Hydrodynamic stability and turbulence in shear flows

Presented by:

Sergey Abdurakipov

Novosibirsk State University

Institute of Thermophysics SB RAS

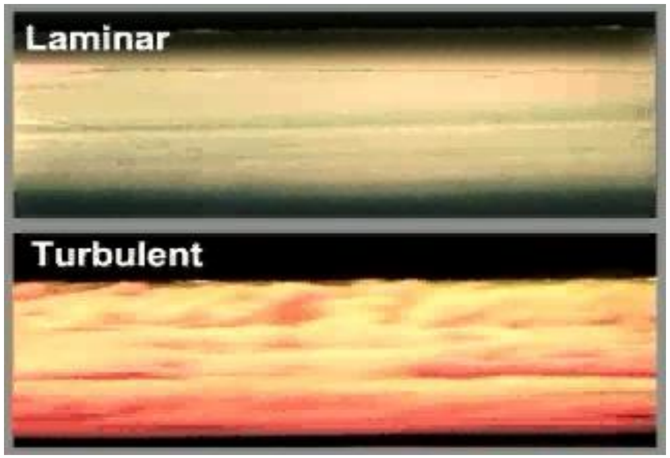
Delft University of Technology, Netherlands

Content

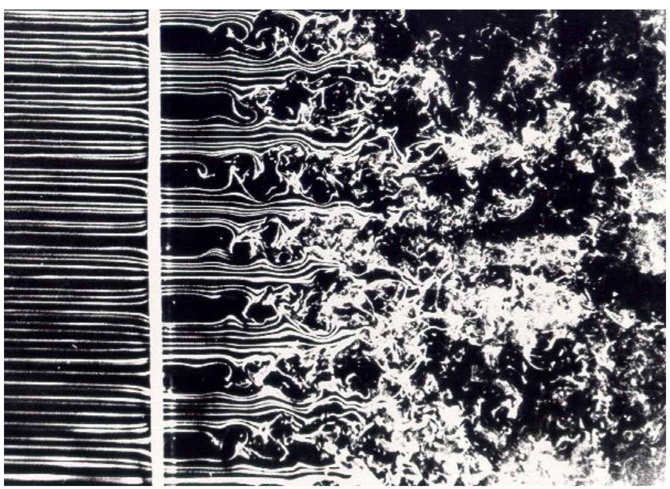
- Laminar and turbulent flows
- Hydrodynamic stability
- Properties of turbulence
- Models and hypotheses of turbulence
- Theory of turbulence
- Numerical simulation
- Experimental approaches

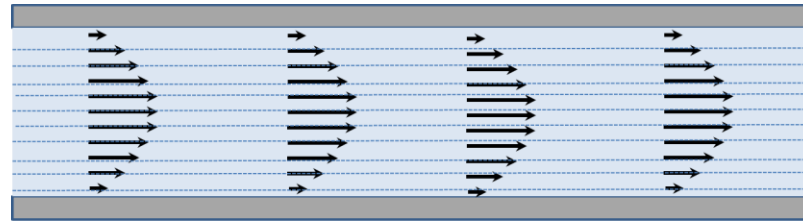
Perhaps the first ever vortex ‘visualization’ by Leonardo da Vinci

