SAND2016-4085C

Wind Turbine Blade Wall-Resolved Large Eddy Simulation

Trinity Phase 1 Open Science Period

Part 1: Science Time Objectives and Preliminary Findings

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University of Utah PSAAP-2 meeting

May 10th, 2016

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NNSA National Nuclear Security Administration

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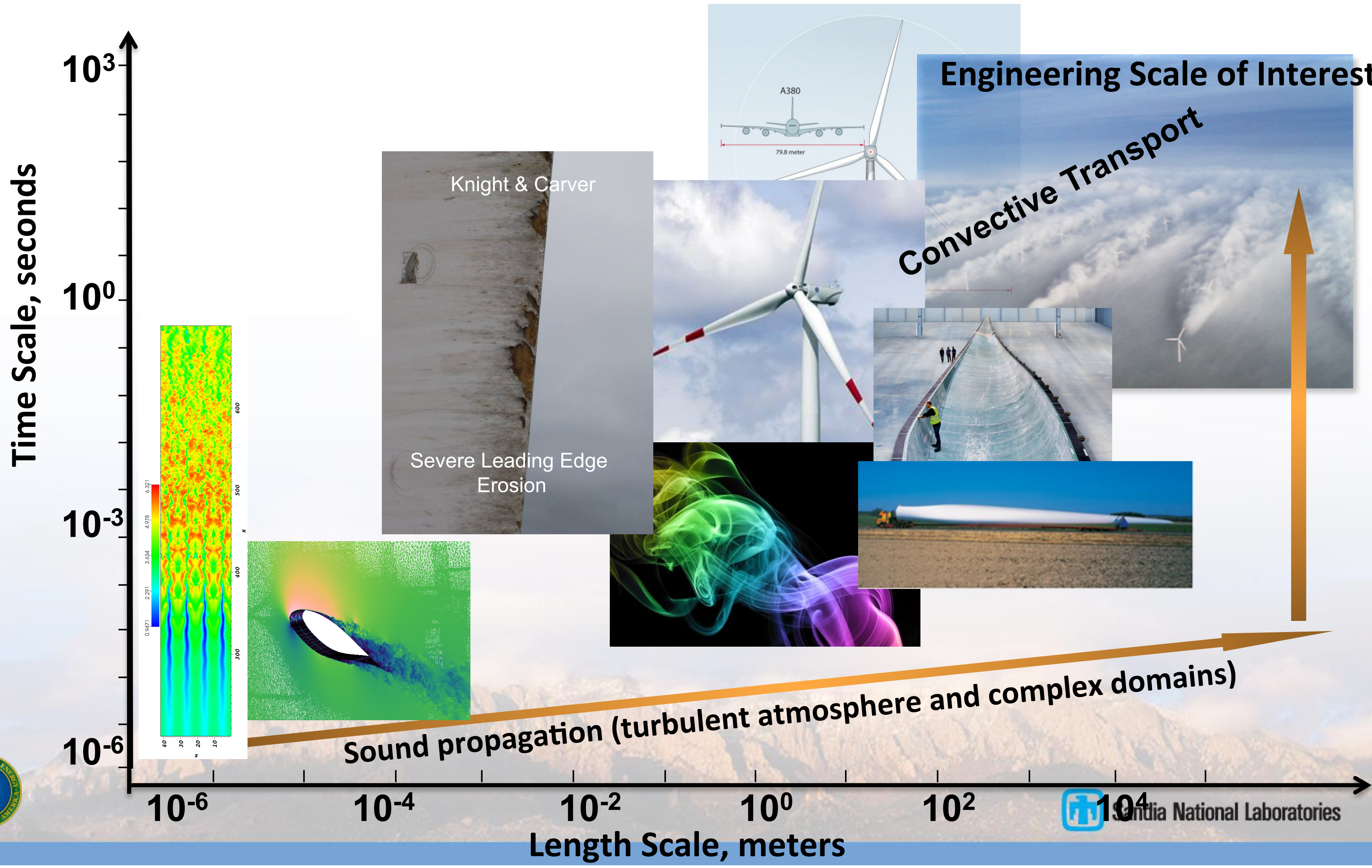
Wind Energy Physics Spans Vast Time and Length Scales



