



Master 1 de Physique Appliquée et Mécanique

2012-2013

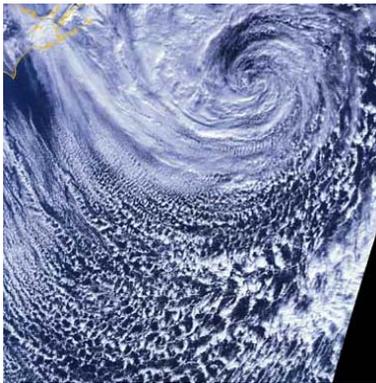
Turbulence

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Plan du cours

www.fast.u-psud.fr/~moisy/cours_turb.html

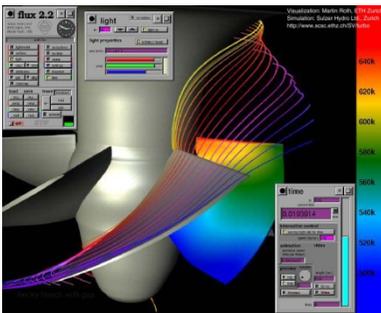


Écoulements géophysiques



Dispersion polluant

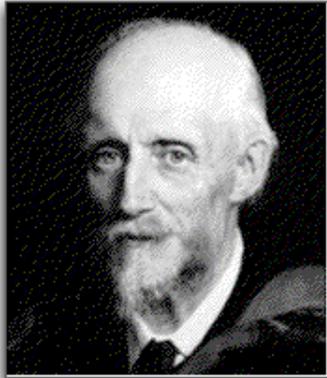
1. Phénoménologie :
laminaire vs turbulent
2. Approche statistique :
Equations de Reynolds
4. Turbulence de paroi
5. Introduction à la
turbulence homogène



Simulation écoulements industriels



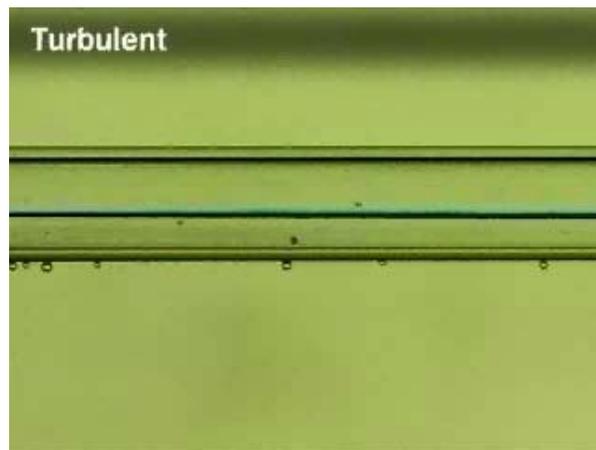
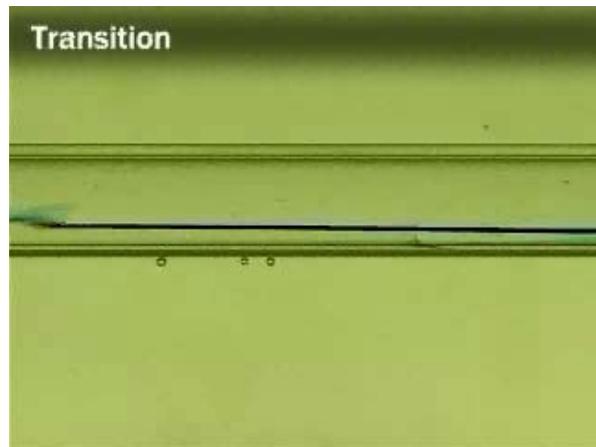
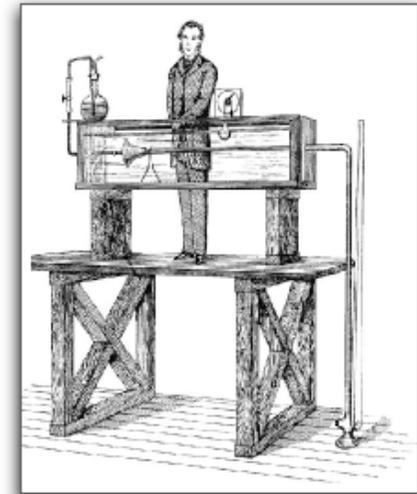
Sillages turbulents



Osborne Reynolds

Ingénieur anglais (1842 - 1912)

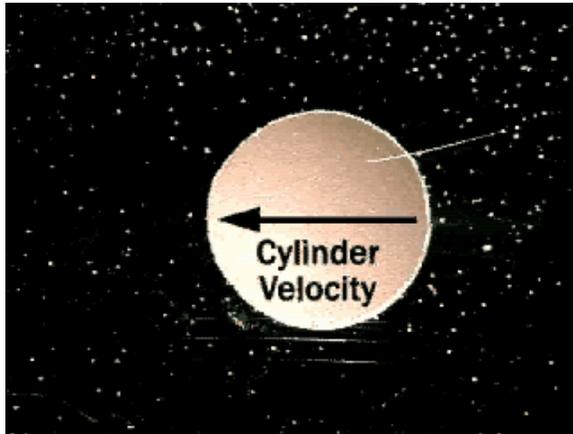
$$Re = U L / \nu$$



Nombre de Reynolds :

$$\text{inertie} / \text{viscosité} = UL / \nu$$

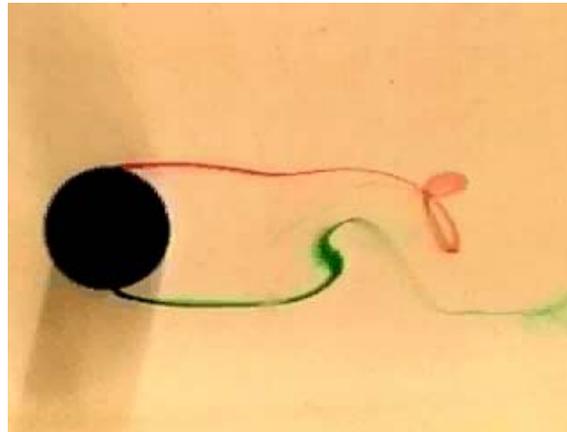
Inertie nulle



"laminaire"
($Re \ll 1$)

$$F \sim v$$

Inertie modérée



"instable"
($Re \sim 1$)
(10-1000...)

Inertie forte

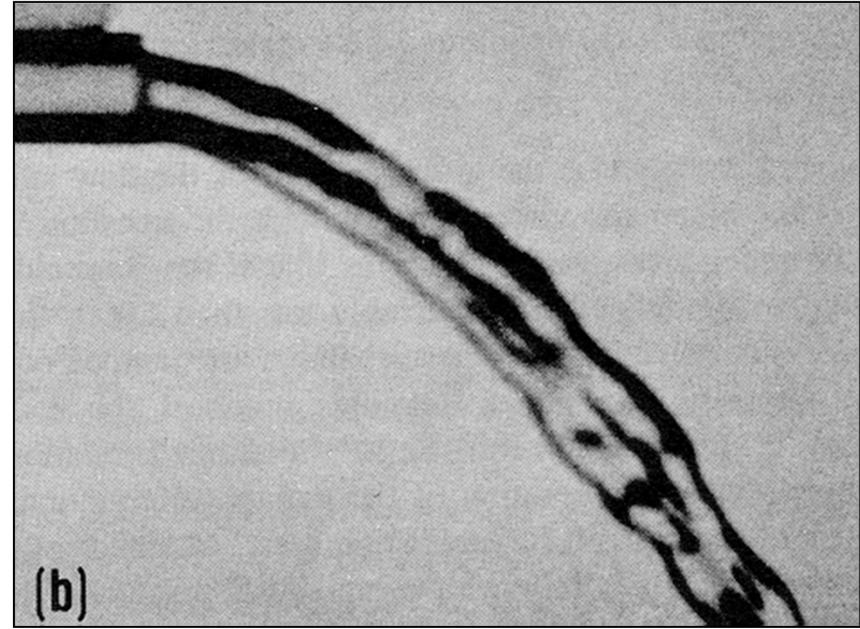
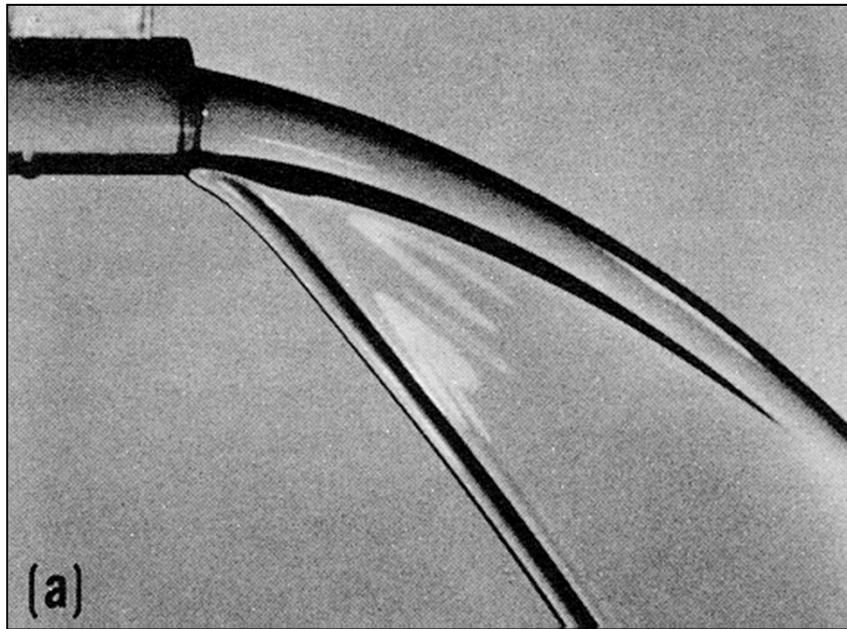


"turbulent"
($Re \gg 1$)

$$F \sim v^2$$

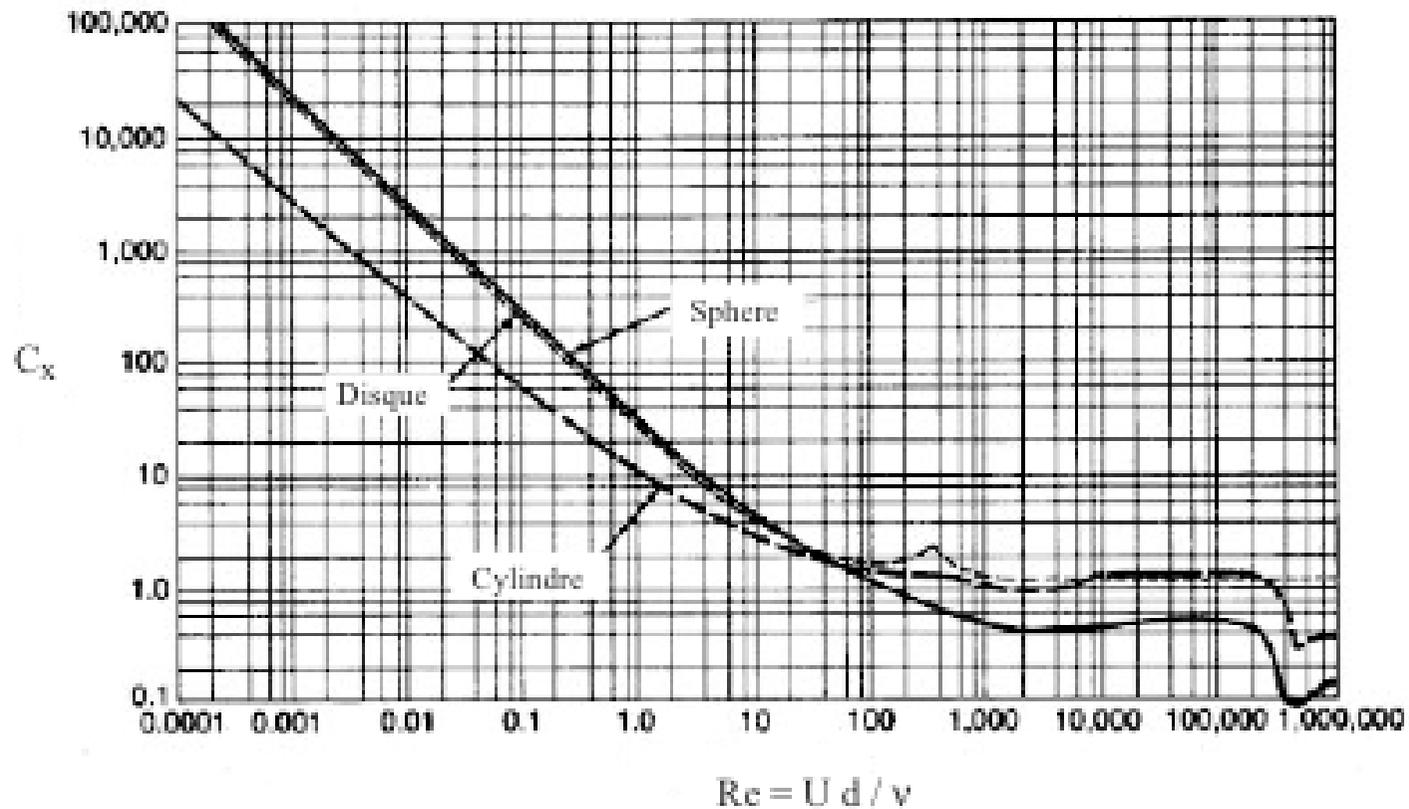
"frotte plus"

