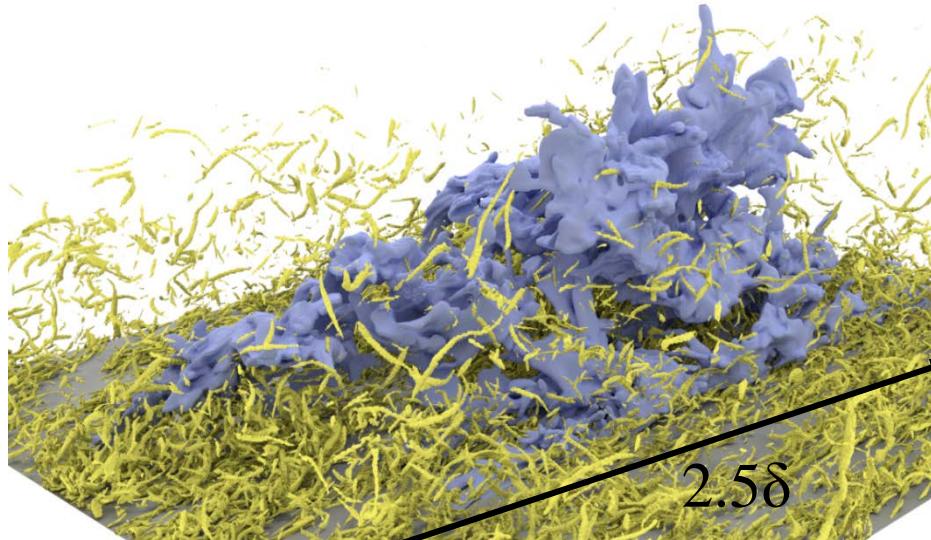


# Where can we find Coherent Structures in Wall-bounded Turbulence?

Javier Jiménez (et al.)

School of Aeronautics, Madrid



TBL:  $Re_\tau = 1800$ ,  $u'^+ = 2$   
J.A. Sillero



# Structures

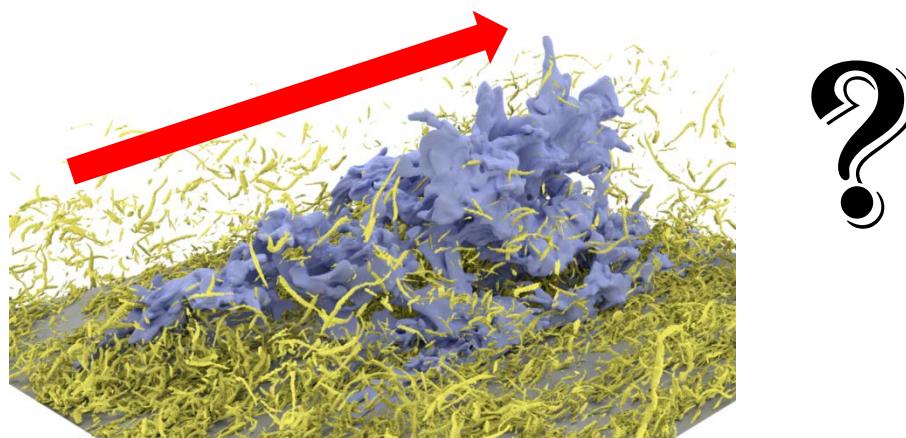
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$$\partial_t \text{structure} = f(\text{structure}) + \dots$$

# Turbulence Structures

---

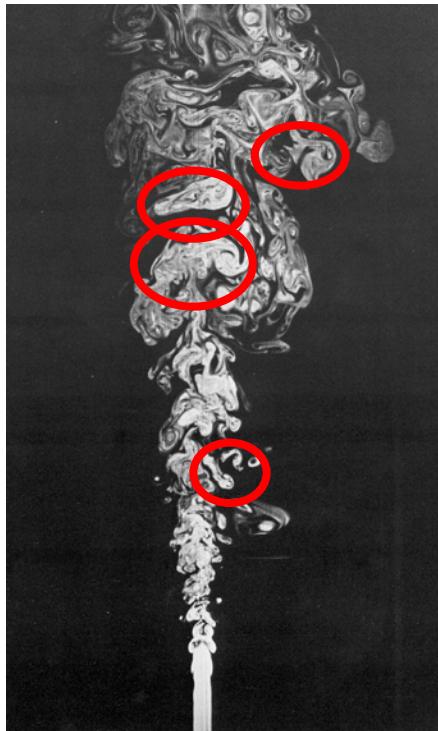
$$\partial_t \text{structure} = f(\text{structure}) + \dots$$



# Turbulence Structures

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$$\partial_t \text{structure} = f(\text{structure}) + \dots$$



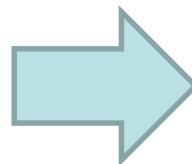
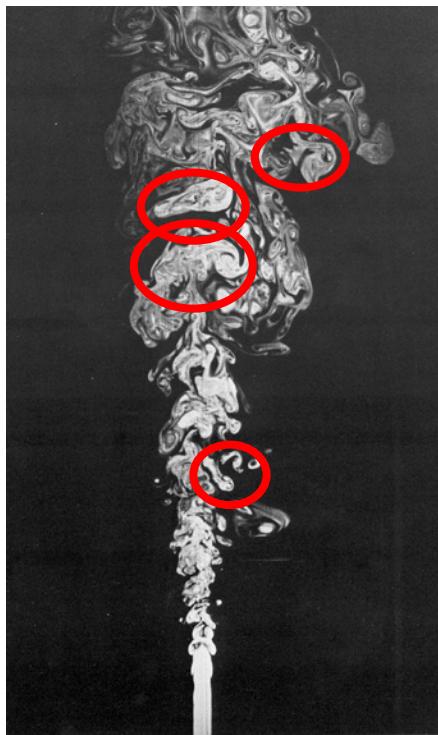
“Kelvin-Helmholtz”

(Dimotakis et al. 1981)

# Turbulence Structures are **useful**

---

$$\partial_t \text{structure} = f(\text{structure}) + \dots$$



(Dimotakis et al. 1981)

(Lee, Reynolds 1982)

# Even if ... most of the flow may be structureless

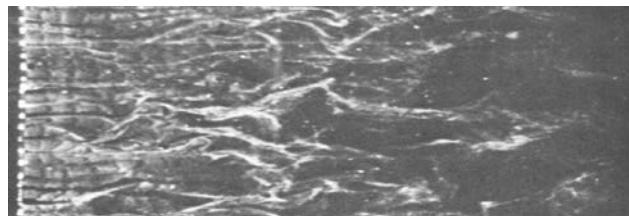
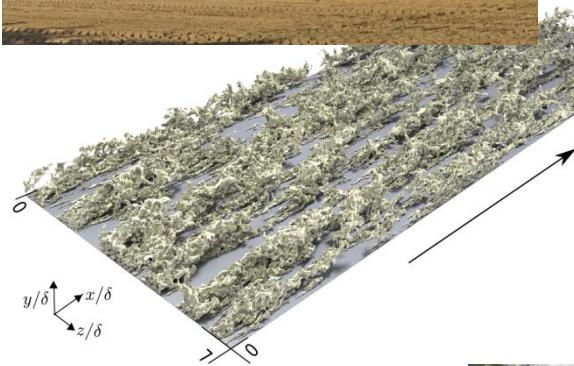
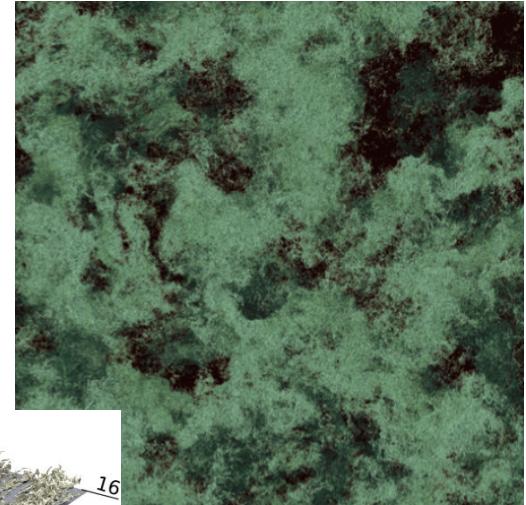
$$\partial_t \text{cloud} = f(\text{cloud}) + \dots$$



NASA

# Structures are Everywhere

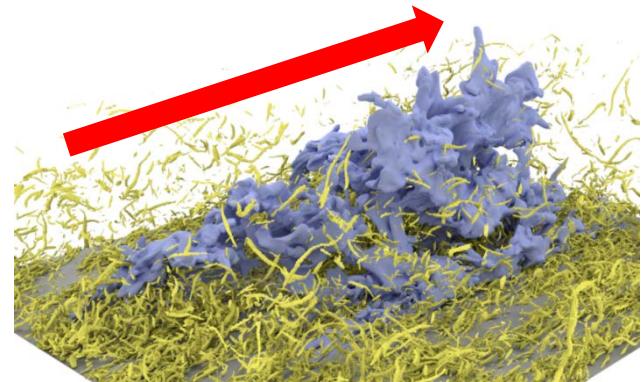
$$\partial_t \text{structure} = f(\text{structure}) + \dots$$



