Outline

- Motivation
- Governing equations for LES
- Boundary conditions
- Subfilter-scale modelling
- Validation of an LES
- Applications
- **Hybrid RANS/LES methods**
- Challenges
- Conclusions

Hybrid RANS/LES Methods

- Many external flows of aerodynamic interest occur at **high Reynolds numbers** and are characterized by regions of massive separation.
- Traditional approach to modelling has been based on solution of the steady or unsteady Reynolds-averaged equations (RANS – URANS)
  - *Calibration range of RANS models based on "standard" eddies.*
- Problems for RANS methods
  - *Structures of massive separations sensitive to geometry, boundary conditions, etc.*

➢ **RANS (or URANS) does not offer a uniformly accurate approach for massively separated flows.**

Cost of a simulation

- Governing equations are discretized in time and space.
- Cost ~ [Number of grid points] × [Integration time]
  ⇒ Cost depends on the solution methodology
- Turbulence theory gives guidance:
  - *RANS Solution:* $Cost \sim Re^{0.6}$
  - *LES (free flows):* $Cost \sim Re^{0.6}$
  - *LES (wall-bounded flows):*
    - Wall Layer Modelled (WMLES): Cost ~ $Re^{0.6}$
    - Wall Layer Resolved: Cost ~ $Re^{2.4}$
  - *DNS:* $Cost \sim Re^{3} \rightarrow Re^{3.6}$

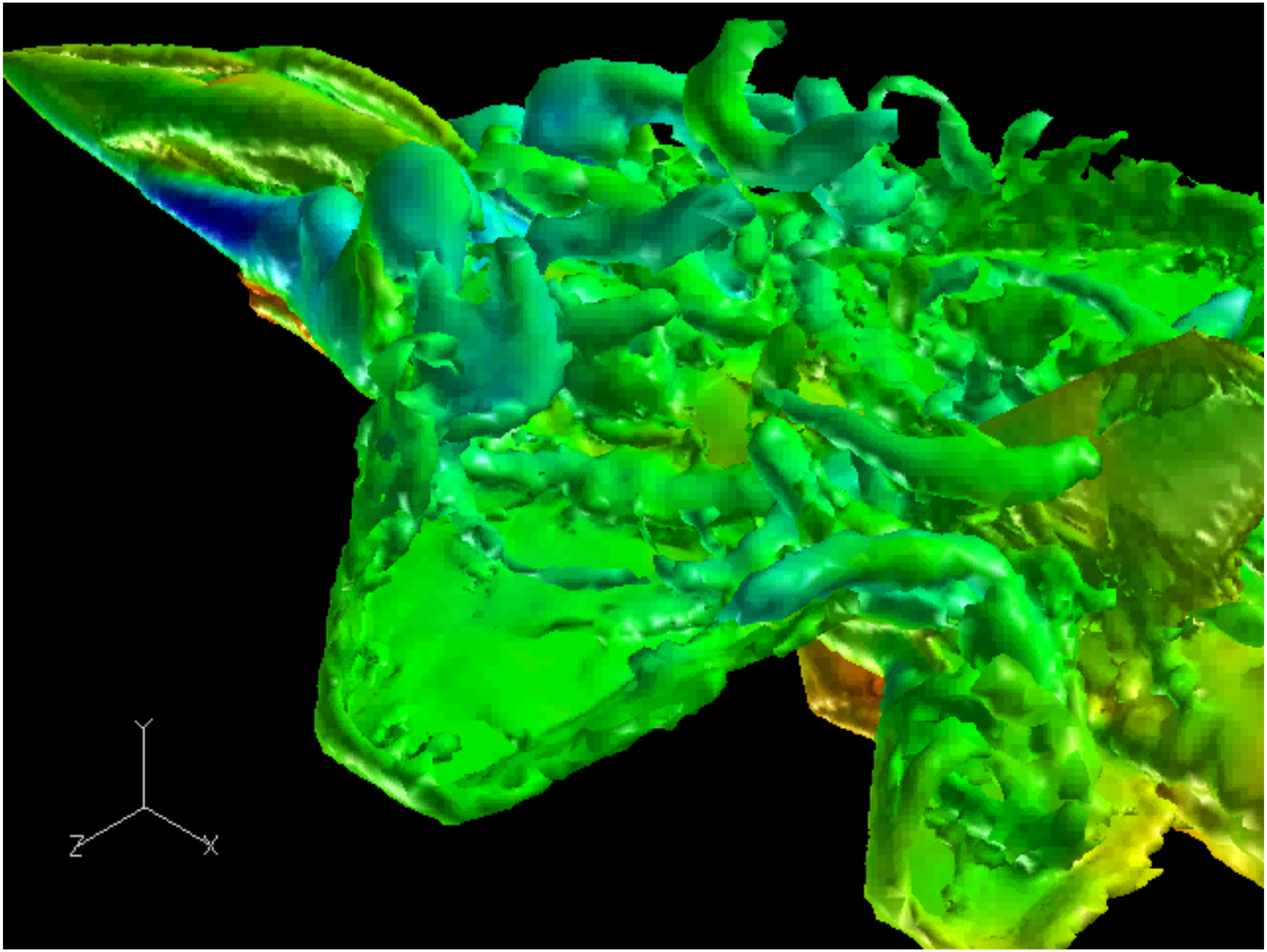
Cost of a simulation

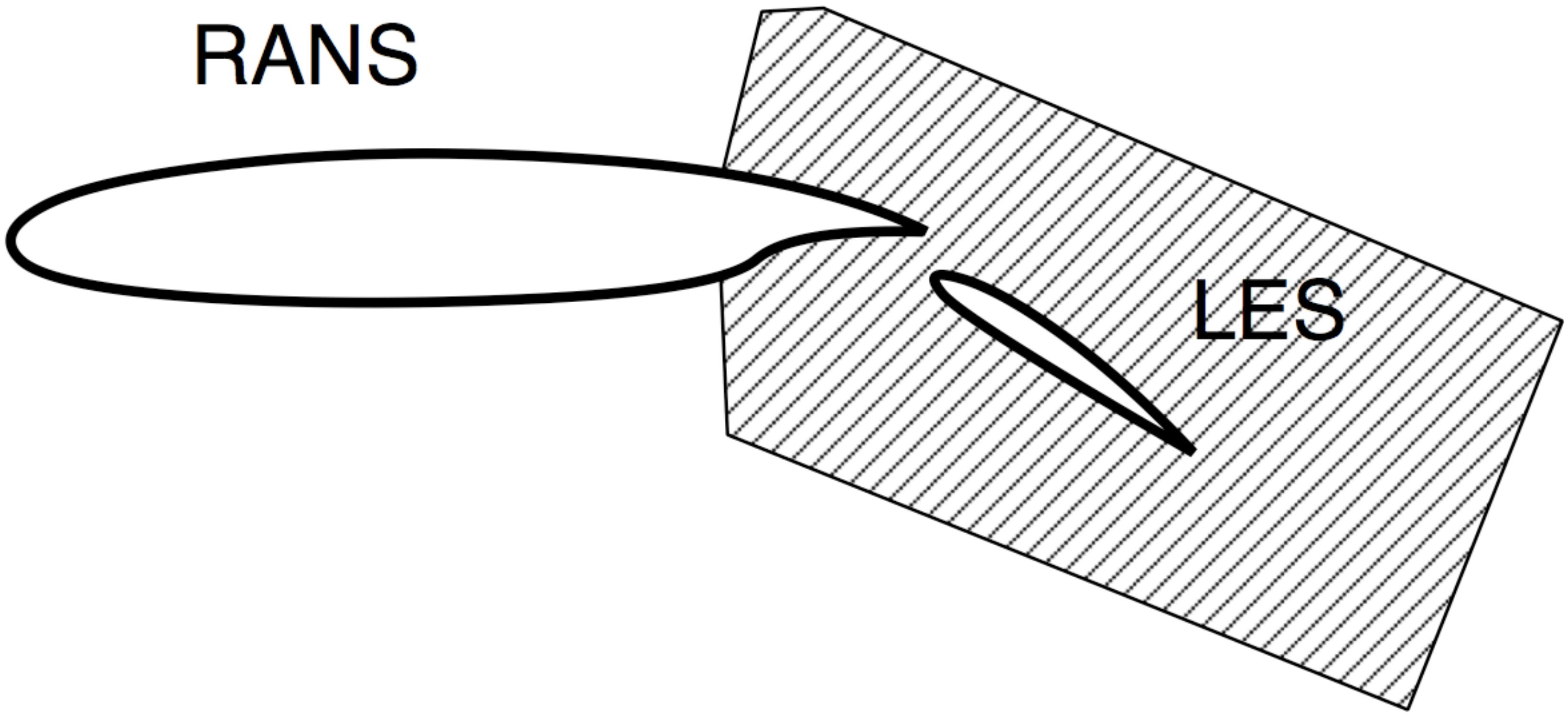
Cost of Computational approaches for the simulation of an aircraft (from Spalart, 2000)

Name	Re-dep.	Empiricism	Grid	Steps	Ready
2DURANS	weak	strong	10^5	$10^{3.5}$	1980
3DRANS	weak	strong	10^7	10^3	1990
3DURANS	weak	strong	10^7	$10^{3.5}$	1995
WMLES	weak	weak	$10^{11.5}$	$10^{6.7}$	2045
LES	strong	weak	10^{15}	$10^{7.3}$	2070
DNS	strong	none	10^{16}	$10^{7.7}$	2080

- Accurate methods are infeasible.
- Feasible methods are (often) inaccurate.
- Hybrid RANS/LES:
  - *Use (U)RANS in regions in which models are accurate.*
  - *Use LES in non-equilibrium regions (separation, 3D mean flow, high pressure gradients) or where structural information is required (noise emission).*

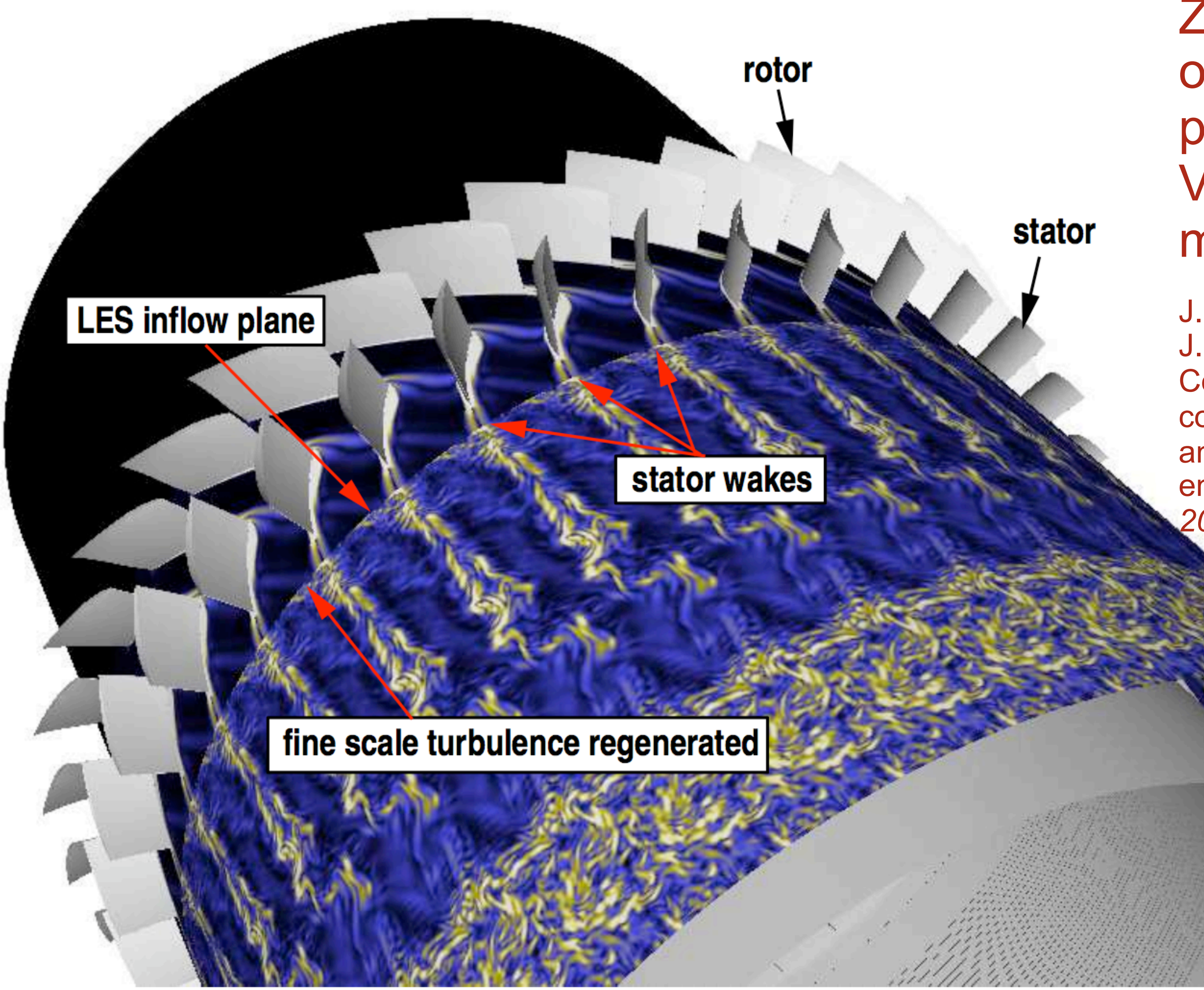
Hybrid RANS/LES Methods





- Attached boundary layer URANS
- LES includes attached & separated flows.

Hybrid RANS/LES
Zonal RANS/LES

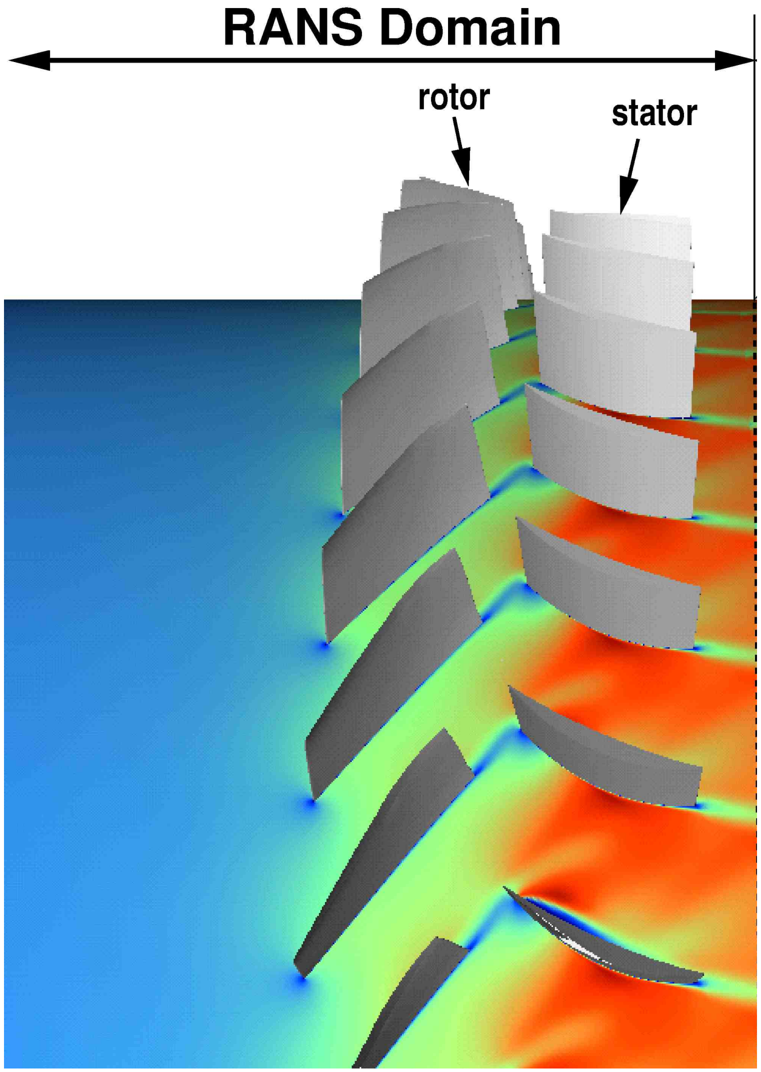


Zonal RANS/LES of a compressor/ prediffuser. Vorticity magnitude.

J. U. Schlüter, X. Wu, S. Kim, J. J. Alonso, and H. Pitsch. Coupled RANS-LES computation of a compressor and combustor in a gas turbine engine. *AIAA Paper 2004-3417*, 2004.

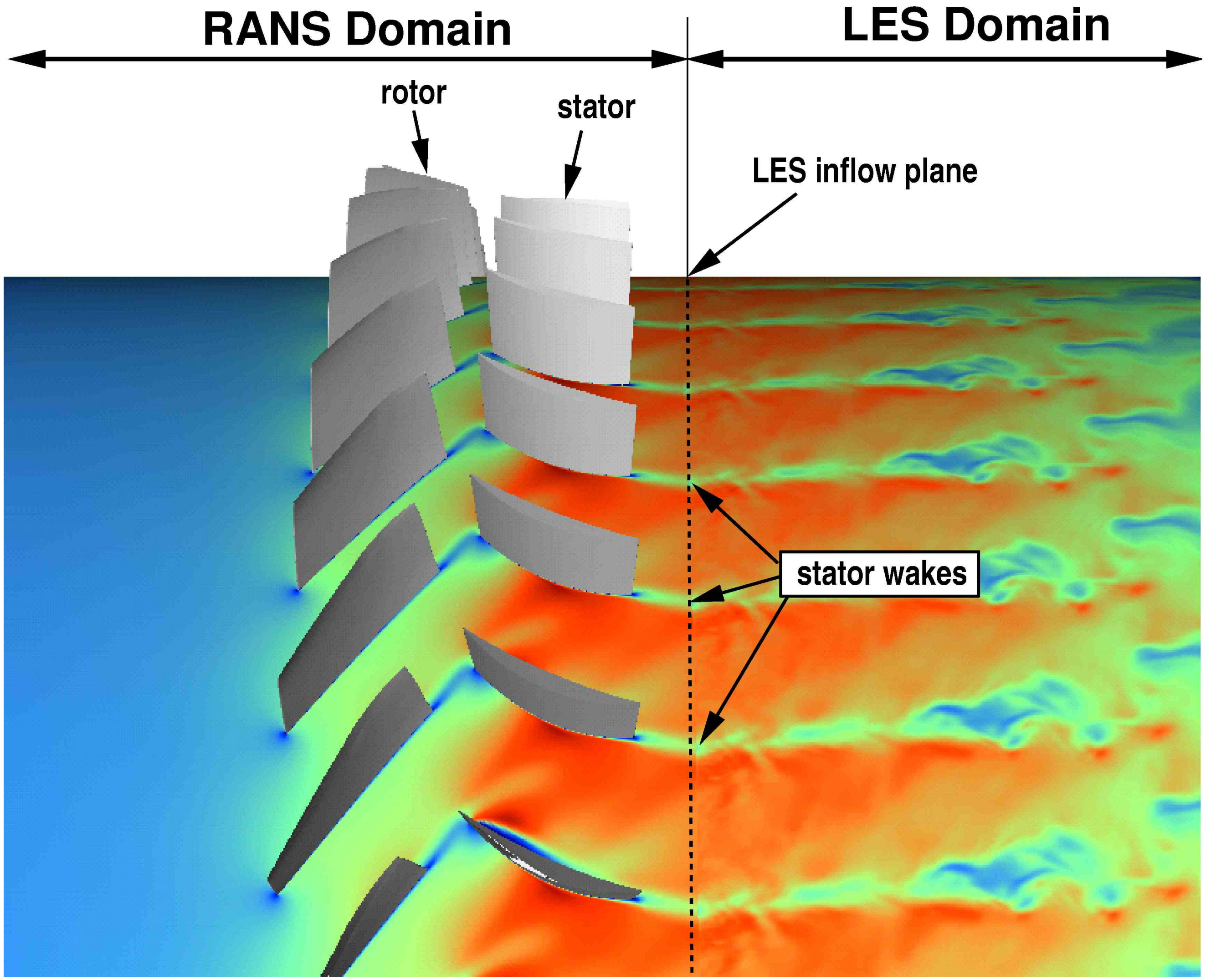
Flow in a compressor and prediffuser.

From Schlüter *et al.*, AIAA Paper 2004-3417

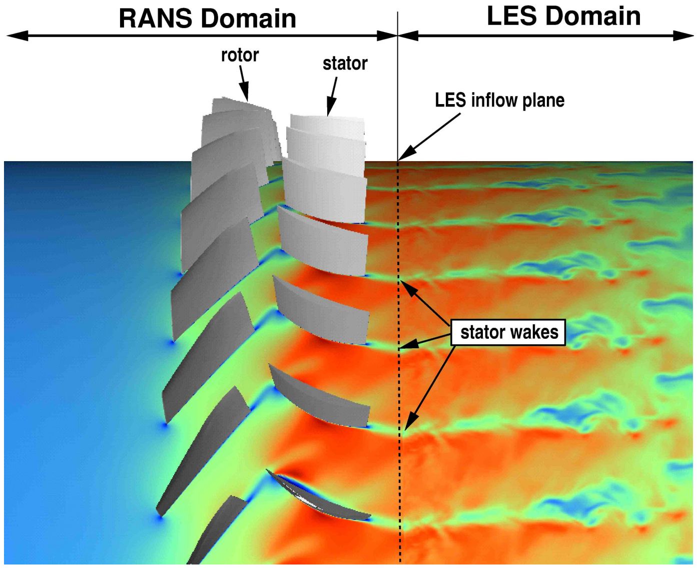


Flow in a compressor and prediffuser.

From Schlüter *et al.*, AIAA Paper 2004-3417



- How is turbulence generated at the RANS/LES interface?
  - *RANS: smooth, Reynolds stress represented through eddy viscosity*
  - *LES: fluctuating, Reynolds stress mostly resolved*

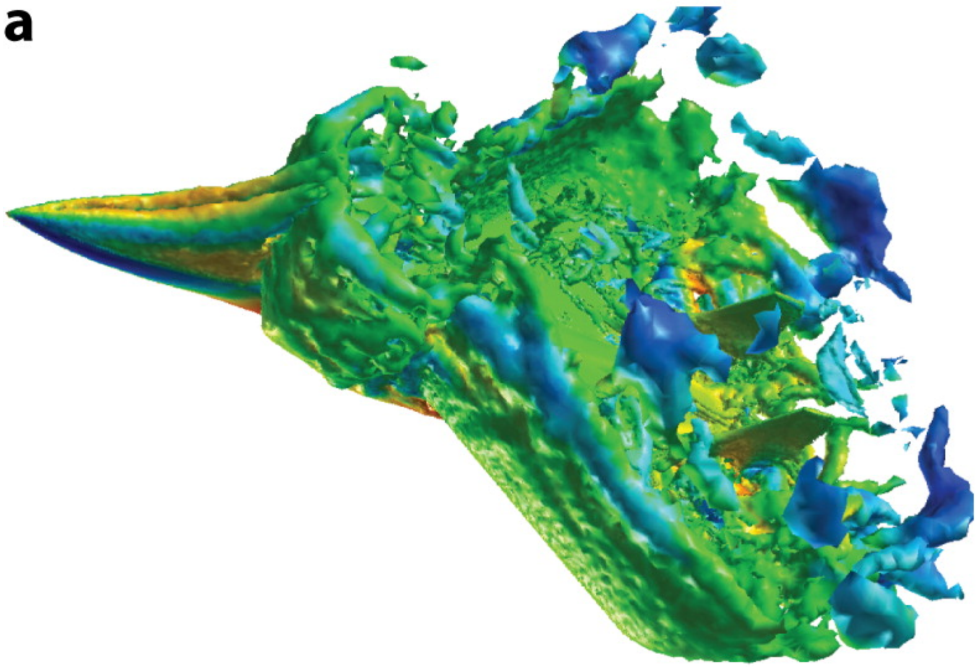


Non-Zonal RANS/LES

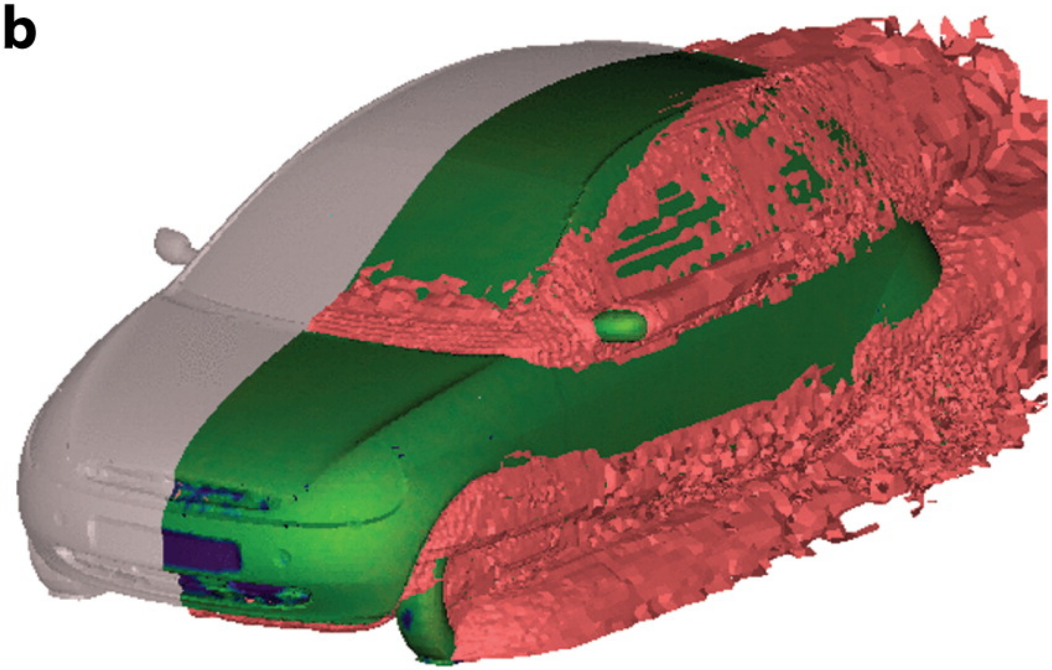
Vorticity isosurfaces colored with pressure over an F-15 jet at a 65° angle of attack (Forsythe et al. 2004).