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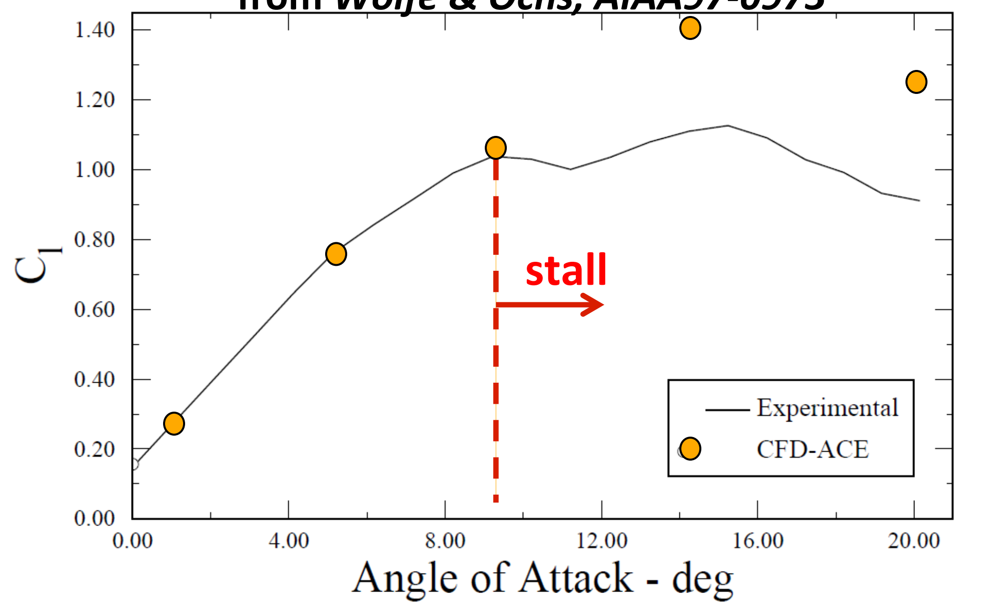
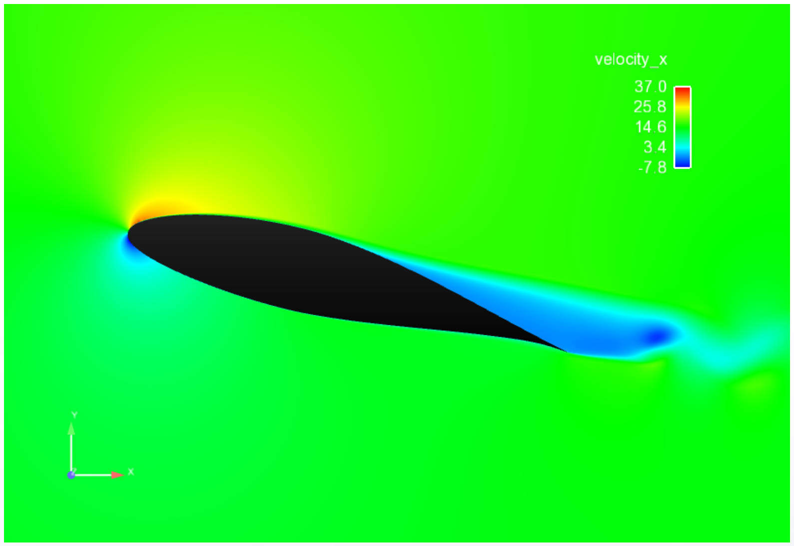
Challenge: Post-stall prediction of airfoil characteristics

Typical 2D RANS prediction of lift, from *Wolfe & Ochs, AIAA97-0973*



Post-stall RANS flowfield, aoa = 15 deg.



- **Problems for RANS models:**
  - Boundary layer transition to turbulence (extra model forms)
  - Issues with strong pressure gradients and smooth BL separation
  - 3D behavior of separated flow

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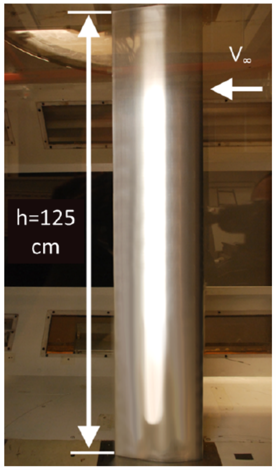
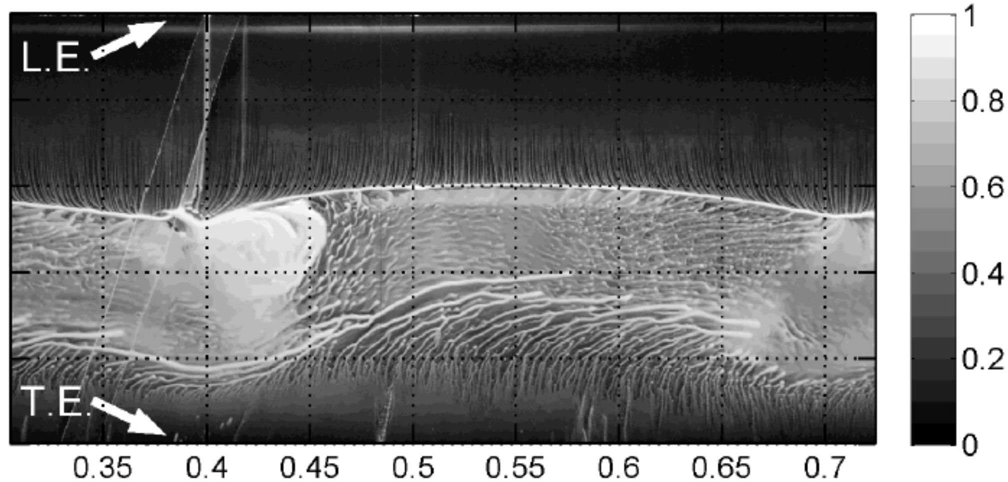
Stall Cells

