The DNS of the Reynolds experiment
ON THE CIRCUMSTANCES WHETHER THE MOTION SHALL BE DIRECT OR SINUOUS

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Our research depends on the Reynolds paper

- Reynolds number definition
- Laminar regime
- Turbulent regime
- To understand transition
-         Theory or experiments
- In 1883 impossible solution of N-S eq.
- Experiments as N-S solvers
- Von Neuman wind tunnels N-S simulators

Reynolds made a clean experiment

- Several large disturbances eliminated
- Others remain non-linear stability
- Control of fluid temperature
- Control of flow parameters U and D
- Smooth wall impossible in 1883
- Definition of $K = \rho \; U \, D/\mu$ obtained
- Changing U , D, T
- DIFFICULT LIFE FOR
- EXPERIMENTALISTS

DNS made our work easy

- Impossibility to have analytical sol. N-S
- Theory + dimensional analysis
  - Reynolds number

  Fast computers to solve N-S

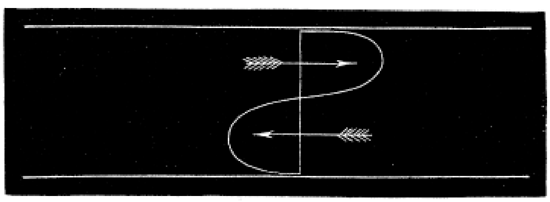
  Control all parameters
  - Small disturbances linear stability
  - Large disturbances non-linear
  - Reynolds was studying non-linear

NUMERICAL TOOLS

- 2° order accuracy more than sufficient
- Stable
- Physical principle reproduced in discrete
- Mass conservation
- Energy conservation $(\mu = 0)$
- Boundary conditions accurate
- Finite difference simple
- Reproduce all the requirements

PHYSICAL QUESTIONS

- Role of viscosity
- Reynolds stated
- Viscosity can not cause the instability
- Inviscid is unstable
- He demonstrated Rayleigh criterium
- through an experiment
- with two inmiscible liquids



DNS of FLOW INFLECTIONAL U(y)

