RECENT DEVELOPMENTS FOR THE EDDY SOLVER

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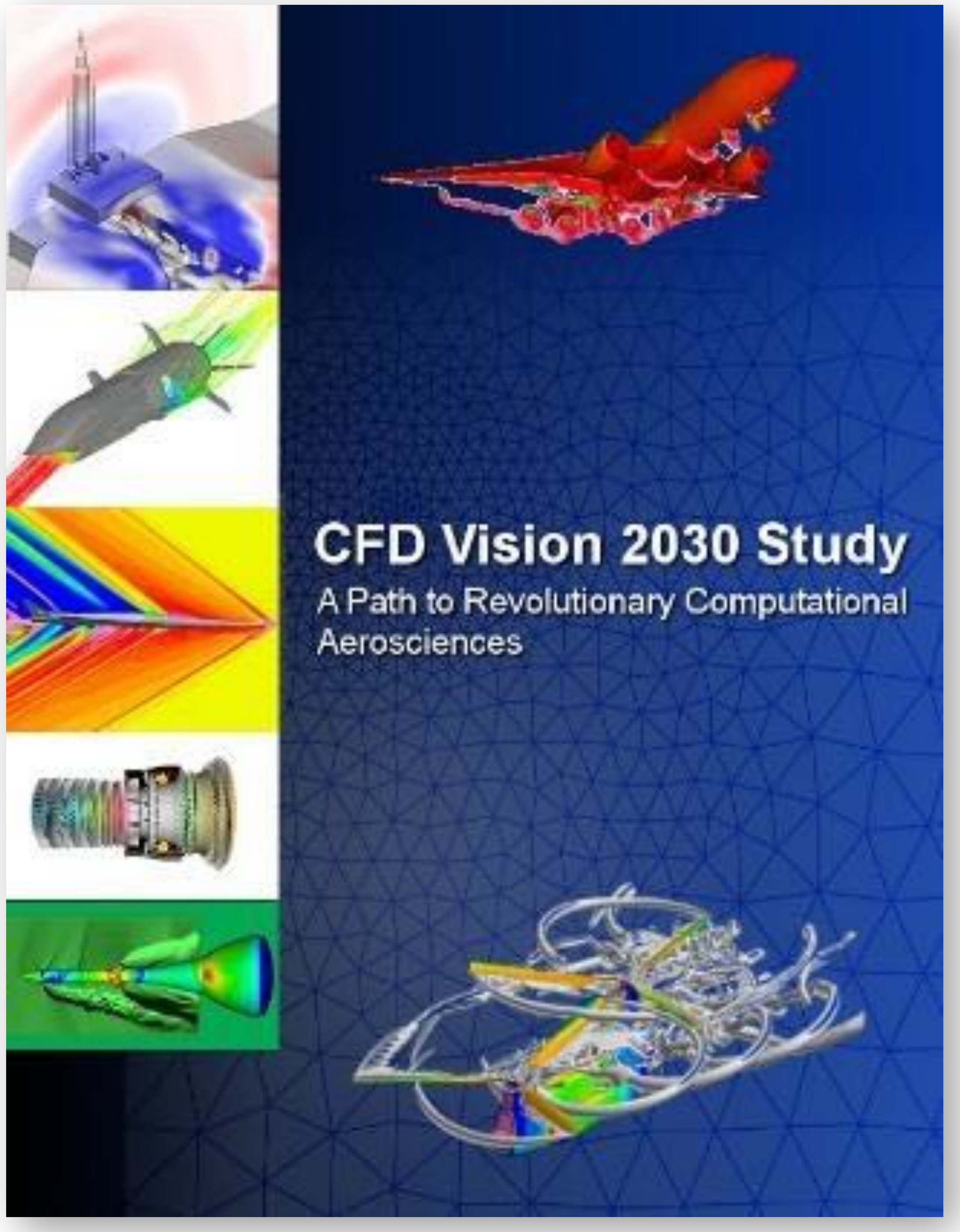
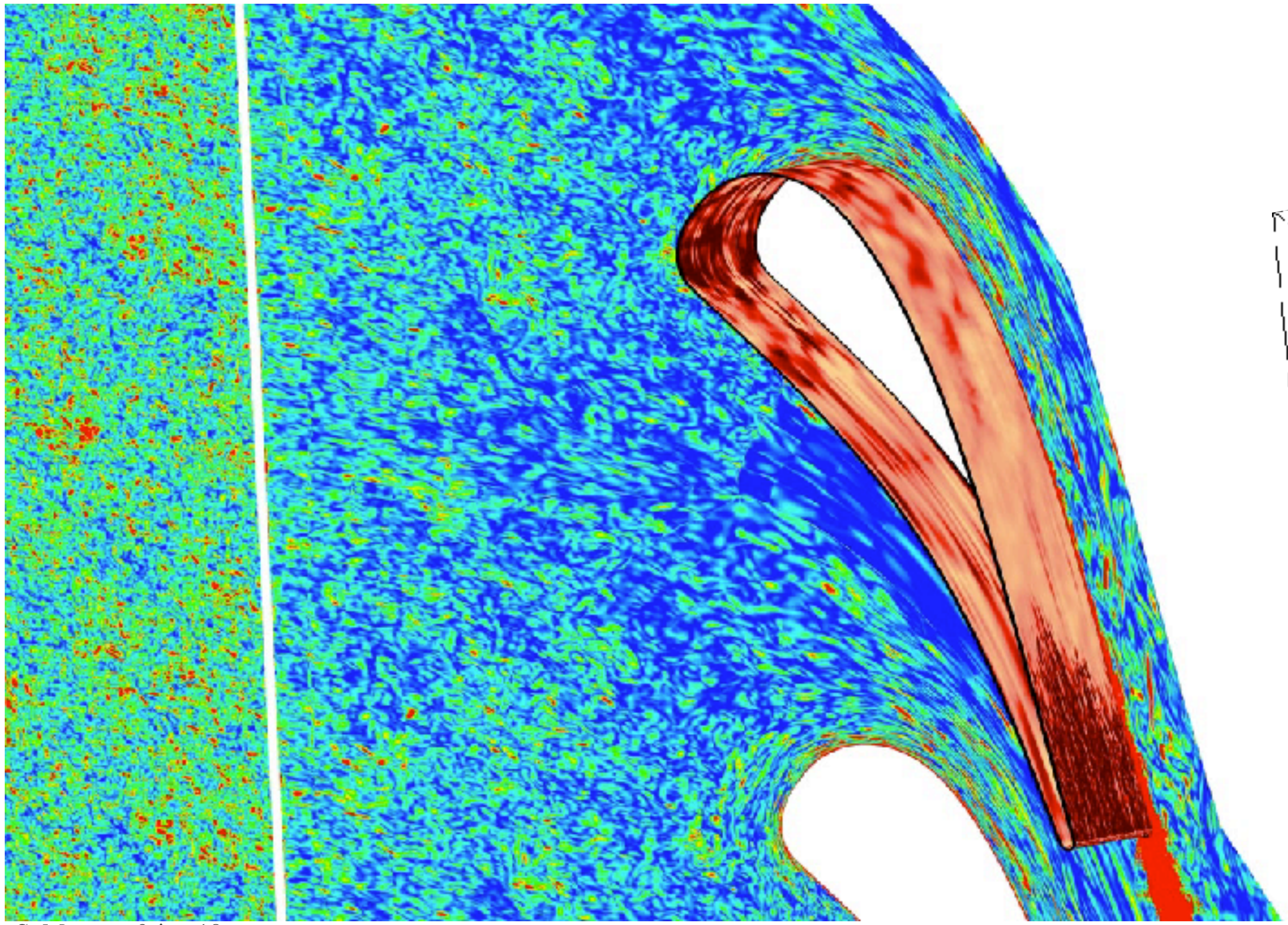
Background

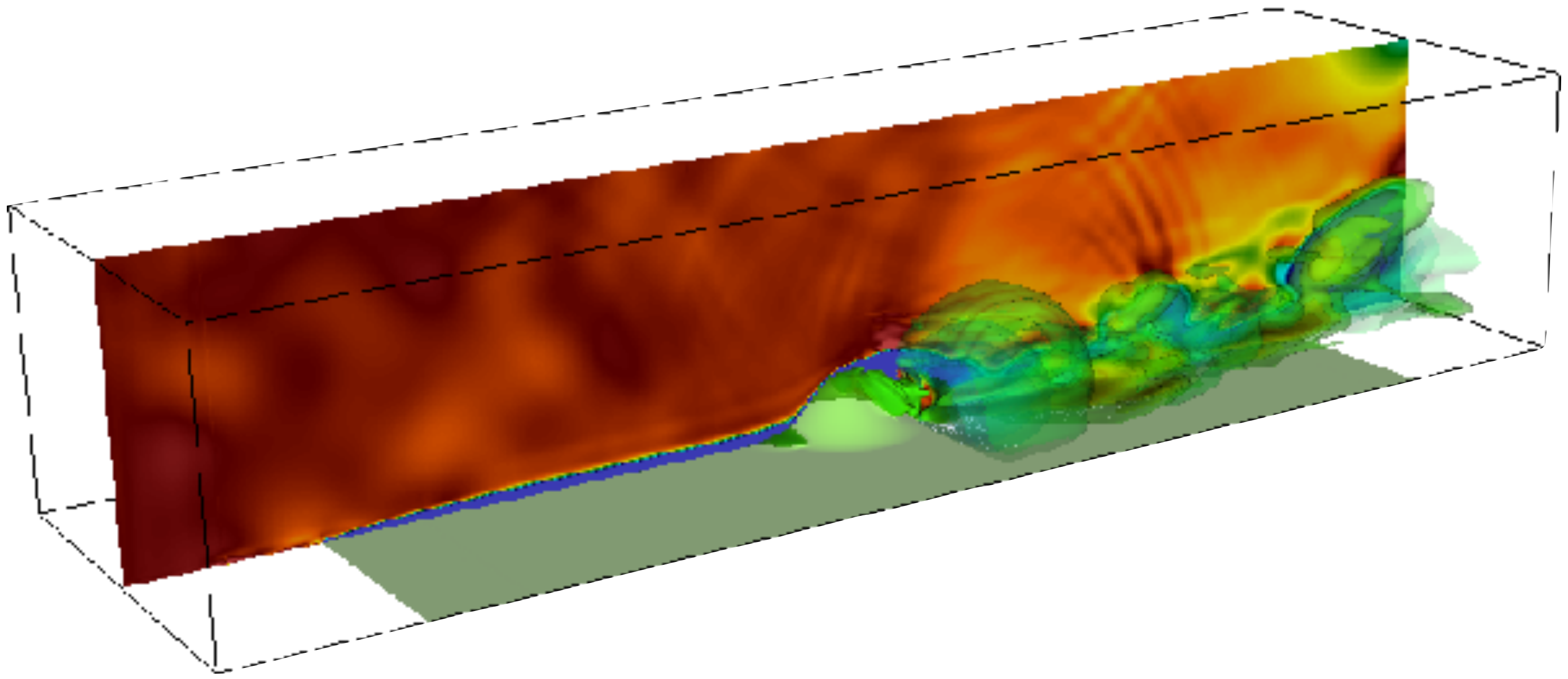
- NASA CFD living off R&D investment from previous generation
  - Steady-state, complex geometry
- Internal/external advocacy for new tools restarted fundamental R&D
  - Primarily numerical methods, turbulence modeling to-date
- Use exascale computing to open new possibilities
  - Certification by simulation
  - Multi-disciplinary, multi-physics, robust error estimates, …



Background

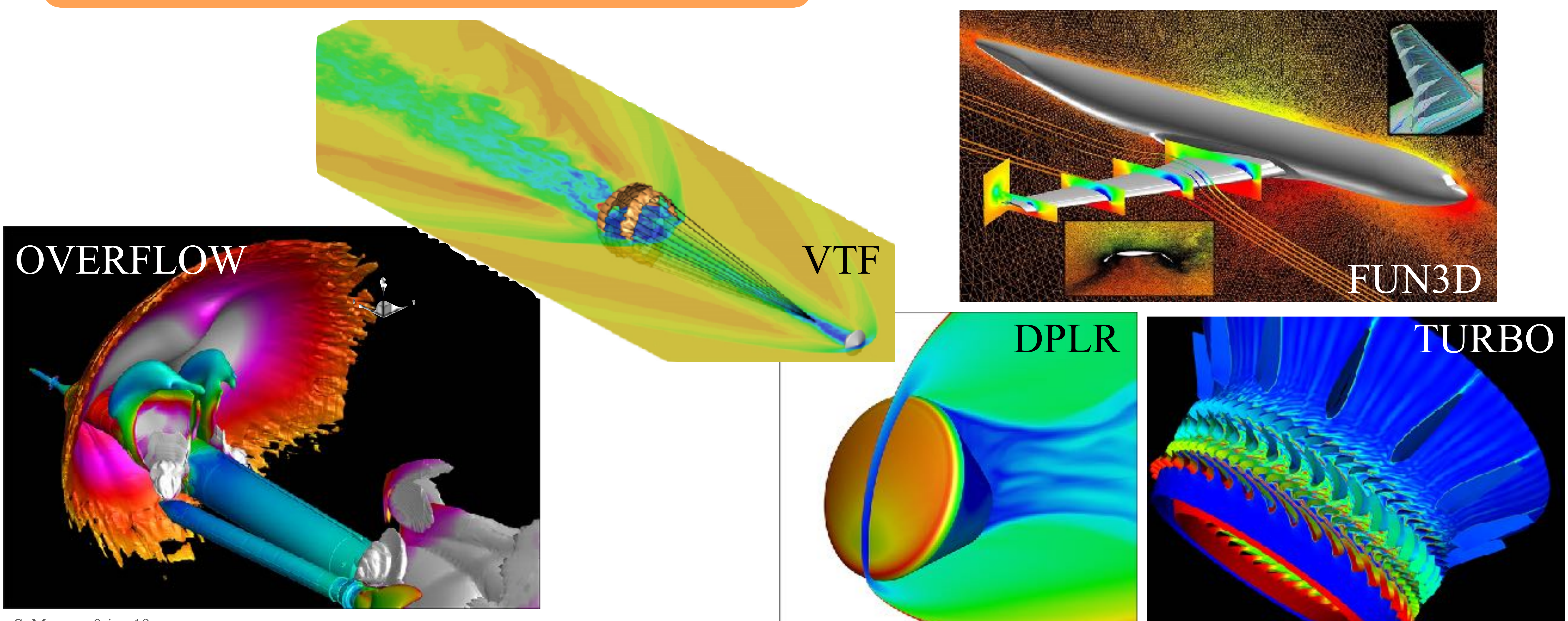
- Our group developing DG spectral-element capability for scale-resolving simulations of separated flows over the past few years
- Infrastructure known as the eddy solver
- Provide overview of goals and technical approach
  - Fill in material not presented at AIAA





