Control of Large-Scale Motions in Turbulent Boundary Layers

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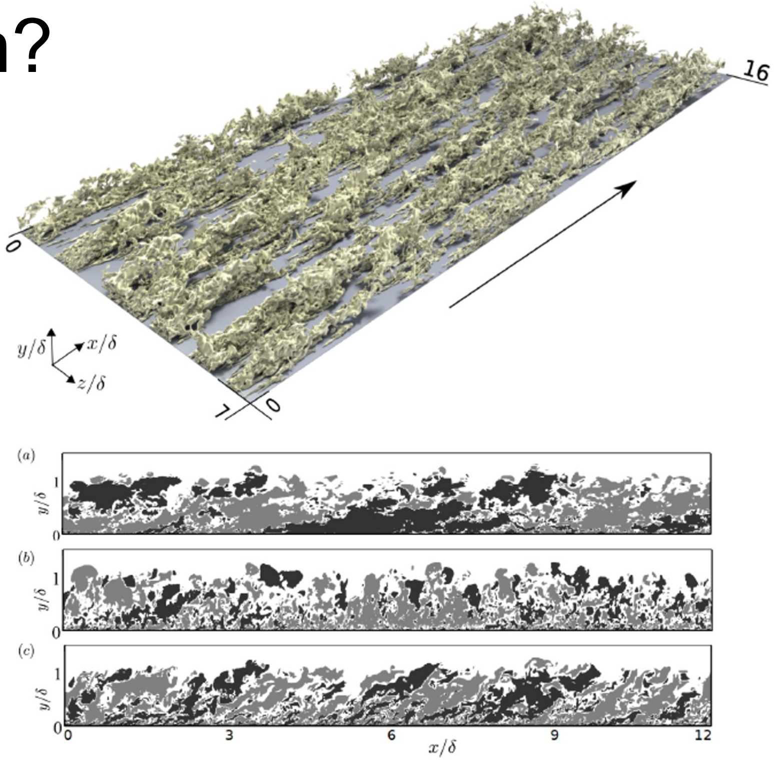
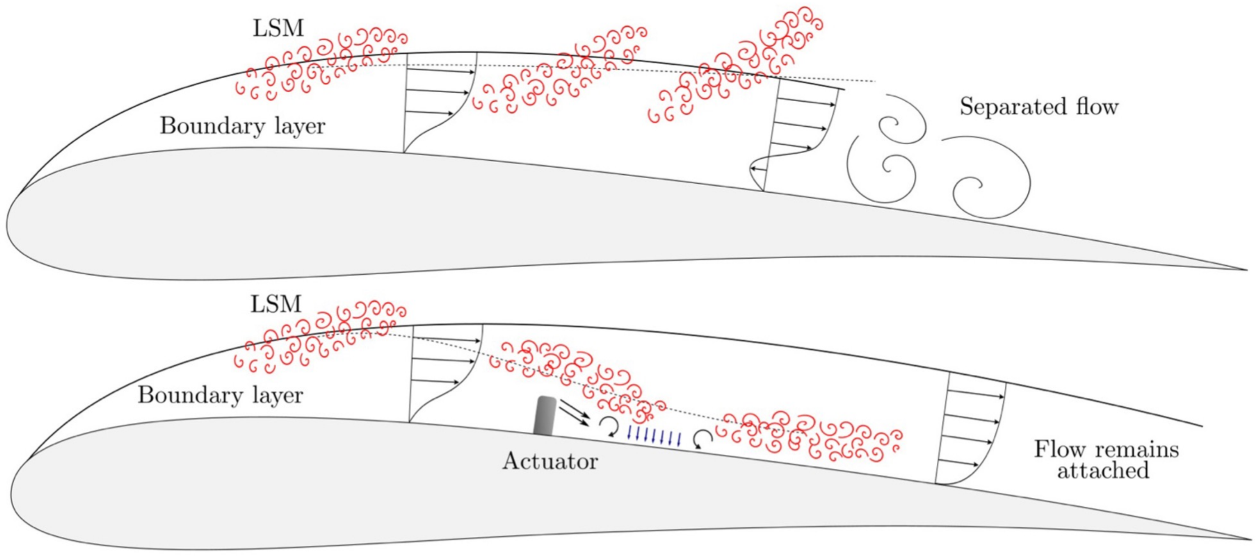
What is a Large-Scale Motion?

- Coherent motions in wall-bounded turbulent flows
- Characteristics:
  - Size in the order of the boundary layer thickness
  - Large fraction of the turbulent kinetic energy
  - Significant contribution to average Reynolds shear stresses
- Consist of smaller structures (e.g. hairpin vortices)



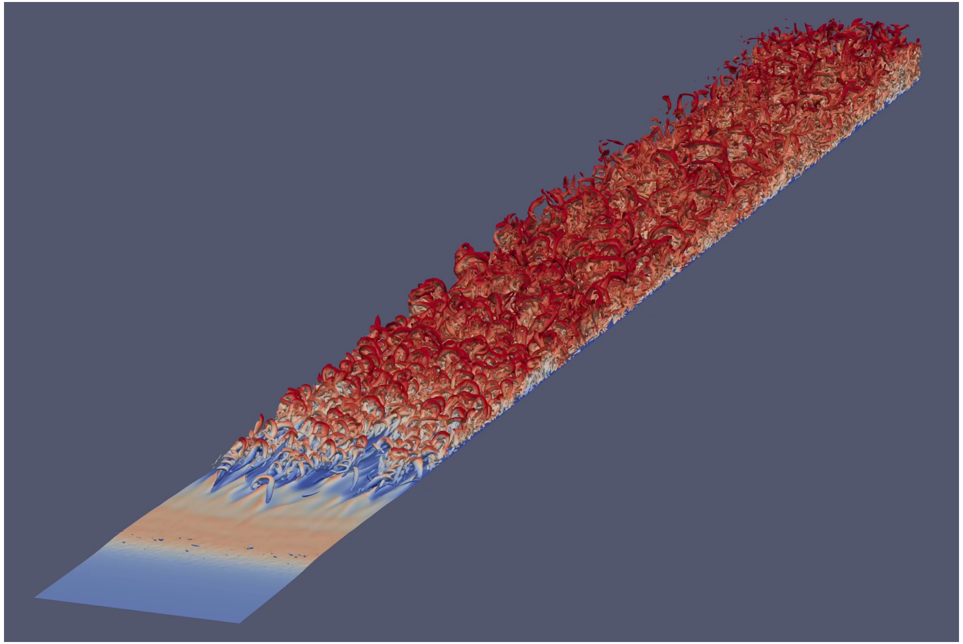
High/low streamwise velocity structures. (Sillero, J., PhD Thesis, 2014)

