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

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NCSA POC: Dr. JaeHyuk Kwack

MISSOURI S&T

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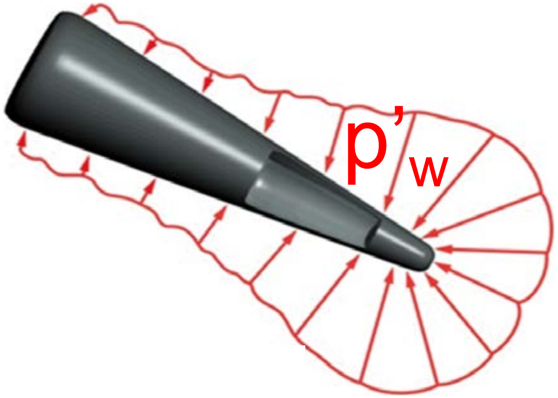
Background

Boundary-Layer-Induced Pressure Fluctuations

- Pressure fluctuations (p') induced by supersonic turbulent boundary layers
  - Theoretical significance
    - Vorticity dynamics (high vorticity ⇔ low pressure)
    - turbulence modeling (pressure-strain terms in the transport equations for the Reynolds stresses) (*Pope 2000*)
  - Engineering applications
    - p'_w → vibrational loading of flight vehicles
    - p'_∞ → freestream noise of supersonic wind tunnels

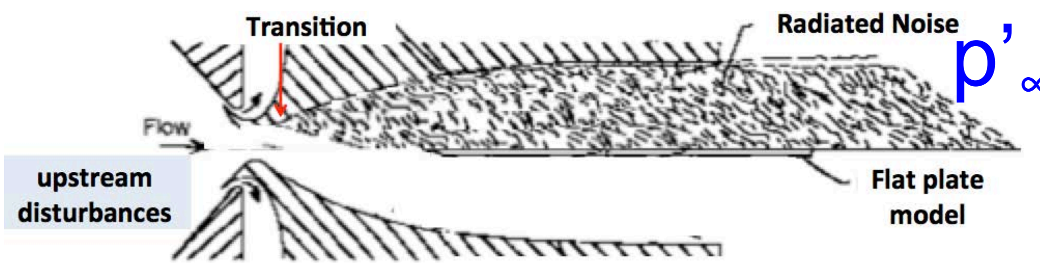
Vehicle Vibration

(Casper et al. 2016)



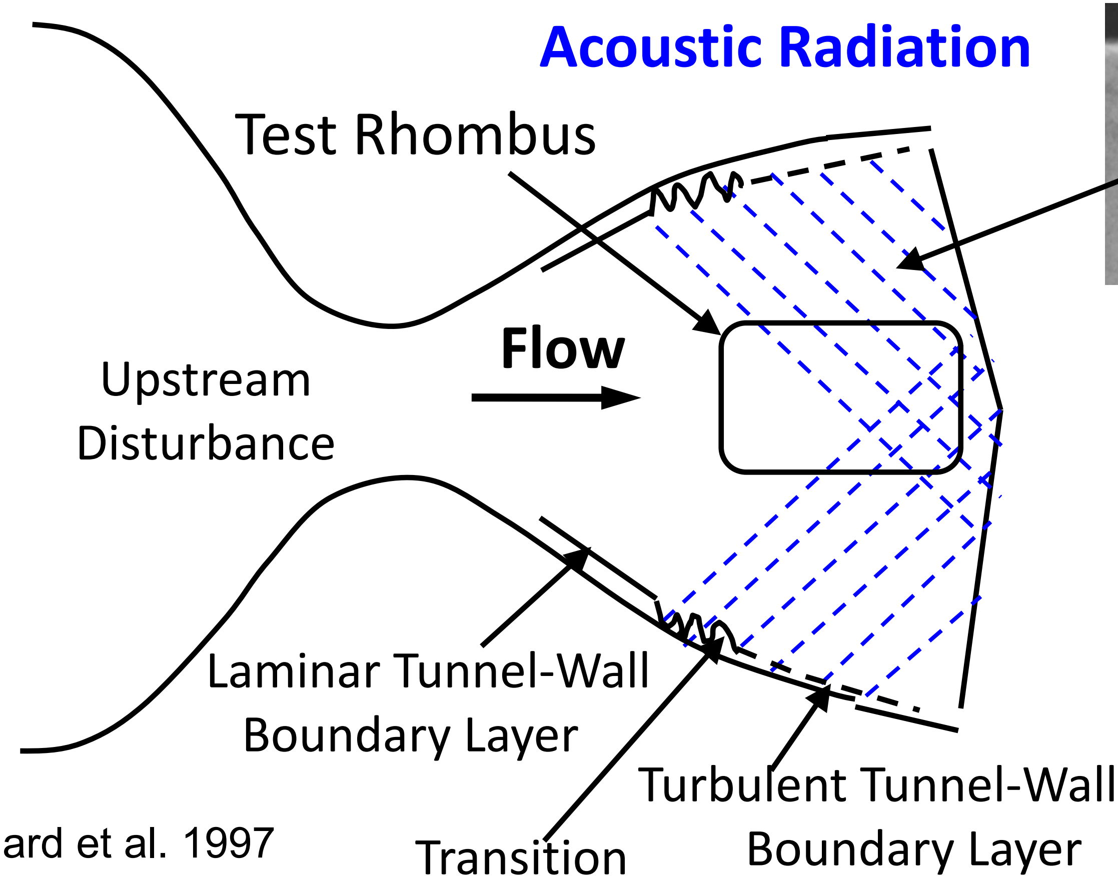
Wind-tunnel Freestream Noise

(Beckwith and Miller, 1990)

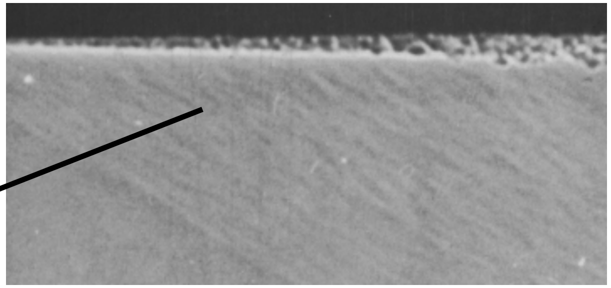


Background

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*)

Background

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)
  - computation
    - largely limited to incompressible boundary layers
    - freestream pressure fluctuations not studied

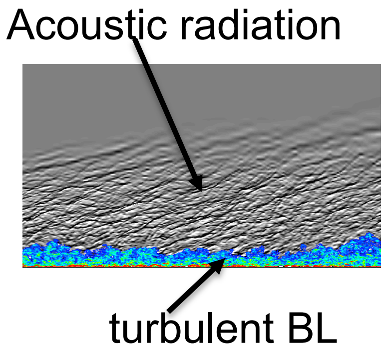
- **Direct Numerical Simulation (DNS)** is used to investigate boundary-layer-induced pressure field
  - statistical and spectral scaling of pressure
  - large-scale pressure structures
  - correlation between regions of extreme pressure and extreme vorticity
  - acoustic radiation in the free stream

Focus of Current Project

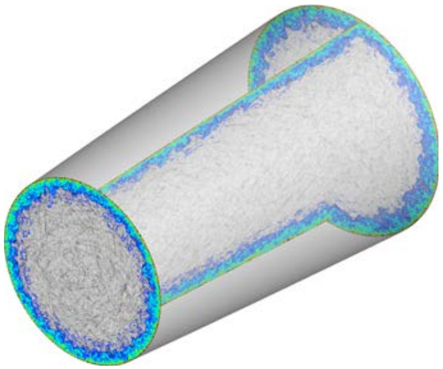
Boundary-Layer-Induced Pressure Fluctuations

- **Single, flat wall** configuration *(Duan et al., JFM 2014, 2016, Zhang et al. JFM, 2017)*
  - Developed a **DNS database** of BL acoustic radiation
    - $M_\infty = 2.5 - 14$
    - $T_w/T_r = 0.18 - 1.0$
    - $Re_\tau \approx 400 - 2000$

Single, flat wall



Axisymmetric nozzle



- **Axisymmetric nozzle** configuration *(Huang et al. AIAA-2017-0067; Duan et al. AIAA-2018-0347)*
  - Effect of **axisymmetry** on turbulent BLs and their acoustic radiation

Why Blue Waters?

Boundary-Layer-Induced Pressure Fluctuations

- World-class computing capabilities of Blue Waters required for DNS of turbulent boundary layers and boundary-layer-induced noise at high Reynolds numbers
  - Extremely fine meshes required to fully resolve all turbulence/acoustics 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

- Production runs require at least 1,000 compute nodes for production science (“High-scalable” runs)

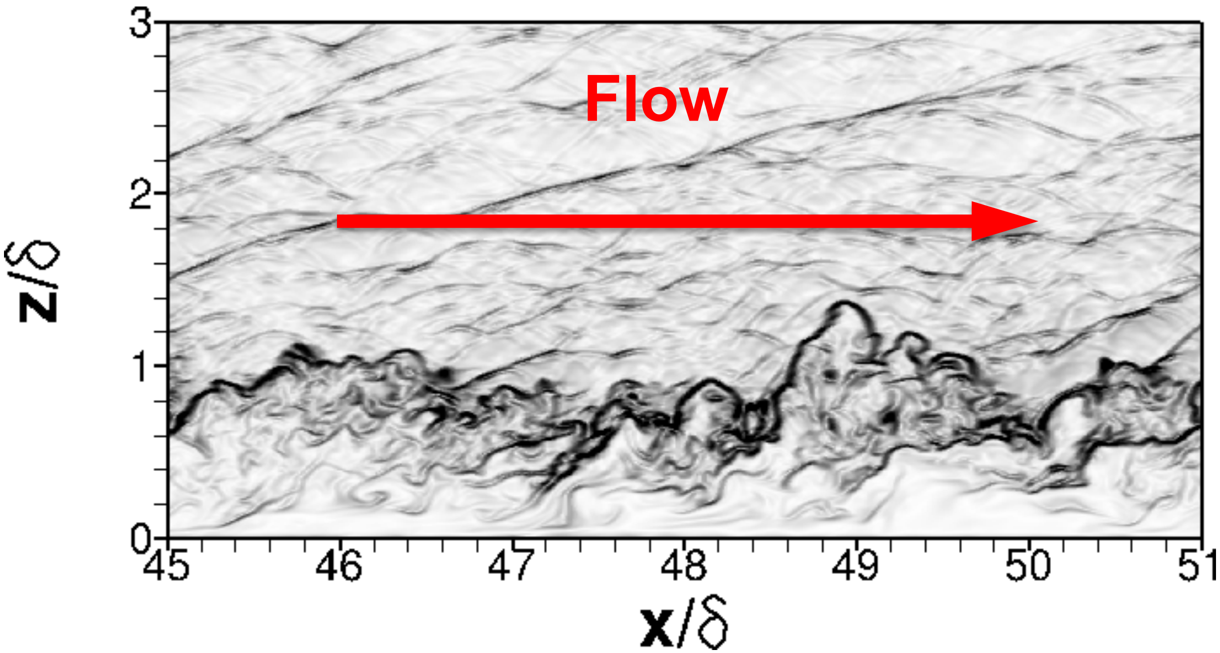
Outline

- DNS methodology
- Software workflow
  - Domain Decomposition Strategy
  - I/O requirement
  - Parallel Performance
- Results of Domain Science
  - Boundary-layer-induced pressure statistics & structures
  - Boundary-layer freestream radiation
- Summary

