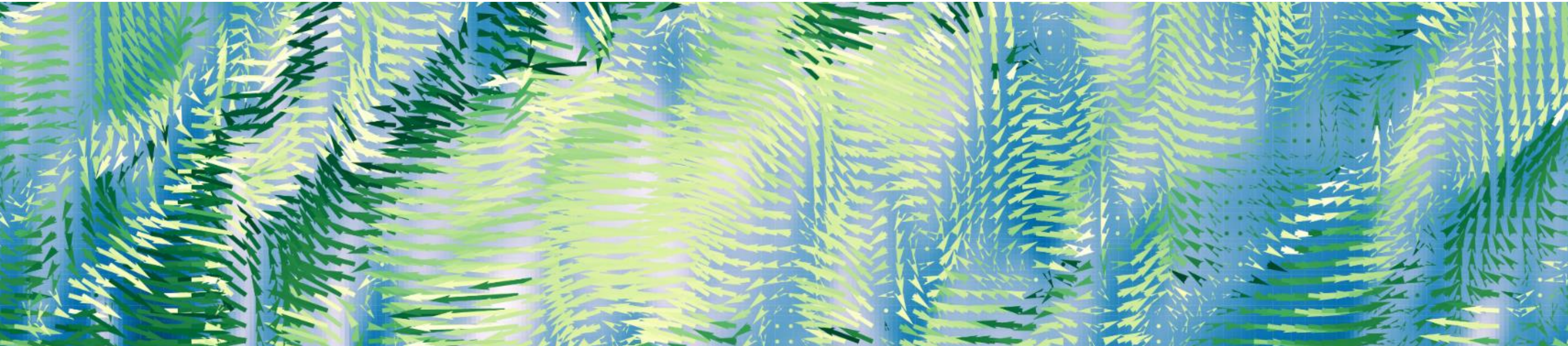
Institute of Aerodynamics and Chair of Fluid Mechanics | RWTH AACHEN UNIVERSITY

Deep Recurrent Neural Networks for Optical Flow Learning in Particle-Image Velocimetry

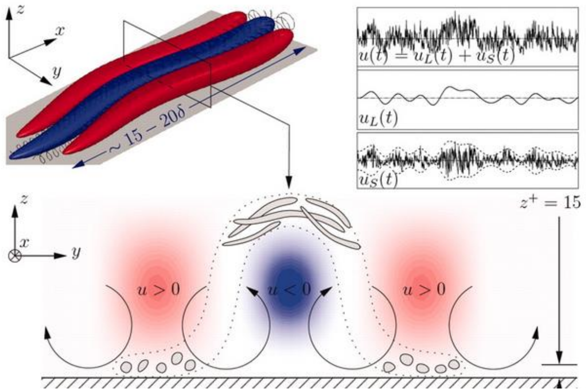
Dr.-Ing. Christian Lagemann



MOTIVATION

Particle-Image Velocimetry is the **most relevant flow measurement technique** in modern **experimental fluid mechanics** research

academia



fundamental research related to turbulent wall-bounded flows

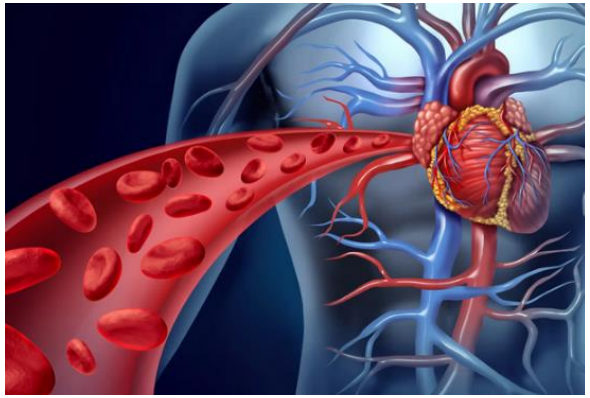
validation of numerical models

transportation

friction drag reduction techniques

efficient gas/liquid transport in public utility infrastructure

human health

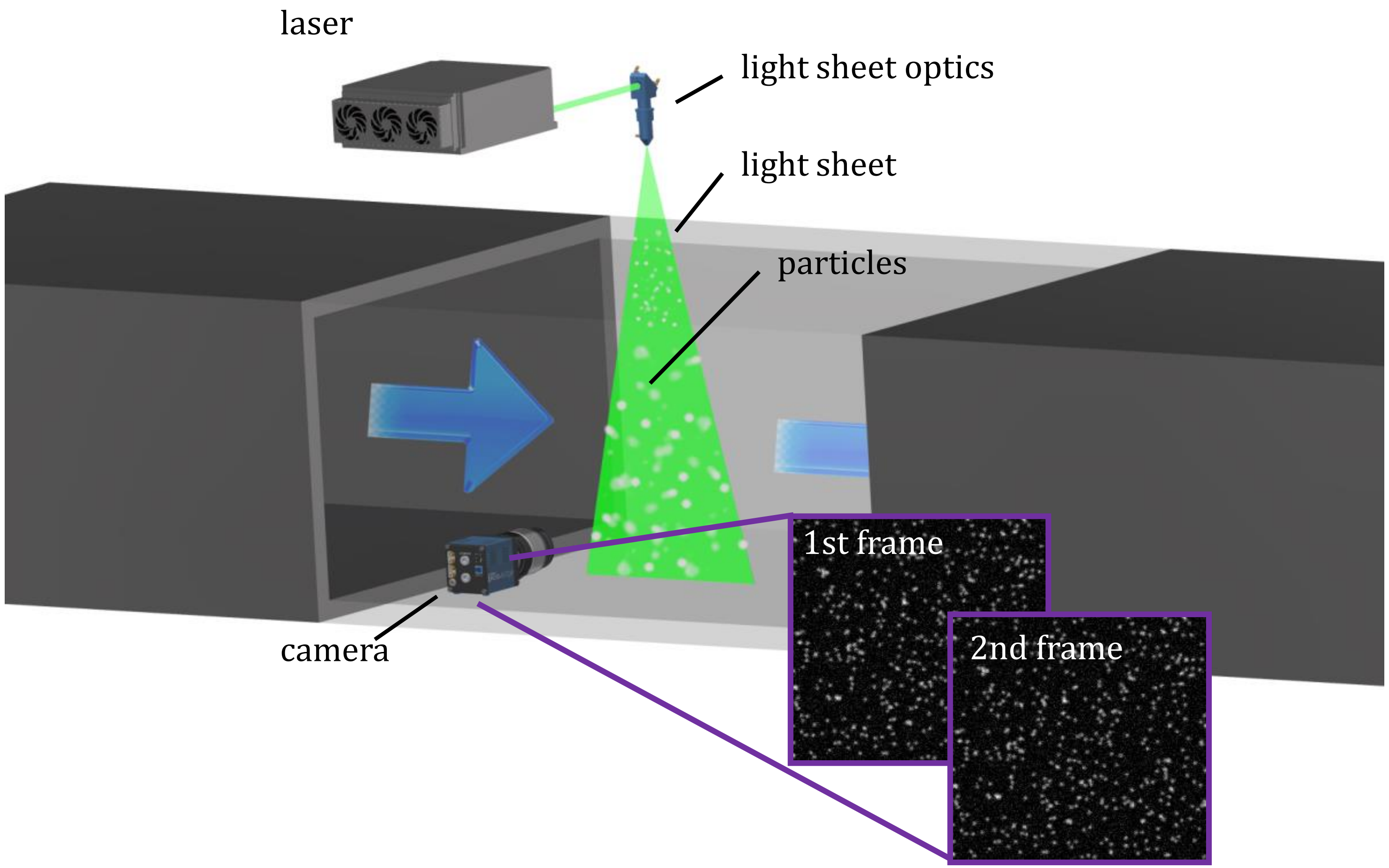


evolution & treatment of atherosclerosis

deposition behavior in human lungs

…

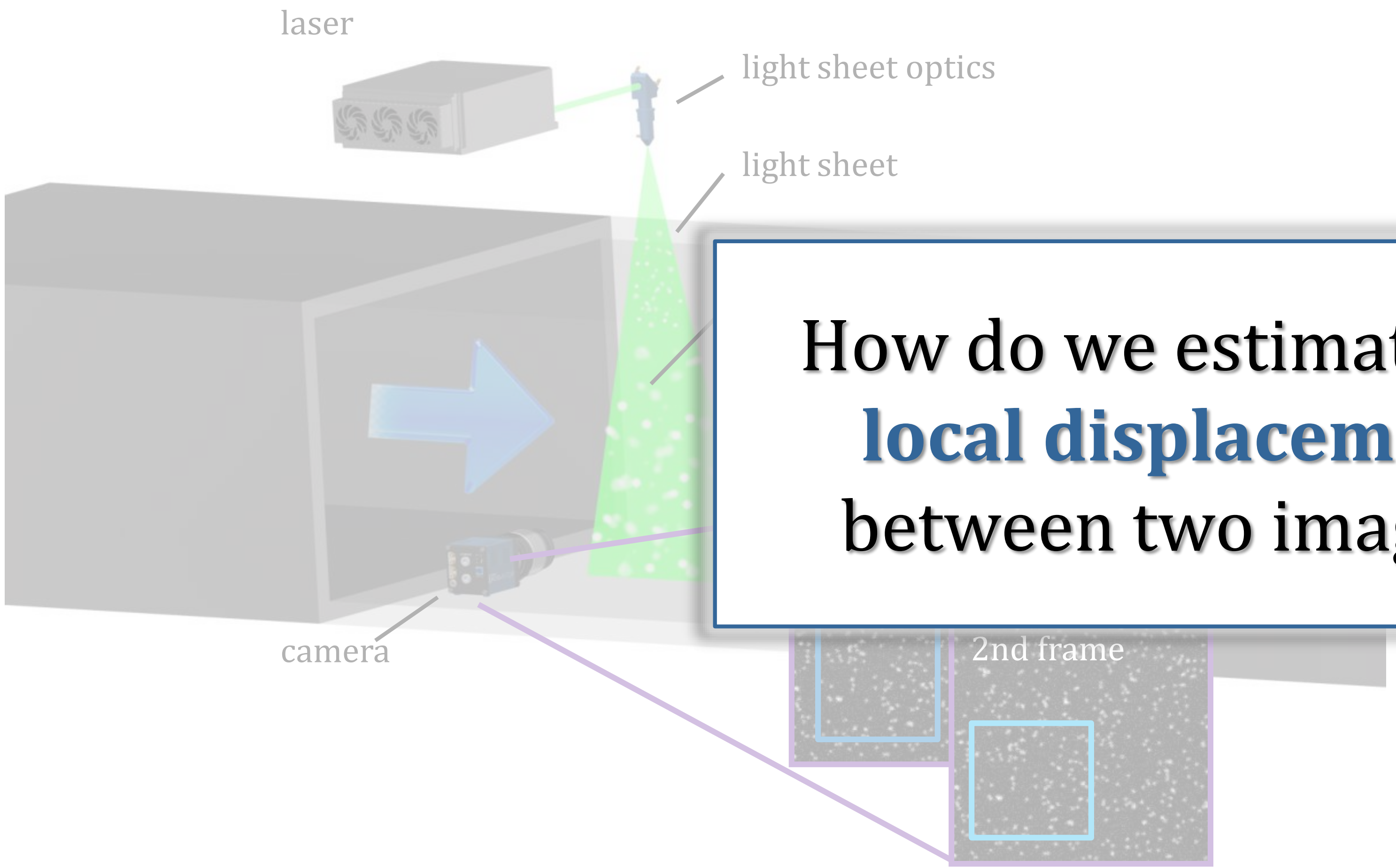
MOTIVATION



Fluid flow measurement in a wind tunnel or a water tunnel using PIV:

