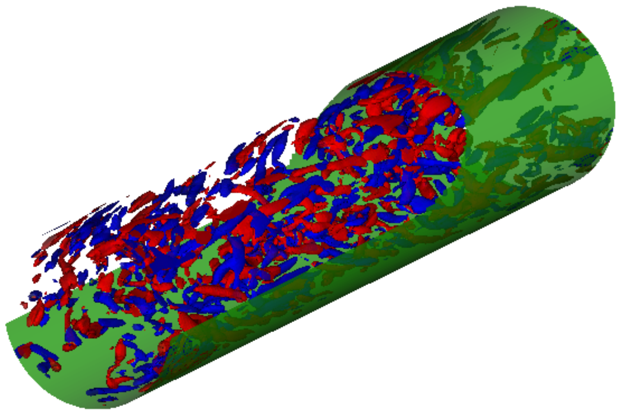
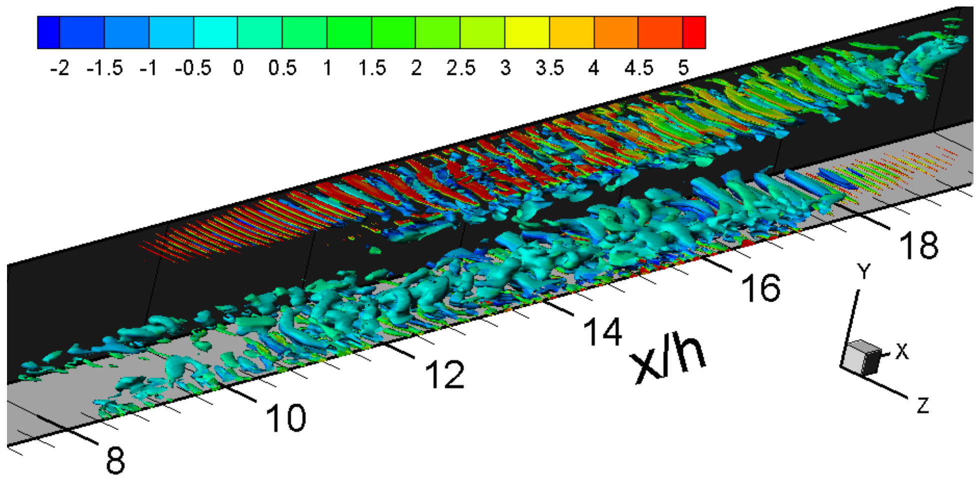
Computational Investigation of Buoyancy Influenced Flows and Benchmarking exercise





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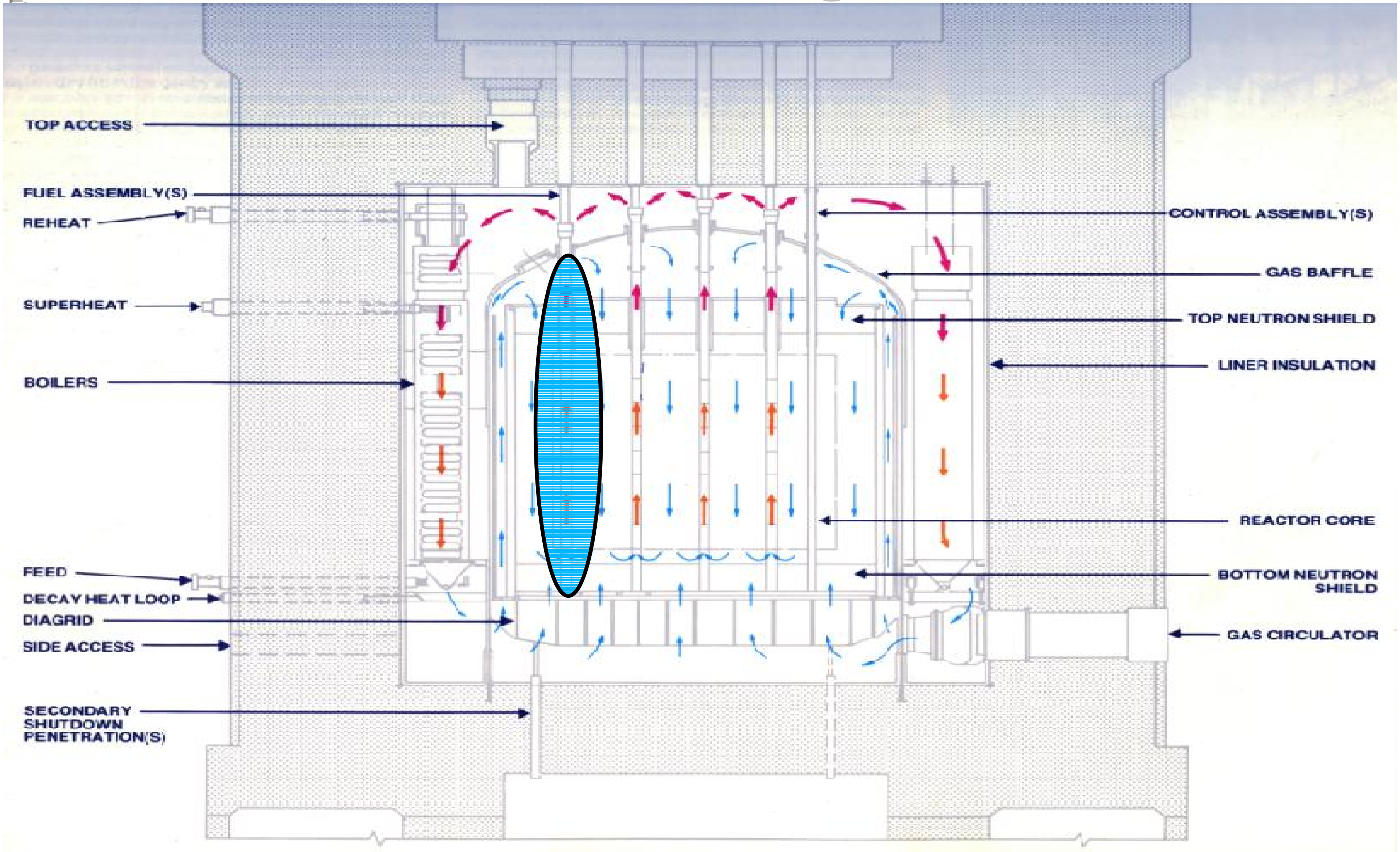
(Collaborators: S. Benhamadouche, R. Howard, F. di Mare)

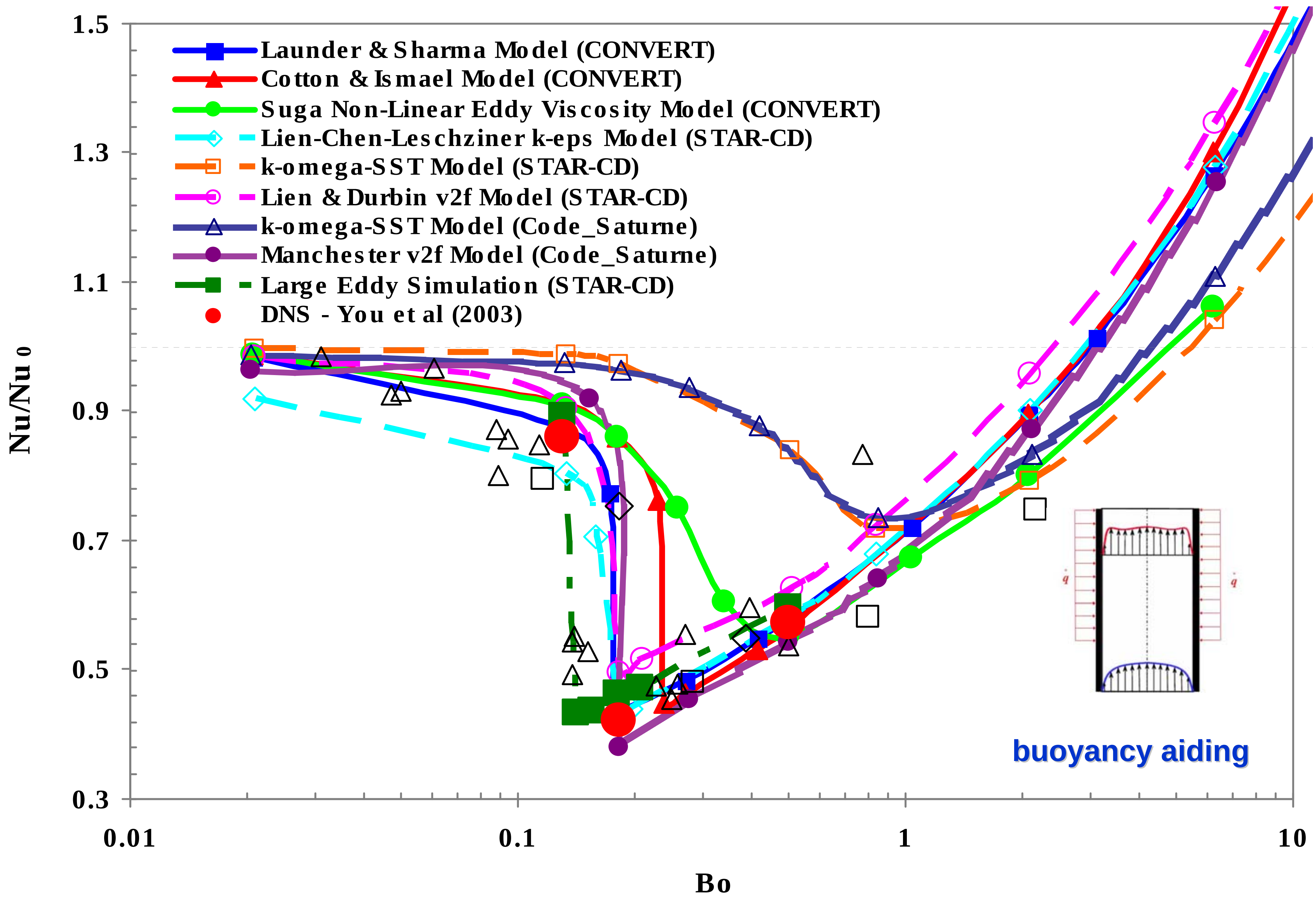
School of Mechanical, Aerospace & Civil Engineering (MACE)

