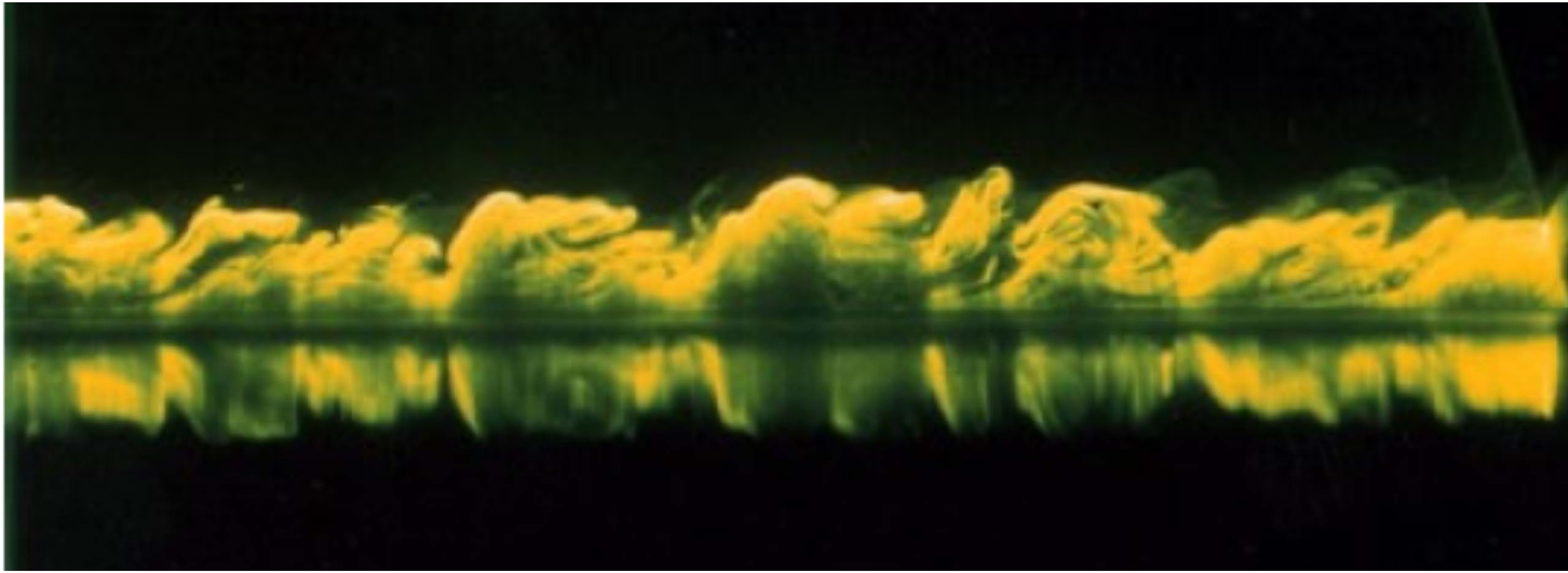
Turbulence

There are no “simple” turbulent flows

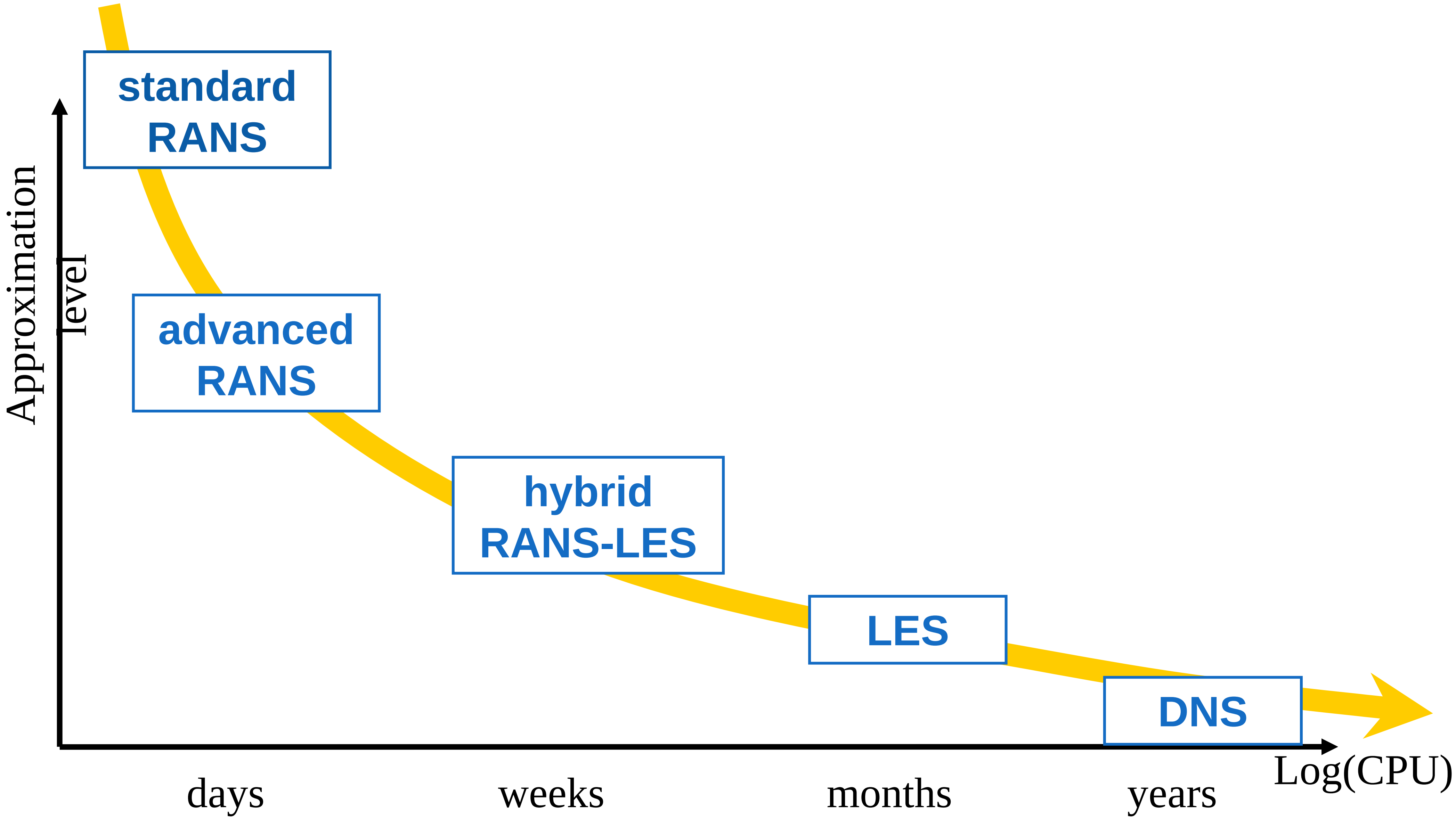
Turbulent boundary layer:

- **Instantaneous velocity field (snapshot)** $u_i(\boldsymbol{x}, t)$

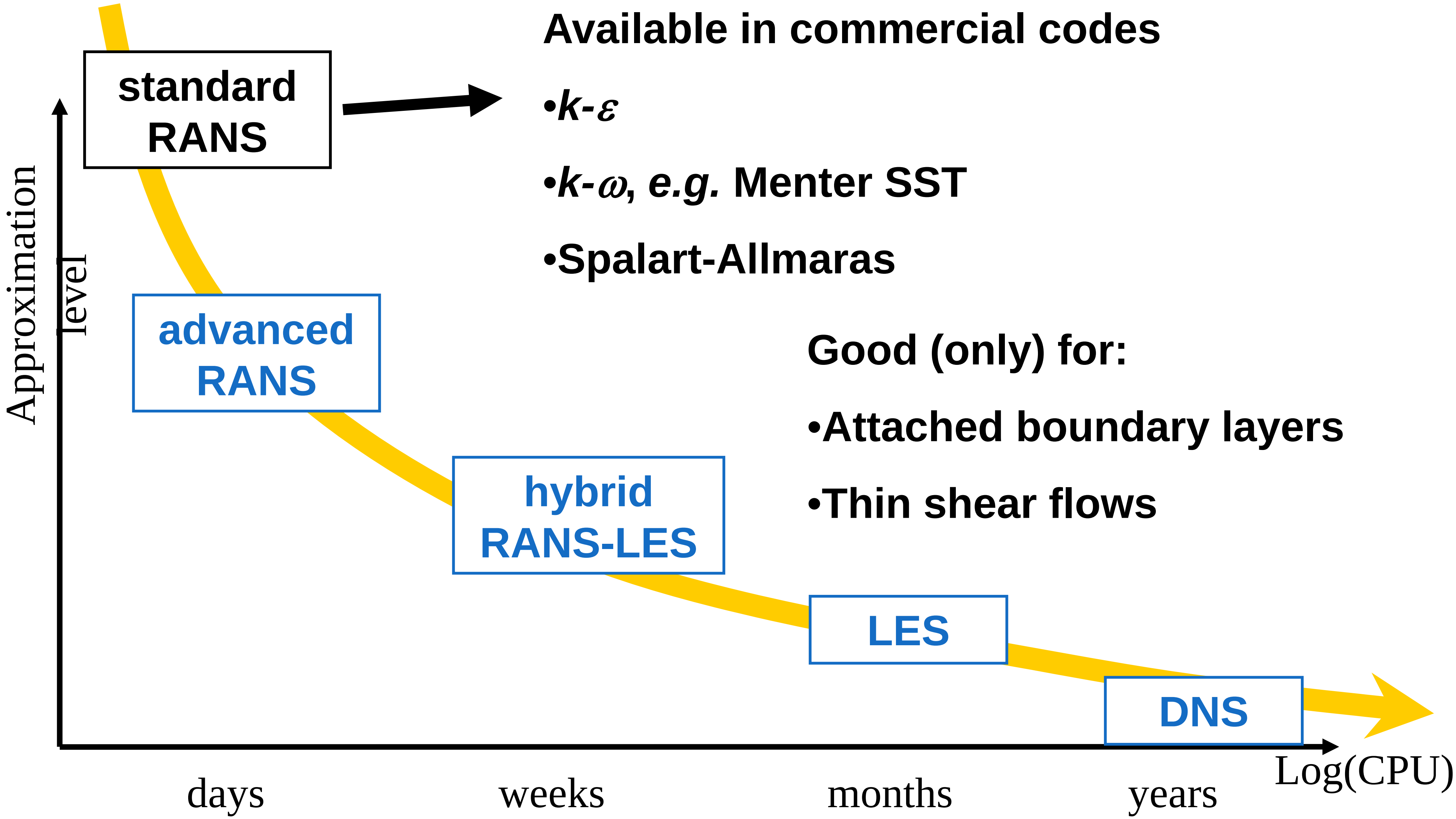


Ref: Prof. M. Gad-el-Hak, University of Notre Dame

Prediction of turbulent flows



Standard RANS models



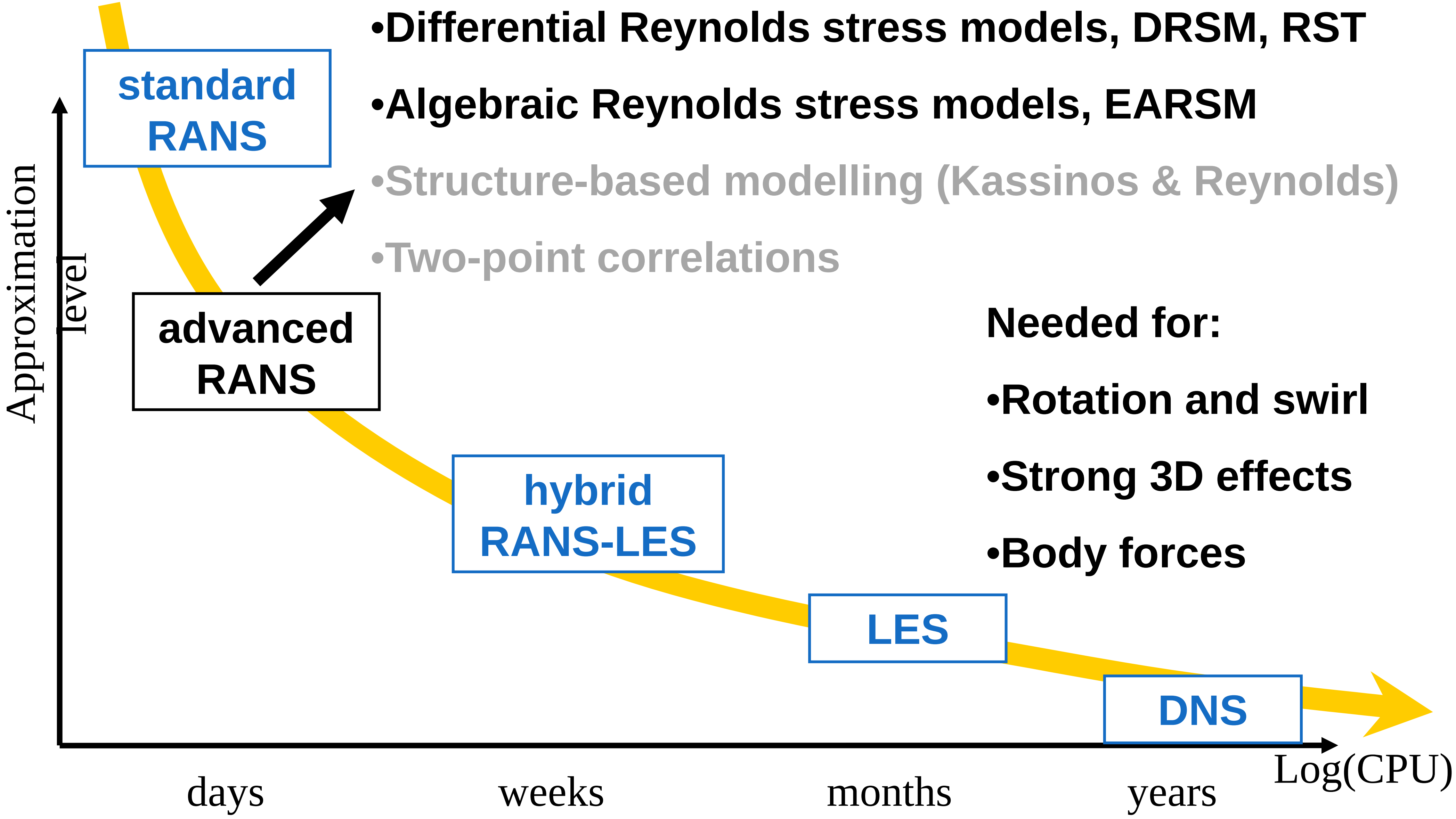
Available in commercial codes

- ***k-ε***
- ***k-ω*, *e.g.* Menter SST**
- **Spalart-Allmaras**

Good (only) for:

- **Attached boundary layers**
- **Thin shear flows**

Advanced RANS models

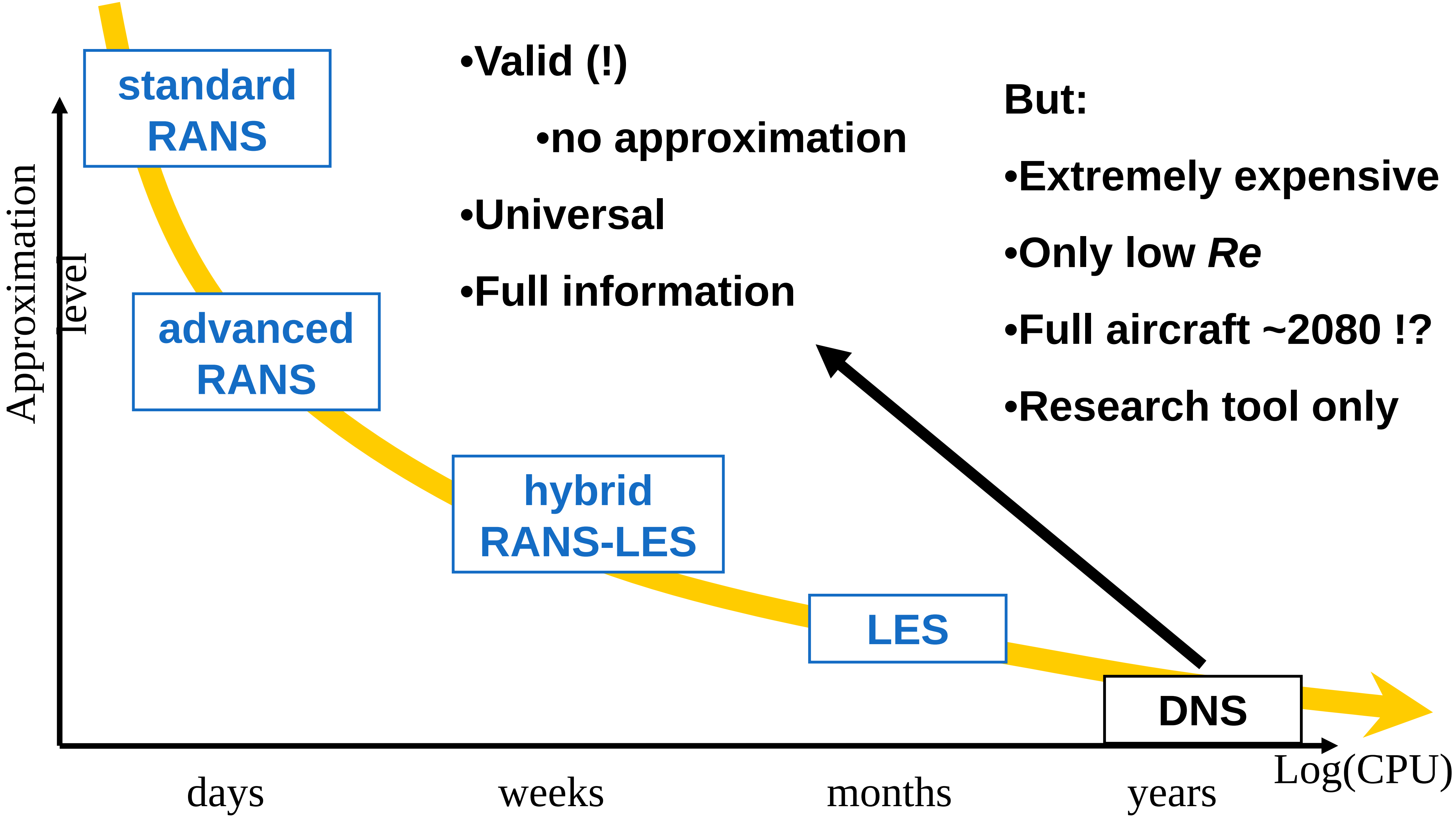


- •Differential Reynolds stress models, DRSM, RST
- •Algebraic Reynolds stress models, EARSM
- •Structure-based modelling (Kassinos & Reynolds)
- •Two-point correlations

Needed for:

- •Rotation and swirl
- •Strong 3D effects
- •Body forces

Direct Numerical Simulation – DNS



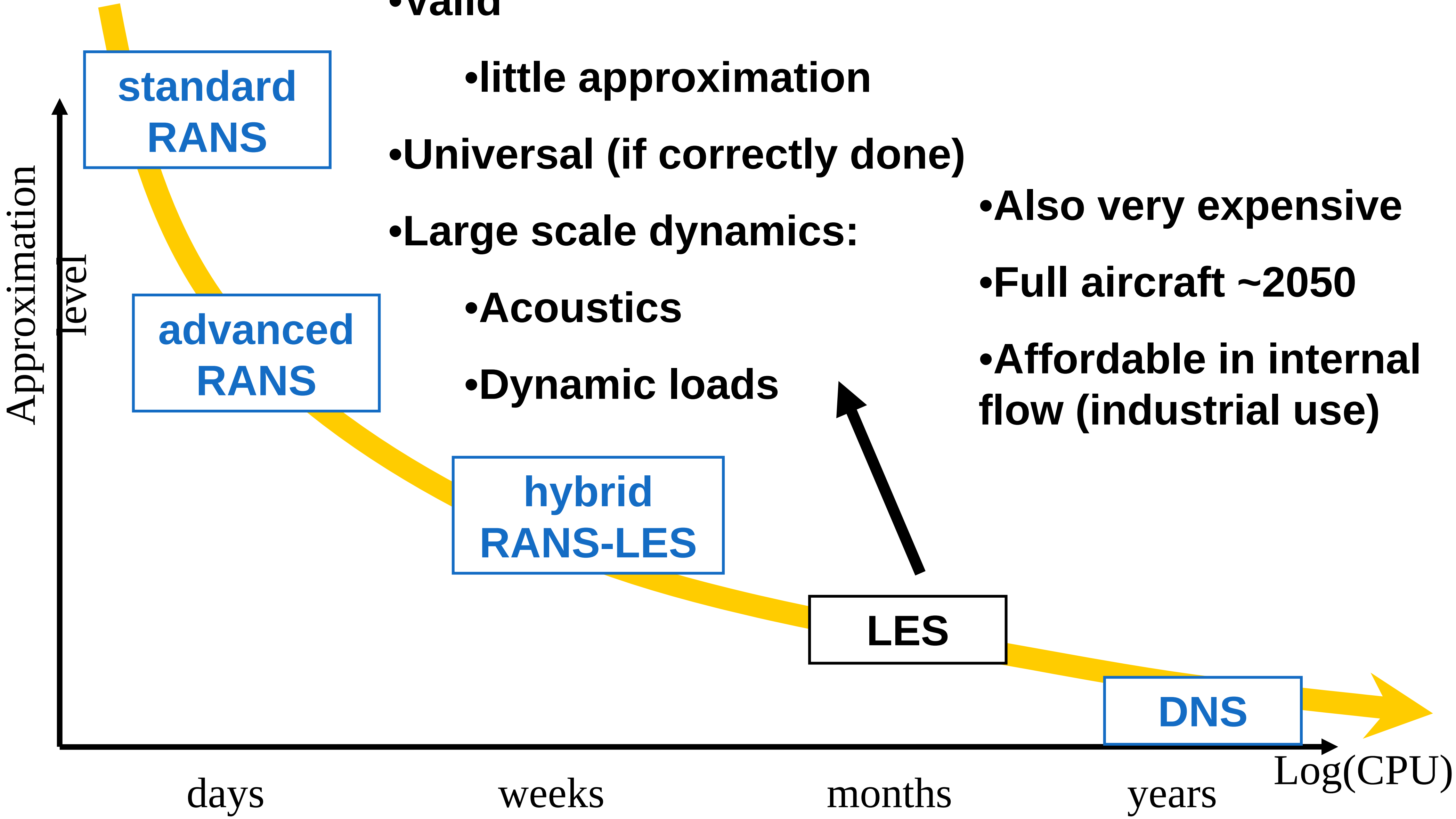
- Valid (!)
    - no approximation
- Universal
- Full information

But:

- Extremely expensive
- Only low *Re*
- Full aircraft ~2080 !?
- Research tool only

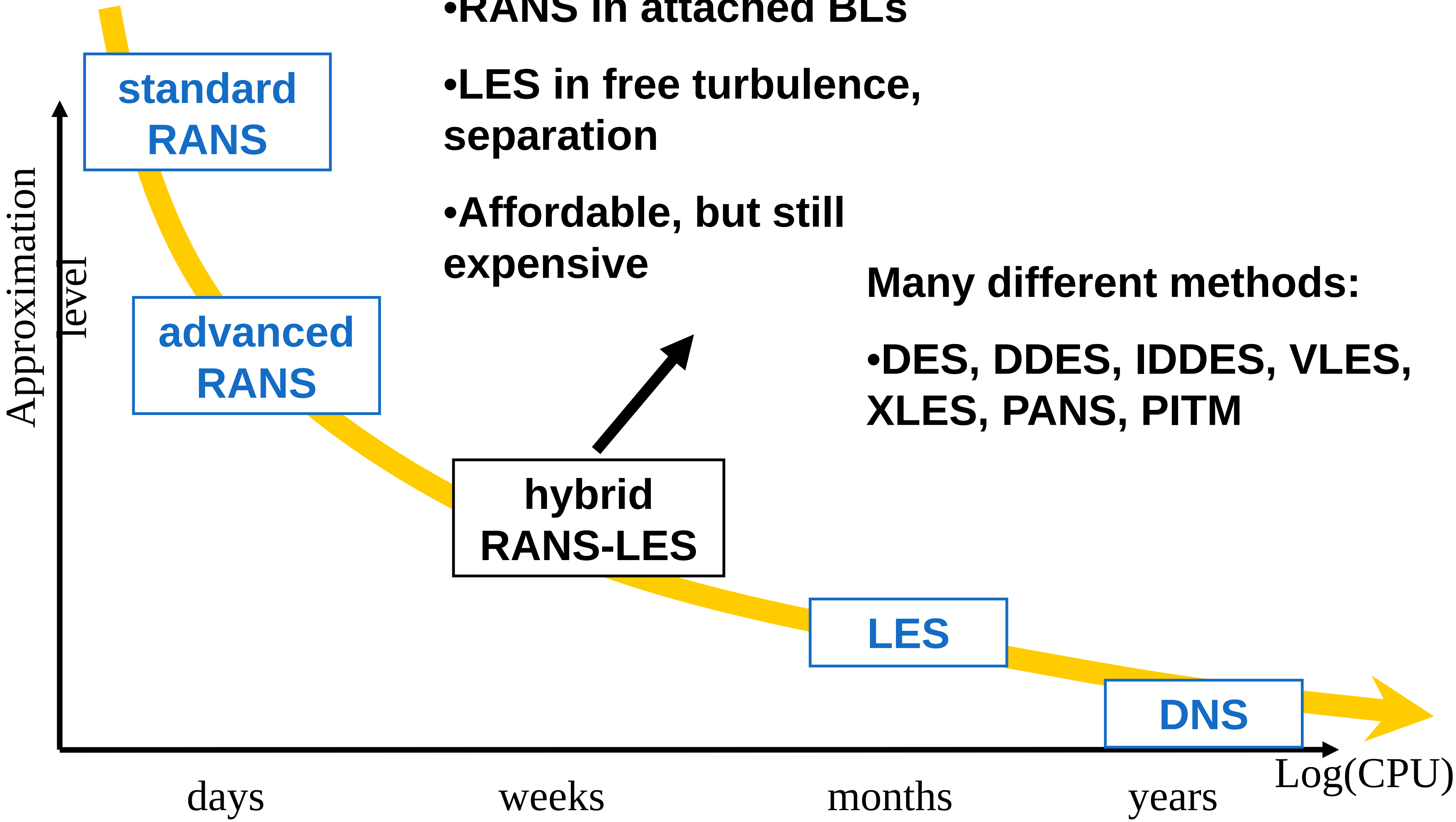
Large Eddy Simulation – LES

- •Valid
    - •little approximation
- •Universal (if correctly done)
- •Large scale dynamics:
    - •Acoustics
    - •Dynamic loads



- •Also very expensive
- •Full aircraft ~2050
- •Affordable in internal flow (industrial use)