- Non-invasive optical measurement technique
- Tracer particles visualize the flow movement

MOTIVATION

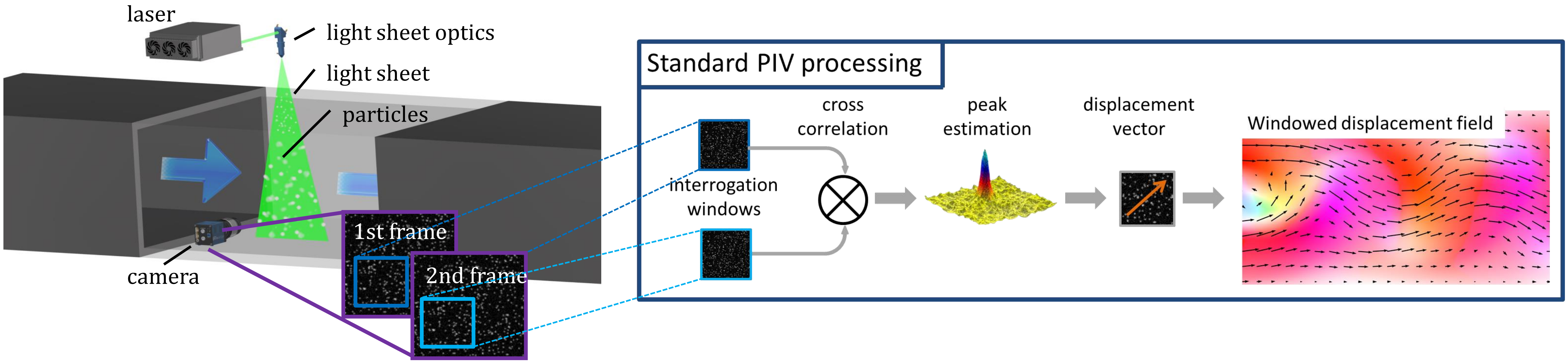


Fluid flow measurement in a wind tunnel or a water tunnel using PIV:

- Non-invasive optical measurement technique
- Tracer particles visualize the flow movement

How do we estimate the **local displacement** between two images?

MOTIVATION


laser
light sheet optics
light sheet
particles
camera
1st frame
2nd frame
Standard PIV processing
interrogation windows
cross correlation
peak estimation
displacement vector
Windowed displacement field

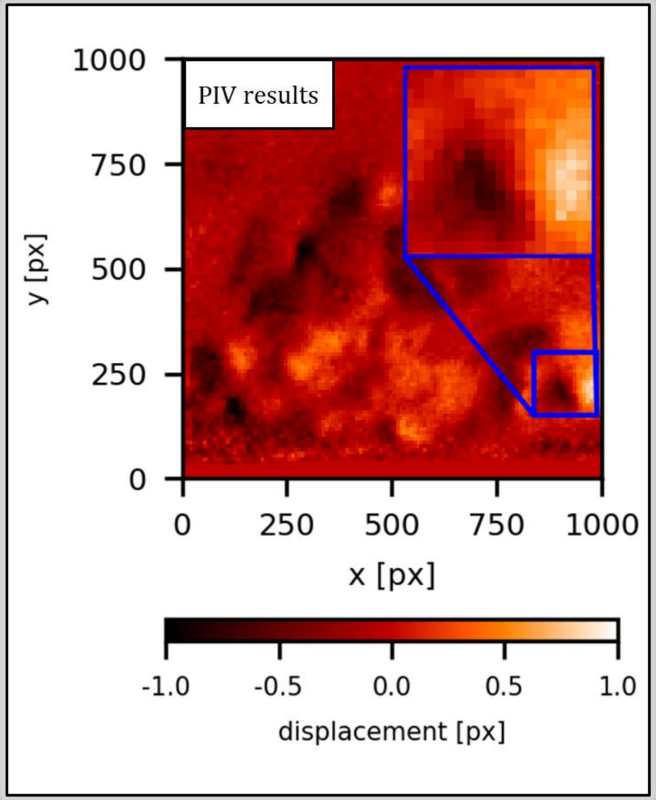
MOTIVATION

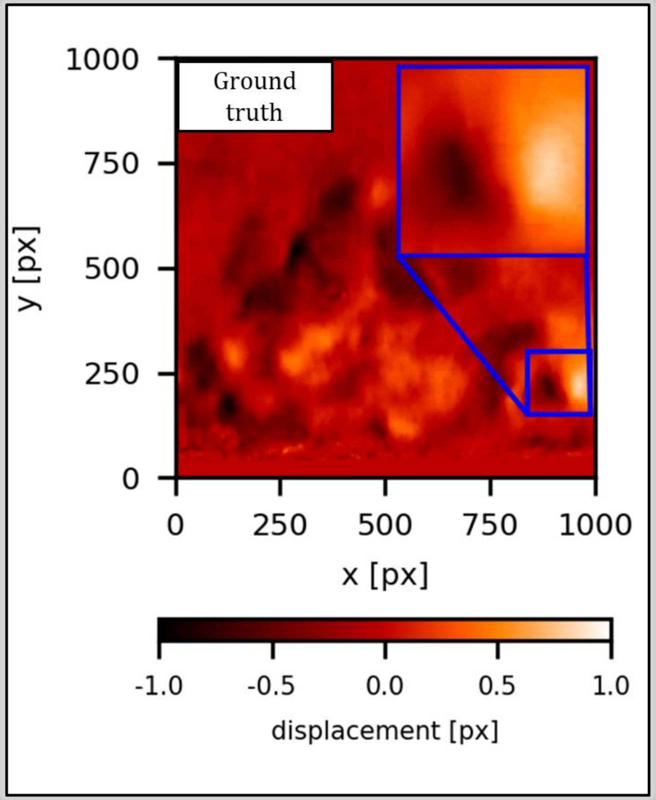
laser

light sheet optics

Standard PIV processing

Cross-correlation yields an inherent avergaging of the underlying flow field!





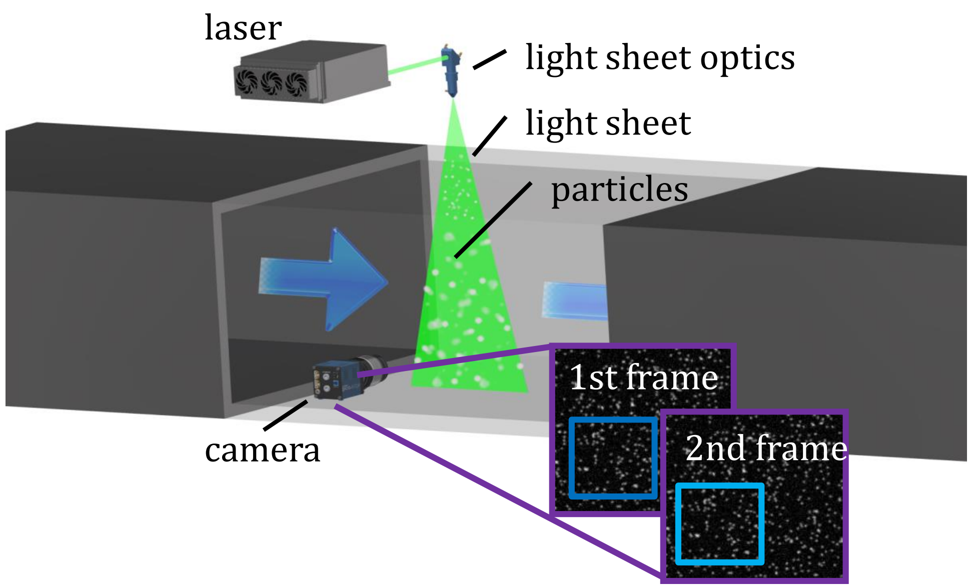
MOTIVATION

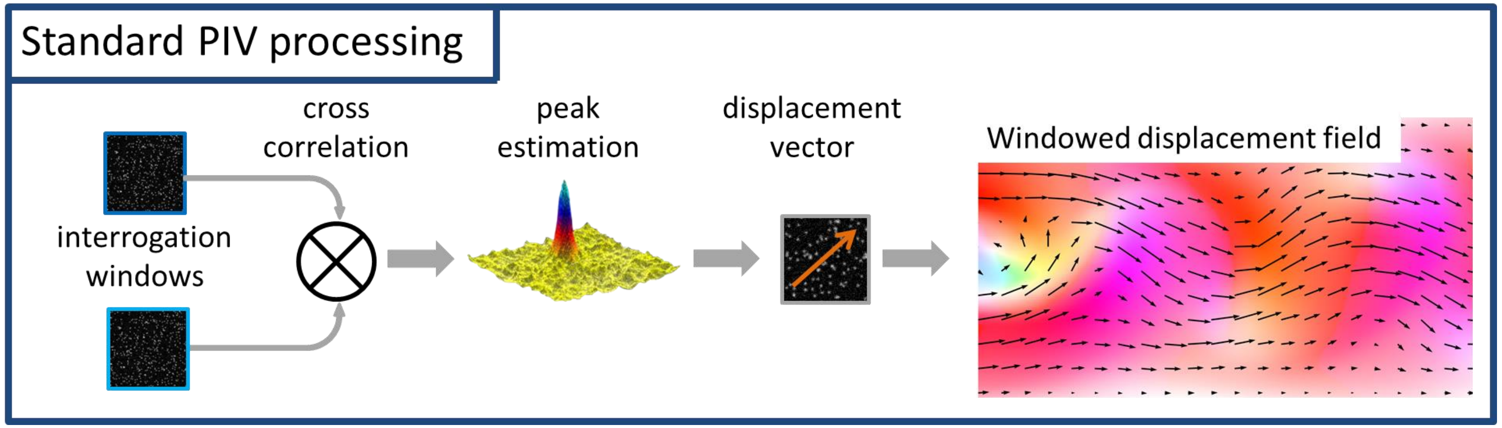
Cross-correlation yields an inherent avergaging of the underlying flow field!

