

Immersion freezing in particle-based cloud μ -physics models

S. Arabas¹, J.H. Curtis², I. Silber³, A. Fridlind⁴, D.A. Knopf⁵, M. West² & N. Riemer²



funding:



University of Washington, Seattle, Jan 23rd 2026



Immersion Freezing in Particle-Based Aerosol-Cloud Microphysics: A Probabilistic Perspective on Singular and Time-Dependent Models

Sylwester Arabas¹ , Jeffrey H. Curtis² , Israel Silber^{3,4} , Ann M. Fridlind⁵ ,
Daniel A. Knopf⁶ , Matthew West⁷ , and Nicole Riemer² 

10.1029/2024MS004770

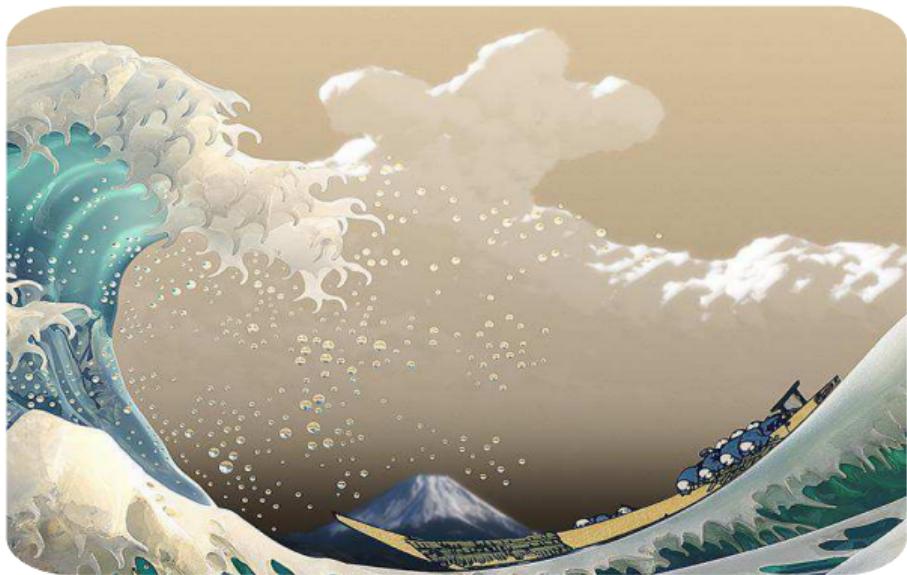
Aerosol-cloud interactions: a conceptual picture

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background image: vitsly / Hokusai

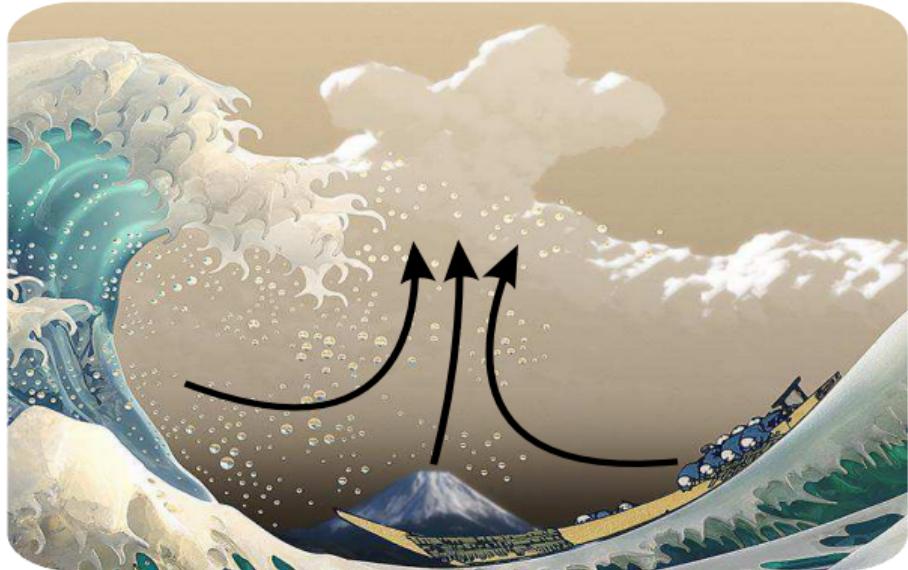
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Aerosol-cloud interactions: a conceptual picture

- ▶ aerosol particles of natural and anthropogenic origin act as condensation/crystallisation nuclei



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two-way interactions:

- aerosol characteristics influence cloud microstructure
- cloud processes influence aerosol size and composition

Aerosol-cloud interactions: μ -physics models

JAMES

Journal of Advances in
Modeling Earth Systems

COMMISSIONED MANUSCRIPT

10.1029/2019MS001689

Key Points:

- Microphysics is an important component of weather and climate models, but its representation in current models is highly uncertain

Confronting the Challenge of Modeling Cloud and Precipitation Microphysics

Hugh Morrison¹ , Marcus van Lier-Walqui² , Ann M. Fridlind³ , Wojciech W. Grabowski¹ , Jerry Y. Harrington⁴, Corinna Hoose⁵ , Alexei Korolev⁶ , Matthew R. Kumjian⁴ , Jason A. Milbrandt⁷, Hanna Pawlowska⁸ , Derek J. Posselt⁹, Olivier P. Prat¹⁰, Karly J. Reimel⁴, Shin-Ichiro Shima¹¹ , Bastiaan van Diedenhoven² , and Lulin Xue¹ 

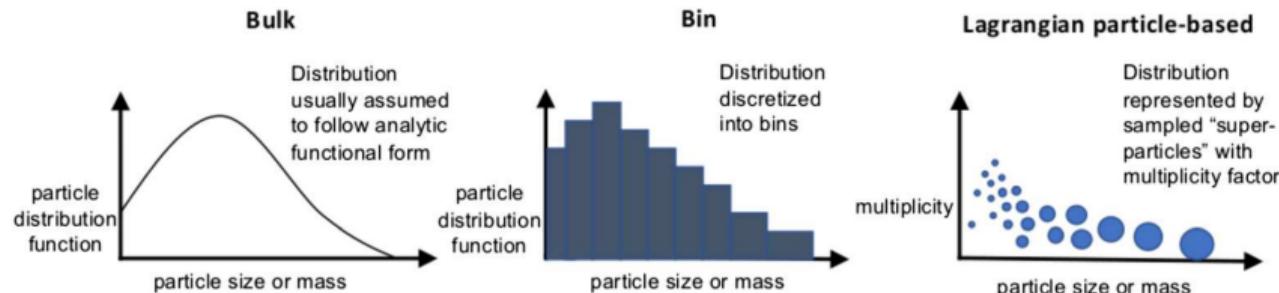


Figure 3. Representation of cloud and precipitation particle distributions in the three main types of microphysics

Aerosol-cloud interactions: μ -physics models

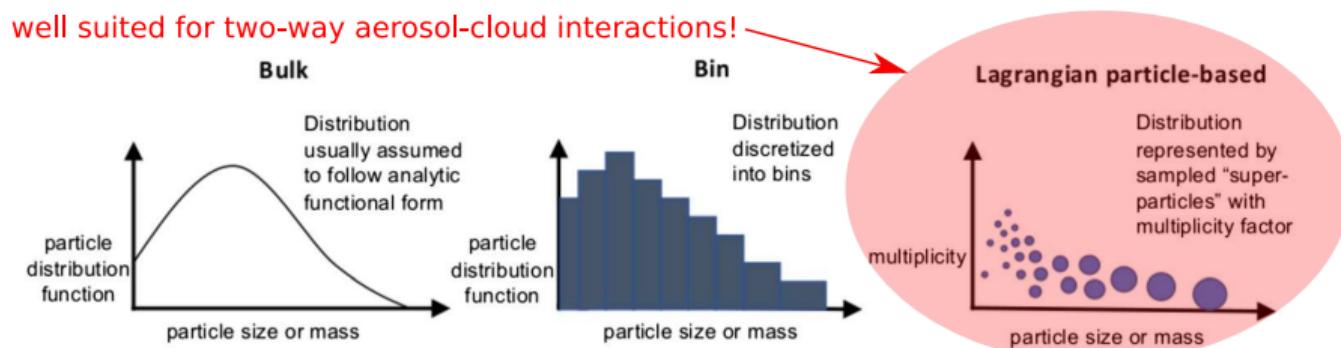
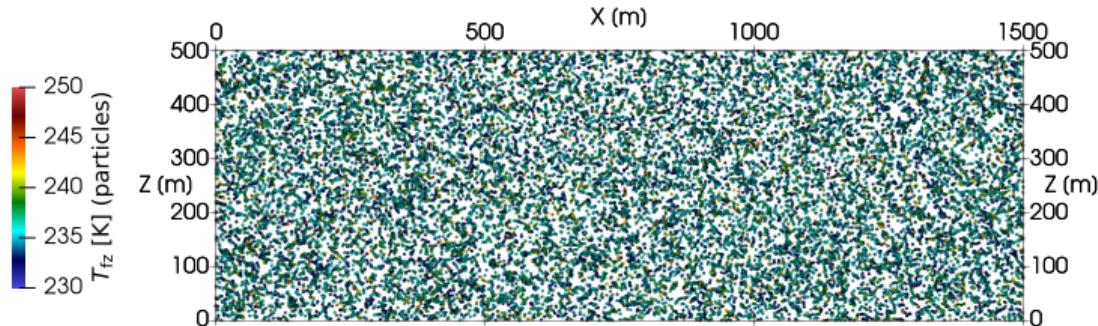


Figure 3. Representation of cloud and precipitation particle distributions in the three main types of microphysics

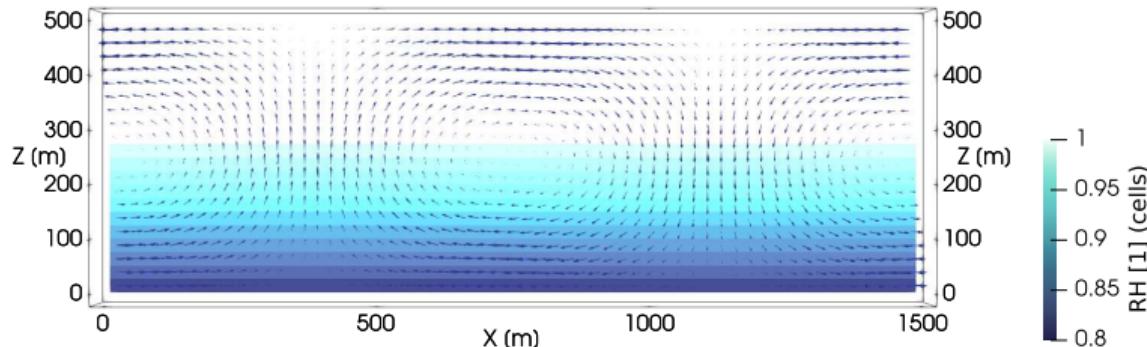
Particle-based μ -physics + prescribed-flow: model state

Lagrangian component



PySDM

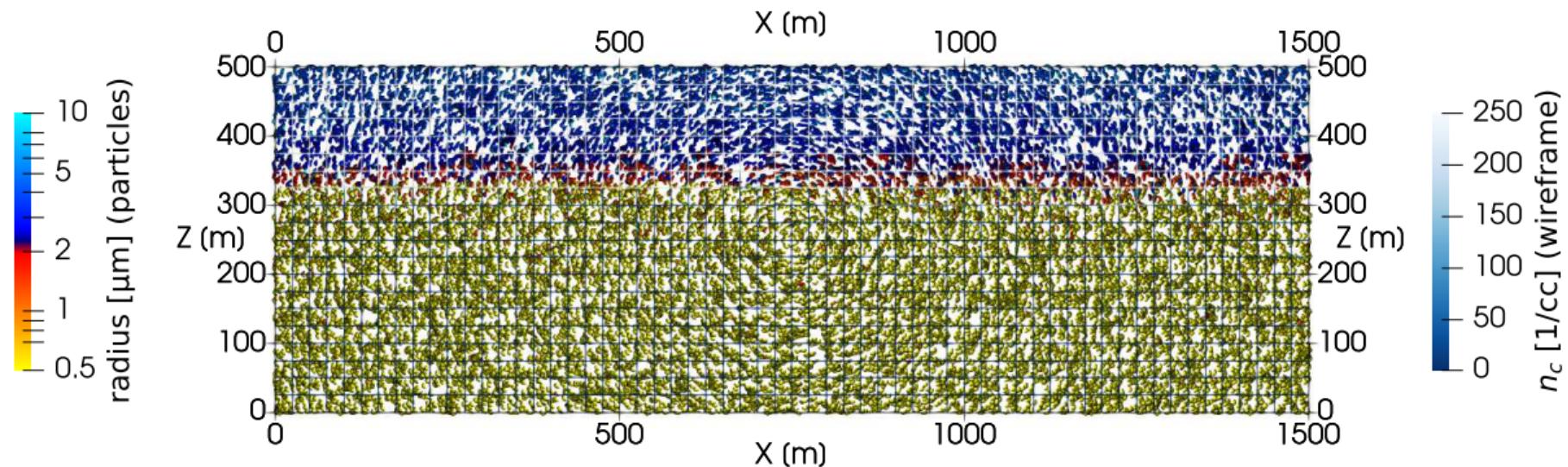
Eulerian component



PyMPDATA

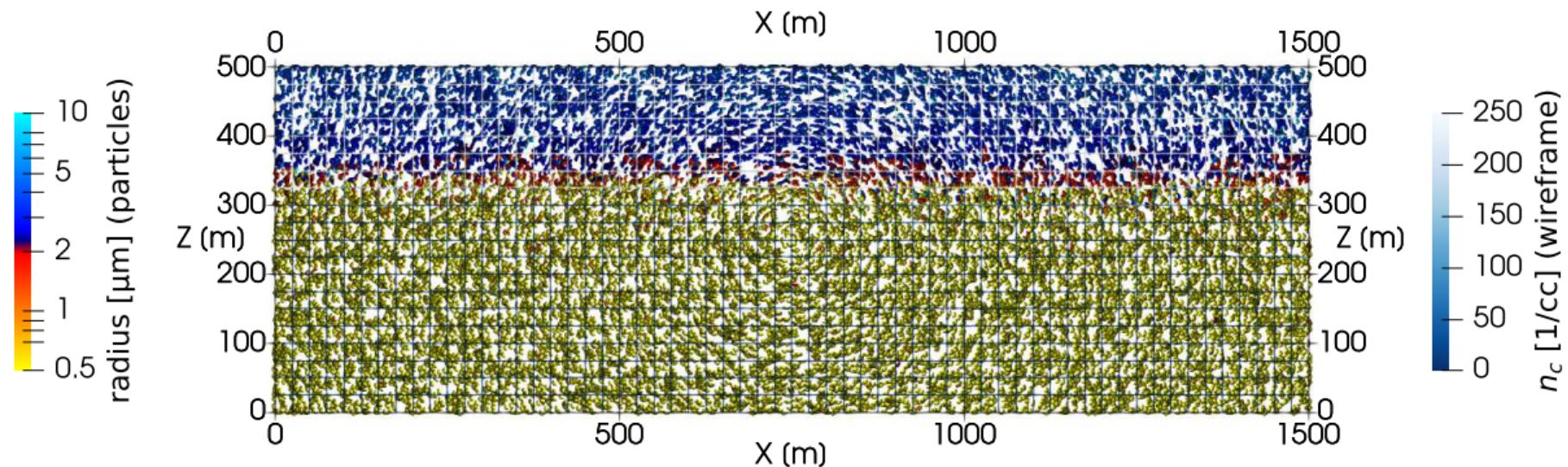
Particle-based μ -physics + prescribed-flow: spin-up

Time: 30 s (spin-up till 600.0 s)



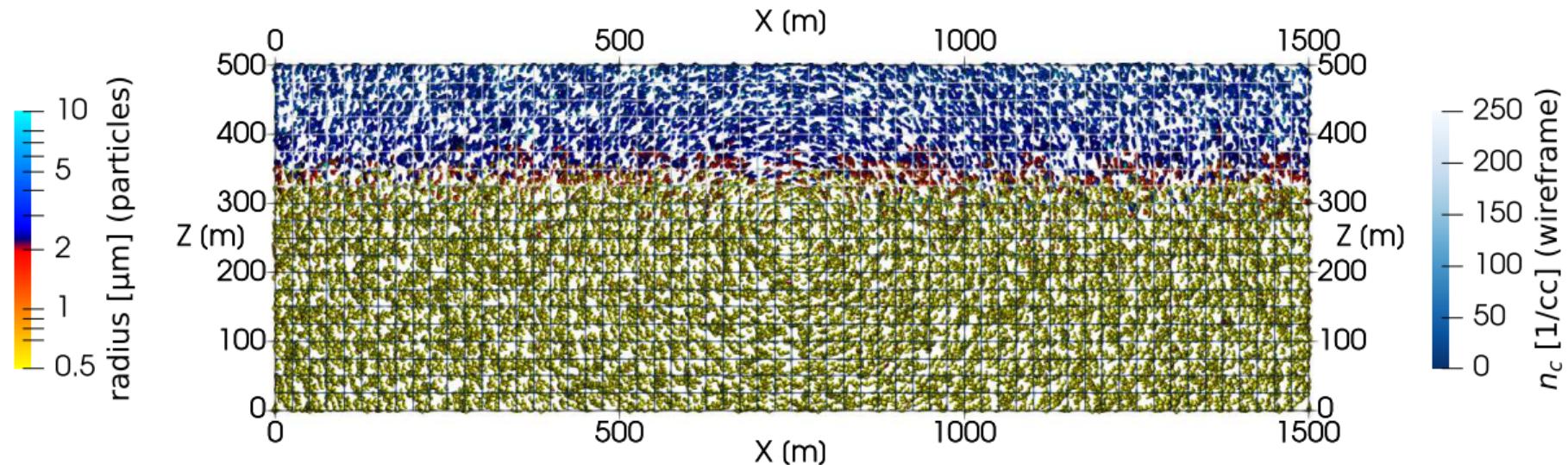
Particle-based μ -physics + prescribed-flow: spin-up

Time: 60 s (spin-up till 600.0 s)



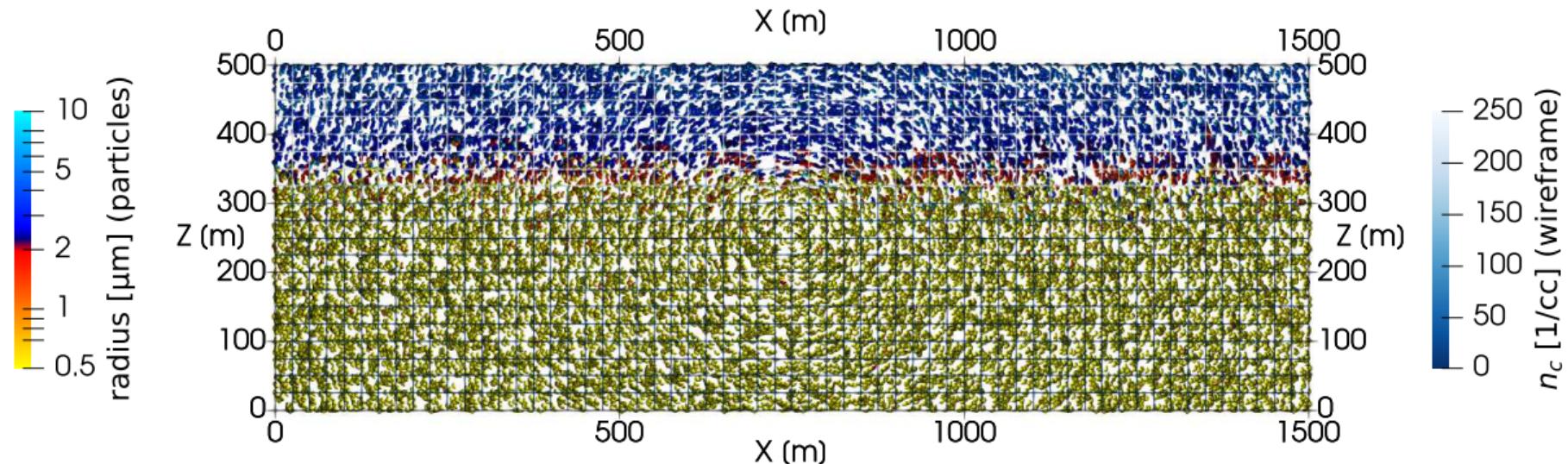
Particle-based μ -physics + prescribed-flow: spin-up

Time: 90 s (spin-up till 600.0 s)



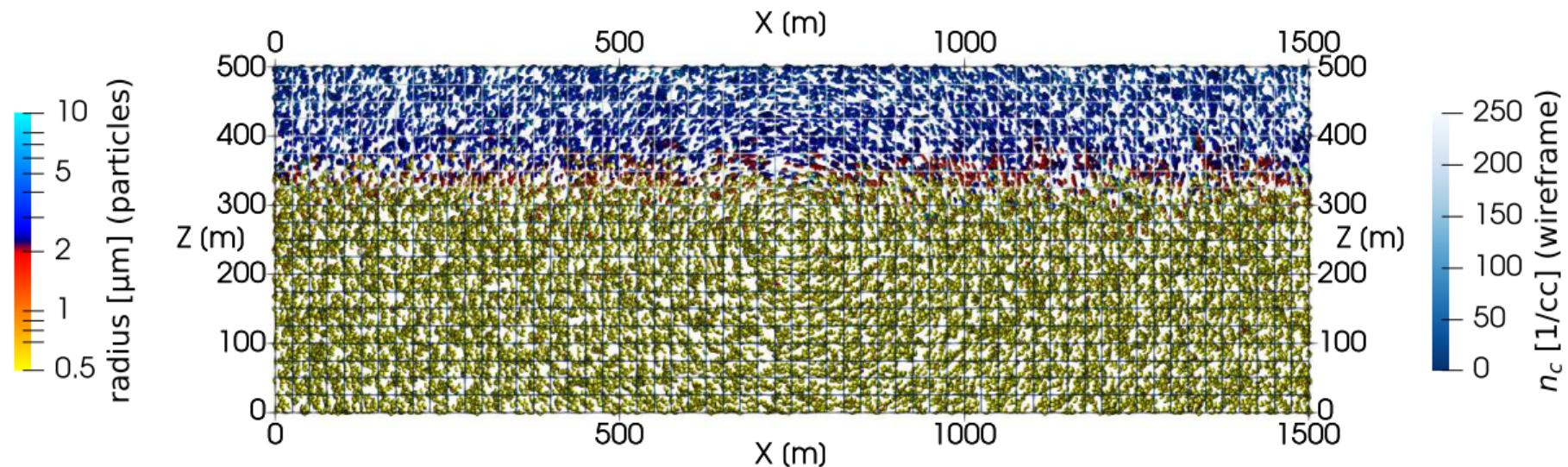
Particle-based μ -physics + prescribed-flow: spin-up

