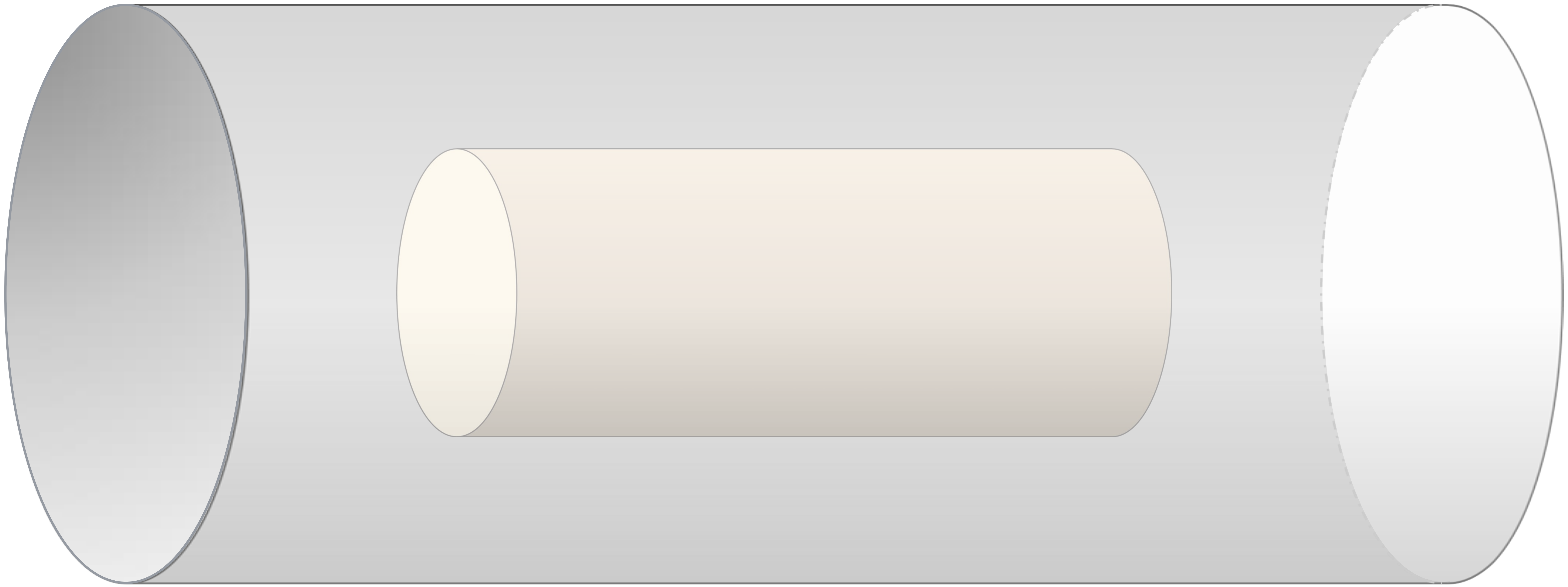
Non-obvious flow physics in an axi-symmetrical domain

Piotr Prusiński, MSc, Eng.
Supervised by Prof. Sławomir Kubacki

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

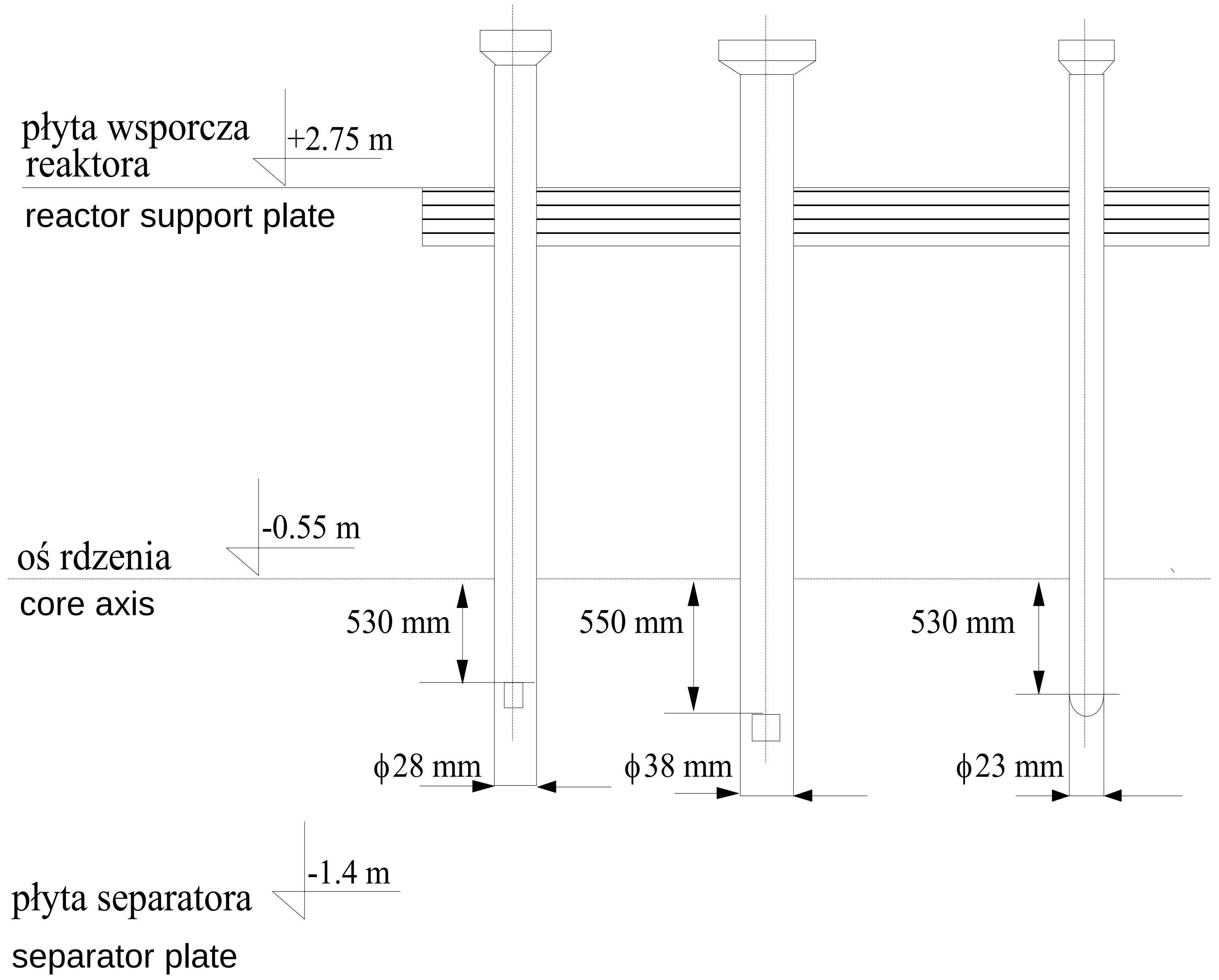
What do you see here?



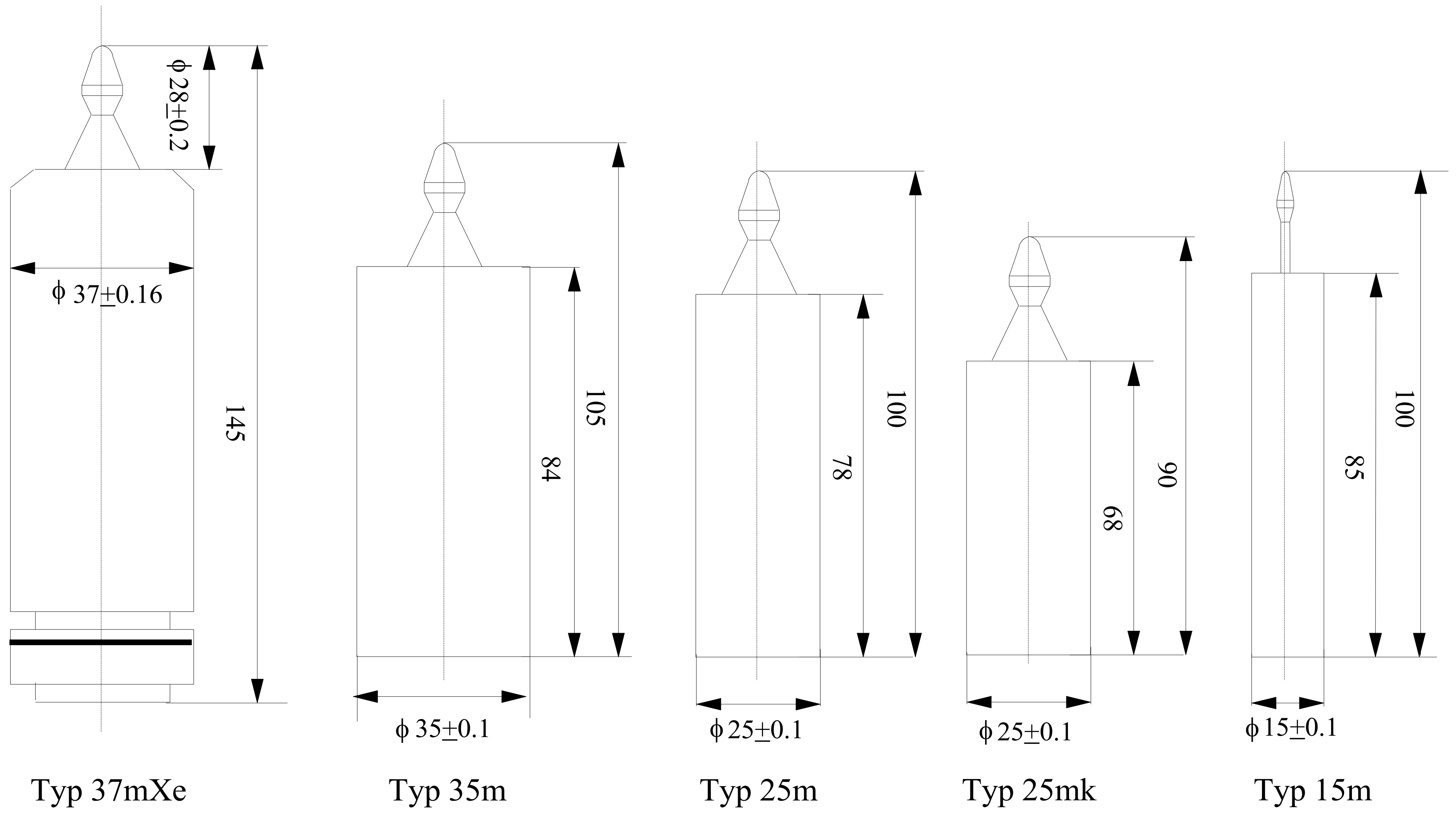
- What kind of industrial application it resembles to you?

What was the true origin? (1/2)

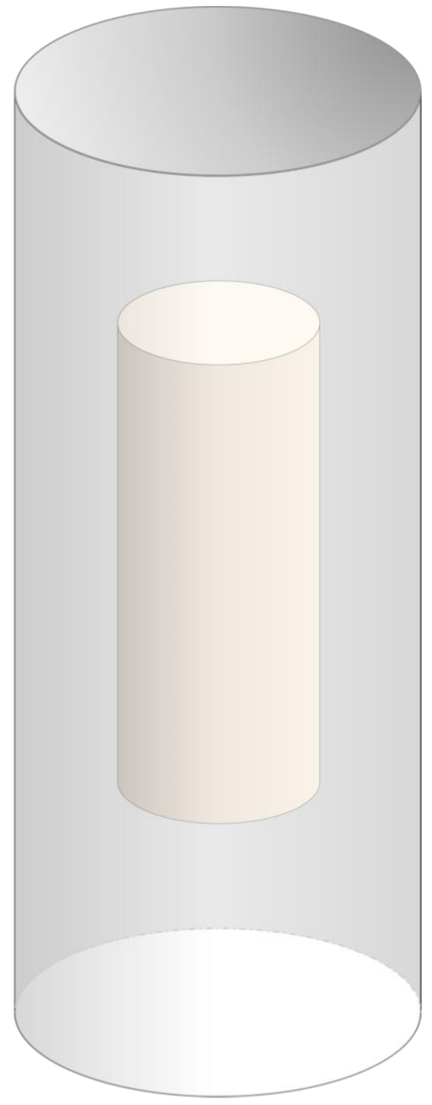
In-core irradiation channels types



Material sample container types



Generic geometry



Courtesy of G. Madejowski (DEJ/NCBJ)

What was the true origin? (2/2)

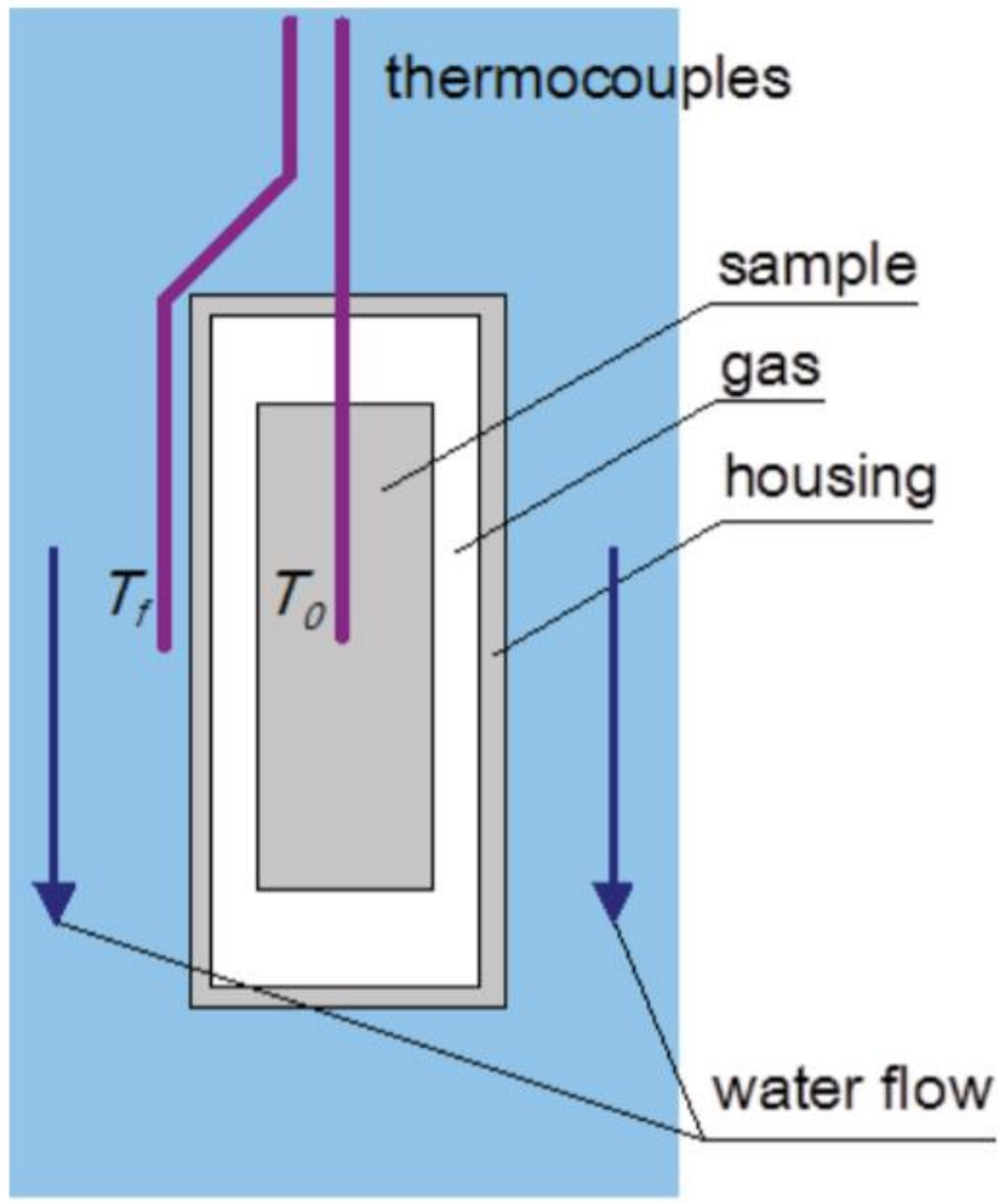
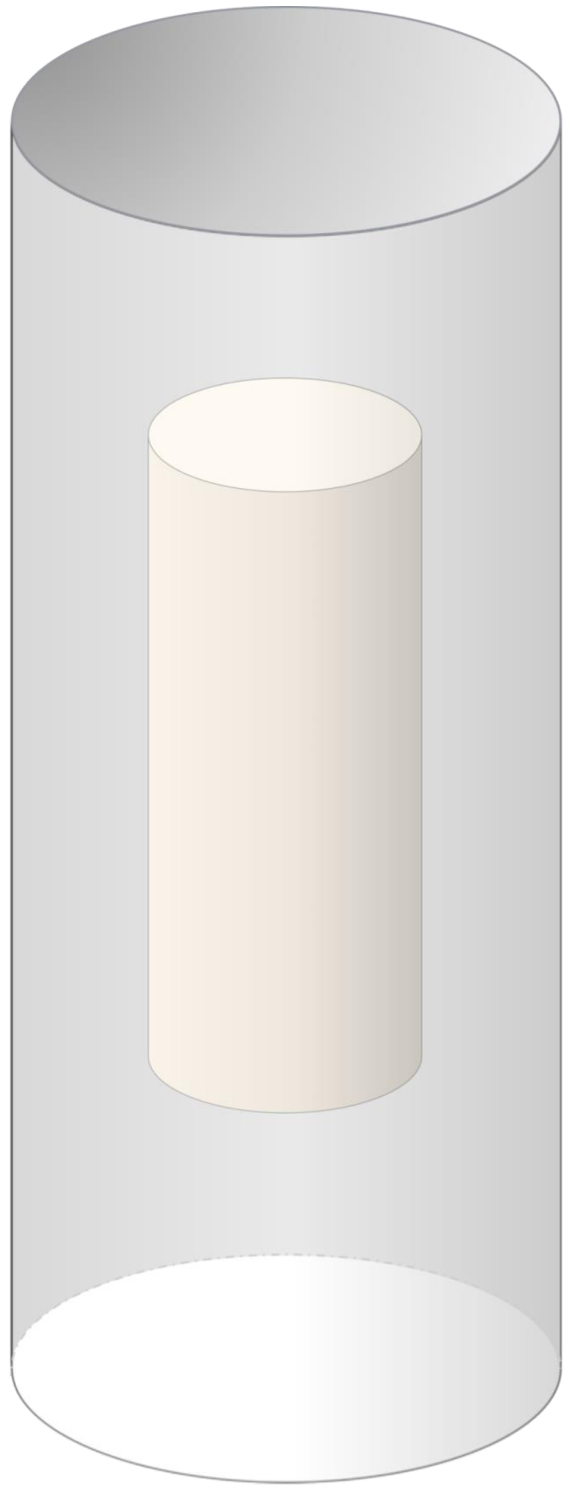


Fig. 1. Schematic cross section of the single-cell calorimeter

„(…) A single-cell calorimeter has been designed for application in the MARIA research reactor in the National Centre for Nuclear Research in Świerk near Warsaw, Poland. Not only the results of this elaboration are to be used in further analysis of the MARIA reactor operation but they are also dedicated for Jules Horowitz Reactor (JHR) analysis by the research centre in Cadarache, France. (…)"

