European Course of Cryogenics 2022

Cryogenic Multiphase Heat & Mass Transfer

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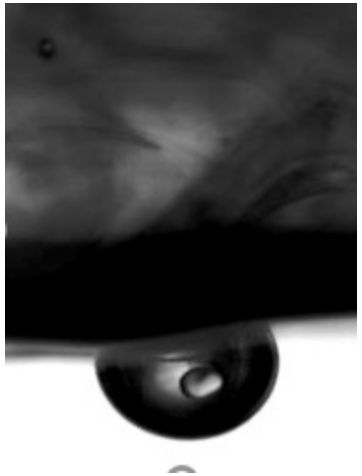
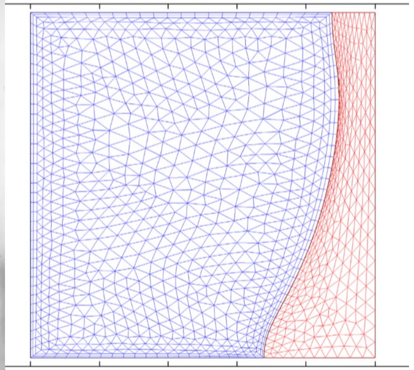
Applied Thermal Sciences lab

Heat and **mass transfer** at low temperature

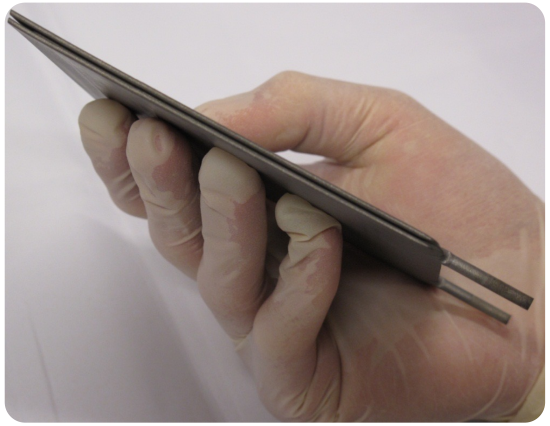
a. Seeking solutions for velocity, pressure and temperature fields in liquid and vapor phases, temperature field in the solid
b. Scaling to real applications in life sciences and energy





Cryogenic environment

a. Low temperatures from 200 K to 20 K
b. Thermo-physical properties change strongly with temperature
c. Heat fluxes always present



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How to participate?

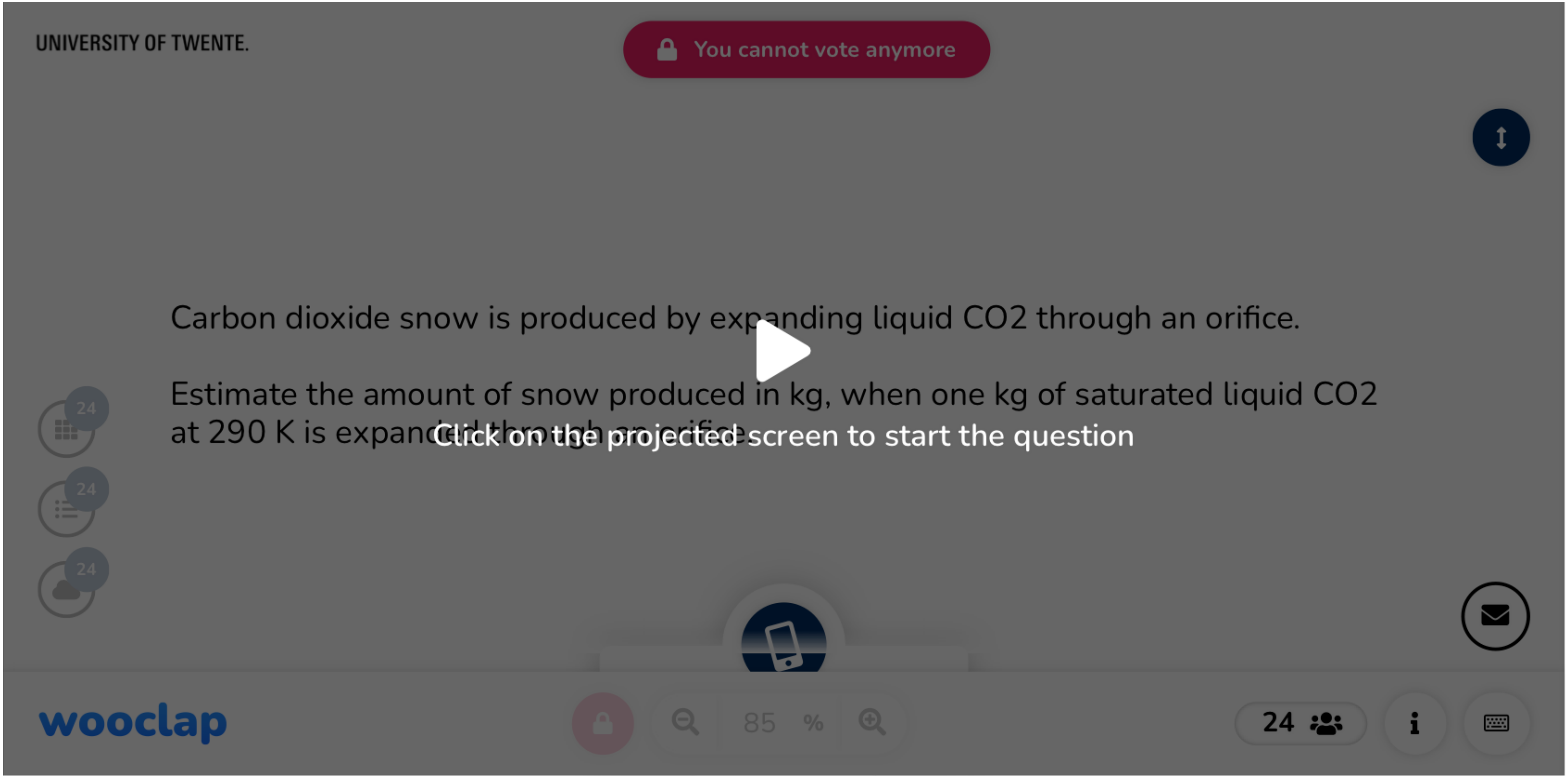
Click on the projected screen to start the question

wooclap

85 %

31

#1 CO2 production



Answer

25 %

CO_2 molecule

#2 CO2 properties

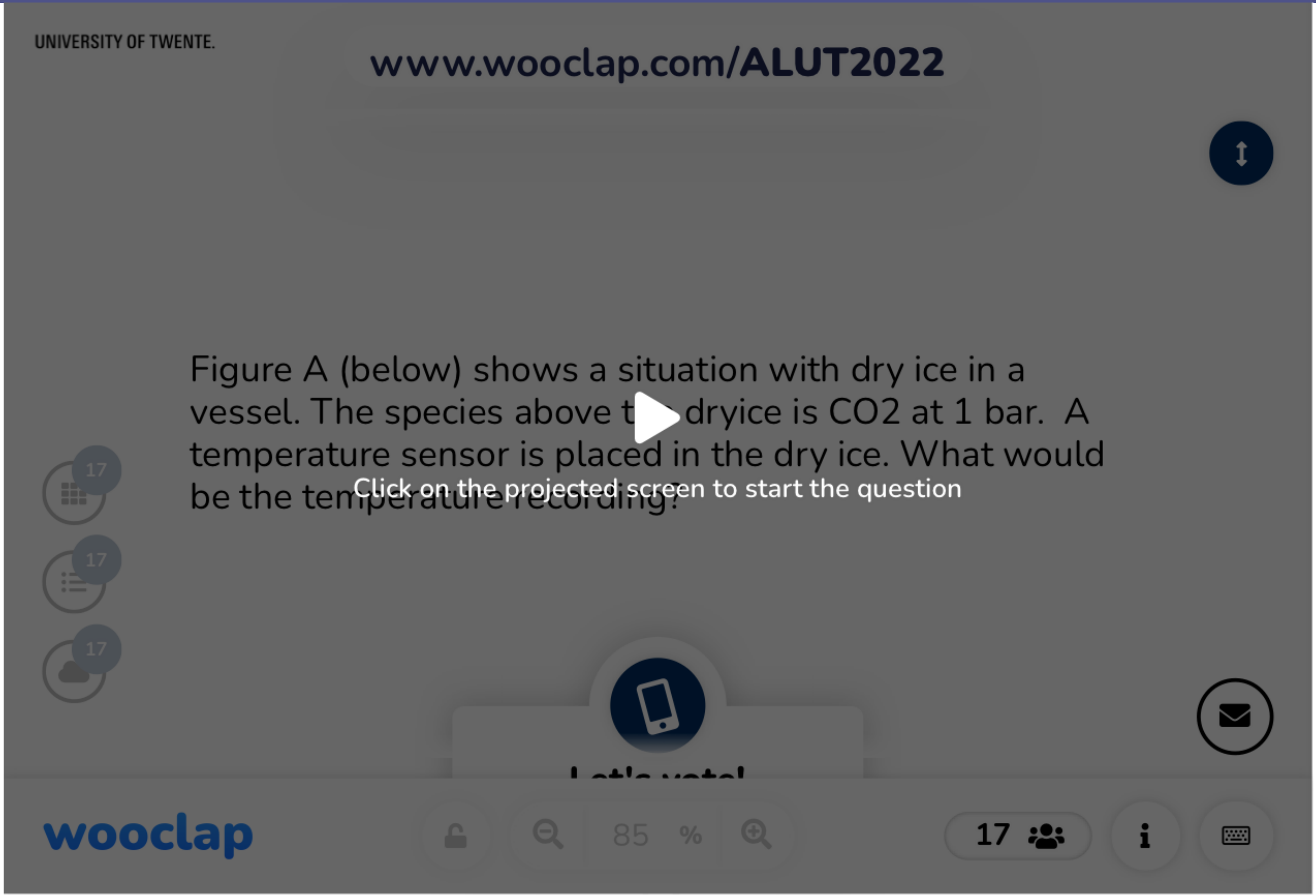
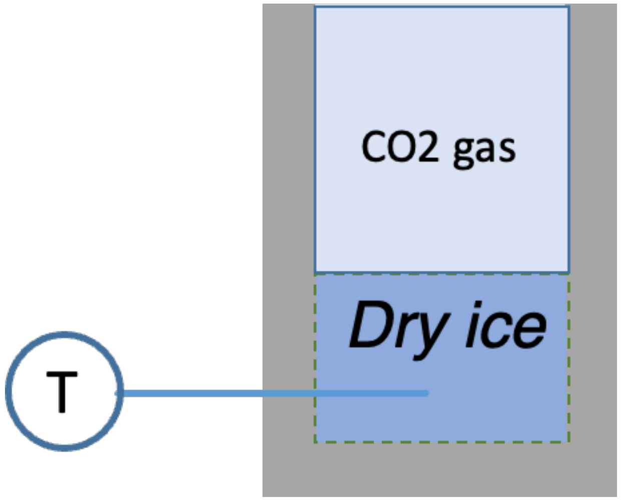
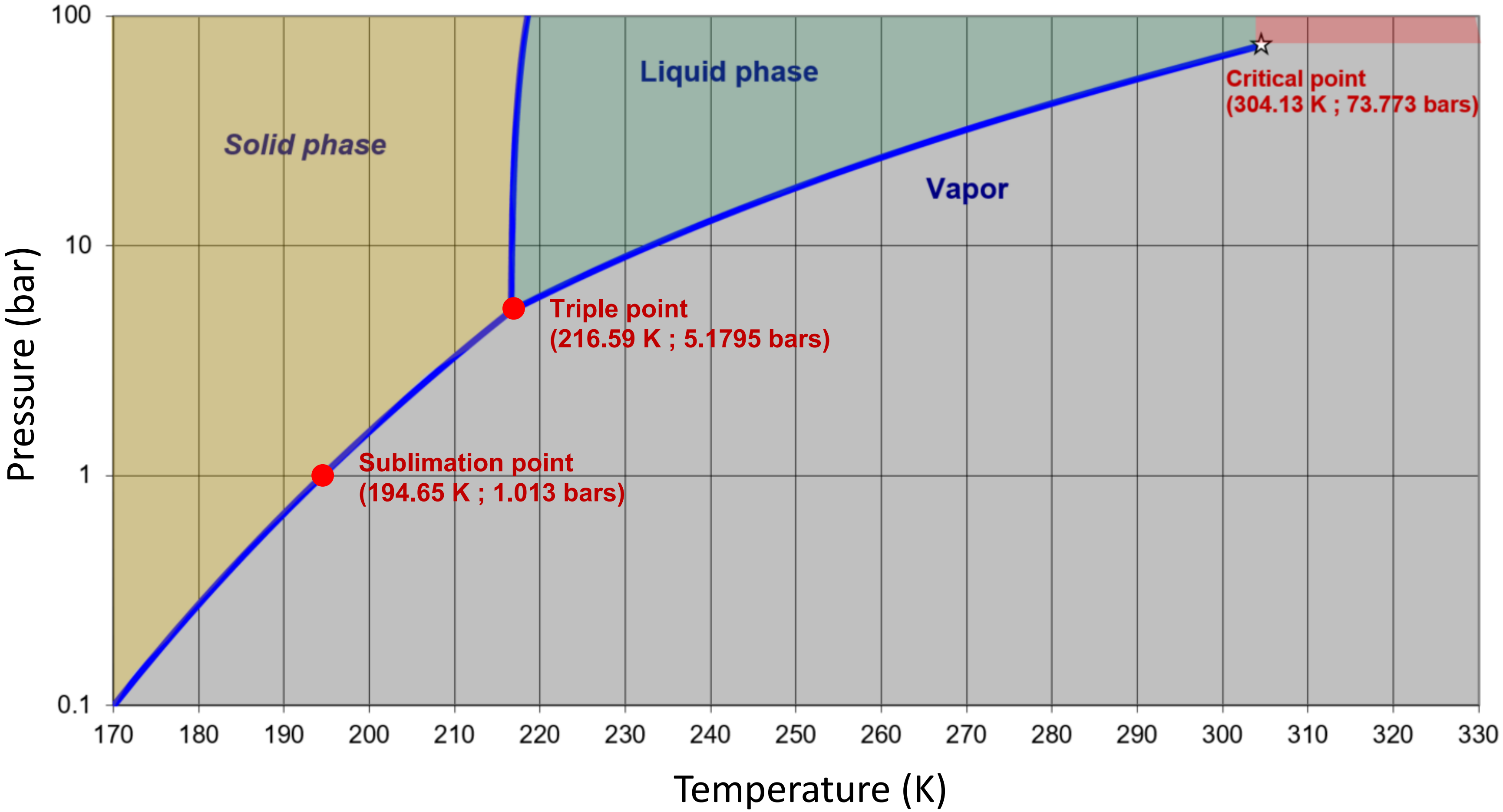


FIGURE A



Dry ice temperature - Thermodynamics

What is the dry ice temperature? -78.5 °C?



#3 CO2 properties

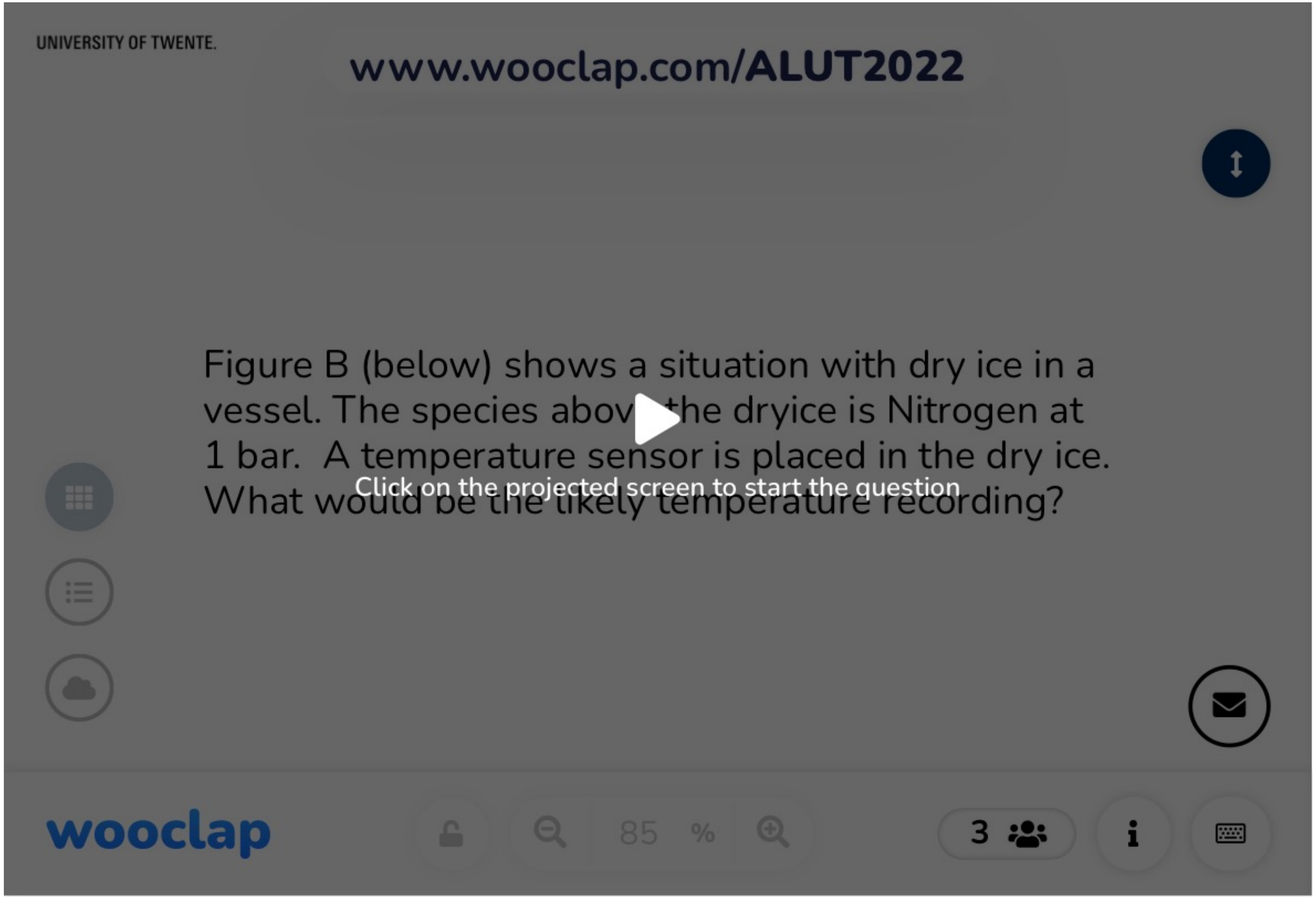
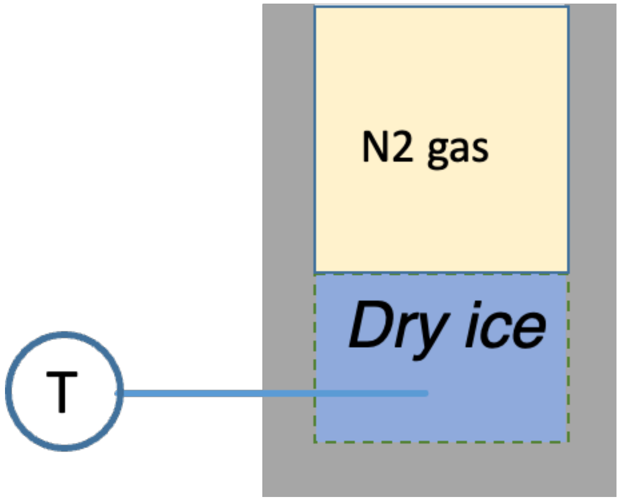
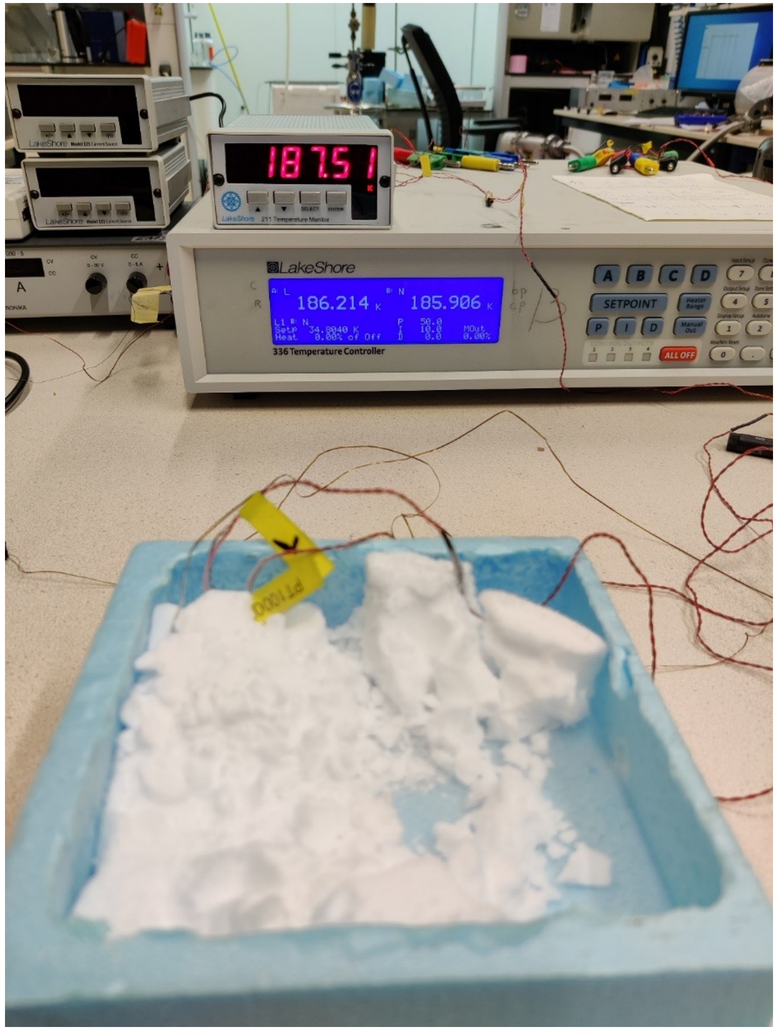