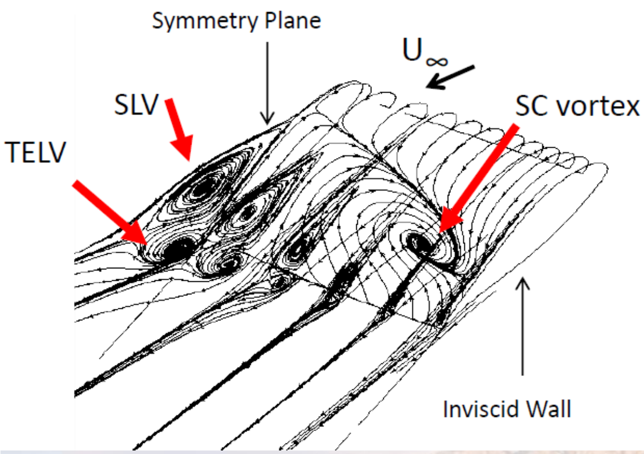


Upper surface of airfoil



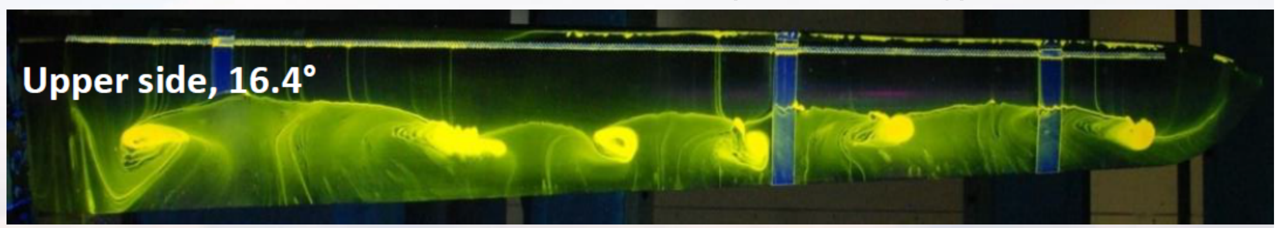
Ragni, 2015

(d) $\alpha = 15\circ$



Manolesos, 2014

Model wind turbine blade (non-rotating)



Boorsma, 2014

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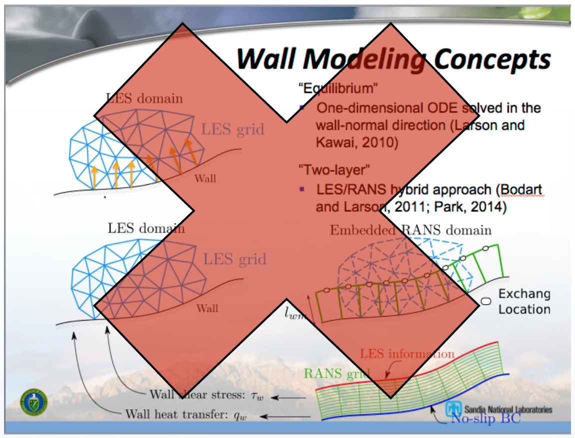
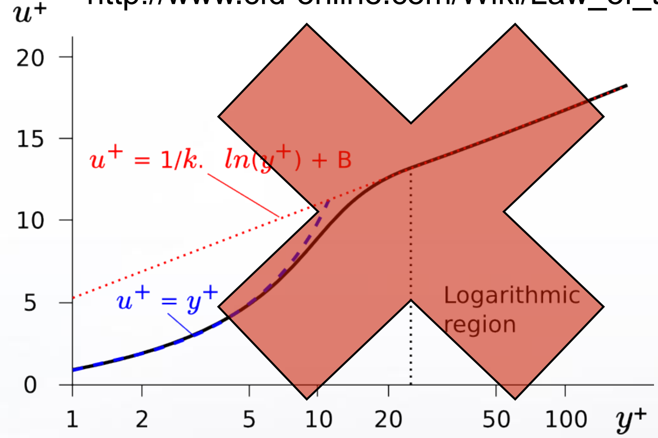
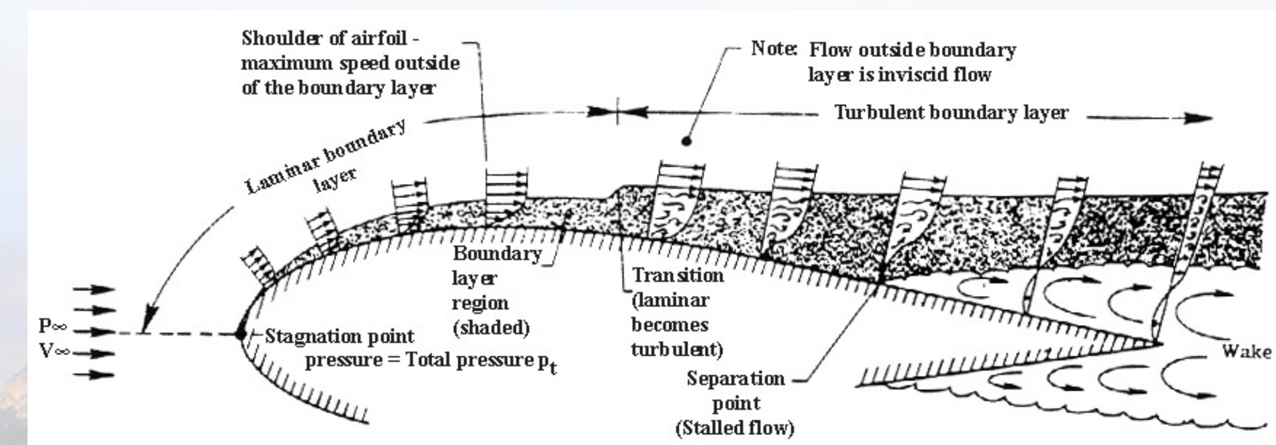
Wall-Resolved LES

