Direct Numerical Simulation of Pressure Fluctuations Induced by Supersonic Turbulent Boundary Layers

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Background

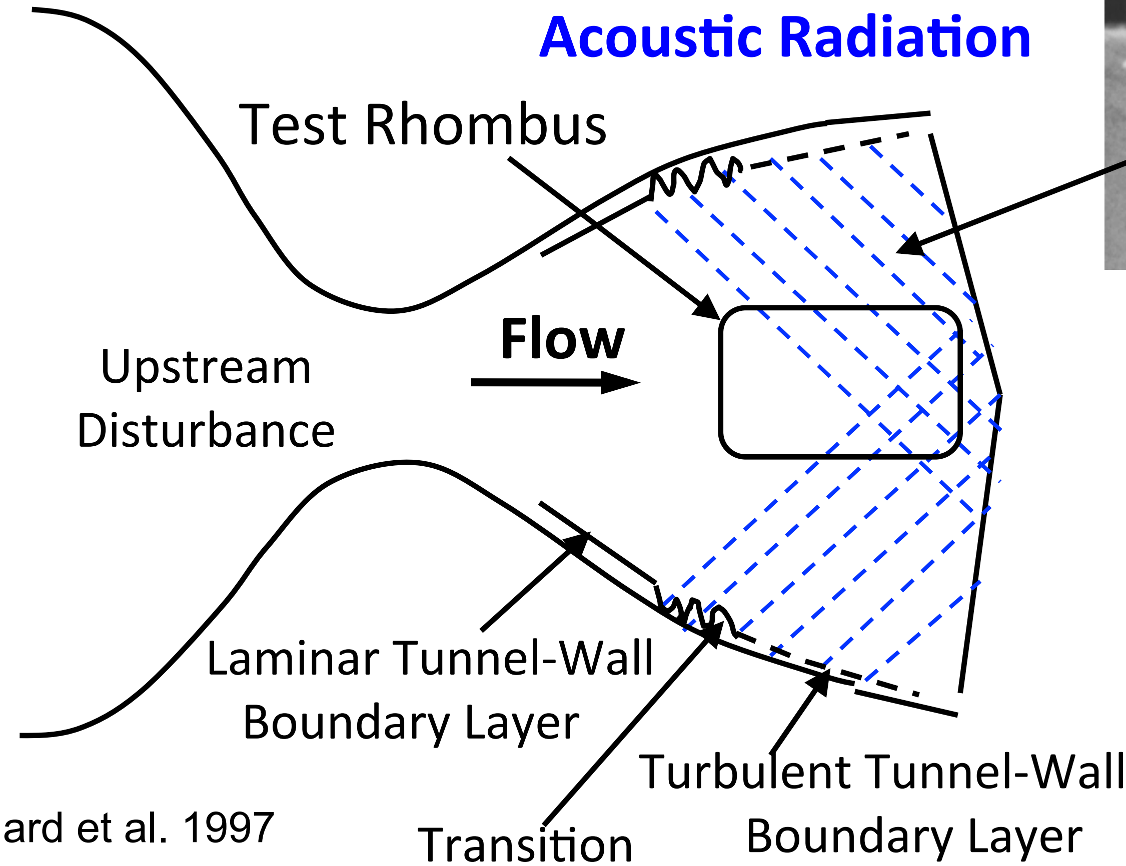
Boundary-Layer-Induced Pressure Fluctuations

- Knowledge of pressure distribution in a flow field is a primary concern in many engineering applications
  - Engineering applications
    - lift and form drag of an aerodynamic body
    - flow-induced vibration & noise (*Blake 1986*)
    - cavitation (*Arndt 2002*)
  - Theoretical significance
    - Vorticity dynamics (high vorticity ⇔ low pressure)
    - turbulence modeling (pressure-strain terms in the transport equations for the Reynolds stresses) (*Pope 2000*)

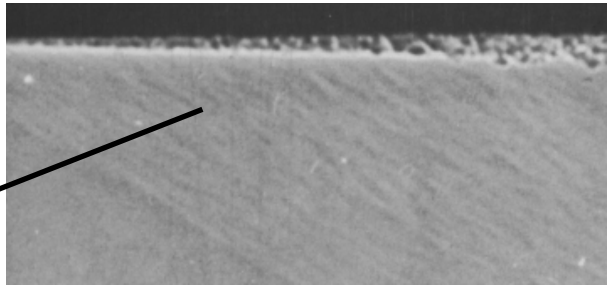
- Pressure fluctuations from supersonic boundary layers
  - p'_w: vibrational loading of flight vehicles
  - p'_∞: freestream noise of supersonic wind tunnels

Background

Application: Freestream noise in High-Speed Wind-Tunnel Facilities



Blanchard et al. 1997



Shadowgraph of the radiated noise from a Mach 3.5 tunnel-wall turbulent boundary layer (courtesy of NASA Langley)

In a conventional tunnel (*M_∞ > 2.5*), tunnel noise is dominated by acoustic radiation from turbulent boundary layers on tunnel side-walls (*Laufer, 1964*)

Motivation

Boundary-Layer-Induced Pressure Fluctuations

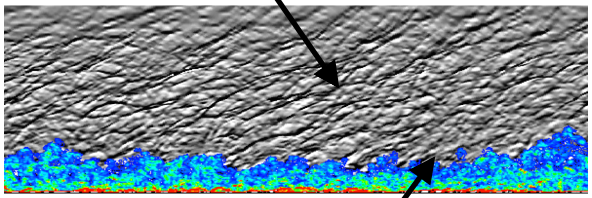
- Limited understanding of global pressure field induced by high-speed turbulent boundary layers
  - theory
    - unable to predict detailed pressure spectrum
  - experiment
    - unable to measure instantaneous spatial pressure distribution
    - susceptible to measurement errors (Beresh 2011)
  - numerics
    - largely limited to incompressible boundary layers
    - freestream pressure fluctuations not studied

- **Direct Numerical Simulation (DNS)** is used to investigate boundary-layer-induced pressure field
  - statistical and spectral scaling of pressure
  - large-scale pressure structures
  - correlation between regions of extreme pressure and extreme vorticity
  - acoustic radiation in the free stream

Focus of Current Project

Boundary-Layer-Induced Pressure Fluctuations

- Develop a **DNS database** of high-speed turbulent boundary layers *(Duan et al., JFM 2014, 2016)*
  - across a broad range of **freestream Mach number**, **wall-to-recovery temperature ratio**, and **Reynolds number**
    - $M_\infty = 2.5 - 14$
    - $T_w/T_r = 0.18 - 1.0$
    - $Re_\tau \approx 400 - 2000$



  - with grids designed to adequately capture both **the boundary layer** and **the near field of acoustic fluctuations** radiated by the boundary layer

- Conduct **statistical and structural analysis** of the global pressure field induced by the boundary layers (*Zhang et al., JFM 2017*)

Why Blue Waters?

Boundary-Layer-Induced Pressure Fluctuations

- World-class computing capabilities of Blue Waters required for DNS of turbulent boundary layers at high Reynolds numbers
  - Extremely fine meshes required to fully resolve all turbulence scales
  - Large domain sizes needed to locate very-large-scale coherent structures
  - large number of time steps required for the study of low-frequency behavior of the pressure spectrum

$N_x \times N_y \times N_z$	L_x/δ_i	L_y/δ_i	L_z/δ_i	Δx^+	Δy^+	$\Delta z^+{}_{min}$	$\Delta z^+{}_{max}$
6700×800×1500	60.0	6.0	30.0	6.5	5.0	0.51	5.33

Estimated computation size for DNS of a supersonic turbulent BL at $Re_\tau = 2000$

- Total number of meshes: ~ 8.0 billion
- Single flow field data size: ~ 320 GB

- Production runs require up to ~10% of the total XE nodes of Blue Waters
  - require up to 2,000 compute nodes
  - belong to the capability class of petascale computing

Outline

- DNS methodology
- DNS code porting
  - Domain Decomposition Strategy
  - Profiling & Parallel Performance
  - Parallel Input/Output (IO)
- Results of Domain Science
  - Boundary-layer-induced pressure statistics & structures
  - Boundary-layer freestream radiation
- Summary and future work

Background

DNS for Compressible Turbulent Boundary Layers

- Conflicting requirements for **numerical schemes**
  - Shock capturing requires numerical dissipation
  - Turbulence needs to reduce numerical dissipation

