Dynamique et modélisation de la Turbulence

- Cours 1-2

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SB Pope, «Turbulent flows» Cambridge University Press

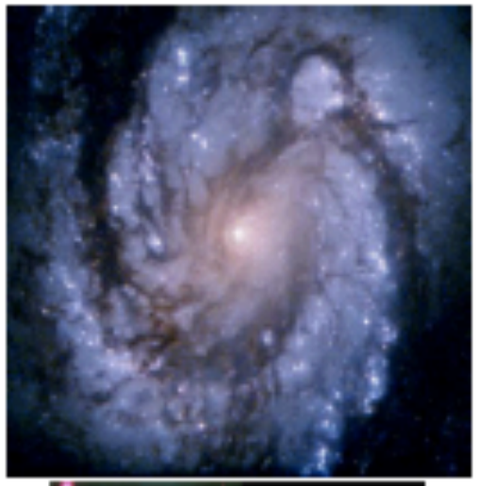
I am an old man now, and when I die and go to Heaven there are two matters on which I hope enlightenment. One is quantum electro-dynamics and the other is turbulence.

About the former, I am really rather optimistic

Sir Horace Lamb (1932)

What's Turbulence

- « Turbulence was probably invented by the Devil on the seventh day of Creation when the Good Lord wasn't looking » (P. Bradshaw, 1994)
- « Turbulence is the graveyard of theories » (H.W. Liepman)
- « ... the absence of a sound theory is one of the most disturbing aspects of the turbulence syndrome » (R.W. Stewart)
- « As a doctorate I proposed to Heisenberg no theme from spectroscopy but the difficult problem of turbulence, in the hope, that if anybody, would solve this problem. However, the problem is until now not solved. » (A. Sommerfeld, 1942)

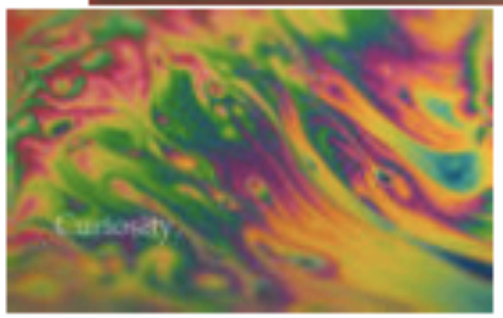


M100 galaxy 10^{23} m

Eagle nebula 10^{18} m

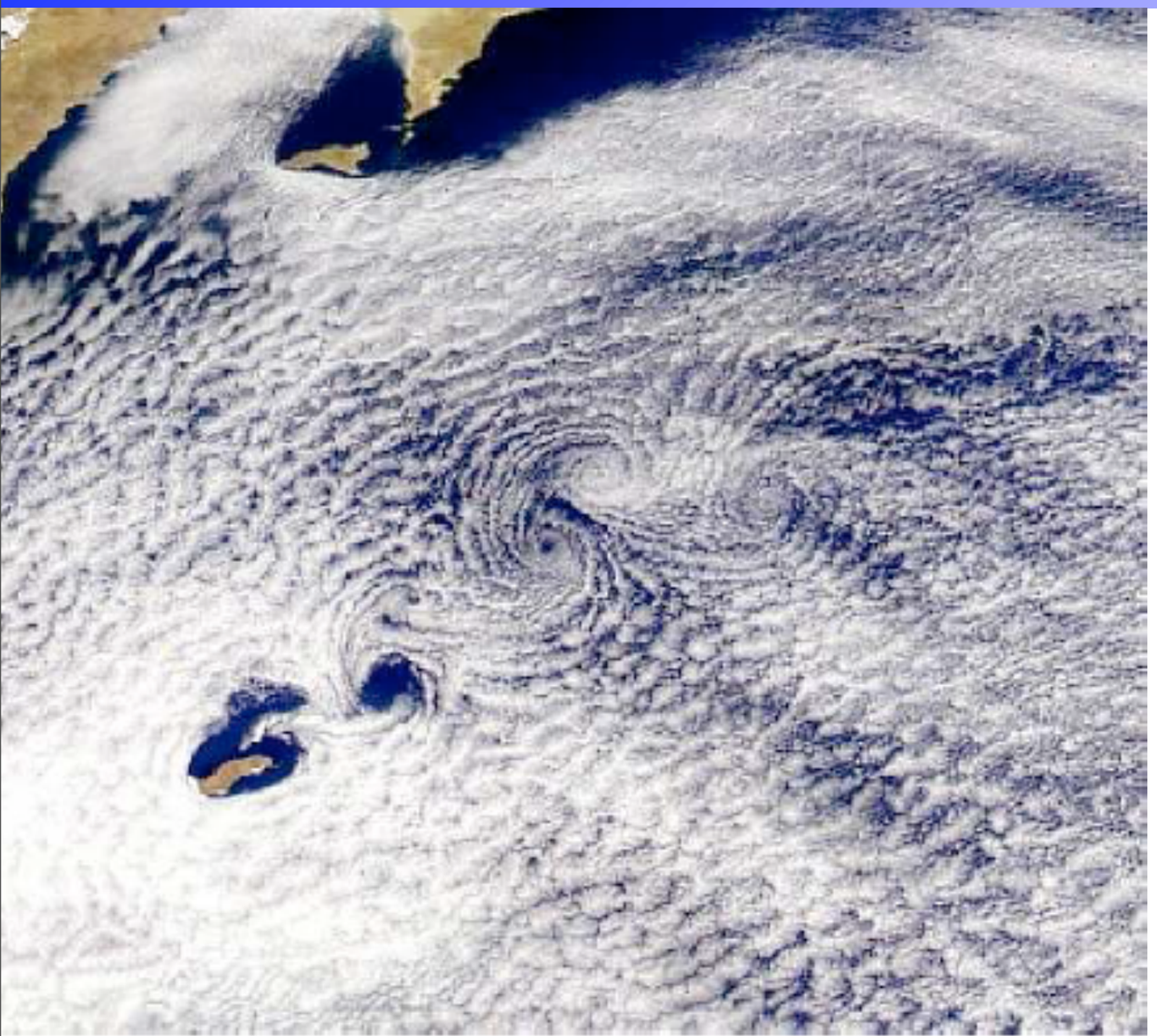
Earth's atmosphere 10^{7} m

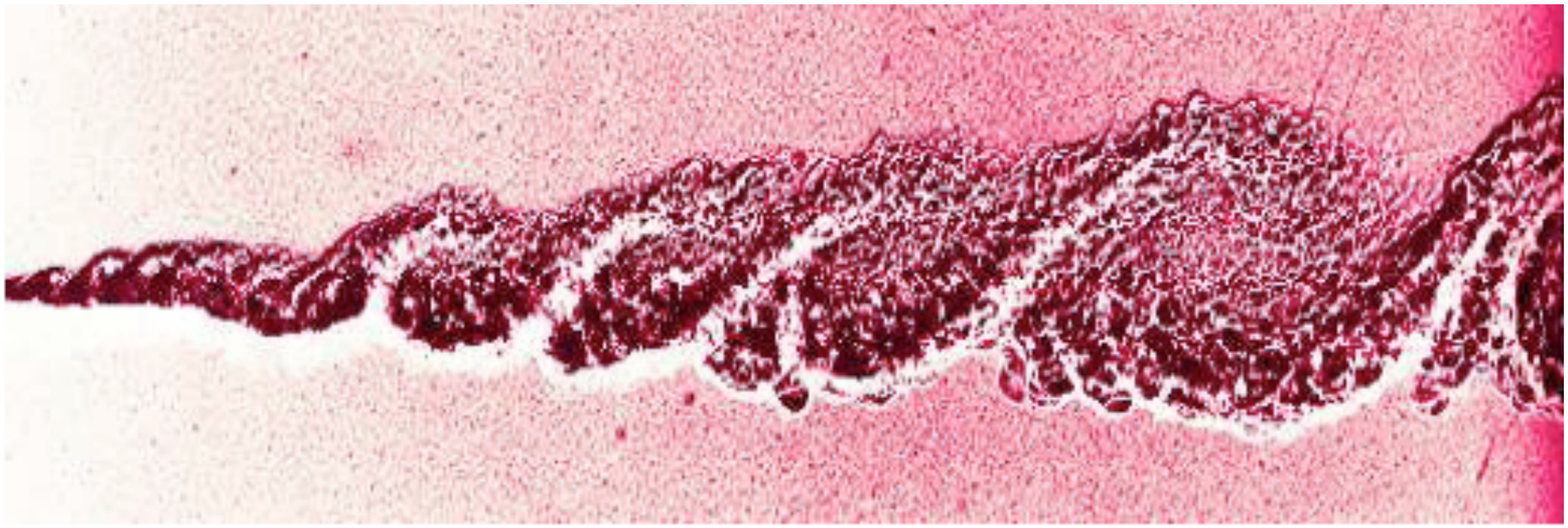
Clouds 10^{3} m



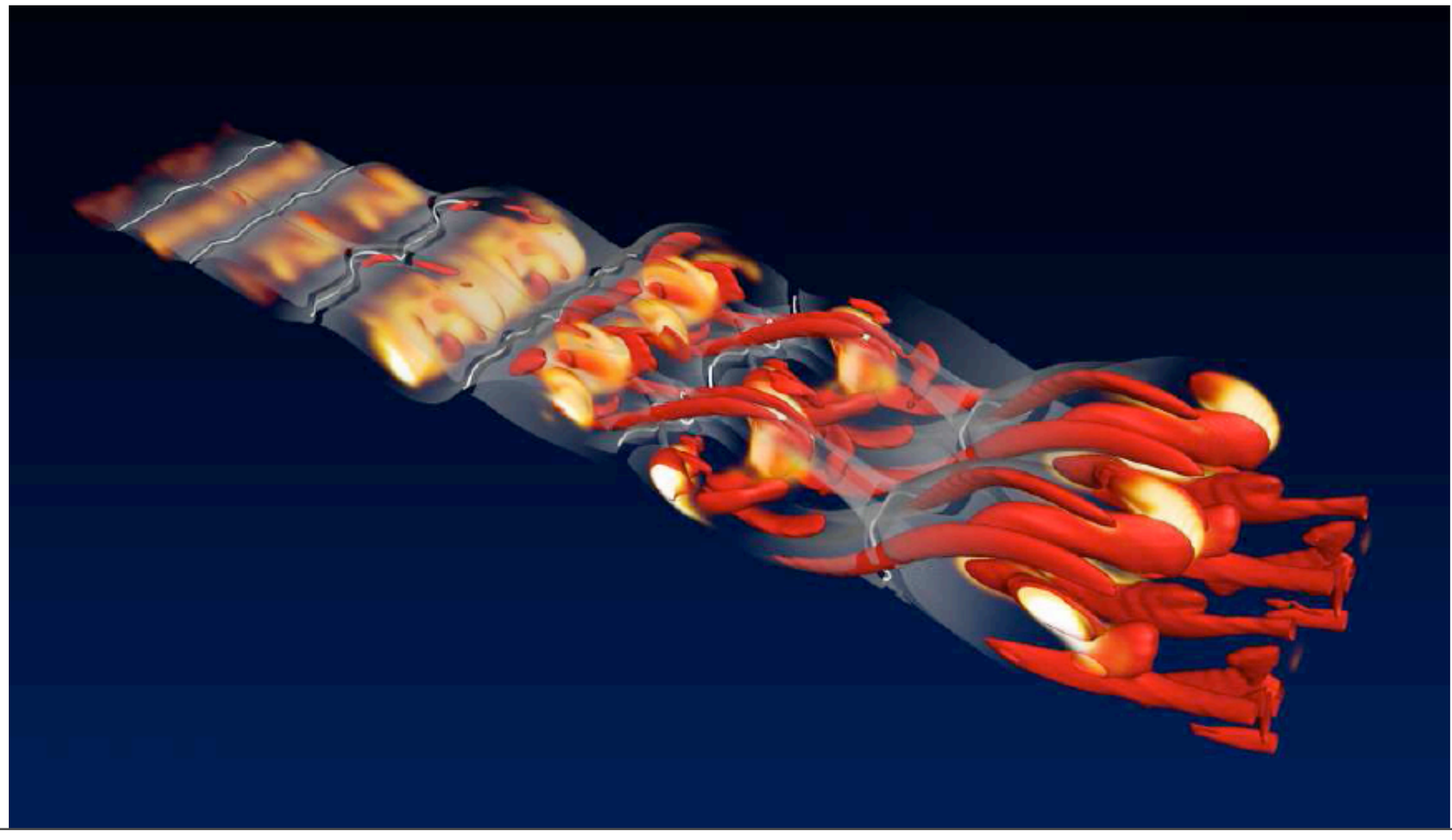
Soap film 10^{-1} m

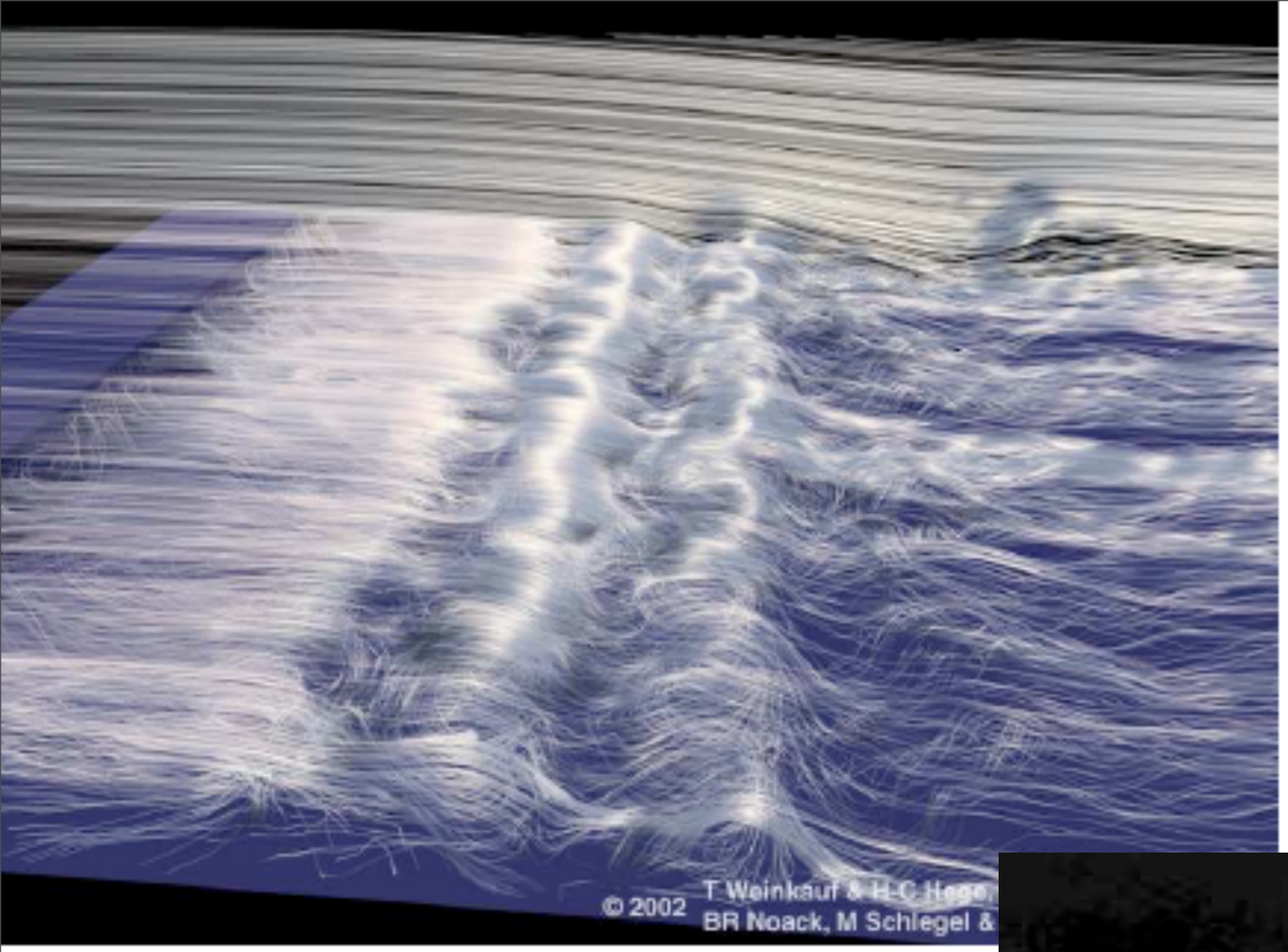
Turbulent flows: illustration and definition



