Spatial Network Investigation of Wall Turbulence

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Introduction & Objectives

- Recent increasing interest in **complex network** applications to physical and **engineering** problems;
- Most network analyses related to fluid flows have been focused on topics including **two-phase** flows [1] and **geophysical** flows [2];
- We propose a filtering-information [3-6] correlation-based **spatial network** investigation of a **turbulent channel** flow;
- The **aim** is to provide a spatial characterization the **flow dynamics** [7,8] by introducing an **alternative technique** to study wall turbulence.

Database & Methods

Reynolds Number	$Re_\tau = 180$
Physical Domain (wall units)	(2262,360,391)
Grid Resolution	$(576 \times 191 \times 288)$
Selected Grid Resolution	$(144 \times 191 \times 150)$
Samples	5000
Time-step	$2.5 \cdot 10^{-4}$

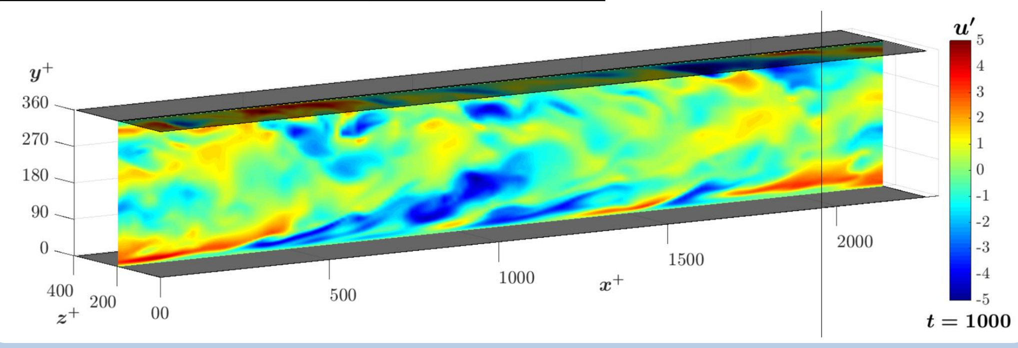


Fig. 1: (*Top*) Simulation parameters. (*Bottom*) 3D view of the channel and u' view of a 2D section at $z^+ = 200$. Dimensionless coordinates: $(x^+, y^+, z^+) = (x, y, z) \cdot u_\tau/\nu$.

- **Data:** from a **direct numerical simulation** of a fully developed turbulent **channel flow** [9]
- **Velocity Field:** $(u, v, w) \rightarrow u' = u - U(y) \rightarrow R_{ij} = \frac{\langle u'_i u'_j \rangle}{\sigma_i \sigma_j}$, **correlation coefficients**
- **Spatial Network:** Nodes ↔ Selected grid points $\rightarrow n \sim 10^6$
- **Network Building:** $A_{ij} = 1,\ if\ |R_{ij}| > \tau = 0.85 \rightarrow L \sim 10^8$
- **Definitions:**
  - ***Volume Weighted Connectivity*** [10,11]: $VWC(i) = \sum_{j=1}^{N} A_{ij} w_j,\ w_j = V_j(y^+)/V_{tot}$
  - ***Region, R:*** set of nodes satisfying a three dimensional 6-connectivity
  - ***Nth cumulative neighborhood*** [12]: $\Gamma_i^{N,c} = \cup_{n=1}^{N} \Gamma_v^1,\ \ v \in \Gamma_i^{n-1}$

