Modal Scale Decomposition in Turbulent Flows

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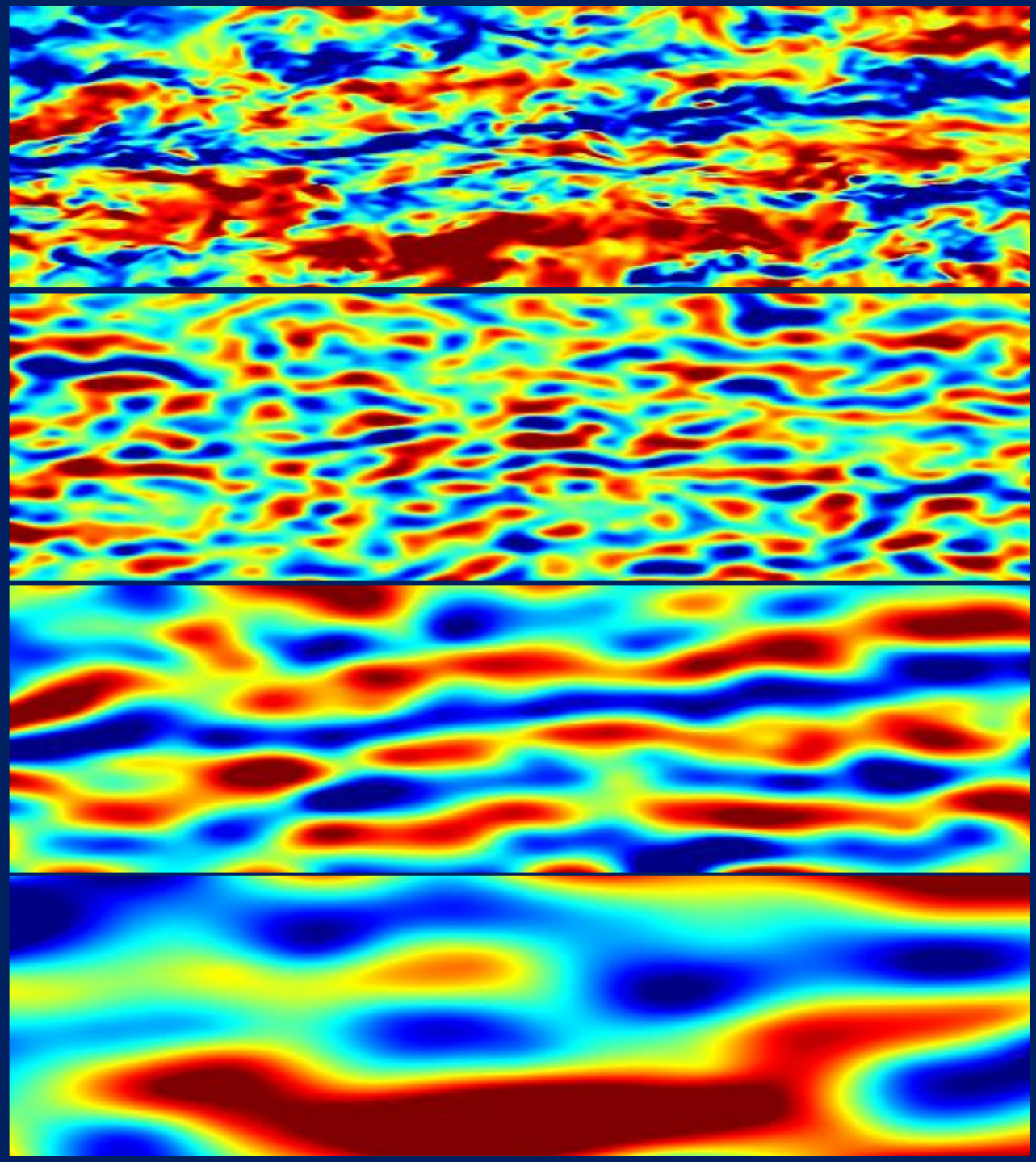
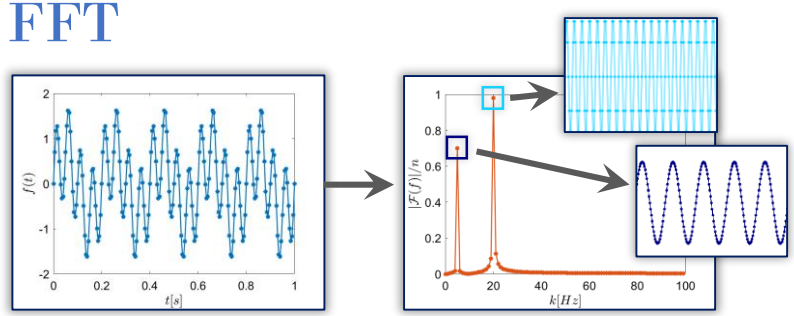
née Mäteling



MOTIVATION

objective:
separate data into purposeful components
to gain new insight into inherent features

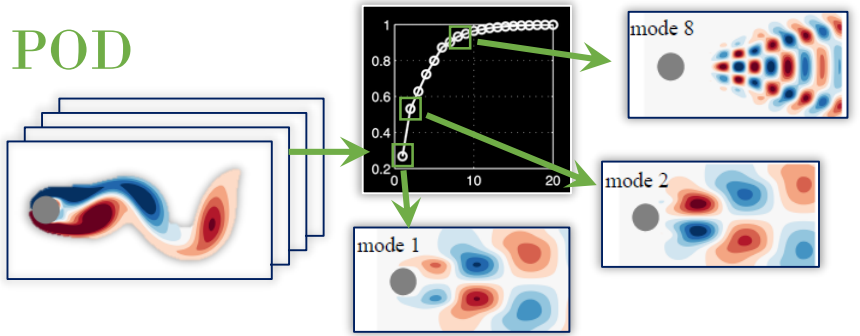
FFT



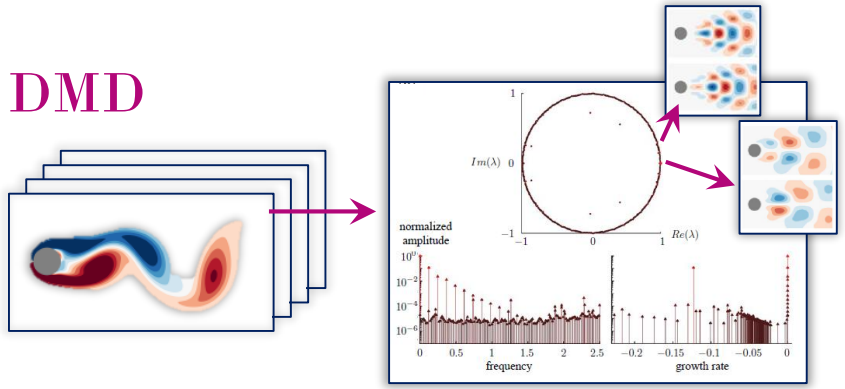
variety of established modal decomposition methods:

- Fast Fourier Transform (FFT)
- Singular Value Decomposition (SVD) / Proper Orthogonal Decomposition (POD)
- Dynamic Mode Decomposition (DMD)
- … a variety of extensions

POD



DMD



MOTIVATION

Why do we need alternative methods for turbulent flows?

