Control of Large-Scale Motions in Boundary Layers

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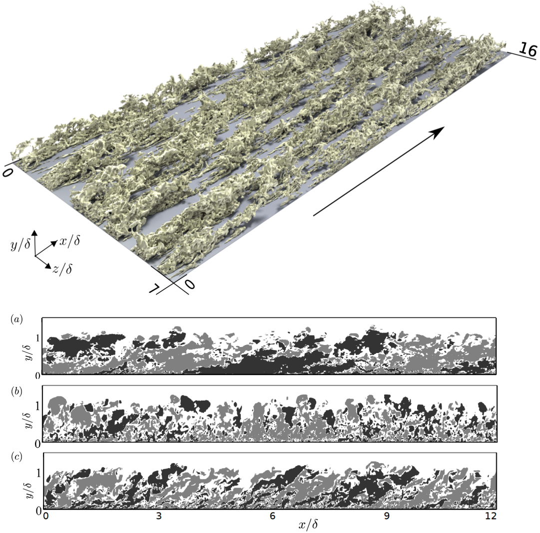
Phoenix, AZ, November 22, 2021

In collaboration with: cfpl Computational Fluid Physics Lab, Rensselaer

Supported by: NSF, Onassis Foundation

What is a Large-Scale Motion?

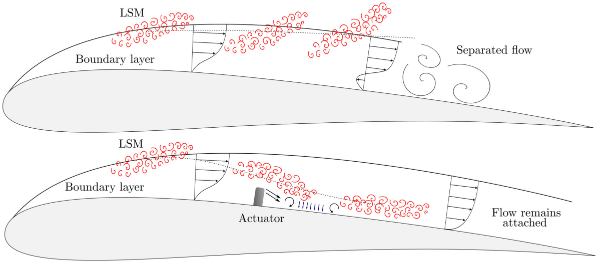
- Coherent motions in **wall-bounded** turbulent flows
- Characteristics:
  - Size in the order of the boundary layer thickness δ
  - Large fraction of the turbulent kinetic energy
  - Significant contribution to average Reynolds shear stresses
- Consist of smaller structures (e.g. hairpin vortices)



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

Targeting Large-Scale Motions for Performance Gains

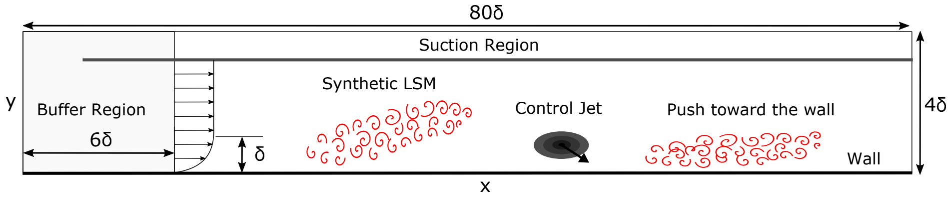
- Pushing LSMs away from the wall: drag reduction[a]
- **Pushing LSMs toward the wall:** mixing enhancement → boundary layer re-energization → separation delay



[a] Abbassi et al., "Skin-friction drag reduction in a high-Reynolds-number turbulent boundary layer via real-time control of large-scale structures".

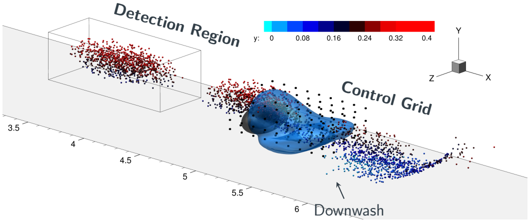
Targeting Large Scale Motions for Performance Gains

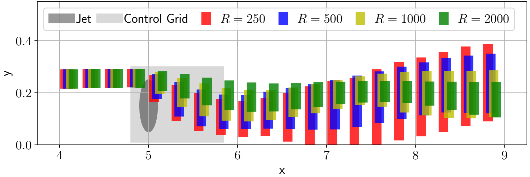
- **Can we target and move LSMs toward the wall?**
- **Can we increase mixing?**
- Numerical Experiments:
  - Generate **synthetic LSMs** in a Direct Numerical Simulation
  - Use a **Gaussian jet** force field to push them toward the wall