Control Scheme



Re-energize the boundary layer by moving LSMs toward the wall

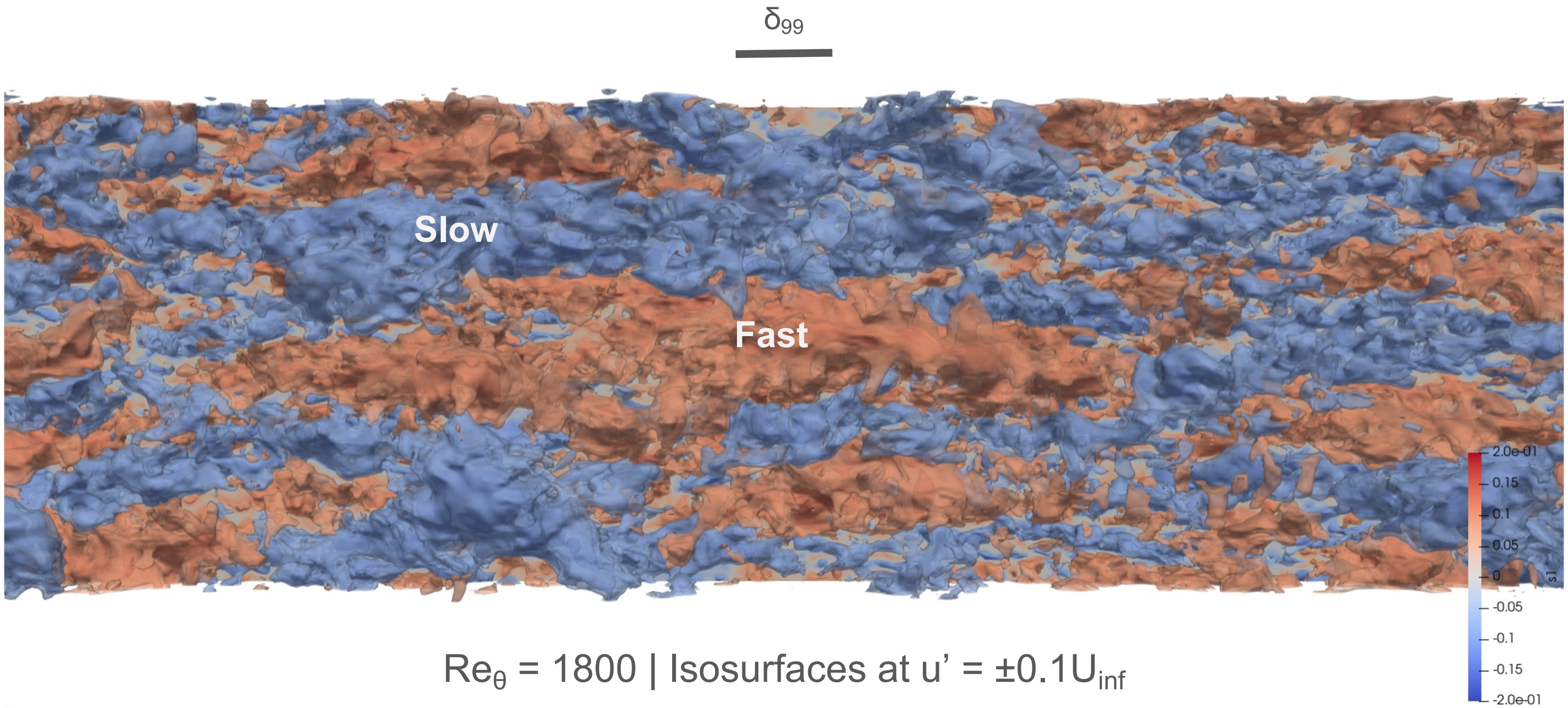
Turbulent Boundary Layer DNS



Q Criterion isosurfaces colored by height

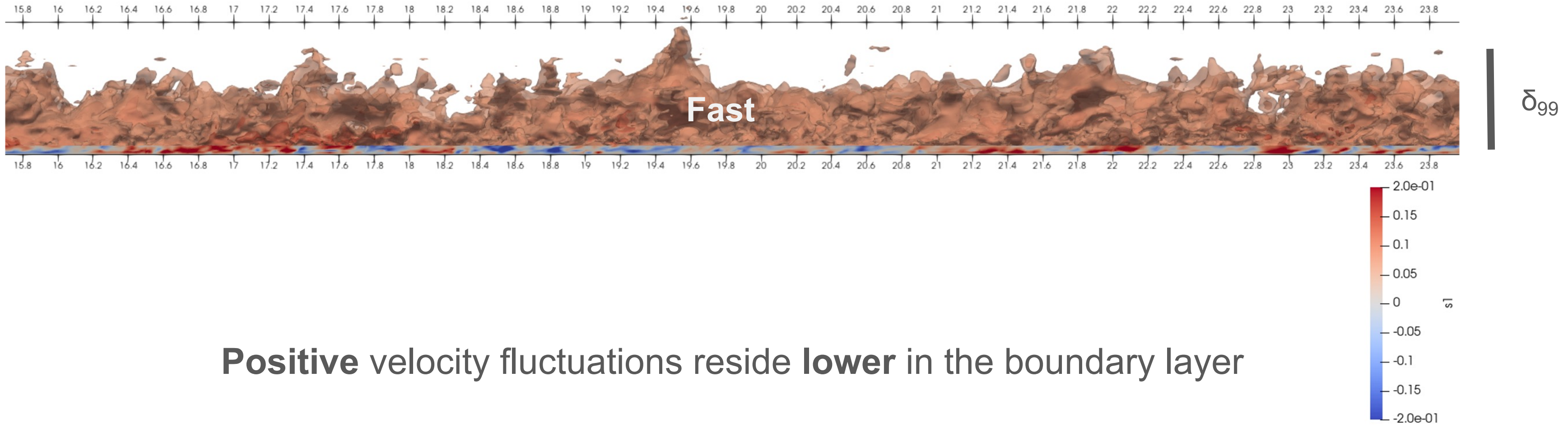
Direct numerical simulation of a turbulent boundary layer at Re_θ = 1100 - 2000 using the spectral element code **Nek5000** | Boundary layer is tripped with random streamwise forcing