- Channel instead pipe
- Different pressure gradient in the two sides

  Balances also non-linear terms

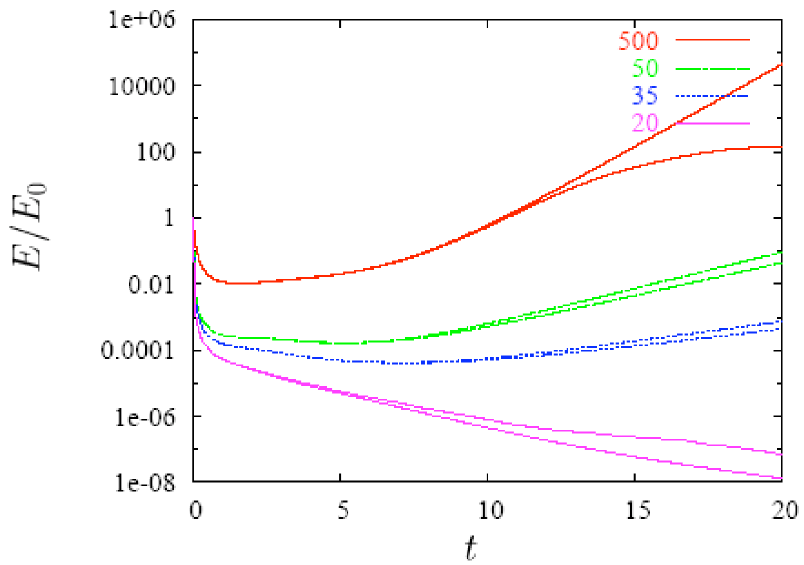
  Non-linear > wall friction

A disturbance ε is added in the central region

ε = 2.5 10-4 linear

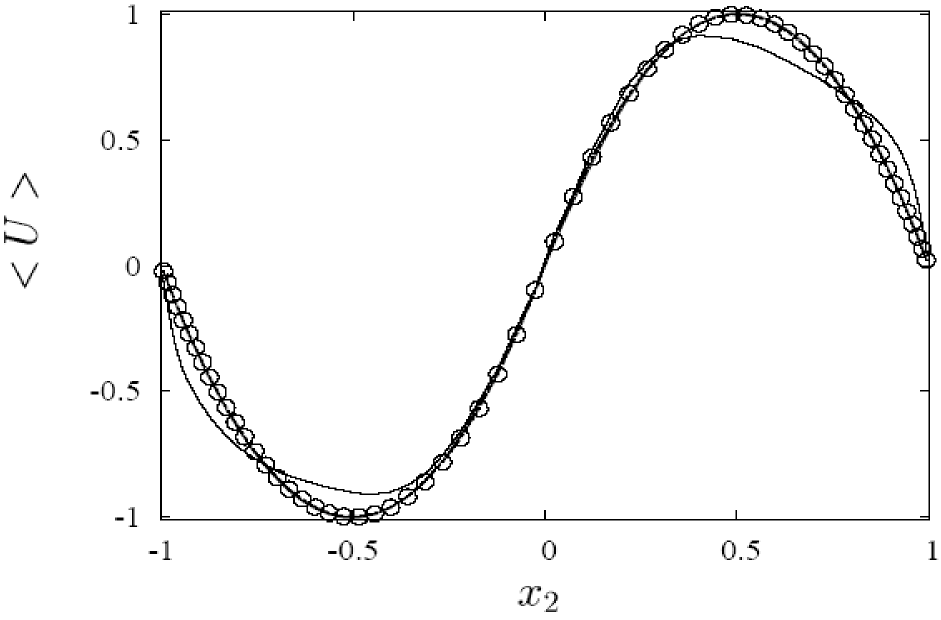
ε = 2.5 10-1 non-linear

DISTURBANCE GROWTH

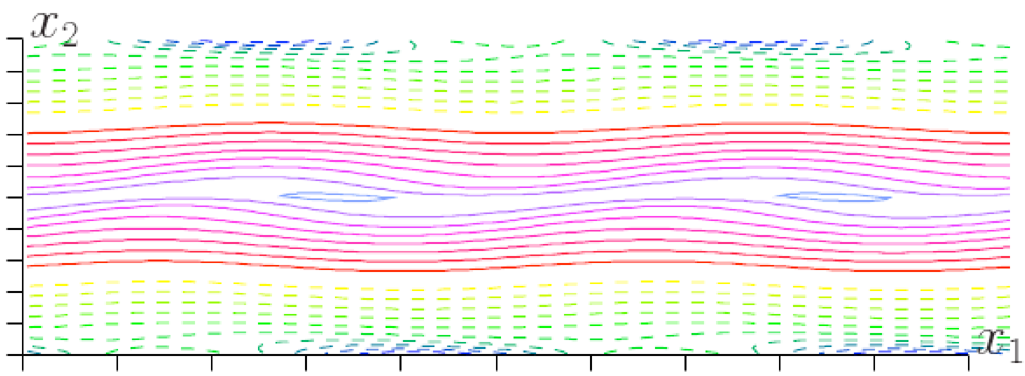


- Linear regime gives K=Re=30
- Non-linear deviates from linear
- due to changes in U(y)

MEAN VELOCITY

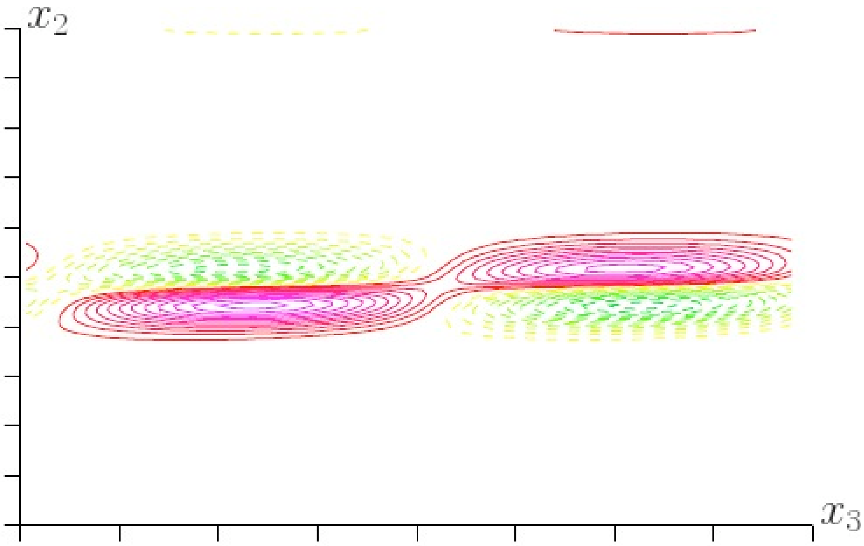


VORTICITY VISUALIZATIONS



Spanwise component
Kelvin-Helmotz instability (today)
Reynolds defined waves sinuosities