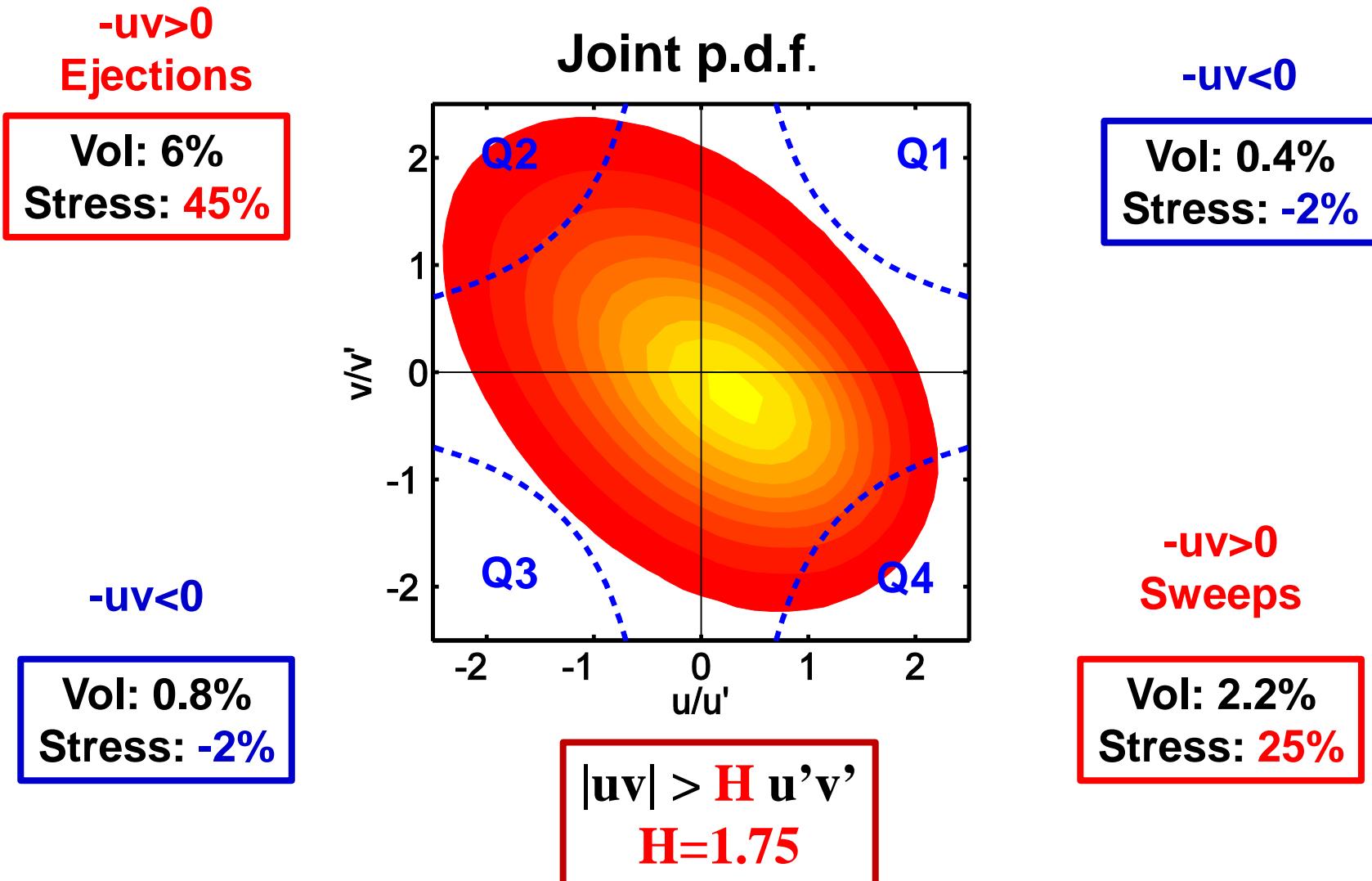
# What do they have in common?

$$\partial_t \text{structure} = f(\text{structure}) + \dots$$

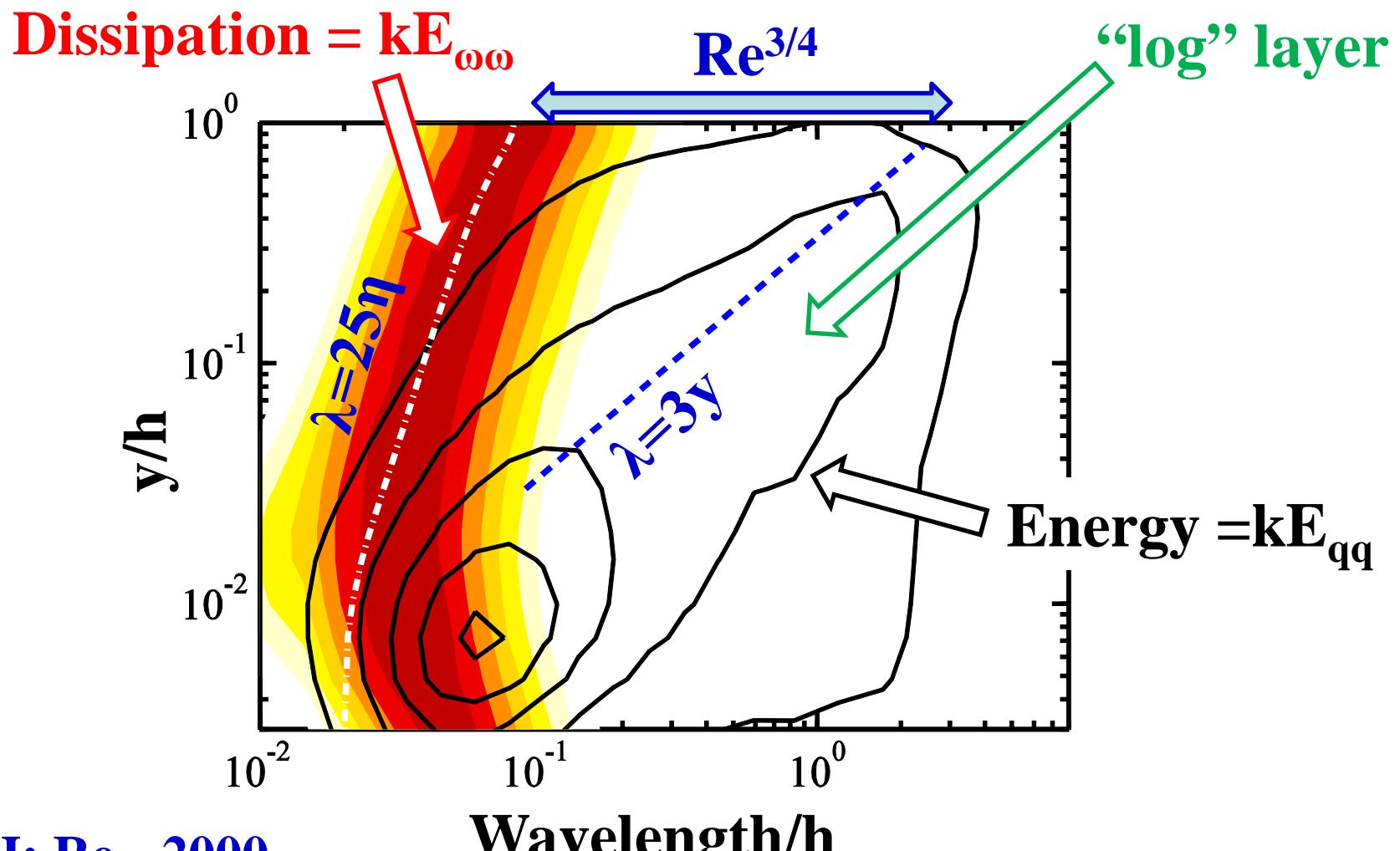
- **Strong**
- **Observable**
- **Relevant**
- either
  - **Energy Producers/Sinks**
  - **Energy Repositories**



# Quadrant Structures

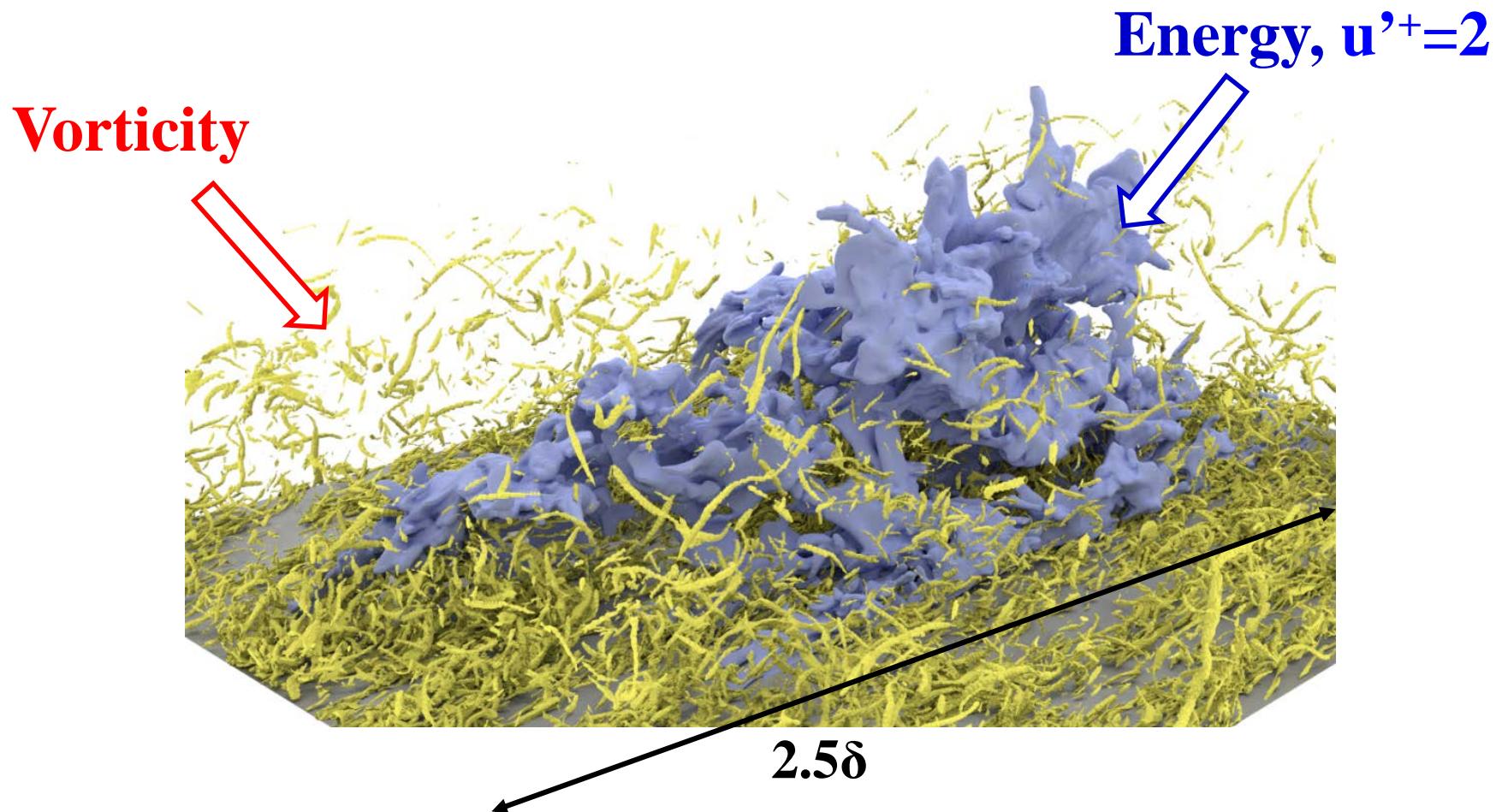


# The Scales of Wall-Bounded Turbulence



CH:  $Re_\tau = 2000$   
Hoyas & J (2006)