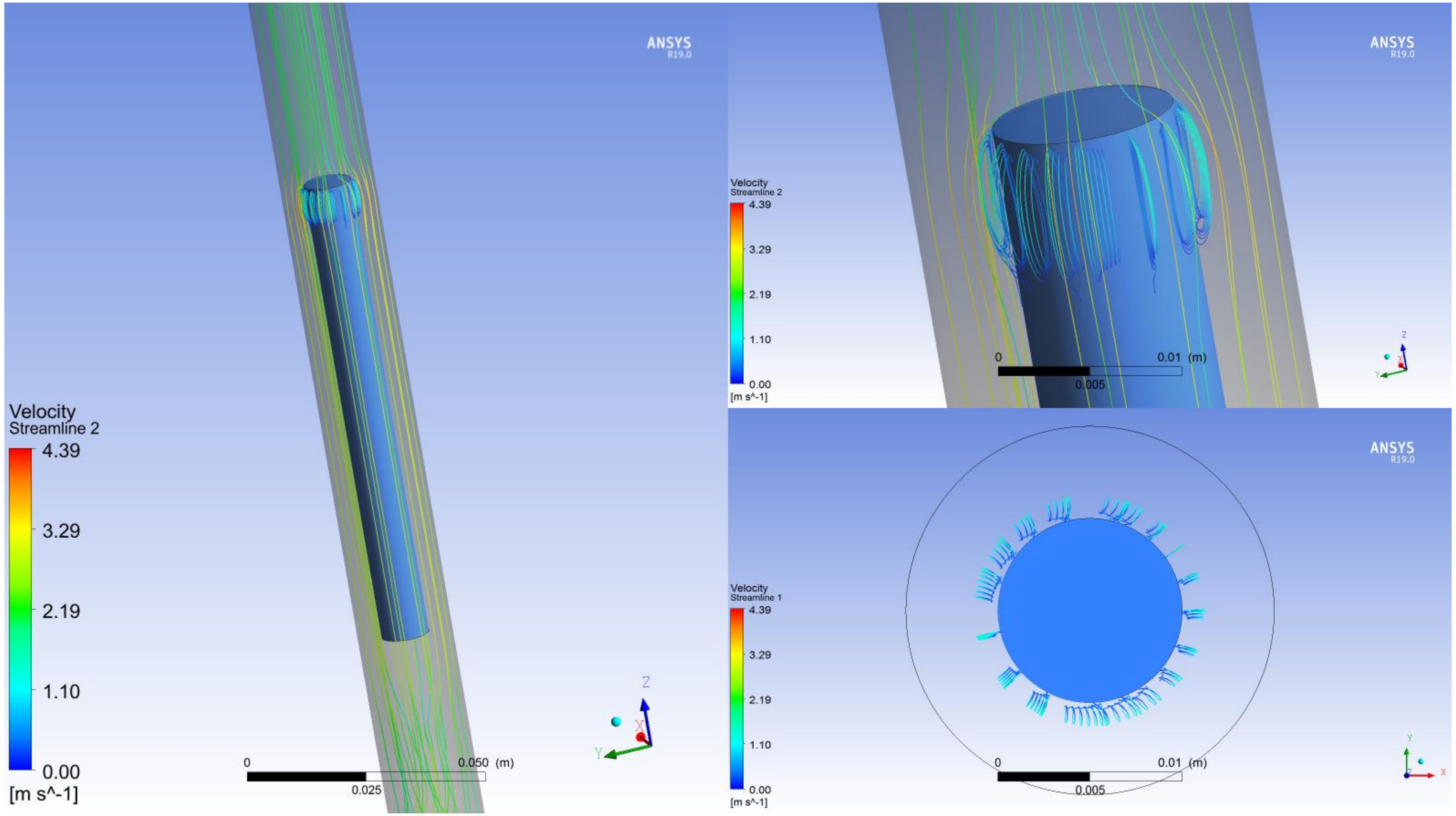
„(…) A two-dimensional model was applied. ***The axial symmetry allows to assume that results from a three-dimensional model should be similar to those from the two-dimensional one.***
The k-ε realizable model of turbulence was selected. It takes the possibility of flow separation from the wall into account. This phenomenon causes higher flow resistance. ***In addition, compared to the the k-ε standard or k-ω turbulence models, it gives a velocity profile closer to the correct ones.***
Because of the Reynolds number of 5.7 × 10^4, the k- ε realizable turbulence model was applied. (…)"



A. Luks et al. (2016) *Modelling of thermal hydraulics in a KAROLINA calorimeter for its calibration methodology validation*, Nukleonika; 61:4, 453-460, DOI: 10.1515/nuka-2016-0074

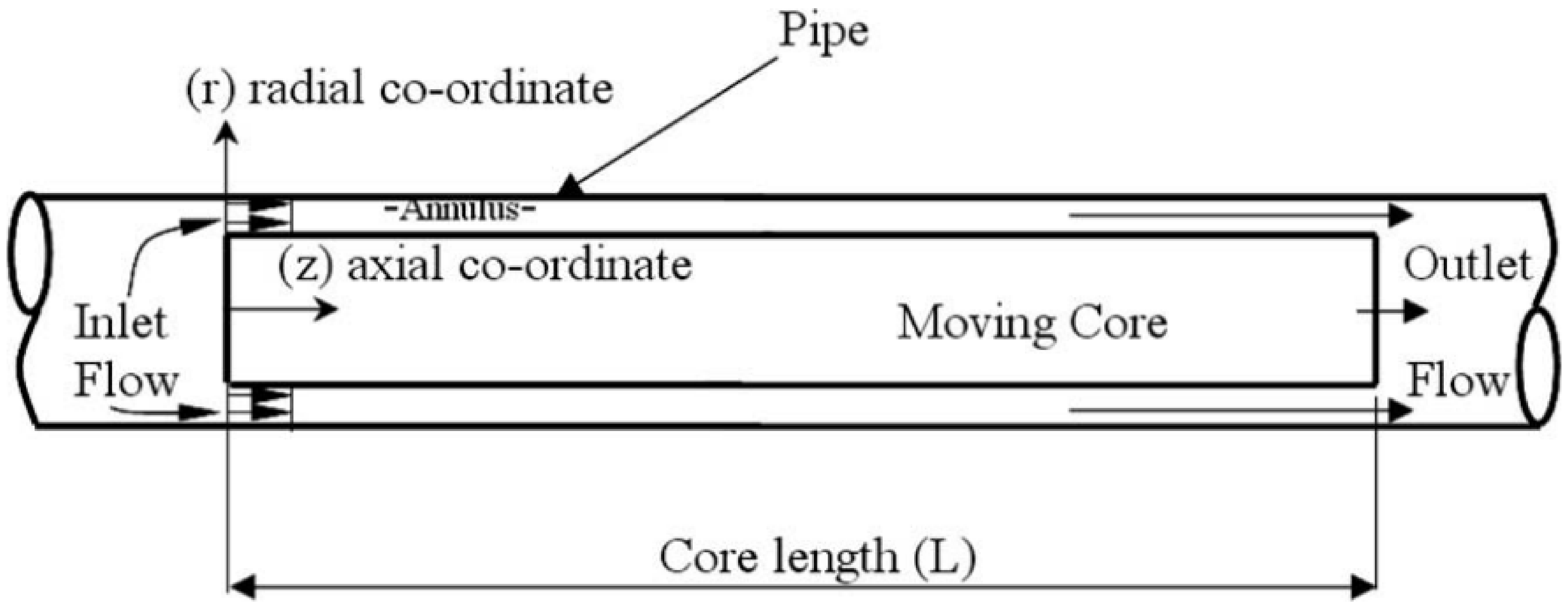
Why it made me so confused?

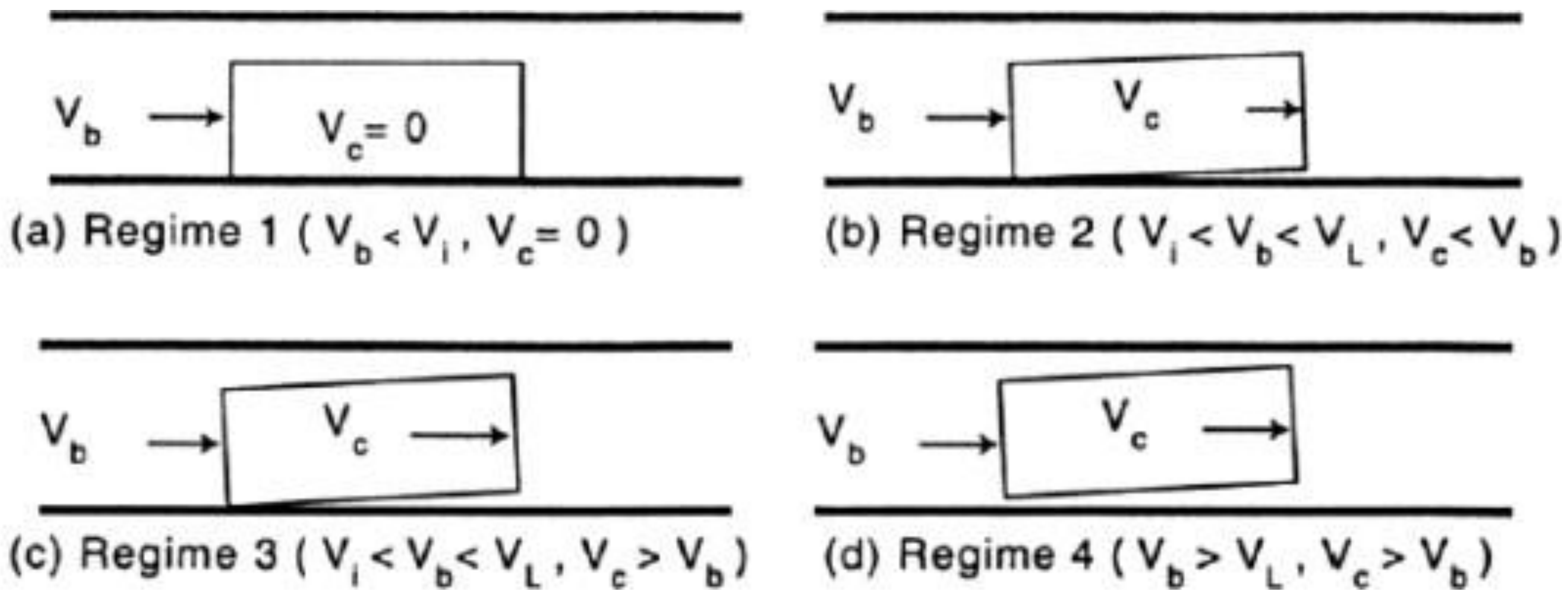
- Non-planar vortices in steady-state RANS (converged) results!



Did anyone tackle this problem before? (1/2)

- Well, not exactly…

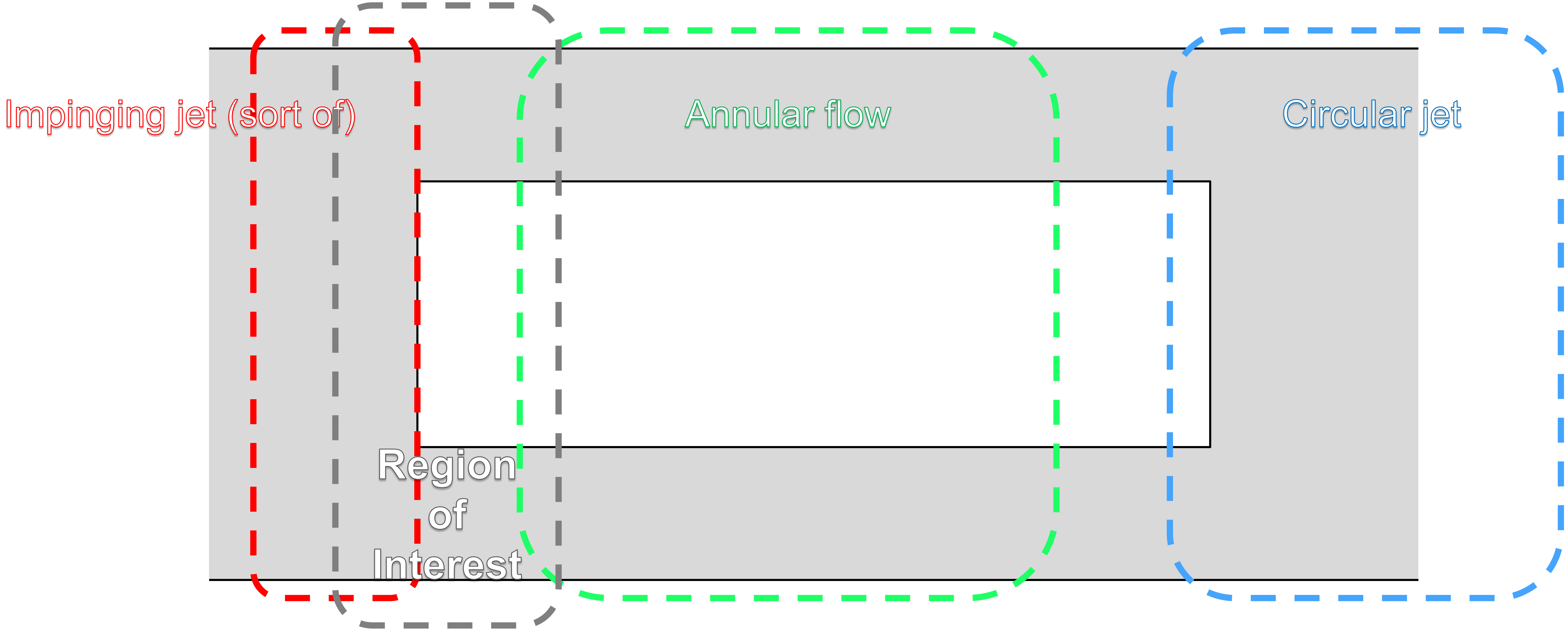




Khalil et al. (2010) *Turbulent flow around single concentric long capsule in a pipe*, Applied Mathematical Modelling, 34:8, 2000-2017, DOI:10.1016/j.apm.2009.10.014

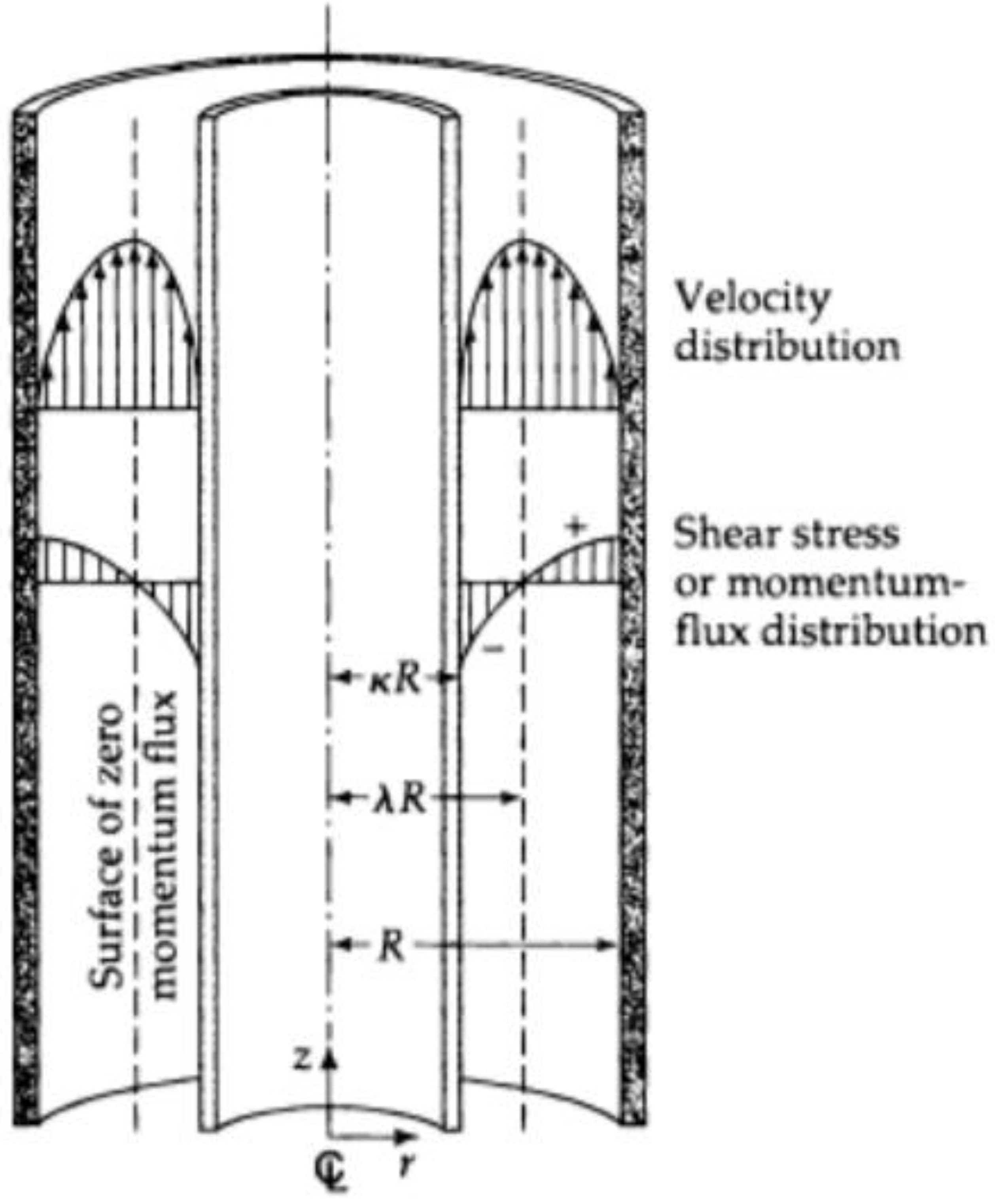
Did anyone tackle this problem before? (2/2)

- However, literature well-covers individual effects



Easy geometry – proven results, right?

- Doubts concerning fundumental parameters of developed turbulent flow in annular geometry
  - Brighton & Jones (1964):
    "Within the accuracy of the experimental results, the zero Reynolds stress and maximum velocity occur at the same point."
  - Rehme (1974)
    "The non-coincidence between zero shear stress and maximum velocity, which had been assumed and measured in a few experiments, was clearly proved."
  - Chung et al. (2002)
    "It is interesting to note that the positions of zero total shear stresses are closer to the inner walls than those of the maximum velocities."
  - Boersma & Breugem (2011)
    „In our direct numerical simulations we observe a coincidence of these points within the numerical accuracy of our model. It is shown that the velocity profile close to the inner annulus is logarithmic."



Nusselt Number in annular ducts

$$\boxed{Nu = \frac{(f_{ann}/8)RePr}{k_1 + 12.7\sqrt{f_{ann}/8}(Pr^{2/3} - 1)}\left[1 + \left(\frac{d_h}{L}\right)^{2/3}\right]F_{ann}K}$$

$$a = \frac{d_i}{d_o} \qquad d_h = d_o - d_i \qquad Re = \frac{Ud_h}{\nu} \qquad Pr = \frac{\nu}{\kappa}$$

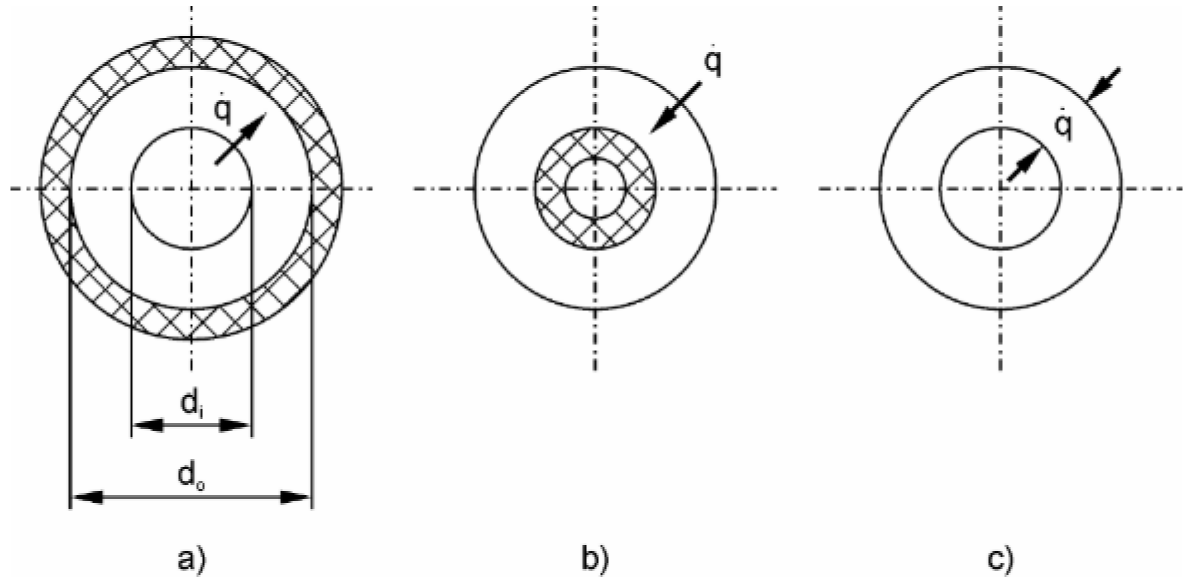


Figure 1 Boundary conditions for concentric annular duct flow: (a) heat transfer from the inner tube (outer tube insulated), (b) heat transfer from the outer tube (inner tube insulated), and (c) heat transfer from both tubes to the annular flow.

