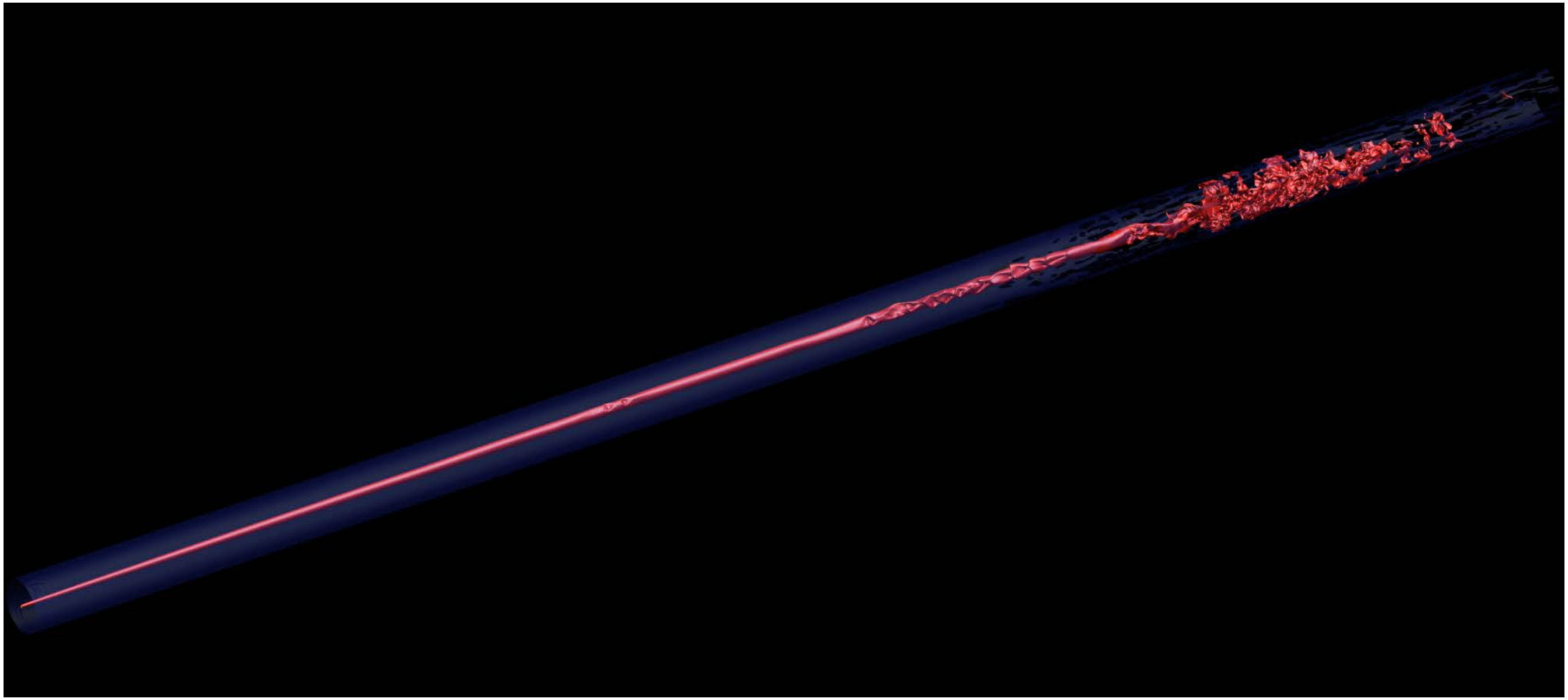
Osborne Reynolds pipe flow

Direct computation and visualization from laminar through transition to fully-developed turbulence



Xiaohua Wu, Parviz Moin and Ronald J. Adrian

Vol 443|7 September 2006|**doi:10.1038/nature05089** **nature**

LETTERS

Finite lifetime of turbulence in shear flows

Björn Hof[1,2], Jerry Westerweel[2], Tobias M. Schneider[3] & Bruno Eckhardt[3]

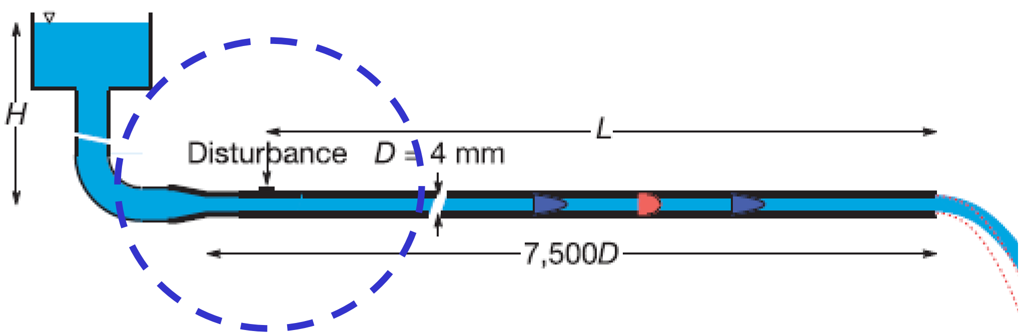
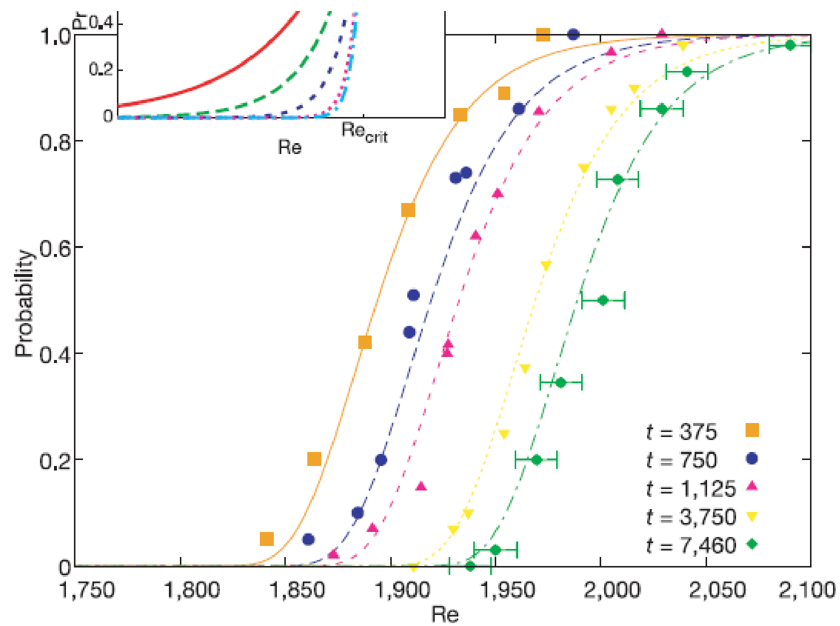


Figure 1 | Sketch of the experimental apparatus. The pipe sections we



$$T_L \propto e^{bRe} \text{ where } b > 0$$

Figure 2 | Lifetime distributions.

Proceedings of the National Academy of Sciences of the United States of America

PNAS | **May 4, 2010** | vol. 107 | no. 18 | **8091–8096**

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Edited by Katepalli R. Sreenivasan, New York University, New York, and approved March 12, 2010 (received for review August 22, 2009)

numbers. For this we use axially periodic pipes of length L and diameter D, where L is both large and is varied as part of the study.

The computational protocol is of the reverse transition type (12, 23–26) where we always first obtain a fully turbulent flow throughout the pipe at $\mathrm{Re} \simeq 3,000$ and then decrease Re. Unlike

> 773, travelling wave appears

> 1650, new puff appears

> 1750, existing puff does not decay

< 2300, puffs are localized

> 2600, continuous turbulence, no puff/slug

Unresolved issue A

What is the perturbation growth rate in a laminar pipe flow ?

undergraduate and graduate text books often silent on pipe transition

Unresolved issue B

How does laminar pipe flow breakdown?
Any connection with boundary layer?

may not have unique answer

Unresolved issue C

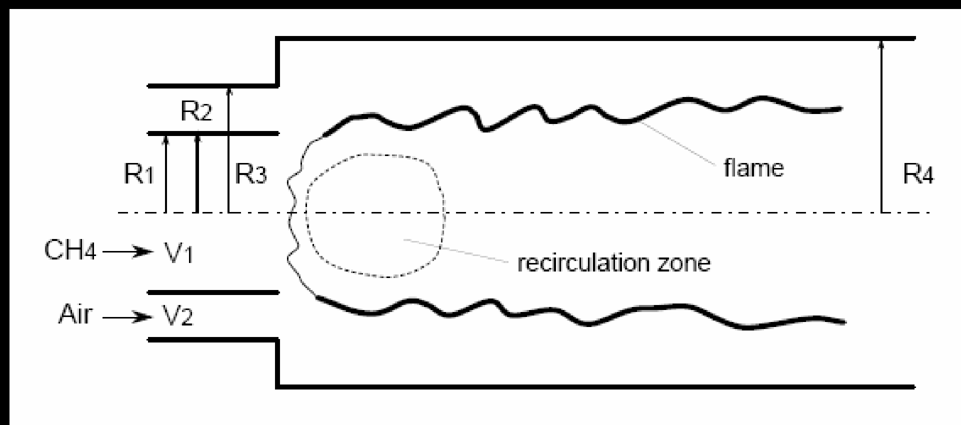
How does skin friction vary with axial distance in pipe transition ?

relevant to oil transport

J. Fluid Mech. (2004), *vol.* 504, *pp.* 73–97. © 2004 Cambridge University Press 73
DOI: 10.1017/S0022112004008213 Printed in the United Kingdom

Progress-variable approach for large-eddy simulation of non-premixed turbulent combustion

By CHARLES D. PIERCE† AND PARVIZ MOIN
Center for Turbulence Research, Stanford University, Stanford, CA 94305-3030, USA



Chuck's Codes:

(1) **Periodic pipe code,** used in Wu & Moin, JFM (2008)

(2) **Boundary layer code,** used in Wu & Moin, JFM (2009), PoF (2010)

(3) **Jet code,** used in the present study

Step 1 towards spatial pipe DNS

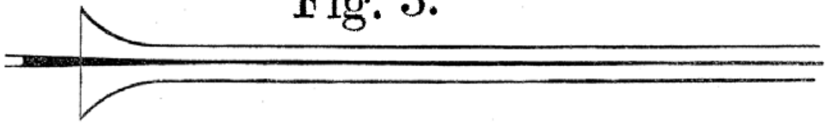
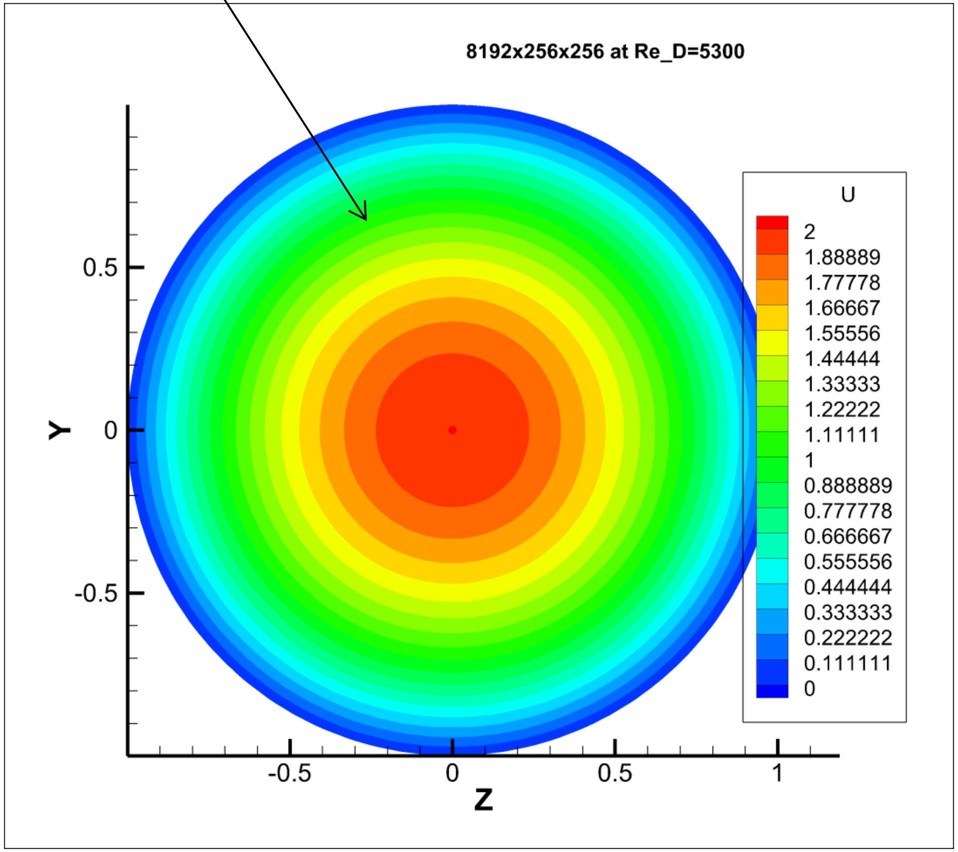
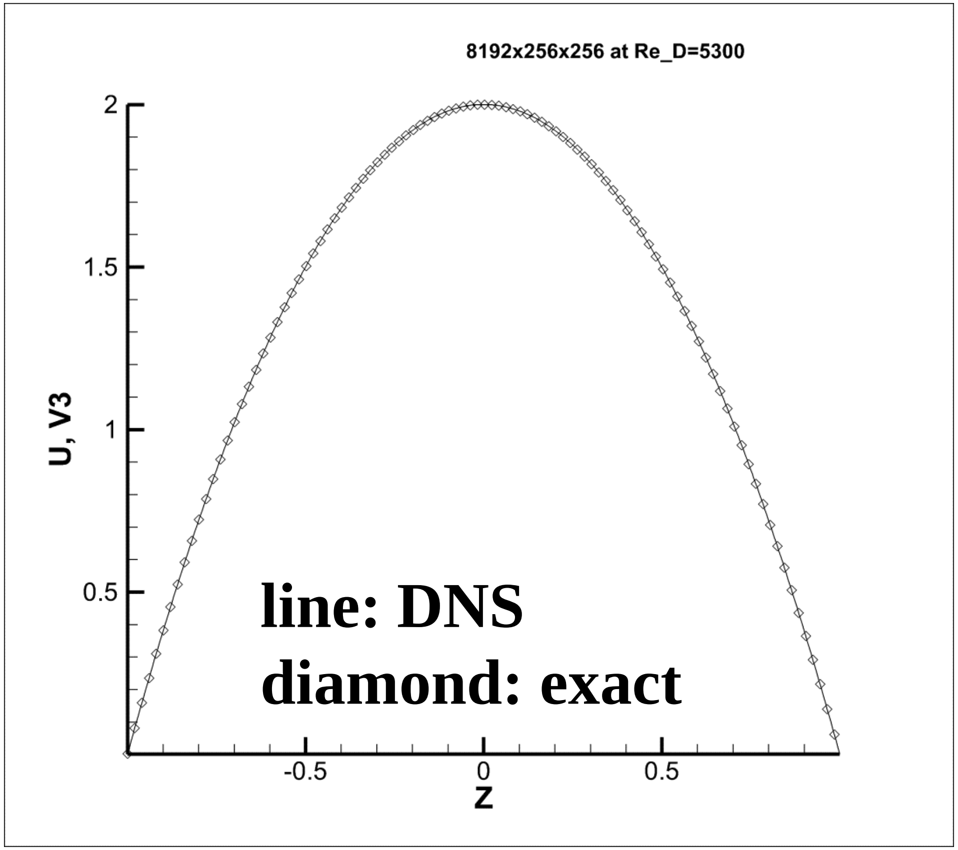


Fig. 3.

DNS of spatial laminar pipe flow

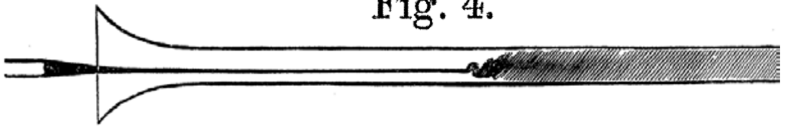
exact parabolic



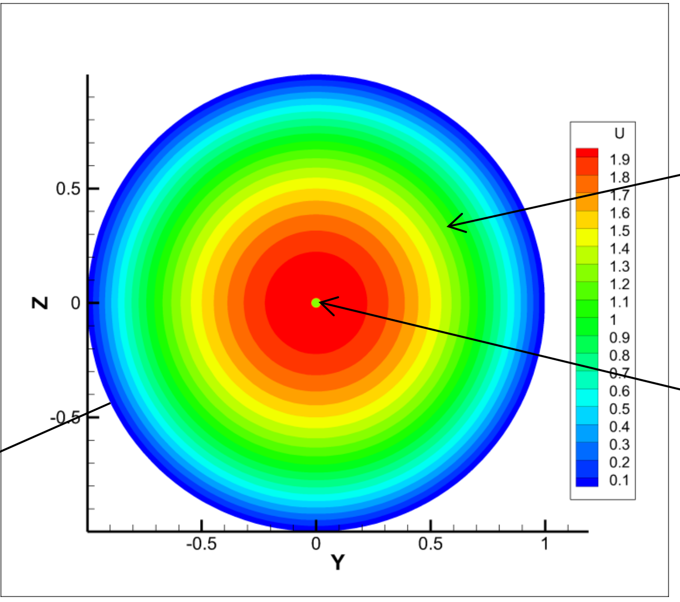


Step 2 towards spatial pipe DNS

Fig. 4.



