An Attempt to Study Coherent Structures and Their Interactions in Viscous Fluid Flows

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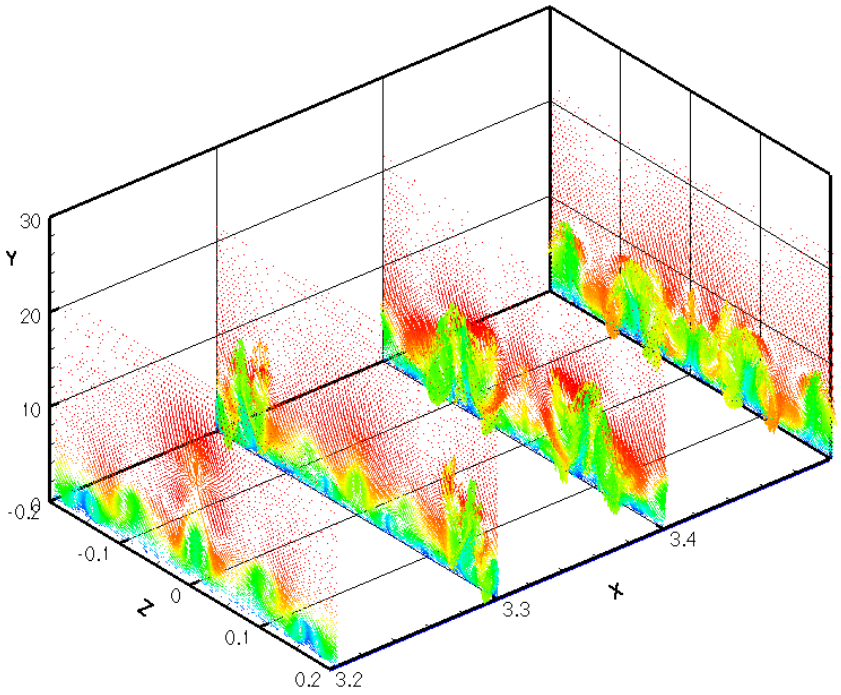
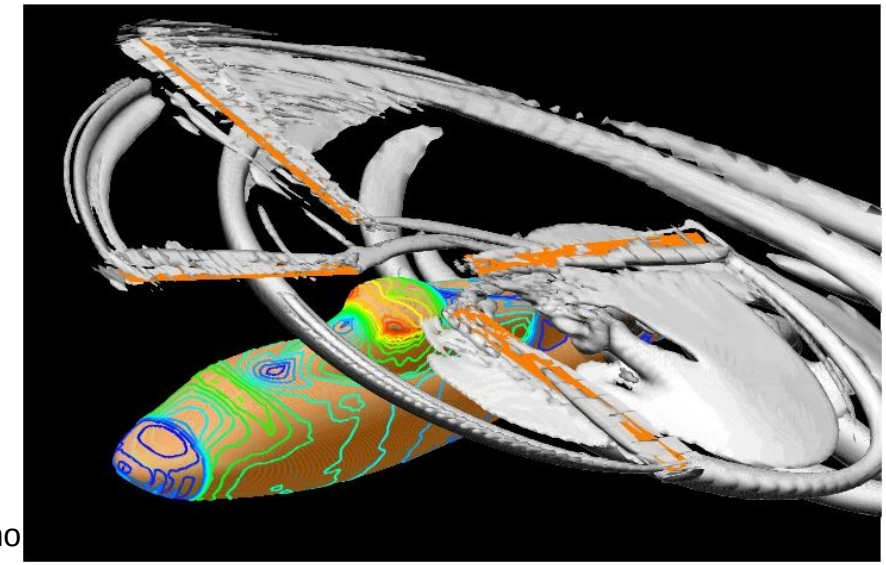
Introduction

Motivation

- Increasingly large data sets
  - CFD (LES, DNS)
  - PIV
- Unsteady problems
  - Fluid-structure interaction
  - Flow induced noise
  - Separation
  - Laminar-turbulent transition
  - Flow control
  - etc.
- Insight & Understanding
  - Can we go beyond a mere data visualization?

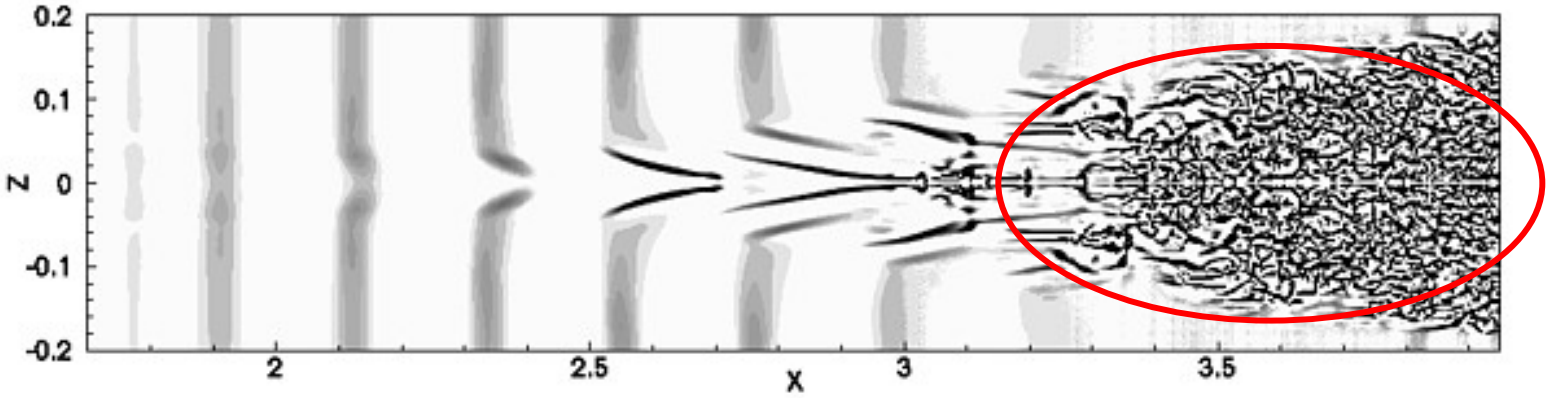




Motivation (1)

Laminar-turbulent transition of a flat-plate boundary layer

projection of boundary layer vortices:



Initial stages:

- Finite number of modes in frequency-wavenumber spectrum
- Compact representation in spectral space
- Wave interactions
- Easily comprehensible

Late stages:

- Infinite number of modes in frequency-wavenumber spectrum
- Impossible to understand

- Structures in physical space
- (Locally) compact representation?
- Vortex interactions
- Possibility to understand ?
- Need for tools !

Motivation (2)

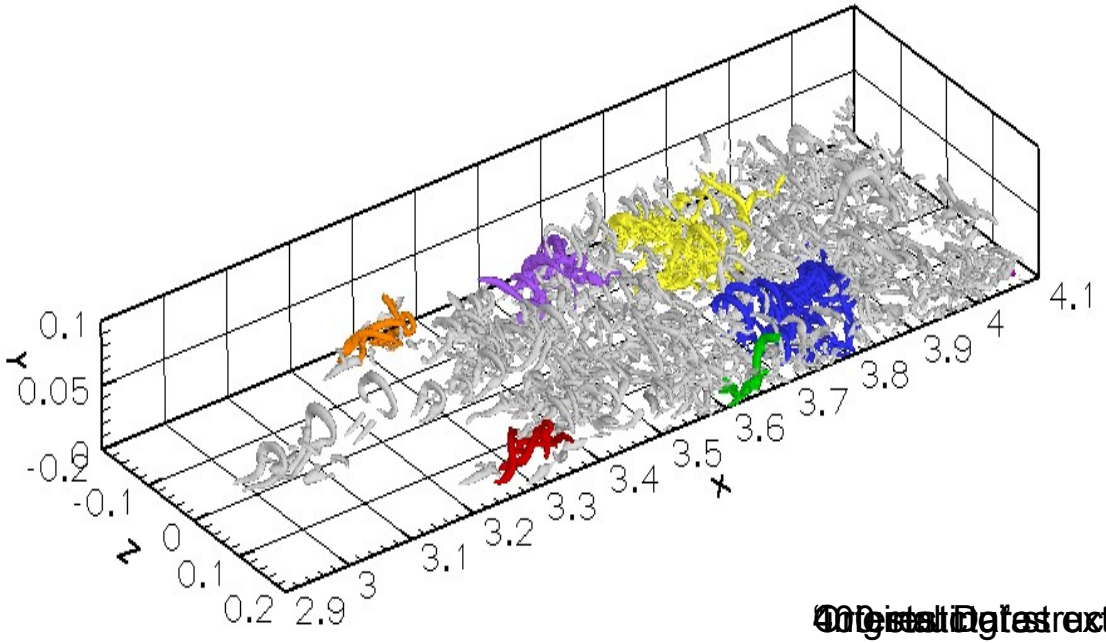
- Transitional data bases available (DNS & experiments)
- Increasing complexity in streamwise direction
- Progress useful for turbulence research (?) & any kind of unsteady flows (!)
- Tools developed will also be applicable for PIV data
- Additional requirements: data smoothing & data reconstruction in gaps
- Two basic structures: vortices & shear layers
- How to quantify / describe their interactions?
- Unsteady problem: need for tracking
- Large data sets: need for data reduction

Two Step Approach:

- First Goal: increase usefulness of visualization as a tool for understanding complicated flows
- Second Goal: reduce raw data to a flow-physical model

“Opening the Can of Worms”

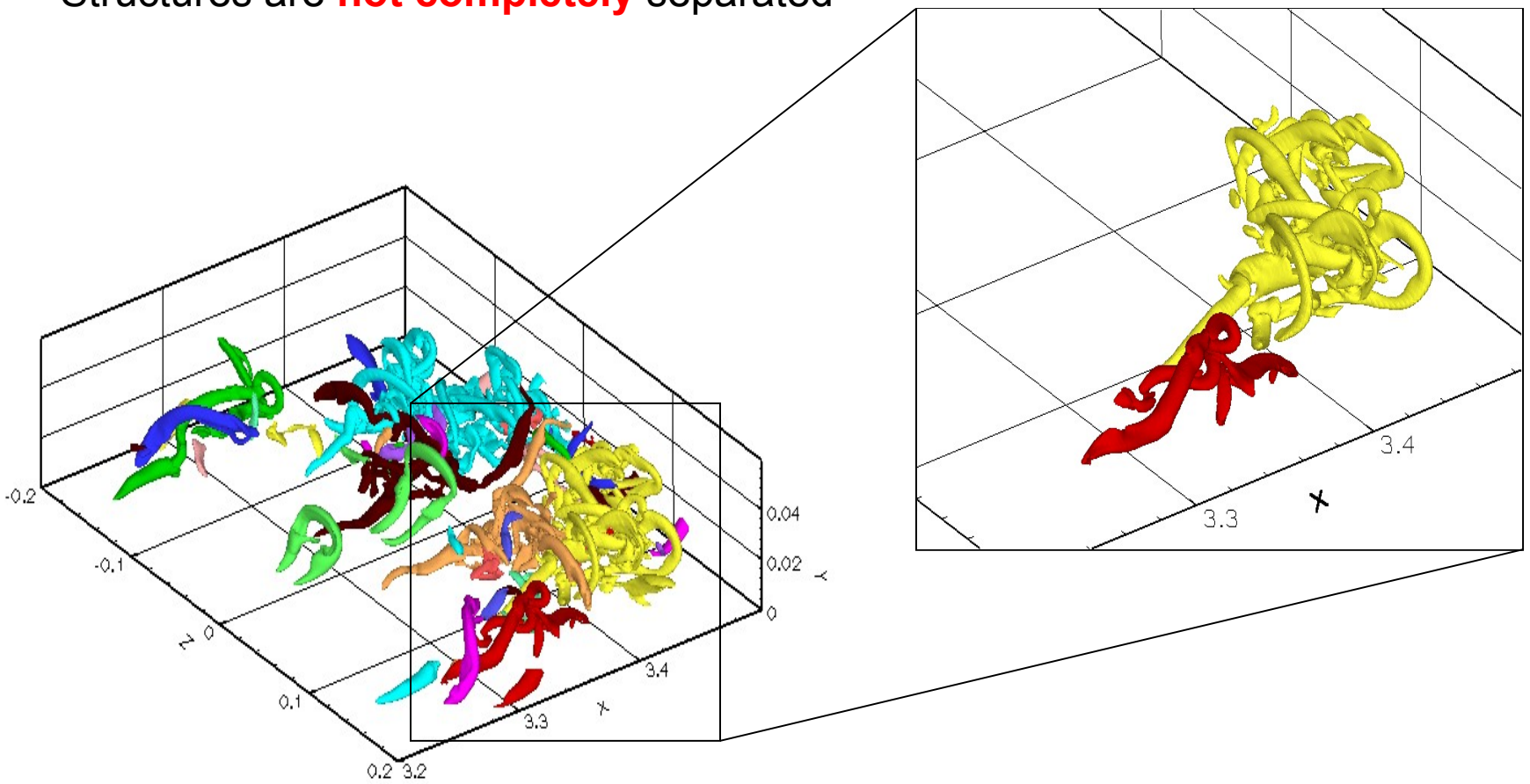
- First attempt at simplification: feature extraction
- Features defined as connected regions bound by an isosurface (here $\lambda_2 = const$)
- Features extracted using simple flood-fill algorithm