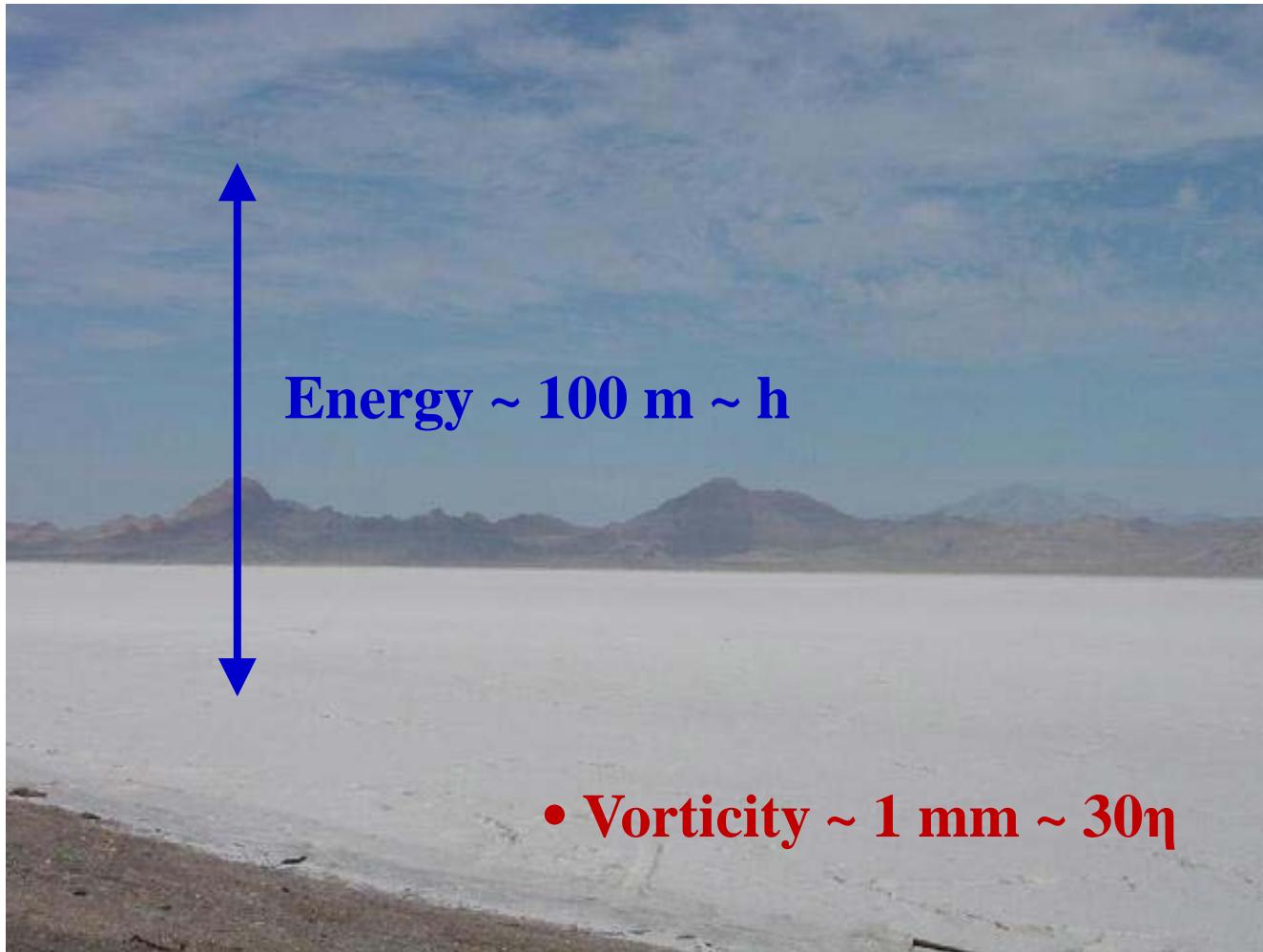
# The Scales of Wall-Bounded Turbulence



TBL:  $Re_\tau = 1800$   
J.A. Sillero (2013)

# The Scales of Wall-Bounded Turbulence

---



Outer/Inner  $\sim 100,000$

# The Coupling with the Shear

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Nonlinear eddy turnover  $\Rightarrow T_{to} = \lambda/u_\lambda = \lambda(kE_{qq})^{-1/2}$

Shear deformation time  $\Rightarrow T_S = S^{-1}$

Corrsin parameter:

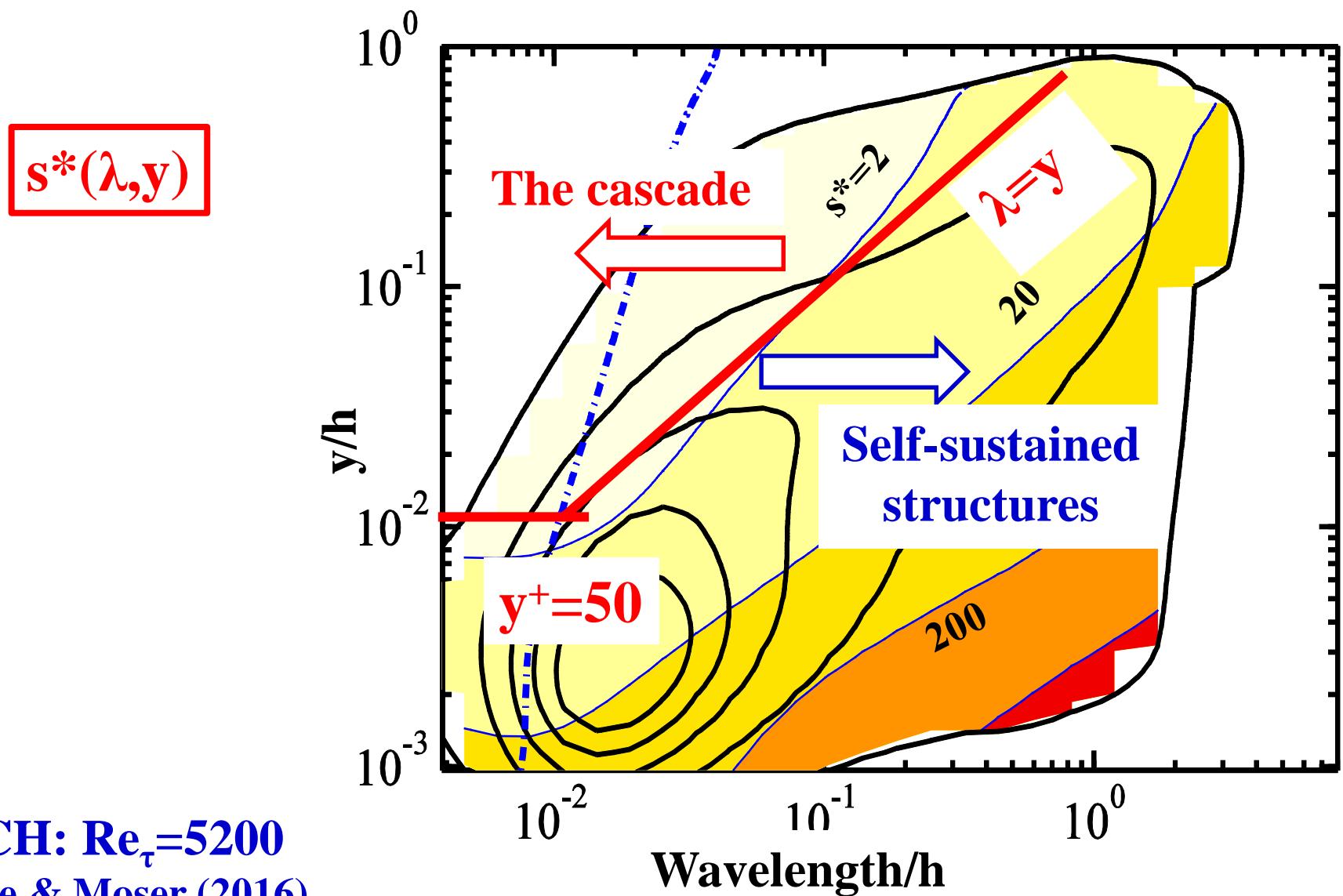
$$s^*(\lambda, y) = T_{to}/T_S = S\lambda / (kE_{qq})^{1/2}$$

$s^* \gg 1 \Rightarrow$  Shear dominated (“linear”, energy input)

$s^* \approx 1 \Rightarrow$  (the playground)

$s^* \ll 1 \Rightarrow$  Shear independent (nonlinear, no input)