- **WRLES neglects wall-function approaches and fully resolves the wall-normal mean shear and important near-wall structures (Dy^{+}~1, Dx^{+}~40, Dz^{+} ~25)**



http://www.cfd-online.com/Wiki/Law_of_the_wall





http://nasa.gov

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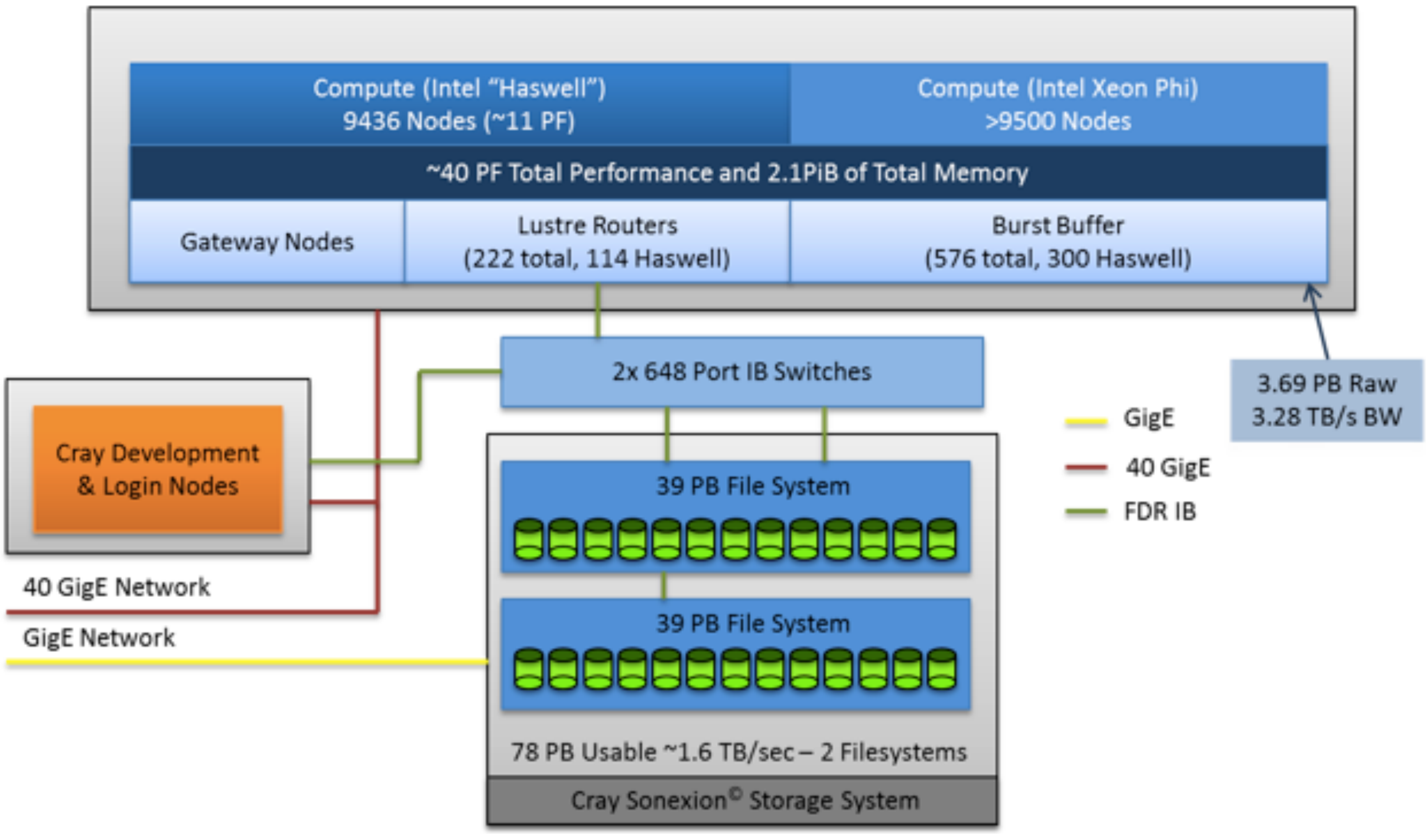
Trinity Open Science Phase 1

- **Objective 1 (wind energy): Use Wall-Resolved Large Eddy Simulation (LES) to predict post-stall performance of a wind turbine airfoil (Re = 1e6, 15 AoA)**

- **Objective 2 (science): Examine the structure of the separated flow region of a stalled airfoil known to exhibit stall cell behavior**

- **Objective 3 (core): Test the parallel and I/O performance of an implicit application code built on the STK and Trilinos infrastructure**

A Note on Trinity

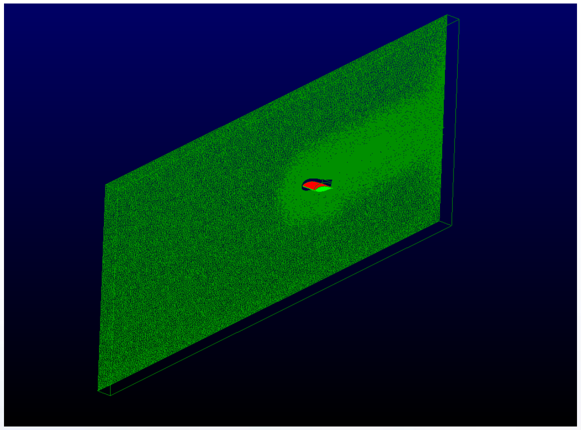


From: Mahesh et al., Performance on Trinity (a Cray XC40) with Acceptance-Applications and Benchmarks; CUG 2016

