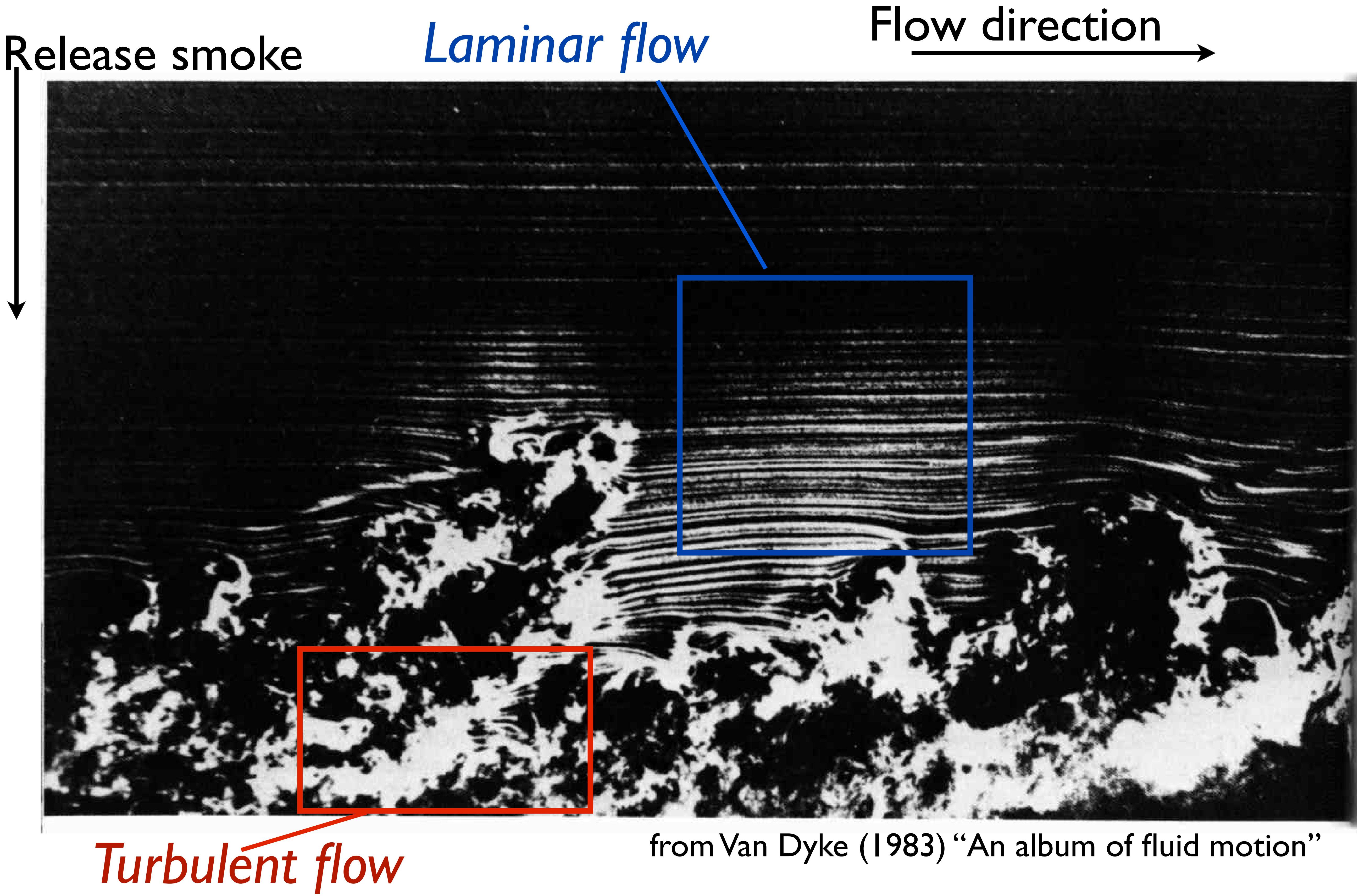
Outline

1. Summary: Turbulent drag
2. Example: Alaska pipeline
3. "Introduction" to turbulent flow
4. Drag reduction in turbulent flow of dilute polymer solutions