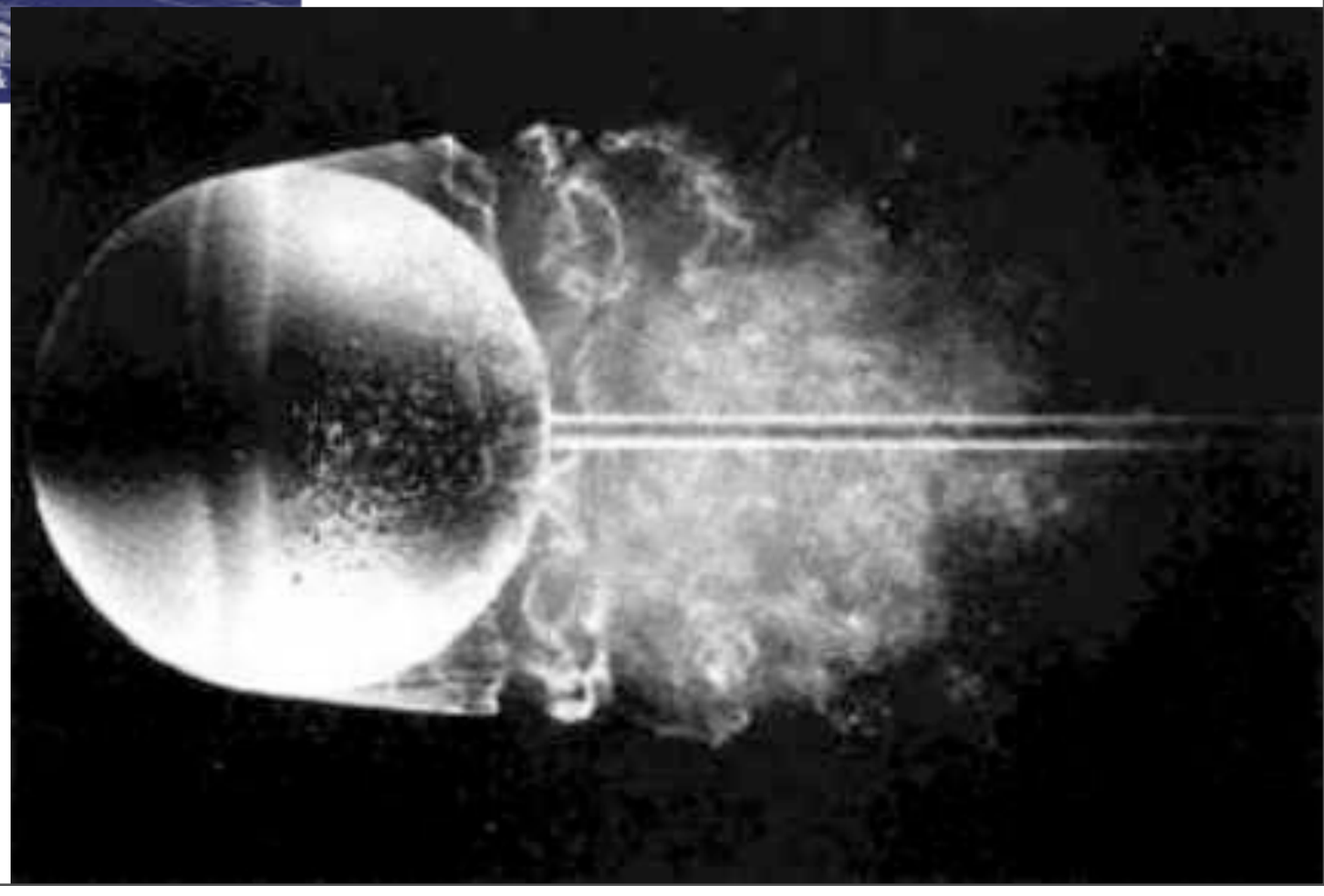


Turbulent mixing layers

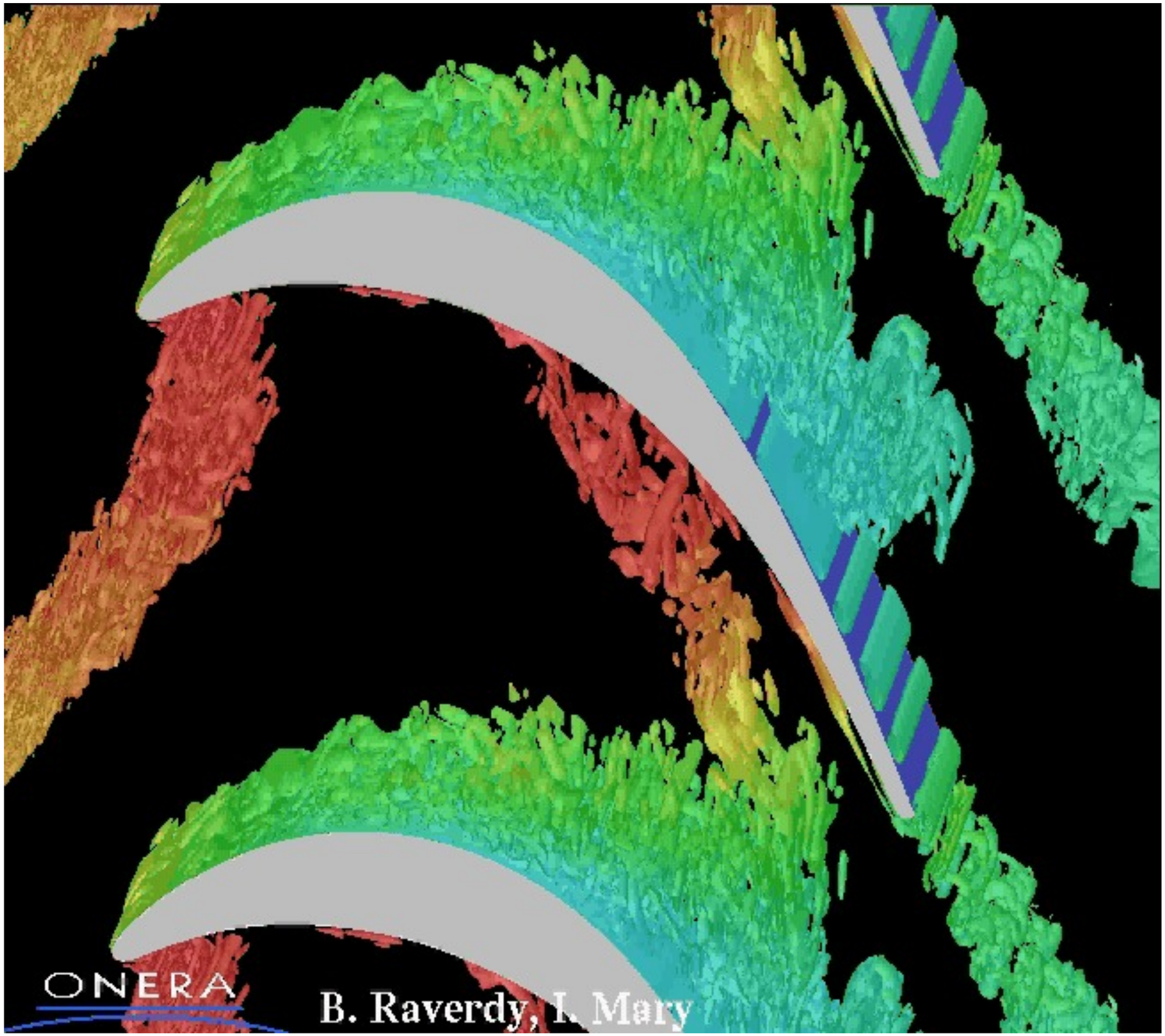


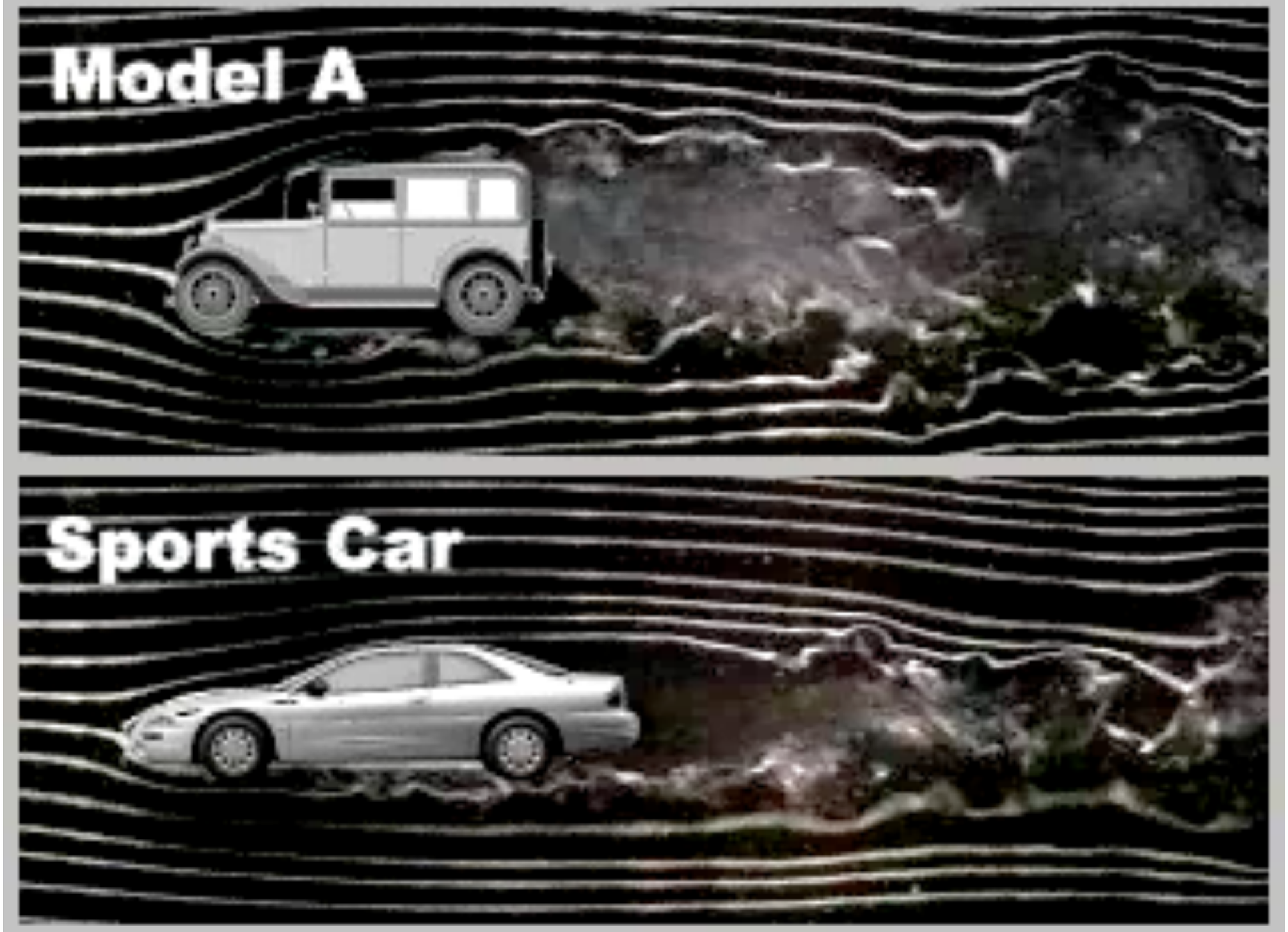


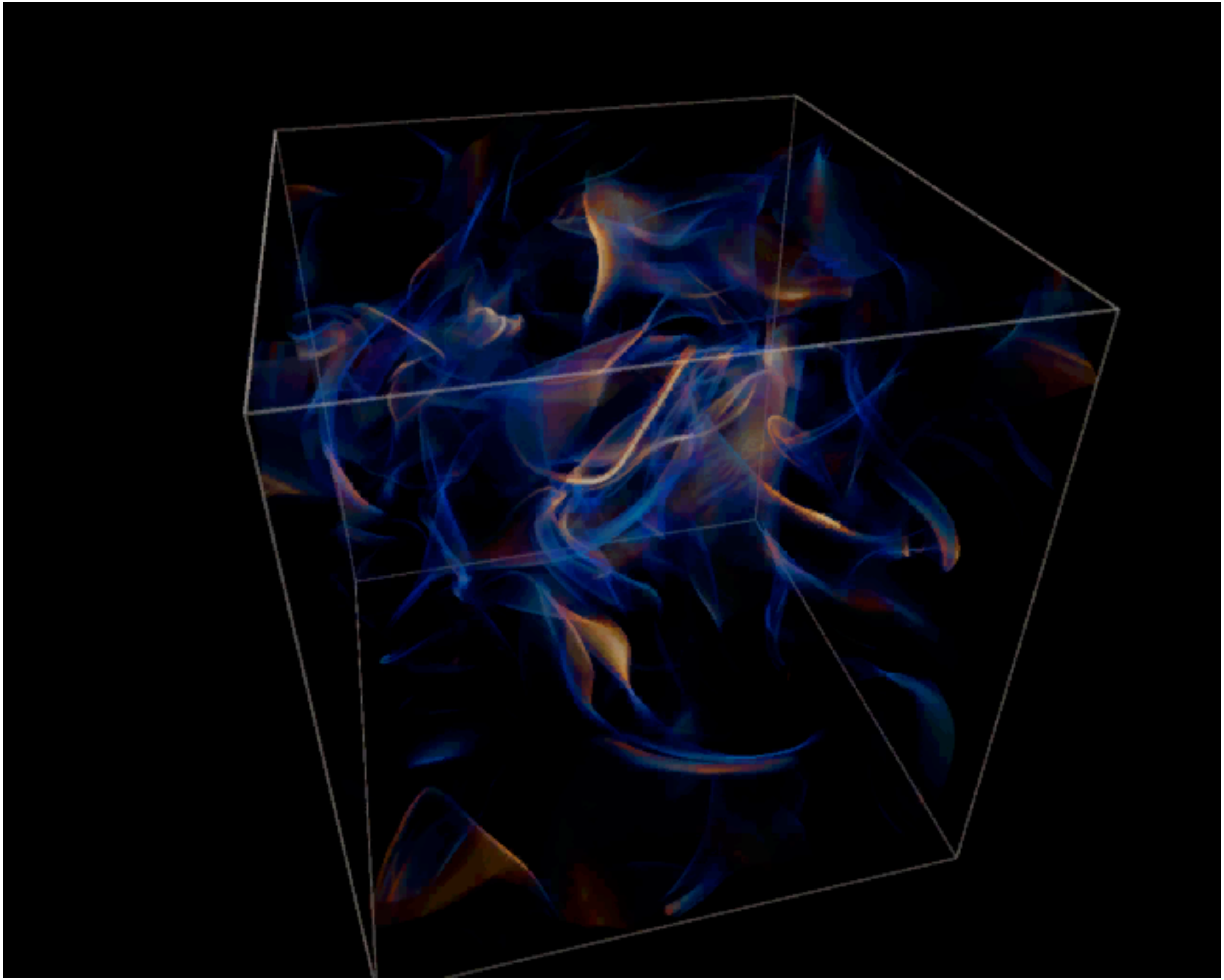
Backward facing step



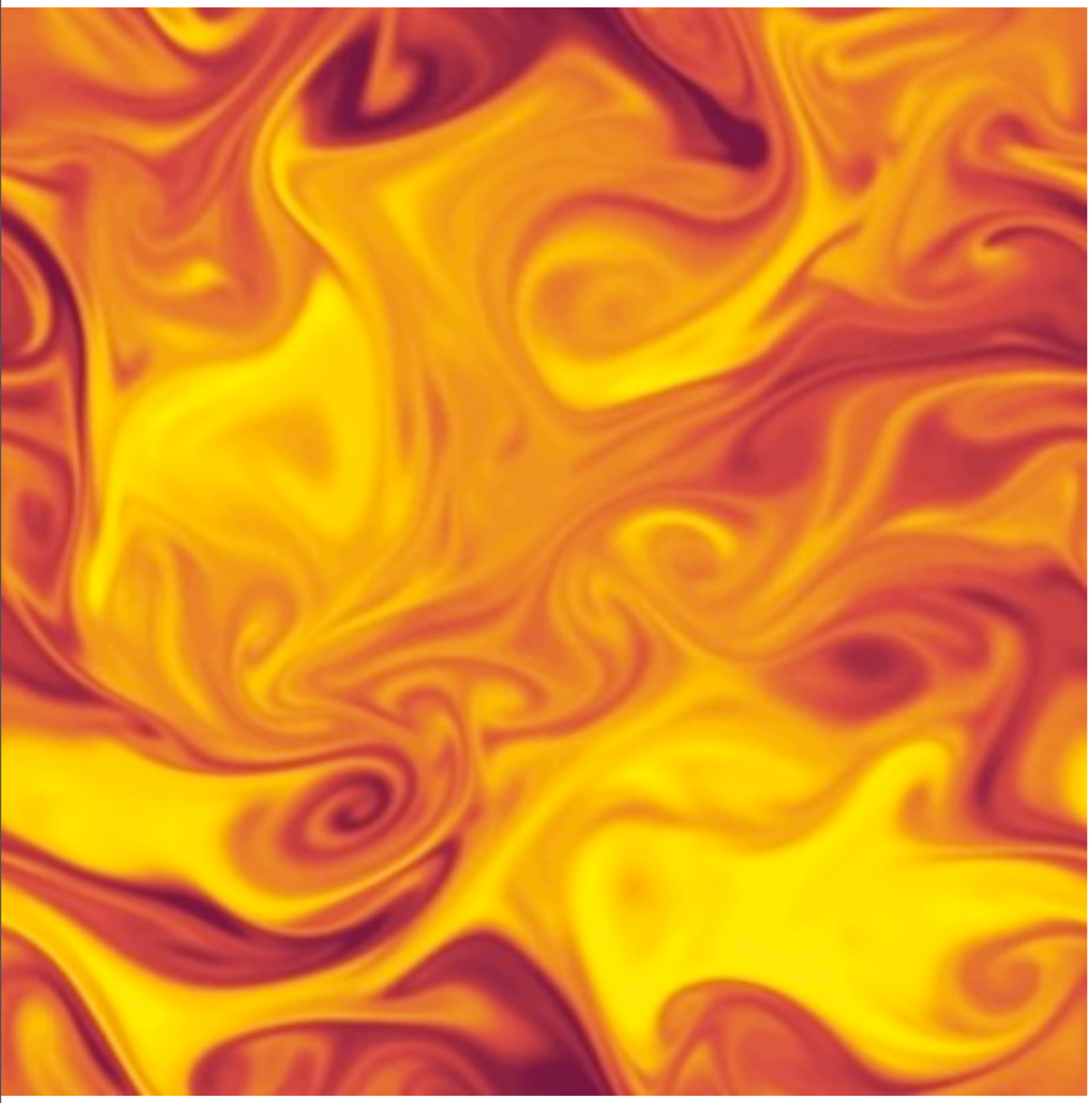
Sphere wake


ONERA
B. Raverdy, I. Mary


Model A
Sports Car

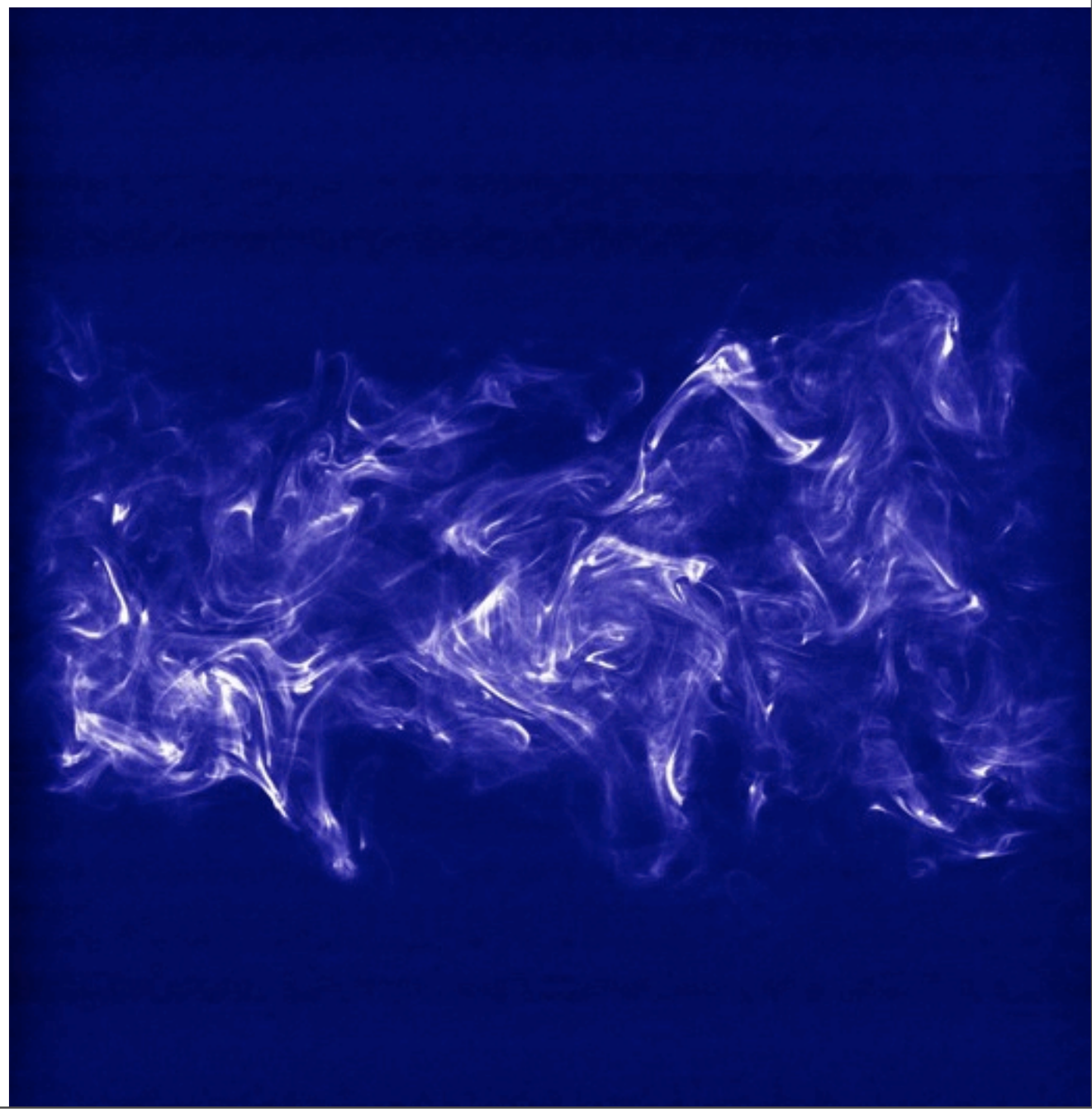


Turbulence & scalar transport



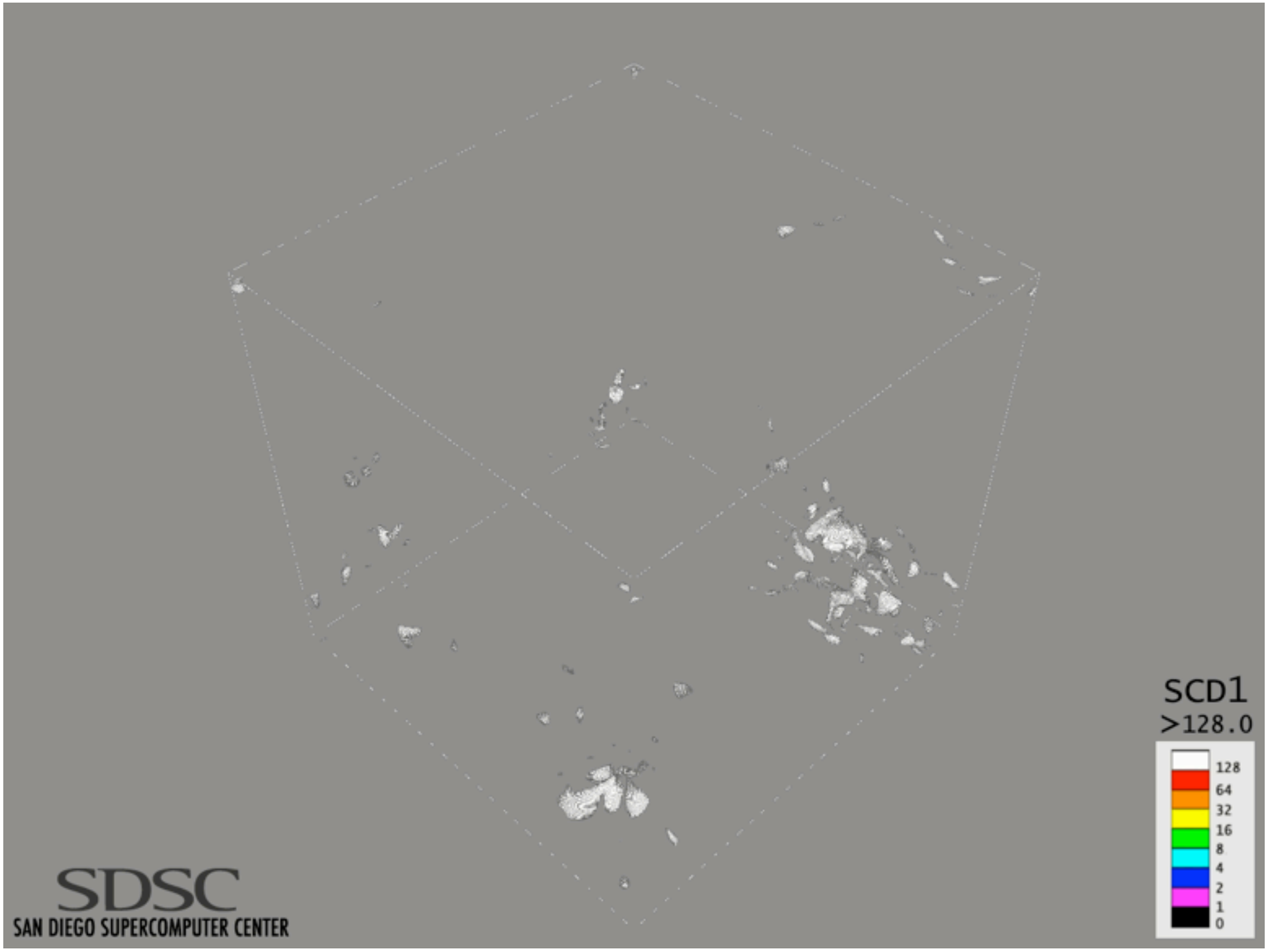
Isotropic turbulence

Turbulent jet



Turbulent kinetic energy dissipation

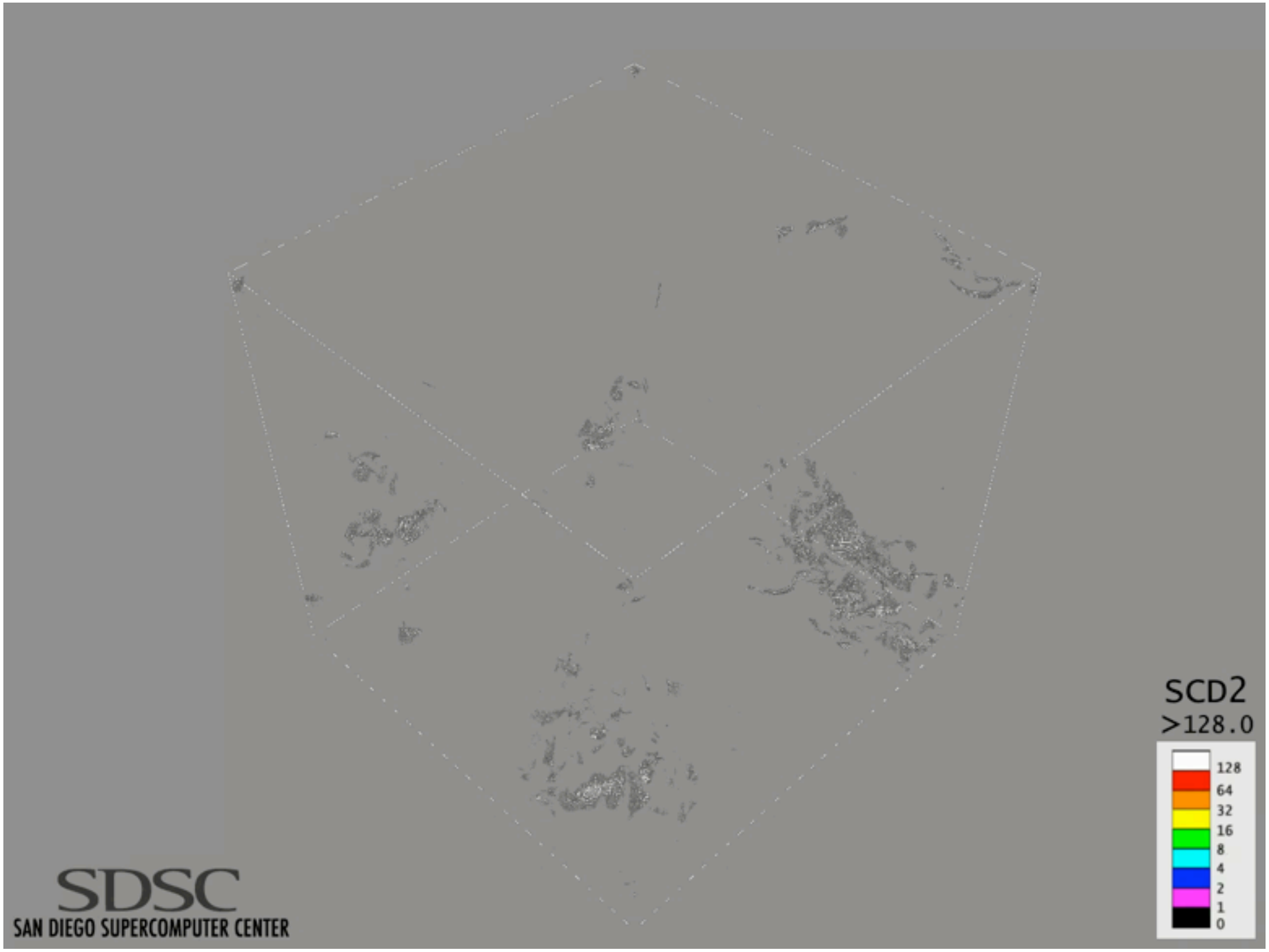
Turbulent kinetic energy dissipation



Turbulent kinetic energy dissipation

Scalar dissipation, Sc = 4

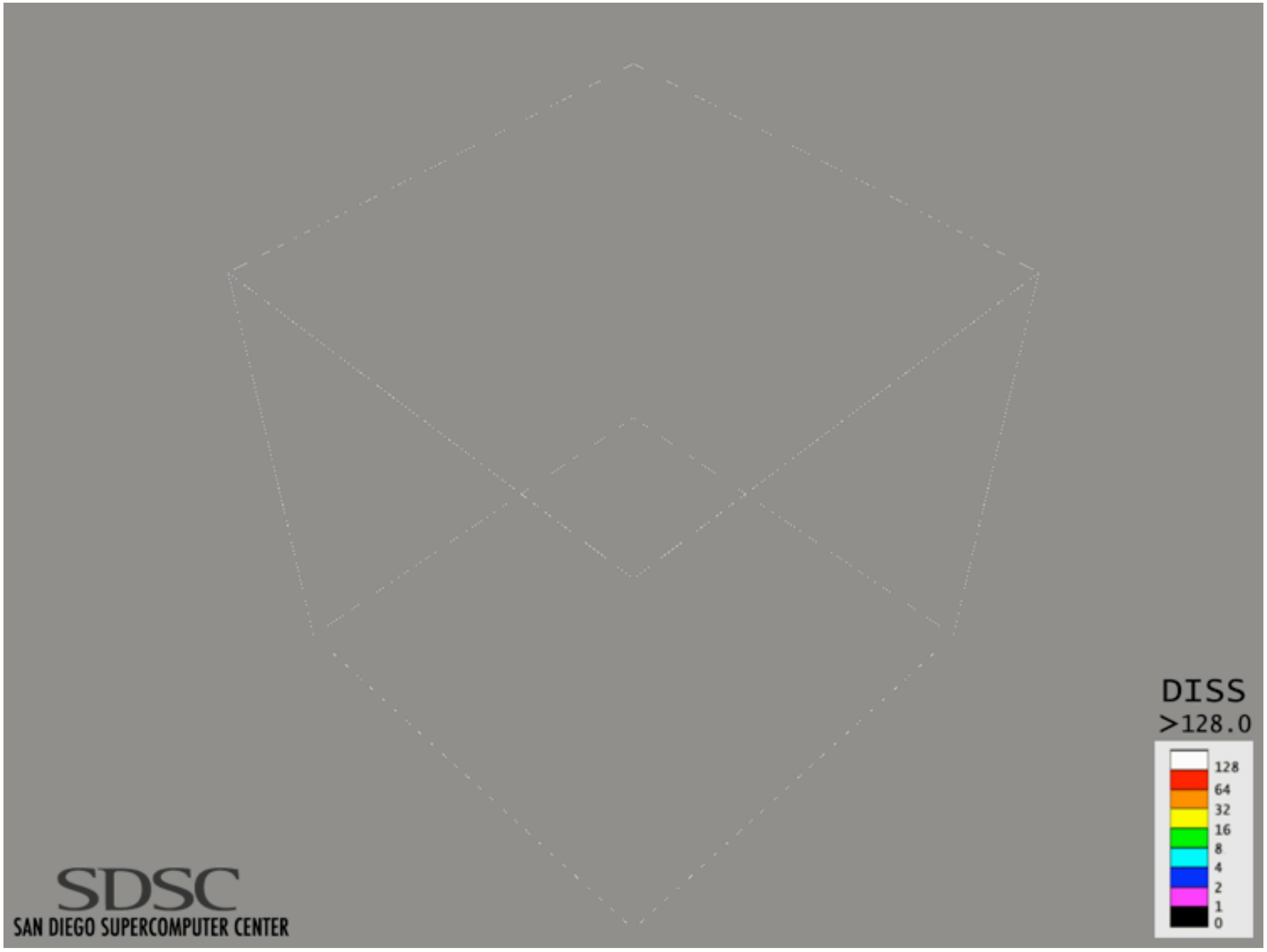
Scalar dissipation, Sc = 4



Scalar dissipation, Sc = 4