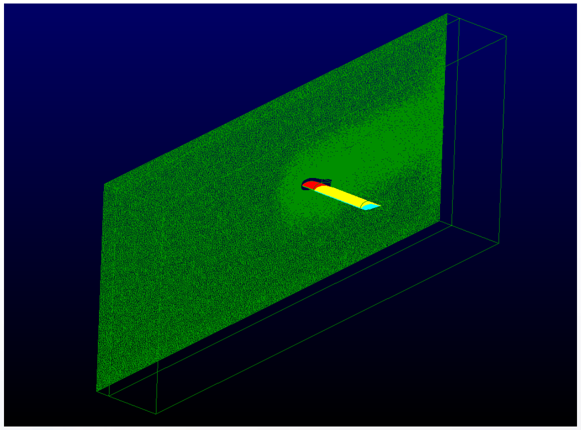
Computational Scale of Interest

- **Goal: Manage mesh size i/o through the usage of compression**

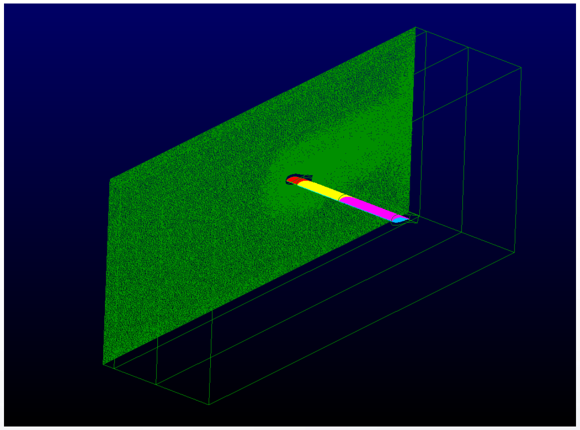
Z = 0.5c: 2000 extrusions
1.4B elements



Z = 2.4c: 9,600 extrusions
6.6B elements



Z = 4.8c: 19,200 extrusions
13.2B elements



- **64bit Gen3D with compression: 13.2B element mesh is stored in 6.1 Gb file (HDF5, ZLib)**
- **Production core counts: 32,768; 65,536; 131,072 (50k elem/core)**

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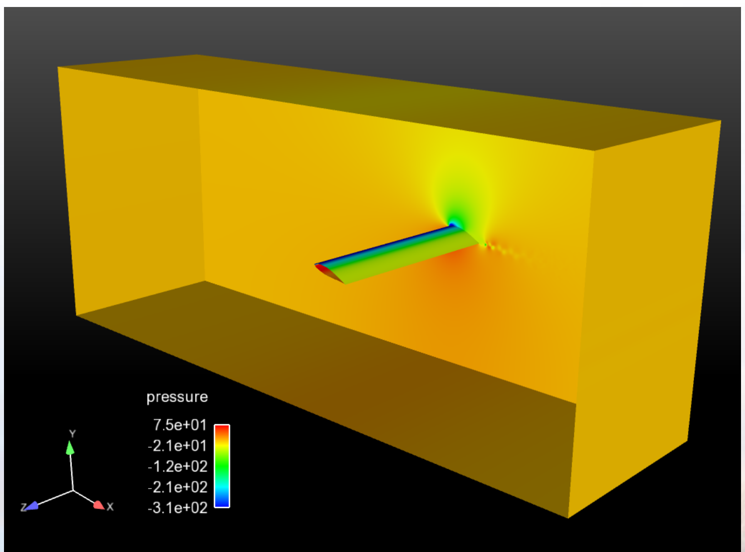
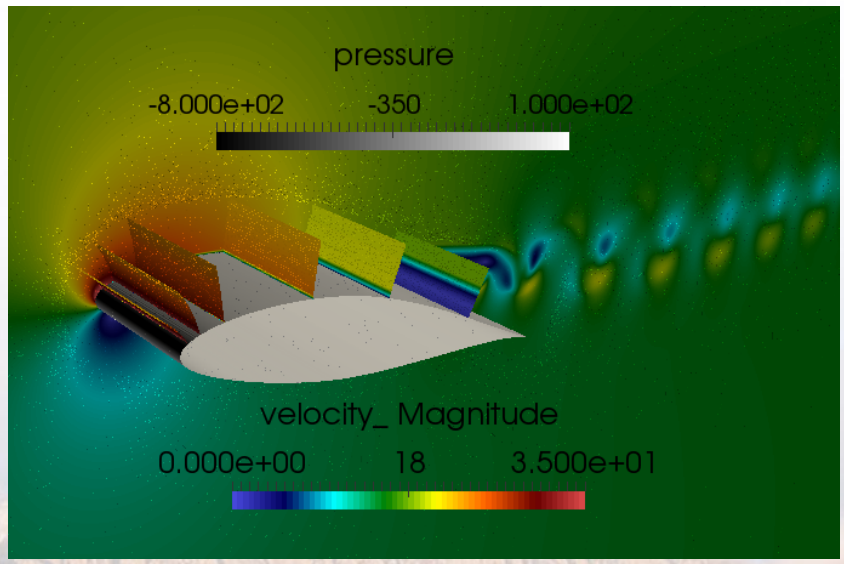
Core: Initial Condition Specification

- **Goal: Transfer quasi-steady RANS solution to LES mesh for IC**
- **Purpose: Greatly reduce initial transient in LES**
  - STK_ghosting, STK_search and STK_transfer