A Closer Look at Velocity Fluctuations



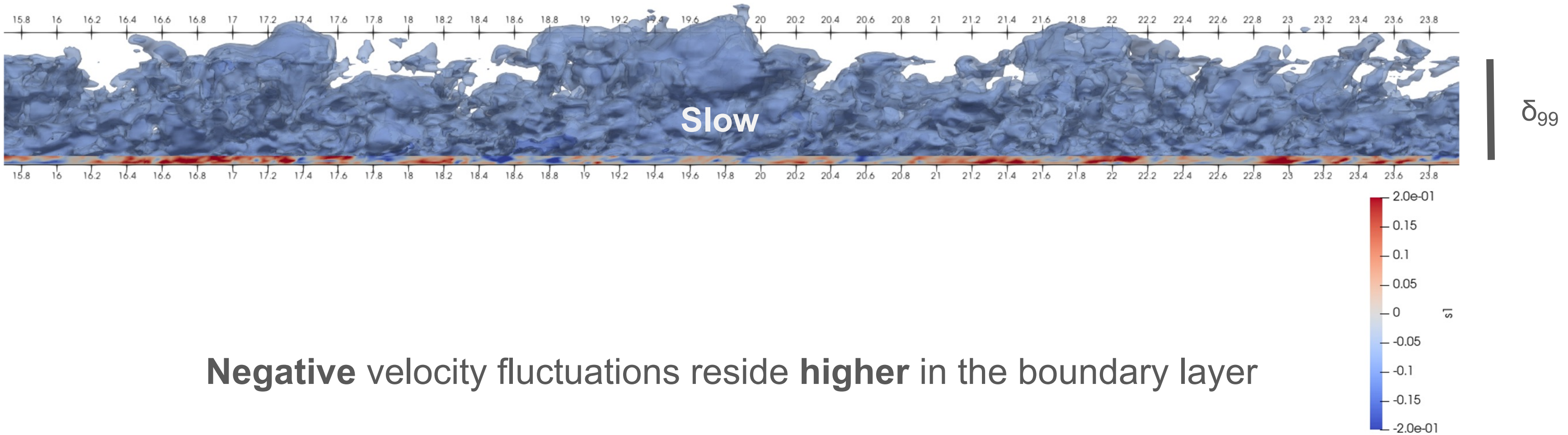
Re_θ = 1800 | Isosurfaces at u' = $\pm 0.1 U_{inf}$

Side View of Positive Fluctuations



Positive velocity fluctuations reside **lower** in the boundary layer

Side View of Negative Fluctuations



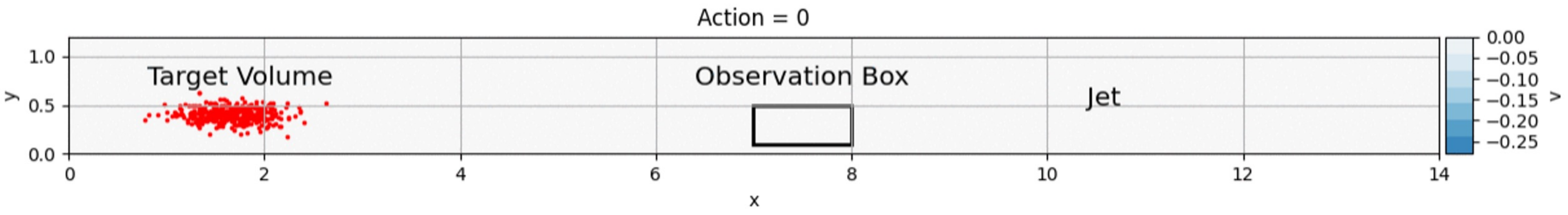
Negative velocity fluctuations reside **higher** in the boundary layer

