Soutenance d'Habilitation à Diriger des Recherches / HDR Defense

Diving into the Complexities of Multi-Scale Wall-Bounded Turbulence Dynamics

Lionel Agostini

18 November 2024

RÉPUBLIQUE FRANÇAISE
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1431 Université de Poitiers
Institut Pprime

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Jury:

Dr. Bérengère Podvin

Prof. Jean-Christophe Robinet

Prof. Nicholas Hutchins

Prof. Jacques Borée

Dr. Laurent Cordier

Prof. Sergei Chernyshenko

Prof. Michael Leschziner

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Shock-wave turbulent boundary layer interaction

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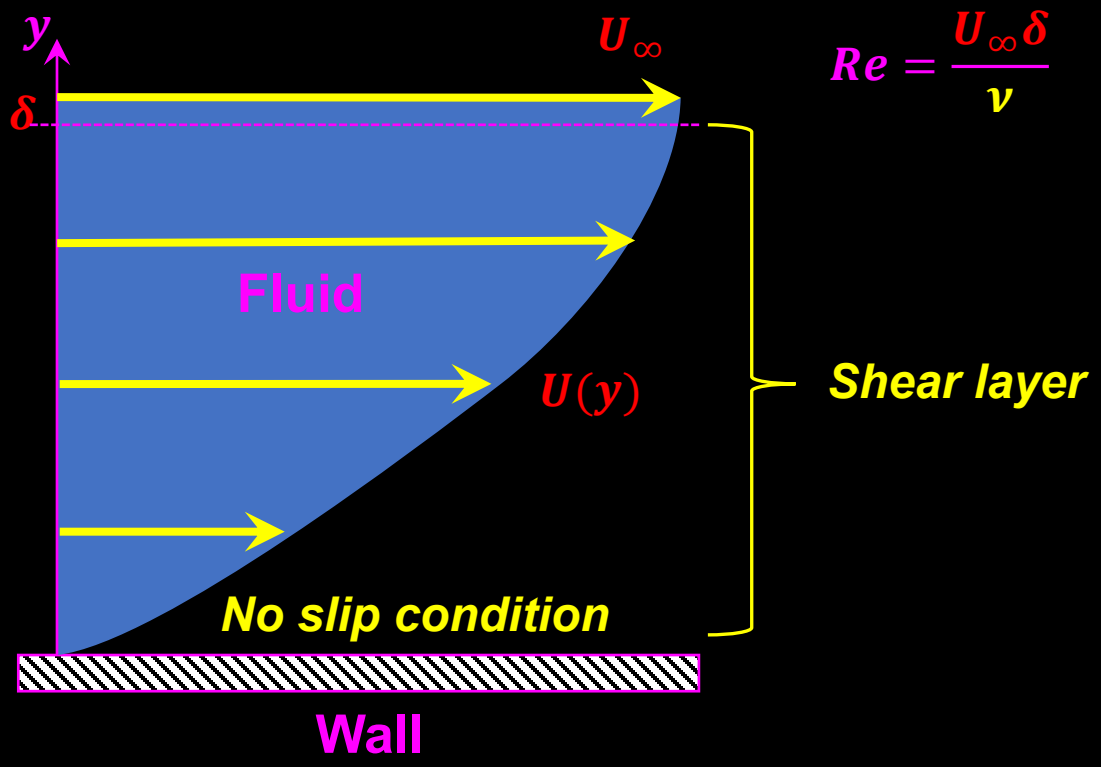
Introduction to Near-wall turbulence
Laminar wall-bounded flow



Reynolds Number

$$Re = \frac{U_\infty \delta}{\nu}$$

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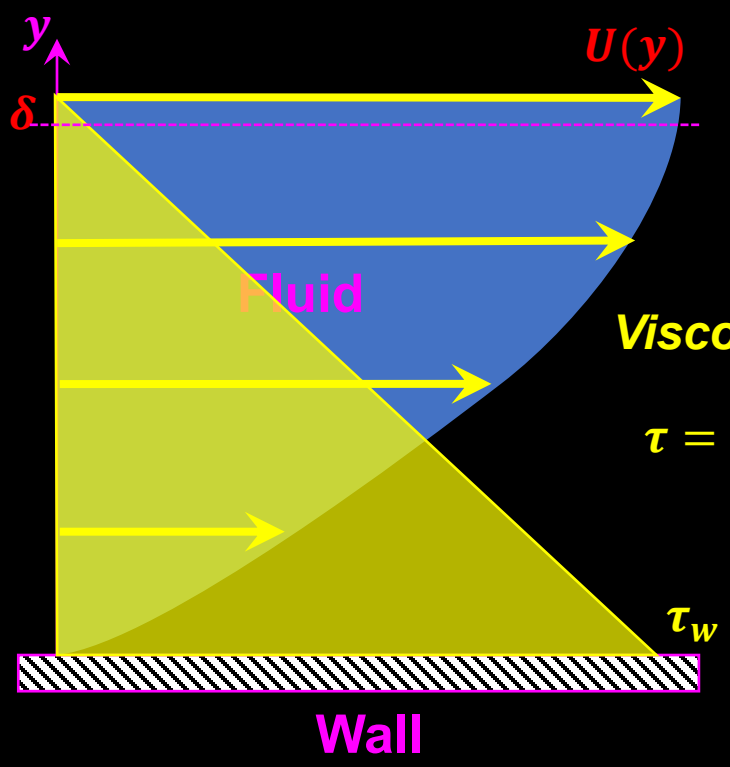

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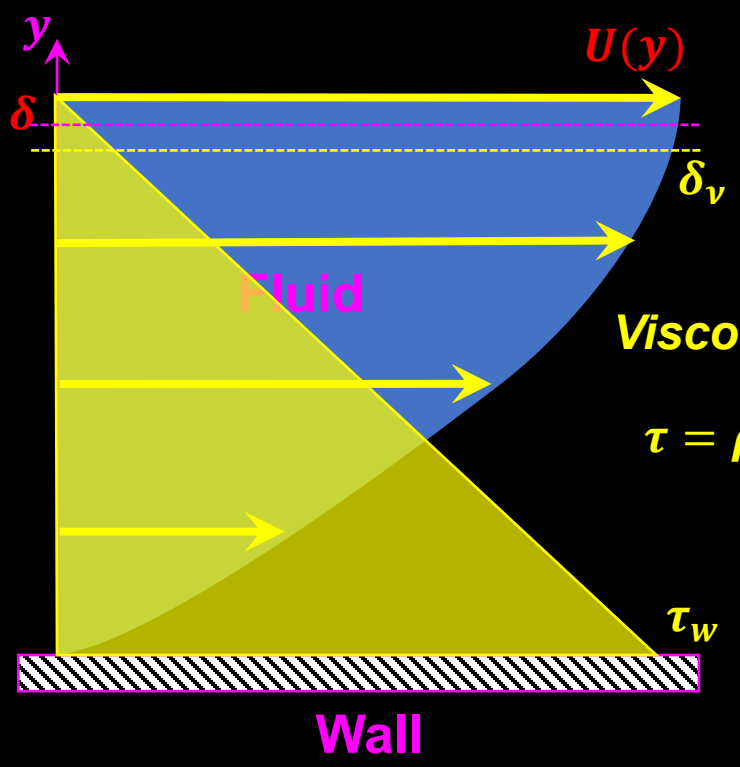

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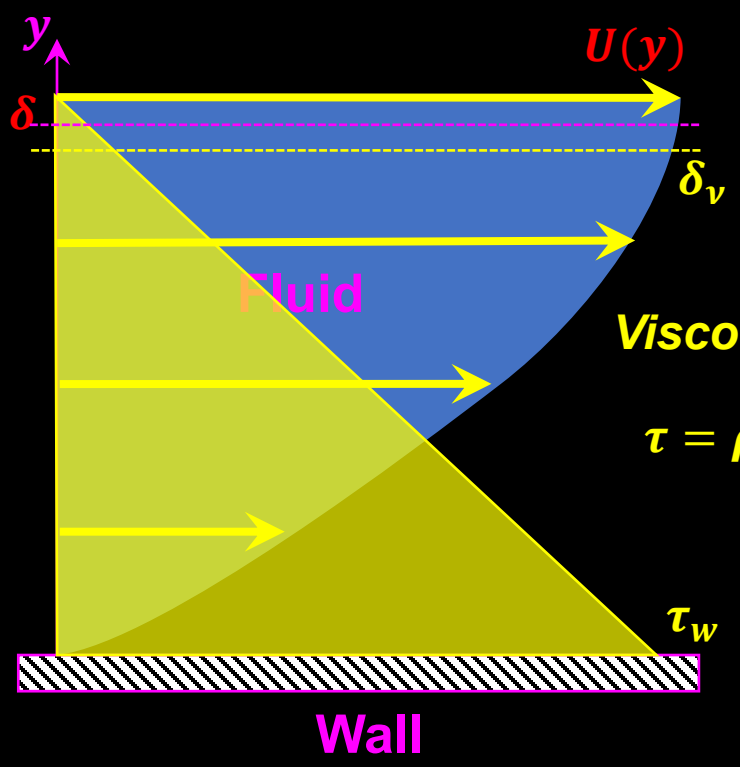
$$\partial_t \boldsymbol{u}^+ + (\boldsymbol{u}^+ . \nabla)\boldsymbol{u}^+ = -\nabla p + \frac{1}{Re_\tau}\Delta \boldsymbol{u}^+$$

$$with\ \boldsymbol{u}^+ = \frac{u}{u_\tau}$$



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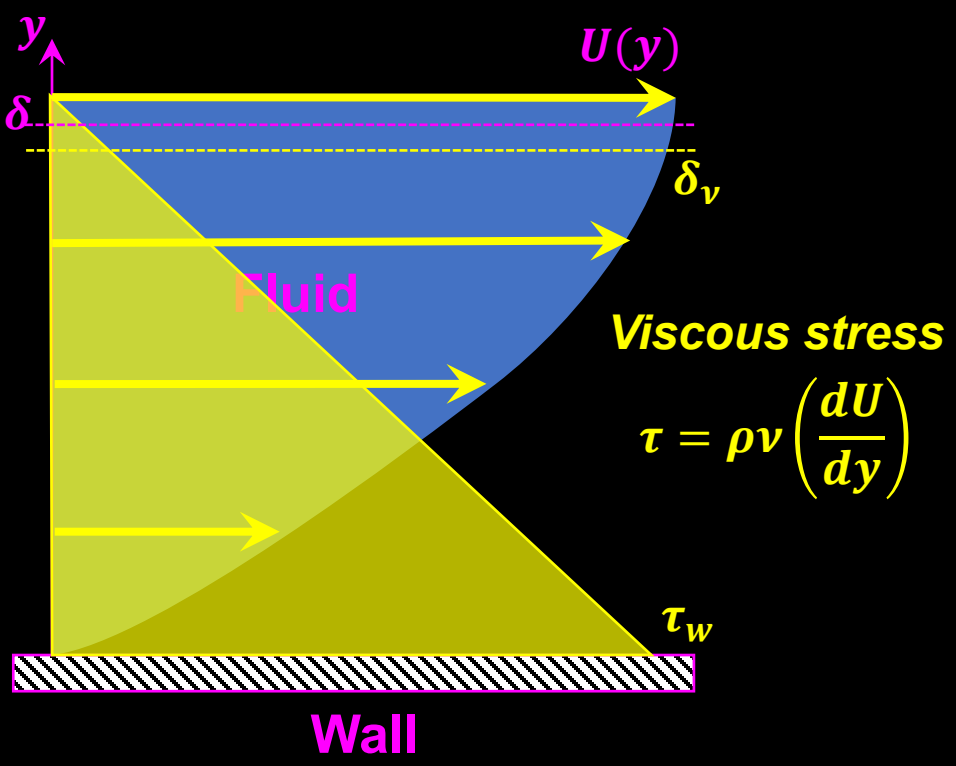

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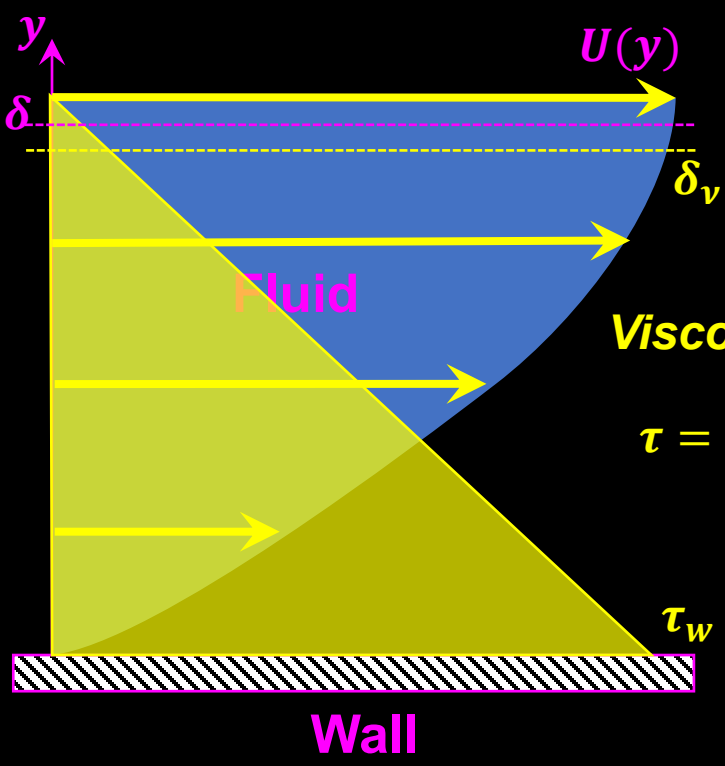

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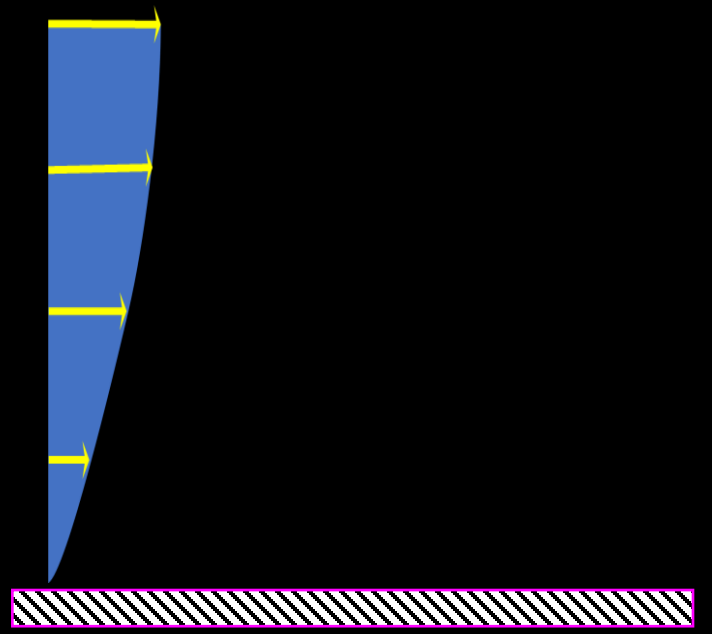

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Turbulent wall-bounded flow

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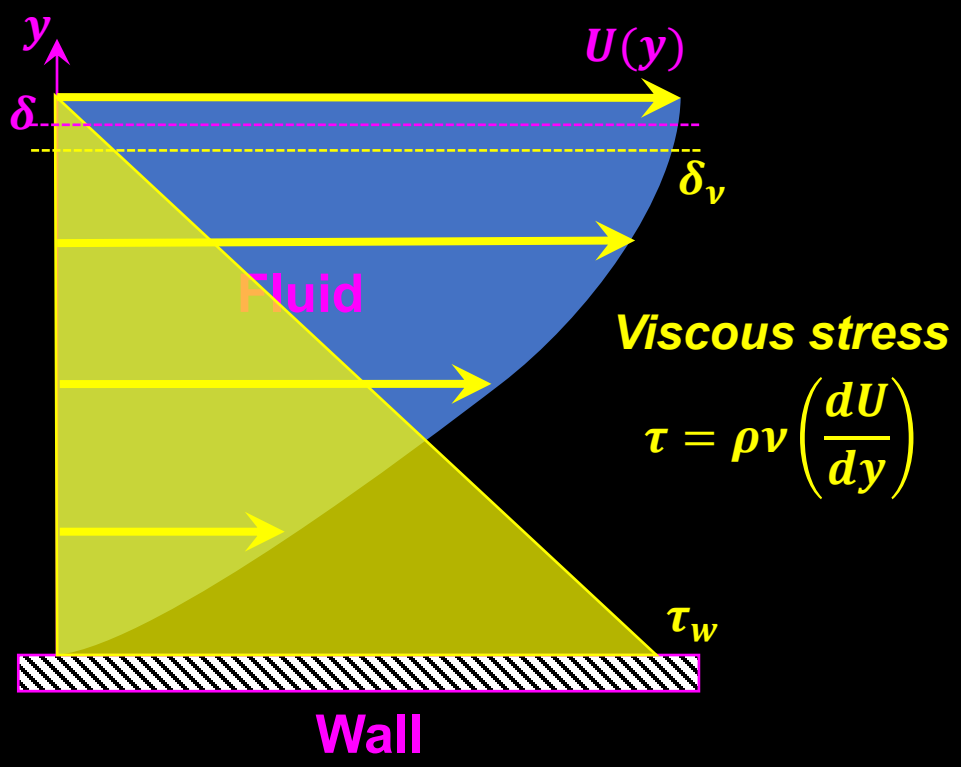
$Re_\tau \gg 1$ Turbulent ? ?



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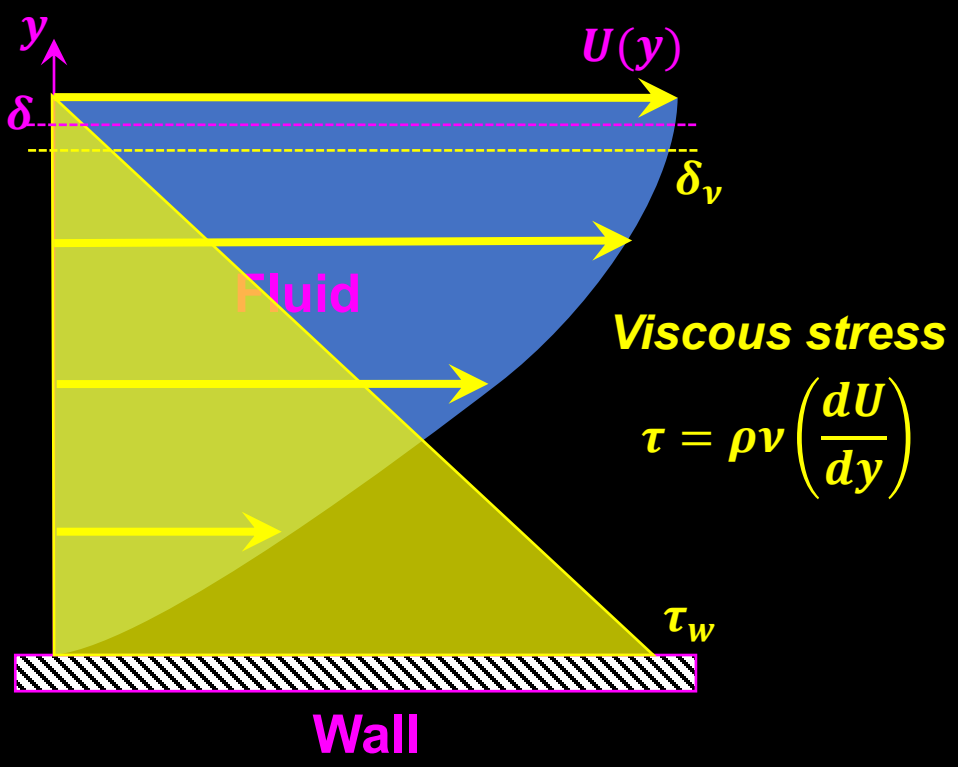

Spatially developing turbulent boundary layer on a flat plate.
Lee, J. H., Kwon, Y. S., Hutchins, N., & Monty, J. P.
arXiv preprint arXiv:1210.3881. (2012).

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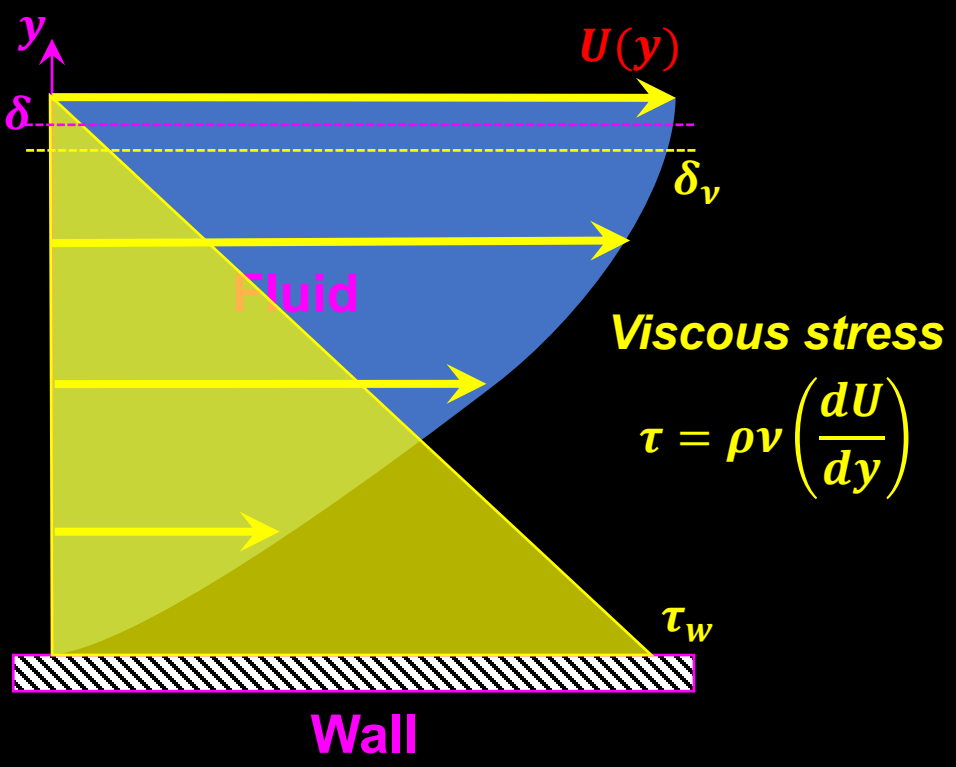

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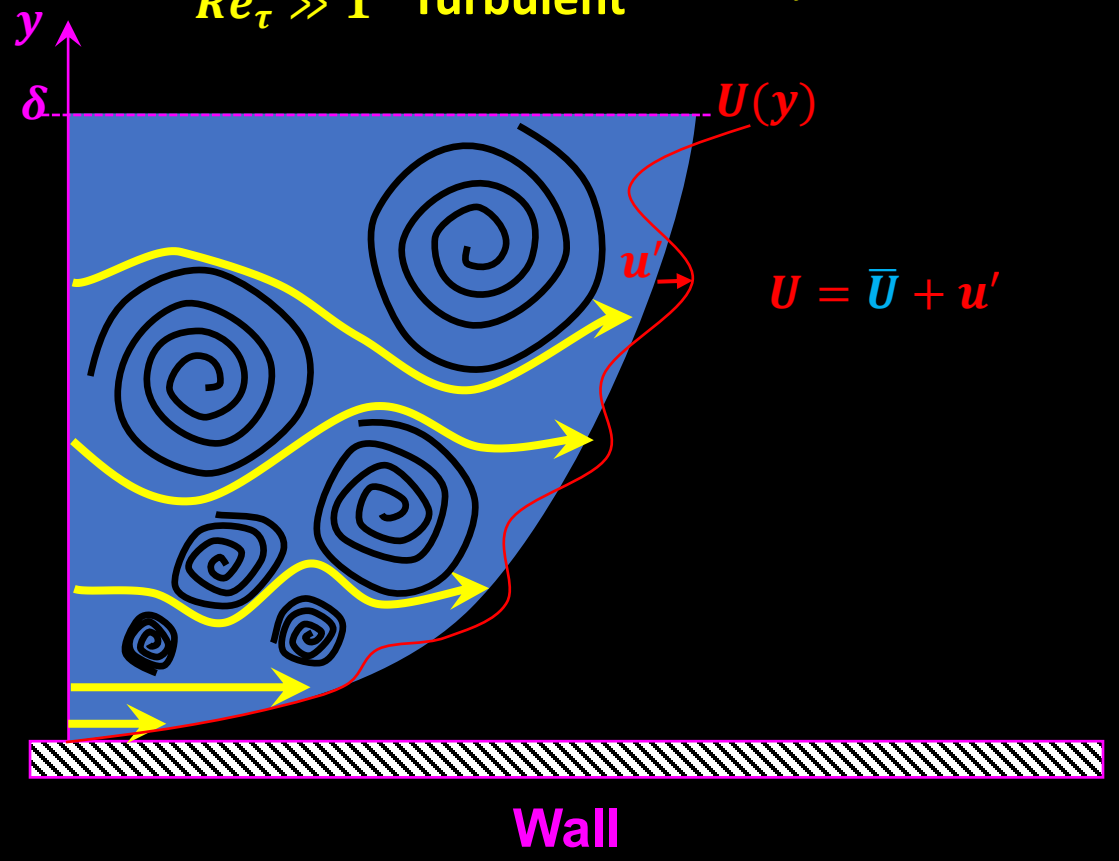

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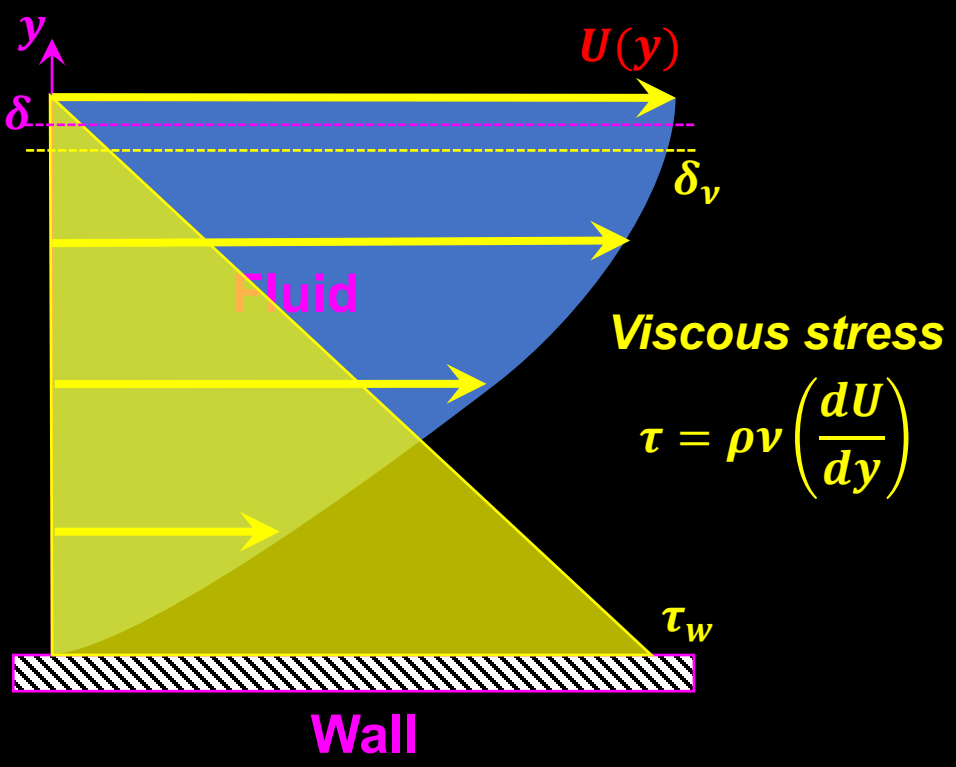

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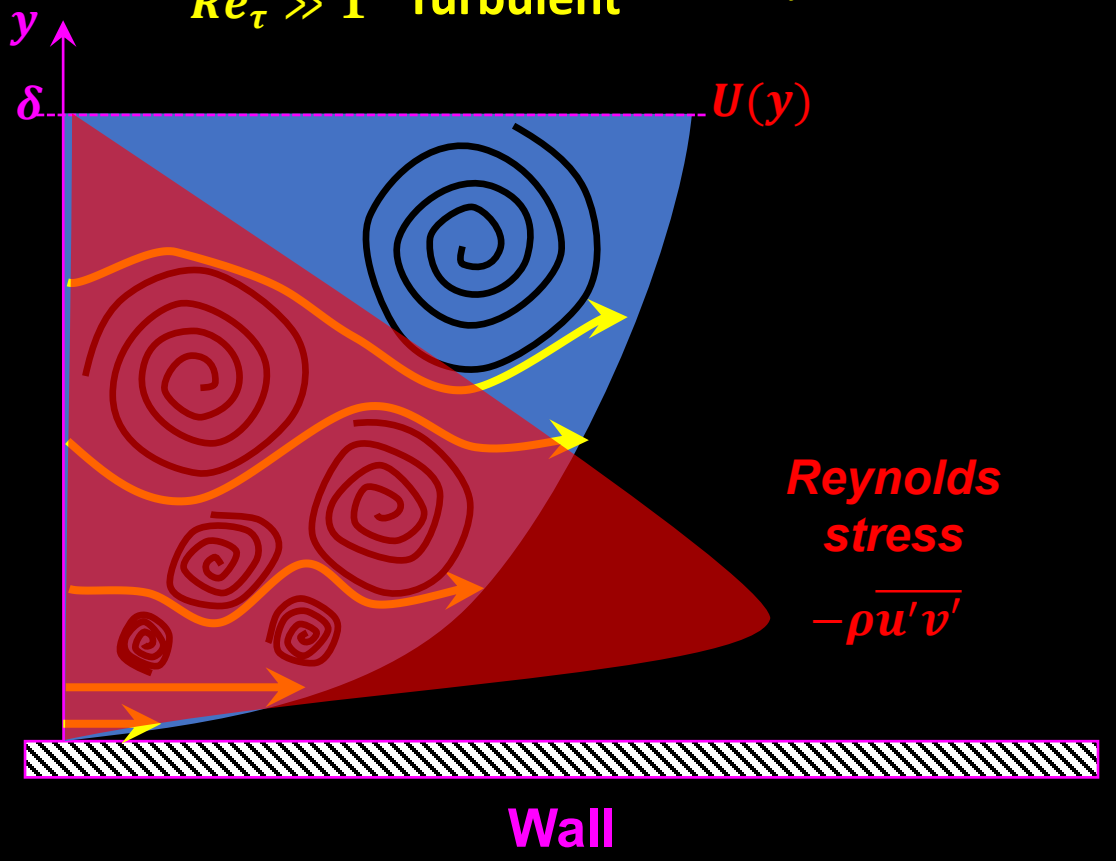

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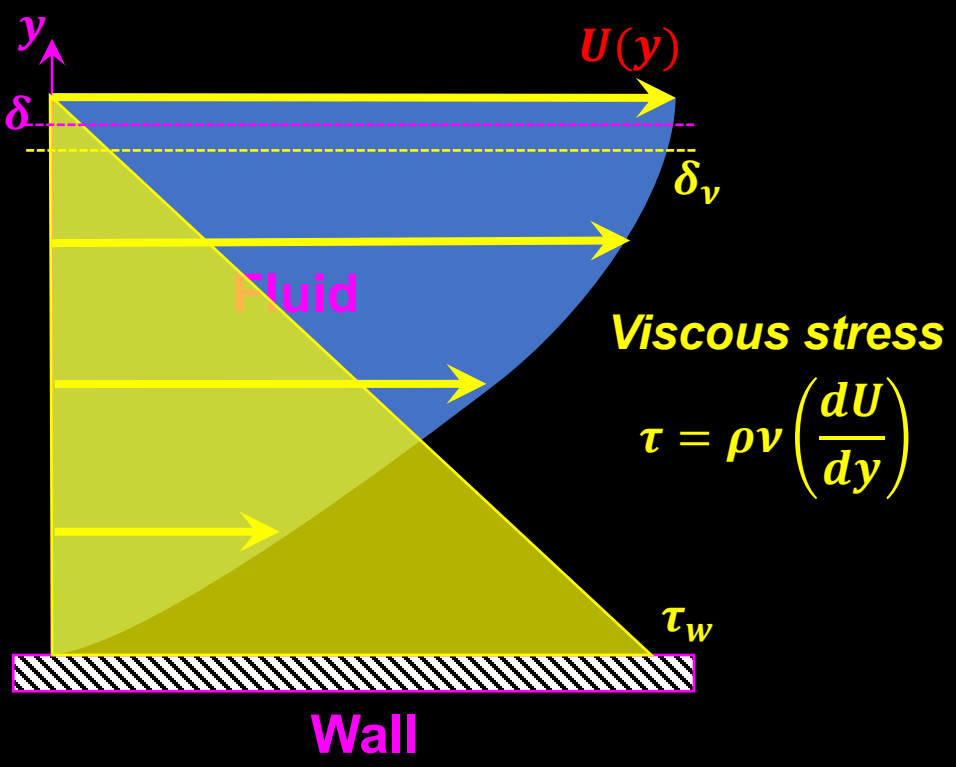

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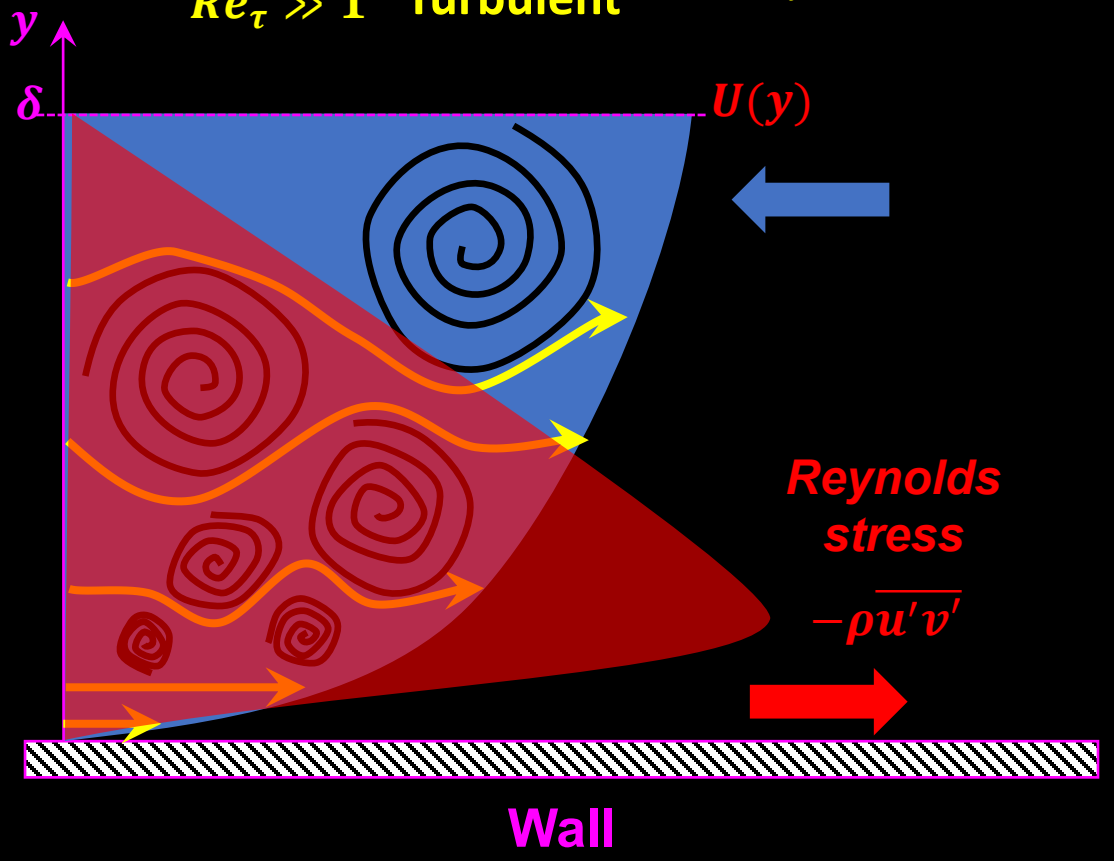

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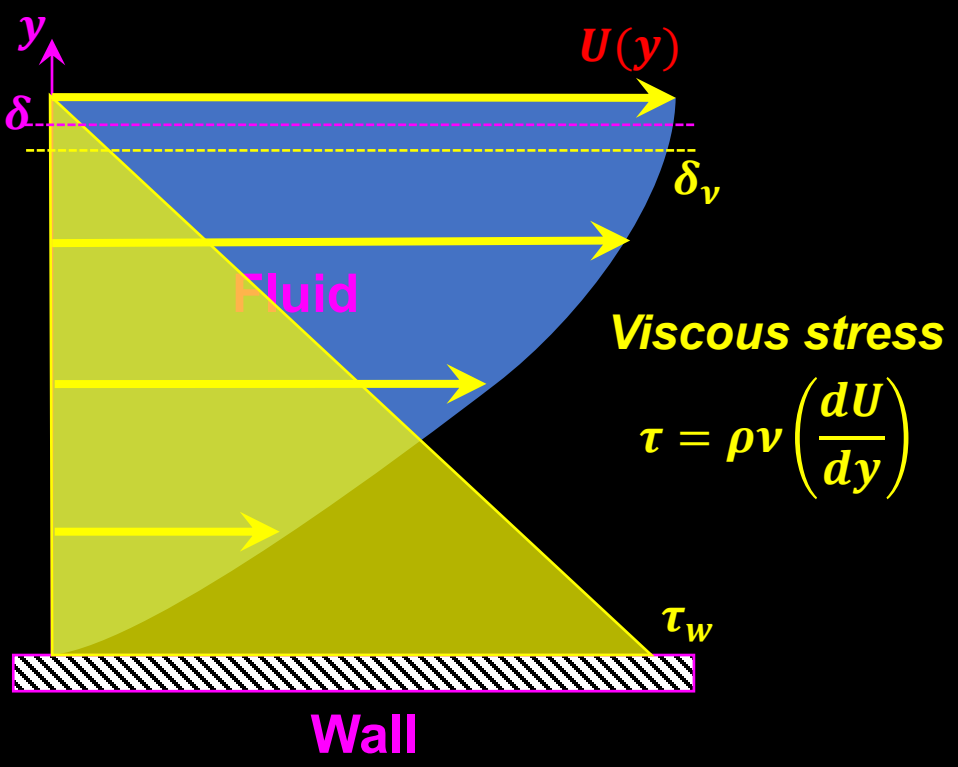

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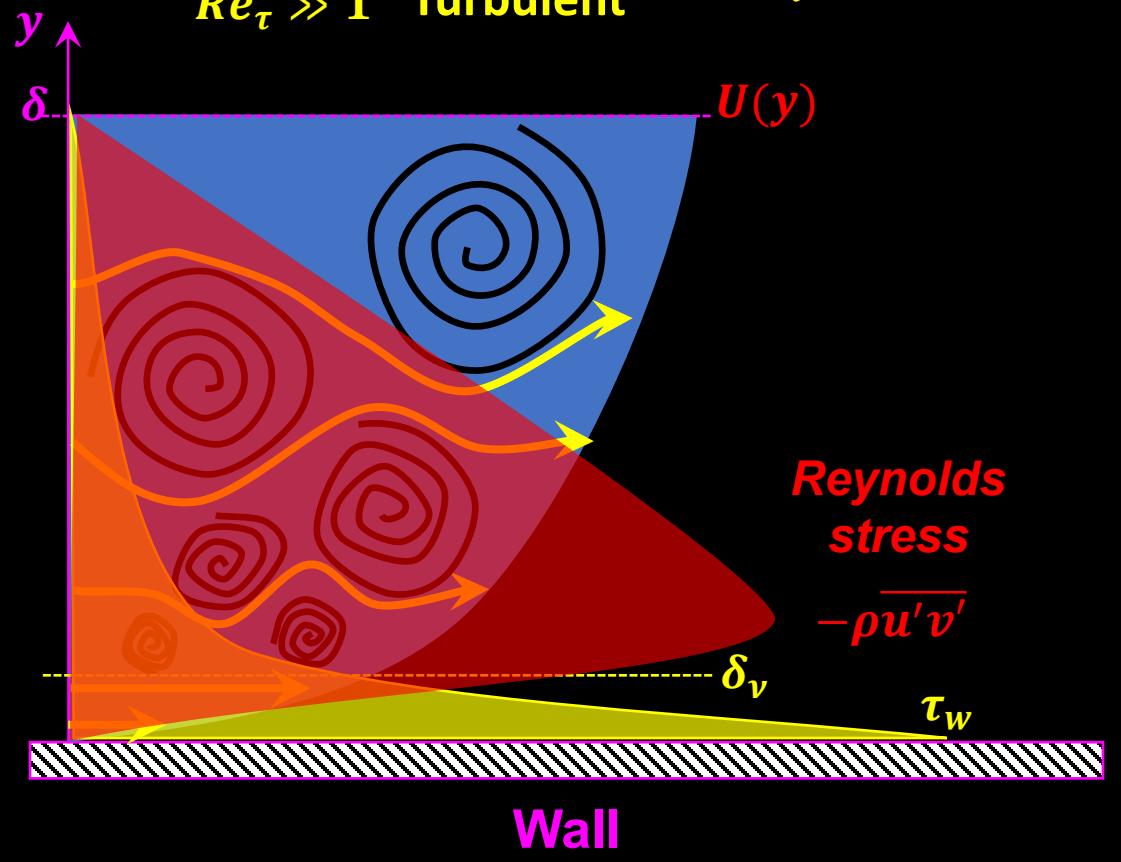

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Near-wall turbulence: From Understanding to Innovation

Motivation - Enhancement of energy efficiency

Drag Reduction

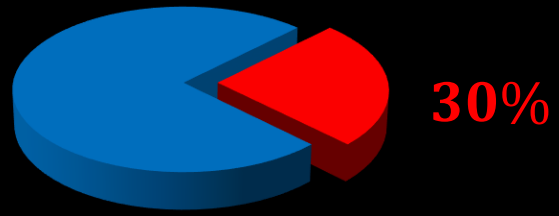
Transports

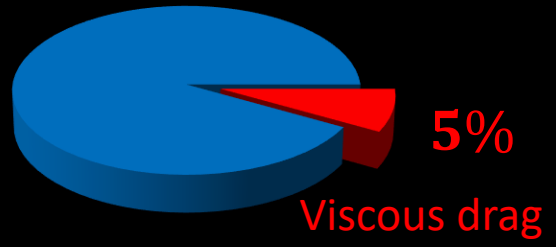



Drag
Energy consumption
Pollutant emissions $(C0_2, NO_x)$

Energy used by the industry

C02 emission





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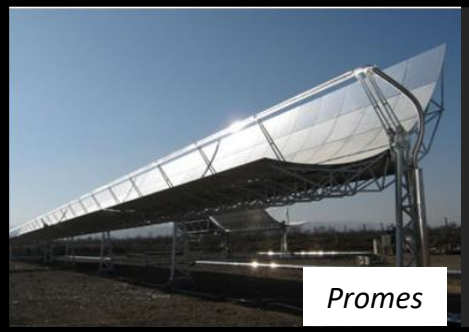
Drag ▭
Energy consumption
Pollutant emissions $(C0_2, NO_x)$

Improving Heat Exchanger

Development of solar energy



Engine Efficiency

Heat transfer

➕ / ➖

Optimal operating regime

Near-wall turbulence: From Understanding to Innovation

Motivation - Enhancement of energy efficiency

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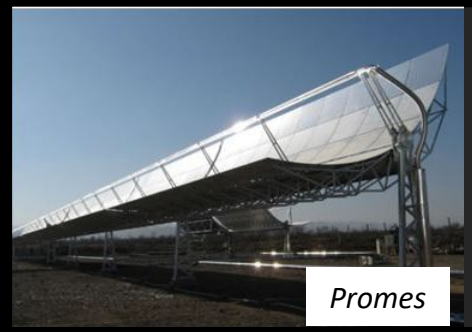
Transports




Improving Heat Exchanger

Development of solar energy



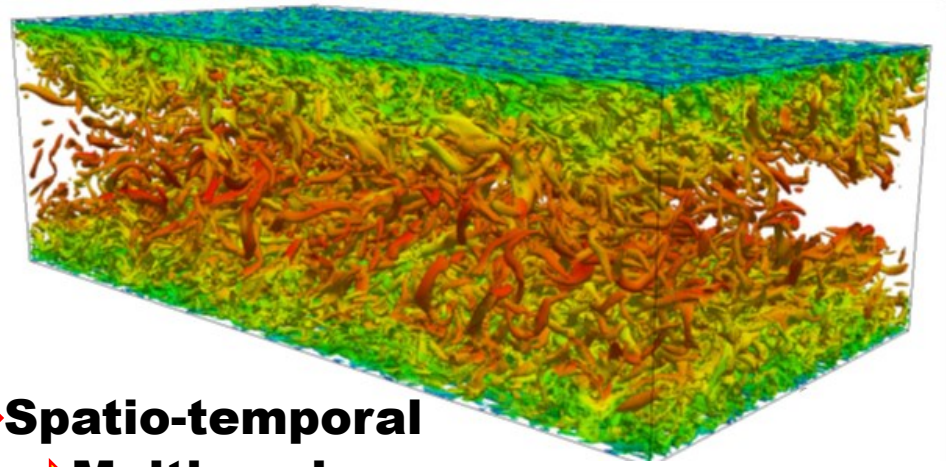
Engine Efficiency

Practical engineering applications and natural systems $Re_\tau \geq 75\,000$

- **Simulations: out of reach**
- **Experiments: under-resolved**

Introduction to Near-wall turbulence
Turbulent wall-bounded flow – Challenges ?

Channel flow at $Re_\tau \approx 590$



- **Spatio-temporal**
  - **Multi scales**
    - **High dimension**
      - **Strongly non linear**

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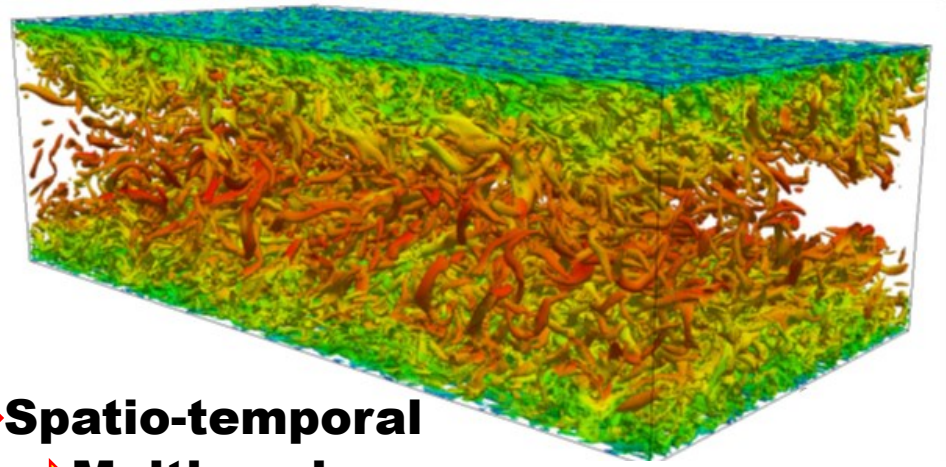

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Challenges :

- Identification
- Modelling
- Control

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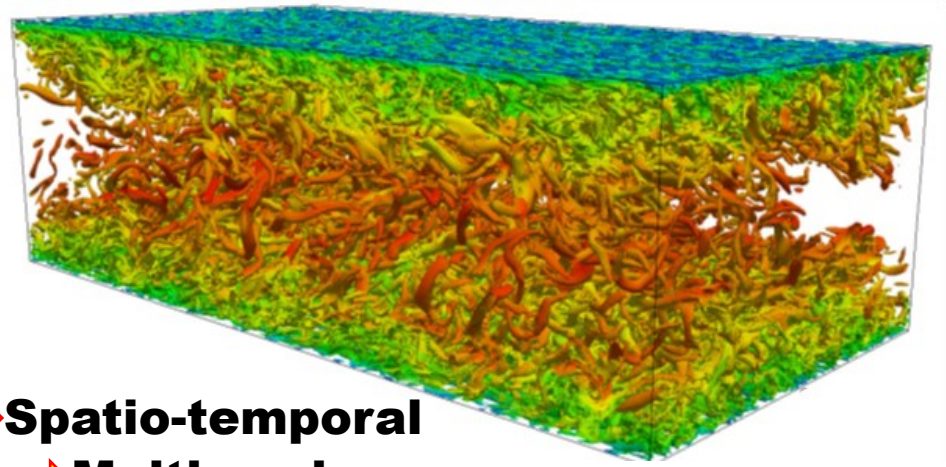

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Challenges :

- Identification
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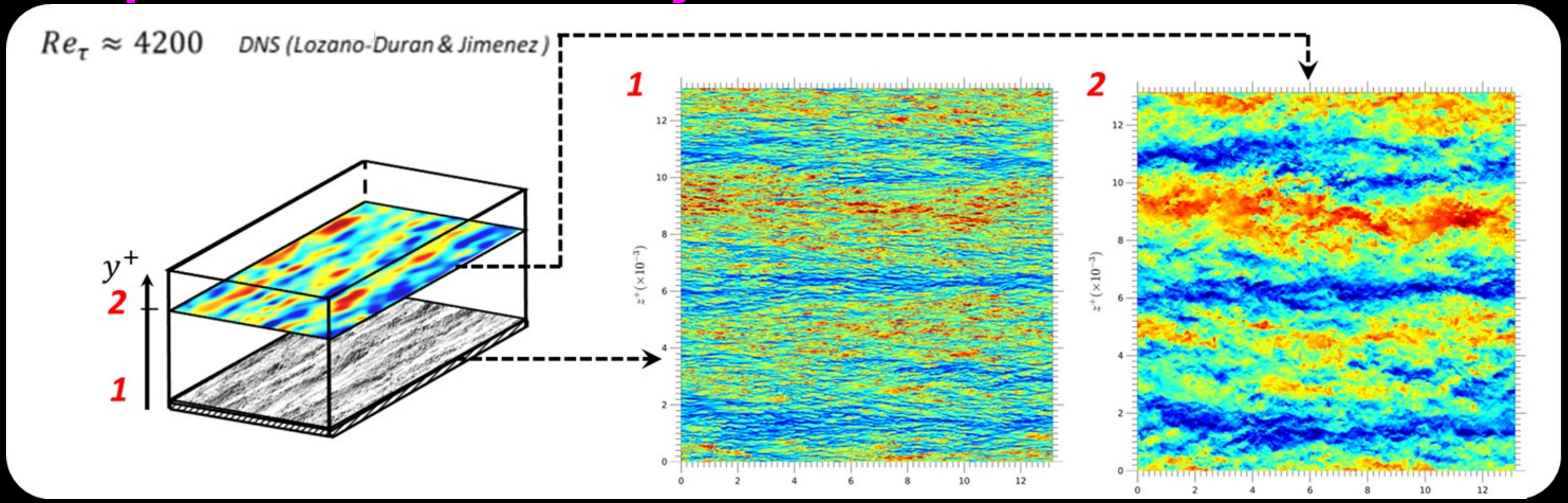
- Control

- What are these structures?
- How are they related?
- What is their influence?
- How does the Reynolds number affect them?

Introduction to Near-wall turbulence
Spatial-wavelength energy Distribution

Snapshot – Streamwise velocity fields



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Spatial-wavelength energy Distribution

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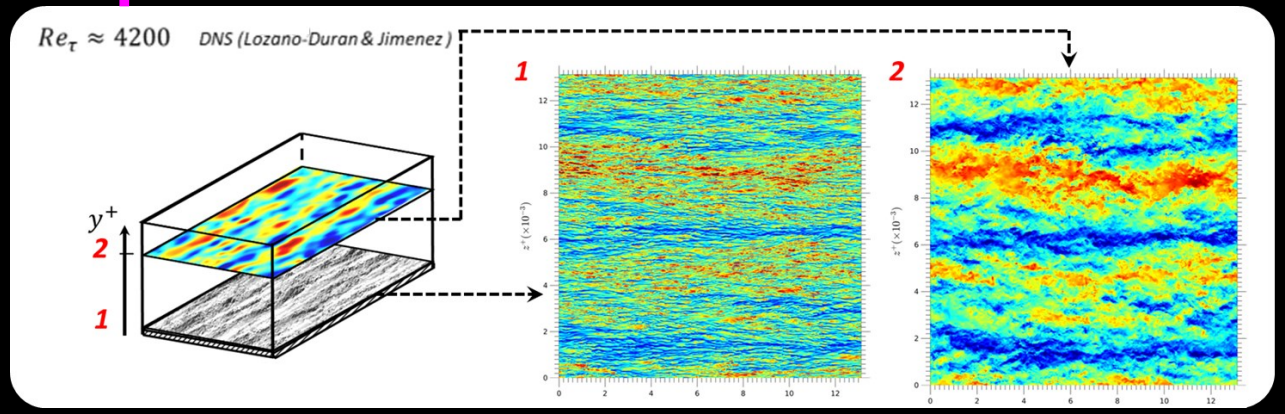
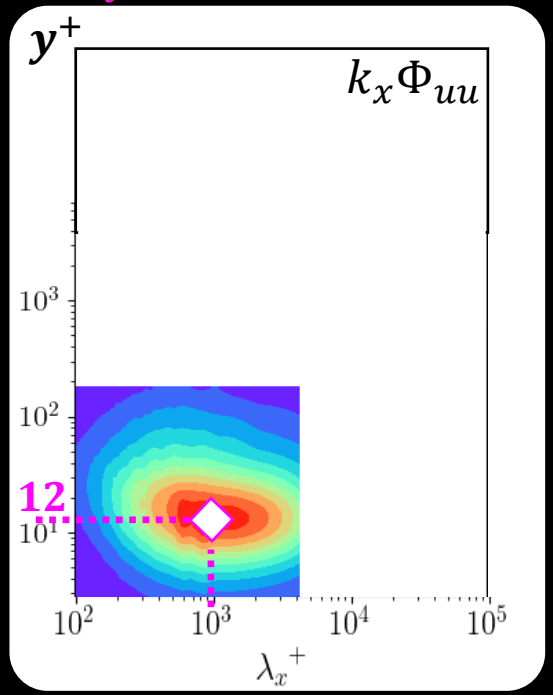
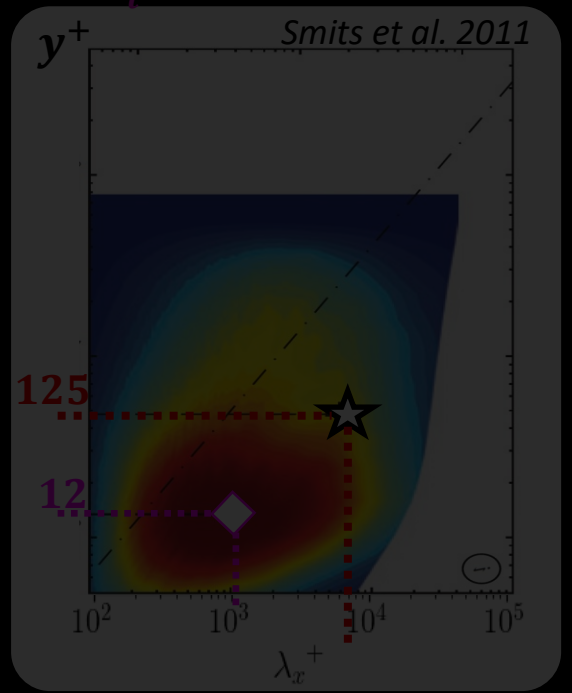


Energy distribution

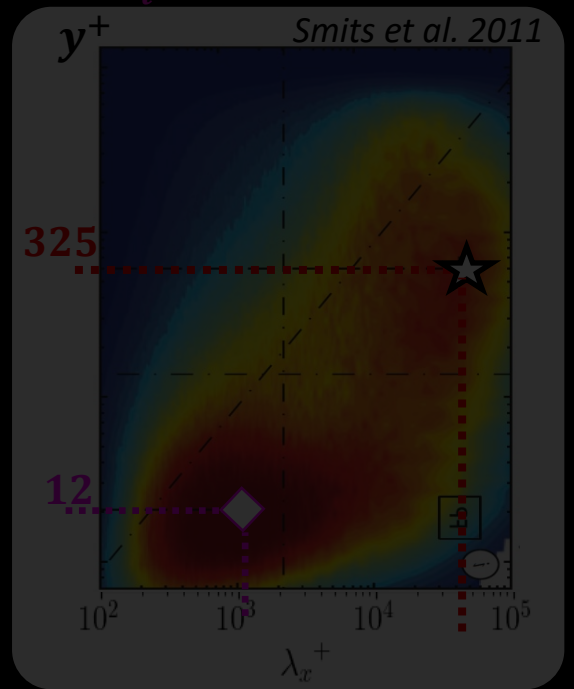
$Re_\tau = 180$

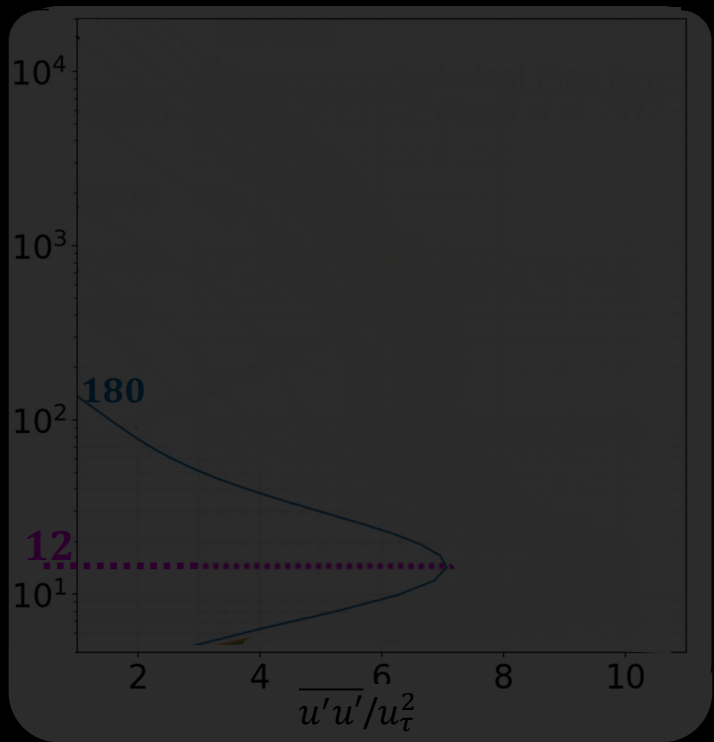


$Re_\tau = 1000$



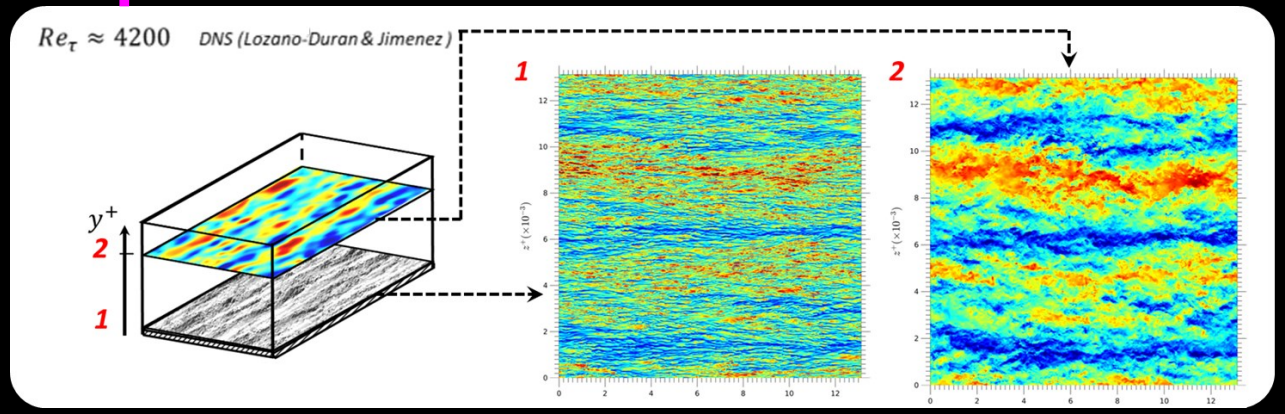
$Re_\tau = 7000$



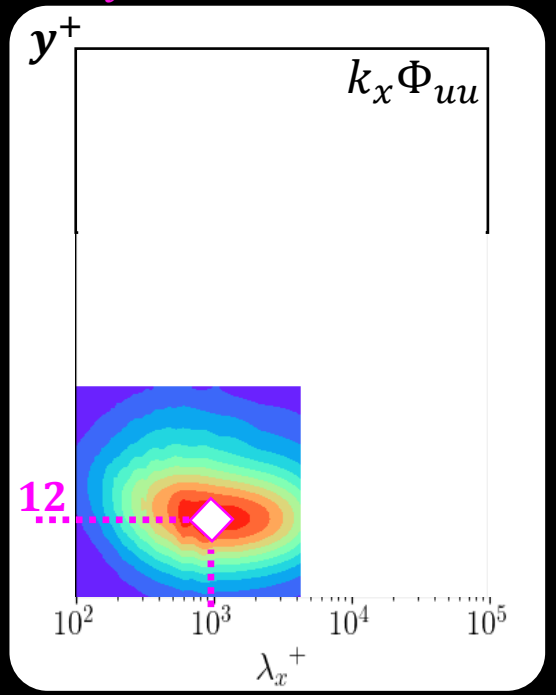


Introduction to Near-wall turbulence
Spatial-wavelength energy Distribution

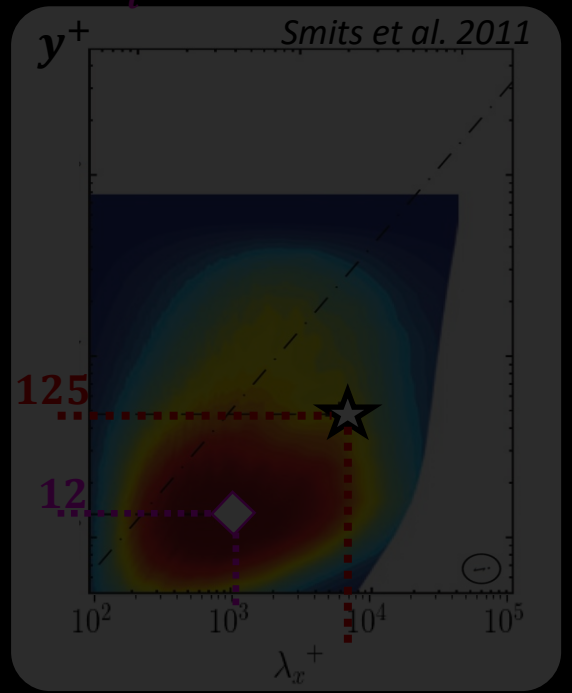
Snapshot



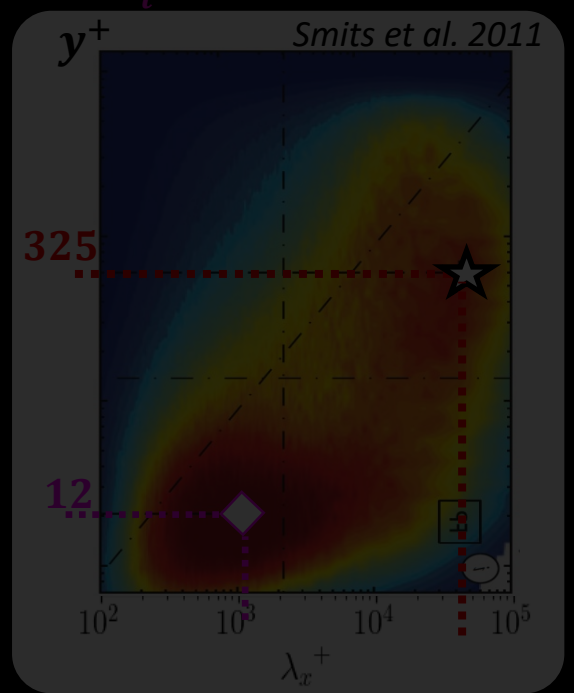
$Re_\tau = 180$

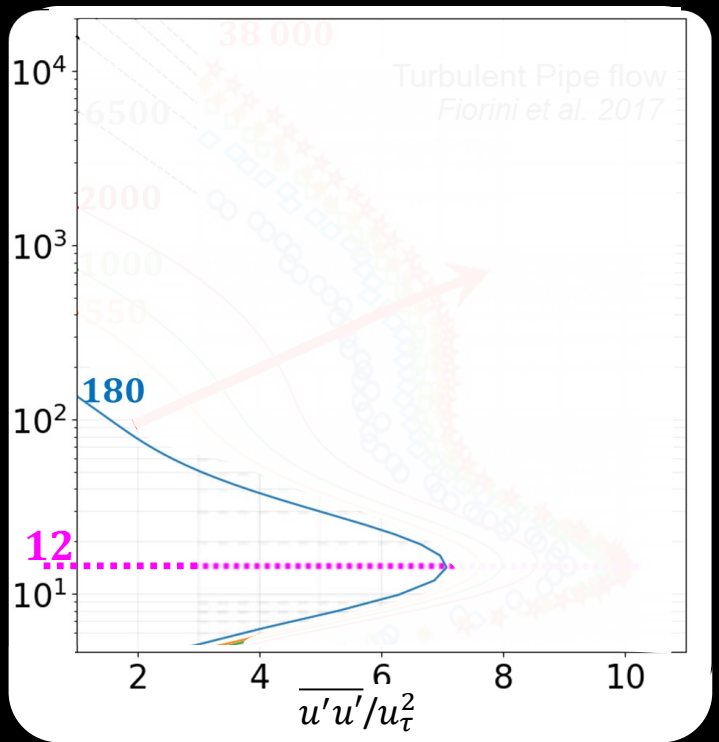


$Re_\tau = 1000$



$Re_\tau = 7000$





Introduction to Near-wall turbulence
Spatial-wavelength energy Distribution

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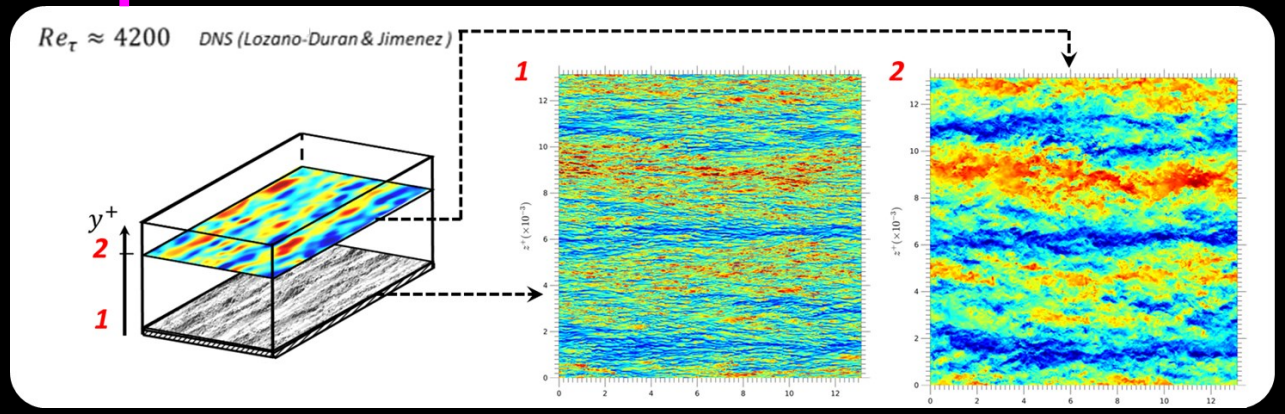

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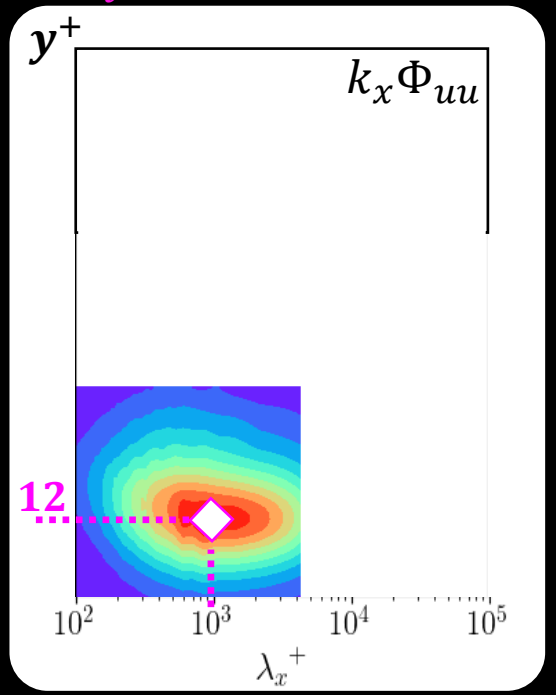

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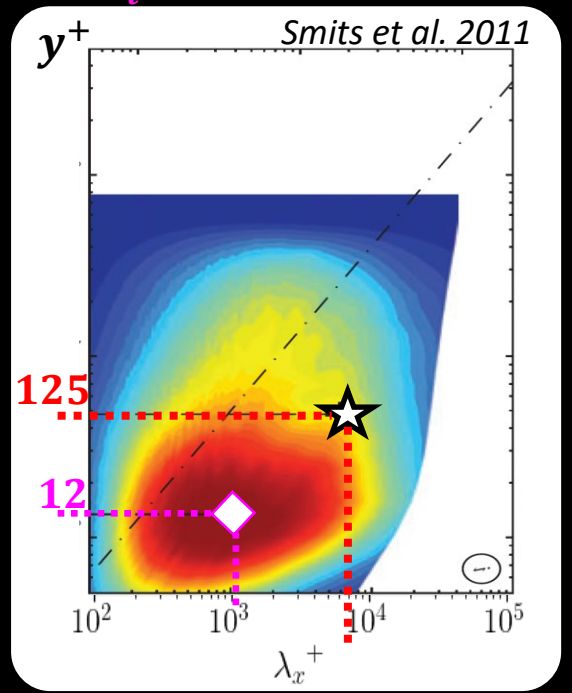
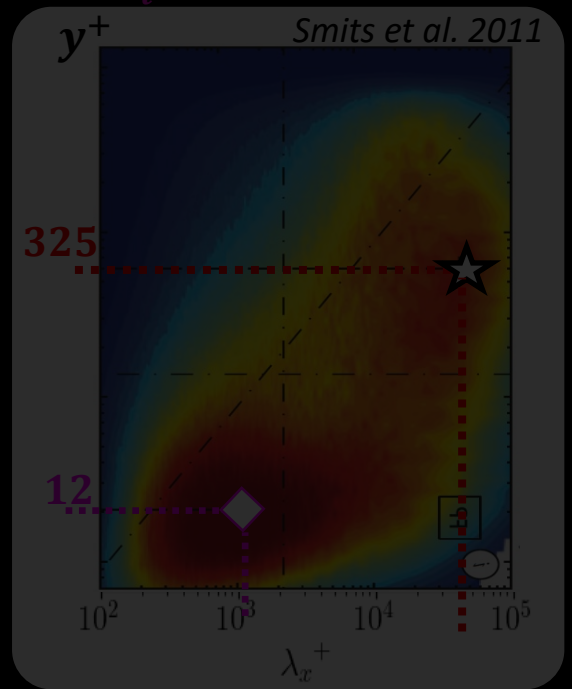
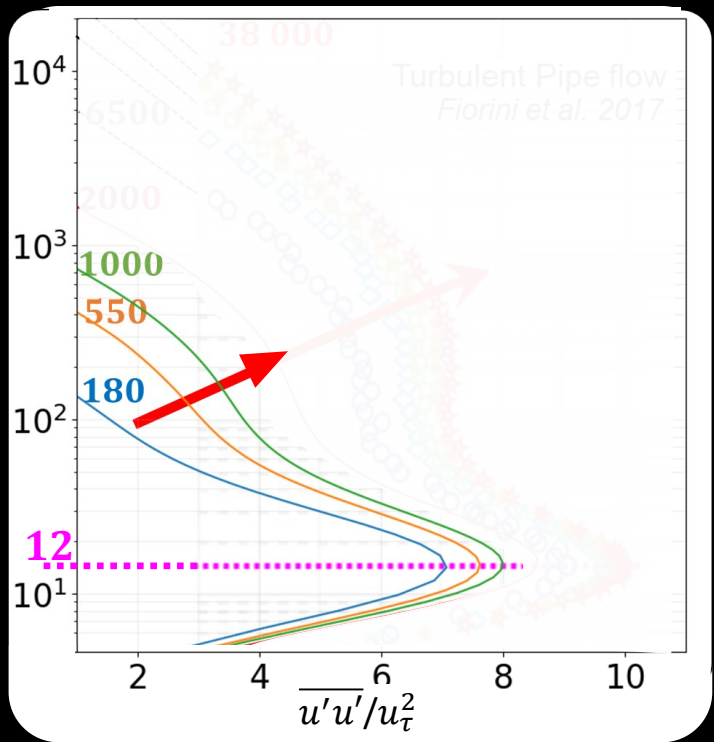


$Re_\tau = 7000$





Introduction to Near-wall turbulence
Spatial-wavelength energy Distribution

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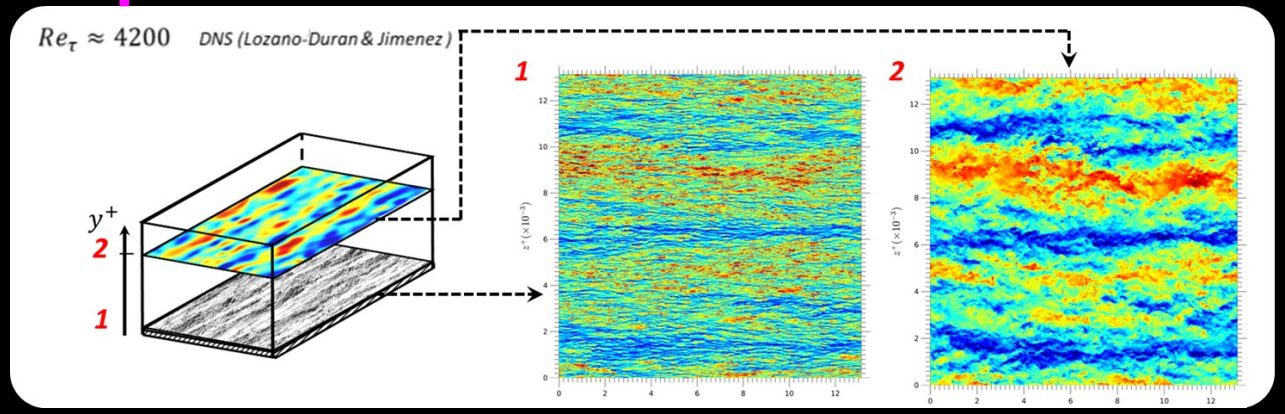

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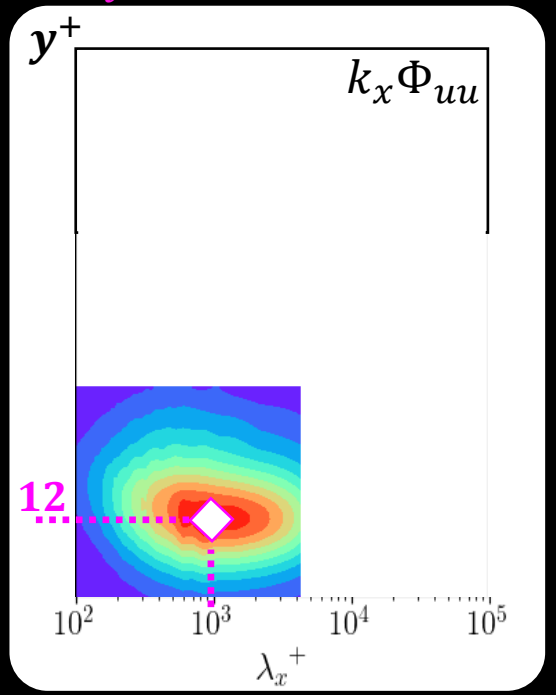

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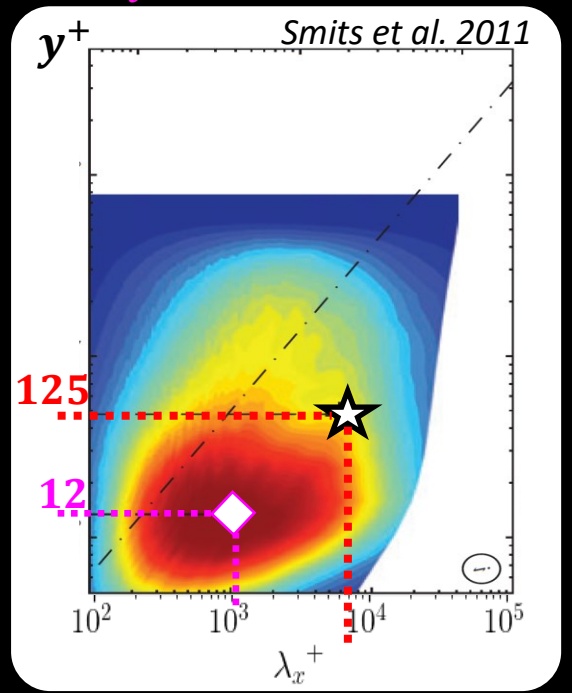
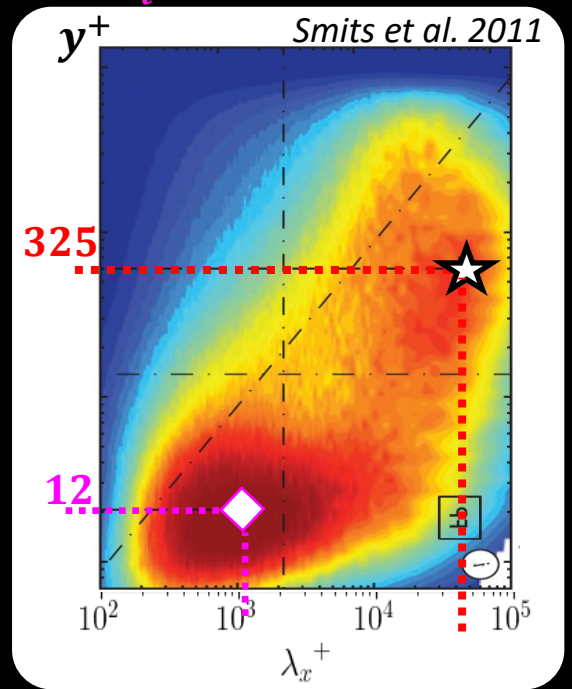
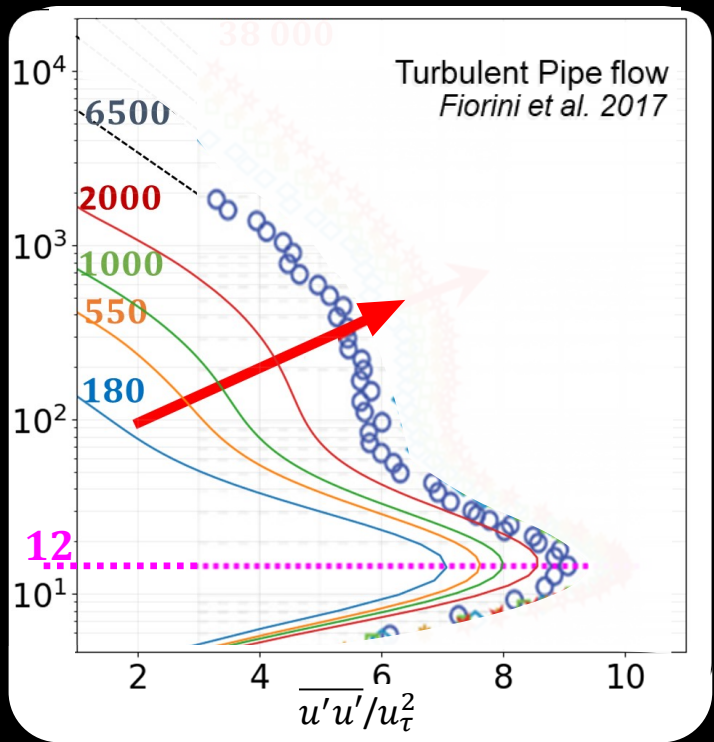


$Re_\tau = 7000$





Introduction to Near-wall turbulence
Spatial-wavelength energy Distribution

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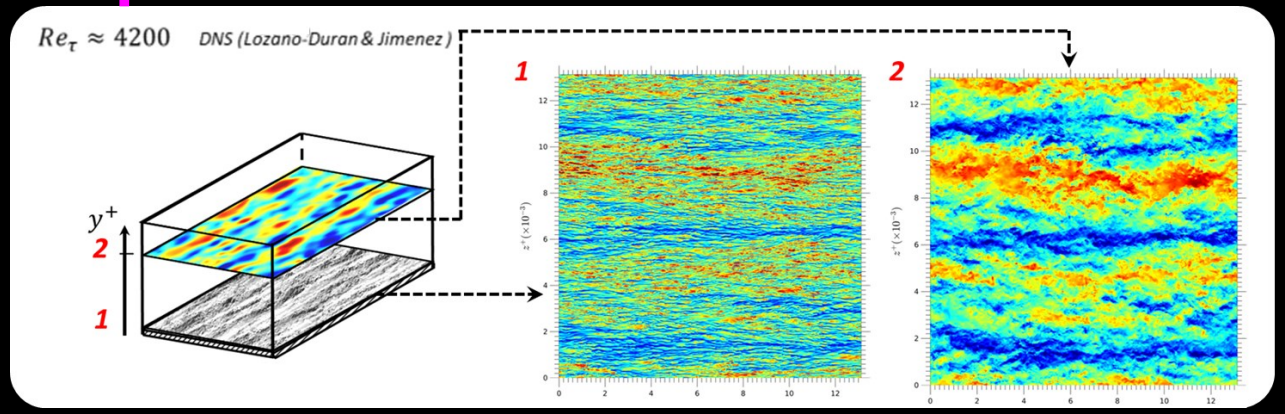

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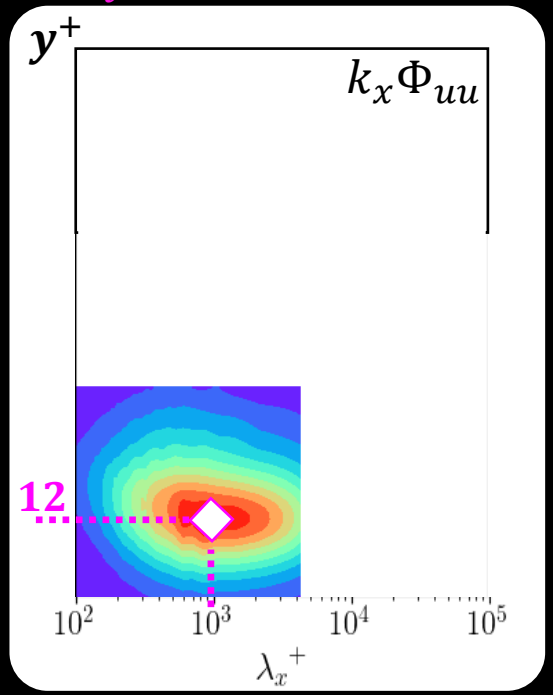

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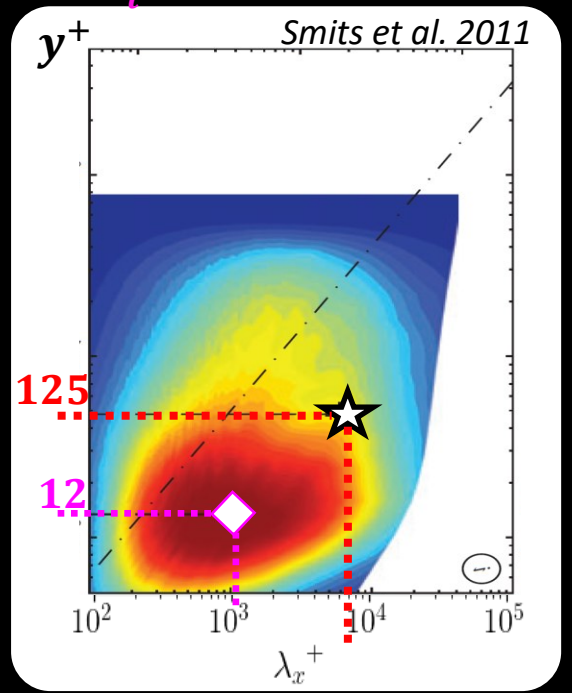