Scalar dissipation, Sc = 64

Scalar dissipation, Sc = 64



Scalar dissipation, Sc = 64

What is a turbulent flow ?

Turbulence and predictions

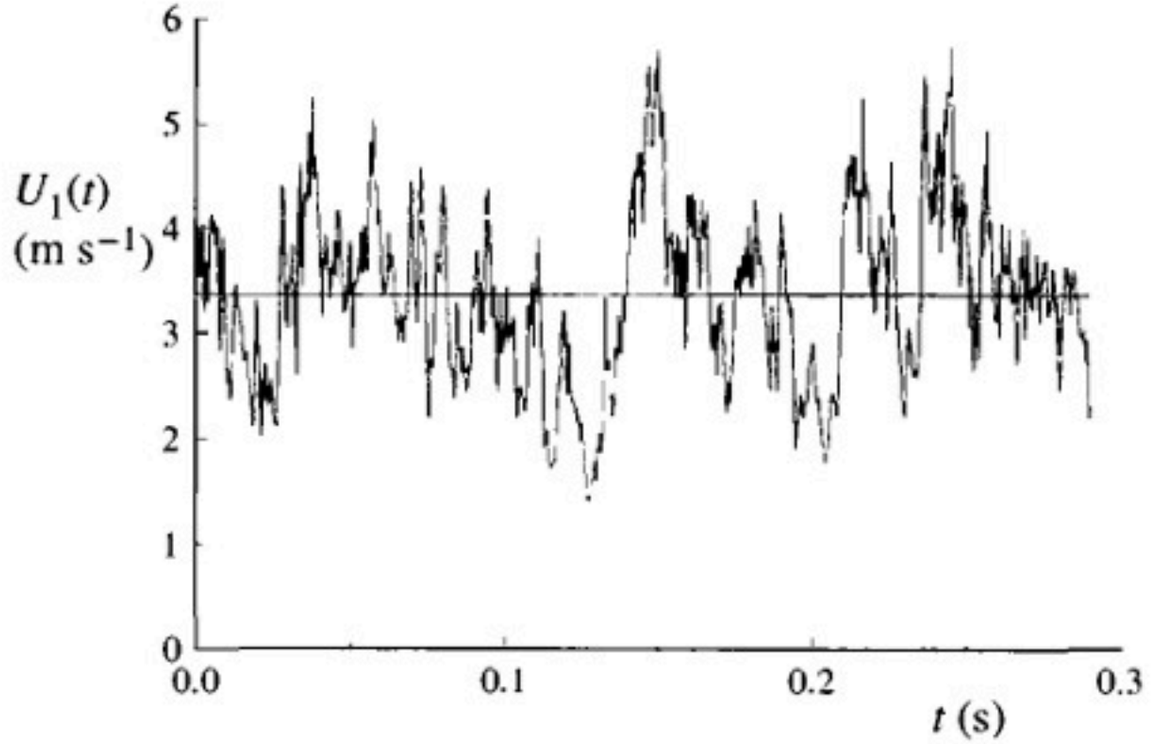


Fig. 1.3. The time history of the axial component of velocity $U_1(t)$ on the centerline of a turbulent jet. From the experiment of Tong and Warhaft (1995).

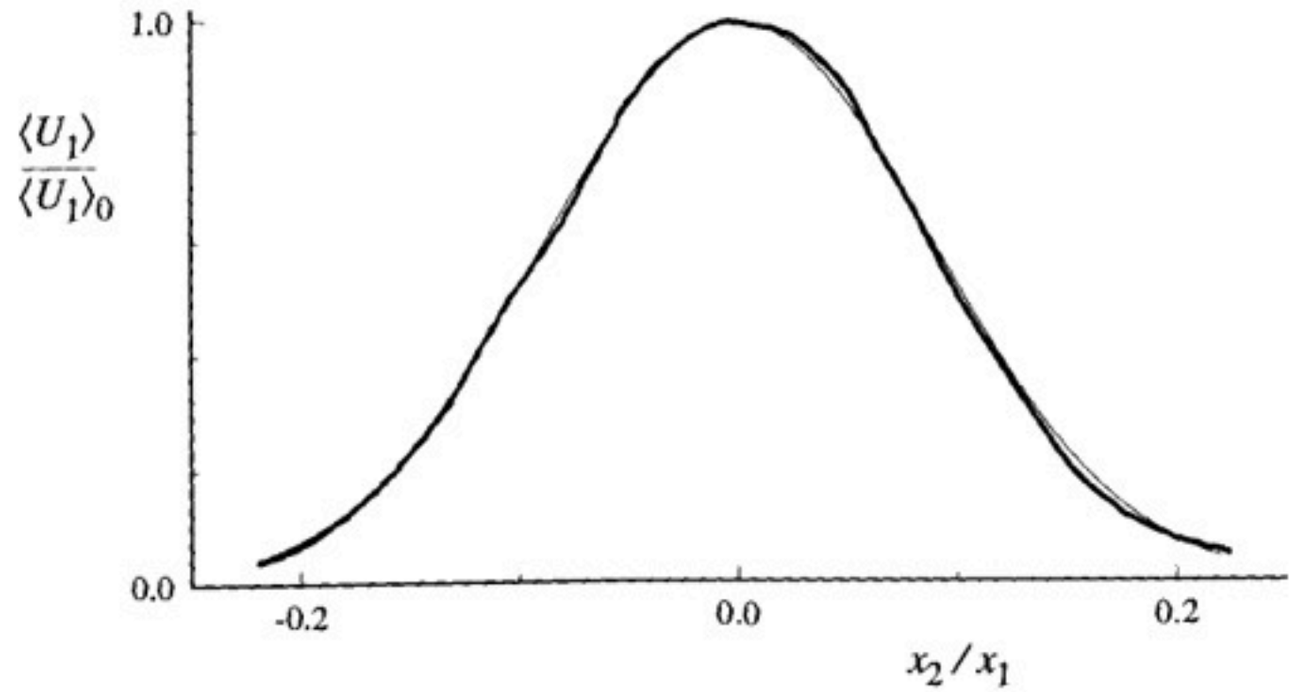
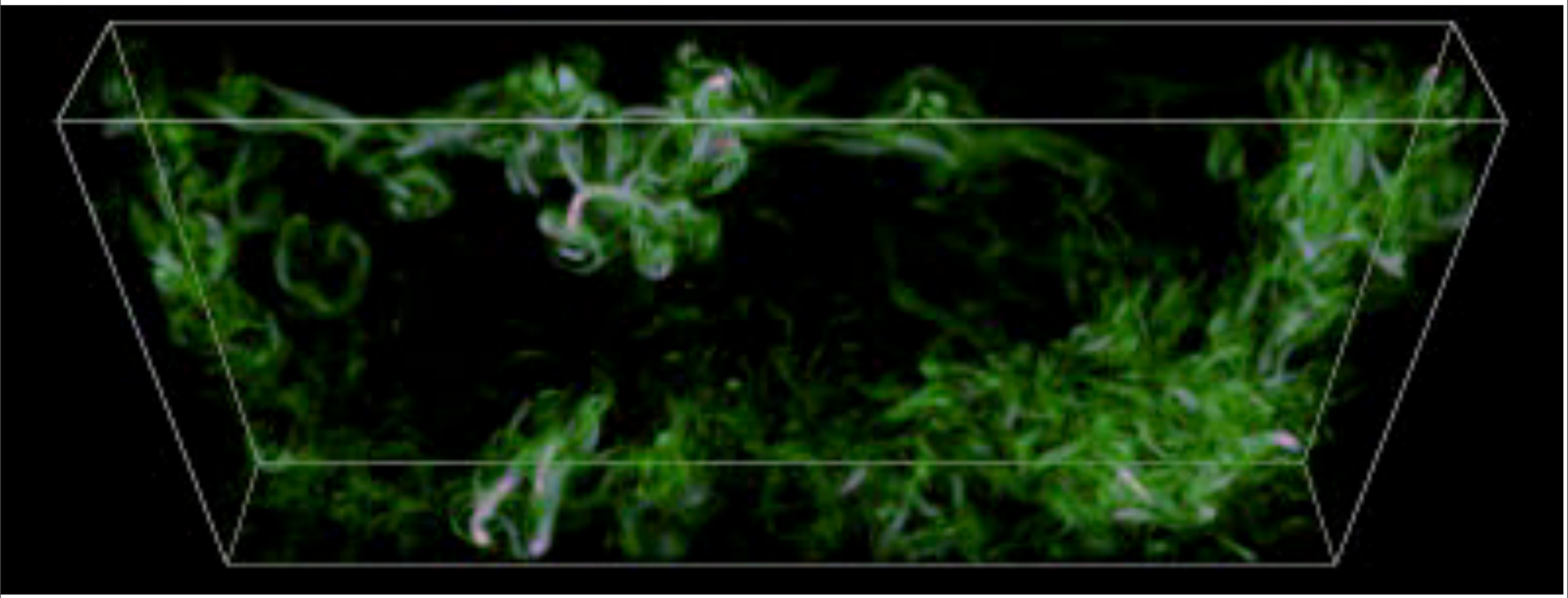


Fig. 1.4. The mean axial velocity profile in a turbulent jet. The mean velocity $\langle U_1 \rangle$ is normalized by its value on the centerline, $\langle U_1 \rangle_0$; and the cross-stream (radial) coordinate x_2 is normalized by the distance from the nozzle x_1. The Reynolds number is 95,500. Adapted from Hussein, Capp, and George (1994).