Model Predictive Control of LSMs

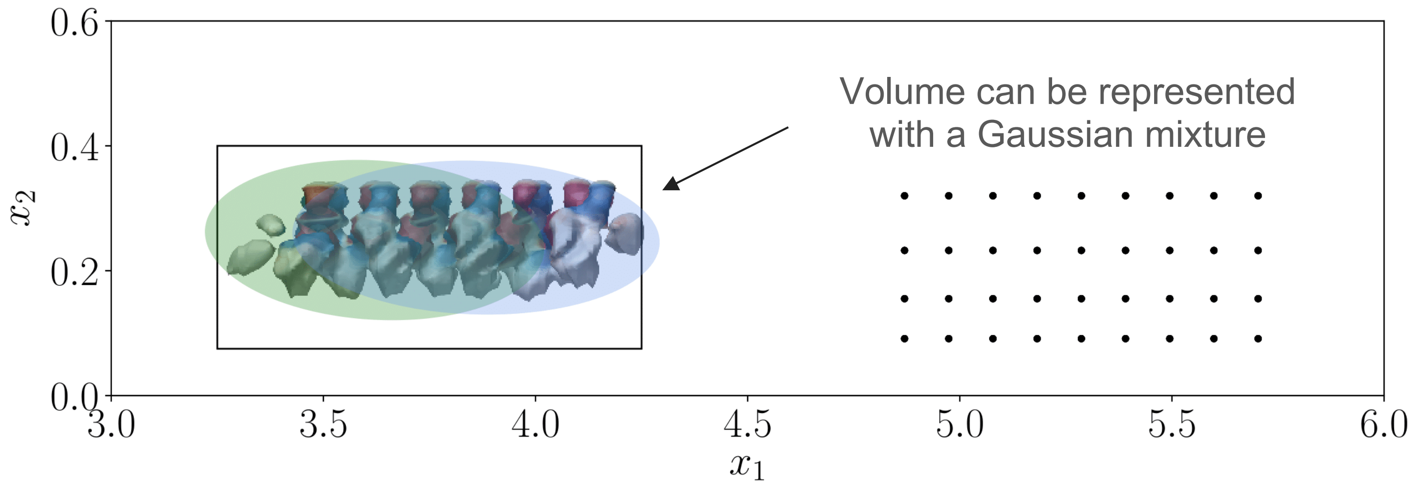
Detect
Volumes of LSMs to target

Predict
LSM Movement

Actuate
Create downwash when LSM is near the actuator

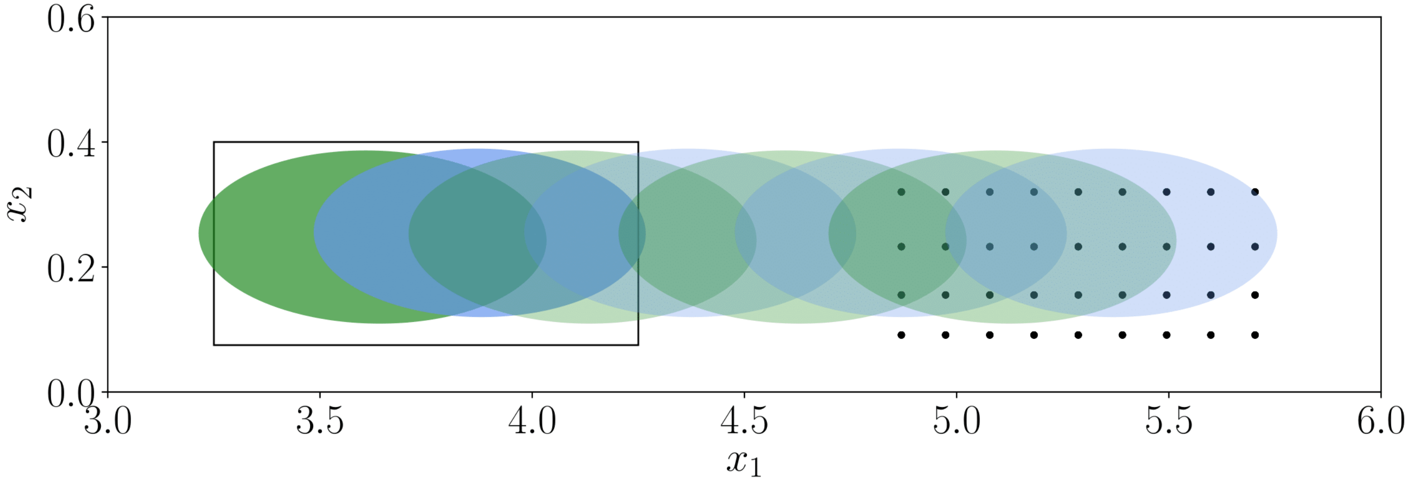


Detect an LSM



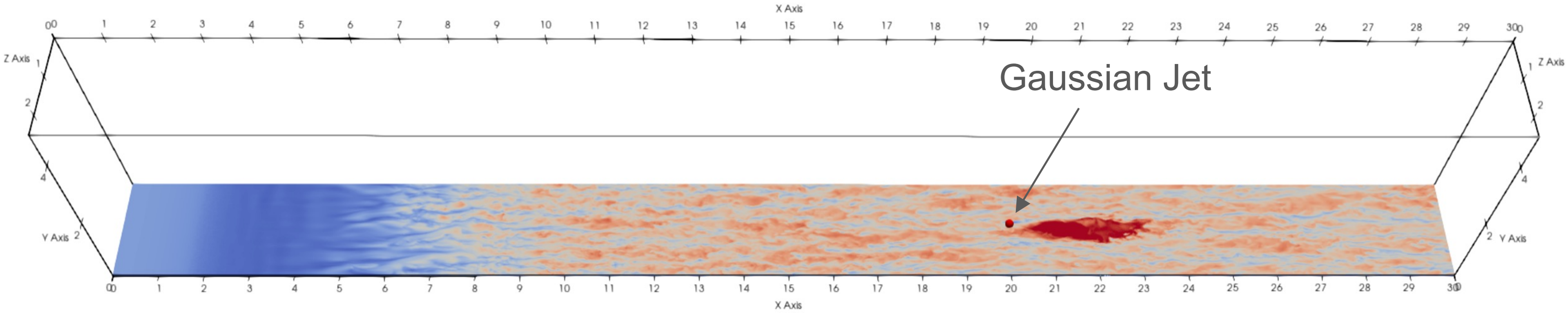
Use the 3D flowfield to directly detect LSMs
(e.g. by low-pass filtering the streamwise velocity fluctuations)

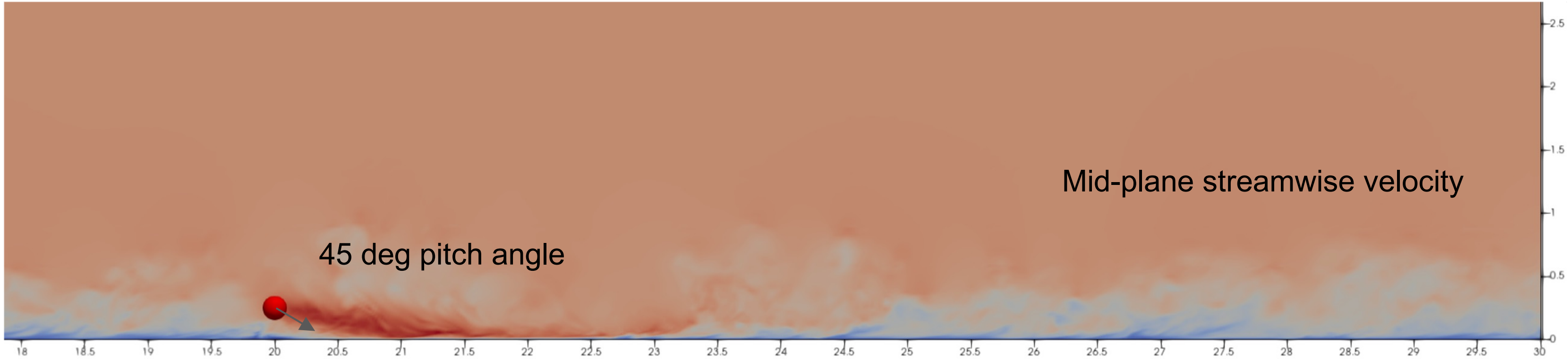
Predict LSM Trajectory



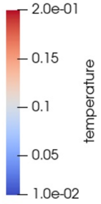
Use **Taylor's hypothesis** to predict the trajectory of an LSM

Creating Downwash



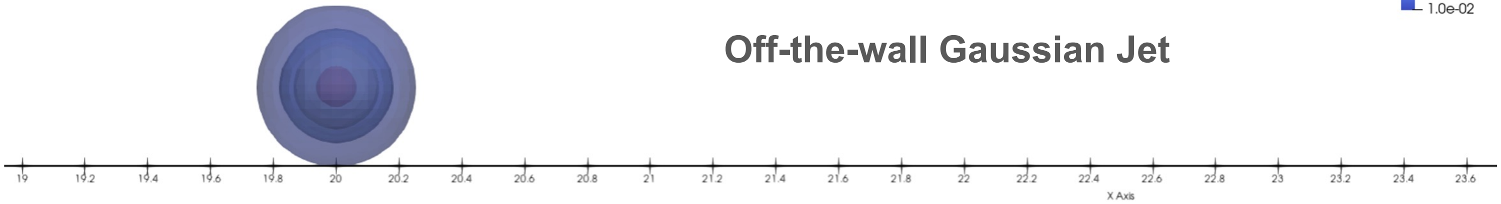


Force Field Distributions (x-y plane)