VORTICITY VISUALIZATIONS



Streamwise component
Rib vortices inclined 45 degrees
Difficult to visualize in esperiments
Easy in DNS

Difference Turbulent Laminar

Turbulent Near wall structures
Laminar Absence of structures
From laminar to turbulence
Creation structures
Importance initial conditions
From turbulence to laminar
Destruction structures
Initial structures solution of N-S Eq.

Transition Lam-Turb

Initial Poiseuille mean velocity profile
+ disturbance
Experimental difficulties and extreme care
Numerically theoretical insights
need to impose appropriate structures
e.g. Random disturbances at all scales
do not create the right size
e.g. Fine grids at any Re lead to
absence of growth

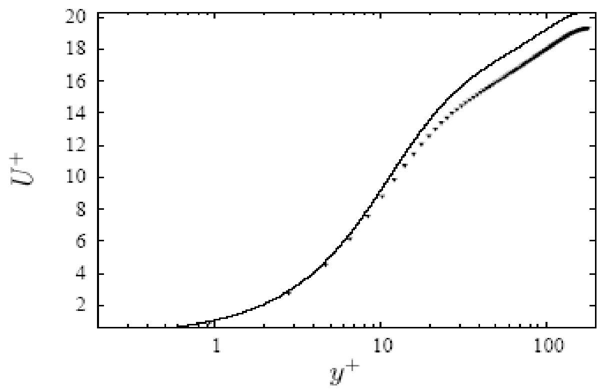
Transition Turb-Lam

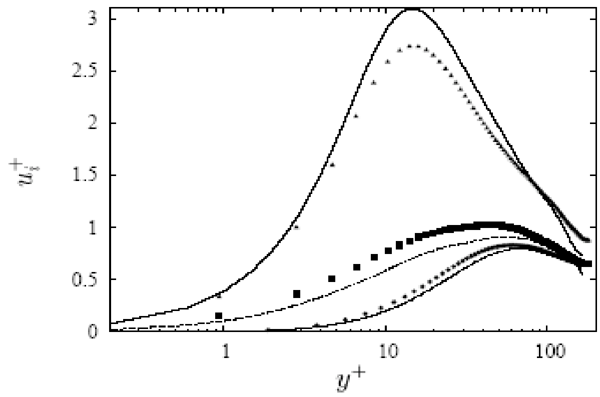
Initial Fully turbulent flow
solution N-S equations
Close to experiments
Space developing simulations need
large grids and ad-hoc inlet
Time developing simulations need
reasonable resolution

Similarity with space developing in
a reference frame translating with
bulk velocity

