High-Fidelity Computational Data of Transitional Boundary Layers for a Data-Driven Approach

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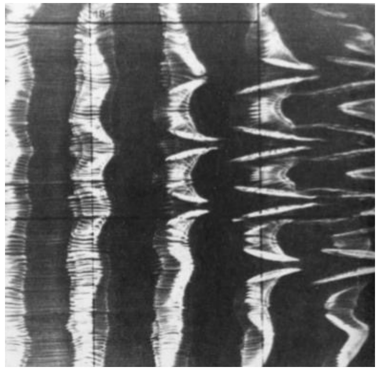
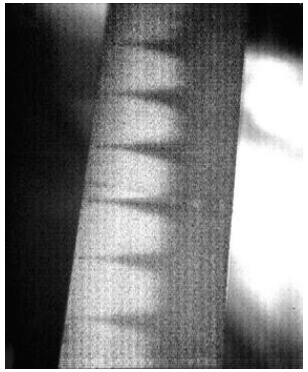
Motivation on Sharing Transition Data

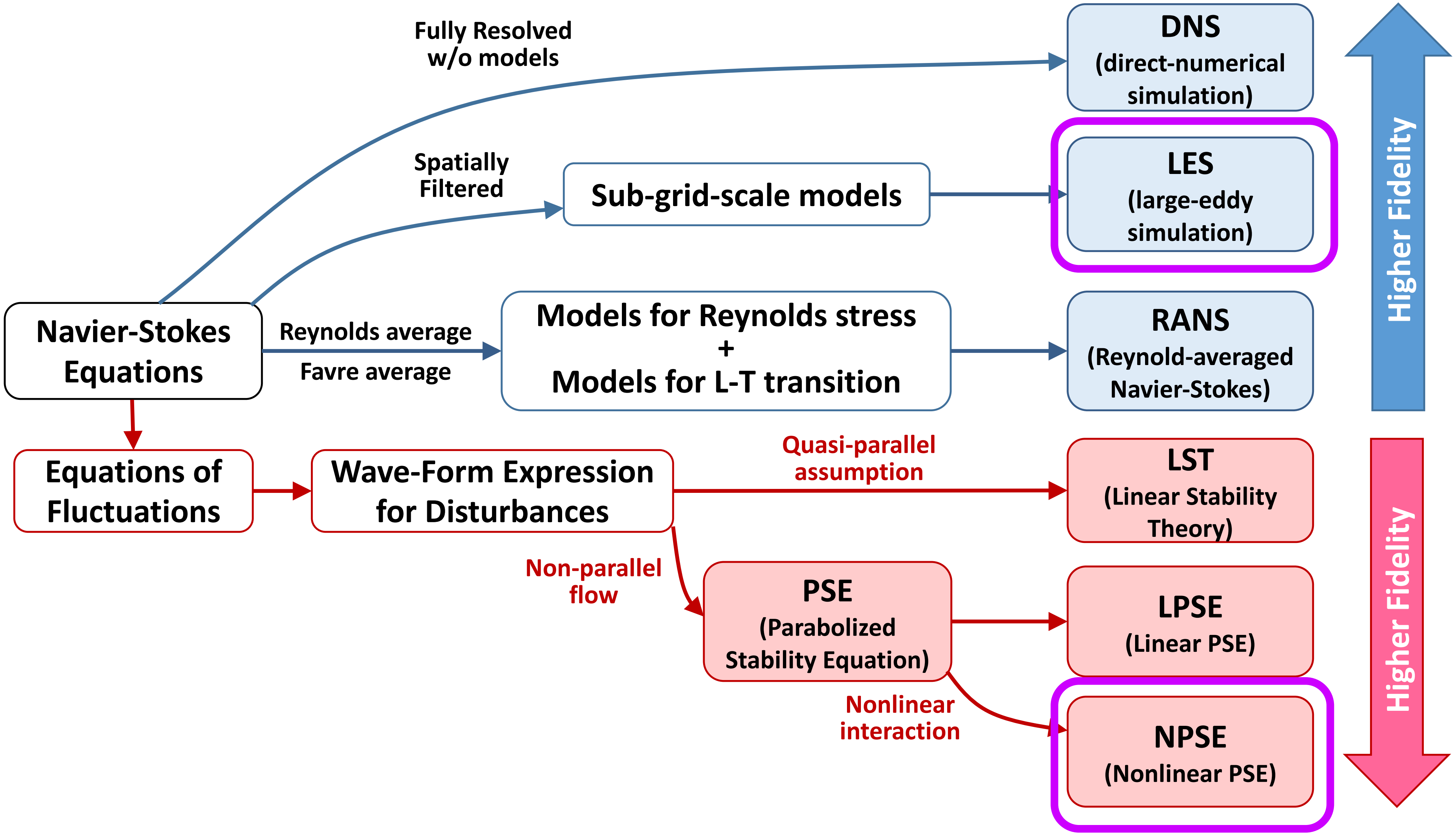
- **A new era of transition modeling with data-driven approaches**





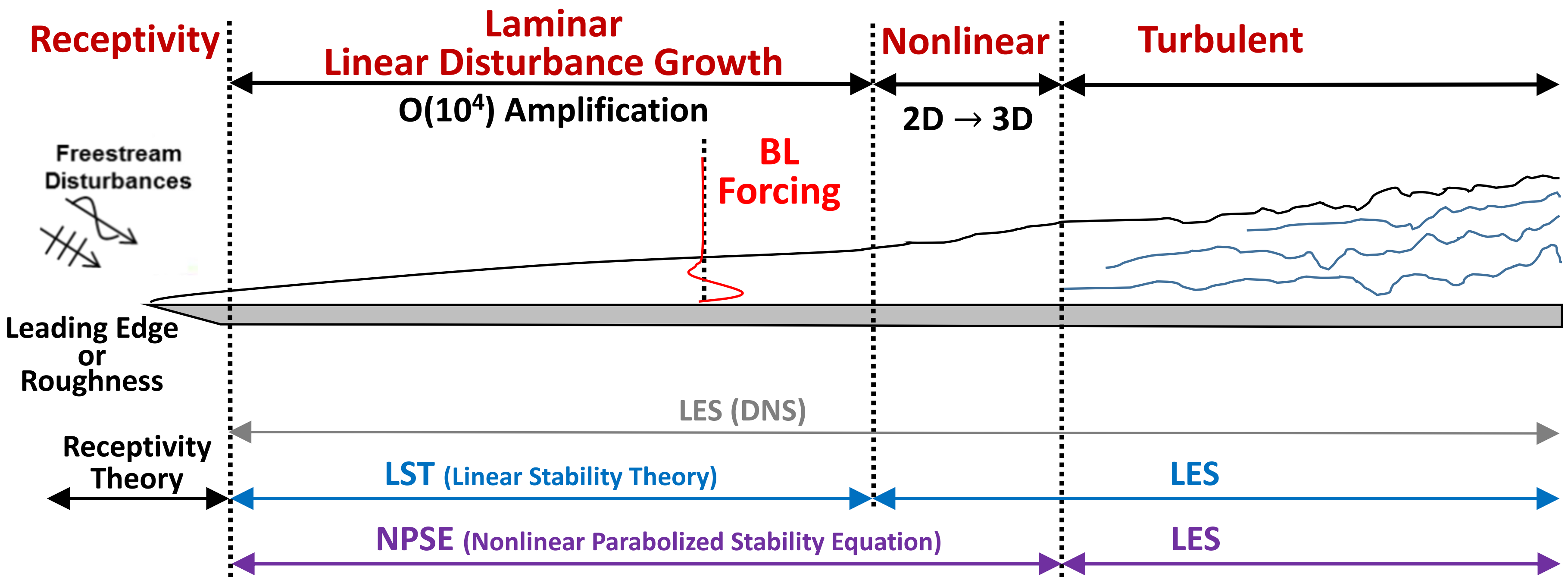
- **What kind of data do we need?**
  - Skin friction
  - Instabilities (fluctuation in the pre-transition region)
    - Mode shape
    - Amplitude
  - Velocity correlation (Reynolds stress)
    - May help to develop a RANS-based transition model
  - Anything else?