- unsteady dynamics
- non-linear phenomena
- broadband data
- multi-scale interactions

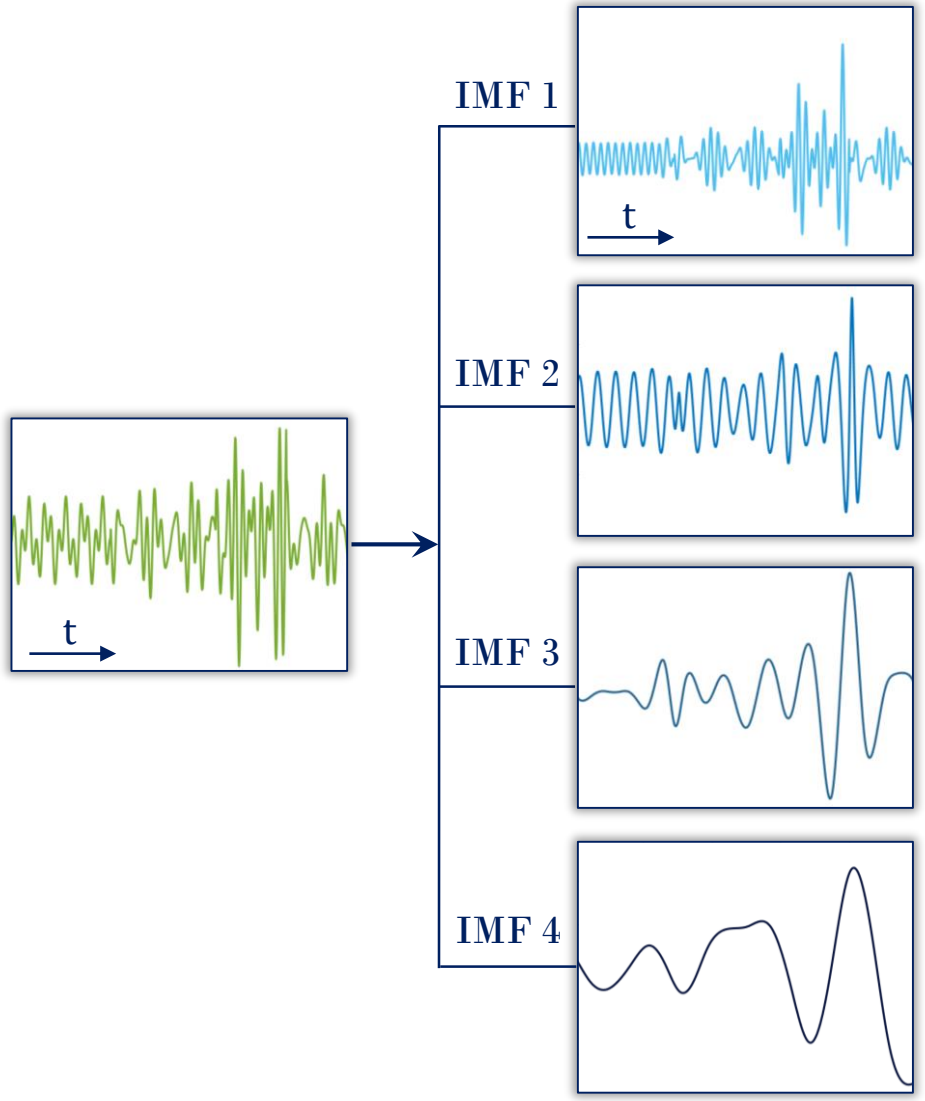
majority of established decomposition methods fails to capture such characteristics

EMPIRICAL MODE DECOMPOSITION

OVERVIEW

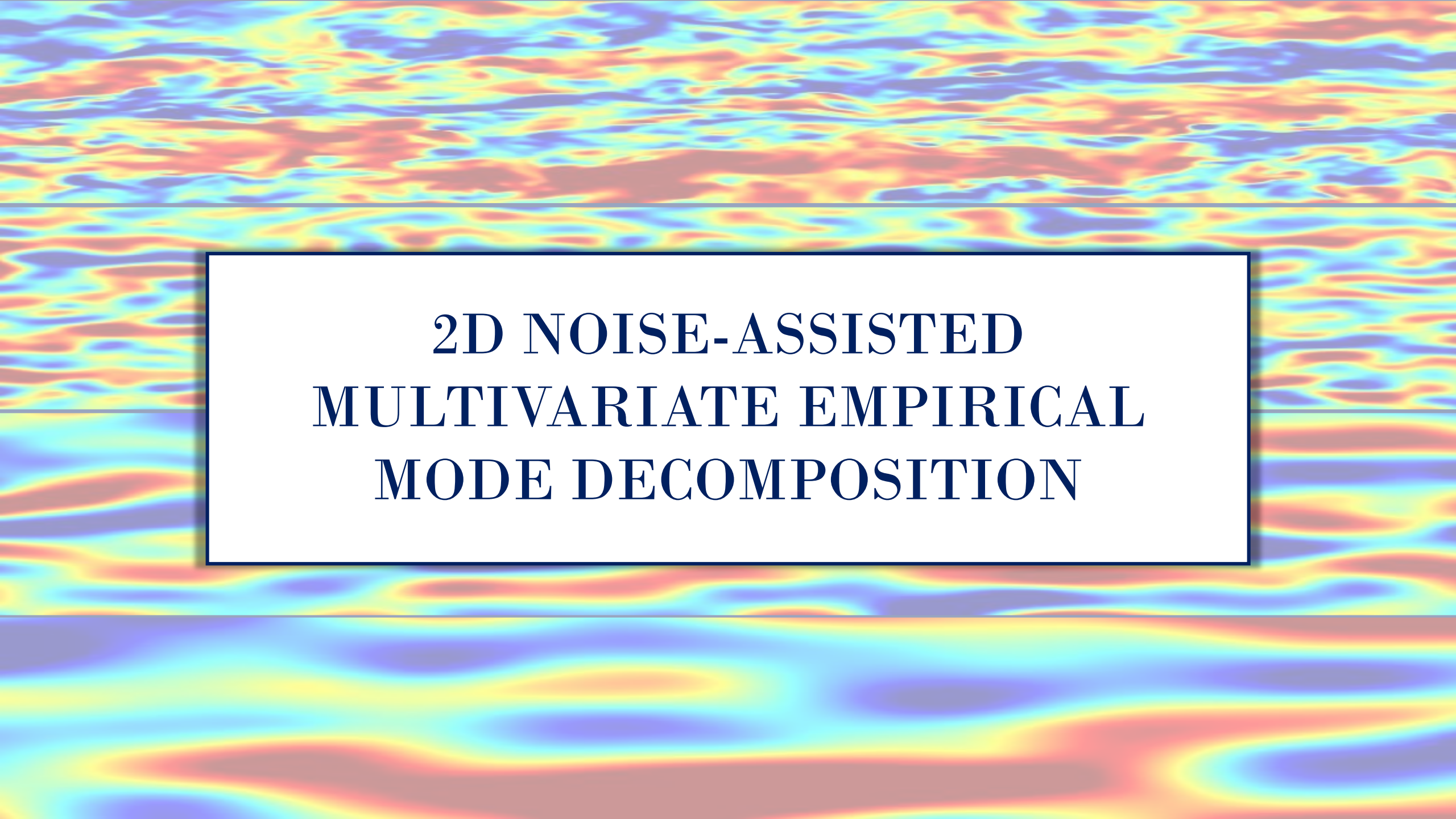
- 1D univariate EMD introduced in 1998
- data-driven decomposition based on intrinsic scales
- modes (IMFs) are sorted with respect to scale size

- ability to process non-linear and unsteady data
- basis system dictated by data
  → modes adaptively biased towards
  locally dominant frequencies/scales