Original Data extracted highlighted

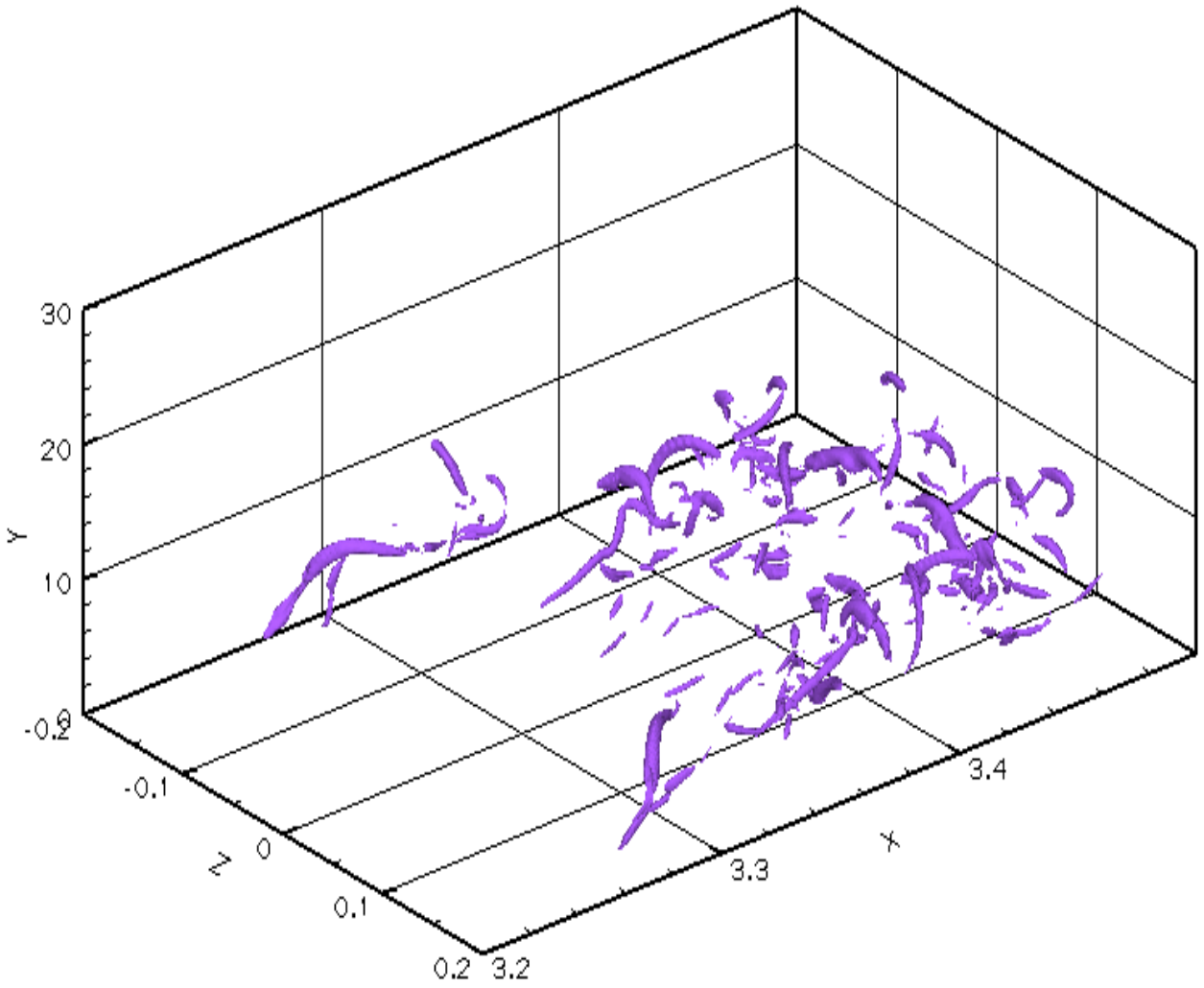
Close-Up

Structures are **not completely** separated



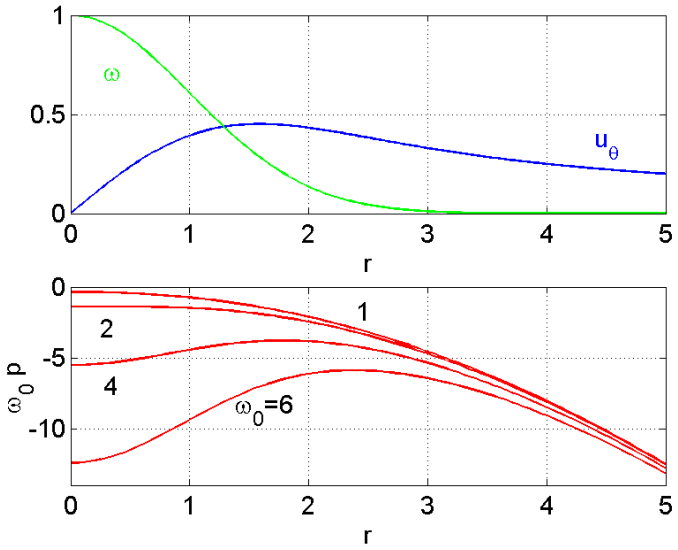
How to proceed?

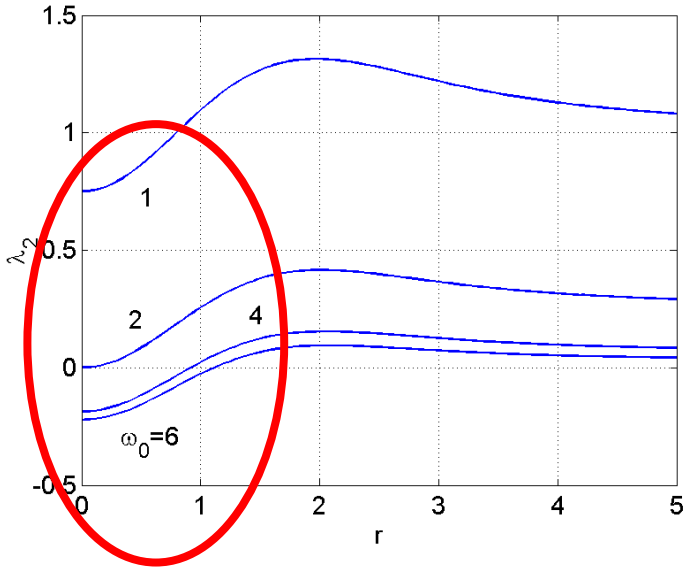
- Increasing threshold → may lose detail



Solution

- Use a lower-order representation of the structures → core lines
- How to define core line (or vortex center)? Look at model vortices
  - λ_2 has local mimimum near “naturally” defined vortex center



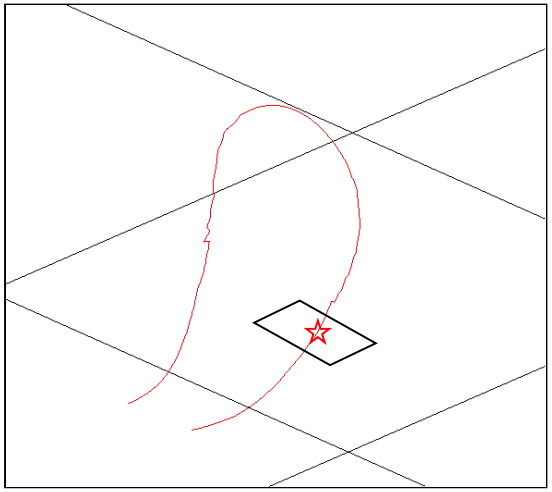


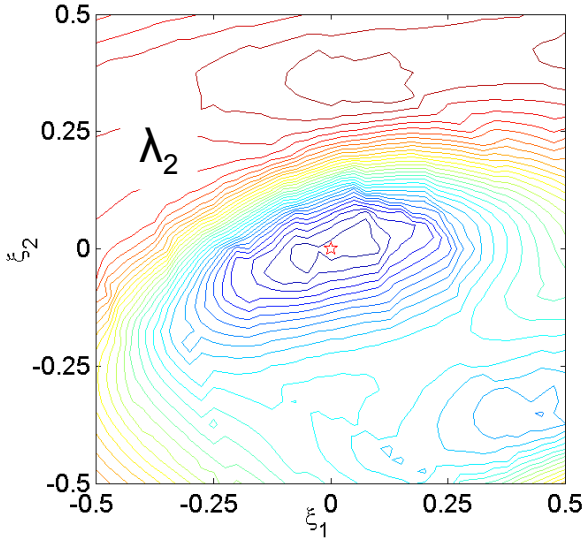
Rankine Vortex Burgers Vortex

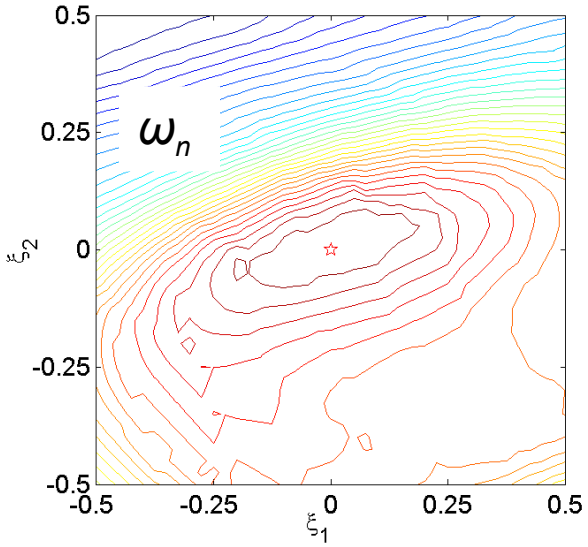
(ω_0 is vorticity at r=0)

Validation (1)

λ_2 and normal vorticity $\omega_n = \boldsymbol{\omega}\cdot\mathbf{e}_3$
in plane spanned by $\mathbf{e}_1$ and $\mathbf{e}_2$

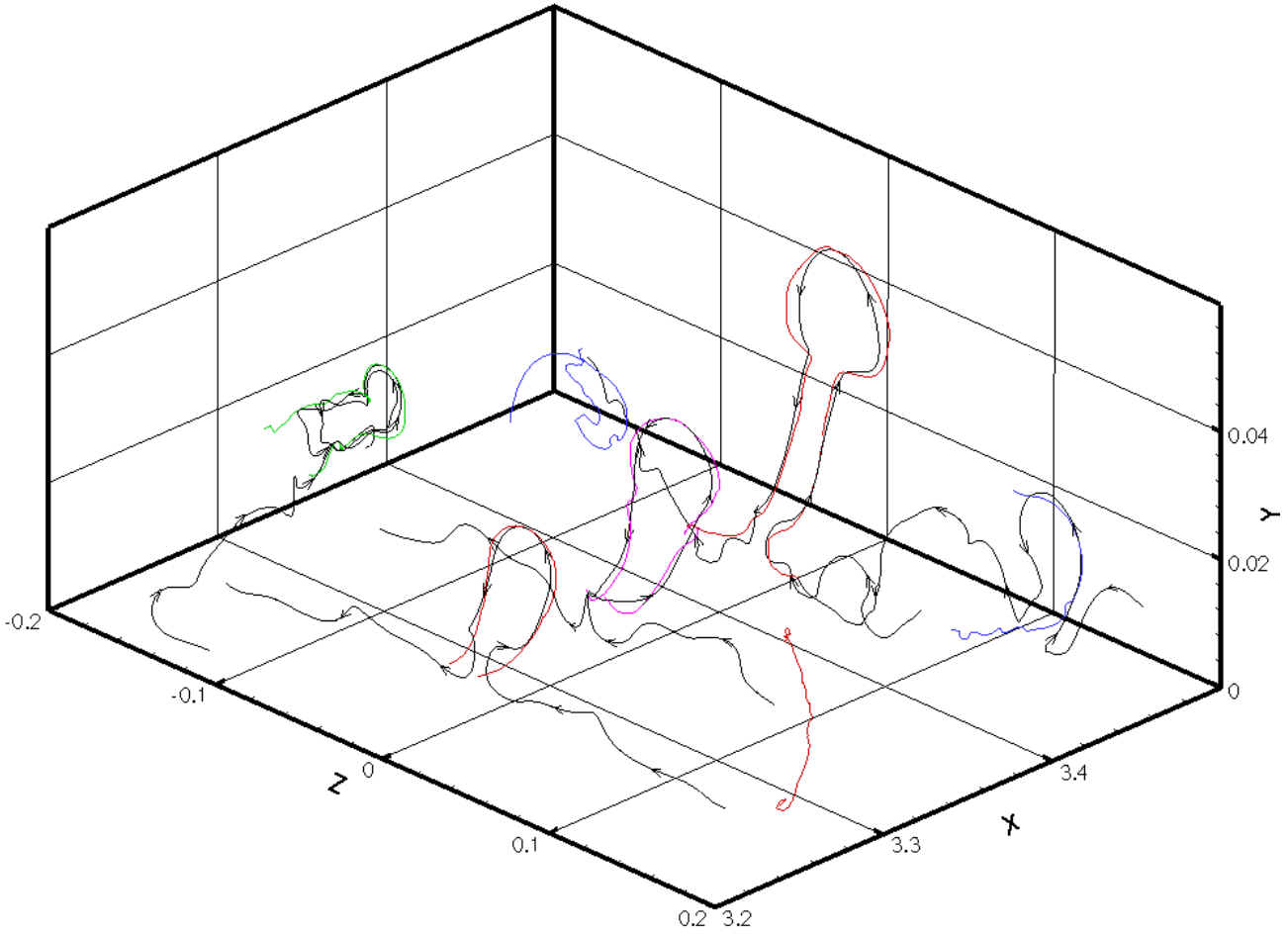




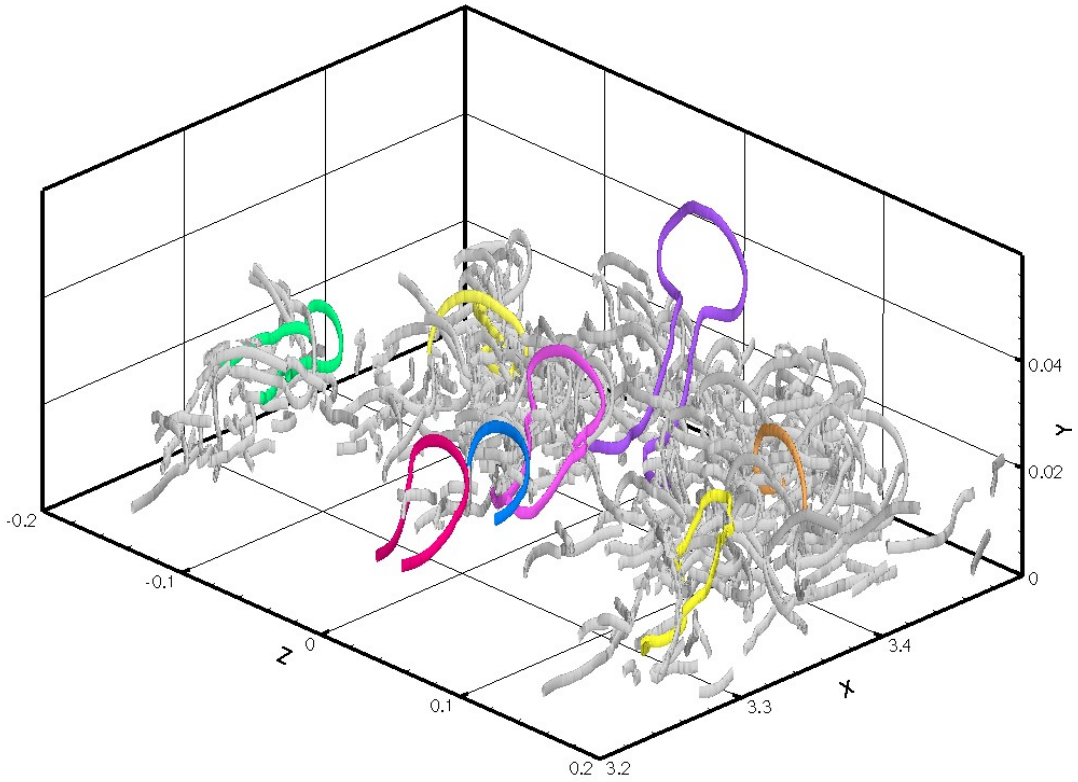


Validation (2)