Target Applications

- Complex geometry - unstructured mesh
- Complex physics - scale-resolving methods
- High-Re, combustion, chemistry - fully implicit methods
- Computational intensive - high-order, adaptive methods
- Multi-disciplinary, multi-physics - robust, extensible methods



Diagonalized ADI Preconditioner

- Matrix-free, Newton-Krylov solver, tensor-product

Upwind Jacobian

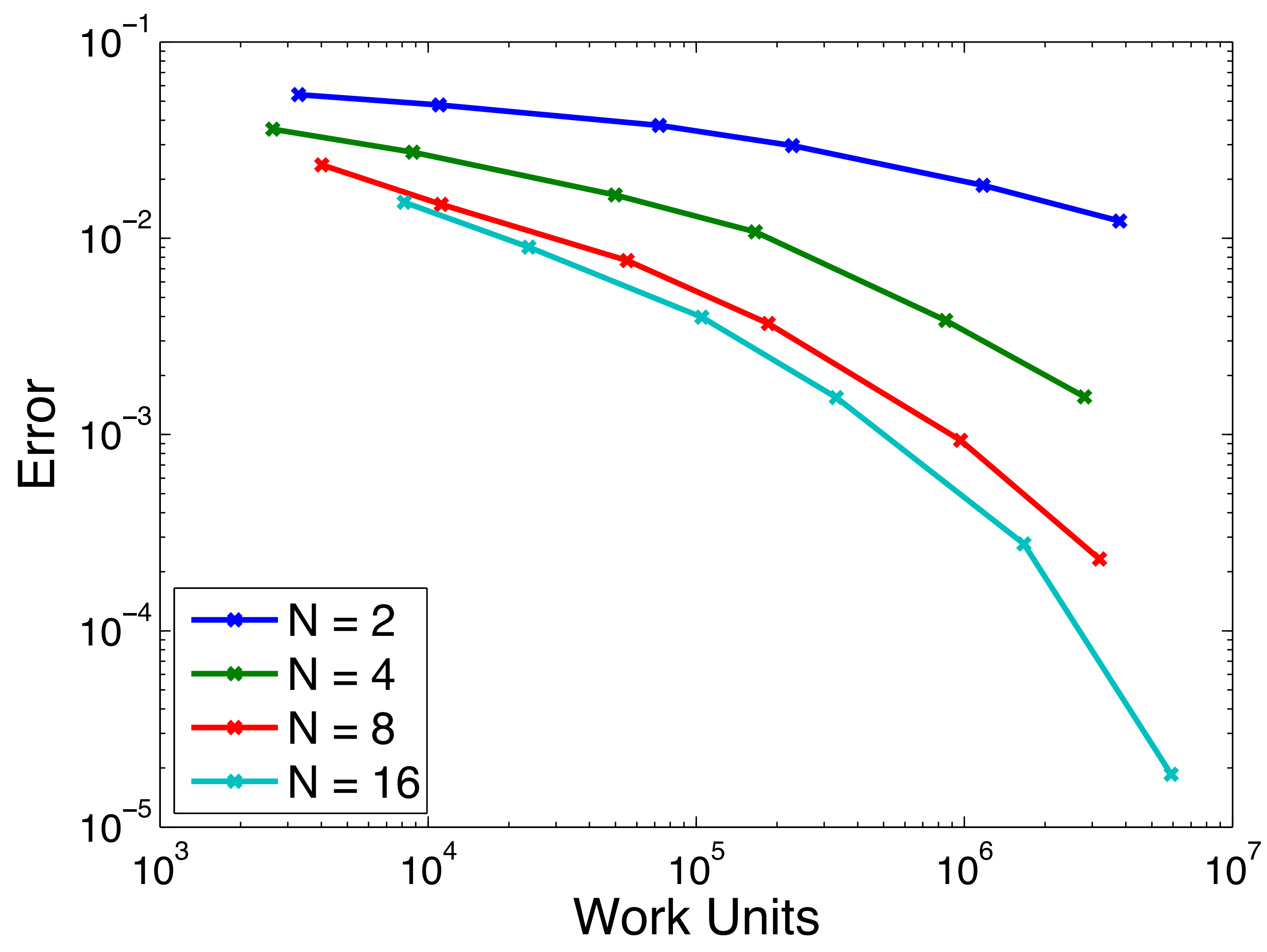
$$A = (D_x^+ \otimes I \otimes A_x^+) + (D_x^- \otimes I \otimes A_x^-) + (D_y^+ \otimes I \otimes A_y^+) + (D_y^- \otimes I \otimes A_y^-)$$

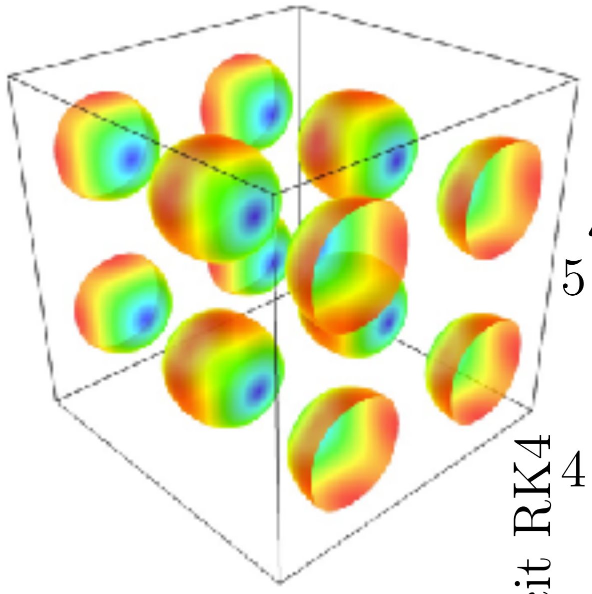
Transform to characteristic variables and factor

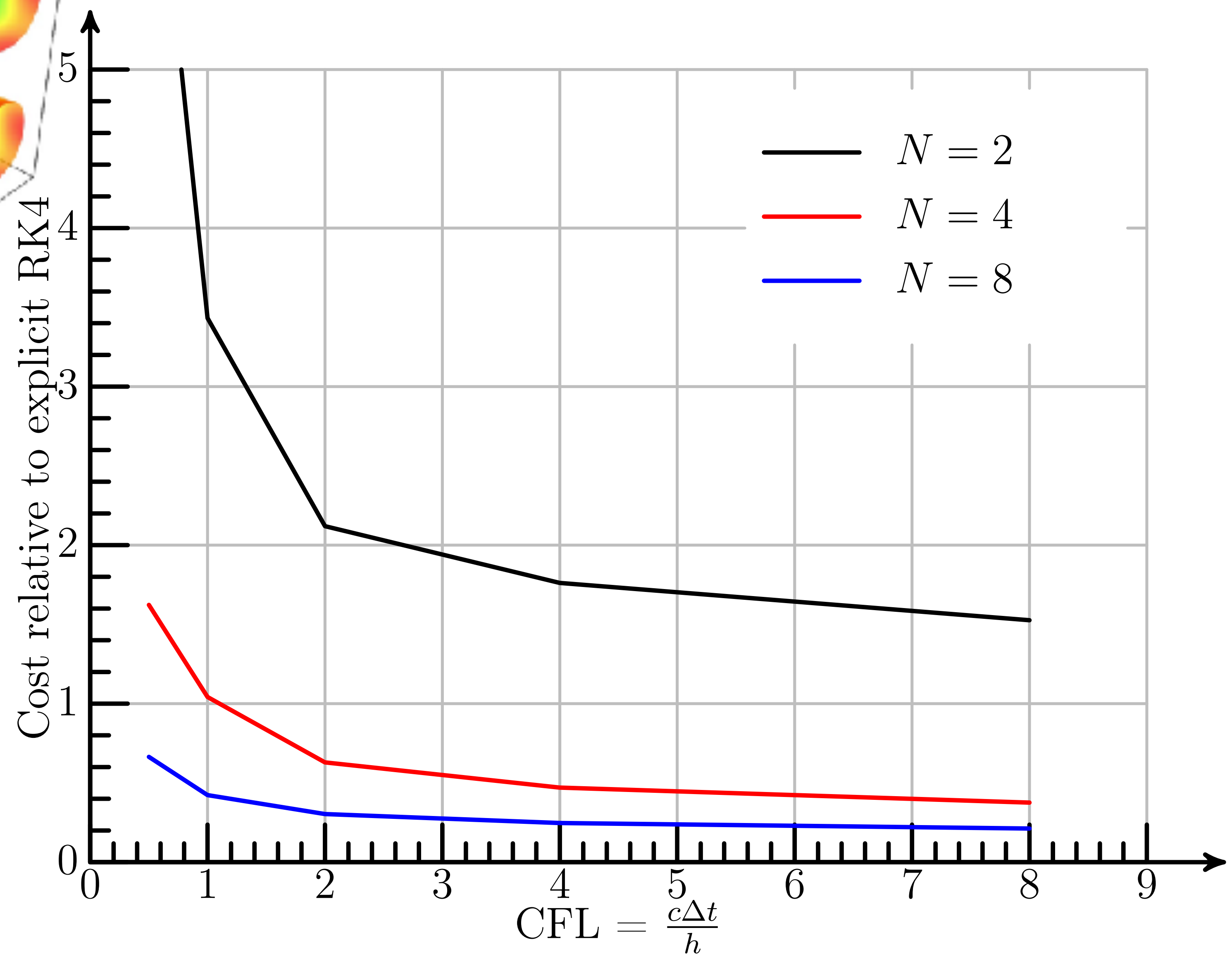
$$\begin{aligned} A = &(I \otimes I \otimes R_x)((D_x^+ \otimes I \otimes \Lambda_x^+) + (D_x^- \otimes I \otimes \Lambda_x^-))(I \otimes I \otimes R_x^T) \\ &+(I \otimes I \otimes R_y)((D_y^+ \otimes I \otimes \Lambda_y^+) + (D_y^- \otimes I \otimes \Lambda_y^-))(I \otimes I \otimes R_y^T) \end{aligned}$$

- Can be simplified using mean speed over element
- Approximate solve using 1D scalar problems in each direction
  - Convert to characteristic variables in X
  - Solve 5 1D scalar problems along lines in X
  - Repeat for Y, Z
- Solve is dominant cost - use optimized matrix-matrix operations

Implicit Performance





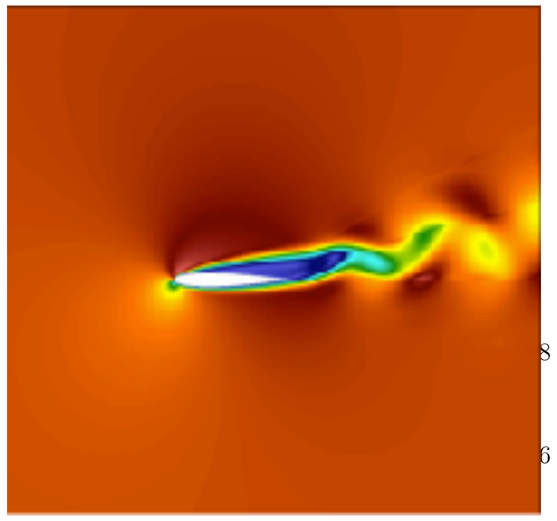


- Same memory usage and better efficiency than explicit scheme
- Implicit enables full space-time entropy-stable formulation
- Current multi-physics work extending to monolithic framework

AIAA 2013-2870, JCP Vol. 330

Turbulence Gradients

- Many groups following similar paths to develop scale-resolving capability
- In order to meet goals need reliable/robust/general methods to calculate gradients
  - Adjoint methods for error estimation, adaptation, design, …
- Turbulence is inherently chaotic and hard to model