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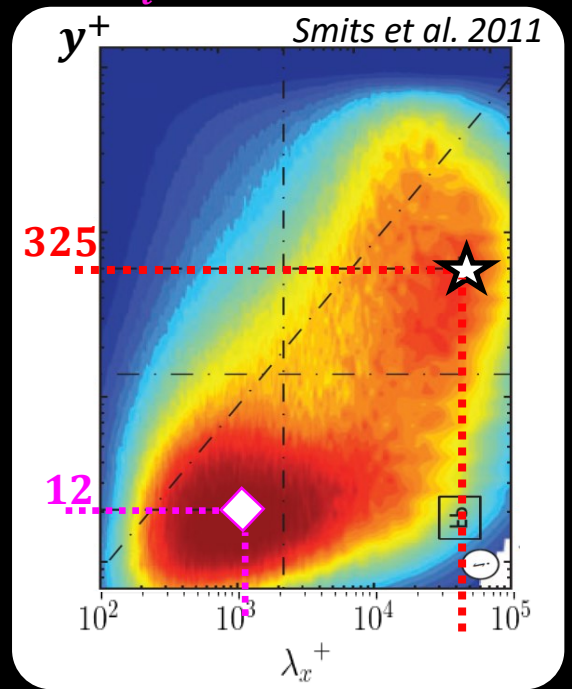

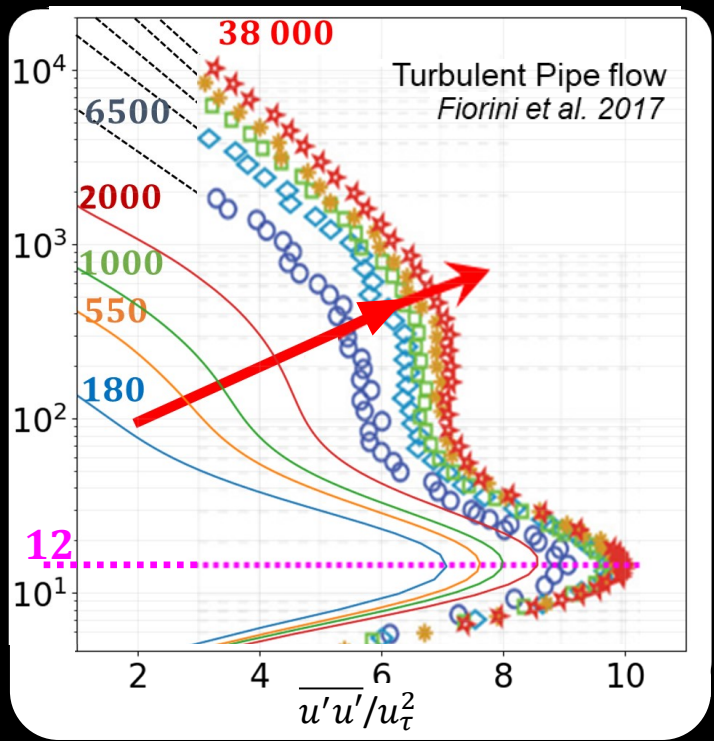

Introduction to Near-wall turbulence
Spatial-wavelength energy Distribution

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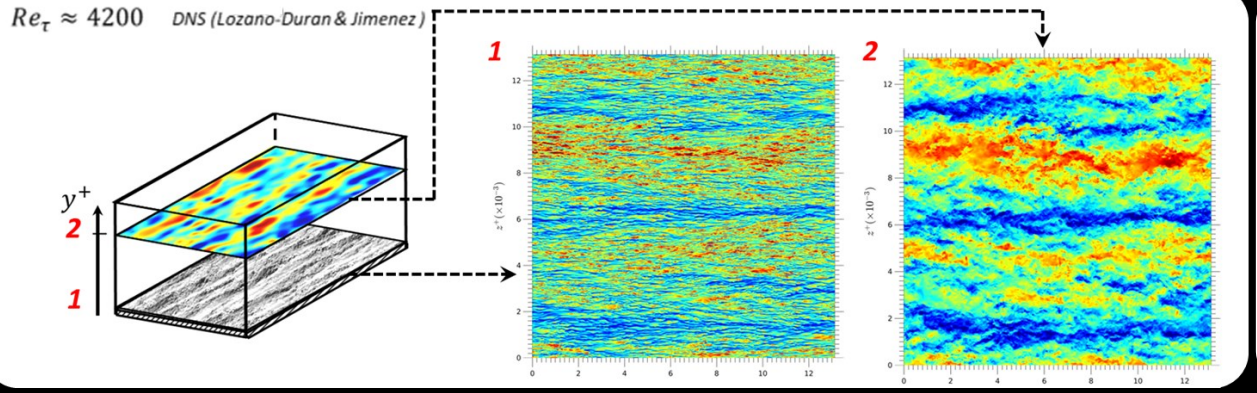
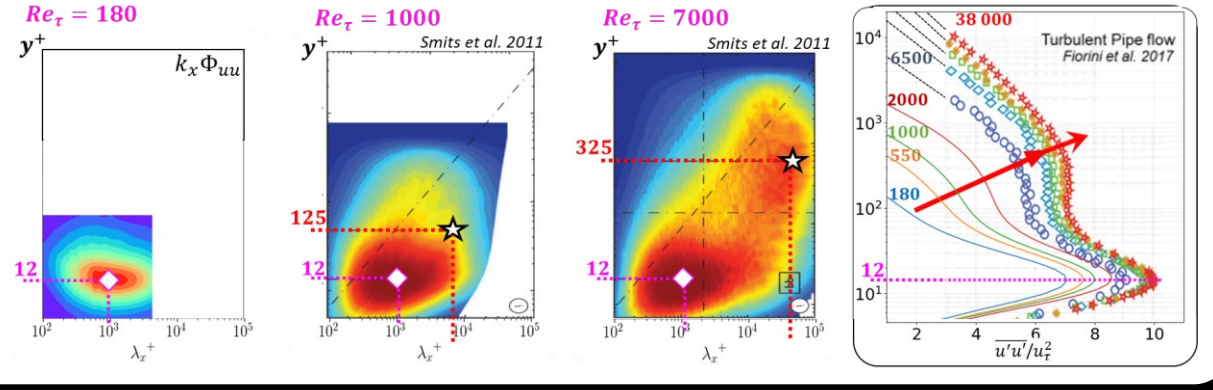


Statistics



Introduction to Near-wall turbulence
Spatial-wavelength energy Distribution

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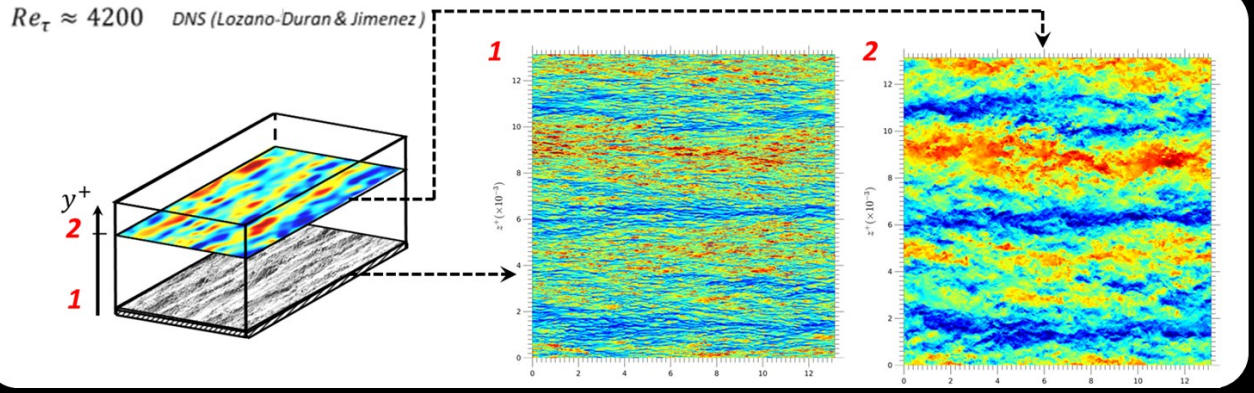

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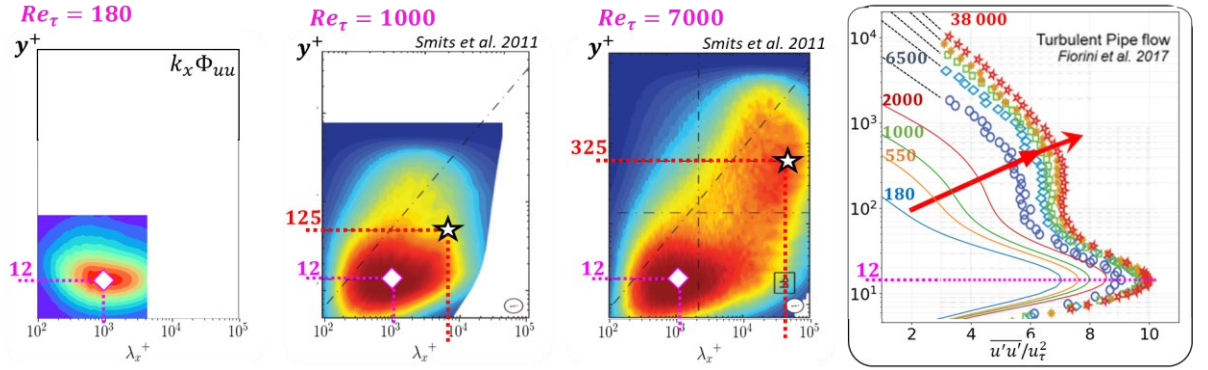
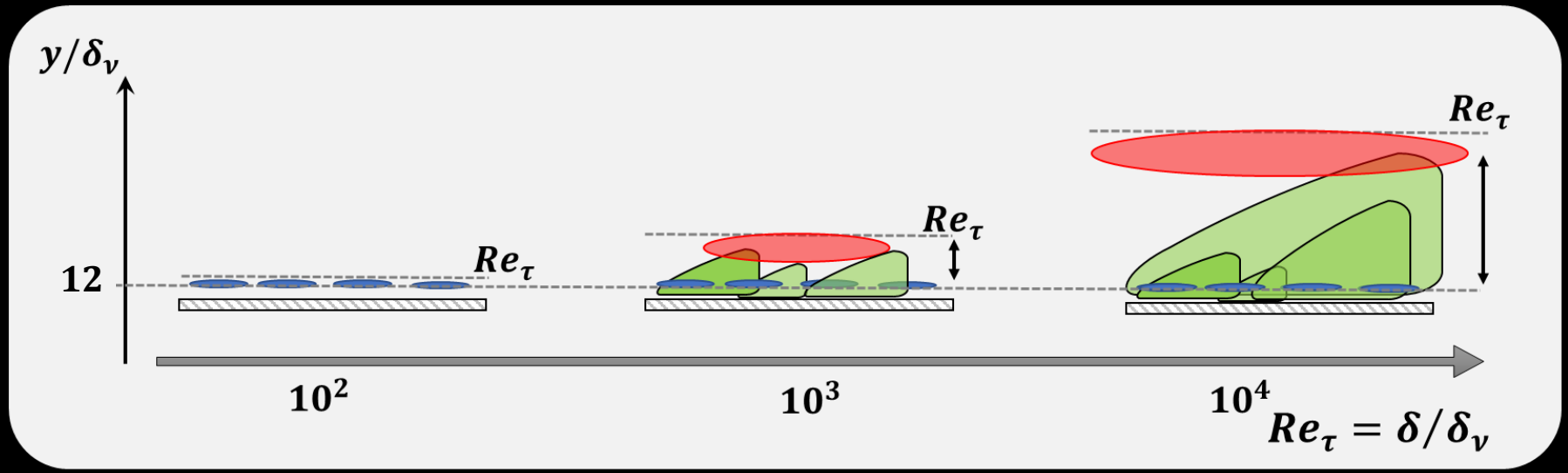




Streaks (small scales)

- Scale with δ_v
- Generate mixing -> Cf ↗

Attached Eddies

- Introduced in 1961 (Townsend)
- Hierarchies of self-similar scales

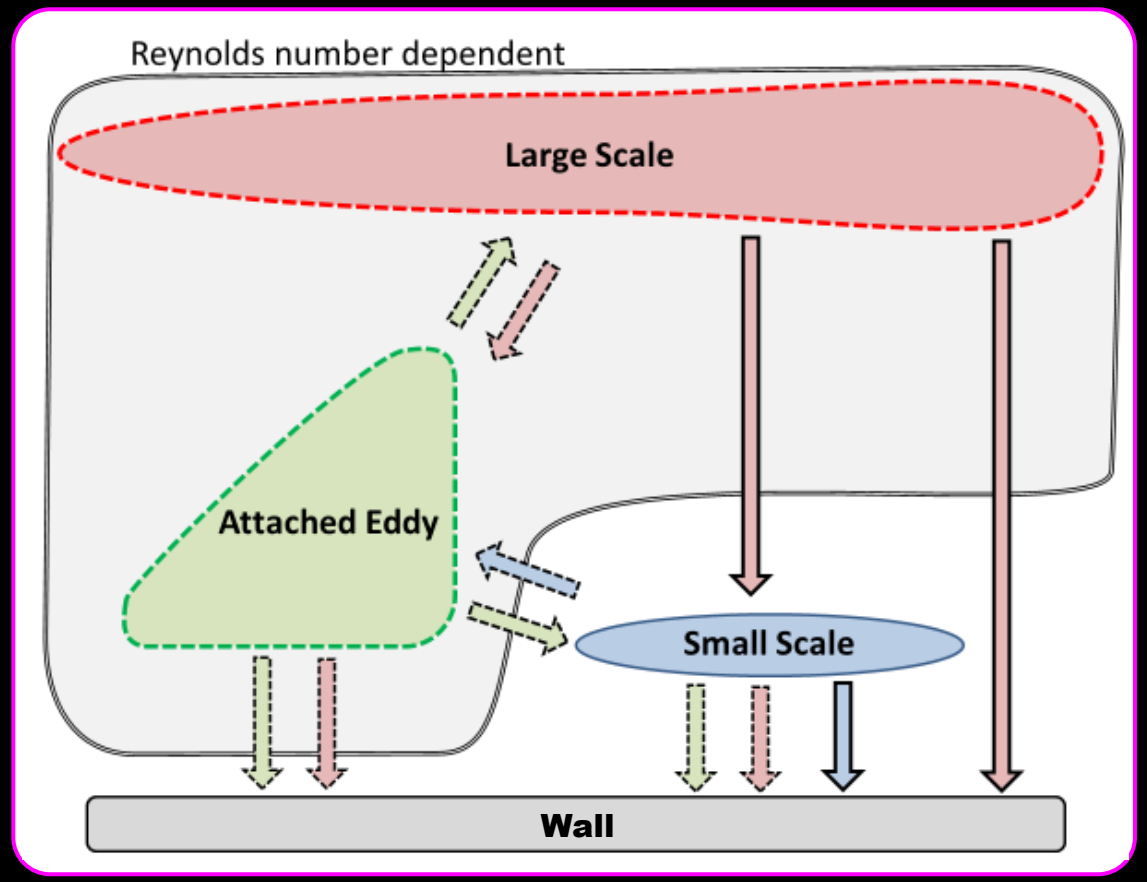
Super Streaks

- Scale with δ
- Alter  & Cf

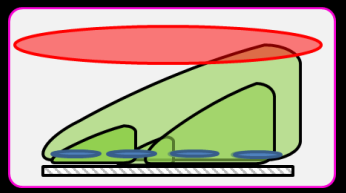
Dynamic of Near-wall turbulence: Skeleton and Relations
Open questions and objectives

Modelling, predicting and controlling near-wall turbulence
through a coupled approach combining machine learning and physical knowledge

⇨ Reducing Drag ⇨ Improving Heat transfer

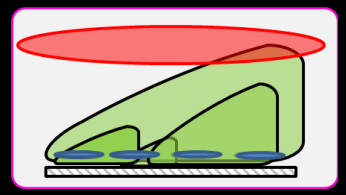


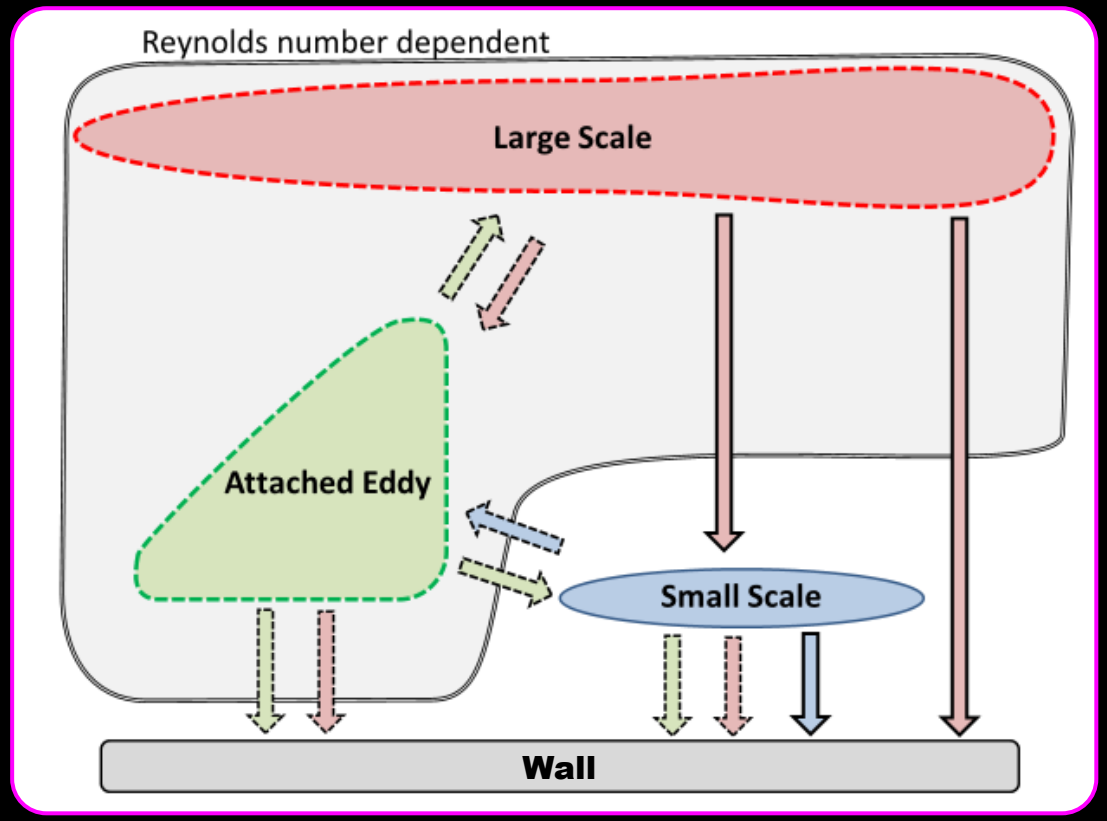
`` Vision Puzzle''



- How to identify them?
- How do they develop?
- How do they interact?
- What are their contributions to mixing Momentum
- How to control them?

Dynamic of Near-wall turbulence: Skeleton and Relations `` Vision Puzzle''
Pieces of the Puzzle



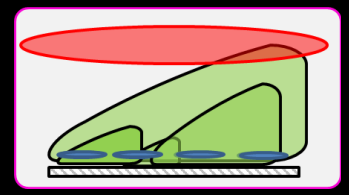


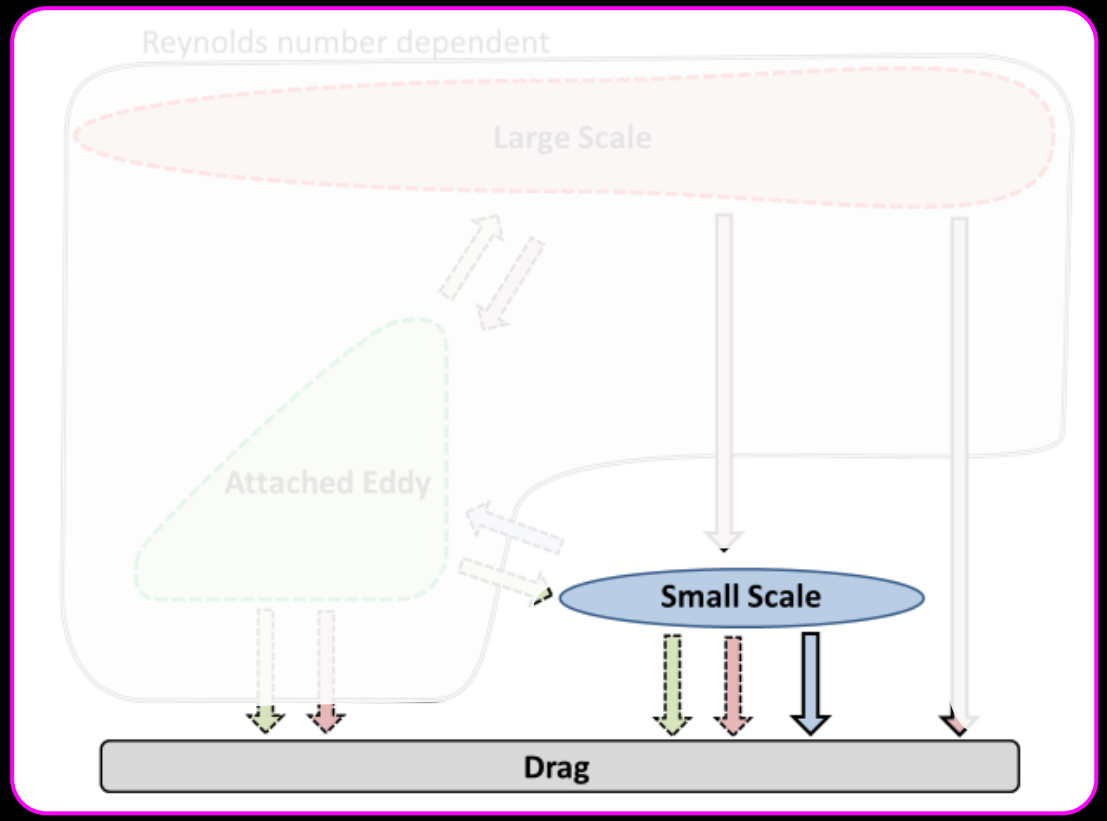
1- Near-wall structure control: drag reduction mechanism

2- Effects of large scales on near-wall small scales and drag

3- Identification and characterisation of energetic structures filling the spectral gap between large and small scales

Dynamic of Near-wall turbulence: Skeleton and Relations `` Vision Puzzle''
Pieces of the Puzzle





1- Near-wall structure control: drag reduction mechanism

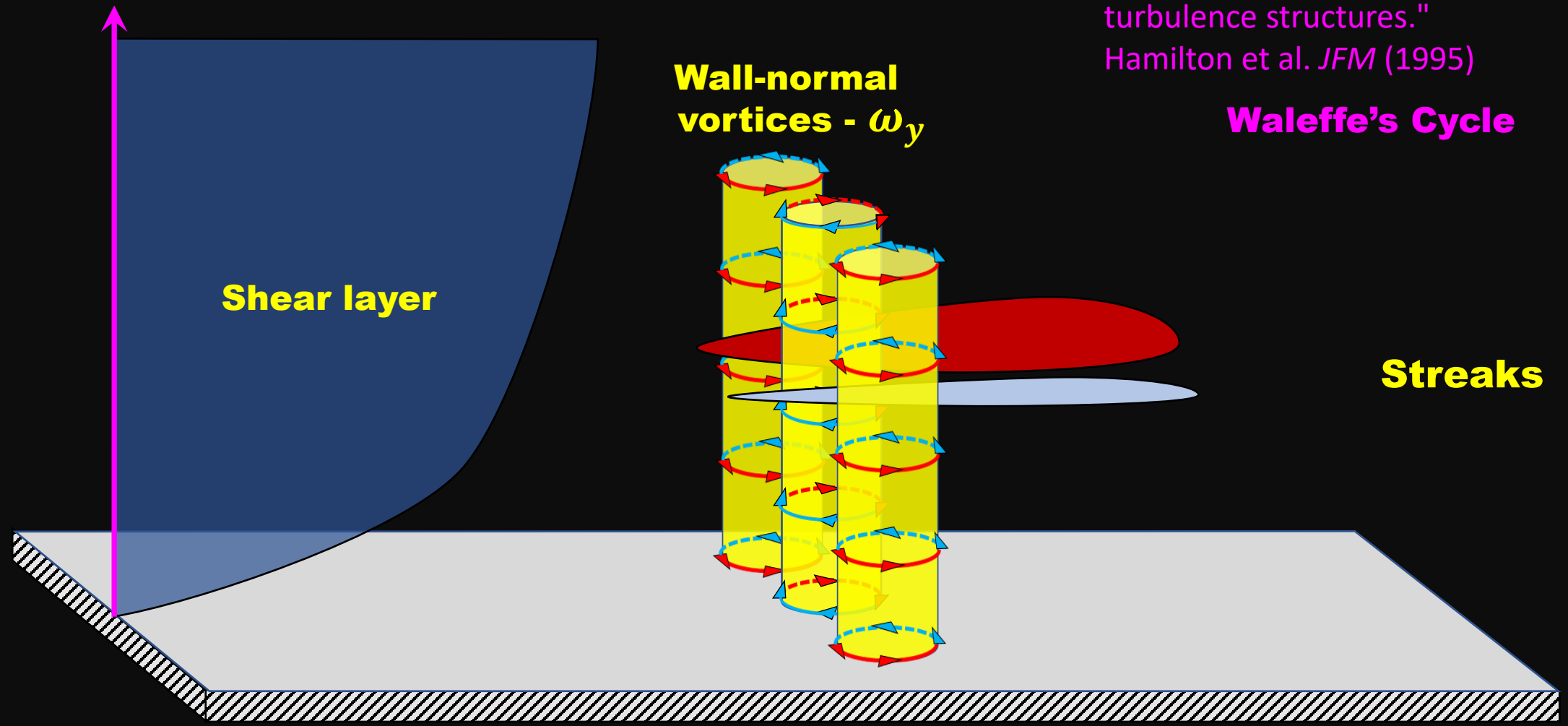
How Manipulation of Near-Wall Coherent Structures Reduces Turbulent Skin Friction ?

Introduction to Near-wall turbulence

Streaks' regeneration process ?

"Regeneration mechanisms of near-wall turbulence structures."
Hamilton et al. *JFM* (1995)

Waleffe's Cycle



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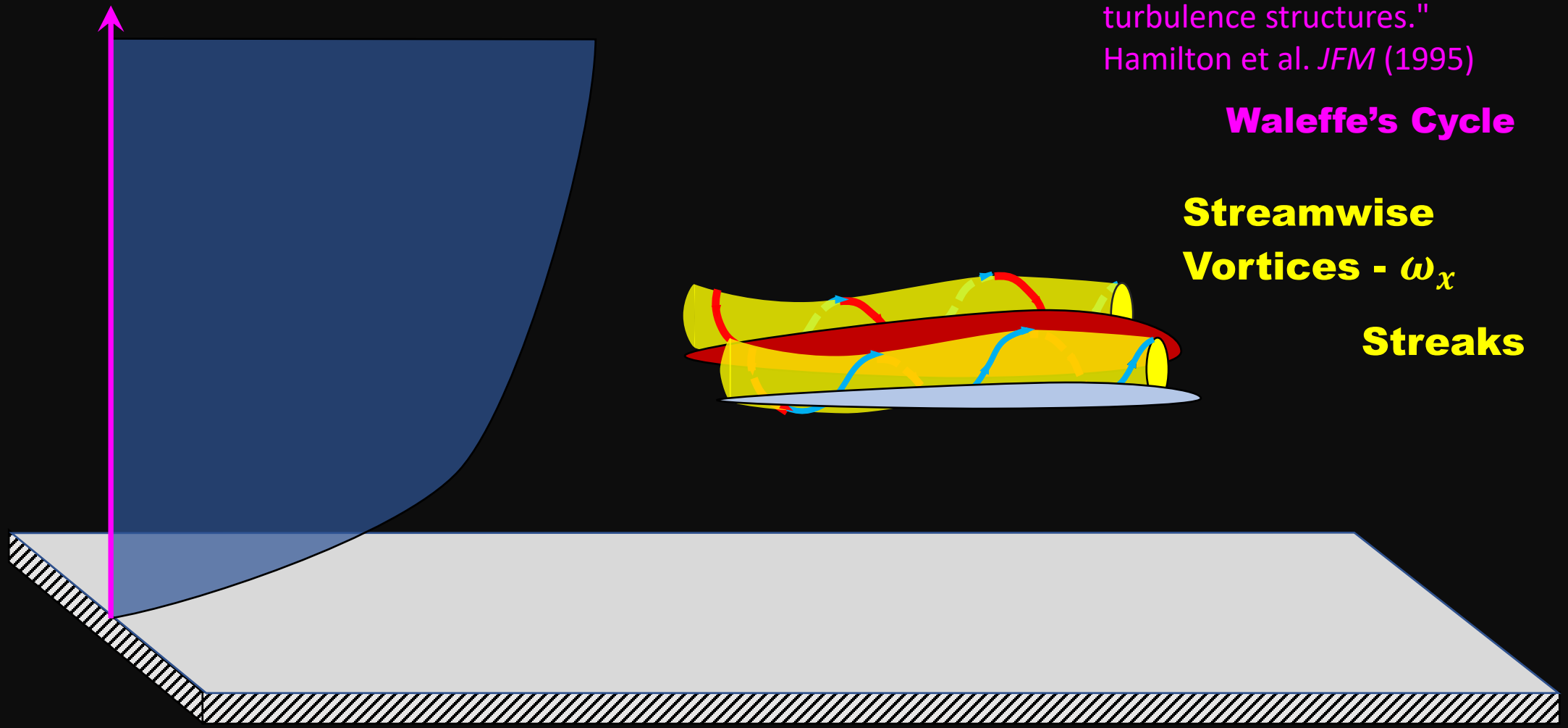
Waleffe's Cycle

Streamwise Vortices - ω_x

Streaks



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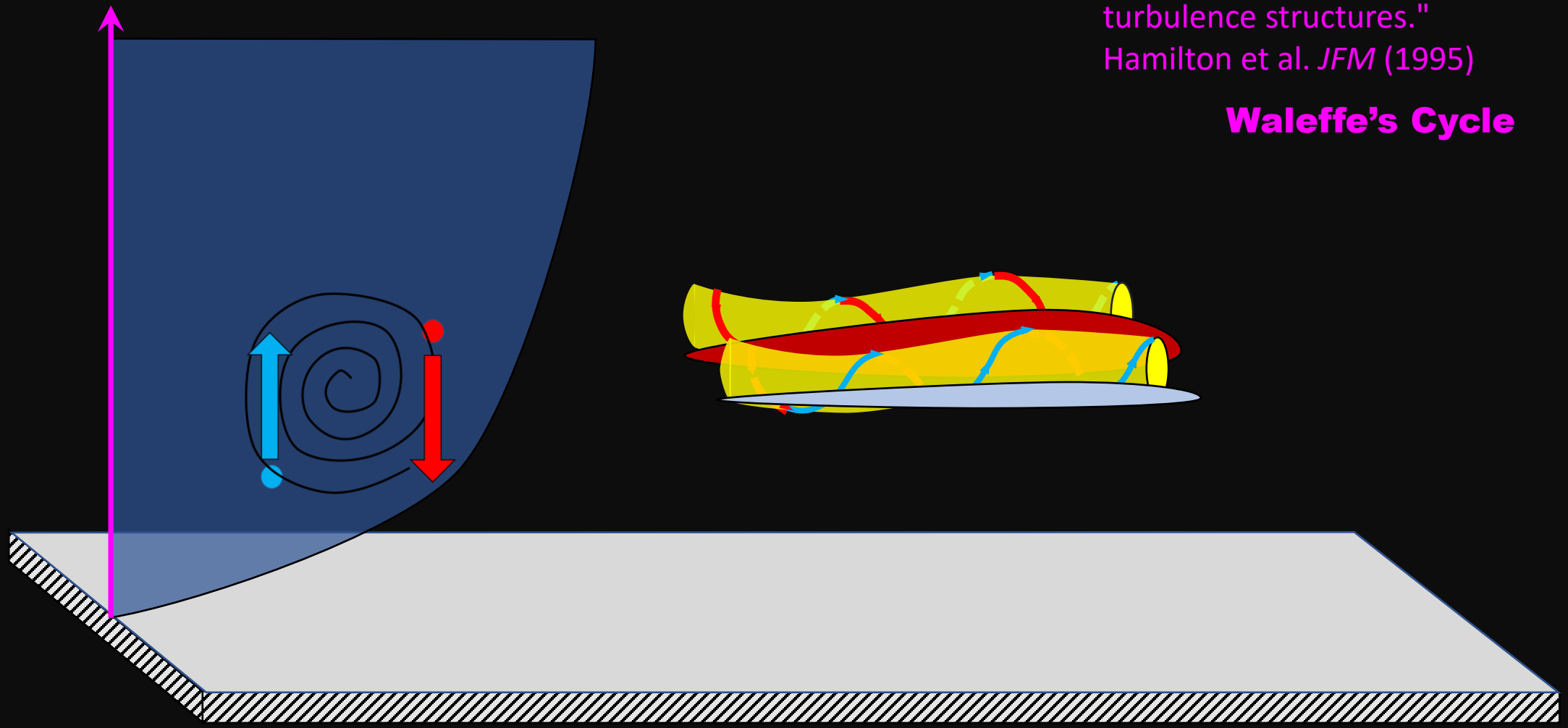

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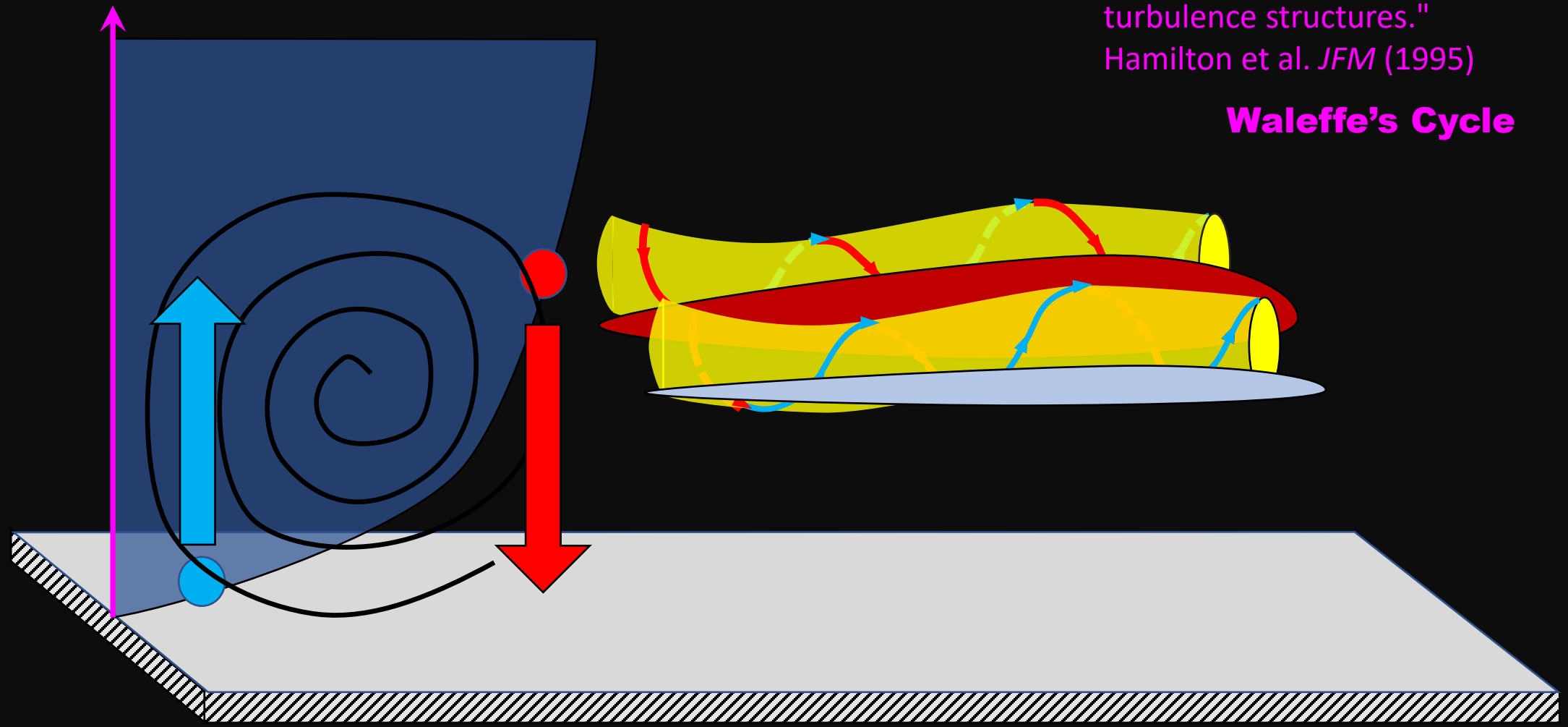

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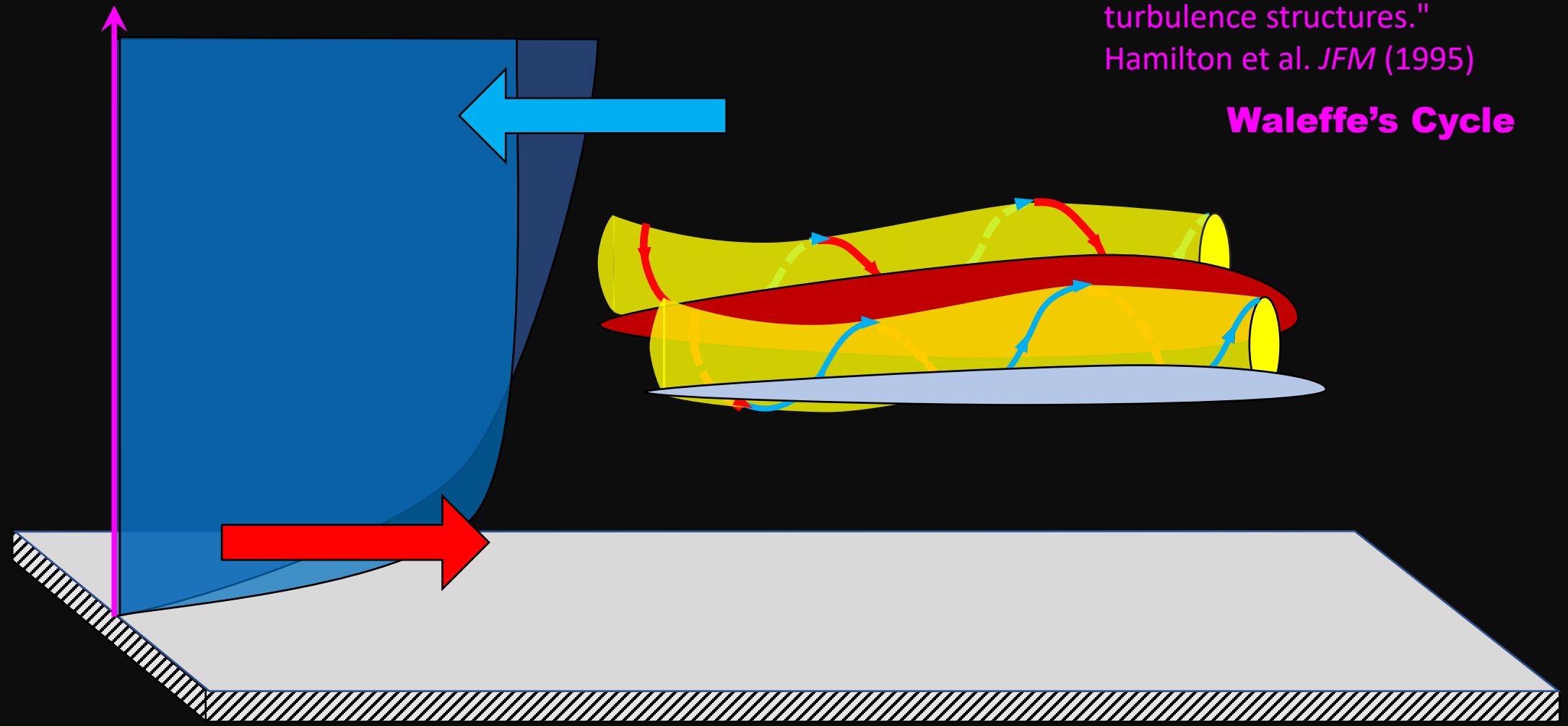

Drag increases

Introduction to Near-wall turbulence
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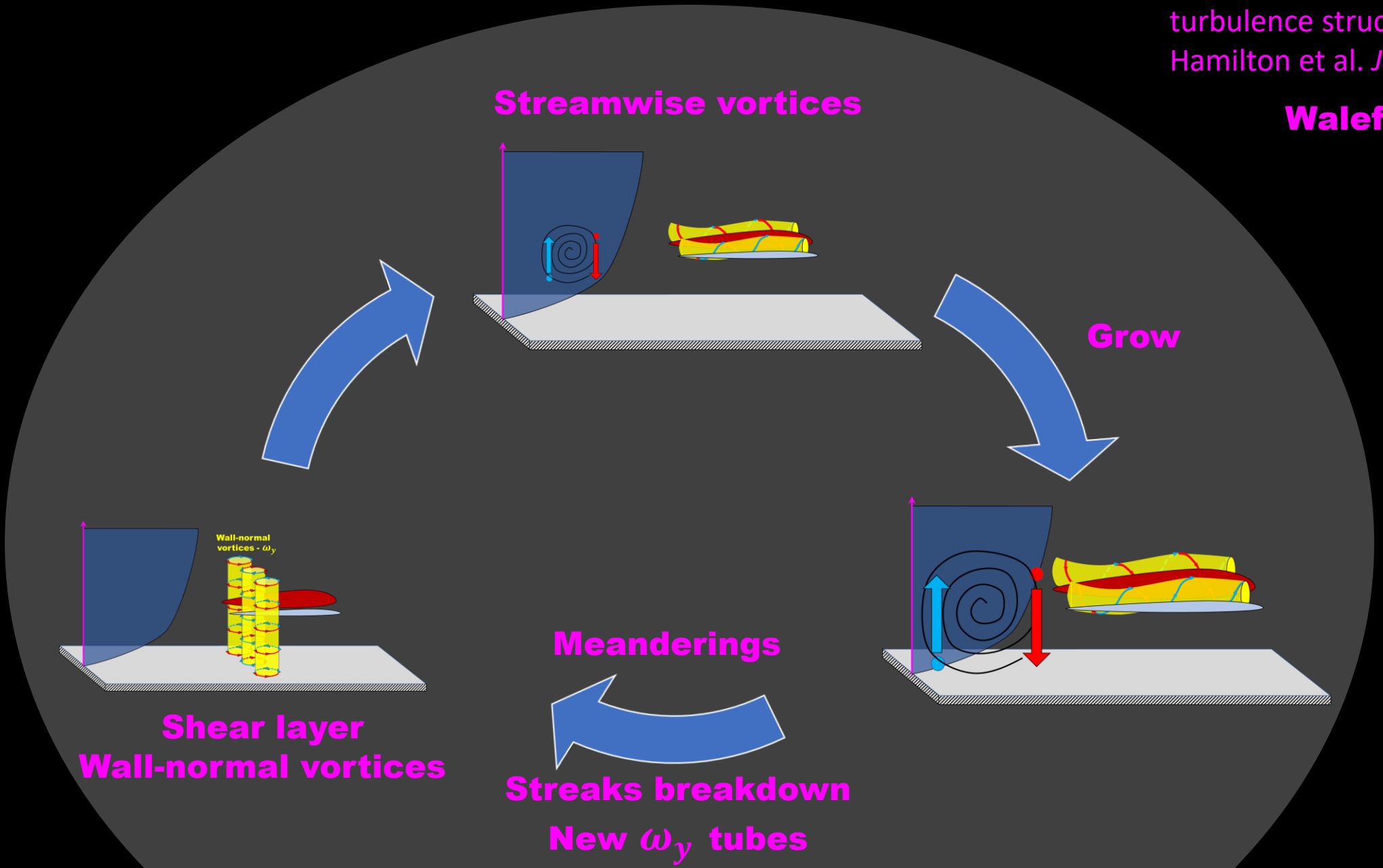
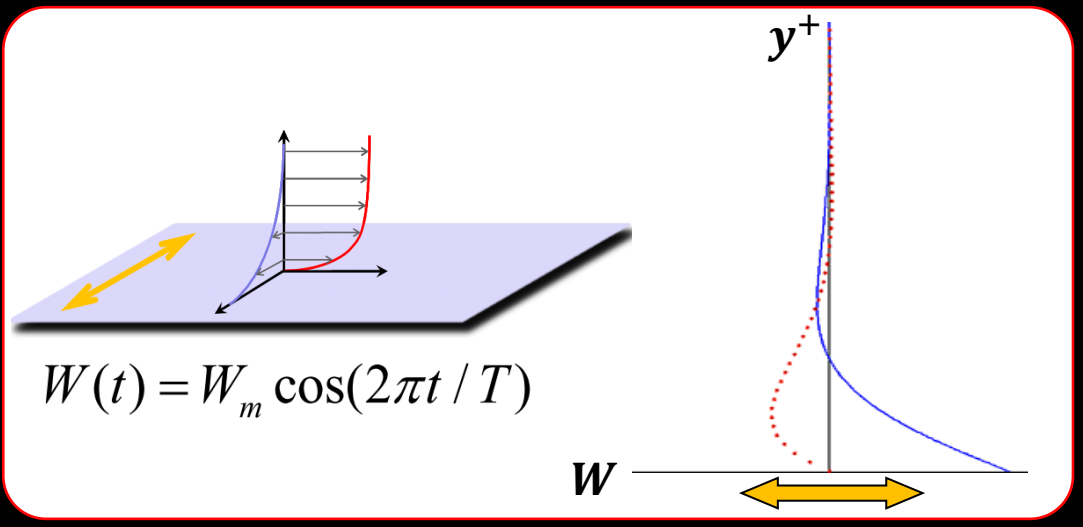
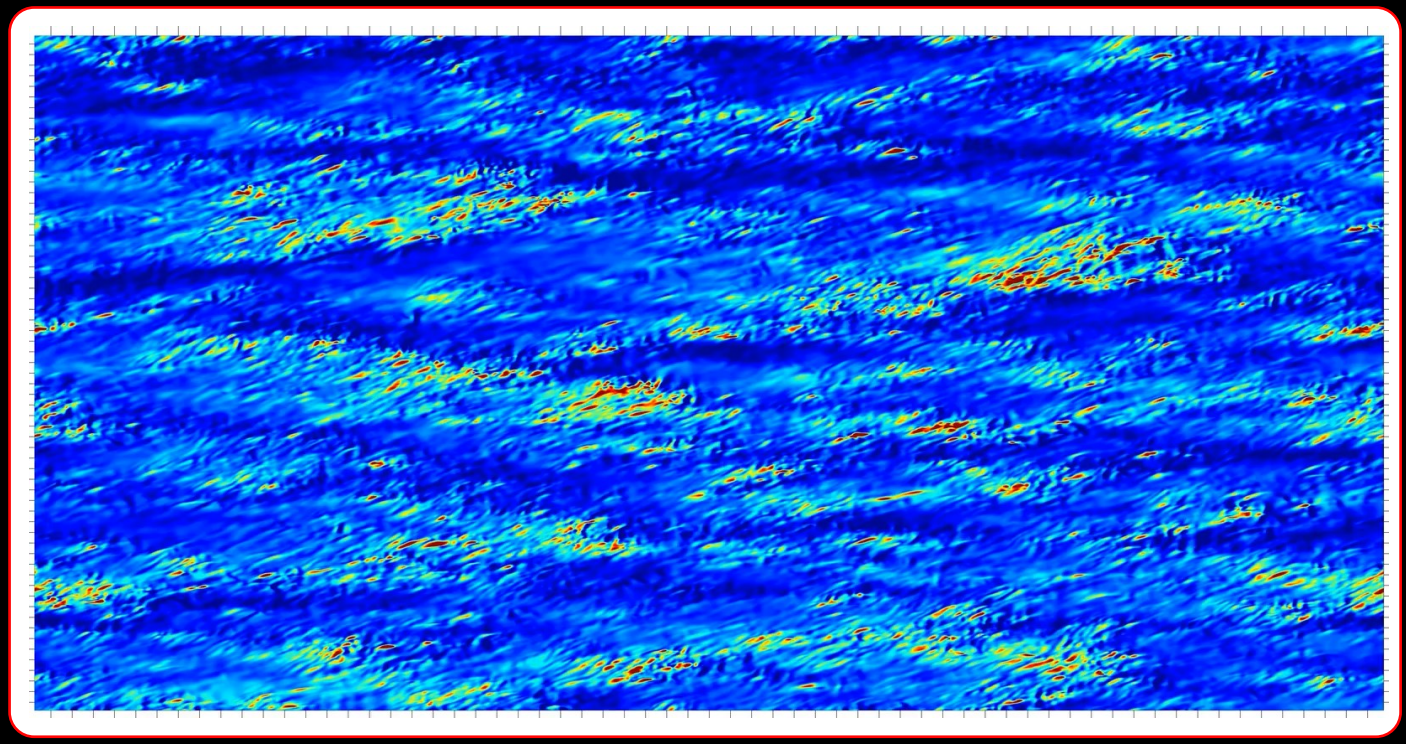


Drag reduction at Relatively low-Reynolds number $(Re_\tau \approx 1000)$
Spanwise wall oscillation – Control Effects ?





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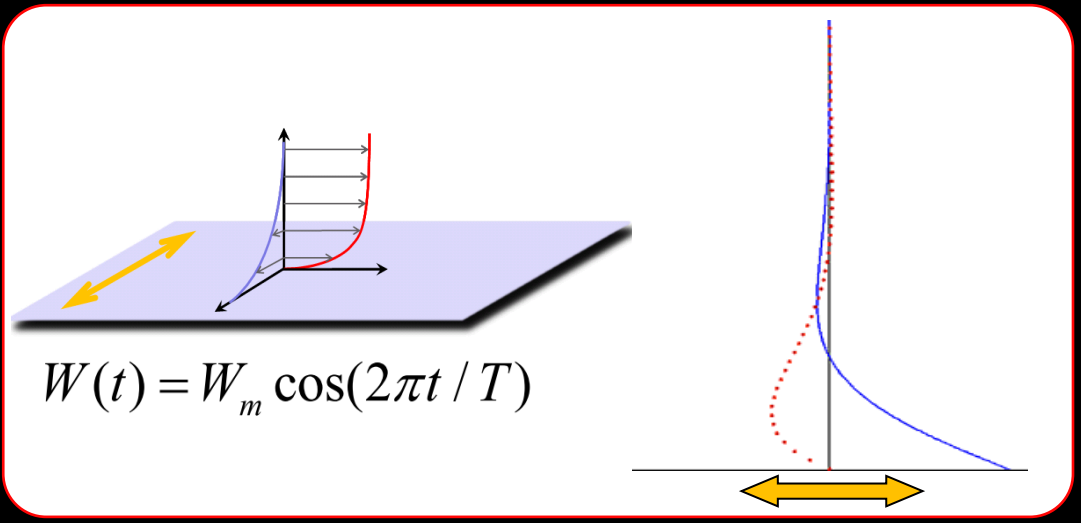
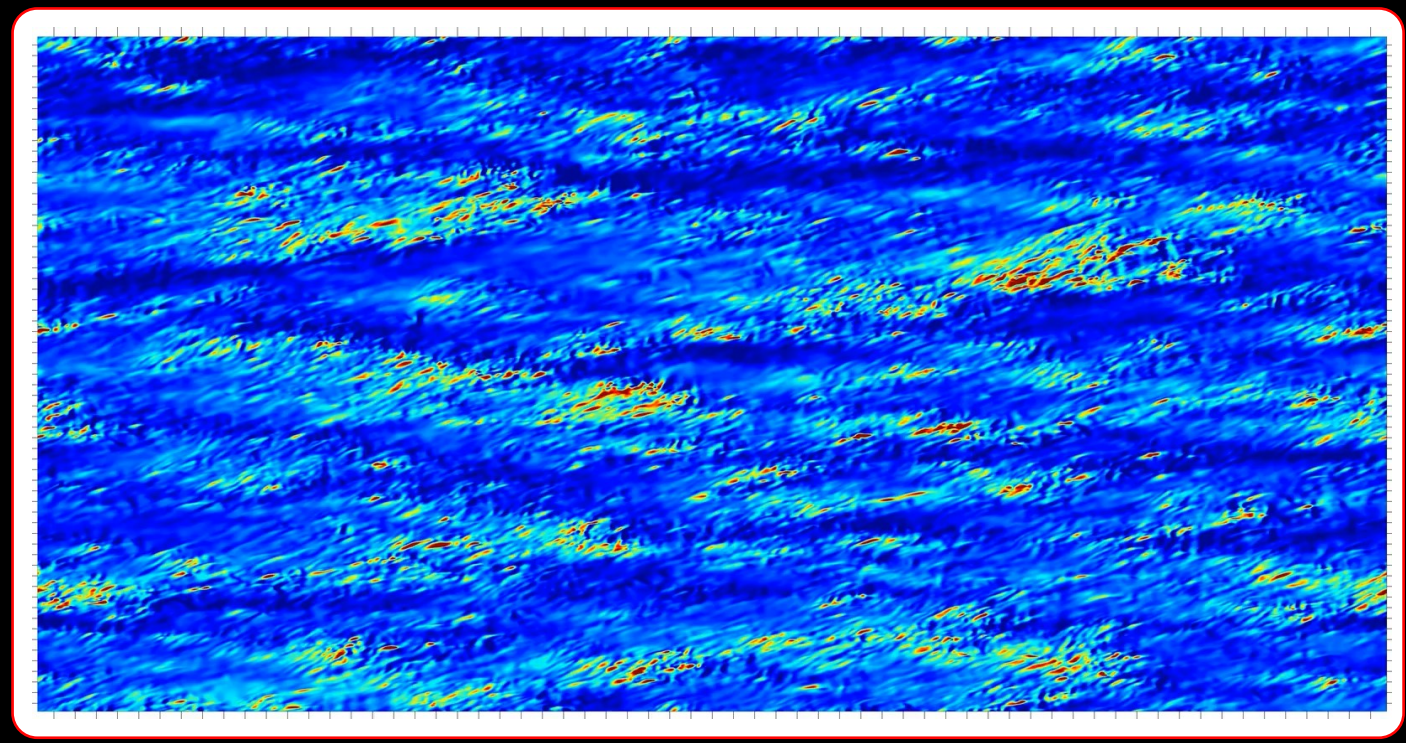
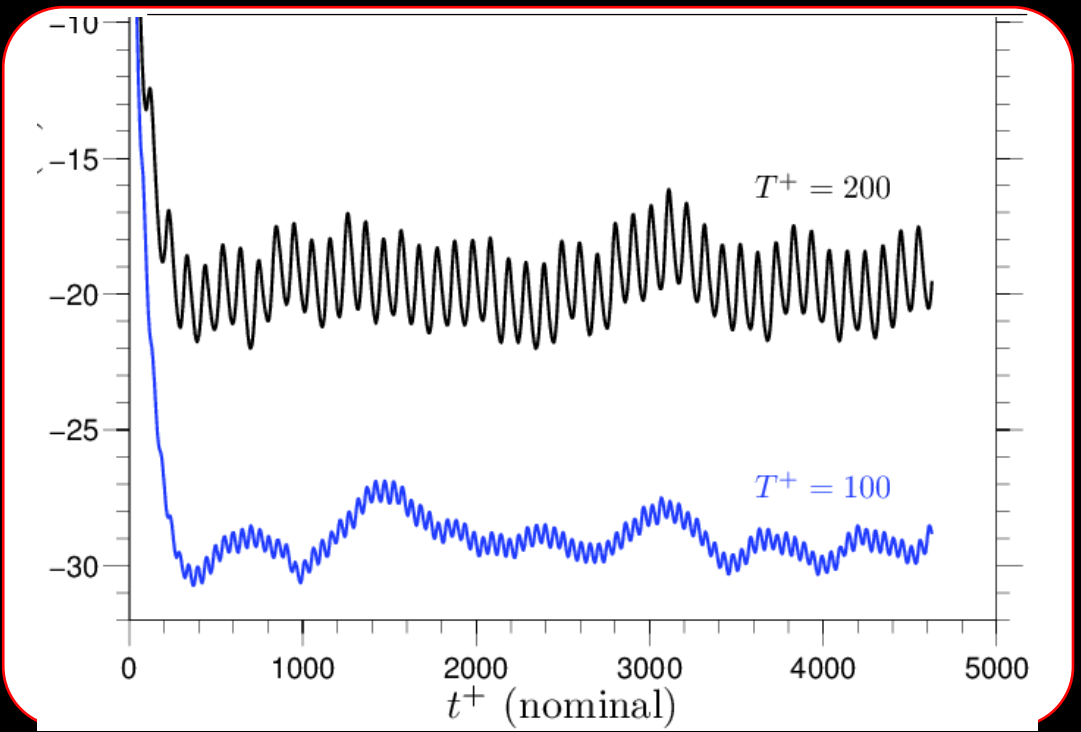


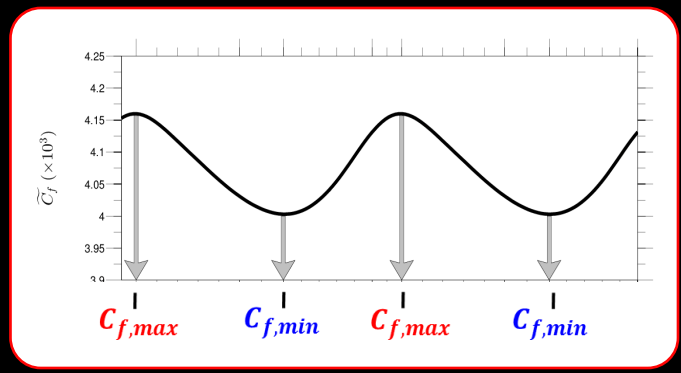




Drag Reduction :

$\approx 30\%$ at $T^+ = 100$

$\approx 20\%$ at $T^+ = 200$

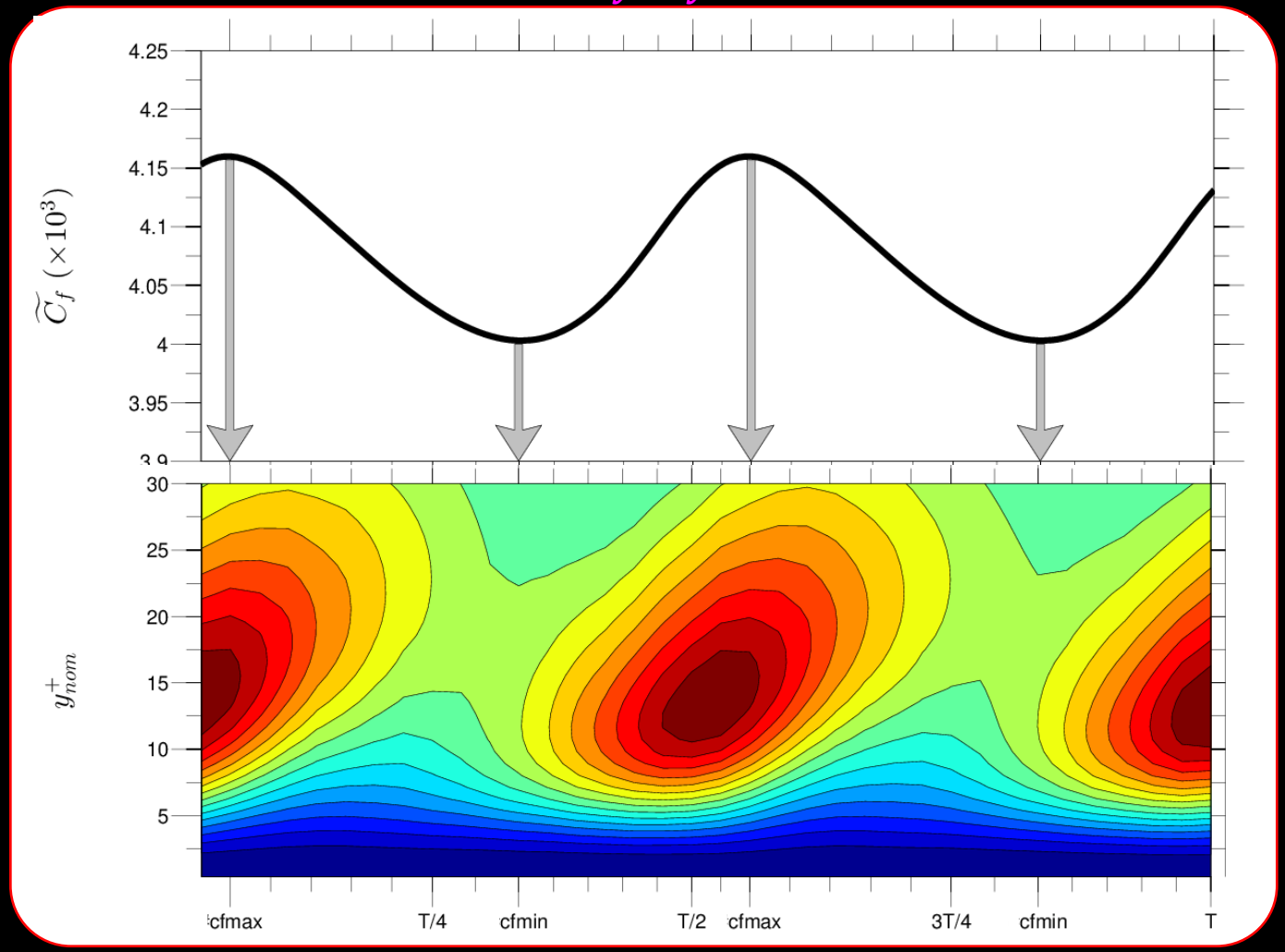


Drag reduction at Relatively low-Reynolds number $(Re_\tau \approx 1000)$
Spanwise wall oscillation – Hysteresis

$$\widetilde{\omega_y'' \omega_y''} \propto \widetilde{\frac{\partial u''}{\partial z}} \widetilde{\frac{\partial u''}{\partial z}}$$

Streaks magnitude

Phase variations of $\widetilde{\omega_y'' \omega_y''}$



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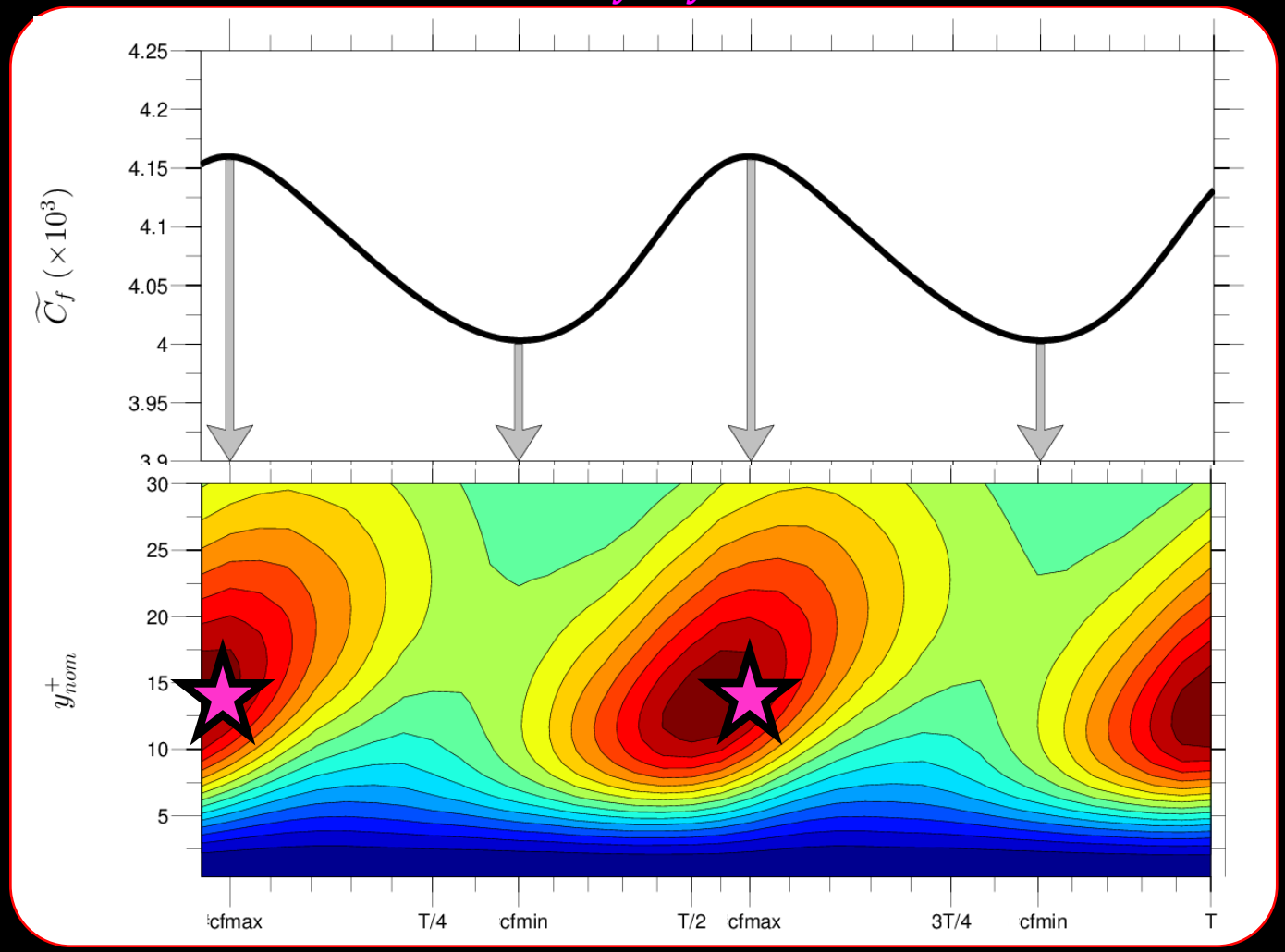
Streaks magnitude

★ Strongest Streaks

Phase variations of $\widetilde{\omega_y'' \omega_y''}$



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Spanwise wall oscillation – Hysteresis

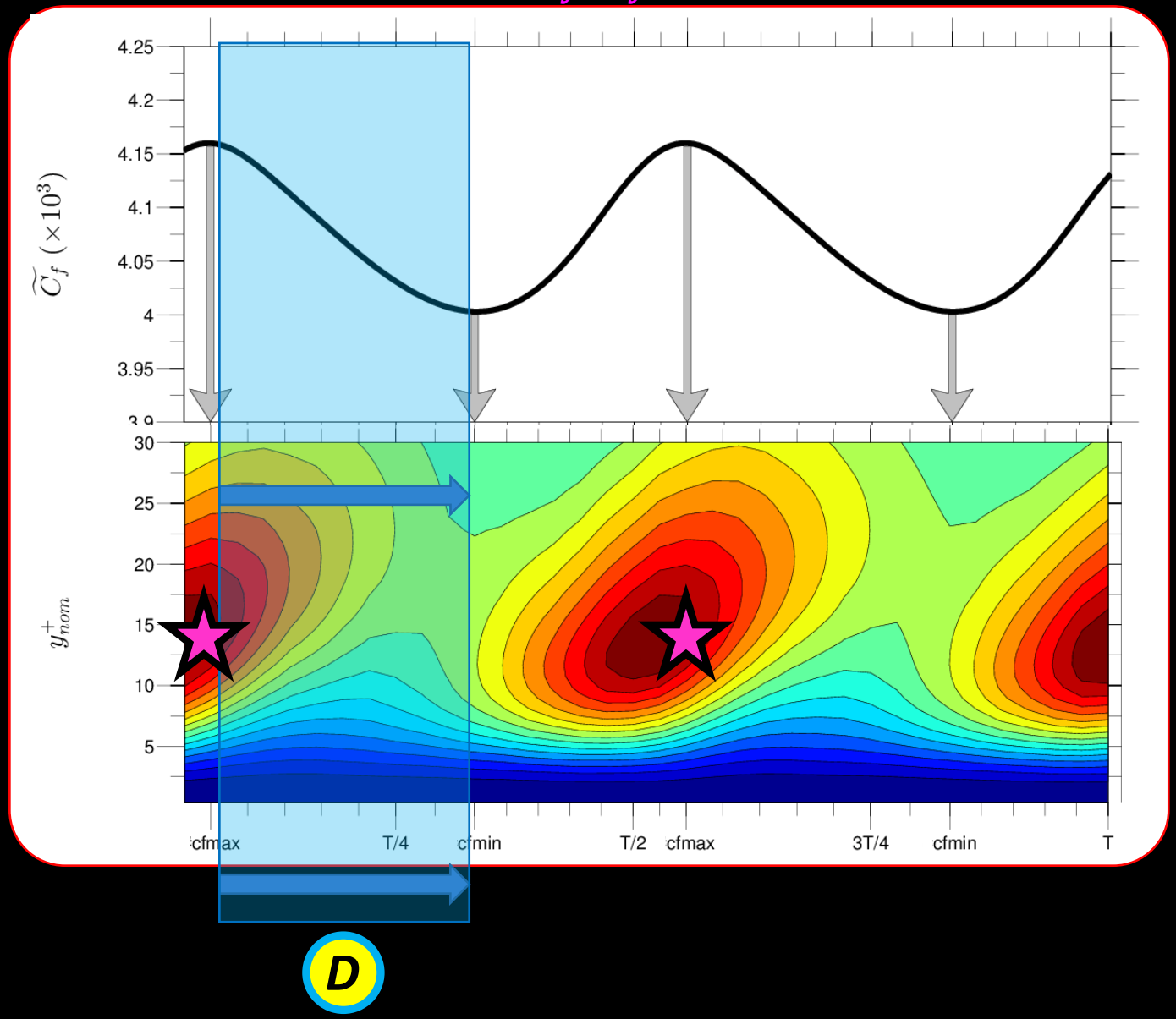
$$\widetilde{\omega_y''\omega_y''} \propto \widetilde{\frac{\partial u''}{\partial z}}\widetilde{\frac{\partial u''}{\partial z}}$$

Streaks magnitude

★ **Strongest Streaks**

D Streaks weaken and move away from the wall

Phase variations of $\widetilde{\omega_y''\omega_y''}$



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$$\widetilde{\omega_y'' \omega_y''} \propto \widetilde{\frac{\partial u''}{\partial z}} \widetilde{\frac{\partial u''}{\partial z}}$$

Streaks magnitude

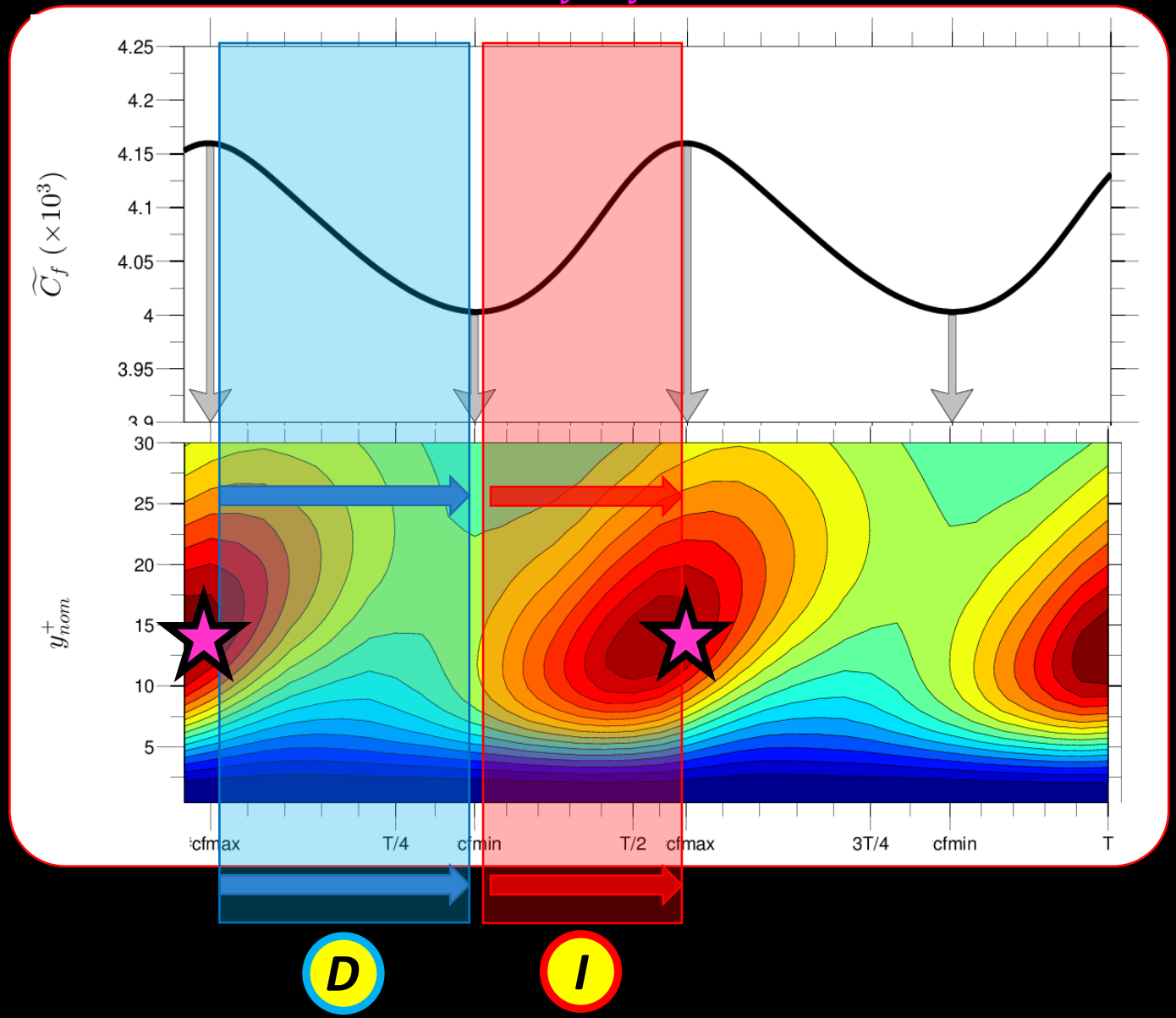
★ **Strongest Streaks**

D Streaks weaken and move away from the wall

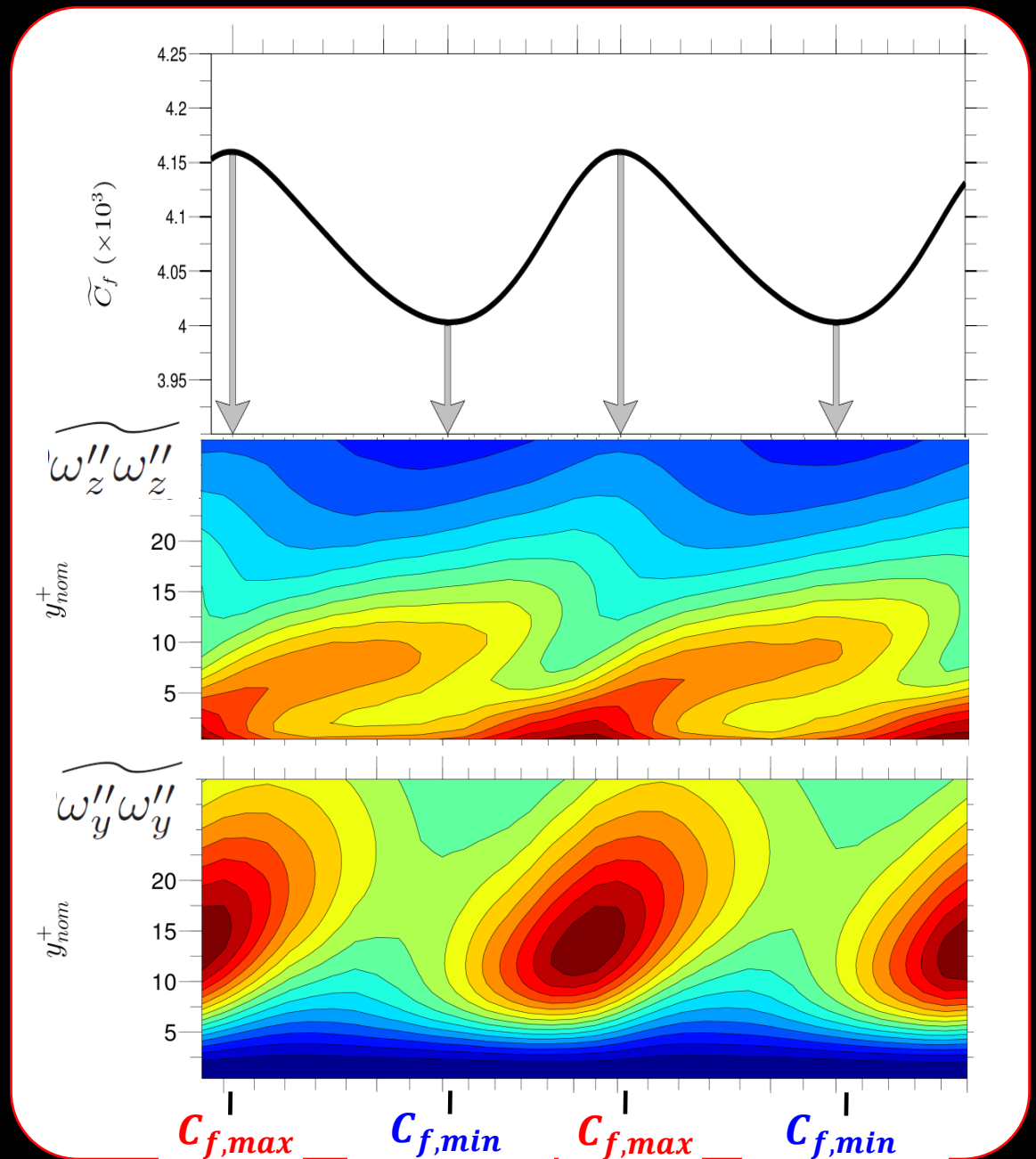
I Generation of new streaks close to the wall

"Hysteresis"

Phase variations of $\widetilde{\omega_y'' \omega_y''}$



Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation – Drag-Reduction mechanism



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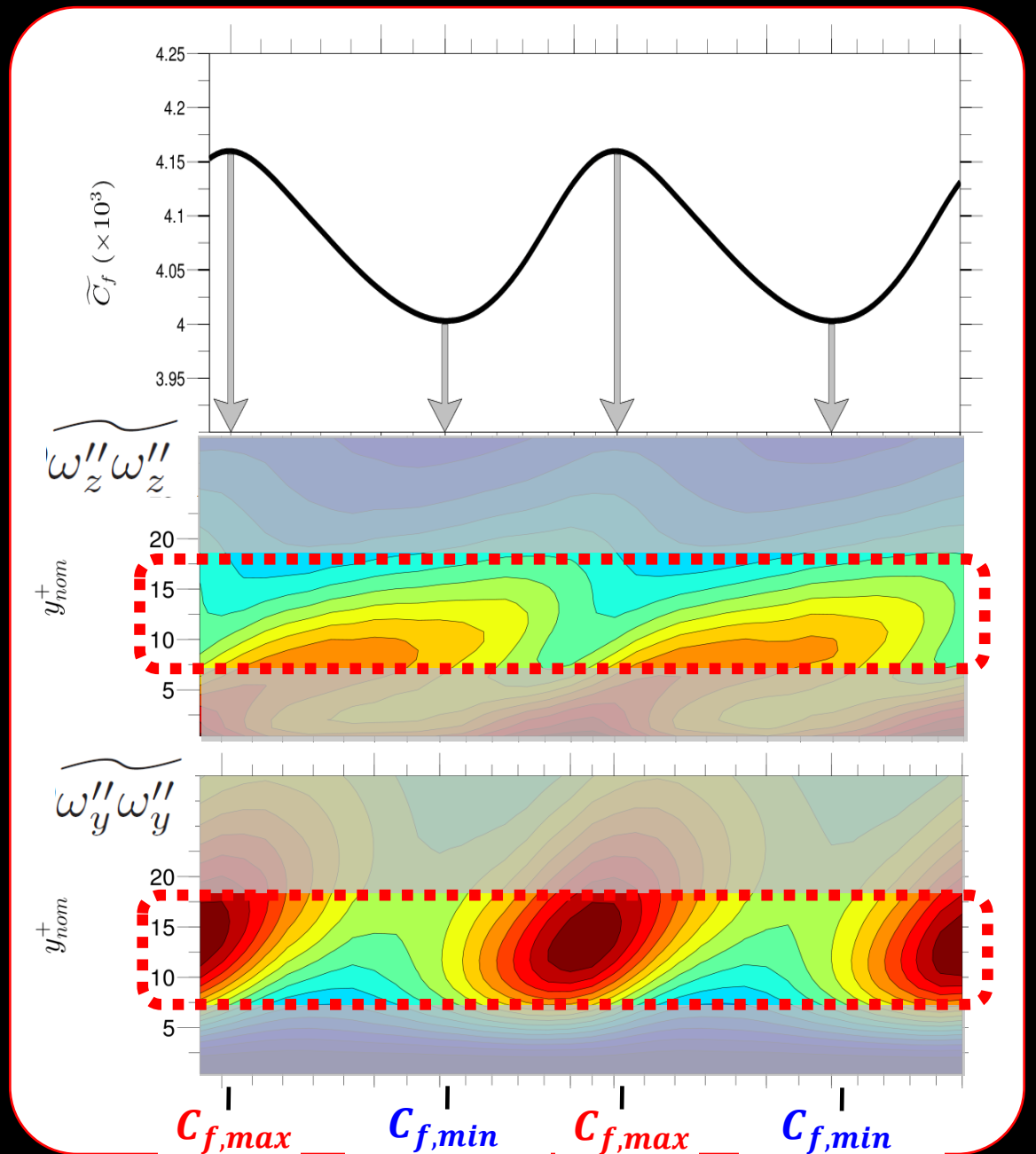