Hybrid RANS – LES methods

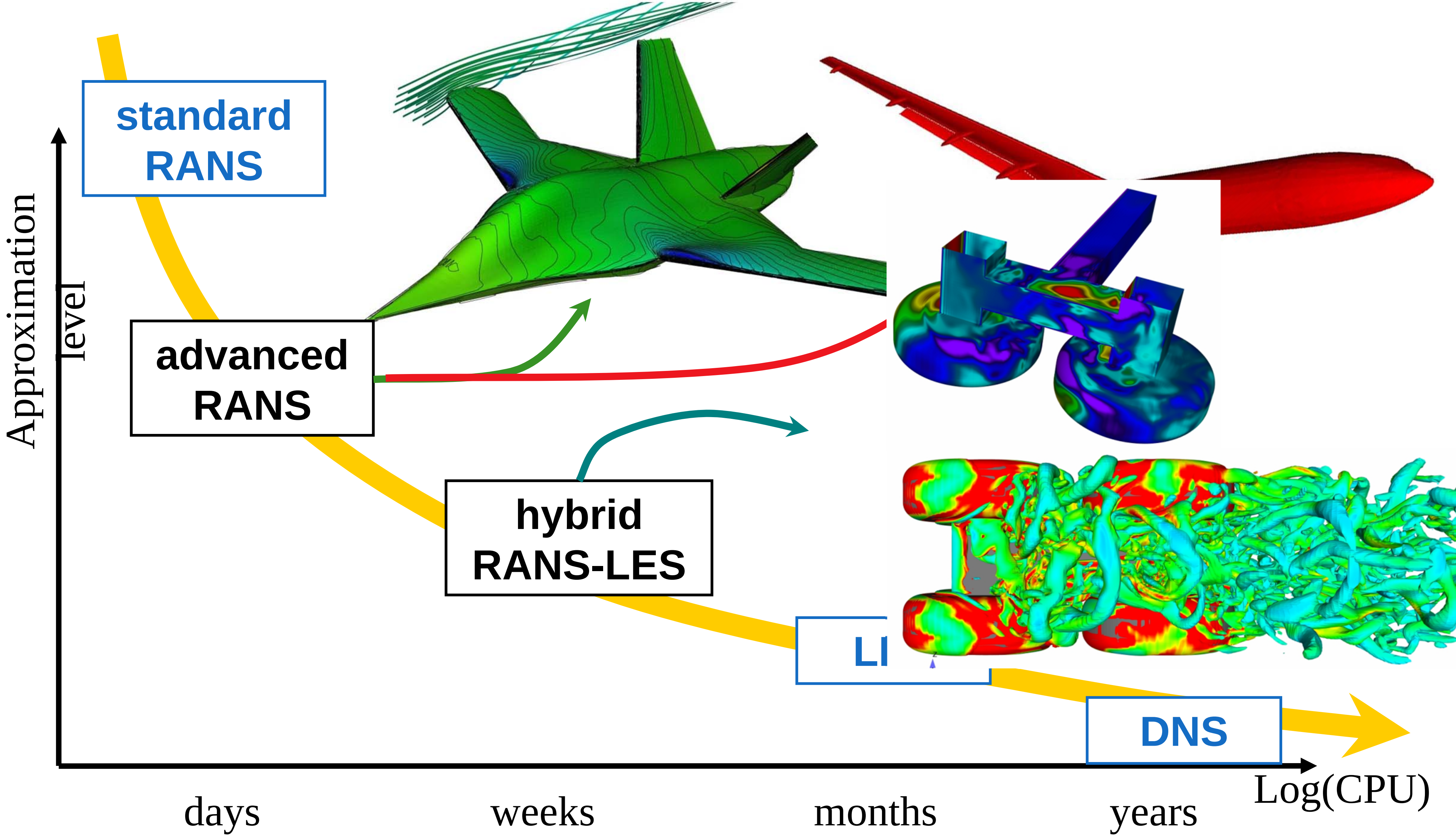


- **RANS in attached BLs**
- **LES in free turbulence, separation**
- **Affordable, but still expensive**

Many different methods:

- **DES, DDES, IDDES, VLES, XLES, PANS, PITM**

Prediction of turbulent flows



standard
RANS

advanced
RANS

hybrid
RANS-LES

LI

DNS

Basic concepts

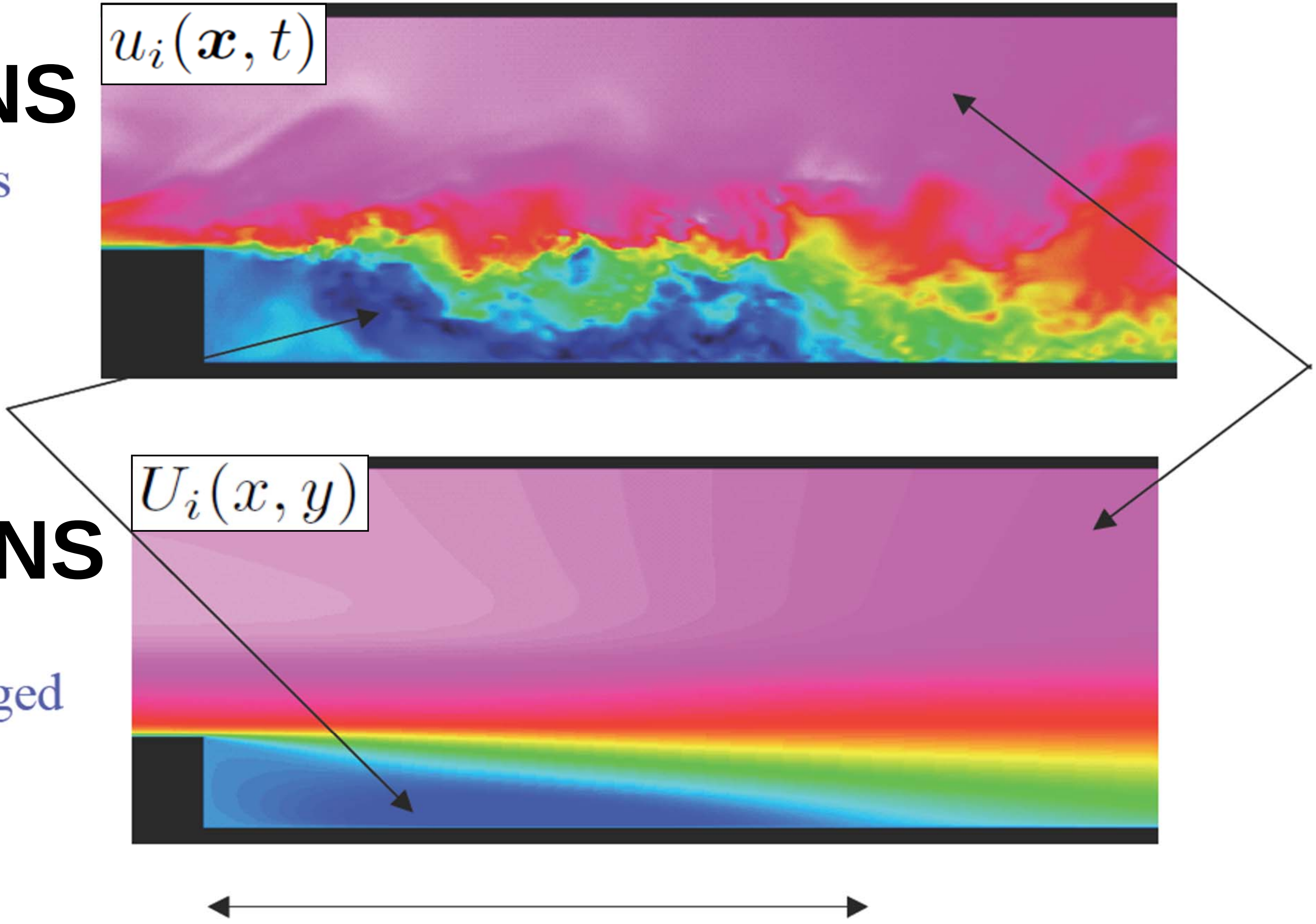
- Turbulence is:
  - random fluctuations
  - 3D
  - time dependent
  - present in most flows of engineering interest
- Energy cascade
  - generated at the largest scales (L and U)
  - large scale vortices breakes down to smaller vortices
  - dissipates to heat at the smallest viscous scales, ε
  - balanced cascade