- Core lines used as seed points to compute vortex lines



Vortex Separation



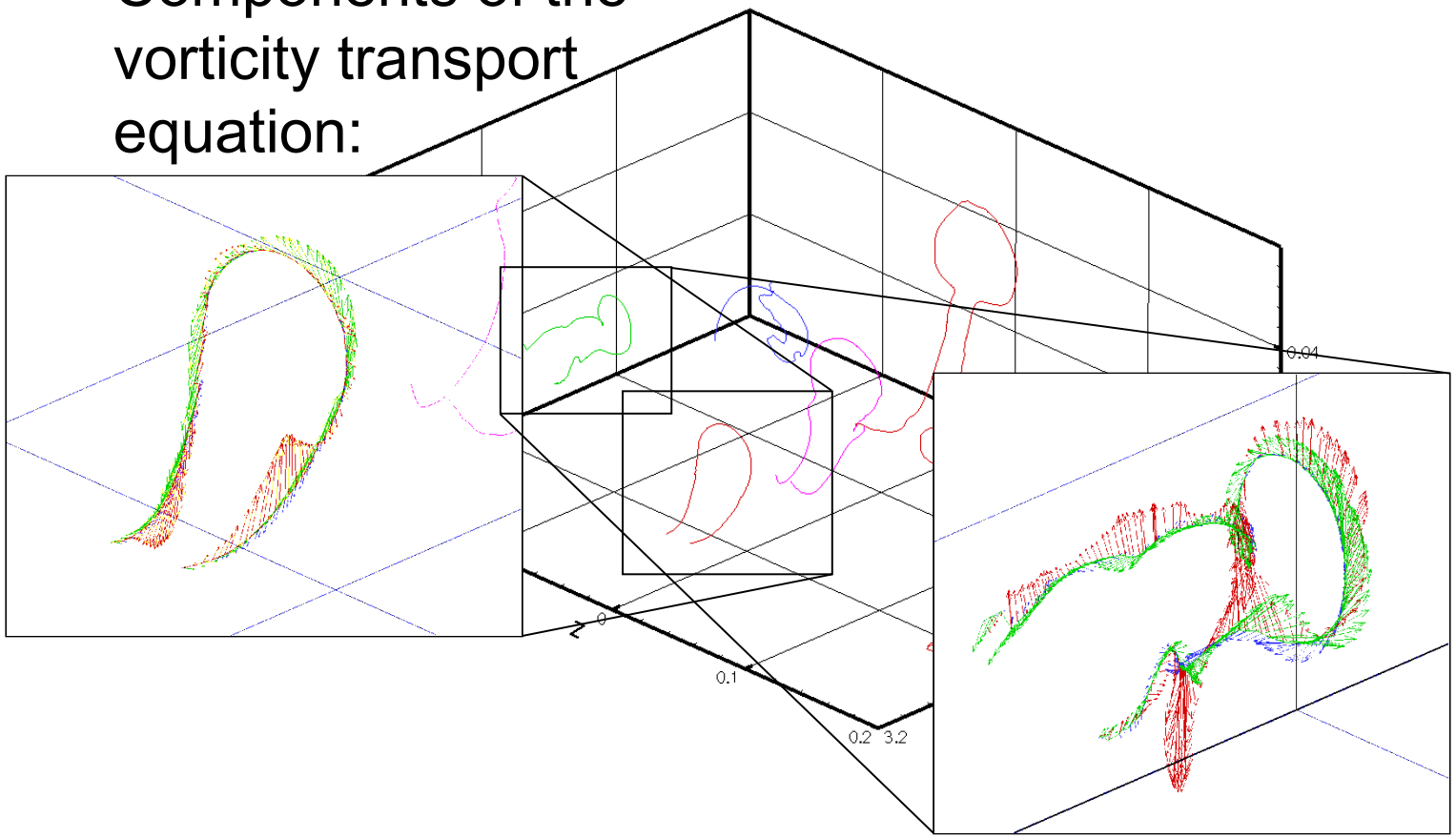
Study of Vortex Dynamics

turn & strain

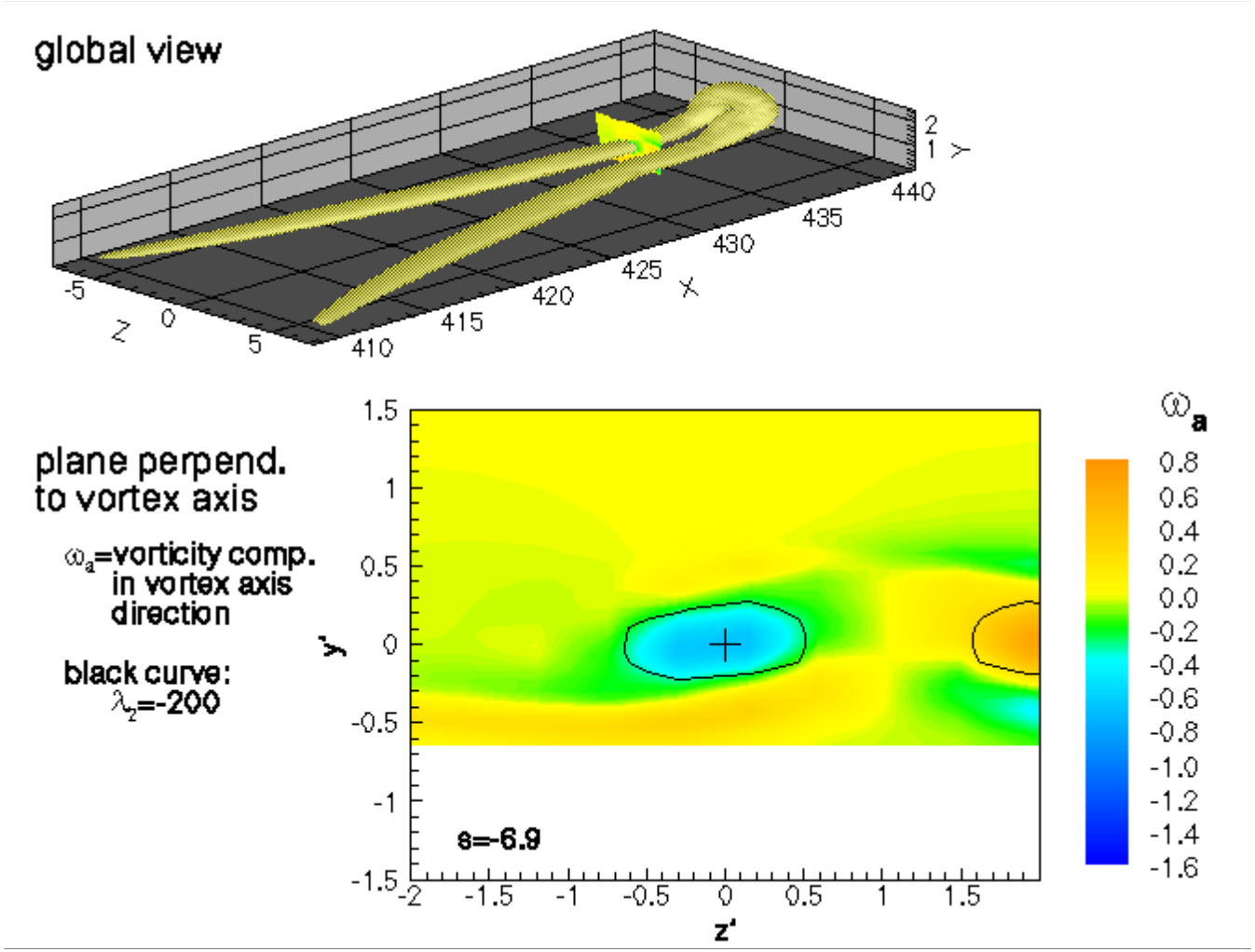
$$\frac{D\omega}{Dt} = \omega \cdot S + \frac{1}{\mathrm{Re}}\nabla^2\omega$$

vorticity diffusion

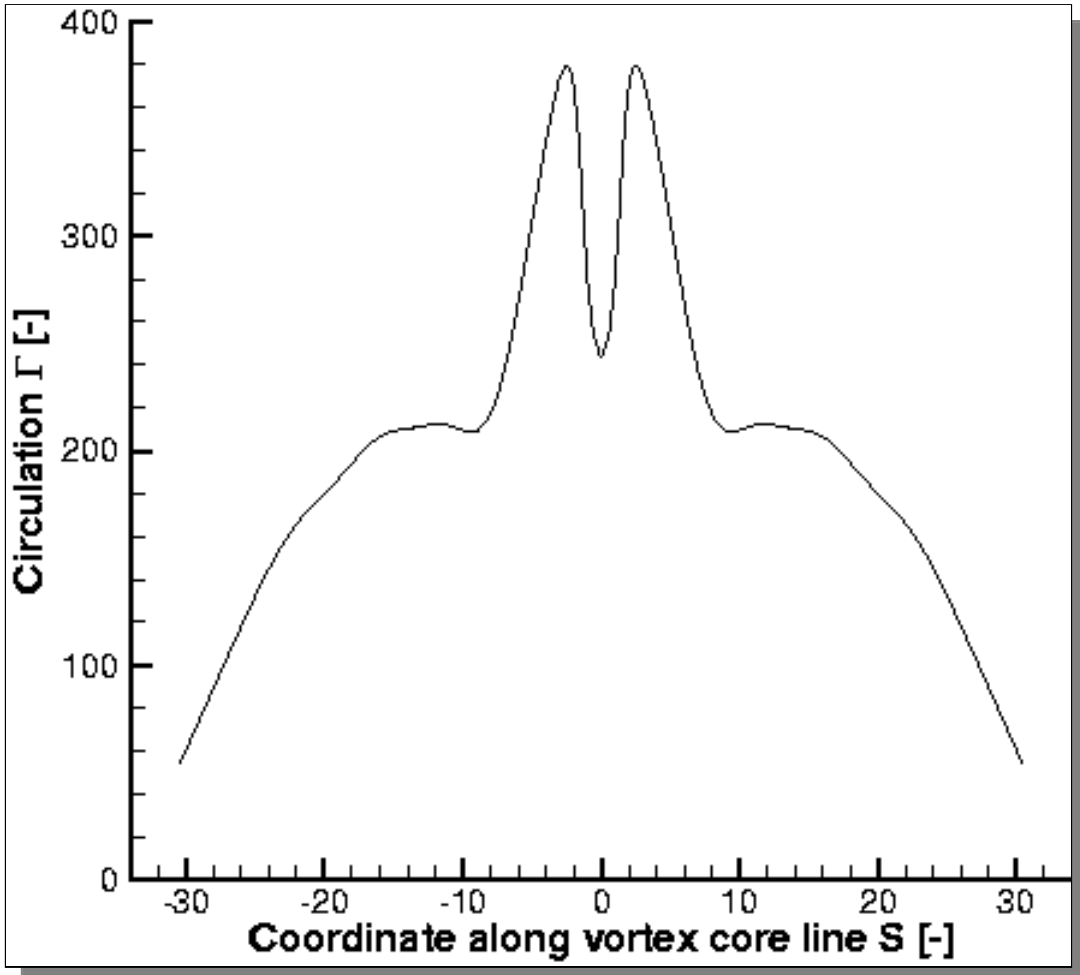
- Components of the vorticity transport equation:

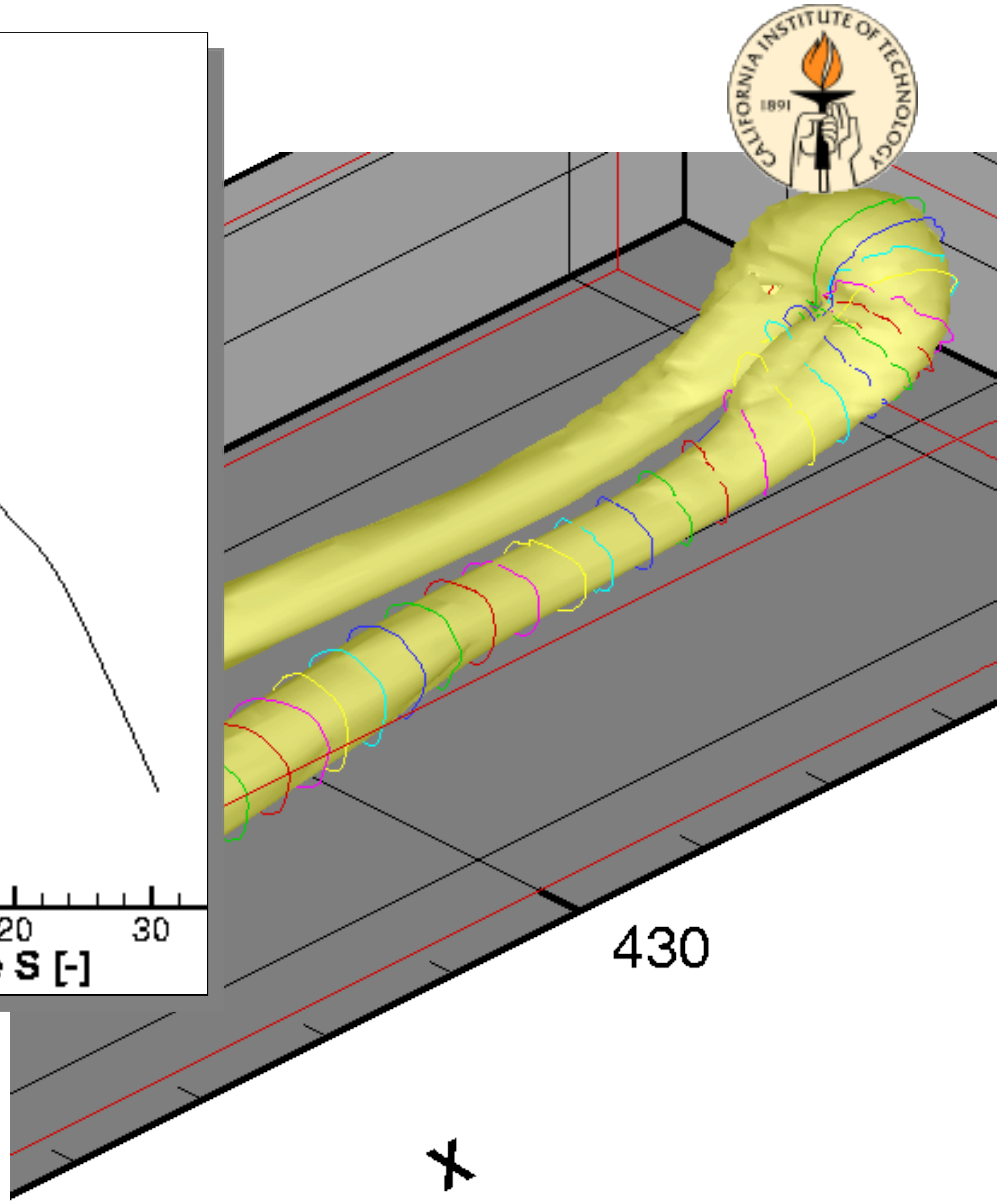


Vortex Quantification (1)



