LES STUDY OF UNSTEADY FLOW PHENOMENA IN AN URBAN GEOMETRY - THE NEED FOR SPECIAL EVALUATION METHODS

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MOTIVATION

- **When we evaluate CFD results, usually mean values are used**
- **Large Eddy Simulation resolves turbulence: it can *also* provide <u>concurrent timeseries</u>**
  - **Can we *get extra knowledge* using LES results?**
  - **Additional *methods are needed to evaluate* the results and compare with other time-dependent data (experimental or numerical) . Can we identify such methods?**

PRESENT OBJECTIVES

- Contribution through examination of a suitable experimental case: “MICHEL-STADT”
  - Focus on unsteady phenomena
  - Some of the unique capabilities of LES will be presented
- Try to find ways to:
  - Extract useful information from a LES simulation
  - Compare transient methodologies’ results (e.g. exp & LES)
  - Identify specific-for-LES evaluation methods

Comment

The present work is leaning towards the ‘start’ not towards the ‘end’ of the problem under investigation

LES EQUATIONS IN ADREA-HF
Compressible volume-filtered Navier-Stokes

- **Filtered equations:**

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial x_i} = 0$$

$$\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial(\tilde{\tau}_{ij}^{l} + \tau_{ij}^{R})}{\partial x_j}$$

$$\tau_{ij}^{R} = -\bar{\rho}\, u_i u_j + \bar{\rho}\,\tilde{u}_i \tilde{u}_j$$

$$\bar{p} = \bar{\rho}\, r\, \bar{T}$$

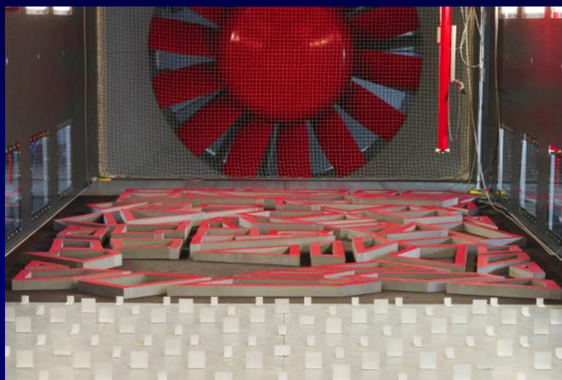
$$\tilde{\tau}_{ij}^{l} + \frac{2}{3}\mu \frac{\partial \tilde{u}_k}{\partial x_k}\delta_{ij} = 2\mu \tilde{S}_{ij}$$

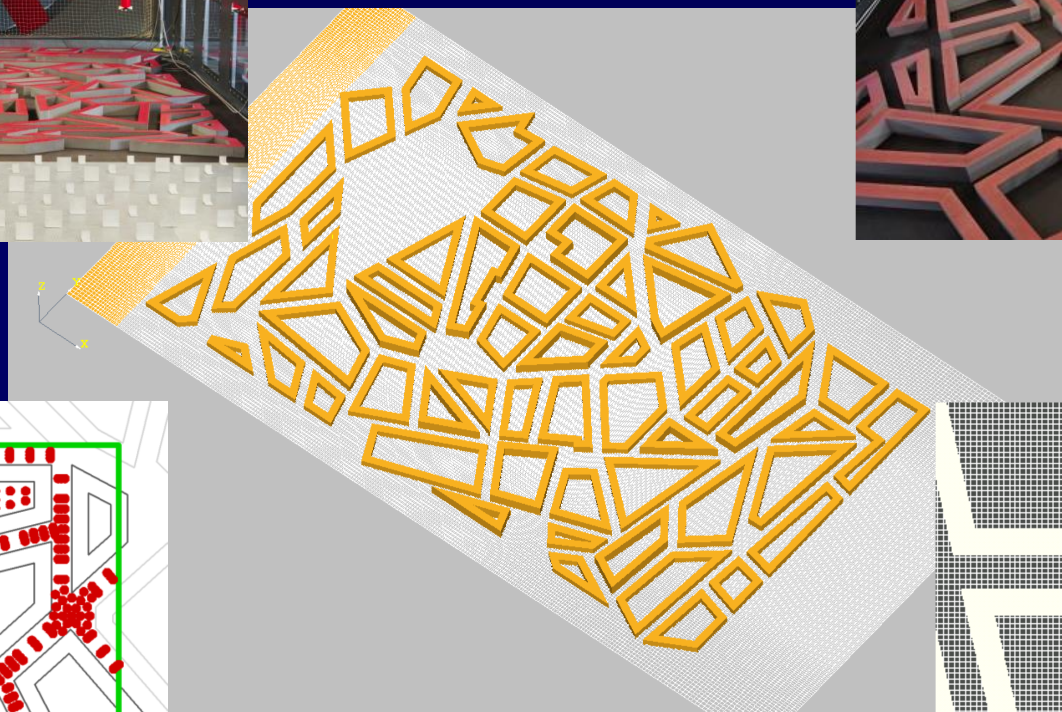
$$\tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$

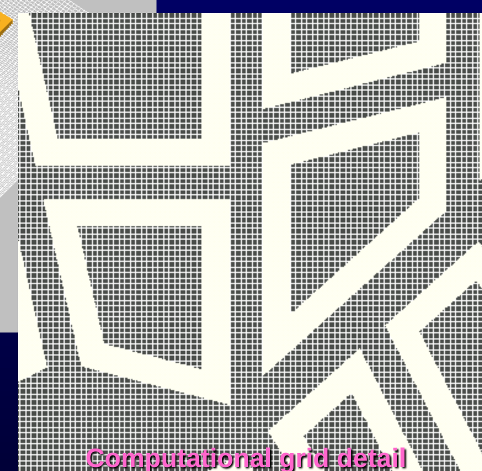
- **Smagorinsky model of the residual stress tensor**

$$\tau_{ij}^{R} + \frac{1}{3}\tau_{kk}\delta_{ij} = 2\mu_t \tilde{S}_{ij}\ ;\ \ \mu_t = \bar{\rho}\left[C_s \Delta\left(1 - e^{-y^{+}/25}\right)\right]^2 \sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}}$$

MICHEL-STADT
Semi-idealized city

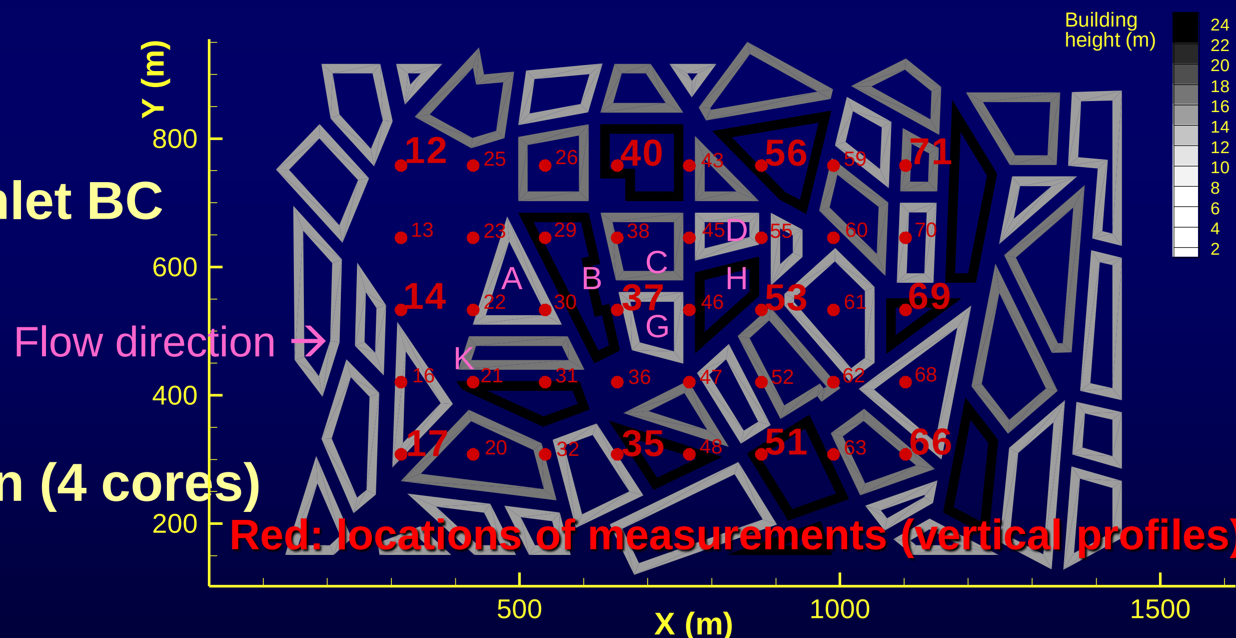






MICHEL-STADT
Case description and setup

- **Data from the CEDVAL-LES wind-tunnel database**
  - **Semi-idealized wind-tunnel city Michel-Stadt examined**
  - **Detailed measurements available**
- **Case setup:**
  - **Full scale**
  - **3 mil. cells**
  - **Langevin inlet BC**
  - z_0**=0.0625m**
  - ***dt*=0.2s**
  - **10000s run**
  - **39 days run (4 cores)**