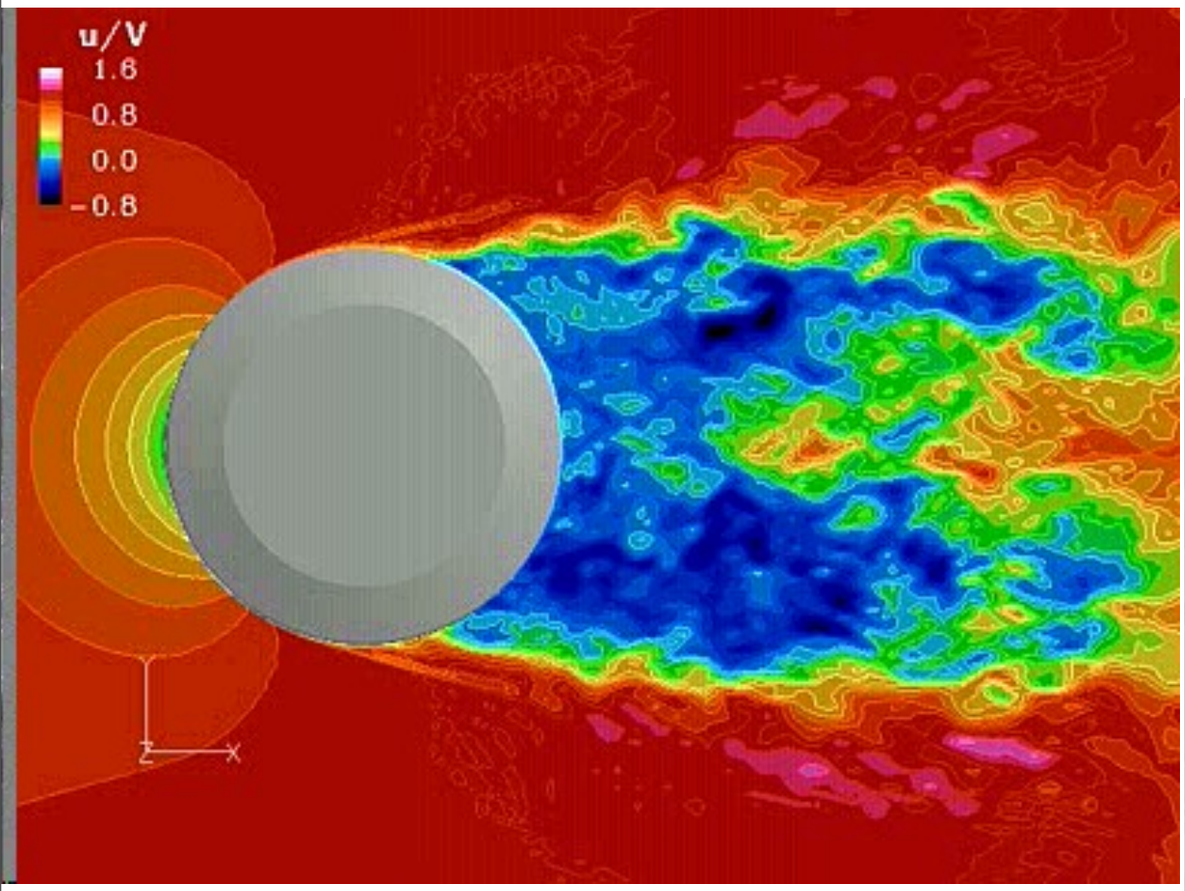
Wave Turbulence

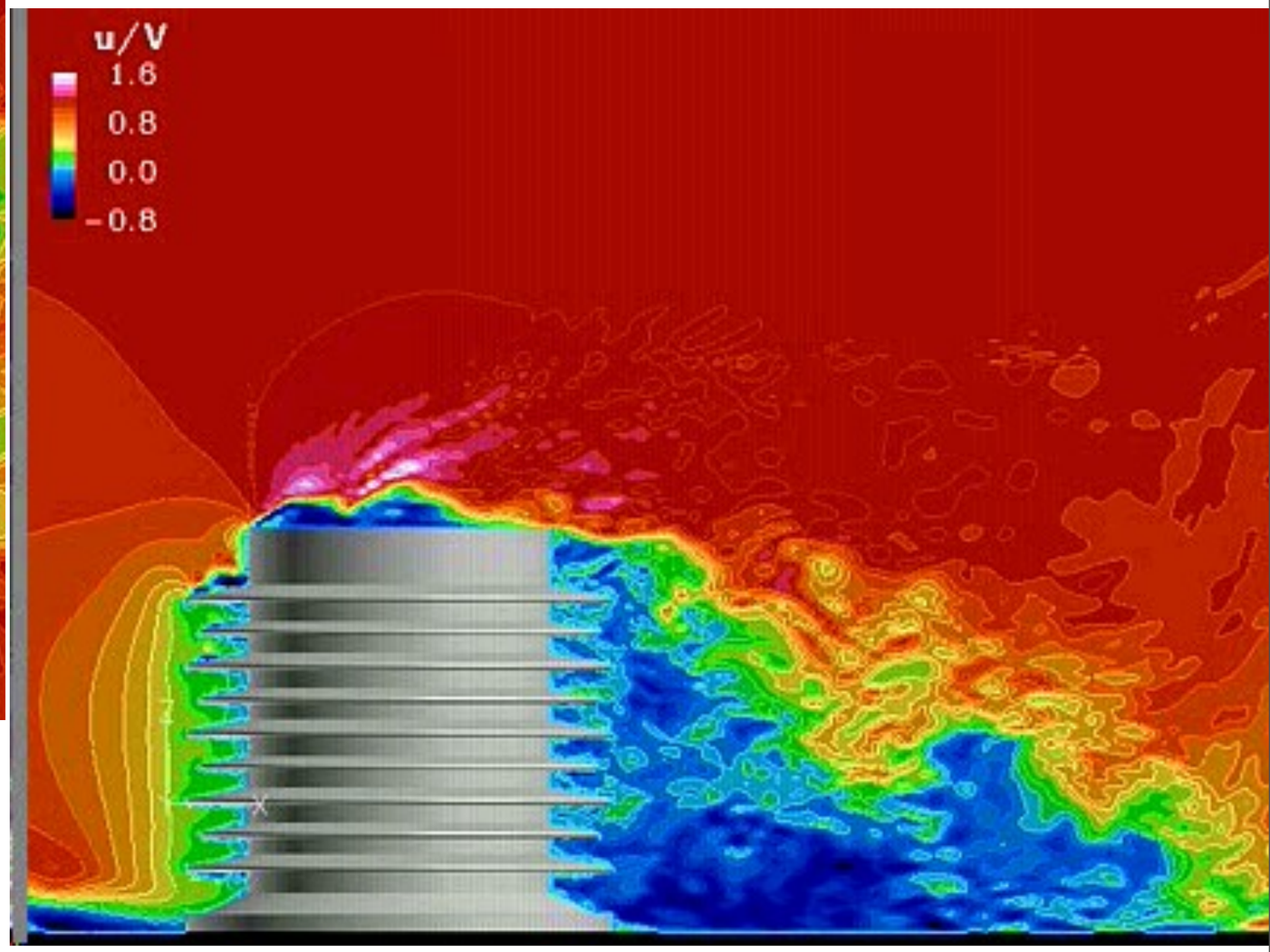
Natural convection

Natural convection



Turbulence & Aeroacoustics

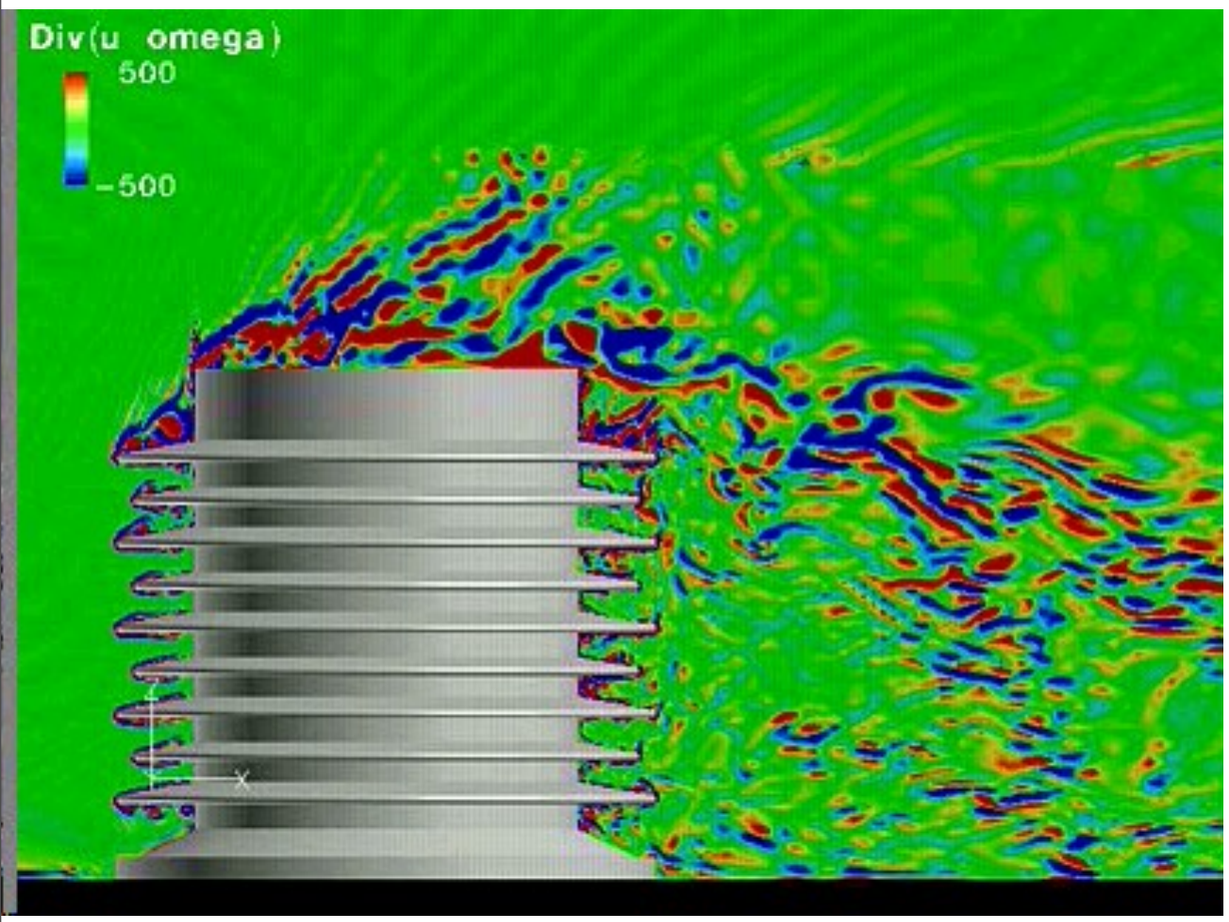


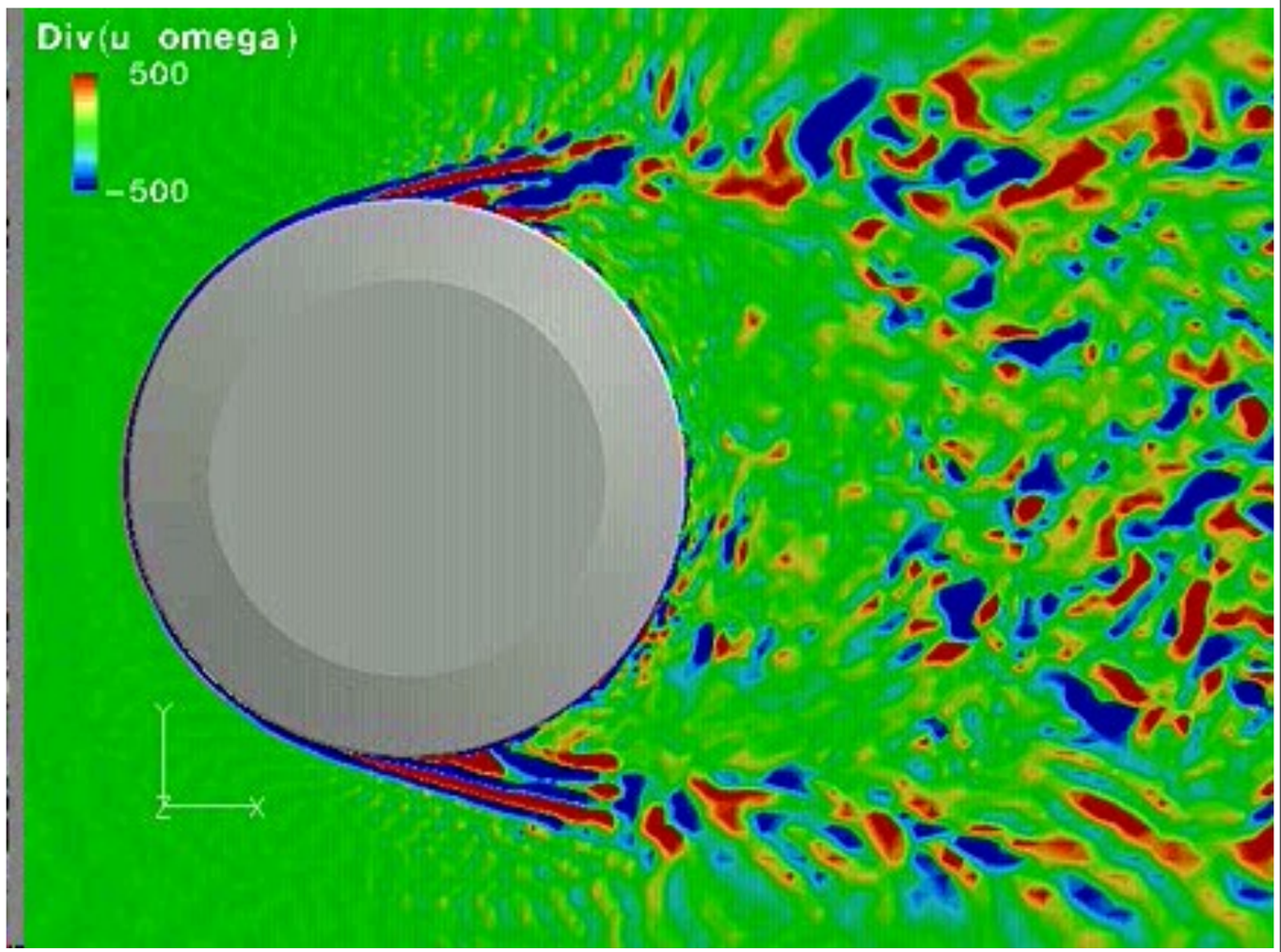


Instantaneous streamwise velocity

Acoustic sources

Div • (u x ω)





Methods of analysis

- Probability
- Dimensional analysis
- Asymptotic invariance
- Local invariance
- Statistical mechanics
- Geometry and Topology

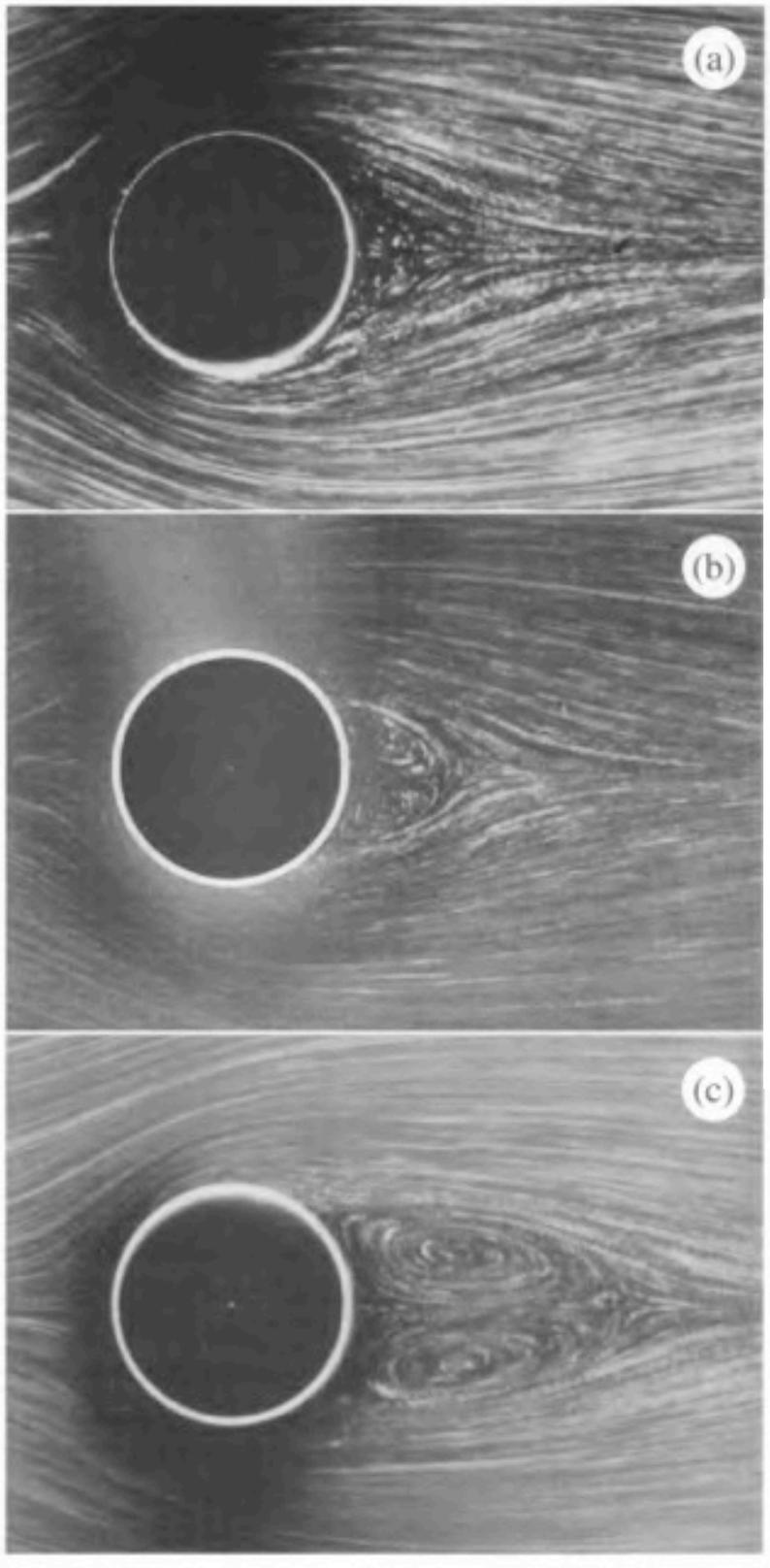
What is a turbulent flow ?

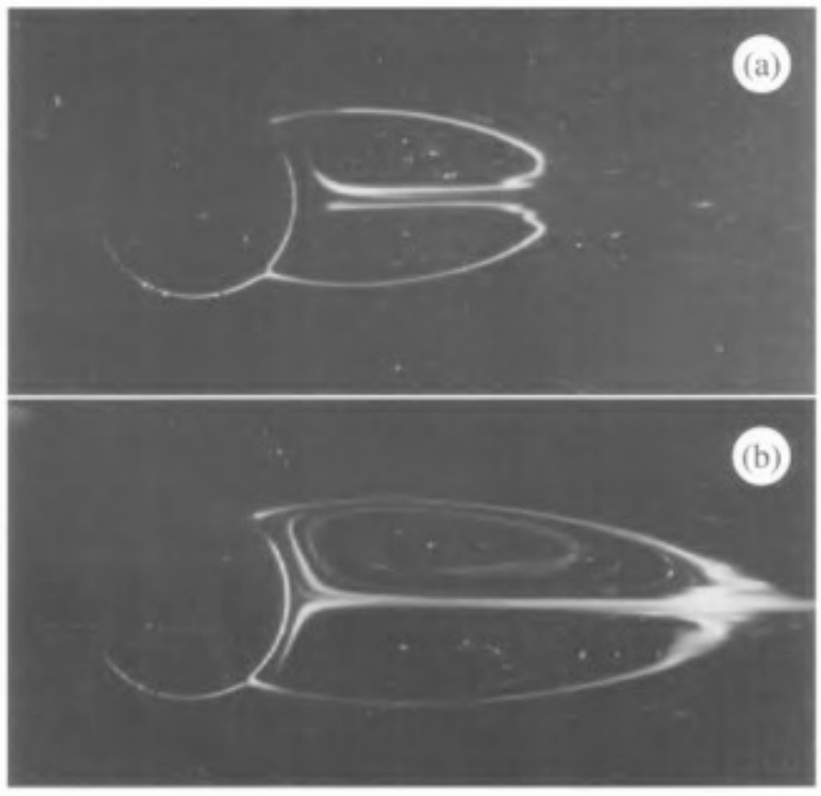
- No rigorous definition of **Turbulence** is available
- Turbulent flows are flows which exhibit the following features:

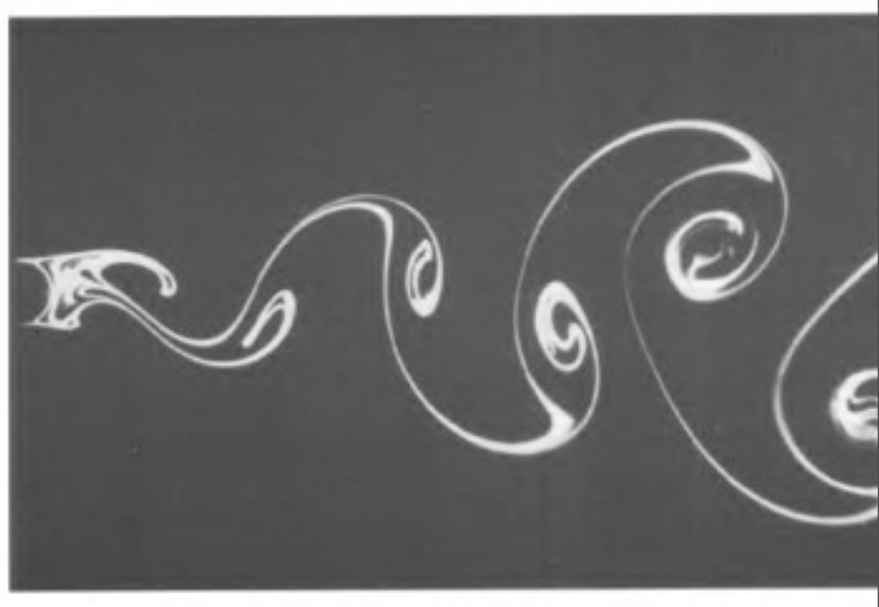
1. Three dimensionality
2. Unsteadiness
3. Chaotic
4. Rotational
5. Dissipative
6. Highly diffusive (high mixing property)
7. Multi-scale (Broadband energy spectrum)

