Snow Numerical Capability

Kilian Köbschall, Jeanette Hussong

WP10

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WP10 Partners

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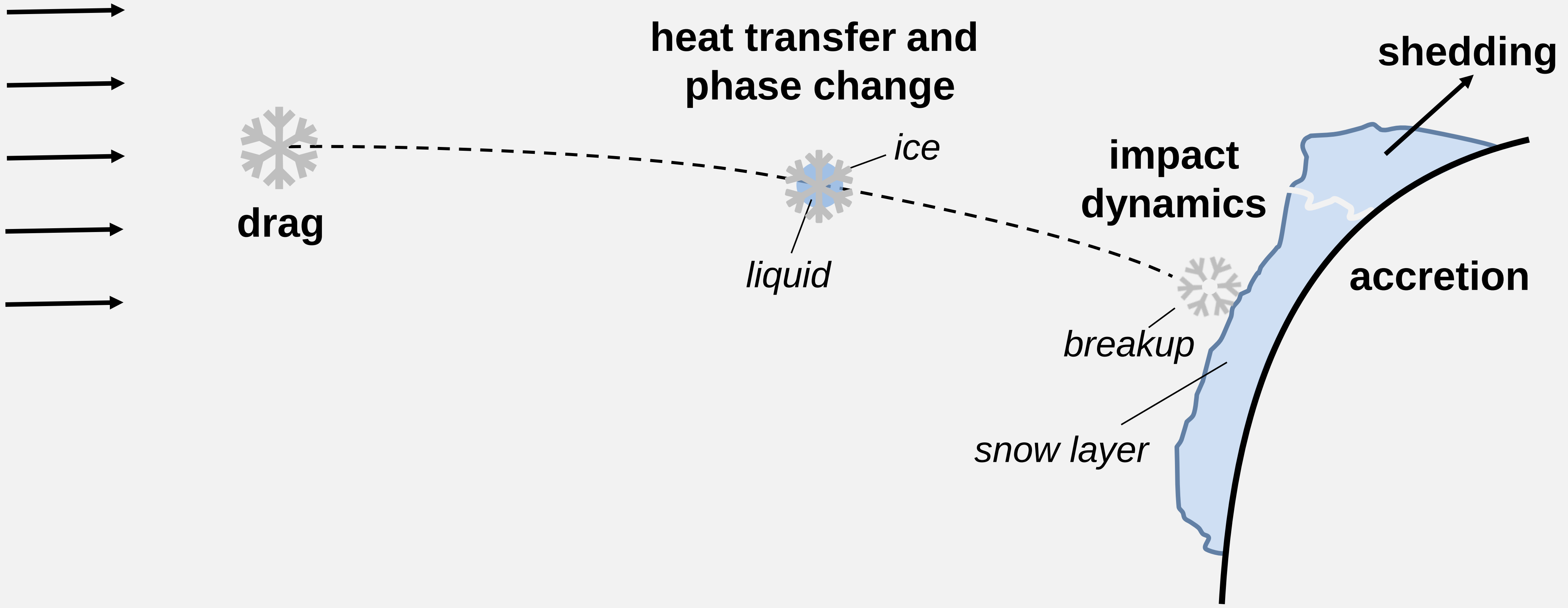
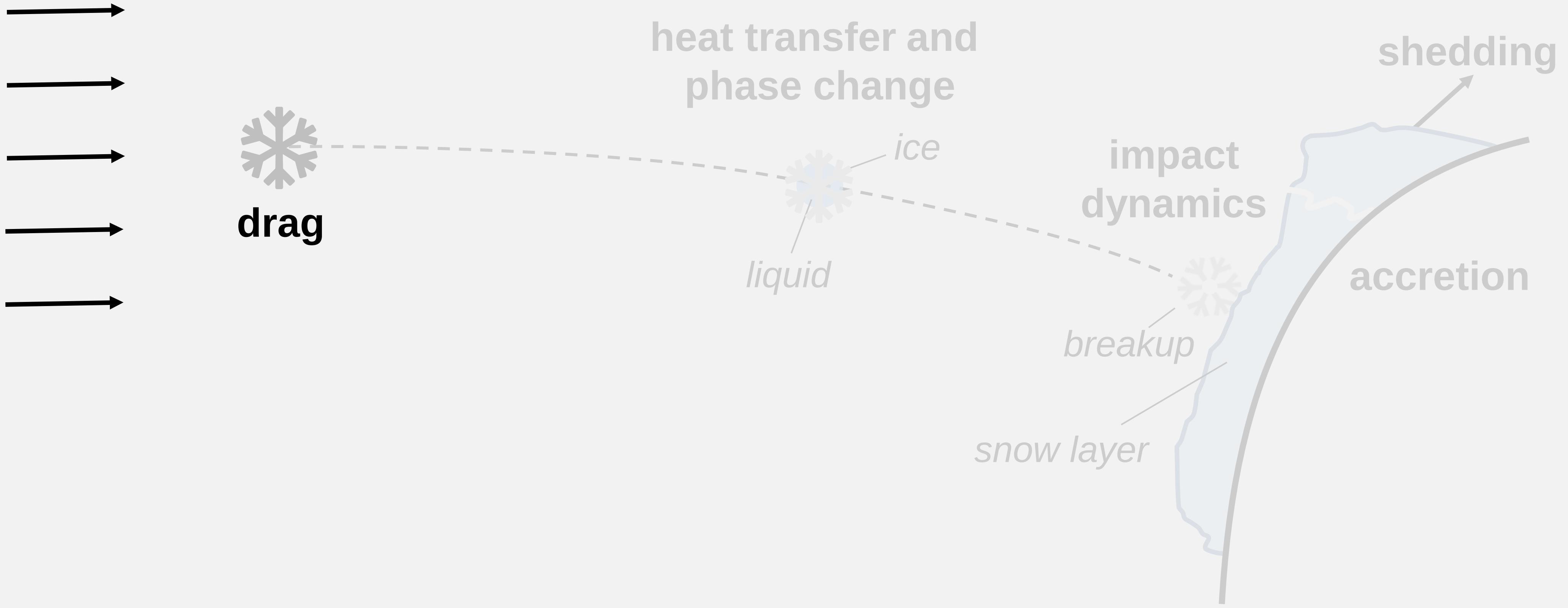
Motivation

Objectives

Improve and validate tools to predict the influence of snow conditions on aircraft, rotorcraft and engines.



Transport / Snowflake Drag

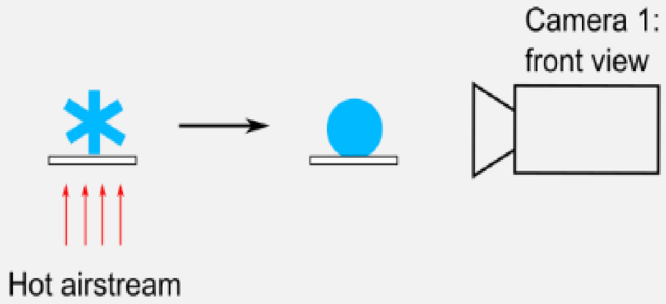


Transport / Snowflake Drag

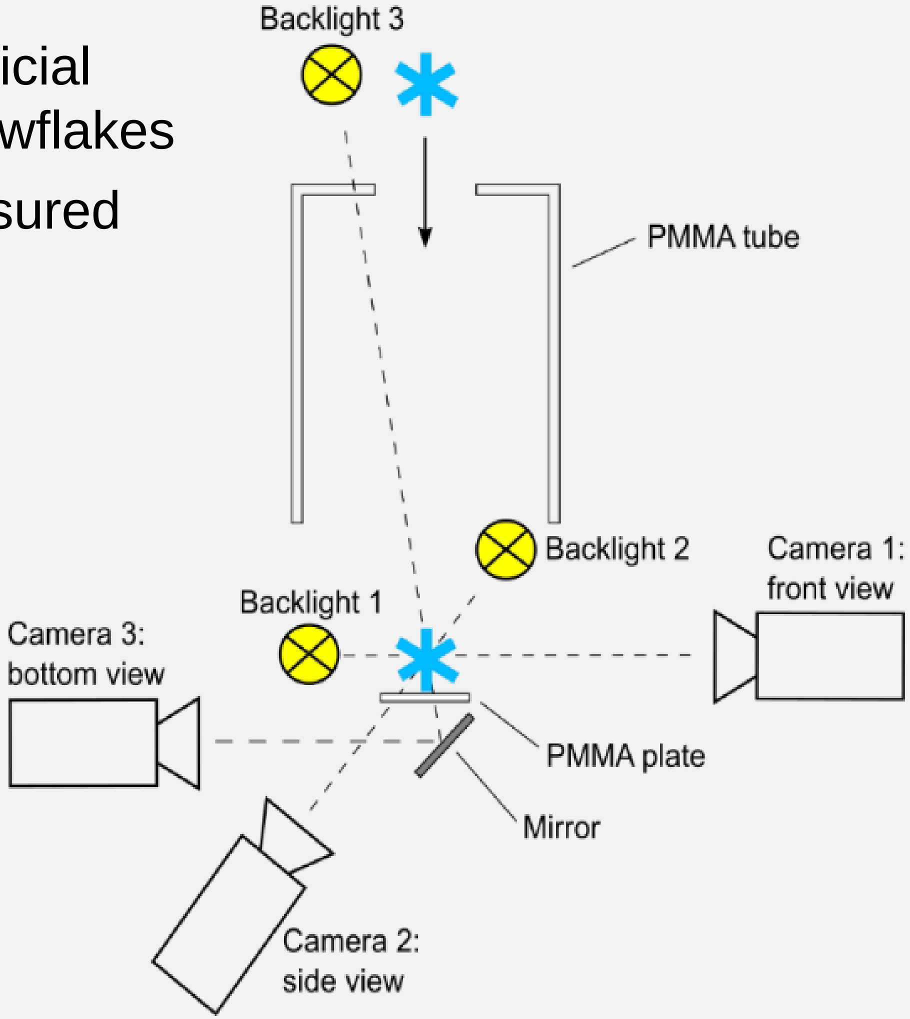
Experiment 1: Free falling snowflakes

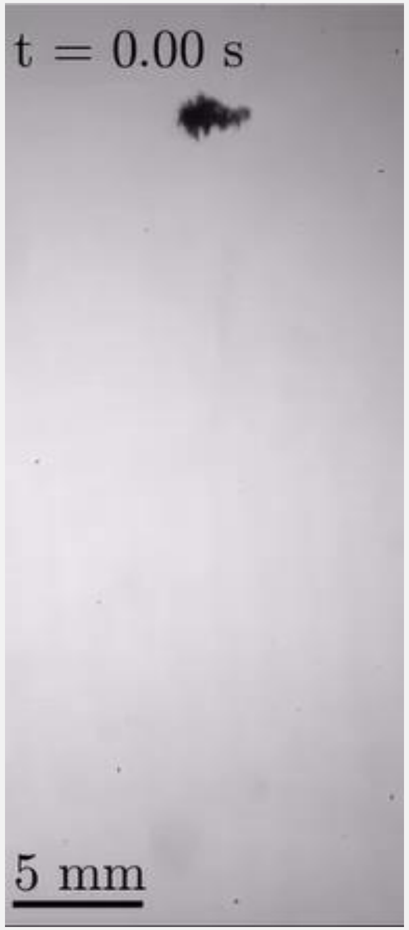
- Terminal velocity is measured using artificial snowflakes (IAG SnowFall) and real snowflakes
- Mass of snowflake is subsequently measured