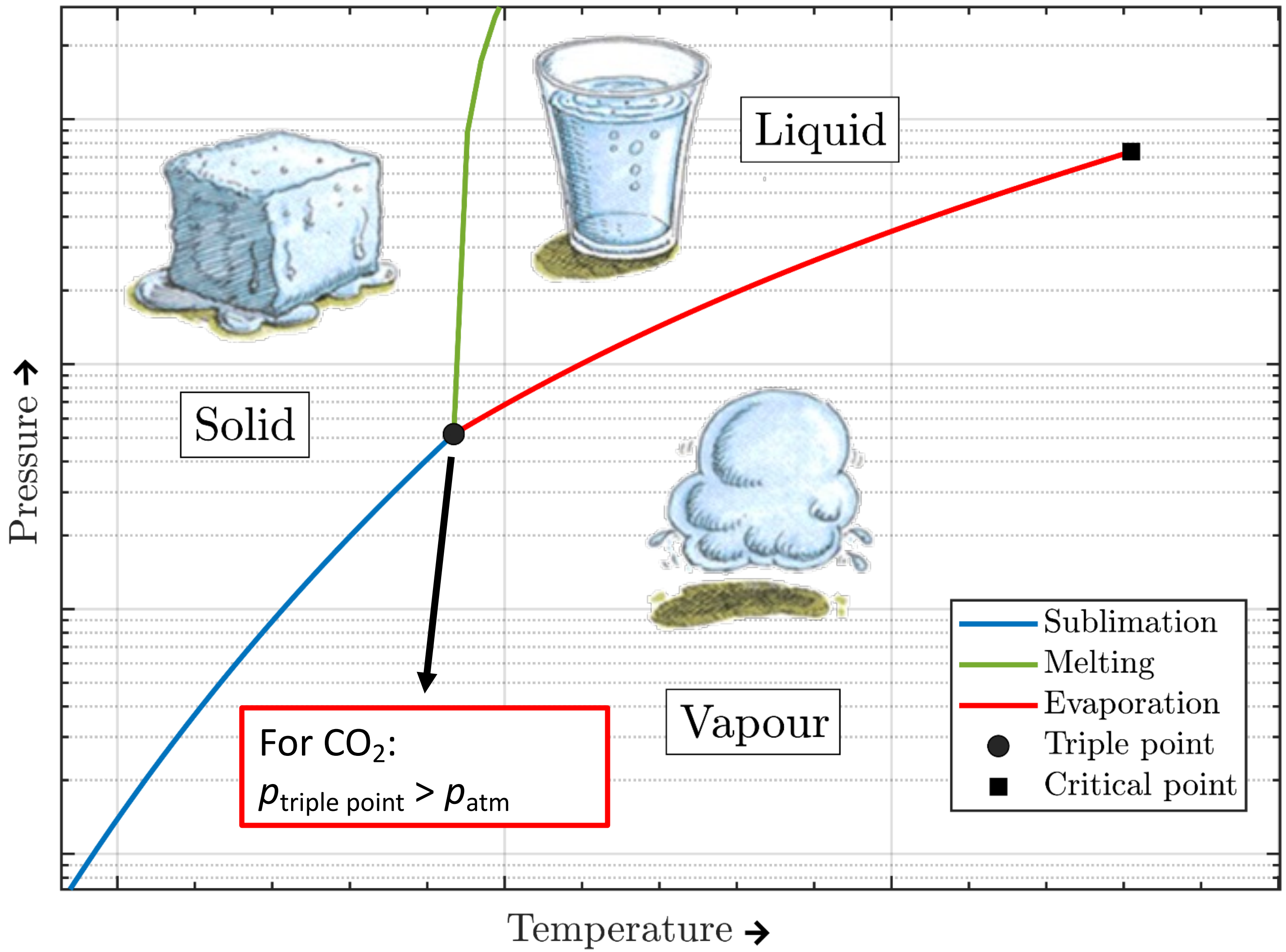
FIGURE B



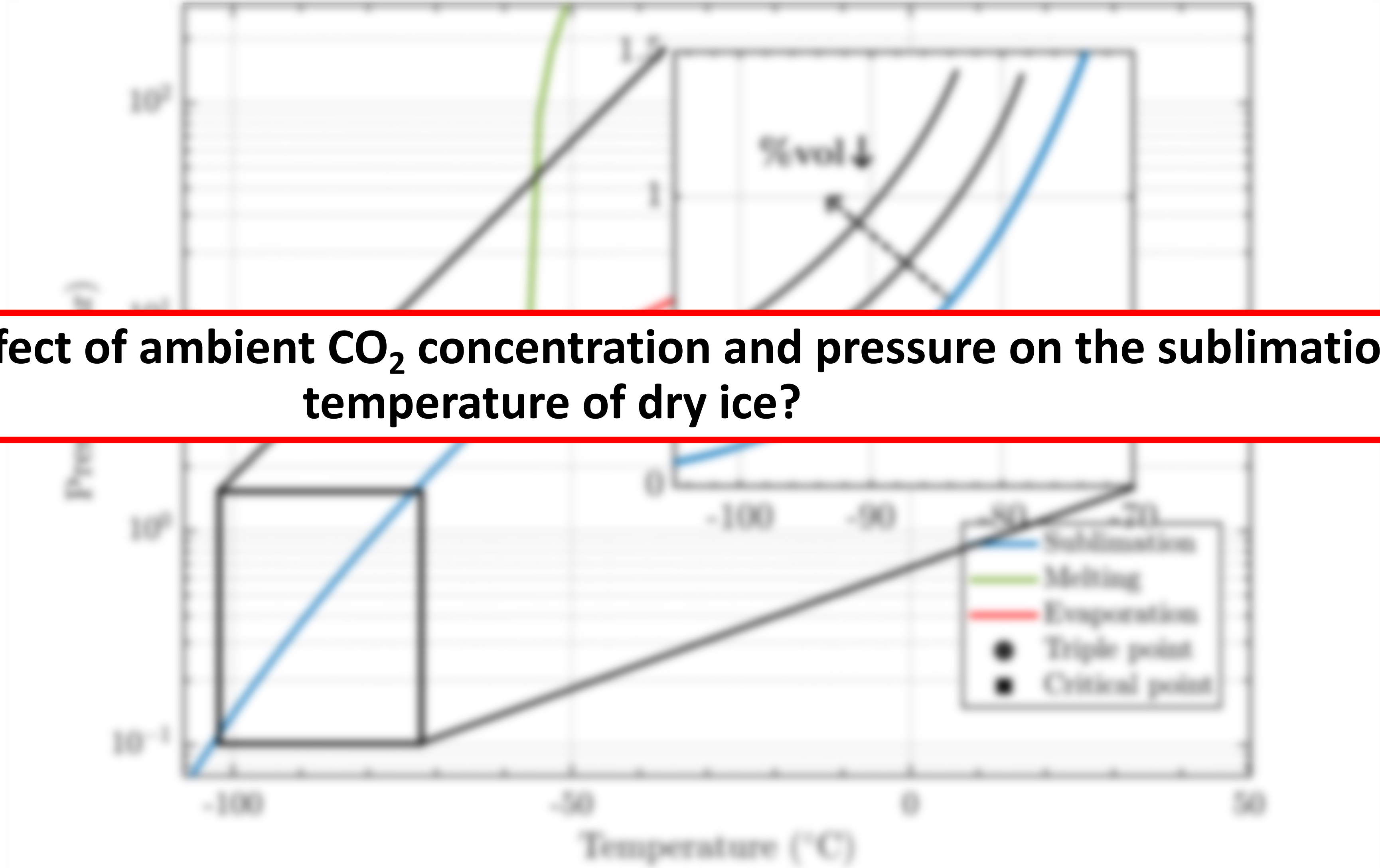
Temperature measurement of dry ice



Thermodynamic phase diagram



Research question



What is the effect of ambient CO_2 concentration and pressure on the sublimation temperature of dry ice?

Model – geometry and assumptions

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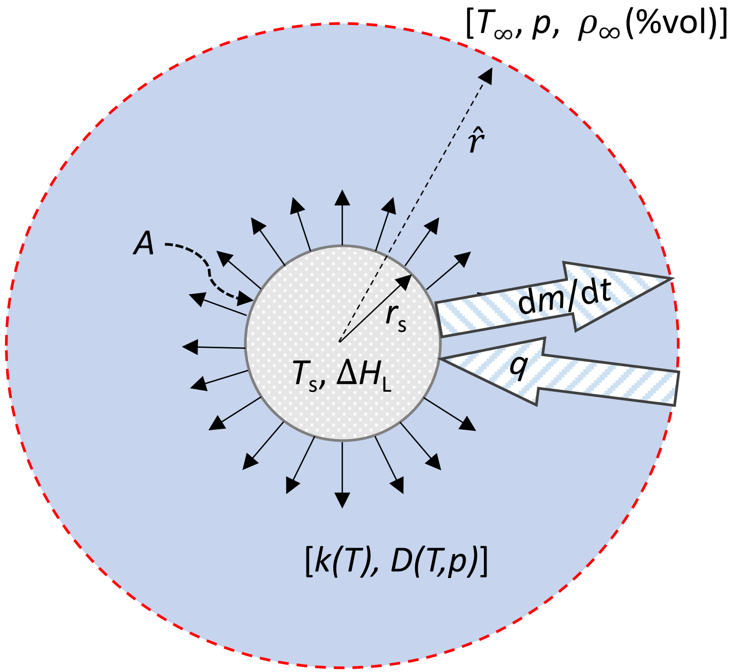
- Based on kinetics:
  heat transfer input and mass transfer output.

- **Lumped** capacitance model
- **Stationary** ambient

- Heat transfer q → conductive
- Mass transfer dm/dt: → diffusive



Physical relations – energy balance

- Heat conduction:

$$q = A \cdot k(T) \cdot \left.\frac{\mathrm{d}T}{\mathrm{d}r}\right|_{r=rs}$$

- Mass diffusion:

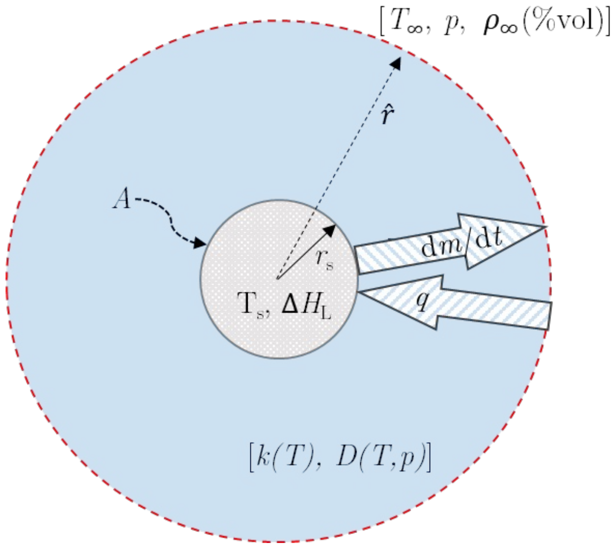
$$\frac{\mathrm{d}m}{\mathrm{d}t} = -A \cdot D(T,p) \cdot \left.\frac{\mathrm{d}\rho}{\mathrm{d}r}\right|_{r=rs}$$

- Linked by latent heat:

$$q = \Delta H_{\mathrm{L}} \cdot \frac{\mathrm{d}m}{\mathrm{d}t}$$

- Combines to:

$$\frac{\mathrm{d}\rho}{\mathrm{d}T} = -\frac{k(T)}{\Delta H_{\mathrm{L}} \cdot D(T,p)}$$



Methodology

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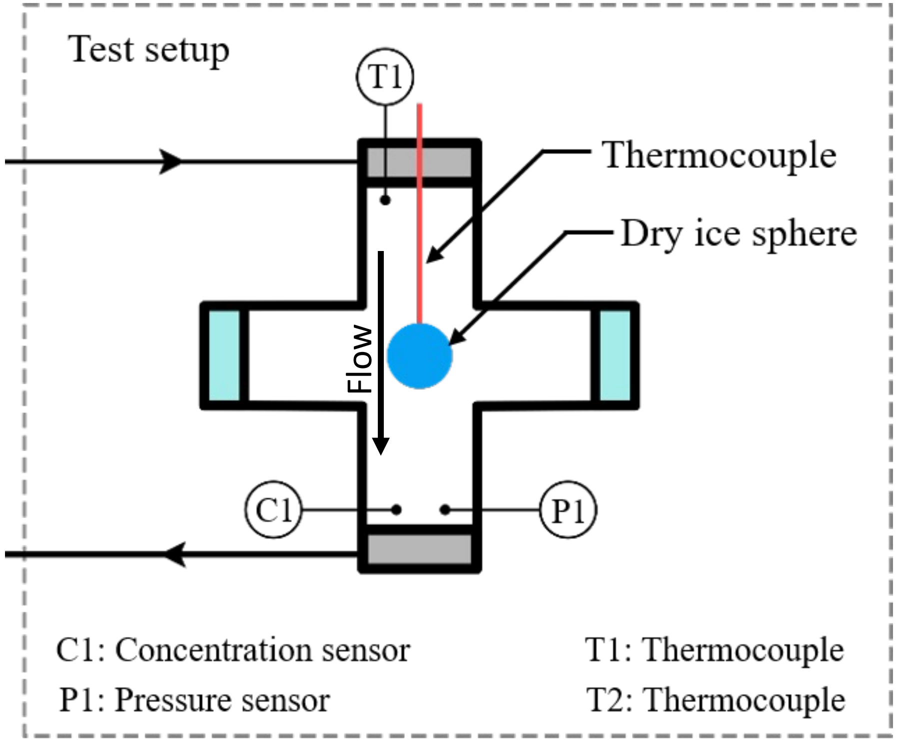
What is needed to characterise this ‘wet-bulb’ temperature?

- Controlled ambient
- Thermocouple inside a dry ice sample



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Flow conditioning

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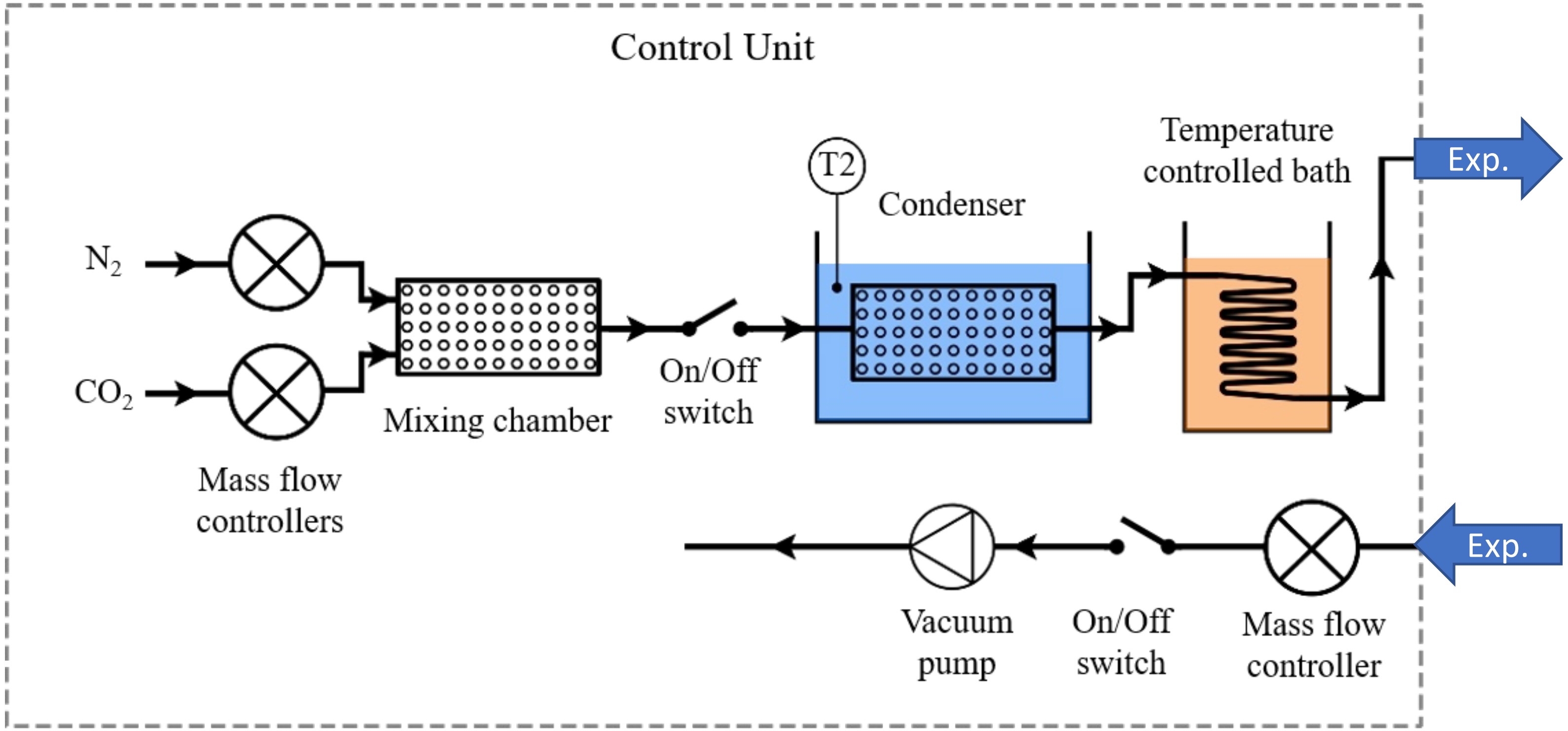
- Gas mixture:

  $CO_2 + N_2$

- Pressure regulation
  - Balancing flow



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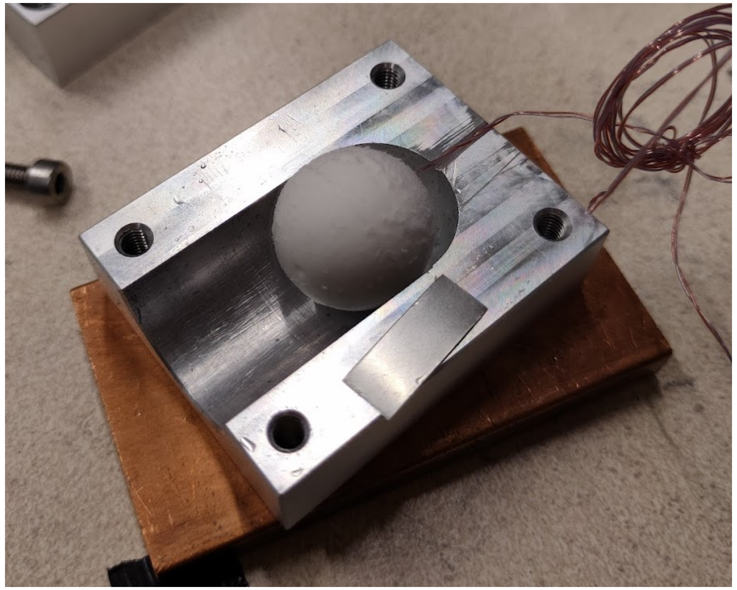
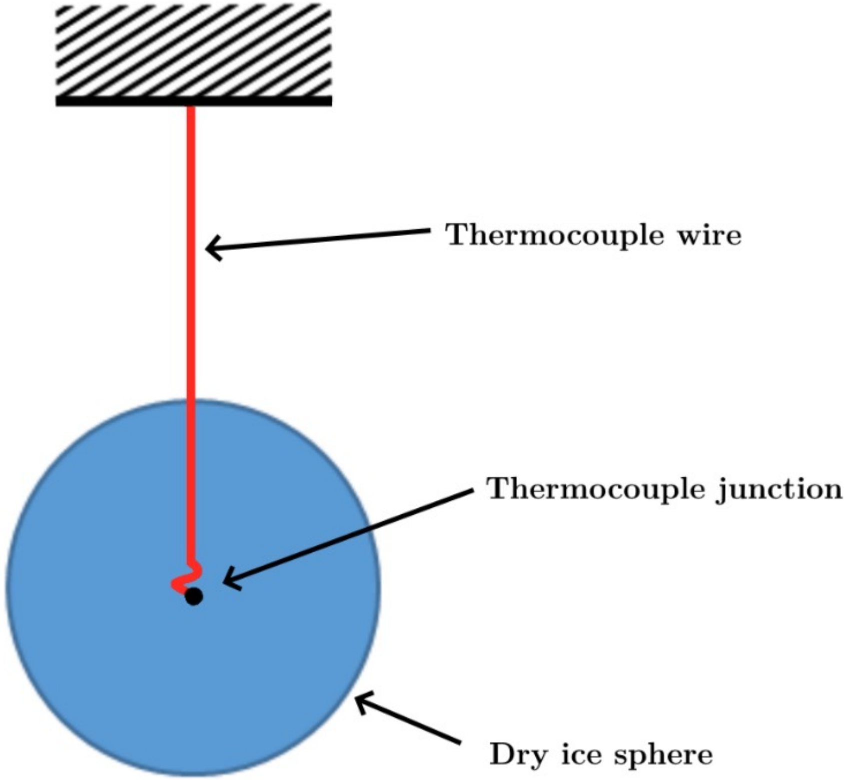
Making dry ice spheres