$$Re^* = Re\frac{(1 + a^2)\ln a + (1 - a^2)}{(1 - a)^2 \ln a}$$

$$k_1 = 1.07 + \frac{900}{Re} - \frac{0.63}{(1 + 10Pr)}$$

$$f_{ann} = (1.8\log_{10} Re^* - 1.5)^{-2}$$

$$K = \left(\frac{Pr_b}{Pr_w}\right)^{0.11} - valid\ for\ liquids$$

$a)\ \ F_{ann} = 0.75a^{-0.17}$

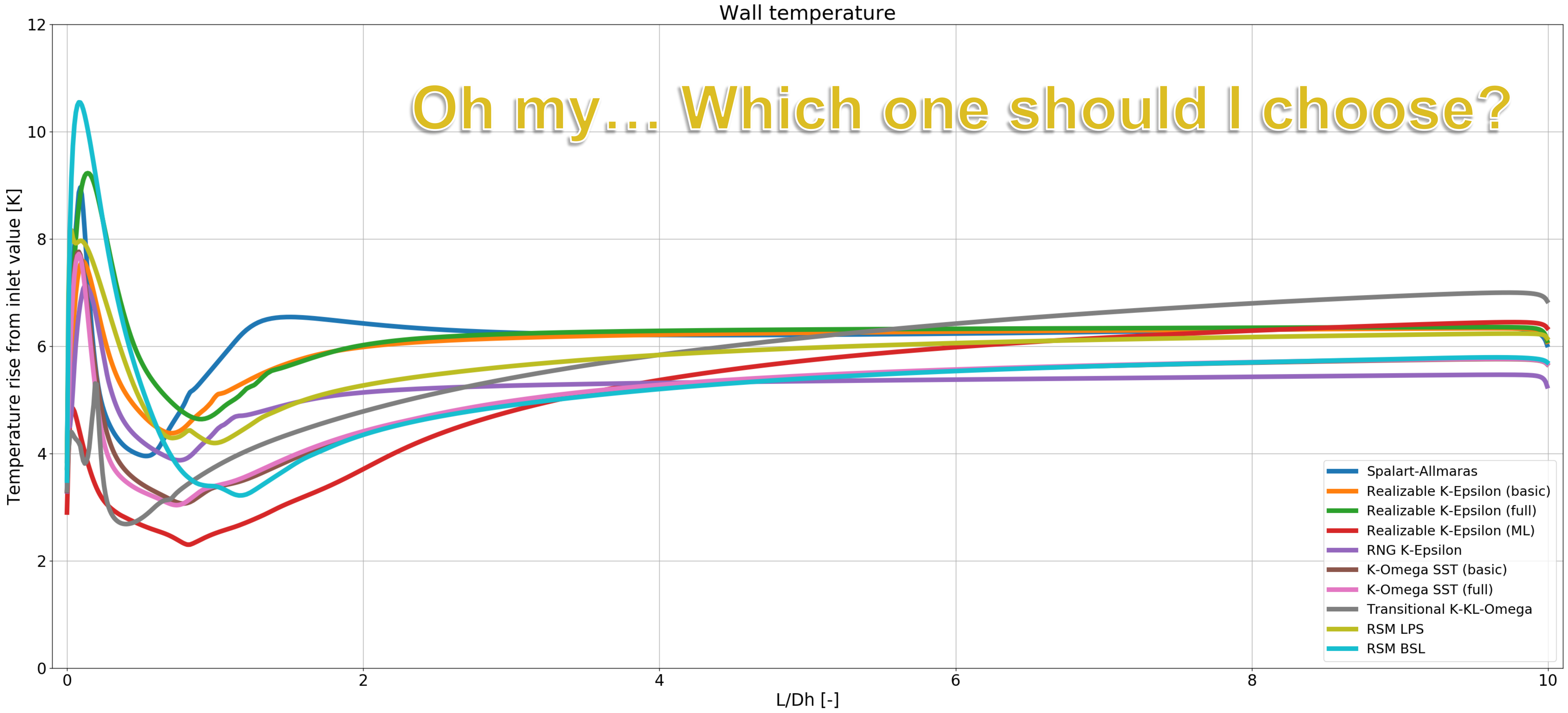
$b)\ \ F_{ann} = 0.9 - 0.15a^{0.6}$

$c)\ \ F_{ann}\ - no\ data\ available$

V. Gnielinski (2009) *Heat Transfer Coefficients for Turbulent Flow in Concentric Annular Ducts*, Heat Transfer Engineering, 30:6, 431-436, DOI: 10.1080/01457630802528661

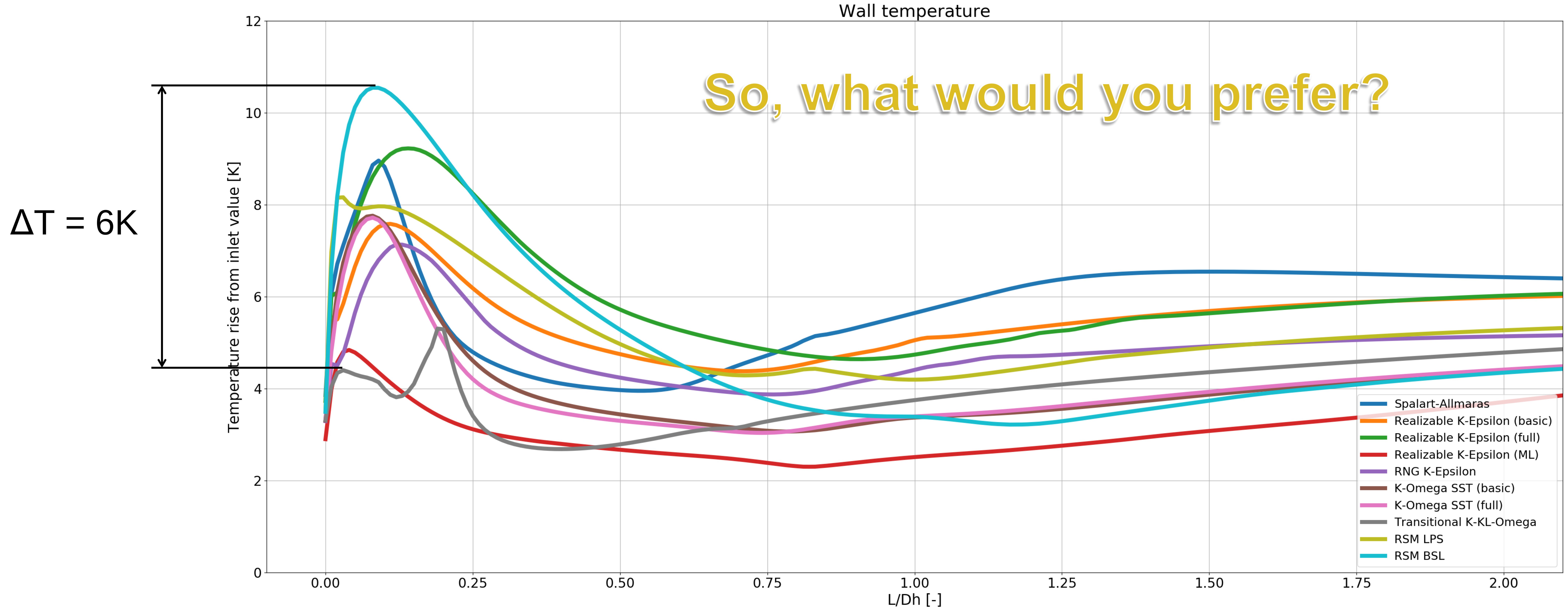
So what is really going on here? (1/6)

- Let's try some RANS modelling first!



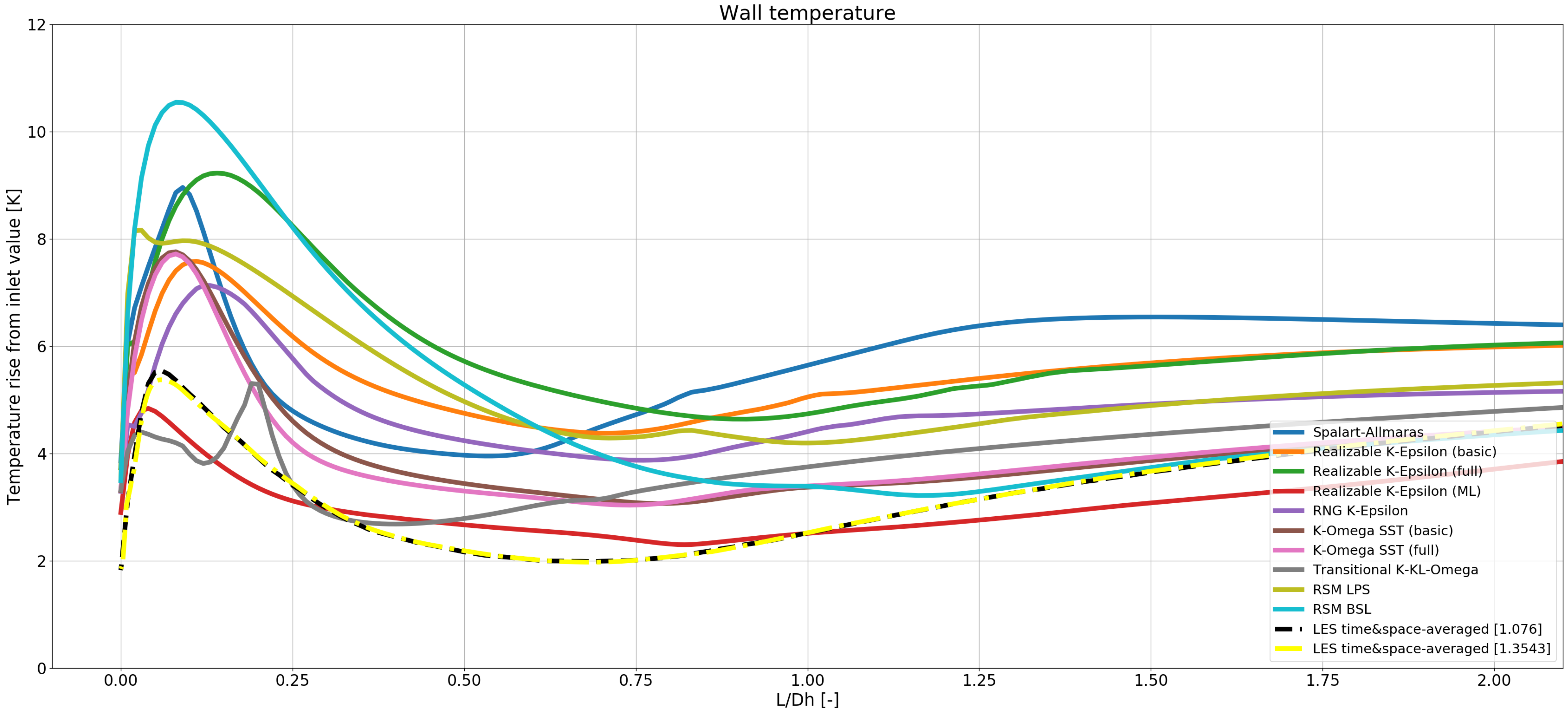
So what is really going on here? (2/6)

- Let's try some RANS modelling first!



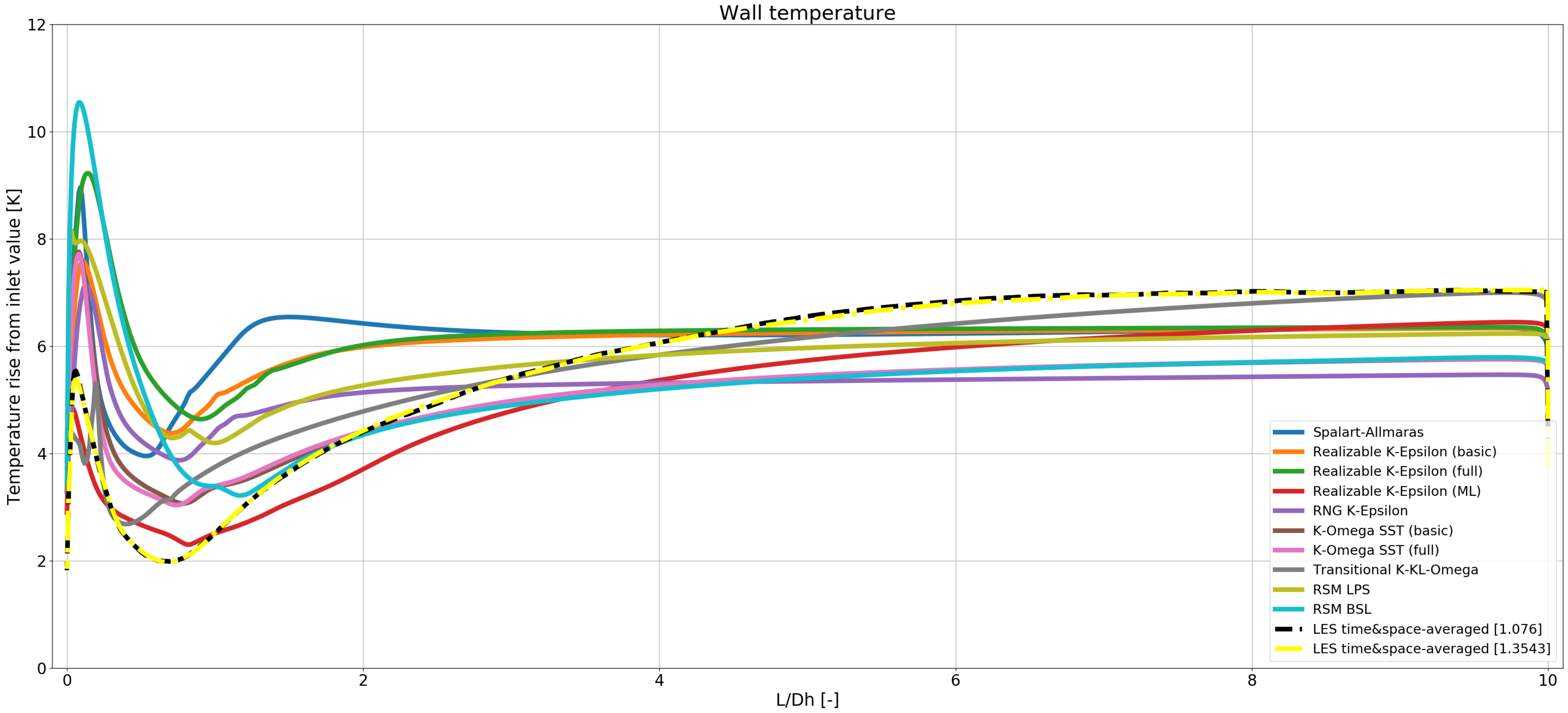
So what is really going on here? (3/6)

- And the answer is…



So what is really going on here? (4/6)

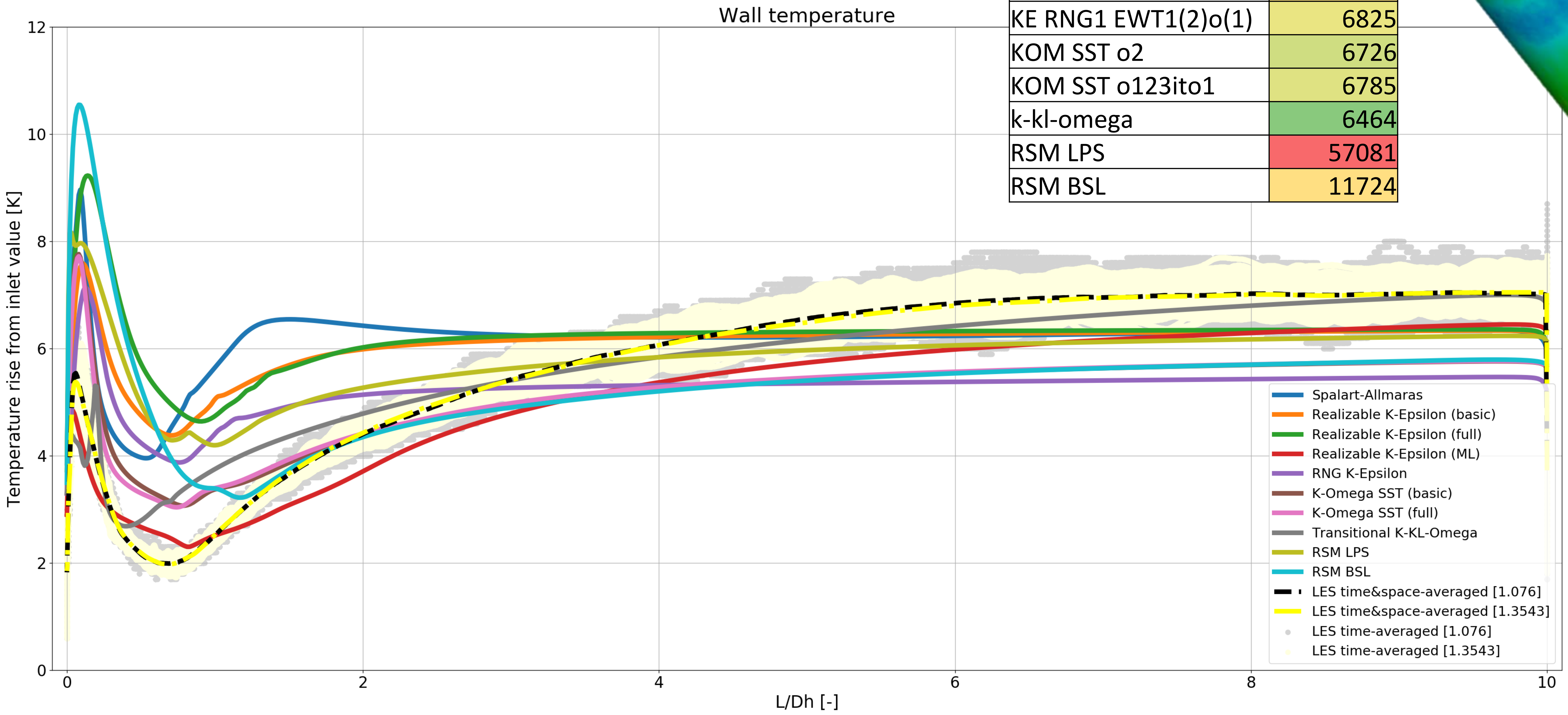
- None of them?

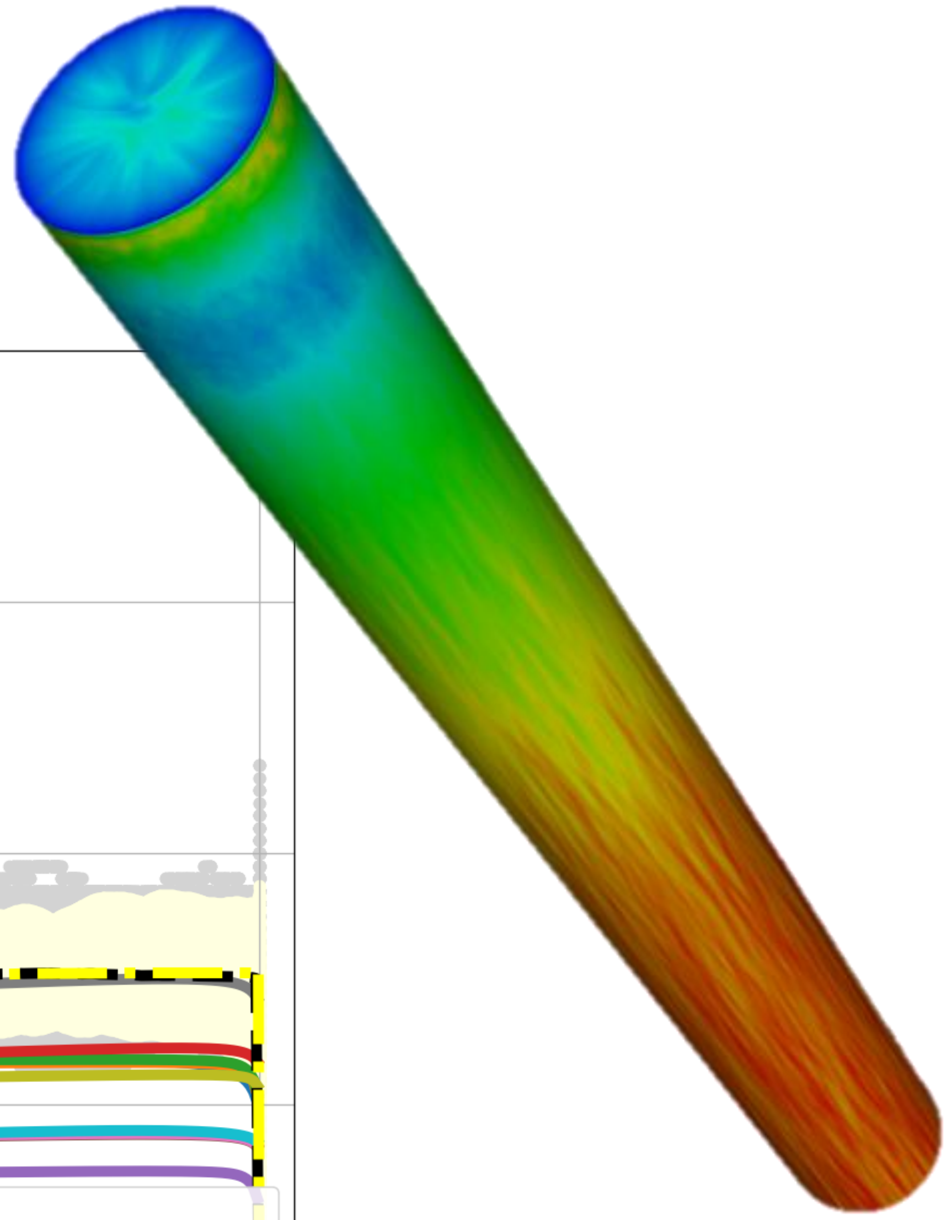


So what is really going on here? (5/6)

- Some candidates?