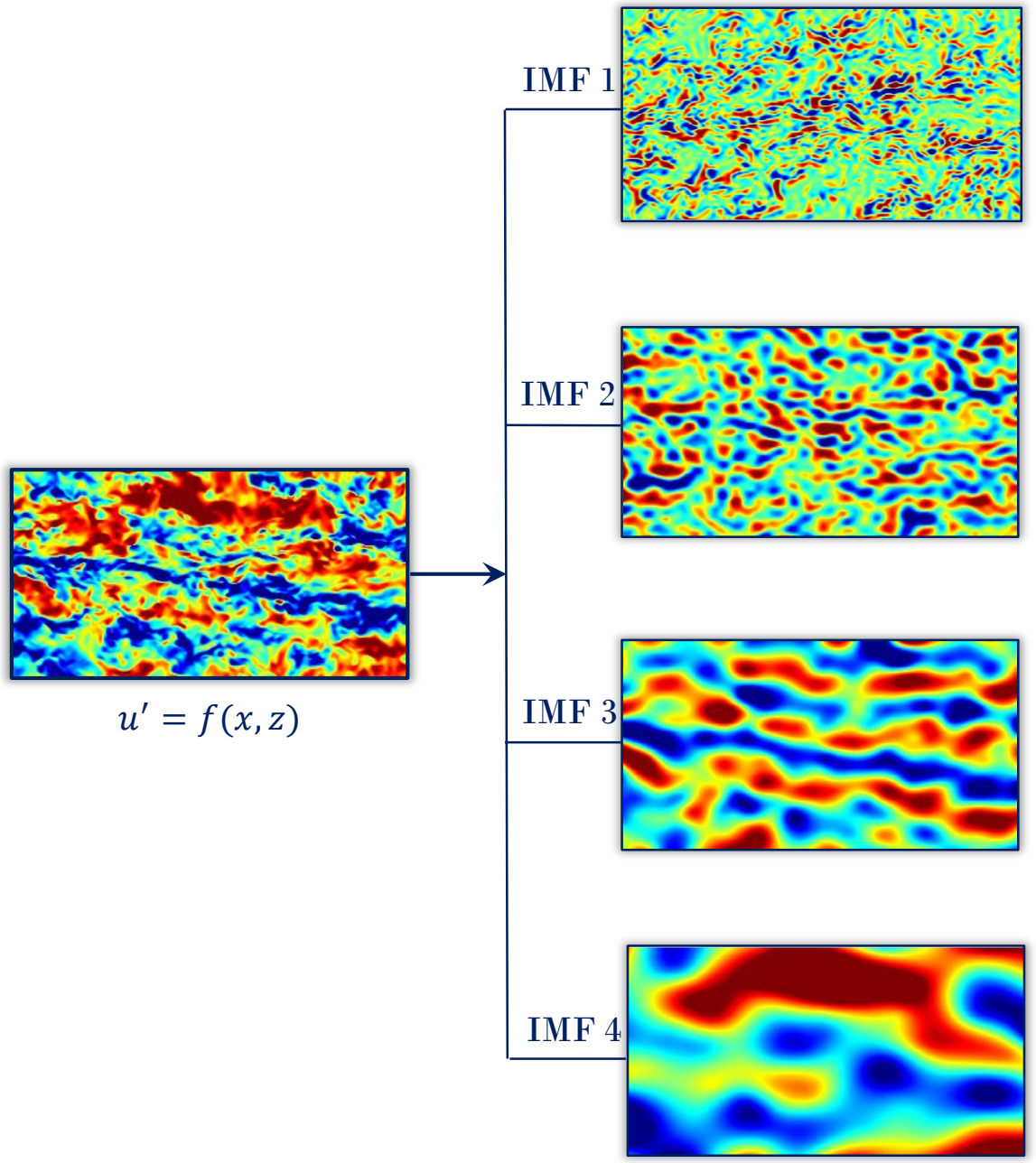
shortcomings for fluid dynamics

- improper mode alignment
- aliasing in time-frequency domain
- problems of uniqueness
- restricted complexity/dimensionality


2D NOISE-ASSISTED
MULTIVARIATE EMPIRICAL
MODE DECOMPOSITION

2D Noise-Assisted Multivariate Empirical Mode Decomposition

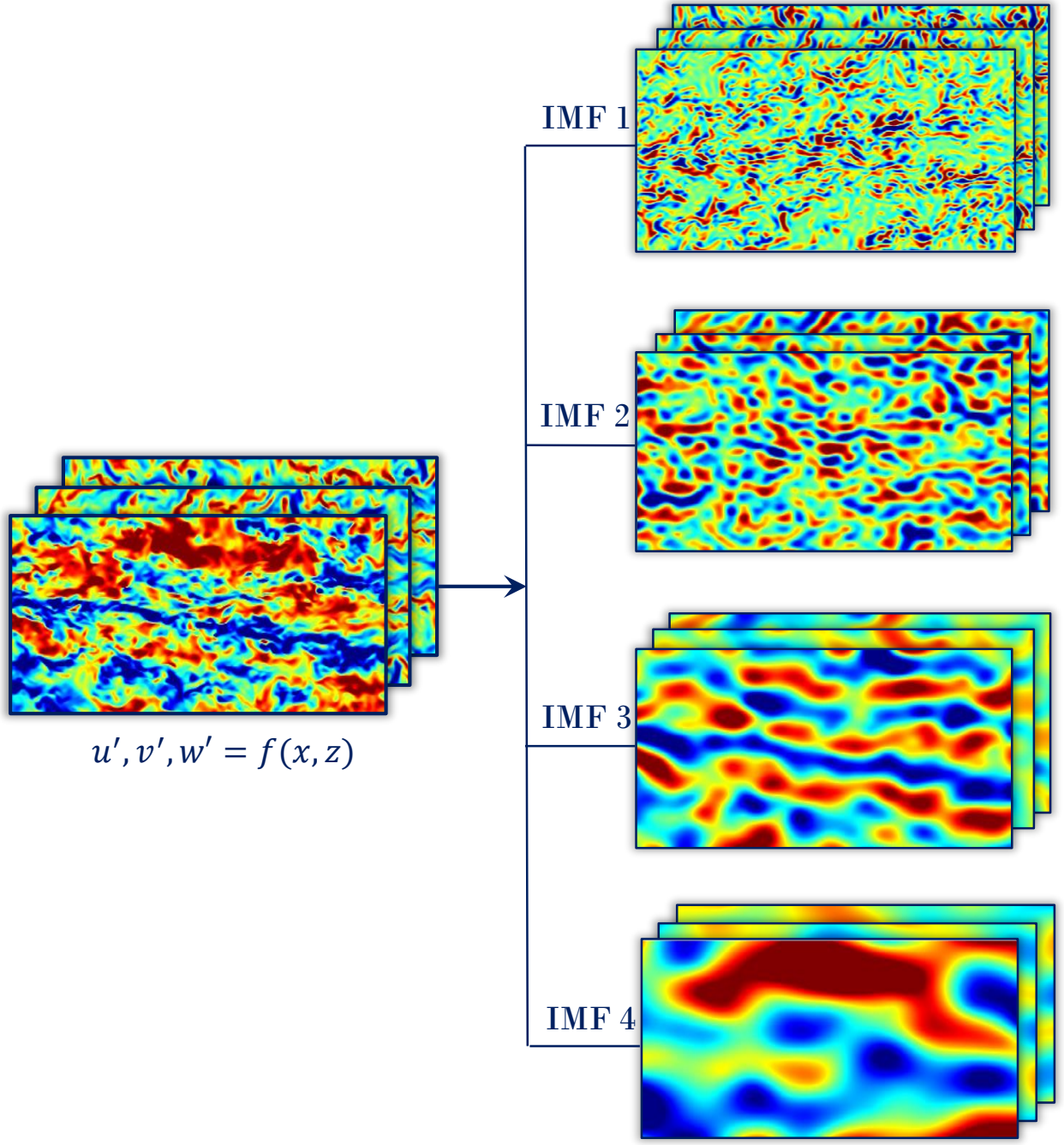
process 2D snapshots



2D Noise-Assisted Multivariate Empirical Mode Decomposition

process 2D snapshots

find & align common features
within multivariate data, e.g.
several velocity components