Acoustic-source isosurface around a Ford Ka automobile (es turbo 3.1) (Mendonça et al. 2002).

a



b



Spalart PR. 2009.
Annu. Rev. Fluid Mech. 41:181–202

Hybrid RANS/LES Methods

- Main approaches:
  - *Blended models*
    - Different models may be used in the different zones
    - Blending functions are used at the RANS/LES interface
    - The interface may be fixed, depend on the grid, or on the state of the turbulence itself.
  - *Unified models*
    - The same model is used everywhere
    - The model “knows” how much of the flow is to be modeled.
      - Reduced model contribution in LES zone

Hybrid RANS/LES Methods

- Main approaches:
  - *Blended models*
    - SST + Smagorinsky (Edwards & co-workers)
    - Limited Numerical Scales (LNS)
    - Two-layer model
    - Hamba (Tokyo), Leschziner (Imperial College), Davidson (Chalmers),…
  - *Unified models*

Blended Models

$$\tau_{ij} = f^{\mathrm{LES}}\tau_{ij}^{\mathrm{LES}} + f^{\mathrm{RANS}}\tau_{ij}^{\mathrm{RANS}}$$

- The model is a blend of the RANS contribution and the LES one (could be different models, e.g. k-ε and Smagorinsky).

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Large-Eddy/Reynolds-Averaged Navier–Stokes Simulation of a Mach 5 Compression-Corner Interaction

Jack R. Edwards,[*] Jung-Il Choi,[†] and John A. Boles[‡]
North Carolina State University, Raleigh, North Carolina 27695

- The SST RANS model is blended with the Smagorinsky SGS model:

$$\nu_T = \Gamma \nu_T^{SST} + (1-\Gamma)\nu_T^{SGS}$$

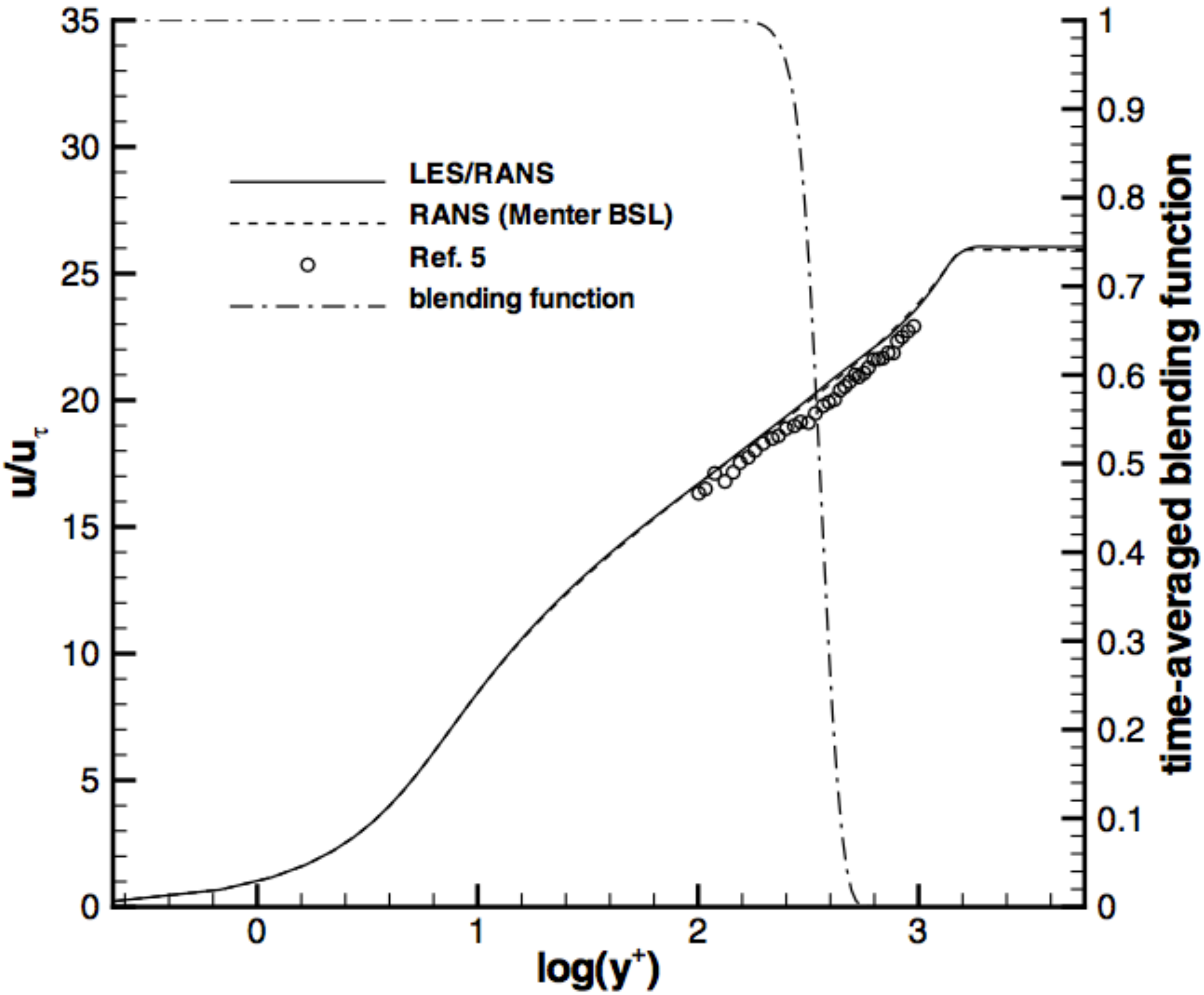
$$\nu_T = \Gamma \nu_T^{SST} + (1-\Gamma)(C_S \Delta)^2 \left|\overline{S}\right|$$

$$\Gamma = f(\text{distance from wall}/\text{Taylor micro scale})$$

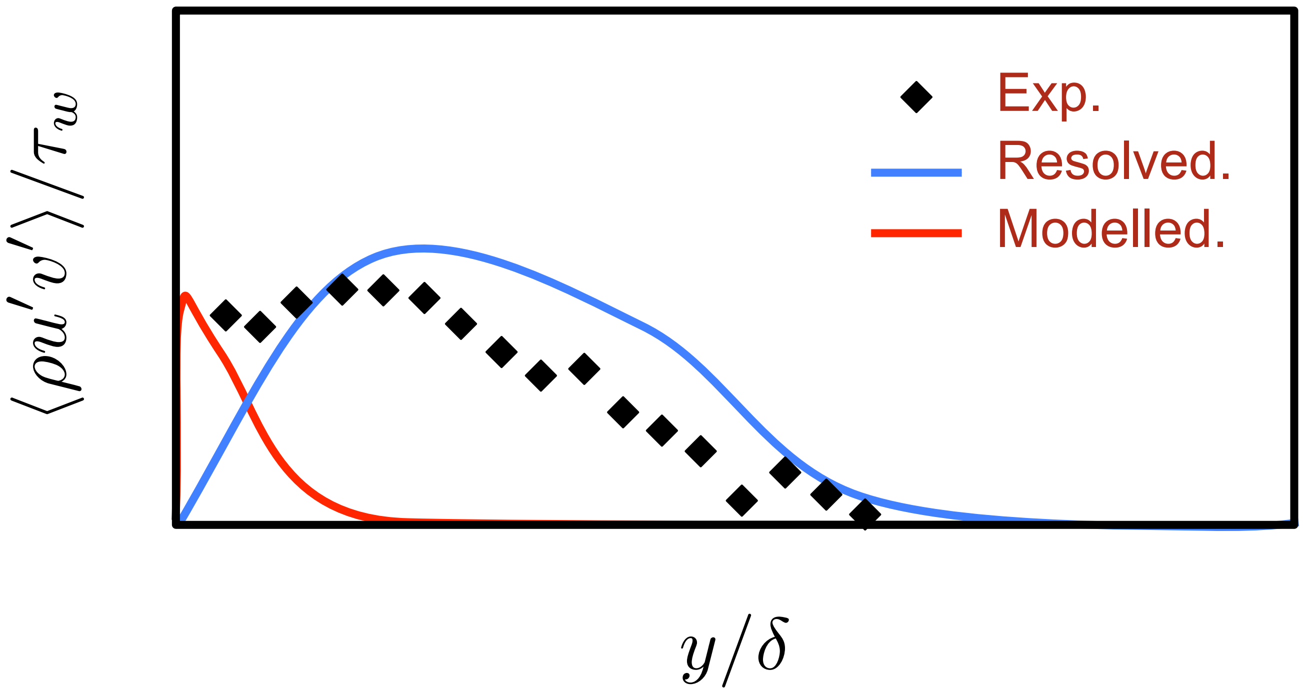
Blended Models

- The location where the solution switches from RANS to LES is determined by
  - *Flow dynamics*
  - *Parameters used in the definition of* Γ
- Calibration performed for one flow (ZPG bl) may not be universal.
- As the filter width approaches 0, the method does not converge to a DNS
  - Δ *does not enter the definition of* Γ.

- Sample application: ZPG boundary layer



- Sample application: ZPG boundary layer



- Sample application: Compression corner

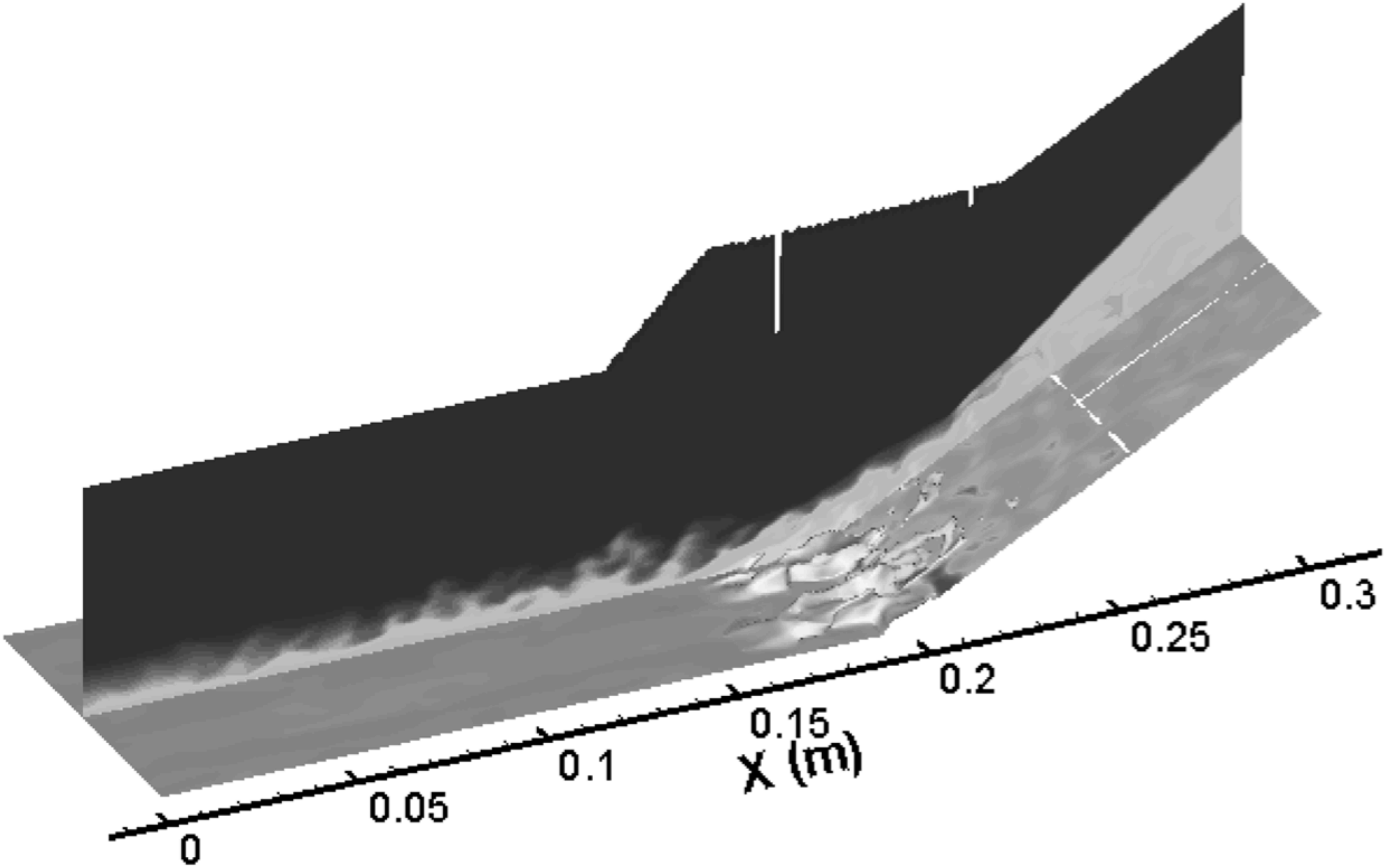


Fig. 5 Isosurfaces of zero axial velocity shaded by temperature.

Blended Models

- Sample application: Compression corner

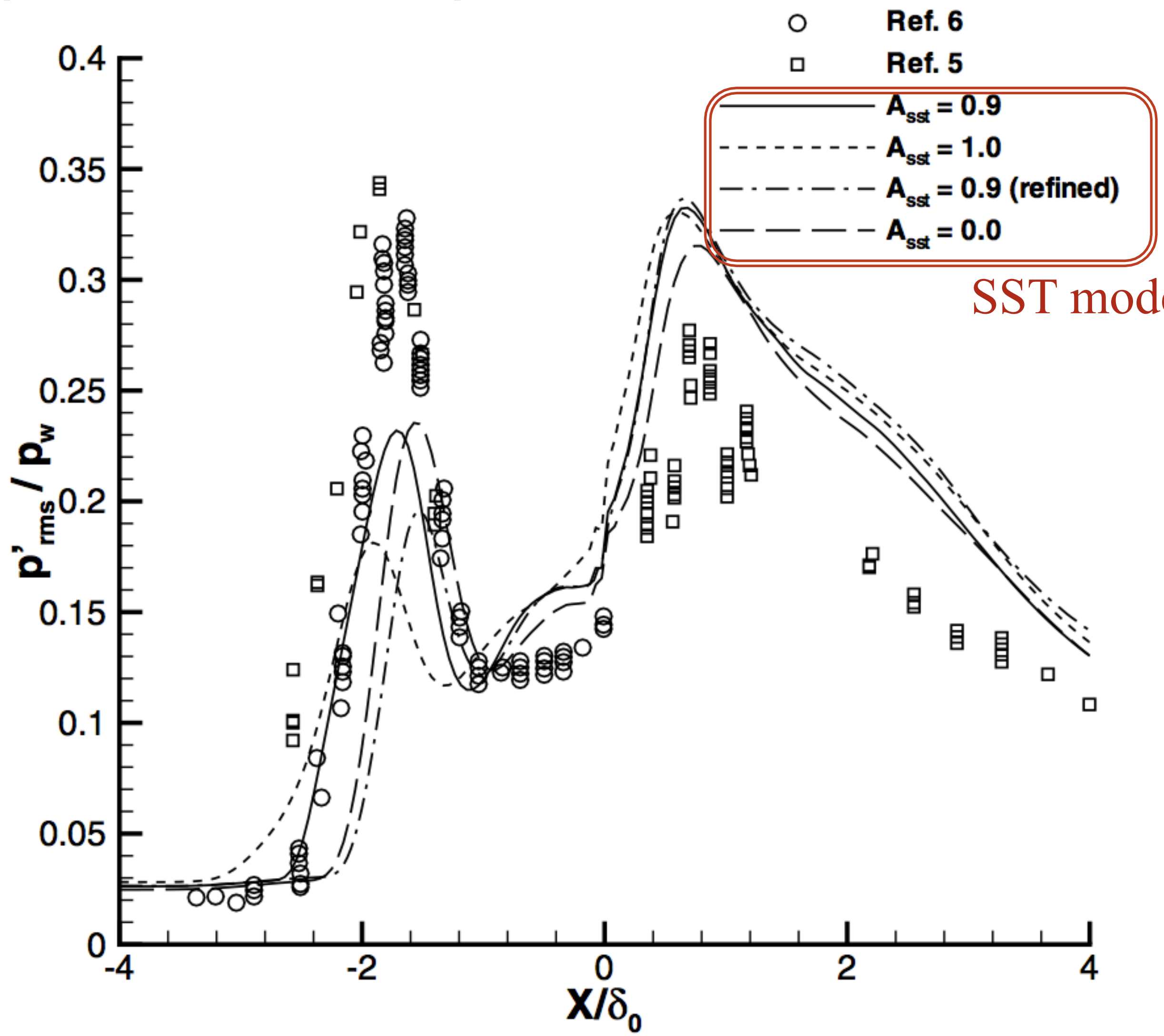


Fig. 14 The rms pressure-fluctuation distributions normalized by local wall pressure.

Blended Models - LNS

- LNS = Limited Numerical Scales
  - *Nonlinear* $\mathcal{K}-\varepsilon$ *model.*
  - *Eddy viscosity reduced by a factor* α

$$\nu_T = \alpha \nu_T^{\mathrm{RANS}}$$

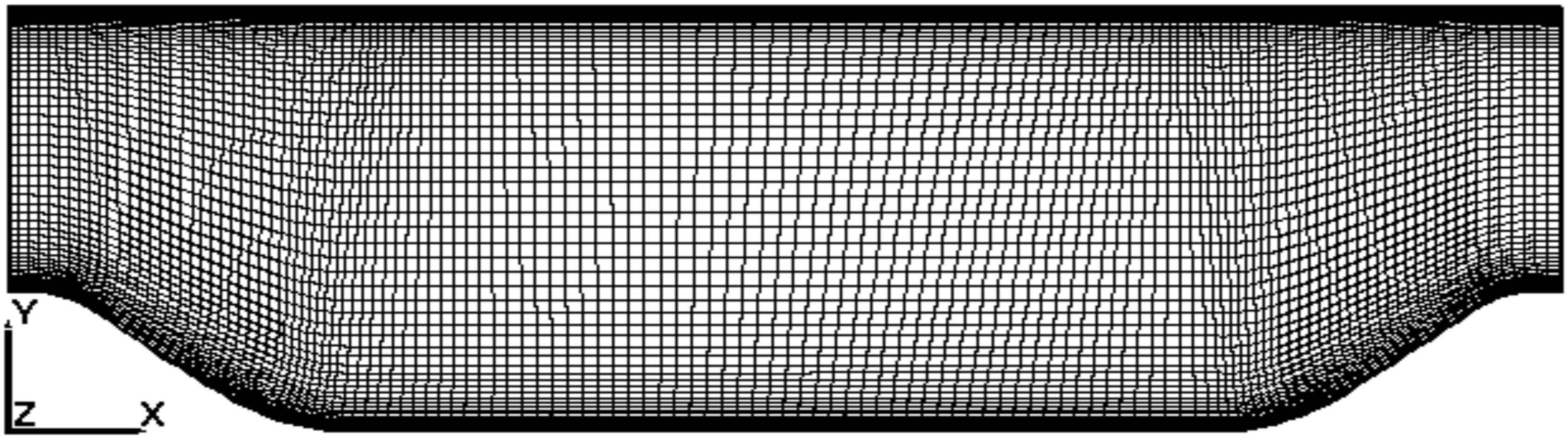
$$\alpha = \frac{\min\left(\nu_T^{\mathrm{Smag}}, \nu_T^{\mathrm{RANS}}\right)}{\nu_T^{\mathrm{RANS}}}$$

  - *Effectively, Smagorinsky model in the LES region*

AIAA 2002-0427
LNS - An Approach Towards Embedded LES

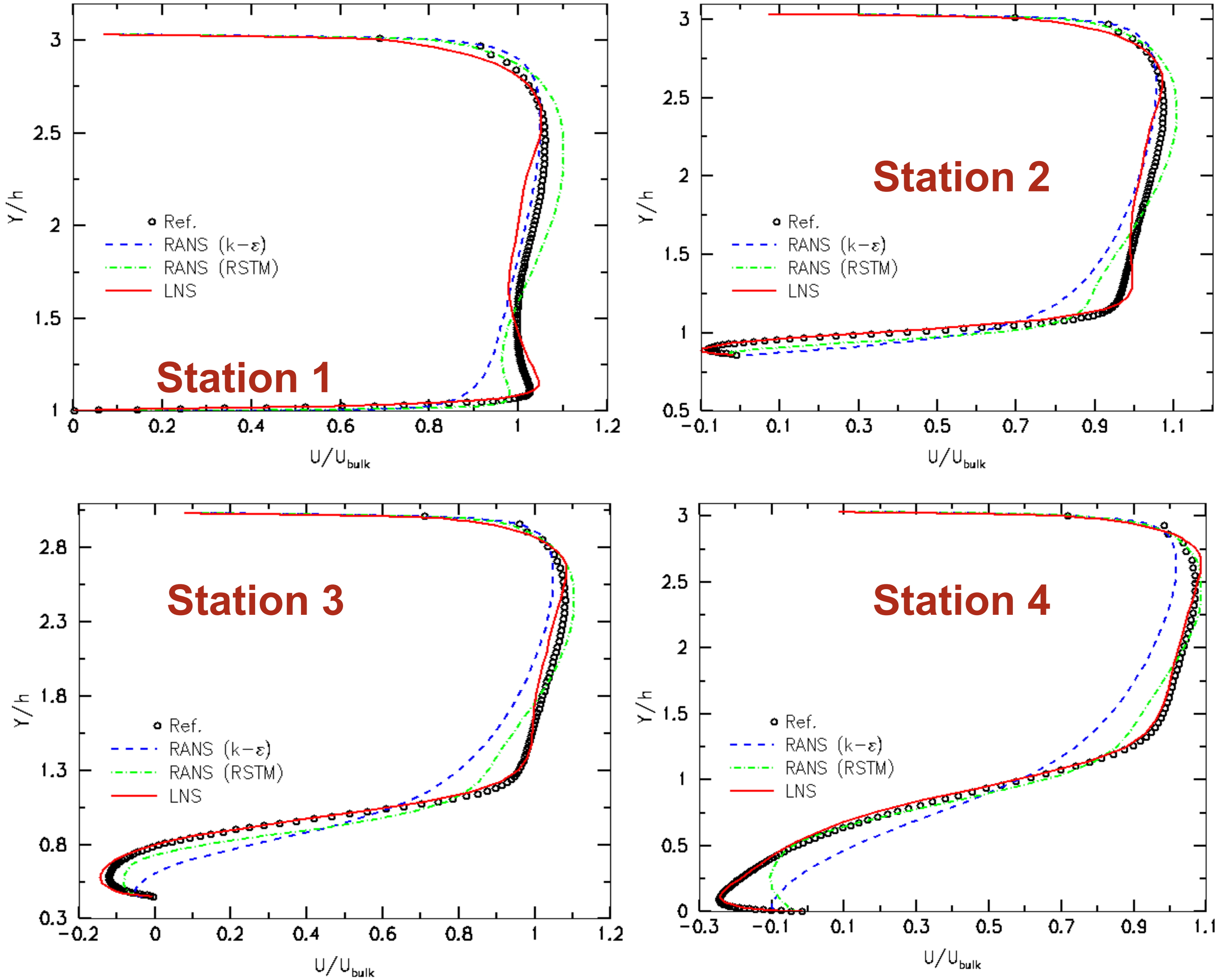
P. Batten, U. Goldberg & S. Chakravarthy
Metacomp Technologies, Inc.
Westlake Village, CA

