High-Resolution Identification of 3D Objective Material Barriers to Momentum Transport

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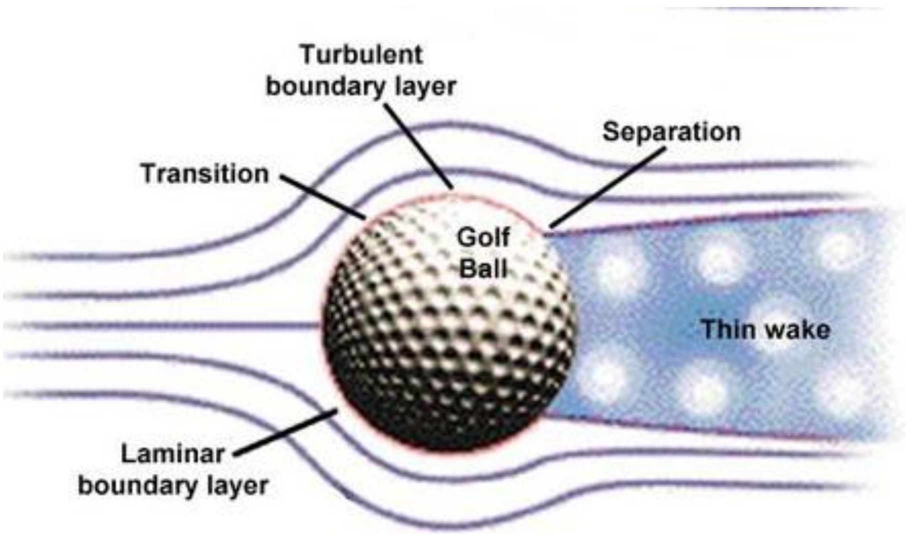
Joint work with George Haller

Nonlinear Dynamics Seminar Series

ETH zürich

Turbulent Boundary Layers

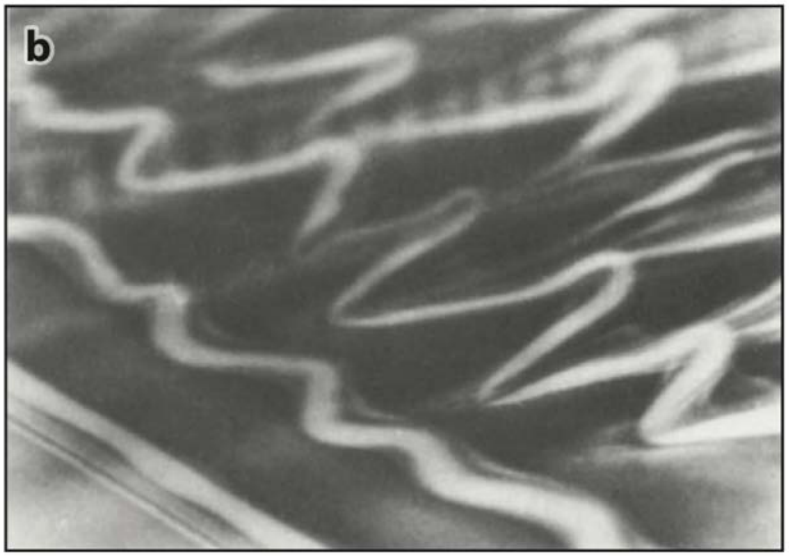
Surface Mixing in Atmosphere[1]



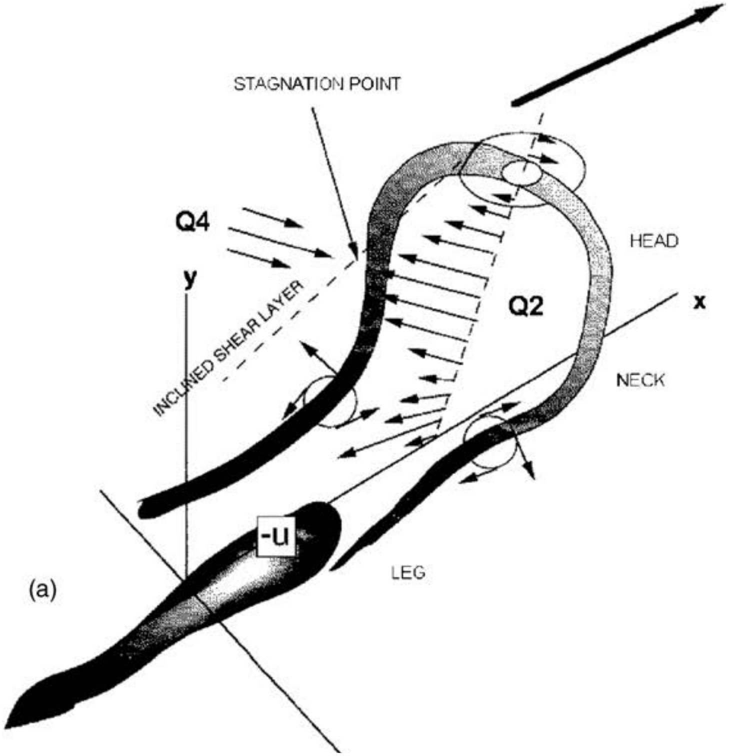
Drag Reduction[2]

(1) http://english.sina.com/china/p/2009/0211/217795.html
(2) http://www.sciencebuddies.org/science-fair-projects/project_ideas/Sports_p012.shtml

Models of Boundary Layer Structures



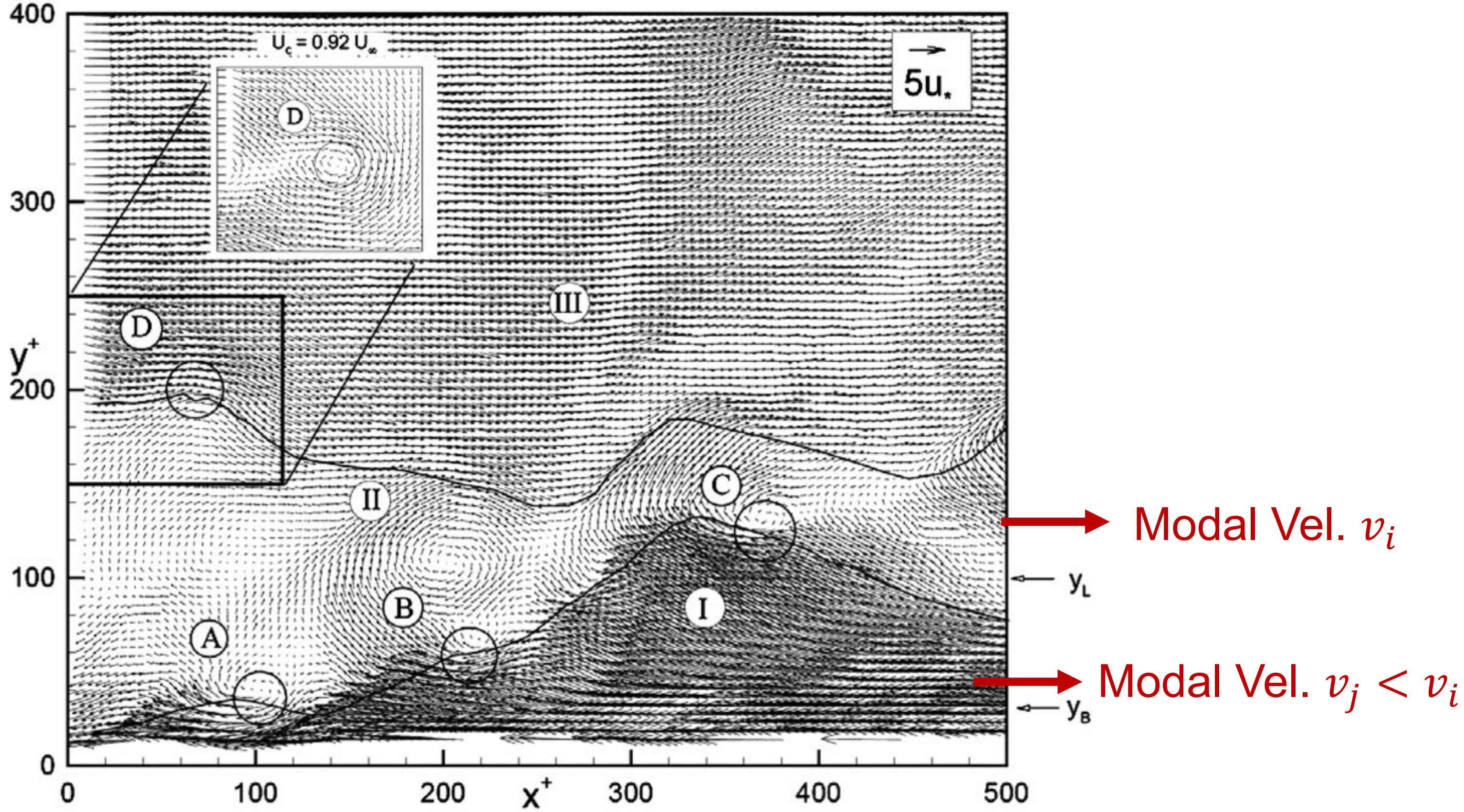
Perry et al. (1981)



Adrian et al. (2000)

R. J. Adrian, C.D.M , and C.D.T, “Vortex organization in the outer region of the turbulent boundary layer,” J. Fluid Mech. **422**, 1 2000.