RANS model	iterations
SA VB VH	6322
RKE EWT	6976
RKE EWT1o23	8541
RKE ML	9359
KE RNG1 EWT1(2)o(1)	6825
KOM SST o2	6726
KOM SST o123ito1	6785
k-kl-omega	6464
RSM LPS	57081
RSM BSL	11724

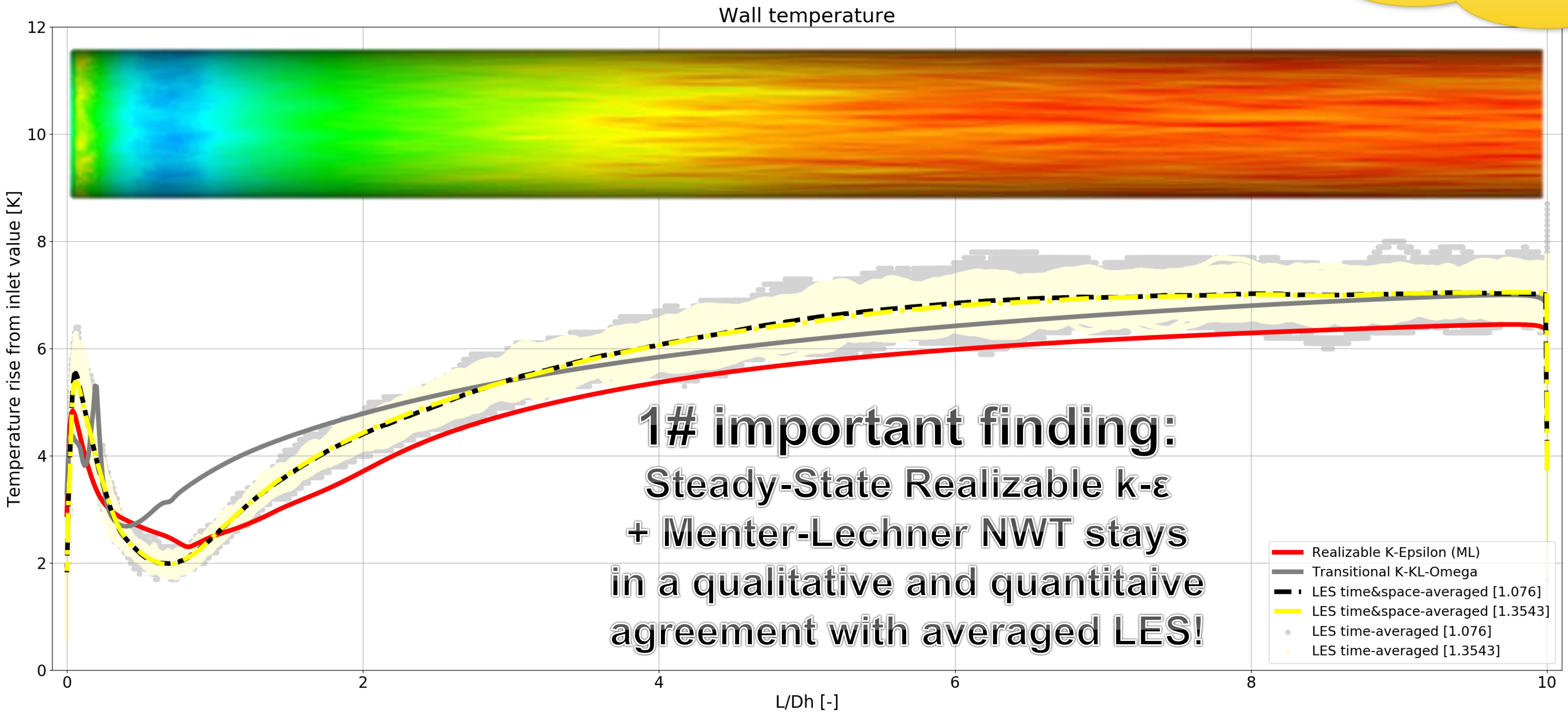




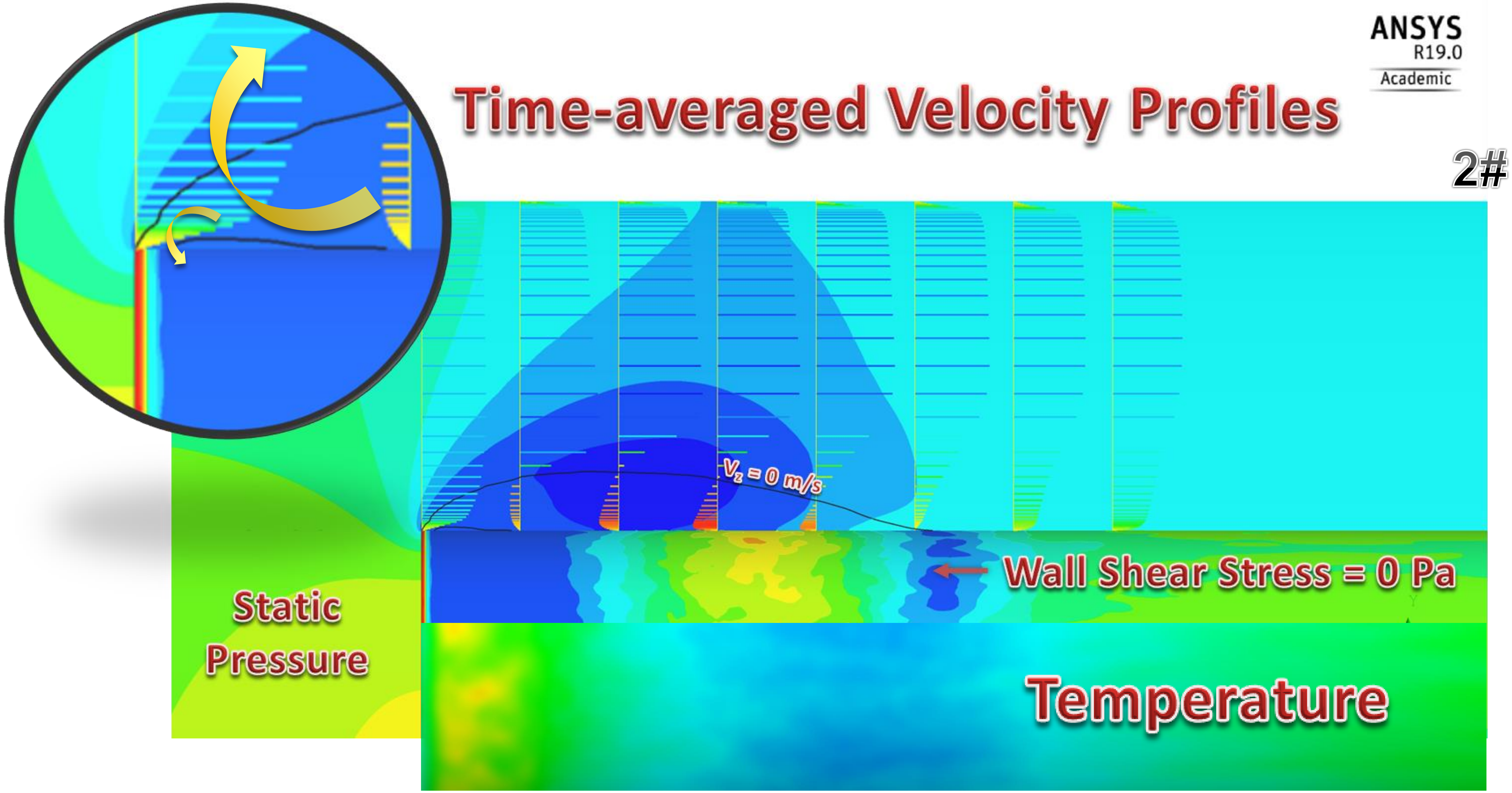
So what is really going on here? (6/6)

- Of course, but not without the drawbacks!

Interesting stripes, aren't they?



Let’s look closer to the vortex structure

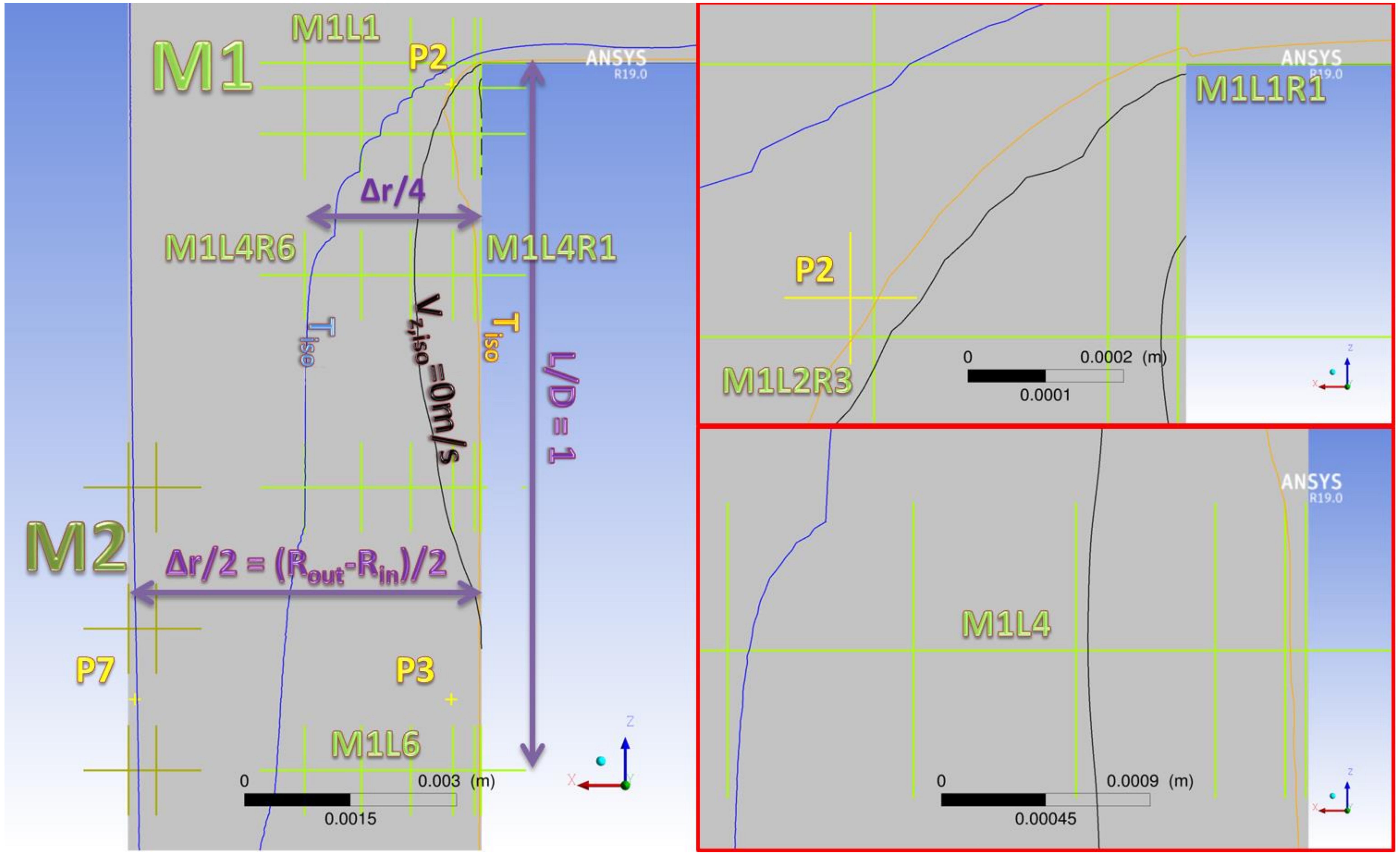


2# important finding:

There is no just one vortex but a complex of at least two counter-rotating toroidal vortices

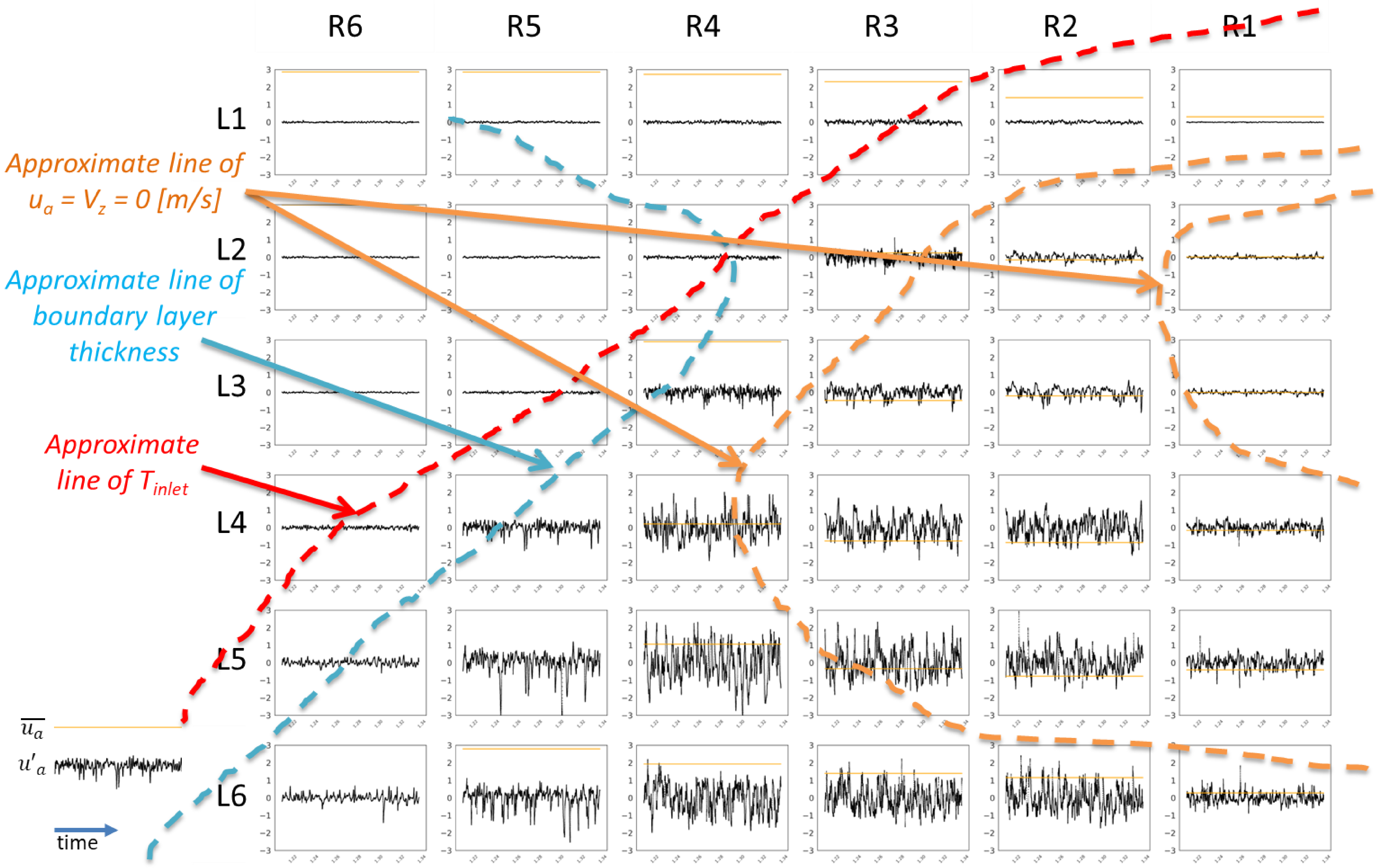
Time Signal Analysis - setup

- Samples out of BigData
  (50+ measurement locations)
  - Quadrant analysis
  - FFT analysis (*)



Fluctuation vs Averaged

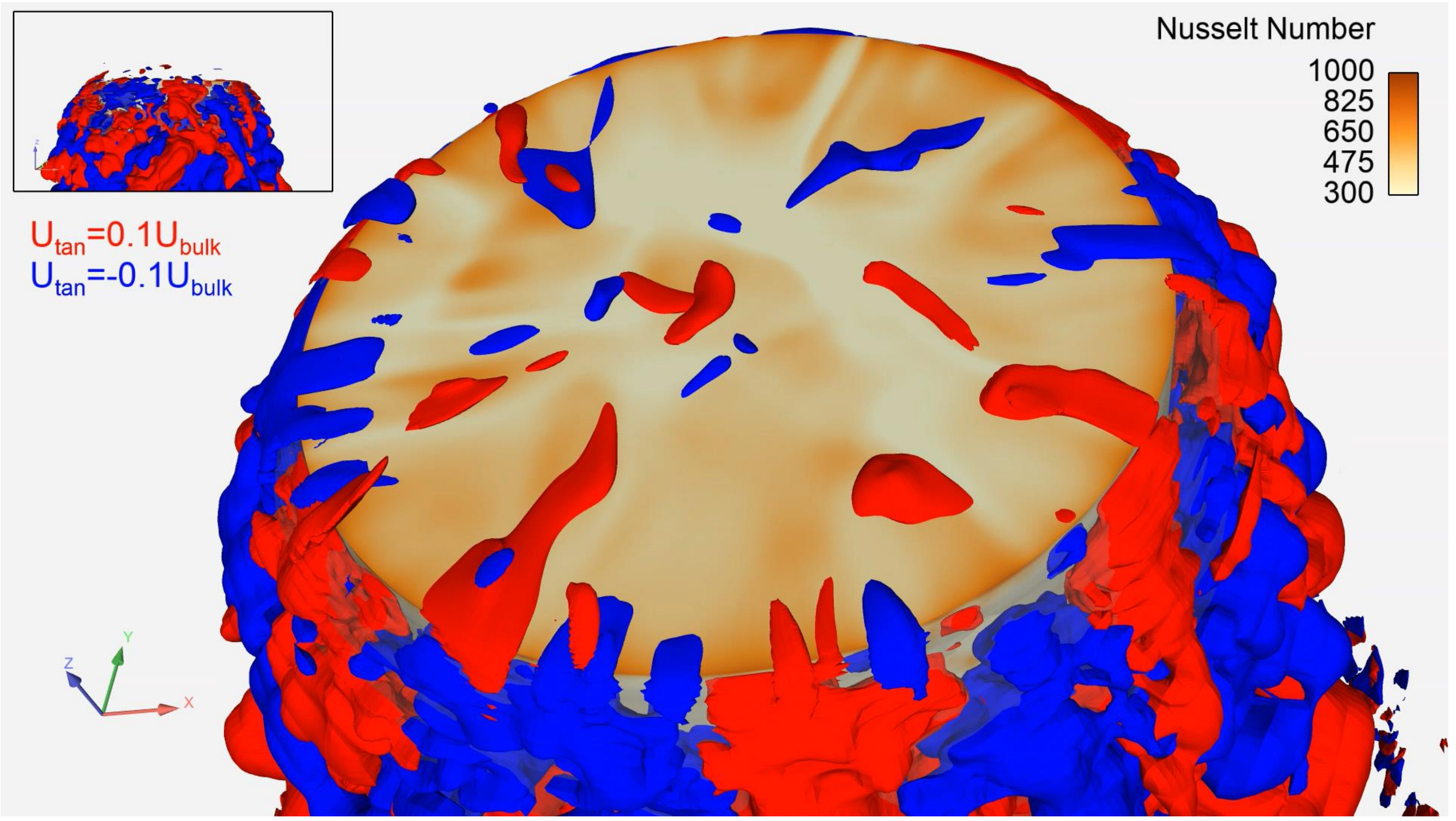
- Let's take a look at spatial distribution of averaged and fluctuative part of each velocity component at specified locations (matrix M1)