Blended Models - LNS

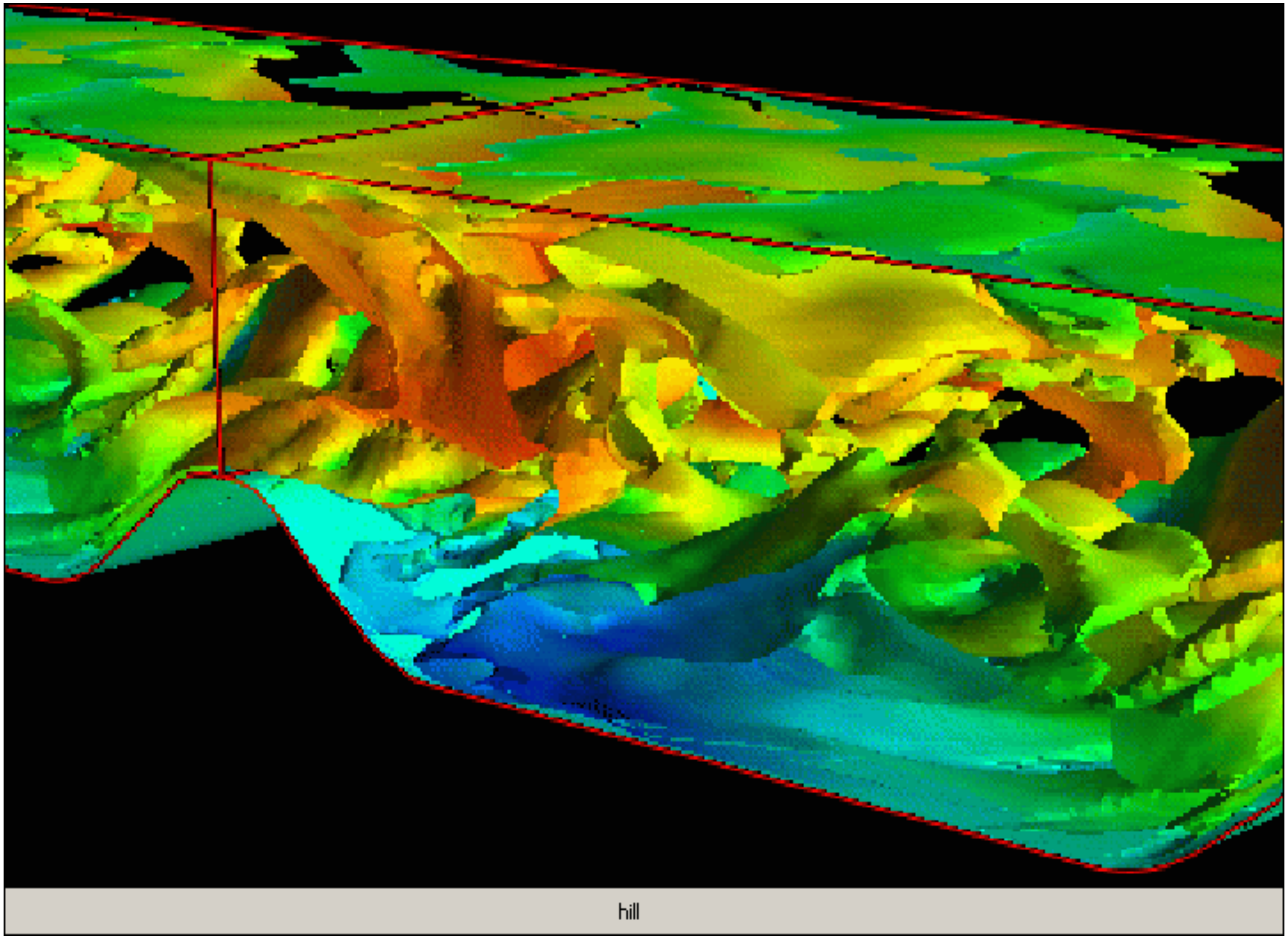


- 128x64x72 mesh
- Ref. LES+no-slip 6000 CPU hours
- LNS 400 CPU hours (PII, 600MHz, 600K cells)

Blended Models - LNS



Blended Models - LNS



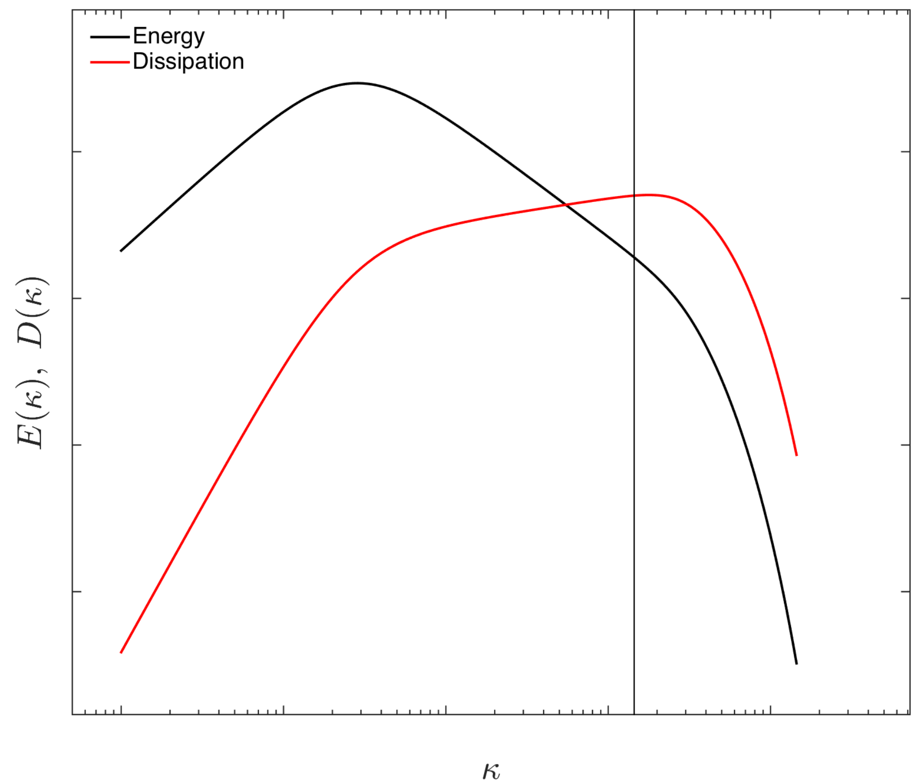
Blended Models - LNS

- LNS = Limited Numerical Scales
  - *Physical interpretation:*

$$(1-\alpha)\mathcal{K} = \text{Resolvable energy}$$

$$(1-\alpha)\varepsilon = \text{Resolvable dissipation}$$

  - *However, α cannot be the same:*
    - For a given resolution (i.e., cutoff) the fraction of energy resolved is larger than the fraction of dissipation resolved



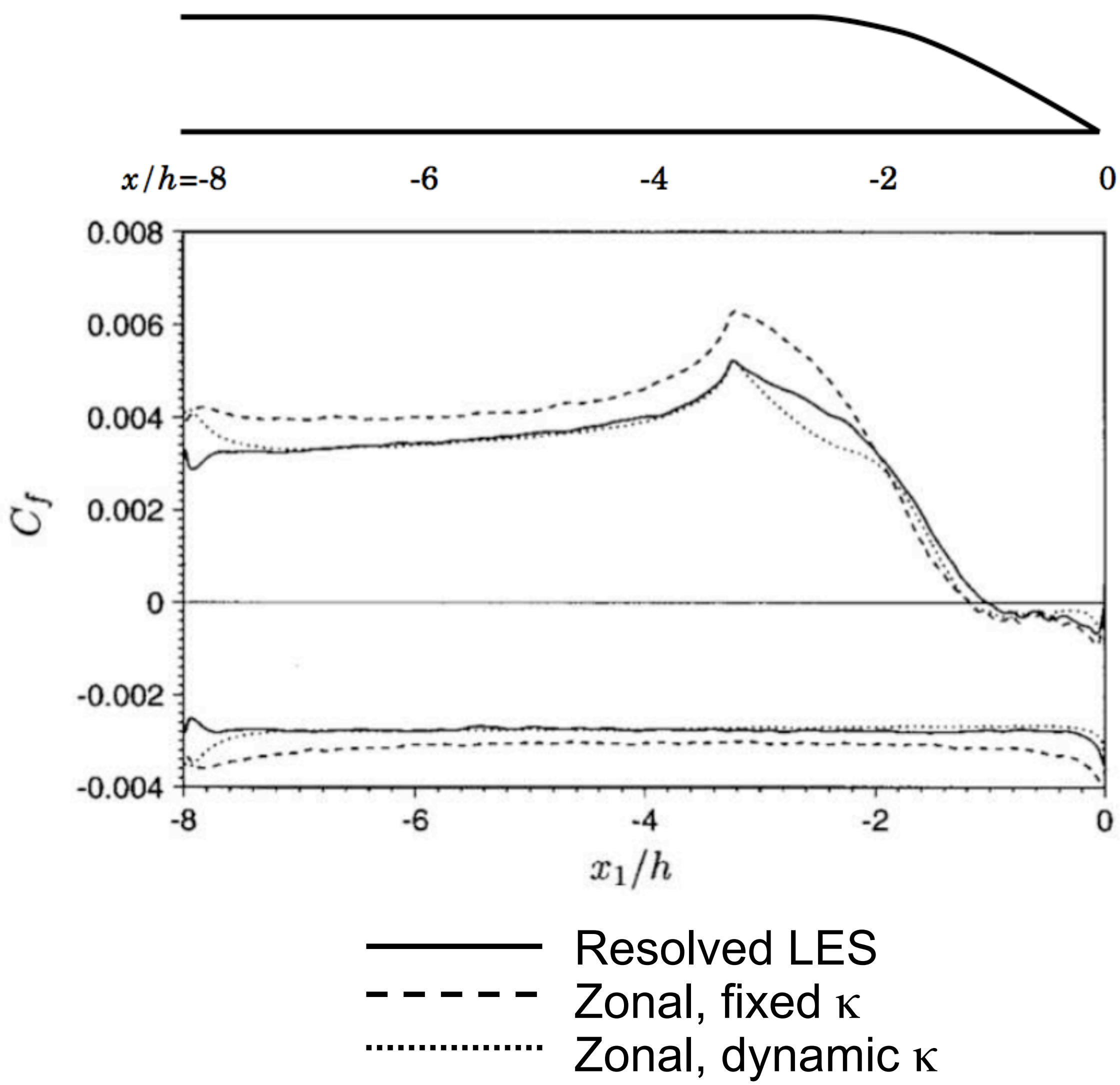
Blended Models:
Two-Layer model

- RANS in the wall layer (y<0.1-0.2δ), LES in the outer layer.
- Interface fixed by the grid
- Balaras and co-workers (1994,1996). Cabot (1995, 1996). Cabot & Moin (2000). Wang and Moin (2000). Diurno et al. (2001). Menon and co-workers (2006, 2007).
- Solve the Reynolds-Averaged b.l. equations on a 1D embedded mesh between the first point in the outer layer and the wall.

$$
\begin{aligned}
\frac{\partial \overline{u}_i}{\partial t} &= -\frac{\partial}{\partial x_j}\overline{u}_i\overline{u}_j - \frac{\partial P_e}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\nu+\nu_T)\frac{\partial \overline{u}_i}{\partial x_j}\right] \qquad \text{for } i=1,3; \\
\overline{u}_2 &= -\int_0^y \left(\frac{\partial \overline{u}_1}{\partial x_1} + \frac{\partial \overline{u}_3}{\partial x_3}\right) dy;
\end{aligned}
$$

Blended Models:
Two-Layer model

- Acoustic emission from a trailing edge (Wang & Moin 2001).
- Hybrid FD-spectral method.
- Eddy viscosity in the mixing length model (i.e., von Kármán constant κ) must be reduced to account for resolved motions.



Hybrid RANS/LES Methods

- Main approaches:
  - *Blended models*
    - SST + Smagorinsky (Edwards & co-workers)
    - Limited Numerical Scales (LNS)
    - Two-layer model
    - Hamba (Tokyo), Leschziner (Imperial College), Davidson (Chalmers),…
  - *Unified models*
    - Detached Eddy Simulation (DES) (Spalart and co-workers)
    - Scale-Adaptive Simulation (SAS) (Menter and co-workers)
    - Partially Averaged Navier-Stokes Equations (PANS) (Girimaji and co-workers)

Unified Models
Partially averaged NS eqns (PANS_

- S. S. Girimaji. Partially Averaged Navier-Stokes method for turbulence: a Reynolds-Averaged Navier- Stokes to direct numerical simulation bridging method. J. Appl. Mech., 73:413–421, 2006.
- Goal:
  - *Bridge DNS to RANS*
- Methodology
  - *Begin with a RANS model*
  - *Identify the appropriate filter width (resolved TKE/total TKE)*
  - *Develop closure for Partially Averaged NS equations (in which more eddies are resolved – at a price)*

Unified Models
Partially averaged NS eqns (PANS_

- Begin with a RANS model (K-ε)

$$\nu_t = C_\mu \frac{K^2}{\varepsilon} S_{ij}$$

$$\frac{\partial K}{\partial t} + \bar{U}_j \frac{\partial K}{\partial x_j} = P - \varepsilon + \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k} \frac{\partial K}{\partial x_j} \right)$$

$$\frac{\partial \varepsilon}{\partial t} + \bar{U}_j \frac{\partial \varepsilon}{\partial x_j} = C_{e1} \frac{P\varepsilon}{K} - C_{e2} \frac{\varepsilon^2}{K} + \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_\epsilon} \frac{\partial \varepsilon}{\partial x_j} \right)$$

- Define the ratio of unresolved-to-resolved TKE and dissipation:

$$f_k = \frac{K_u}{K}, \quad f_\varepsilon = \frac{\varepsilon_u}{\varepsilon}$$

- PANS governing equations

$$\frac{\partial K_u}{\partial t} + U_j \frac{\partial K_u}{\partial x_j} = P_u - \varepsilon_u + T_{ku}$$

$$\frac{\partial \varepsilon_u}{\partial t} + U_j \frac{\partial \varepsilon_u}{\partial x_j} = C_{e1} f_k \left(\frac{P_u}{f_k} - \frac{\varepsilon_u}{f_\varepsilon f_k}(f_\varepsilon - f_k) \right) \frac{\varepsilon_u}{K_u} - C_{e2} \frac{f_k}{f_\varepsilon} \frac{\varepsilon_u^2}{K_u}$$

$$+ \frac{\partial}{\partial x_j} \left(\frac{\nu_t}{\sigma_\epsilon} \frac{\partial \varepsilon_u}{\partial x_j} \right) + (U_j - \bar{U}_j) \frac{\partial \varepsilon_u}{\partial x_j}$$

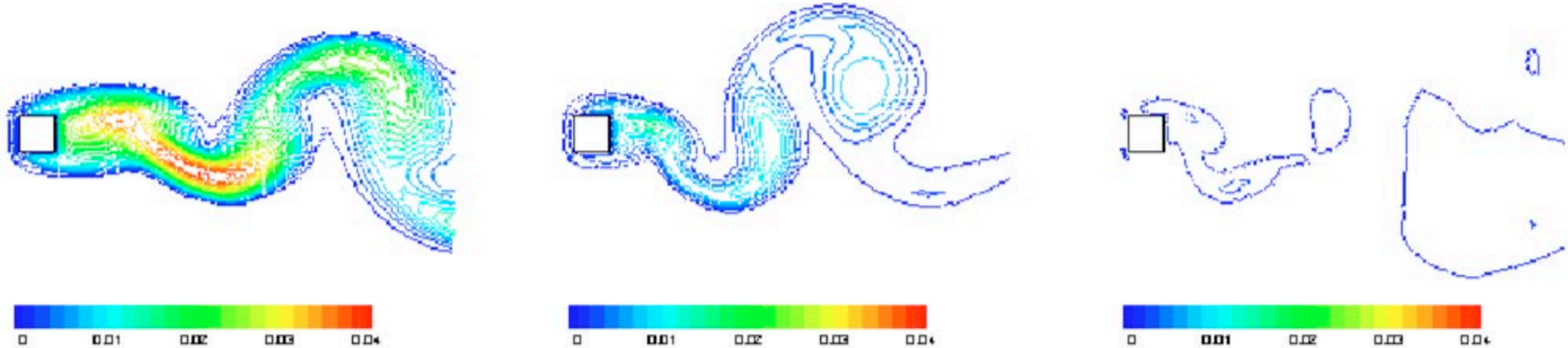
$$= C_{e1} \frac{P_u \varepsilon_u}{K_u} - C_{e2}^* \frac{\varepsilon_u^2}{K_u} + \frac{\partial}{\partial x_j} \left(\frac{\nu_u}{\sigma_{\epsilon u}} \frac{\partial \varepsilon_u}{\partial x_j} \right)$$

- Setting f_ε=1 (dissipation entirely provided by model), f_k is the parameter that determines whether the calculation is in RANS model (f_k=1) or in LES mode (0<f_k<1)
- Also extended to k-ω

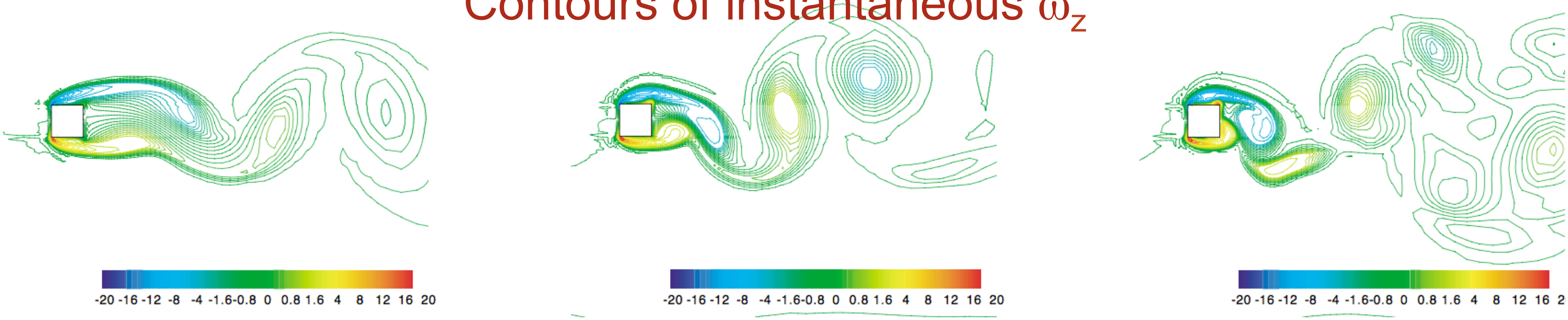
Unified Models
Partially averaged NS eqns (PANS_

f_k=1.0 f_k=0.7 f_k=0.4

Contours of instantaneous ν_T



Contours of instantaneous ω_z



- Detached Eddy Simulation (DES) and Scale-Adaptive Simulation (SAS):
  - *Solve a transport equation for the eddy viscosity*

$$\frac{D\nu_T}{Dt} = \text{Production} + \text{Diffusion} + \text{Destruction}$$

  - *The "Destruction of eddy viscosity" term is modified in LES regions to decrease the eddy-viscosity.*

- KE1E-SAS model (Menter et al. 2003):
  - *Transport equation for ν_T*
  - *Modification of the destruction term:*

$$\frac{\partial(\rho\nu_t)}{\partial t}+\frac{\partial(\rho U_j\nu_t)}{\partial x_j}=c_1\mu_t S-c_2\rho\left(\frac{\nu_t}{L_{\nu K}}\right)^2+\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma}\frac{\partial\nu_t}{\partial x_j}\right)$$

$$L_{\nu K-URANS}=\frac{(S\cdot S)}{\left(\frac{\partial S}{\partial x_j}\cdot\frac{\partial S}{\partial x_j}\right)}$$

$$L_{\nu K-SAS}=\left|\frac{\frac{\partial U_i}{\partial x_j}\frac{\partial U_i}{\partial x_j}}{\frac{\partial^2 U_l}{\partial x_m^2}\frac{\partial^2 U_l}{\partial x_n^2}}\right|$$

  - *The SAS length scale reflects better the effects of the small-scale turbulence*

- Extension to *k*-ω SST model (Menter & Egorov 2010):

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial\left(\rho U_j k\right)}{\partial x_j} = P_k - c_\mu^{3/4}\cdot\rho\frac{k^2}{\Phi} + \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)$$

$$\frac{\partial\rho\omega}{\partial t} + \frac{\partial\rho U_j\omega}{\partial x_j} = \frac{\omega}{k}P_k\left(1-\zeta_1+\zeta_2\left(\frac{L}{L_{\nu K}}\right)^2\right) - \rho\omega^2\left(c_\mu - c_\mu^{1/4}\zeta_3\right)$$

$$+\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\Phi}\frac{\partial\omega}{\partial x_j}\right) + \frac{2\rho}{\sigma_\Phi}\left(\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} - \frac{k}{\omega^2}\frac{\partial\omega}{\partial x_j}\frac{\partial\omega}{\partial x_j}\right)$$

$$+\ \max\left[\rho\zeta_2 S^2\left(\frac{L}{L_{\nu K}}\right)^2 - C_{SAS}\frac{2\rho k}{\sigma_\Phi}\max\left(\frac{1}{k^2}\frac{\partial k}{\partial x_j}\frac{\partial k}{\partial x_j}, \frac{1}{\omega^2}\frac{\partial\omega}{\partial x_j}\frac{\partial\omega}{\partial x_j}\right), 0\right]$$

- Extension to k-ω SST model (Menter & Egorov 2010):

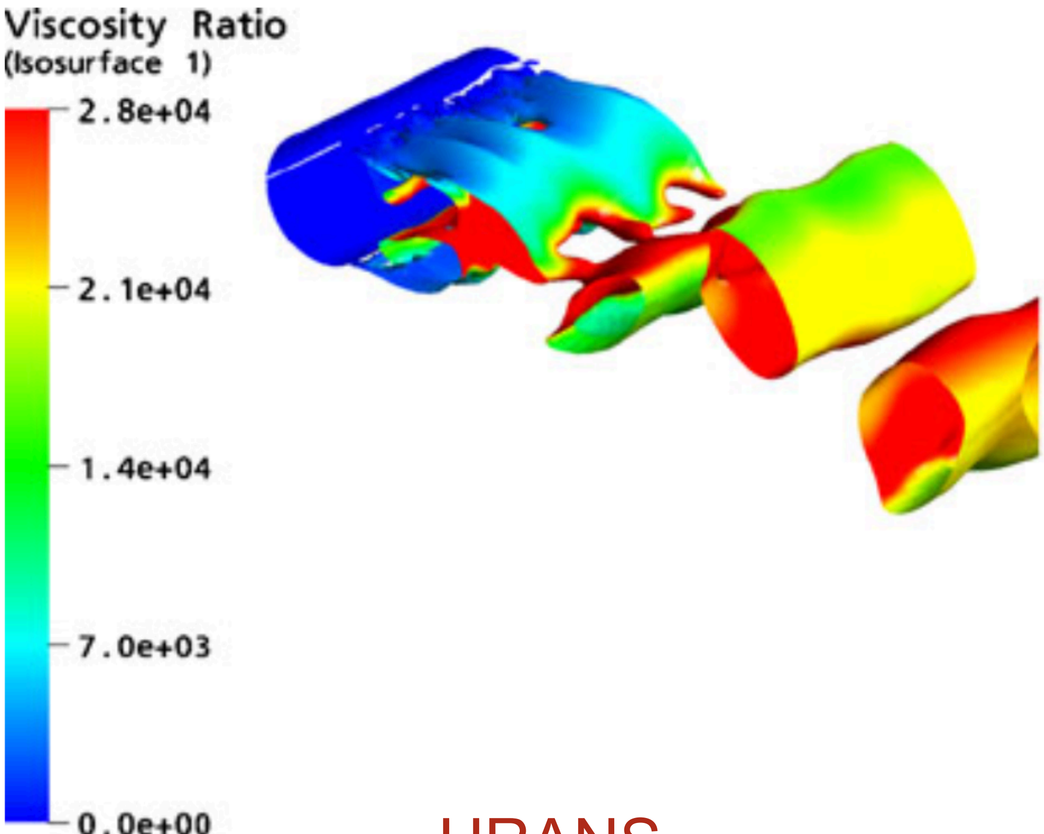
$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial\left(\rho U_j k\right)}{\partial x_j} = P_k - c_\mu^{3/4} \cdot \rho \frac{k^2}{\Phi} + \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)$$

$$\frac{\partial \rho\omega}{\partial t} + \frac{\partial \rho U_j \omega}{\partial x_j} = \frac{\omega}{k} P_k \left(1 - \zeta_1 + \zeta_2 \left(\frac{L}{L_{\nu K}}\right)^2\right) - \rho\omega^2\left(c_\mu - c_\mu^{1/4}\zeta_3\right)$$