LES EQUATIONS IN ADREA-HF
Langevin-type inlet boundary condition

- **For the fluctuation u_i' we postulate :**

$$u_i'(t+\Delta t) = \left(1-\frac{\Delta t}{T_{u_i}}\right) u_i'(t) + \sigma_{u_i}\left(\frac{2\Delta t}{T_{u_i}}\right)^{1/2}\xi$$

coherent part random part

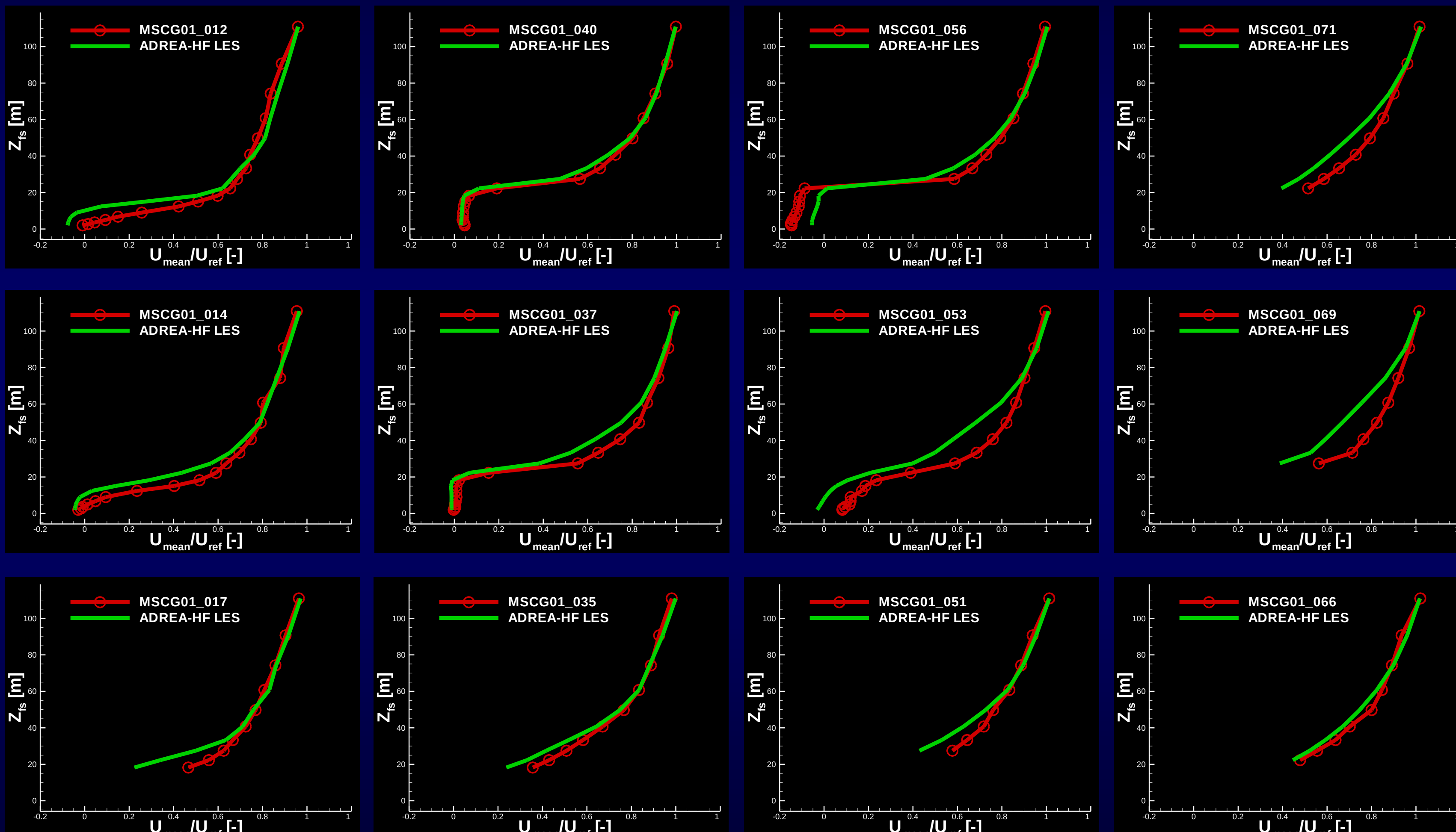
Needed at each boundary cell: U_{mean}, standard deviation σ_u, integral time scale T_u. ξ is a random number

- More general formulation (to achieve spatial correlation also):

$$u_i'(t+\Delta t) = \left(1-\frac{\Delta t}{T_{u_i}}\right) f\left(r_i \cdot u_i'(t) + (1-r_i)\frac{1}{4}\sum_{\gamma=1-4} u_{i\gamma}'(t)\right) + \sigma_{u_i}\left(\frac{2\Delta t}{T_{u_i}}\right)^{1/2}\xi$$

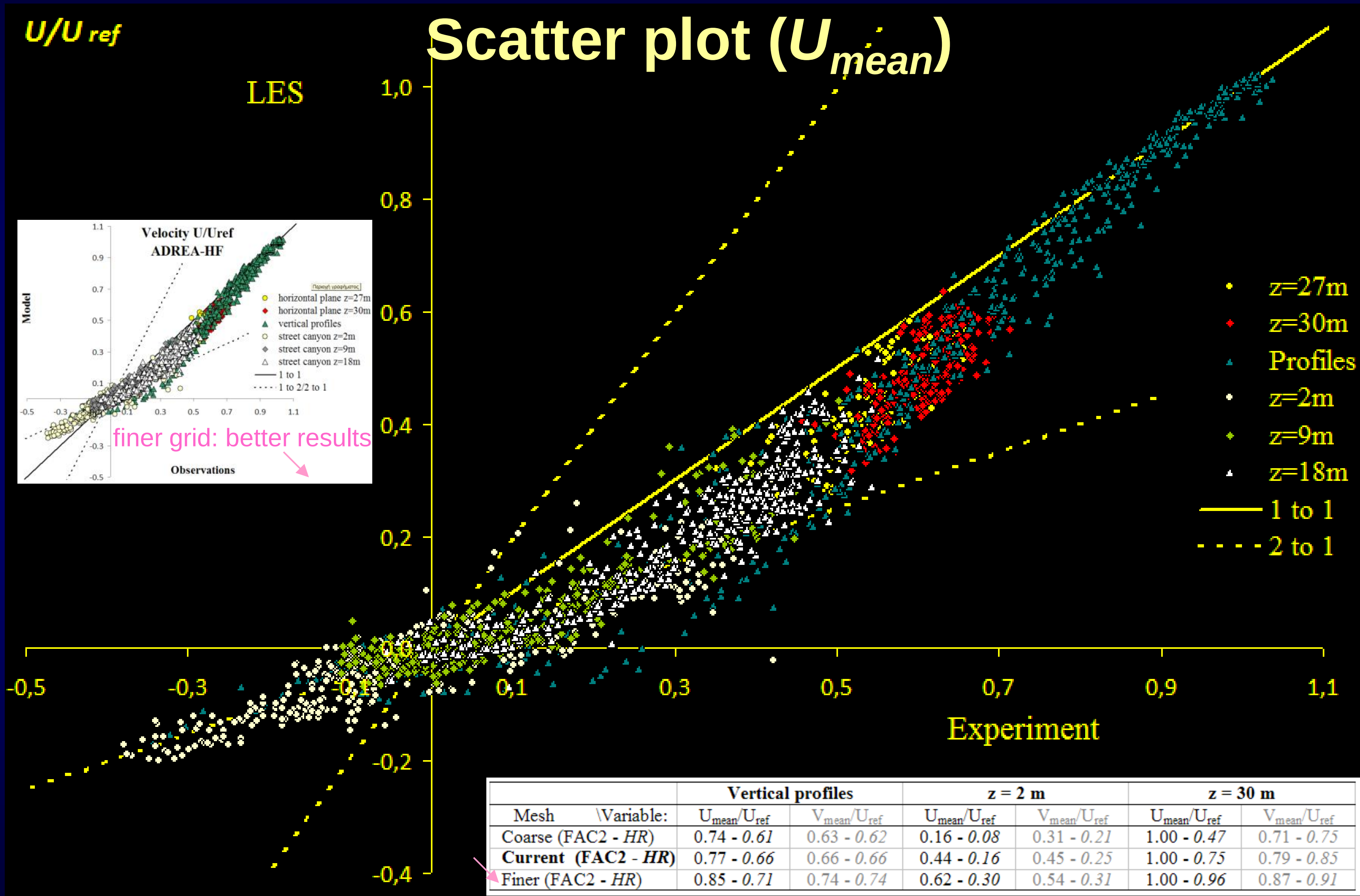
γ : neighboring cells, r : localization factor (0-1), f : enforcing factor (default 1)

MICHEL-STADT
Comparison with experimental profiles (U_{mean})