- Snow via Joule-Thompson expansion
- Compress into a **sphere**
- Radii of r_s = 10 mm & r_s = 5 mm

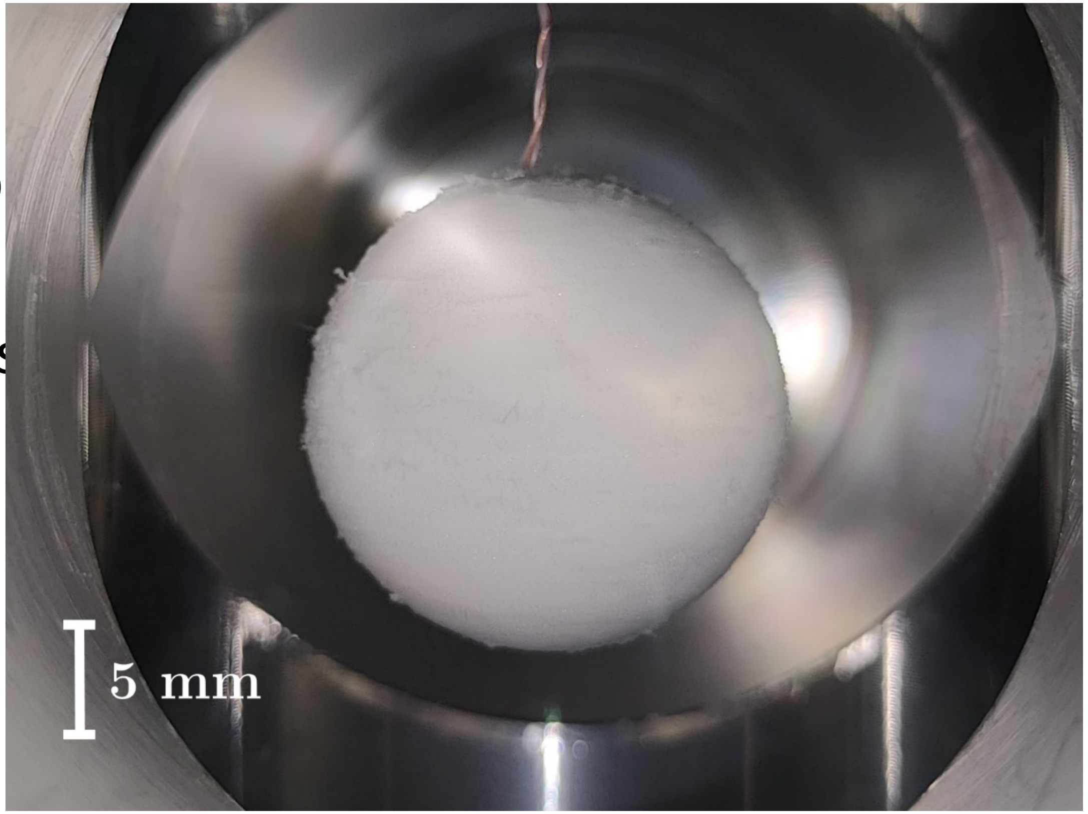




Methodology – Experimental

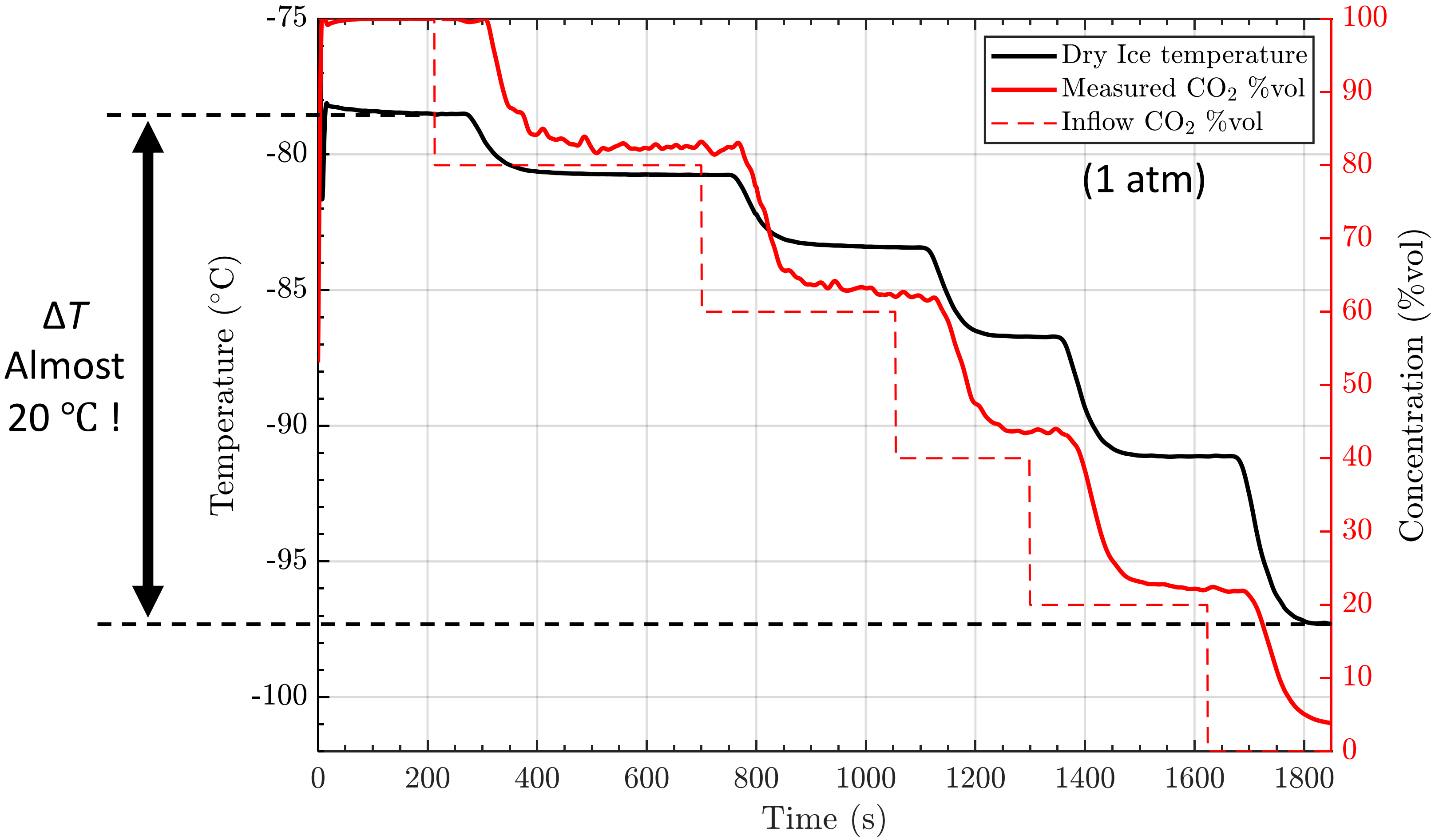
- Constant pressure exp
  - Starting at 100 %vol
  - Vary concentration in s

- Repeat for pressures
  - 0.6 to 1.3 bar
  - 100 mbar increments

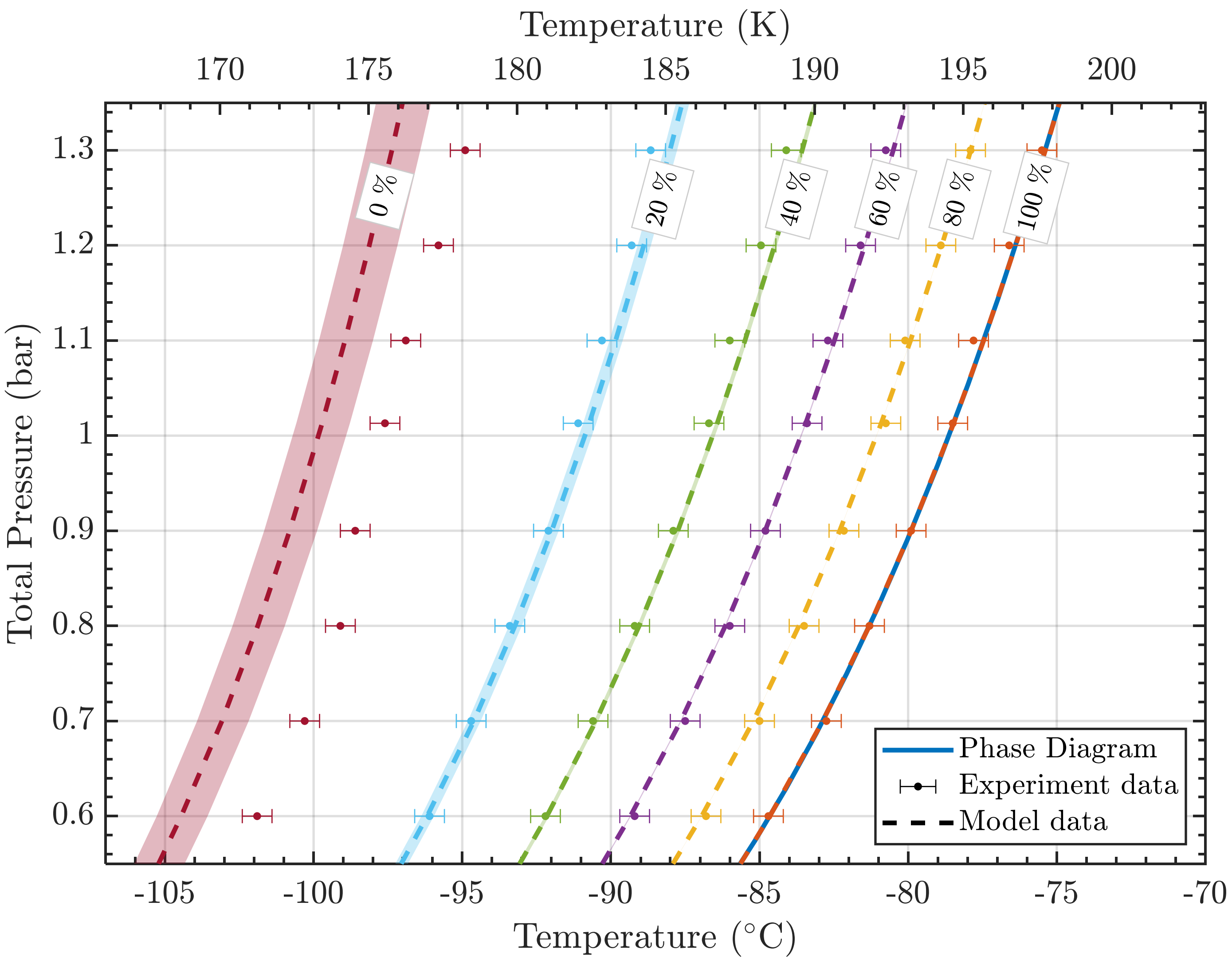


Experimental results

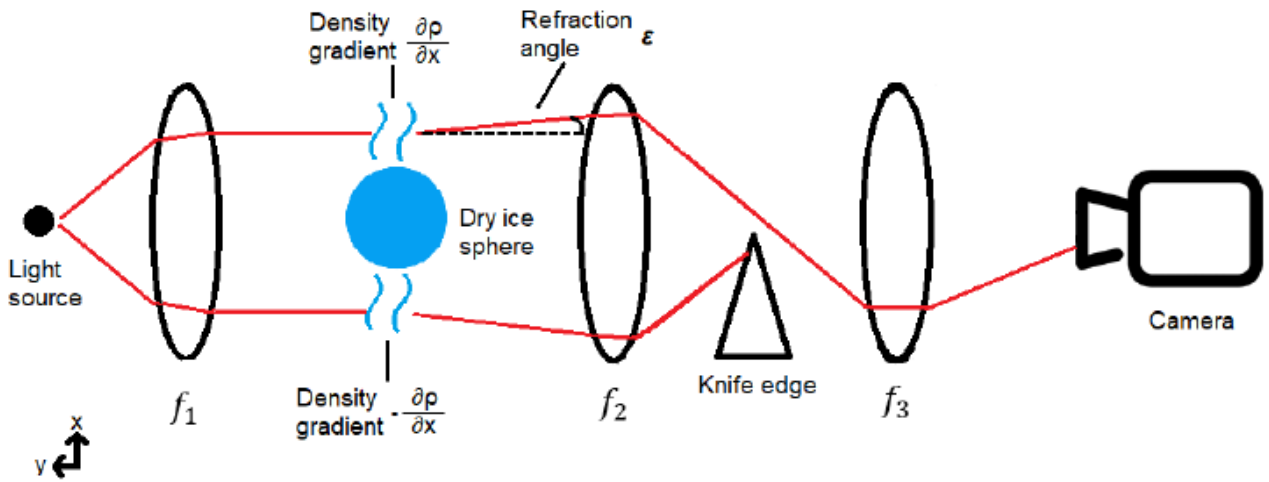
- What does such an experiment look like?

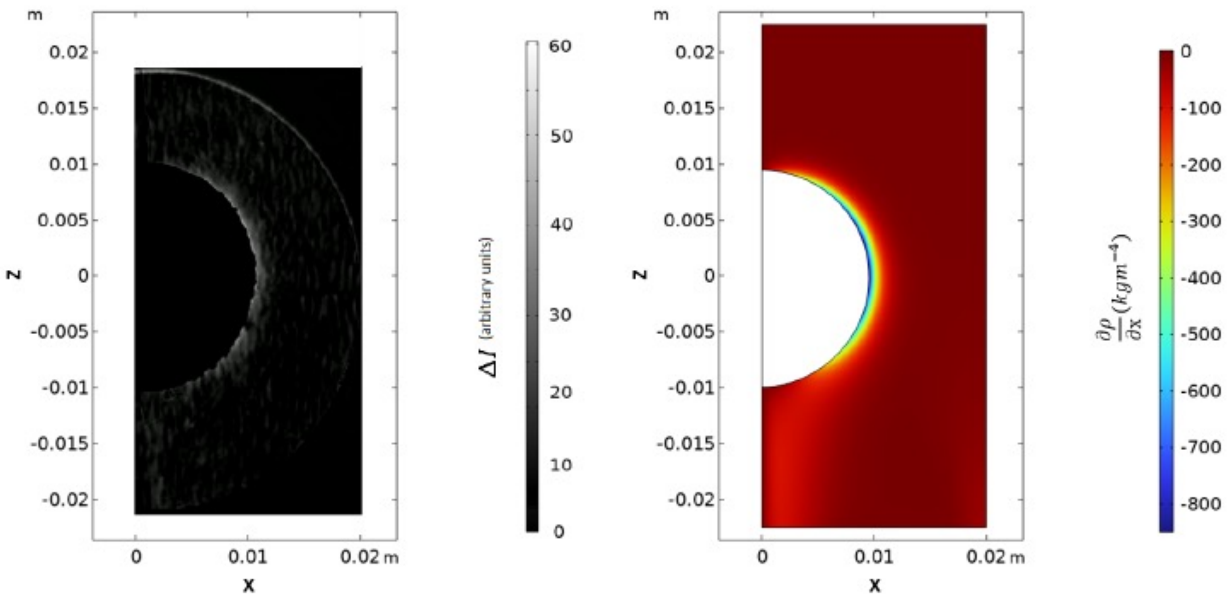


Extended phase diagram – results



Schlieren imaging





Quantifying Leidenfrost vapor layer

Leidenfrost dynamics

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“Leidenfrost Effect – Hot pan + Water”, Youtube, uploaded by LaserFloyd, 30-05-2014

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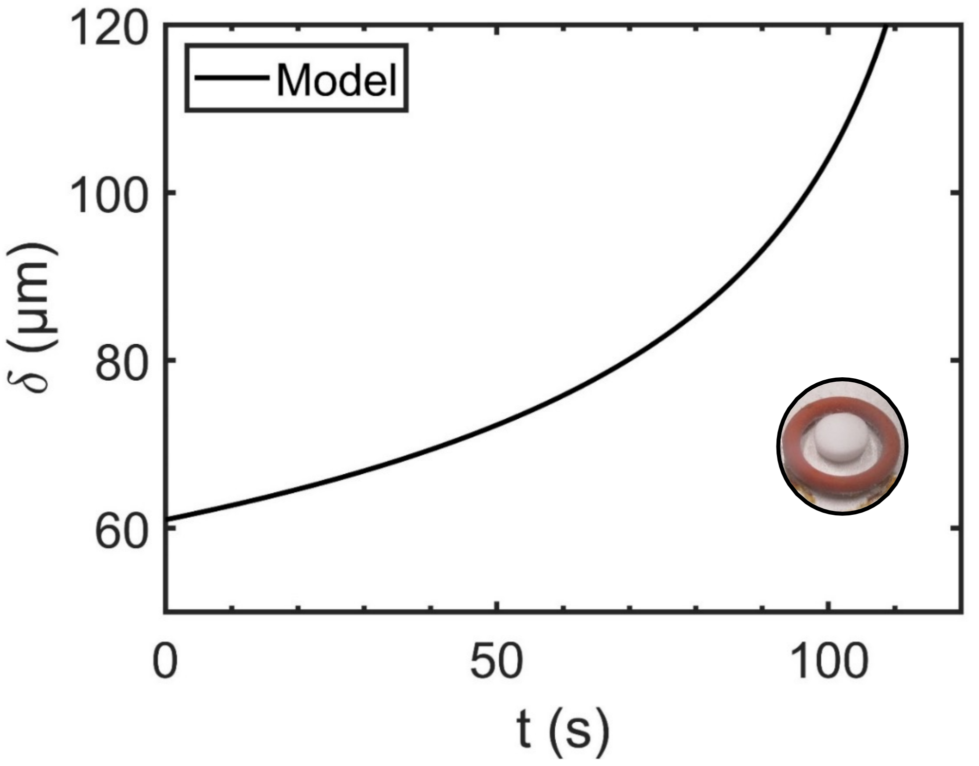
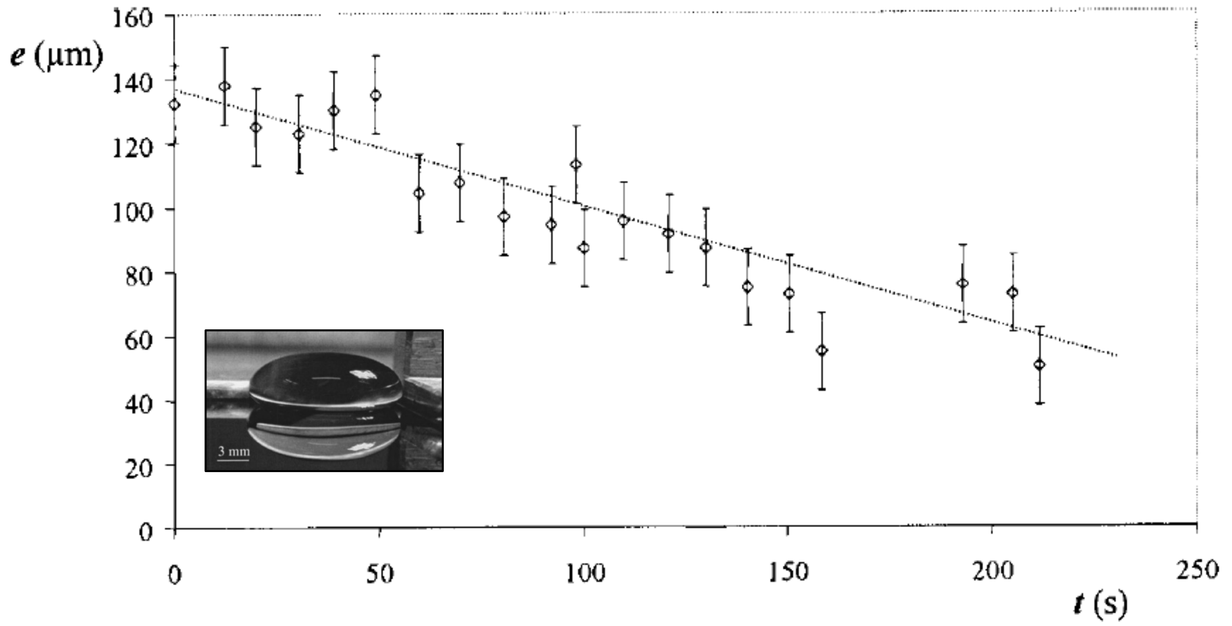
Observation