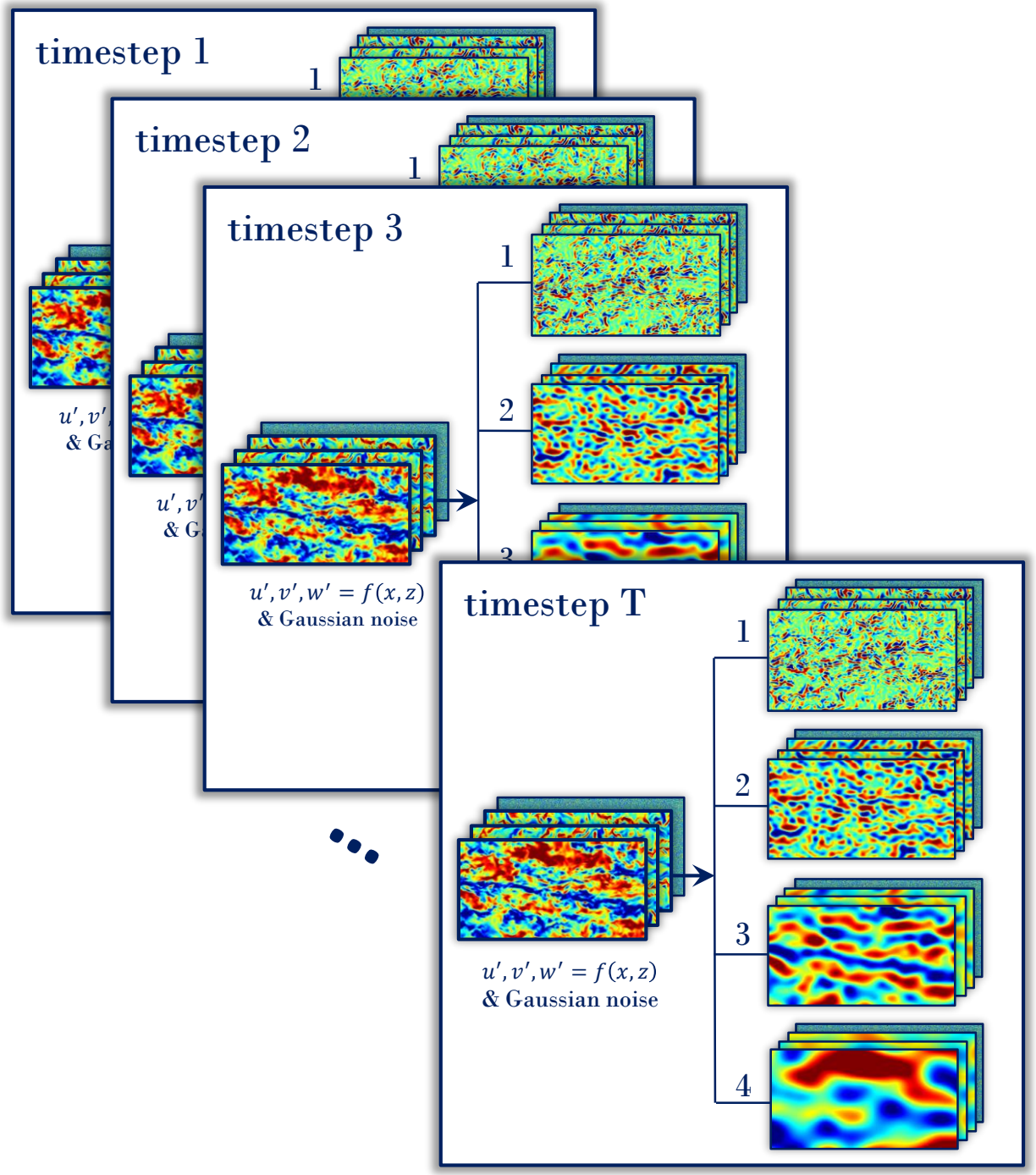


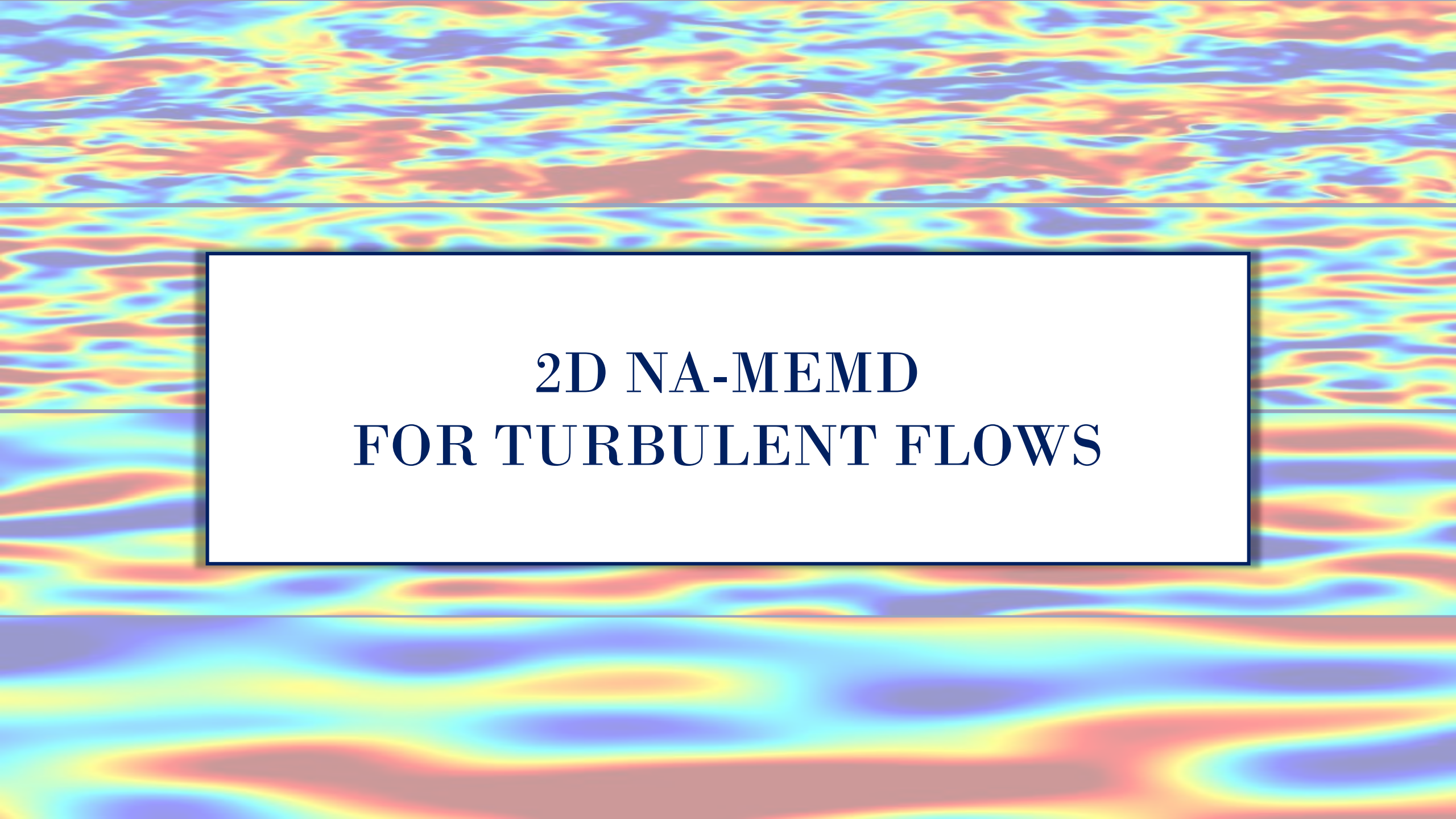
2D Noise-Assisted Multivariate Empirical Mode Decomposition

process 2D snapshots

find & align common features
within multivariate data, e.g.
several velocity components

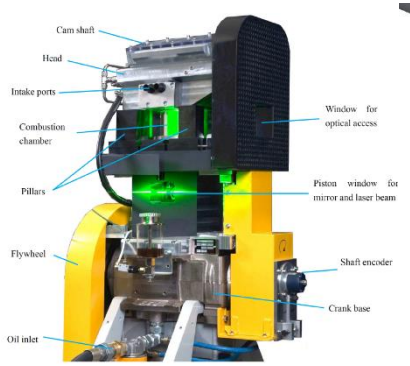
improve mode separation and
coherence across decompositions
by variates of Gaussian noise

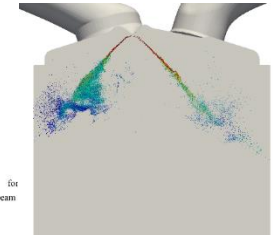


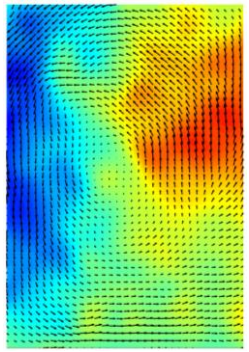

2D NA-MEMD
FOR TURBULENT FLOWS

APPLICATIONS

in-cylinder flow







- dynamics of large-scale tumble vortex
- varying field of view
- instantaneous mean field can replace ensemble mean