Models of Boundary Layer Structures

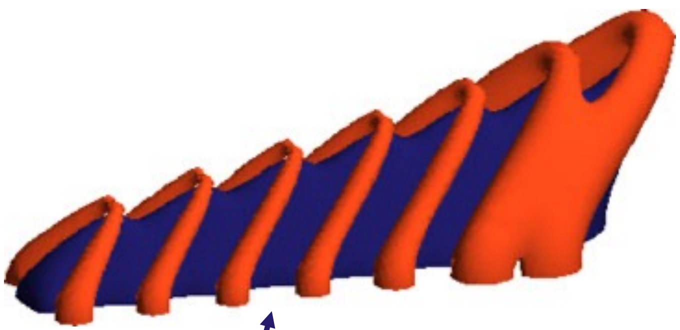


2D PIV velocity with subtracted "convection velocity"

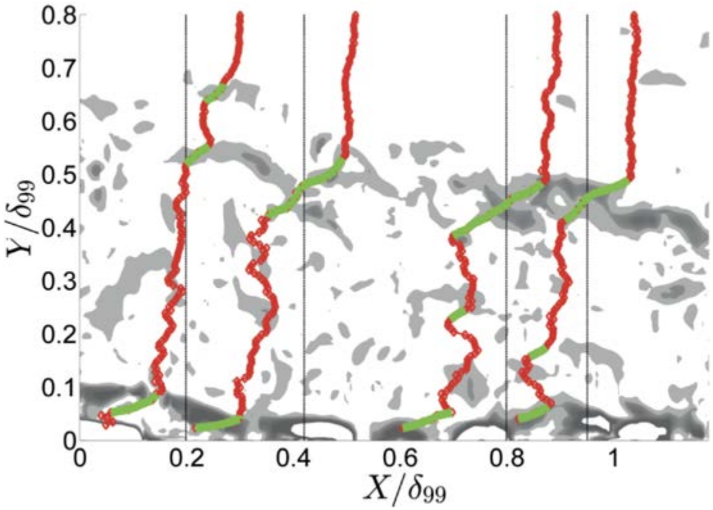
$$\tilde{\mathbf{v}} = \mathbf{v} - \langle \mathbf{v}_{c_1}, \mathbf{0} \rangle$$

R. J. Adrian, C.D.M , and C.D.T, "Vortex organization in the outer region of the turbulent boundary layer," J. Fluid Mech. **422**, 1 2000.

Models of Boundary Layer Structures



Low streamwise momentum zone[1]



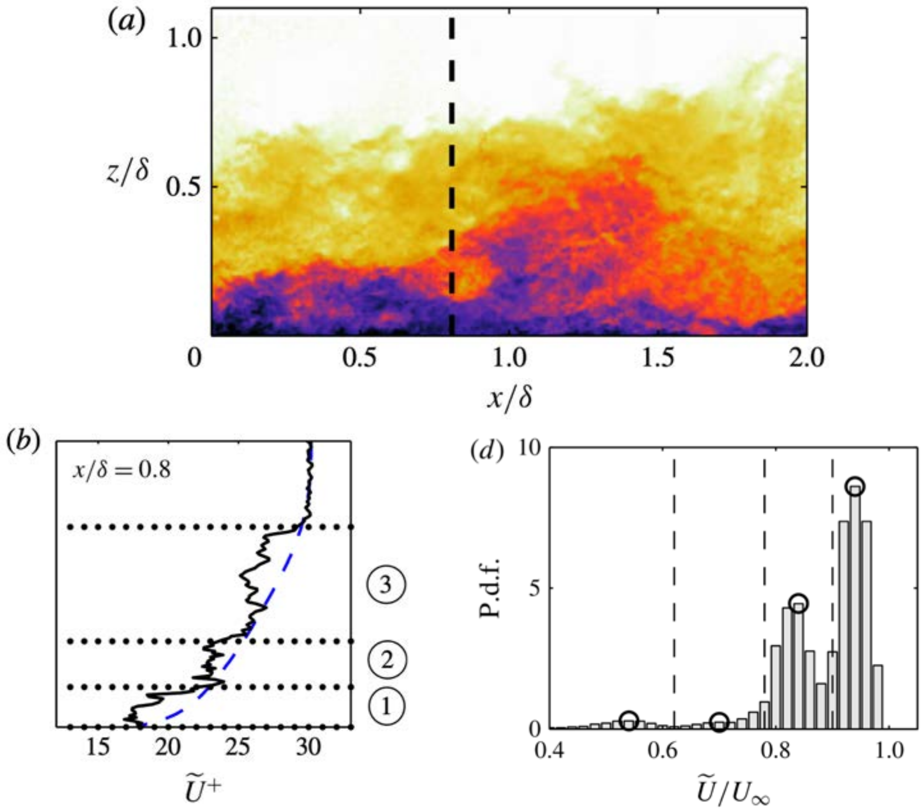
Shear interfaces separate zones[2]

Concept: Vortices block flow and create separate momentum zones

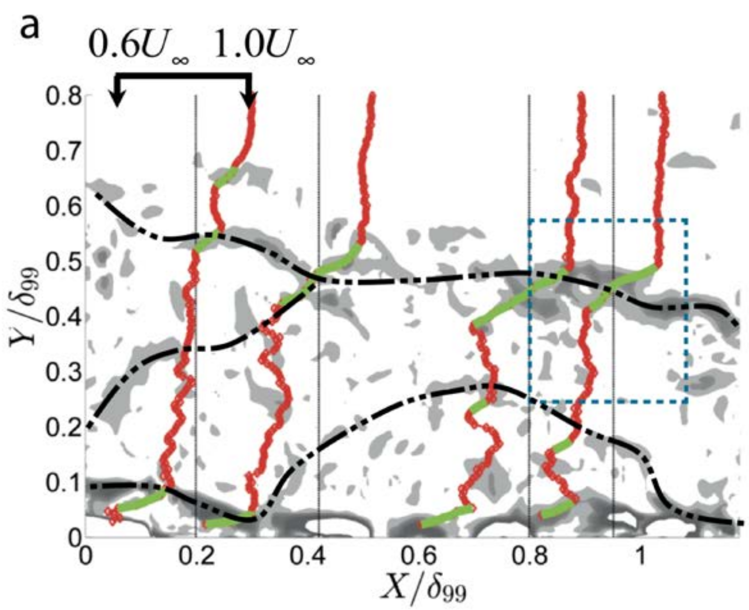
(1) De Silva, C. M., N. Hutchins, and I. Marusic (2015), Uniform momentum zones in turbulent boundary layers, J. Fluid Mech., 786
(2) Eisma, J., J. Westerweel, G. Ooms, and G. E. Elsinga (2015), Interfaces and internal layers in a turbulent boundary layer, Phys. Fluids, 27

Uniform Momentum Zone Interfaces

^
(Streamwise)



"Zonal structure" in flow[1]



Shear Interfaces[2]

Both ideas based on similarity to TNTI

(1) De Silva, C. M., N. Hutchins, and I. Marusic (2015), Uniform momentum zones in turbulent boundary layers, J. Fluid Mech., 786
(2) Eisma, J., J. Westerweel, G. Ooms, and G. E. Elsinga (2015), Interfaces and internal layers in a turbulent boundary layer, Phys. Fluids, 27

Linear Momentum Barrier Derivations

Streamwise momentum flux is not frame-invariant

$$\cancel{\int |\rho u_x(\boldsymbol{u}\cdot\boldsymbol{n})|dA}$$

What observer-independent flux should we be minimizing with respect to?

$$\Psi(M_0) = \int_{M_0} \left|\boldsymbol{b}_{t_0}(\boldsymbol{x}_0)\cdot\boldsymbol{n}_{\mathbf{0}}\right| dA_0$$

$$\boldsymbol{b}_{t_0}(\boldsymbol{x}_0) = ?$$

Assuming Fickian-type diffusion for an active vector field $\boldsymbol{u}$:

$$\frac{\partial\boldsymbol{u}}{\partial t} + (\nabla\boldsymbol{u})\boldsymbol{u} = \boxed{\boldsymbol{h}(\boldsymbol{x},t,\boldsymbol{u},\boldsymbol{v})} + \boxed{\nu\boldsymbol{g}(\boldsymbol{x},t,\boldsymbol{v})}$$

Inertial (frame-dependent)

Generalized diffusive forces

Haller, G., S. Katsanoulis, M. Holzner, and D. Gatti (2020), Obj. material barriers to the transport of momentum and vorticity, In Review: *JFM.*

