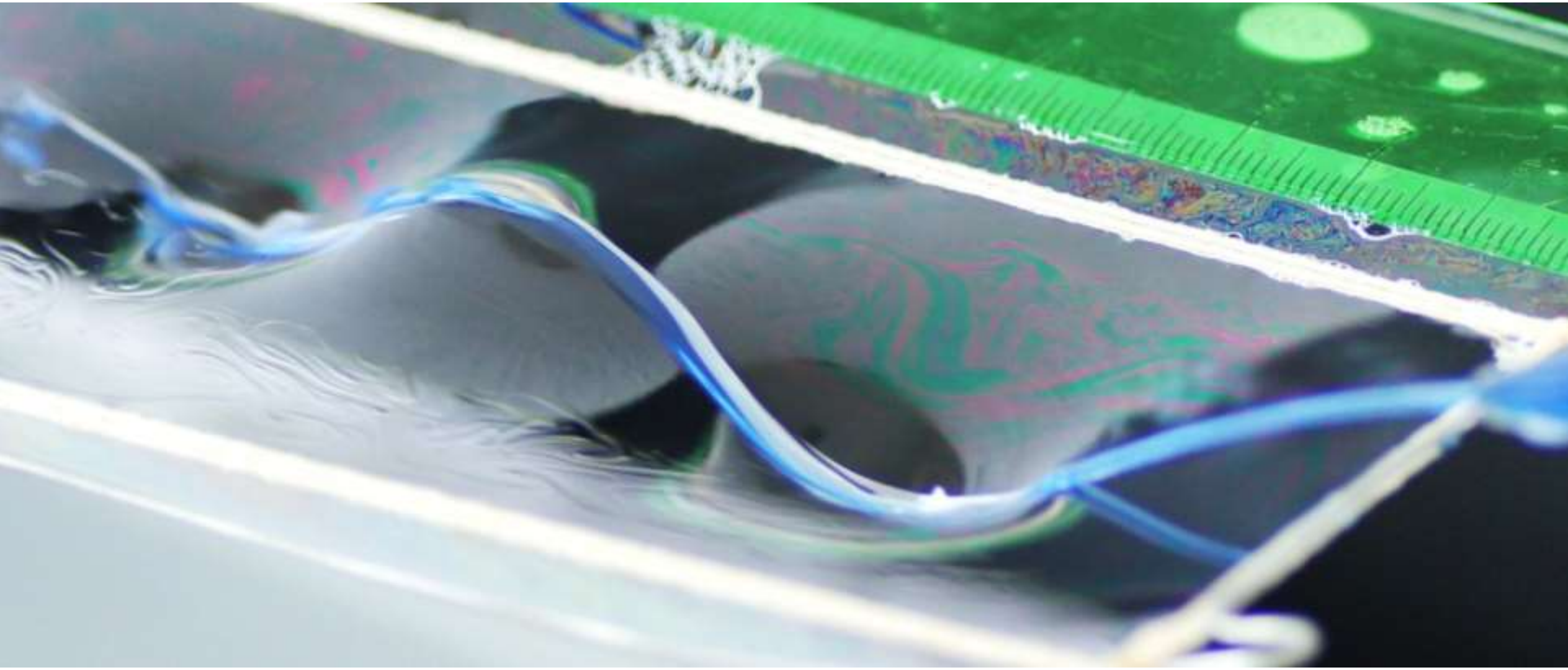
Undulation

Undulation

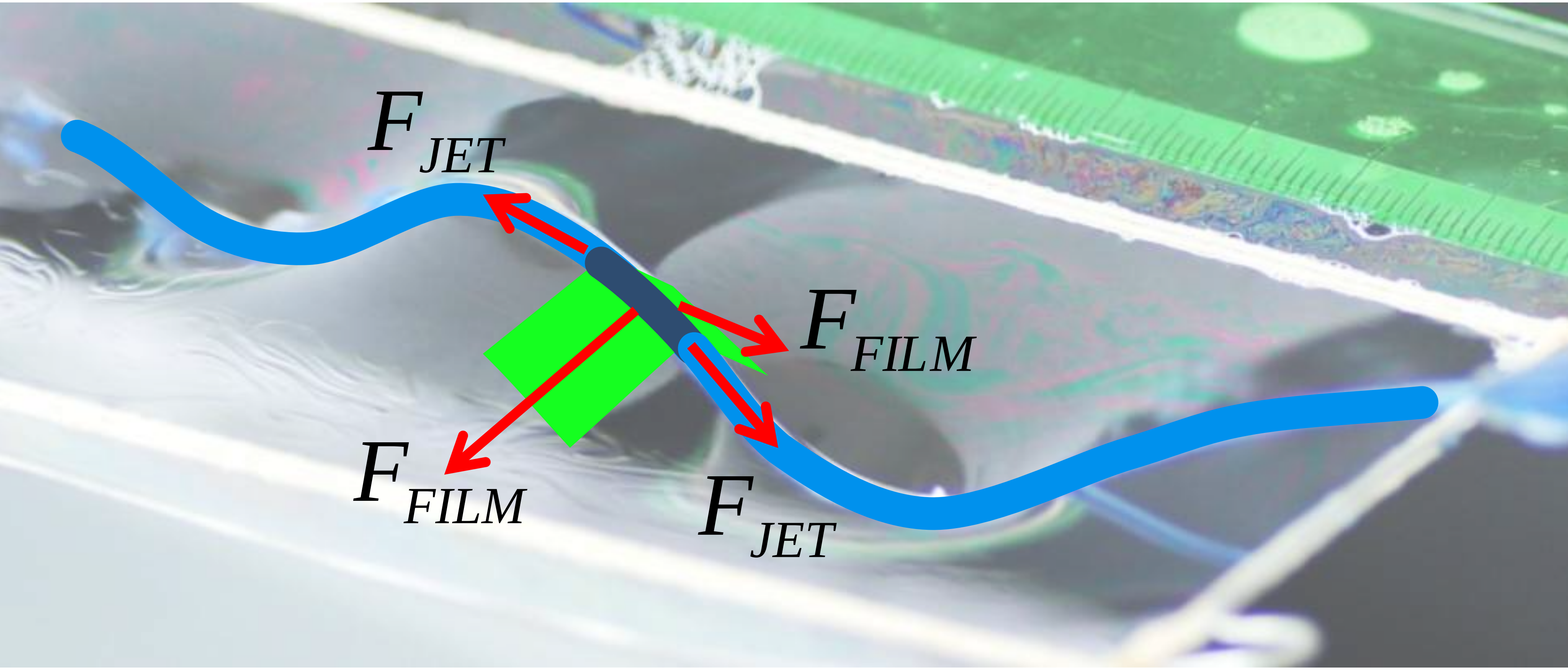


(Jet coloured by blue ink)