Time: 120 s (spin-up till 600.0 s)



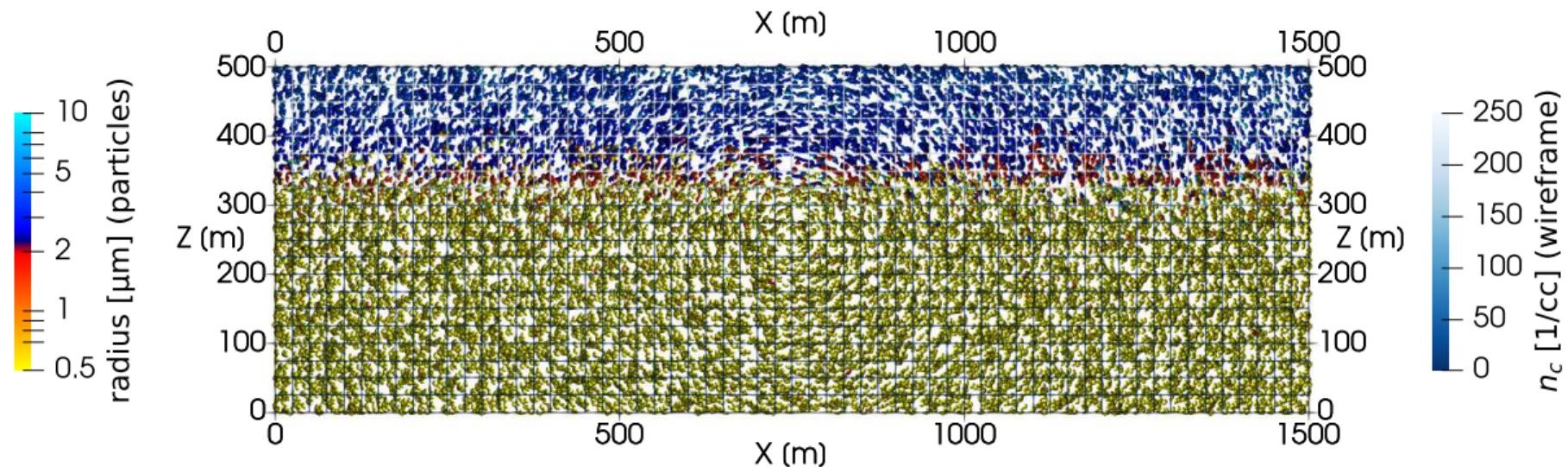
Particle-based μ -physics + prescribed-flow: spin-up

Time: 150 s (spin-up till 600.0 s)



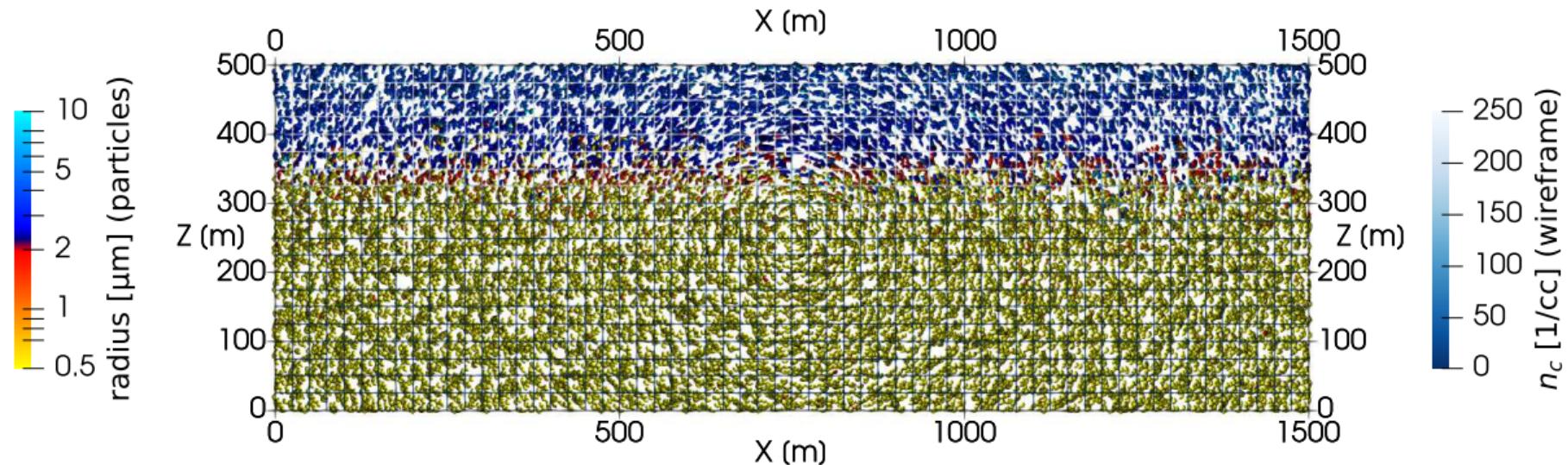
Particle-based μ -physics + prescribed-flow: spin-up

Time: 180 s (spin-up till 600.0 s)



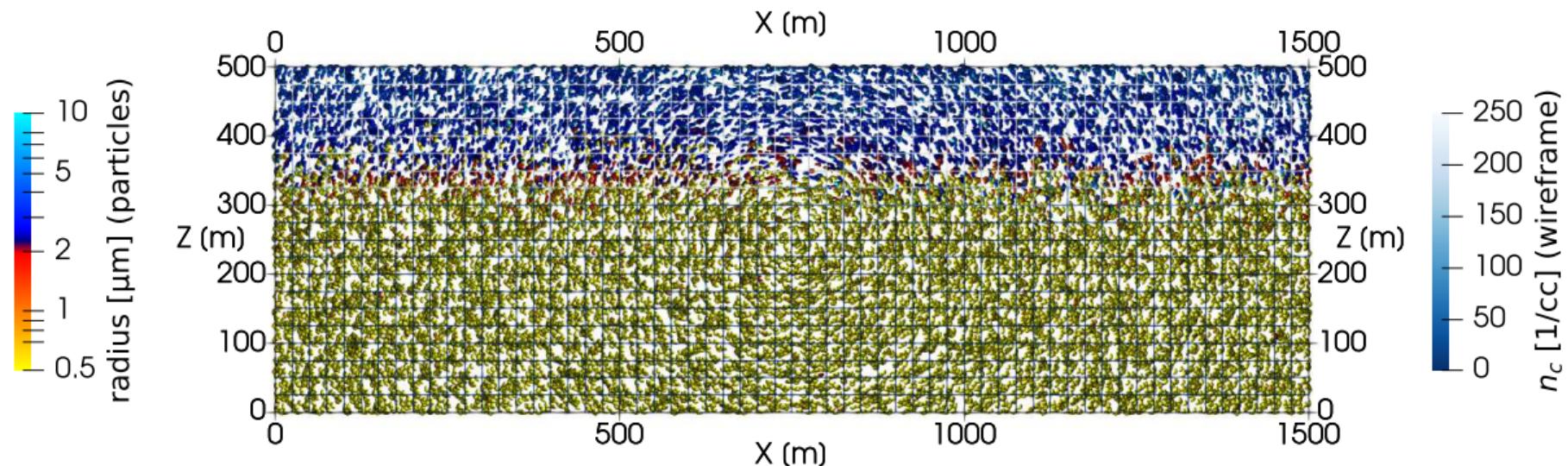
Particle-based μ -physics + prescribed-flow: spin-up

Time: 210 s (spin-up till 600.0 s)



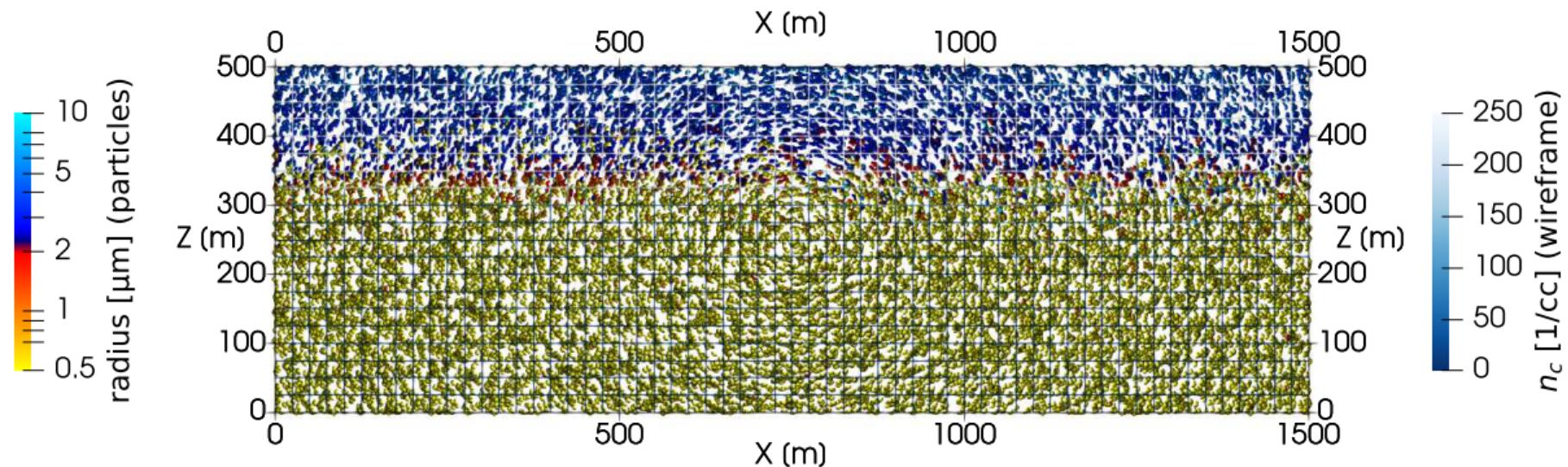
Particle-based μ -physics + prescribed-flow: spin-up

Time: 240 s (spin-up till 600.0 s)



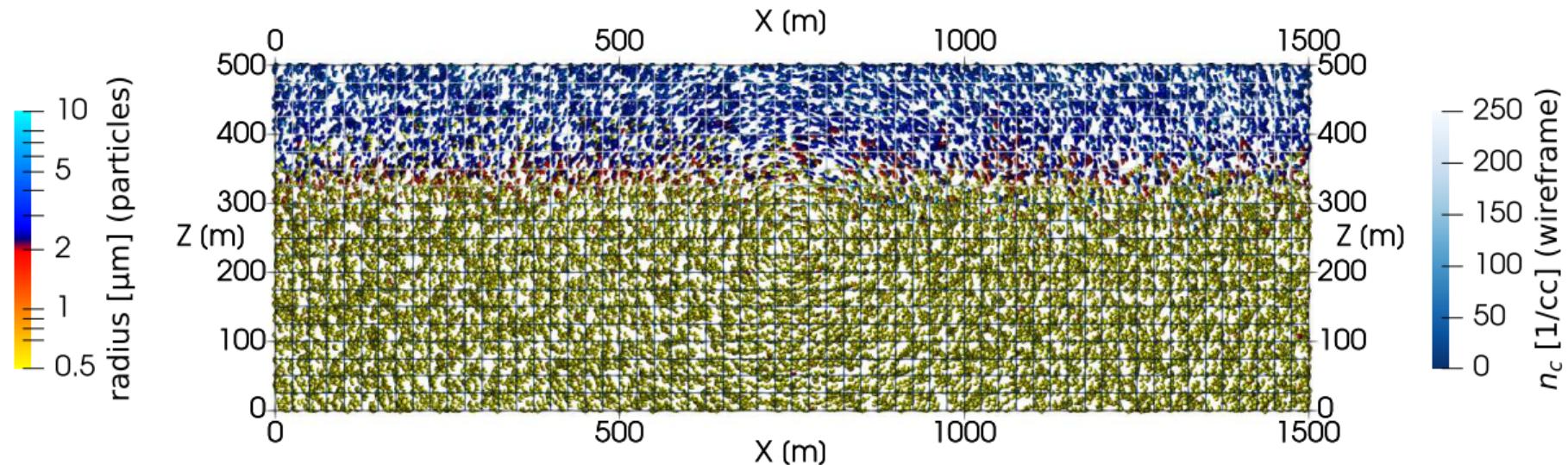
Particle-based μ -physics + prescribed-flow: spin-up

Time: 270 s (spin-up till 600.0 s)



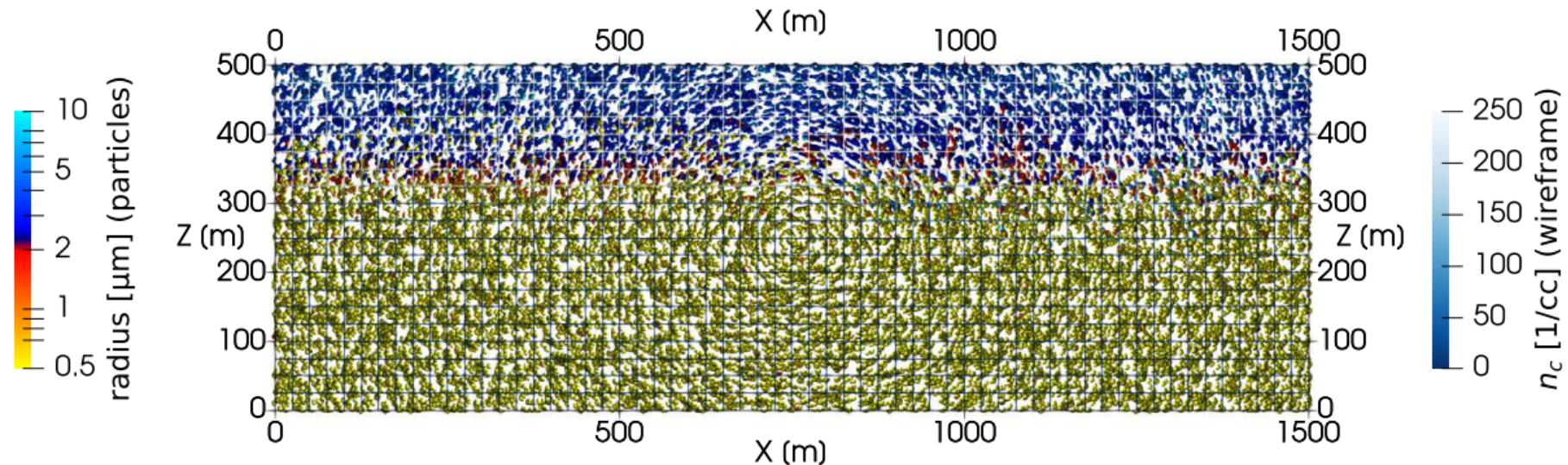
Particle-based μ -physics + prescribed-flow: spin-up

Time: 300 s (spin-up till 600.0 s)



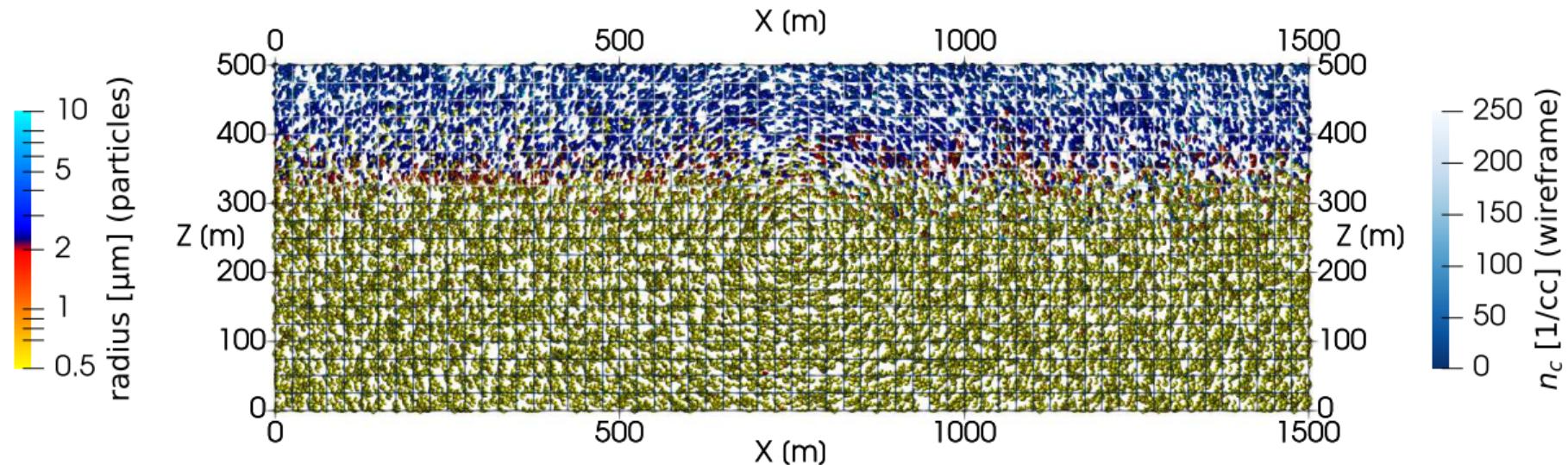
Particle-based μ -physics + prescribed-flow: spin-up

Time: 330 s (spin-up till 600.0 s)



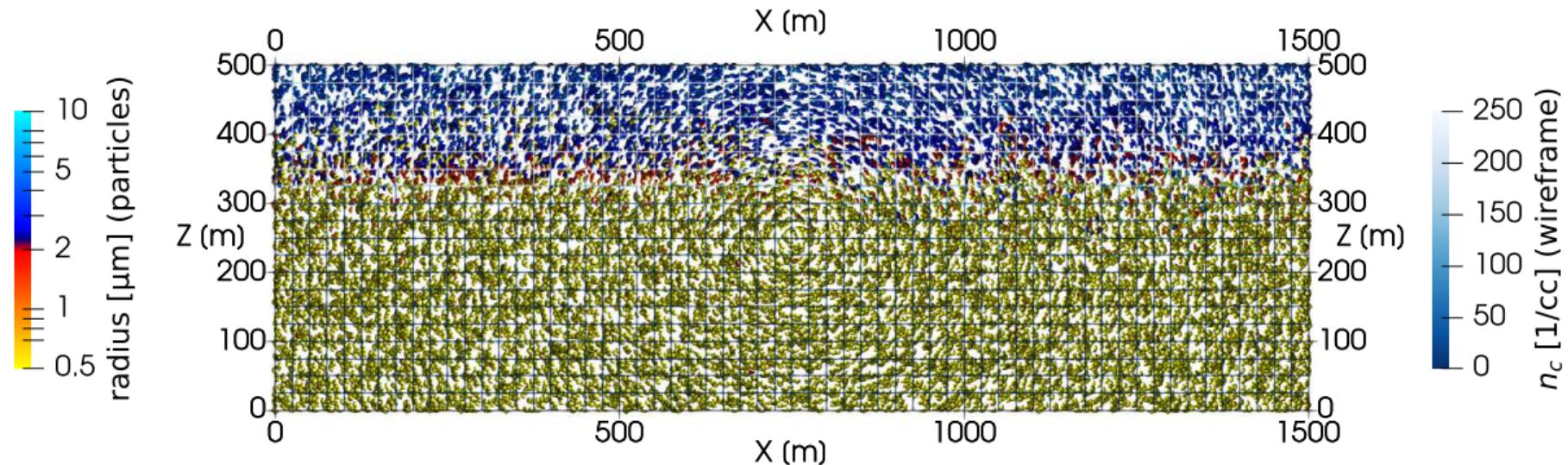
Particle-based μ -physics + prescribed-flow: spin-up

Time: 360 s (spin-up till 600.0 s)



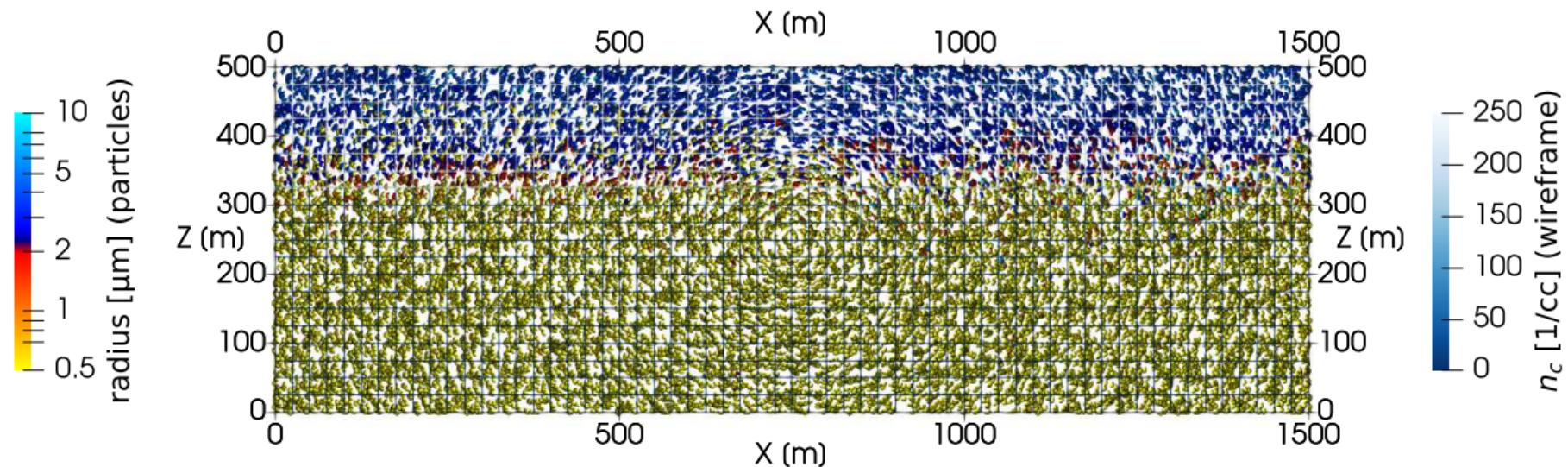
Particle-based μ -physics + prescribed-flow: spin-up

Time: 390 s (spin-up till 600.0 s)