#4 Heat transfer

Vapor layer thickness – model prediction



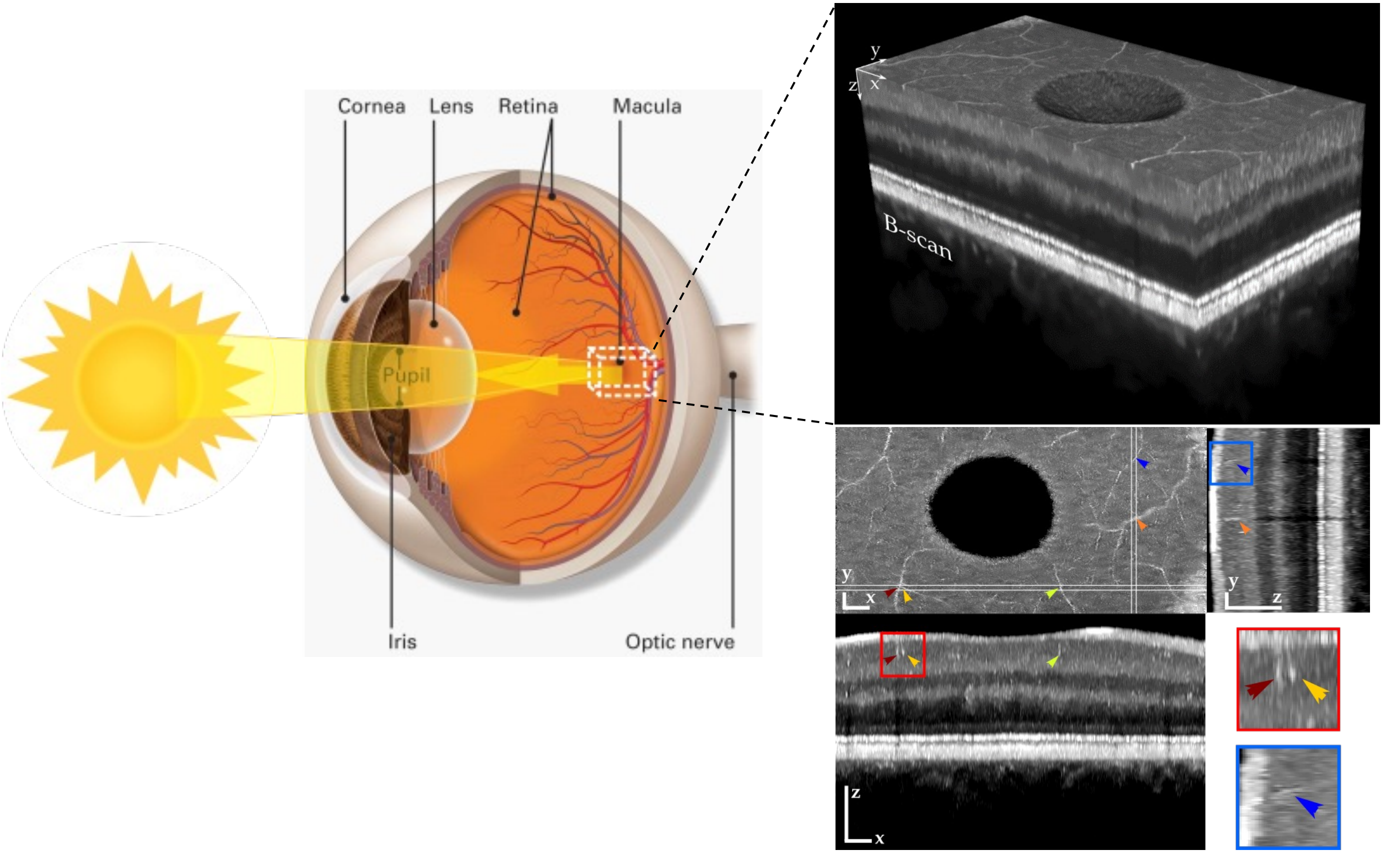
Predicted time variation of vapor layer thickness for dry ice pellet (h_i = 5 mm ; d_{ci} = 10 mm) placed on a hot substrate



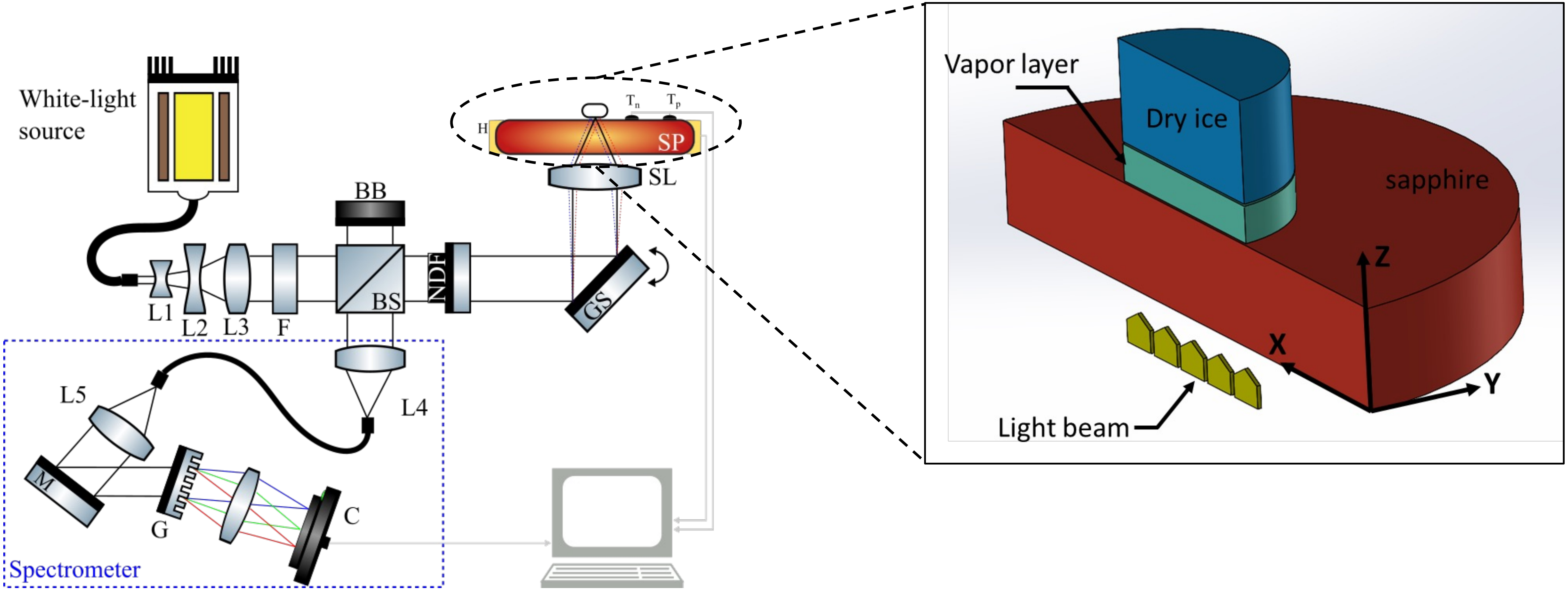
Predicted and measured time variation of vapor layer thickness for water drop (d_{ci} = 20 mm) placed on a hot substrate*

Optical Coherence Tomography (OCT)

Medical **imaging technique** based on low-coherence **interferometry** which produces **high-resolution images** of scattering media such as tissue.

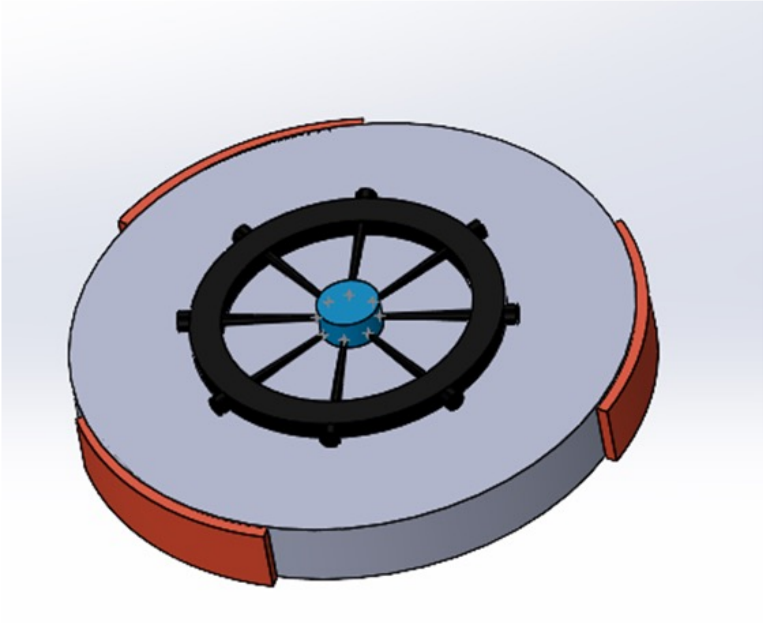


Measuring vapor layer thickness with OCT

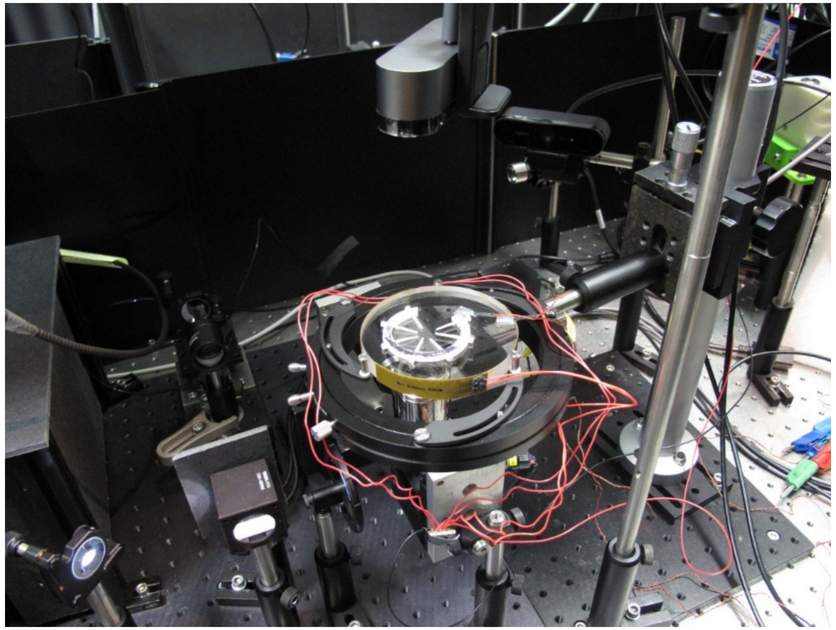


Experimental setup

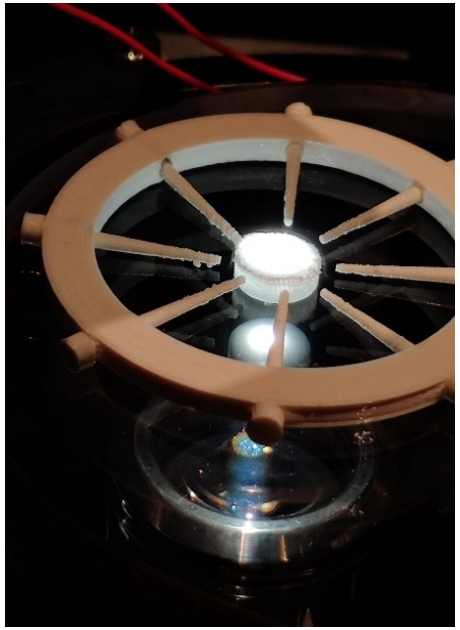
Test section assembly



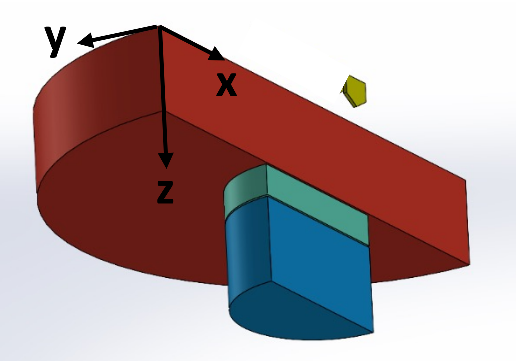
Test section in setup

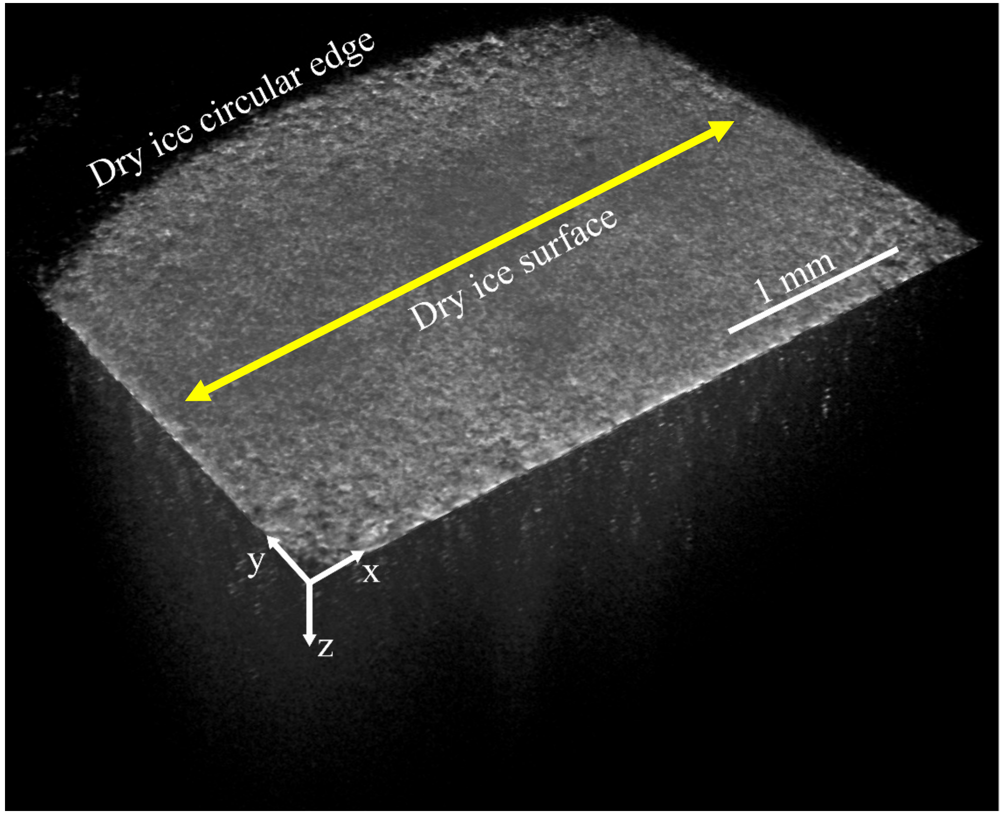


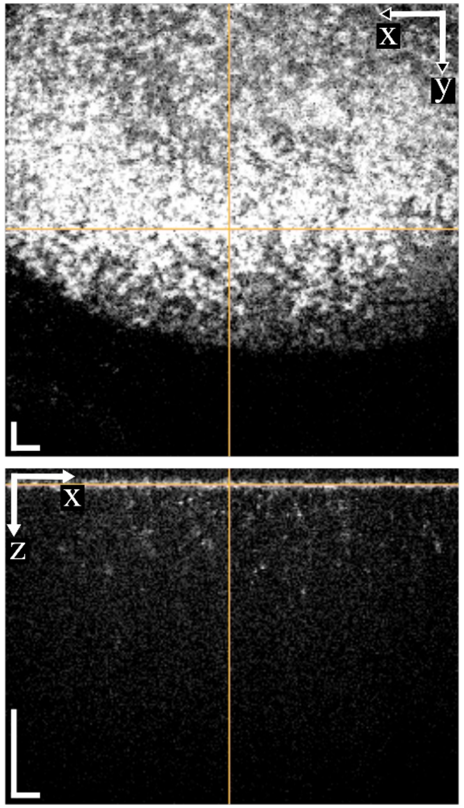
Retaining ring + dry ice



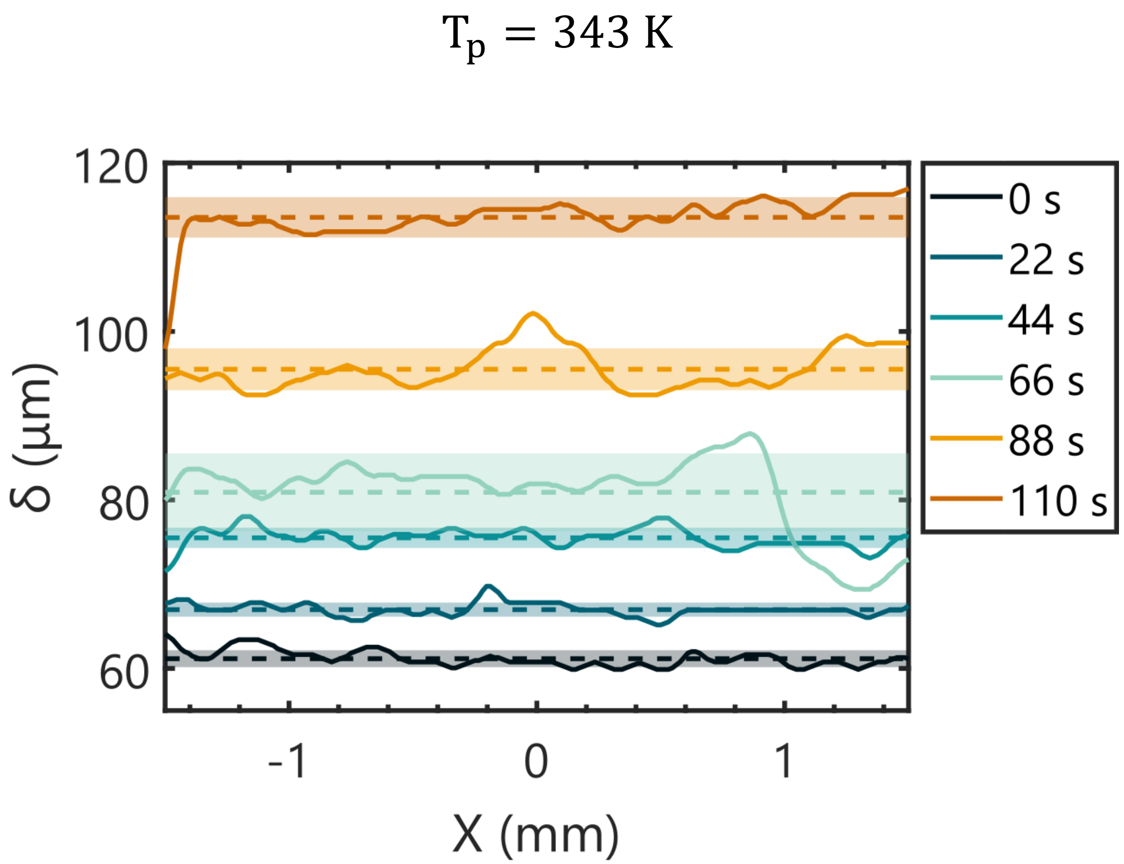
Scanning



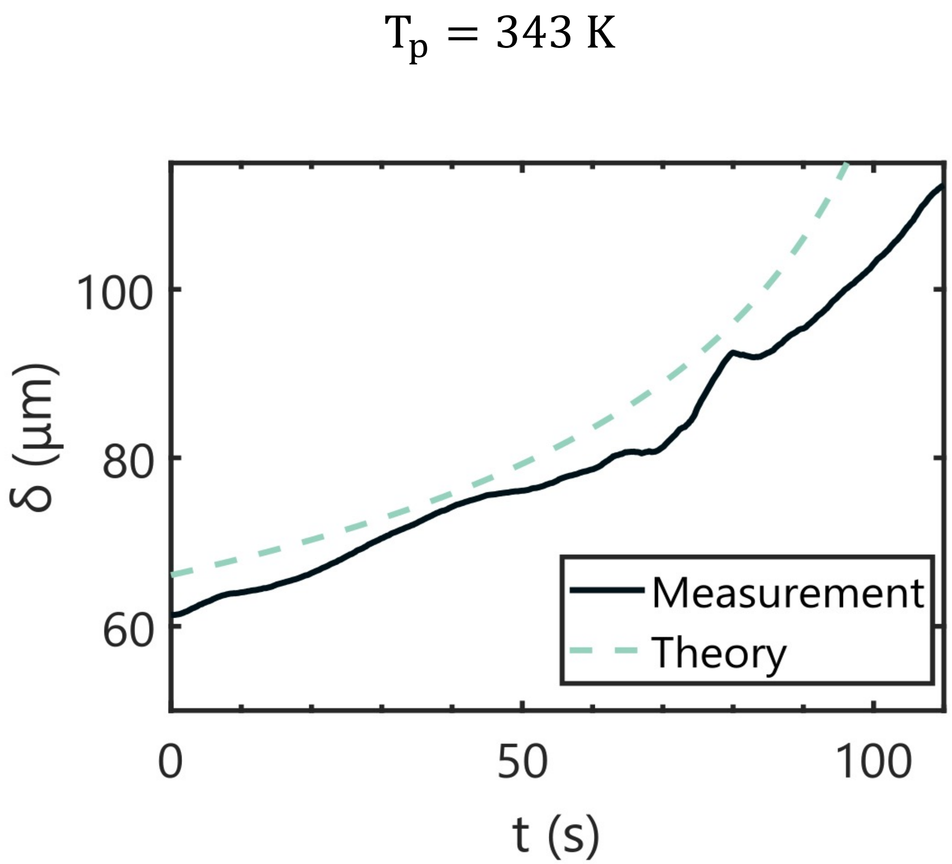




Line scan

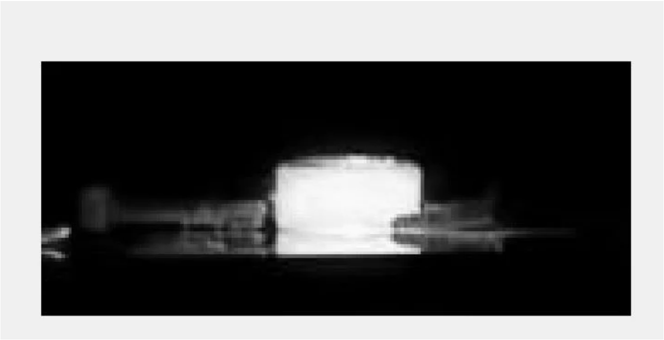


Measured vapor layer profile for dry ice pellet (h_i = 5 mm ; d_{ci} = 10 mm) placed on a hot substrate