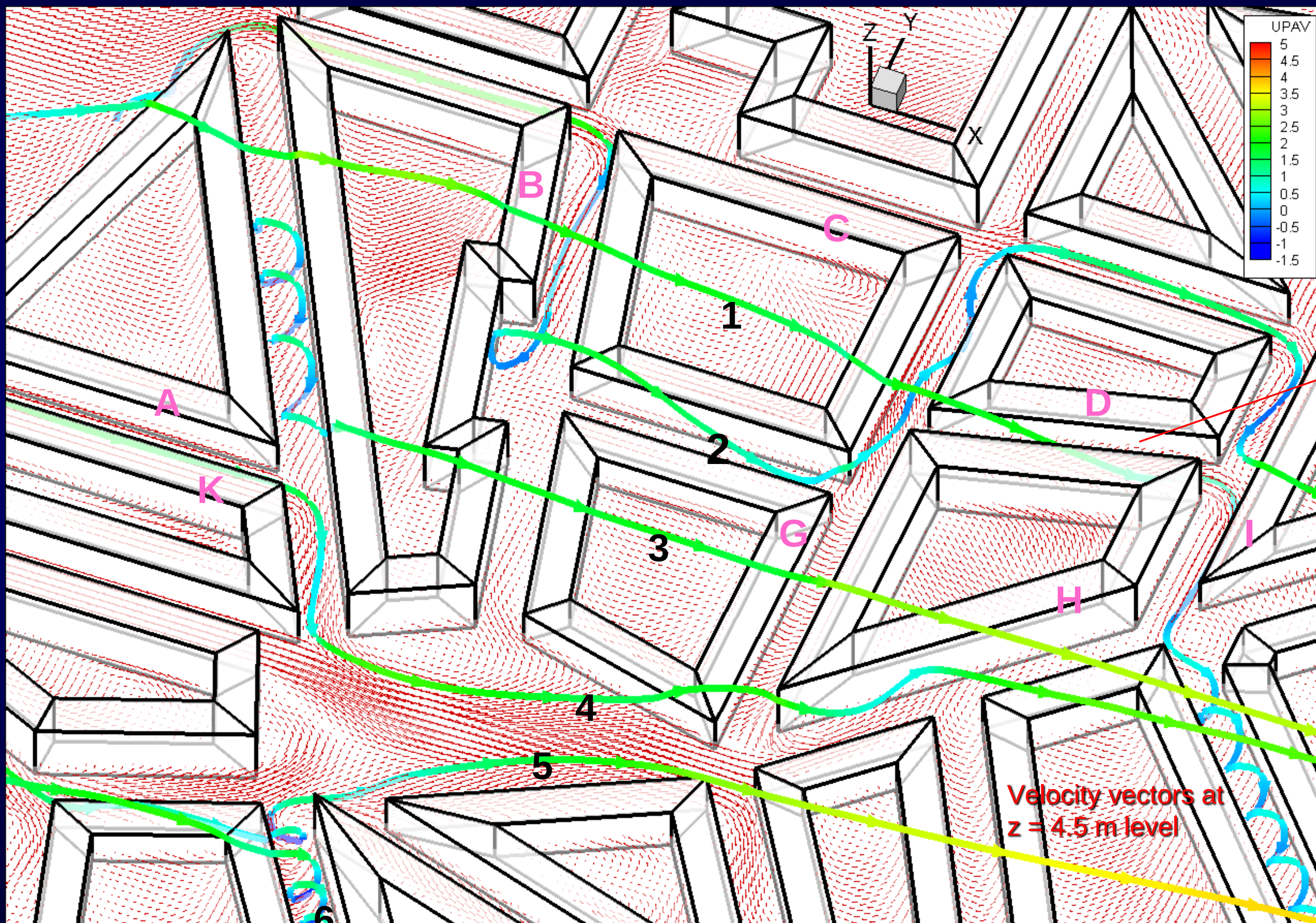
MICHEL-STADT

Scatter plot (U_{mean})

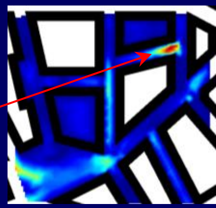


Mesh \Variable:	Vertical profiles U_{mean}/U_{ref}	Vertical profiles V_{mean}/U_{ref}	z = 2 m U_{mean}/U_{ref}	z = 2 m V_{mean}/U_{ref}	z = 30 m U_{mean}/U_{ref}	z = 30 m V_{mean}/U_{ref}
Coarse (FAC2 - *HR*)	0.74 - *0.61*	0.63 - *0.62*	0.16 - *0.08*	0.31 - *0.21*	1.00 - *0.47*	0.71 - *0.75*
Current (FAC2 - *HR*)	0.77 - *0.66*	0.66 - *0.66*	0.44 - *0.16*	0.45 - *0.25*	1.00 - *0.75*	0.79 - *0.85*
Finer (FAC2 - *HR*)	0.85 - *0.71*	0.74 - *0.74*	0.62 - *0.30*	0.54 - *0.31*	1.00 - *0.96*	0.87 - *0.91*

MICHEL-STADT
3D Streamtraces of mean flow at central city



Lux at 2m



MICHEL-STADT
Mean velocity vectors at *z* = 2 m (LES vs. EXP)

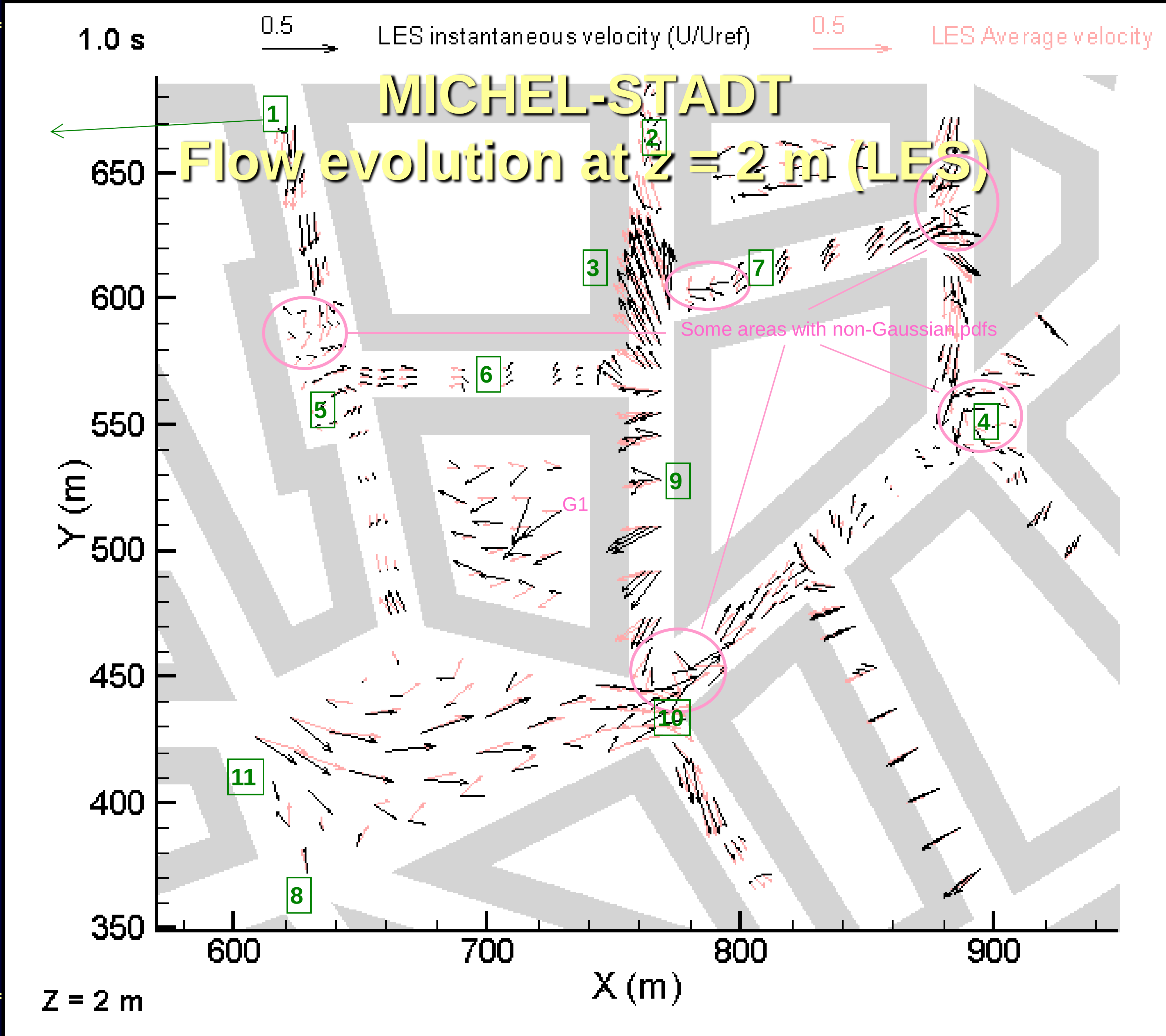
- Mean flow characteristics are captured
- Channeling at many canyons
- Point 4: persistent vortex
  Point 8: higher discrepancies

Beyond the mean flow..

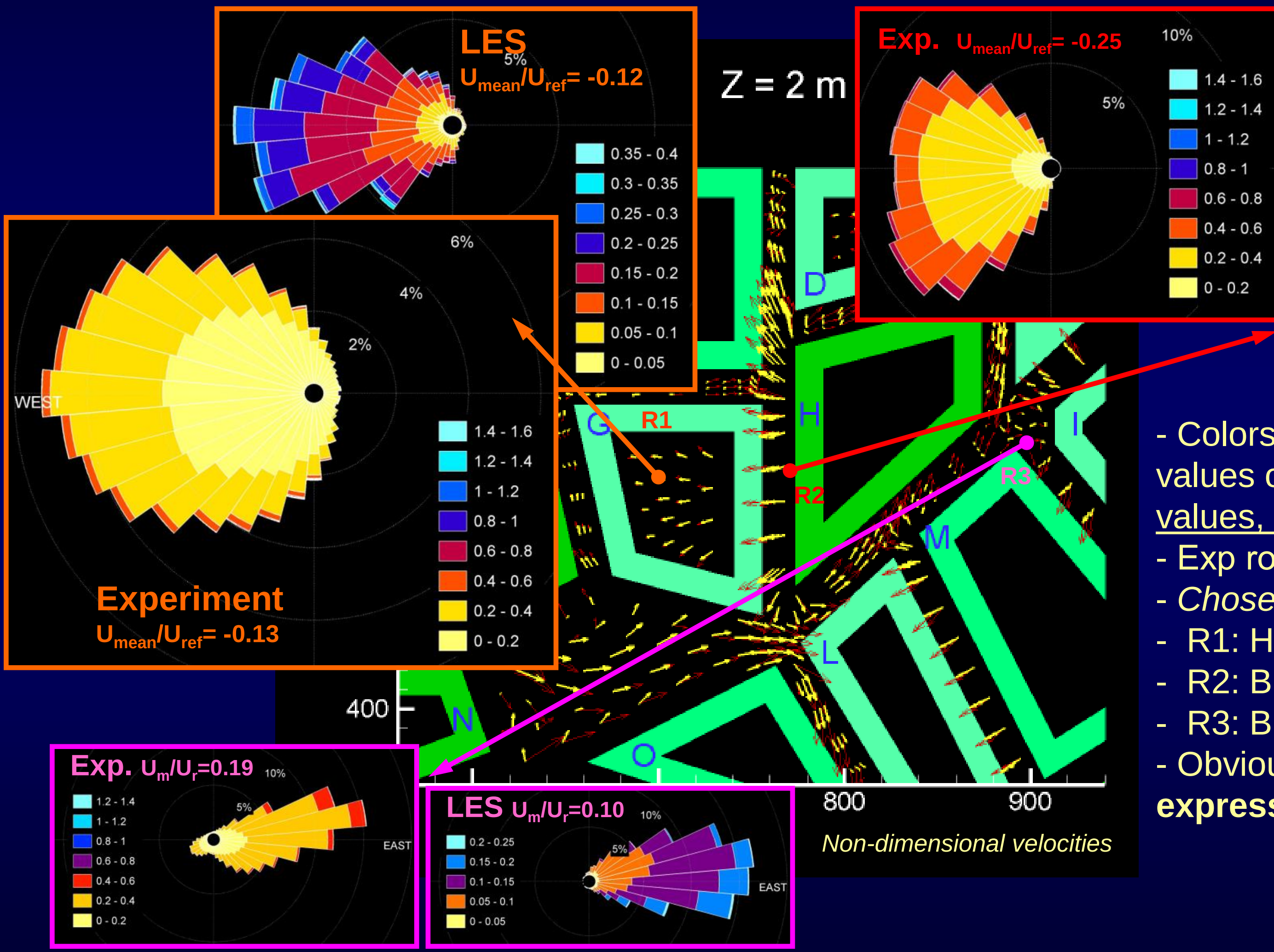
For example:

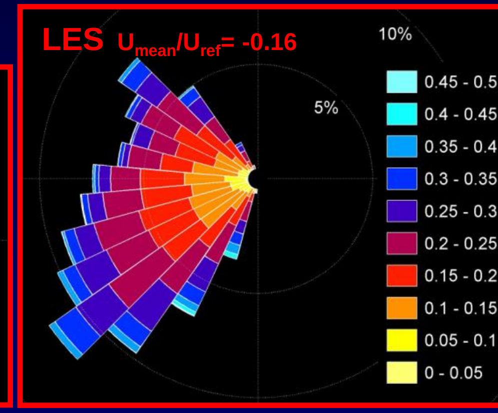
- **Time evolution of velocity field**
- In-depth comparison of time series characteristics: frequency distributions (e.g. direction and wind speed in terms of **wind rose diagrams**)
- Identification of important **coherent structures** (e.g. hairpin vortices, vorticity sheets etc)

MICHEL-STADT
Flow evolution at z = 2 m (LES)



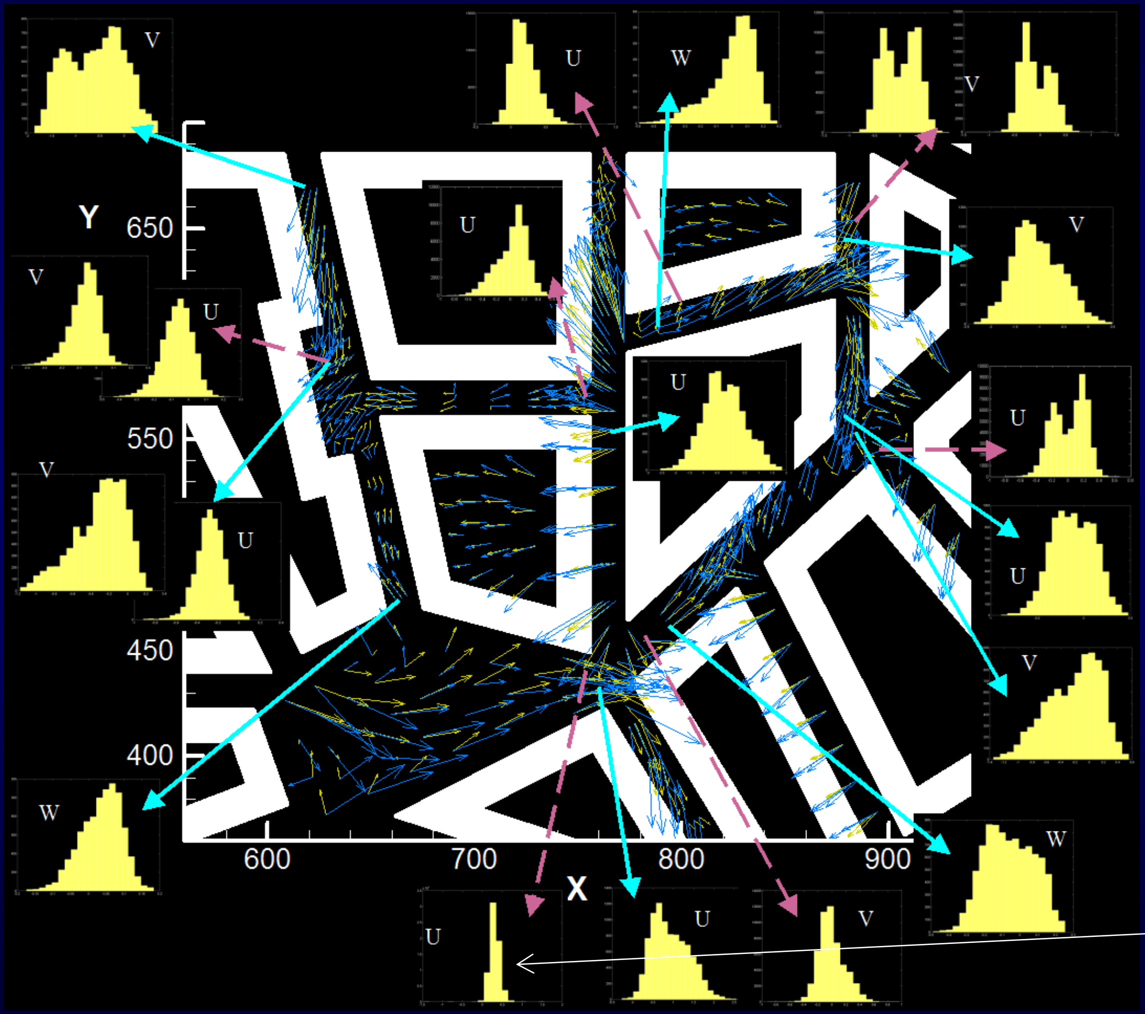
MICHEL-STADT
Wind roses at *z* = 2 m





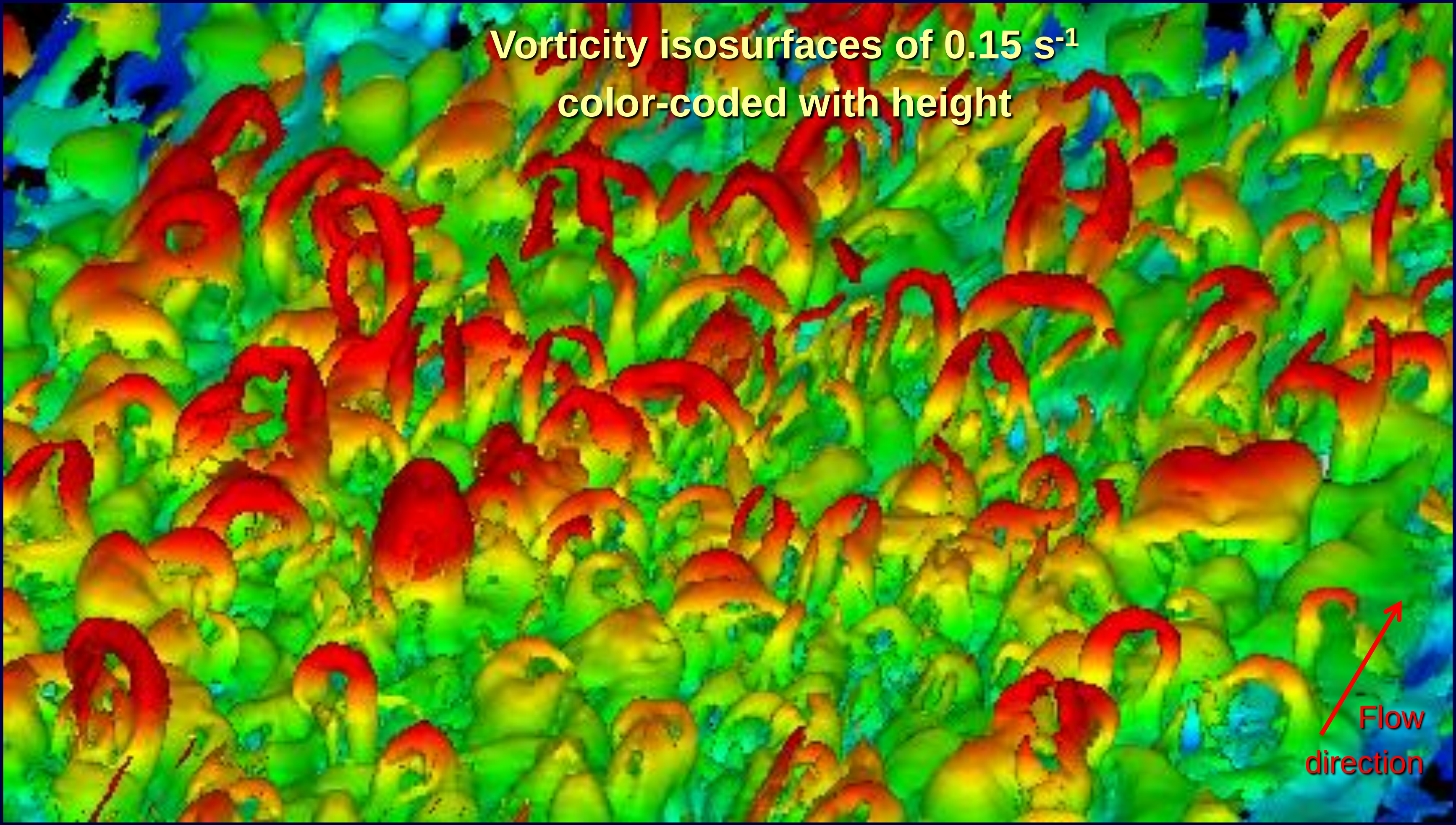
- Colors are different due to high peak values of exp. <u>Even with similar mean values, several differences at roses</u>!
- Exp roses are generally “smoother”
- *Chosen* roses (glimpse to unsteady phenom):
- R1: High direction variability
- R2: Bimodal behavior in direction
- R3: Bimodal/ opposite directions (exp)
- Obviously just **mean values cannot express all that information**