Snowflake melting and mass measurement



$$F = \frac{1}{2} C_{\mathrm{D}} A \rho U^2 = mg$$

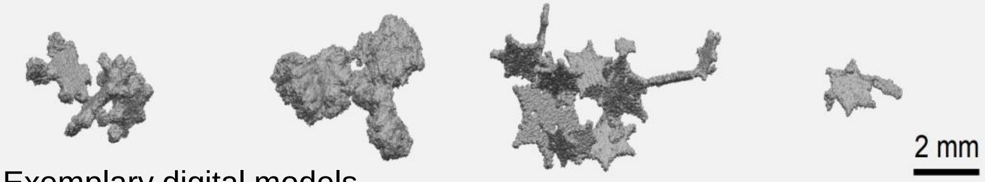




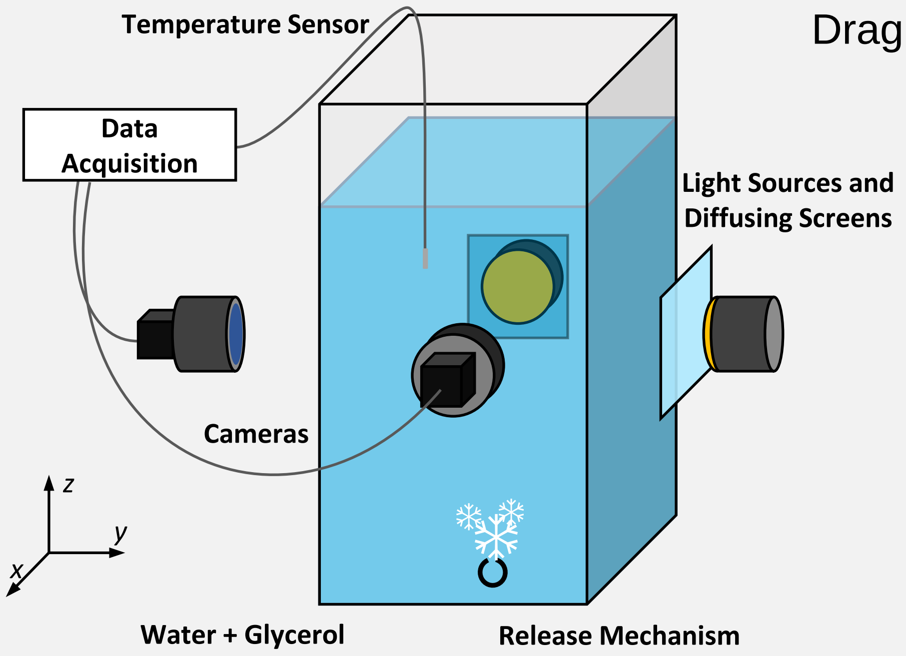
Transport / Snowflake Drag

Experiment 2: Terminal velocity of 3D-printed snowflakes

- Full geometry known
- Available all year around for multiple measurements

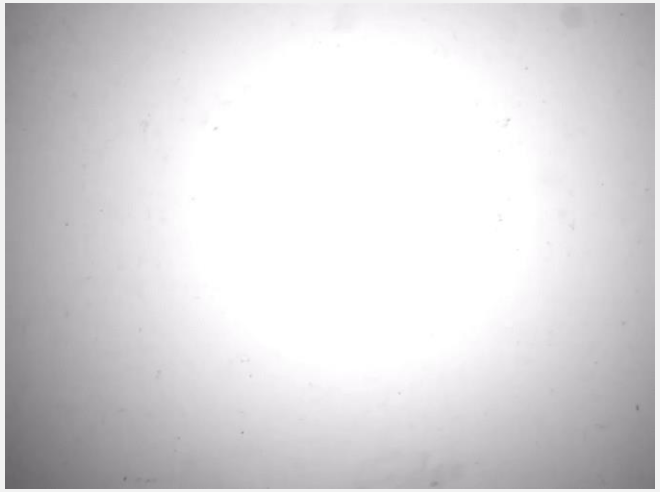


Exemplary digital models

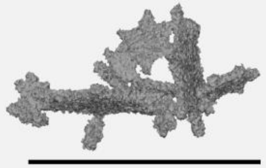


Drag in glycerol–water mixture

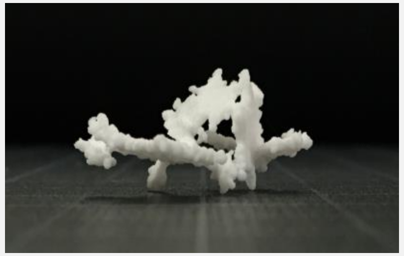
➔ $50 < Re_{D_{\max}} < 1000$



3 – 30 monomers



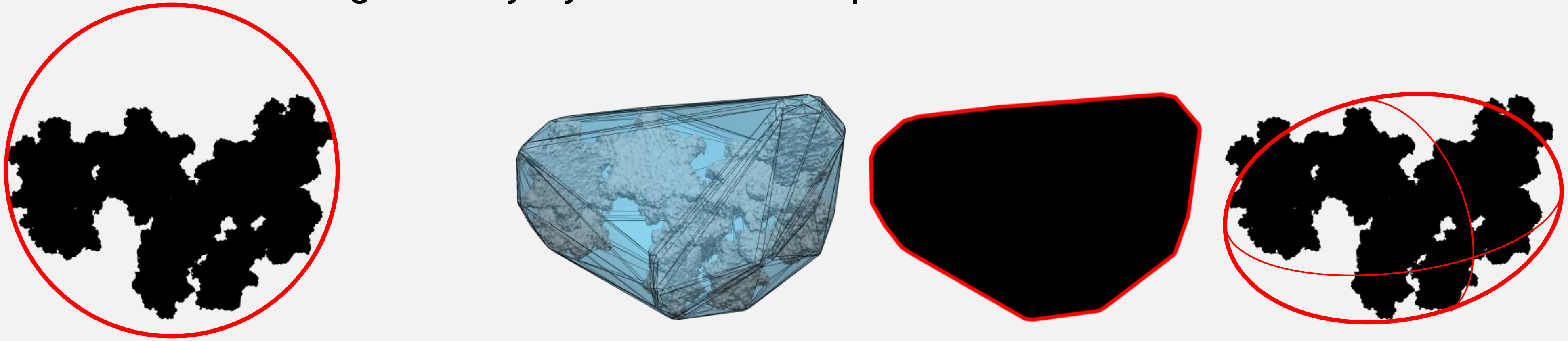
20 mm



Transport / Snowflake Drag

New models for drag coefficient of snowflakes:

- Approximation of snowflake geometry by a convex shape



Heymsfield & Westbrook (2010) | 3D convex hull | 2D convex hull | spheroid

(3D convex hull, 2D convex hull, spheroid: new)

- Calculation of drag coefficient of simplified shape from Hölzer and Sommerfeld (2008) model

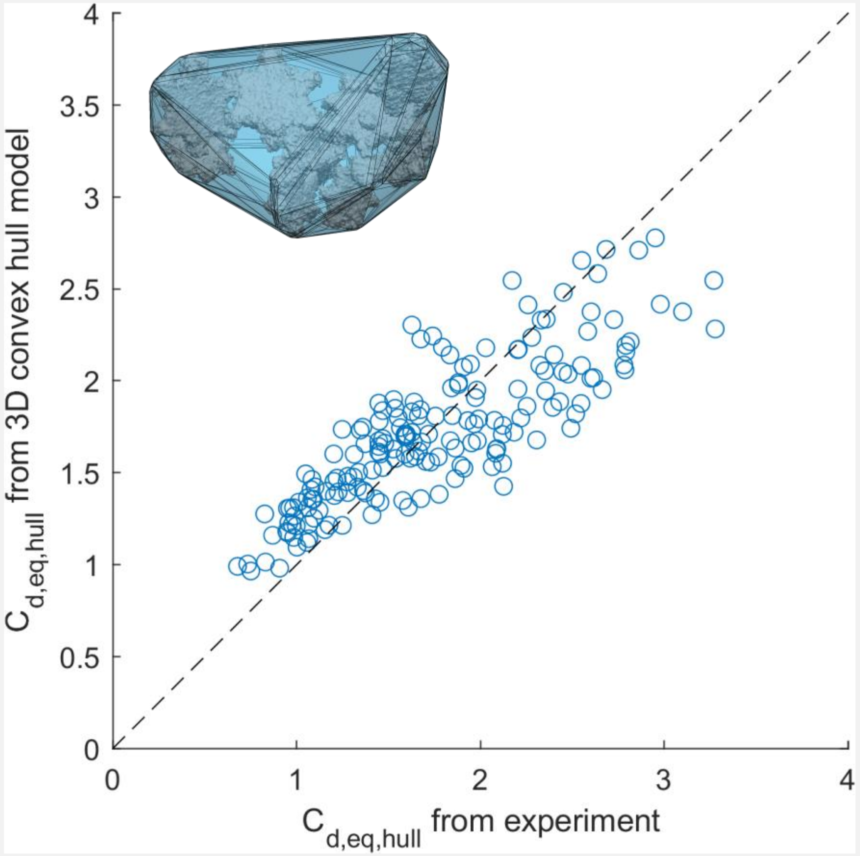
$$C_{\mathrm{d}} = f(\underbrace{Re, \Phi, \Phi_{\perp}}_{\text{based on convex shape}})$$

Heymsfield, A. J., & Westbrook, C. D. (2010). Advances in the Estimation of Ice Particle Fall Speeds Using Laboratory and Field Measurements, *Journal of the Atmospheric Sciences*, *67*(8), 2469-2482.
Aguilar, B. et al. (2022). Ice Crystal Drag Model Extension to Snowflakes: Experimental and Numerical Investigations, *AIAA Journal 0* 0:0, 1-14.