$$\varepsilon \sim \frac{U^3}{L}$$

  - turbulent kinetic energy

$$K \sim U^2$$

DNS / LES – RANS



DNS

Istantaneous

low velocity regions

high velocity regions

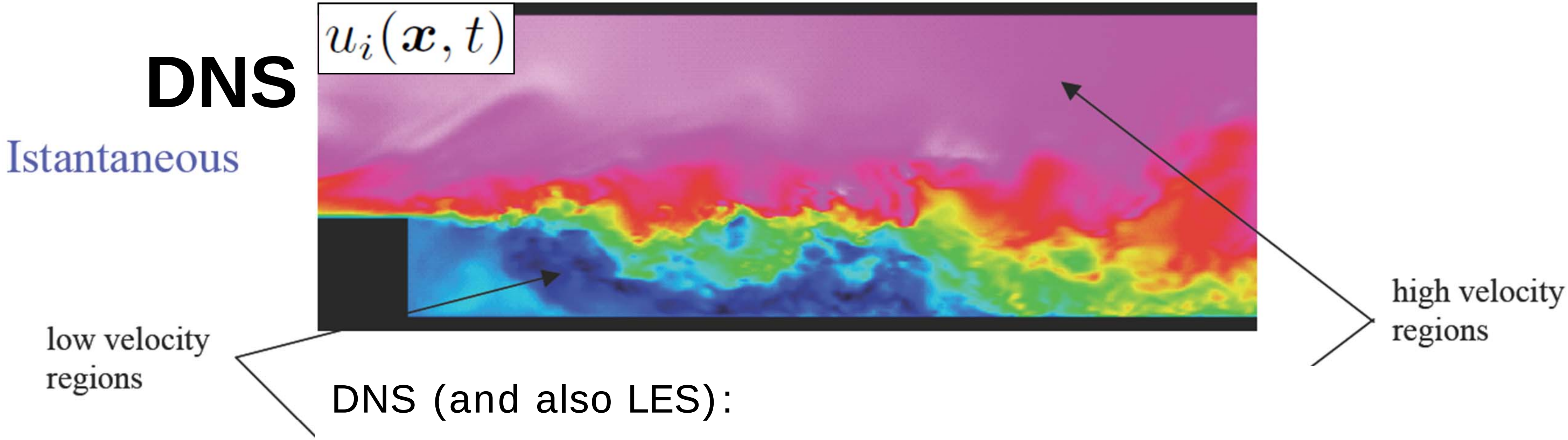
RANS

Time averaged

Length of the recirculation region is of engineering interest

DNS / LES – RANS

DNS



DNS (and also LES):

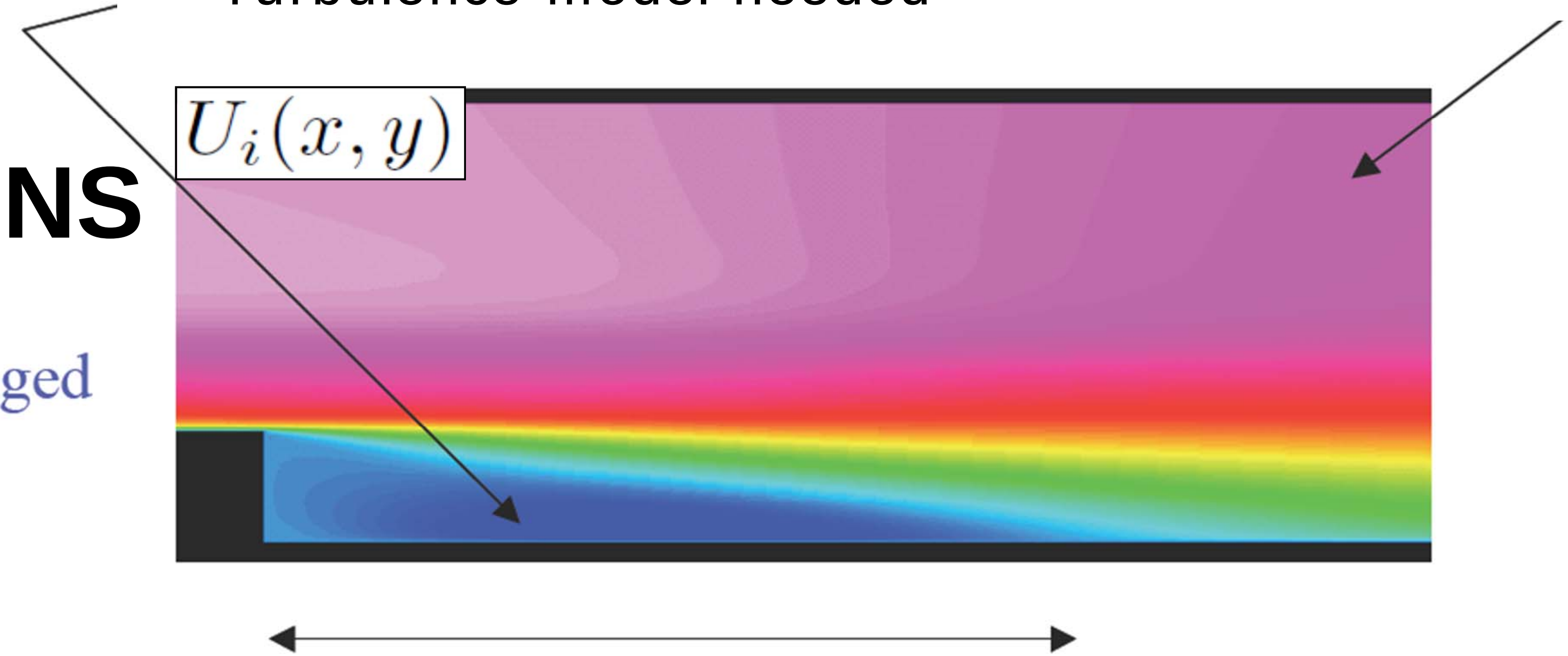
- 3D
- Time dependent
  - Full information of turbulence scales
  - Acoustics and dynamic loads
  - No (limited) turbulence modelling
- Huge Reynolds number dependency

Expensive!

