Towards Accurate Contrail Simulation In the Jet and Vortex Phases by Combining Space- and Time-Developing Paradigms

Denis-Gabriel Caprace, Matthieu Duponcheel, Philippe Chatelain
Institute of Mechanics, Materials, and Civil Engineering
UCLouvain, Belgium

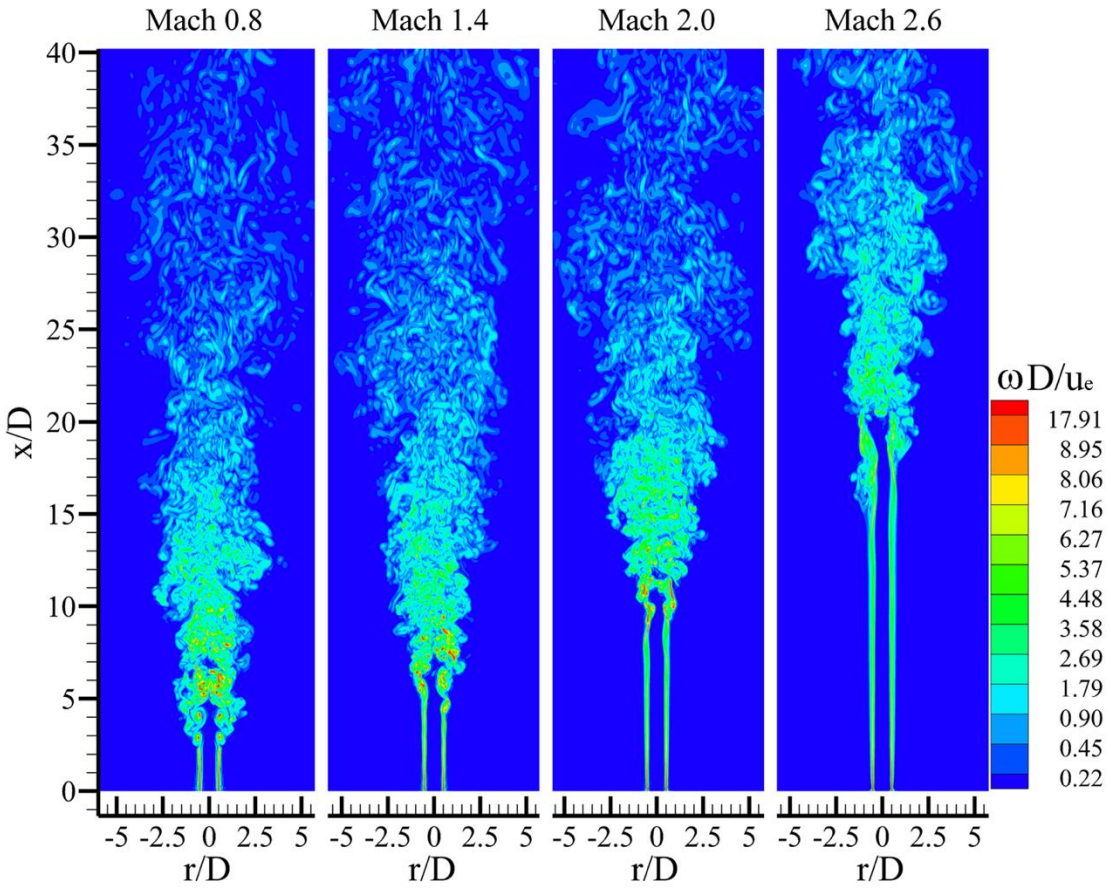
Friday May 2nd, 2025

EGU 2025 – Session AS3.19 – EGU25-17034

UCLouvain iMMC

Introduction

Space-developing Large Eddy Simulation



Bonelli *et al.*, Flow Turb. Comb., 2024

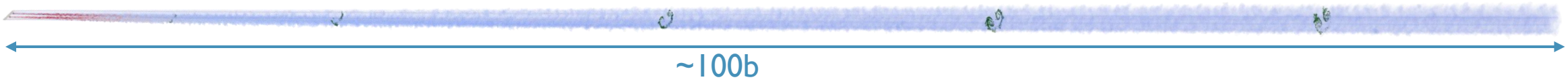
Time-developing Large Eddy Simulation



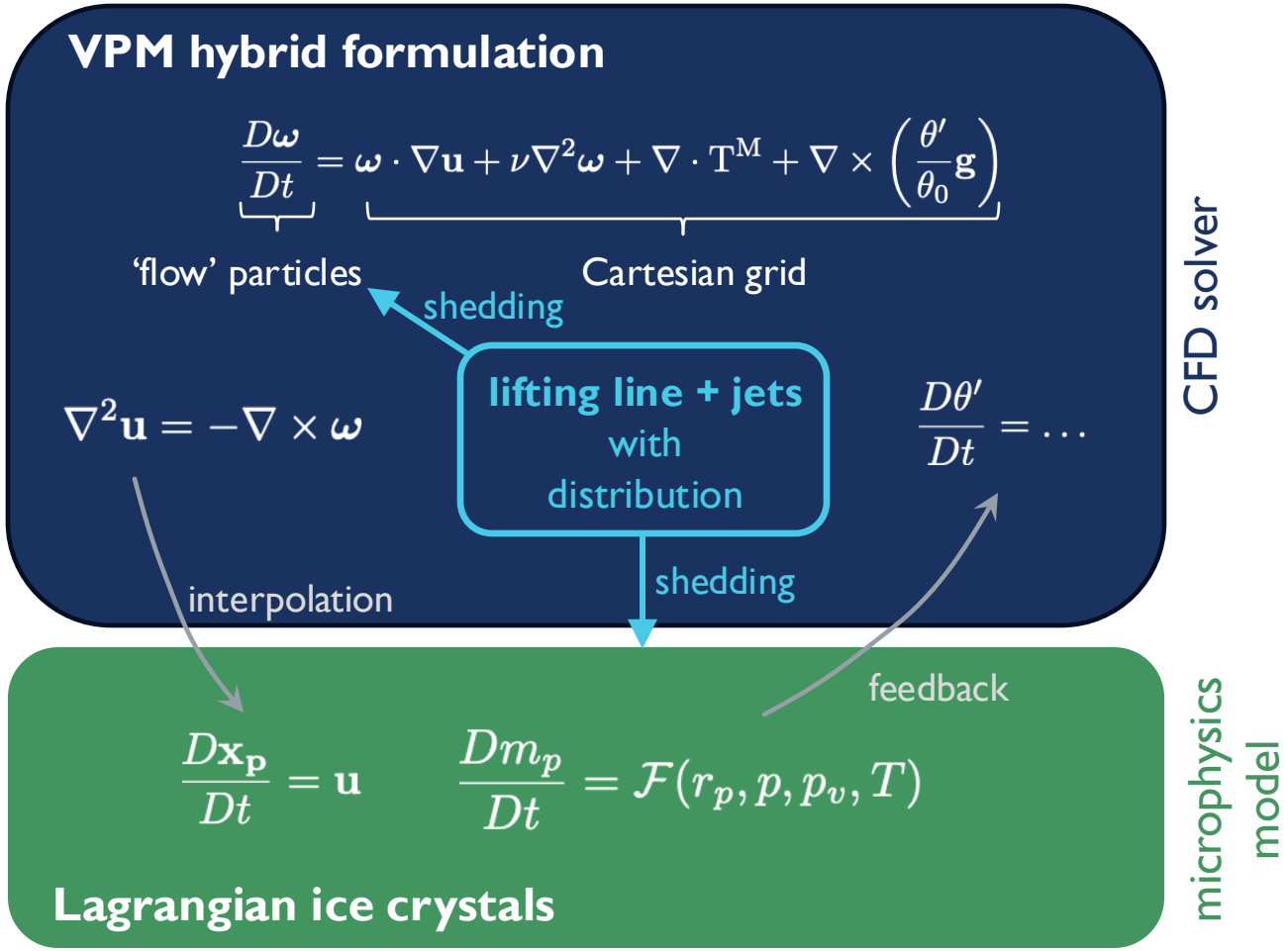
Ferreira *et al.*, CTR SP, 2024

➢ **Motivation**: connect the two approaches through a **consistent transition** between jet and vortex phases