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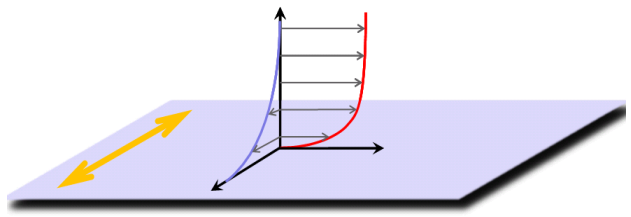
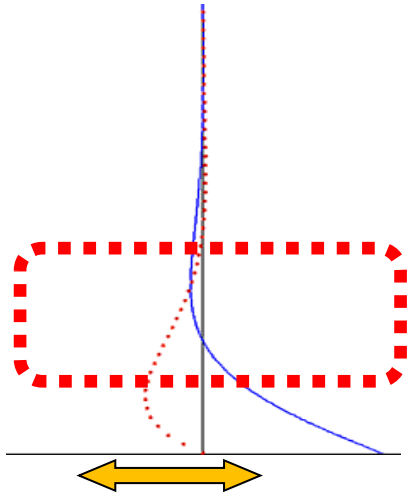
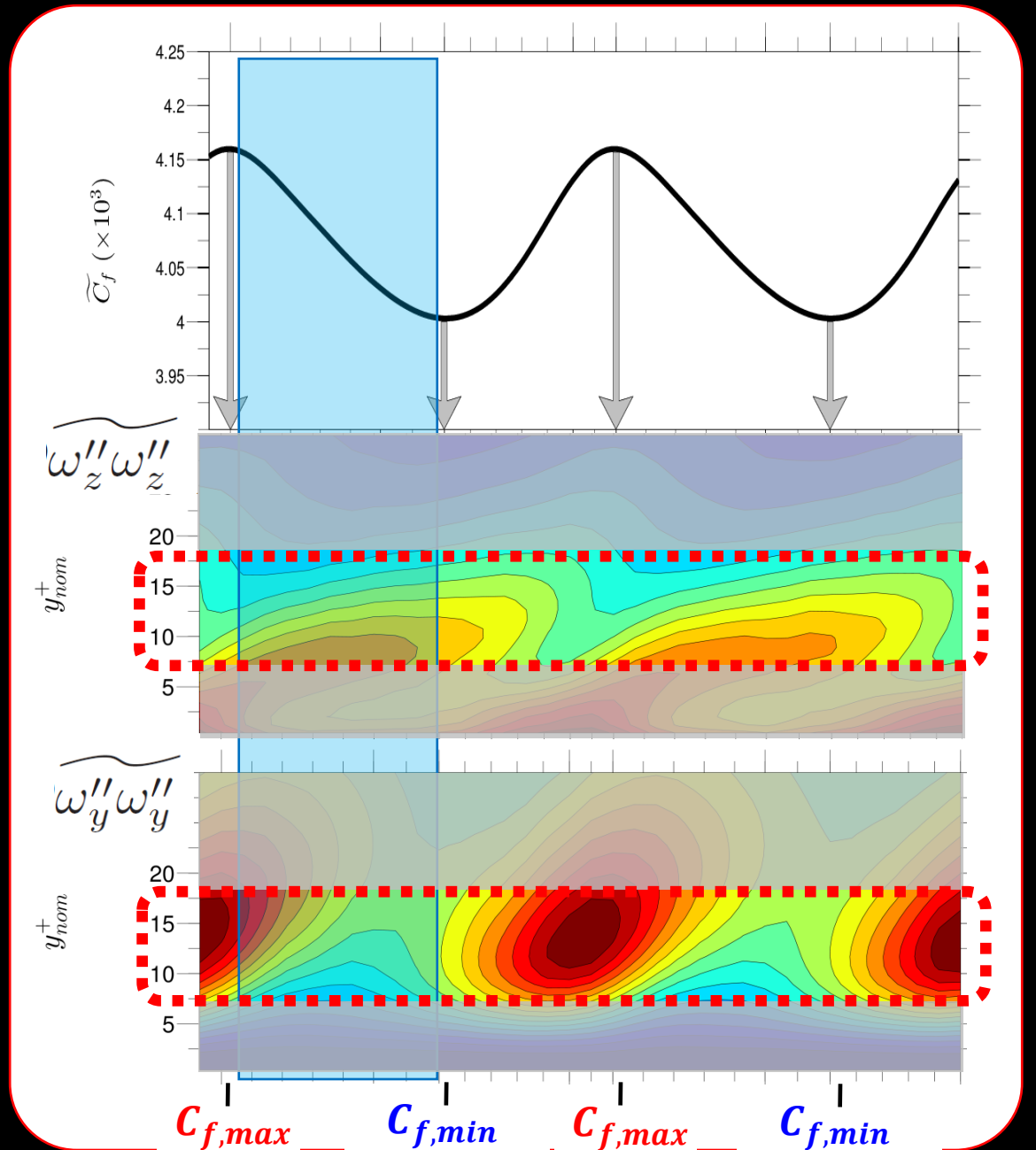
Spanwise wall oscillation – Drag-Reduction mechanism

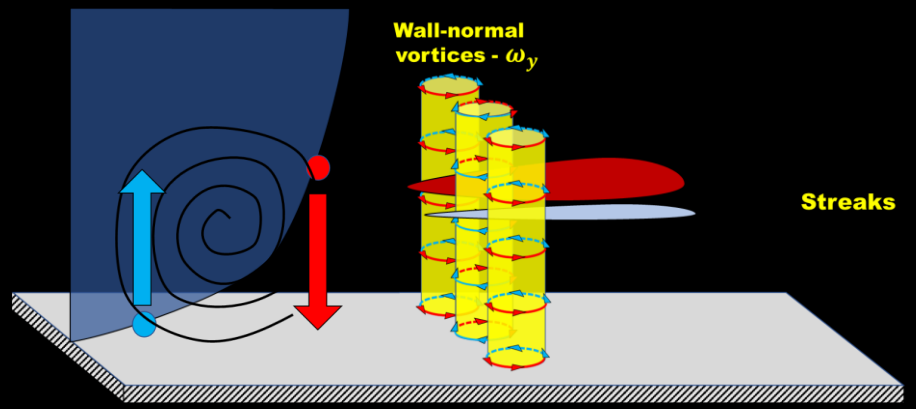


$$W(t) = W_m \cos(2\pi t / T)$$



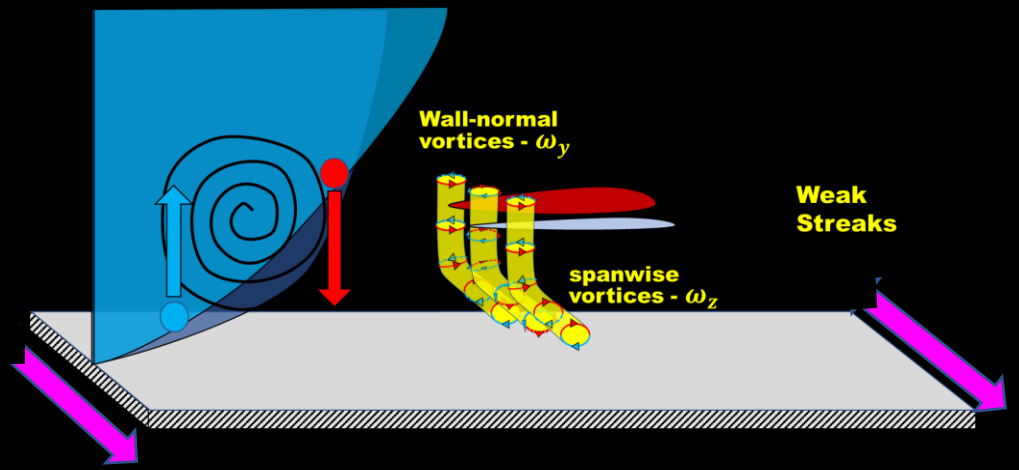


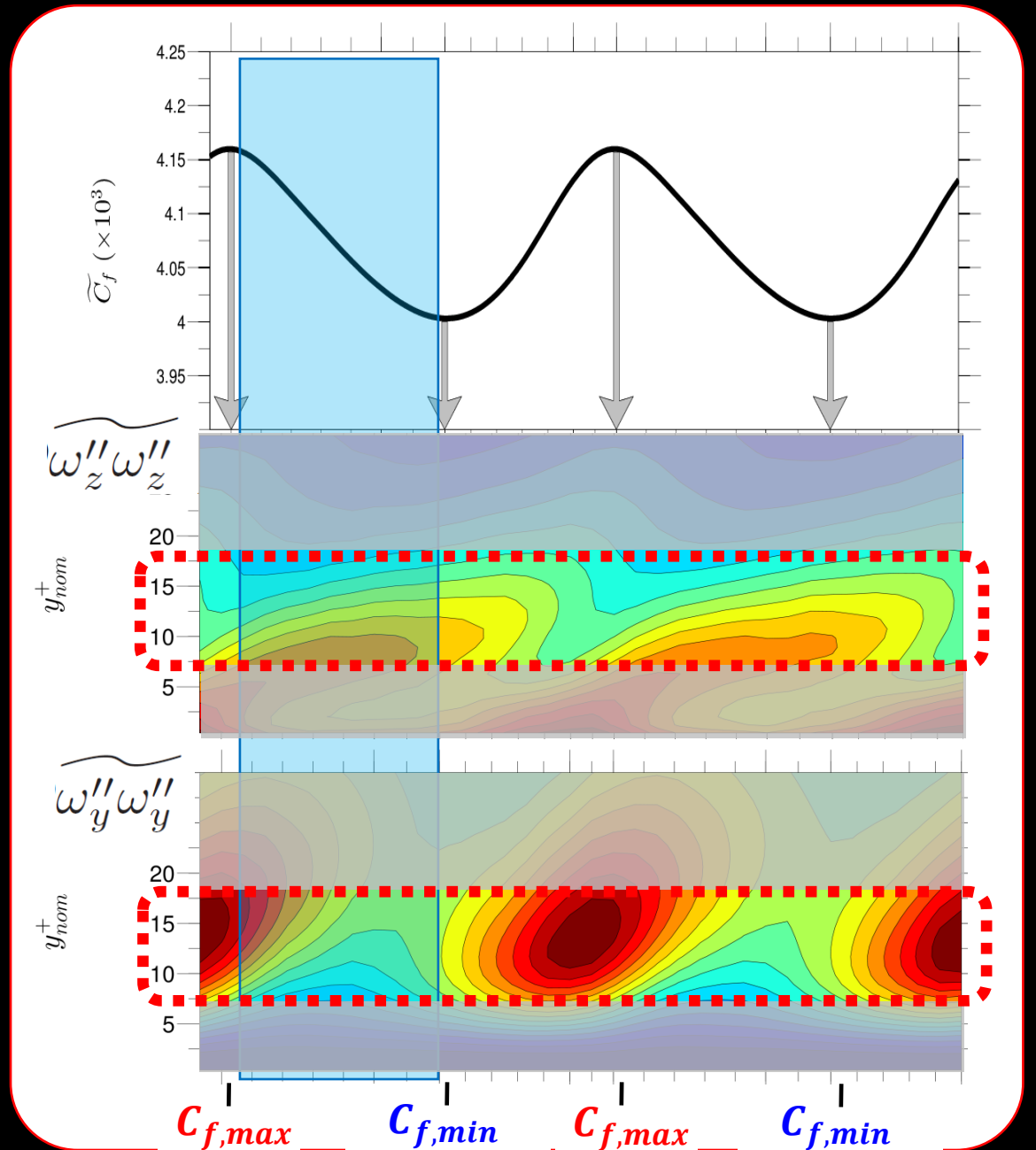
Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation – Drag-Reduction mechanism



"Tilting"

D $\quad \omega_y'' \Rightarrow \omega_z''$



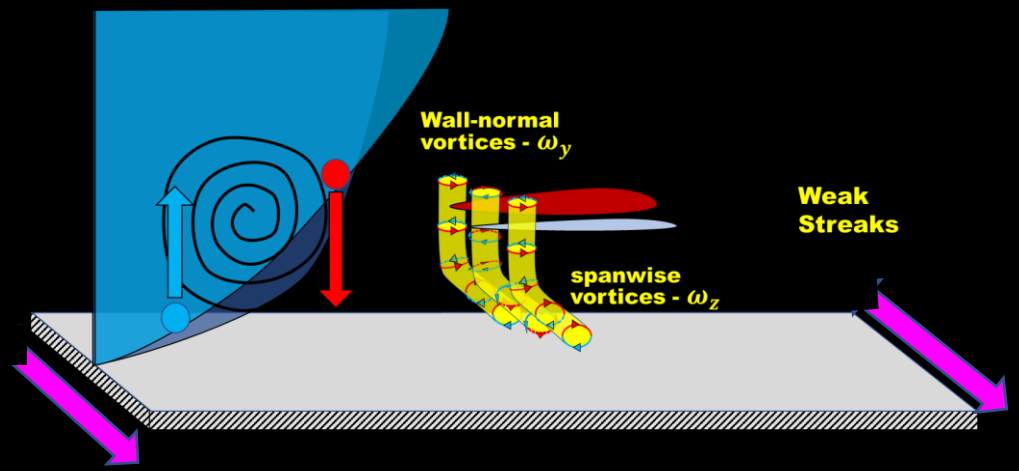


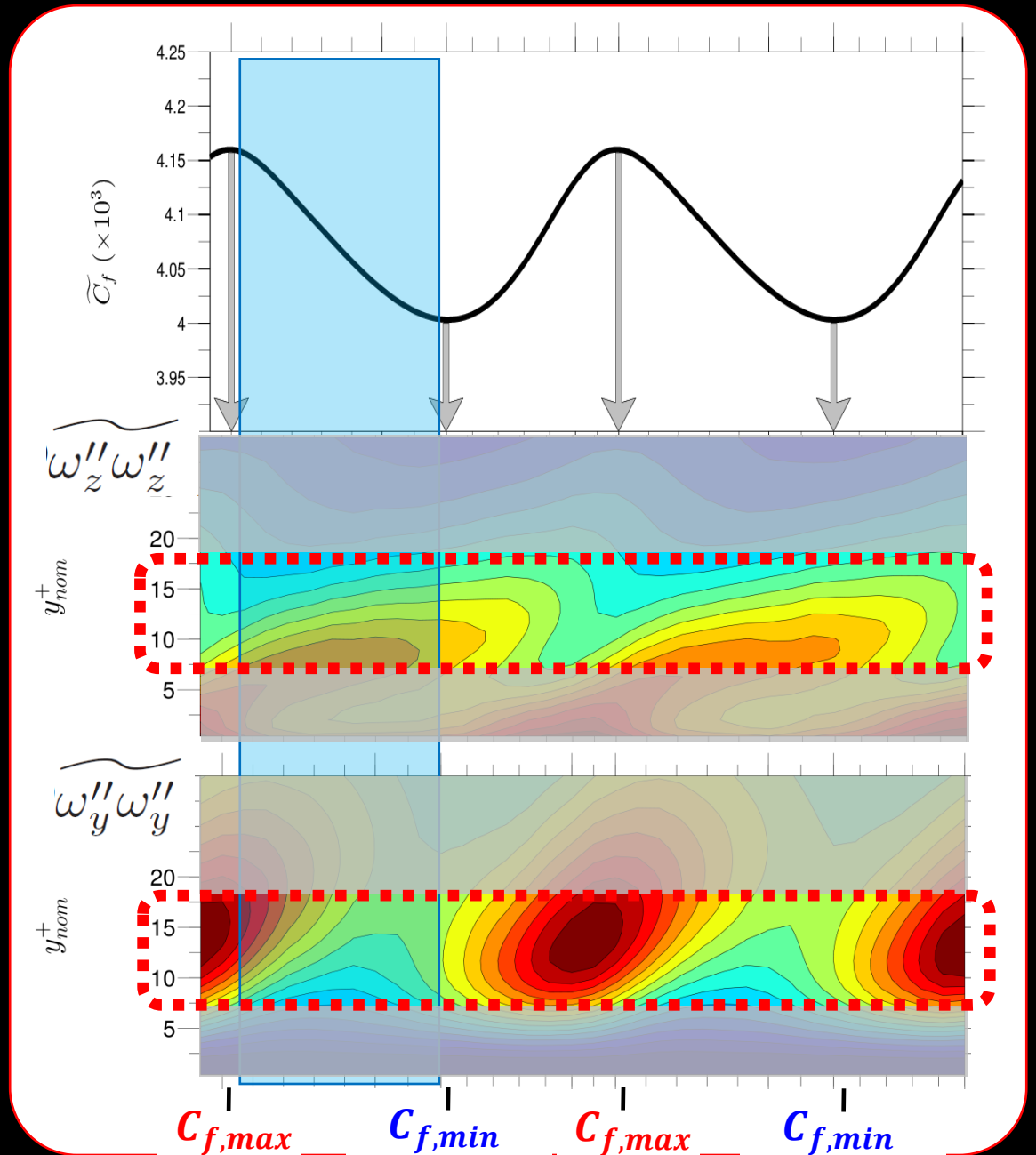
Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation – Drag-Reduction mechanism

the streaks-formation process is blocked

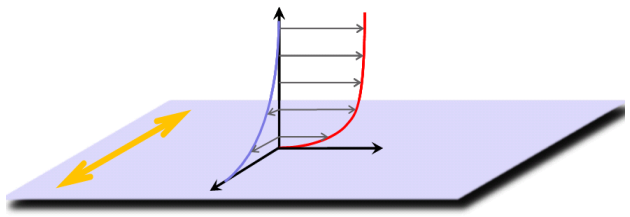
"Tilting"

D $\omega_y'' \Rightarrow \omega_z''$

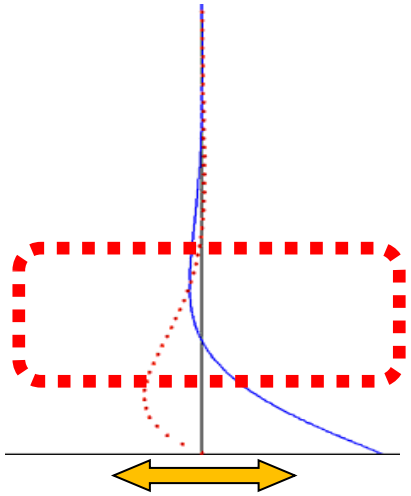


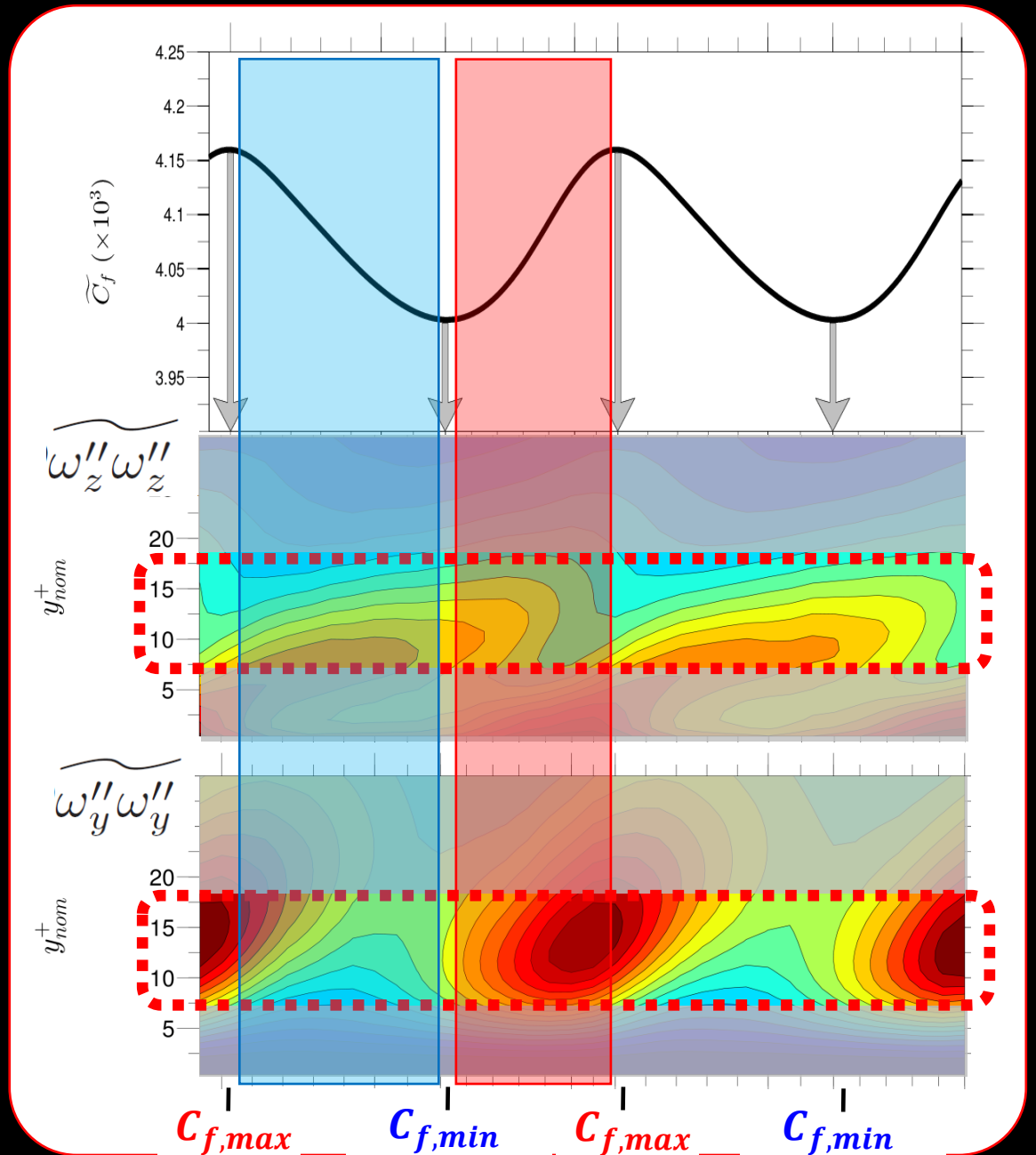


Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation – Drag-Reduction mechanism



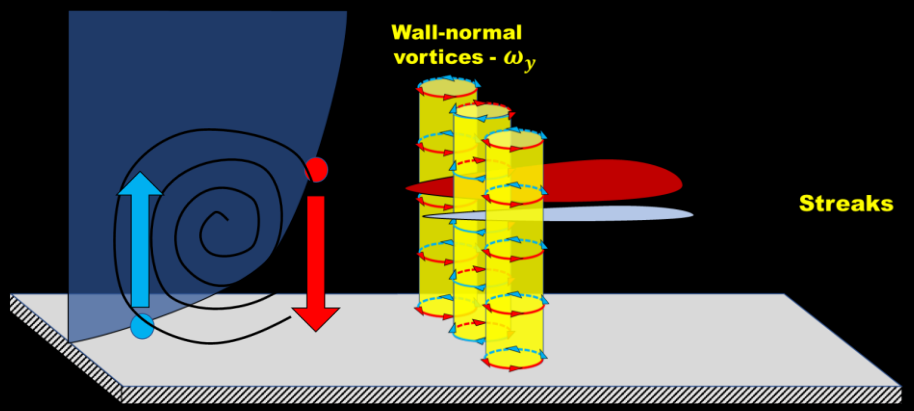
$$W(t) = W_m \cos(2\pi t / T)$$

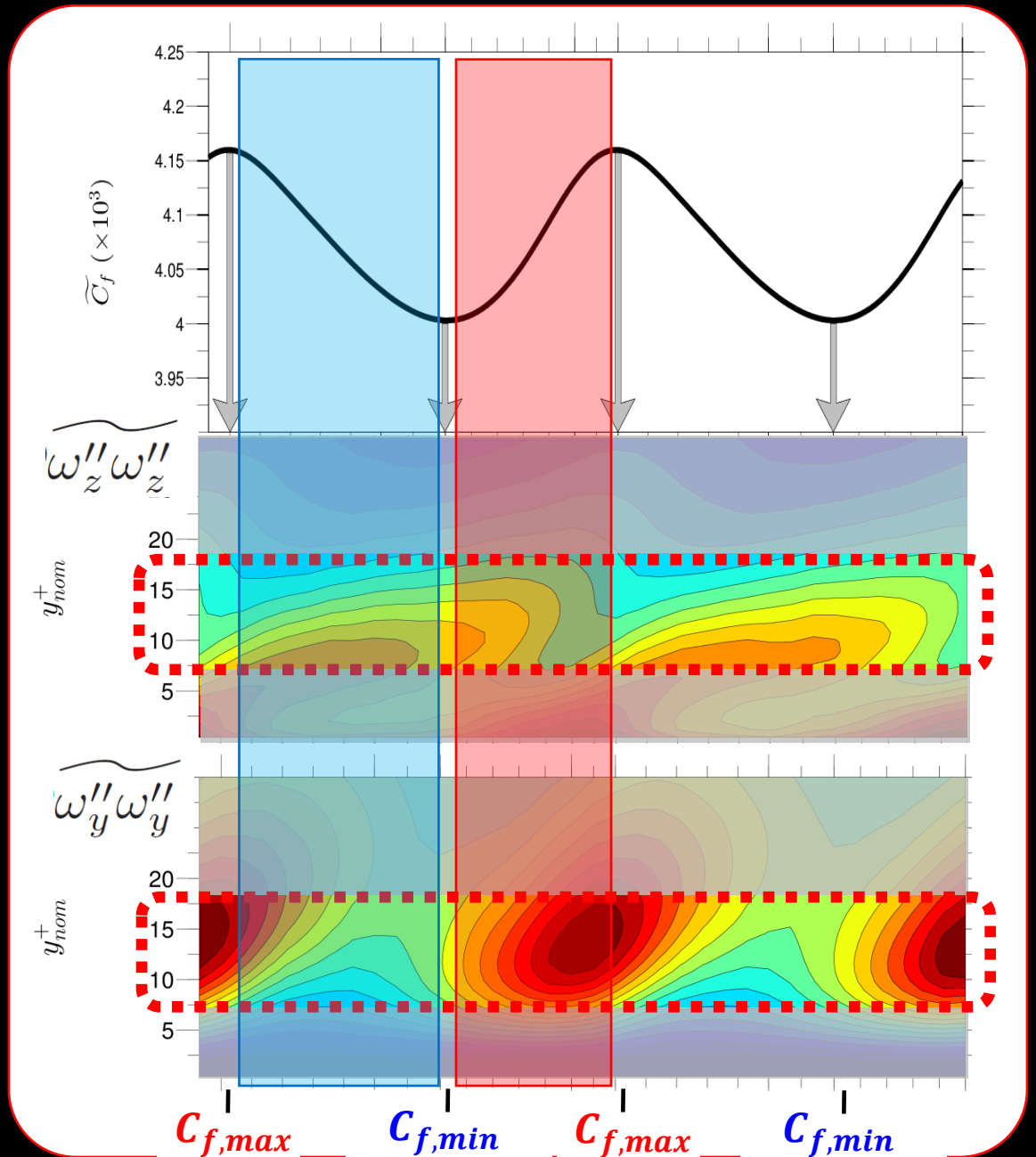




Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation – Drag-Reduction mechanism

I *No "Tilting"* ω_y''

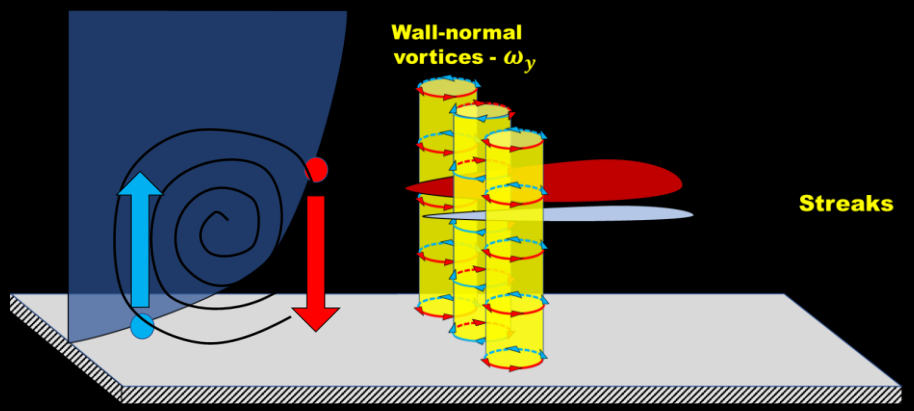


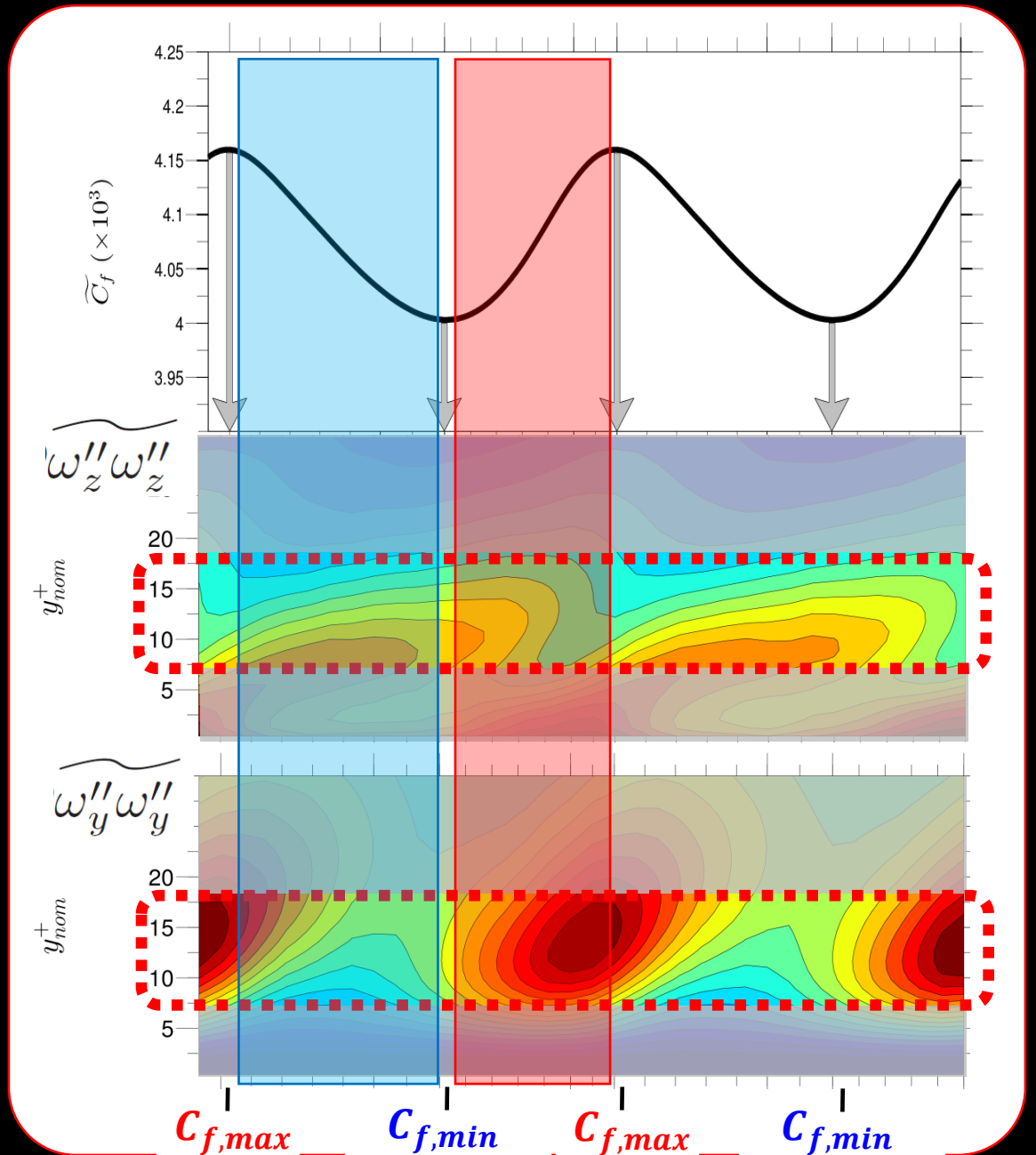


Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation – Drag-Reduction mechanism

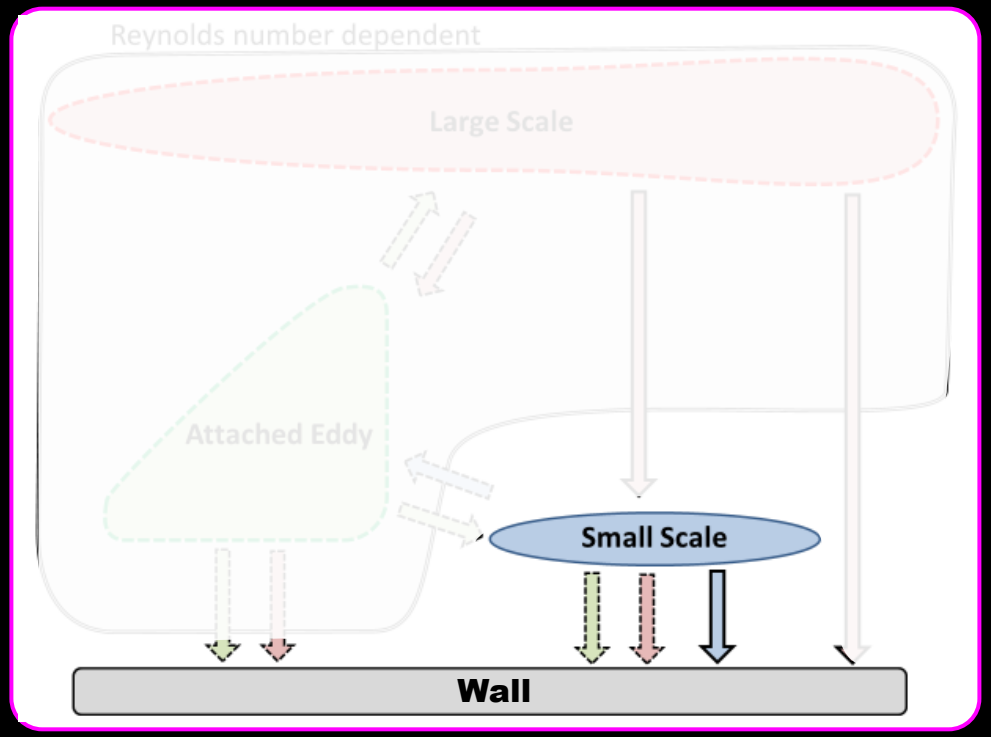
the streaks-formation process <u>resumes</u>

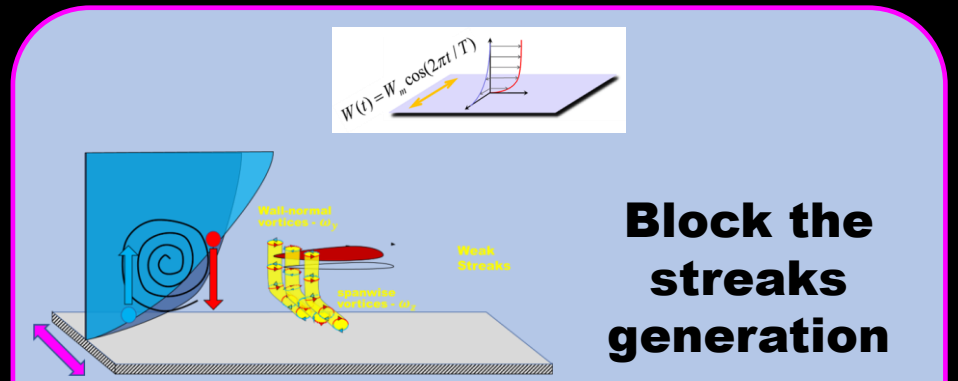
I *No "Tilting"* ω_y''





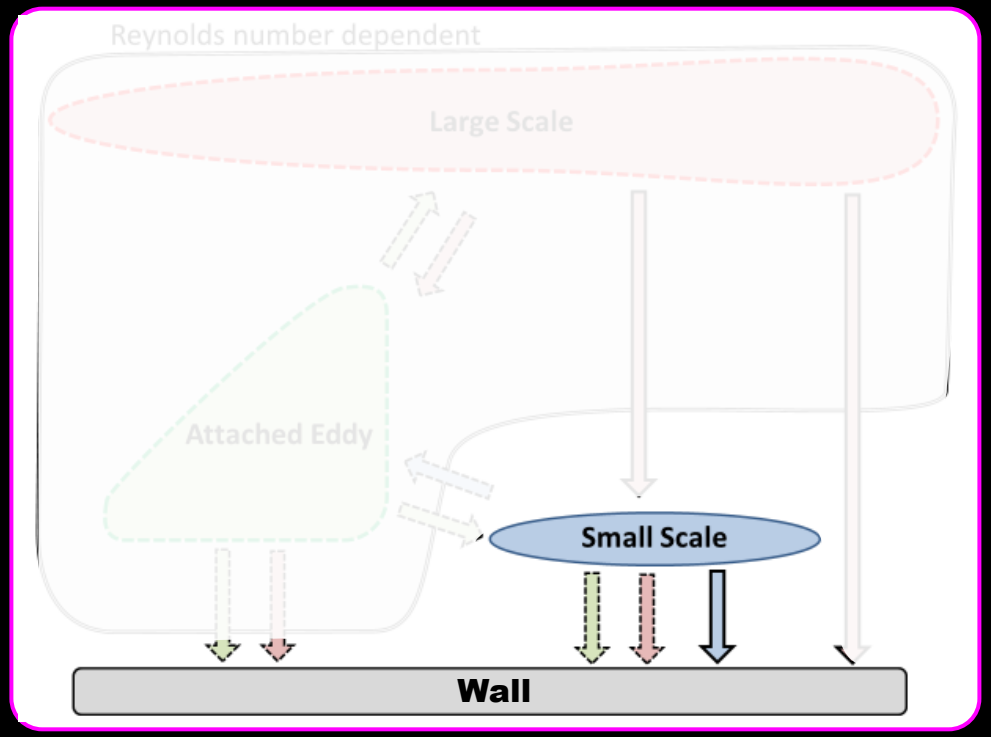
Near-wall turbulence
Multi-scale dynamic – Drag-Reduction mechanism

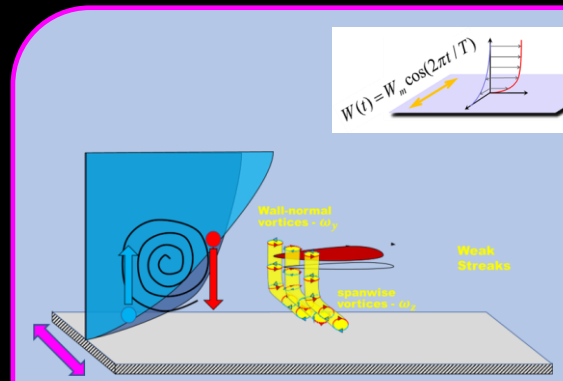




Block the streaks generation

Near-wall turbulence
Multi-scale dynamic – Drag-Reduction mechanism



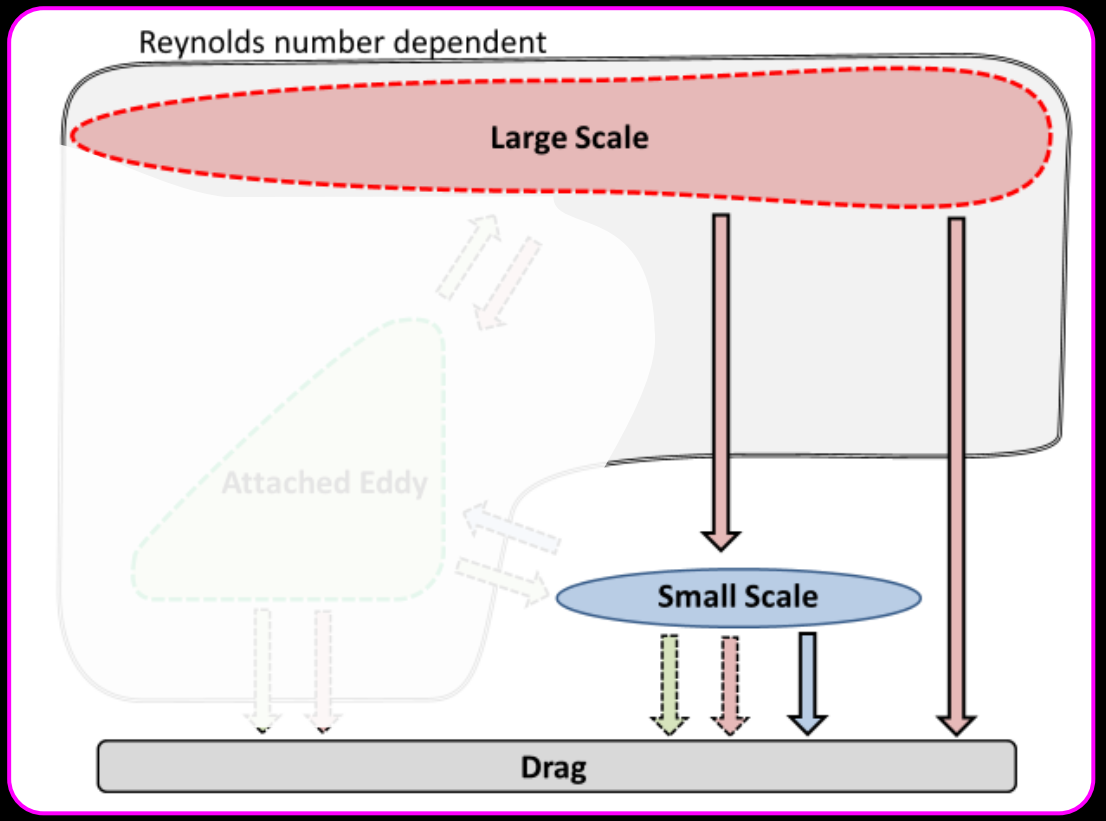


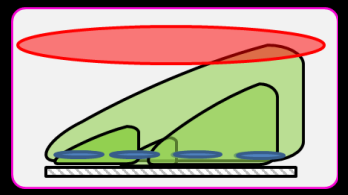
Block the streaks generation

⇨ Drag reduction
$\approx 40\%$ at $Re_\tau = 200$
$\approx 30\%$ at $Re_\tau = 1000$

Dynamic of Near-wall turbulence: Skeleton and Relations ``Vision Puzzle''

Pieces of the Puzzle





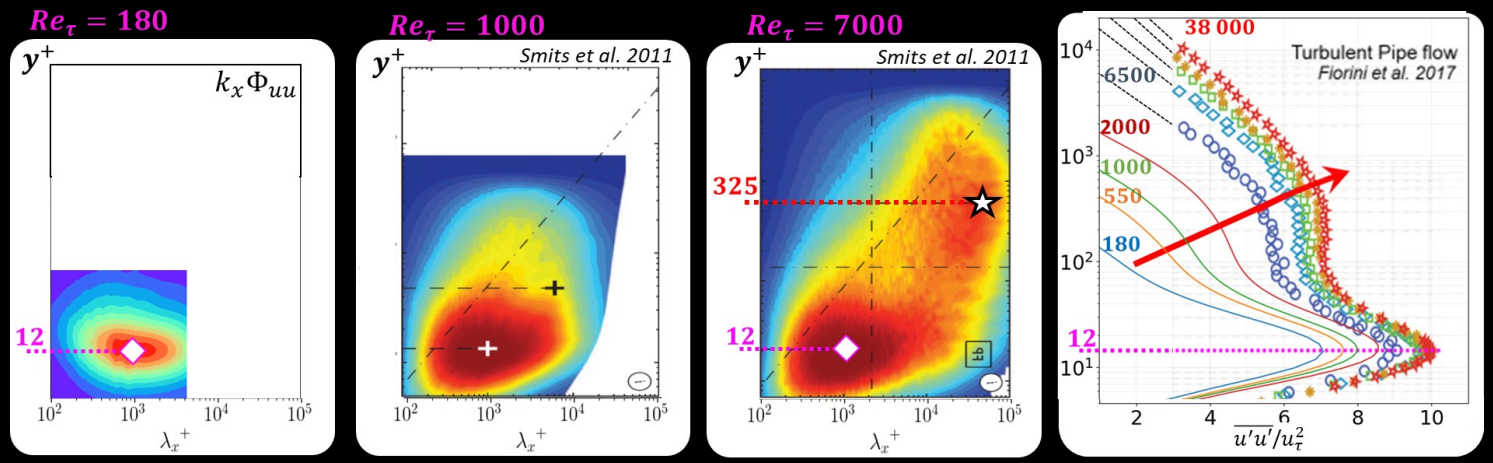
1- Near-wall structure control: drag reduction mechanism

2- Effects of large scales on near-wall small scales and drag

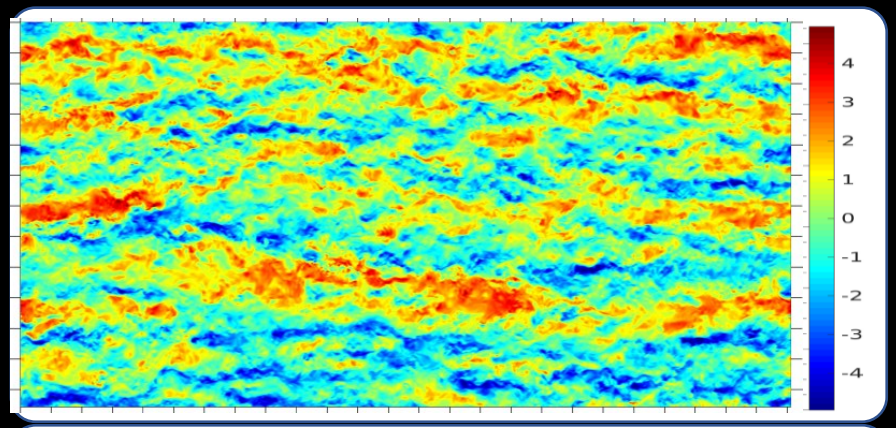
Actuated

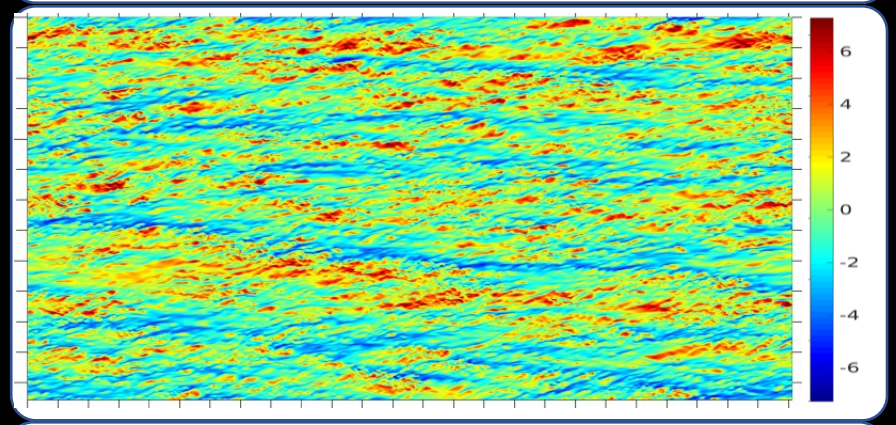
3- Identification and characterisation of energetic structures filling the spectral gap between large and small scales

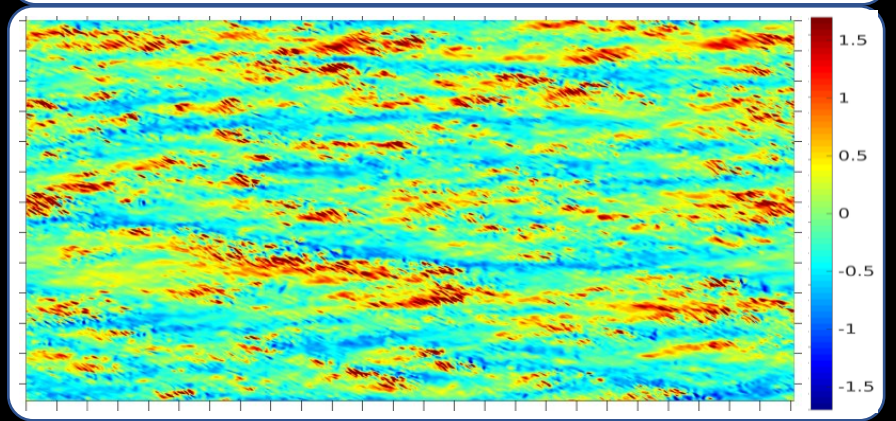
Drag Reduction
Effect of the Reynolds number



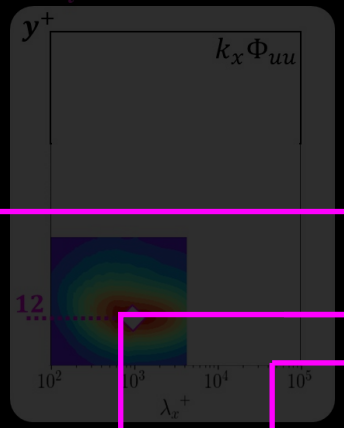
Drag Reduction
Effect of the Reynolds number



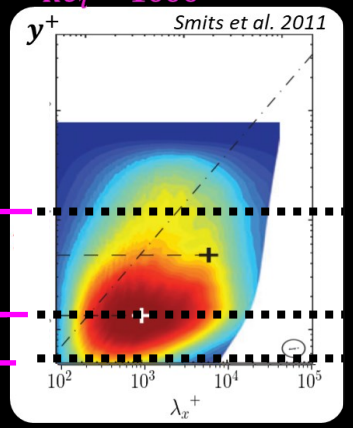




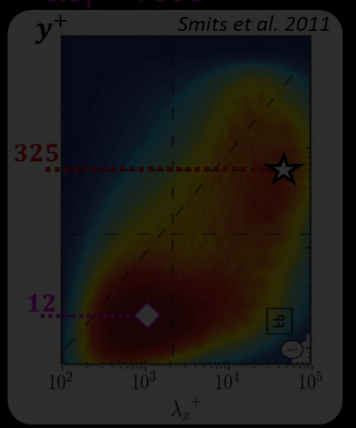
$Re_\tau = 180$

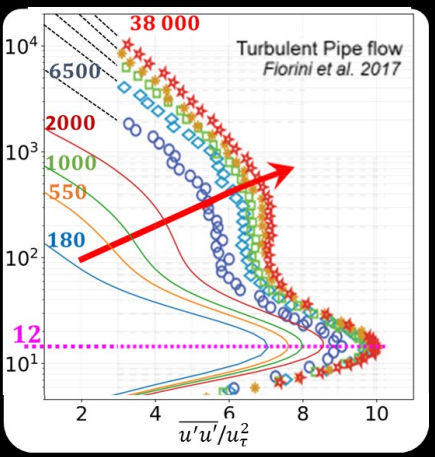


$Re_\tau = 1000$

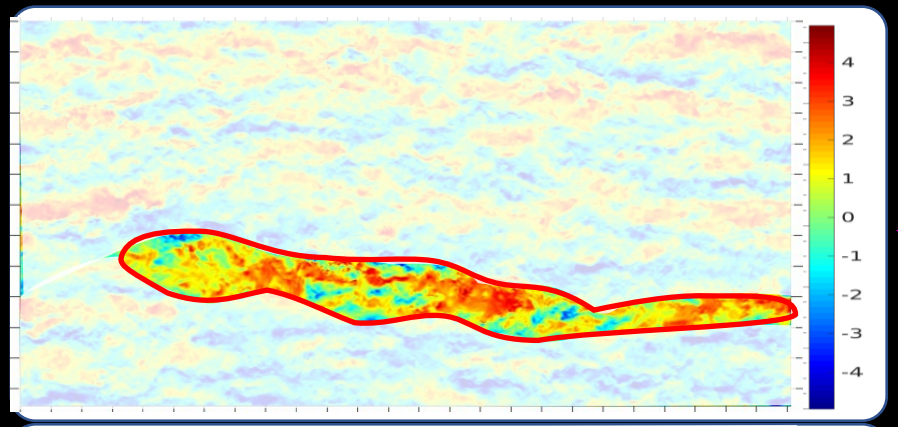


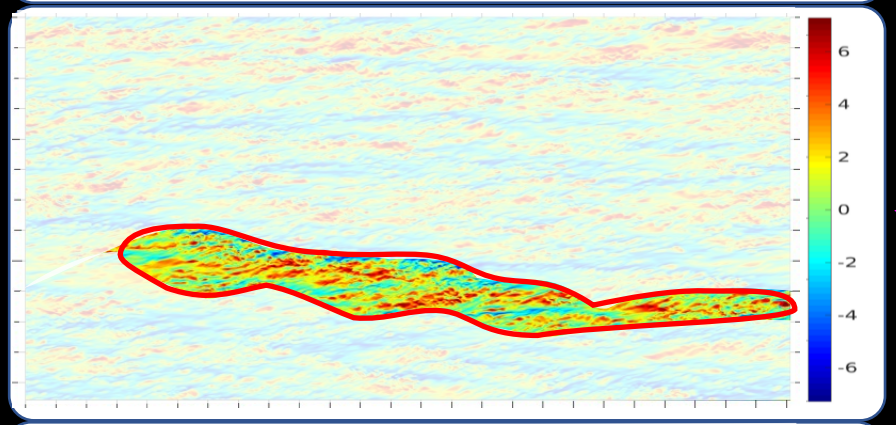
$Re_\tau = 7000$

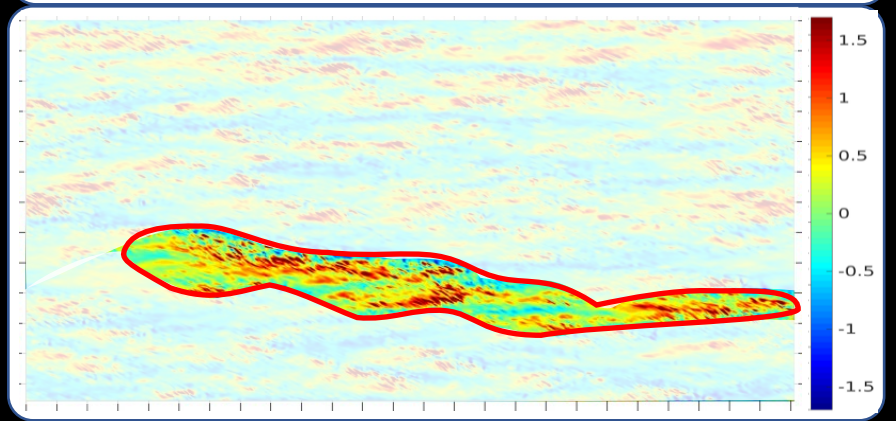


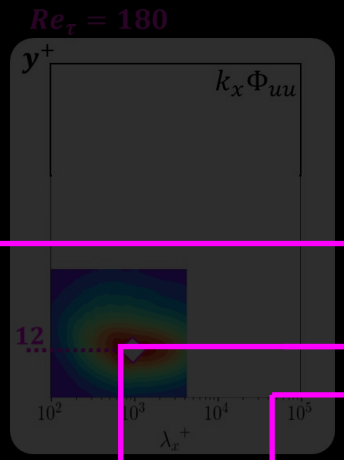


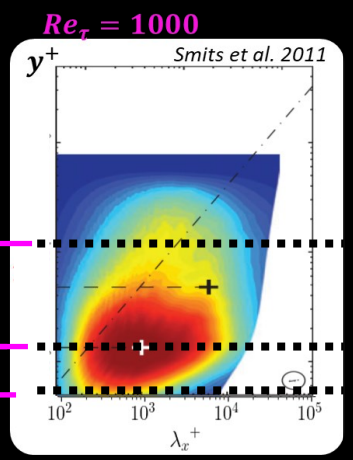
Drag Reduction
Effect of the Reynolds number – Large-Scale footprints

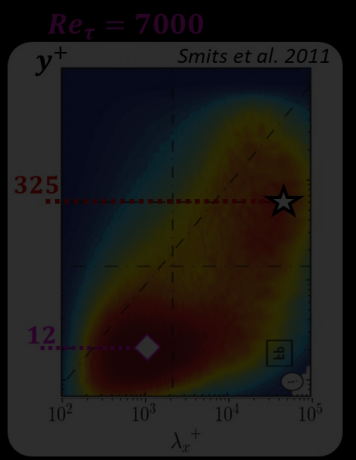


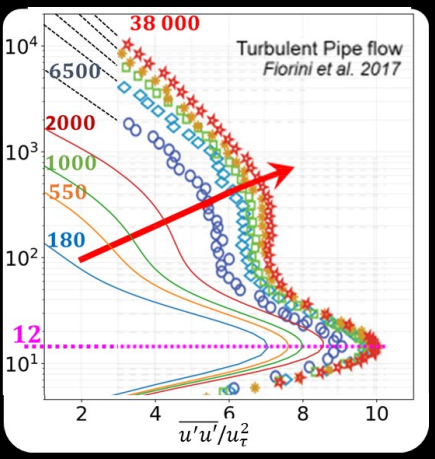






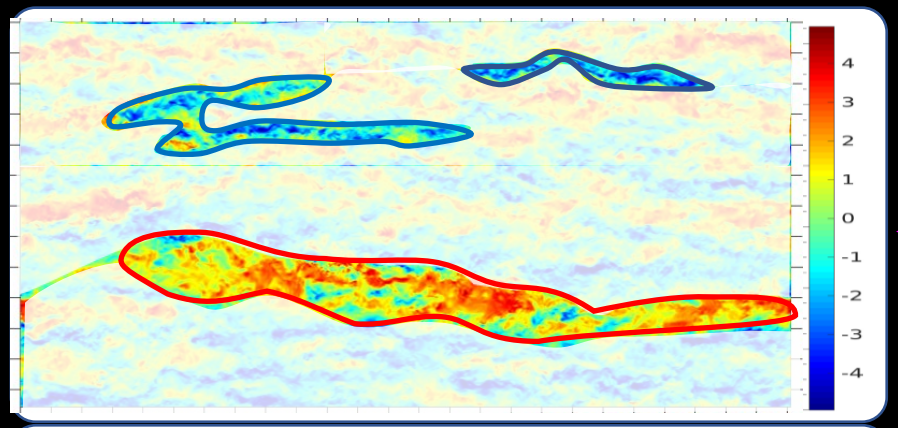


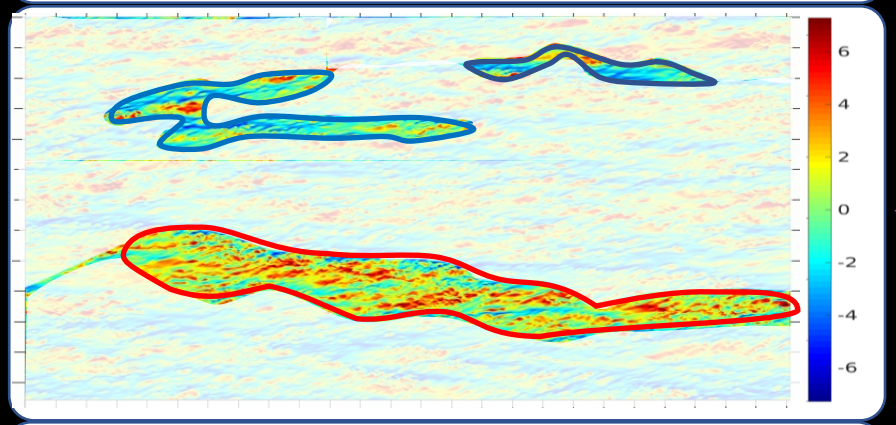


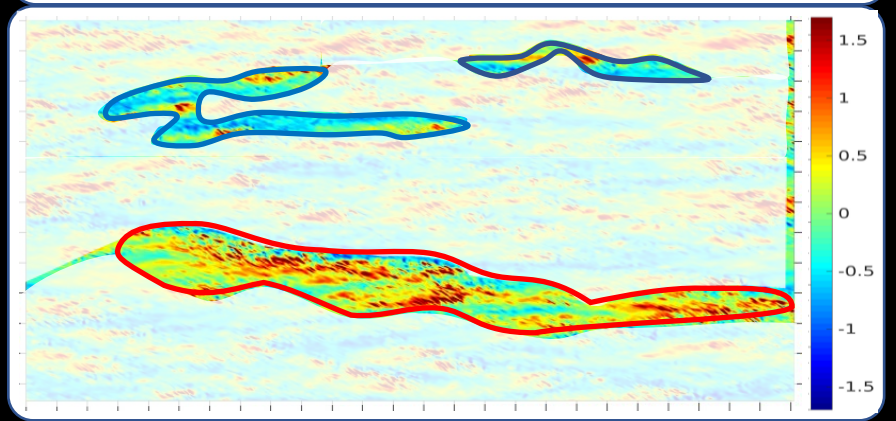


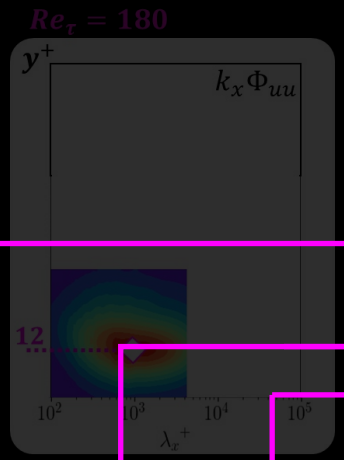
Positive LS motions ➡ streak amplification

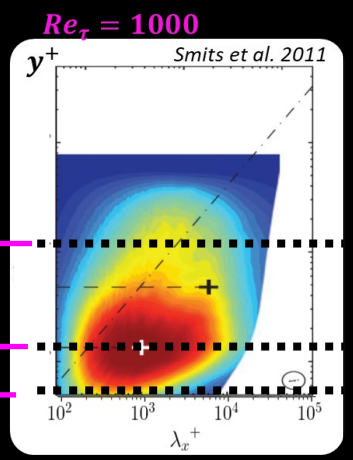
Drag Reduction
Effect of the Reynolds number – Large-Scale footprints

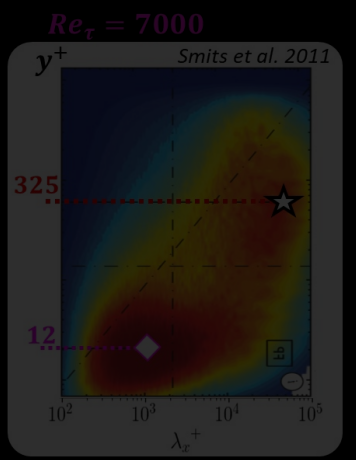


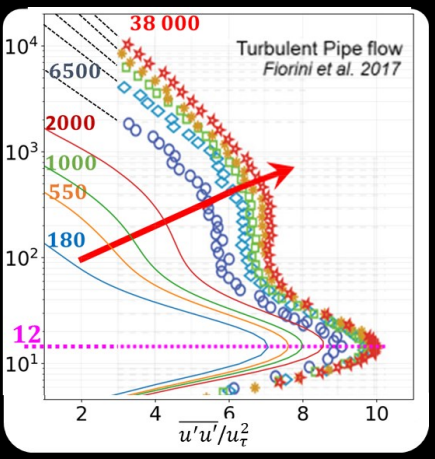








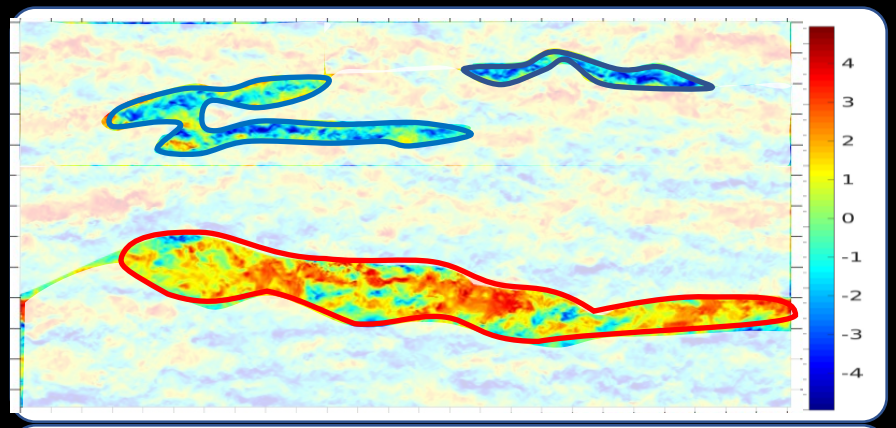


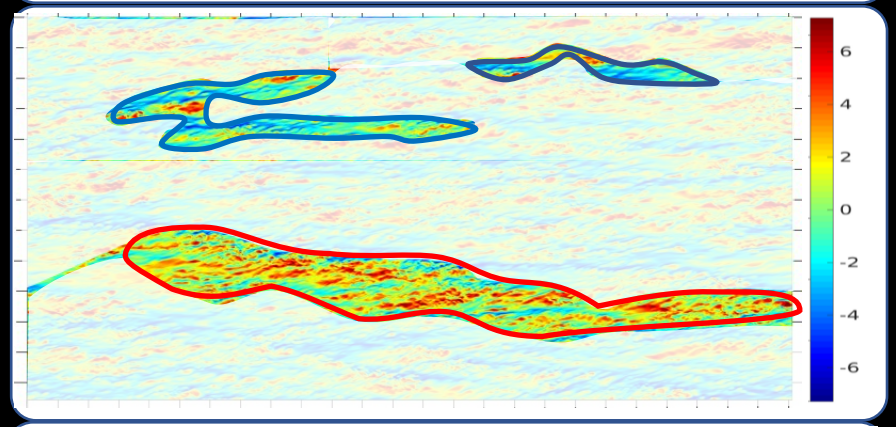


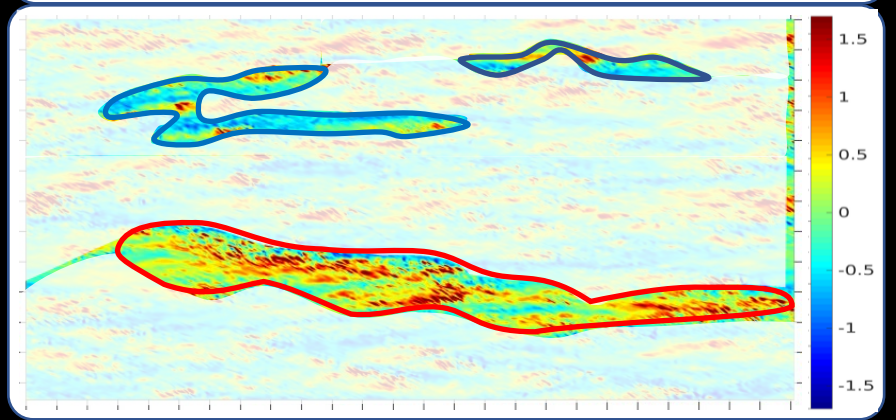
Positive LS motions ➡ streak amplification

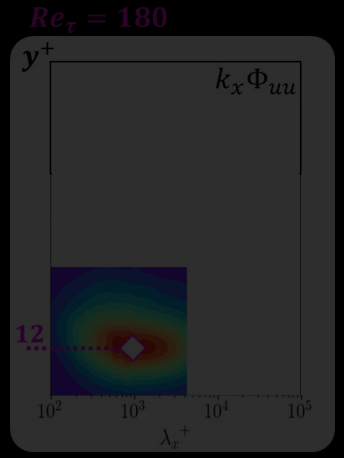
Negative LS motions ➡ streak attenuation

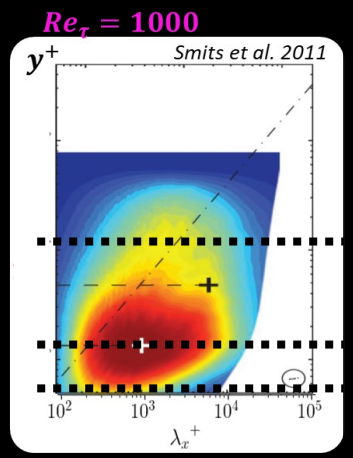
Drag Reduction
Effect of the Reynolds number – Large-Scale footprints

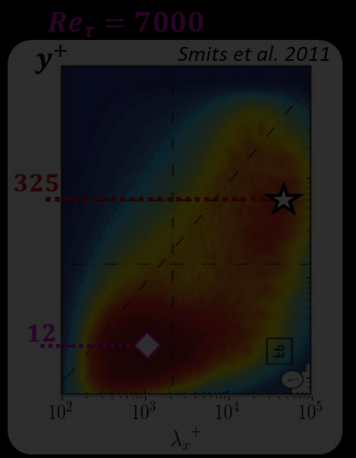


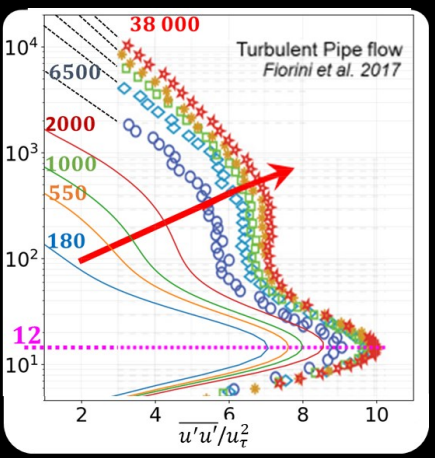












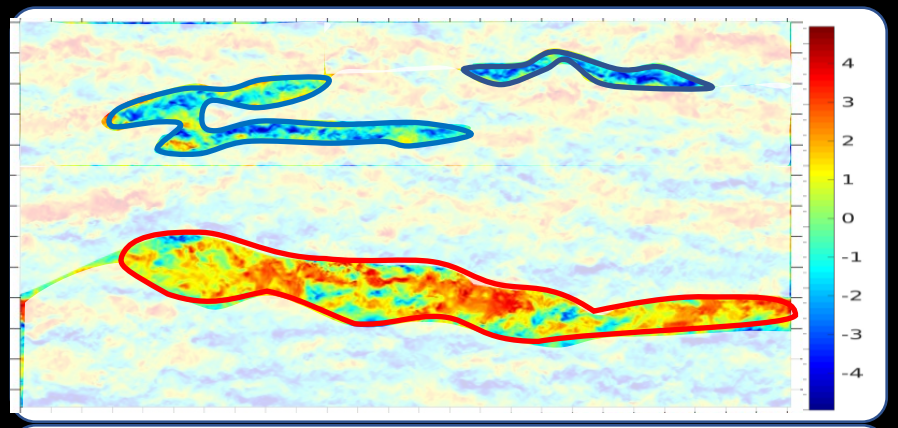
Positive LS motions ➡ streak amplification

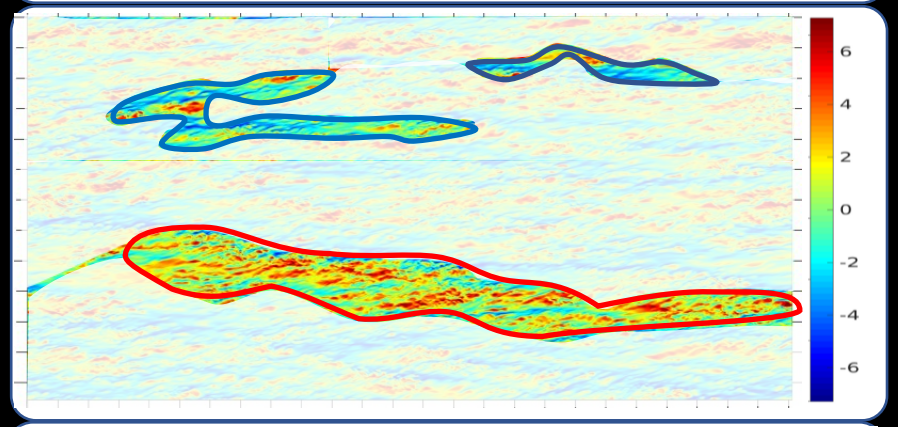
Negative LS motions ➡ streak attenuation

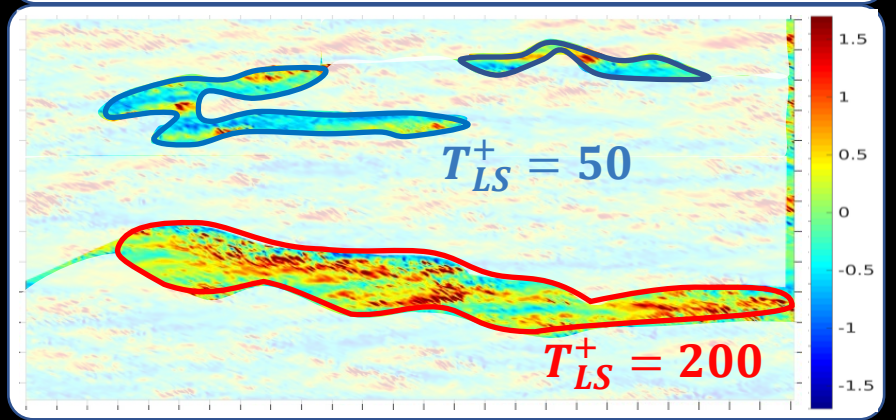
$$T^+ = \overline{T}^+ + T_{LS}^+$$

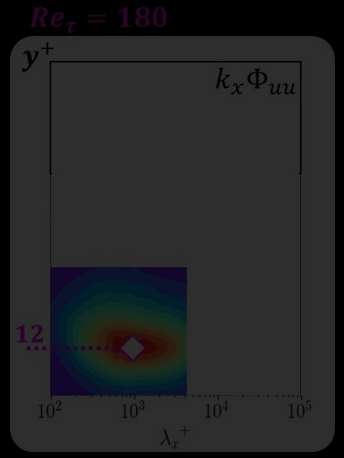
$$with\ T_{LS}^+ = \frac{T\,u_{\tau,LS}^2}{\nu}$$

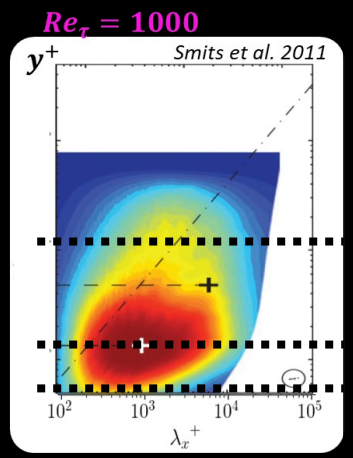
Drag Reduction
Effect of the Reynolds number – Large-Scale footprints

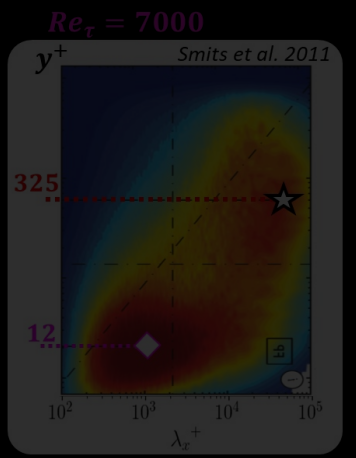


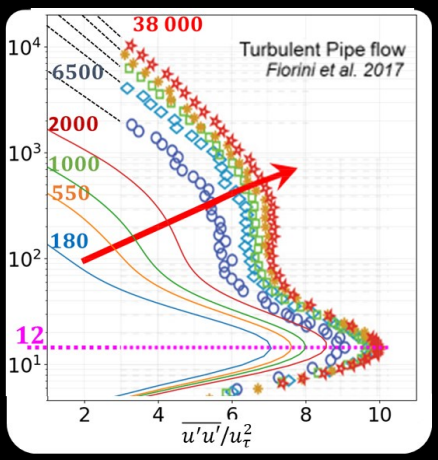










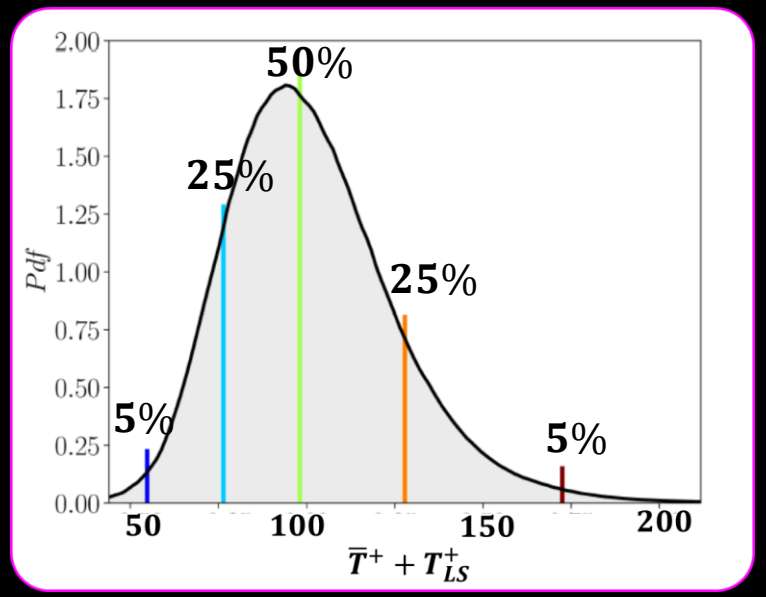


Positive LS motions ➡ streak amplification

Negative LS motions ➡ streak attenuation

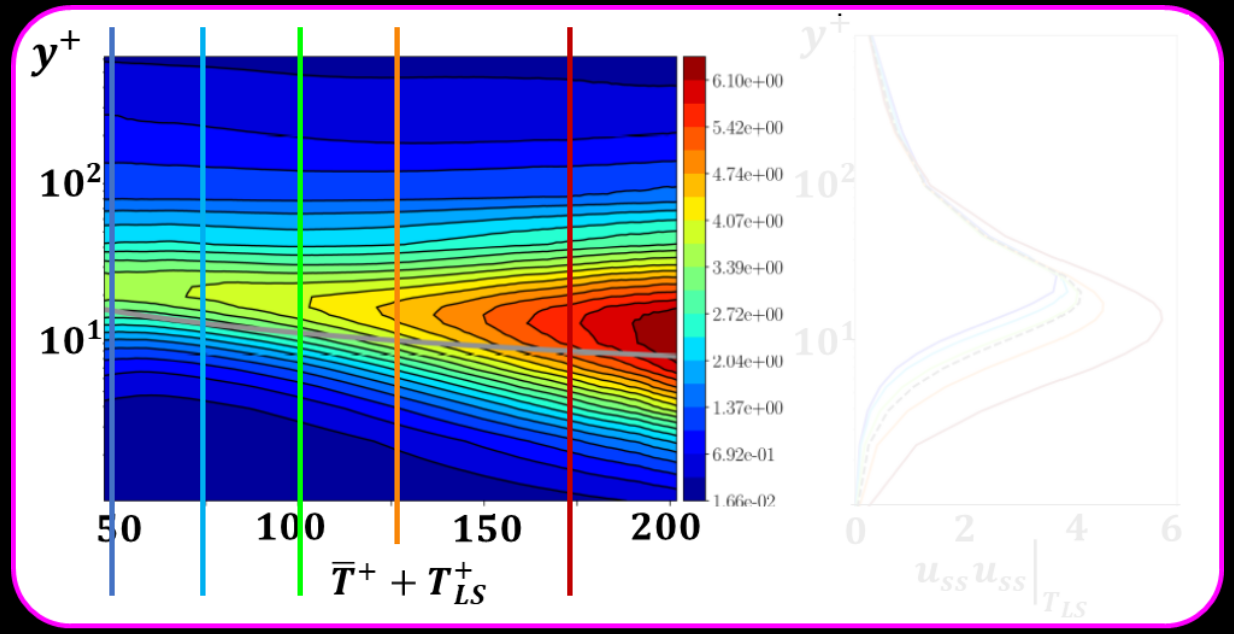
$$T^+ = \overline{T}^+ + T^+_{LS}$$

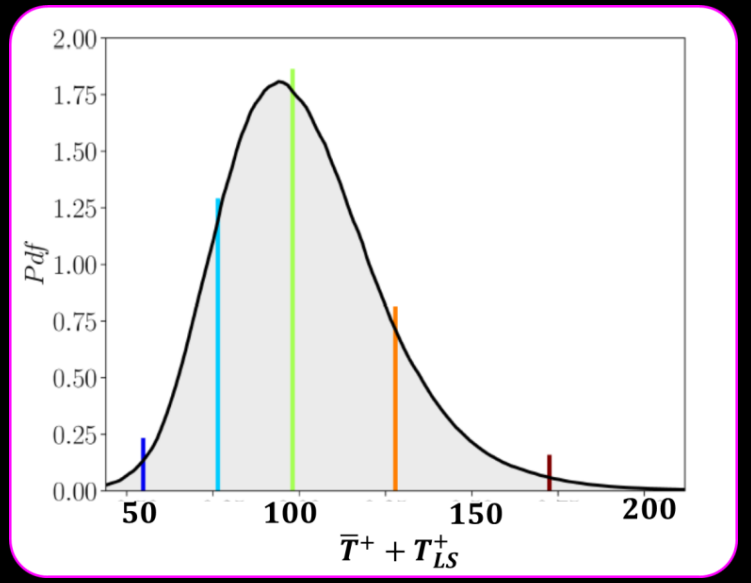
$$with\ T^+_{LS} = \frac{T\,u^2_{\tau,LS}}{\nu}$$



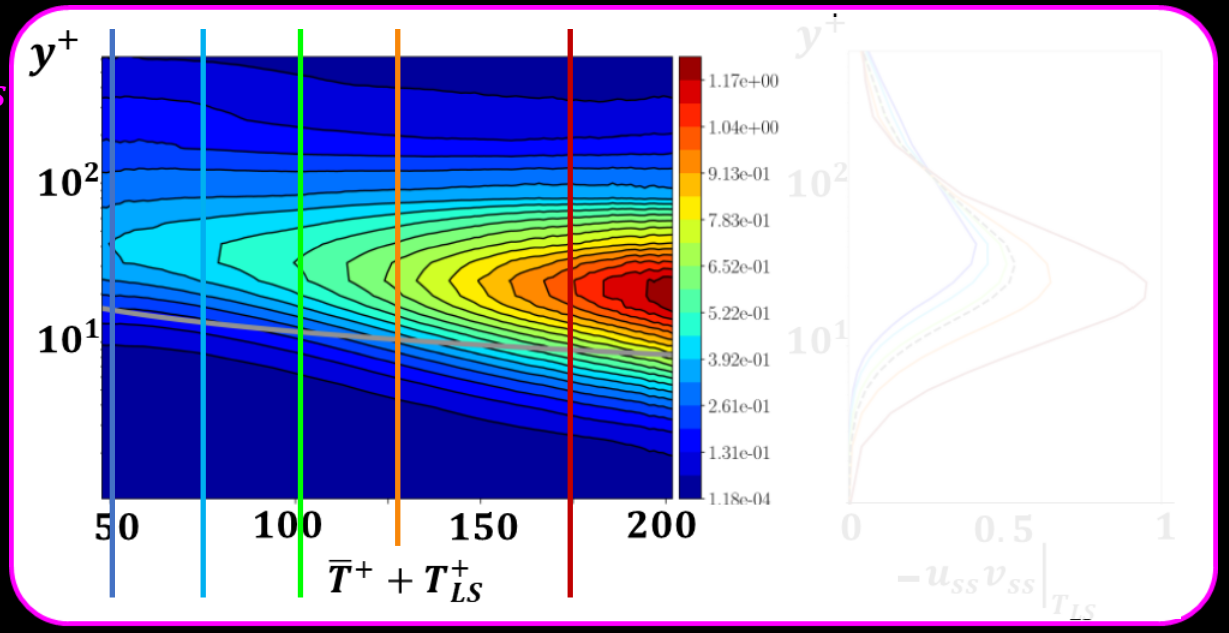
Drag Reduction
Effect of the Reynolds number – Conditional response to T_{LS}^{+}