Momentum Barrier Derivations

Let, $\boldsymbol{f} = \rho \boldsymbol{u}$**,** then the equations of motion for compressible, possibly non-Newtonian, 3D time-dependent flows:

$$\frac{\mathrm{D}\mathbf{f}}{\mathrm{Dt}} = -\nabla p + \boldsymbol{q} - \frac{D\rho}{Dt}\boldsymbol{u} + \boxed{\nu \nabla \cdot \boldsymbol{\sigma}}$$

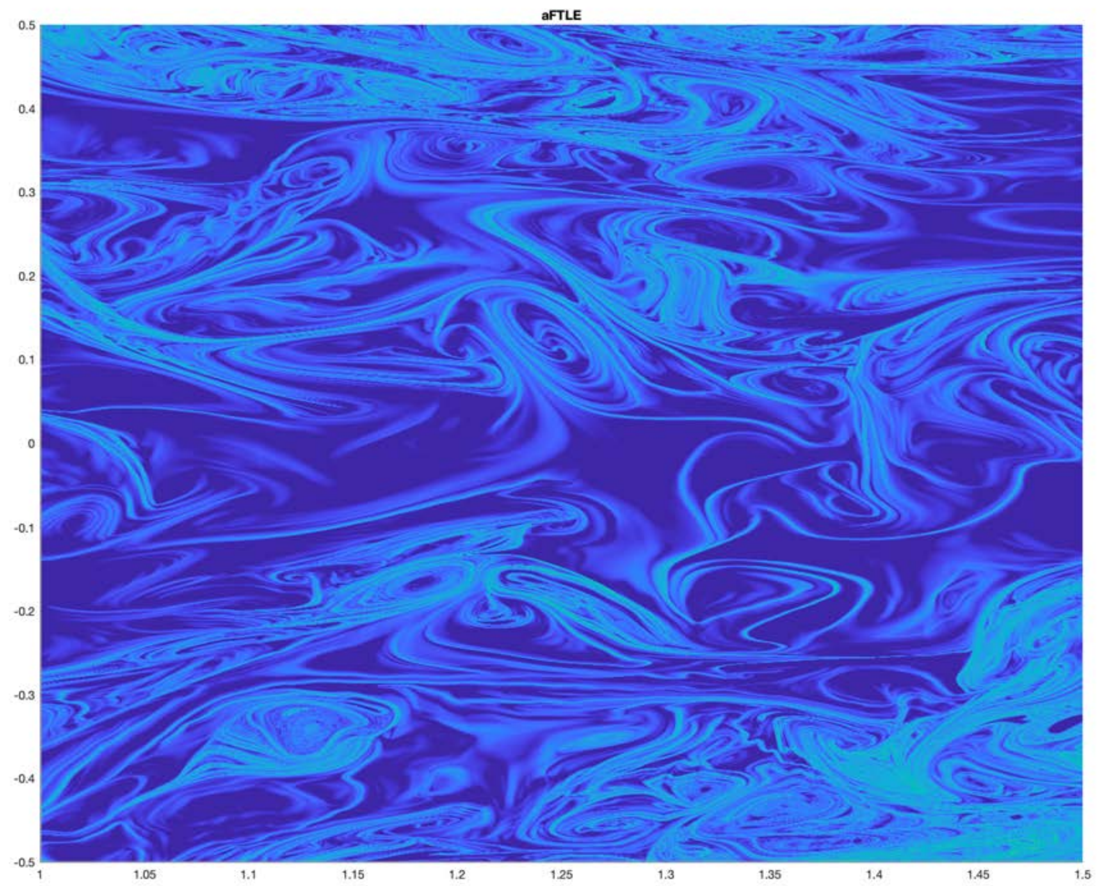
Theorem 1: For incompressible, uniform-density Navier-Stokes flows, instantaneous barriers for linear momentum take the form[1]

$$\boldsymbol{x}' = \nabla \cdot \boldsymbol{\sigma}(\mathbf{x}, t) = \Delta \mathbf{v}(\mathbf{x}, t)$$

Objective momentum flux is $\Psi(M_0) = \int_{M_0} |\Delta \mathbf{v}(\mathbf{x}, t_0) \cdot \boldsymbol{n}_{\mathbf{0}}| dA_0$

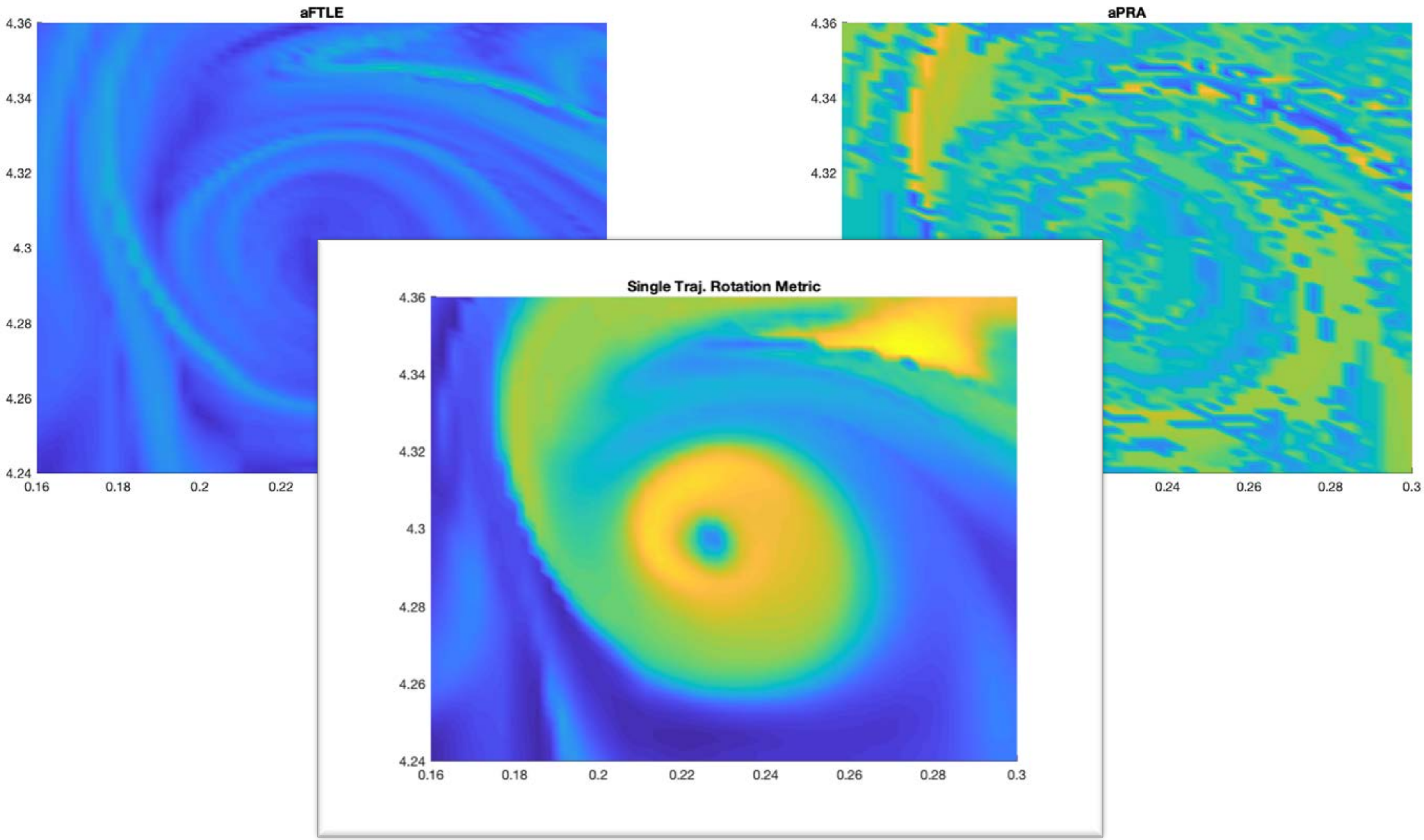
1) Haller, G., S. Katsanoulis, M. Holzner, and D. Gatti (2020), Obj. material barriers to the transport of momentum and vorticity, In Review: *JFM.*

