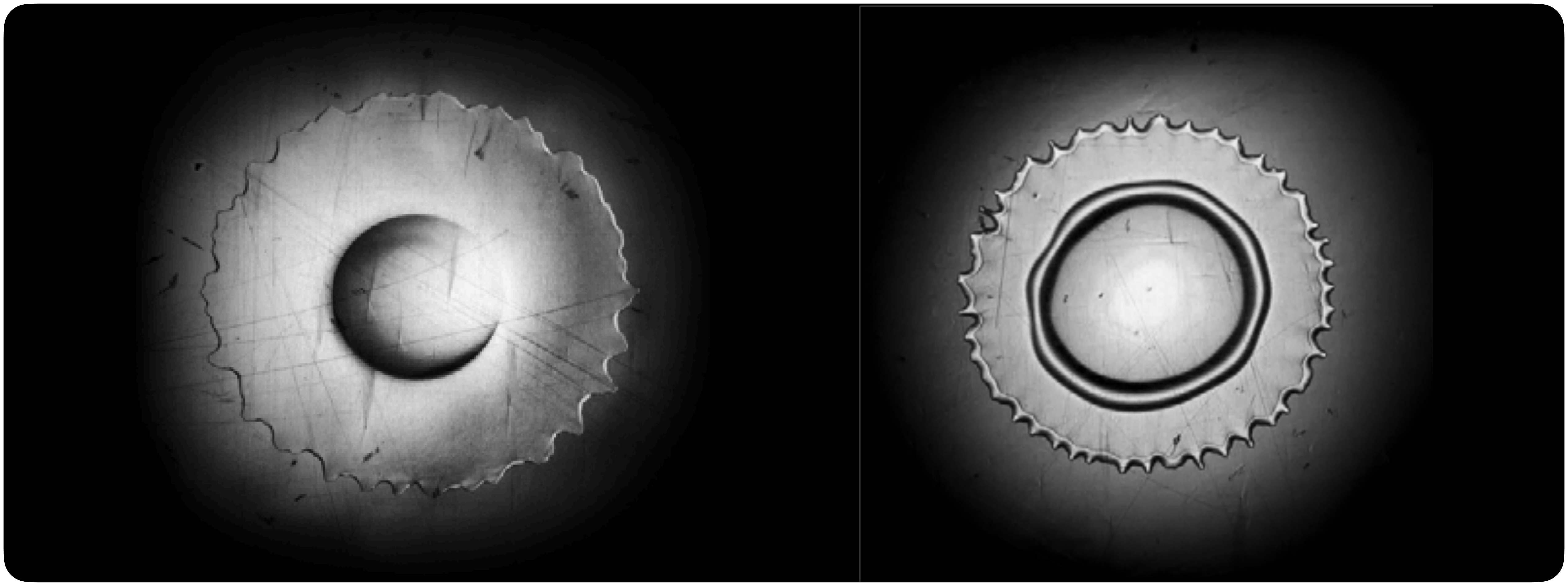
STORY OF A FREEZING DROP IMPACT



Thomas Séon, Virgile Thiévenaz
(Institut ∂'Alembert, CNRS & UPMC, Paris, France)
Christophe Josserand
(LadHyX, École Polytechnique, Palaiseau)

CONTEXT IN ENVIRONMENT

Ice waterfall,
ice stalagmite,
icicle ...

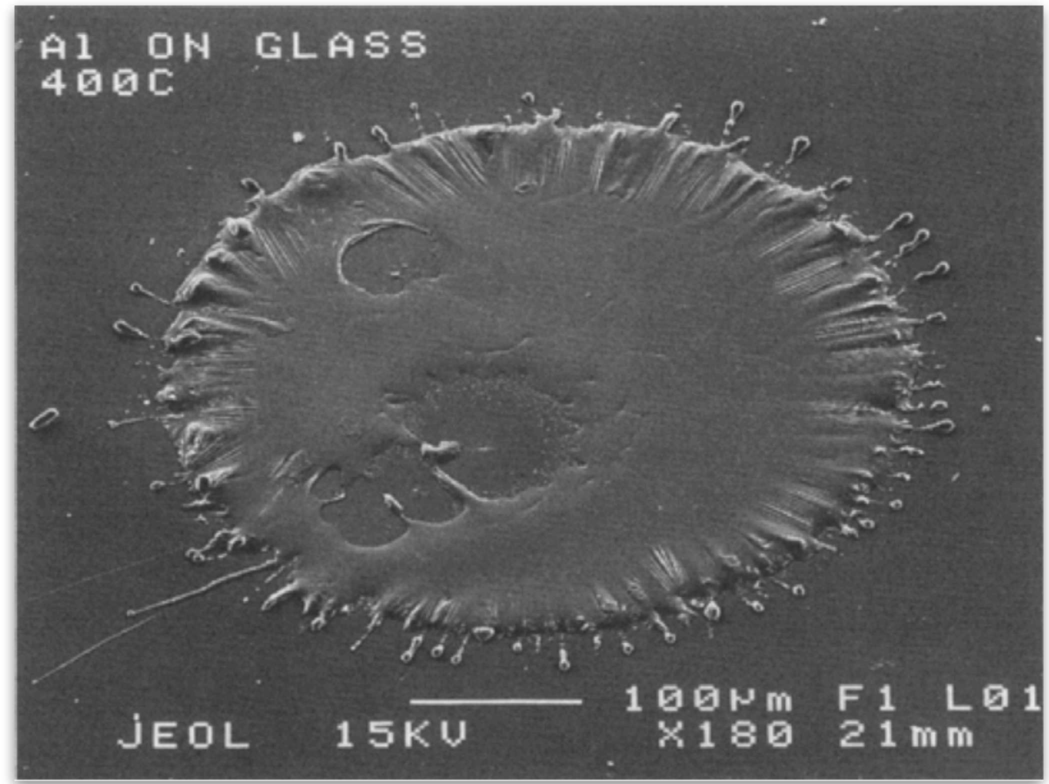
CONTEXT IN INDUSTRY

Ice accretion

Aircraft icing (wings, pitot sensors …)