La turbulence "frotte plus" (dissipe plus)



Augmentation de la perte de charge en régime turbulent

Traînée turbulente : C_x (ou C_d)



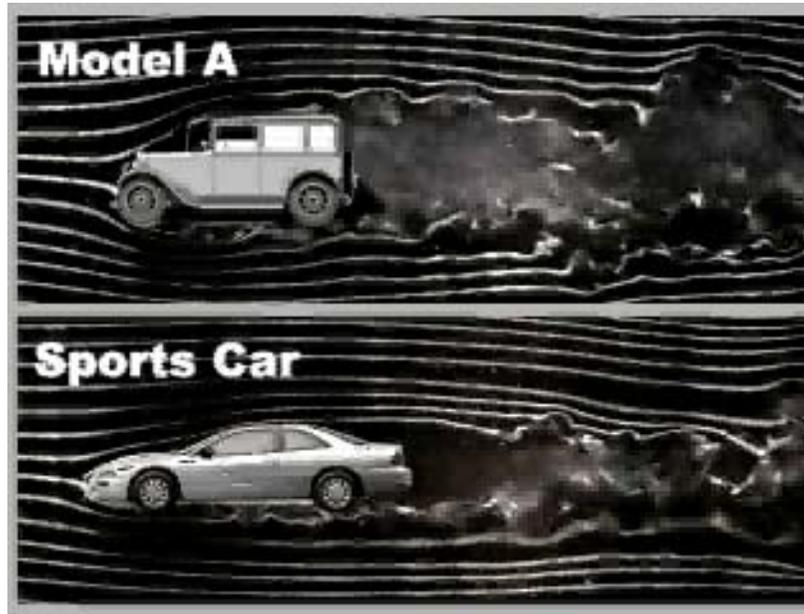
Laminaire : $C_x \sim 1/Re$

Turbulent : $C_x \sim \text{cste}$

Le nombre de Reynolds ne décrit pas tout...

$$\text{Force de traînée} = \frac{1}{2} \rho U^2 S C_x$$

$$C_x = f(\text{Re, géométrie...})$$



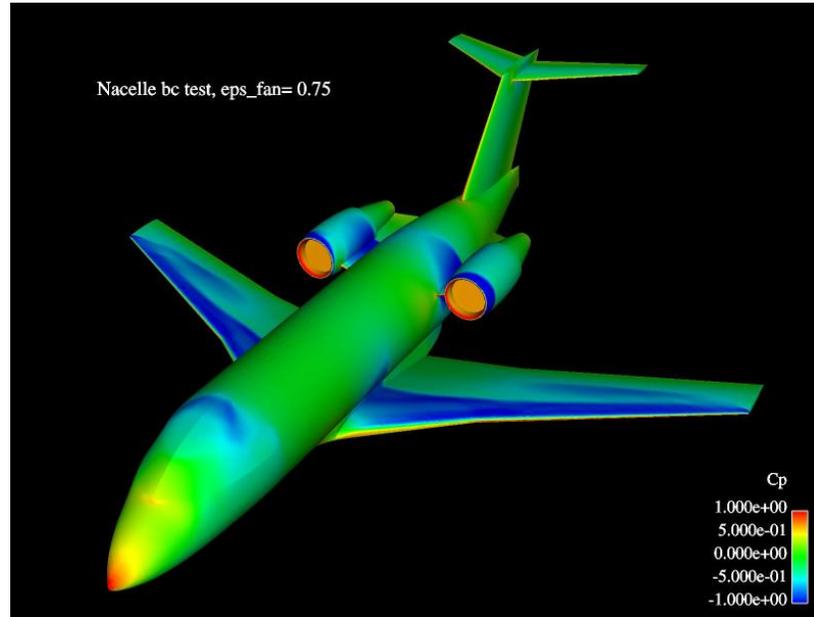
$$C_x = 0.6$$

$$C_x = 0.3$$

(Video CD-ROM MFM)

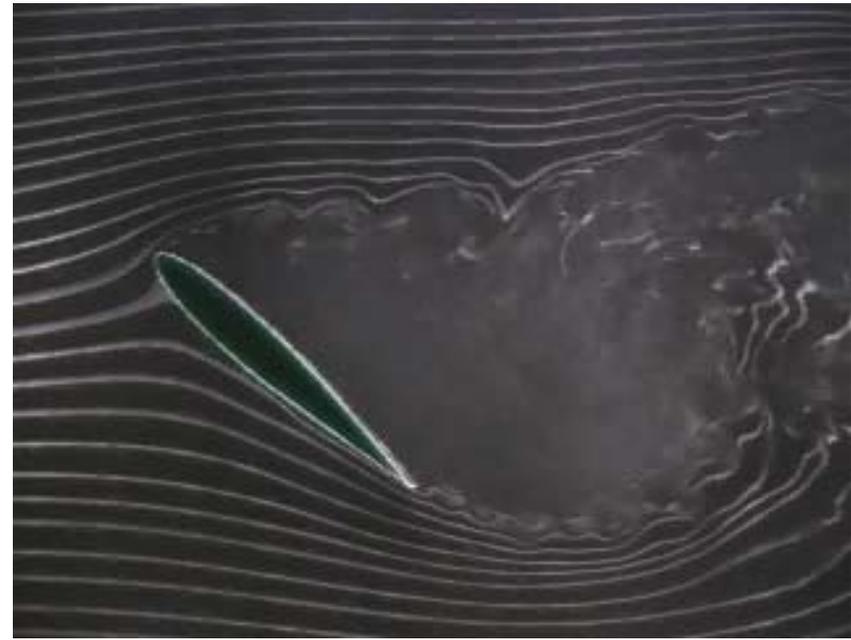
C_x d'une Citroen Cx ?

D'une formule 1 ?...



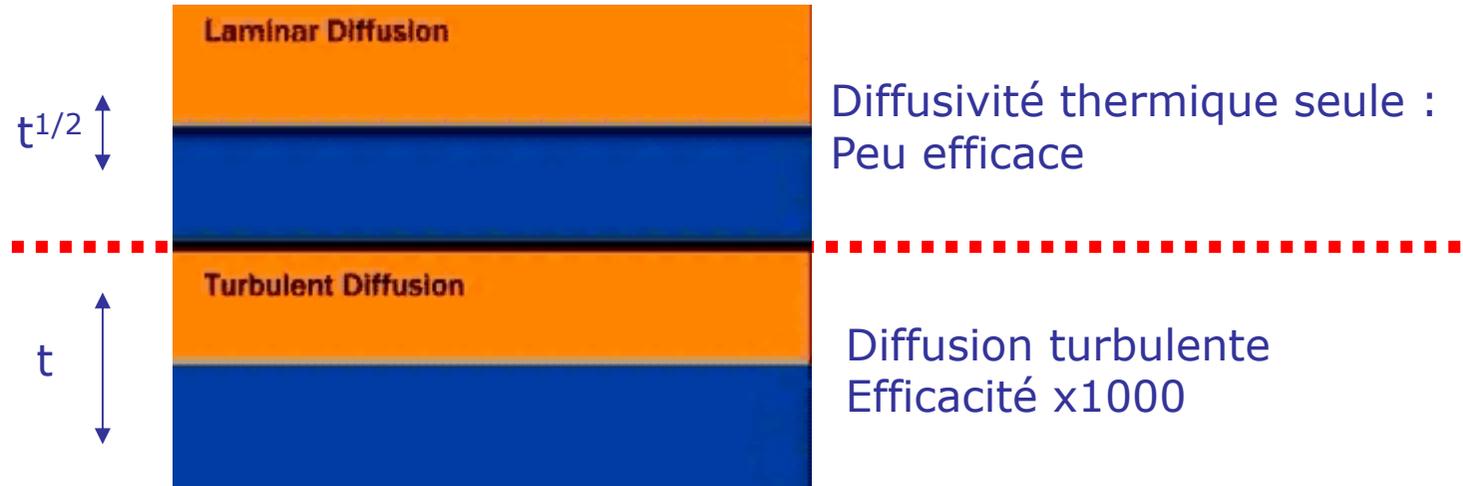
$C_x -1\% \Rightarrow$
-350\$ / Paris-NY

(Video CD-ROM MFM)





Advection turbulente : Convection, mélange...



Advection turbulente : Convection, mélange...

Avantages

et ...

Inconvénients



Transfert de chaleur
(convection naturelle / forcée)