Determining Initial Conditions



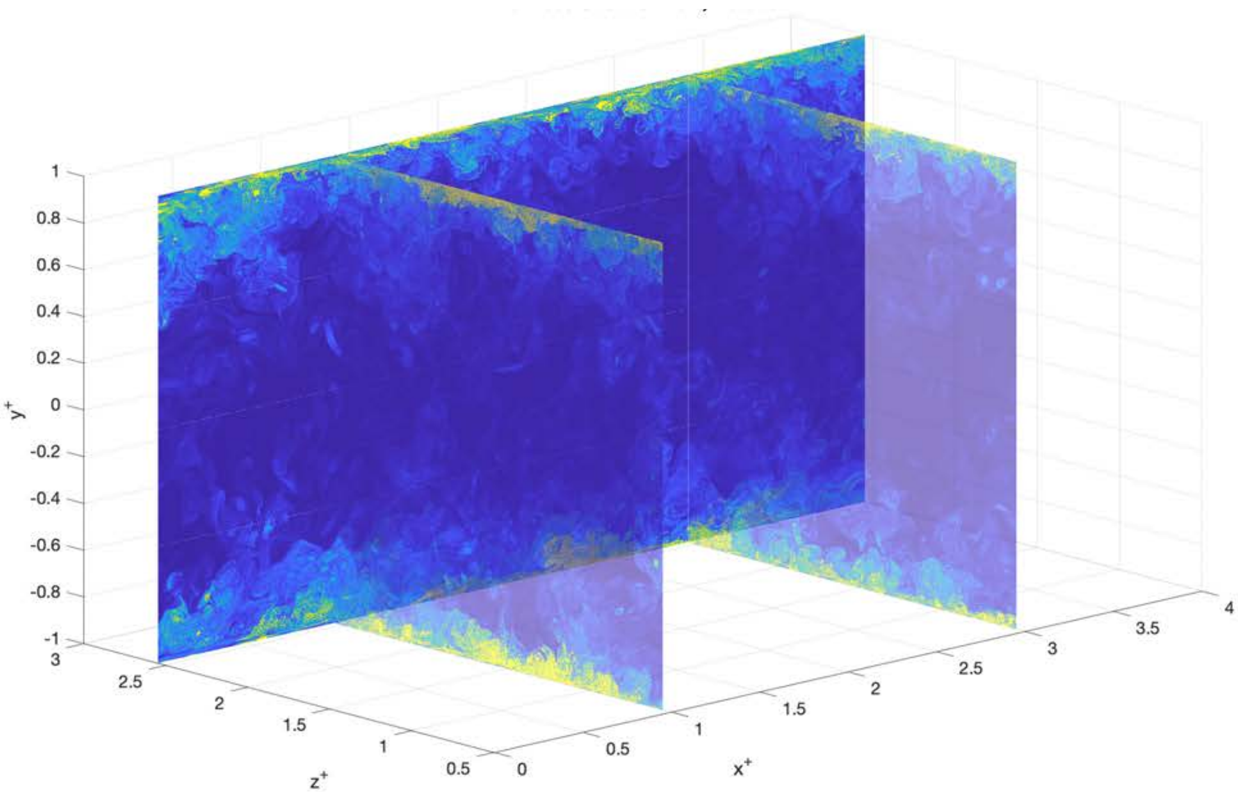
Example flow from Johns Hopkins Turbulence Database
$Re\_\tau = 1000$ Channel Flow
Fully resolved DNS (x, y, z, t)

Determining Initial Conditions



Newly derived simple rotation metric, β

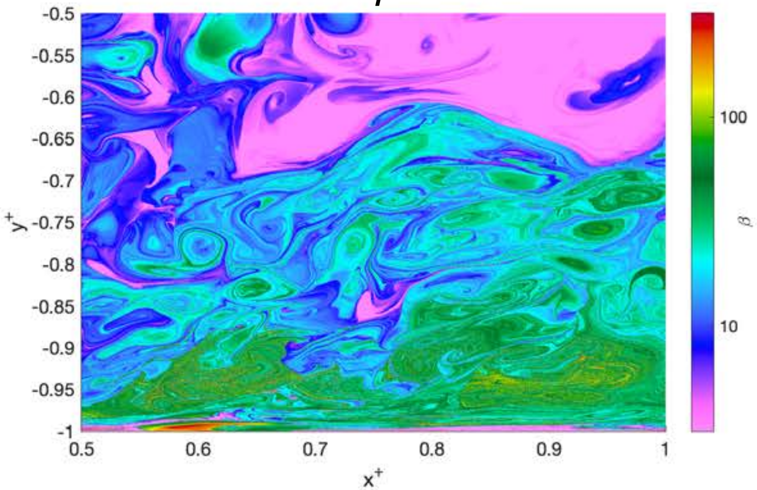
Single Trajectory Rotation Metric



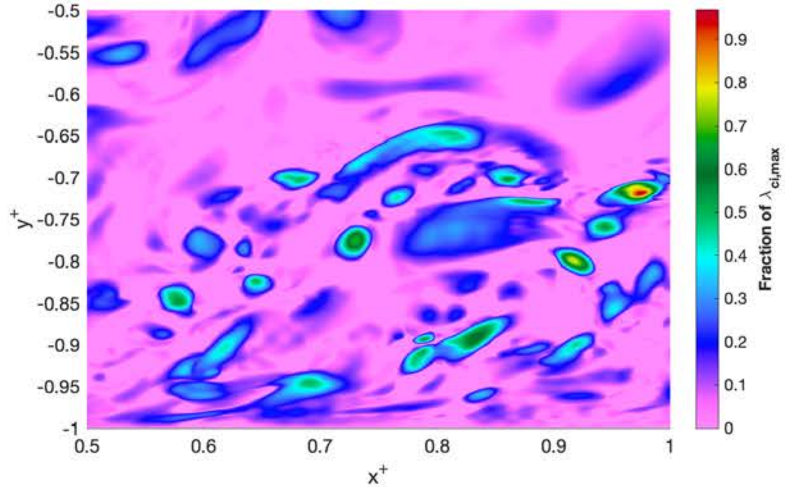
- β computed from single fluid particle trajectories
- Does not rely on spatial derivatives
- β not objective unless underlying flow field is objective

Metric Comparisons

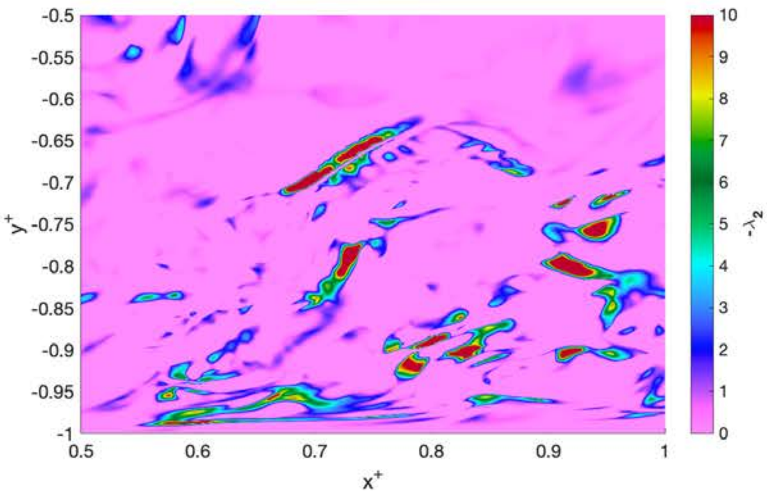
β



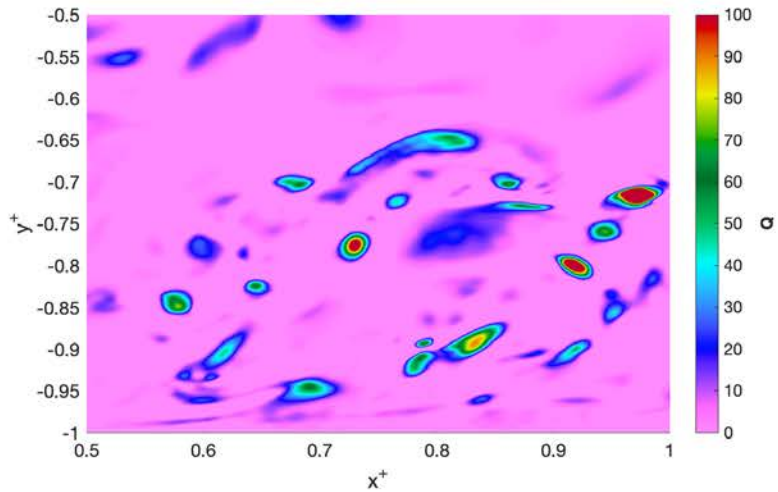
"Swirling Strength"