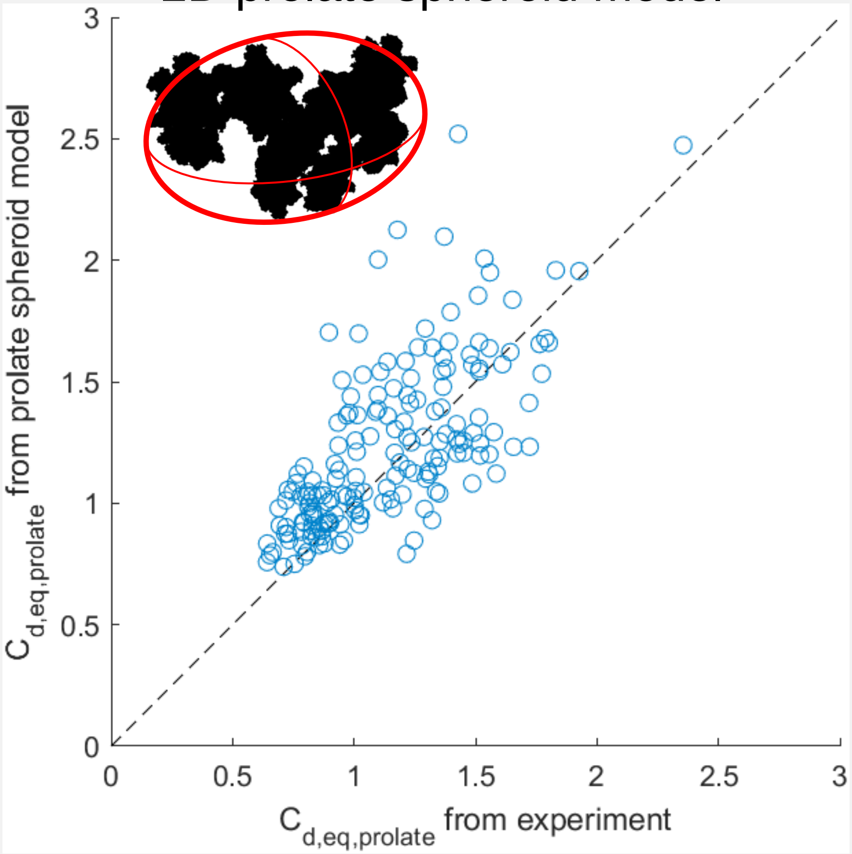
Transport / Snowflake Drag

Validation of two exemplary newly developed models

3D convex hull model

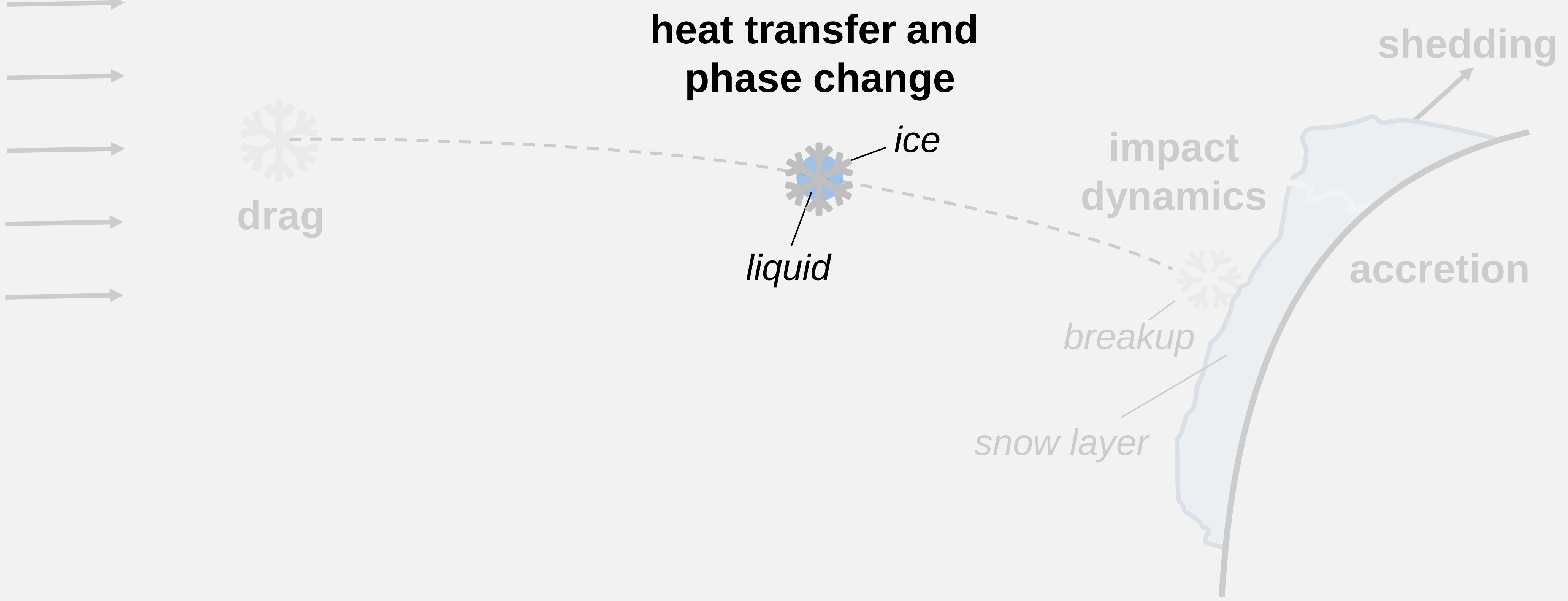


2D prolate spheroid model



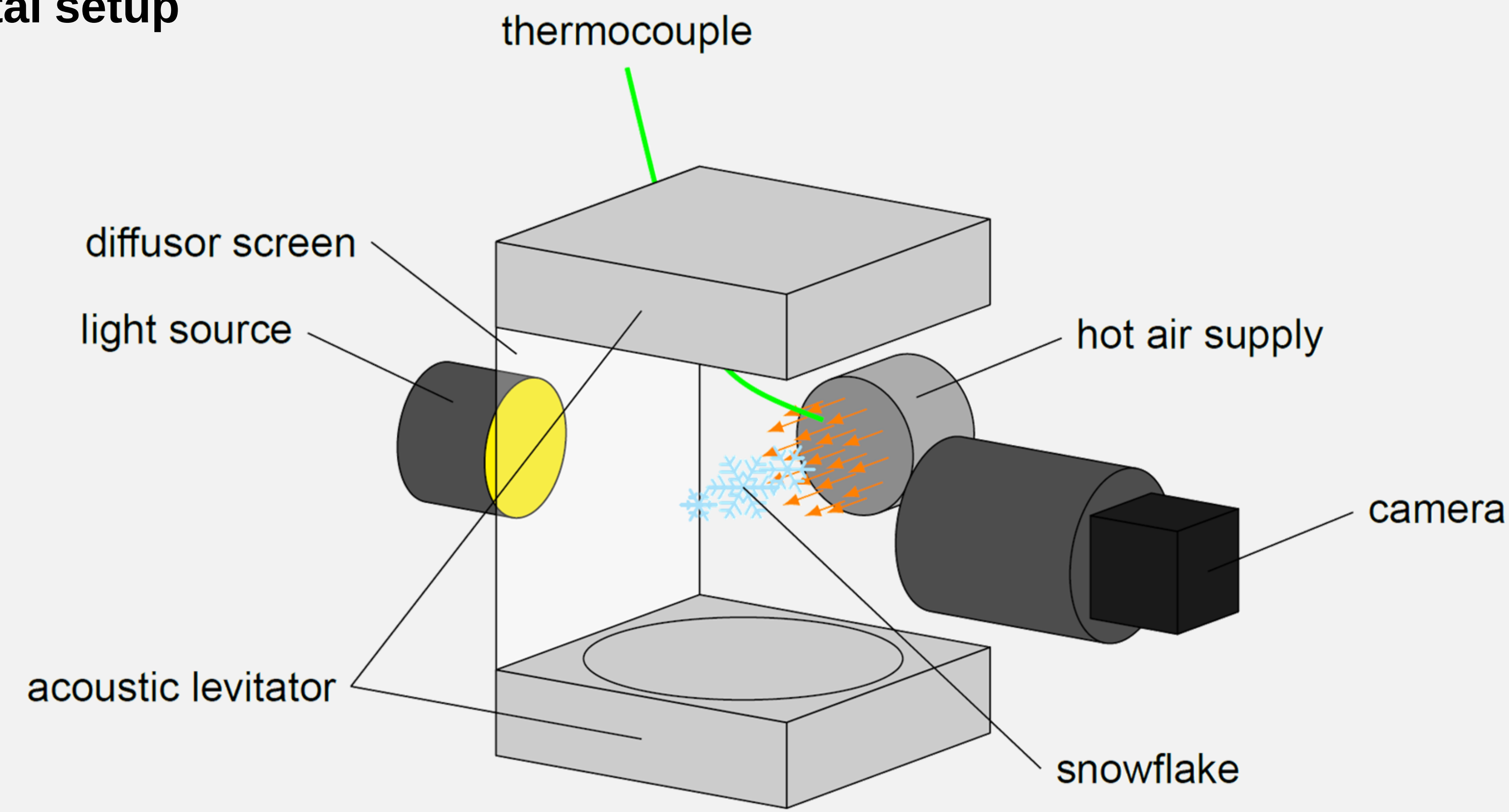
Boris Aguilar et al., Ice Crystal Drag Model Extension to Snowflakes: Experimental and Numerical Investigations, *AIAA Journal 0* 0:0, 1-14

Transport / Snowflake Melting



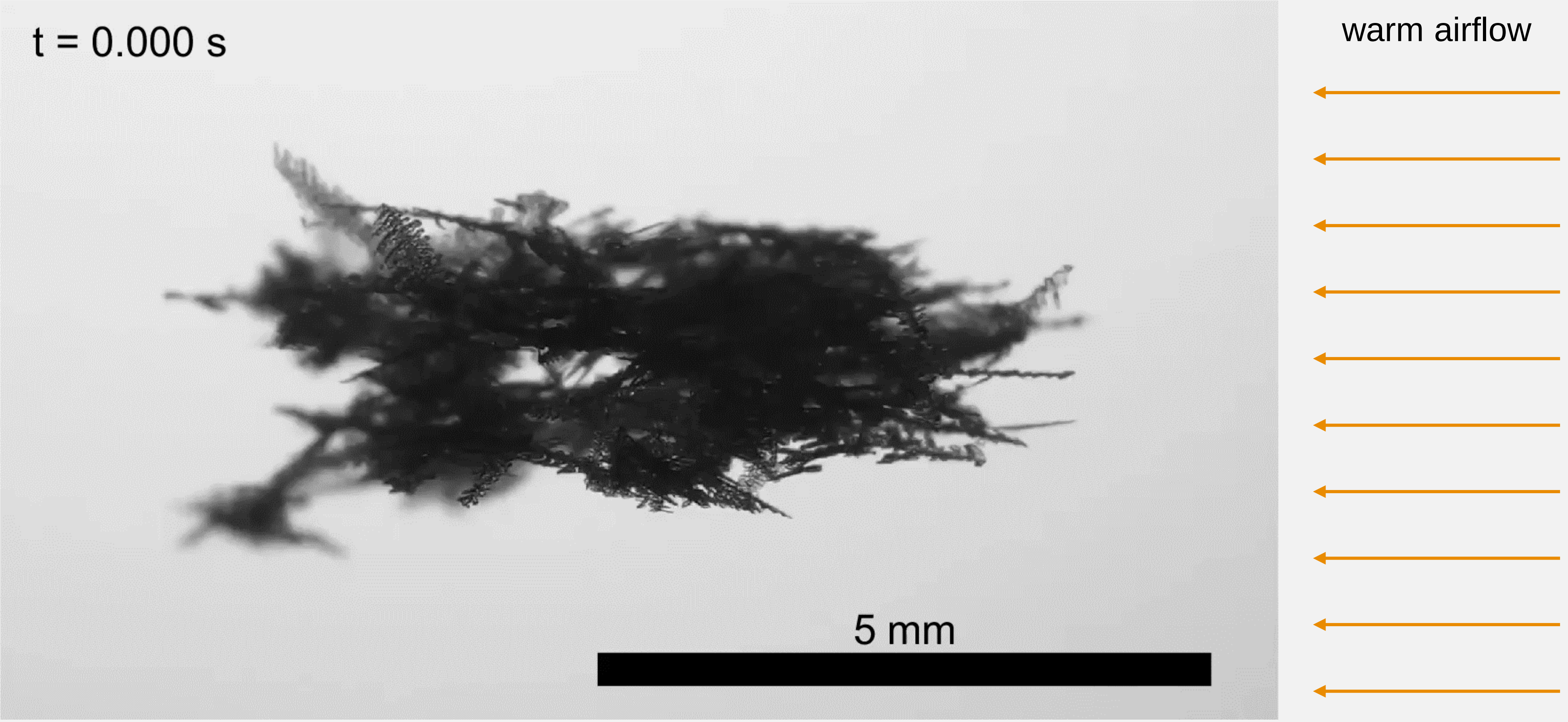
Transport / Snowflake Melting

Experimental setup



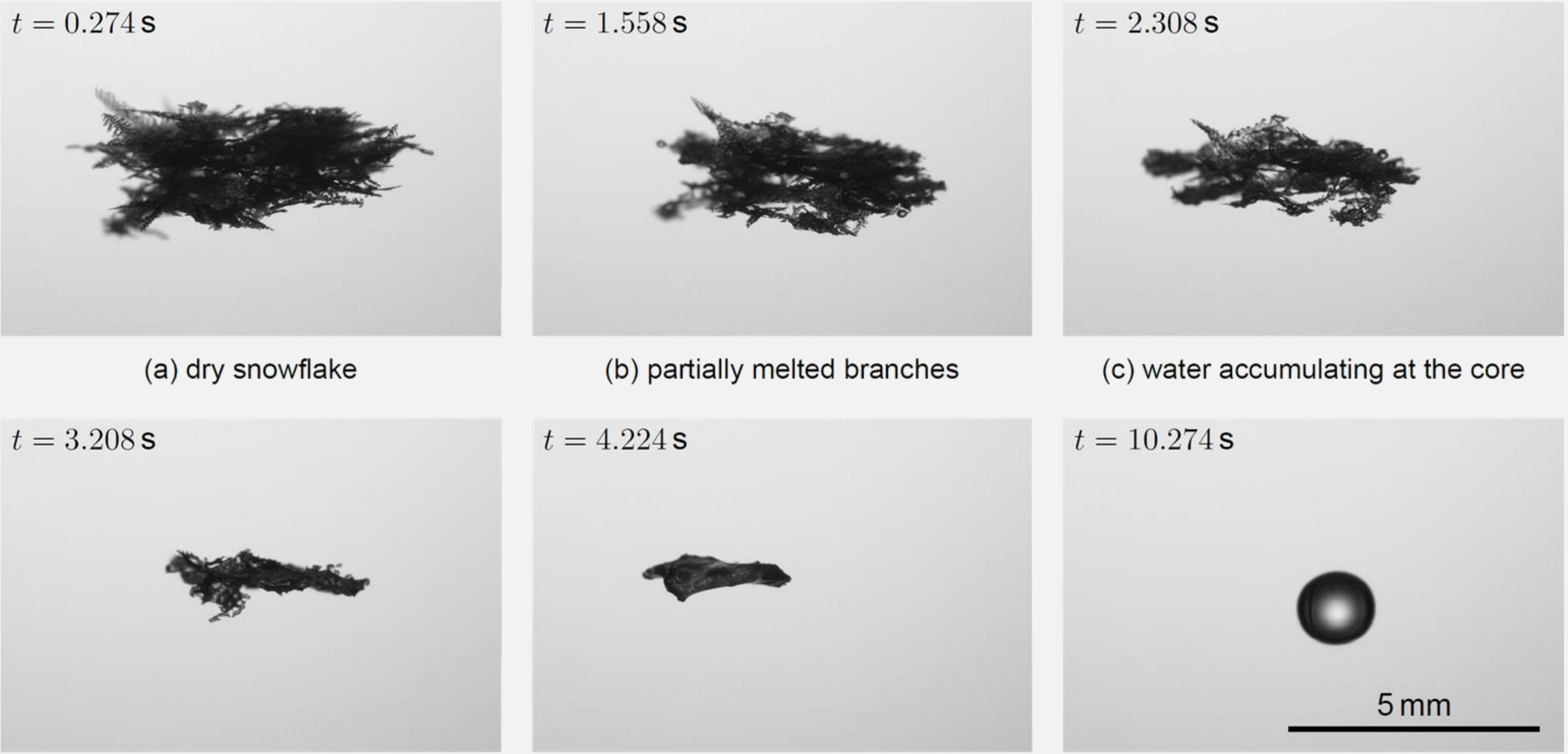
Köbschall, K. et al. (2022). Shape Evolution of a Melting Snowflake, AIAA 2022-3371. *AIAA AVIATION 2022 Forum*.

Transport / Snowflake Melting



Köbschall, K. et al. (2022). Shape Evolution of a Melting Snowflake, AIAA 2022-3371. *AIAA AVIATION 2022 Forum*.

Transport / Snowflake Melting



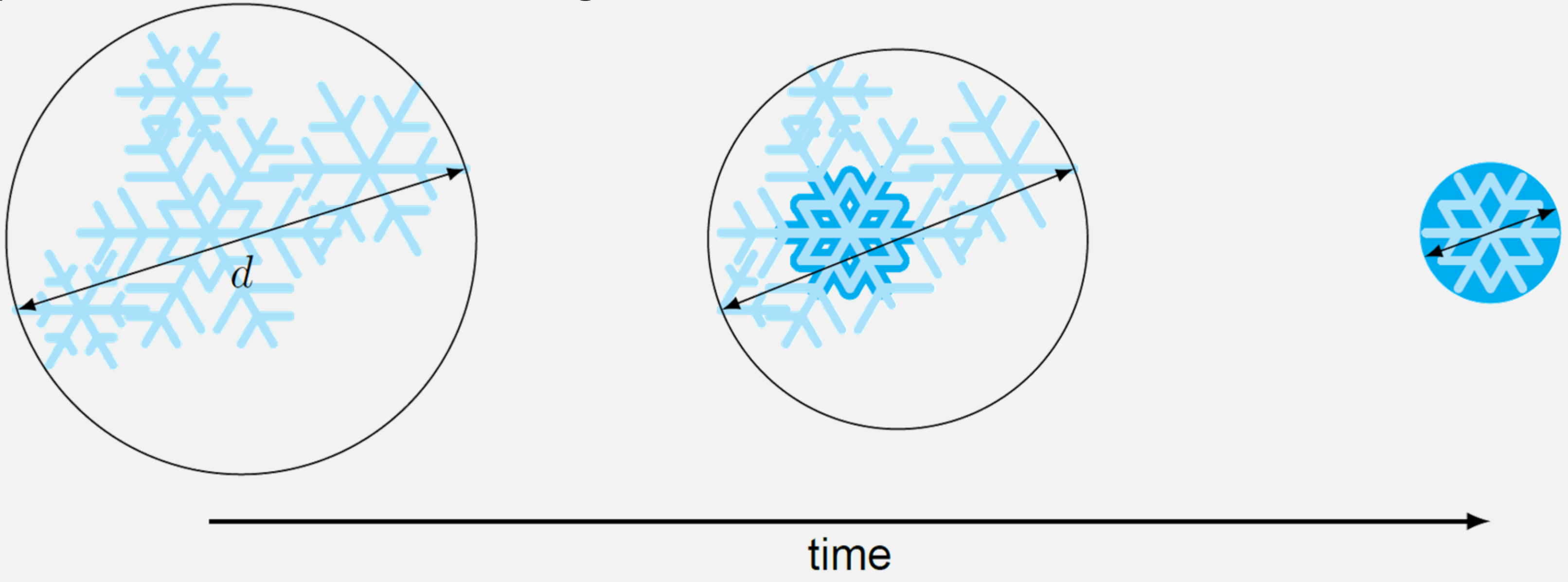
(a) dry snowflake (b) partially melted branches (c) water accumulating at the core

(d) main ice frame (e) wetted ice core (f) liquid drop

Köbschall, K. et al. (2022). Shape Evolution of a Melting Snowflake, AIAA 2022-3371. *AIAA AVIATION 2022 Forum*.