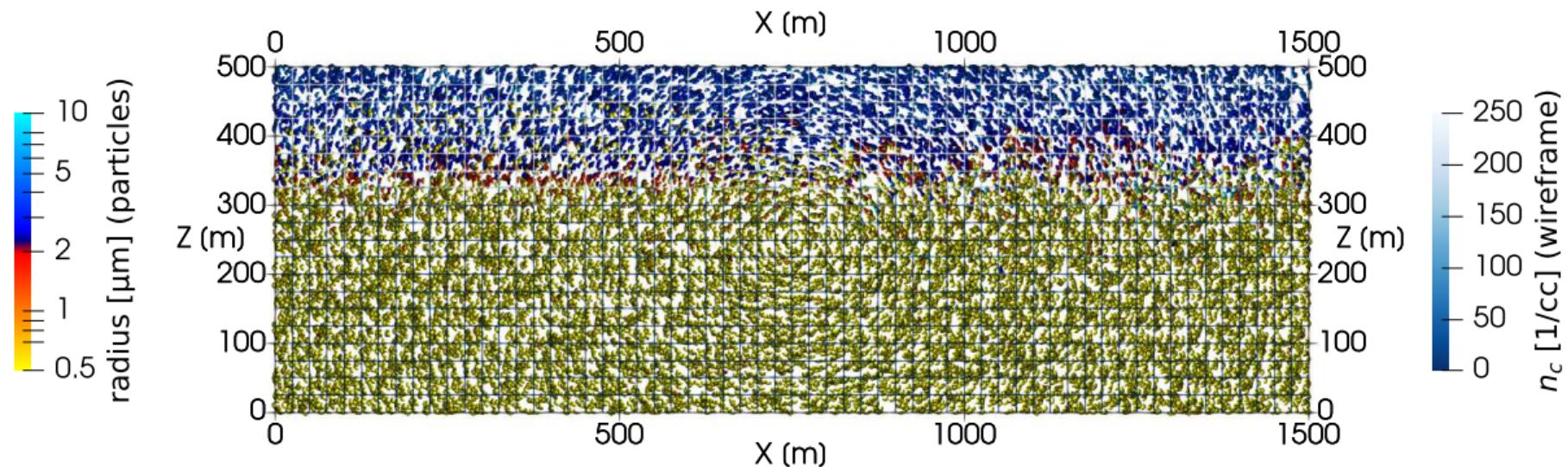
Particle-based μ -physics + prescribed-flow: spin-up

Time: 420 s (spin-up till 600.0 s)



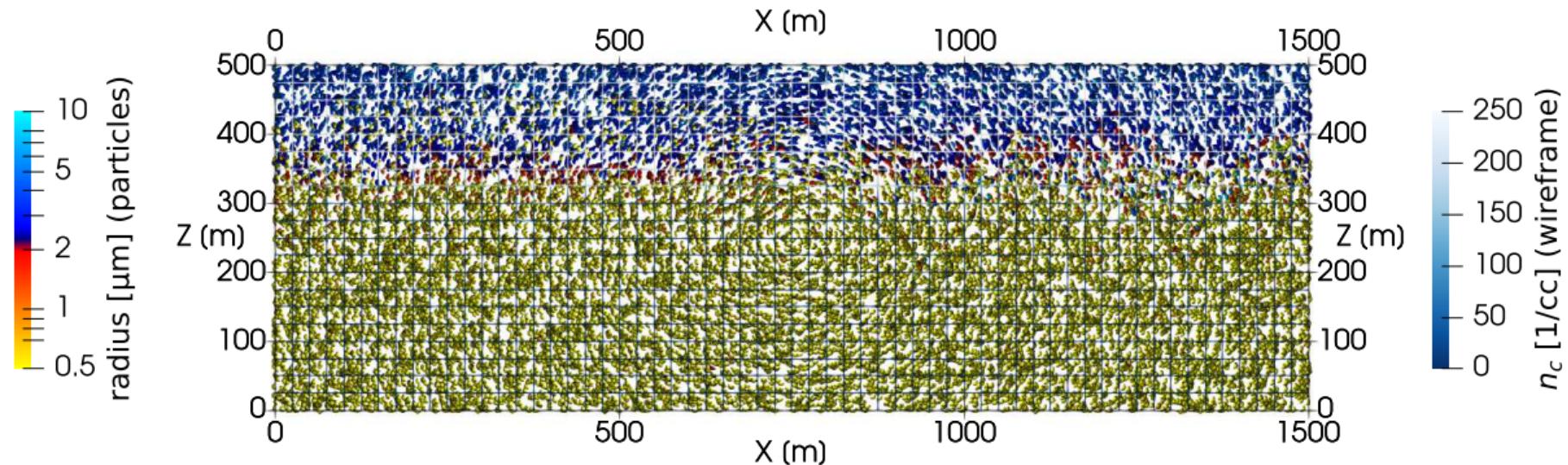
Particle-based μ -physics + prescribed-flow: spin-up

Time: 450 s (spin-up till 600.0 s)



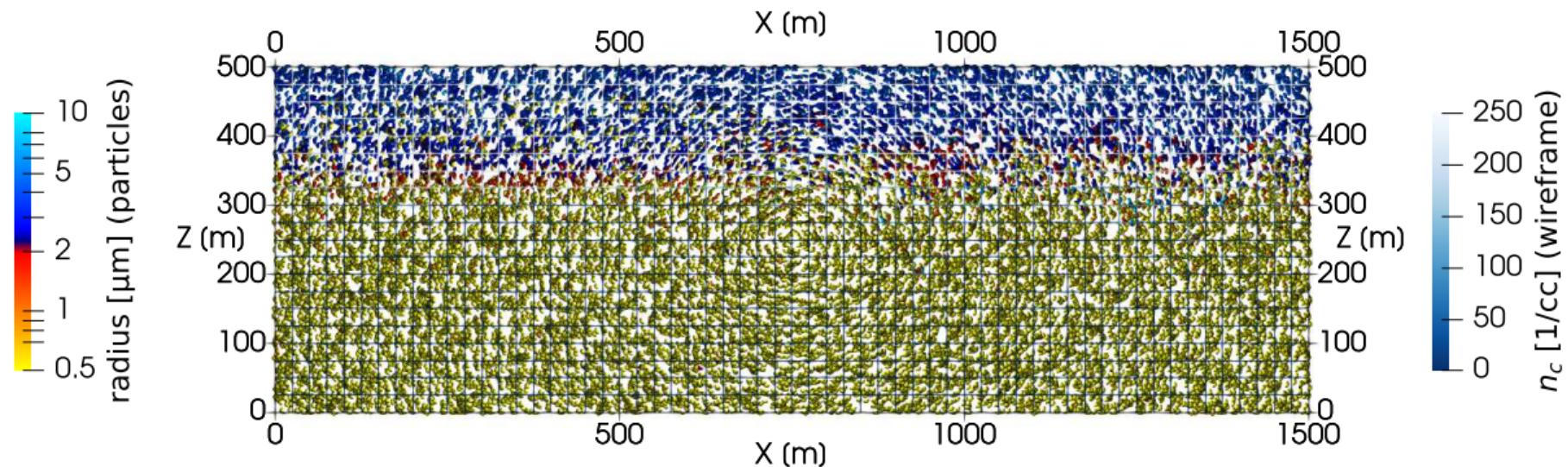
Particle-based μ -physics + prescribed-flow: spin-up

Time: 480 s (spin-up till 600.0 s)



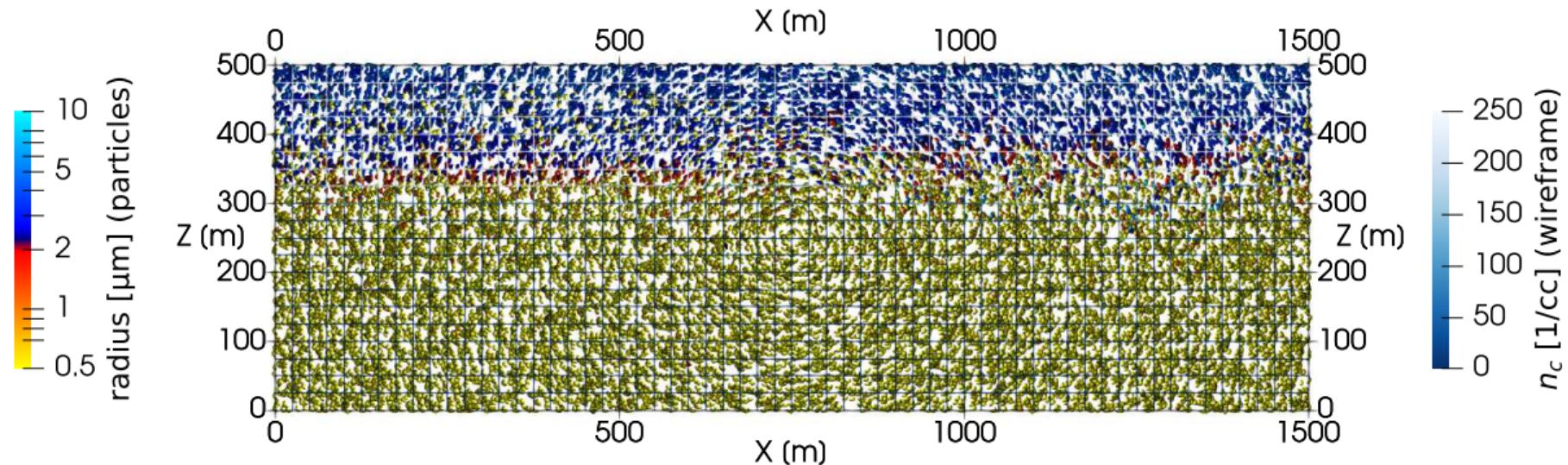
Particle-based μ -physics + prescribed-flow: spin-up

Time: 510 s (spin-up till 600.0 s)



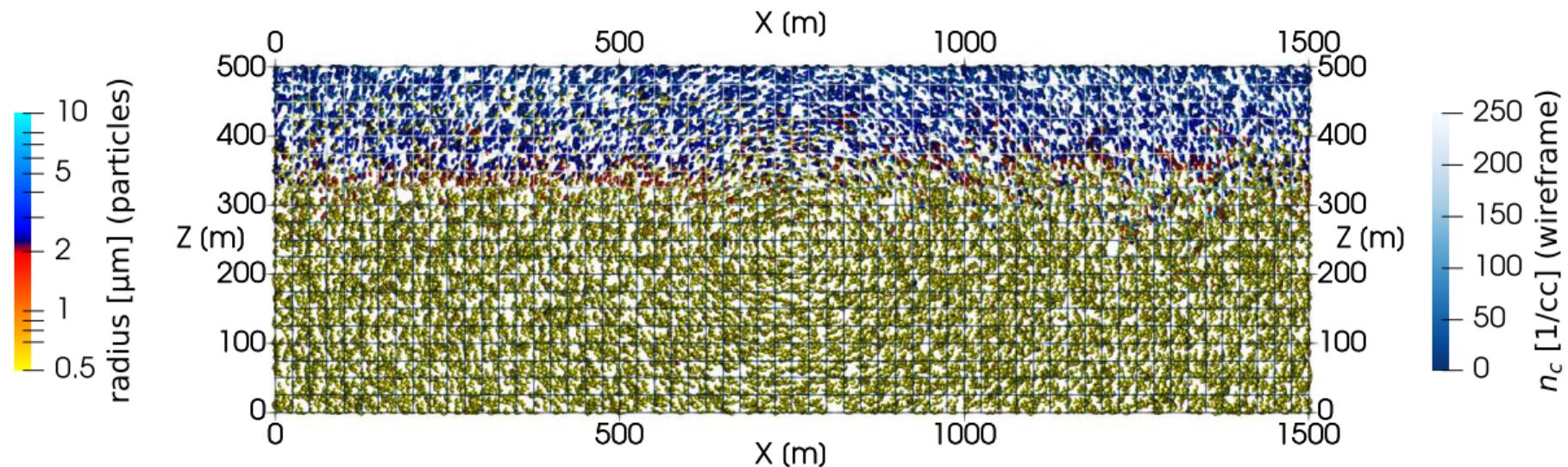
Particle-based μ -physics + prescribed-flow: spin-up

Time: 540 s (spin-up till 600.0 s)



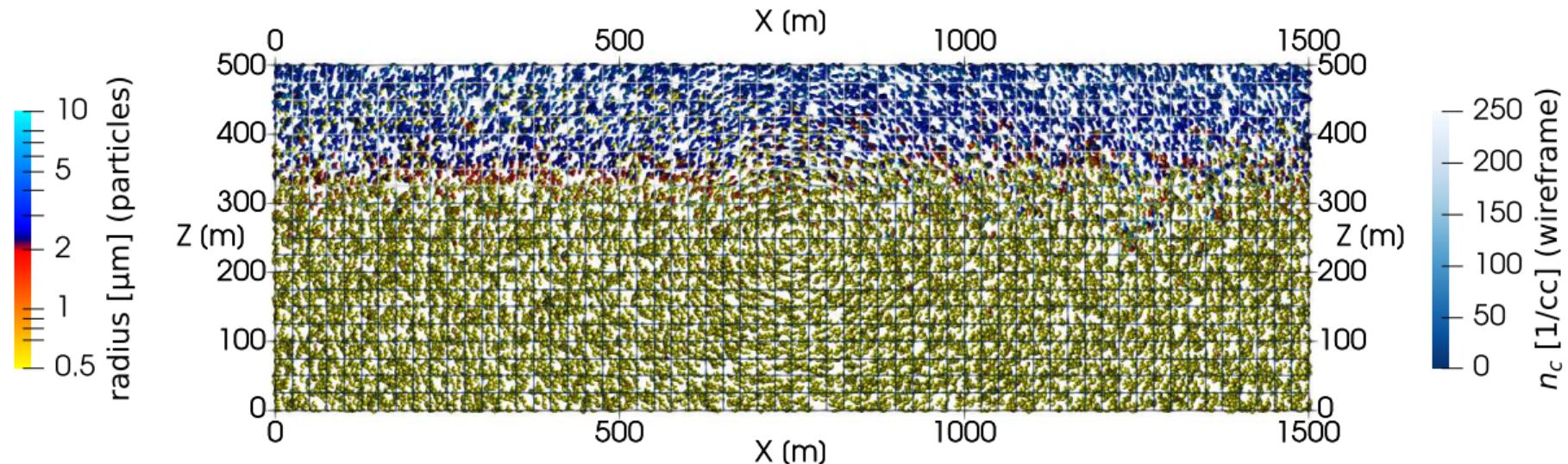
Particle-based μ -physics + prescribed-flow: spin-up

Time: 570 s (spin-up till 600.0 s)



Particle-based μ -physics + prescribed-flow: spin-up

Time: 600 s (spin-up till 600.0 s)



Shima, Sato, Hashimoto & Misumi 2020 (GMD):

Predicting the morphology of ice particles in deep convection using the super-droplet method

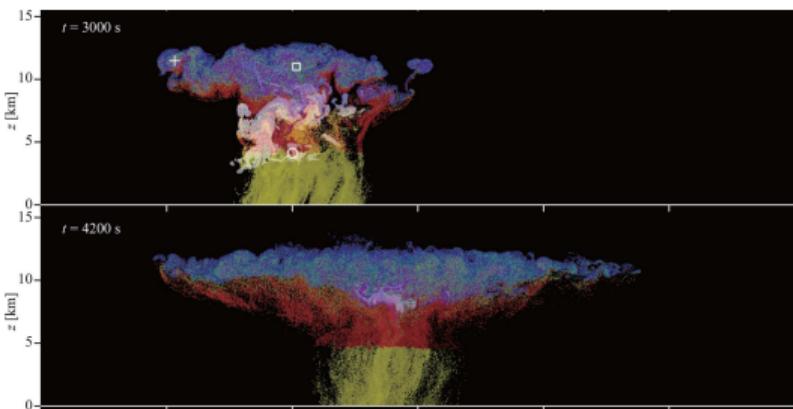
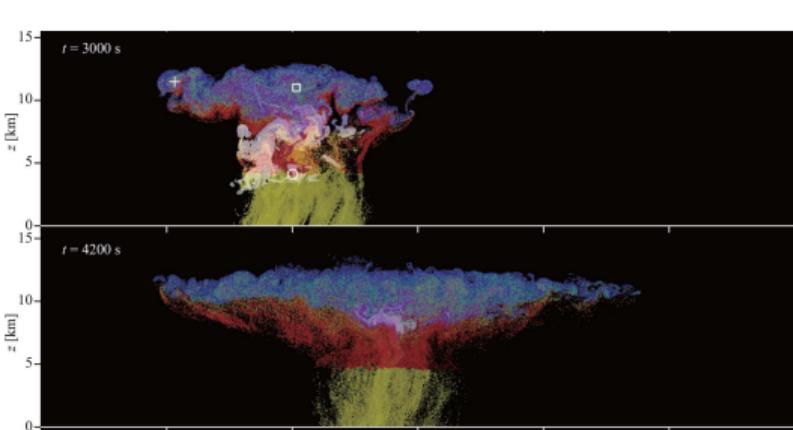


Figure 1. Typical realization of CTRL cloud spatial structures at $t = 2040, 2460, 3000, 4200$, and 5400 s. The mixing ratio of cloud water, rainwater, cloud ice, graupel, and snow aggregates are plotted in fading white, yellow, blue, red, and green, respectively. The symbols indicate examples of unrealistic predicted ice particles (Sects. 7.3 and 9.1). See also Movie 1 in the video supplement.

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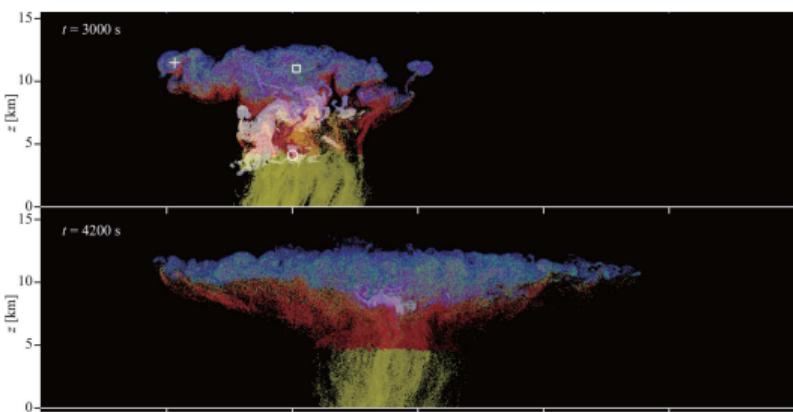


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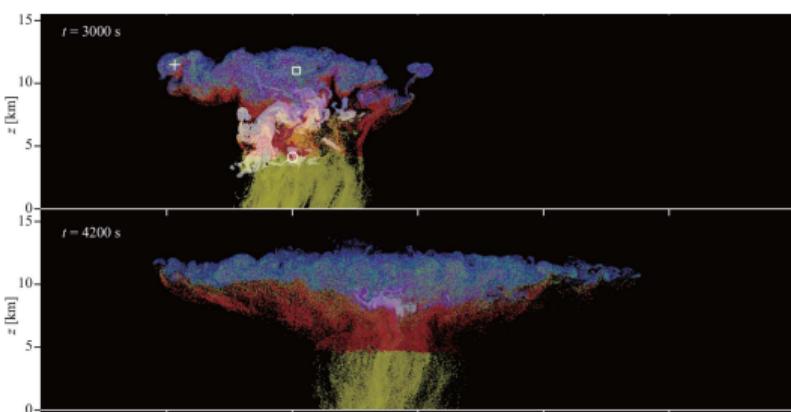


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- ▶ particle-resolved processes:
 - advection and sedimentation
 - homogeneous and immersion freezing (singular)
 - melting
 - condensation and evaporation (incl. CCN [de]activation)
 - deposition and sublimation
 - collisions (coalescence, riming, aggregation, washout)

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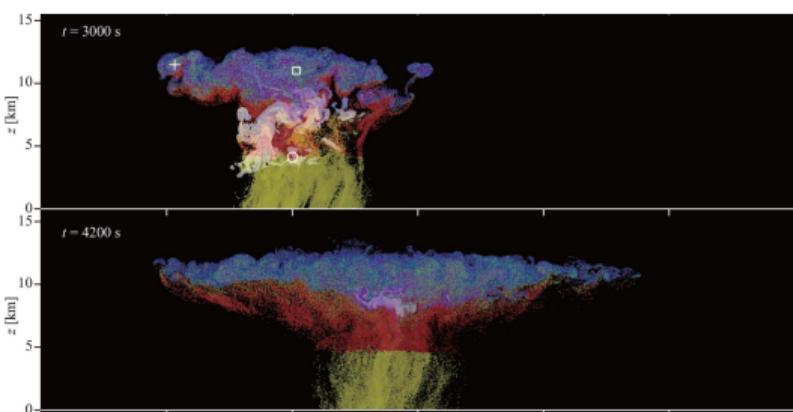


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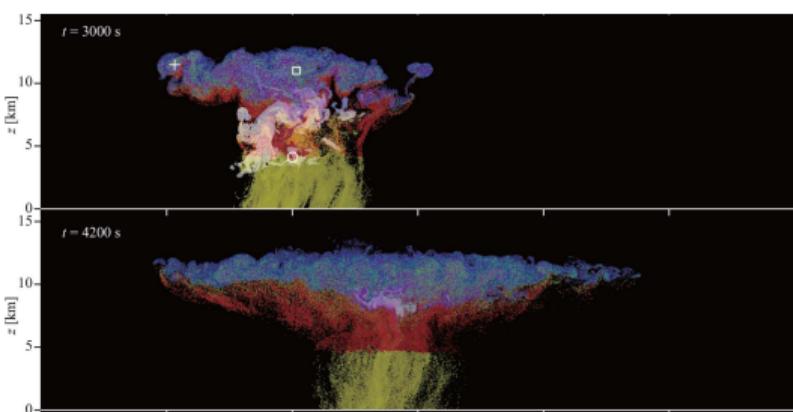
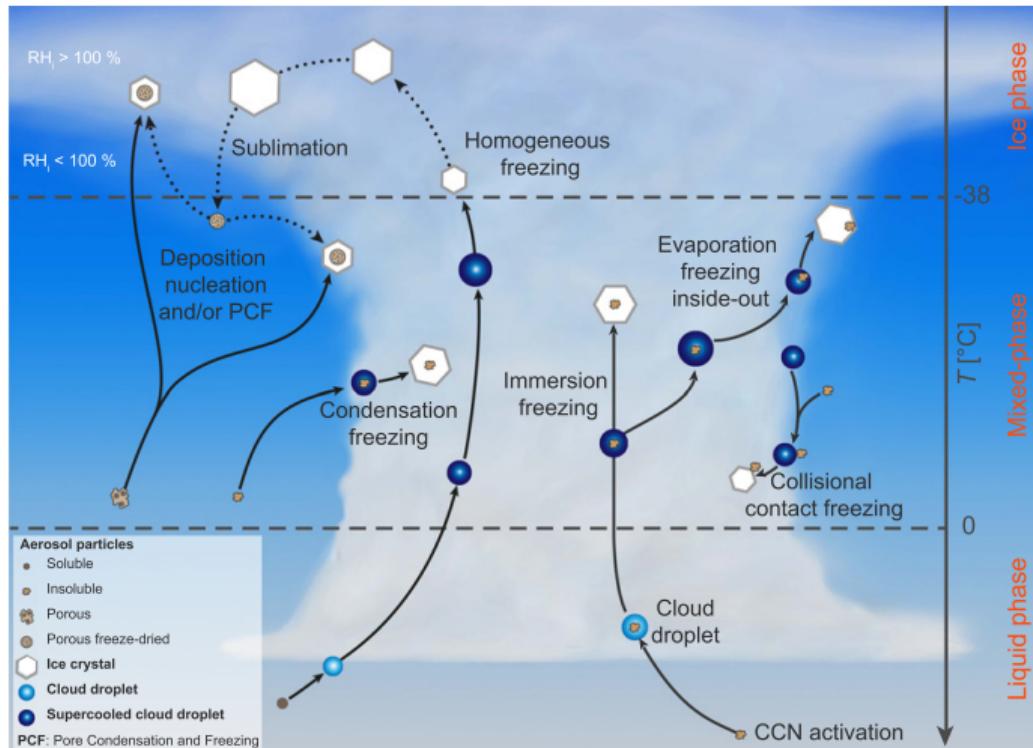