The University of Manchester

AGR working scheme

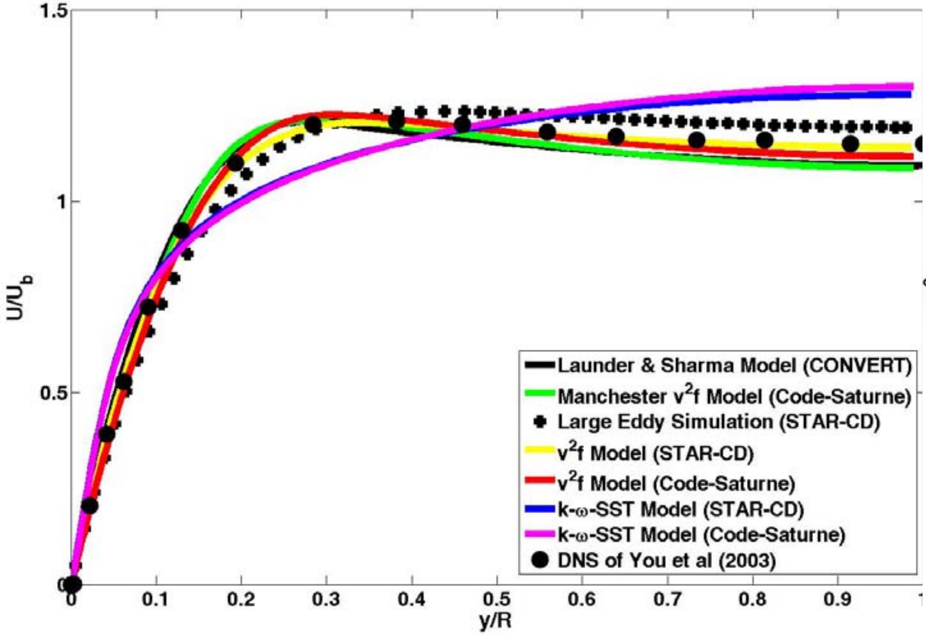


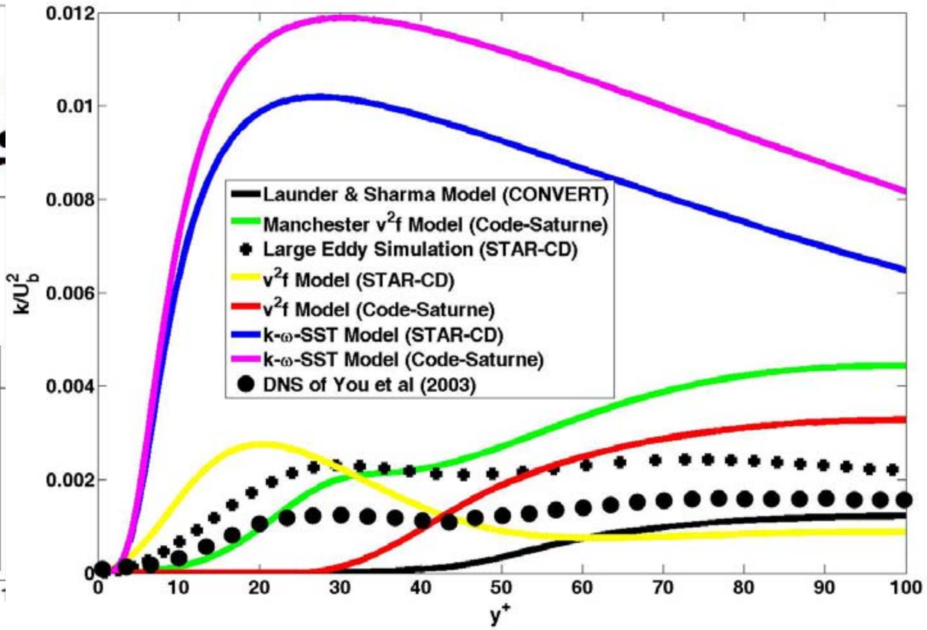
RANS models predictions

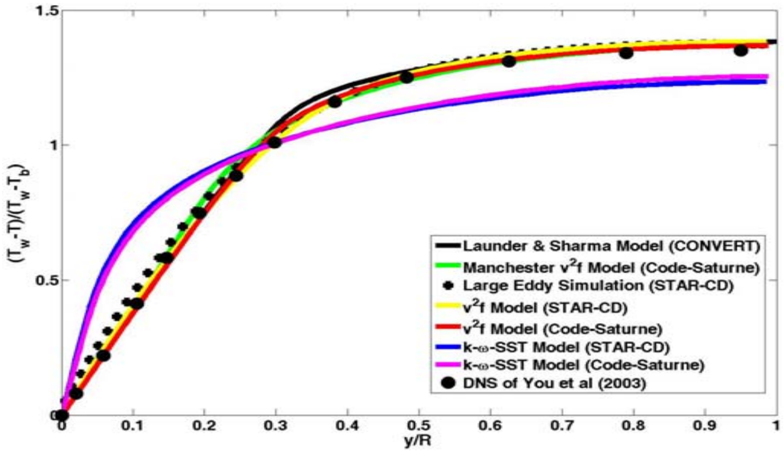


Buoyancy aided heated pipe flow

Gr/Re**2 = 0.087 (relaminarization)







Launder & Sharma Model (CONVERT)

Manchester v^2f Model (Code-Saturne)

Large Eddy Simulation (STAR-CD)

v^2f Model (STAR-CD)

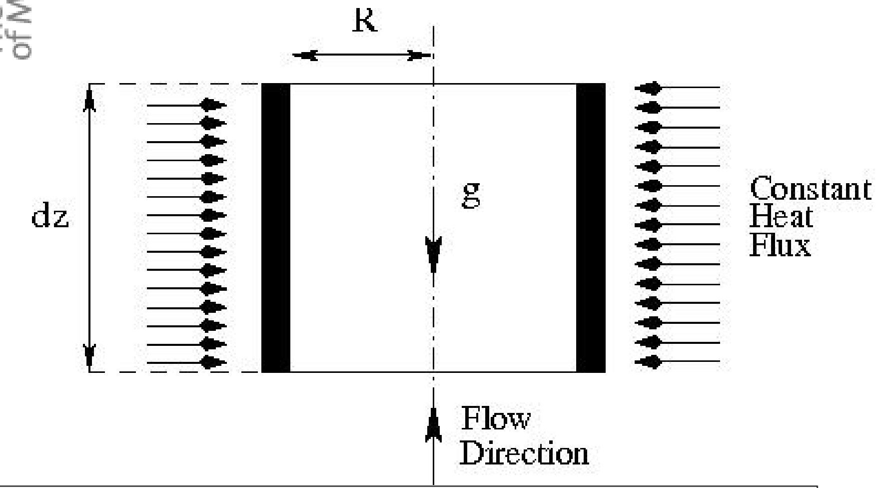
v^2f Model (Code-Saturne)

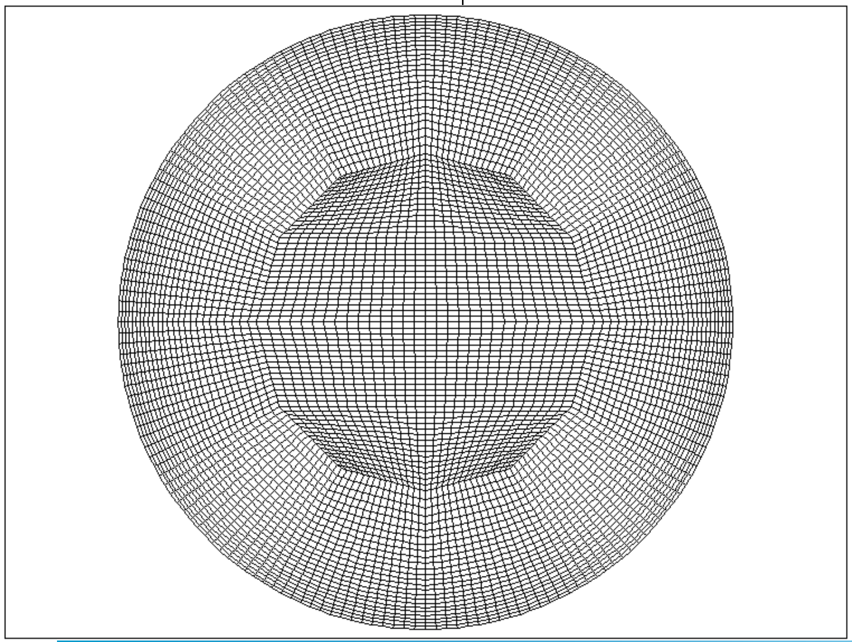
k-ω-SST Model (STAR-CD)

k-ω-SST Model (Code-Saturne)

DNS of You et al (2003)

Test Case Description





- **Re=180** based on R and u_{τ}.
- **Boussinesq** Approximation.
- Periodic Flow.
- Lz=30R

- **Grid1:** 1.61 million
- **Grid2:** 4.83 million

- Grid1 Resolution: Δr^{+}_{min}=1.0, $\Delta\phi^{+}$=6.28, Δz^{+}=18.

- Grid2 Resolution: Δr^{+}_{min}=1.0, $\Delta\phi$+=6.28, Δz+=7.03.

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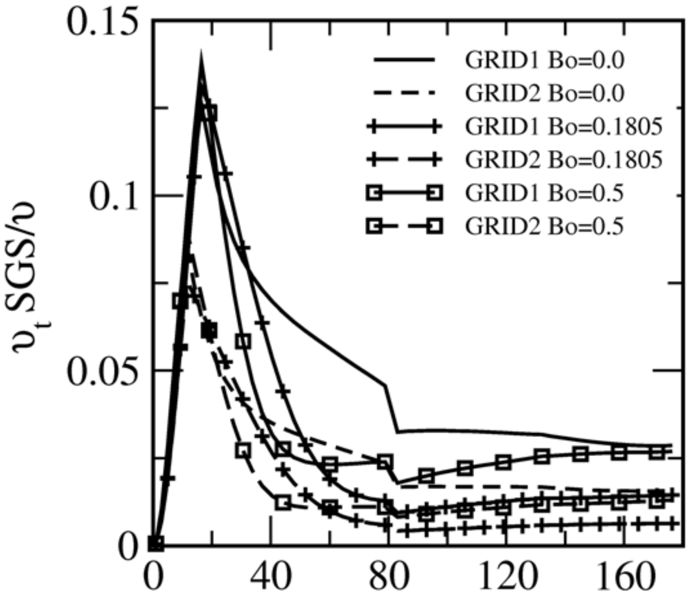
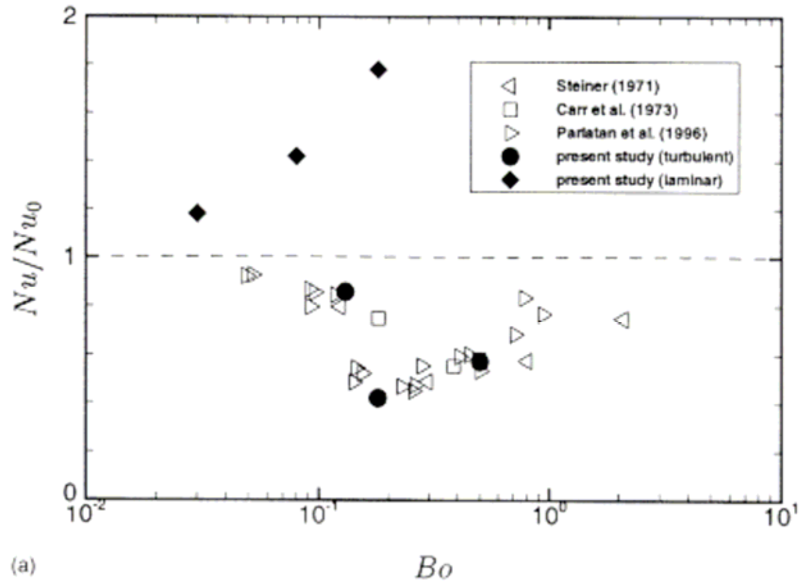
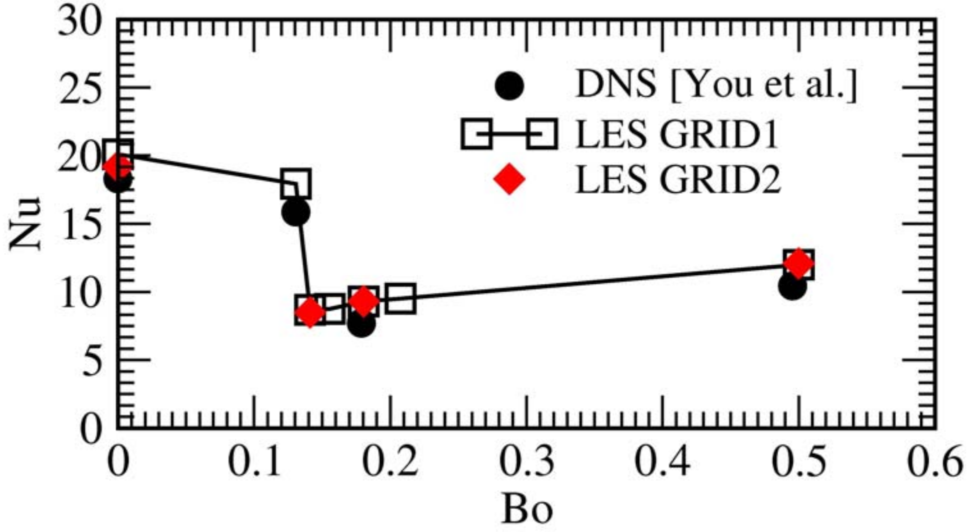
Ratio of SGS to molecular viscosity