Methods (1/2) – Solvers



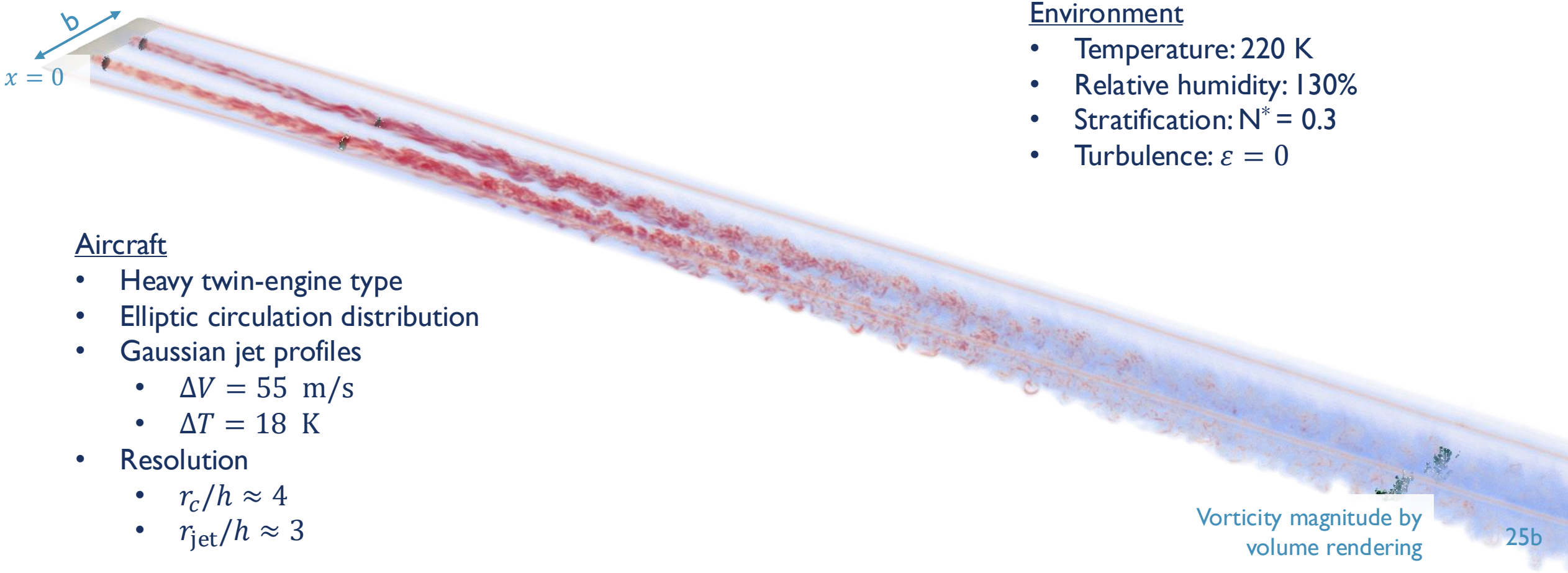
- Vortex Particle-Mesh (VPM) method
  Large eddy simulation
  & lifting line method
- Boussinesq approximation
  +1 eq. for potential temperature
- Moisture
  +1 eq. for scalar density ratio
- Ice growth by deposition:
  condensation + sublimation
  +1 eq. for ice volume
- All particles "activated" initially



Refs.: Chatelain *et al.*, Comput. Methods Appl. Mech. Eng. 2008; Caprace et al., Theoret. Comput. Fluid Dynamics., 2020

A Space-developing Example





Environment

- Temperature: 220 K
- Relative humidity: 130%
- Stratification: $N^* = 0.3$
- Turbulence: $\varepsilon = 0$

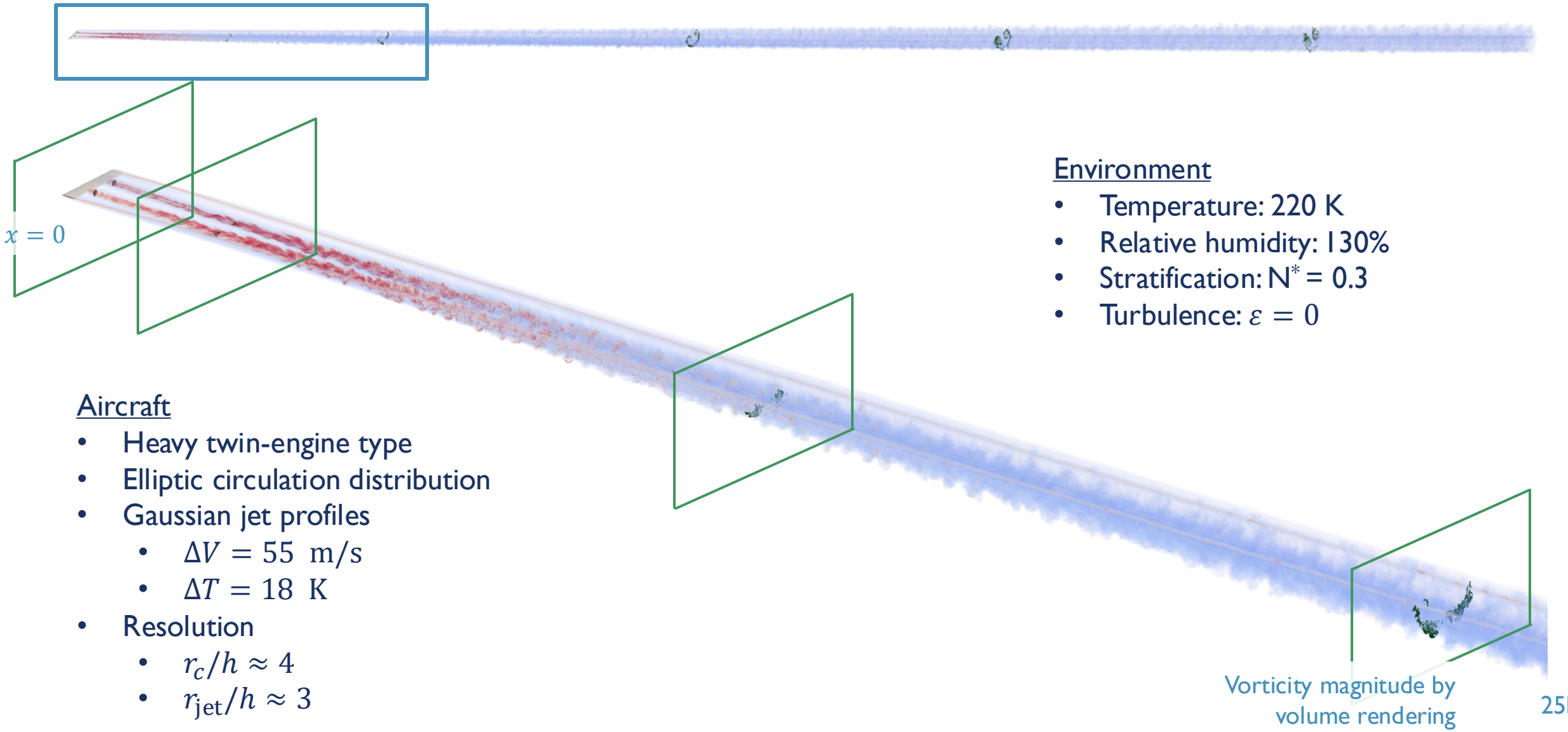
Aircraft

- Heavy twin-engine type
- Elliptic circulation distribution
- Gaussian jet profiles
  - $\Delta V = 55\ \mathrm{m/s}$
  - $\Delta T = 18\ \mathrm{K}$
- Resolution
  - $r_c/h \approx 4$
  - $r_{\mathrm{jet}}/h \approx 3$