An LSM as a Material Volume*

- Approximation:
  - Target a **passive material volume** in a **Blasius** boundary layer
- **Model-based controller**:
  - Model the flow with Dynamic Mode Decomposition
  - Mark targets with Gaussian mixture
  - Use model predictive control to maximize downwash at LSM
- Result:
  - Particles move closer to the wall (on average)

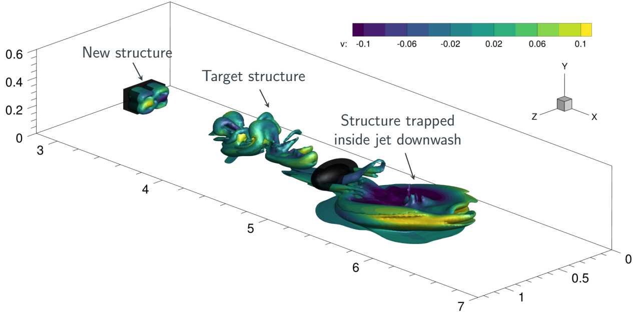


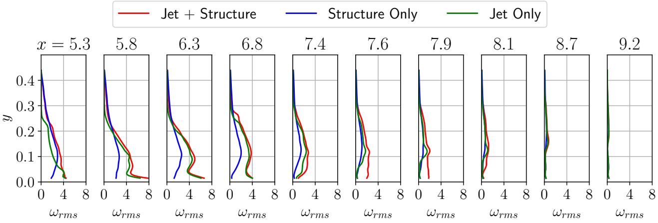


*Tsolovikos et al., "Model Predictive Control of Material Volumes with Application to Vortical Structures".

An LSM as a Weak Disturbance†

- Approximation:
  - Target a **weak vortical structure** (disturbance) in a **Blasius** boundary layer
- Control objective:
  - Maximize the downwash the target structure sees
- Result:
  - Near-wall vorticity RMS (proxy for turbulent mixing) increases

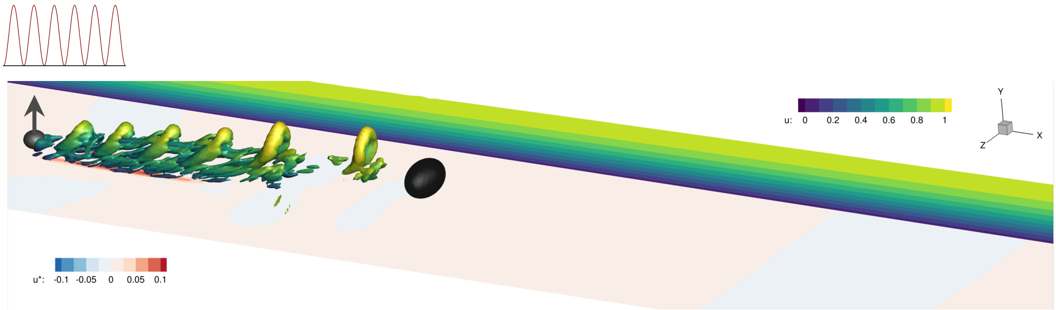




†Tsolovikos et al., "Model Predictive Control of Material Volumes with Application to Vortical Structures".

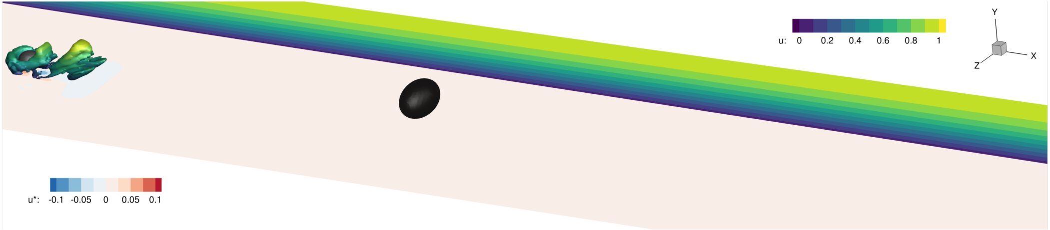
An LSM as a Series of Hairpin Vortices

- Approximation:
  - Target a series of **hairpin vortices** in a **Blasius** boundary layer
- Control objective:
  - Maximize the downwash the target hairpins see