DNS/LES – RANS

RANS:

- Reduction of dimensions –> cheap
  Here: 2D and steady
- Only statistical information of turbulence scales:
  Time and length scales
  rms values
- Turbulence model needed



low velocity regions

RANS

Time averaged

Length of the recirculation region is of engineering interest

Scale separation

- Large scales L and U related to geometrical scales
- Small viscous scales (related to ν and ε)

$$l_K = \eta \sim \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}, \quad t_K \sim \sqrt{\frac{\nu}{\varepsilon}}$$

- Scale separation

$$\frac{L}{\eta} \sim Re^{3/4}, \quad \frac{t}{t_K} \sim Re^{1/2}$$

- Reynolds number

$$Re = \frac{LU}{\nu}$$

Different Reynolds numbers

- Based on global scales

$$Re_L = \frac{LU}{\nu}$$

- Based on distance x from leading edge (flat plate)

$$Re_x = \frac{xU}{\nu}$$

- Based on boundary layer thickness (δ)

$$Re_\delta = \frac{\delta U}{\nu}$$

- Based on wall skin friction

$$Re_\tau = \frac{\delta u_\tau}{\nu}$$

Viscosity

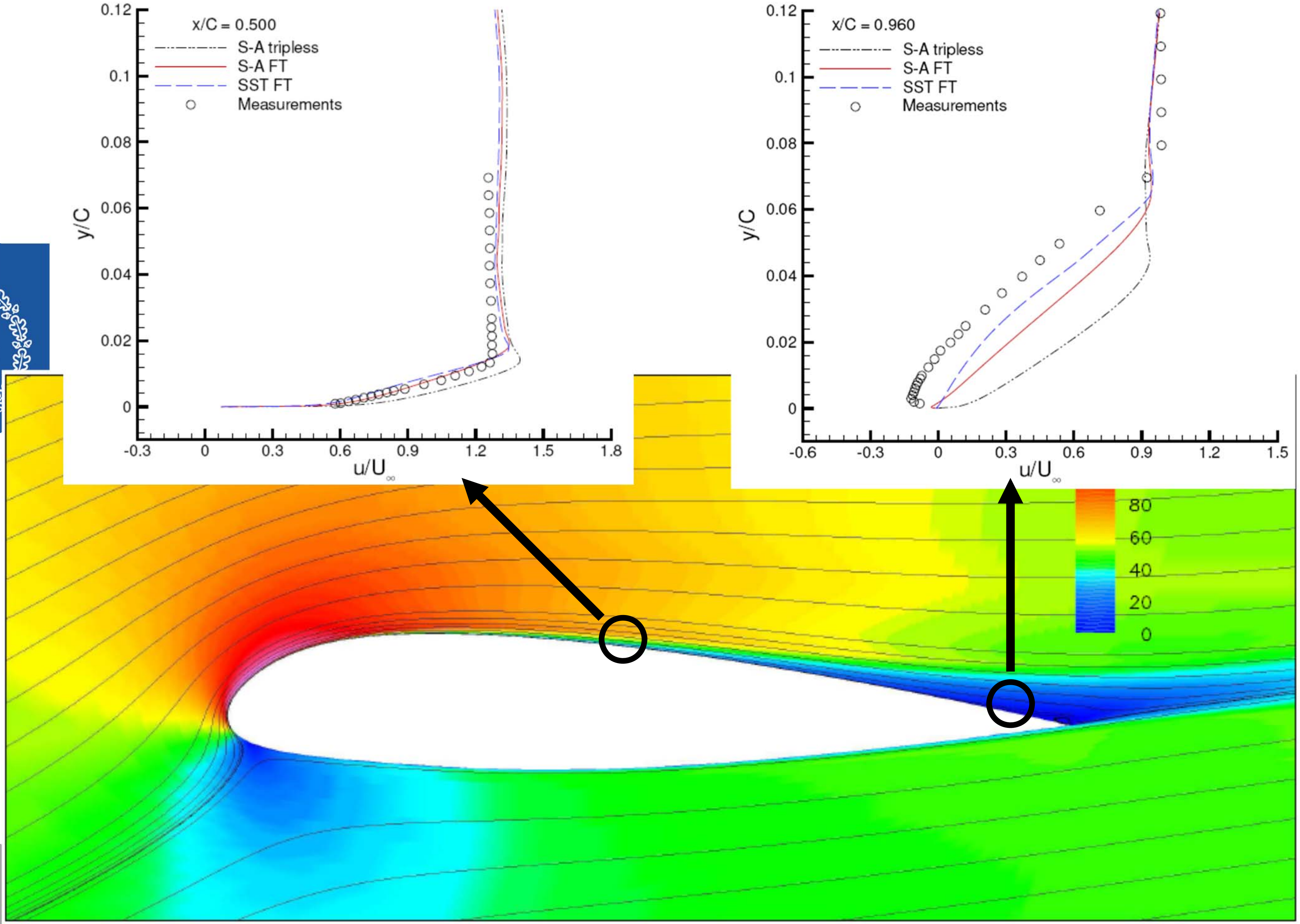
- Kinematic viscosity, ν
- Dynamic viscosity, μ
- Density, ρ

$$\mu = \rho\nu$$

Boundary layers (BL)

- Thin layers
  - Thickness Reynolds number dependent
- Laminar boundary layers
  - Thickness related to wall skin friction
- Turbulent boundary layers
  - Inner and outer scales separated
  - Scale separation Reynolds number dependent

BL on the ONERA A-profile

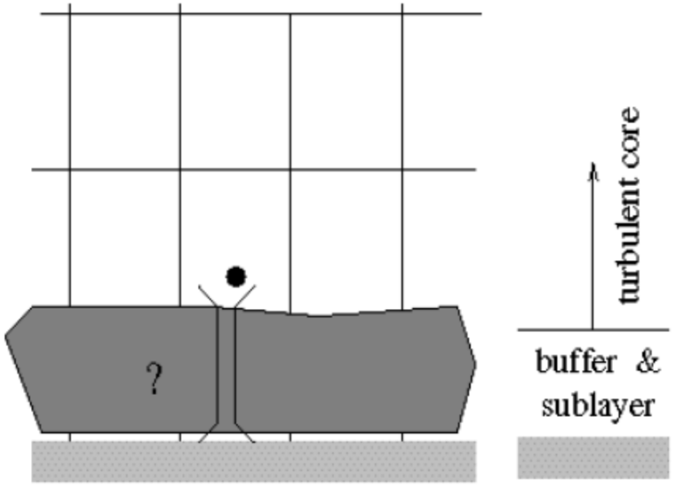


Approximation of BLs

- Slip wall boundary condition
  - Boundary layer completely neglected
  - Euler (non-viscous) computations possible
  - Slip BC can also be applied to viscous & turbulent CFD
- No slip boundary condition
  - Boundary layer completely resolved ($y^+=1$)
  - Extreme resolution needed (Δy=1-100μm)
  - 40-80 grid points within the boundary layer
- Log-law boundary condition (turbulence)
  - First grid point within log layer ($y^+>20$ AND $y<0.1\delta$)
  - 10-20 grid points within the boundary layer
  - Warning: standard log-law BCs inconsistent with too small grid size. READ SOLVER DOCUMENTATION !!!