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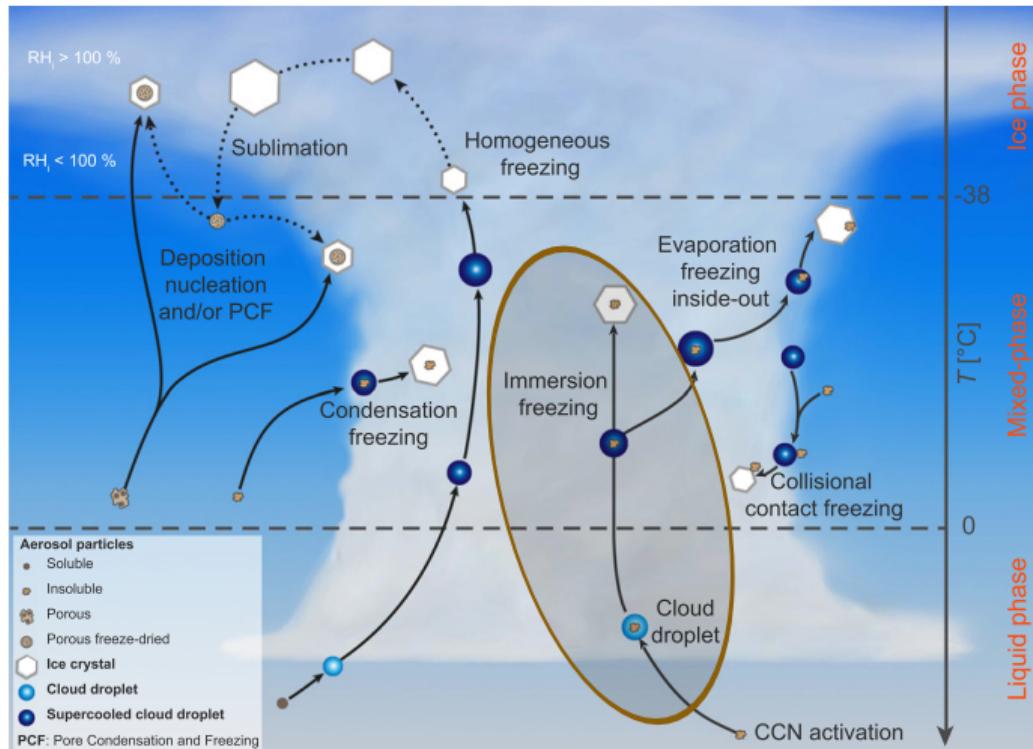
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Immersion freezing and other ice crystal formation pathways in clouds



Kanji et al. 2017, graphics F. Mahrt, <https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0006.1>

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Immersion freezing: bacteria and the Olympics

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2016JD025251

Key Points:

- Very ice active Snomax protein aggregates are fragile and their ice nucleation ability decreases over months of freezer storage
 - Partitioning of ice active protein aggregates into the immersion oil reduces the droplet's measured freezing temperature
- Freezing is measured in the core of

The unstable ice nucleation properties of Snomax® bacterial particles

Michael Polen¹, Emily Lawlis¹, and Ryan C. Sullivan¹

¹Center for Atmospheric Particle Studies, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

Abstract Snomax® is often used as a surrogate for biological ice nucleating particles (INPs) and has recently been proposed as an INP standard for evaluating ice nucleation methods. We have found the immersion freezing properties of Snomax particles to be substantially unstable, observing a loss of ice nucleation ability

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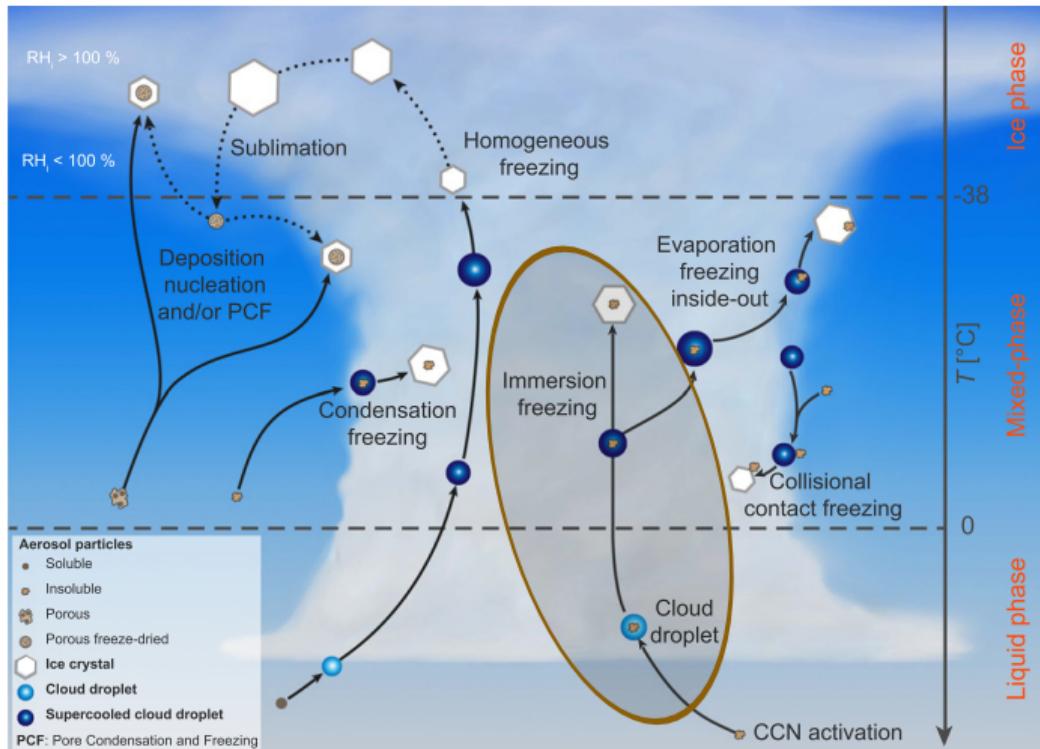
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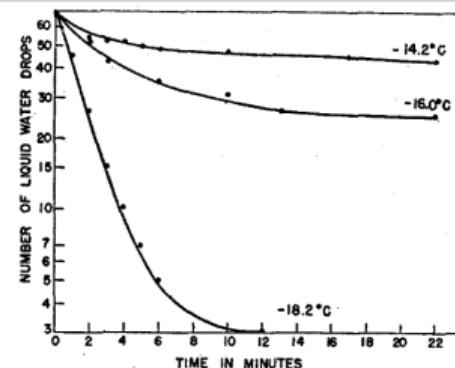


<https://www.reuters.com/markets/commodities/making-snow-stick-wind-challenges-winter-games-slope-makers-2021-11-29/>

Immersion freezing and other ice crystal formation pathways in clouds

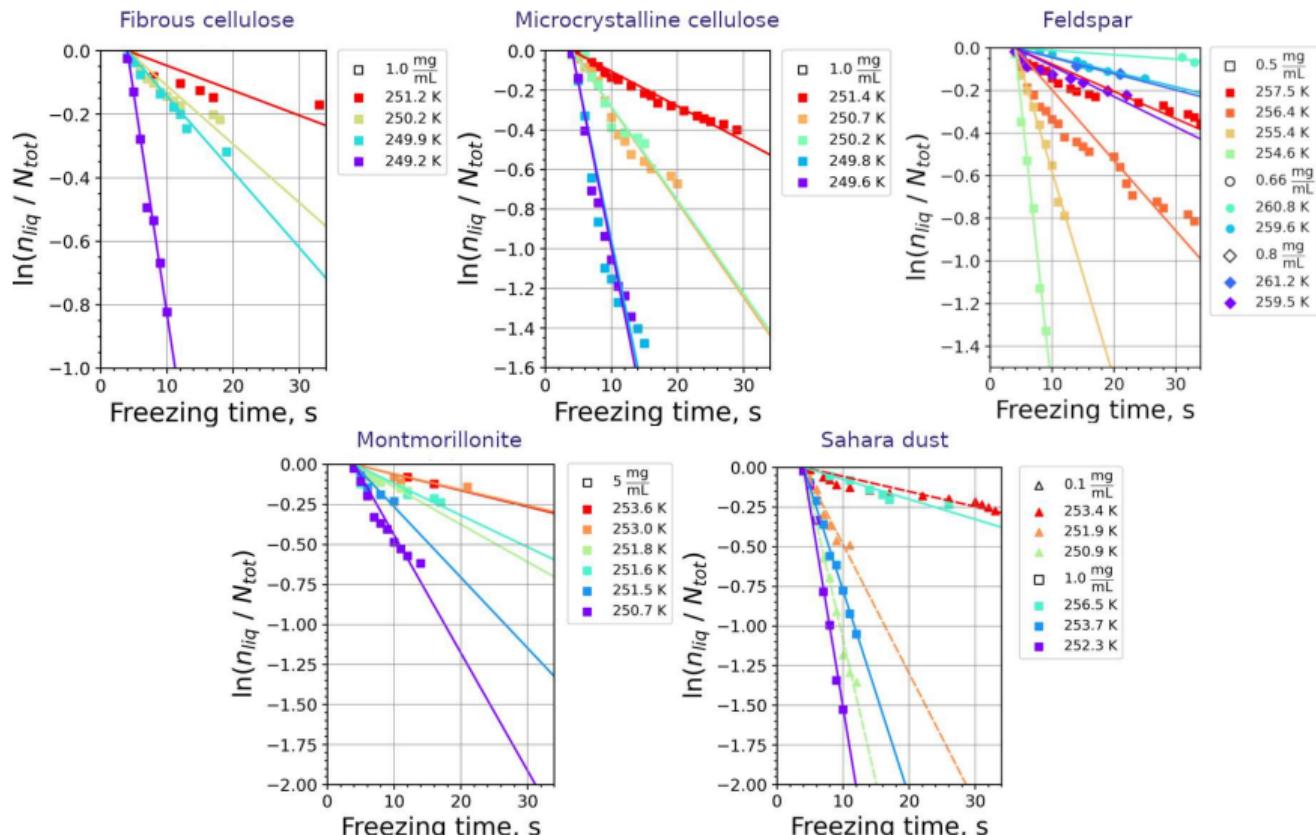


Vonnegut 1948 (J. Colloid Sci.)



Fraction of water drops remaining unfrozen as a function of time.

Szakáll et al. 2021, ACP 21: isothermal experiments



Heterogeneous Nucleations is a Stochastic Process

by

J. S. MARSHALL

McGill University, Montreal, Canad.

*Presented at the International Congress on the Physics of Clouds (Hailstorms)
at Verona 9-13 August 1960.*

Poissonian model of freezing & Ice Nucleation Active Sites (INAS)

theory (in modern notation)

(Bigg '53, Langham & Mason '58, Carte '59, Marshall '61)

Poisson counting process with rate r :

$$P^*(k \text{ events in time } t) = \frac{(rt)^k \exp(-rt)}{k!}$$

$$P(\text{one or more events in time } t) = 1 - P^*(k = 0, t)$$

$$\ln(1 - P) = -rt$$

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introducing $J_{\text{het}}(T)$, $T(t)$ and INP surface A :

$$\ln(1 - P(A, t)) = -A \underbrace{\int_0^t J_{\text{het}}(T(t')) dt'}$$

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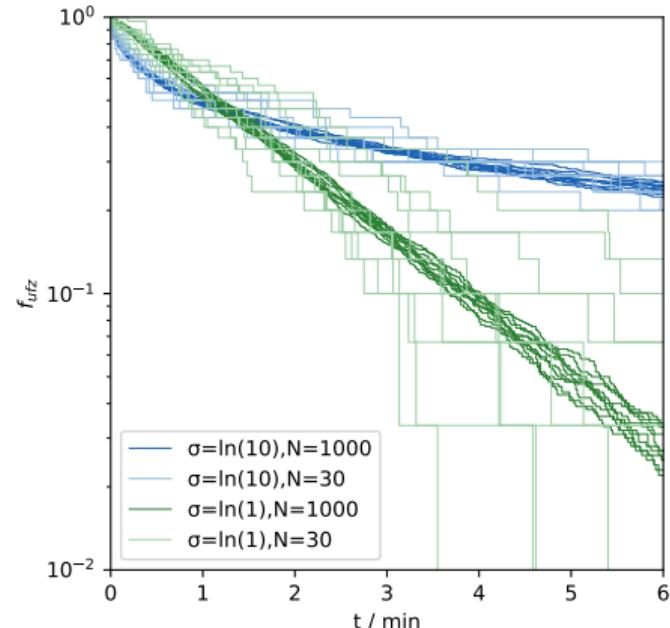
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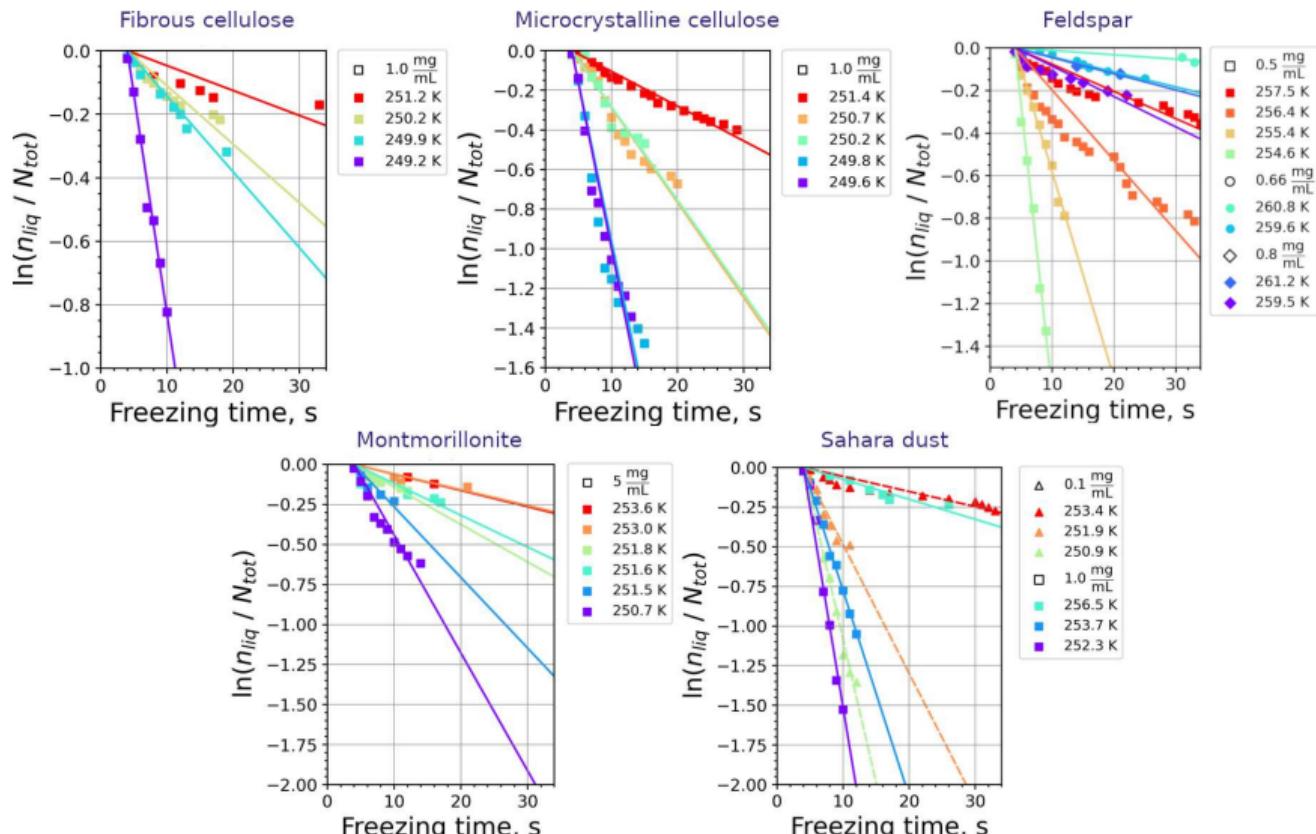
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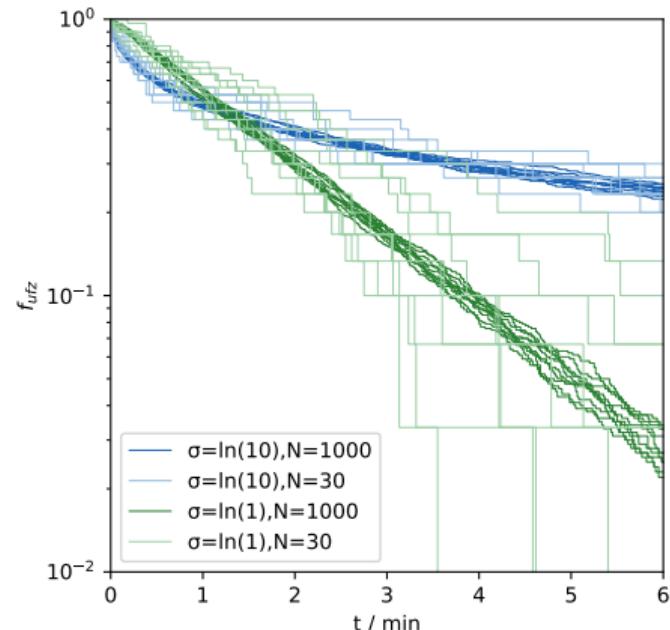
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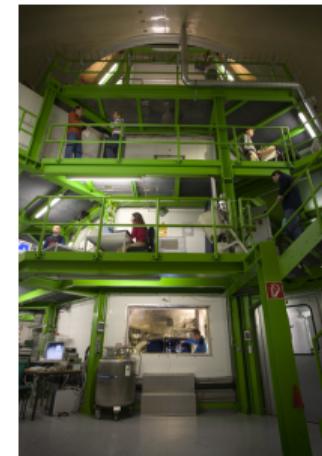
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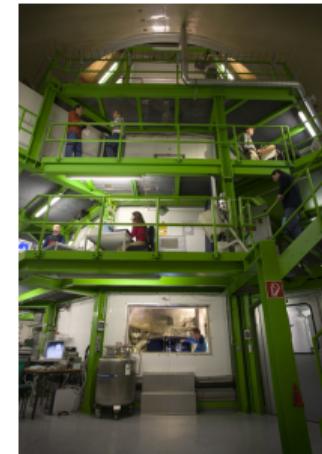
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AIDA @ KIT



(<https://www.imk-aaf.kit.edu/>, photo: KIT/Ottmar Möhler)

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AIDA cooling rate: ca. $0.5\text{ K}/\text{min}$

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"Interpretations of the experimental results face considerable difficulties ... two separate ways of interpreting the same observations; one assigned primacy to time the other emphasized the temperature-dependent impacts of the impurities ... dichotomy – the stochastic and singular models"

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 Atmospheric Chemistry and Physics

Heterogeneous ice nucleation: exploring the transition from stochastic to singular freezing behavior

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www.atmos-chem-phys.net/11/8767/2011/
doi:10.5194/acp-11-8767-2011
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npj | climate and atmospheric science

Article | [Open access](#) | Published: 17 January 2020

Stochastic nucleation processes and substrate abundance explain time-dependent freezing in supercooled droplets

D. Niedermeyer¹, R. A. Shaw², S. Hartmann¹, H. Wex¹, T. Clauss¹, J. Voigtlander¹, and F. Stratmann¹

¹Leibniz Institute for Tropospheric Research, 04318 Leipzig, Germany
²Dept. of Physics, Michigan Technological University, Houghton, Michigan 49931, USA

Received: 24 June 2011 – Accepted: 19 August 2011 – Published in Atmos. Chem. Phys. Discuss.: 28 January 2011
Revised: 24 June 2011 – Accepted: 19 August 2011 – Published in Atmos. Chem. Phys. Discuss.: 30 August 2011

Minimal cooling rate dependence of ice nuclei activity in the immersion mode

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 10,201–10,214, 2013
DOI: 10.1002/jgrd.50253

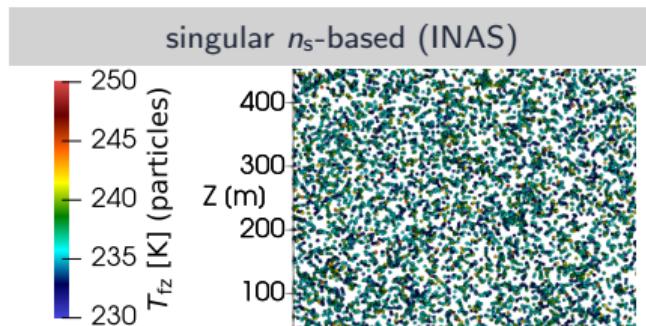
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Received 12 April 2013; revised 4 September 2013; accepted 5 September 2013; published 23 September 2013.