Nusselt number as a function of the buoyancy parameter



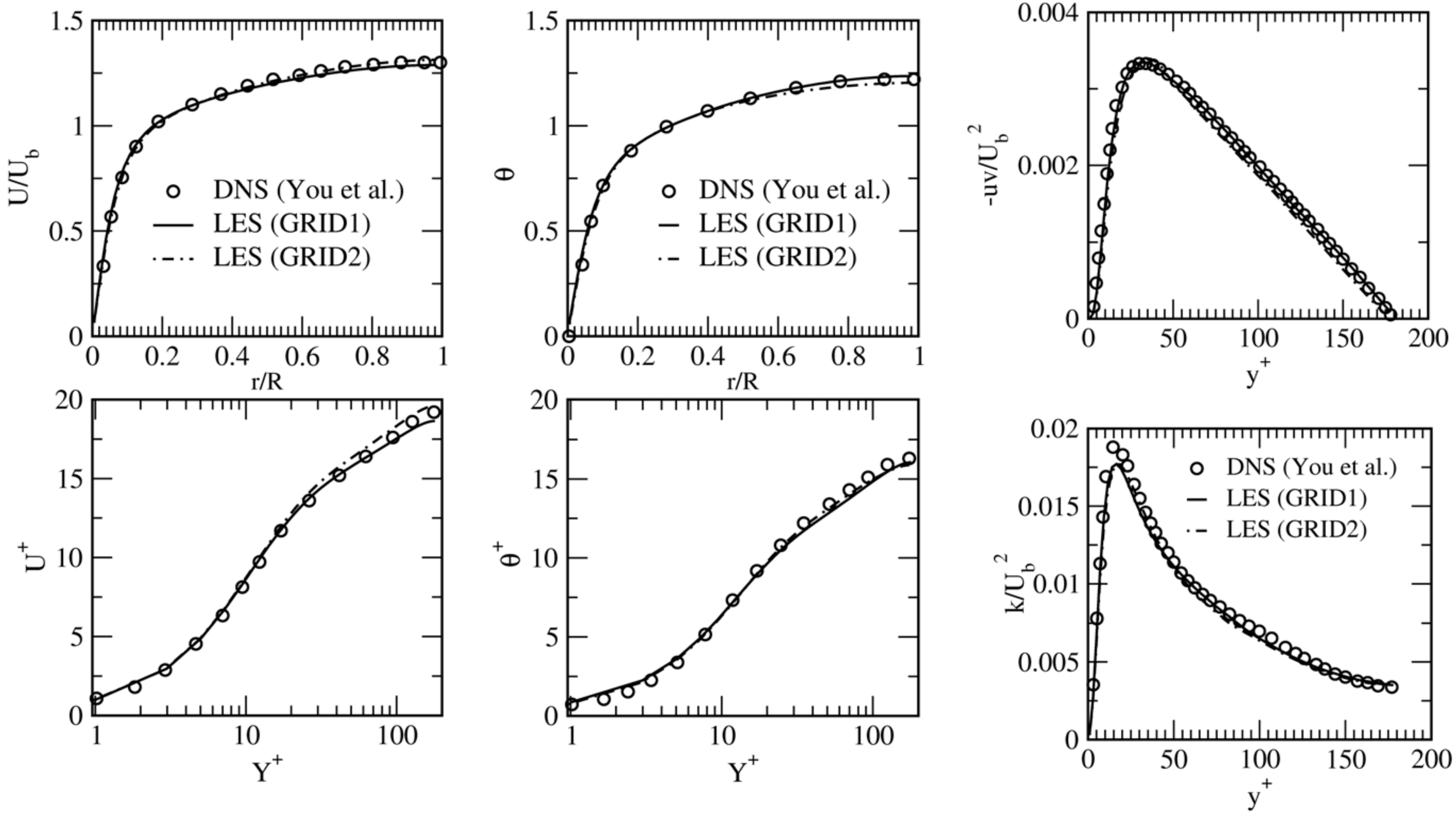


from You et al.

For RANS models predictions, see the paper by Amir Keshmiri et al.

Buoyancy effects on turbulence in VHTR channels: WR-LES

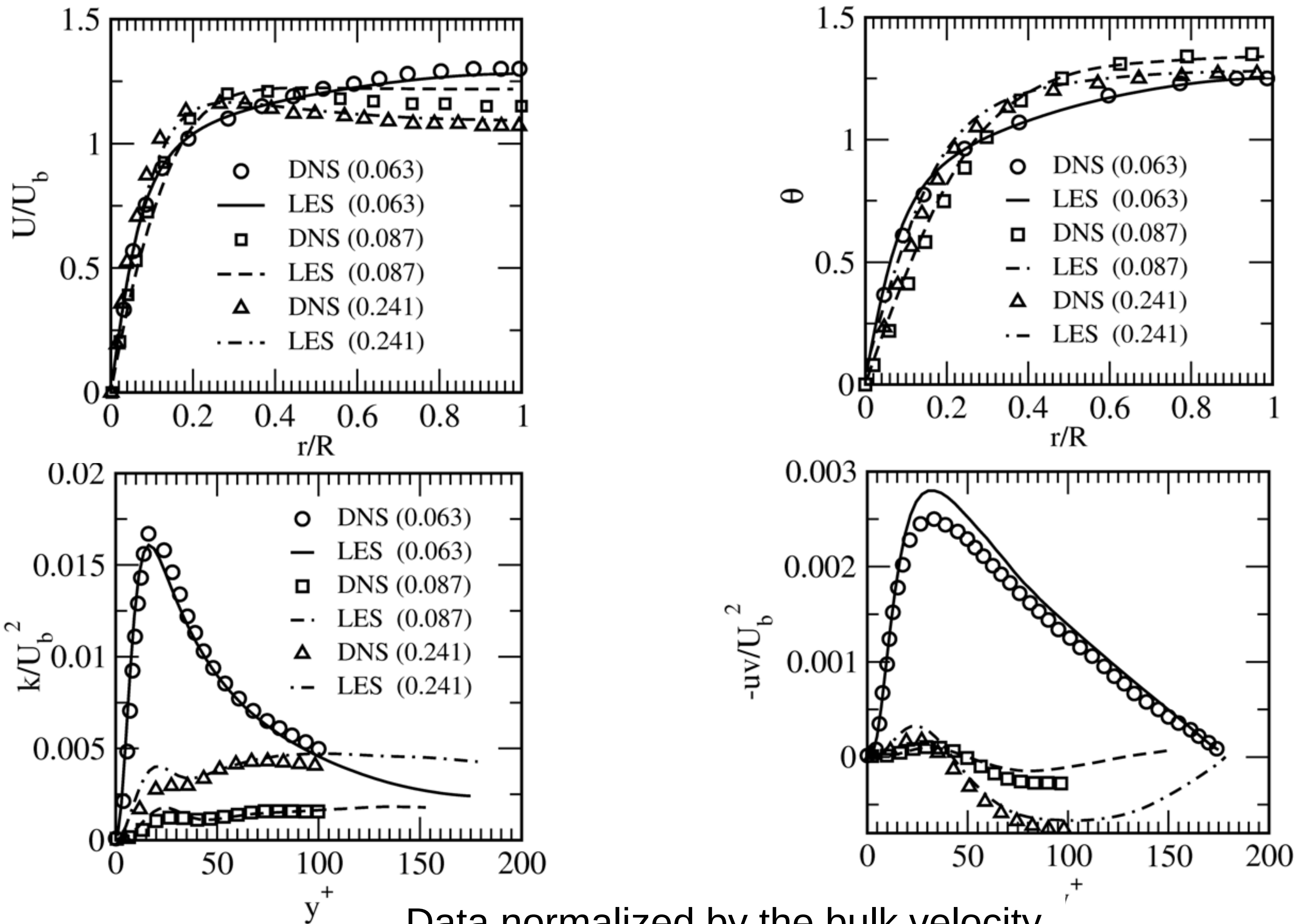
Case1: Forced convection $Gr/Re^2=0.0$



Data normalized by the bulk velocity

Buoyancy effects on turbulence in VHTR channels: WR-LES

Cases from Gr/Re^2=0.063 to Gr/Re^2=0.241

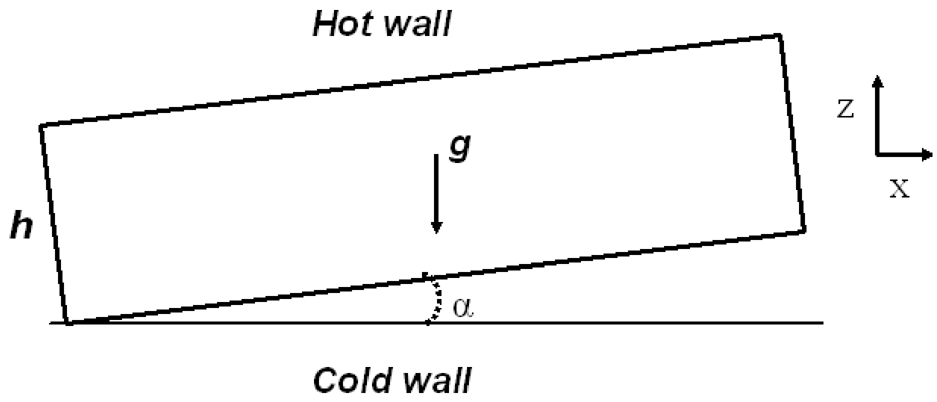


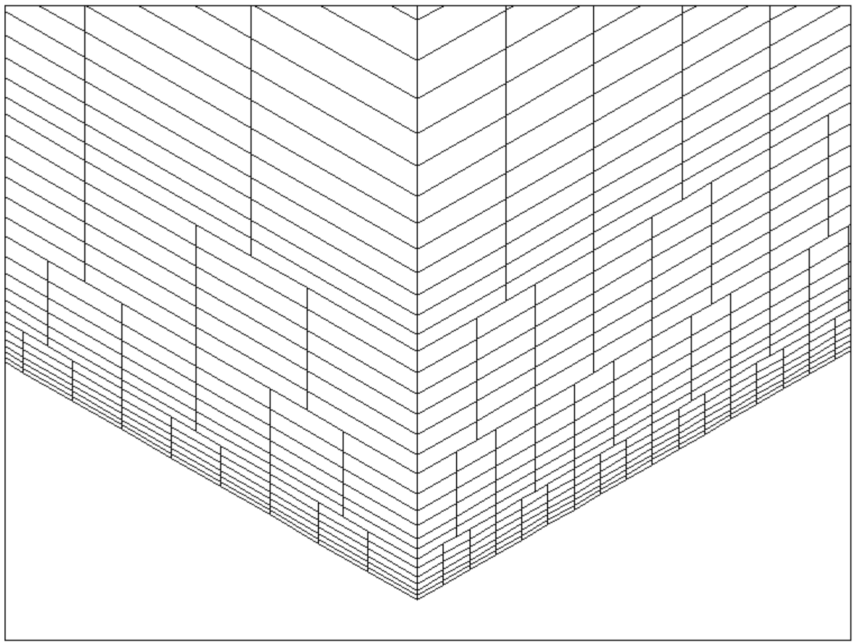
Data normalized by the bulk velocity

NEARLY-HORIZONTAL SHALLOW CAVITY TEST CASE

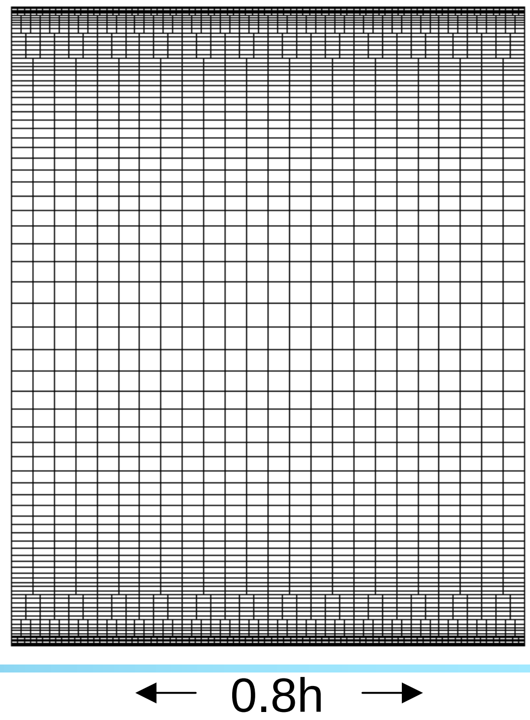
LES Grid (Case1)

- Ra= 4.16×10^8
- NCELL= 3 million
- Boussinesq approximation
- Pr=0.71 (Air)
- α=5°