# The Corrsin Parameter



# The “Wave” Velocity

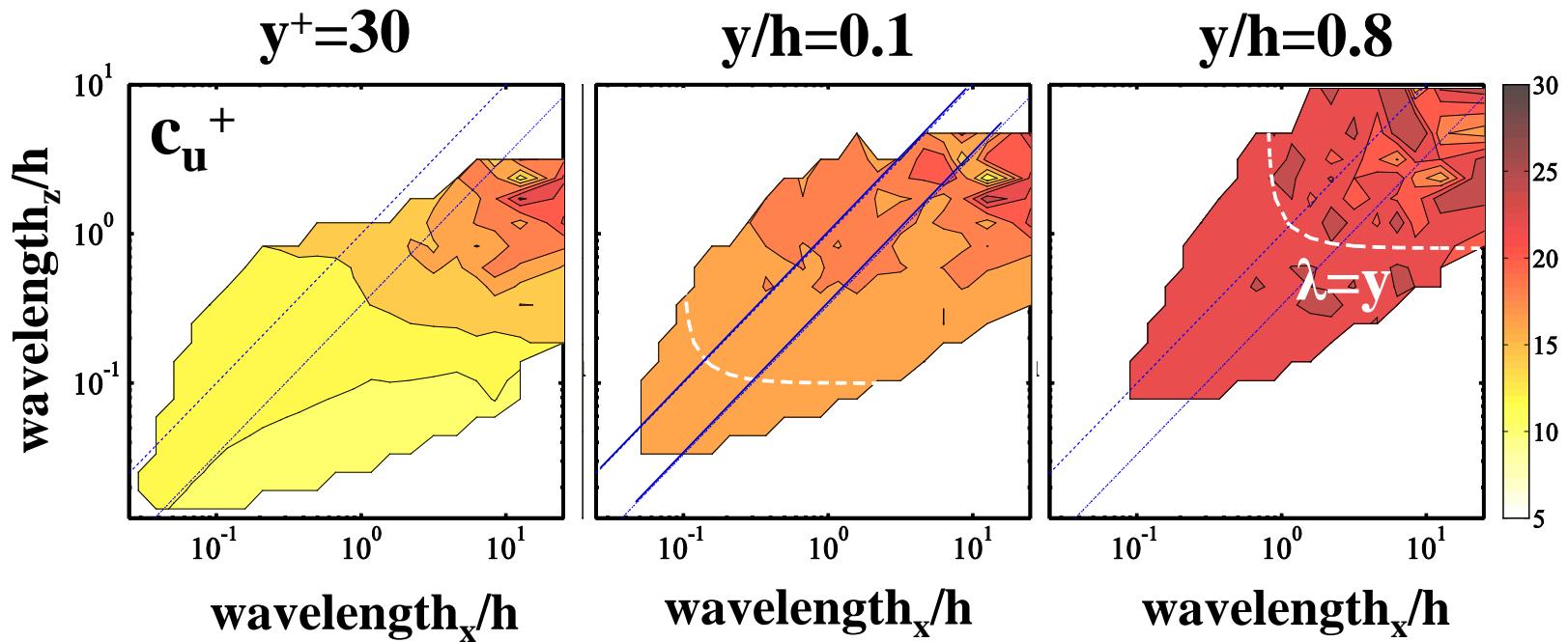
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$$\text{Minimise: } \langle (\partial_t u + \color{red}{c} \partial_x u)^2 \rangle$$
$$\color{red}{c} = -\frac{\langle \partial_t u \partial_x u \rangle}{\langle (\partial_x u)^2 \rangle} \Rightarrow -\frac{\text{Im} \langle \hat{u}^* \partial_t \hat{u} \rangle}{k_x \langle |\hat{u}|^2 \rangle}$$

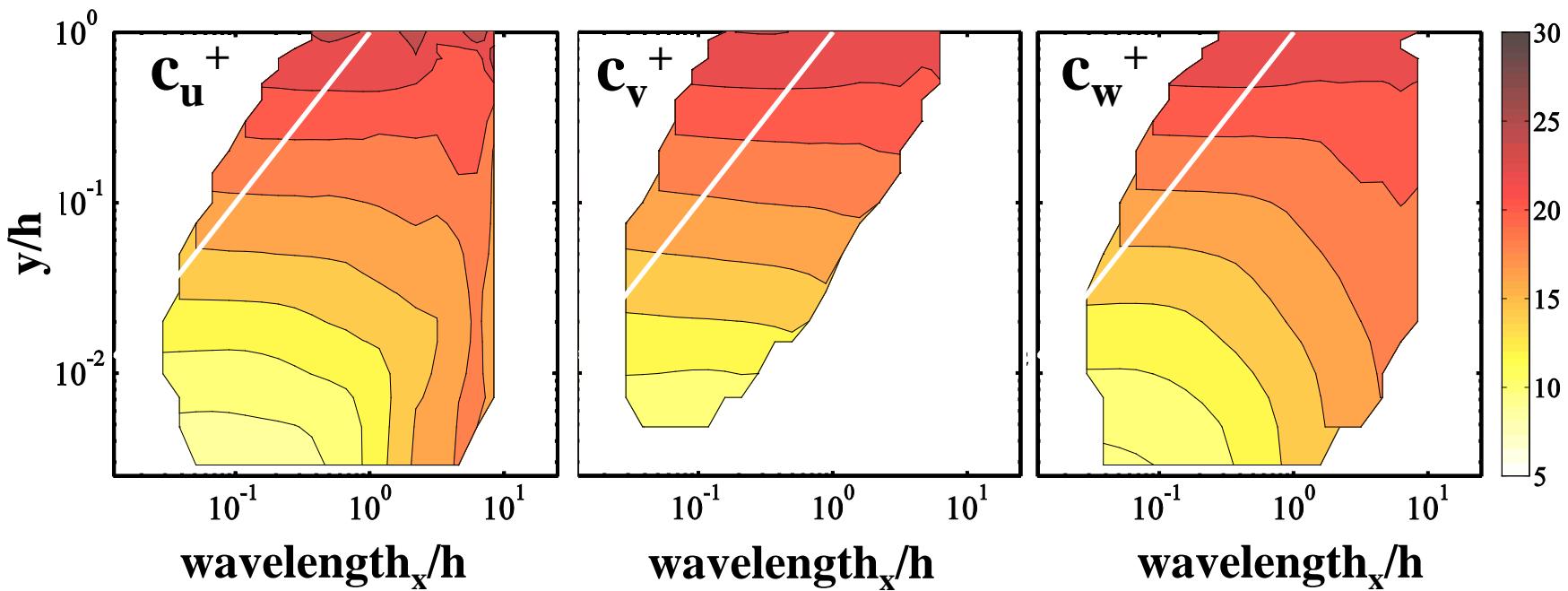
# The “Wave” Velocity

Minimise:  $\langle (\partial_t u + c \partial_x u)^2 \rangle$

$$c = -\frac{\langle \partial_t u \partial_x u \rangle}{\langle (\partial_x u)^2 \rangle} \Rightarrow -\frac{\text{Im} \langle \hat{u}^* \partial_t \hat{u} \rangle}{k_x \langle |\hat{u}|^2 \rangle}$$



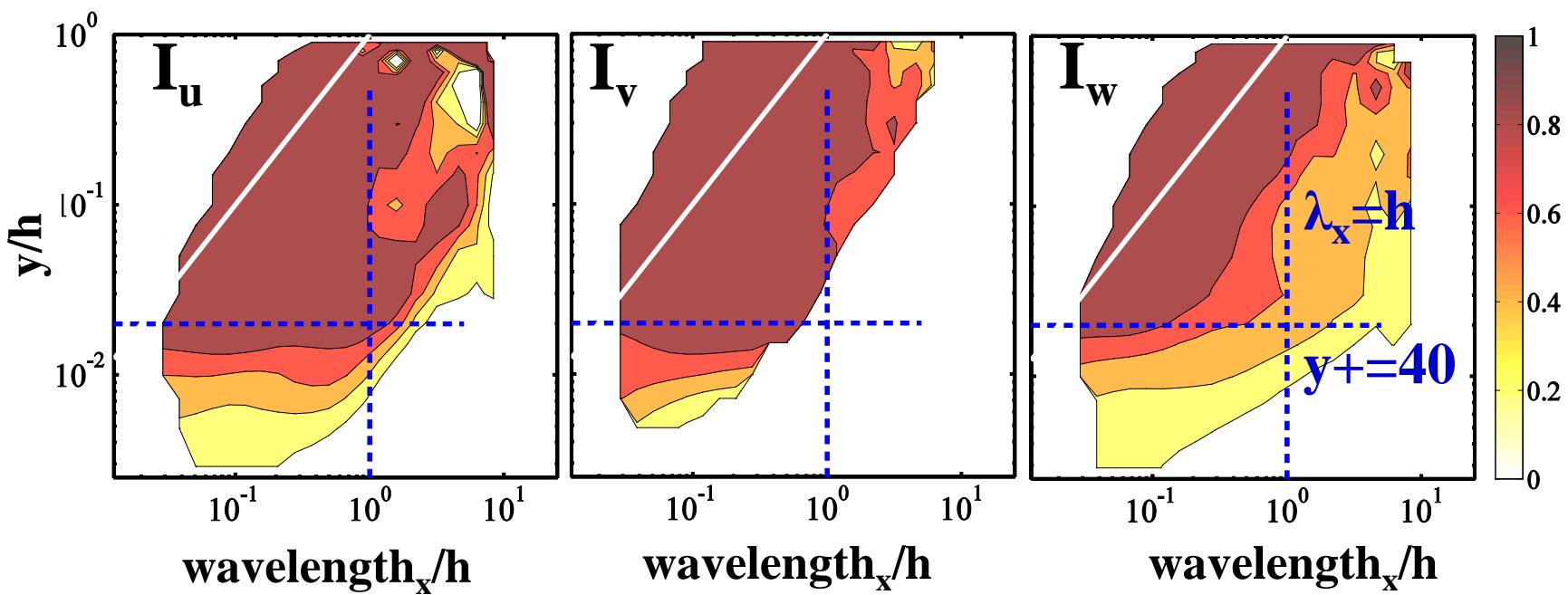
# The “Wave” Velocity



CH:  $\text{Re}_\tau=2000$ , Hoyas & J (2006)