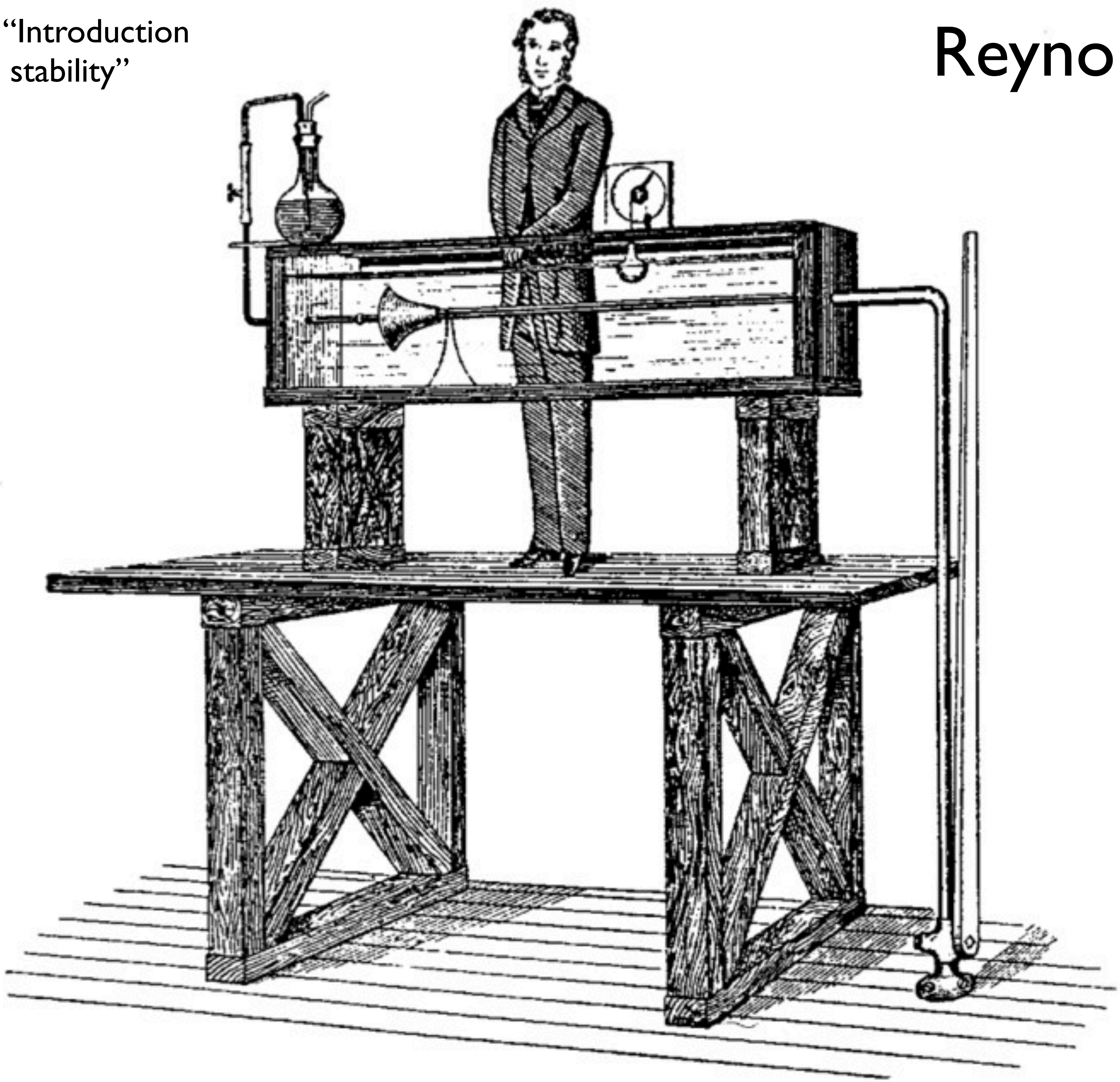
from Van Dyke (1983) "An album of fluid motion"

Turbulent boundary layer developed in a flat plate

Reynolds “famous”experiment

Pictures from Drazin “Introduction to hydrodynamic stability”