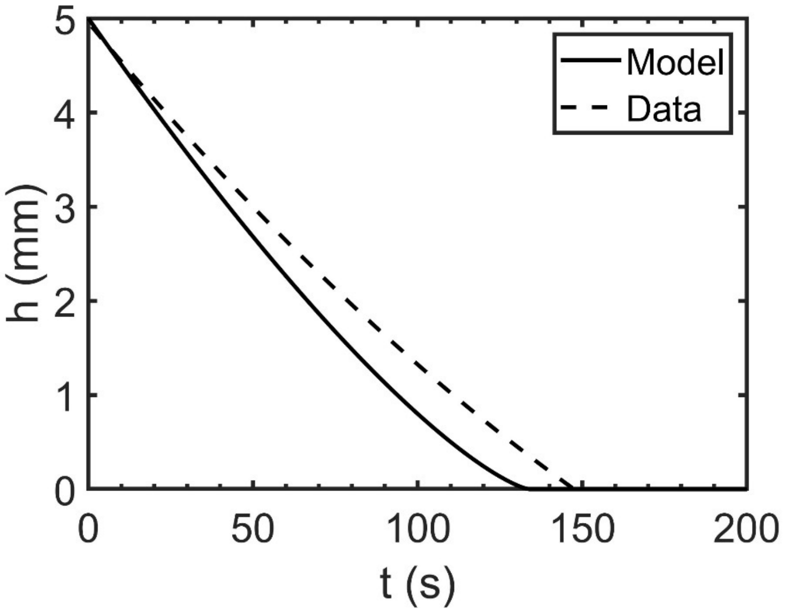
Measured and predicted time variation of vapor layer thickness for dry ice pellet (h_i = 5 mm ; d_{ci} = 10 mm) placed on a hot substrate

Pellet height

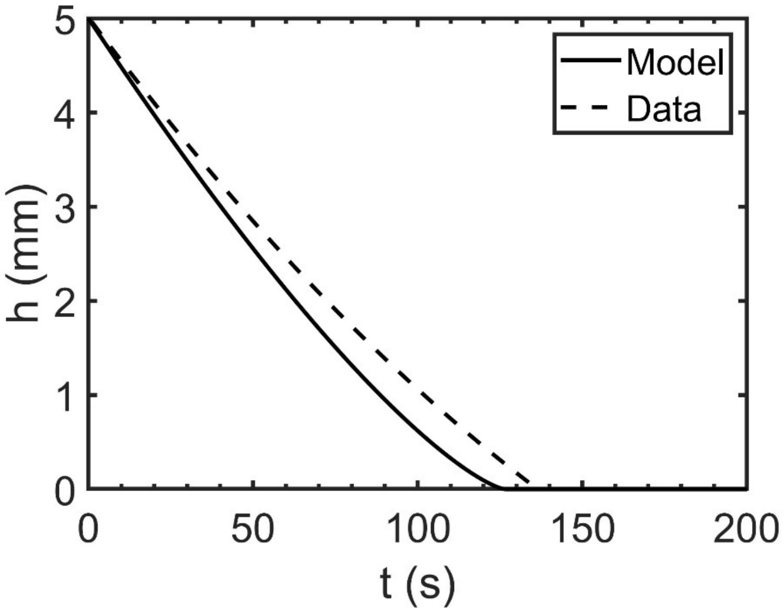


Height variation of dry ice pellet (h_i = 5 mm ; d_{ci} = 10 mm) placed on a hot sapphire substrate

$T_p = 323$ K

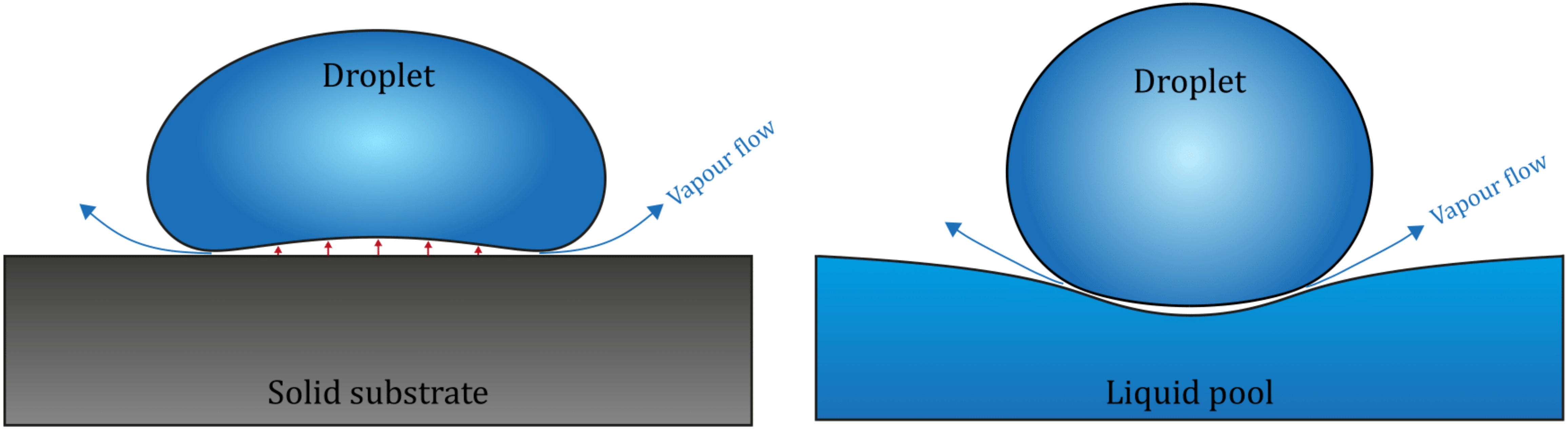


$T_p = 333$ K



Liquid nitrogen droplets

Leidenfrost dynamics



Liquid nitrogen jet/drop dispenser

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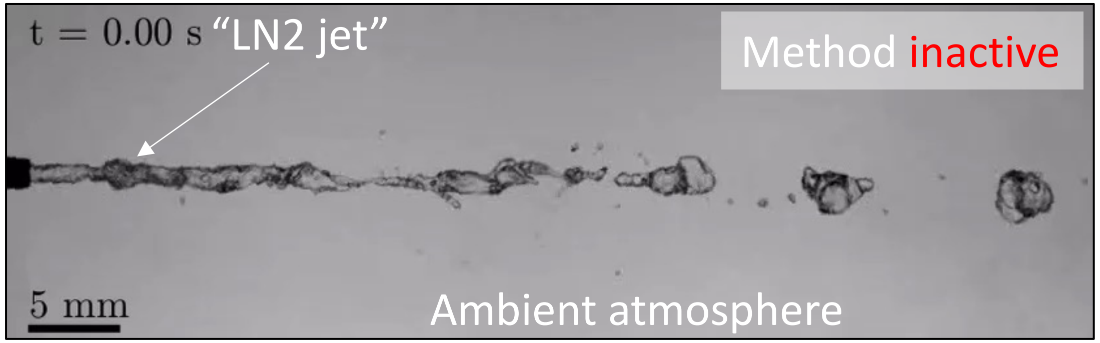
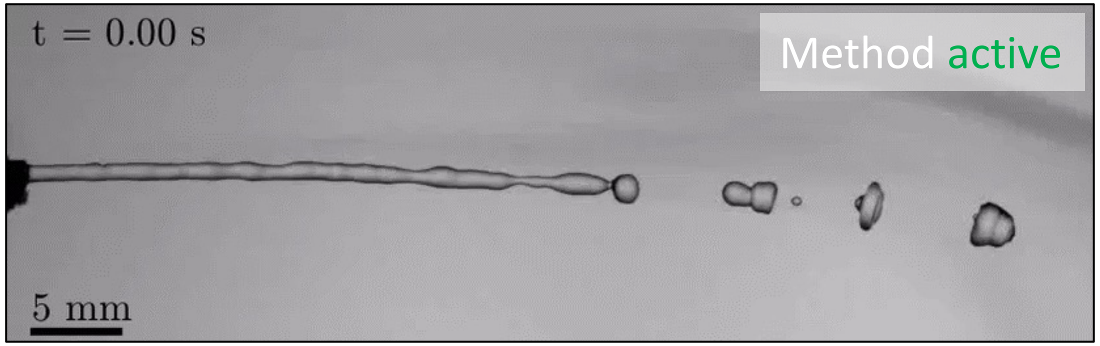


<u>Common case for a needle tube supplied from a pressurized dewar with liquid nitrogen</u>:

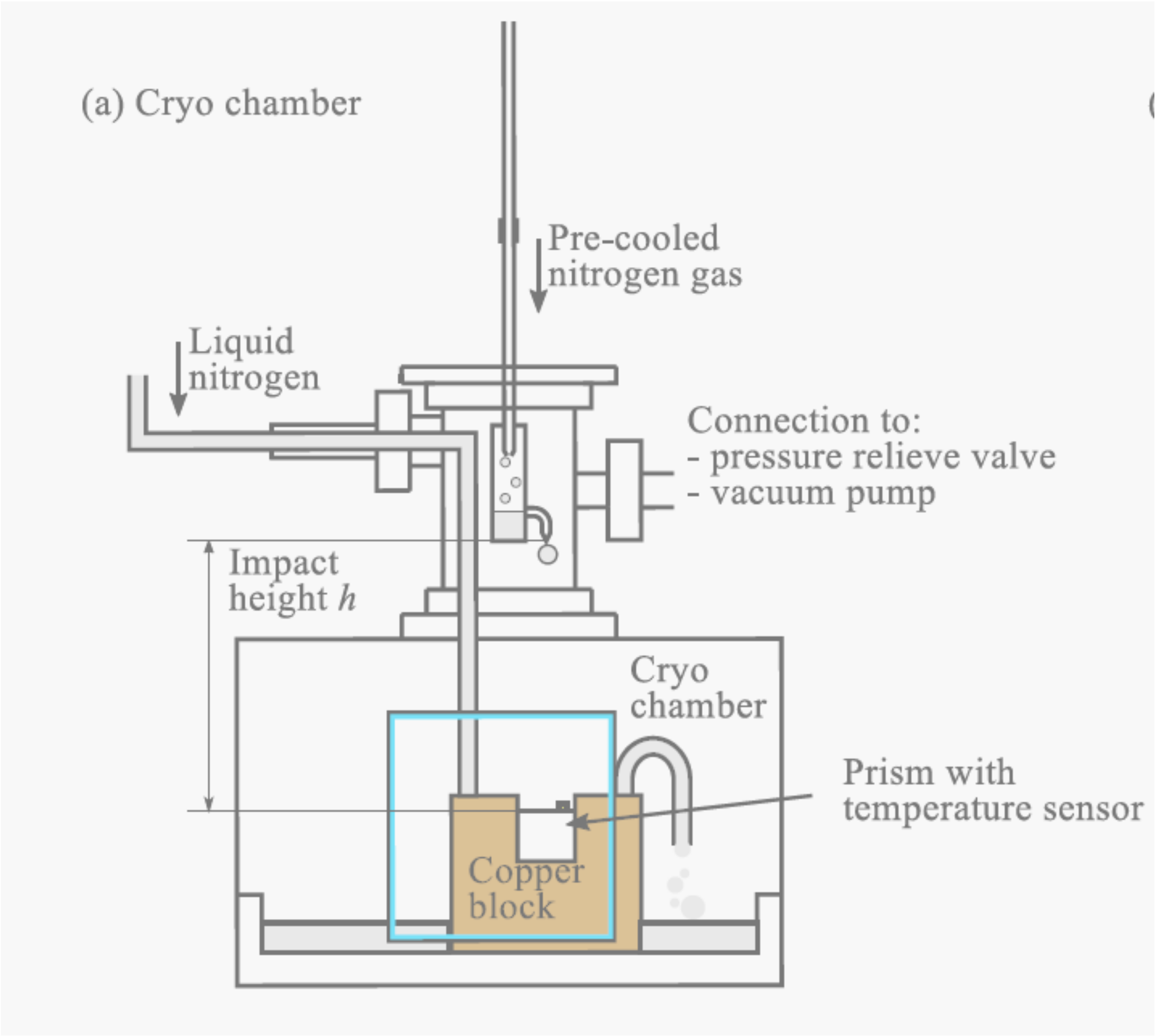
Multiphase flow at nozzle exit due to evaporation in hose

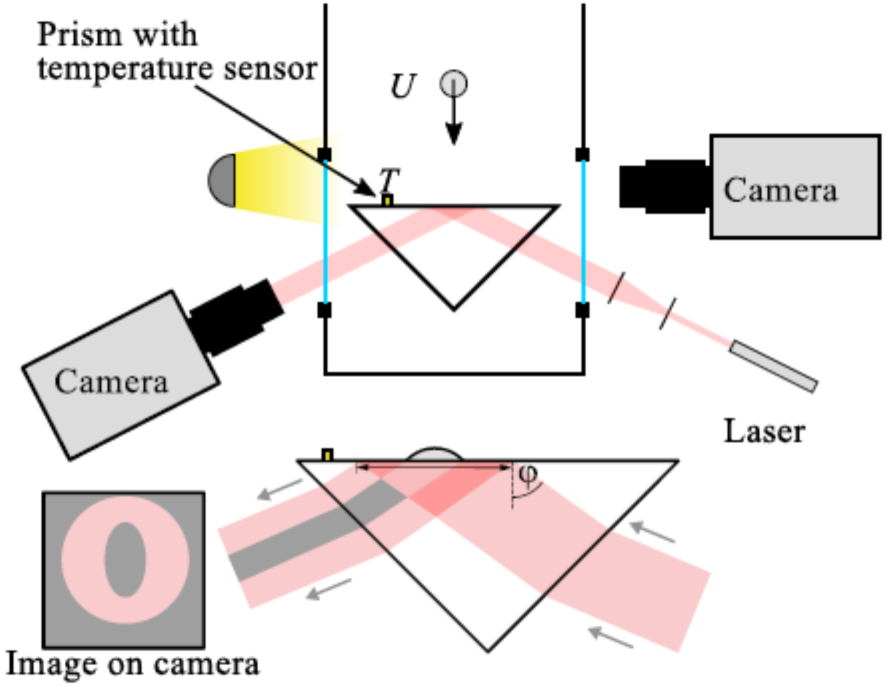
New method prevents evaporation in the hose resulting in et of pure liquid nitrogen



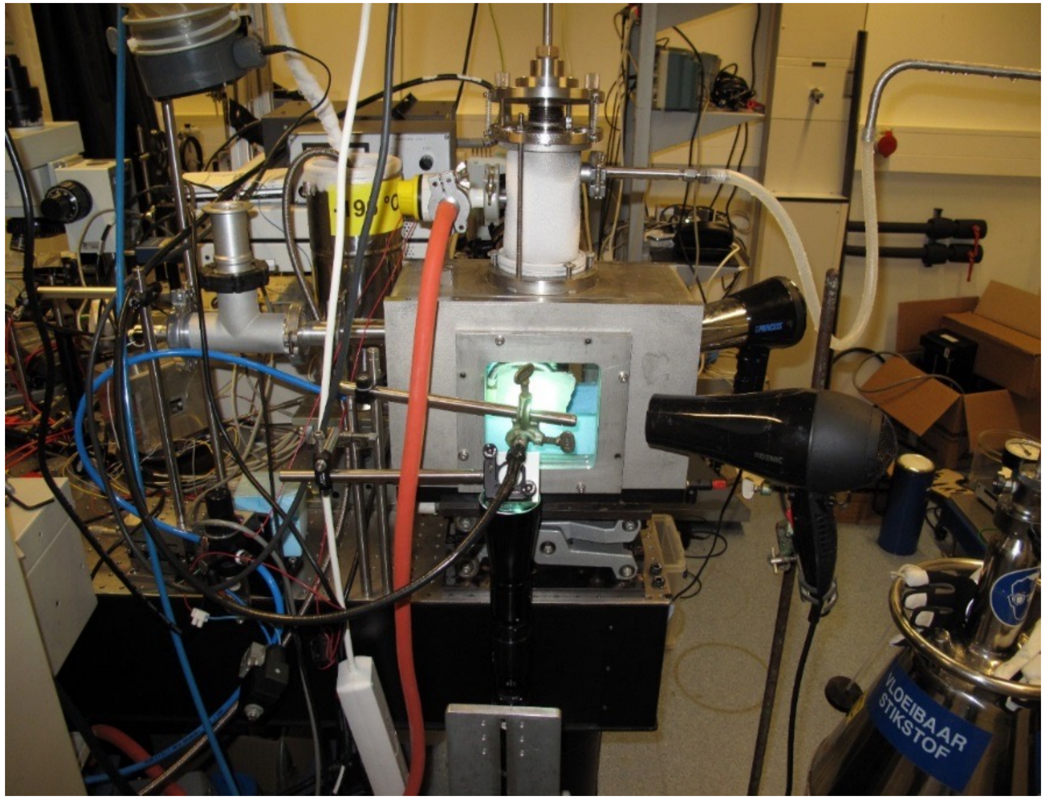
Many opportunities for doing research with cryogenic liquid jets or single droplets