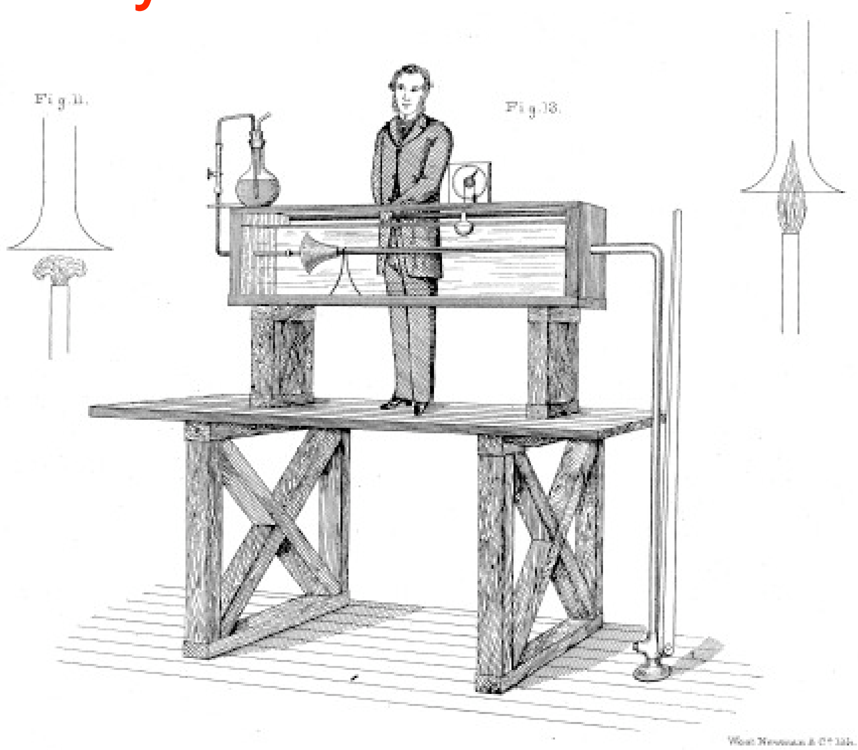
INITIAL CONDITIONS

- Insufficient resolution with 128 X 64 X64
- Wall structures captured





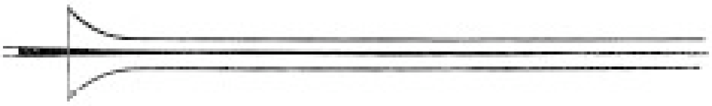
Reynolds visualizations



Laminar

(1.) When the velocities were sufficiently low, the streak of colour extended in a beautiful straight line through the tube, fig. 3.

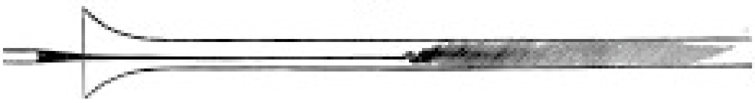
Fig. 3.



Unsteady or turbulent

(3.) As the velocity was increased by small stages, at some point in the tube, always at a considerable distance from the trumpet or intake, the colour band would all at once mix up with the surrounding water, and fill the rest of the tube with a mass of coloured water, as in fig. 4.

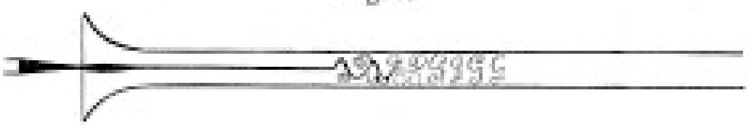
Fig. 4.



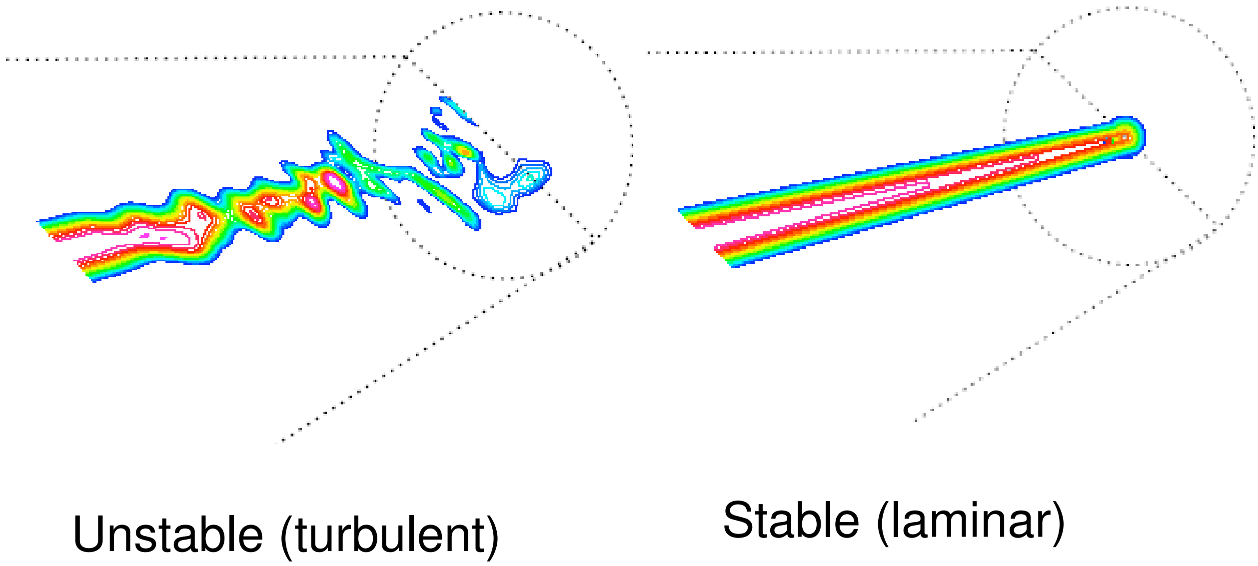
Any increase in the velocity caused the point of break down to approach the trumpet, but with no velocities that were tried did it reach this.