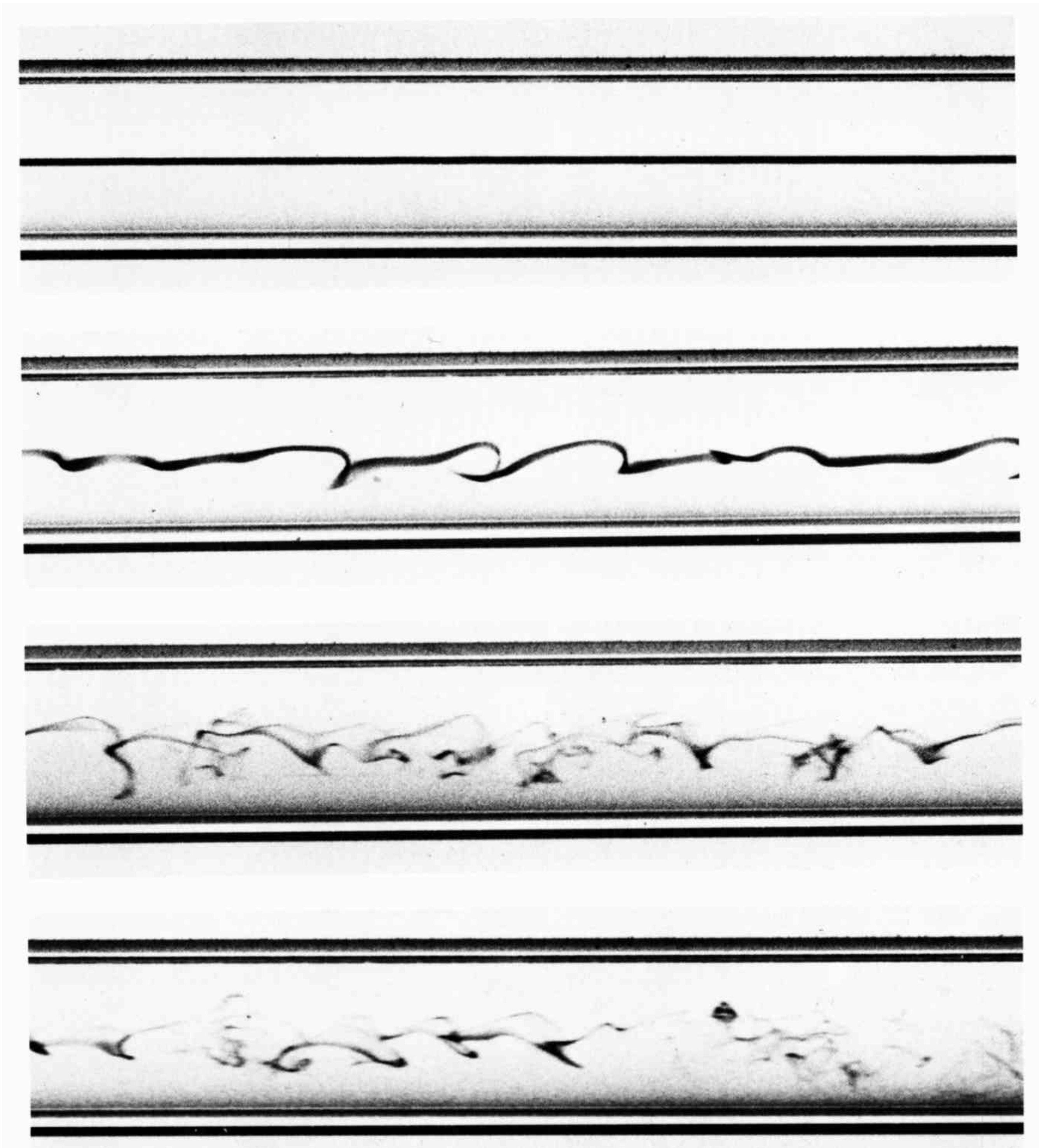
Reynolds (1883)



The original apparatus survives in Mancester in England.

Repetition of Reynolds' experiment

$Re \uparrow$



From "An album of fluid motion" by Van Dyke (1982)

By N. H. Johannesen
and C. Lowe
@ University of Manchester
(1993)

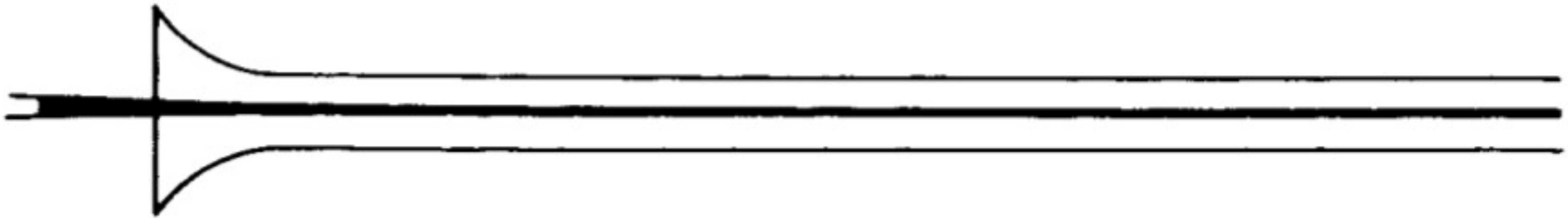
Modern traffic in the streets of Manchester made the critical Reynolds number lower than the value 13,000 found by Reynolds

$$Re_{c,1993} \sim 11,700 < Re_{c,1983} \sim 13,000$$

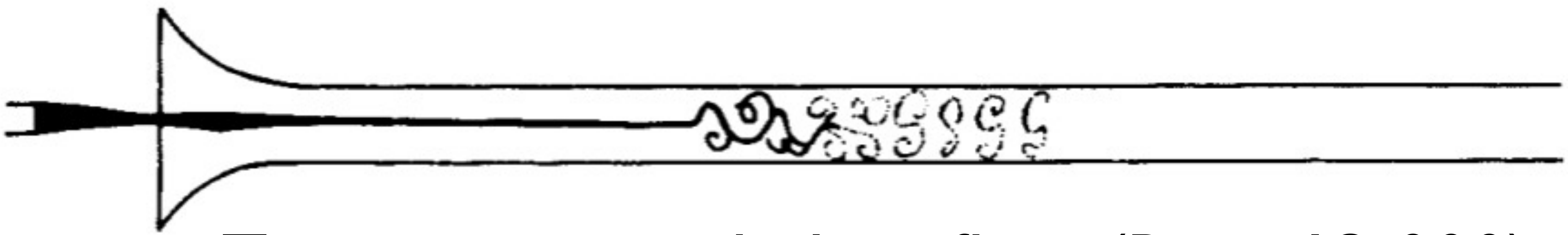
Turbulent phenomena are sensitive to disturbances around flows
⇒Closely related to stability.