Results

Global Scale

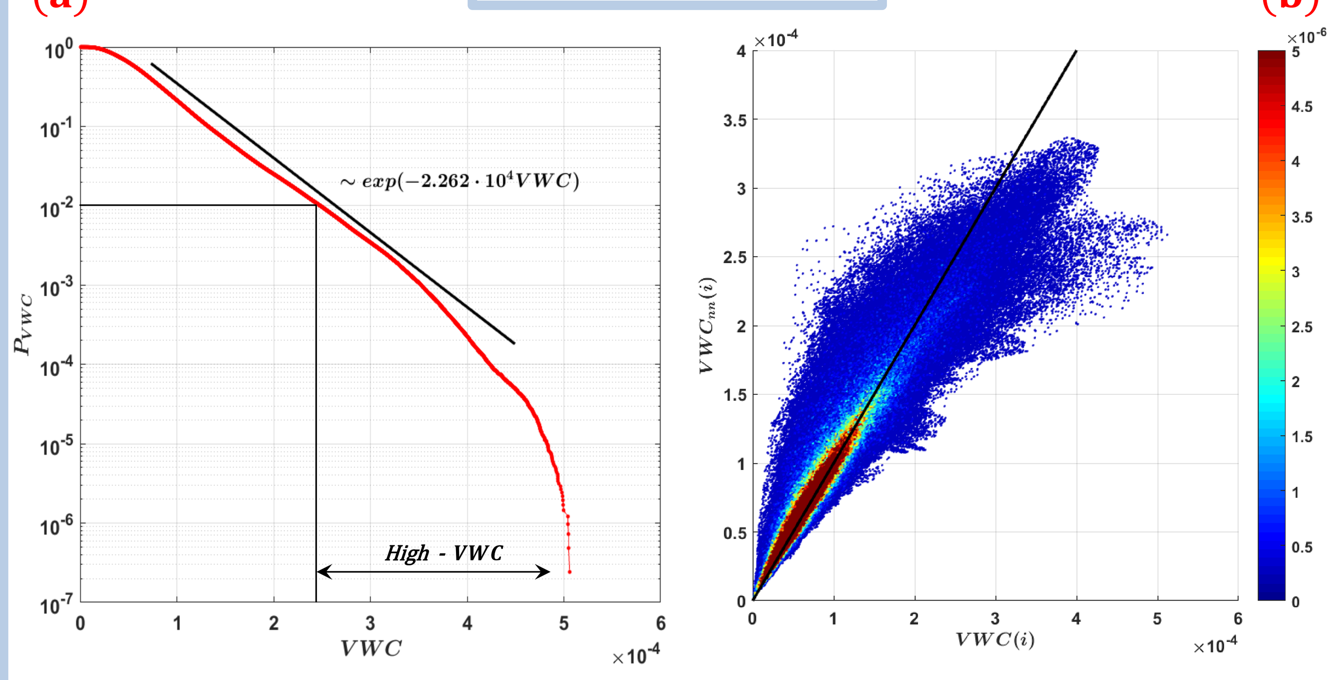


Fig. 2: **(a)** Cumulative VWC distribution and exponential fitting. **(b)** Weighted k-nearest neighbors assortativity measure, $VWC_{nn}(i)$. Colors indicate the joint probability to have a node i with values $VWC(i)$ and $VWC_{nn}(i)$.