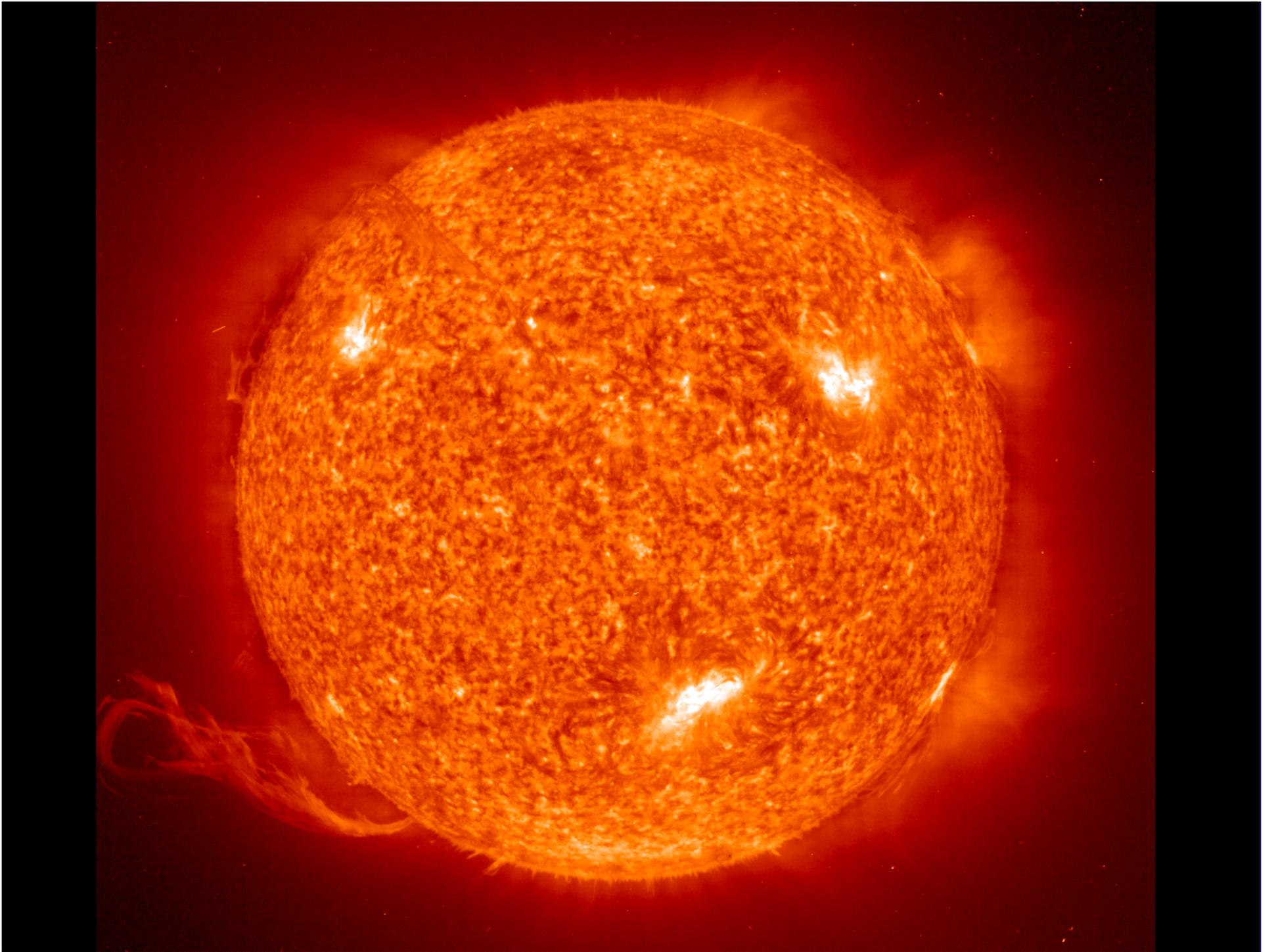


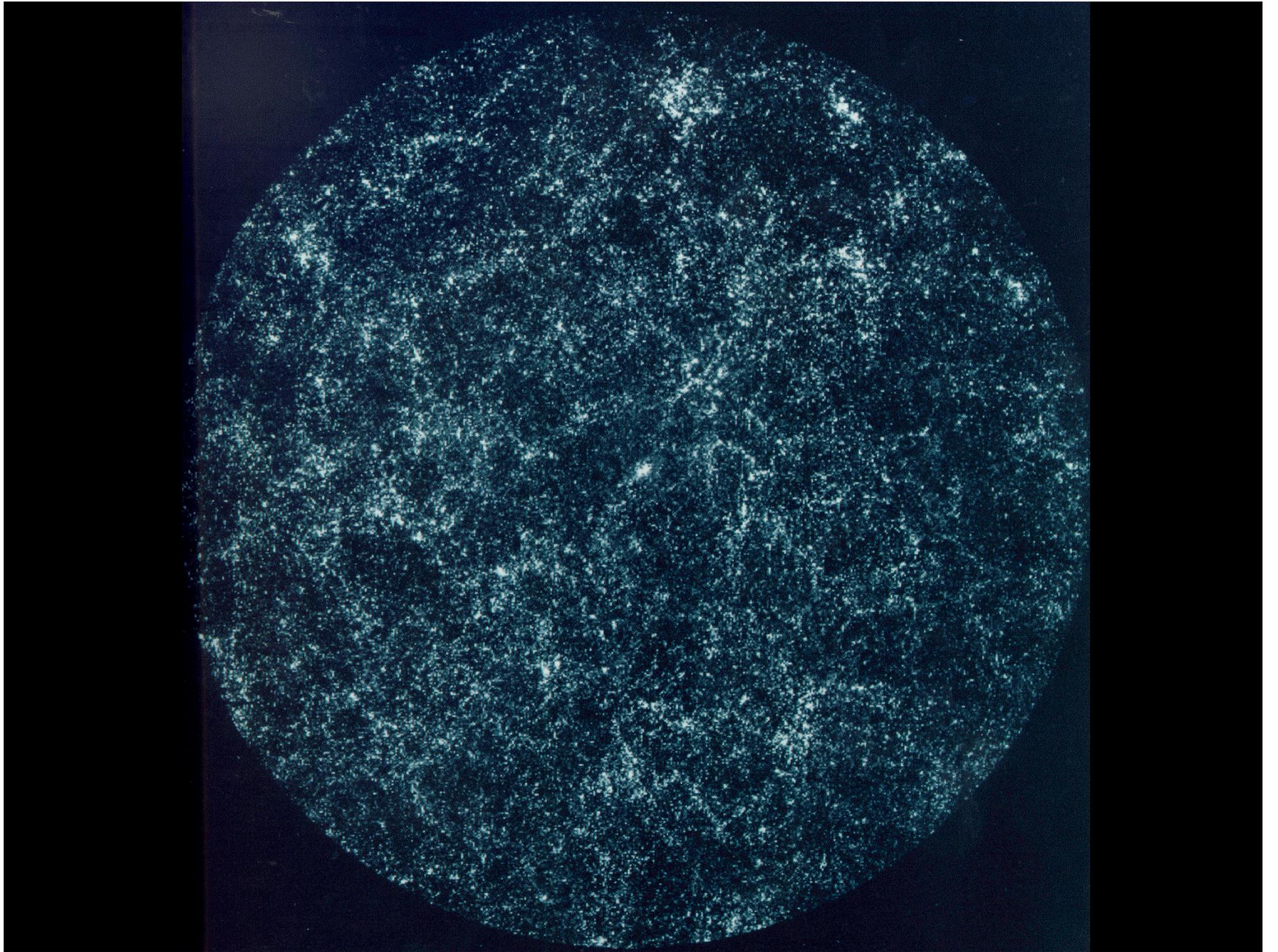
Dispersion d'un polluant



Exemples d'écoulements turbulents

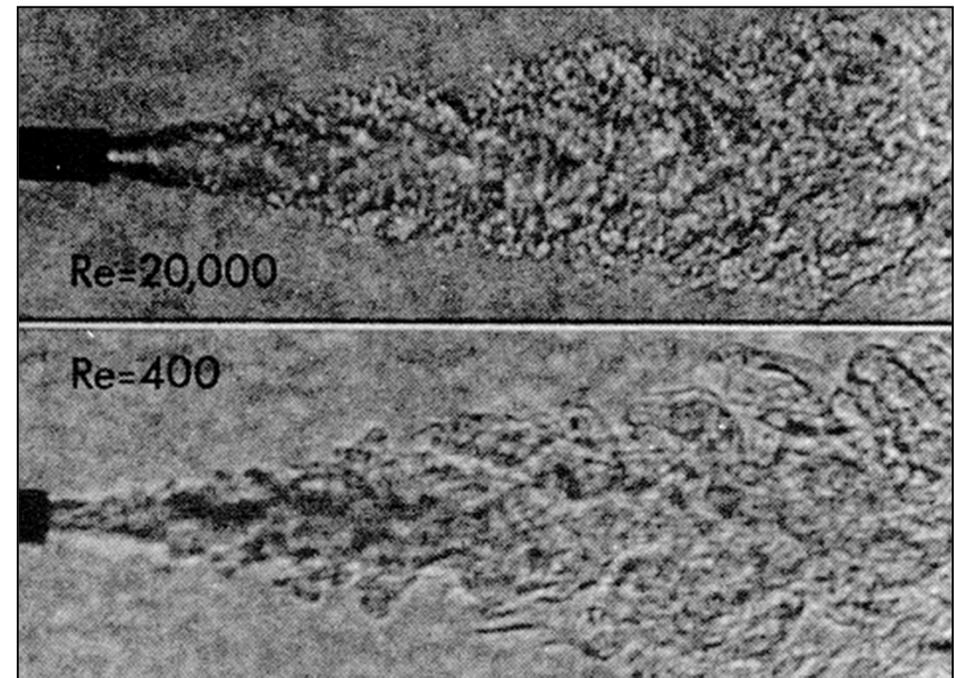
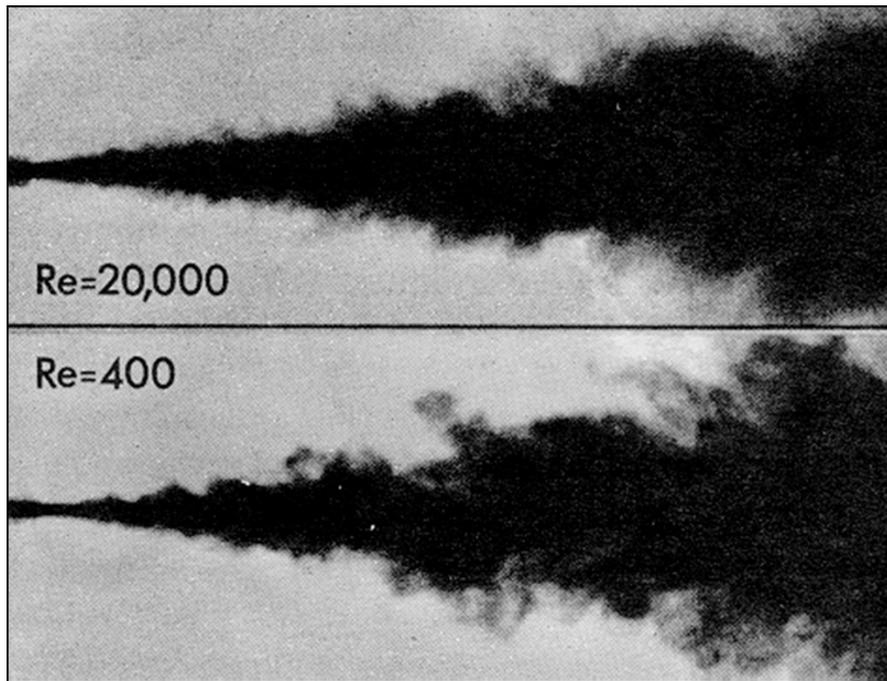






Aspects universels de la turbulence

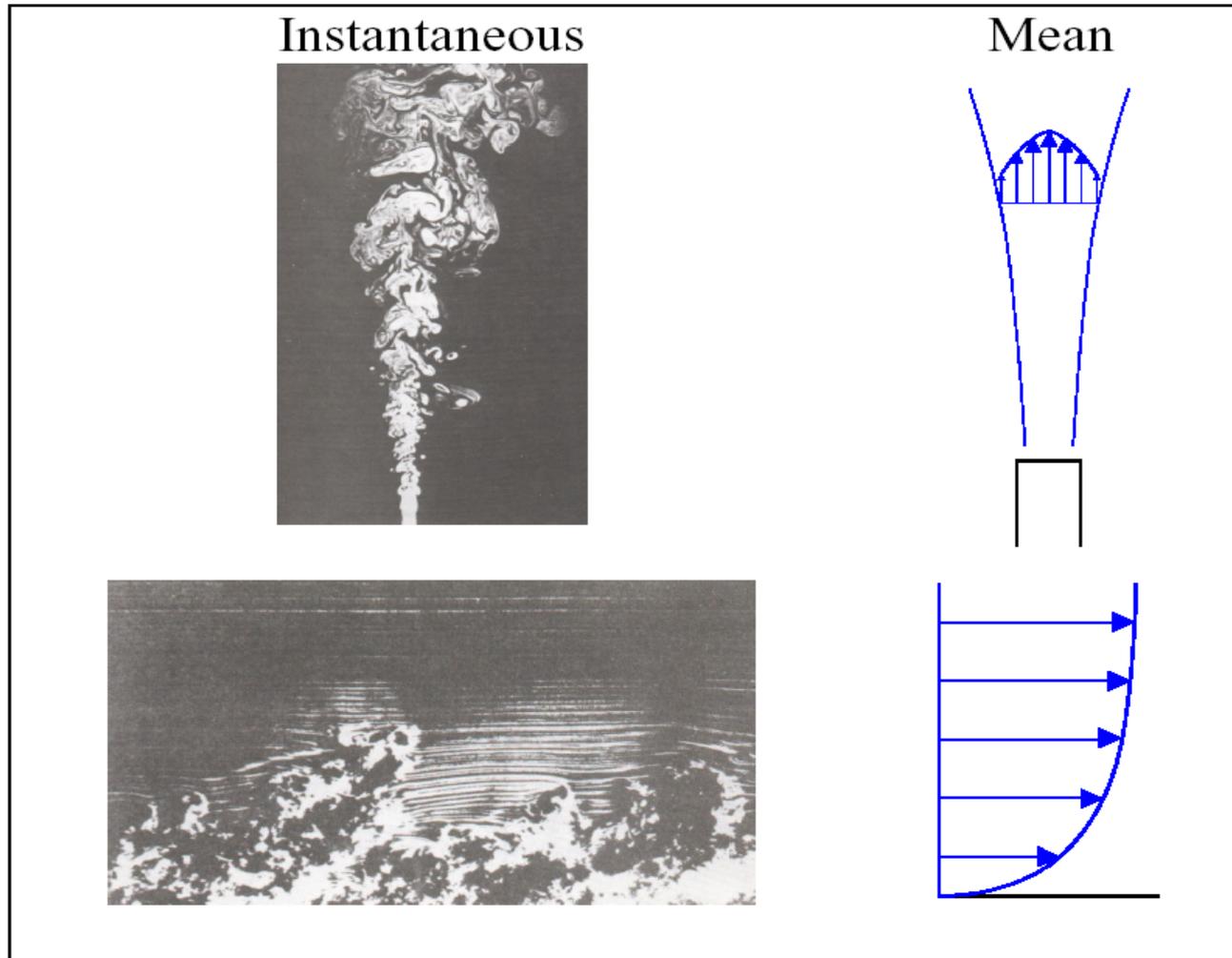
Propriétés macroscopiques indépendantes
du nombre de Reynolds