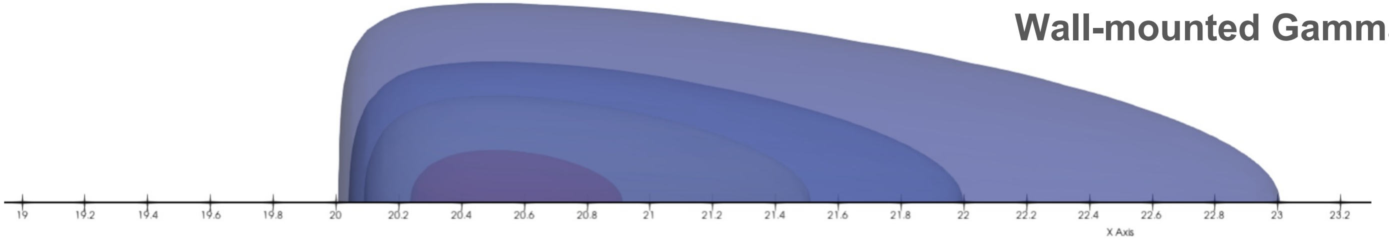


Fx = -Fy

Off-the-wall Gaussian Jet



Wall-mounted Gamma Distribution Jet



Plasma Actuators*

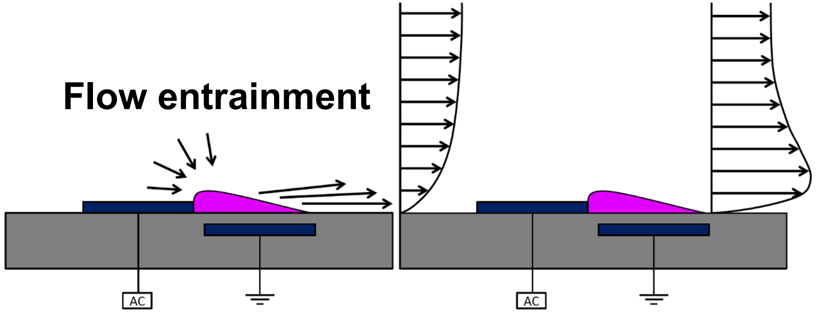
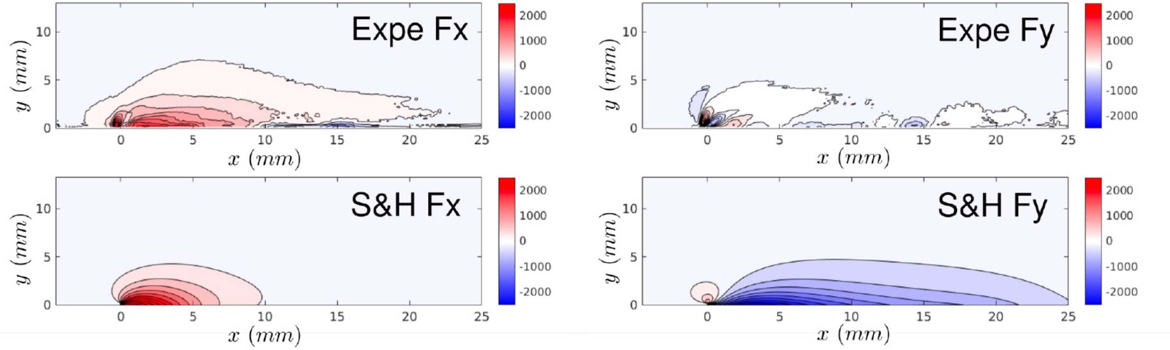


Figure 1. Sketch of the effect of a dielectric barrier discharge (DBD) plasma actuator in a quiescent ambient fluid (left) and in a boundary layer (right).