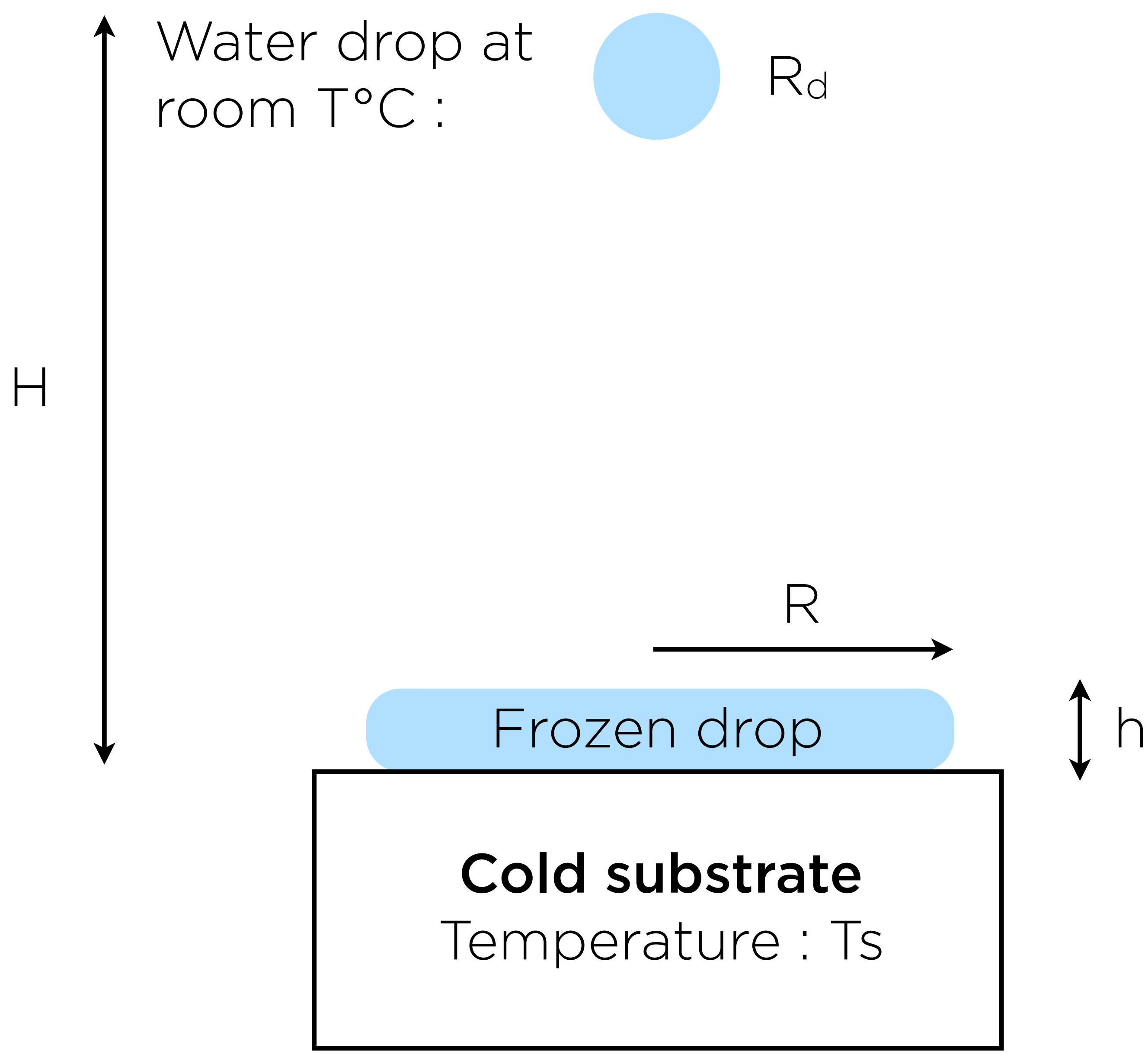
Wind turbine

Coating metallurgy



3D printing

EXPERIMENTAL SETUP

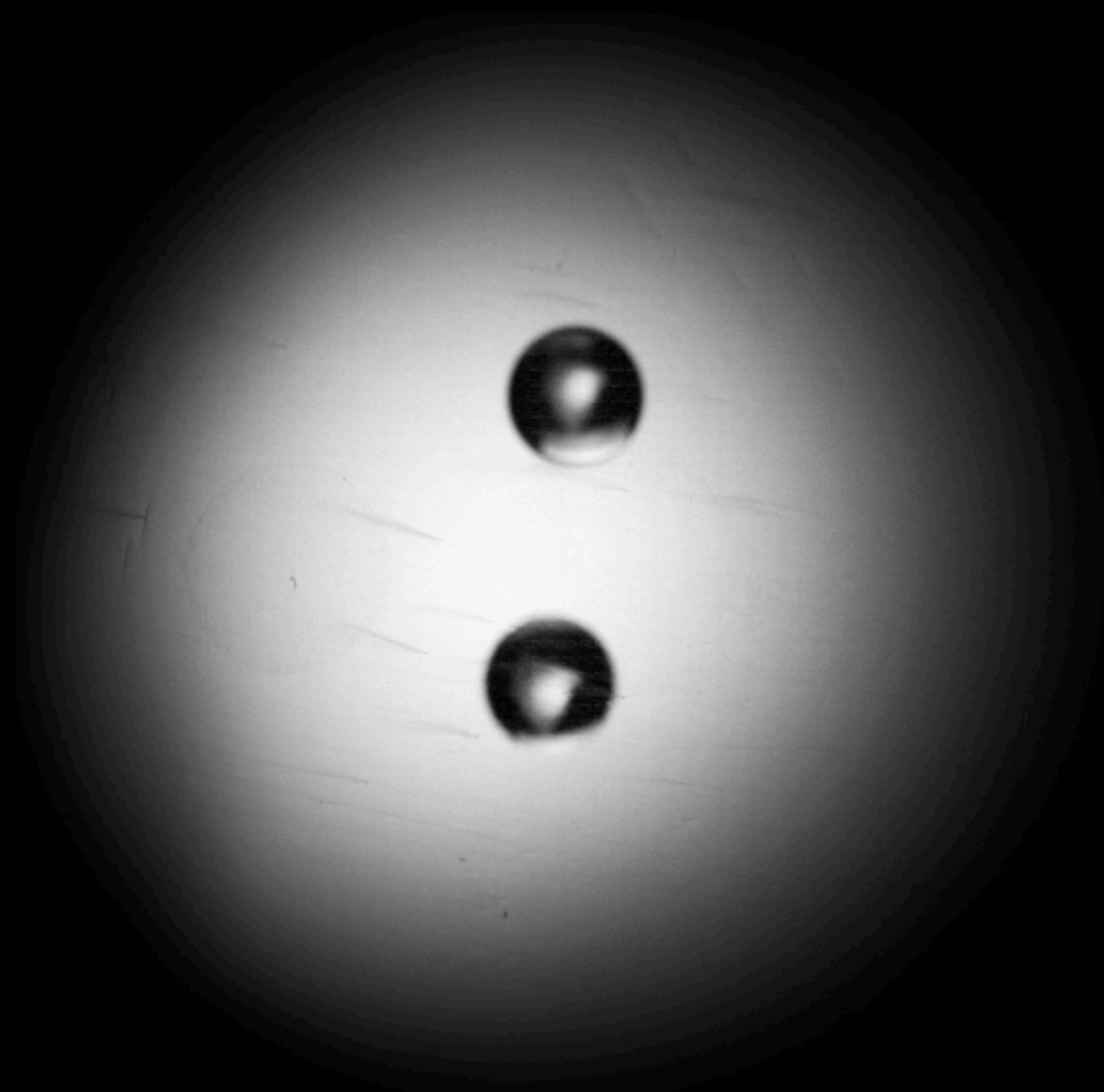


- High speed imaging
- Optical Profilometer
- Dry air at room T°C

H = 10 - 50 cm
R_d = 1 - 2 mm
Ts = 20- **-80°C**
Material : Cu, steel, marble

R ~ 10 mm
h ~ 0.2 mm

DROP IMPACT AT ROOM T°C



300x slower

Classic Impact

T = 20ºC

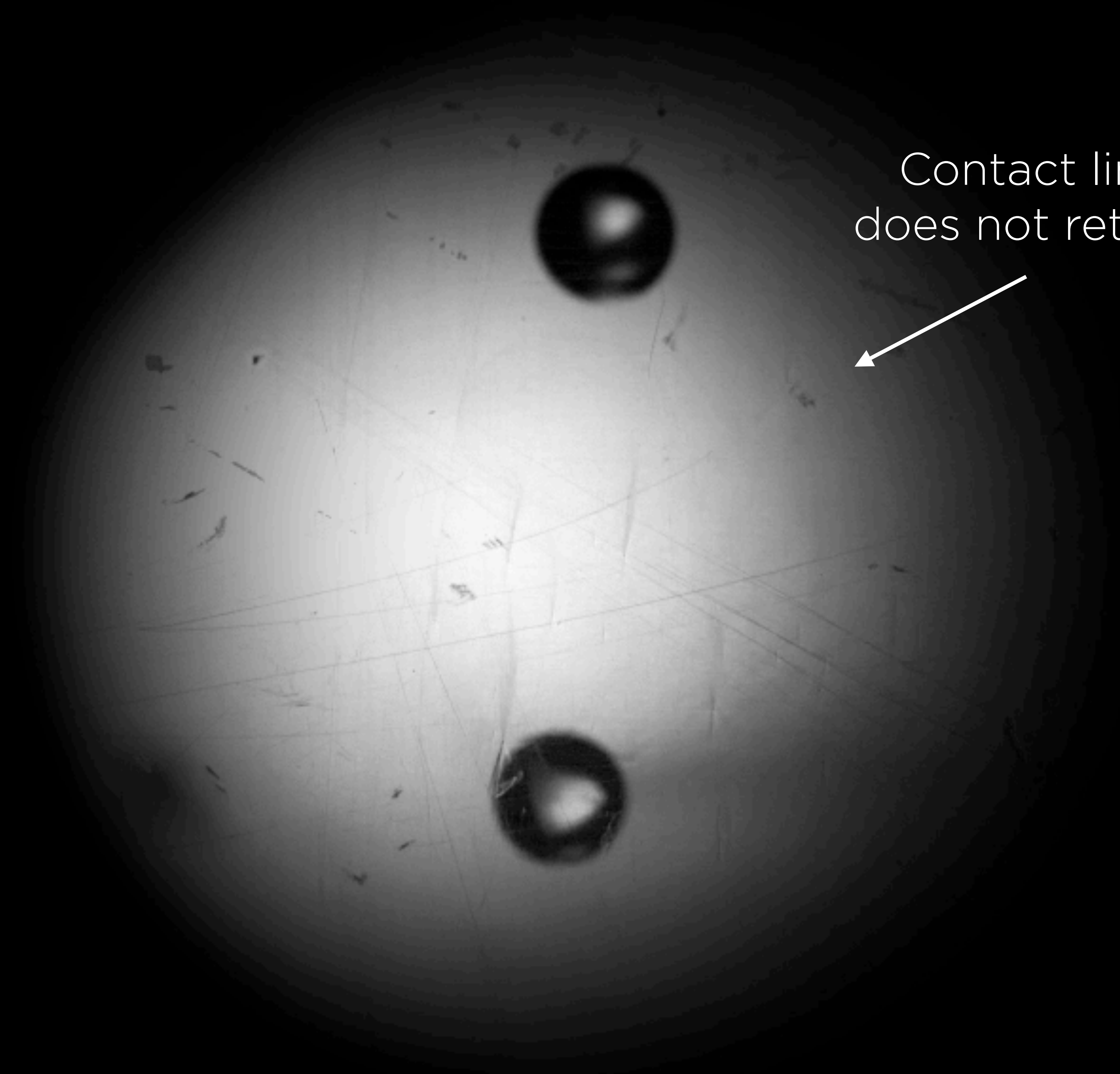
DROP IMPACT AT ROOM T°C

60x slower

Classic Impact

T = 20ºC

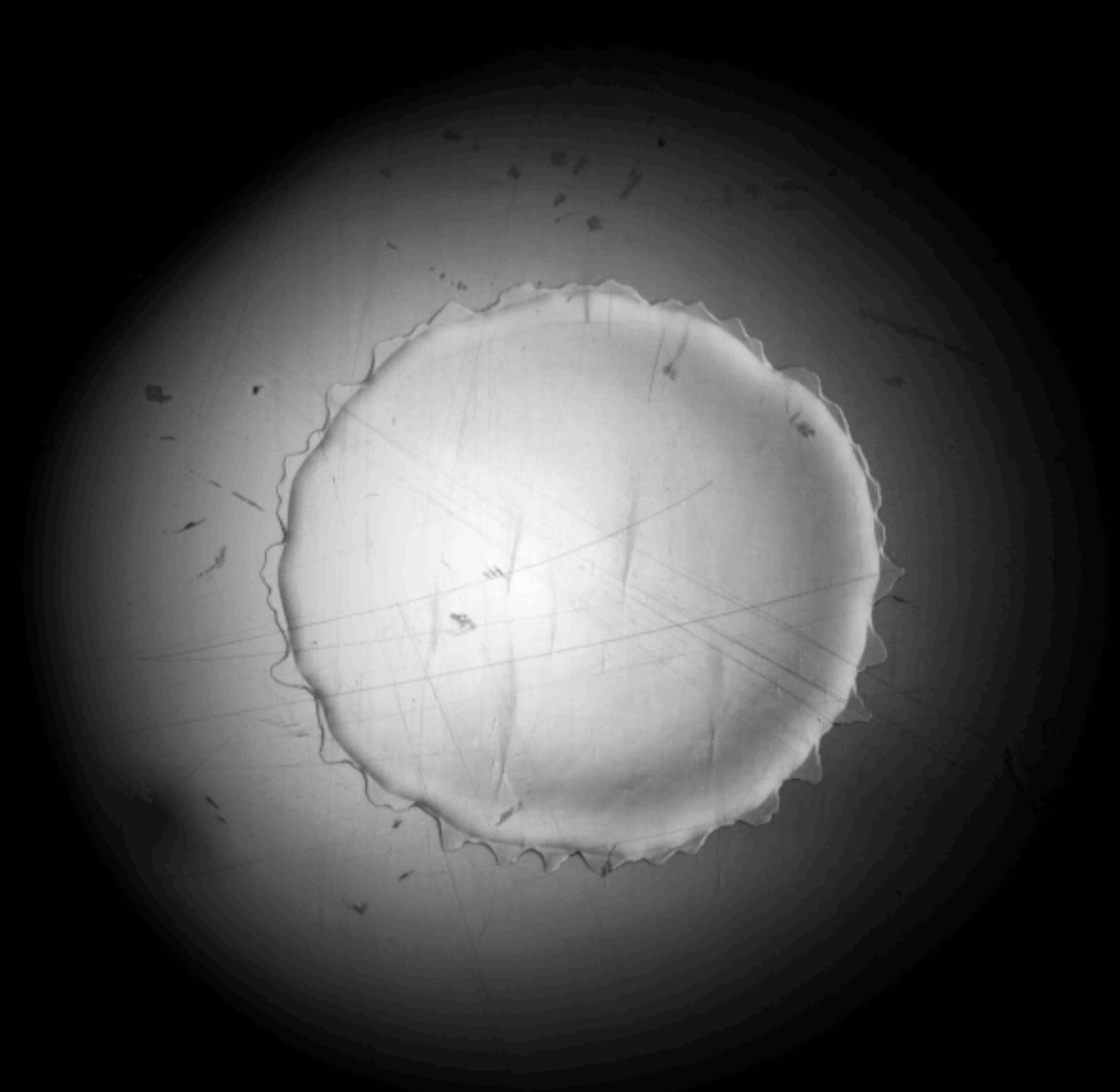
IMPACT & FREEZING T=-10°C



300x slower

T = -10ºC

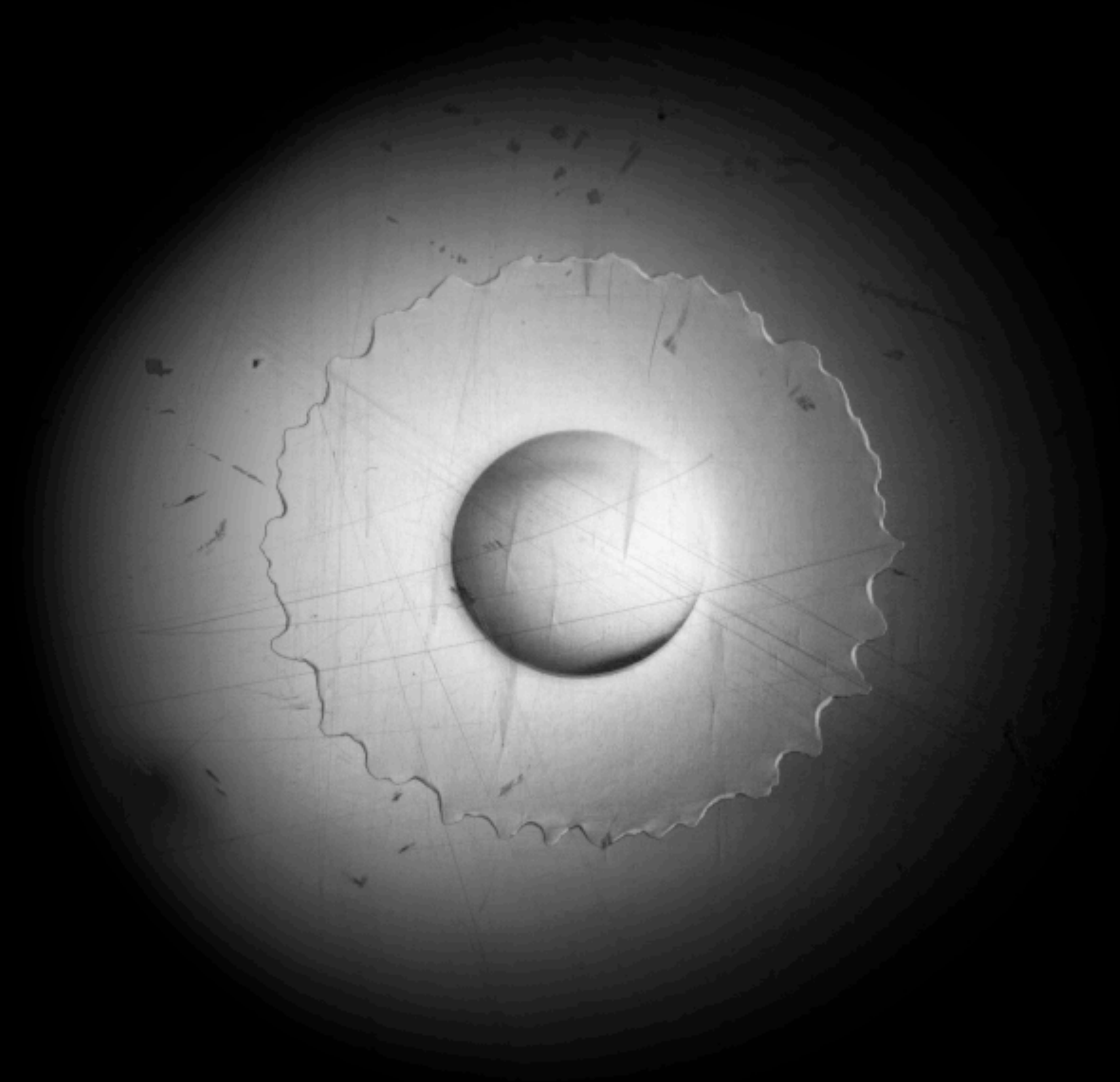