High-Fidelity and Cost-Effective Computational Method : LES + PSE



S. Jee, et al, *J. Fluids Engineering*, 2018; M. Kim, et al, *Comp. & Fluids*, 2019; M. Kim, et al, *Comp. Methods in Applied Mech. and Eng.*, 2020;
M. Kim, et al, *JFM*, 2021; J. Lim, et al, *Aerospace Sci. and Tech.*, 2021

High-Fidelity and Cost-Effective Computational Method : LES + PSE



- **LES before L-T Transition is practically DNS**
- **A few modes of instability trigger L-T Transition**
- **Efficient method: stability theory -> forcing terms at LES Inlet**
- **LES + PSE method is motivated by Philippe Spalart's early work**

[Bertolotti, F. P., Herbert, T., & Spalart, P. R. (1992). Linear and nonlinear stability of the Blasius boundary layer. *Journal of fluid mechanics*, 242, 441-474]

S. Jee, et al, *J. Fluids Engineering*, 2018; M. Kim, et al, *Comp. & Fluids*, 2019; M. Kim, et al, *Comp. Methods in Applied Mech. and Eng.*, 2020; M. Kim, et al, *JFM*, 2021; J. Lim, et al, *Aerospace Sci. and Tech.*, 2021

Two Canonical Transitional Boundary Layers

- **Case 1 : Incompressible BL**
  - ZPGBL on a flat plate
  - Subharmonic-mode breakdown (H-type transition)
  - Major instabilities
    - Fundamental planar wave (Tollmien-Schlichting wave)
    - Subharmonic oblique wave
  - Solver: openFOAM
    - SGS model: WALE

- **Case 2 : Compressible BL**
  - Mach = 3
  - ZPGBL on a flat plate
  - Oblique-mode breakdown
    - Oblique mode by itself is unstable for Mach range 2-4
  - Solver: rhoEnergyFOAM [Modesti and Pirozzoli, *Comp. & Fluids*, 2017]
    - SGS model: WALE

S. Jee, et al, *J. Fluids Engineering*, 2018; M. Kim, et al, *Comp. & Fluids*, 2019; M. Kim, et al, *Comp. Methods in Applied Mech. and Eng.*, 2020;
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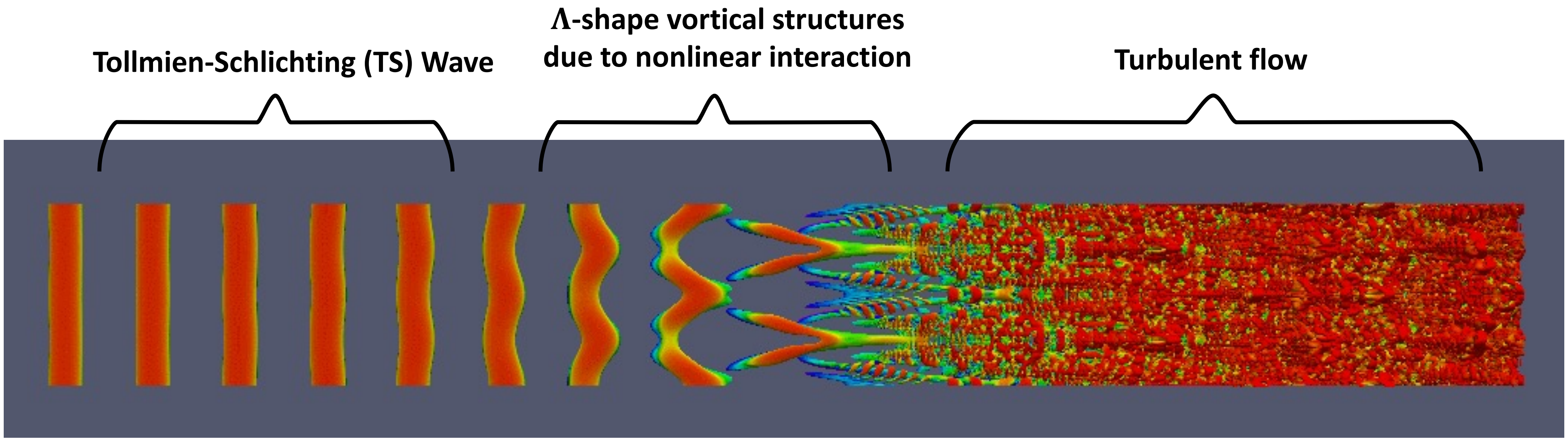
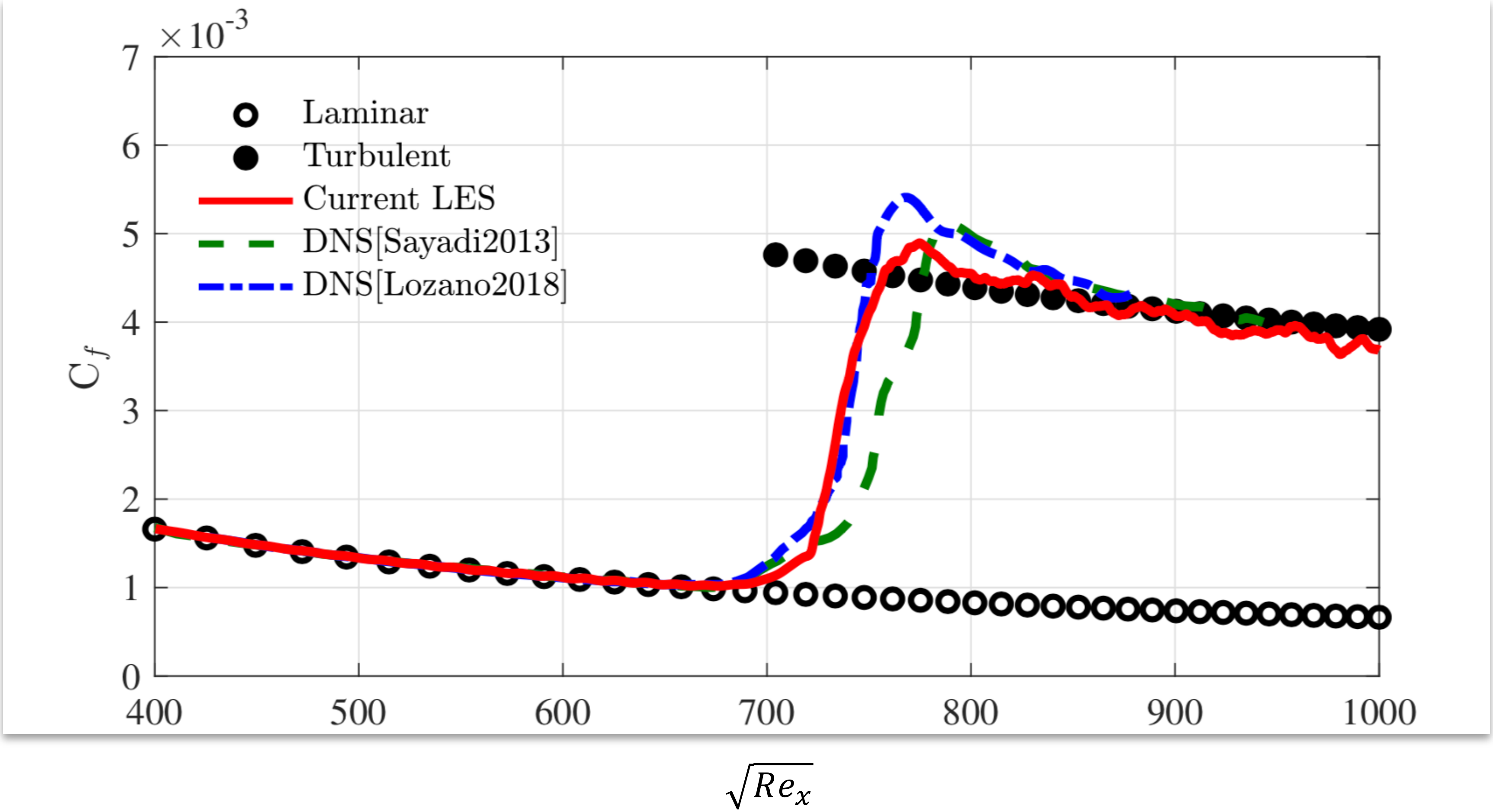
Overview on Case 1 (Incompressible BL Transition, H-type)