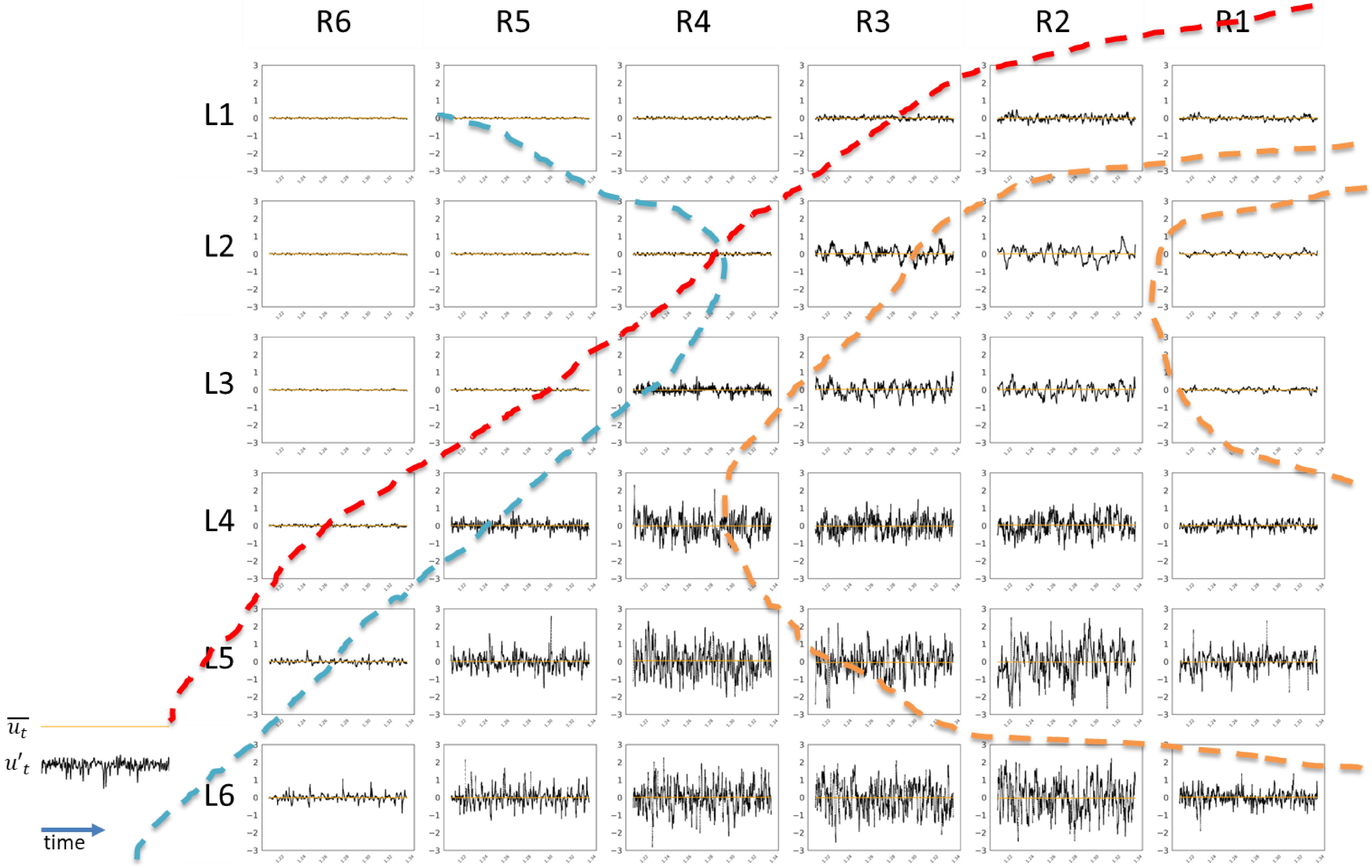


Tangential velocity

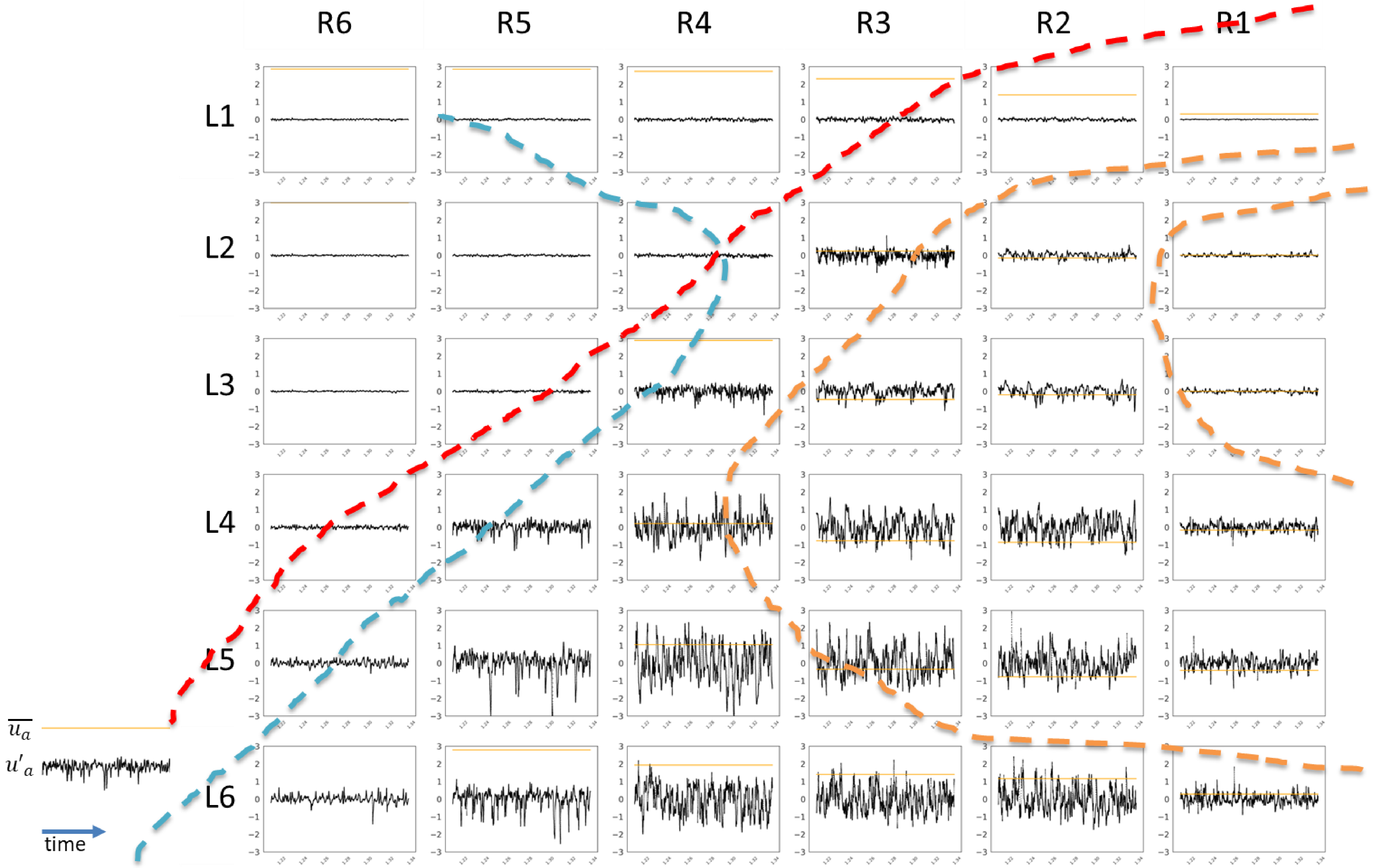
3# important finding:

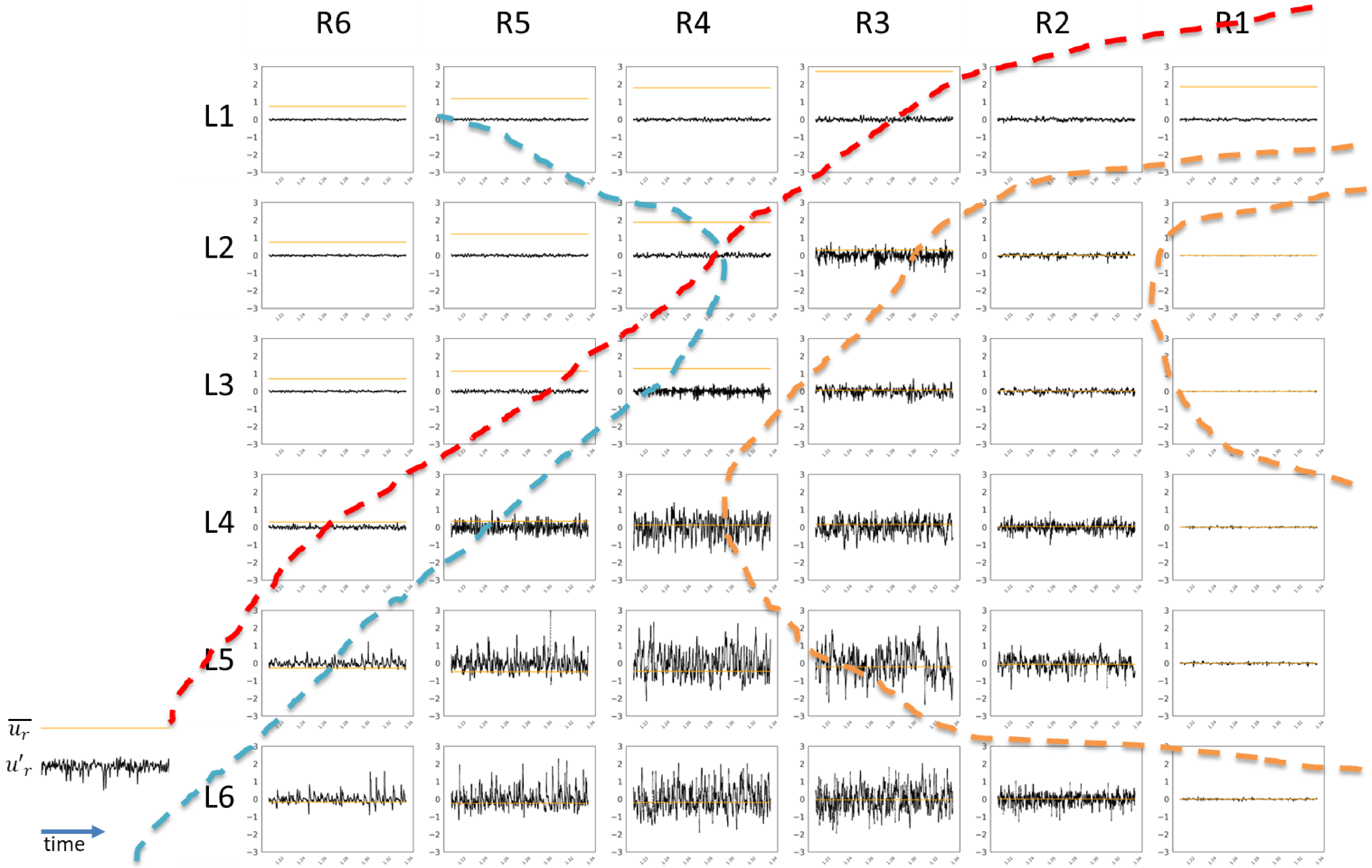
Instant tangential velocity component just after sudden contraction and the average inlet axial componet are of the same value!





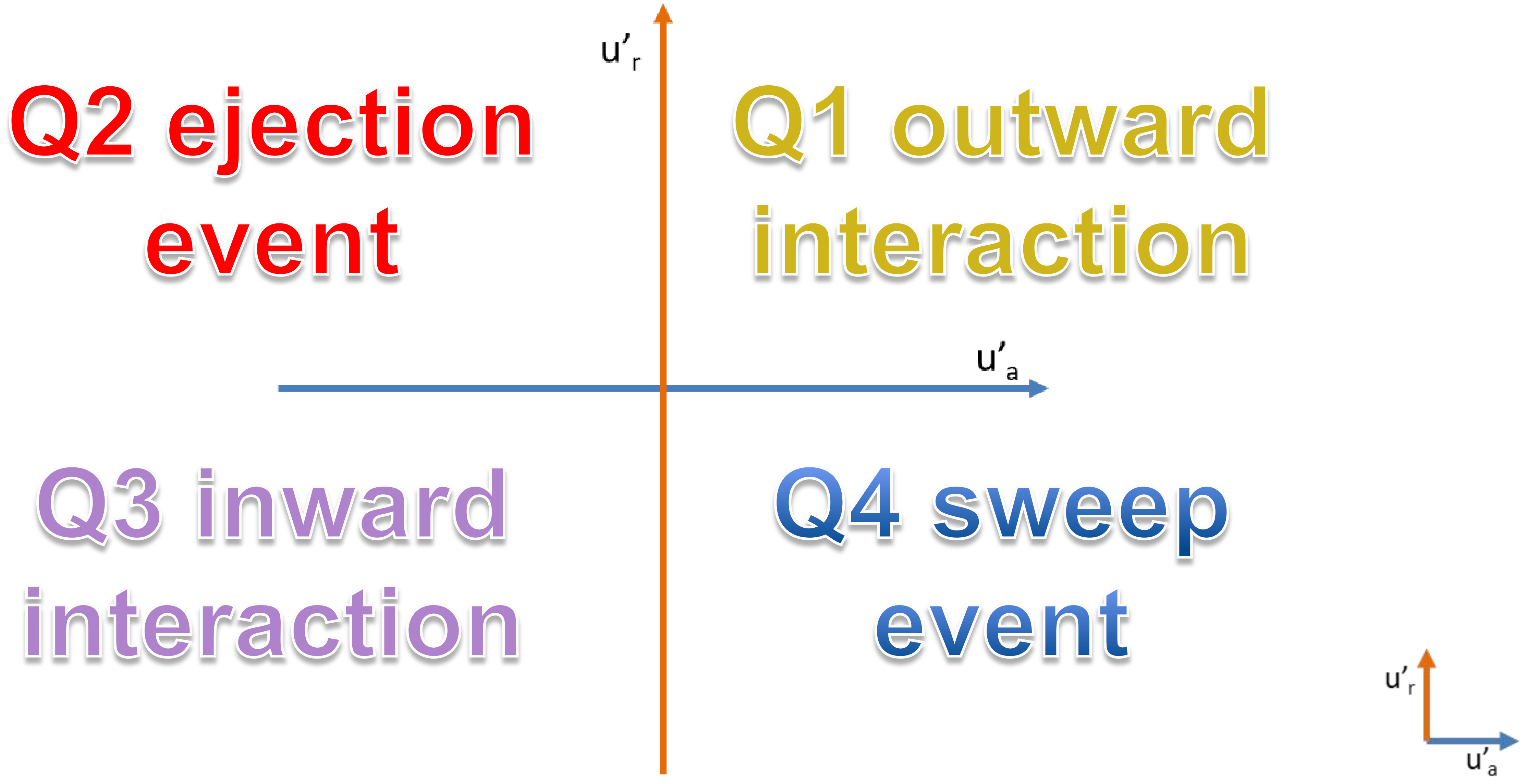
Axial and Radial velocity

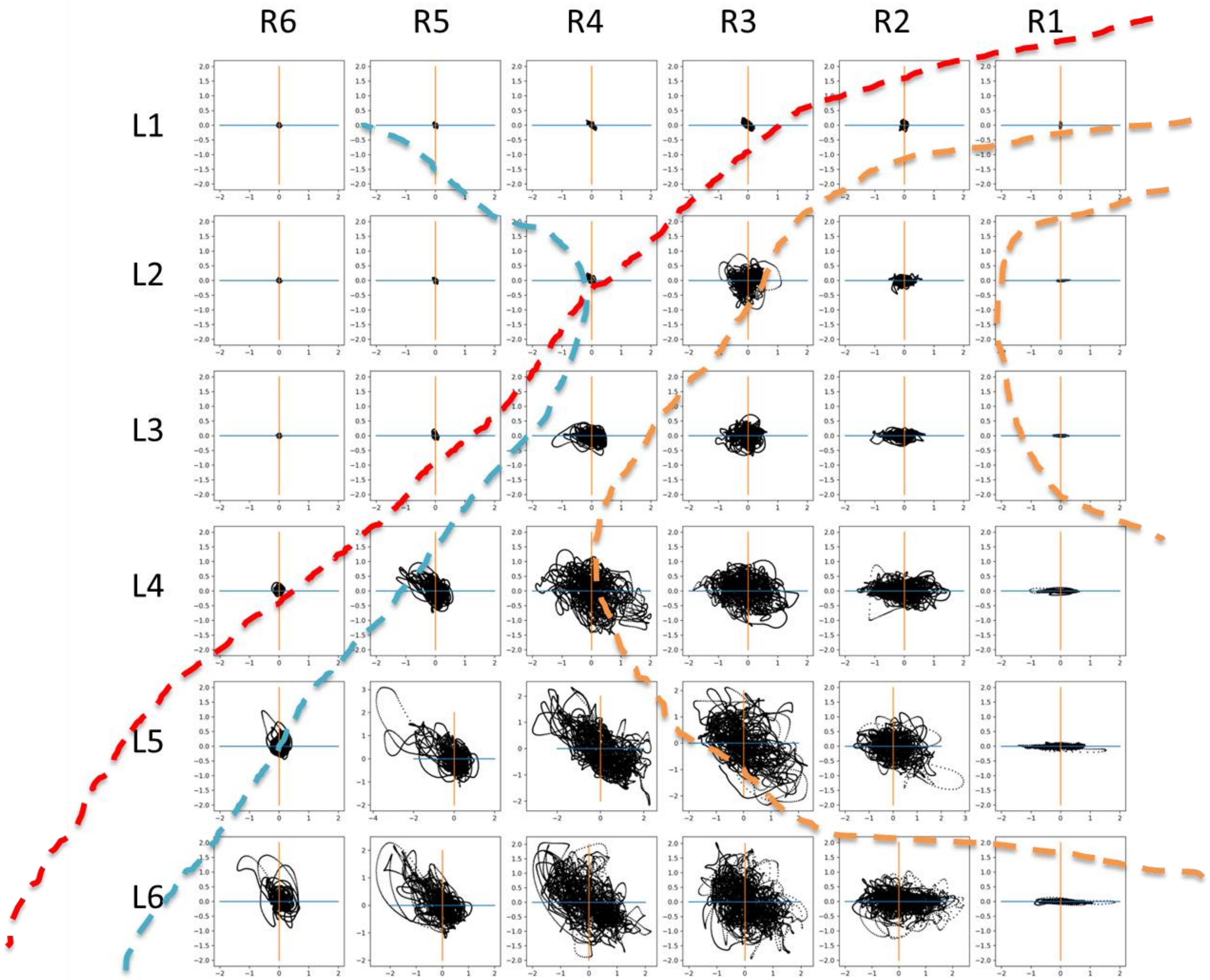




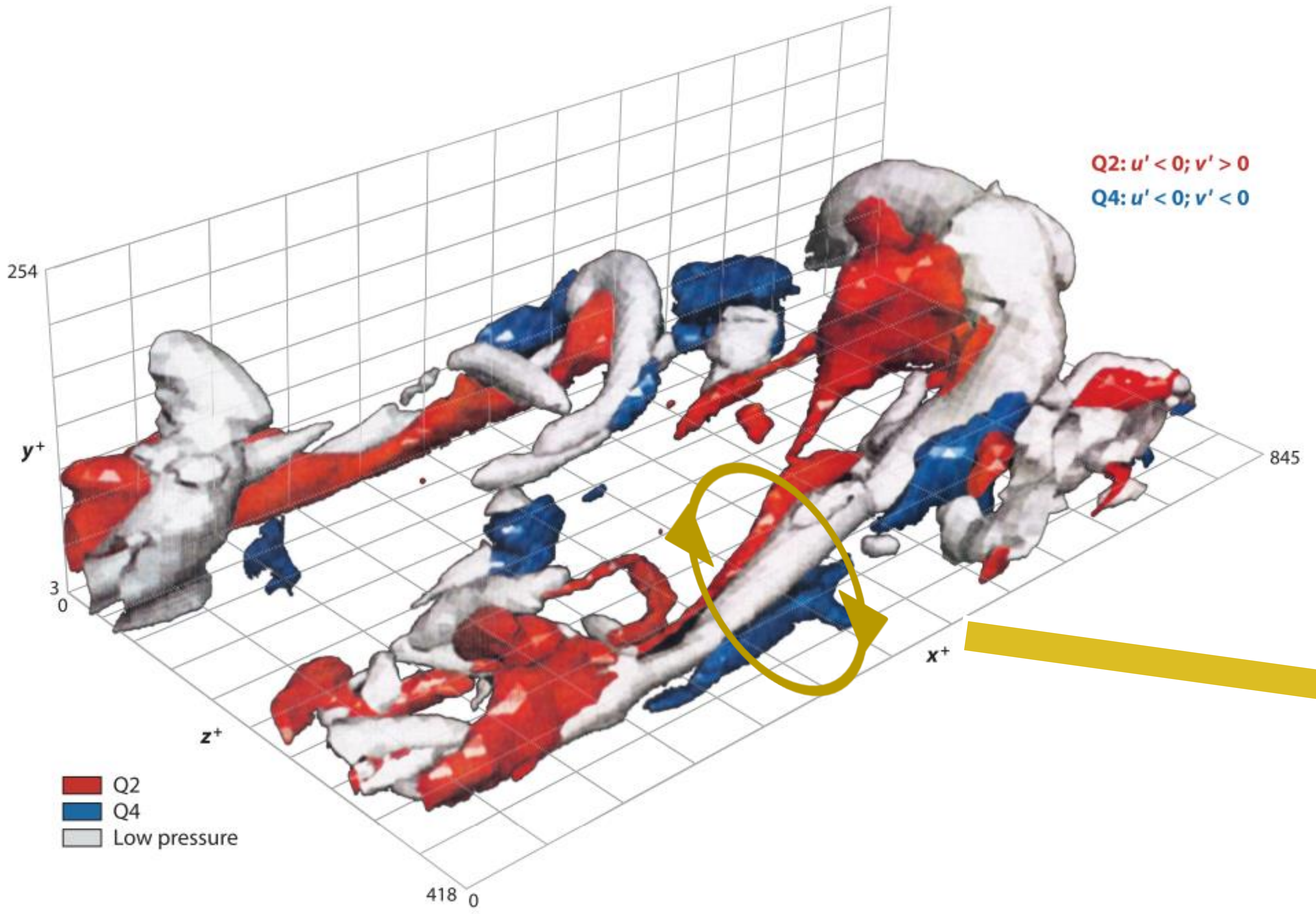
Quadrant Analysis - $u'_a\ u'_r$

- What if we look just at correlation between fluctuations of parallel velocity components?