Droplet impact on a plate






OLYMPUS
ST Series


VLOEIBAAR
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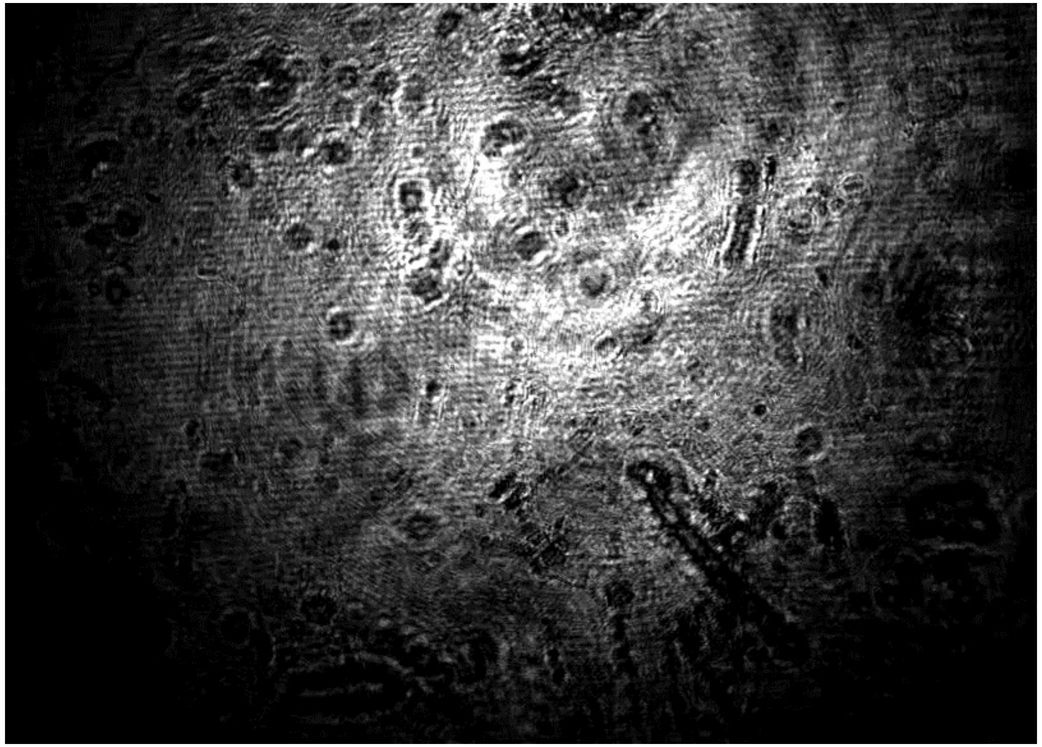
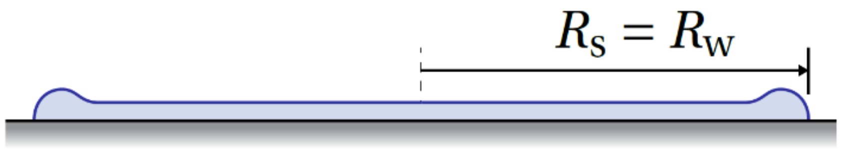
Results

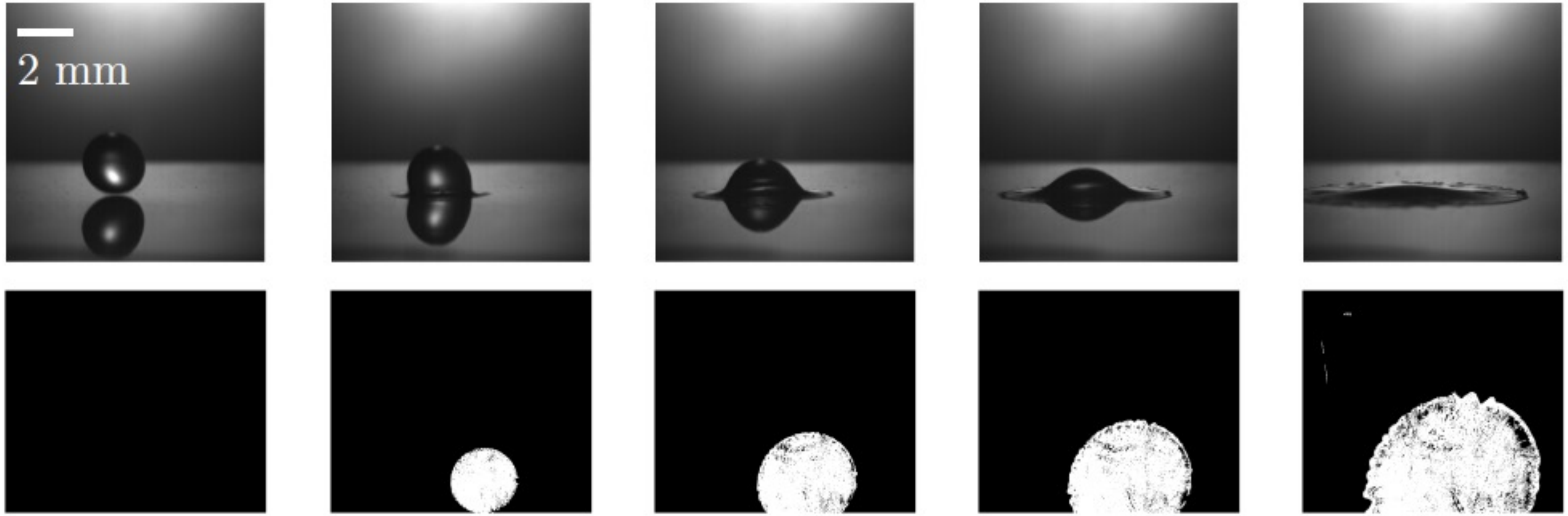
U=1.3 m/s T=89 K





Contact boiling

Slowed down 500x



$t = 0$ ms 0.4 ms 0.8 ms 1.2 ms 2.4 ms

Results: Increasing prism temperature

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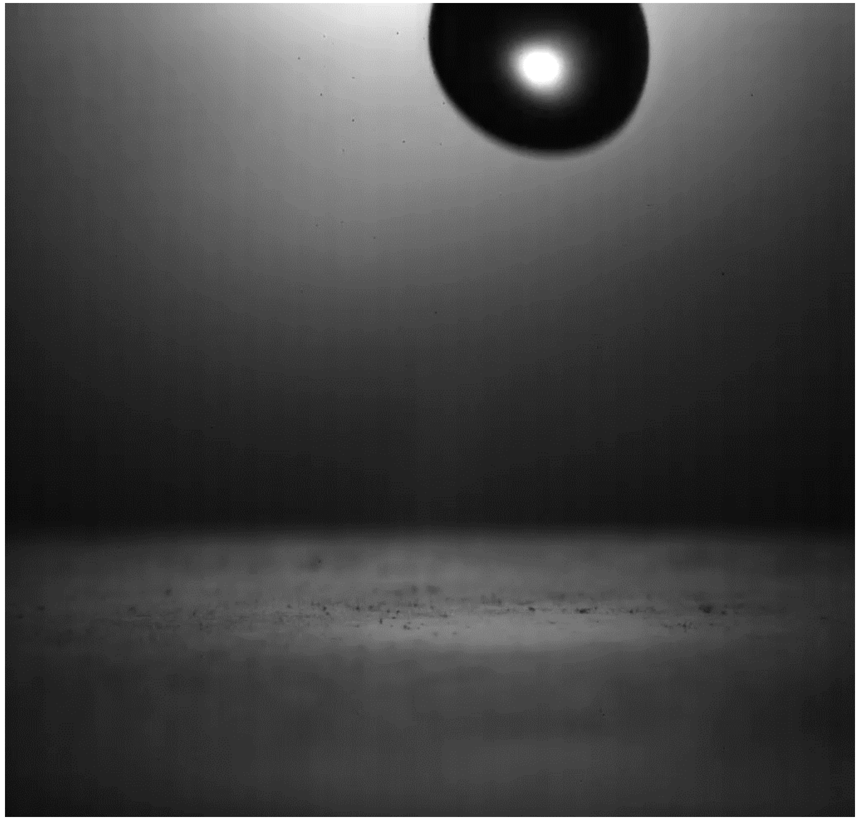
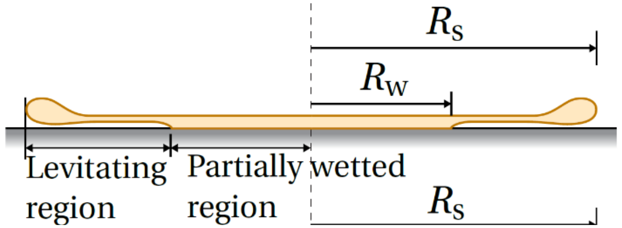
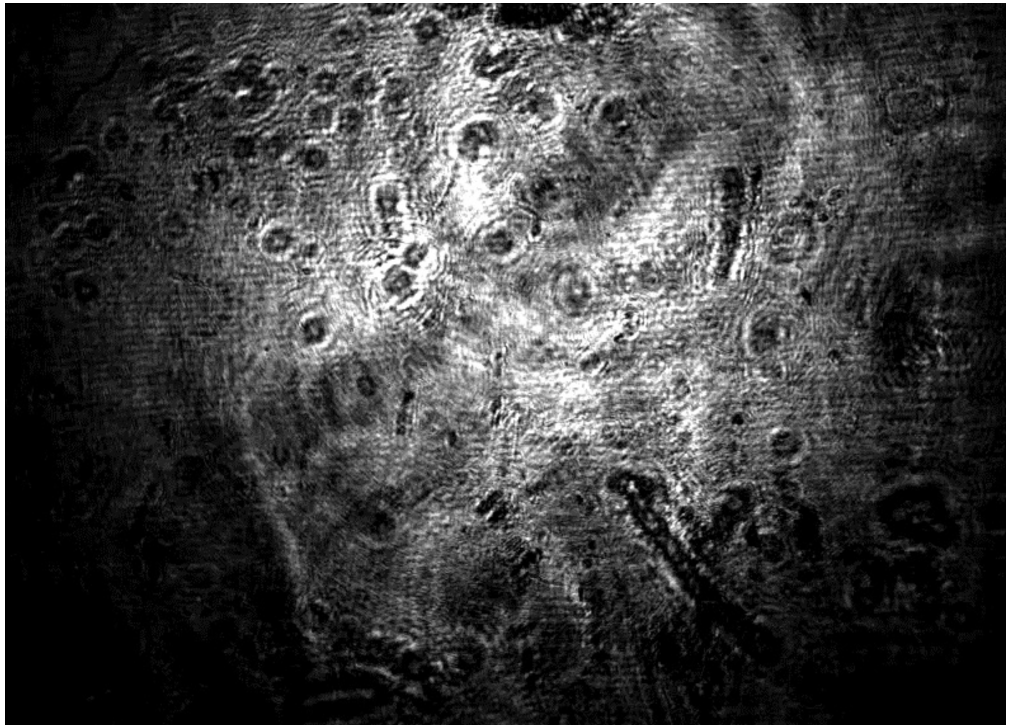
U=1.3 m/s T=92 K





Transition boiling



Slowed down 500x

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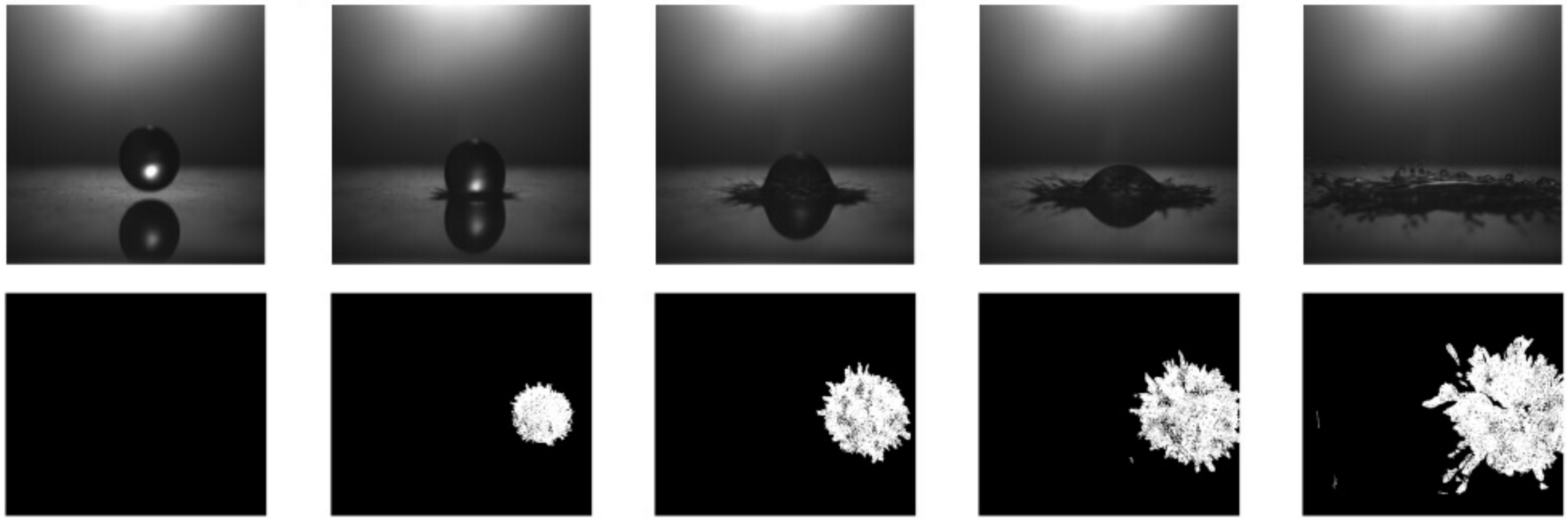
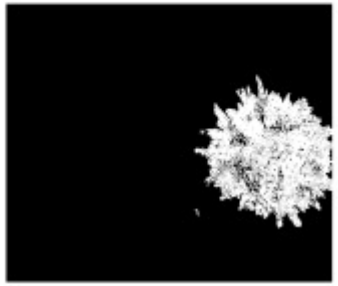
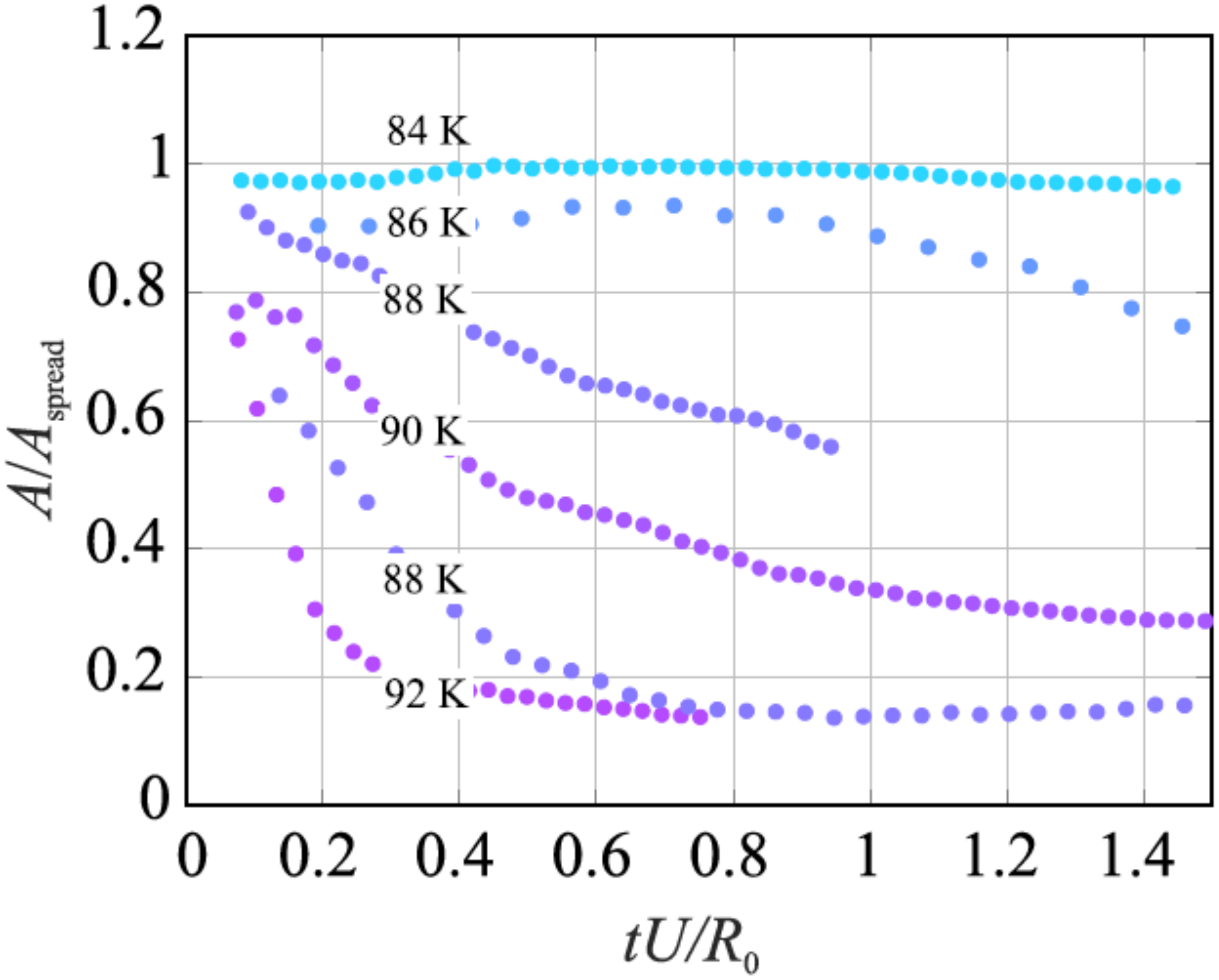


$t = 0$ ms   0.4 ms   0.8 ms   1.2 ms   2.4 ms

Results: Transition boiling





Results: Increasing plate temperature

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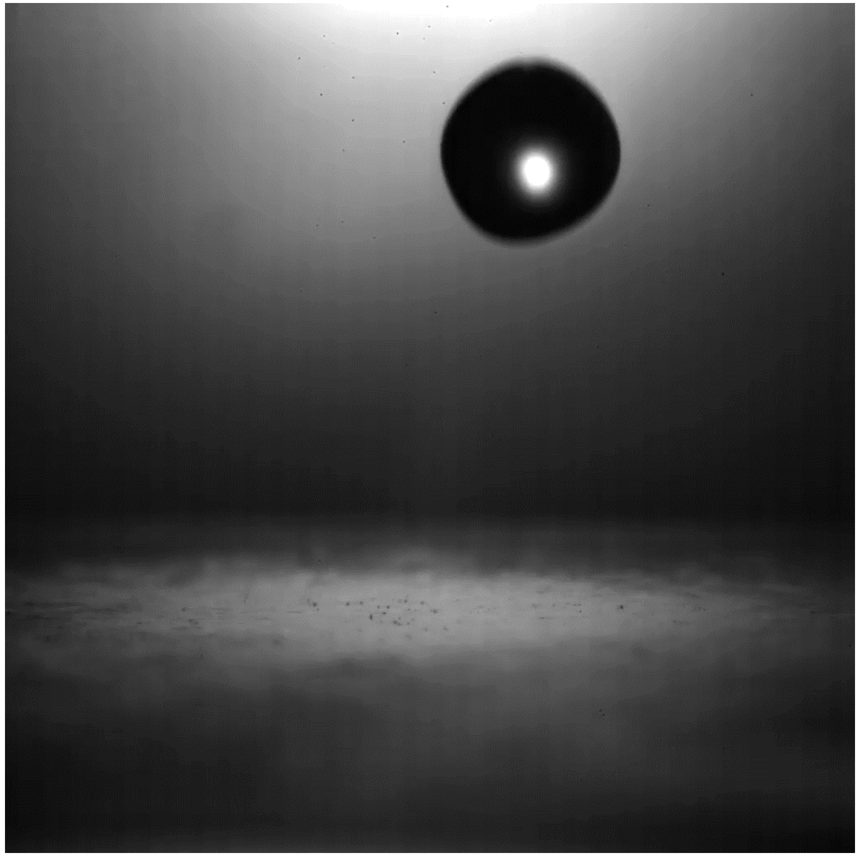
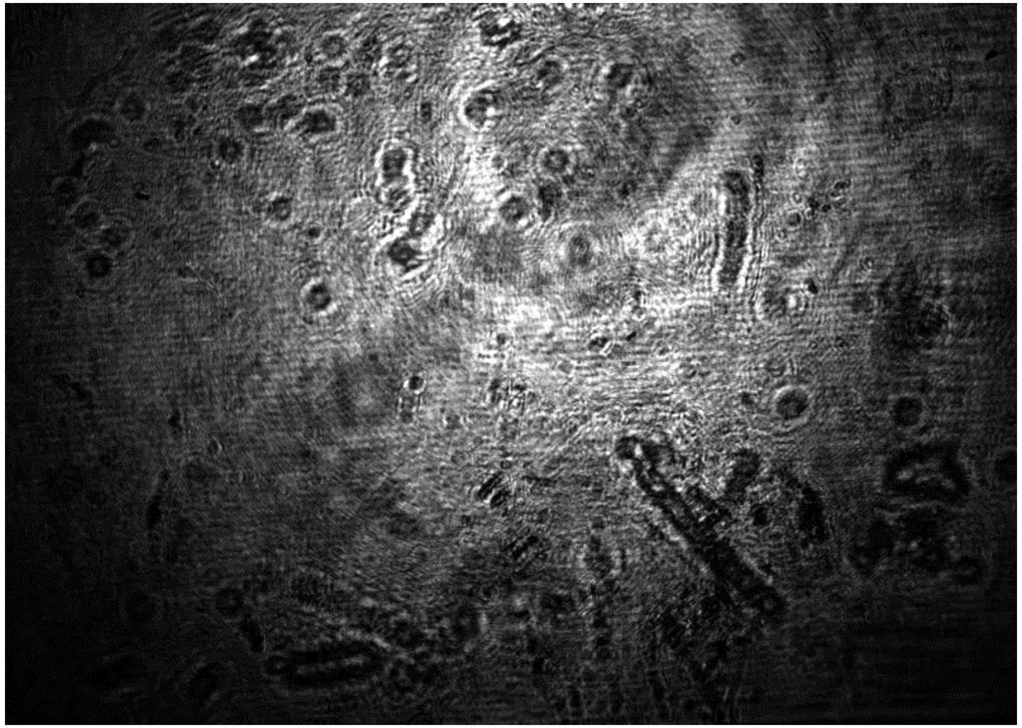
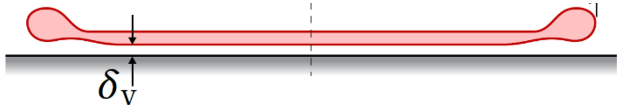
U=1.3 m/s T=102 K