MICHEL-STADT
z = 2 m – non-Gaussian velocity pdf

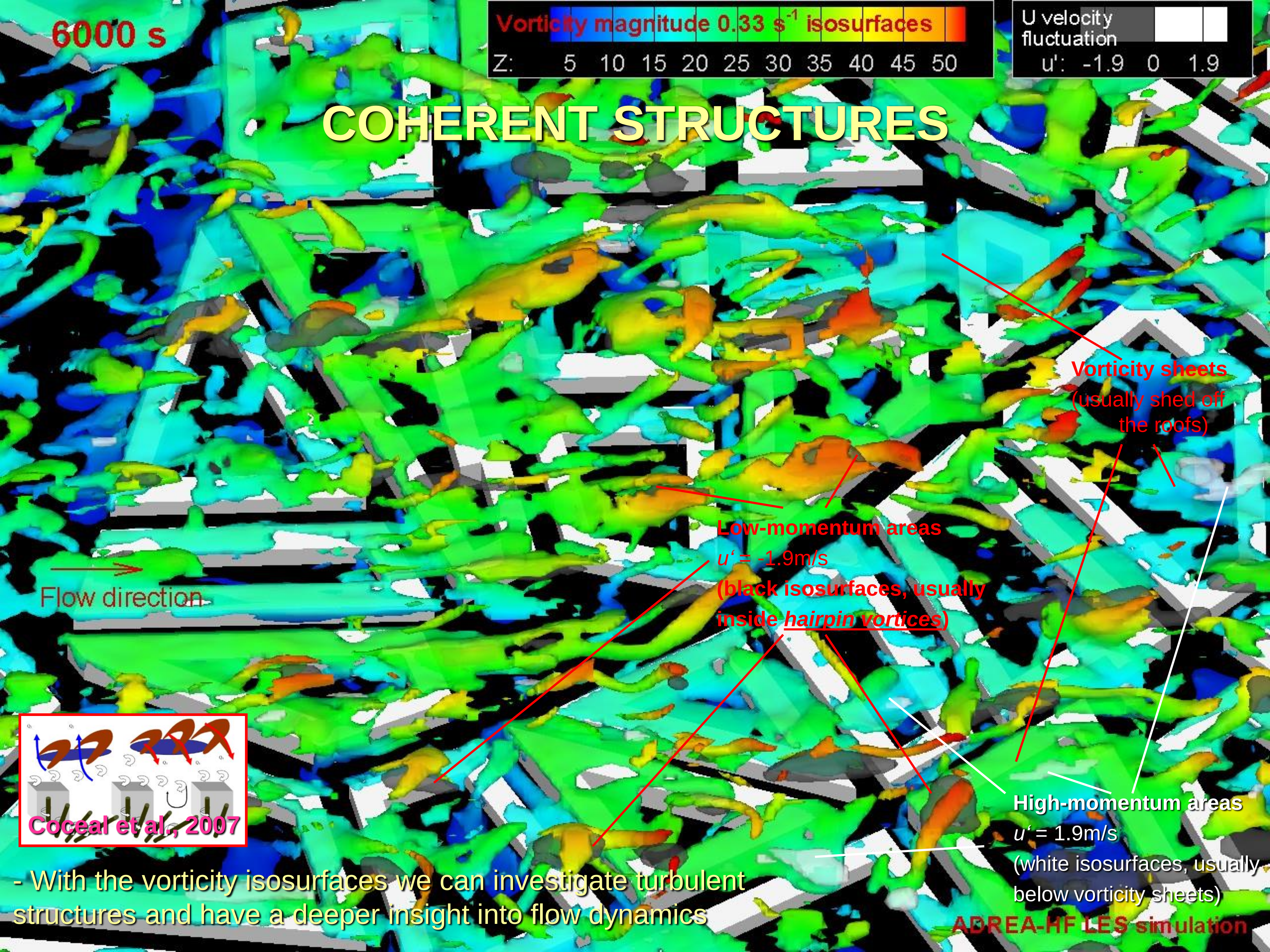


- LES can provide skewed or bimodal velocity probability density distributions (observed in EXP)
- They can usually be found in areas of high unsteadiness, like at vortex limits
- Most non-Gaussian spots are near street junctions
- At points of bimodal (or skewed) behavior, <u>the average value might not have a physical meaning</u>

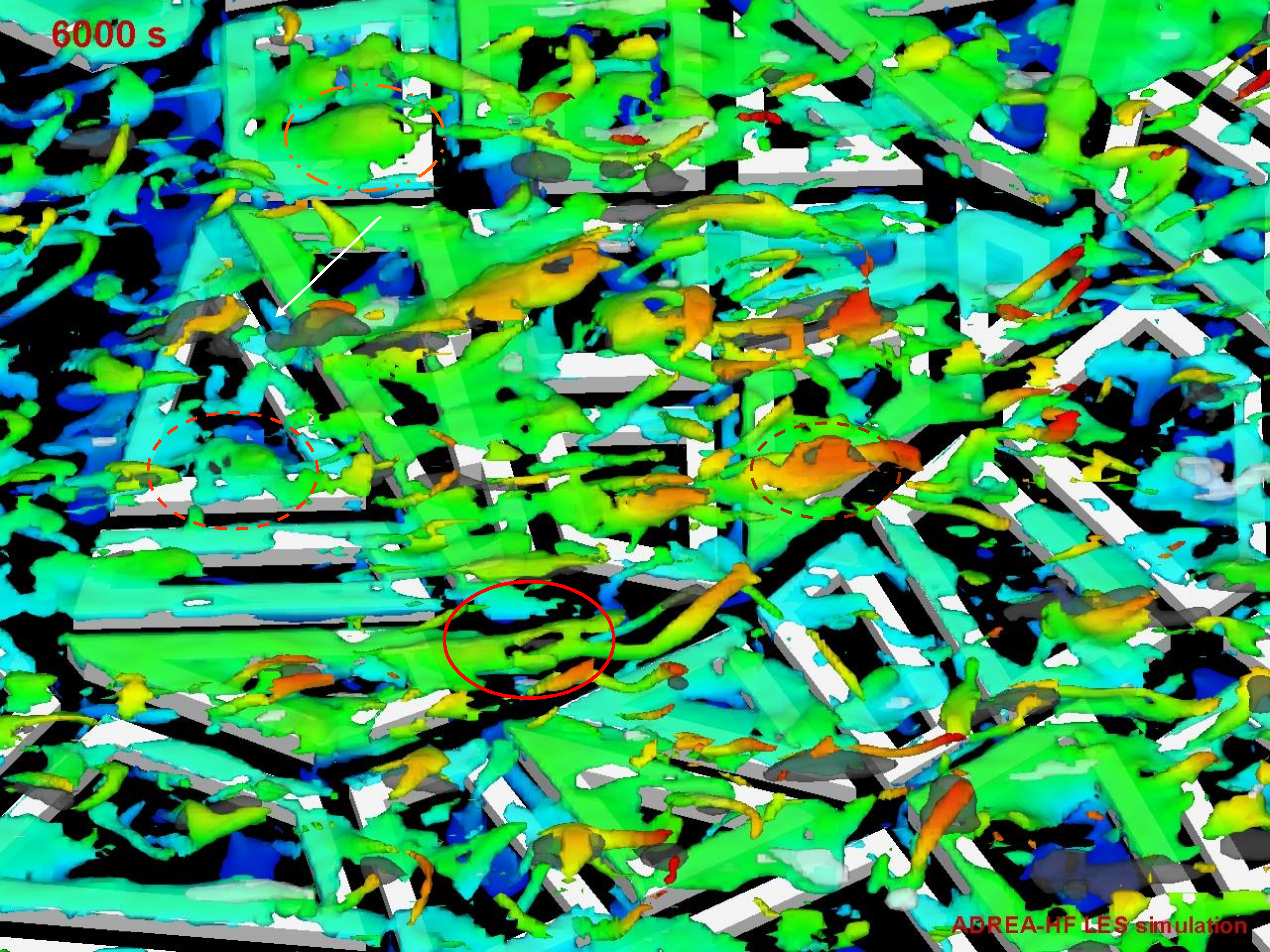
MICHEL-STADT
Hairpin vortices above the city