Background

DNS for Compressible Turbulent Boundary Layers

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



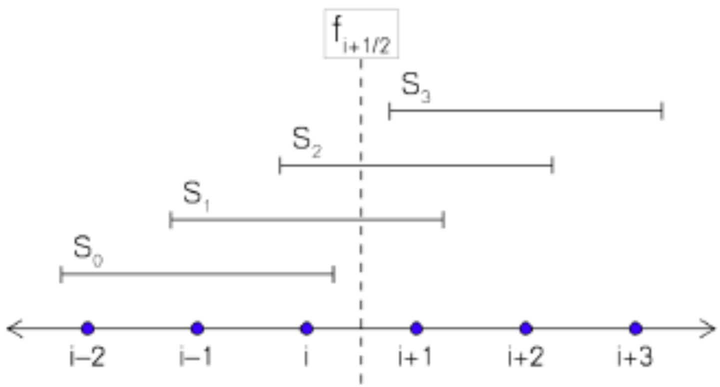
Numerical schlieren (NS) of a Mach 14 turbulent boundary layer

$$NS = 0.8 \exp\left[-10 \frac{|\nabla \rho|}{\max(|\nabla \rho|)} \right]$$

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-Oscillatory (WENO) adaptation for capturing shock waves *(Jiang & Shu JCP 1996,* Martin et al. JCP, 2006*)*



Flux: weighted sum of candidates source of non-linearity

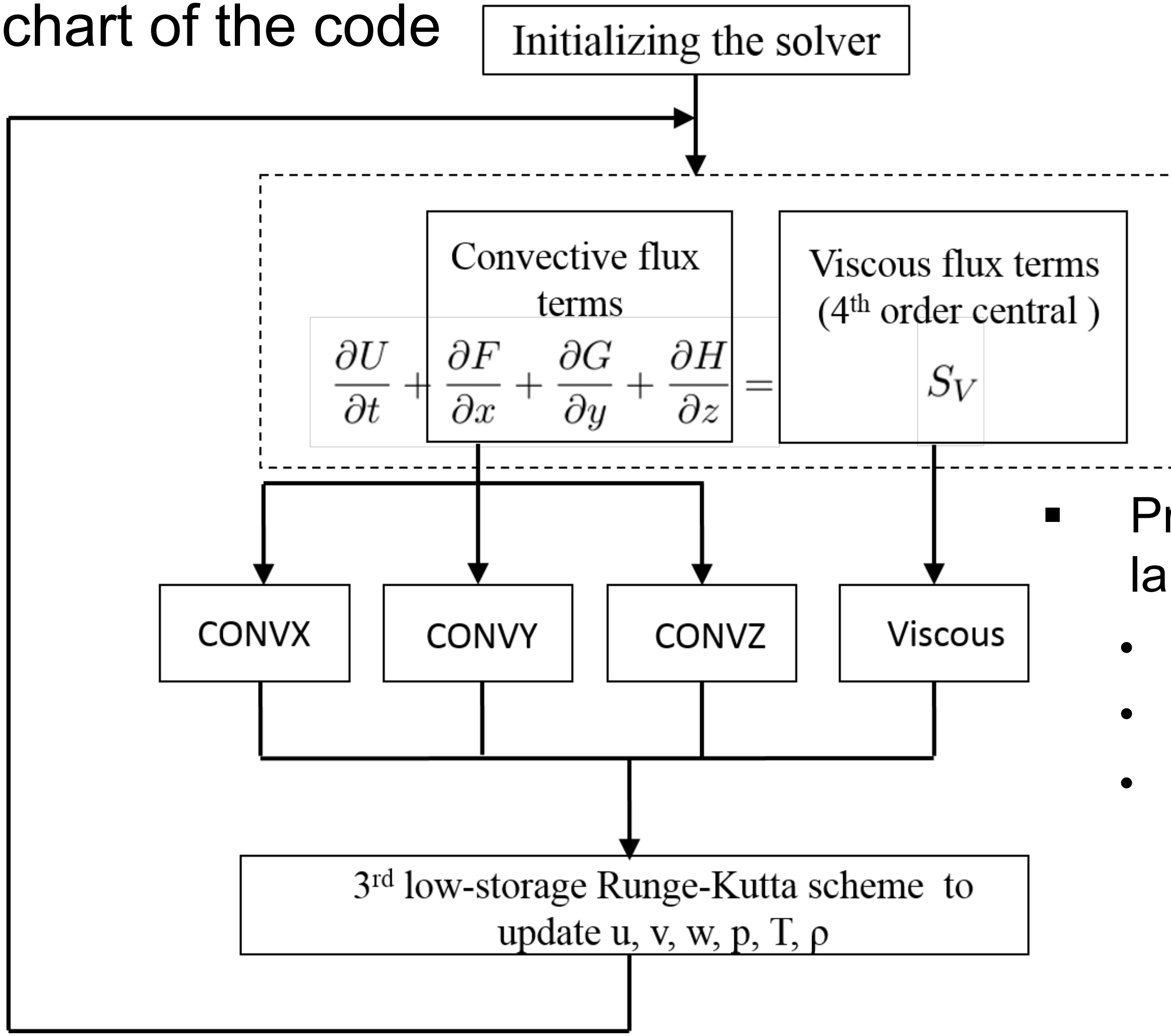
$$\hat{f}_{i+1/2} = \sum_{k=0}^{r} w_k q_k^r$$

  - 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

Software Structure

Flow chart of the code



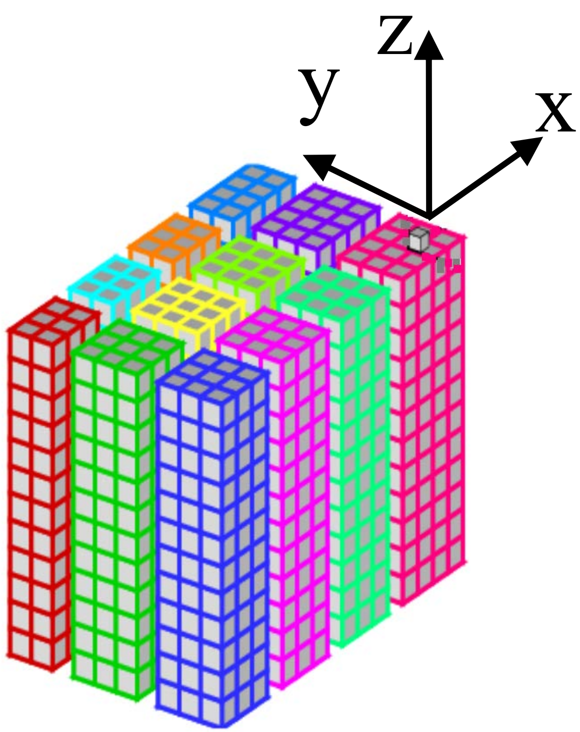
- Programming language and model
  - Fortran 2003
  - Parallel MPI-only
  - I/O in parallel HDF5