J. Knöll, E. **Mäteling**, M. Braun, M. Klaas, & W. Schröder. *Analysis of the in-cylinder flow of a DISI engine using high-speed particle image velocimetry*. LX Laser (2022)

APPLICATIONS

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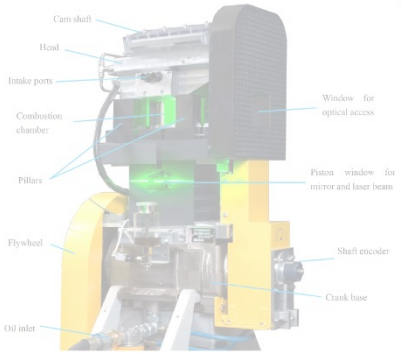

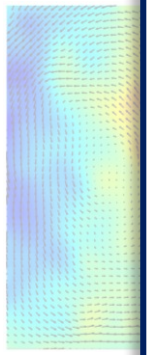

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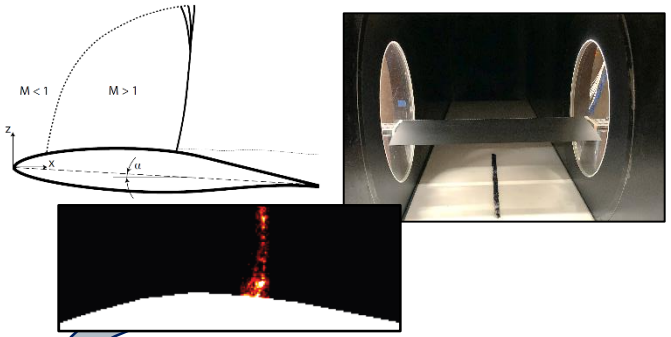
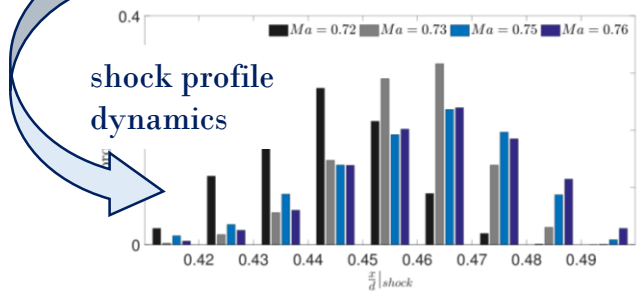
transonic airfoil buffet

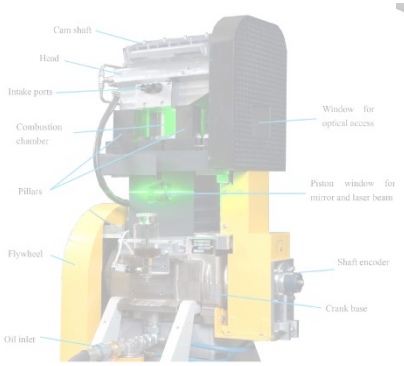


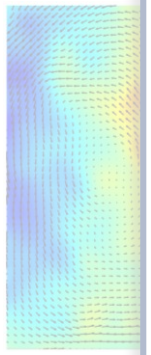


C. Lagemann, E. **Mäteling**, M. Klaas, & W. Schröder. *Analysis of PIV Images of Transonic Buffet Flow by Recurrent Deep Learning Based Optical Flow Prediction*. LX Laser (2022)

APPLICATIONS

in-cylinder flow





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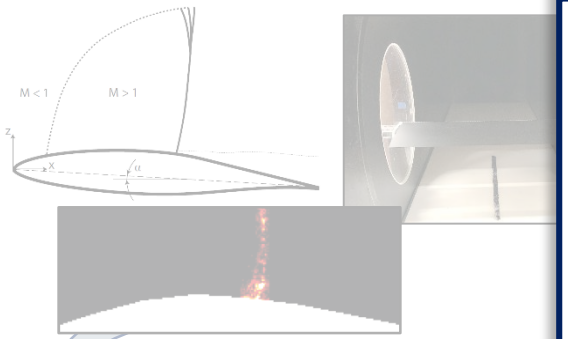

shock profile dynamics

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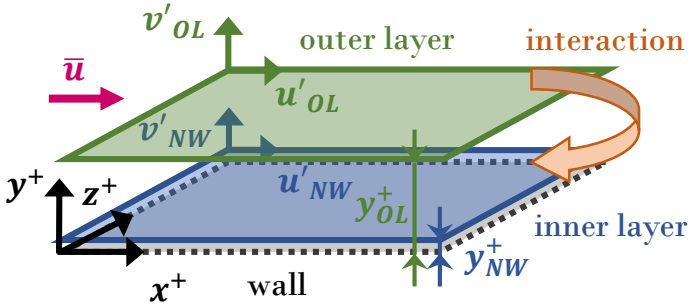
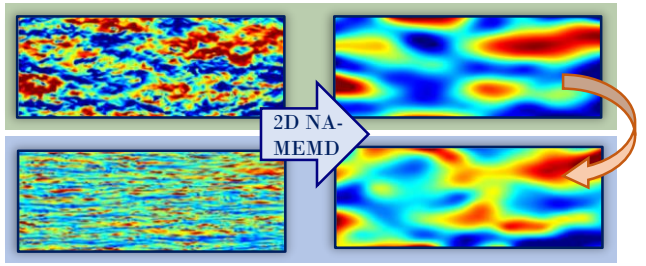
inner-outer interaction





E. **Mäteling** & W. Schröder. *Analysis of spatiotemporal inner-outer large scale interactions in turbulent channel flow by multivariate empirical mode decomposition.* Physical Review Fluids 7.3 (2022), p. 034603

APPLICATIONS

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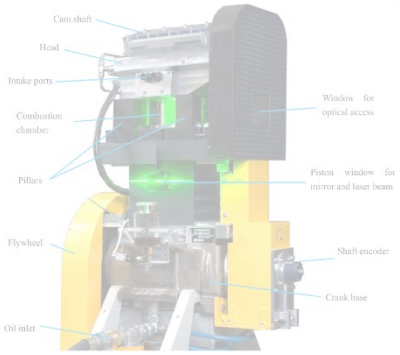

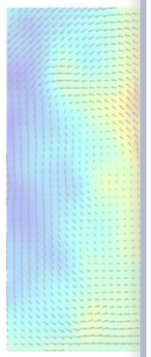

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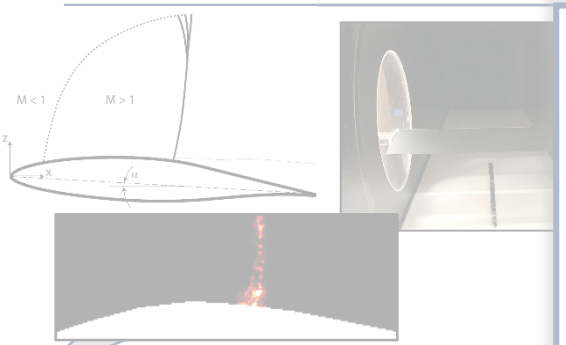

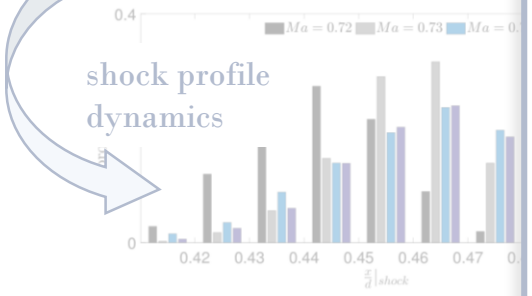

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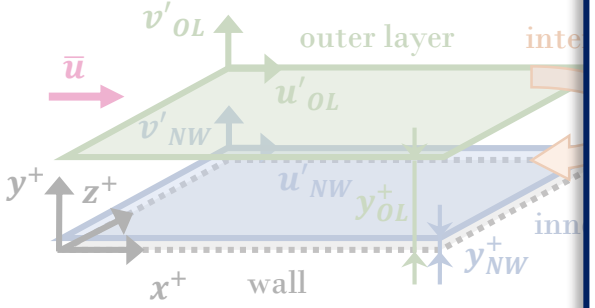

