Reconstruction of Large-Scale Coherent Structures in Turbulent Separation Bubbles Using Phase-Consistent DMD

AIAA Aviation Forum 2023

Session: Reduced-Complexity Modeling and Machine Learning I

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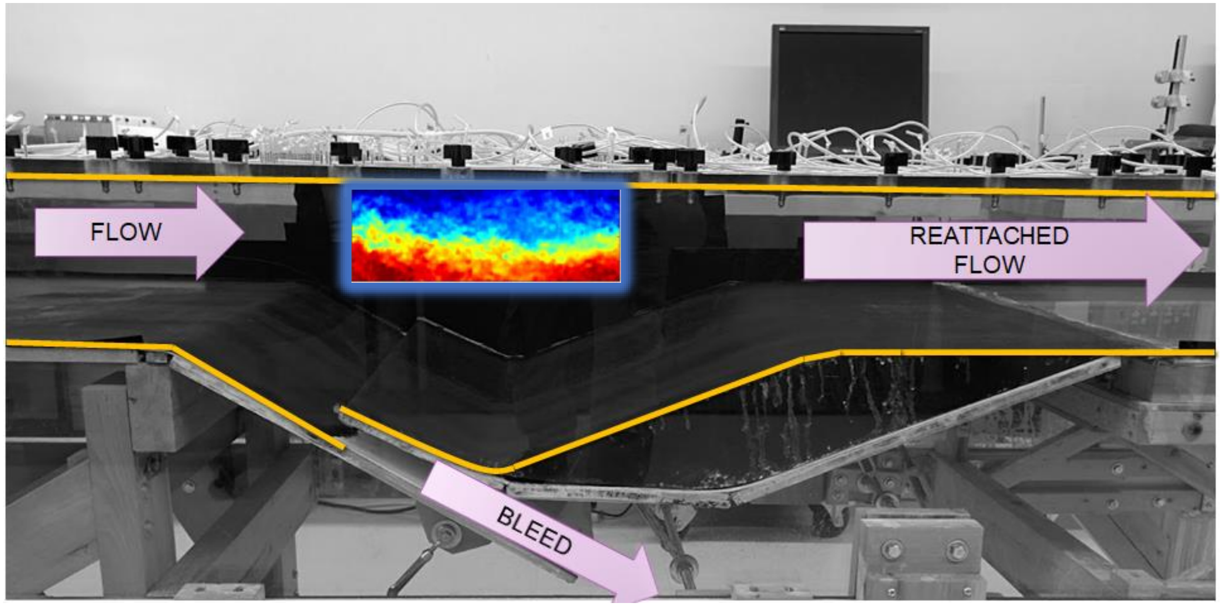
A Turbulent Separation Bubble (TSB)

- Shear layer detaches and reattaches further downstream
- Issues : sources of unsteadiness on a wide range of frequencies
- Various industrial applications:
  - airfoil, turbine blade, sudden expansion in ducts
- Lead to noise, vibrations, thermal loads etc.
- Long term goal: how to control it? Need to better understand it.



Large Scale Unsteady Motions

- Former results indicated a low-frequency cycle, called “***breathing motion***” that was observed in horizontal and vertical planes
- Pressure and velocity signatures are consistent
- Field of views only cover a relatively small part of the global flow :
  - Use of 2-point cross correlations
  - Pressure-velocity correlations at different spanwise stations to infer a quasi-2D flow

➔ Statistical averages can be done, but what about the global dynamic motion?

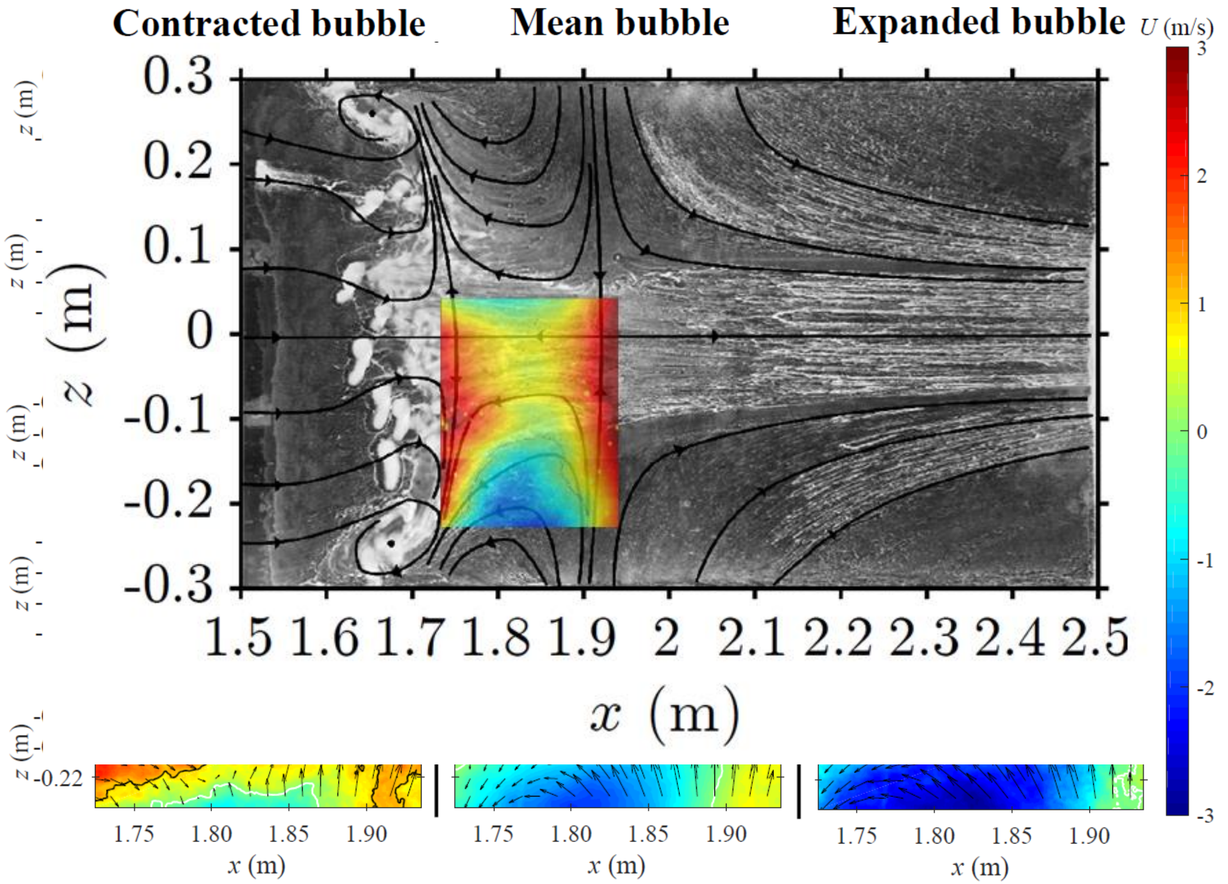


Illustration of the “***breathing motion***” in horizontal planes
(Le Floc’h et al. 2018)