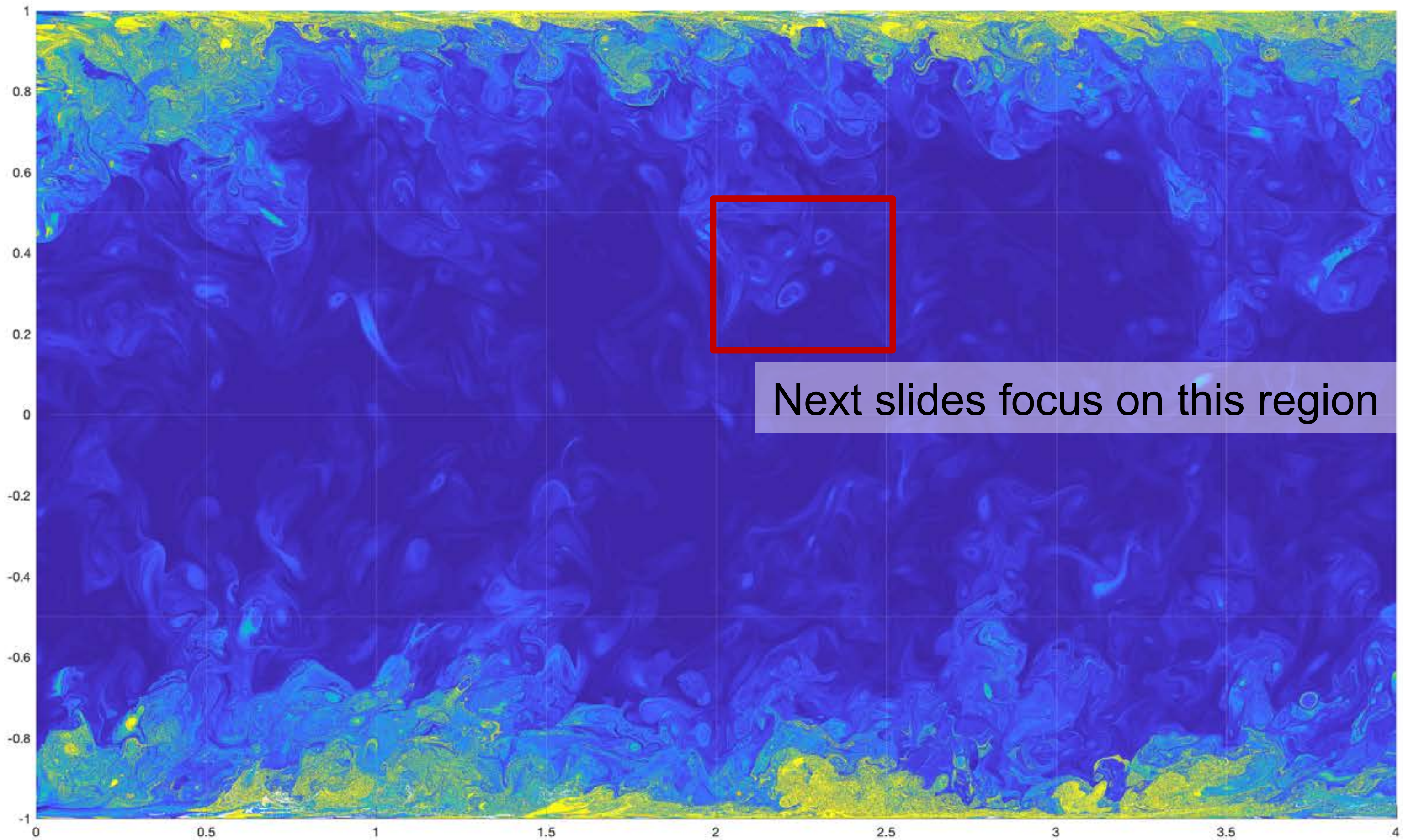
Lambda 2 Criterion



Q Criterion

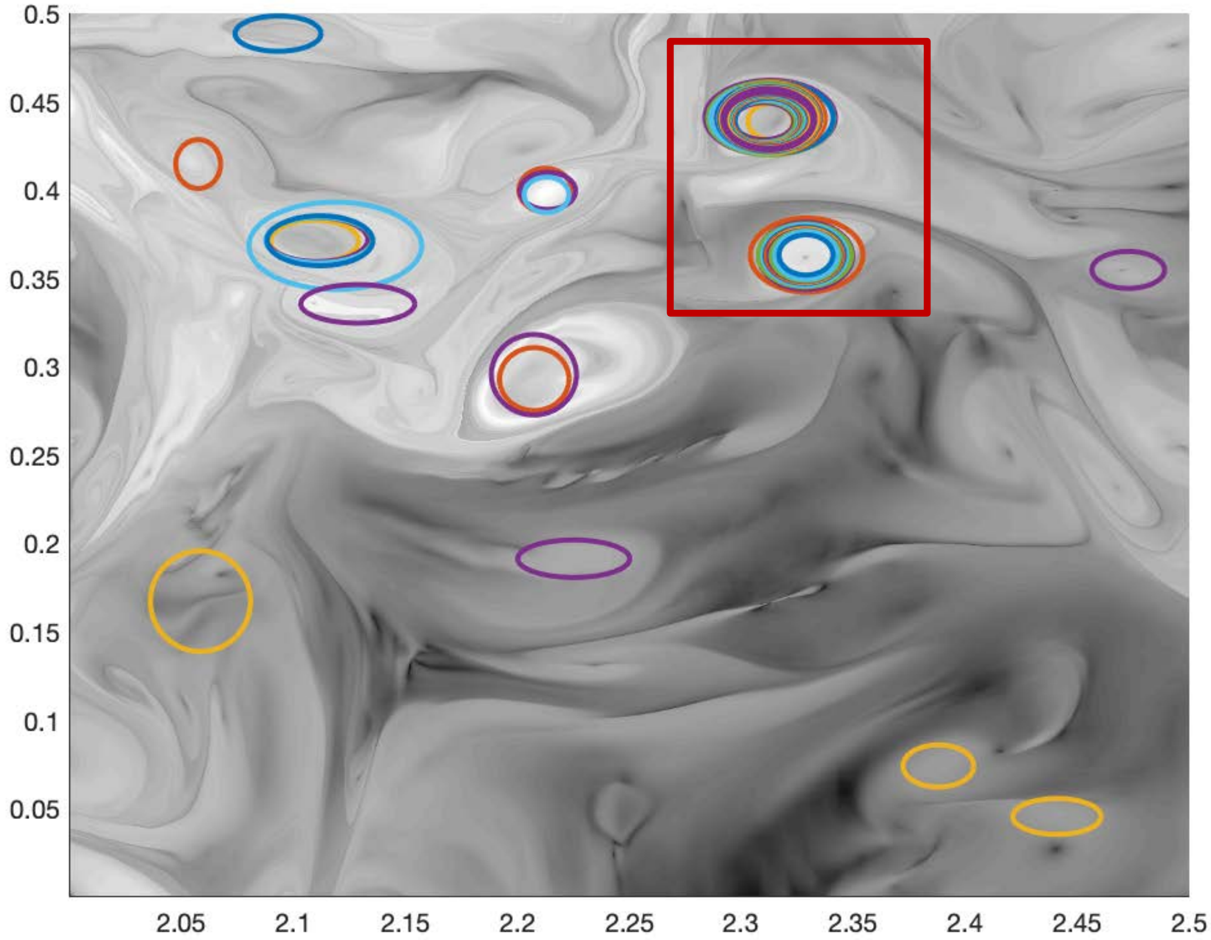


Single Trajectory Rotation Metric

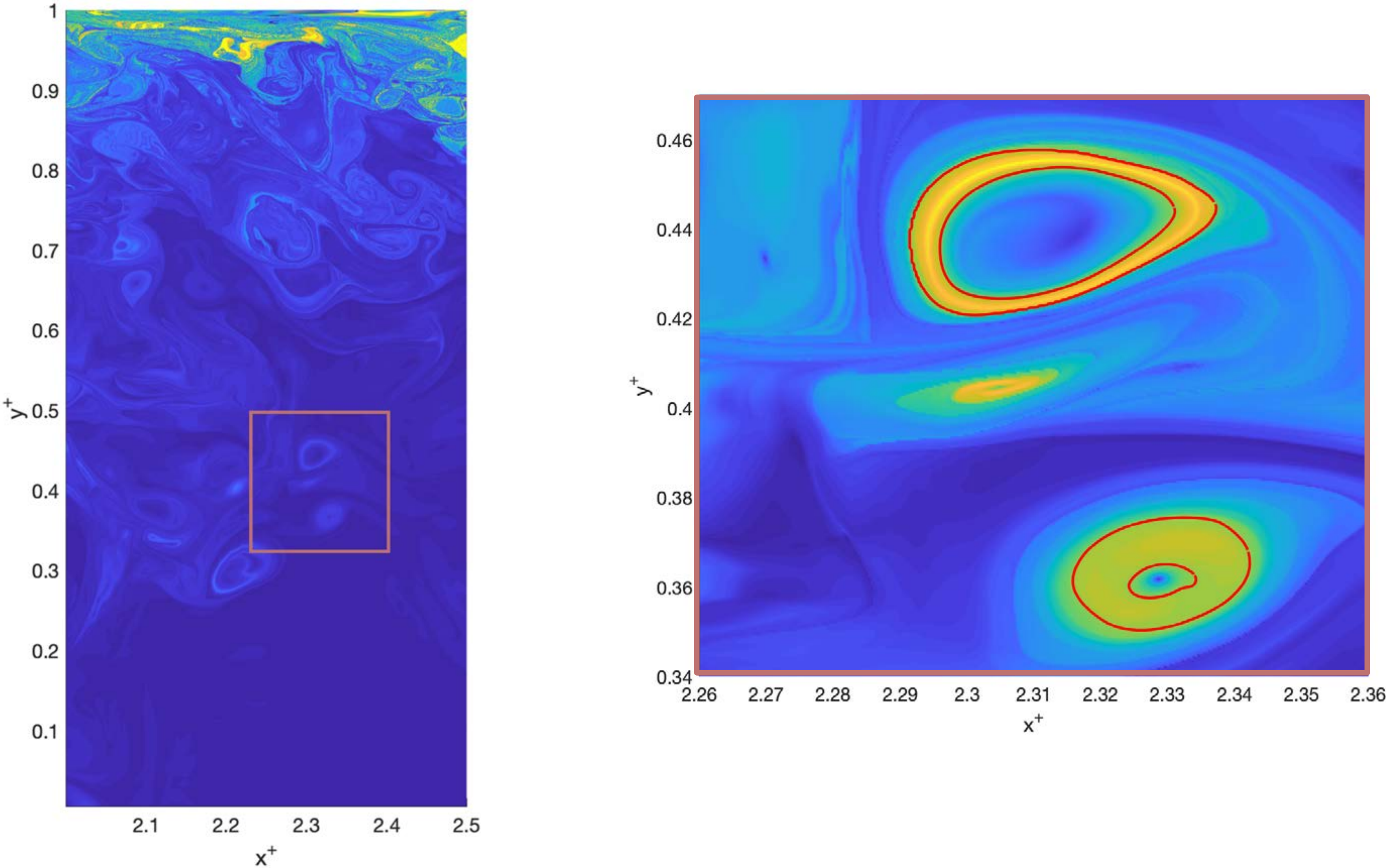


x-y plane

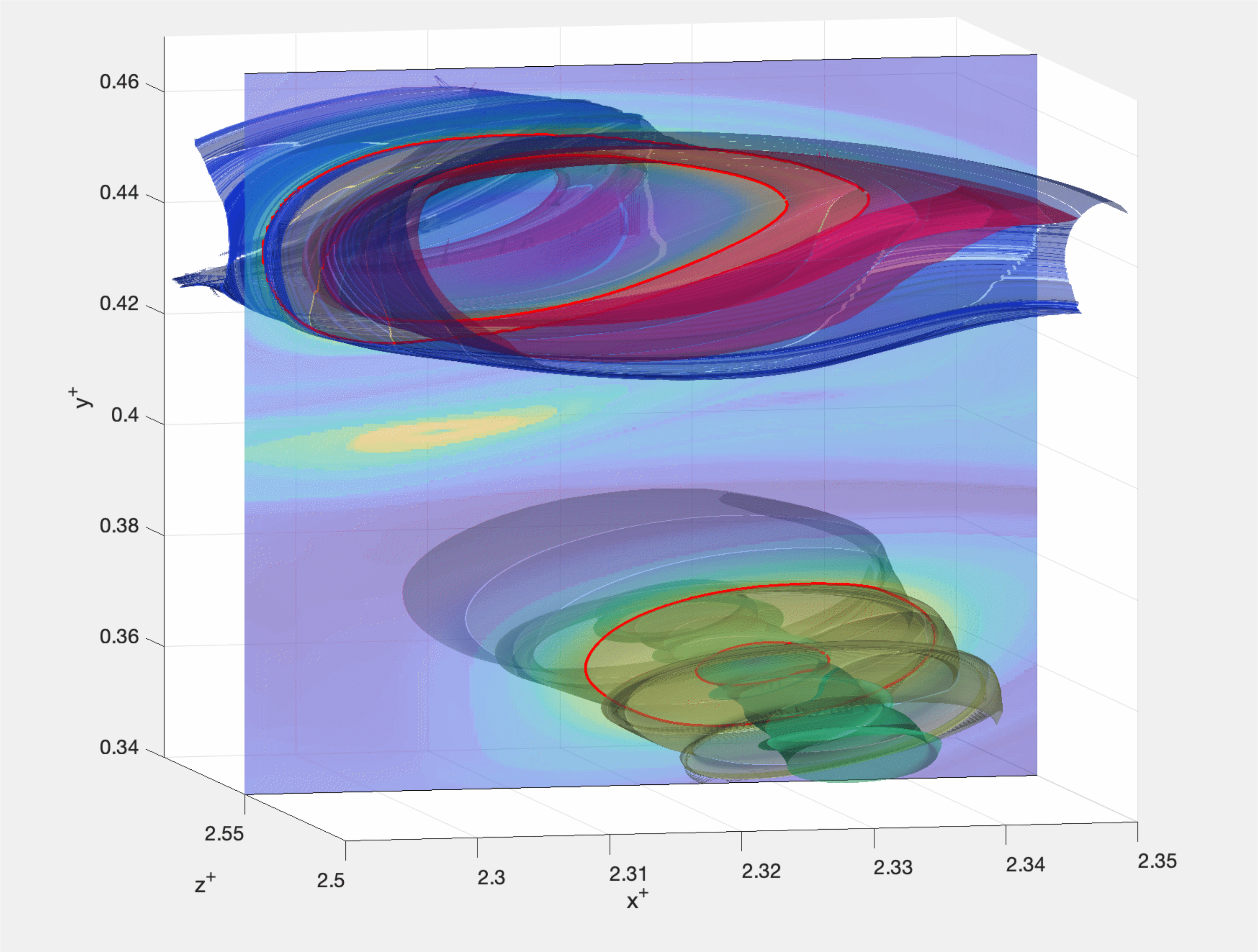
Automated Rotational Barrier Extraction