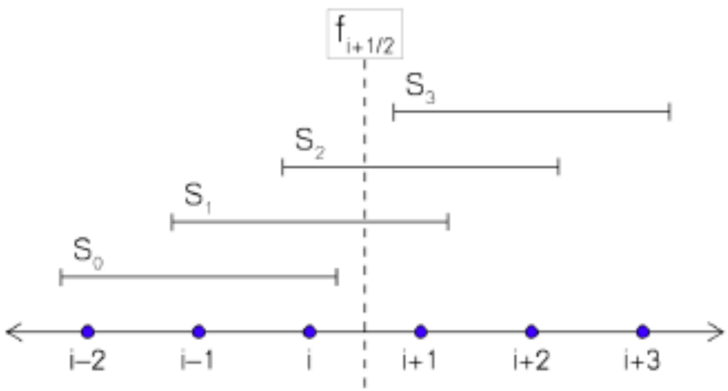
- Starting a simulation from a laminar/random **initial condition**
  - very costly
  - hard to control final flow conditions

- Require continuous **inflow conditions**
  - Boundary layer is inhomogeneous in the streamwise direction

DNS Methodology

Numerical Methods

- Hybrid WENO/Central Difference Method
  - High-order non-dissipative central schemes for capturing broadband turbulence (Pirozzoli, JCP, 2010)
  - Weighted Essentially Non-Ocillatory (WENO) adaptation for capturing shock waves *(Jiang & Shu JCP 1996,* Martin et al. JCP, 2006*)*



Flux: weighted sum of candidates
source of non-linearity

$$\hat{f}_{i+1/2} = \sum_{k=0}^{r} w_k q_k^r$$

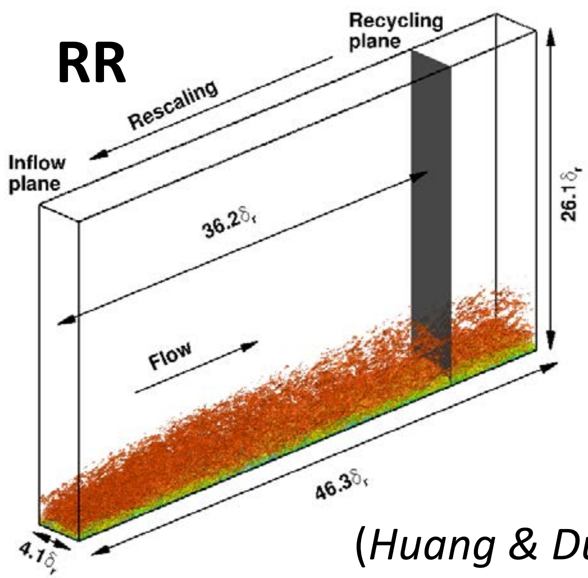
  - Rely on a shock sensor to distinguish shock waves from smooth turbulent regions
    - physical shock sensor based on vorticity and dilatation (Ducro, JCP, 2000)
    - numerical shock sensor based on WENO smoothness measurement and limiter (Taylor et al, JCP 2007)

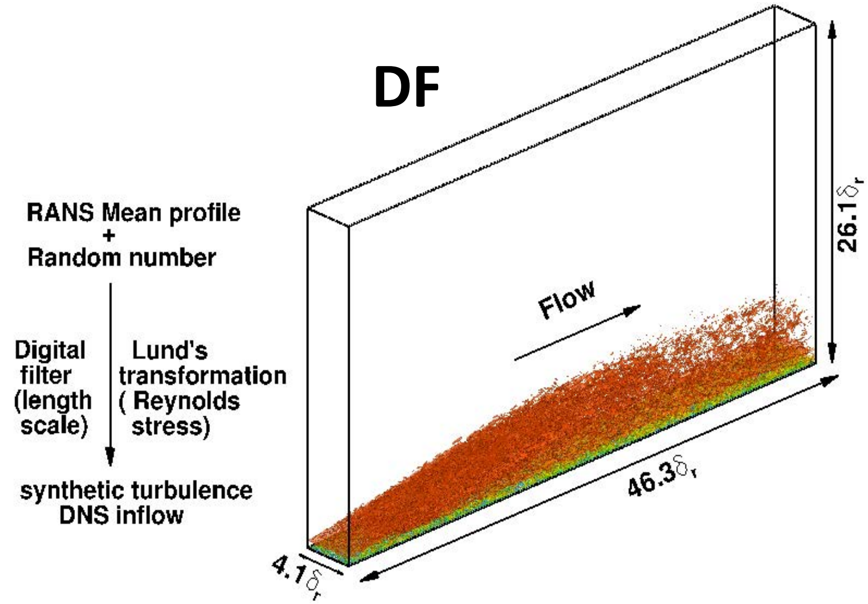
DNS Methodology

Inflow turbulence generation

- **Recycling-rescaling (RR)** based method *(Xu & Martin Phys Fluids, 2004)*
  - based on recycling and rescaling turbulence structures within the DNS/LES domain
  - an equilibrium region required to invoke scaling arguments

- **Digital-filtering (DF)** based method *(Touber & Sandham, Theor. Compt. Fluid Dyn. 200*
  - inflow mean flow and Reynolds-stress profiles required from RANS
  - inflow profiles seeded



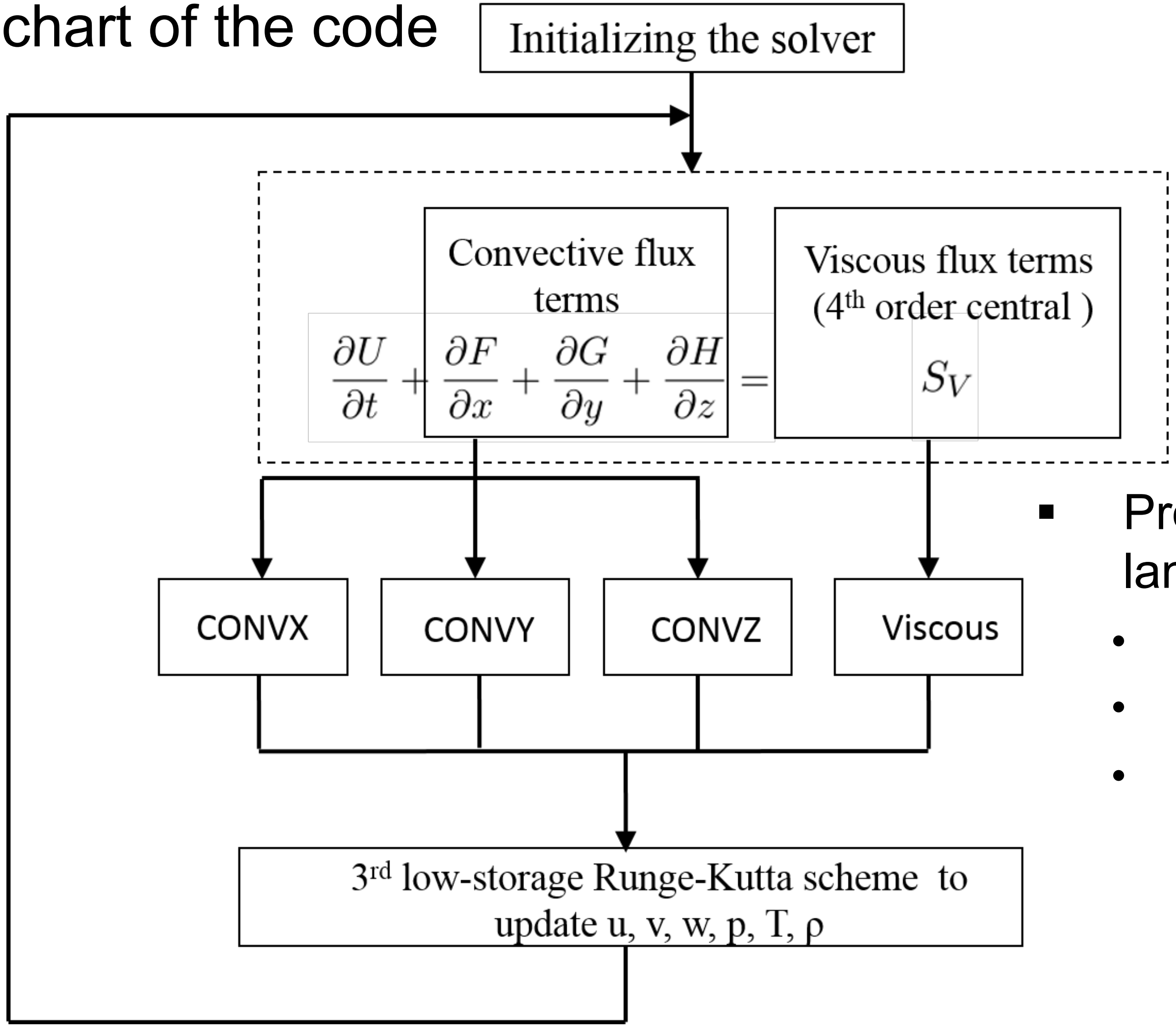


(*Huang & Duan, AIAA 2016-3639*)