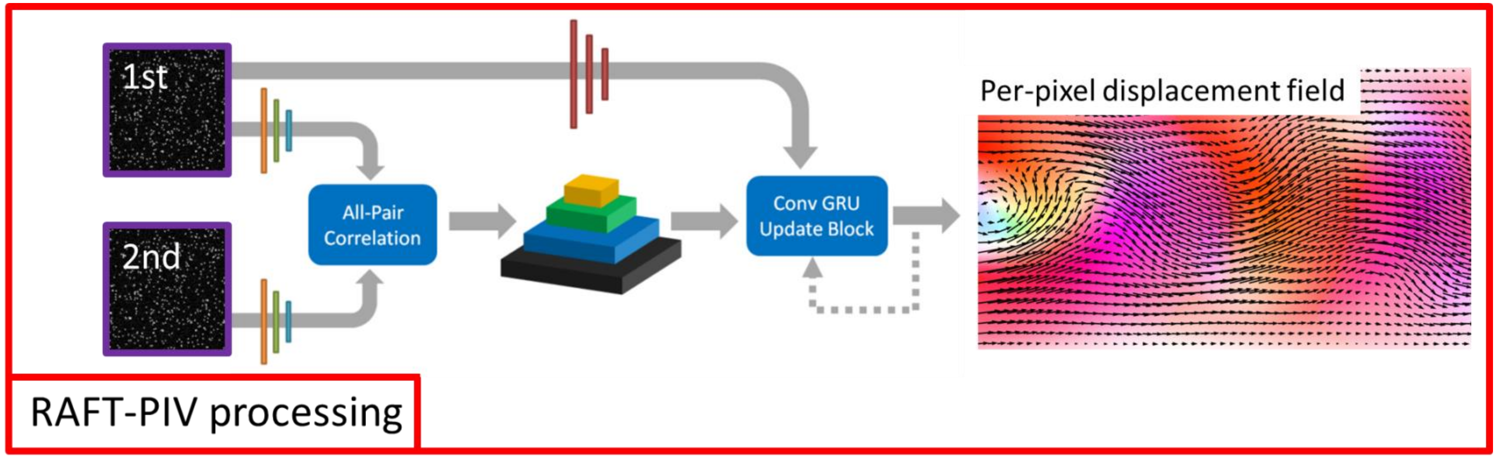
A new image processing method is required that

- extracts the **rich small-scale information** in PIV images
- has a very **high spatial resolution**
- possesses a **high accuracy**/physical significance
- preferably **simple experimental setup**

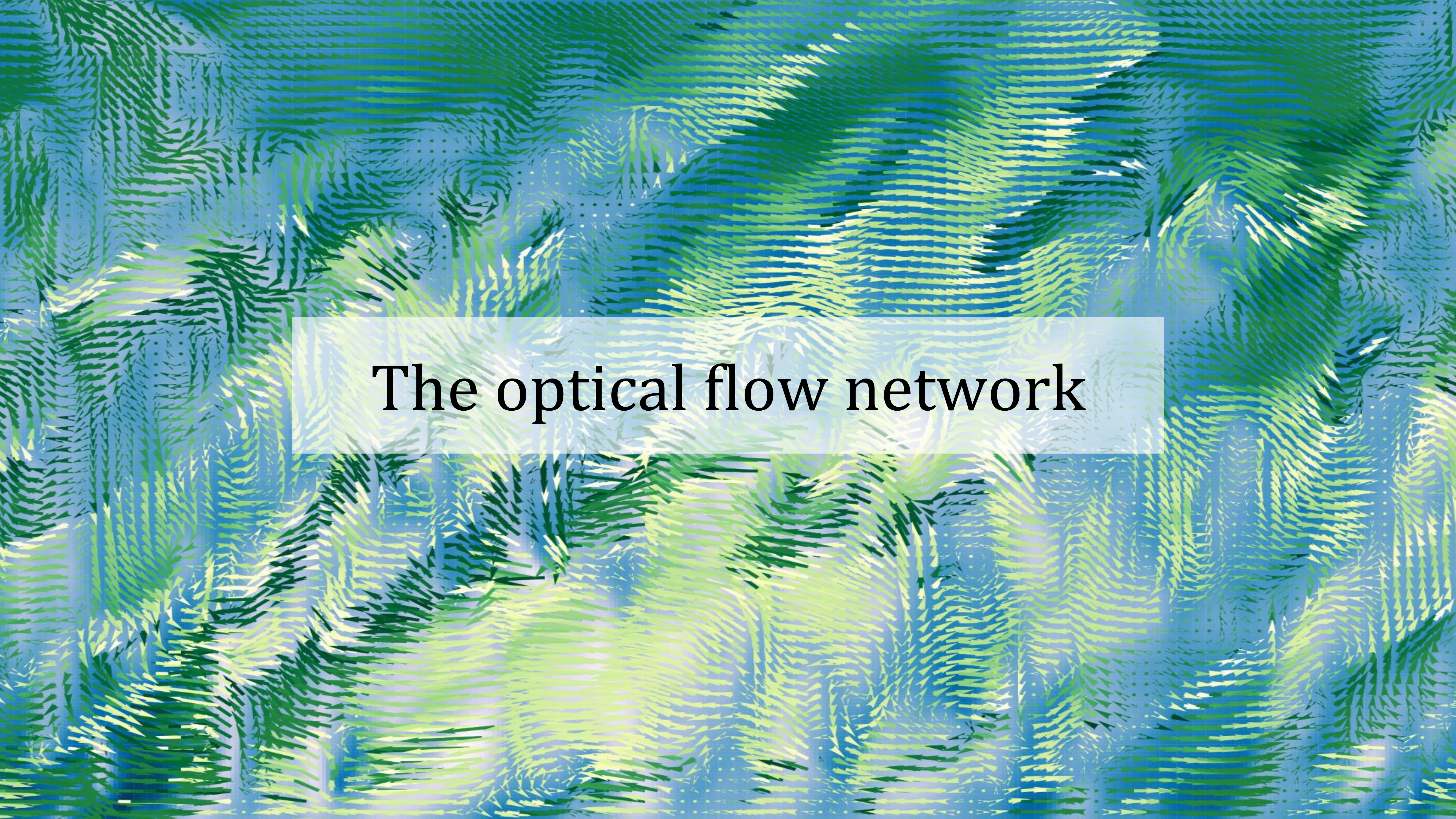
MOTIVATION



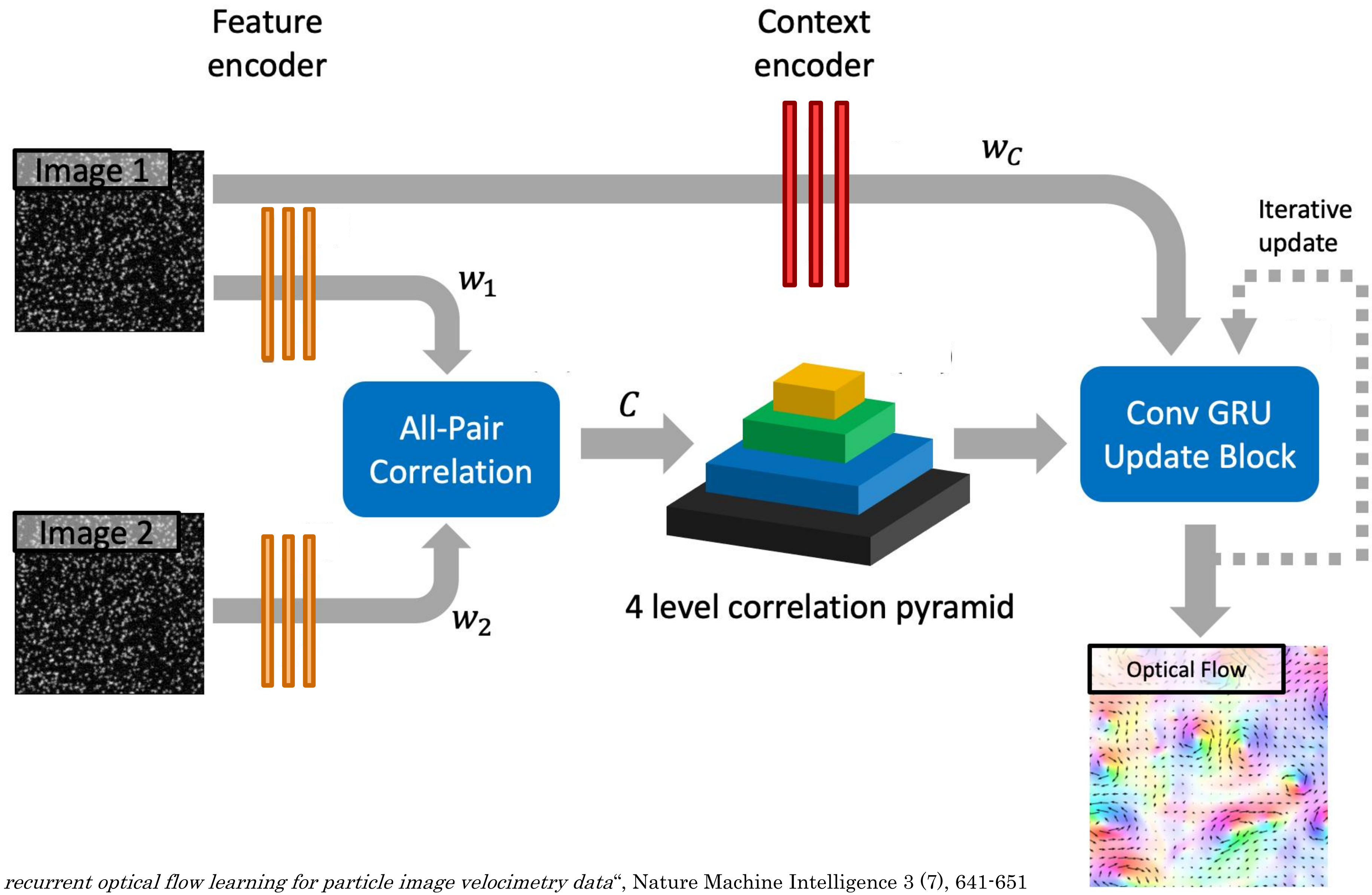




RAFT-PIV allows an **unmatched spatial per-pixel resolution**


The optical flow network

RAFT-PIV: An overview

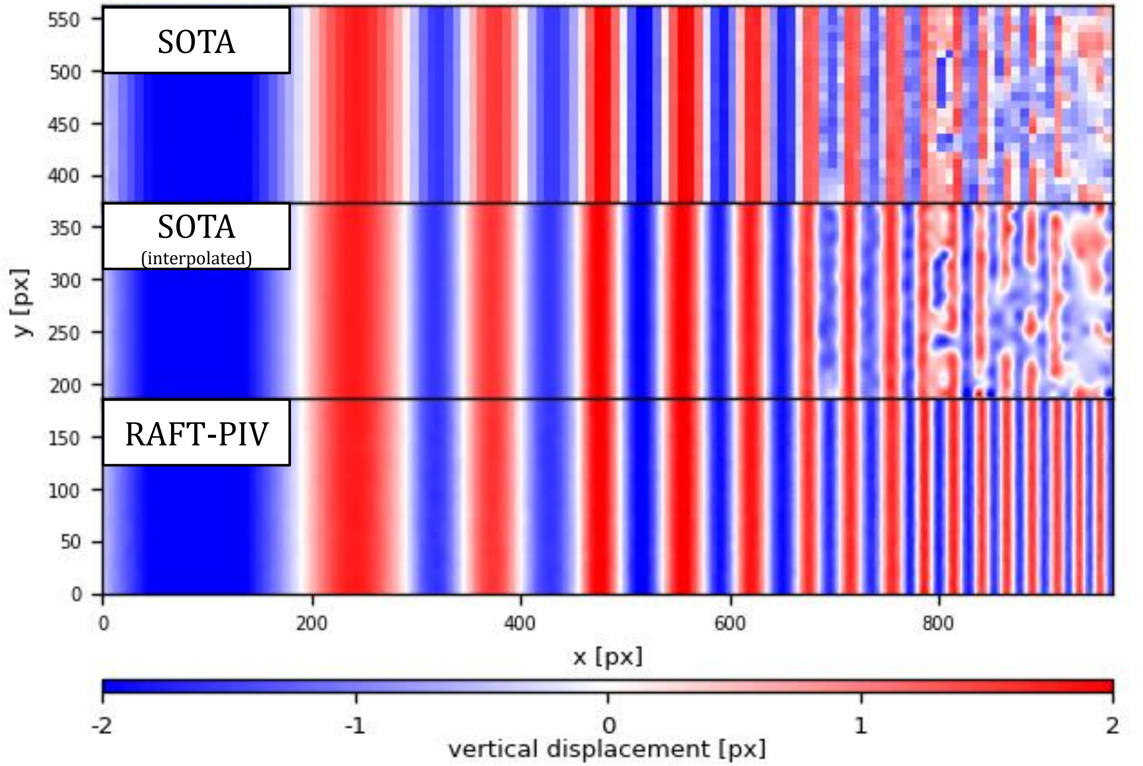


Lagemann et al., "*Deep recurrent optical flow learning for particle image velocimetry data*", Nature Machine Intelligence 3 (7), 641-651