A survey of critical experiments

Transition to turbulence and symmetries

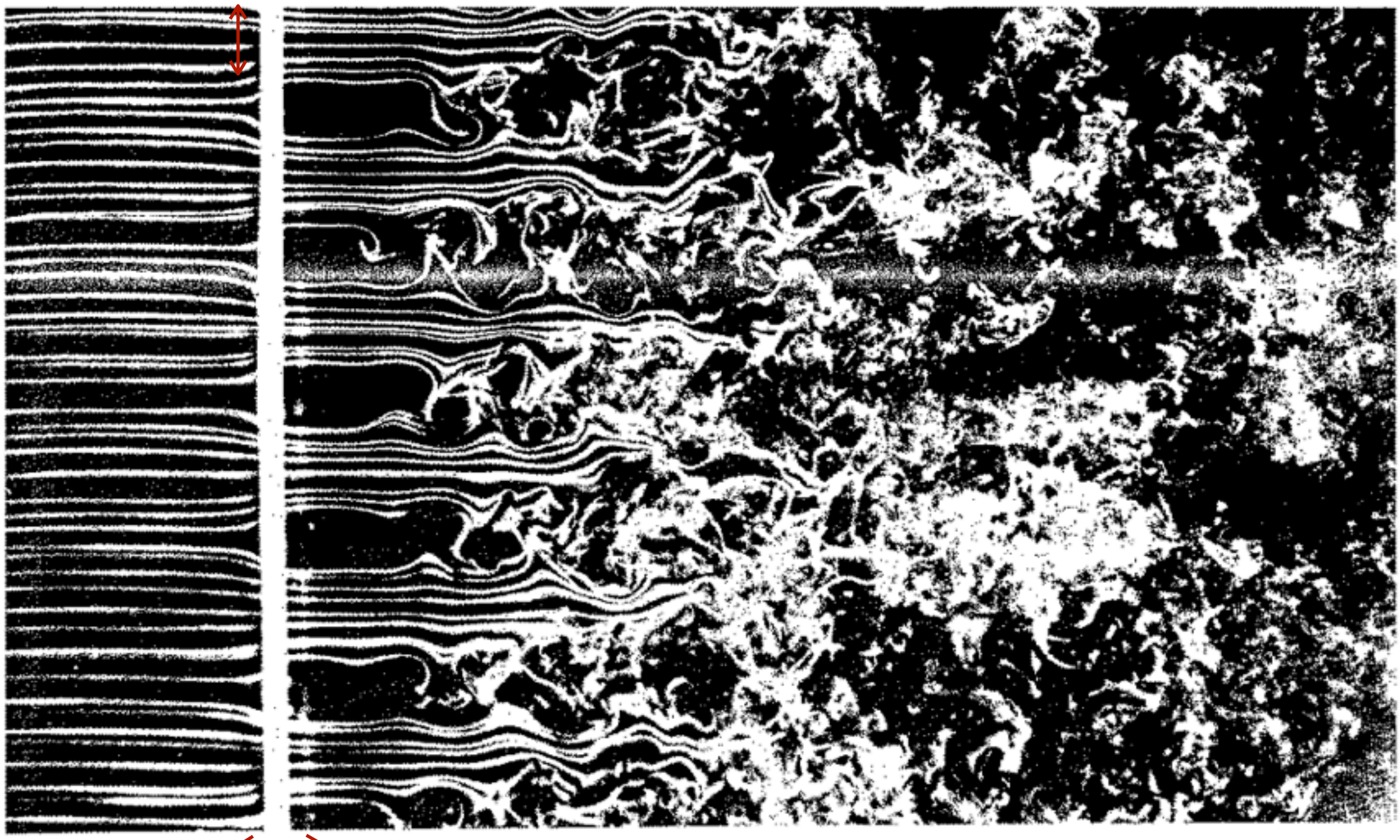






Grid Turbulence

h = 1/6 cm;

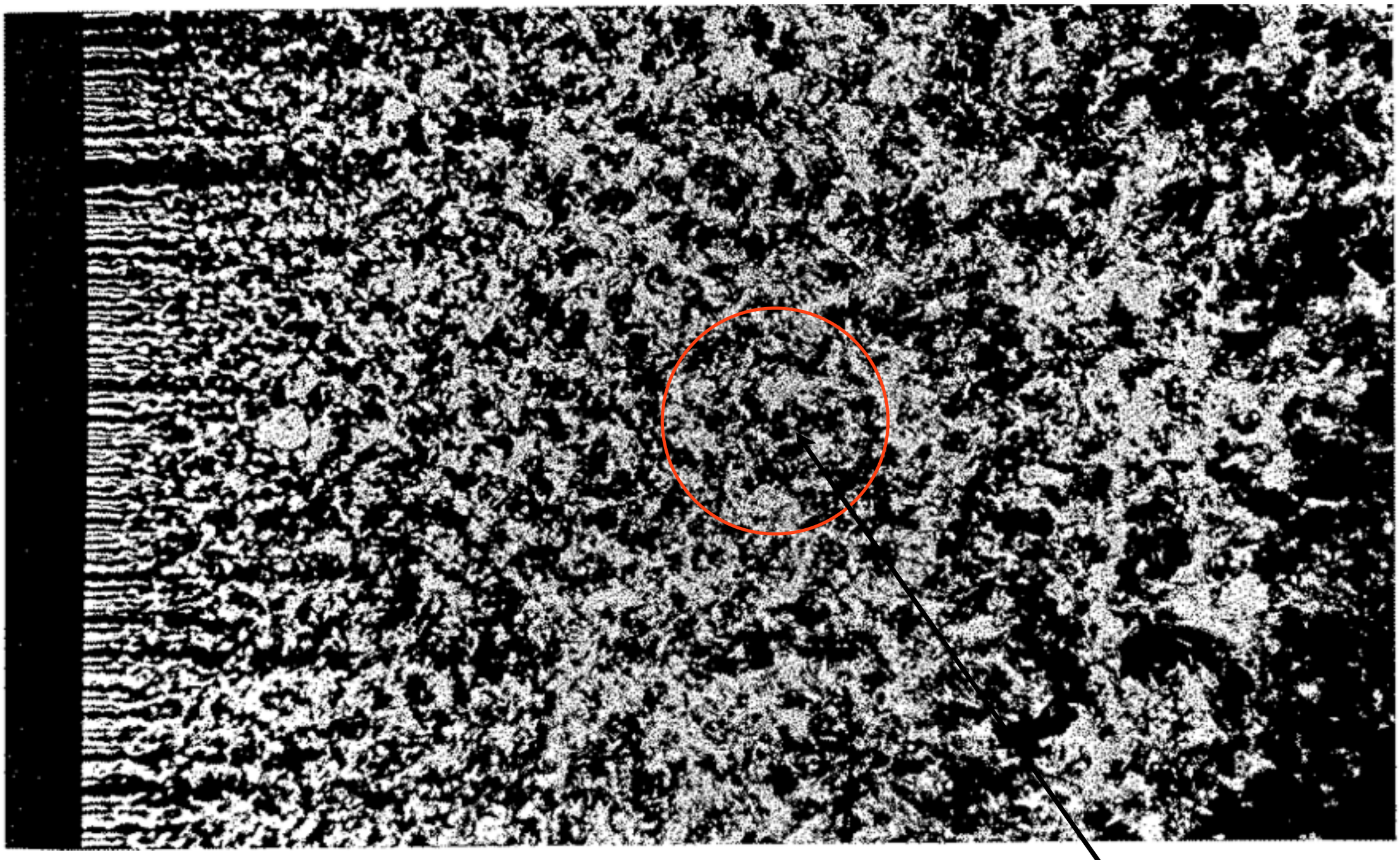


w = 6cm

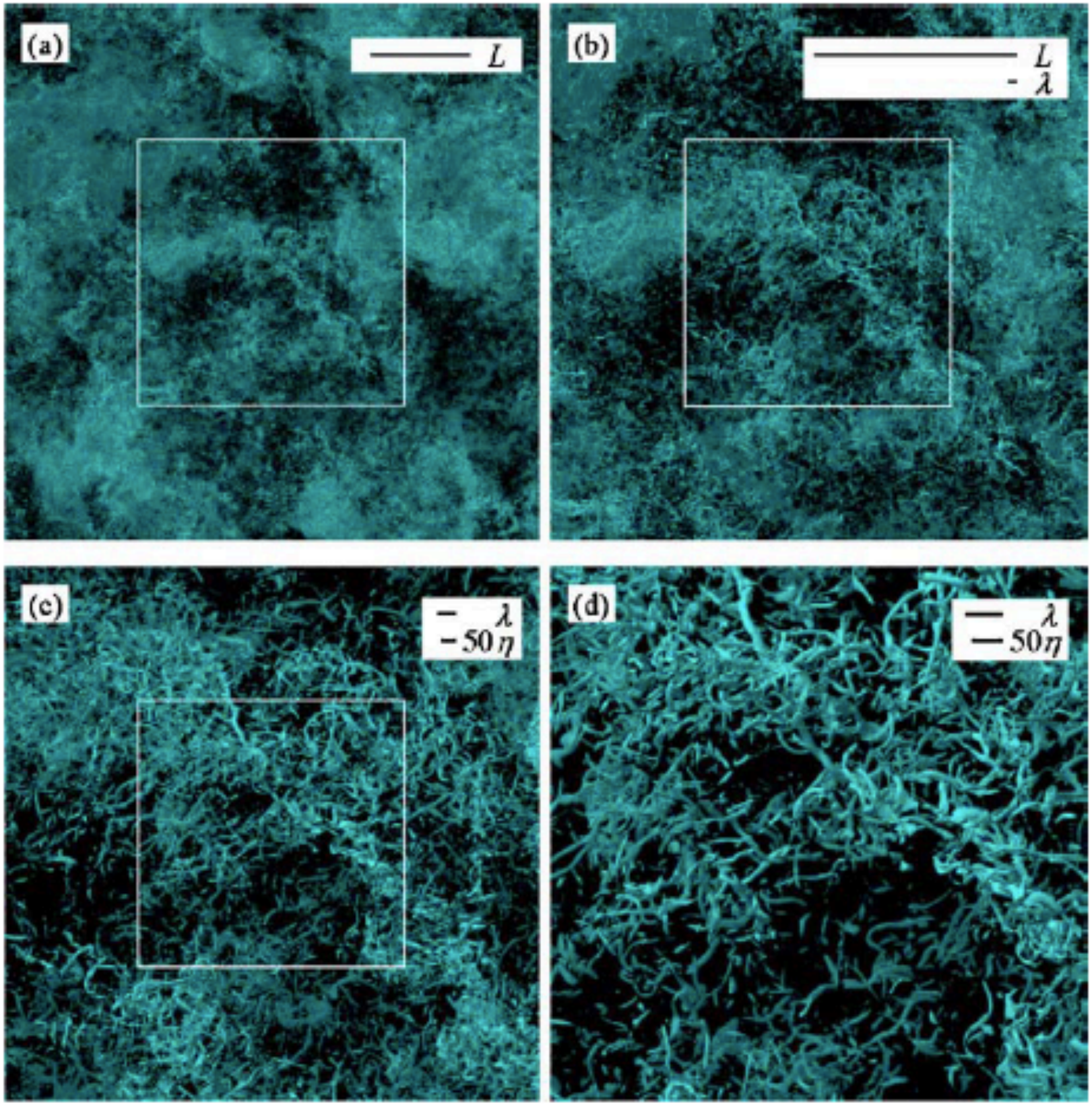
Re=1500

(Van Dyke, Album of fluid motion 1982)

Grid Turbulence: homogeneous

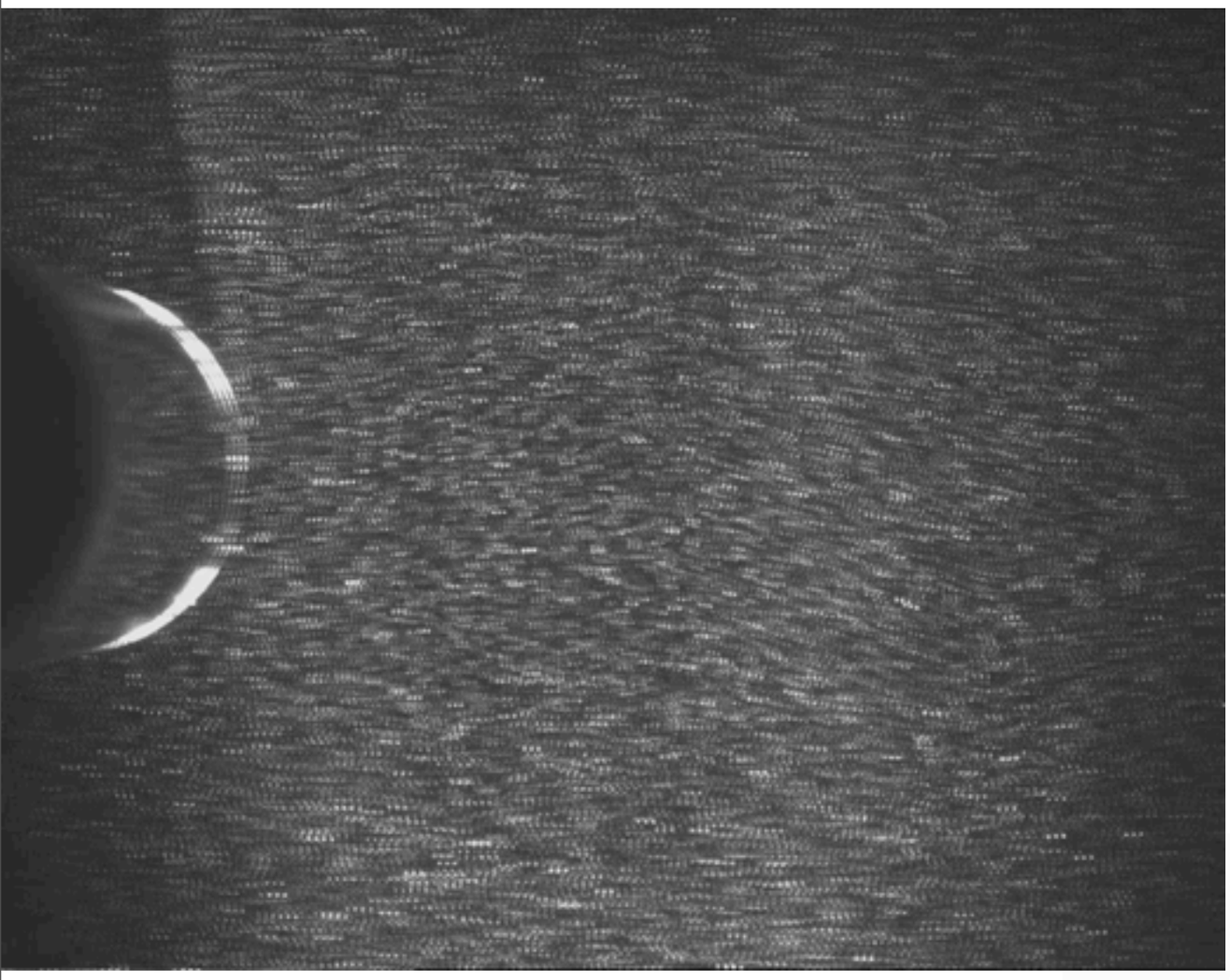


Self-similarity



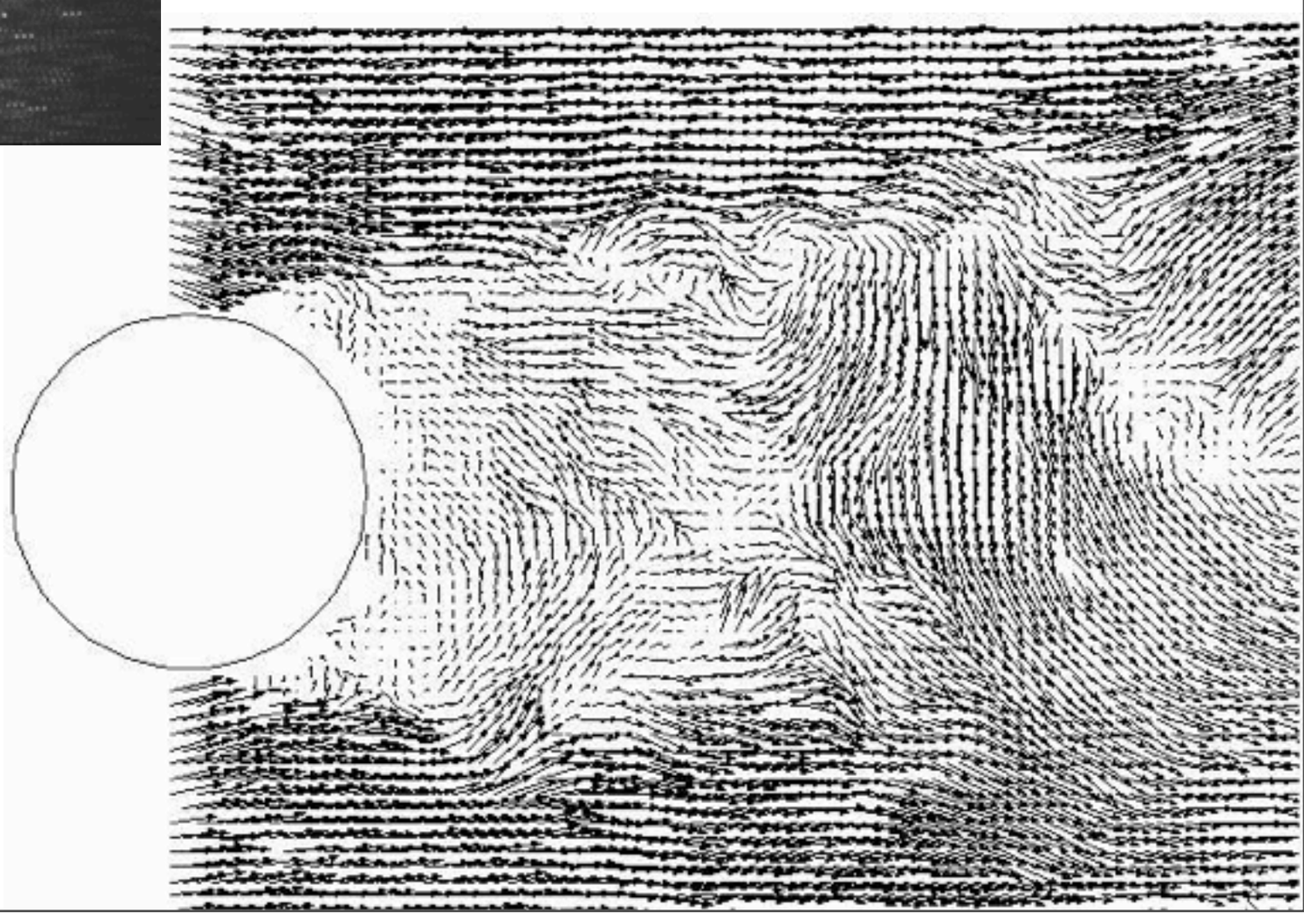
Kaneda & Ishihara
JOT 2006

Figure 3. Intense-vorticity isosurfaces showing the region where $\omega > \langle\omega\rangle + 4\sigma_\omega$. $R_\lambda = 732$. (a) The size of the display domain is $(5984^2 \times 1496)\,\eta^3$, periodic in the vertical and horizontal directions. (b) Close-up view of the central region of (a) bounded by the white rectangular line; the size of display domain is $(2992^2 \times 1496)\,\eta^3$. (c) Close-up view of the central region of (b); $1496^3\eta^3$ (d) Close-up view of the central region of (c); $(748^2 \times 1496)\,\eta^3$.