IMPACT & FREEZING T=-10°C



50x slower

T = -10ºC

IMPACT & FREEZING T=-10°C

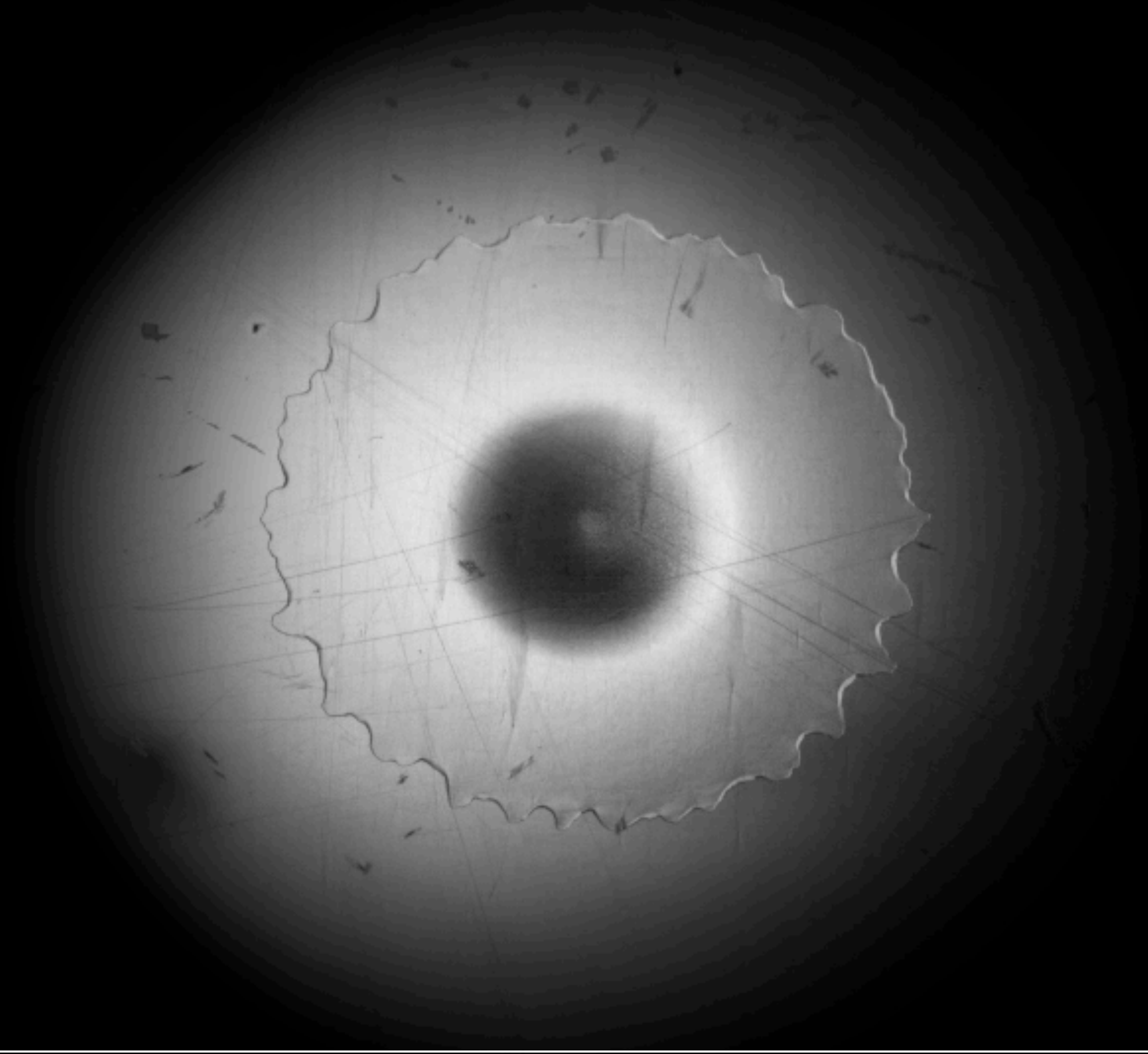


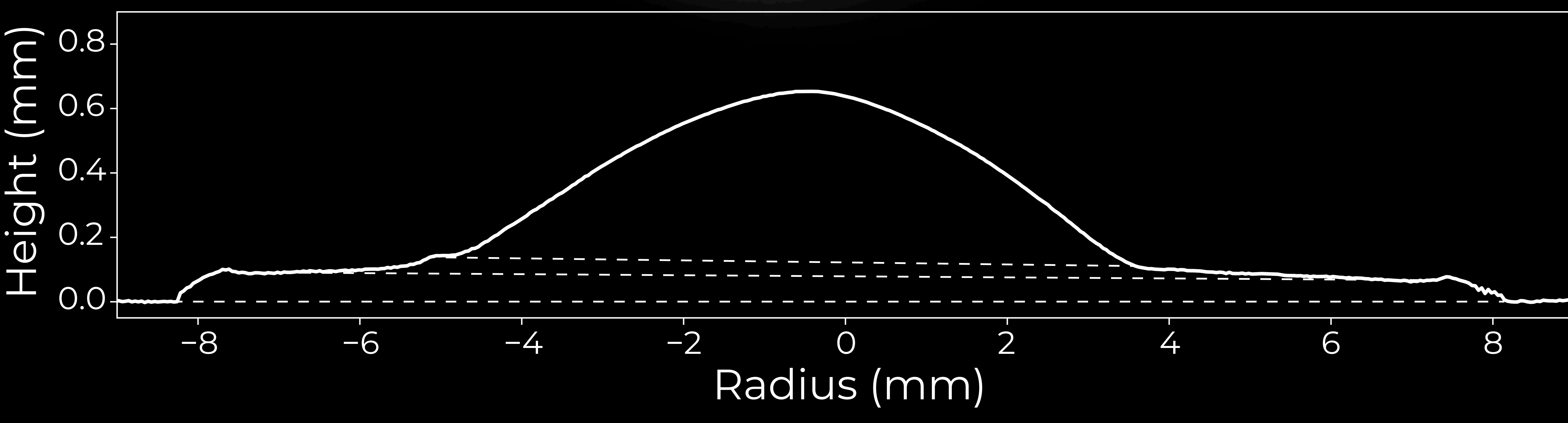
10x slower

The Cap shape

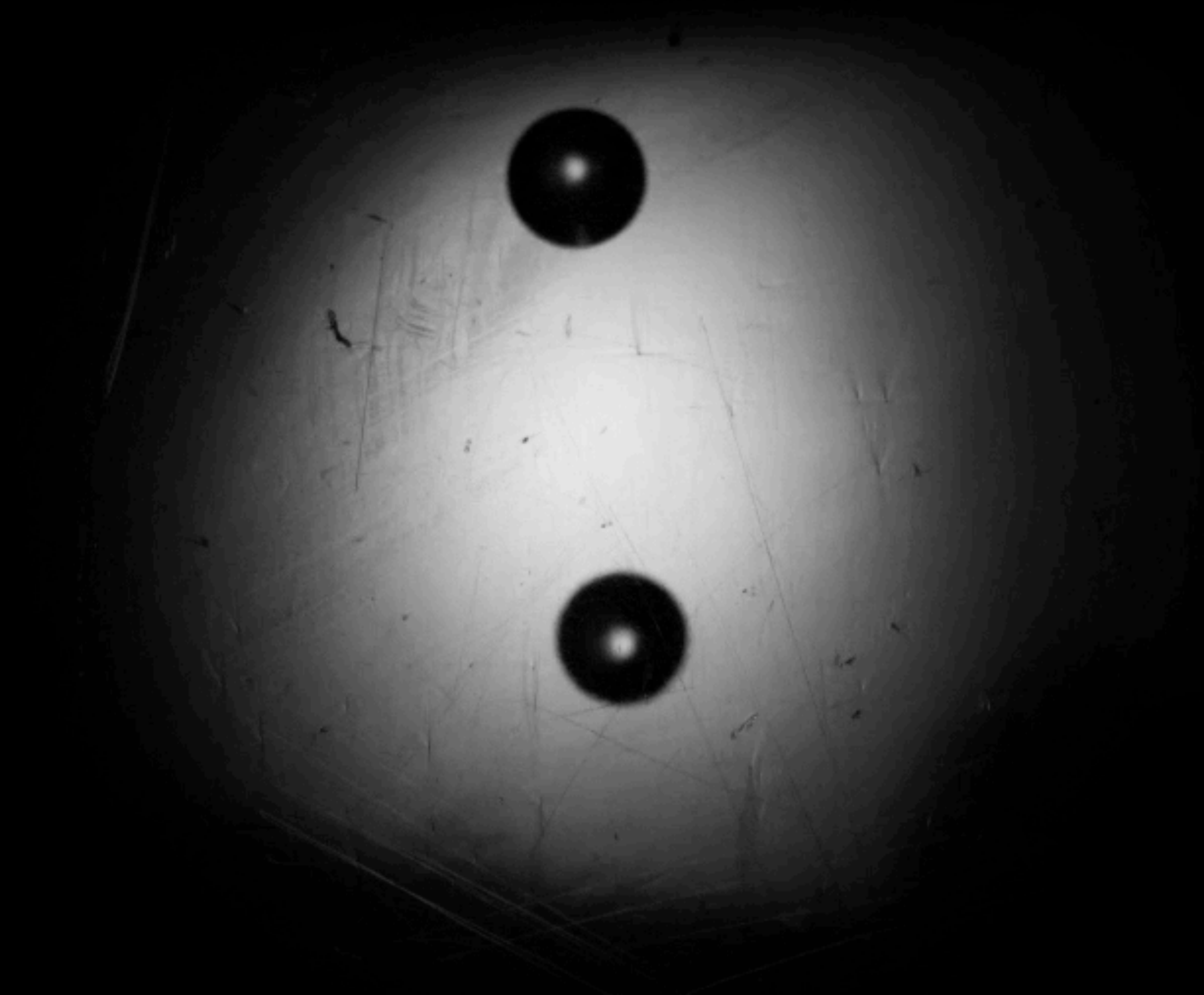
T = -10ºC

IMPACT & FREEZING T=-10°C





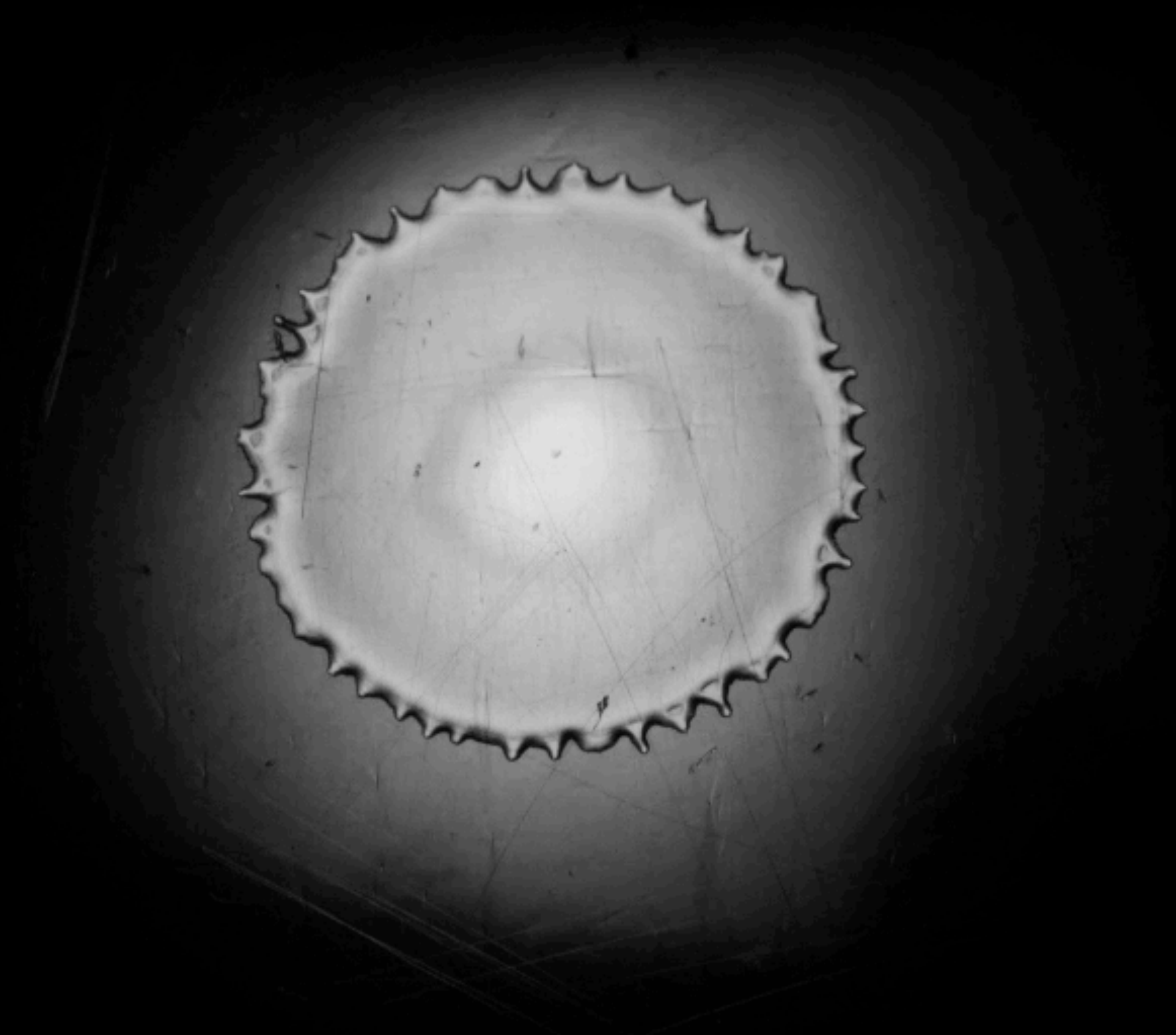
IMPACT & FREEZING T=-30°C



200x slower

T = -30ºC

IMPACT & FREEZING T=-30°C

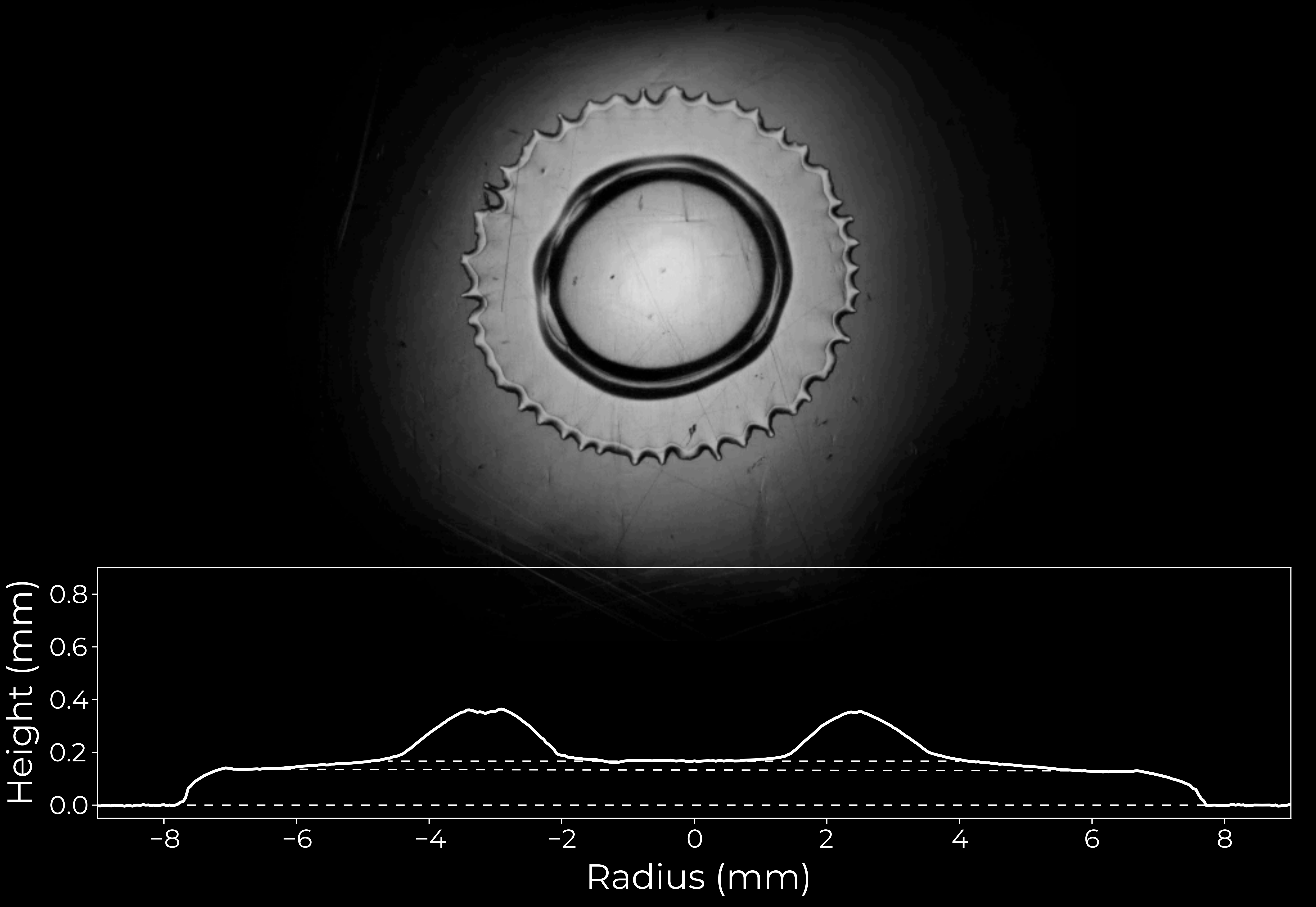


30x slower

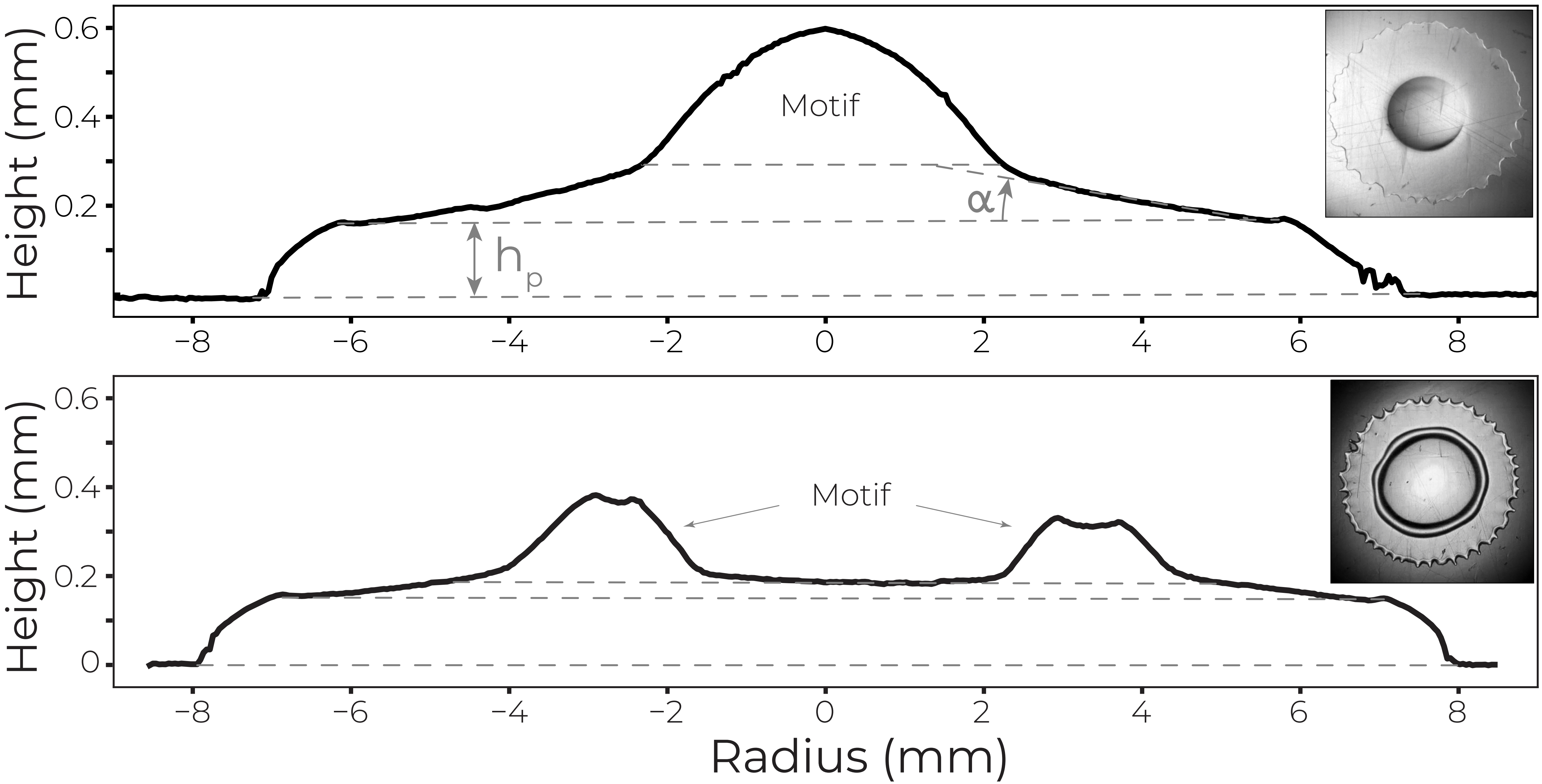
The Ring shape

T = -30ºC

IMPACT & FREEZING T=-30°C



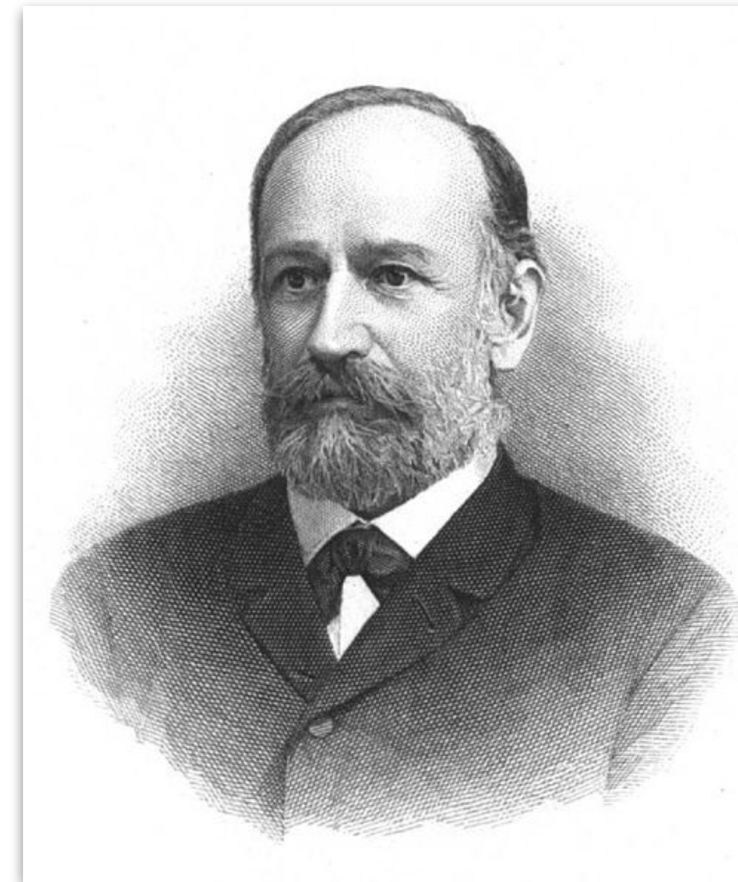
SHAPE OF A FROZEN DROP