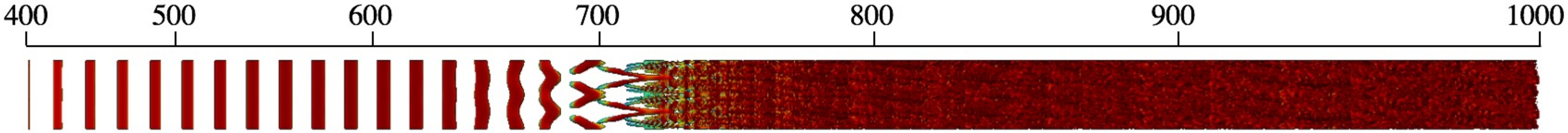


Vortical structures visualized with Q criteria

M. Kim, et al, *Comp. & Fluids*, 2019

Selected Data from Case 1 (Incompressible BL Transition, H-type)





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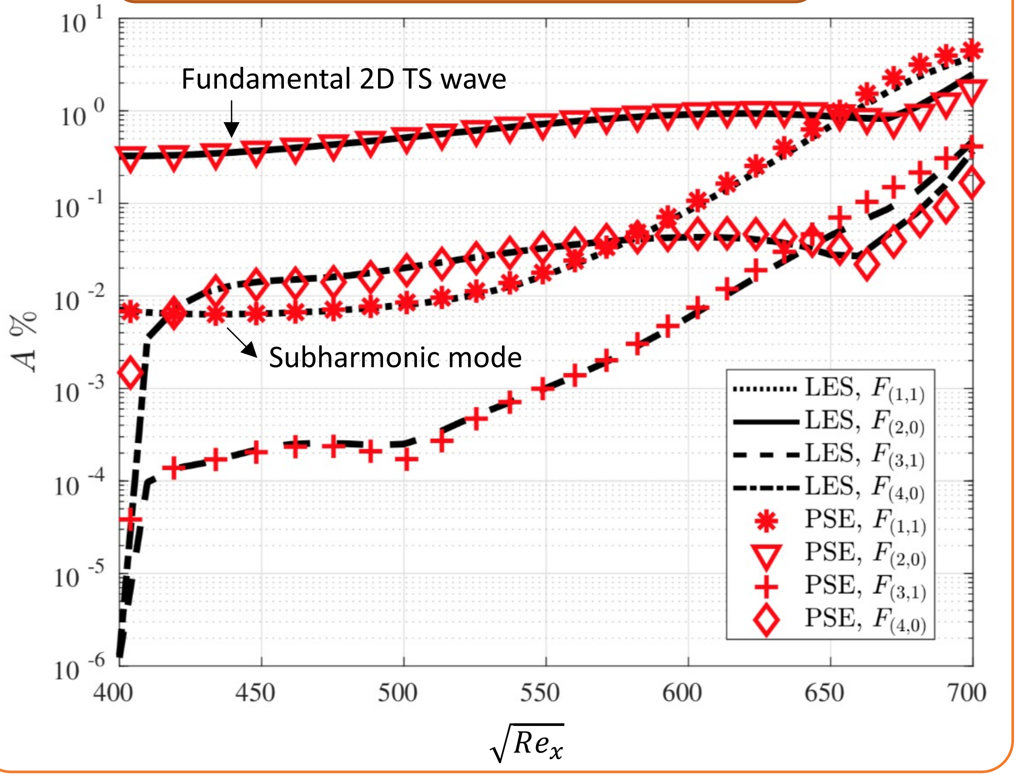
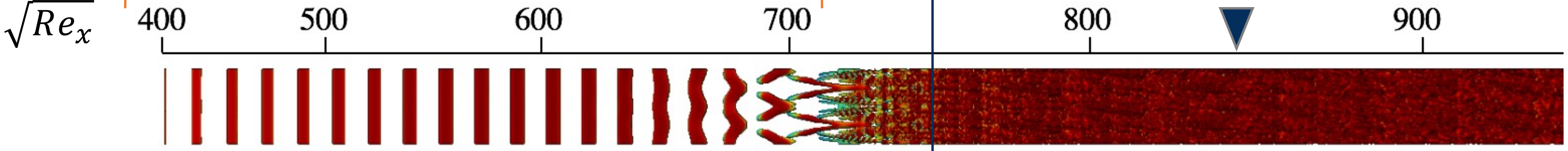
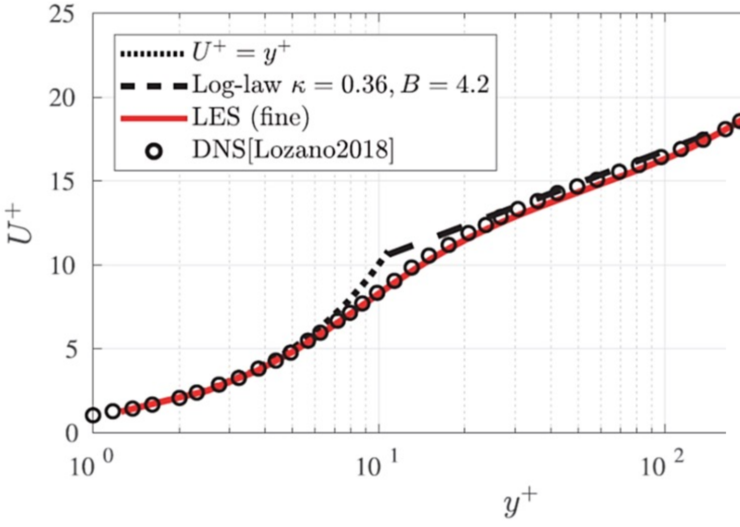
Selected Data from Case 1 (Incompressible BL Transition, H-type)