DNS Methodology

Domain Decomposition

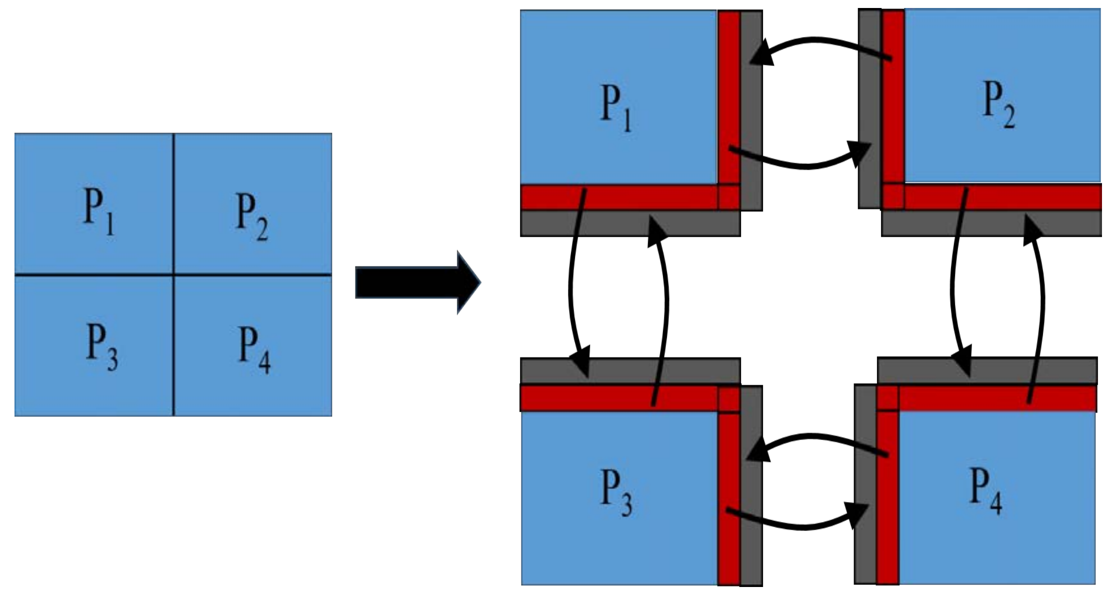
2D domain decomposition

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



x-node = 4
y-node = 3

- computational domain
- copied part of computational domain
- ghost cells

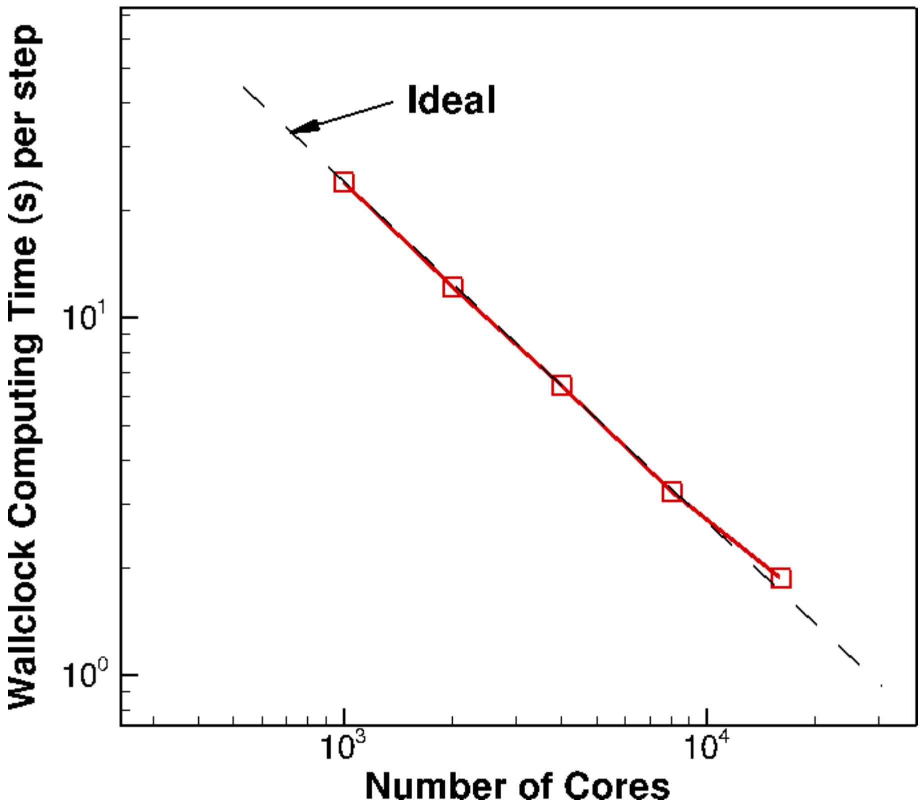


Static data decomposition and ghost cell update between four processors

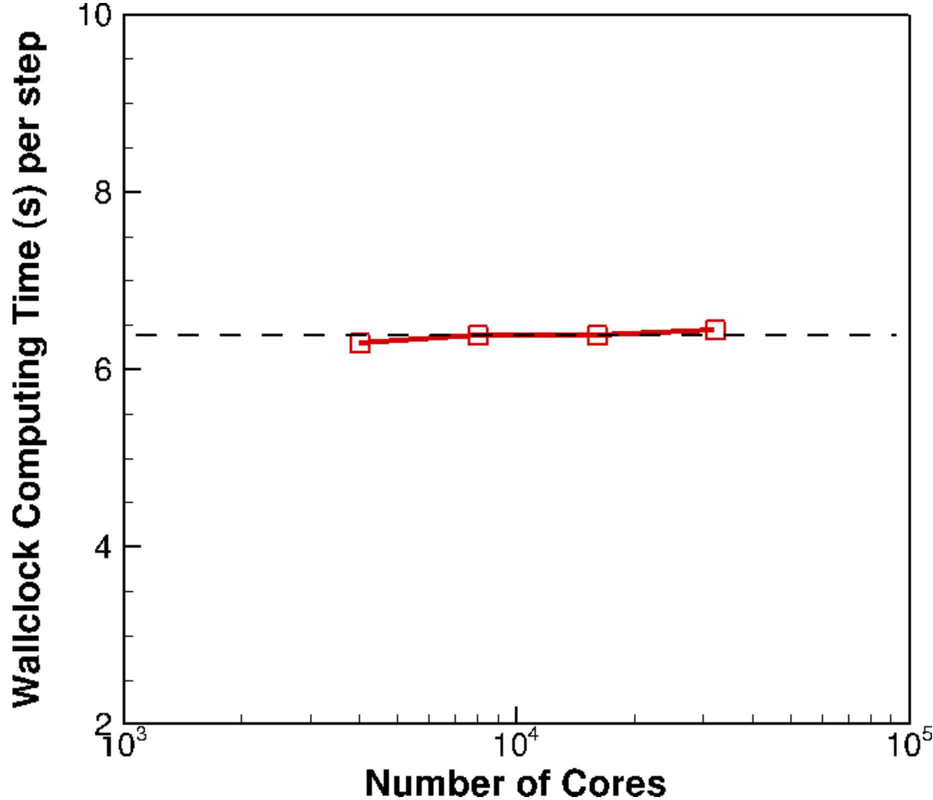
DNS Methodology

Computational Performance

Strong Scaling (Computation Time only)



Weak Scaling (Computation Time only)



- Computation scales well to 1000 XE nodes (32,000 cores)
- **Strong Scaling**: mesh size fixed at 3200x320x500, increase # of cores
- **Weak Scaling**: pencil size fixed at 16x16x500, increase # of cores and mesh size

DNS Methodology

IO Workflow

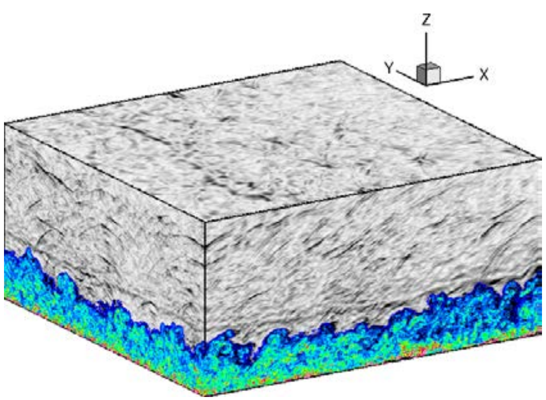
- I/O requirements
  - Restart I/O
    - five floating-point quantities per grid point consisting of all the primitive flow variables
      (~ **1.0 TB** per dump, ~ **50** dumps per production run)
  - Analysis I/O
    - ASCII dumps of running-averaged statistics and boundary-layer integral quantities (< **1.0 GB** per dump)
    - data-intensive HDF5 time series: 2D plane cuts and 3D subsets of the calculated flow volume for statistical/spectral analyses and visualization (~ **200 GB** per dump, ~ **200** dumps per production run)
  - Data archival
    - All the ASCII dumps and HDF5 timeseries files for post-processing (~ **40 TB**)
    - up to 10 restart files (~ **10 TB**)

DNS Methodology

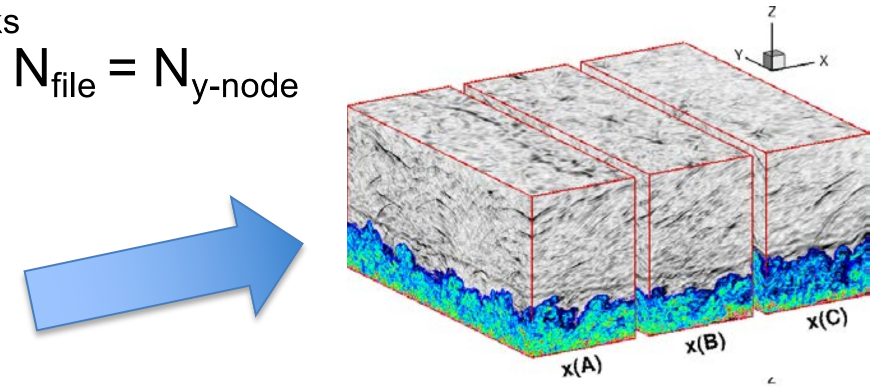
IO Workflow

❑ I/O Methodology

- **“One-file” mode**: All processes collectively write into the same restart or timeseries file (N_{file} = 1) using parallel HDF5 (< 100 GB per dump)
- **“Multiple-file” mode**: restart and timeseries dump written into a small number of file using parallel HDF5 (> 100 GB per dump)
  - $N_{file} << N_{MPI\text{-}ranks}$
  - $N_{file} = N_{x\text{-}node}$ or $N_{file} = N_{y\text{-}node}$