Wake-flow

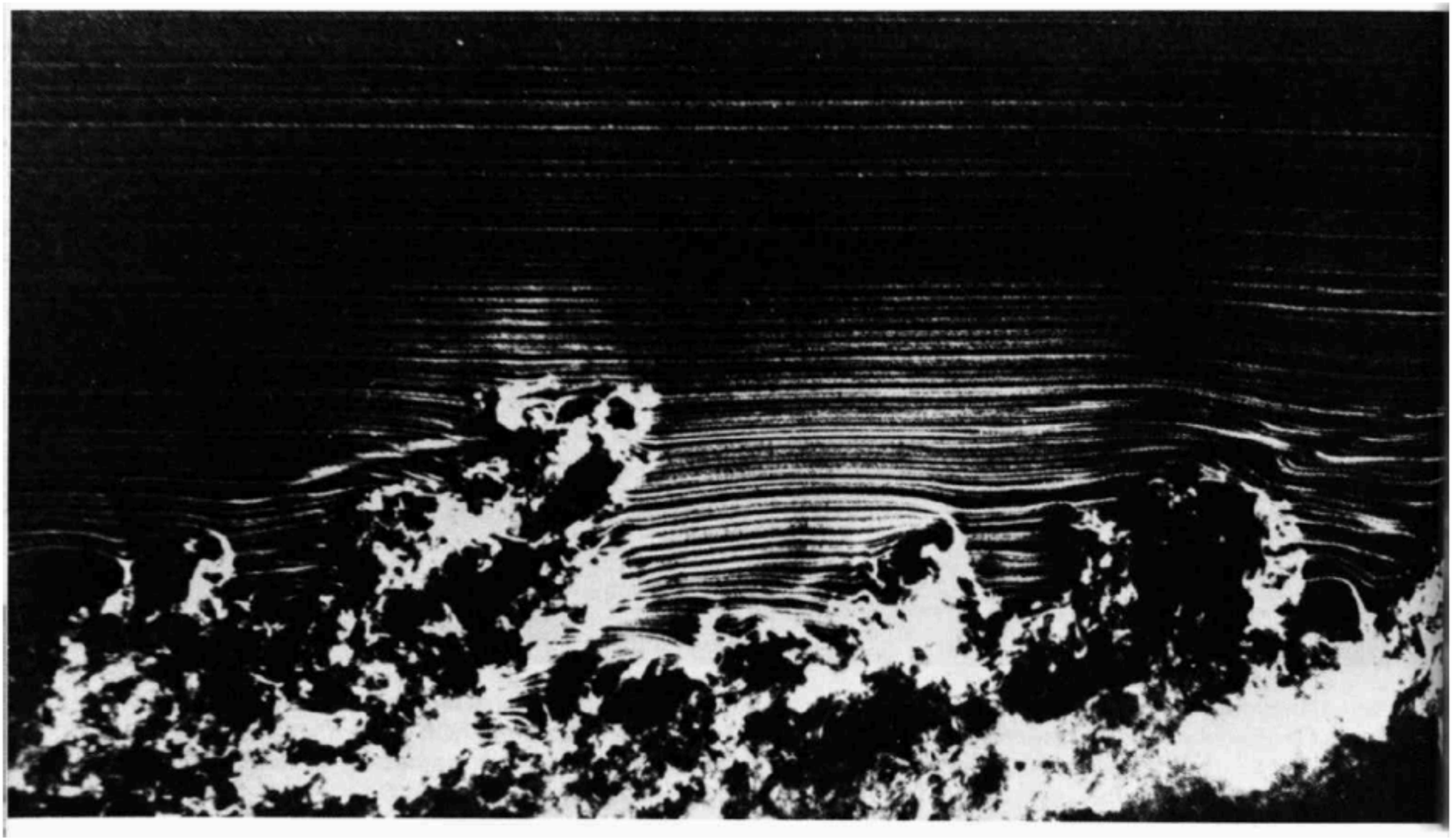
PIV



Turbulent boundary layer

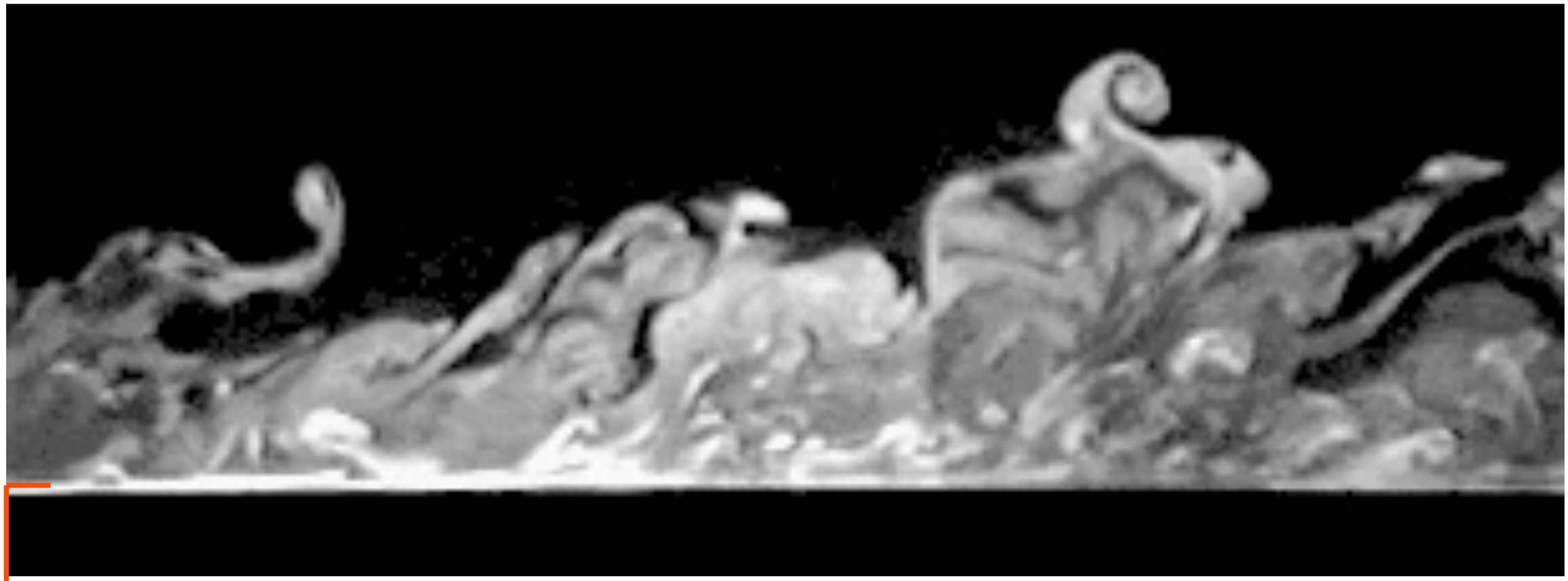
Re=3500

Intermittency



3,3m

Wall-bounded flows: the 2-scale problem

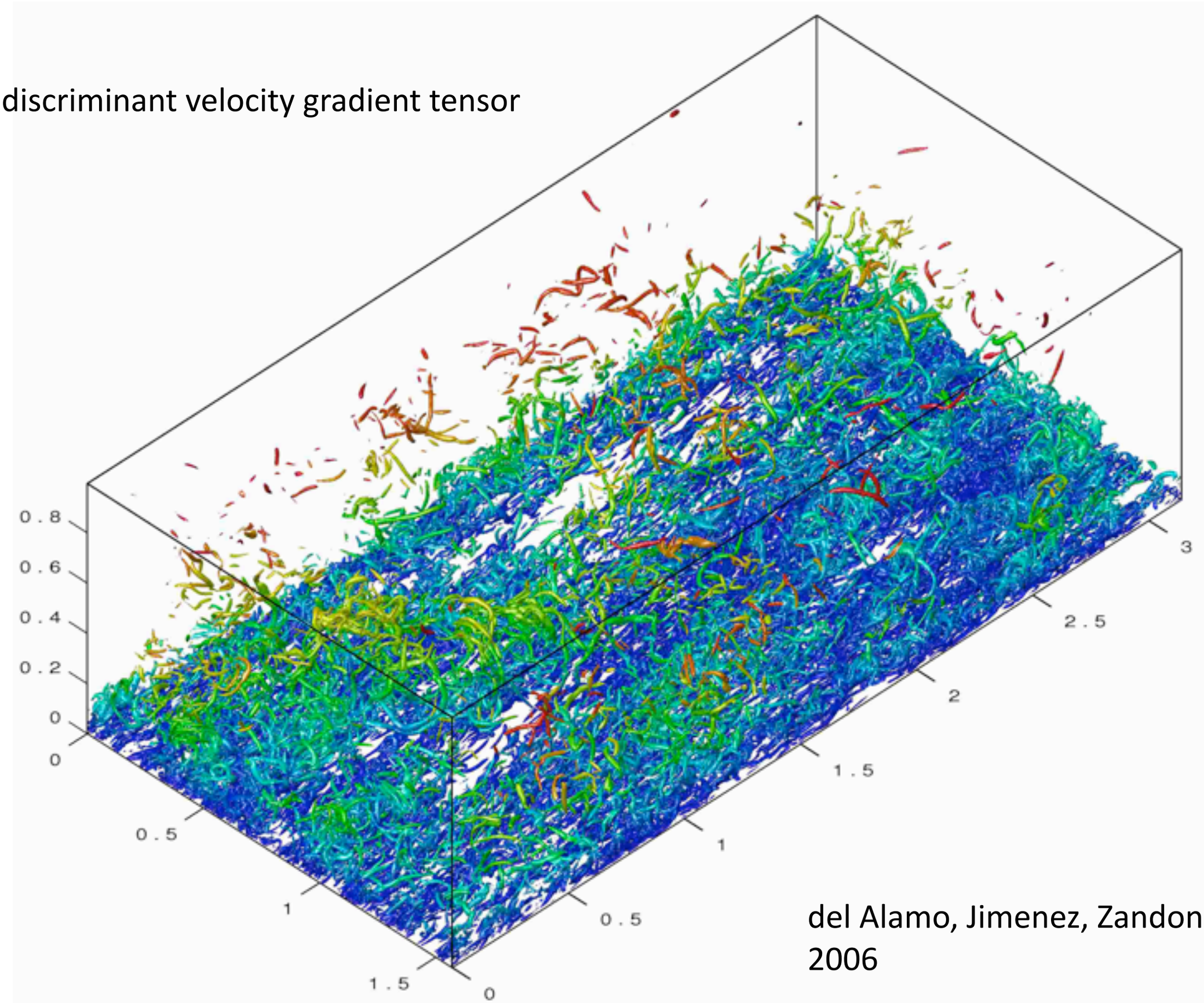


Inner region
- Production
- Dissipation
- Structures: streaks

Outer region
- Dissipation
- Stucture size ~ δ

Turbulent channel

discriminant velocity gradient tensor

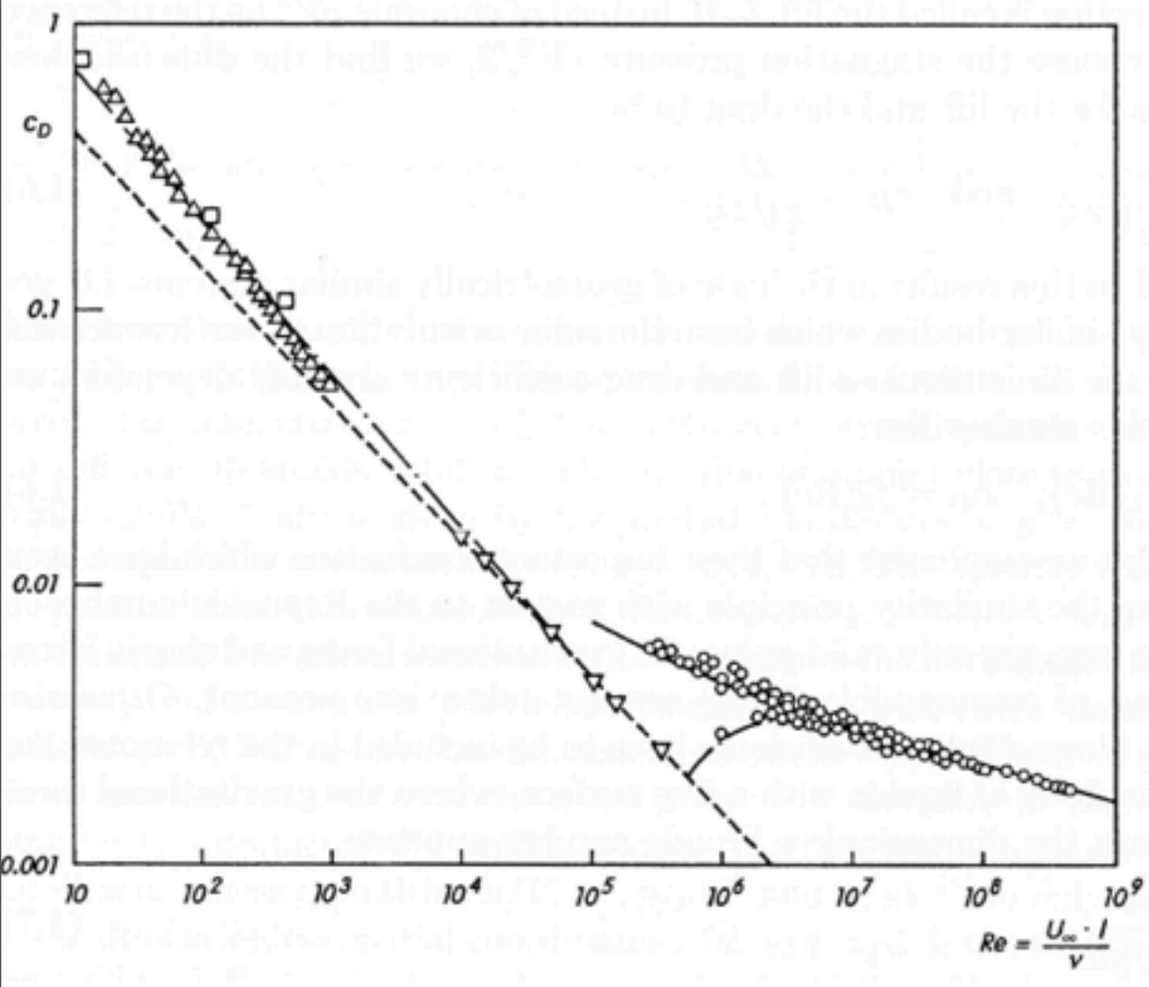


del Alamo, Jimenez, Zandonade, Moser JFM 2006

Drag Coefficient and dissipation

Landau & Lifshitz FM

Plaque plane



Cylindre

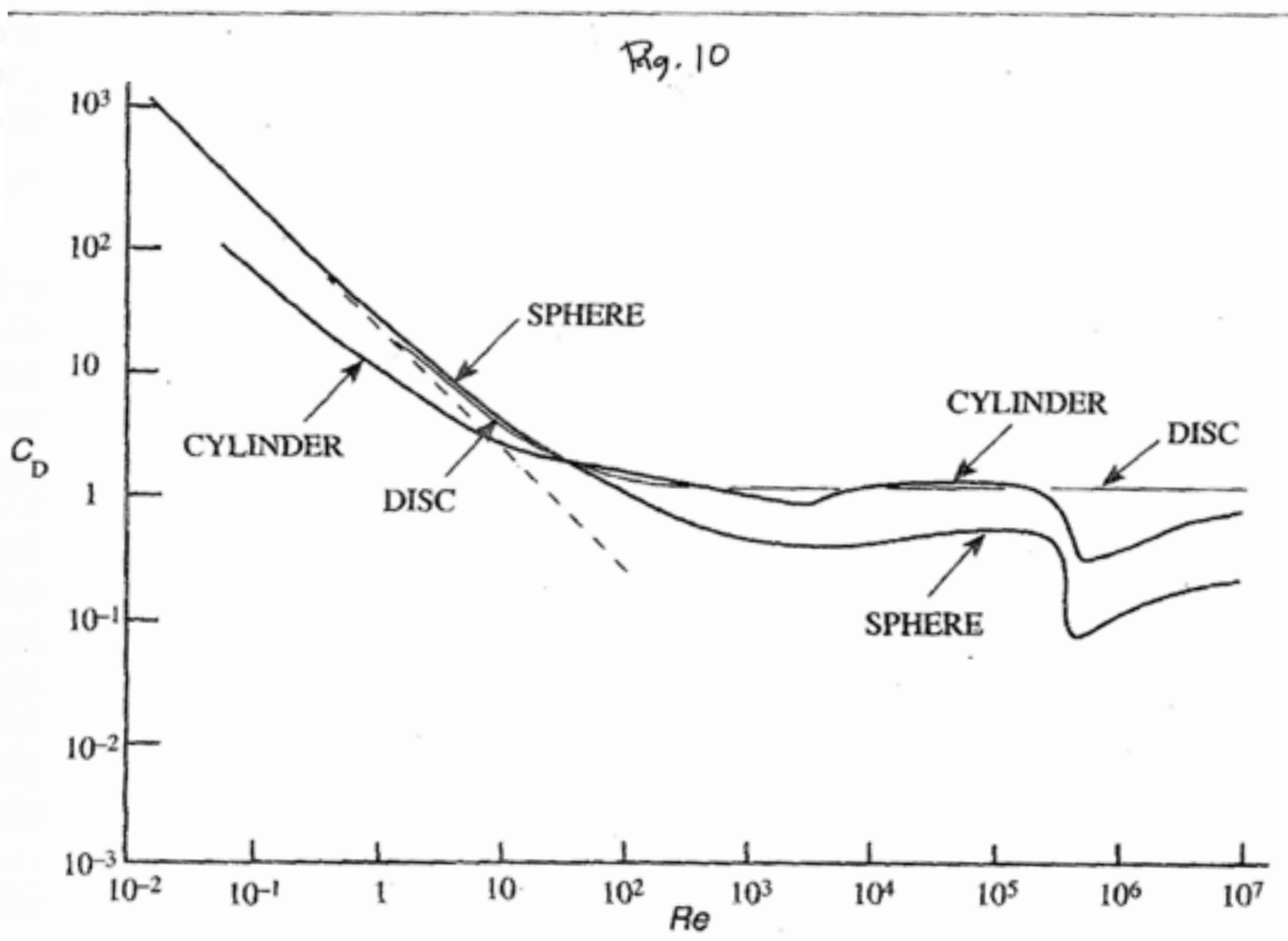


Figure 7.13 Log–log plot of drag coefficient C_D as a function of Reynolds Number *Re* for spheres, transverse cylinders, and face-on discs. The broken straight line represents Stokes's law.

Boundary layer

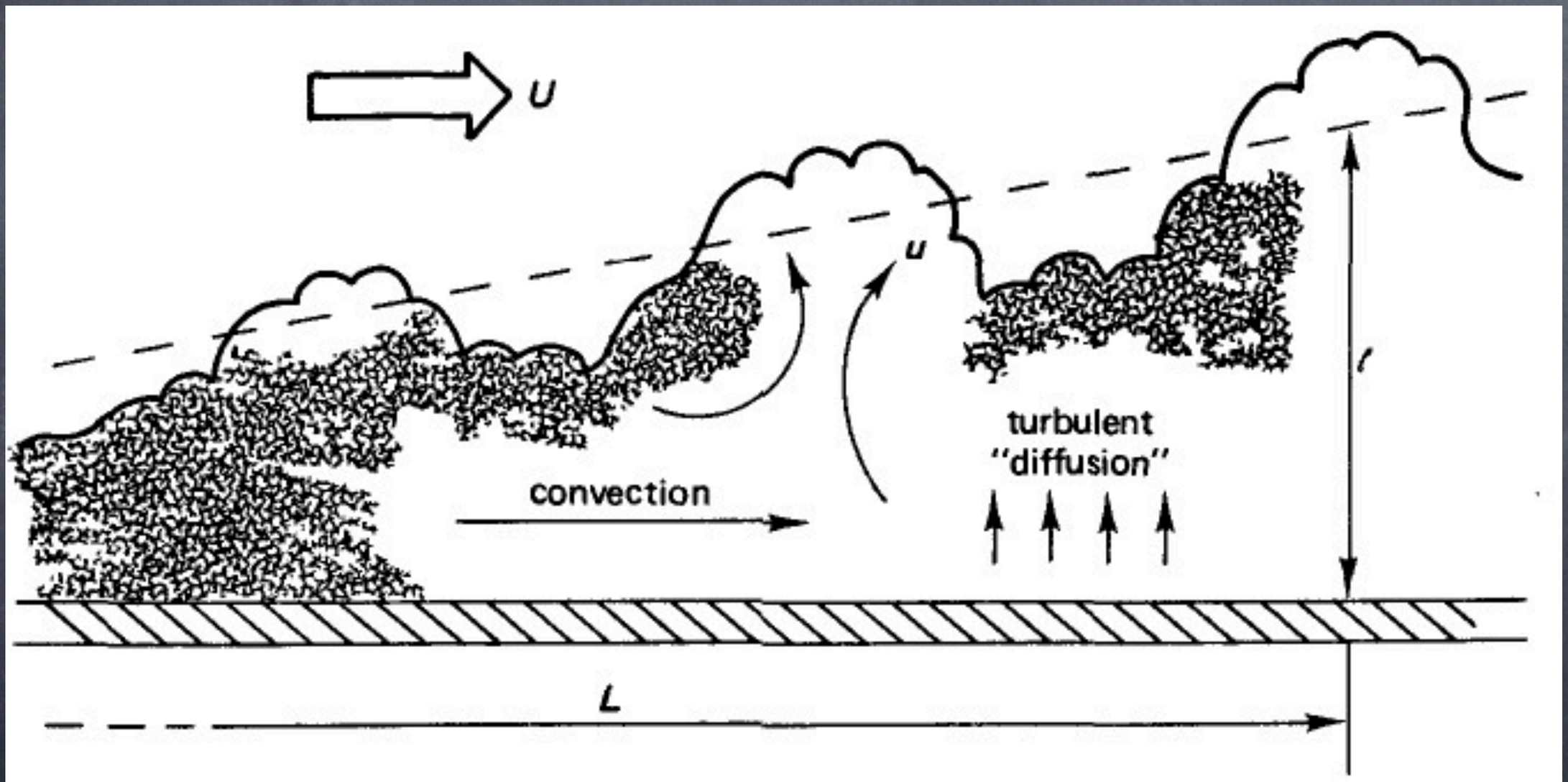


Figure 1.3. Length and velocity scales in a turbulent boundary layer. The time passed since the fluid at *L* passed the origin of the boundary layer is of order *L/U*.