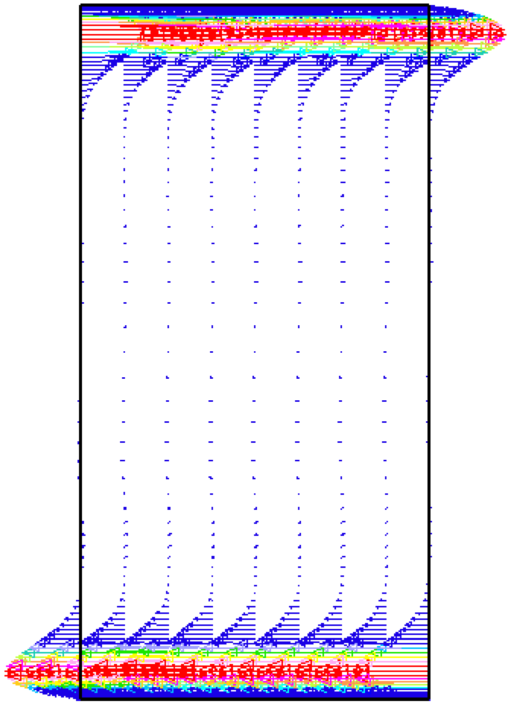


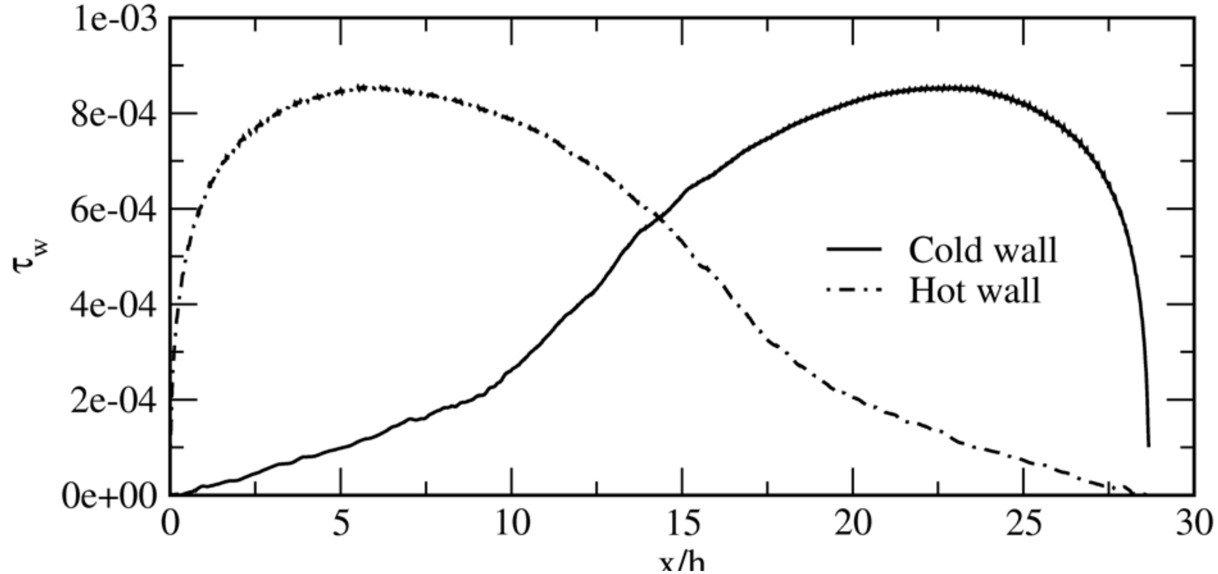
Plan Y-Z



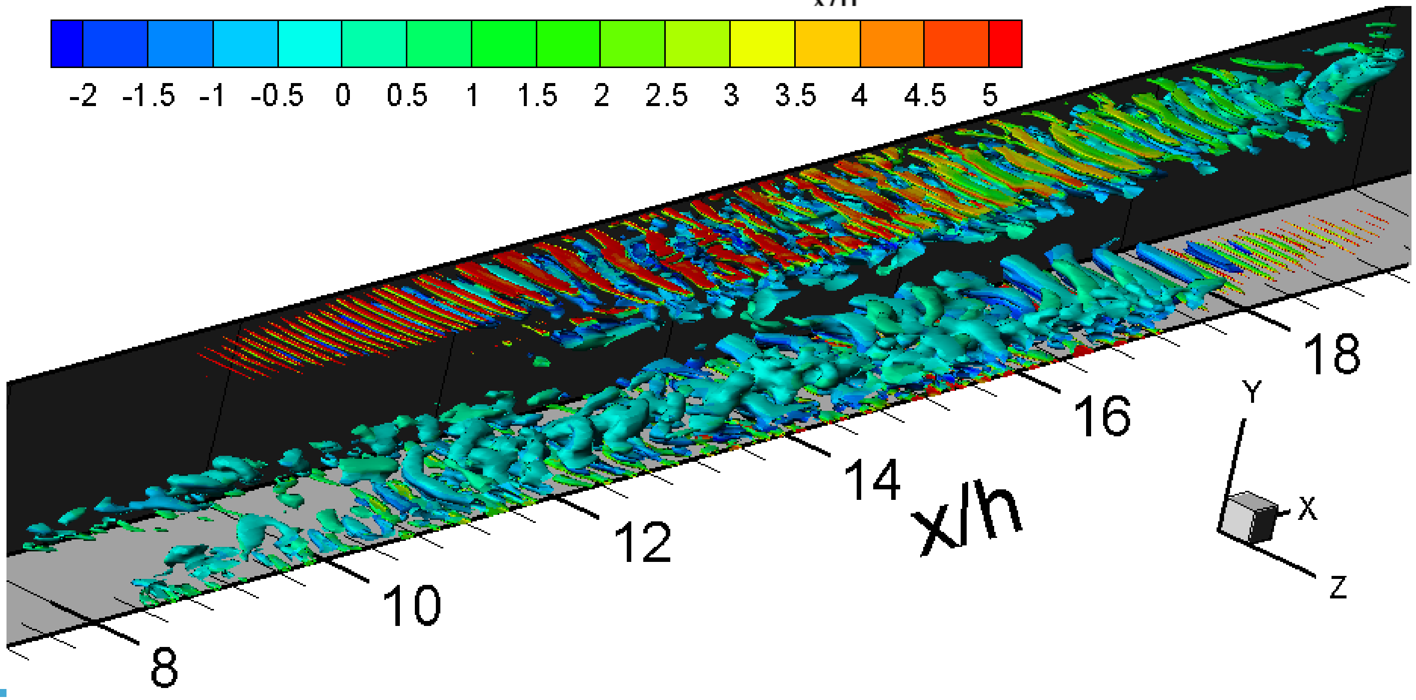
NEARLY-HORIZONTAL SHALLOW CAVITY TEST CASE

LES RESULTS





Q=0.05



NEARLY-HORIZONTAL SHALLOW CAVITY TEST CASE

RANS RESULTS

Low-Re. models tested:

•k-ε Lien *et al.* (1996)

•k-ω Wilcox (1998)

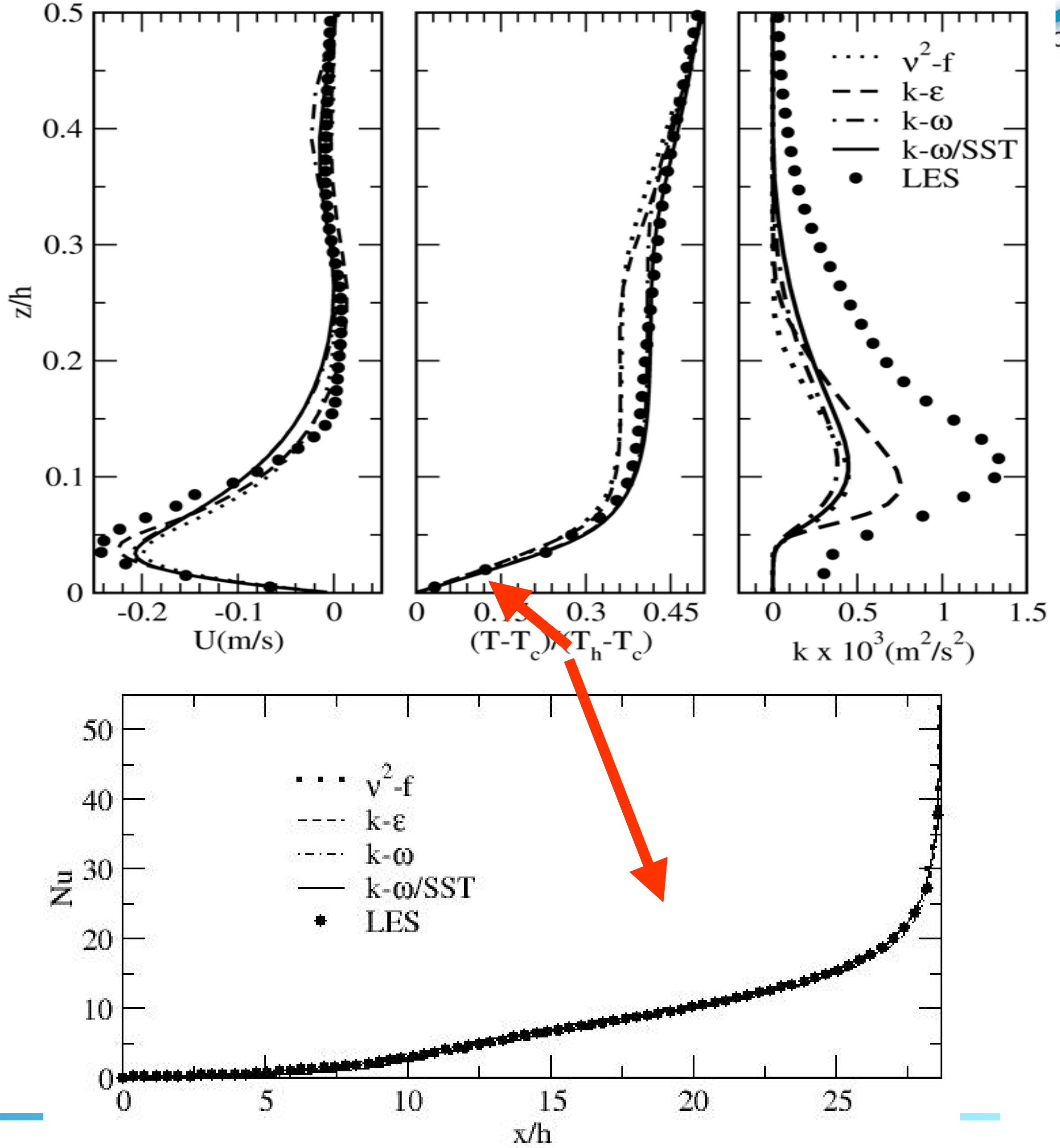
•k-ω SST Menter (1993)

•v^2-f Lien & Durbin (1996)

- Buoyancy term included in k-equation

- thermal fluxes

$$\overline{\rho}\,\overline{u'_j h'} = -\frac{\mu_t}{\sigma_{h,t}}\frac{\partial h}{\partial x_j}$$



Code_Saturne via Star-CD in LES approach

Code_Saturne:

❖ Unstructured (polyhedral).

❖ Collocated Finite Volume.

❖ SIMPLEC algorithm for the Vel/pres coupling.

❖ Time scheme: Crank-Nicolson. The mass flux non-linear term treated with Adams-Bashforth extrapolation.

❖ Spatial discretisation: Fully CD.

❖ Implicit Gradient reconstruction with Gauss method or least-squares.

Star-CD version 4.xx:

❖ Unstructured (polyhedral).

❖ Collocated Finite Volume.

❖ SIMPLE algorithm for the Vel/pres coupling.

❖ Time scheme: Three-time levels

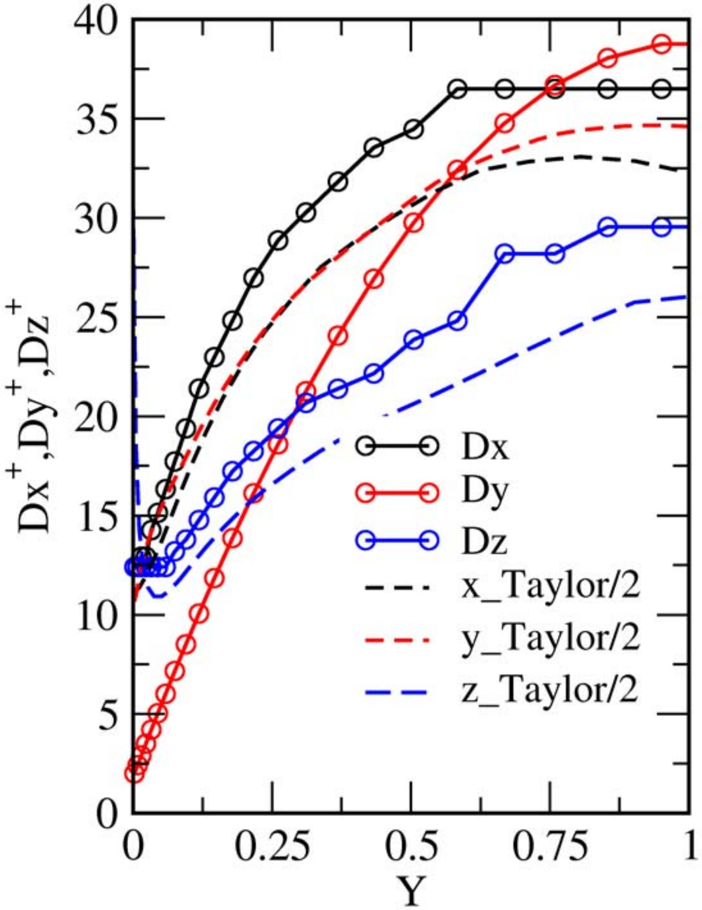
❖ Spatial discretisation: CD (deferred correction → cross-diffusion term computed using explicit values).