Body Forces of a Plasma Actuator



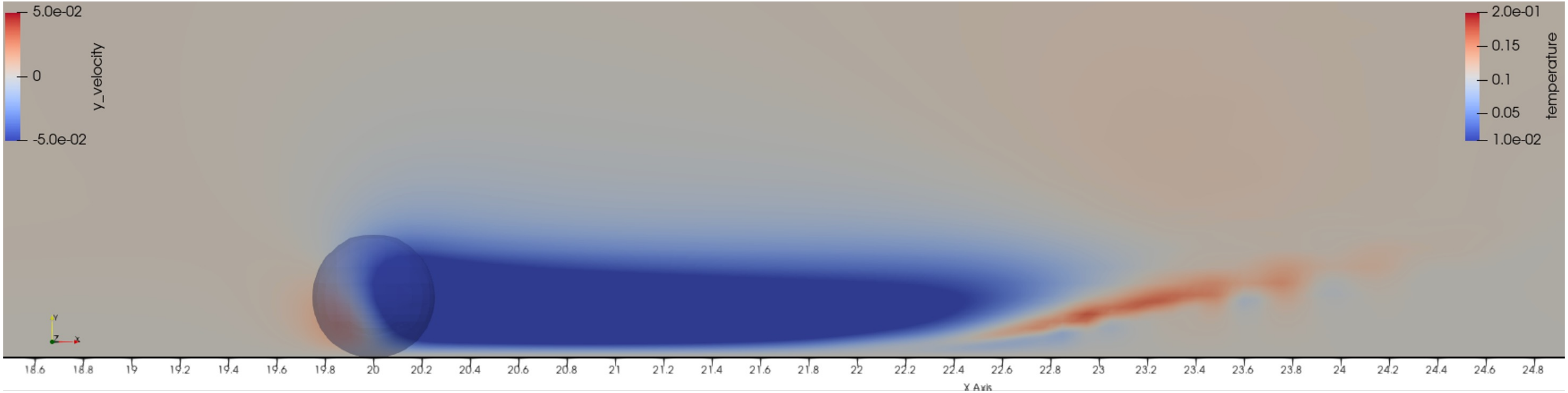
Experiment

Suzen & Huang Model

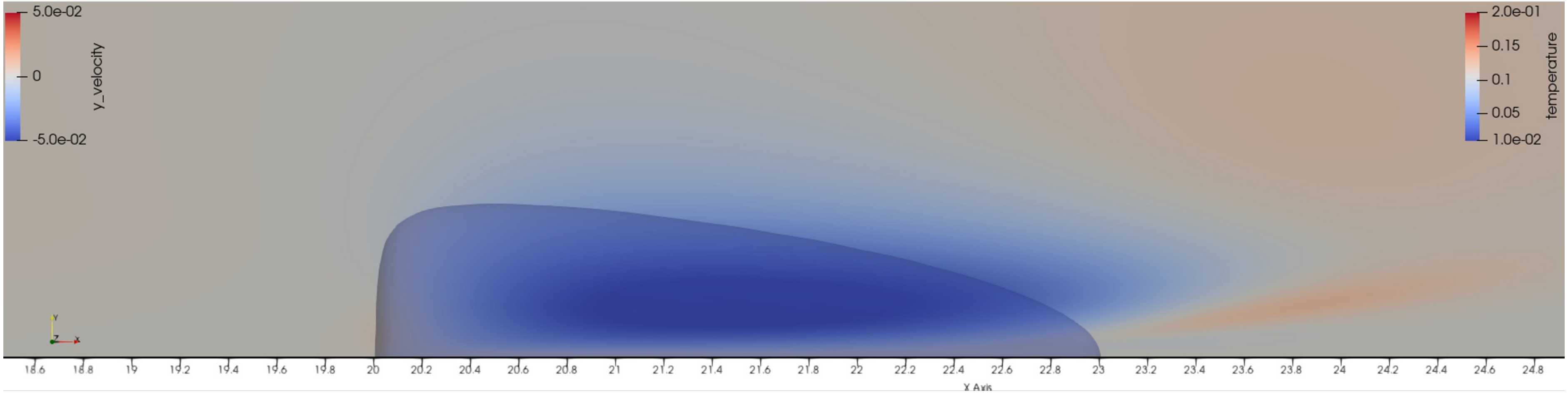
Figure 7. Spatial distribution of the wall-parallel (left) and wall-normal (right) components of the forcing term from the experimental data (top), from the Suzen & Huang model (bottom).

*Brauner, T., Laizet, S., Benard, N. and Moreau, E., 2016. Modelling of dielectric barrier discharge plasma actuators for direct numerical simulations. In *8th AIAA Flow Control Conference* (p. 3774).

Gaussian Jet: Mid-plane Wall-Normal Velocity



Gamma Jet: Mid-plane Wall Normal Velocity



Optimal Output Tracking Control

$$U_k^* = \underset{U_k}{\operatorname{argmin}} \quad \|y(k+N|k) - y_{\text{des}}(k+N|k)\|_P^2 + \sum_{i=k}^{k+N-1} \|u(i|k)\|_R^2 + \|y(i|k) - y_{\text{des}}(i|k)\|_Q^2$$

Optimal Control Inputs
Jet Magnitude

Minimize Control Effort

Maximize Downwash

We need a model for predicting the downwash for a given input

Optimal Output Tracking Control

$$U_k^* = \underset{U_k}{\text{argmin}} \quad \|y(k+N|k) - y_{\text{des}}(k+N|k)\|_P^2 + \sum_{i=k}^{k+N-1} \|u(i|k)\|_R^2 + \|y(i|k) - y_{\text{des}}(i|k)\|_Q^2$$

$$\text{subject to} \quad \begin{aligned} & z(i+1|k) = Az(i|k) + Bu(i|k) \\ & y(i|k) = Cz(i|k) \\ & 0 \le u(i|k) \le 1 \\ & z(k|k) = z(k) \end{aligned}$$

Optimal Control Inputs
Jet Magnitude

Minimize Control Effort

Maximize Downwash

ROM Dynamics
+
Input Constraints

We need a model for predicting the downwash for a given input

Sparsity-Promoting DMD with Control

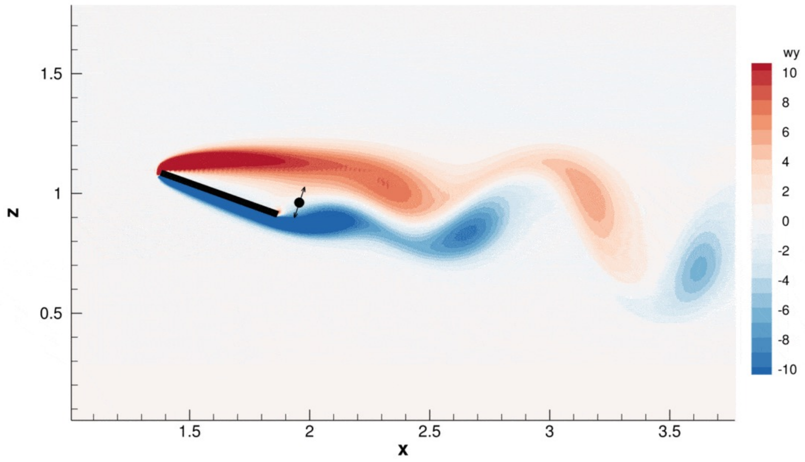
DMDc Reduced-Order Model:

$$\psi_{k+1} = \Lambda \psi_k + \Gamma \mathbf{u}_k$$
$$\mathbf{y}_k \approx \Phi \psi_k$$

Sparsity-Promoting Optimization:

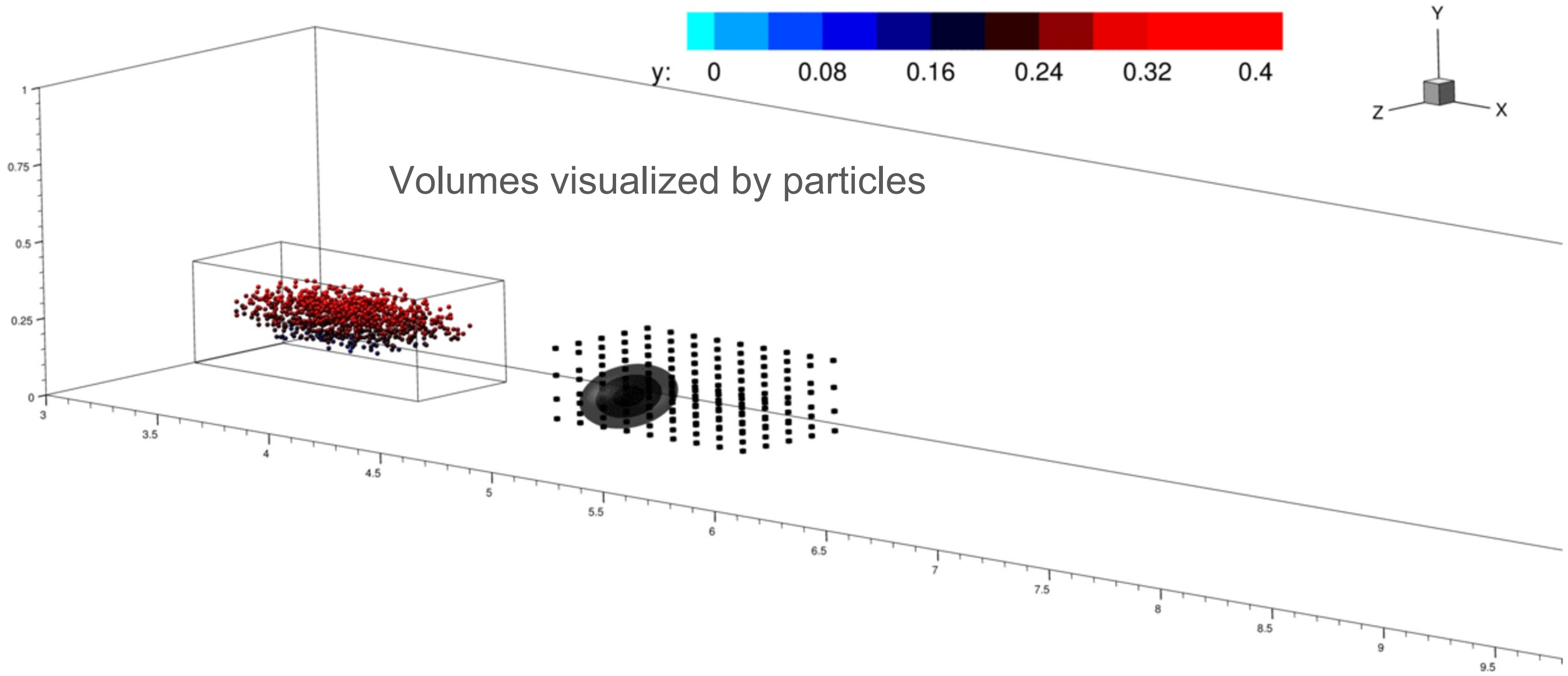
$$\min_{\boldsymbol{\alpha}} \|\mathbf{Y}' - \Phi \mathrm{diag}\{\alpha\} \mathbf{R}\|_F^2 + \varepsilon \|\boldsymbol{\alpha}\|_0$$

Use reweighted L1 norm instead



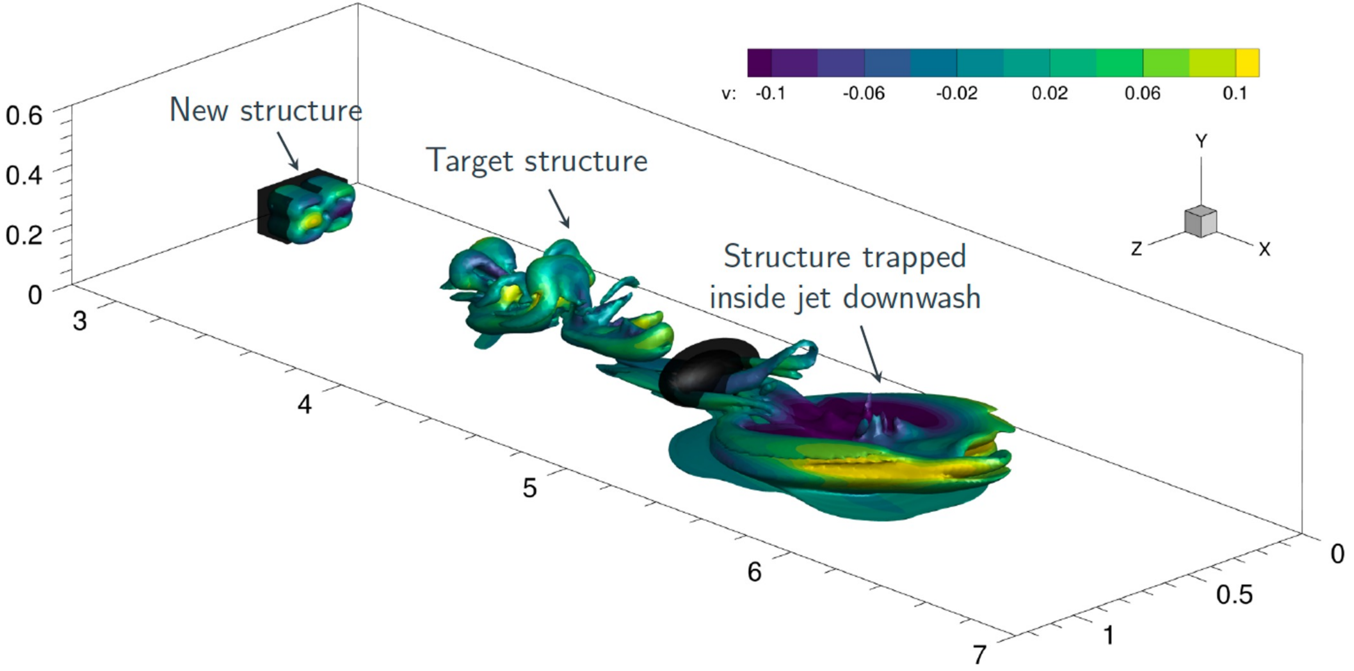
Tsolovikos et al., Estimation and Control of Fluid Flows Using Sparsity-Promoting Dynamic Mode Decomposition, IEEE Control Systems Letters, 2021