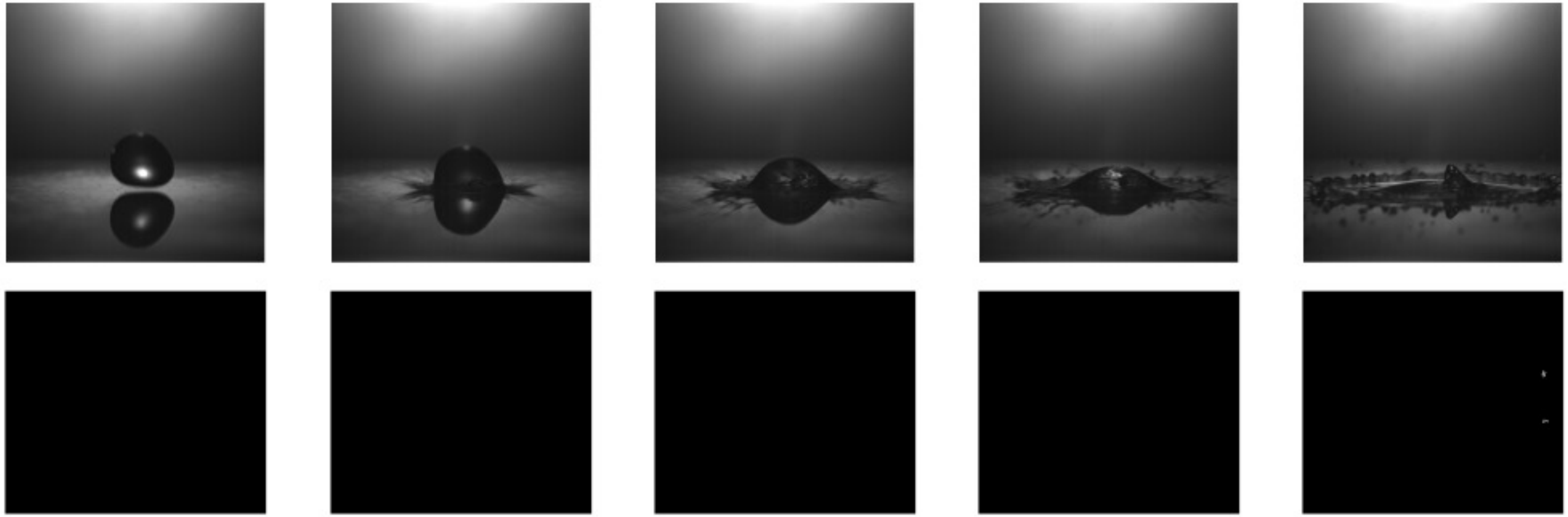




Slowed down 500x

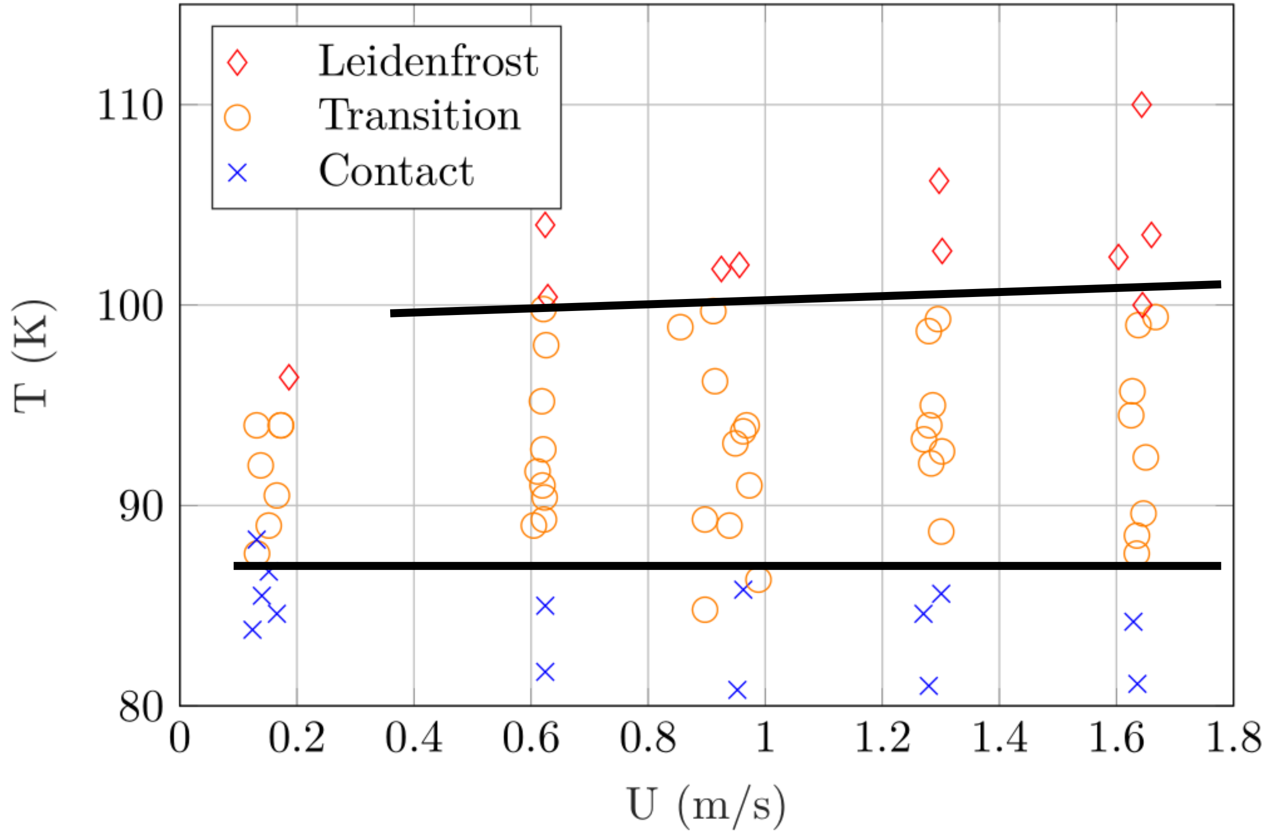


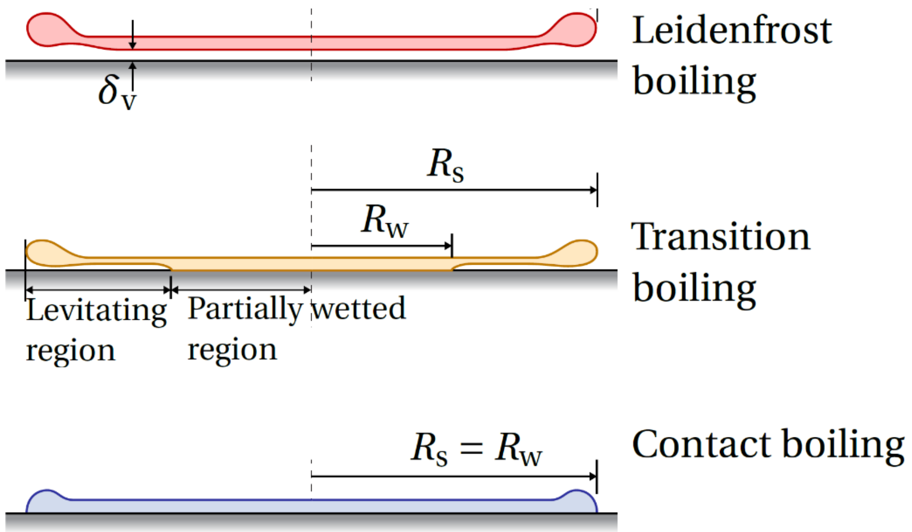
Leidenfrost
boiling



$t = 0$ ms   0.4 ms   0.8 ms   1.2 ms   2.4 ms

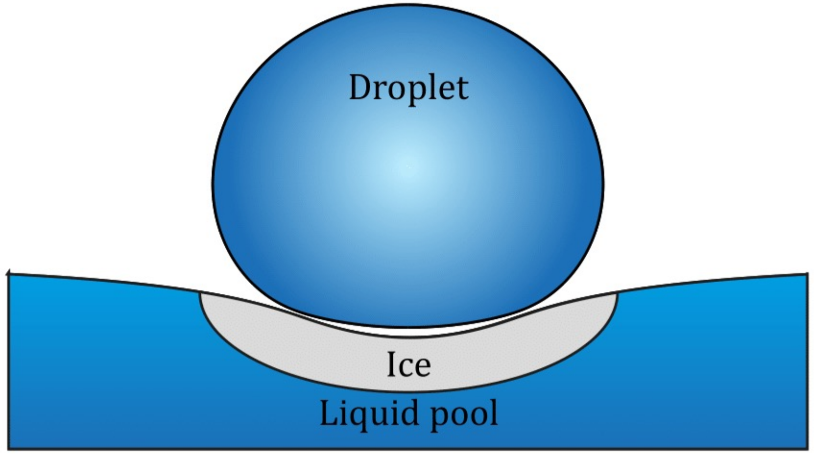
Phase diagram





Leidenfrost droplet on a liquid pool

Investigate both theoretically and experimentally the dynamics of a Leidenfrost droplet (liquid nitrogen) on a liquid pool (water)



Leidenfrost droplet on a liquid pool

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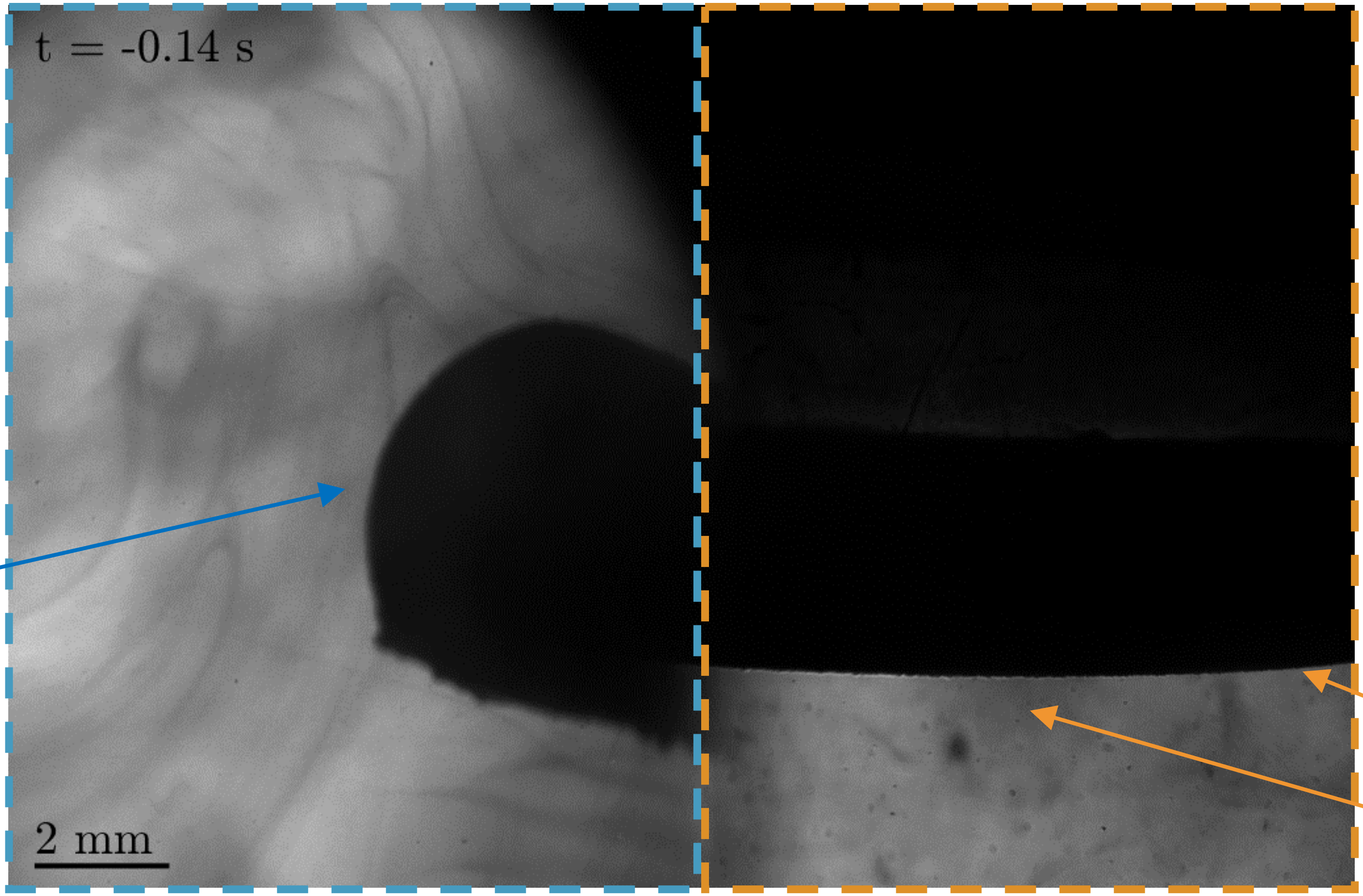
Top view

Droplet



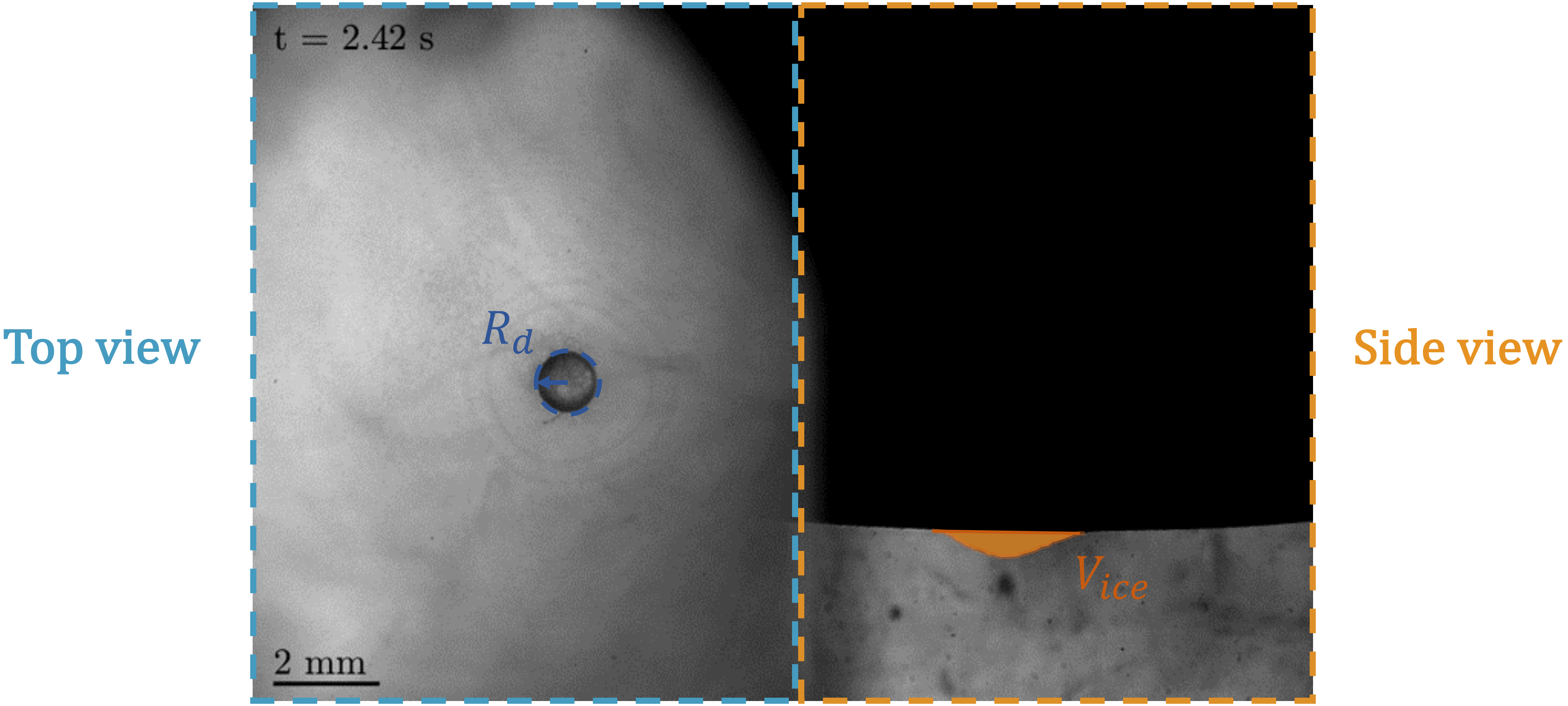
Side view

Water meniscus

Ice

ATS

Leidenfrost droplet on a liquid pool



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Outer part droplet

- Laplace pressure equals hydrostatic pressure

$$\gamma_d \kappa = -\rho_d g z$$

- Let κ_{top} be the input variable to determine the size

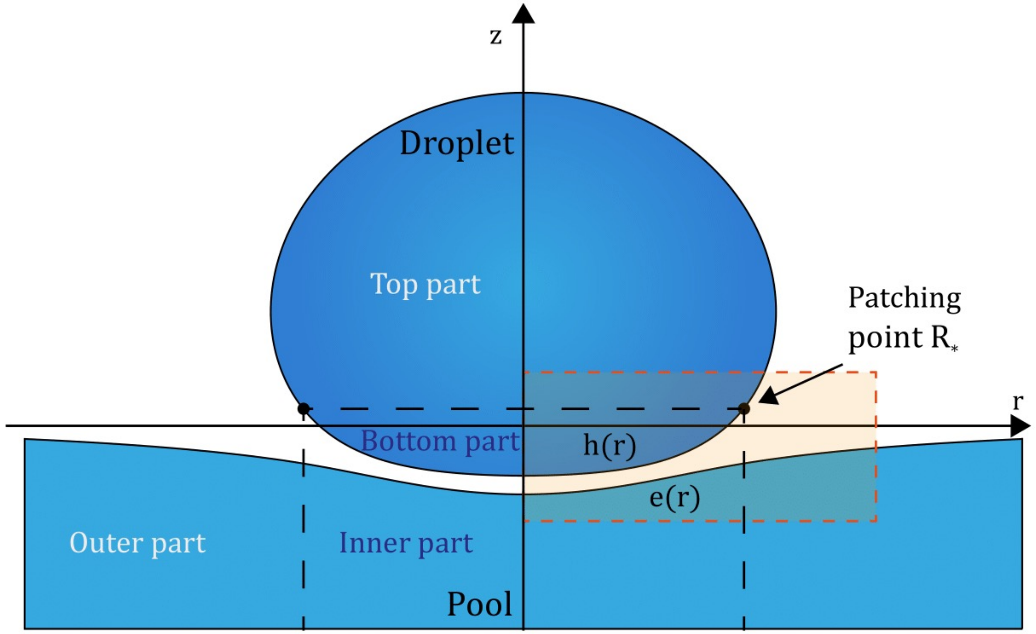
$$\tilde{\kappa}_{top} + \tilde{z}_{top} = \tilde{\kappa} + \tilde{z}$$

- Write in terms of arclength s

$$\frac{\partial \theta}{\partial s} = -\frac{\sin(\theta)}{r} - h + \kappa_{top}$$

$$\frac{\partial h}{\partial s} = \sin(\theta), \qquad \frac{\partial r}{\partial s} = \cos(\theta)$$

- Integrate from $s = 0$ to $s = s_t$ with $\theta(0) = 0, h(0) = z_{top},, r(0) = 0, \theta(s_t) = -\pi$