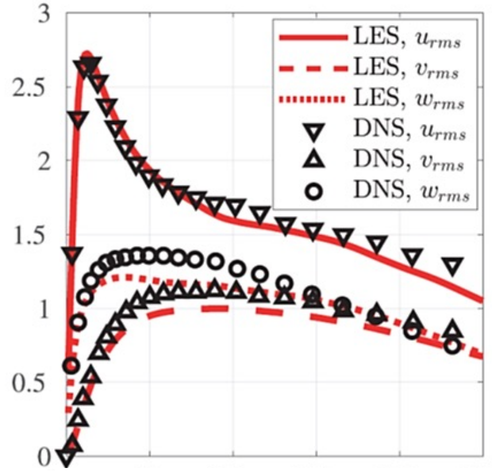
Instabilities in Pre-Transition Regime

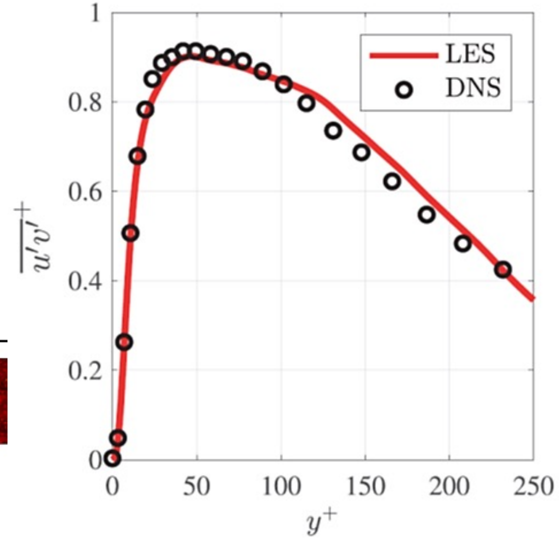




Turbulent Regime

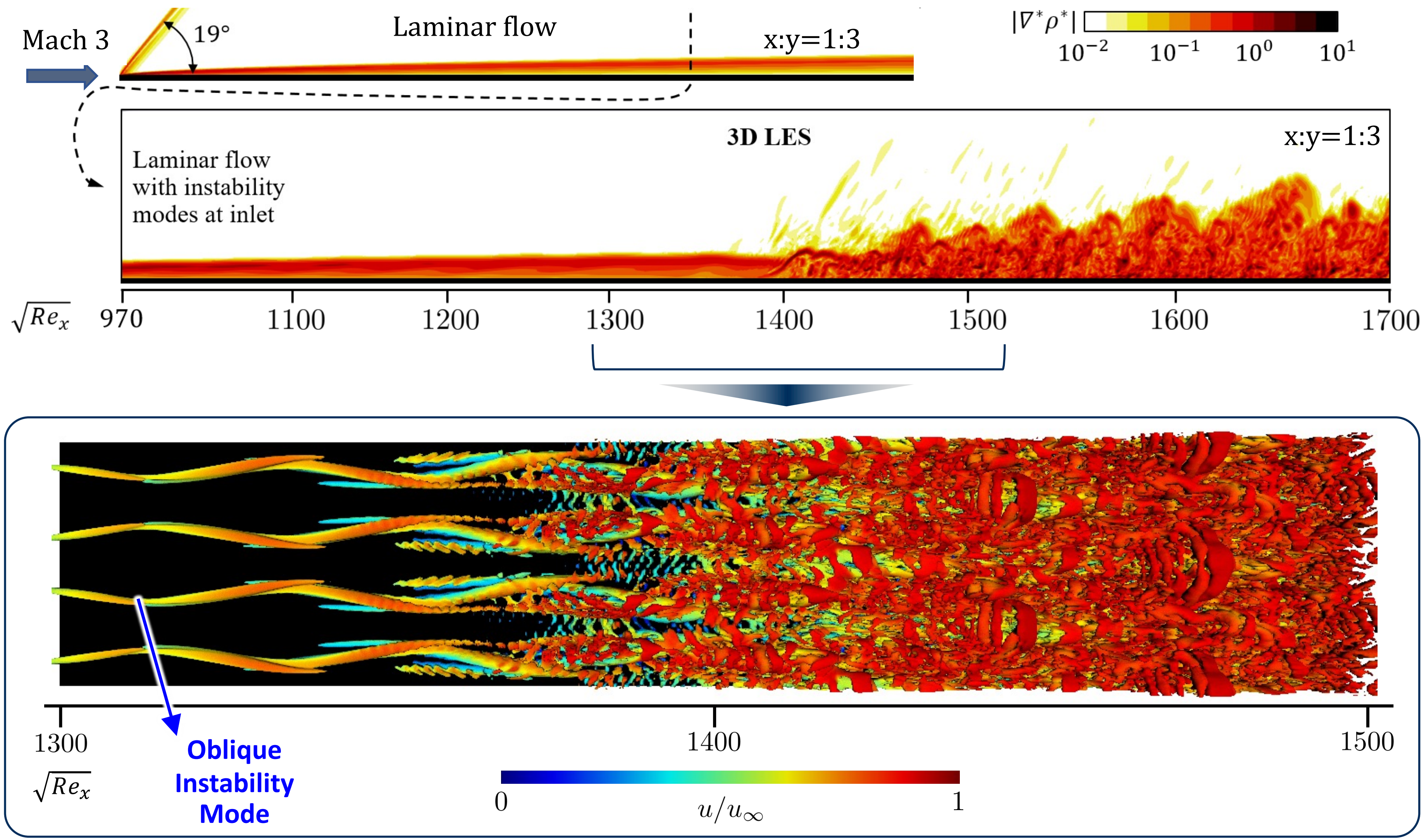






M. Kim, et al, *Comp. & Fluids*, 2019

Overview on Case 2 (Supersonic BL Transition at Mach 3)



J. Lim, et al, *Aerospace Sci. and Tech.*, 2021

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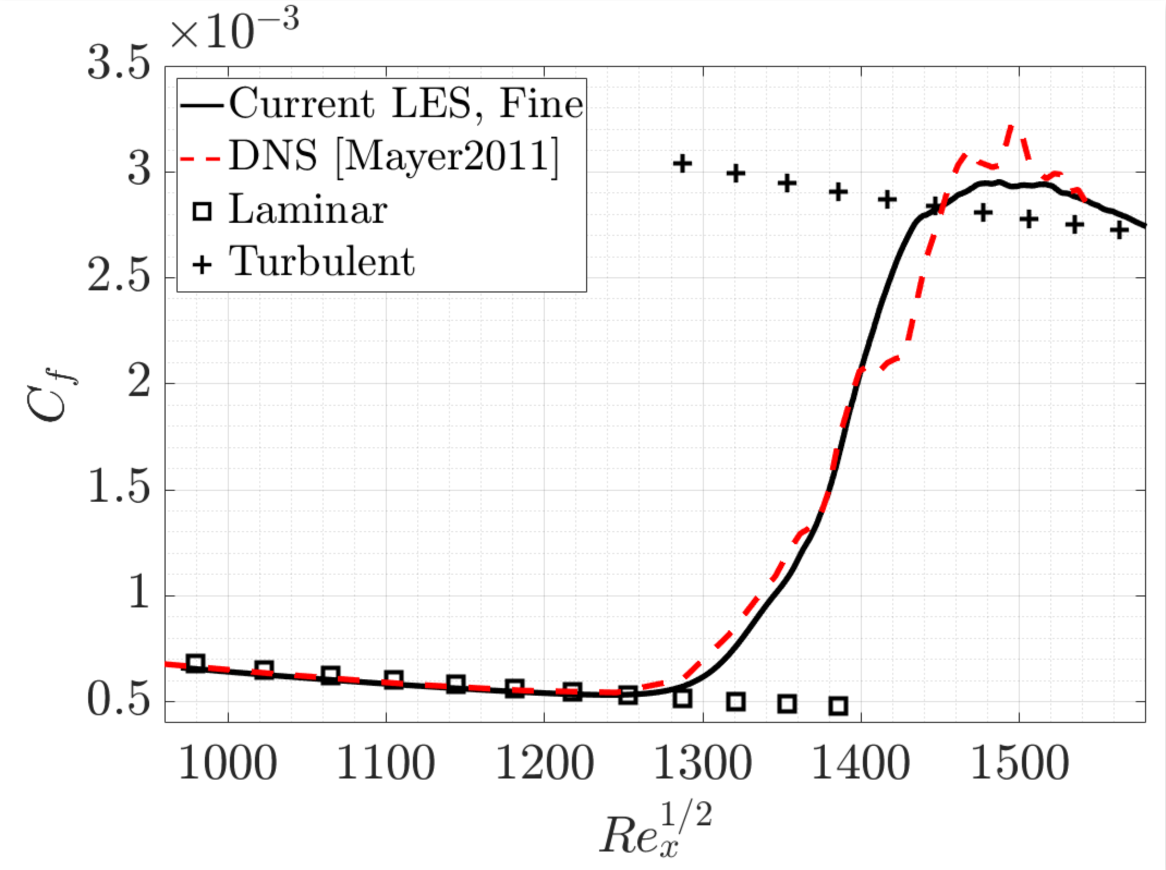