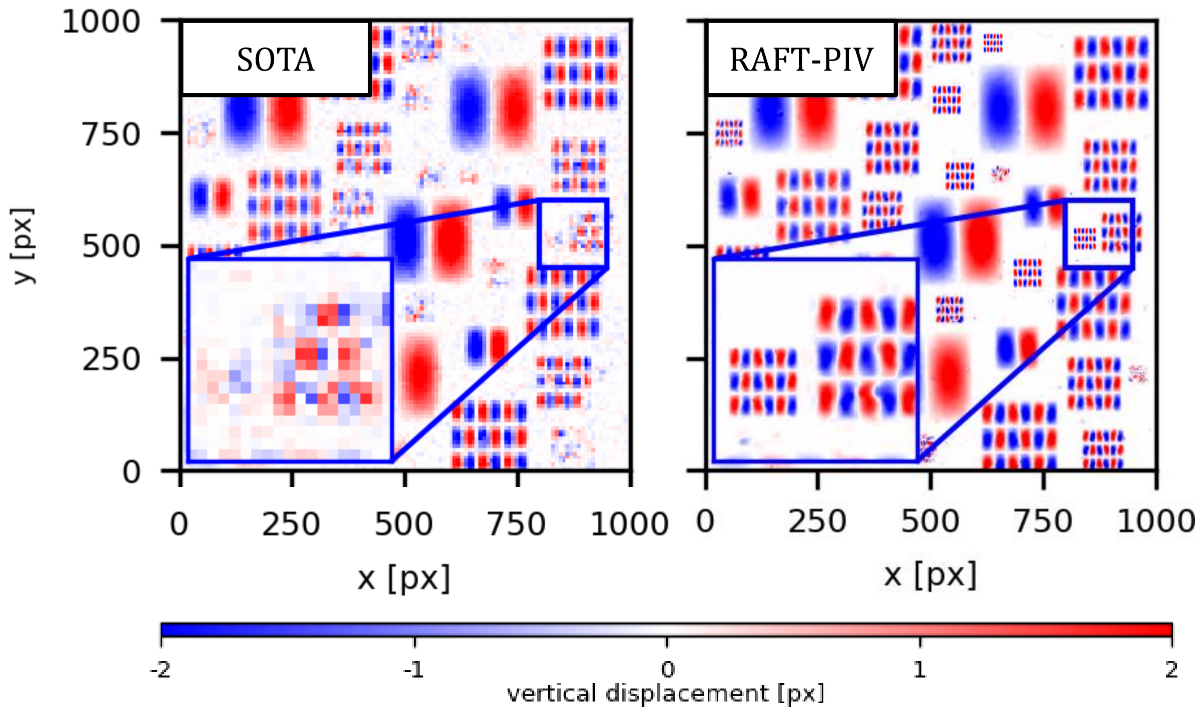
Spatial resolution ability

RAFT-PIV: Spatial resolution ability

Benchmark: 1D frequency modulated sine wave



Benchmark: isolated vortex packages with varying spatial gradients



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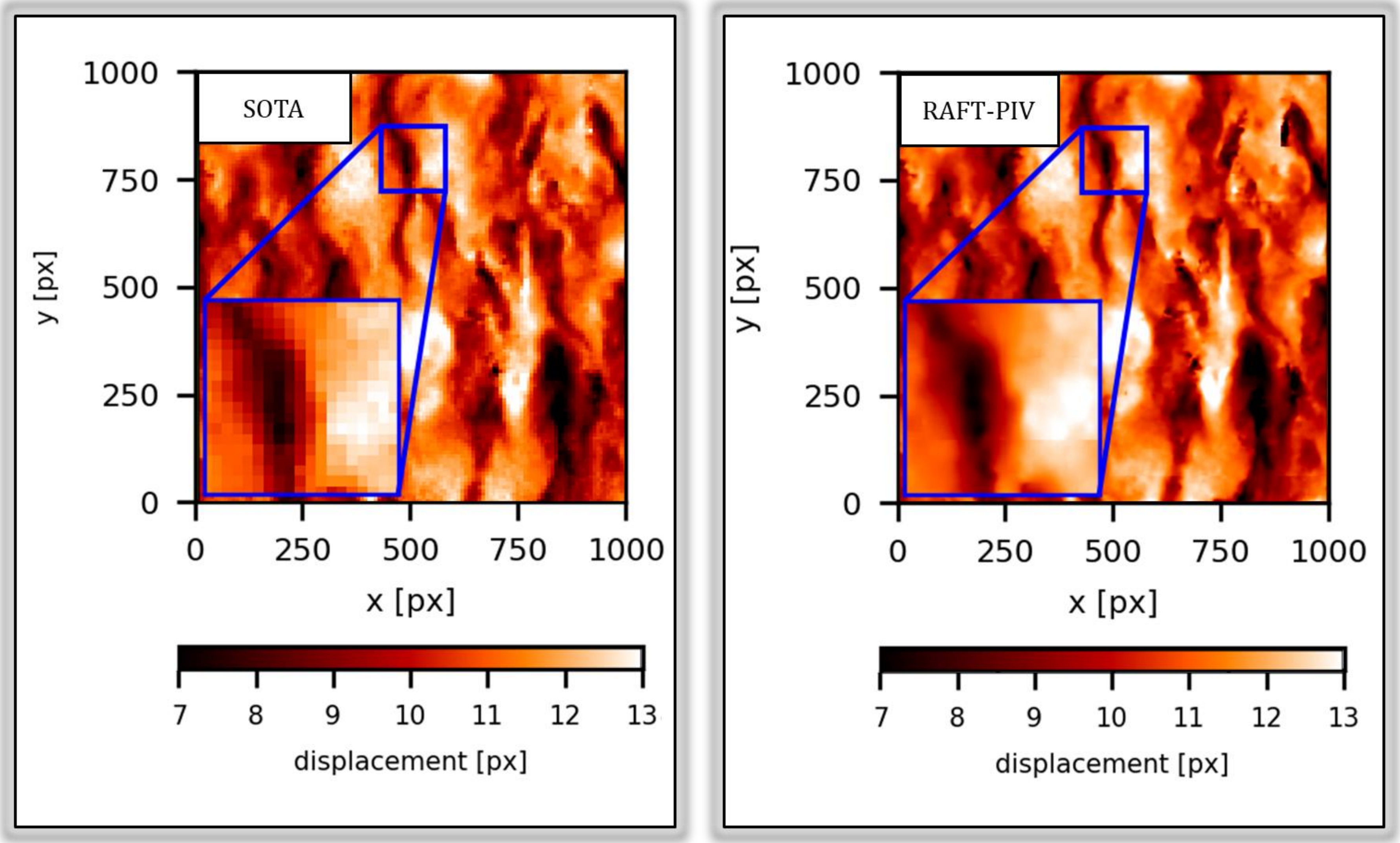
Lagemann et al., "*Generalization of deep recurrent optical flow estimation for particle-image velocimetry data*", Measurement Science and Technology 33 (9), 094003

Real-world measurement results

RAFT-PIV: Generalization ability

wall-parallel measurement of a turbulent channel flow



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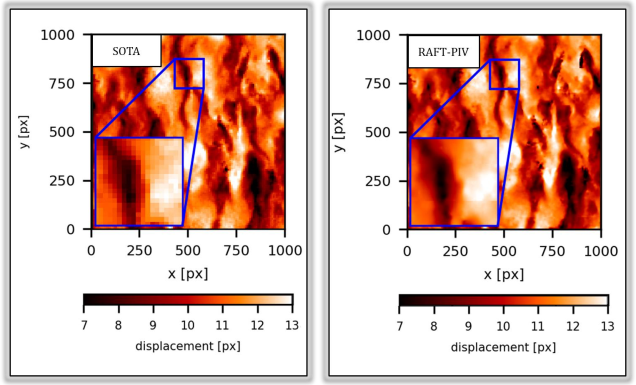
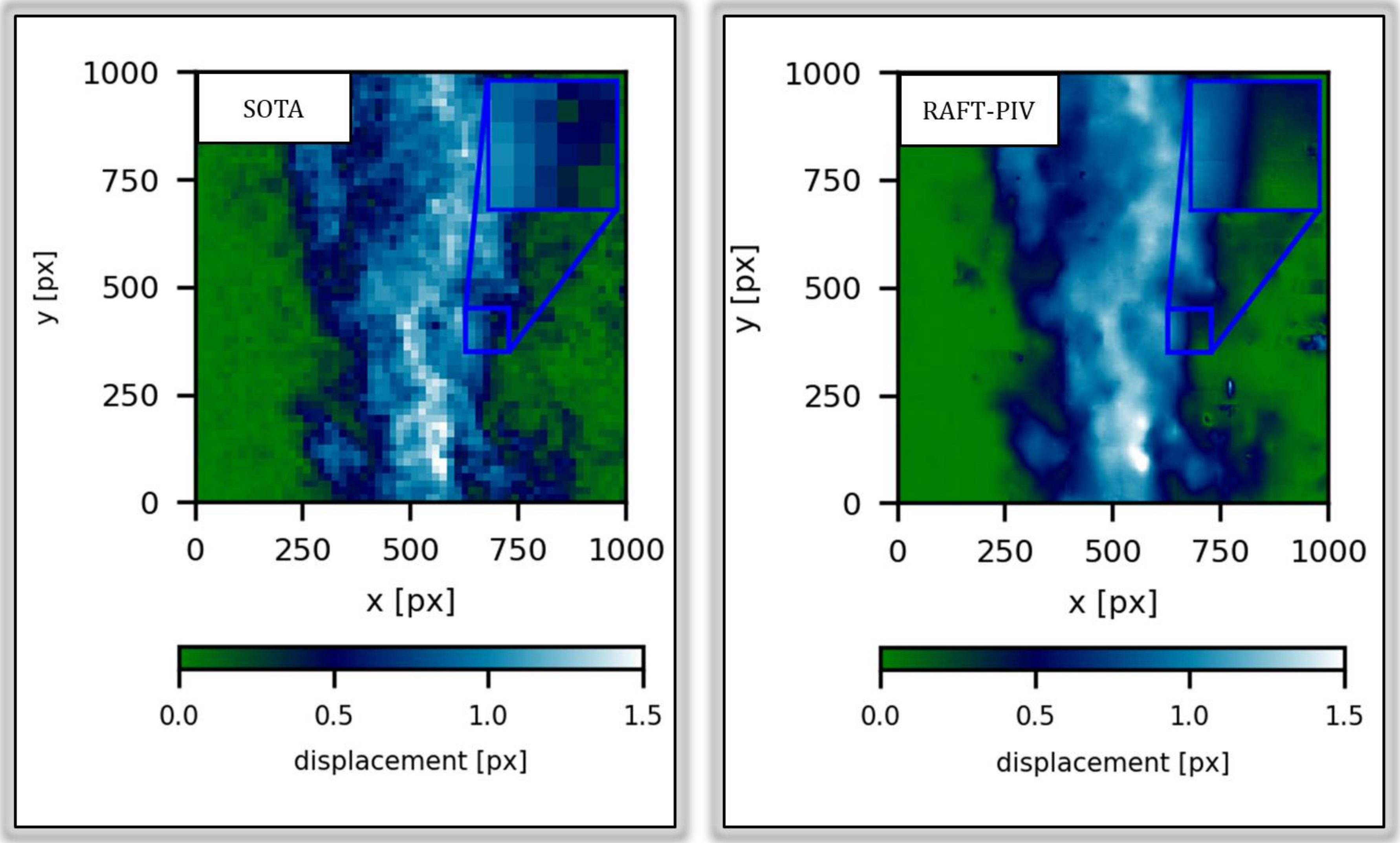
RAFT-PIV: Generalization ability