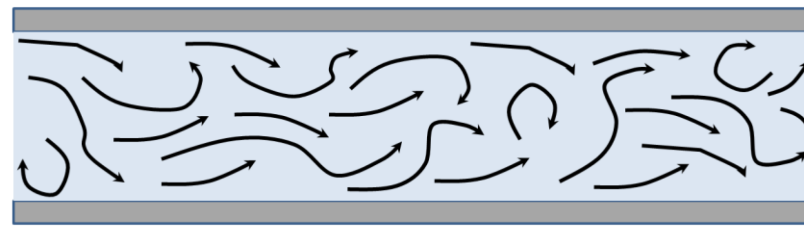
Two kinds of flows



Flow in a boundary layer

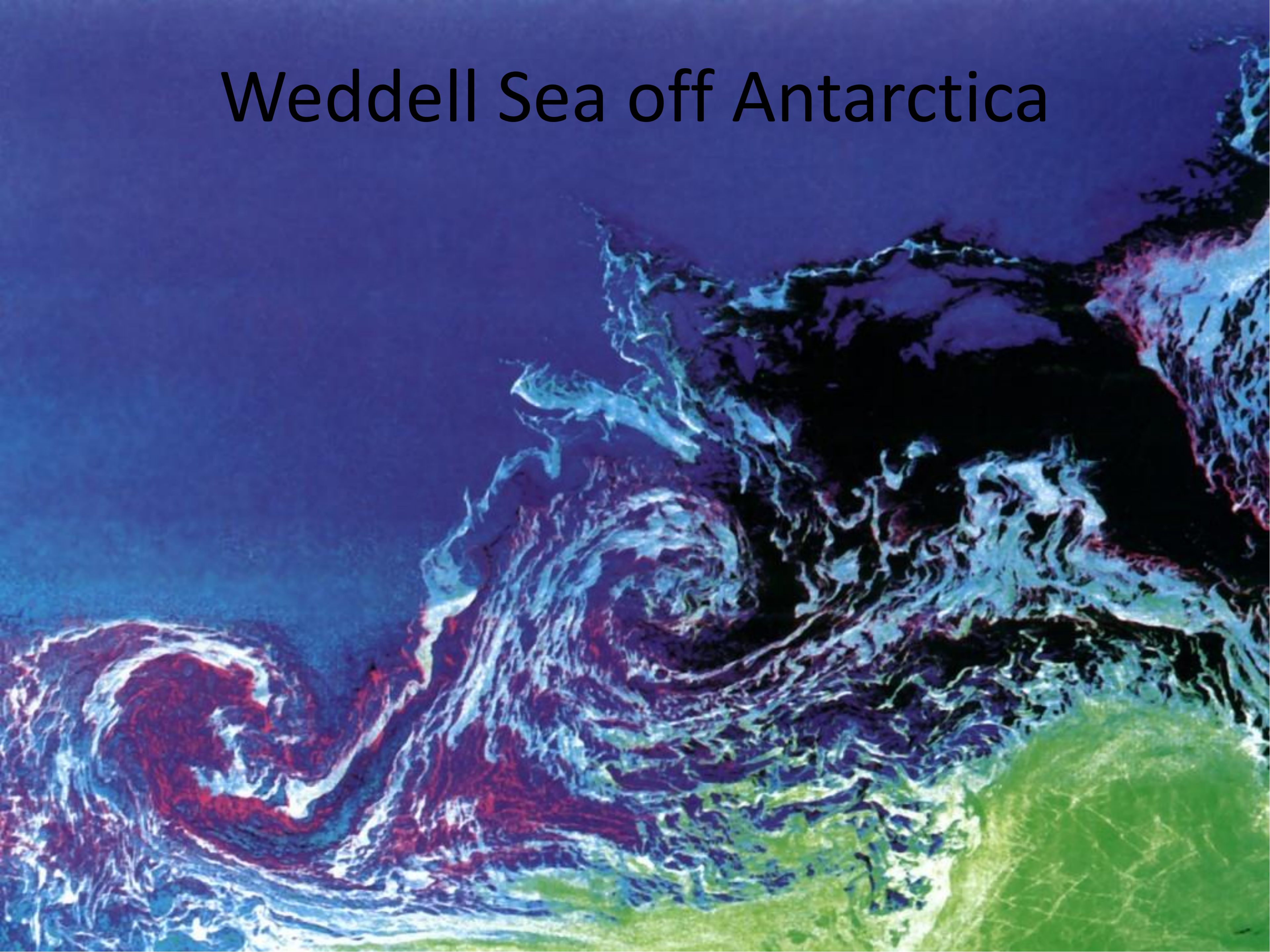

Transition to turbulent flow after grid


Laminar


Turbulent

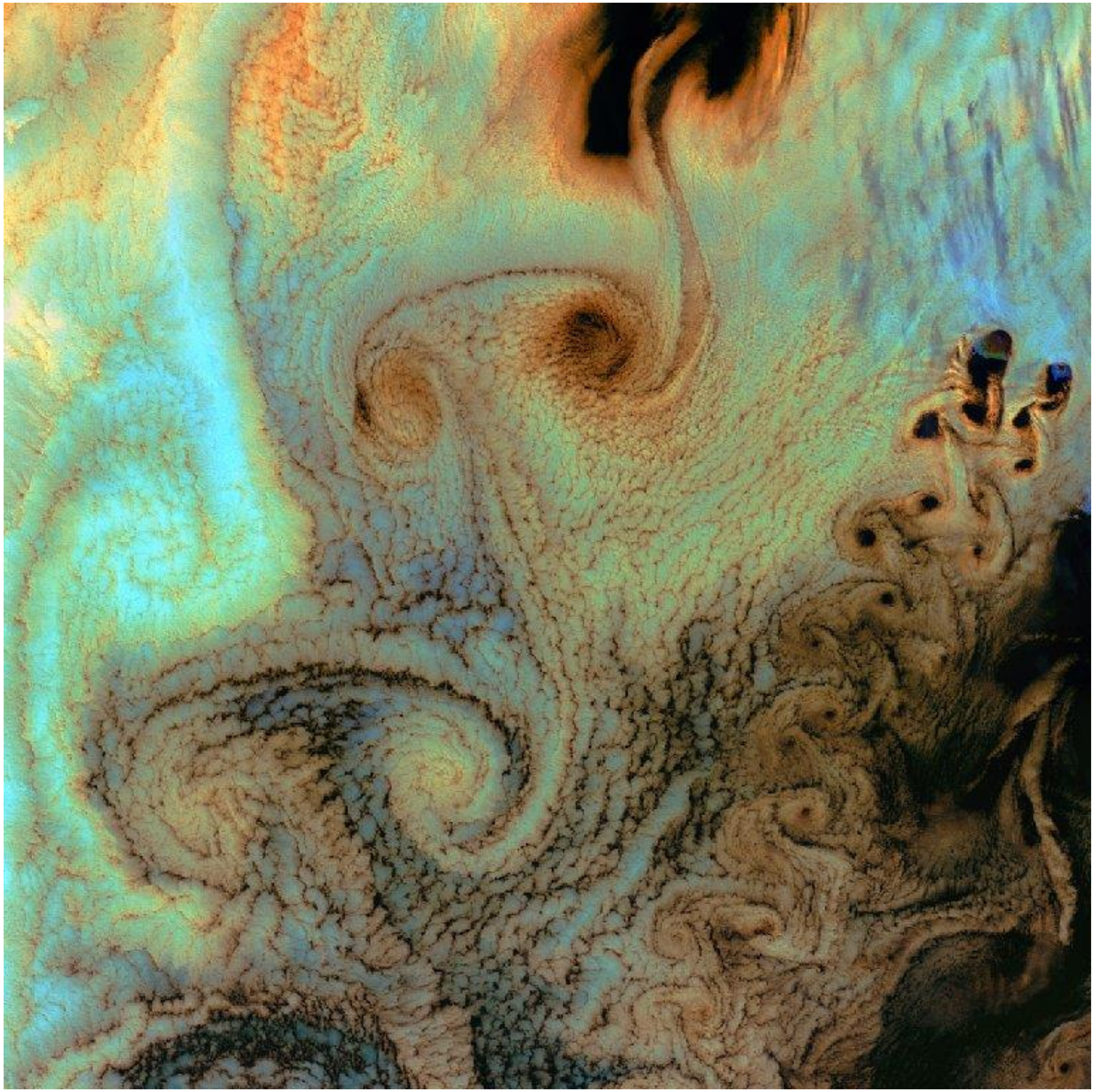
Turbulent flow - type of fluid (gas or liquid) flow in which the fluid undergoes irregular fluctuations, or mixing, in contrast to laminar flow, in which the fluid moves in smooth paths or layers.