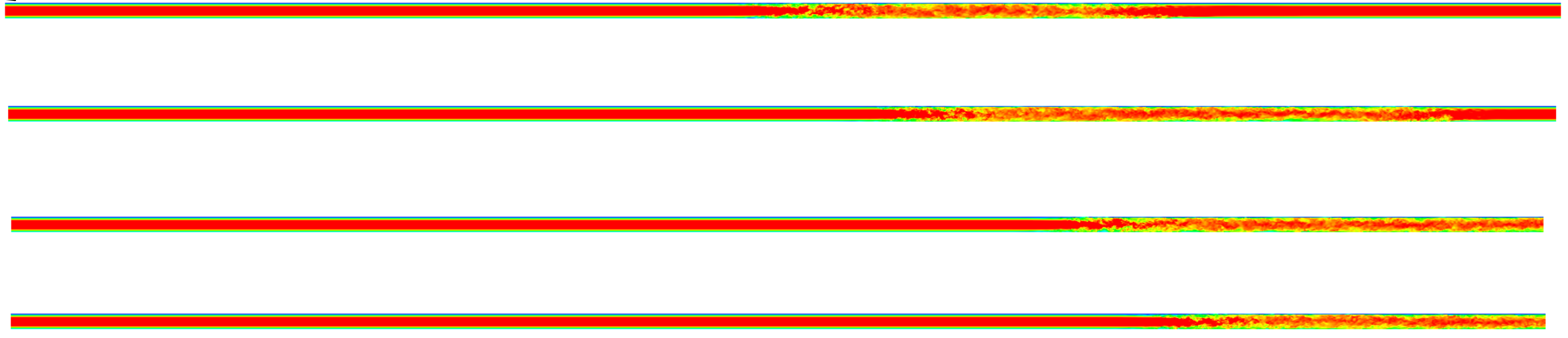
Many failed transition tests at Re_D = 5300



exact parabolic

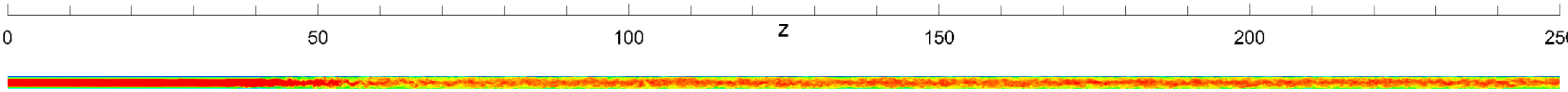
perturbation

inflow



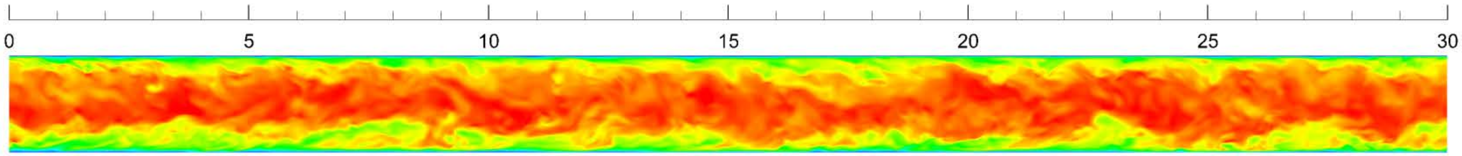
Step 3: DNS results at Re_D = 8000

Spatial DNS over 250R domain on 8196 x 200 x 256 mesh

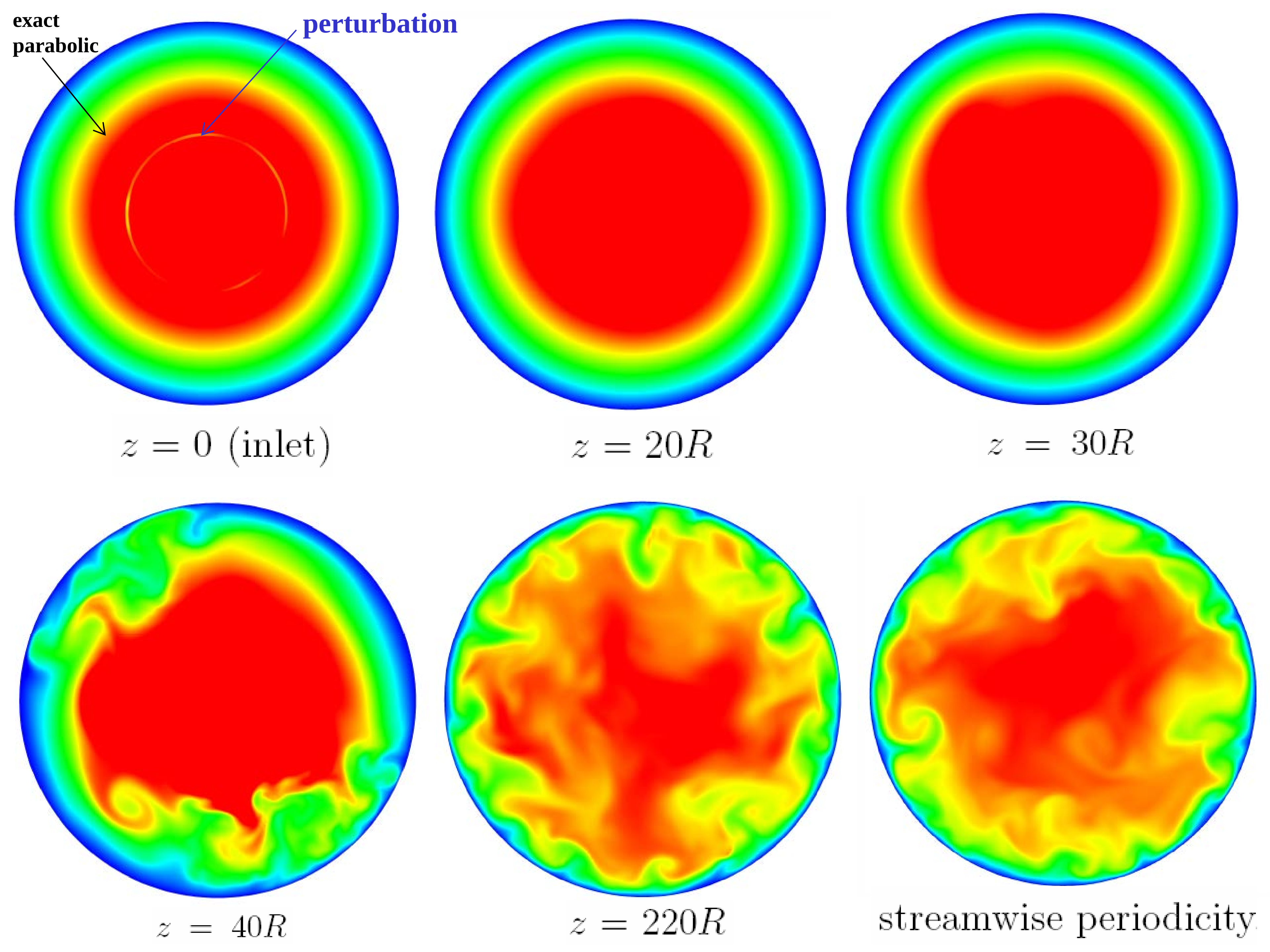


R+ = 258.48, Dz+ = 7.9 (after transition)

Periodic DNS over 30R domain on 2048 x 256 x 512 mesh



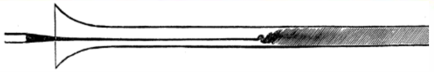
R+ = 258.48, Dz+ = 3.8

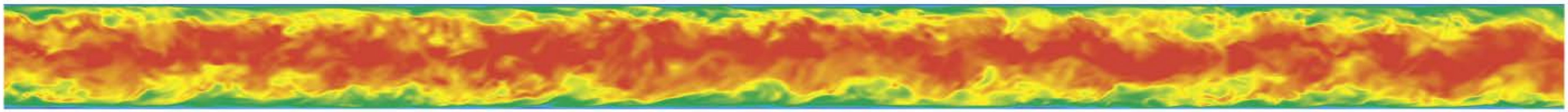

exact
parabolic
perturbation
$z = 0$ (inlet)
$z = 20R$
$z = 30R$
$z = 40R$
$z = 220R$
streamwise periodicity

Contours of u at a random instant over the $\theta = 0^\circ$ and 180° planes

$0 \leq z \leq 250R$ (full range)

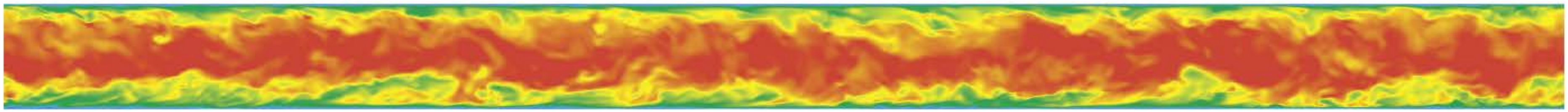
$0 \leq z \leq 60R$



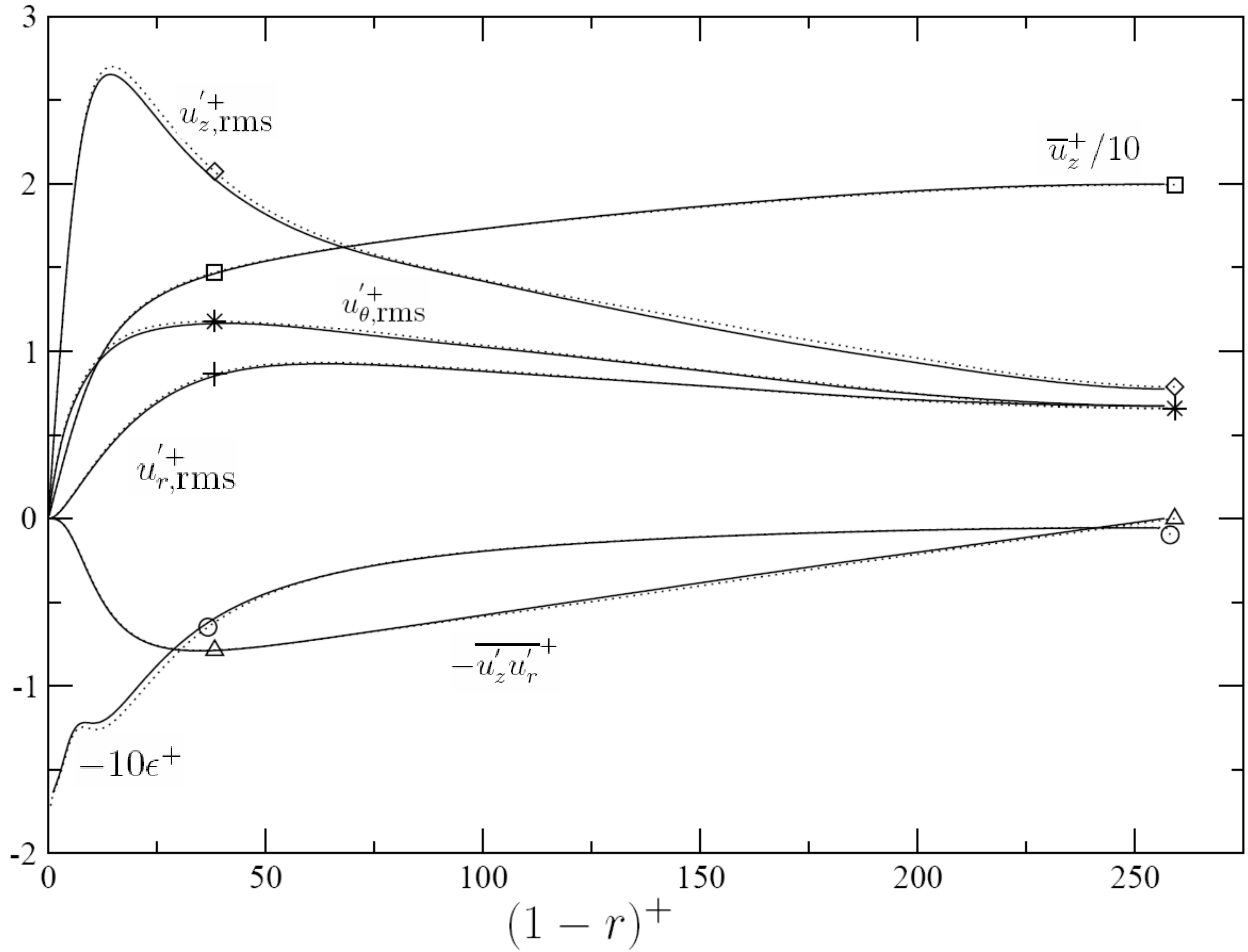


$210R \leq z \leq 240R$

additional pipe flow DNS with streamwise periodicity,



$0 \leq z \leq 30R$

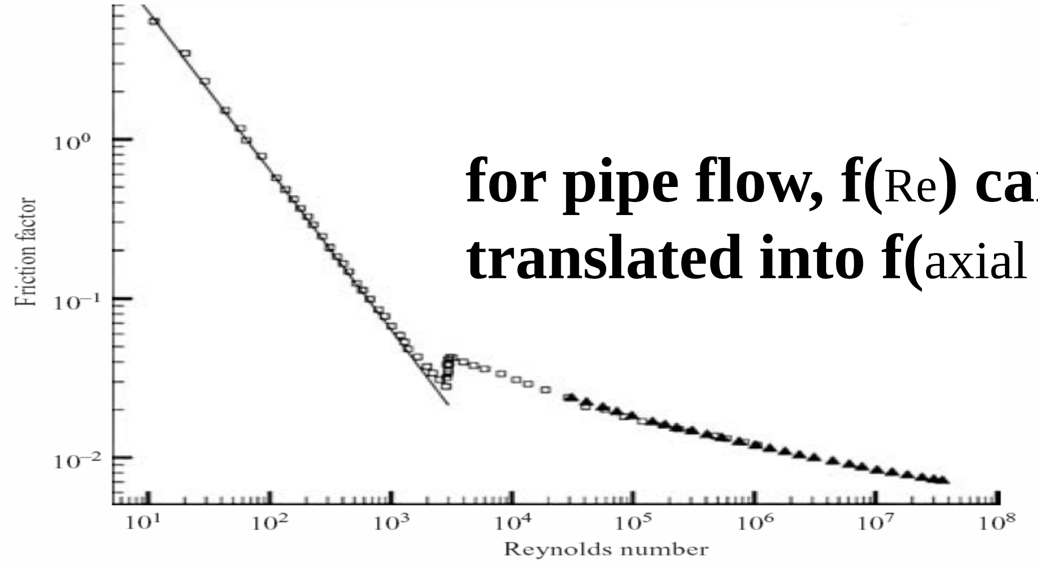


Solid present DNS sampled in time and averaged in the region of $210R < z < 240R$

dotted additional $30R$-long pipe flow DNS with streamwise periodicity.