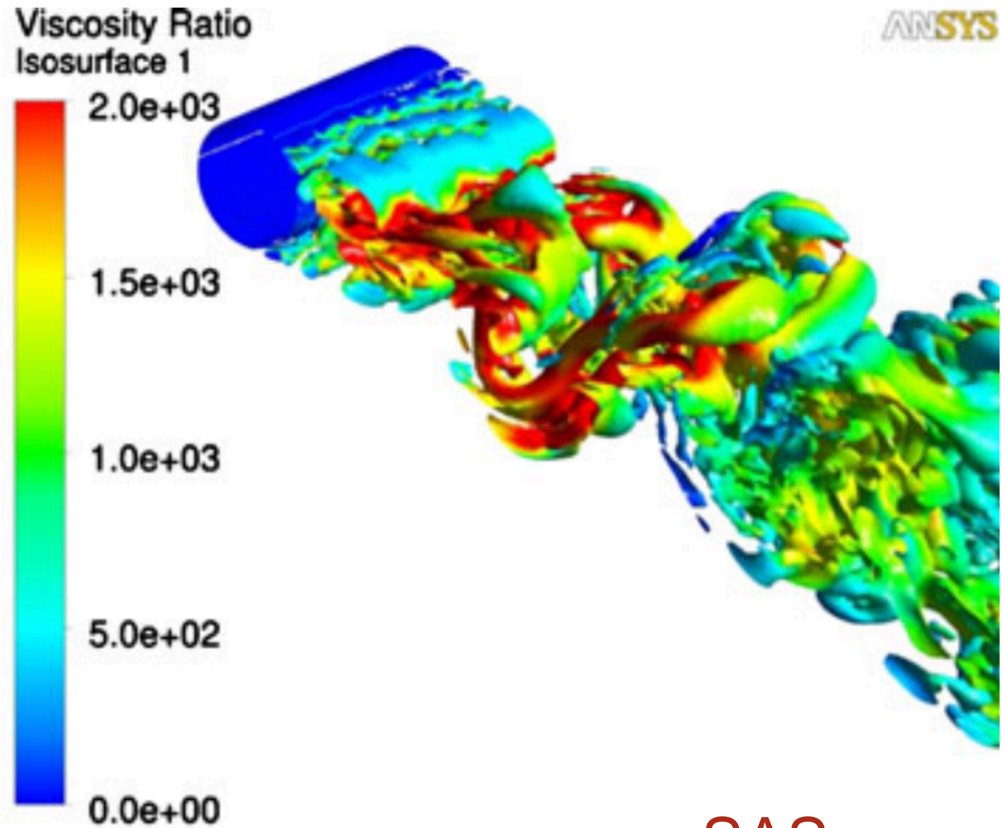
$$+ \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\Phi}\frac{\partial \omega}{\partial x_j}\right) + \frac{2\rho}{\sigma_\Phi}\left(\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} - \frac{k}{\omega^2}\frac{\partial \omega}{\partial x_j}\frac{\partial \omega}{\partial x_j}\right)$$

$$\boxed{+ \max\left[\rho\zeta_2 S^2 \left(\frac{L}{L_{\nu K}}\right)^2 - C_{SAS}\frac{2\rho k}{\sigma_\Phi}\max\left(\frac{1}{k^2}\frac{\partial k}{\partial x_j}\frac{\partial k}{\partial x_j}, \frac{1}{\omega^2}\frac{\partial \omega}{\partial x_j}\frac{\partial \omega}{\partial x_j}\right), 0\right]}$$

Unified Models
Scale-Adaptive Simulation

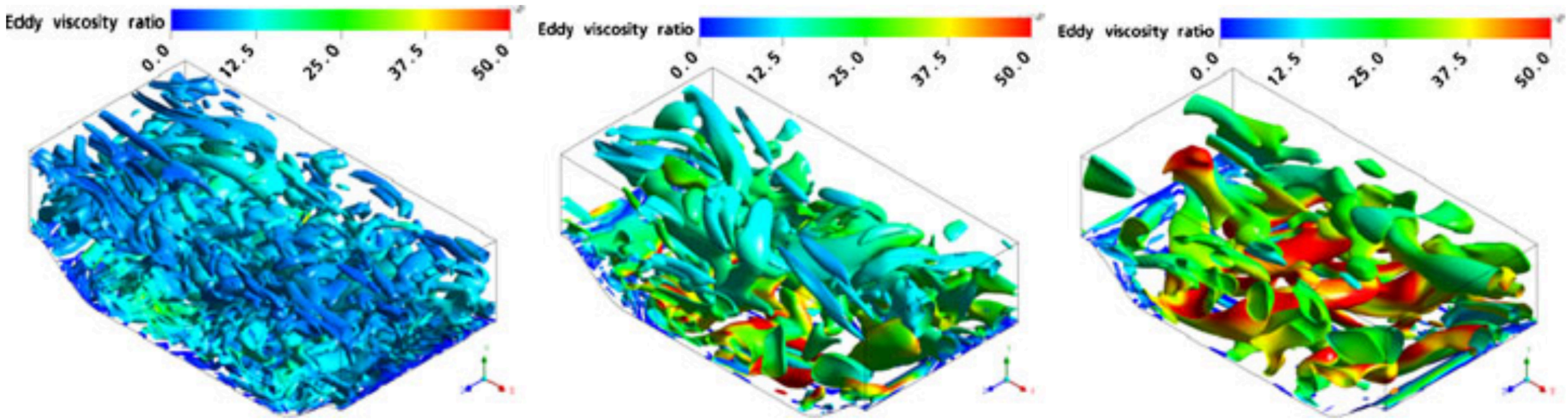


URANS



SAS

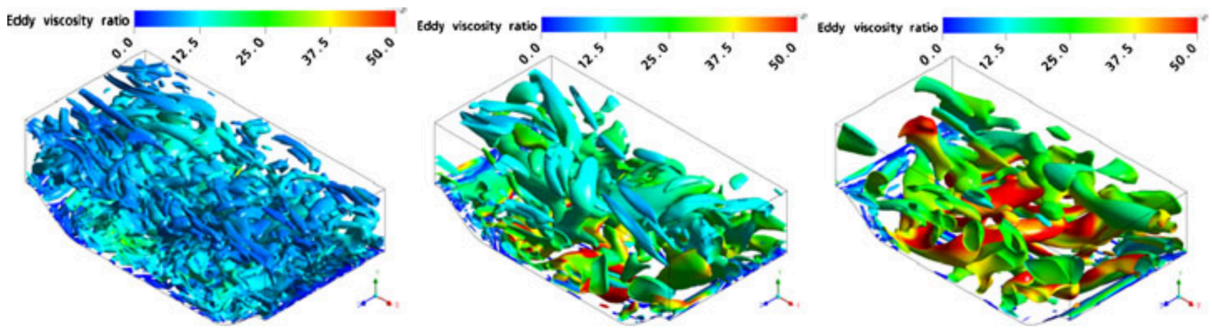
Isosurfaces of Q coloured by ν_T

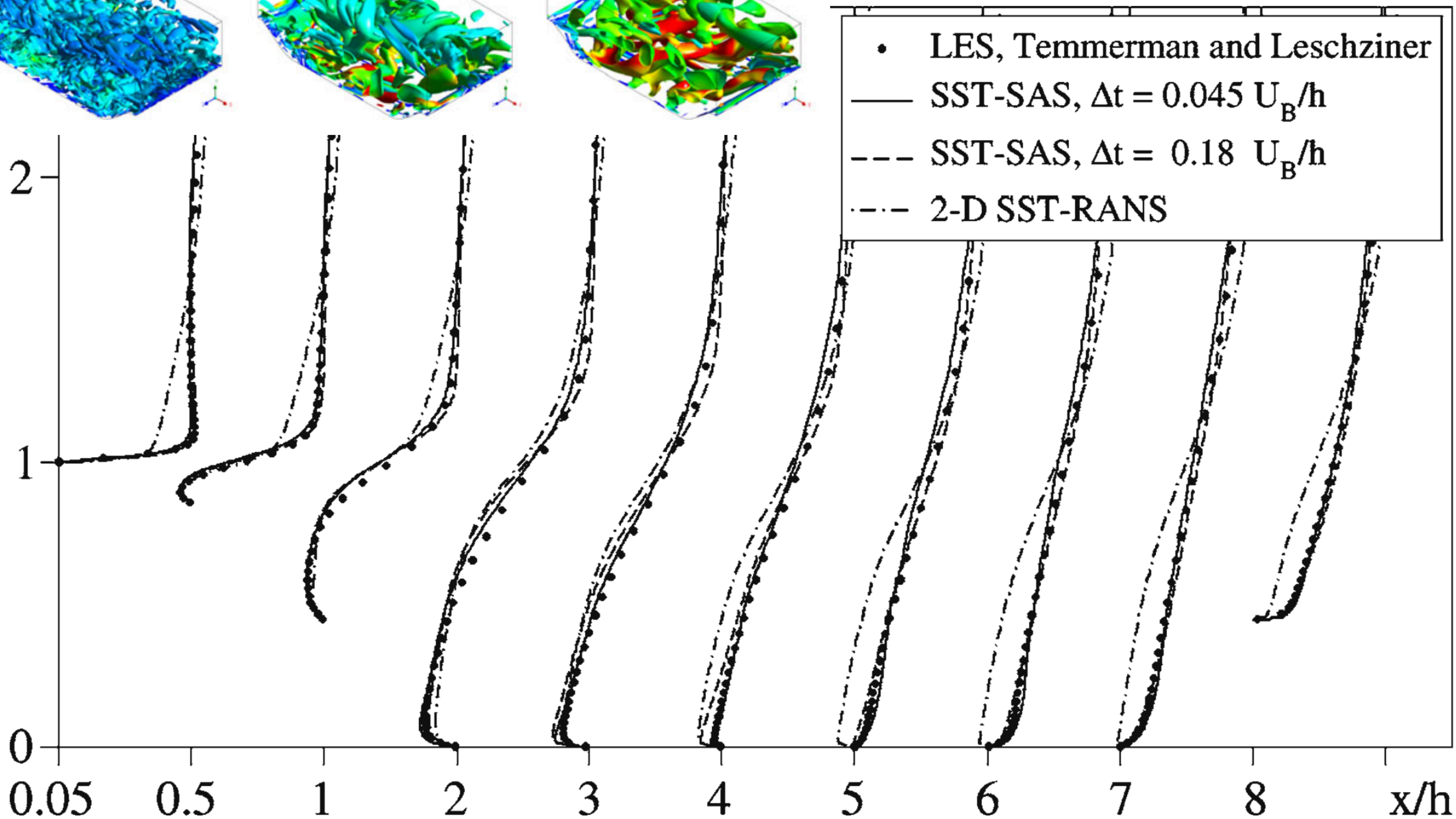


Increasing Δt

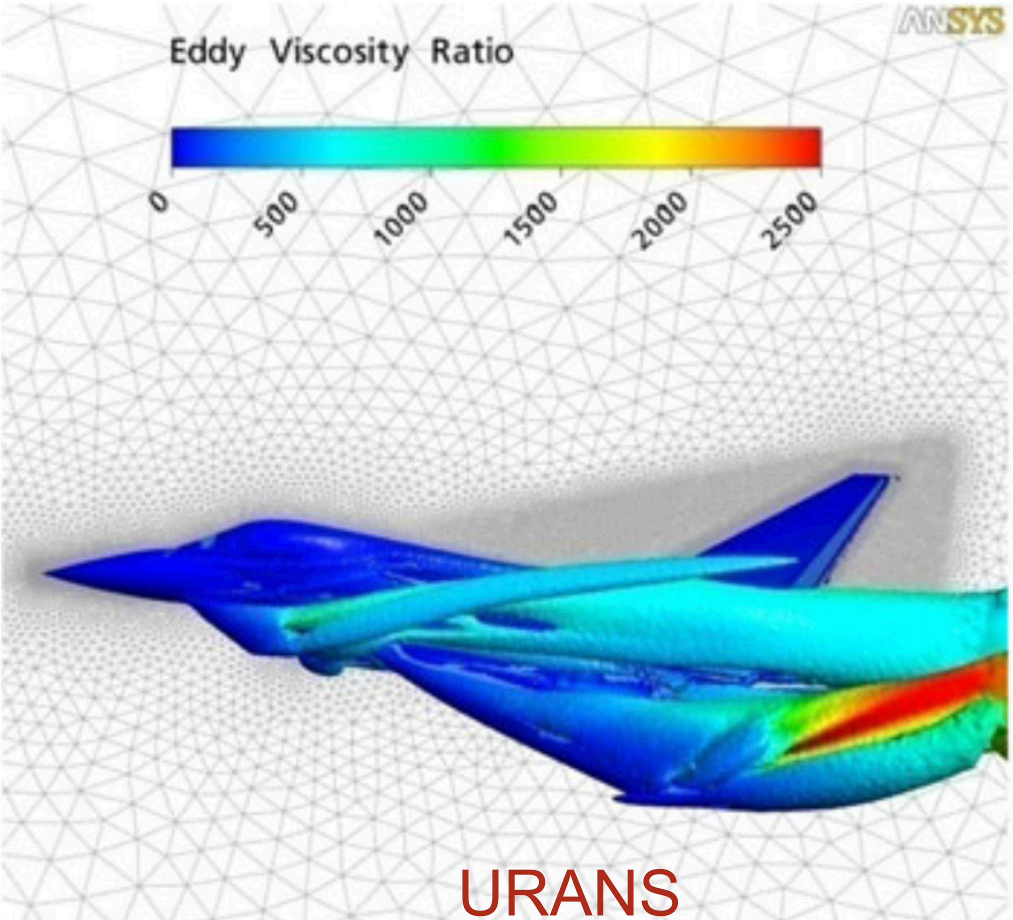
Isosurfaces of Q coloured by ν_T

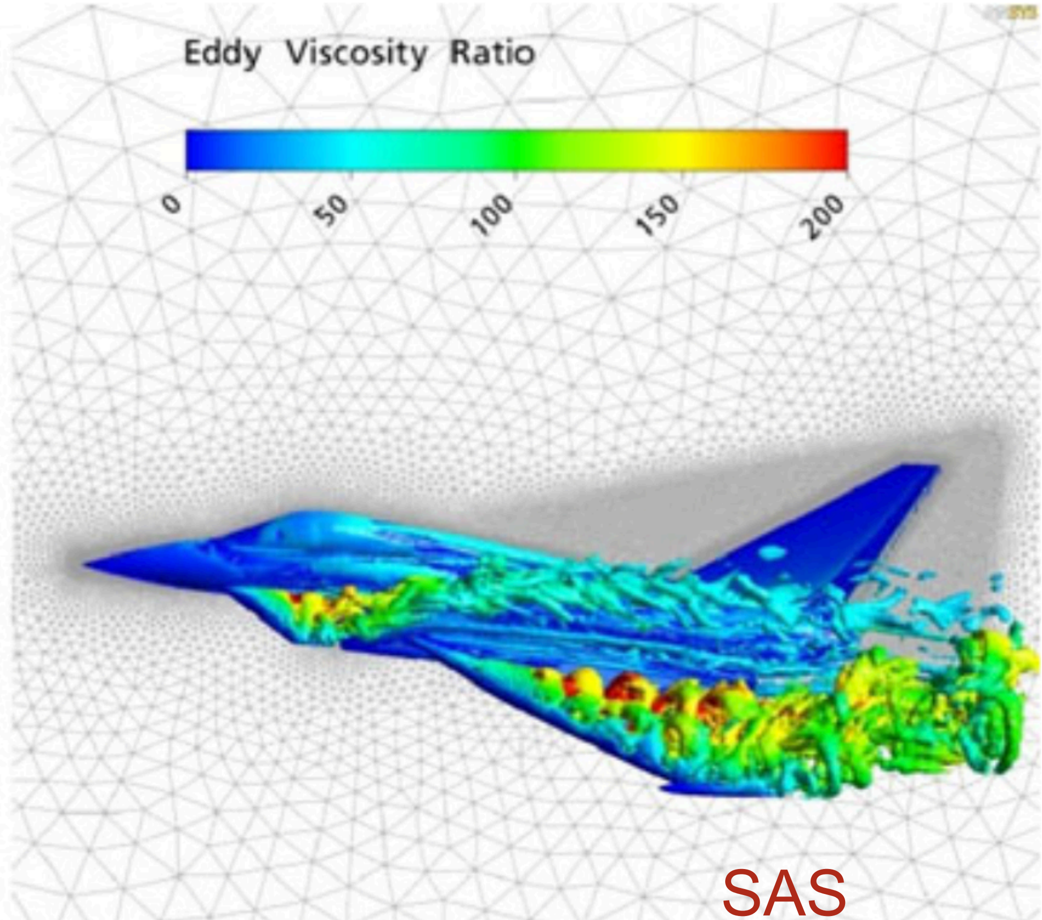
Unified Models
Scale-Adaptive Simulation



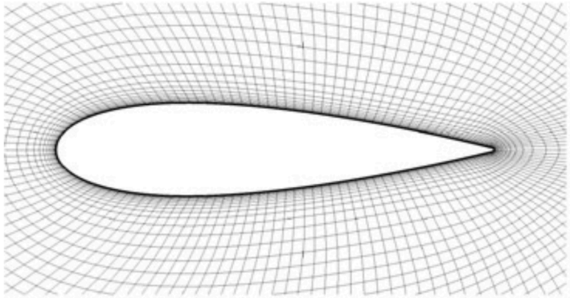


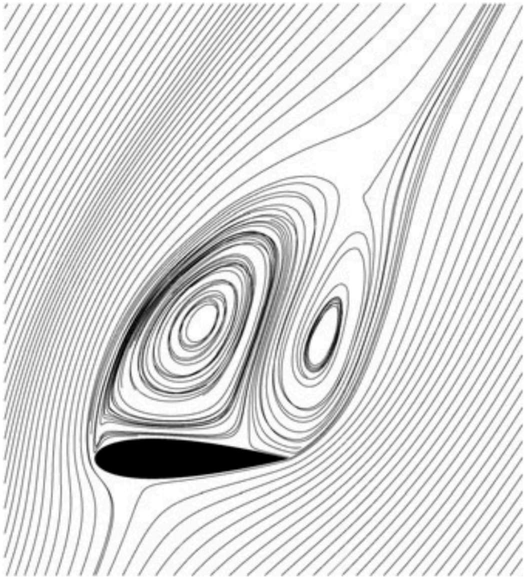
Unified Models
Scale-Adaptive Simulation

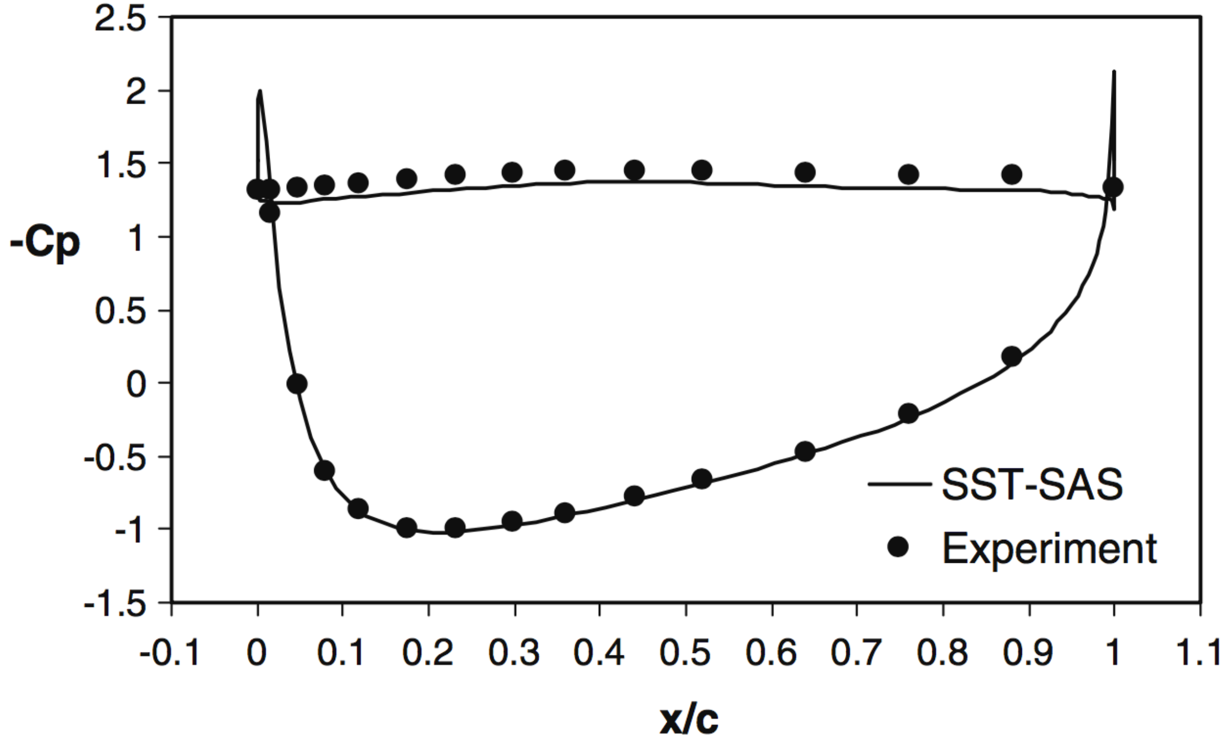


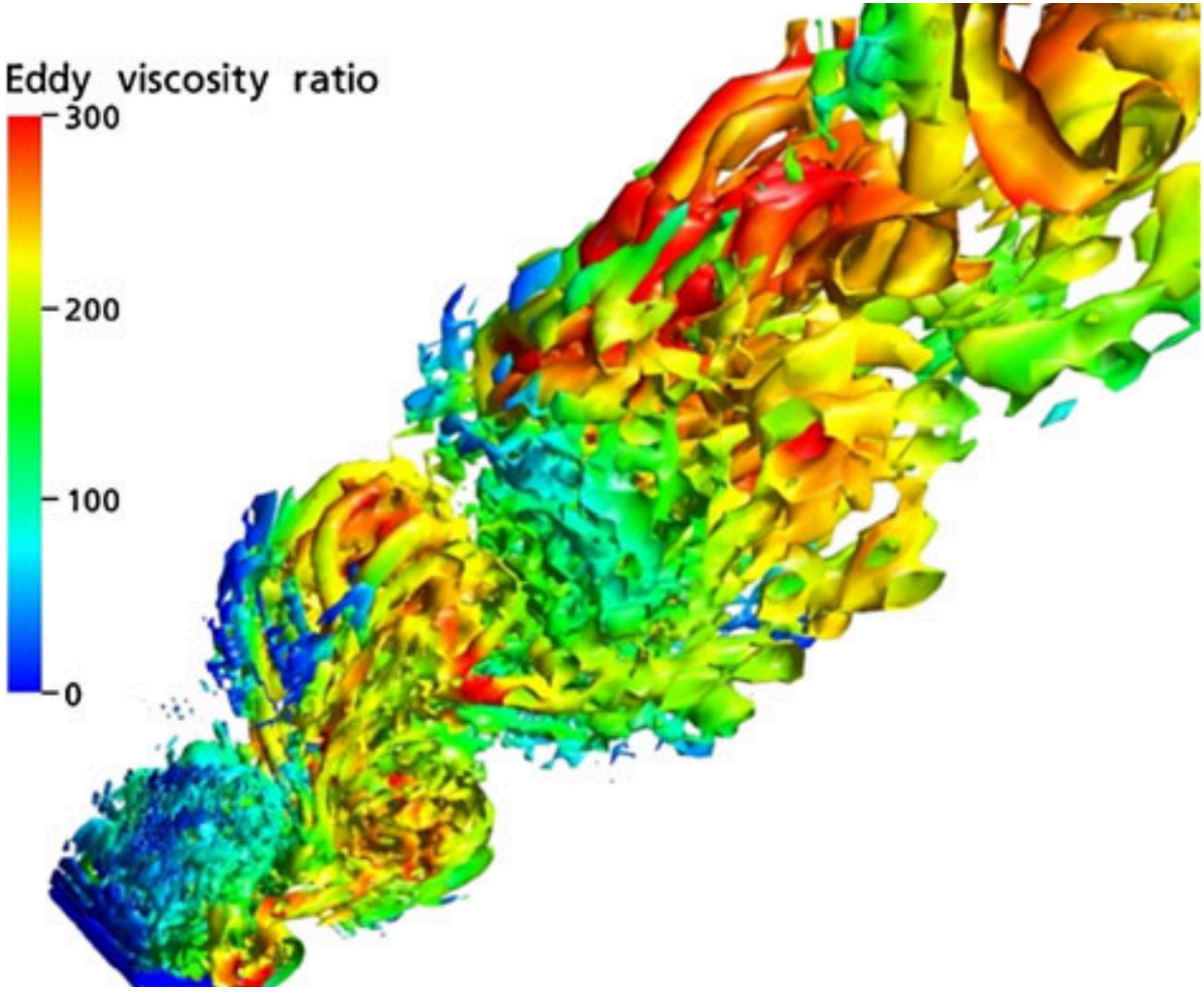


Isosurfaces of Q coloured by ν_T

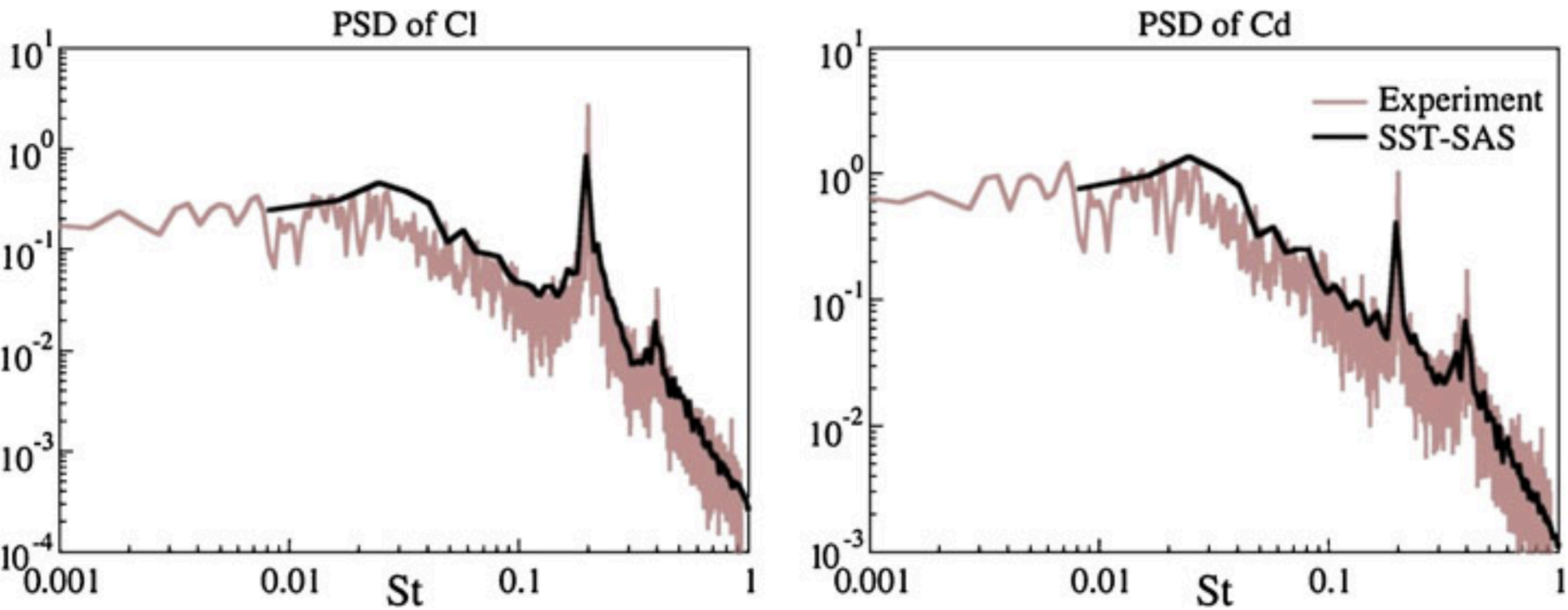





2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-Cp
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
x/c
SST-SAS
Experiment



Eddy viscosity ratio
300
200
100
0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Detached Eddy Simulation

- Hybrid RANS-LES approach proposed by Spalart *et al*. (1997).