$u_{ss}u_{ss}\big|_{T_{LS}}$



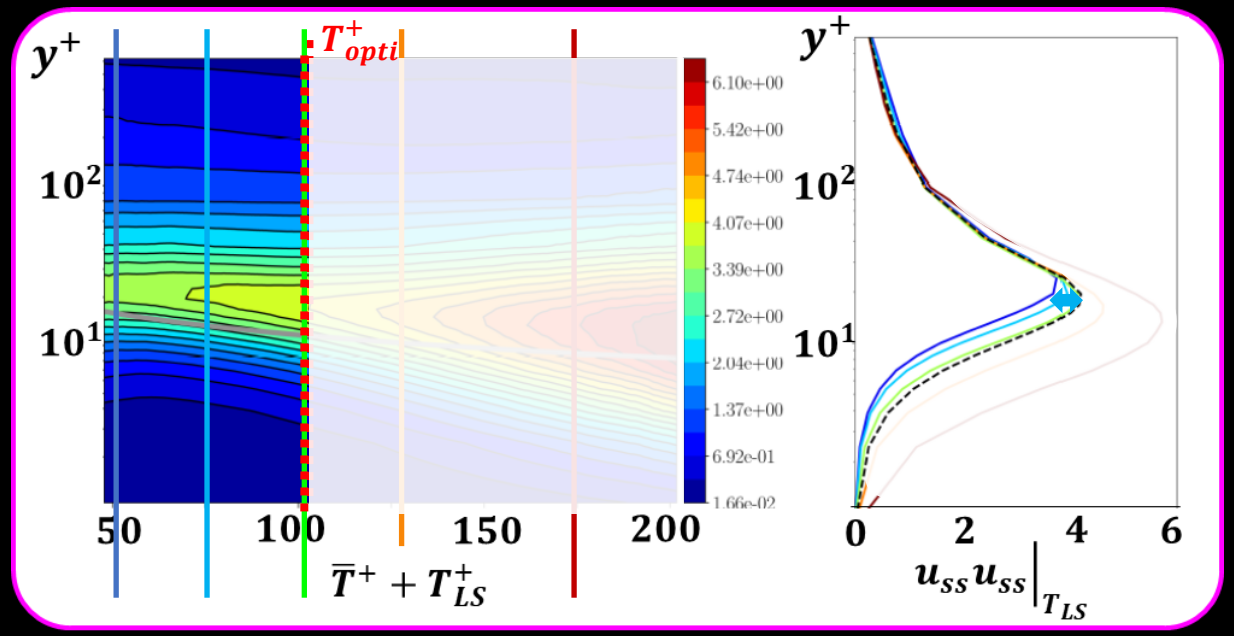


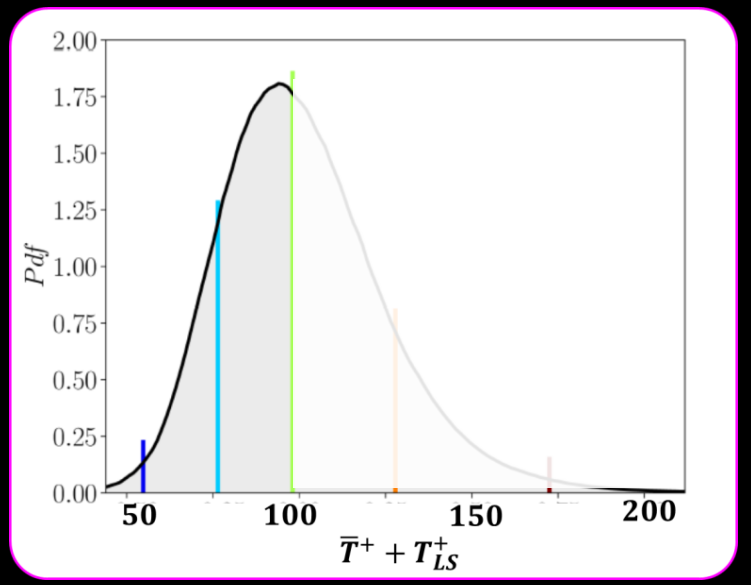
$-u_{ss}v_{ss}\big|_{T_{LS}}$



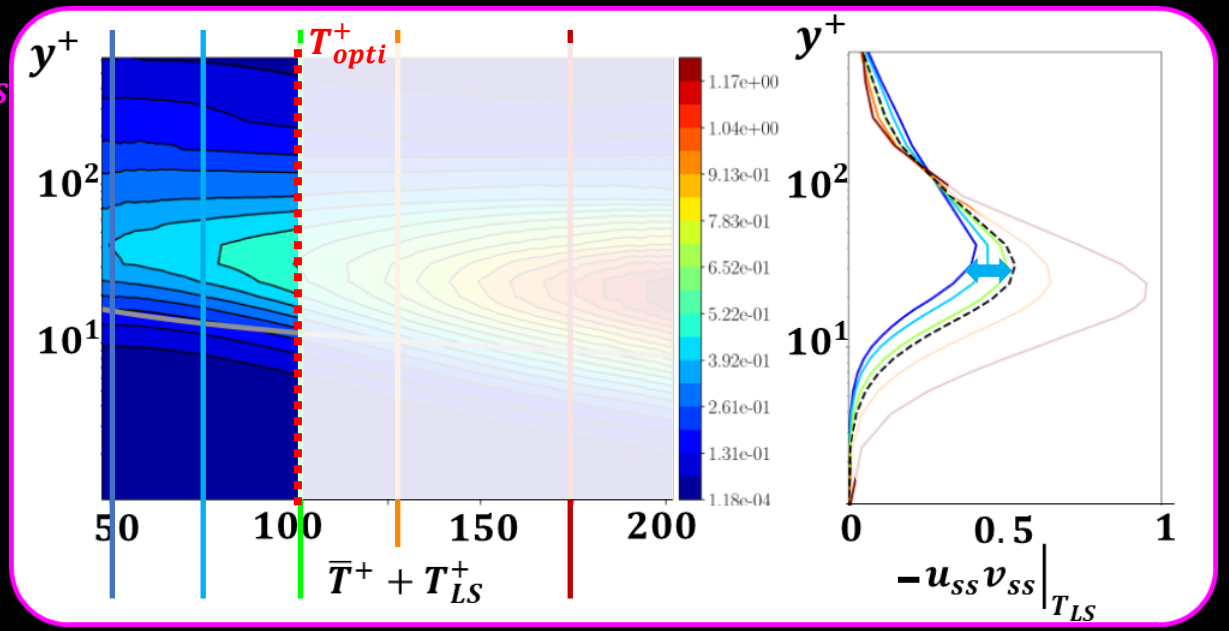
Drag Reduction
Effect of the Reynolds number - Conditional response to T^+_{LS}

$u_{ss}u_{ss}\big|_{T_{LS}}$





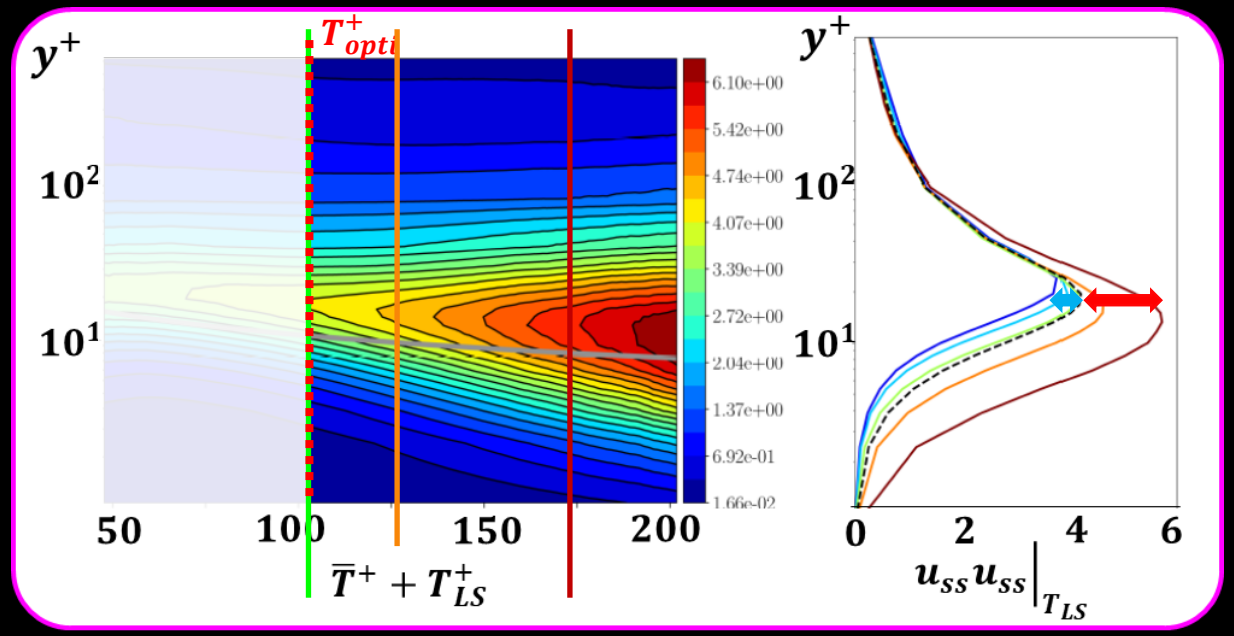
$-u_{ss}v_{ss}\big|_{T_{LS}}$

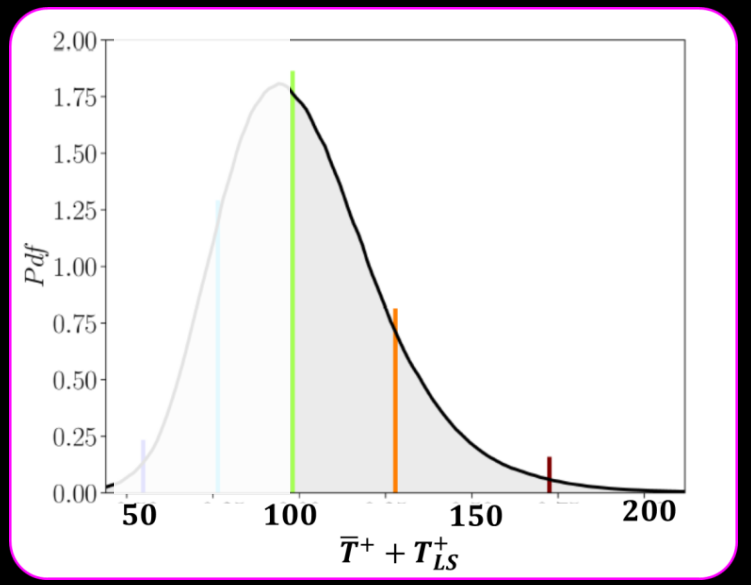


$T^+ < T^+_{opti}$ ⟷ $u_{ss}u_{ss}\big|_{T_{LS}}$ ⟷ $-u_{ss}v_{ss}\big|_{T_{LS}}$

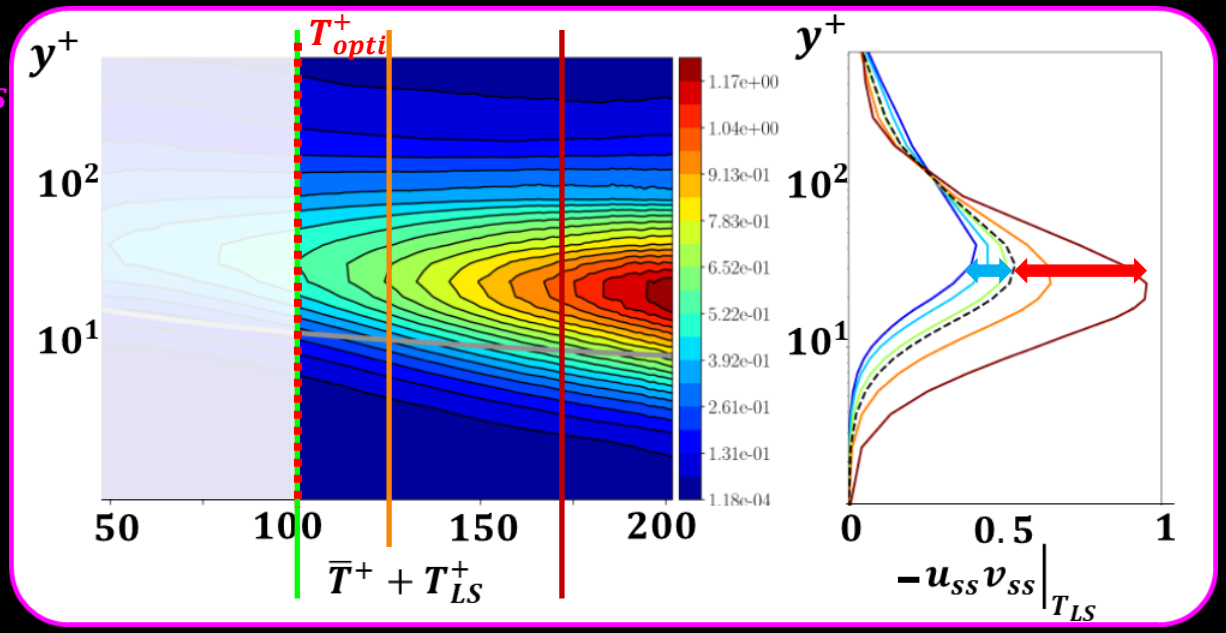
Drag Reduction
Effect of the Reynolds number - Conditional response to T^+_{LS}

$u_{ss}u_{ss}\big|_{T_{LS}}$





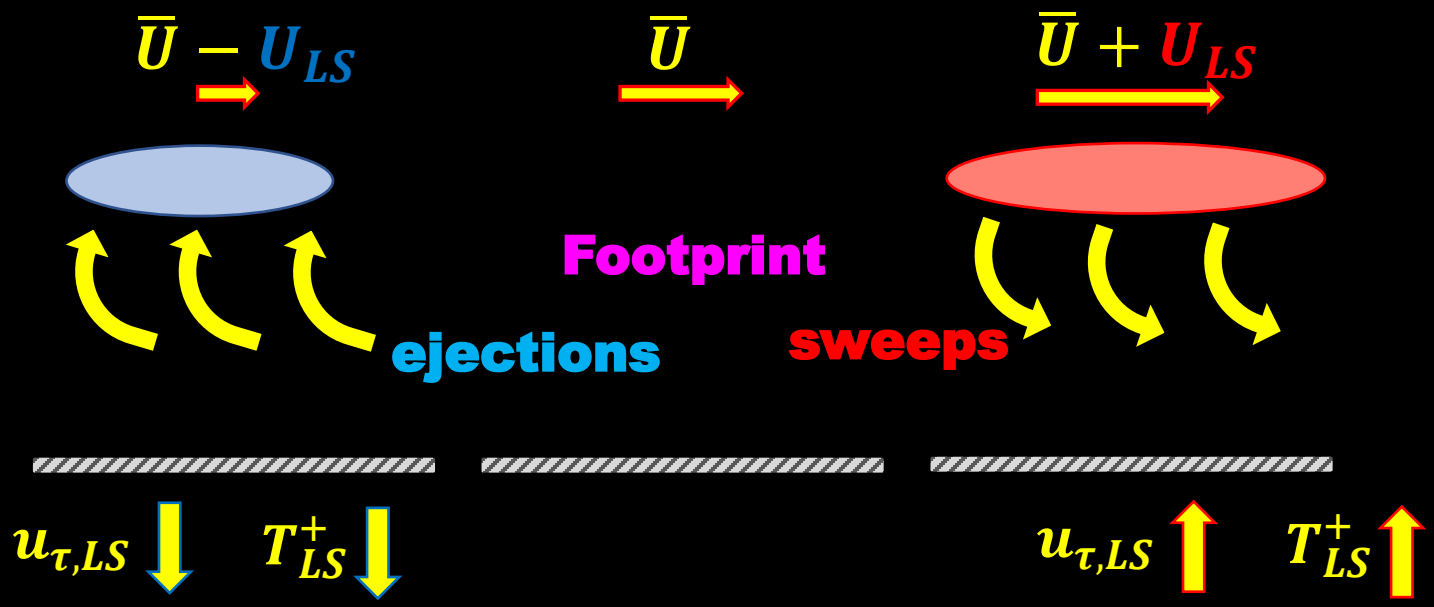
$-u_{ss}v_{ss}\big|_{T_{LS}}$



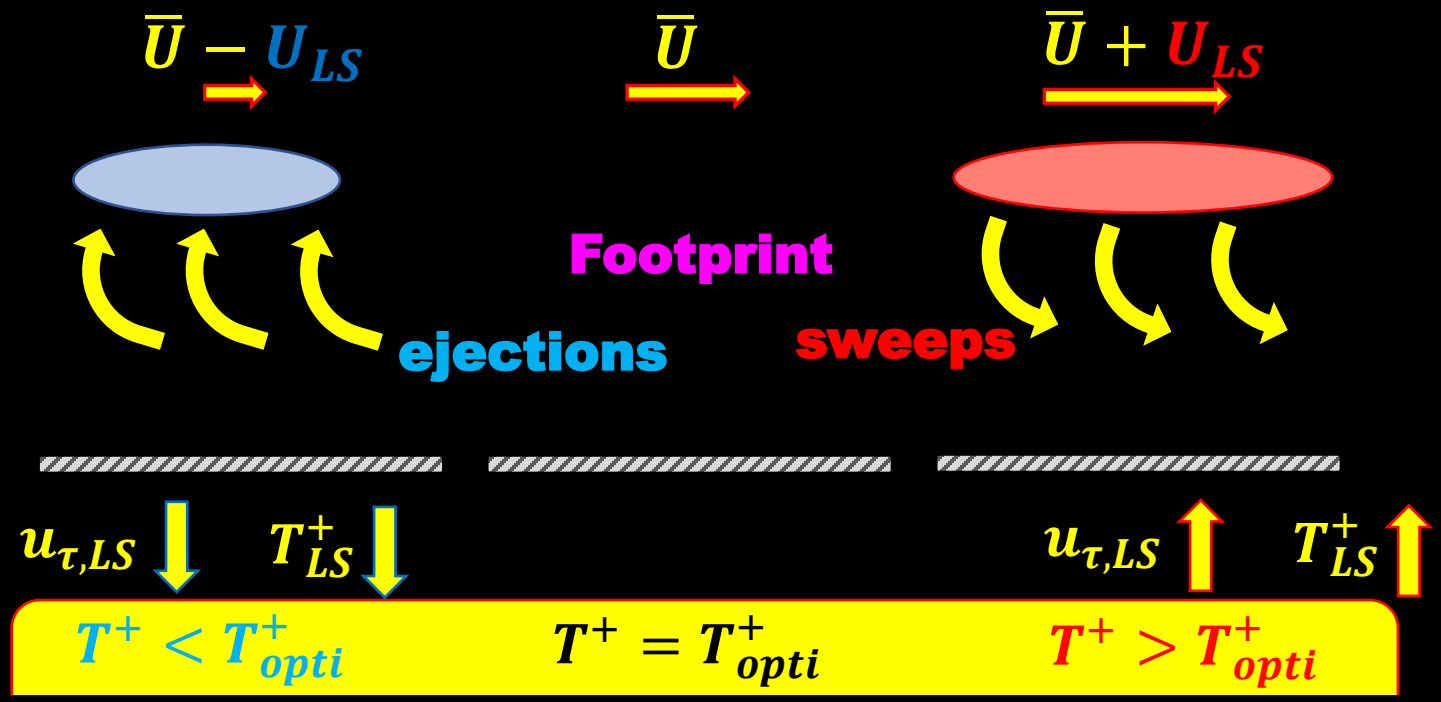
	$u_{ss}u_{ss}\big\|_{T_{LS}}$	$-u_{ss}v_{ss}\big\|_{T_{LS}}$
$T^+ < T^+_{opti}$	↔	↔
$T^+ > T^+_{opti}$	⟷	⟷

$T^+ < T^+_{opti}$	$T^+ > T^+_{opti}$
No Generation	**Generation**

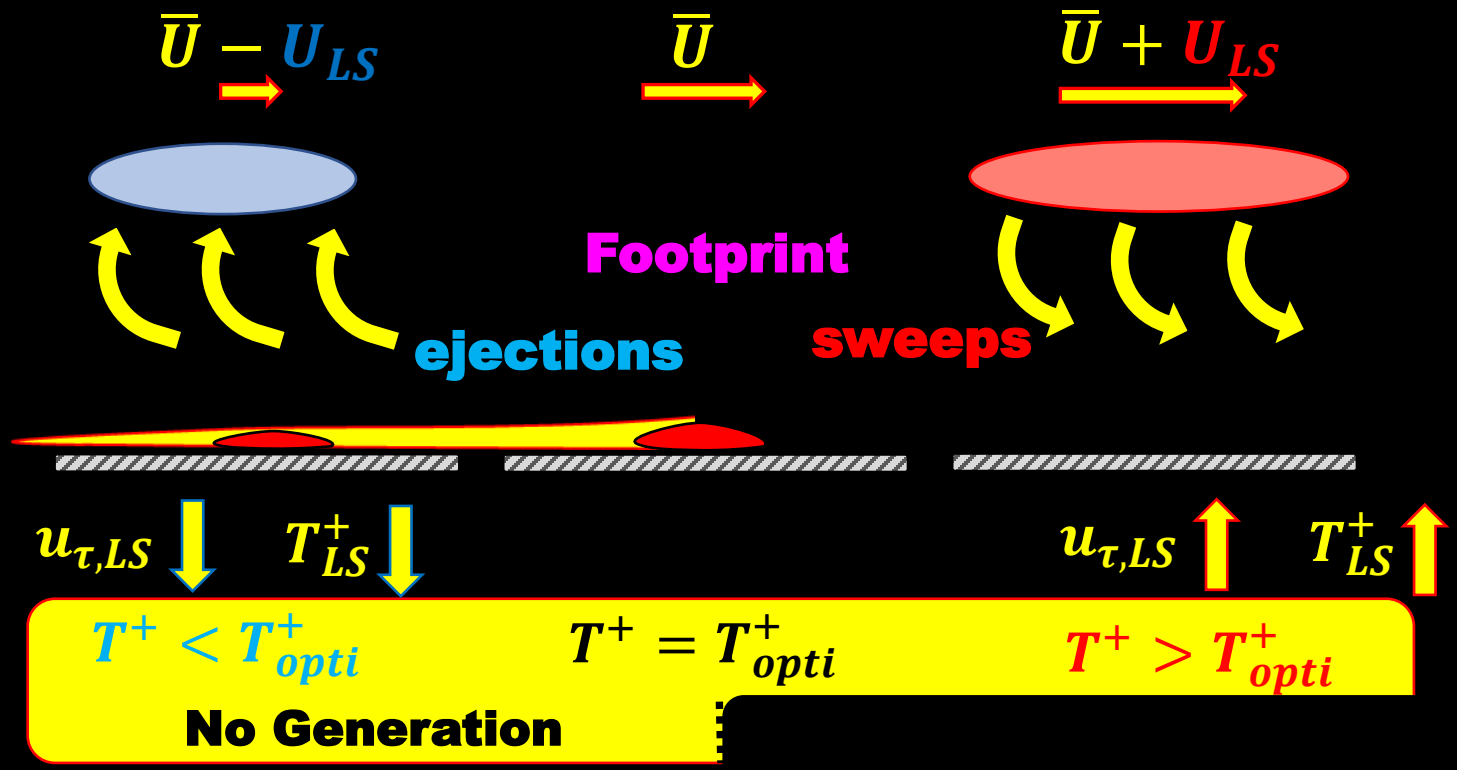
Drag Reduction
Effect of the Reynolds number – Conceptual Representation



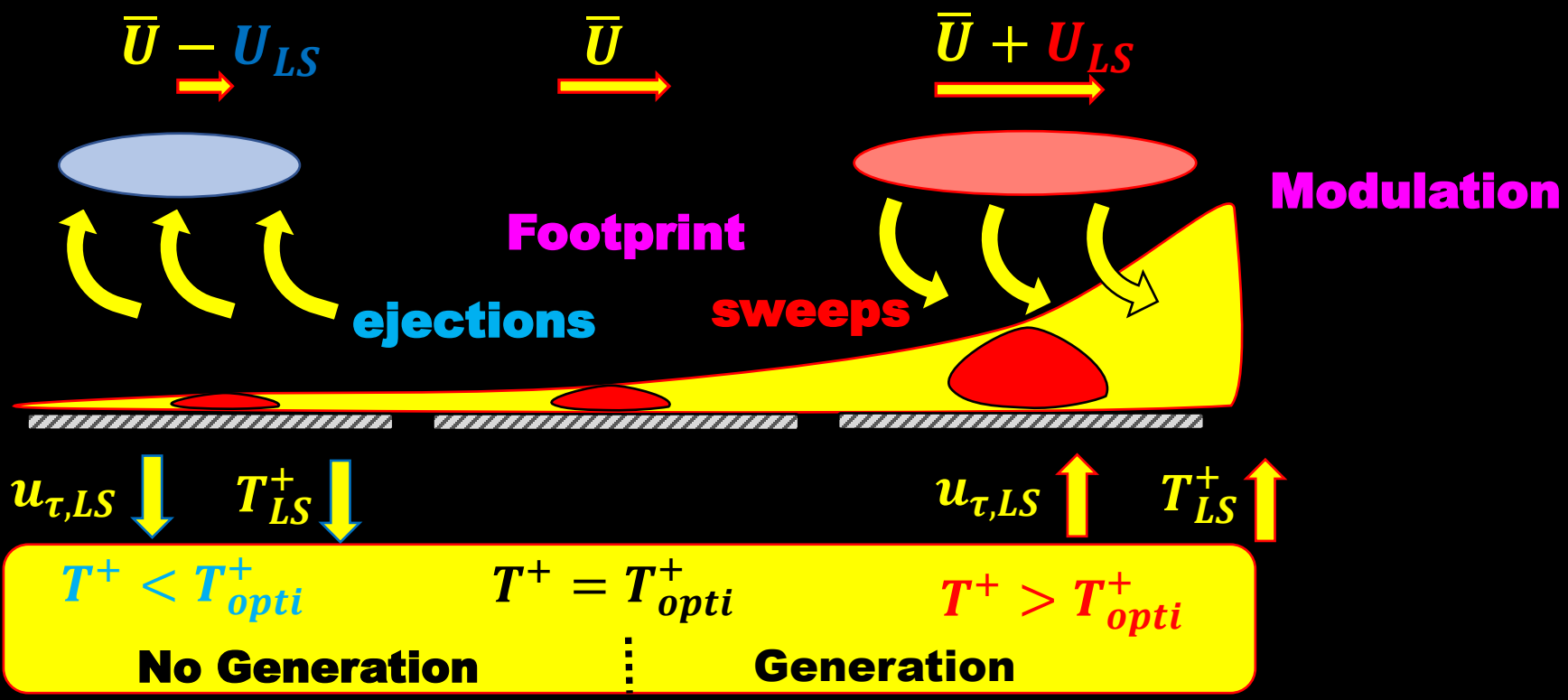
Drag Reduction
Effect of the Reynolds number - Conceptual Representation



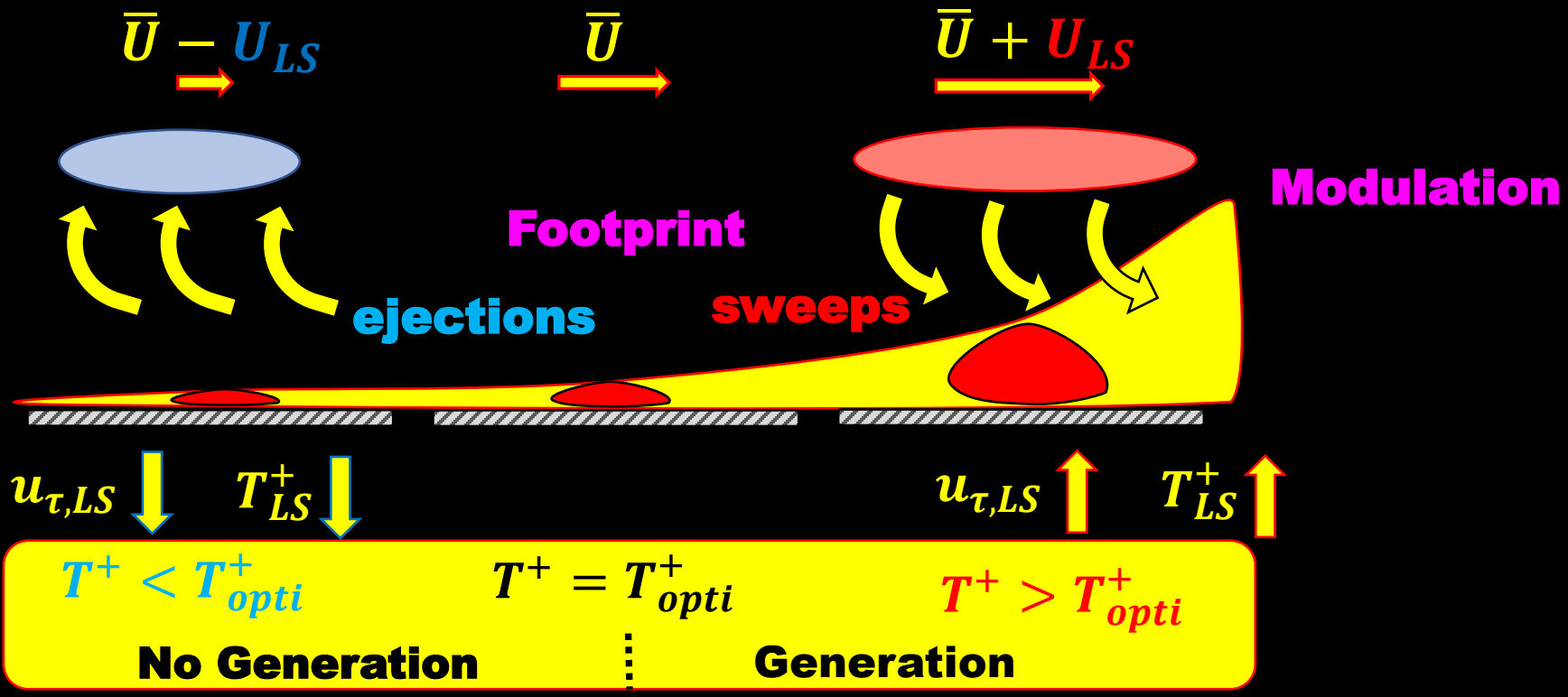
Drag Reduction
Effect of the Reynolds number - Conceptual Representation

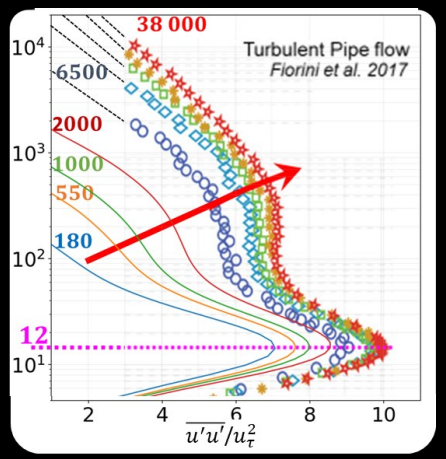


Drag Reduction
Effect of the Reynolds number - Conceptual Representation



Drag Reduction
Effect of the Reynolds number

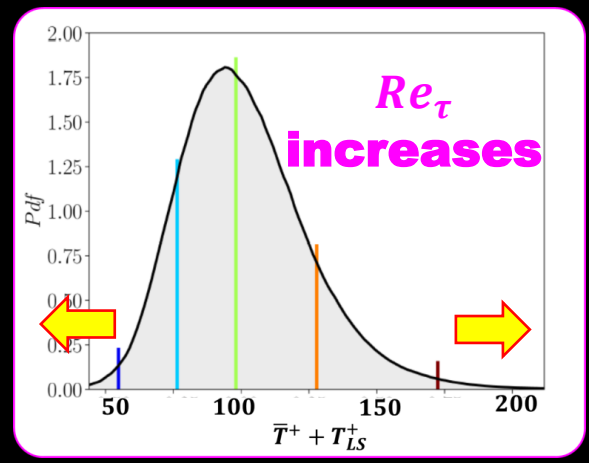




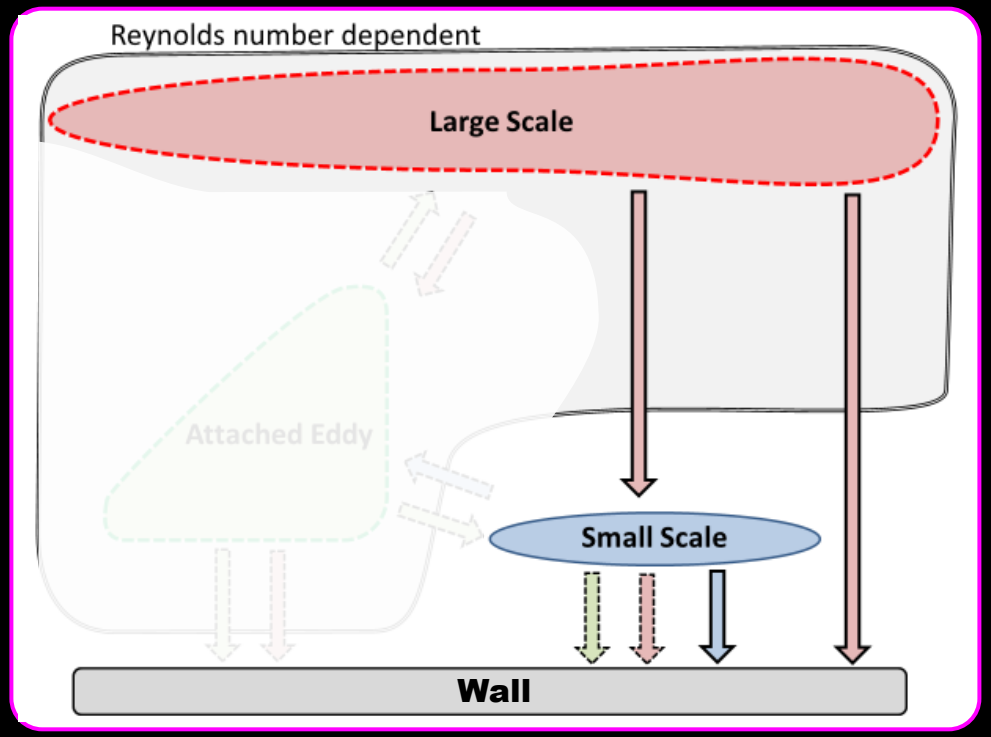
Re_τ **increases**

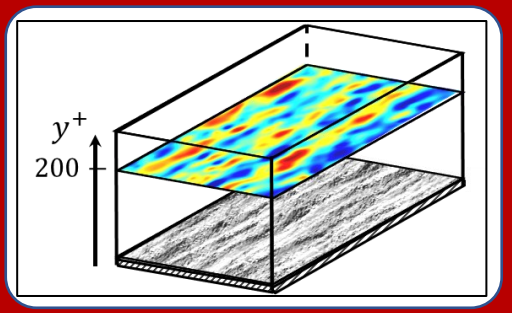
Outer-flow structures strengthen

Control of small-scale becomes less and less efficient

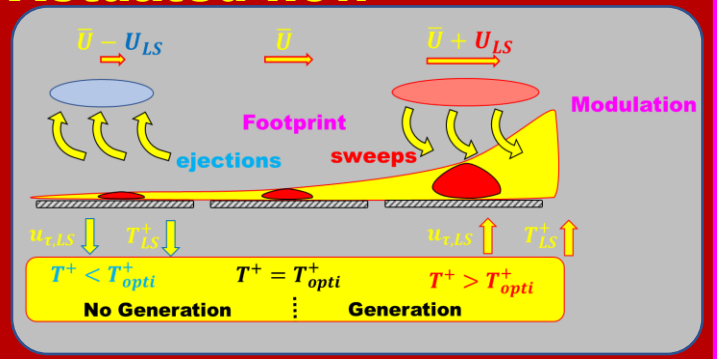


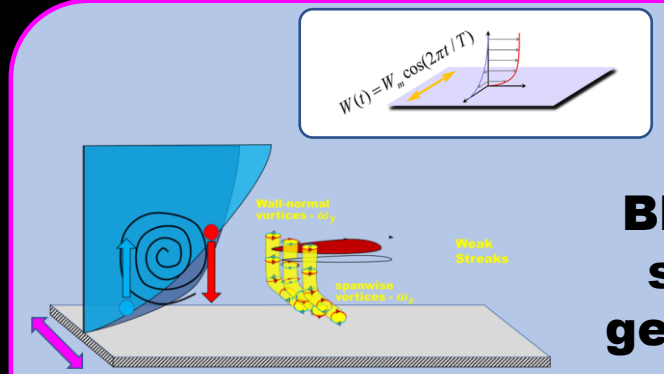
Near-wall turbulence
Multi-scale dynamic – Drag Reduction / Outer-flow structures' effects





Actuated flow

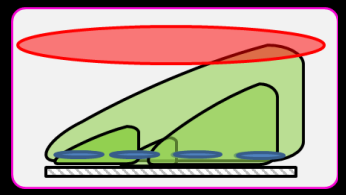


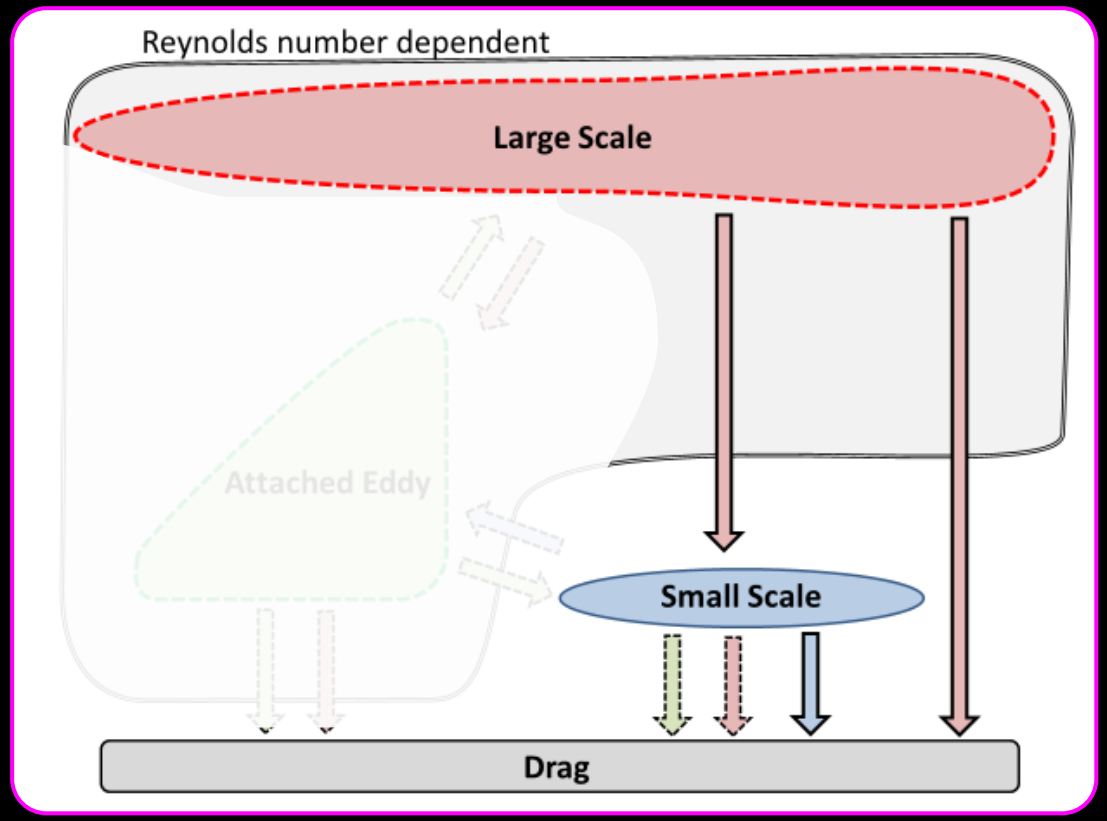


Block the streaks generation

Dynamic of Near-wall turbulence: Skeleton and Relations `` Vision Puzzle''

Pieces of the Puzzle





1- Near-wall structure control: drag reduction mechanism

2- Effects of large scales on near-wall small scales and drag

Actuated

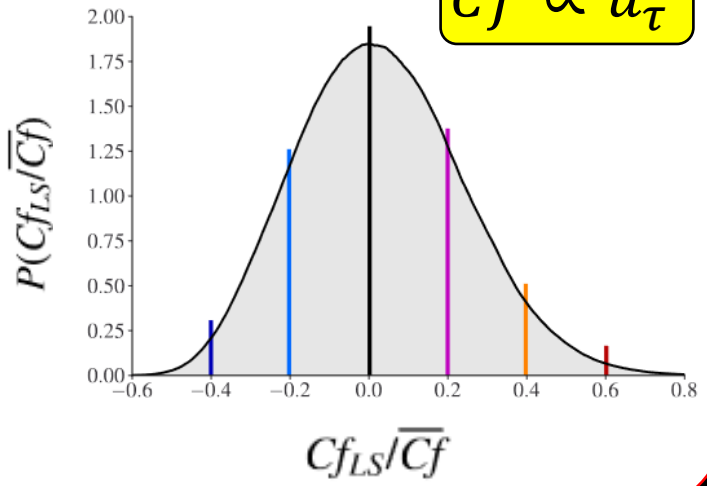
Canonical

3- Identification and characterisation of energetic structures filling the spectral gap between large and small scales

Conditional response to the large-scale skin friction
Modulation of Streamwise energy

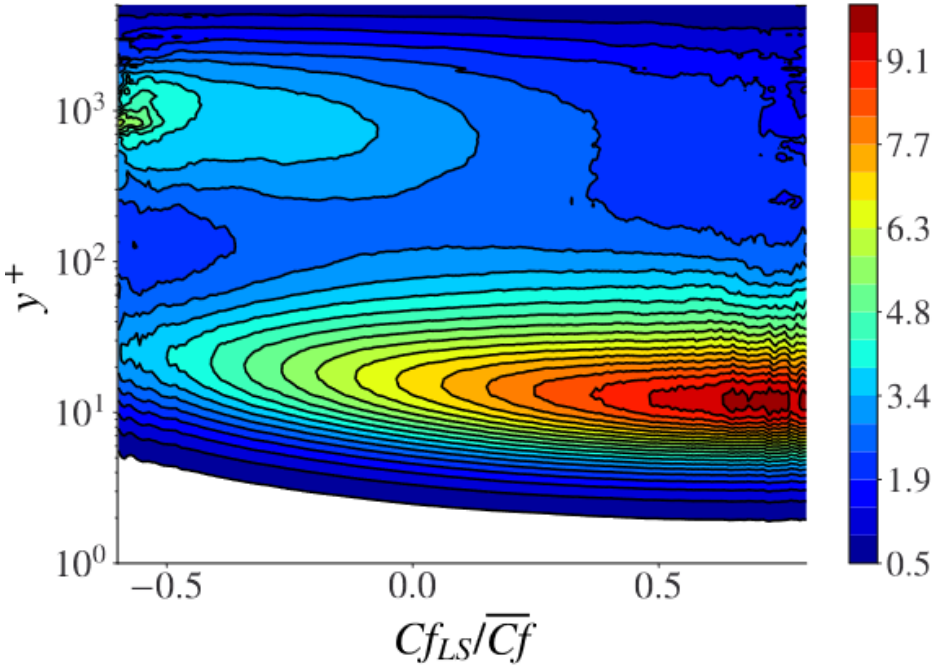
PDF of Cf_{LS}:

$Cf \propto u_\tau^2$



Normalisation by mean skin friction

$\overline{uu}|_{Cf_{LS}} / \overline{u_\tau}^2$



Conditional response to the large-scale skin friction
Modulation of Streamwise energy

PDF of Cf_{LS}:

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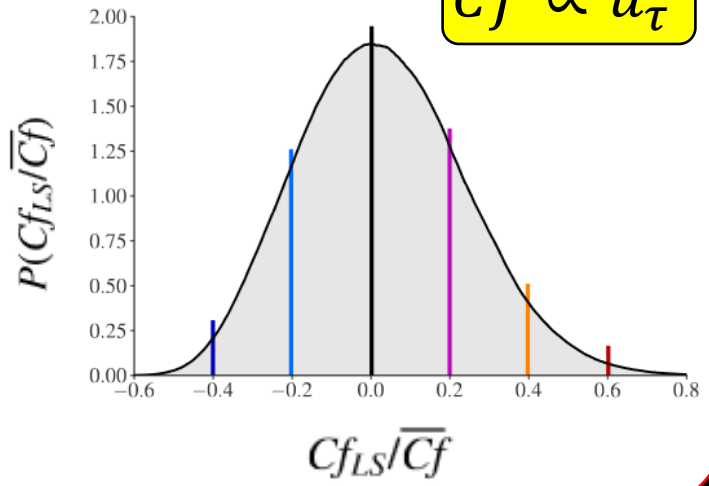

Normalisation by mean skin friction

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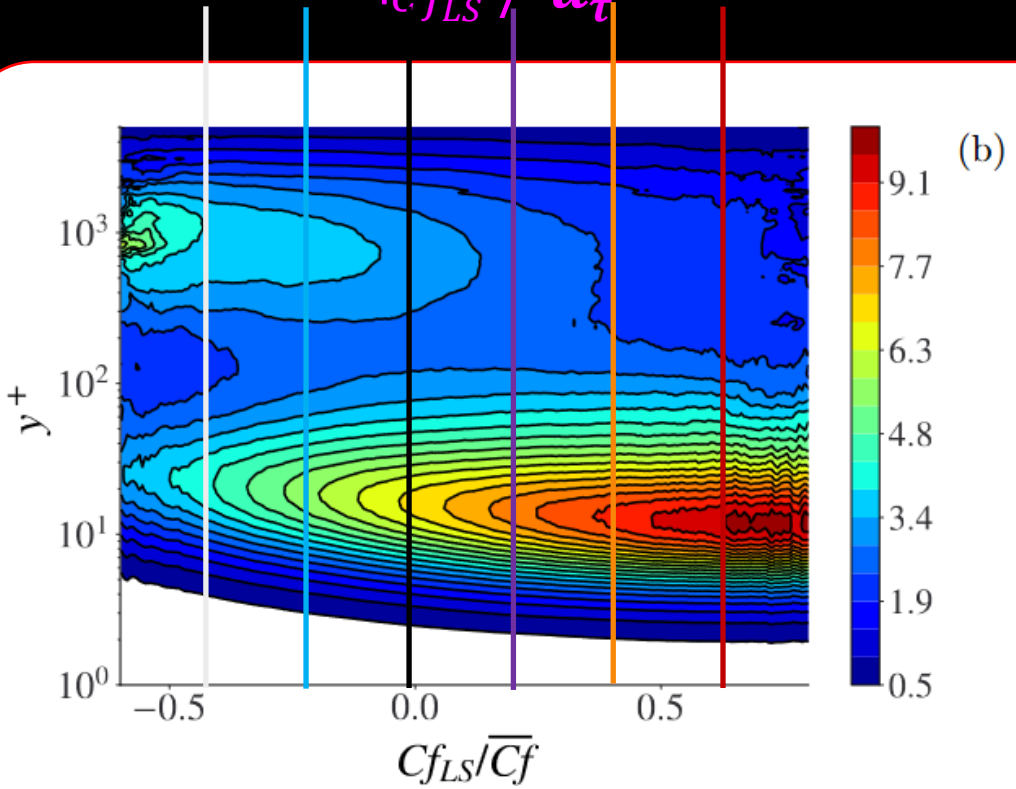
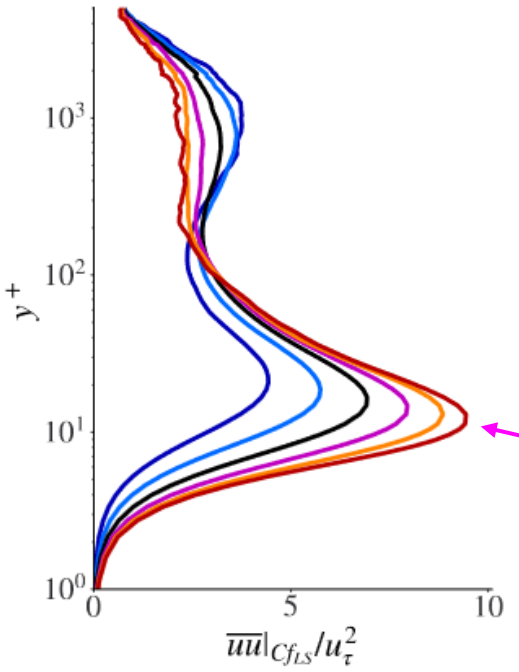




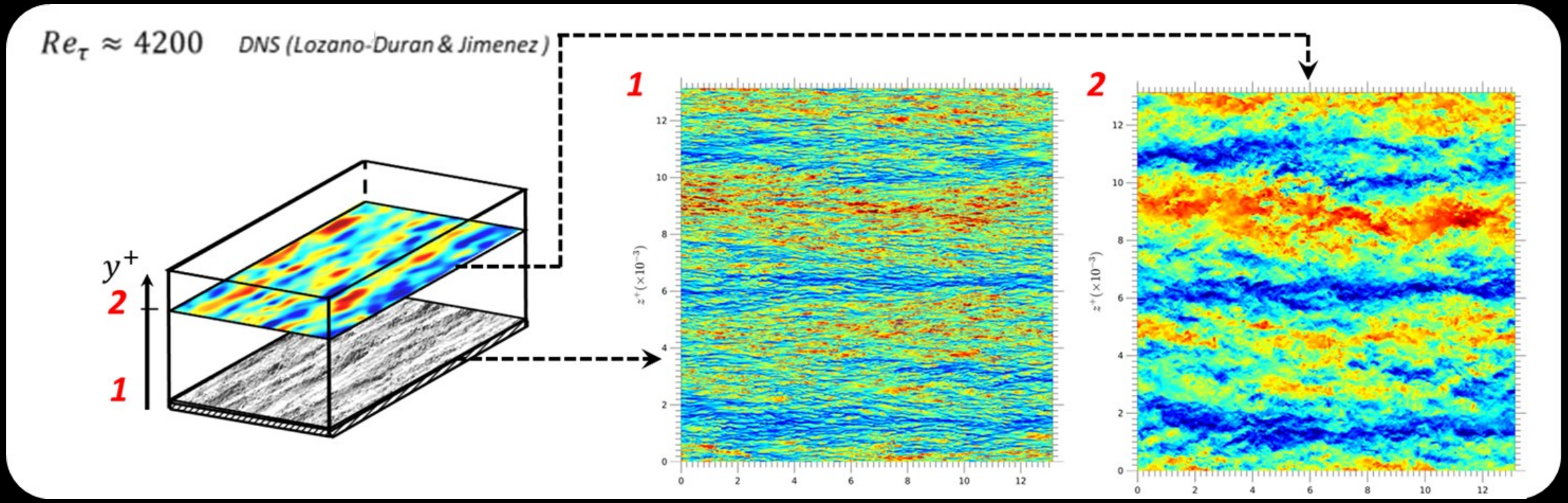
⇨ **Intensity increases**

⇨ **Viscous sublayer thinner**

Buffer layer: streaks

Conditional response to the large-scale skin friction
Modulation of Streaks – Quasi-steady Hypothesis

Snapshot – Streamwise velocity fields



Can statistics be made universal by normalising by large-scale fluctuations?

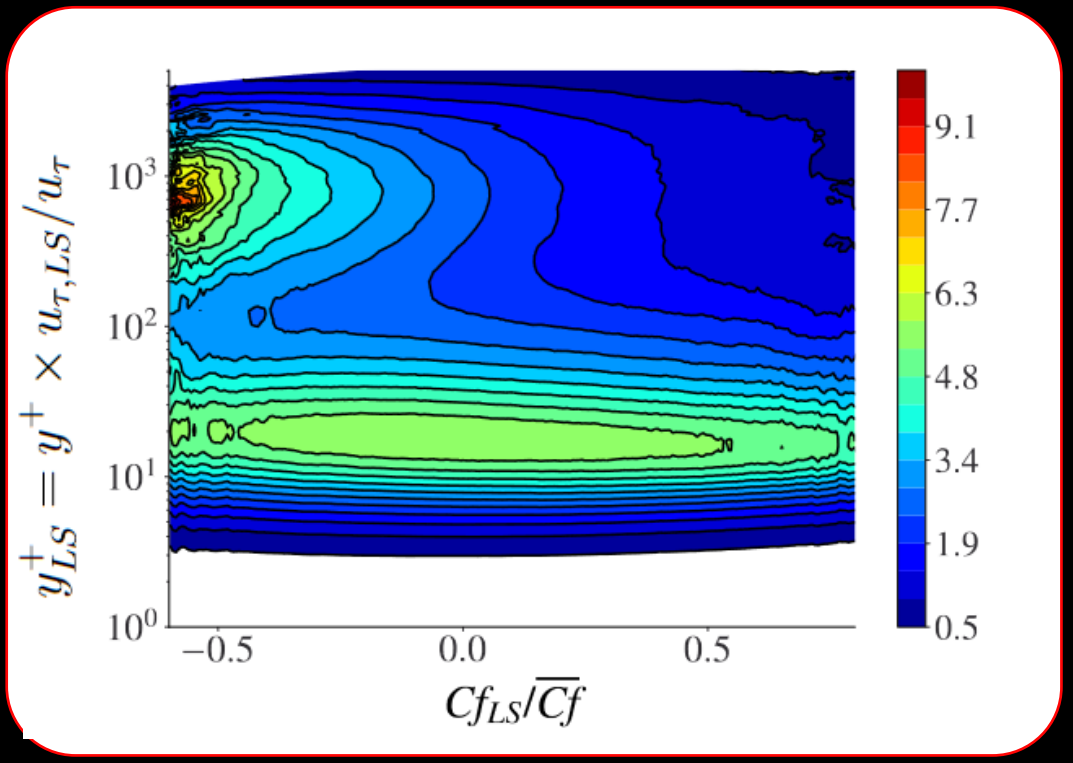
$\overline{u_\tau}$ ➡ $u_{\tau,LS}$

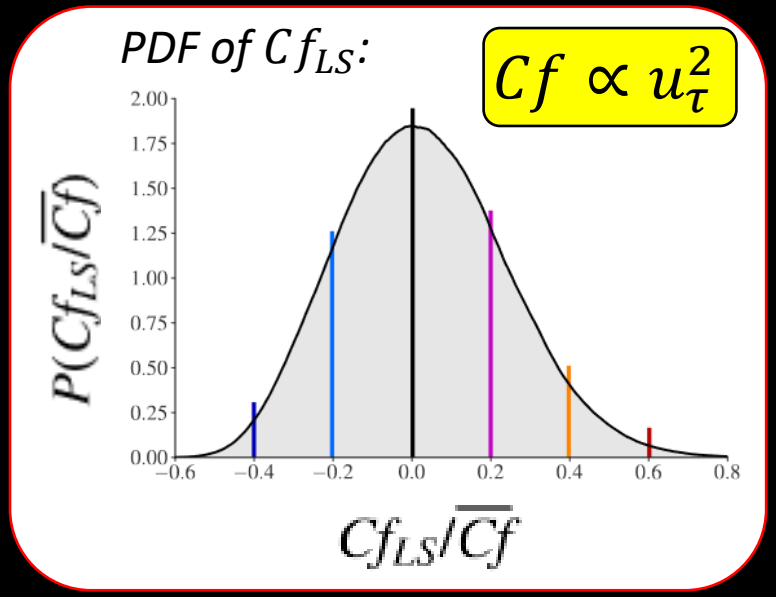
S. Chernyshenko, I. Marusic, and R. Mathis, Quasi-steady description of modulation effects in wall turbulence, arXiv:1203.3714 [physics] (2012).

Conditional response to the large-scale skin friction
Modulation of Streamwise energy

$\overline{uu}|_{Cf_{LS}} / \overline{u_{\tau,LS}}^2$

Normalisation by local large-scale skin friction

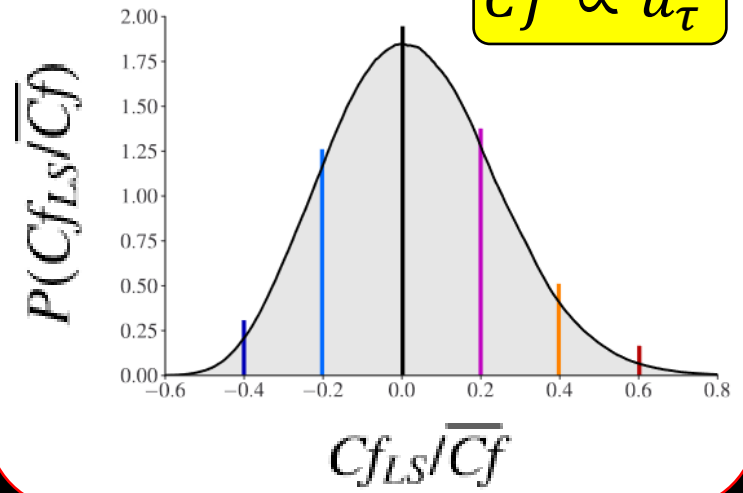




Conditional response to the large-scale skin friction
Modulation of Streamwise energy

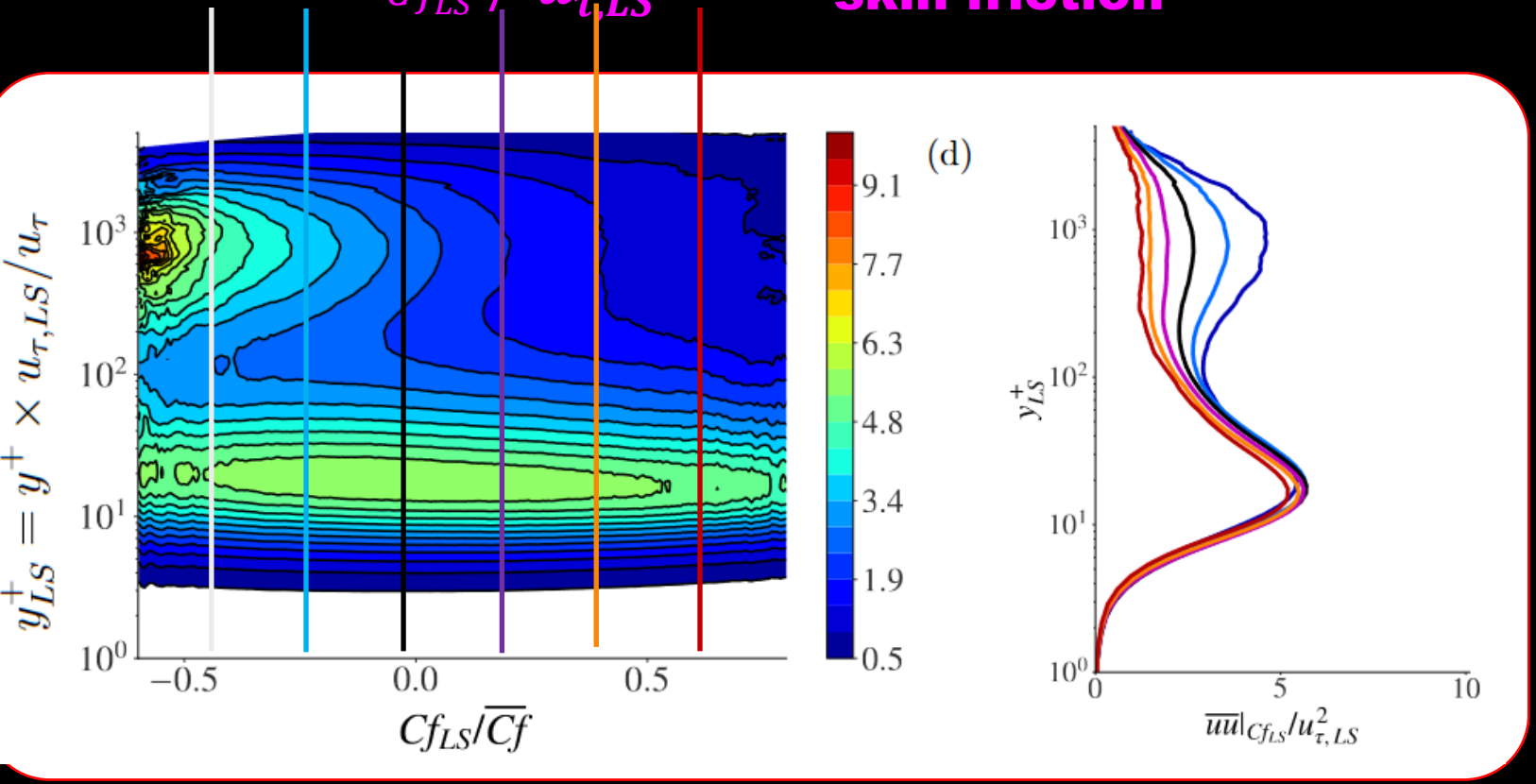
PDF of Cf_{LS}:

$Cf \propto u_\tau^2$



Normalisation by local large-scale skin friction

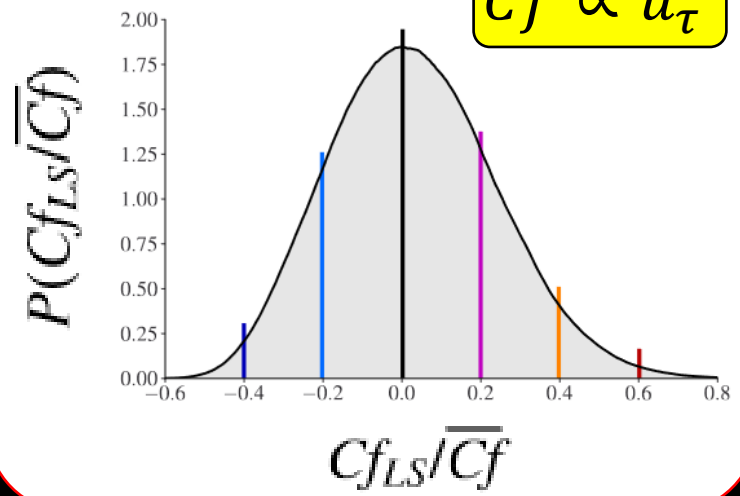
$\overline{uu}|_{Cf_{LS}} / \overline{u_{\tau,LS}}^2$



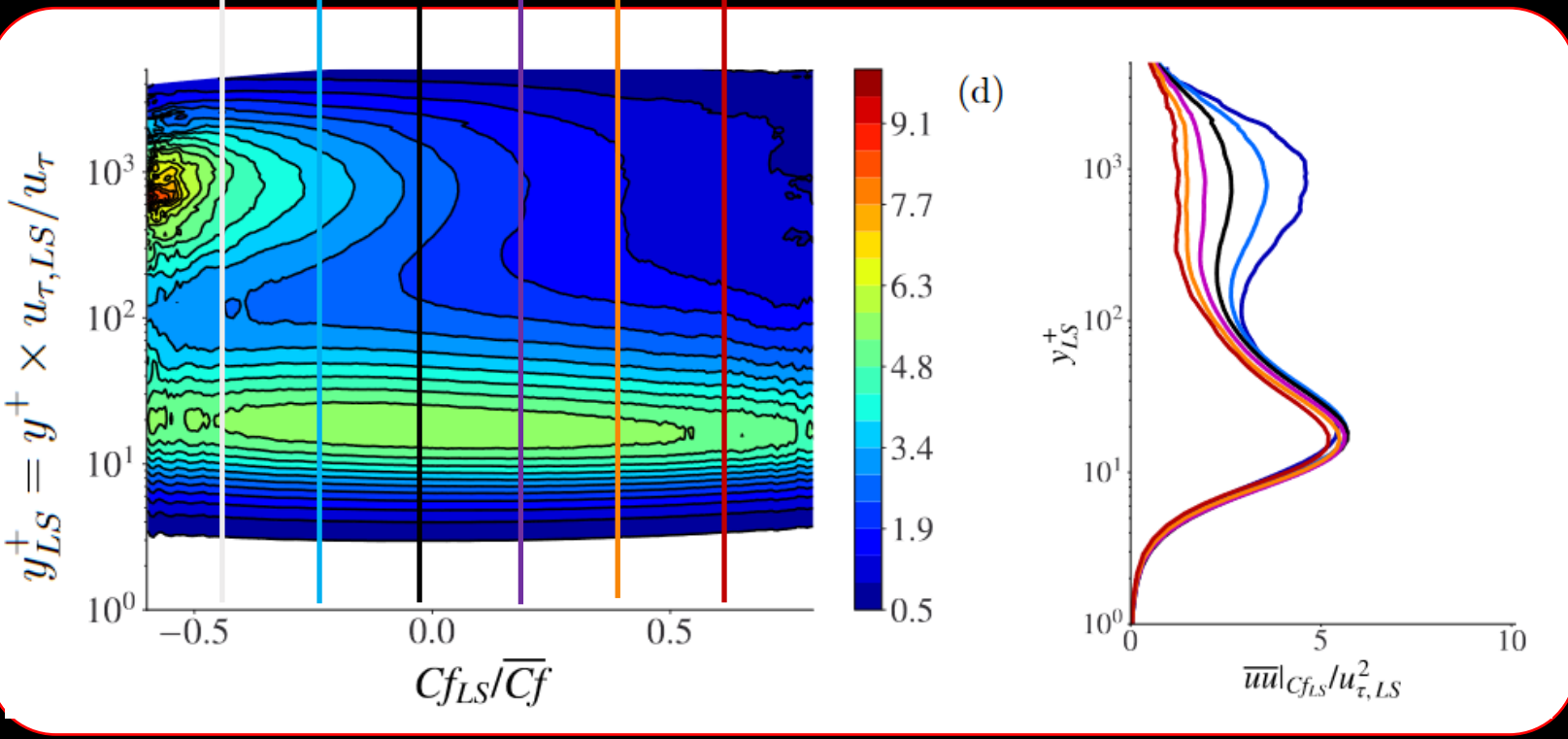
Conditional response to the large-scale skin friction
Modulation of Streamwise energy

PDF of Cf_{LS}:

$Cf \propto u_\tau^2$



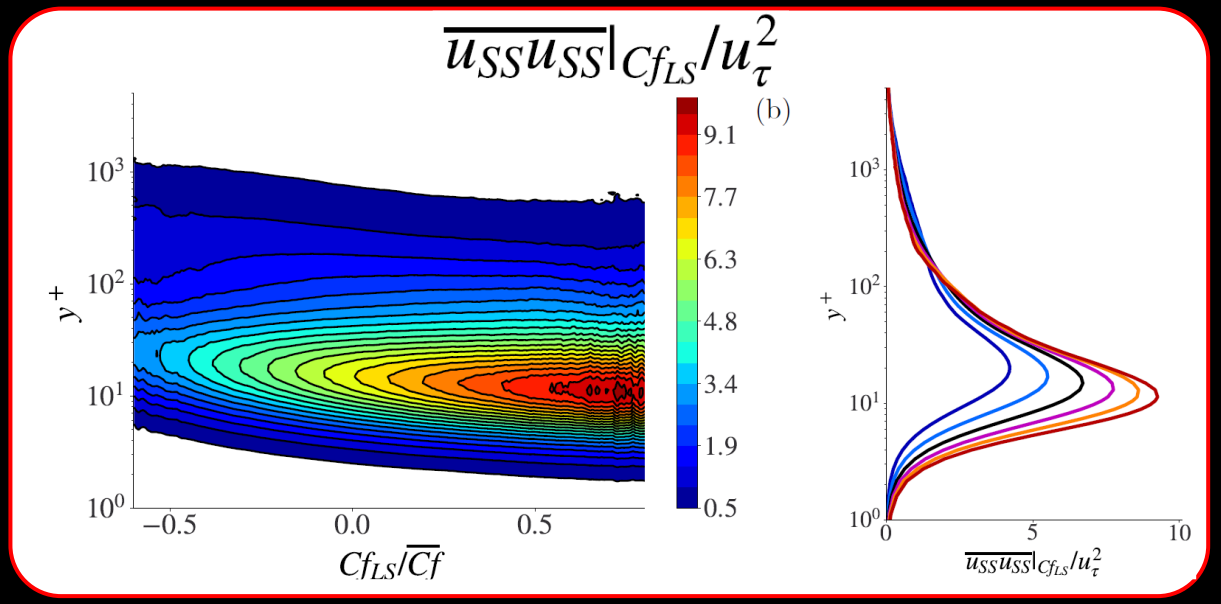
$\overline{uu}|_{Cf_{LS}} / \overline{u_{\tau,LS}}^2$ ← **Normalisation by local large-scale skin friction**

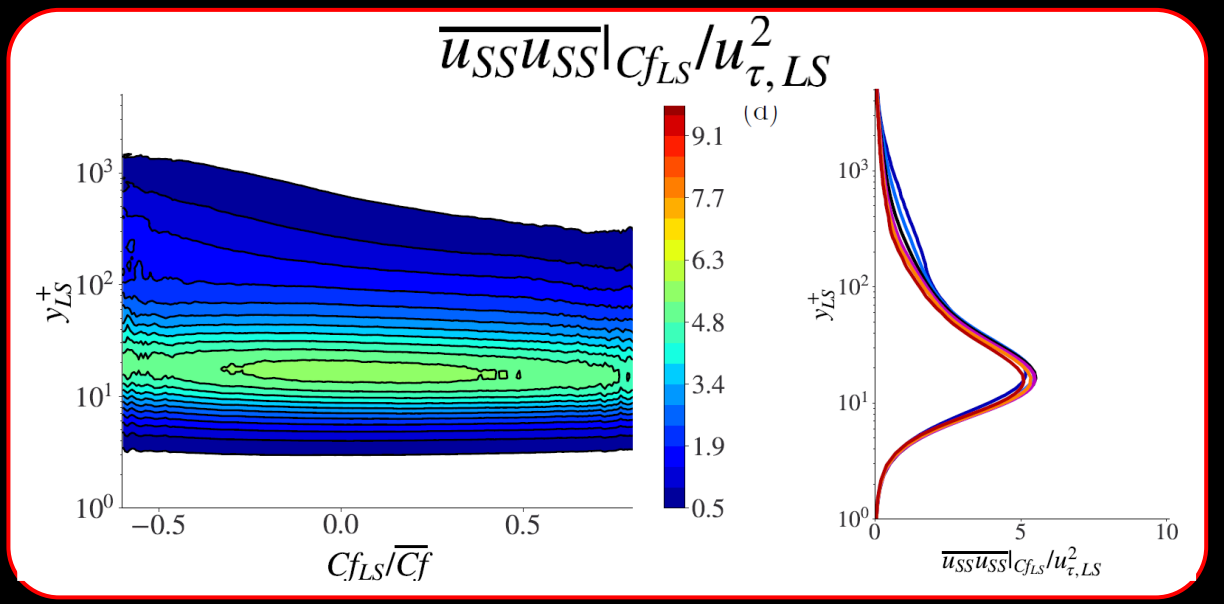


- **Intensity constant**
- **Viscous sublayer constant**

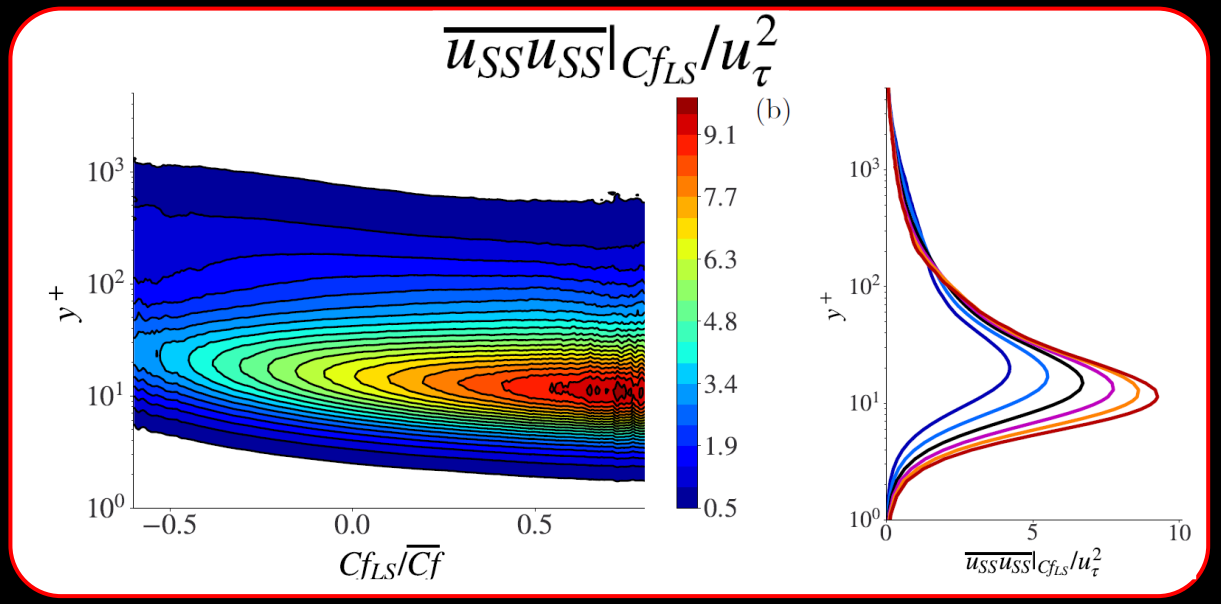
Quasi-steady hypothesis Valid but only close to wall

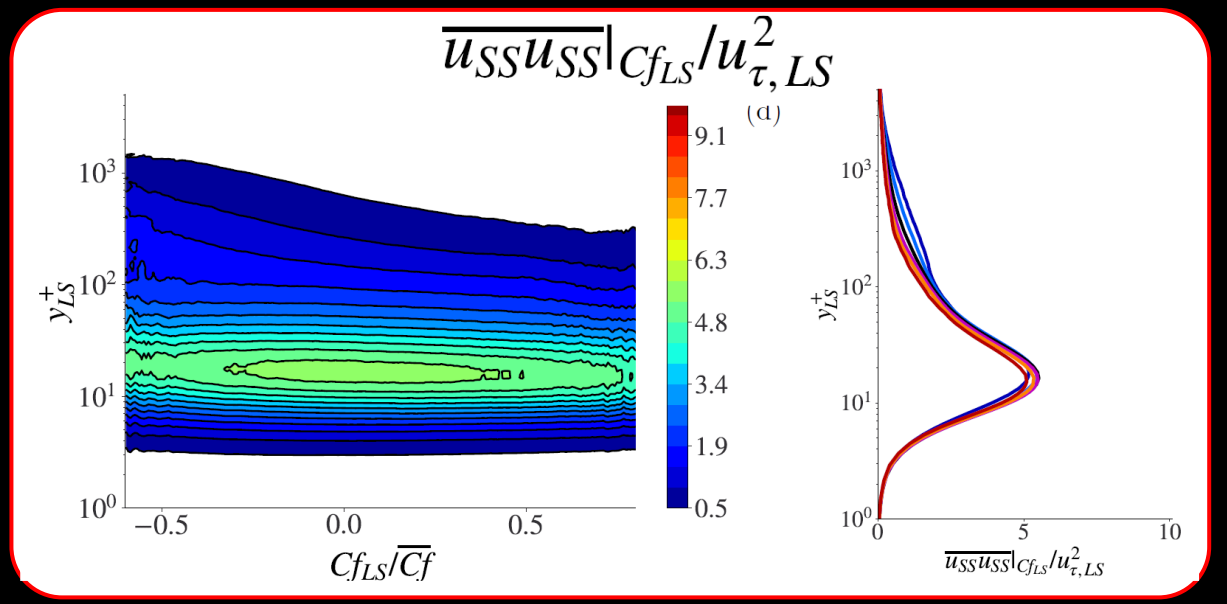
Conditional response to the large-scale skin friction
Modulation of Small-scale eddies

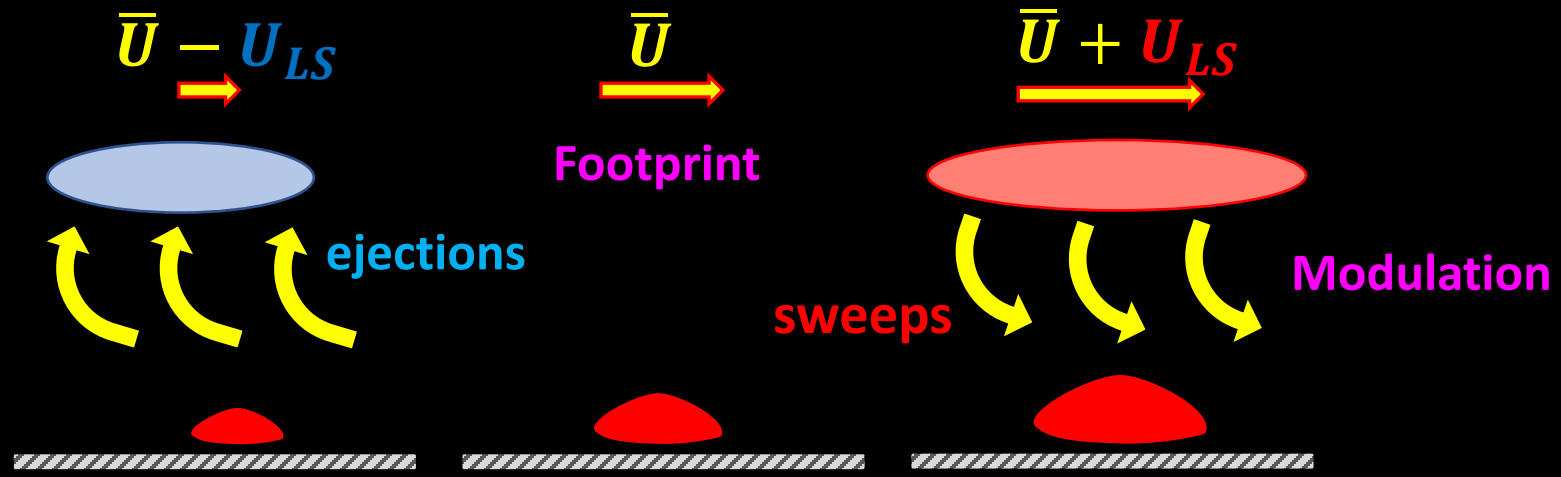




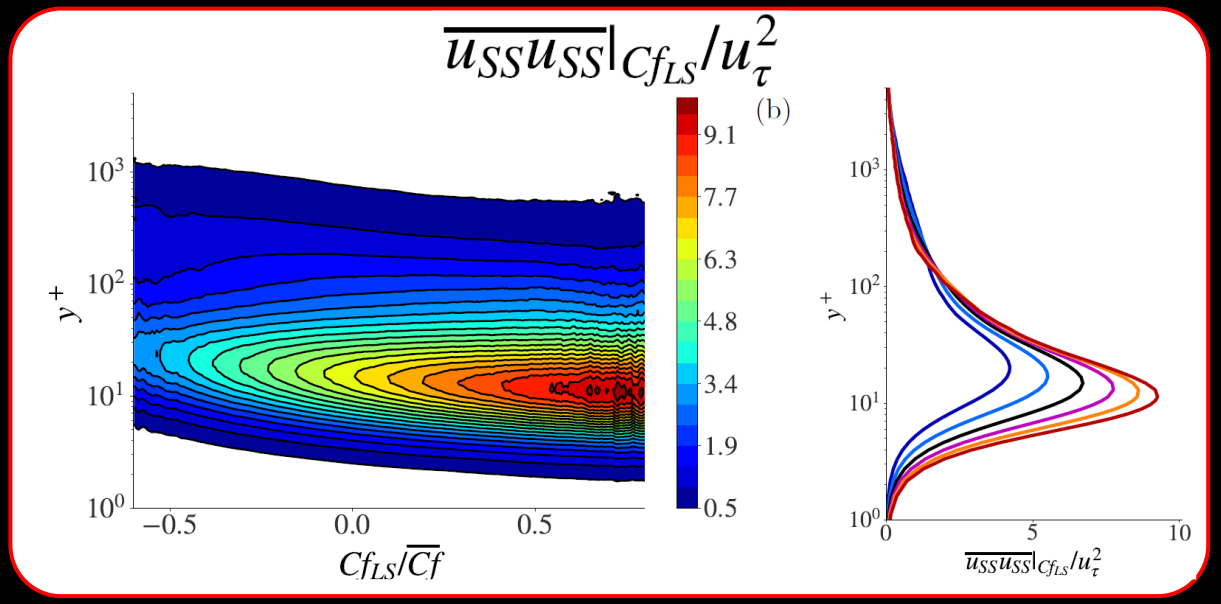
Conditional response to the large-scale skin friction
Modulation of Small-scale eddies

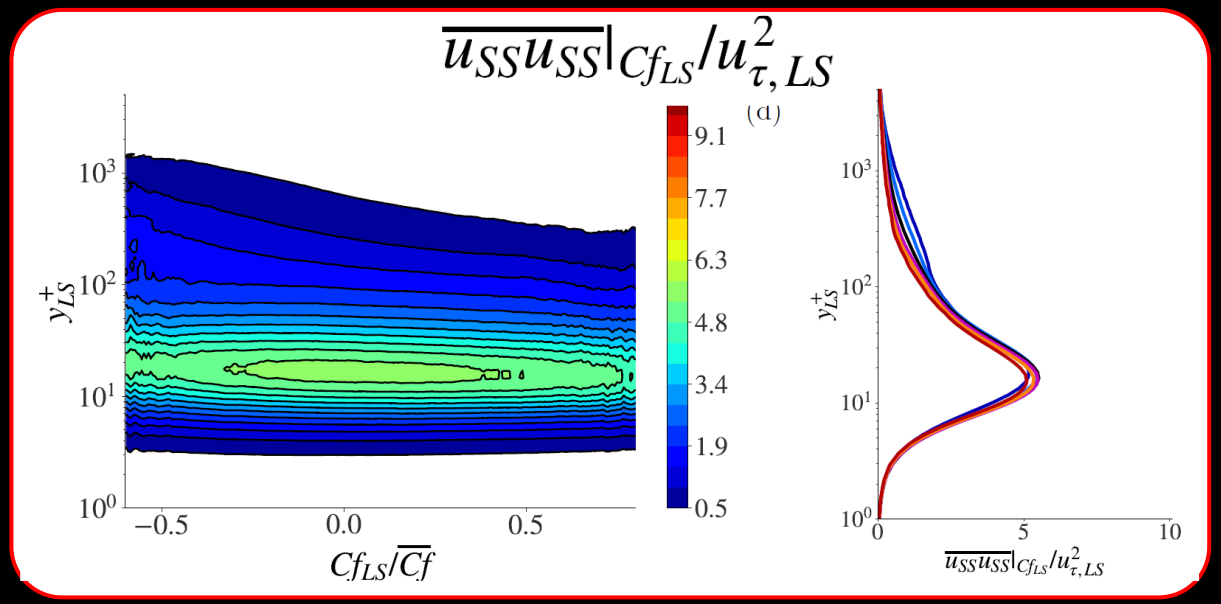


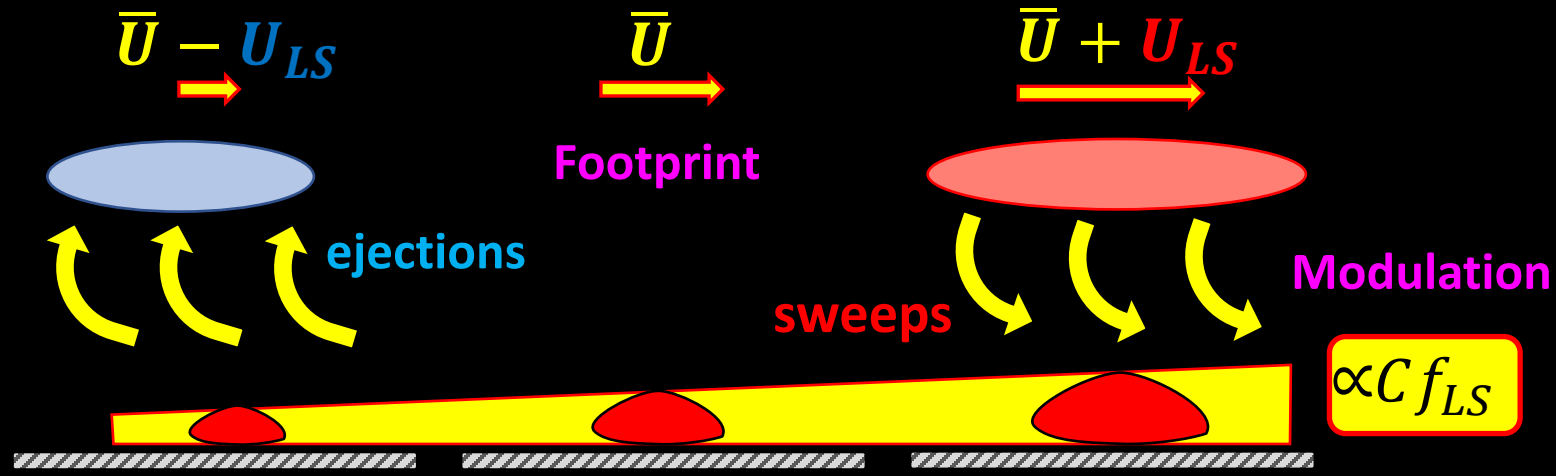




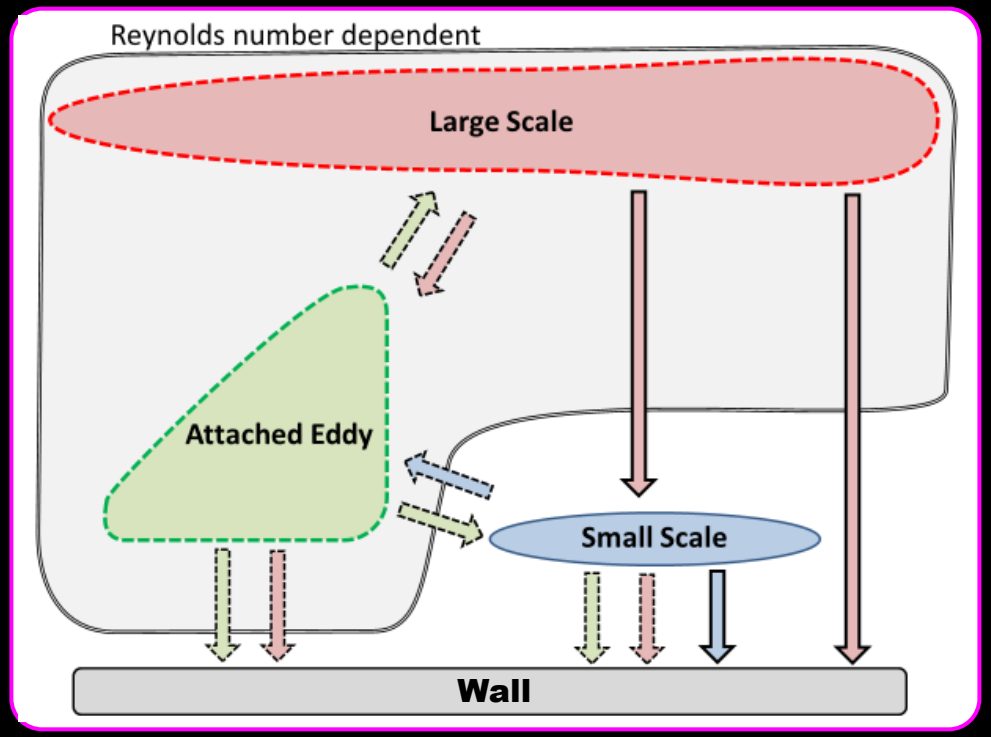
Conditional response to the large-scale skin friction
Modulation of Small-scale eddies