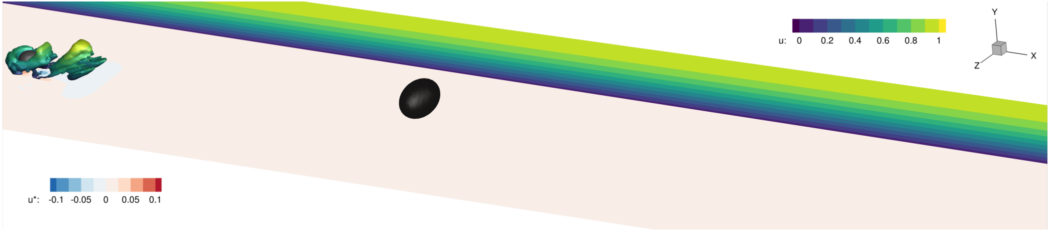


An LSM as a Series of Hairpin Vortices

Without Control

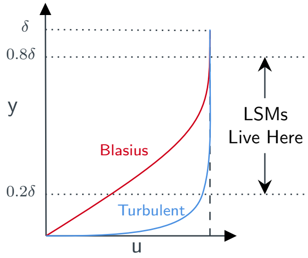


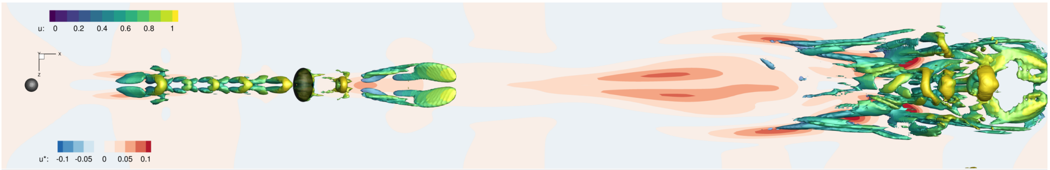
With Control



Issues: Disturbances in Laminar Boundary Layers Turn into Spots

- A Blasius boundary layer is inherently unstable
- Large shear in the outer region compared to turbulent boundary layers
- Is a slip-wall laminar flow better for approximating an LSMs in a turbulent boundary layer?





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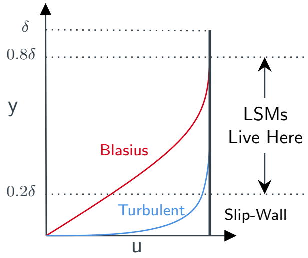
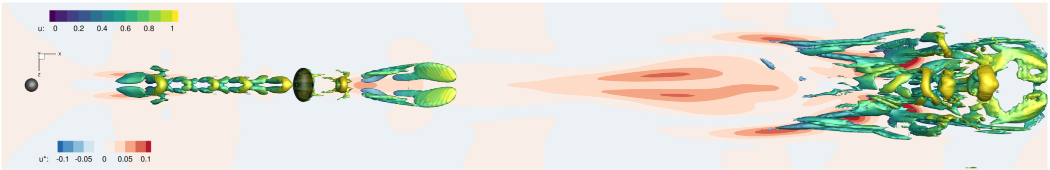
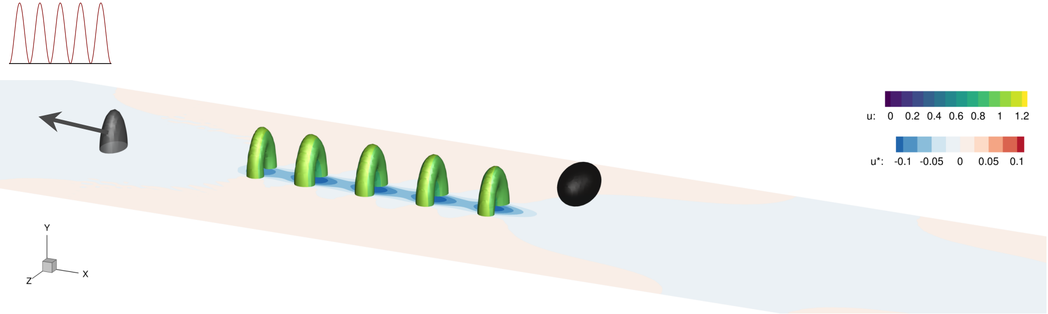