Control of Fluid Volumes | Laminar Boundary Layer

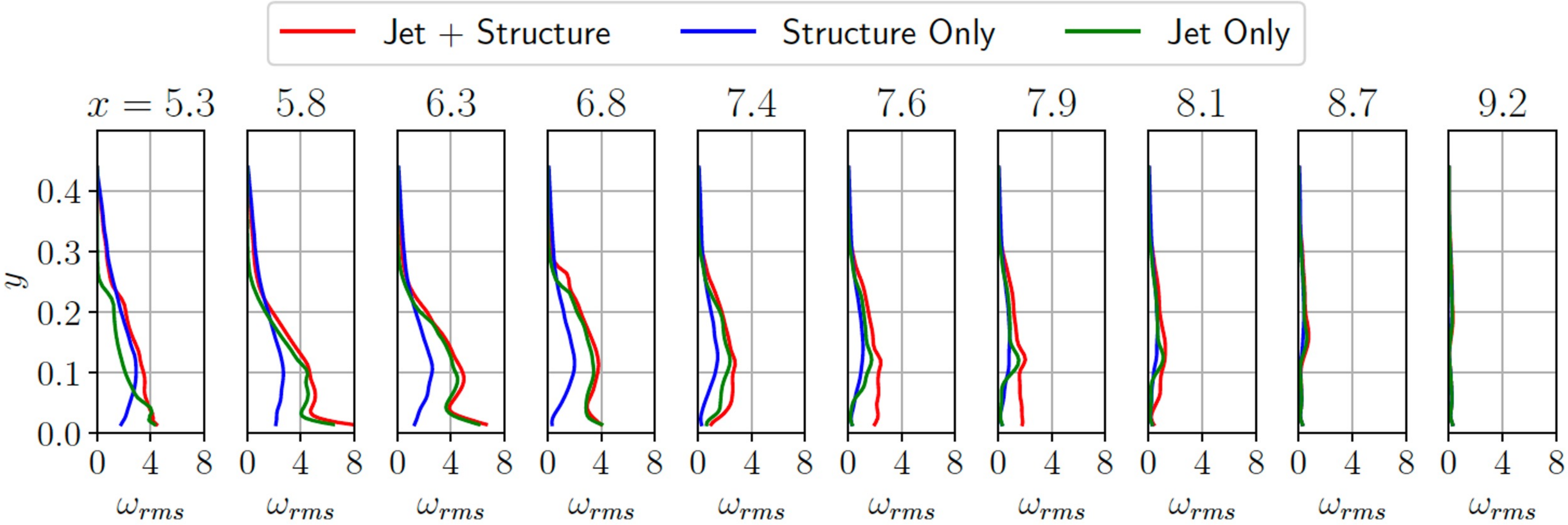


Tsolovikos et al., Model Predictive Control of Material Volumes with Application to Vortical Structures, AIAA Journal, 2021

Control of Synthetic LSMs | Laminar Boundary Layer

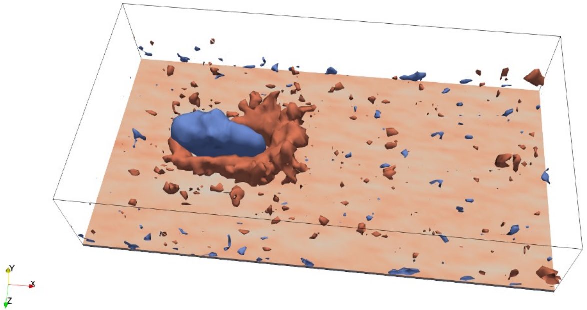


Control of Synthetic LSMs

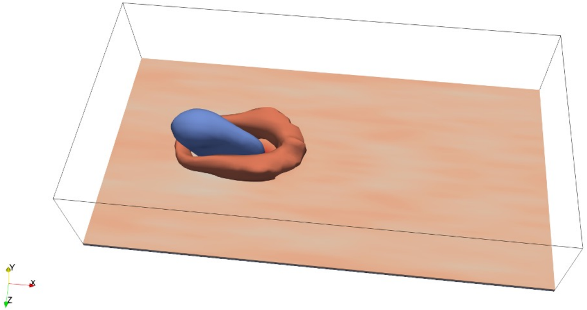


Change in **Vorticity Fluctuation RMS** when targeting a synthetic LSM

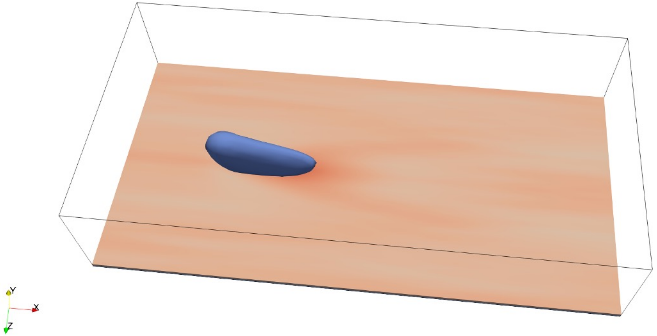
Reduced-Order Models for Downwash Prediction



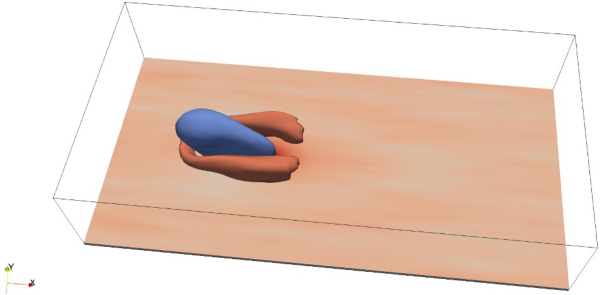
DNS
Ensemble
Average



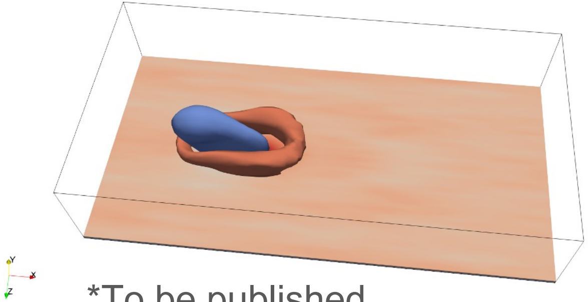
Best POD
Projection



DMDc



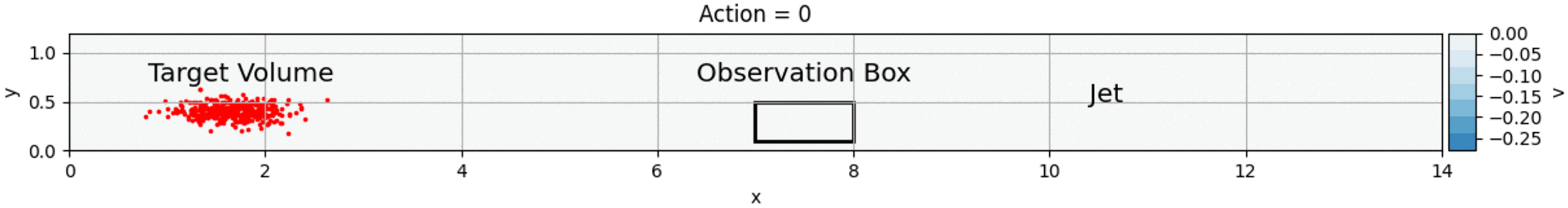
tlsDMDc



tlsDMDc + GP*

*To be published

Reinforcement Learning (No Model Needed)



Proximal Policy Optimization with LSTM policy and discrete actions (jet is on/off)

Next Steps

- LSMs in an **adverse pressure gradient** turbulent boundary layer
- MPC control of LSMs for **separation delay**
- Large-eddy simulations to speed up computations
- **Dynamic Mode Decomposition + Gaussian Processes** for more accurate flowfield predictions
- **Reinforcement learning** for LSM control

alextsolovikos.github.io