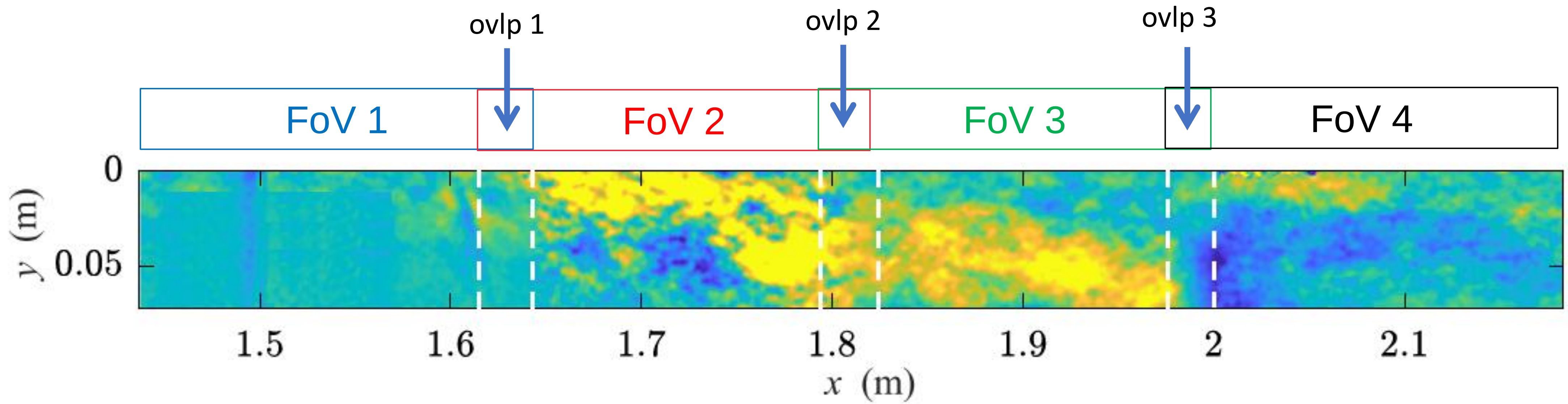
Towards A More Global Approach

- **Main objective**
  - Identify the global dynamic motion of a medium-size TSB (from AIAA 2018 Le Floc'h *et al*.)

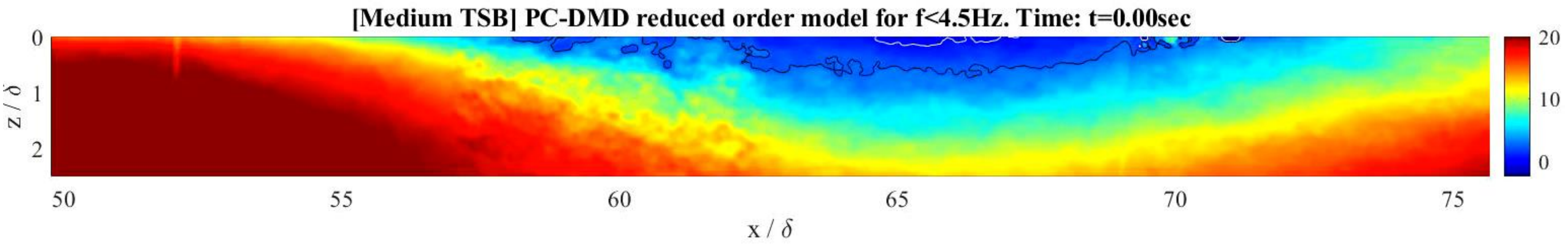
- **Specific objectives**
  - Use of recent algorithm, named "*Phase-consistent DMD*" from Nair *et al*. 2020 to recombine dynamic for horizontal and vertical planes
  - Illustrate the motion for both separation and reattachment points together simultaneously
  - Inform on the flow physics, including the breathing motion

Towards a More Global Information: PC-DMD

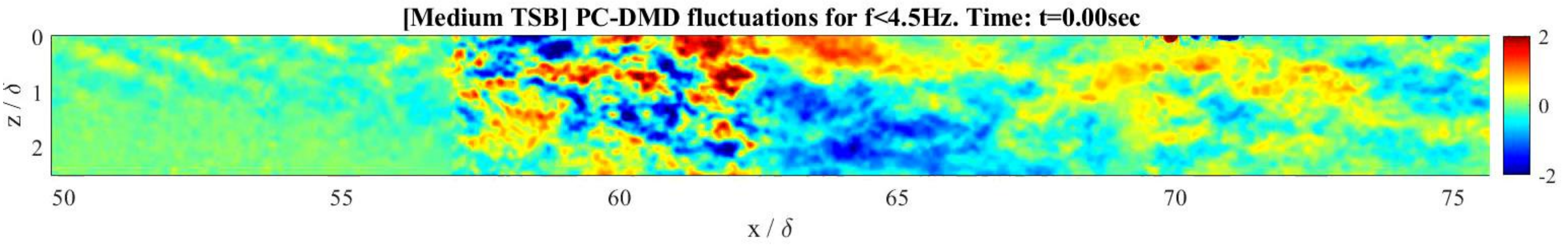
- **Methodology from Nair et al. 2020 enables promising features:**
  - modes with spatial and temporal coherence
  - useful for studies with limited FOV (just a pair of cameras)
- **Main steps:**
  - Perform DMD on concatenated data
  - Align the phase for each overlap regions ovlp1, ovlp2 and ovlp3
  - Build a reduced order model for a range of low frequencies