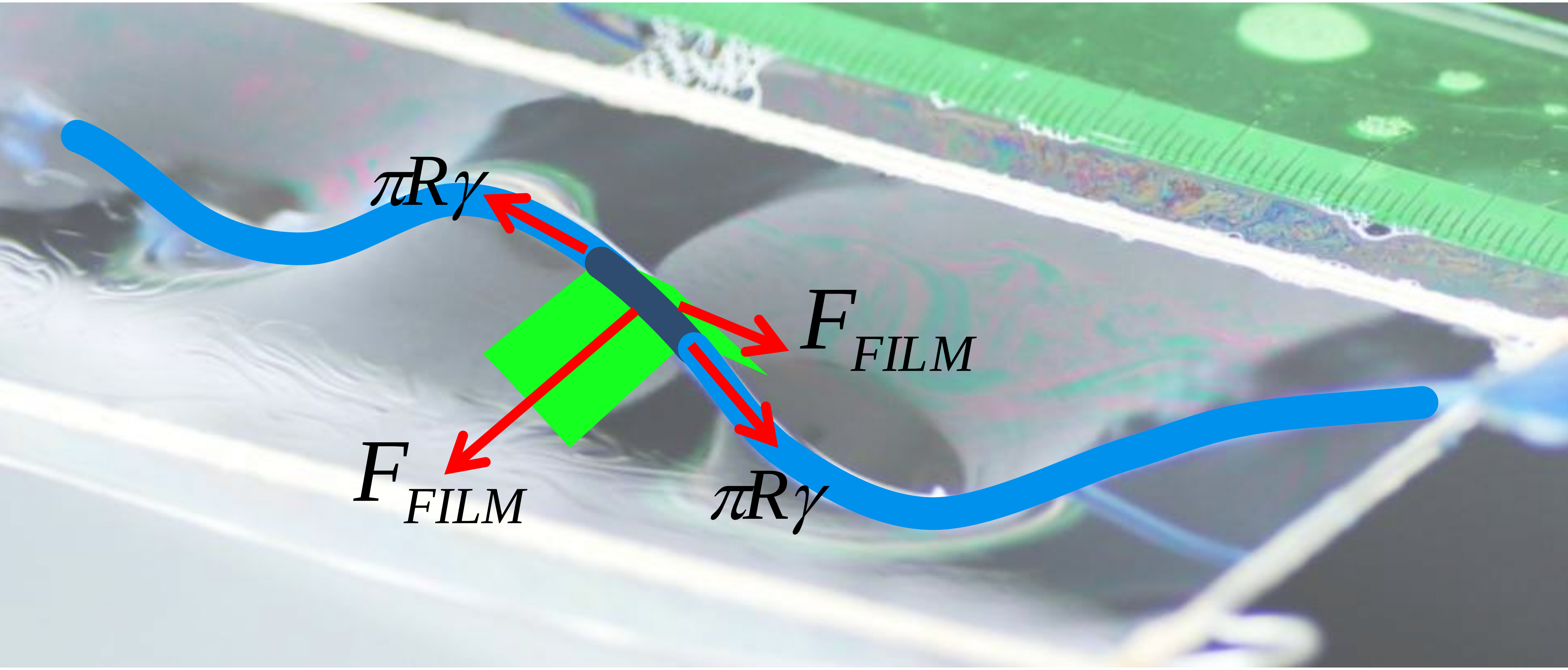
Force analysis



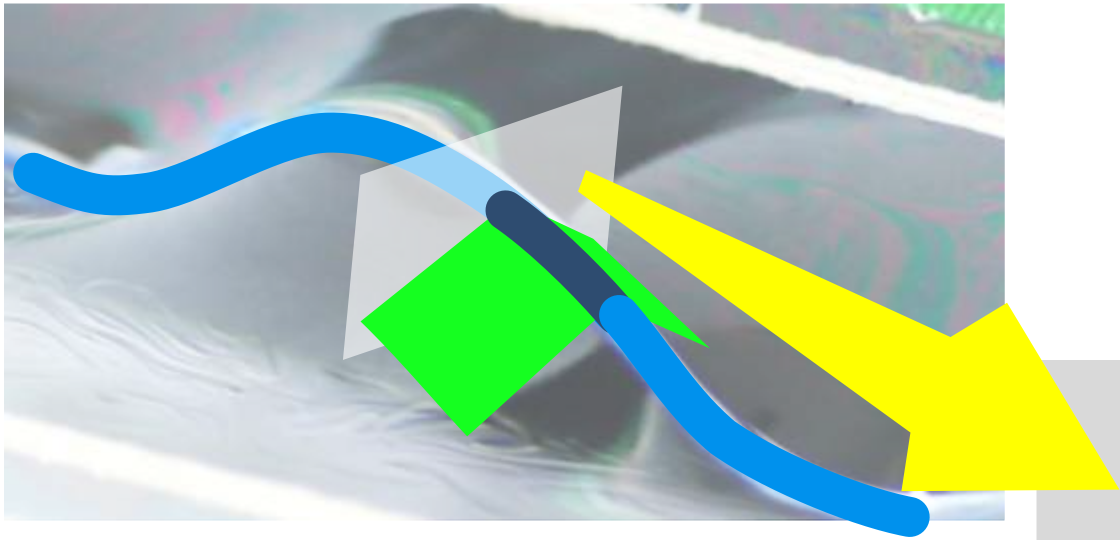
Forces on jet element

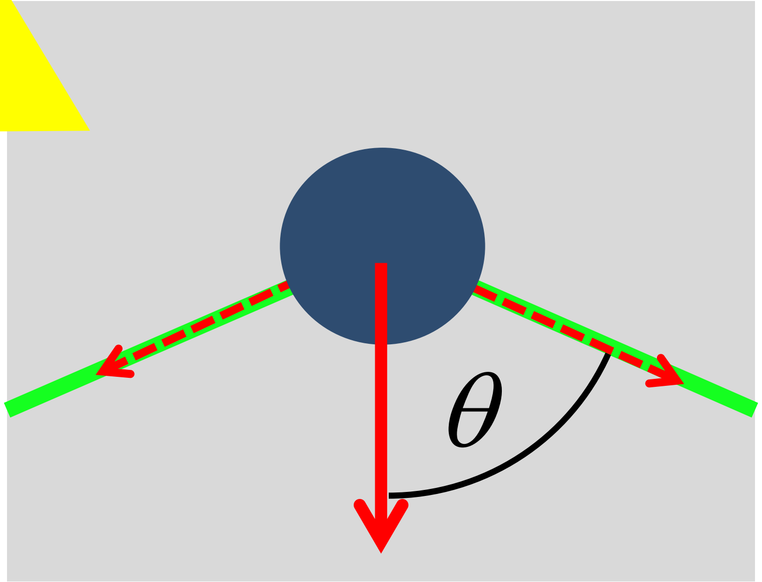


Forces on jet element



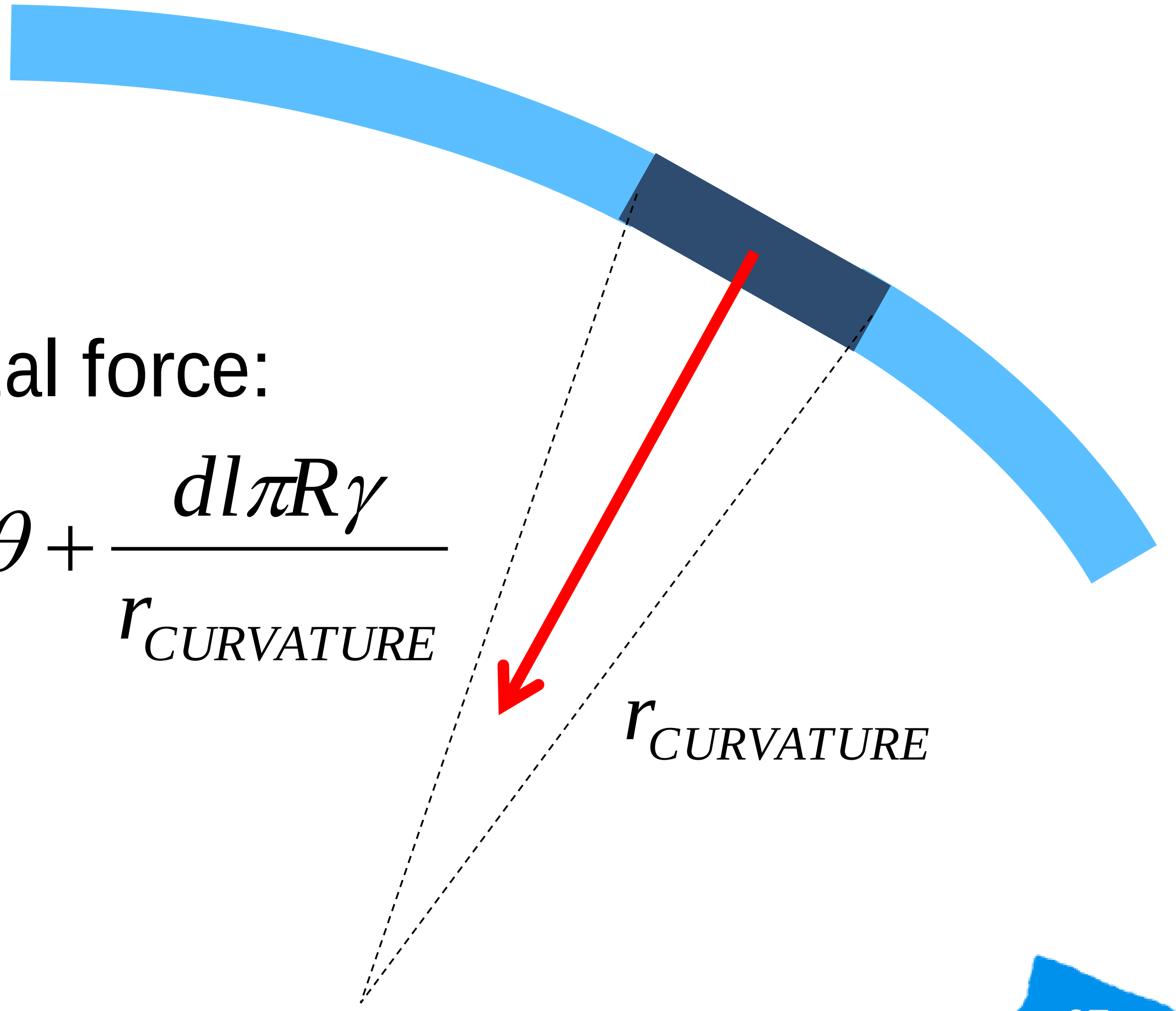
Force of the film – jet cross section





$$F_{FILM} = 4dl\gamma\cos\theta$$

Net force on jet element

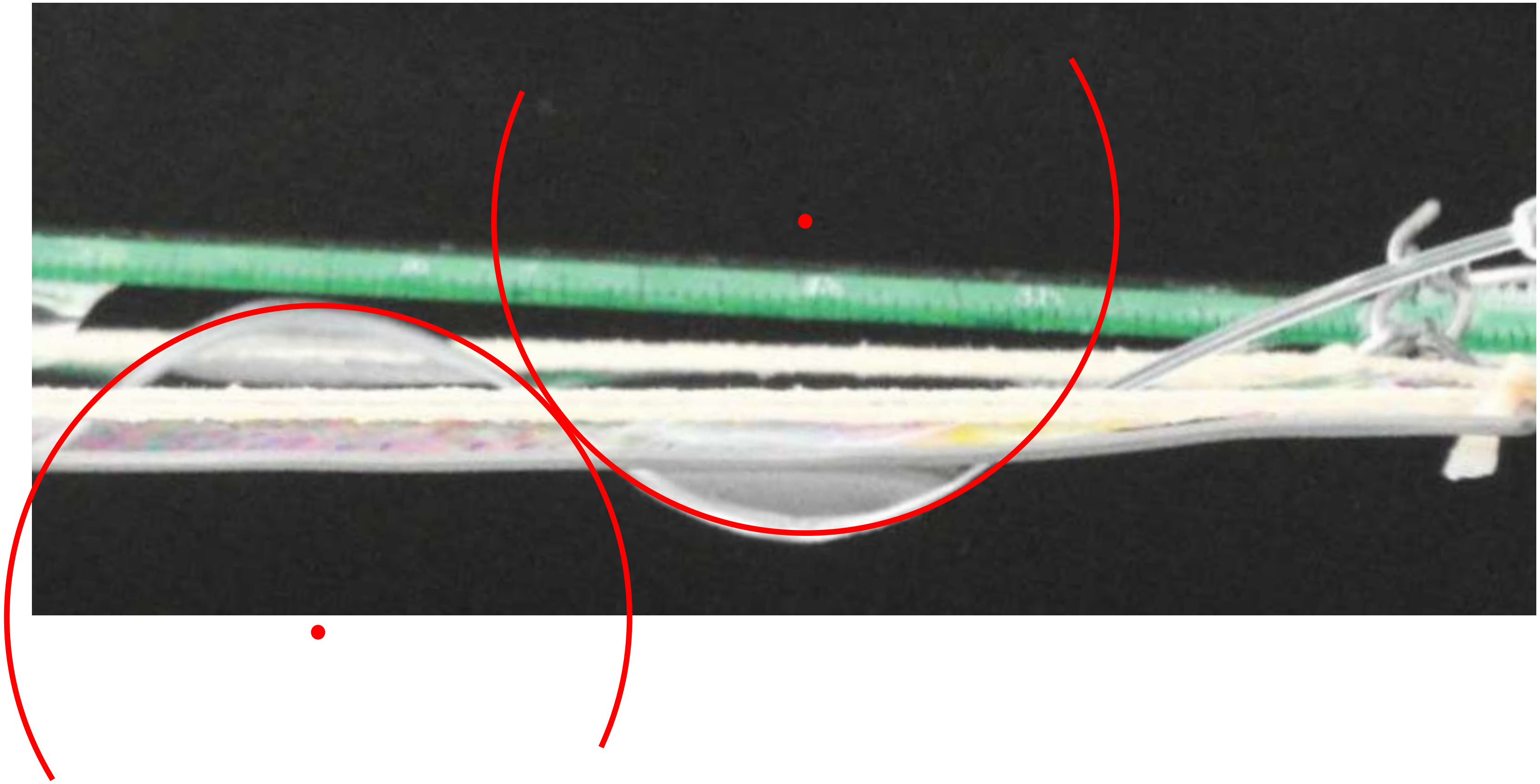


Centripetal force:

$$4dl\gamma\cos\theta+\frac{dl\pi R\gamma}{r_{CURVATURE}}$$

Kirstetter: Approximation – circle arcs

- Constant centripetal force



Kirstetter: Theoretical prediction

- Radius of curvature (based on centripetal force):

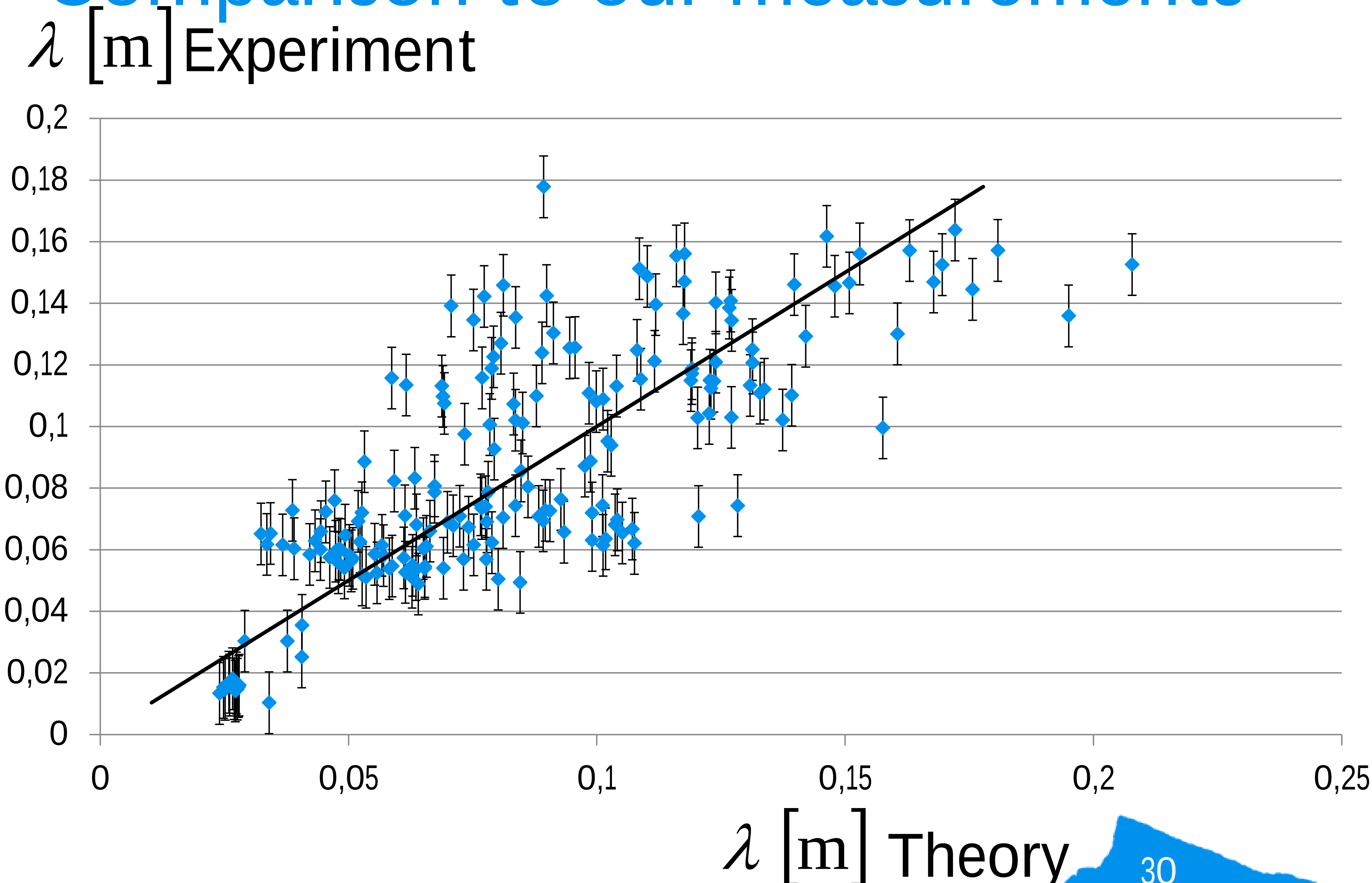
$$r_{CURVATURE} = \frac{\pi R(W_e - 1)}{4\cos\theta} \qquad W_e = \frac{\rho v^2 R}{\gamma}$$

- Assuming: $|\cos\theta|$ is constant (i.e. circle arcs):

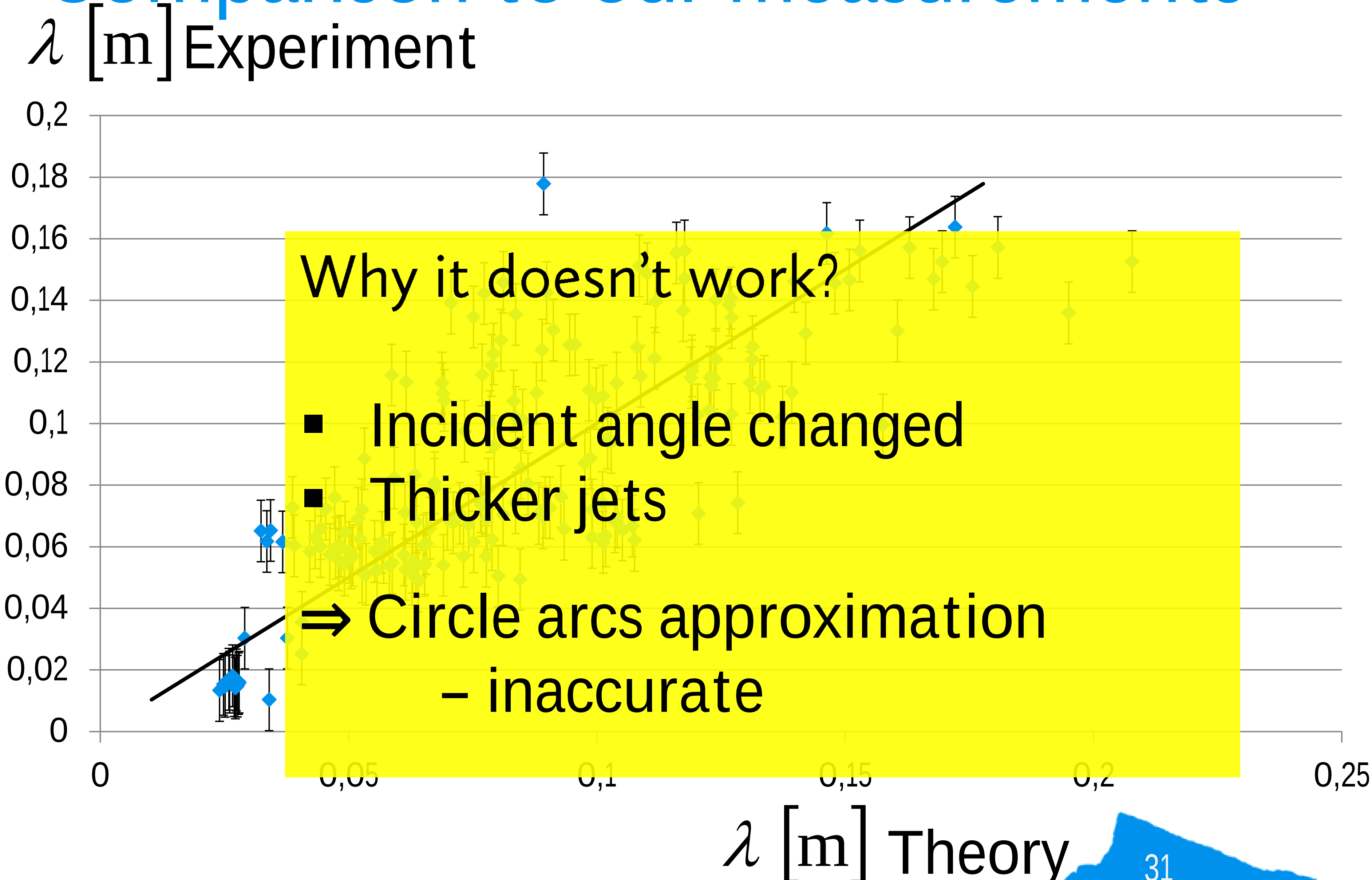
$$\lambda = \frac{\pi}{|\cos\theta|} R(W_e - 1)\sin\alpha_{INCIDENT}$$