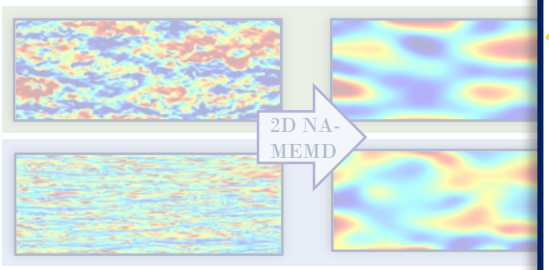

E. Mäteling & W. Schröder. *Analysis of spati*
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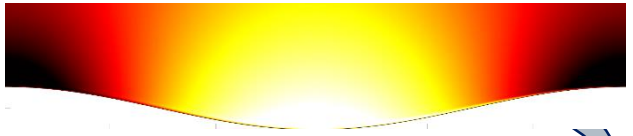
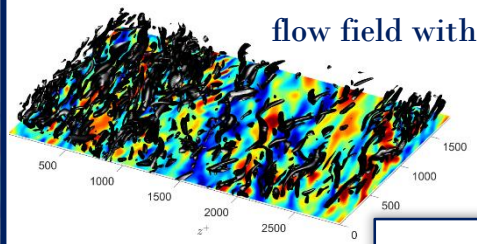
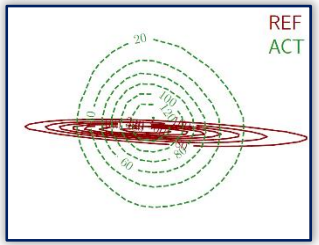
Physical Review Fluids 7.3 (2022), p. 03

drag reduction mechanism



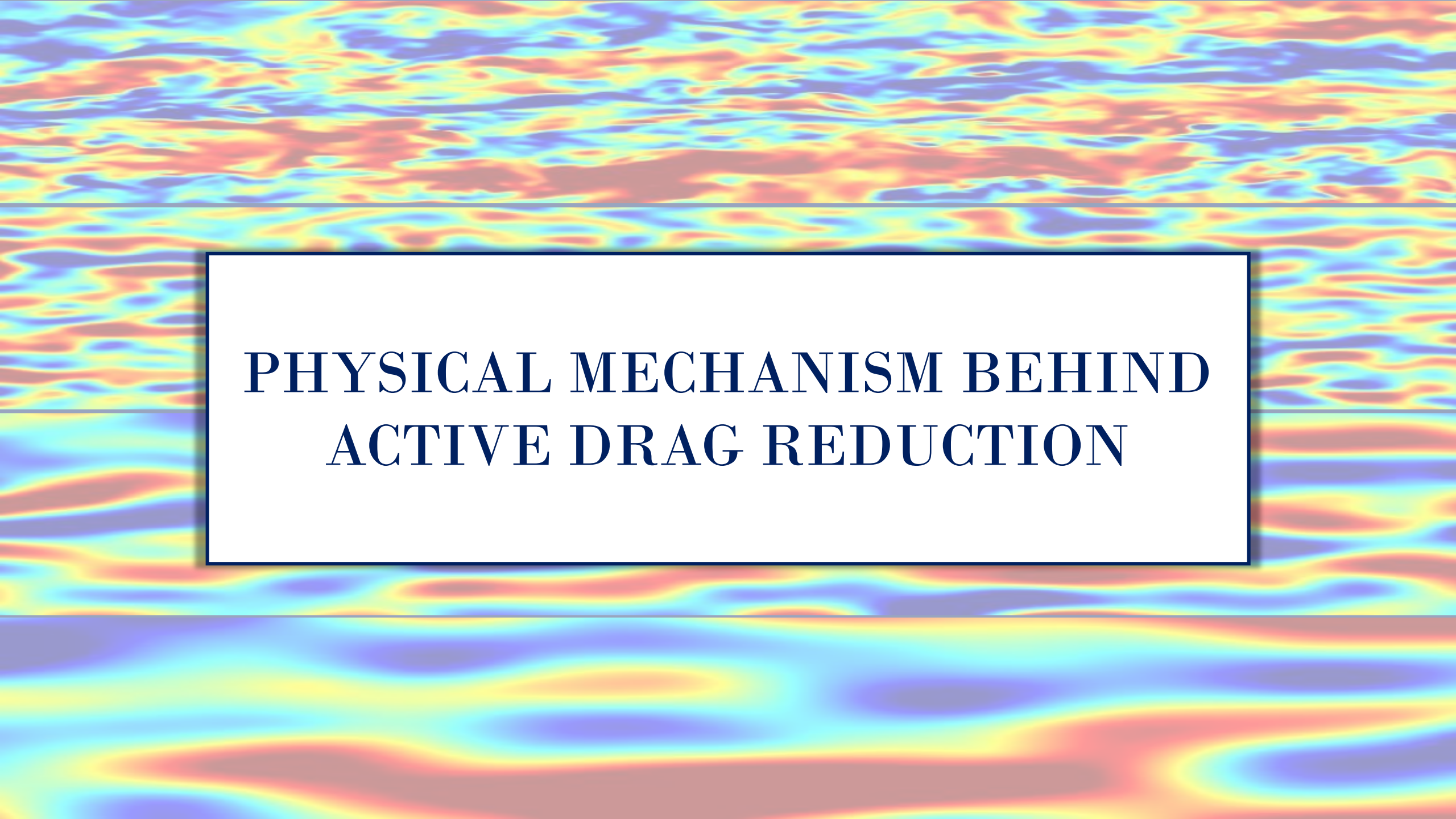
interaction of secondary flow field with vortices





modified inner-outer interaction due to near-wall ejections

E. Mäteling, M. Albers & W. Schröder. *How spanwise travelling transversal surface waves change the near-wall flow.* Journal of Fluid Mechanics 957 (2023), A30


PHYSICAL MECHANISM BEHIND
ACTIVE DRAG REDUCTION

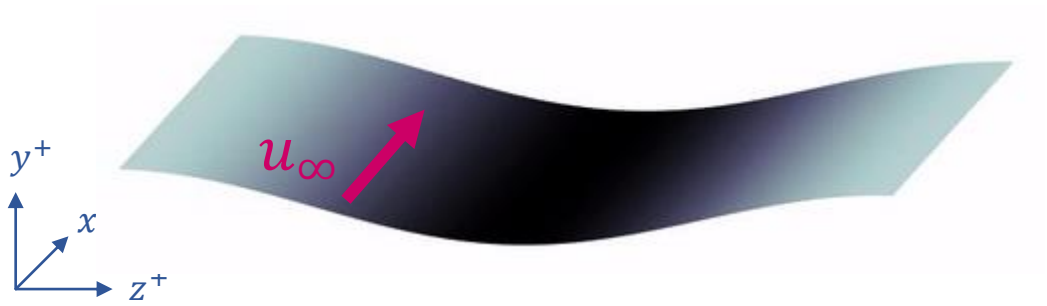
MOTIVATION

How do active drag reduction methods manipulate
the internal flow structure to achieve drag reduction?