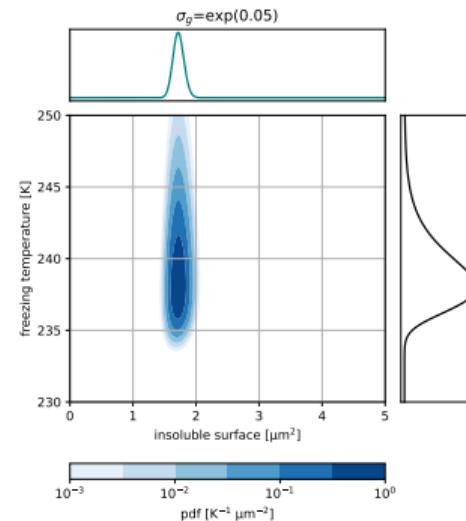
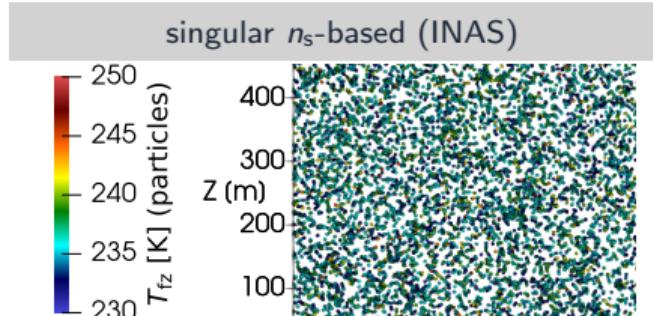
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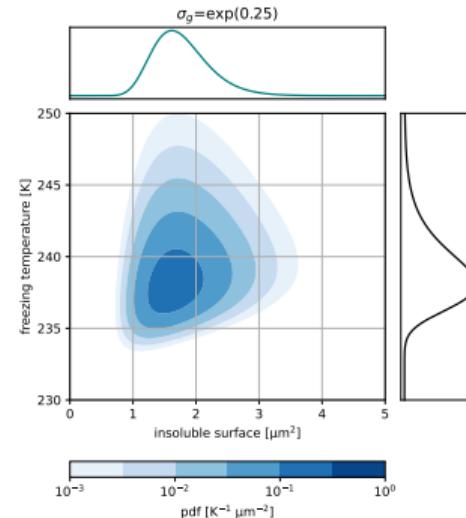
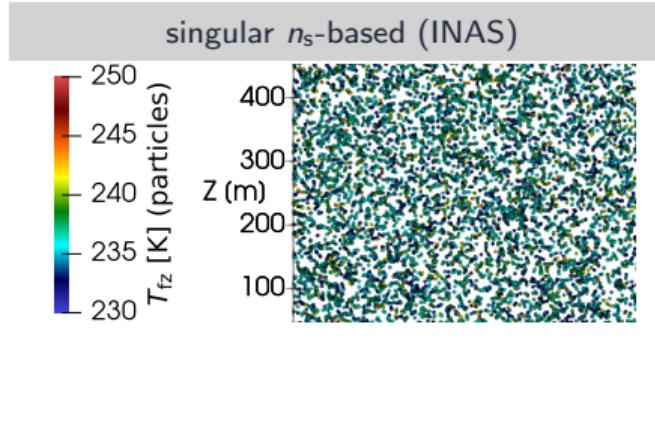
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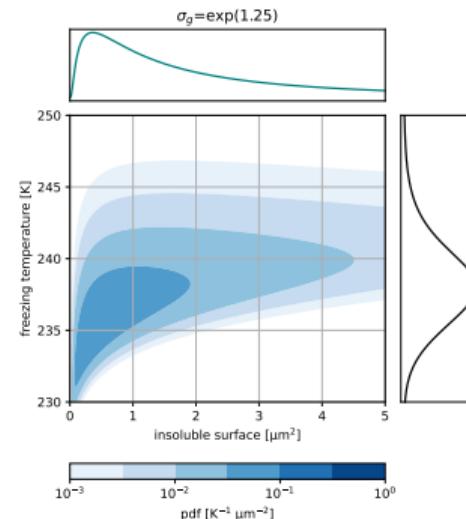
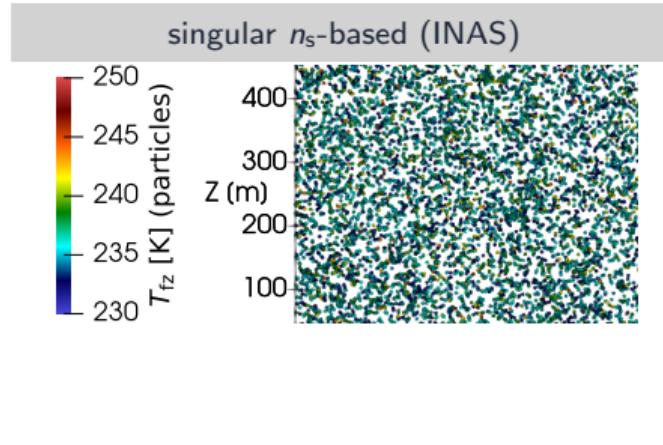
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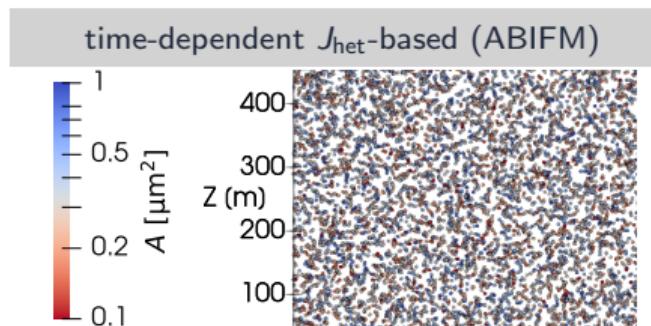
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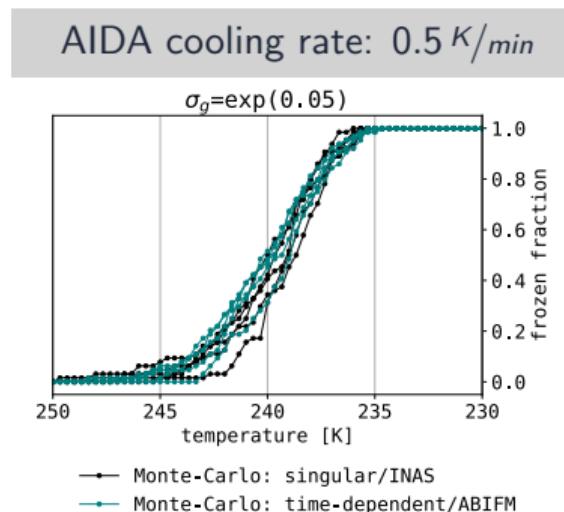
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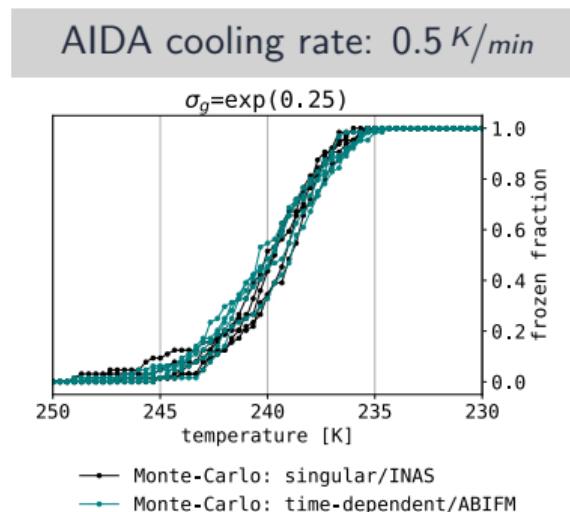
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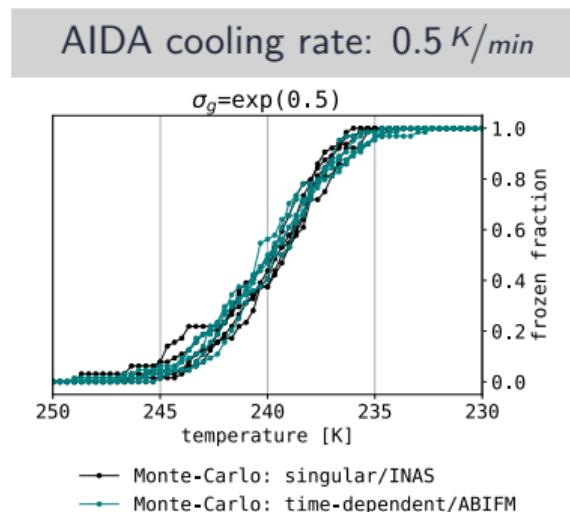
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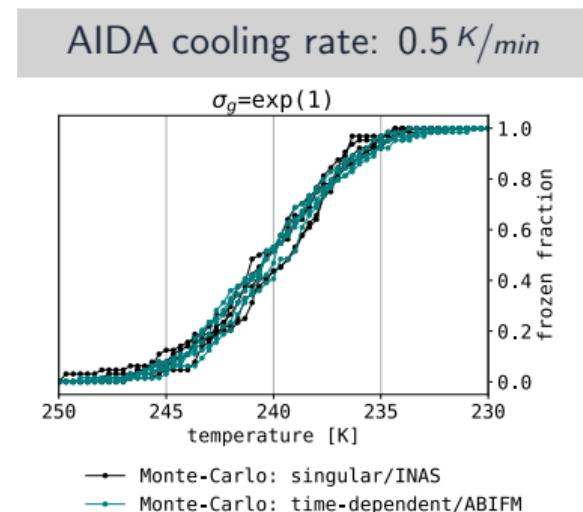
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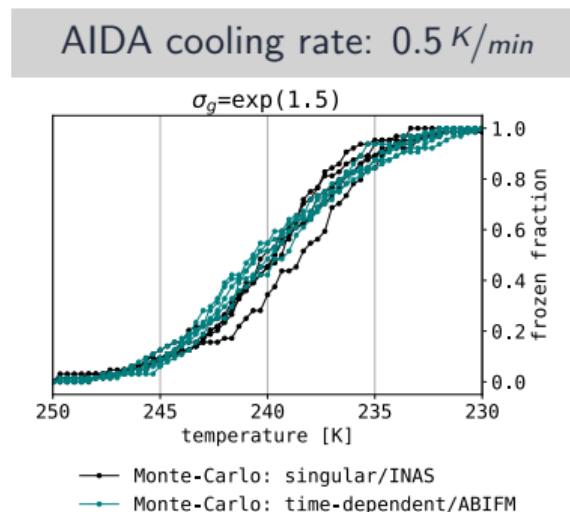
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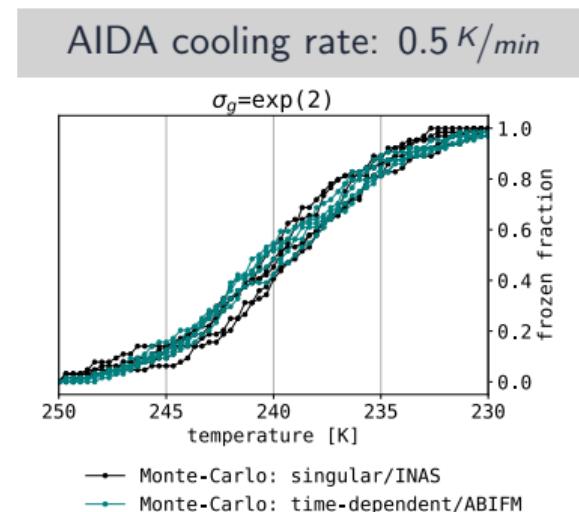
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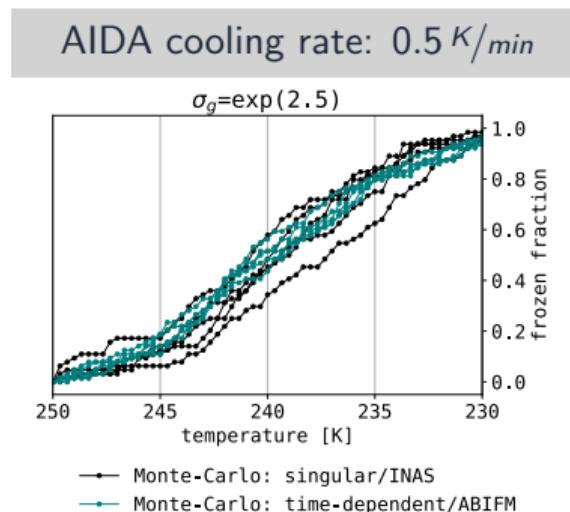
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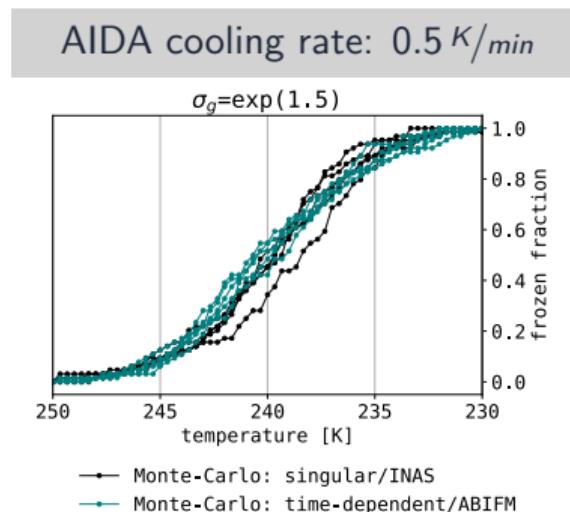
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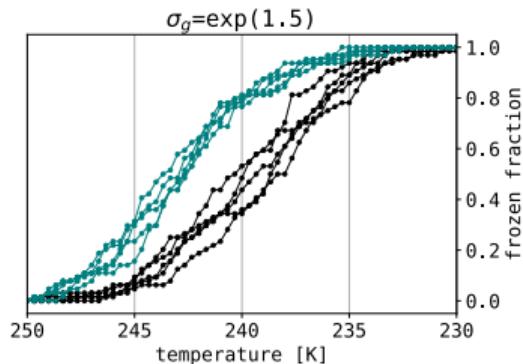


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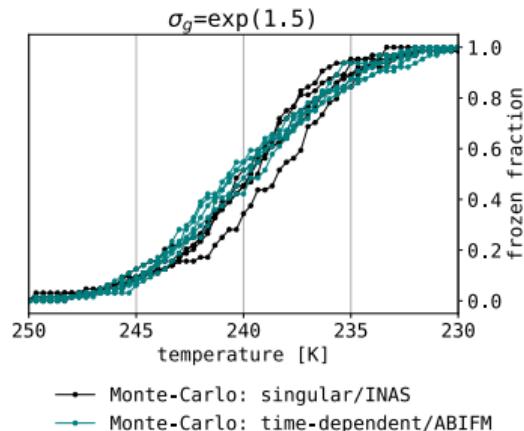
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AIDA cooling rate: 0.5 K/min

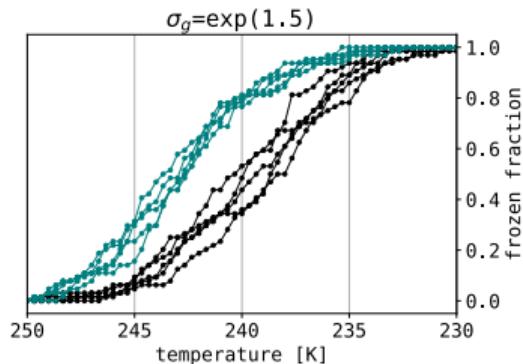


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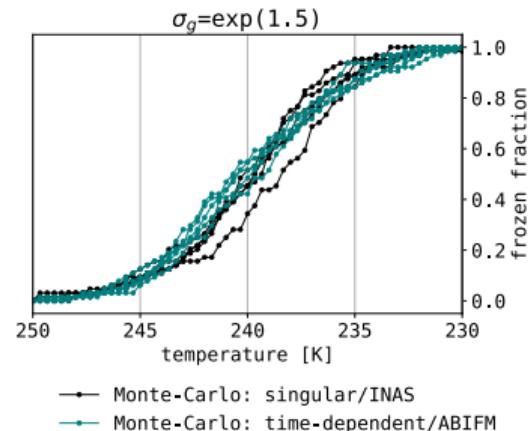
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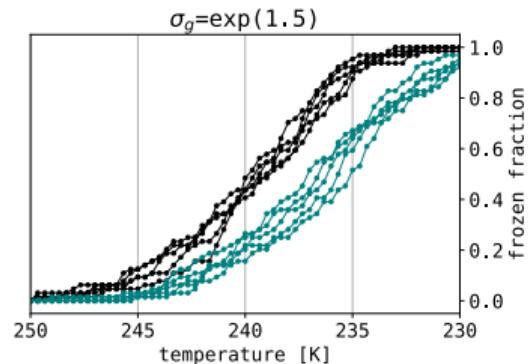
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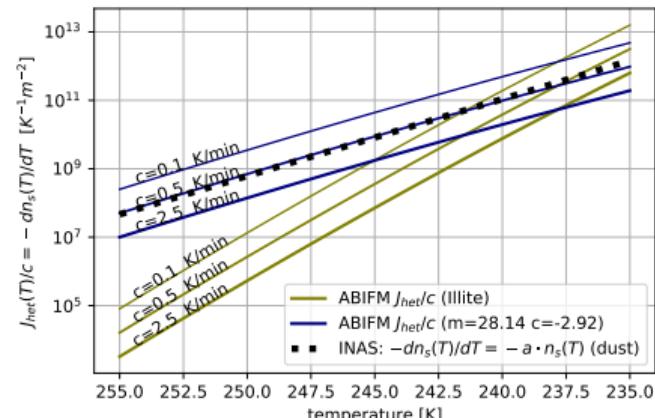
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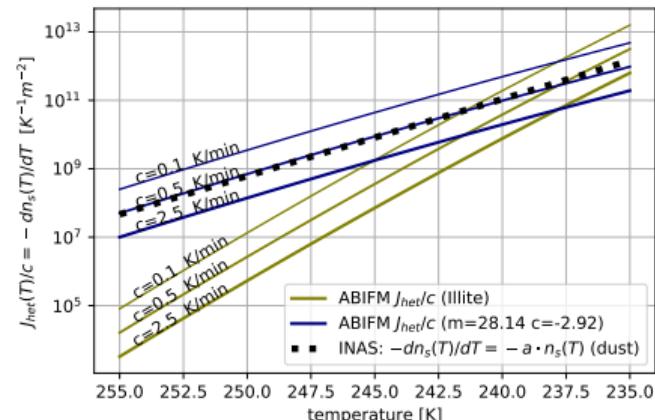
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cf. Vali & Stansbury '66; modified singular model (Vali '94, Murray et al. '11)
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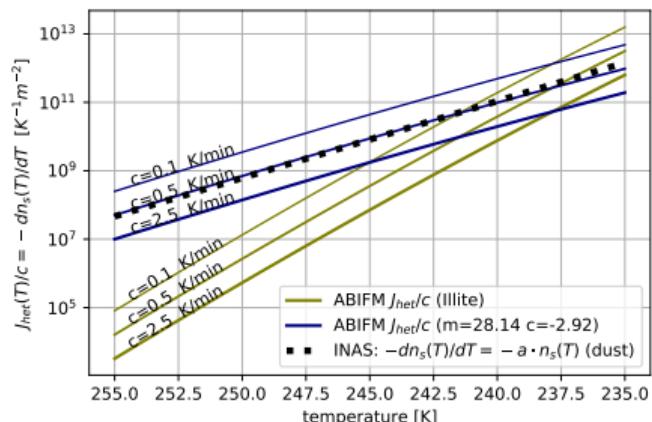
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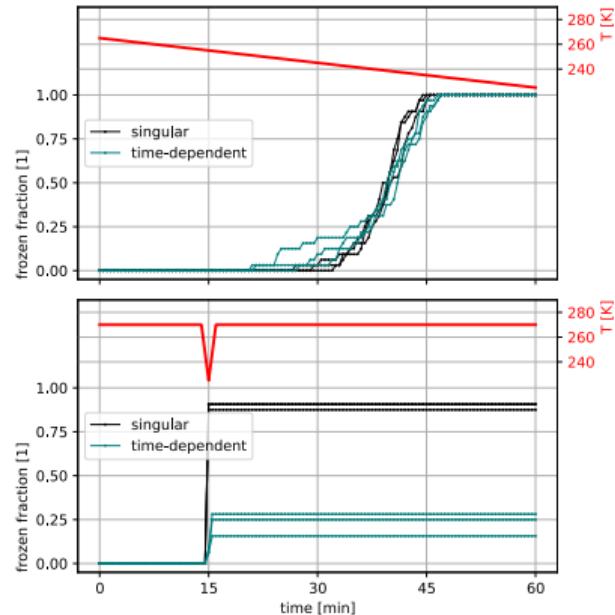
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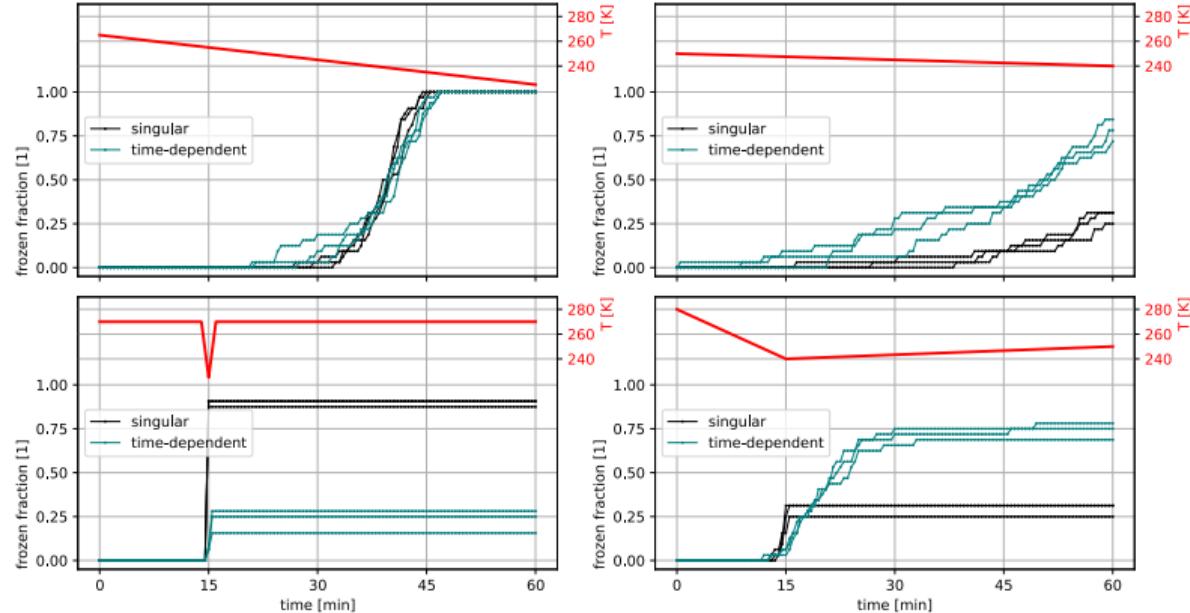