VERTICAL (X-Y) PLANES: R.O.M. VS FLUCTUATIONS VIDEO

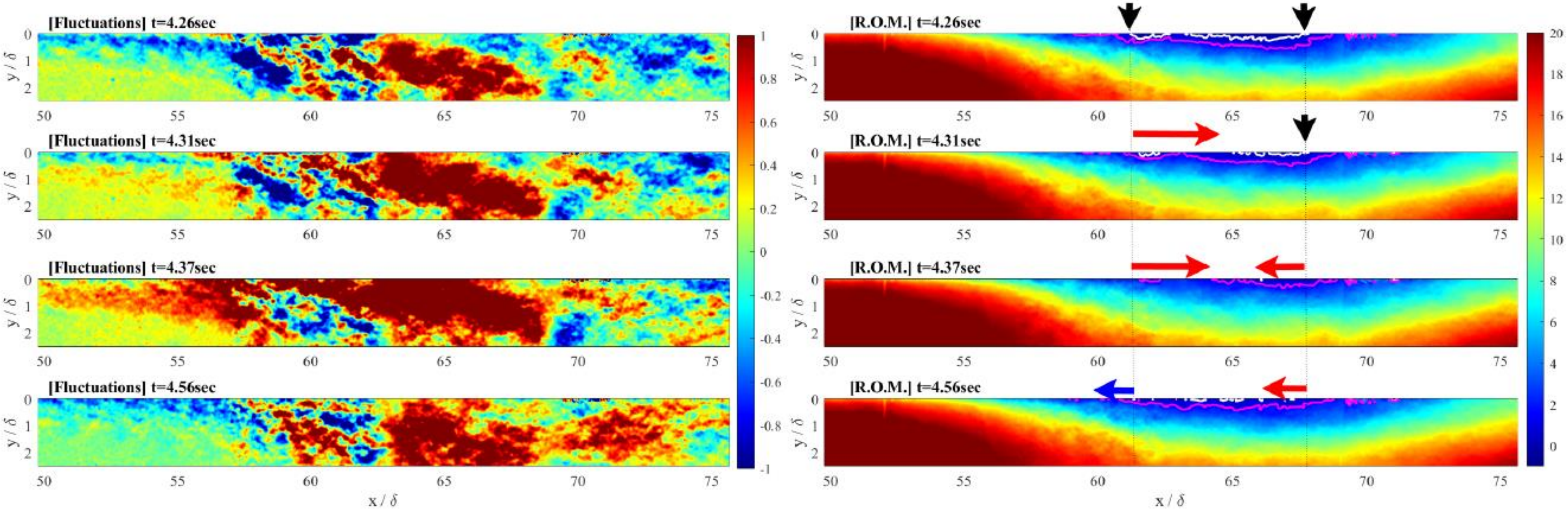


As if we had used 8 cameras ! ☺



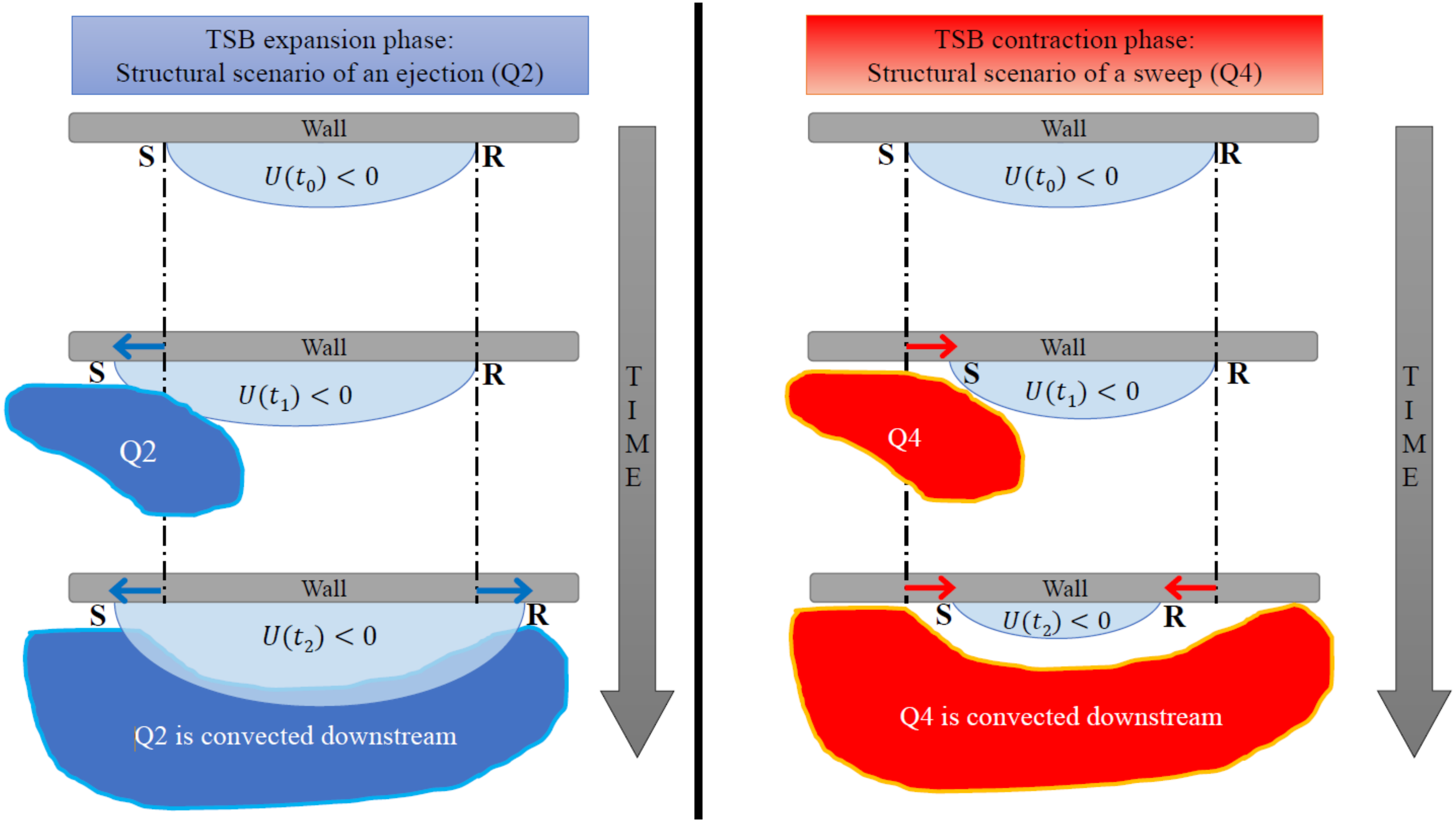
VERTICAL (X-Y) PLANES: PASSAGE OF A Q4

- **First time visualization of a high-speed streak over the entire TSB:**
  - Symmetric effect : a high-speed streak first influences separation, and reattachment later
  - The arrival of a subsequent low speed streaks forces the subsequent expansion cycle