- Can we understand and predict the shape of these particular ice structures ?

STEFAN PROBLEM (1889)

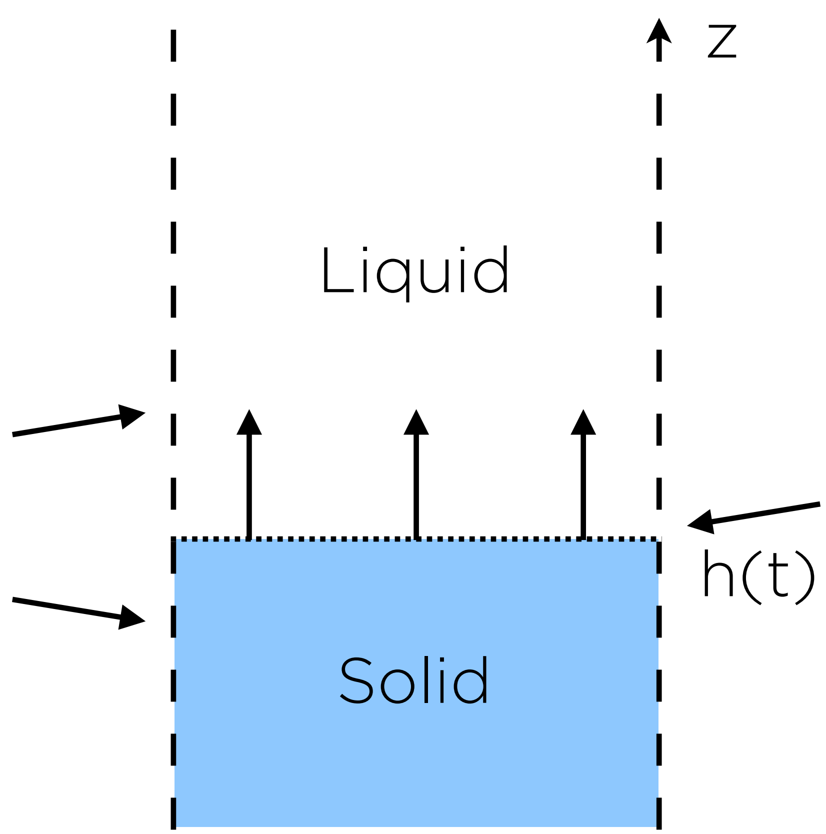
Josef Stefan



1835-1893

- The **classical Stefan problem** aims to describe an homogeneous medium undergoing a phase change (ice - water) by solving the **heat equation** and the **Stefan condition**, on the evolving boundary. In 1D :

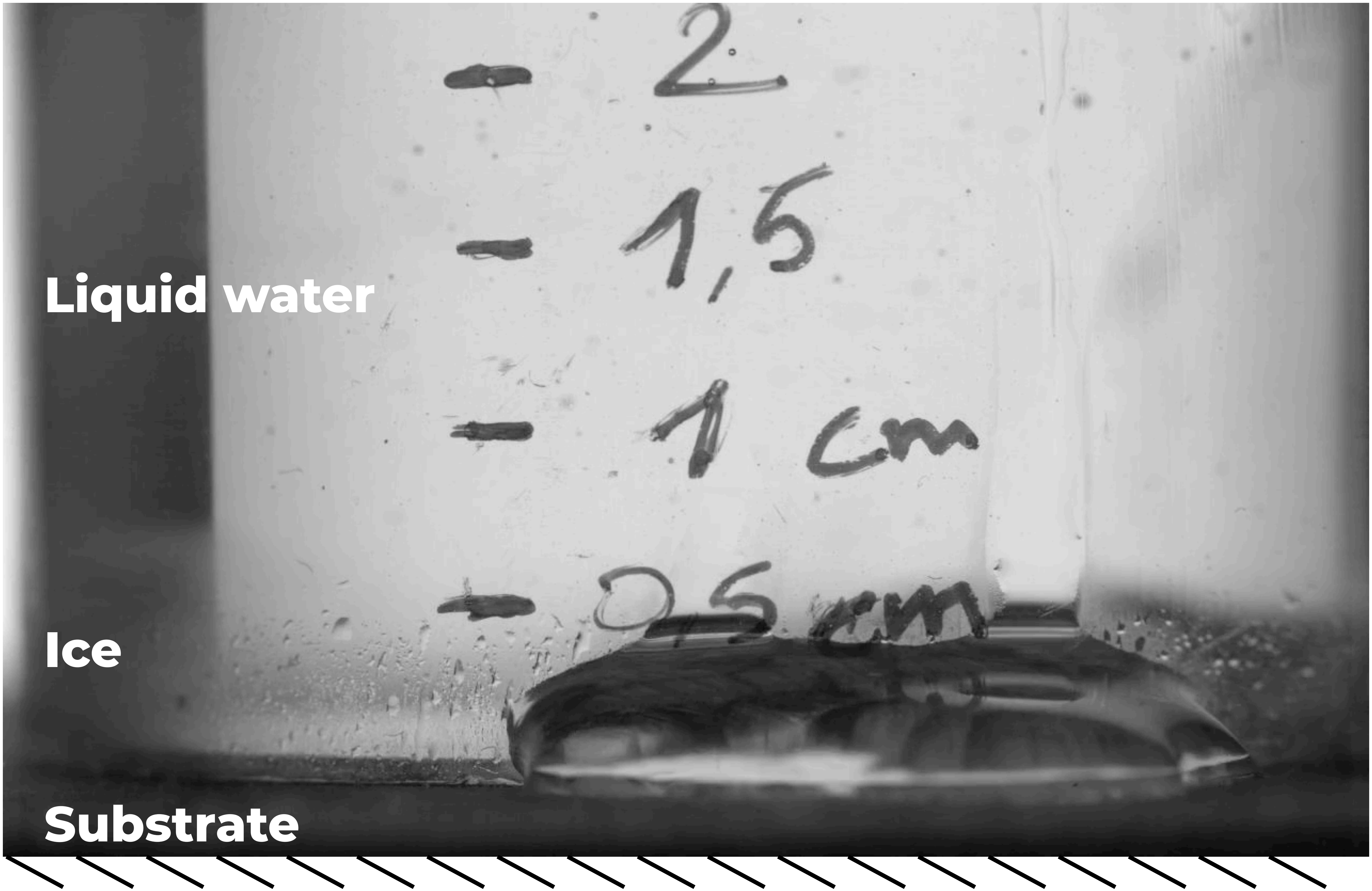
$$\frac{\partial T(z,t)}{\partial t} = D\frac{\partial^2 T(z,t)}{\partial z^2}$$



$$\rho_s L\frac{dh}{dt} = \lambda_s\frac{\partial T_s}{\partial z} - \lambda_l\frac{\partial T_l}{\partial z}$$