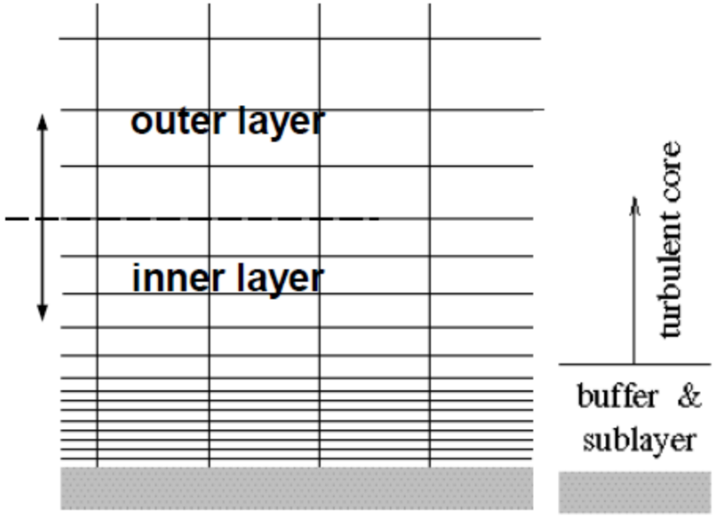
What's in Fluent?

- Standard and Non-Equilibrium Wall Functions:
  - "Wall adjacent cells should have y+values between 30 and 300–500" – (remember $y < 0.1\delta$!)
  - "The mesh expansion ratio should be small (no larger than around 1.2)"
  - "Non-equilibrium wall function method attempts to improve the results for flows with higher pressure gradients, separations, reattachment and stagnation"
- Scalable Wall Functions:
  - Consistent for all y+values



What’s in Fluent? …

- Enhanced Wall Treatment Option
  - Combines a blended law-of-the wall and a two-layer zonal model.
  - Suitable for low-Re flows or flows with complex near-wall phenomena.
  - Generally requires a fine near-wall mesh capable of resolving the viscous sublayer
  - y+< 5, and a minimum of 10–15 cells across the “inner layer” for best results
  - Valid for all y+
  - Available for all k-e and k-w models
  - Not yet for Spalart-Allmaras (y+<3 OR y+>15)



Recommendations for Fluent

- For K-ε models
  - use Enhanced Wall Treatment: EWT-ε
- If wall functions are favored with K-ε models
  - use scalable wall functions
- For K-ω models
  - use the default: EWT-ω

Wall bounded turbulence

- Viscous wall scales

$$l_* = \frac{\nu}{u_\tau}, \quad t_* = \frac{\nu}{u_\tau^2}$$

- Wall friction velocity

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} = \sqrt{\nu \frac{\partial U}{\partial y}\bigg|_{\text{wall}}} = U\sqrt{\frac{1}{2}C_f}$$

- Friction coefficient

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U^2} = 2\left(\frac{u_\tau}{U}\right)^2$$

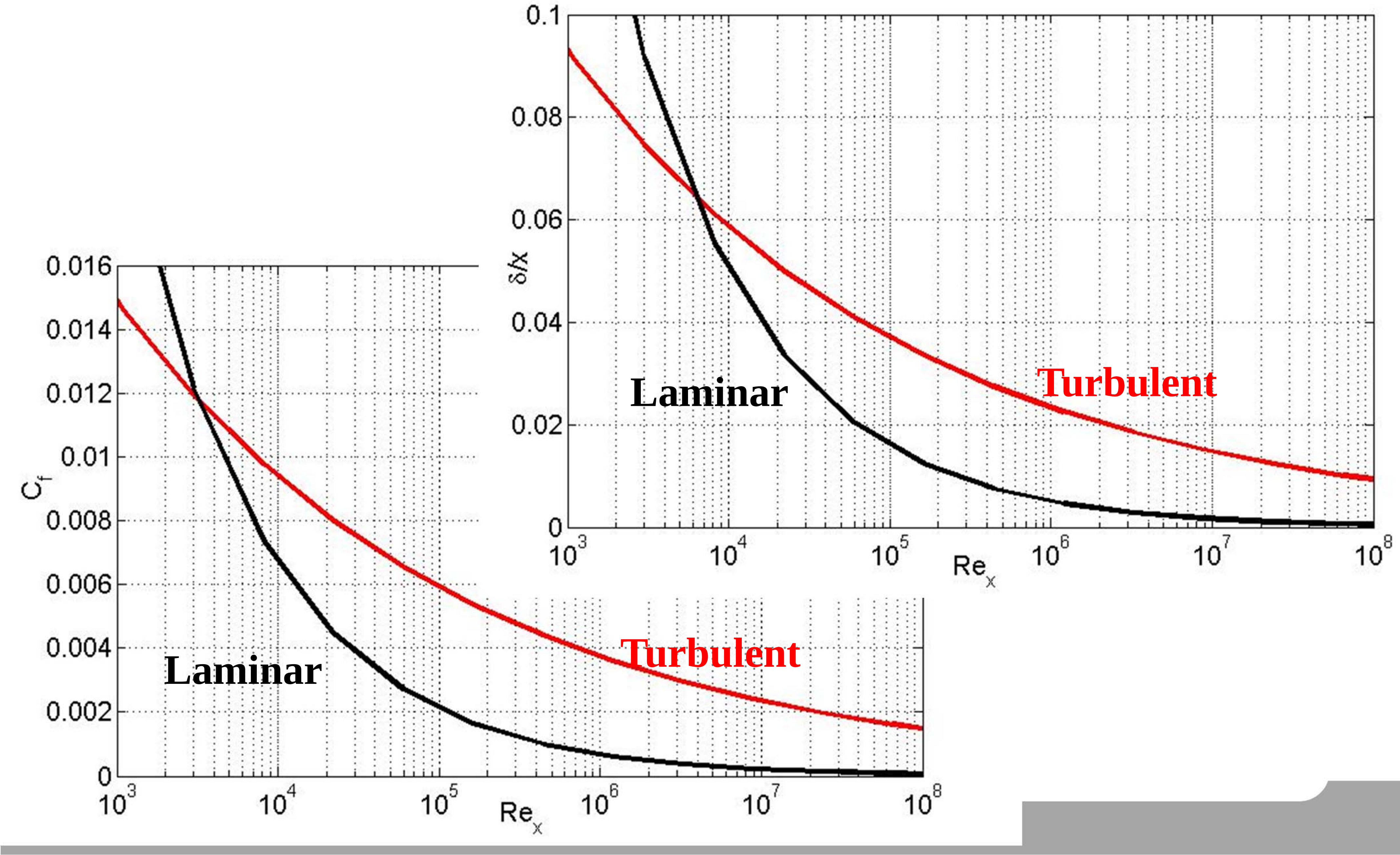
- Viscous wall distance

$$y^+ = \frac{y}{l_*} = \frac{y u_\tau}{\nu}$$

Empirical relations for BLs

- Friction coefficient
  - Turbulent $\dfrac{C_f}{2} \approx 0{,}0296 Re_x^{-1/5}$
  - Laminar $\dfrac{C_f}{2} = 0{,}332 Re_x^{-1/2}$
- Boundary layer thickness
  - Turbulent $\dfrac{\delta}{x} \approx 0{,}37 Re_x^{-1/5}$
  - Laminar $\dfrac{\delta}{x} = 5{,}0 Re_x^{-1/2}$

Empirical relations plotted



Empirical relations plotted