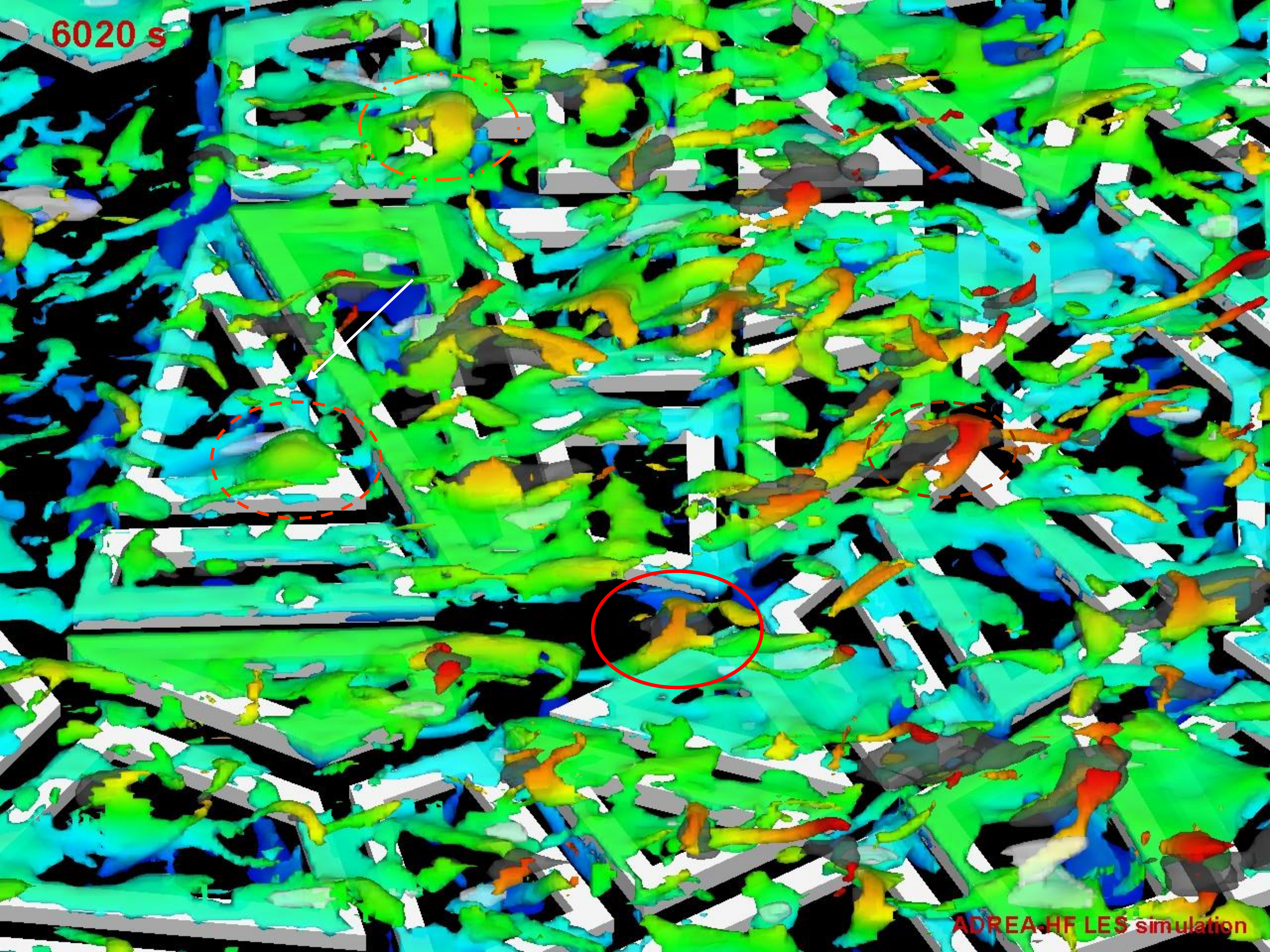
COHERENT STRUCTURES

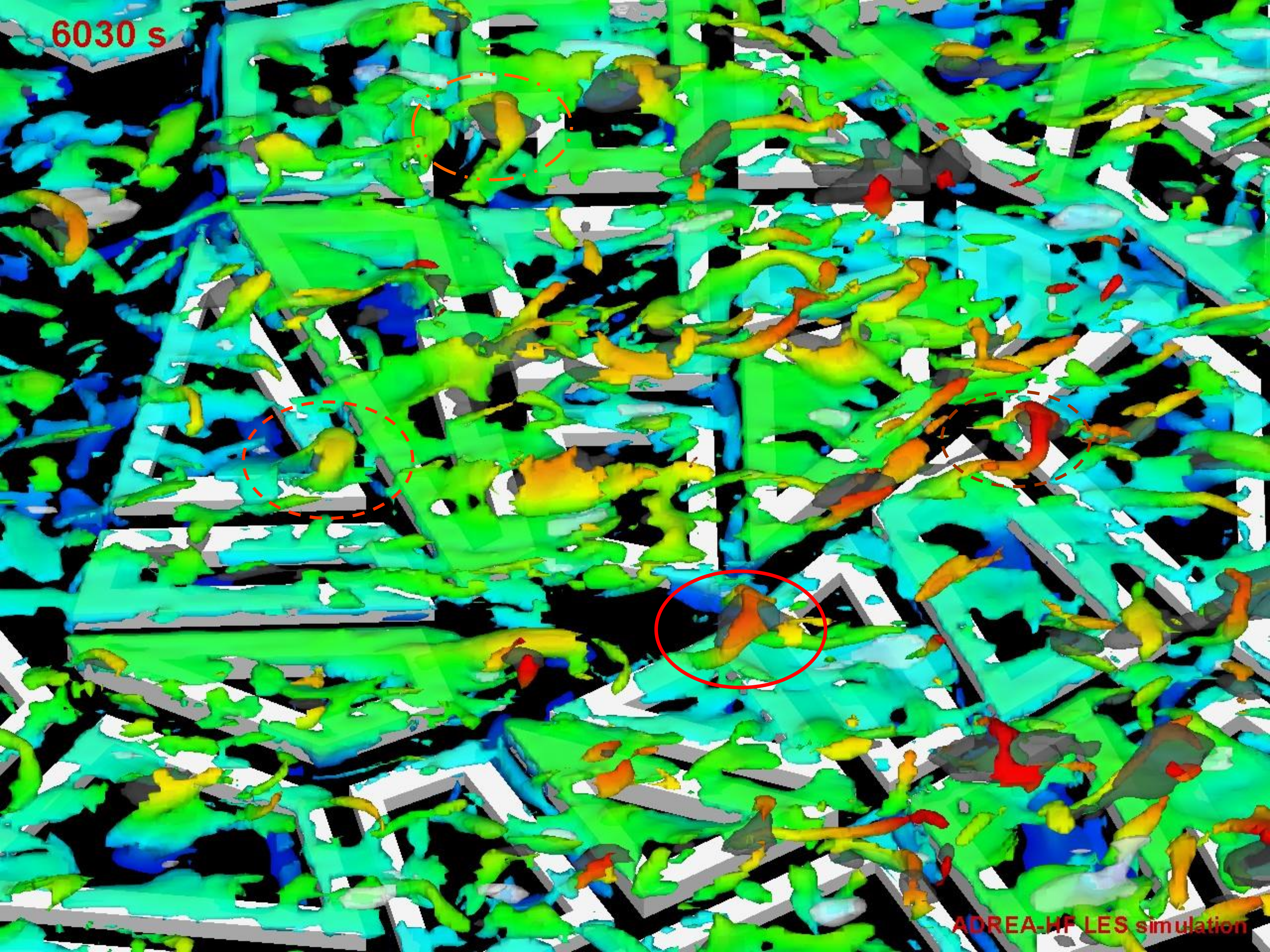


- With the vorticity isosurfaces we can investigate turbulent structures and have a deeper insight into flow dynamics