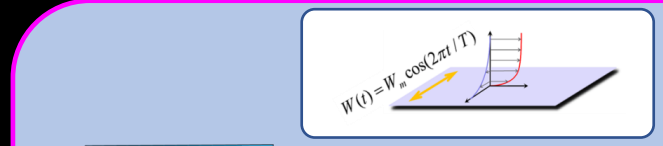


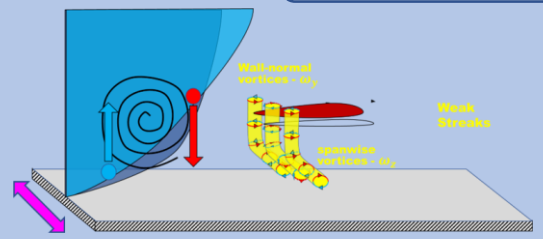




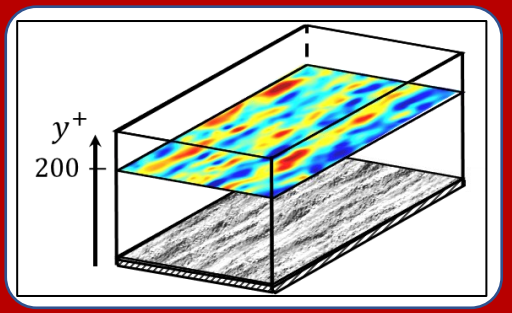
Near-wall turbulence
Multi-scale dynamic – Quasi-steady Hypothesis



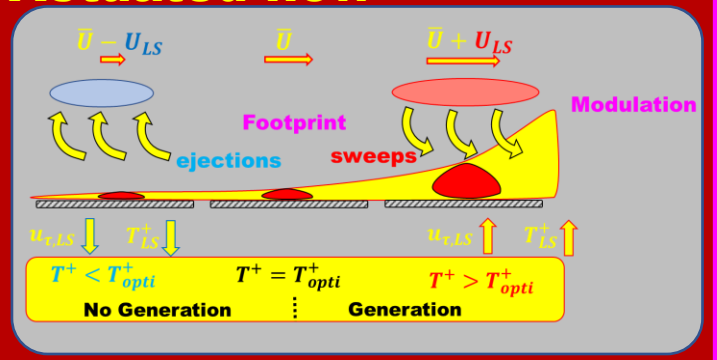




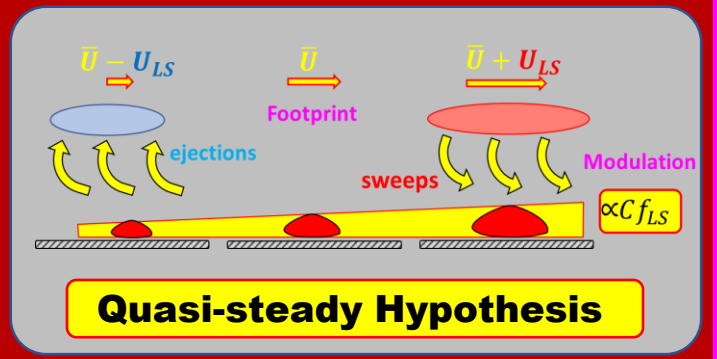
Block the streaks generation



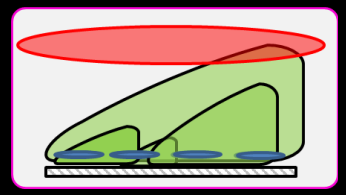
Actuated flow

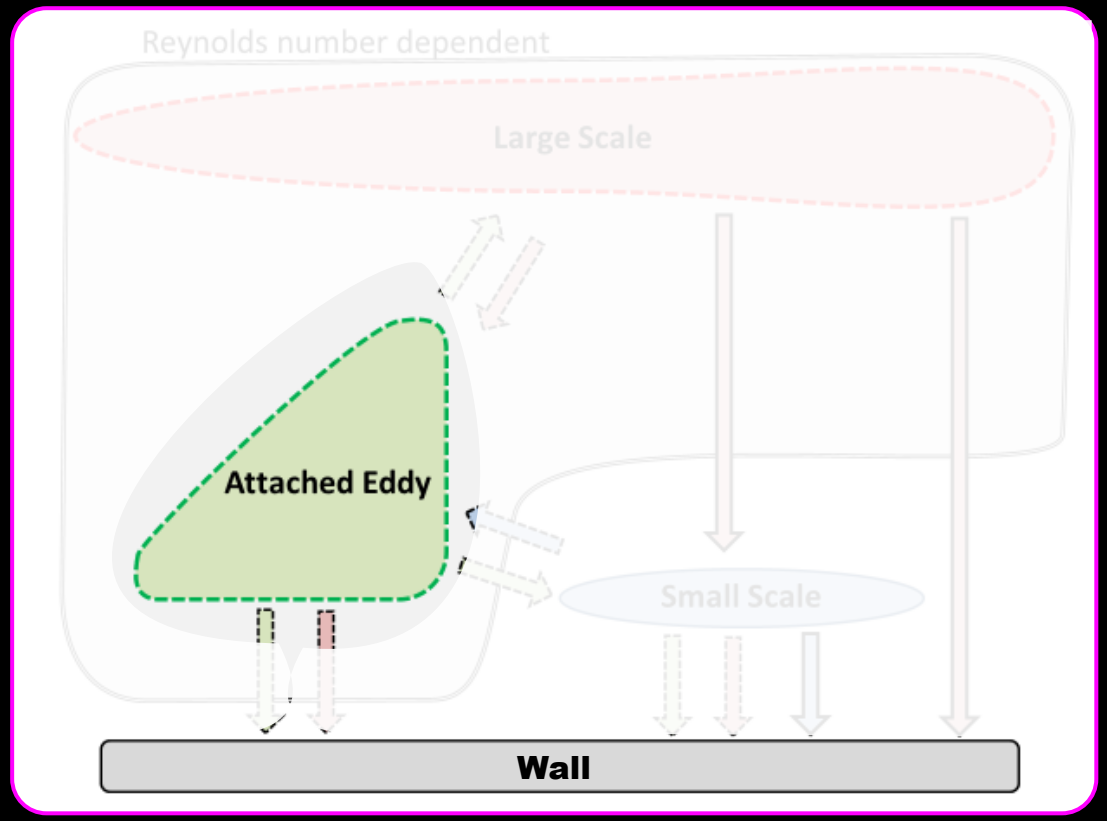


Canonical flow



Dynamic of Near-wall turbulence: Skeleton and Relations ``Vision Puzzle''
Pieces of the Puzzle



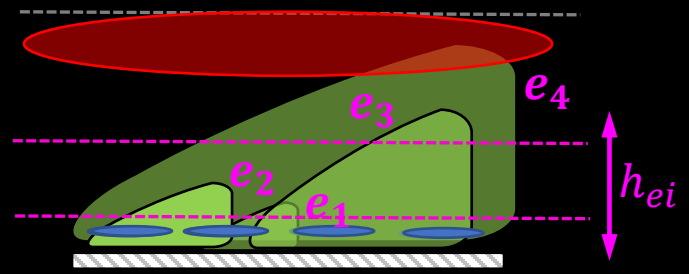


3- **Identification and characterisation of energetic structures filling the spectral gap between large and small scales**

Dynamic of the outer-flow part
Conceptual view of Attached Eddies Hypothesis

Townsend (JFM 1961)

It was postulated that :
the wall-bounded flow was
populated by **self-similar eddies**



Their size and their induced motions scale with their distance to the wall

Dynamic of the outer-flow part
Conceptual view of Attached Eddies Hypothesis

Townsend (JFM 1961)

It was postulated that :
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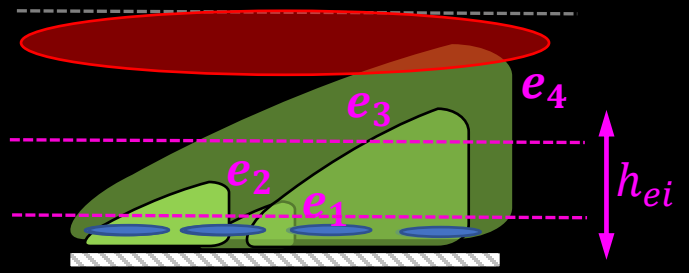
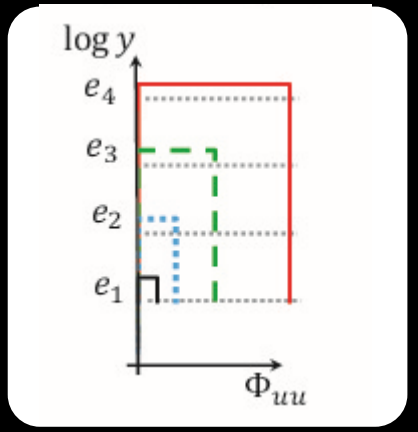


Energy density profiles associated to  :

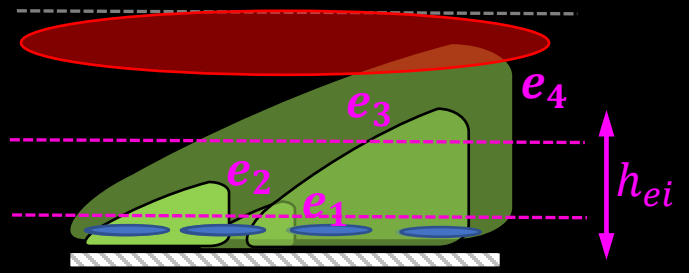


Their size and their induced motions scale with their distance to the wall

Dynamic of the outer-flow part
Conceptual view of Attached Eddies Hypothesis

Townsend (JFM 1961)

It was postulated that :
the wall-bounded flow was
populated by **self-similar eddies**



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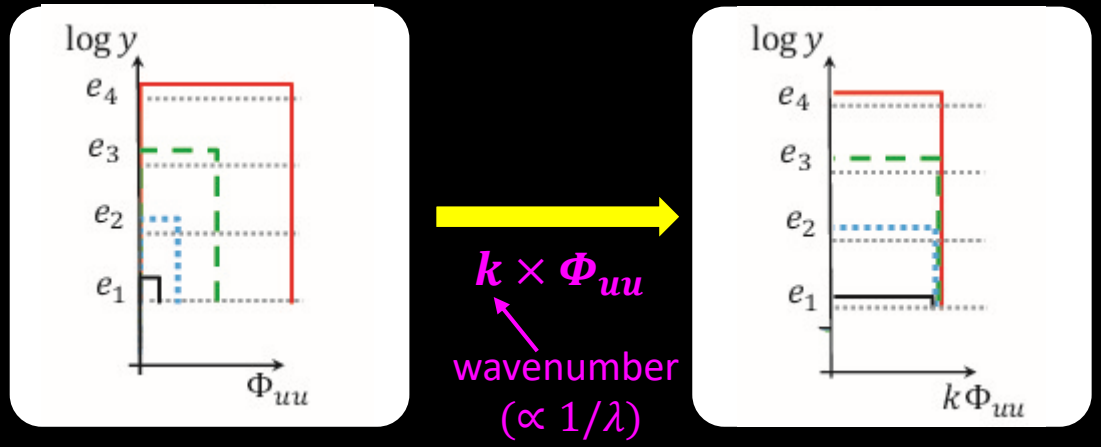

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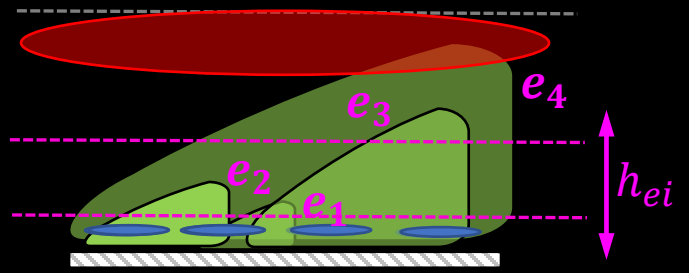

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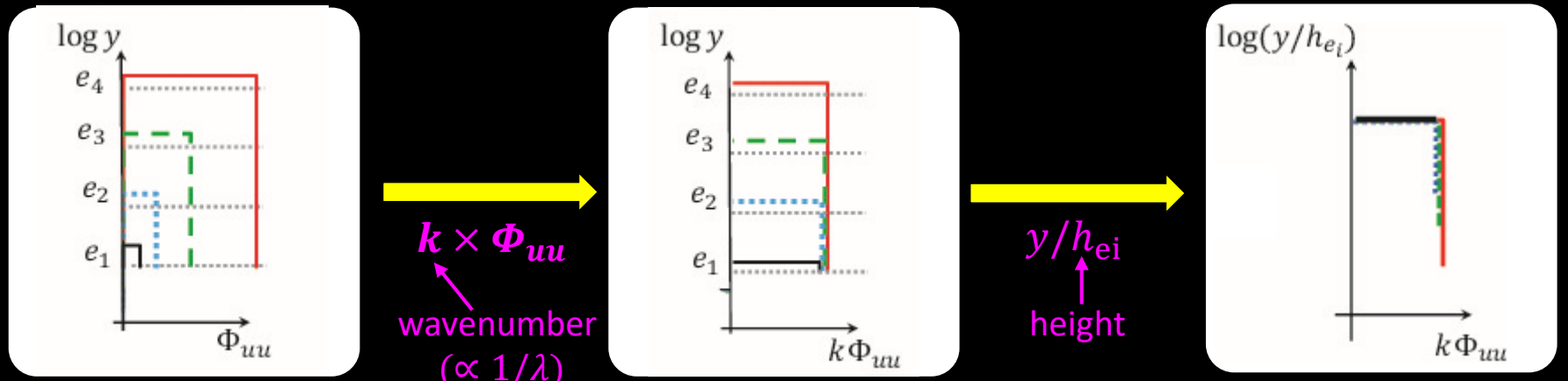
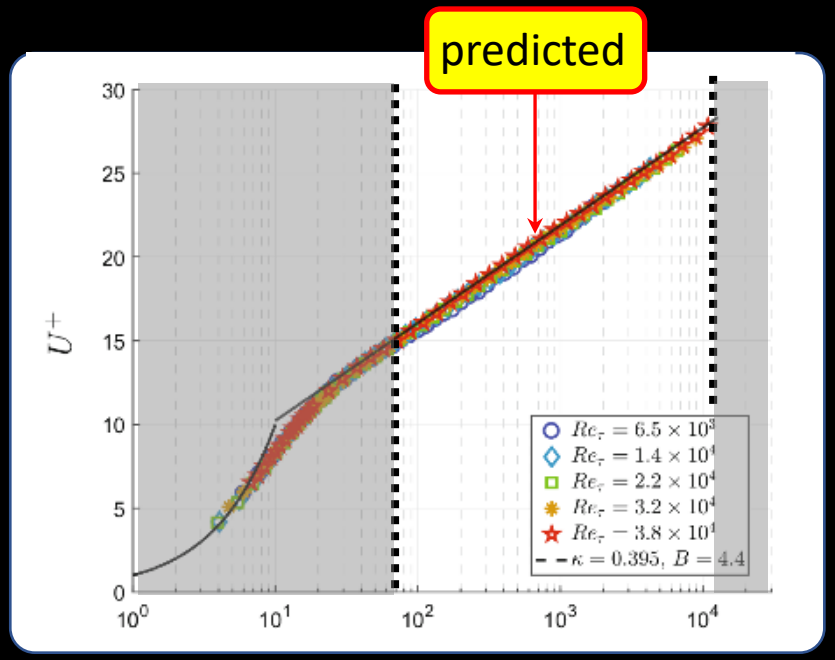


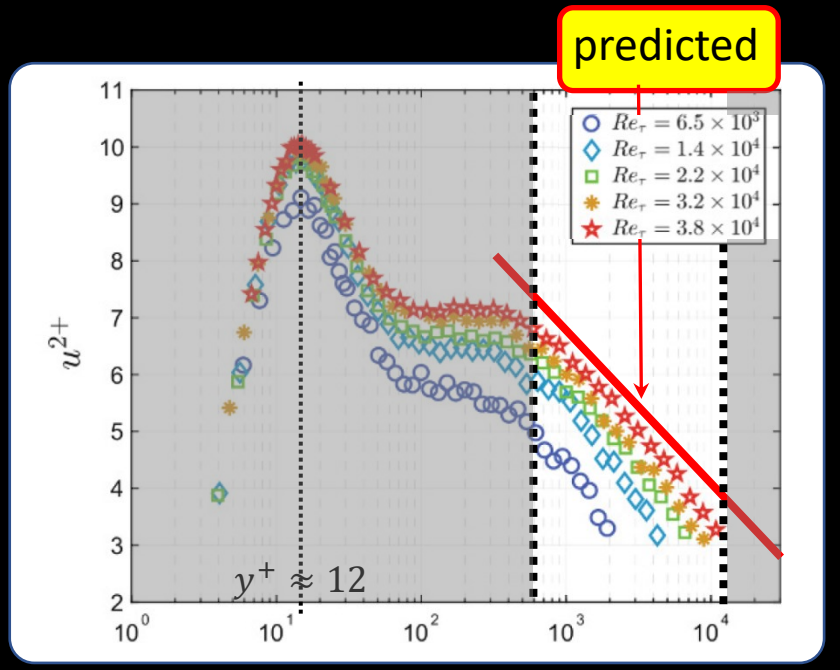
Their size and their induced motions scale with their distance to the wall

Dynamic of the outer-flow part
Implication of AEH



$$\Rightarrow \quad \bar{U}^+ = \frac{1}{\kappa}\log y^+ + B$$

Perry et al. (JFM 82 & 86)
Woodcock & Marusic. (PoF 2015)

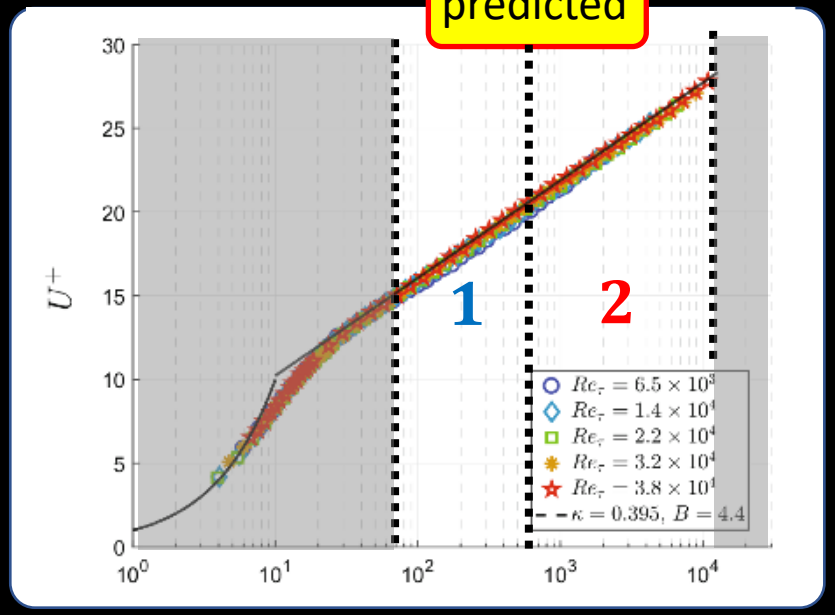


$$\Rightarrow \quad \overline{u'u'} = -1.26\,\log(y^+) + B(Re_\tau)$$

Townsend (62)

Dynamic of the outer-flow part
Implication of AEH

predicted



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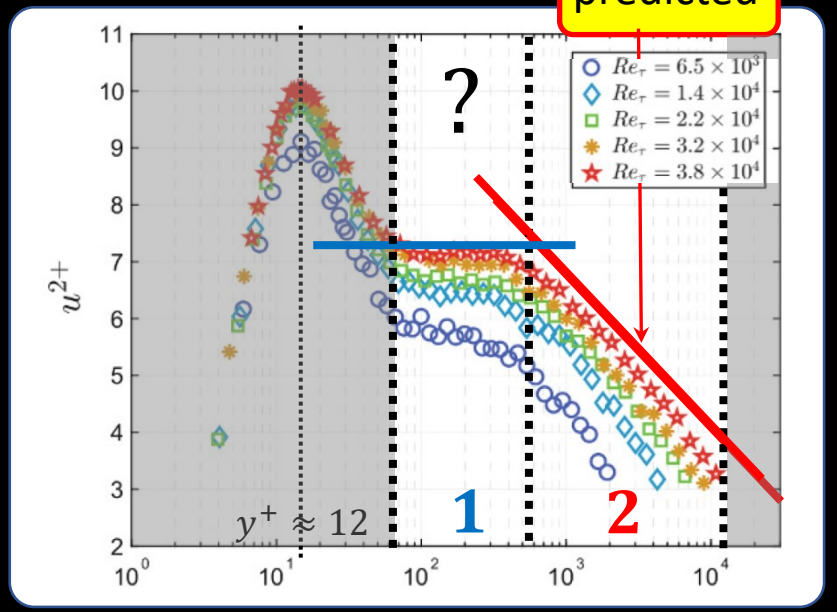

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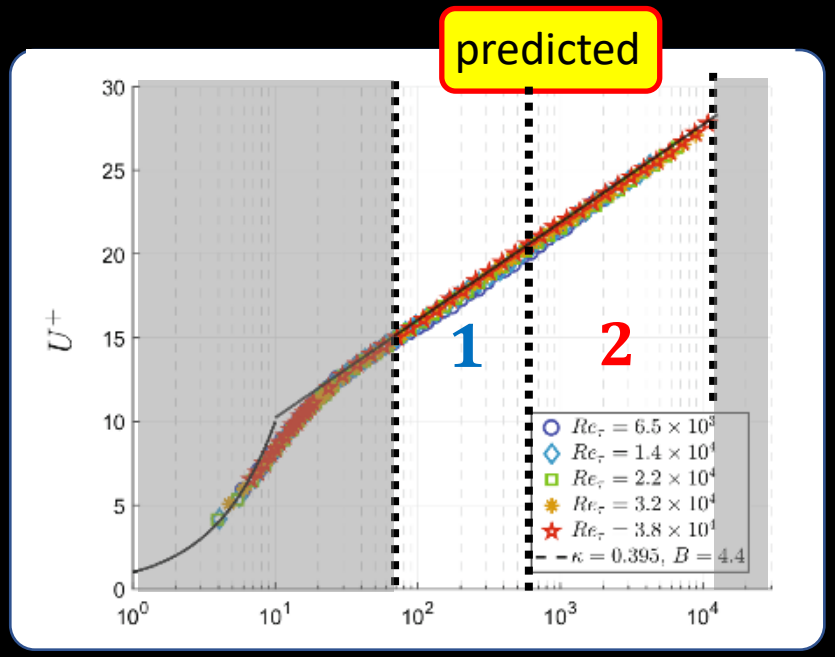

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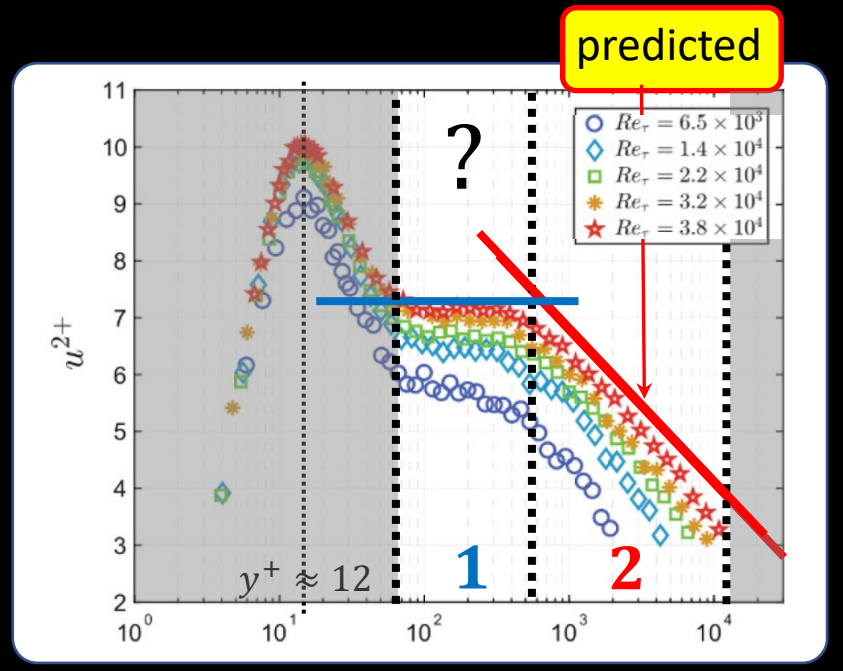


$$\Rightarrow \quad \overline{u'u'} = -1.26\log(y^+) + B(Re_\tau)$$

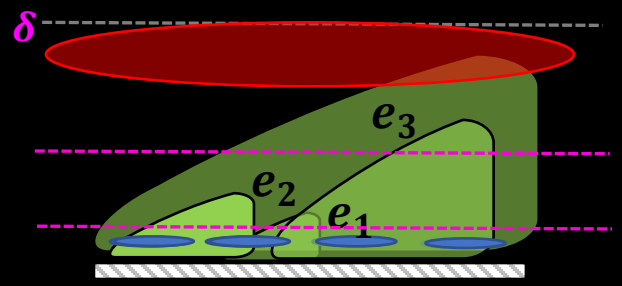
Townsend (62)

Is AEH valid in region 2 ?

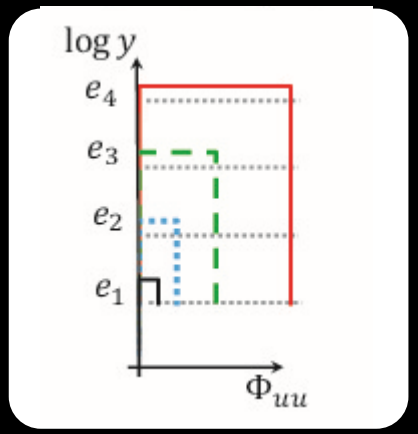
Does the AEH apply in the plateau region (region 1) ?

Does the plateau derive from AEH ?

Dynamic of the outer-flow part
Implication of AEH – Streamwise stress $\overline{u'u'}$



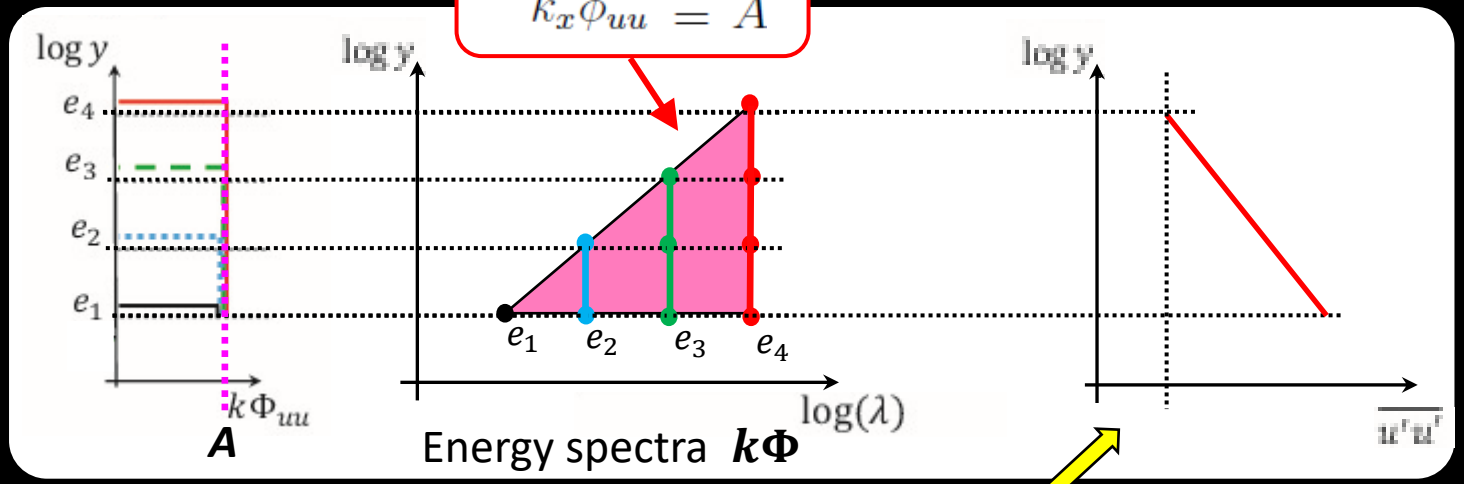
Energy density profiles associated to  :



$k \times \Phi_{uu}$

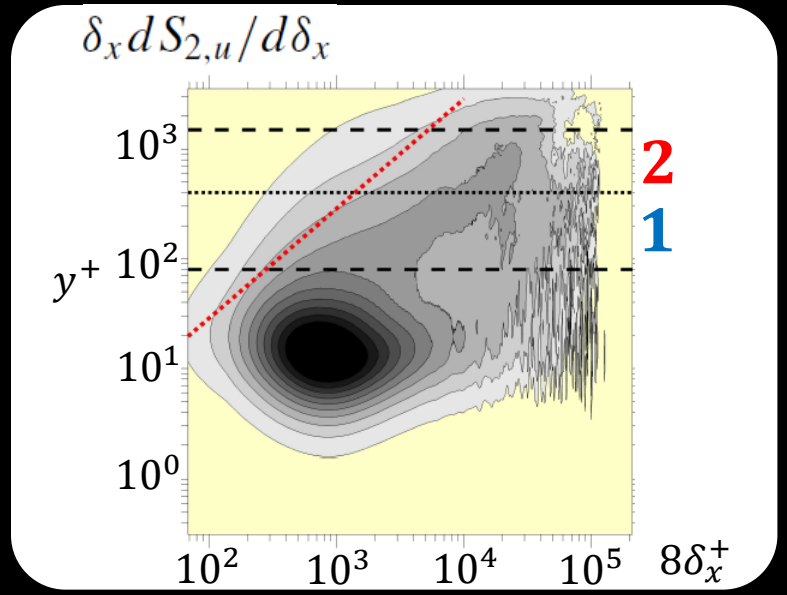
wavenumber ($\propto 1/\lambda$)

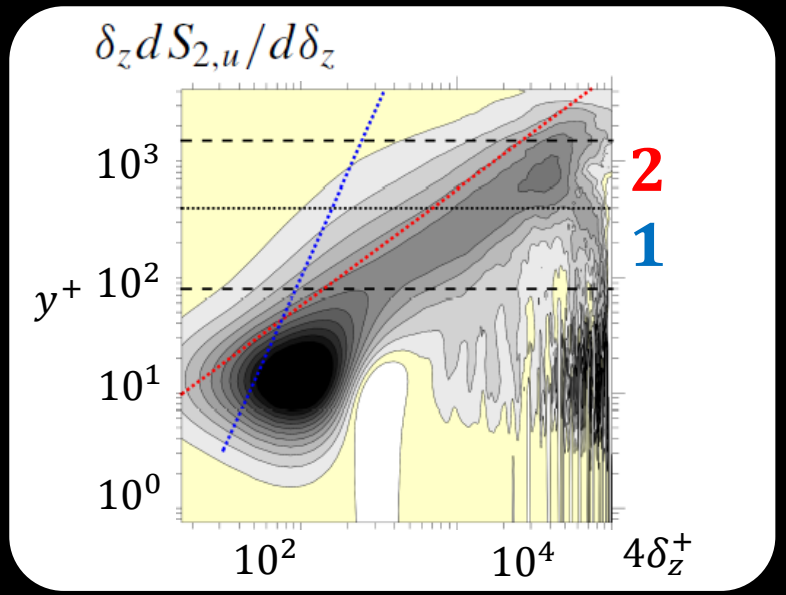
"triangle"
$k_x \phi_{uu} = A$



$$\overline{u'u'} = \int_{Cy^+}^{cst} A d\log(\lambda_x^+) = -A\log(y^+) + B(Re_\tau)$$

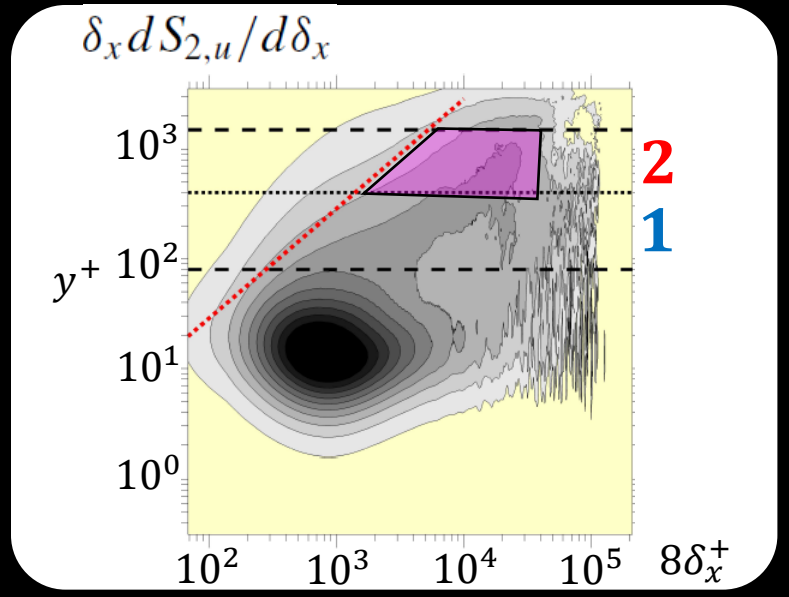
Dynamic of the outer-flow part
AEH validity – Scale distribution of the Energy

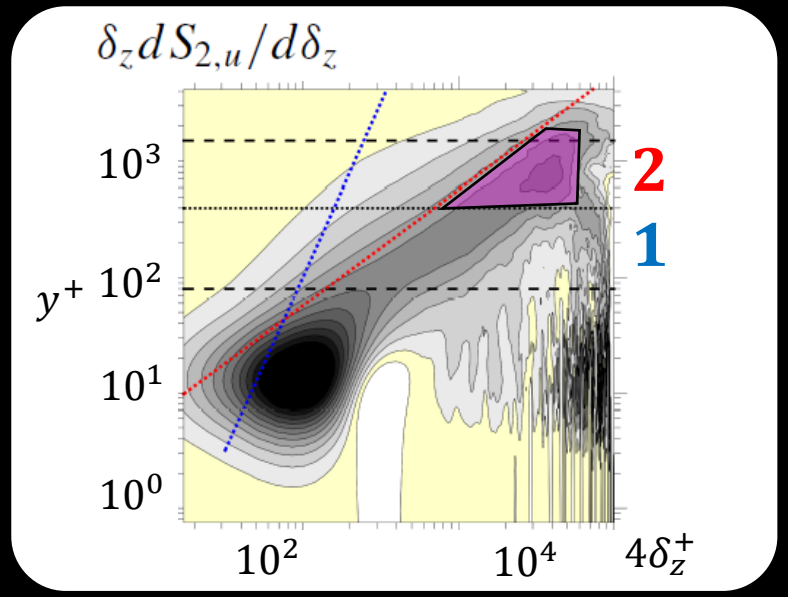




Channel flow
($Re_\tau \approx 4200$)

Dynamic of the outer-flow part
AEH validity – Scale distribution of the Energy





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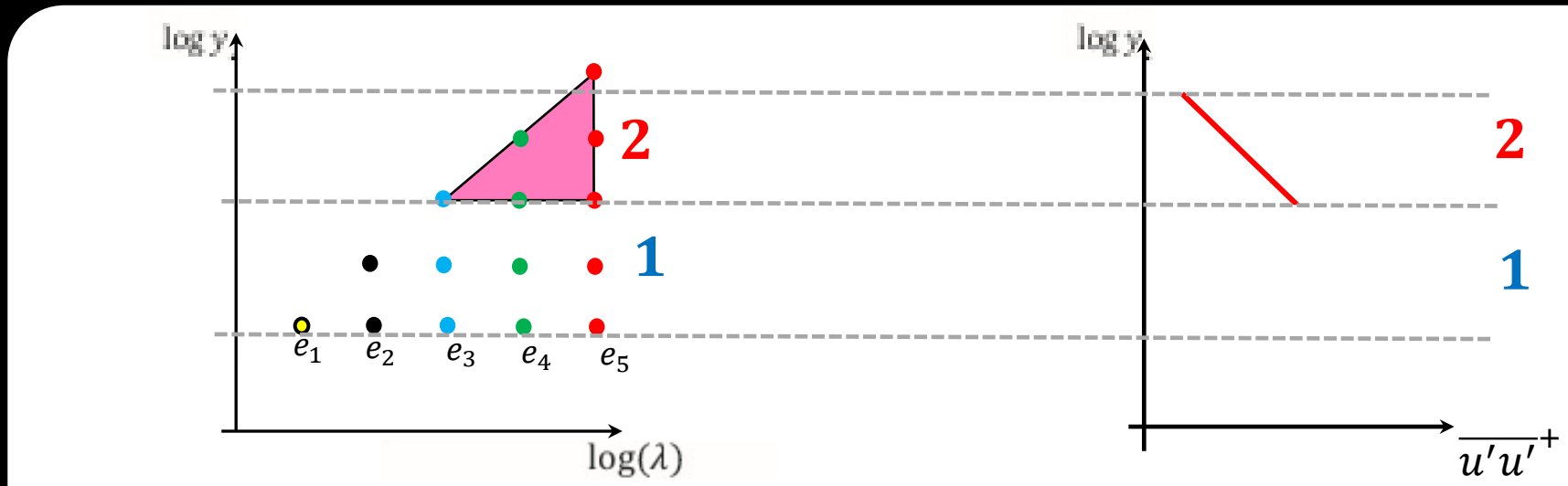
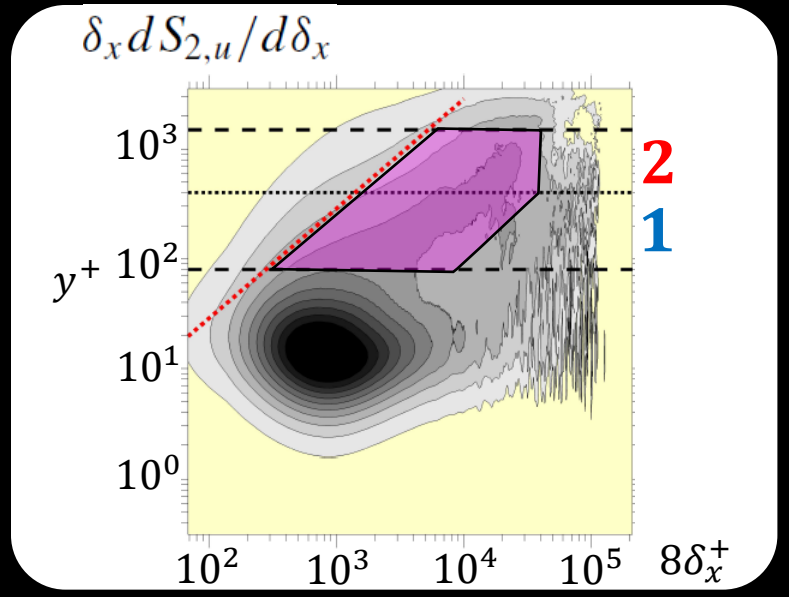
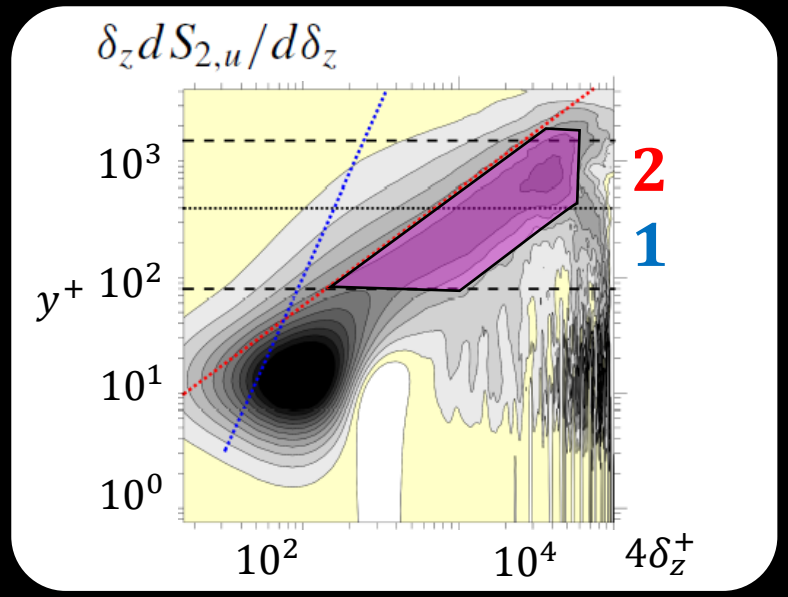


$$\overline{u'u'} = \frac{1}{2}\int_{\diagup}^{\delta_{e_M}} \delta \frac{dS_{2,u}}{d\,\delta} dlog(\delta)$$

Dynamic of the outer-flow part
AEH validity – Scale distribution of the Energy





Channel flow
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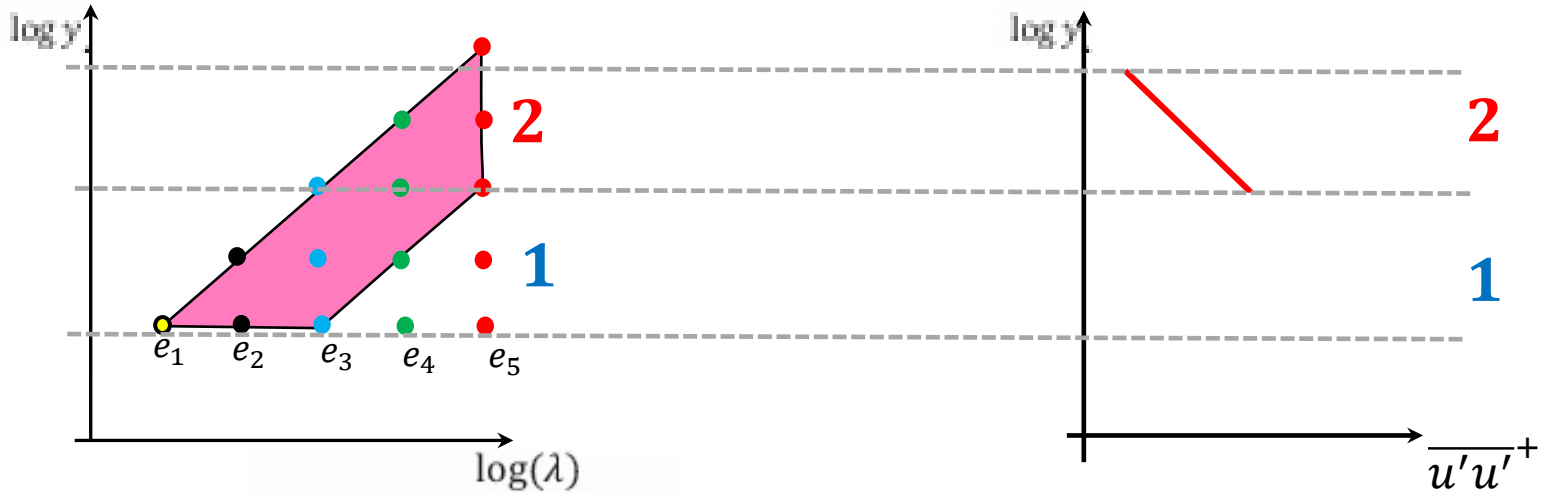
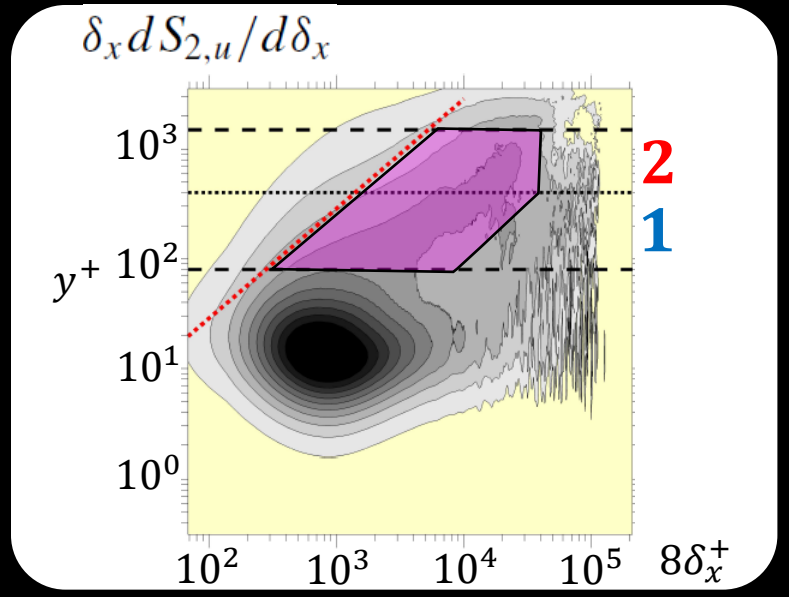
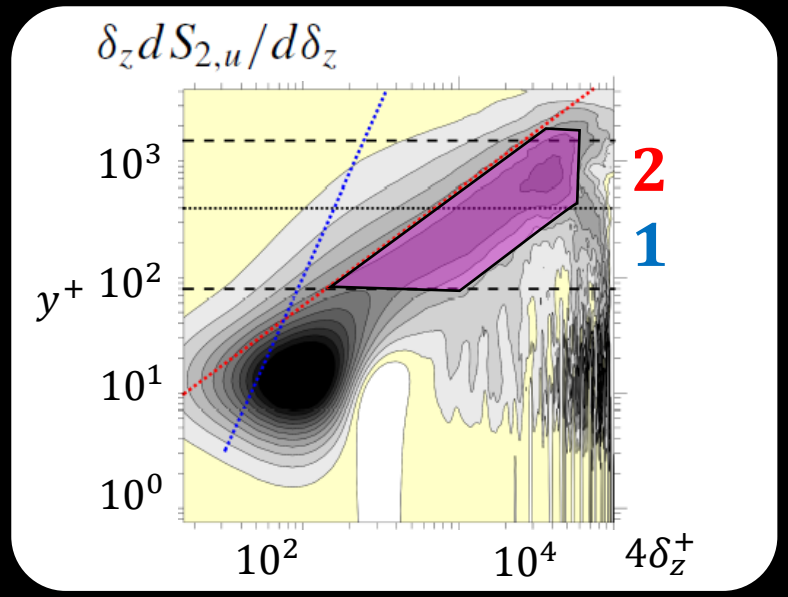


$$\overline{u'u'} = \frac{1}{2}\int \delta \frac{dS_{2,u}}{d\,\delta} dlog(\delta)$$

Dynamic of the outer-flow part
AEH validity – Scale distribution of the Energy





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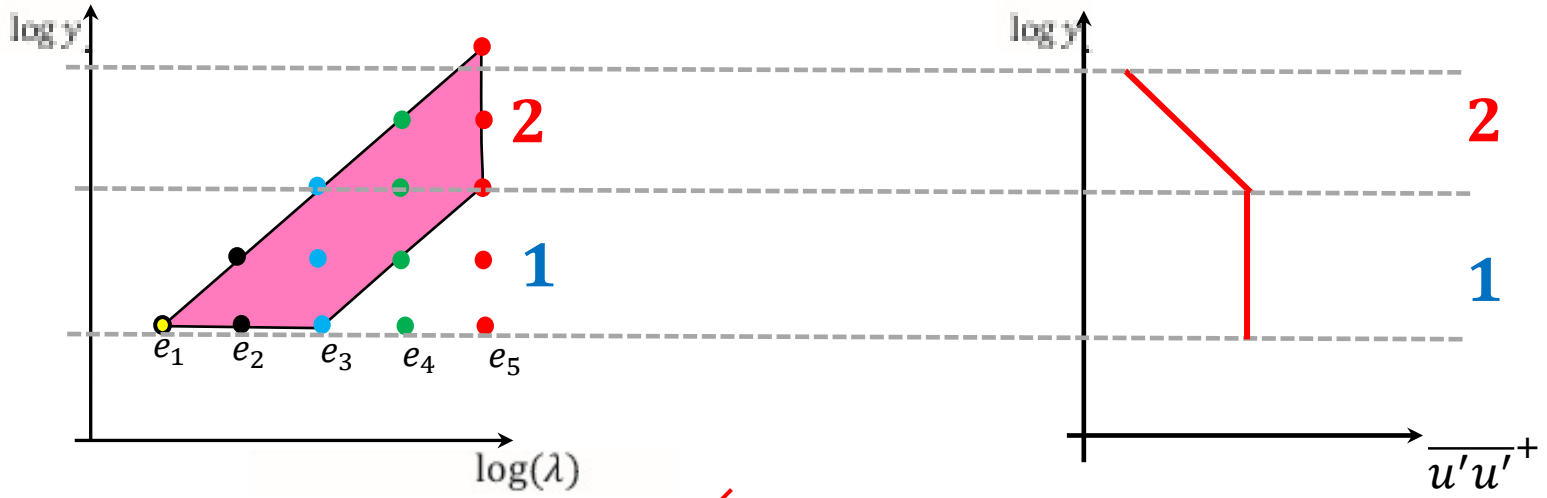
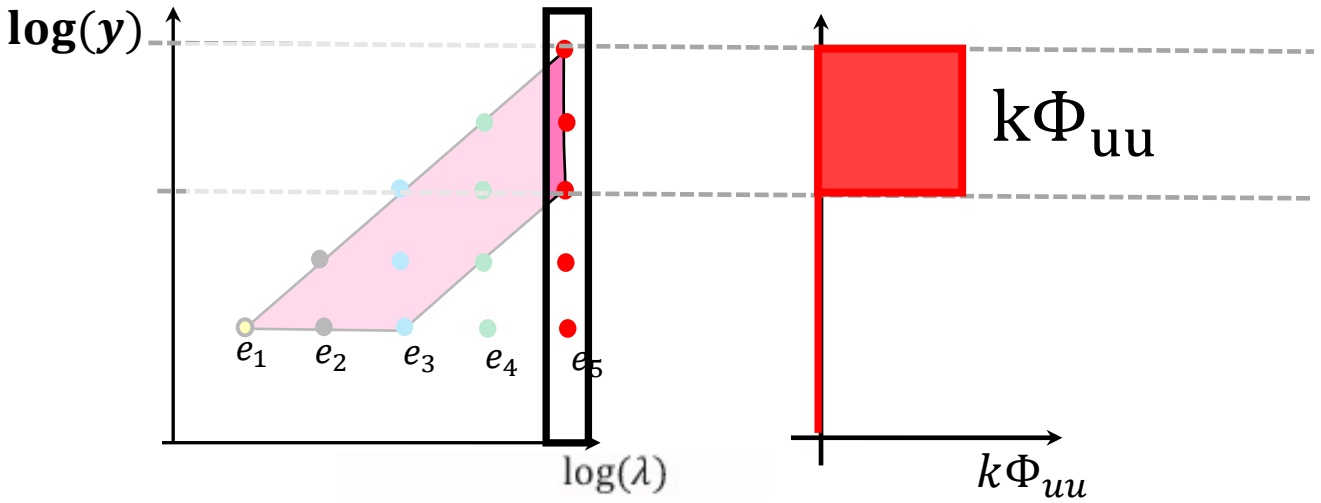
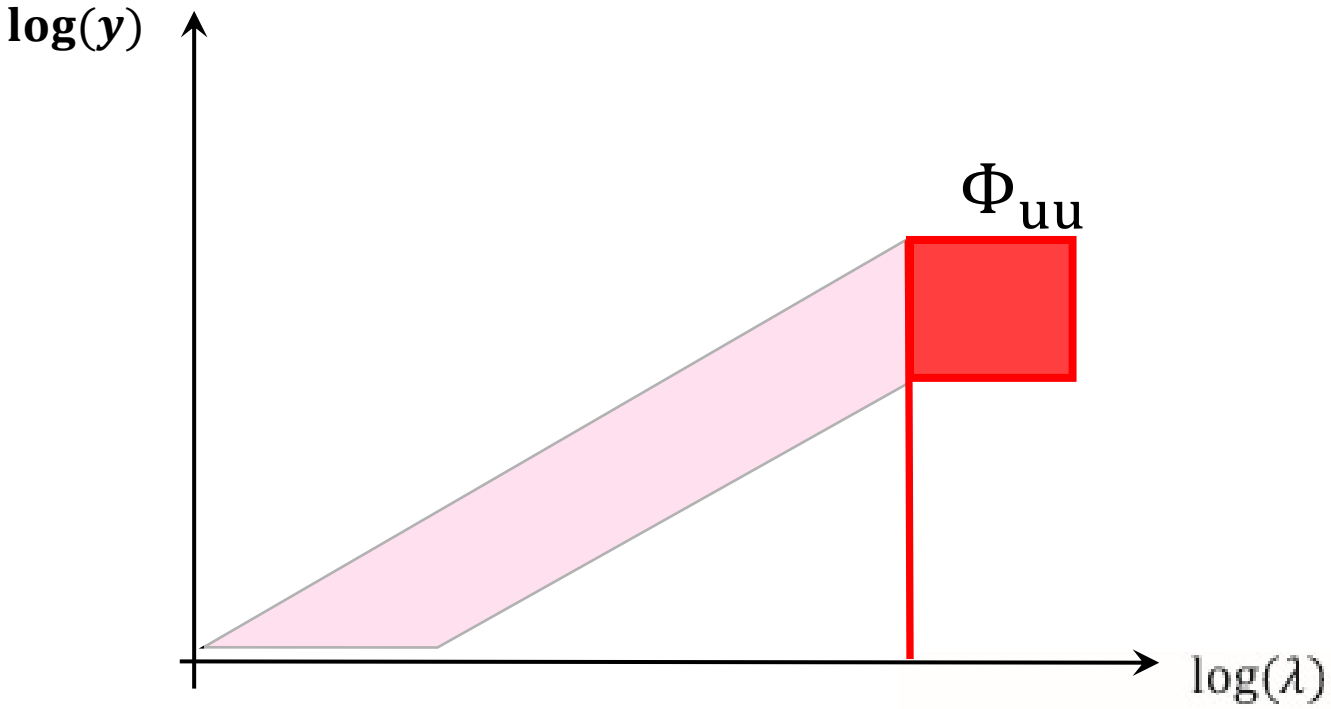


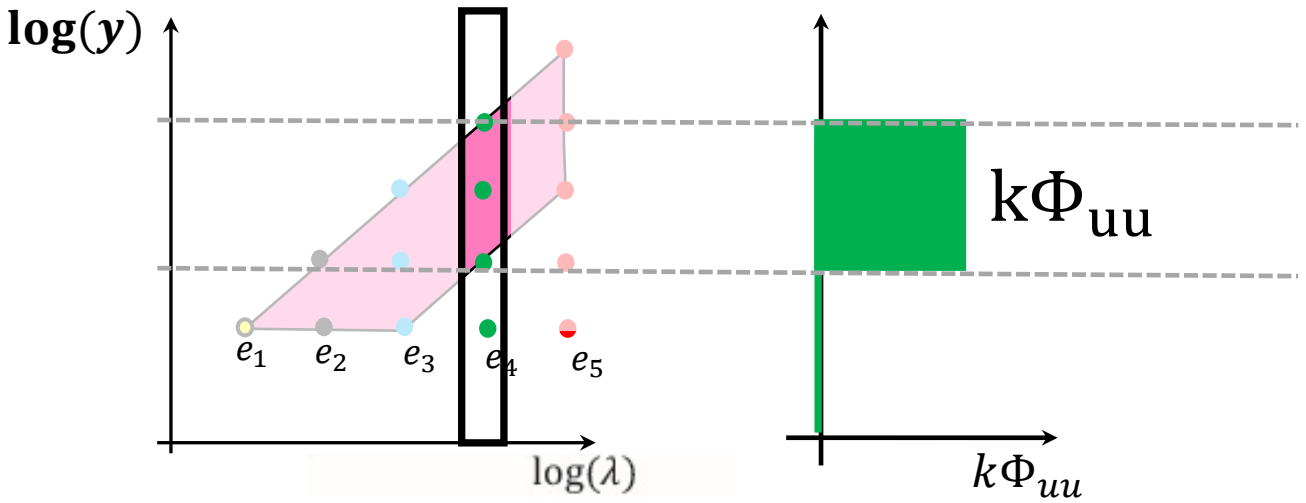
$$\overline{u'u'} = \frac{1}{2}\int \delta \frac{dS_{2,u}}{d\,\delta} dlog(\delta)$$

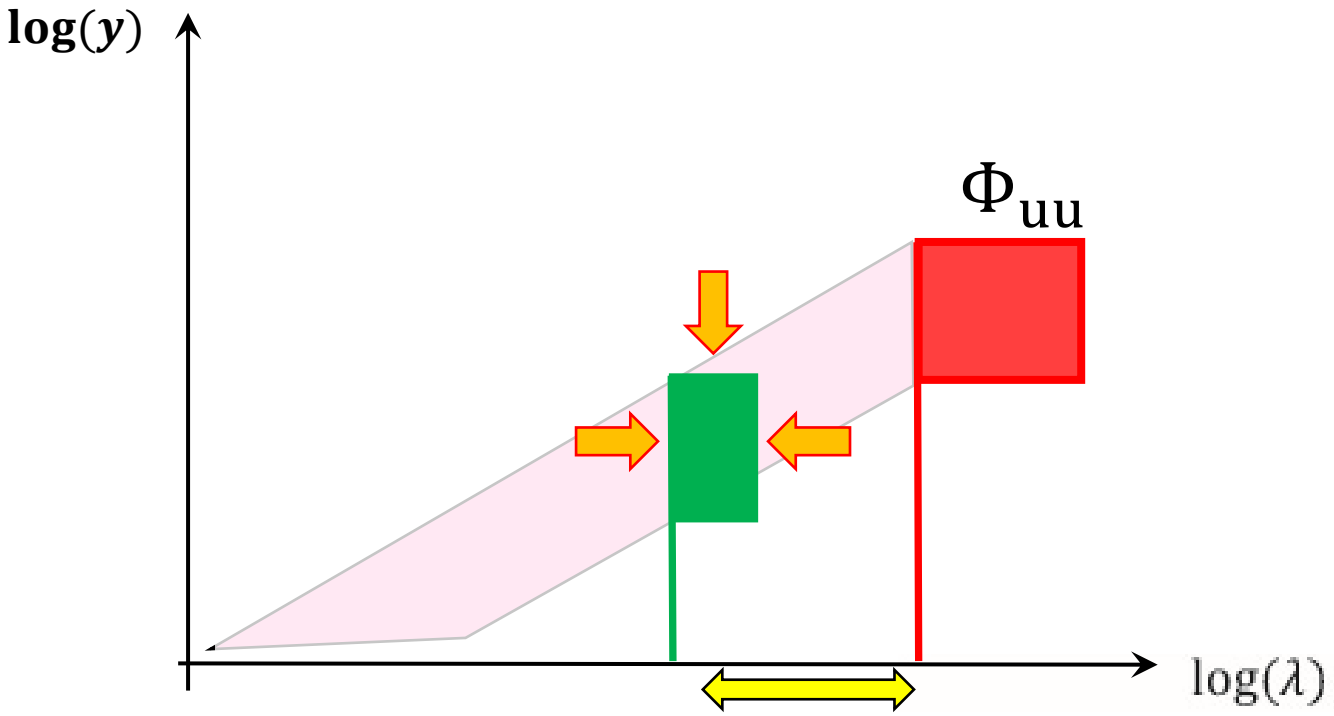
Dynamic of the outer-flow part
AEH validity –Attached-Eddies Self-similarity





Dynamic of the outer-flow part
AEH validity –Attached-Eddies Self-similarity





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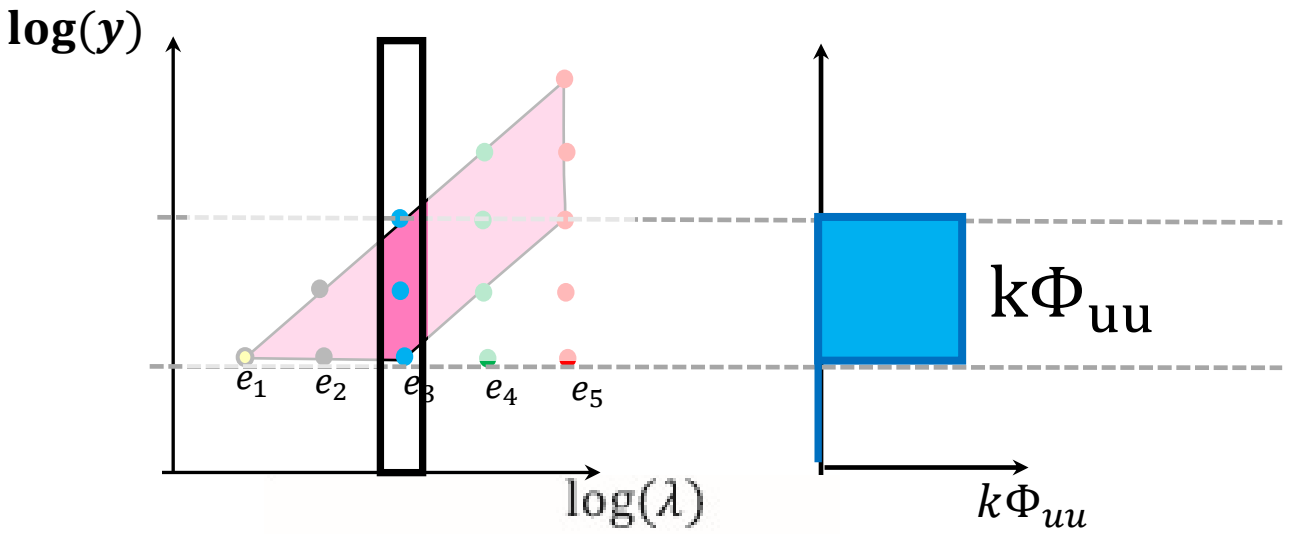
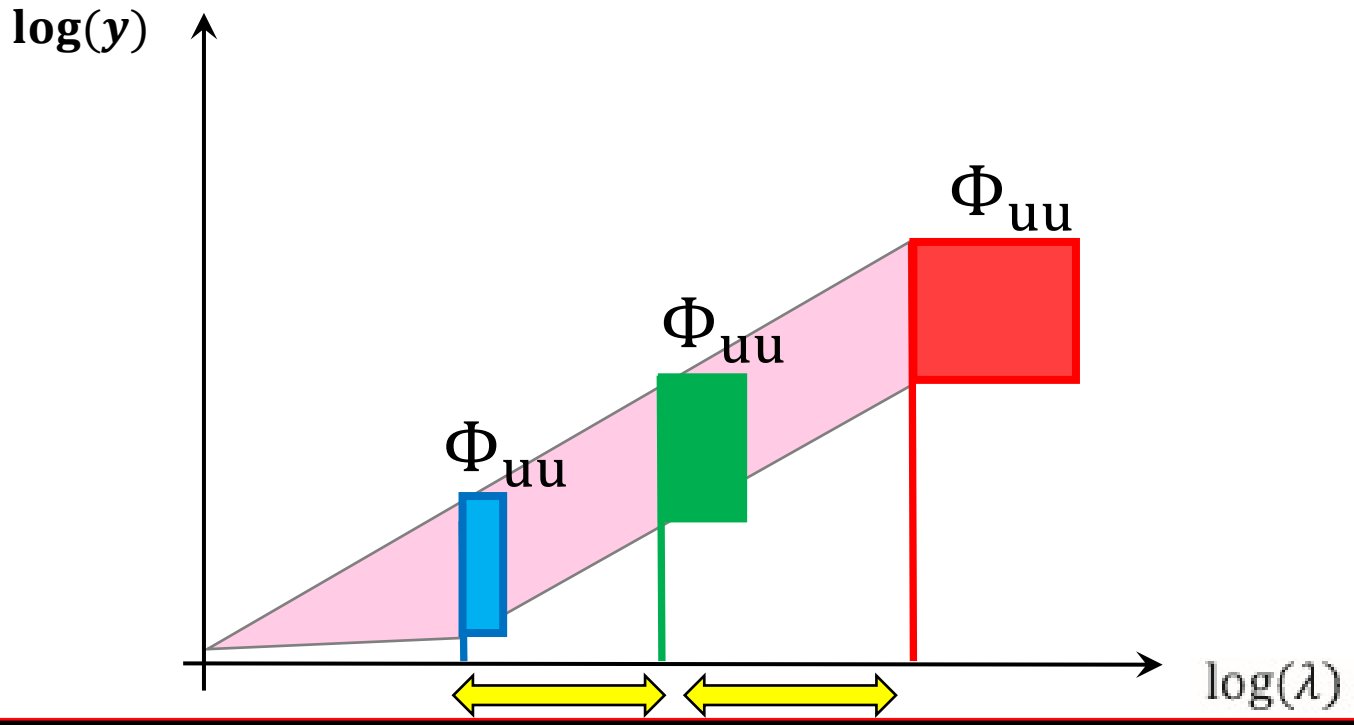
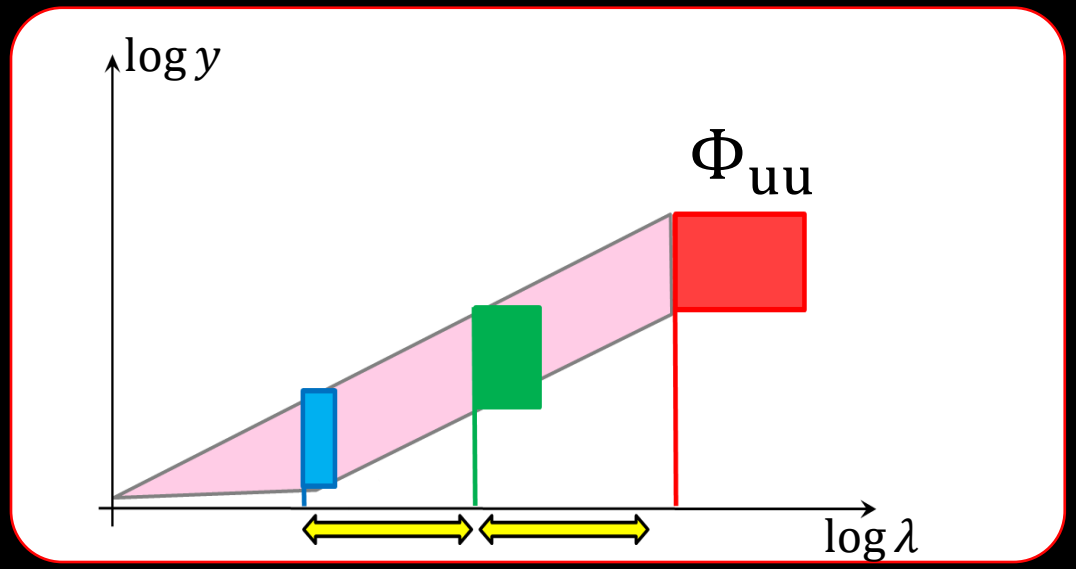
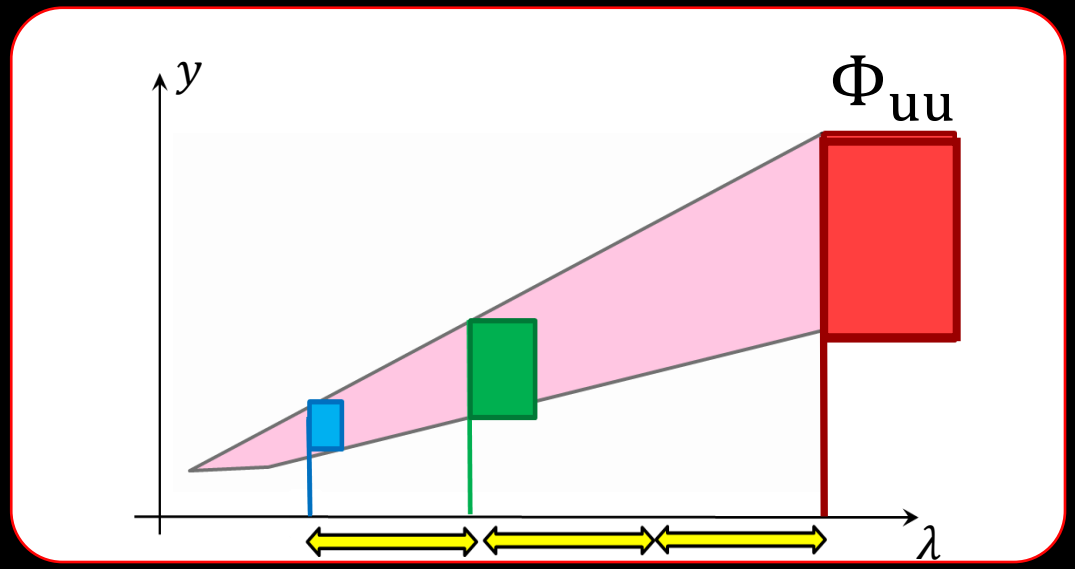




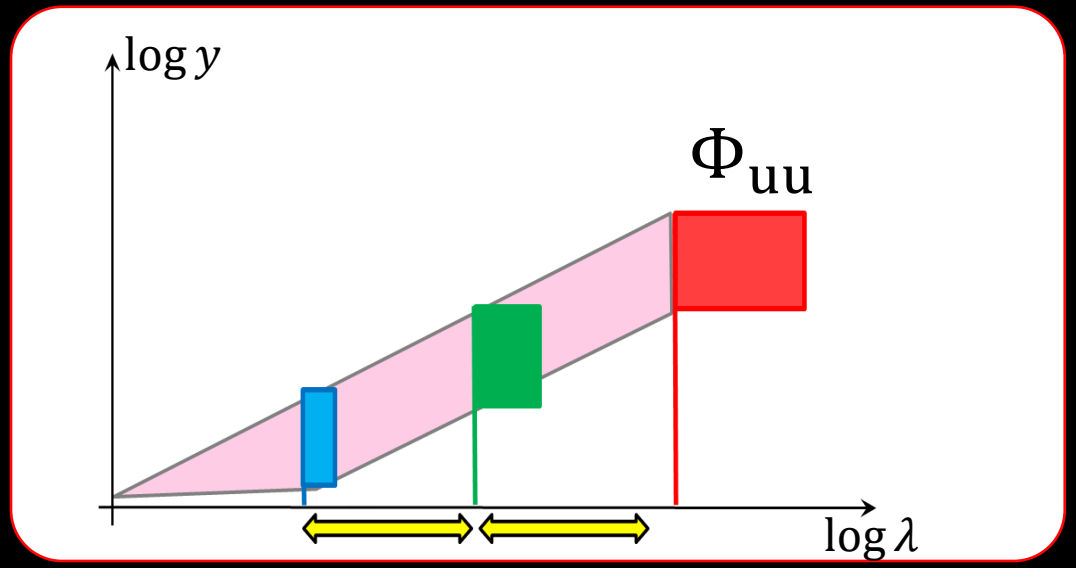
Dynamic of the outer-flow part

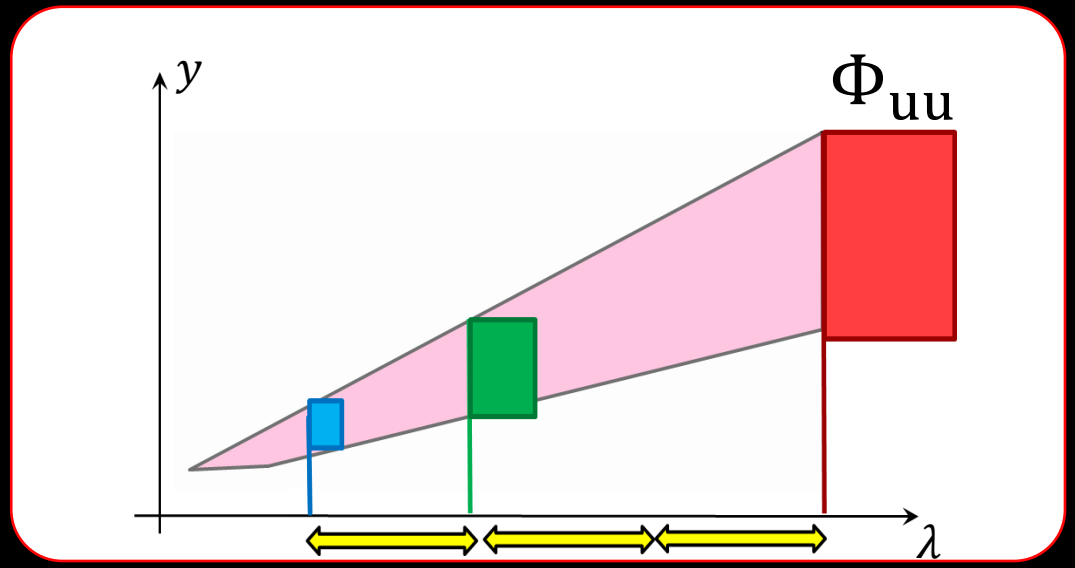
AEH validity – Attached-Eddies Self-similarity



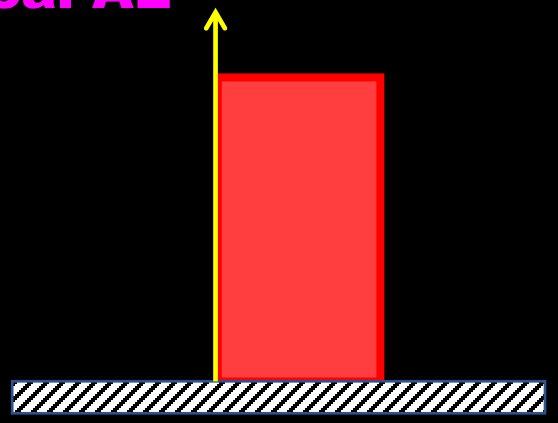


Dynamic of the outer-flow part
AEH validity – Extended conceptual Attached Eddies model

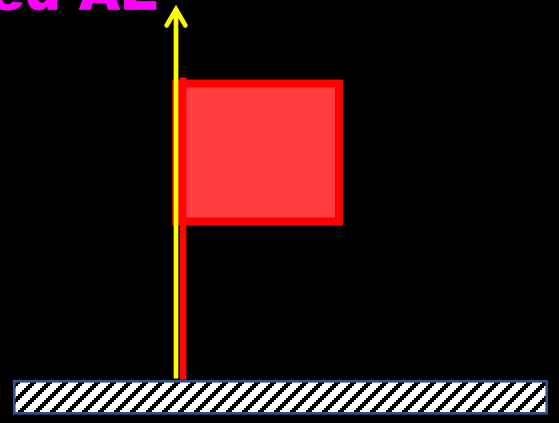




Classical AE

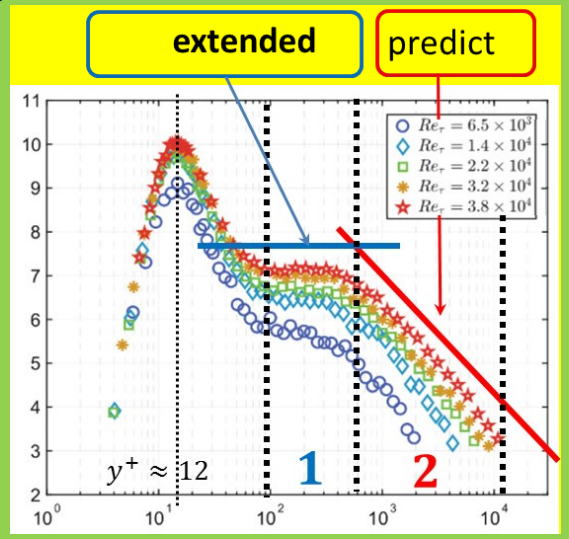


Extended AE

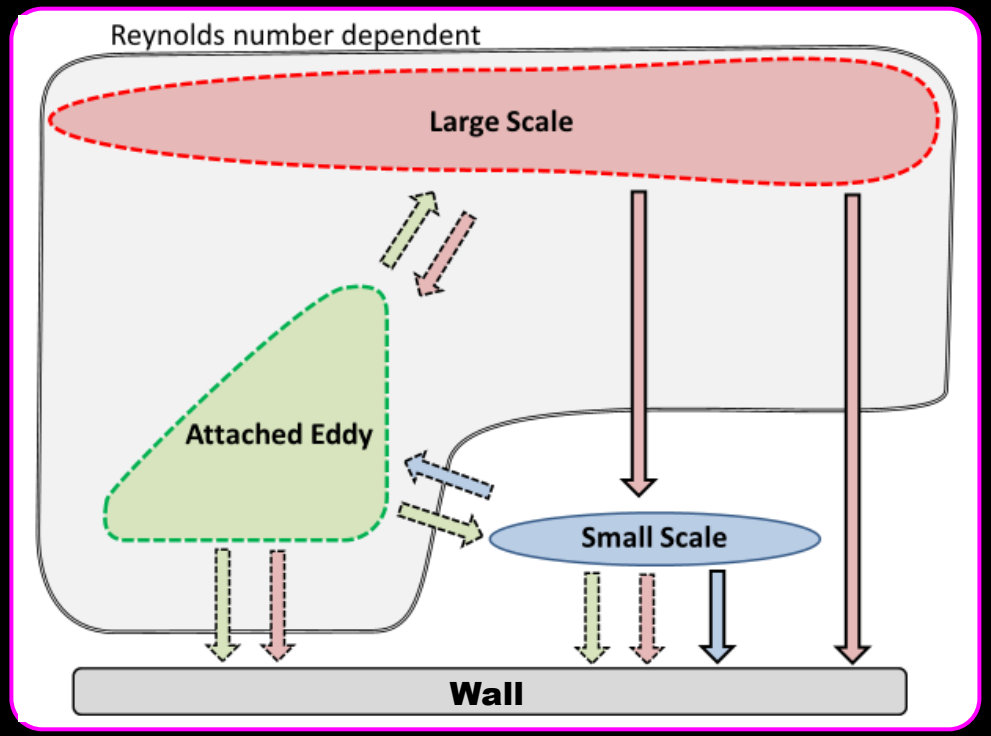


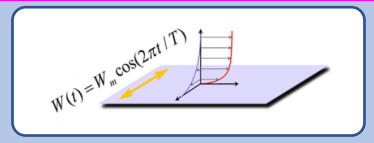
The self-similarity hypothesis of the AE is preserved

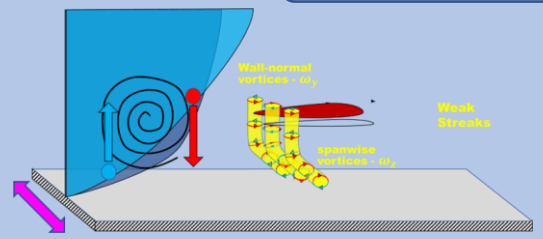
Near-wall turbulence
Multi-scale dynamic – Attached Eddies



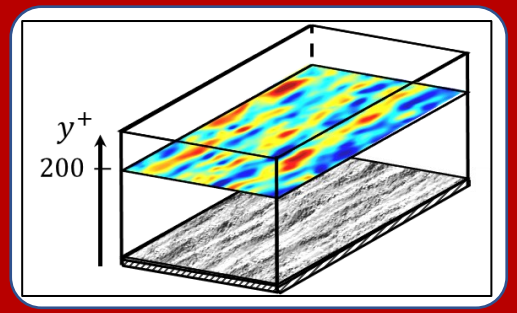
- Corroborate the existence of 
- Extend the theory of the AEH
- Predict the evolution of the streamwise stress



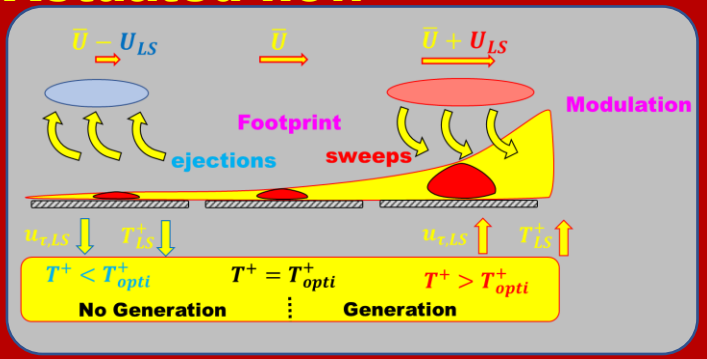




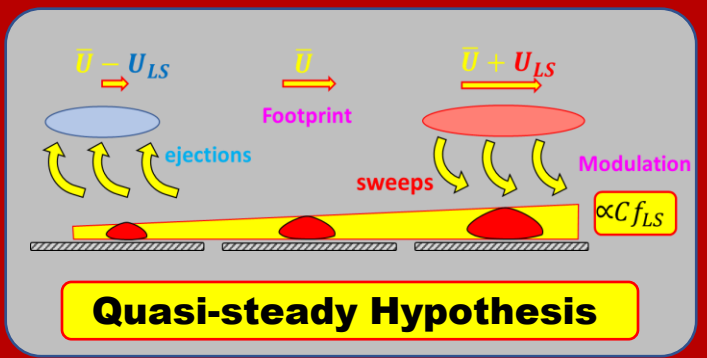
Block the streaks generation



Actuated flow

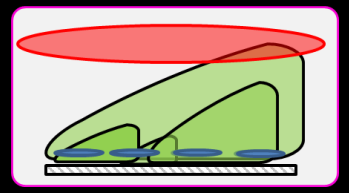


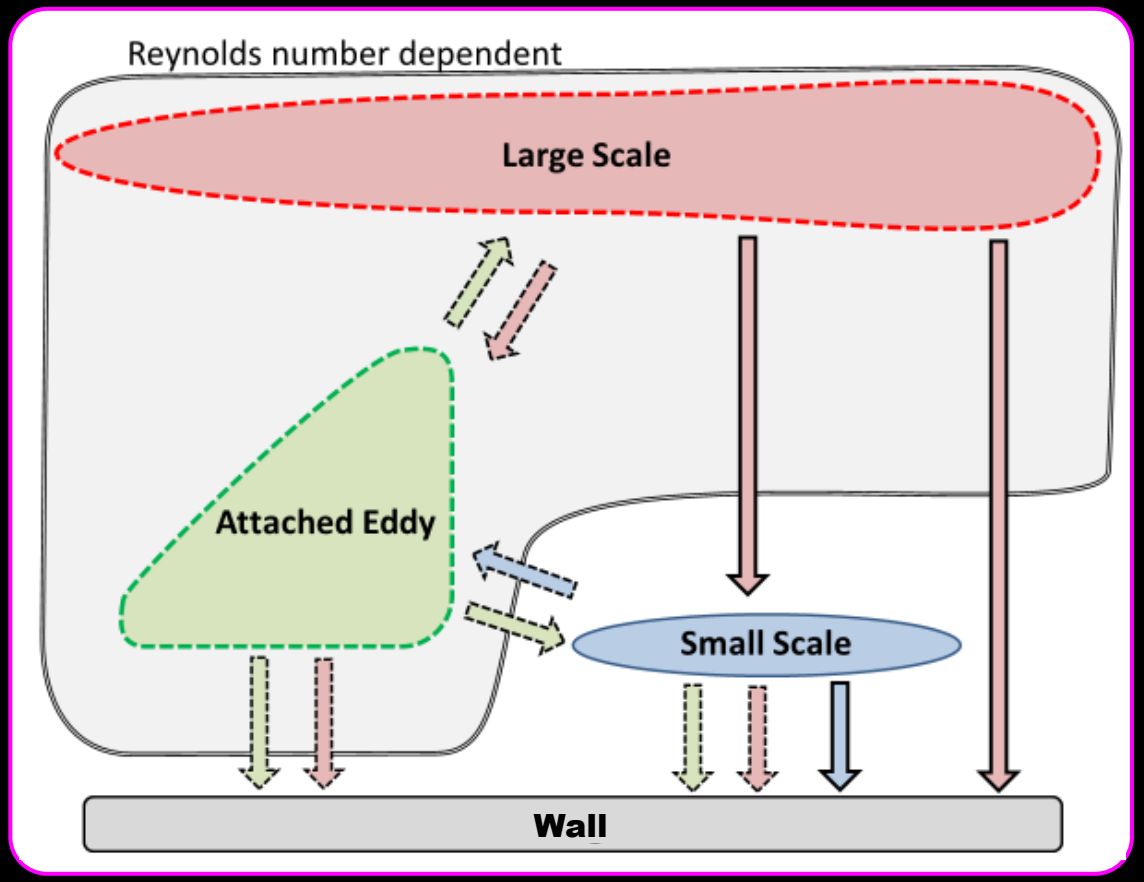
Canonical flow



Quasi-steady Hypothesis

Dynamic of Near-wall turbulence: Skeleton and Relations ``Vision Puzzle''
Open questions and objectives





➪ **How to identify them?**
- What are the identification methods?
- What are their characteristic signatures?
- How to detect their presence?