→ tailor methods to any flow configuration with highest efficiency

turbulent boundary layer flow subjected to
spanwise traveling transveral surface waves

$$y^+_{wall} = A^+ cos\left(\frac{2\pi}{\lambda^+} z^+ + \frac{2\pi}{T^+} t^+\right) \quad \text{with} \quad A^+ = 100, \quad \lambda^+ = 3000, \quad T^+ = 50$$

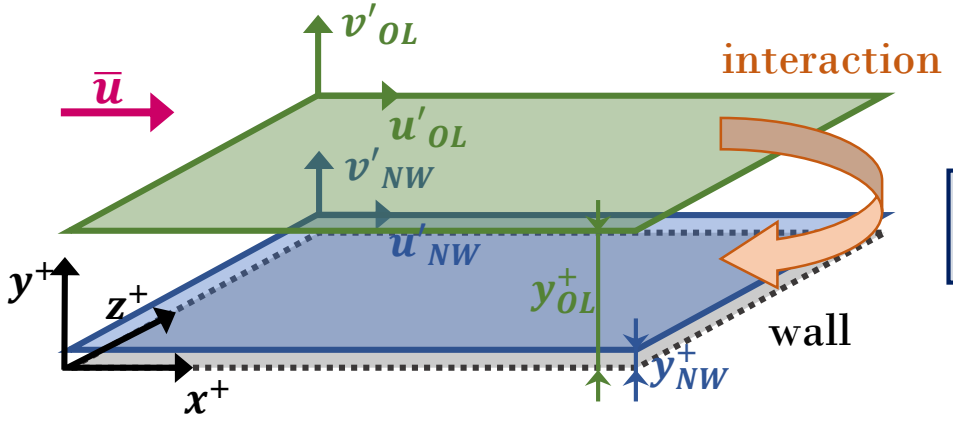


$\mathrm{Re}_\tau \approx 1500$: $\Delta c_d \approx 26.5\%$

Albers et al. (2020) Flow, Turbulence and Combustion 105, pp. 125–157

INNER-OUTER INTERACTION

OL: outer layer (logarithmic layer)



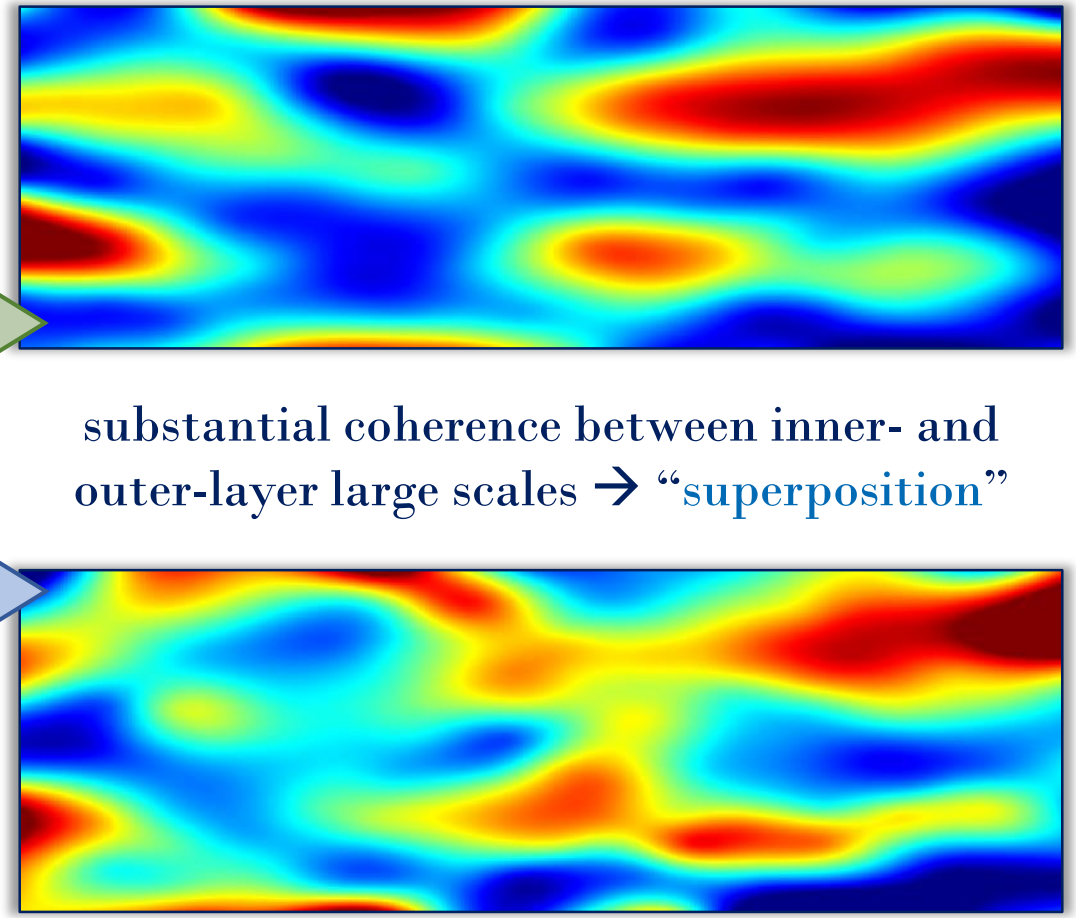
NW: inner layer (near-wall region)

2D NA-MEMD

large-scale mode

OL

NW



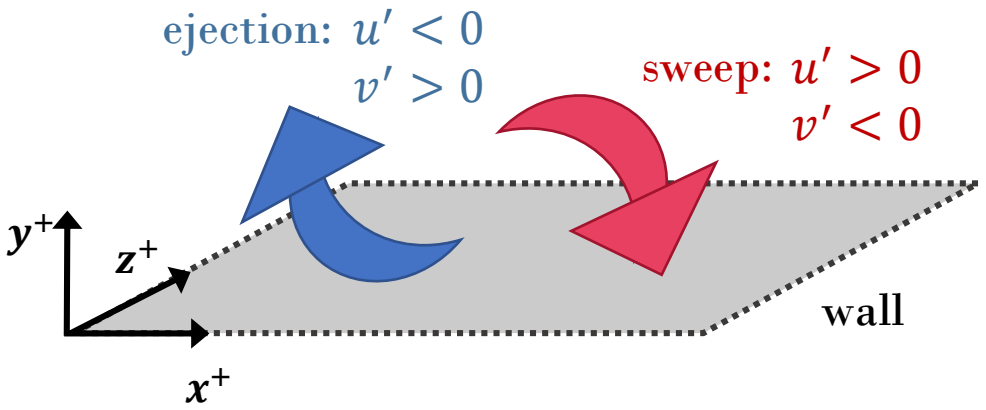
substantial coherence between inner- and outer-layer large scales → "superposition"

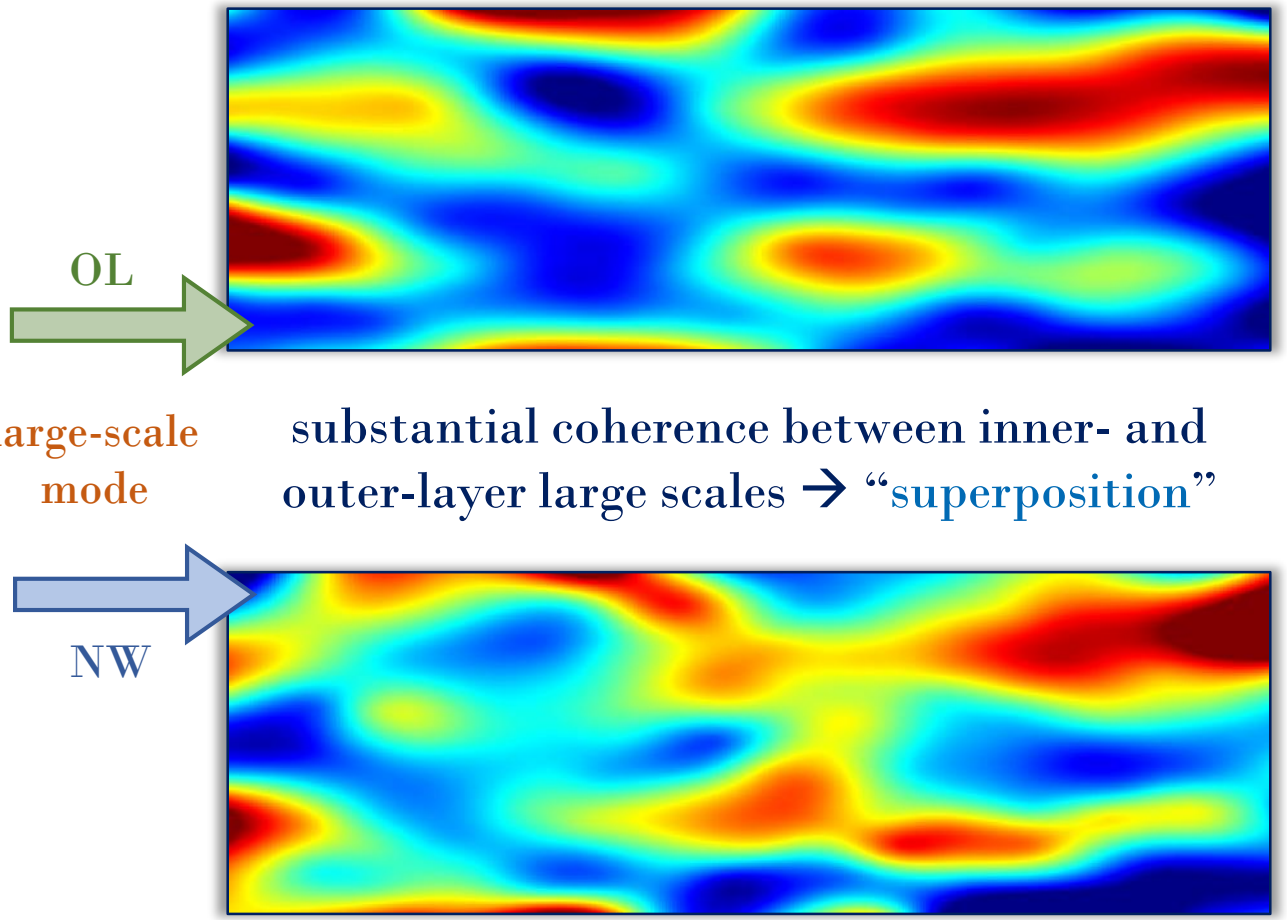
Mäteling et al. (2020) Physical Review Fluids, 5(11), 114610.
Mäteling & W. Schröder (2022) Physical Review Fluids 7.3, p. 034603