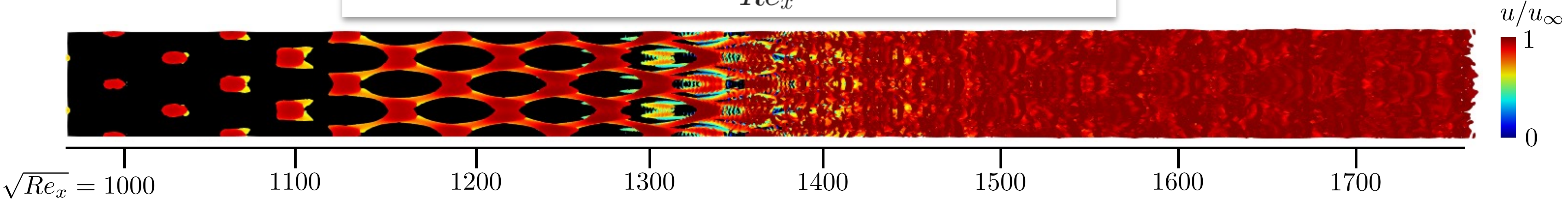

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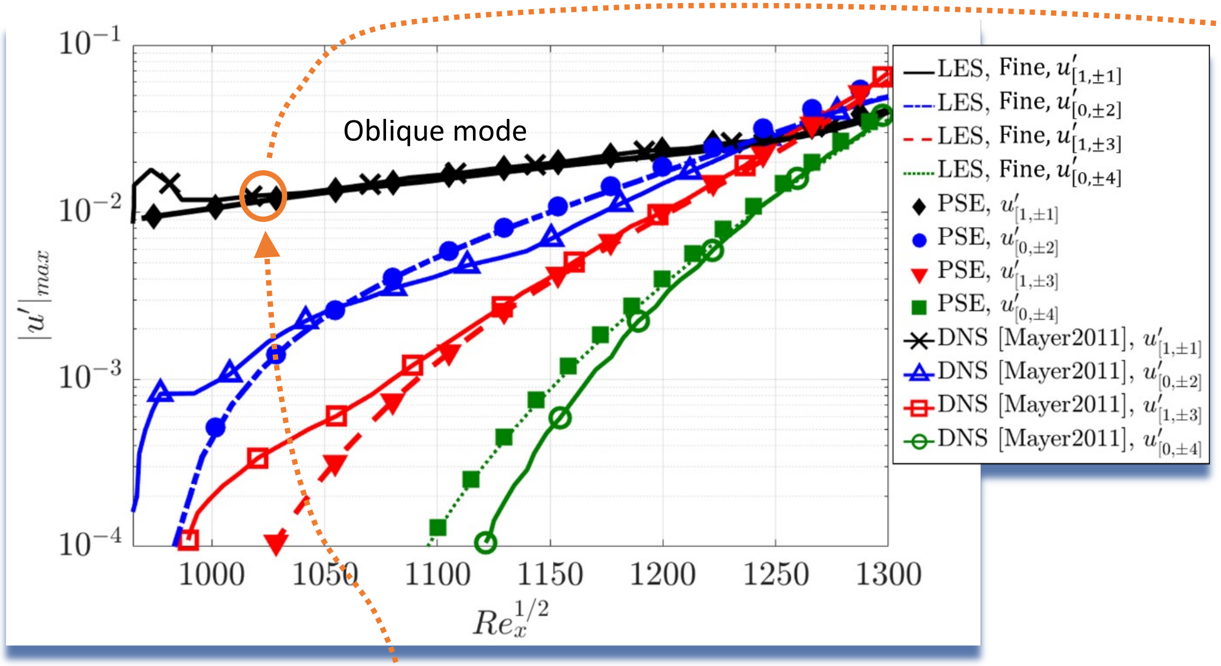