➪ **How do they develop?**
- What are their growth mechanisms?
- What influences their evolution?
- What are their development stages?

➪ **How do they interact?**
- What are the scale-to-scale interactions?
- What are their coupling mechanisms?

➪ **What are their contributions to mixing Momentum :**
- What are the effects on the Drag ?
- What are the effects on Heat exchange ?

➪ **How to control them?**
- What are the possible control strategies?
- How to implement effective control?
- What are the limitations of control methods?

Near-wall turbulence: From Understanding to Innovation
Projects in Progress & Perspectives

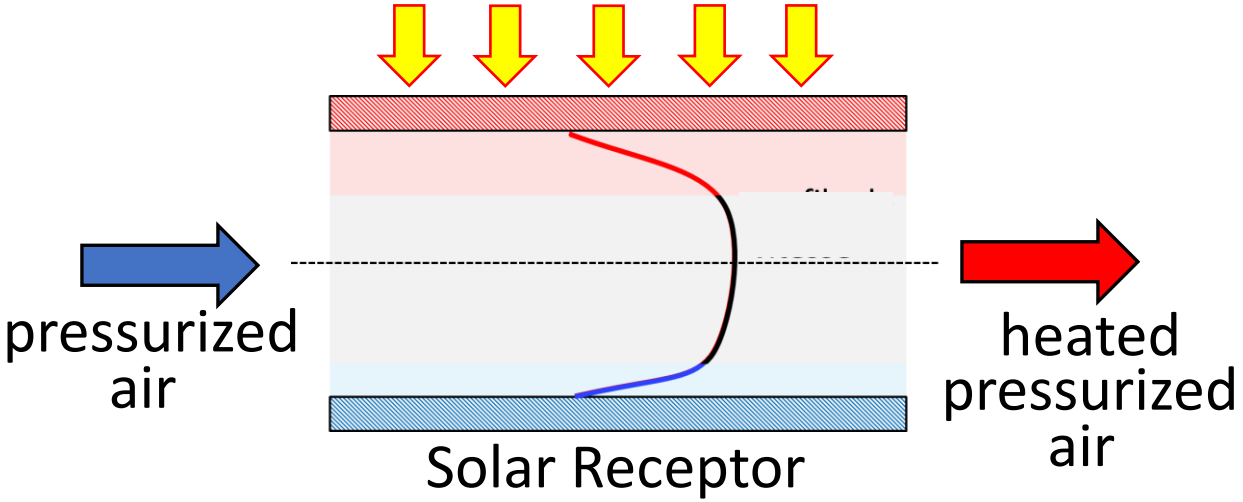
2022 **ANR-Solaire - LISN, PROMES et Pprime**

Phd candidate: Lou Guerin 2022-2025

Heat transfer, Theory + Control (ML)

The optimisation of high-temperature solar receptor

Solar Energy



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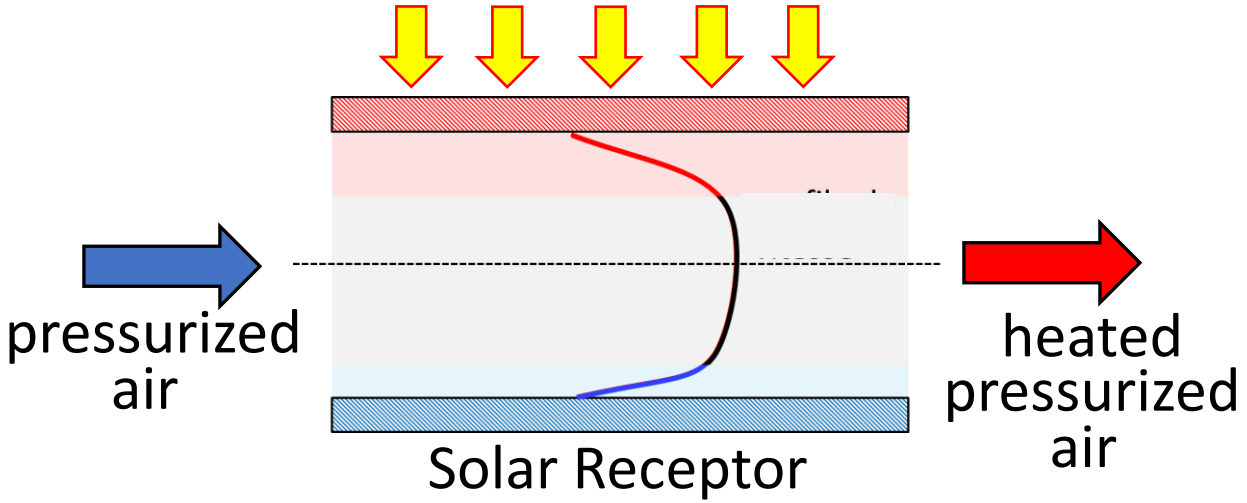

$T^+ = 100$

Drag reduction

Heat transfer reduction

Reynolds analogy conserved

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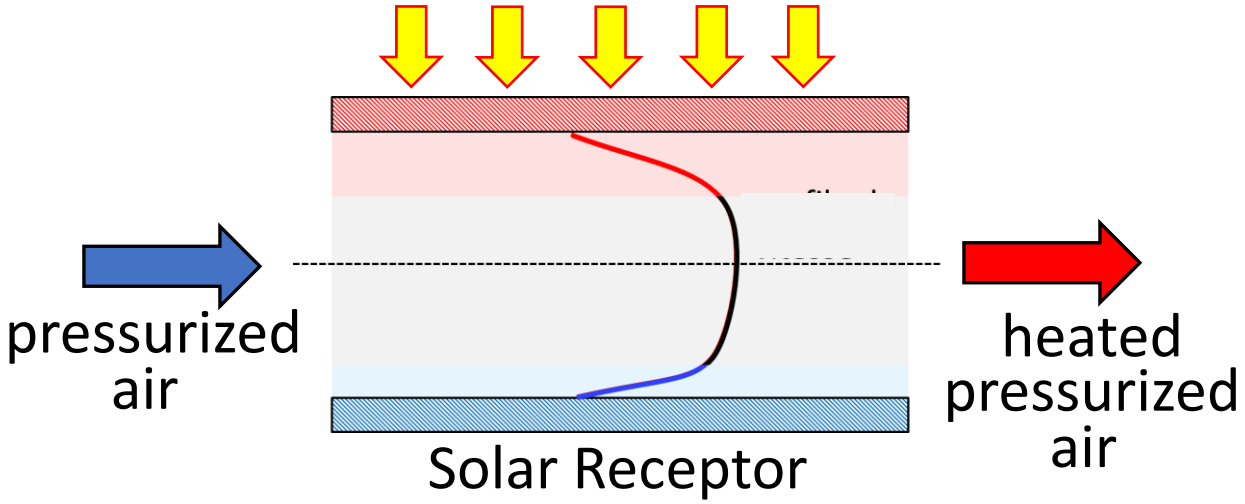


$T^+ = 100$

Drag reduction

Heat transfer reduction

Reynolds analogy conserved

Using ML algorithms

$T^+ \approx 500$ & $W^+ \approx 30$

➡ **15% Heat-transfer increase**

7% Drag increase

Reynolds analogy NOT conserved

Near-wall turbulence: From Understanding to Innovation
Projects in Progress & Perspectives

ANR-JCJC-Inference - Pprime

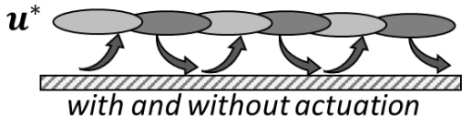
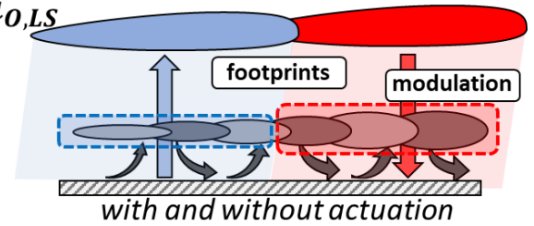
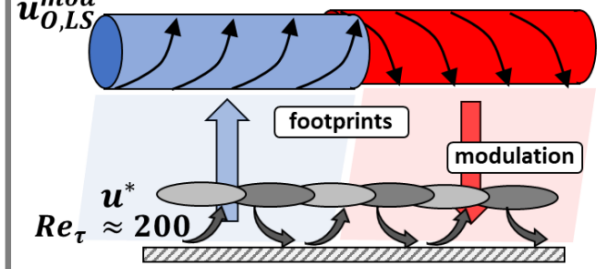
Phd candidate: Blessing Akinpelu 2024-2027

Postdoc 2025-2027

Heat transfer – Effect of the Reynolds number + Control

2024

Outer-flow structures effects (Reynolds number)

	$Re_\tau \approx 200$	$Re_\tau \approx 1000 \rightarrow 5200$	$Re_\tau \approx 200$ ✚ Synthetic outer-flow structures
open-ended questions	 **Q1** – How skin friction and heat transfer are related and driven by wall-bounded structures?	 $Q2$ – What are the effects of outer-flow large-scale structures on wall-bounded flow: ➡ Streaks ➡ Skin friction ➡ Heat transfer	Low-order dynamical modelling of outer-flow structures  $Q3$ – Modelling of the ***Re*** effects on the turbulent boundary layer.
Achievements	➪ Relation between drag and convective heat transfer. ➪ How effective is spanwise wall motion in increasing or decreasing the heat transfer? ➪ Map of ***Nu*** variation depending on control parameters & identified set of parameters for maximising ***Nu***.	➪ Predict the effects of outer-flow structure on drag and heat transfer for both canonical and actuated flows. ➪ Revise the empirical relationship : $u_p^+ = u^*\,[1 + \beta u^+_{O,LS}(y^+_O, \theta_{LS})] + \alpha u^+_{O,LS}(y^+_O, \theta_{LS}),$ ➪ Introduce a relation for the ***Nu*** taking under consideration the effect of large-scale motions	➪ Modelling the near-wall turbulence, or at least the variation of the skin friction and heat transfer, using simulation at low Reynolds with synthetic outer-flow structures obtained by reduced order model.

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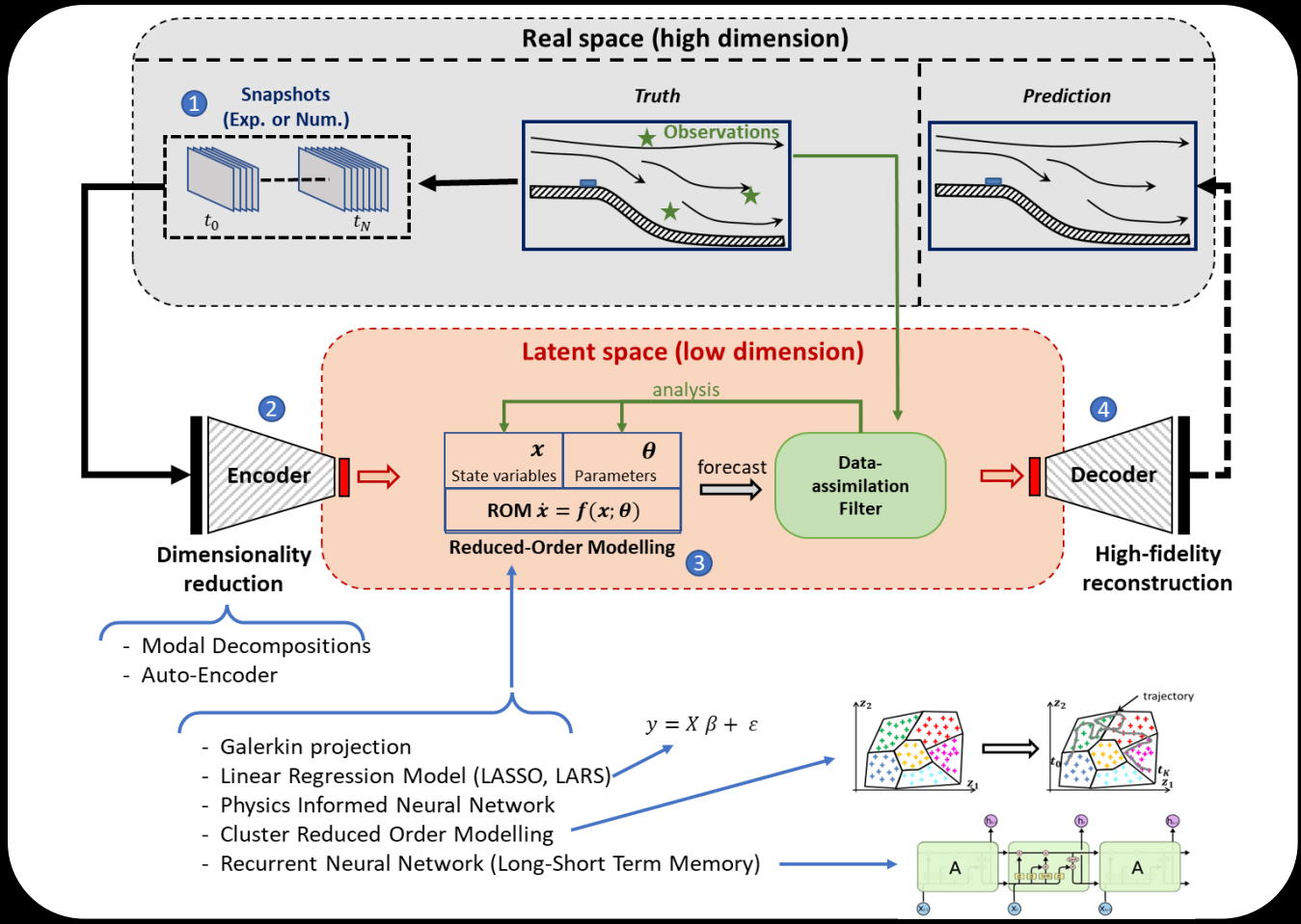
2023

KTH /EUR Intree – Ricardo Vinuesa et Pprime

Phd candidate: Niccolo Tonioni 2023-2026

Reduced order modelling using ML



Near-wall turbulence: From Understanding to Innovation
Projects in Progress & Perspectives

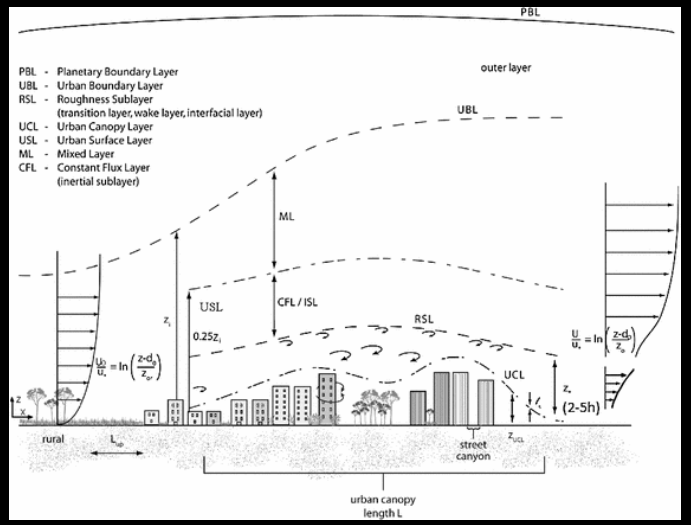
2023

ANR-MUFDD - LHEEA, IMFT et Pprime

Postdoc: Dr. Nishant Kumar 2023-2025

Reduced order modelling using ML

Urban-Canopy Flow



Zajic et al, 2015

Near-wall turbulence: From Understanding to Innovation
Projects in Progress & Perspectives

2022 **ANR-Solaire** - **LISN, PROMES et Pprime**

Phd candidate: Lou Guerin 2022-2025

Heat transfer, Theory + Control (ML)

2023 **KTH /EUR Intree** – **Ricardo Vinuesa et Pprime**

Phd candidate: Niccolo Tonioni 2023-2026

Canonical Boundary Layer – Reduced order modelling using ML

ANR-MUFDD - **LHEEA, IMFT et Pprime**

Postdoc: Dr. Nishant Kumar 2023-2025

Canopy flow – Prediction + Modelling

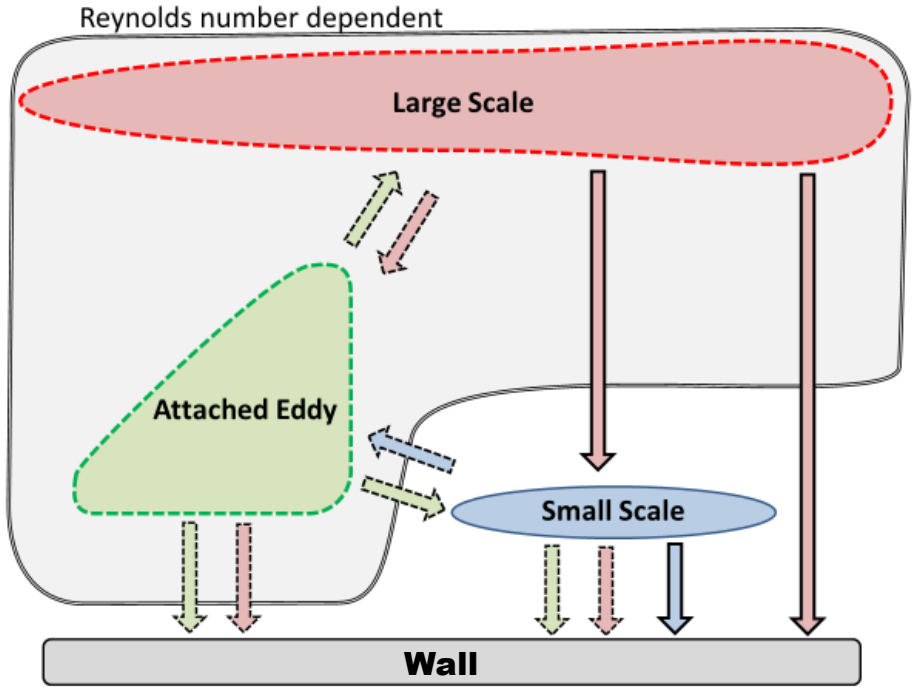
2024 **ANR-JCJC-Inference** - **Pprime**

Phd candidate: Blessing Akinpelu 2024-2027

Postdoc 2025-2027

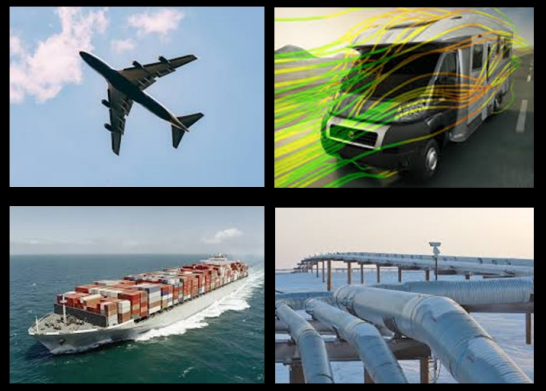
Heat transfer – Effect of the Reynolds number + Control

Near-wall Turbulence
From Understanding to Innovation



Drag Reduction

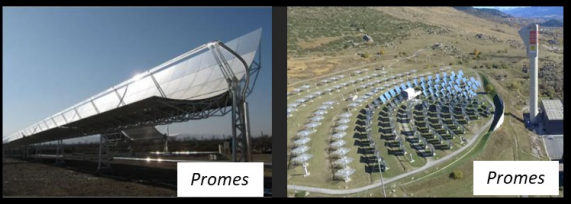
Transports



Drag ▭
Energy consumption
Pollutant emissions (CO_2, NO_x)

Improving Heat Exchanger

Development of solar energy



Engine Efficiency

Heat transfer
✚ / ▭
Optimal operating regime

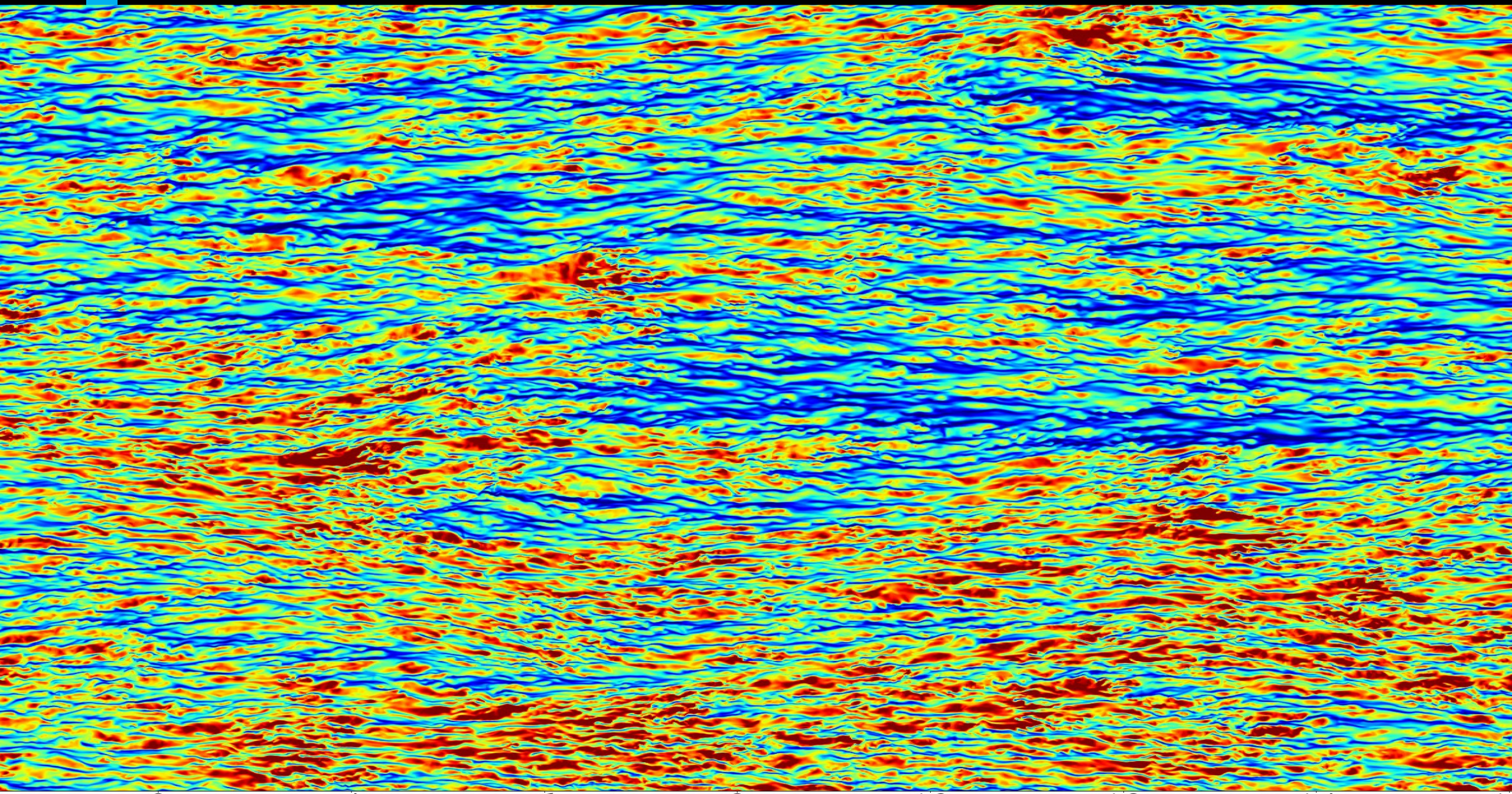
Modelling, predicting and controlling near-wall turbulence

⇨ **Reducing Drag**

⇨ **Improving Heat transfer**

Thank you for your attention

Near-wall turbulence: From Understanding to Innovation

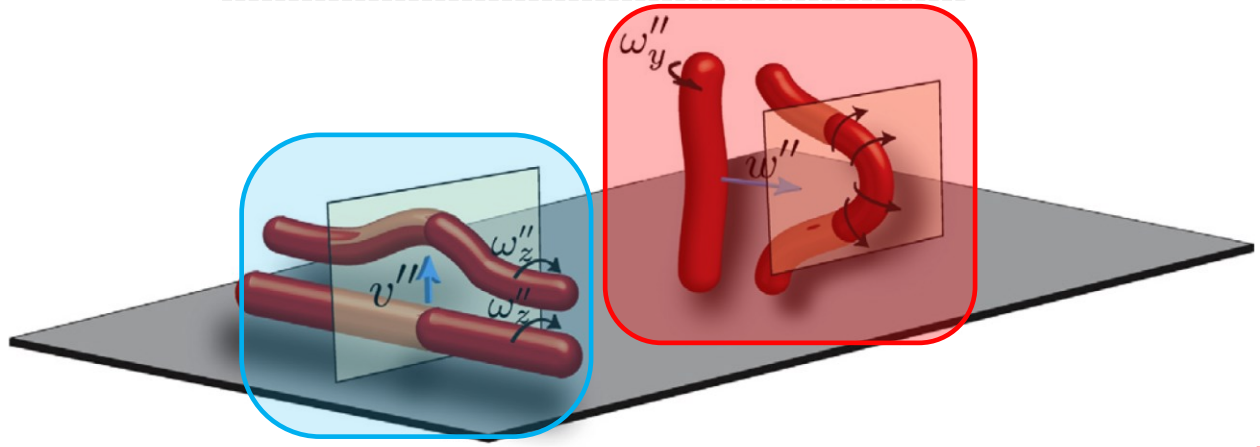


Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation - Shear-stress / Vorticity-field relationship

Momemtum equation :

$$\frac{\partial \widetilde{U}}{\partial \varphi} = \frac{1}{Re}\left[\frac{\partial^2 \widetilde{U}}{\partial y^2} - Re\left(\frac{\partial \widetilde{u''v''}}{\partial y}\right)\right]$$

$$-\frac{\partial \widetilde{u''v''}}{\partial y} = \widetilde{v''\omega_z''} - \widetilde{w''\omega_y''}$$



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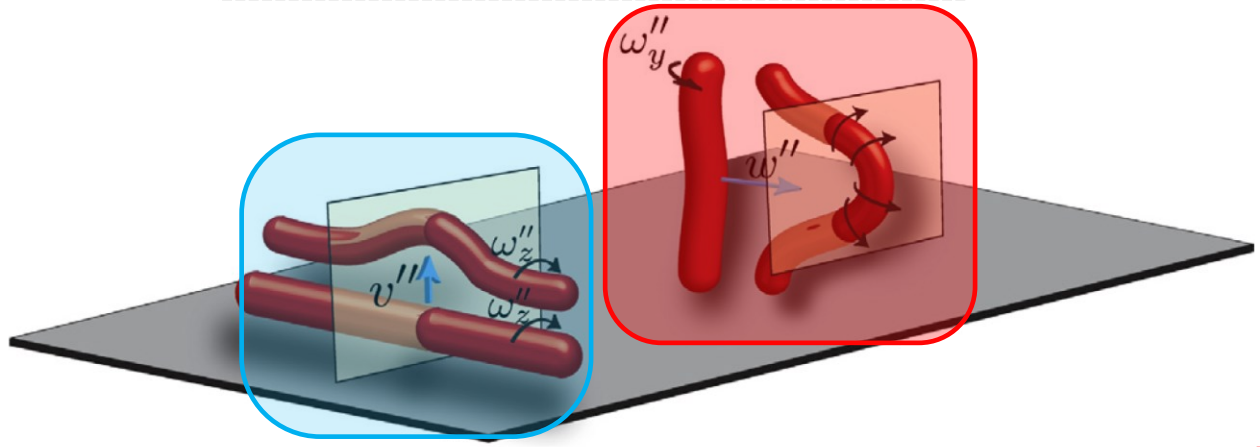
$$\widetilde{\omega_z} = -\frac{\partial \widetilde{U}}{\partial y}$$

$$-\frac{\partial \widetilde{u''v''}}{\partial y} = \widetilde{v''\omega_z''} - \widetilde{w''\omega_y''}$$

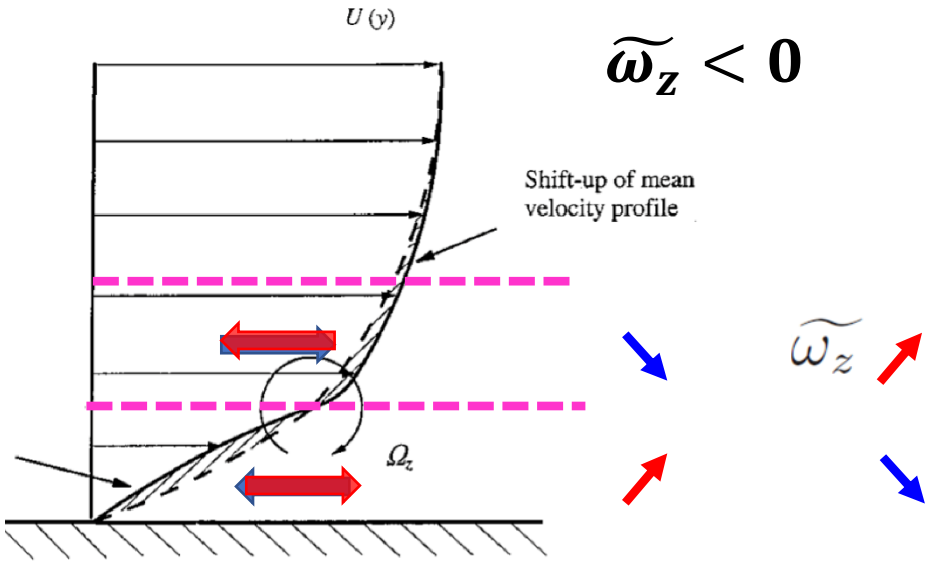


Spanwise vorticity equation :

$$\frac{\partial \widetilde{\omega_z}}{\partial \varphi} = \frac{1}{Re}\left[\frac{\partial^2 \widetilde{\omega_z}}{\partial y^2} - Re\left(\frac{\partial \widetilde{v''\omega_z''}}{\partial y} - \frac{\partial \widetilde{w''\omega_y''}}{\partial y}\right)\right]$$

Drag reduction at Relatively low-Reynolds number
Spanwise wall oscillation - Variation of $\widetilde{\omega_z} = -\partial\widetilde{U}/\partial y$

$$\frac{\partial\widetilde{\omega_z}}{\partial\varphi} = \frac{1}{Re}\left[\frac{\partial^2\widetilde{\omega_z}}{\partial y^2} - Re\left(\frac{\partial\widetilde{v''\omega_z''}}{\partial y} - \frac{\partial\widetilde{w''\omega_y''}}{\partial y}\right)\right]$$



Choi, Phys. Fluids 2002

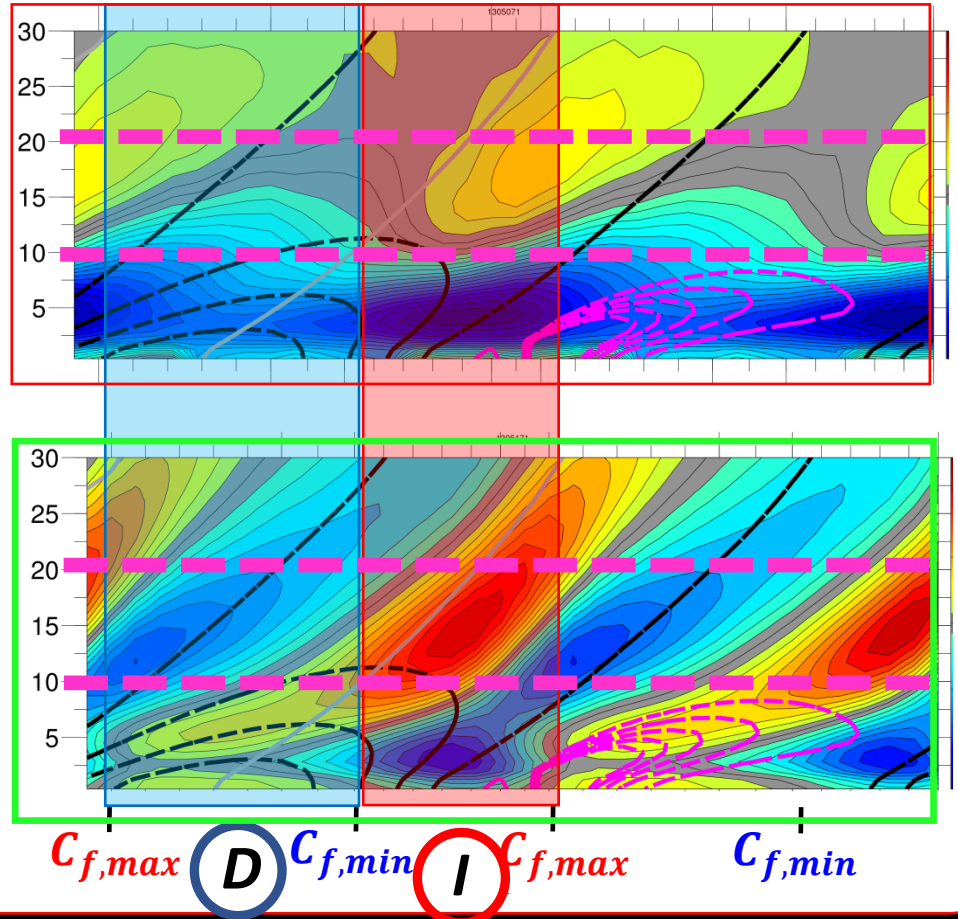
$\widetilde{\omega_z} < 0$

$\widetilde{\omega_z}$

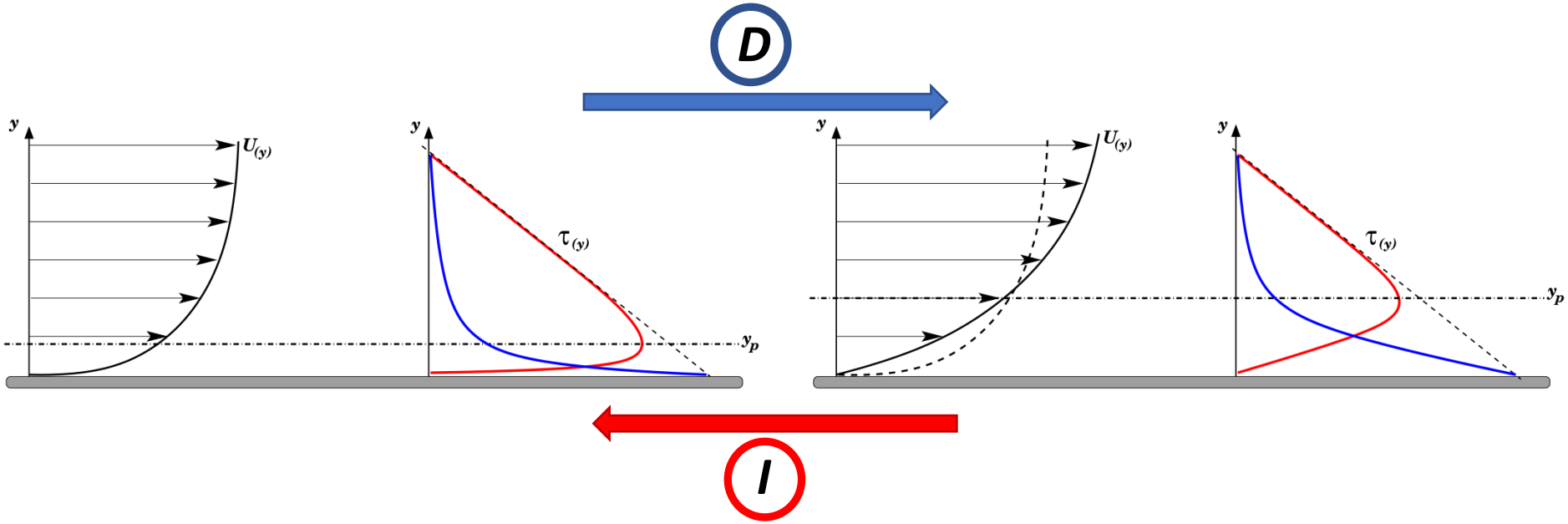
near the wall :

Weak stretching

Strong stretching



Drag reduction process

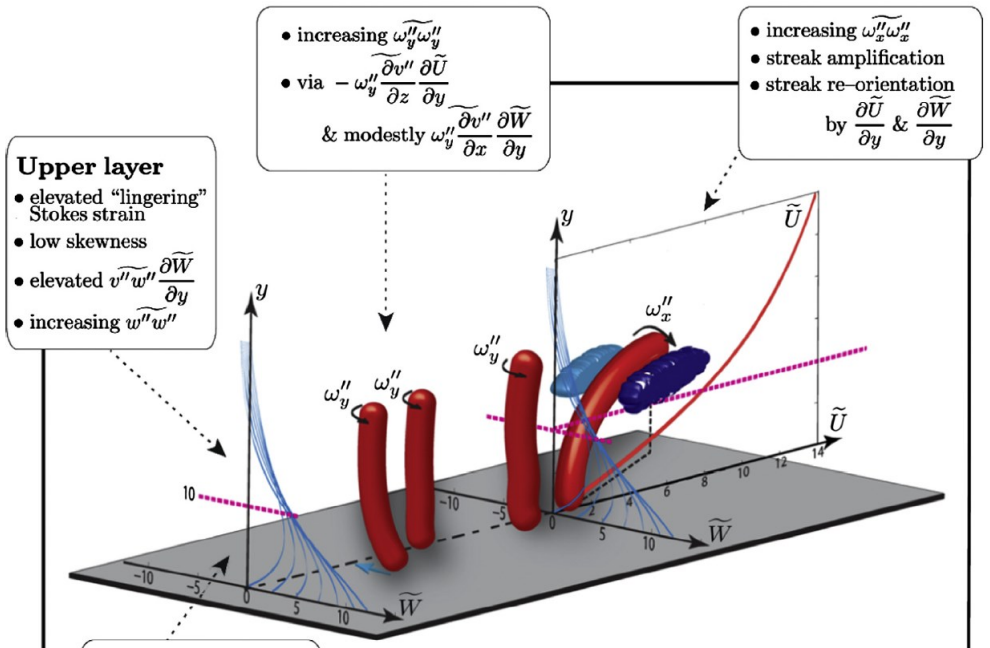


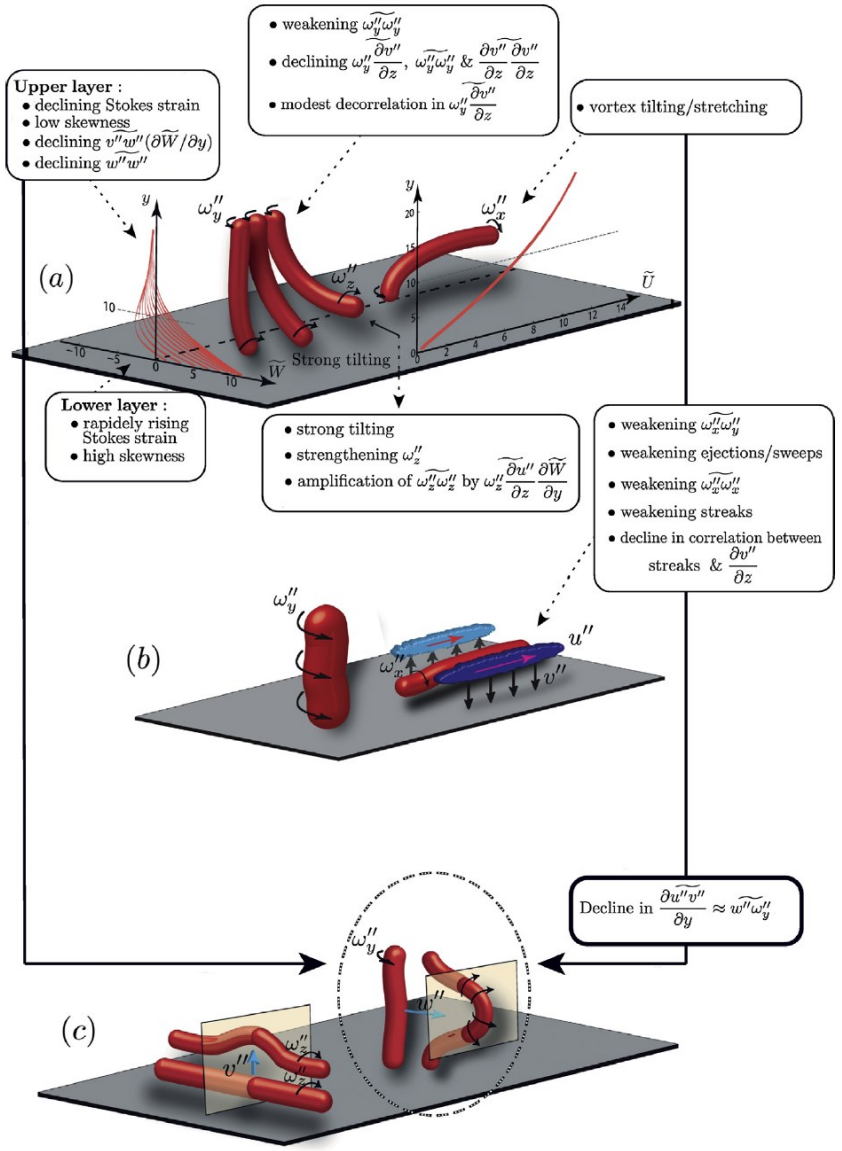
High Stokes strain ⇨ ω_y'' ↘ by "Tilting" ⇨ $\widetilde{u''v''}$ ↘

D Drag decreases

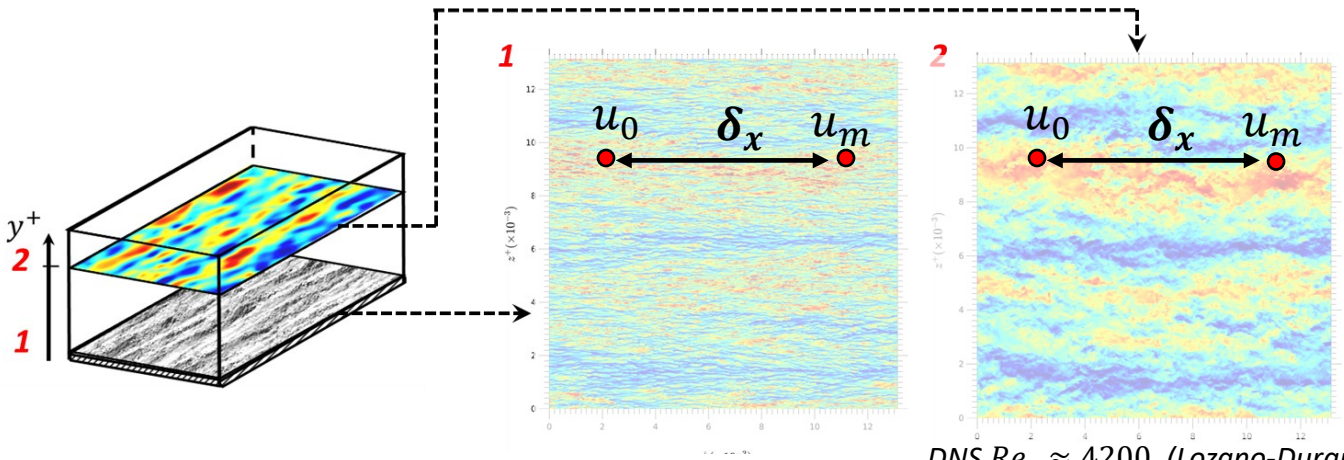
Streamwise strain ⇨ ω_y'' ↗ by "Stretching" ⇨ $\widetilde{u''v''}$ ↗

I Drag increases


• increasing $\widetilde{\omega_y''\omega_y''}$
• via $-\widetilde{\omega_y''\frac{\partial v''}{\partial z}}\frac{\partial \widetilde{U}}{\partial y}$
& modestly $\widetilde{\omega_y''\frac{\partial v''}{\partial x}}\frac{\partial \widetilde{W}}{\partial y}$
• increasing $\widetilde{\omega_x''\omega_x''}$
• streak amplification
• streak re–orientation
by $\frac{\partial \widetilde{U}}{\partial y}$ & $\frac{\partial \widetilde{W}}{\partial y}$
Upper layer
• elevated "lingering" Stokes strain
• low skewness
• elevated $\widetilde{v''w''}\frac{\partial \widetilde{W}}{\partial y}$
• increasing $\widetilde{w''w''}$
Lower layer
• weak tilting
• declining Stokes strain
• declining skewness
• declining $\widetilde{\omega_z''\omega_z''}$
Increase of $\frac{\partial \widetilde{u''v''}}{\partial y} \approx \widetilde{w''\omega_y''}$


• weakening $\widetilde{\omega_y''\omega_y''}$
• declining $\omega_y''\frac{\partial \widetilde{v''}}{\partial z}$, $\widetilde{\omega_y''\omega_y''}$ & $\frac{\partial v''}{\partial z}\frac{\partial \widetilde{v''}}{\partial z}$
• modest decorrelation in $\omega_y''\frac{\partial \widetilde{v''}}{\partial z}$
• vortex tilting/stretching
Upper layer :
• declining Stokes strain
• low skewness
• declining $\widetilde{v''w''}(\partial \widetilde{W}/\partial y)$
• declining $\widetilde{w''w''}$
(a)
Strong tilting
Lower layer :
• rapidly rising Stokes strain
• high skewness
• strong tilting
• strengthening ω_z''
• amplification of $\widetilde{\omega_z''\omega_z''}$ by $\omega_z''\frac{\partial \widetilde{u''}}{\partial z}\frac{\partial \widetilde{W}}{\partial y}$
• weakening $\widetilde{\omega_x''\omega_y''}$
• weakening ejections/sweeps
• weakening $\widetilde{\omega_x''\omega_x''}$
• weakening streaks
• decline in correlation between streaks & $\frac{\partial v''}{\partial z}$
(b)
Decline in $\frac{\partial \widetilde{u''v''}}{\partial y} \approx \widetilde{w''\omega_y''}$
(c)

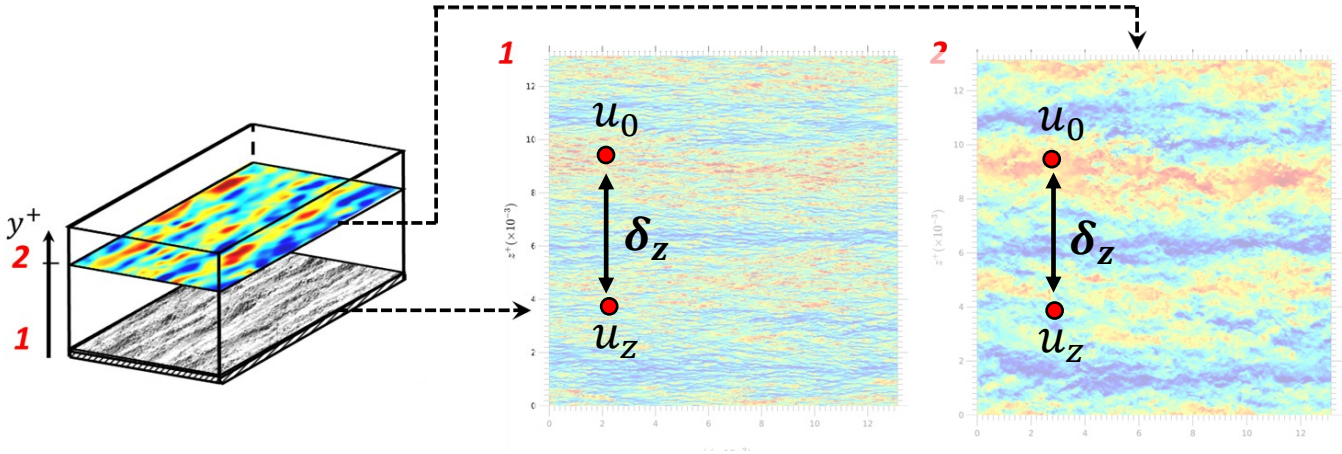
Energy distribution by scale – 2^{nd} order Structure function



DNS $Re_\tau \approx 4200$ (Lozano-Duran & Jimenez PoF 2014)

$$S_{2,u}(y,\delta_x) = \langle [u(y,x) - u(y,x+\delta_x)]^2 \rangle_{z,t}$$

Energy distribution by scale – 2^{nd} order Structure function



$$S_{2,u}(y,\delta_z) = \langle [u(y,z) - u(y,z+\delta_z)]^2 \rangle_{x,t},$$

$$S_{2,u}(\delta) = 2\overline{u'u'}[1 - F_u(\delta)],$$

Represents the total **energy** contained within the range of **eddies with a size $\leq \delta$**

$$\frac{dS_{2,u}(\delta)}{d\delta} = -2\overline{u'u'}\frac{dF_u(\delta)}{d\delta}.$$

Represents the **energy distribution by scale**

Townsend 1980, Davidson et al. JFM 2006 …

➡ **The premultiplied derivation of S_2:**

$$\overline{u'u'} = \frac{1}{2}\int_0^\infty \delta \frac{dS_{2,u}}{d\,\delta} dlog(\delta)$$

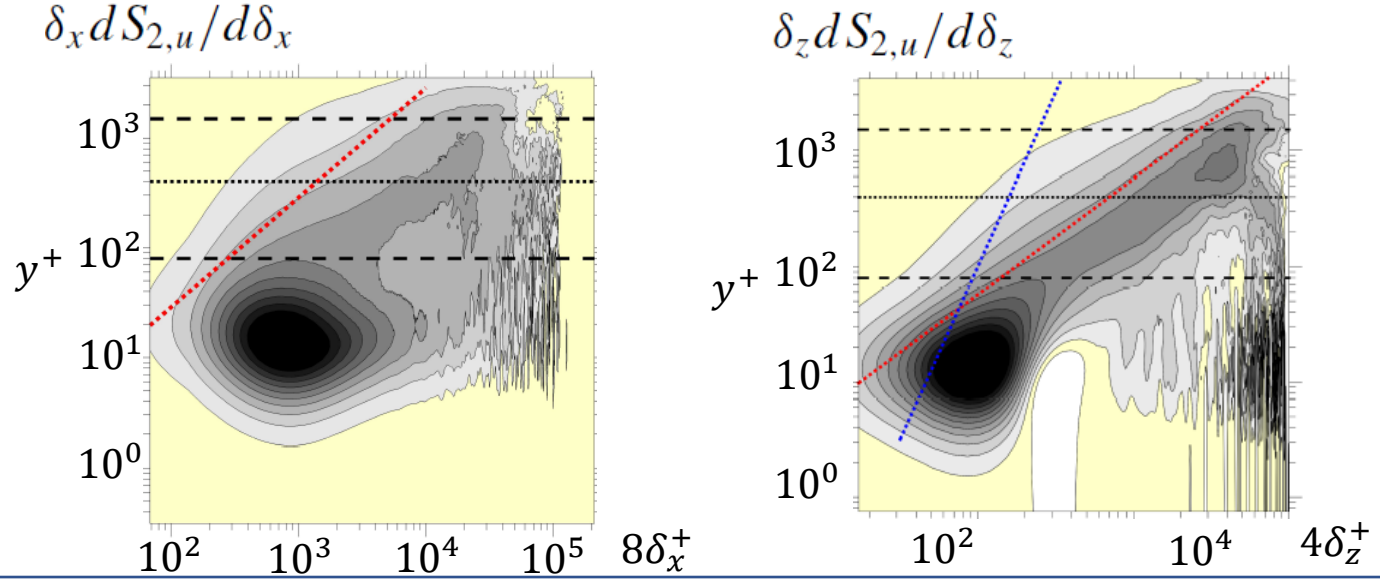
Surrogate of $k\Phi_{uu}$

Energy distribution : $\delta dS_{2,u}/d\delta$ vs. $k\Phi_{uu}$

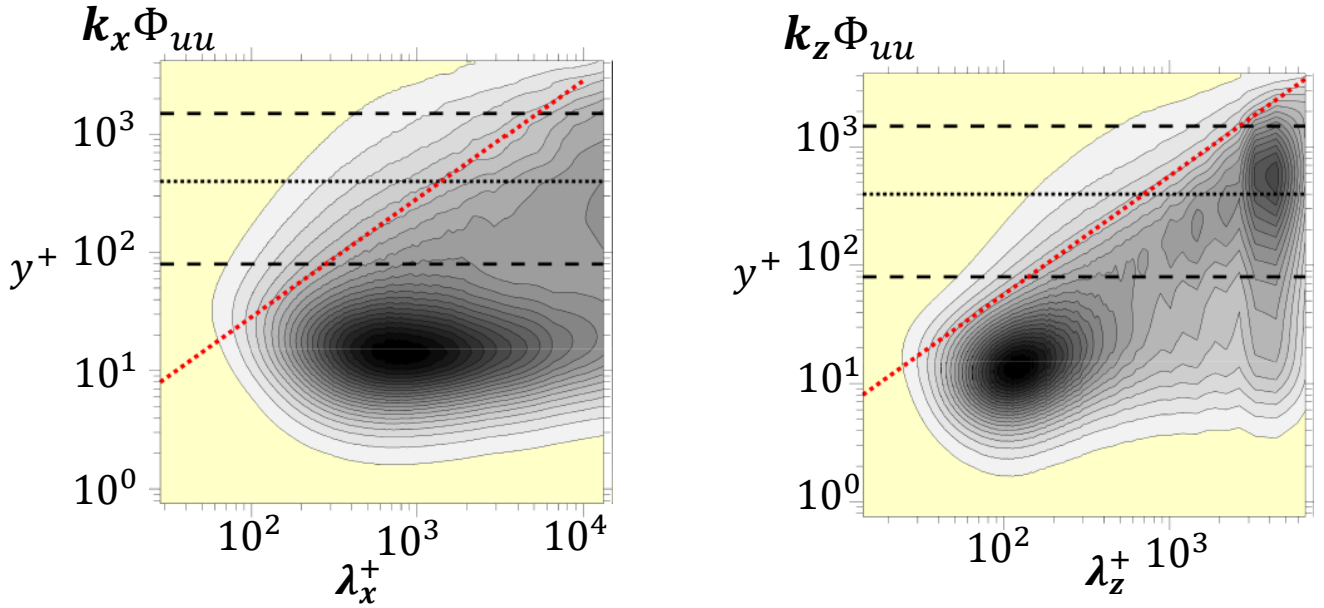
Streamwise

Spanwise

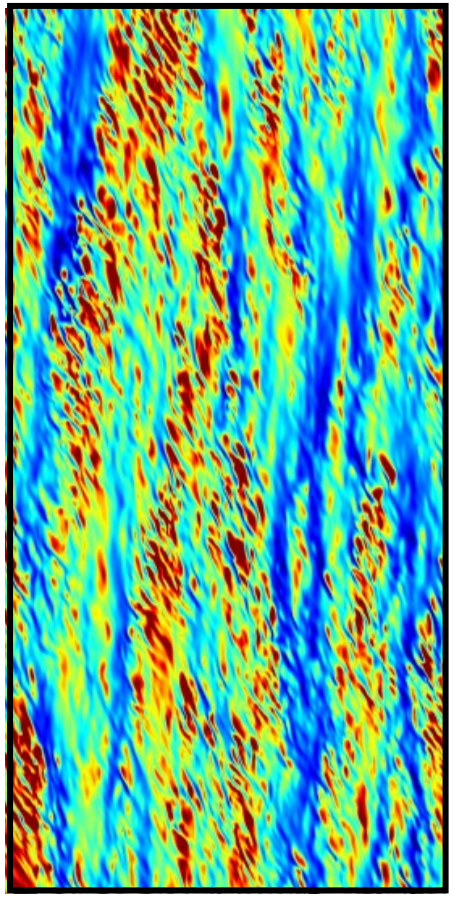
$\delta \dfrac{dS_{2,u}}{d\delta}$



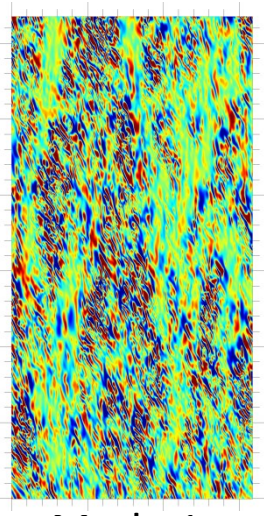
$k\Phi_{uu}$



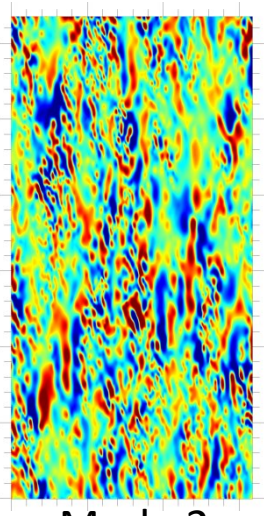
Raw field



Small-scale - SS

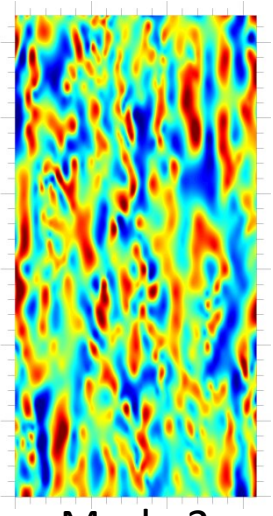


Mode 1



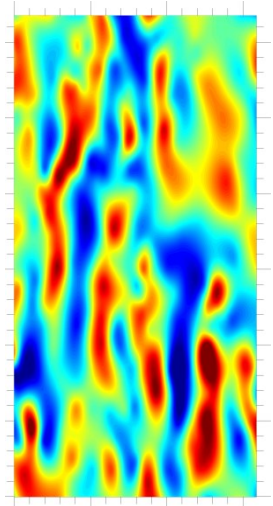
Mode 2

Intermediate - AE

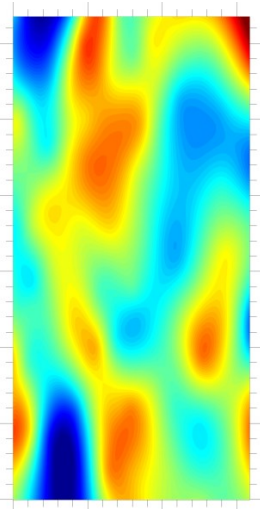


Mode 3

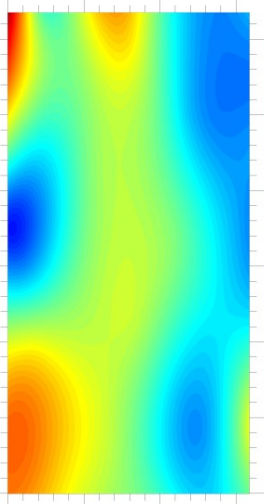
Large-scale - LS



Mode 4



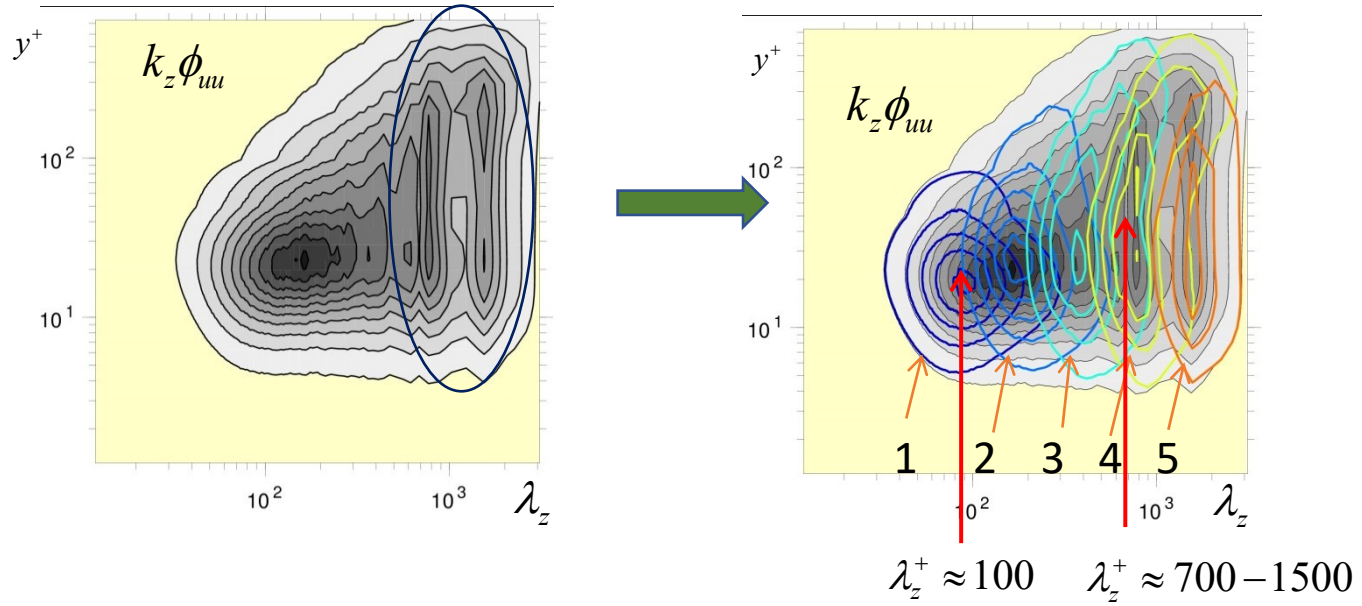
Mode 5



Mode 6

Large-scale/small-scale splitting

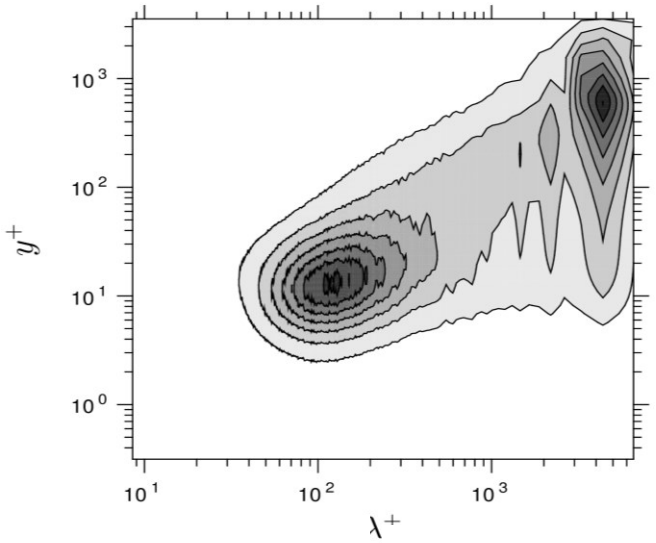
- 3D mode-wise fields used to derive mode-wise spectra
- Mode-wise split of pre-multiplied spanwise spectra of streamwise velocity fluctuations; 6 modes $Re_\tau = 1020$

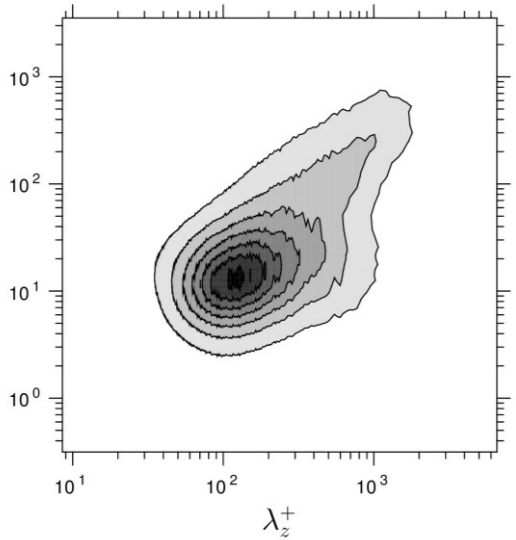


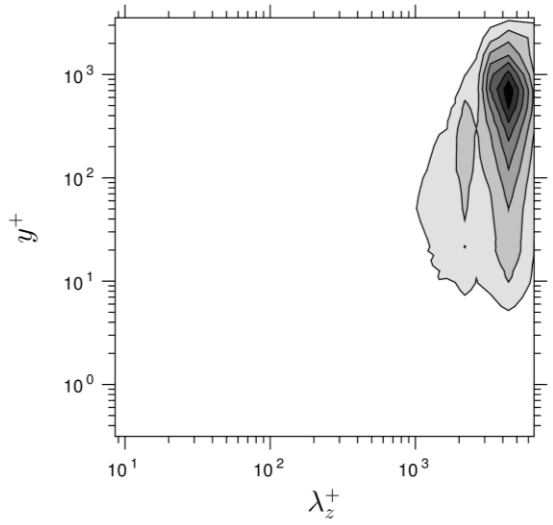
- Modes 1+2 regarded as small-scale
- Modes 4+5+6 regarded as large scale
- Mode 3 intermediate “attached-eddy

Séparation grandes/petites échelles

- Spectre des fluctuations de vitesses longitudinales $Re_\tau = 4200$



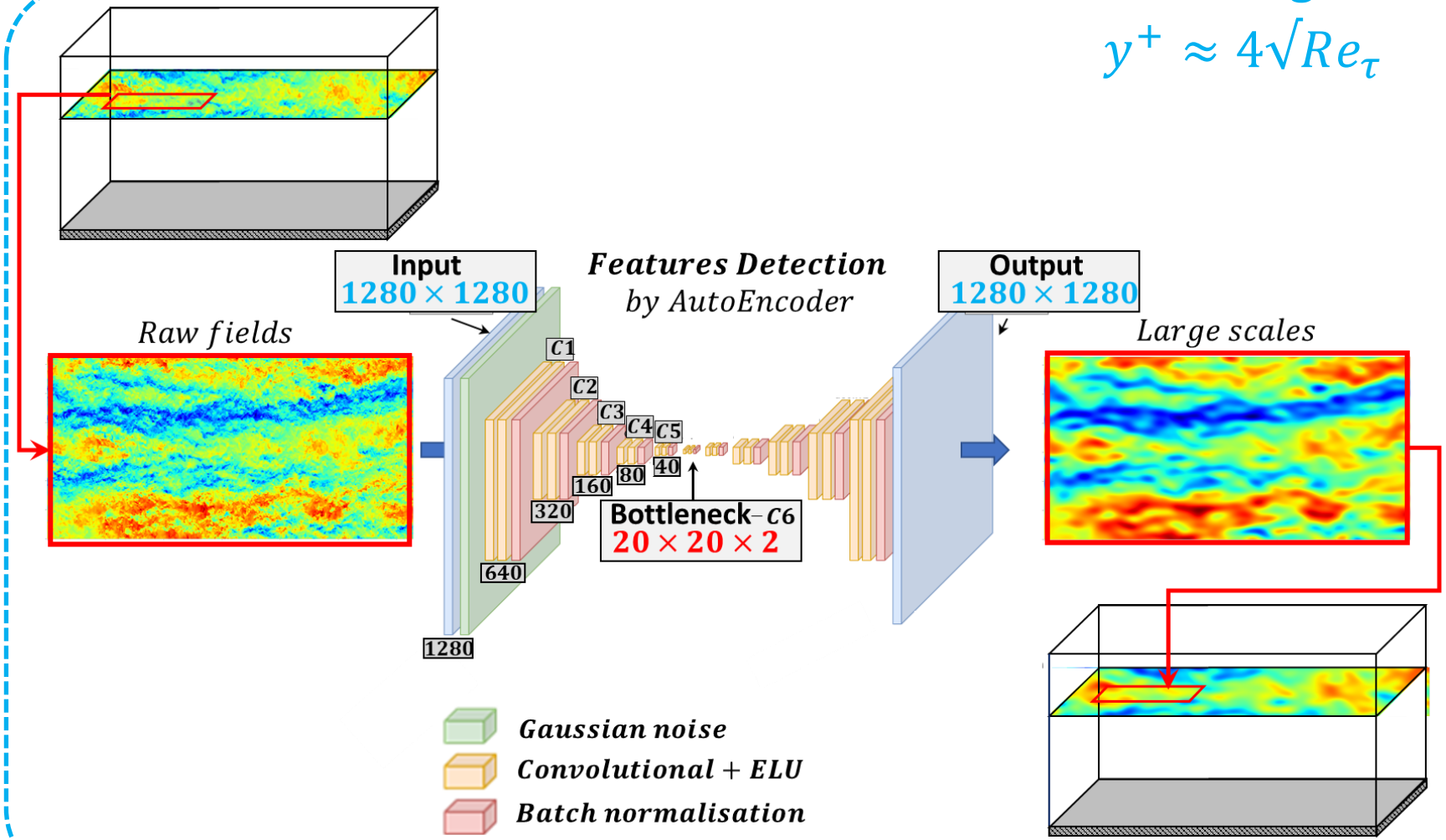




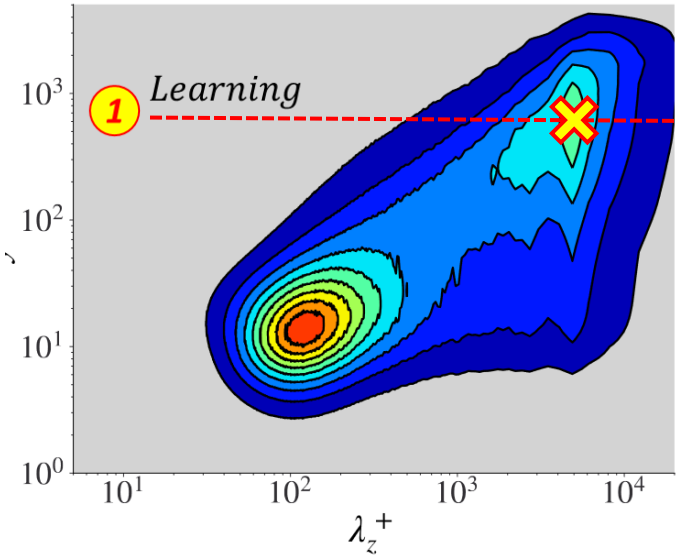
Auto-encoders
Identification of large-scale structures

Learning

$$y^+ \approx 4\sqrt{Re_\tau}$$

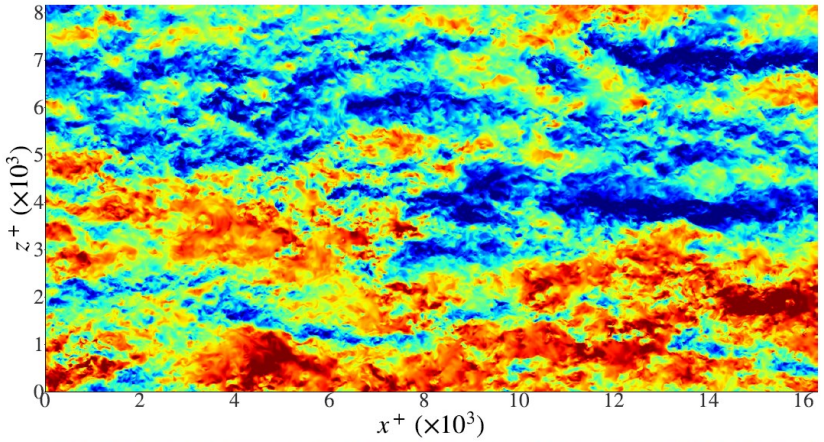


Energy Spectrum :

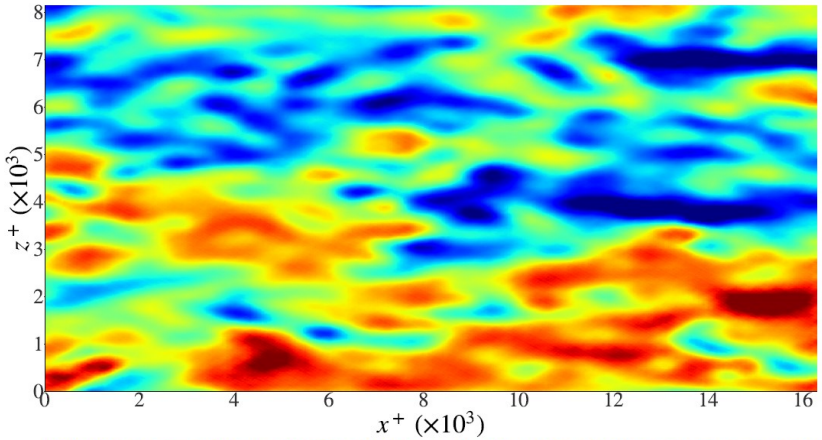


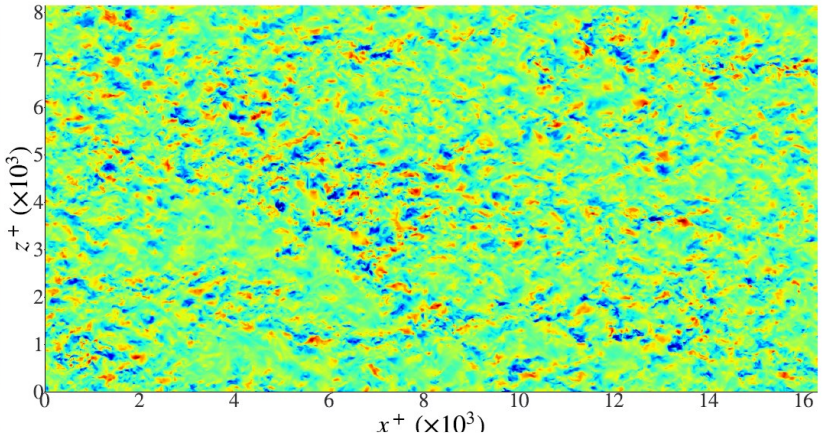
Auto-encoders
Identification of large-scale structures

Input

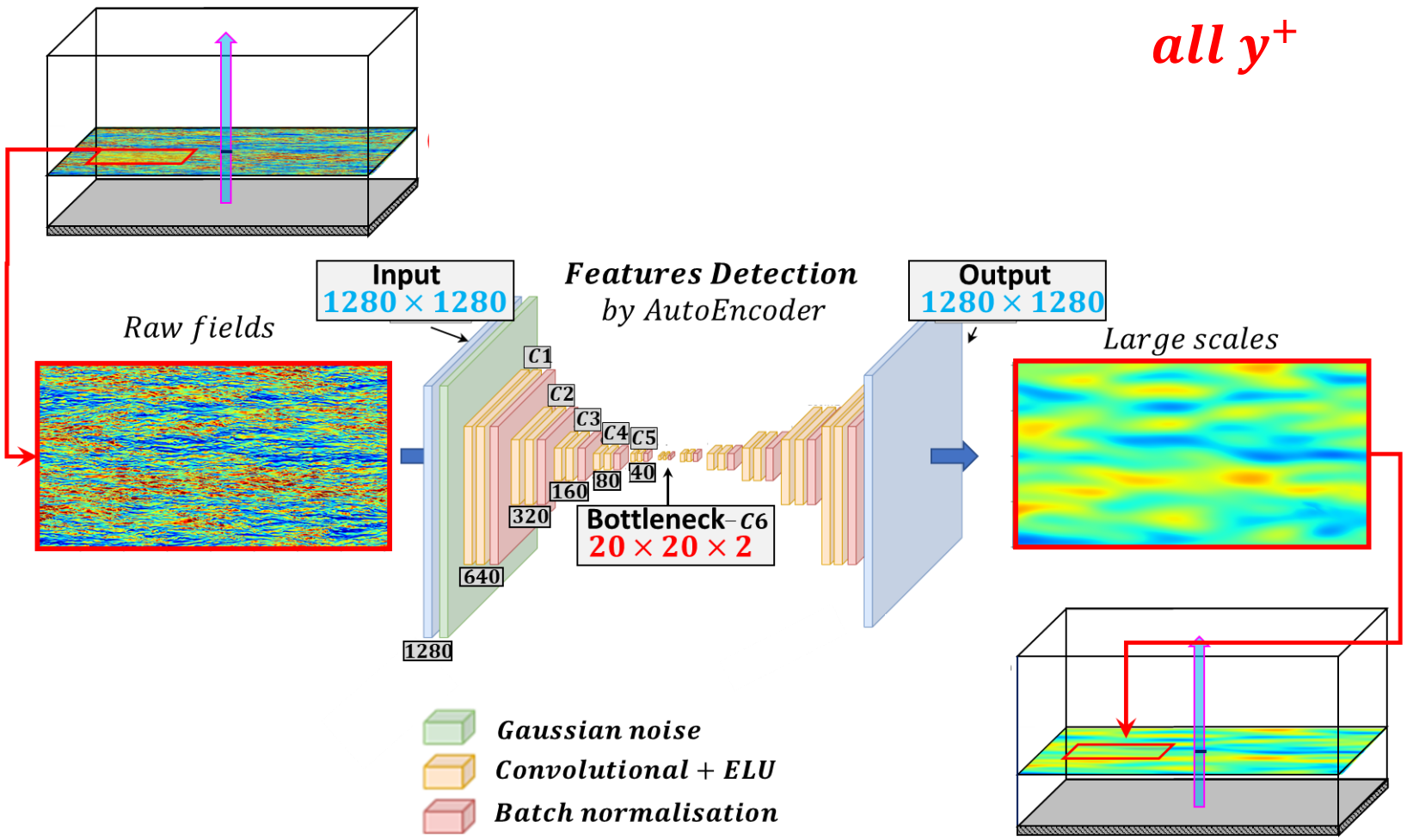


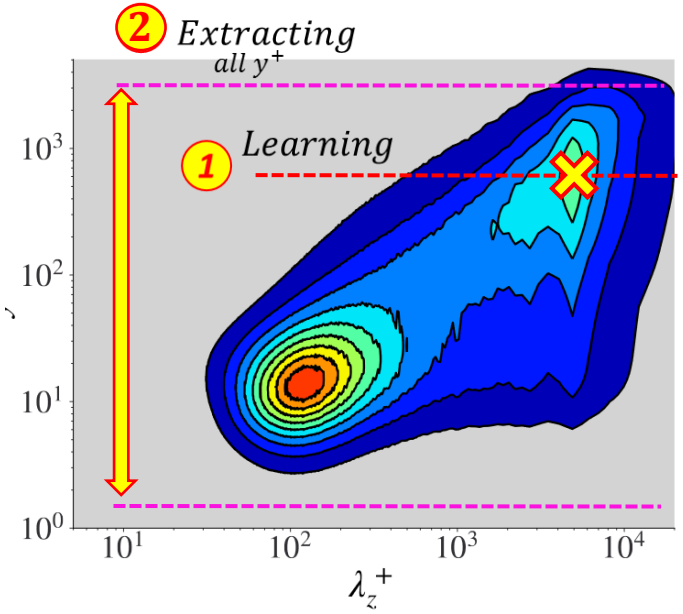
Output





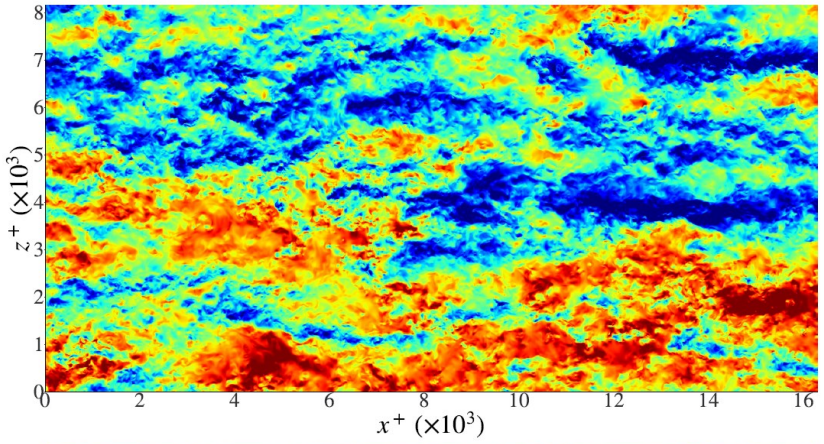
Auto-encoders
Extraction of large-scale structures



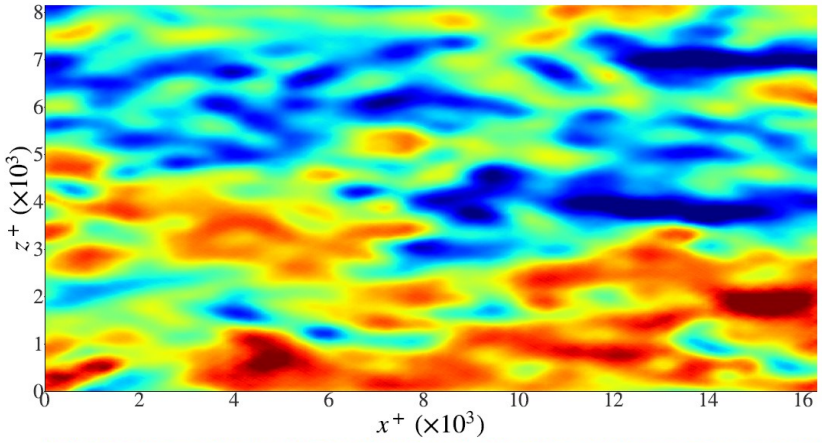


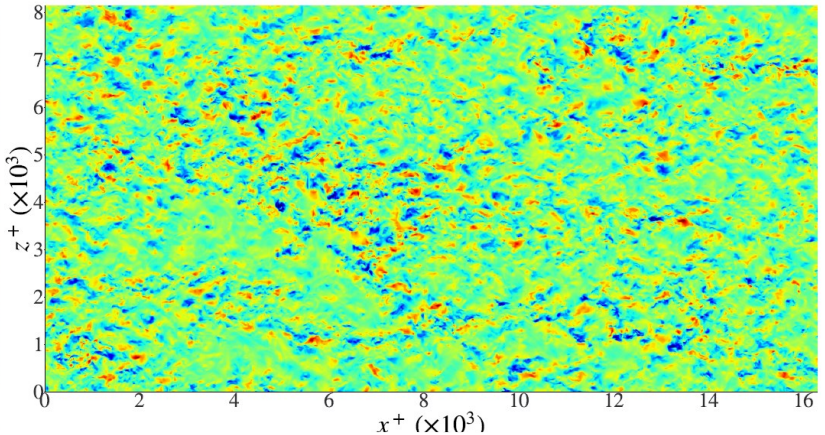
Auto-encoders
Extraction of large-scale structures