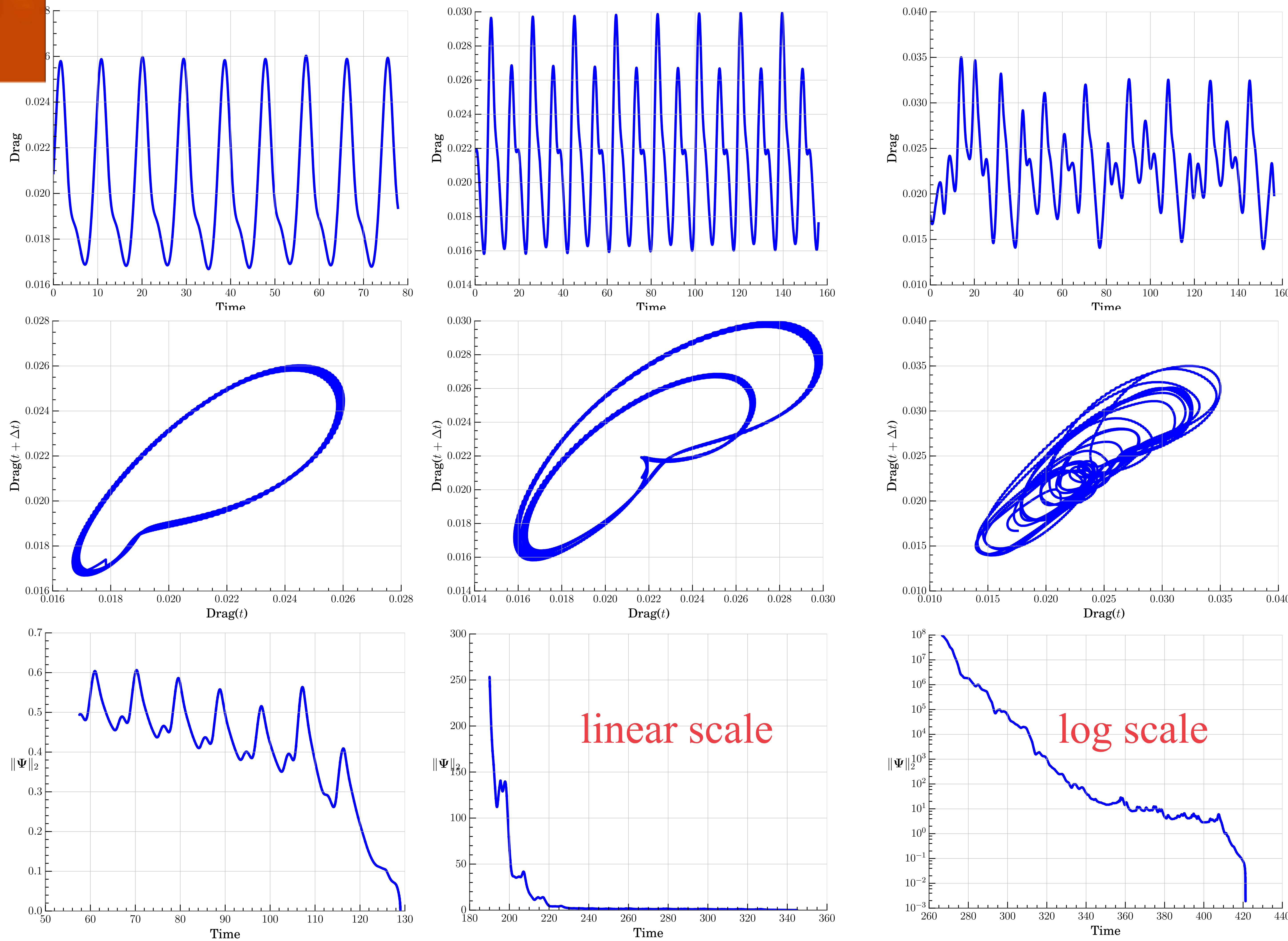
NACA 0012 Ma=0.2, α = 20°

Re=800 | Re=1600 | Re=2400

Time

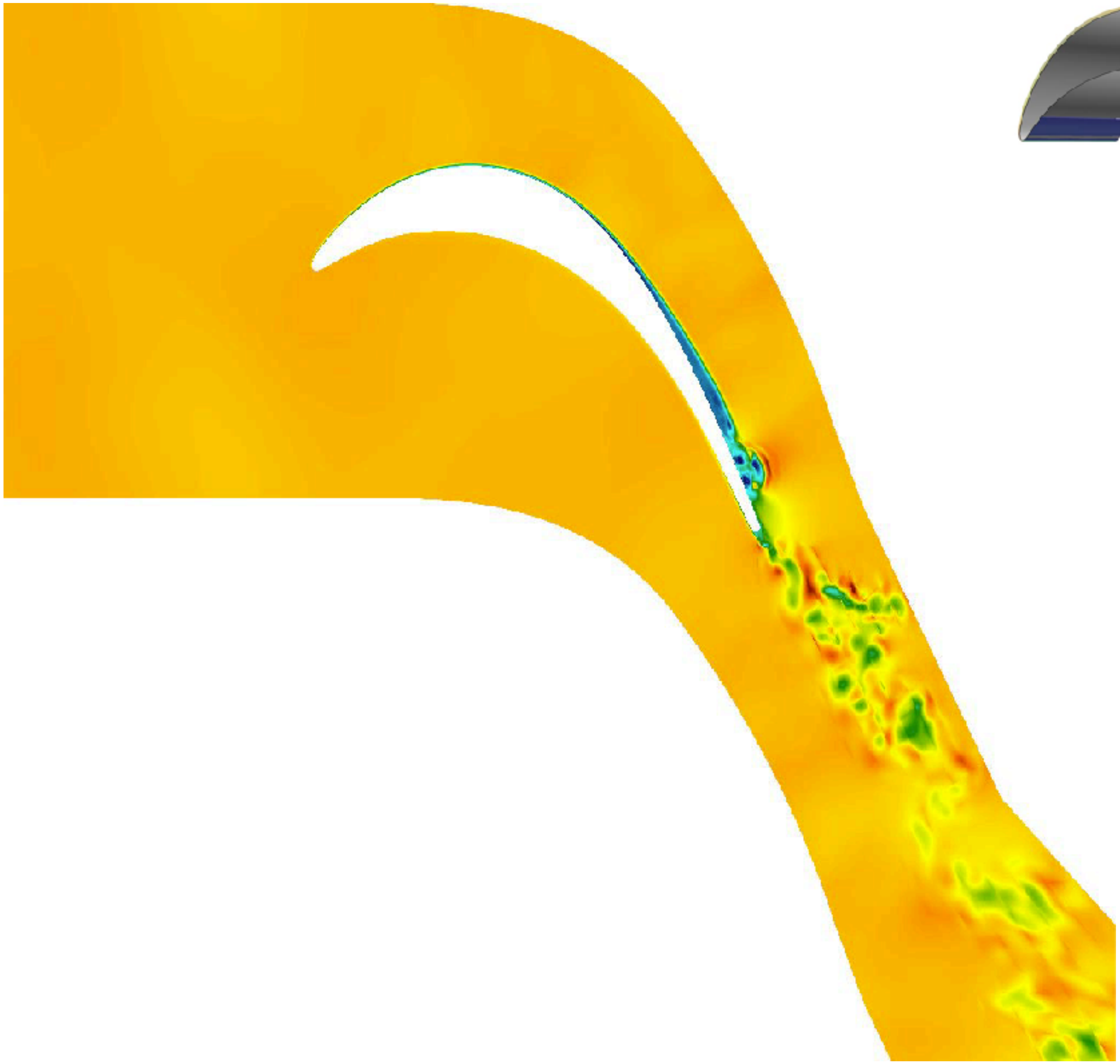
Phase

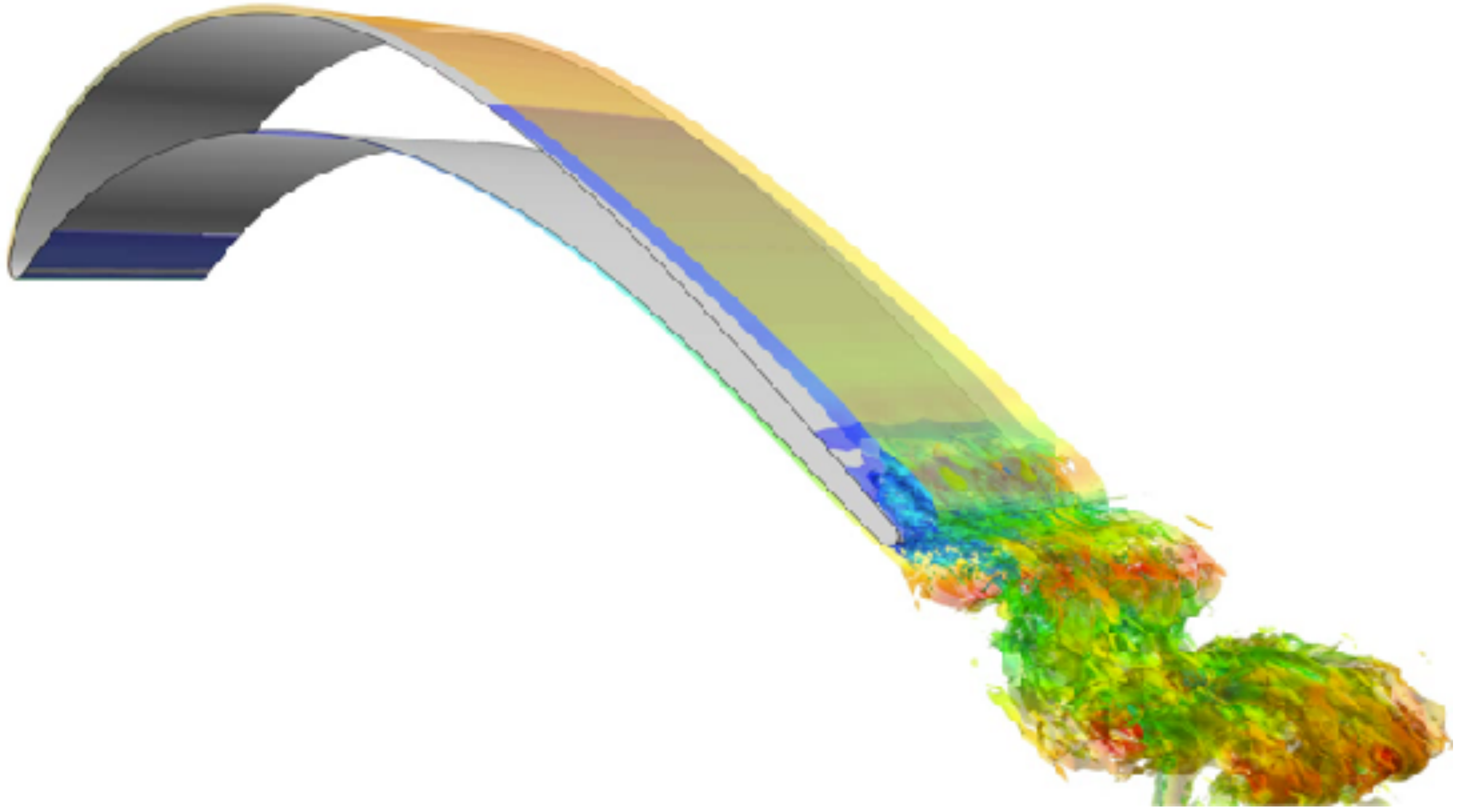
Adjoint



T106 Low Pressure Turbine

Re = 80,000, Min = 0.243, α = 32.7, Mout = 0.65

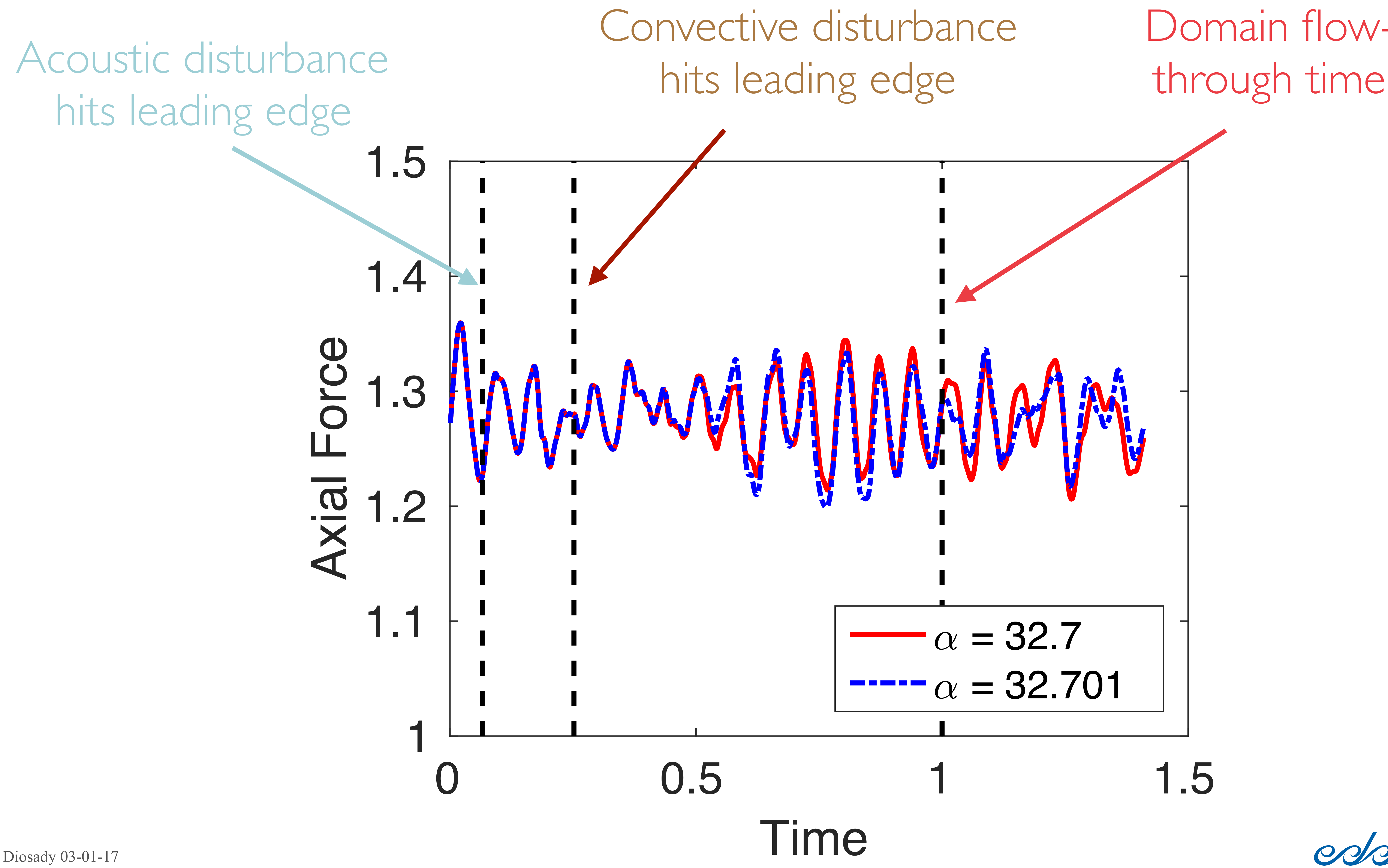




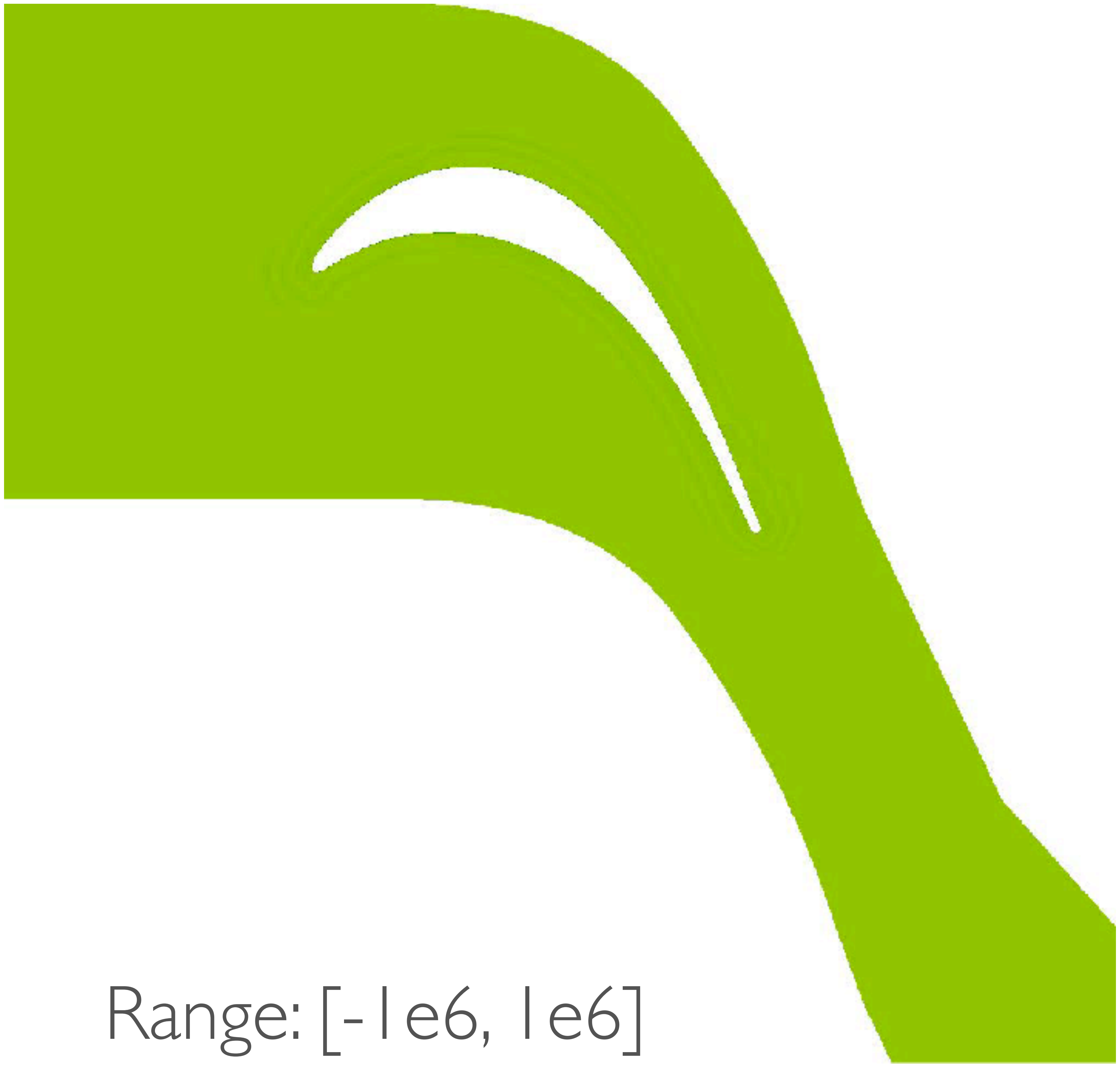
- DNS - assume minimal modeling errors
- Separation leading to transition/vortex shedding on suction-side of blade
- Fully turbulent wake

Sensitivity to Inflow Boundary Condition

- Modify inlet flow angle from α = 32.7 to α = 32.701



Adjoint of mean Axial Force



Range: [-1e6, 1e6]

$$\bar{J} = \frac{1}{T}\int_0^T F_x(u(\tau))d\tau$$

- Output is integrated axial force