Vorticity magnitude by volume rendering

25b

A Space-developing Example



Vorticity magnitude by volume rendering

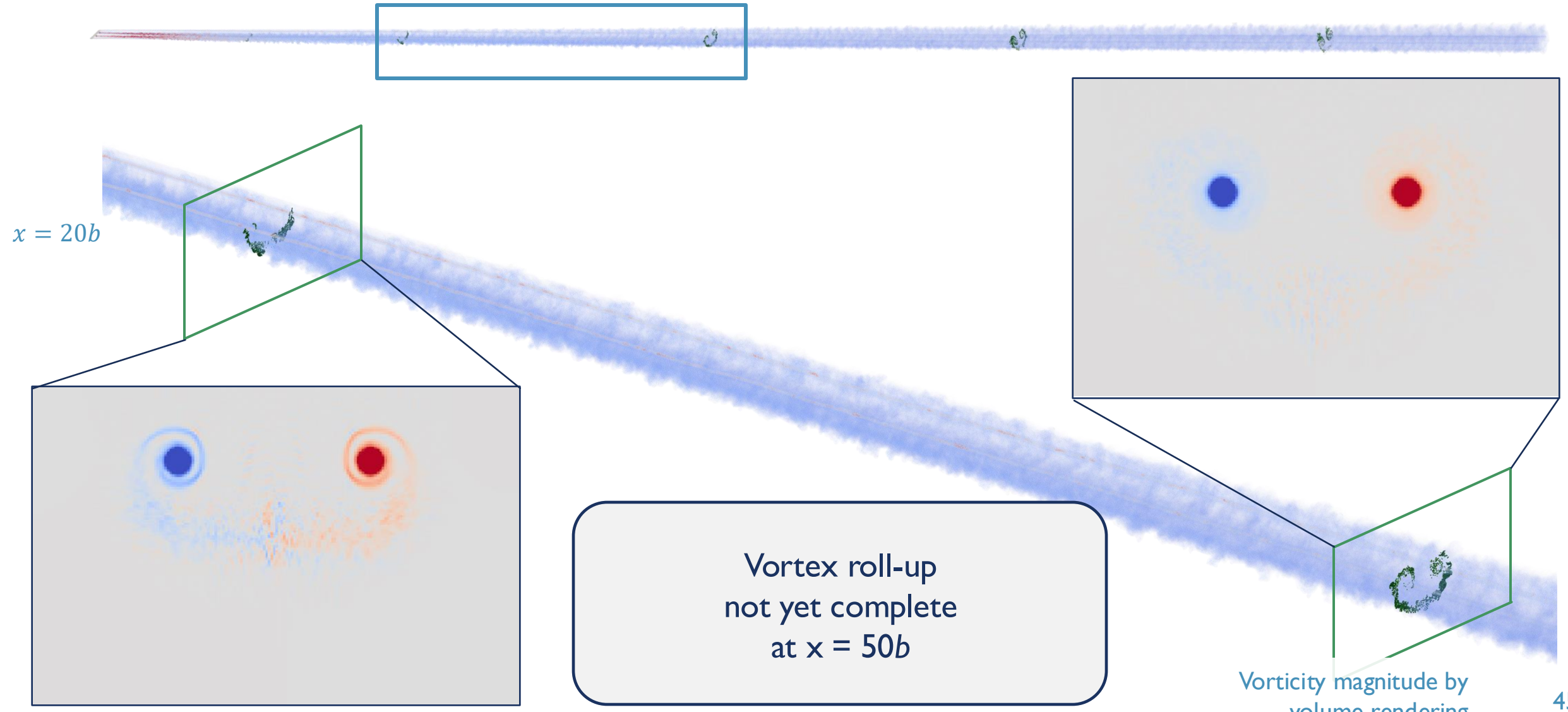
Aircraft

- Heavy twin-engine type
- Elliptic circulation distribution
- Gaussian jet profiles
  - $\Delta V = 55\ \mathrm{m/s}$
  - $\Delta T = 18\ \mathrm{K}$
- Resolution
  - $r_c/h \approx 4$
  - $r_{\mathrm{jet}}/h \approx 3$

Environment

- Temperature: 220 K
- Relative humidity: 130%
- Stratification: $N^* = 0.3$
- Turbulence: $\varepsilon = 0$

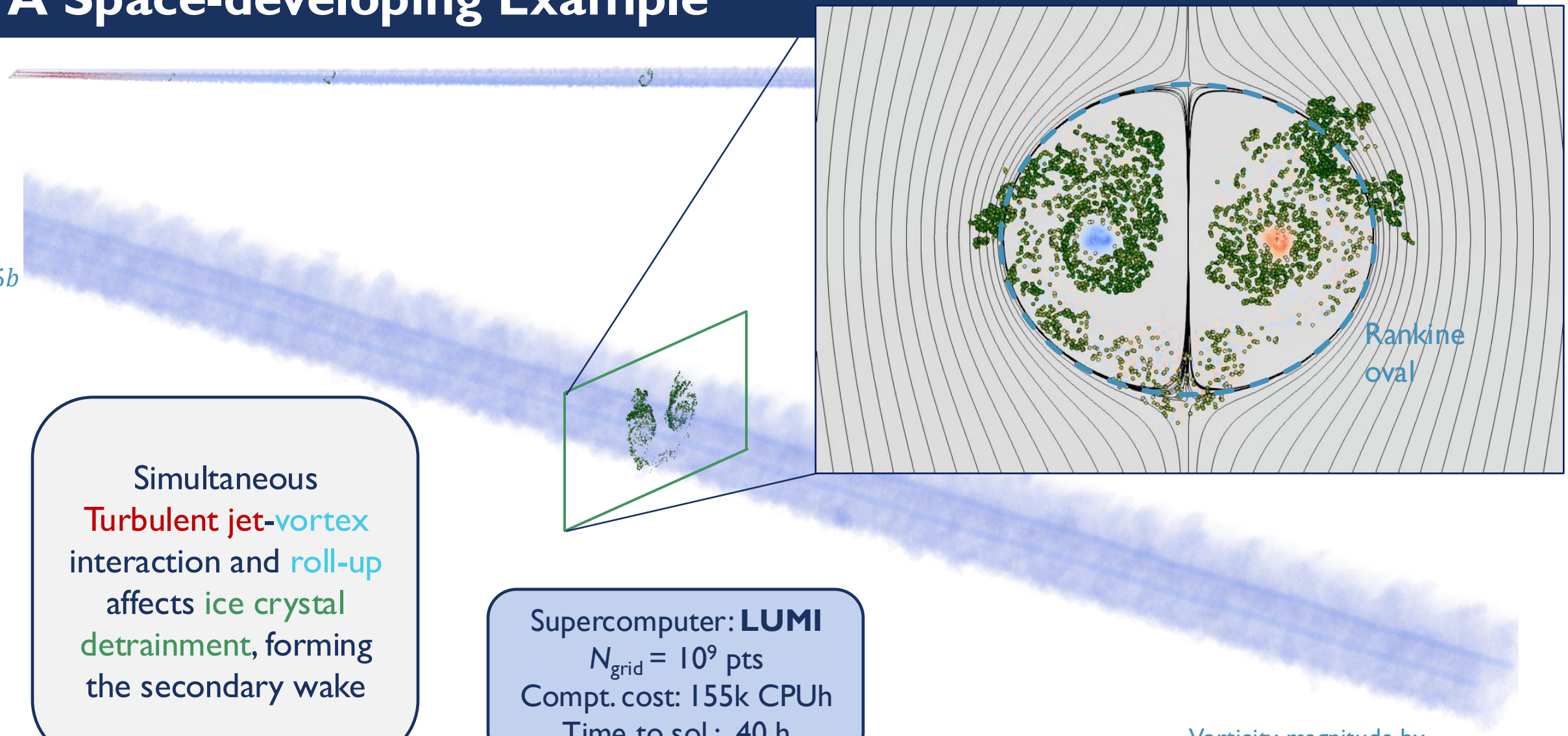
A Space-developing Example



Vortex roll-up
not yet complete
at x = 50b

Vorticity magnitude by
volume rendering

A Space-developing Example



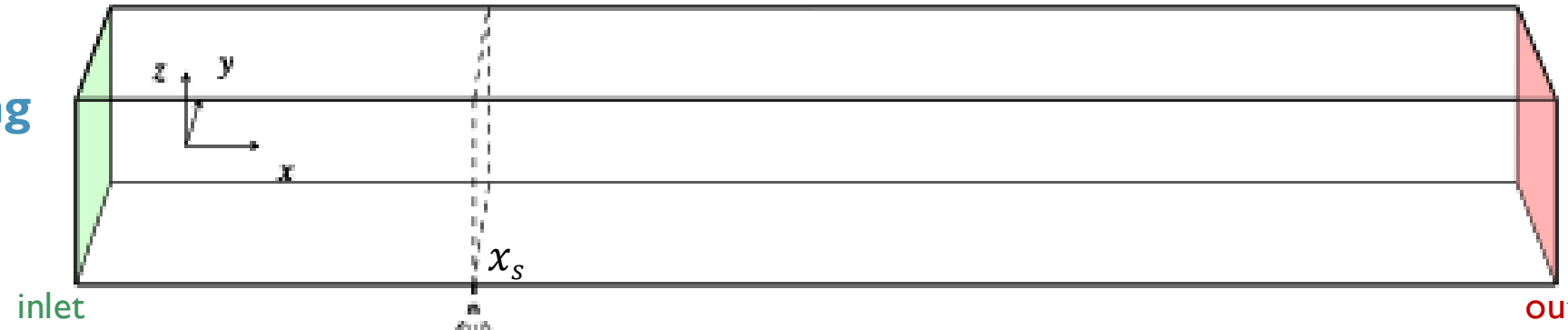
Simultaneous Turbulent jet-vortex interaction and roll-up affects ice crystal detrainment, forming the secondary wake