B. J. McKeon, C. J. Swanson, M. V. Zagarola, R. J. Donnelly and A. J. Smits

pipe



for pipe flow, f(Re) can not be translated into f(axial distance)

boundary layer

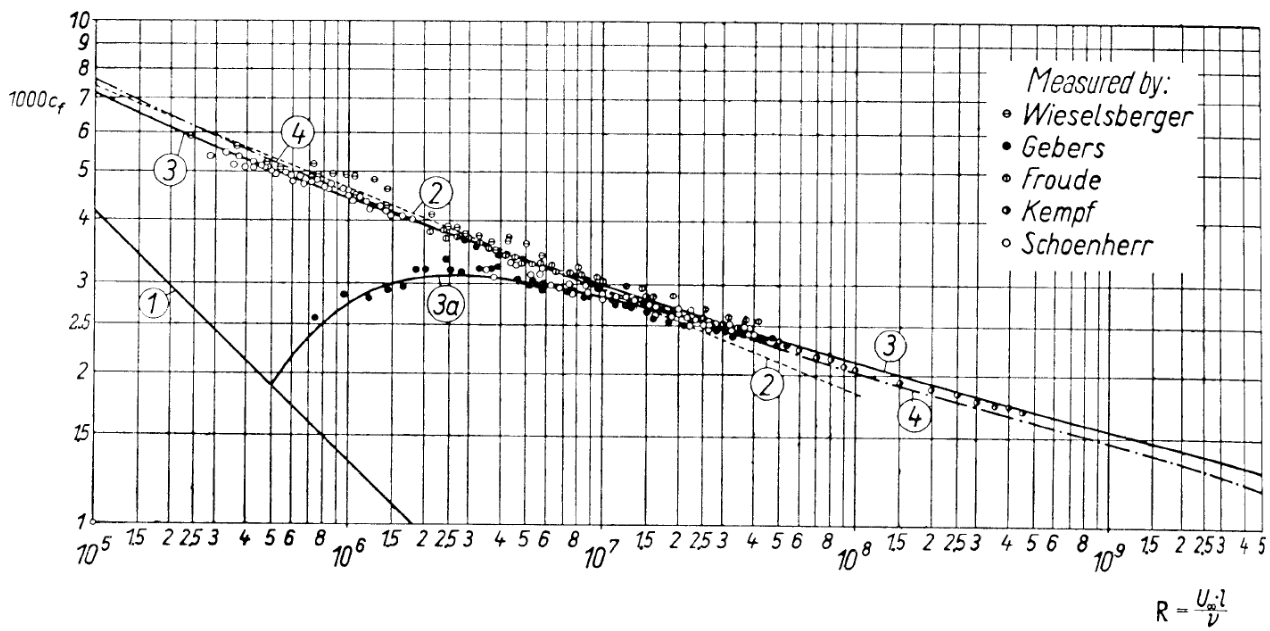
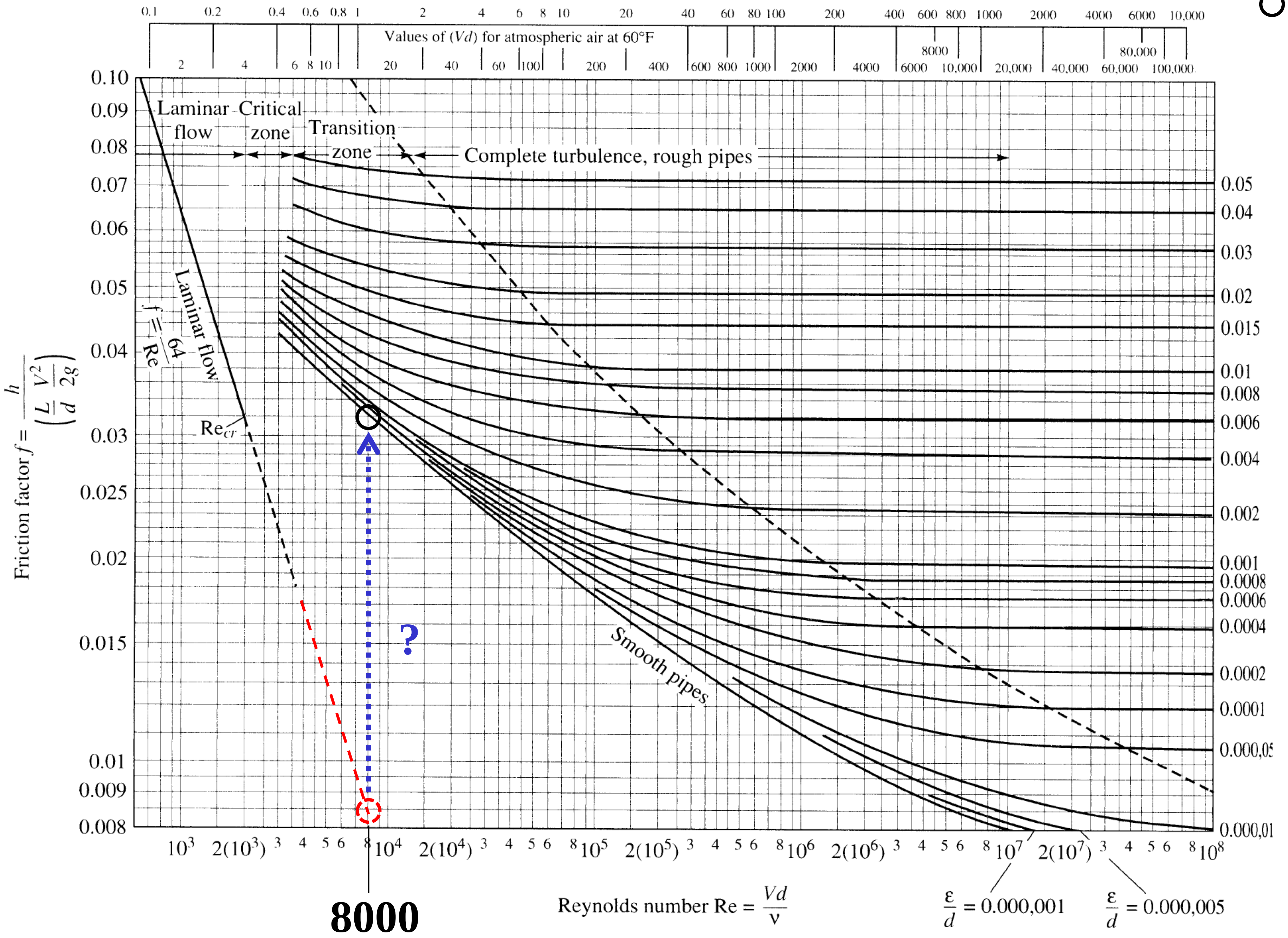
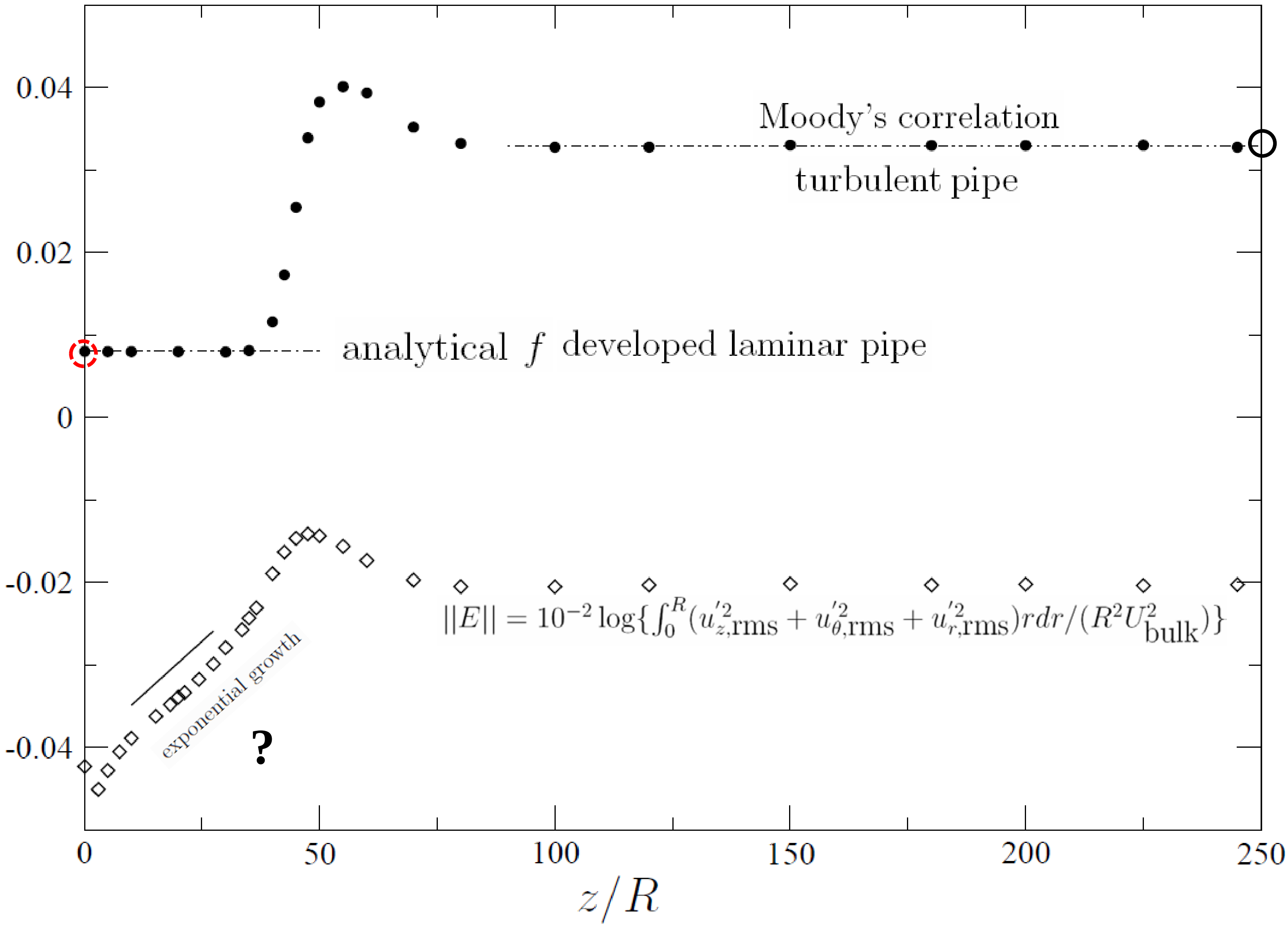


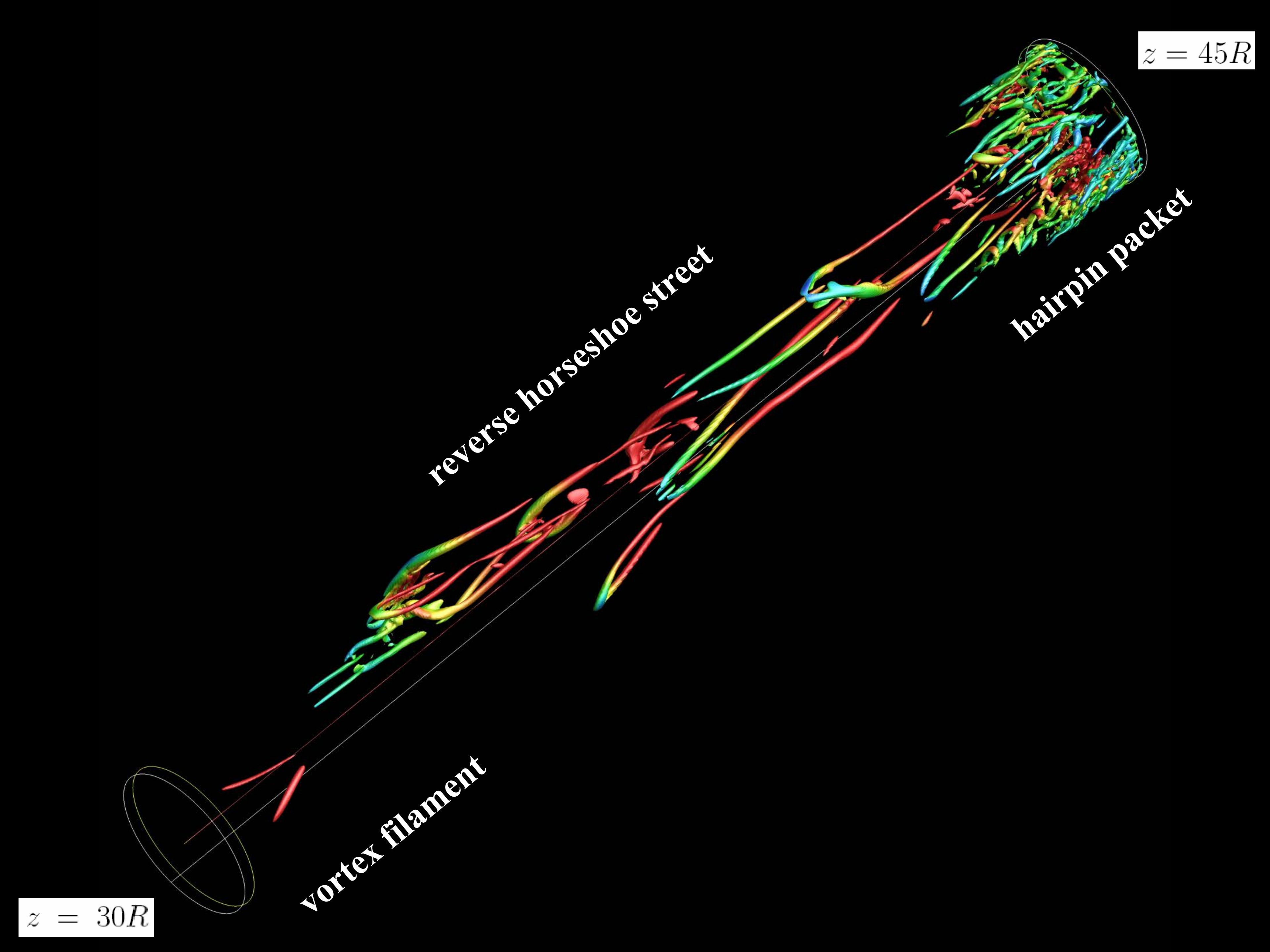
Fig. 21.2. Resistance formula for smooth flat plate at zero incidence; comparison between theory and measurement



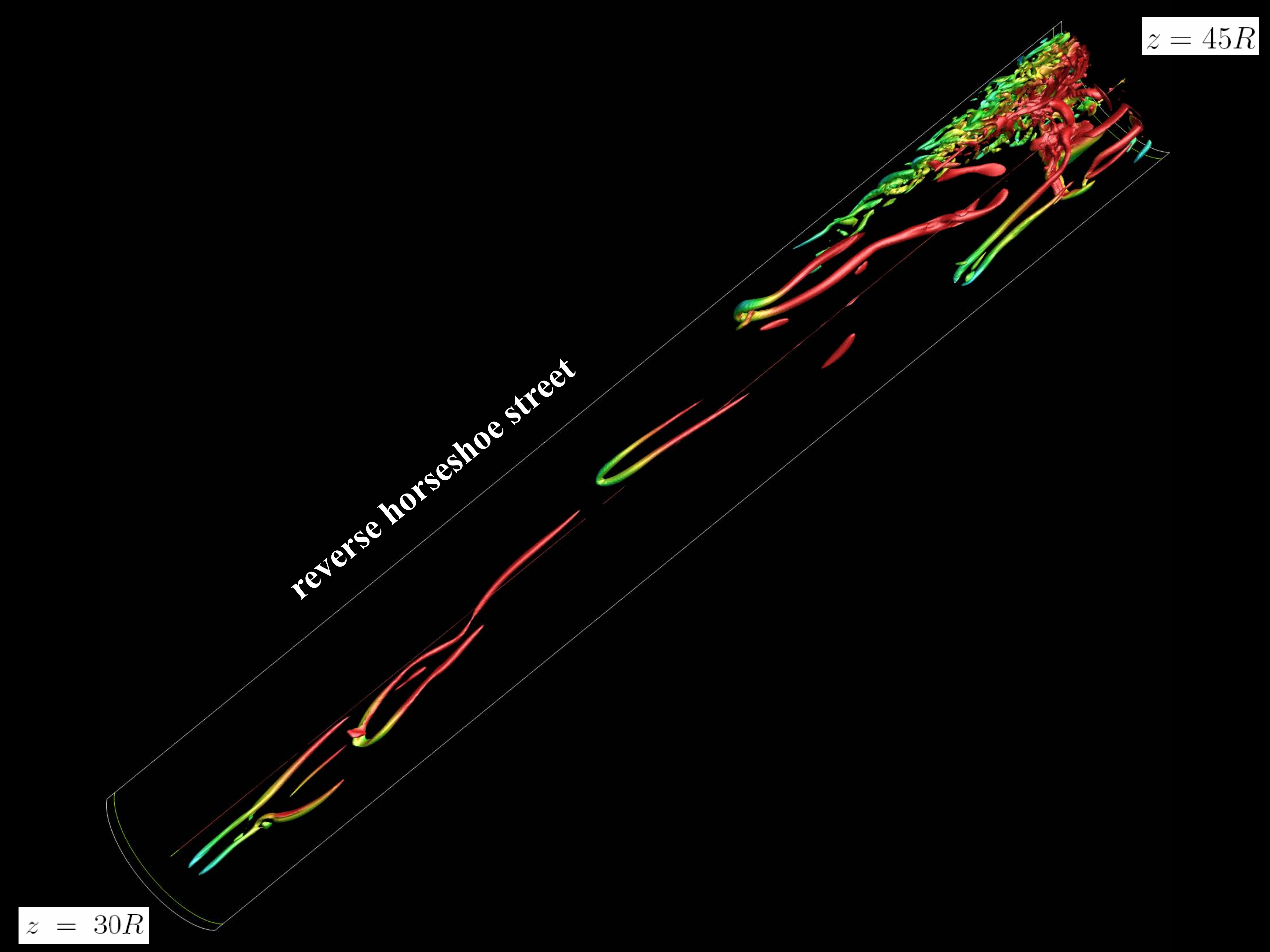
Values of (Vd) for atmospheric air at 60°F
Laminar flow
Critical zone
Transition zone
Complete turbulence, rough pipes
Laminar flow
f = 64/Re
Re_cr
Smooth pipes
Friction factor f = h / ((L/d)(V²/2g))
Reynolds number Re = Vd/ν
ε/d = 0.000,001
ε/d = 0.000,005
?
8000