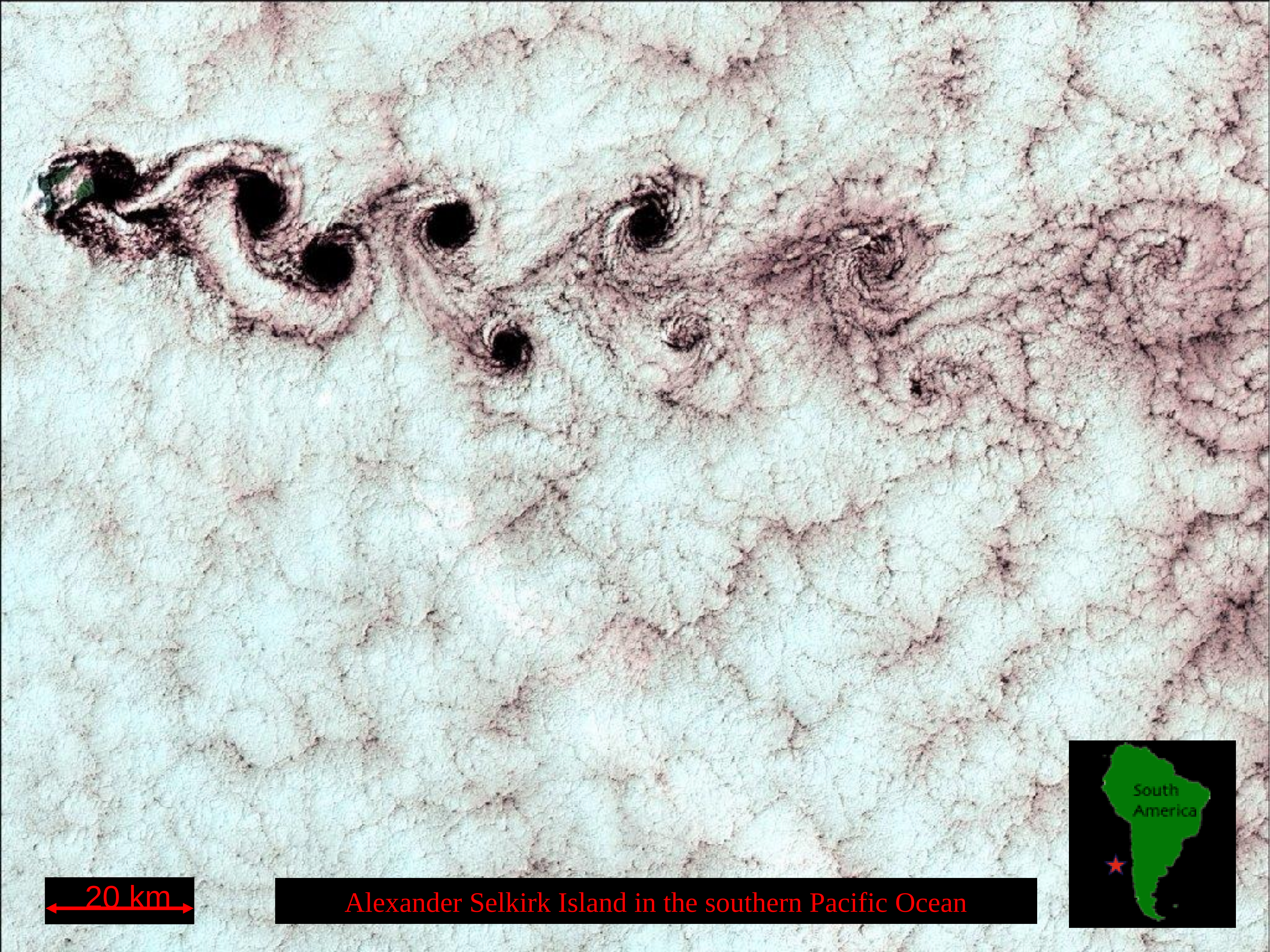
Weddell Sea off Antarctica

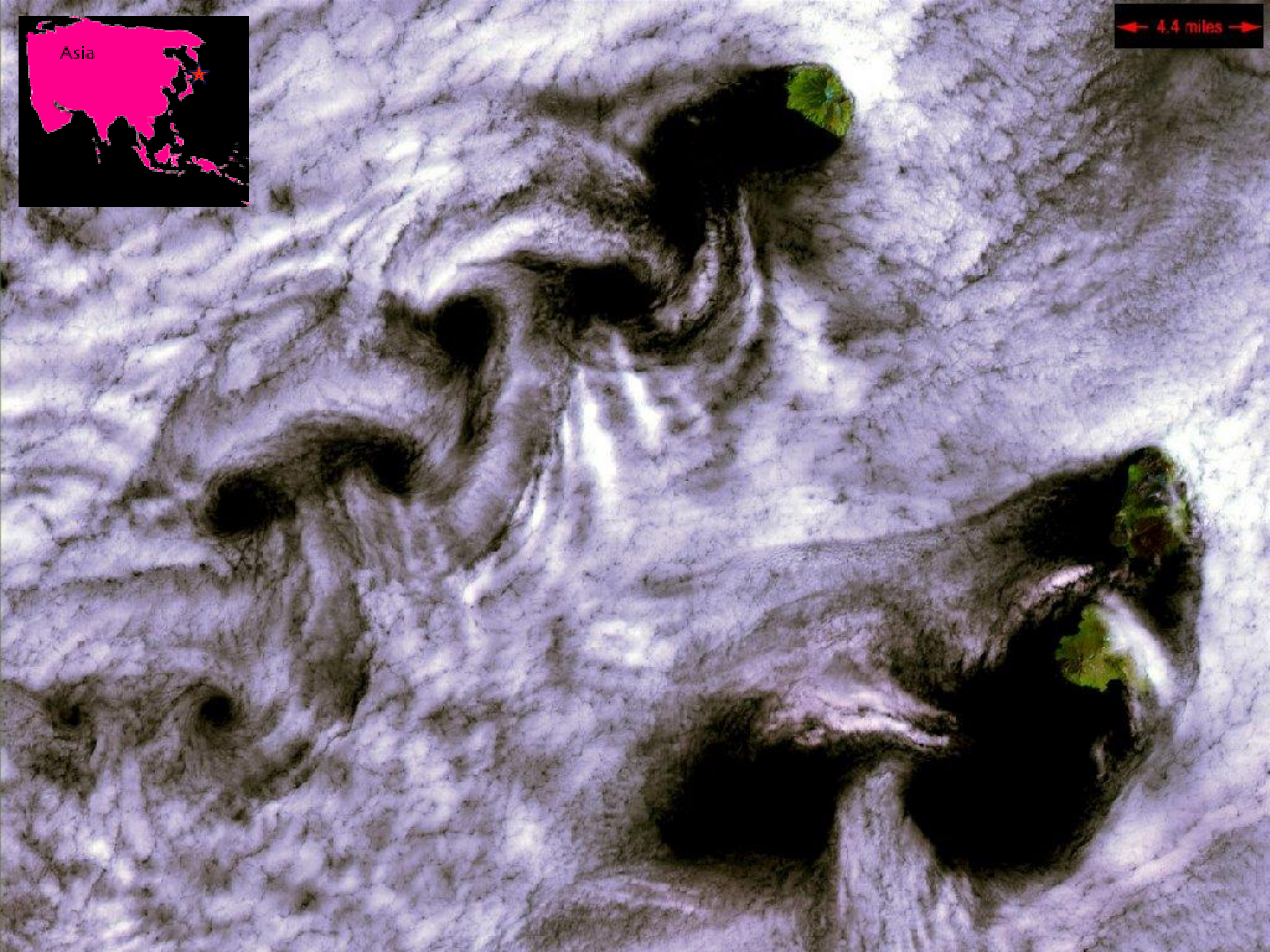


Alaska's Aleutian Islands

- As air flows over and around objects in its path, spiraling eddies, known as Von Karman vortices, may form.
- The vortices in this image were created when prevailing winds sweeping east across the northern Pacific Ocean encountered Alaska's Aleutian Islands




20 km
Alexander Selkirk Island in the southern Pacific Ocean
South America


Asia
4.4 miles

Navier-Stokes equations

$\nabla \cdot \mathbf{u} = 0$ Continuity equation

$$\frac{\partial \mathbf{u}}{\partial t} = -\left(\mathbf{u} \cdot \nabla\right)\mathbf{u} + \upsilon\, \nabla^2 \mathbf{u} - \frac{1}{\rho}\nabla p$$

$$\boxed{\frac{\partial \mathbf{u}}{\partial t} = -\left(\mathbf{u} \cdot \nabla\right)\mathbf{u} + \frac{\nabla^2 \mathbf{u}}{Re} - \nabla p}$$

The convection term is a quadratic function of velocities – source of nonlinearities and turbulent phenomena

Change in velocity with time	=	Convection term	+	Viscous term	+	Pressure

Turbulence

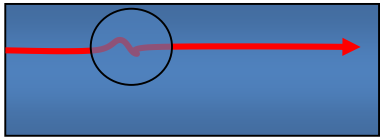
Relative magnitude of inertial and viscous terms is Reynolds number

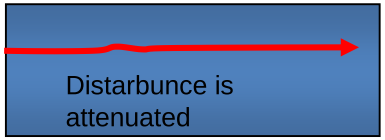
$$\mathrm{Re} = \frac{\rho \nabla \cdot (\vec{u}\vec{u})}{\mu \nabla^2 \vec{u}} = \frac{\rho u D}{\mu}$$

Increasing Re increases nonlinearity of NS equations. This nonlinearity leads to sensitivity of NS solution to flow disturbances.

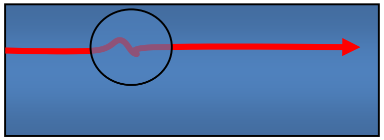
Osborn Reynolds experiment 1883:
Dye into center of pipe

Laminar flow: $\mathrm{Re}<\mathrm{Re}_{crit}$

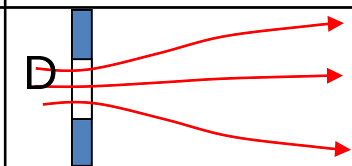
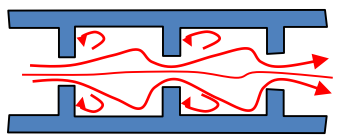
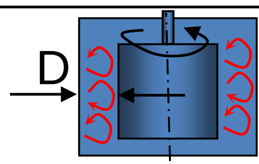
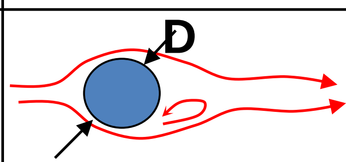
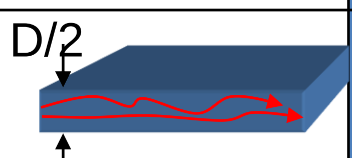


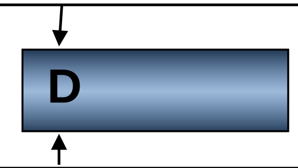
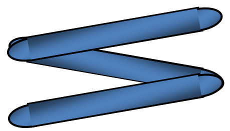
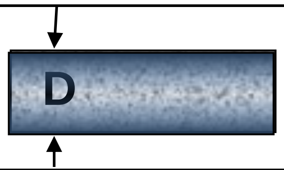
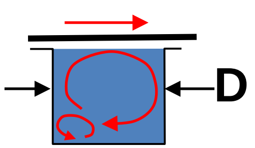
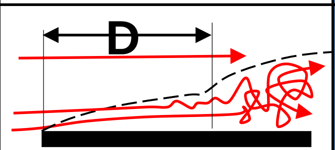


Turbulent flow: $\mathrm{Re}>\mathrm{Re}_{crit}$



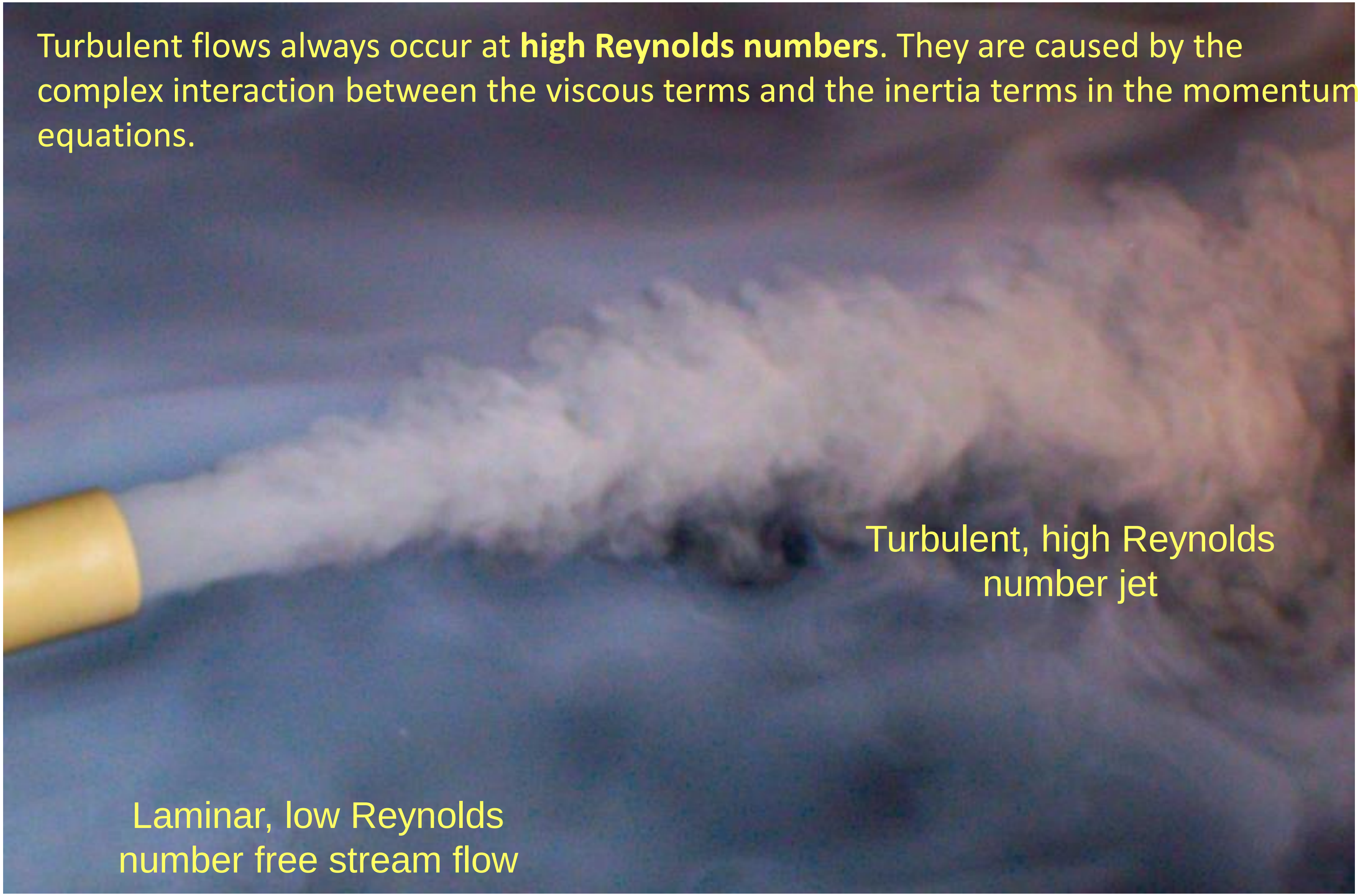
Transition Laminar-Turbulent

	Geometry	Re_{crit}
Jets		5-10
Baffled channels		100
Couette flow		300
Cross flow		400
Planar channel		1000