Transport / Snowflake Melting

Model for shape evolution of a melting snowflake

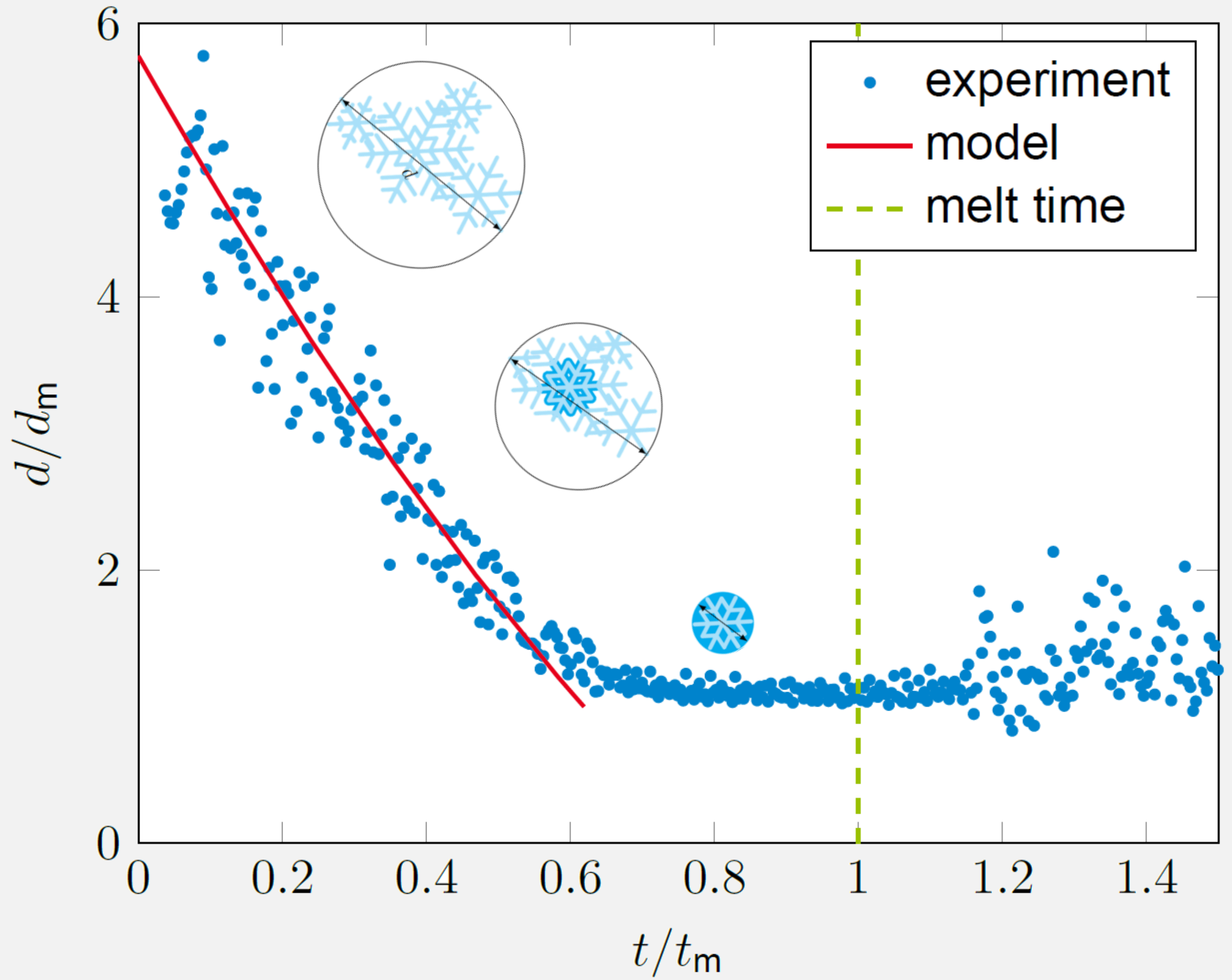


With the structural model $m_\mathrm{i} = \alpha d^{\beta}$ the following differential equation yields the size evolution of the particle

$$\frac{\mathrm{d}d}{\mathrm{d}t} = -\frac{\dot{m}_\mathrm{f}}{\alpha d^{\beta-1}} = -\frac{\pi d^{2-\beta}}{\alpha L_\mathrm{f}}\left[\mathrm{Nu}k_\mathrm{a}(T_\mathrm{a} - T_\mathrm{f}) + \mathrm{Sh}\rho_\mathrm{a} D_{\mathrm{v,a}}(\omega_\mathrm{a} - \omega_\mathrm{s}) L_\mathrm{v}\right]$$

Köbschall, K. et al. (2022). Shape Evolution of a Melting Snowflake, AIAA 2022-3371. *AIAA AVIATION 2022 Forum*.

Transport / Snowflake Melting

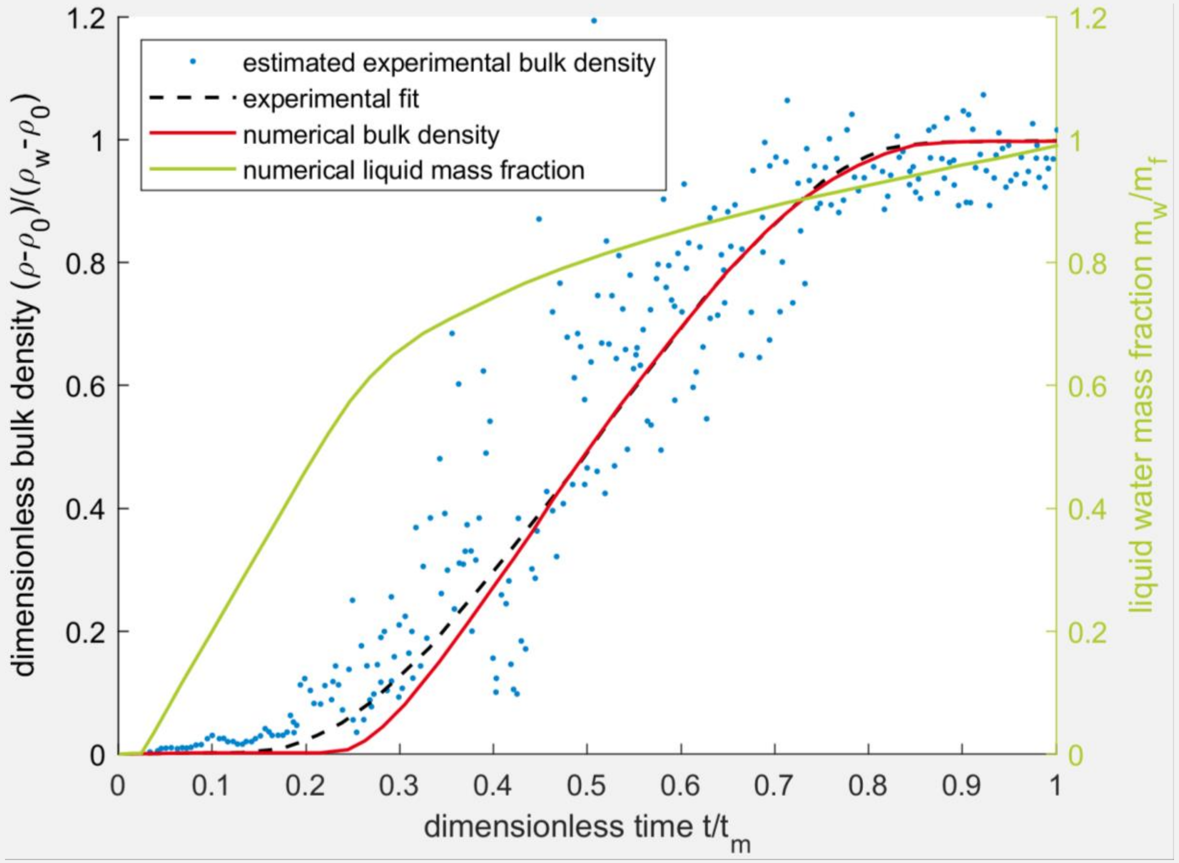


m	1.515 mg
d	8.21 mm
t_m	4.38 s
T_a	27 °C
u	0.58 m/s
RH	66.5 %

Köbschall, K. et al. (2022). Shape Evolution of a Melting Snowflake, AIAA 2022-3371. *AIAA AVIATION 2022 Forum*.

Transport / Snowflake Melting

Model for liquid water fraction of a melting snowflake



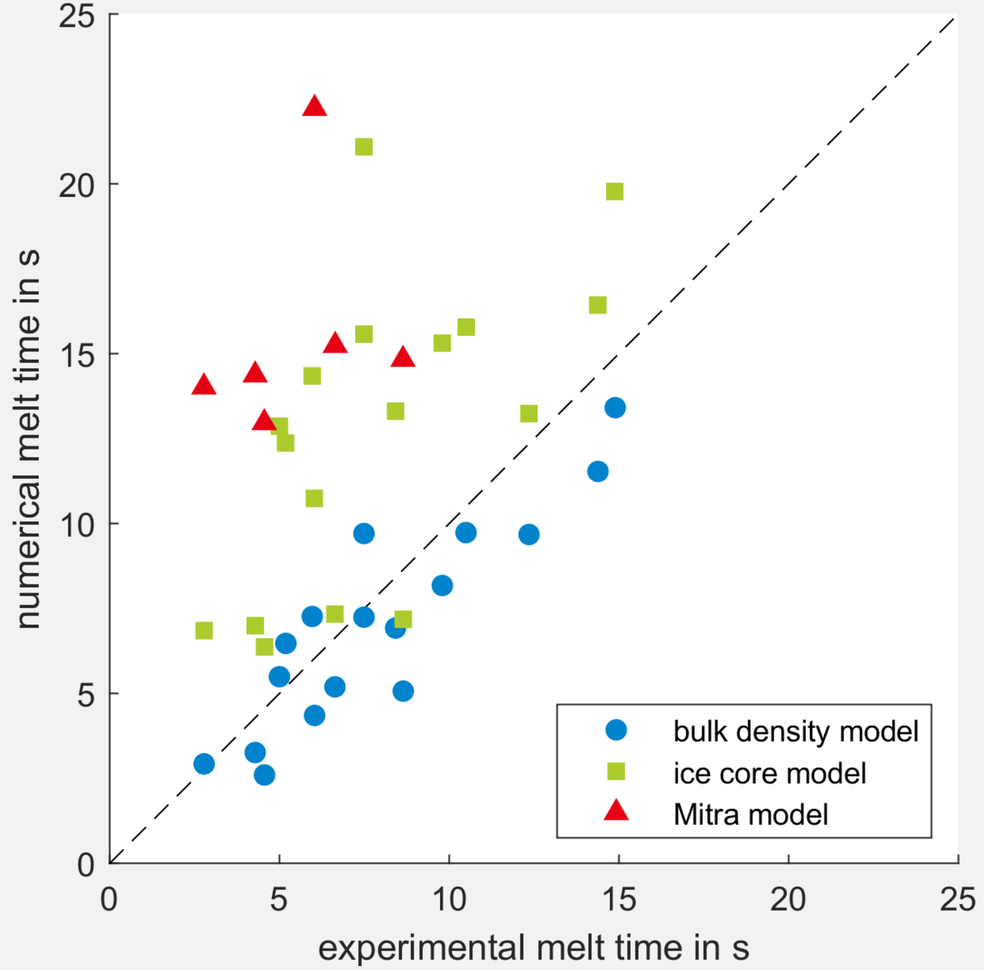
Derived from the proposed snowflake bulk density

$$\rho_\mathrm{p} = \frac{\rho_\mathrm{p0} + \rho_\mathrm{w}}{2} + \frac{\rho_\mathrm{w} - \rho_\mathrm{p0}}{2} \tanh\left(\frac{c_1}{1 - {Y_\mathrm{w}}^{c_2}} - \frac{c_1}{{Y_\mathrm{w}}^{c_2}}\right)$$