Vortex Quantification (2)

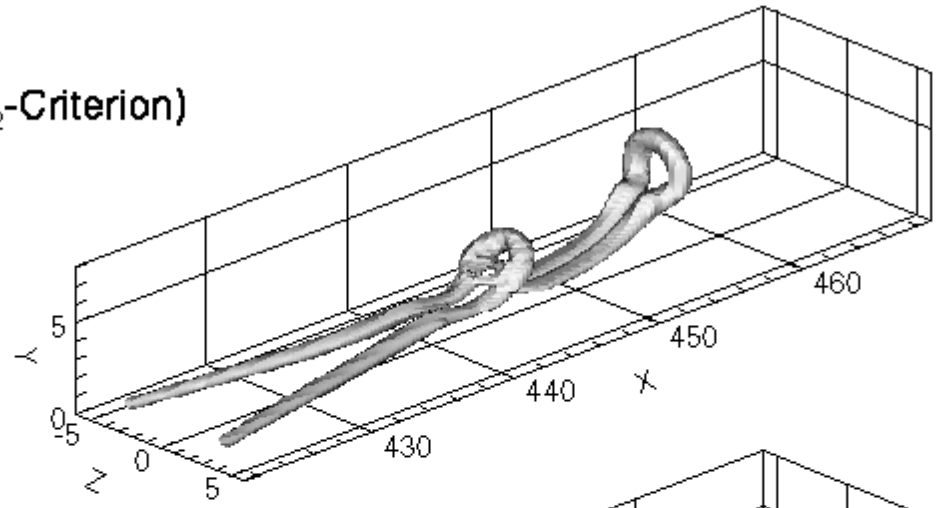




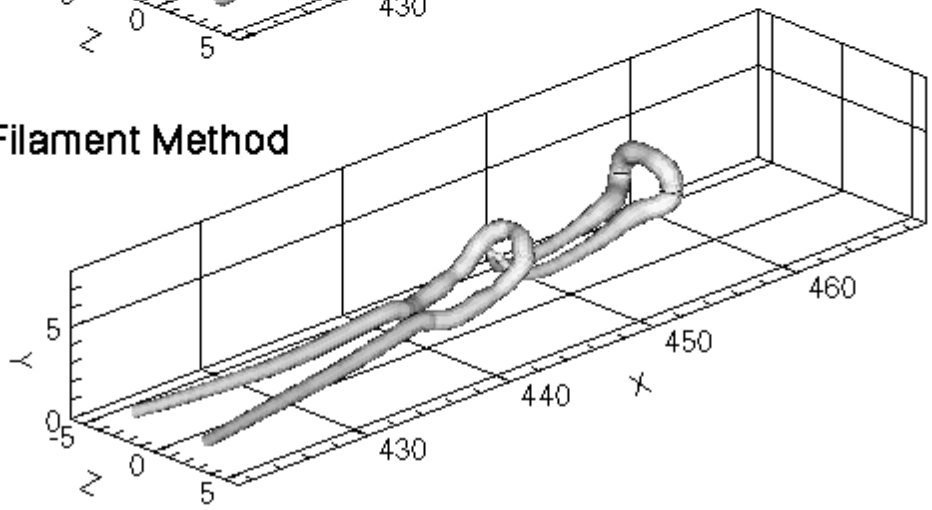
Vortex Quantification (3)

Evolution of Λ-vortex

DNS (λ_2-Criterion)



Vortex Filament Method

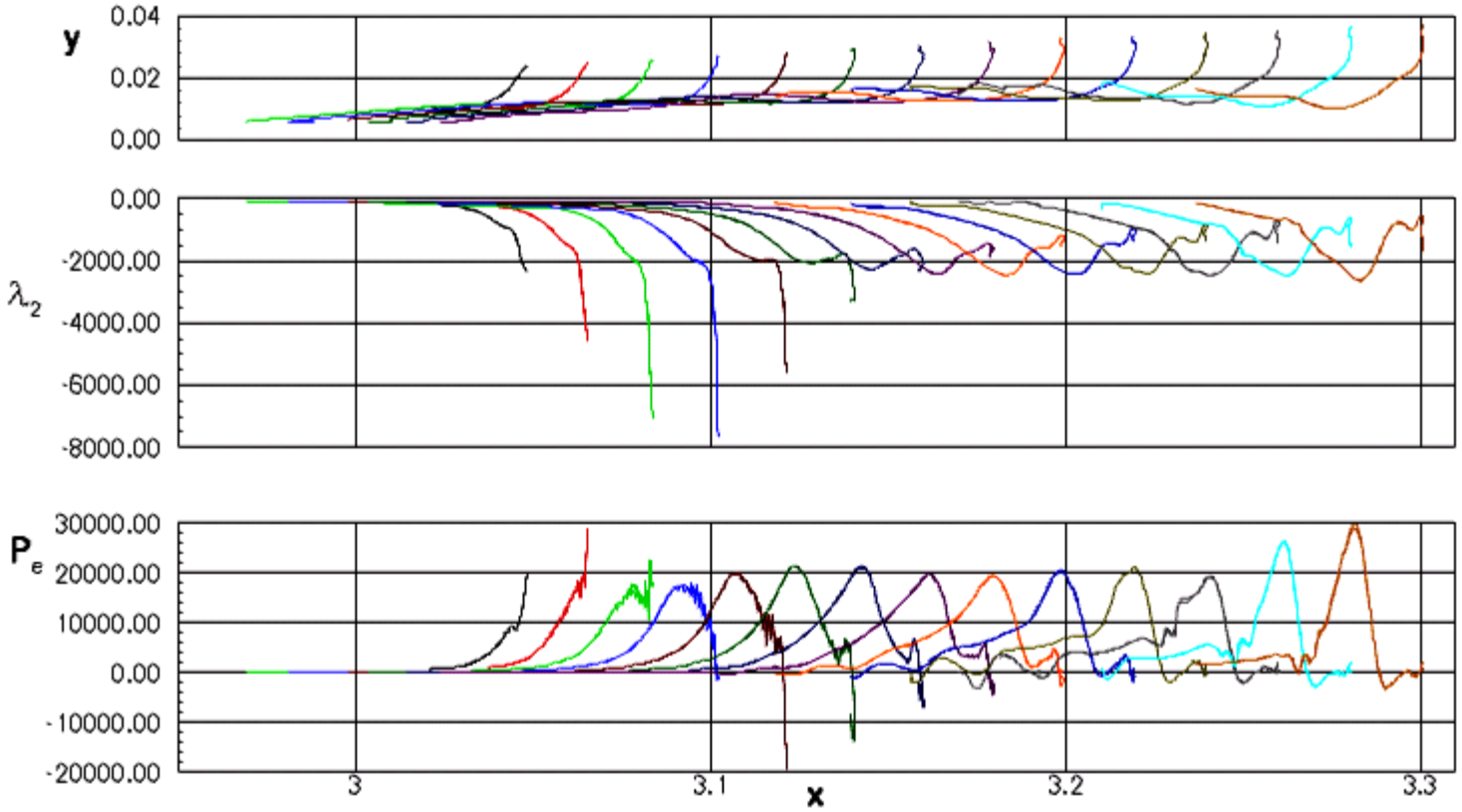


Vortex Quantification (4)