DNS Methodology

Software Structure

Flow chart of the code



- Programming language and model
  - Fortran 2003
  - Parallel MPI-only
  - I/O in parallel HDF5

DNS Methodology

Domain Decomposition

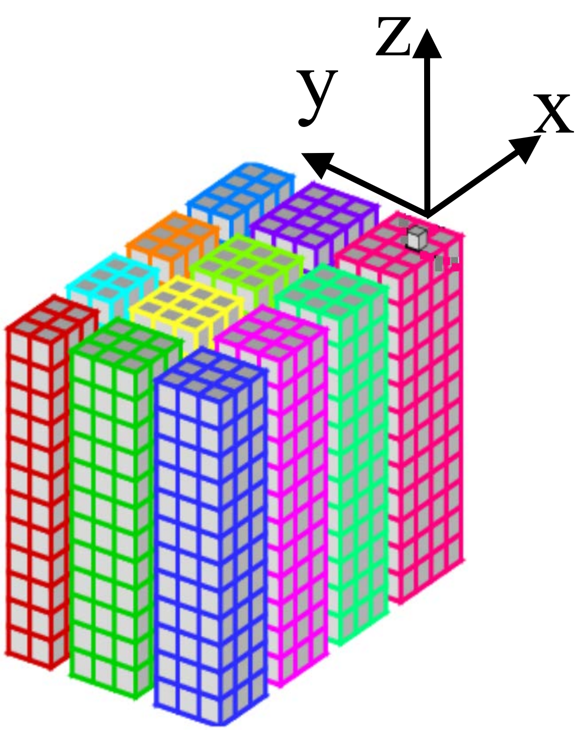
computational domain

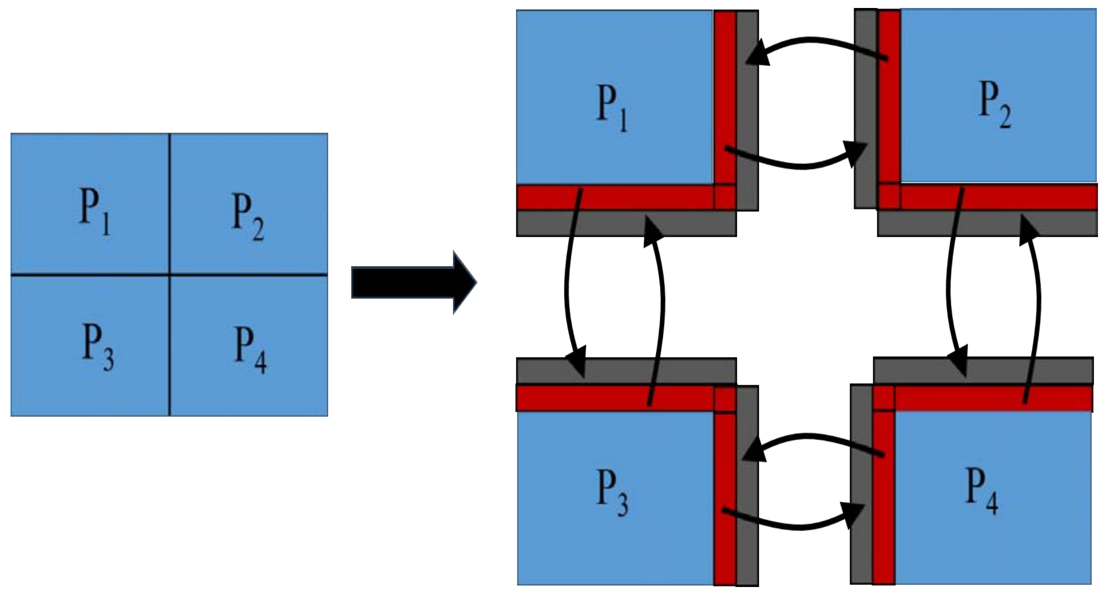
copied part of computational domain

ghost cells

2D domain decomposition

- z pencil used
- z is the wall-normal direction



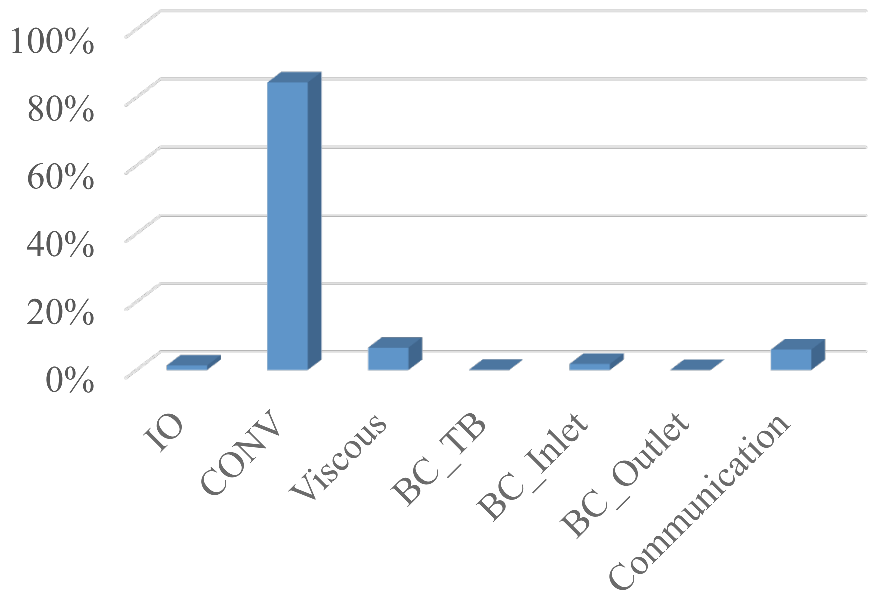


Static data decomposition and ghost cell update between four processors

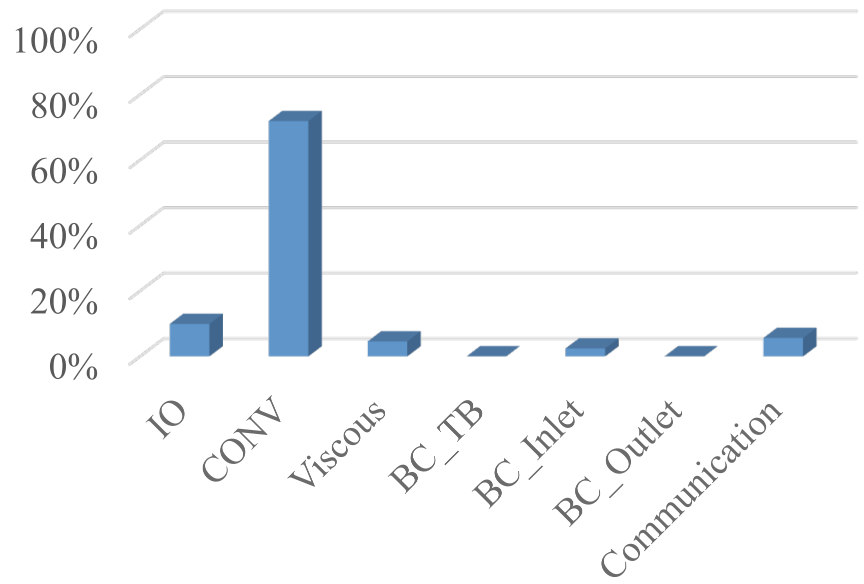
DNS Methodology

Software Profiling

Total compute time breakdown (6400x320x500)



Total compute time breakdown (6400x1280x500)



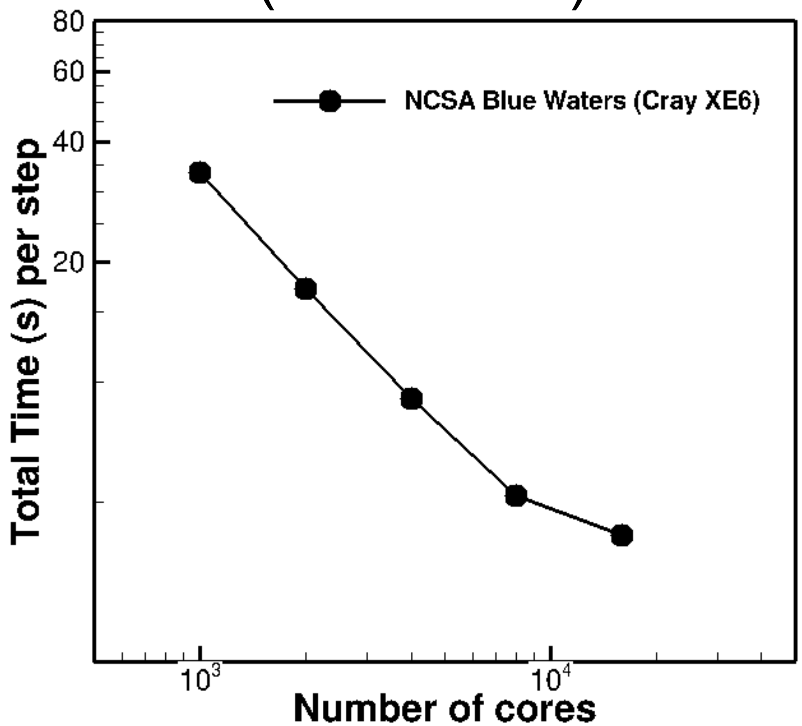
XE Nodes: **250** nodes, 8000 cores
Pencil size: 16x16x500
Computing time: 90%
IO time: 3%