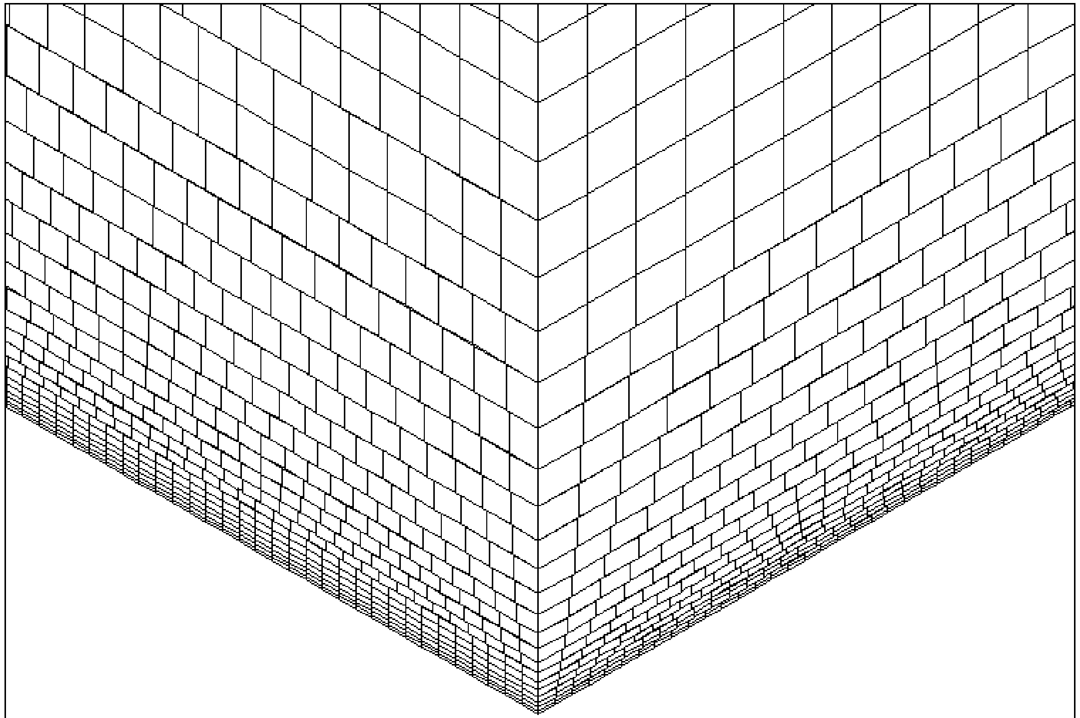
❖Gradient reconstruction with Gauss method for pressure and velocity.

Channel flow test case

- Re=395
- Domain $2\pi\delta \times 2\delta \times \pi\delta$
- LES Ncells= 443,272
- DNS Ncells = 9,486,336

(Ref: Moser et al. 1999)





Unstruct. “Taylor” mesh, Nt=0.44 M, Re = 395

	N x	Ny	Nz
LES	68 to 200	46	42 to 100
DNS	256	193	192

Unstruct. “Taylor” mesh, Nt=0.44 M, Re = 395

Time history at different points

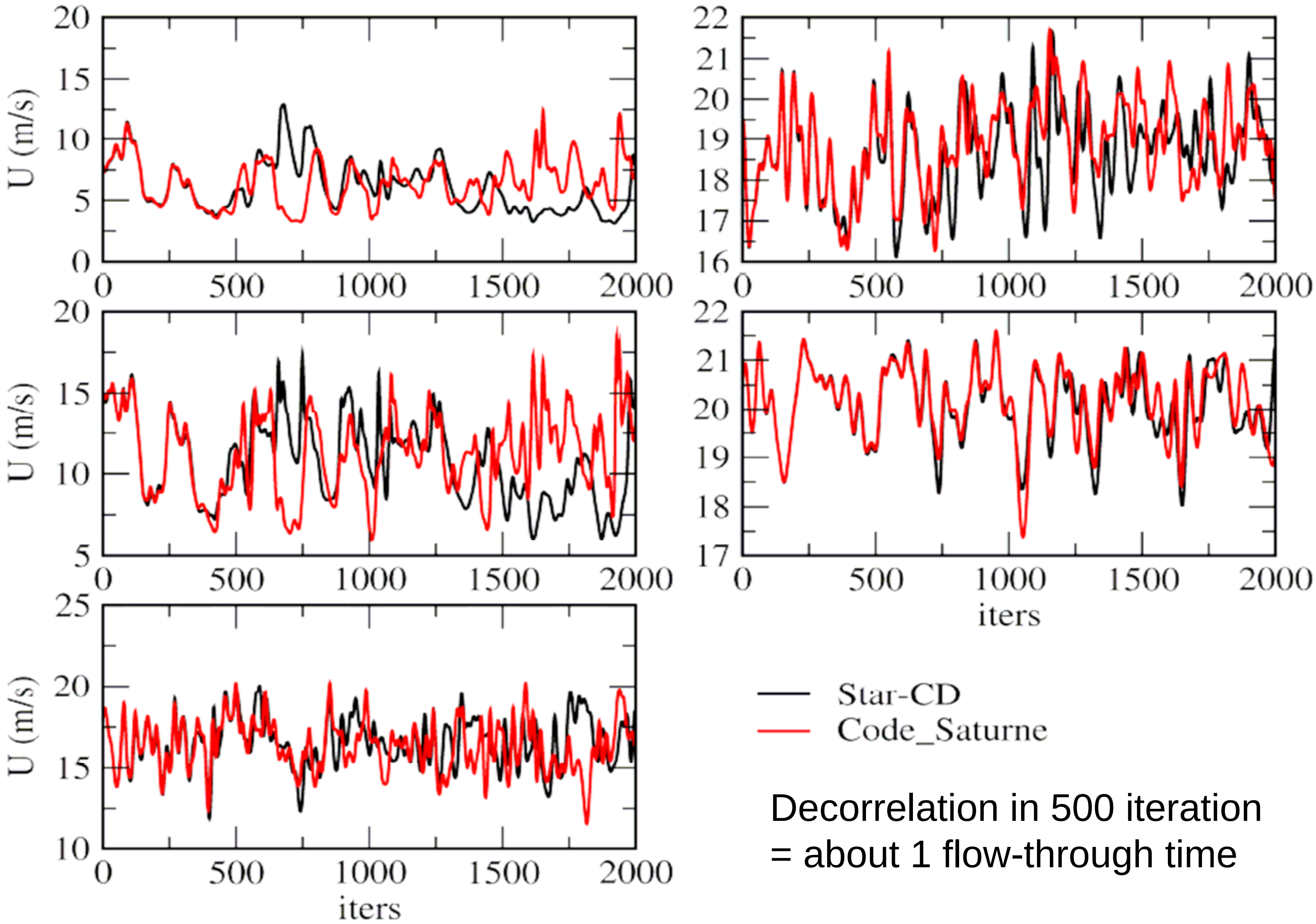
- History of the flow at 5 monitoring cells
- Number of iters. = 2000
- Time (T)= 2s
- Time for one Pass (T_{pass}) = 0.4432725 s
- $T/T_{pass} = 4.51$

Probes	Y^+
1	5.88
2	12.95
3	70.67
4	199.43
5	375.61

	Star-CD	Saturne
Res Vel	1.00E-005	1.00E-004
Res P	1.00E-005	1.00E-003
Res Vel/P Coupling	1.00E-005	1.00E-003
Rec RHS	? (1 most probably)	Vel 10 P 5