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu} + \text{diffusion} - c_{w1}f_w\left[\frac{\tilde{\nu}}{d}\right]^2$$

d = distance to the nearest wall

production *destruction*

- Balance between production and destruction terms yields Smagorinsky-like eddy viscosity if length scale in the destruction is made sensitive to the grid.
  - *Redefine the length scale d to preserve RANS model near solid walls*

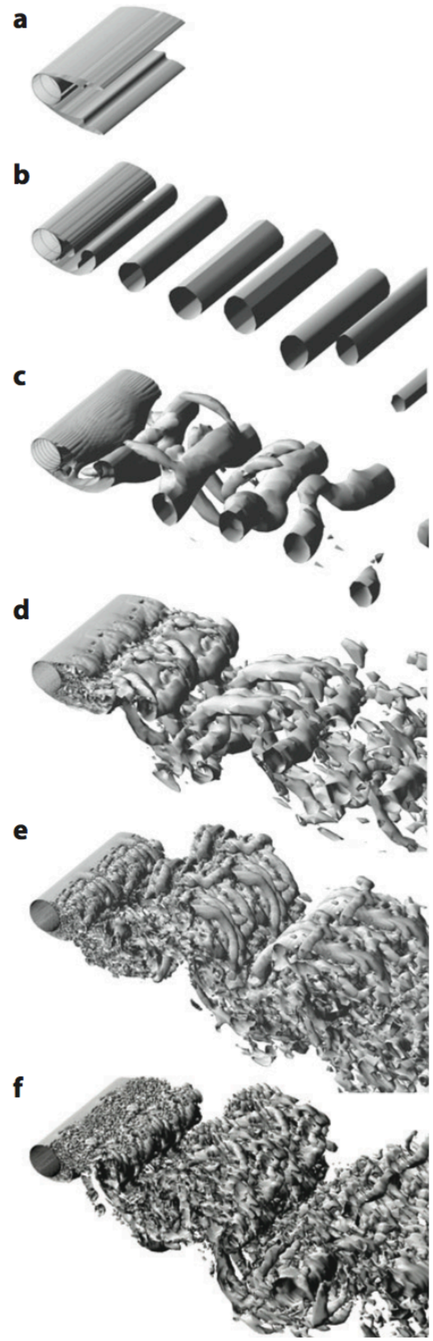
$$\tilde{d} = \min(d, C_{DES}\Delta) \qquad \Delta = \max(\Delta_x, \Delta_y, \Delta_z)$$

- Additional constant C_{DES} (= 0.65) set in homogeneous turbulence (Shur et al. 1999).

Detached Eddy Simulation

- 3D unsteady numerical solution using a single turbulence model
  - *LES in regions where grid density is sufficient*
  - *RANS model in other regions*
  - *"RANS Region" and "LES Region" separated by an interface dictated by the grid*
- Advantages
  - *Non-zonal formulation, single equation (RANS characteristic)*
  - *Possible to "steer" solution to regions where "physics" are desired (LES characteristic).*
- Design applications:
  - *Entire boundary layer treated by RANS*
  - *At the interface between RANS and LES the separated shear layer generates eddy content.*
  - *Designed for thin shear layers followed by massive separation.*

Detached Eddy Simulation



SST, steady, 2D

SST, unsteady, 2D

SST, unsteady, 3D

SA-DES, coarse

SA-DES, fine

SST-DES, fine

DES - Flow over a sphere

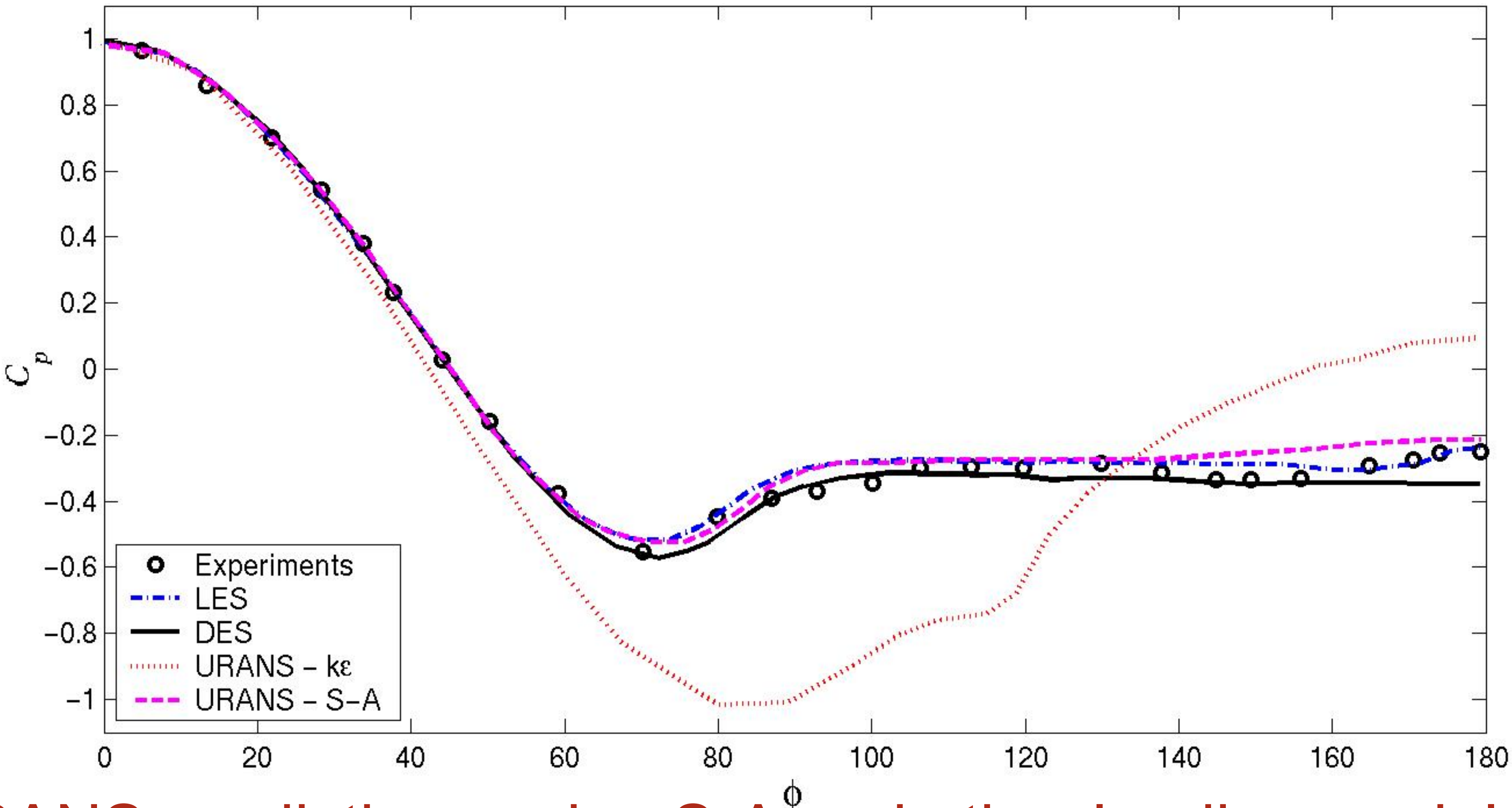
G. S. Constantinescu, M. Chapelet, and K. D. Squires, *Turbulence modeling applied to flow over a sphere*, AIAA J., 41 (2003), pp. 1733–1742.

G. S. Constantinescu, R. Pacheco, and K. D. Squires, *Detached eddy simulation of flow over a sphere. AIAA Paper 2002-0425*, 2002.

G. S. Constantinescu and K. D. Squires, *LES and DES Investigations of Turbulent Flow over a Sphere at* $Re = 10,000$, Flow, Turb. Combust., 70 (2003), pp. 267–298.

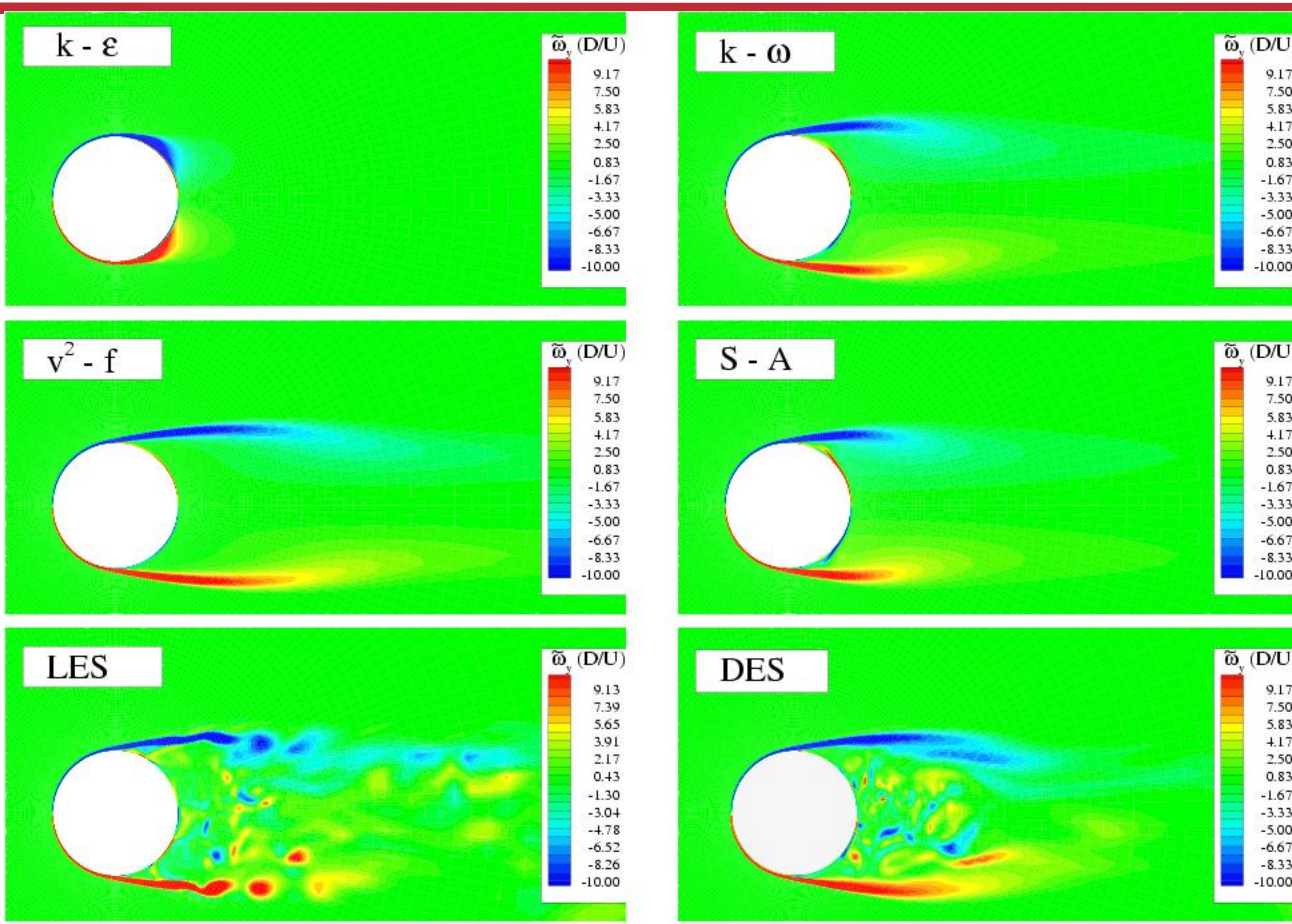
- Non-trivial separation prediction.
- Sub-critical (laminar separation) (Re = 10K, 100K) and supercritical (Re = 1,100K) cases.
- O(10^6) cells, resolved wall-layer.
- Laminar separation using tripless approach of Travin et al. (2000)
    - *Disables turbulence model up to separation*
- Turbulent separation studied using fully turbulent computations.
- Comparison between RANS, URANS, DES and resolved LES.

DES - Flow over a sphere



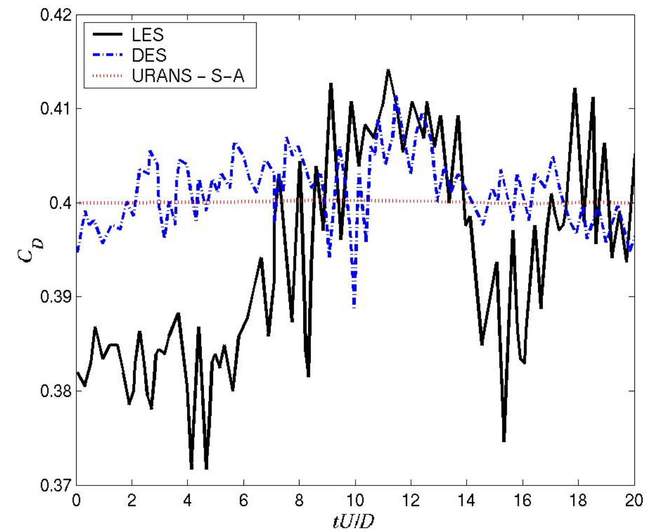
- URANS predictions using S-A and other leading models yield reasonable predictions of the drag.
- k-ε based URANS are inadequate.

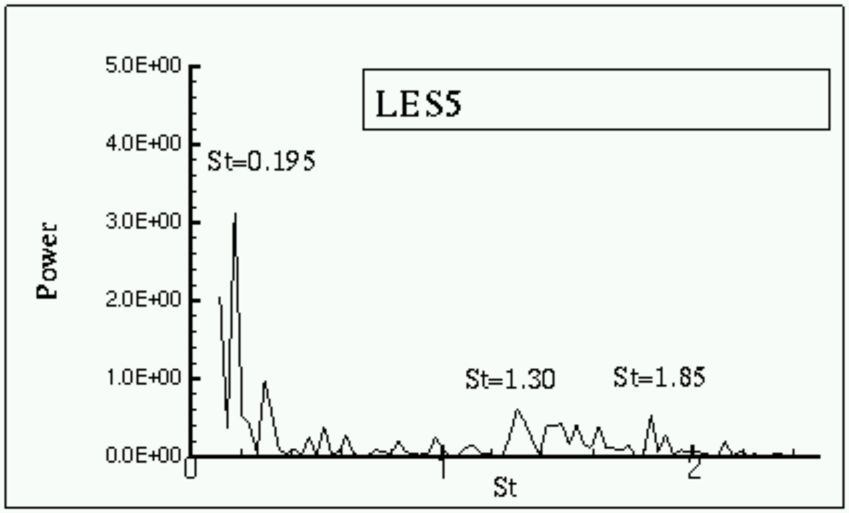
DES - Flow over a sphere

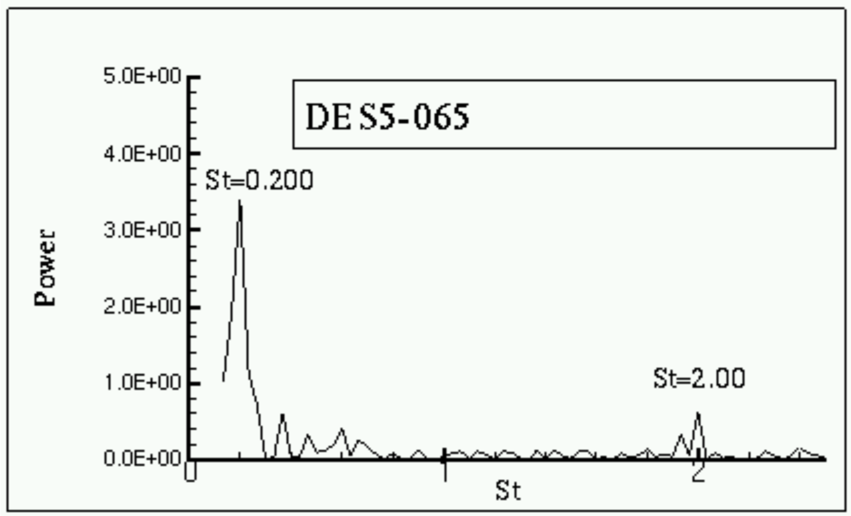


Vorticity contours

DES - Flow over a Sphere

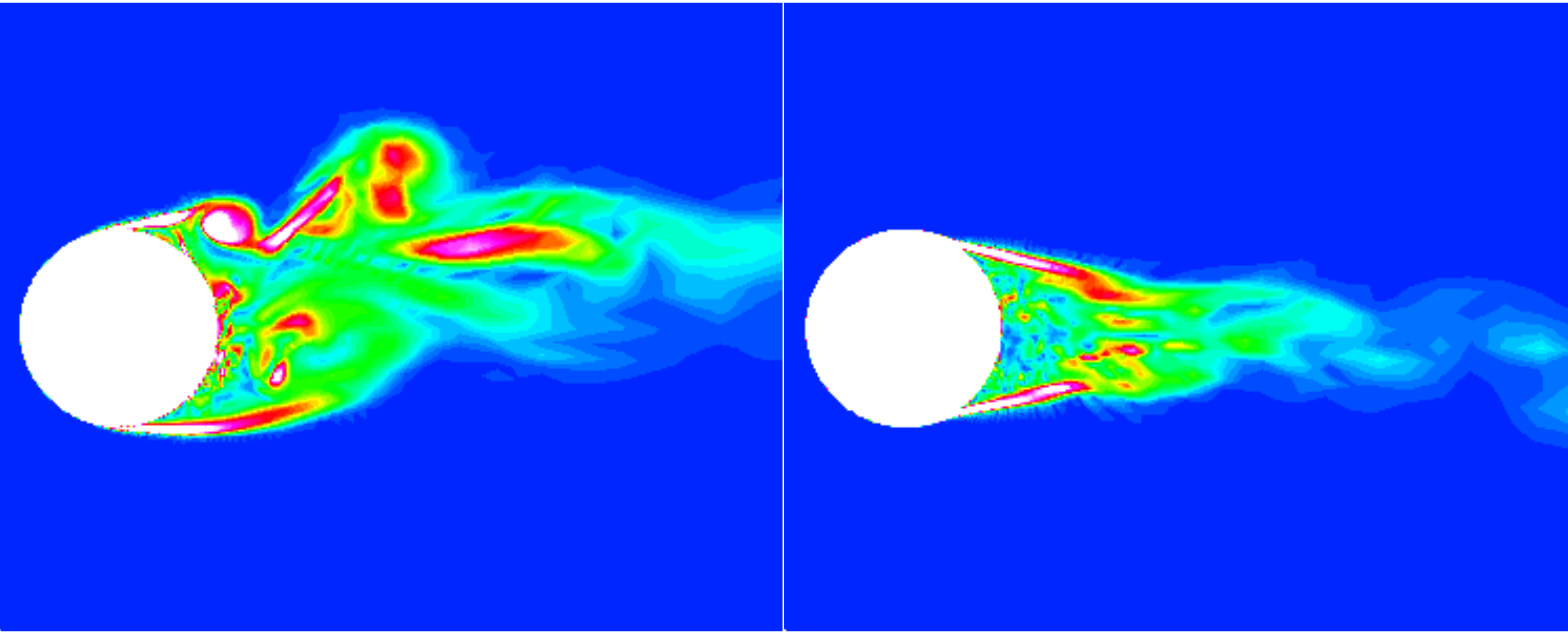






- URANS calculations predict a significantly smoother flow.
- Errors in the spectra in the shear layer.
- The temporal development of the force coefficients is predicted incorrectly by all URANS models.