Approche statistique

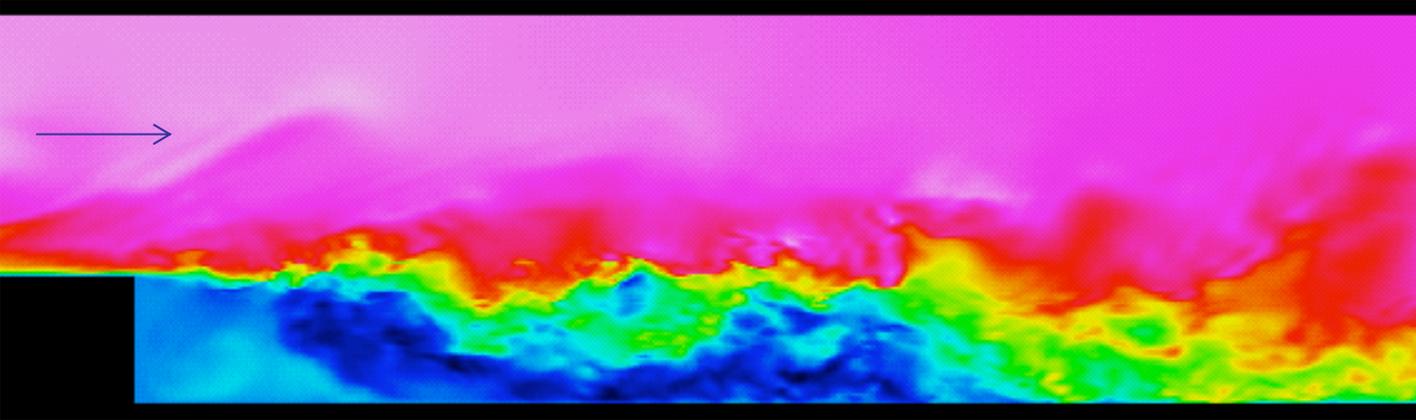
Décompositions de Reynolds

Moyenne (d'ensemble) + fluctuations

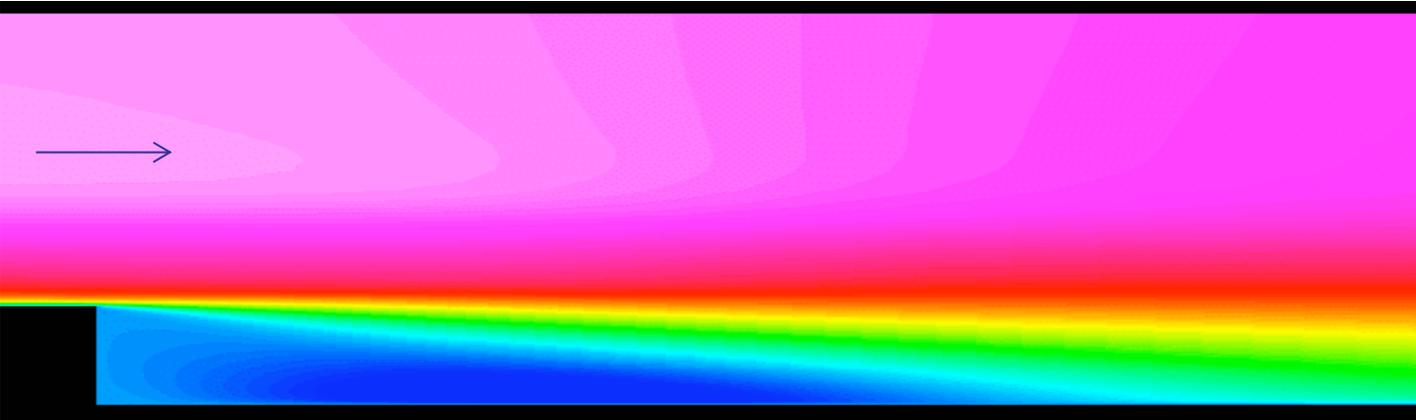


Exemple : écoulement derrière une marche

Champ instantané



Champ moyen



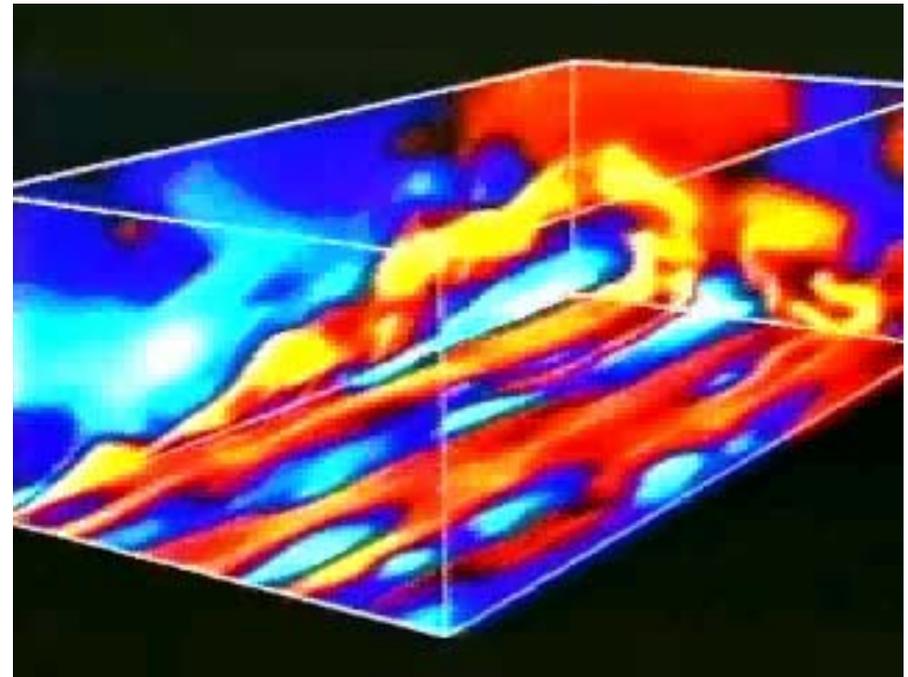
Simulation d'écoulements turbulents :

Reynolds number: 5100

Expansion ratio: 1.2

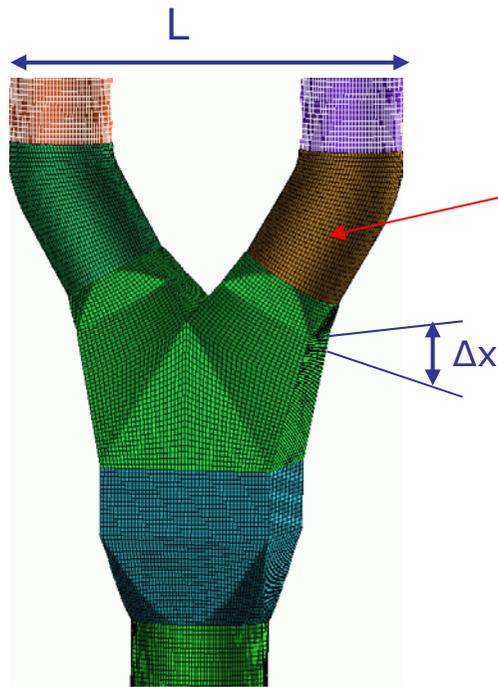
Grid: 768 x 192 x 64

**Normalization based on
step height H and
free-stream velocity at inlet**



Couche limite turbulente

Simulation d'écoulements turbulents : temps de calcul



$$u_x, u_y, u_z, \rho = f(x_i, y_i, z_i, t)$$

Résolution complète de Navier-Stokes :

Taille du maillage : $\Delta x \sim L \text{Re}^{-3/4}$

Soit $(L/\Delta x)^3 \sim \text{Re}^{9/4}$ mailles

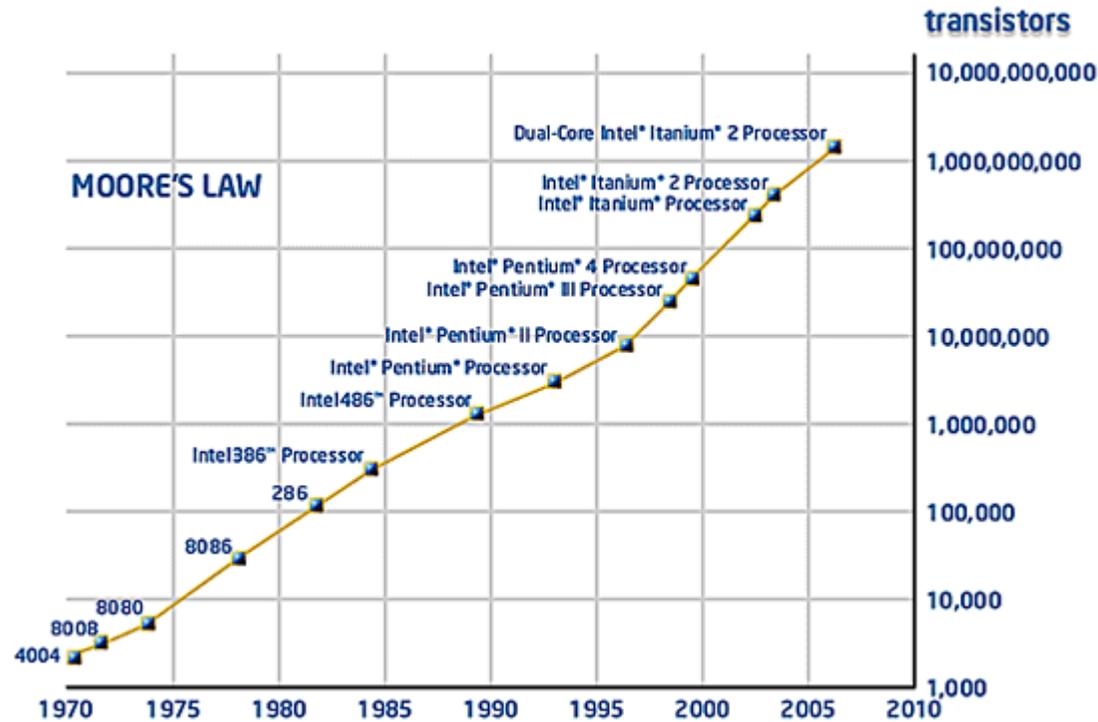
Pas de temps : $\Delta t \sim (L/U) \text{Re}^{-1/2}$

Soit Temps CPU (**float operations, flop**) $\sim \text{Re}^{11/4} \sim \text{Re}^{2.75}$

Object	Re	grid	flop	Gflop/s ³	Memory GB	GB/s
square cylinder	10^4	10^7	10^{14}	0.3	1	
golf ball	10^5	$3 \cdot 10^9$	10^{17}	300	300	100
car	10^{12}	10^{12}	10^{20}	$3 \cdot 10^5$	$1 \cdot 10^5$	$1 \cdot 10^5$

(Run 300 h)

Simulation d'écoulements turbulents : la Loi de Moore



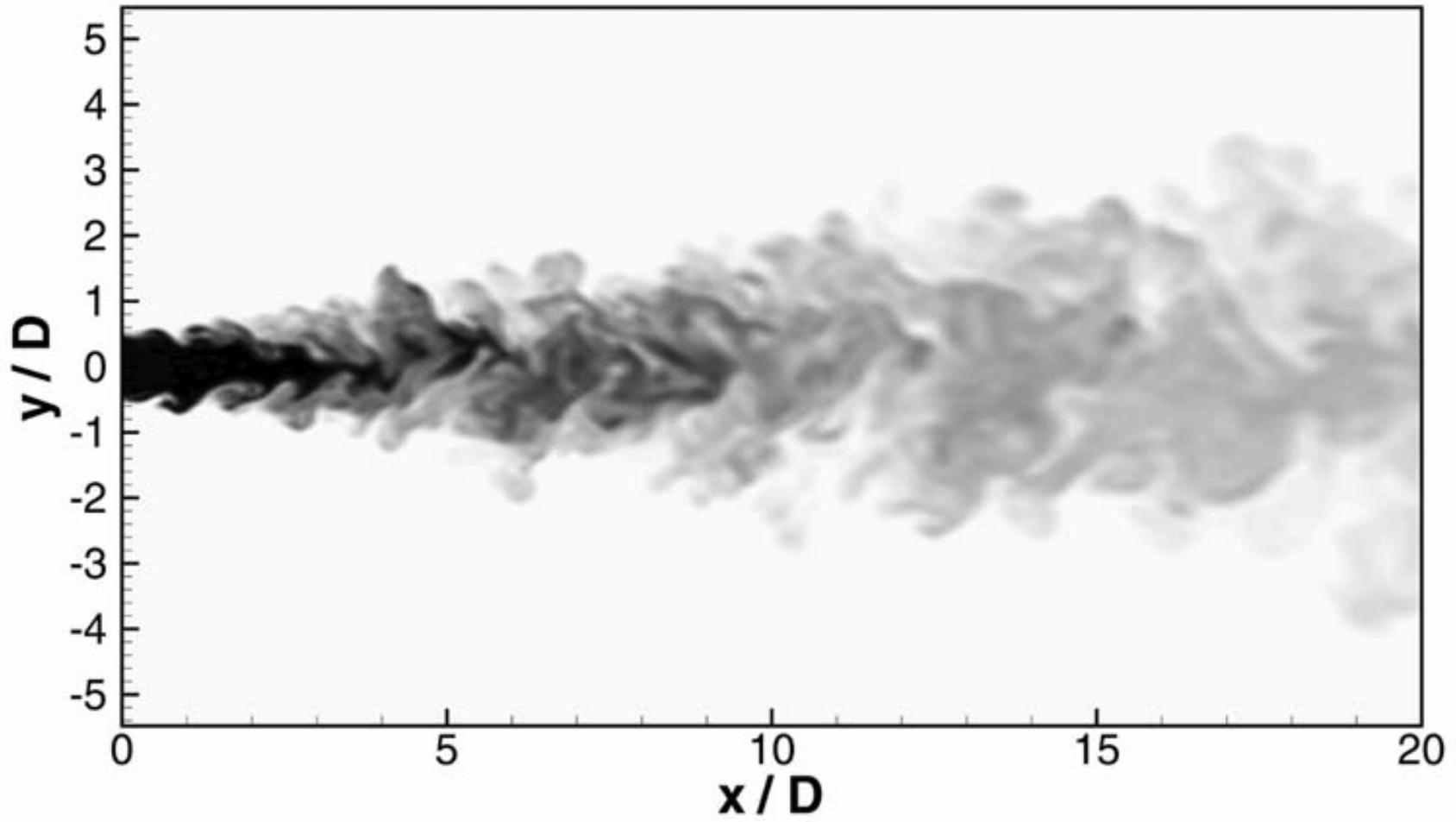
Puissance ordinateurs : $\times 2$ tous les 2 ans
($\times 1000$ tous les 20 ans)

$Re \sim 10^6$ en 2017

$Re \sim 10^9$ (Airbus) en 20xx (*calculez !*)...