0.04
0.02
0
-0.02
-0.04
0
50
100
150
200
250
z/R
Moody's correlation
turbulent pipe
analytical f developed laminar pipe
exponential growth
?
||E|| = 10^{-2} log{∫_0^R (u'^2_{z,rms} + u'^2_{θ,rms} + u'^2_{r,rms}) r dr/(R^2 U^2_{bulk})}



$z = 45R$
hairpin packet
reverse horseshoe street
vortex filament
$z = 30R$



$z = 45R$
reverse horseshoe street
$z = 30R$

Iso-surfaces of swirling strength λ_{ci} coloured by local values of u_z

continuous transition without spots between 30R< z < 45R

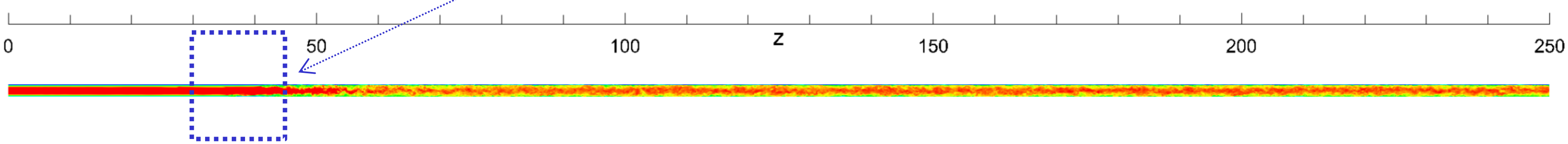
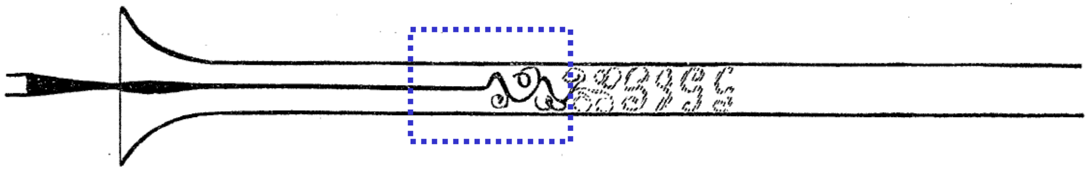
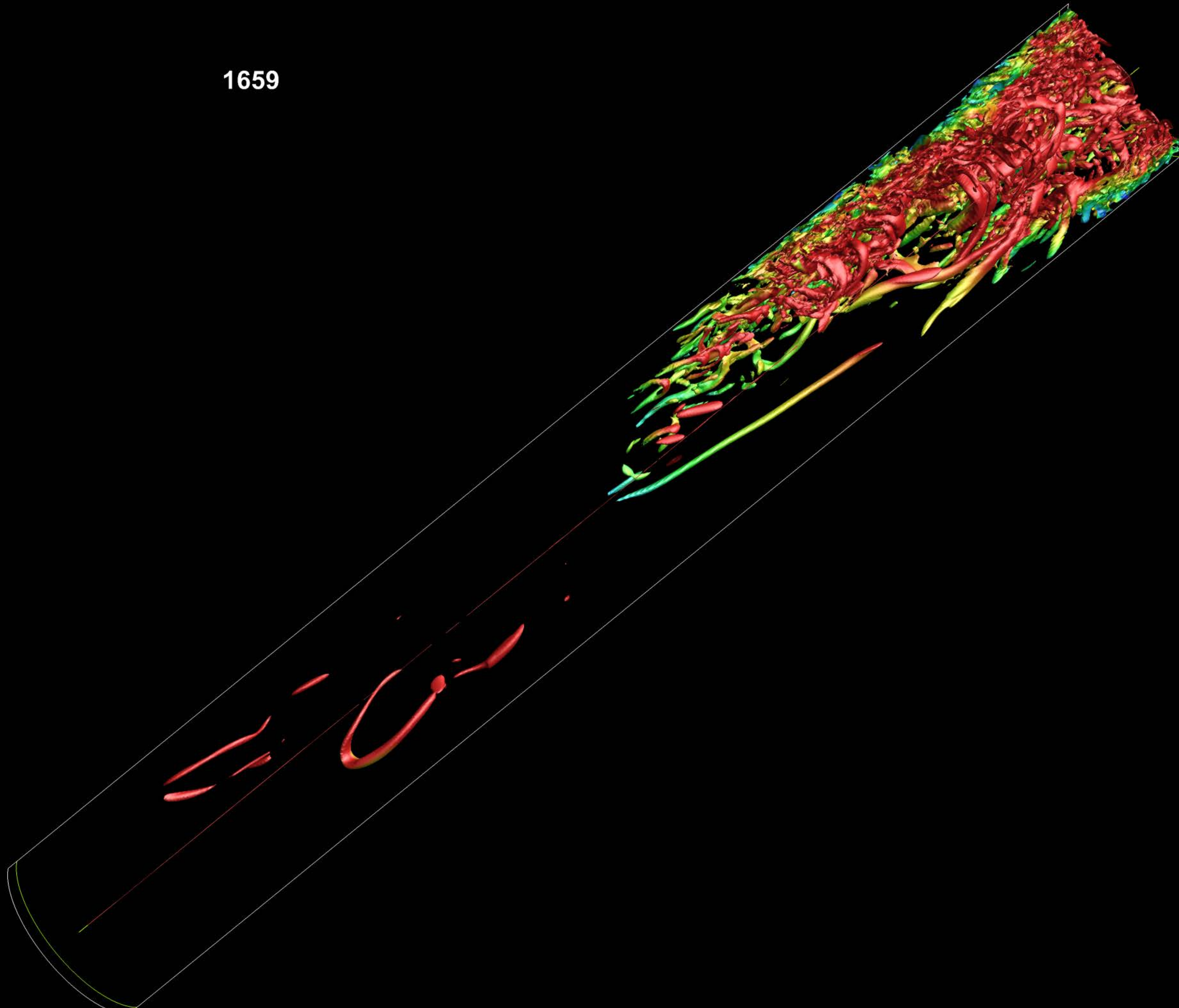


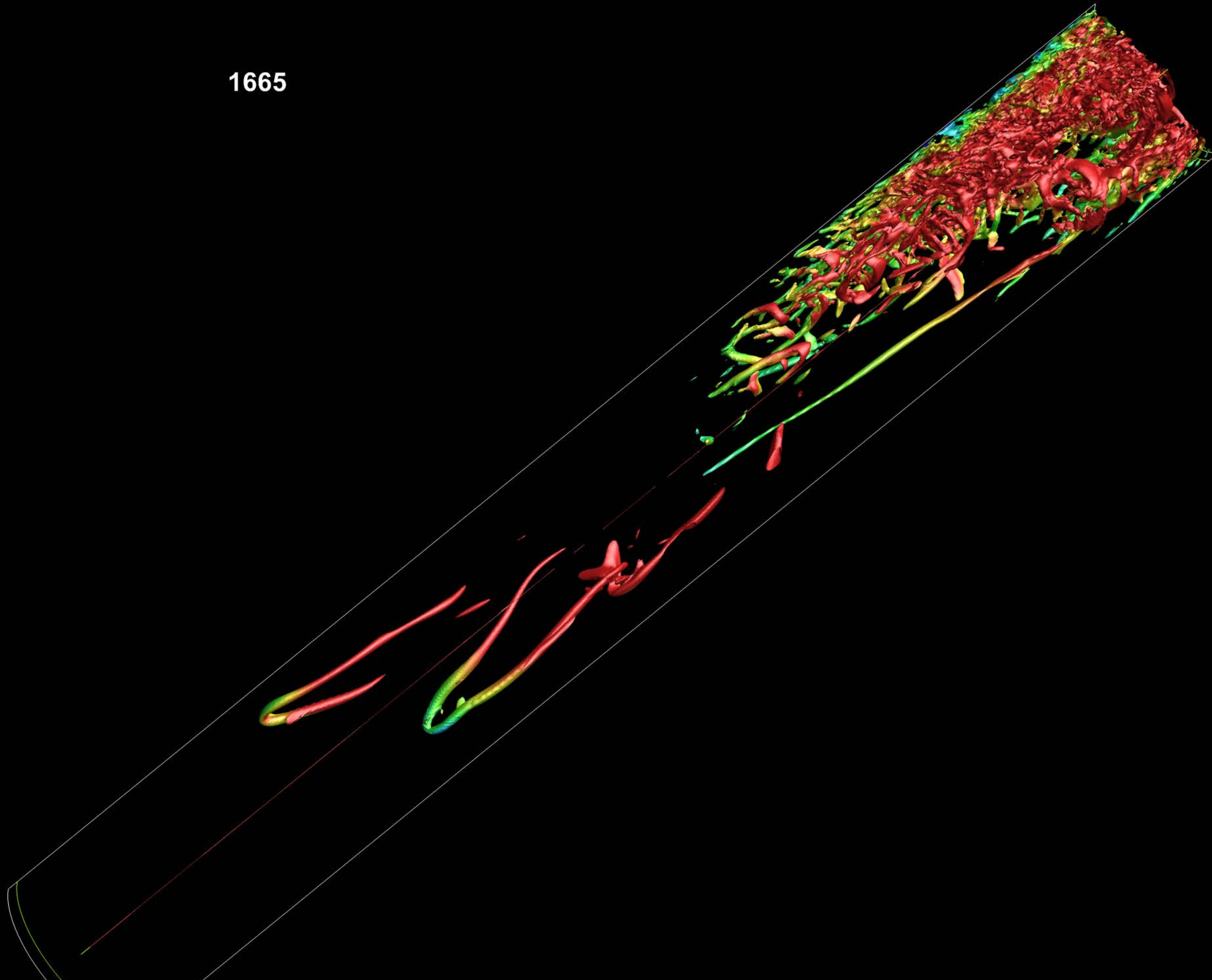
Fig. 5.



1659



1665



Partial answer to issue A (growth rate)

Weak, localized, finite perturbations may grow exponentially in a laminar pipe flow

Partial answer to issue B (breakdown)

For the particular type of disturbance

breakdown involves vortex filament, reverse horseshoe, and hairpin packet

transition almost continuous in space, no turbulent spot

Partial answer to issue C (friction)

For the particular type of disturbance skin friction overshoots Moody's correlation during pipe transition

New questions

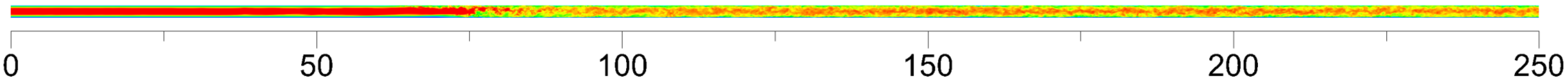
Repeatability, only one case

Effect of Re on the observations

Any travelling wave

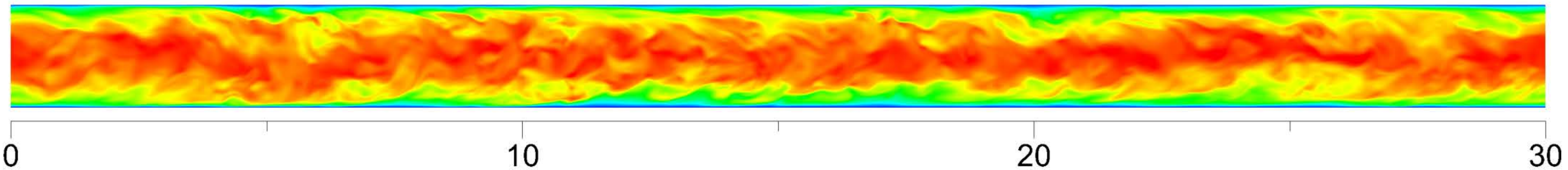
Step 4: Reducing Re_D to 6000 (does not transition at 5700)

Spatial DNS over 250R domain on 8196 x 200 x 256 mesh

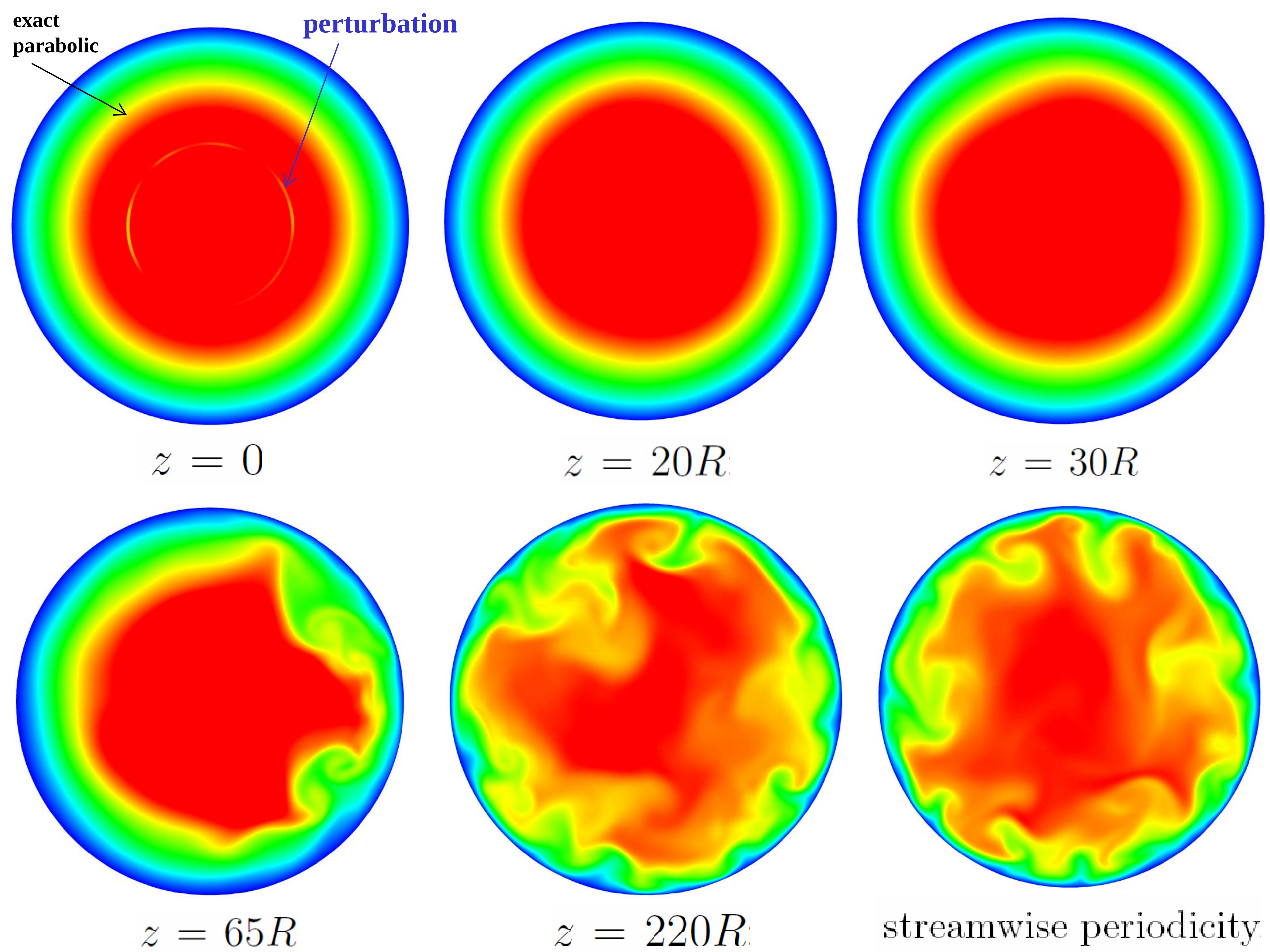


R+ = 201.6, Dz+ = 6.1 (after transition)