RANS solution on 1-cell-wide mesh



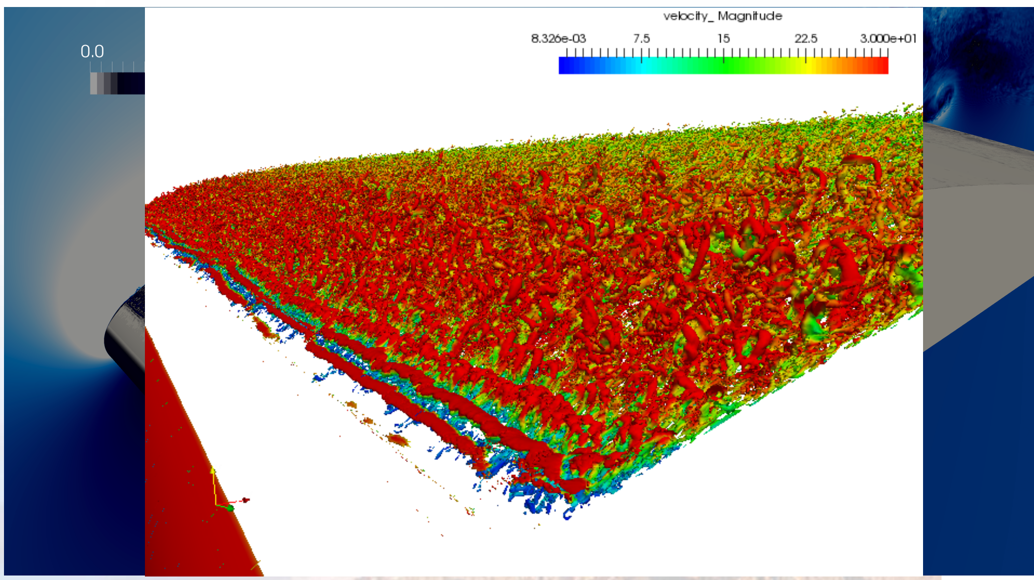
LES mesh IC



Core: Efficient i/o

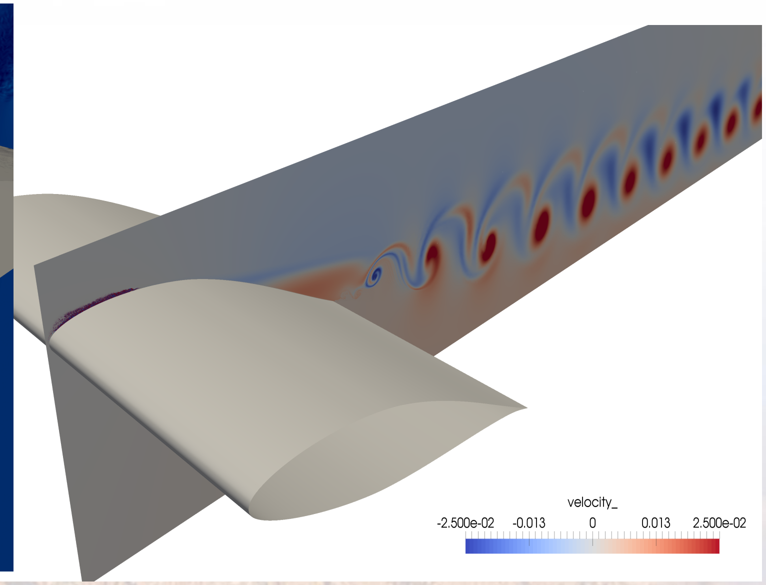
- **Goal: Lightweight output datasets for viz and post-processing; in situ via Catalyst**
- **Transfer full-field solution to user-defined exodus output surfaces**
  - STK_ghosting, STK_search and STK_transfer