Progress from laminar to turbulent flow

Sketches by Reynolds (1883)



Laminar flow (Low Reynolds number)



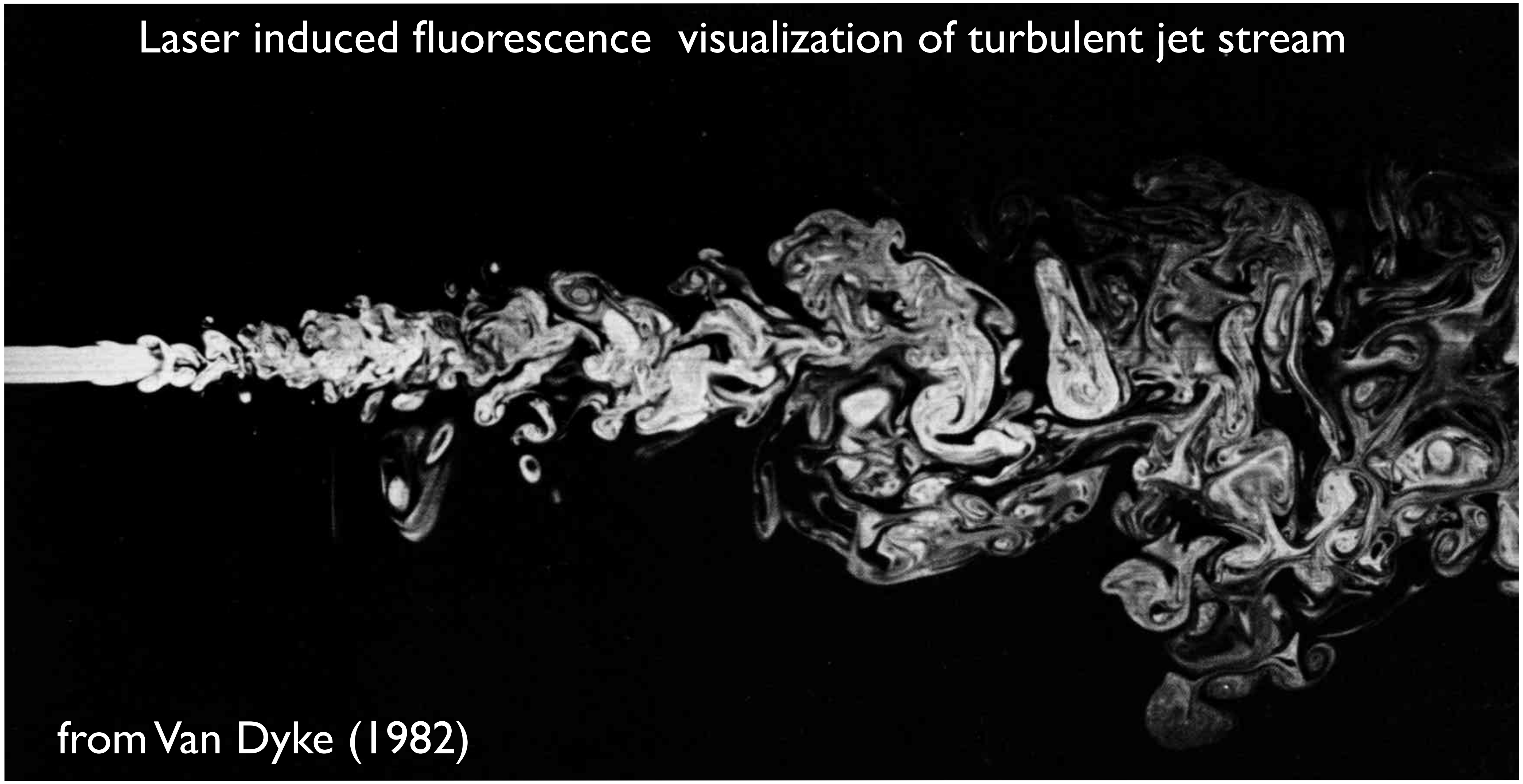
Transition to turbulent flow (Re > 13 000)

This "disordered" motion of fluid has a universal character : "cascading" eddy structure .