On viewing the tube by the light of an electric spark, the mass of colour resolved itself into a mass of more or less distinct curls, showing eddies, as in fig. 5.

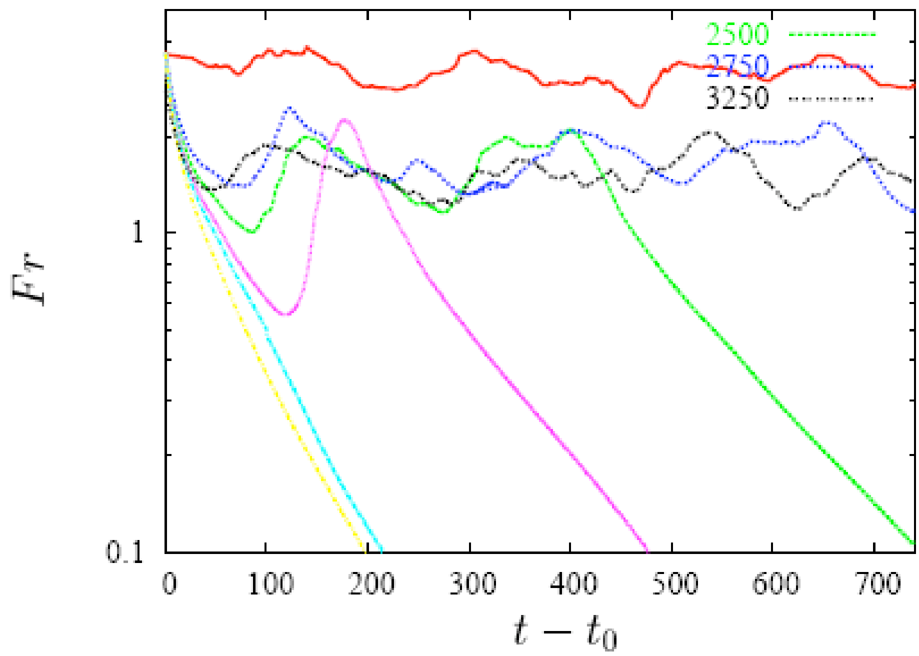
Fig. 5.