- Correlation with experiments with fitted $|\cos\theta|$

Comparison to our measurements



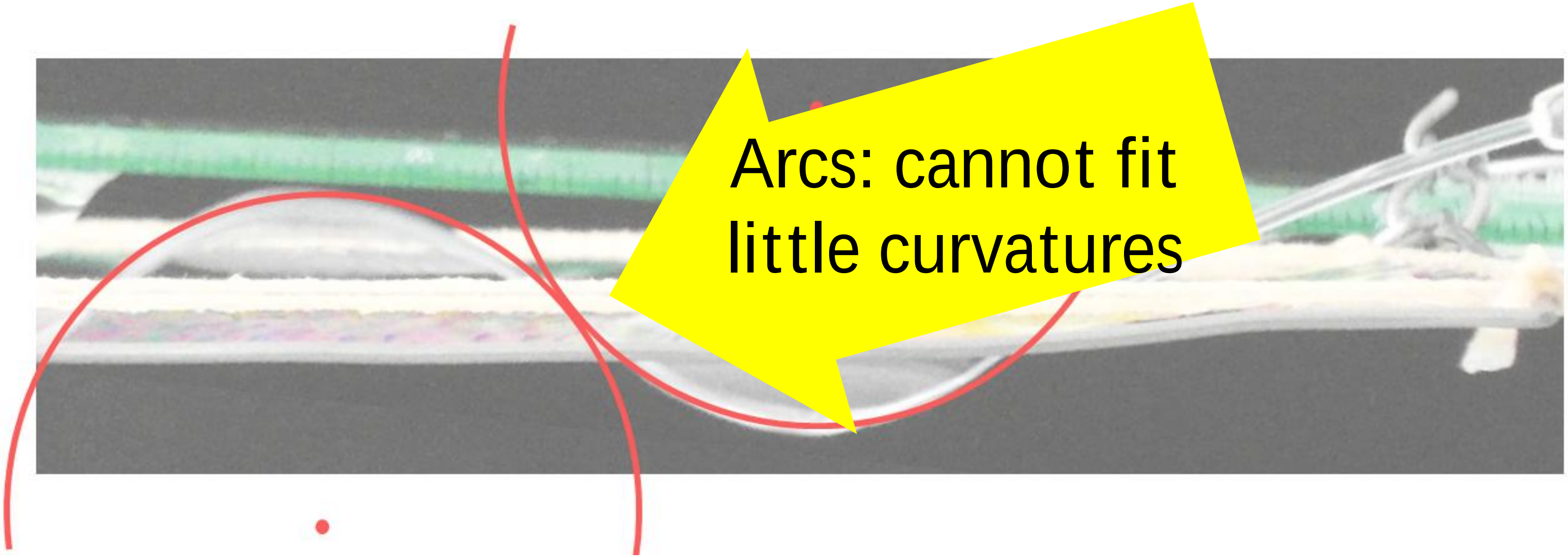
Comparison to our measurements



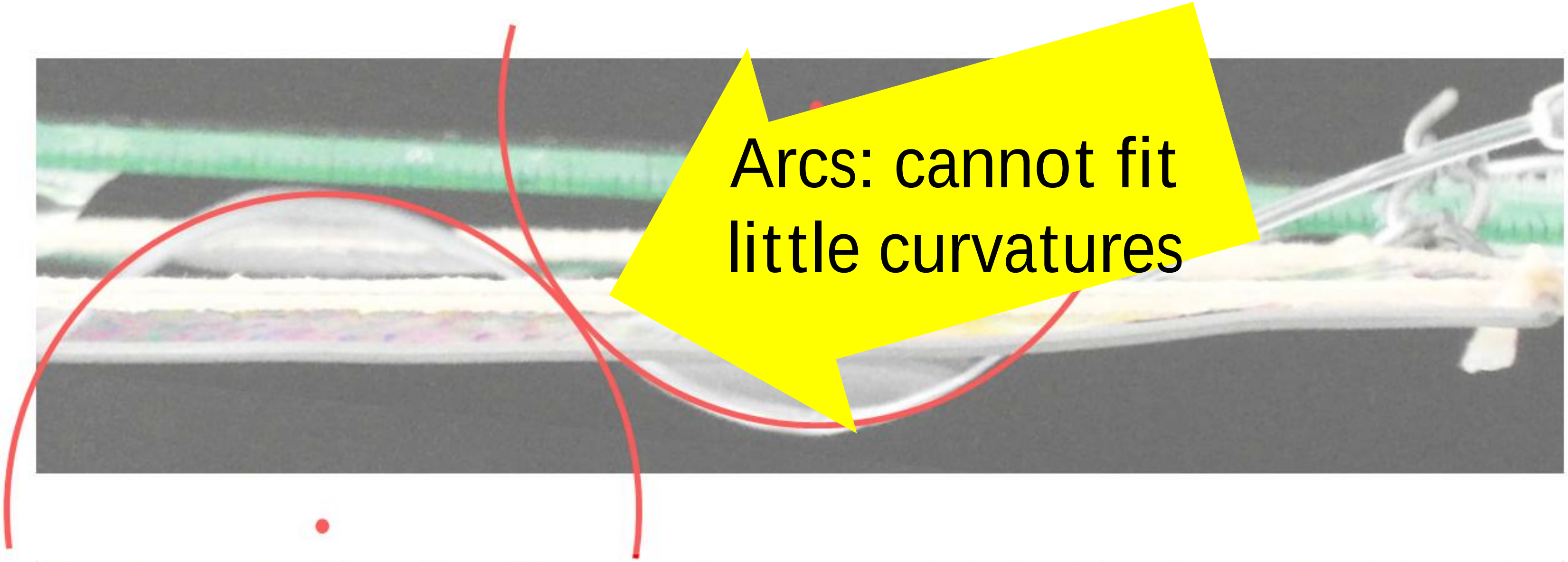
Why it doesn't work?