turbulent jet flow



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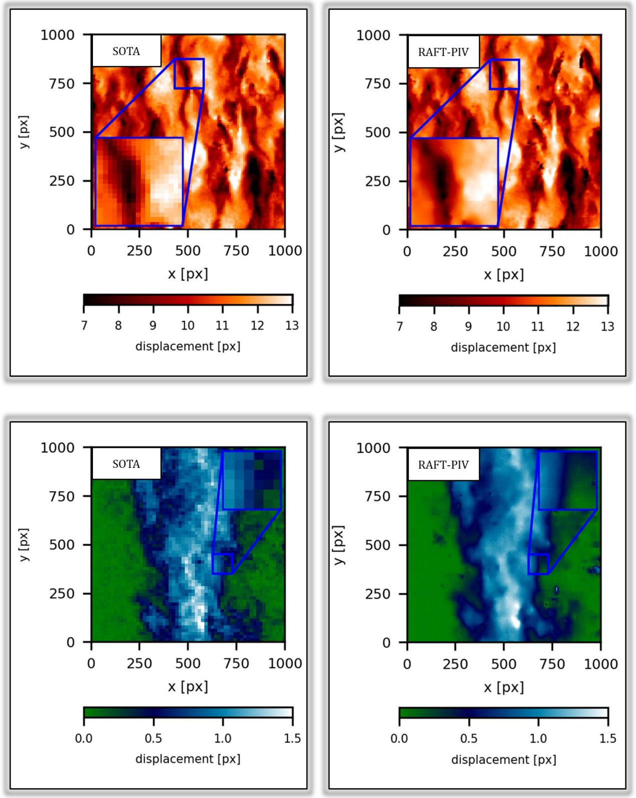
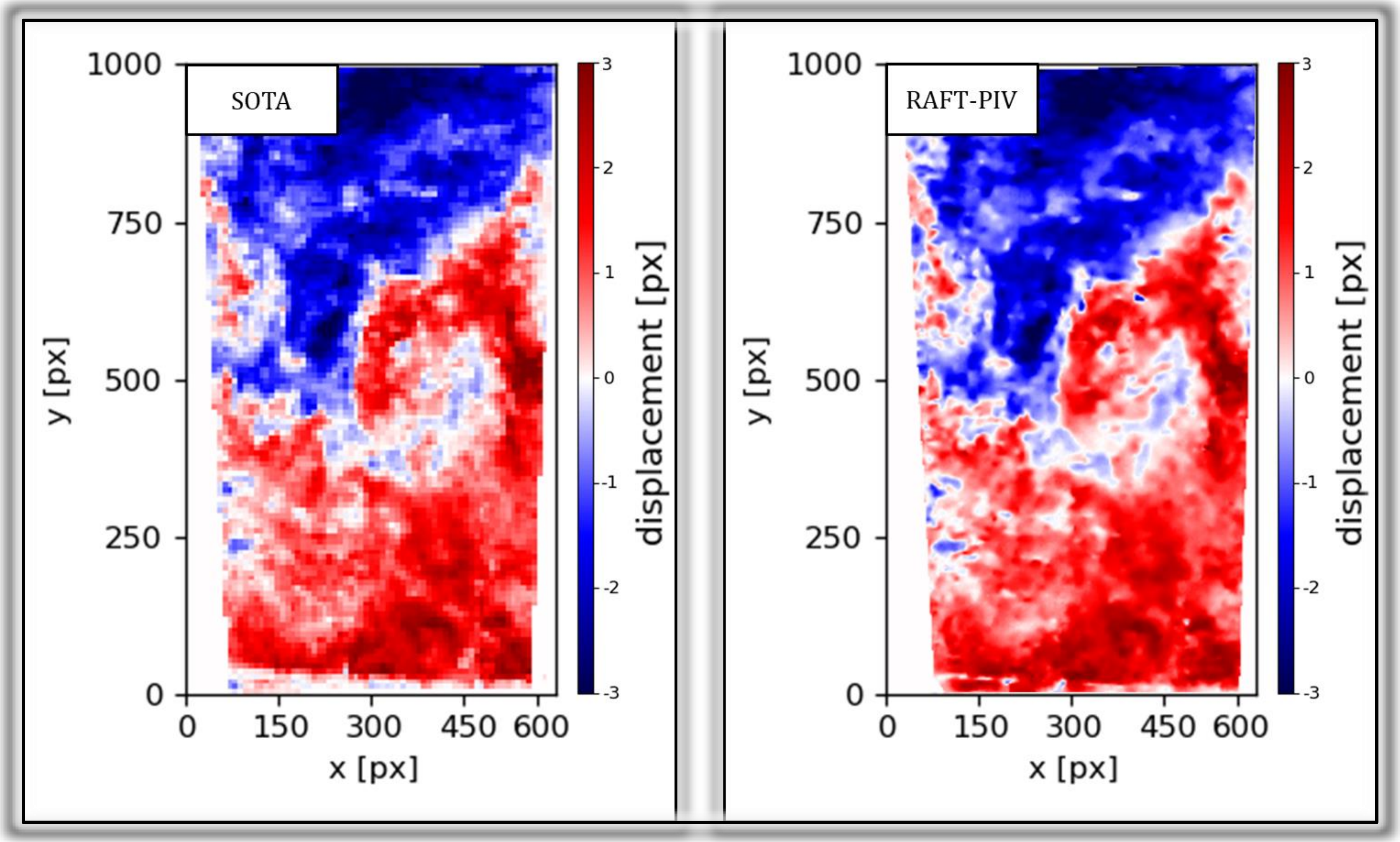


flow inside an internal combustion engine



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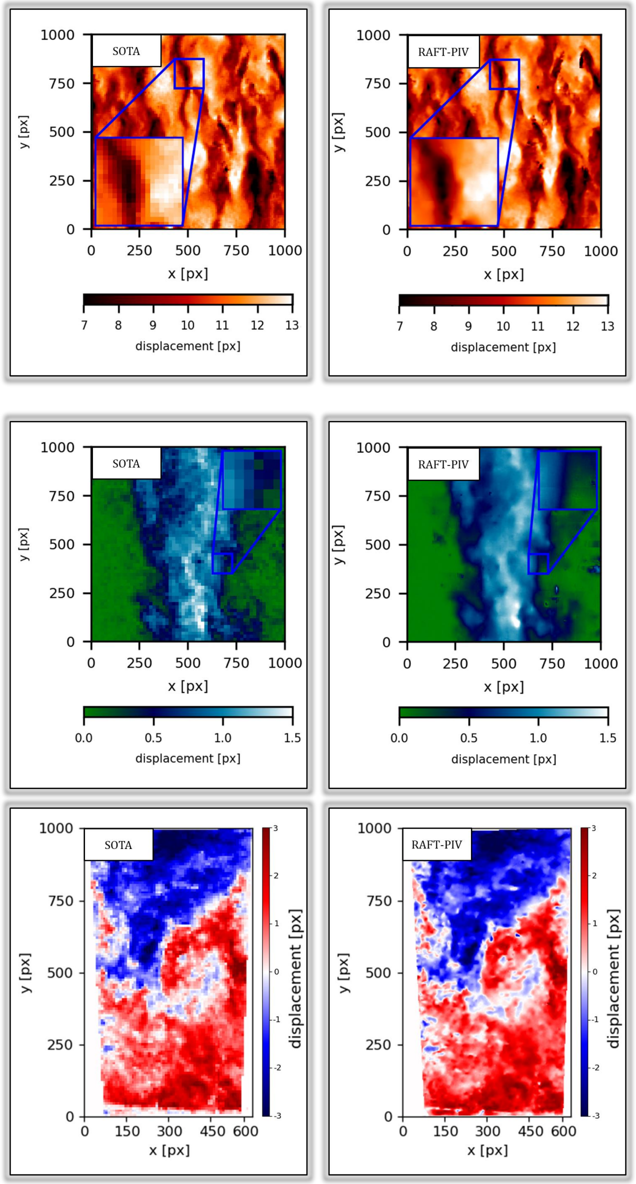
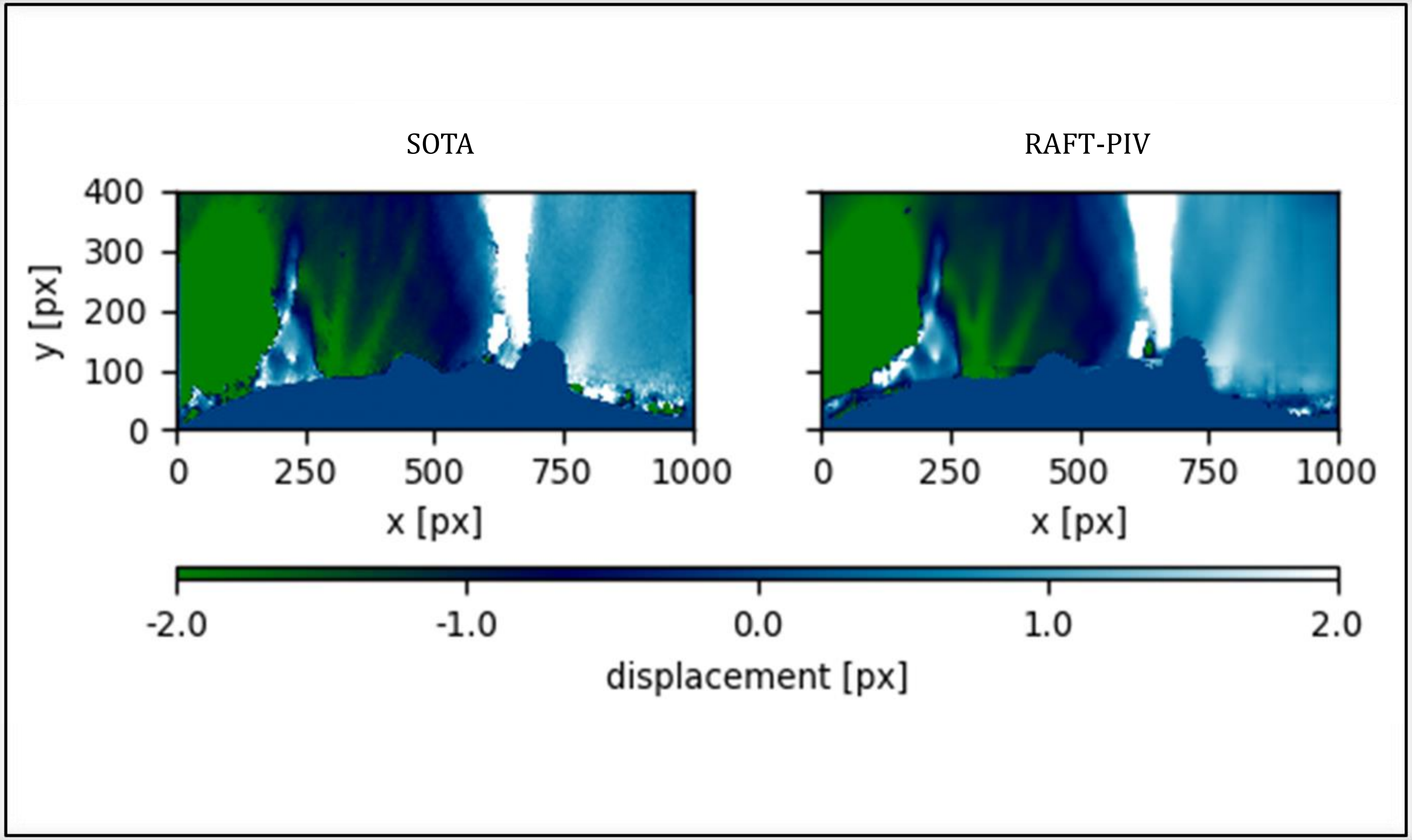
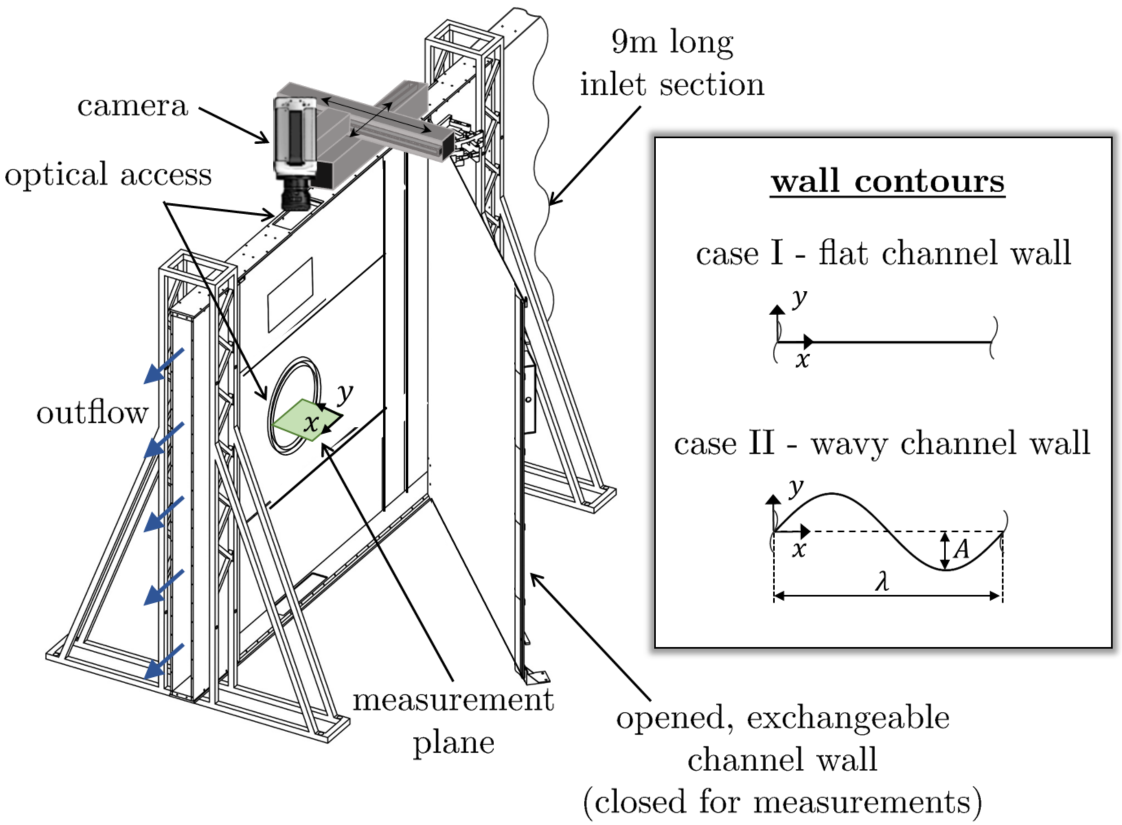