DNS visualizations

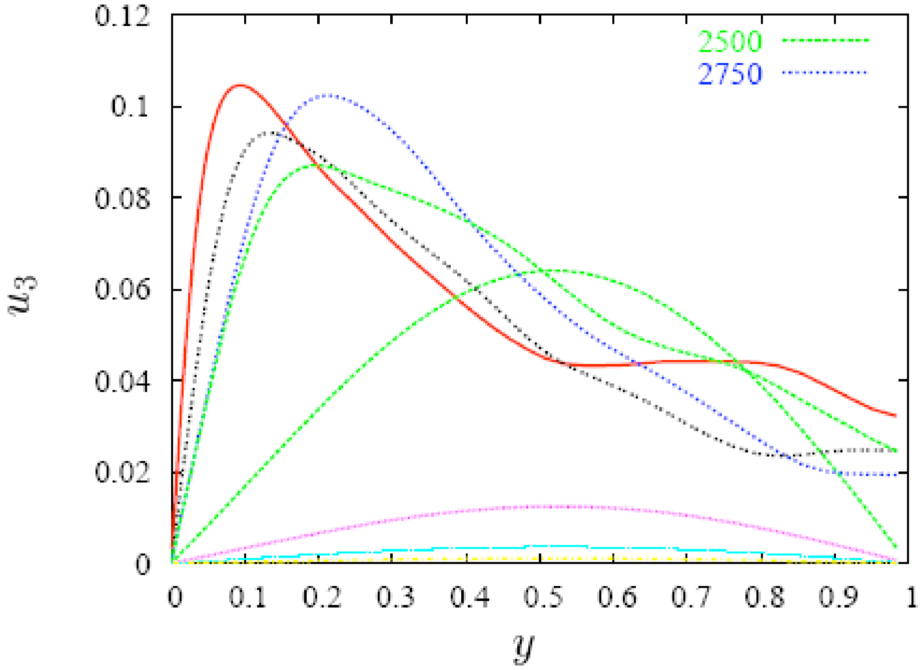


Friction for long time



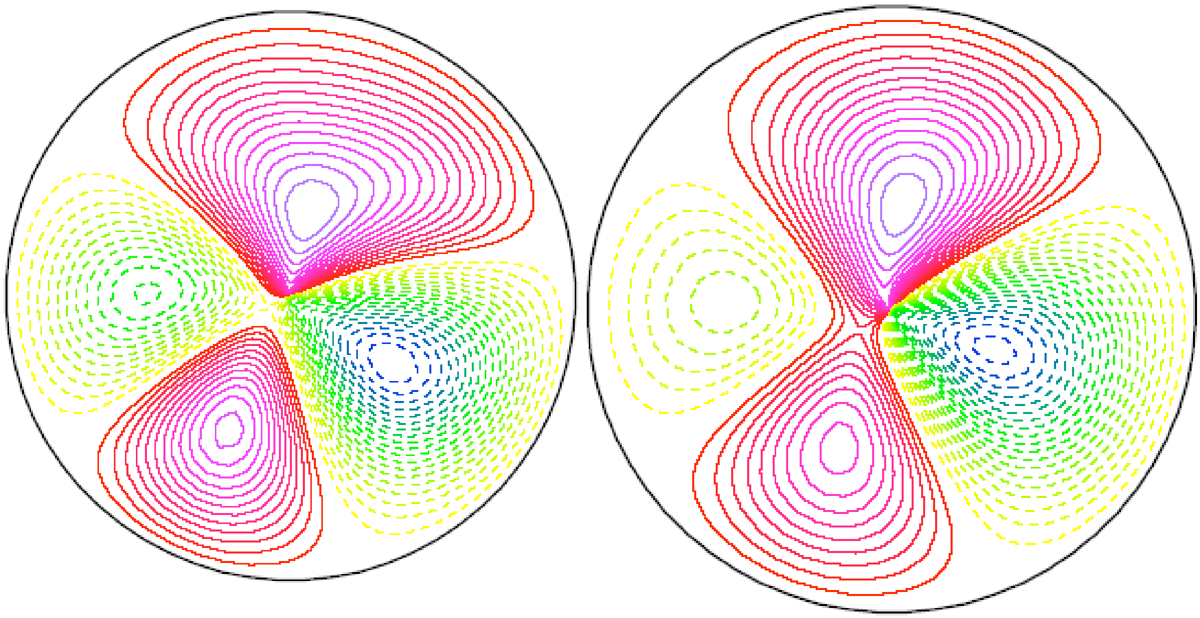
Turbulent for Re> 2500

Normal stress profiles



Reynolds could not measure

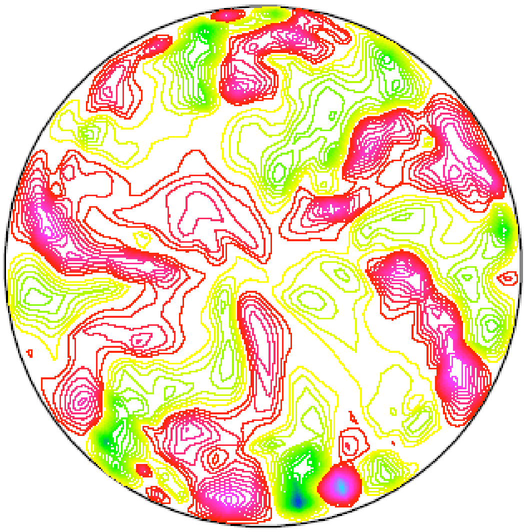
Vortical structures laminar



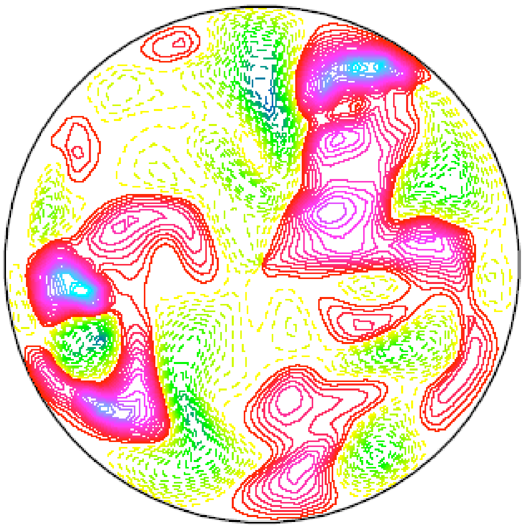
Only by DNS

Obtained also from Poiseuille + disturbance

Vortical structures turbulent



$Re = 4900, R_\tau = 170$



$Re = 2500, R_\tau = 100$

To remain turbulent radius 20 wall units