Cascading eddy structures

Big whorls have ***little*** whorls
Which feed on their velocity;
And ***little*** whorls have ***lesser*** whorls,
And so on to **viscosity**
(in the molecular sense)

From page 66 of Richardson (1922)

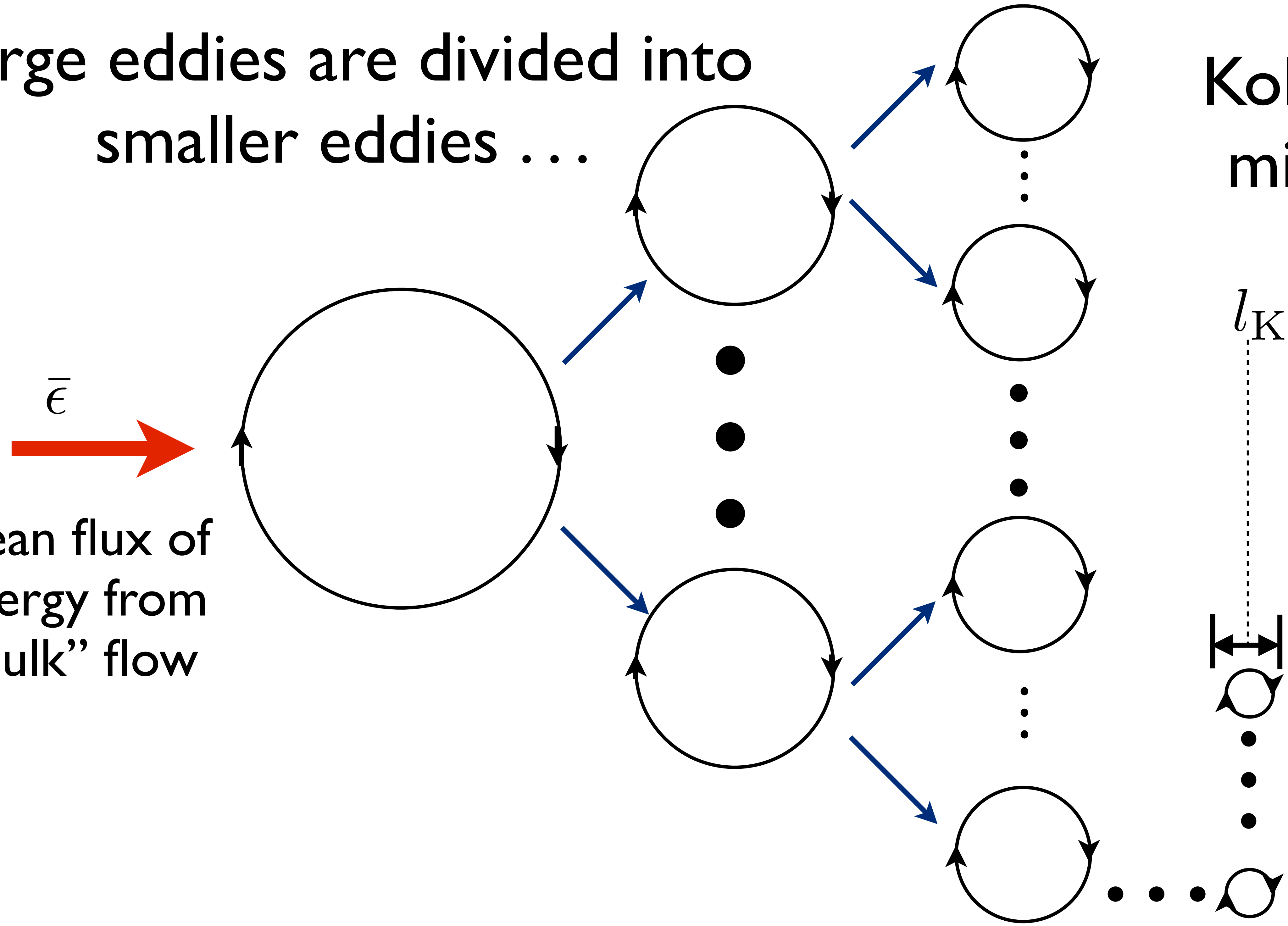


Laser induced fluorescence visualization of turbulent jet stream

from Van Dyke (1982)

“Theory of locally isotropic turbulence “ by K. N. Kolmogorov (1941)

Large eddies are divided into smaller eddies …



Kolmogorov microscale

$$l_{\mathrm{K}} = \left(\frac{\nu^3}{\bar{\epsilon}}\right)^{1/4}$$

Mean flux of energy from “bulk” flow

No more “eddy” or become “heat”

Below size of l_k, the viscosity of the fluid can effectively dissipate kinetic energy into internal energy …