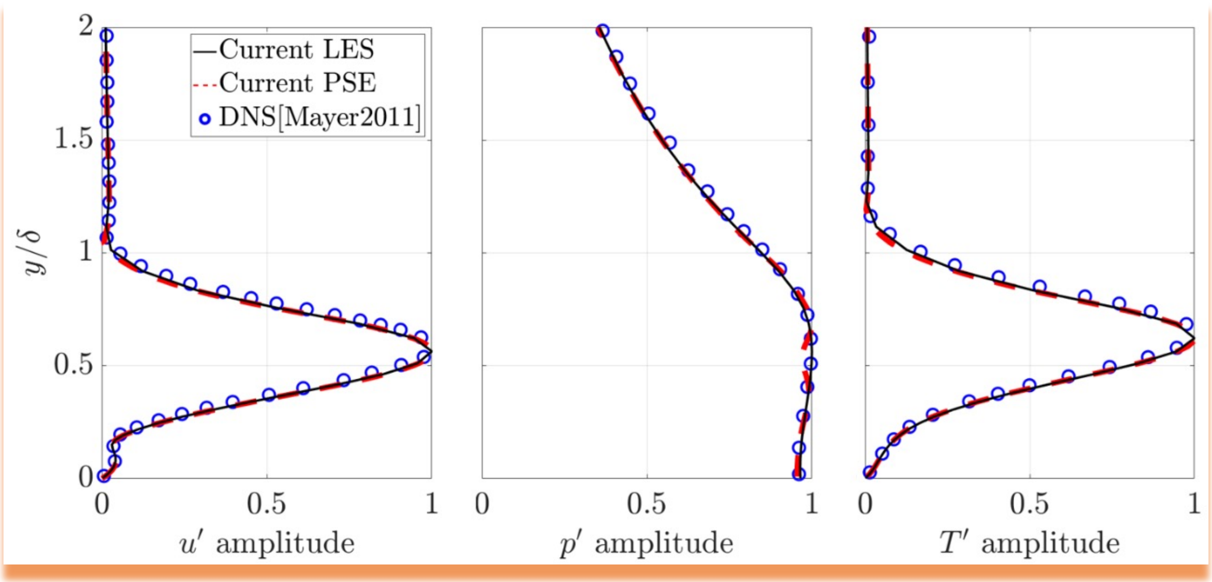

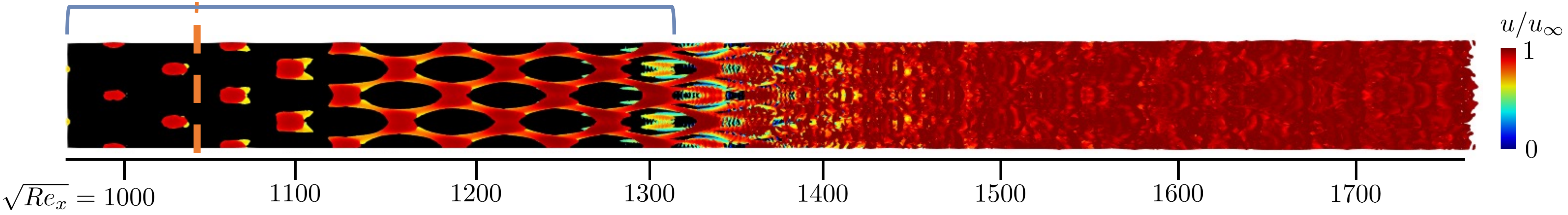

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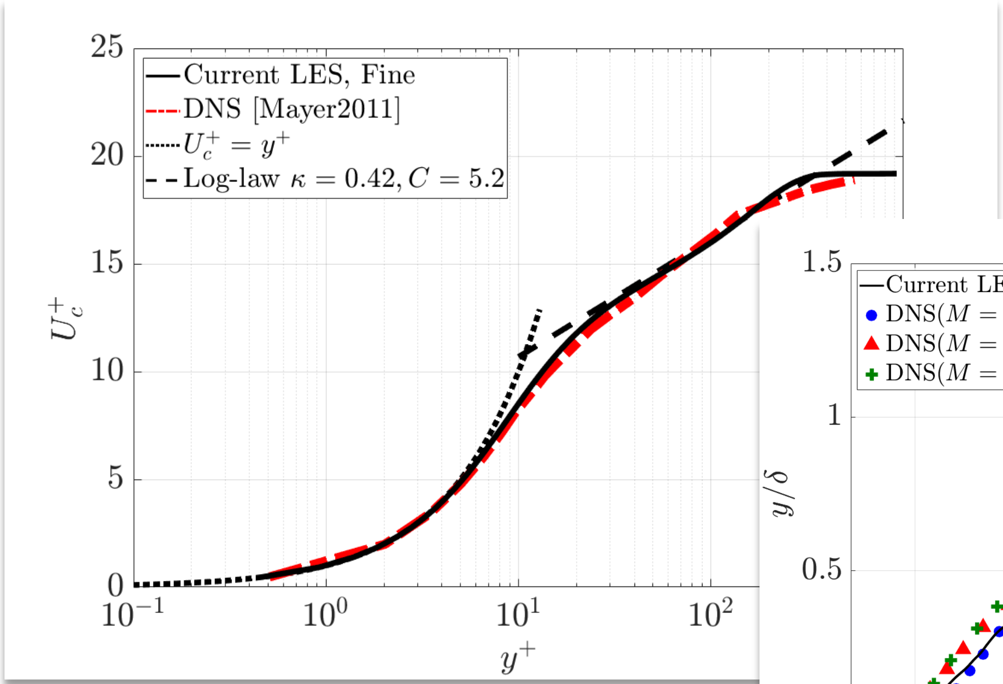
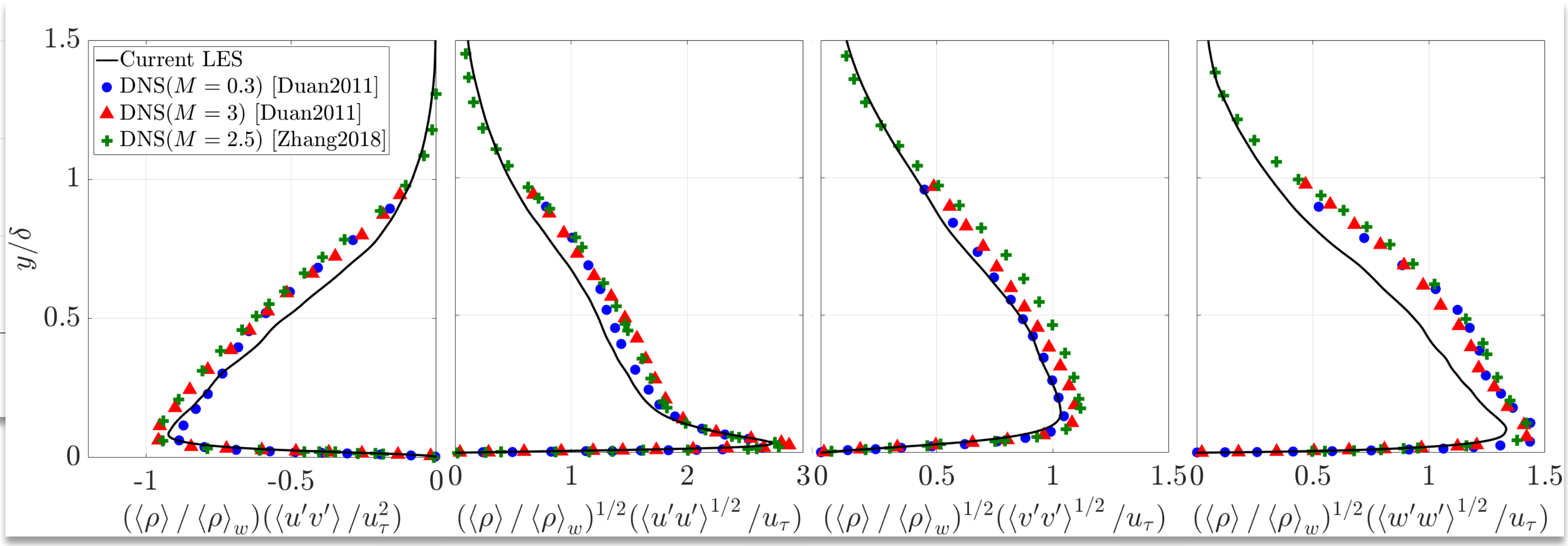
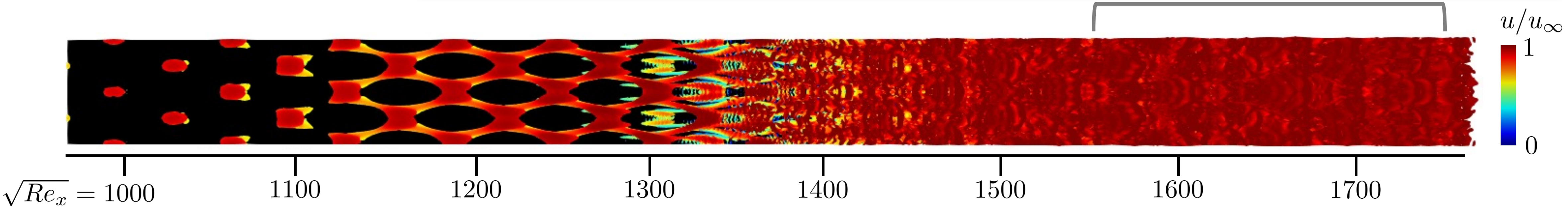
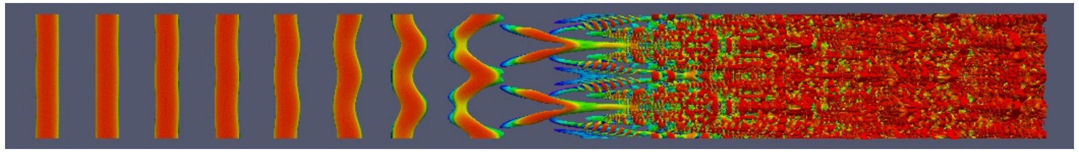