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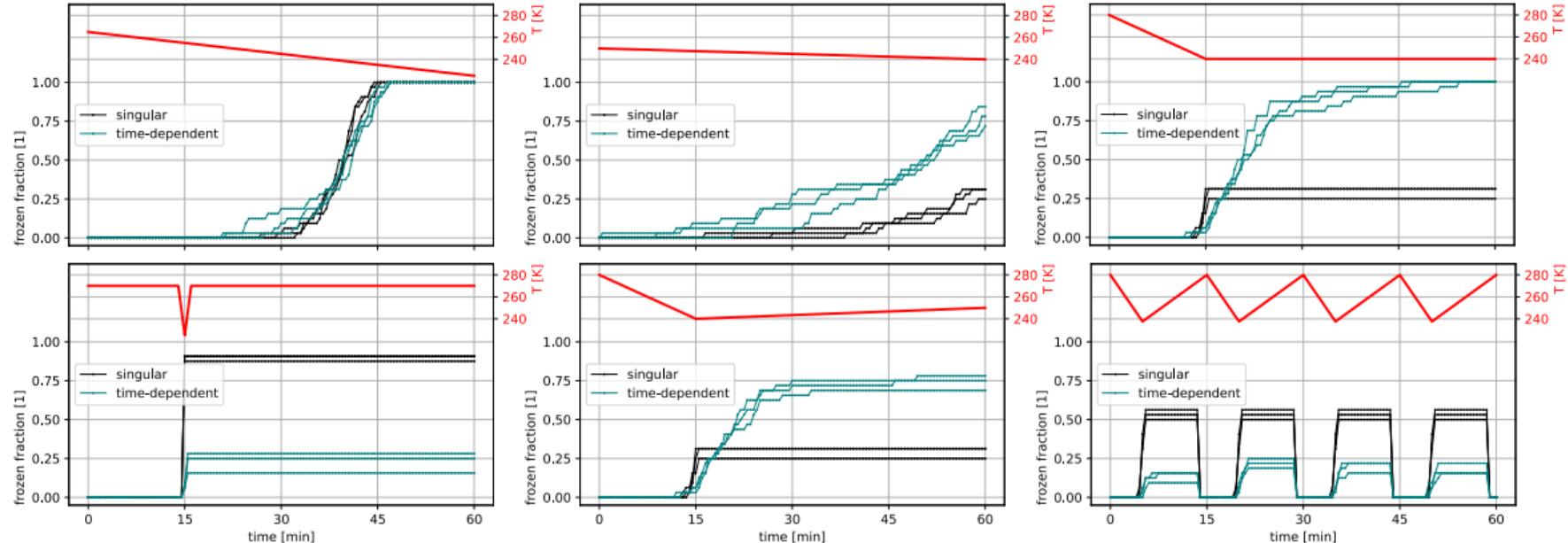
Testing different cooling-rate profiles in a box model



Testing different cooling-rate profiles in a box model

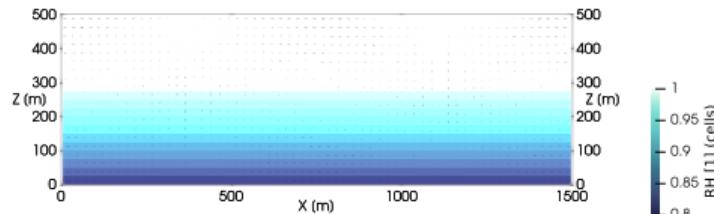


Testing different cooling-rate profiles in a box model



Testing three flow regimes and two immersion freezing representations

$w_{\max} \approx 1/3 \text{ m/s}$

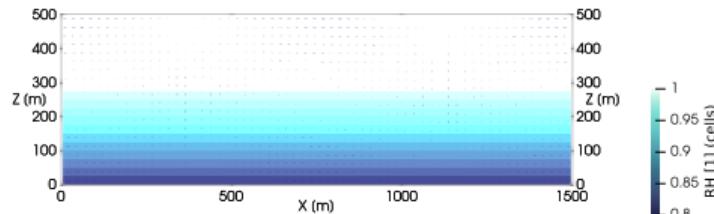


$w_{\max} \approx 1 \text{ m/s}$

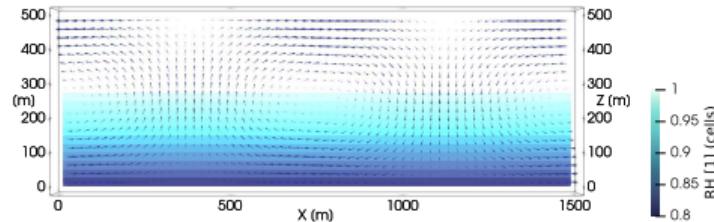
$w_{\max} \approx 3 \text{ m/s}$

Testing three flow regimes and two immersion freezing representations

$w_{\max} \approx 1/3 \text{ m/s}$



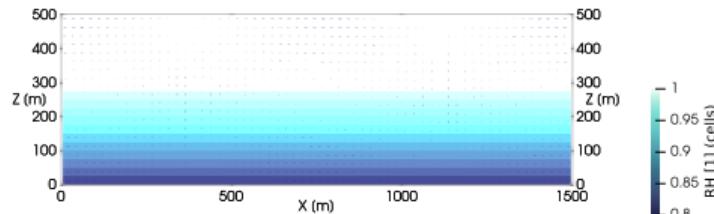
$w_{\max} \approx 1 \text{ m/s}$



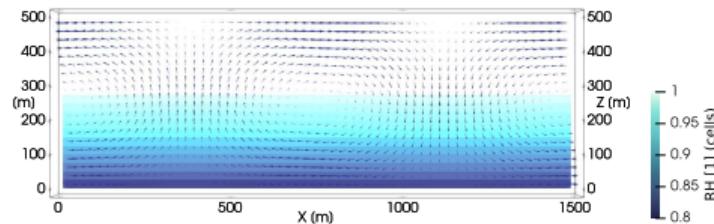
$w_{\max} \approx 3 \text{ m/s}$

Testing three flow regimes and two immersion freezing representations

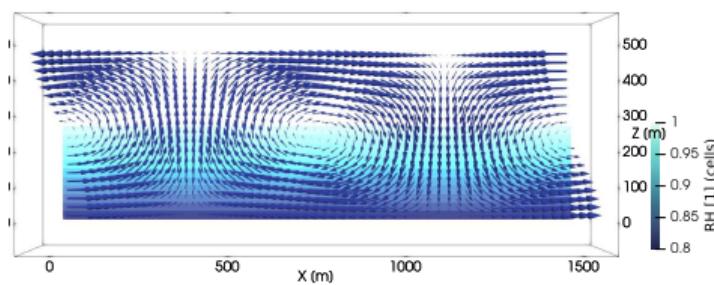
$w_{\max} \approx 1/3 \text{ m/s}$



$w_{\max} \approx 1 \text{ m/s}$

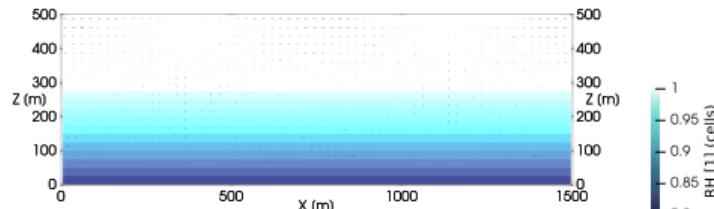


$w_{\max} \approx 3 \text{ m/s}$

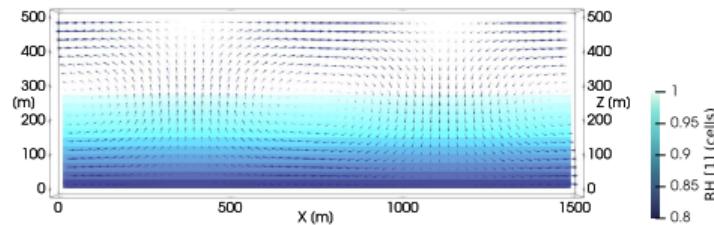


Testing three flow regimes and two immersion freezing representations

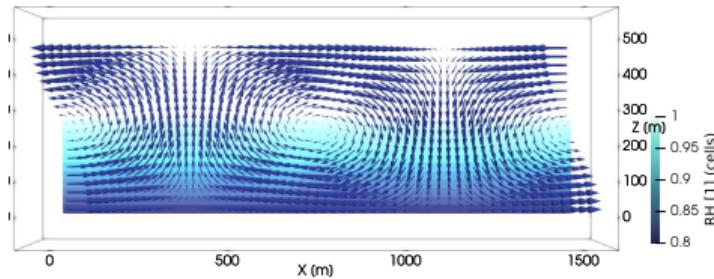
$w_{\max} \approx 1/3 \text{ m/s}$



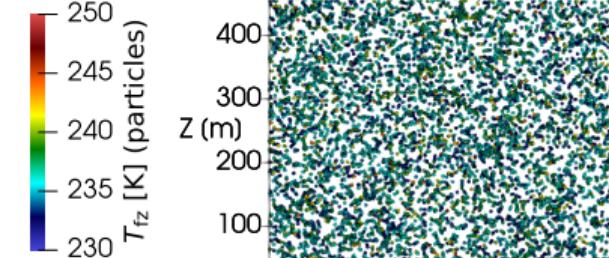
$w_{\max} \approx 1 \text{ m/s}$



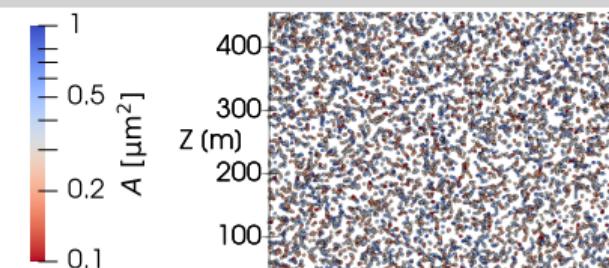
$w_{\max} \approx 3 \text{ m/s}$



singular (INAS)

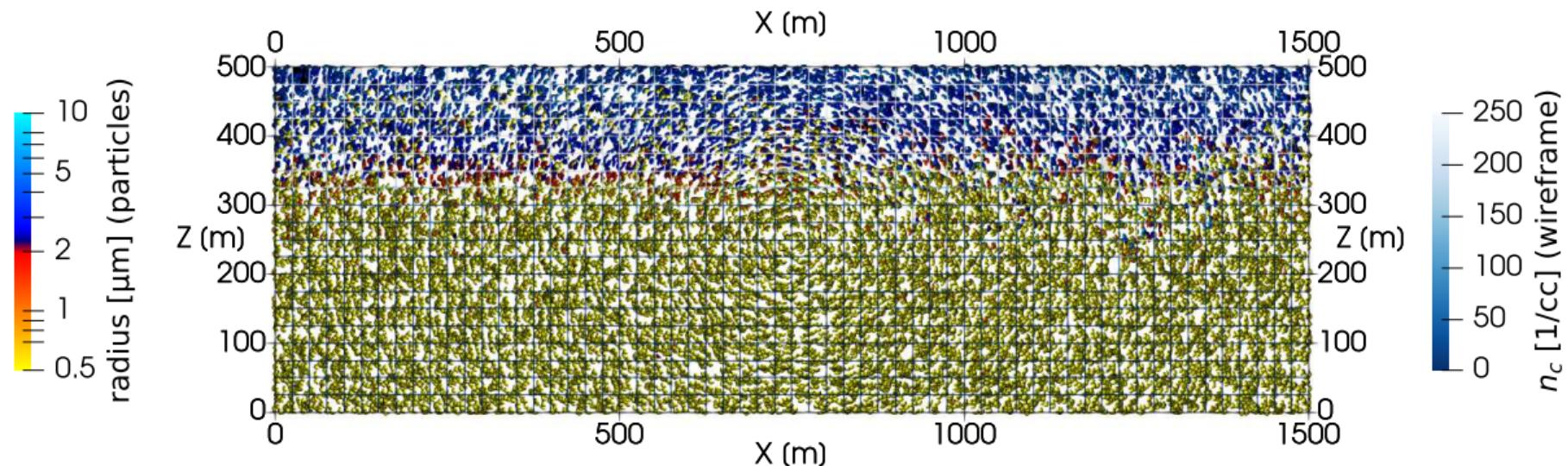


time-dependent (J_{het})



Particle-based μ -physics + prescribed-flow: glaciation

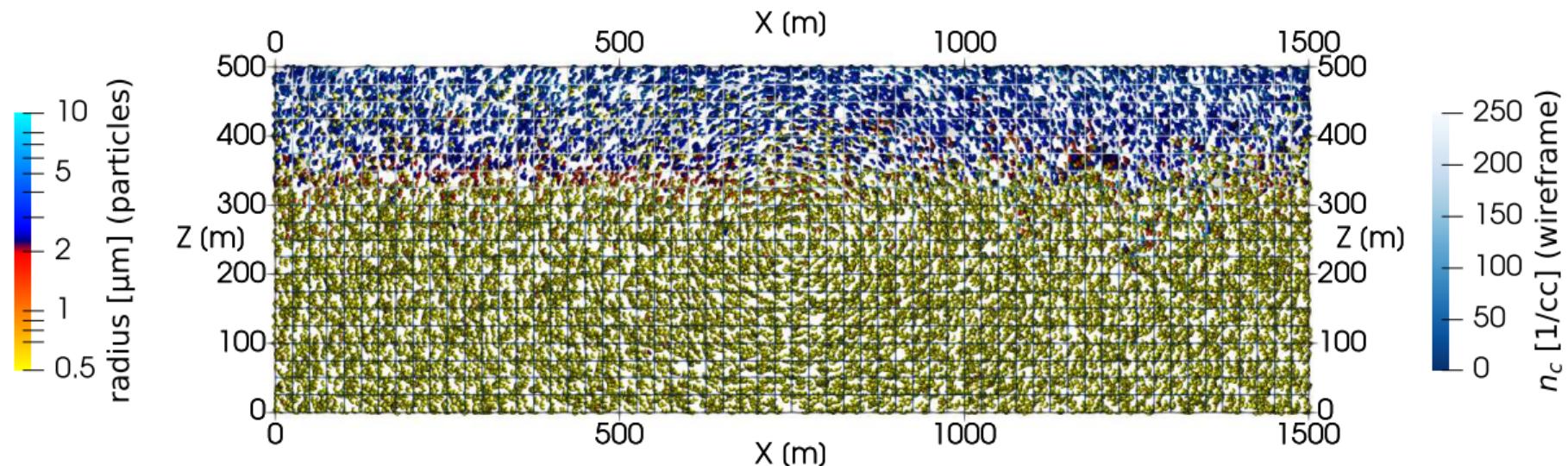
Time: 630 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

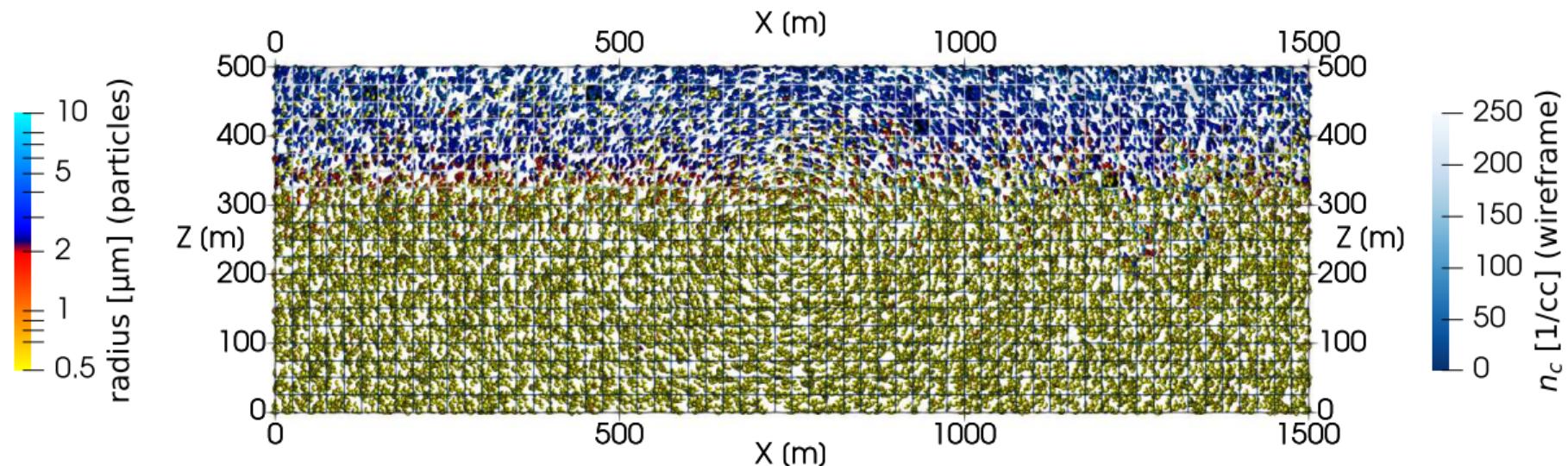
Time: 660 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

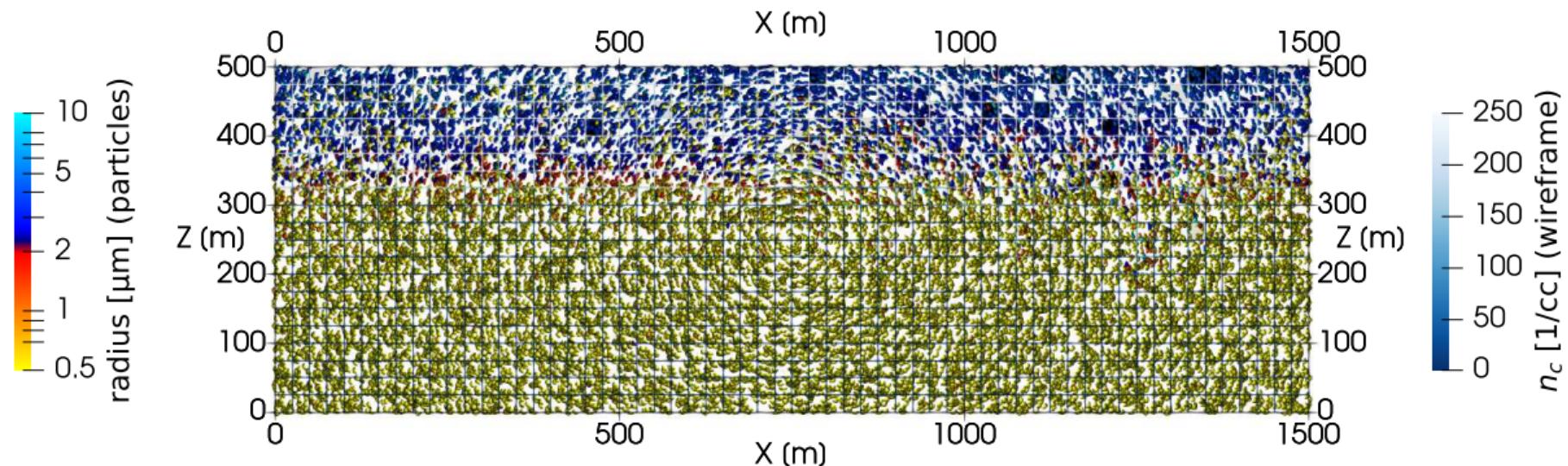
Time: 690 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

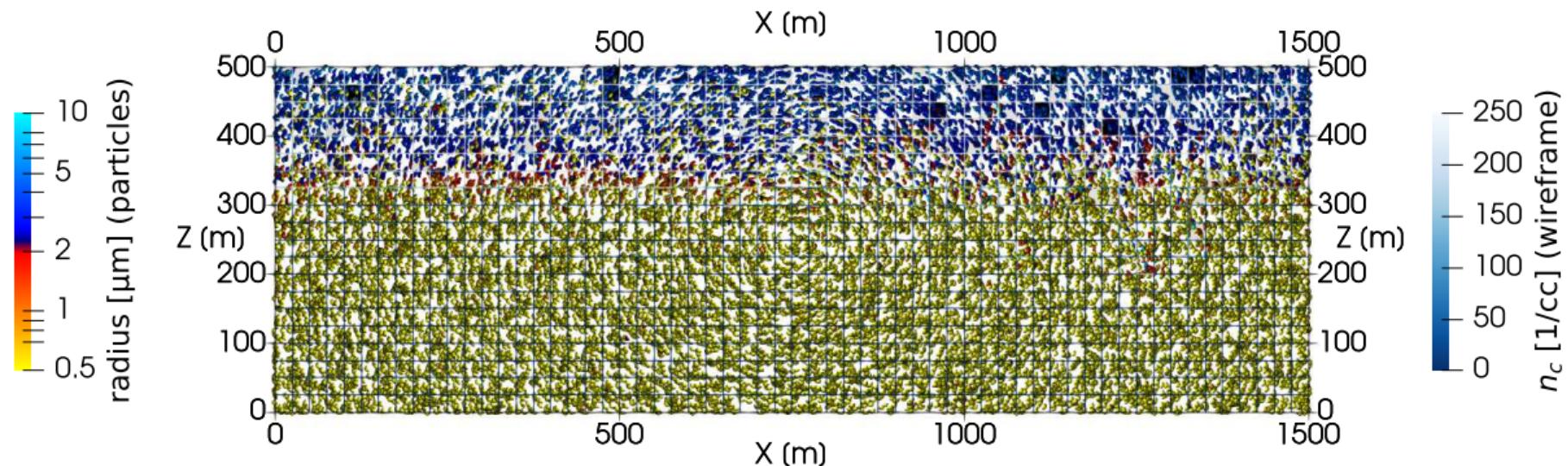
Time: 720 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ }\mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

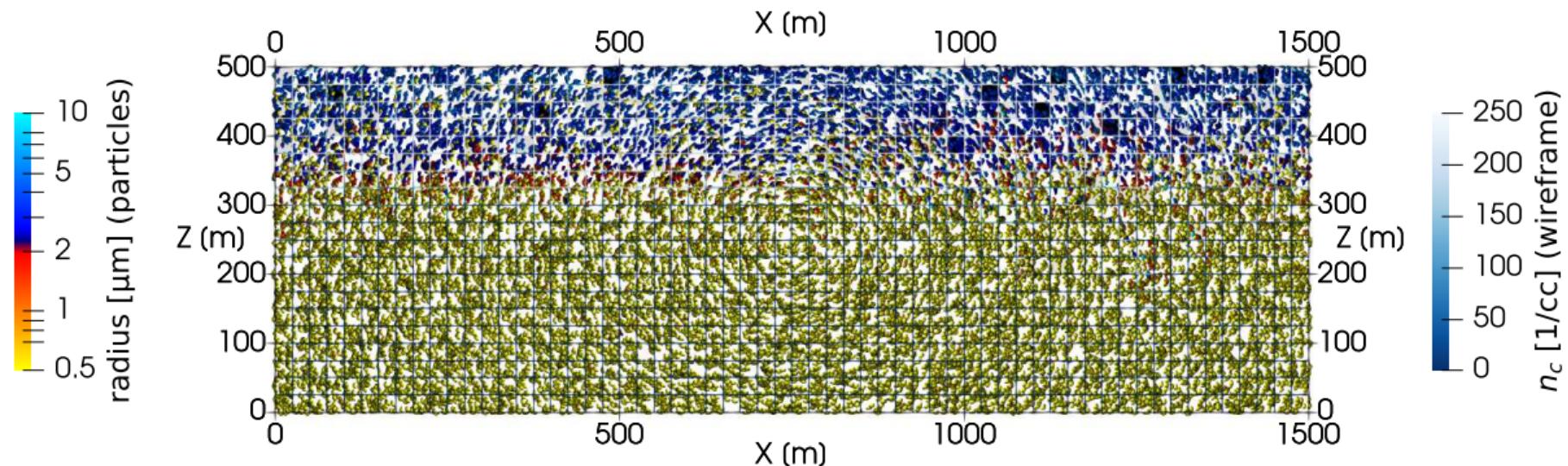
Time: 750 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