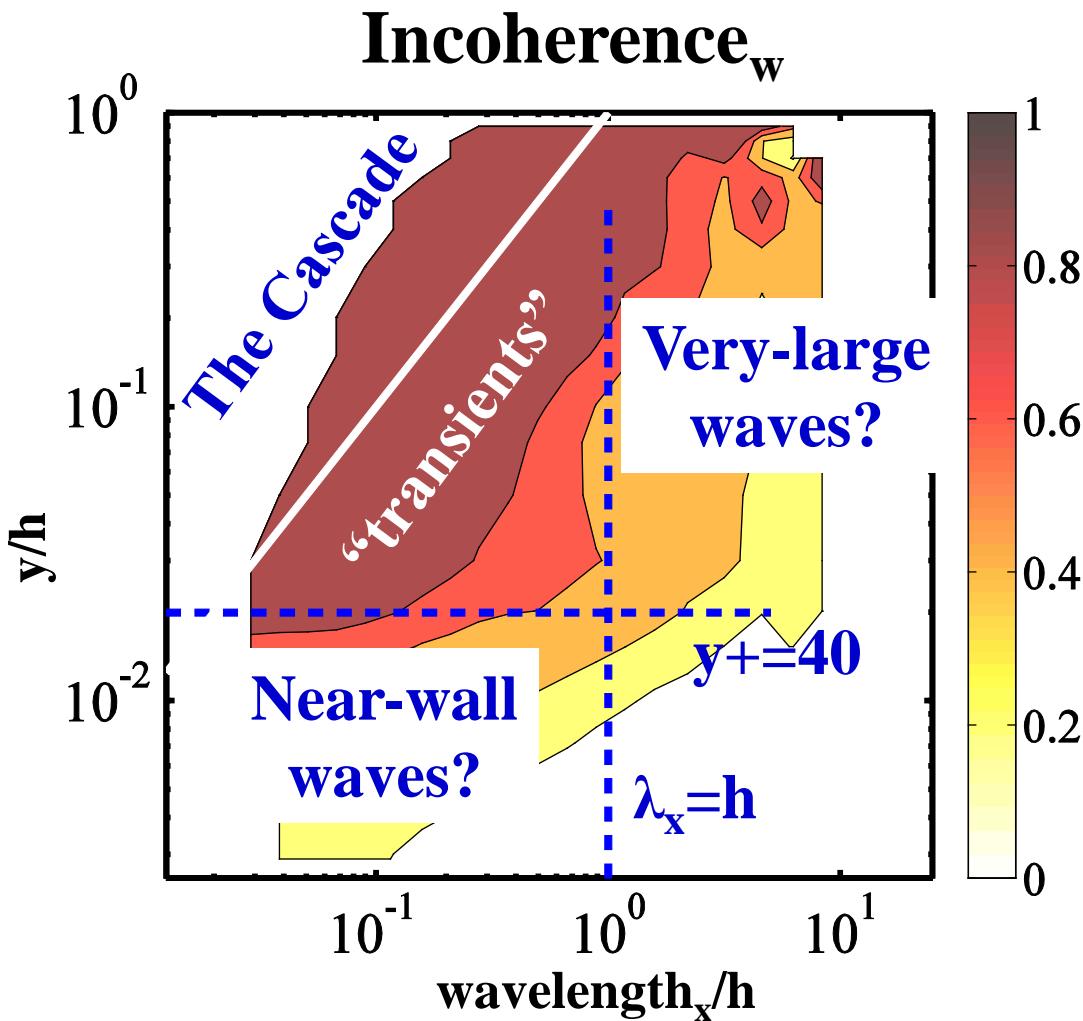
# The “Wave” (In)-Coherence

$$I = (\partial_y C)/S$$

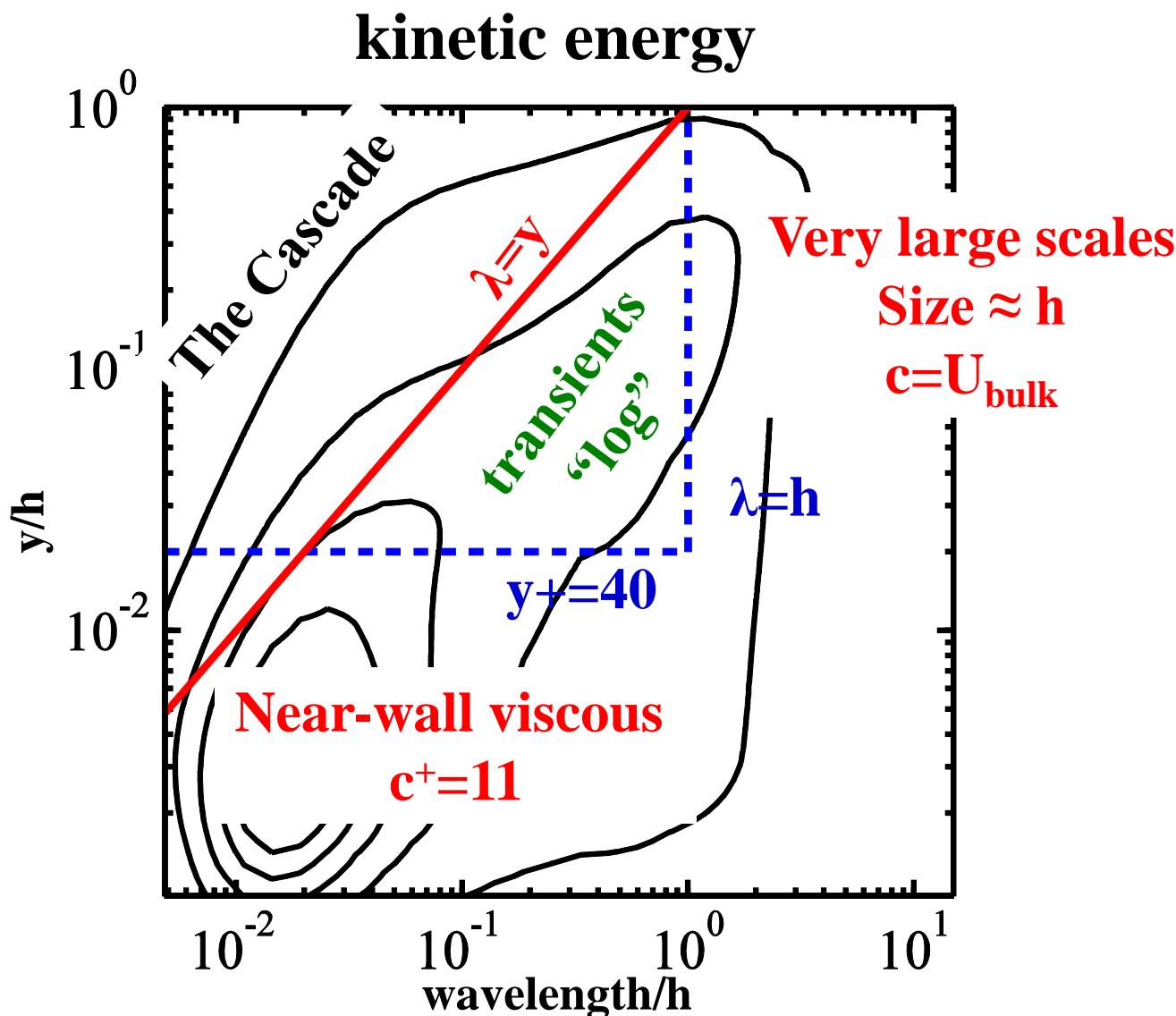


CH:  $Re_\tau = 2000$ , Hoyas & J (2006)