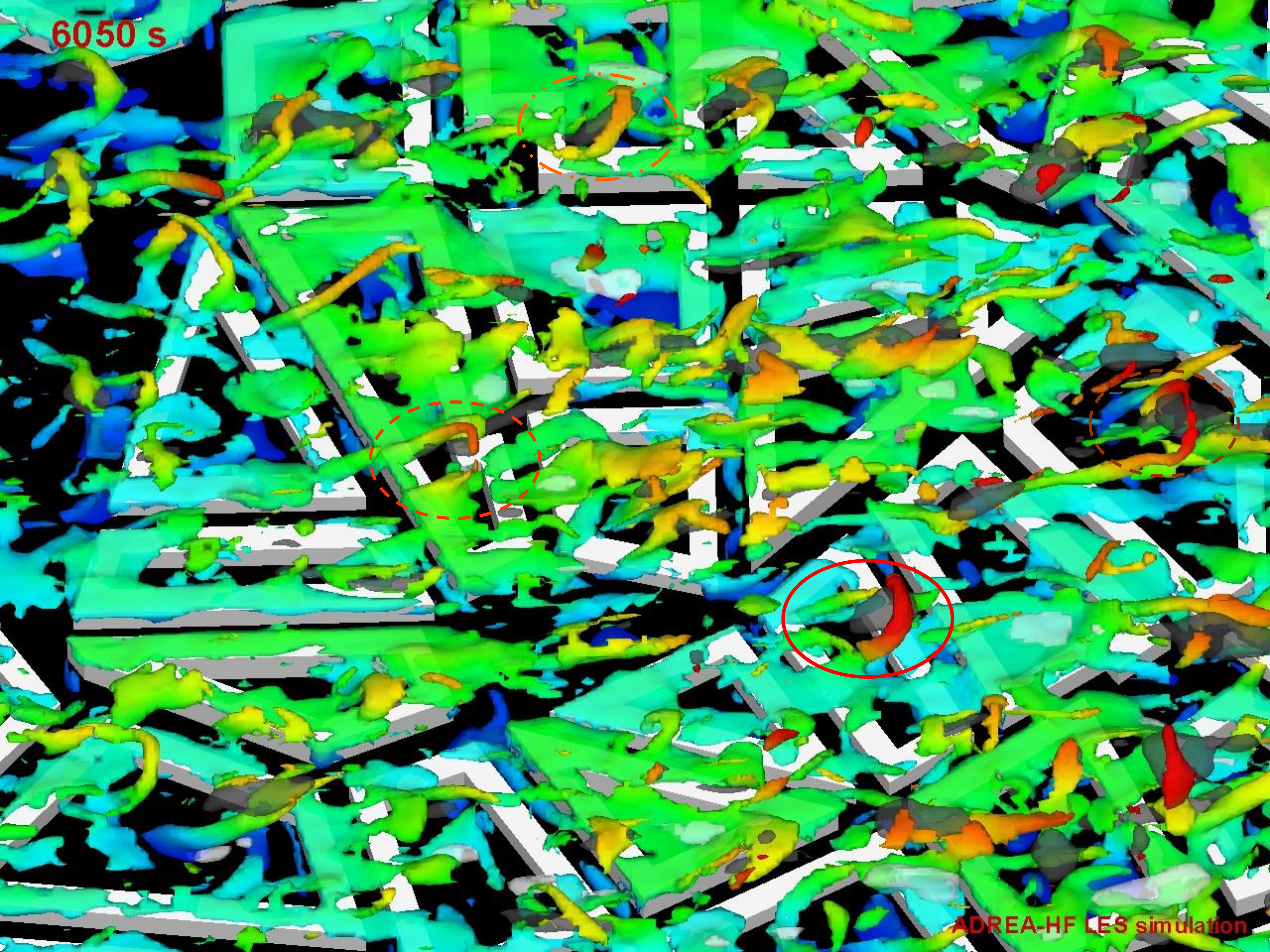

6000 s
ADREA-HF LES simulation

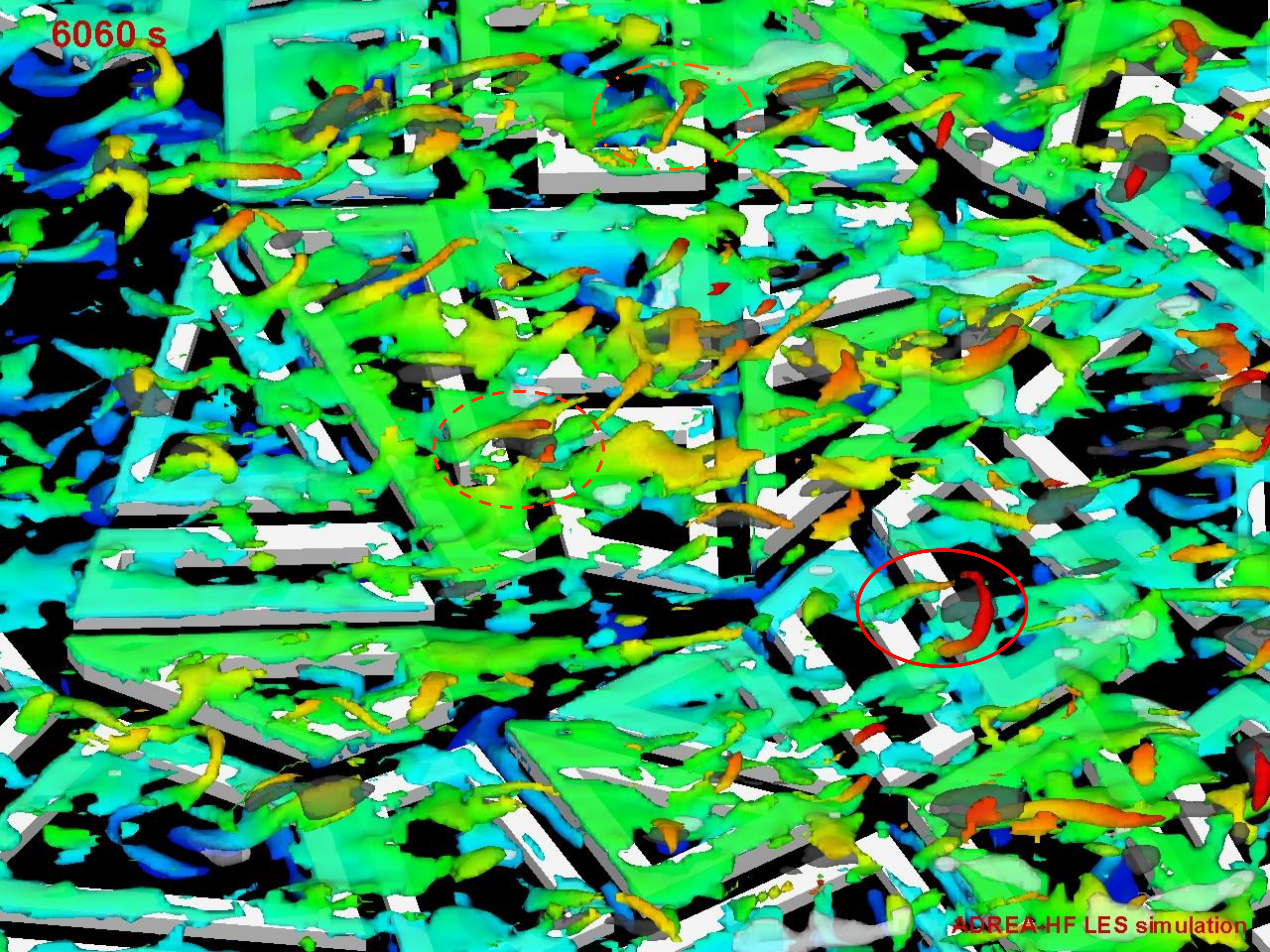

6010 s
ADREA-HF LES simulation


6020 s
ADREA-HF LES simulation

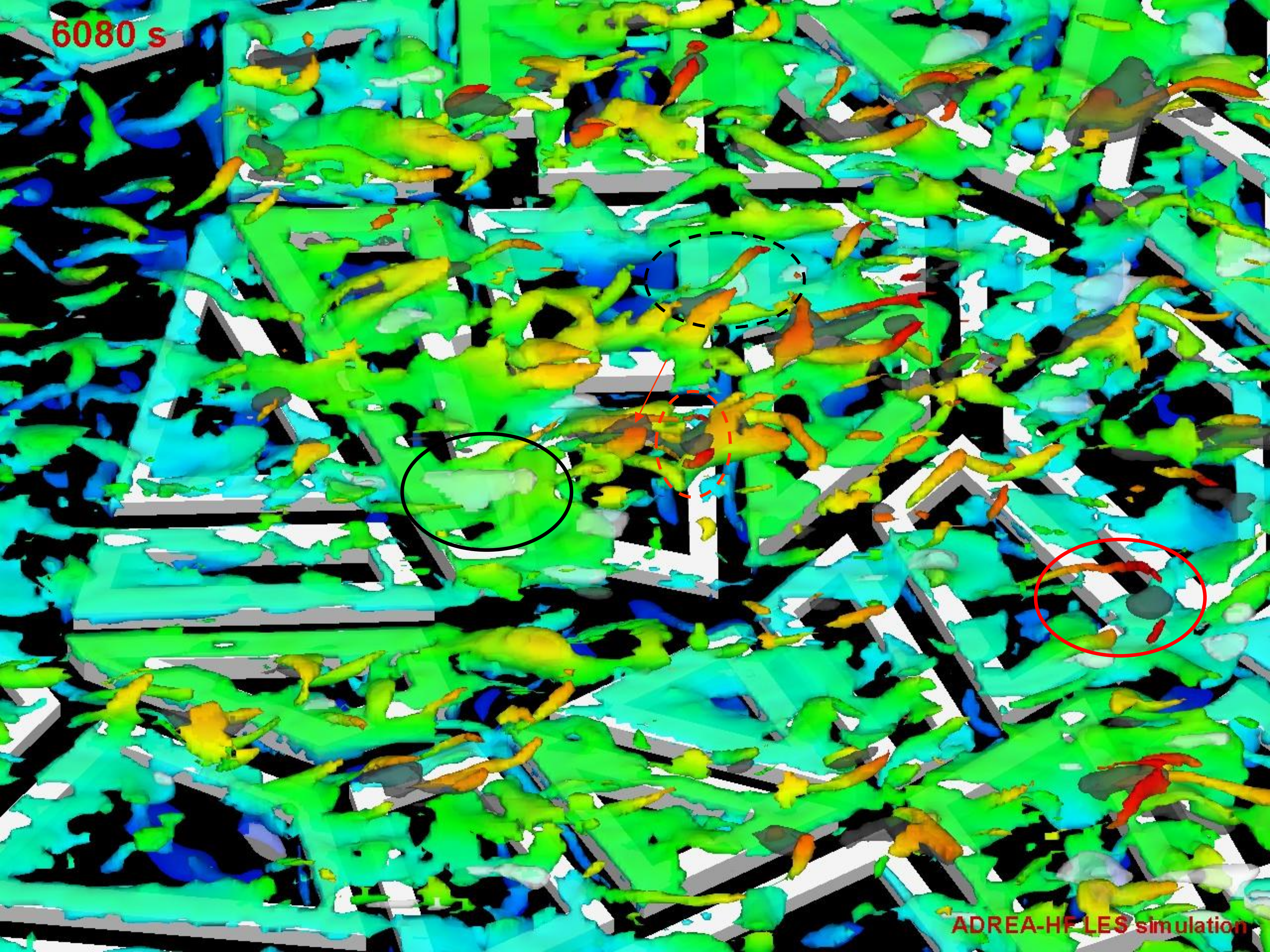

6030 s
ADREA-HF LES simulation


6040 s
ADREA-HF LES simulation

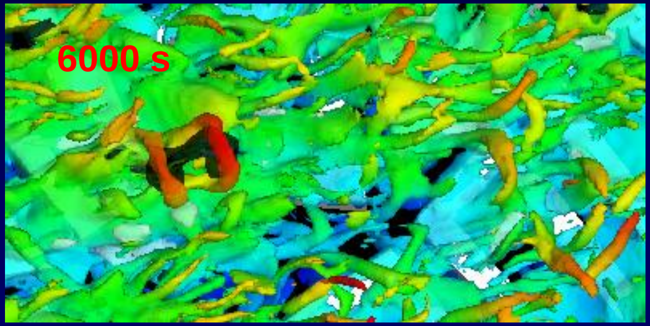

6050 s
ADREA-HF LES simulation

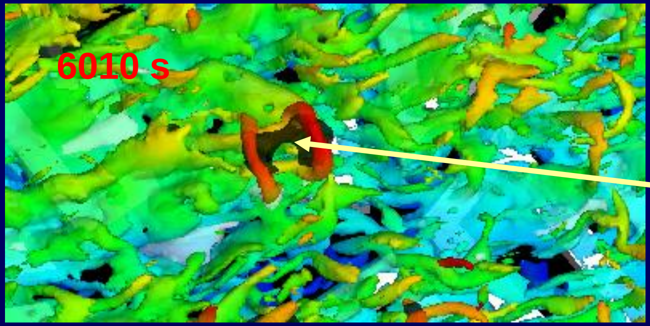

6060 s
ADREA-HF LES simulation

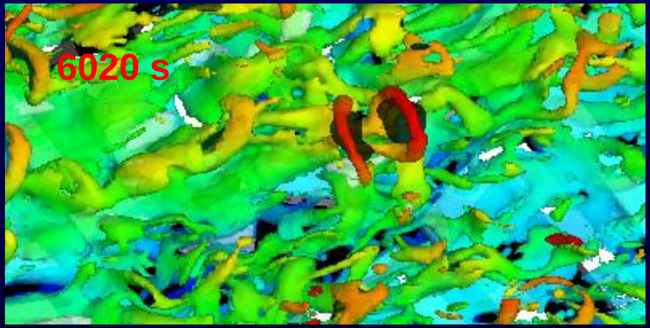

6070 s
ADREA-HF LES simulation


6080 s
ADREA-HF LES simulation

MICHEL-STADT
Finer grids reveal finer structures







Grid of
7 million cells
(preliminary results from run performed at the ARIS national Supercomputer, 190000 GFlops)