Background Oriented Schlieren images



Impact on measurement analysis

EXPERIMENTAL SETUPS



- Eiffel type wind tunnel with exchangeable side wall → TCF and TWCF measurements in the same facility
- wall-normal mono PIV (2D-2C)
- TWCF: $A = 0.1h, \lambda = 2h$ (h: flat channel half-height)

	Re_τ	laser	camera	lens
case I TCF	1120	Darwin Duo 40	Photron SA3	Tamron 180mm
case II TWCF	200	New Wave Solo 200XT	PCO edge 5.5 sCMOS	Zeiss 100mm

Lagemann et al., "*Uncovering wall-shear stress dynamics from neural-network enhanced fluid flow measurements*", Nature Computational Science, 2023 - *(under review)*

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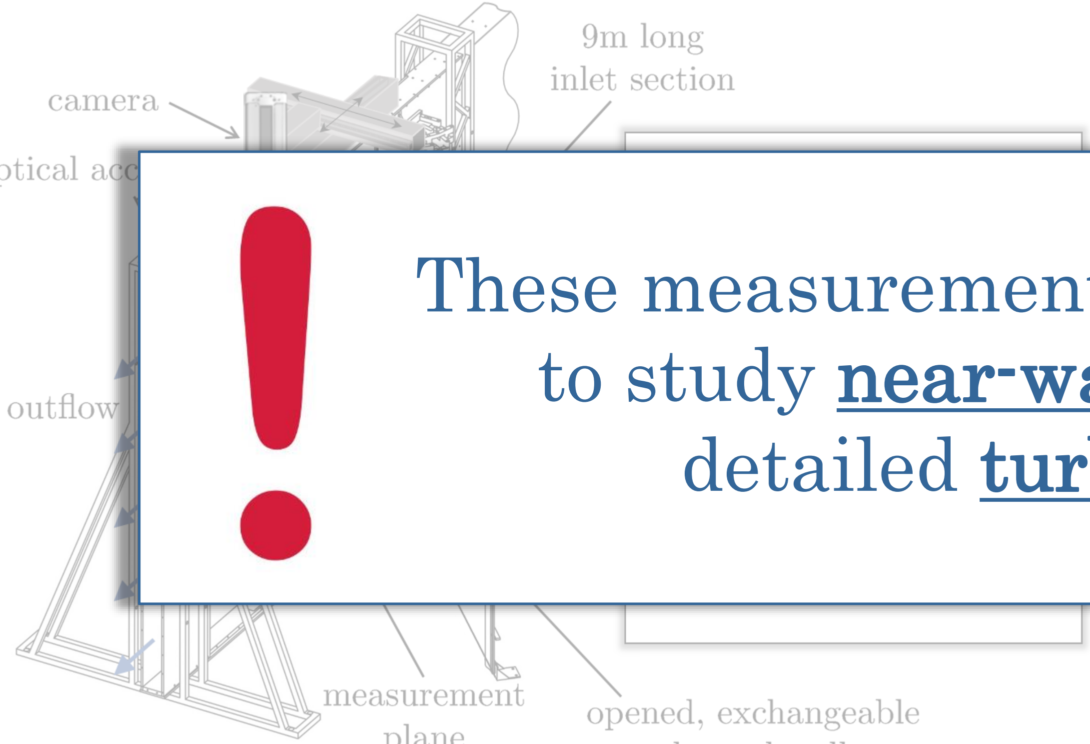

- Eiffel type wind tunnel with exchangeable side wall → TCF and TWCF measurements

These measurements **have not been designed** to study **near-wall flow quantities** and detailed **turbulence statistics**!

	Re_τ	laser	camera	lens
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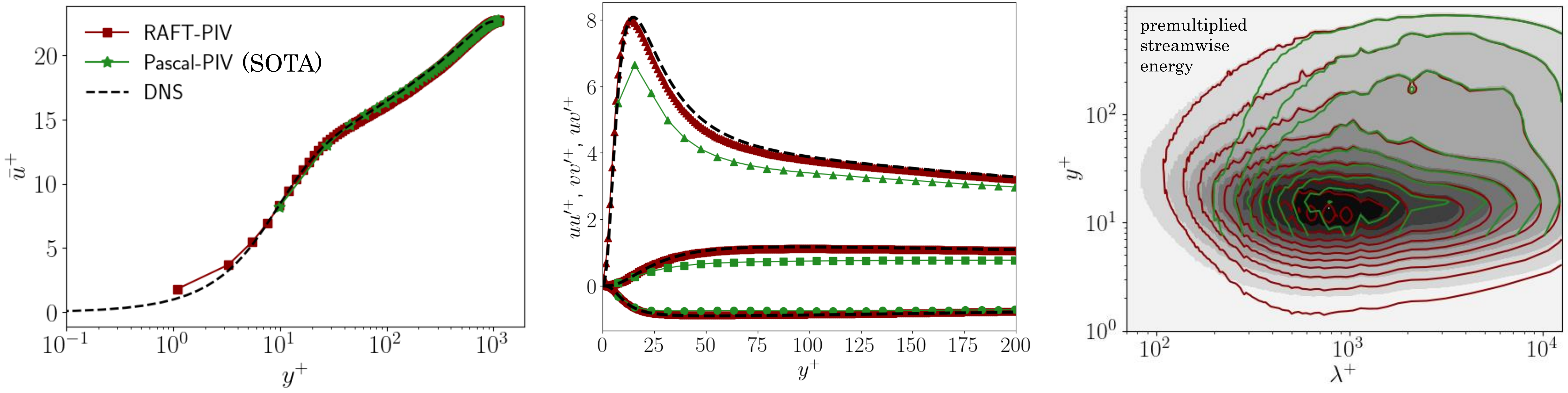
CASE I: TCF



advantages of RAFT-PIV compared to state-of-the-art PIV processing

- significantly increased spatial resolution
- resolves viscous sublayer with high accuracy
- resolves near-wall velocity gradients

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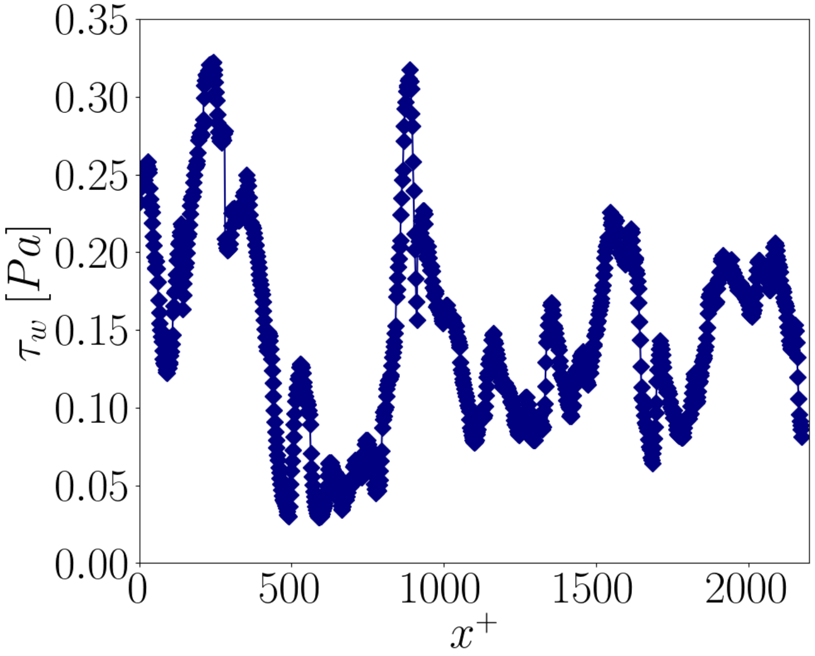