Rτ = 100 marginal Rτ = 170 fully turbulent

Reasons for transition

Is the mean flow or the disturbance the cause ?

Explanation possible by DNS

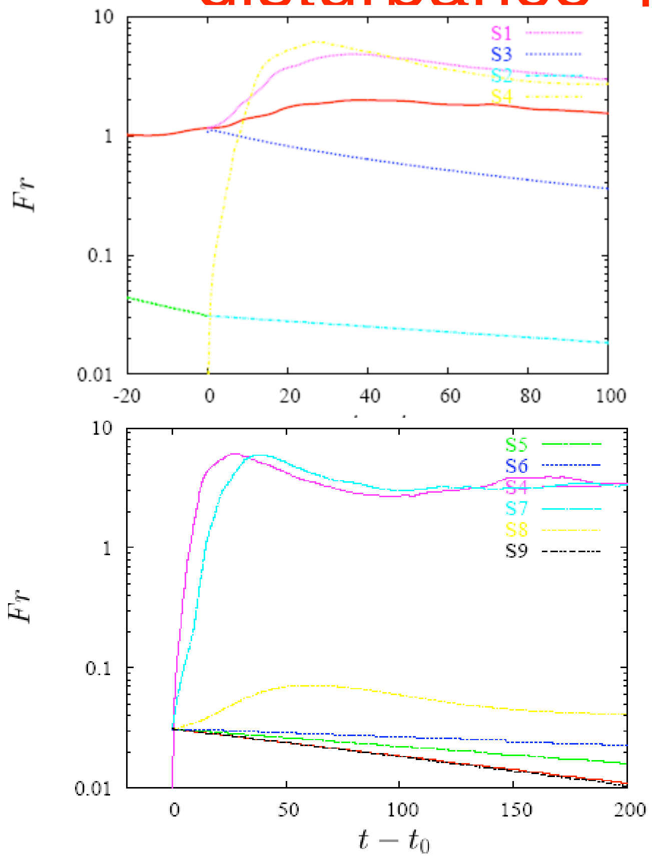
Through combination of I.C.

<U>t (r) u't(θ ,r,x)

<U>l (r) u'l(θ ,r,x)

$case$	$Average$	$Fluct$	K
S_1	$< U >_t$	q'_t	4900
S_2	$< U >_l$	q'_l	4900
S_3	$< U >_t$	q'_l	4900
S_4	$< U >_l$	q'_t	4900
S_5	$< U >_l$	q'_l	7500
S_6	$< U >_l$	q'_l	15000
S_7	$< U >_l$	$q'_t/2$	4900
S_8	$< U >_l$	$q'_t/10$	4900
S_9	$< U >_l$	$q'_t/100$	4900