Pair of
hairpin vortices

- More complicated and more detailed structures can be seen
- More interactions between structures
- Groups of hairpin vortices can be identified (so-called LSM: Large Scale Motions)

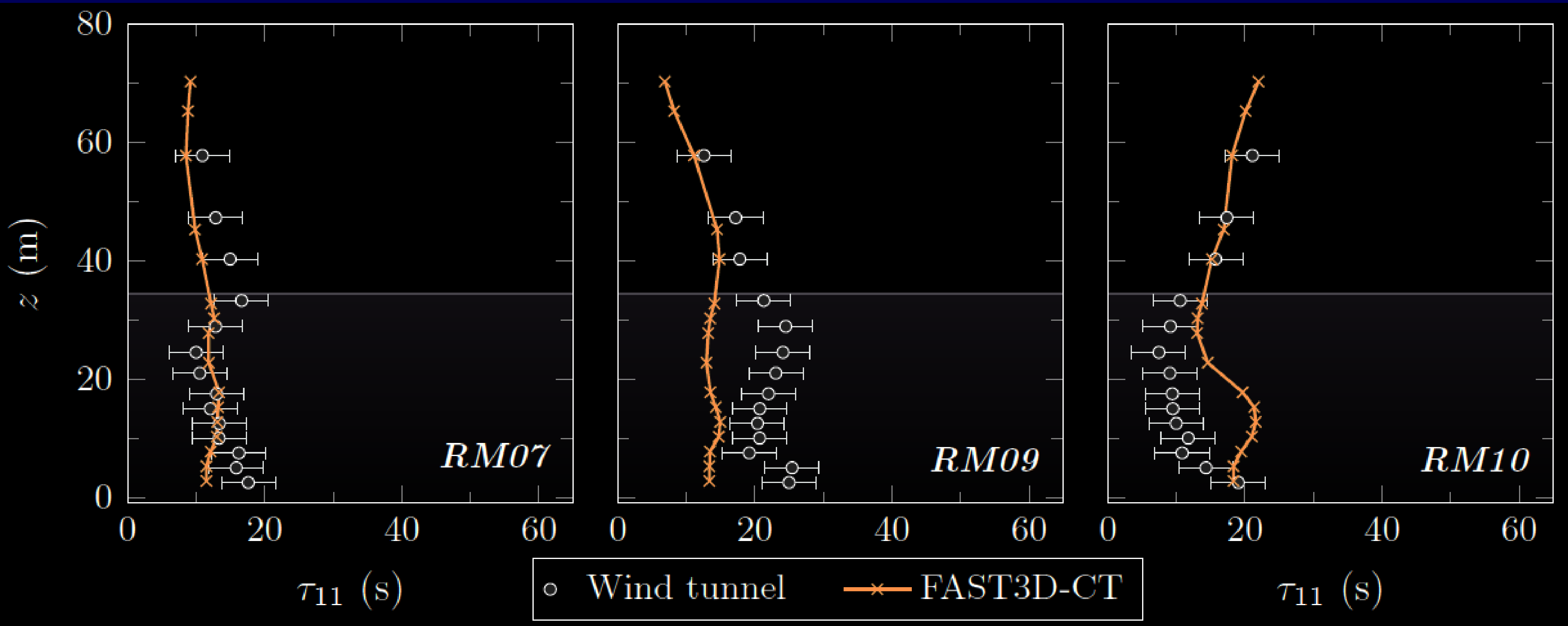
On LES Model Evaluation

- It is obvious from the above that LES has significant capabilities
- In order to assess the quality of the simulation we need to extend the validation
- e.g. look at comparison of:
  - Frequency distributions (shape parameters)
  - Eddy statistics (integral length & time scales, turbulence spectra, structure functions)
  - Flow pattern analyses (conditional resampling/averaging, joint time-frequency analysis, orthogonal decomposition, stochastic estimation)

Hertwig 2013, On aspects of large-eddy simulation validation for near-surface atmospheric flows. PhD thesis, University Hamburg
Hertwig et al. 2011, J Wind Eng Ind Aerodyn 99, 296-307

EXAMPLES OF MORE EVALUATION METHODS
Autocorrelation time scales

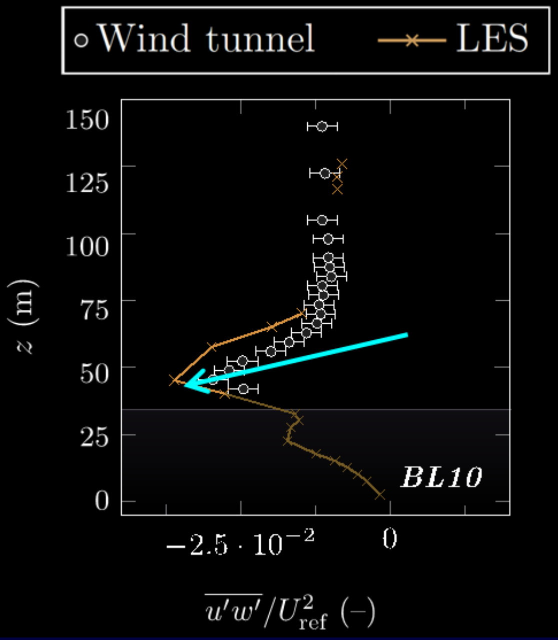
- **Vertical profiles of integral time scales for both LES and EXP**

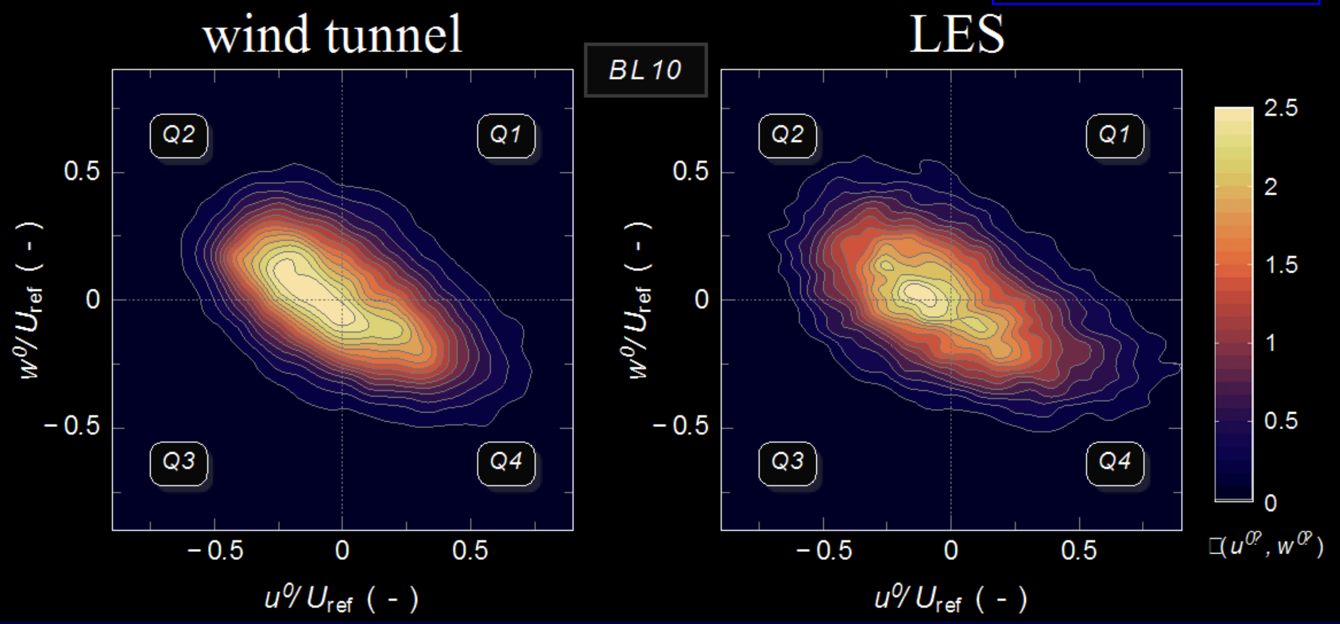


Hertwig 2013, On aspects of large-eddy simulation validation for near-surface atmospheric flows. PhD thesis, University Hamburg

EXAMPLES OF MORE EVALUATION METHODS
Joint probability distributions

- **In-depth comparison of vertical momentum flux**
- **Joint probability distributions of *u'* and *w'***





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CONCLUSIONS

- LES can contribute to a more fundamental understanding of turbulent flow phenomena
- New ways of evaluating results emerge
- There is a need to identify and standardize methods to analyze LES results and to compare them with experimental/reference data;
- There is a need of parallel work of experimentalists and modellers, in both the design of the experiments and the interpretation of the model results

Ευχαριστώ
Thank you