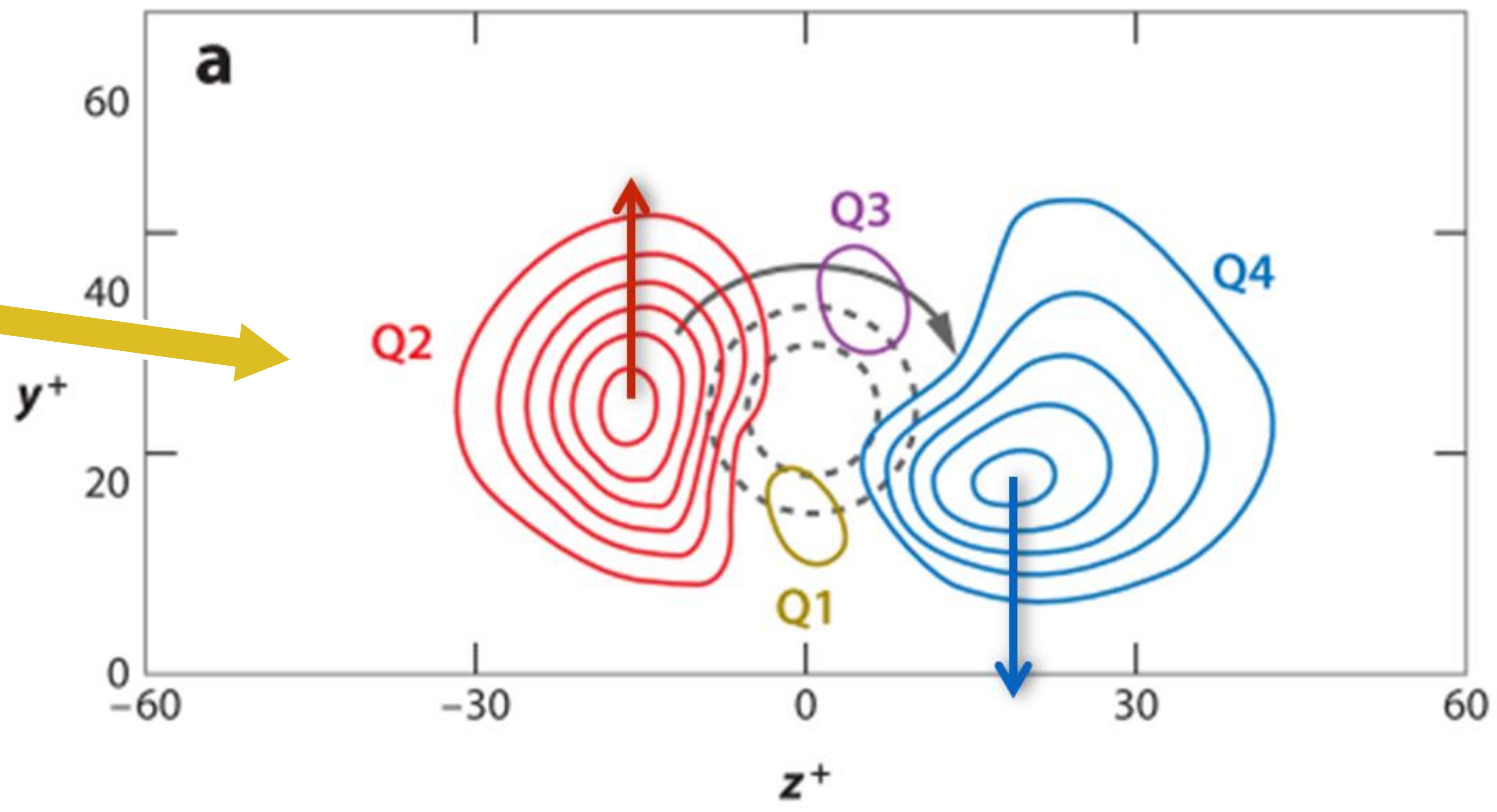




Quadrant Analysis

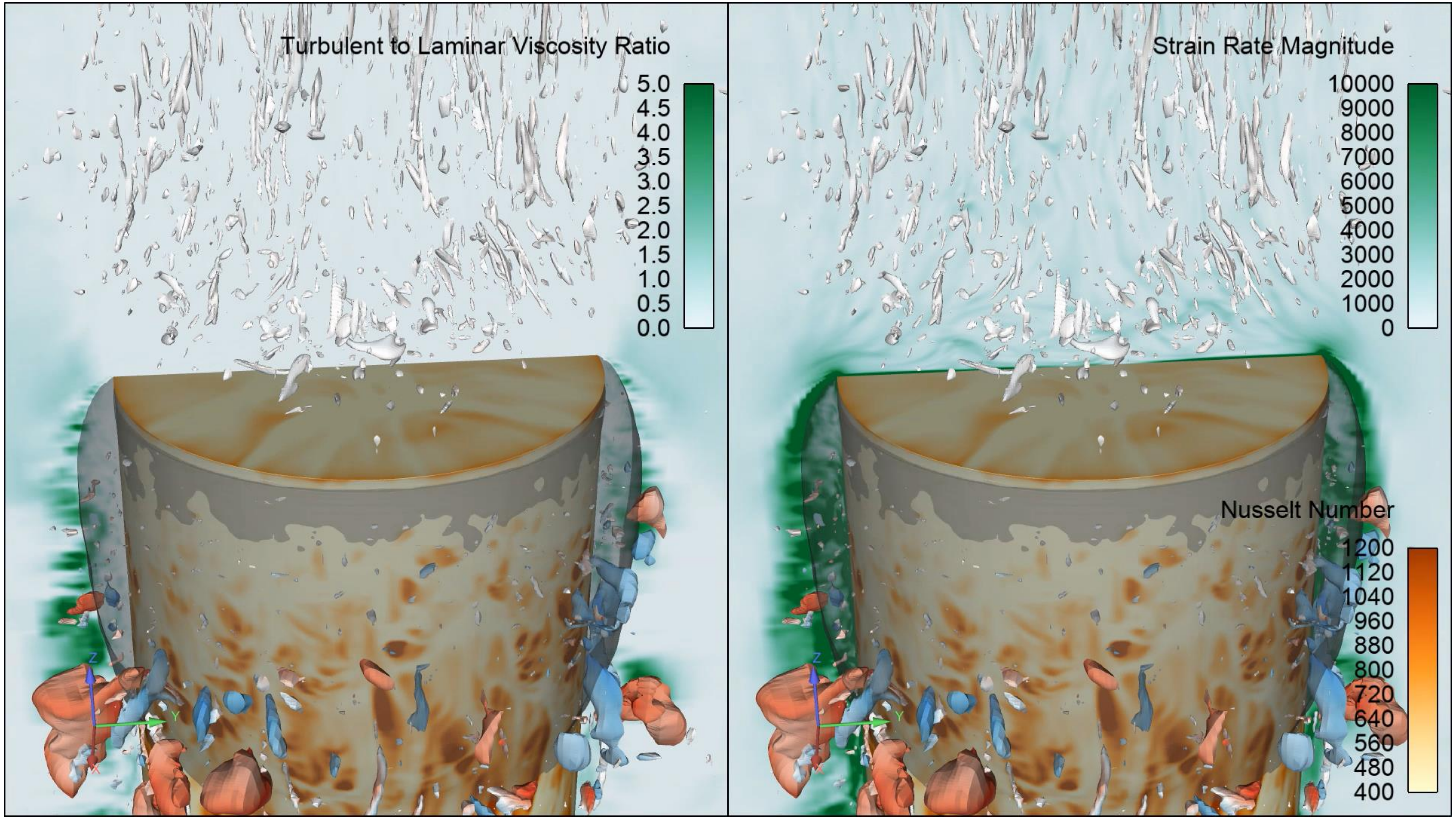


- Smart tool for vortical structures indication



J. M. Wallace (2016) *Quadrant Analysis in Turbulence Research: History and Evolution*, Annu. Rev. Fluid Mech. 48:1, 131–158, DOI: 10.1146/annurev-fluid-122414-034550

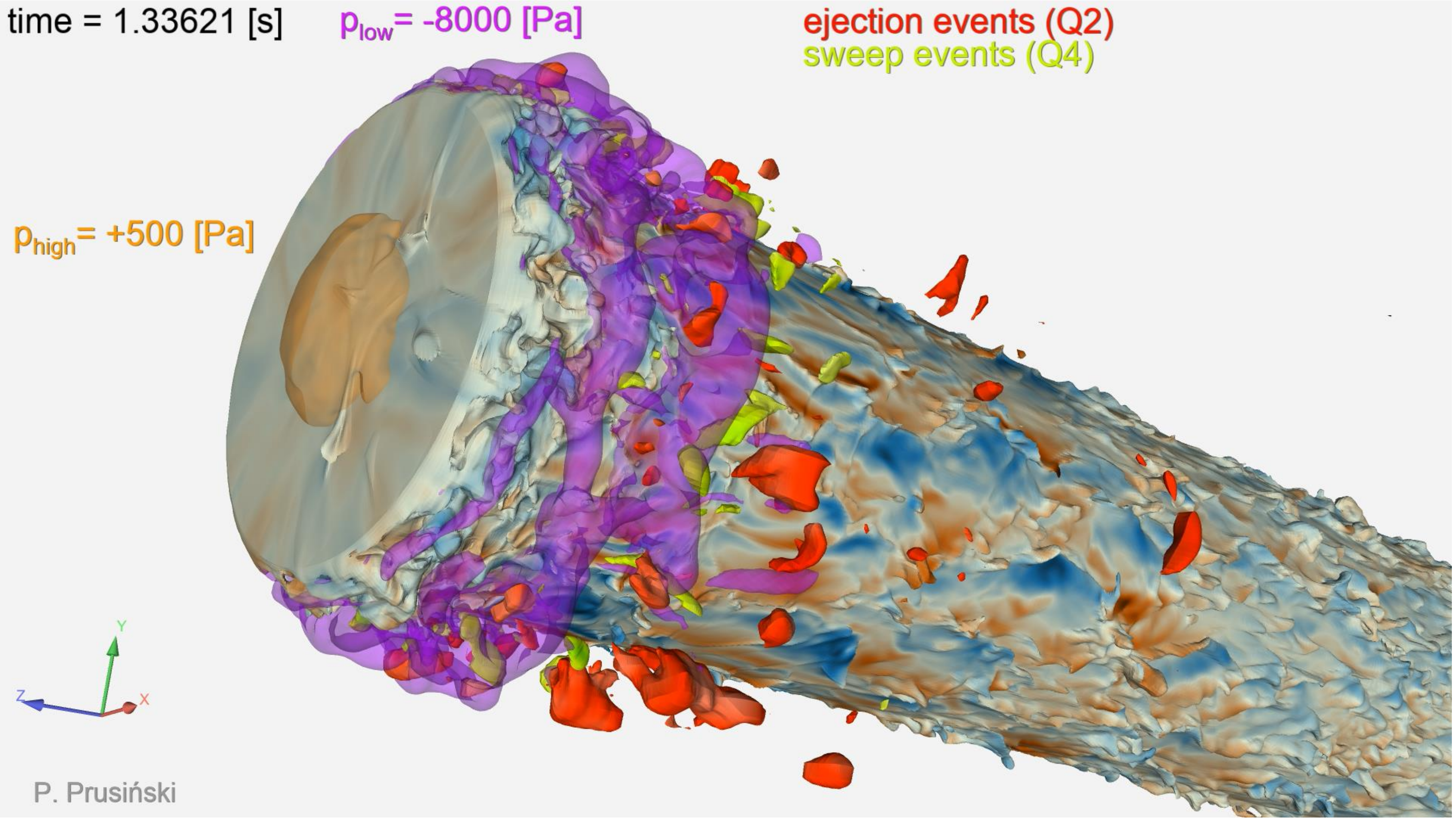
Quadrant Analysis in practice (1/2)



4# important finding:
Surface of zero axial velocity as a surface of maximum strain rate becomes a breader for strong vortical structures

5# important finding:
Sweep touching the surface bursts local heat transfer

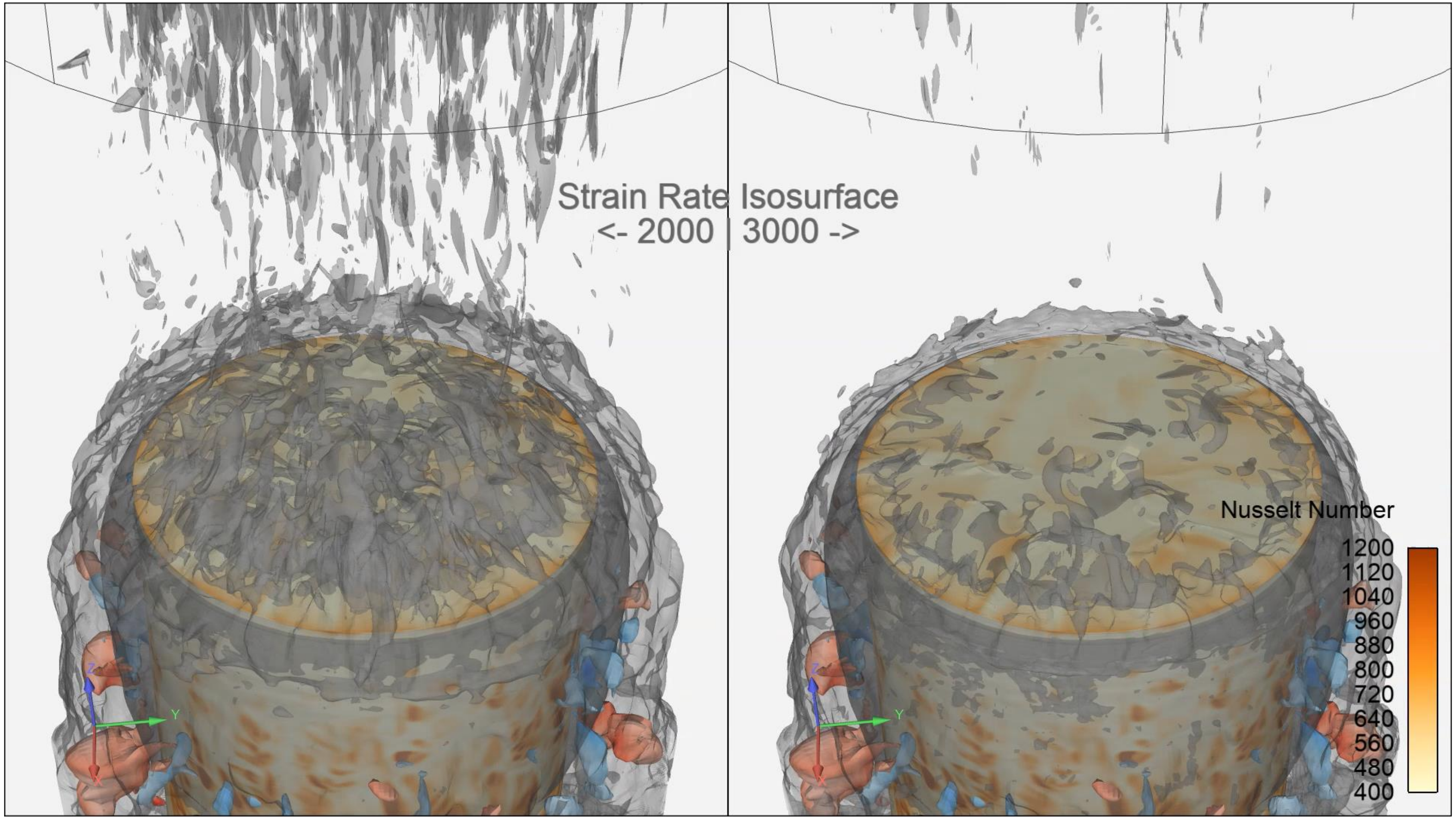
Quadrant Analysis in practice (2/2)



6# important finding:

Choaking (pressure pulsation) due to sudden bluff-body-type contraction has no effect on turbulent structures emerging in annular zone

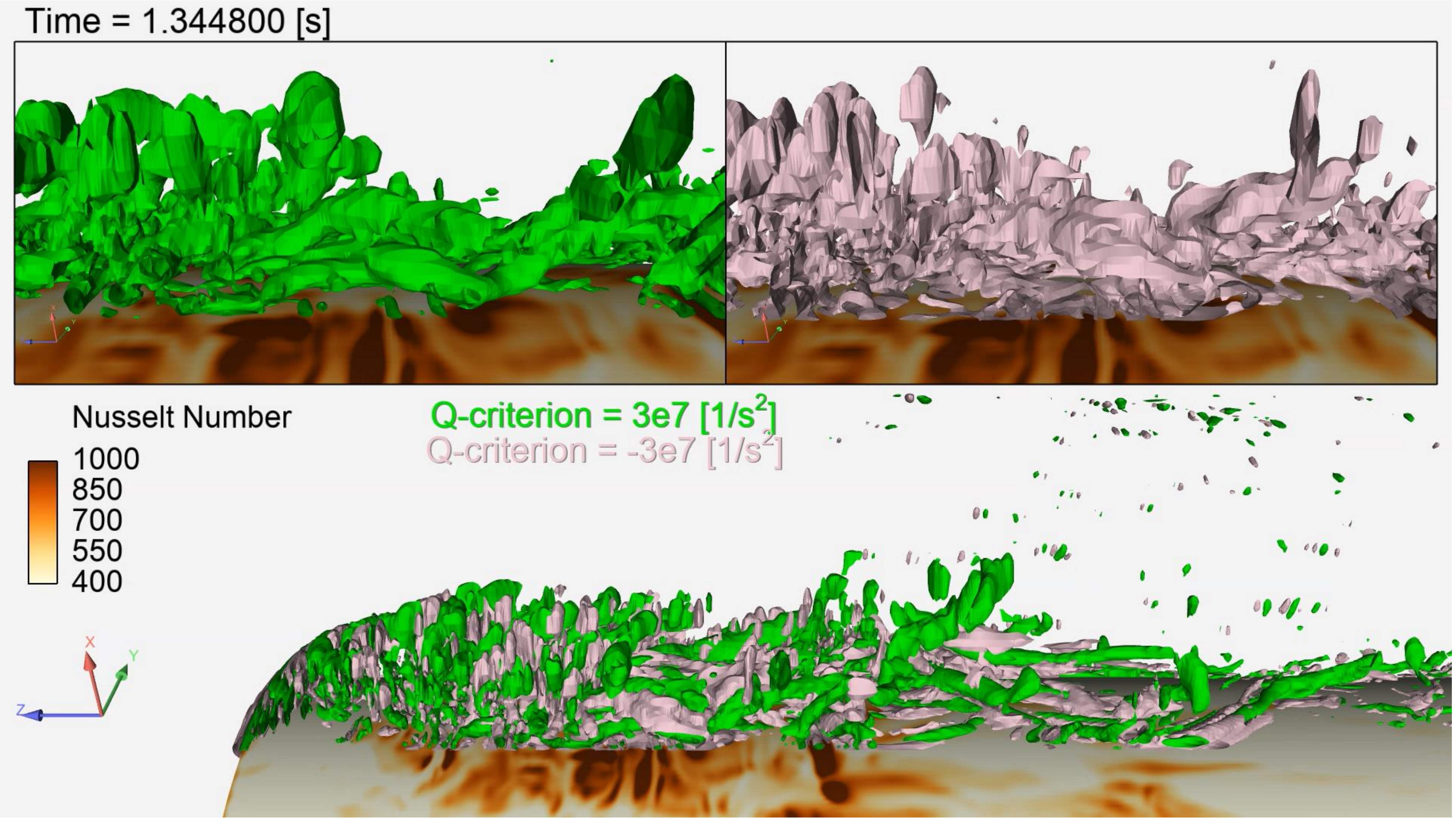
Flow before the obstacle



- The closer to the flat front the stronger strain rate and tangential velocity become!