Input

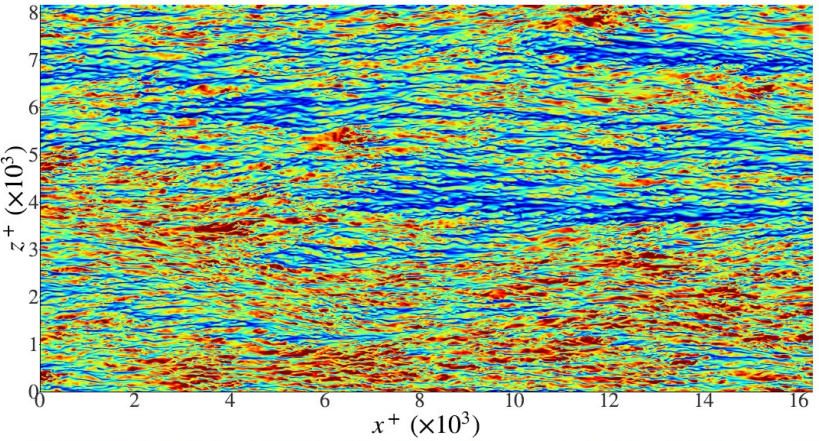


Output

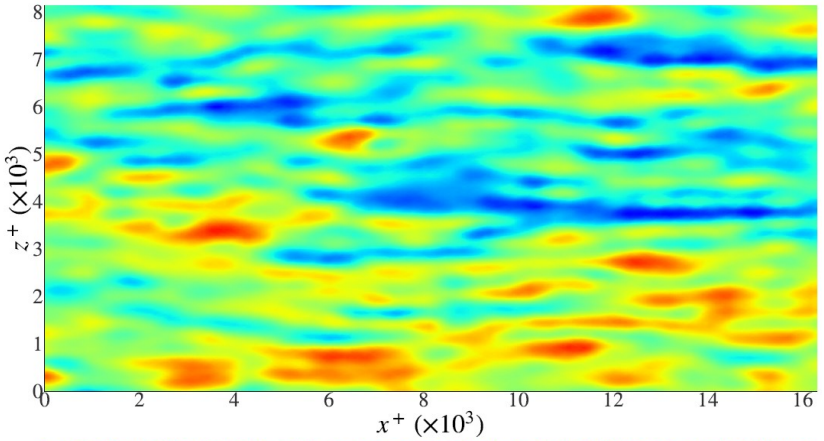


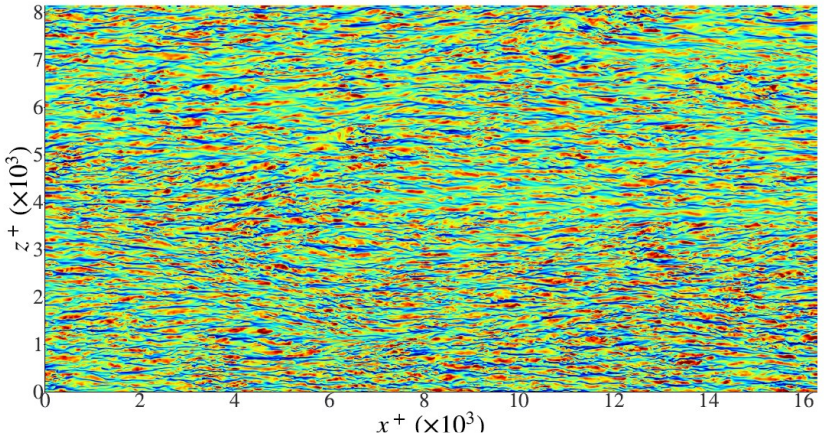


Input

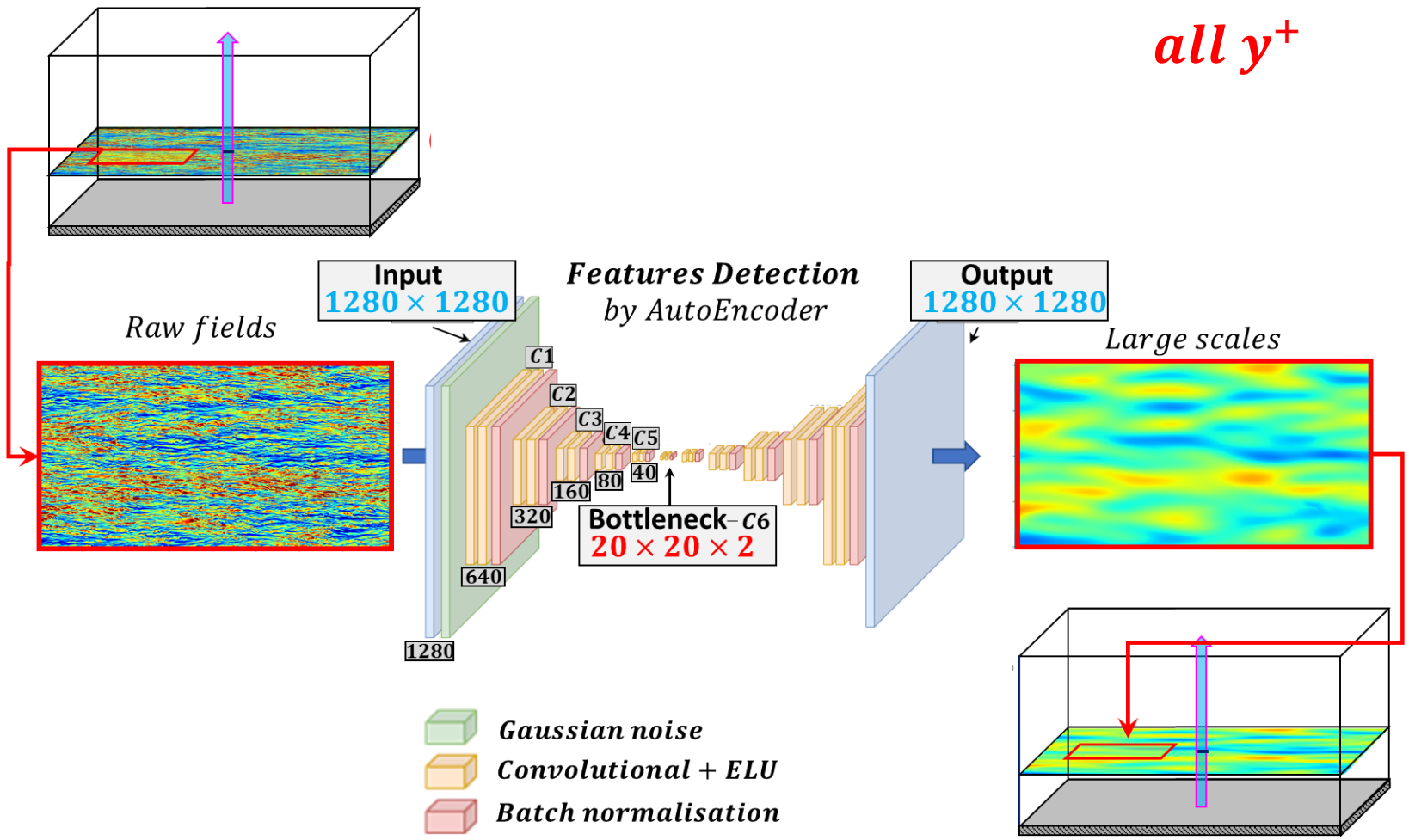


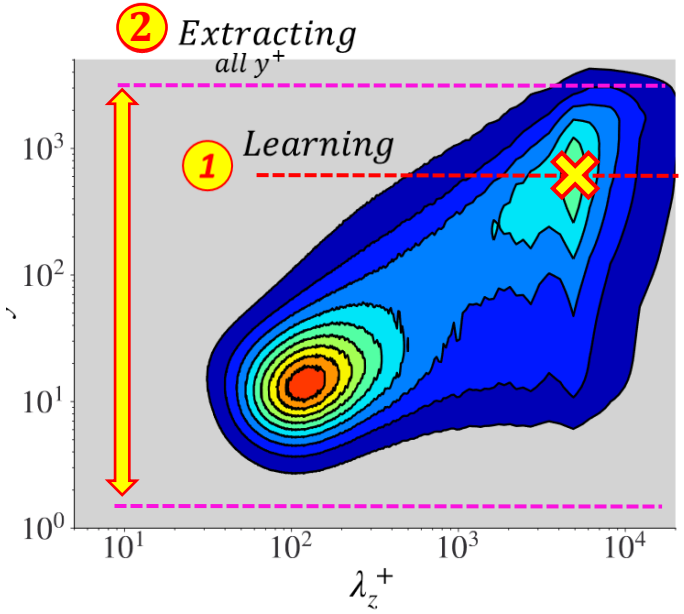
Output

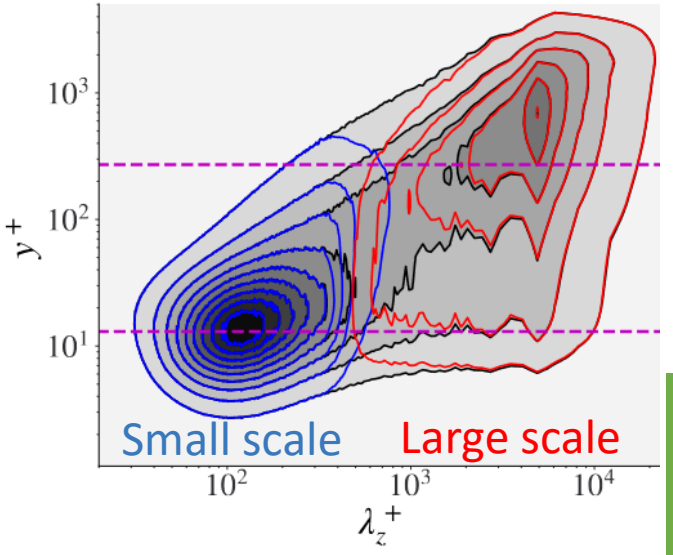




Auto-encoders
Extraction of large-scale structures

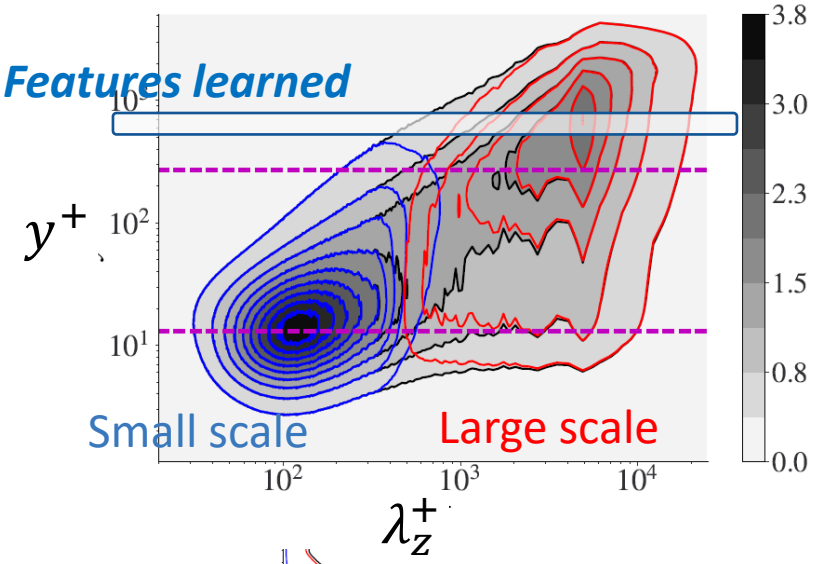


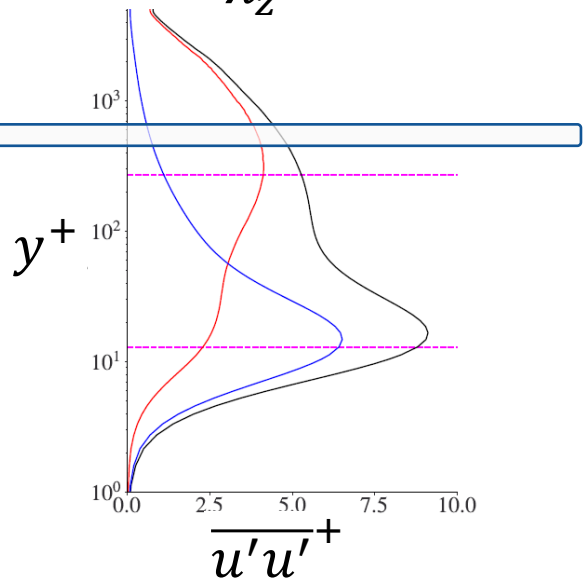


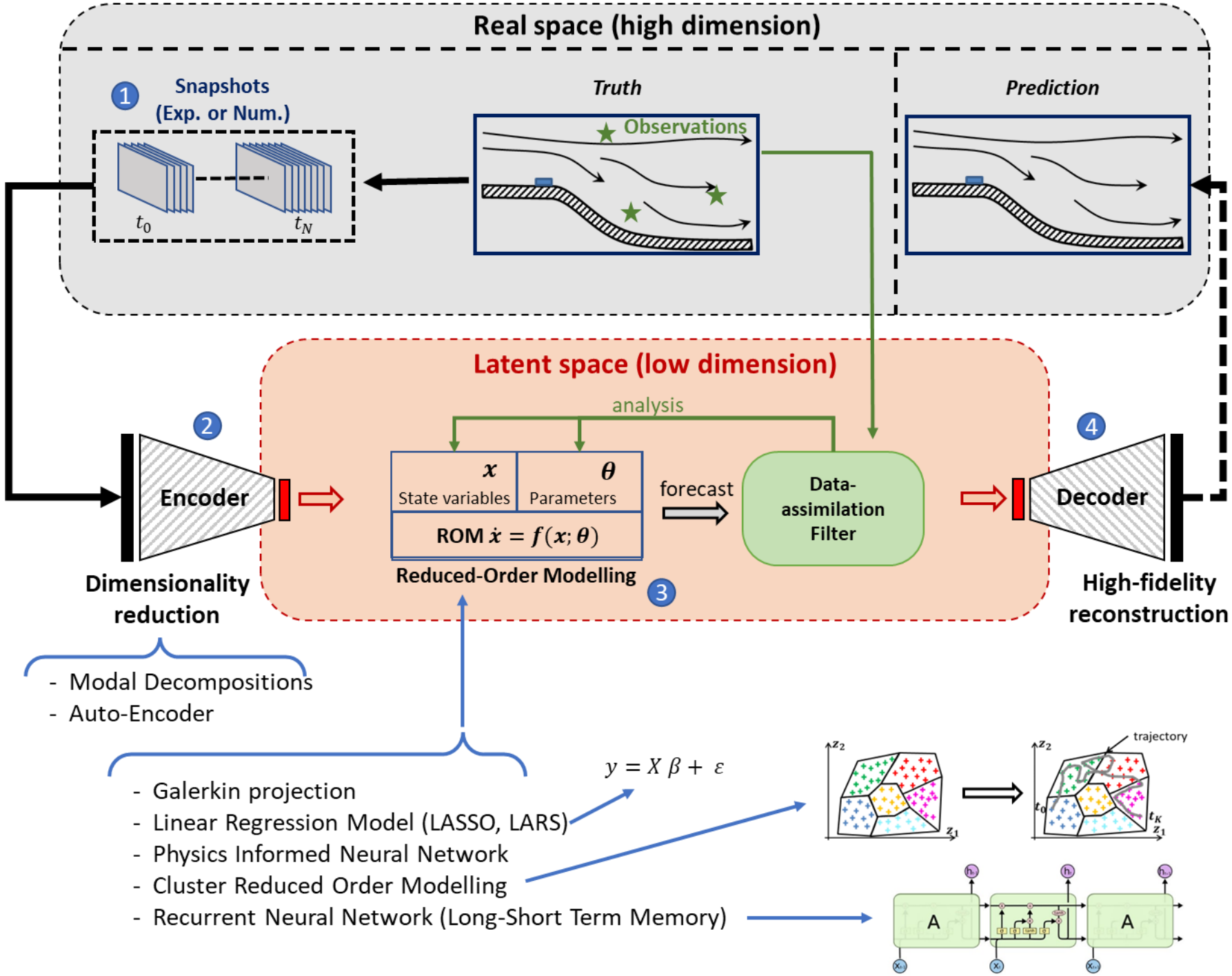


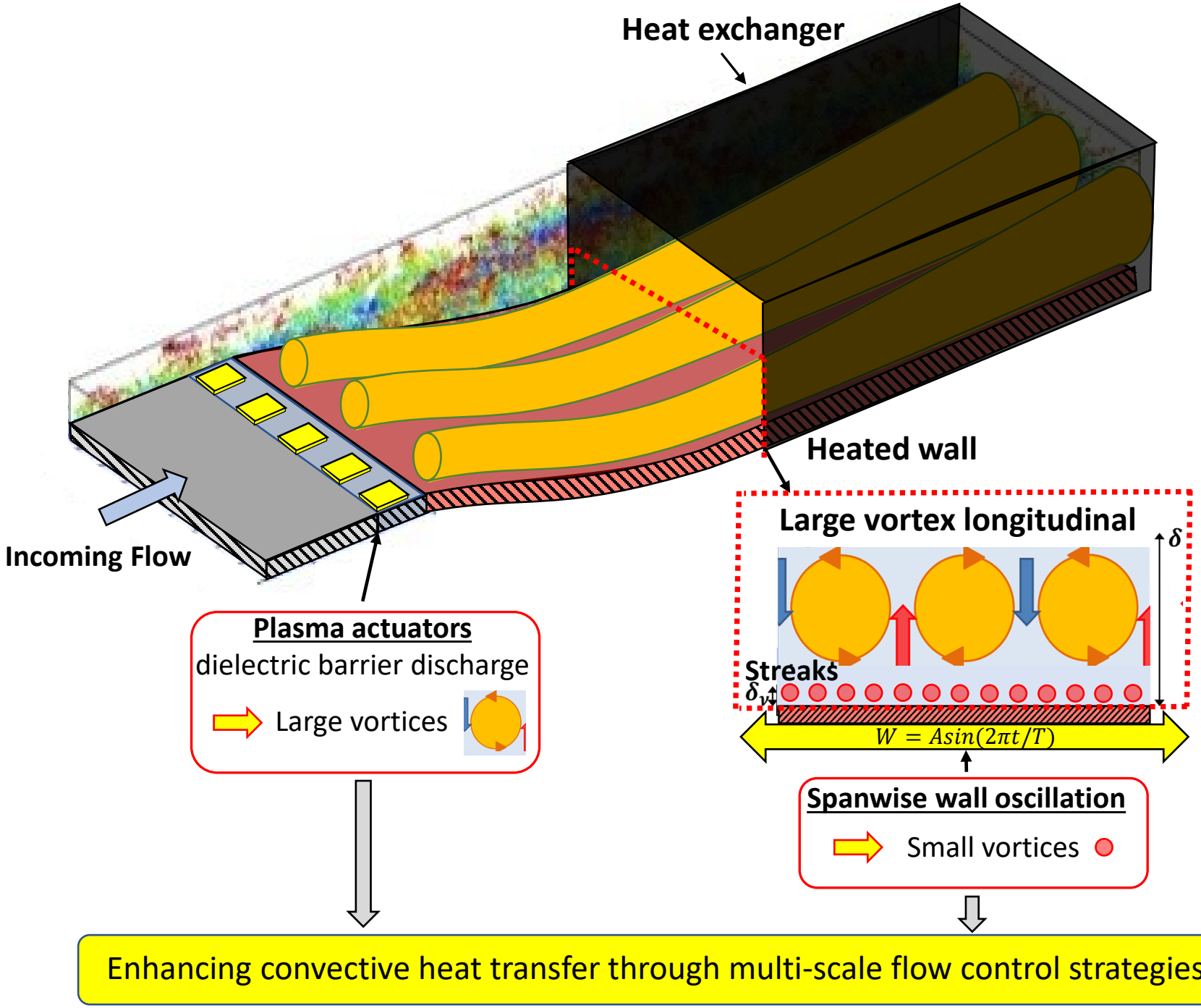
Auto-encoders
Extraction of large-scale structures

streamwise





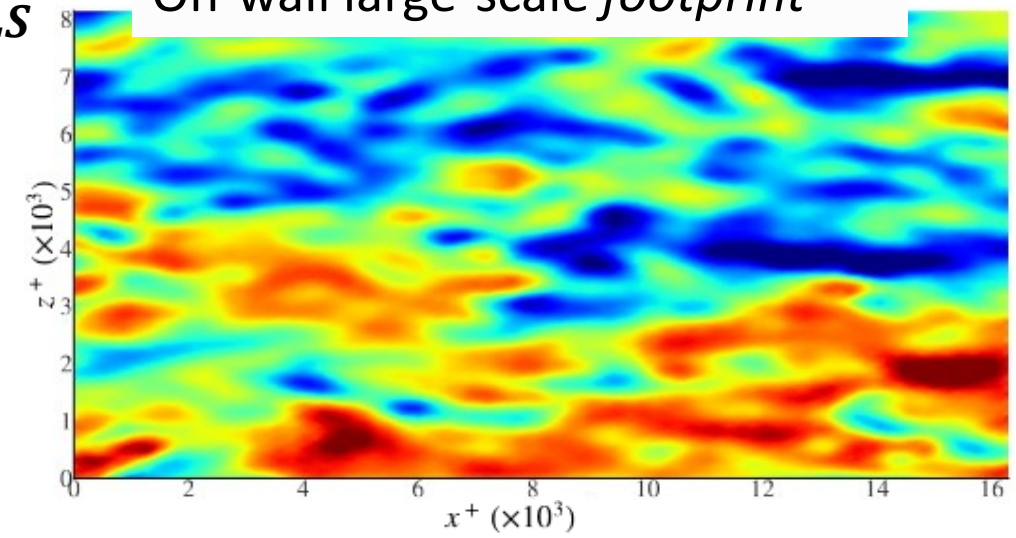

Real space (high dimension)
1
Snapshots
(Exp. or Num.)
t_0
t_N
Truth
Observations
Prediction
Latent space (low dimension)
analysis
2
Encoder
x
State variables
θ
Parameters
ROM $\dot{x} = f(x;\theta)$
Reduced-Order Modelling
3
forecast
Data-assimilation Filter
4
Decoder
Dimensionality reduction
High-fidelity reconstruction
- Modal Decompositions
- Auto-Encoder
- Galerkin projection
- Linear Regression Model (LASSO, LARS)
- Physics Informed Neural Network
- Cluster Reduced Order Modelling
- Recurrent Neural Network (Long-Short Term Memory)
$y = X\,\beta + \varepsilon$
trajectory
A
A


Heat exchanger
Heated wall
Incoming Flow
Large vortex longitudinal
δ
Streaks
δ_{visc}
$W = Asin(2\pi t/T)$
Plasma actuators
dielectric barrier discharge
Large vortices
Spanwise wall oscillation
Small vortices
Enhancing convective heat transfer through multi-scale flow control strategies

Conditional response to the large-scale skin friction
Classical Approach

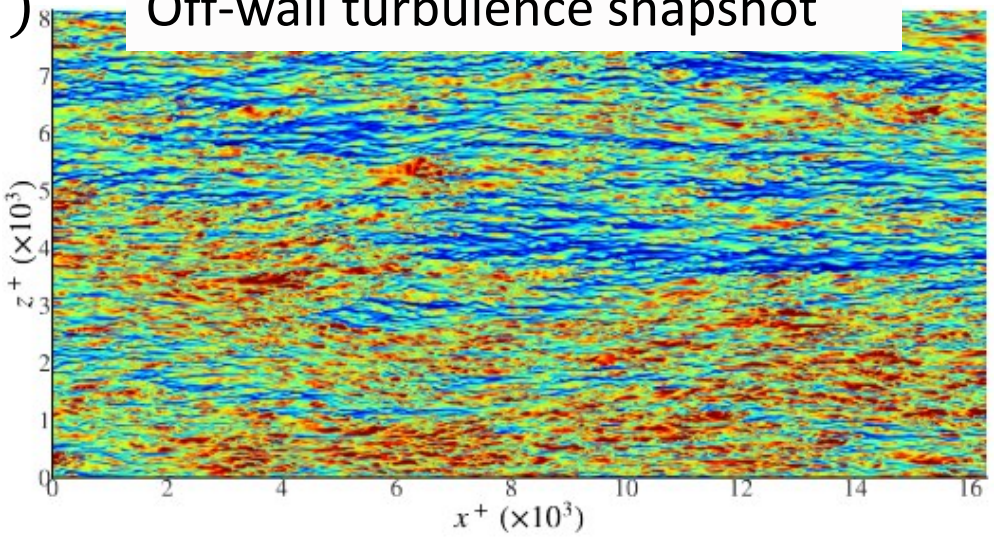
$u_{\tau,LS}$

On-wall large-scale *footprint*



$u(y^+)$

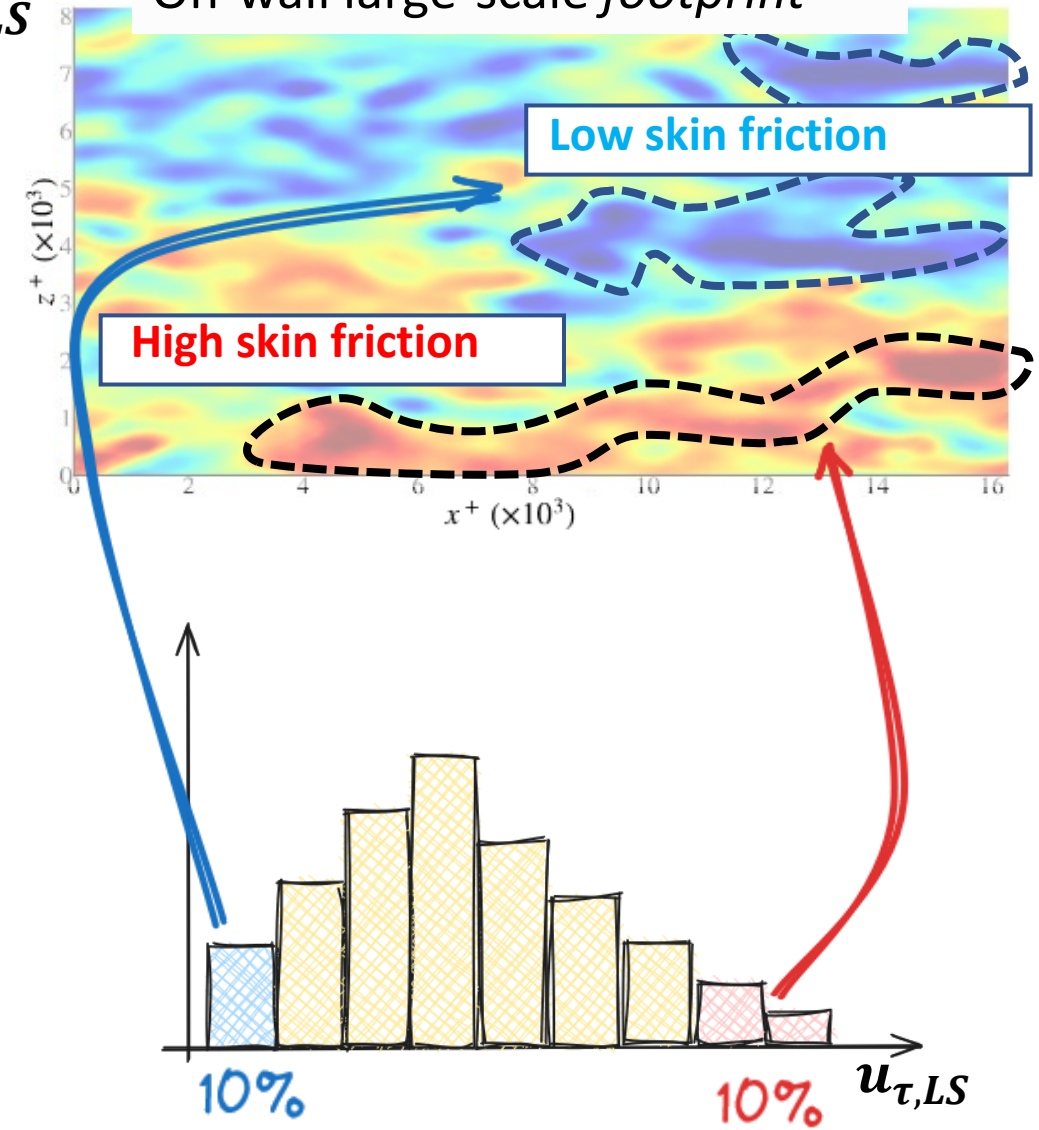
Off-wall turbulence snapshot



Conditional response to the large-scale skin friction
Classical Approach

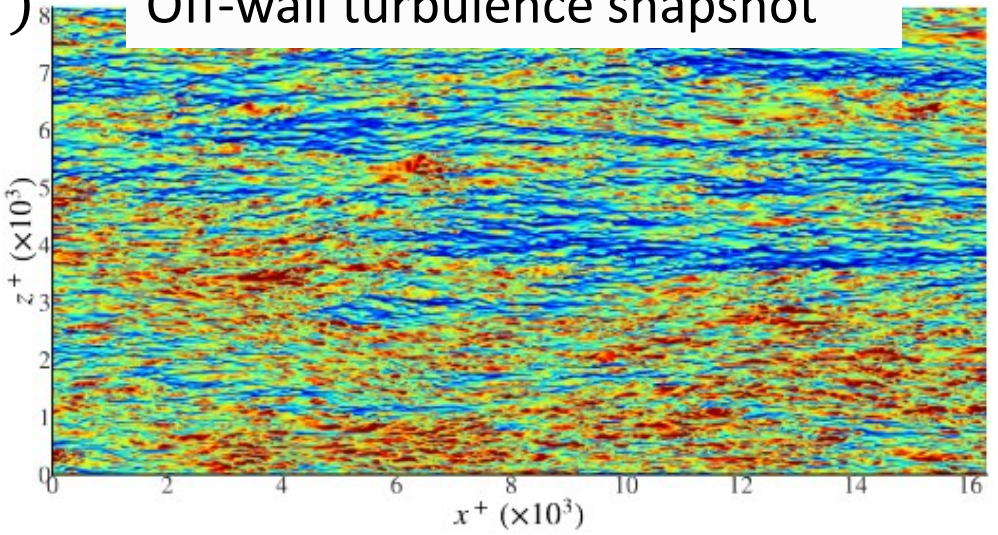
$u_{\tau,LS}$

On-wall large-scale *footprint*



$u(y^+)$

Off-wall turbulence snapshot



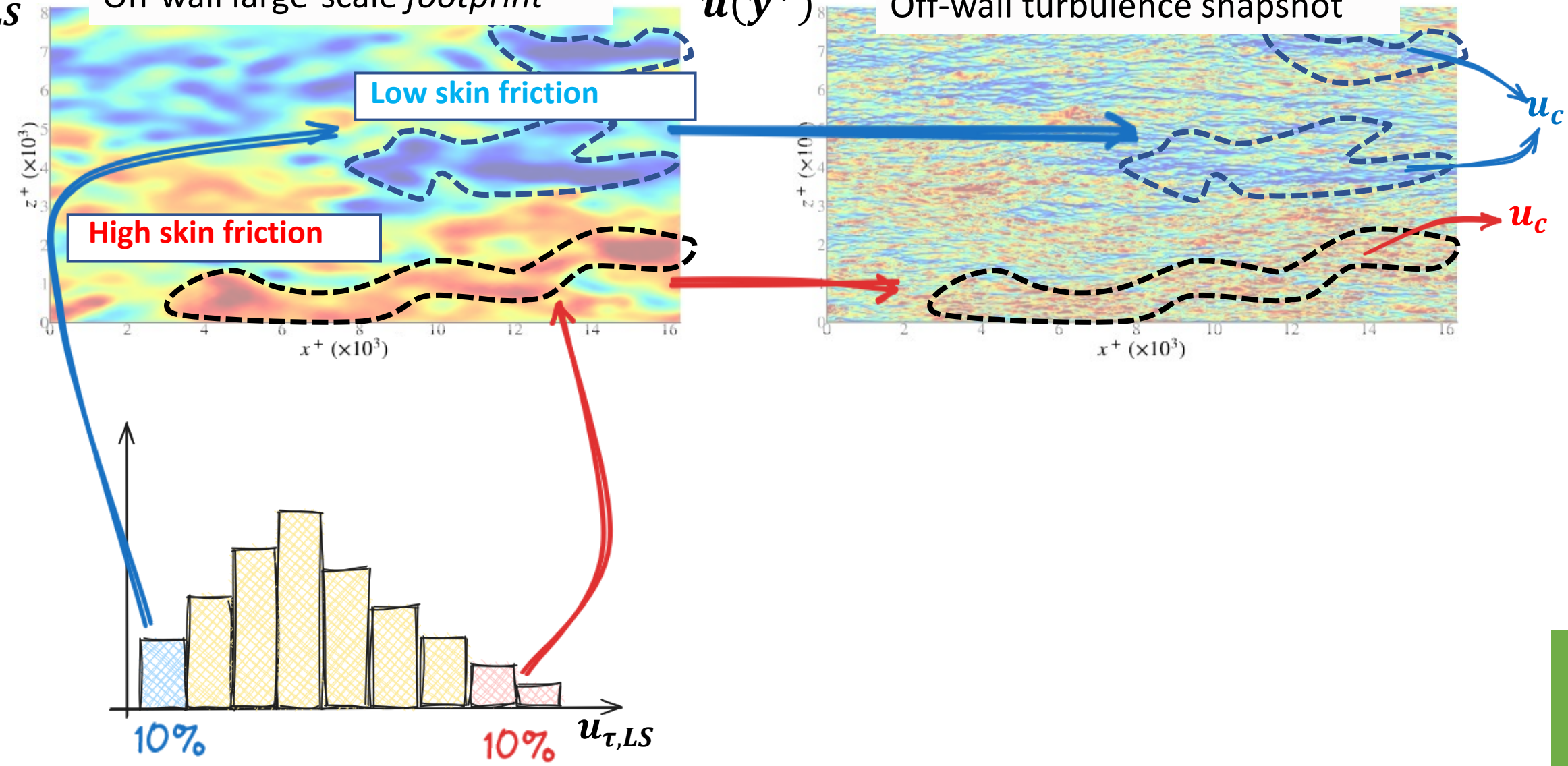
Conditional response to the large-scale skin friction
Classical Approach

$u_{\tau,LS}$

On-wall large-scale *footprint*

$u(y^+)$

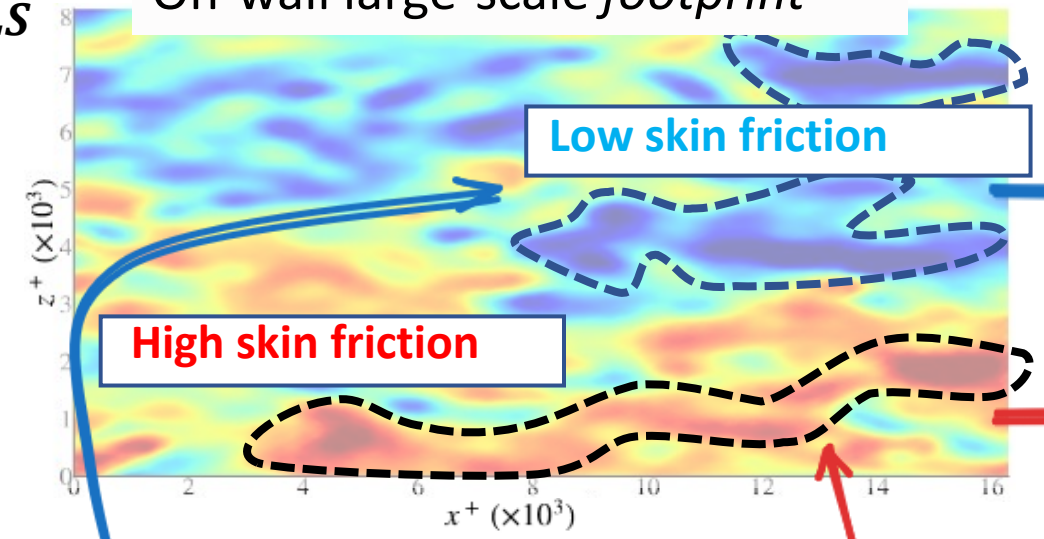
Off-wall turbulence snapshot



Conditional response to the large-scale skin friction
Classical Approach

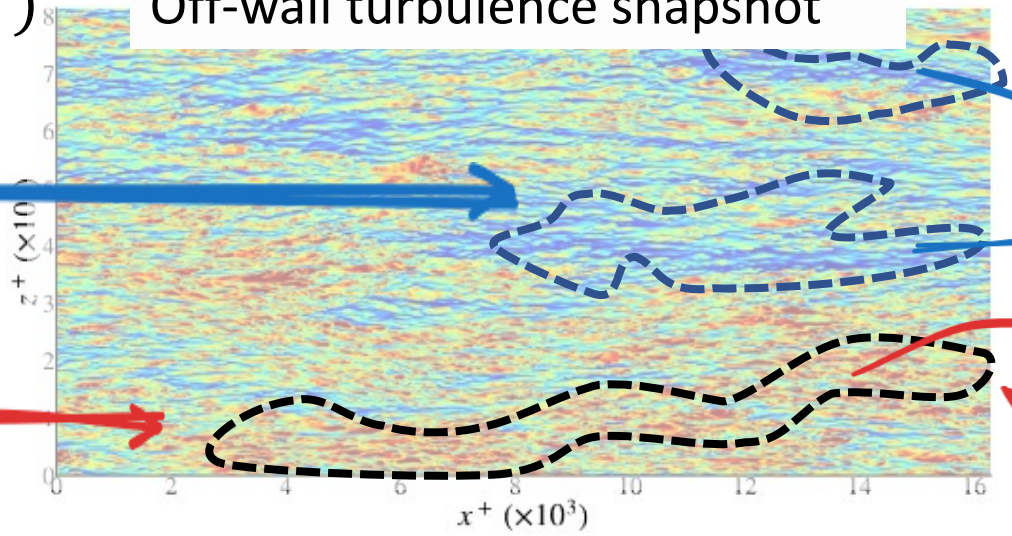
$u_{\tau,LS}$

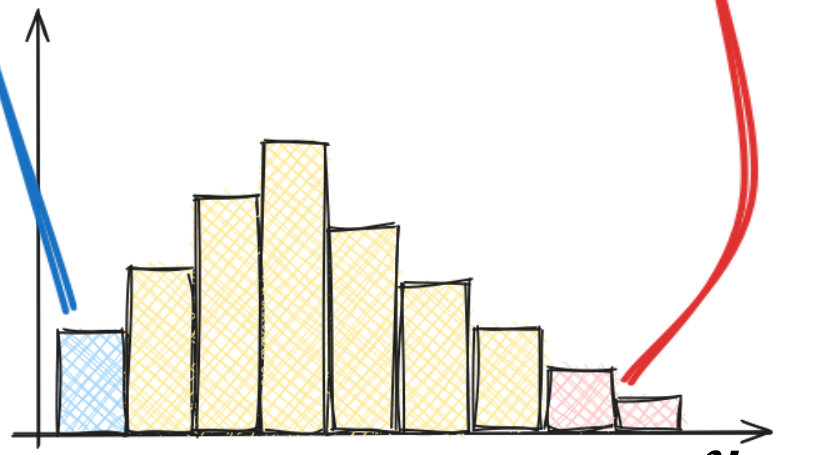
On-wall large-scale *footprint*



$u(y^+)$

Off-wall turbulence snapshot

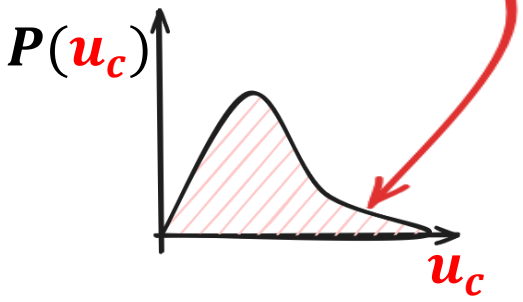




$\overline{u_c}$, $\overline{u_c'u_c'}$

u_c

u_c



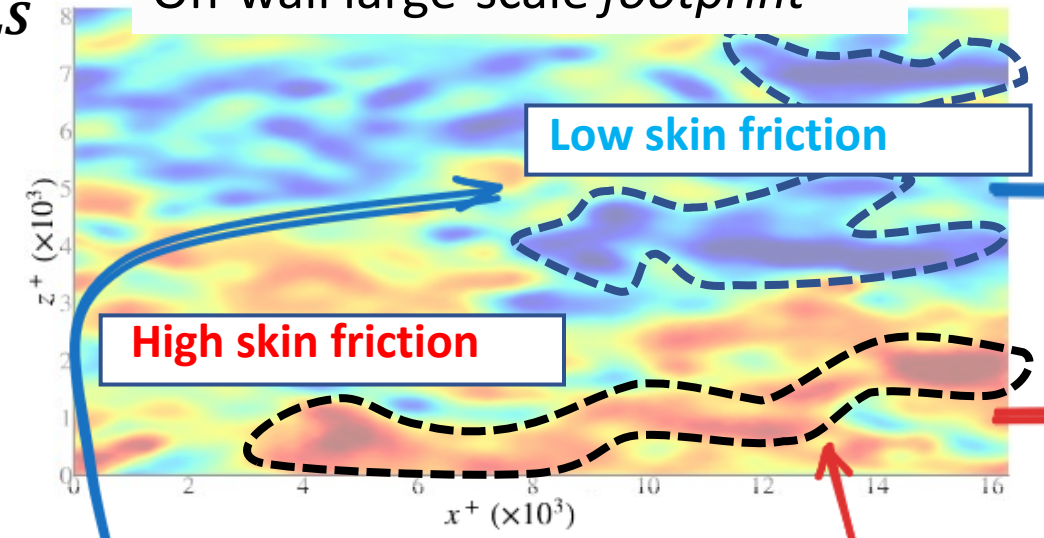
$$\overline{u_c} = \int u_c \, P(u_c) du_c$$

$$\overline{u_c'u_c'} = \int (u_c - \overline{u_c})^2 \, P(u_c) du_c$$

Conditional response to the large-scale skin friction
Classical Approach

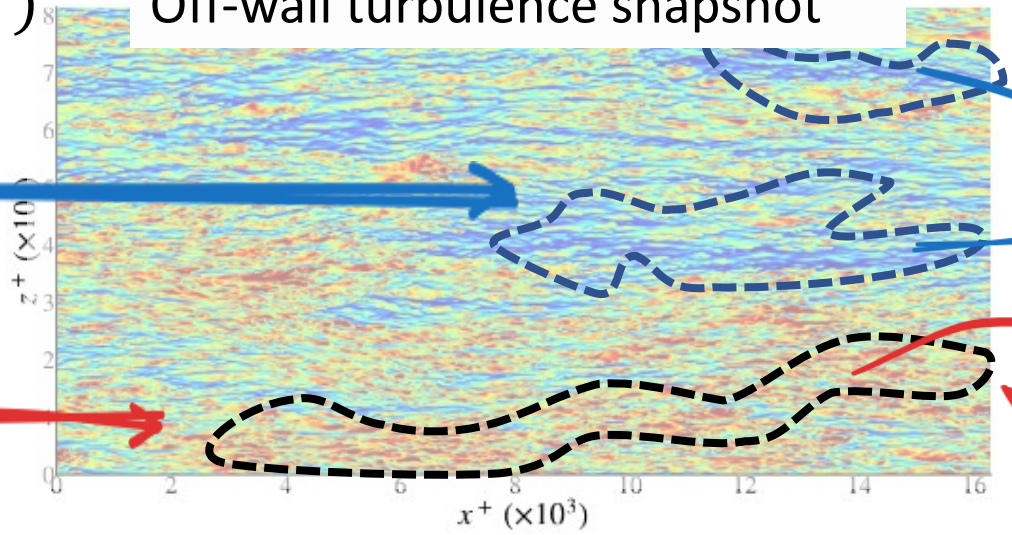
$u_{\tau,LS}$

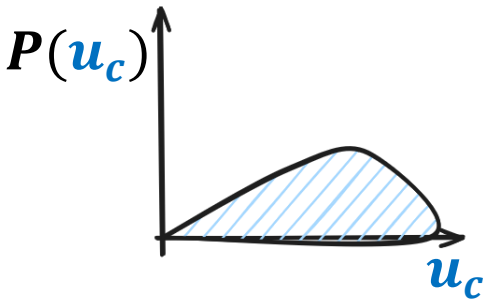
On-wall large-scale *footprint*

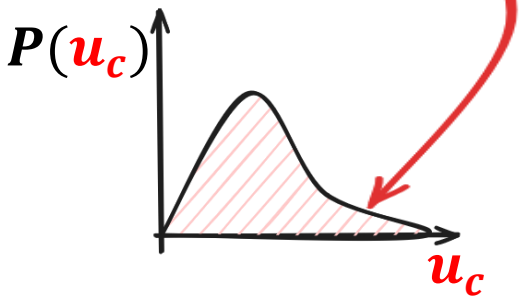


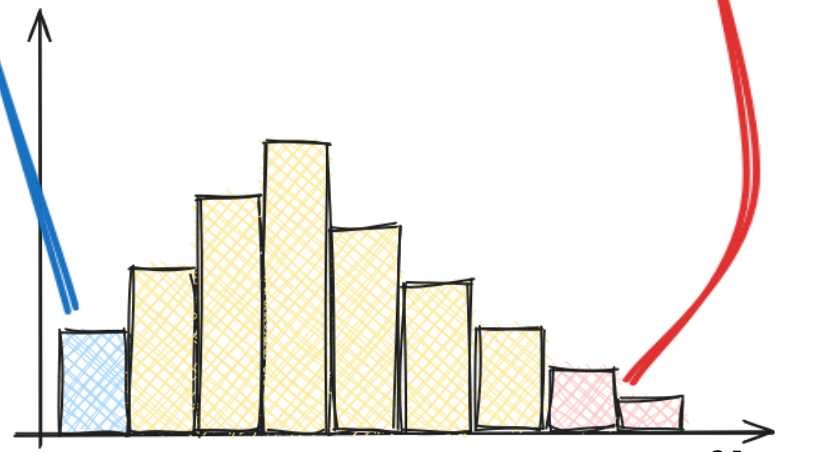
$u(y^+)$

Off-wall turbulence snapshot









$\overline{u_c}$, $\overline{u_c'u_c'}$

$\overline{u_c}$, $\overline{u_c'u_c'}$

$$\overline{u_c} = \int u_c \, P(u_c) du_c$$

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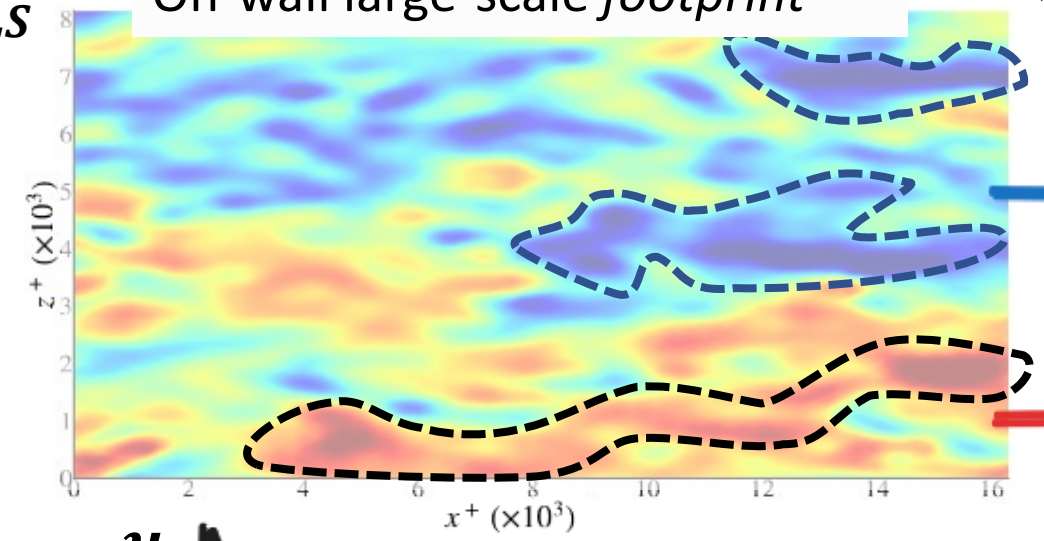
Conditional response to the large-scale skin friction
Approach leveraging Multivariate Joint Pdfs

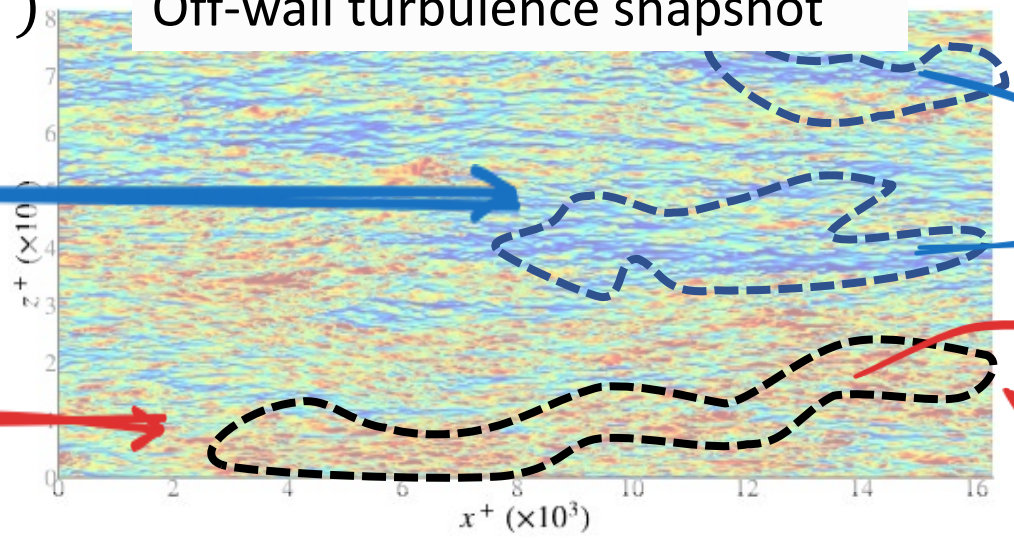
$u_{\tau,LS}$

On-wall large-scale *footprint*



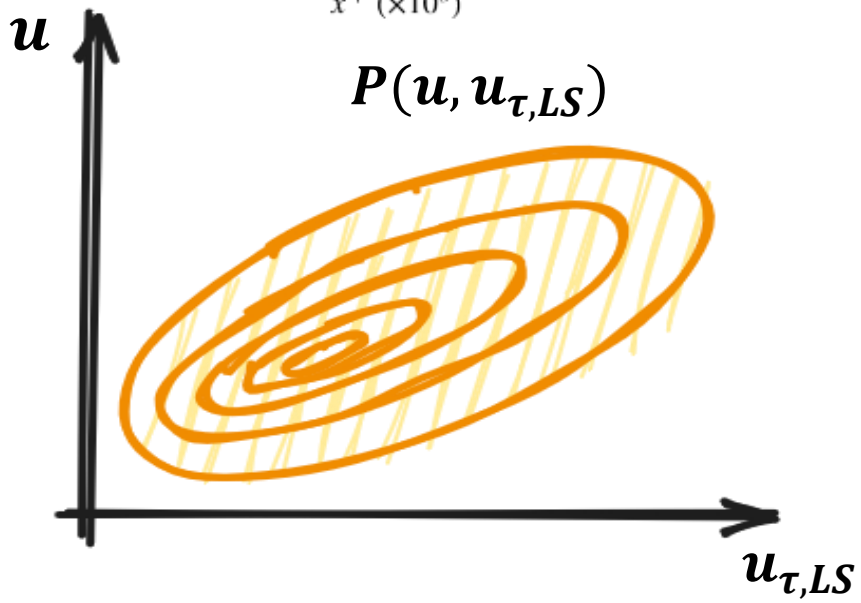
$u(y^+)$

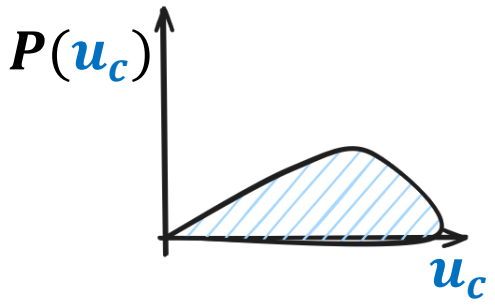
Off-wall turbulence snapshot

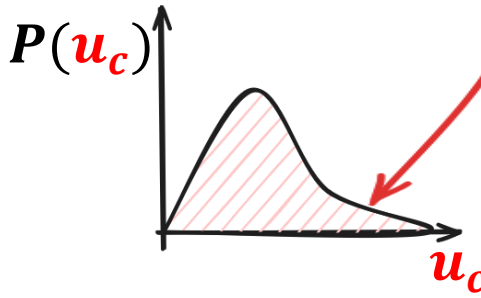


u_c

u_c







$$\overline{u_c} = \int u_c \, P(u_c) du_c$$

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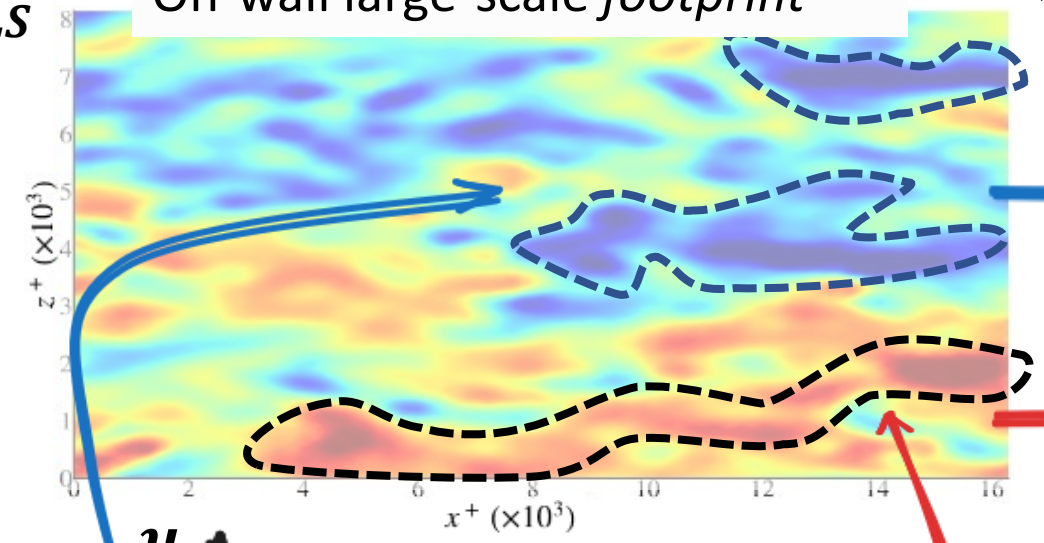
Conditional response to the large-scale skin friction
Approach leveraging Multivariate Joint Pdfs

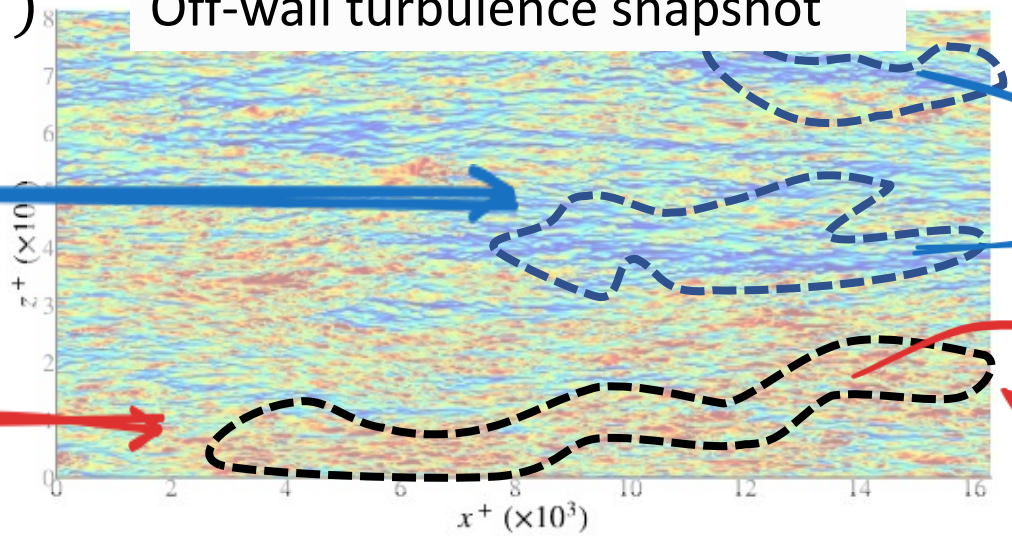
$u_{\tau,LS}$

On-wall large-scale *footprint*



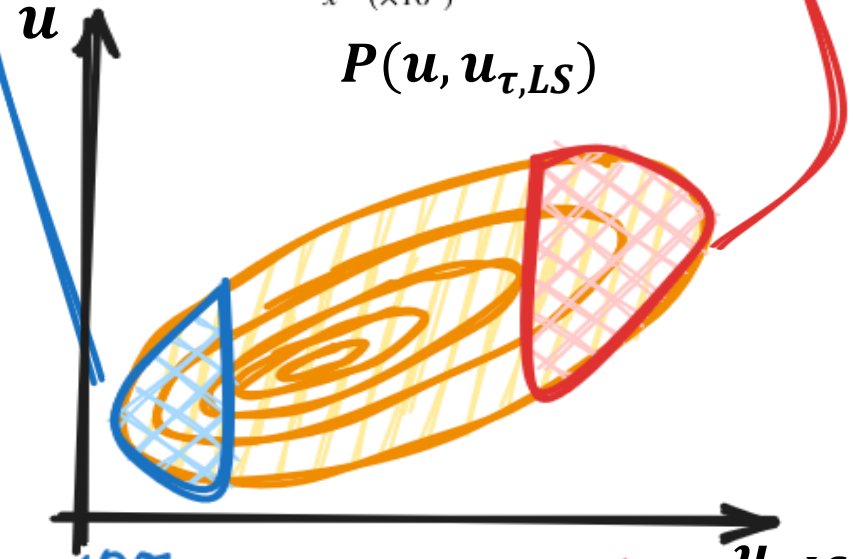
$u(y^+)$

Off-wall turbulence snapshot



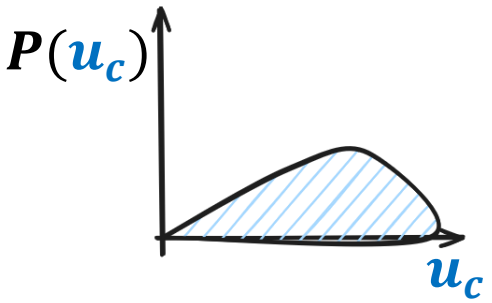
u_c

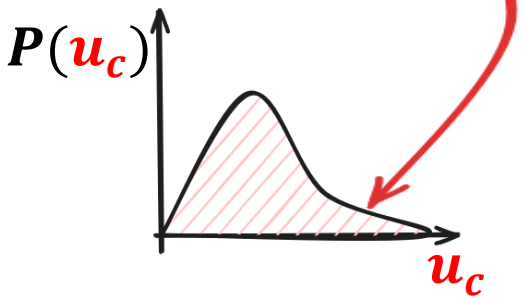
u_c



$\overline{u_c}$, $\overline{u_c'u_c'}$

$\overline{u_c}$, $\overline{u_c'u_c'}$





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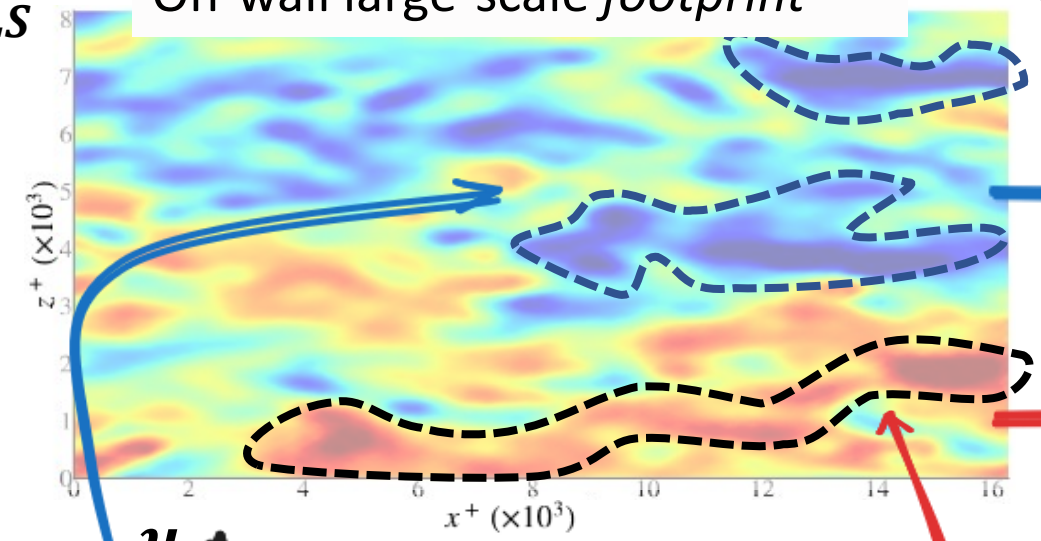
Conditional response to the large-scale skin friction
Approach leveraging Multivariate Joint Pdfs

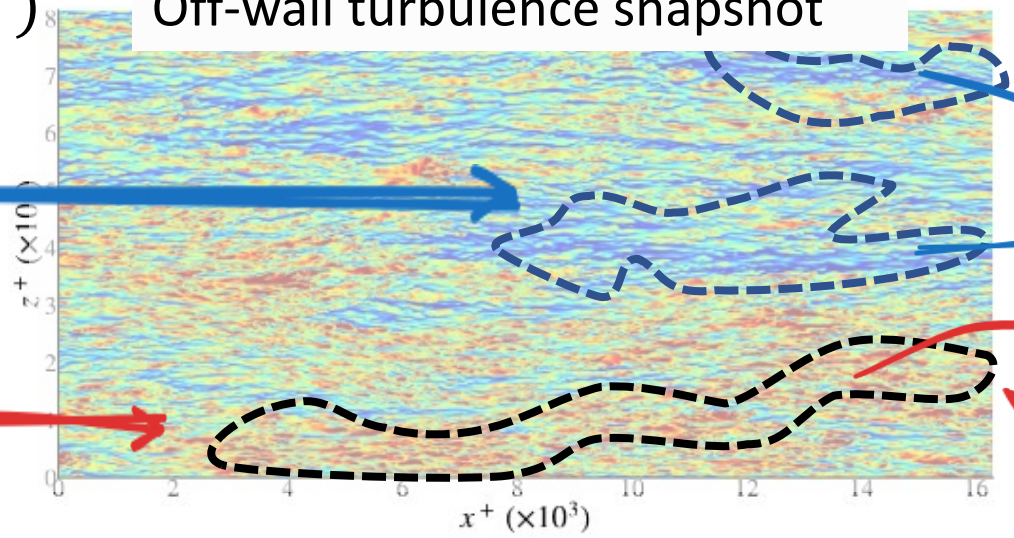
$u_{\tau,LS}$

On-wall large-scale *footprint*



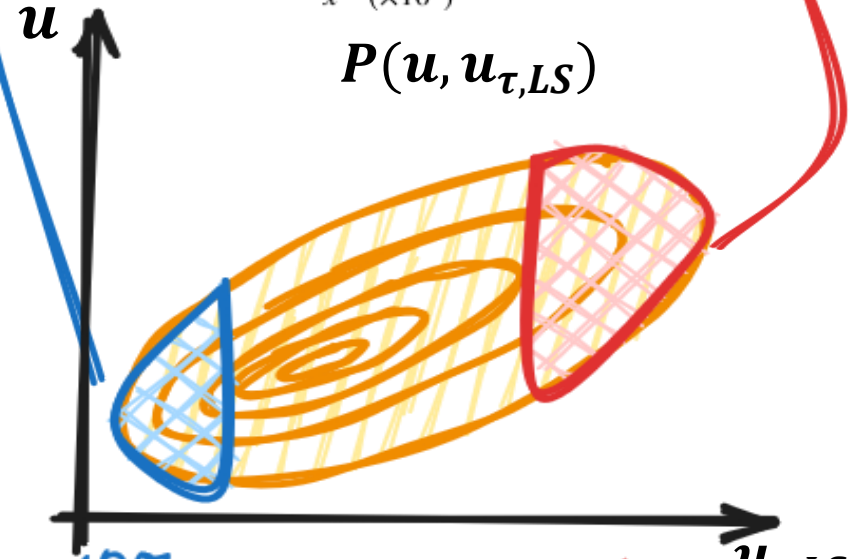
$u(y^+)$

Off-wall turbulence snapshot



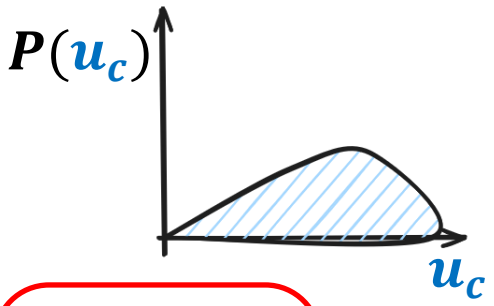
u_c

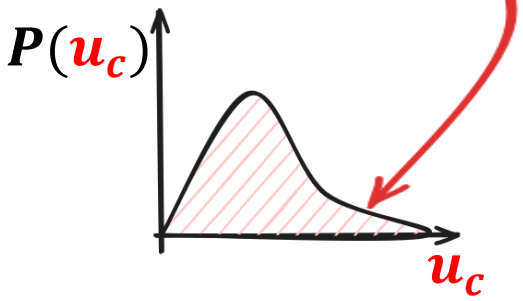
u_c



$\overline{u_c}$, $\overline{u_c'u_c'}$

$\overline{u_c}$, $\overline{u_c'u_c'}$





$$P(u_c) \Leftrightarrow \frac{P(u, u_{\tau,LS})}{P(u_{\tau,LS})}$$

$$\overline{u_c} = \int u_c \, P(u_c) du_c$$

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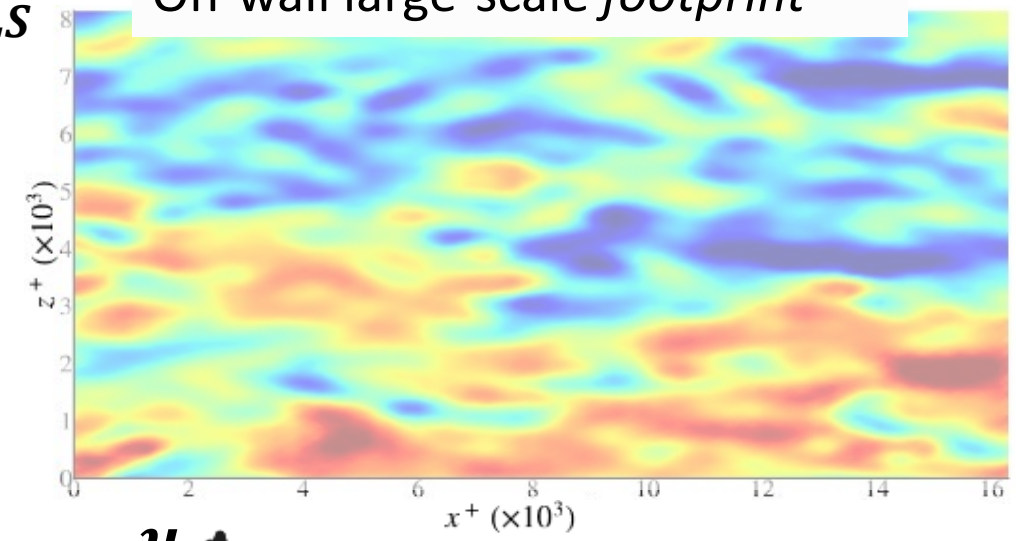
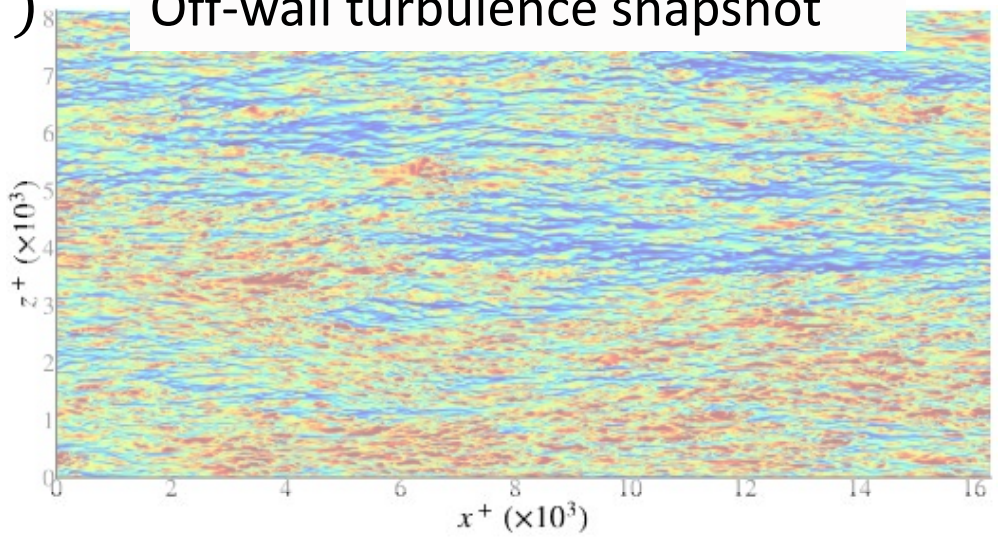
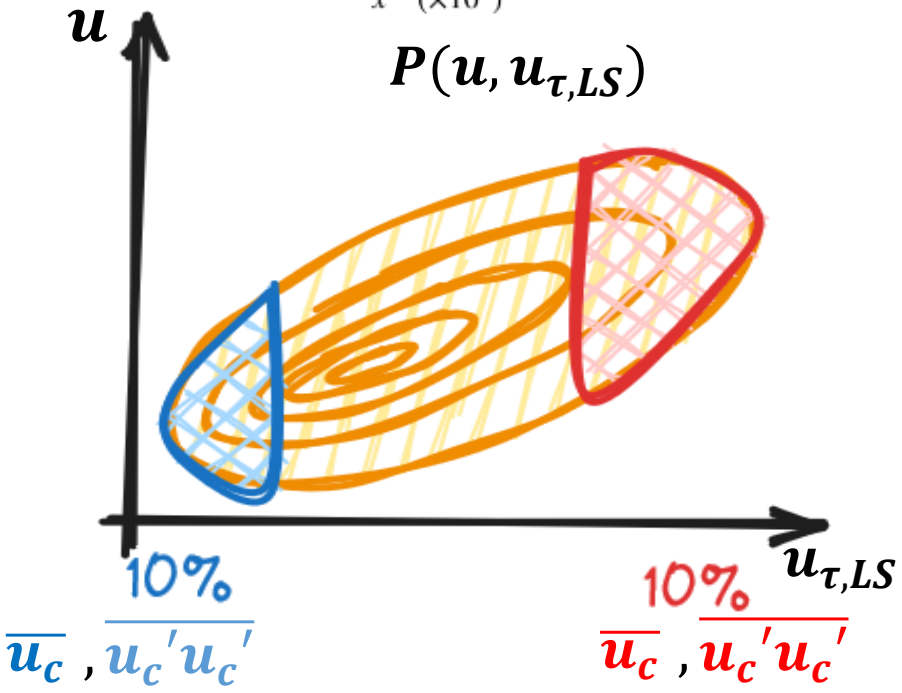
Conditional response to the large-scale skin friction
Classical Approach

$u_{\tau,LS}$ On-wall large-scale *footprint*



$u(y^+)$ Off-wall turbulence snapshot





Conditional :

- mean

$$\overline{u}|_{u_{\tau,LS}} = \iint u \frac{P(u, u_{\tau,LS})}{P(u_{\tau,LS})} du\, du_{\tau,LS}$$

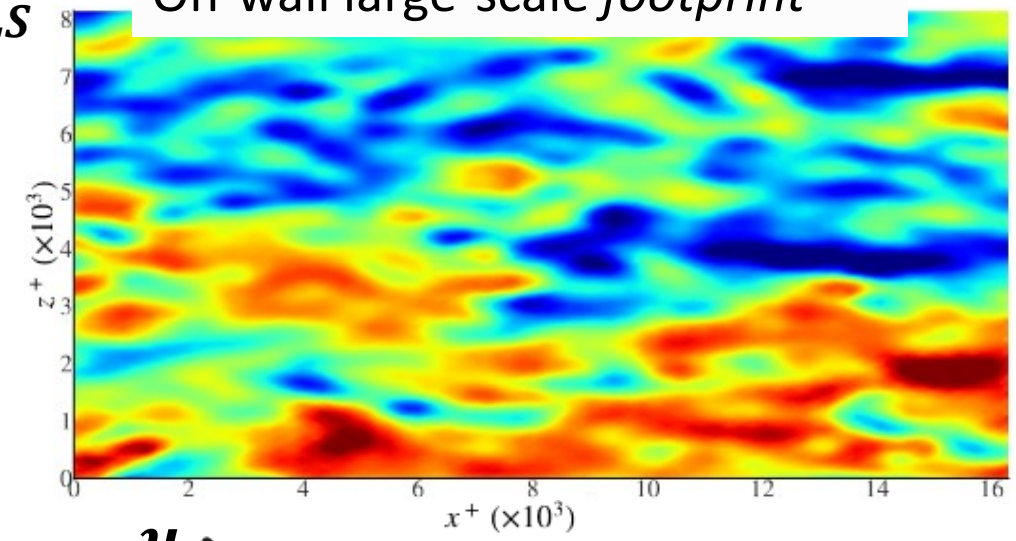
- variance

$$\overline{uu}|_{u_{\tau,LS}} = \iint (u - \overline{u}|_{u_{\tau,LS}})^2 \frac{P(u, u_{\tau,LS})}{P(u_{\tau,LS})} du\, du_{\tau,LS}$$

Conditional response to the large-scale skin friction
Classical Approach

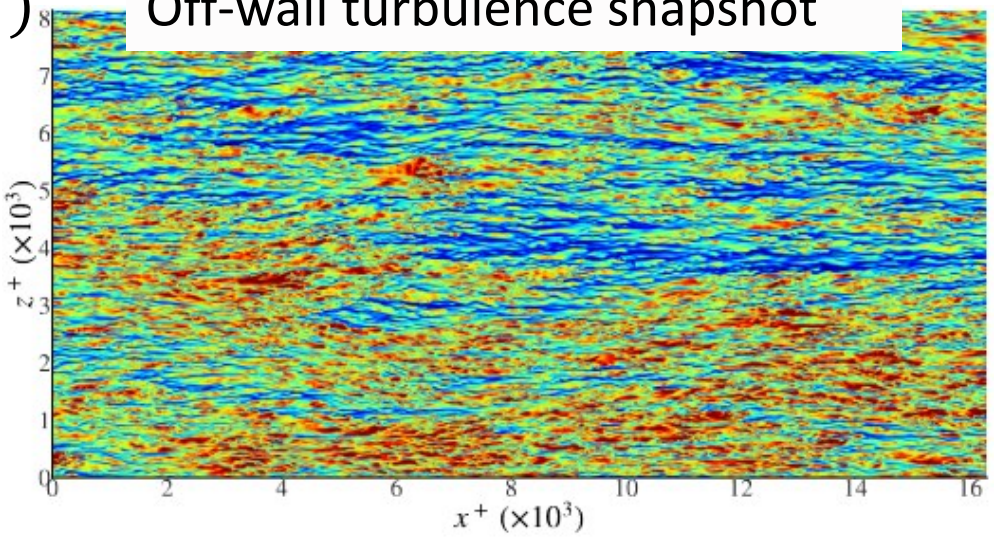
$u_{\tau,LS}$

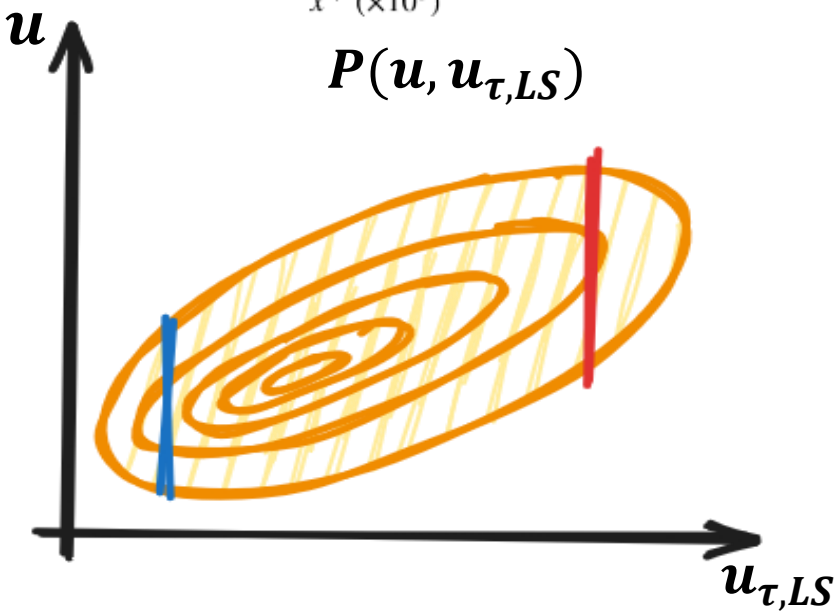
On-wall large-scale *footprint*



$u(y^+)$

Off-wall turbulence snapshot





Conditional :

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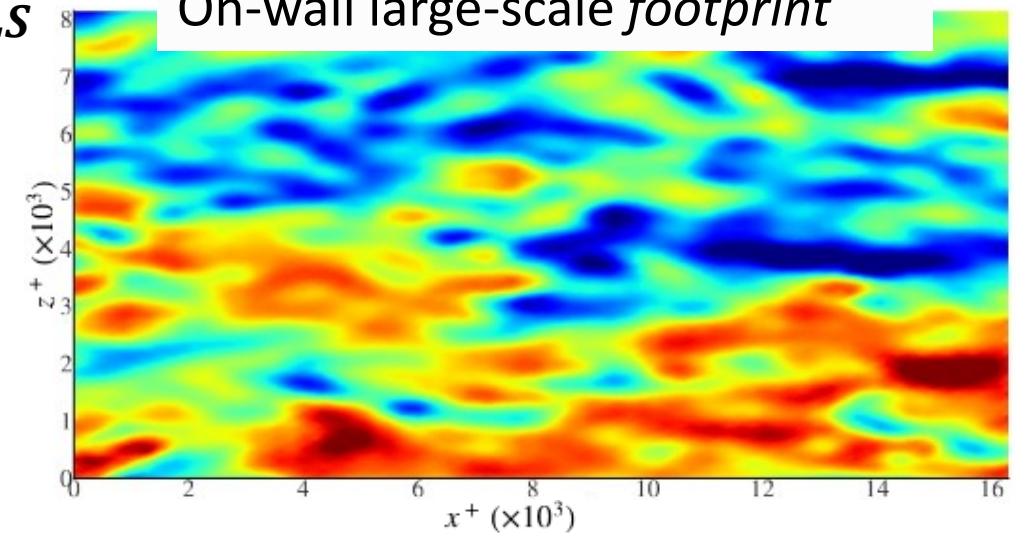
- variance

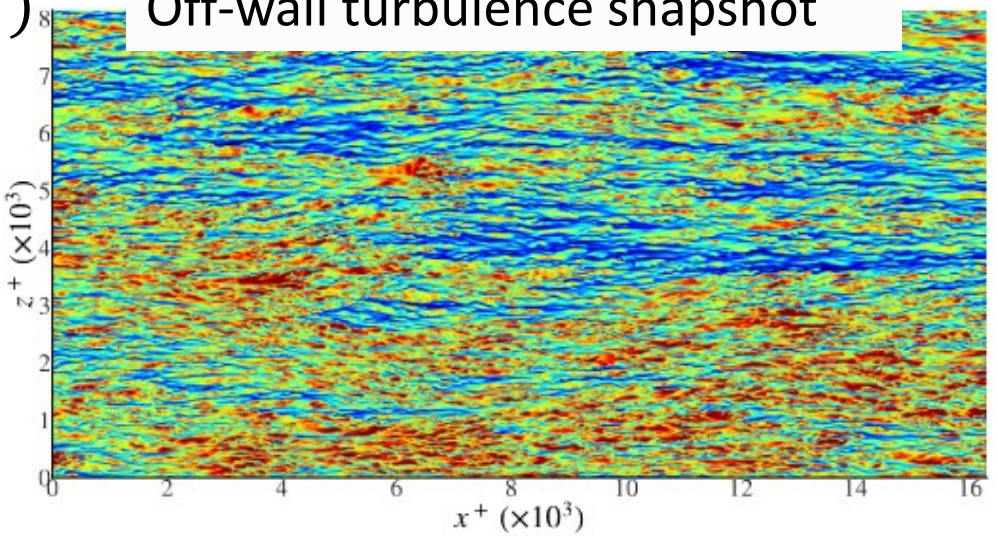
$$\overline{uu}|_{u_{\tau,LS}} = \iint (u - \overline{u}|_{u_{\tau,LS}})^2 \frac{P(u, u_{\tau,LS})}{P(u_{\tau,LS})} du\, du_{\tau,LS}$$

Conditional response to the large-scale skin friction

$u_{\tau,LS}$ On-wall large-scale *footprint*



$u(y^+)$ Off-wall turbulence snapshot

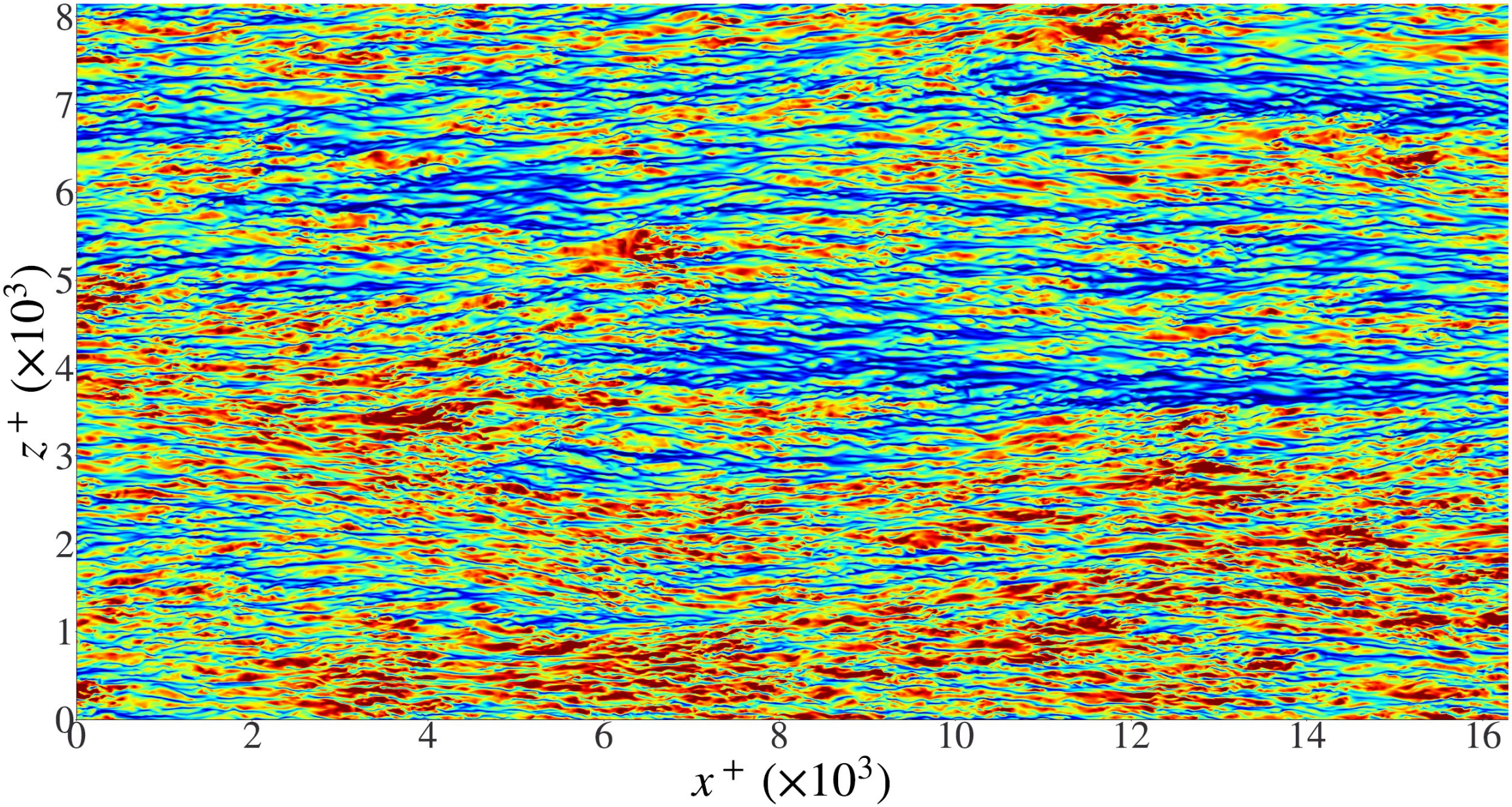


⇨ Multivariate-PDF : $\boldsymbol{P(u, v, w, u_{\tau,LS})}$

- All statistics to any order
- Others terms such as : skewness, production …

L. Agostini and M. Leschziner. "The connection between the spectrum of turbulent scales and the skin-friction statistics in channel flow at $Re_\tau \approx 1000$". In: *Journal of Fluid Mechanics* 871 (2019), pp. 22–51.