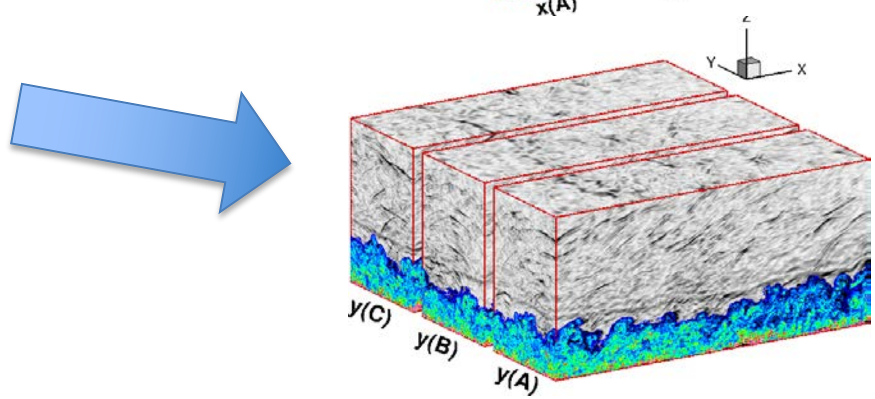


N_{file} = 1



x-node = 3

$N_{file} = N_{x\text{-}node}$

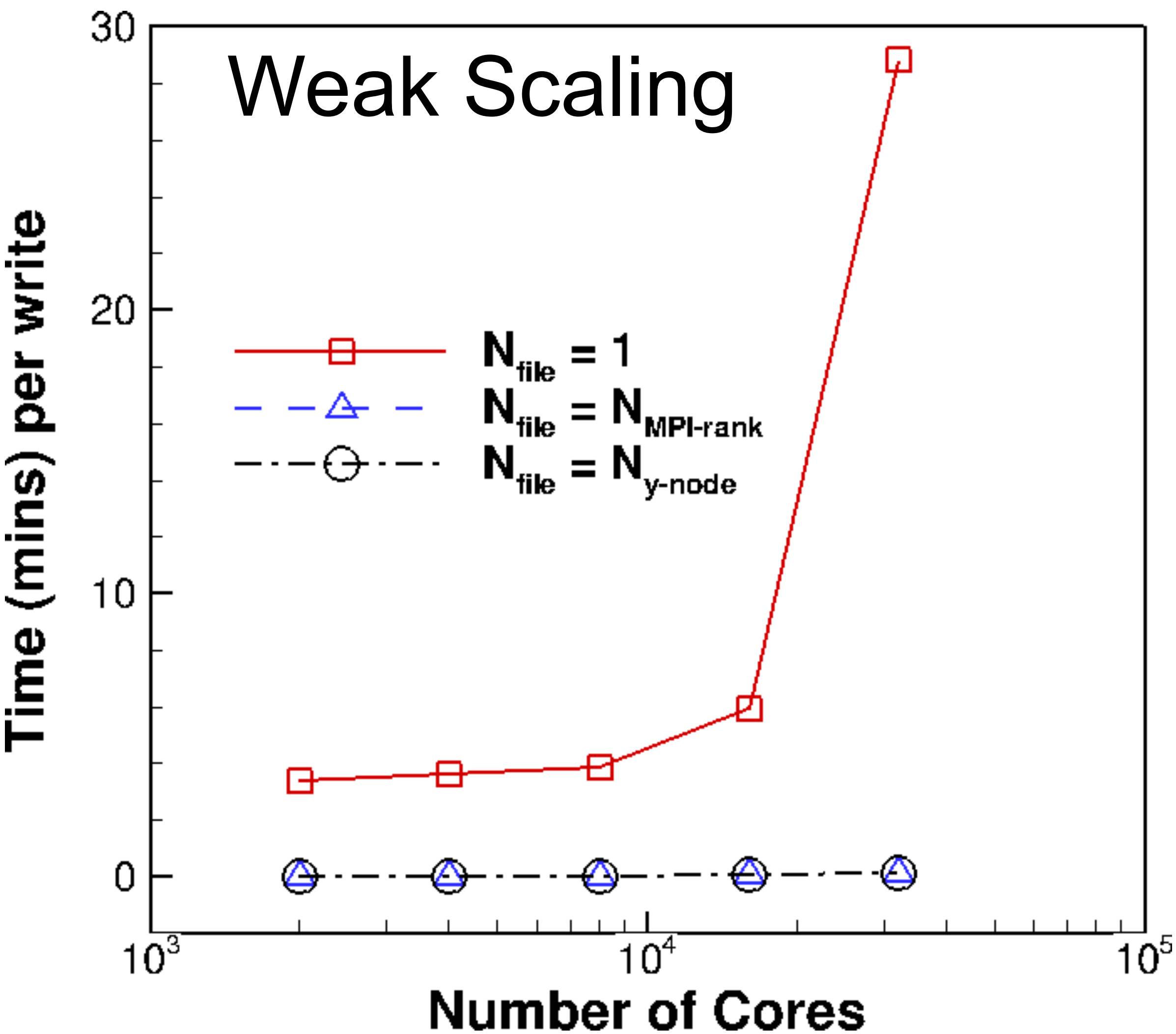


y-node = 3

$N_{file} = N_{y\text{-}node}$

DNS Methodology

IO performance



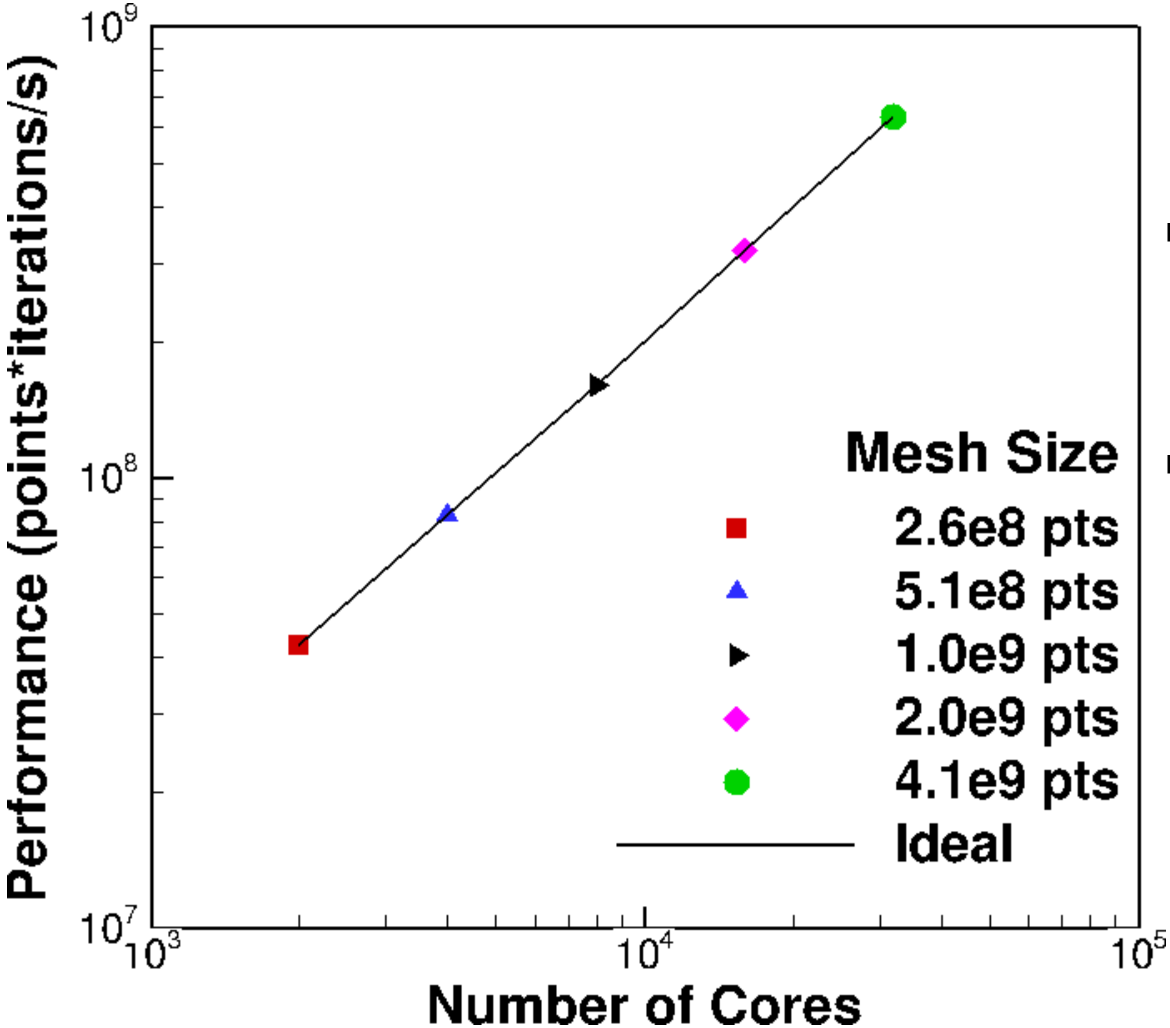
For a run with $N_{MPI-rank}$ = 32,000 and per-dump file size of 160 GB

N_{file} = 1:
28.9 minutes per dump

N_{file} = N_{y-node}= 80:
0.1 minutes per dump

DNS Methodology

Overall performance

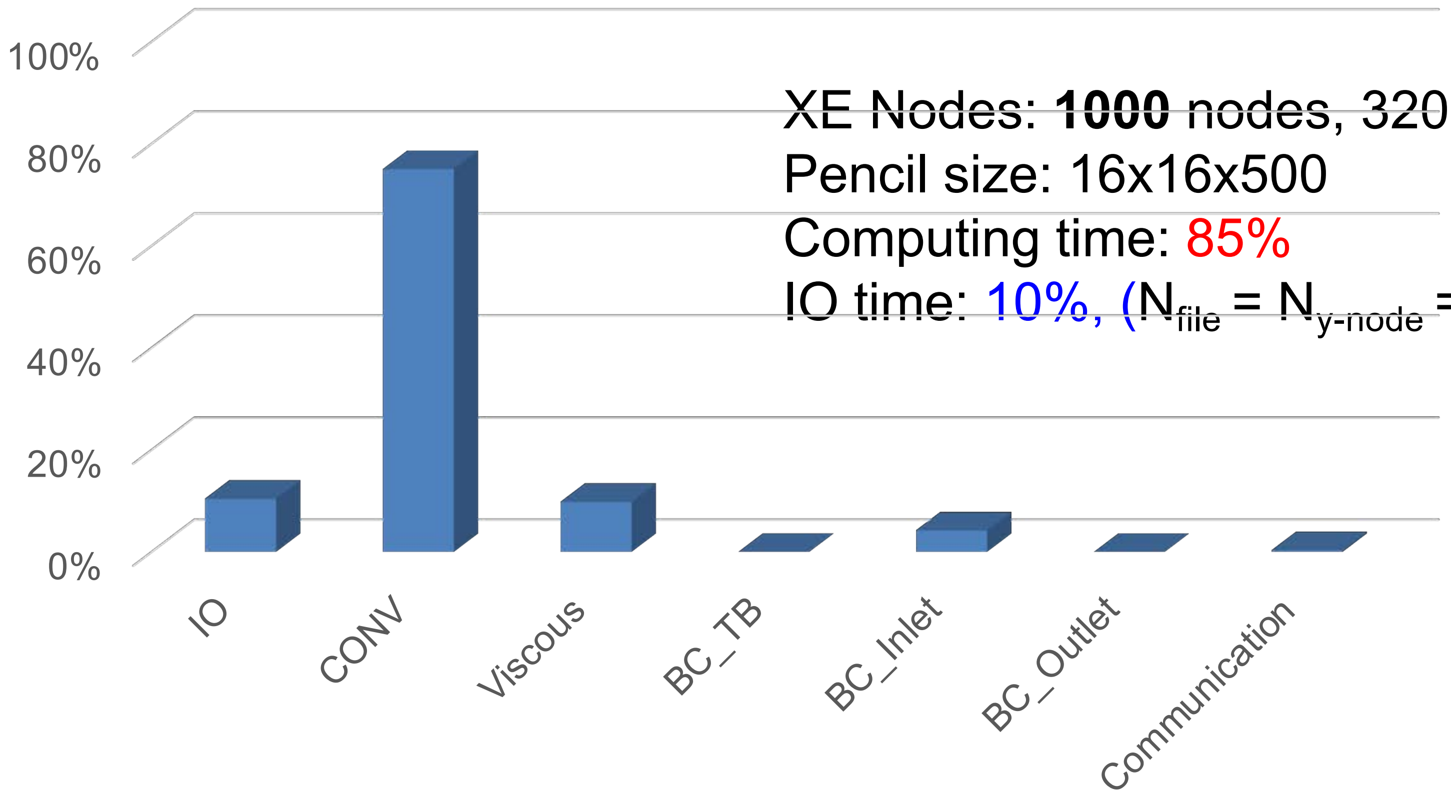


- Weak Scaling with pencil size fixed at 16x16x500
- Blue Waters XE Nodes with **32** cores/node

DNS Methodology

Software Profiling

Time breakdown (6400x1280x500, 160GB per dump)



XE Nodes: **1000** nodes, 32000 cores

Pencil size: 16x16x500

Computing time: 85%

IO time: 10%, ($N_{file} = N_{y\text{-}node} = 80$)

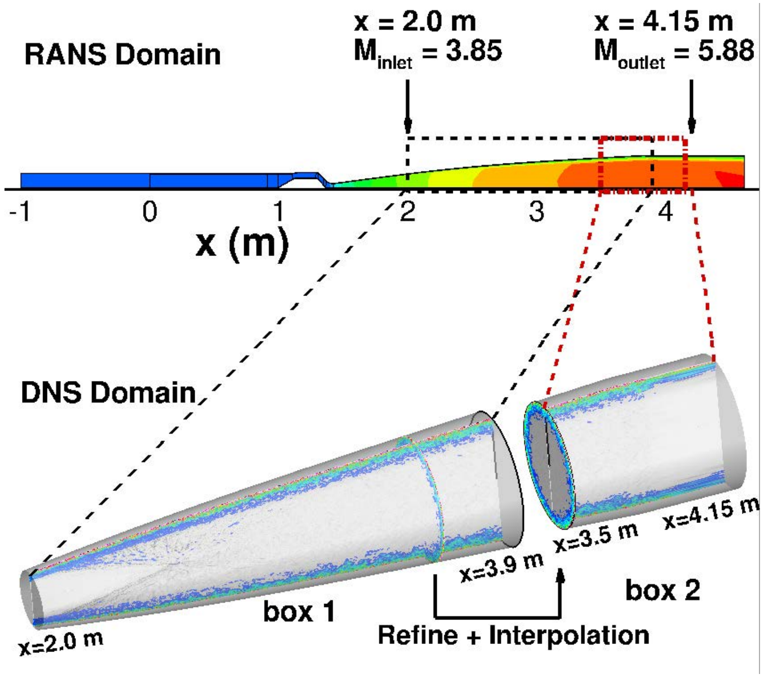
Results of Domain Science

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

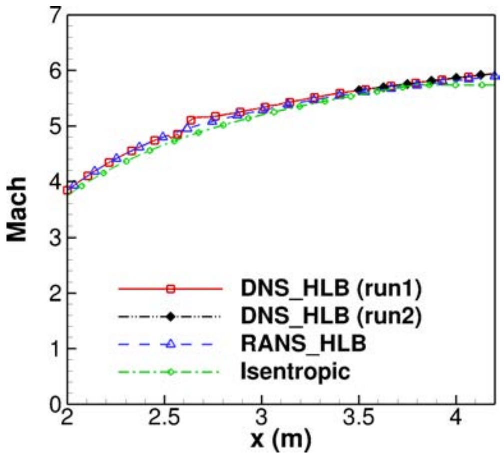
DNS of Tunnel Freestream Acoustic Disturbances

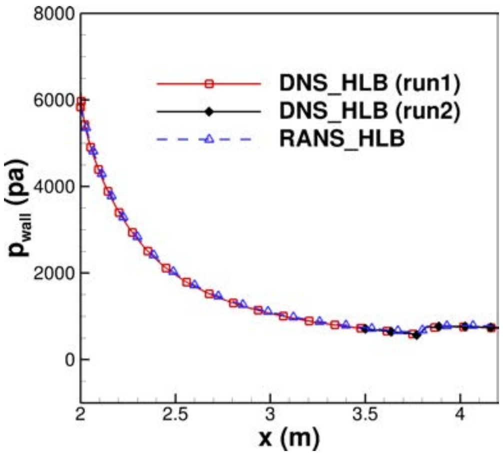
Acoustic Disturbances in the Full-Scale Nozzle of a Hypersonic Wind Tunnel

- Nozzle geometry and flow conditions match those of the Mach 6 Hypersonic Ludwieg Tube Braunschweig (HLB)
  - p_0 = 722 kPa, T_0 = 469 K, T_w = 293 K
- "Embedded" DNS method
  - DNS inflow provided by a full-domain RANS (-1.0 m < x < 4.2)
  - DNS domain enclosed in RANS domains
    - run1: 2.0 m – 3.9 m
    - run2: 3.5 m – 4.15 m