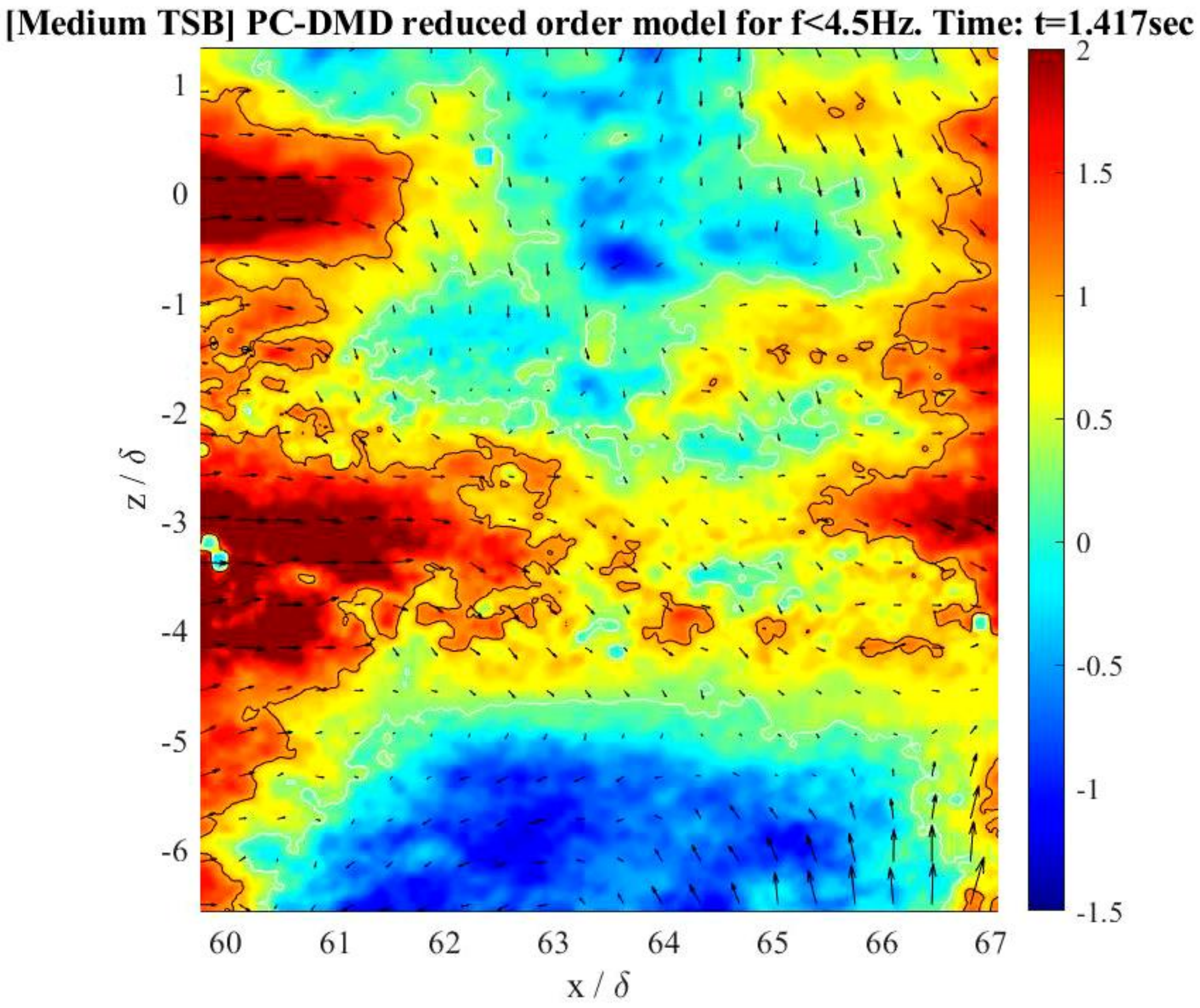


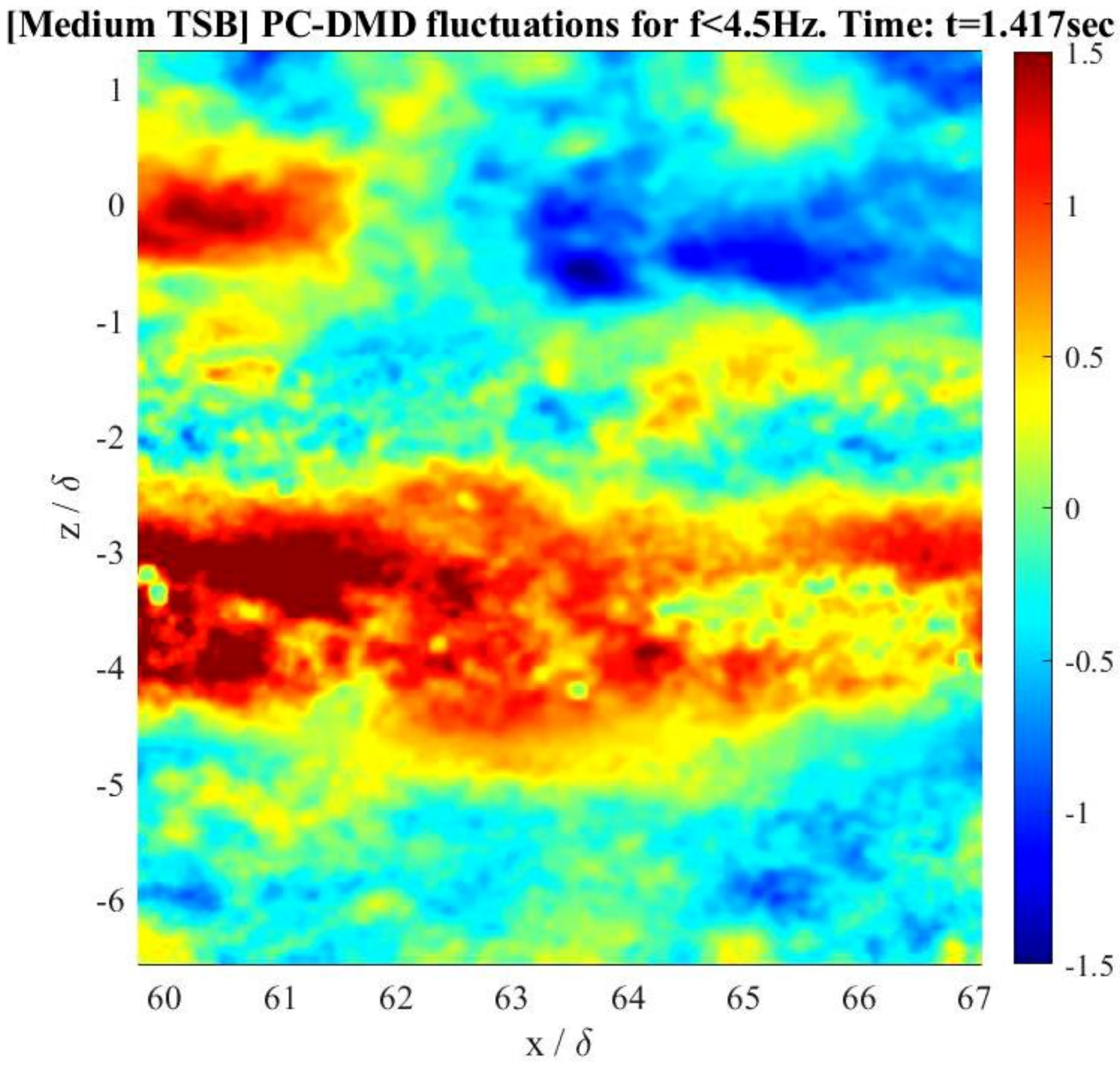
VERTICAL (X-Y) PLANE: STRUCTURAL BREATHING HYPOTHESIS

- **Summary of vertical analysis:**
  - Motion advected downstream
  - Not symmetric motion
- **Validation of previous results with individual FoVs**
- **What about the 3D nature of the breathing?**
  - Is it a quasi 2D or fully 3D motion?
    ➔ **Horizontal results**



HORIZONTAL (X-Z) PLANES: R.O.M. VS FLUCTUATIONS VIDEO



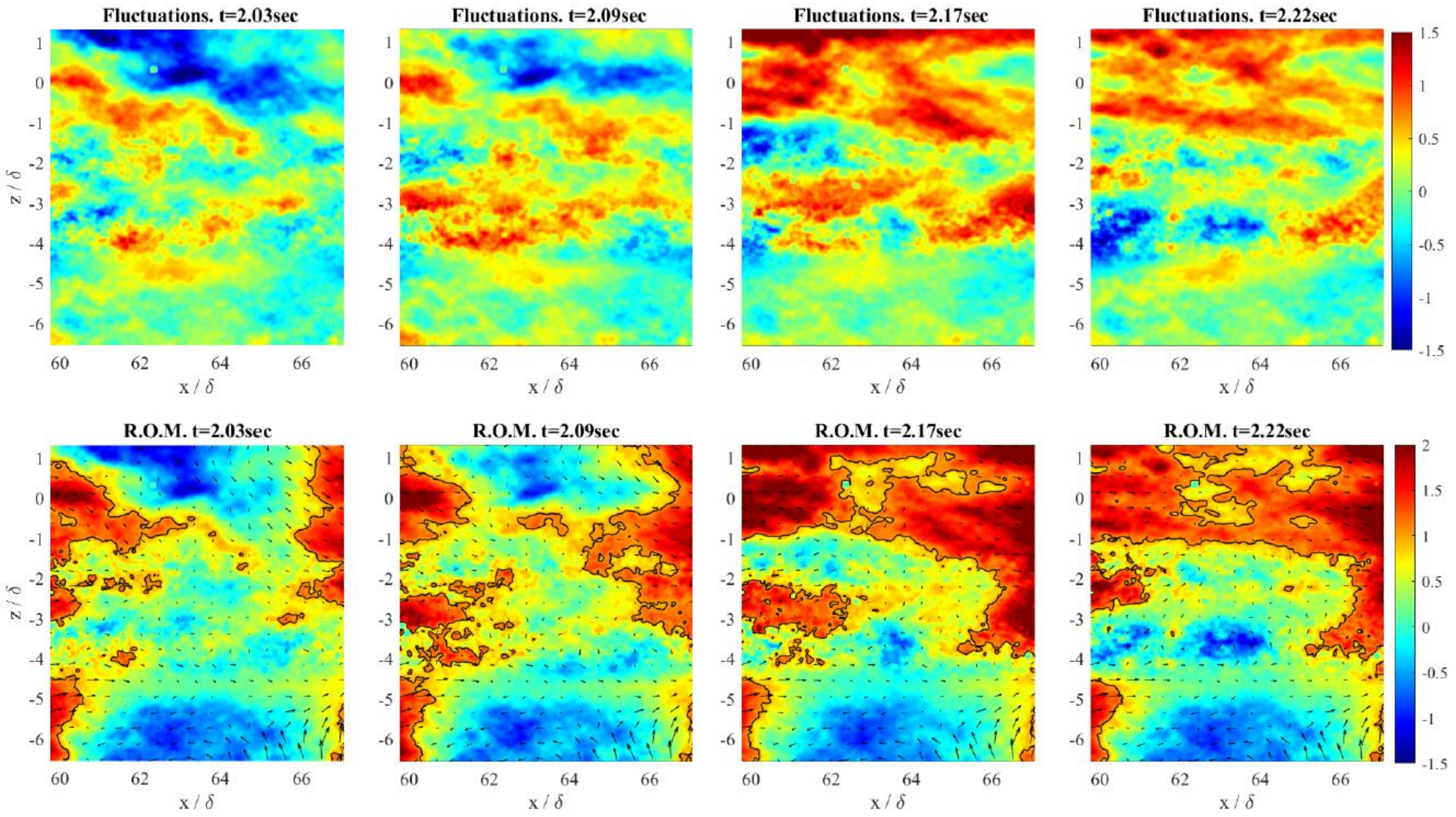


HORIZONTAL (X-Z) PLANES: PASSAGE OF MULTIPLE Q4S

- First time visualization of **high-speed streaks** over 7 δ in span:

- Multiple streaks arrive in the TSB simultaneously across the spanwise direction

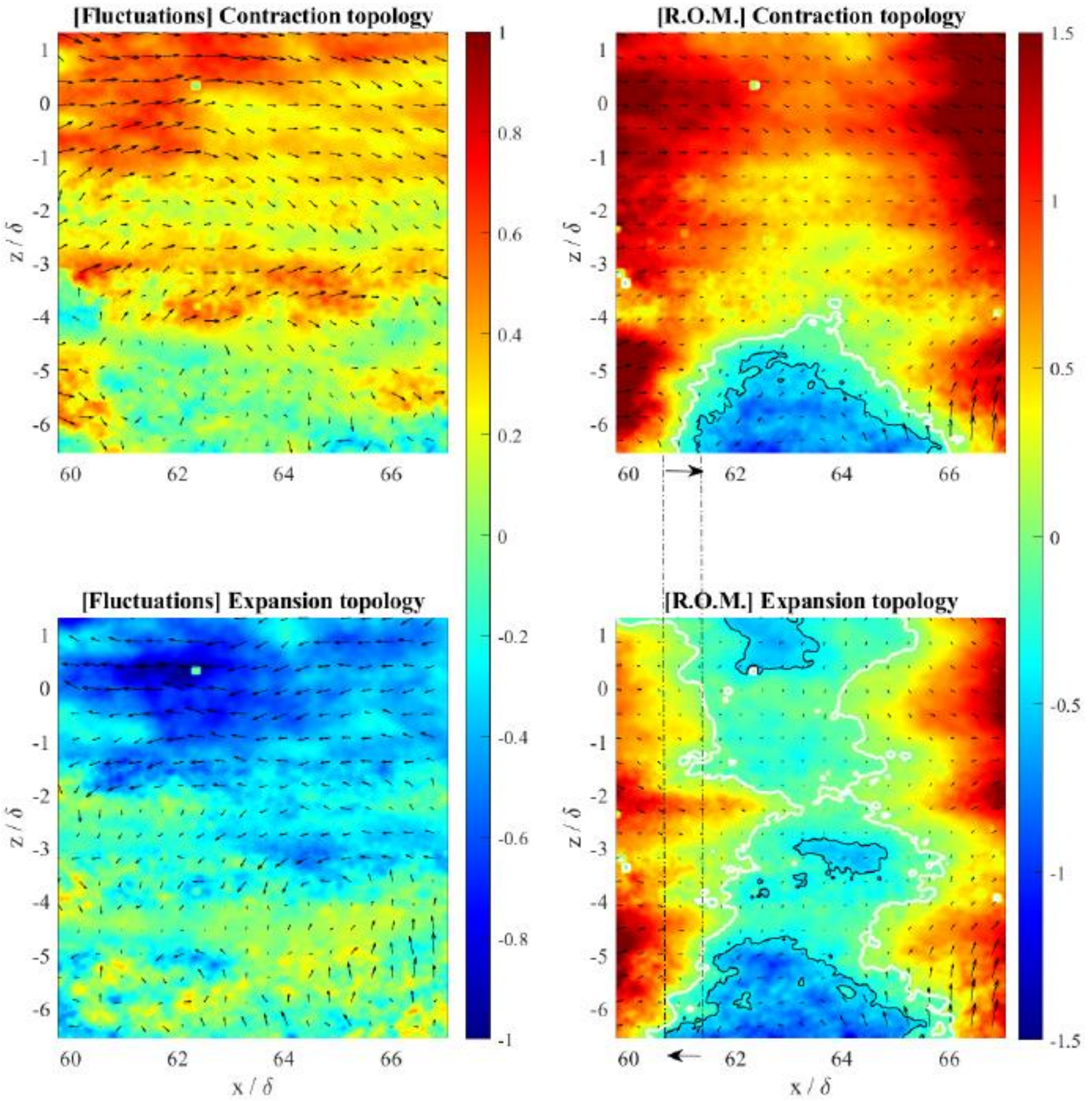
- Intrusion of high-speed streaks make the recirculation region disappear



HORIZONTAL (X-Z) PLANES: A WIDE BREATHING MOTION

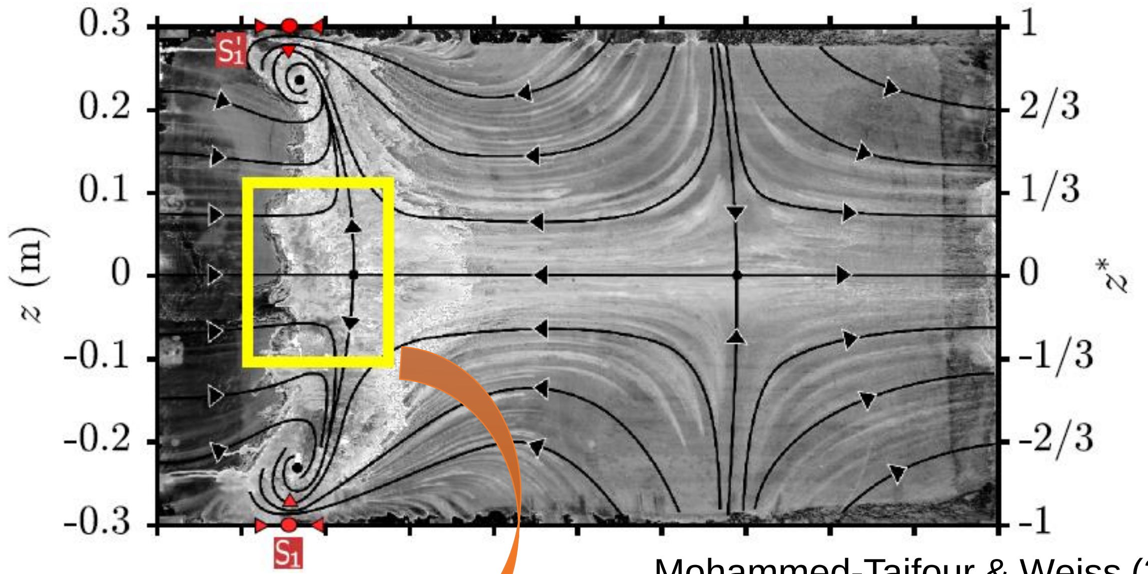
- **First time visualization of a phase-consistent expansion-contraction cycle:**
    - Matches well with conditional averages of the streamwise velocity fluctuations (Le Floc'h *et al*. 2018)
    - ➢ Coherent lift-up yields extreme topology events of the breathing motion
    - ➢ A quasi 2D motion over a range larger than 6δ