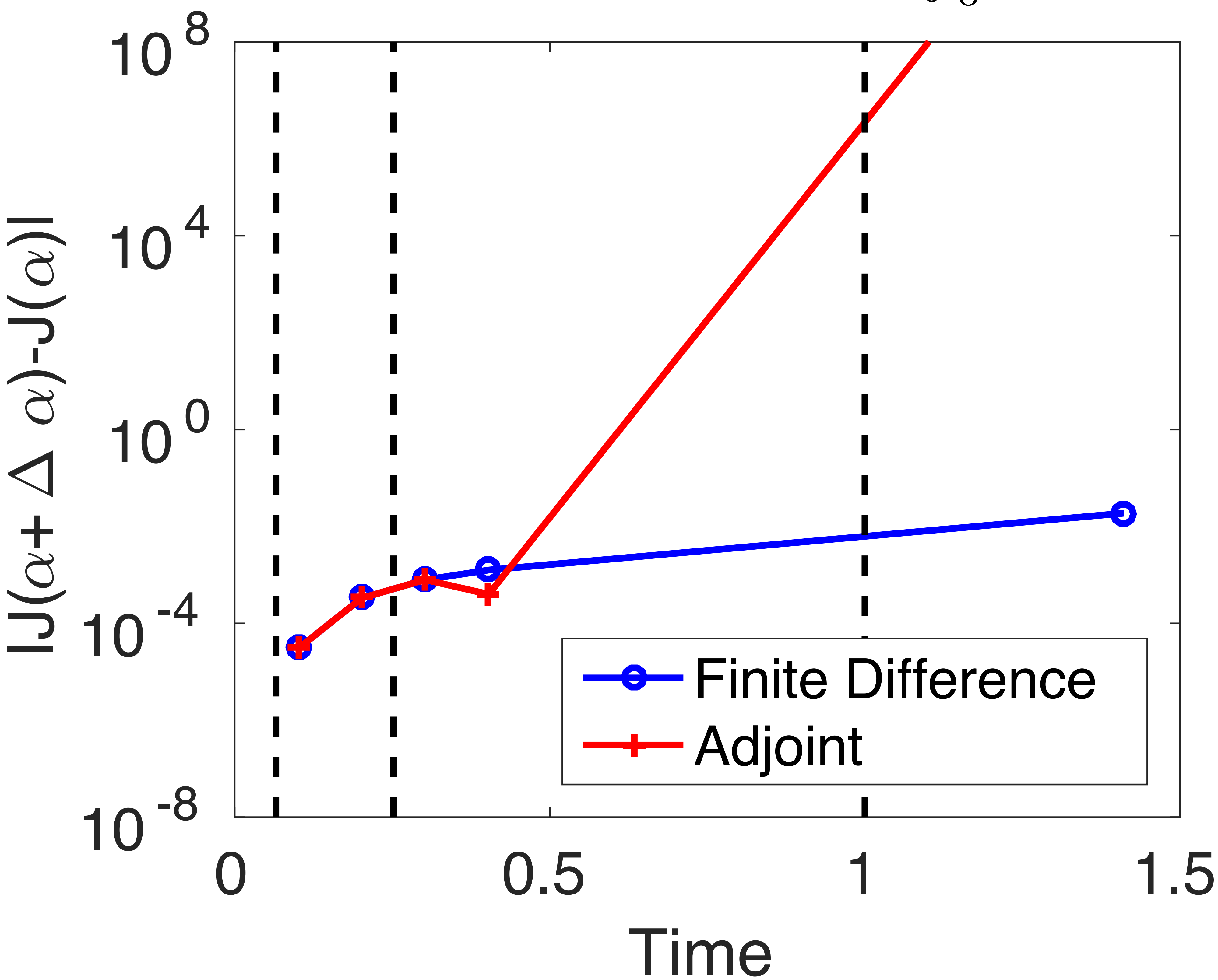
$$J(t) = \int_0^t F_x(u(\tau))d\tau$$

- Also define output without temporal normalization

Sensitivity computed using adjoint

$$\Delta J(t) = J(t;\alpha + \Delta\alpha) - J(t;\alpha) = \int_0^t F_x(u(\tau;\alpha + \Delta\alpha)) - F_x(u(\tau;\alpha))d\tau$$

$$\approx \int_0^t \Psi(\tau;t,\alpha)^T R(u(\tau);\alpha + \Delta\alpha)$$



- Sensitivity computed using adjoint only valid for very short time windows
- Adjoint computed using long time window blows up
- Sensitivity computed using short time window, not representative long time behavior

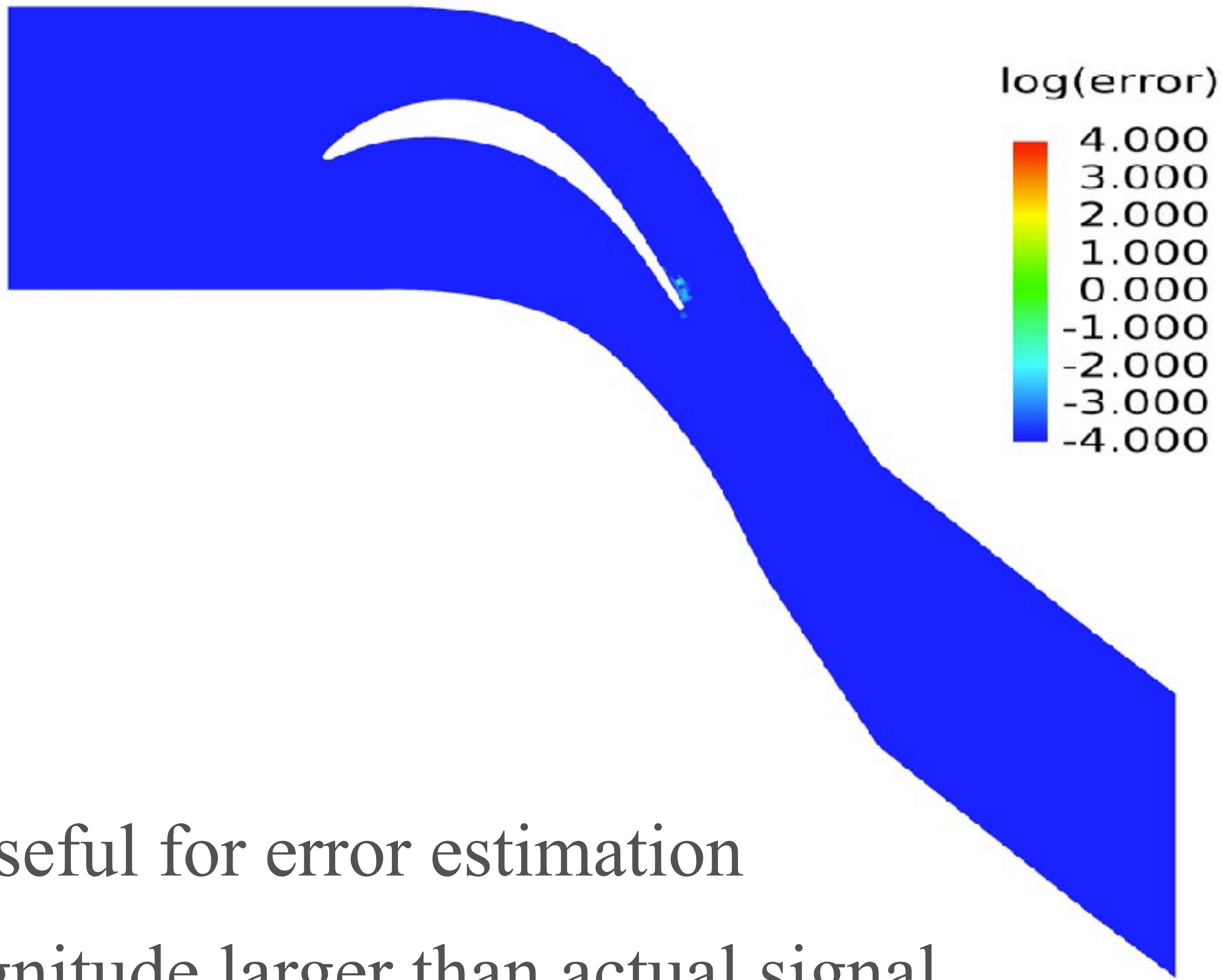
Adjoint-based error indicator

- Estimate error using dual-weighted residual method (Becker & Rannacher 1995)