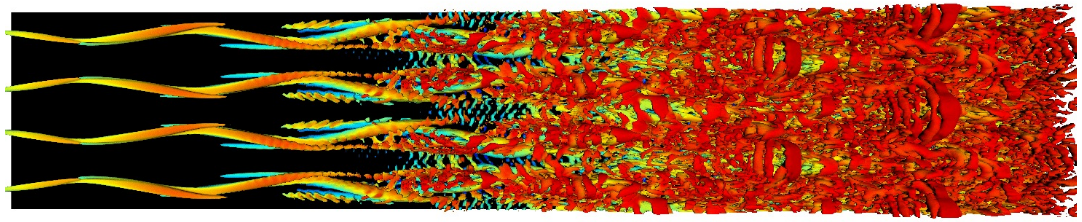


J. Lim, et al, *Aerospace Sci. and Tech.*, 2021

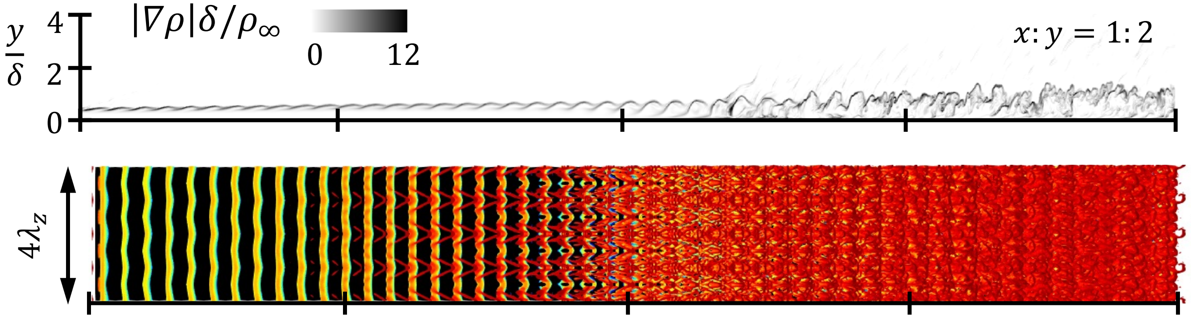
- **Two canonical BL transition cases are available**
  - Incompressible BL: subharmonic breakdown (H-type)



  - Supersonic BL at Mach 3: oblique-mode breakdown



- **More cases could be added**
  - Hypersonic BL transition at Mach 6: Mack 2nd mode and fundamental oblique mode

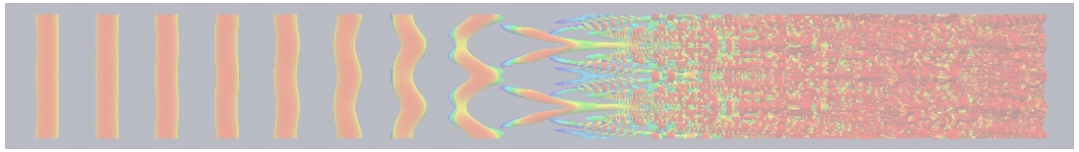


- **Vortical structures in pre-transition regions may provide insights for physics-based, data-driven transition modeling**
- **Machine learning may pick up relevant flow features for transition models**

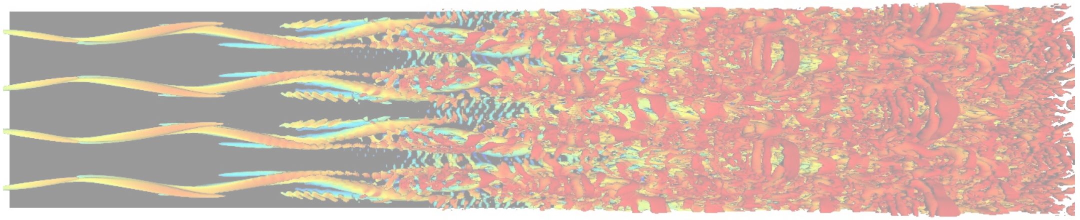
Summary – 2/2

Two canonical BL transition cases are available

- Incompressible BL: subharmonic breakdown (H-type)

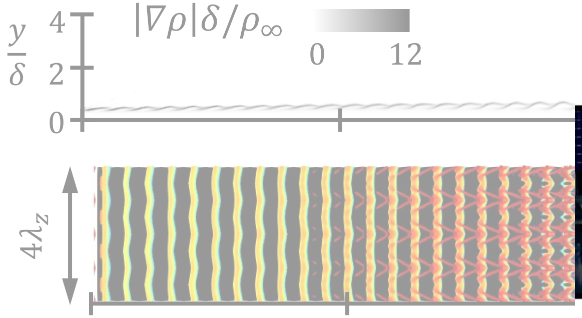


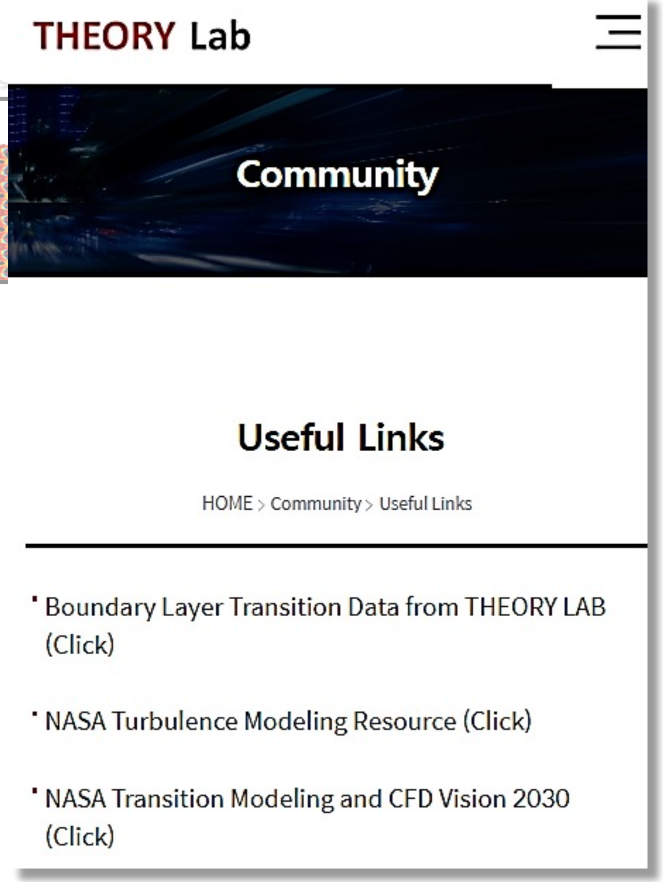
- Supersonic BL at Mach 3: oblique-mode breakdown



More cases could be added

- Hypersonic BL transition at Mach 6: Mack 2nd mode and fundamental oblique mode





Data available

- Skin friction, mean flow info, anything else in papers
- Spatial and temporal development of instabilities
- Unsteady dynamics of major instability modes
- Any other upon request