XE Nodes: **1000** nodes, 32000 cores
Pencil size: 16x16x500
Computing time: 76%
IO time: 13%

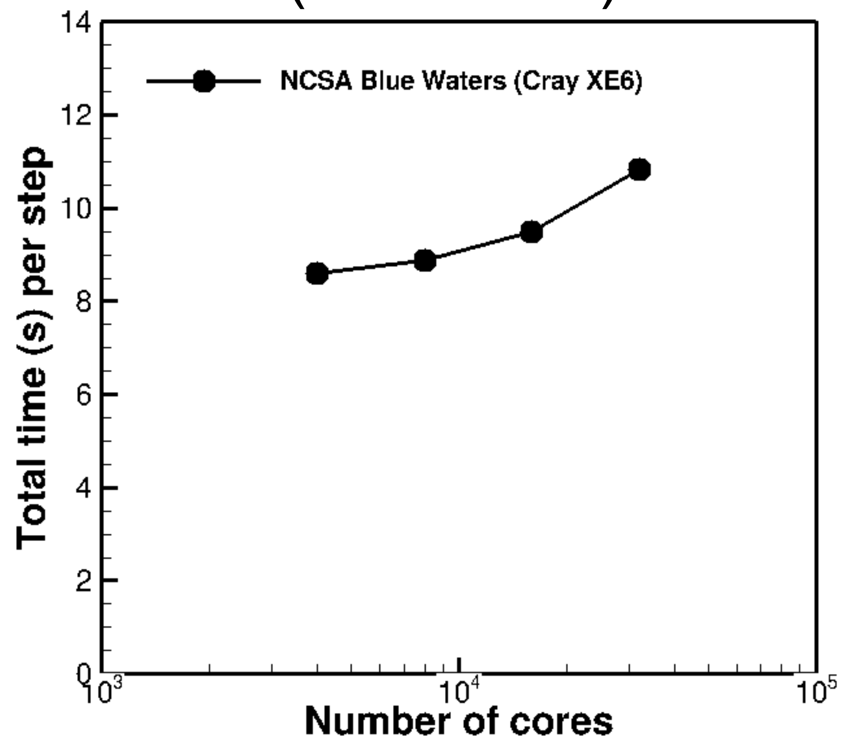
DNS Methodology

Parallel Performance

Strong Scaling (Total Time)



Weak Scaling (Total Time)

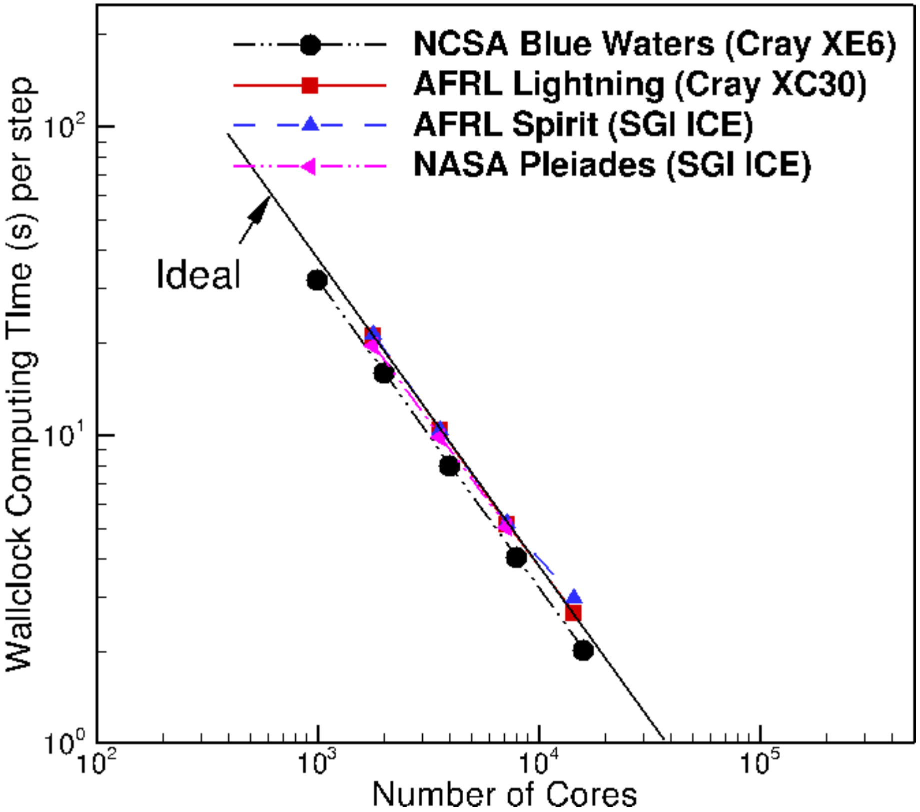


- Software scales well up to 500 XE nodes (16,000 cores)
- Scalability deteriorate at 1,000 XE nodes (32,000 cores)

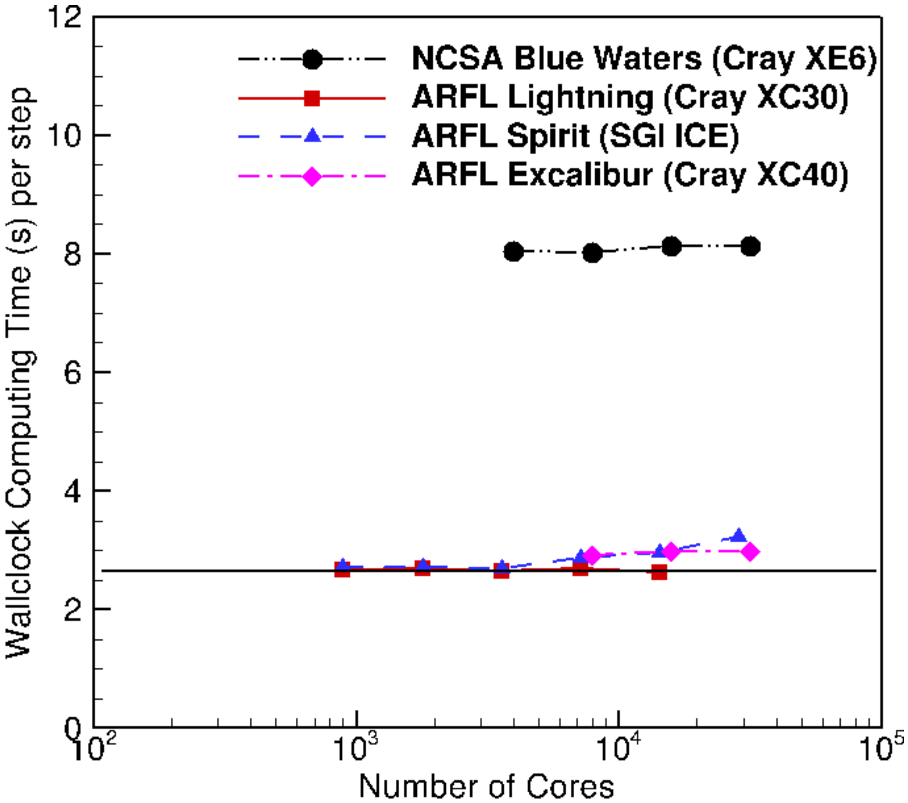
DNS Methodology

Computation Performance

Strong Scaling (Computation Time only)