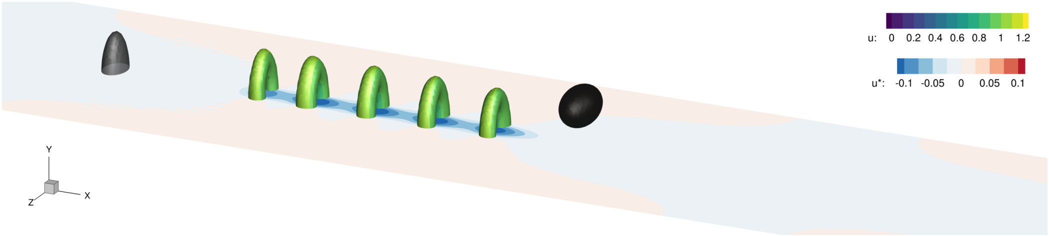
Slip-Wall Laminar Flow: A Better Approximation?

- Approximation:
  - Target a series of half-ring vortices in a slip-wall laminar flow
- Control objective:
  - Maximize the downwash that the rings see

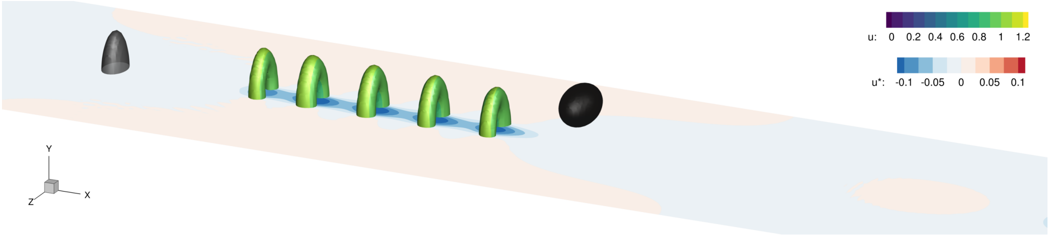


Slip-Wall Laminar Flow: A Better Approximation?

Without Control



With Control



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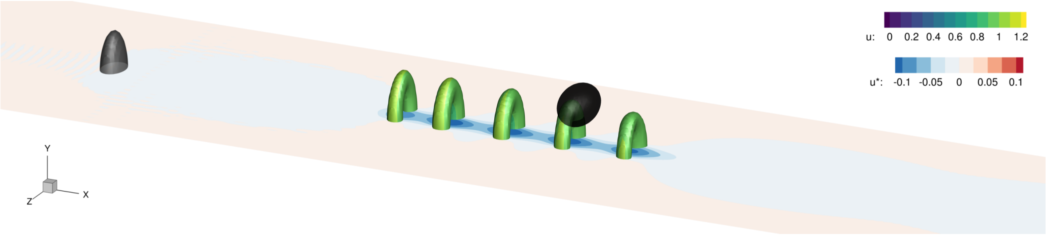

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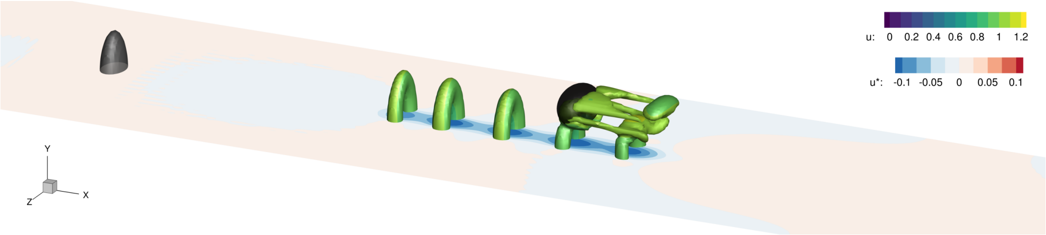

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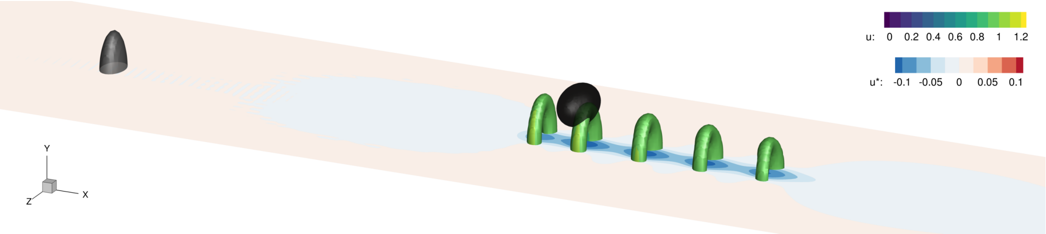