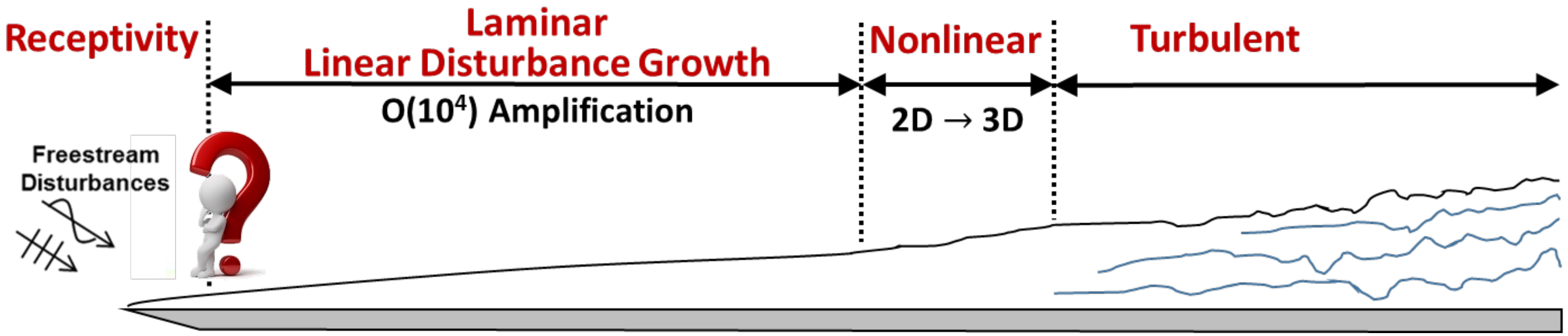
Where : theory.gist.ac.kr

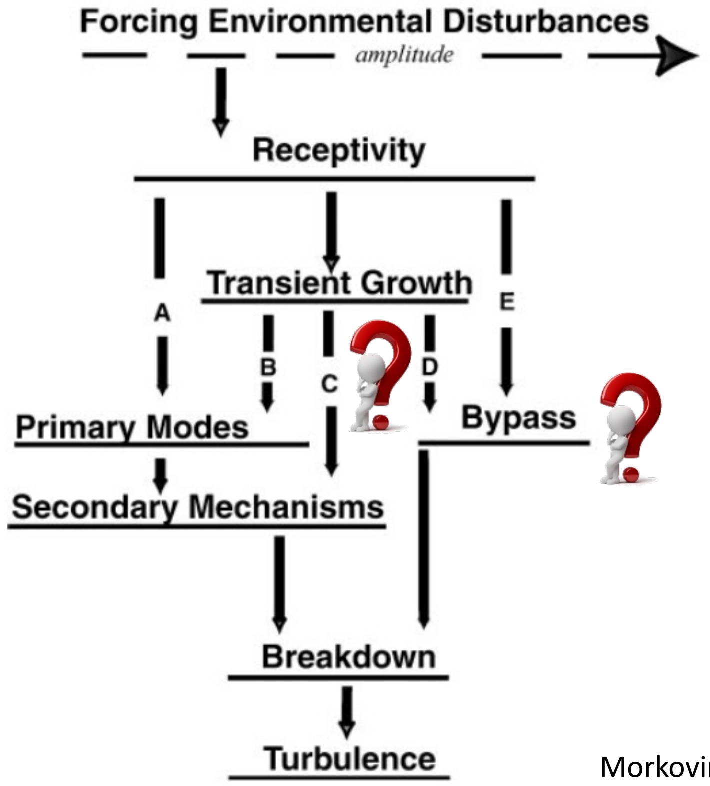
- Feel free to contact me (sjee@gist.ac.kr) for transition data

S. Jee, et al, *J. Fluids Engineering*, 2018; M. Kim, et al, *Comp. & Fluids*, 2019; M. Kim, et al, *Comp. Methods in Applied Mech. and Eng.*, 2020; M. Kim, et al, *JFM*, 2021; J. Lim, et al, *Aerospace Sci. and Tech.*, 2021

Final Remarks

- What else data do we need?
- Freestream disturbances?
- Other than natural transition – bypass and transient growth path?





Morkovin (1969)

Acknowledgements

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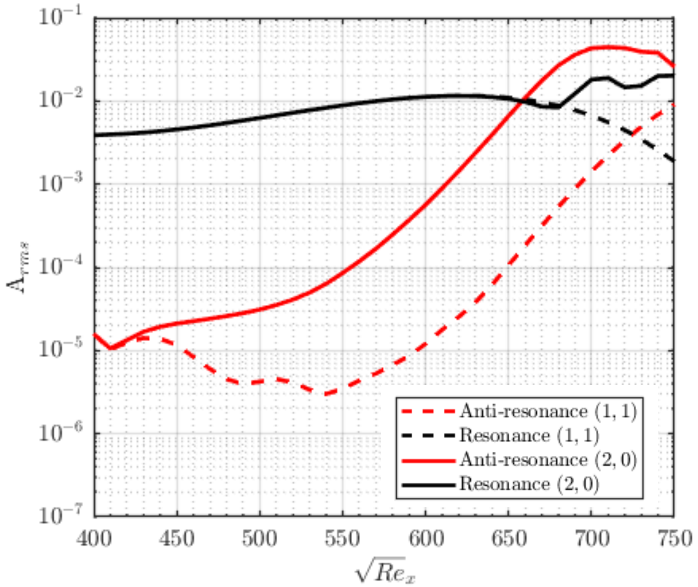
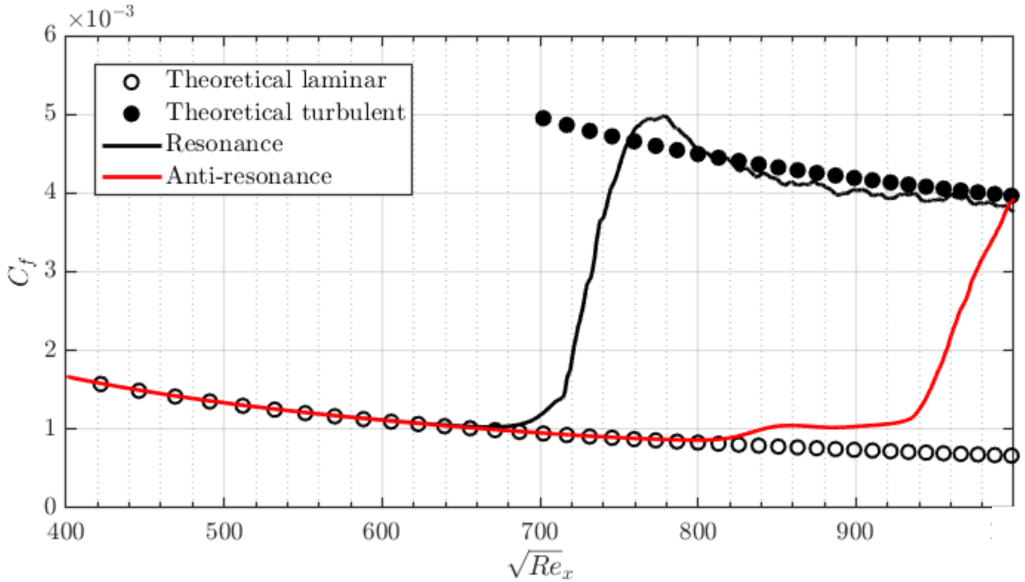
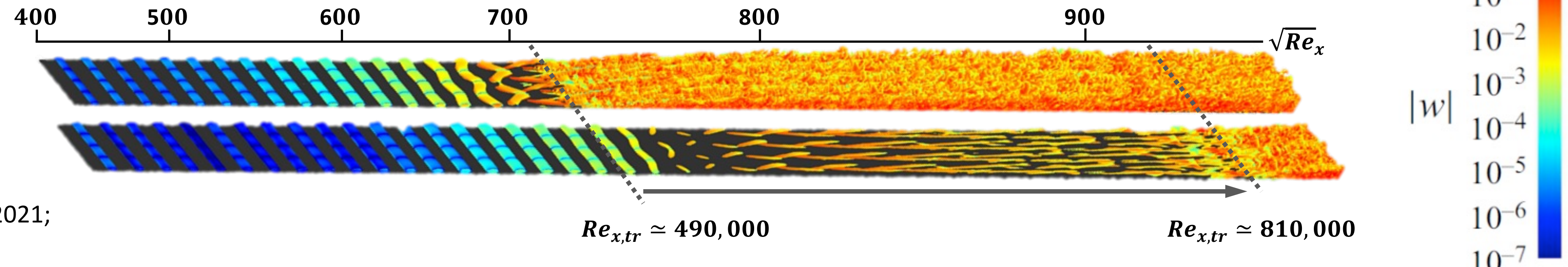
Selected Data from Case 1 (Incompressible BL Transition, H-type)

- **Vortical structures in pre-transition region may provide a clue for transition location**
- **Here, different evolution of vortical structure comes from initial phase difference between two modes (2,0) and (1,1) at inlet $\sqrt{Re_x} = 400$**
  - Resonance : subharmonic mode (1,1) grows exponentially almost from the beginning
  - Anti-resonance : subharmonic mode (1,1) initially damps then grow







M. Kim, et al, *JFM*, 2021;