DES - Flow over a sphere



Laminar separation, Re=100k Boundary layer separation around 85 degrees	Turbulent separation, Re=1100k boundary layer separation at around 114 degrees

F-18C at 30 Degrees α

THE 5TH ASIAN COMPUTATIONAL FLUID DYNAMICS CONFERENCE
BUSAN, KOREA, OCTOBER 27 ~ 30, 2003

Detached-Eddy Simulations of Full Aircraft Experiencing Massively Separated Flows

S.A. Morton [1], J.R. Forsythe [2], K.D. Squires [3], R.M. Cummings [4]

- $Re = 13.9 \times 10^6$, $Ma = 0.28$
- Leading Edge Extension used to increase lift, twin tails canted for increased maneuverability
  - *Tail buffet at large incidence due to vortex breakdown*
- Baseline mesh of 5.9×10^6 cells
- Solution-based adaptation to 6.2×10^6 cells

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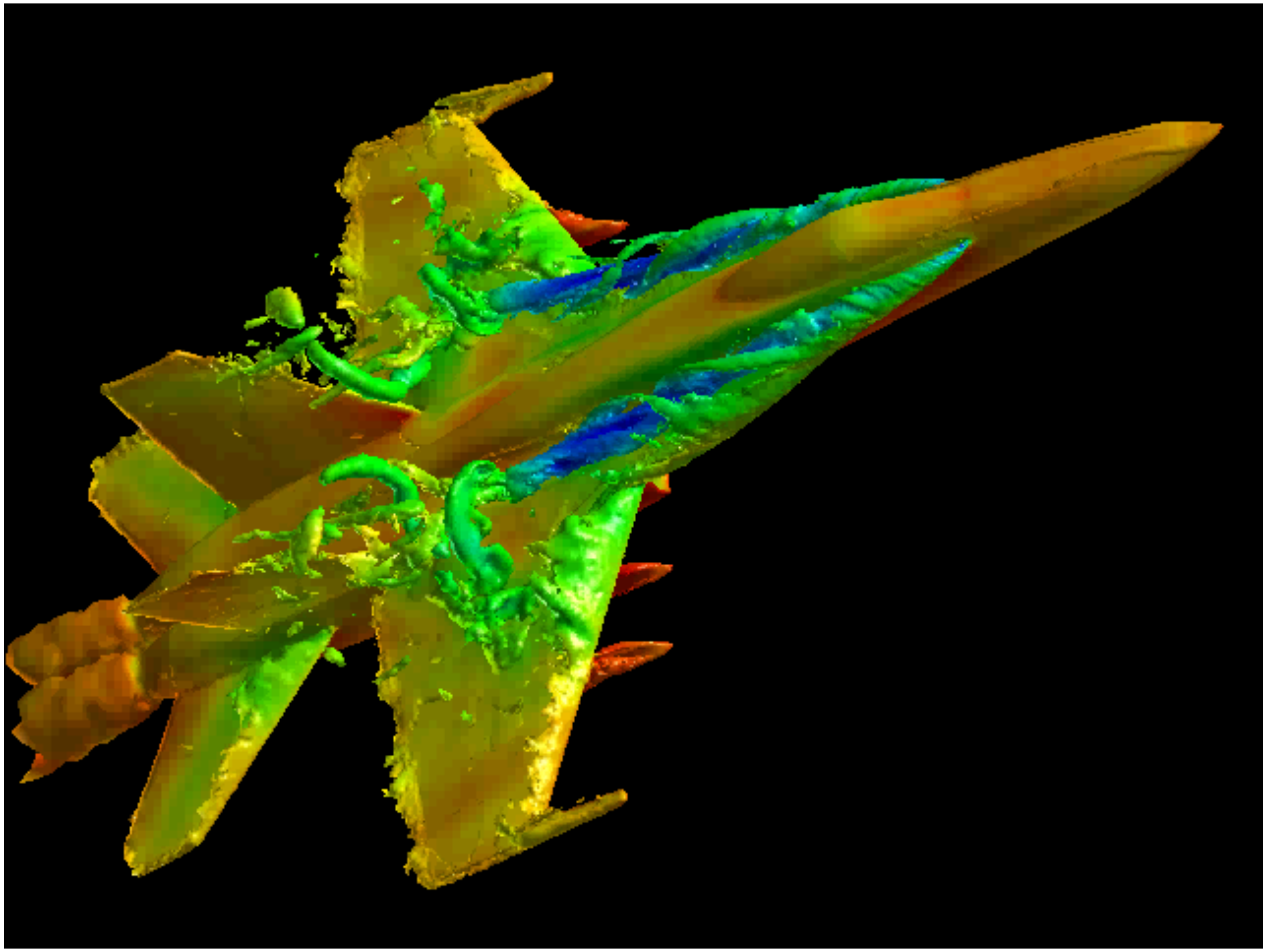
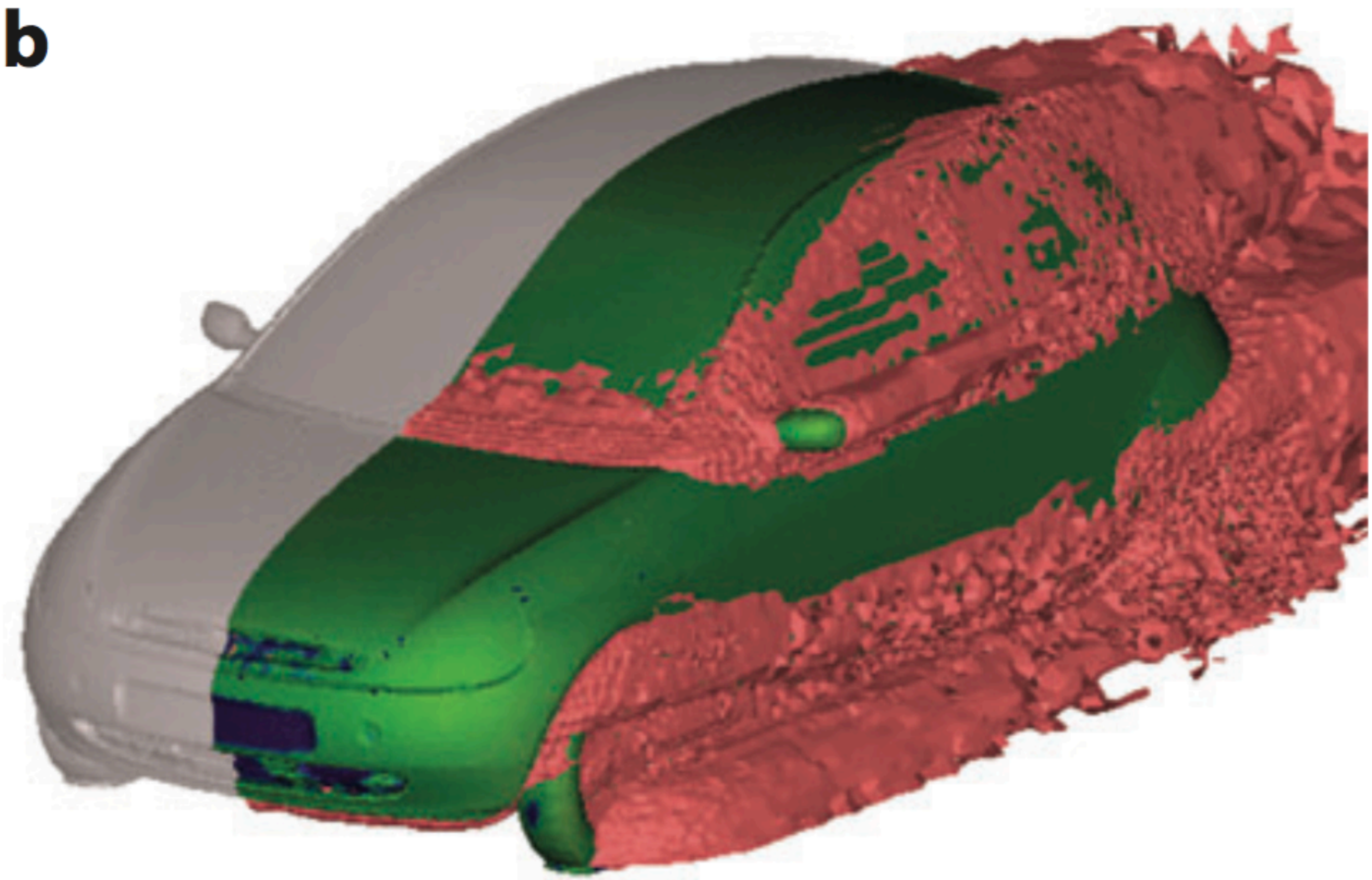
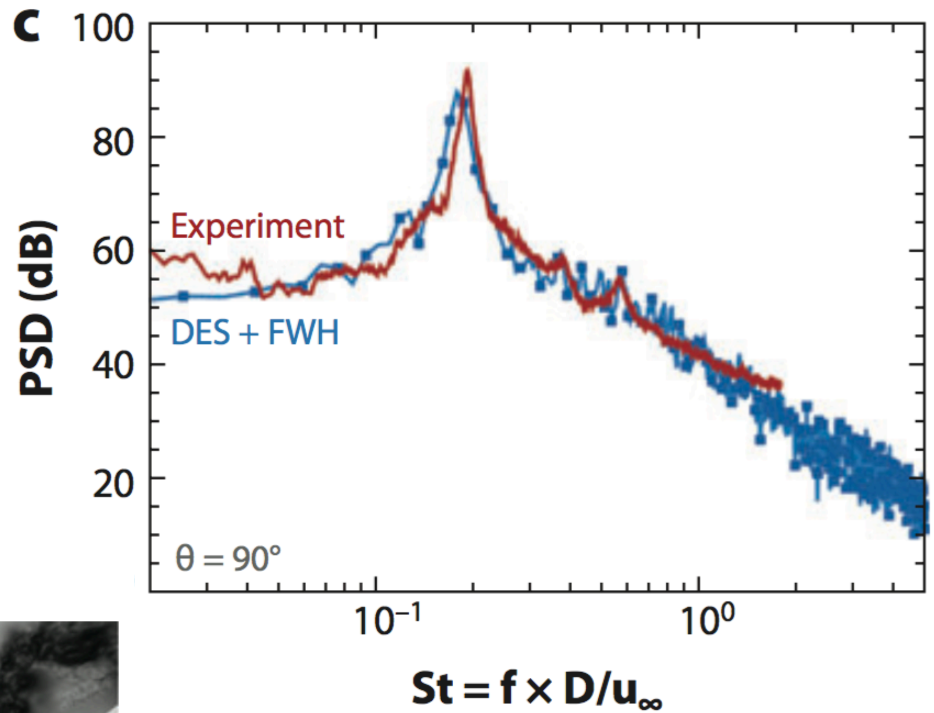


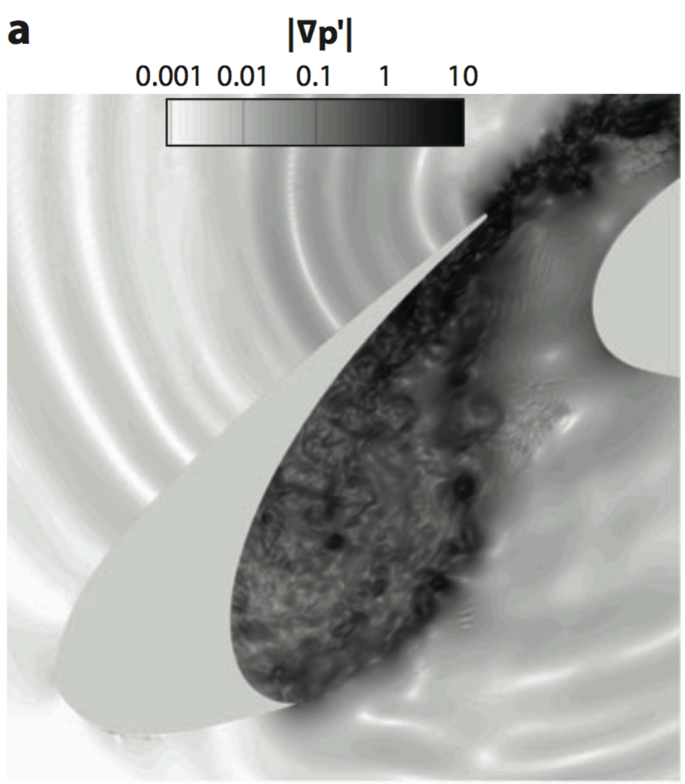
Instantaneous Vorticity Field

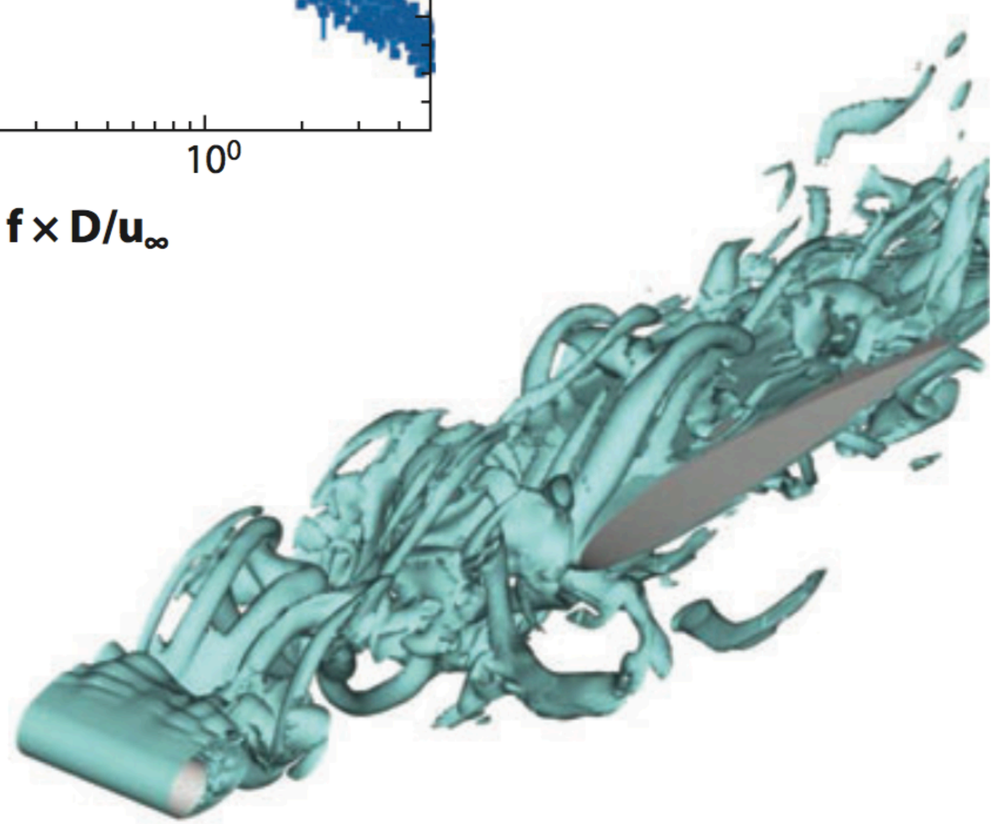
DES: Other applications



DES: Other applications







Summary – Strengths

- DES is simple, well-defined.
- Using present computers, DES predictions of full aircraft are possible

    Lift and drag predictions of the F-15E are excellent.

    - DES carries a higher computational cost than traditional modeling, but is feasible today.

- DES naturally provides unsteady (broadband) information.

    Essential in many applications (multidisciplinary problems).

    Resolved range increases with grid/timestep refinement.

- Very good prediction of bluff body flows

    Sub- and super-critical flows over the sphere.

    Pressure distribution around aircraft forebody much more accurate than possible using URANS.

Caveats

- DES works well when…
  - *RANS: when the grid in any direction is much larger than the natural mixing length of the flow*
  - *LES: when the grid is much smaller than the natural mixing length of the flow*
    - Resolved turbulence should dominate modeled turbulence (as in classical LES).

Caveats

- Grey areas…
  - *Intermediate grids*
    - Grid resolution not sufficient to support resolved turbulence
    - Eddy viscosity reduced below RANS level because grid is smaller than the natural mixing length
    - Steady RANS obtained with insufficient eddy viscosity.
      - Gradual refinement from RANS grid might initially degrade the solution.
  - *Grids that are adequate for RANS may be insufficient for DES.*
  - *Path from RANS to DES is not gradual.*

Outline

- Motivation
- Governing equations for LES
- Boundary conditions
- Subfilter-scale modelling
- Validation of an LES
- Applications
- Hybrid RANS/LES methods
- **Challenges**
- Conclusions

Outline

- Motivation
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- Applications
- Hybrid RANS/LES methods
- **Challenges**
  - *Commercial codes*
  - *Wall-layer modelling*
- Conclusions

LES using commercial codes

- Commercial software is increasingly offering LES options.
- Advantages:
  - *Robustness*
  - *Geometric flexibility*
  - *Technical support*
- Disadvantages:
  - *Cost (CPU, memory)*
  - *Accuracy*

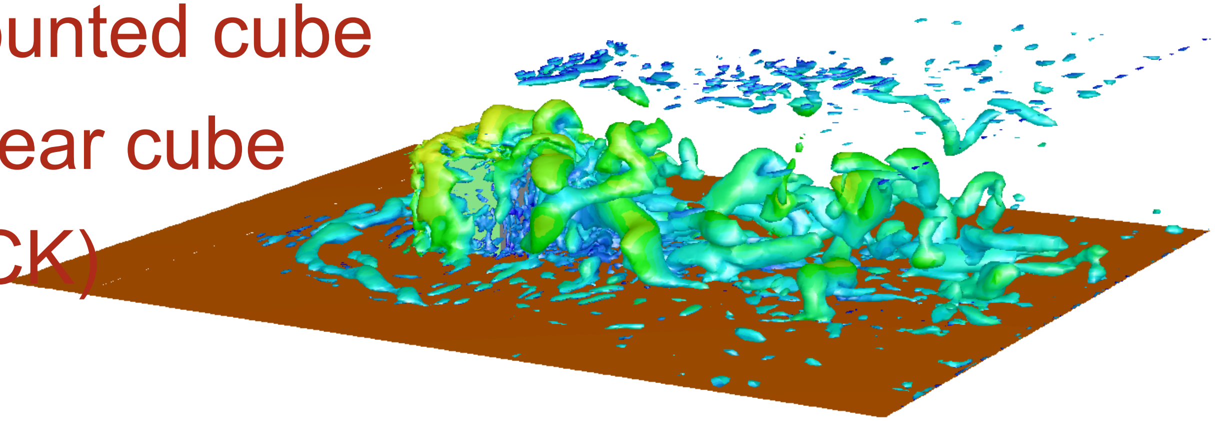
LES using commercial codes

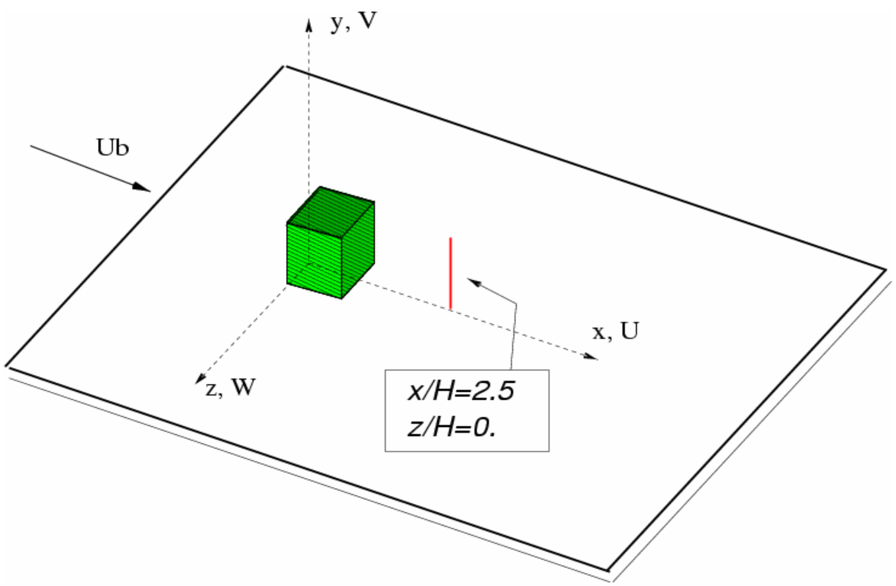
- Significant improvements in algorithms. Example: Fluent™, Inc.
  - *Spatial discretization*
    - High-order upwind schemes (SOU, QUICK, MUSCL)
    - Central differencing (CD) scheme
    - Bounded central differencing (BCD) scheme
    - Low-diffusion flux scheme
  - *Time advancement*
    - Second-order in time, non iterative
    - PISO
    - Fractional step
  - *Various SFS models*
    - Dynamic eddy viscosity, One-equation, Spalart-Allmaras...

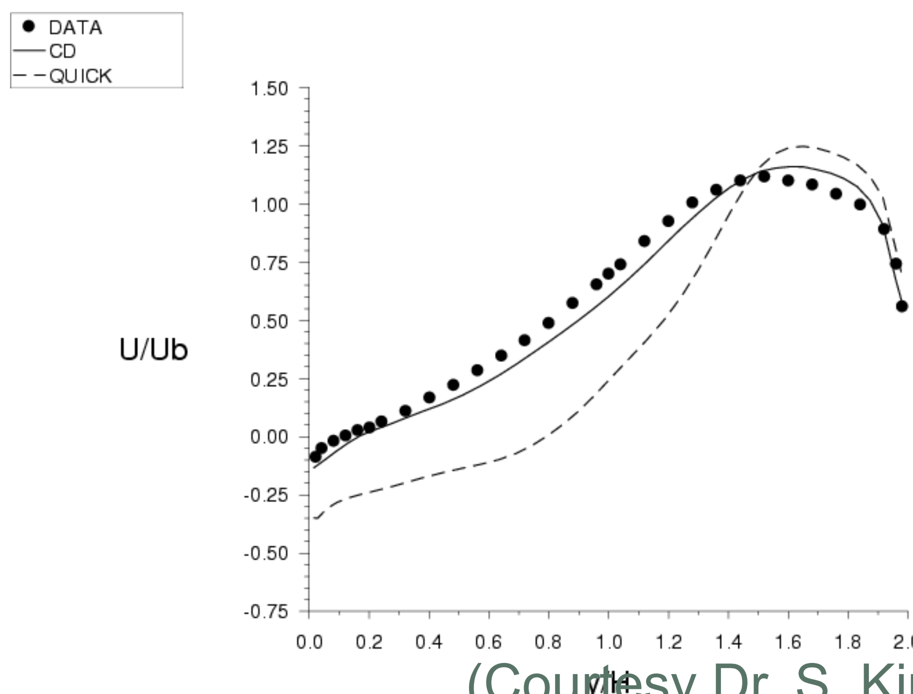
Ugo Piomelli is not affiliated with Fluent™, Inc.; other software may produce similar results, or offer similar features. The present results are only shown as representative examples of LES performed using commercial software, and do not constitute an endorsement of the software.

LES USING COMMERCIAL CODES

- Flow over a surface-mounted cube
- 0.9M points clustered near cube
- Upwind schemes (QUICK) are diffusive and result in incorrect prediction of the wake flow.

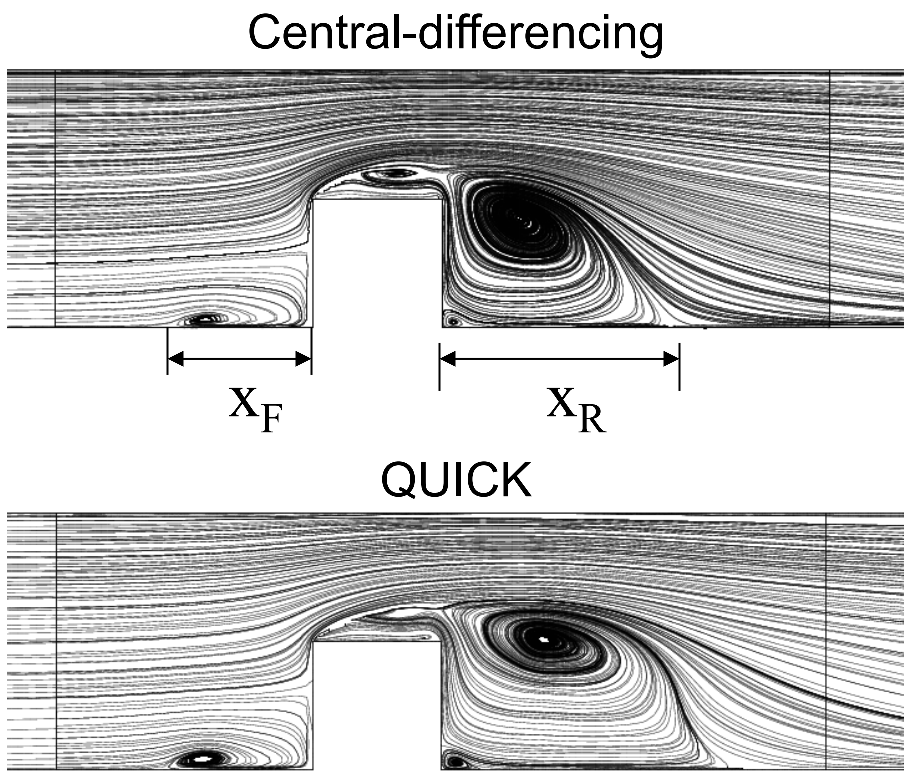






(Courtesy Dr. S. Kim)

LES using commercial codes



Time-averaged streamlines on the mid-plane

Separation and reattachment points predicted by FLUENT and others

	X_F	X_R
Exp.(Martinuzzi and Tropea 1993)	1.04	1.61
FLUENT (LES + CD)	1.18	1.78
FLUENT (LES + QUICK)	1.26	2.40
Breuer *et al*. LES	1.23	1.70

(Courtesy Dr. S. Kim)

LES using commercial codes

- Open source codes are also available
  - *OpenFOAM®*
  - *Code_Saturne®*
  - *Unstructured finite-volume codes*
  - *LES capabilities*

Code_Saturne Application

- Flow over a NACA 0020 airfoil with a sinusoidal leading edge
- Courtesy: Alex Skillen, UMIST

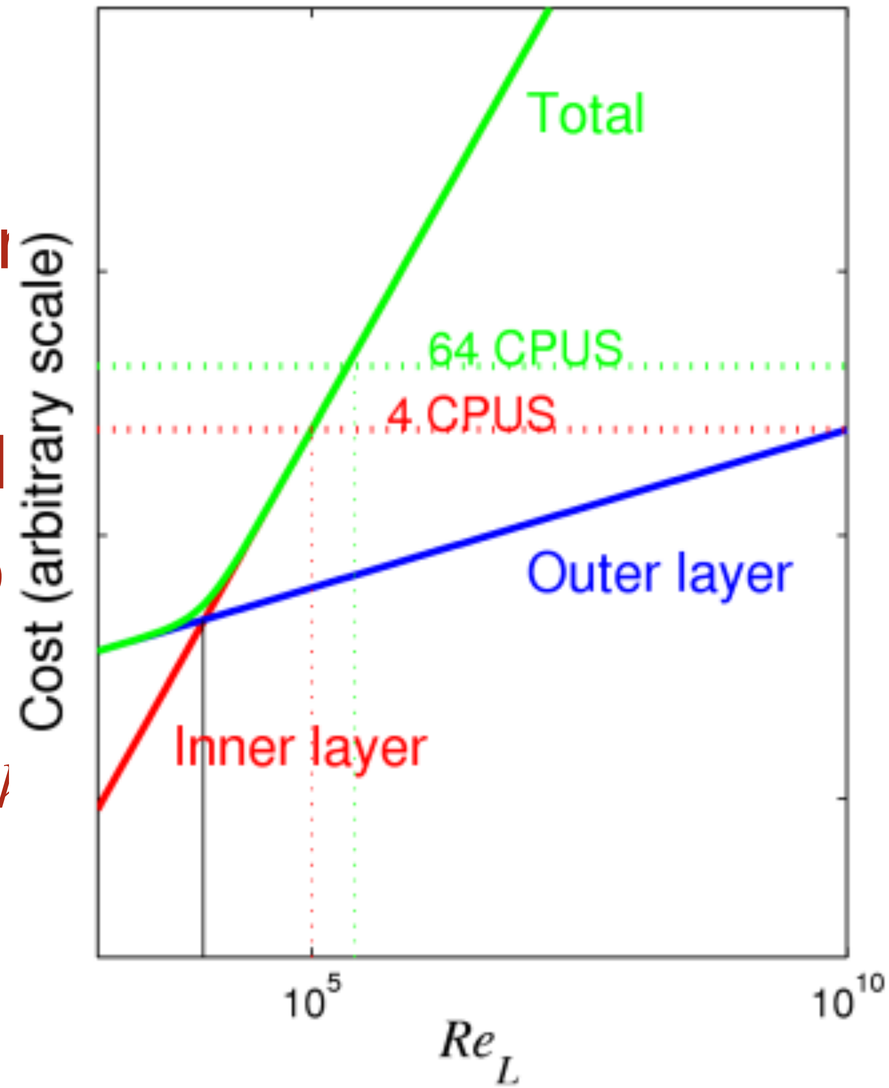
LES using commercial codes

- Accurate simulations of benchmark problems can be performed LES with commercial software.
- User choices are crucial:
  - *Differencing schemes (non-diffusive preferred)*
  - *Time advancement (accuracy, order)*
  - *SFS model*
  - *Wall treatment (wall models - see next section)*
  - *Grid resolution*
- Cost higher than “research” codes:
  - *CPU, memory usage > 5 times higher*