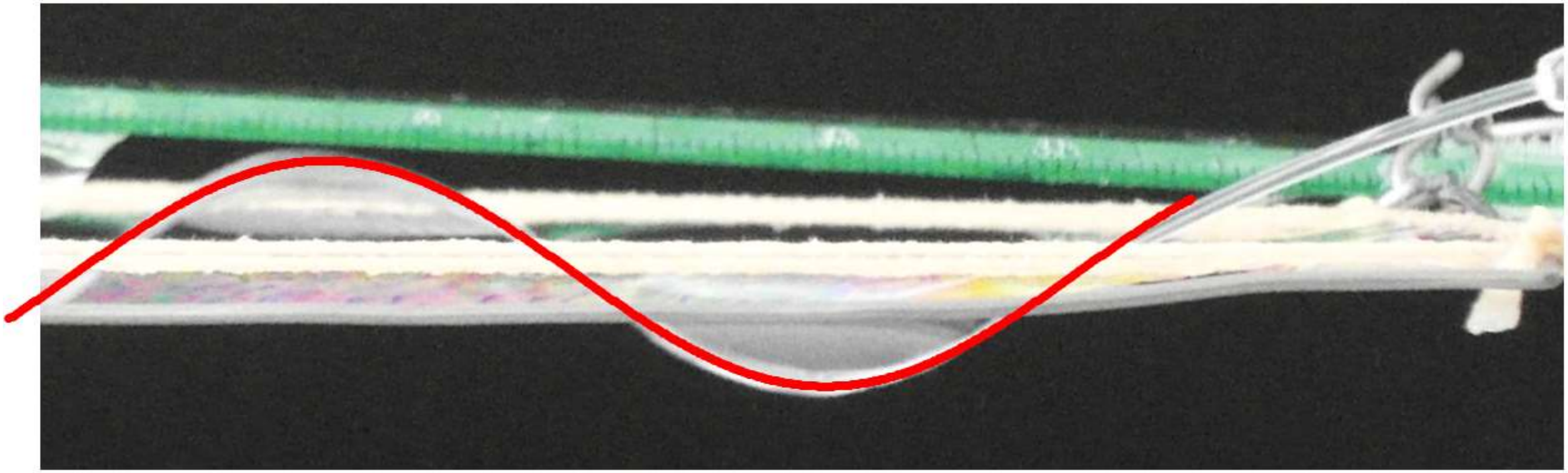
- Incident angle changed
- Thicker jets

⇒ Circle arcs approximation – inaccurate

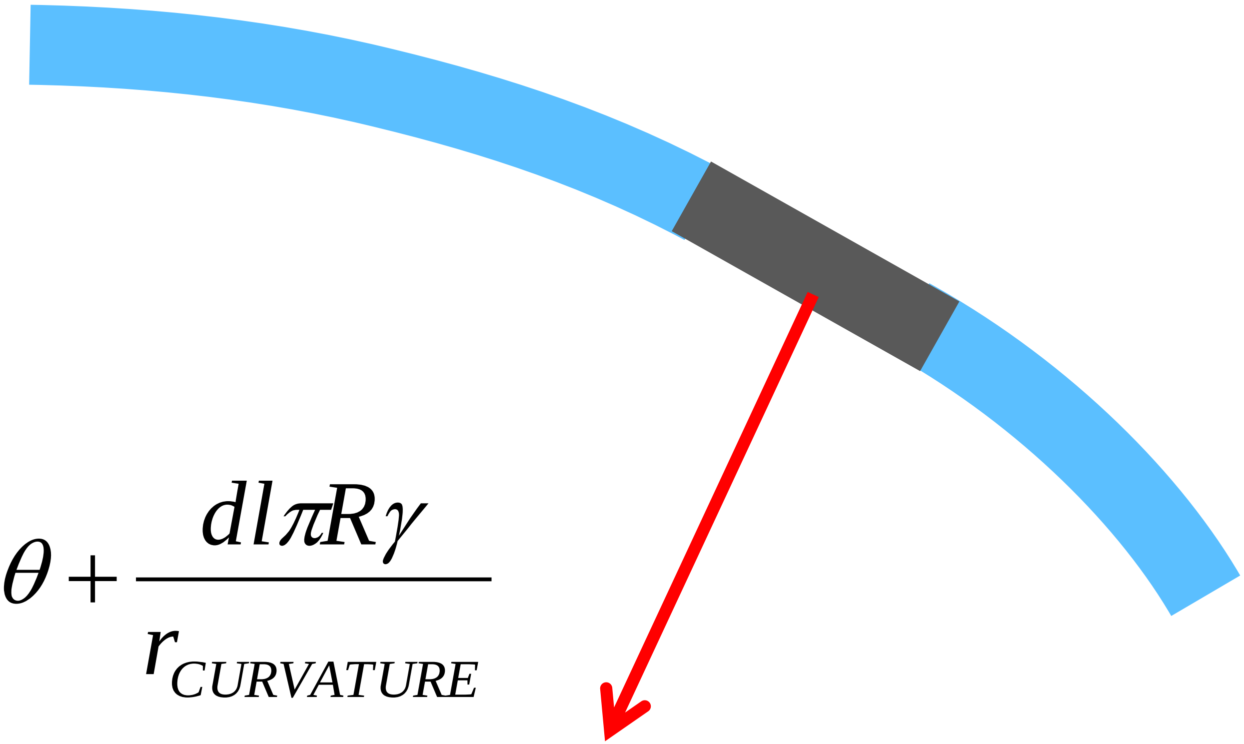

Arcs: cannot fit
little curvatures

Our approximation: sine function





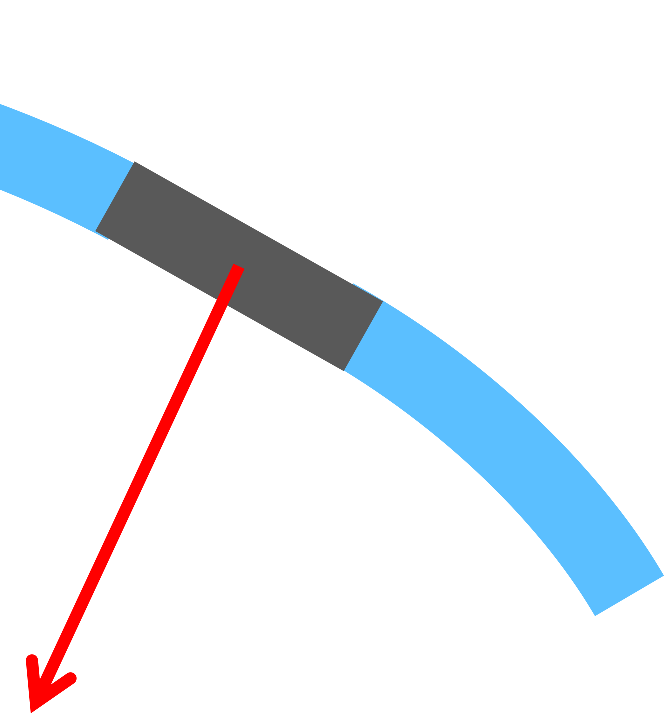
Sine shape approximation



$$4dl\gamma\cos\theta + \frac{dl\pi R\gamma}{r_{CURVATURE}}$$

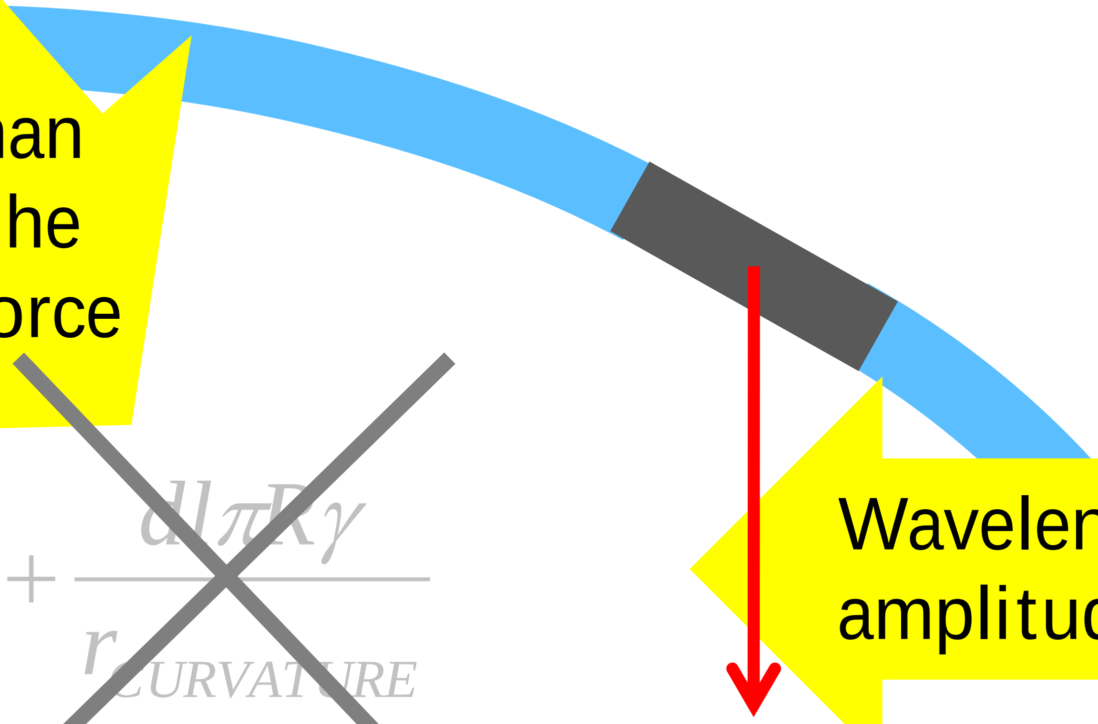
Sine shape approximation

Less than 3% of the total force



$$4dl\gamma\cos\theta + \frac{dl\pi R\gamma}{r_{CURVATURE}}$$

Sine shape approximation



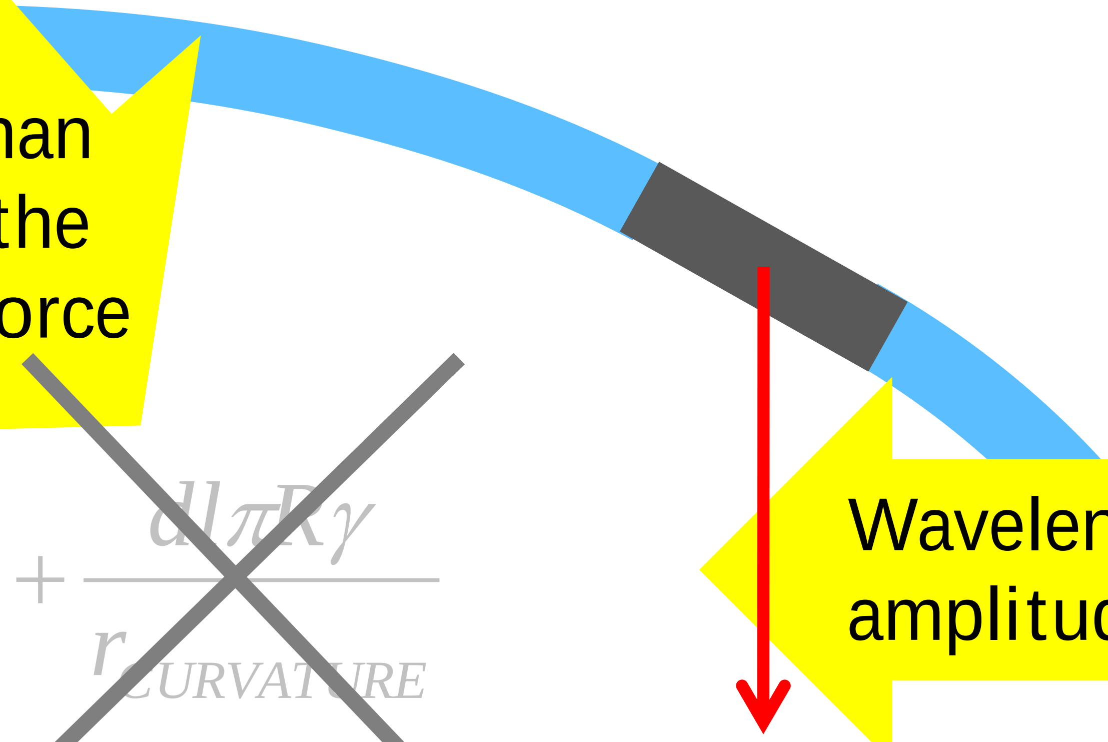
Less than 3% of the total force

$$4dl\gamma\cos\theta + \frac{dl\pi R\gamma}{r_{CURVATURE}}$$

Wavelength >> amplitude

Sine shape approximation

Less than 3% of the total force



Wavelength >> amplitude

$$4dl\gamma\cos\theta + \frac{dl\pi R\gamma}{r_{CURVATURE}}$$

$$\cos\theta = -ky$$

Zero force at y=0, increases with |y|

Shape – theoretical prediction

Constant speed in x direction,
harmonic oscillations in y direction

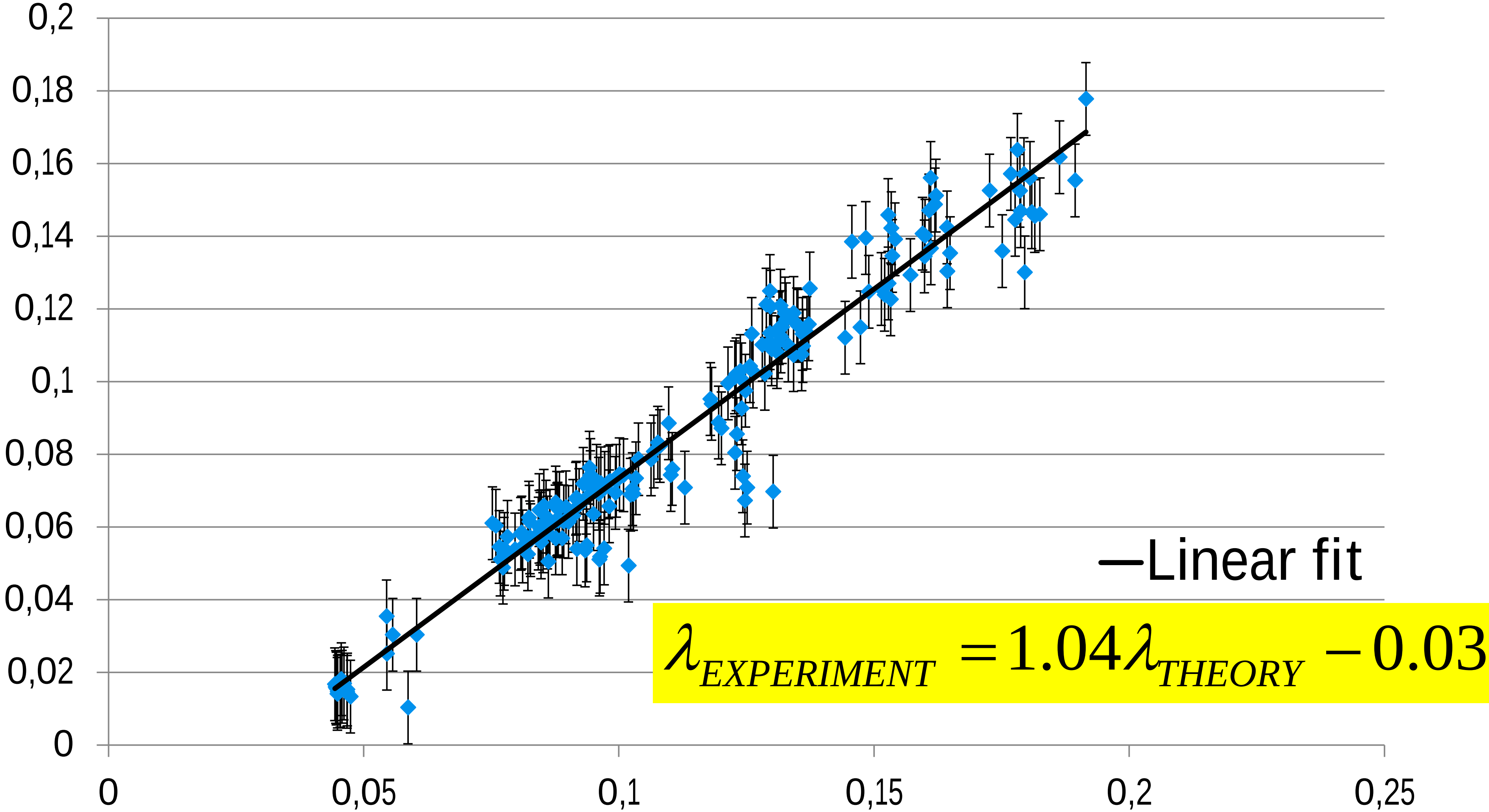
$$y(x) = A\sin\left(\frac{2\pi}{\lambda}x\right)$$

Wavelength $$\lambda = \pi R v \sin\alpha \sqrt{\frac{\pi\rho}{\gamma k}}$$

Amplitude $$A = \frac{1}{2} R v \cos\alpha \sqrt{\frac{\pi\rho}{\gamma k}}$$

free parameter $\boldsymbol{k}$

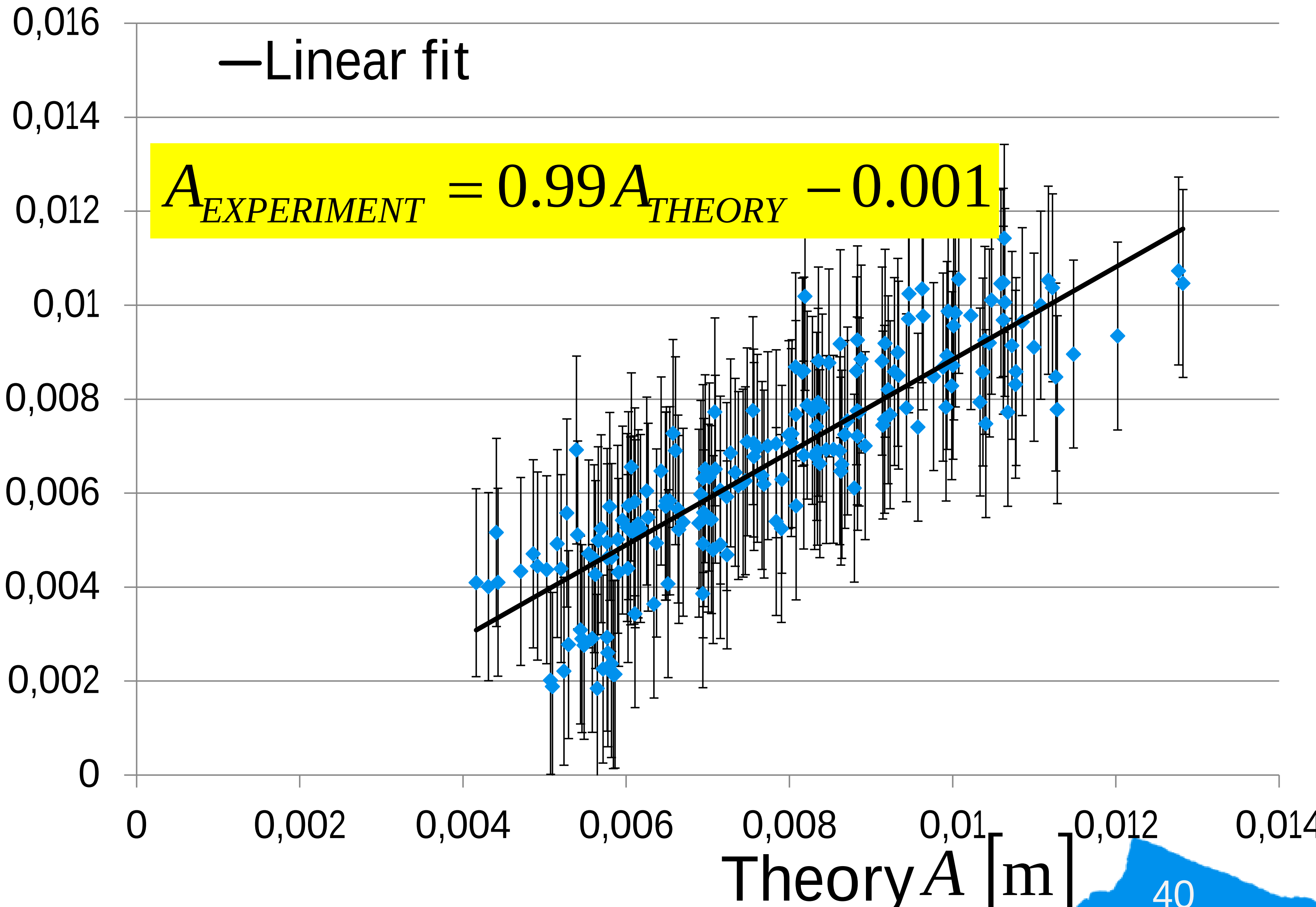
λ [m] Experiment $\quad k = 114 m^{-1}$



Theory λ [m]