$$\epsilon = J(u) - J(u_H) \approx R_H(u_H, \psi_h)$$

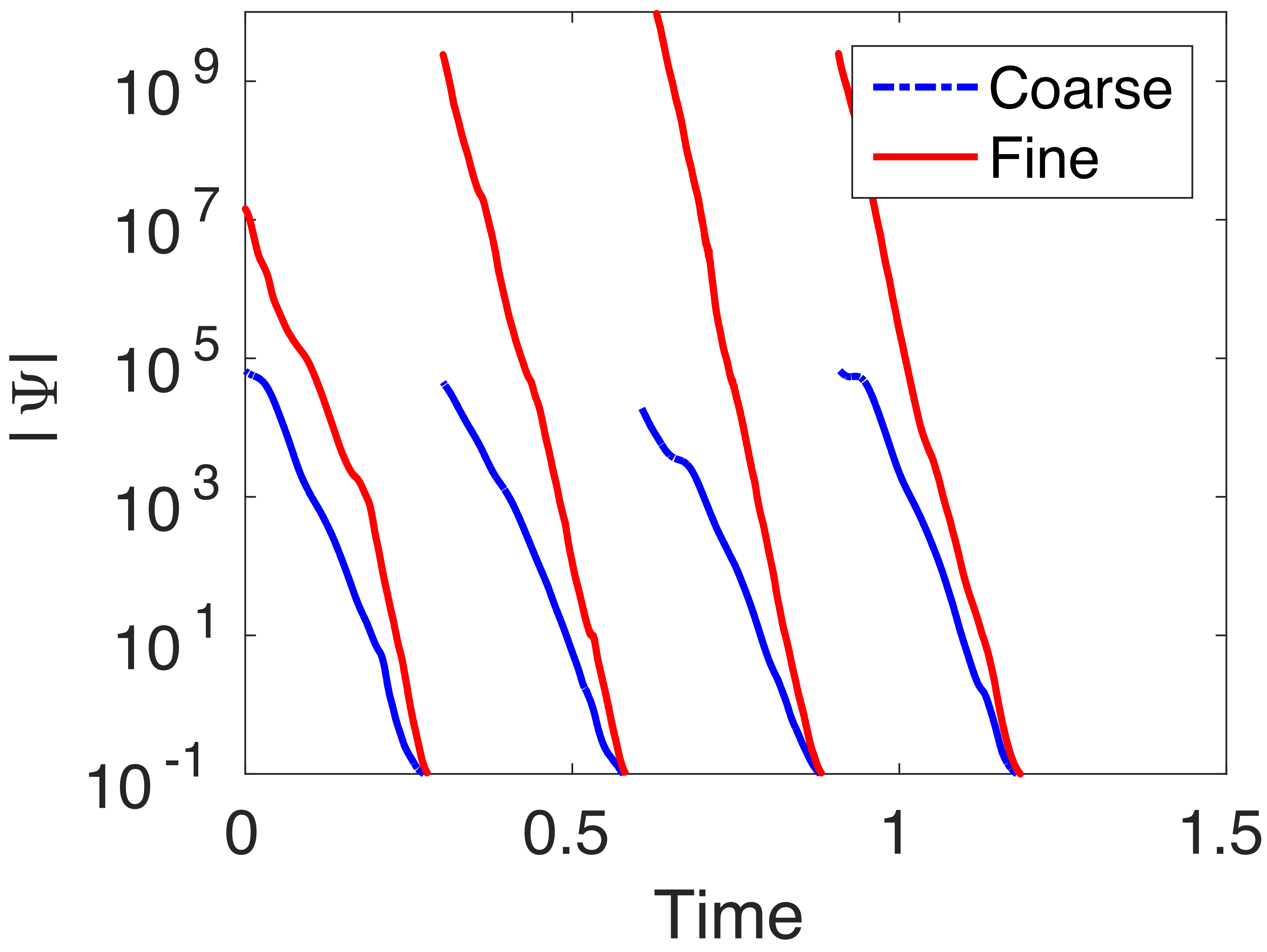
- Localize error

$$\epsilon_\kappa \equiv R_H(u_H, \psi_h|_\kappa)$$



- Unbounded adjoint not useful for error estimation
- Estimate is orders of magnitude larger than actual signal
- Error localization simply flags regions where adjoint is large

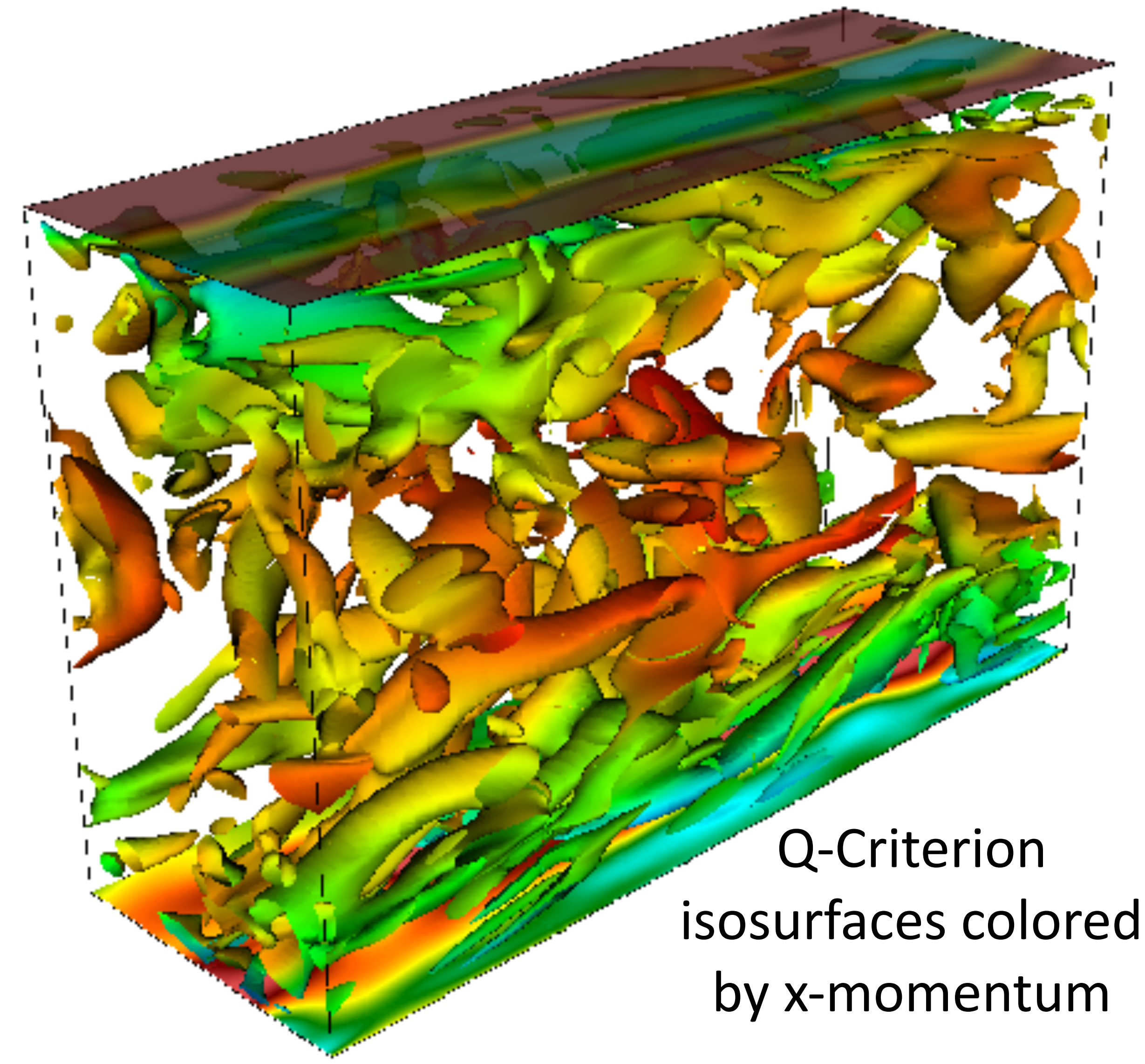
Adjoint growth with mesh resolution

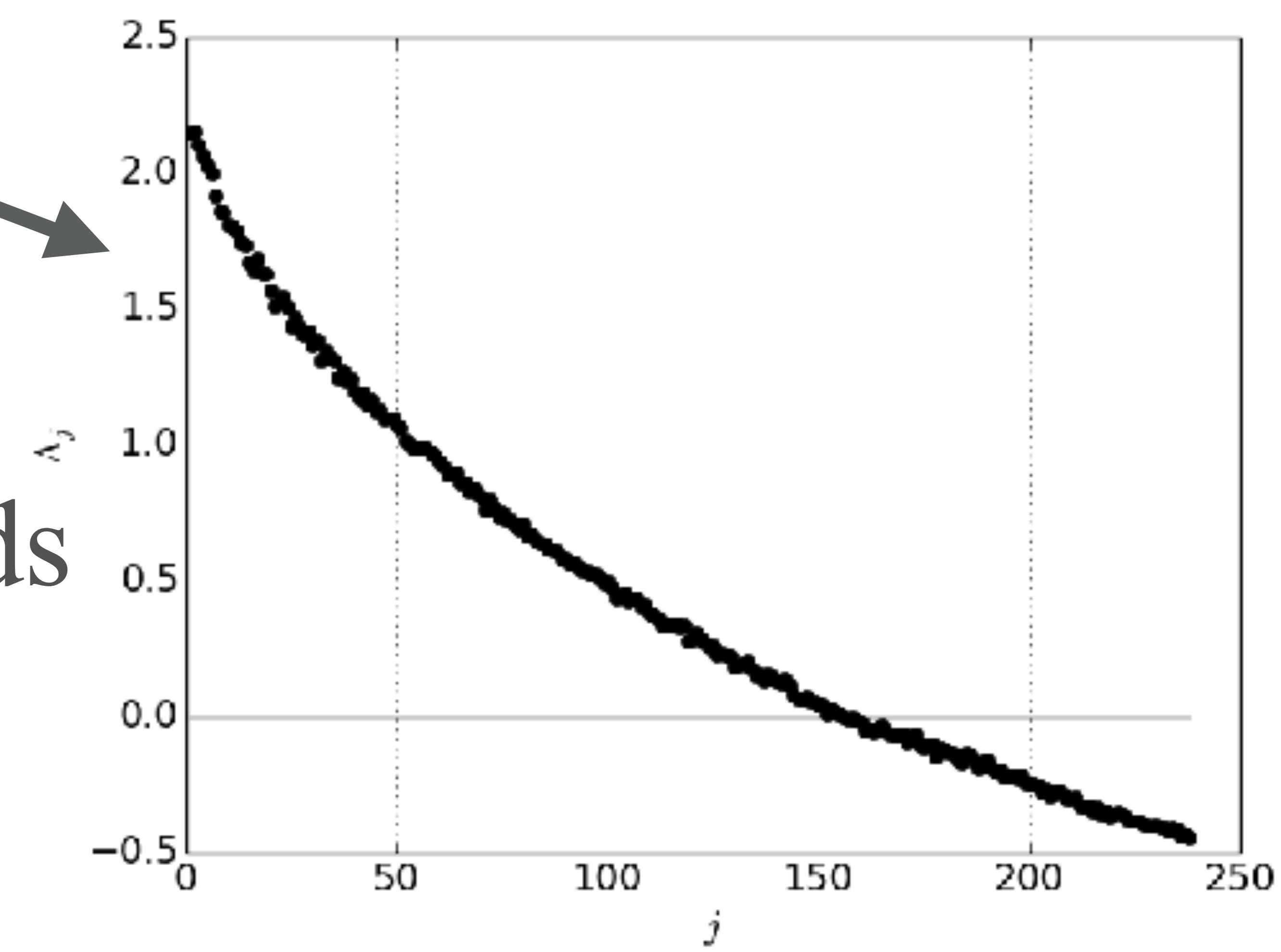


- Refined mesh has essentially double mesh resolution near separation region
- Increase mesh resolution results in faster growth of adjoint (i.e. larger Lyapunov exponent)
- Adaptation mechanism is not convergent

Minimum Turbulent Flow Unit

- Smallest channel that can sustain turbulent flow (Jimenez and Moin, 1991).
  - Very good agreement with turbulent channel statistics below $y^+=40$
- Roughly 150 positive Lyapunov exponents
- Compute sensitivity of total kinetic energy using adjoint shadowing methods