Meso Scale

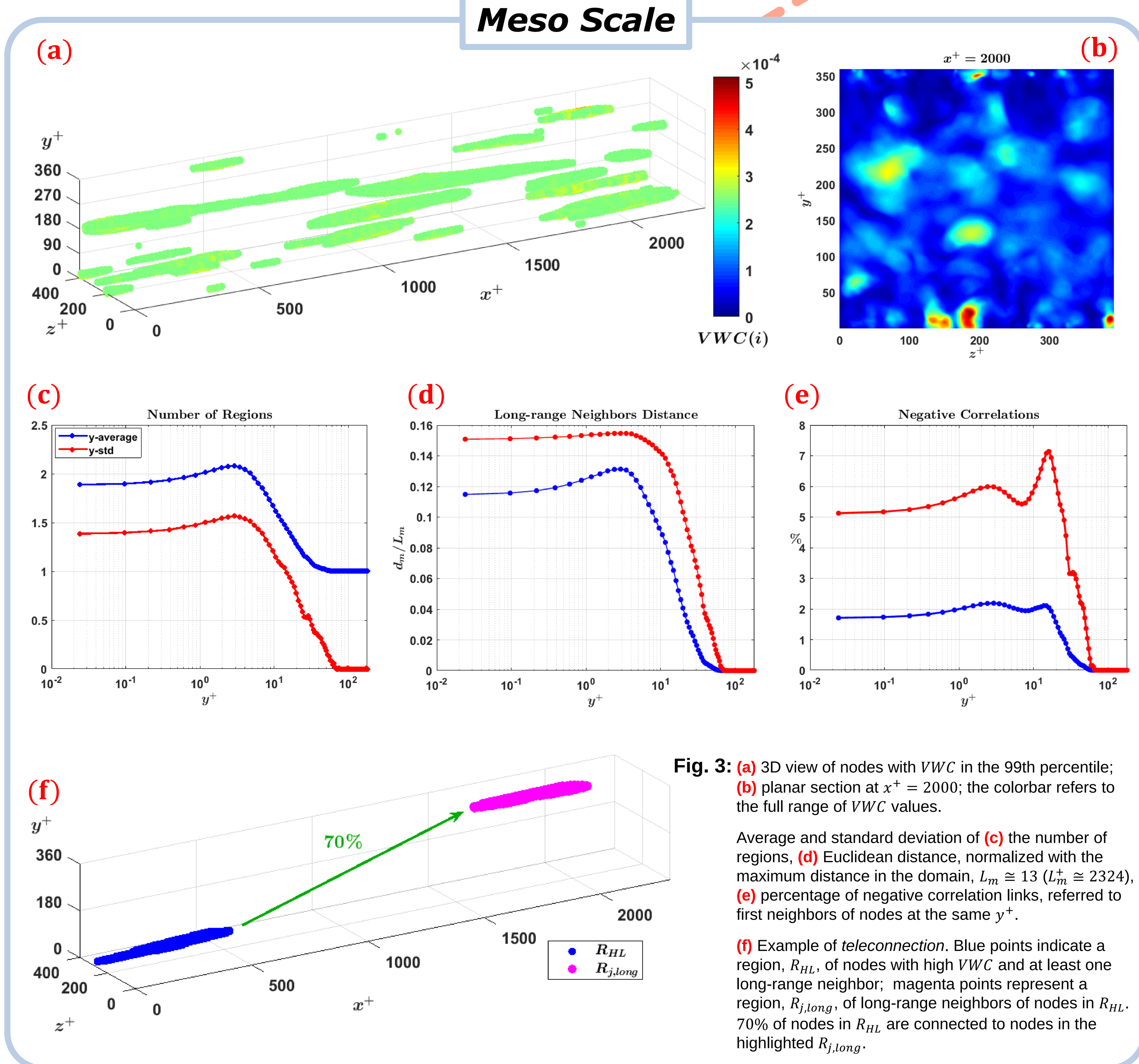