Turbulent scales

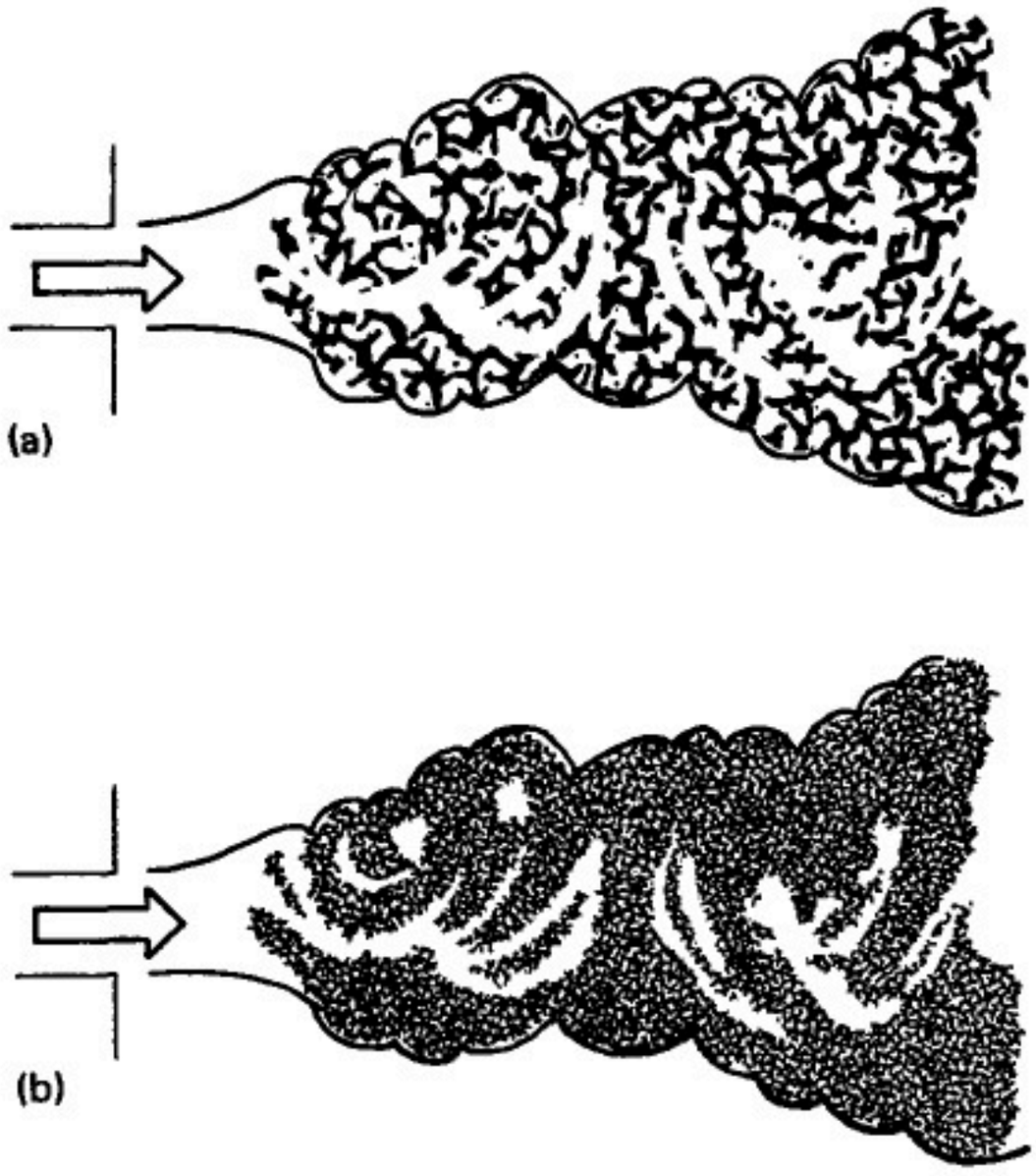
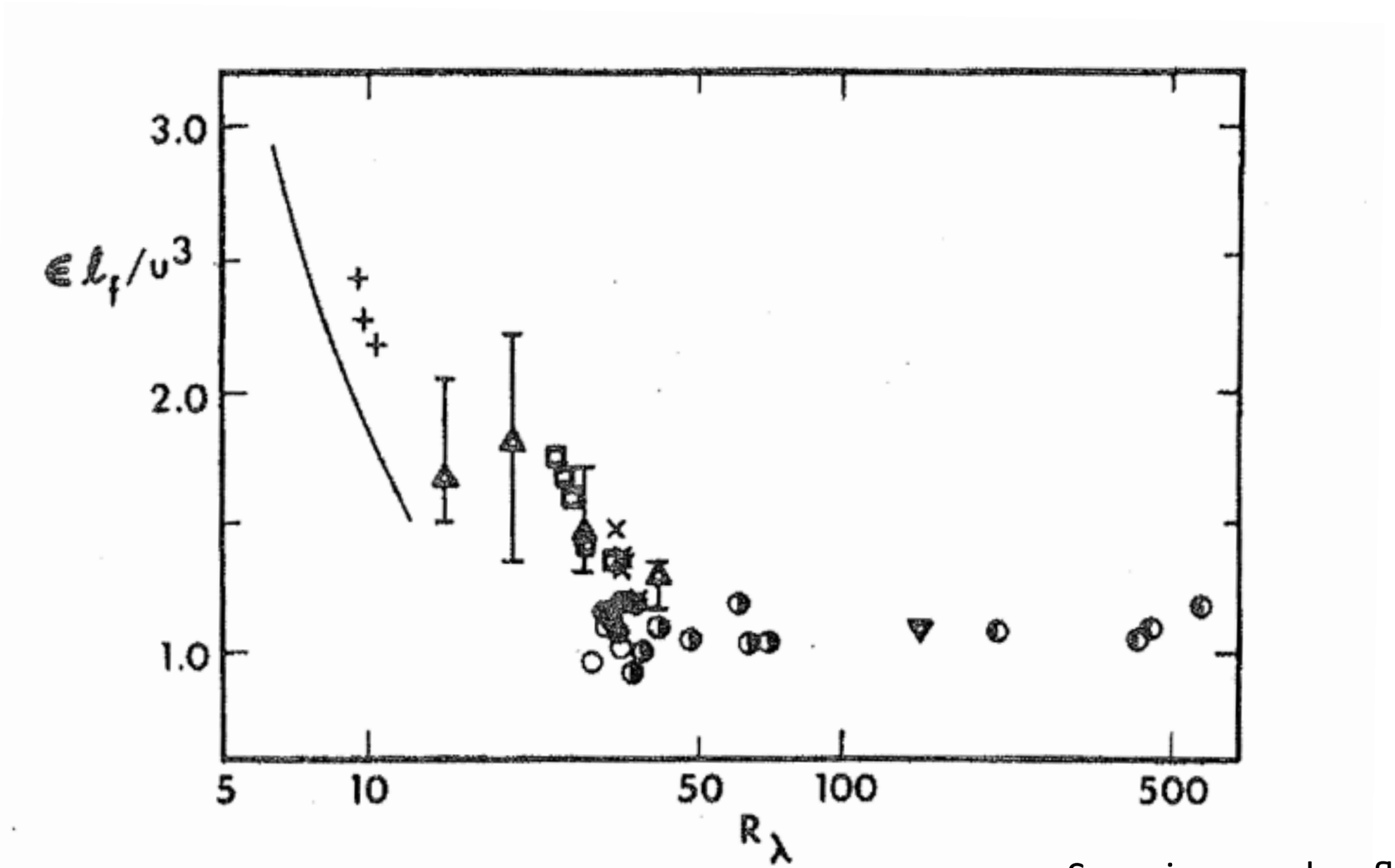


Figure 1.6. Turbulent jets at different Reynolds numbers: (a) relatively low Reynolds number, (b) relatively high Reynolds number (adapted from a film sequence by R. W. Stewart, 1969). The shading pattern used closely resembles the small-scale structure of turbulence seen in shadowgraph pictures.

Zeroth law of Turbulence

GI Taylor 1935



Sreenivasan phys fluids 1984

FIG. 1. The quantity $\epsilon L_f/u^3$ for biplane square-mesh grids. All data except + are for the initial period of delay, and are explained in Table I. + indicate typical data[13] in the final period of decay. — corresponds to Eq. (1).

Zeroth law of Turbulence

Kaneda et al.

Phys. Fluids, Vol. 15, No. 2, February 2003

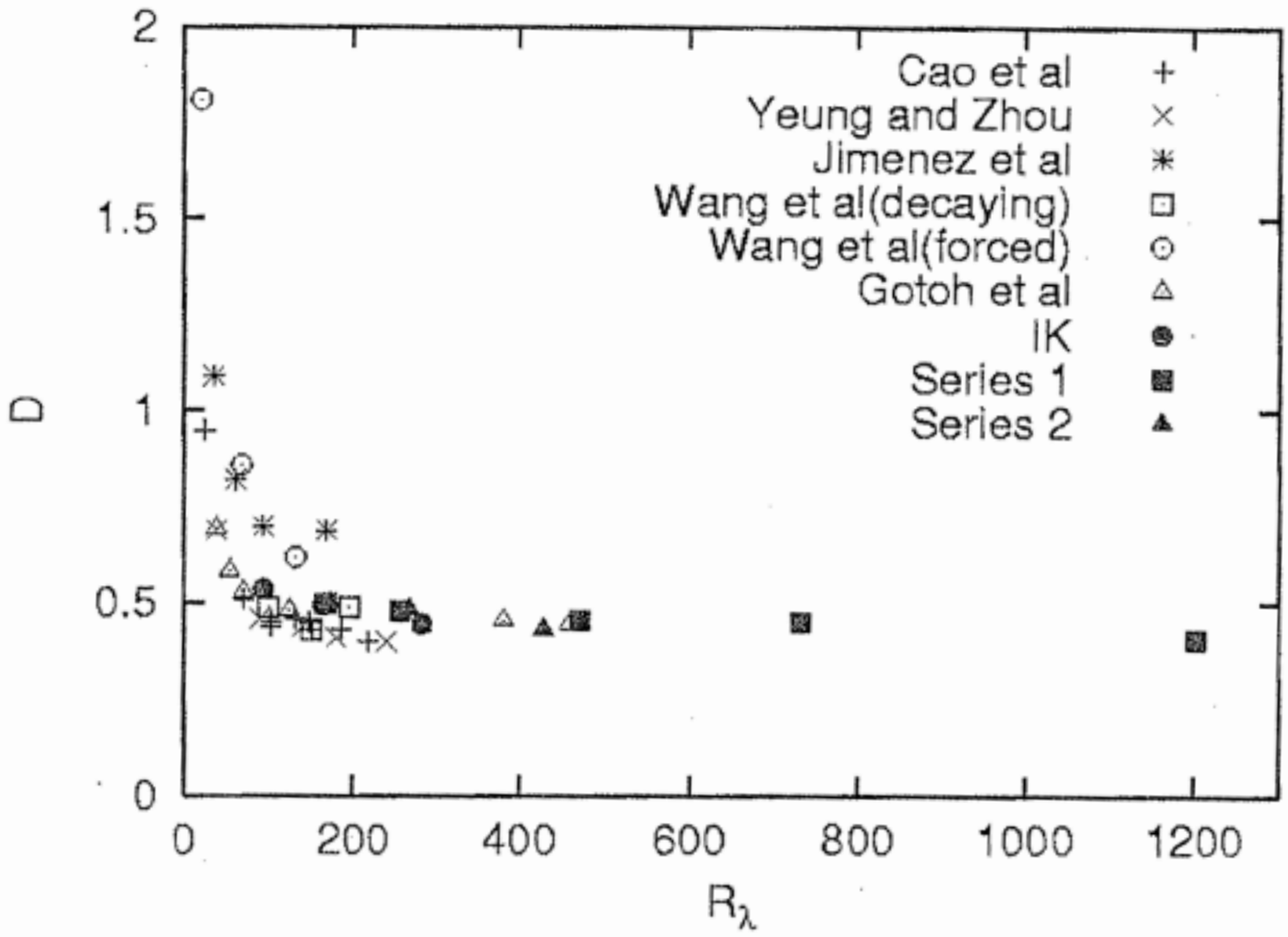
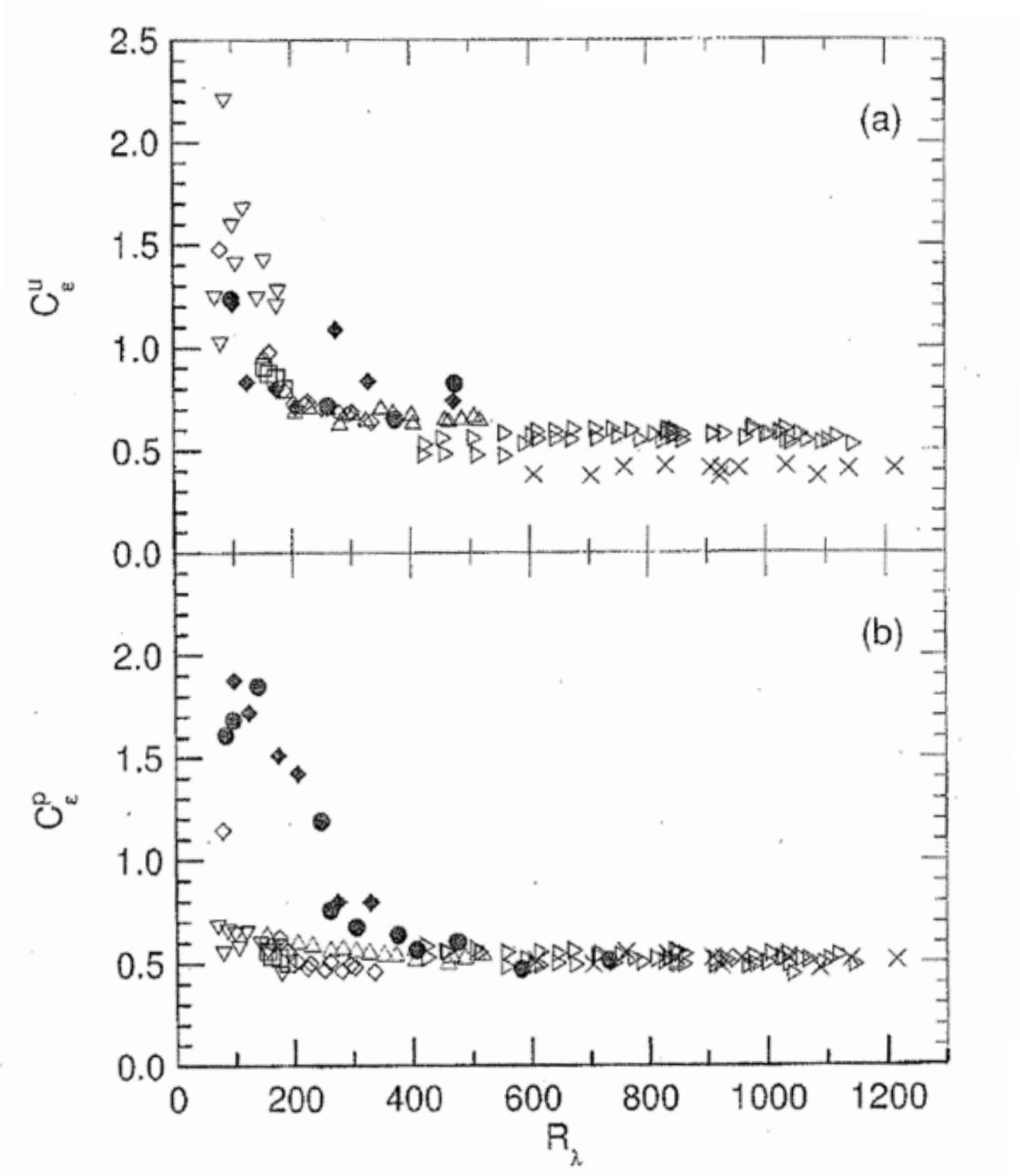


FIG. 3. Normalized energy dissipation rate D versus R from Ref. 5 data up to R 250), Ref. 3 , , and the present DNS databases , .

Zeroth law of Turbulence



Pearson et al. Phys Fluids 2002

FIG. 1. Normalized dissipation rate for a number of shear flows. Details as found in this work and Refs. 14–16. a C^u Eq. 3 ; b C^p Eq. 4 . , circular disk, 154 R 188; , pipe, 70 R 178; , normal plate, 79 R 335; , NORMAN grid, 174 R 516; NORMAN grid slight mean shear, dU/dy dU/dy $_{max}/2$, 607 R 1217; , NORMAN grid zero mean shear , 425 R 1120; , "active" grid Refs. 14, 15, 100 R 731; , "active" grid, with L_u estimated by Ref. 16. For Ref. 14 data, we estimate L_p 0.1 m and for Ref. 15 data we estimate L_p 0.225 m.

Bounded Flows

Cadot et al. PRE 1997

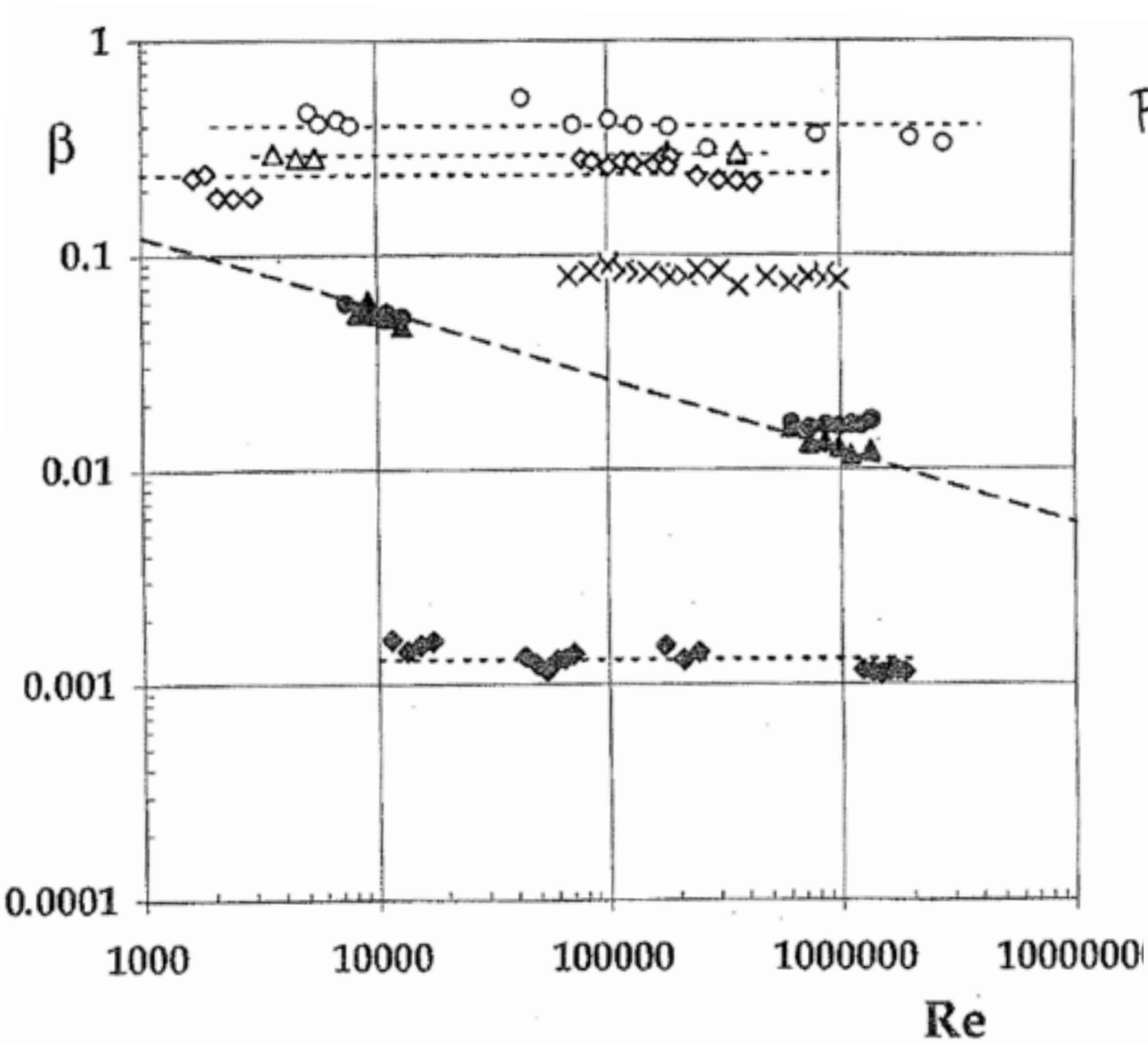
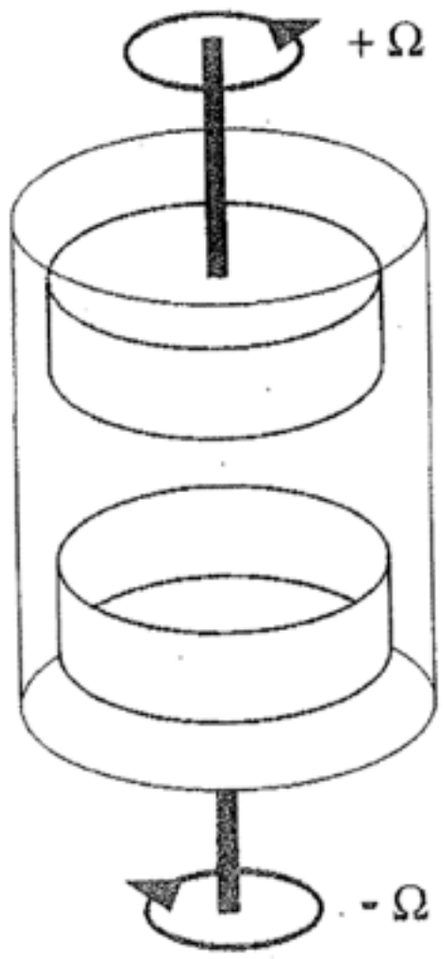


Fig.