Box-1 points: 3.05×10^9
Box-2 points: 4.26×10^9



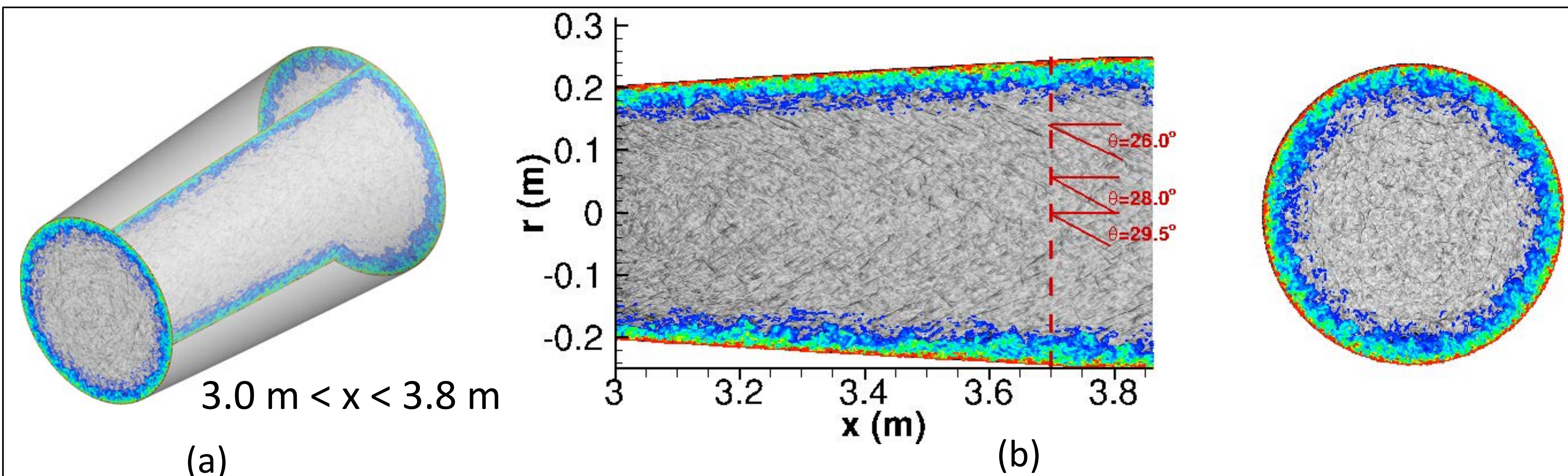


DNS of Tunnel Freestream Acoustic Disturbances

Acoustic Disturbances in the Full-Scale Nozzle of a Hypersonic Wind Tunnel

- ❑ The wave fronts exhibit a preferred orientation with respect to nozzle centerline with in the x-r plane
- ❑ The density gradients reveal the omnidirectional origin of the acoustic field within a given cross-section of the nozzle

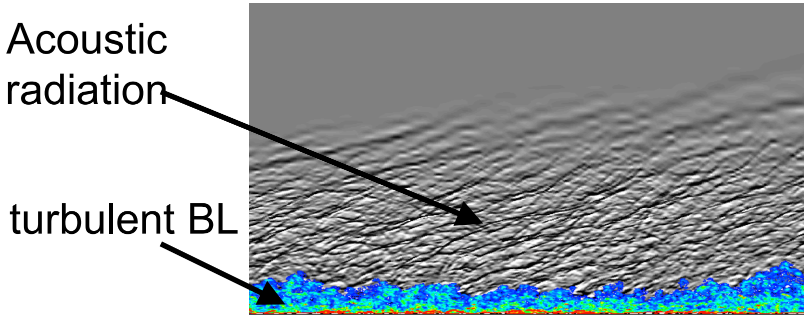
Grayscale: numerical schlieren
Colors: vorticity magnitude



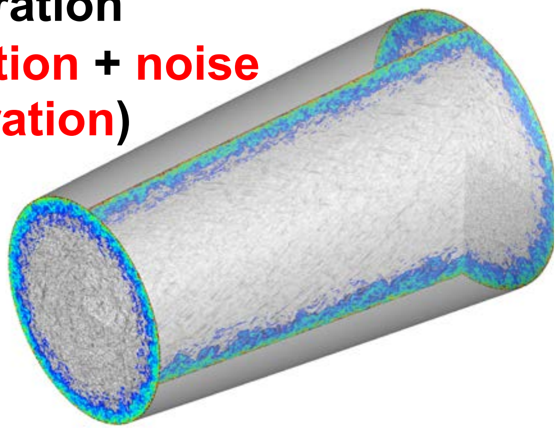
DNS of Tunnel Freestream Acoustic Disturbances

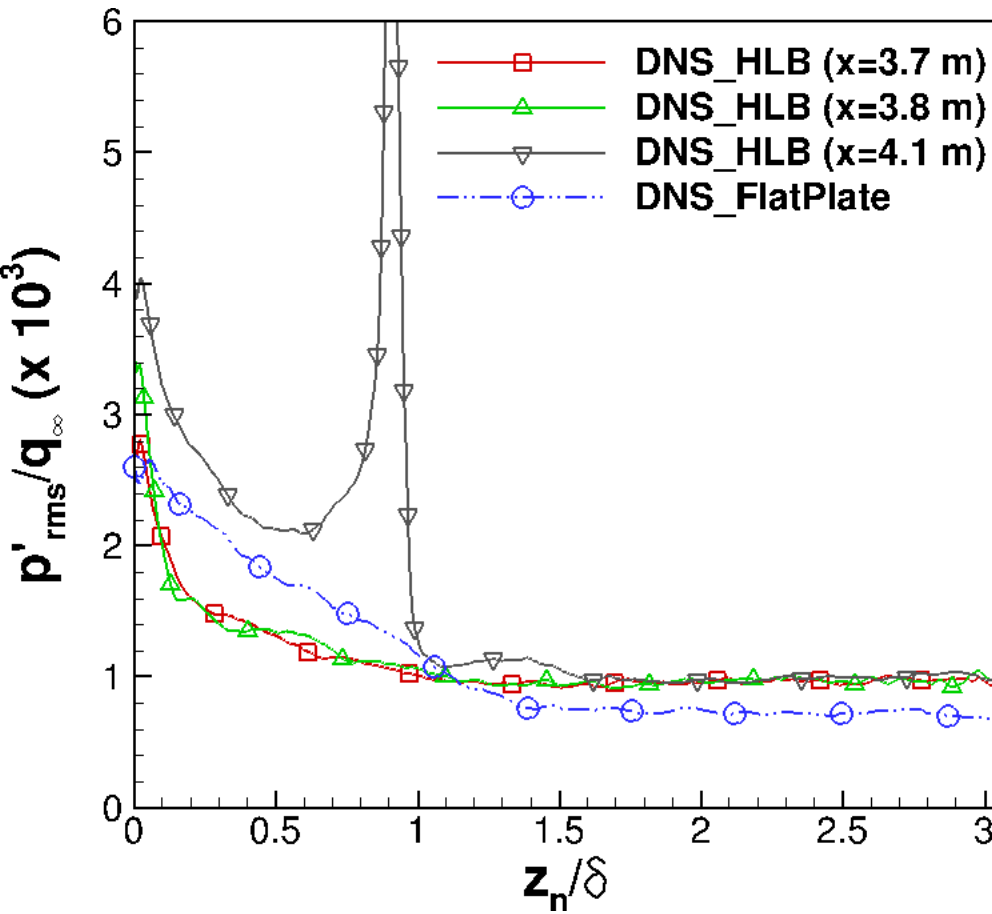
RMS Pressure Fluctuation

Single, flat wall configuration
(noise generation)



Enclosed "nozzle" configuration
(noise generation + noise reverberation)





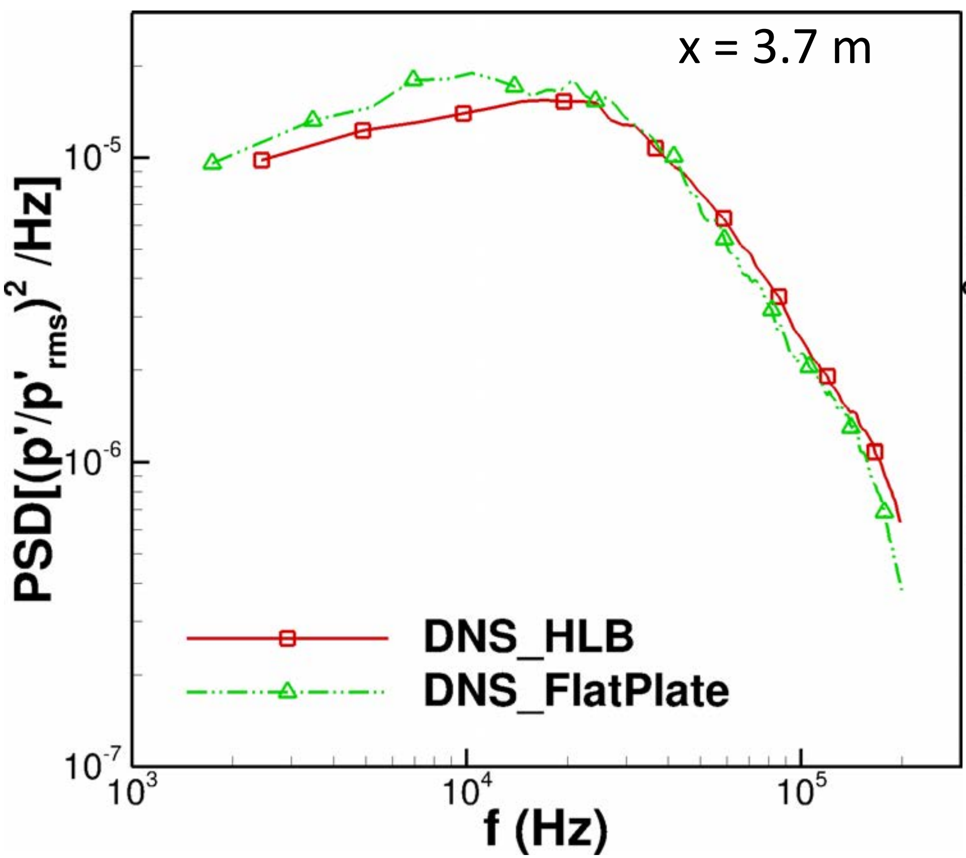
z_n : wall normal distance

- Noise reverberation seems to significantly influence p'_{rms} within the axisymmetric nozzle, leading to a faster decay to its freestream level and increased freestream intensity for the nozzle case

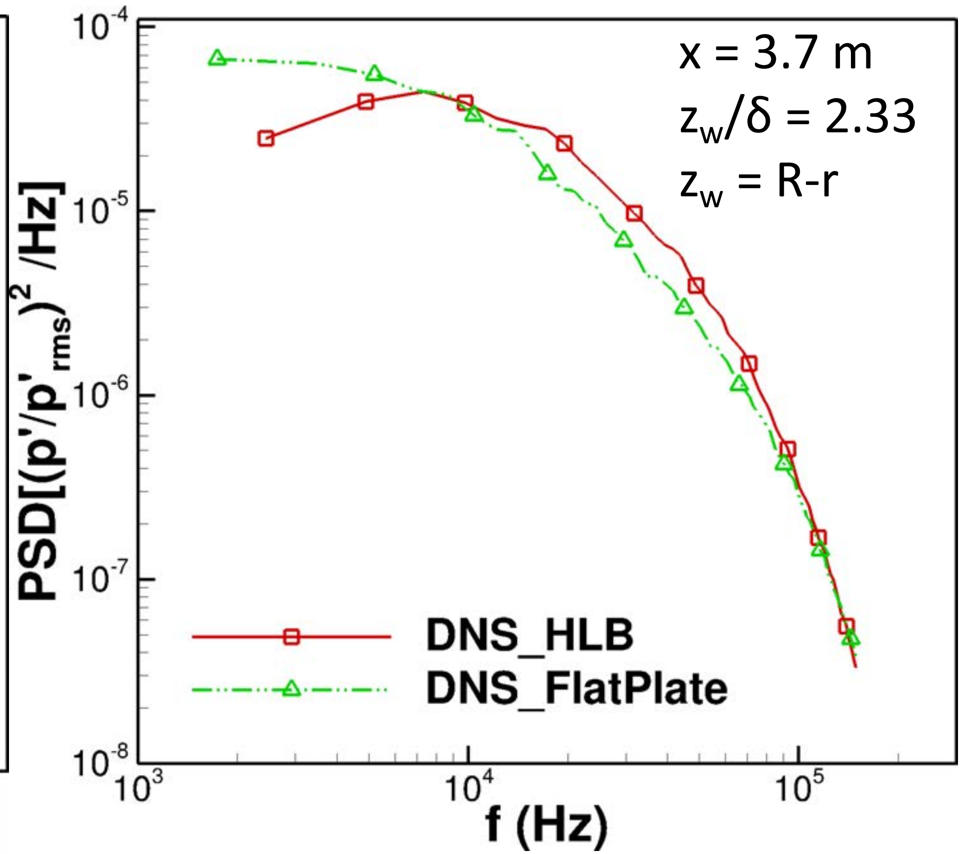
DNS of Tunnel Freestream Acoustic Disturbances