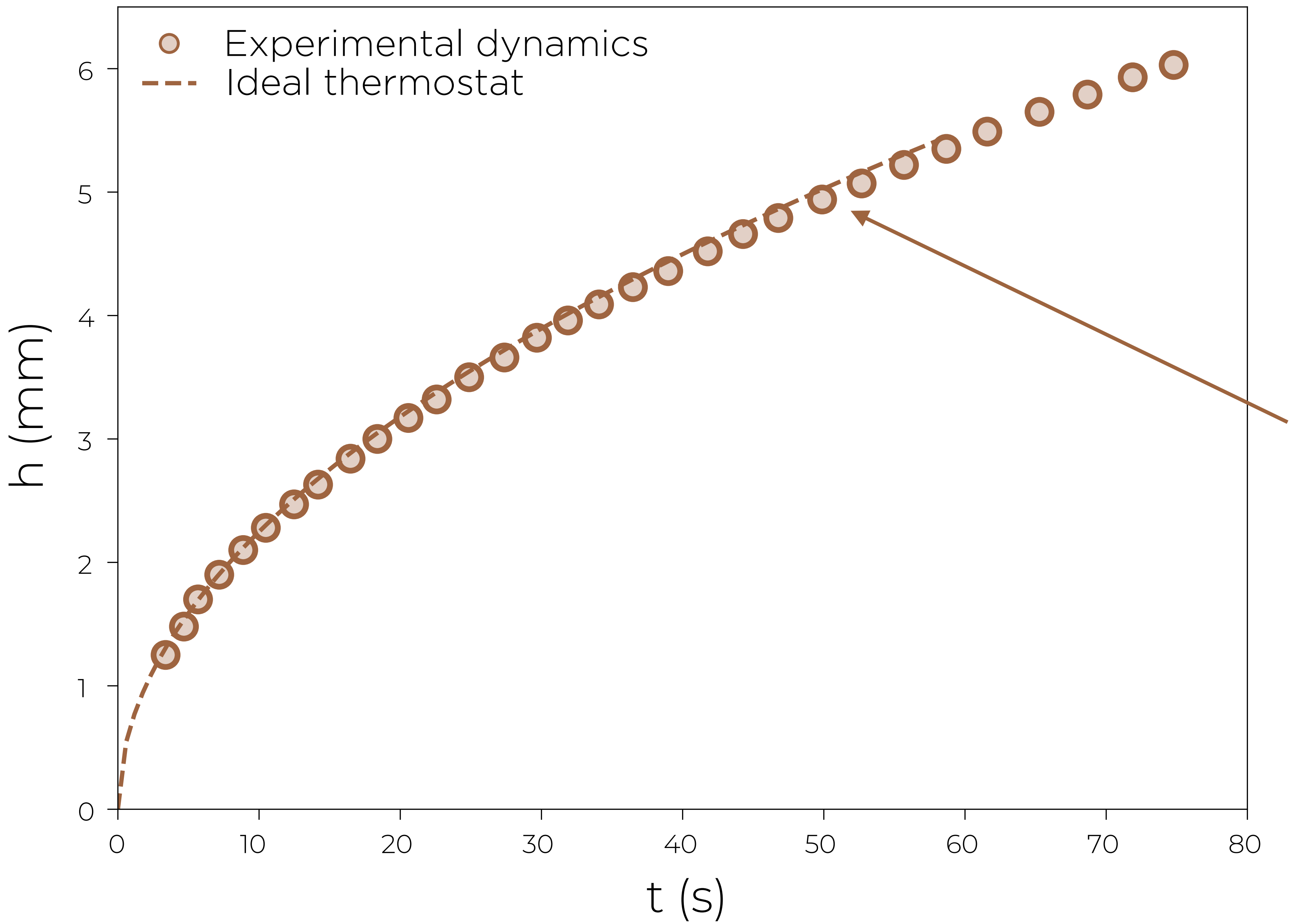
$$h(t) = \sqrt{D_{\text{eff}}t}$$

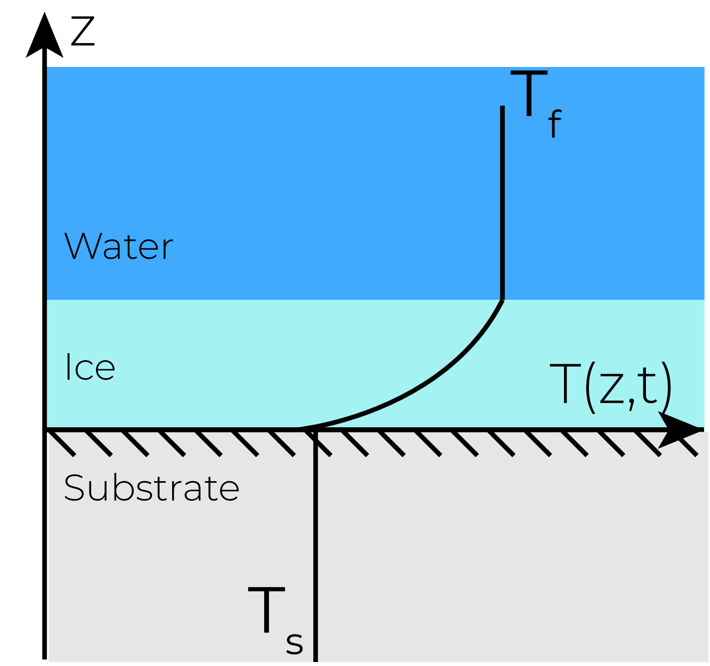
OUR STEFAN PROBLEM



COMPARISON WITH STEFAN

- Solidification of a water column on a **copper** substrate

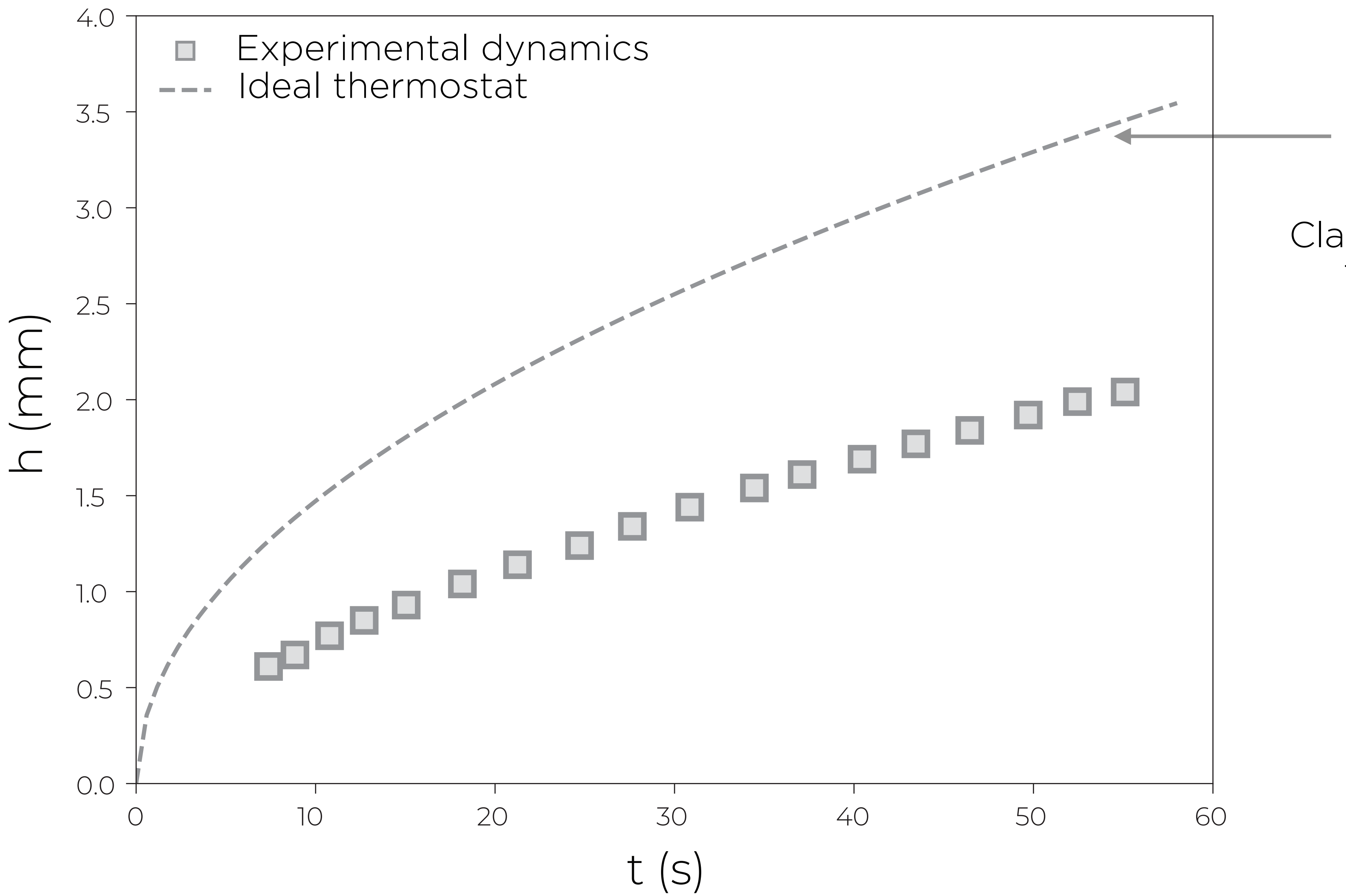


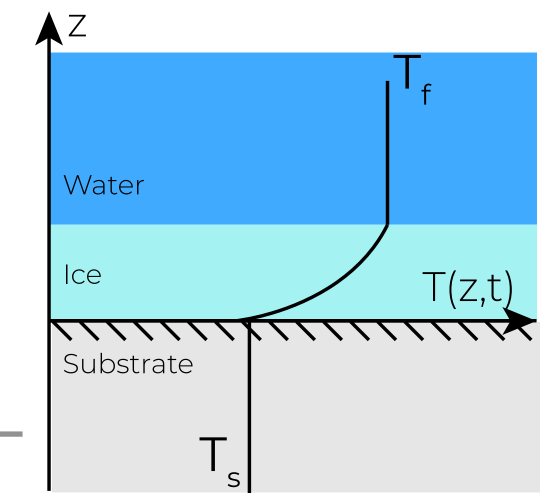


Classical Stefan problem. The substrate is an **ideal thermostat**

COMPARISON WITH STEFAN

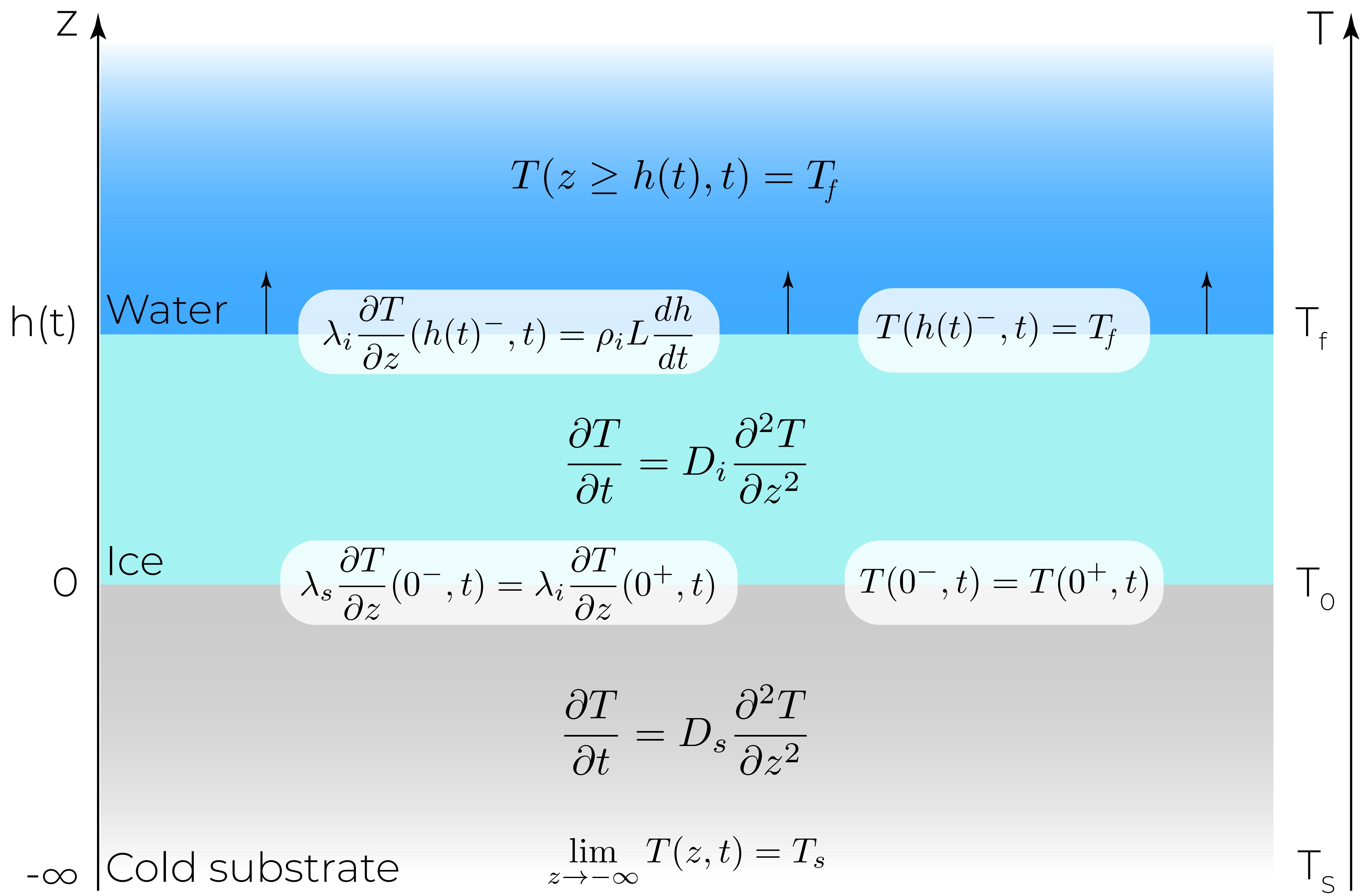
- Solidification of a water column on a **steel** substrate





Classical Stefan problem.
The substrate is an
ideal thermostat

NEW SOLIDIFICATION MODEL

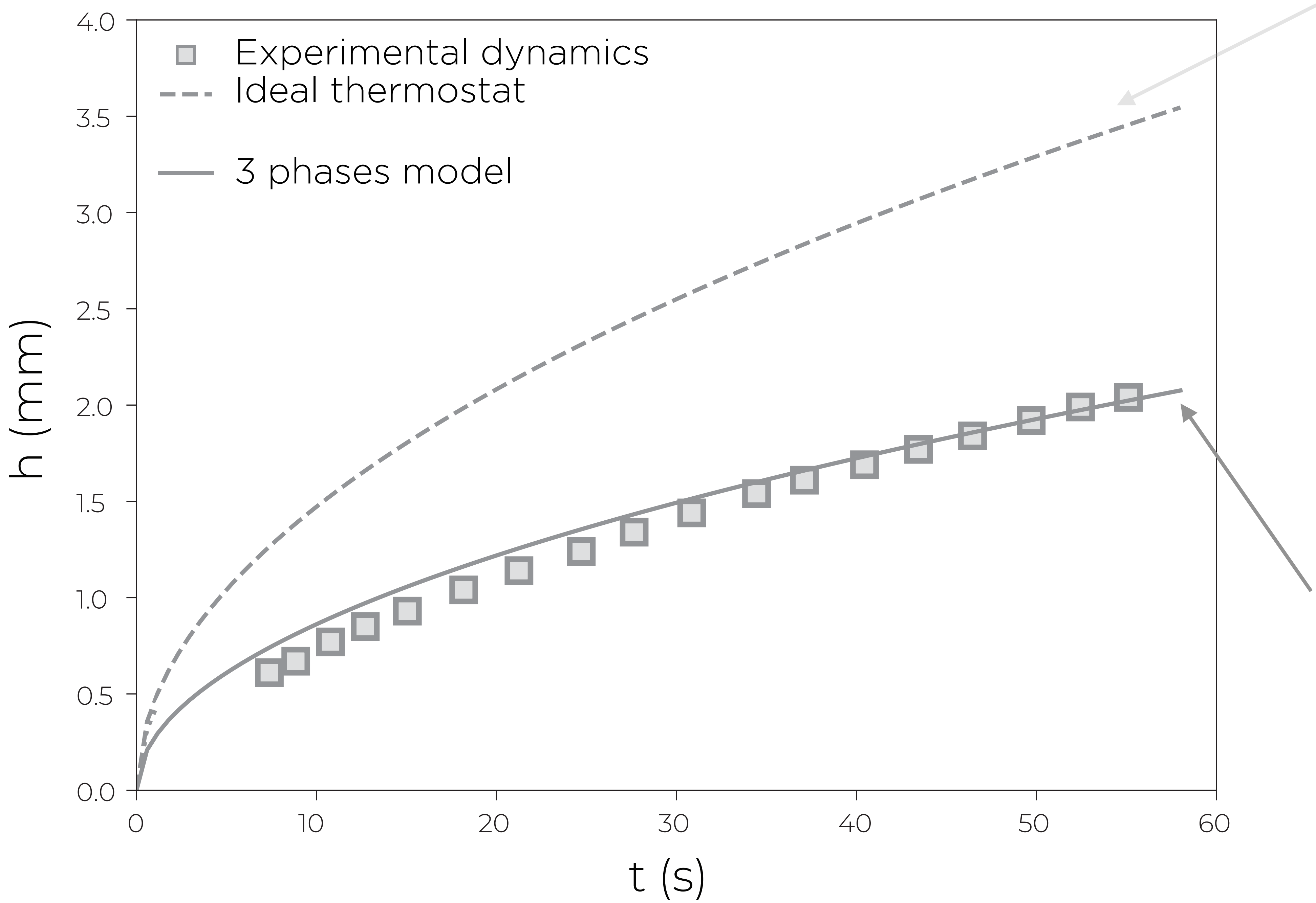


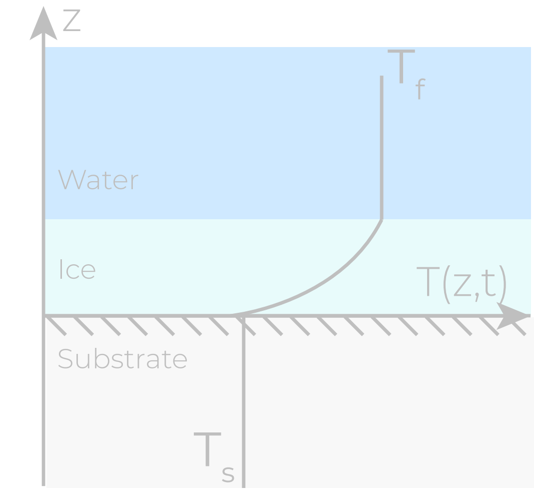
- Self-similar growth : $h(t) = \sqrt{D_{\mathrm{eff}}\, t}$
- D_{eff} depends on the thermal parameters of the system (ice & substrate).