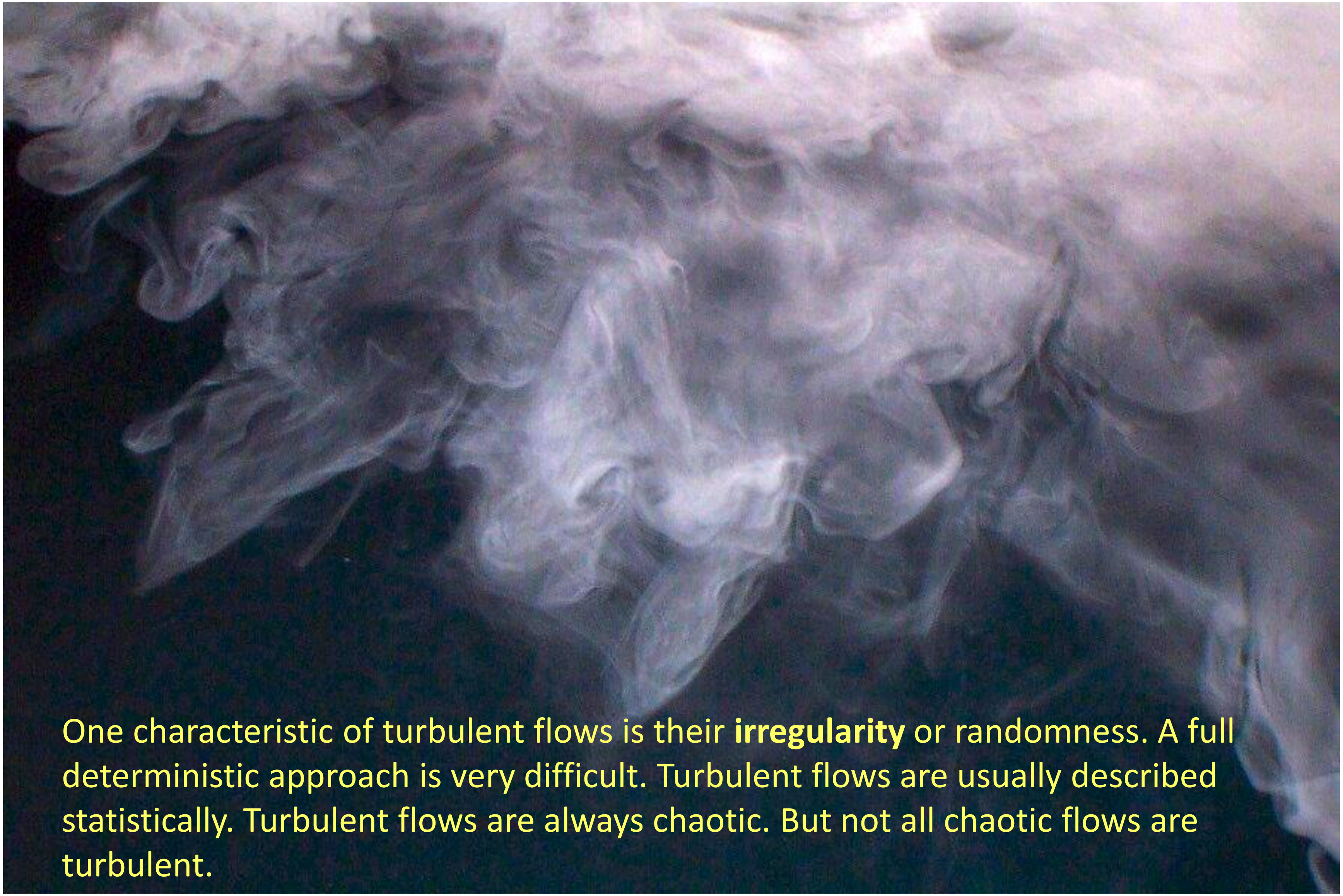
	Geometry	Re_{crit}
Circ.pipe		2000
Coiled pipe		5000
Suspension in pipe		7000
Cavity		8000
Plate		500000

Turbulence: high Reynolds numbers

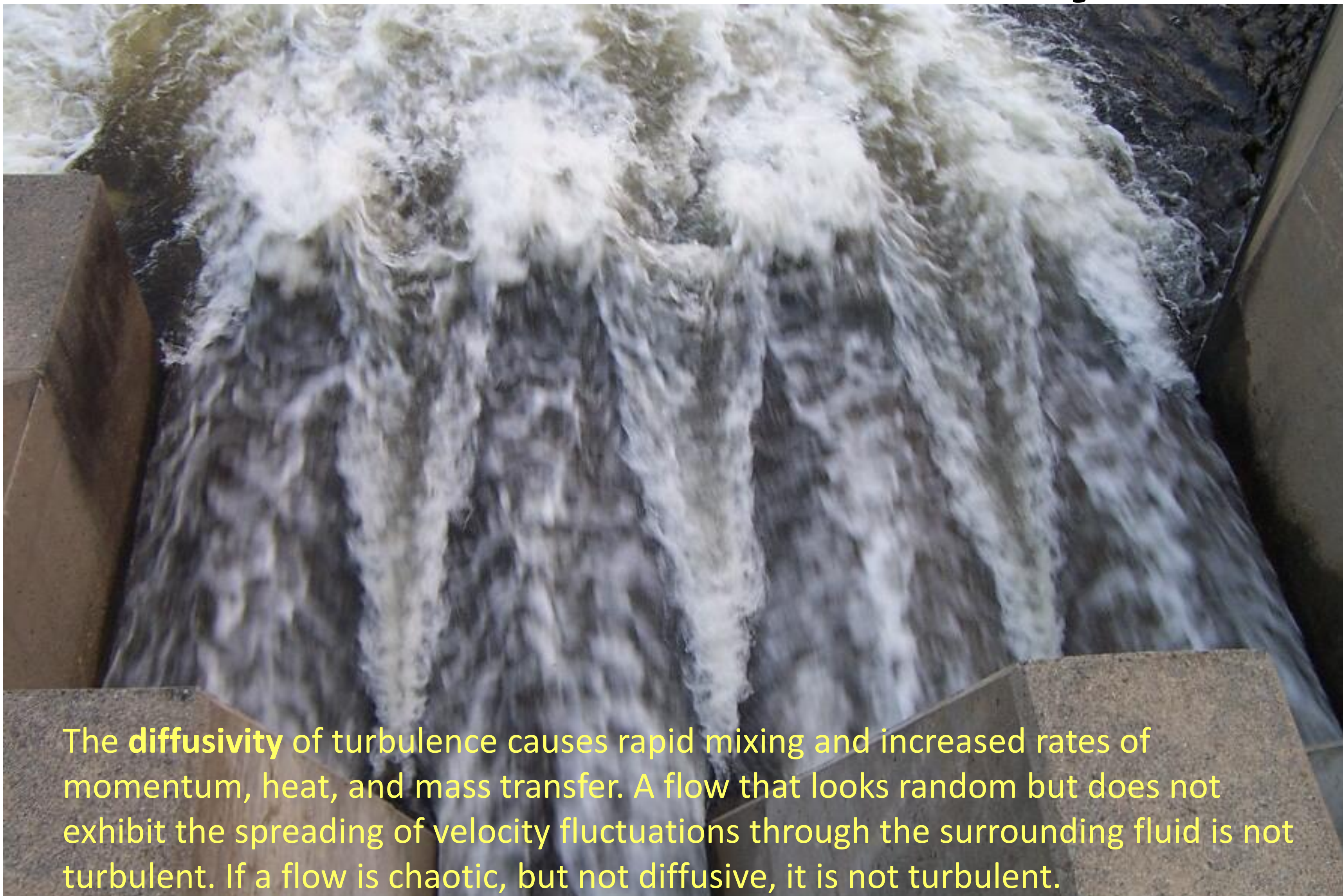
Turbulent flows always occur at **high Reynolds numbers**. They are caused by the complex interaction between the viscous terms and the inertia terms in the momentum equations.