$A\,[\mathrm{m}]$ Experiment

$k = 114 m^{-1}$



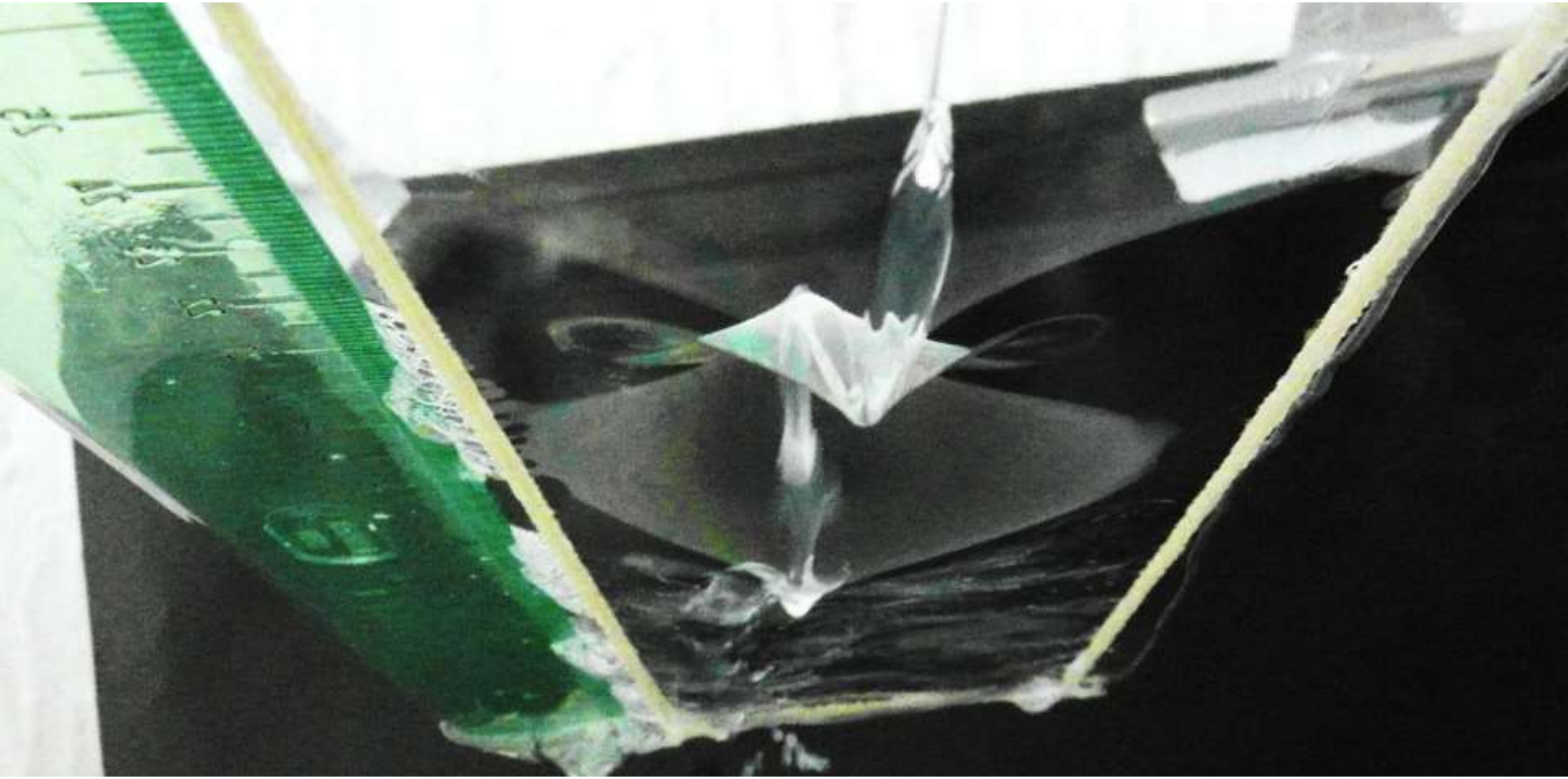
Summary

- 3 modes of interaction studied
- Existing theory verified, discrepancies explained, novel approach in case of undulation
- Greater jet radii, incident angle changed and amplitude investigated

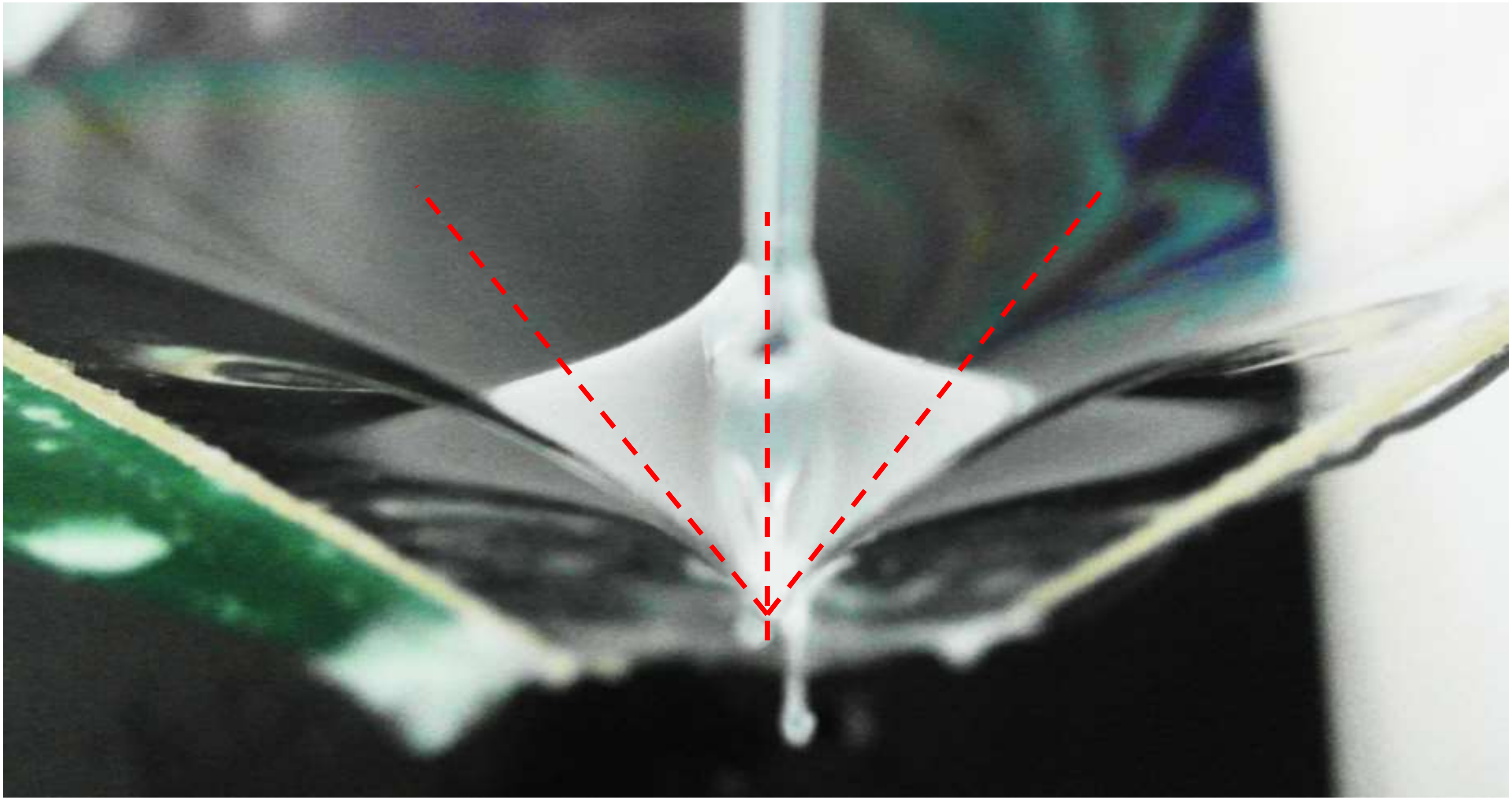
APPENDICES

8. Jet and film

View from below the film



View from below the film



Parameters

Fixed:

- Liquid $\rho = 1000 kg/m^3$ $\gamma = 0.025 kg/s^2$

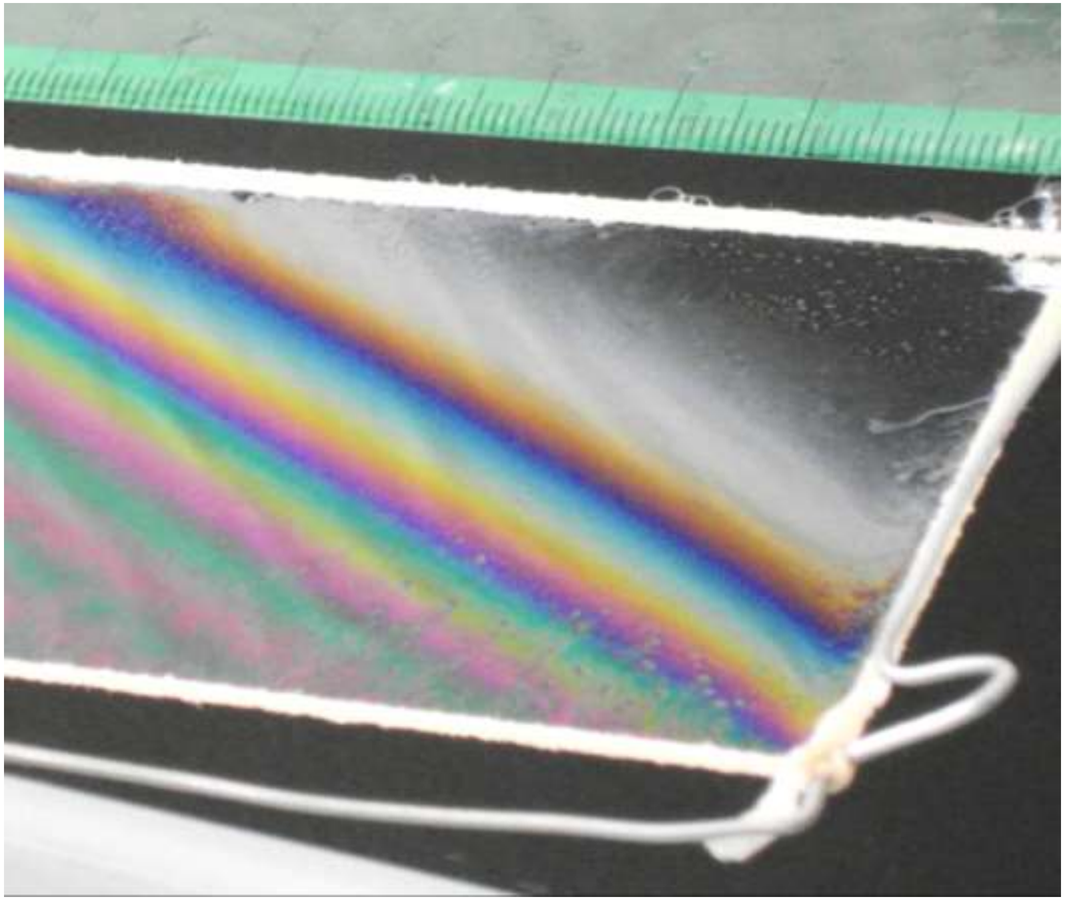
Varied:

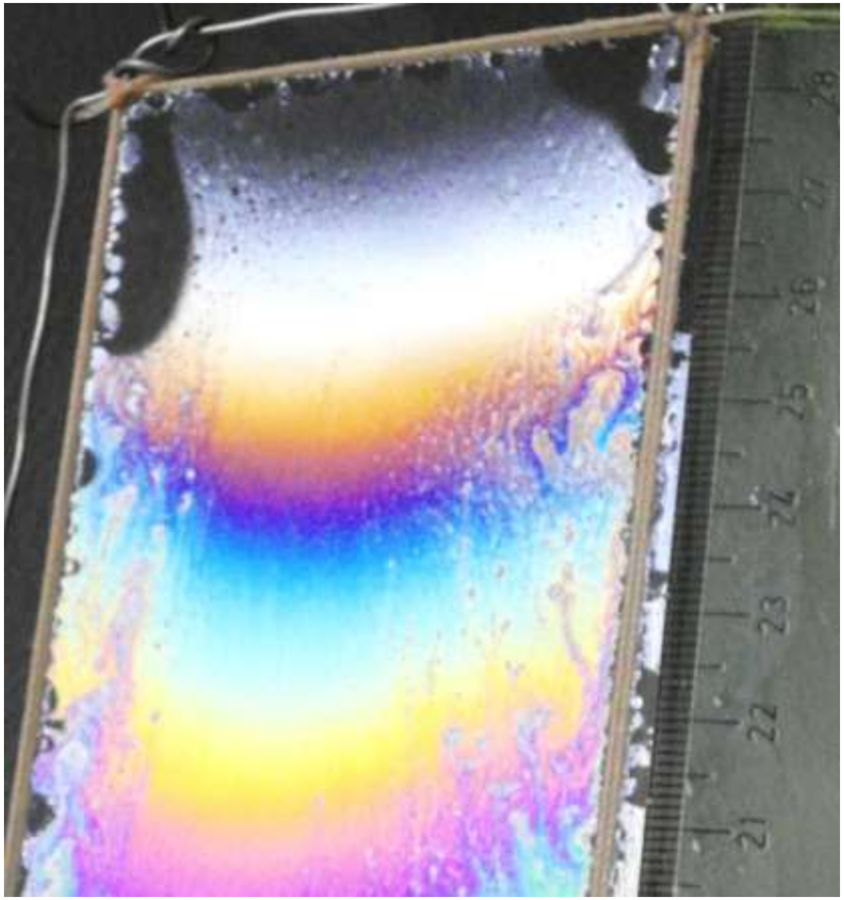
- Jet radius $r = 0.36mm;\ r = 0.52mm$
- Incident angle $30° < \alpha < 80°$ *waves*
  $12° < \alpha < 45°$ *refraction*
- Incident speed $1.5m/s < v < 5m/s$ *waves*
  $v = 1.7m/s$ *refraction*

Surface tension measurement

- Counting drops from a pipet
- Comparing to number of drops of deionized water (known surface tension)
- Calculating the mass of a single drop; $$\frac{m_1}{\gamma_1} = \frac{m_2}{\gamma_2}$$
- Soap water $m_2 \approx 0.02g$
- Deionized water $m_2 \approx 0.06g$

Thickness of the film

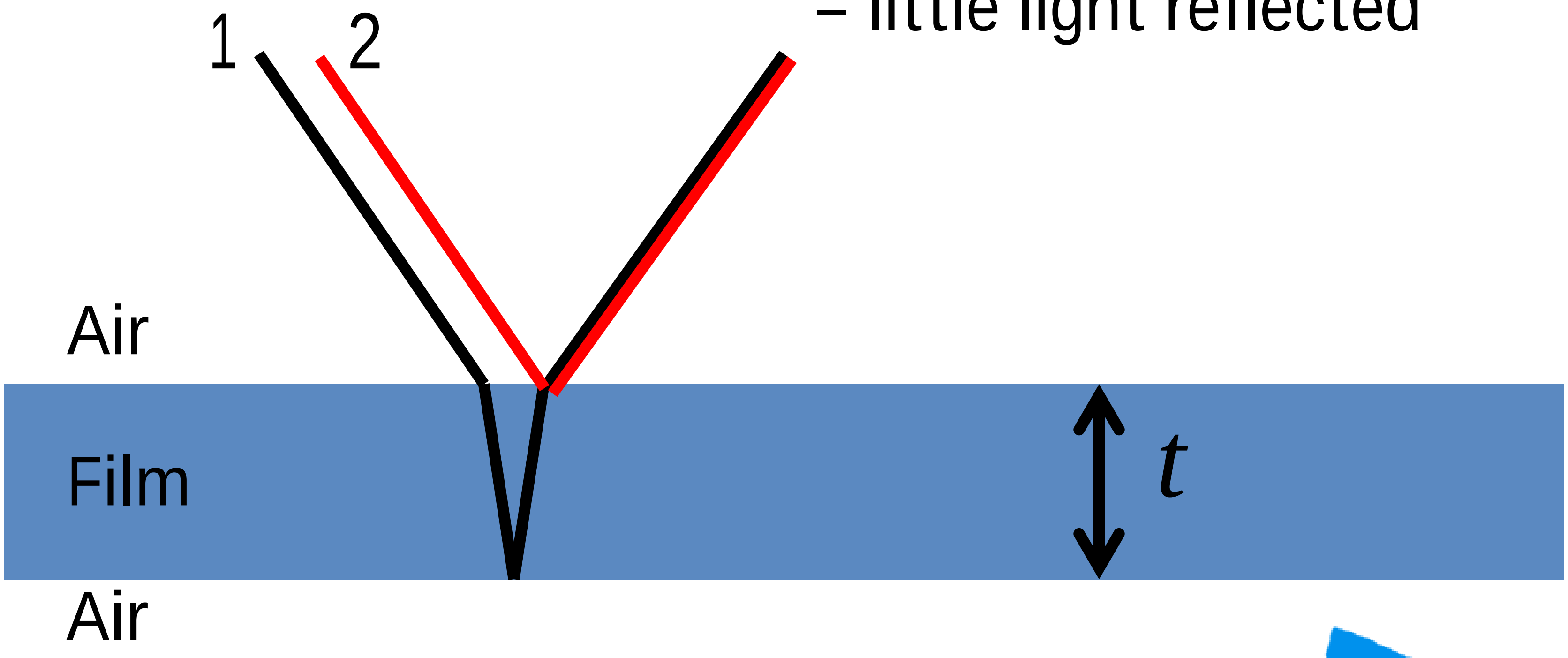




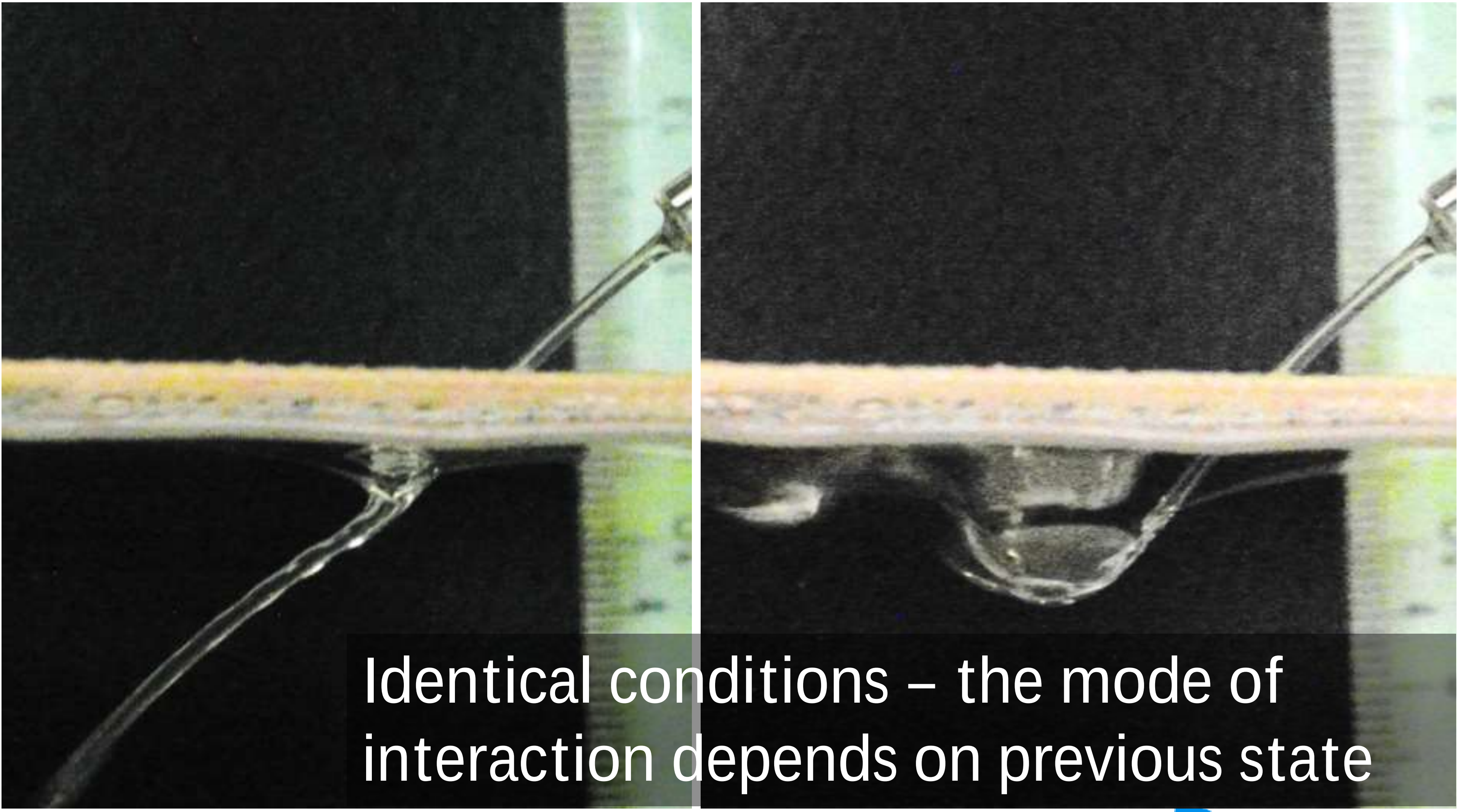
Interference on a thin film

- Path difference $\propto t$
- 180° phase shift (beam 2)

Small t:
Destructive interference of all visible light
– little light reflected



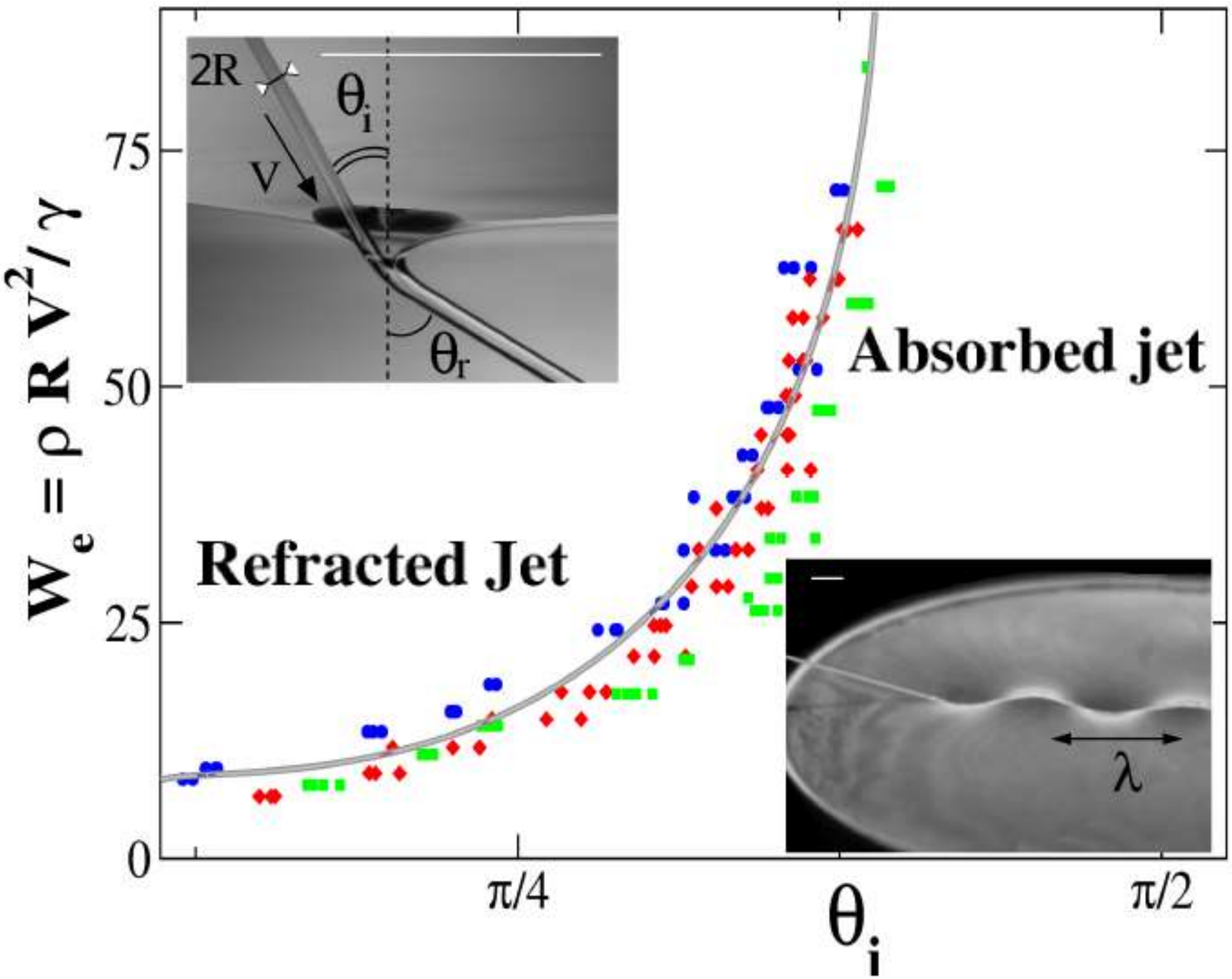
"Hysteresis"