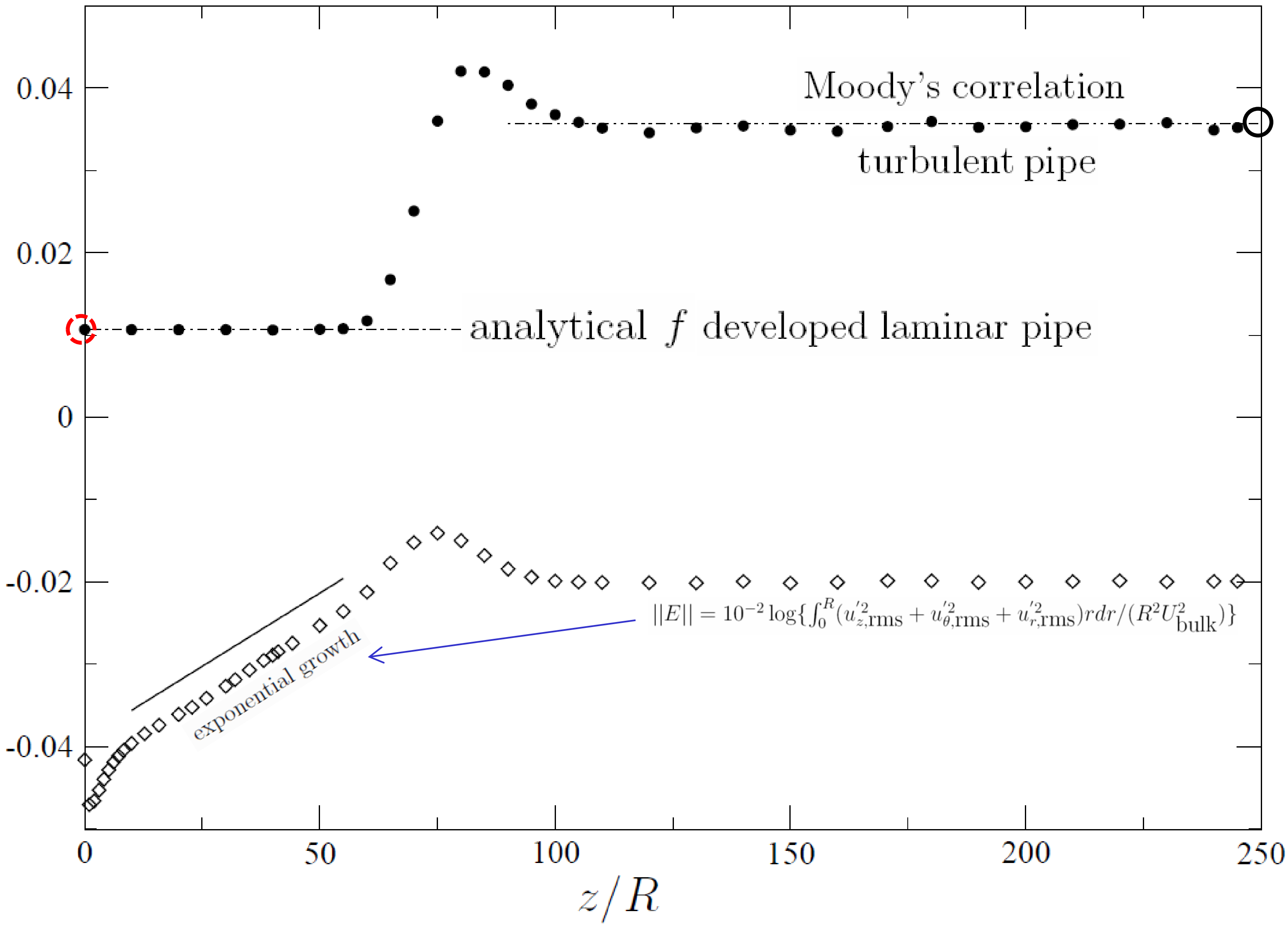
Periodic DNS over 30R domain on 2048 x 256 x 512 mesh



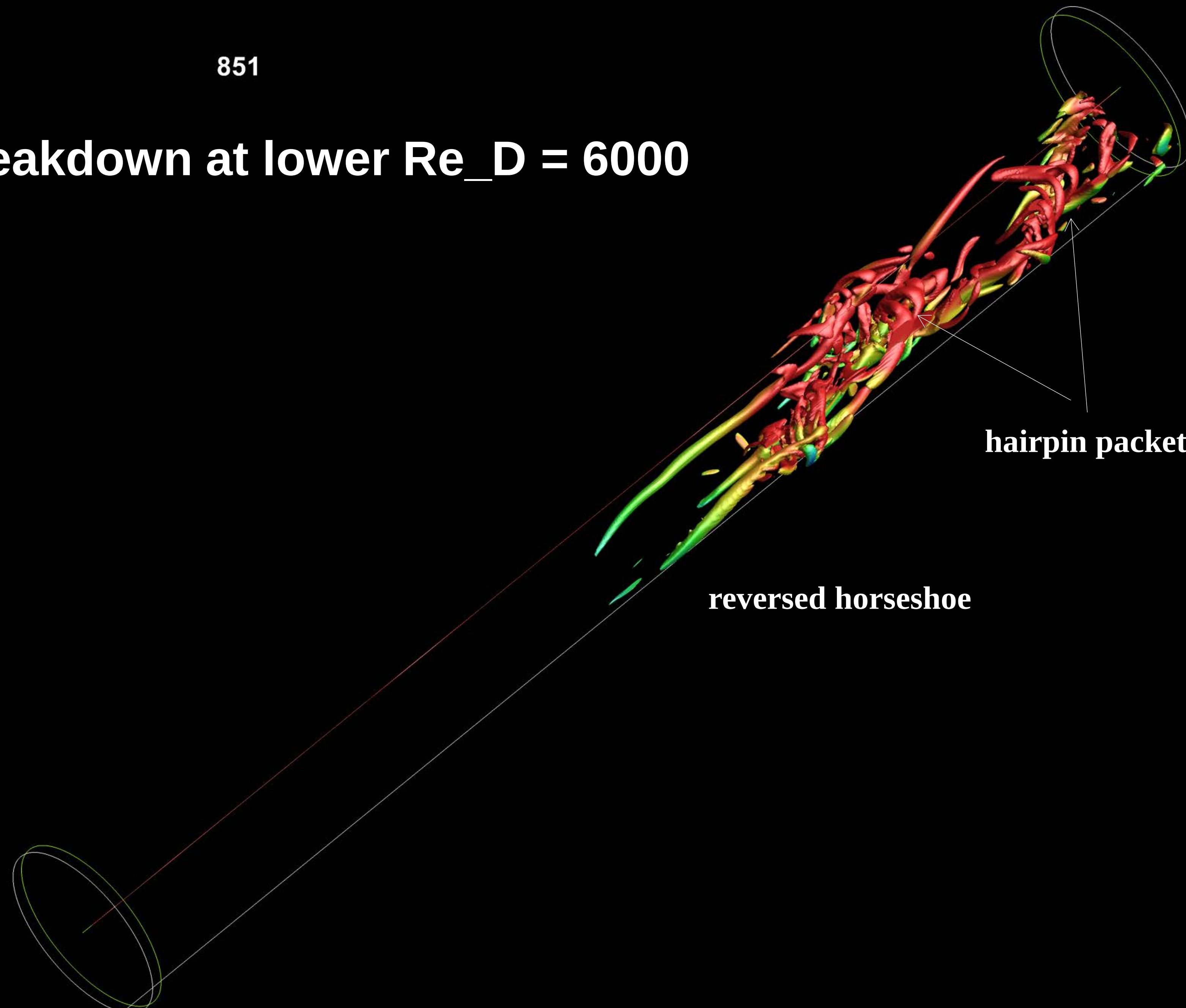
R+ = 201.6, Dz+ = 3.0

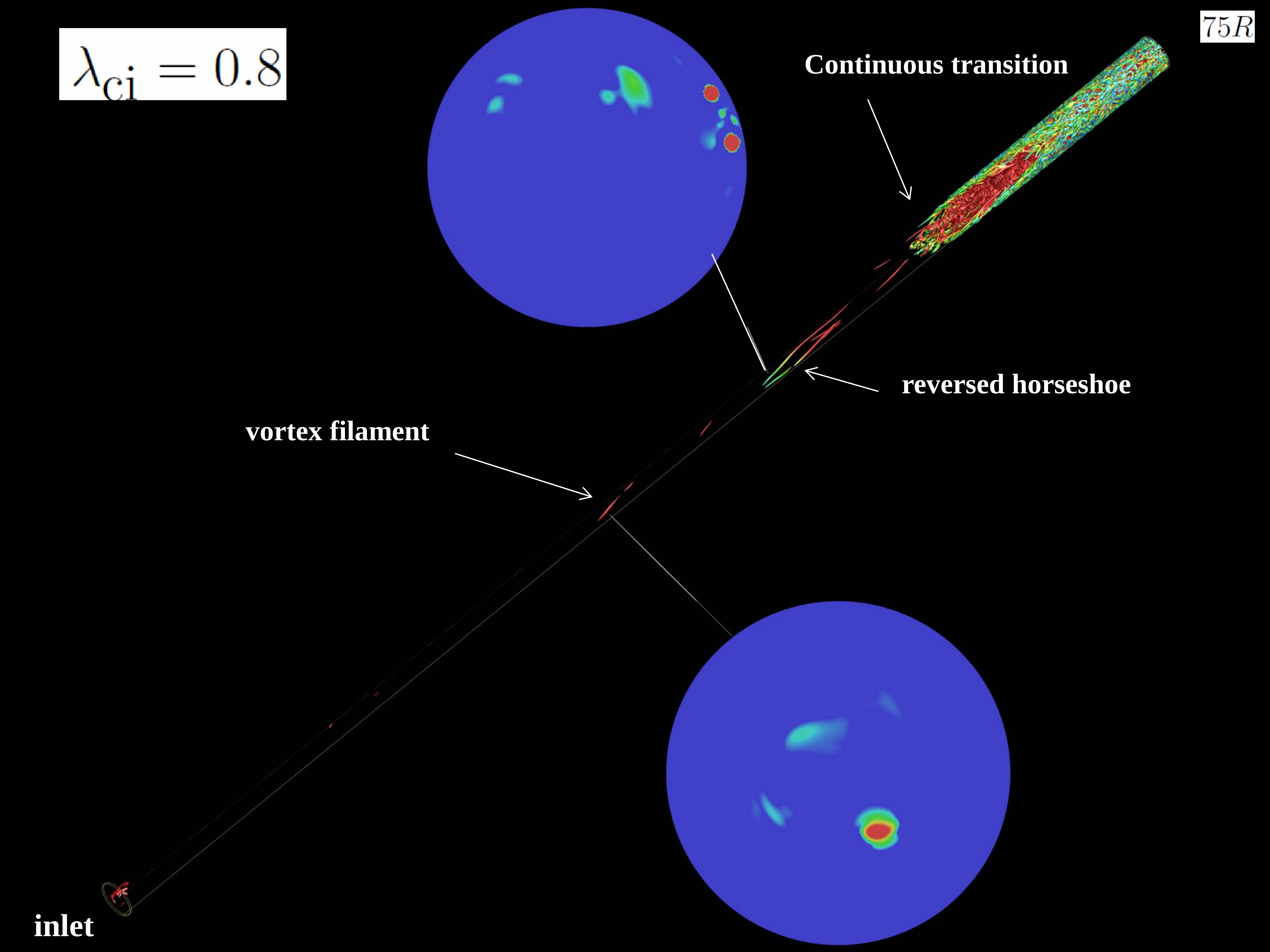

exact
parabolic
perturbation
$z = 0$
$z = 20R$
$z = 30R$
$z = 65R$
$z = 220R$
streamwise periodicity

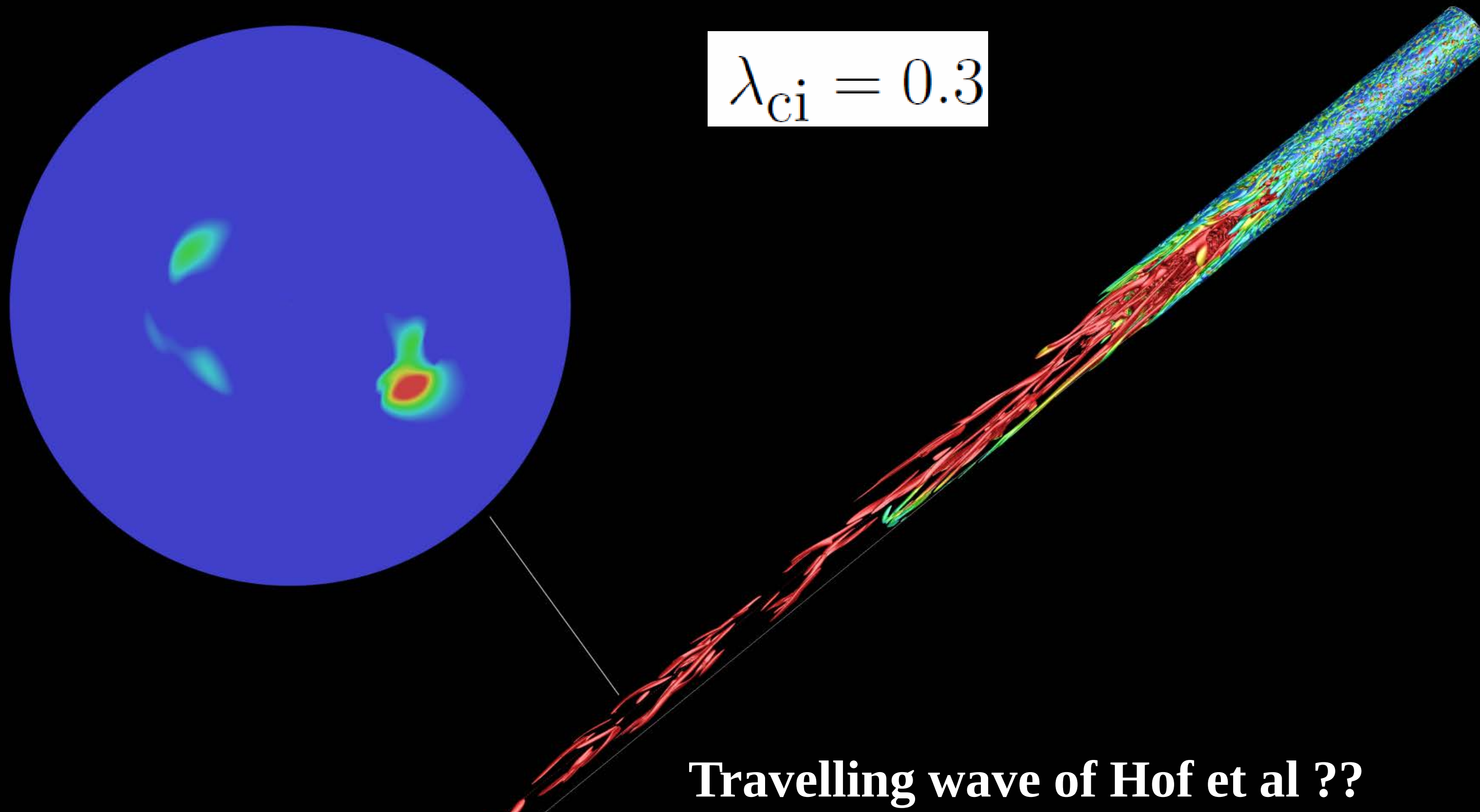
Reynolds number reduced to 6,000

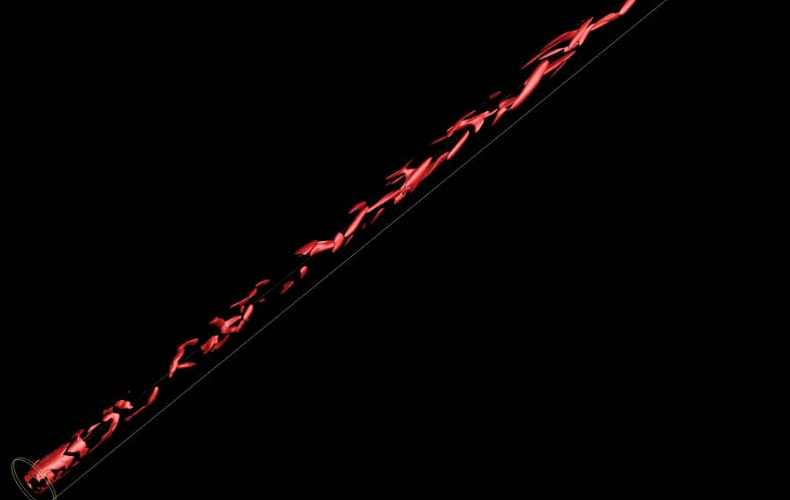


breakdown at lower Re_D = 6000




$\lambda_{ci} = 0.8$
$75R$
Continuous transition
reversed horseshoe
vortex filament
inlet





inlet

Travelling wave of Hof et al ??