Turbulent flows are chaotic

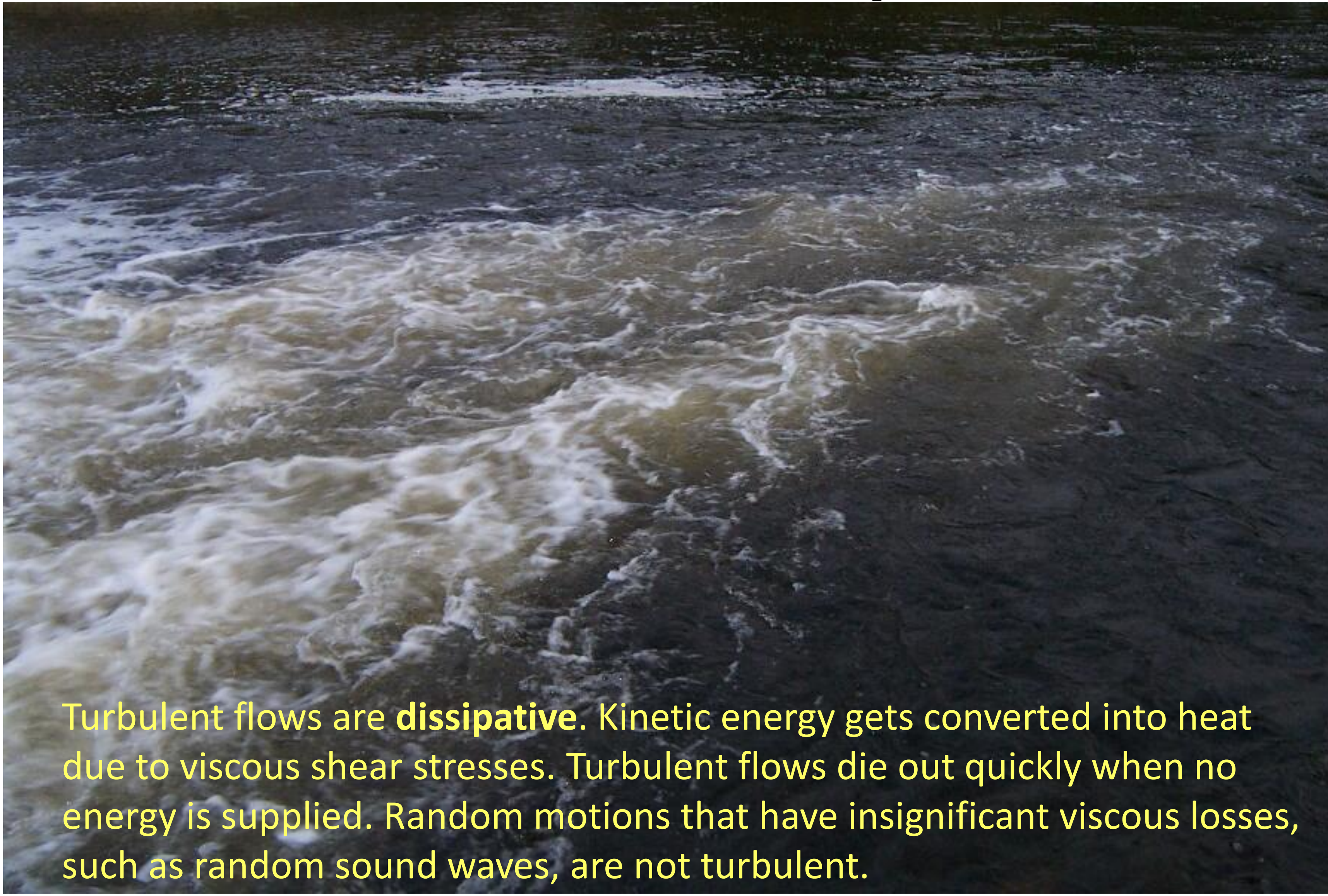


Turbulence: diffusivity



The **diffusivity** of turbulence causes rapid mixing and increased rates of momentum, heat, and mass transfer. A flow that looks random but does not exhibit the spreading of velocity fluctuations through the surrounding fluid is not turbulent. If a flow is chaotic, but not diffusive, it is not turbulent.