Freestream Acoustic Spectrum

Wall



Outside BL ("free stream")

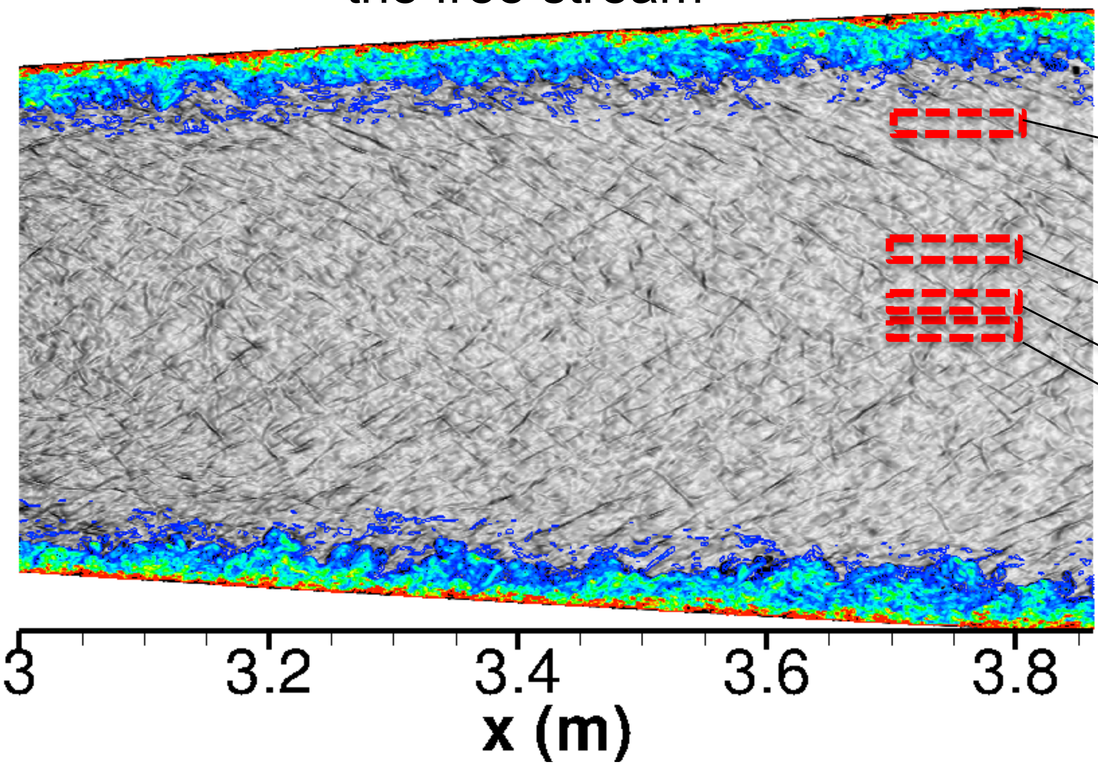


- ❑ Reasonable agreement in PSD between the flat-plate and nozzle cases, especially in high frequencies

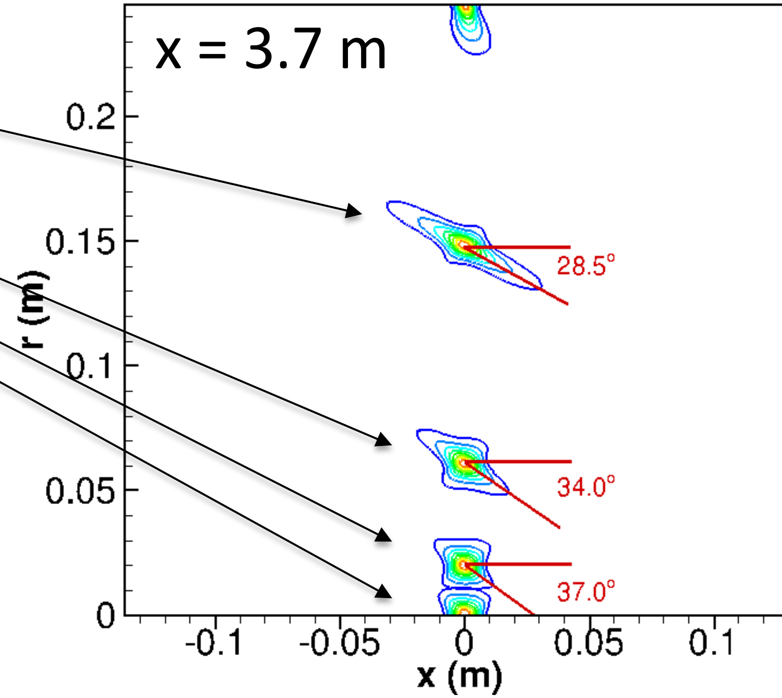
DNS of Tunnel Freestream Acoustic Disturbances

Freestream Pressure Structures

Instantaneous pressure structure in the free stream



Time-averaged pressure correlation in the free stream



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

- Simultaneous presence of waves propagating in both upward and downward directions within the streamwise-radial plane

Summary

- Cutting-edge computational power of the Blue Waters is used to generate a **DNS database** of high-speed turbulent boundary layers
  - Single, flat-wall configuration
  - Axisymmetric nozzle configuration
- 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

Acknowledgment

- Dr. Meelan Choudhari at NASA Langley Research Center
  - for collaboration
- Funding Support
  - AFOSR (Award No. FA9550-14-1-0170)
- Computing resources
  - NCSA through NSF PRAC (Award No. ACI-1640865)

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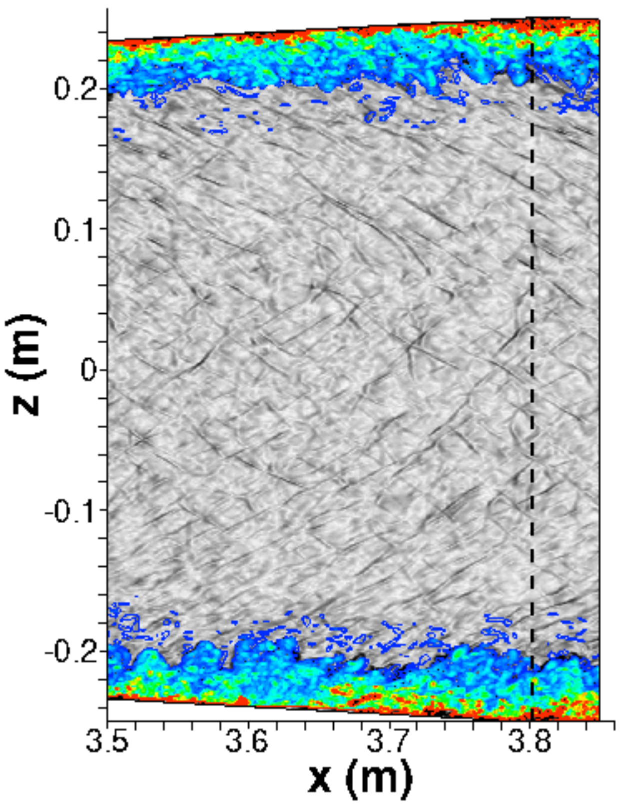
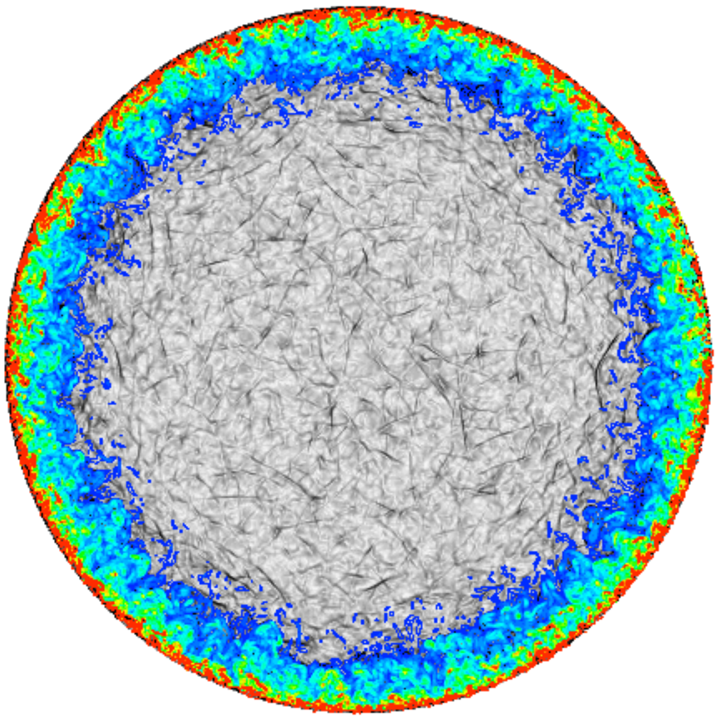
Questions?

Backup

DNS of Tunnel Freestream Acoustic Disturbances

Acoustic Disturbances in the Full-Scale Nozzle of a Hypersonic Wind Tunnel





Grayscale: numerical schlieren
Colors: vorticity magnitude

Acknowledgment

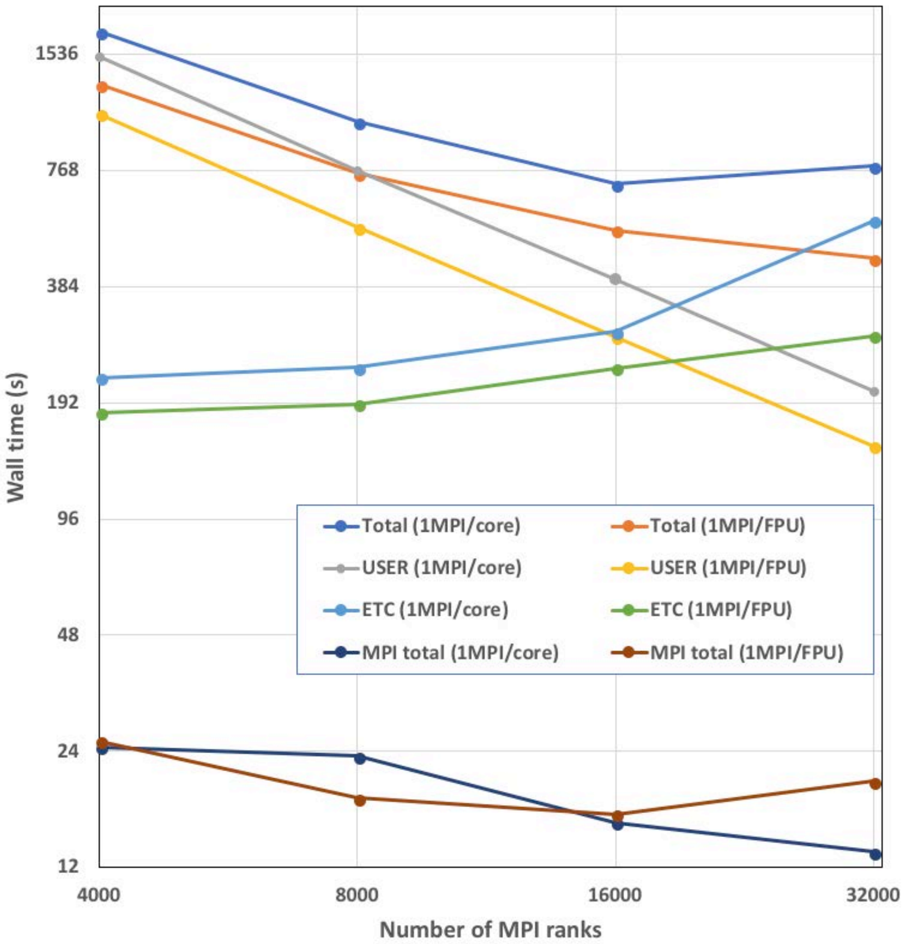
- Dr. Meelan Choudhari at NASA Langley Research Center
  - for collaboration
- Dr. JaeHyuk Kwack at NCSA
  - for his support to software profiling and MPI-OpenMP hybridization
- Funding Support
  - AFOSR (Award No. FA9550-14-1-0170)
- Computing resources
  - NCSA through NSF PRAC (Award No. ACI-1640865)