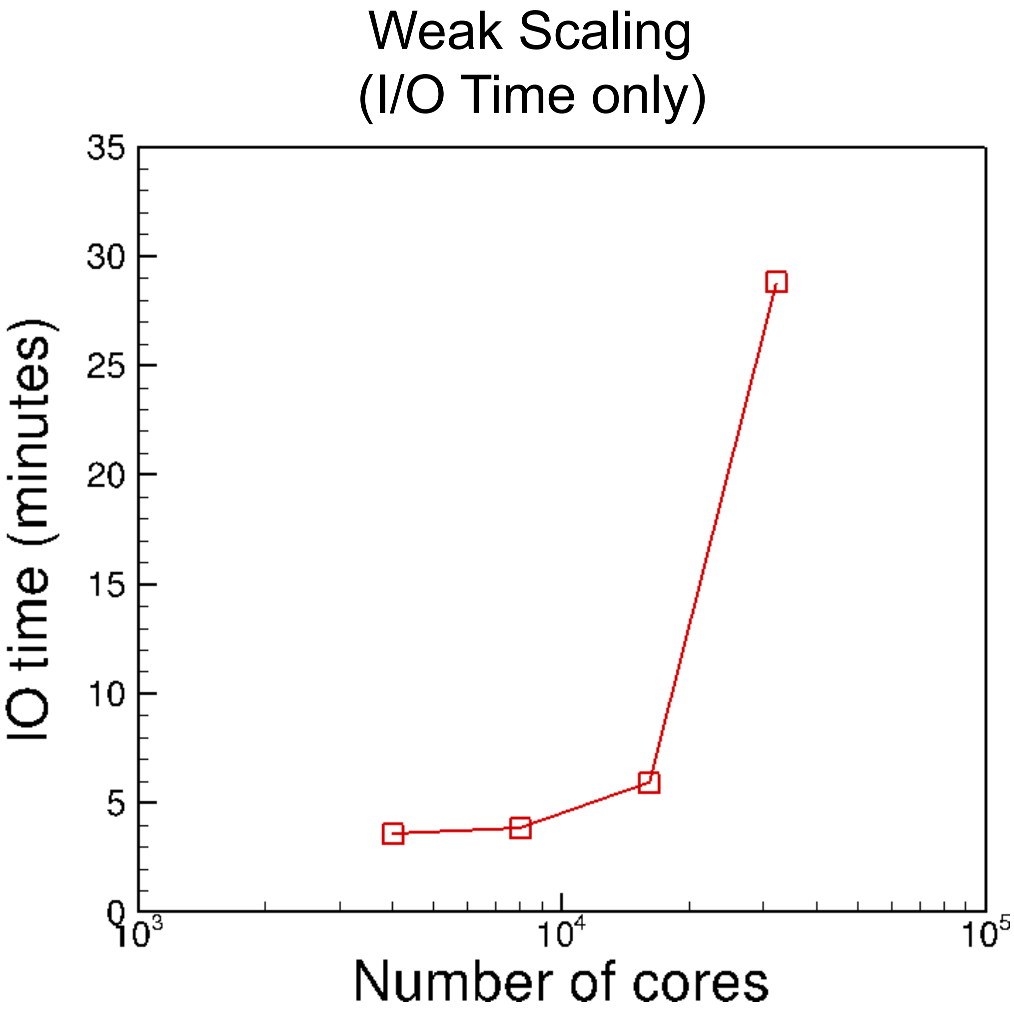


Weak Scaling (Computation Time only)



- Computation scales well to 1000 XE nodes (32,000 cores)

DNS Methodology
IO Performance



Parallel IO: parallel HDF5
Pencil size: 16x16x500
Data Size/core: 7.6 MB on each core
Stripe count = 4

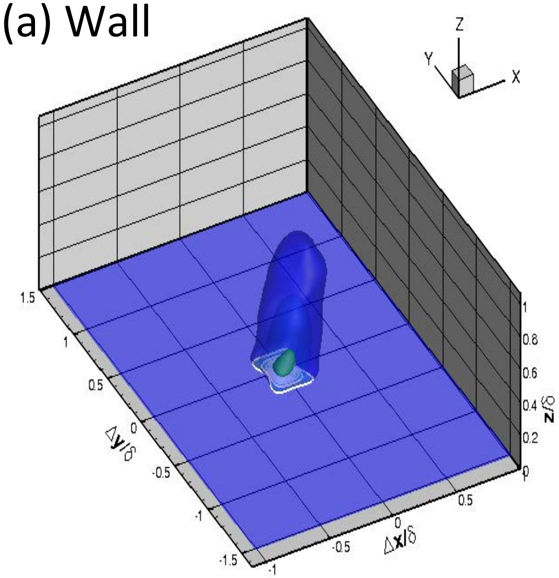
- IO Scalability deteriorate at 1,000 XE nodes (32,000 cores)

Results of Domain Science

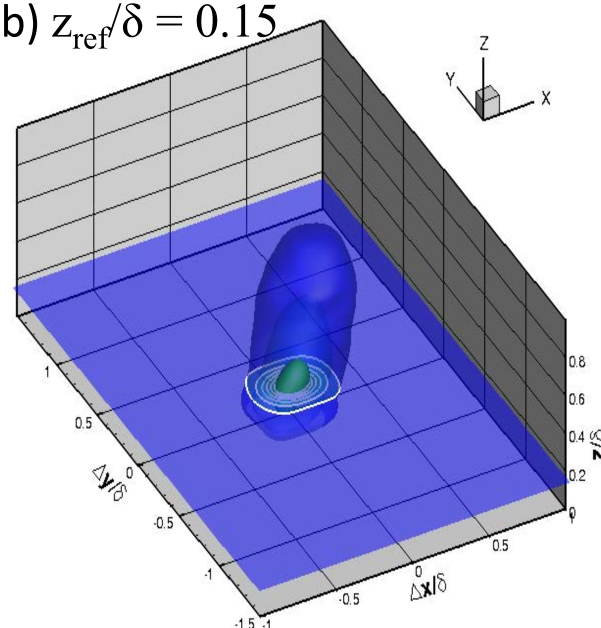
Multivariate statistics and structure of global pressure field induced by high-speed turbulent BLs