Supercomputer: **LUMI**
N_{grid} = 10^9 pts
Compt. cost: 155k CPUh
Time to sol.: 40 h

Vorticity magnitude by volume rendering

Methods (2/2) – The Paradigm Shift

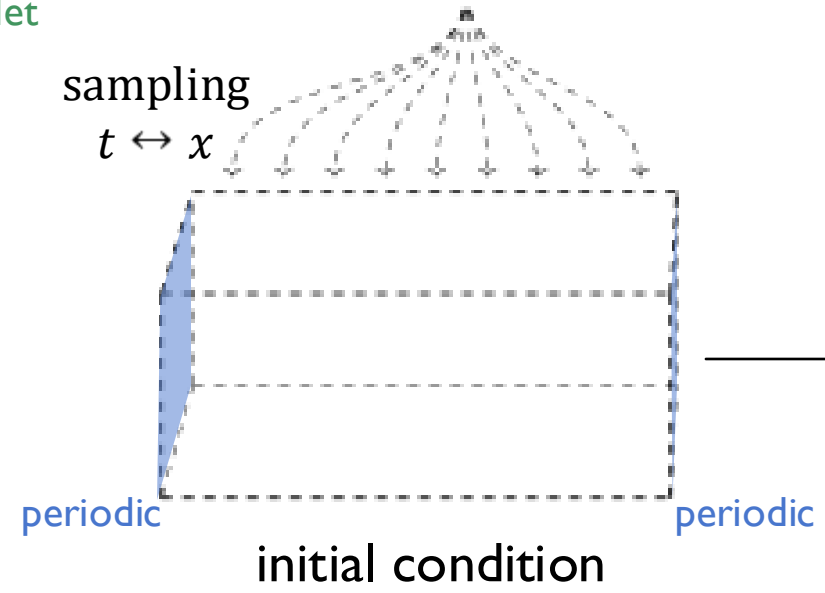
Space-developing
simulation

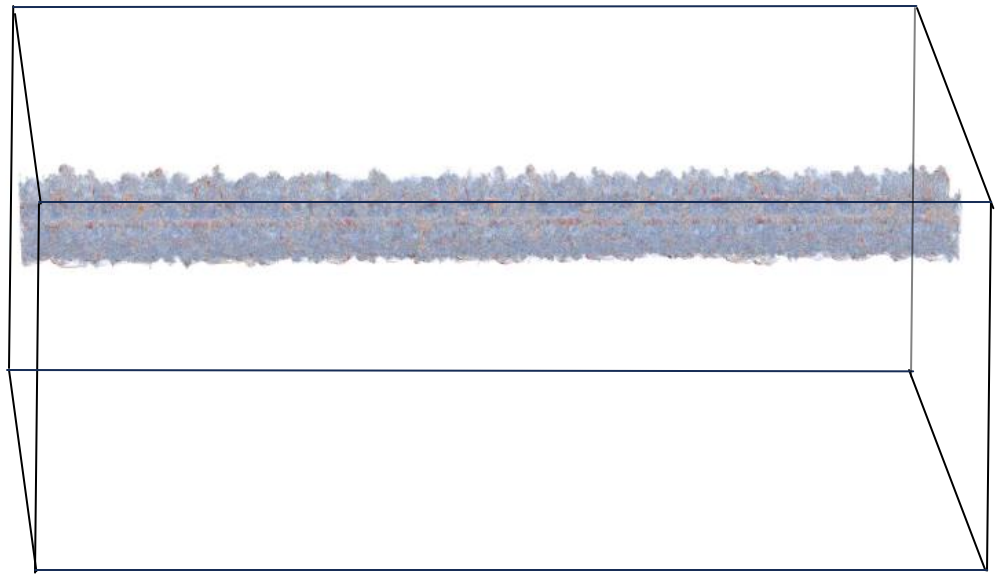


$x \approx 5\,\mathrm{km}$
$\approx 100b$

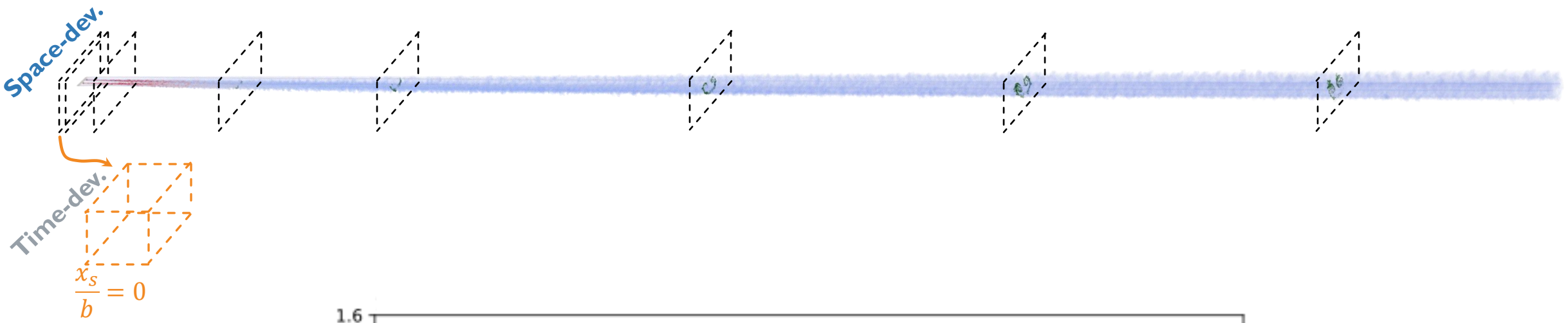
$t \approx 19\,\mathrm{s}$
$\approx 0.85T_0$