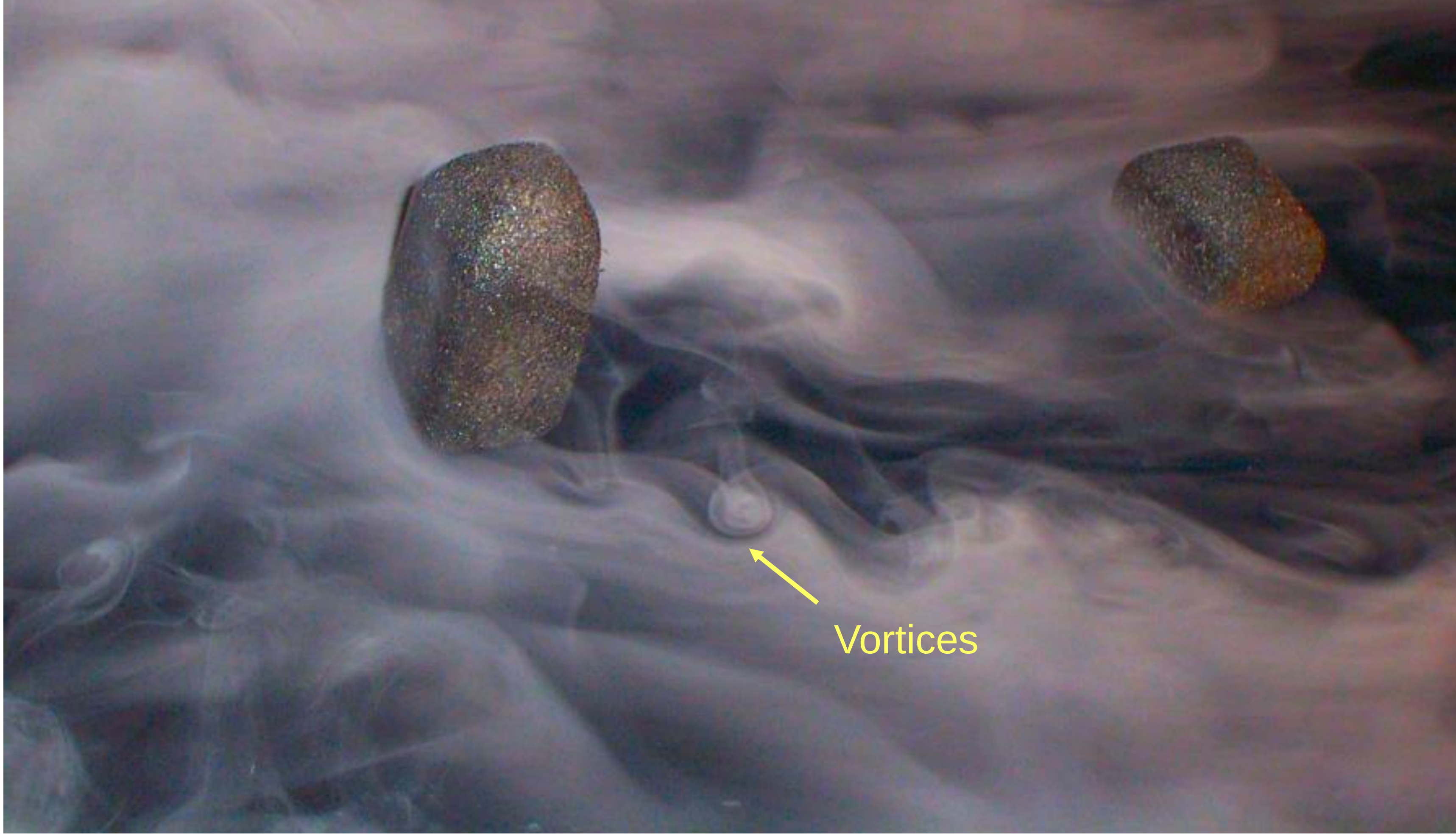
Turbulence: dissipation



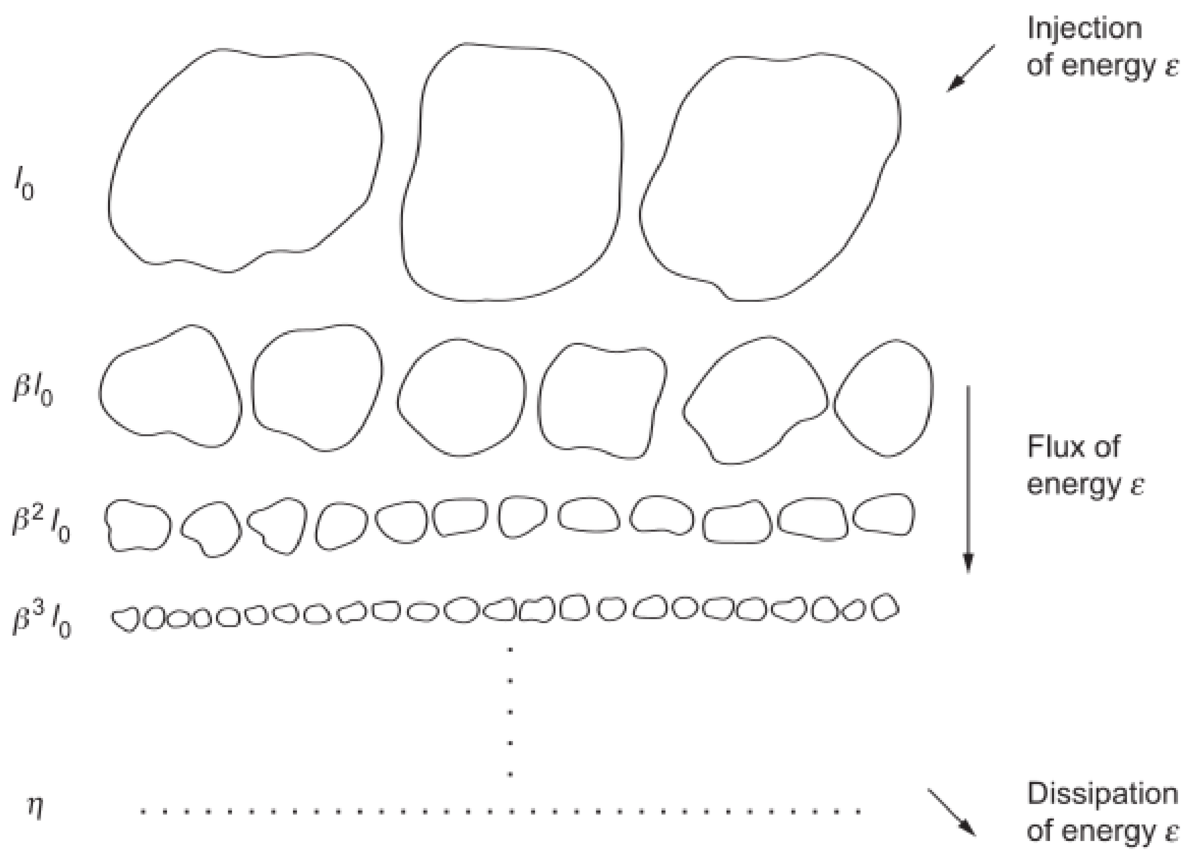
Turbulent flows are **dissipative**. Kinetic energy gets converted into heat due to viscous shear stresses. Turbulent flows die out quickly when no energy is supplied. Random motions that have insignificant viscous losses, such as random sound waves, are not turbulent.

Turbulence: rotation and vorticity

Turbulent flows are **rotational**; that is, they have non-zero vorticity. Mechanisms such as the stretching of three-dimensional vortices play a key role in turbulence.



Model of turbulence: Richardson's cascade



Estimation of dissipation scale:

$$\mathrm{Re}_\eta = 1 \qquad \eta u_\eta = \nu$$

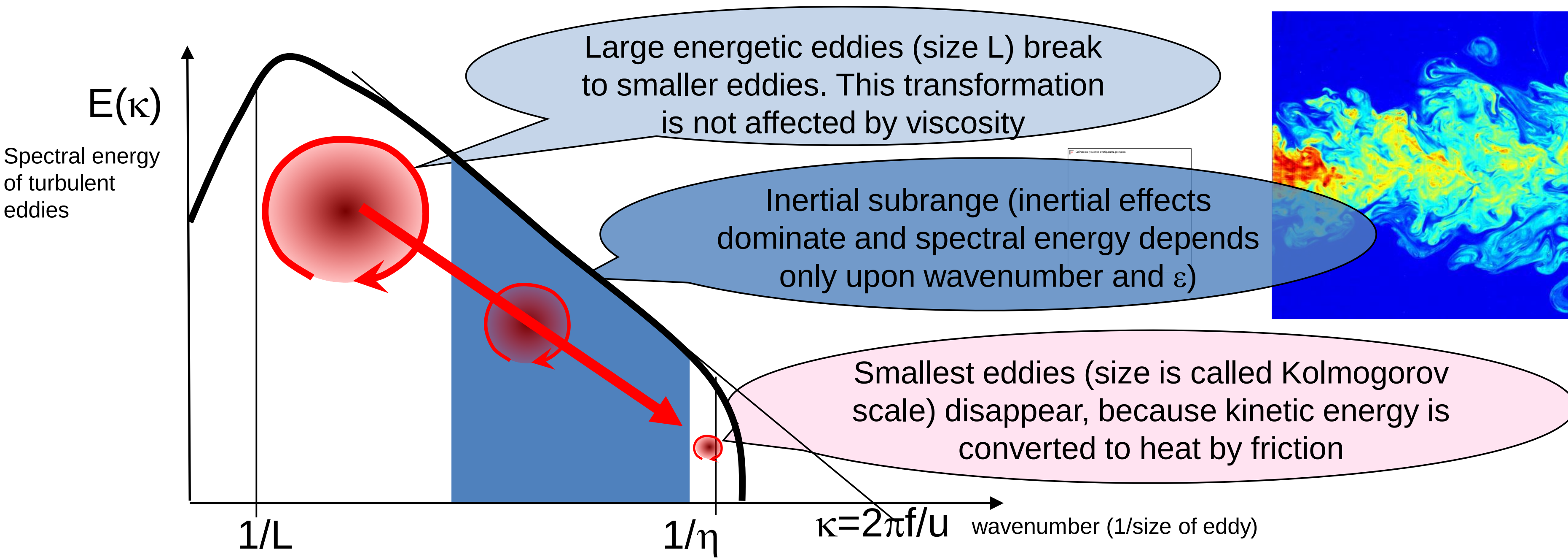
$$\mathrm{Re}_l = \frac{ul}{\nu} \gg 1$$

$$\mathrm{Re}_l = \frac{ul}{\nu} \ll 1$$

Kolmogorov's hypotheses

Kolmogorov used the idea of the physical dimension ε:

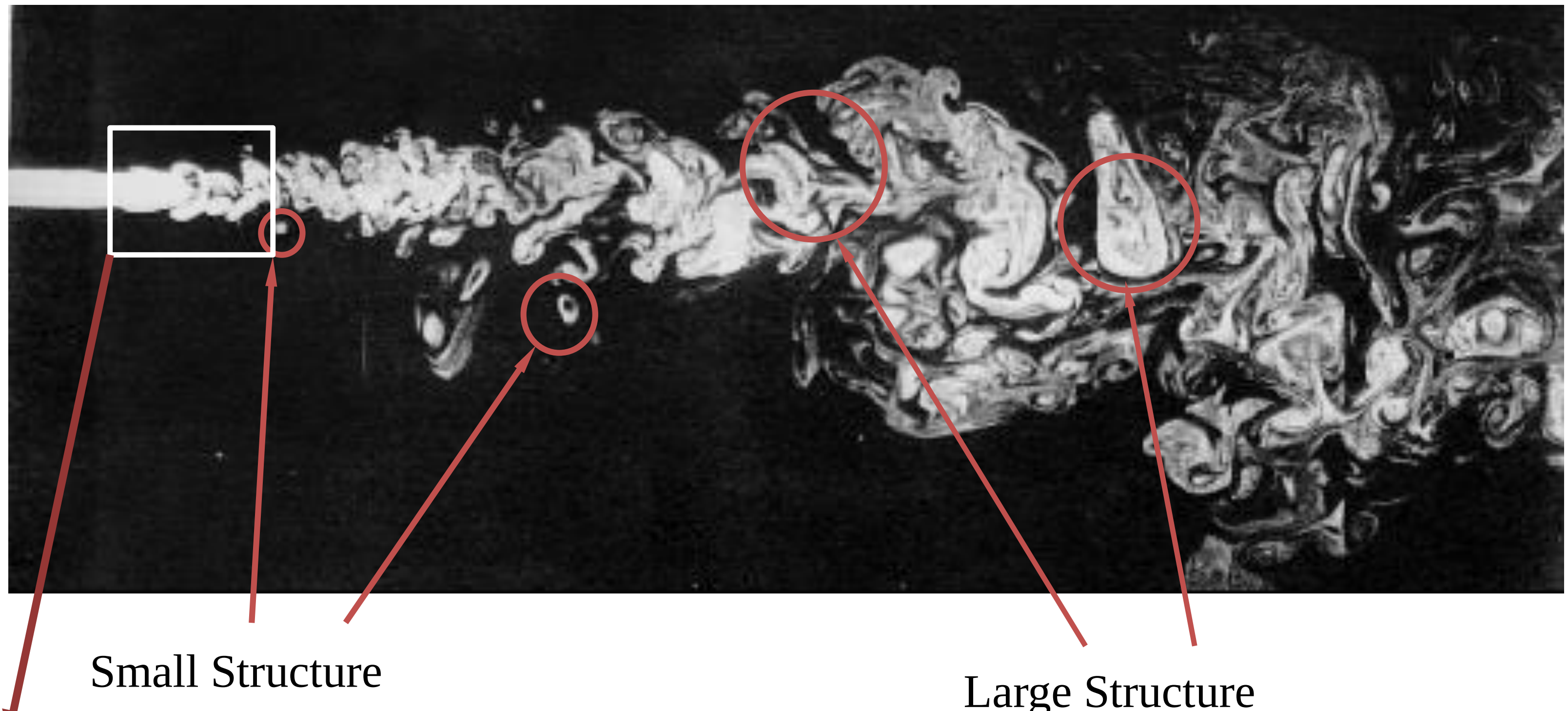
$$[\varepsilon] = \frac{[u^3]}{[l]} \qquad \varepsilon \sim \frac{u_l^{\,3}}{l} \qquad u_l \sim (l\varepsilon)^{1/3} \qquad E(\kappa) = C\,\frac{\varepsilon^{2/3}}{\kappa^{5/3}}$$