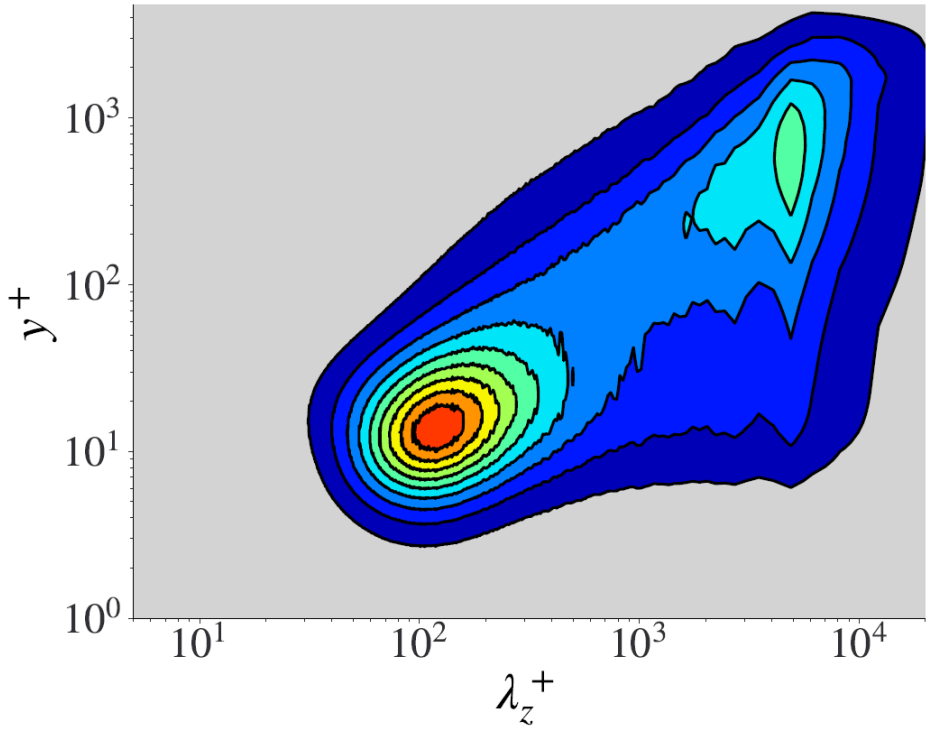
Extension of the Quasi-Steady Hypothesis to Length-scale Modulation



Length-scale modulation
Energy Distribution

Spectral Approach

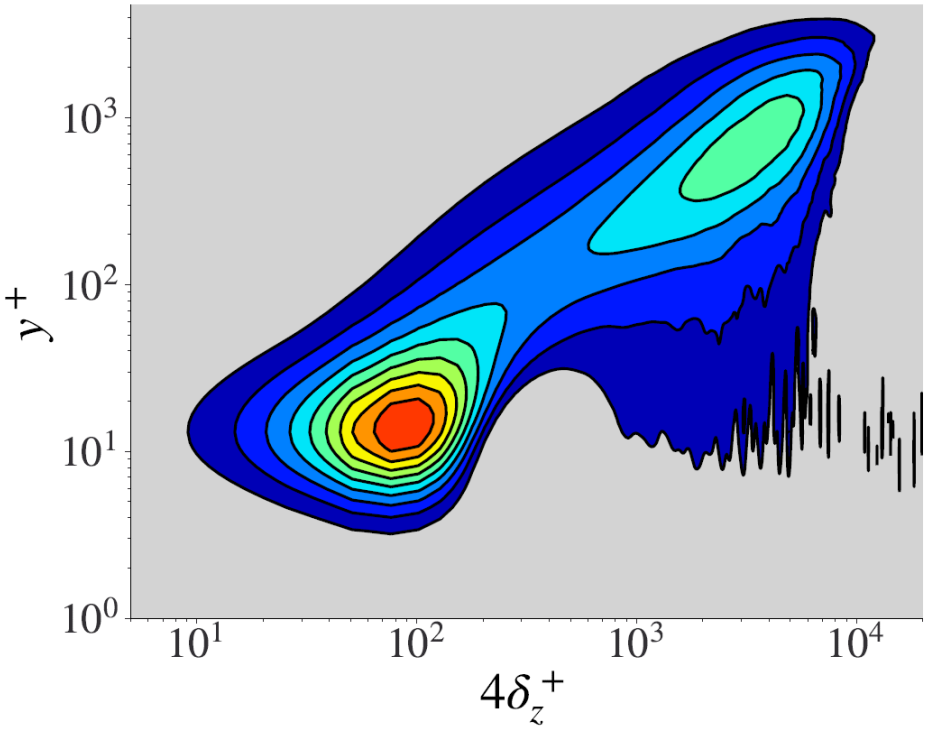
$$k_z \Phi_{uu}$$



Statistical Approach

$$S_u^n(\delta z) = \langle |u(x, z + \delta z) - u(x, z)|^n \rangle$$

$$\delta z \frac{dS_u^2(\delta z)}{d\delta z}$$



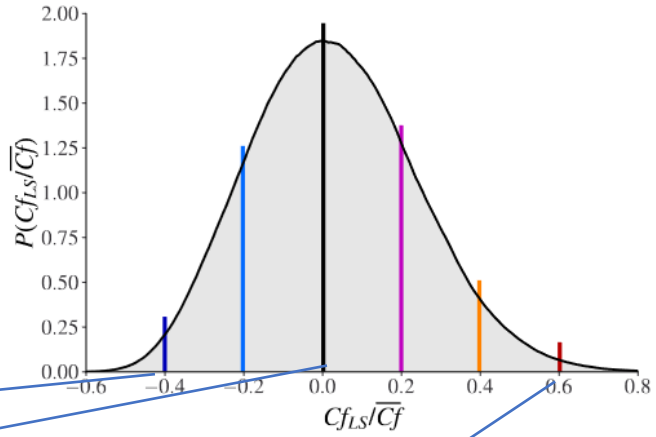
L. Agostini and M. Leschziner, Spectral analysis of near-wall turbulence in channel flow at $\mathrm{Re}_\tau = 4200$ with emphasis on the attached-eddy hypothesis, Phys. Rev. Fluids **2**, (2017).

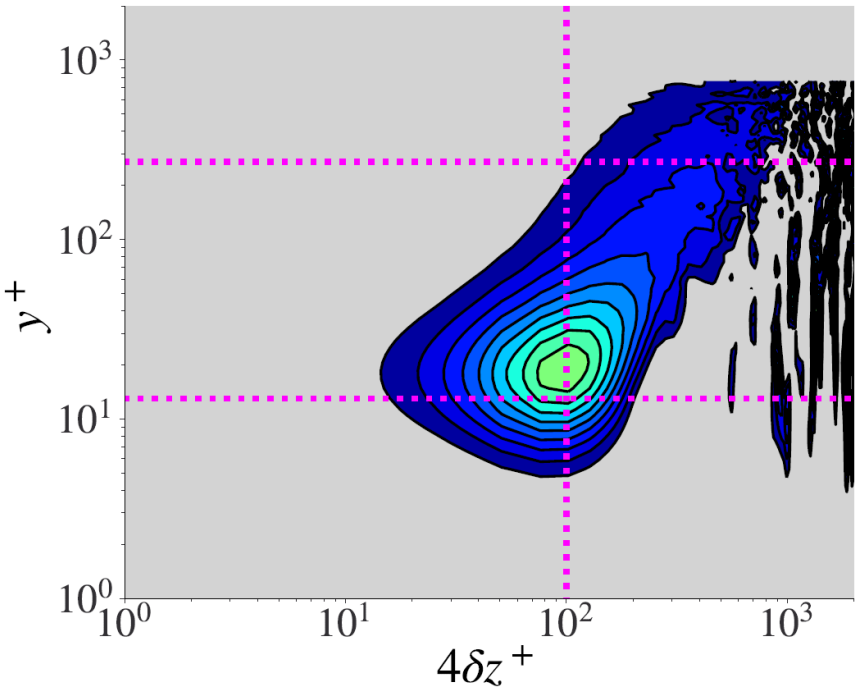
Length-scale modulation
Conditional Wavelength Modulation

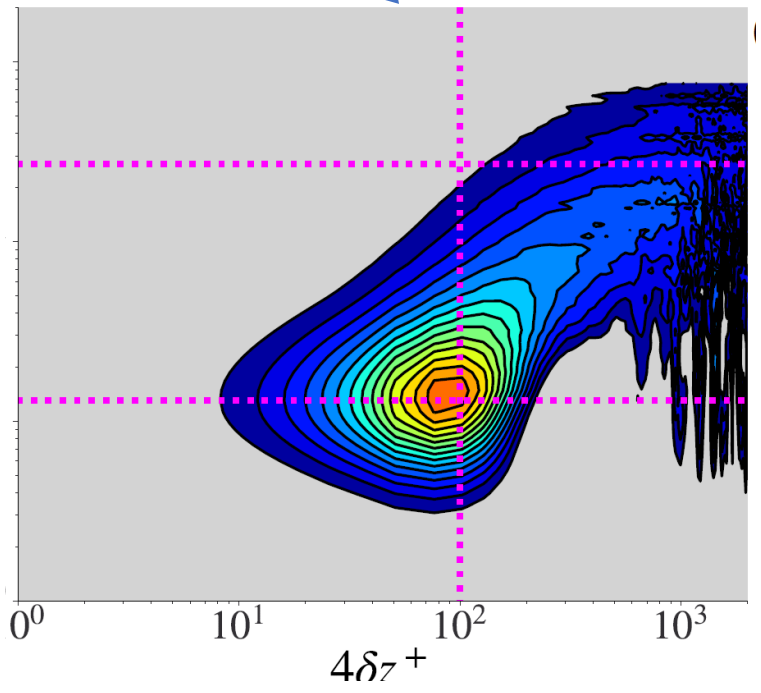
$$S_u^n(\delta z)|_{Cf_{LS}} = \int s_{u,\delta z}^n \frac{P(s_{u,\delta z}, Cf_{LS})}{P(Cf_{LS})} ds_{u,\delta z}$$

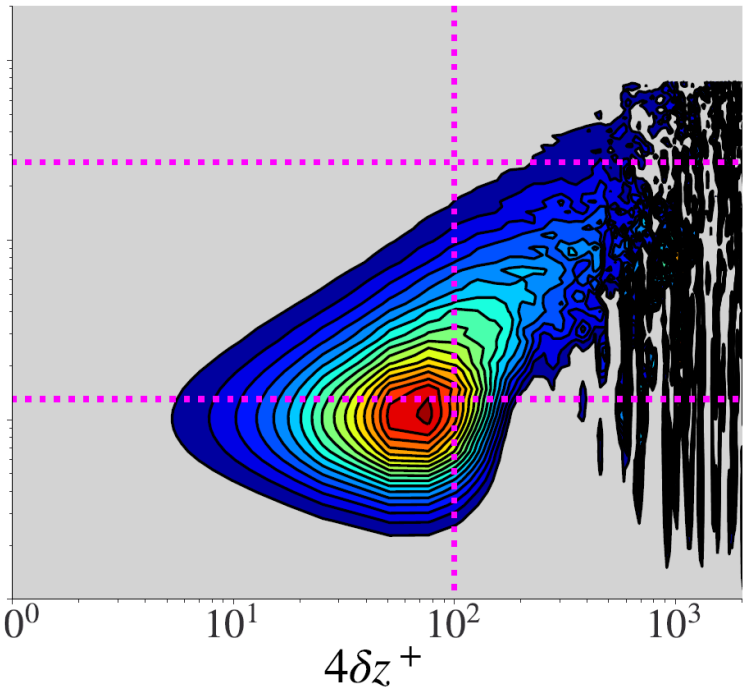
$$with \quad s_{u,\delta z} = u(x, z+\delta z) - u(x, z)$$

PDF of Cf_{LS}*:*





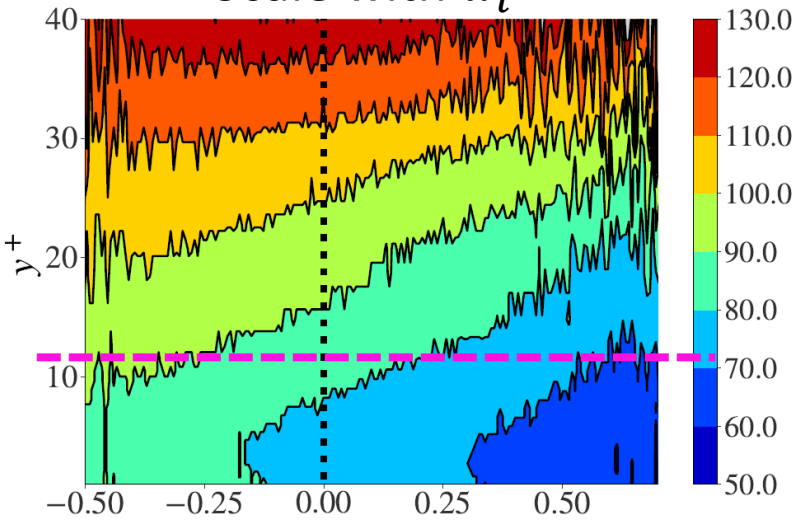


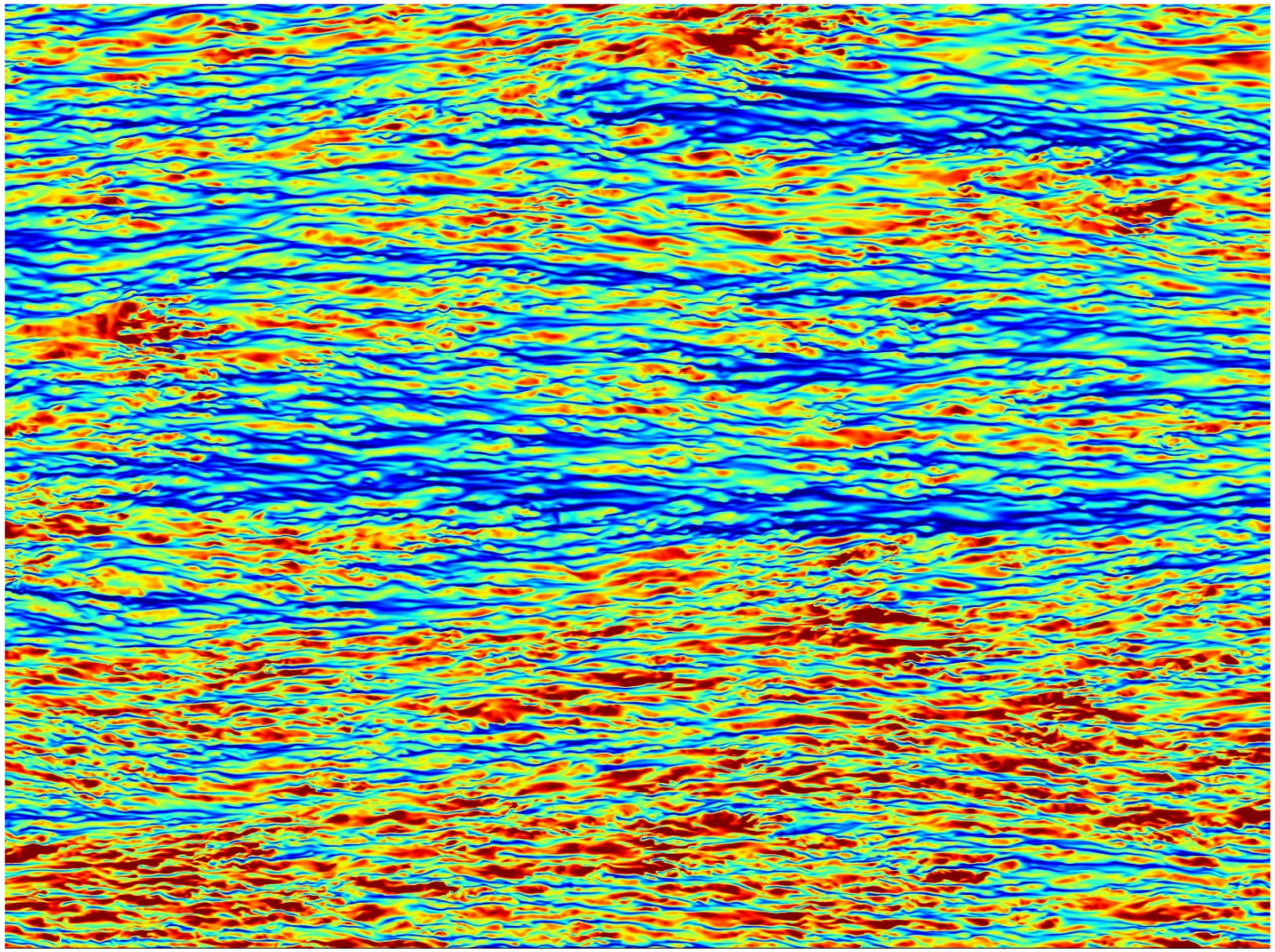


$$\delta z \frac{dS_u^2(\delta z)}{d\delta z}|_{Cf_{LS}}$$

Length-scale modulation
Conditional Wavelength Modulation

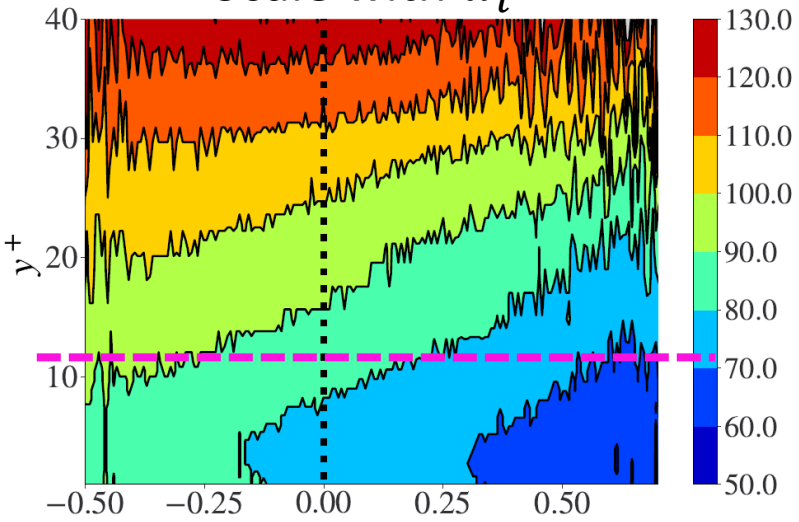
Scale with u_τ



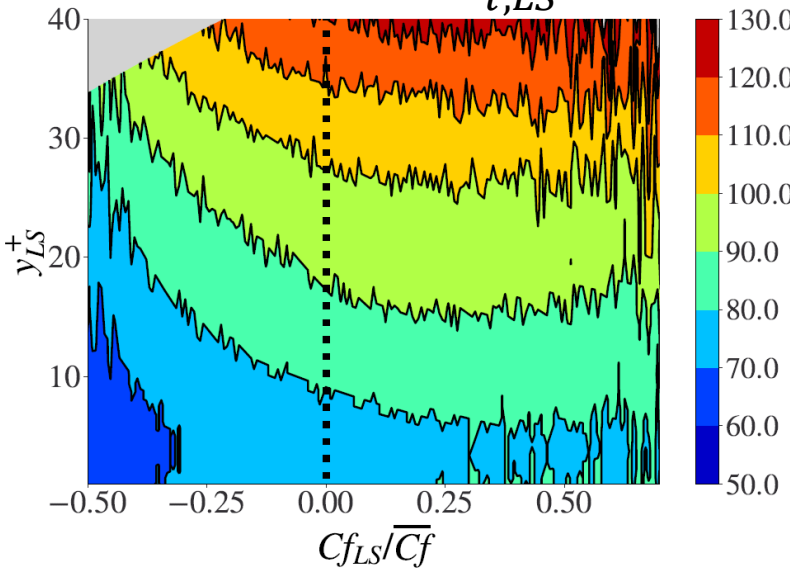


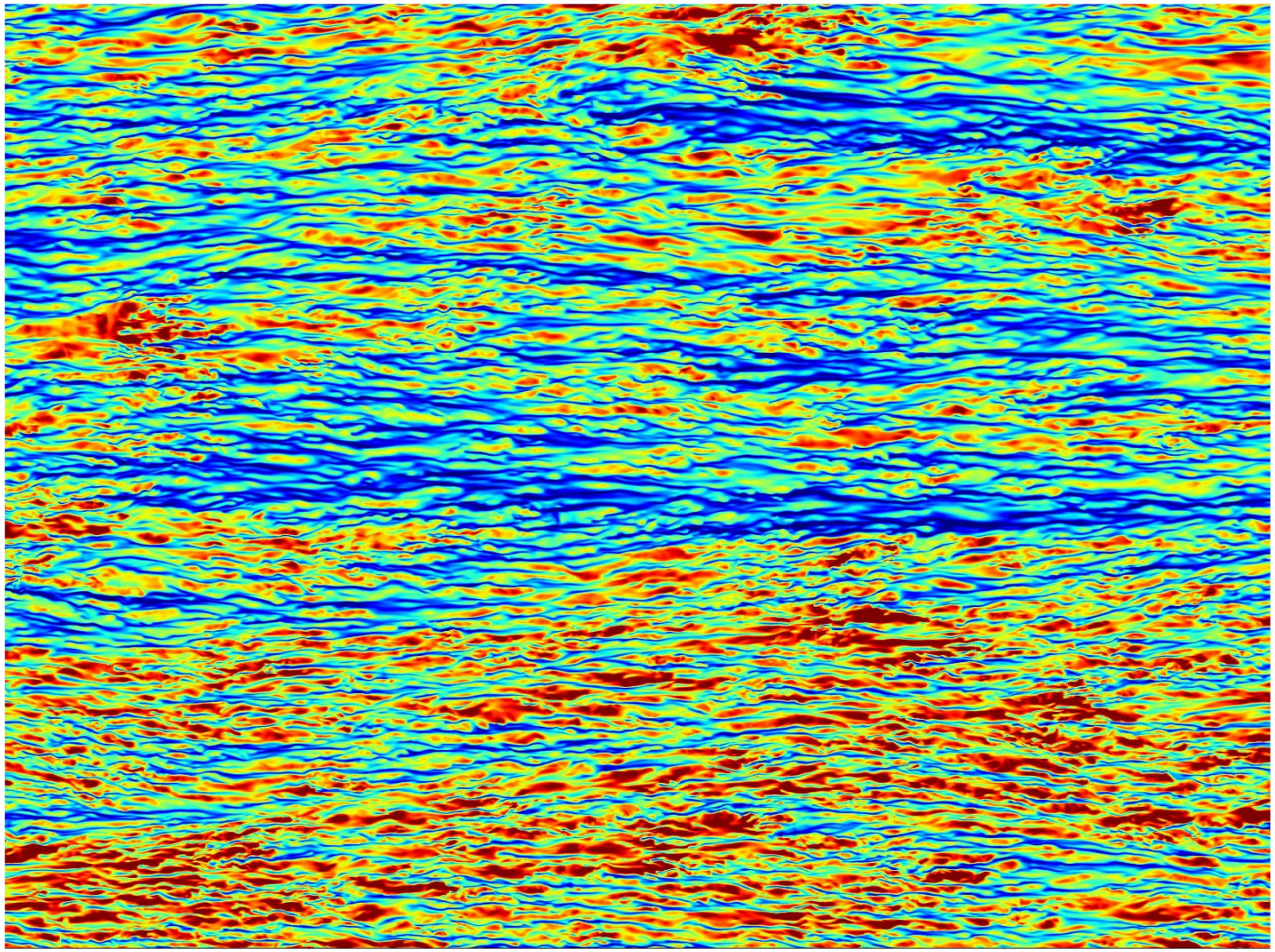
Length-scale modulation
Conditional Wavelength Modulation

Scale with u_τ

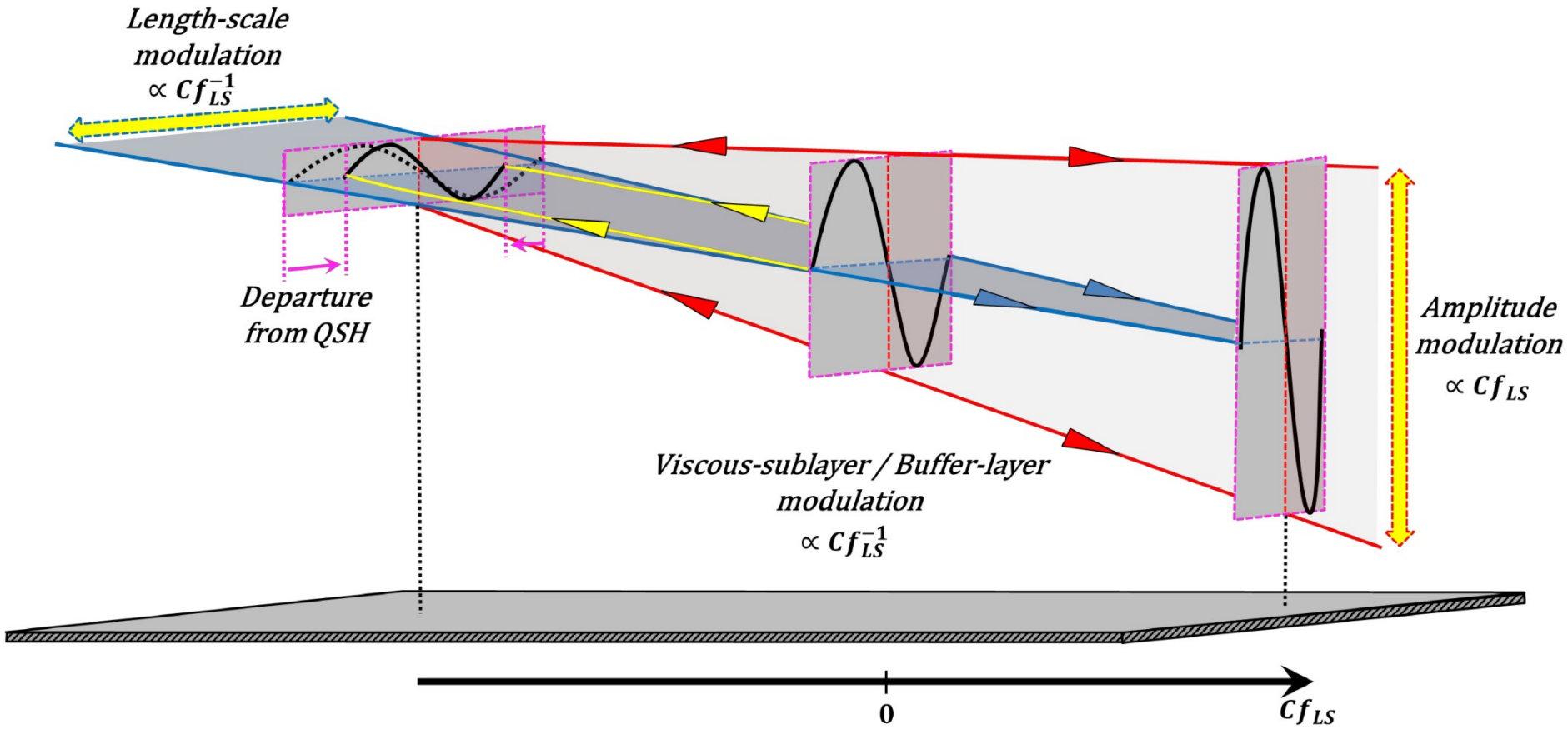


Scale with $u_{\tau,LS}$



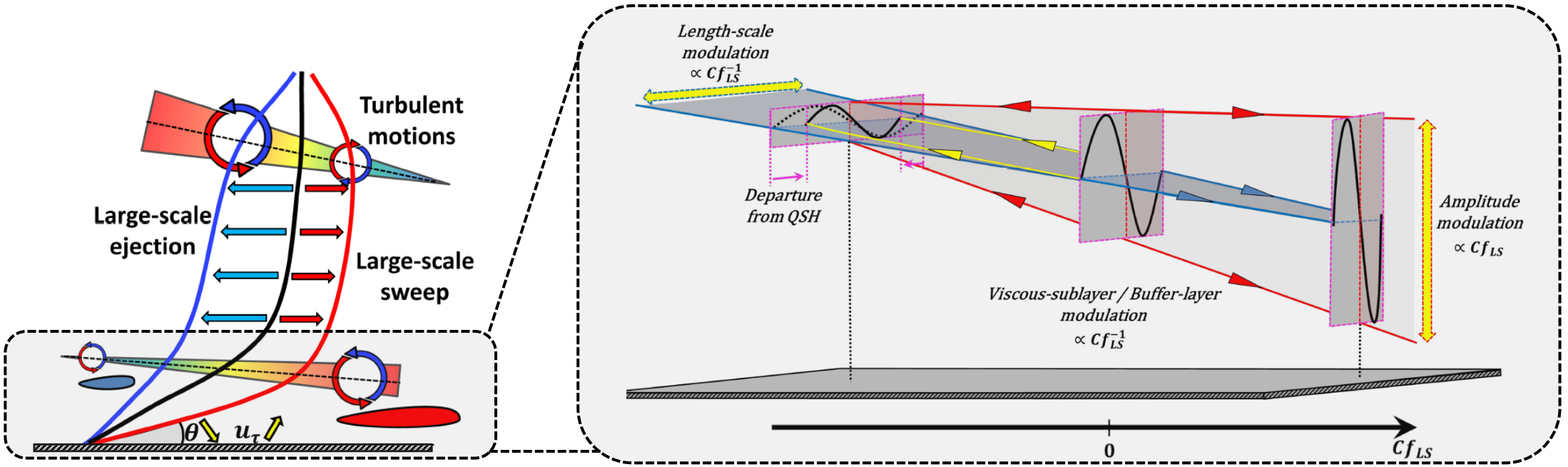


Summary
Quasi-steady Hypothesis

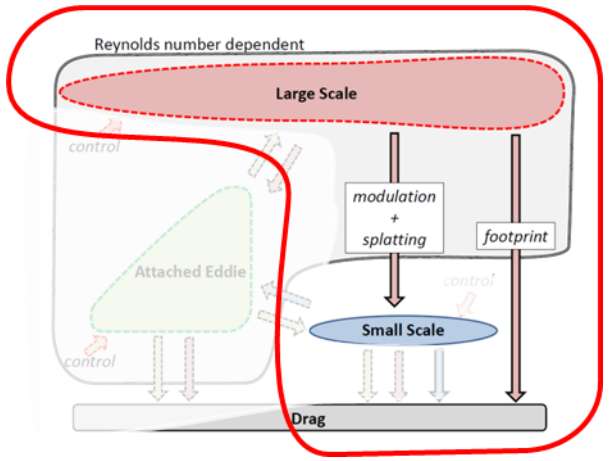


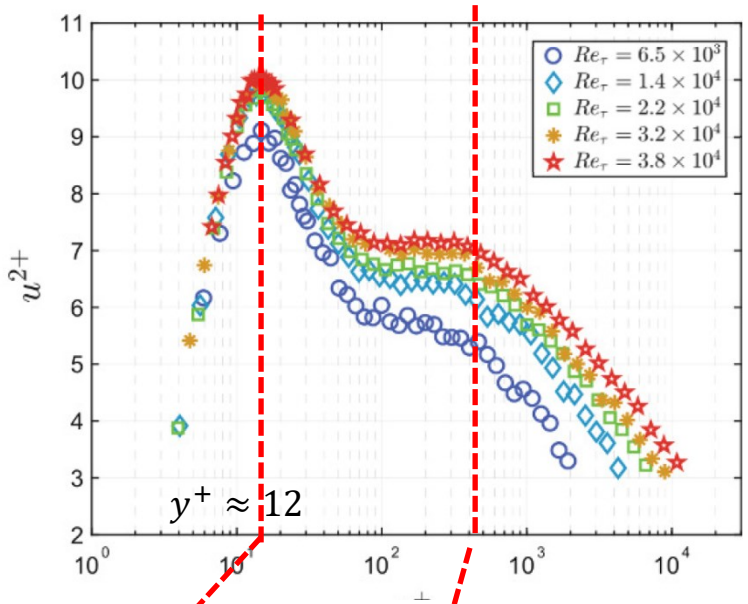
L. Agostini and M. Leschziner. "Auto-encoder-assisted analysis of amplitude and wavelength modulation of near-wall turbulence by outer large-scale structures in channel flow at friction Reynolds number of 5200". In: *Physics of Fluids* 34.11 (2022), p. 115142.

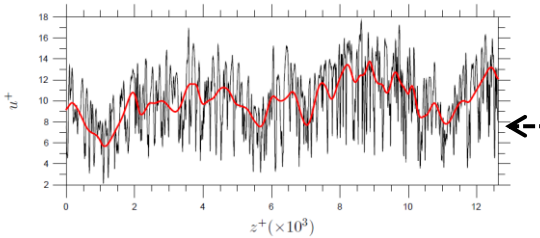
Graphical Overview of Quasi-Steady Hypothesis



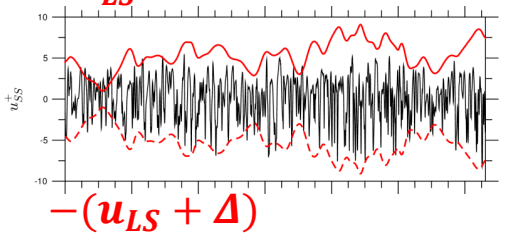
Effets des grandes structures sur la turbulence de proche paroi





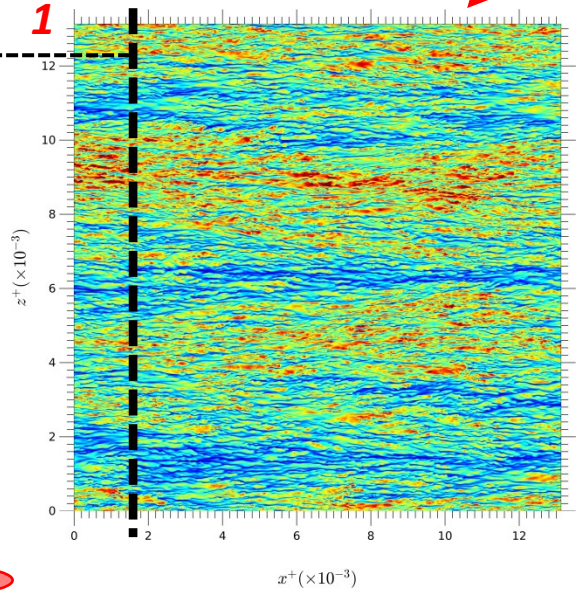


Empreintes des

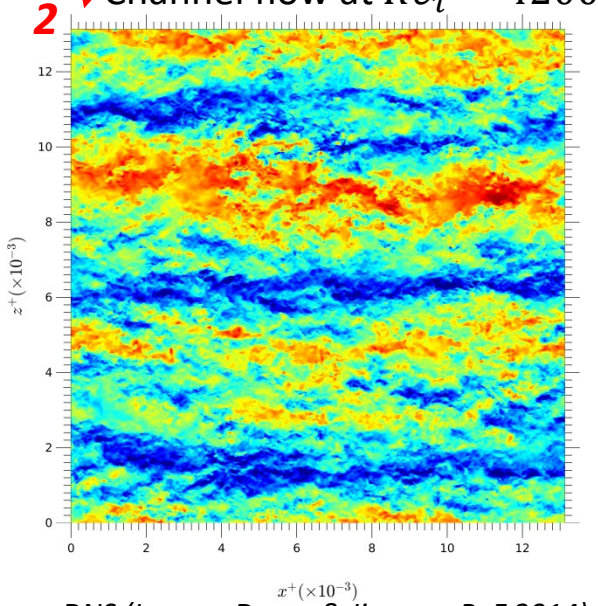


u_{SS}

Modulation des par

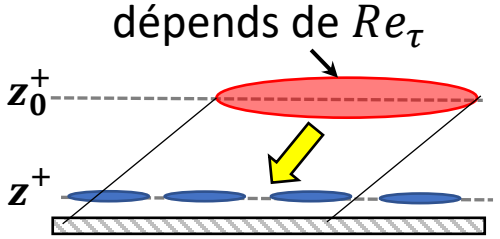


Channel flow at $Re_\tau \approx 4200$



DNS (Lozano-Duran & Jimenez PoF 2014)

Prédiction de la turbulence de proche paroi



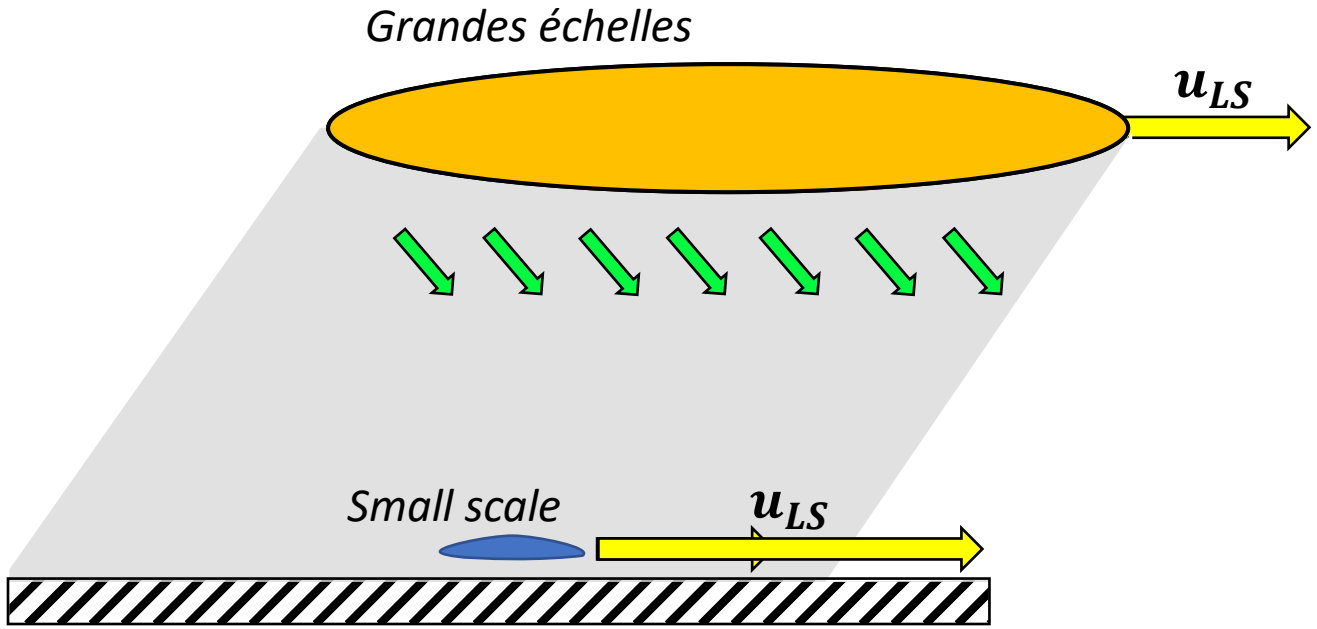
Model proposé par Mathis et al. (JFM 2009):

$$u_p^+(z^+) = u^*(z^+)\left\{1 + \beta\, u_{OL}^+(z_O^+, \theta_L)\right\} + \alpha\, u_{OL}^+(z_O^+, \theta_L)$$

u_p prediction = **u^* universel** × **modulation** (β & u_{LS}) + **superposition** (α & u_{LS})

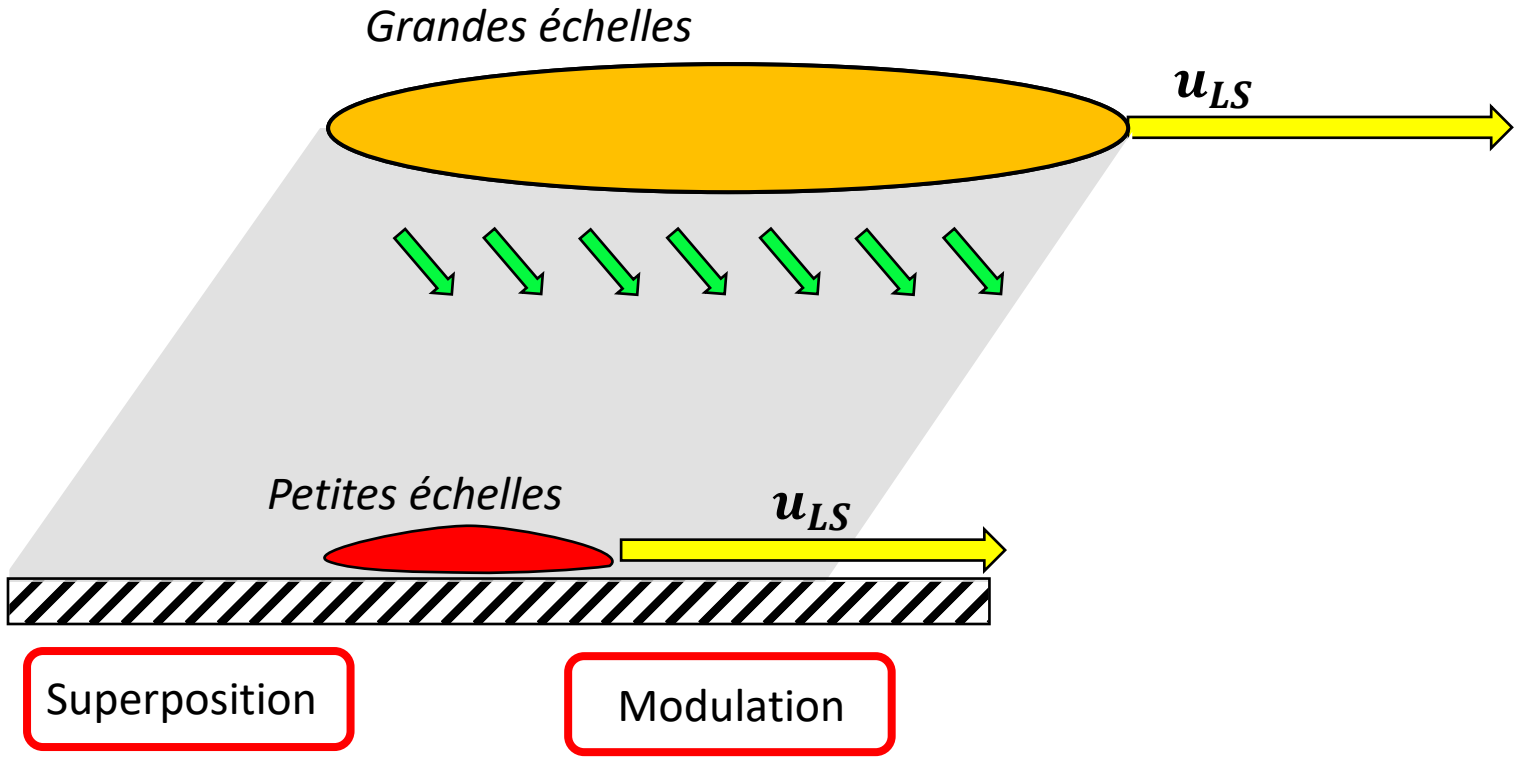
superposition + **Symétrique modulation**

Représentation conceptuelle des interactions entre petites et grandes échelles

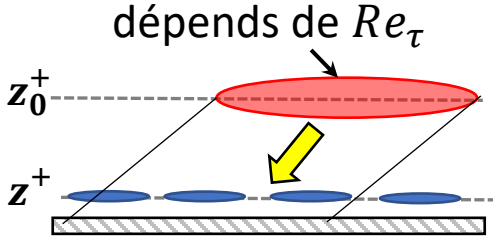


Superposition

Représentation conceptuelle des interactions entre petites et grandes échelles



Prédiction de la turbulence de proche paroi



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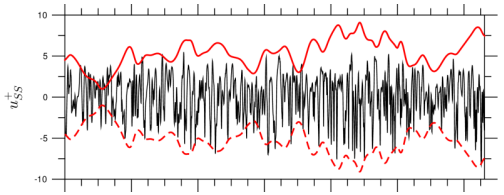
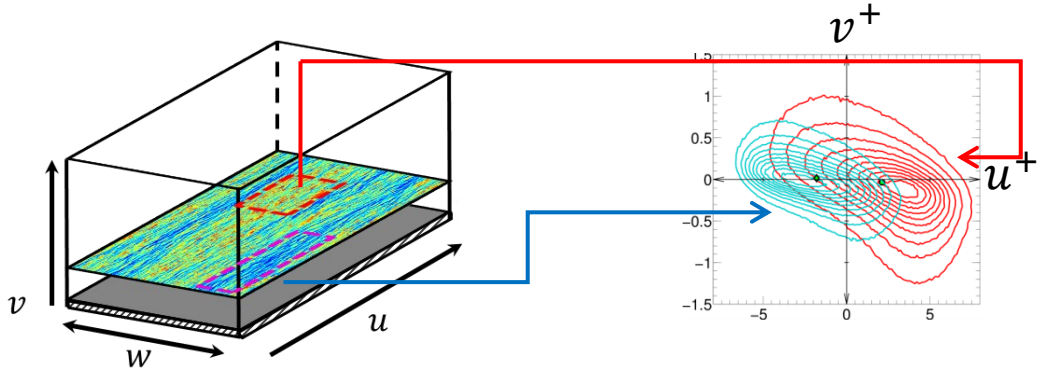
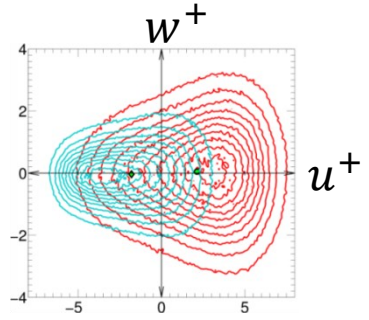
u_p prediction = u^* universel × modulation (β & u_{LS}) + superposition (α & u_{LS})

modulation + superposition

- **β** et **α** sont des facteurs **empiriques** *:*
- prédit uniquement ***u***
- modulation **symétrique**

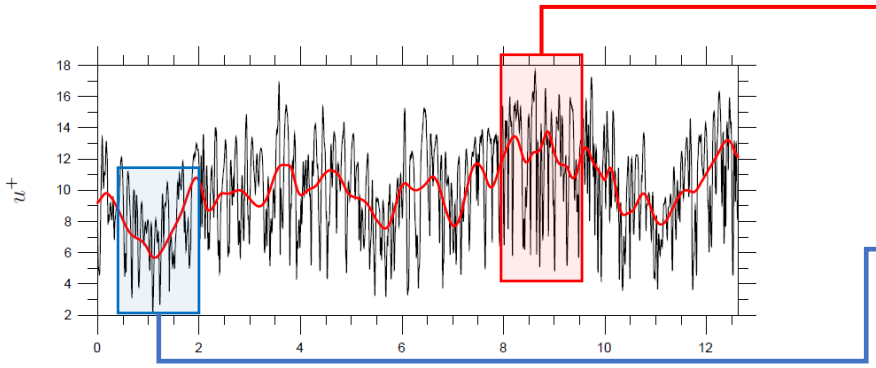




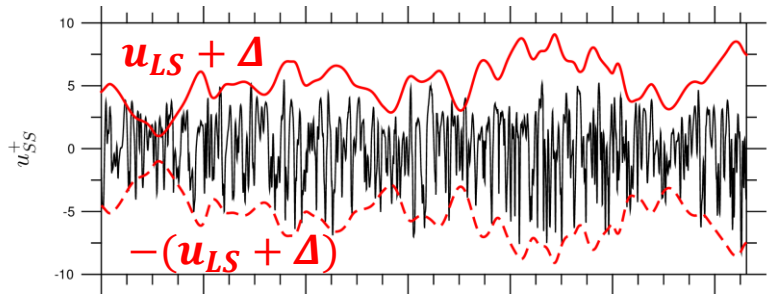


10% maxima 10% minima

Validation du modèle de prédiction



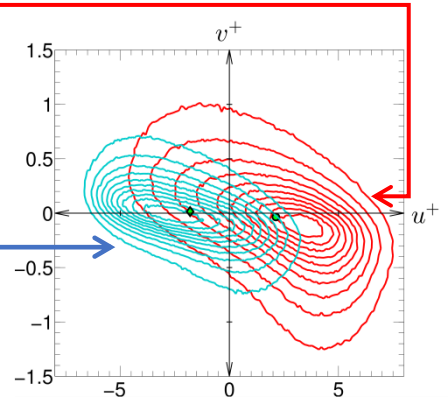
Superposition supprimée

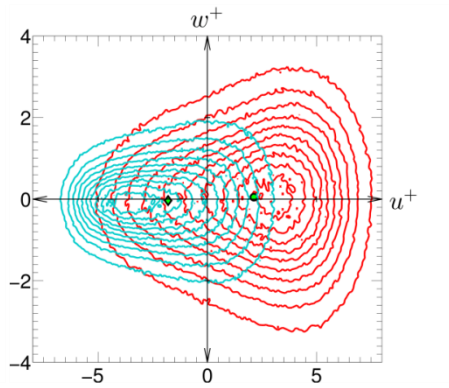


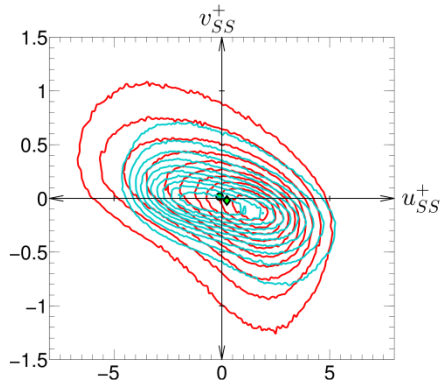
Modulation supprimée

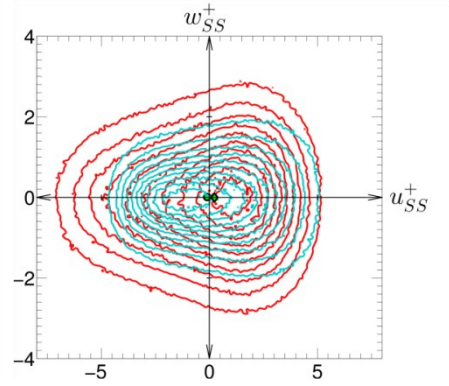
se superposent

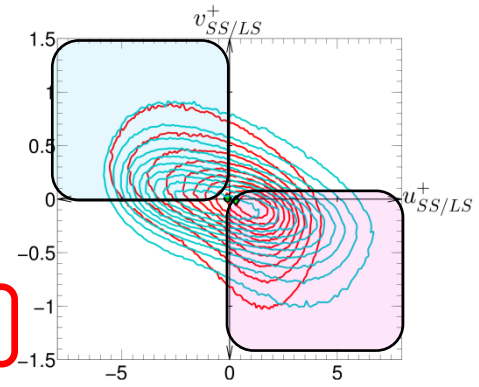
ne se superposent pas

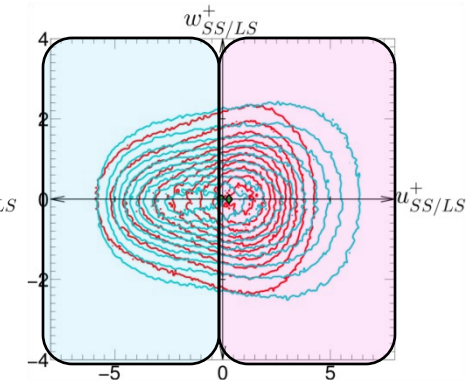






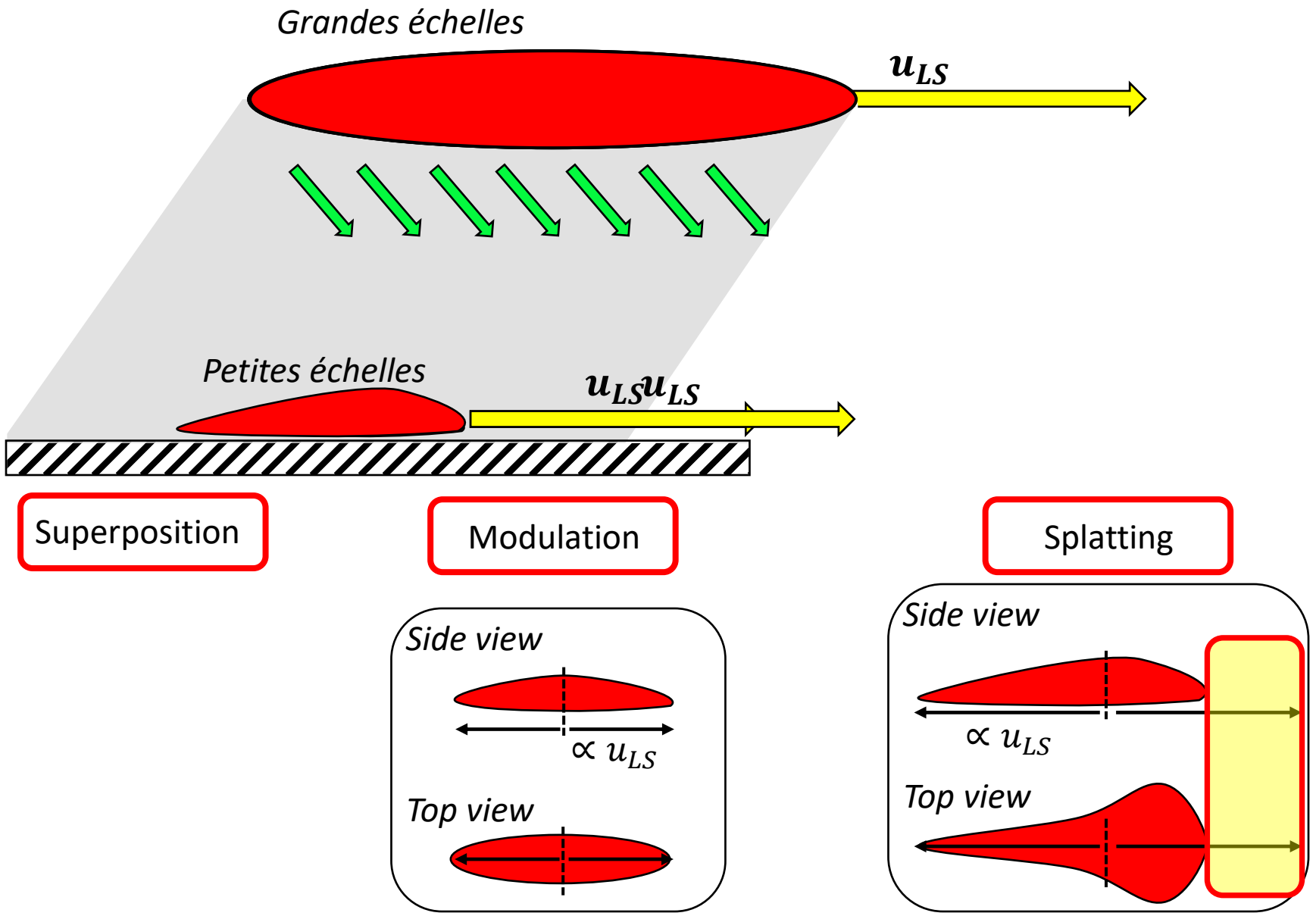






Joint-Pfds différent ⇨ signal **n'est pas universel**

Représentation conceptuelle des interactions entre petites et grandes échelles



Modèle de prédiction raffiné

Mathis et al. (JFM 2009)

Superposition

+

Modulation (symétrique)

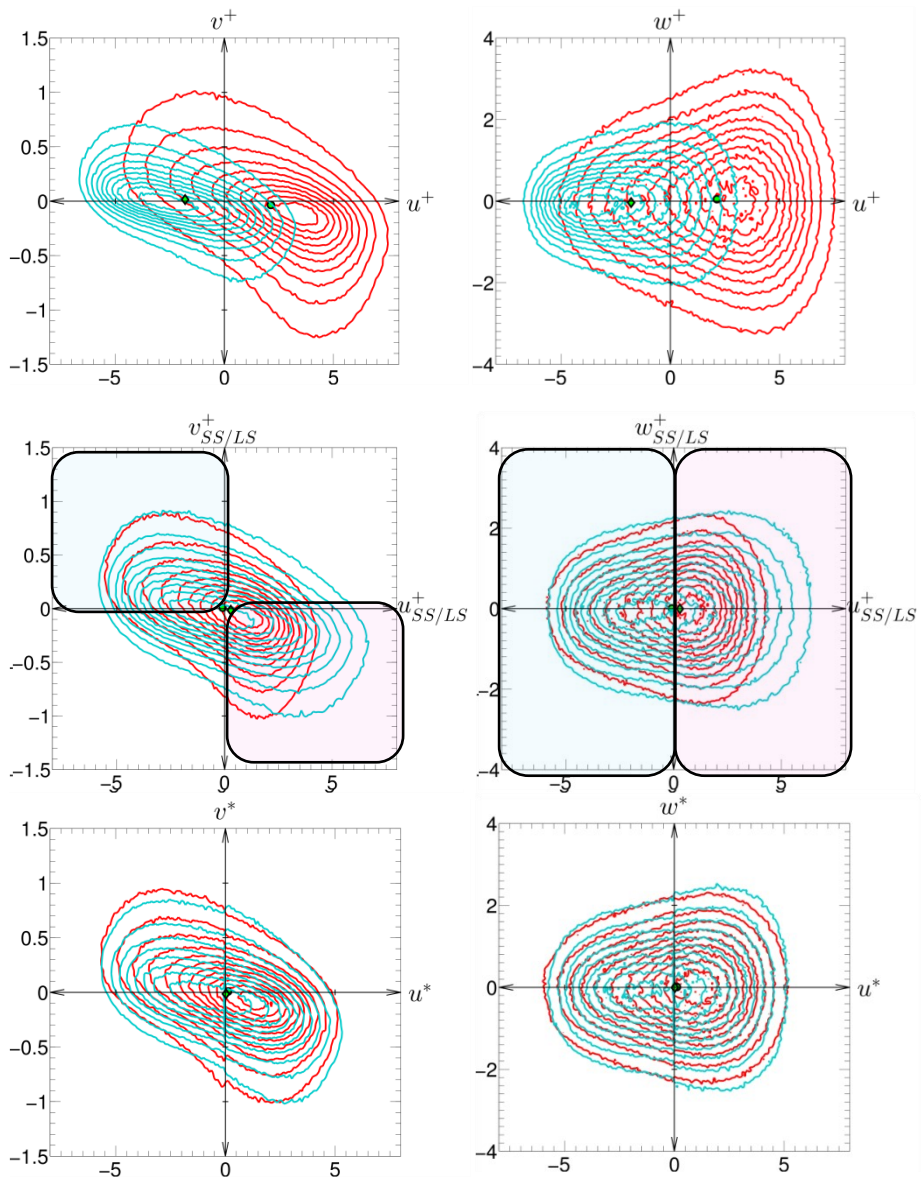
Agostini & Leschziner

+

"Splatting"
(modulation dissymétrique)

=

Joint-PDfs coïncident ⟺ Signal universel

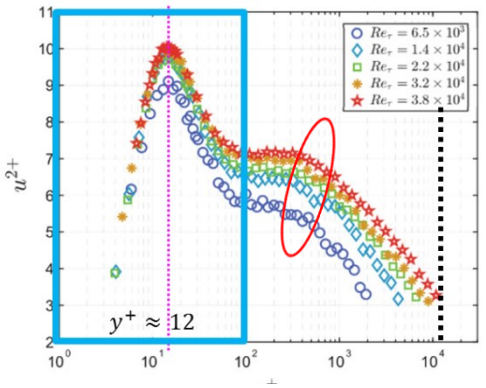


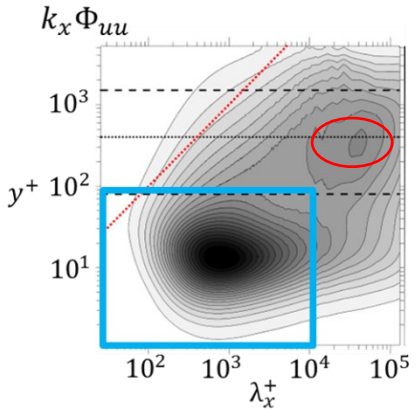
Étalement (splatting)

- modulation **dissymétrique**
- $\boldsymbol{\beta = f(u_{OL}, sign(u^*))}$
- prédit $\boldsymbol{u}$, $\boldsymbol{v}$ et $\boldsymbol{w}$

Prédiction des caractéristiques de la turbulence proche paroi

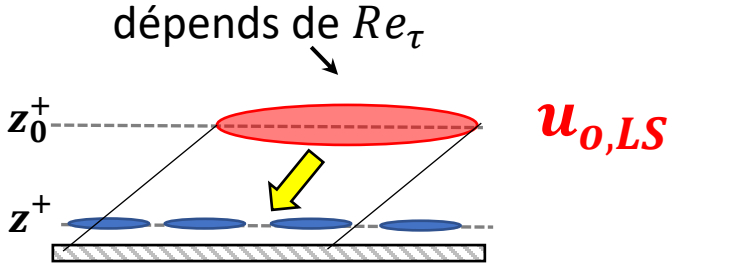
1- Définir un champ universel u^*
i.e indépendant du Re_τ



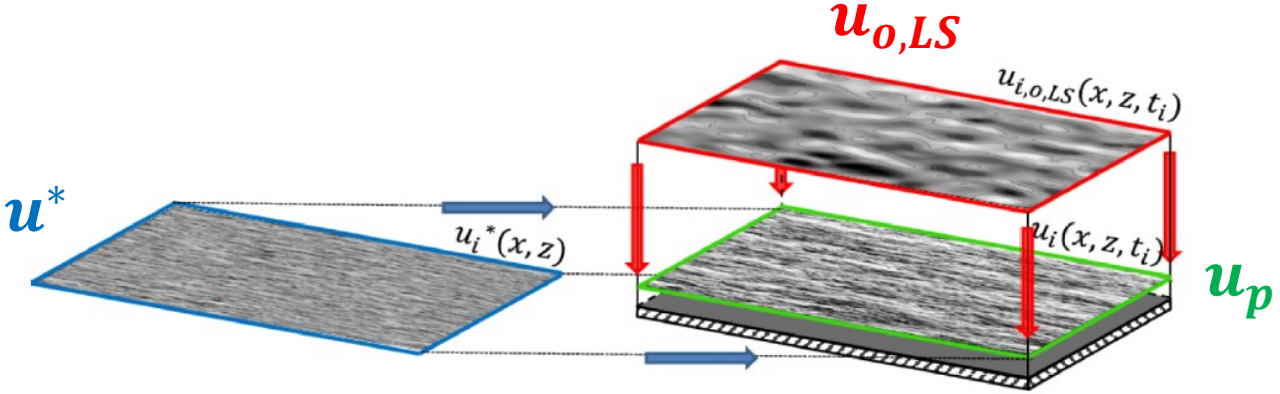


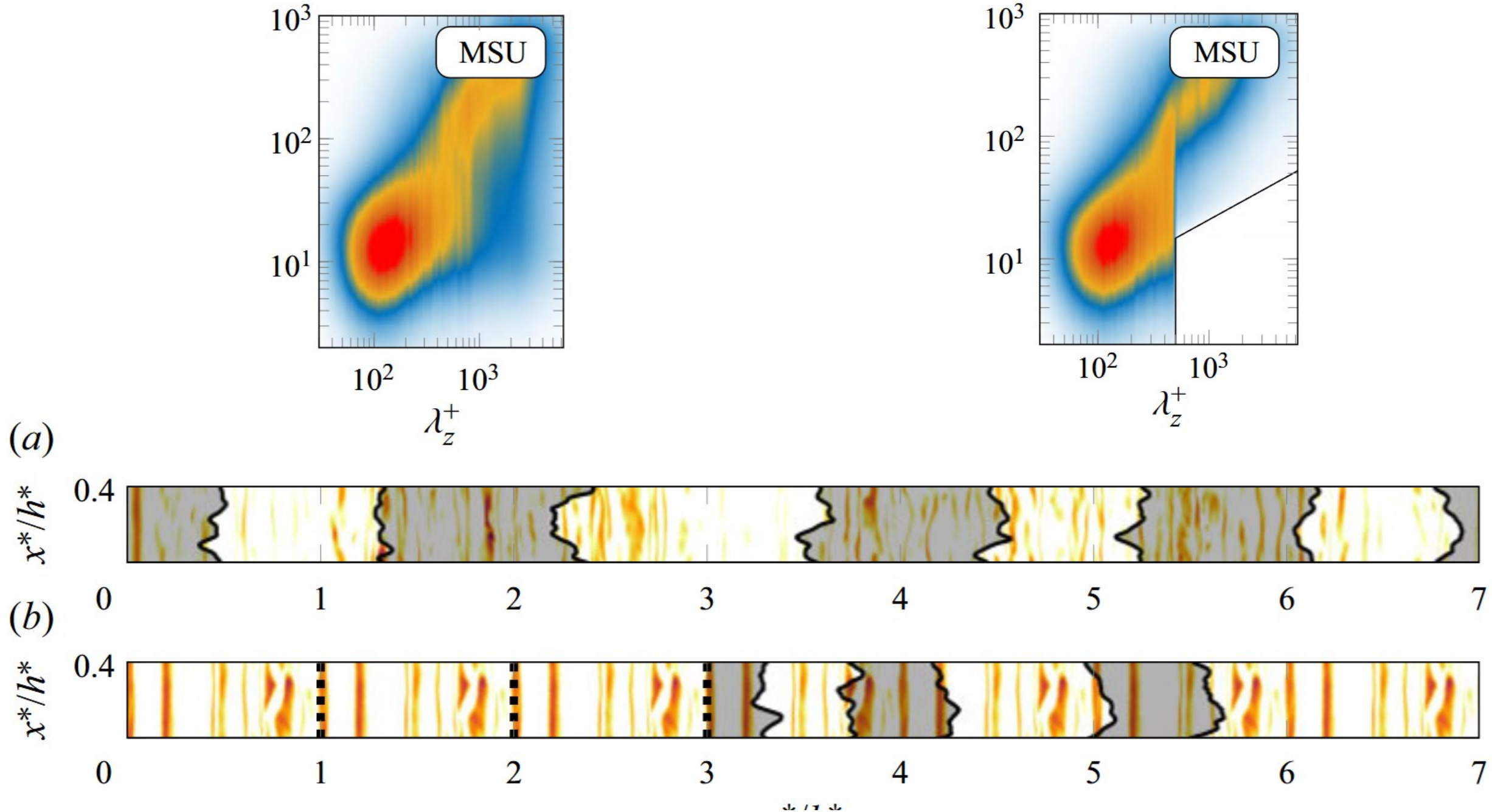
2- Recueillir les fluctuations produites par les larges structures extérieures (mesures ou LES)

3- Déterminer les effets des larges structures extérieures sur la turbulence proche paroi

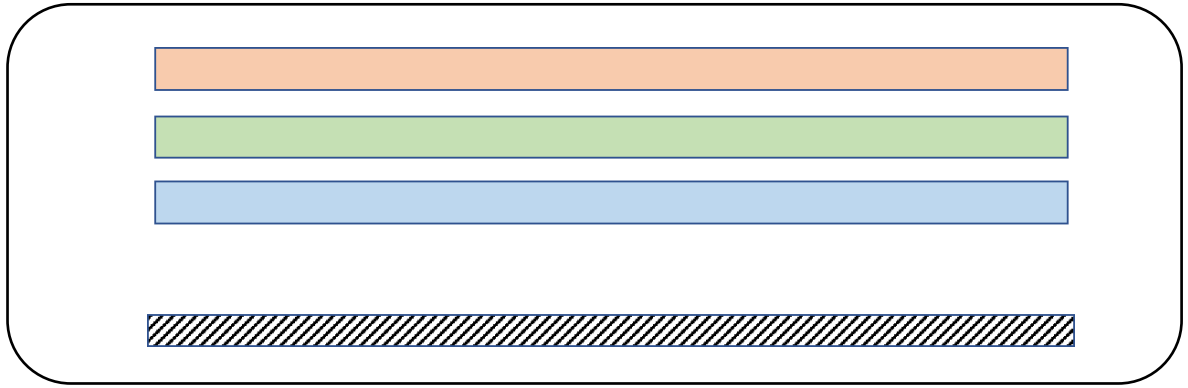


prédiction modélisation

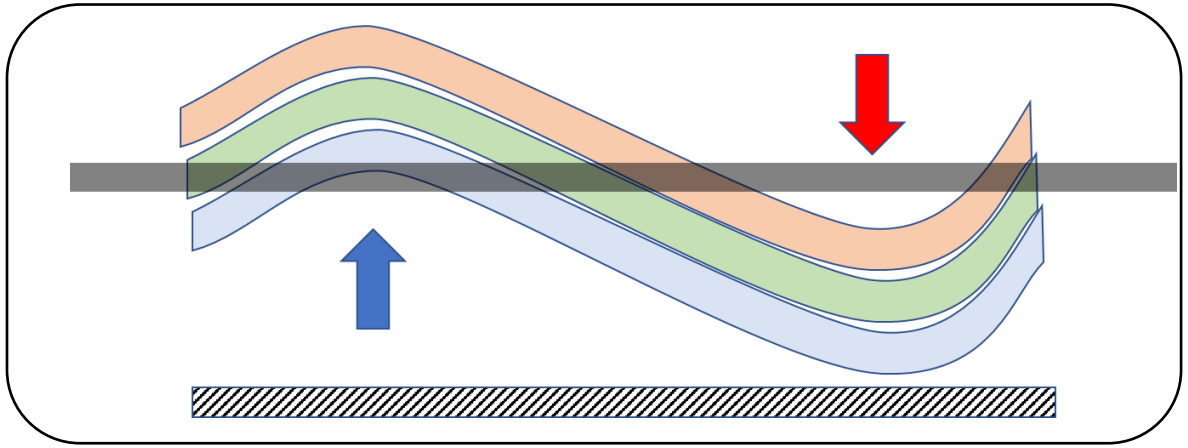



MSU
MSU
10^3
10^2
10^1
10^2
10^3
λ_z^+
(a)
(b)
x^*/h^*
0.4
0
1
2
3
4
5
6
7

Without Large-Scale Motion



Superposition

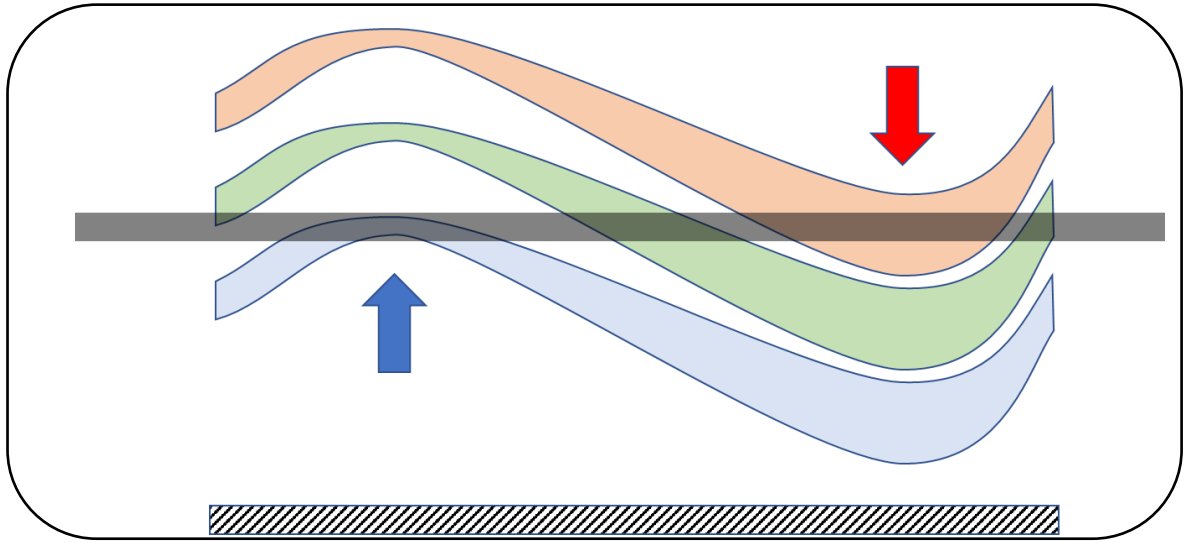


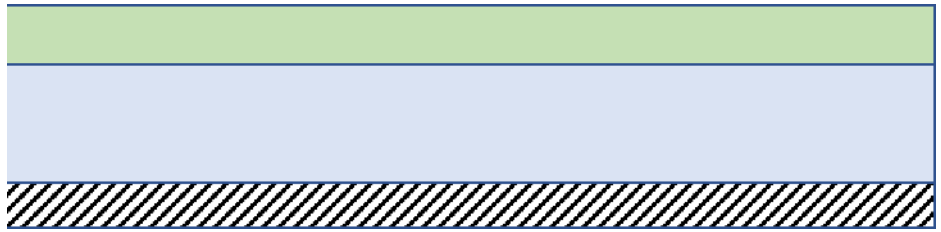
At y^+ fixed -- ``Modulation''

Superposition

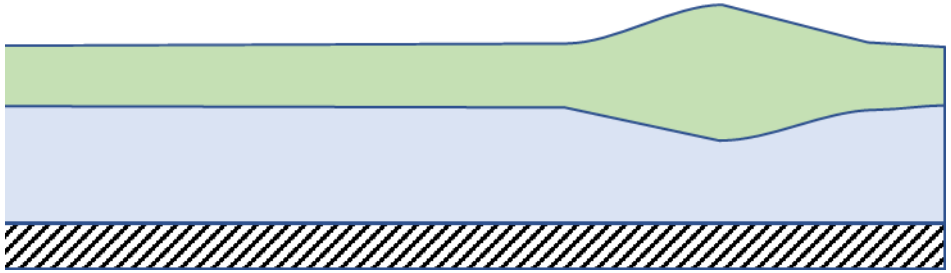
+

Modulation - $\frac{dU}{dy}$





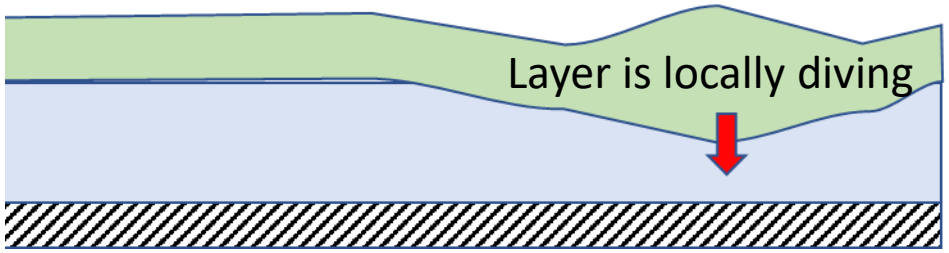
Local modulation



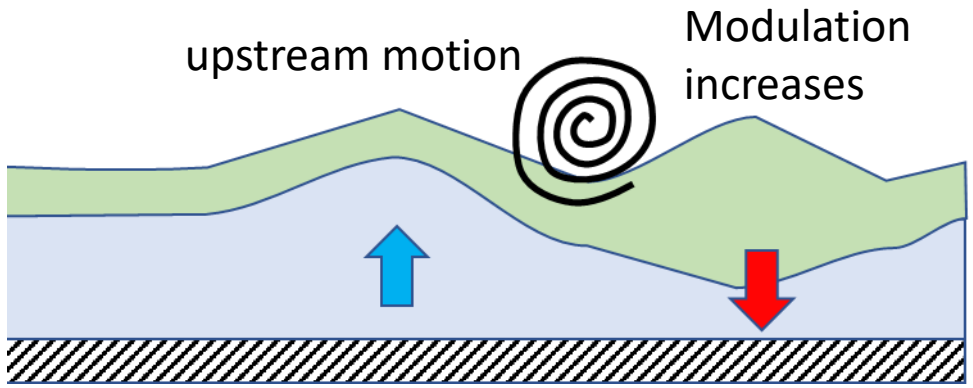
Streaks are locally stronger

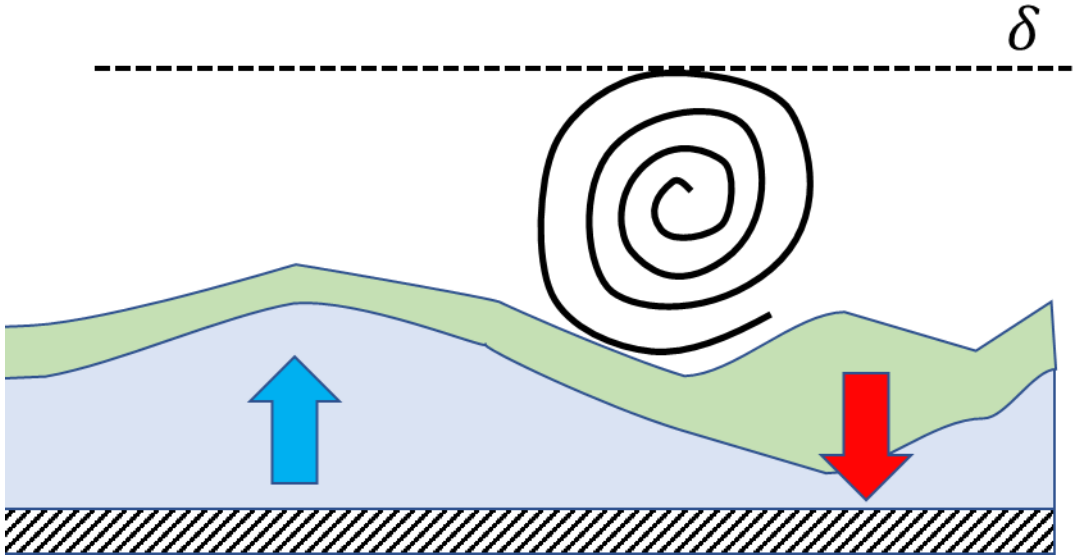
$u'v'$ locally increases

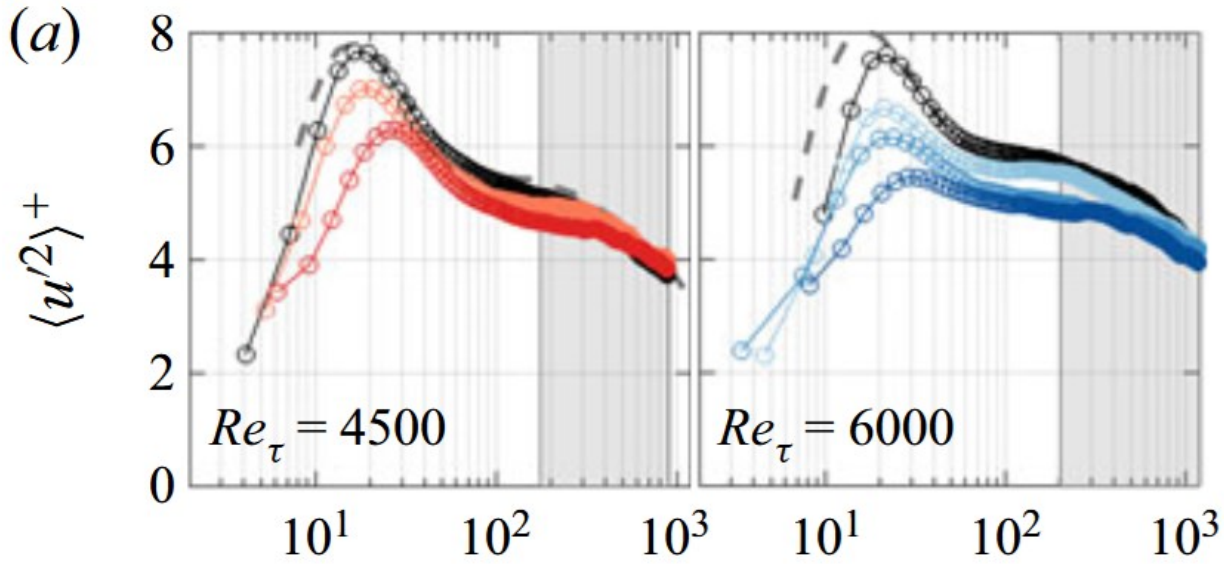
$\frac{dU}{dy}$ locally increases

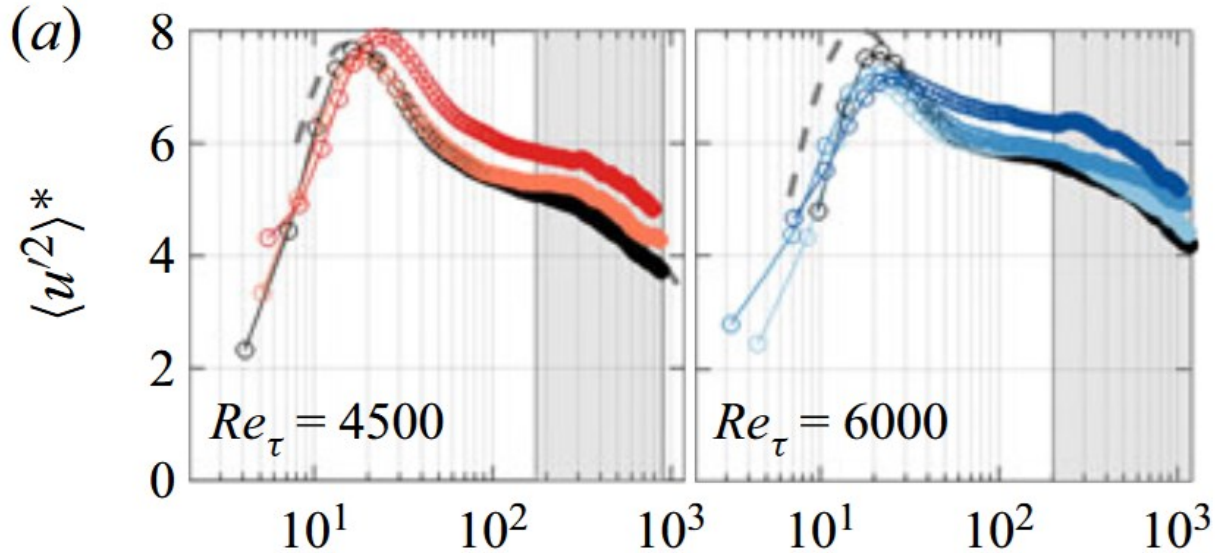


Friction increases






(a)
$\langle u'^2 \rangle^+$
8
6
4
2
0
$Re_\tau = 4500$
$Re_\tau = 6000$
10^1
10^2
10^3
10^1
10^2
10^3


(a)
$\langle u'^2 \rangle^*$
8
6
4
2
0
$Re_\tau = 4500$
$Re_\tau = 6000$
10^1
10^2
10^3
10^1
10^2
10^3