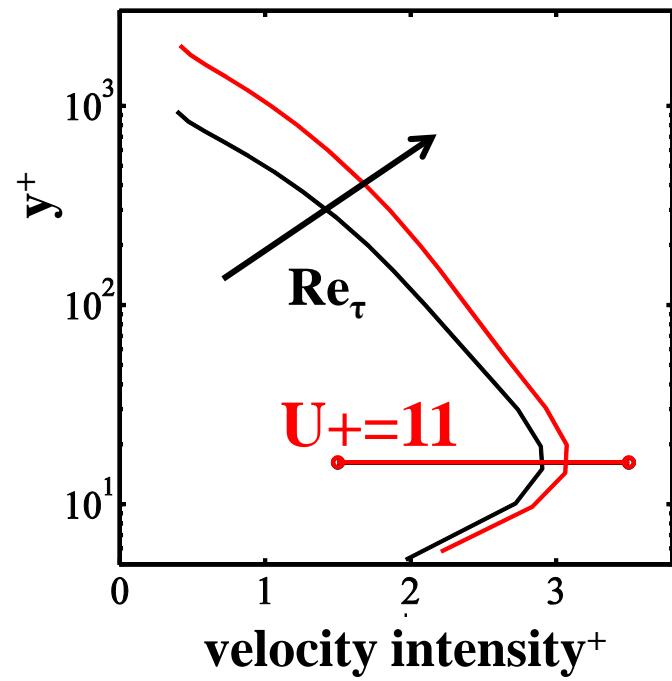
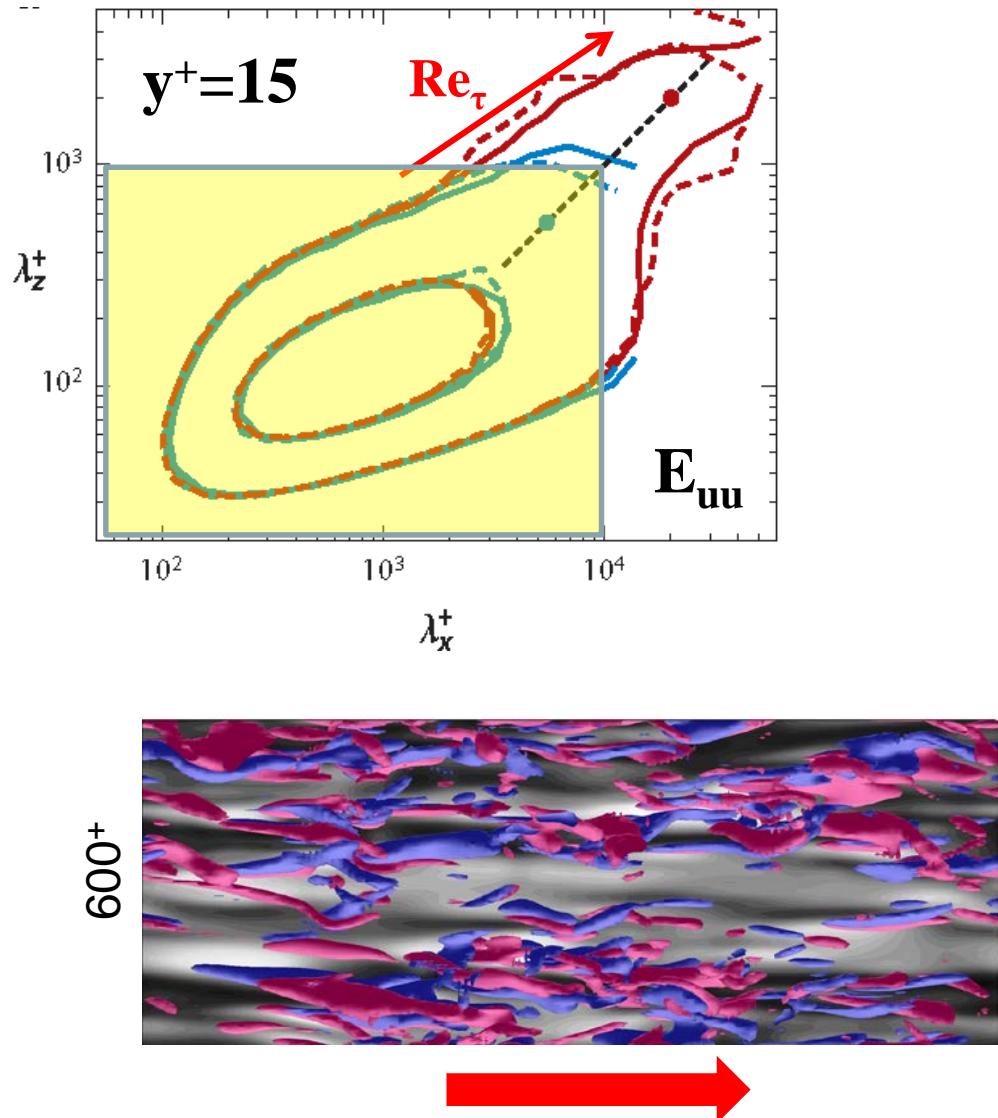
# Structural Regimes



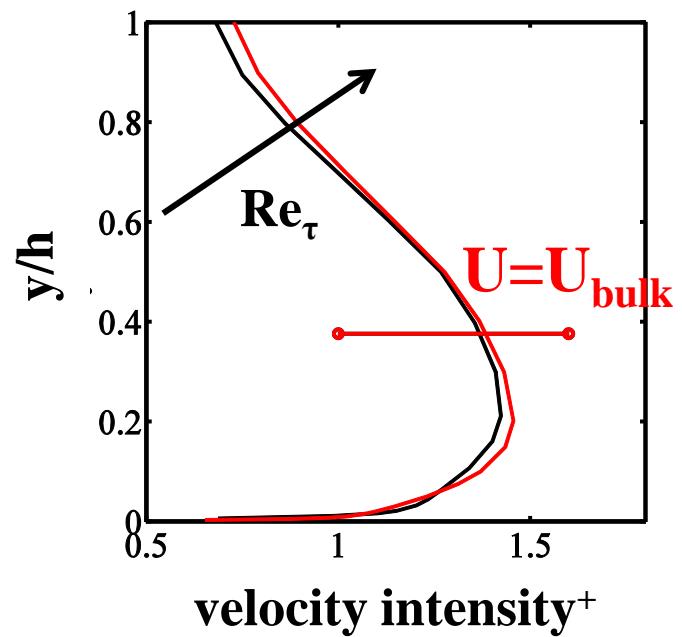
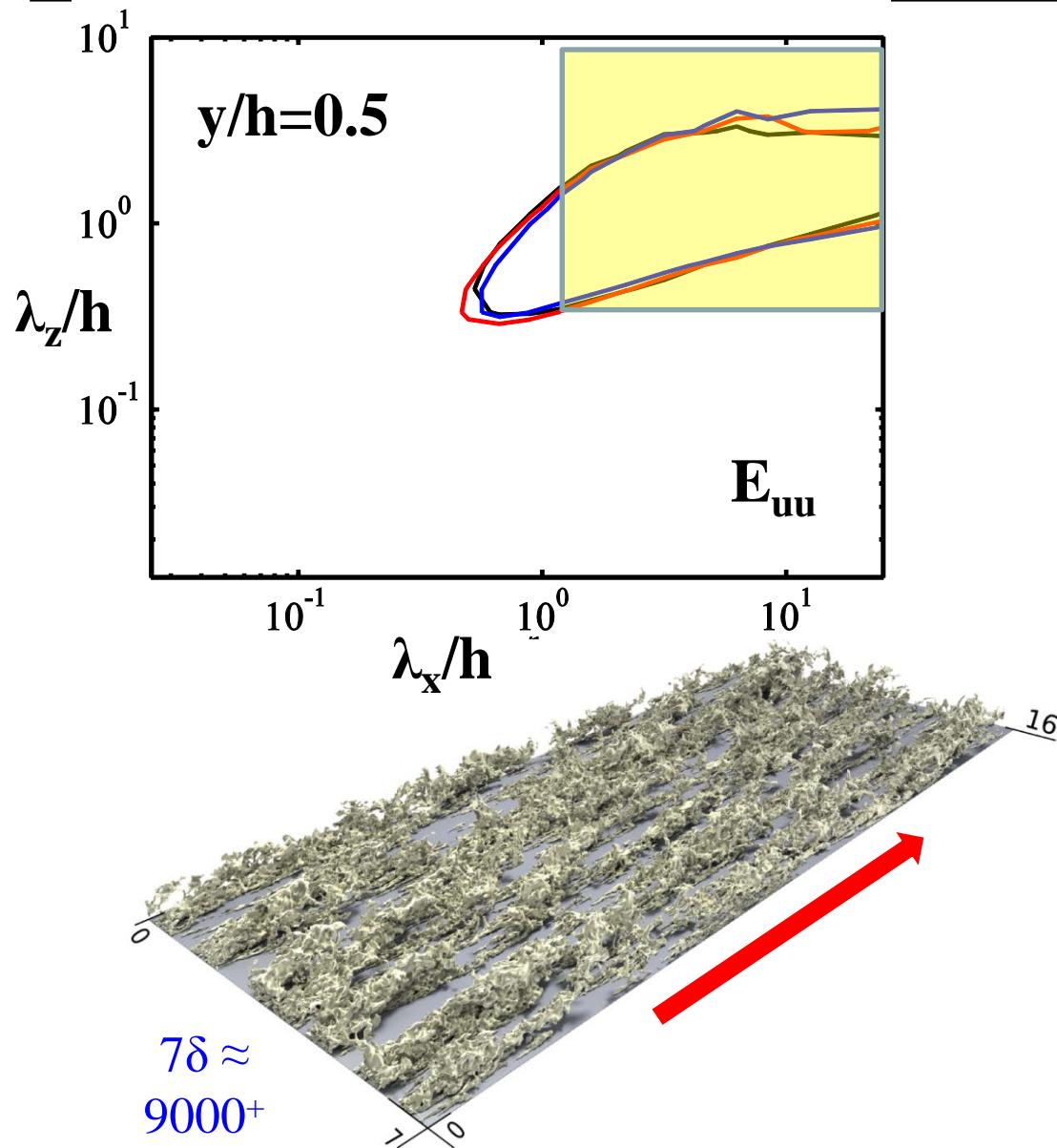
# Structural Regimes