INNER-OUTER INTERACTION

<u>interaction phenomena:</u>

- superposition (S)
  - interaction via sweeps (sw)
  - interaction via ejections (ej)
- amplitude modulation
- frequency modulation





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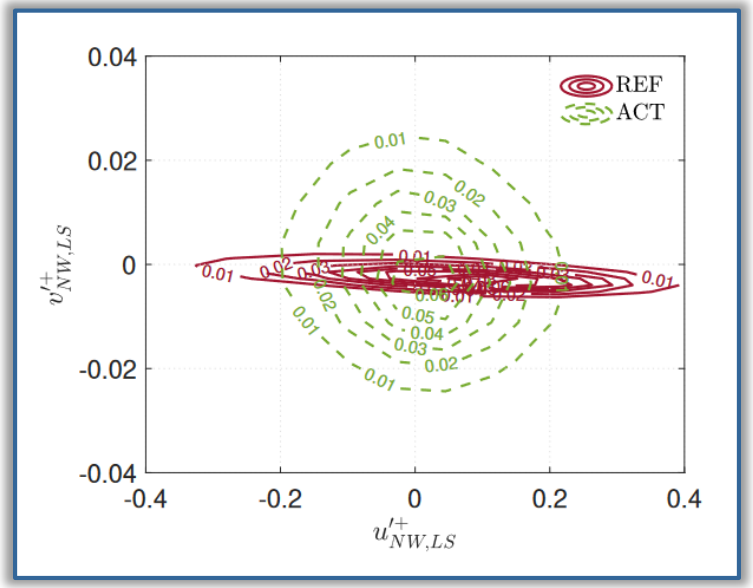
INNER-OUTER INTERACTION

degree of inner-outer coherence via spatial cross-correlation coefficient

	$\overline{R}_s$	$\overline{R}_{sw}$	$\overline{R}_{ej}$
REF	0.61	0.60	0.36
ACT	0.51	0.51	0.52

- overall, less outer-layer impact on near-wall dynamics ($\overline{R}_S$)
- reduced top-down communication via sweeps ($\overline{R}_{sw}$)
- increased bottom-up inference related to ejections ($\overline{R}_{ej}$)

joint PDF of large-scale velocity fluctuations close to the wall



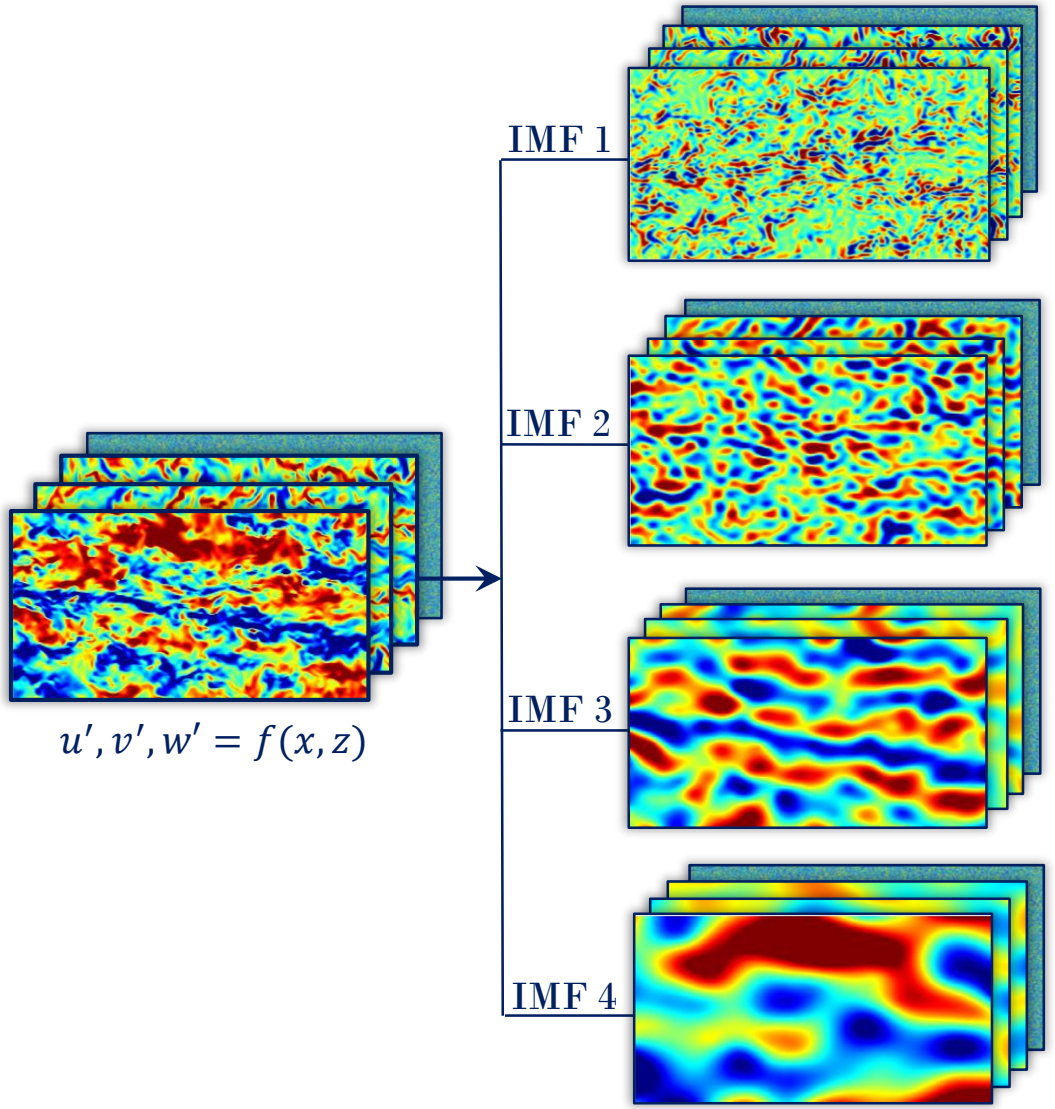
increased number & intensity of near-wall ejections → balance outer-layer sweeps → wall-shear stress reduction

Mäteling et al. (2023) Journal of Fluid Mechanics 957 (2023), A30

SUMMARY

SUMMARY

- introduction of the 2D NA-MEMD for spatio-temporal turbulent flow analyses
  - ➢ captures unsteady, non-linear, and multi-scale phenomena
- broad range of applicability
  - ➢ numerical & experimental data
  - ➢ internal & external flows
  - ➢ fundamental turbulence research & real-world/industry-related cases
- example: new insight in physical mechanism behind active drag reduction



Thank you very much for your attention!

Questions?

2D NA-MEMD code