Feature Extraction

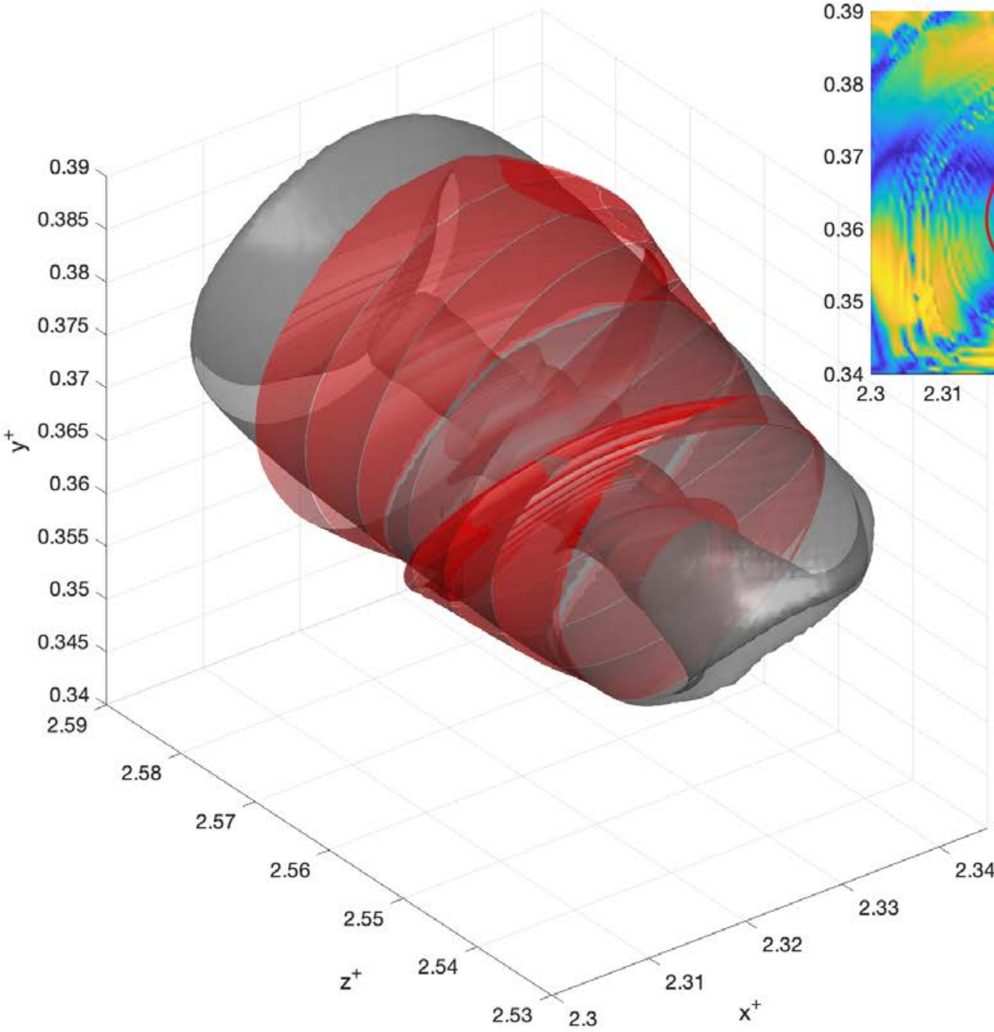


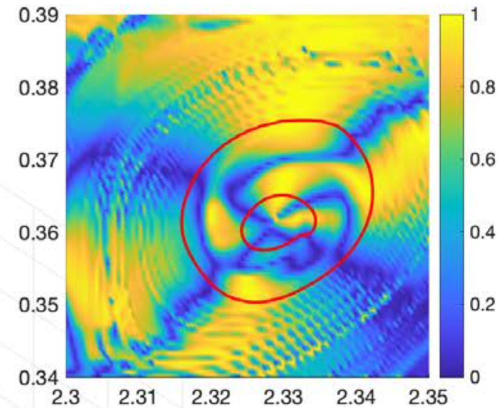
Stream surfaces in Barrier Field



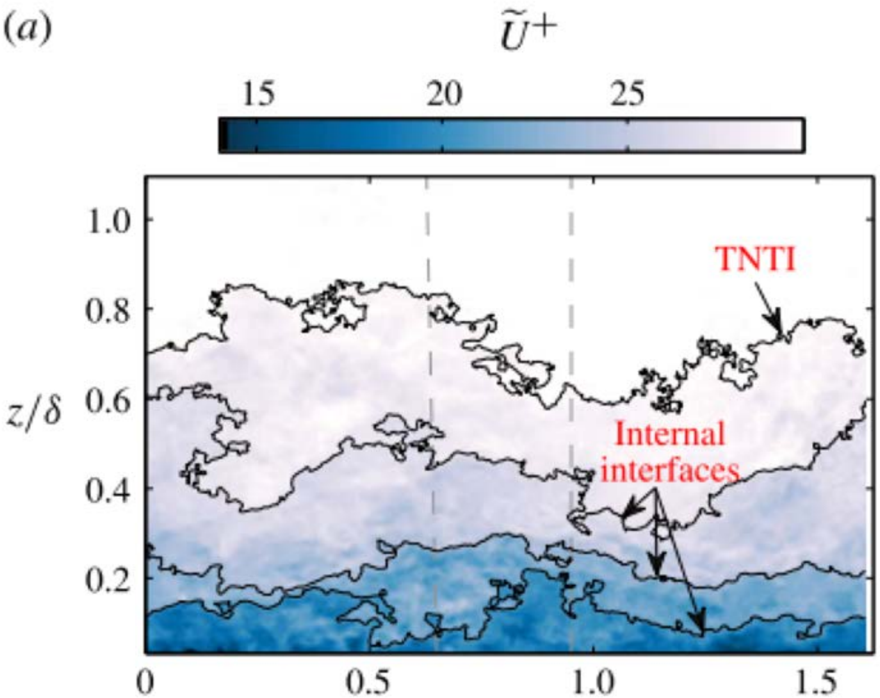
Barrier Field β Isosurfaces

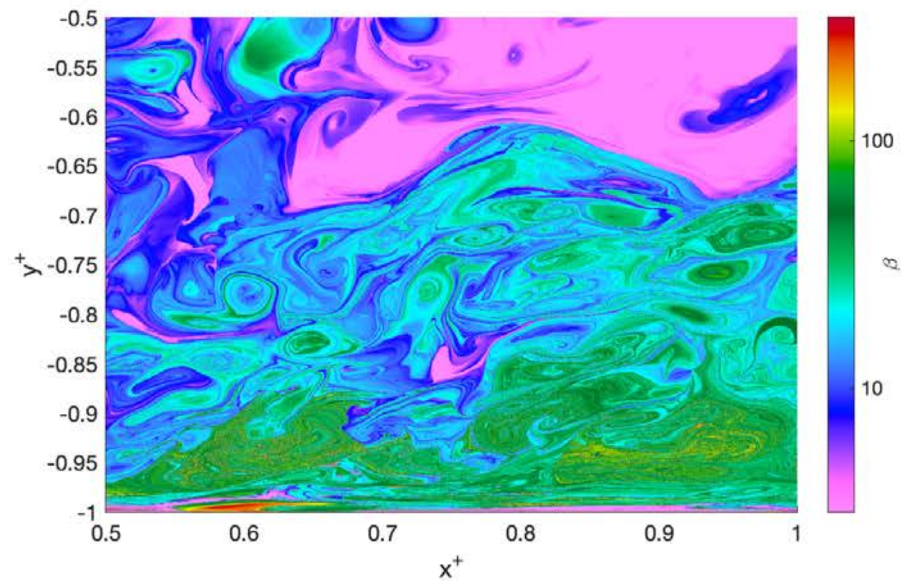
(Bulk Approach)