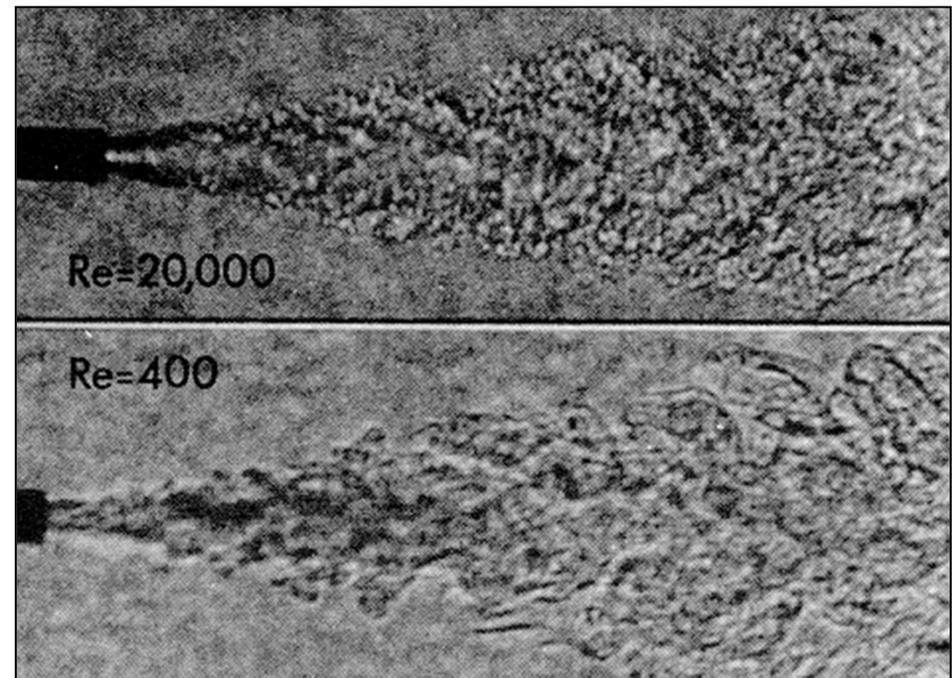
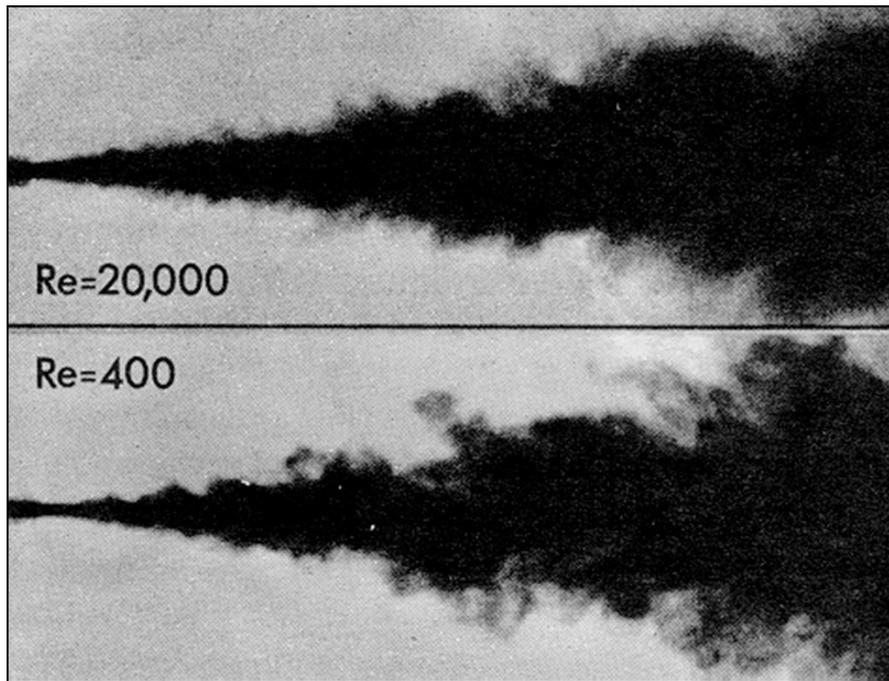
-> **Modélisation indispensable** (équations de Reynolds)

Jet turbulent



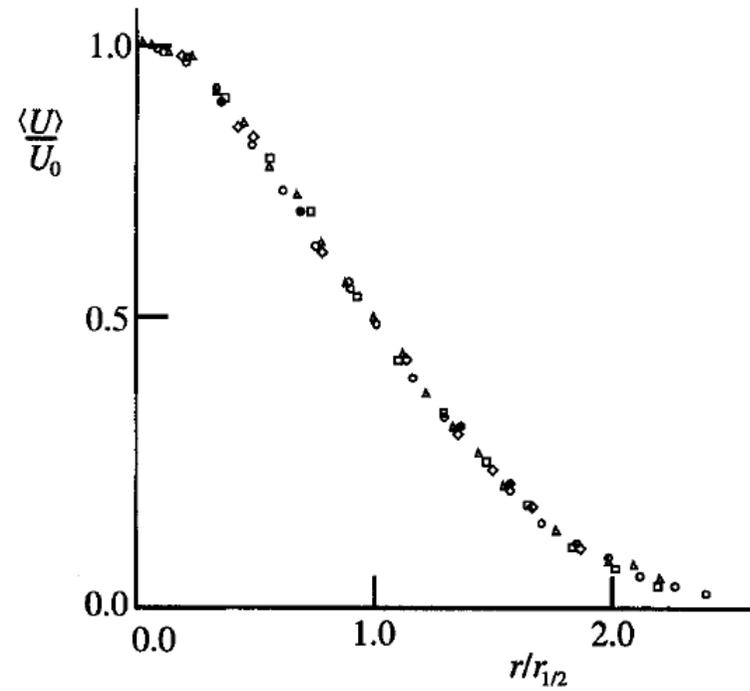
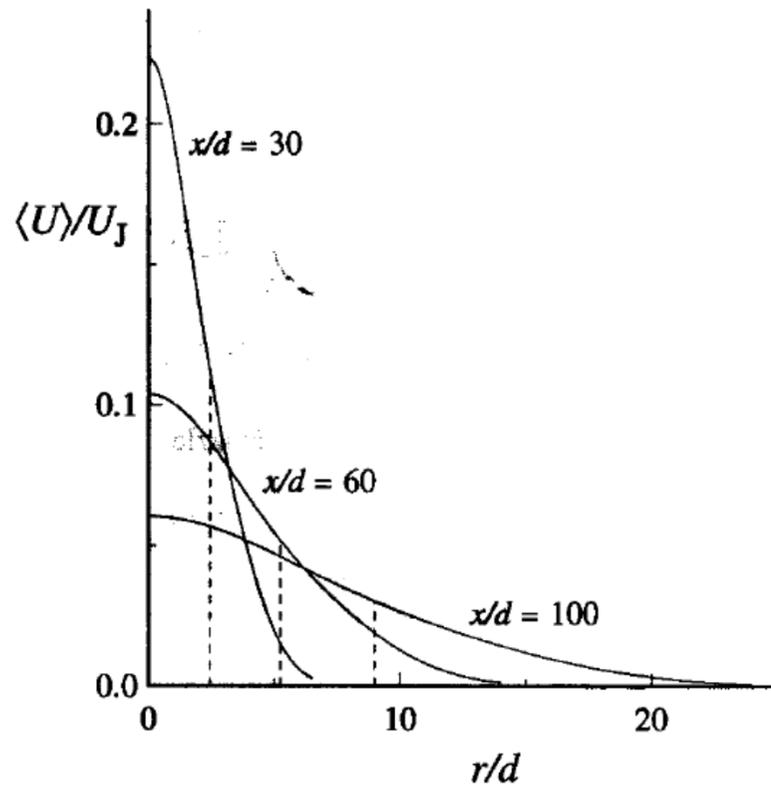
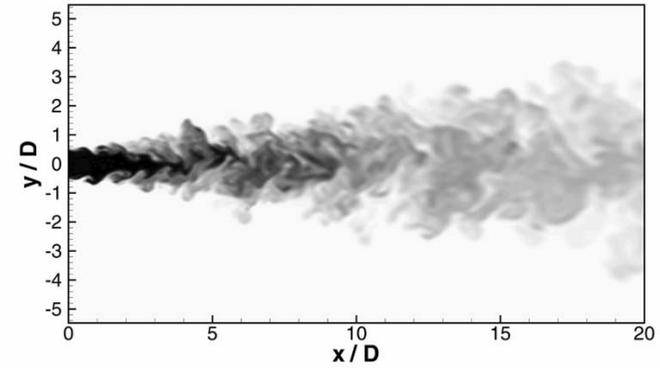
Aspects universels de la turbulence

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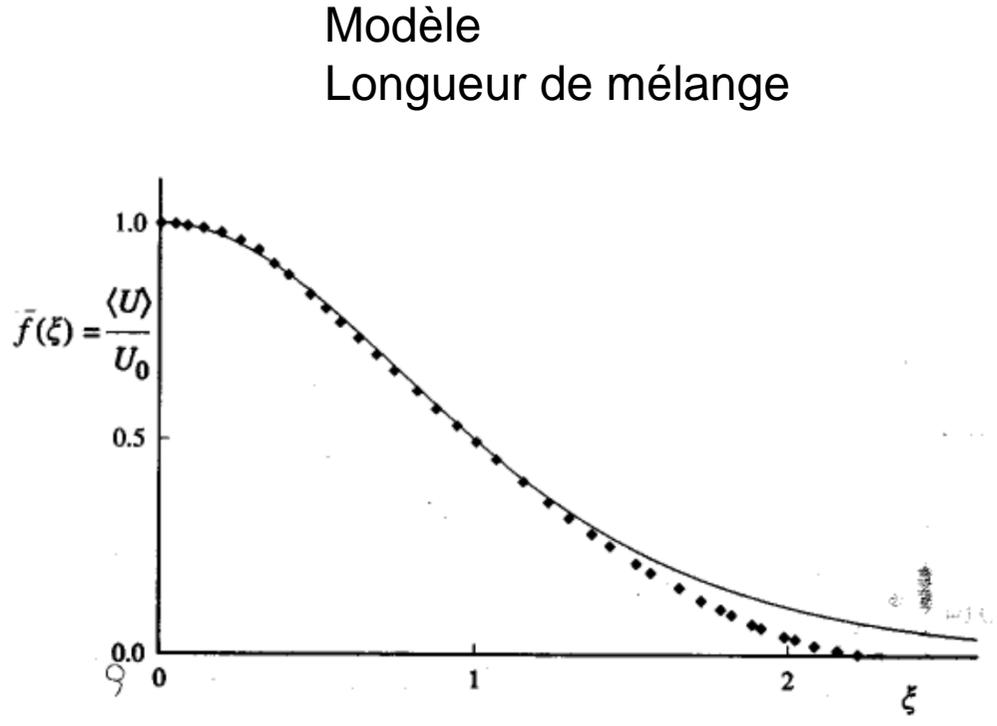
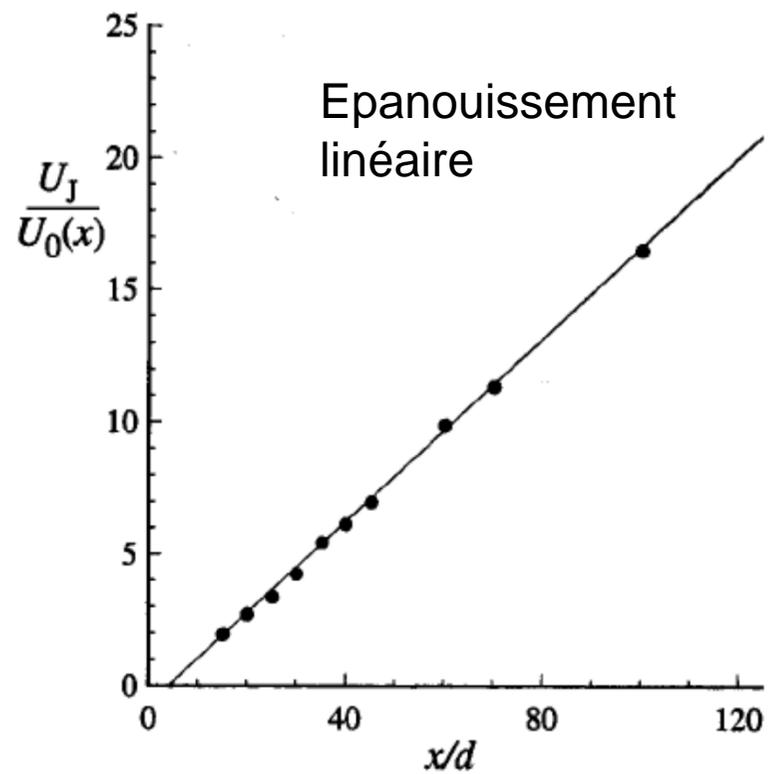
Jet turbulent :