Turbulent drag reduction

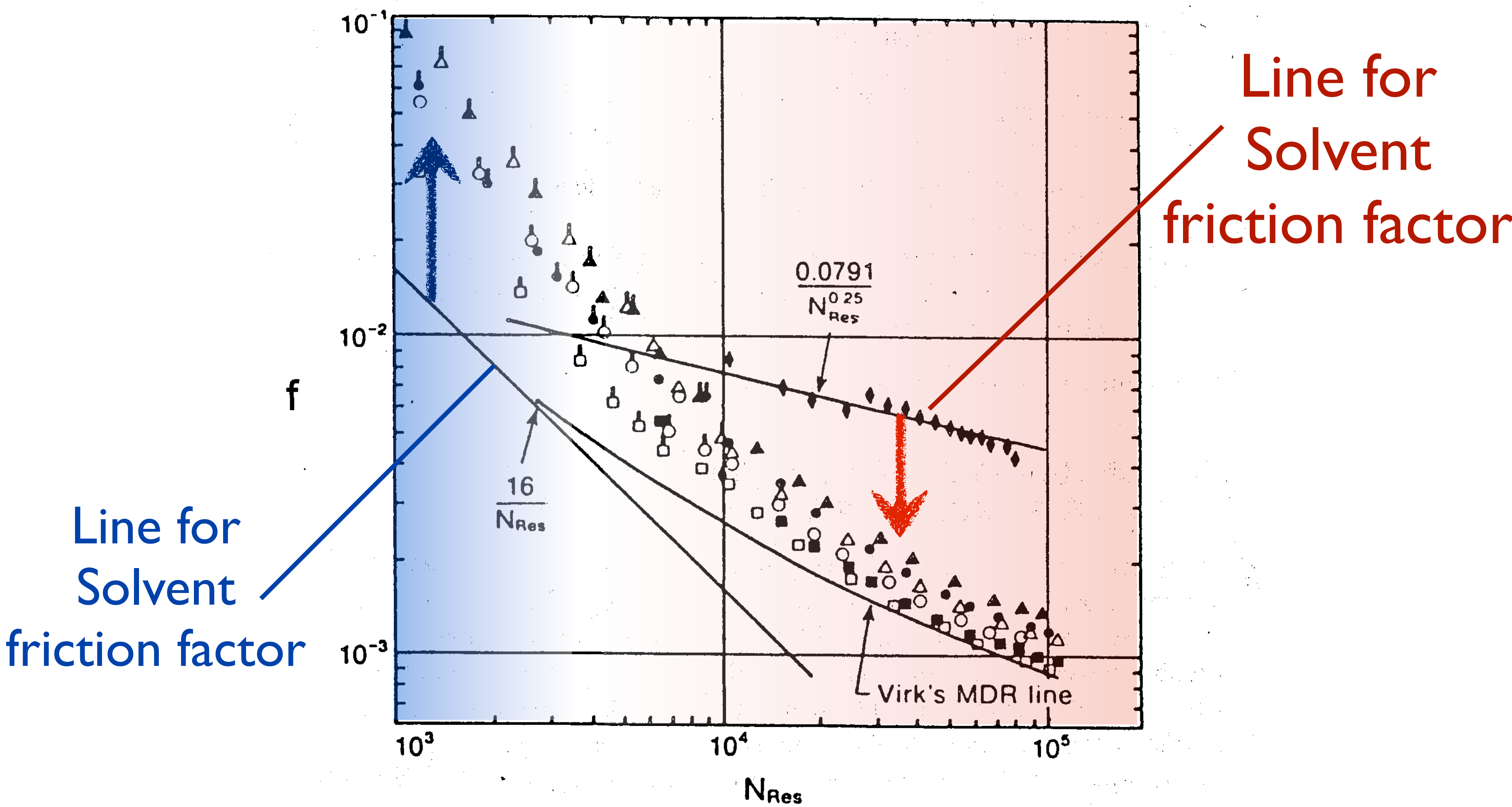
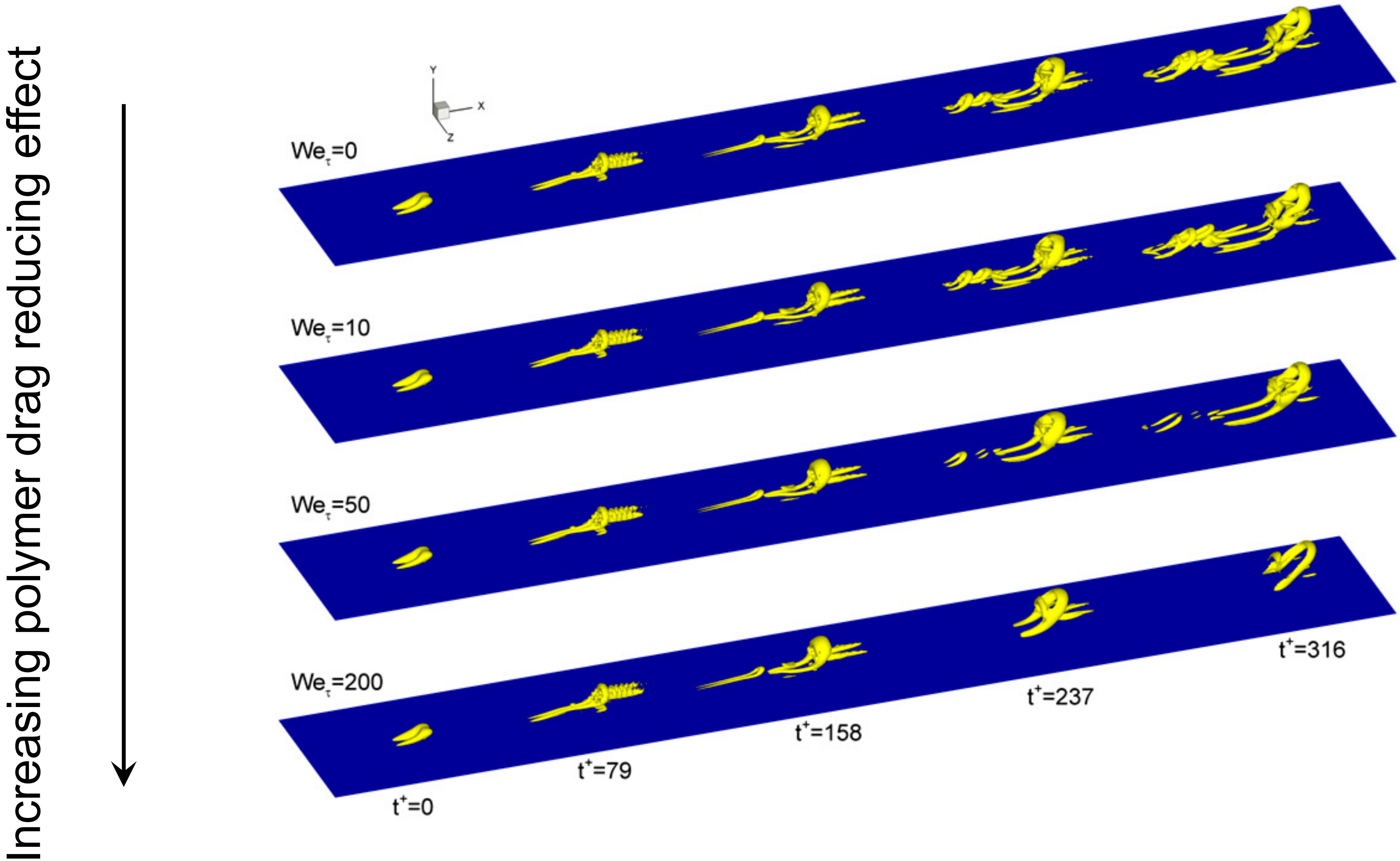