with $c_1 = 1.5$ and $c_2 = 3.5$

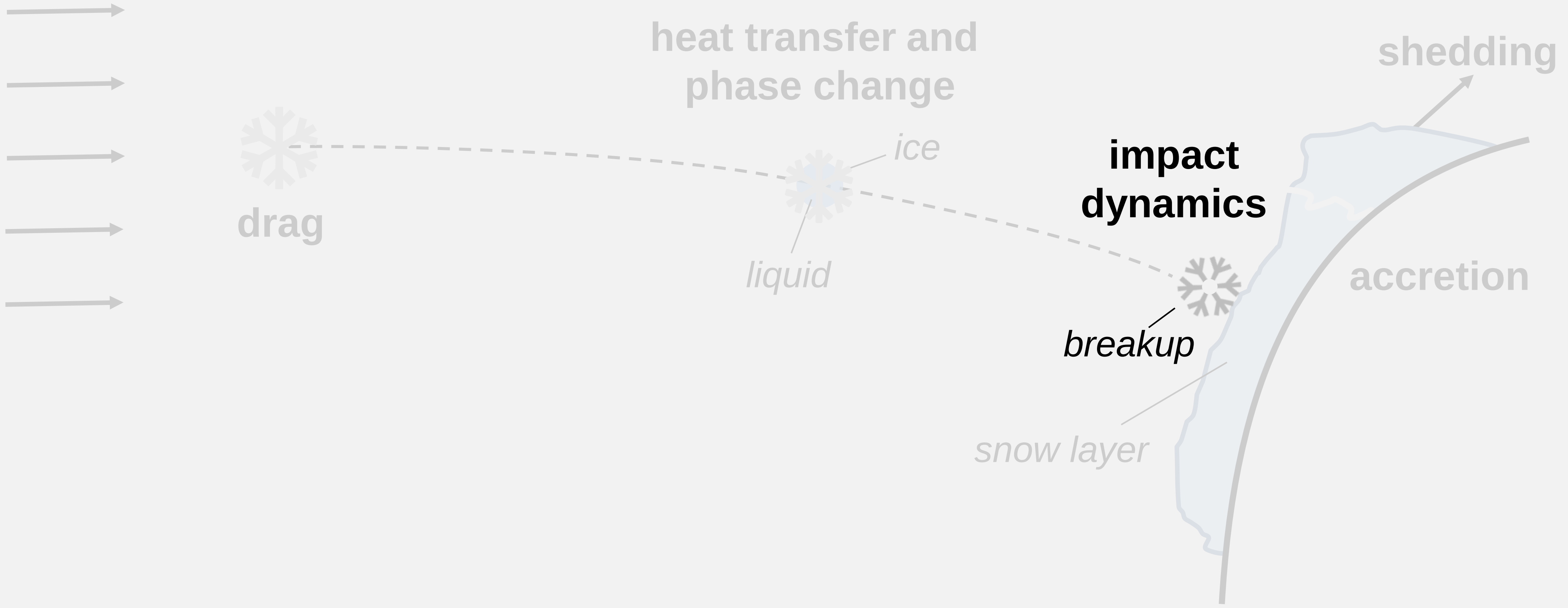
Transport / Snowflake Melting

Melt time model



- Melt time prediction significantly improved in comparison to previously available models
- Oblate spheroid assumption for the approximate volume of the spheroid applied
- In case of an unknown snowflake mass, mass-size relationships are required → WP5

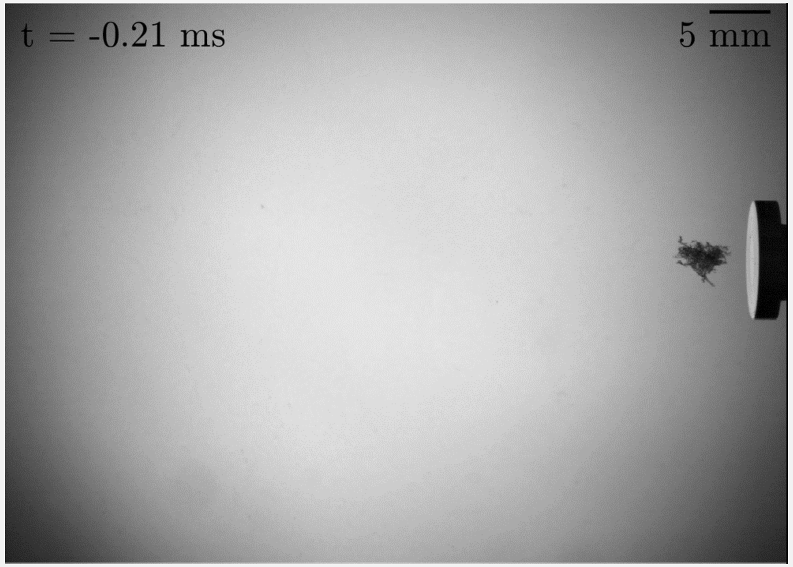
Snowflake Impact



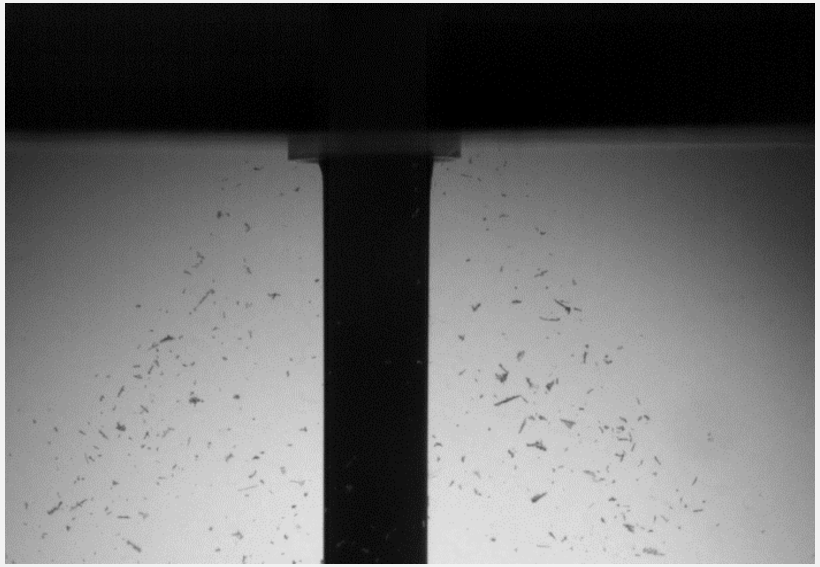
Snowflake Impact

- Breakup threshold investigated experimentally and modeled
- Snowflake fragmentation studied and particle size distribution of secondary particles captured
- Snowflake impact at 11 m/s onto a clean solid substrate

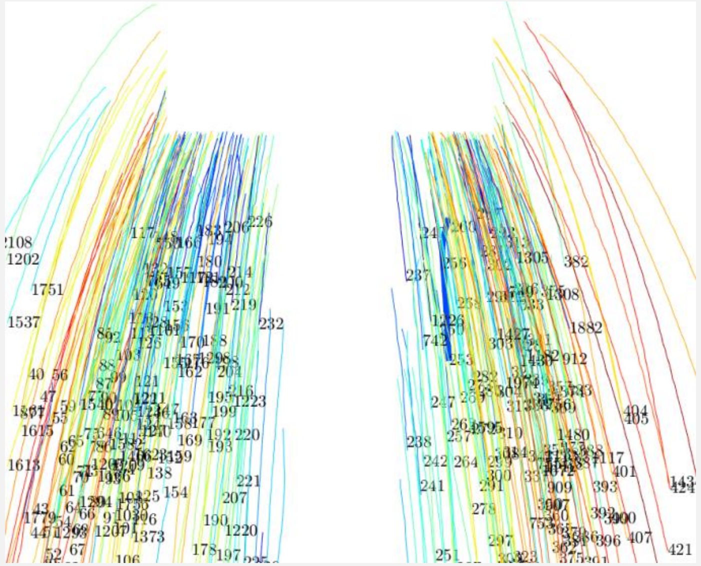
raw video



analysis video



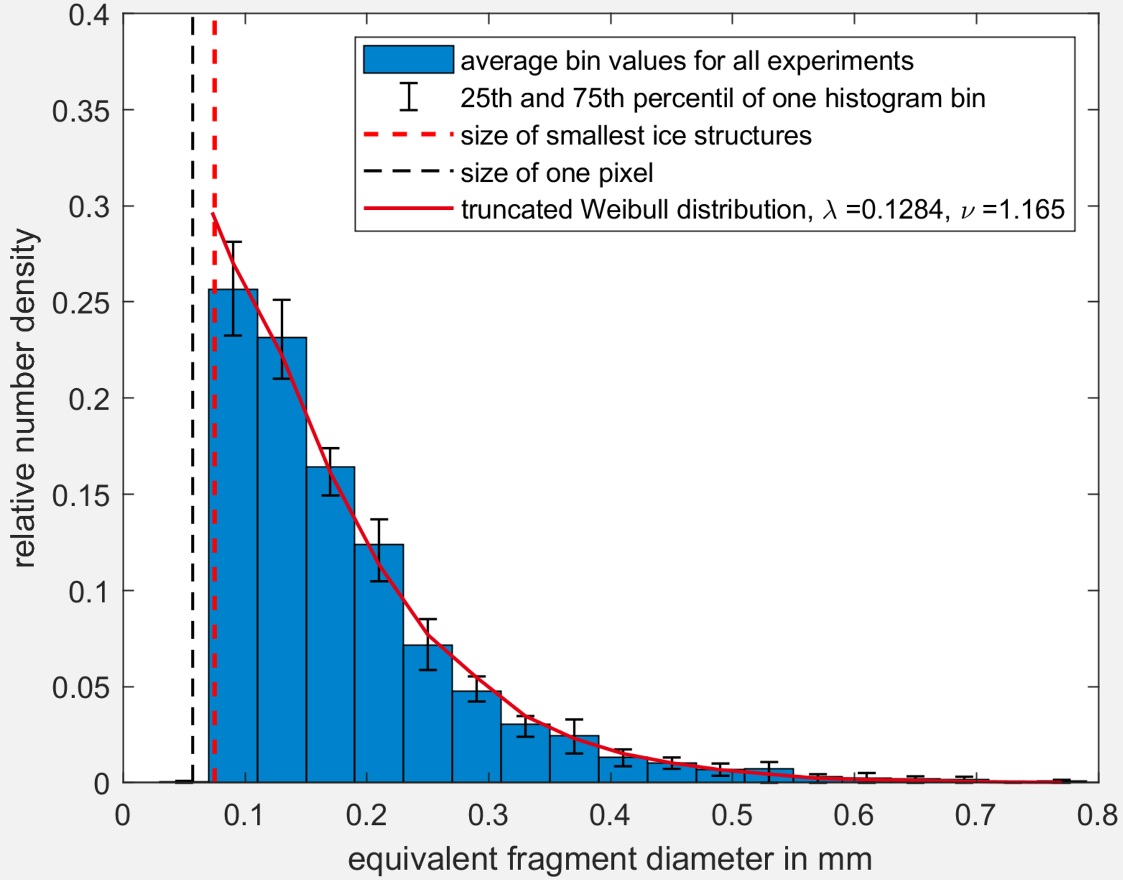
analyzed particle tracks



Snowflake Impact

Results

- 19 experiments, impact velocity of $U_0 = 11\ \mathrm{m}/s$
- Fit of left truncated Weibull distribution, truncation value: $d = 0.073\ \mathrm{mm}$ → size of smallest ice structures

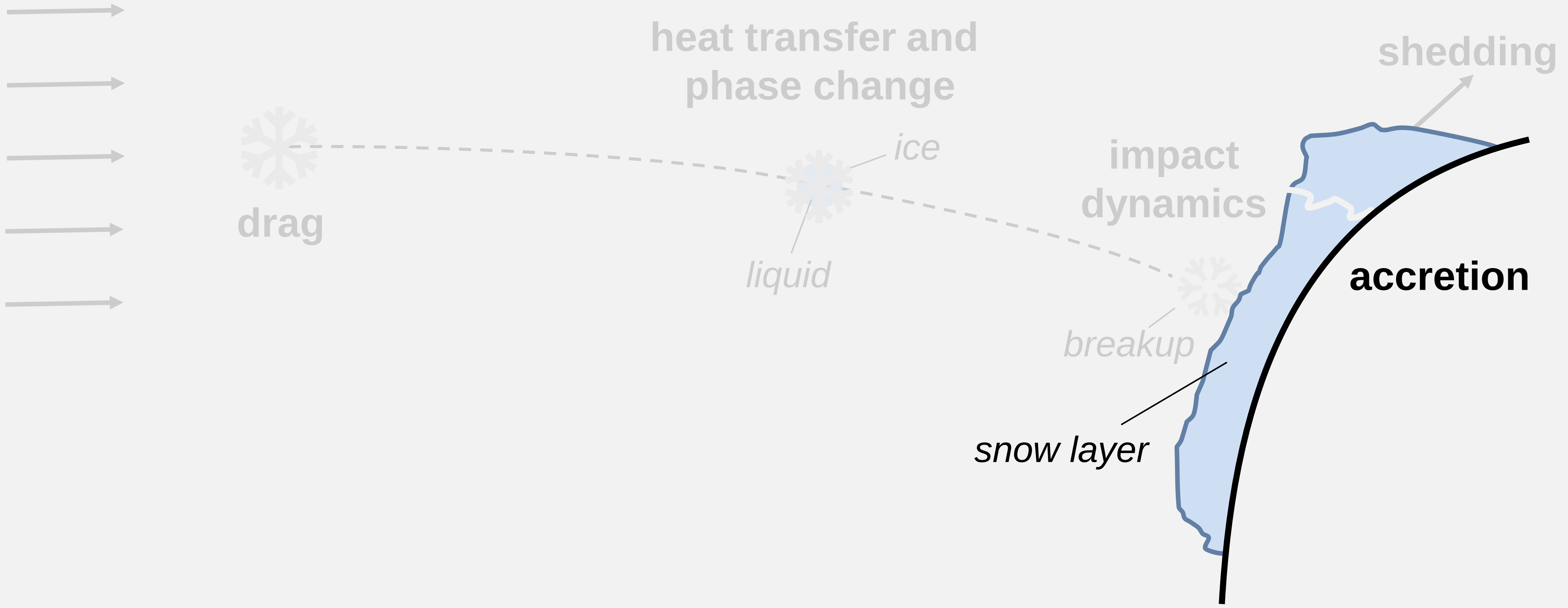


Truncated Weibull probability density function:

$$f(d) = \frac{\nu}{\lambda} \cdot \left(\frac{d}{\lambda}\right)^{\nu-1} \cdot \exp\left(-\left(\frac{d}{\lambda}\right)^{\nu}\right) \quad \text{if } d > 0.073\ \mathrm{mm}$$

$$\lambda = 0.1284, \nu = 1.165$$

Snow Accretion



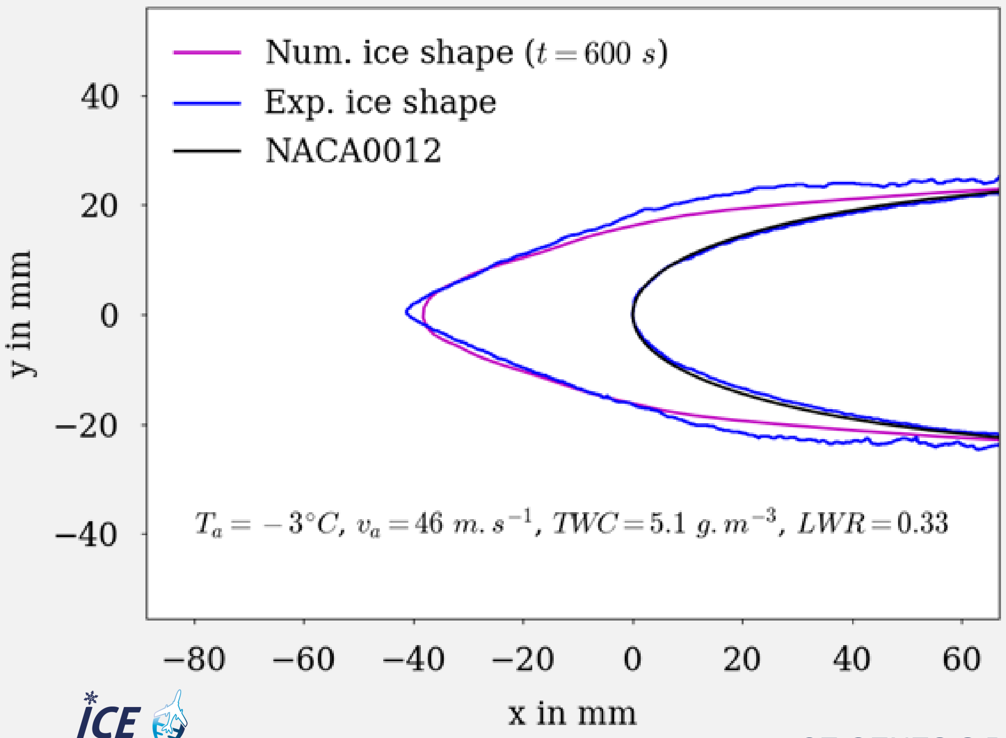
Snow Accretion

Optimization of **model coefficients** for snow accretion

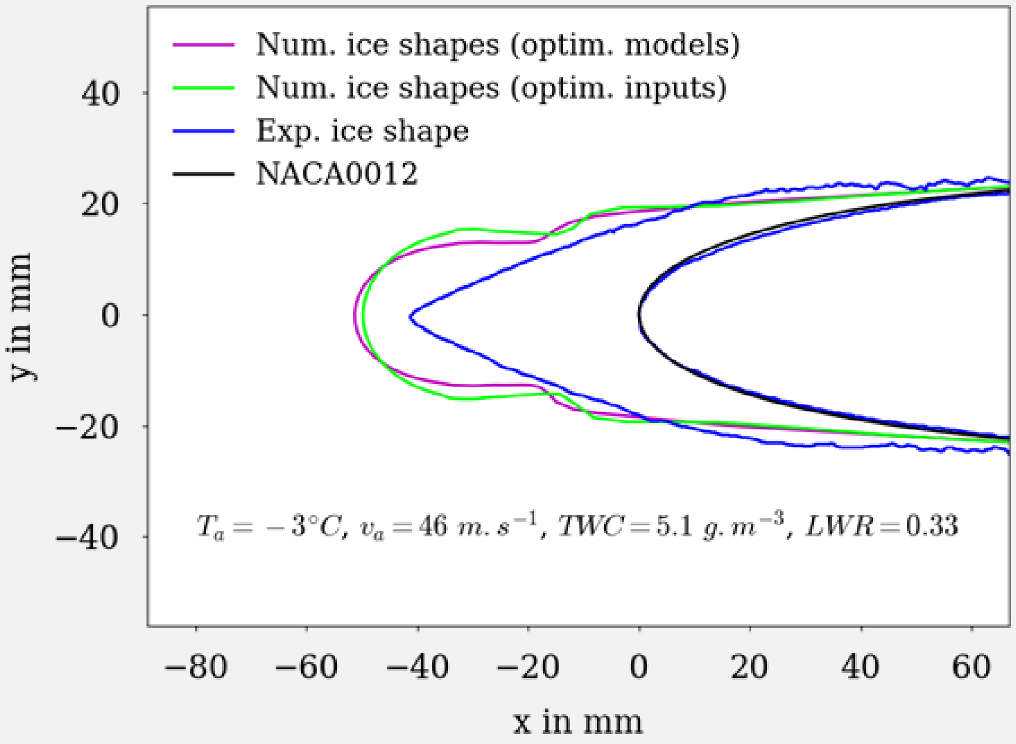
$$\varepsilon_s = F(\eta_m) = (K_c - 2)\eta_m^3 + (3 - 2K_c)\eta_m^2 + K_c\eta_m$$

$$\varepsilon_{er} = E\left(\frac{V_{imp,c}^t}{V_0}\right)^2 \frac{y_{l,0}}{y_{l,0} - \min(y_l, y_{l,0})}\left[1 + (l_0\kappa)^2\right]$$

$K_c = 0.92, E = 0.62$ and $y_{l,0} = 0.77$

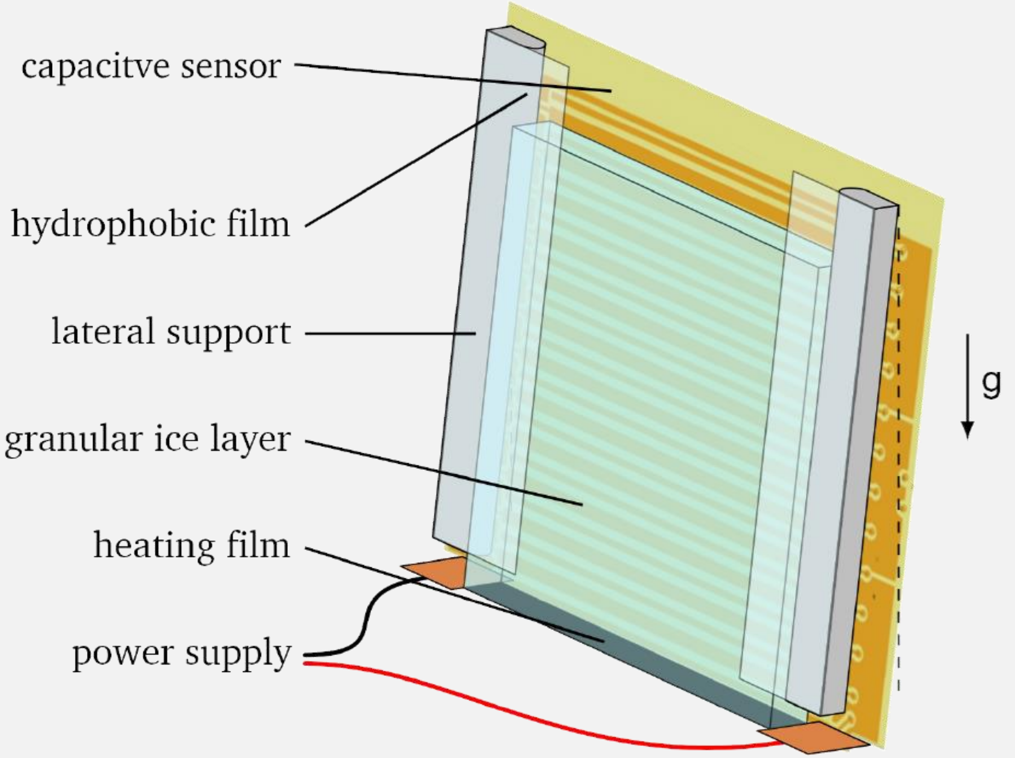


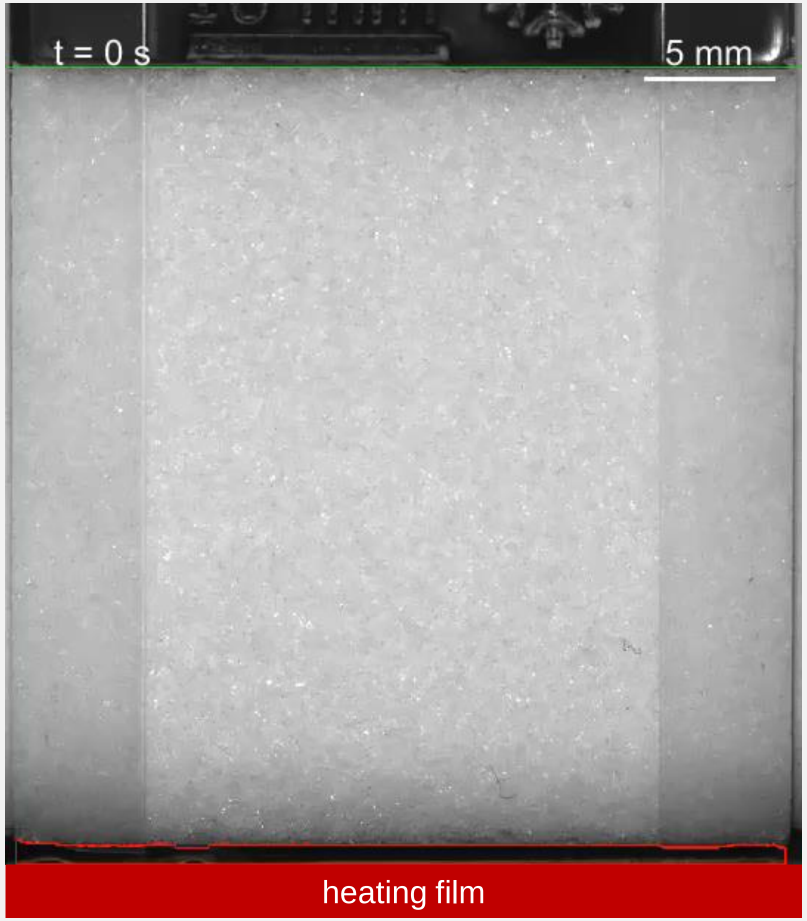
$\overline{K_c} = 1.32, \bar{E} = 0.47$ and $\overline{y_{l,0}} = 0.58$



Snow Accretion

Water transport in melting snow layers



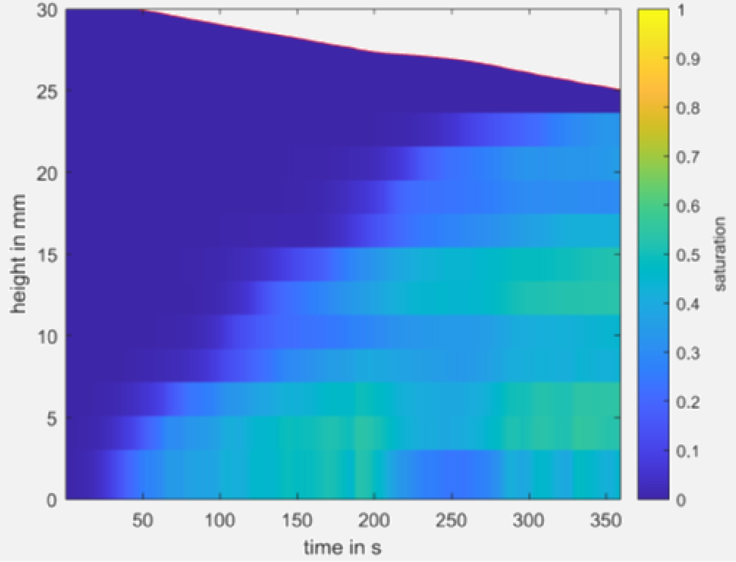


Snow Accretion

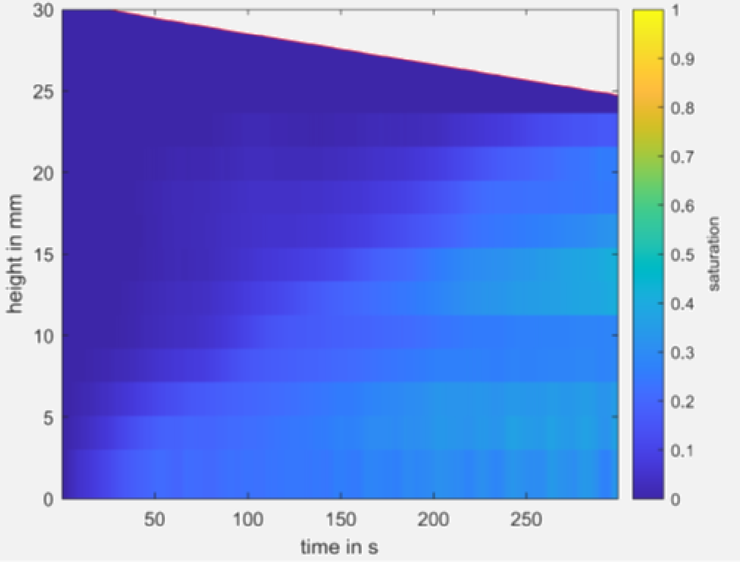
Evolution of saturation (liquid volume fraction in pores)