side view

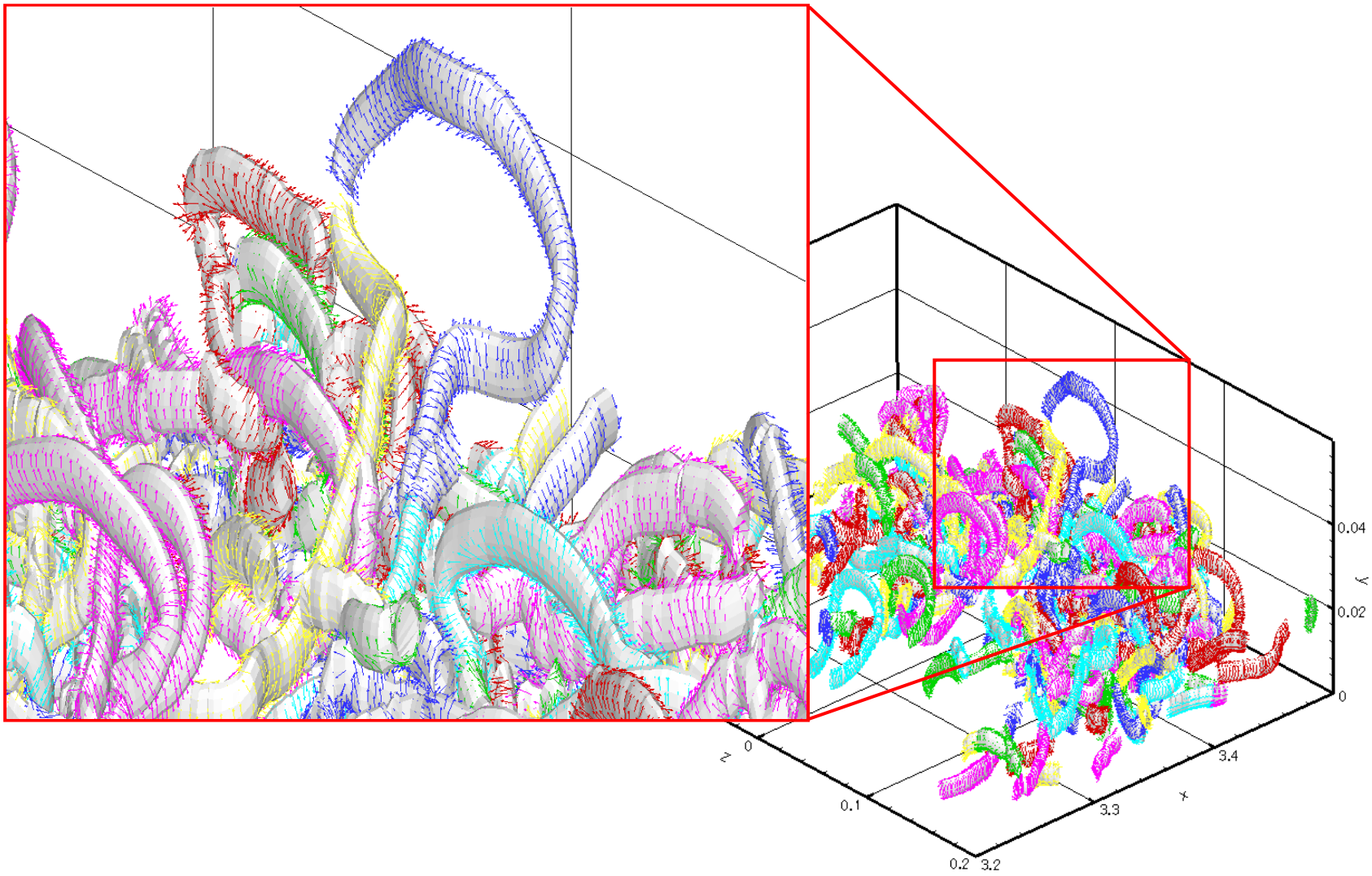
vortex strength

enstrophy production

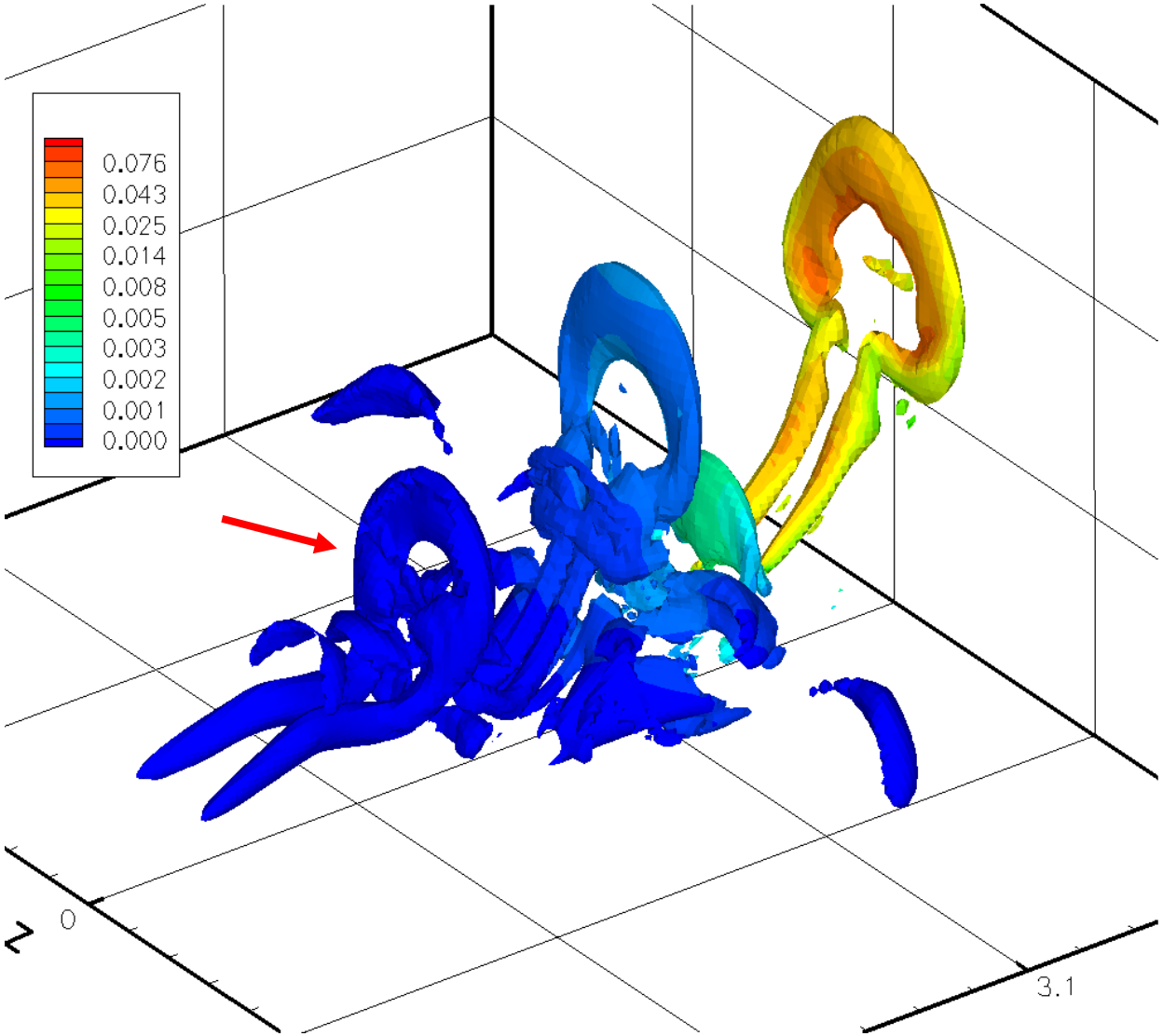


Enhanced Visualization

- Vortex surface velocity relative to core velocity

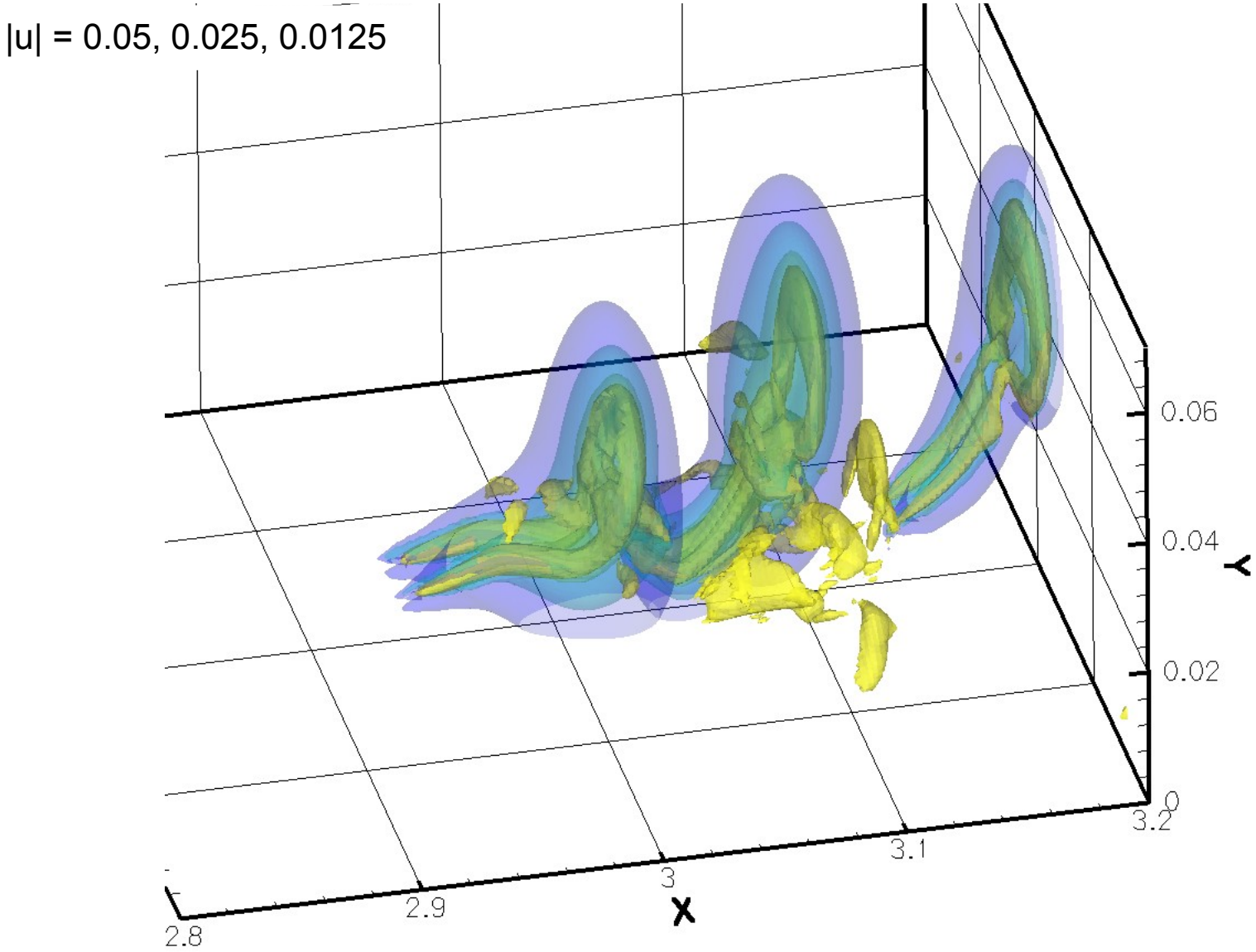


Playing with Biot-Savart

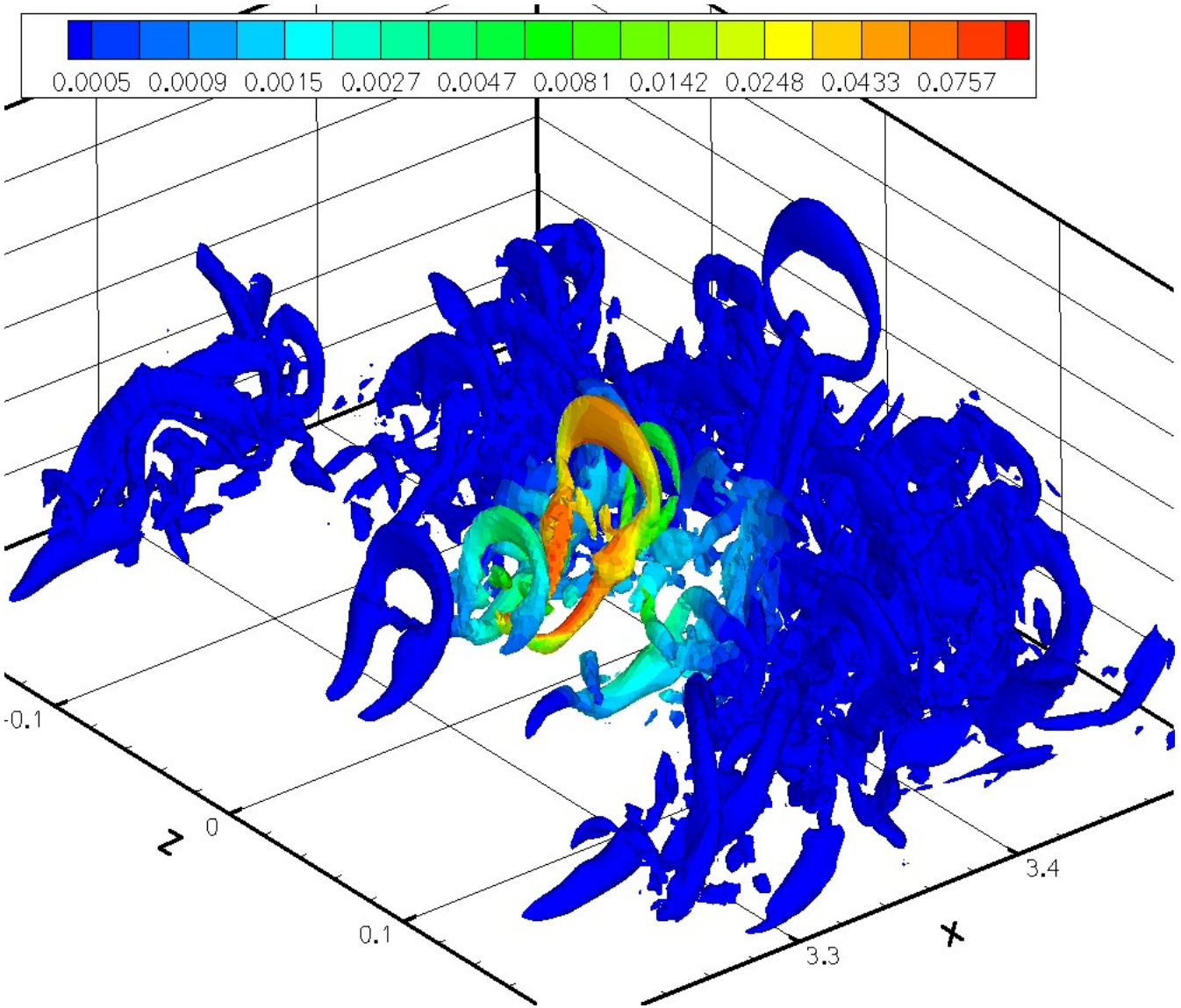


Induced Velocity Magnitude

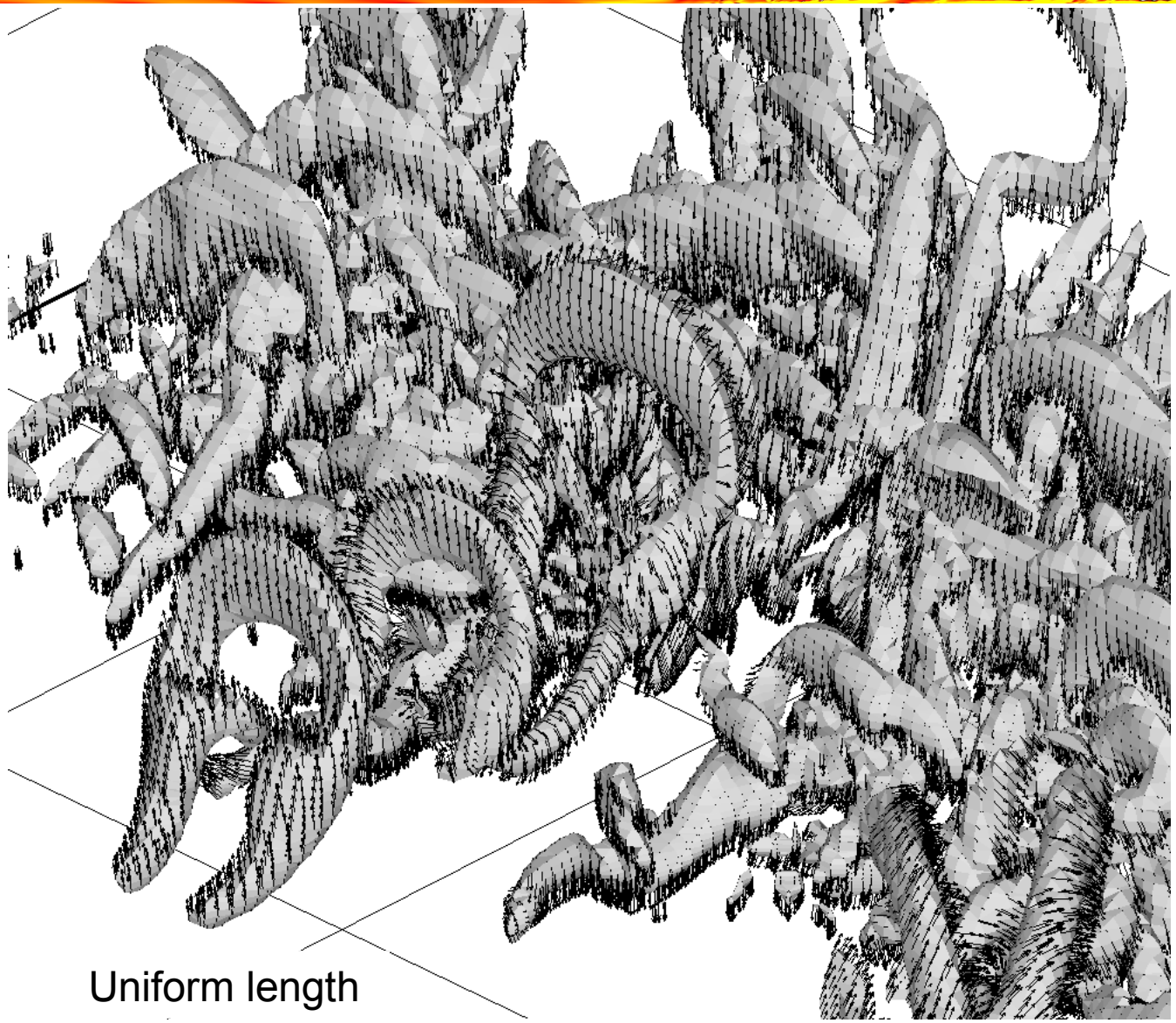
Induced Velocity Magnitude According to Biot-Savart