hypothèse de similitude



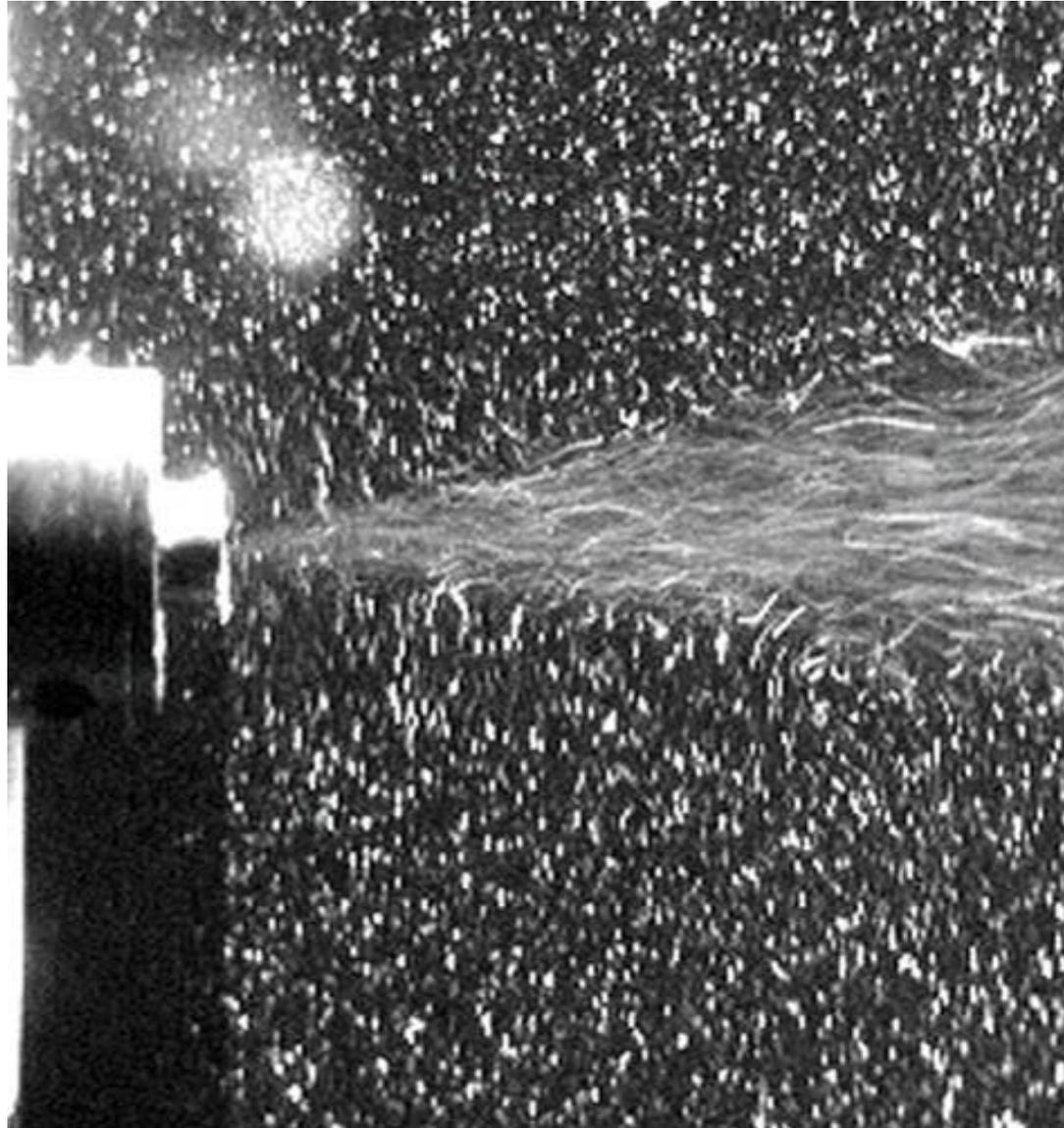
(d'après Pope)

Jet turbulent : hypothèse de similitude

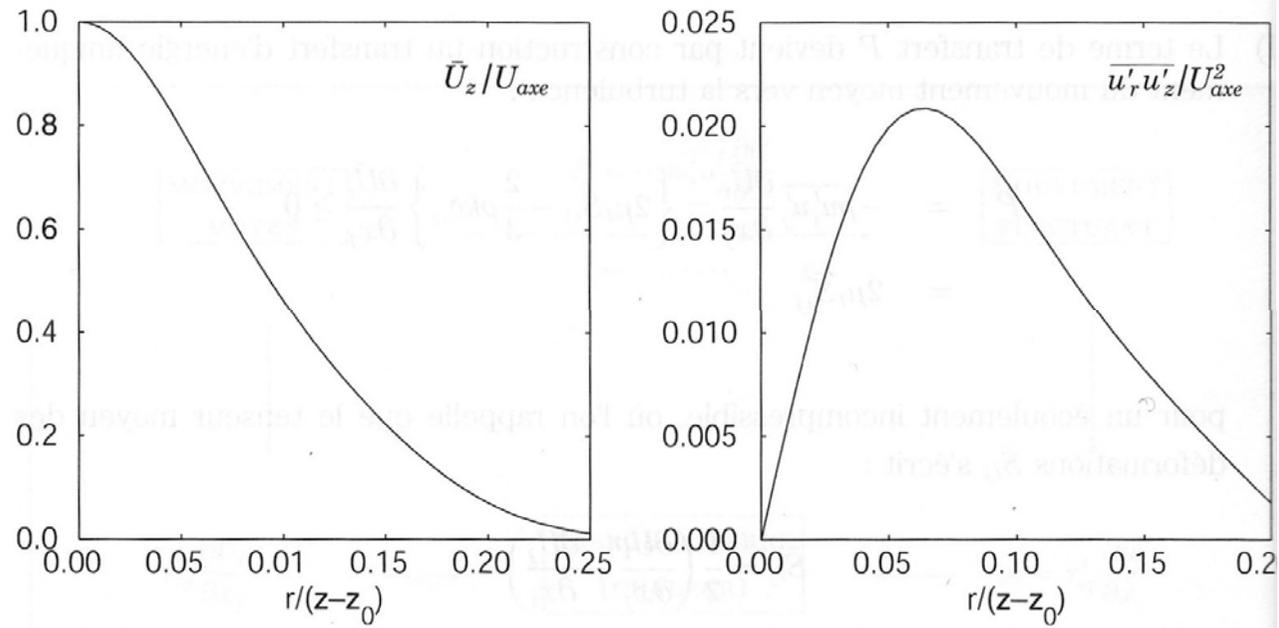


Hesketad 1965, d'après Pope

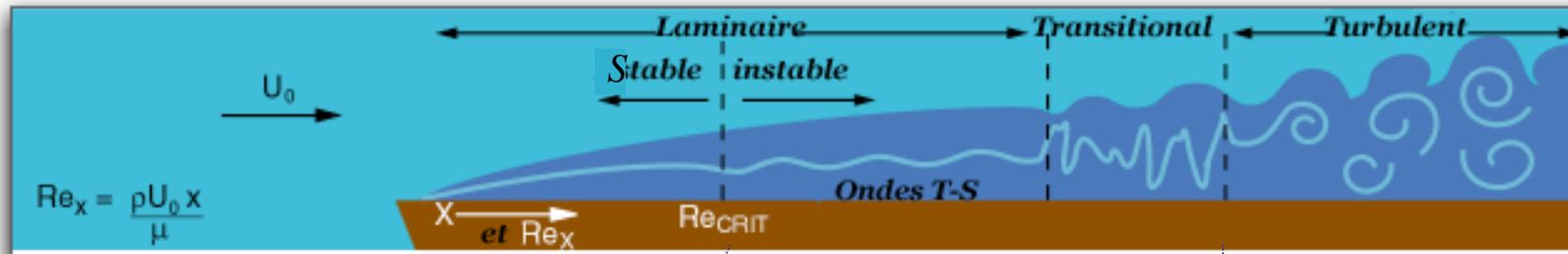
**Jet turbulent : épanouissement
Et entraînement latéral**



Jet turbulent : Tenseur de Reynolds

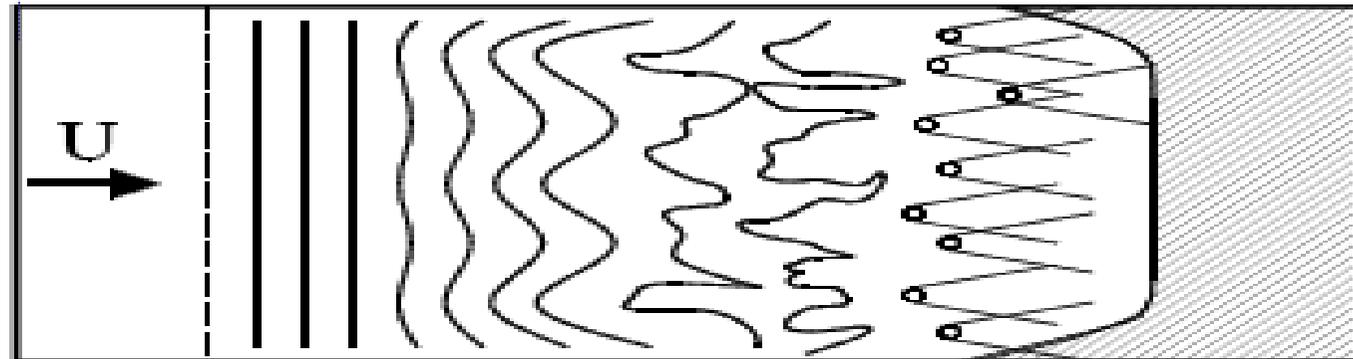


Couches limites



Blasius
 $\delta(x) \sim x^{1/2}$

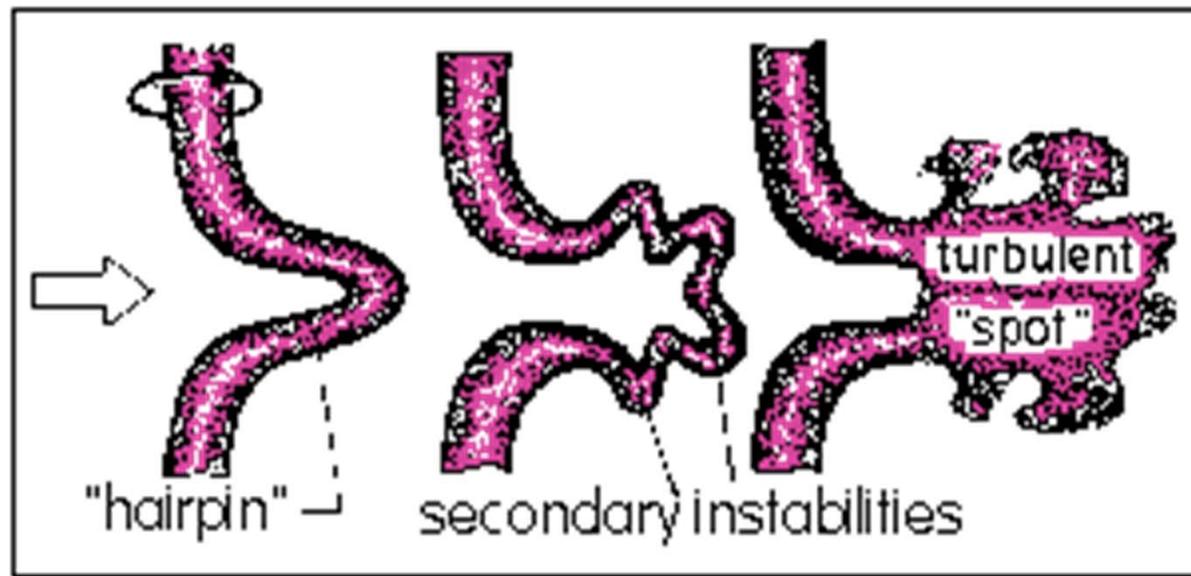
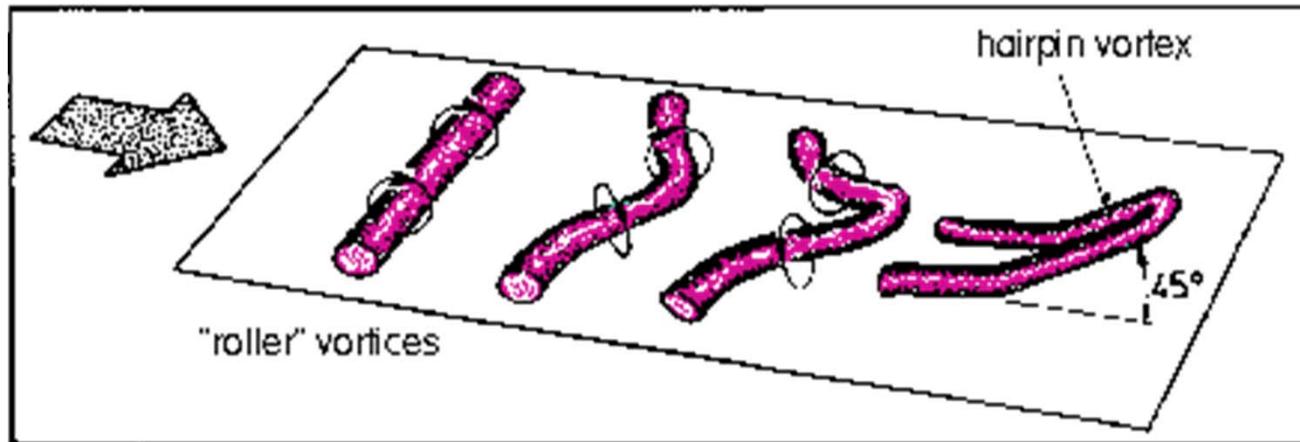
Turbulent
 $\delta(x) \sim x$