FIGURE 6-5 Drag reduction data for polyacrylamide solutions (Darby and Pivsa-Art, 1991). (N_{Res} is the Reynolds number based on solvent properties.)

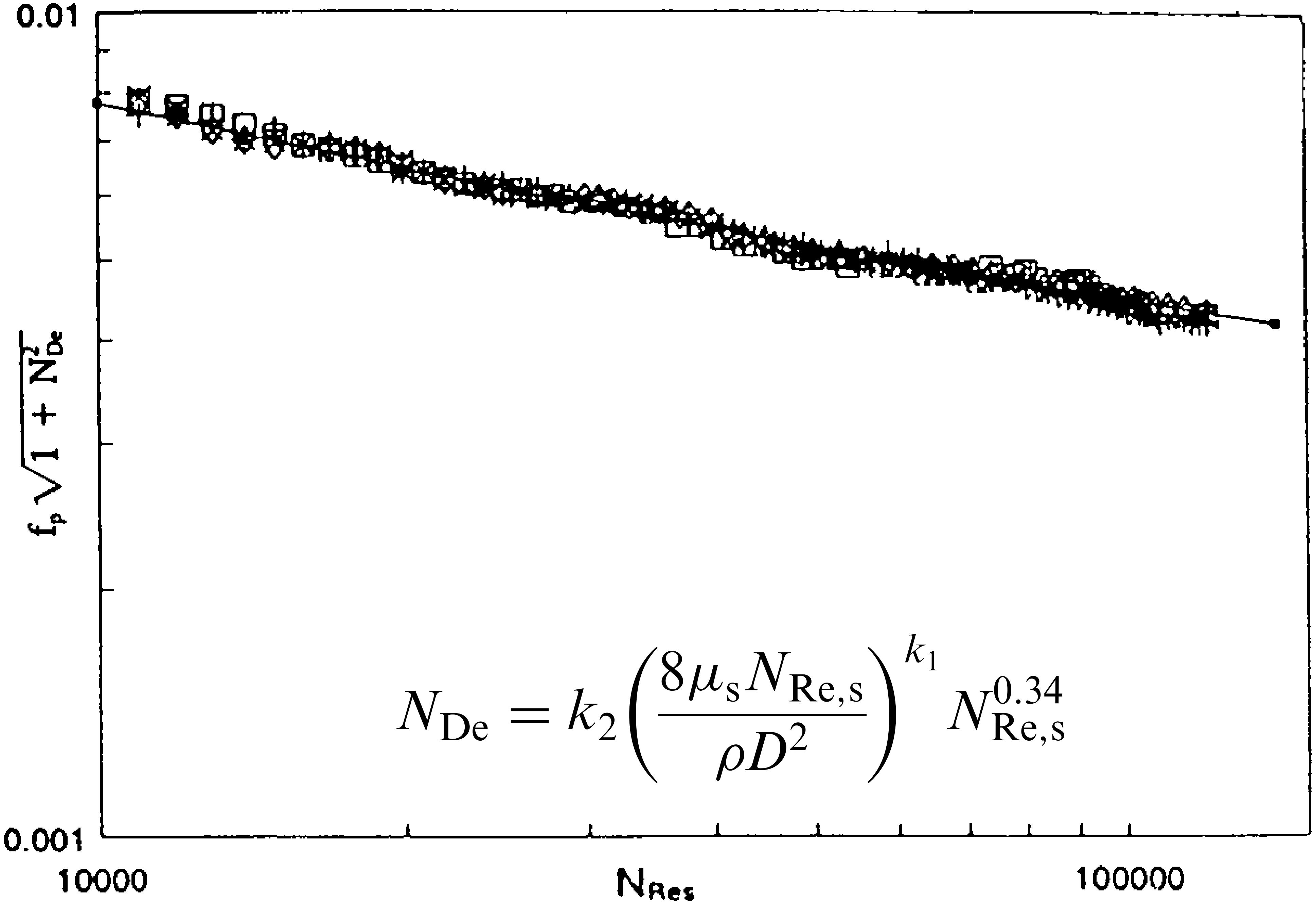
From Darby (Chemical Engineering Fluid Mechanics)