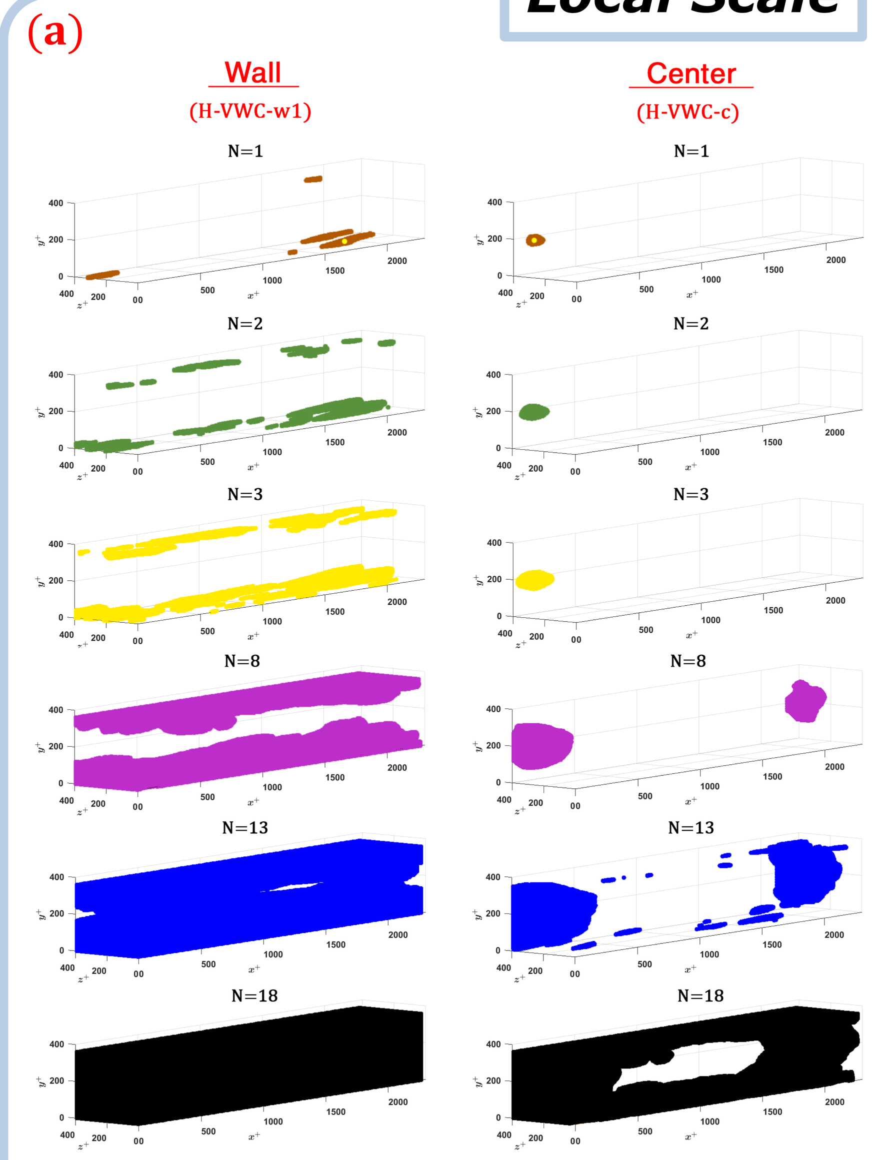