Ondes de Tollmien

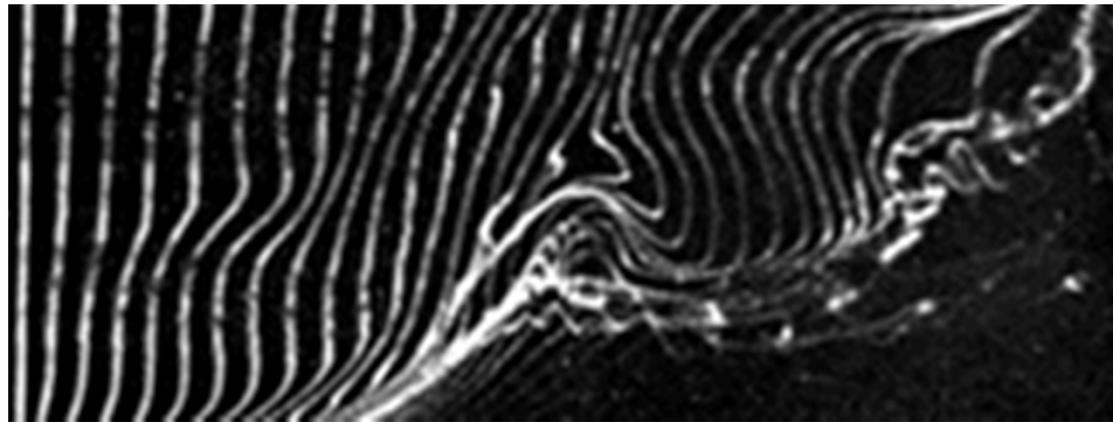
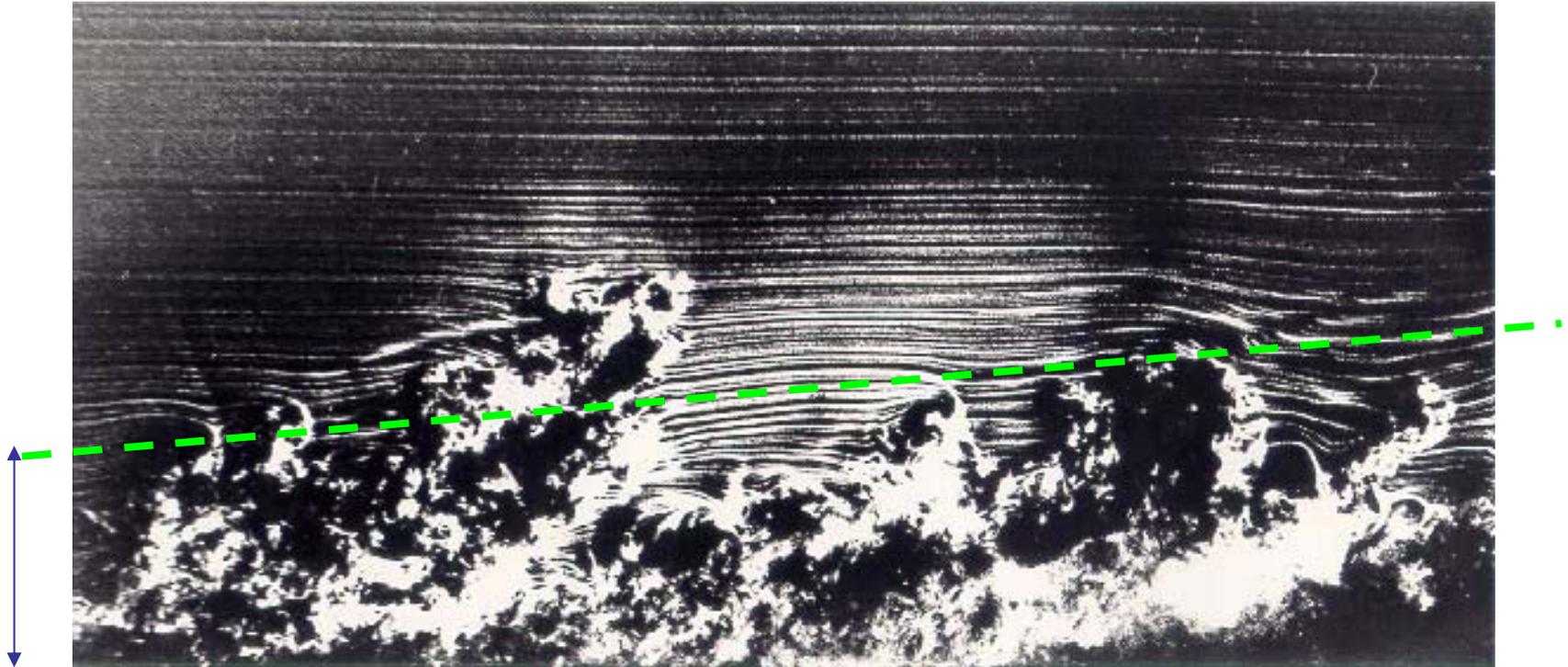
Seuil turbulence :
 $Re \sim 10^6$ ($\pm 50\%$!!!)

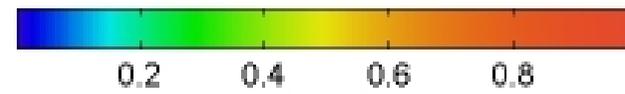
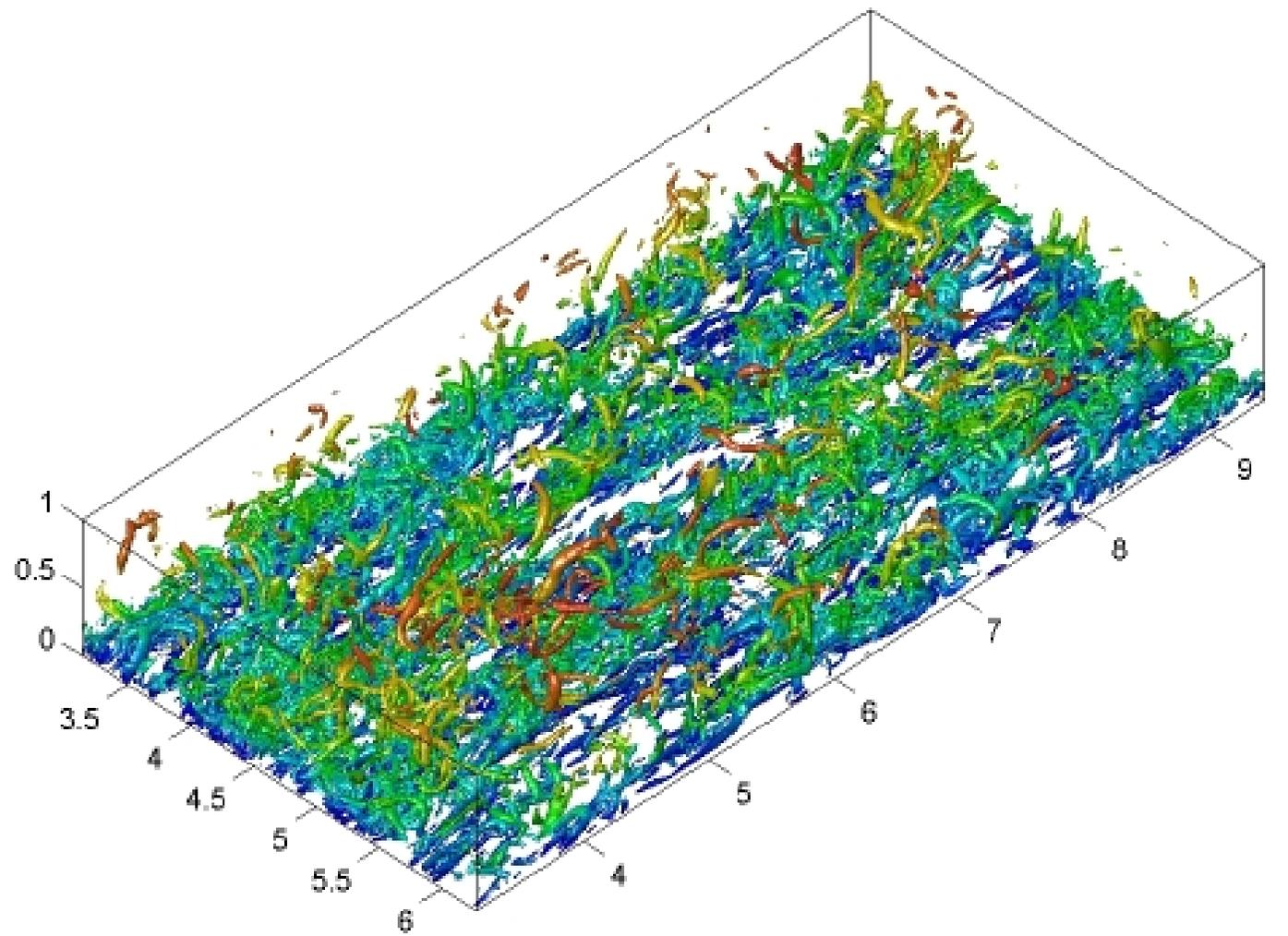
Couche limite : instabilités et transition vers la turbulence



Couche limite turbulente

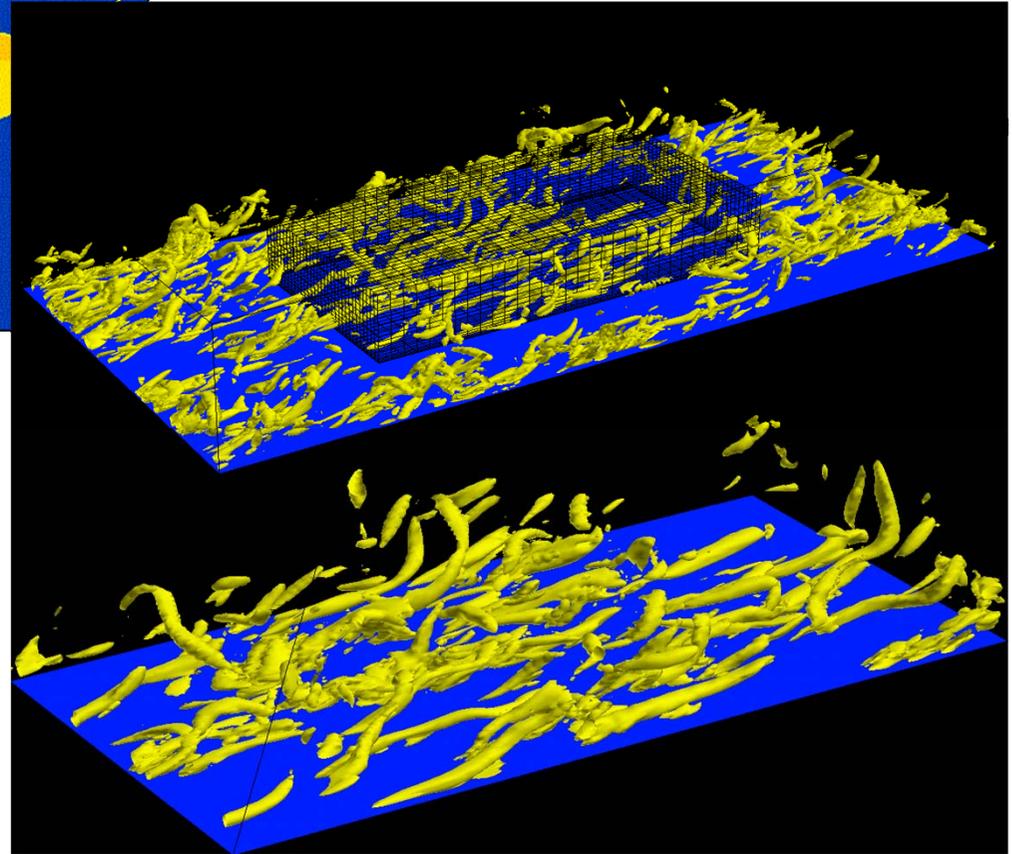
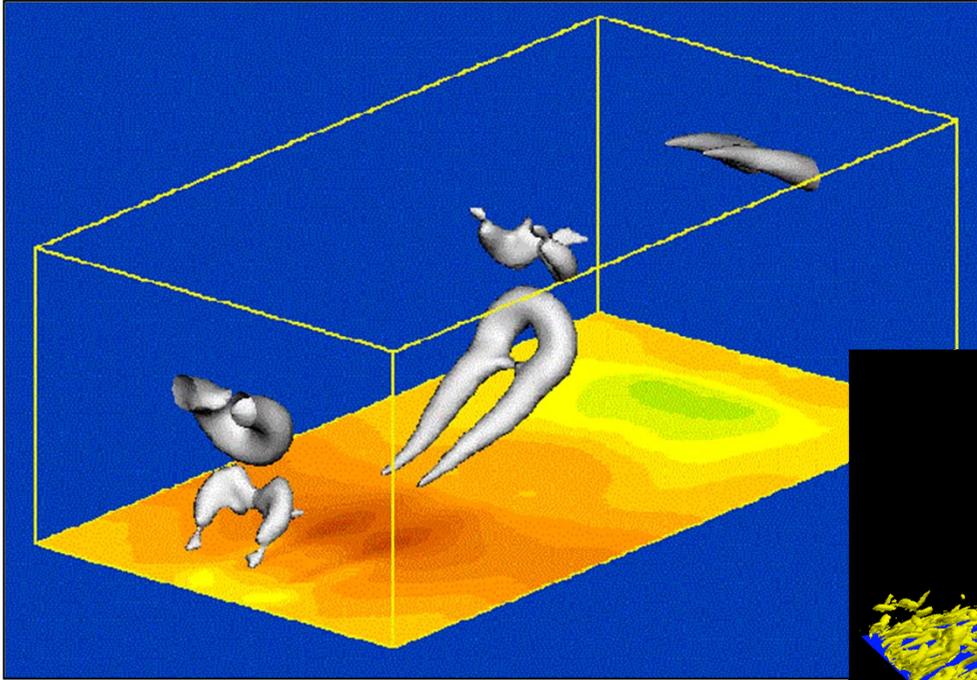
$\delta(x)$