Exodus database of output surfaces



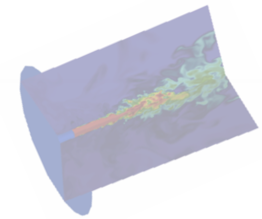
Instantaneous velocity field

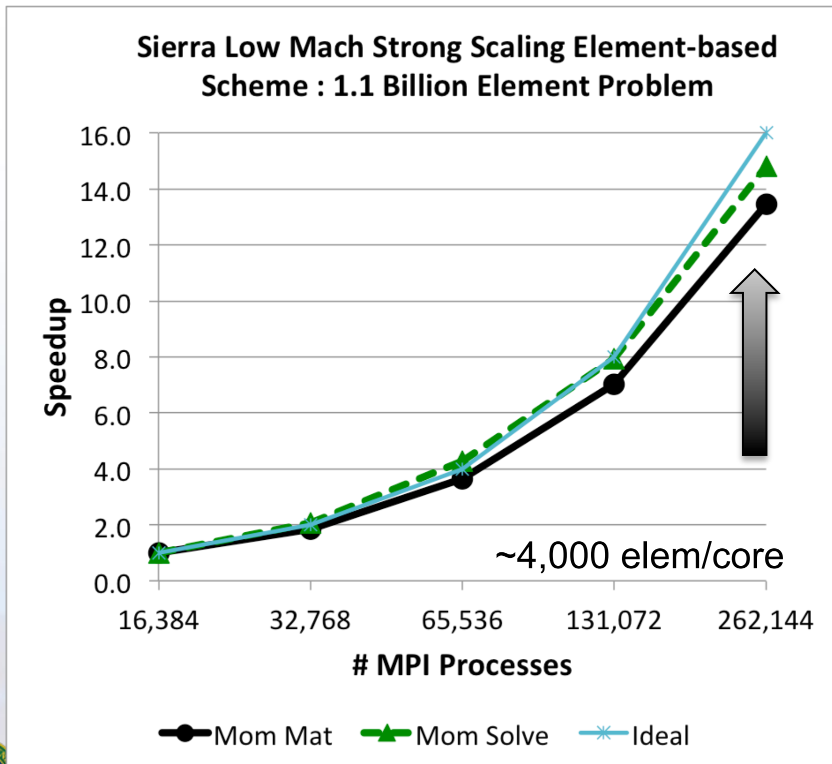
In situ output using Catalyst

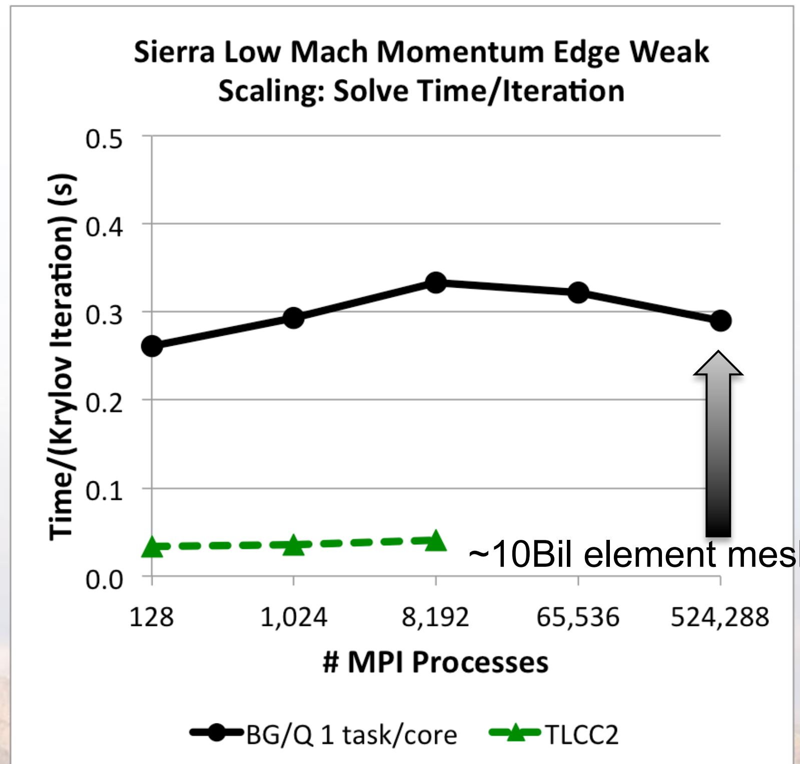


Core: Solver Performance

- **Background: Scaling studies performed as part of Trinity**
  - Phase 1 Acceptance has been idealized (user perspective)
- **Goal: Capture performance based on a *real* analysis effort**







Prediction of fully implicit low Mach turbulent round jet (Sequoia)

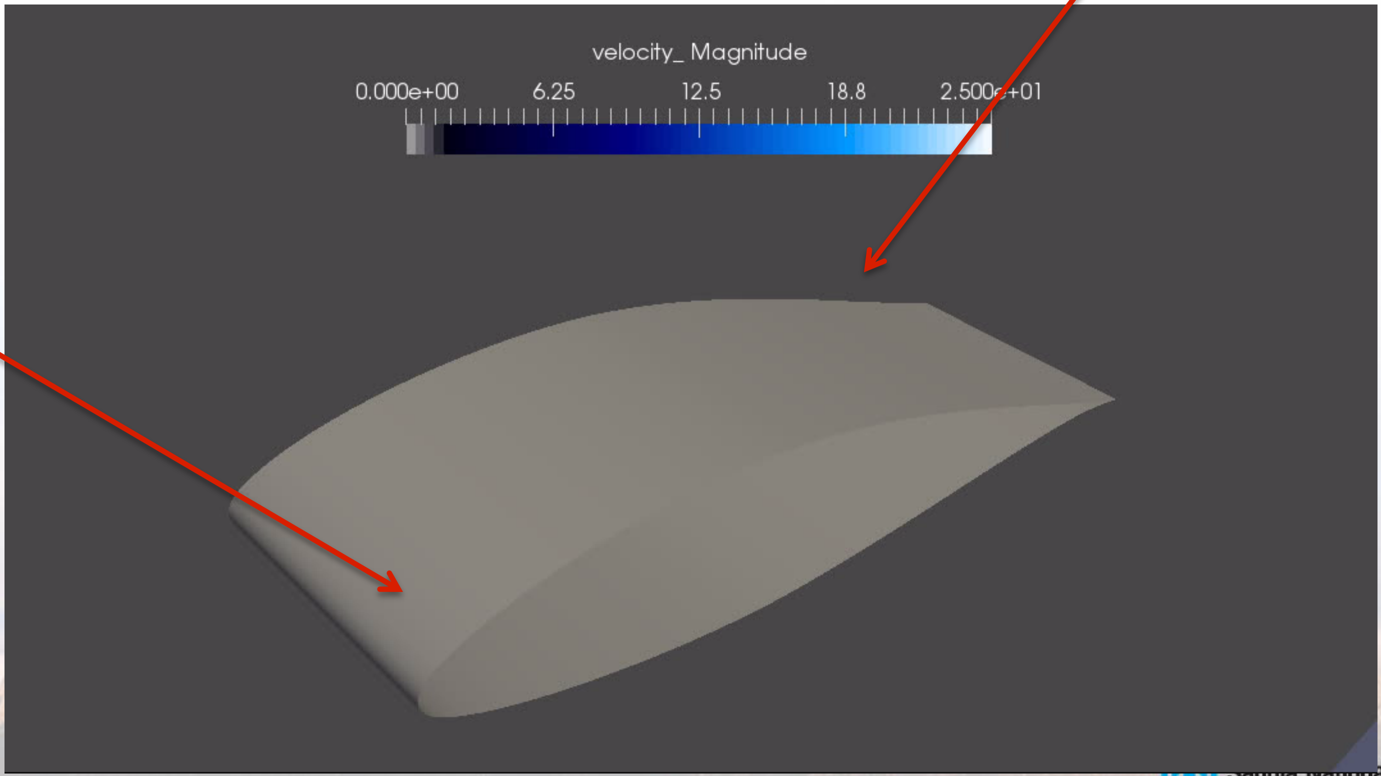
Lin *et al*. Parallel Processing Letters, 2014; Strong ASC investments in STK and Trilinos

Preliminary Result; Transition and Separation

- **Successful massively parallel analysis on mesh sizes ranging from 1.6 to 6.4 *billion* computational elements on ~32,000 to ~135,000 core counts with newly prototyped *in situ* visualization (35 million CPU)**