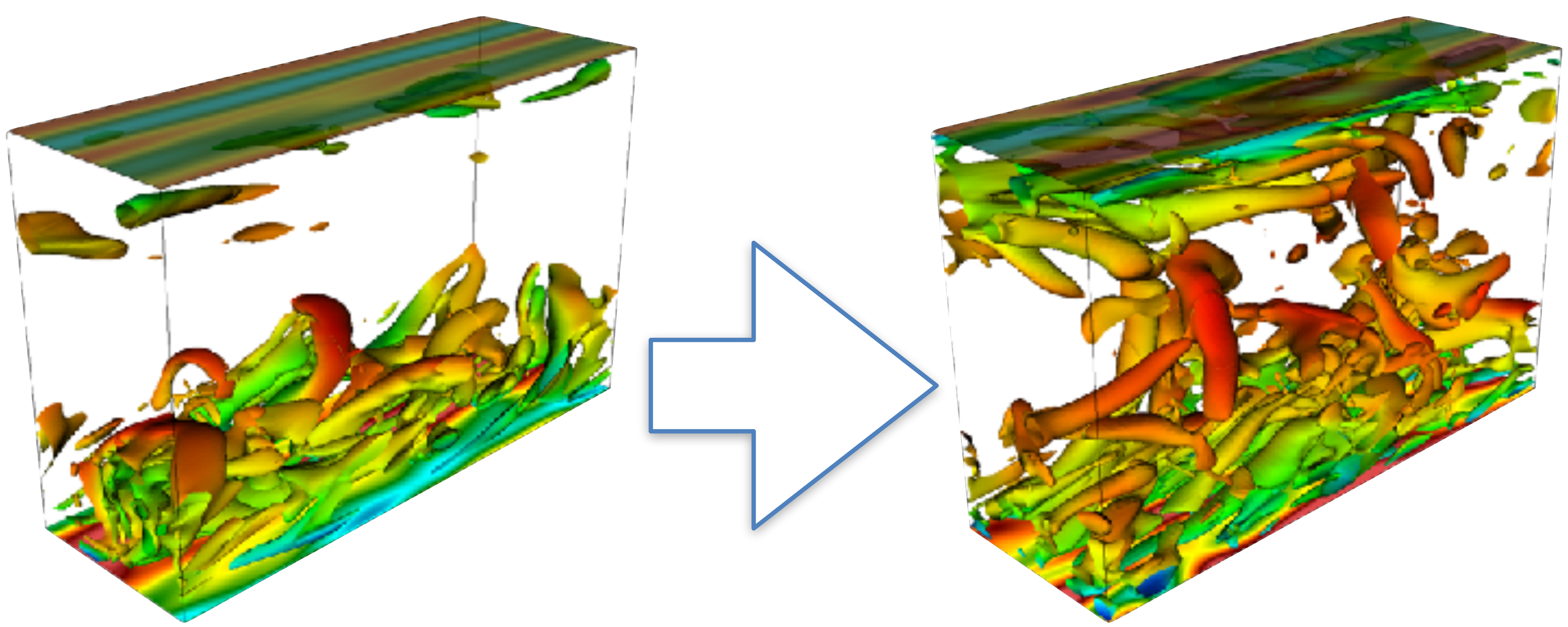


Blonigan et al. AIAA 2016-0296, JCP Vol. 348

Least-Squares Shadowing Adjoint

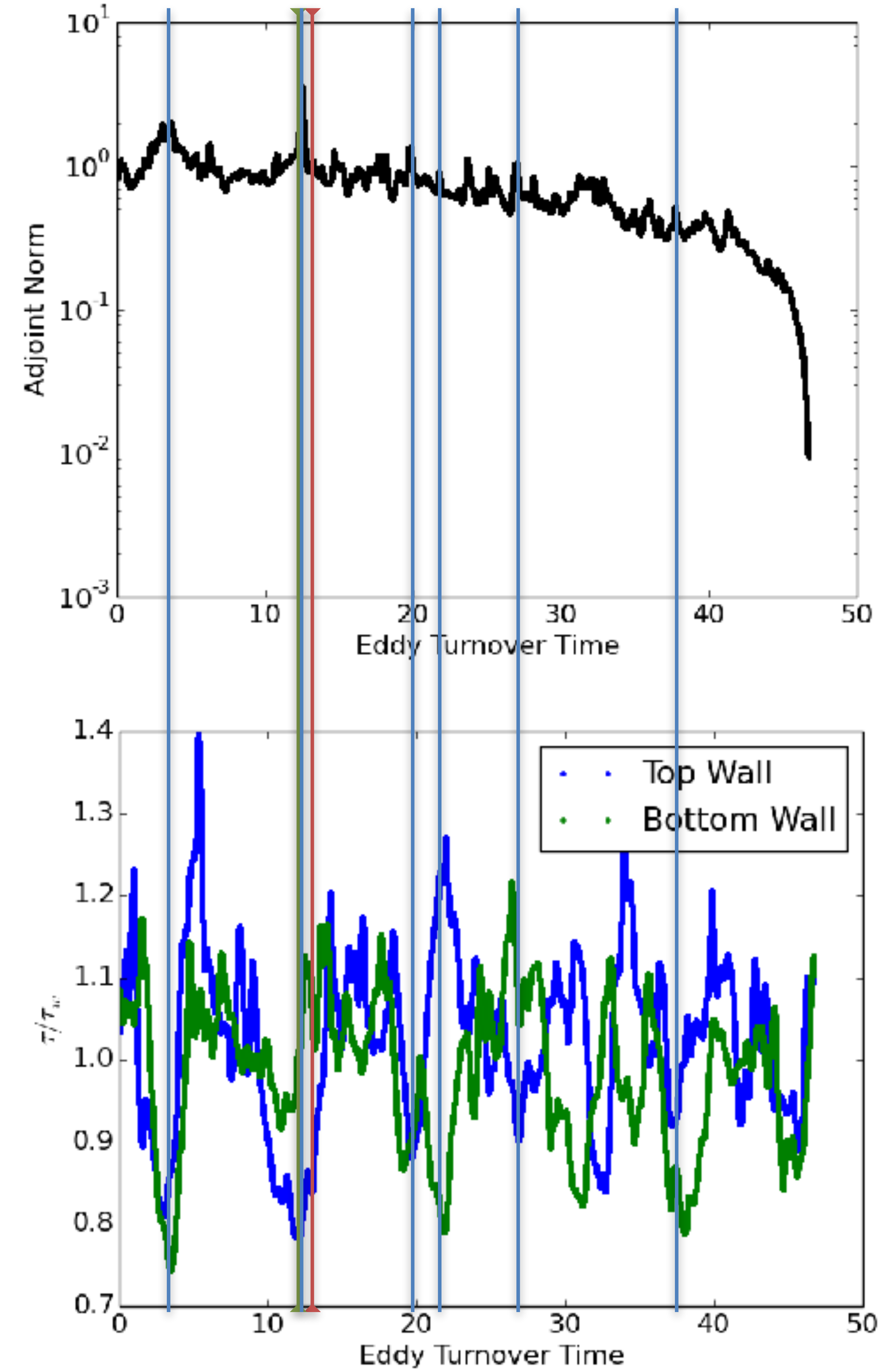
- Shadowing adjoint does not exhibit exponential growth
- Adjoint provides physical insights
  - Largest adjoint magnitudes occur before "bursting/blooming" of turbulence indicated by wall shear stress τ.

Turbulence "Bursting"