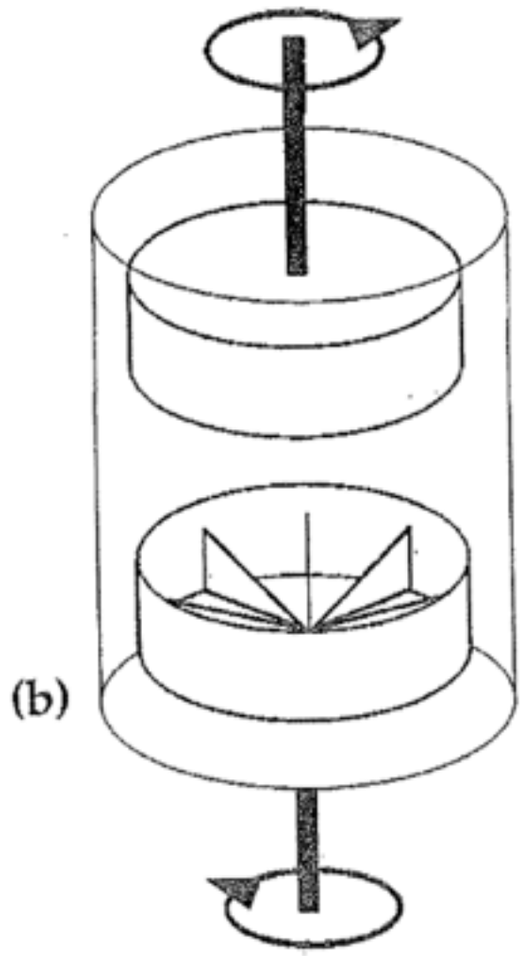
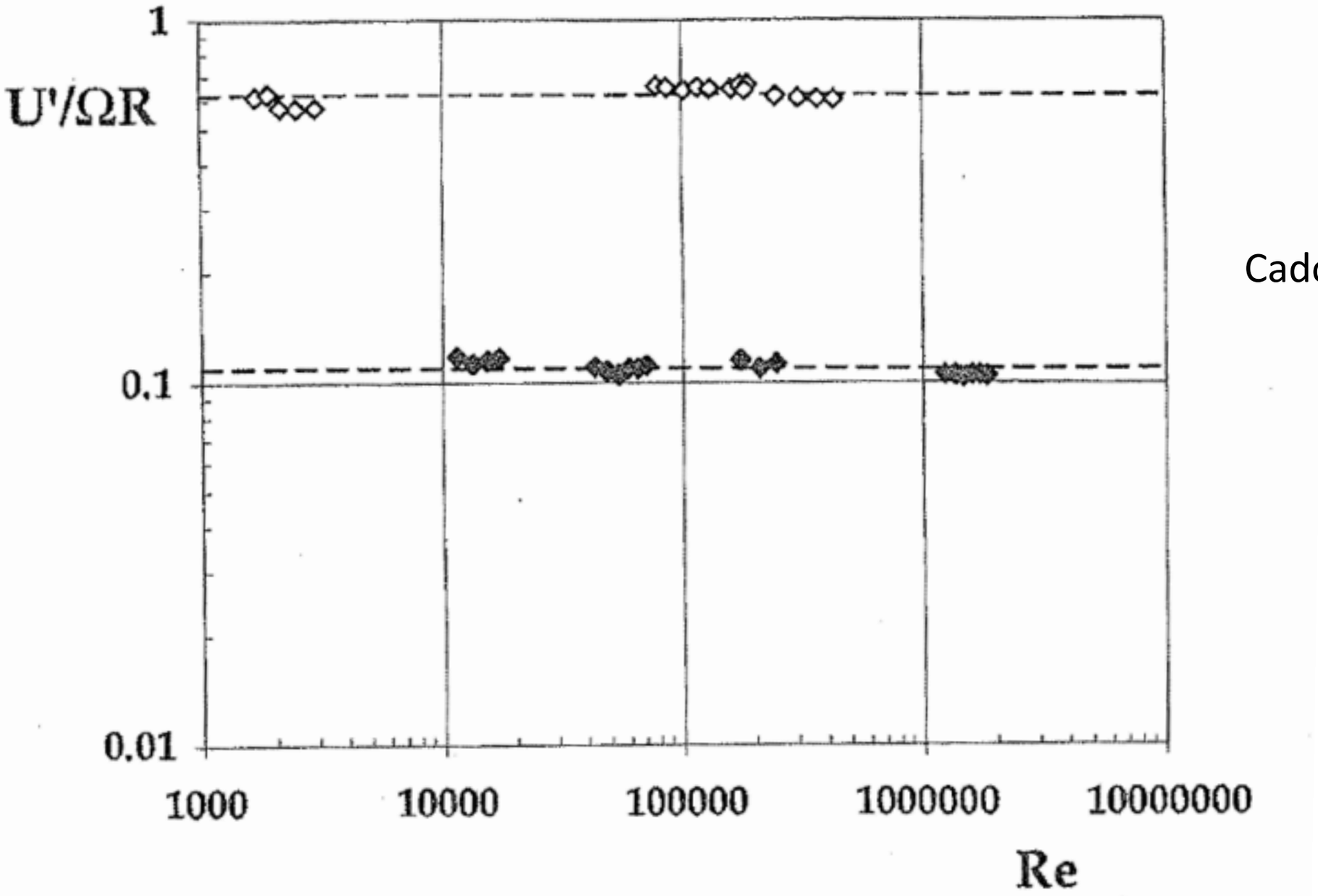


FIG. 2. Experiment A: Logarithmic plots of the nondimensional rate of energy injection β_I and dissipations β_D and β_B as a function of the Reynolds number for the three variants of the experiment. Black symbols: results obtained with smooth stirrers. Triangles (▲), rate of energy dissipation β_D; circles (●), rate of energy injection β_I; diamonds (◆), estimate of the rate of energy β_B dissipated in the bulk of the fluid as estimated from the pressure fluctuations. The dashed line shows a power law dependence proportional to $\mathrm{Re}^{-1/4}$. Open symbols: results obtained with the very rough (or inertial) stirrers. Triangles (△), rate of energy dissipation β_D; circles (○), rate of energy injection β_I; diamonds (◇), rate of energy dissipation β_B. Results are obtained with the stirrers having smaller platelets. × is the mean rate of the energy dissipation β_D.

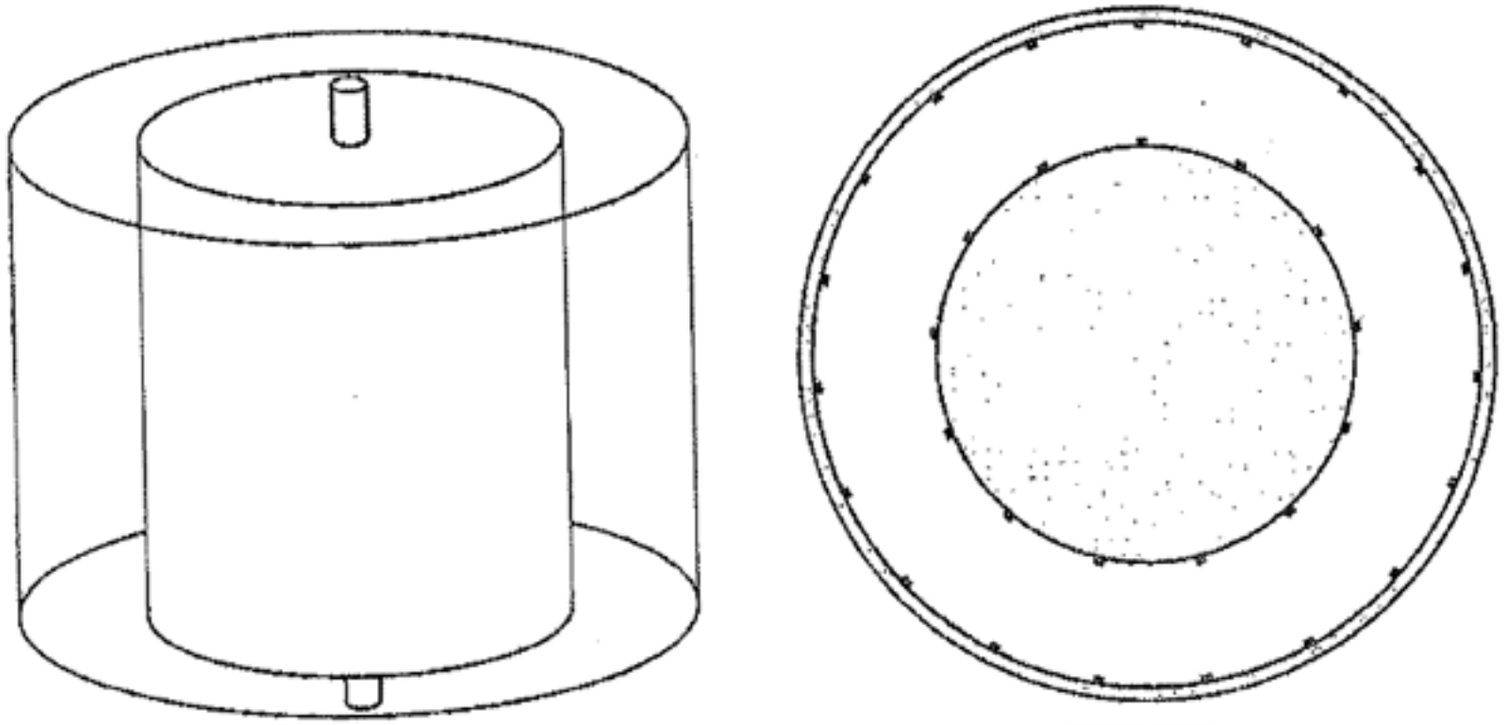
Bounded Flows



Cadot et al. PRE 1997

FIG. 3. Plot of the typical velocity U' in the bulk of the flow as deduced from the histograms of the pressure fluctuations [see Eq. (7)]. The black triangles (▲) are the data obtained with smooth stirrers, and the open ones (△) correspond to the data obtained with the rough ones.

Bounded Flows



a)

Cadot et al. PRE 1997

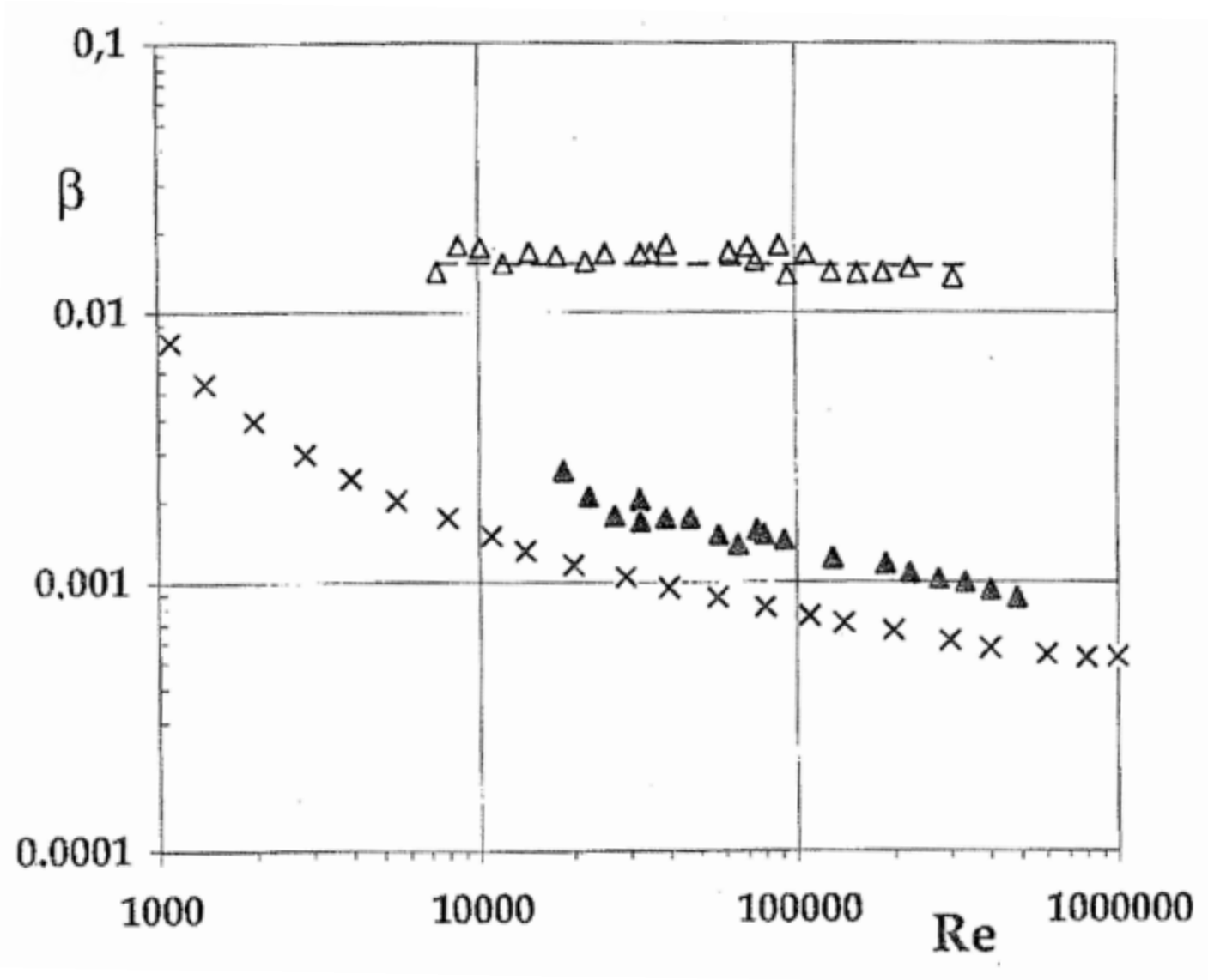


FIG. 5. Couette-Taylor experiments. Logarithmic plots of the nondimensional rates of energy dissipation β_D as a function of the Reynolds number. The black triangles (▲) are the results obtained with smooth cylinders, and the open ones (△) correspond to those obtained with the ribbed ones. The crosses (×) show for comparison the rates of energy injection β_D deduced from the data obtained with smooth cylinders by Lathrop, Finenberg, and Swinney [8].

Present physical model

Framework:

- Incompressible flow
- Single phase flow
- Single species flow
- Newtonian flow
- passive scalar for temperature/pollutant modelling
- no coupled dynamical field (magnetic field, density, ...)

Governing equation

$$\rho\left(\frac{\partial}{\partial t}\underline{u}+\underline{\nabla}\cdot(\underline{u}\otimes\underline{u})\right)=-\underline{\nabla}p+\mu\Delta\underline{u}+\underline{f}$$

$$\underline{\nabla}\cdot\underline{u}=0$$

$$\rho\left(\frac{\partial}{\partial t}T+\underline{\nabla}\cdot(\underline{u}T)\right)=\kappa\Delta T$$

Preliminary remarks

Poisson equation for pressure (elliptic equation)

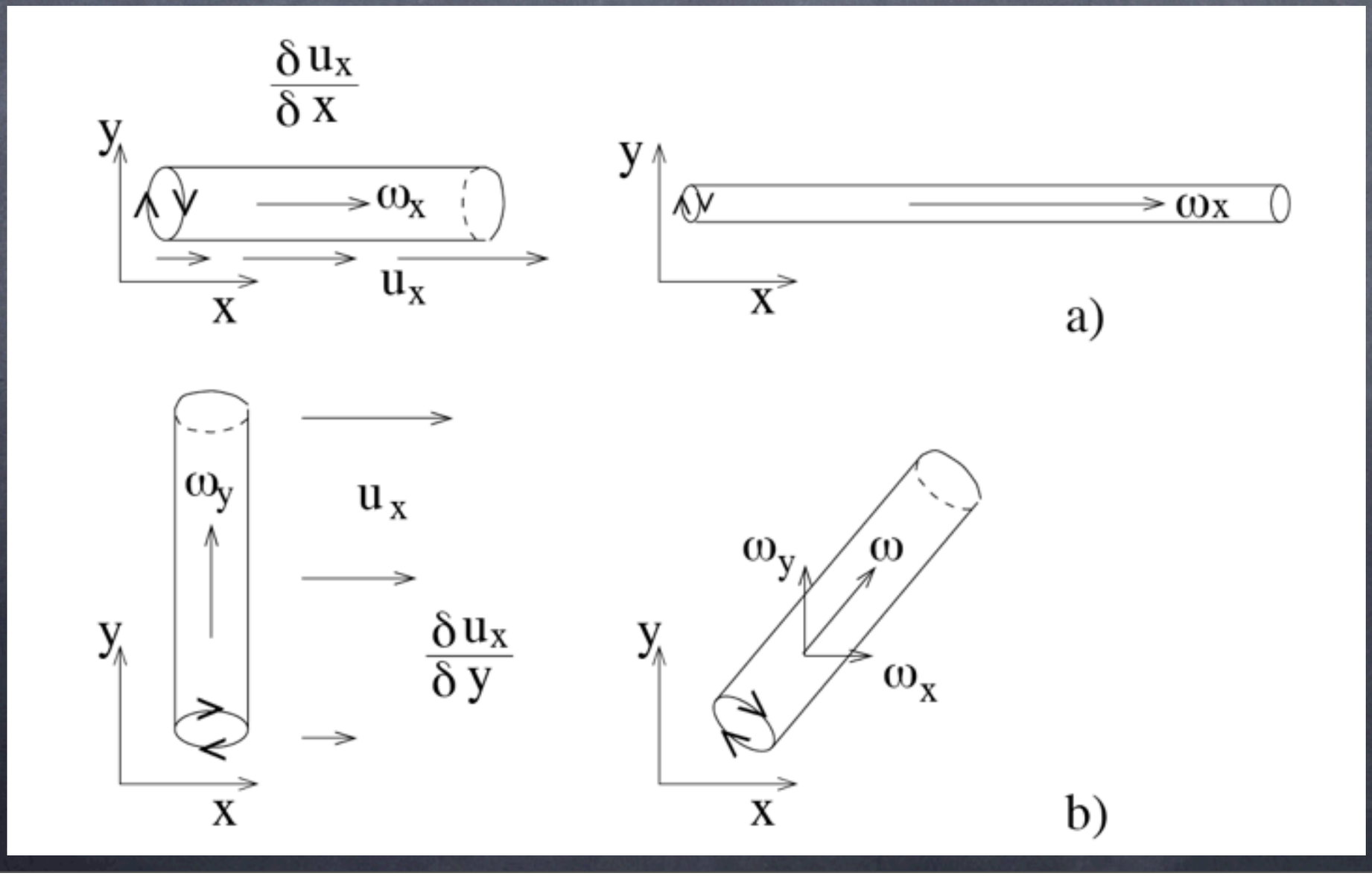
$$-\Delta p = \underline{\nabla} \cdot \underline{\nabla} \cdot (\underline{u} \otimes \underline{u}) - \underline{\nabla} \cdot \underline{f}$$

General Green-function-based solution

$$p(\underline{x}, t) = \iiint - \left[\underline{\nabla} \cdot \underline{\nabla} \cdot (\underline{u} \otimes \underline{u}) + \underline{\nabla} \cdot \underline{f}\right] (\underline{y}, t) \mathcal{G}(\underline{x}, \underline{y}) d\underline{y}$$

Consequences:
physical inconsistency in the acoustic limit
pressure = enslaved Lagrangian, not independent physical variable

vortex stretching



Equation simmetry