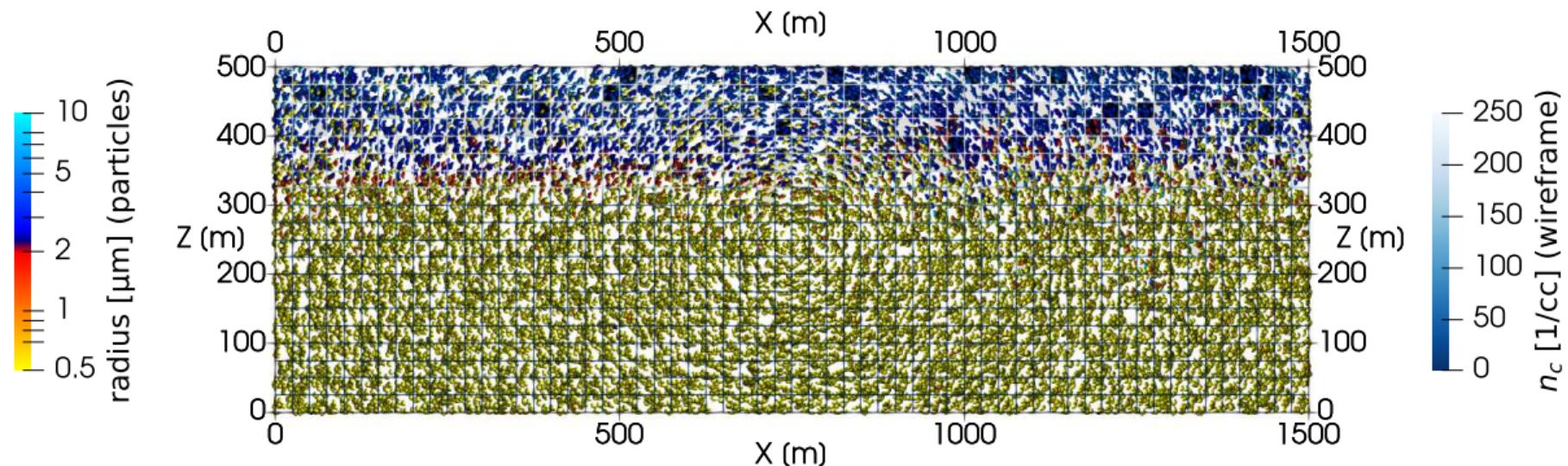
Time: 780 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

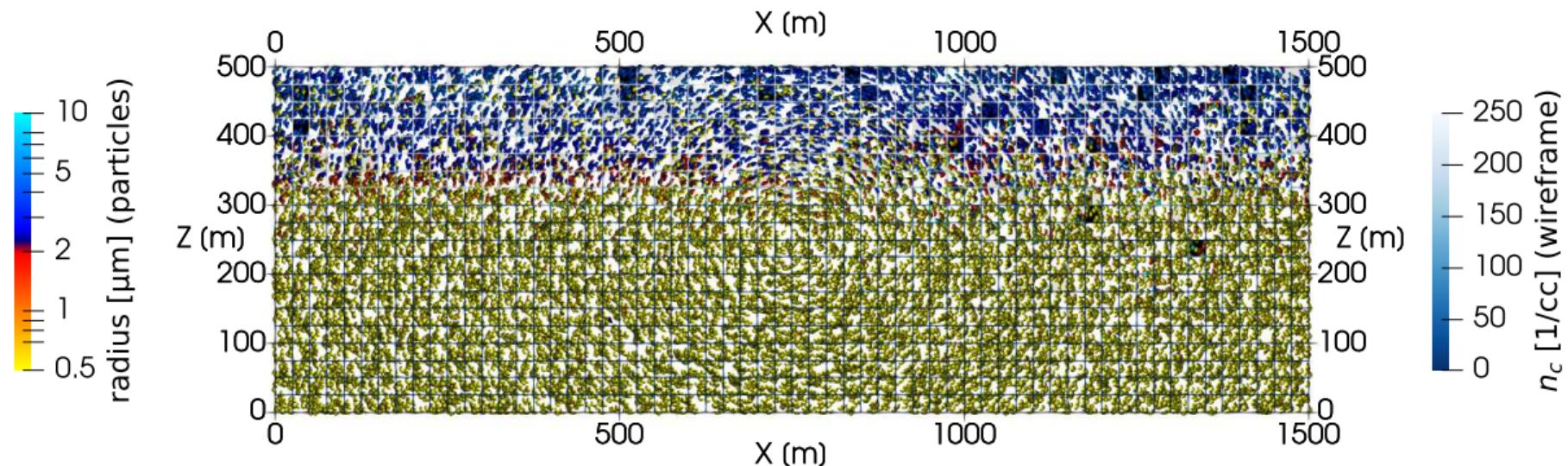
Time: 810 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

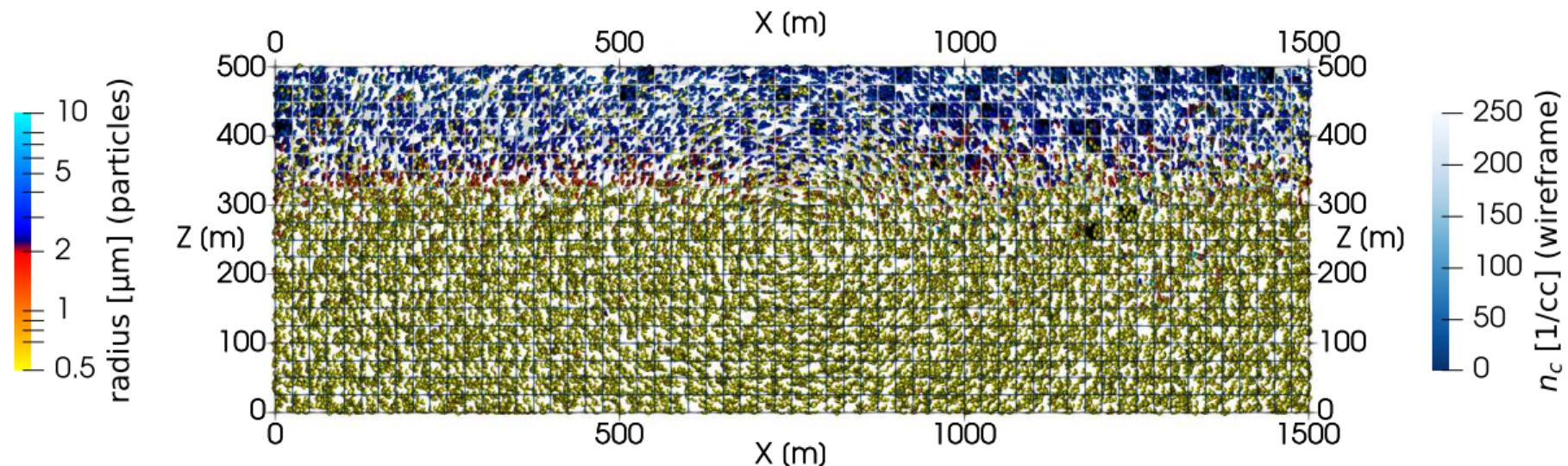
Time: 840 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

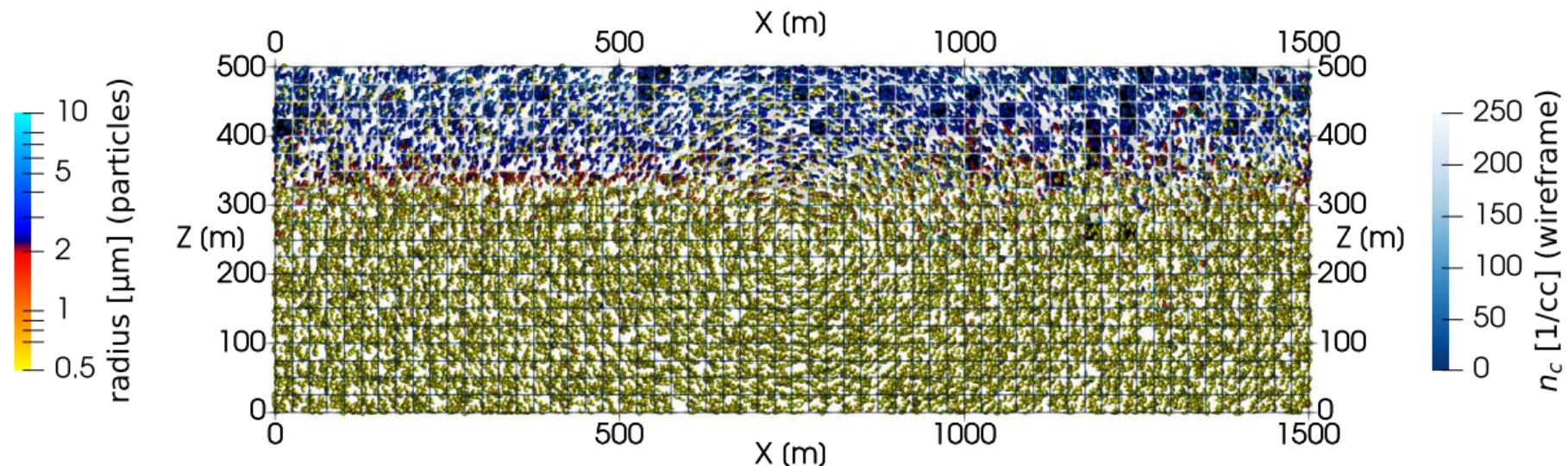
Time: 870 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

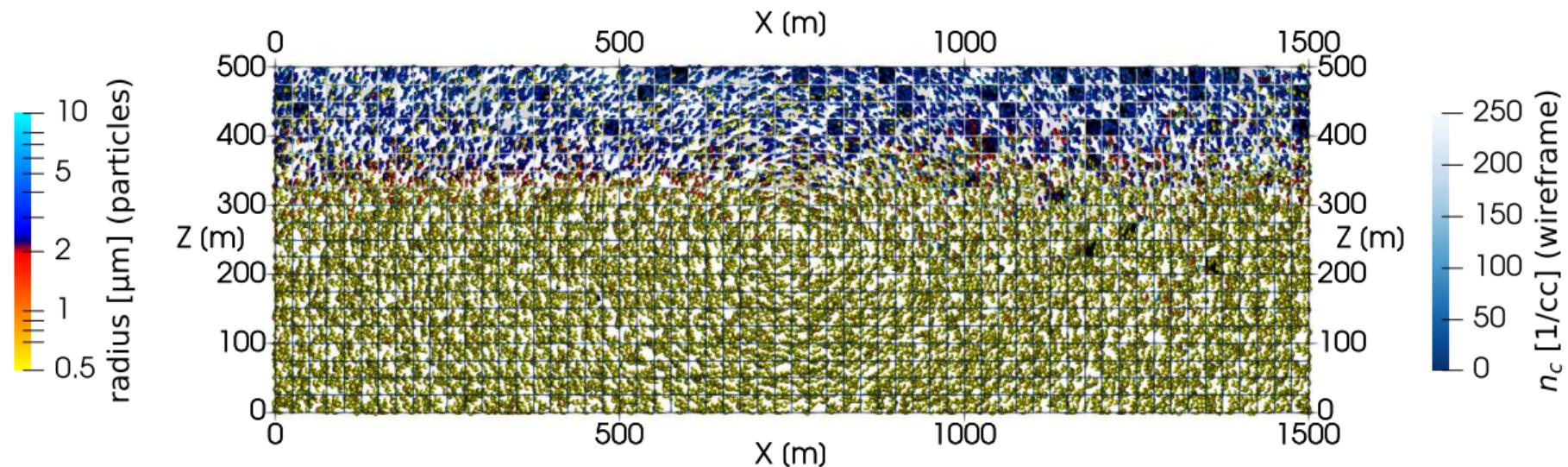
Time: 900 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ μm}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

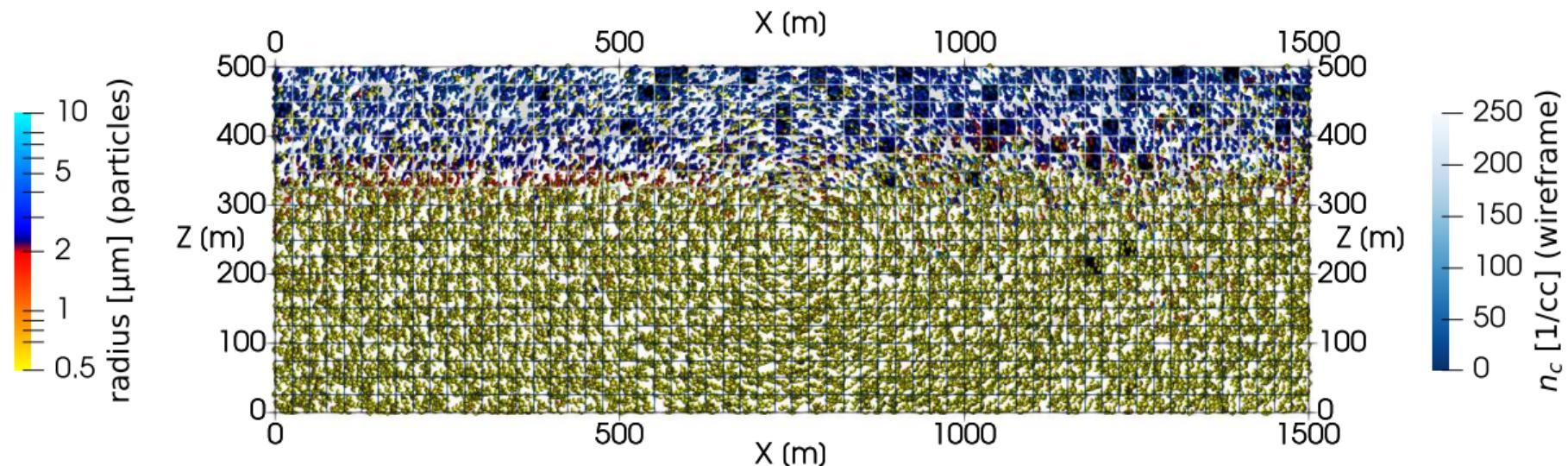
Time: 930 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

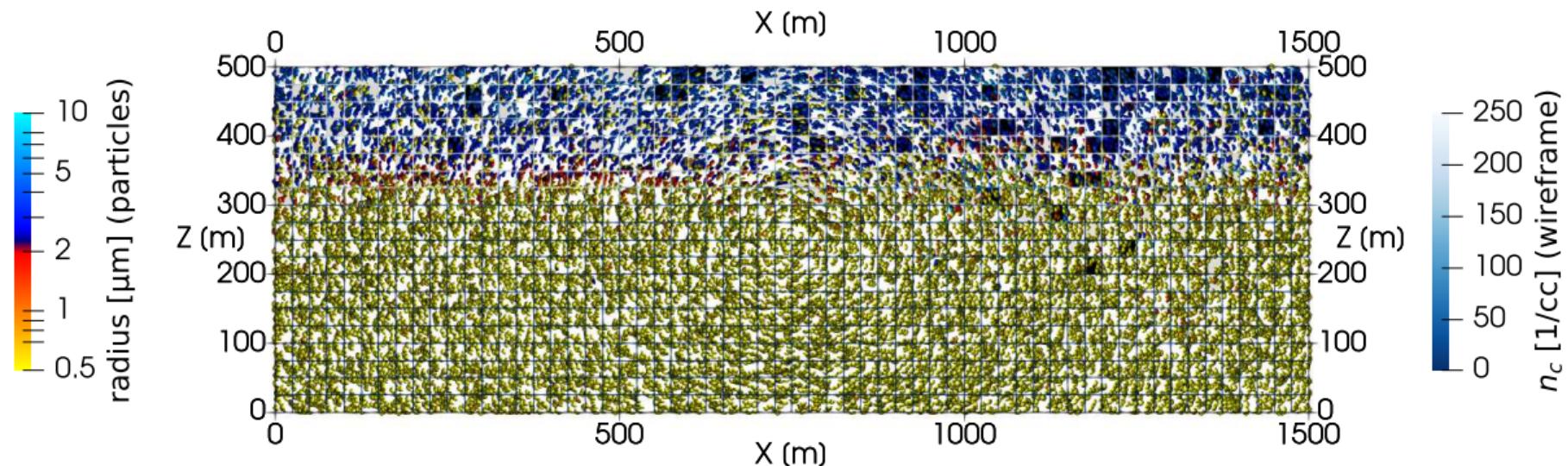
Time: 960 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

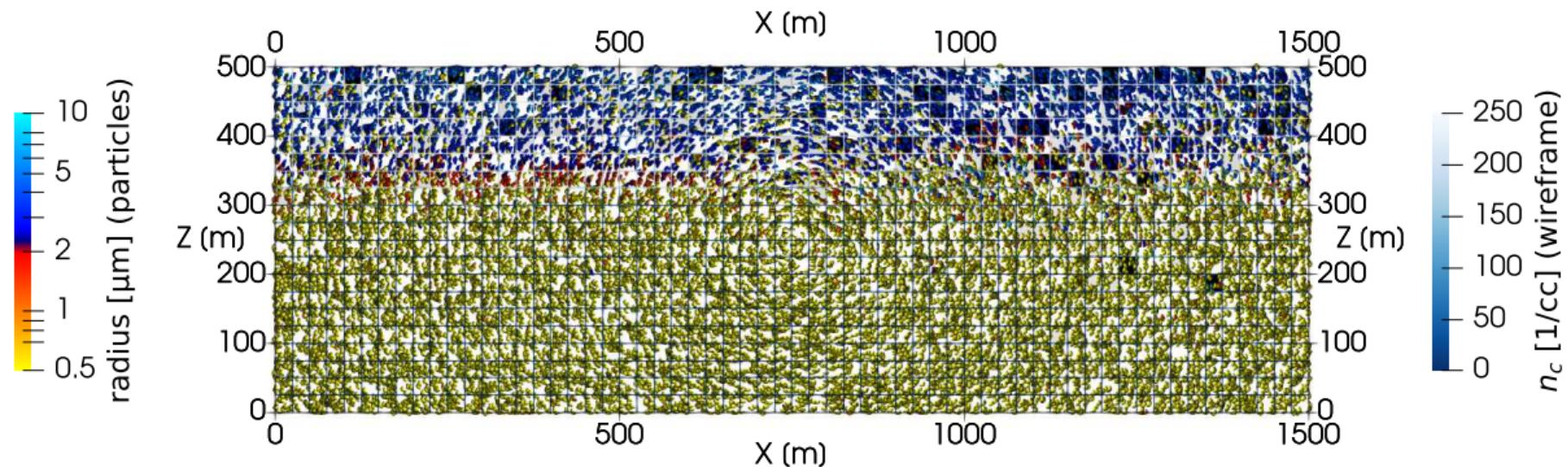
Time: 990 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

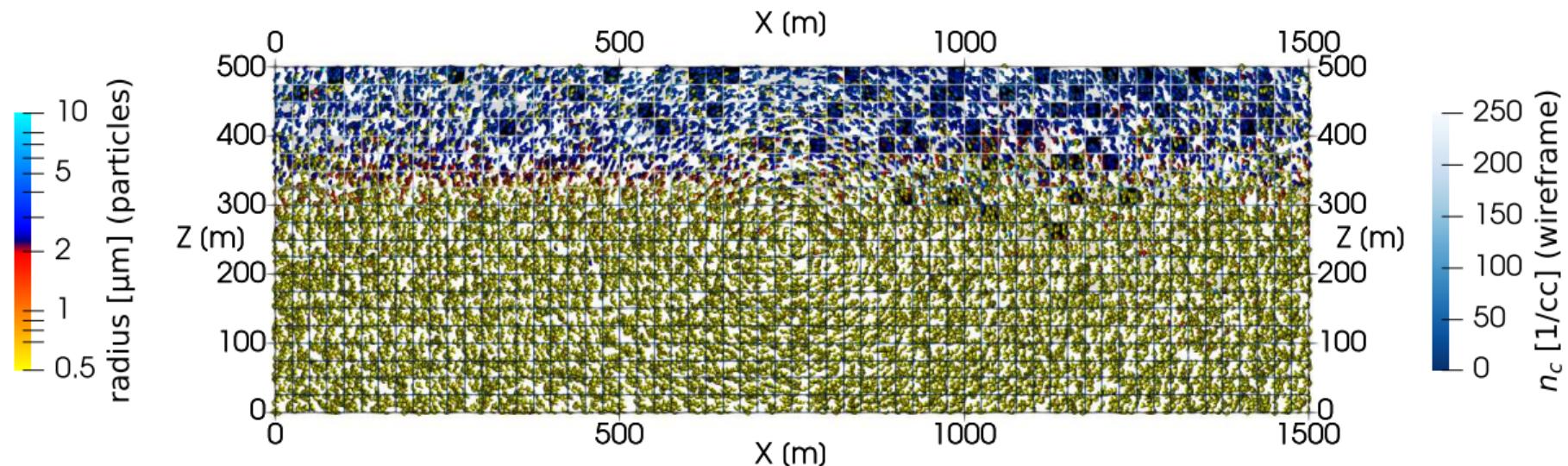
Time: 1020 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

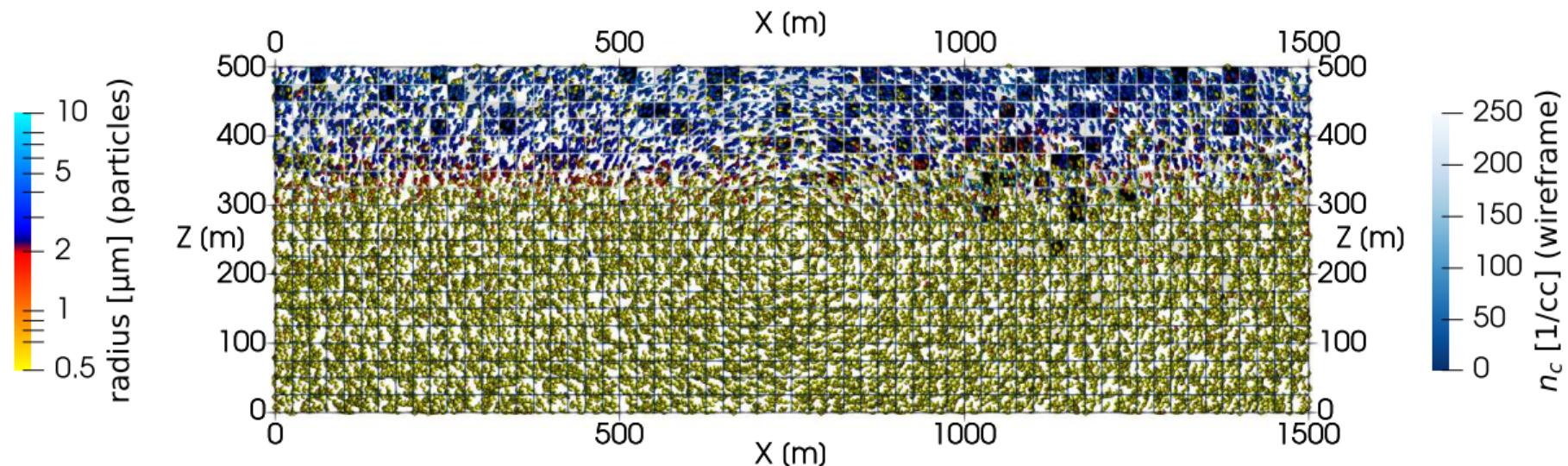
Time: 1050 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