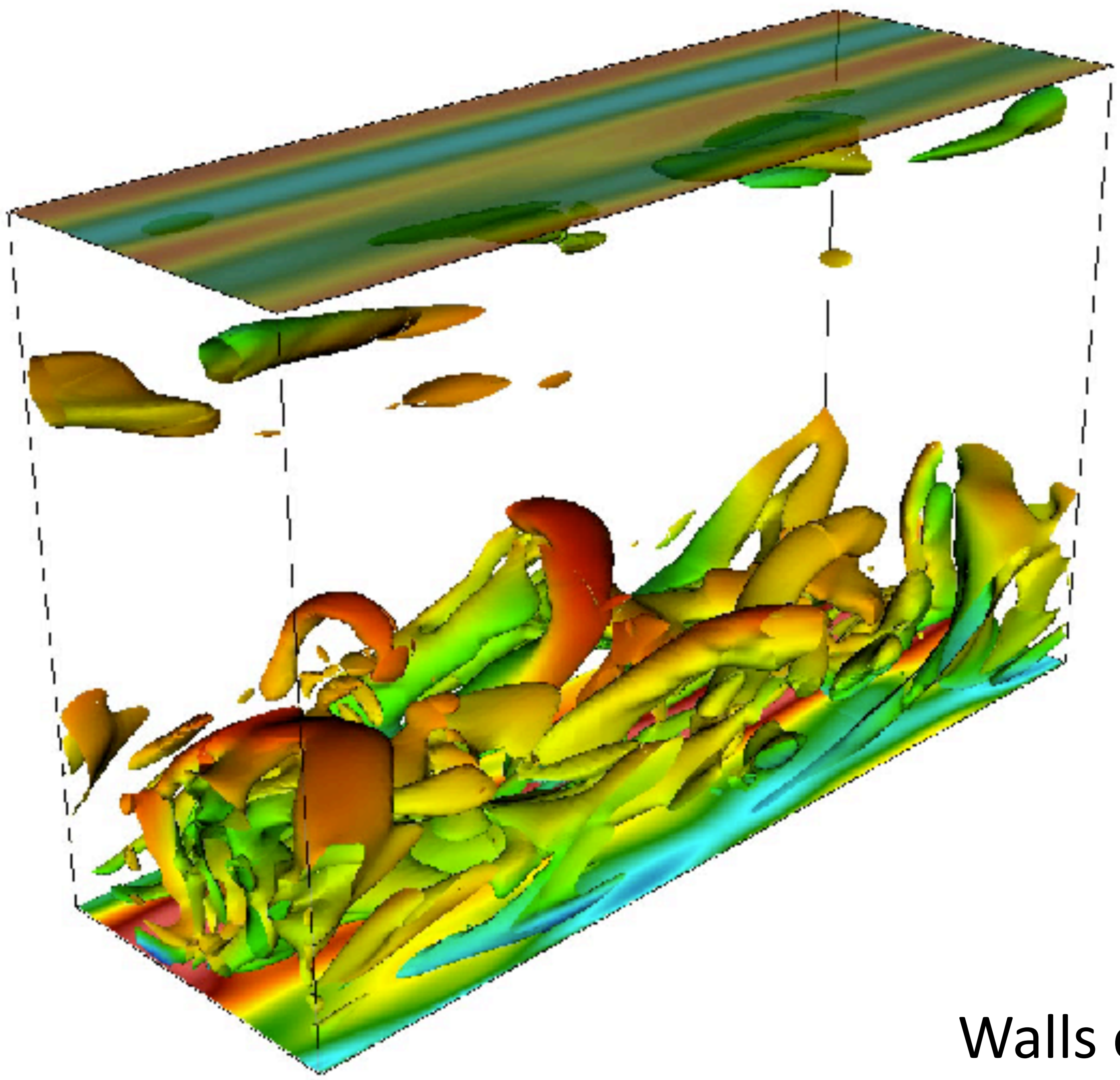
t=12.13 t=13.18

Q-Criterion isosurfaces colored by x-momentum

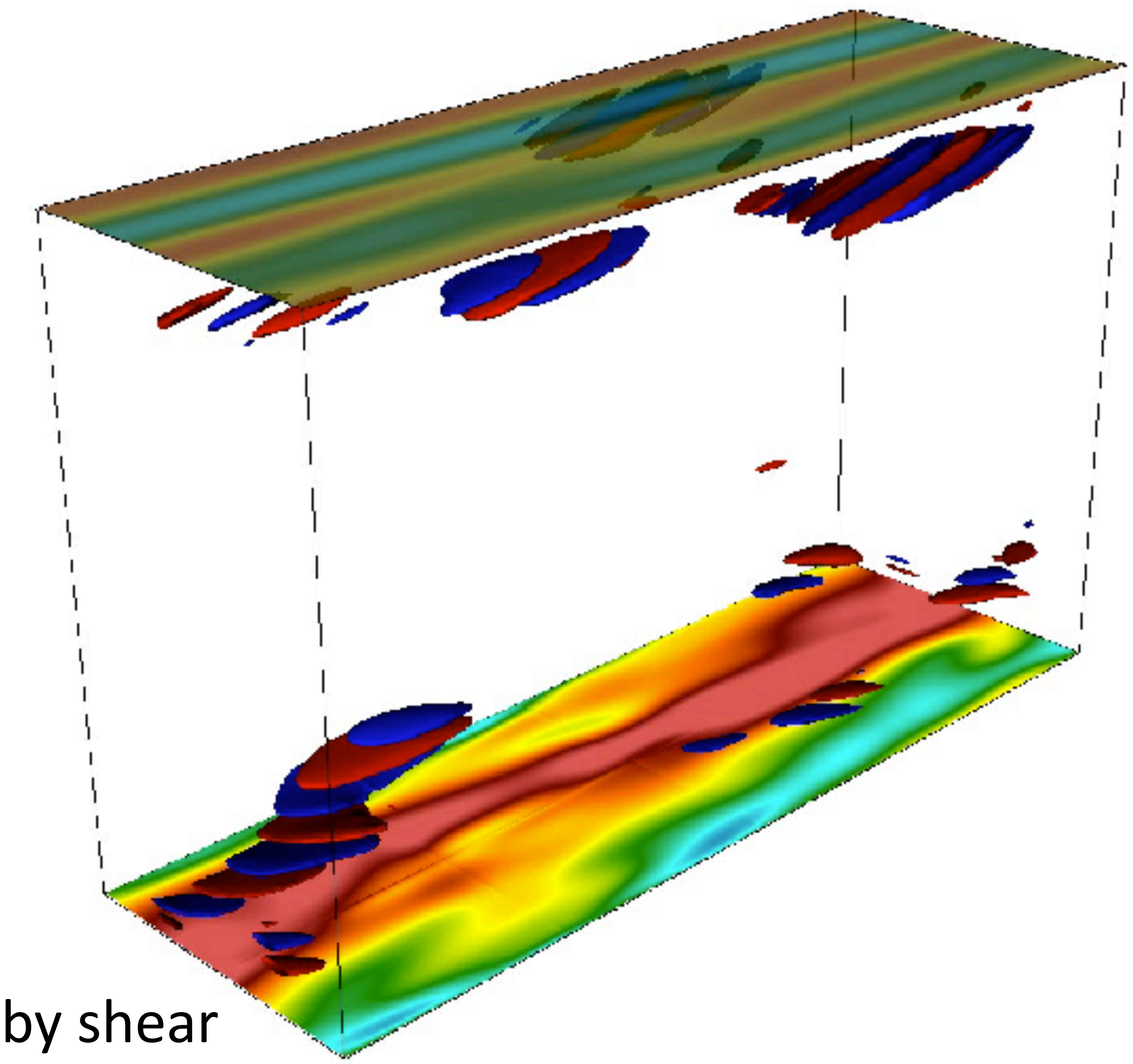


Flow Unit Adjoint Field

Q-Criterion isosurfaces colored by x-momentum



Adjoint X-momentum isocontours for ±2.0

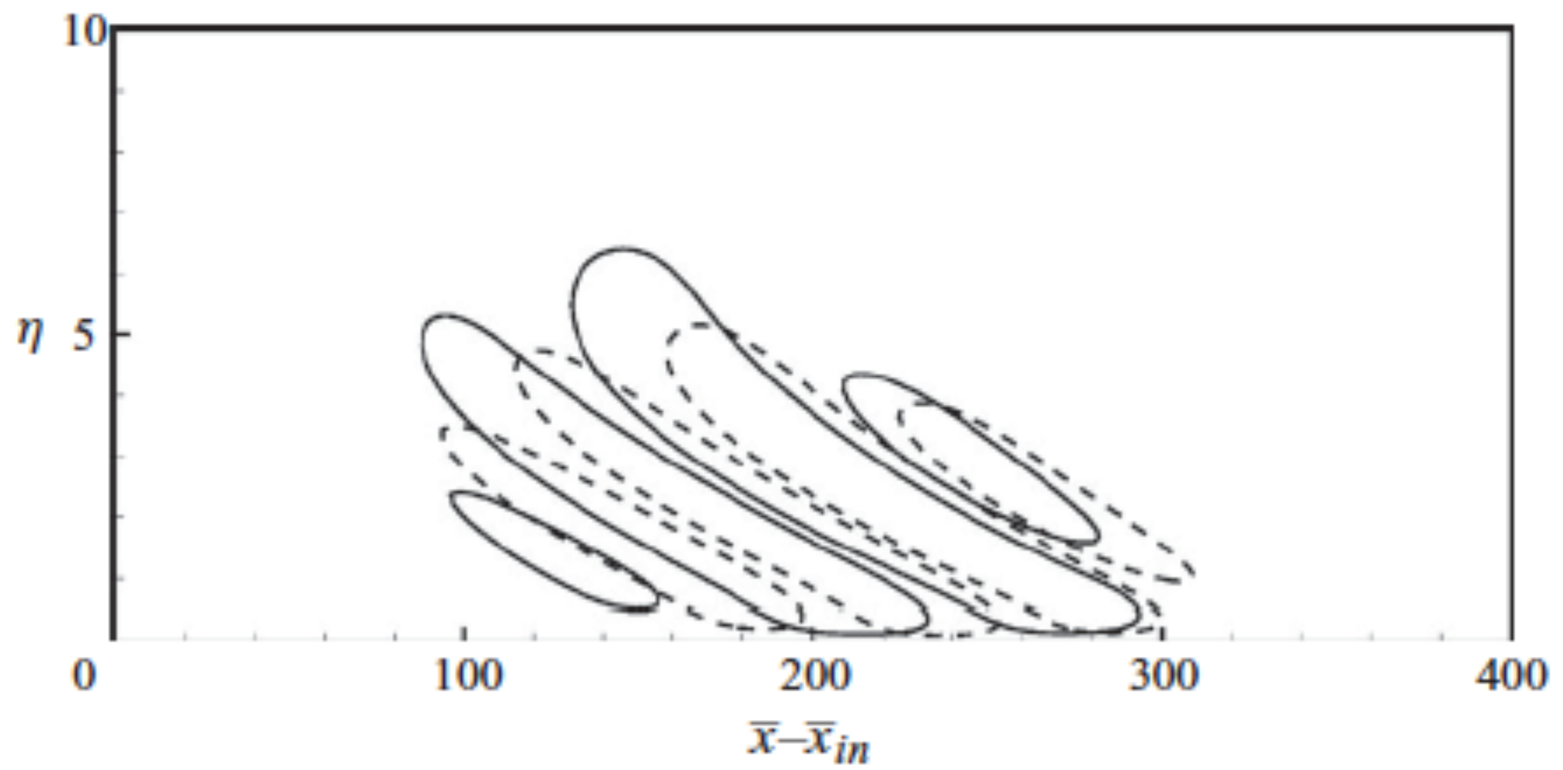


Walls colored by shear force Magnitude

- Integrated kinetic energy adjoint shows when and where flow is most susceptible to flow instabilities

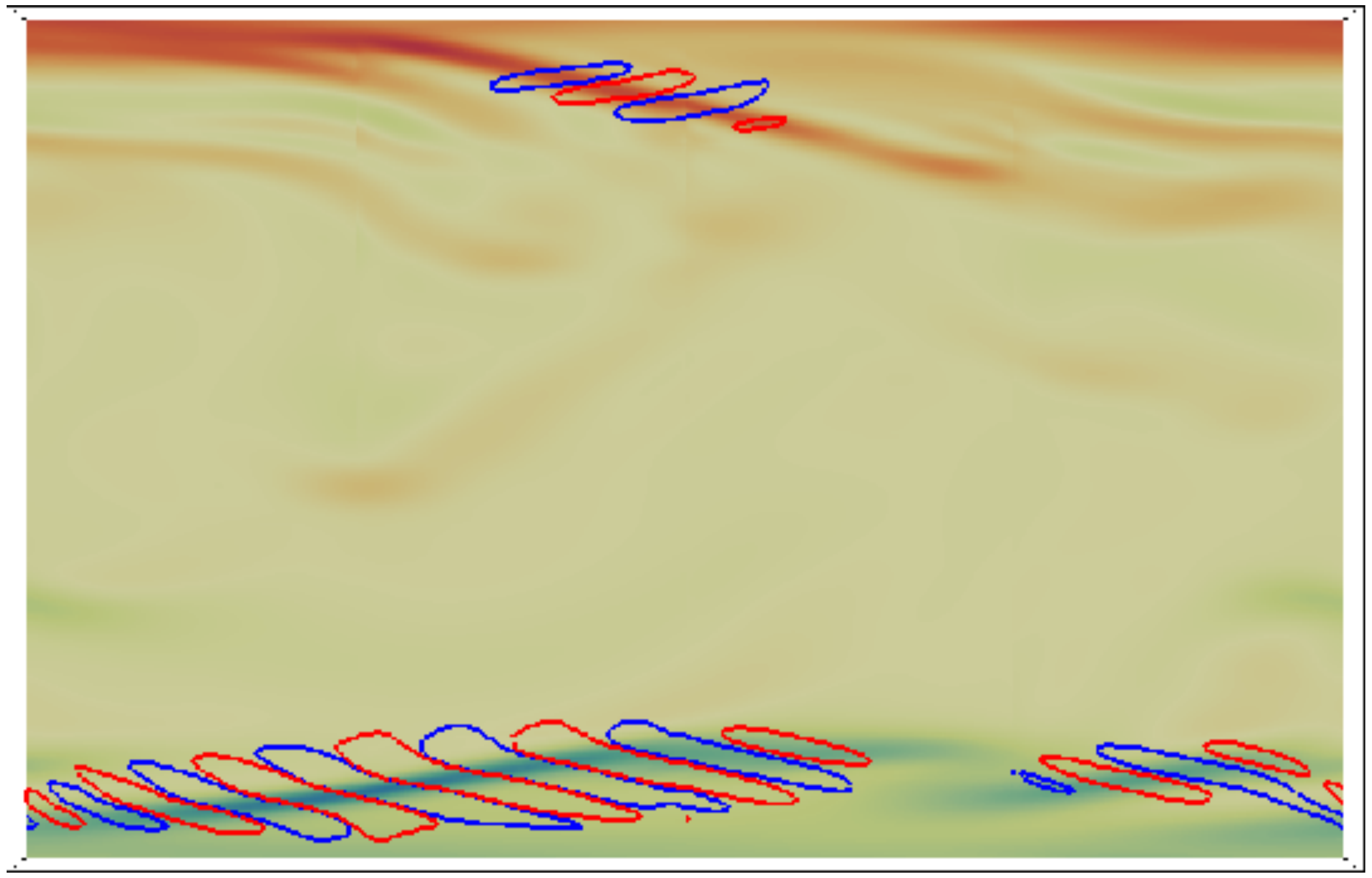
Optimal Perturbation for Transition

- Streamwise velocity magnitude contours for a flow perturbation optimized to increase the kinetic energy of Re=610 flow over a flat plate (Cherubini et al. 2010, JFM):



Solid lines: domain length = 400 units
Dotted lines: domain length = 800 units

- Adjoint X-momentum field for flow unit prior to turbulence "blooming":

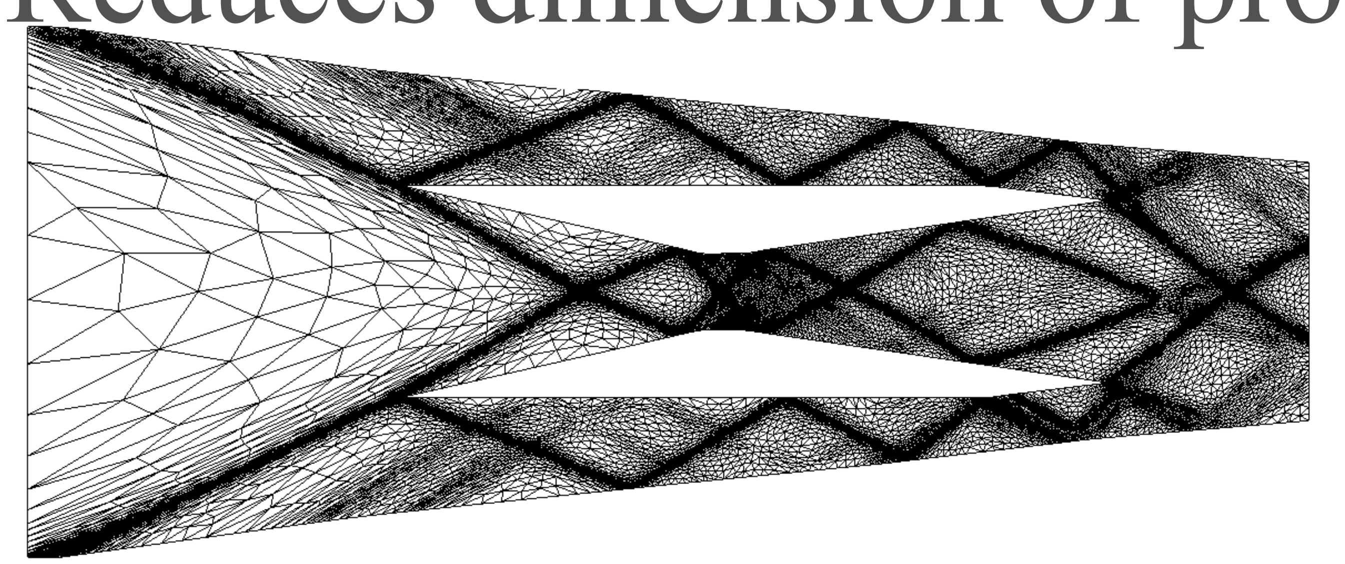


Contour lines: X-momentum adjoint
Color map: Z-vorticity

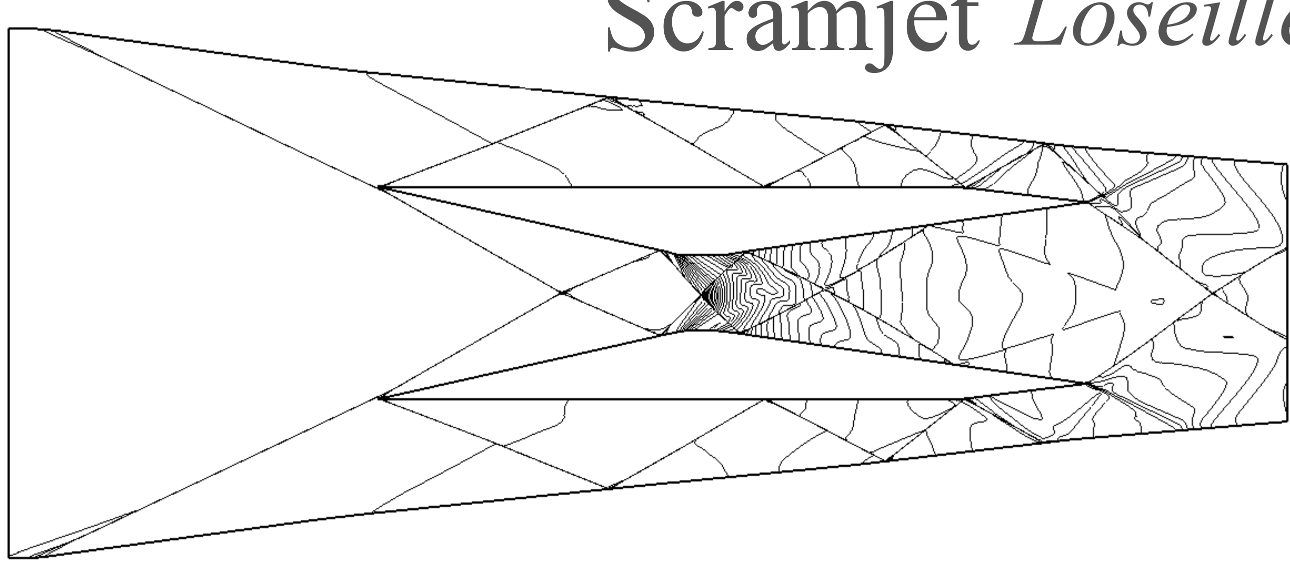
→ **X-momentum perturbations suggested by the adjoint are similar to the optimal velocity perturbations computed by Cherubini et al.**