Unstruct. “Taylor” mesh, Nt=0.44 M, Re = 395

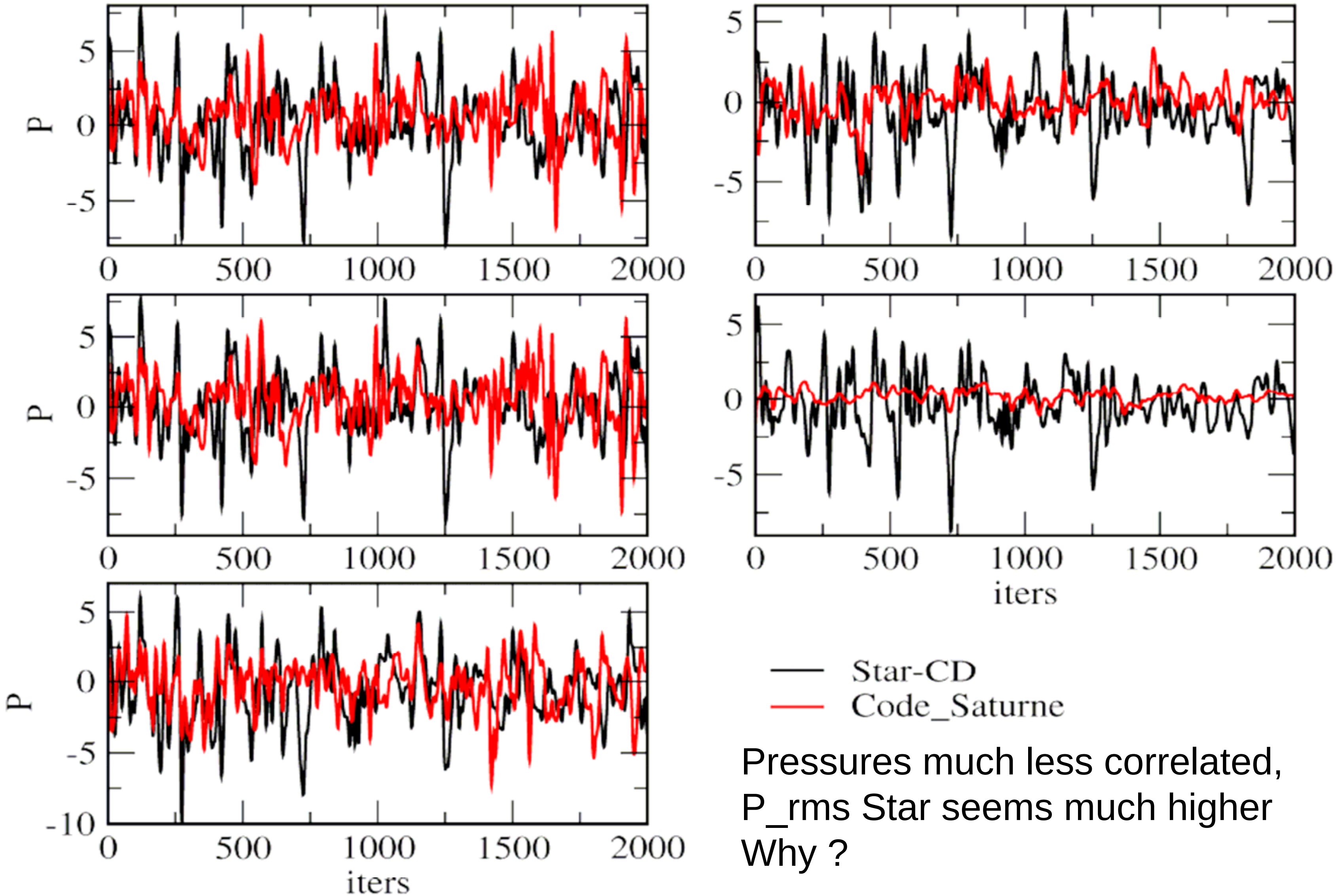
Time history at different points



Decorrelation in 500 iteration
= about 1 flow-through time

Unstruct. “Taylor” mesh, Nt=0.44 M, Re = 395

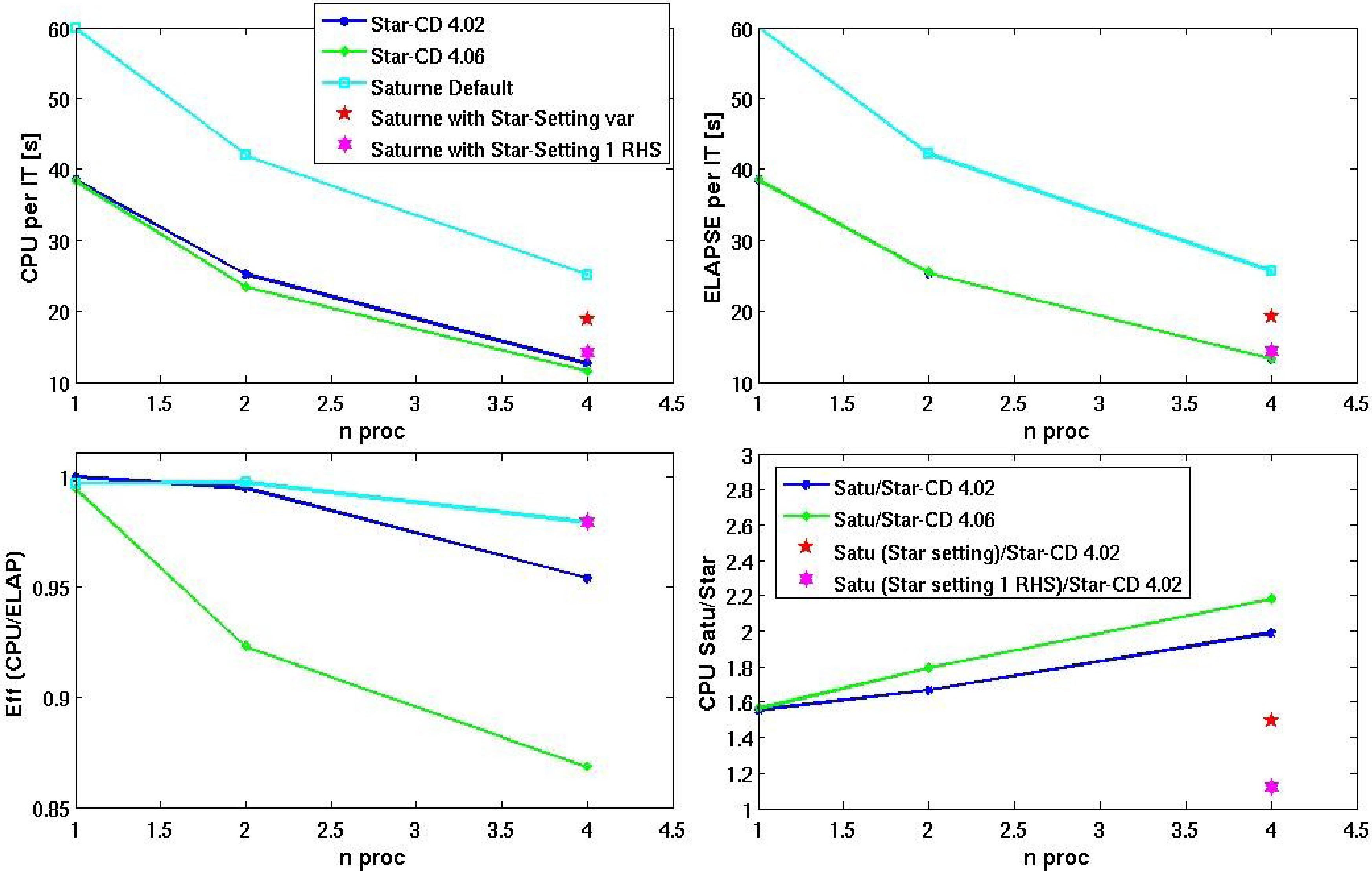
Time history at different points



Pressures much less correlated,
P_rms Star seems much higher
Why ?

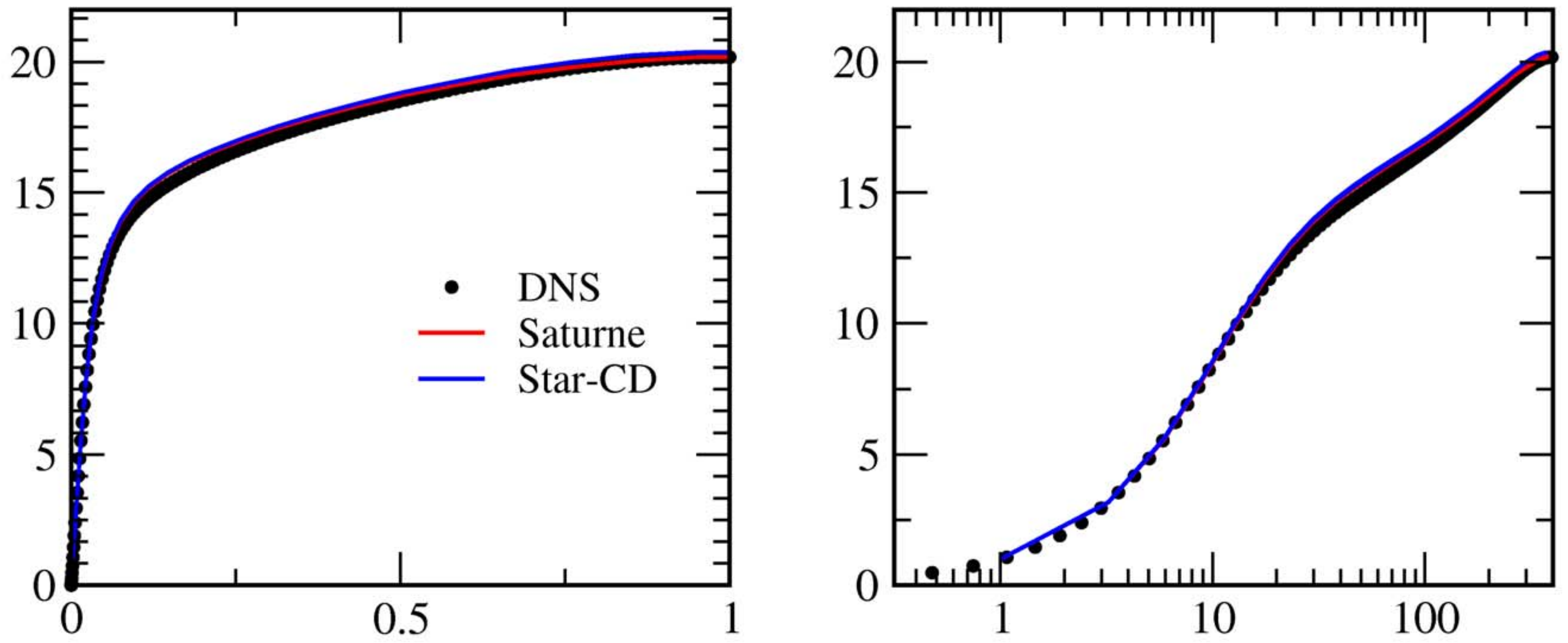
Saturne / Star CD CPU times & elapased

Unstruct. “Taylor” mesh on 1, 2, 3, 4 procs



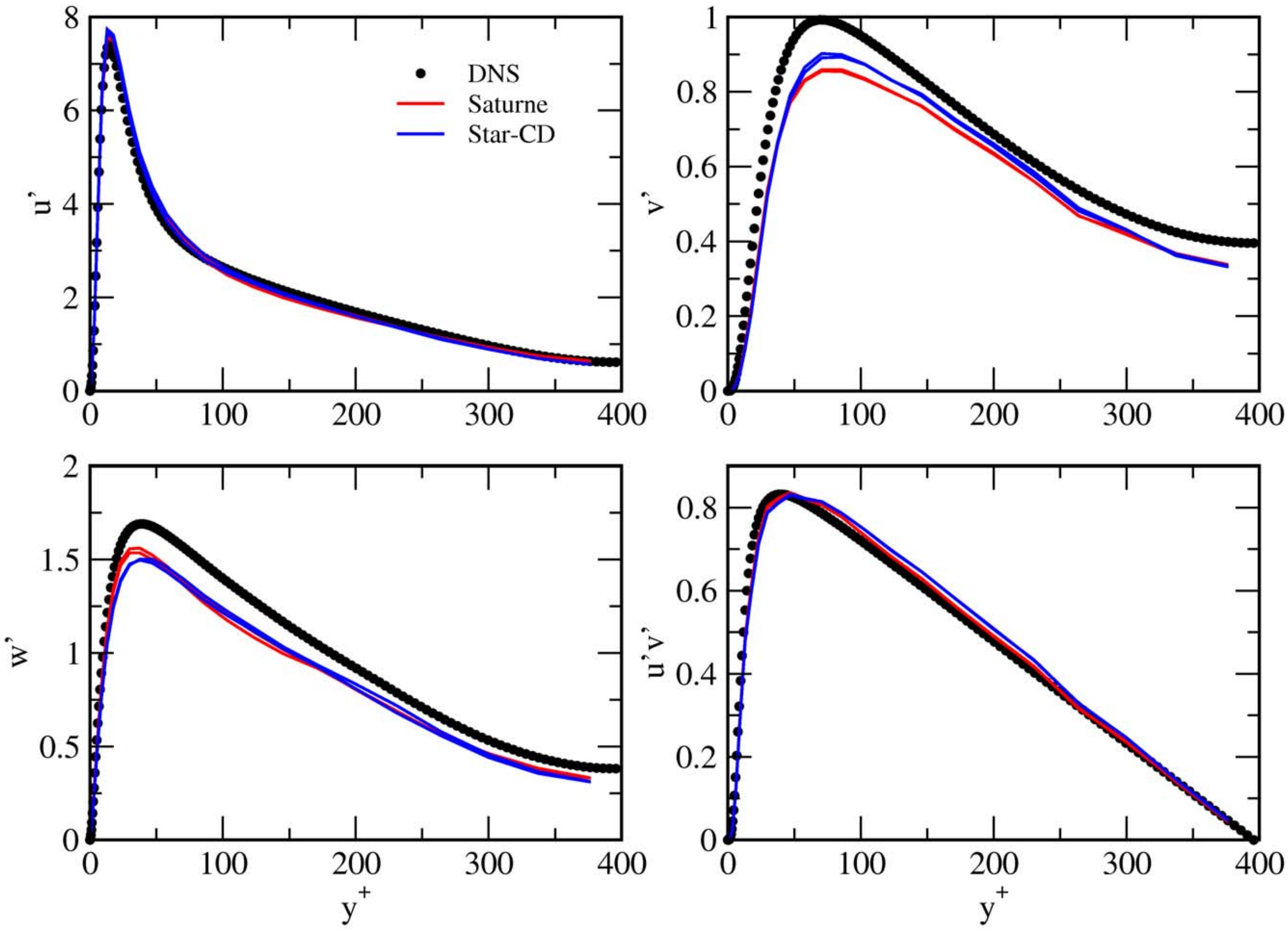
Unstruct. “Taylor” mesh, Nt=0.44 M, Re = 395