Exemplary results at 5340 W/m^2 heat flux

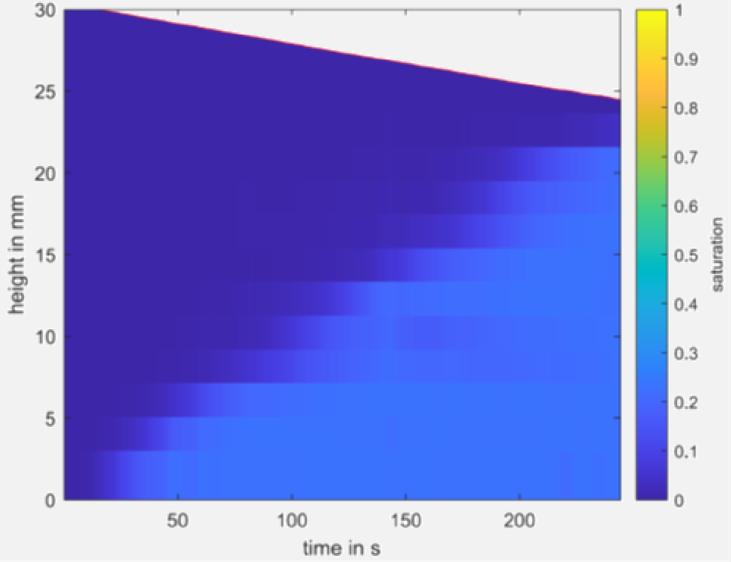
30 % porosity



40 % porosity



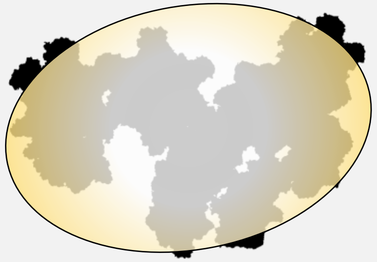
50 % porosity

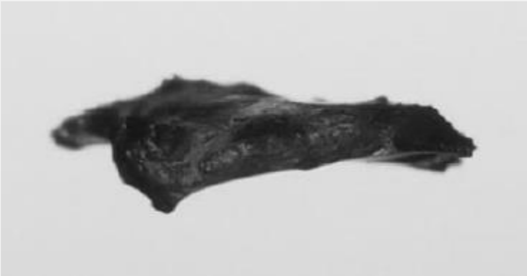


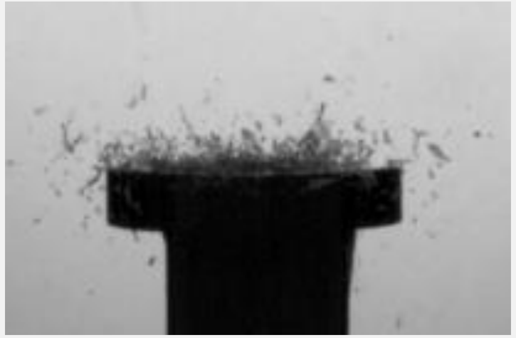
Conclusion

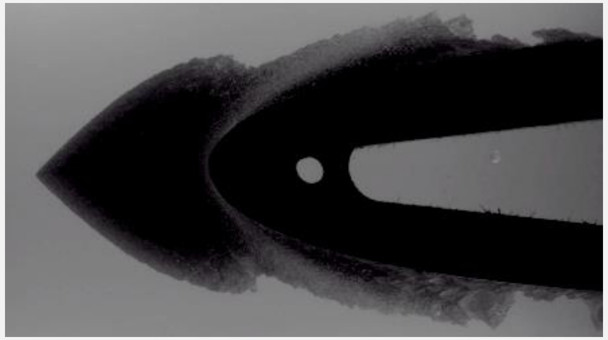
Highlights

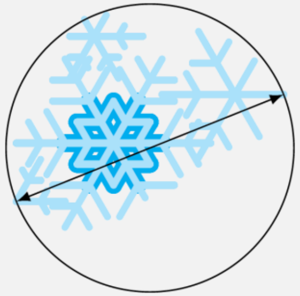
- Improved prediction of snowflake drag and melting
  - Snowflake trajectory and liquid water fraction can be predicted
- Impact and fragmentation of snowflakes investigated
  - Breakup threshold and fragment size distribution characterized
- Coefficients in ice crystal accretion model optimized to improve prediction of snow accretion

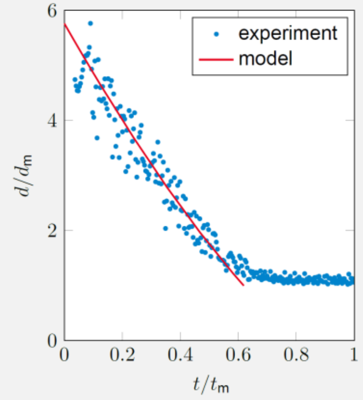












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Backup

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Objectives

Improve and validate current 2D and 3D numerical tools with respect to snow conditions, so that they can be used for both design and certification of aircraft, rotorcraft and engines.

- Experimental data and models exist for drops and ice particles, but mechanics, dynamics and thermodynamics of snowflakes are less well documented
- De-risk power plant system design before in-flight demonstration
- Secure future program development and certification

Timeline & Milestones

2019 — 2020 — 2021 — 2022

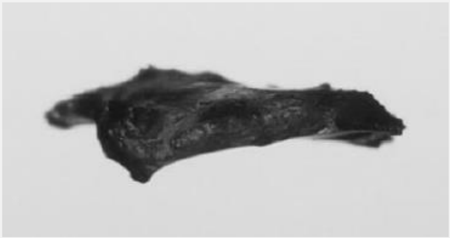
WP10: Snow numerical capability

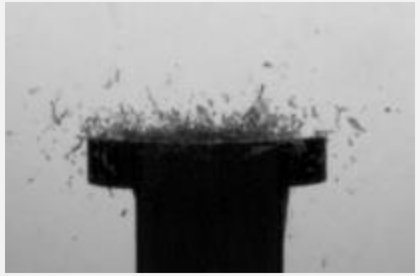
Milestones:
- first set of basic experiments
- final set of basic experiments
- snow models
- snow model integration

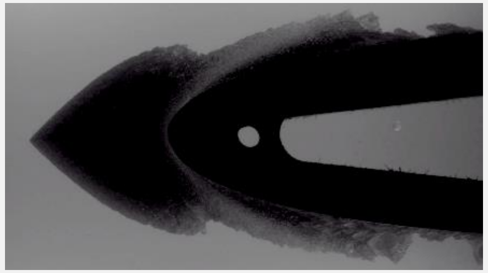
Task 10.1: Experiments ✓

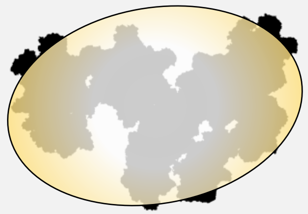
Task 10.2: Model development (✓)