Momentum Zone Stratigraphy

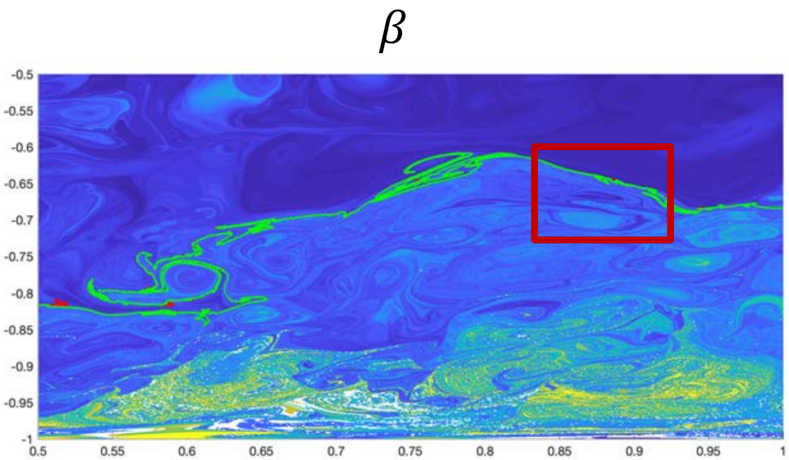




de Silva et al., 2017

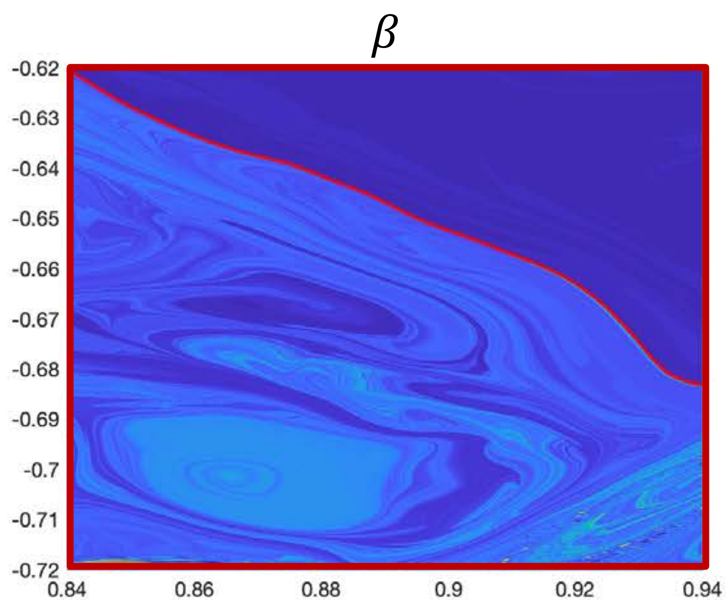
De Silva, C. M., J. Philip, N. Hutchins, and I. Marusic (2017), Interfaces of uniform momentum zones in turbulent boundary layers, *J. Fluid Mech.*, *820*, 451–478.