disturbance is the cause



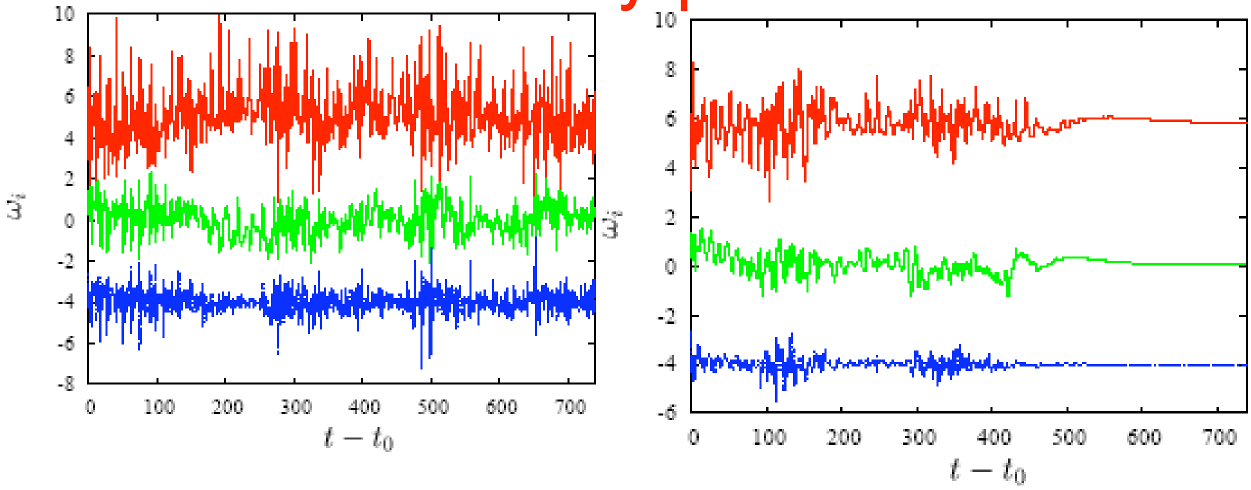
case	Average	Fluct	K
S_1	$< U >_t$	q'_t	4900
S_2	$< U >_t$	q'_t	4900
S_3	$< U >_t$	q'_t	4900
S_4	$< U >_t$	q'_t	4900
S_5	$< U >_t$	q'_t	7500
S_6	$< U >_t$	q'_t	15000
S_7	$< U >_t$	$q'_t/2$	4900
S_8	$< U >_t$	$q'_t/10$	4900
S_9	$< U >_t$	$q'_t/100$	4900

Conclusions

- Reynolds experiment today by DNS
  - All quantities can be measured
  - All quantities can be visualized
  - All quantities can be controlled
  - Physics can be fully understood
  - Structures important for instability
  - Structures cause the friction
  - To control the flow action on the structures

FUTURE WORK REPRODUCE NIKURADSE EXPERIMENT

Vorticity probe

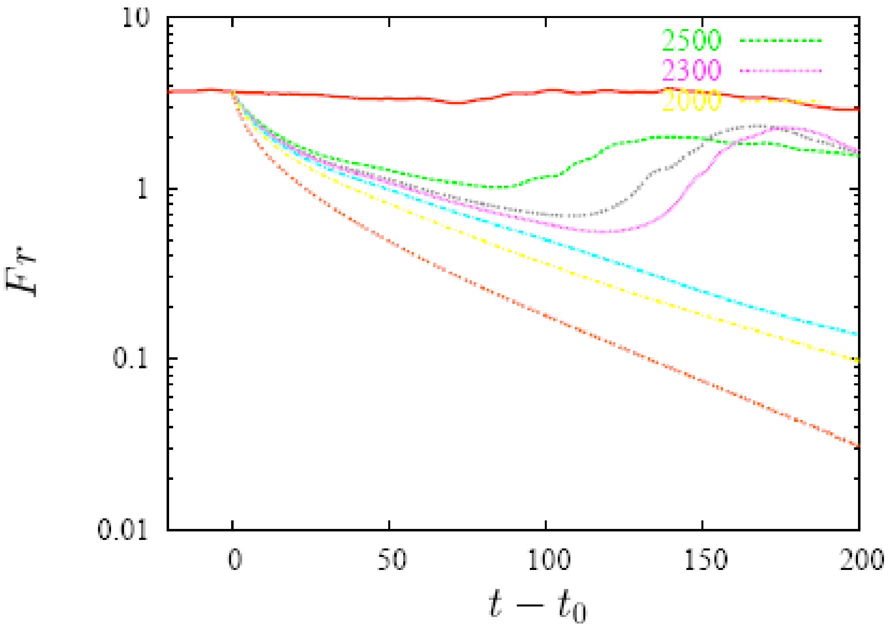


Reynolds experiment in pipes

I mportance of inlet conditions
Usually Poiseuille + disturbance
Here fully turbulent closer to Reynolds
Visualizations of passive scalar as Reynolds
Experiment space developing

DNS flow time developing
scalar space developing
Resolution 128 X 64 X 64

Friction for short time



Turbulent for K=Re > 2200; 2300
Fr = du/dr|wall -2