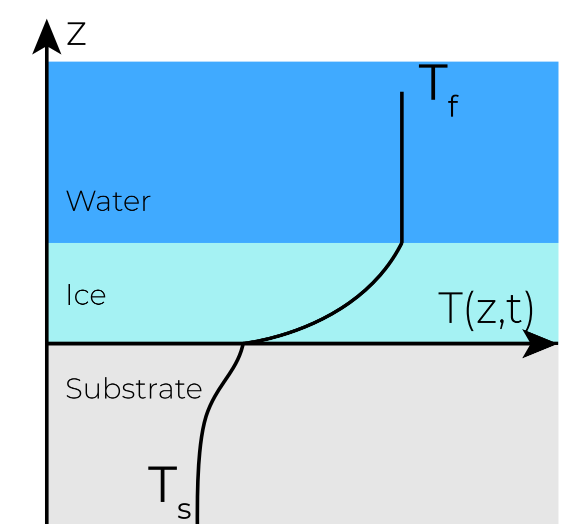
V. Thiévenaz *et al., J. Fluid Mech.* (2019)

COMPARISON WITH OUR 3 PHASES MODEL

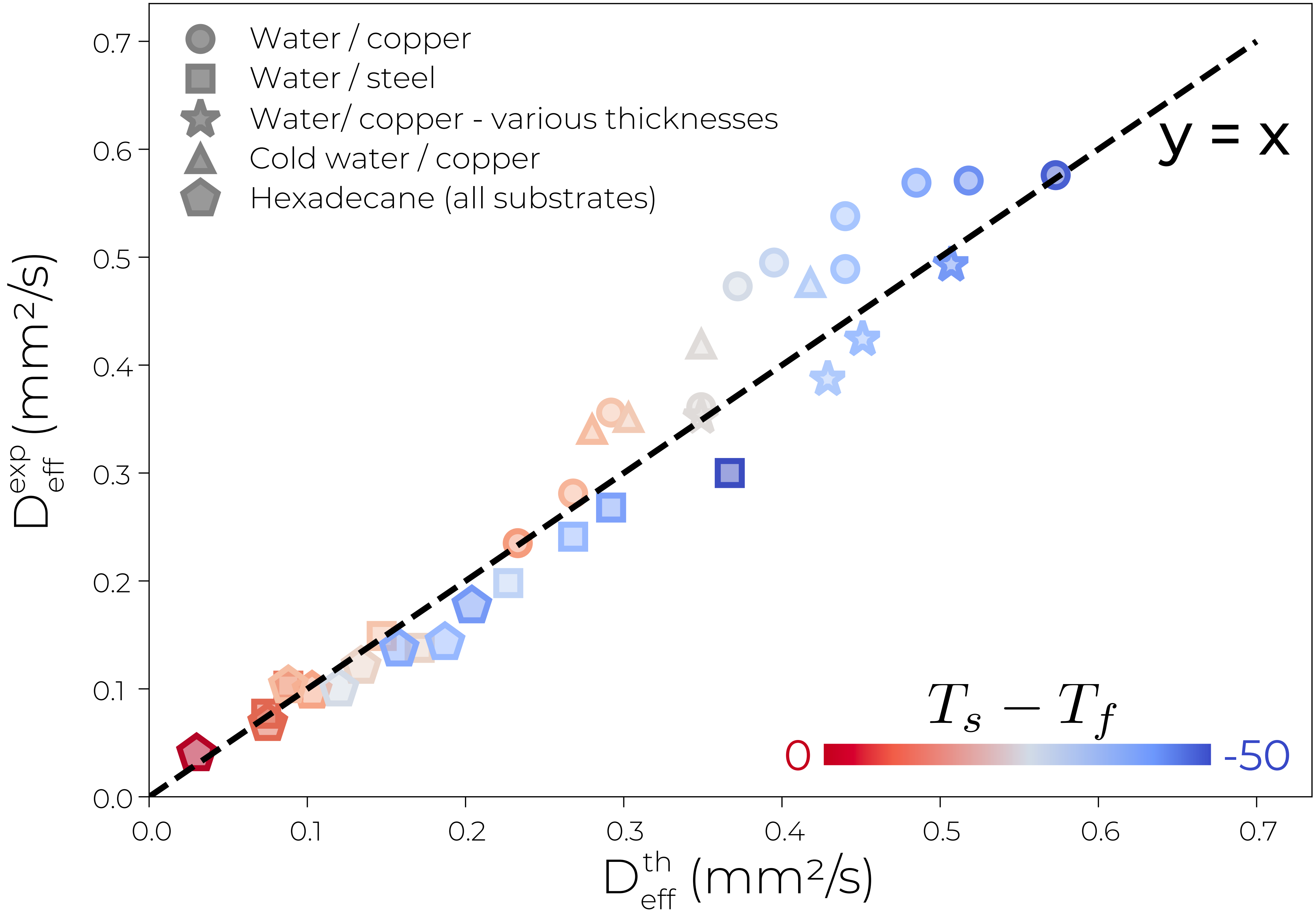
- Solidification of a water column on a **steel** substrate





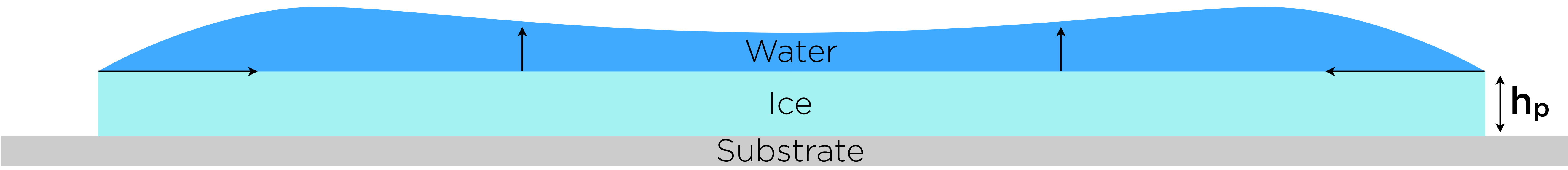


COMPARISON WITH OUR 3 PHASES MODEL



ICE PANCAKE THICKNESS

$$h(t) = \sqrt{D_{\text{eff}}\ t}$$

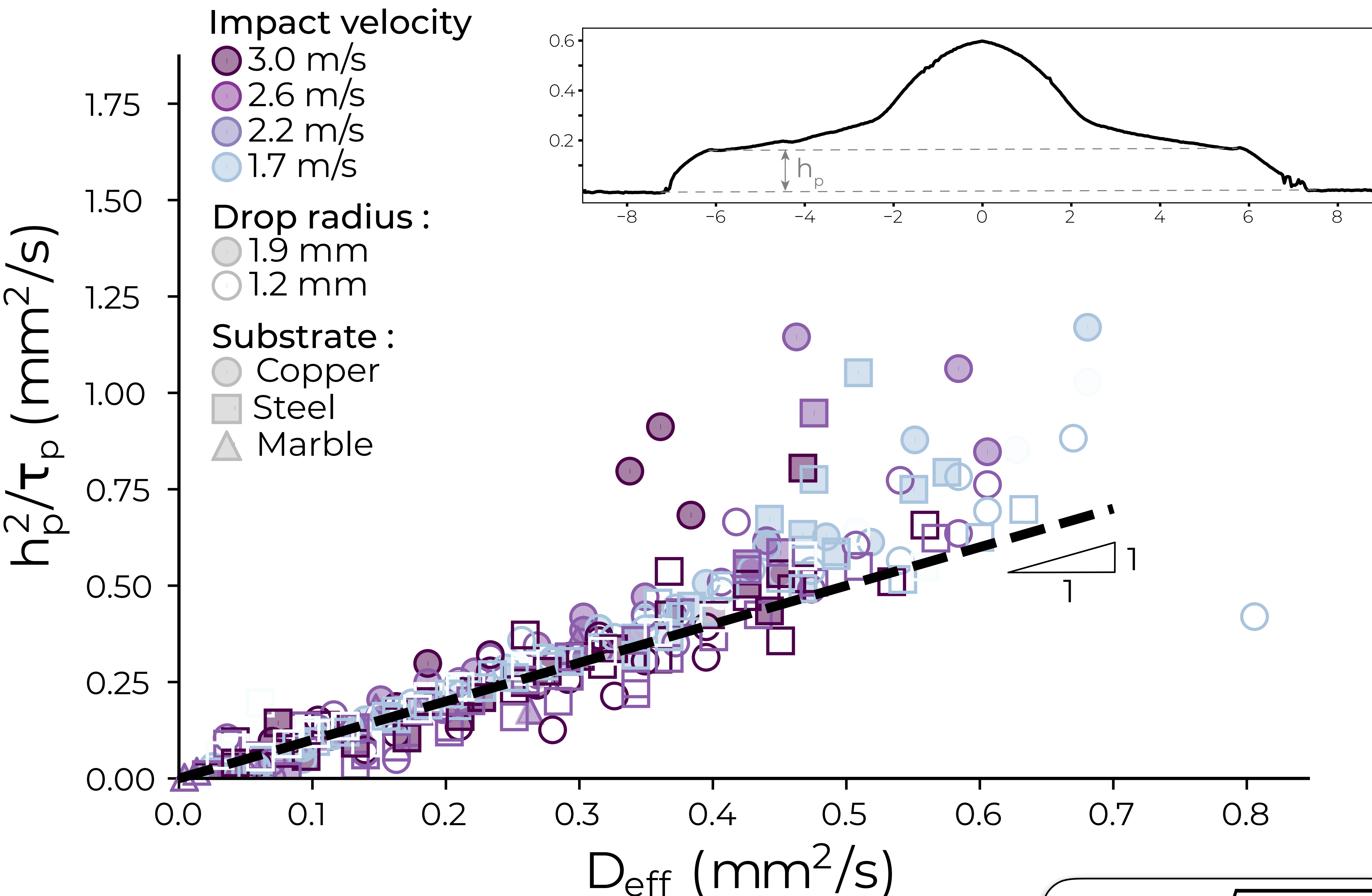


$$\text{Finally} : h_p = \sqrt{D_{\text{eff}}\ \tau_{\text{p}}}$$

?

- Ice pancake thickness h_p, with τ_p the solidification time before retraction.

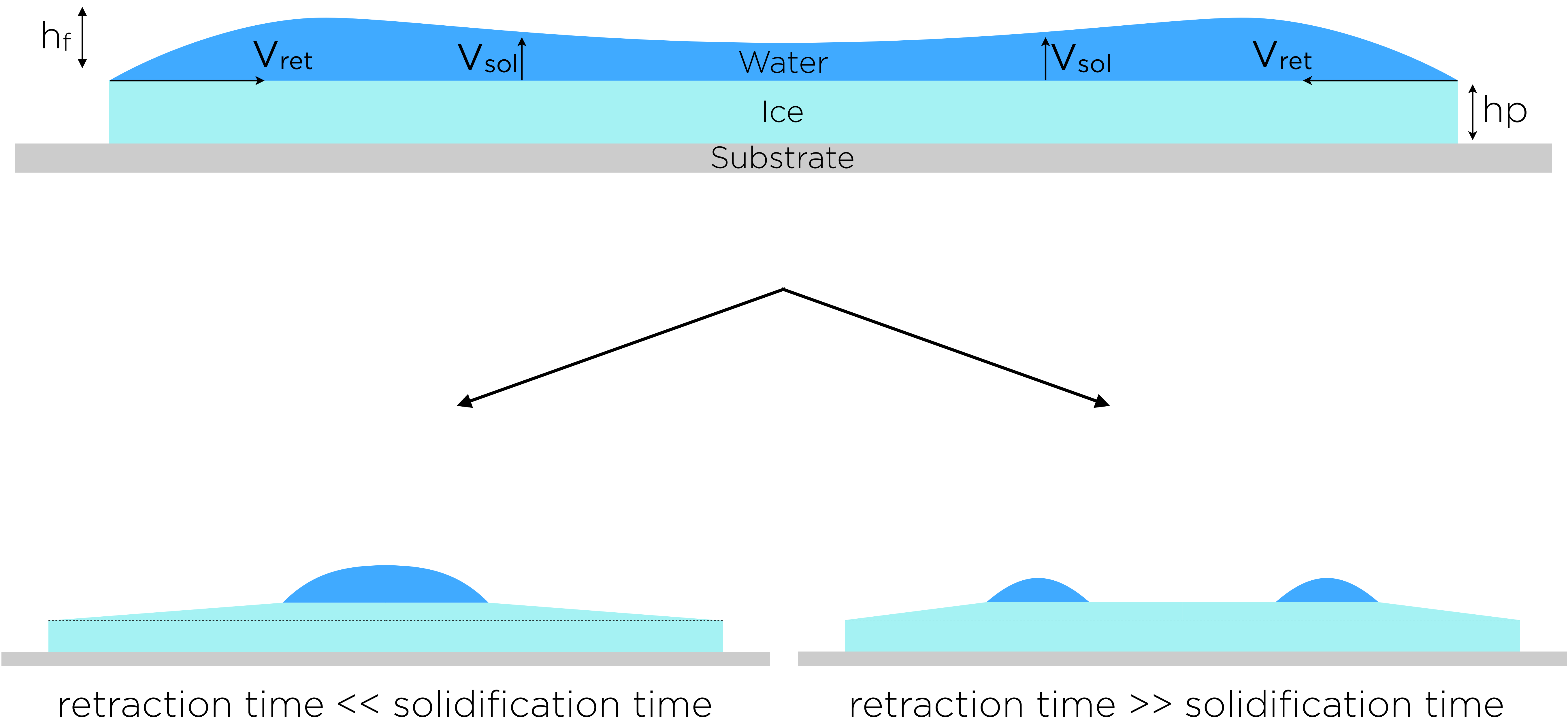
ICE PANCAKE THICKNESS



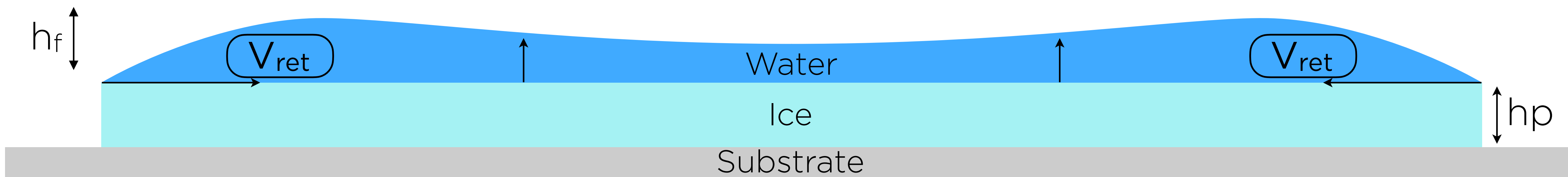
$$h_p \simeq \sqrt{D_{\text{eff}}\ \tau_p}$$