UMZ-Type Momentum Barriers



Automated search algorithm for spanning interface

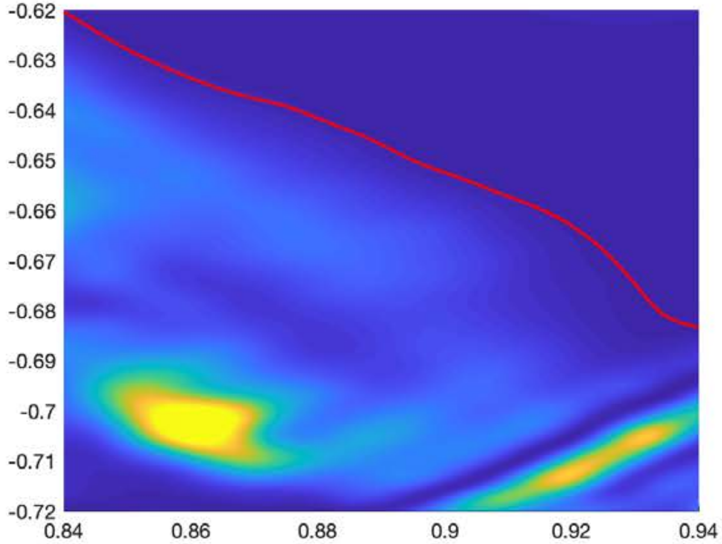
Minimizes curvature of barrier



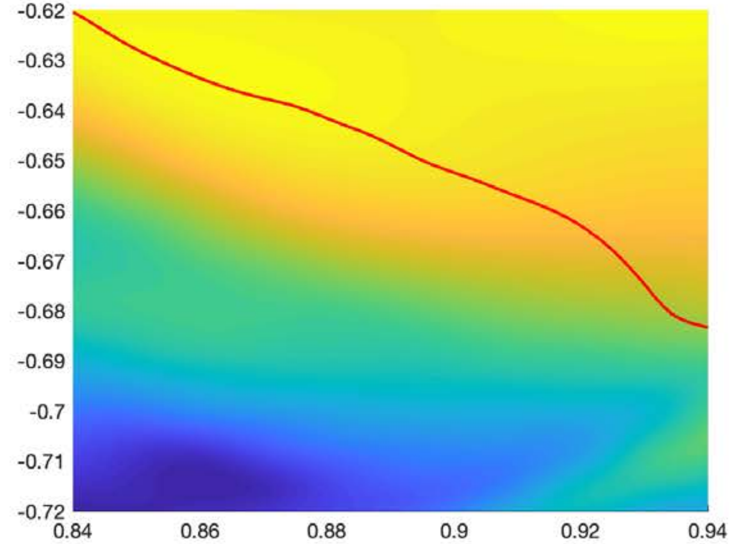
Less turbulent

Very turbulent

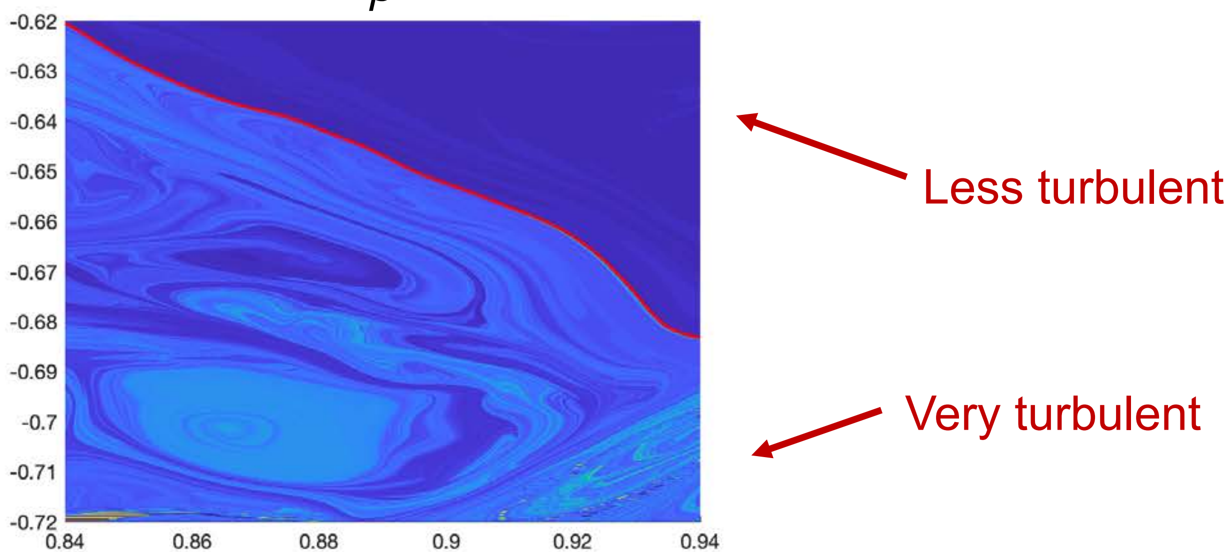
Enstrophy



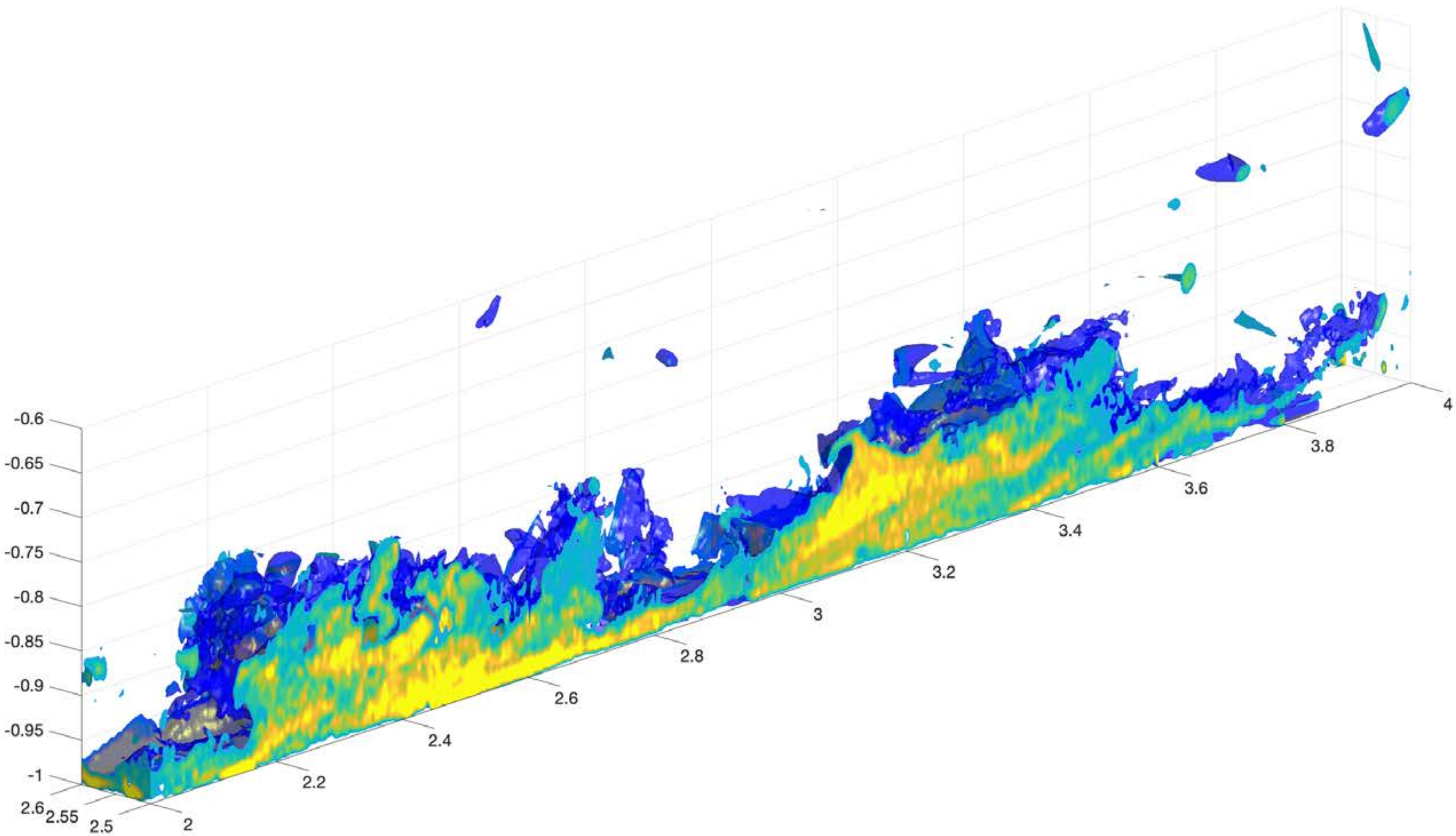
Streamwise Velocity



β

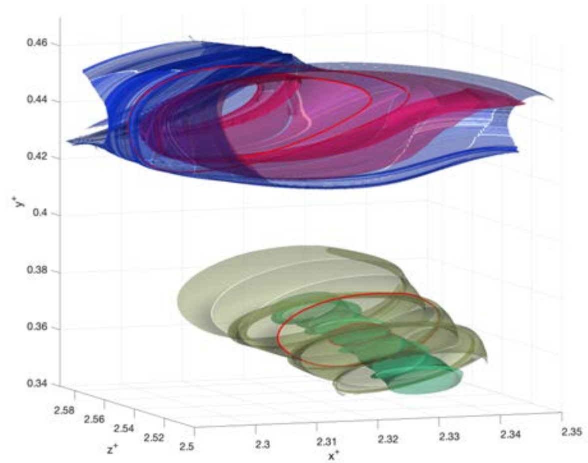


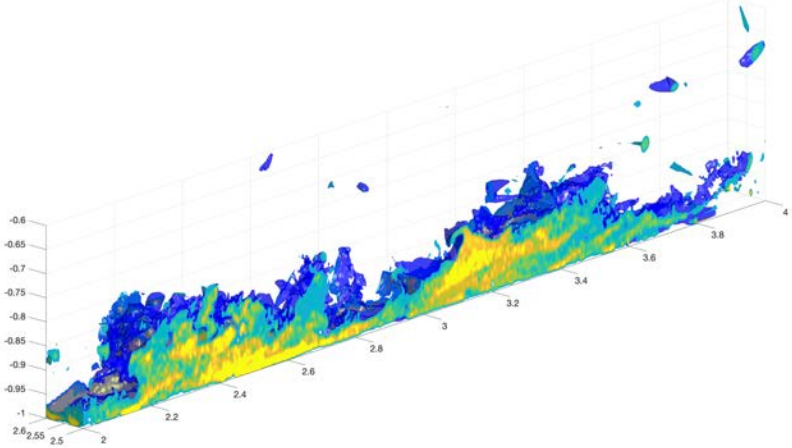
TNTI-Type Momentum Barriers



Now: Understand organization of turbulent boundary layers with these objective momentum barrier building blocks

Thank you.


0.46
0.44
0.42
0.4
0.38
0.36
0.34
2.58
2.56
2.54
2.52
2.5
2.3
2.31
2.32
2.33
2.34
2.35


-0.6
-0.65
-0.7
-0.75
-0.8
-0.85
-0.9
-0.95
-1
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4