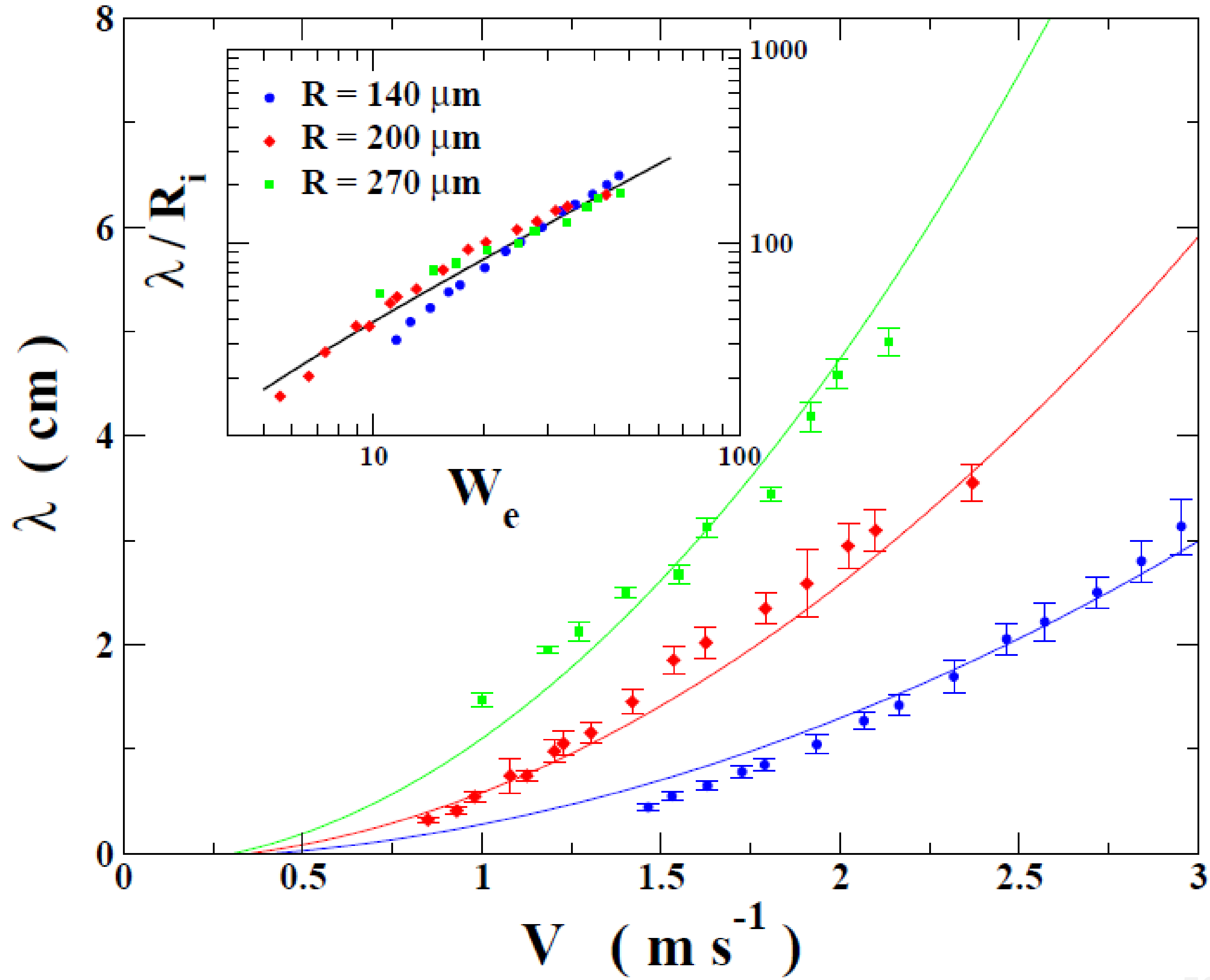
Identical conditions – the mode of interaction depends on previous state

Apparatus

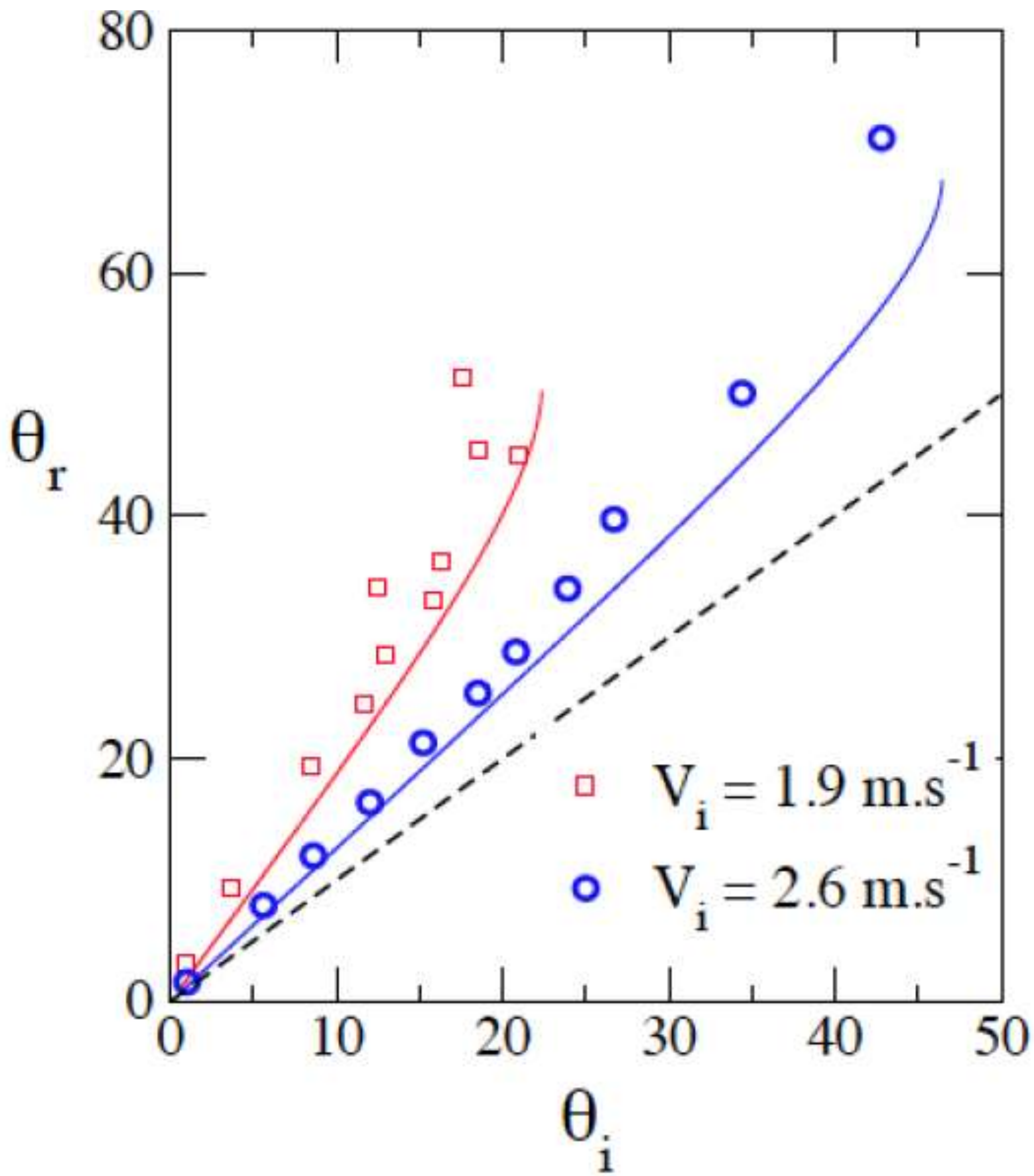
Diagram (regions)



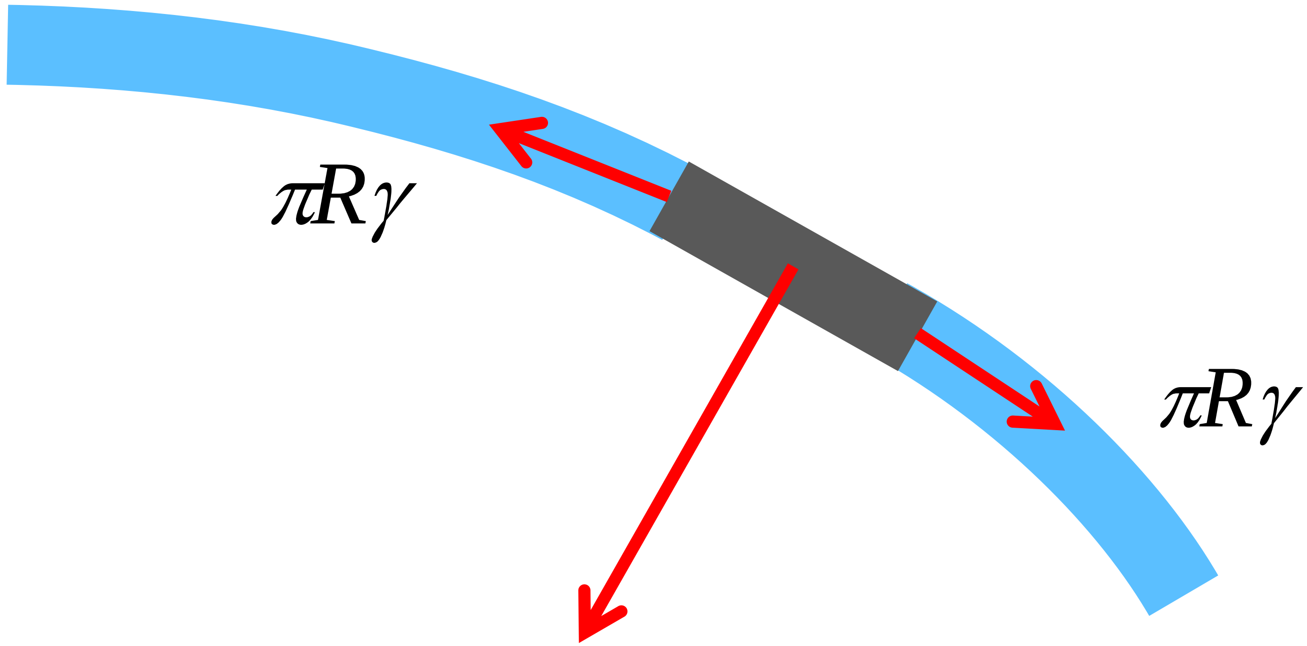
Undulation


8
6
4
2
0
λ (cm)
0
0.5
1
1.5
2
2.5
3
V (m s-1)
R = 140 µm
R = 200 µm
R = 270 µm
λ / Ri
1000
100
10
100
We