Spatial Pressure Structure

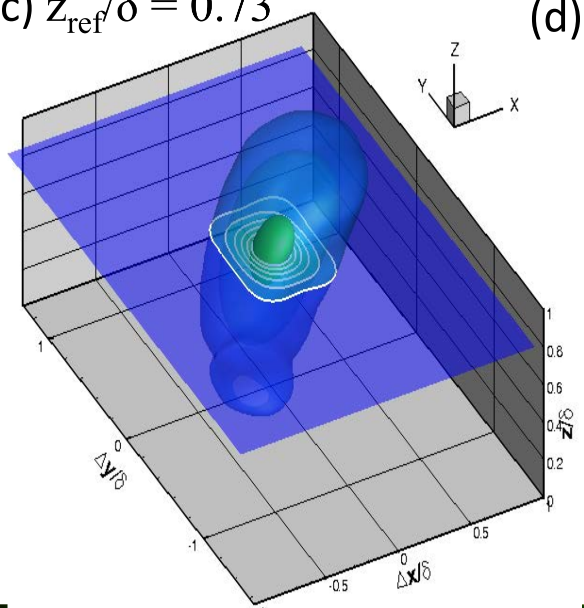
(a) Wall



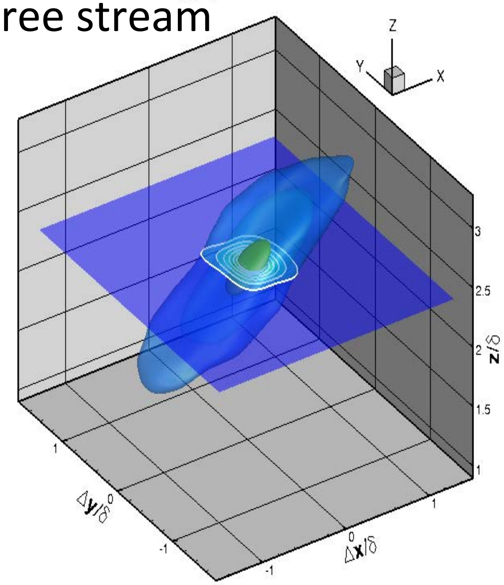
(b) $z_{ref}/\delta = 0.15$



(c) $z_{ref}/\delta = 0.73$



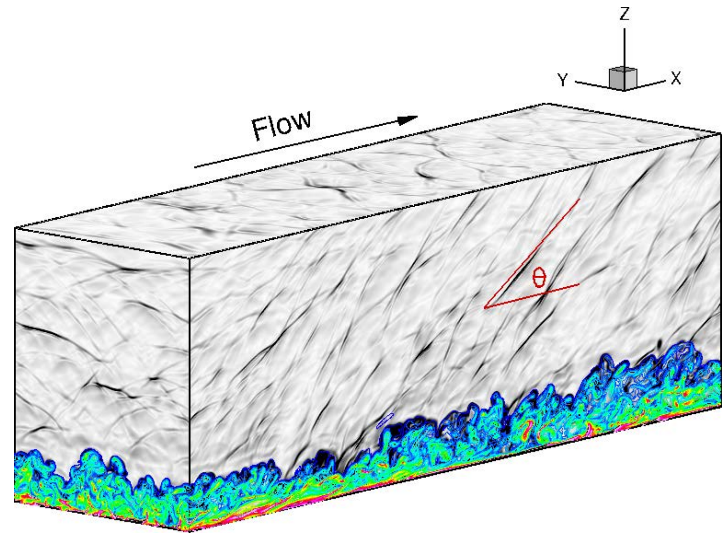
(d) Free stream



$M_\infty = 5.86$, $T_w/T_r = 0.25$

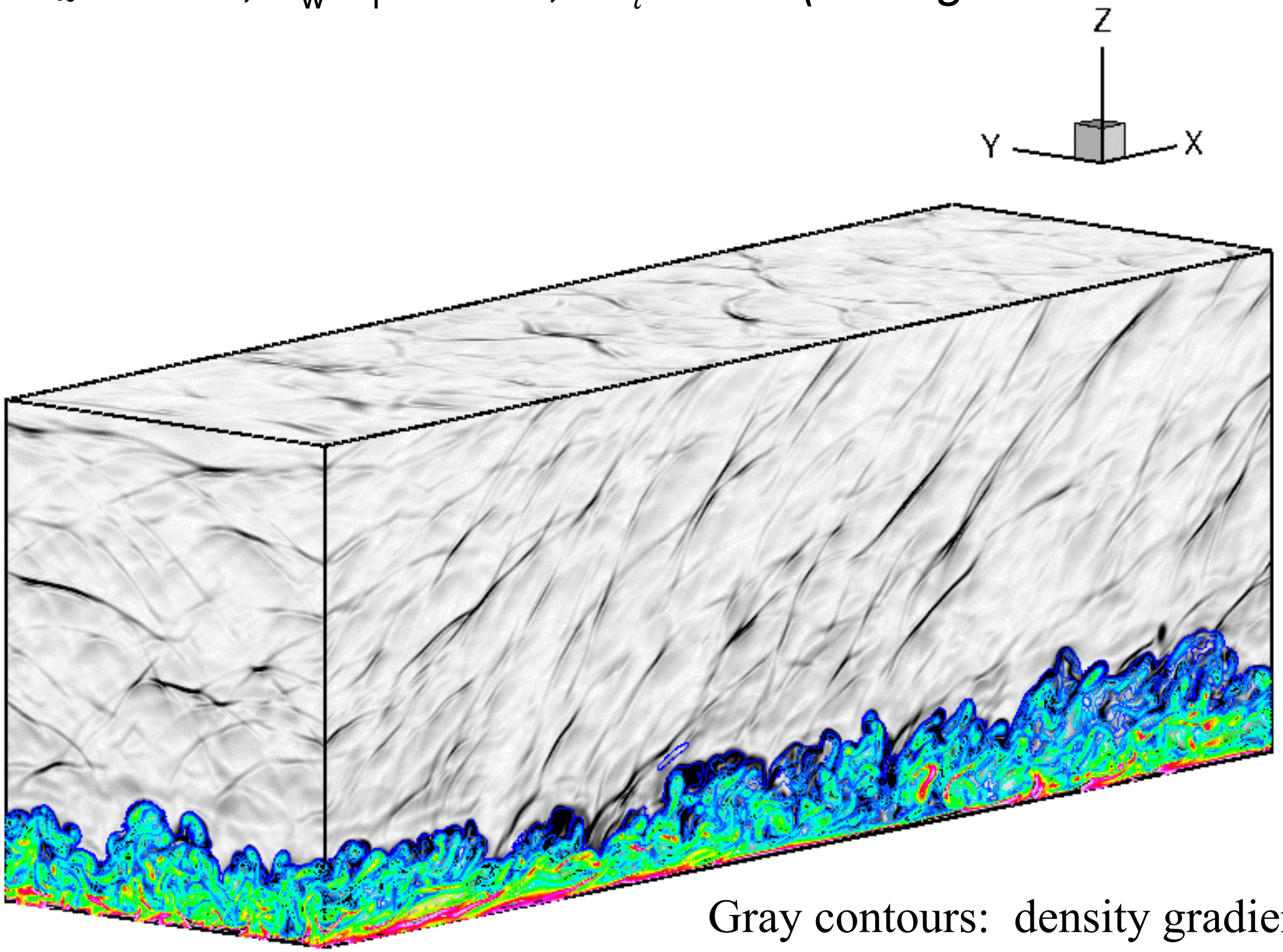
$Re_\tau = 450$ *(Zhang et al. JFM 2017)*

$$C_{pp}(\Delta x, \Delta y, z, z_{ref}) = \frac{\overline{p'(x, y, z_{ref}, t)\, p'(x+\Delta x, y+\Delta y, z, t)}}{\left(\overline{p'^2(x, y, z_{ref}, t)}\right)^{1/2} \left(\overline{p'^2(x+\Delta x, y+\Delta y, z, t)}\right)^{1/2}}$$