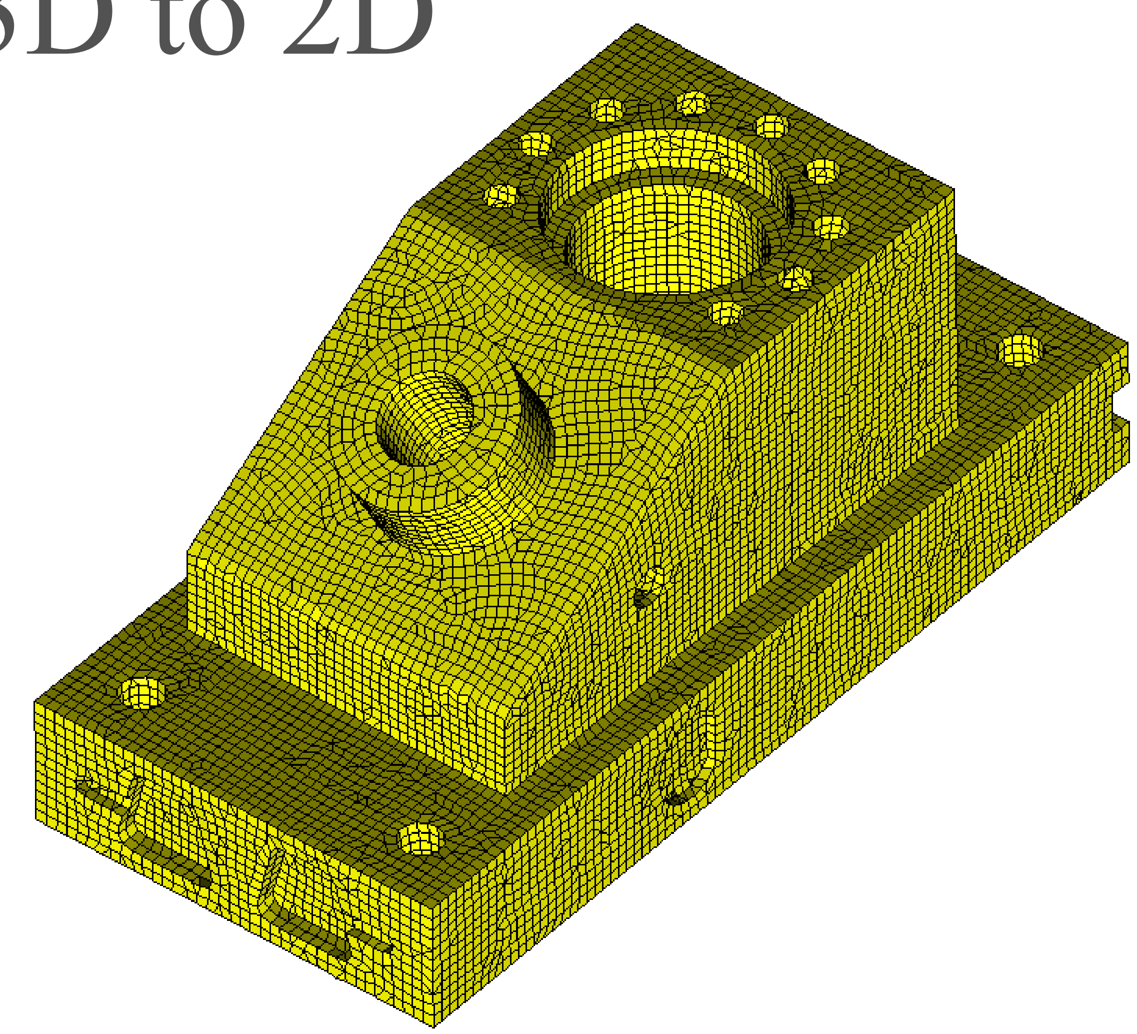
Metric-based Mesh Adaptation

- Meshing/adaptation uses similar strategy as solver development
  - Design from scratch to meet objectives
  - Automatic, hex-dominant, feature-aligned, …
  - Based on mathematically robust / provable algorithms
- Align using Riemannian metric field
  - Error estimates, surface curvature, …
- Reduces dimension of problem, e.g. 3D to 2D



Scramjet *Loseille et al.*



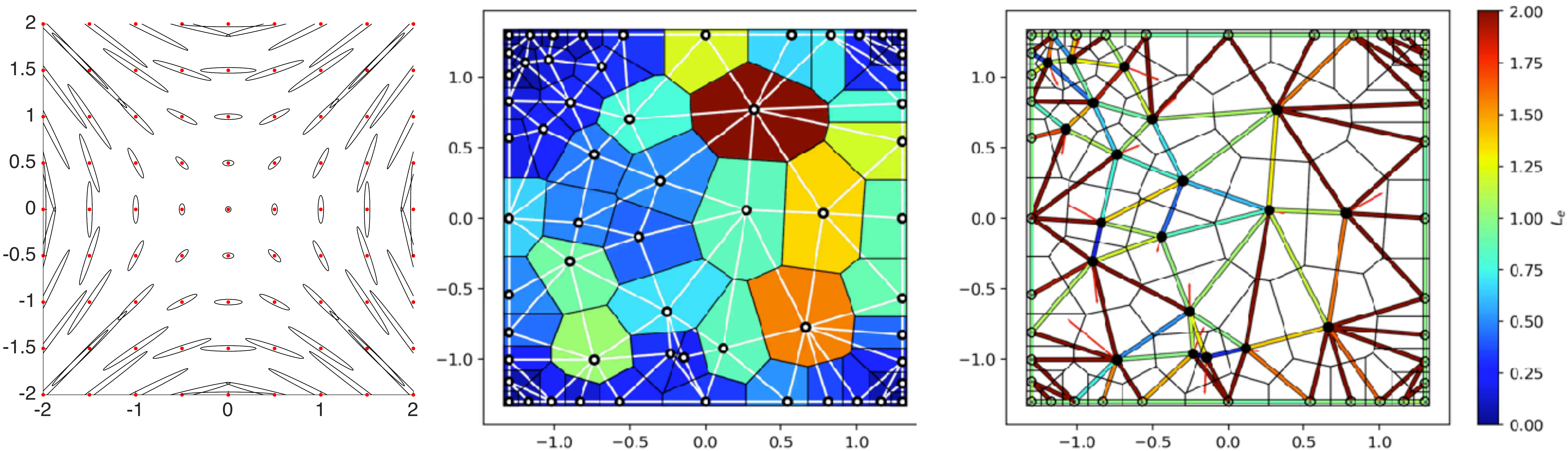


Lévy & Liu

Bounded L_p-CVT Mesh Adaptation

- Extend Lévy & Liu approach to bounded/finite domain
- Hierarchical approach: edges -> surfaces -> volumes
- Preliminary 2D proof of concept

Ekelschot et al. AIAA 2018-1501



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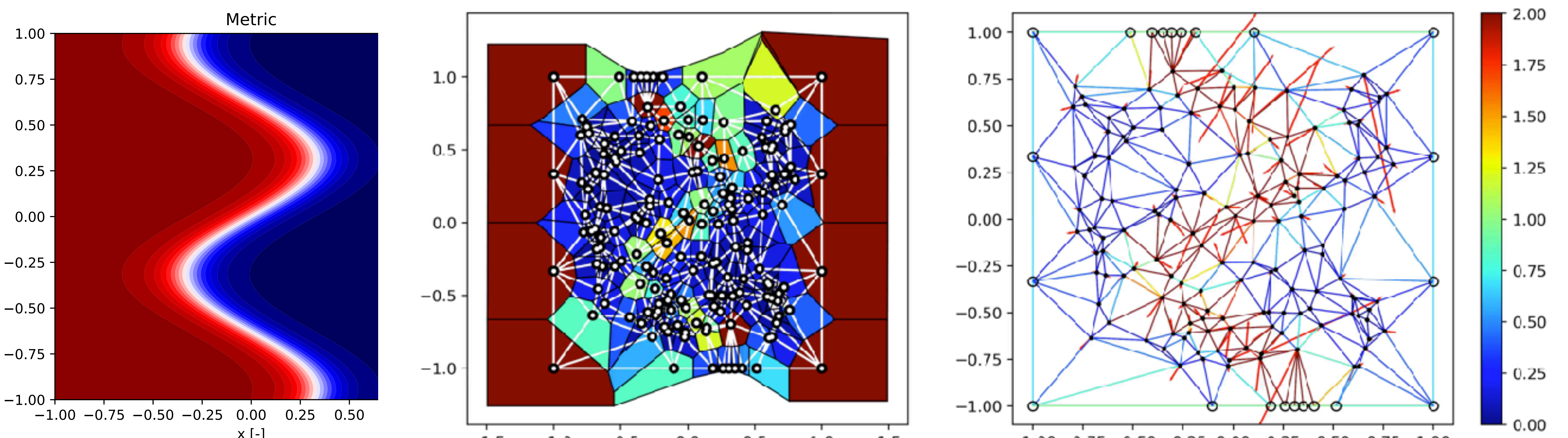
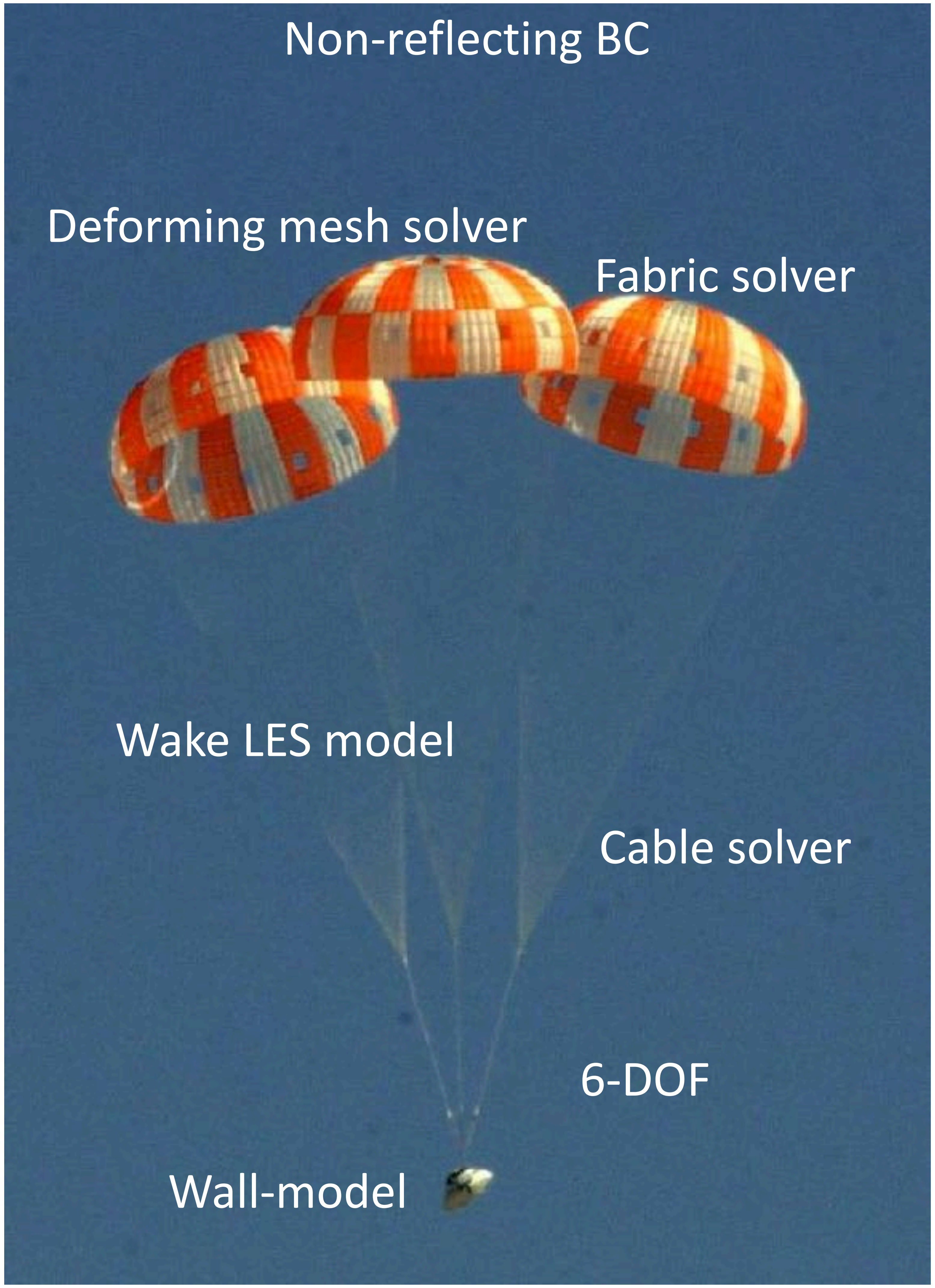


Multi-physics Approach

- Each module is a separate physics/set of equations to solve
- Physics are coupled
- General approach is required
  - Shock capturing
  - Chemistry
  - Combustion
  - …



Multi-physics Capability

- General monolithic implicit multi-physics solver
  - Exploits software-design to modularize physics, discretization, *etc.* without sacrificing efficiency
  - Similar to partitioned approach but w/o loss of conservation, accuracy, stability
- Automatically support primal, adjoint, and tangent equations for any system
  - All leverage same optimized kernels, solver, etc.
- Supports CG, DG, C^1-DG discretizations
  - Easily extends, *e.g.* HDG, optimized basis for b.c.
- Does not require researcher to understand entire code to leverage

Carton de Wiart et al. AIAA 2018-1400

Current Status

- Synergy between R&D led by RCA and engineering projects
- Internal focused engineering partnerships
  - Turbomachinery (ARMD AATT)
  - Transonic buffet (SLS and NESC)
  - Parchute FSI (Orion CPAS, STMD, and NESC)
  - Aft-body aeroheating and JI (Orion CPAS, STMD)
- External collaborations
  - Public domain license
  - MIT, Michigan, Stanford, UIUC, UNM, U. Colorado, UTIAS, Boeing, Cenaero
  - Currently supporting 4 PhD projects

Backup

Context

- NASA has healthy infrastructure of CFD tools
  - OVERFLOW, FUN3D, Cart3D, Loci/CHEM, DPLR
  - Primarily FD/FV, RANS-based technology
- Goal is to complement existing suite, not replace
  - Unsteady complex physics, e.g. separation, shock/BL interaction, …
- Use mathematically robust algorithms and procedures
  - Required for error estimates, uncertainty quantification, and automation
  - Achieve efficiency by improved methods, not short-cuts