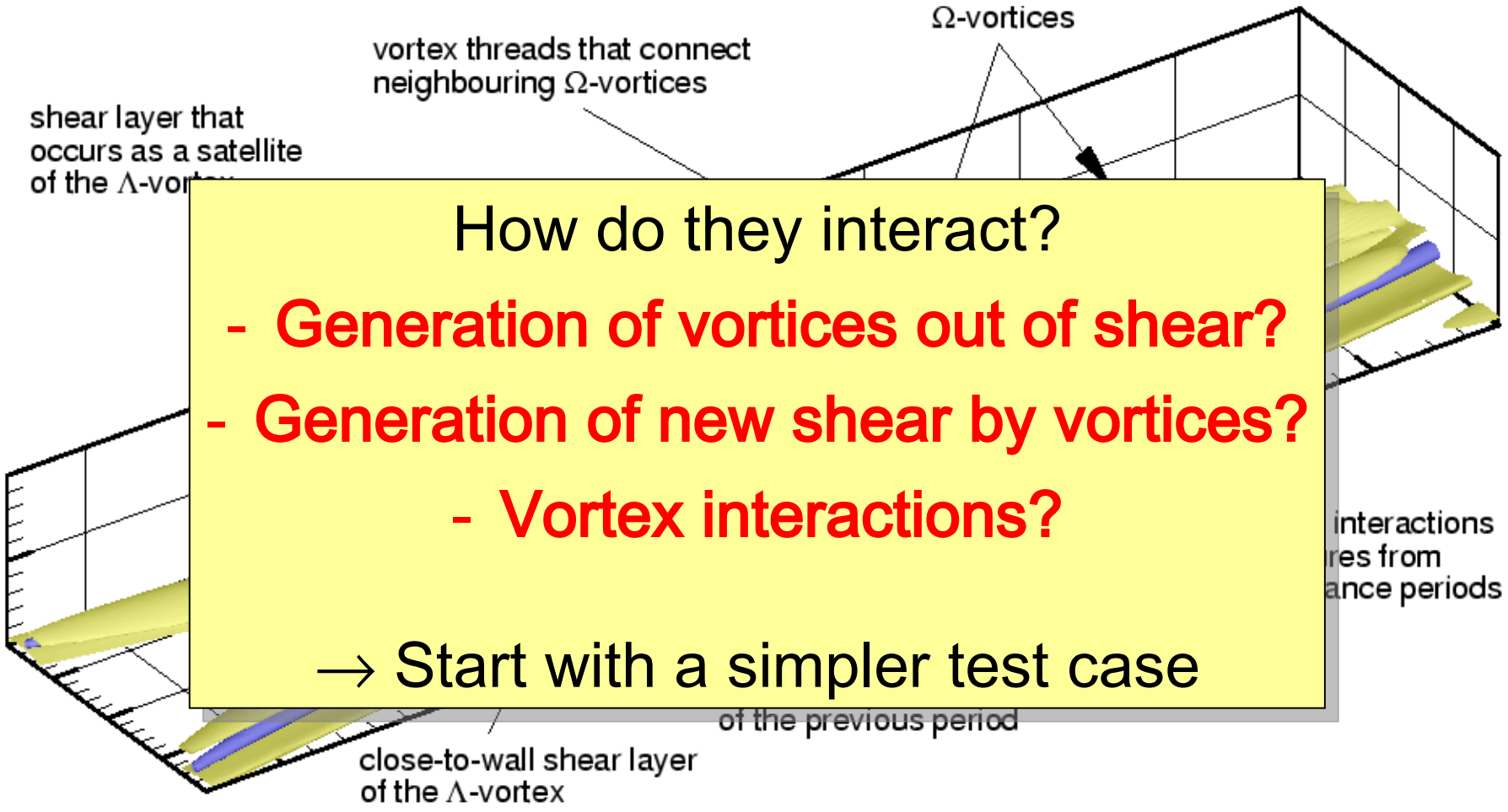
Induced Velocity Magnitude According to Biot-Savart



Induced Velocity According to Biot-Savart



Vortices and Shear Layers



How do they interact?

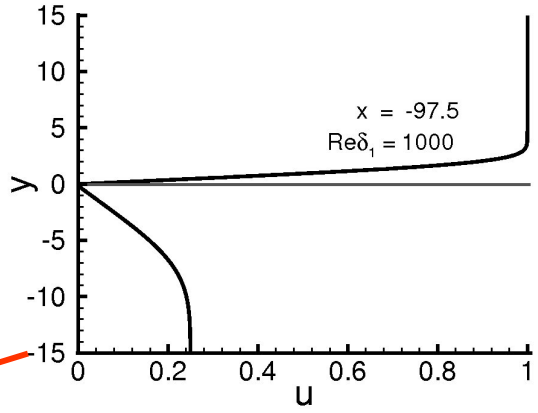
- Generation of vortices out of shear?
- Generation of new shear by vortices?
- Vortex interactions?