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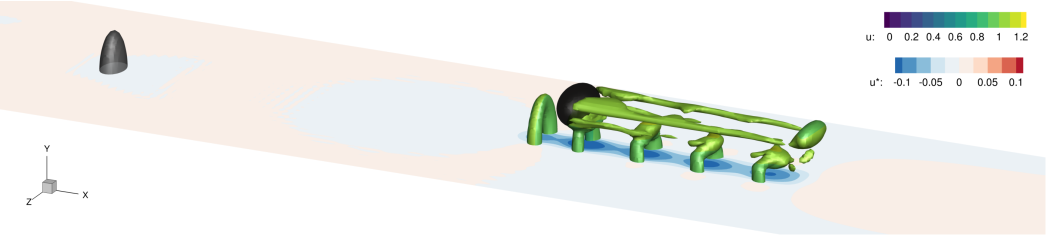

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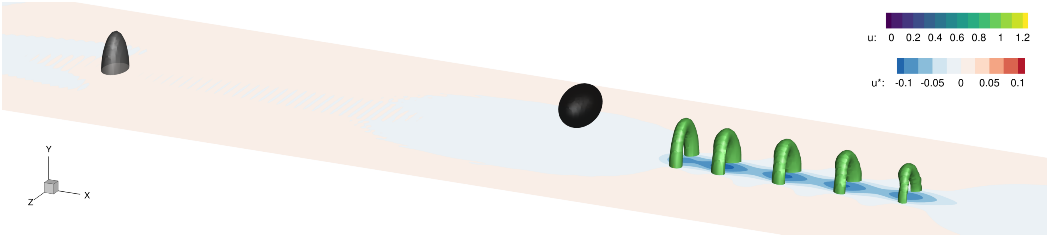

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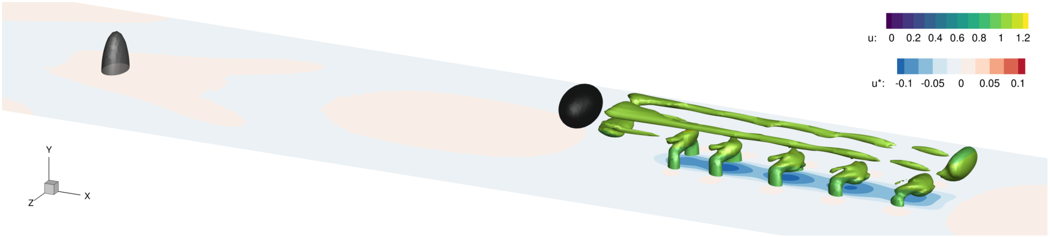
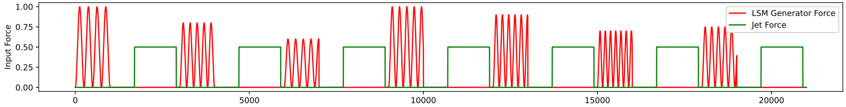
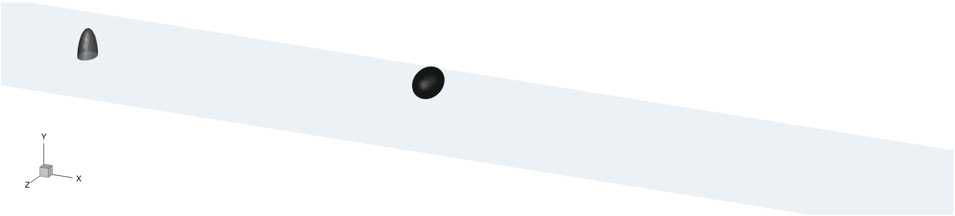


Moving Vortical Structures in Slip-Wall Laminar Flows

- Experiment: Create and target a series of synthetic LSMs
- Goal: Move LSMs closer to the wall