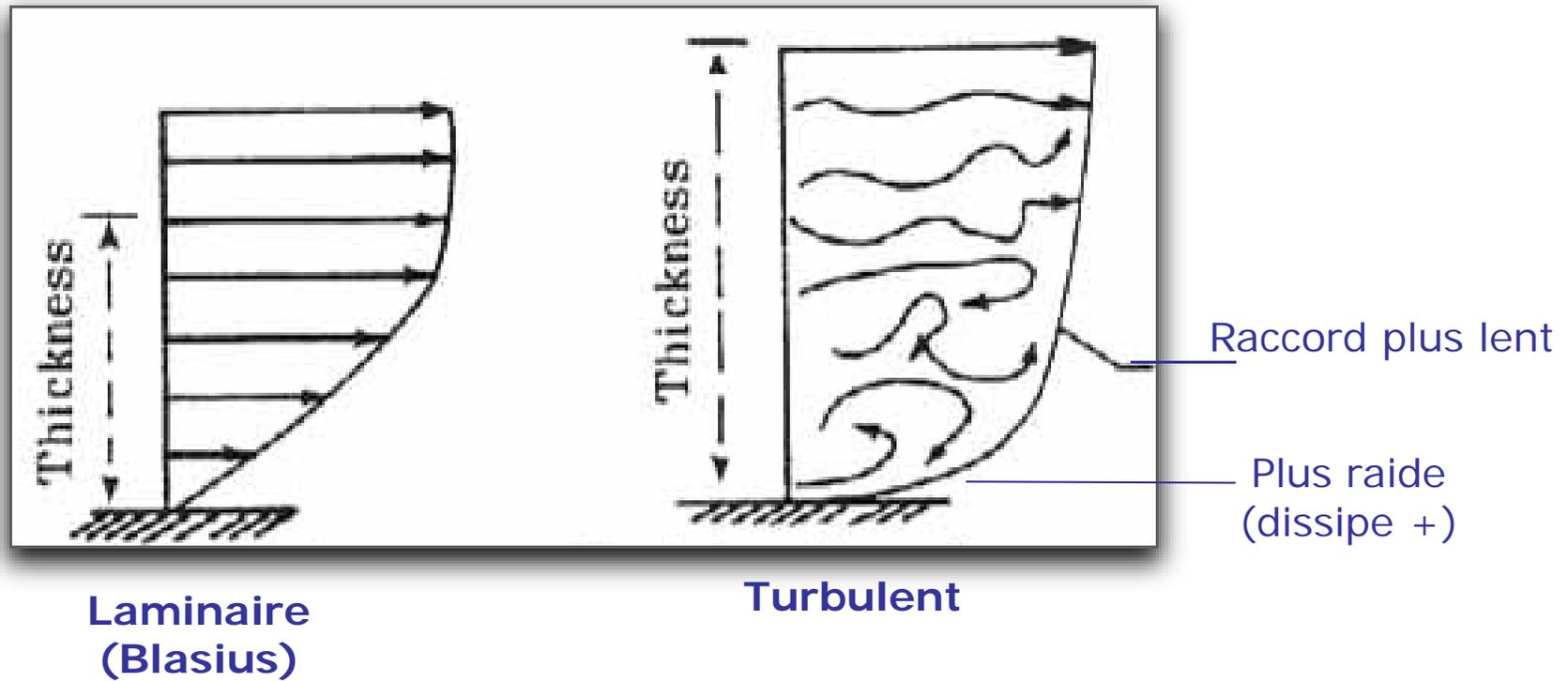


Inln.cnrs.fr

DNS de couche limite turbulente



Profils de vitesse : Laminaire vs. Turbulent



Profils de couche limite

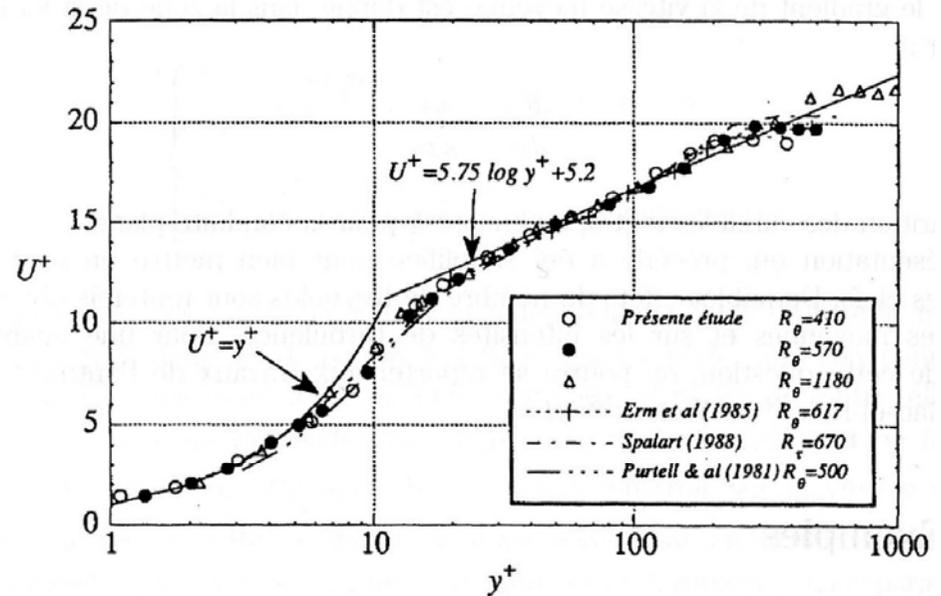
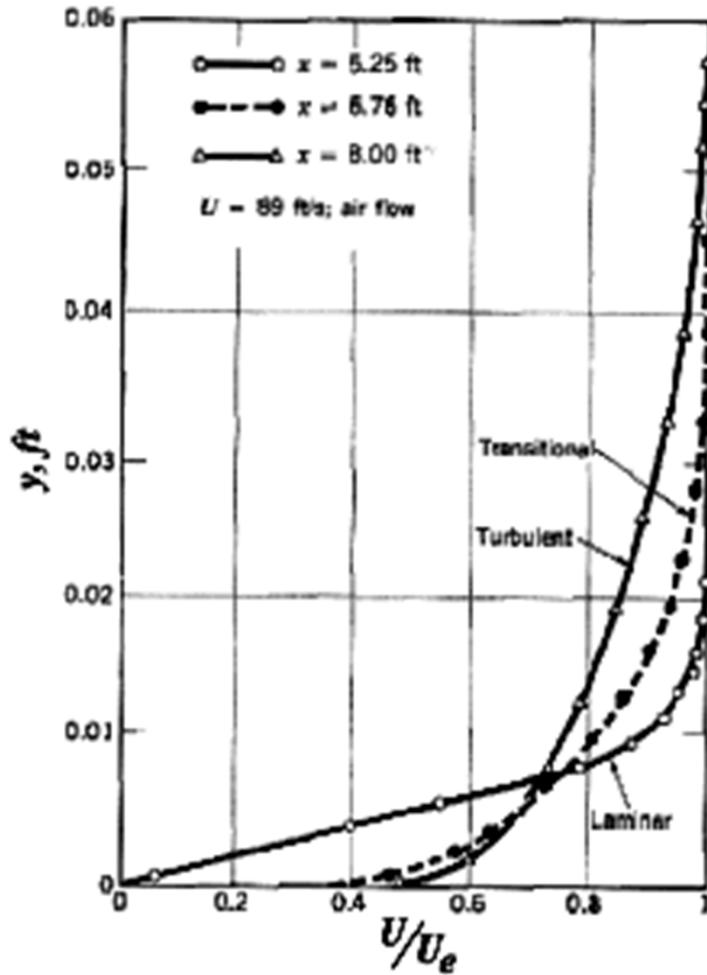
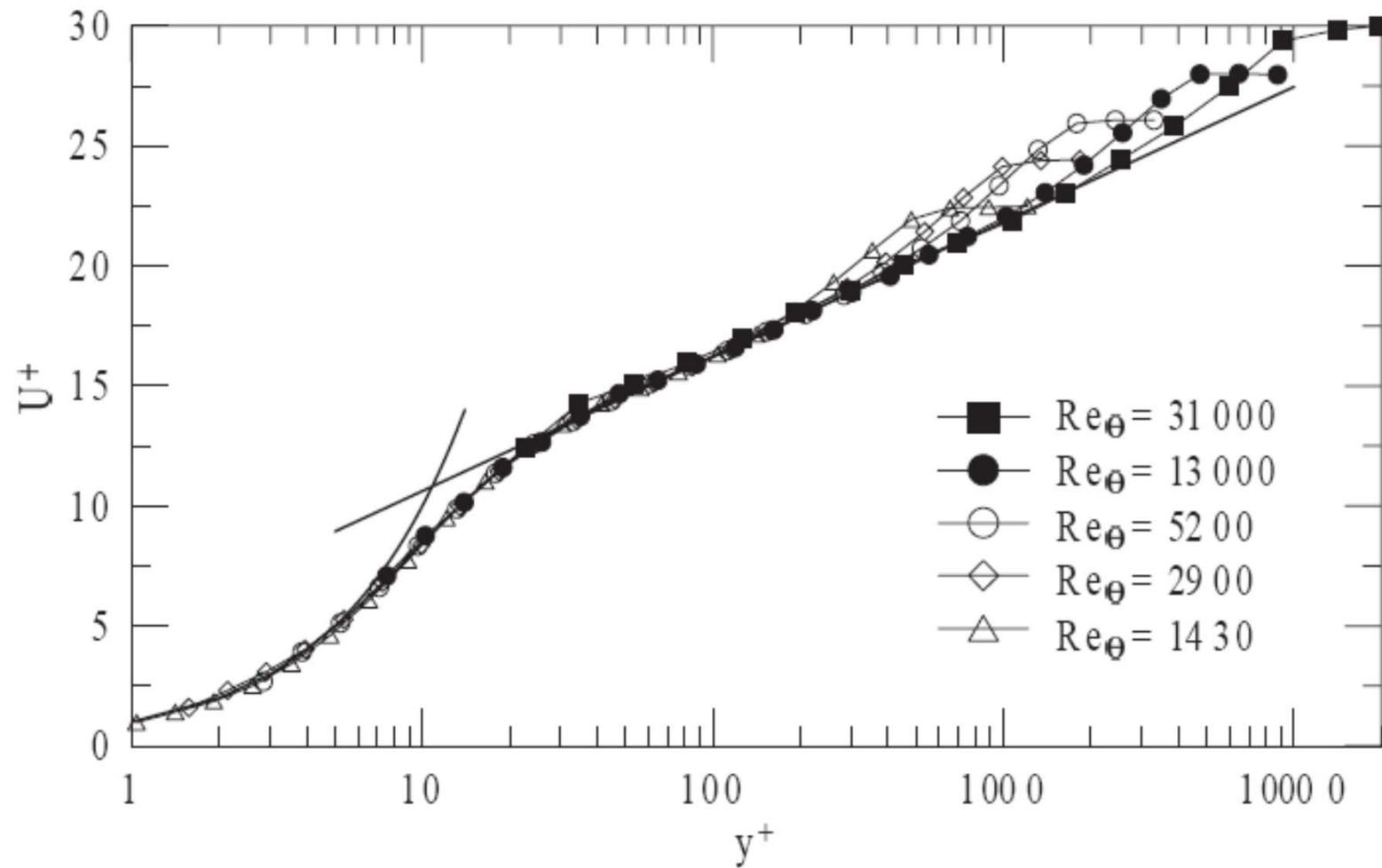


Figure 3.4 : Profil des vitesses moyennes pour une couche limite dans l'eau, avec référence prise à la paroi. On observe le film visqueux pour $y^+ = x_2^+ \leq 5$, une zone tampon pour $5 \leq x_2^+ \leq 30$, la zone logarithmique à partir de $x_2^+ \simeq 30$ et son extension vers les x_2^+ croissants lorsque le nombre de Reynolds augmente. Pour $Re_{\delta_0} = Re_{\theta} = U_{e1} \delta_{\theta} / \nu = 410$, on a $Re_{\delta} = 4\,500$, $U_{e1} = 5.8$ cm.s $^{-1}$, $u_f = 0.30$ cm.s $^{-1}$ et $\delta = 7.7$ cm. Ainsi, $x_2^+ = 1$ correspond à $x_2 = 0.033$ cm, en se rappelant que $\nu_{\text{eau}} = 1 \times 10^{-6}$ m 2 .s $^{-1}$. D'après LAADHARI F.⁵³³.

Profils de couche limite



Perte de charge en conduite rugueuse : Nikuradse (1932)