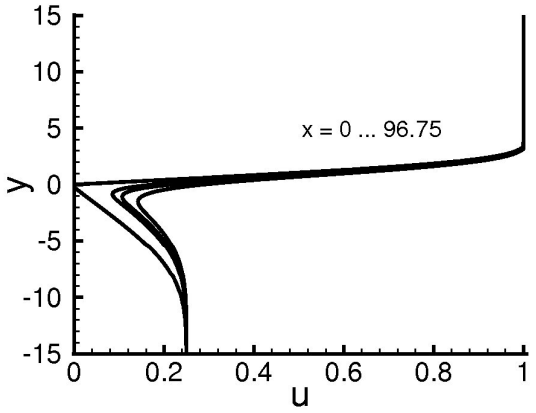
→ Start with a simpler test case

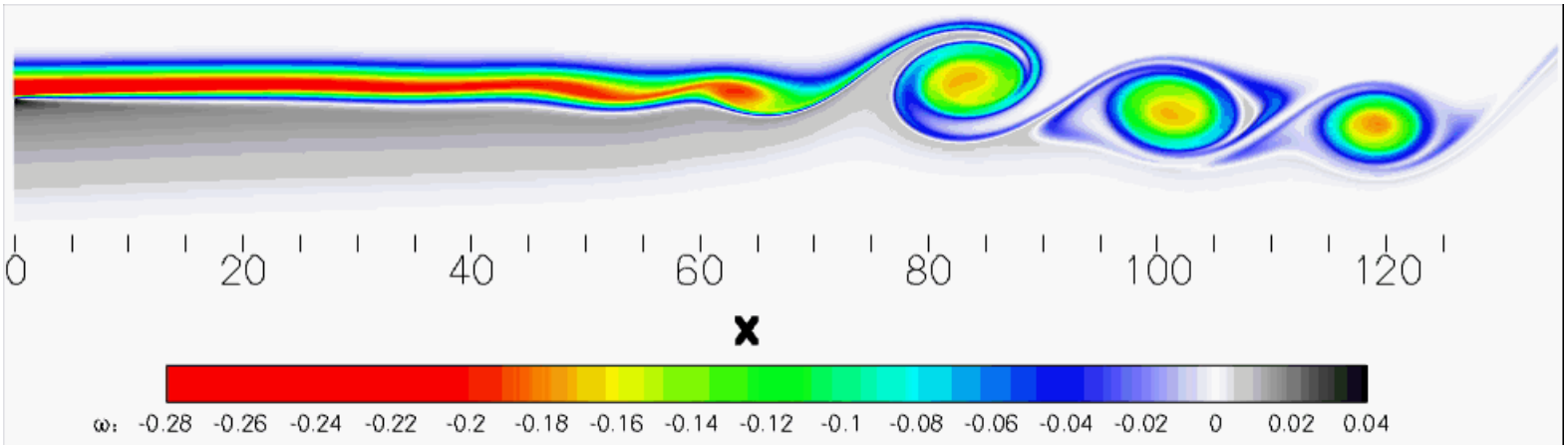
2D Test Case

Plane Mixing Layer Behind a Flat Plate

$$\frac{u_{upper}}{u_{lower}} = 4$$

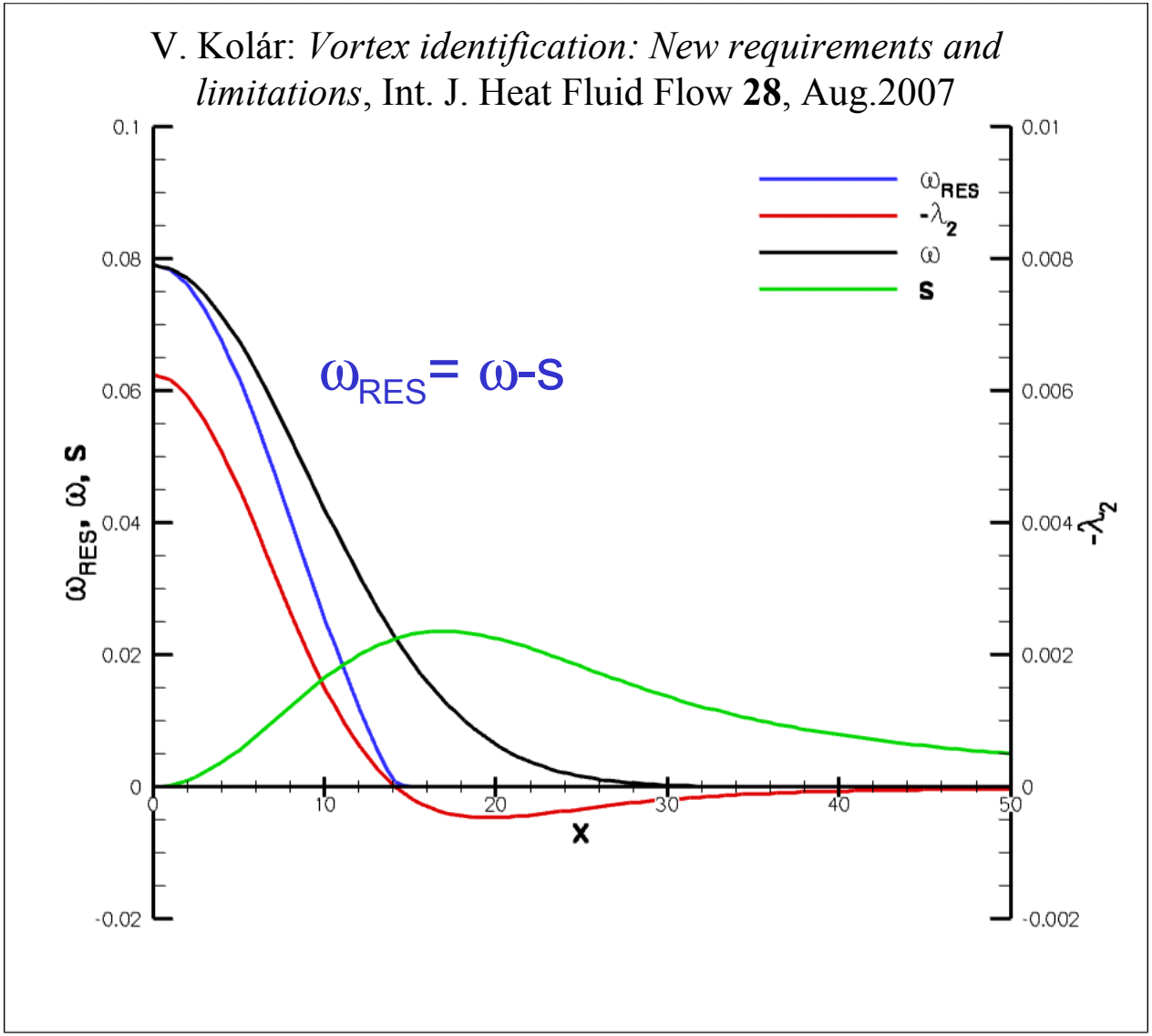






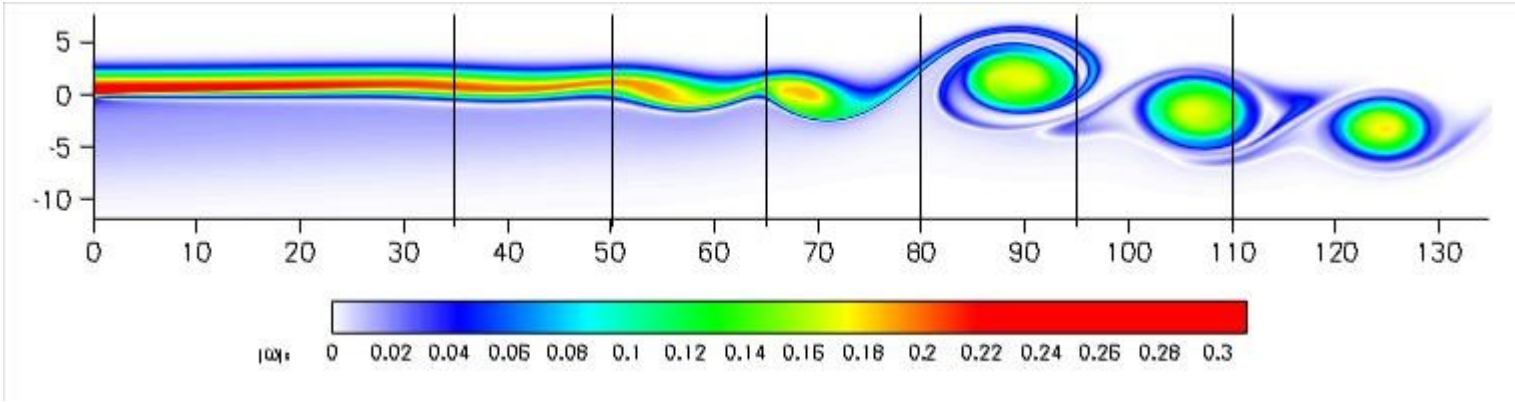
Triple Decomposition of Vorticity

V. Kolár: *Vortex identification: New requirements and limitations*, Int. J. Heat Fluid Flow **28**, Aug.2007

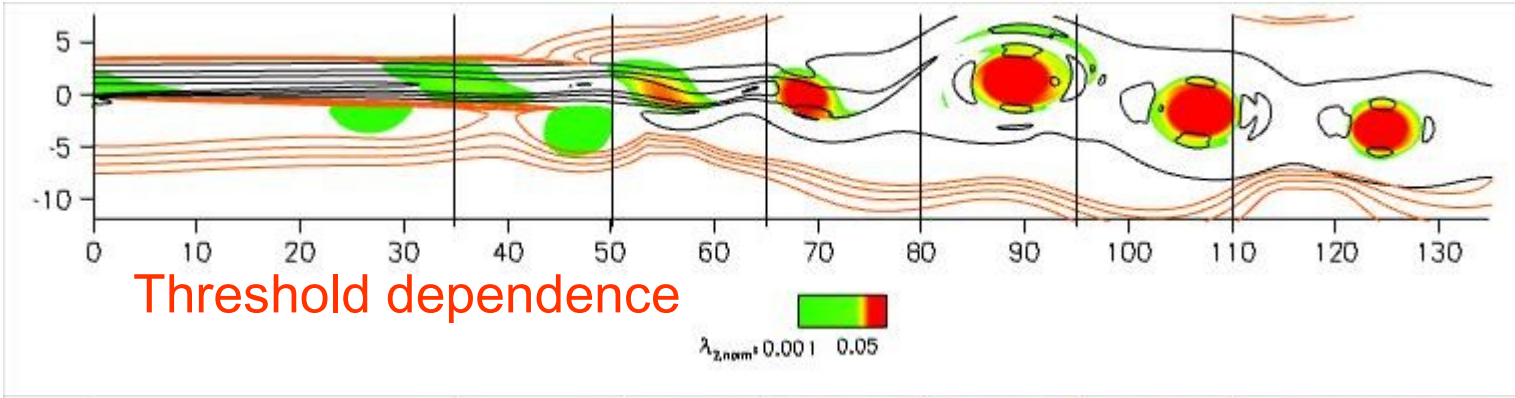


Decomposition of Vorticity

vorticity

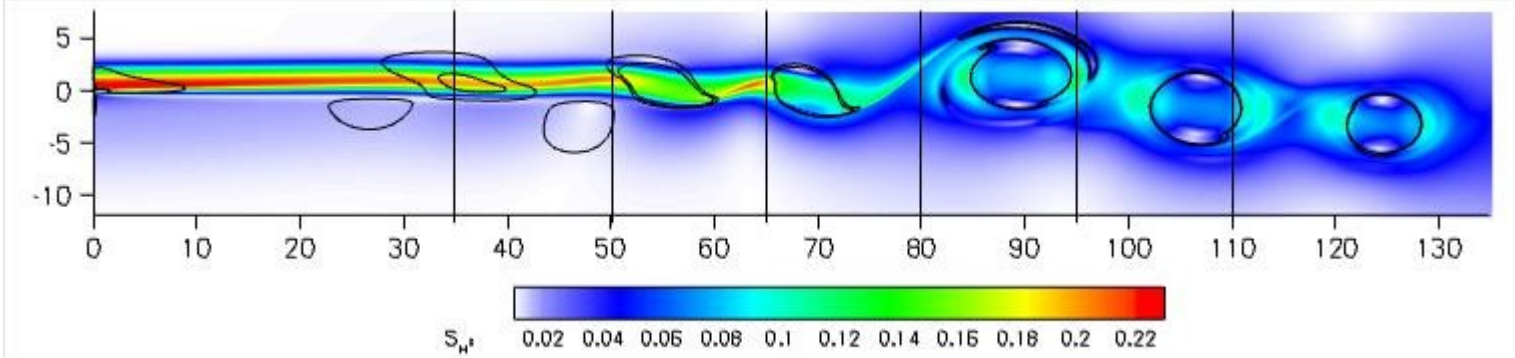


vortices



Threshold dependence

shear

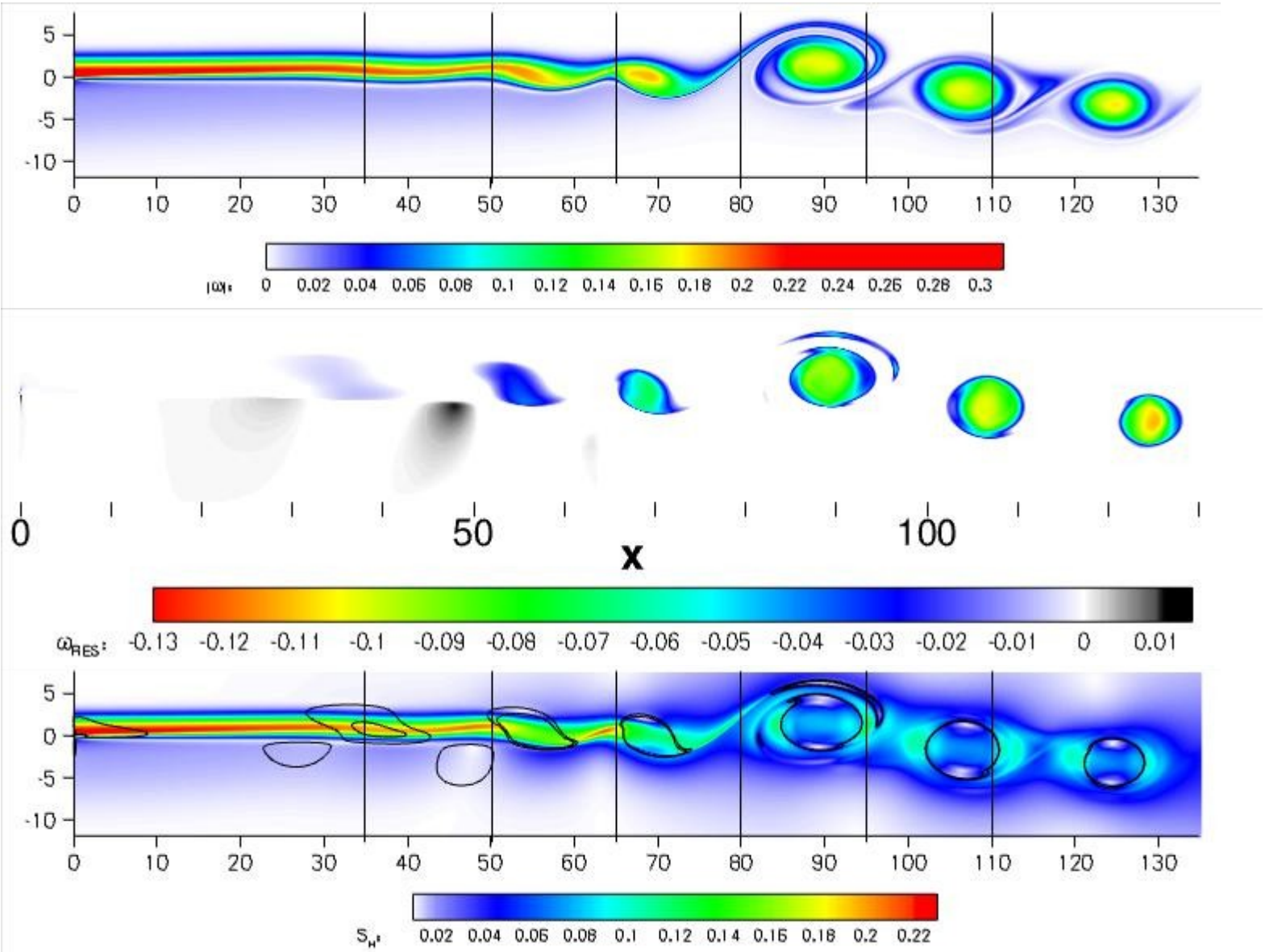


Decomposition of Vorticity

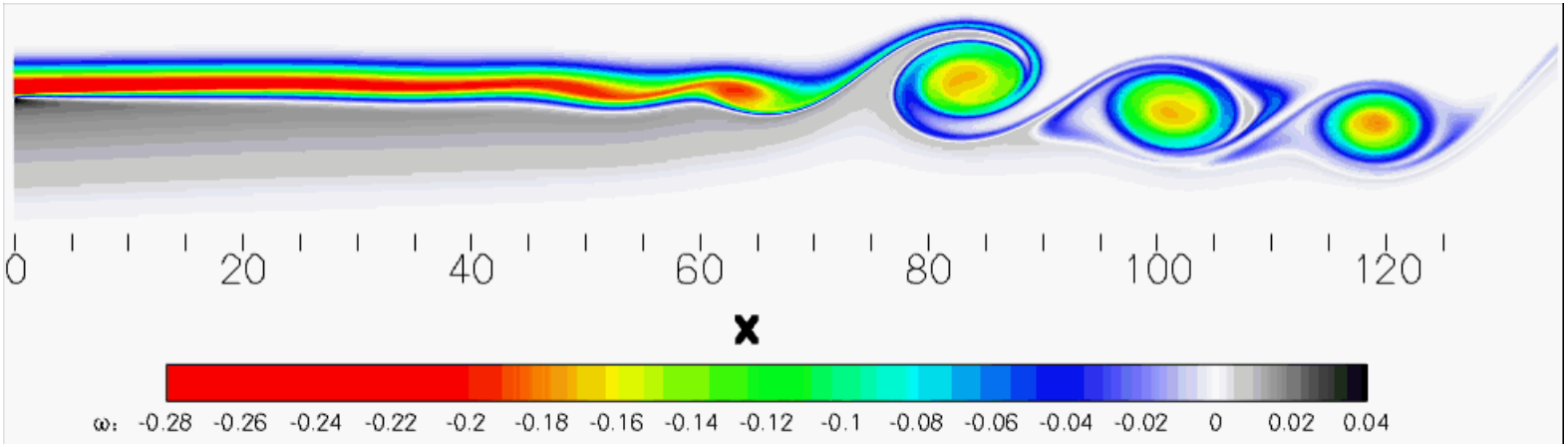
vorticity

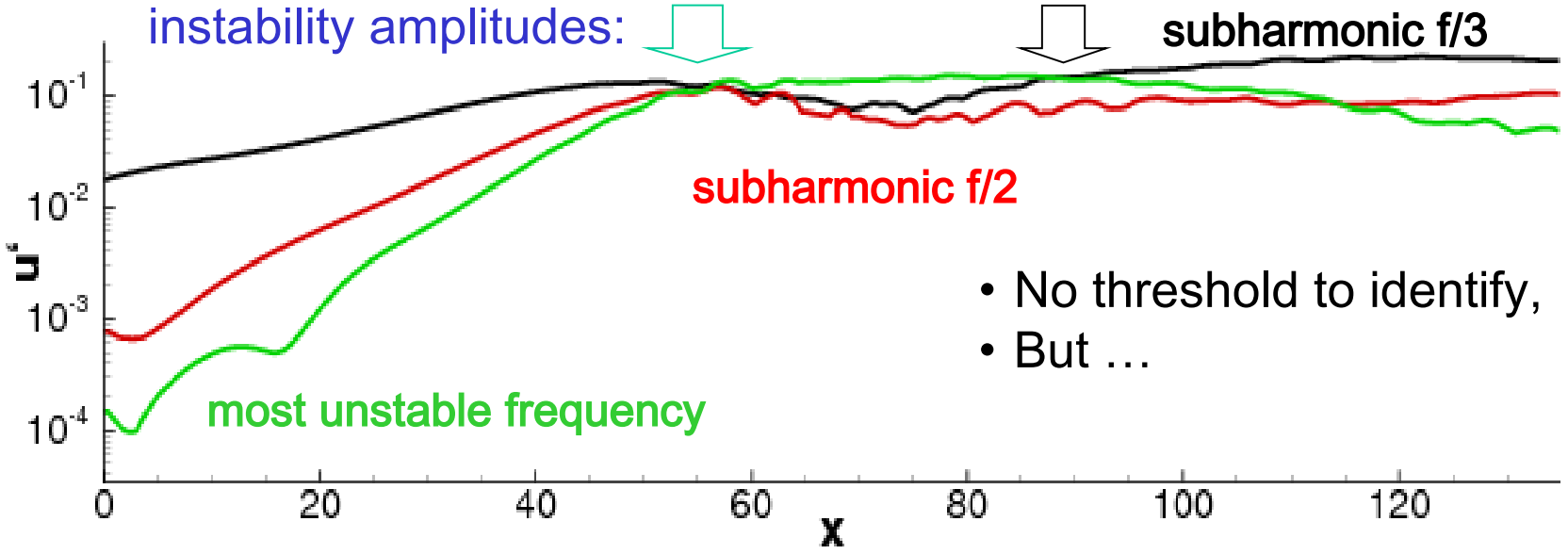
ω_{RES}

shear



Vortex generation out of shear





- No threshold to identify,
- But …

Streamwise Development (1)