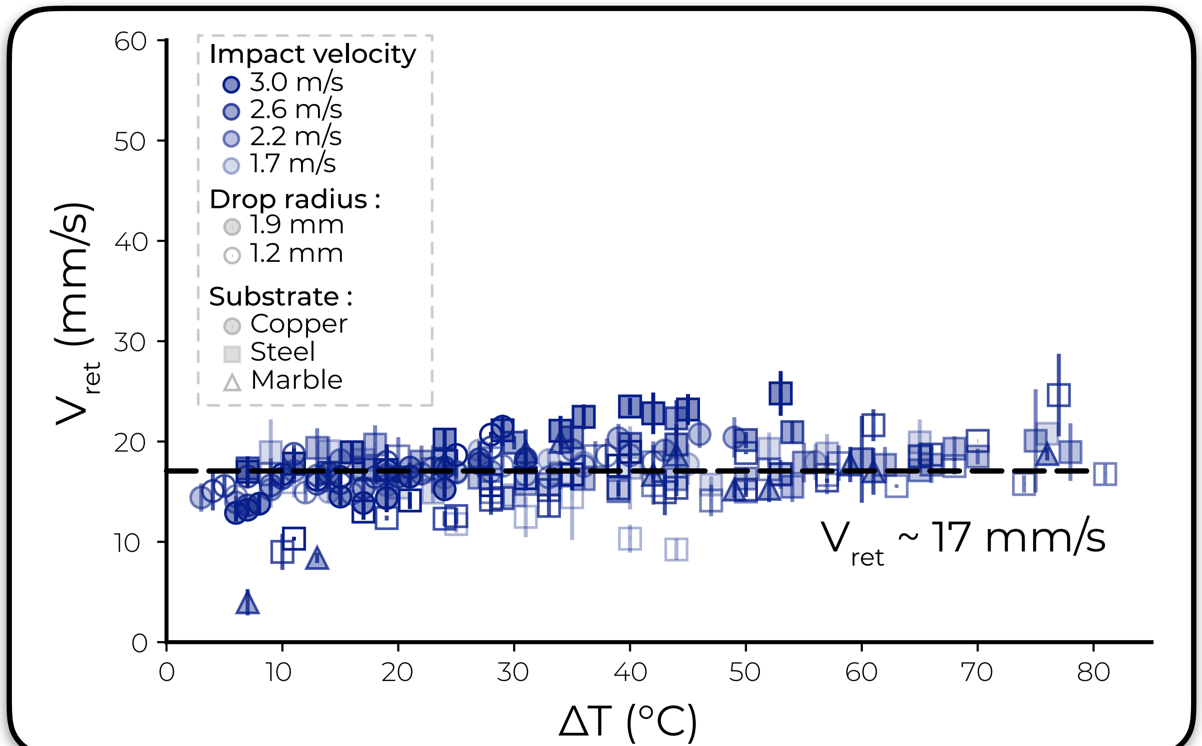
- Pancake thickness obey to a 1D heat propagation model and is built during contact line relaxation

RETRACTION VS FREEZING



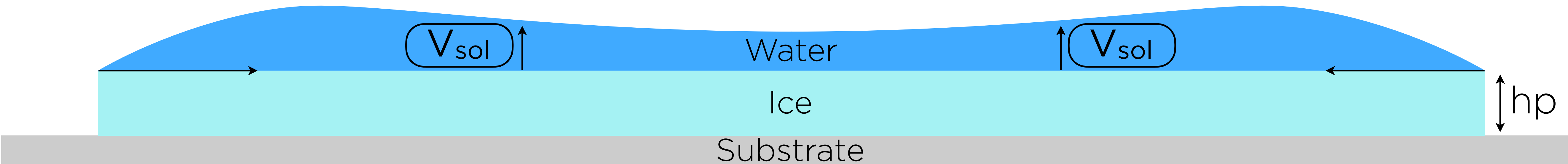
RETRACTION VELOCITY





Constant retraction velocity : $V_{\mathrm{ret}} \simeq (2.3 \times 10^{-4}) \dfrac{\gamma}{\mu}$

SOLIDIFICATION VELOCITY

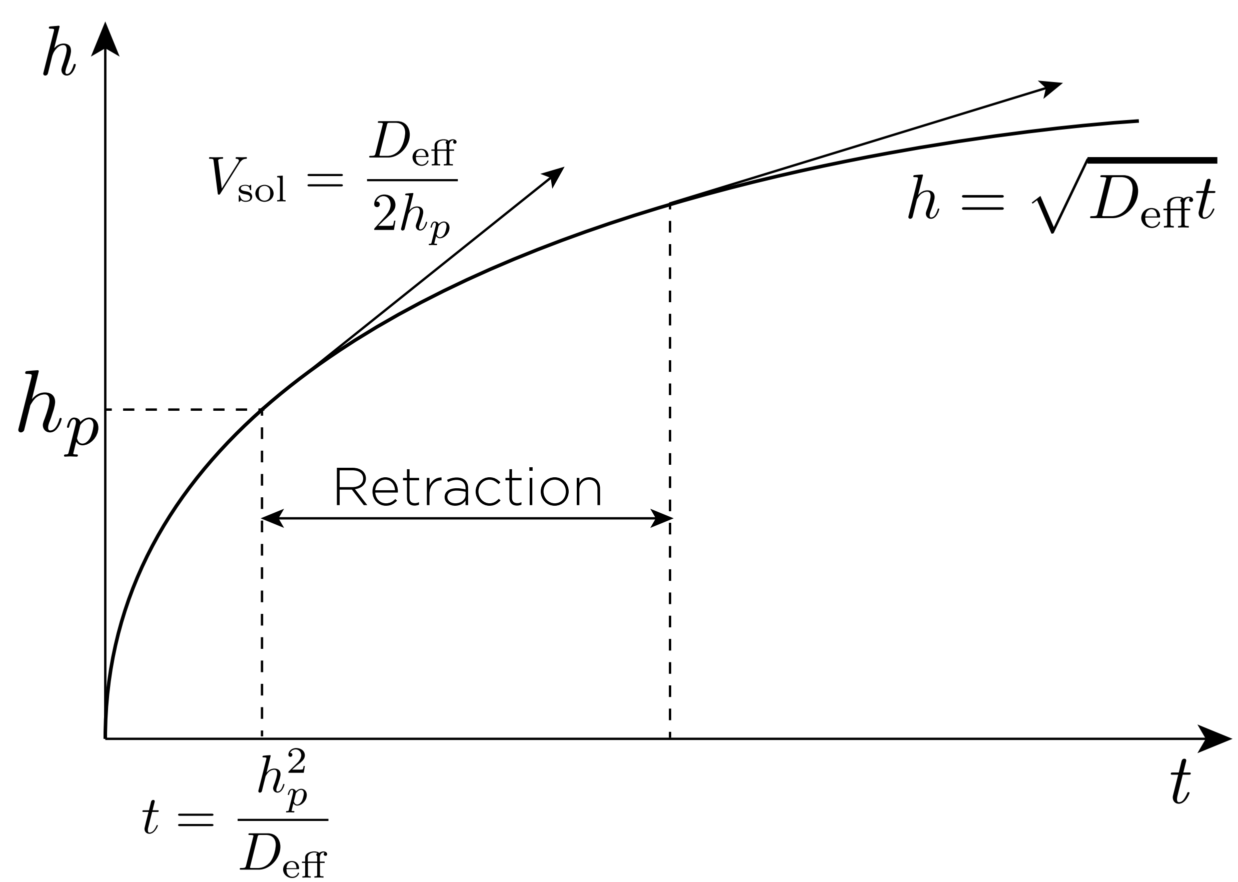


We have $h(t) = \sqrt{D_{\text{eff}} t}$

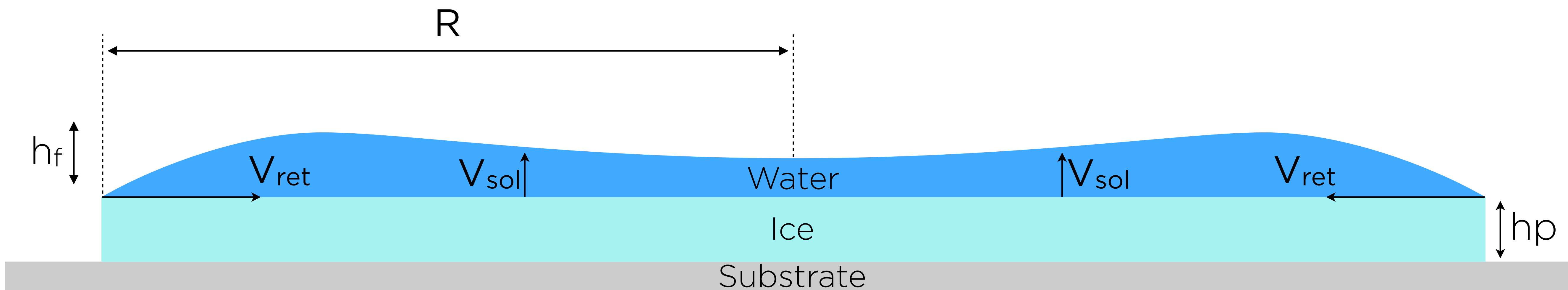
so $\dfrac{dh}{dt} = \dfrac{1}{2}\sqrt{\dfrac{D_{\text{eff}}}{t}}$

at $t = \dfrac{h_p^2}{D_{\text{eff}}}$

we obtain $$\boxed{V_{\text{sol}} = \frac{D_{\text{eff}}}{2h_p}}$$



RETRACTION & FREEZING TIME



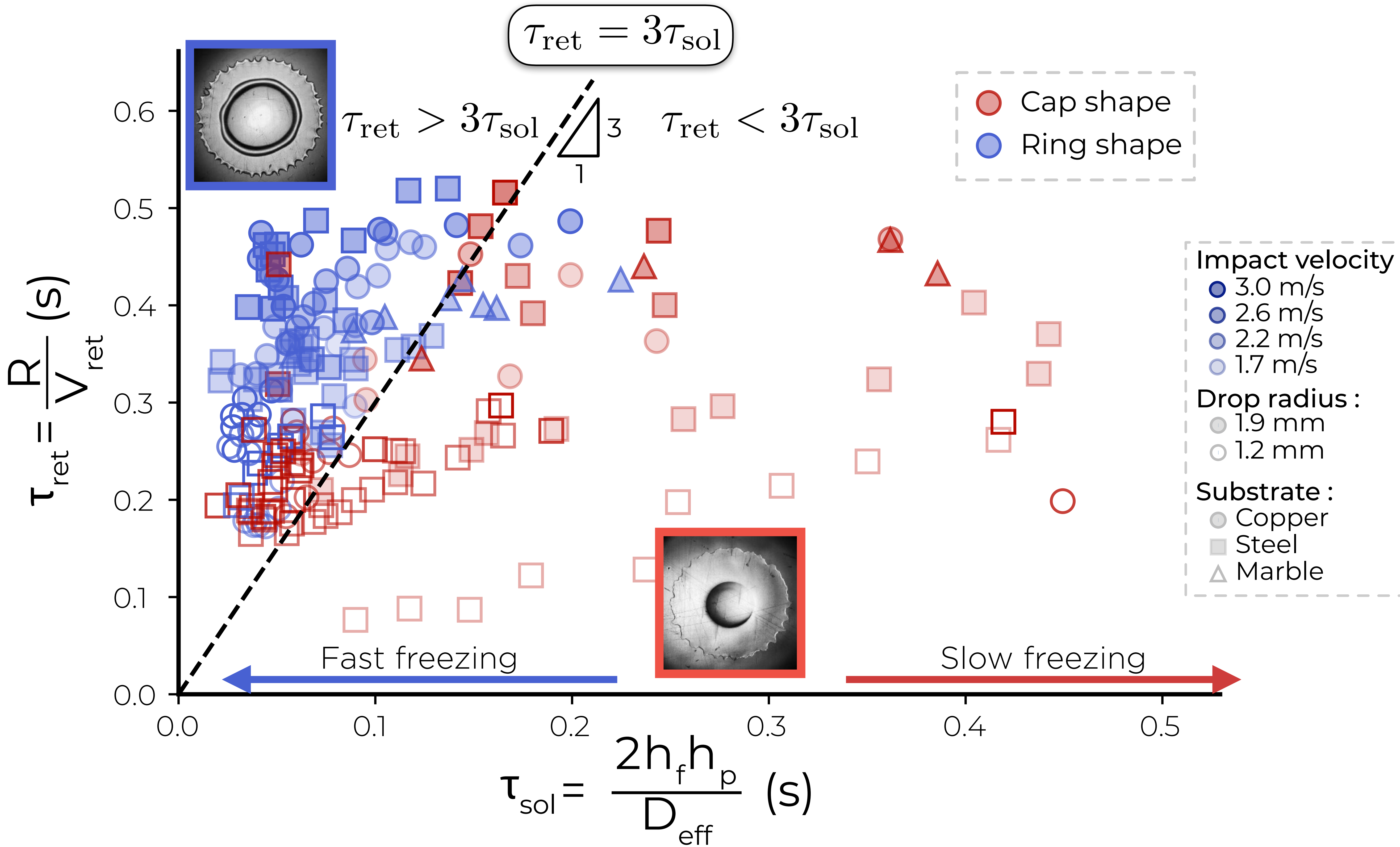
- Solidification time :

$$\tau_{\mathrm{sol}} = \frac{h_{\mathrm{f}}}{V_{\mathrm{sol}}} = \frac{2h_{\mathrm{f}}h_{\mathrm{p}}}{D_{\mathrm{eff}}}$$

- Retraction time :