➔ **How do these streaks evolve from upstream ?**

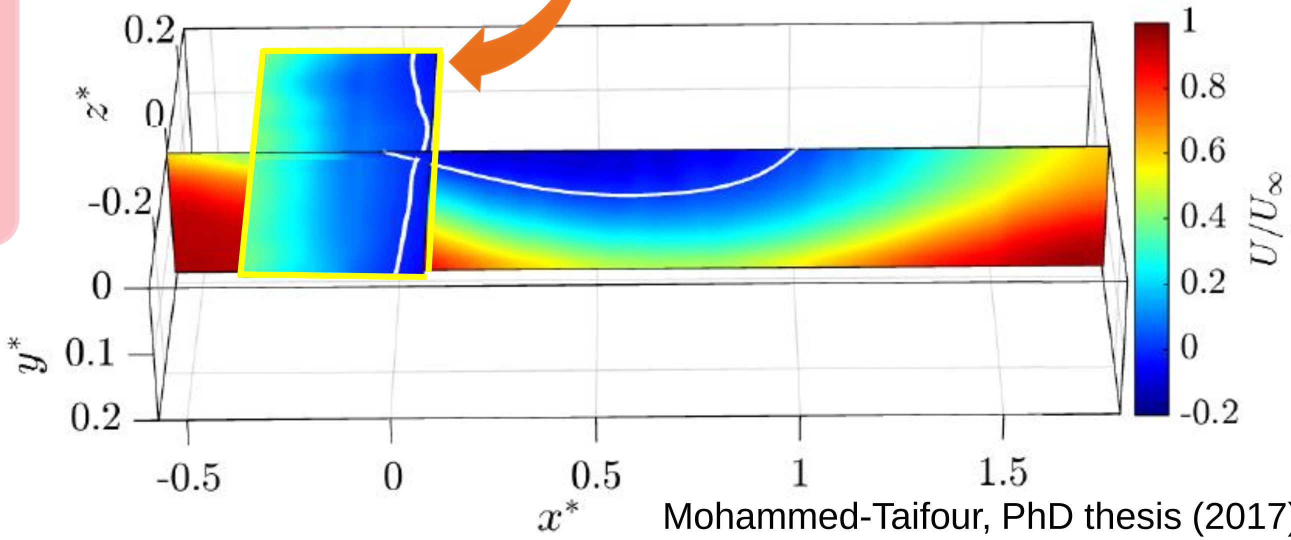


Extension To A Large TSB

- **Investigation of PIV data in the upstream region of a massively separated flow**
  - Original setup: $L_{sep} \approx 0.4$m
  - (x-y) plane: 5 FoVs for the complete TSB region
  - (x-z) plane: 3 FoVs in the APG region **upstream** of the mean separation

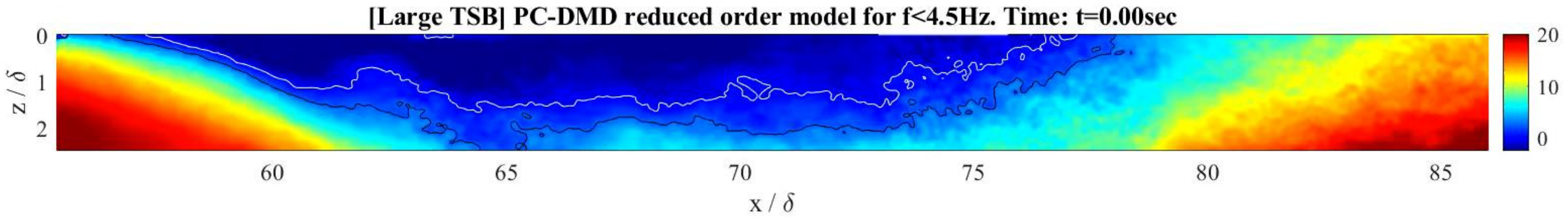


Mohammed-Taifour & Weiss (2016)

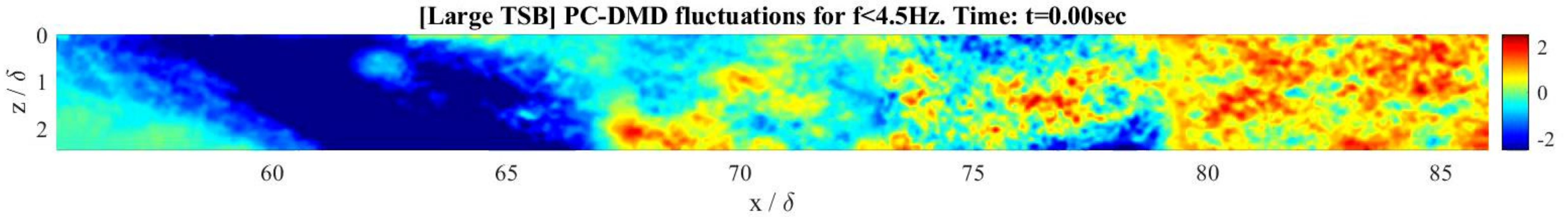


Mohammed-Taifour, PhD thesis (2017)

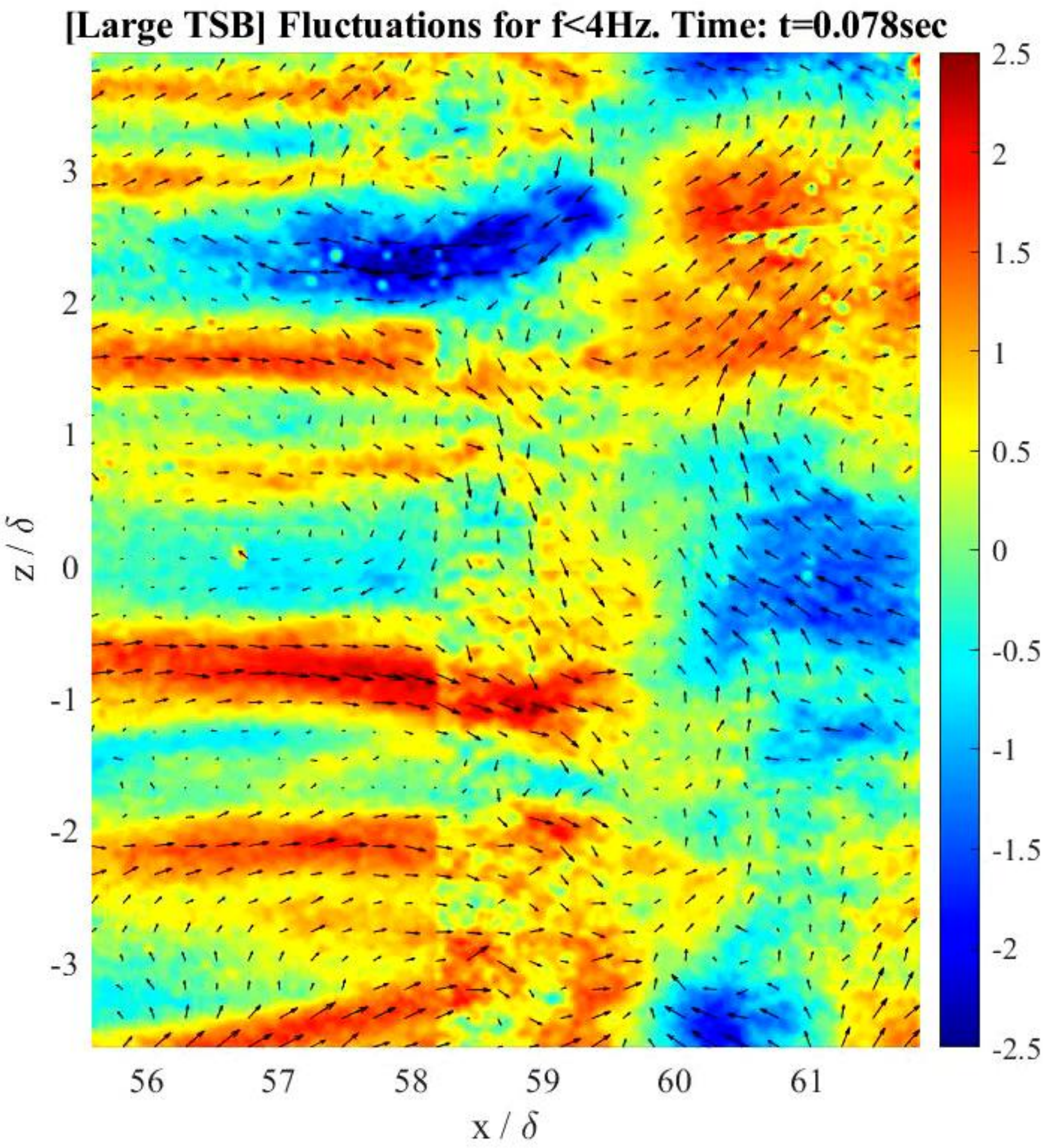
EXTENSION TO A LARGE TSB: VERTICAL PLANE