Capture of detail of near-surface turbulence on tens of microns scale

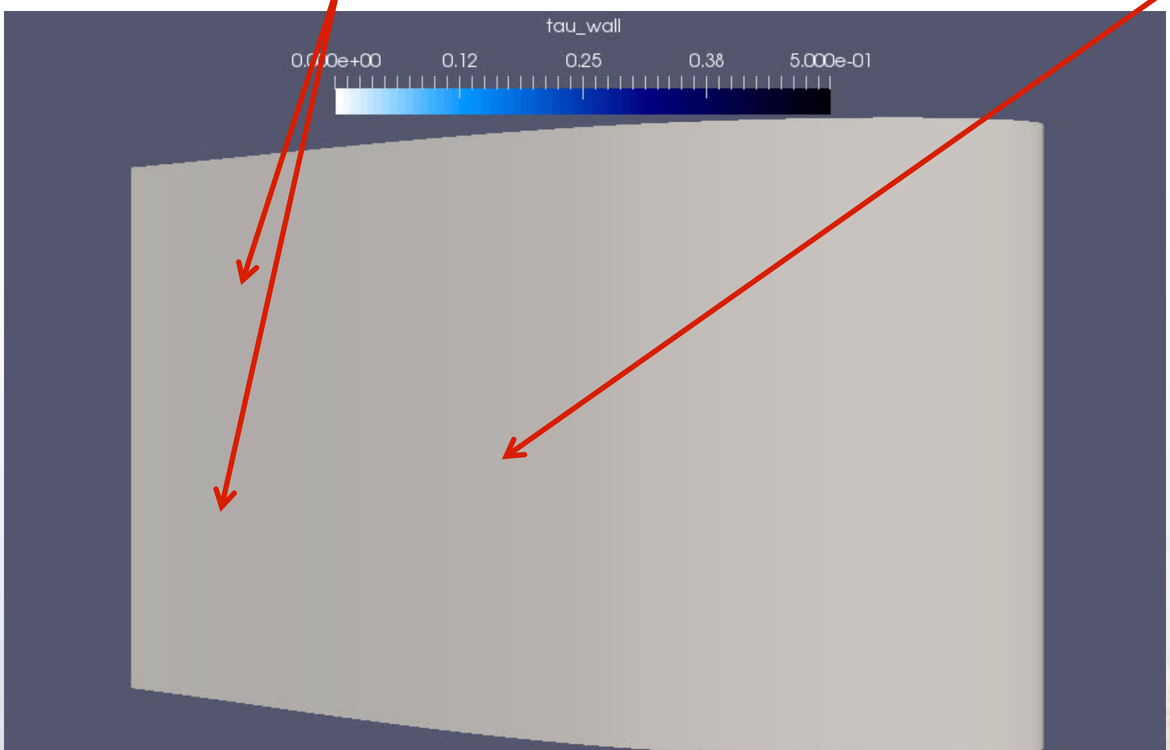
Boundary layer separation and resulting thick airfoil wake



Preliminary Result; Possible Stall Cell Formation

Evidence of 3D "stall cell" structure

Beginning of separated flow region

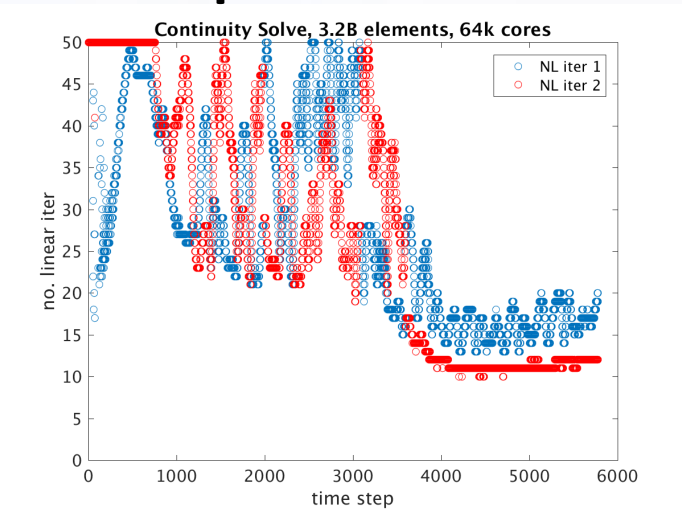


Flow

We require ~4 million CPU hours more for proper statistics…

Preliminary Result; Solver Performance

- **Production runs at ~50k elem/core; novel P=1 CVFEM/EBVC**
  - O(5) seconds per time step
  - O(100,000) time steps (after transient IC, O(4) flow through times)
- **Trilinos Momentum solver performance was, as expected, ideal; monolithic momentum solve required O(5) linear iterations**
- **Trilinos Muelu Continuity solver plateau around 15 linear iterations per linear solve after start-up**



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Conclusions

- **Does the underlying ASC infrastructure (STK and Trilinos) support state-of-the-art wind energy analysis? Yes!**
  - Successful production analysis using the ASC infrastructure (STK and Trilinos) on mesh sizes ranging from 1.6 to 6.4 billion elements on 32,000 to 130,000 core counts with newly prototyped *in situ* I/O (35 million CPU hours!) (bottlenecks)
- **Can high fidelity WRLES be used to predict airfoil post-stall performance? Yes!**
  - Lift and drag predicted using high-fidelity WRLES on complex turbine configurations
- **Can the complex turbulent structure of the separated region of stall known to exhibit stall cells be observed? Very possibly yes!**
  - Possible evidence of stall cells (complex three-dimensional turbulent structures) noted in the production simulations; more flow through times for converged statistics required in addition to full volume rendered viz