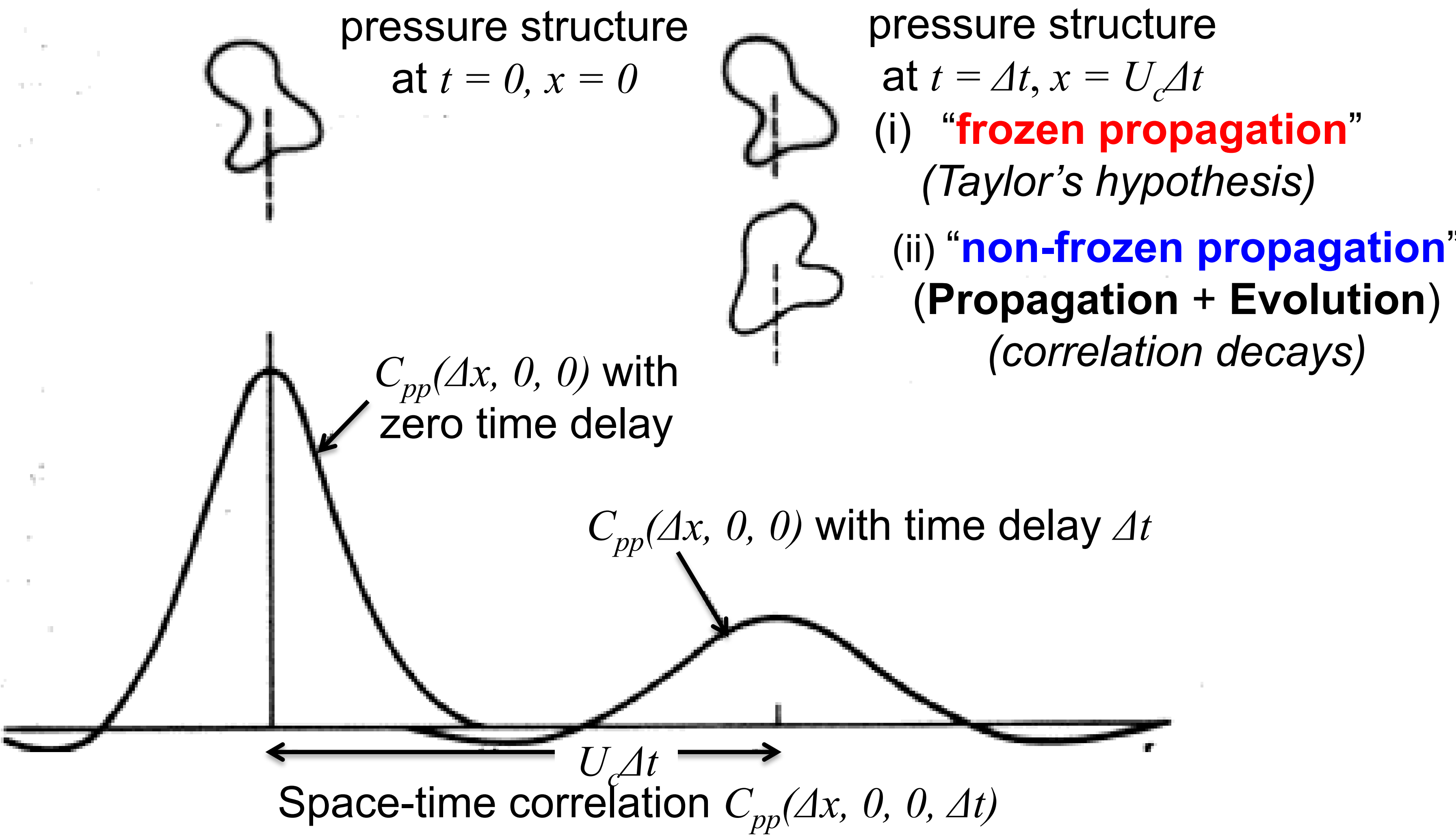
Freestream Acoustic Radiation

$M_\infty = 5.86$, $T_w/T_r = 0.25$, $Re_\tau = 450$ *(Zhang et al. JFM 2017)*



Gray contours: density gradient
Color contours: magnitude of vorticity

Spatial-Temporal Correlation of Pressure Structures

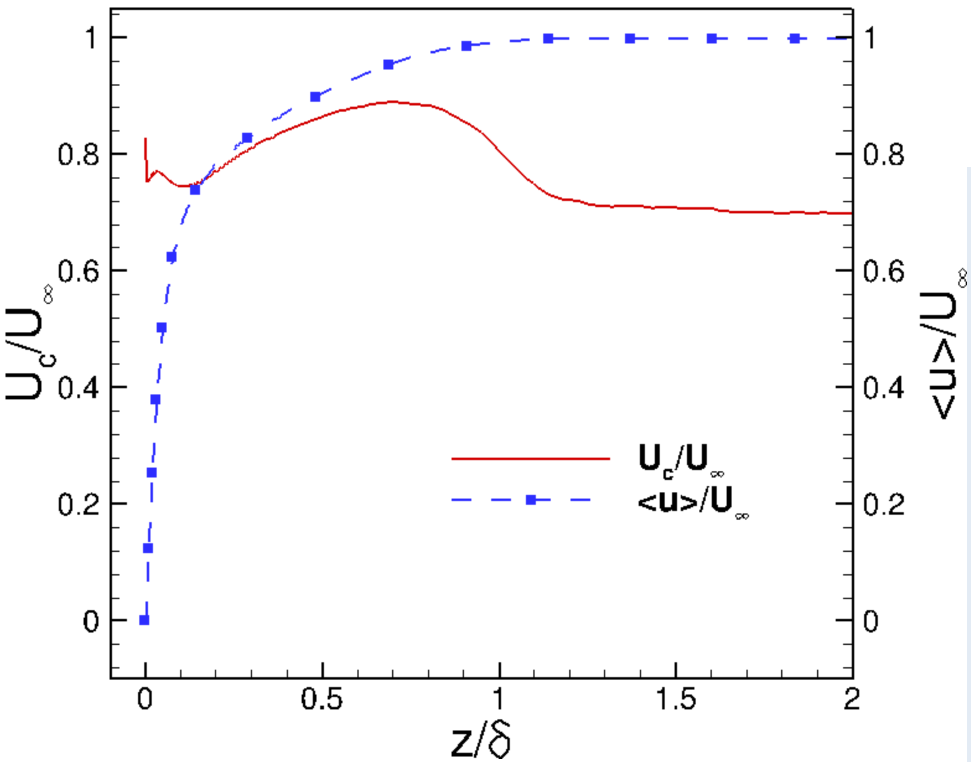


Propagation of Pressure Structures

$M_\infty = 5.86$, $T_w/T_r = 0.25$, $Re_\tau = 450$ *(Zhang et al. JFM 2017)*

Propagation speed defined by finding a value of U_c that minimizes the difference between the **real time evolution** of *p(x, t)* and a **frozen wave** $p(x - U_c t)$ *(Del Alamo & Jimenez, JFM 2009)*

$$U_c \equiv -\frac{\overline{(\partial p/\partial t)(\partial p/\partial x)}}{\overline{(\partial p/\partial x)^2}}$$

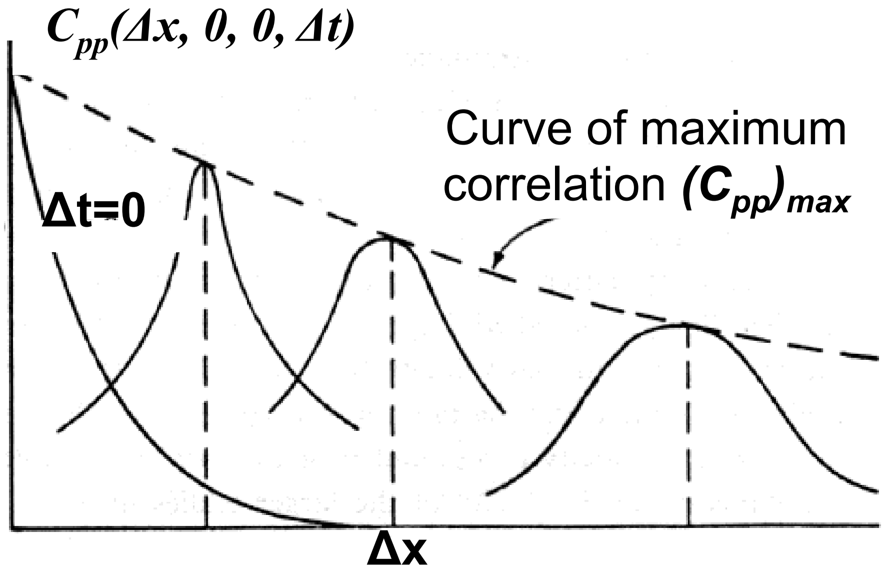


- Within most of the boundary layer, $U_c \approx <u>$ (similar to incompressible flow results by *Kim & Hussain 1993*)

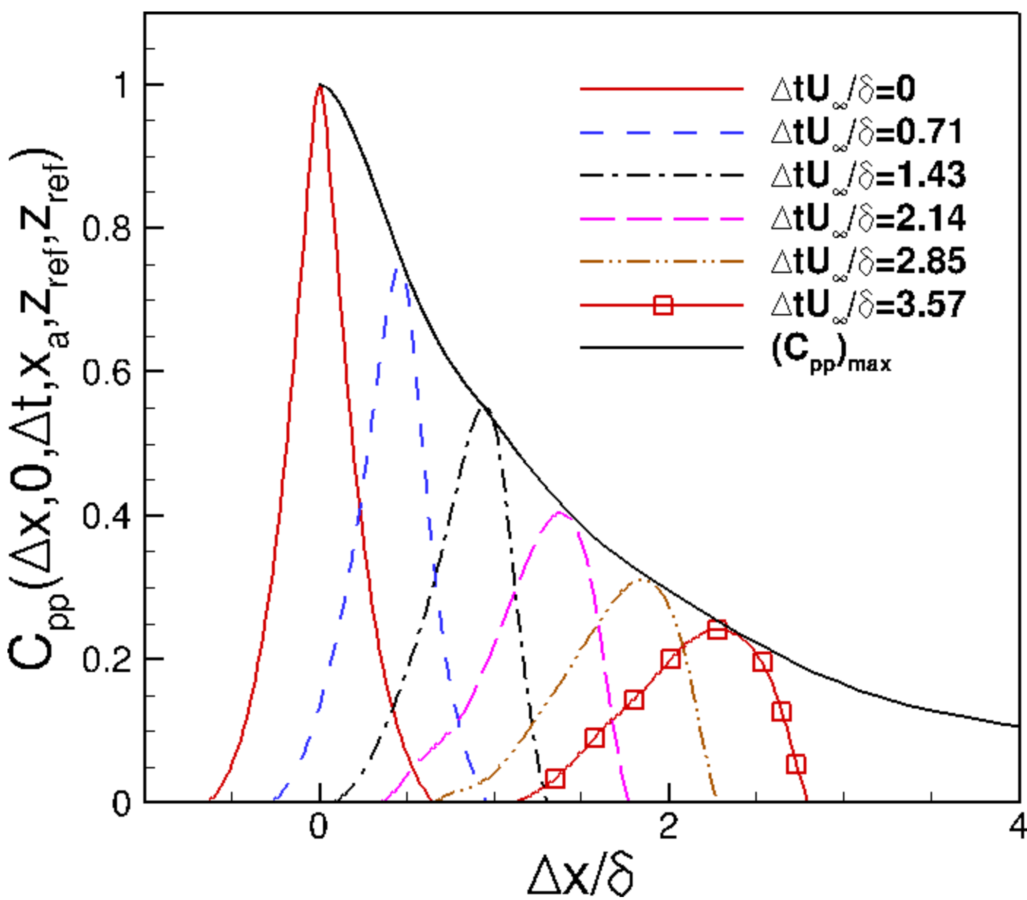
- **In the free stream**, U_c departs from **Taylor's hypothesis** and is significantly lower than the local mean velocity <u>

Evolution of Pressure Structures

$M_\infty = 5.86$, $T_w/T_r = 0.25$, $Re_\tau = 450$ *(Zhang et al. JFM 2017)*



$(C_{pp})_{max}$ measures the **rate of evolution** and defines the **Lagrangian decorrelation length** of coherent pressure structures or wavepackets