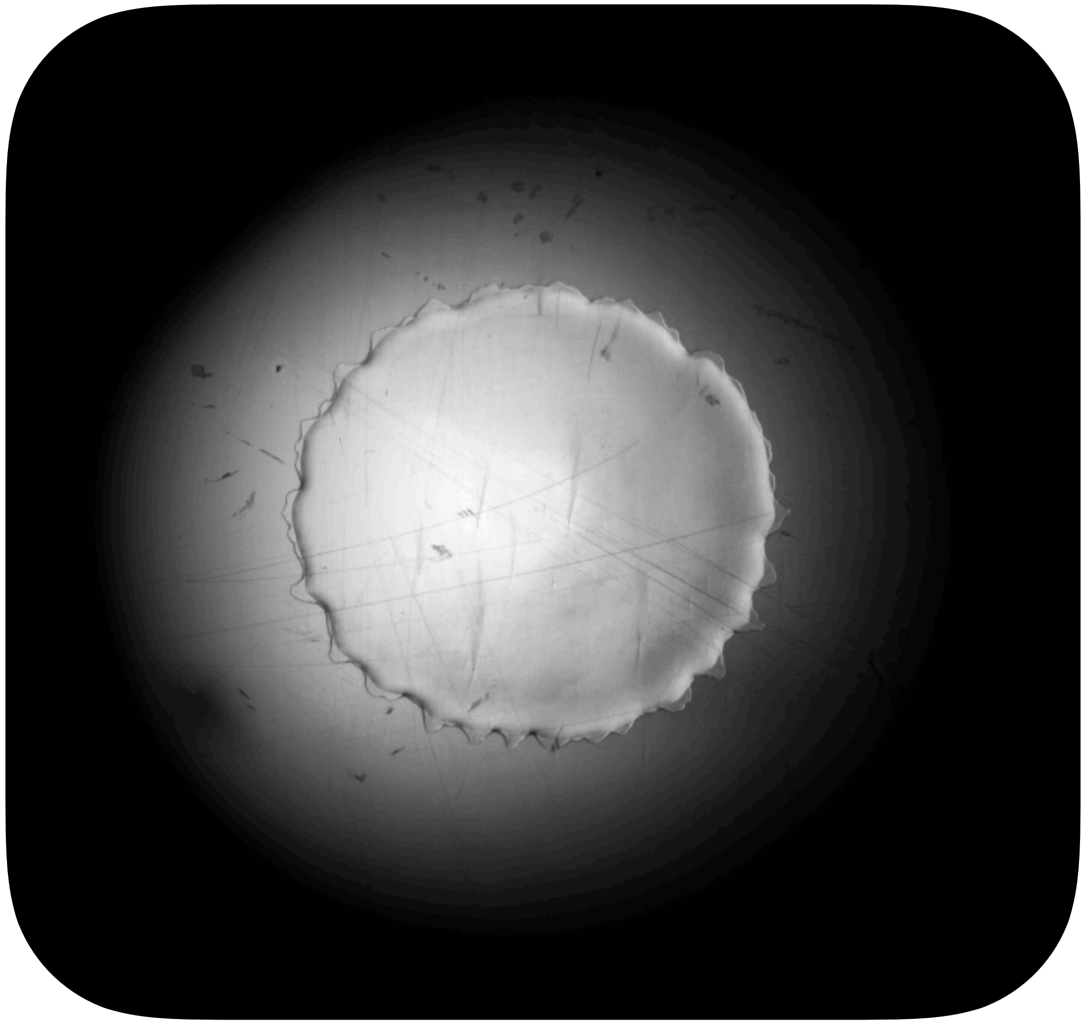
$$\tau_{\mathrm{ret}} = \frac{R}{V_{\mathrm{ret}}}$$

THE FROZEN PATTERNS

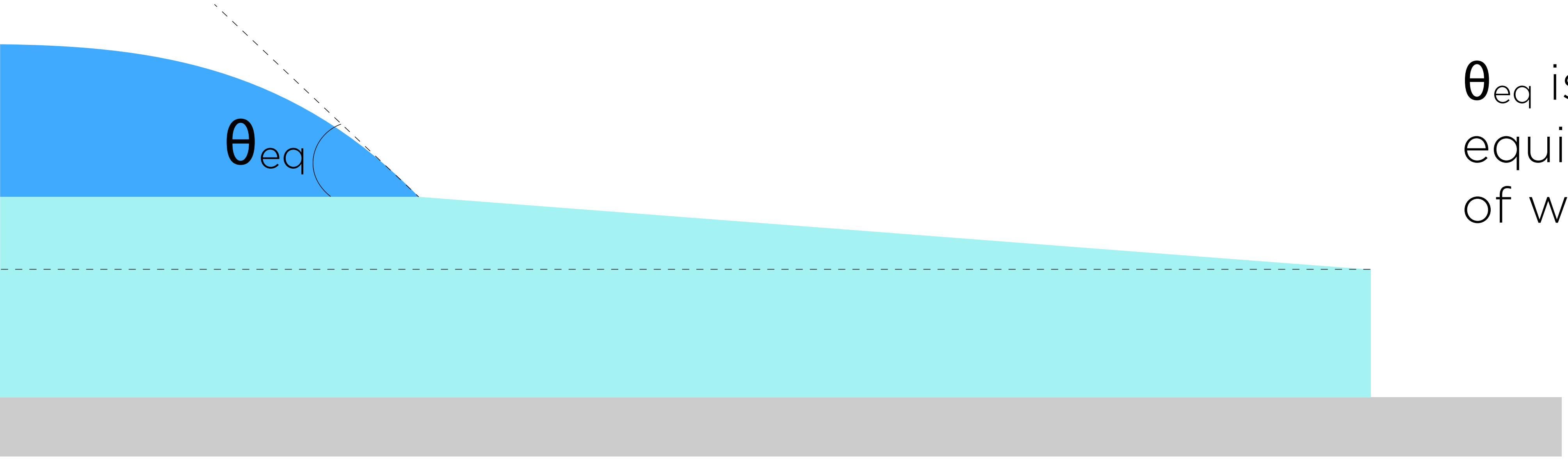


The different patterns are a consequence of the competition between capillary retraction and solidification

WATER/ICE CONTACT ANGLE

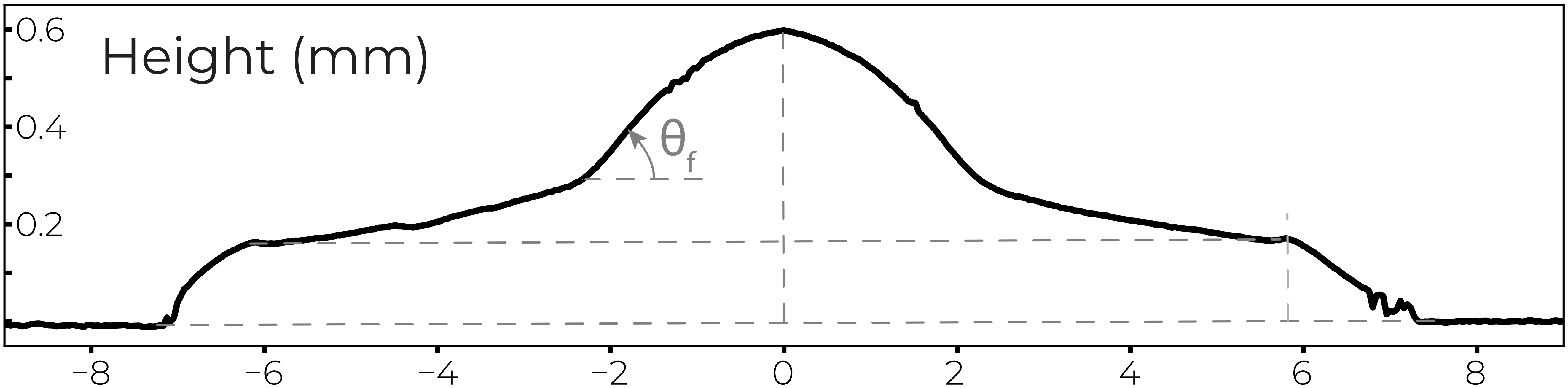


- In the case $\tau_{ret} < \tau_{sol}$, water stops retracting when it found its equilibrium shape and contact angle.



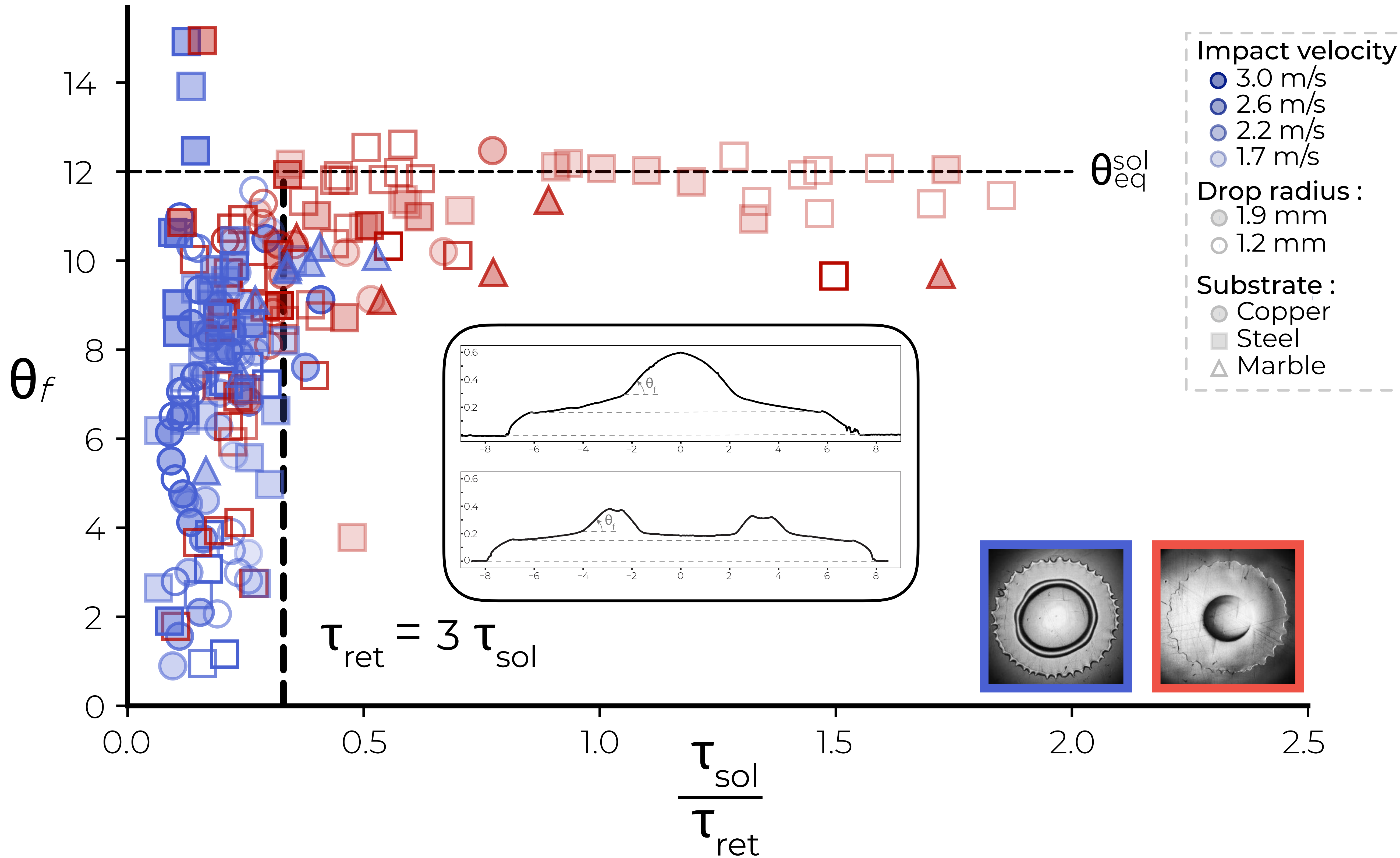
θ_{eq} is expected to be the equilibrium contact angle of water on ice !

HEIGHT PROFILES



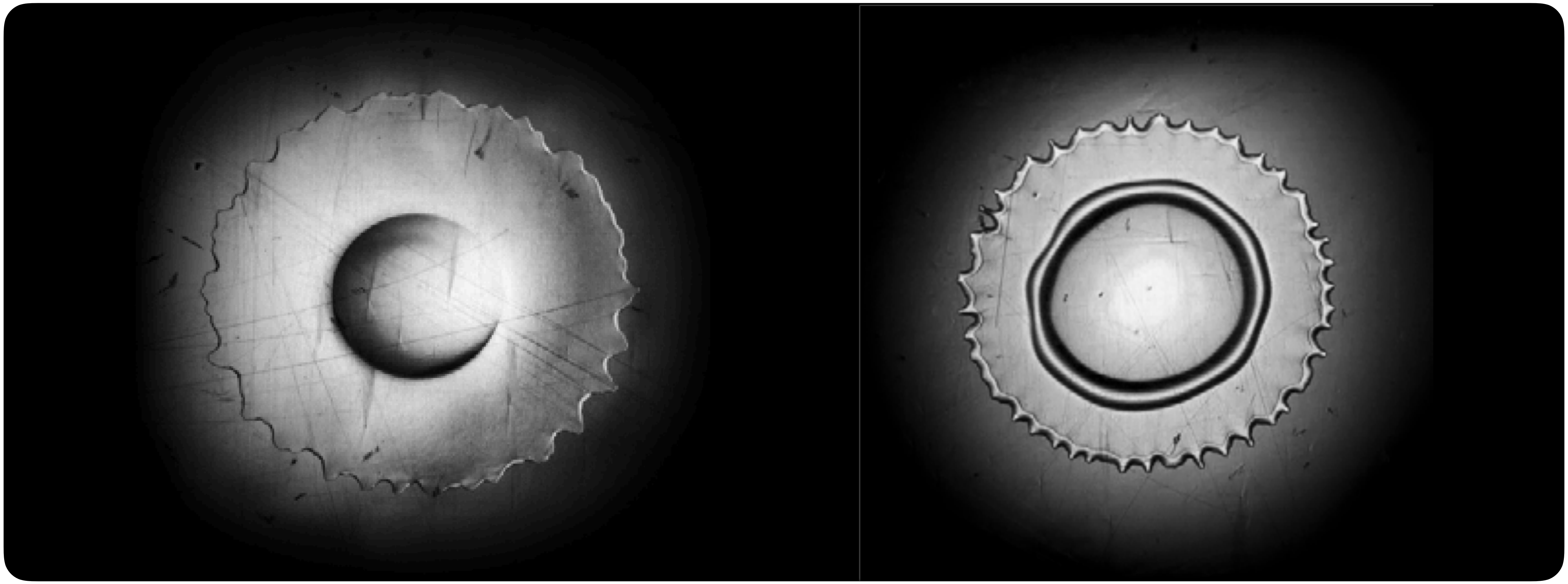
θ_f is related to the contact angle that water made with ice at the moment it has been frozen.

WATER/ICE CONTACT ANGLE



θ_f reaches $\theta_{eq}^{sol} = 12°$ which gives an estimation of the equilibrium contact angle of water on ice !

CONCLUSION



- Thermal properties of the substrat strongly influences the freezing dynamics.

- The understanding of the competition between capillary hydrodynamics and solidification is crucial to predict the shape of such a frozen structure.

- This experiment gives an interesting estimation of the equilibrium contact angle of water on ice : 12°.

FIN