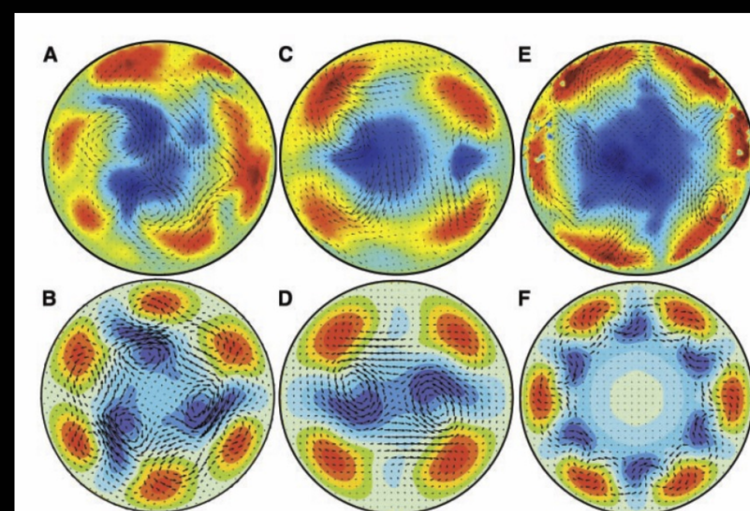
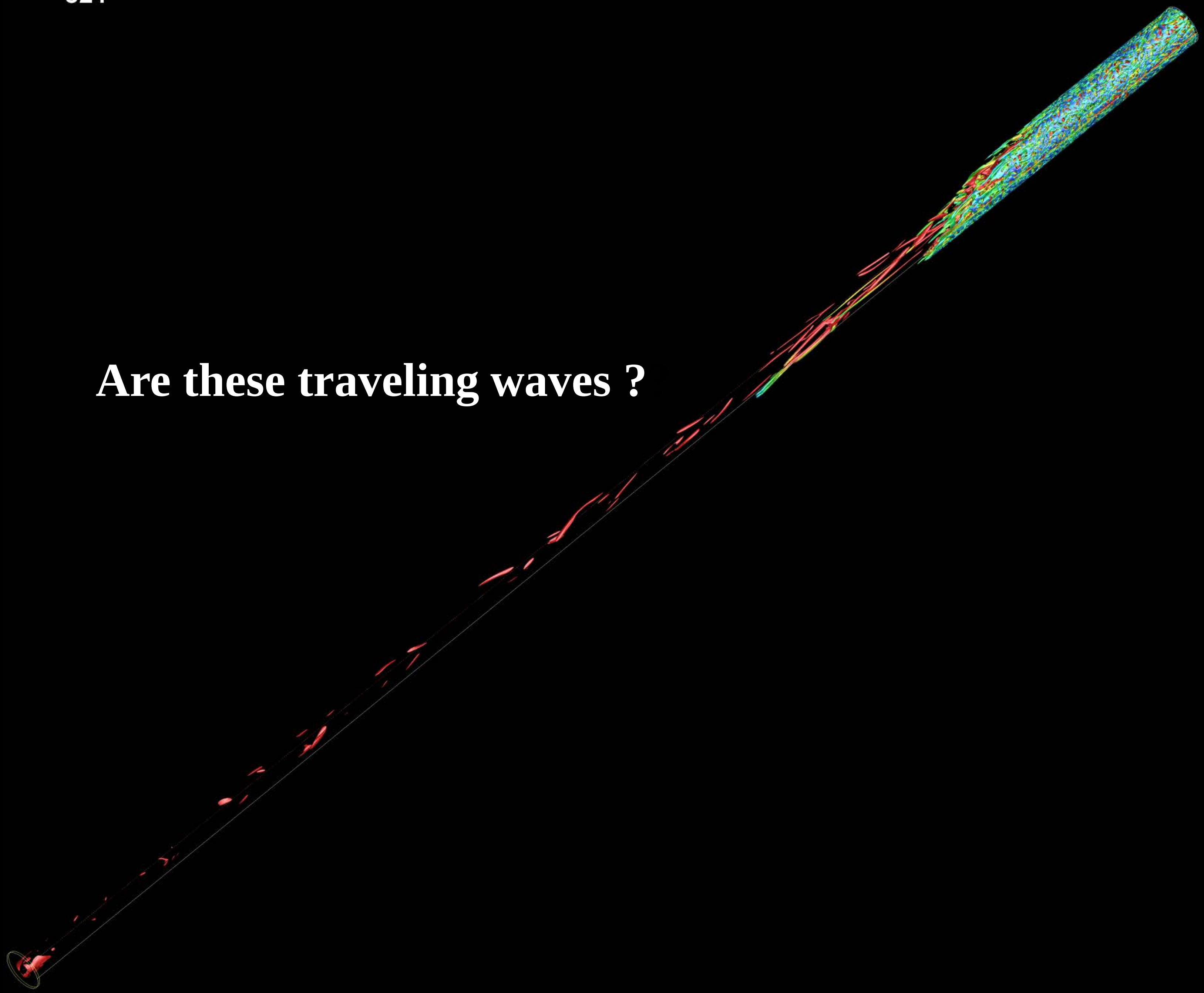


Fig. 2. Comparison of experimentally (top) and numerically (bottom) observed streak patterns.

Are these traveling waves ?



Improved answer to issue A (growth rate)

Confirmed that

weak, localized, finite perturbations can grow exponentially in a laminar pipe flow

Improved answer to issue B (breakdown)

confirmed that

for the particular type of disturbance

breakdown involves vortex filament, reverse horseshoe, and hairpin packet

transition almost continuous in space, no turbulent spot

unclear if vortex filament is traveling wave

Improved answer to issue C (friction)

Confirmed that

for the particular type of disturbance skin friction overshoots Moody's correlation during pipe transition

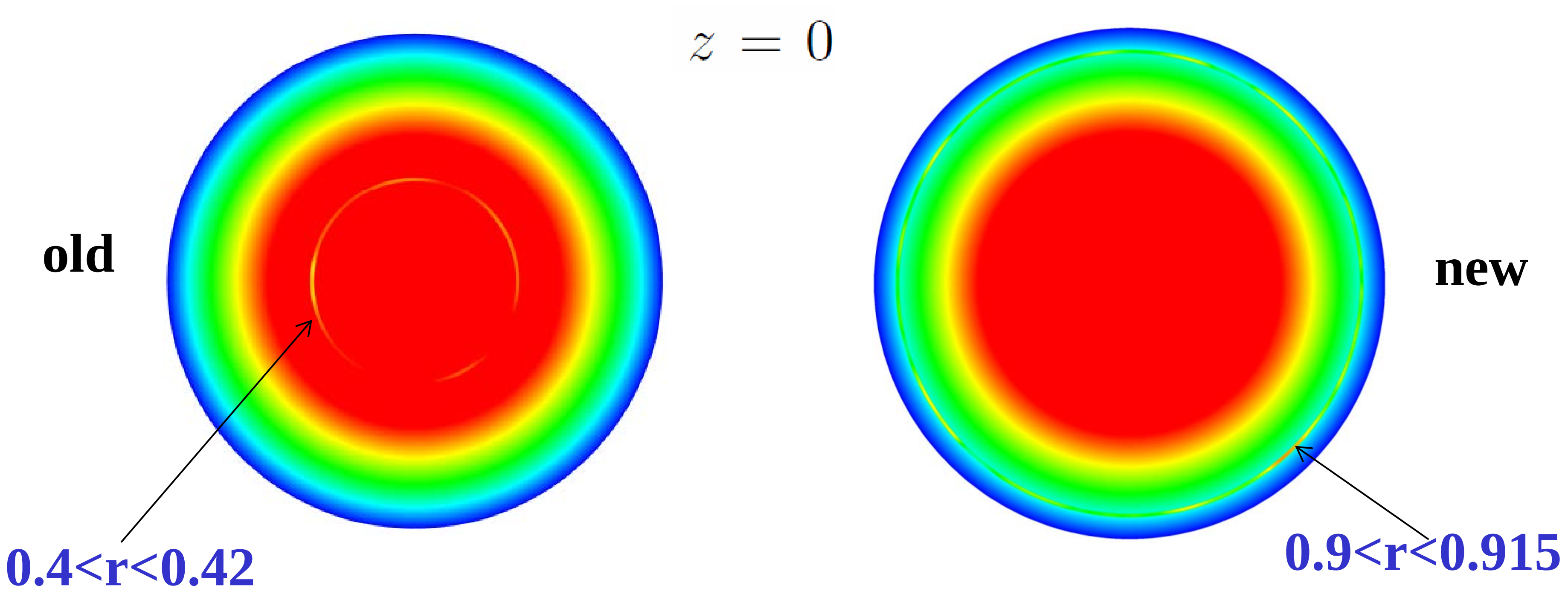
More new questions

Effect of inlet disturbance on results

Why no spots as in boundary layer
Why reversed horseshoe vortex
Add “numerical” dye as in Reynolds

Step 5: Modify inlet disturbance at Re_D = 8000

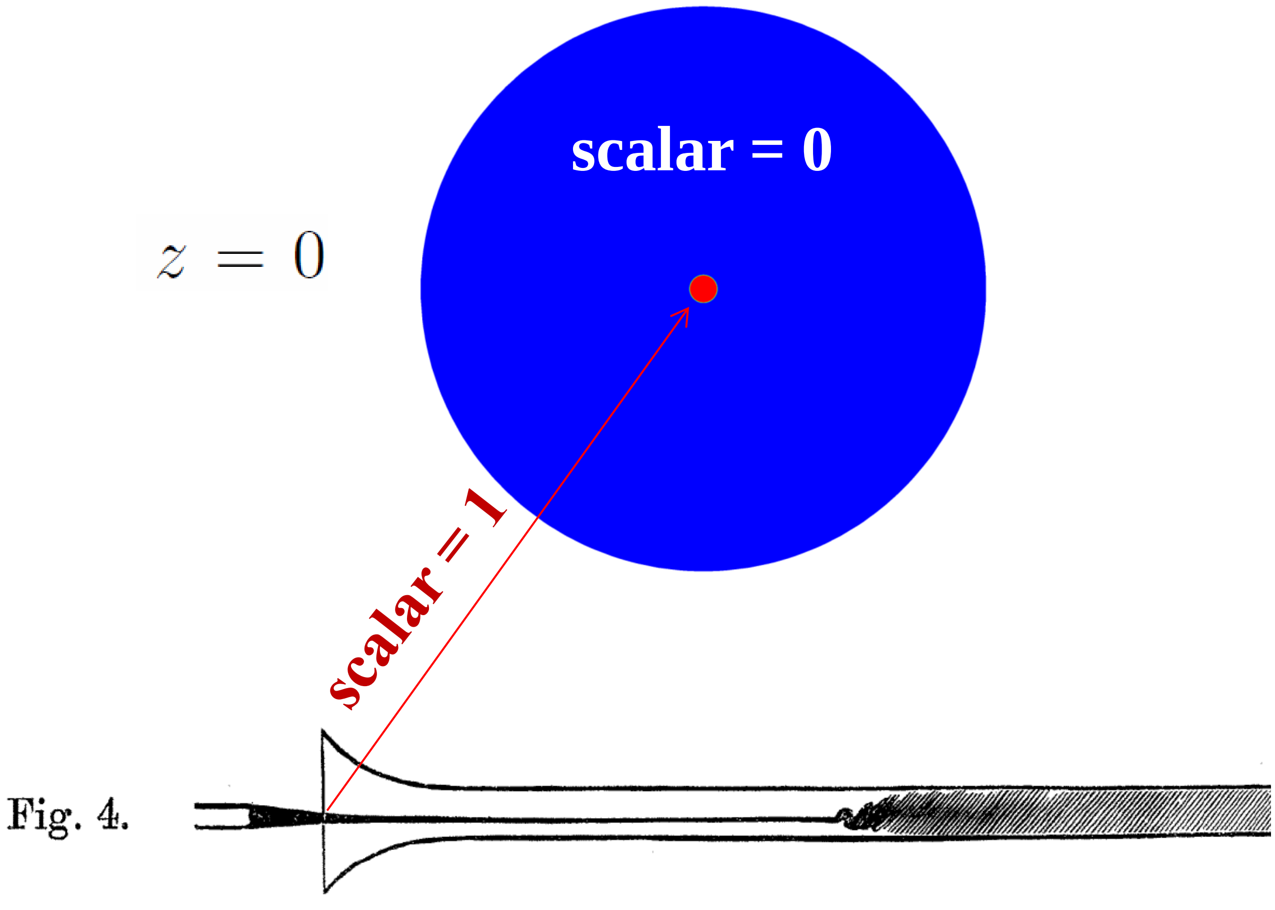
8196 x 200 x 256 mesh, 16384 x 200 x 512 mesh



if inlet disturbance 0.9<r<0.92, transitions right away
if inlet disturbance 0.9<r<0.91, no transition

Step 5: Modify inlet disturbance at Re_D = 8000

Also, added passive scalar as dye in the Reynolds' experiment



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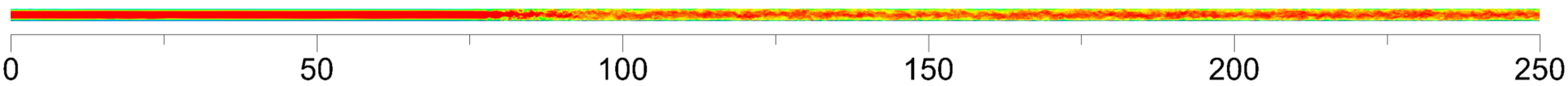
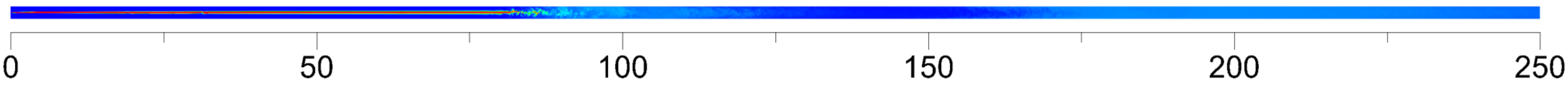
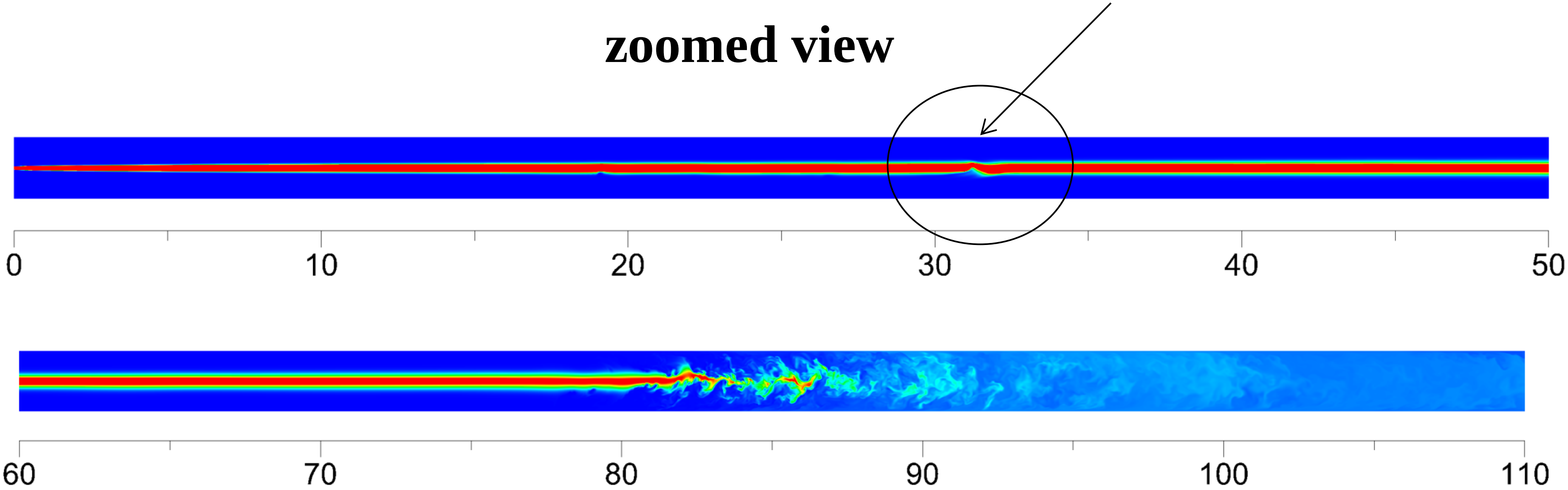
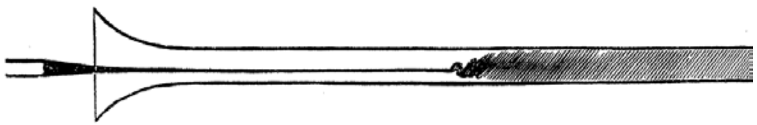