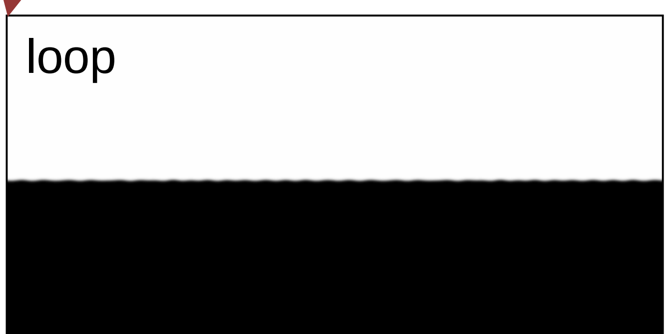


Typical values of frequency f~10 kHz, Kolmogorov scale η~0.01 up to 0.1 mm

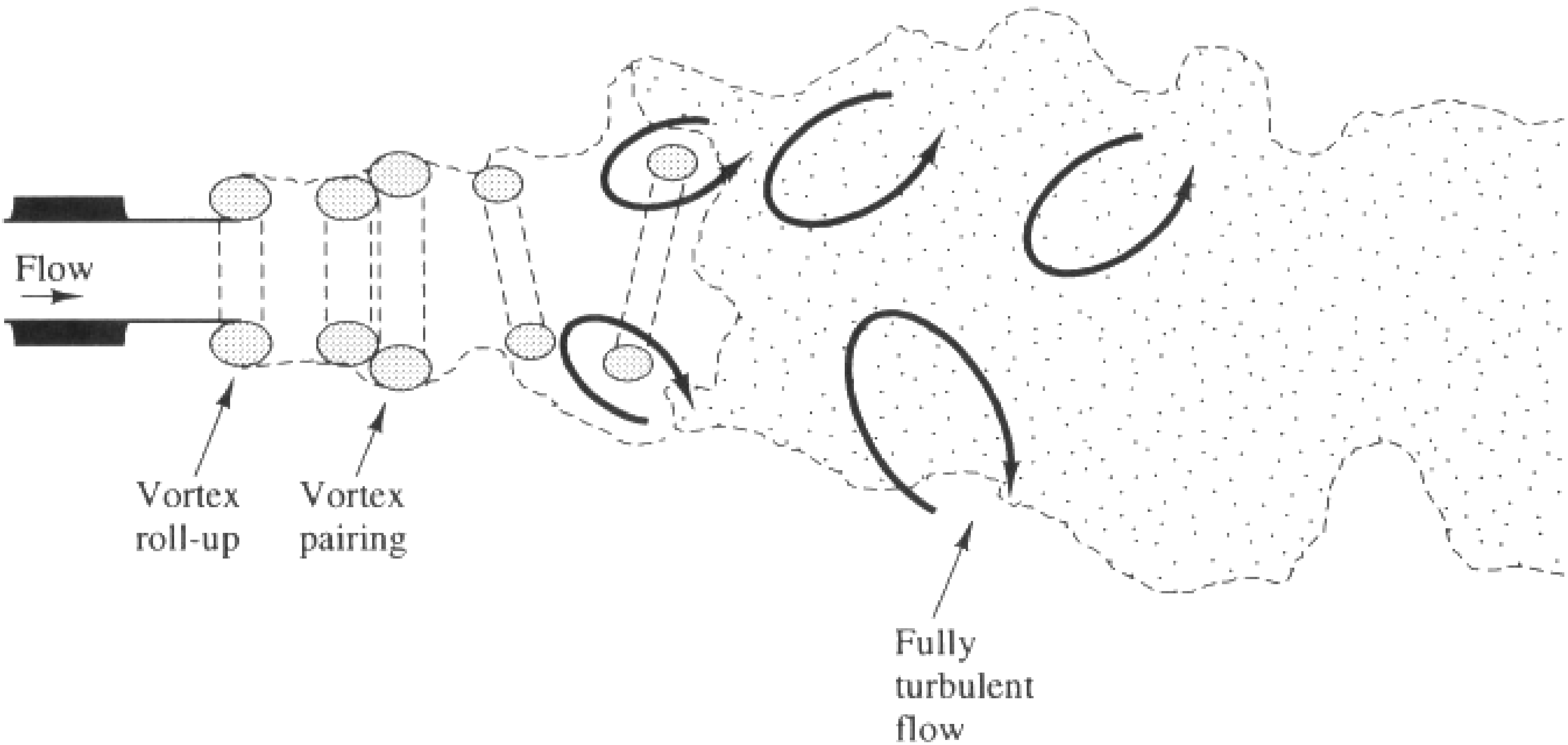
Kolmogorov scale η decreases with the increasing Re

Turbulence in jet flow





Turbulence in jet flow



Theory of turbulence

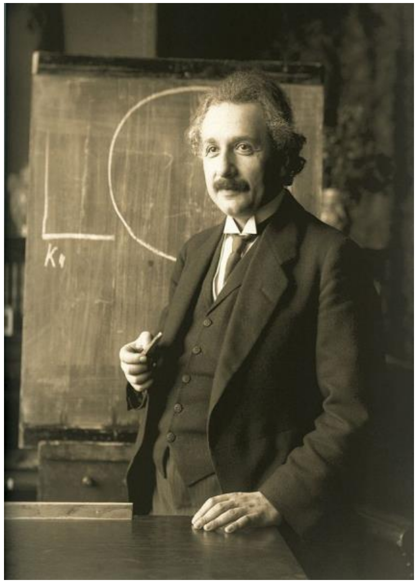
The theory of turbulence has not been developed yet!!!

Nobel Laureate Richard Feynman described turbulence as "the most important unsolved problem of classical physics."

"When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first."

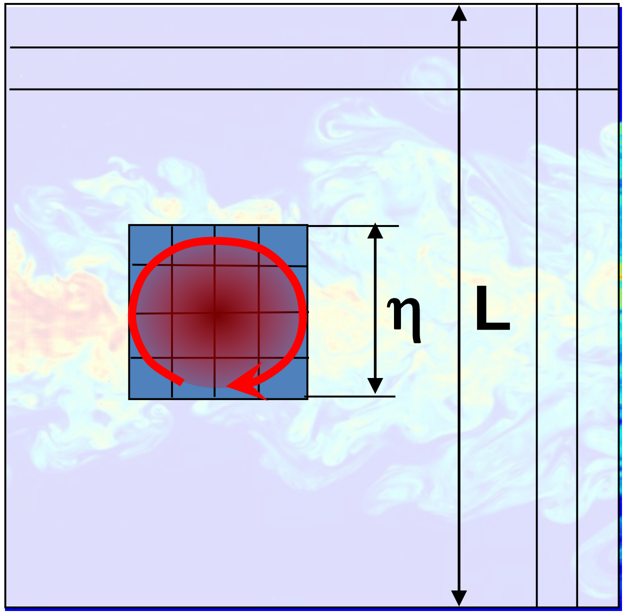
Richard Feynman

Werner Heisenberg



Albert Einstein

DNS Direct Numerical Simulation



In order to resolve all details of turbulent structures it is necessary to use mesh with grid size less than the size of the smallest (Kolmogorov) eddies. N-grid points in one direction should be

$$N > \frac{L}{\eta} \qquad \varepsilon \sim \frac{u^3}{L} \text{ (based upon dimensional ground)}$$

$$N^3 > \frac{L^3}{\eta^3} = \frac{L^3 \varepsilon^{3/4}}{\nu^{9/4}} = \frac{L^3 u^{9/4}}{\nu^{9/4} L^{3/4}} = \left(\frac{Lu}{\nu}\right)^{9/4} = \mathrm{Re}_\tau^{9/4}$$

Velocity scale u in previous expression is related to magnitude of turbulent fluctuations (rms of u', or $\sqrt{k}$). The Re_τ related to the velocity fluctuation is called turbulent Reynolds number.