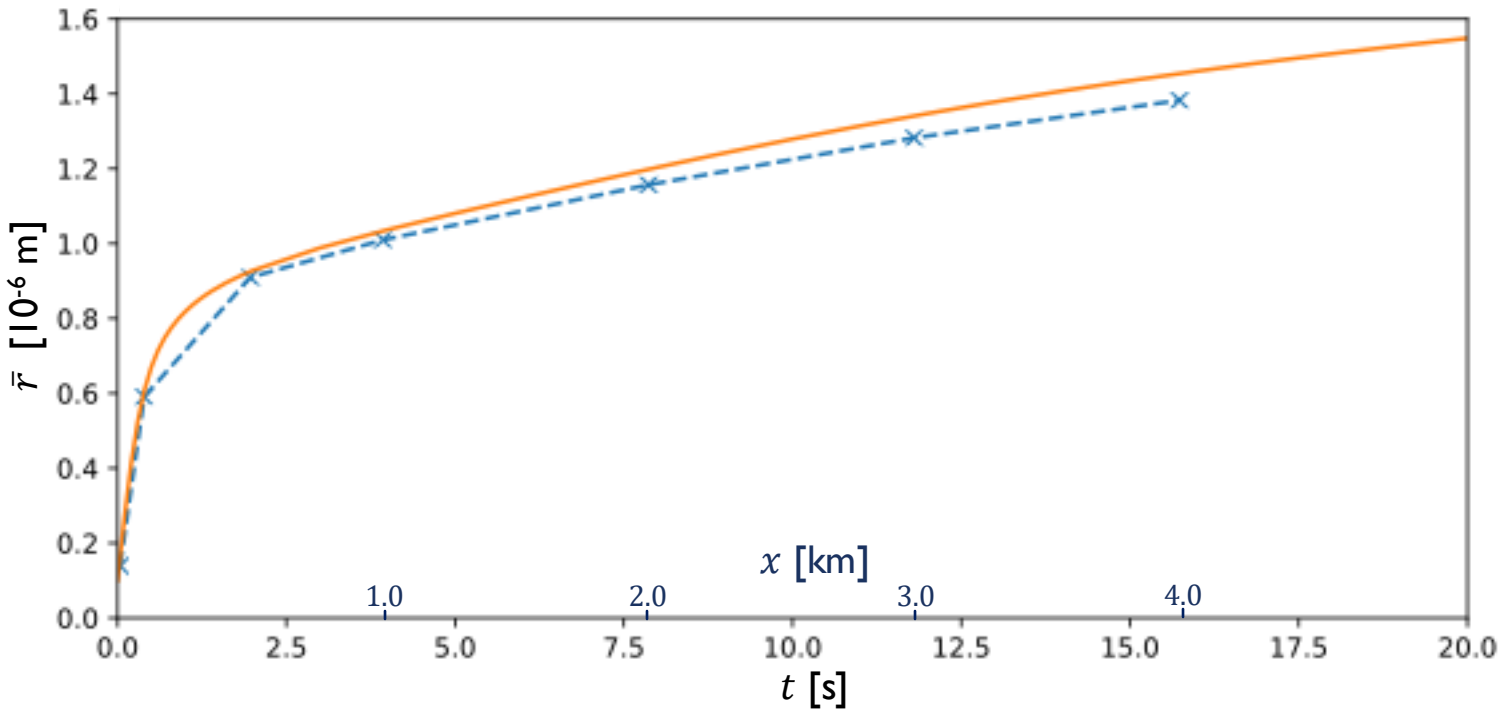
Time-developing
simulation



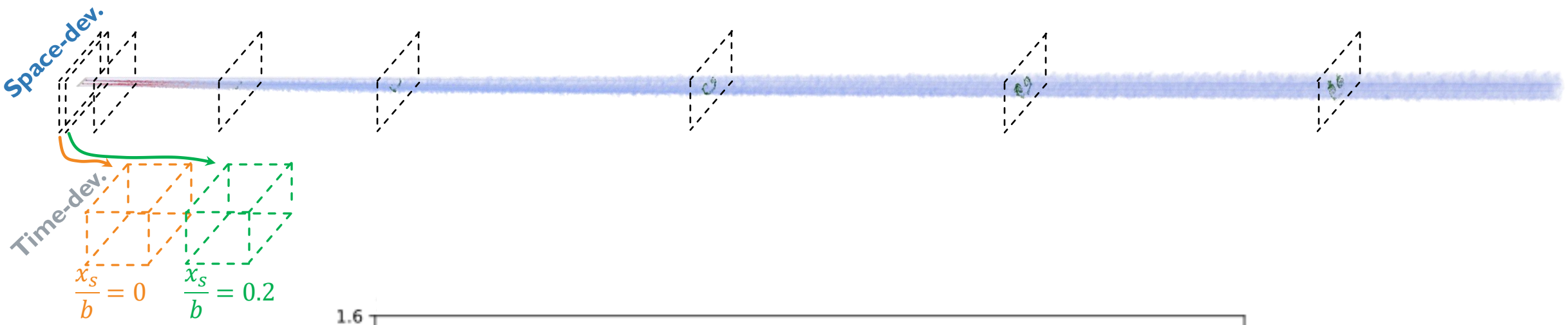


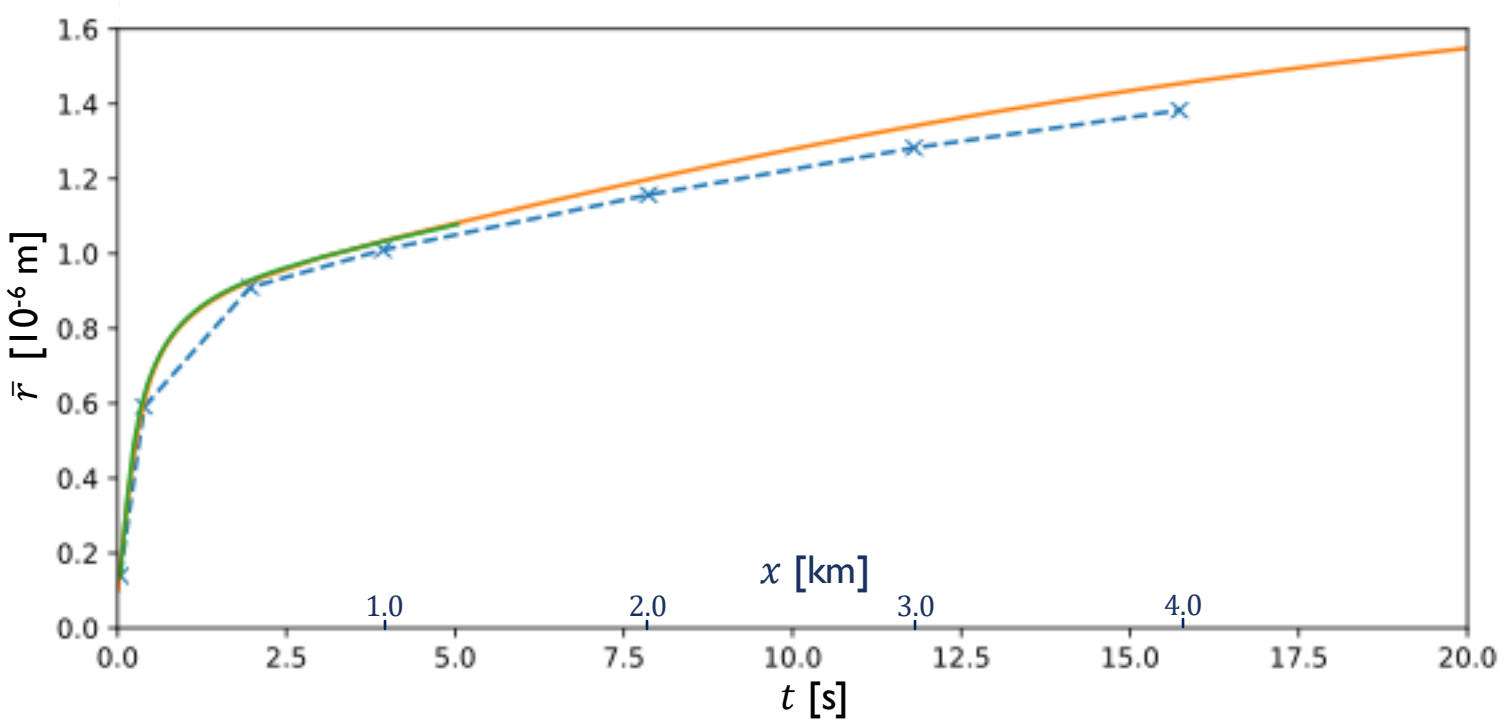
Consistent Switch From Space to Time



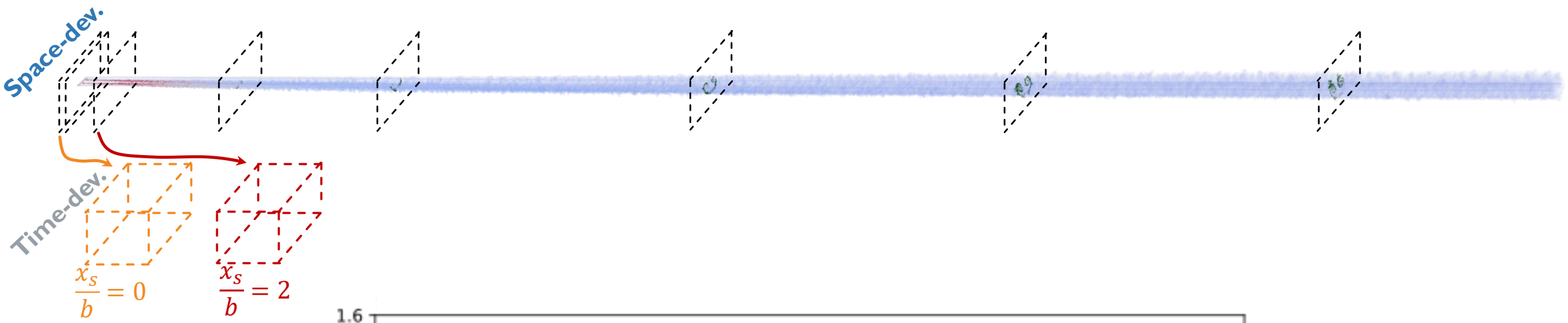


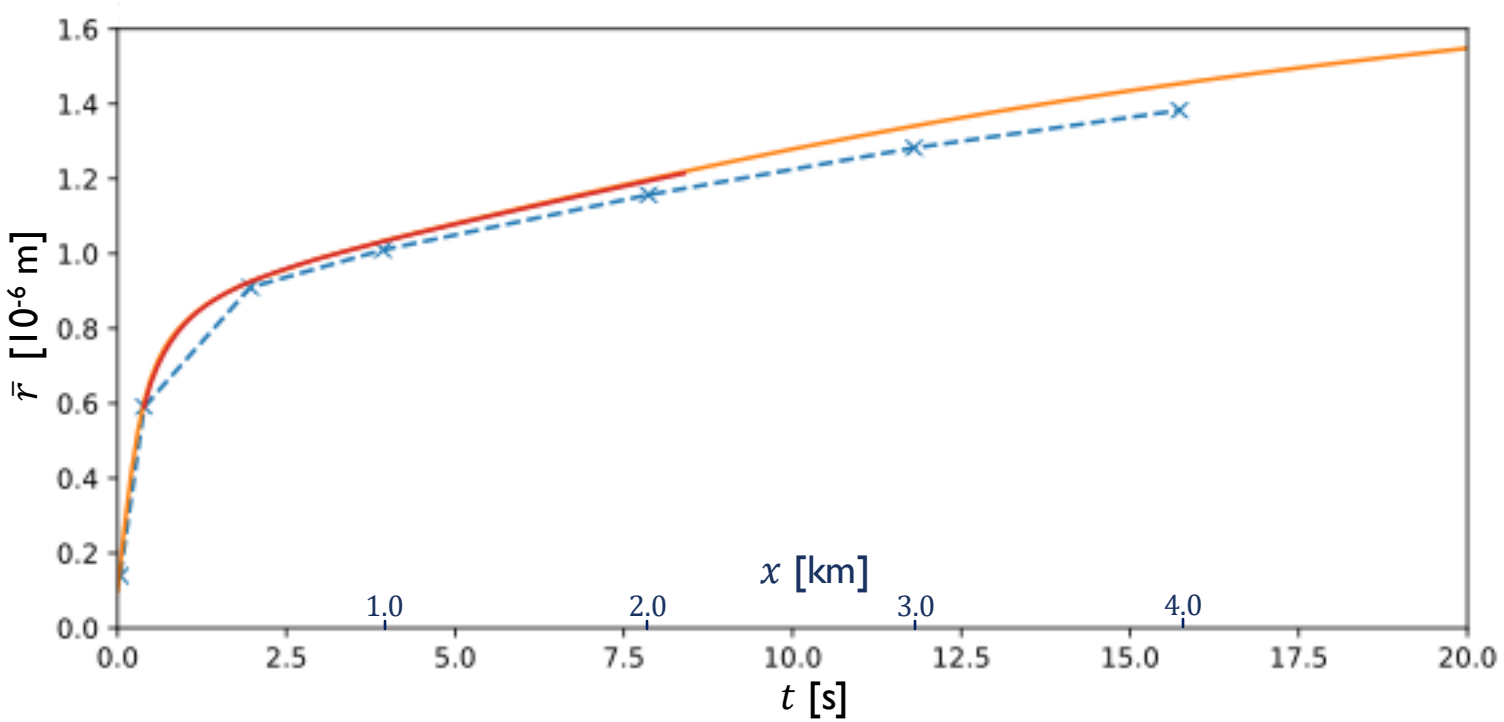
Consistent Switch From Space to Time



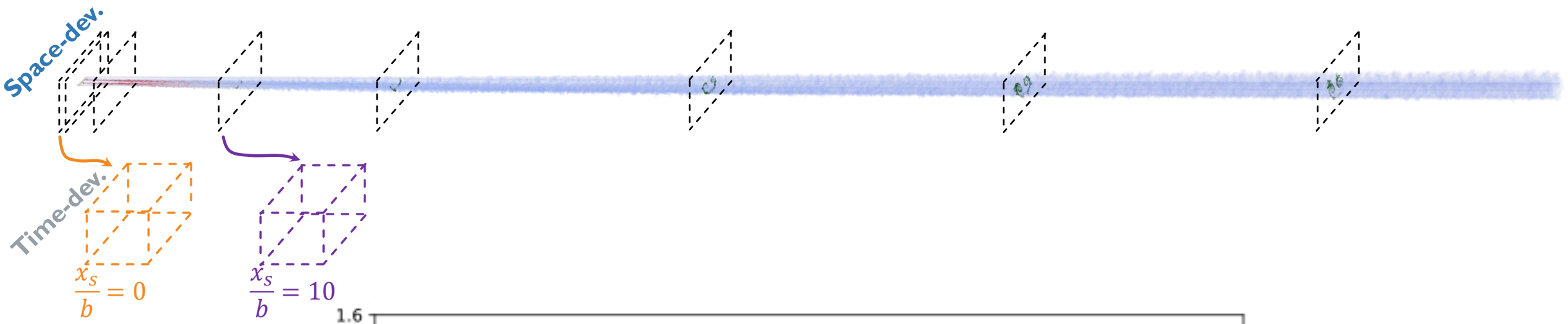


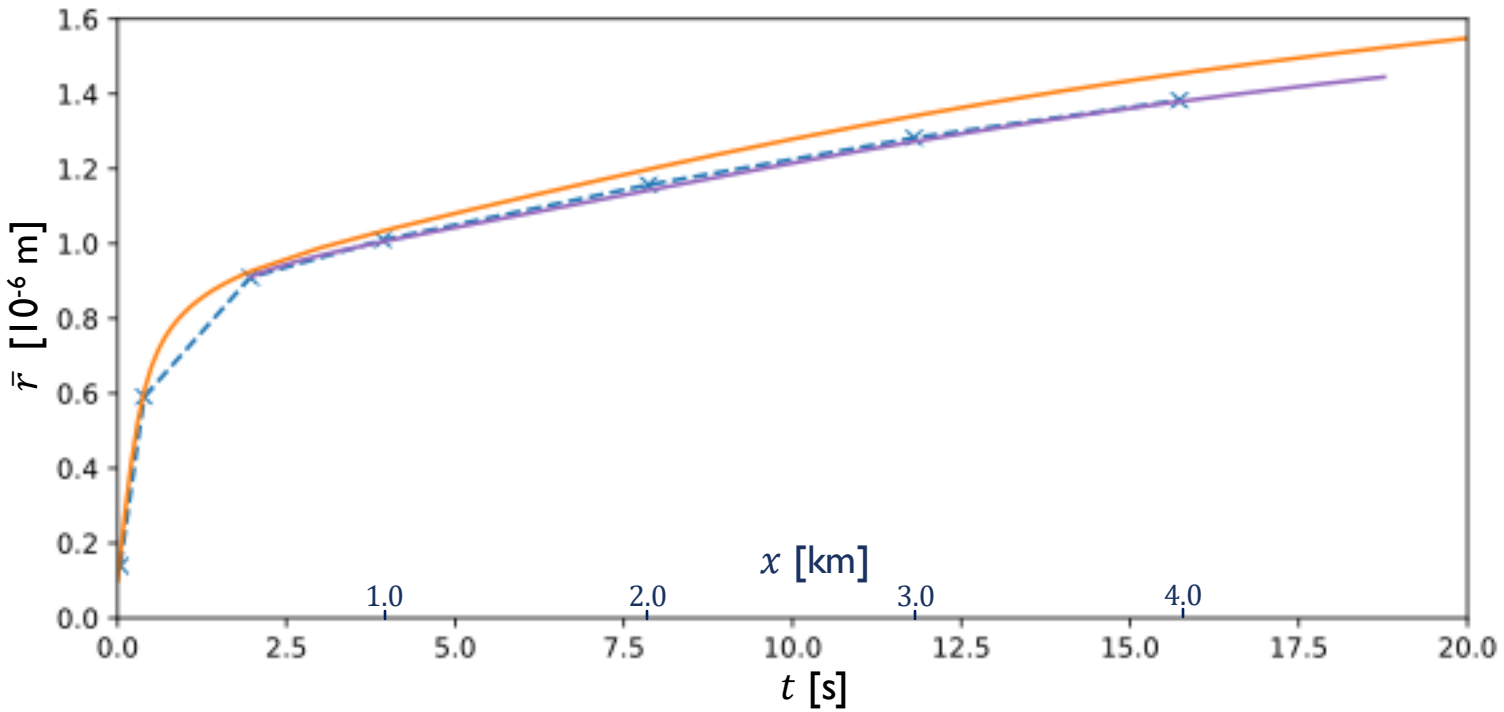
Consistent Switch From Space to Time



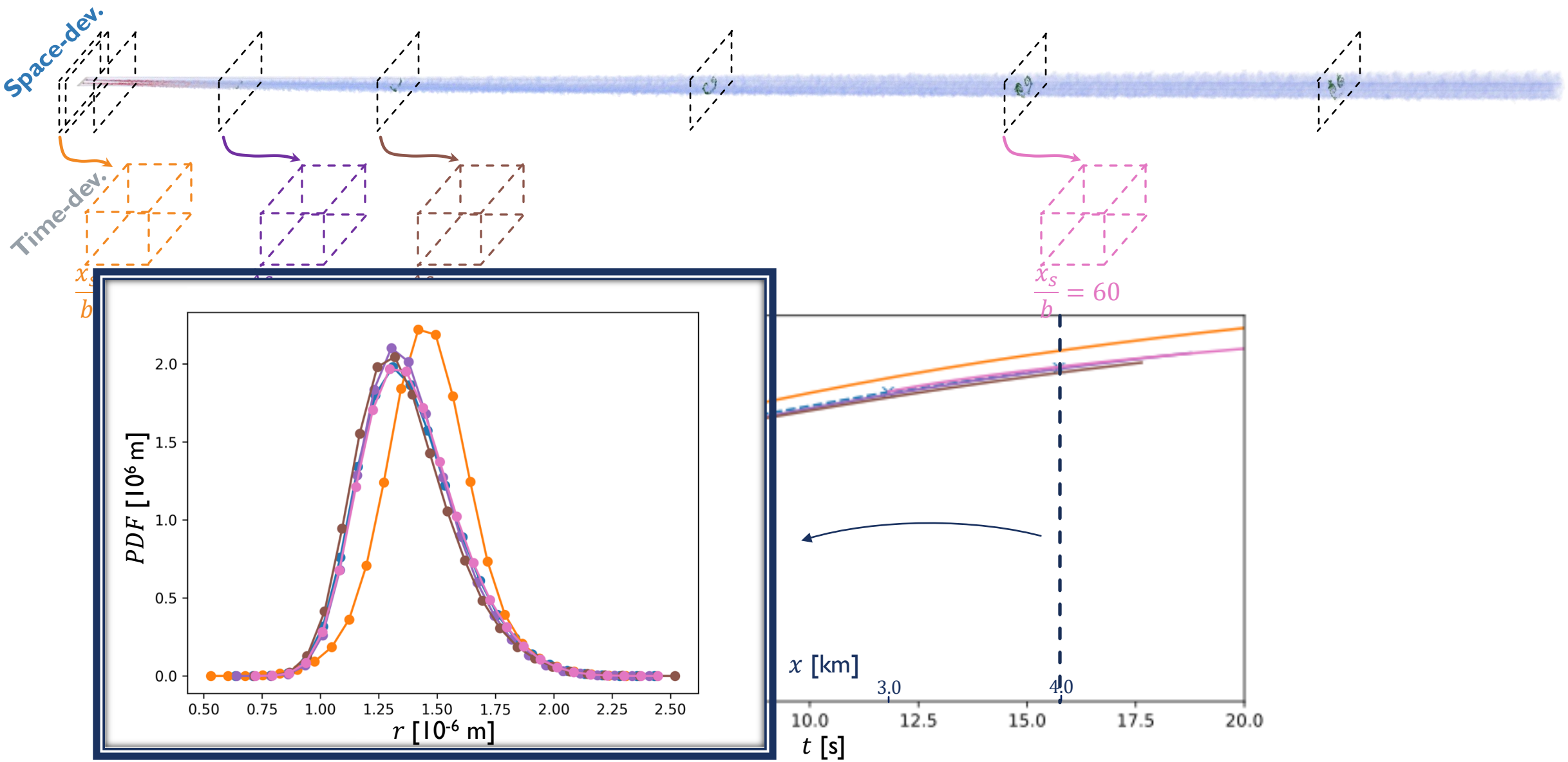


Consistent Switch From Space to Time

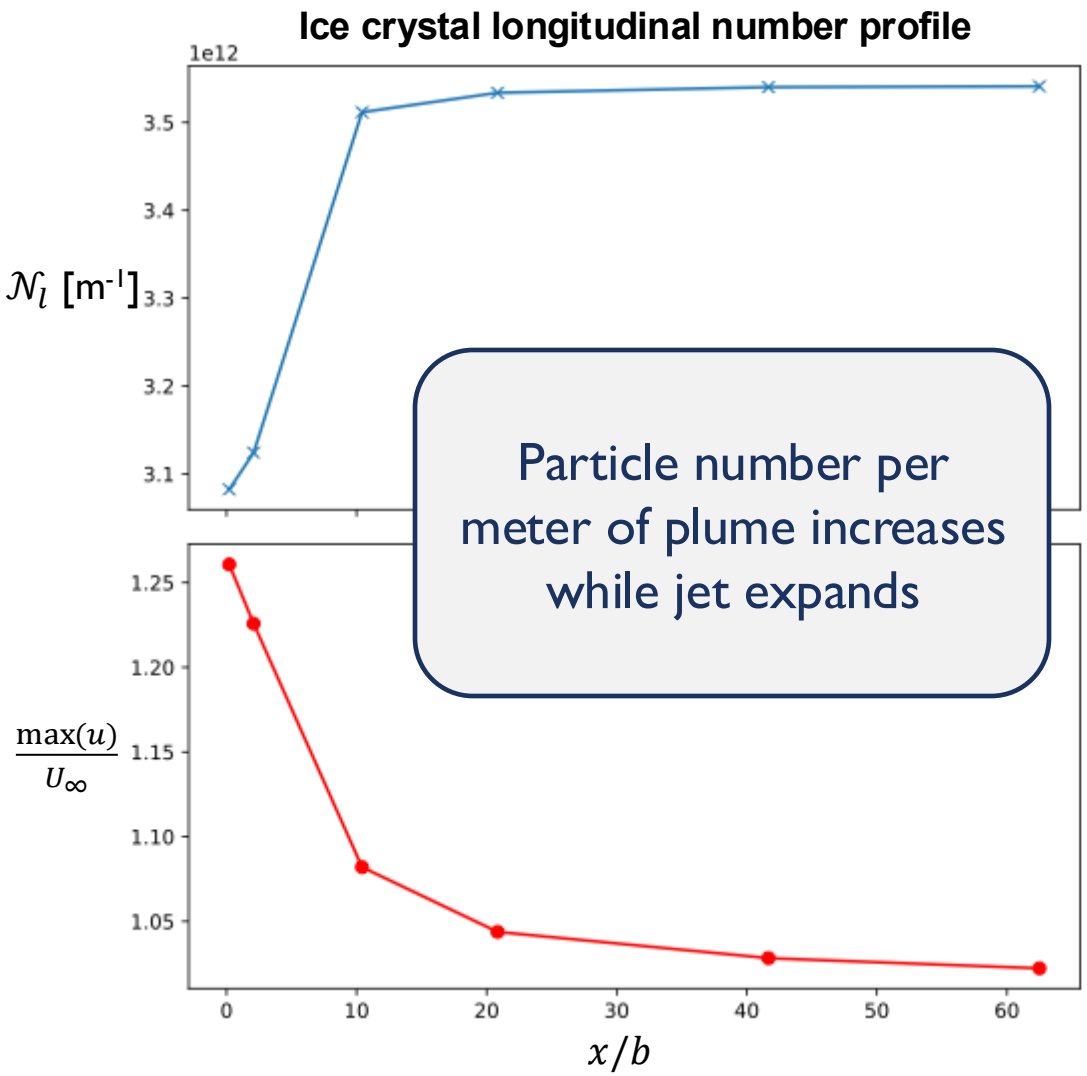




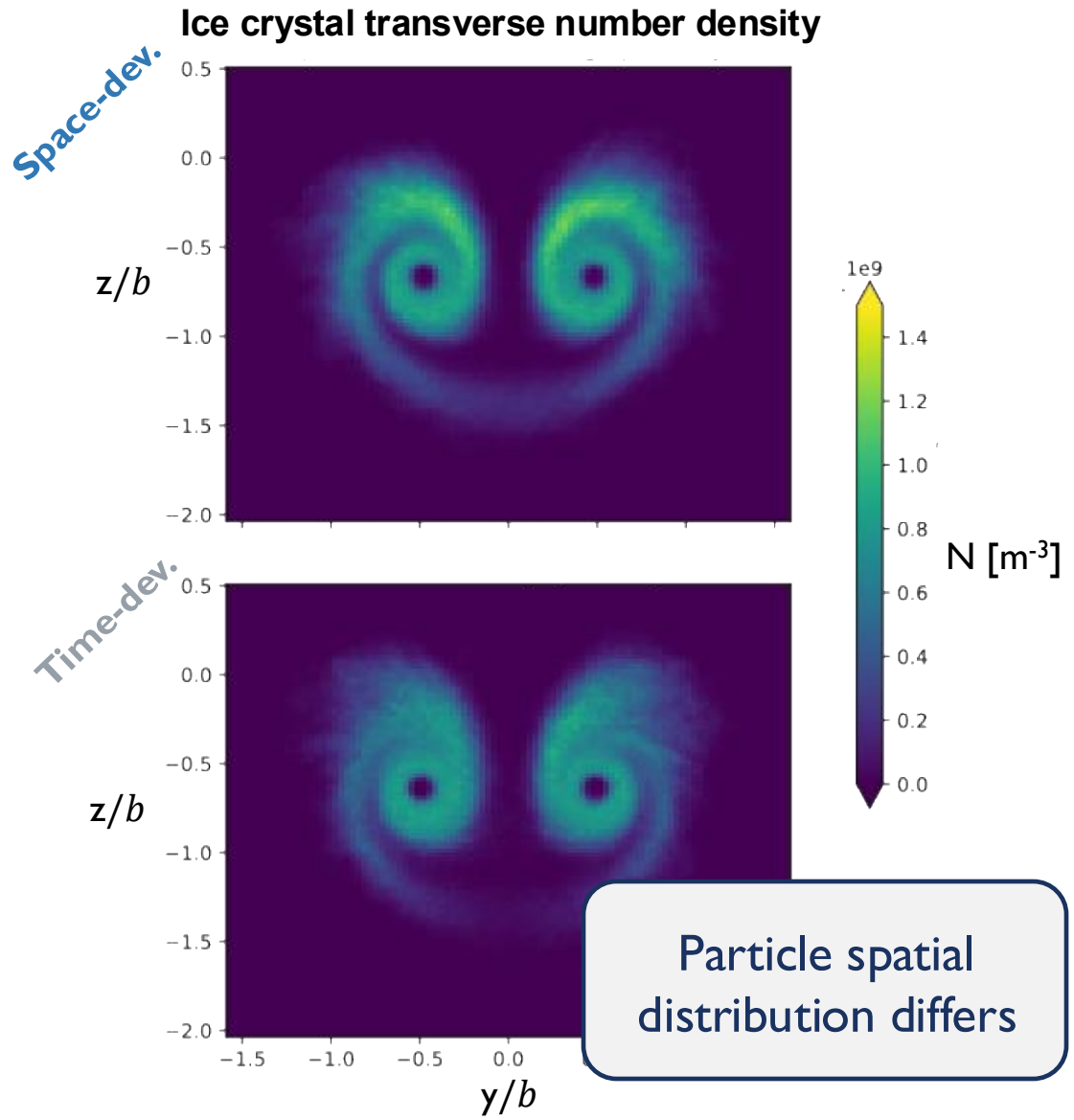
Consistent Switch From Space to Time



Capturing the Jet Expansion Matters



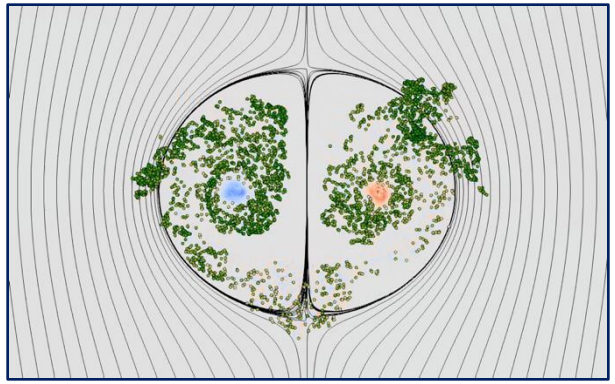
Particle number per meter of plume increases while jet expands



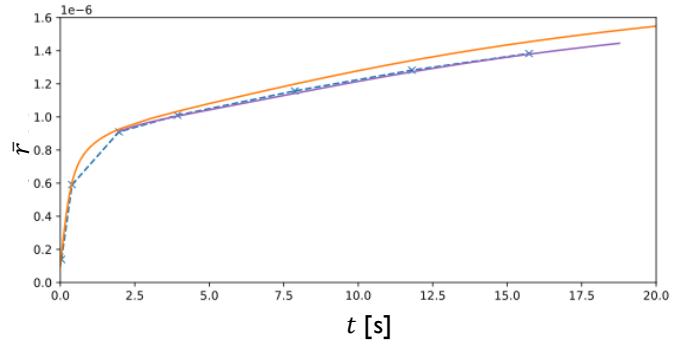