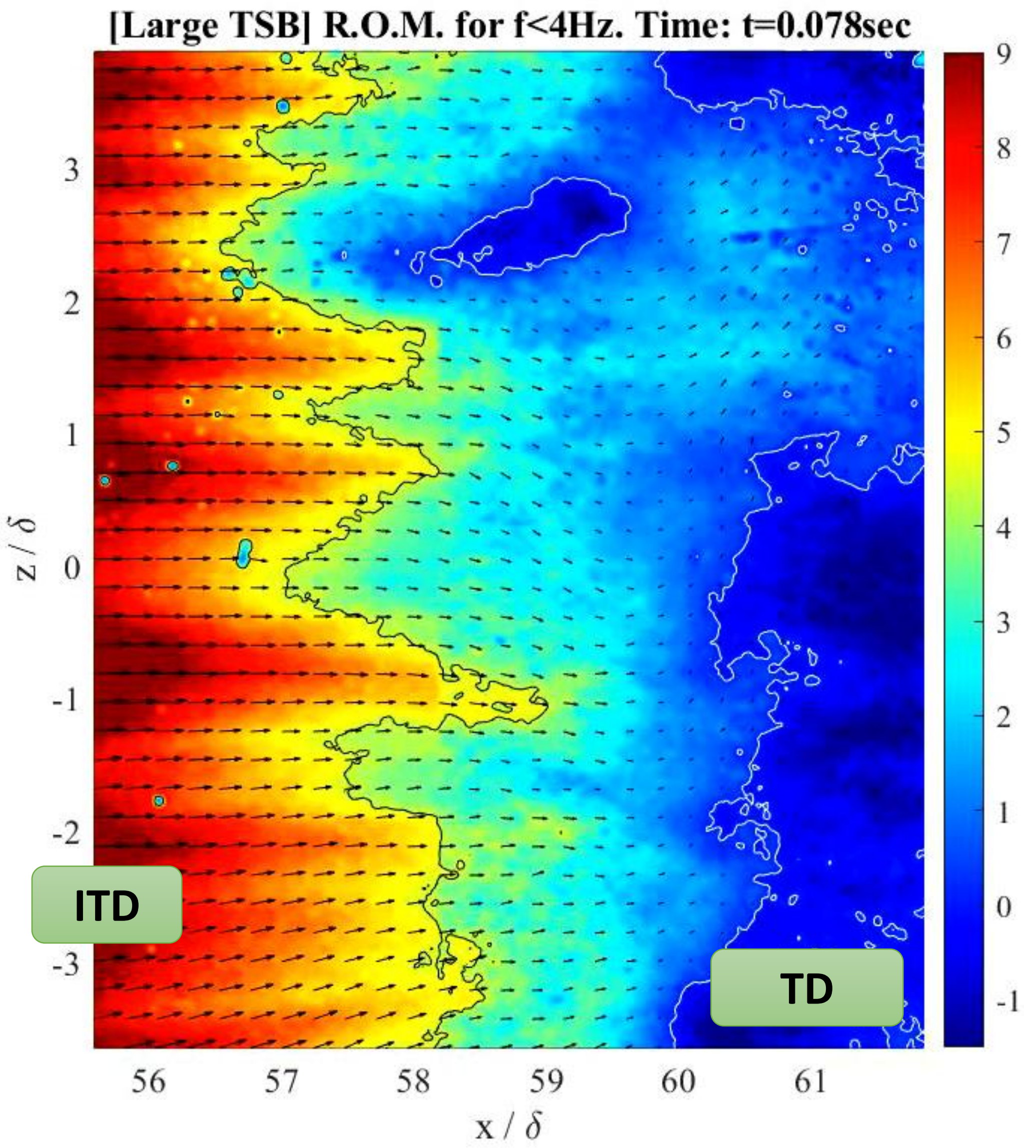


As if we had used 10 cameras ! ☺

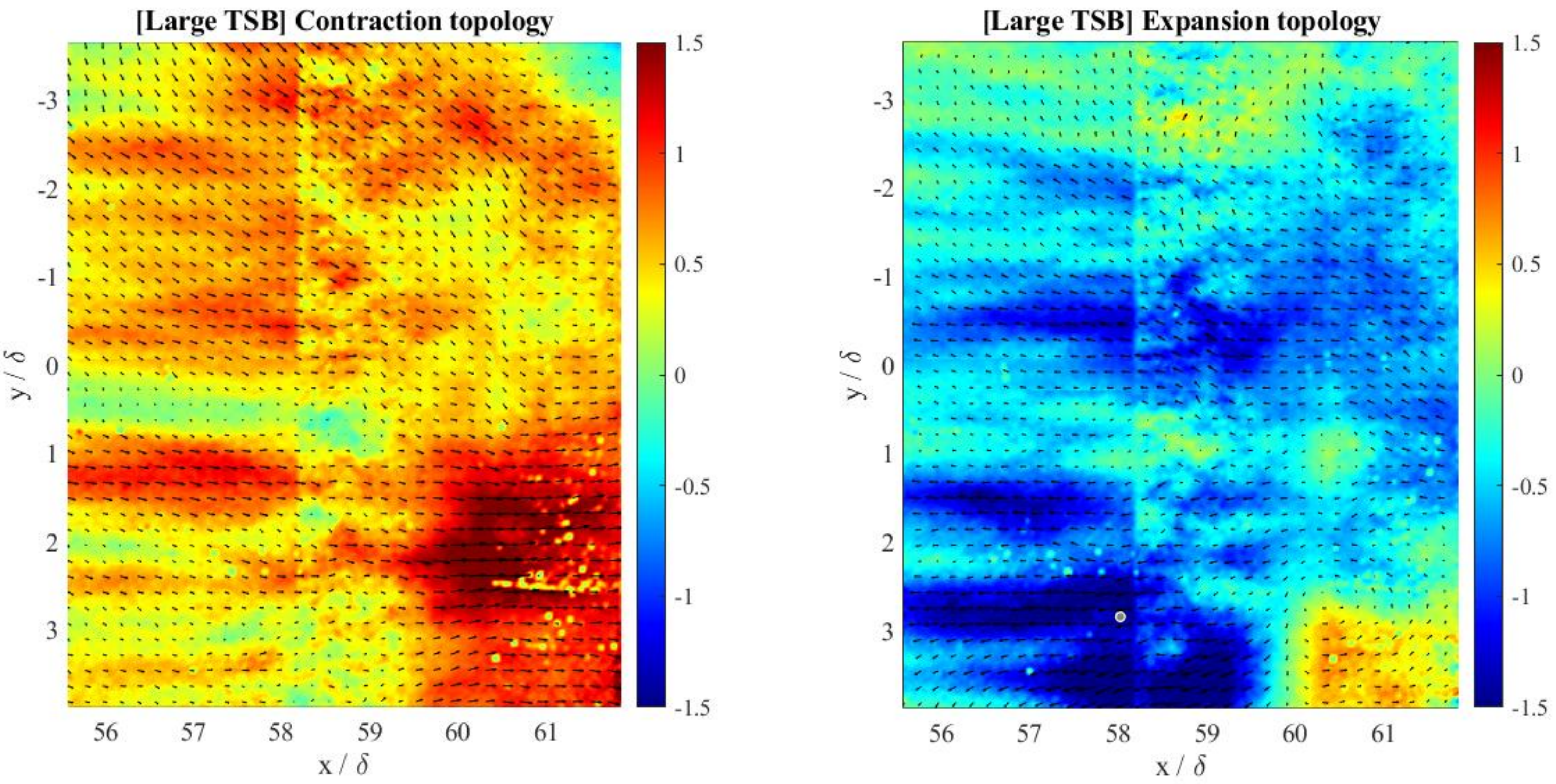


Extension To A Large TSB: Horizontal Plane (APG Region)