$\mathrm{Re} = \frac{\overline{u}L}{\nu}$	$\mathrm{Re}_\tau = \frac{uL}{\nu}$	No.of grid points in DNS	No.of time steps
12300	380	6.7 M	32 k
30800	800	40 M	47 k
61600	1450	150 M	63 k
230000	4650	2100 M	114 k

$$N_{DNS} \sim \mathrm{Re}_\tau^{9/4}$$

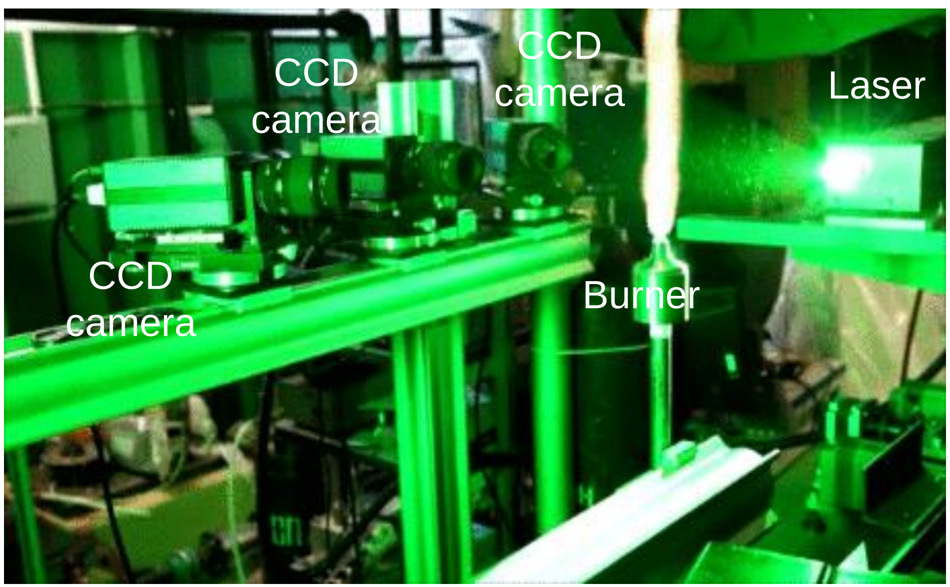
$$N_{time\_steps} \sim \mathrm{Re}_\tau^{3/4}$$

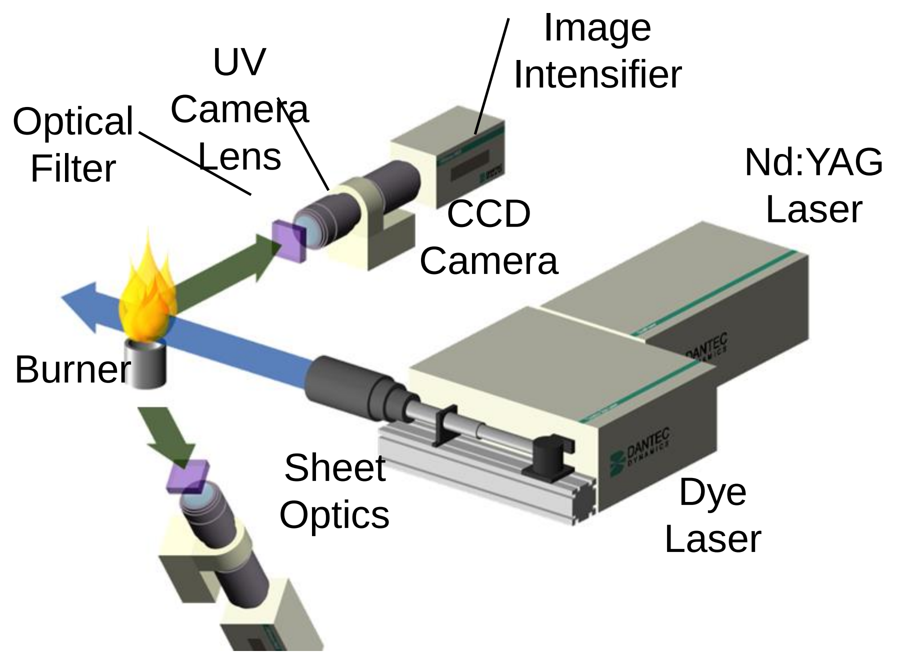
Remark: Re~10^6 or 10^7 at flow around a car or flow around wings

Full time of calculation > 300 years

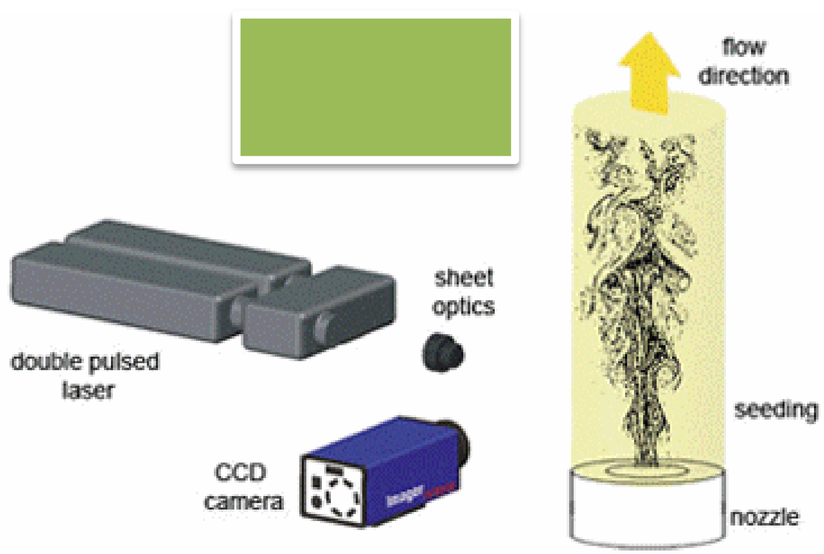
Optical diagnostic of flows

Combined Particle Image Velocimetry, Laser Induced Fluorescence, Raman Spectroscopy measuring system





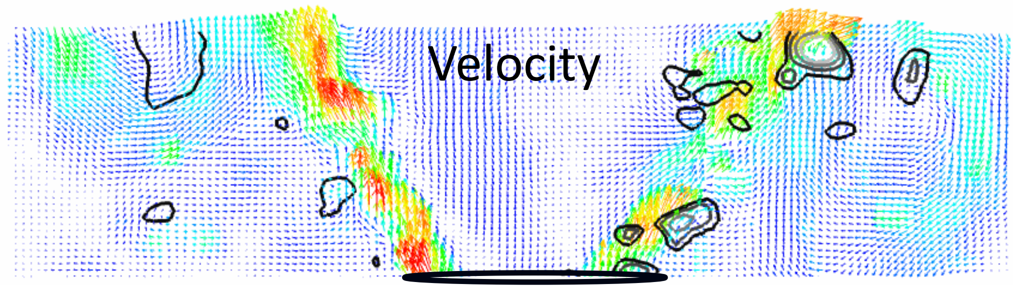
PIV and LIF techniques



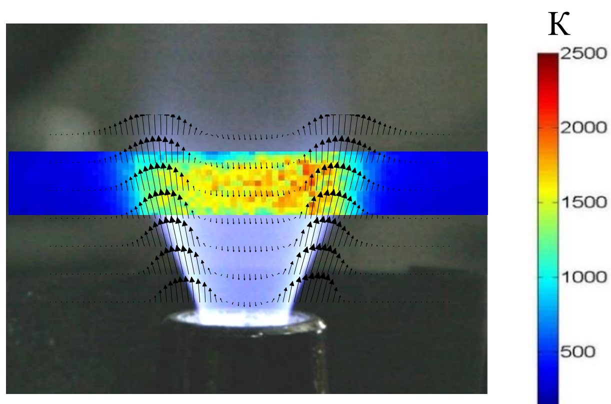
<u>Particle Image Velocimetry (PIV)</u> measures whole velocity fields by taking two images shortly after each other and calculating the distance individual particles travelled within this time. From the known time difference and the measured displacement the velocity is calculated.

Optical diagnostic of flows

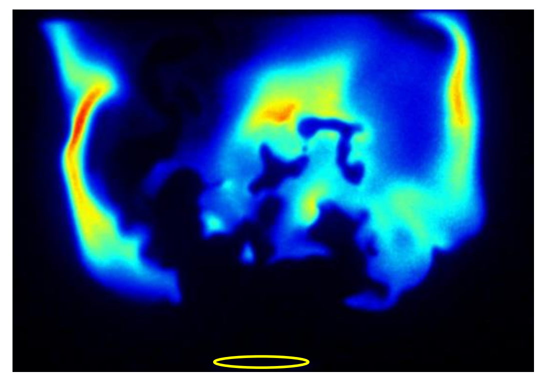
Velocity, temperature, concentration, radicals can be measured



Concentration



Temperature



Radicals CH*, OH*