Channel flow test case: Mean Velocity predictions



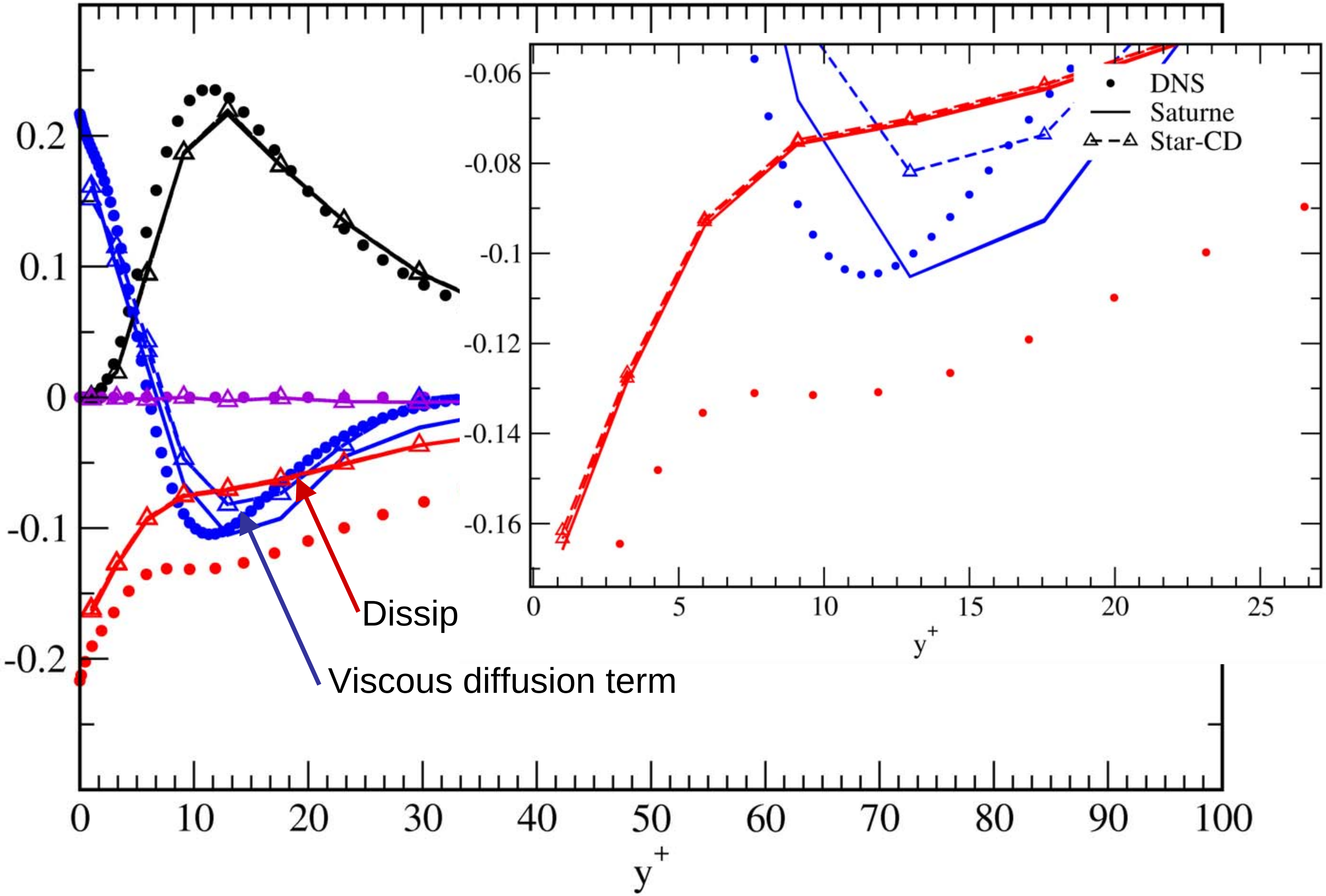
Unstruct. “Taylor” mesh, Nt=0.44 M, Re = 395

Channel flow test case: Reynolds Stresses



Unstruct. "Taylor" mesh, Nt=0.44 M, Re = 395

Channel flow test case: Budget for k



Budgets of the Reynolds stress components

$$\underbrace{\langle \overline{U_k}\rangle \frac{\partial \langle u'_i u'_j \rangle}{\partial x_k}}_{C_{ij}} = \underbrace{-\left(\langle u'_k u'_i \rangle \frac{\partial \langle \overline{U_j}\rangle}{\partial x_k} + \langle u'_k u'_j \rangle \frac{\partial \langle \overline{U_i}\rangle}{\partial x_k} \right)}_{P_{ij}} + \underbrace{\left\langle \frac{p'}{\rho}\left(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right) \right\rangle}_{\Phi_{ij}}$$

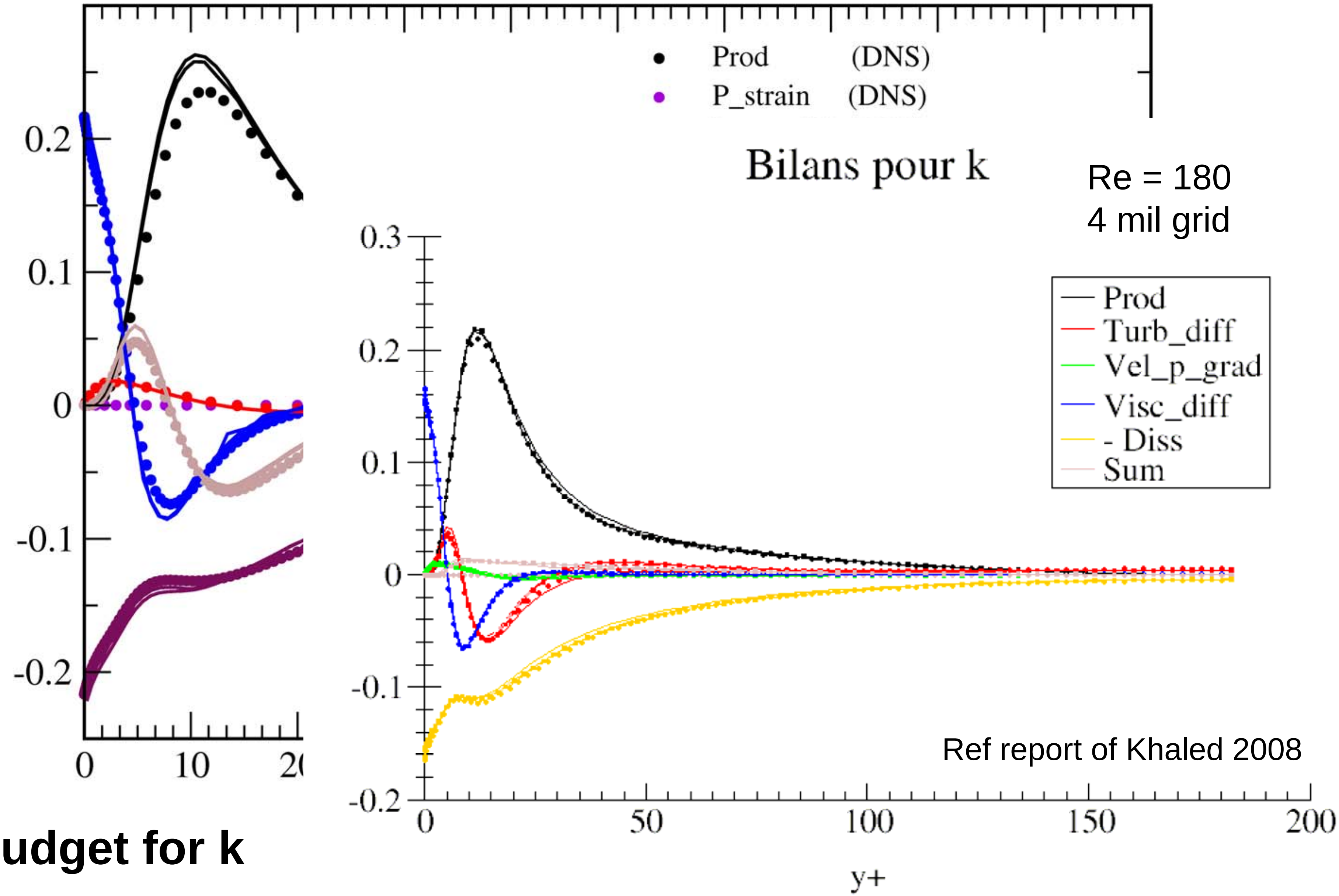
$$\underbrace{-\frac{\partial \langle u'_k u'_i u'_j \rangle}{\partial x_k}}_{D^t_{ij}} \underbrace{-\frac{\partial}{\partial x_k}\left(\langle p' u'_i \rangle \delta_{jk} + \langle p' u'_j \rangle \delta_{ik} \right)}_{D^p_{ij}} + \underbrace{\nu \frac{\partial^2 \langle u'_i u'_j \rangle}{\partial x_k^2}}_{D^\nu_{ij}} \underbrace{-2\nu \left\langle \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_j}{\partial x_k} \right\rangle}_{\varepsilon_{ij}}$$

$$\underbrace{-\frac{\partial \langle u'_j \tau'_{ik} + u'_i \tau'_{jk} \rangle}{\partial x_k}}_{D^{SGS}_{ij}} + \underbrace{\left\langle \tau'_{ik} \frac{\partial u'_j}{\partial x_k} + \tau'_{jk} \frac{\partial u'_i}{\partial x_k} \right\rangle}_{\varepsilon^{SGS}_{ij}}$$

neglected

Ref: T. Omori et al. Int. J. Heat and fluid flow 2008

STAR: Grid (141x184x177) = 4.59 million
DNS : Grid (256x193x192)= 9.48 million



Budget for k

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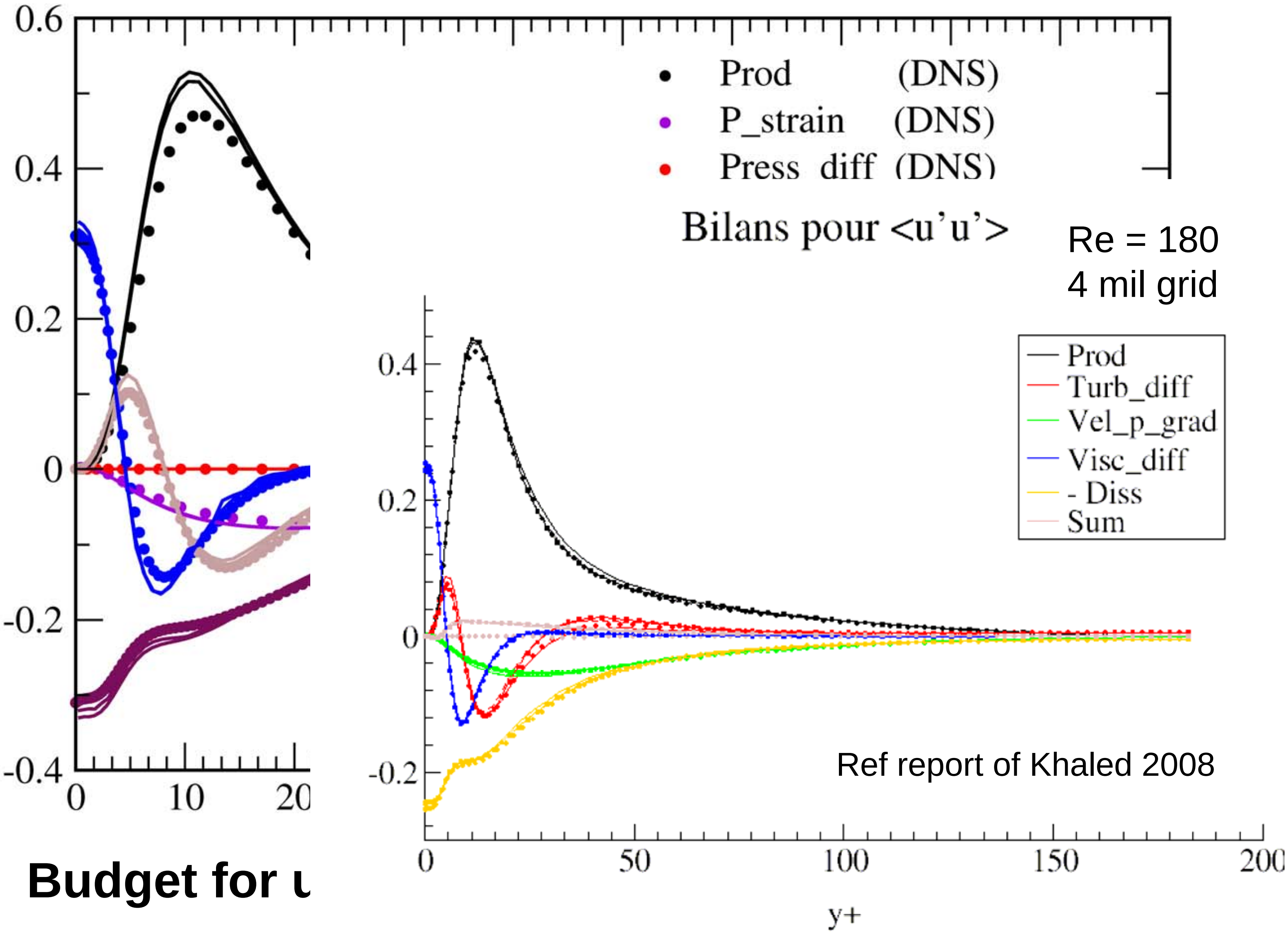
STAR: Grid (141x184x177) = 4.59 million