Particle spatial distribution differs

Take-home Messages

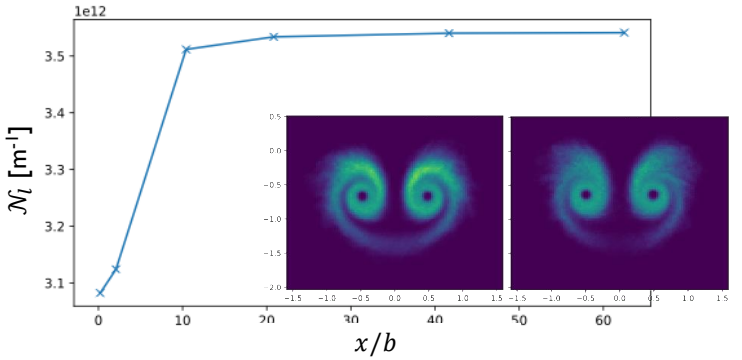
- **Particle detrainment** aggravated during jet-vortex roll-up
  - Sensitivity to initial circulation distribution to be explored



- **Consistent connection** between space- and time-developing paradigms **for $x_s \geq 10\ b$**



- Time-developing paradigm neglects **jet expansion and 3-dimensional effects**
  - affects ice crystal growth and detrainment



Questions?

Acknowledgements

Dr. Tania Ferreira (Stanford U.), Prof. Roberto Paoli (Polytech. Mtl) , Dr. Karim Shariff (NASA Ames)
for sharing of ideas, and support in conceptualization and implementation

Dr. Unterstrasser (DLR), Ms. Pauen (DLR)
for insightful discussion

Funding
was provided by a FSR Incoming Post-doctoral Fellowship granted by UCLouvain.