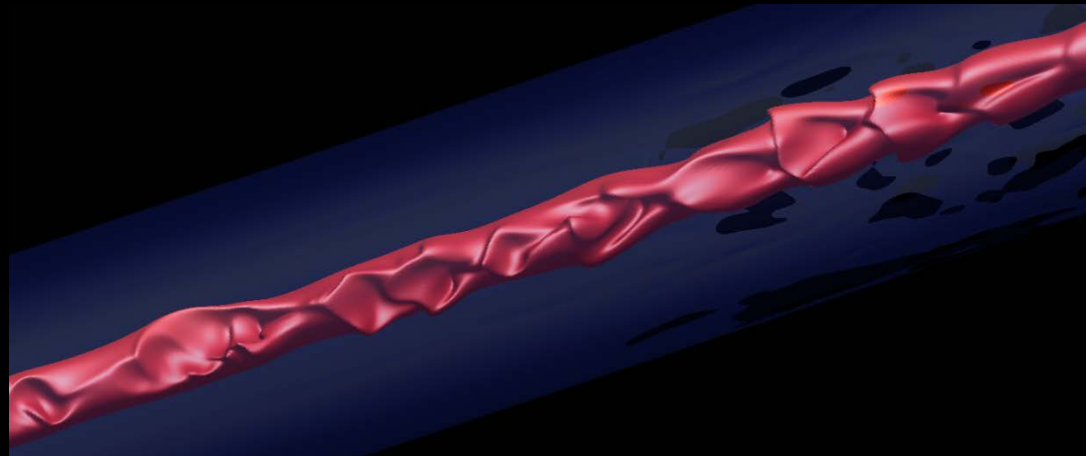
scalar, blue=0, red (>0.05)

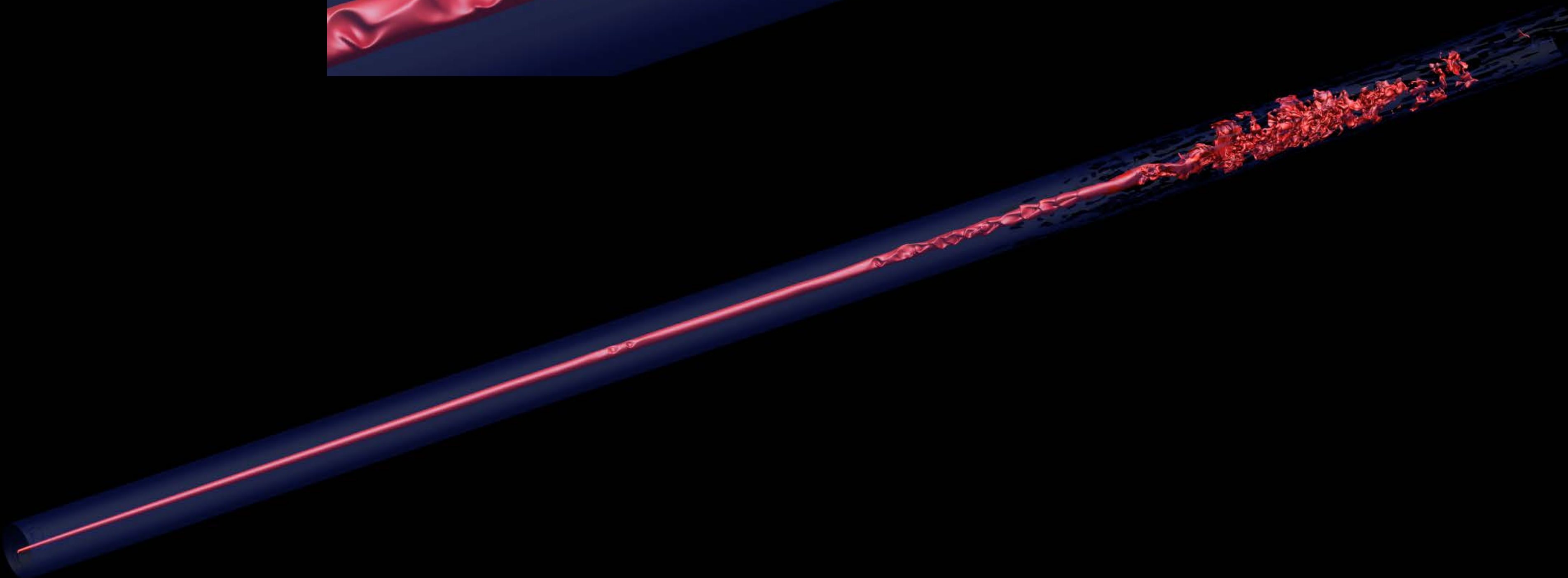


zoomed view

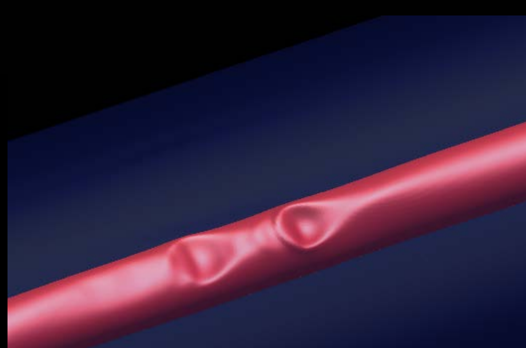


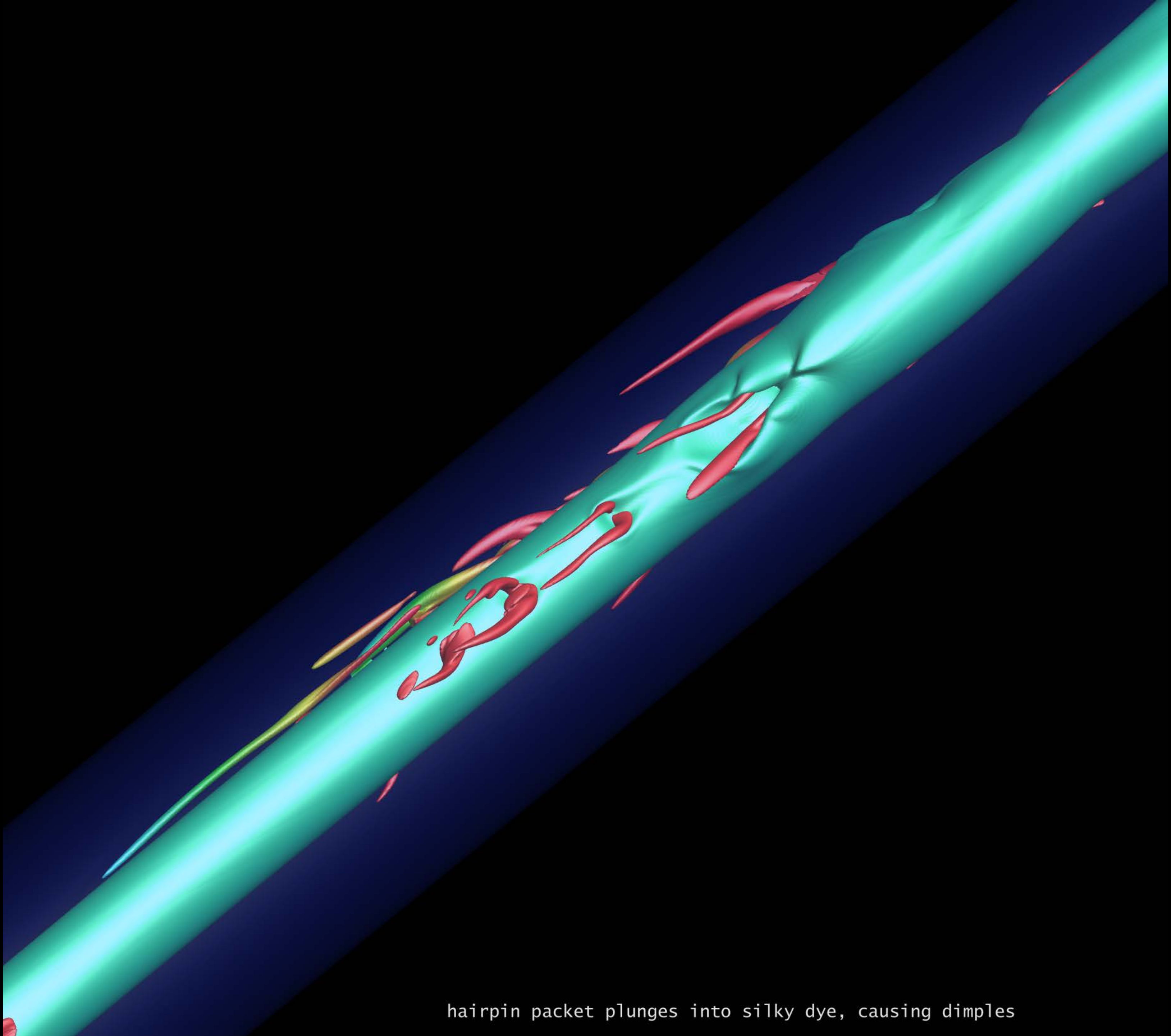




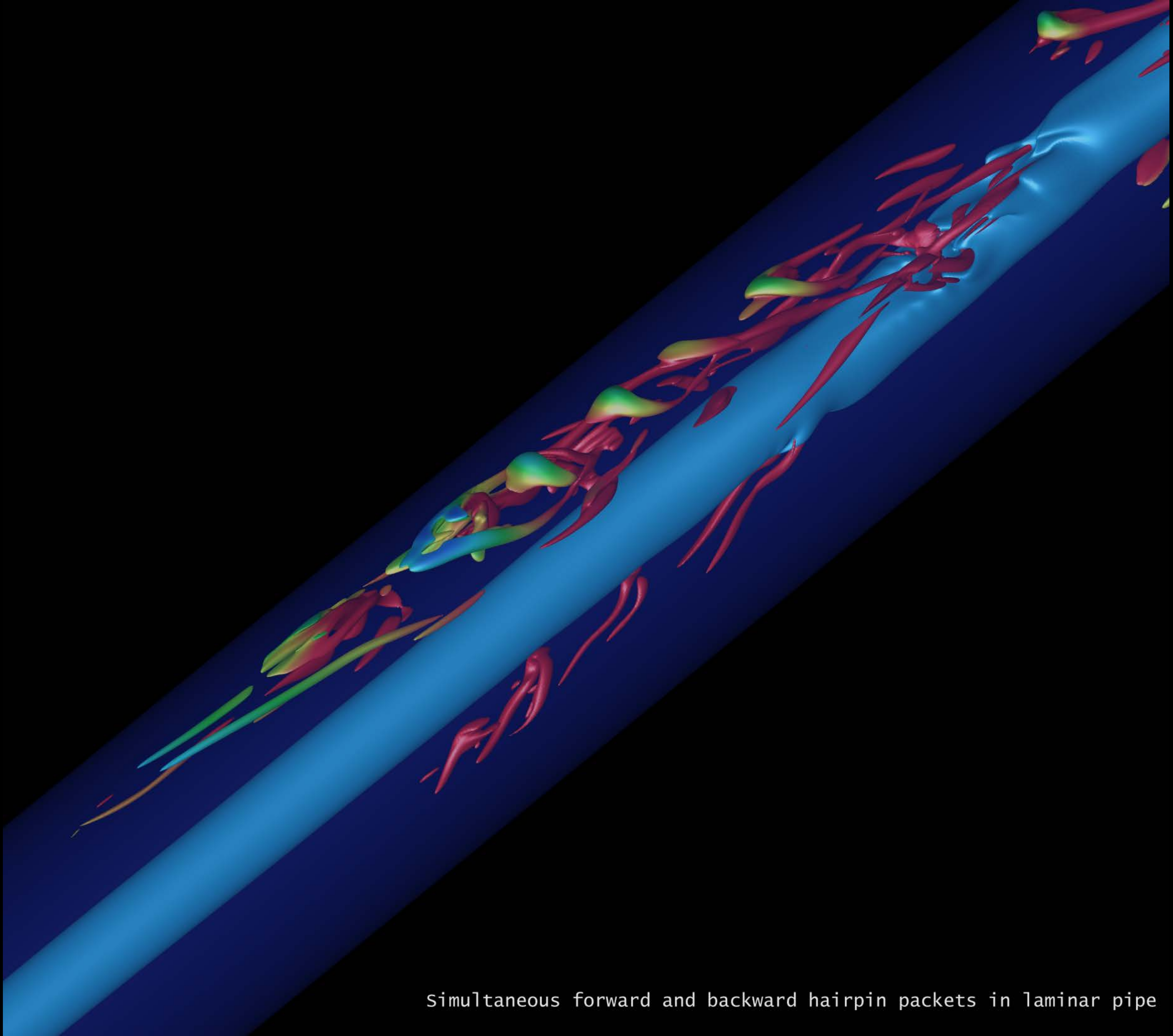


dye brought into laminar pipe, as in Osborne Reynolds (1883), exhibiting dimples





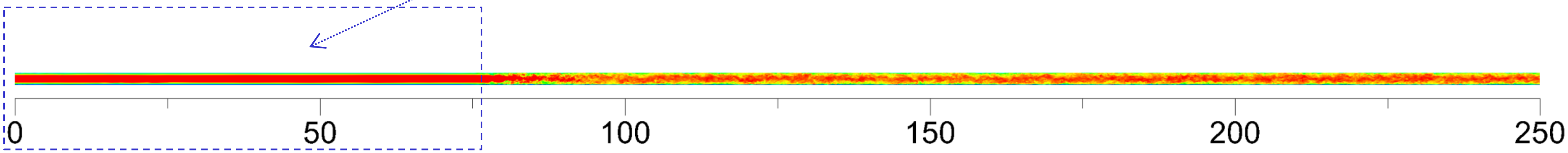
hairpin packet plunges into silky dye, causing dimples