Wall-Modelled LES (WMLES)

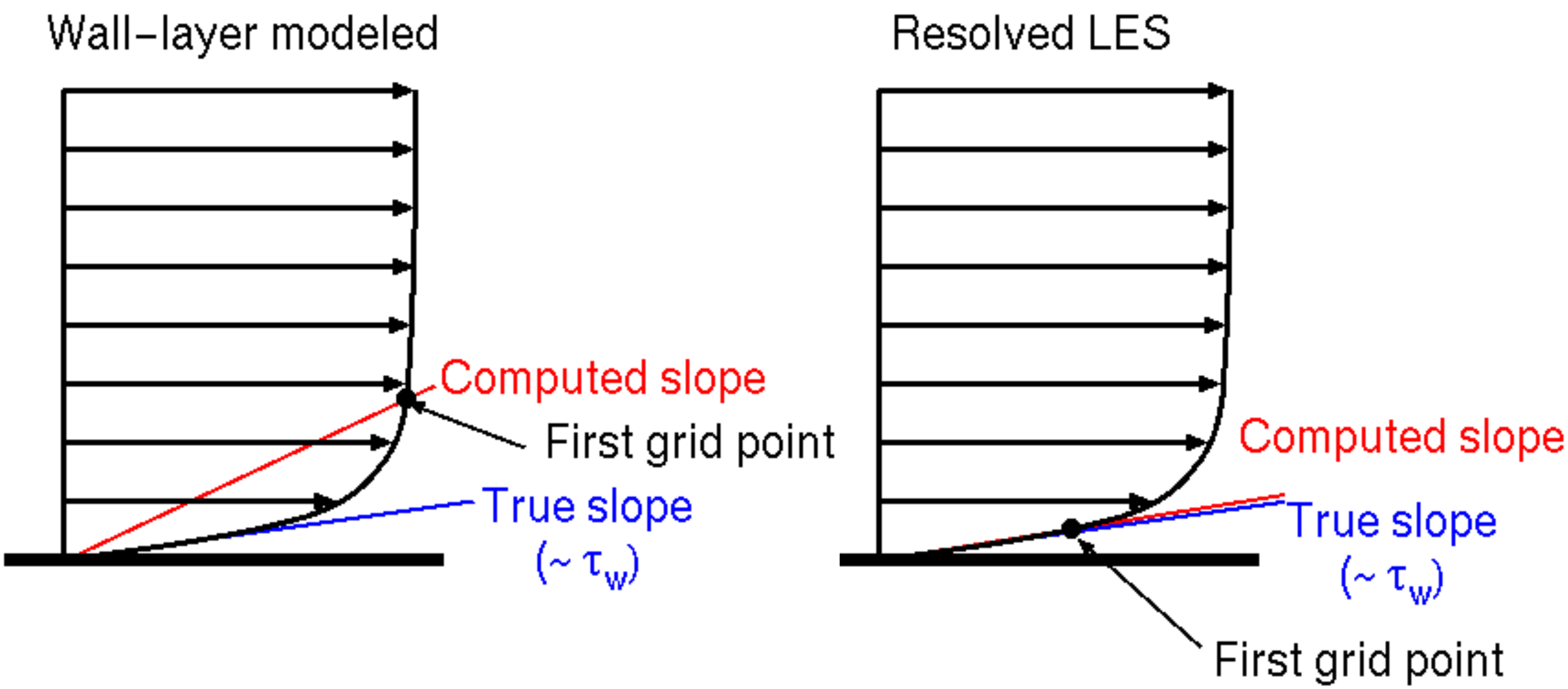
- Outer layer: Cost ~ $Re^{0.6}$
- Inner layer: Cost ~ $Re^{2.4}$
- An increasing percentage of poi layer.
- Computational capabilities are q
- Alternative for high Re applicatio
  - *Bypass the wall layer*
  - *Model its effects in a global (RANS-lil*

⇒ Wall-modelled LES (WMLES)



Wall-Modelled LES (WMLES)

- Purpose: relate the wall stress to the velocity in the outer layer locally and instantaneously.



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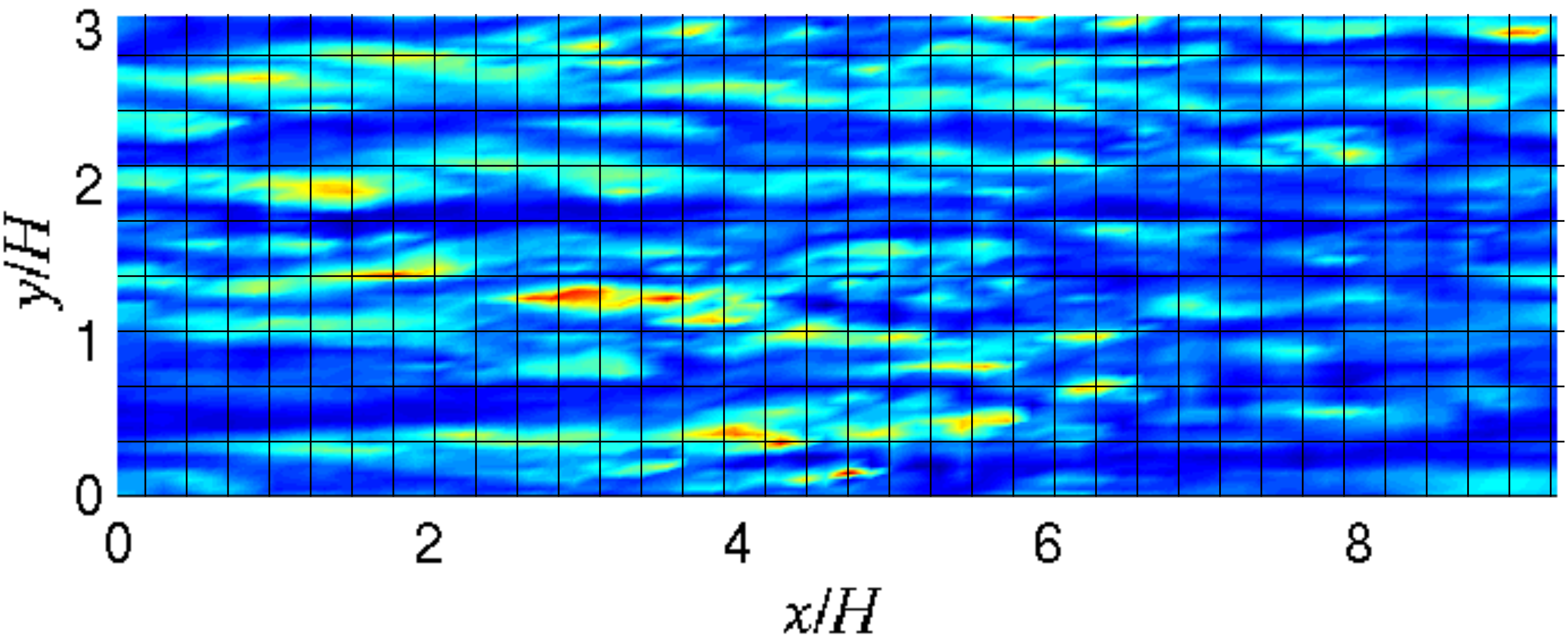
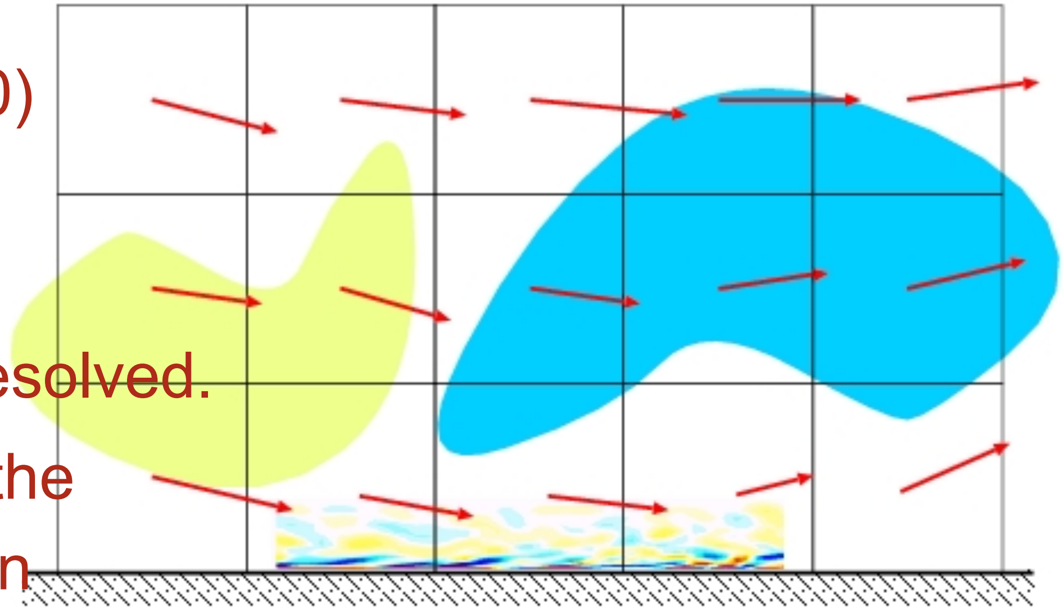


Contours of τ_w in a plane channel.

Wall-Modelled LES (WMLES)



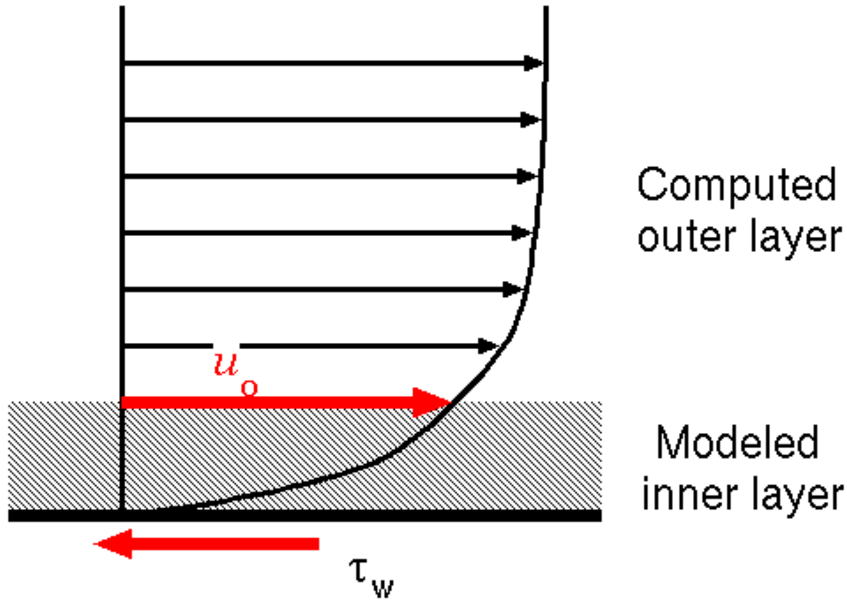
- Outer-layer eddies (L/d > 1/10) are captured.
- Inner-layer scales (1/10 > L/d >Re-0.8) are not resolved.
- The effect of these eddies on the average wall-stress is unknown and must be modelled.
- Classical approach: assumed velocity profile.
  - *Range of phenomena that can be reproduced accurately is limited.*
- Modern approach: zonal solution.
  - *Easier to account for non-equilibrium physics.*
  - *Transition between averaged flow and eddy-resolving zone may cause problems.*

EQUILIBRIUM STRESS LAYER

- In Zero-Pressure Gradient boundary layers:
  - *The vertical momentum transport due to the near-wall eddies results in an equilibrium-stress layer.*
  - *The law-of-the-wall holds*

    $$\frac{u_o}{u_\tau} = \frac{1}{\kappa} \log \frac{y u_\tau}{\nu} + B$$

  - *We can solve it for u_τ, given u_o.*
  - *Deardorff* (1970), *Schumann* (1974), *applications in meteorology and oceanography.*

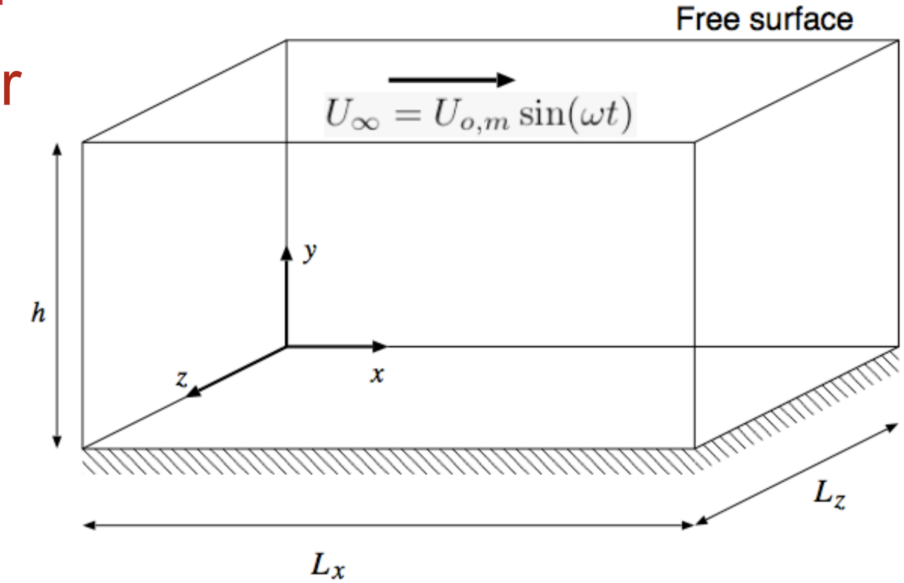


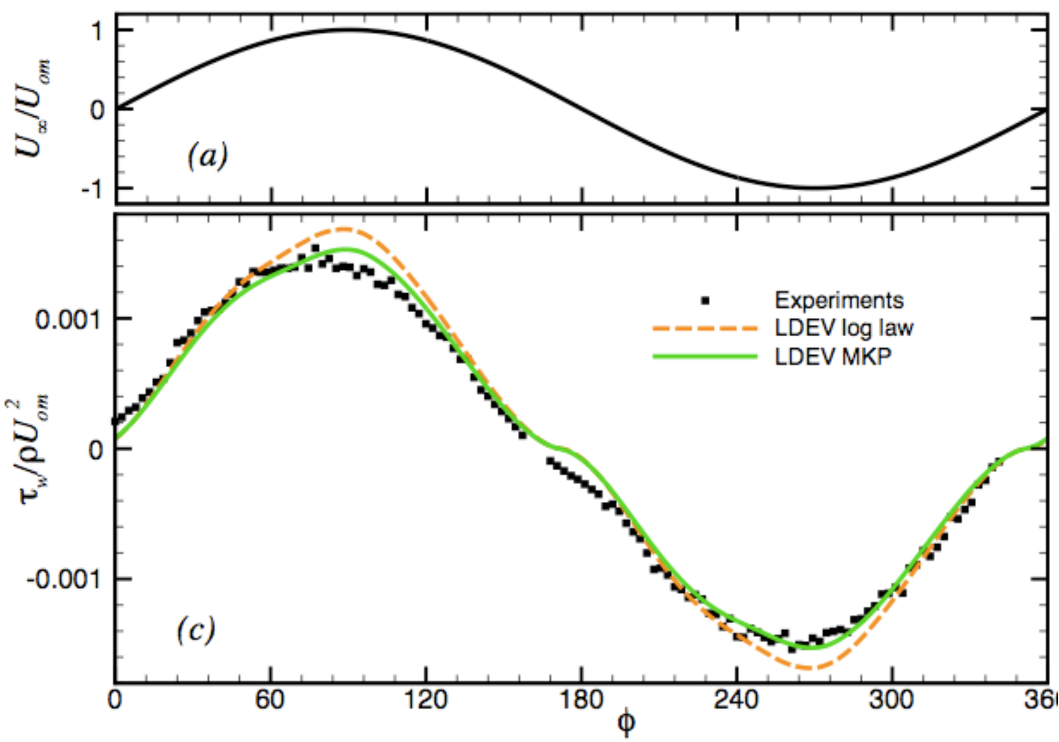
Equilibrium stress layer

- The outer flow imposes its length-and time-scales on the inner flow.
  - *Not accurate when the perturbation propagates from the wall to the outer layer.*
- ZPG b.l. solution, mixing length turbulence model.
  - *The logarithmic law is built into the model.*
  - *Modifications can account for:*
    - Moderate pressure gradients
    - Roughness
    - Stratification
- Flows with no log-law:
  - *Strong pressure gradients*
  - *Curvature*
  - *Separation*
  - *Rotation effects*

Equilibrium-stress layer

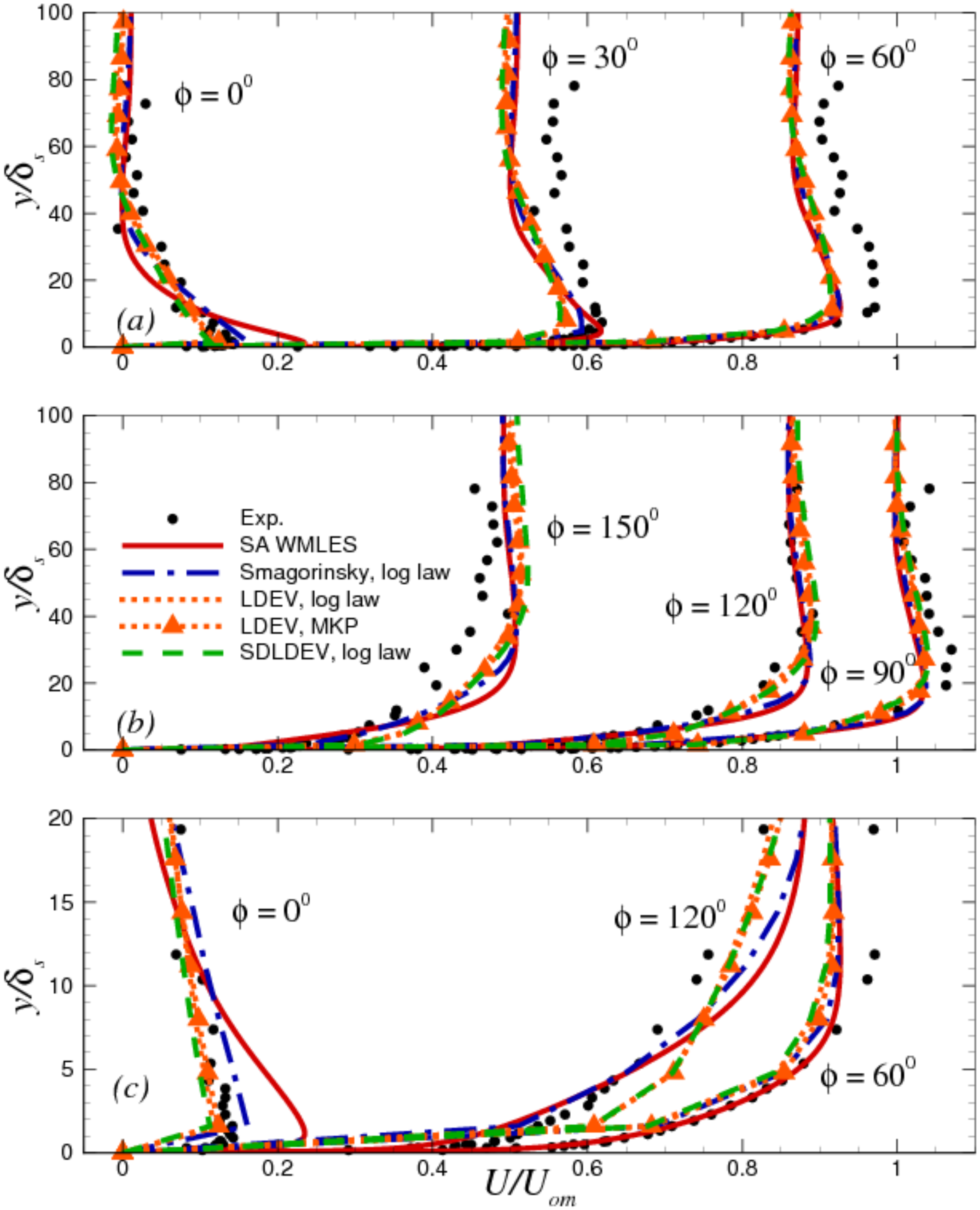
- Flow in an oscillating boundary layer (Radhakrishnan & Piomelli, *J. Geophys. Res.-Oceans*, 2008).
- Oscillating freestream causes favorable and adverse presure gradients.
- Parameters:
  - $Re_\delta = \frac{(2\nu/\omega)^{1/2} U_{om}}{\nu} = 3,600$
  - $Re_{99} = \frac{\delta_{.99} U_{om}^{\nu}}{\nu} = 2 - 3.5 \times 10^5$
  - *Finite-volume, 2nd-order code*
  - *Various wall-layer treatments and SG models.*
  - *Between 120x32x60 and 240x80x120 points.*



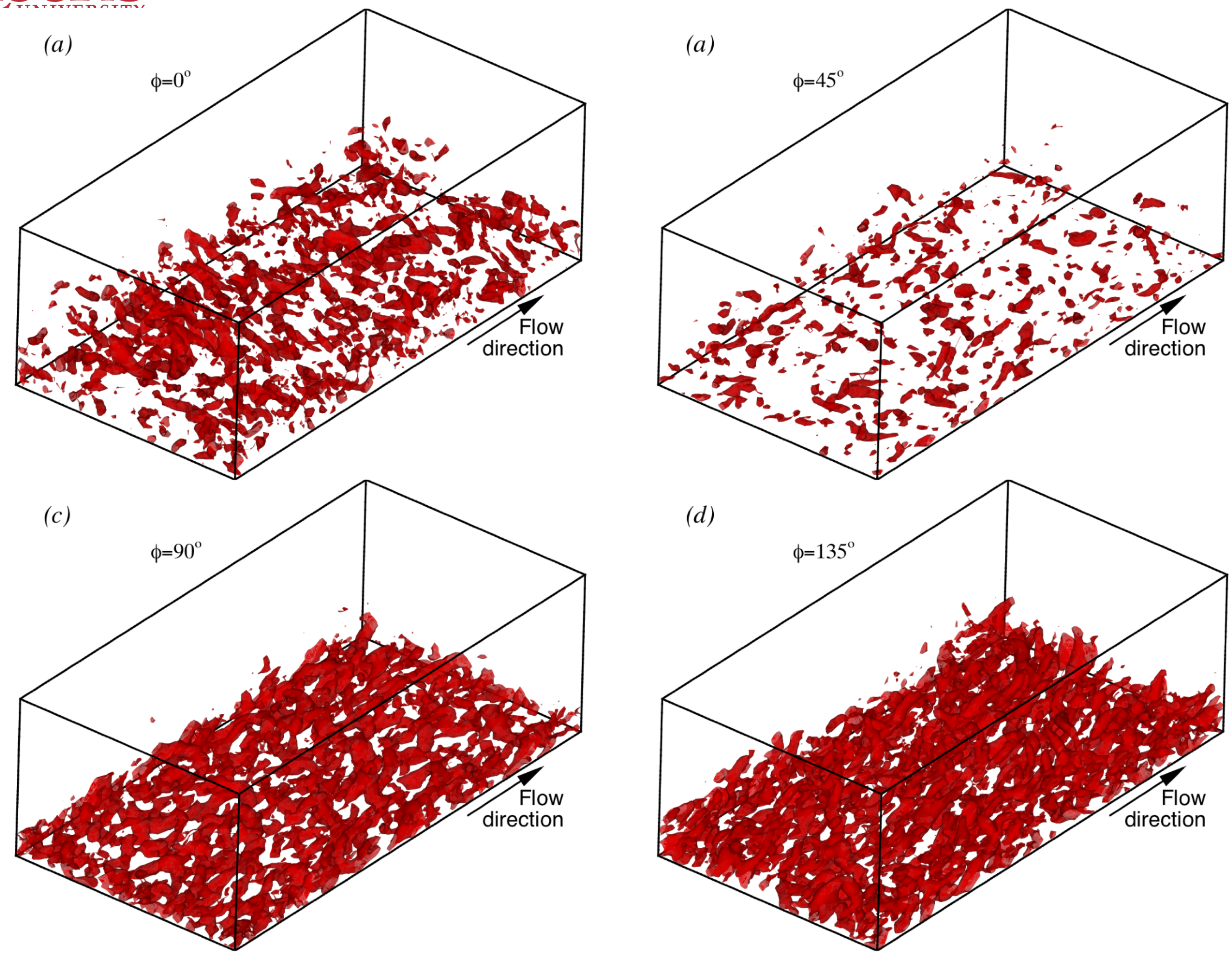


Equilibrium-stress layer

- The logarithmic-law predicts te flow accurately throughout most of the period (even near reversal).
- The MKP modification gives improved accuracy in the wall-stress prediction.
- SGS modeling errors affect the flow, especially near the wall.