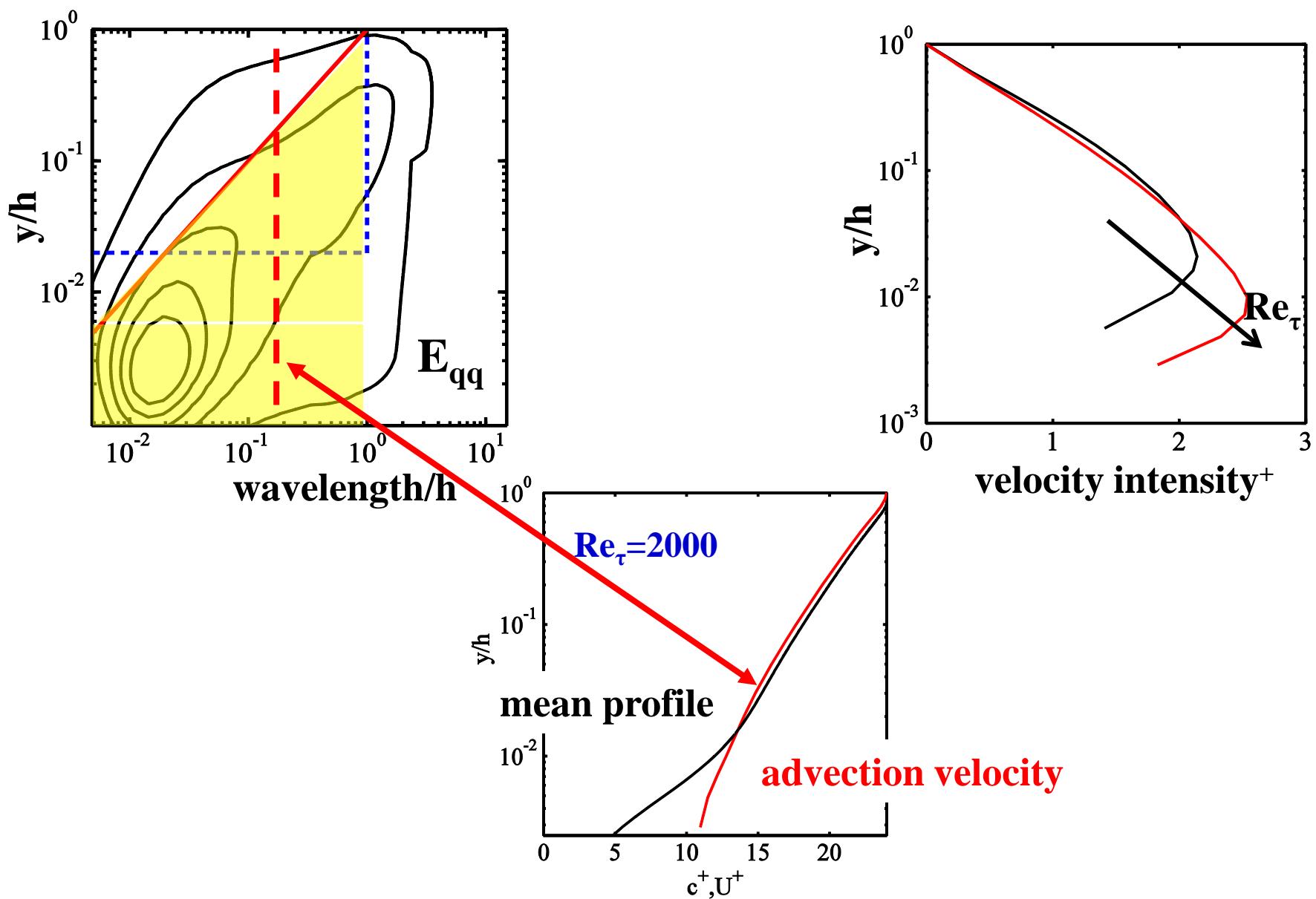
# Near-wall “waves” ( $C^+=11$ )



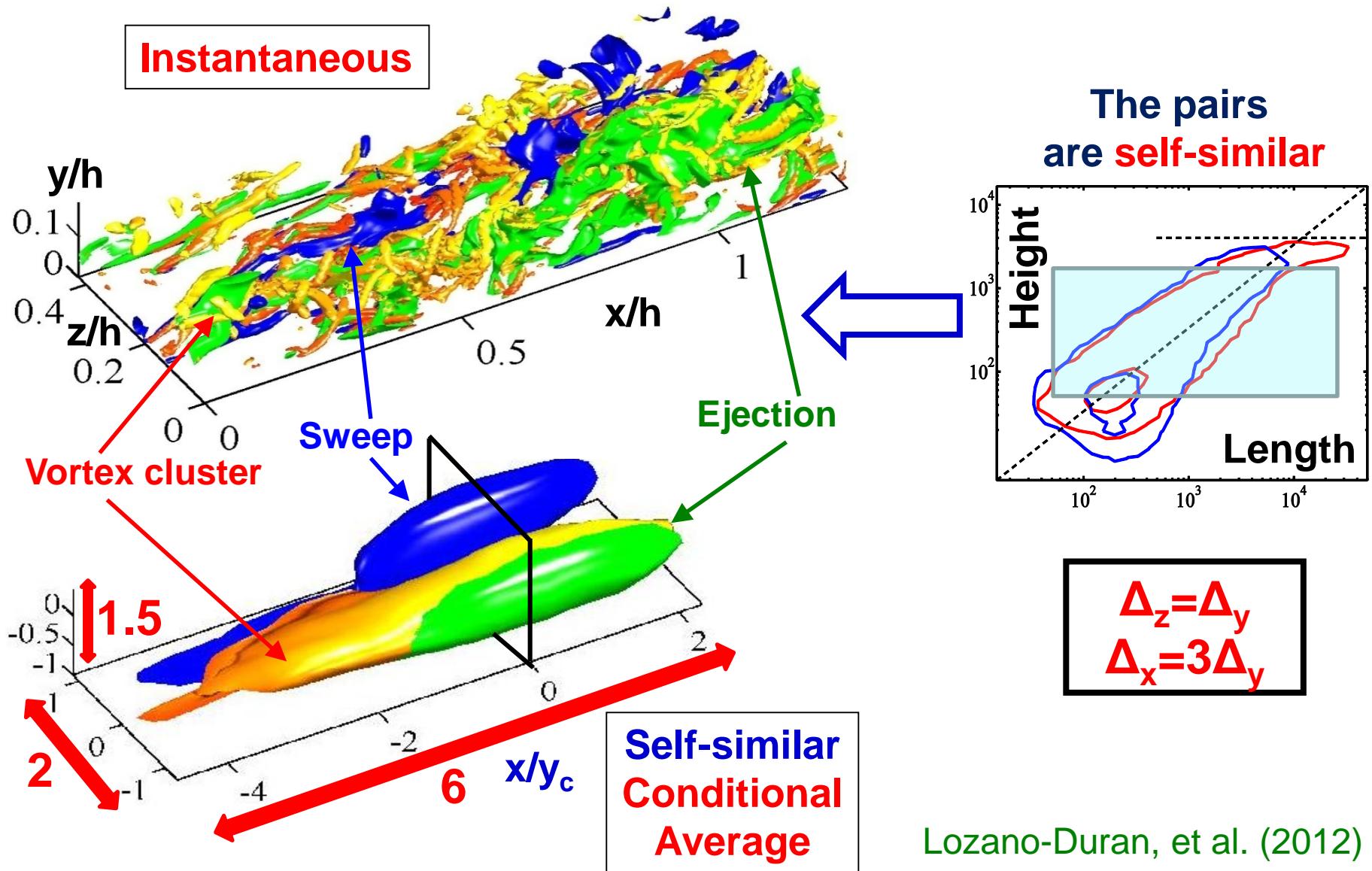
# Very-Large “waves” ( $C=U_{\text{bulk}}$ )



# Logarithmic Layer ( $c=U$ )

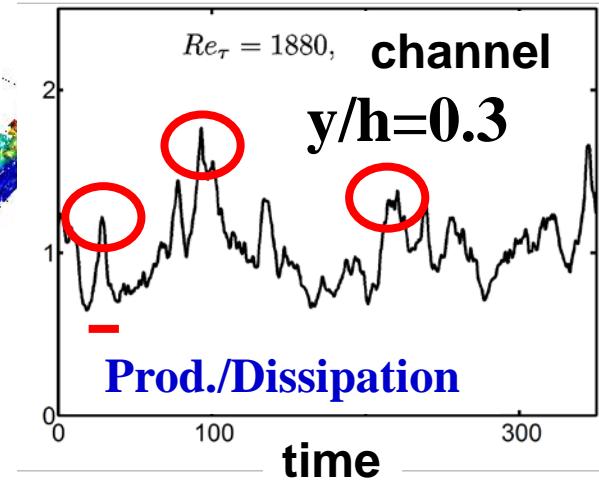
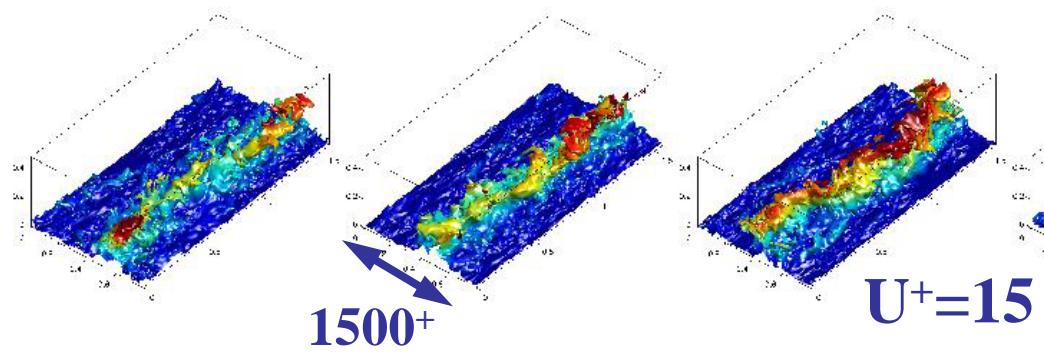


# The Log-Layer Structures

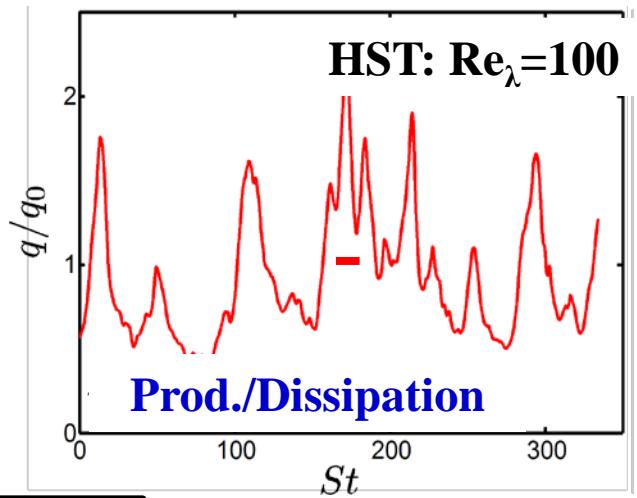
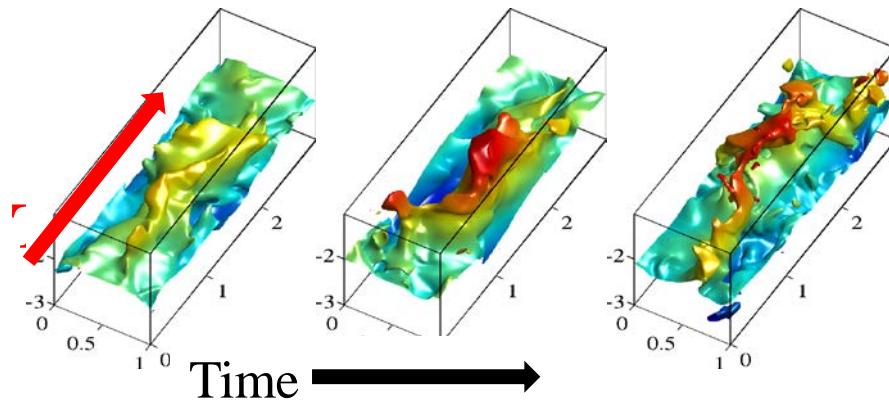