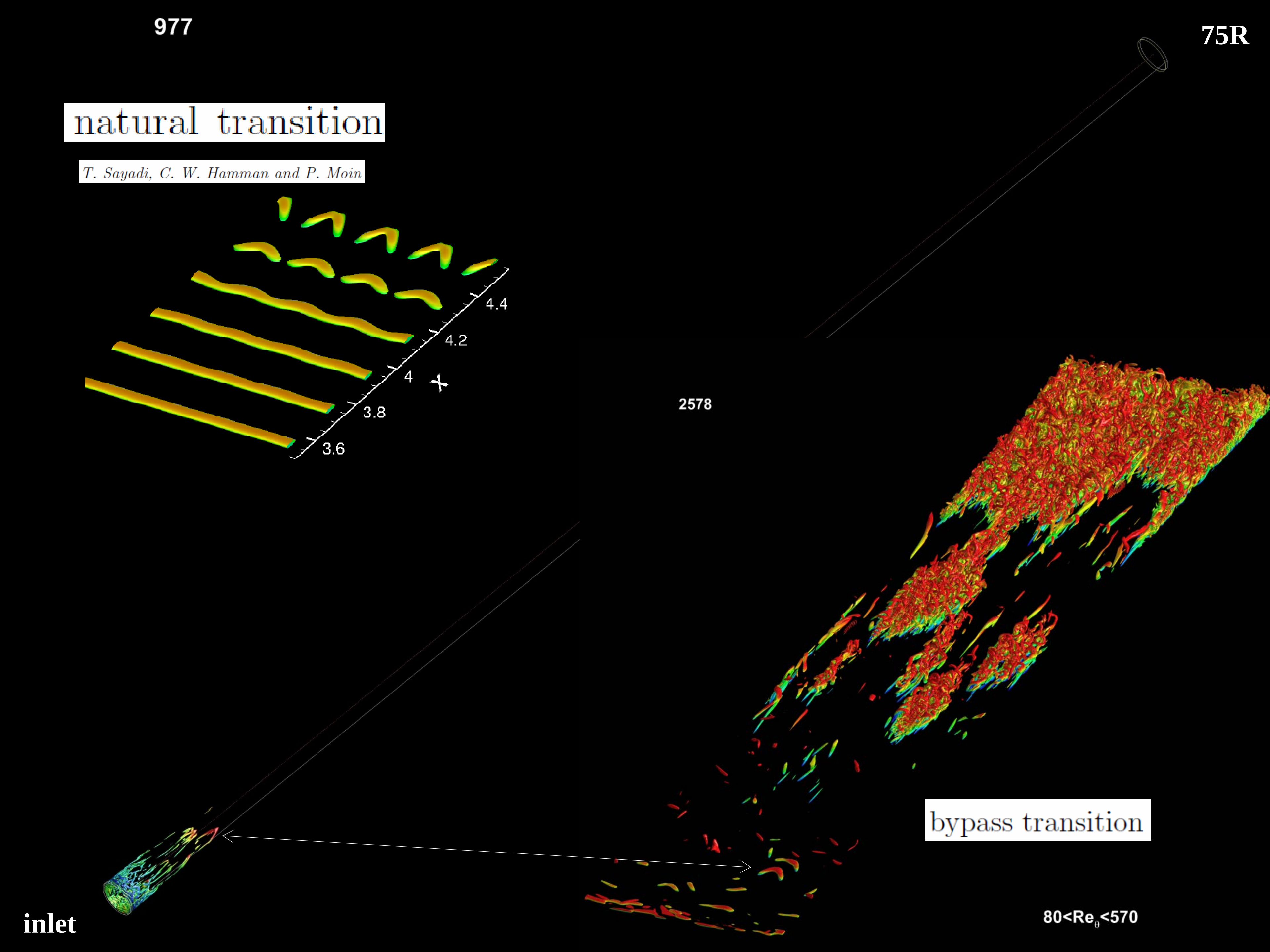


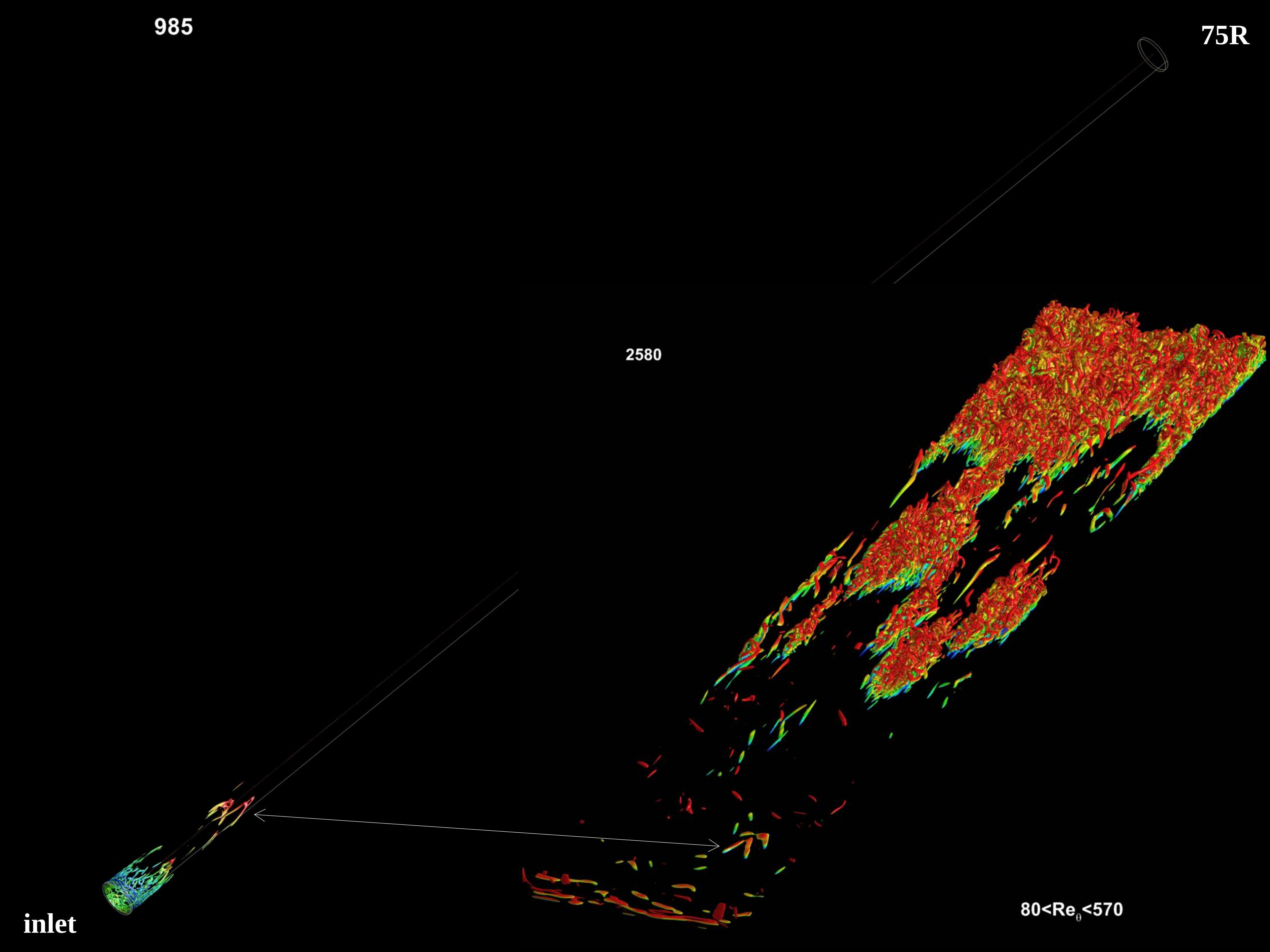
Simultaneous forward and backward hairpin packets in laminar pipe

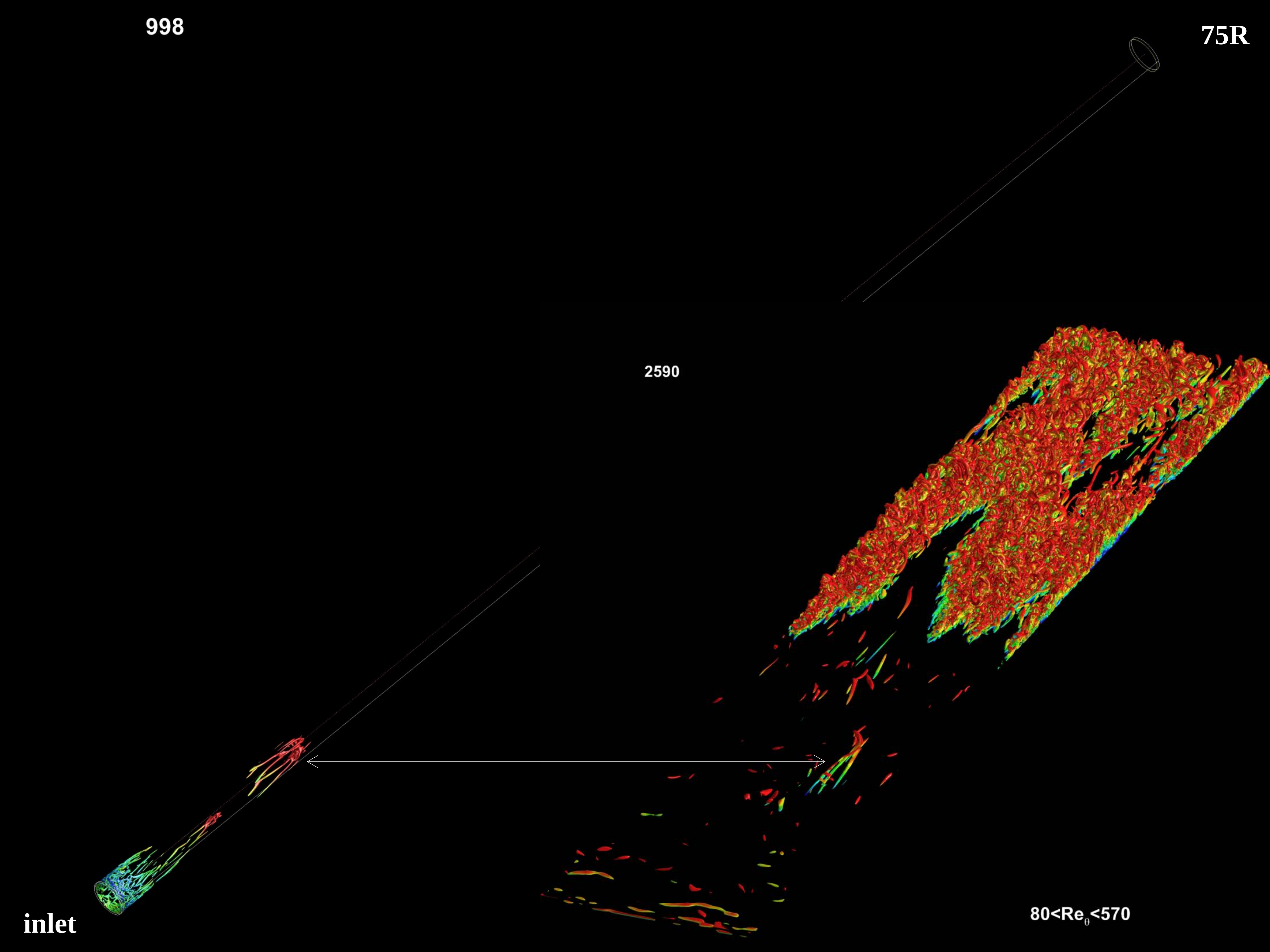
Iso-surfaces of swirling strength λ_{ci} coloured by local values of u_z

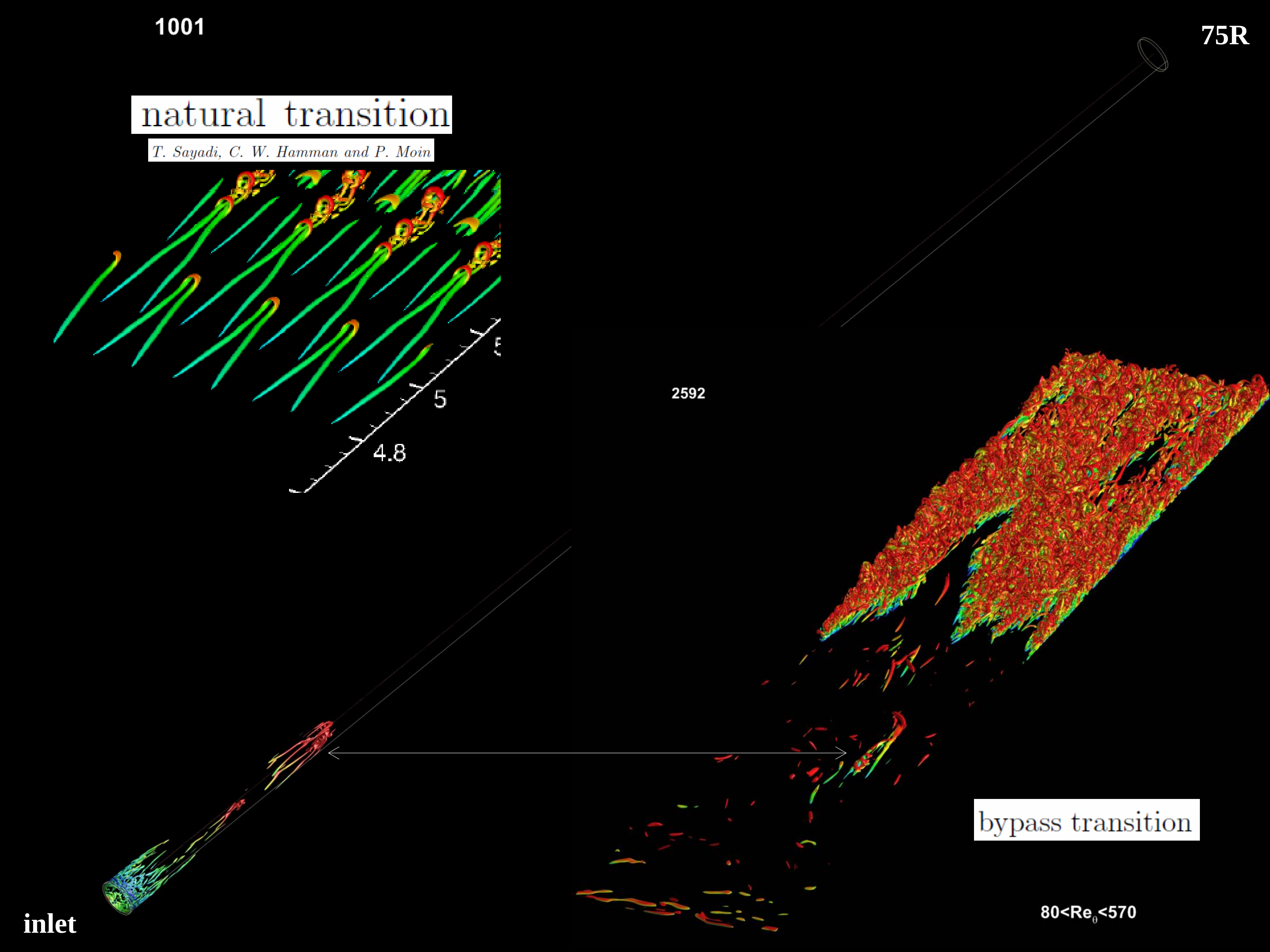
discrete pipe transition with spots between 0< z < 75R

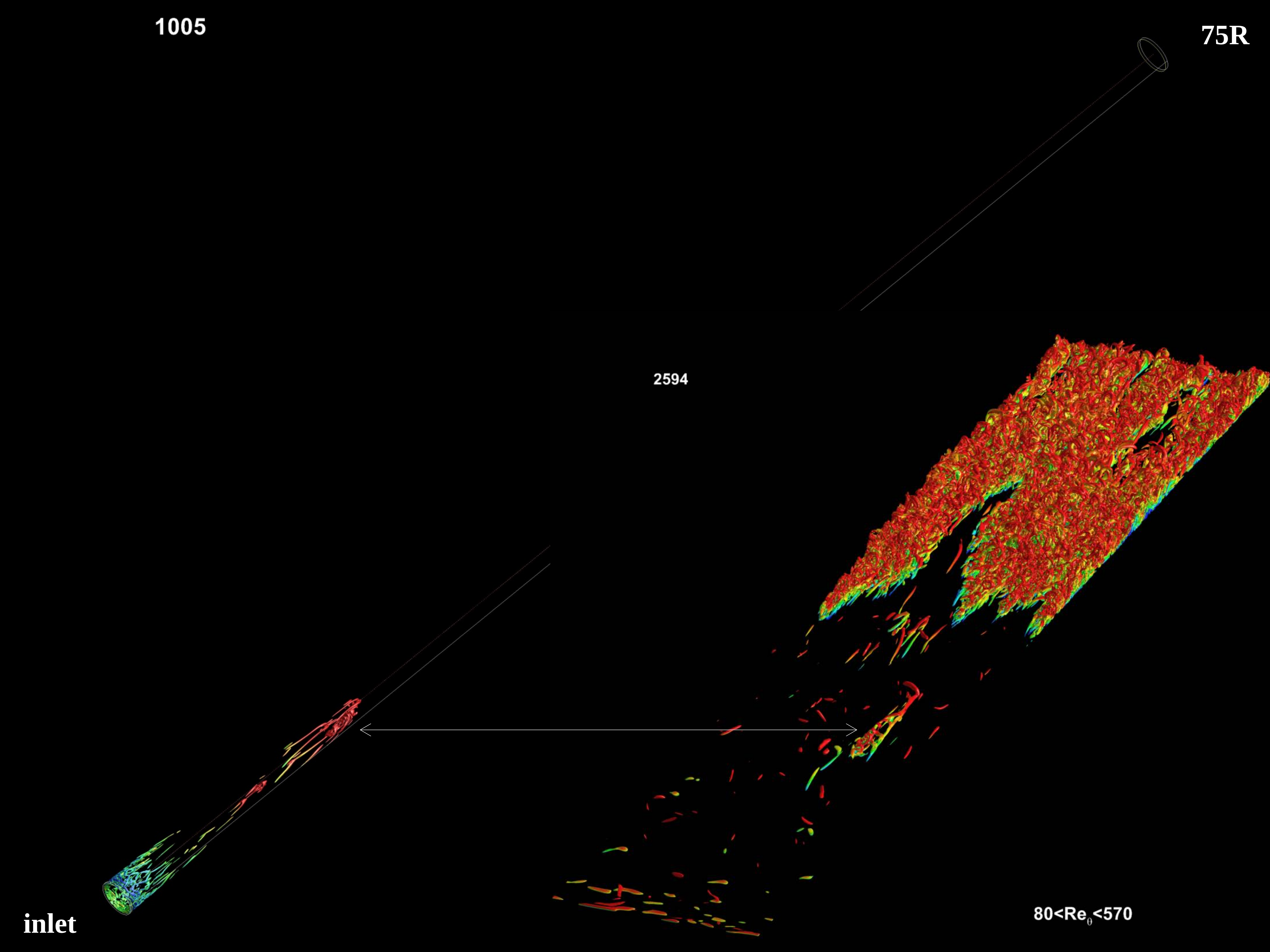



977
75R
natural transition
T. Sayadi, C. W. Hamman and P. Moin
4.4
4.2
4
x
3.8
3.6
2578
bypass transition
inlet
$80<Re_\theta<570$


985
75R
2580
inlet
80<Re$_\theta$<570


998
75R
2590
inlet
80<Re$_\theta$<570


1001
75R
natural transition
T. Sayadi, C. W. Hamman and P. Moin
5
4.8
2592
bypass transition
inlet
80<Re$_\theta$<570


1005
75R
2594
inlet
80<Re$_\theta$<570