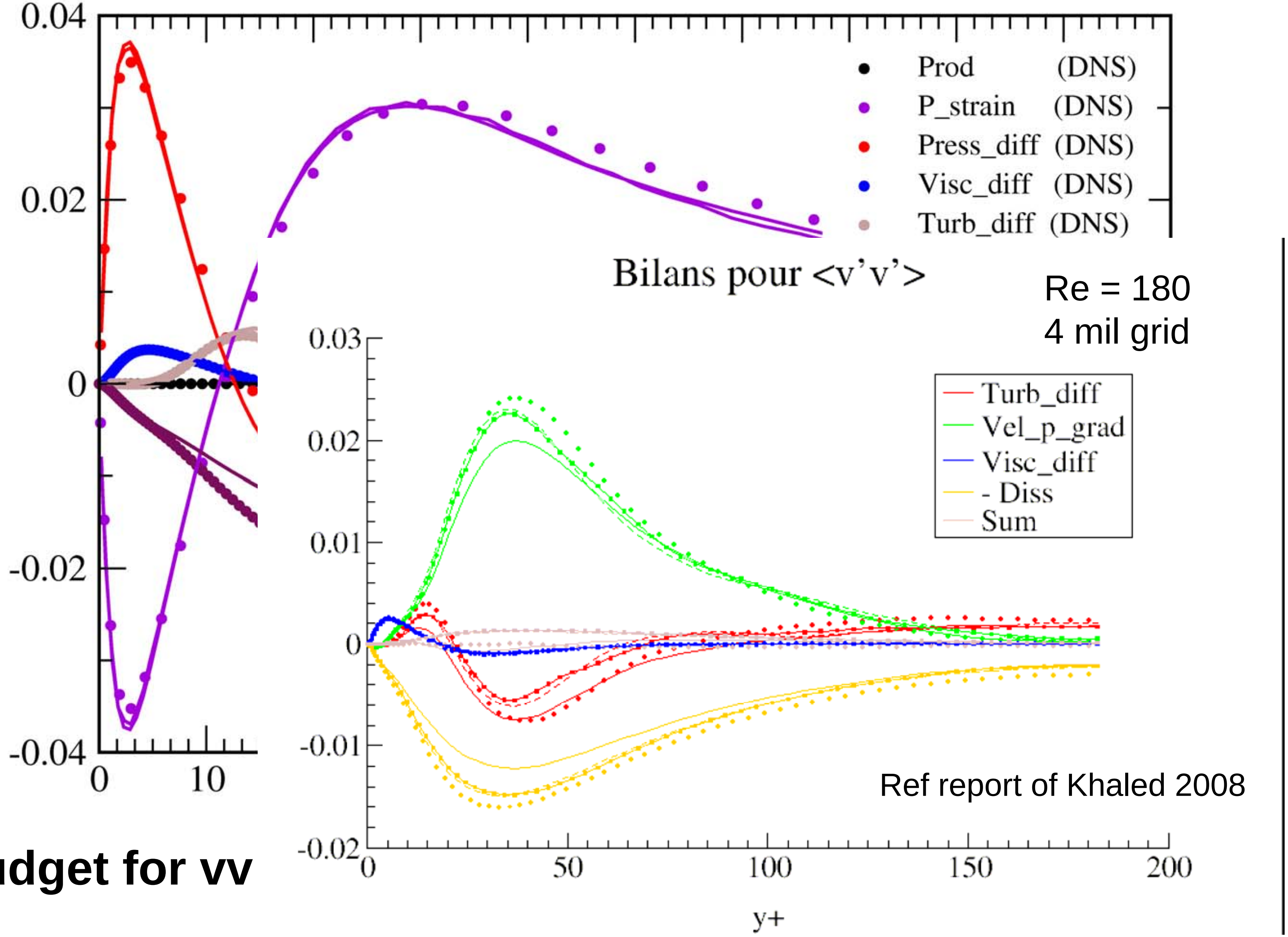
DNS : Grid (256x193x192)= 9.48 million



Budget for u

STAR: Grid (141x184x177) = 4.59 million

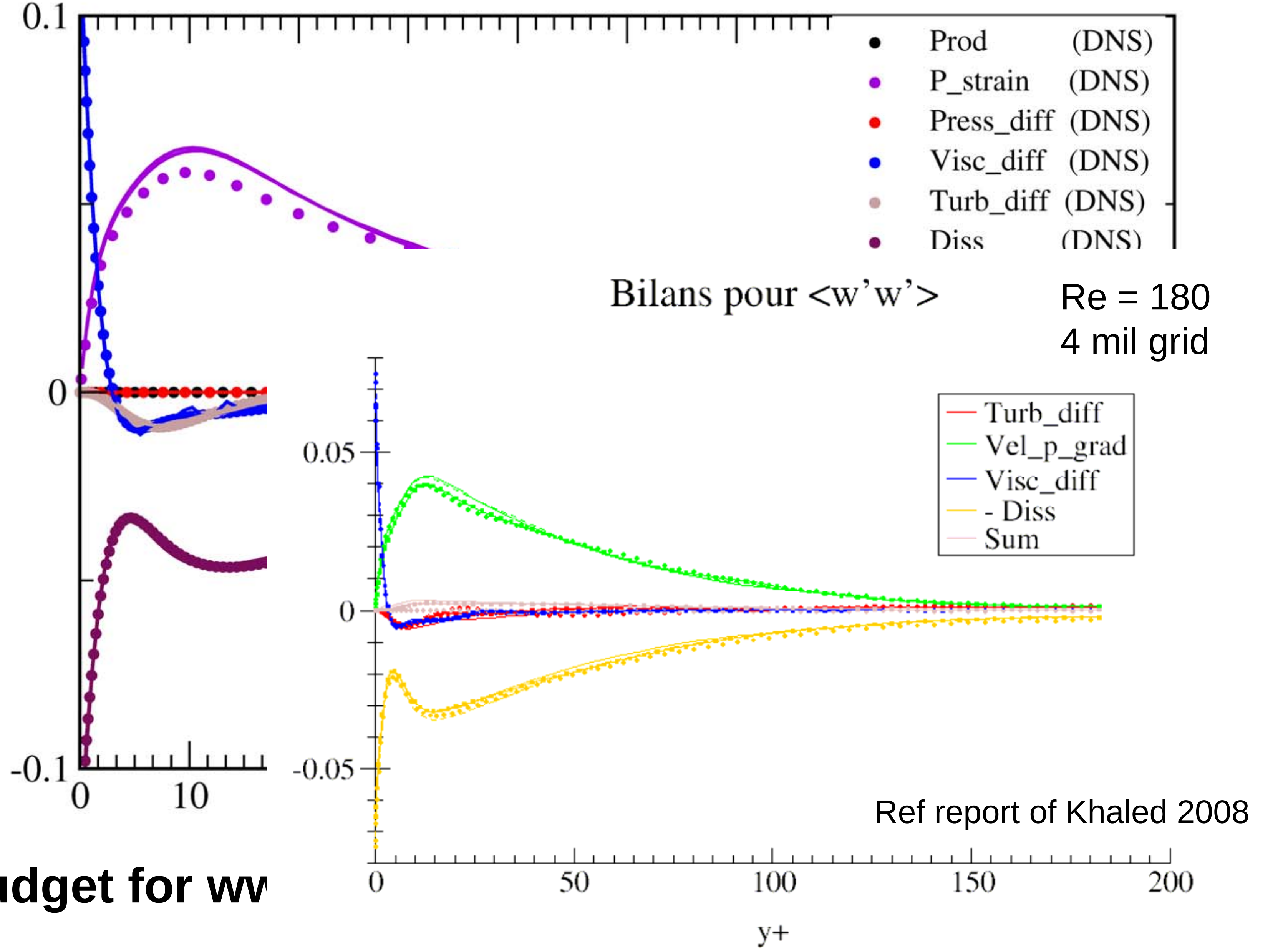
DNS : Grid (256x193x192)= 9.48 million



Budget for vv

STAR: Grid (141x184x177) = 4.59 million

DNS : Grid (256x193x192)= 9.48 million

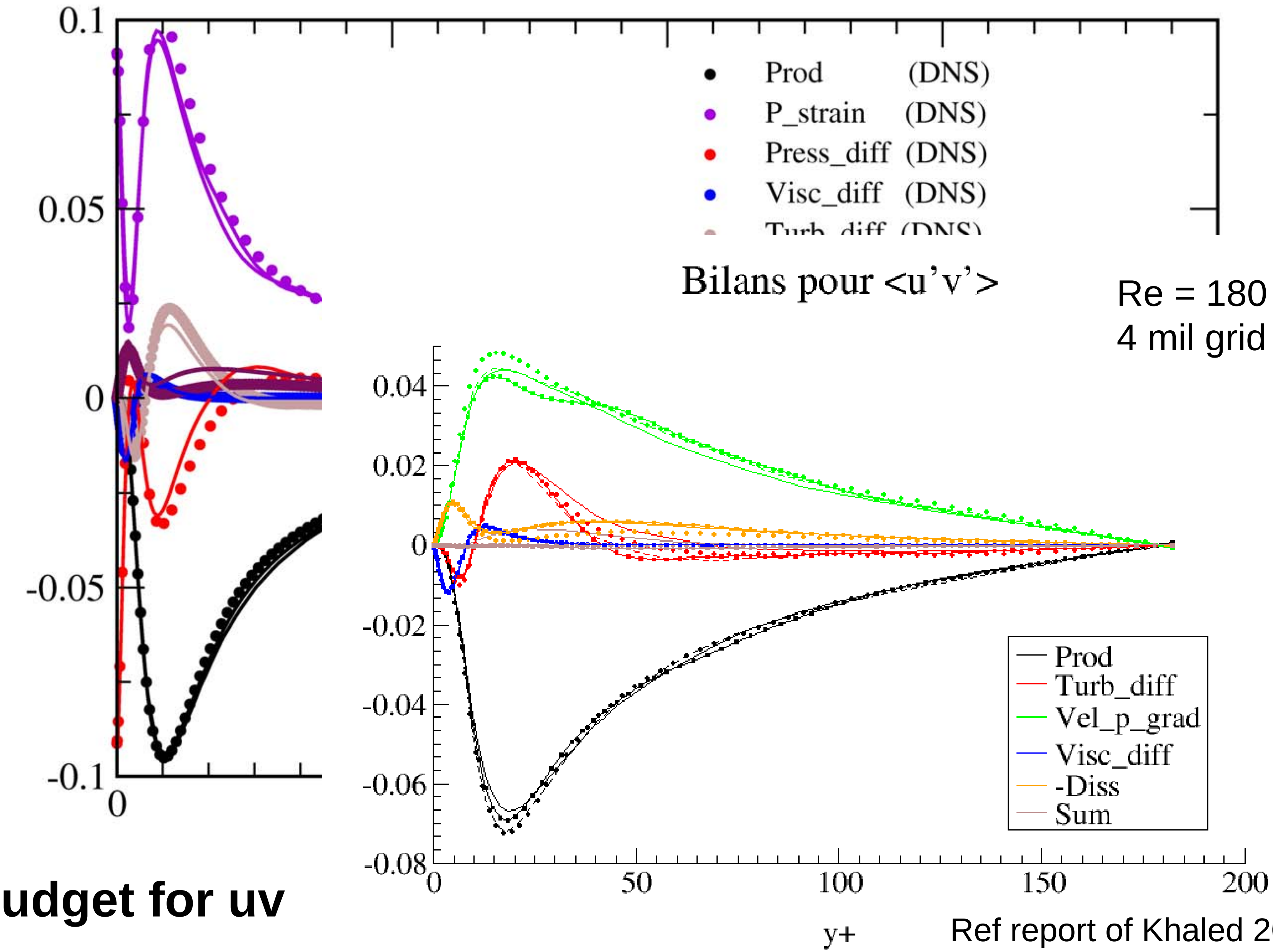


Re = 180
4 mil grid

Ref report of Khaled 2008

Budget for ww

STAR: Grid (141x184x177) = 4.59 million
DNS : Grid (256x193x192)= 9.48 million



Re = 180
4 mil grid

- **Budget for uv**

Ref report of Khaled 2008

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Conclusions and Future work

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Conclusions:

-**DNS possible with only 2nd order FV (and true Central DS**)
-NB: with *C_S* and S-C DNS not only limited to Channel Flows !
=> whole range of PhD topics
(pipes, bends, particles, heat exchangers, thermal fatigue)
-Default precision parameters seem too severe in *C_S* (cost +50%)

Future work:

- Future tests on complex grids (polyhedral cells), and publish!
- Further investigation on quality criteria for LES is needed.
- Wider range of test cases relevant to the nuclear industry (suggestions are more than welcome !)

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EPSRC funding under grant EP/C549465/1 for PDRA and Computer resources