LSM + Jet





Moving Vortical Structures in Slip-Wall Laminar Flows

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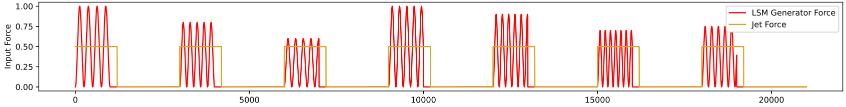
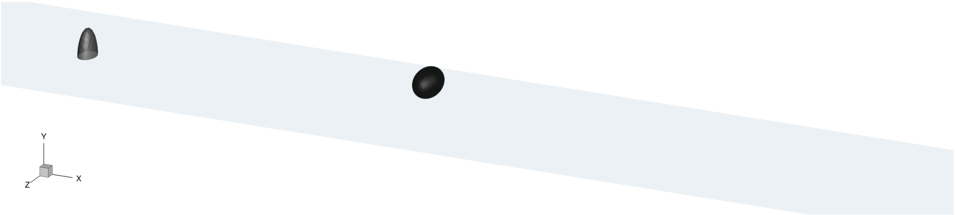
LSM + Asynchronous Jet (Blind Actuation)

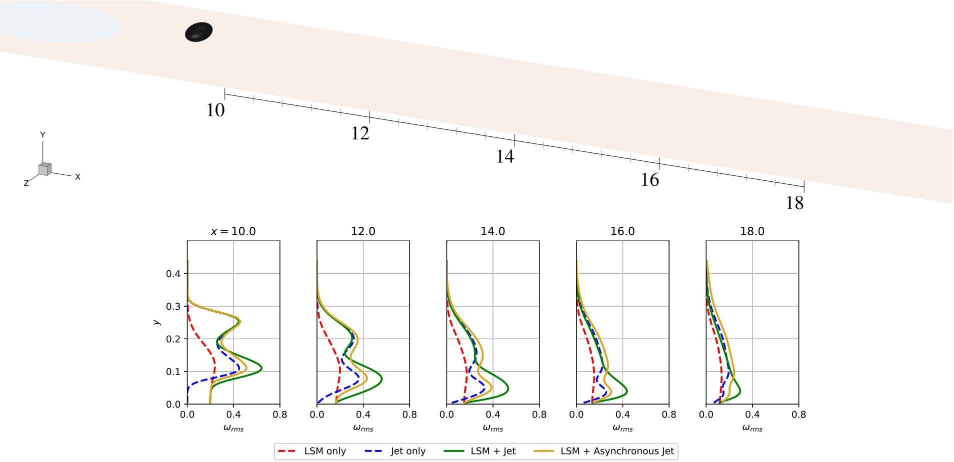




Moving Vortical Structures in Slip-Wall Laminar Flows

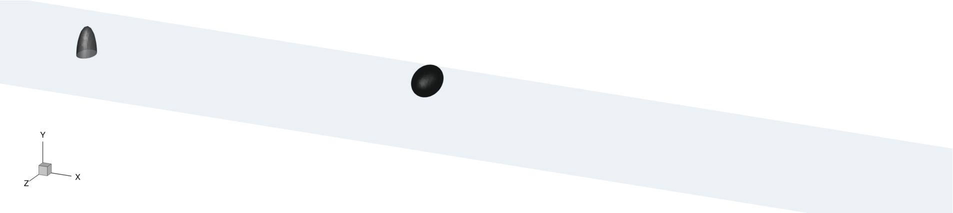
- Proxy for turbulent mixing: Vorticity fluctuation RMS

$$\omega_{RMS}(x_i,y)=\sqrt{\frac{1}{T\times 5\delta}\int_{t=0}^{t=T}\int_{z=0}^{z=5\delta}(\|\omega'\|_2^2)dzdt}$$



Conclusions and Future Work

- Sucessfully targeted:
  - Material Volumes (Blasius)[a]
  - Weak Disturbances (Blasius)
  - Series of Hairpins (Blasius)
  - Series of Half-Rings (Slip-Wall)
- Results: **By targeting LSMs, near-wall mixing increases**
- Next: Model-based bontrol of LSMs in a **turbulent boundary layer**



alextsolovikos.github.io

[a] Tsolovikos et al., "Model Predictive Control of Material Volumes with Application to Vortical Structures".

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