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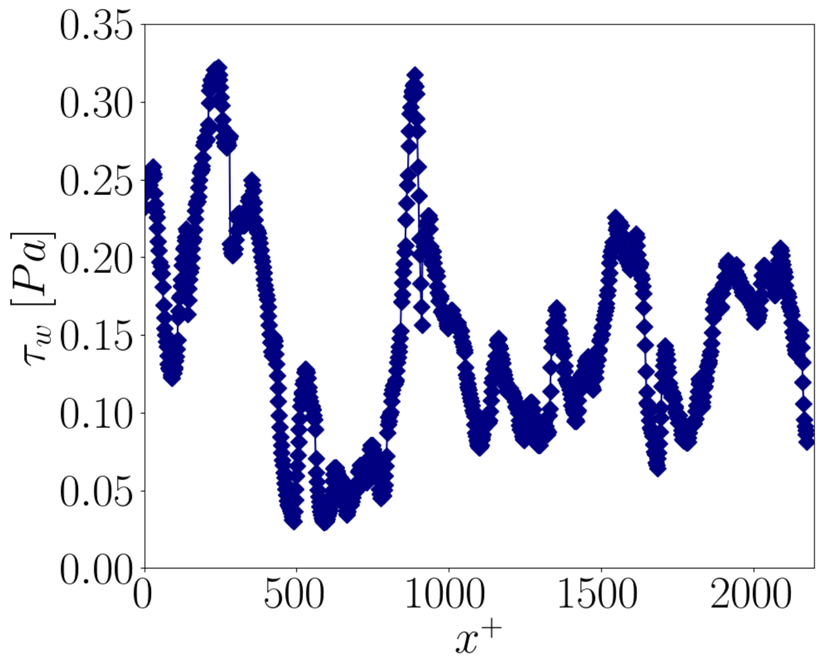

temporally and spatially averaged wall-shear stress:

$$\left.\begin{aligned}\bar{\tau}_{w,theory} &= 0.127\ Pa\\ \bar{\tau}_{w,RAFT} &= 0.135\ Pa\end{aligned}\right\}\ \Delta\bar{\tau}_w = 6.2\%$$

→ verification on an instantaneous level requires **ground truth** information
→ using **synthetic particle images** where underlying distribution is known

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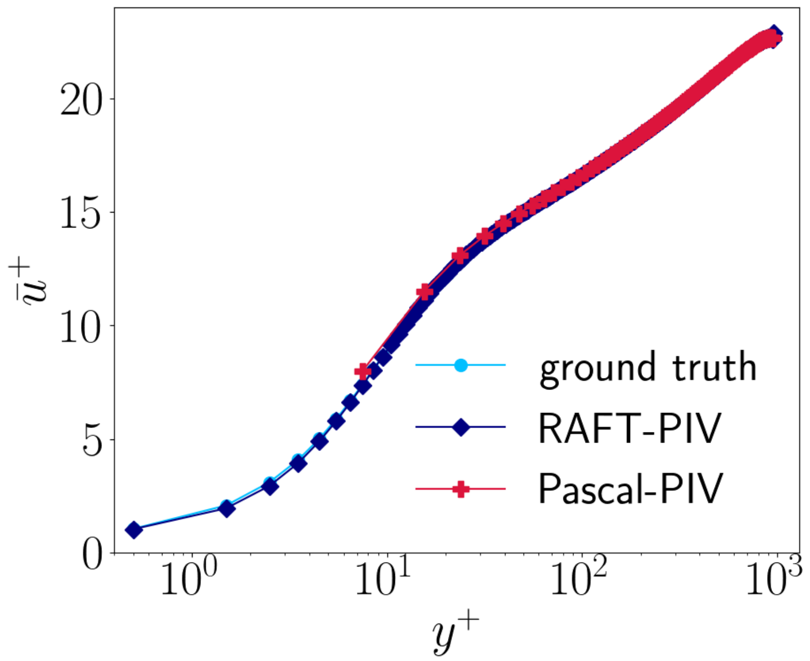
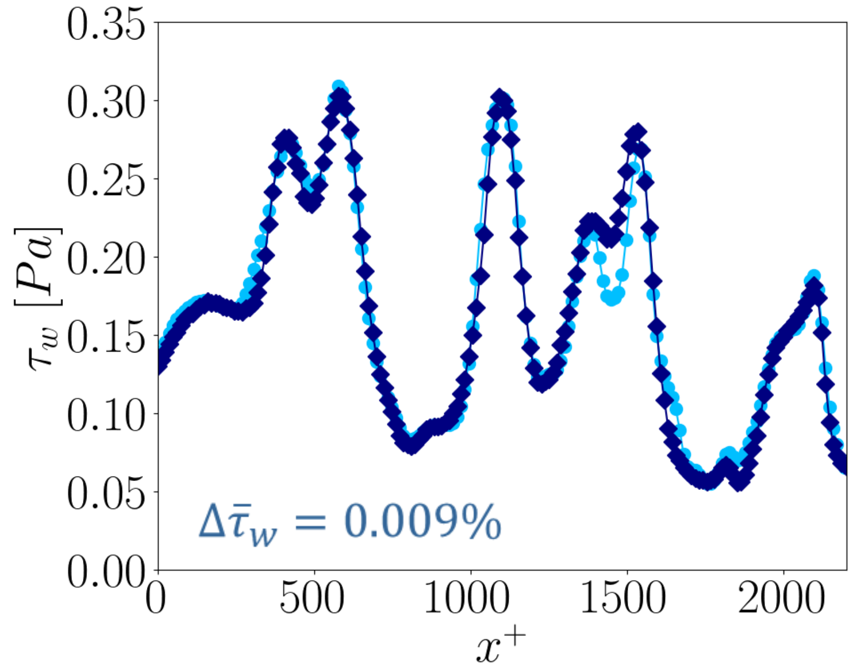
CASE I: TCF

synthetic particle images based on DNS flow (ground truth)





→ RAFT-PIV estimates a reliable velocity and wall-shear stress distribution **matching the ground truth** remarkably well

→ RAFT-PIV provides **physically meaningful instantaneous & spatially resolved wall-shear stress** distributions

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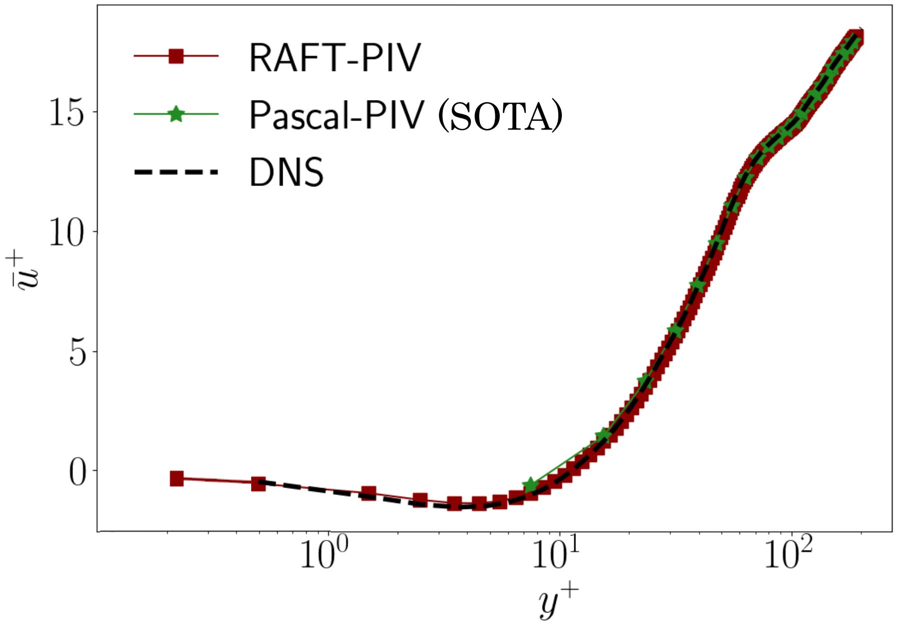
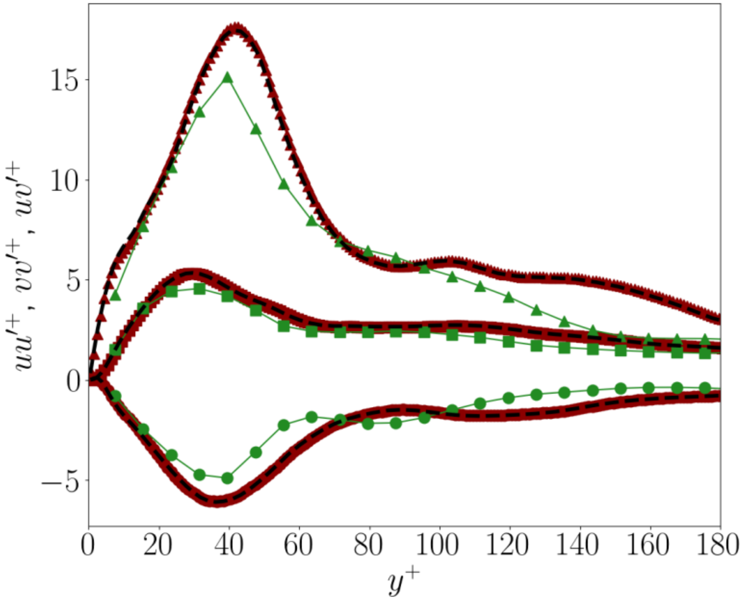
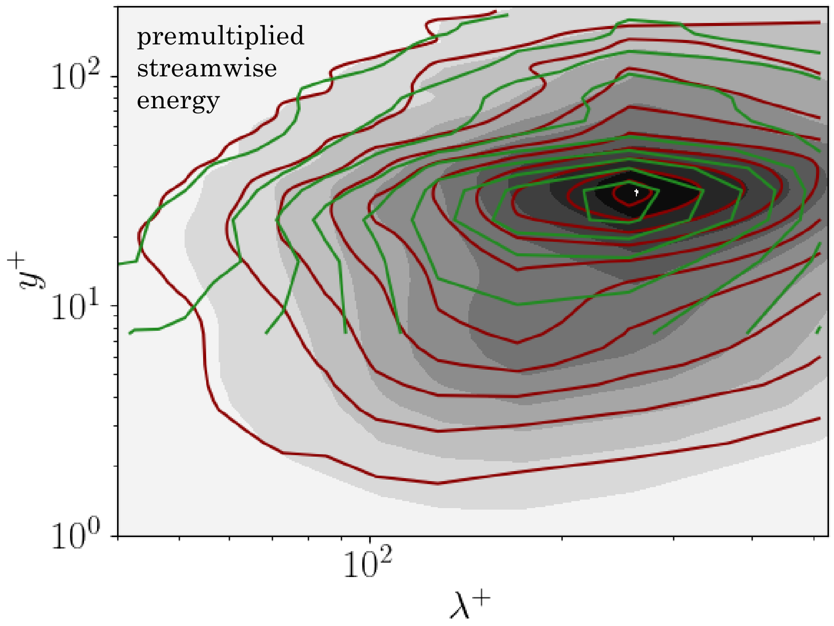
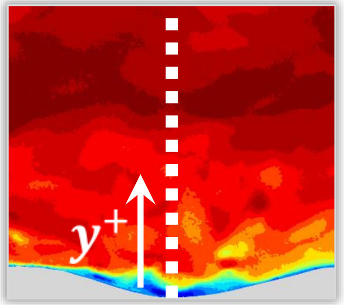
CASE II: TWCF









statistics at wave trough

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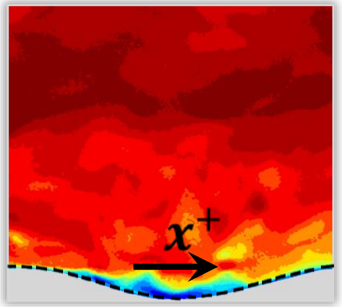