Extension To A Large TSB: Horizontal Plane

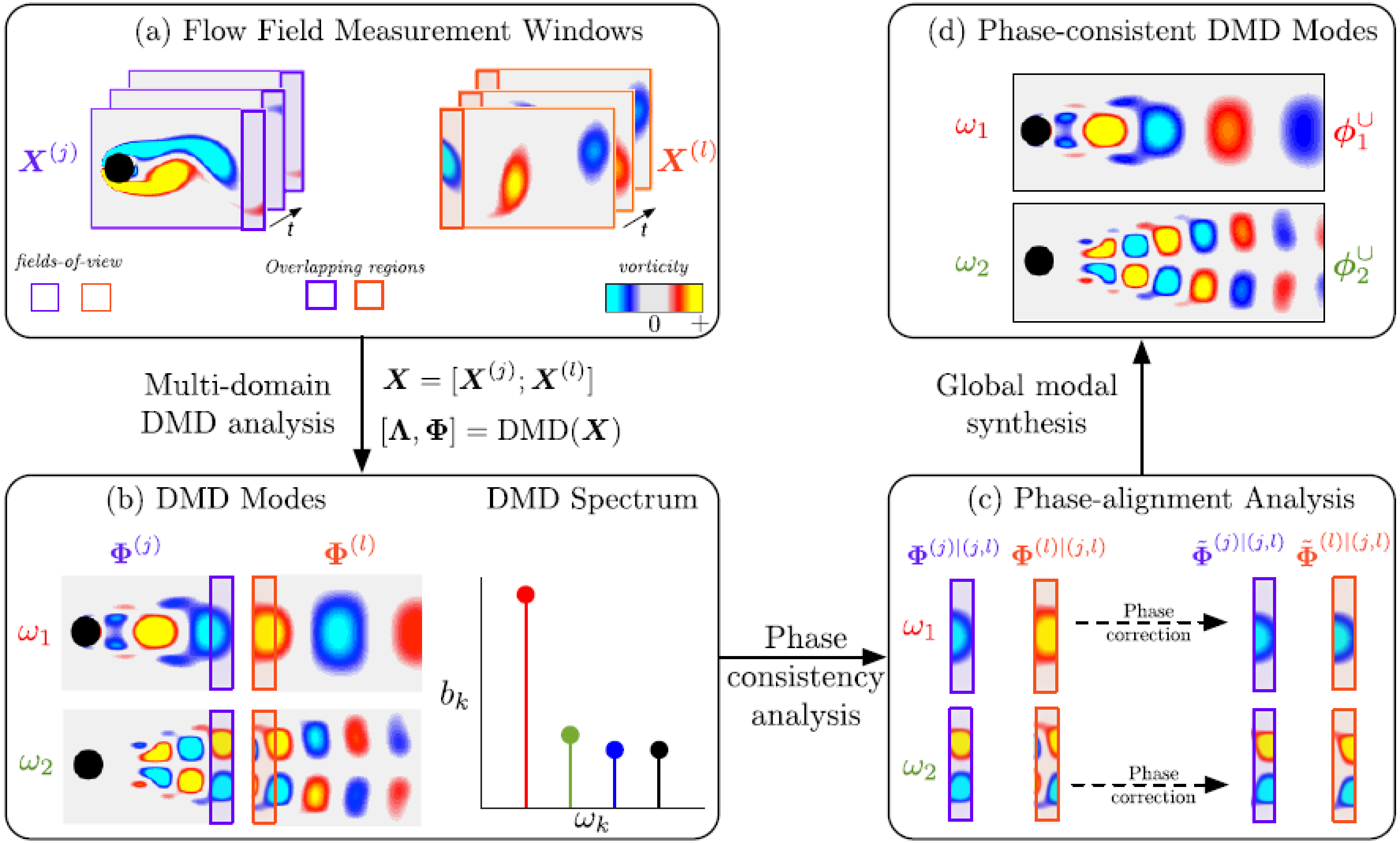


Conclusion

- **Reconstruction of large-scale coherent structures**
  - Promising for the identification of the global dynamic motion in turbulent flows
  - Allowed us to recombine in horizontal and vertical PIV planes.
  - ➢ First time observations of the breathing spanning the entire streamwise and spanwise directions
- **Physics of the global breathing motion**
  - Validation of conditional averages from individual FoVs.
  - APG acts as an amplifier of incoming ZPG coherent structures.
  - Coherent lift-up has a key role as multiple streaks enter the TSB.
- **Future work**
  - Apply PC-SPOD (Hill et al. AIAA SciTech 2023) to use multiple realizations
  - Focus on the role of the APG solely ➔ document the amplification upstream of the mean separation.

Thank you!

BACK-UP: ALGORITHM FROM NAIR ET AL. (2020)



BACK-UP: ALGORITHM FROM NAIR ET AL. (2020)

In fact, any arbitrary phase shift $\boldsymbol{\Psi}$ may be factored out of the DMD modes $\boldsymbol{\Phi} = X' V \Sigma^{-1} W$ and incorporated into the exponential time dynamics, or the mode amplitudes.

$$\tilde{\boldsymbol{\Phi}} = \boldsymbol{\Phi} \exp(i\boldsymbol{\Psi}) \quad \Longrightarrow \quad \boldsymbol{x}(t) = \tilde{\boldsymbol{\Phi}} \exp(\boldsymbol{\Omega} t - i\boldsymbol{\Psi})\boldsymbol{b} = \tilde{\boldsymbol{\Phi}} \exp(\boldsymbol{\Omega} t)\tilde{\boldsymbol{b}}$$

$$\begin{aligned} \boldsymbol{x}^{(1)|(1,2)}(t) &= \boldsymbol{\Phi}^{(1)|(1,2)} \exp(\boldsymbol{\Omega} t)\boldsymbol{b}, \\ &= \tilde{\boldsymbol{\Phi}}^{(2)|(1,2)} \exp(\boldsymbol{\Omega} t)\boldsymbol{b}, \\ &= \boldsymbol{\Phi}^{(2)|(1,2)} \exp(i\boldsymbol{\Psi}) \exp(\boldsymbol{\Omega} t)\boldsymbol{b}. \end{aligned}$$

Concatenated DMD allows to have the same eigenvalue and amplitude on different FoVs… but different phases of the modes !
➔ Phase-shift operator

the phase shift $\exp(i\boldsymbol{\Psi})$ yields:

$$\exp(i\boldsymbol{\Psi}) \approx (\boldsymbol{\Phi}^{(2)|(1,2)})^{\dagger} \boldsymbol{\Phi}^{(1)|(1,2)}.$$