Computational resources
have been provided by the **Consortium des Équipements de Calcul Intensif (CÉCI)**, funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under Grant No. 2.5020.11 and by the Walloon Region.

The present research benefited from computational resources made available on **Lucia**, the Tier-1 supercomputer of the Walloon Region, infrastructure funded by the Walloon Region under the grant agreement n°1910247.

We acknowledge EuroCC Belgium for awarding this project access to **the LUMI supercomputer**, owned by the EuroHPC Joint Undertaking, hosted by CSC (Finland) and the LUMI consortium through EuroCC Belgium.

References

1. F. Bonelli, A. Viggiano, and V. Magi. High-speed turbulent gas jets: an les investigation of mach and reynolds number effects on the velocity decay and spreading rate. Flow, Turbulence and Combustion, 107(3):519–550, 2021.

2. T. S. Ferreira, D.-G. Caprace, R. Paoli, K. Shariff, and S. K. Lele. Can inducing the crow instability reduce contrail radiative forcing? In Proceedings of the Summer Program 2024, volume XIV of Study- ing Turbulence Using Numerical Simulation Databases, pages 13–22. Center for Turbulence Research, Stanford University, CA, 2024.

3. P. Chatelain, A. Curioni, M. Bergdorf, D. Rossinelli, W. Andreoni, and P. Koumoutsakos. Billion vortex particle Direct Numerical Simulations of aircraft wakes. Computer Methods in Applied Mechanics and Engineering, 197(13):1296–1304, Feb 2008.

4. D.-G. Caprace, G. Winckelmans, and P. Chatelain. An immersed lifting and dragging line model for the vortex particle-mesh method. Theoretical and Computational Fluid Dynamics, 34:21–48, 2020.