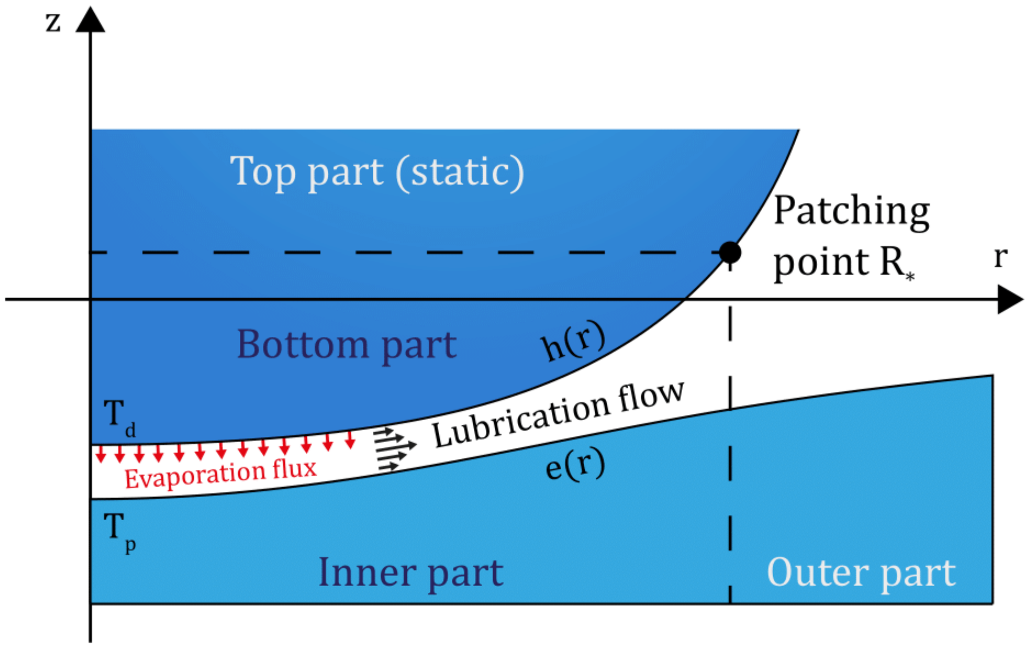


ATS

Theoretical model

Inner part droplet

- Excess pressure in vapour film p_v can be found by balancing all forces normal to the drop surface
$$\tilde{p}_v + \tilde{\kappa} = \tilde{\kappa}_{top} + (\tilde{z}_{top} - \tilde{h})$$
- This pressure drives a lubrication flow with no-slip conditions on both sides
$$\vec{q}_v = -\frac{\nabla p_v}{12\mu_v}(h-e)^3$$
- The local evaporation flux is equal to
$$J = \frac{q}{L} = \frac{1}{L}\frac{\lambda_v\left(T_p - T_d\right)}{(h-e)}$$
- Finally, mass conservation gives us
$$\vec{\nabla} \cdot q_v = \frac{J}{\rho_v}$$



Numerical model shape

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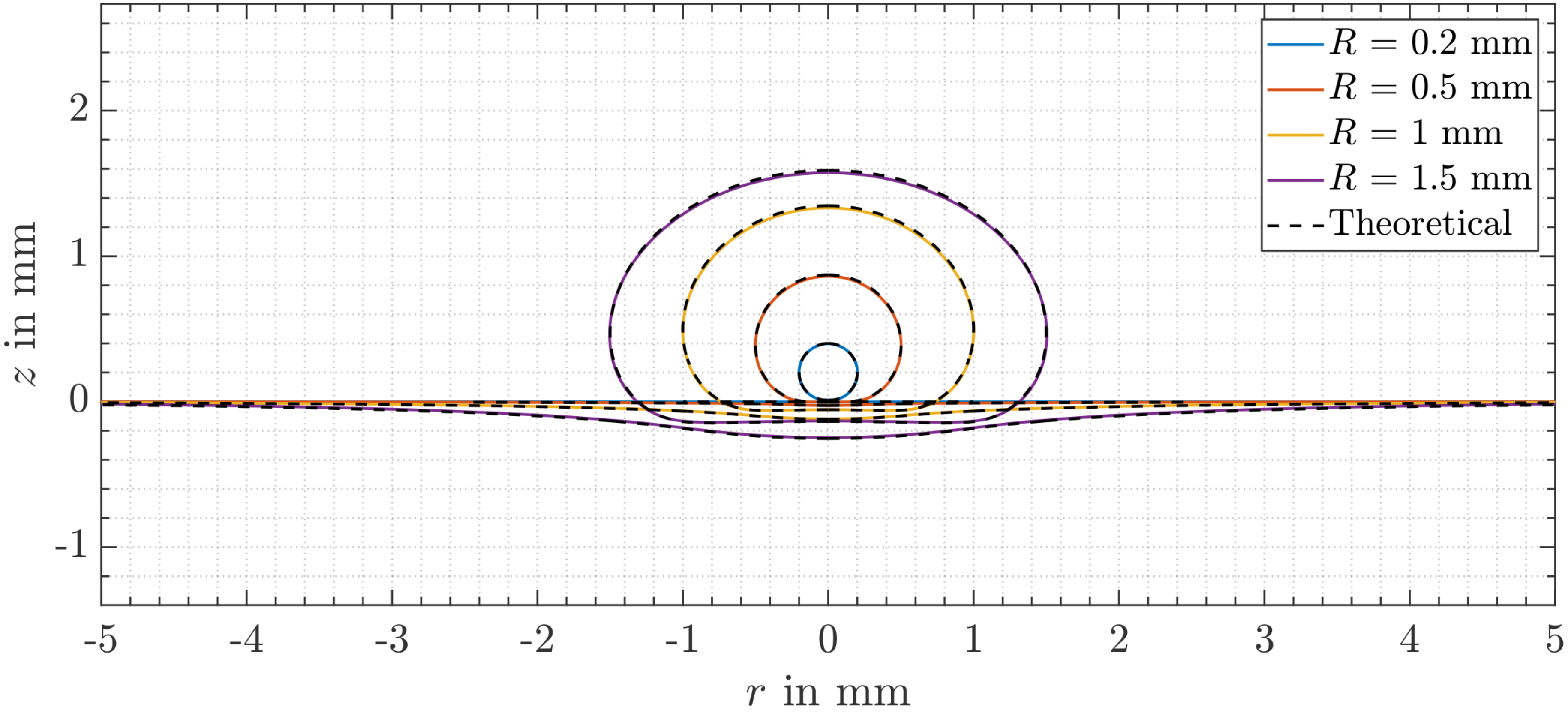

Experimental results $R(t)$ ($T\_(p,0)$=273.15 K)

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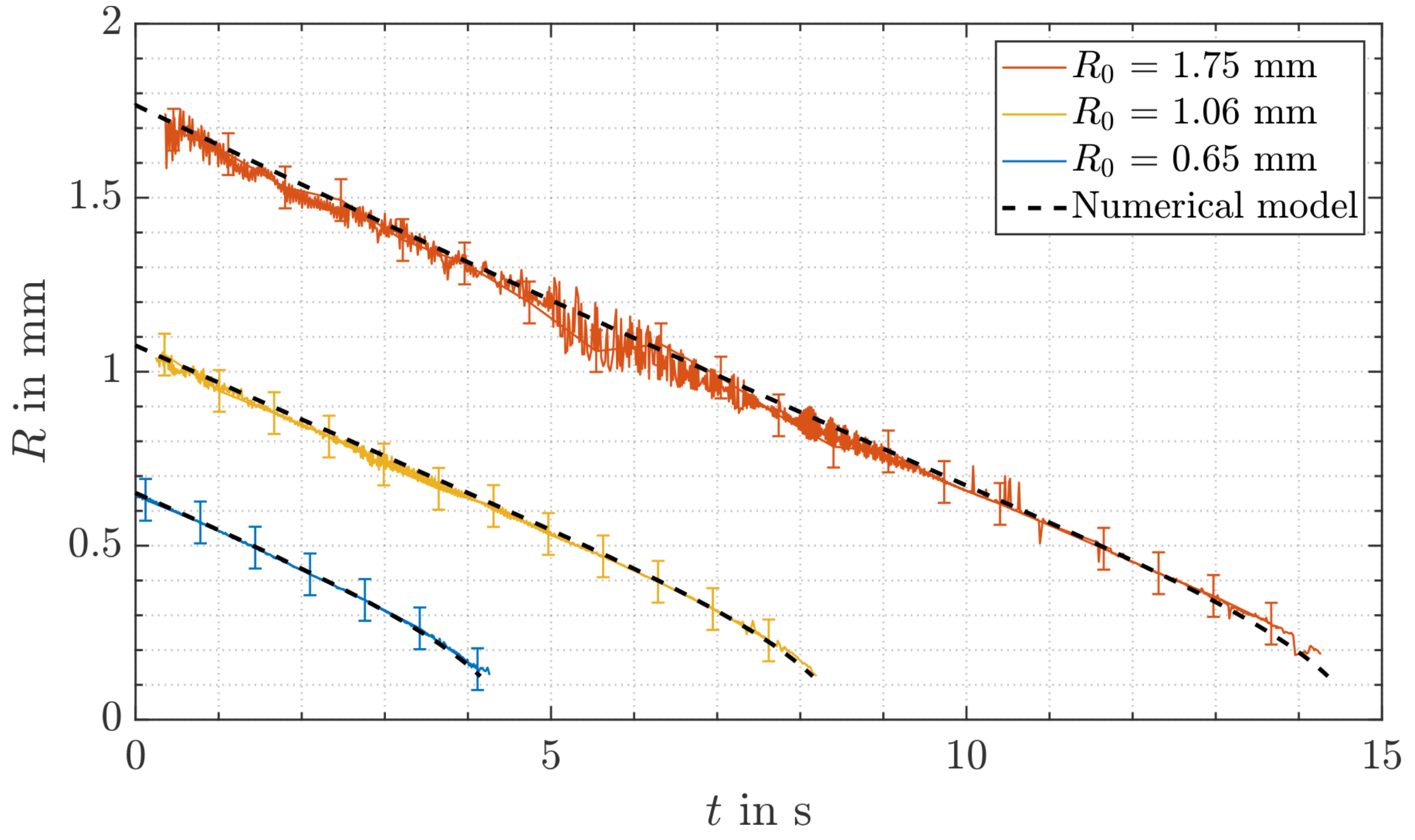
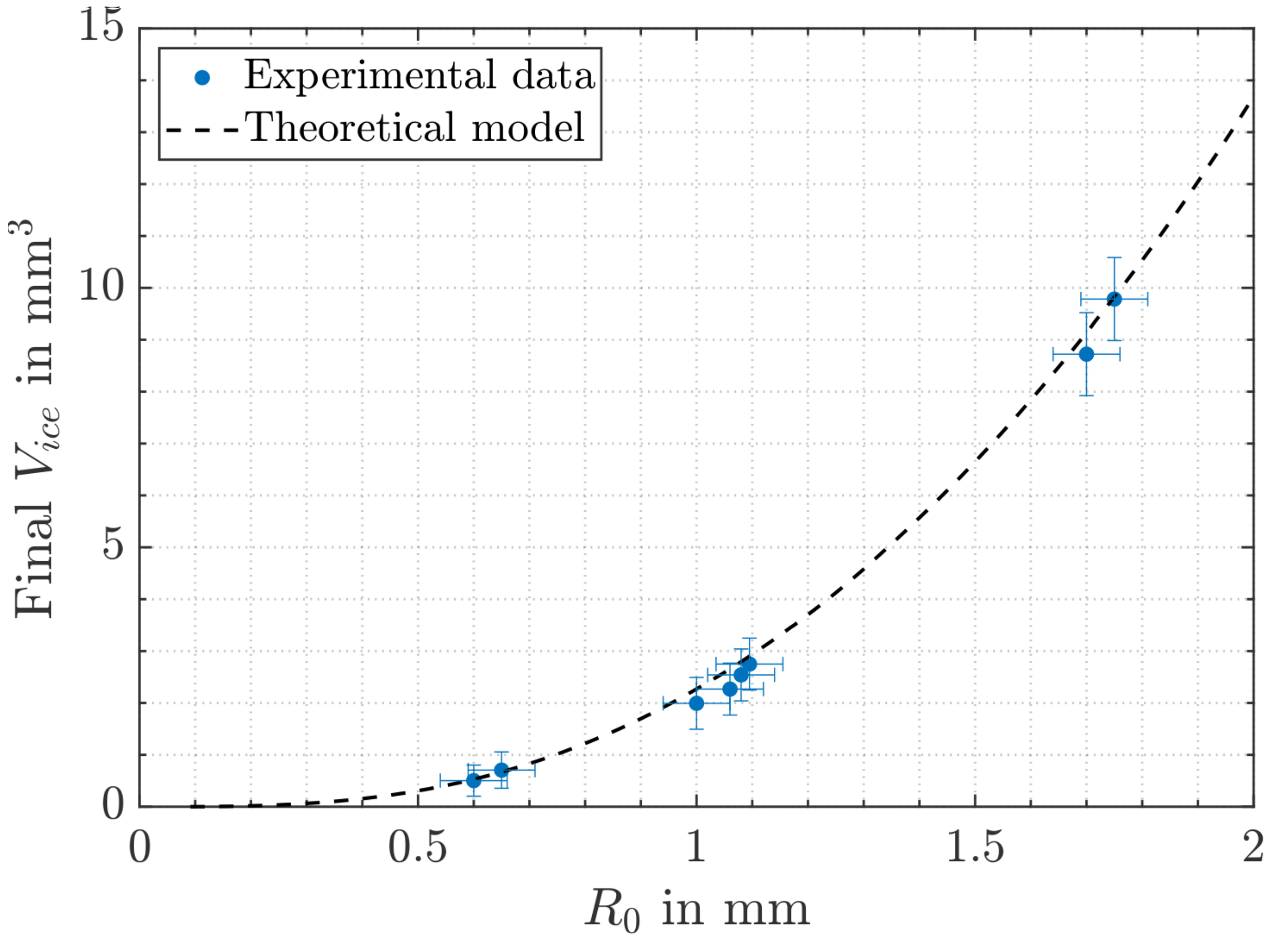
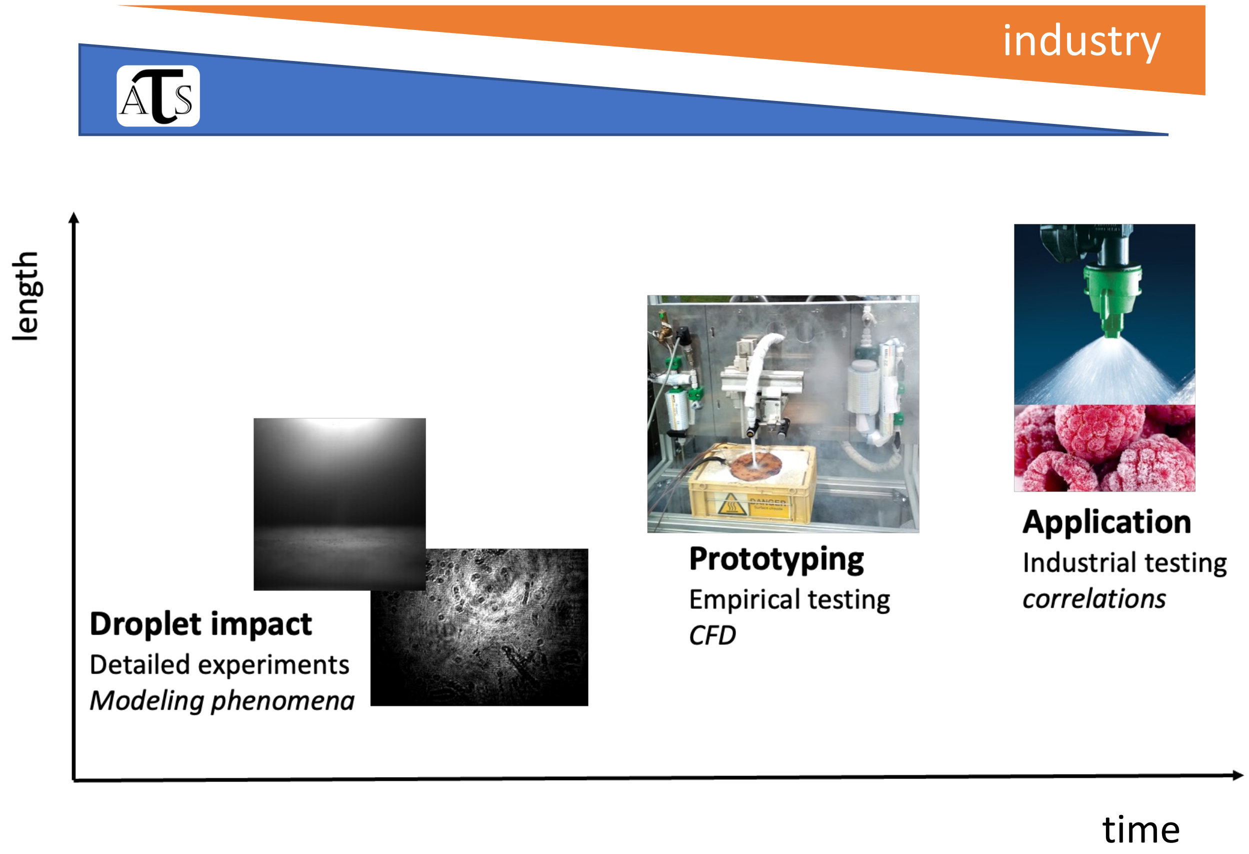


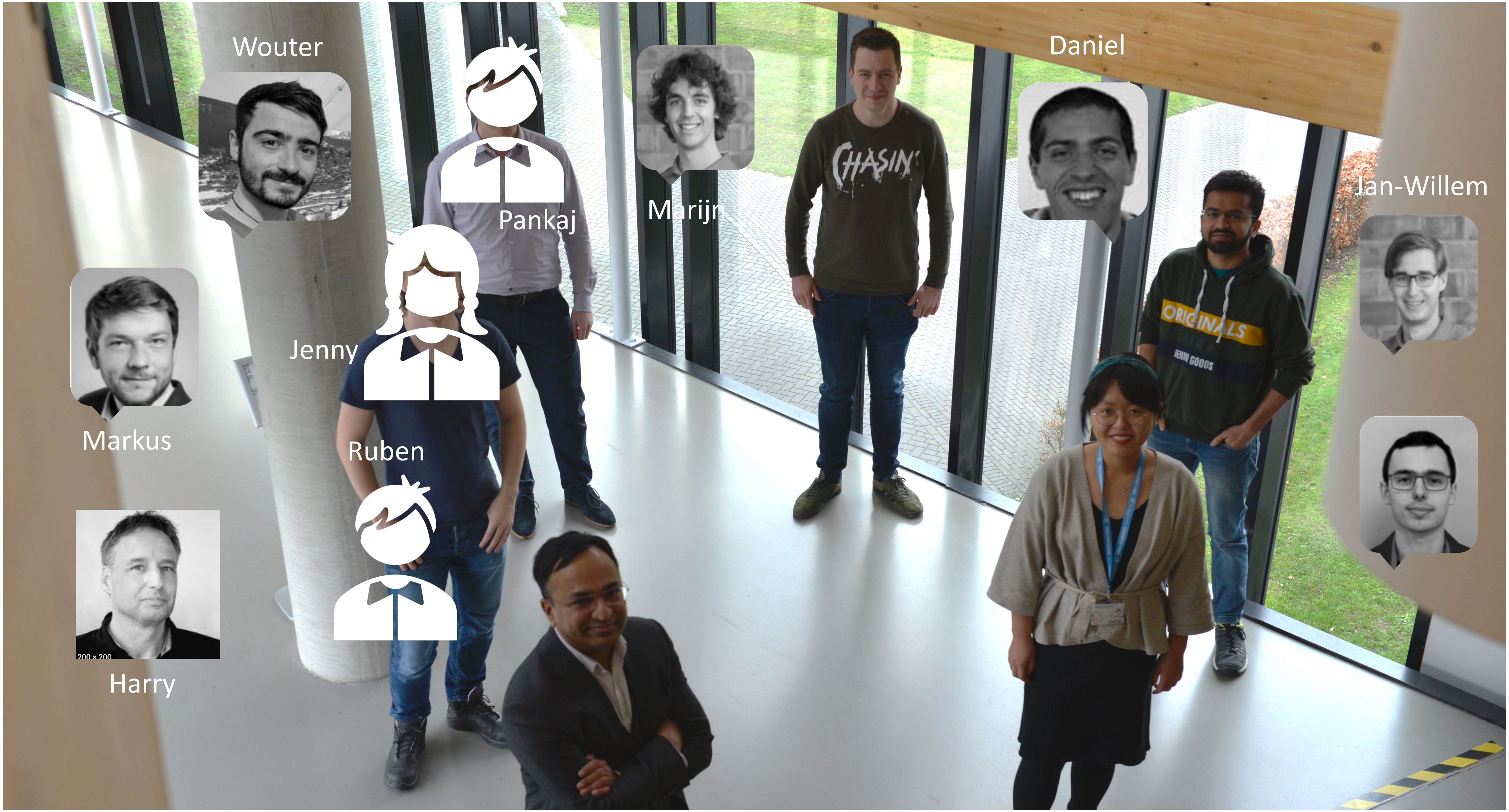
Experimental results V_ice $(T\_(p,0)=273.15\ K)$



MISSION & APPROACH

to identify specific phenomena and mechanisms that are key in understanding the cryogenic cooling processes and propose engineering models.




Wouter
Pankaj
Marijn
Daniel
Jan-Willem
Markus
Jenny
Ruben
Harry
200 x 200