Sources of Freestream Acoustic Radiation

$M_\infty = 5.86$, $T_w/T_r = 0.25$, $Re_\tau = 450$ *(Zhang et al. JFM 2017)*

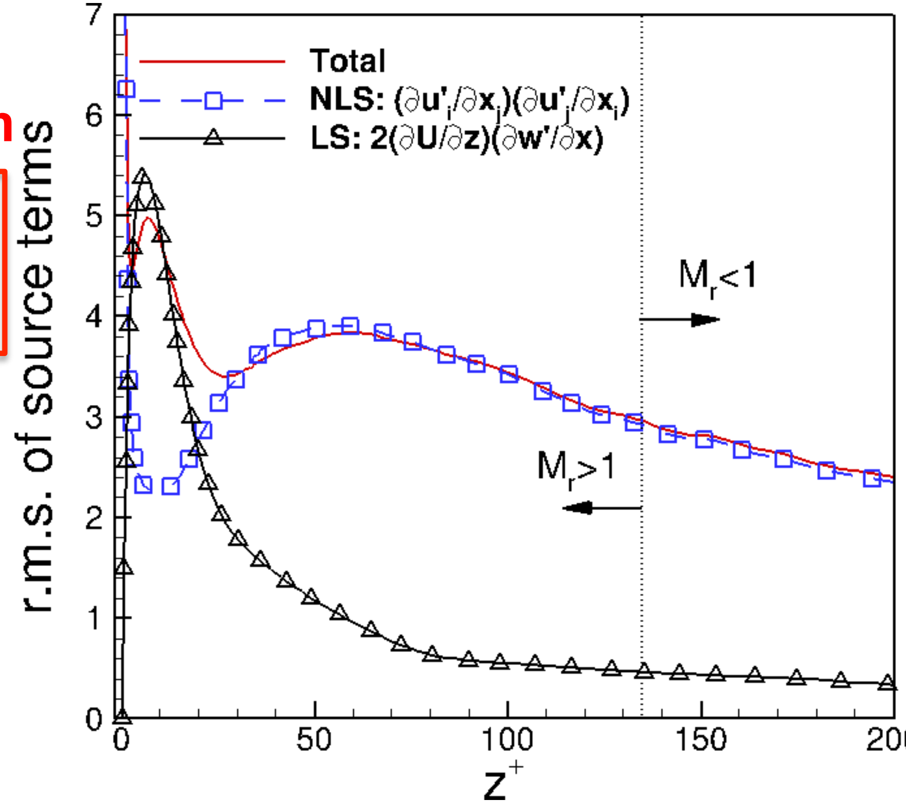
Acoustic analogy (*Phillips 1960*)

Wave Operator | **Acoustic source term**

$$\boxed{\left\{\frac{D^2}{Dt^2} - \frac{\partial}{\partial x_i} a^2 \frac{\partial}{\partial x_i}\right\} \log\left(\frac{p}{p_0}\right)} = \boxed{\gamma \frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_i}}$$

Linear source | **Nonlinear source**

$$\frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_i} = \boxed{2\frac{\partial U}{\partial z}\frac{\partial w'}{\partial x}} + \boxed{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_j'}{\partial x_i}}$$



- Nonlinear source (NLS) dominates over linear source (LS)
- Total acoustic source term peaks in the buffer layer ($z^+_{pk} \approx 20$)

Summary

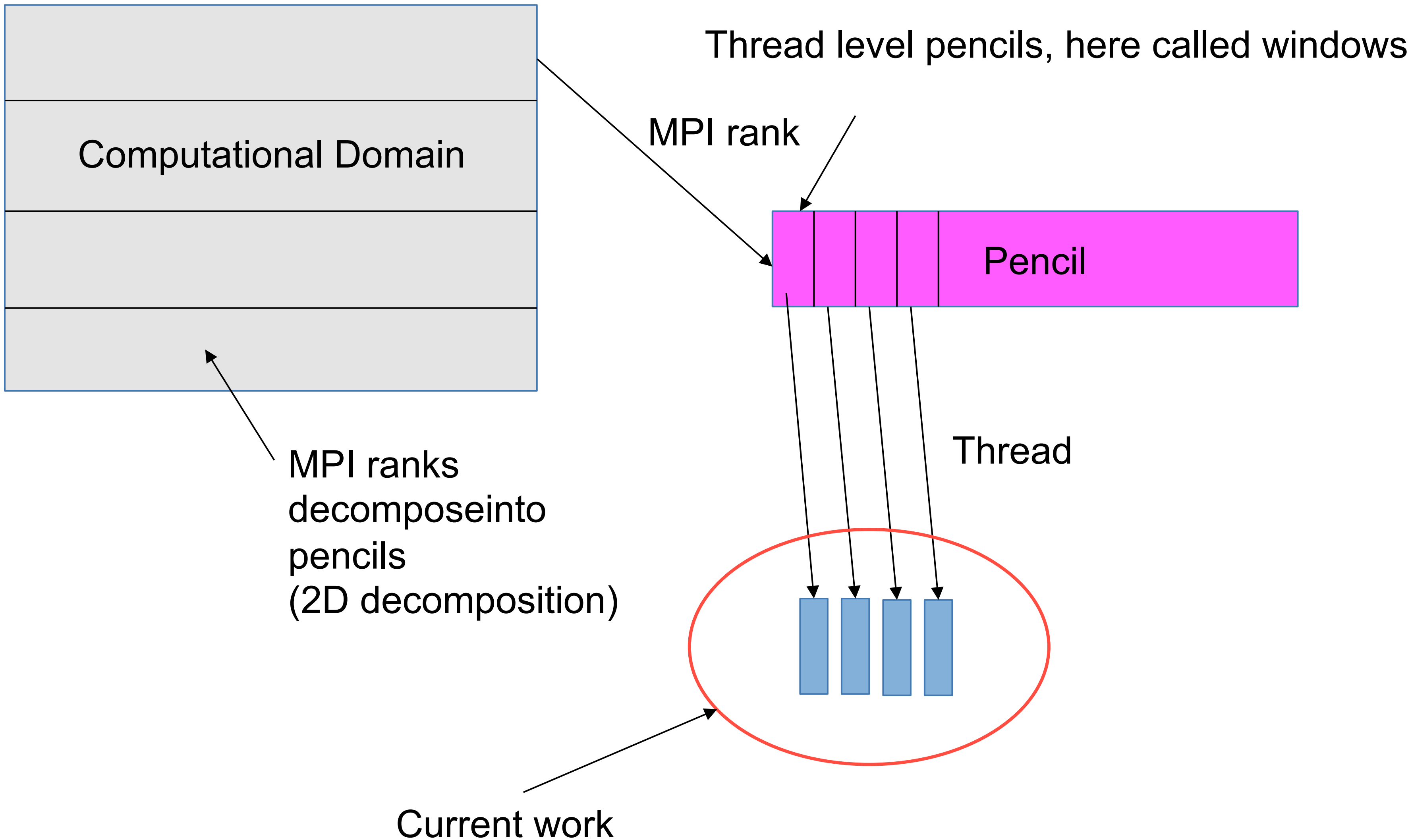
- Cutting-edge computational power of the Blue Waters is used to generate a **DNS database** of high-speed turbulent boundary layers
  - $M_\infty = 2.5 – 14$
  - $T_w/T_r = 0.18$ - 1.0
  - $Re_\tau \approx 400 – 2000$
- DNS database is used to study the boundary-layer-induced **global pressure field**
  - pressure statistics and structures
  - freestream acoustic radiation
- DNS code is being modernized on the Blue Waters to enable **petascale** simulations at higher Reynolds numbers
  - Software profiling
  - Parallel I/O
  - Hybrid MPI-OpenMP

Future Work

- Conduct DNS of supersonic turbulent boundary layers at $\mathrm{Re}_\tau \approx 2000$
  - investigate statistical and spectral scaling of the global pressure field
  - dependence of the induced pressure field on **Reynolds number**

- DNS code modernization
  - hybrid MPI-OpenMP parallel structure
  - An additional dimension of domain decomposition

MPI-OpenMP Hybridization



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  - NASA Advanced Supercomputing Division

Publications

- J. Huang and L. Duan, "Turbulent Inflow Generation for Direct Simulations of Hypersonic Turbulent Boundary Layers and Their Freestream Acoustic Radiation", *AIAA Paper 2016-3639*, 46th AIAA Fluid Dynamics Conference, Washington, DC, June, 2016. http://arc.aiaa.org/doi/abs/10.2514/6.2016-3639
- C. Zhang and L. Duan, "Multivariate Statistics Analysis of the Pressure Field Induced by High-Speed Turbulent Boundary Layers", *AIAA Paper 2016-3090*, 46th AIAA Fluid Dynamics Conference, Washington, DC, June, 2016. http://arc.aiaa.org/doi/abs/10.2514/6.2016-3190
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Questions?

Backup