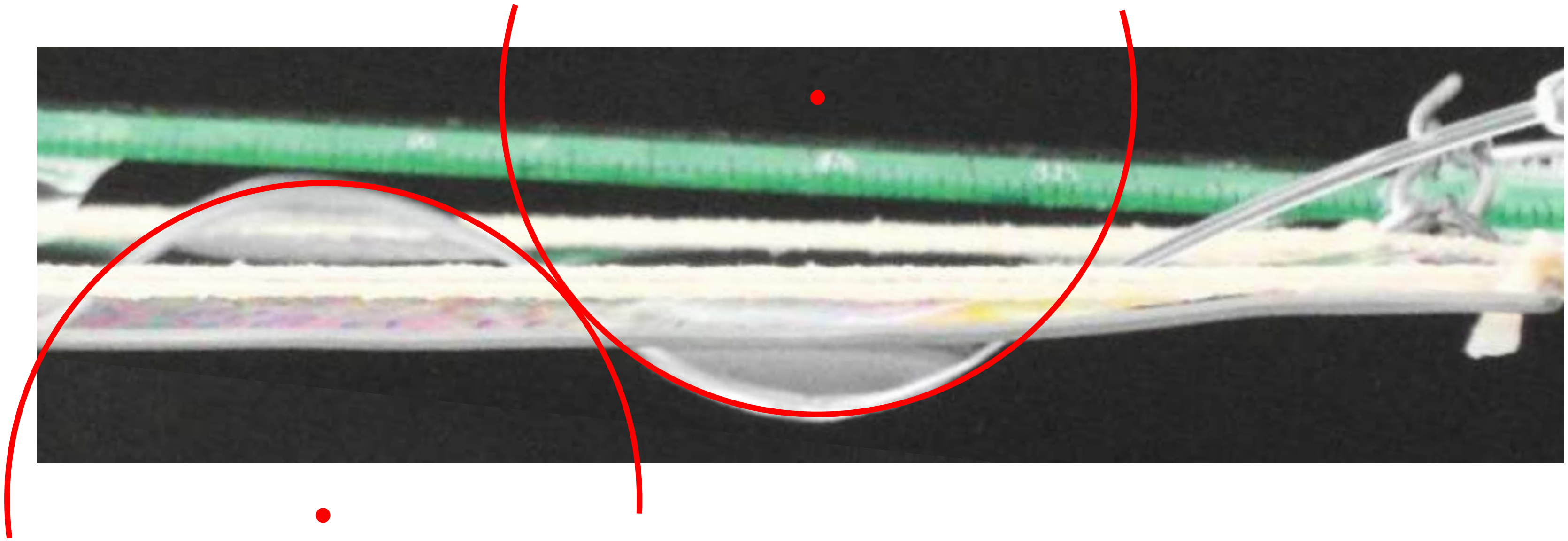
Refraction

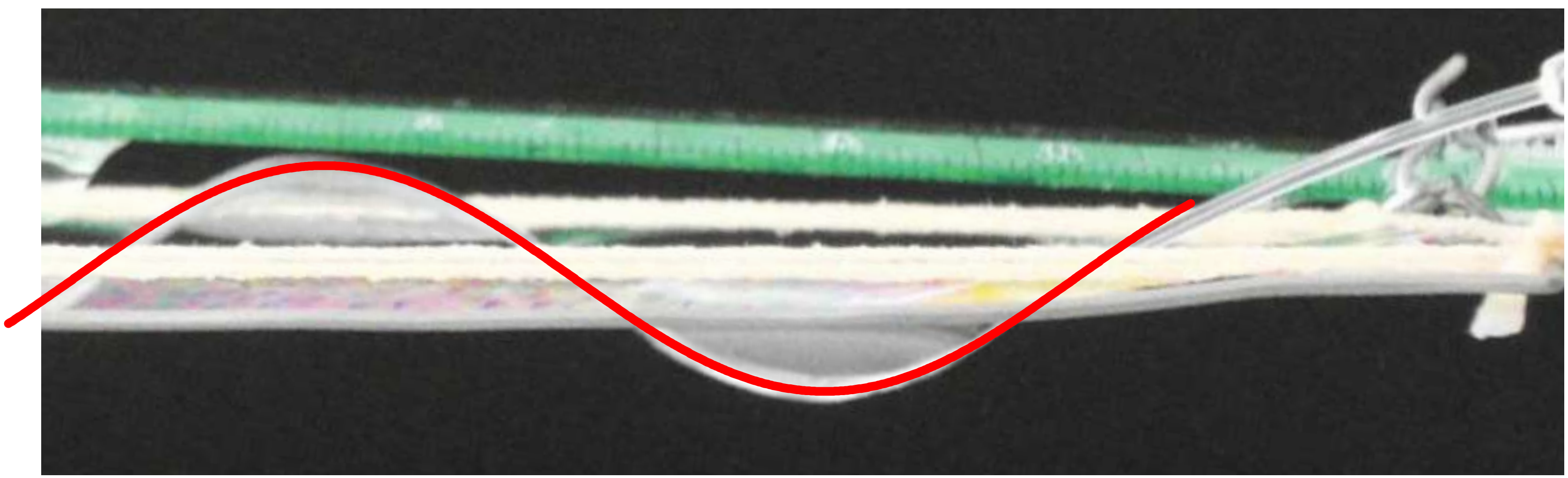


Forces on jet element

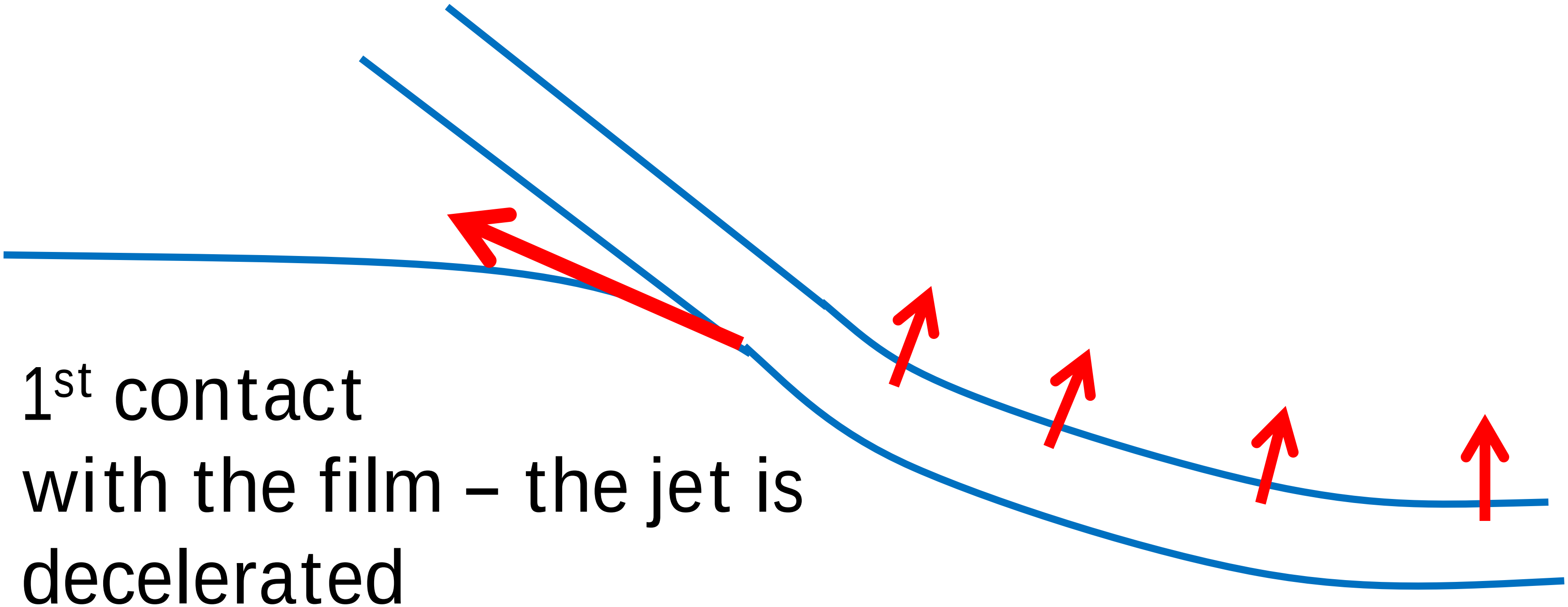


$$F_{FILM} = 4dl\gamma\cos\theta$$





Velocity change upon impact

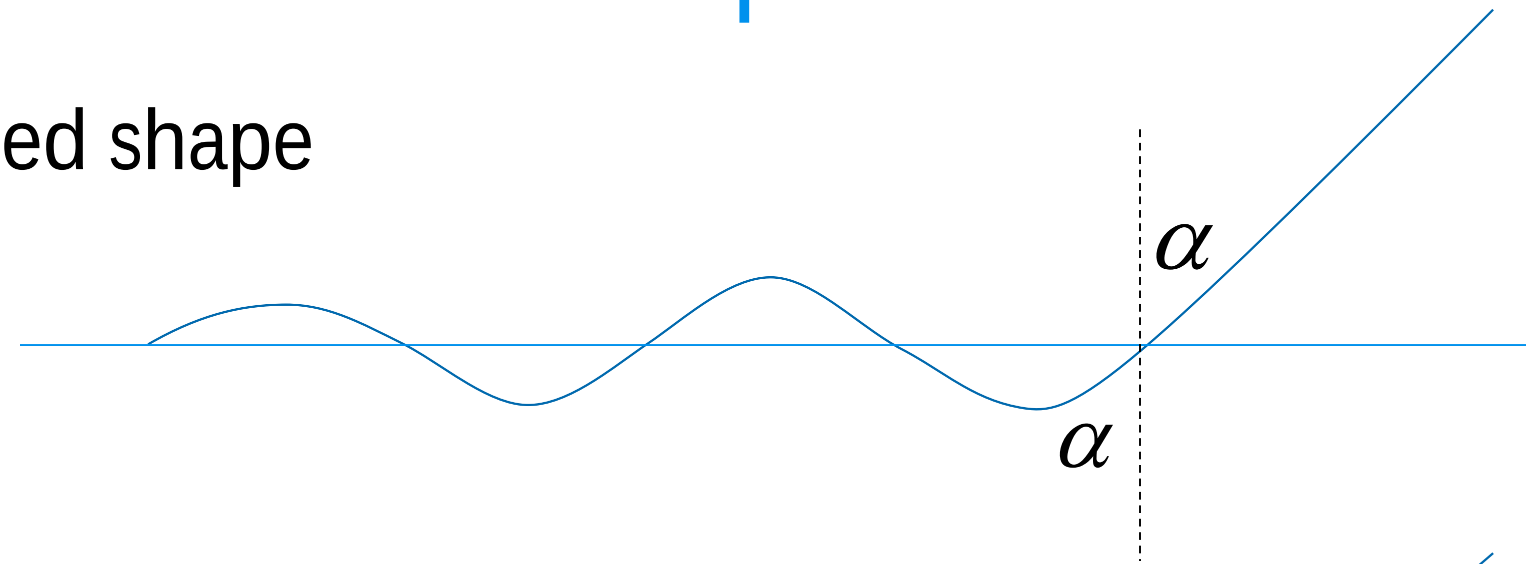


1st contact with the film – the jet is decelerated

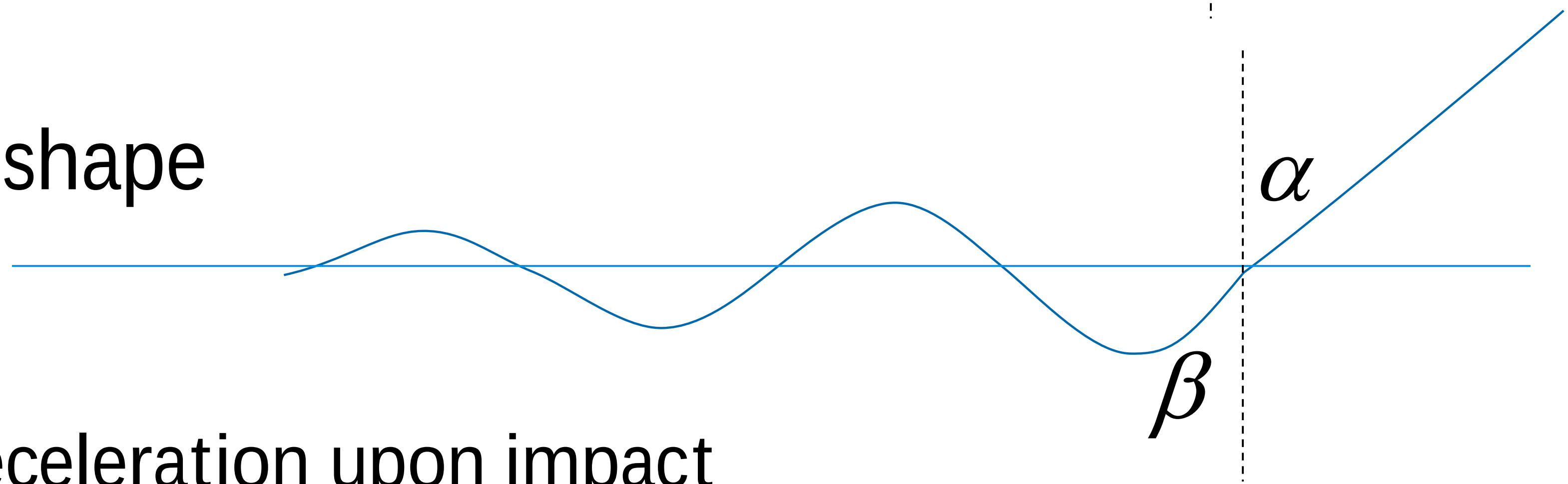
→ Smaller waves than we would expect

Undulation – sine shape

- Expected shape

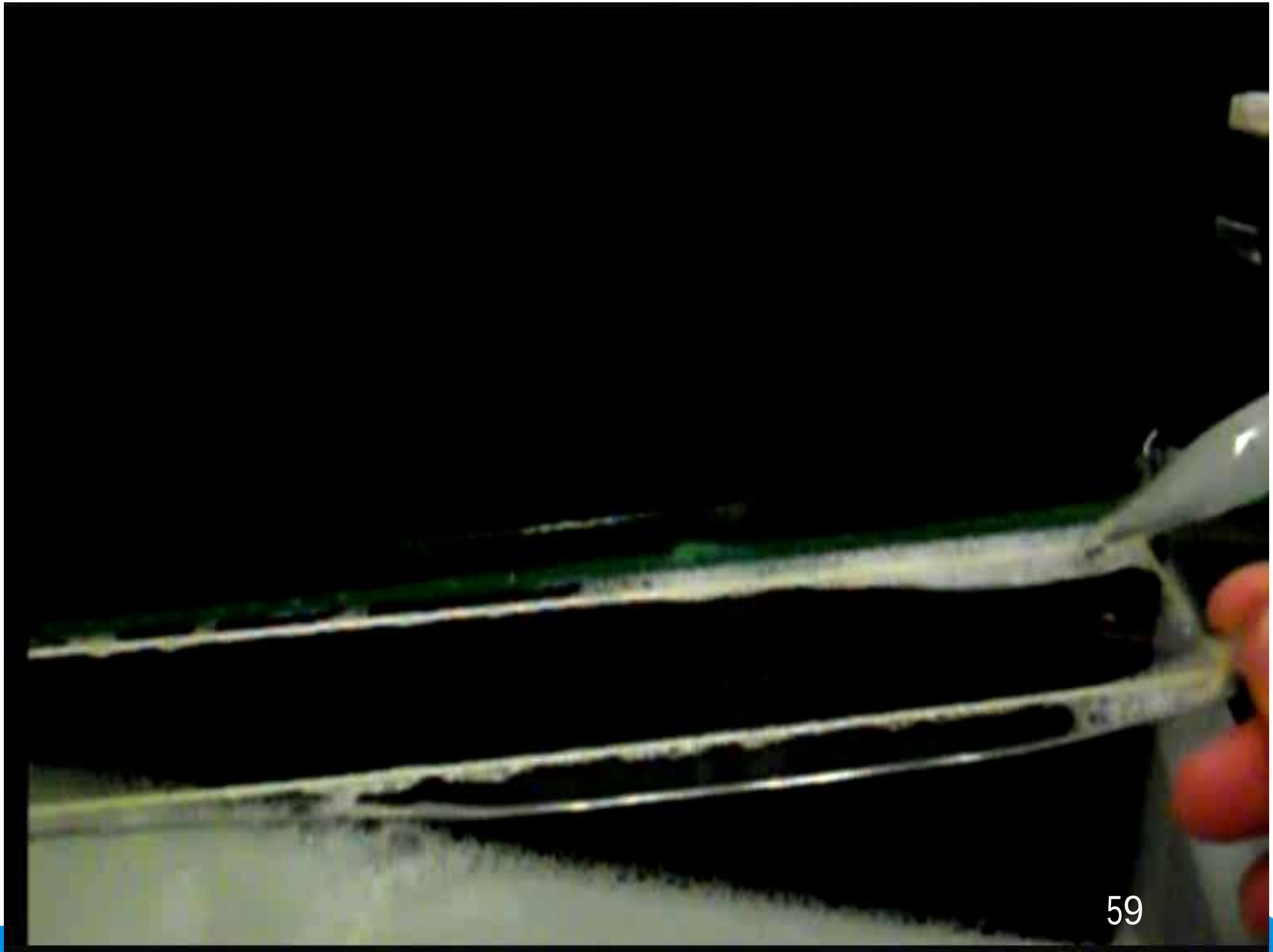


- Real shape



  - Deceleration upon impact

Whole video



“Refraction” of the jet