Equilibrium-stress layer

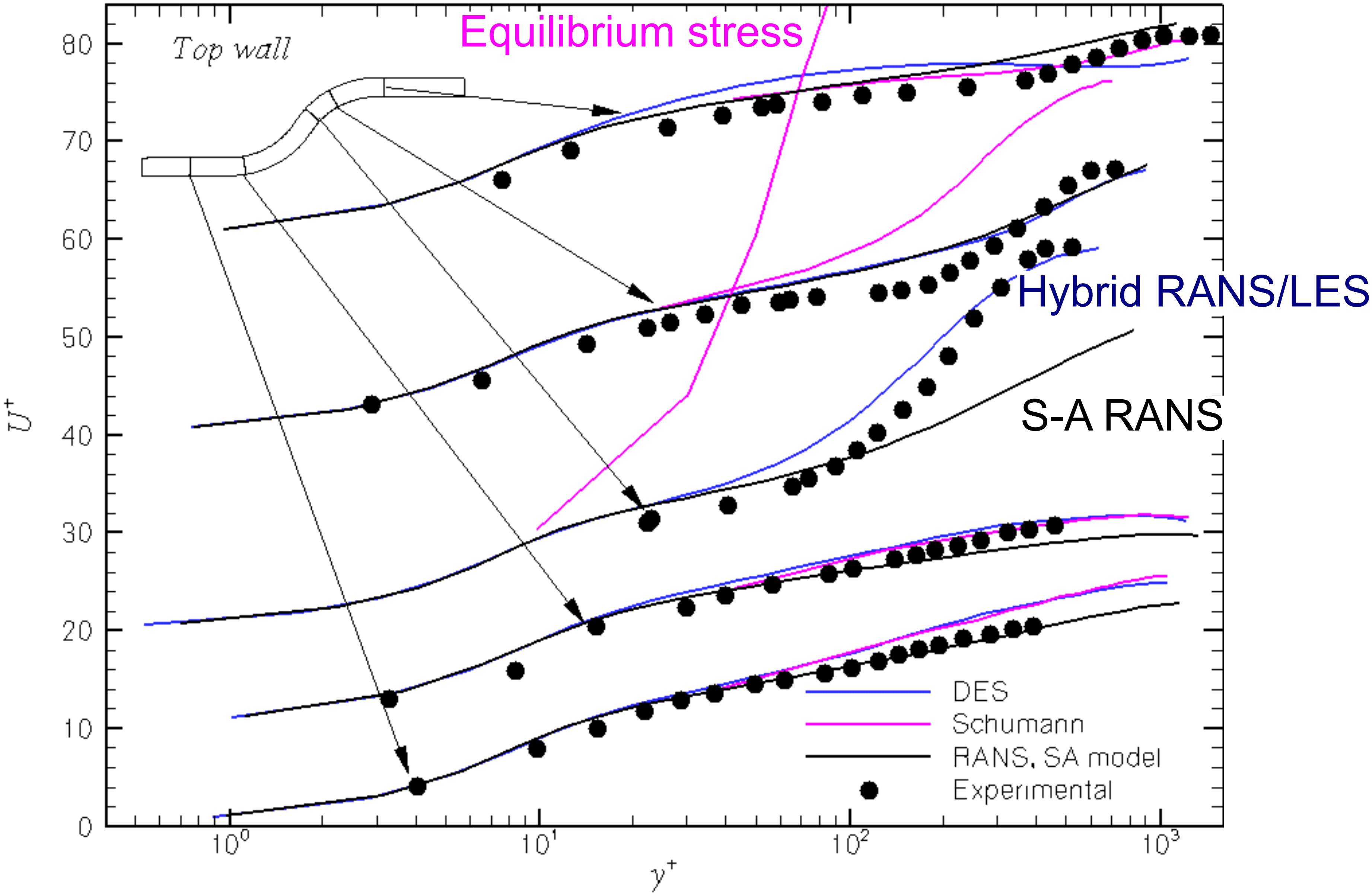


Isosurfaces of

$$Q = -\frac{1}{2}\frac{\partial \overline{u_i}}{\partial x_j}\frac{\partial \overline{u_j}}{\partial x_i}$$

- The turbulence structure in the outer layer is realistic.

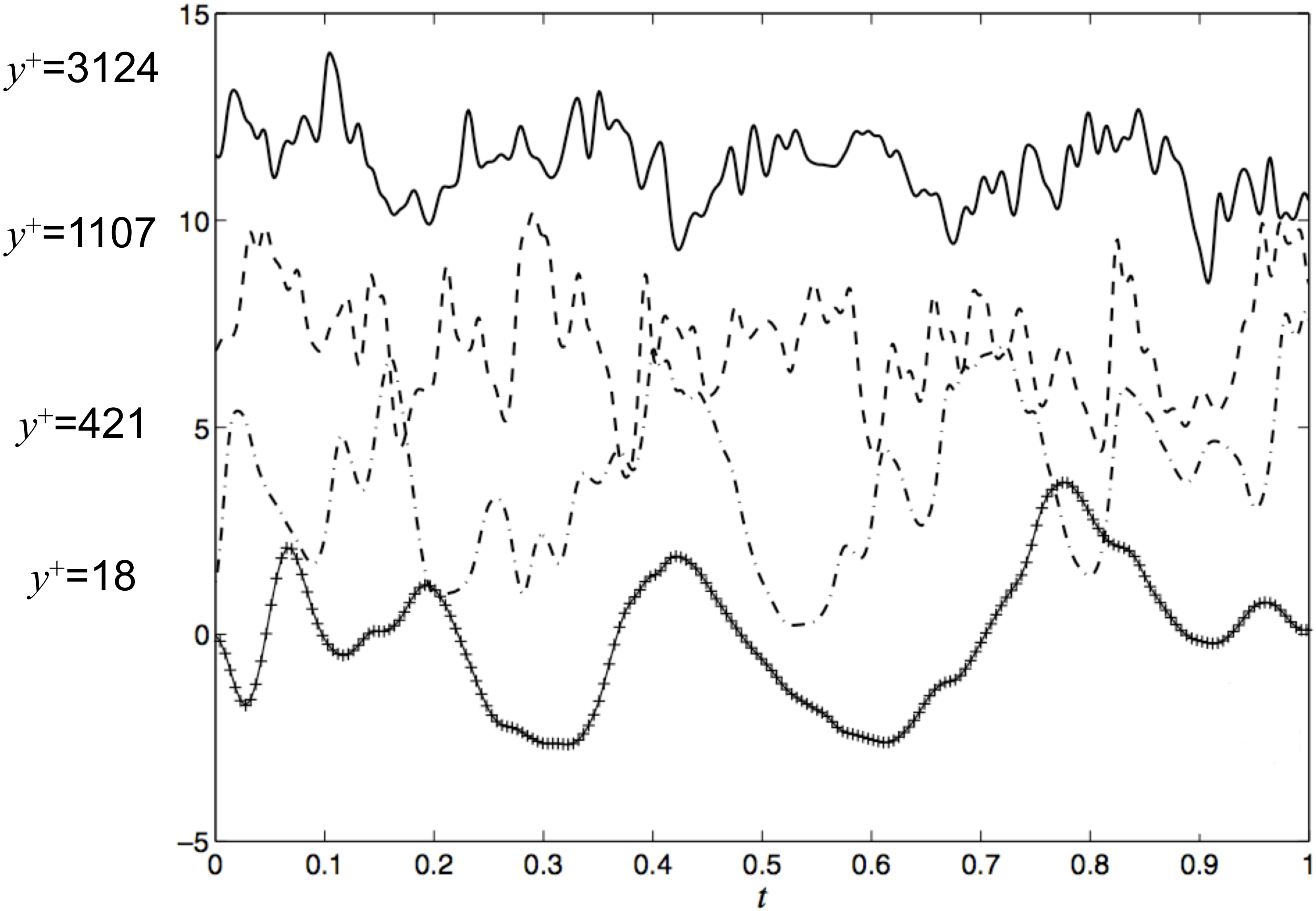
Applications: S-duct



Hybrid RANS/LES

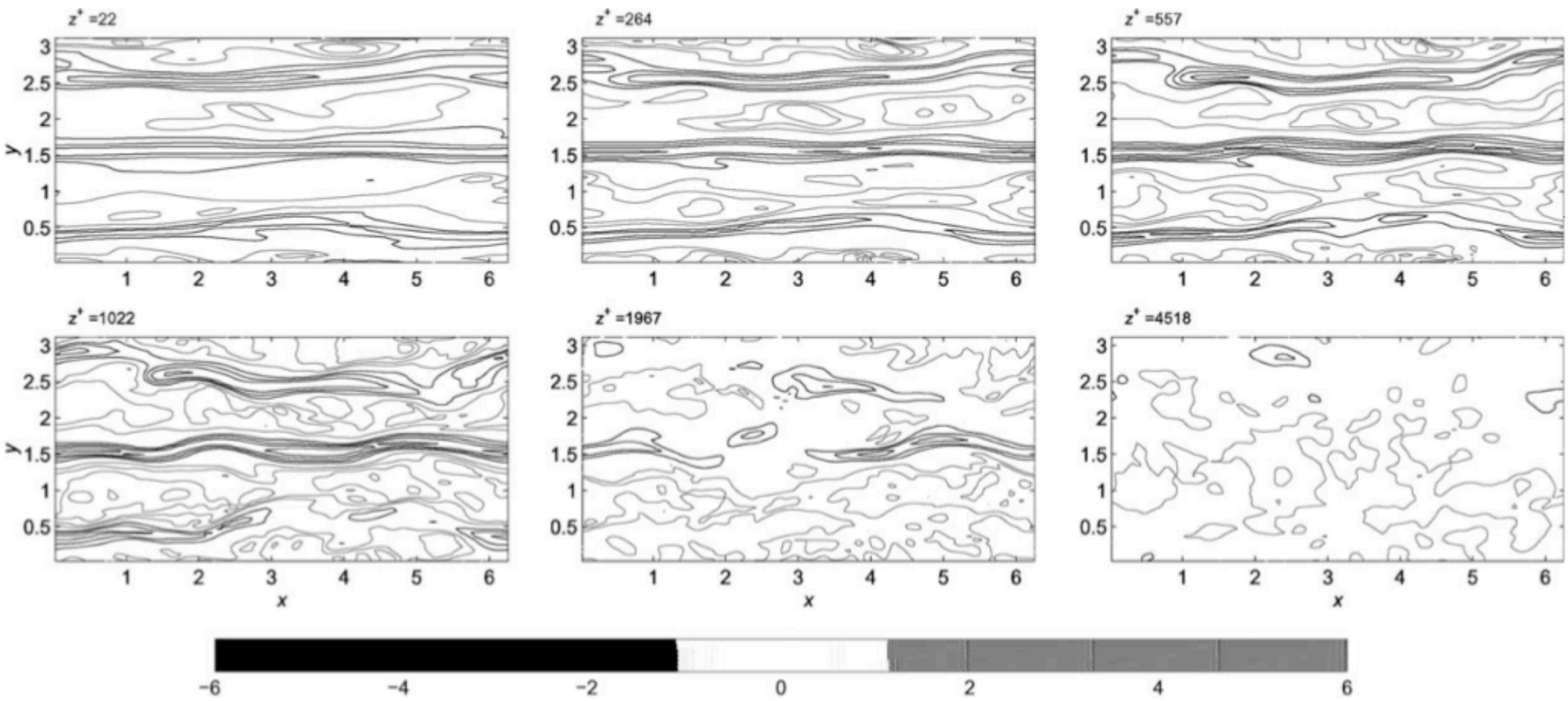
- Equilibrium-stress layer and zonal models work well when the outer layer drives the inner layer.
- Complex flows require models that include more physics.
- Solve a different set of differential equations in the inner layer $\Rightarrow$ Hybrid RANS/LES approaches.

- RANS/LES coupling issues example
  - *Plane channel flow*
  - Re_τ*=5,000.*
  - *SA-WMLES (SA model in DES mode, RANS/LES switch inside b.l.).*
  - *Nominal RANS/LES interface at* y^+*=225.*
  - *Staggered 2nd-order FD code.*



Time history of streamwise velocity fluctuations

Hybrid RANS/LES



Contours of streamwise velocity fluctuations in planes parallel to the wall

Hybrid RANS/LES

- The lack of energy-carrying eddies above the RANS/LES interface results in insufficient resolved shear stress.
- The eddy viscosity is lower than predicted by a plain RANS model.
- The velocity gradient must increase to conserve global momentum ⇒ **Logarithmic Layer Mismatch (LLM)**
- 15% error in skin friction coefficient.
- Energetic super-streaks→ high rms levels.

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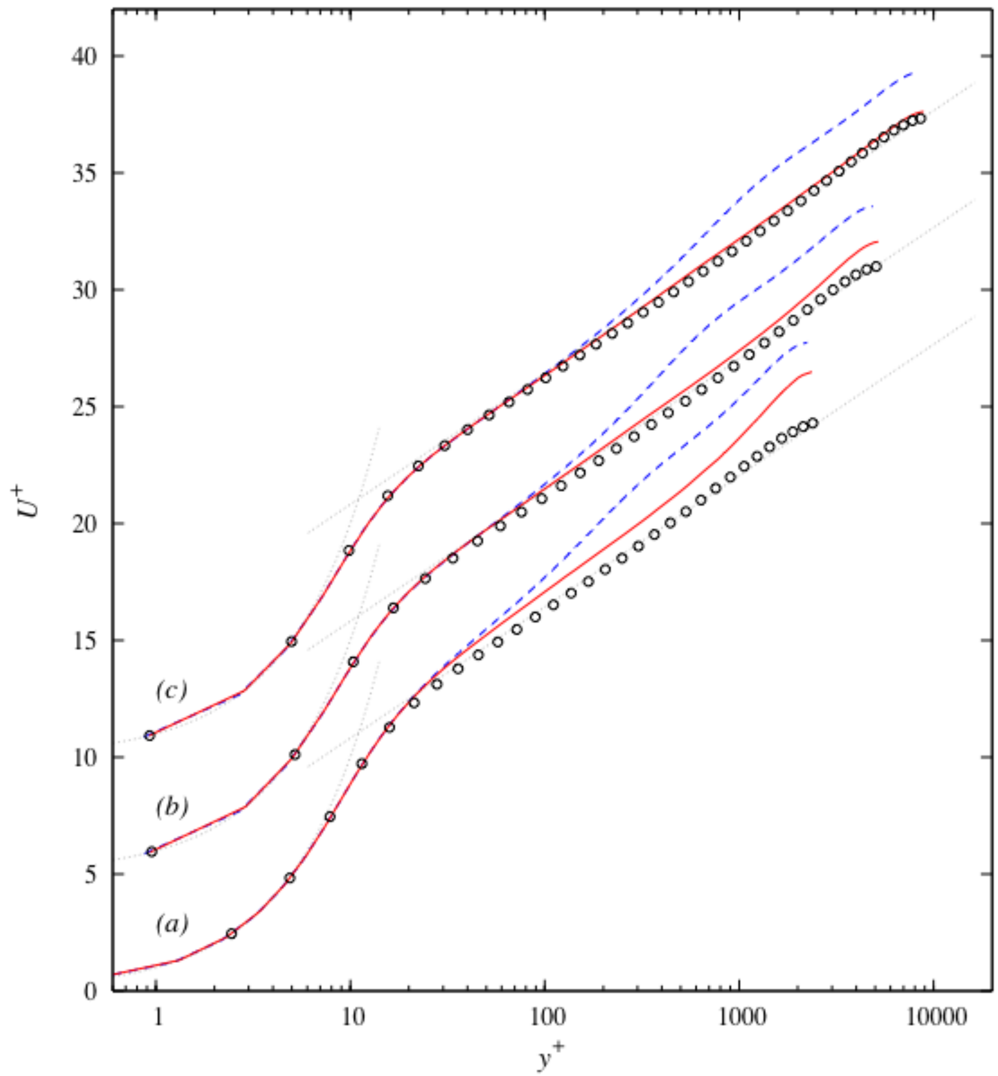


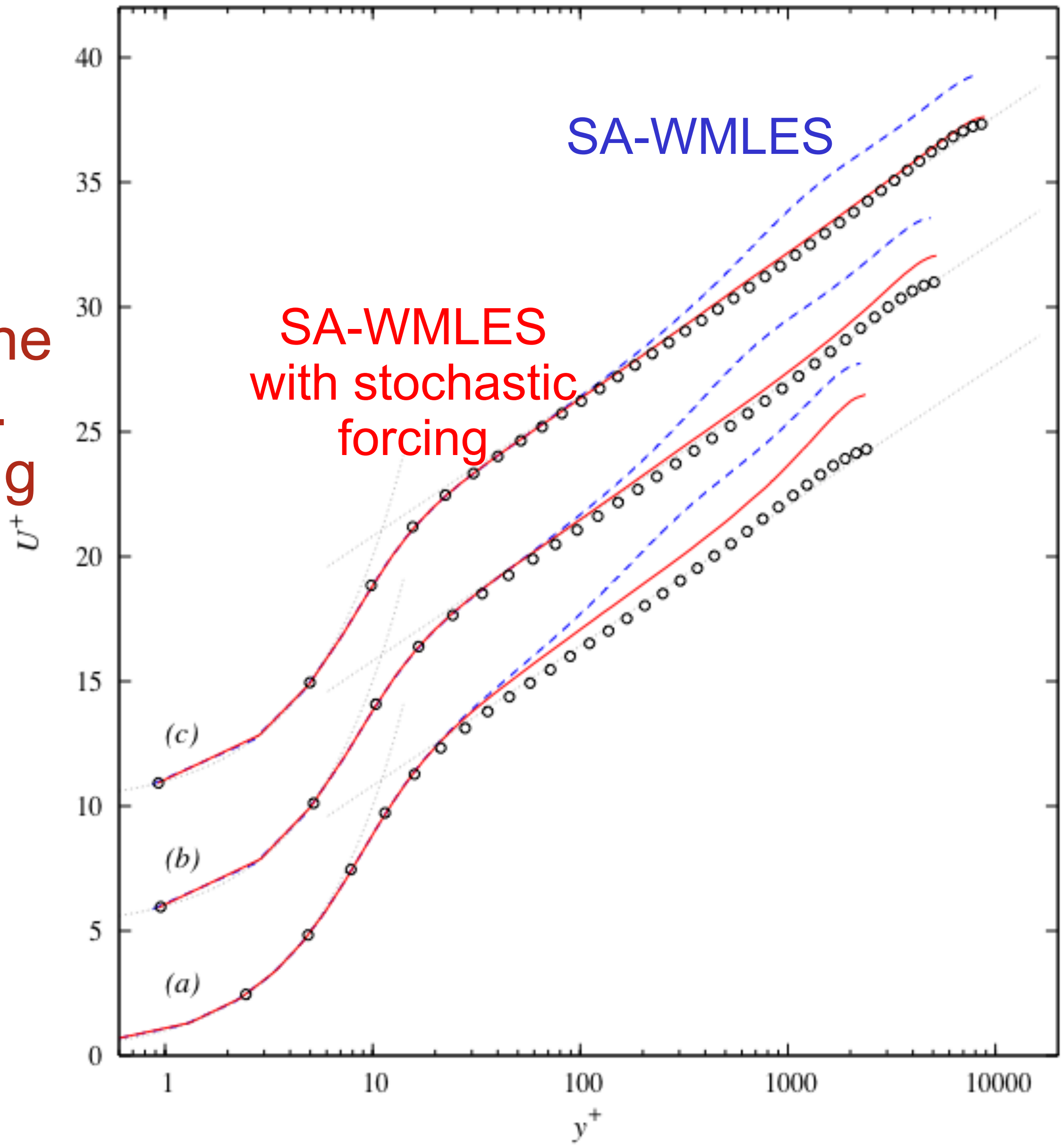
Mean velocity profiles in plane channel flow. SA-WMLES

Hybrid RANS/LES

- LLM has been observed both with DES-like methods and with blending functions.
- Much research aimed at removing LLM.
- Goal: increase the fluctuations at the RANS/LES interface.
  - *Forcing with stochastic fluctuations, DNS databases...*
    - Kick the flow to accelerate “transition”.
  - *Decrease the eddy viscosity near the interface*
    - Allow natural perturbations to be amplified more rapidly

Hybrid RANS/LES

Mean velocity profiles in plane channel flow. SA-WMLES. Stochastic forcing by Keating and Piomelli (2006)



URANS vs. LES

URANS

- Only the mean-flow unsteadiness is captured
- The vorticity due to the turbulent eddies is modelled
  ⇒ Calculations can be 2D
- Only statistical information is required at the inflow
- Only the mean gradients are resolved

LES

- The unsteady turbulent eddies are captured
- The vorticity due to the turbulent eddies is computed
  ⇒ Calculations must be 3D
- The instantaneous field is required at the inflow
- The unsteady turbulent eddies are resolved

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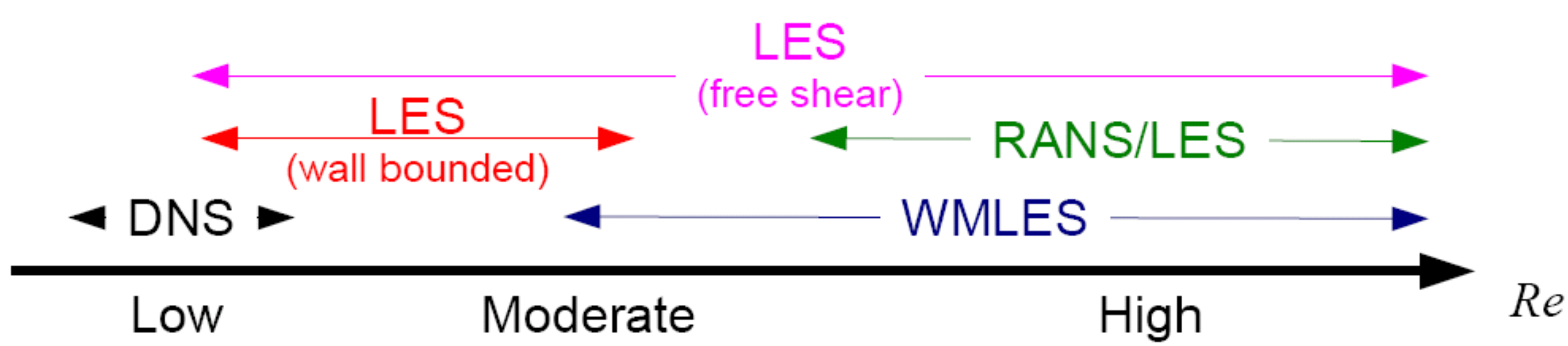
Conclusions

- Eddy-resolving methods for the numerical simulation of turbulent flows have resulted in
  - *Improved understanding of the flow physics*
  - *Novel flow-control ideas*
- Direct Numerical Simulations (DNS):
  - *No empiricism, Low Re, physics, simple geometry.*
- Large-Eddy Simulations (LES):
  - *Little empiricism, medium Re, physics.*
- WMLES and Hybrid RANS/LES:
  - *Stronger empiricism, high Re, physics and design, complex geometry.*
- These methods cover the full spectrum of fluid-dynamical applications.



Conclusions

- Eddy-resolving methods require substantial computational resources.
  - *Thousands of CPU hours*
  - *Terabytes of data generated*
  - *Flow visualization (esp. animation) is demanding.*

Conclusions

- Eddy-resolving methods require substantial computational resources.
  - *Thousands of CPU hours*
  - *Terabytes of data generated*
  - *Flow visualization (esp. animation) is demanding.*
- Directions for improvement:
  - *Physical modeling*
    - Optimum stirring at interfaces
    - Small-scale effects on combustion, particle motion …
  - *Algorithm development*
    - Optimal LES
      - Grid refined adaptively to maintain a given level of resolution of the eddies.
      - Requires advances in physical modelling, algorithms.

Conclusions

- Eddy-resolving methods require substantial computational resources.
  - *Thousands of CPU hours*
  - *Terabytes of data generated*
  - *Flow visualization (esp. animation) is demanding.*
- Directions for improvement:
  - *Physical modeling*
  - *Algorithm development*
  - *Real-time visualization*
- The potential returns are large
  - *Eddy-resolving methods can be applied in many fields*

Benefits of eddy-resolving methods