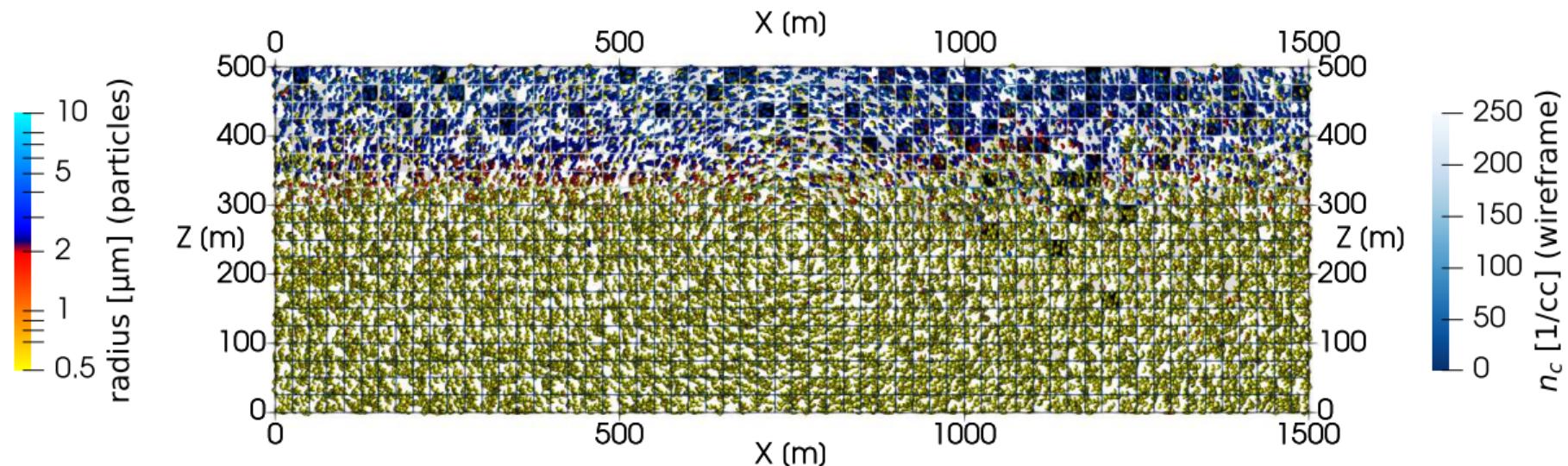
Time: 1080 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

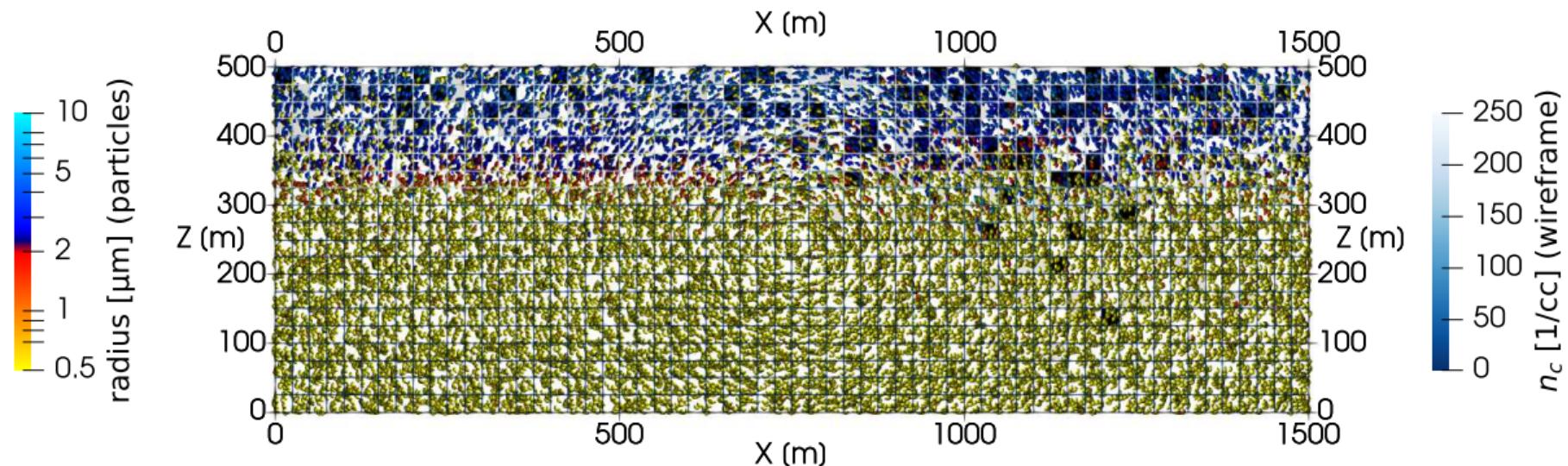
Time: 1110 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ }\mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

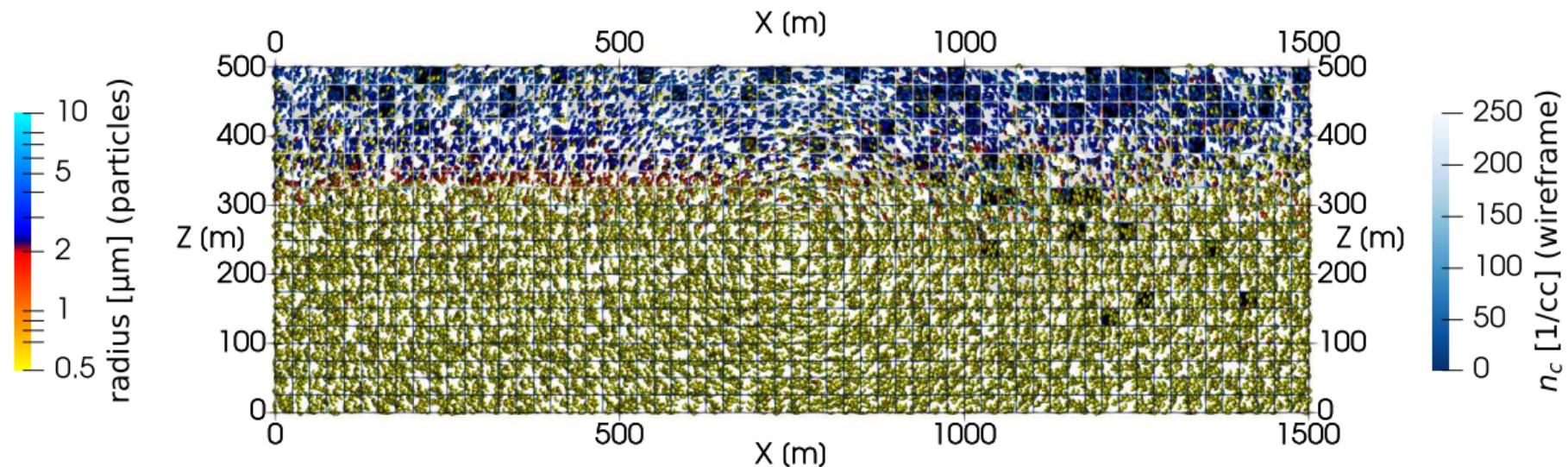
Time: 1140 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Particle-based μ -physics + prescribed-flow: glaciation

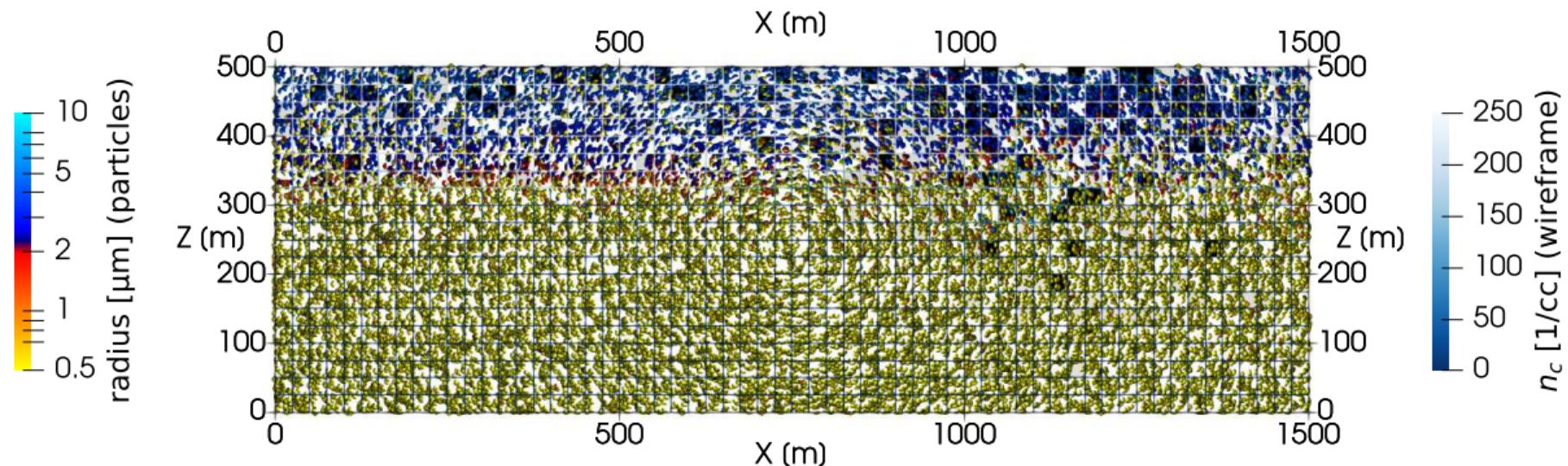
Time: 1170 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

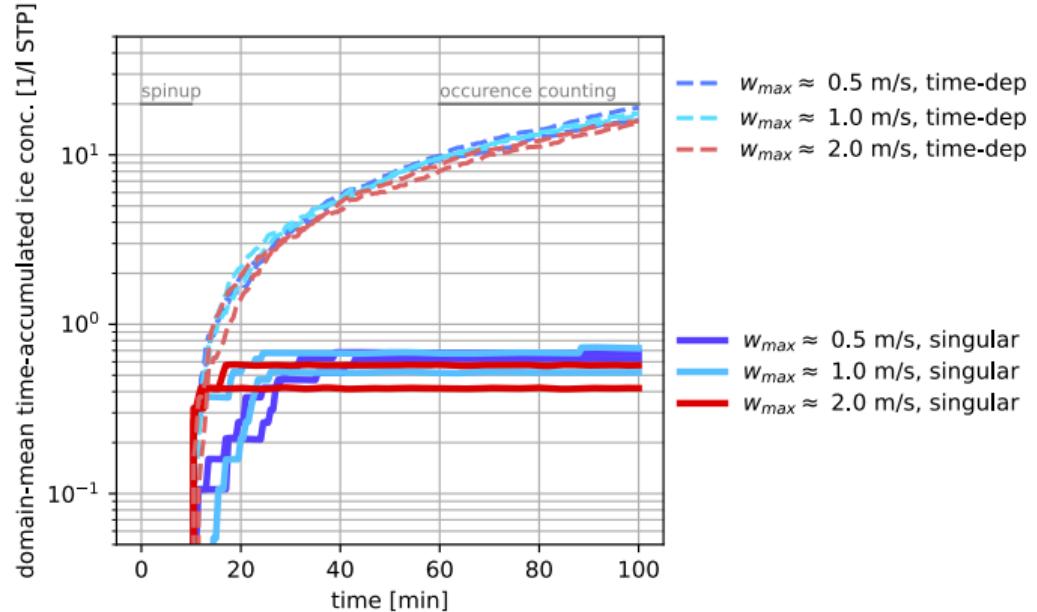
Particle-based μ -physics + prescribed-flow: glaciation

Time: 1200 s (spin-up till 600.0 s)

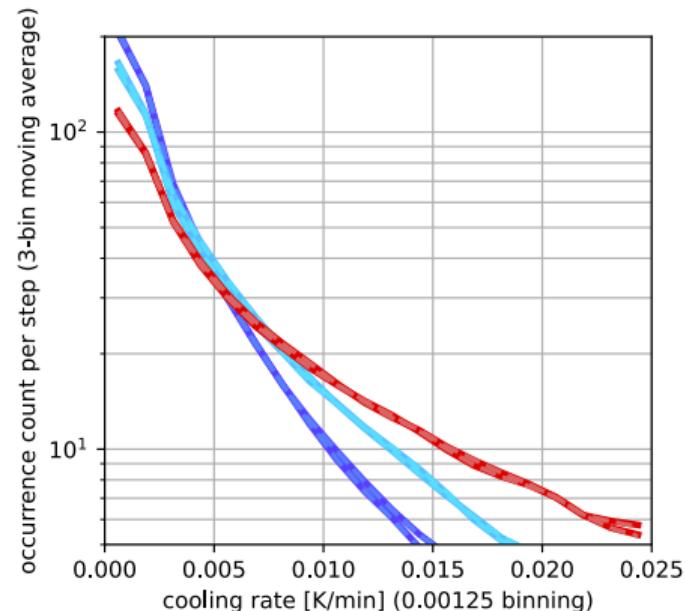
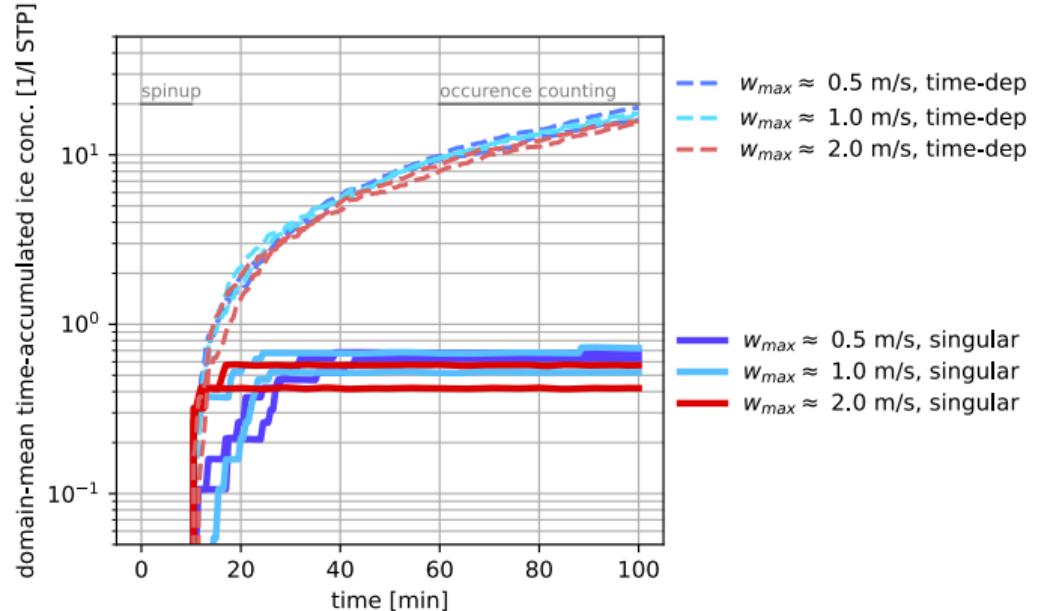


16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

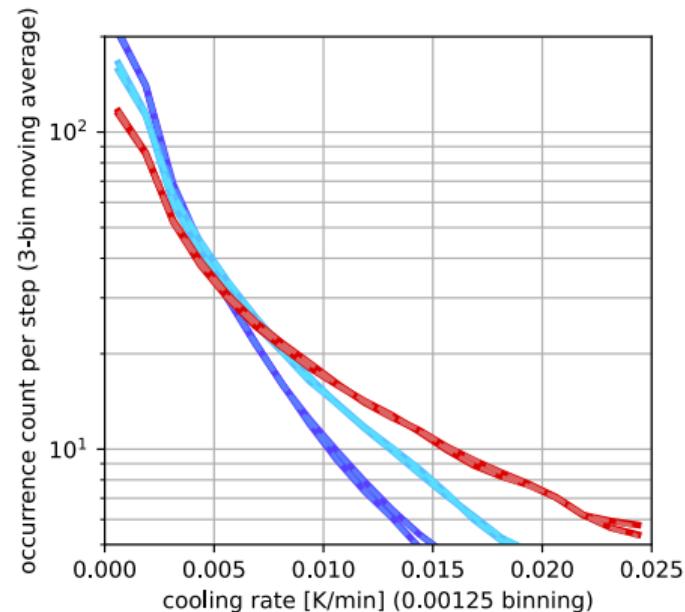
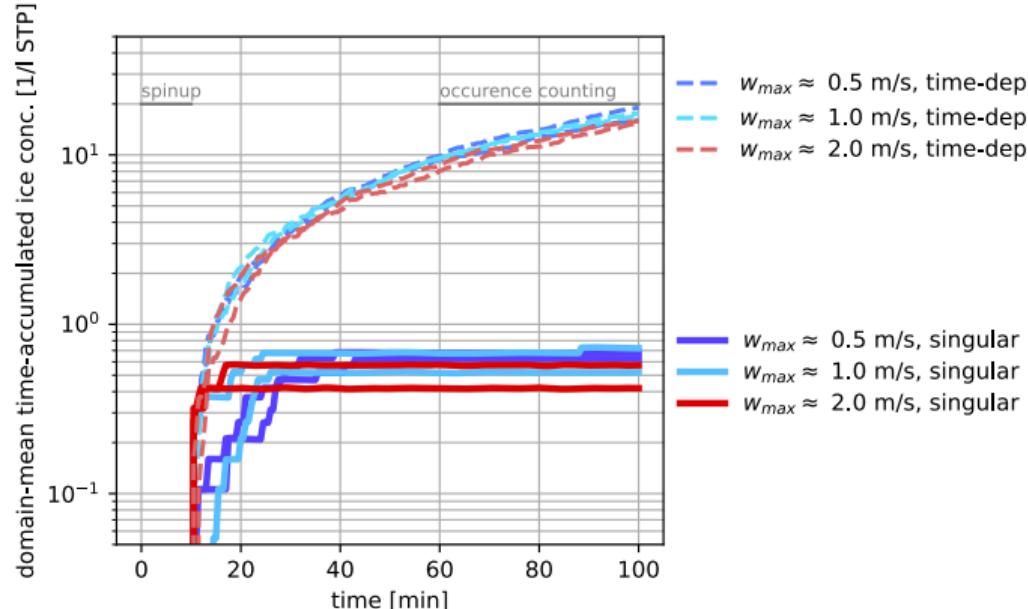
Testing three flow regimes and two immersion freezing representations



Testing three flow regimes and two immersion freezing representations

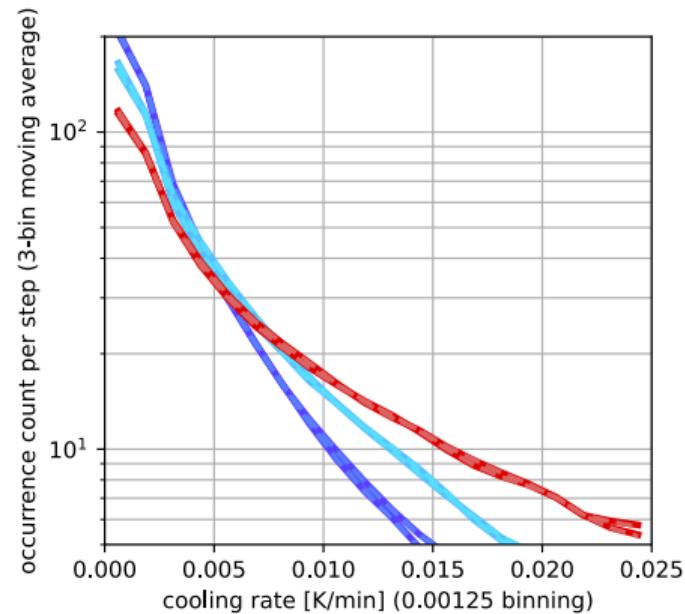
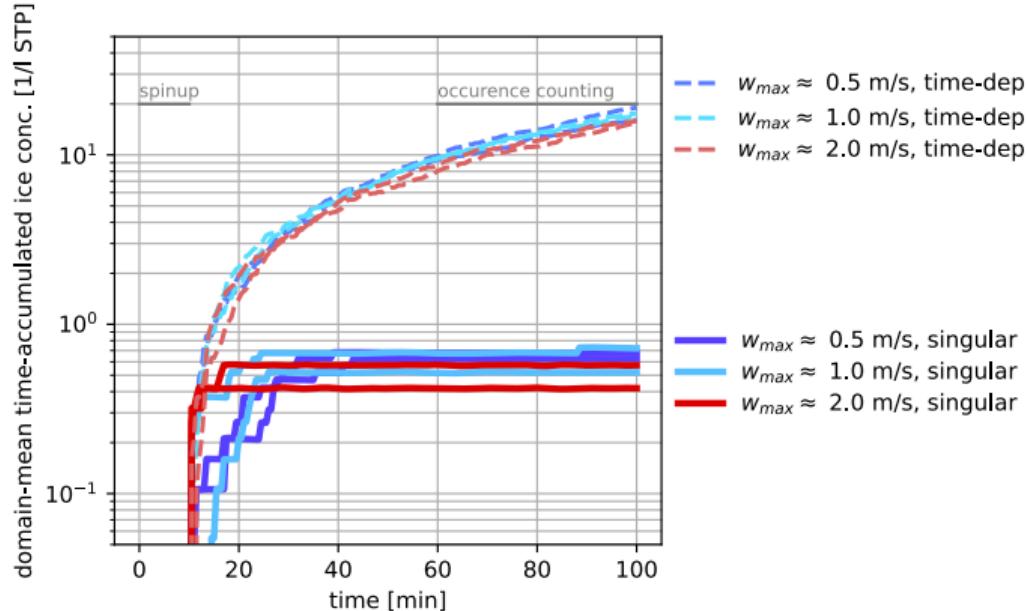


Testing three flow regimes and two immersion freezing representations



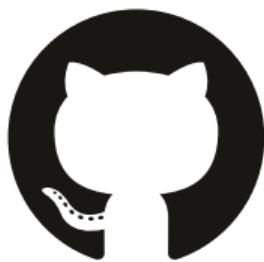
- range of cooling rates in simple flow (far from 0.5 K/min for AIDA as in Niemand et al. 2012)

Testing three flow regimes and two immersion freezing representations



- range of cooling rates in simple flow (far from 0.5 K/min for AIDA as in Niemand et al. 2012)
- **only time-dependent scheme robust across flow regimes** (consistent with box model & theory)

100%  python™ open-source code:



/ OPEN**ATMOS** / PySDM





Thank you for your attention

Thanks to  Erasmus+ & Rob for making the workshop possible!

sylwester.arabas@agh.edu.pl