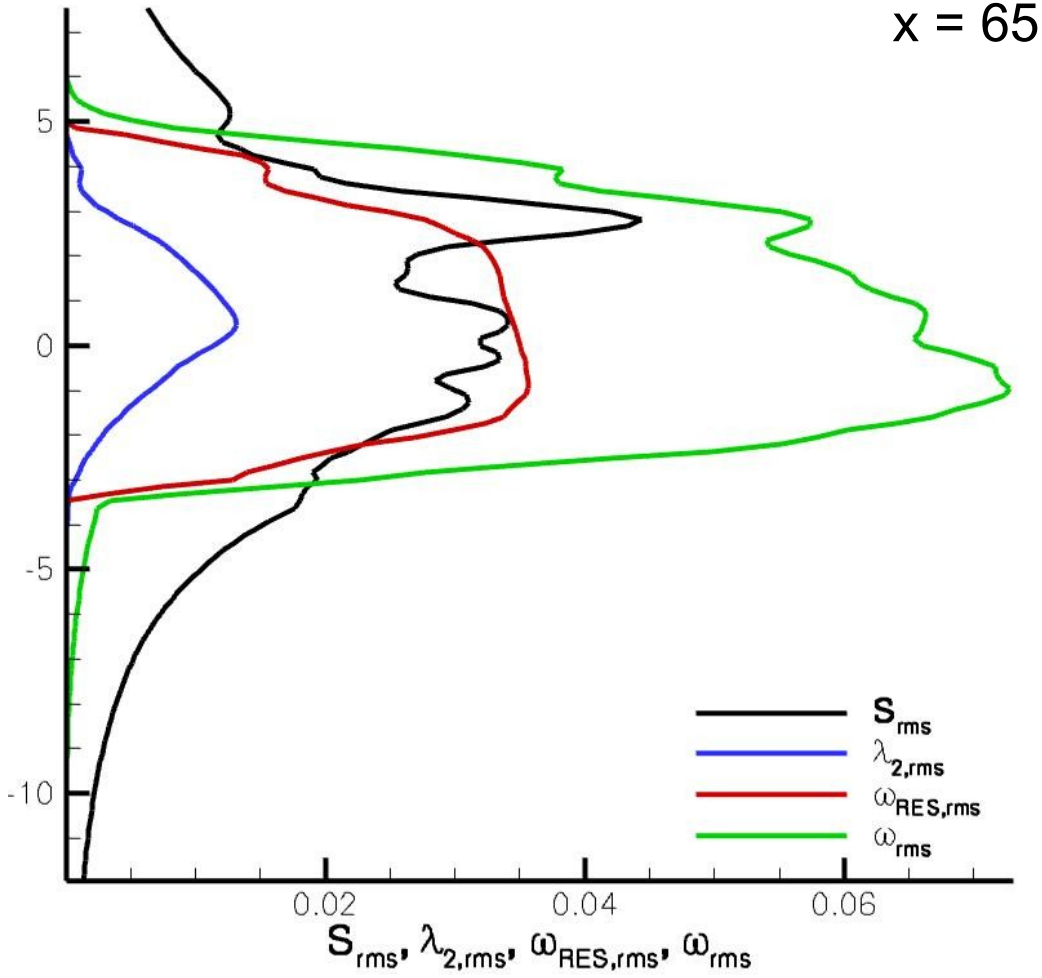
x = 65

vorticity

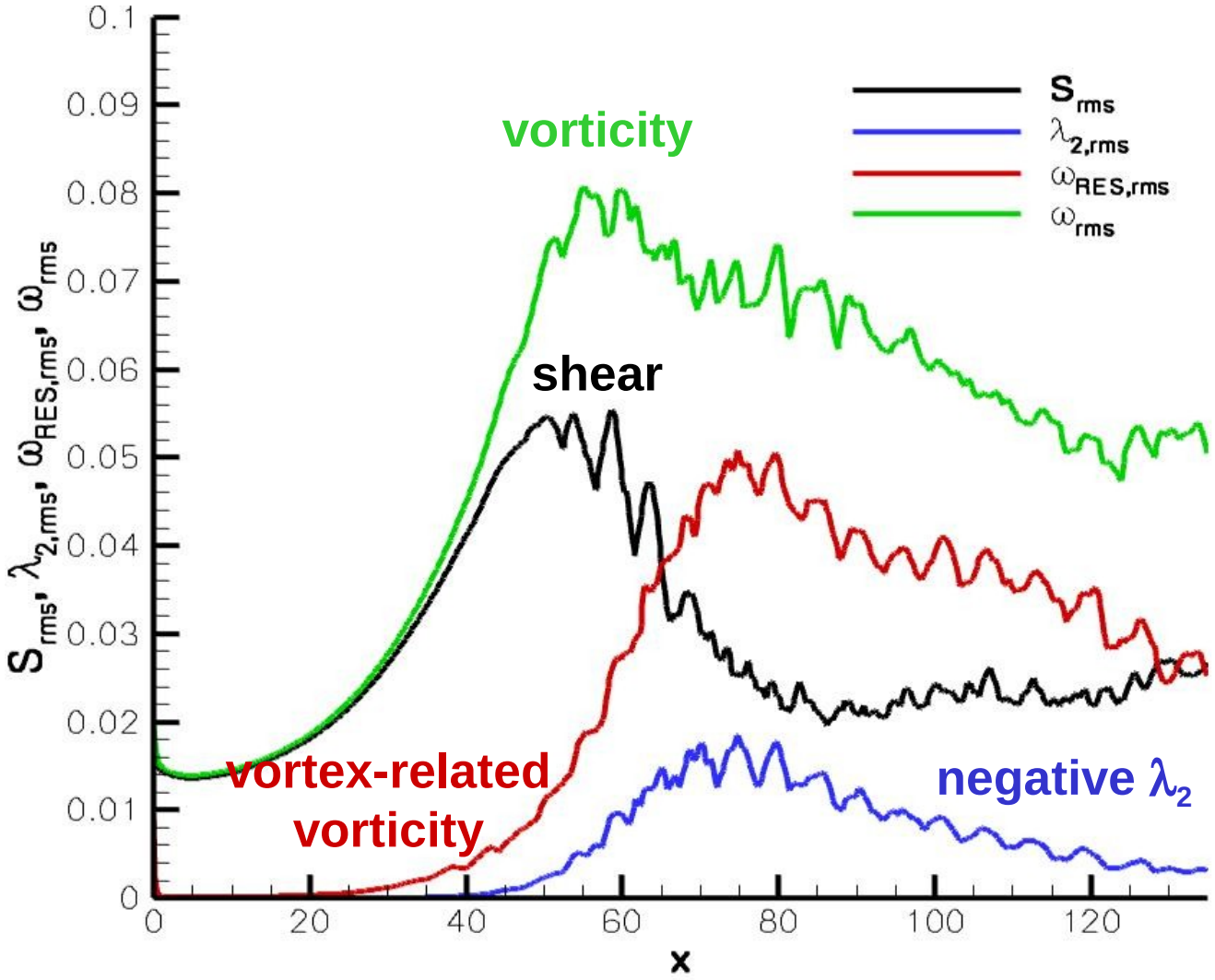
shear

vortex-related vorticity

negative λ_2

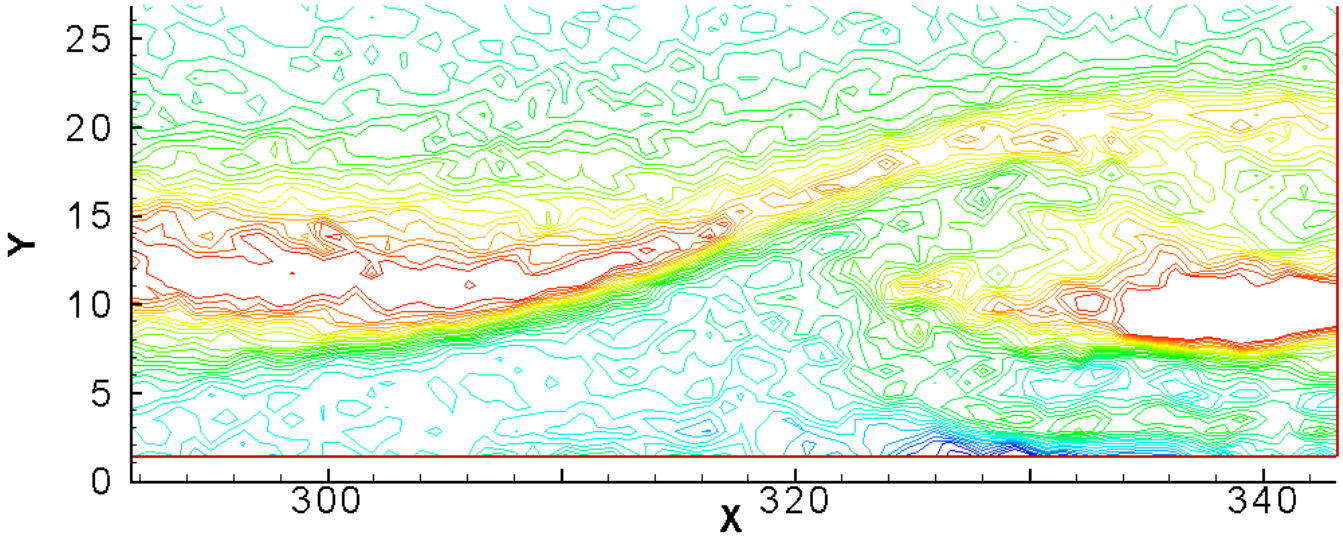


Streamwise Development (2)

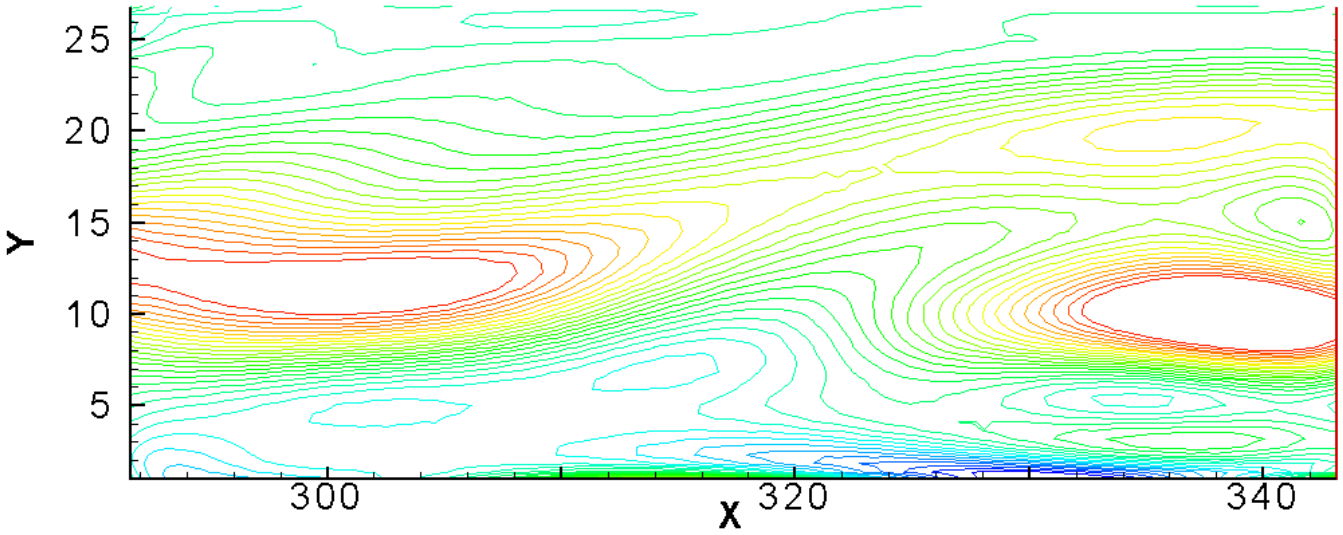


Data Smoothing and Data Recovery (PIV)

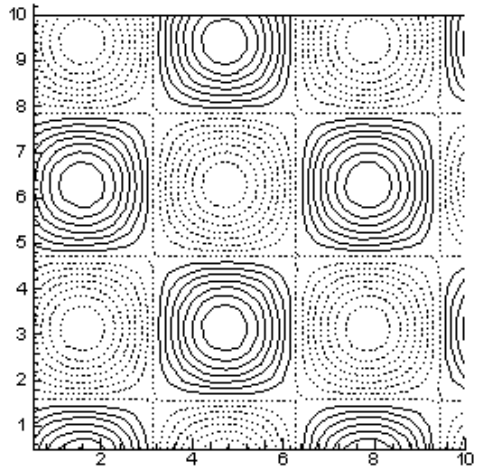
Original PIV data (76x38)

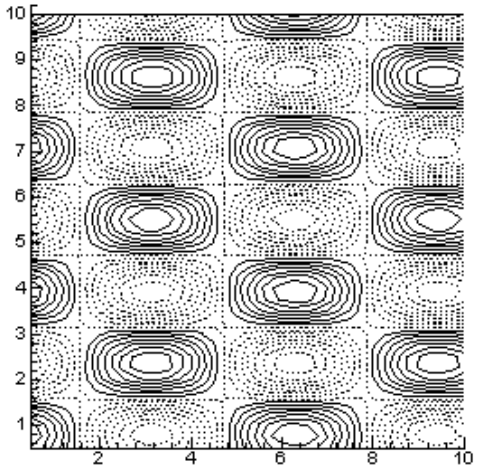


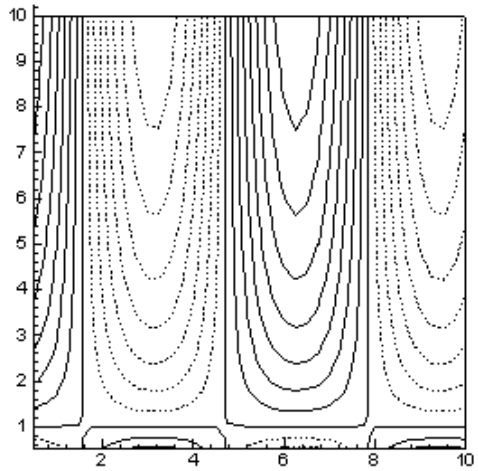
Kriged data (100x60)



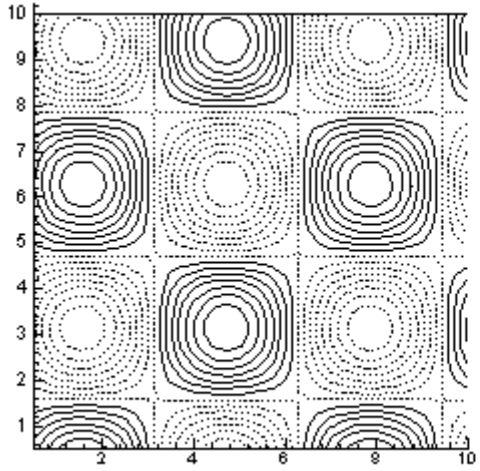
Reconstruction of Missing Zones Using Kriging

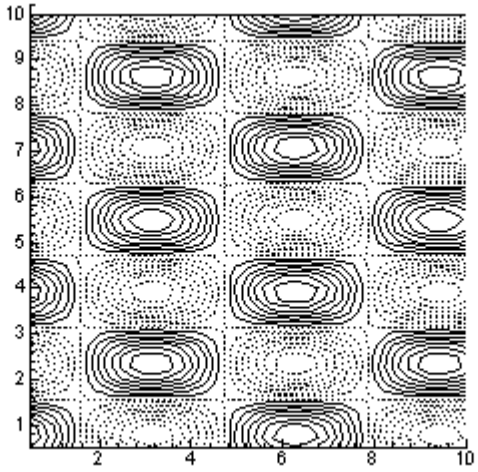


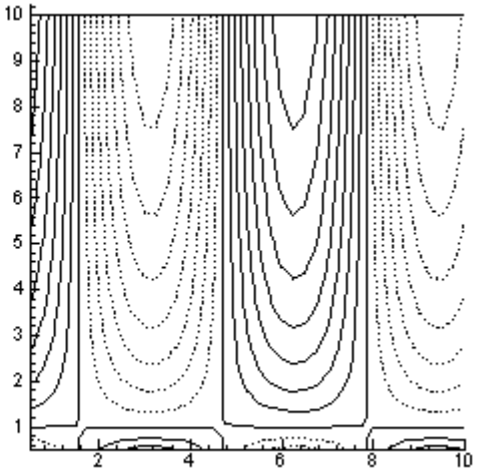




$f_1(x,y) = \sin(x)\cos(y)$, $f_2(x,y) = \cos(x)\sin(2y)$, $f_3(x,y) = \cos(x)\ln(y)$







Conclusions & Outlook

- Feature extraction is important for large data sets:
  - Data reduction, ‘better’ visualizations (more meaningful, clearer, better serving a given purpose, etc.)
  - Higher level of abstraction
- Which are the ‘important’ physical features?
  - Vortices, shear layers, low- and high-speed streaks
- How to define “Interaction”?
  - Biot-Savart not sufficient!
  - Need to study generic cases
- Present findings
  - Triple decomposition of vorticity proposed by Kolar seems to make sense
  - Vortex formation out of a shear layer is a continuous process, driven by instability
- Extension to 3-D difficult
  - Vorticity becomes a vector
  - Computation of a base-reference system for each grid point is time consuming
  - Streamwise shear influences vortex detection