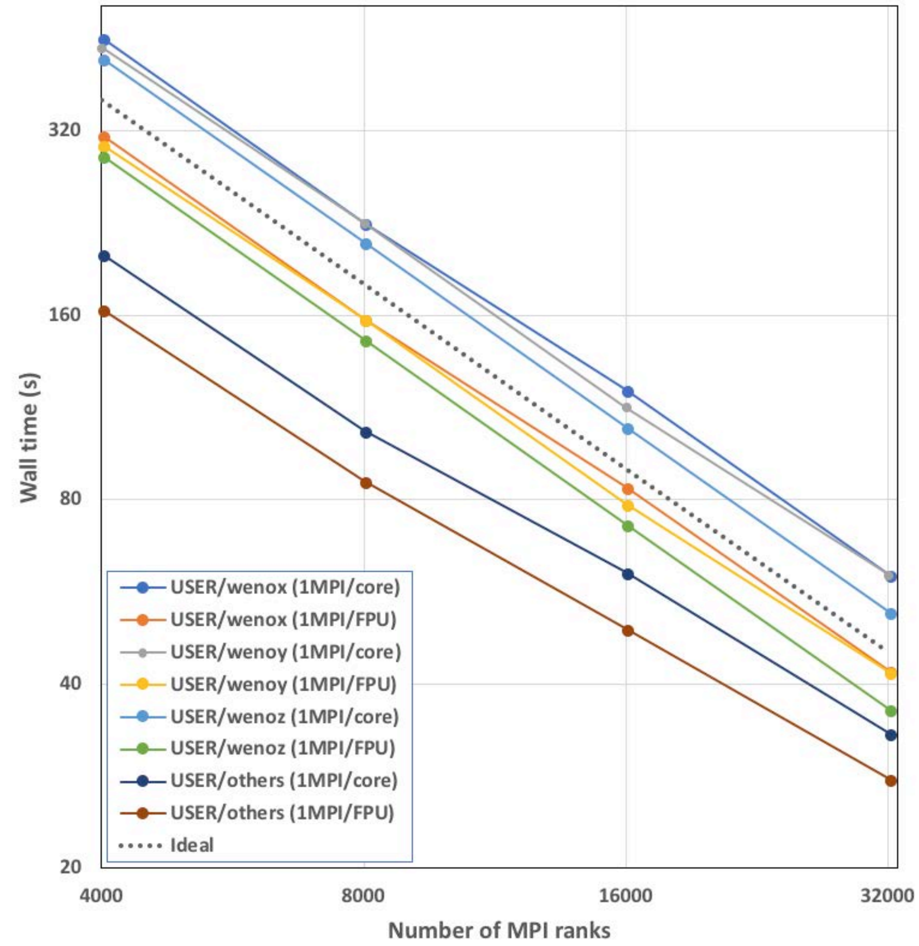
Results from JaeHyuk

DNS Performance

Wall Time

The testing case is 3200x640x500. The results are based on 100 time steps.



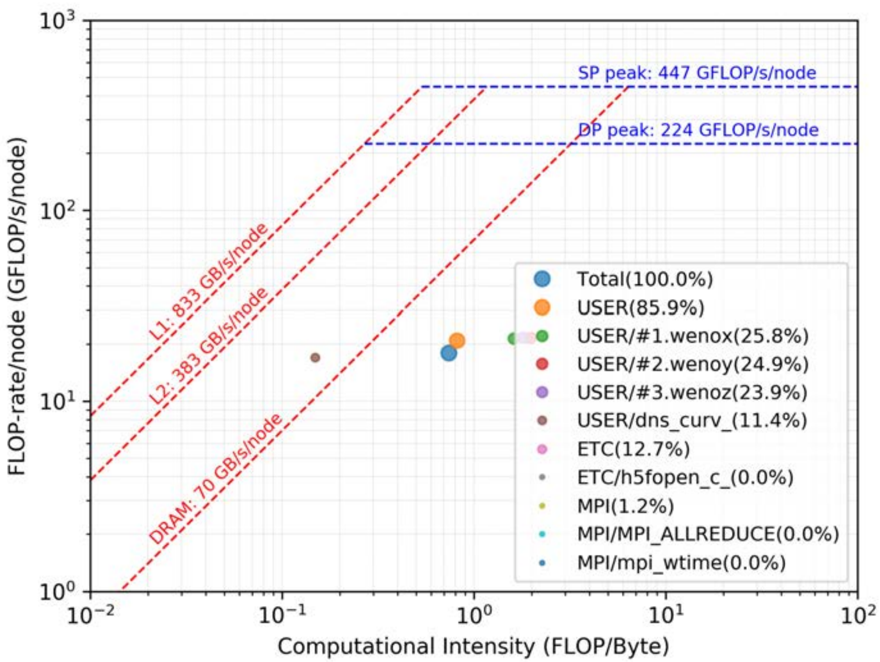


HDF5 parts are labeled as ETC. USER/(WENOX+WENOY+WENOZ+Others)

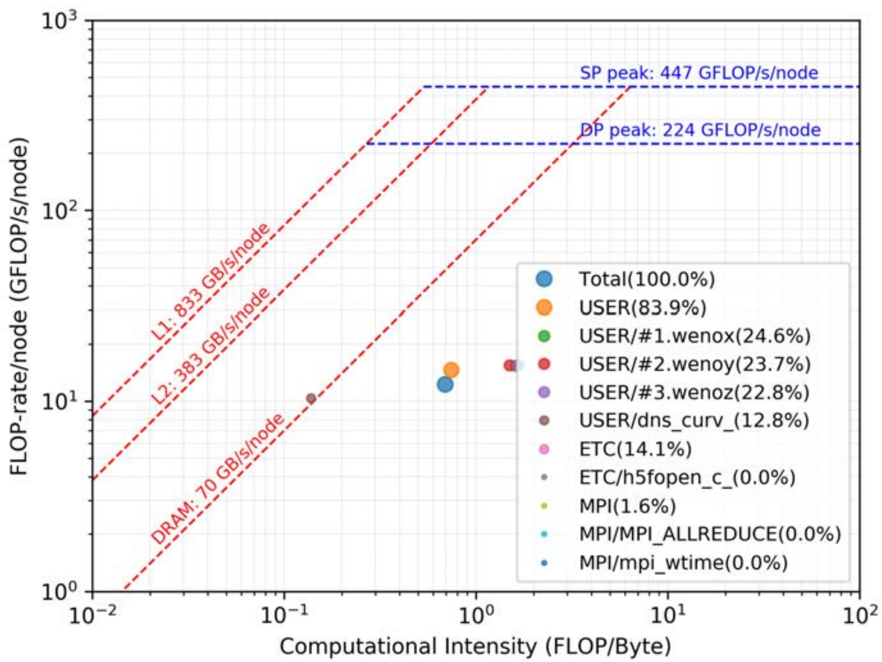
DNS Performance

roofline analysis

4000 MPIs (integer core)



4000 MPIs (FPU)

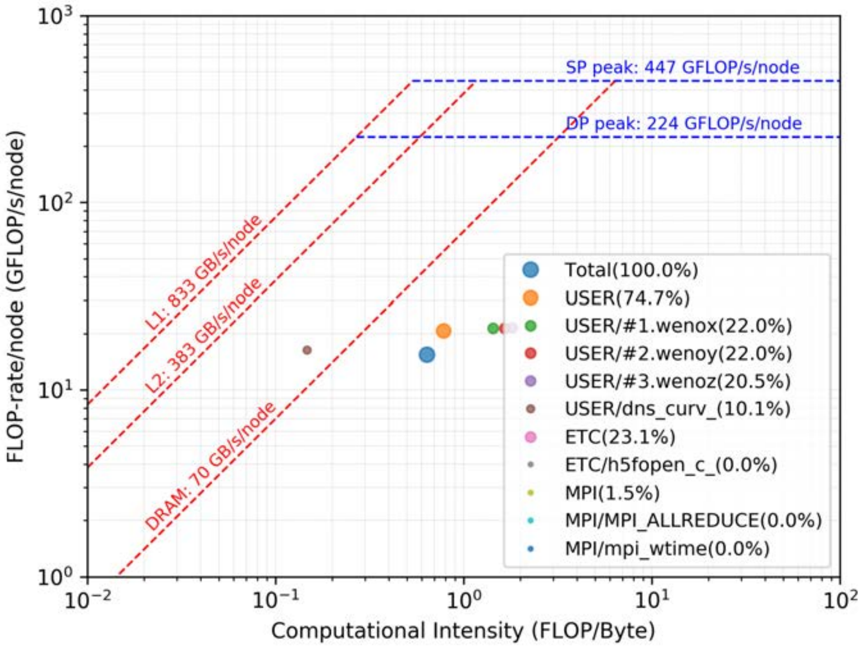


The testing case is 3200x640x500. The results are based on 100 time steps.