7# important finding:
Annular flow pattern is just a result of upstream flow history, i.e. strain rate distribution that amplifies when approaching flat front!

Possible scenario

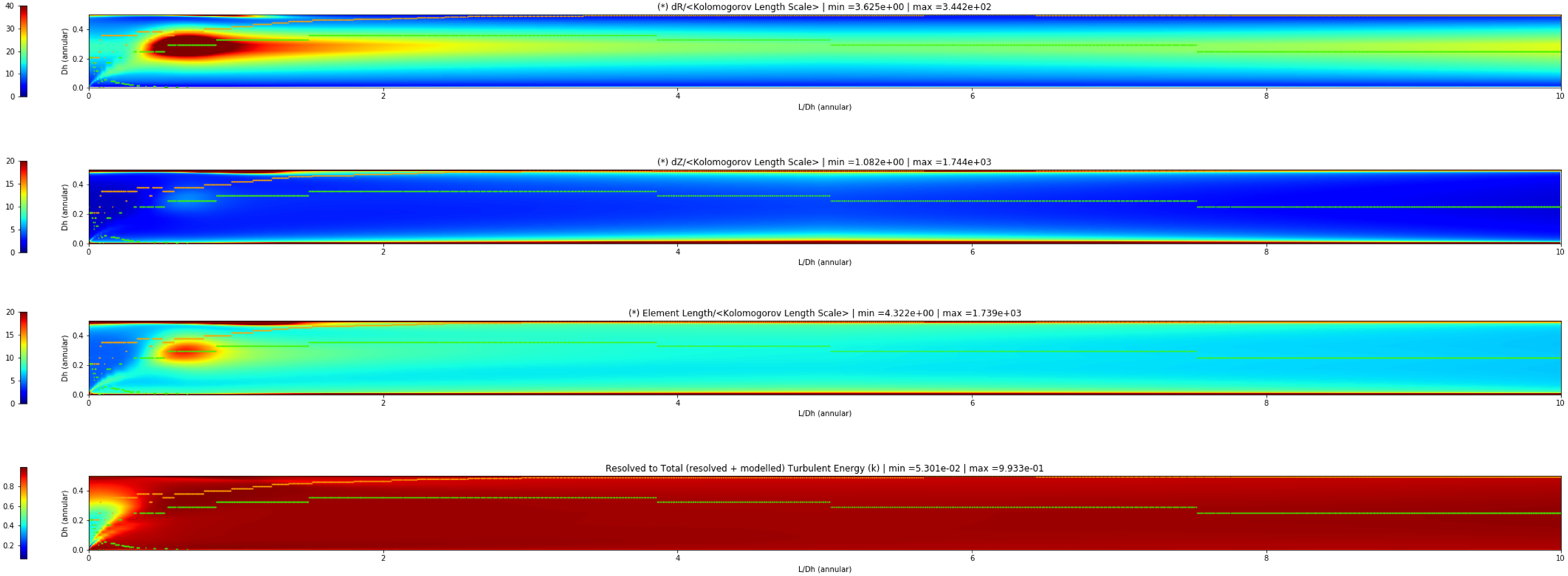


1. Developed turbulent flow, passing smooth pipe of inlet section, carries some weak streamwise voritcal structures. Those structures become condensed and hence stronger when approaching flat front of bluff body.
2. When passing a leading edge, they shift their shape into rings along the maximum strain rate surface, getting even stronger due to toroidal vortex pair.
3. The maximum strain rate surface breads Q-event structures.
4. Some fraction of vortical structures detach from the surface close to vena contracta (probably) due to ejection events.
5. At the same time, sweep events burst local heat transfer when hitting inner rod surface.
6. When detached, strong turbulent vortical structures start to reorient thier axes towards streamwise direction and elongates.
7. Elongated structures of alternate (+/-) rotataion pattern imprint either on fluid temperature isosurfaces and on inner rod wall surface.

But how do we know the LES results are valid?

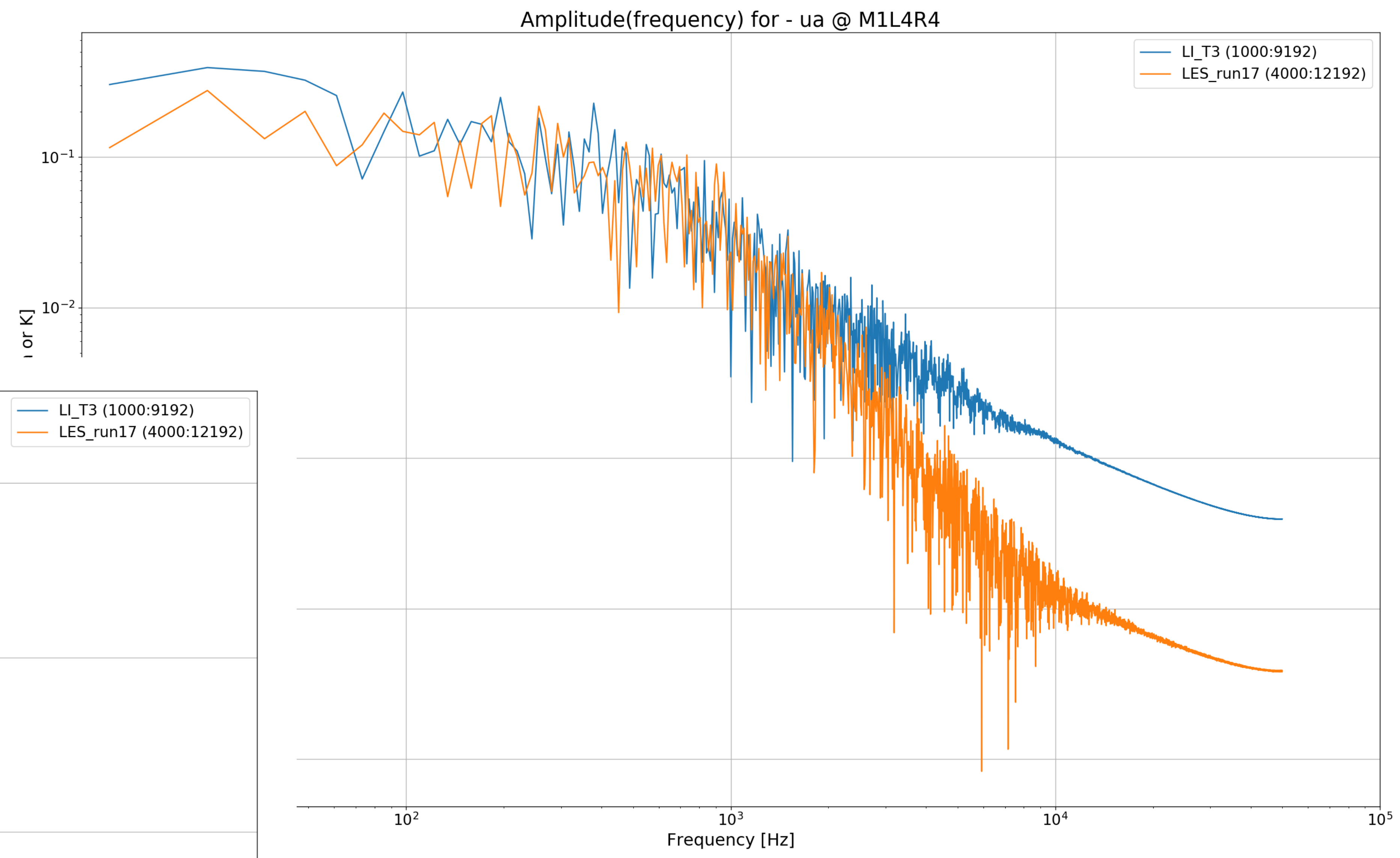
- Exactly! No predecessor in the literature of subject, no experimental database available, so how to prove the numerical results are valid?
  - Let’s try to:
    - assure LES approach accuracy
      - Mesh resolution
        - » Kolmogorov length scale
        - » How Turbulent Kinetic Energy resolved, how much modelled
      - Proven boundary condition
        - » Do the results depend on the inlet location?
        - » Is the inlet velocity profile trully developed?
          - Periodical smooth pipe with anisotropic turbulence model
            - Accidential discovery regarding spatial-isotropic nature of RSM BSL
          - Random Flow Generator by Smirnov
      - Why Dynamic Smagorinsky LES?
    - be conservative and critical (expecially when pre- and post-processing)
      - Avoid unnecessary calculations
      - Avoid unnecessary interpolations

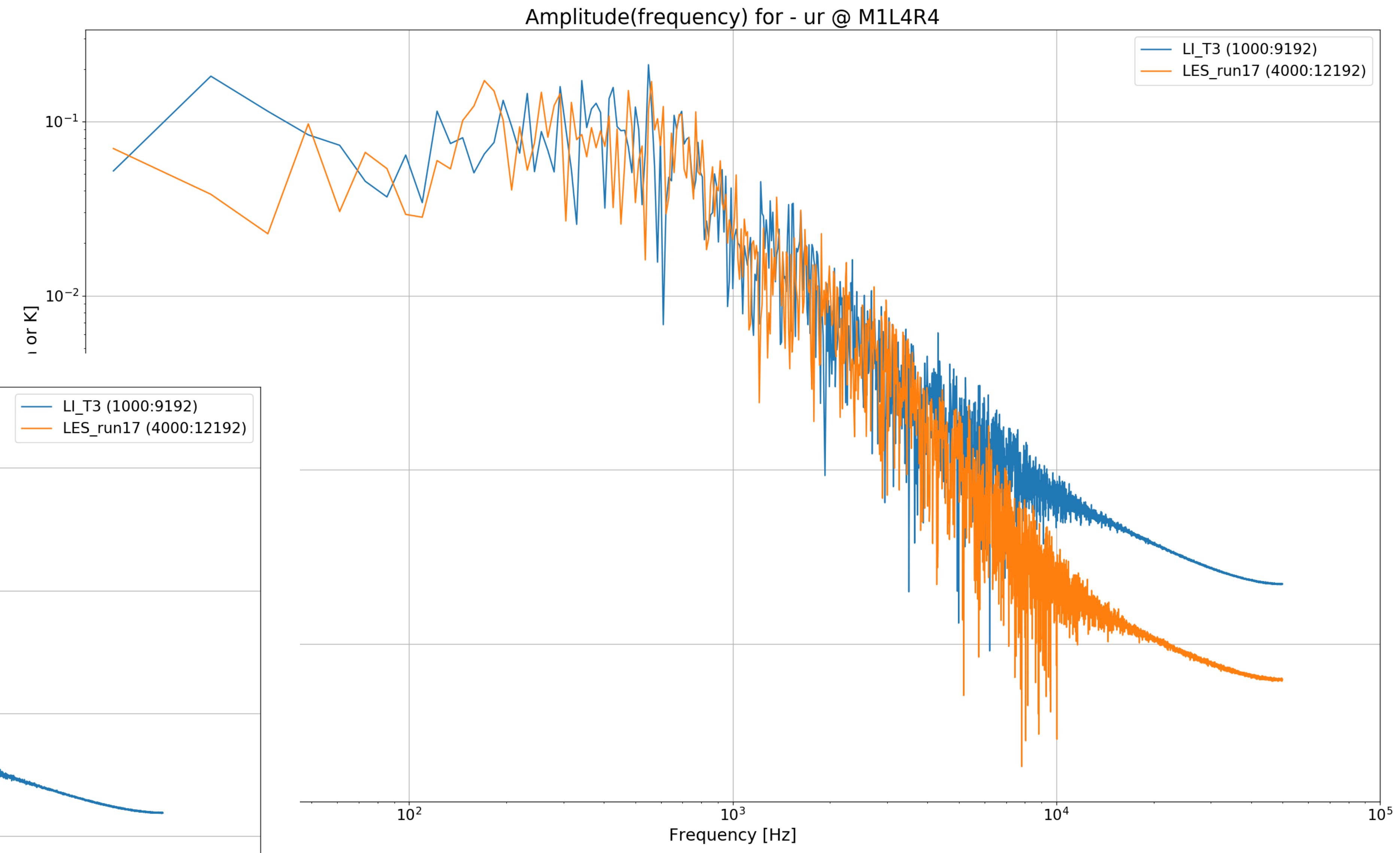
Mesh resolution

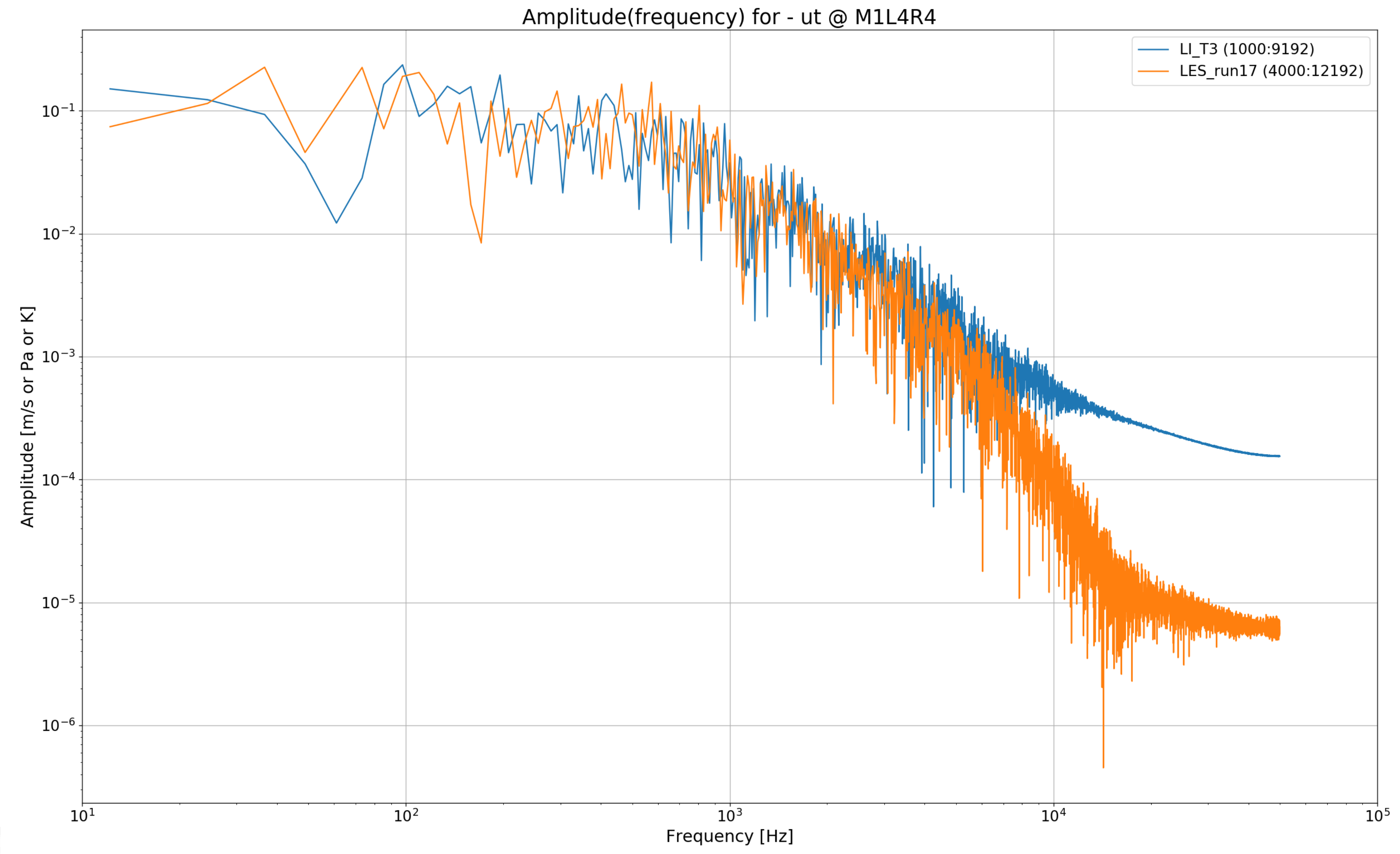


Do the results depend on the inlet location?

- Acceptably small difference even for the toughest example (and short sampling period ≈ 0.08 s)







Why Dynamic Smagorinsky LES?

- Because of its proven superiority

„(…) Slightly better agreement with the PIV measurement can be seen for the DSM SGS model, compared to the WALE SGS model. This is an effect of the dynamic constant of the DSM SGS model, which makes it more suitable for a variety of different flows. (…)”

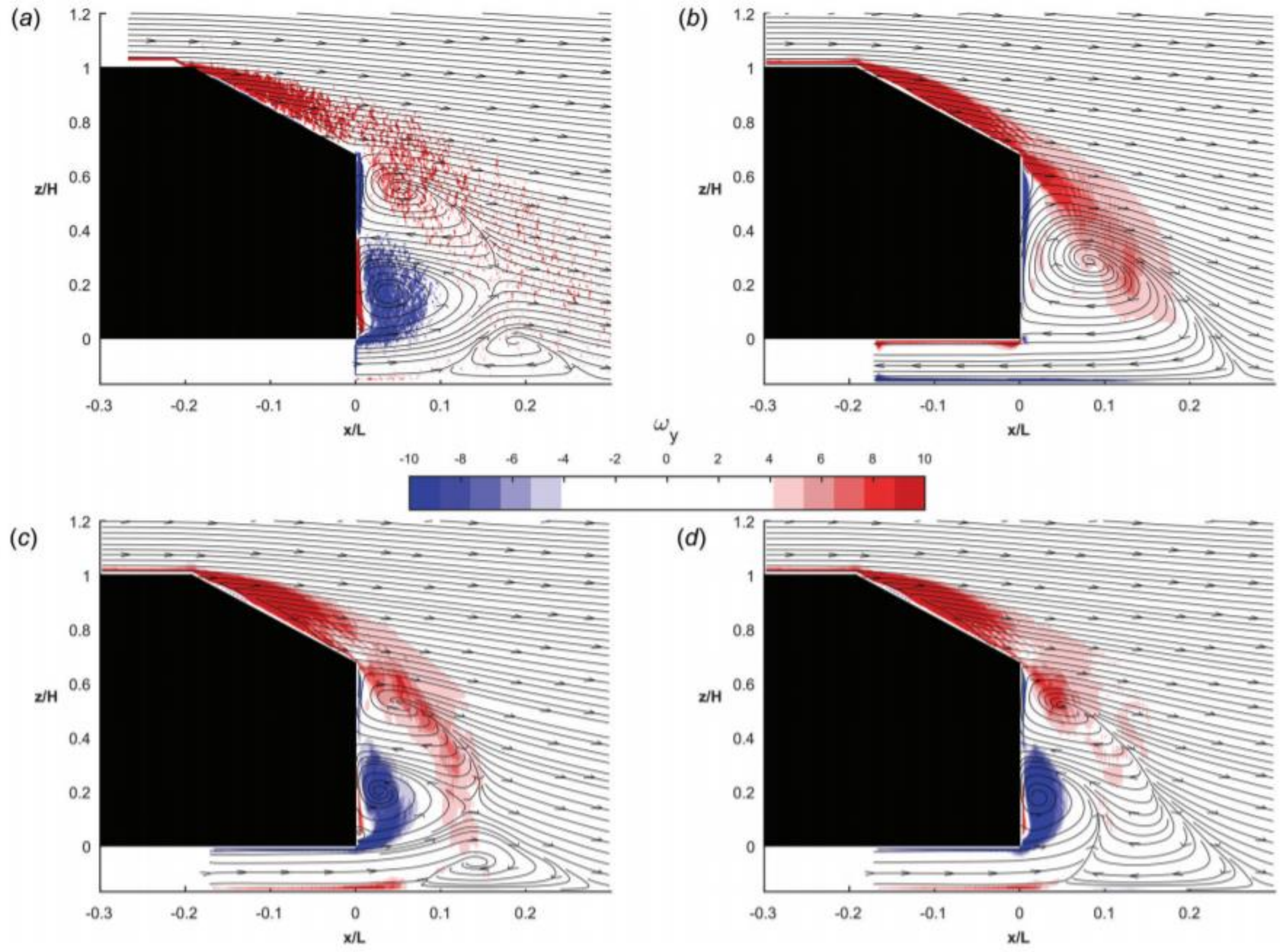
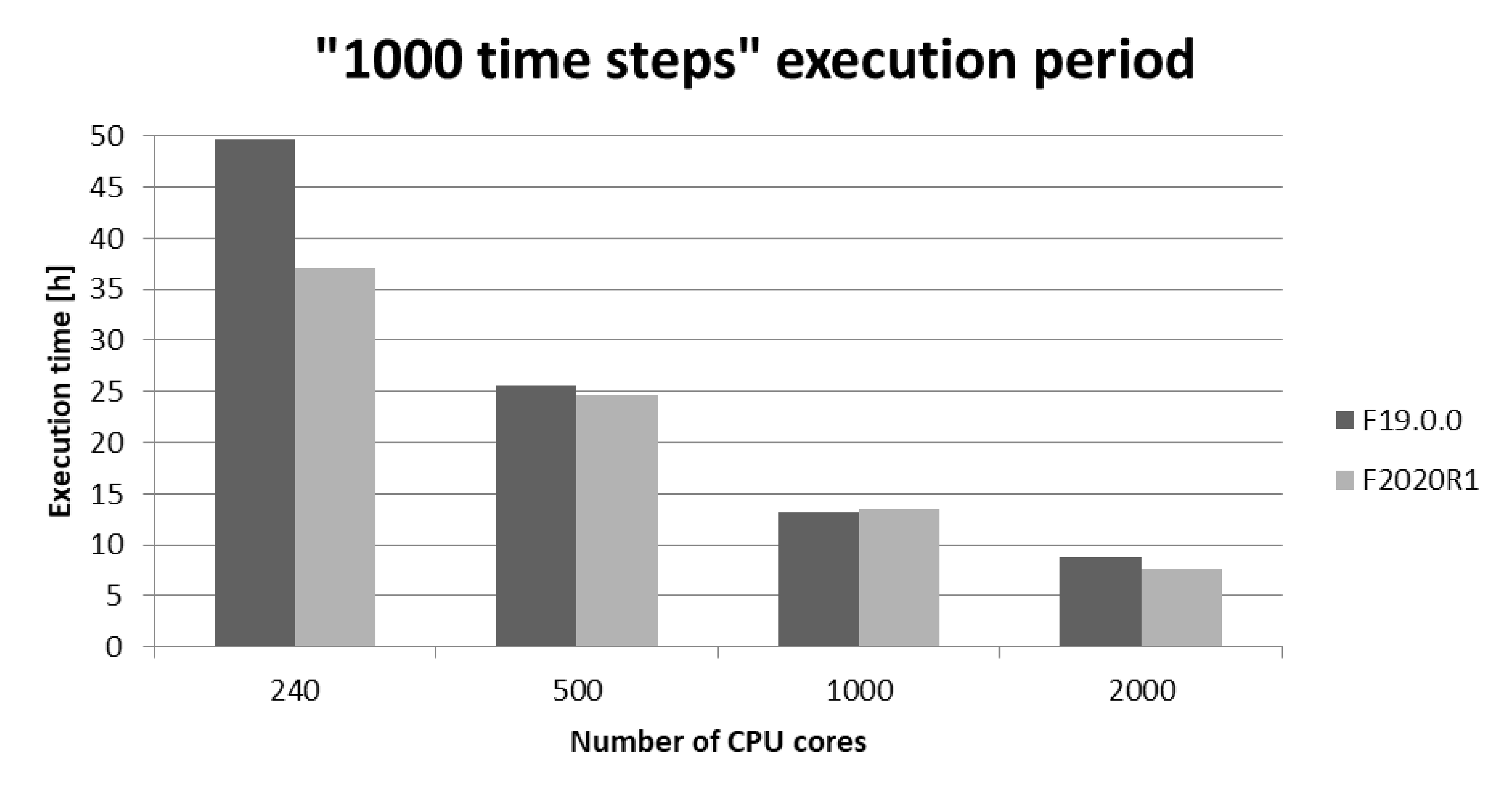