# Structures “Burst”

## Logarithmic Layer

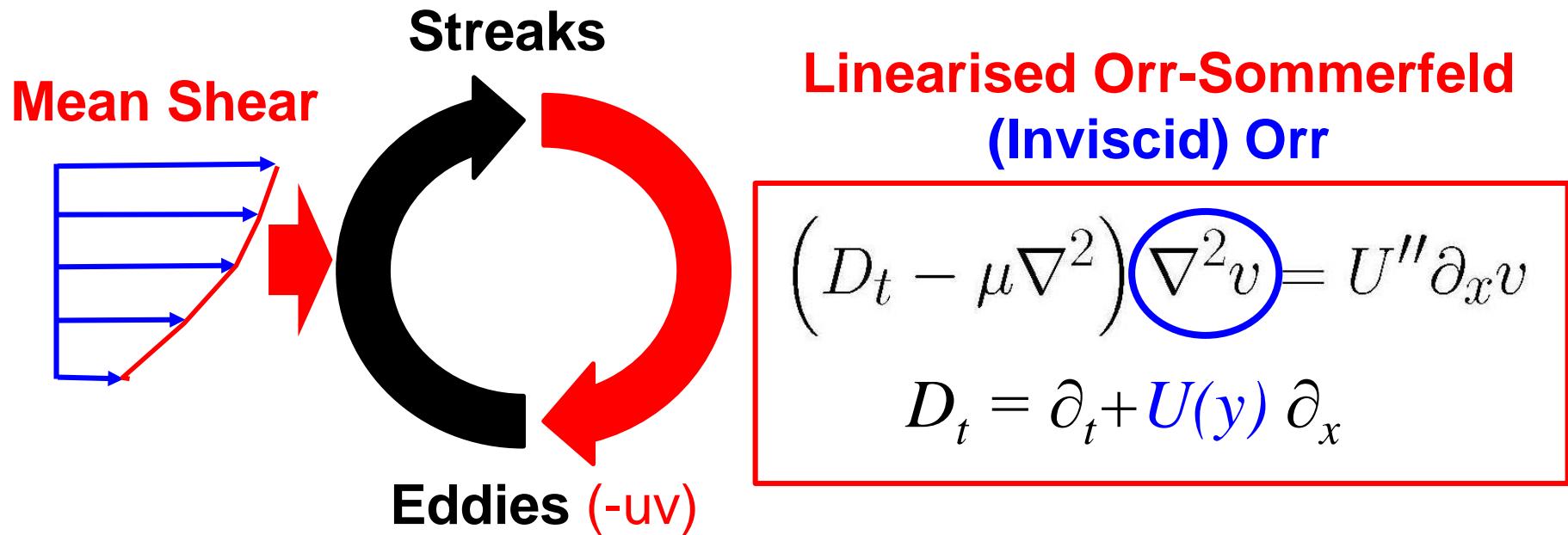


## Homogeneous Shear (no wall)

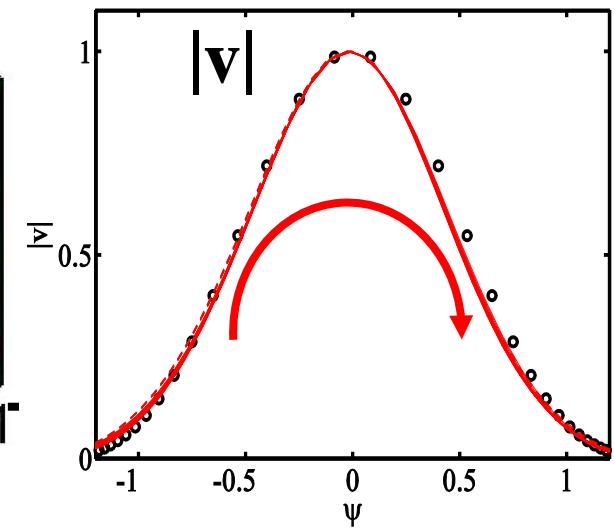
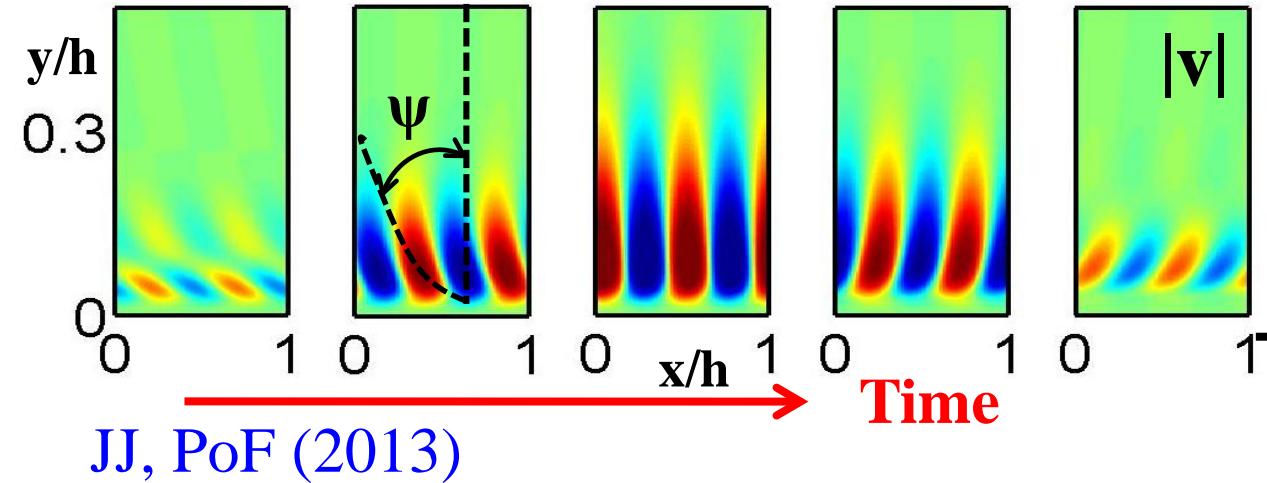


60% Stress in 8% Volume

# Sheared Structures ‘burst’

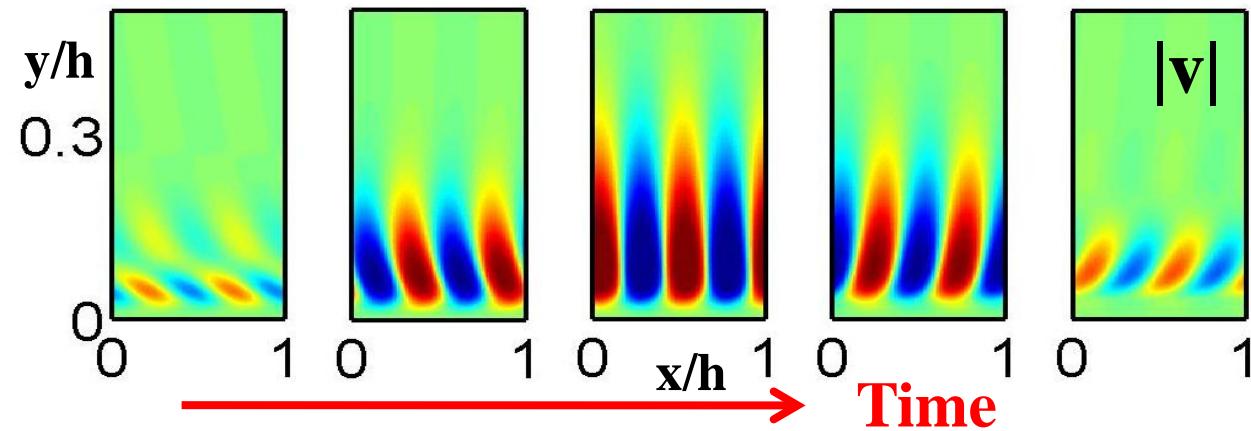


Channel,  $h^+ = 2000$ .  $\lambda/h = 0.5$



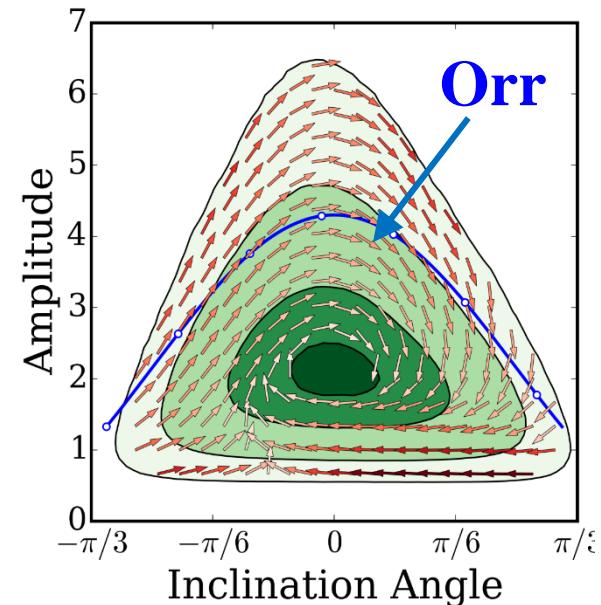
# Sheared Structures ‘burst’

And they can be traced in real (DNS) channels...



Linear Model

DNS



# Summary

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- **Structures in Turbulence: Rare but Relevant**
- **8% volume (60% drag)**
- **Very Small and Very Large structures behave like waves**
- **Log layer structures are self-similar, transient and quasi-linear**
- **Shear-driven (not wall-driven)**
- **Everything “bursts”** (mostly viscous and log)

Thank you