Simulations with polymer solutions (Sureshkumar)



Size of eddy structures (hairpin vortices) decreases as elastic effect increases . . .

Turbulent drag reduction



$$N_{\mathrm{De}} = k_2\left(\frac{8\mu_{\mathrm{s}} N_{\mathrm{Re,s}}}{\rho D^2}\right)^{k_1} N_{\mathrm{Re,s}}^{0.34}$$

FIGURE 6-6 Drag reduction data replotted in terms of generalized friction factor. (From Darby and Pivsa-Art, 1991.)

$$N_{\mathrm{De}} = k_2 \left(\frac{8 \mu_{\mathrm{s}} N_{\mathrm{Re,s}}}{\rho D^2} \right)^{k_1} N_{\mathrm{Re,s}}^{0.34}$$

TABLE 6-2 Parameters for Eqn (6-90) for Various Polymer Solutions

Polymer	Conc. (mg/kg)	Diam. (cm)	k_1	k_2 (s^{k_1}) units	Reference
Guar gum (Jaguar A-20-D)	20	1.27	0.05	0.009	Wang (1972)
	50		0.06	0.014	
	200		0.07	0.022	
	500		0.10	0.029	
	1000		0.16	0.028	
Guar gum	30		0.05	0.008	White (1966)
	60		0.06	0.010	
	240		0.08	0.016	
	480		0.11	0.018	
Polyacrylamide, fresh (Separan AP-30)	100	0.176 to 1.021	0.093	0.0342	Darby (1991)
	250		0.095	0.0293	
	500		0.105	0.0244	
Polyacrylamide, degraded	100		0.088	0.0431	
	250		0.095	0.0360	
	500		0.103	0.0280	
(AP-273)	10	1.090	0.12	0.0420	White (1975)
(PAM E198)	10	0.945	0.21	0.0074	Virk (1970)
	280			0.0078	
	300	2.0 & 3.0	0.40	0.0050	
(PAA)	700		0.53	0.0049	Hoffmann (1975)
	125	0.69	0.47	0.00037	
(ET-597)	250	1.1, & 2.05	0.39	0.0013	Astarita (1969)
	500		0.30	0.0061	
Hydroxyethyl cellulose (OP-100M)	100	2.54	0.10	0.0074	Wang (1972)
	200		0.16	0.0072	
	500		0.24	0.0068	
	1000		0.35	0.0063	
(HEC)	2860	4.8, 1.1 & 2.05	0.02	0.0310	Savins (1969)
Polyethylene oxide (WSR 301)	10	5.08	0.22	0.017	Goren (1967)
	20		0.21	0.016	
	50		0.19	0.014	
(W205)	10	0.945	0.31	0.0022	Virk (1970)
	105		0.26	0.0080	
Xanthan gum (Rhodopol 23)	1000	0.52	0.02	0.046	Bewersdorff (1988)

Source: Darby and Pivsa-Art(1991).

Turbulent drag reduction

$$f = \frac{0.41}{[\ln(N_{Res}/7)]^2}\left(\frac{1}{(1+N_{De}^2)^{1/2}}\right)$$

Approximate expression for Fanning factor for Newtonian fluids in smooth pipes (Colebrook equation)

Reduction due to the Drag Reducing Agent (polymer, surfactant, etc.)

N_{De} Typically 1 to 5, can be up to 10

N_{De}	reduction
1	29.3%
5	80.4%
10	90.1%