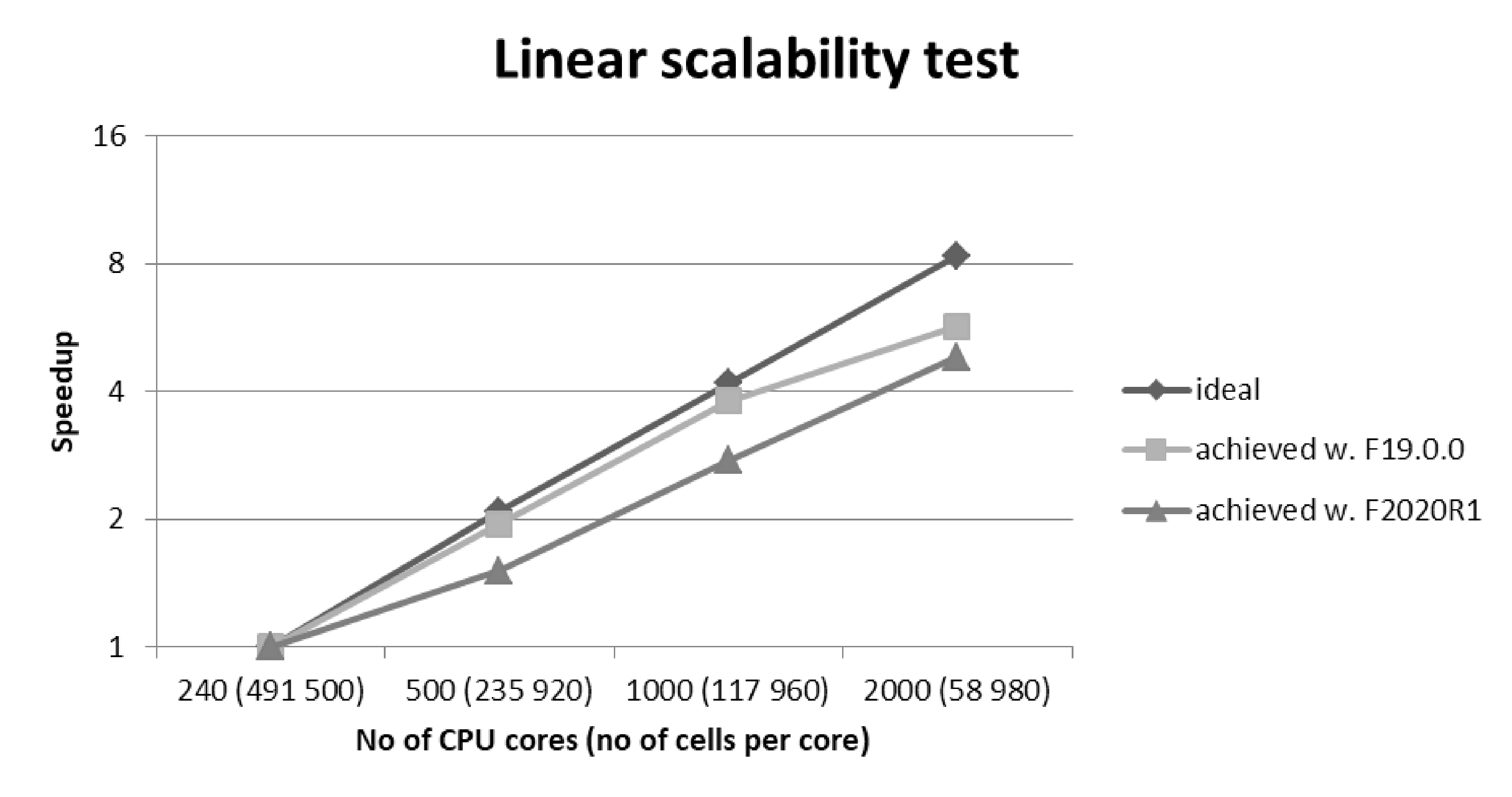
Fig. 7 Time-averaged 2D streamlines and spanwise vorticity in the *y/W* = 0 plane for PIV measurement (*a*), SM model (*b*), DSM (*c*), and WALE (*d*)

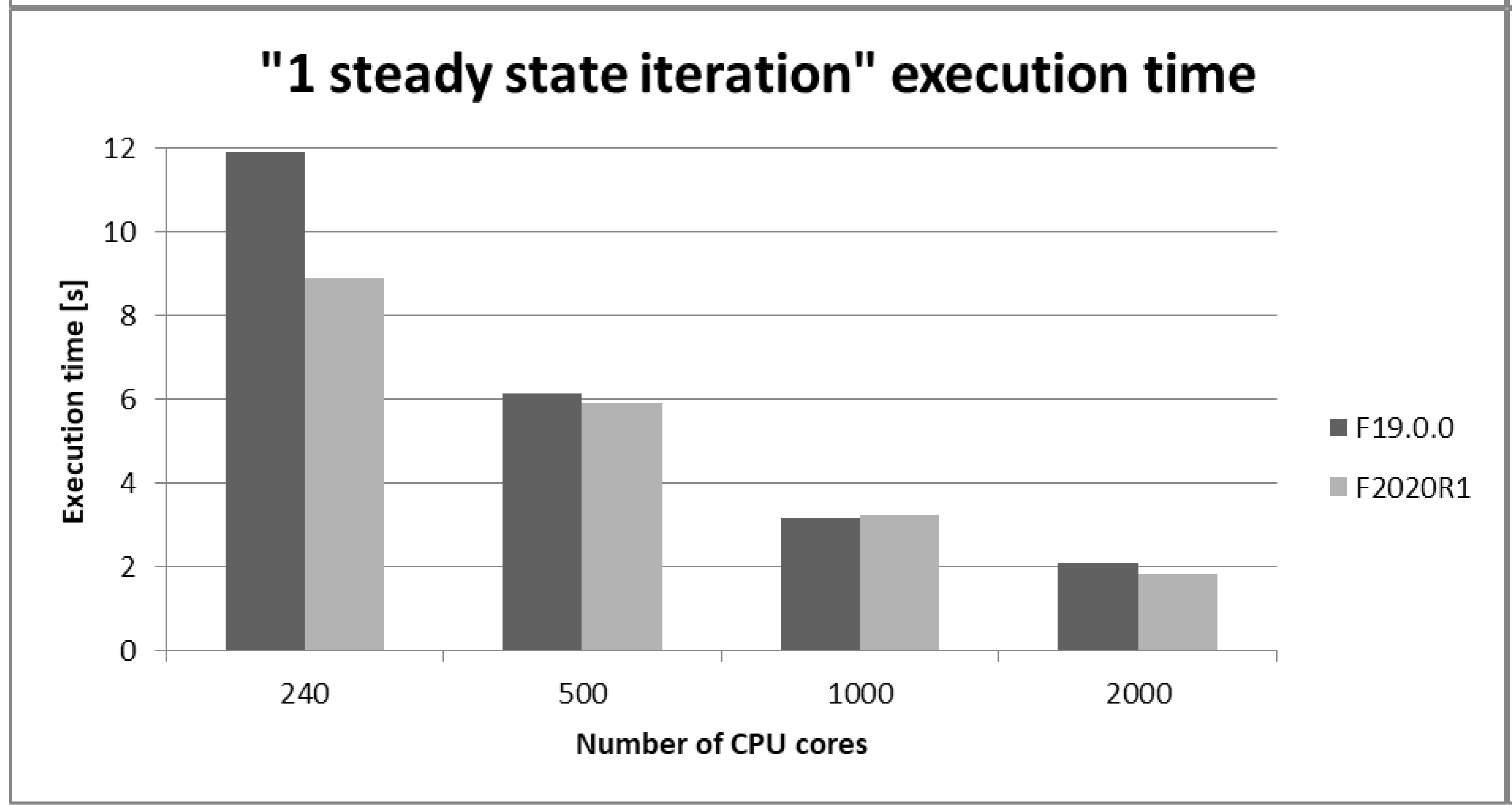
P. Ekman et al. (2021) *Importance of Sub-Grid Scale Modeling for Accurate Aerodynamic Simulations*, Journal of Fluids Engineering, 148, TBD, DOI: 10.1115/1.4048351

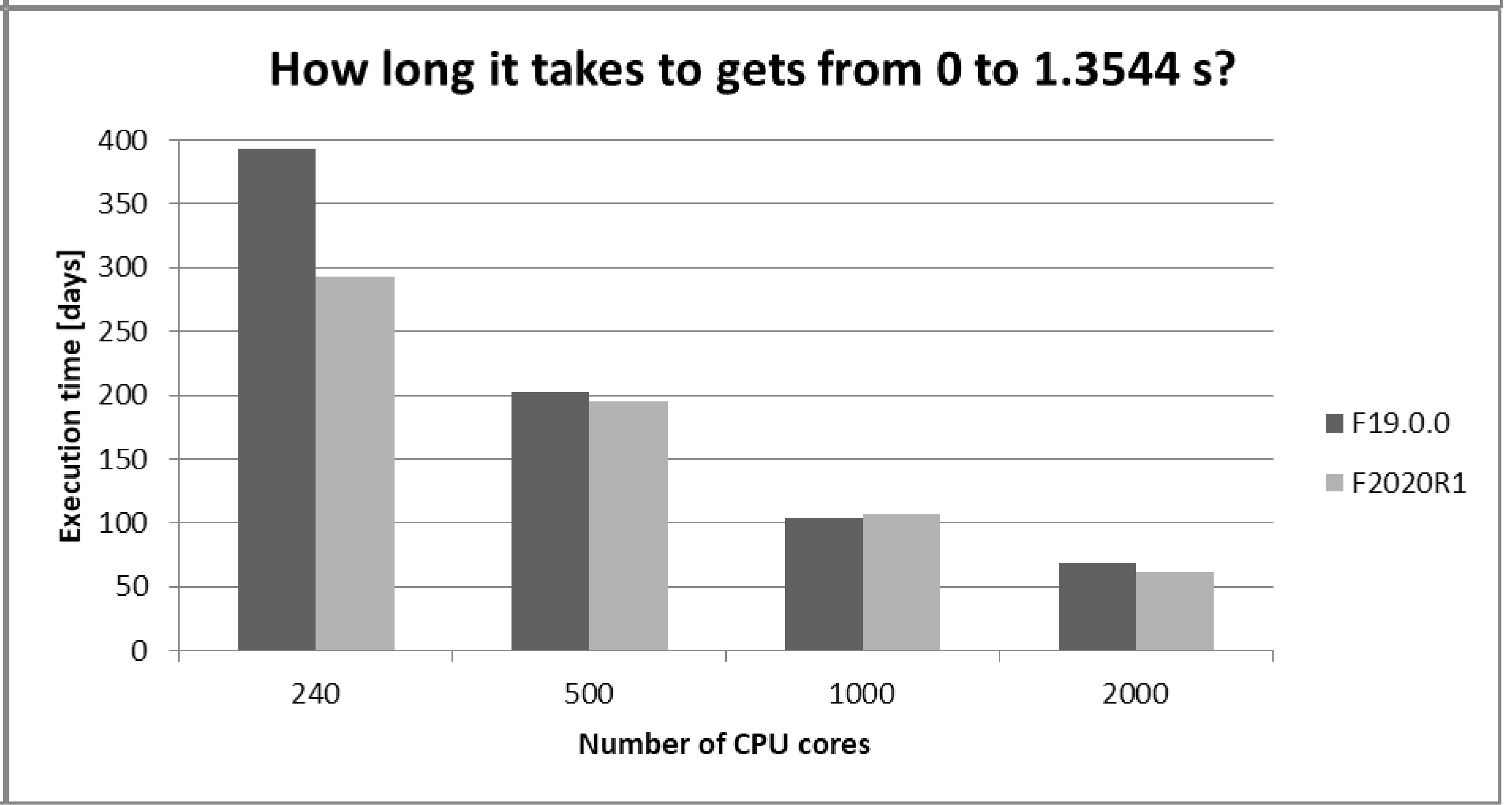
Why it takes so long?

- Up to now LES went through 135 440 timesteps (2 849 100 it)
- Computational time is tangled with number of software licences available, i.e. 1 licence = 1 CPU core









Other limitations (1/2)

- Fluent input size (120M hex, LES): 11.4 GB (*.cas) + 93.3 (*.dat)
- Disk space occupancy: 300 TB+, mainly due to post-processing files

2020_R1 Fluent (time)				
physical CPU cores	cdat	cgns	plt	Averaged out of X samples
900	00:25:17	01:32:07	28:18:36	8
(pure mesh) 900	-	00:05:51	00:19:38	9
(no surfaces) 900	00:27:47	-	01:34:49	12
(no interior) 900	00:23:47	-	00:09:02	10
(interior only) 900	00:23:45	-	01:21:42	5
(inplc) 900	00:26:32	-	02:02:47	6
(inplc) 2000	00:18:18	-	03:59:13	5
460	00:10:59	01:15:20	22:21:09	6
220	00:13:44	01:11:32	19:16:59	7

2020_R1 Fluent (file size in GB)			
physical CPU cores	cdat	cgns	plt
900	142.74	79.60	44.45
(pure mesh) 900	-	9.57	6.05
(no surfaces) 900	142.74	-	39.36
(no interior) 900	56.63	-	0.81
(interior only) 900	141.0	-	43.6
(inplc) 900	141.0	-	43.9
(inplc) 2000	144.0	-	45.0
460	141.45	79.60	43.80
220	140.31	79.60	43.23

Other limitations (1/2)

- Post-processing machine:
  – GPU107 (HPC visualisationworkstation)

Server info:	
• Model:	ASUS - ESC4000 G3 Series
CPU info:	
• Model CPU:	Intel(R) Xeon(R) CPU E5-2680 v3
• CPU / server:	2
• No of cores / CPU:	12
• No of threads / CPU core:	2
• Total No of cores / server:	24
• Total No of threads / server:	48
• CPU frequency (nominal/TurboBoost):	2500MHz / 3300MHz
RAM info:	
• Available RAM:	256/512 GB (normal/evaluation period*)
• Type:	DDR4
GPU info:	
• No of GPU:	2
• GPU type:	NVidia Tesla K80 (24GB VRAM)
• GPU unit:	GK210GL
• GPU driver version:	418.39
• CUDA driver version:	10.1
• CUDA compute capability:	3.5

Intel OpenCL:	
• Intel OpenCL library version:	16.2
• OpenCL compute capability:	1.2
Interconnections:	
• Interconnect:	1 x Ethernet (1Gbit/sec per port) 1 x Infiniband FDR (56Gbit/sec per port)
File systems:	
• /scratch:	• Local File System (non-shared); • Drive space / server: 250 GB; • File system: (ext4) over SATA • Bandwidth: up to 500MB/sec (read); up to 200MB/sec (write)
• /mnt/home:	• Shared File System; • Interconnect: Ethernet 1Gbit/sec; • Bandwidth: do 100MB/sec;
• /mnt/lustre/home:	• Shared File System; • Interconnect: Infiniband 56Gbit/sec; • Bandwidth: up to 2.5GB/sec;

Conclusions

- New generic geometrical problem of no predecessor in literature has been presented with a focus on:
  – non-obvious asymmetrical flow phenomena, i.e. a persistent pair of vorticies at leading edge
  – thier impact on heat transfer
- Model validity criteria introduced and confirmed as no reference is known up to this moment.
- Physics of flow and its possible root cause has been explained.
- Typical technical issues and limitations are also presented.

Selected literature

- B. Boersma & W. Breugem (2011) *Numerical Simulation of Turbulent Flow in Concentric Annuli*, Flow, Turbulence and Combustion, 86:1, 113-127, DOI: 10.1007/s10494-010-9295-y
- J. Brighton & J. Jones (1964) *Fully Developed Turbulent Flow in Annuli*, Journal of Basic Engineering, 86:4, 835-842, DOI: 10.1115/1.3655966
- S. Chung et al. (2002) Direct numerical simulation of turbulent concentric annular pipe flow part 1: Flow field, International Journal of Heat and Fluid Flow, 23:4, 426-440, DOI: 10.1016/S0142-727X(02)00140-6
- P. Ekman et al. (2021) *Importance of Sub-Grid Scale Modeling for Accurate Aerodynamic Simulations*, Journal of Fluids Engineering, 148, TBD, DOI: 10.1115/1.4048351
- V. Gnielinski (2009) *Heat Transfer Coefficients for Turbulent Flow in Concentric Annular Ducts*, Heat Transfer Engineering, 30:6, 431-436, DOI: 10.1080/01457630802528661
- M. Khalil et al. (2010) *Turbulent flow around single concentric long capsule in a pipe*, Applied Mathematical Modelling, 34:8, 2000-2017, DOI: 10.1016/j.apm.2009.10.014
- A. Luks et al. (2016) *Modelling of thermal hydraulics in a KAROLINA calorimeter for its calibration methodology validation*, Nukleonika; 61:4, 453-460, DOI: 10.1515/nuka-2016-0074
- K. Rehme (1974) *Turbulent flow in smooth concentric annuli with small radius ratios*, Journal of Fluid Mechanics, 64:2; 263-287, DOI: 10.1017/S0022112075003023
- J. M. Wallace (2016) *Quadrant Analysis in Turbulence Research: History and Evolution*, Annu. Rev. Fluid Mech. 48:1, 131–158, DOI: 10.1146/annurev-fluid-122414-034550

Thank you for your attention

Piotr Prusiński, MSc. Eng. | CFD Analysis Group
Division of Nuclear Energy and Environmental Studies (UZ3)
Departament of Complex Systems (DUZ)
National Centre for Nuclear Research (NCBJ)
A. Sołtana 7, 05-400 Otwock-Świerk
e-mail: piotr.prusinski@ncbj.gov.pl
tel: +48 22 273 11 26