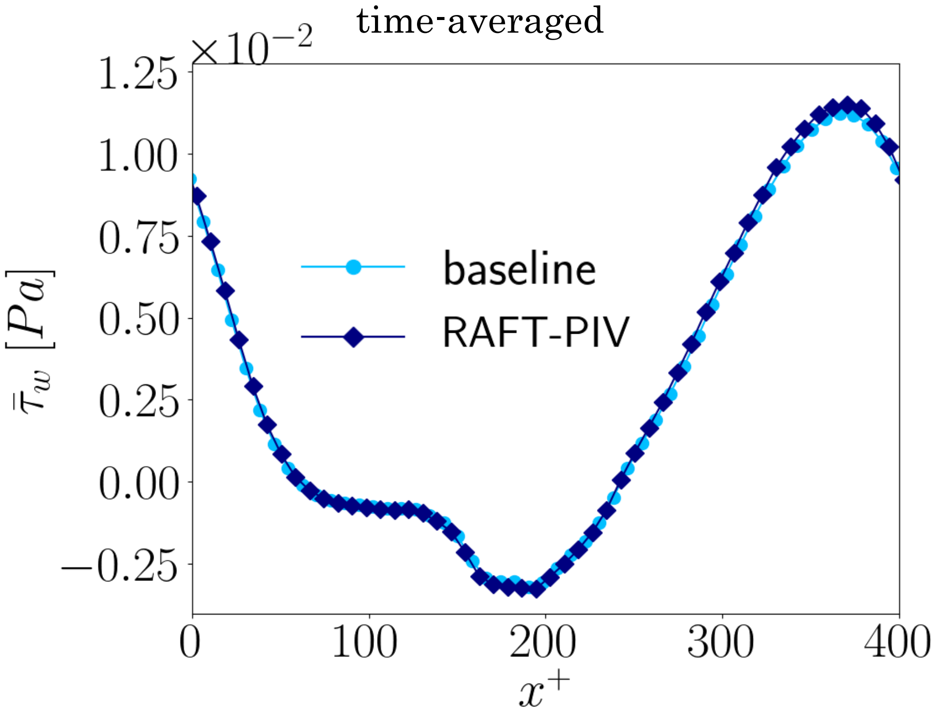

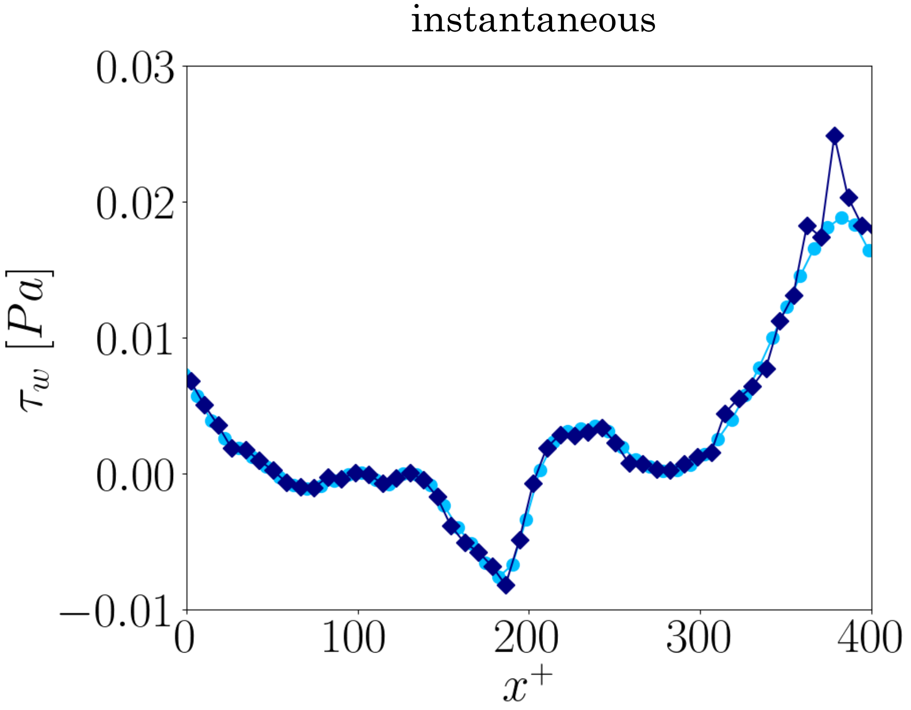

→ highly accurate wall-shear stress prediction of time-averaged and instantaneous quantities

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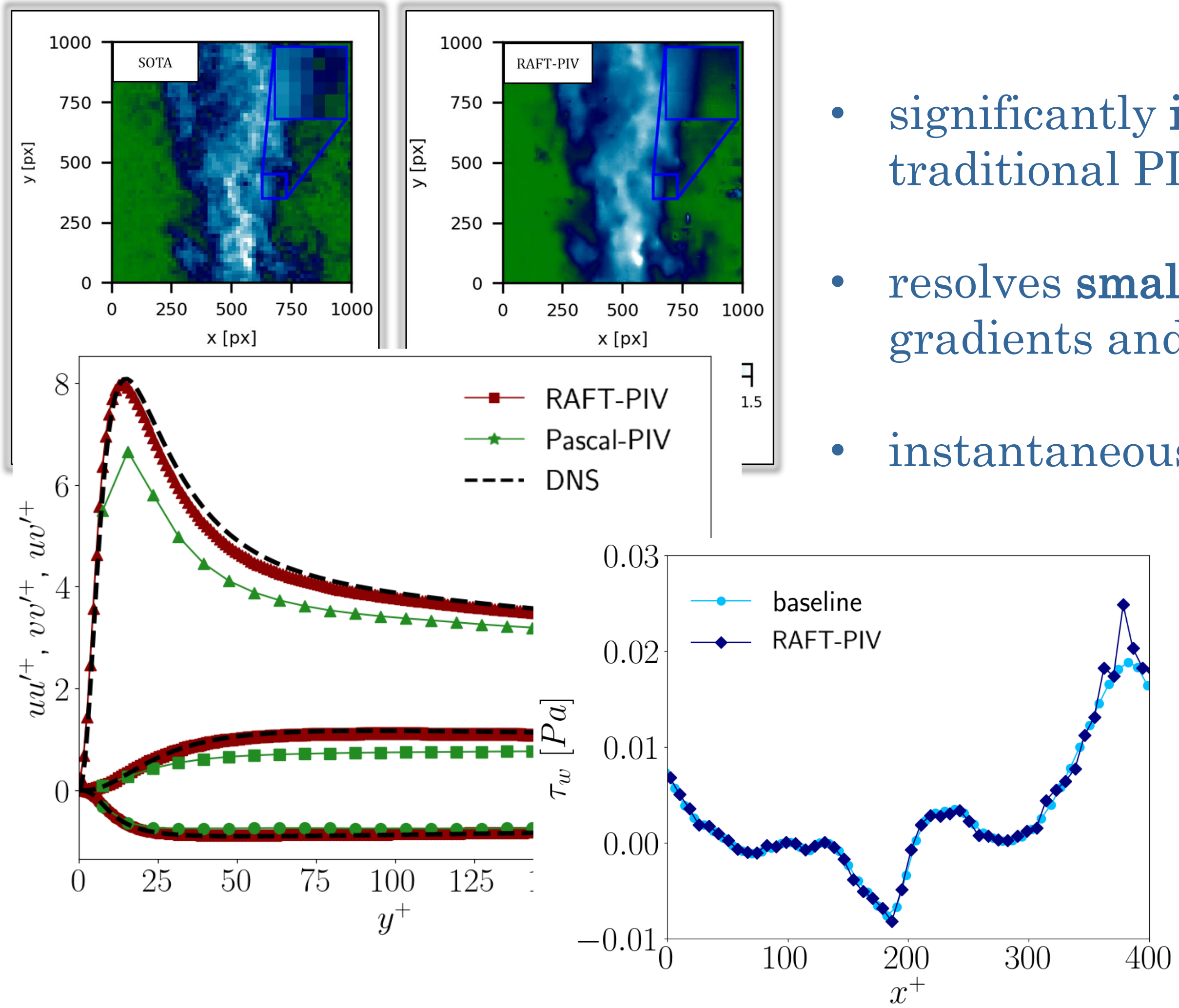
SUMMARY

RAFT-PIV: deep optical flow network for PIV applications



- significantly **increased spatial resolution** compared to traditional PIV processing (operates on input resolution)
- resolves **small-scale structures, near-wall velocity**, velocity gradients and statistics accurately
- instantaneous **wall-shear stress dynamics** can easily be derived

→ advances **accuracy** and **feature richness** of experimental fluid dynamics without altering the experimental setup itself

→ facilitates comparison to numerics and data assimilation

Thank you very much for your attention!

Open-source repository with ready-to-go compute capsule avaible at Code Ocean:

https://codeocean.com/capsule/7226151/tree/v1

Published work using RAFT-PIV:

Lagemann et al., “*Deep recurrent optical flow learning for particle image velocimetry data*“, Nature Machine Intelligence 3 (7), 641-651

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Lagemann et al., “*Instantaneous wall-shear stress distribution based on wall-normal PIV measurements using deep optical flow*“, 15th ISPIV 2023

Lagemann et al., “*Key aspects of unsupervised optical flow models in PIV applications*“, 15th ISPIV, 2023

Lagemann et al., “*Exploiting the full potential of deep neural networks for PIV applications*“, 30th GALA, 2023

Lagemann et al., “*High-accuracy turbulence statistics from particle images using a deep optical flow neural network*“, 18th ETC, 2023

Lagemann et al., “*Analysis of PIV Images of Transonic Buffet Flow by Recurrent Deep Learning Based Optical Flow Prediction*“, 16th LXLaser, 2022

Lagemann et al., “*Unsupervised Recurrent All-Pairs Field Transforms for Particle Image Velocimetry*“, 14th ISPIV, 2021

Lagemann et al., “*Deep artificial neural network architectures in PIV applications*“, 13th ISPIV, 2019

Thank you for your attention