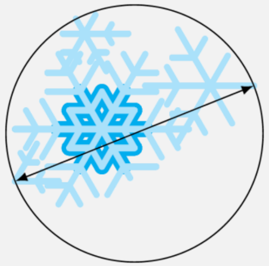
Task 10.3: Model integration …

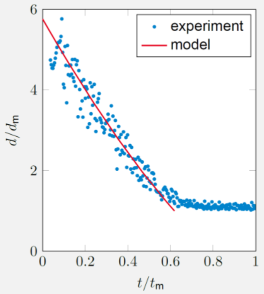






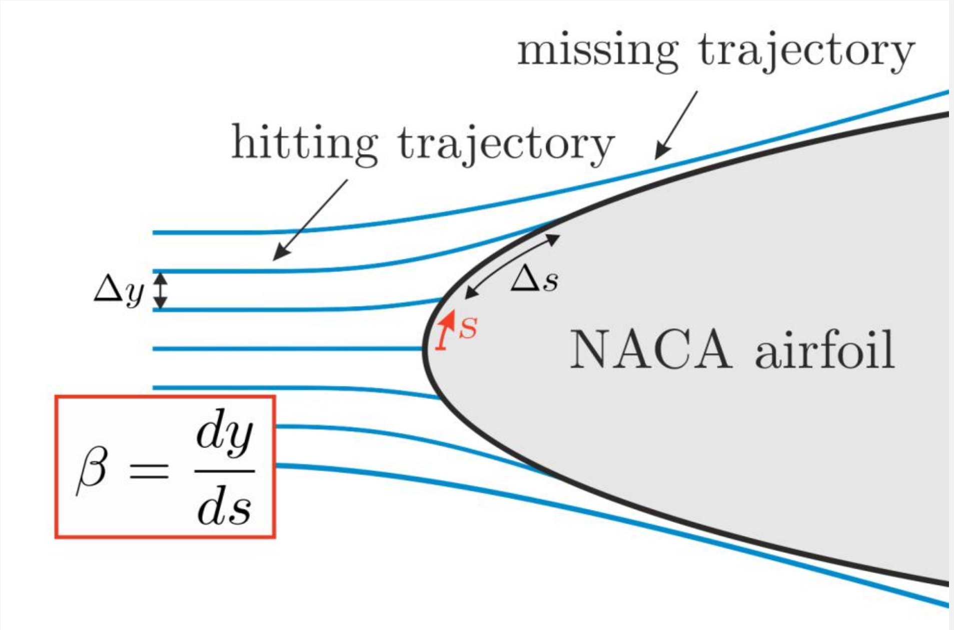


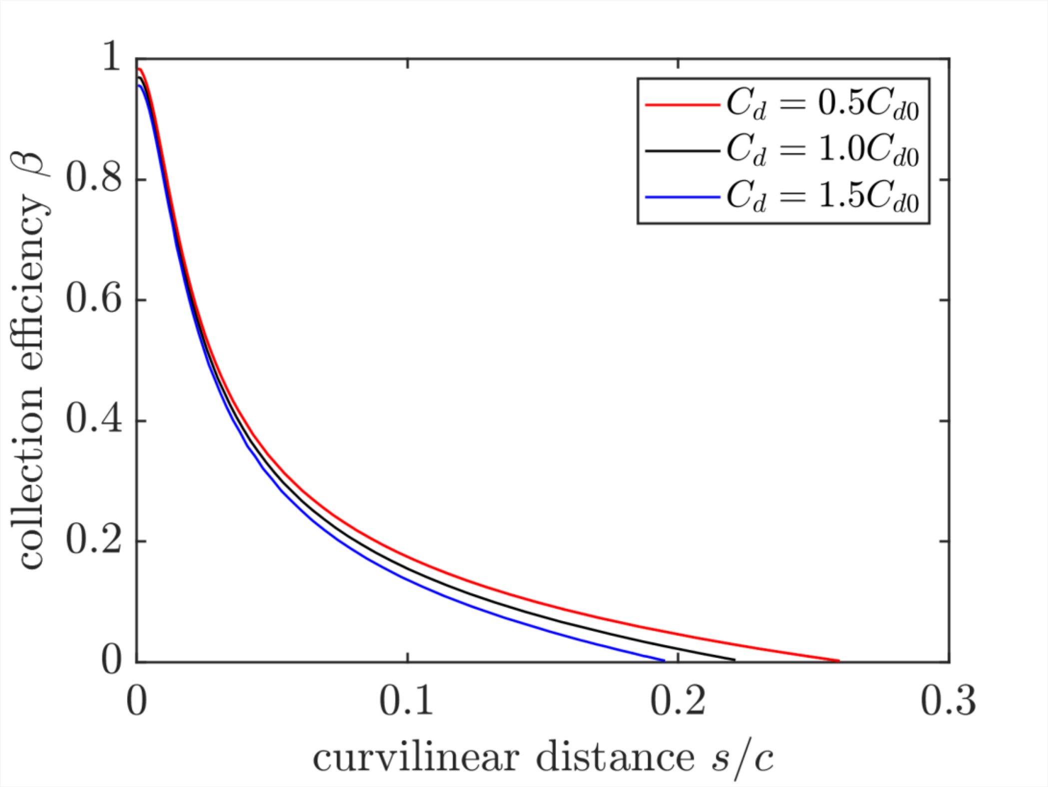




Transport / Drag

- Sensitivity study with a NACA0012

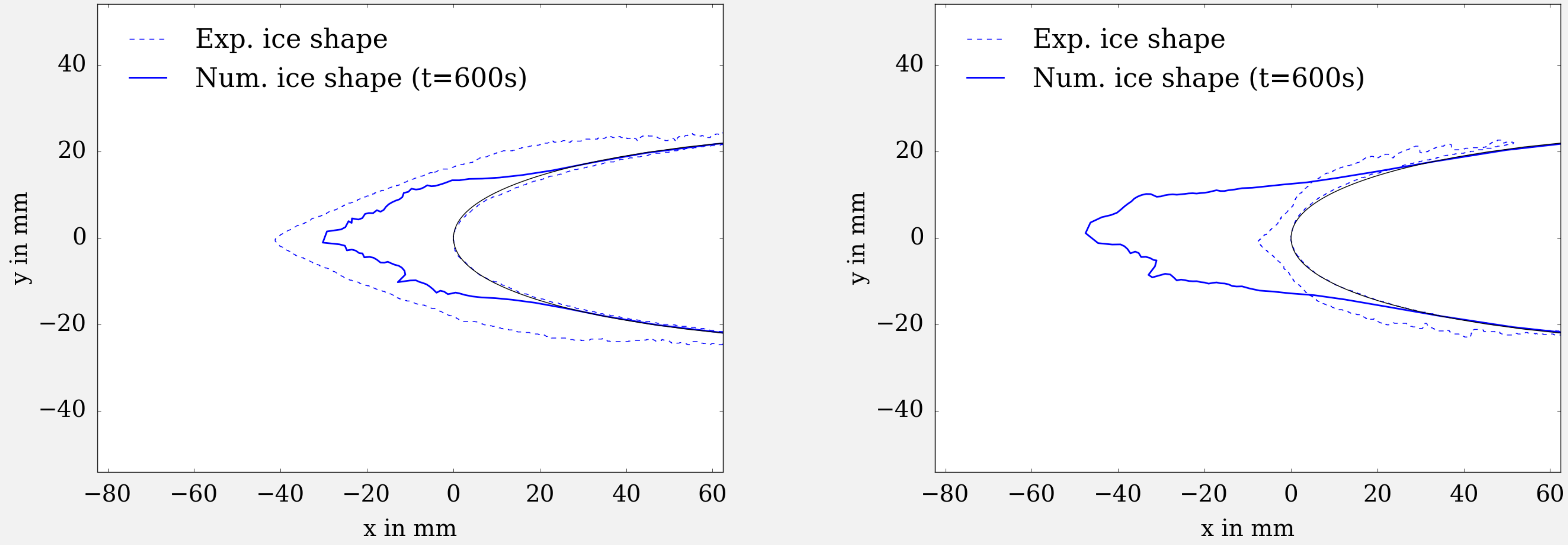




Snow Accretion

Preliminary study to **improve erosion and sticking model** for accretion

- Preliminary study based on CSTB test campaign database
- First numerical simulations done with HAIC sticking and erosion model[1]



[1] "A comprehensive accretion model for glaciated icing conditions", P. Trontin, P. Villedieu,, *International Journal of Multiphase Flow, 2018.*

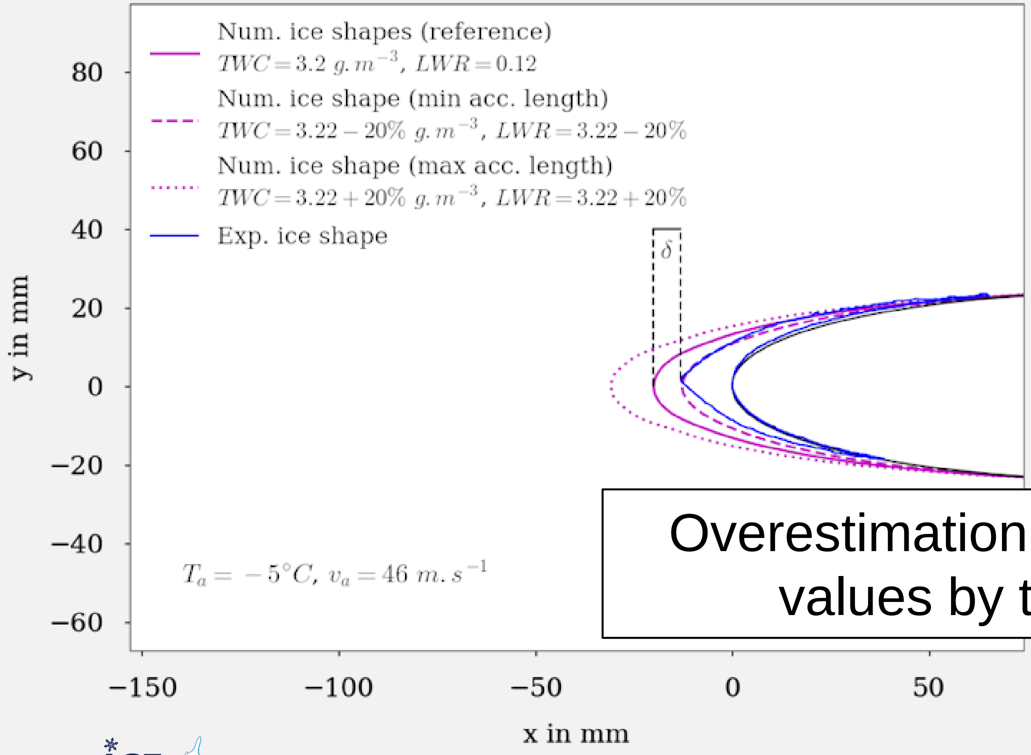
Snow Accretion

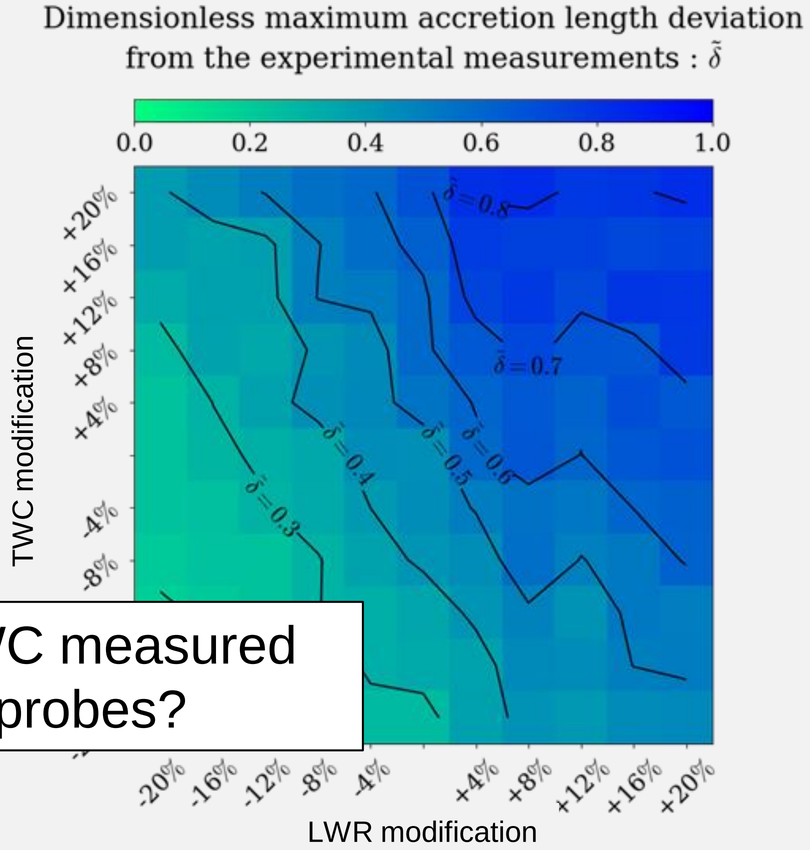
Sensitivity with respect to TWC and LWR

Goal: Characterize the error on final ice shapes calculated with HAIC erosion and sticking models with uncertain water concentration

$$\bar{\delta}_{i,j} = \frac{1}{N}\sum_{k=1}^{N} \frac{(\delta_{i,j})_k - \min_{i,j}(\delta_{i,j})_k}{\max_{i,j}(\delta_{i,j})_k - \min_{i,j}(\delta_{i,j})_k}$$

N = 8 runs
i = TWC uncertainty
j = LWR uncertainty





Overestimation of TWC & LWC measured values by the wcm2000 probes?

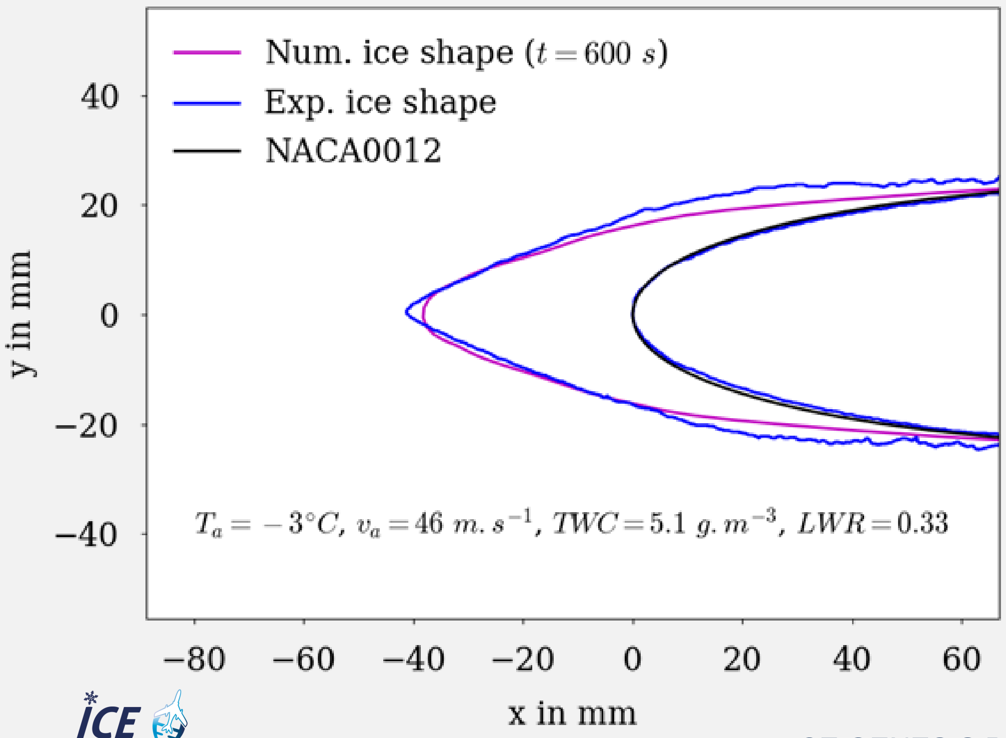
Snow Accretion

Optimization of **model coefficients** for snow accretion

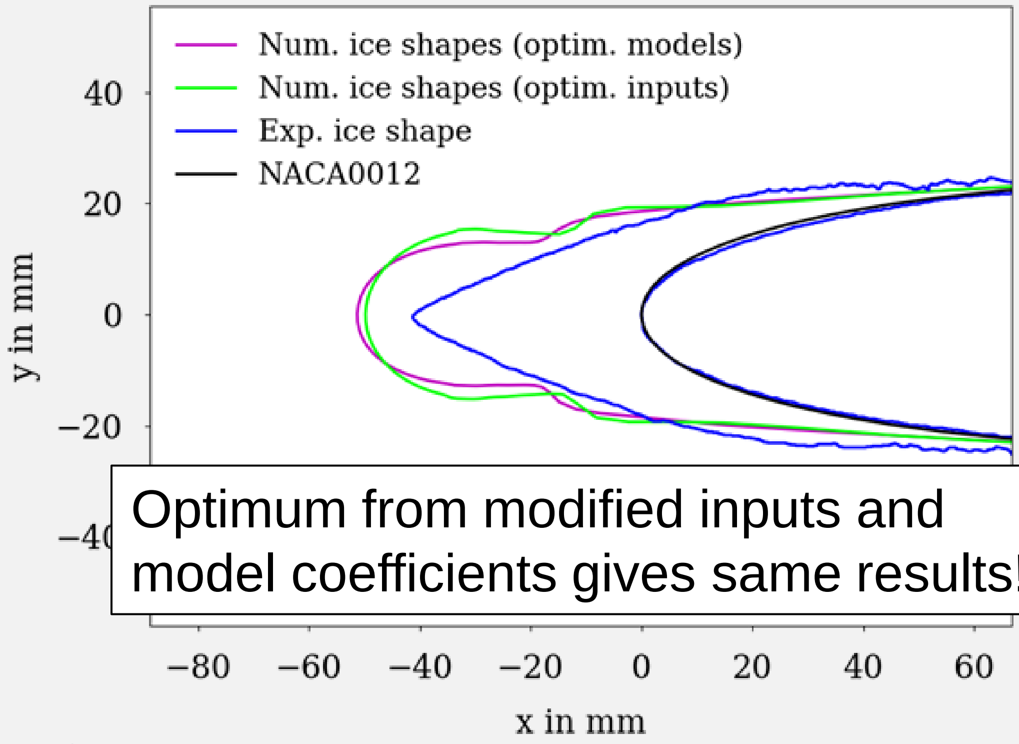
$$\varepsilon_s = F(\eta_m) = (K_c - 2)\eta_m^3 + (3 - 2K_c)\eta_m^2 + K_c\eta_m$$

$$\varepsilon_{er} = E\left(\frac{V_{imp,c}^t}{V_0}\right)^2 \frac{y_{l,0}}{y_{l,0} - \min(y_l, y_{l,0})}\left[1 + (l_0\kappa)^2\right]$$

$K_c = 0.92, E = 0.62$ and $y_{l,0} = 0.77$



$\overline{K_c} = 1.32, \bar{E} = 0.47$ and $\overline{y_{l,0}} = 0.58$



Optimum from modified inputs and model coefficients gives same results!