Fig. 3: **(a)** 3D view of nodes with VWC in the 99th percentile; **(b)** planar section at $x^+ = 2000$; the colorbar refers to the full range of VWC values.

Average and standard deviation of **(c)** the number of regions, **(d)** Euclidean distance, normalized with the maximum distance in the domain, $L_m \cong 13$ ($L_m^+ \cong 2324$), **(e)** percentage of negative correlation links, referred to the first neighbors of nodes at the same y^+.

(f) Example of *teleconnection*. Blue points indicate a region, R_{HL}, of nodes with high VWC and at least one long-range neighbor; magenta points represent a region, $R_{j,long}$, of long-range neighbors of nodes in R_{HL}. 70% of nodes in R_{HL} are connected to nodes in the highlighted $R_{j,long}$.

Local Scale



(b)

Pair	y^+	VWC ($\times 10^4$)	# Regions
w1	3.5	4.88 (H)	5
		0.04 (L)	1
w2	356.5	4.24 (H)	8
		0.03 (L)	1
c	180	3.70 (H)	1
		0.16 (L)	1
m	111.1	3.49 (H)	1
		0.53 (L)	1

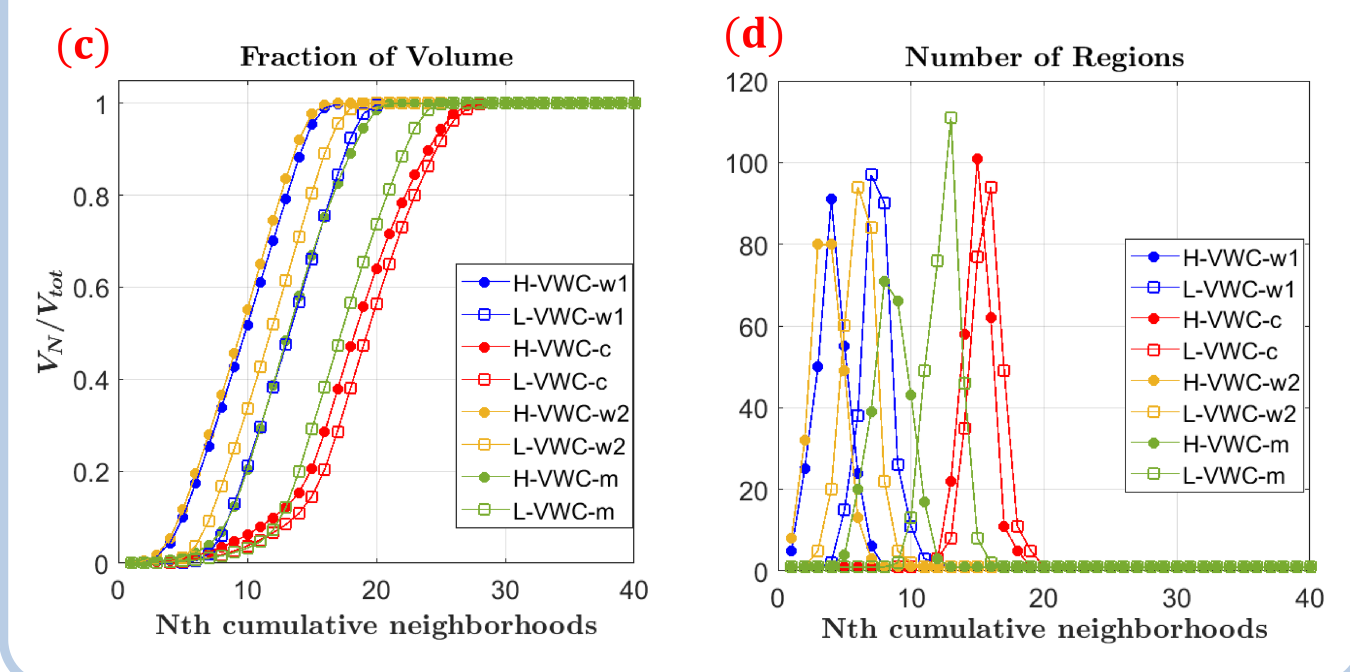


Fig. 4: **(a)** 3D views of the Nth cumulative neighborhoods of $H - VWC$ nodes (marked in yellow in the N = 1 panels). (*Left*) node close to the wall; (*Right*) node at the center of the channel.

(b) Features of the four pair of selected nodes. The number of regions is referred to the first neighborhood.

(c) Fraction of volume of the Nth cumulative neighborhoods for the four selected pairs of nodes.

(d) The number of different regions of the Nth cumulative neighborhoods for the four selected pairs of nodes.

Discussion & Conclusions

- ✓ In the network there are **hubs** highly connected to other parts of domain (**$H - VWC$ nodes, Fig. 2a**) ;
  - Such hubs tend to group into **x-elongated clusters of hubs**, CoH, both close to the walls and the center (**Fig. 3a**).
- ✓ The **neighbors** of the $H - VWC$ nodes tend to group into **short-range** (**R_S**) and **long-range** (**R_L**) regions (**Fig. 3c**);
  - $H - VWC$ nodes close to the walls have **different topological features** than $H - VWC$ nodes at the center (**Fig. 3 c-e**).
  - Long-range neighbors are **not scattered** in space but (as the relative CoH) tend to cluster into regions **$R_{j,long}$** (**Fig. 3f**) .
- ✓ The CoH and the regions of long-range neighbors constitute **strongly correlated** parts of domain;
  - Nodes in the R_S and R_L regions have **unique correlation sign** with the nodes in the corresponding CoH.
- ✓ The behavior of $\Gamma_i^{N,c}$ of nodes with different VWC and y^+ highlight the **kinematic information flows** in the domain (**Fig. 4**);
  - The high-correlation network based on the u-velocity is a **framework** where the kinematic message flow among nodes.
- ✓ The effect of the **turbulent dynamics** on the correlation field influences the behavior of the metrics at various y^+;
  - This leads to the formation of **coherence patterns** with different features:
    - long-range and anisotropic close to the wall,
    - short-range almost isotropic around the center of the channel.

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