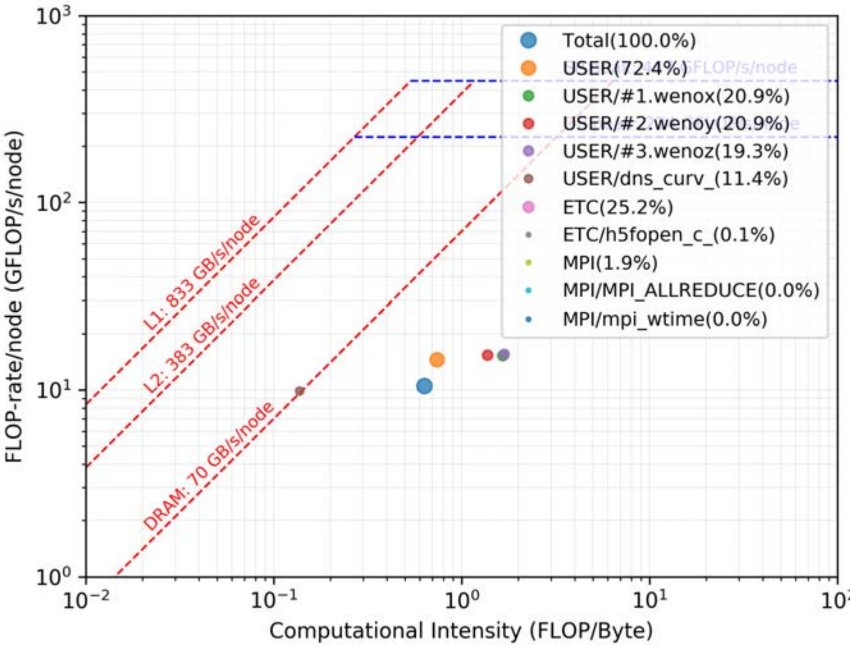
DNS Performance

roofline analysis

8000 MPIs (integer core)



8000 MPIs (FPU)

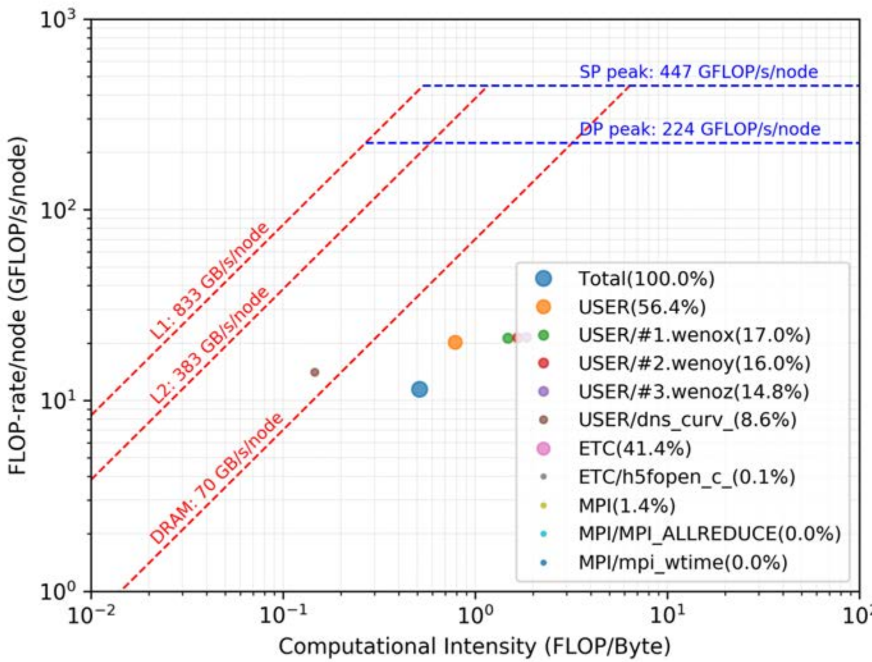


The testing case is 3200x640x500. The results are based on 100 time steps.

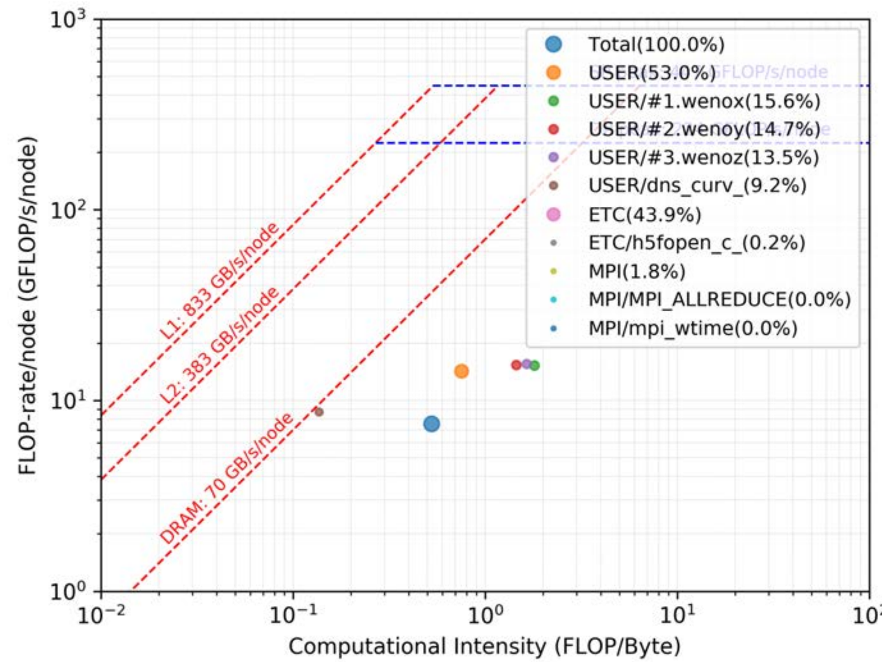
DNS Performance

roofline analysis

16000 MPIs (integer core)



16000 MPIs (FPU)

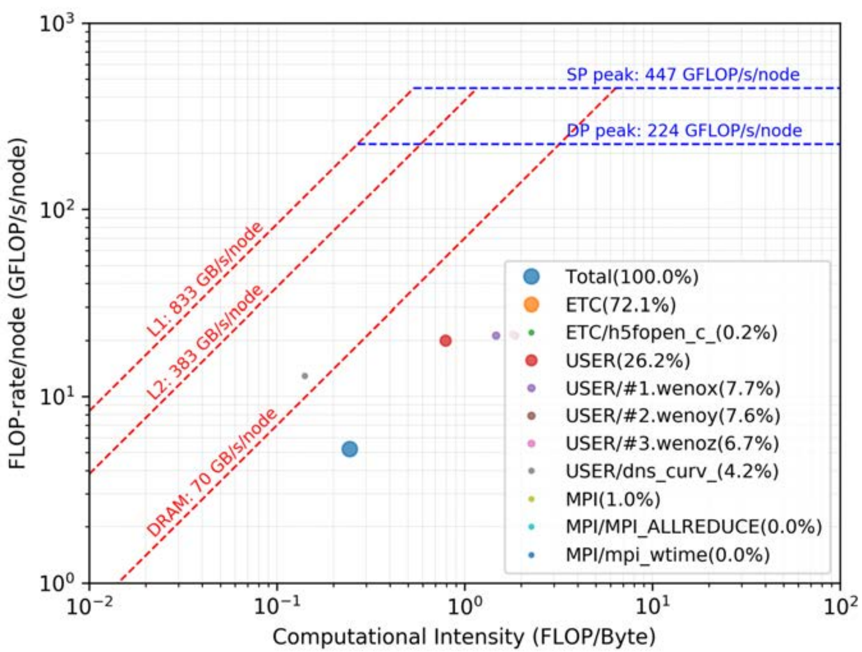


The testing case is 3200x640x500. The results are based on 100 time steps.

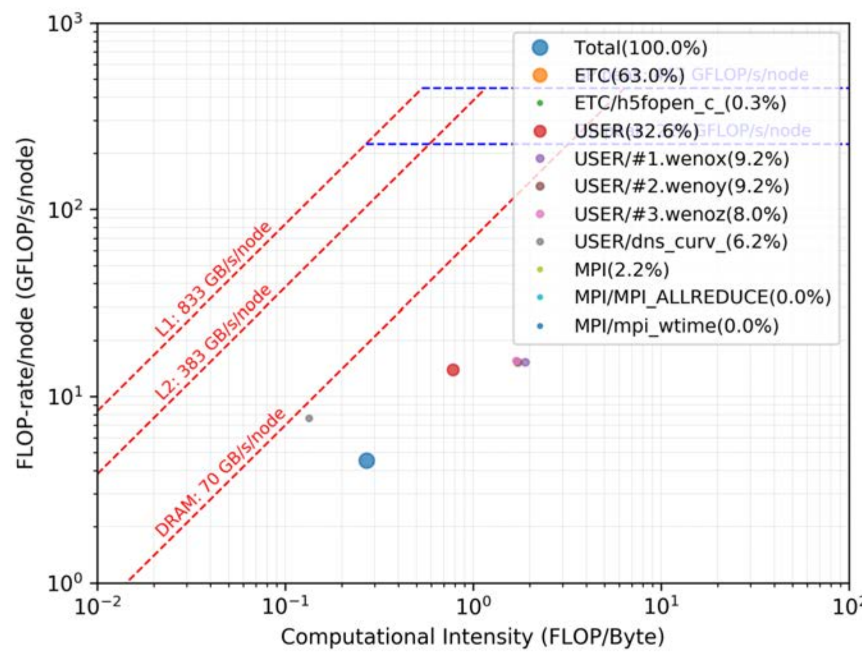
DNS Performance

roofline analysis

32000 MPIs (integer core)



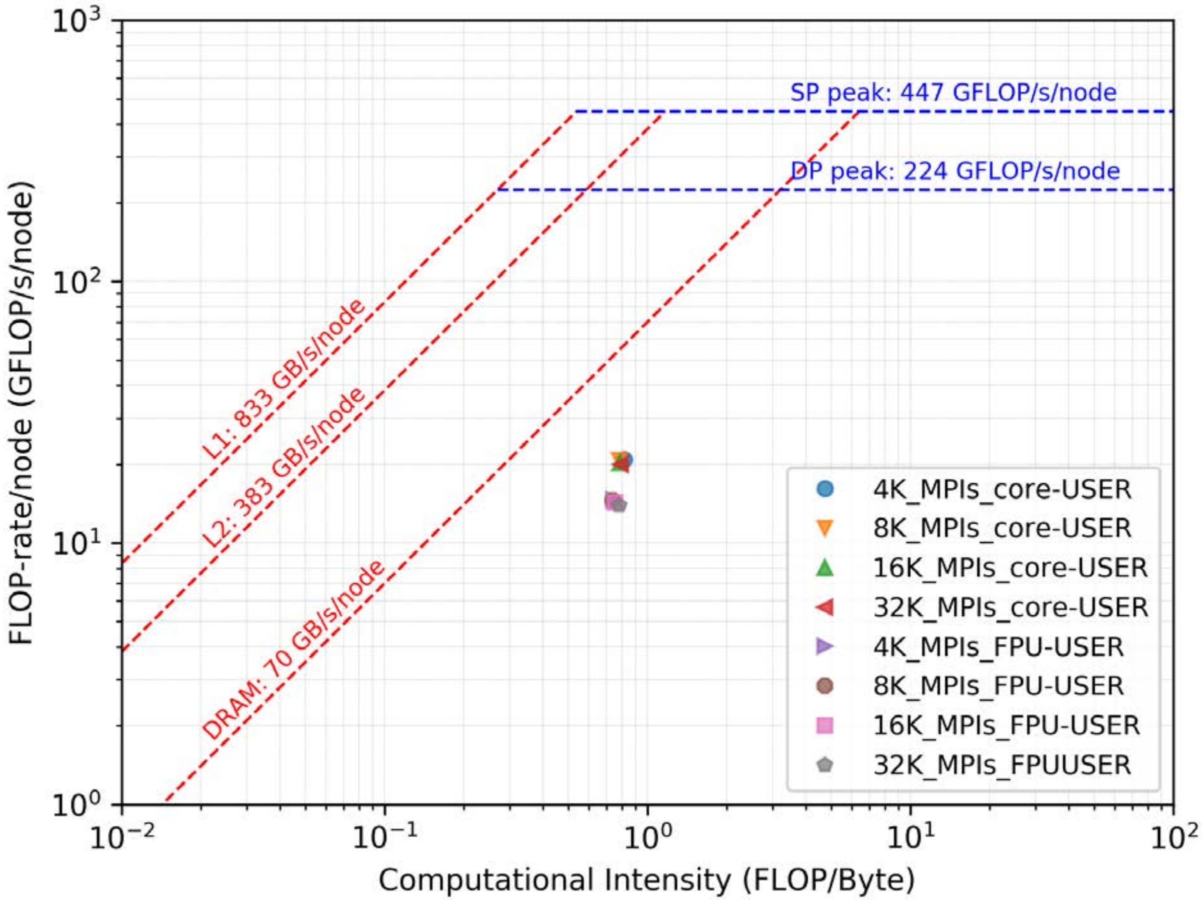
32000 MPIs (FPU)



The testing case is 3200x640x500. The results are based on 100 time steps.

DNS Performance

per-node performance



USER/(WENOX+WENOY+WENOZ+Others)

The testing case is 3200x640x500. The results are based on 100 time steps.

DNS Performance

per-node performance