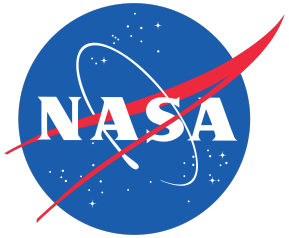
Prediction of real-world external aerodynamics using wall-modeled large-eddy simulation

Adrián Lozano-Durán

Center for Turbulence Research
Stanford University





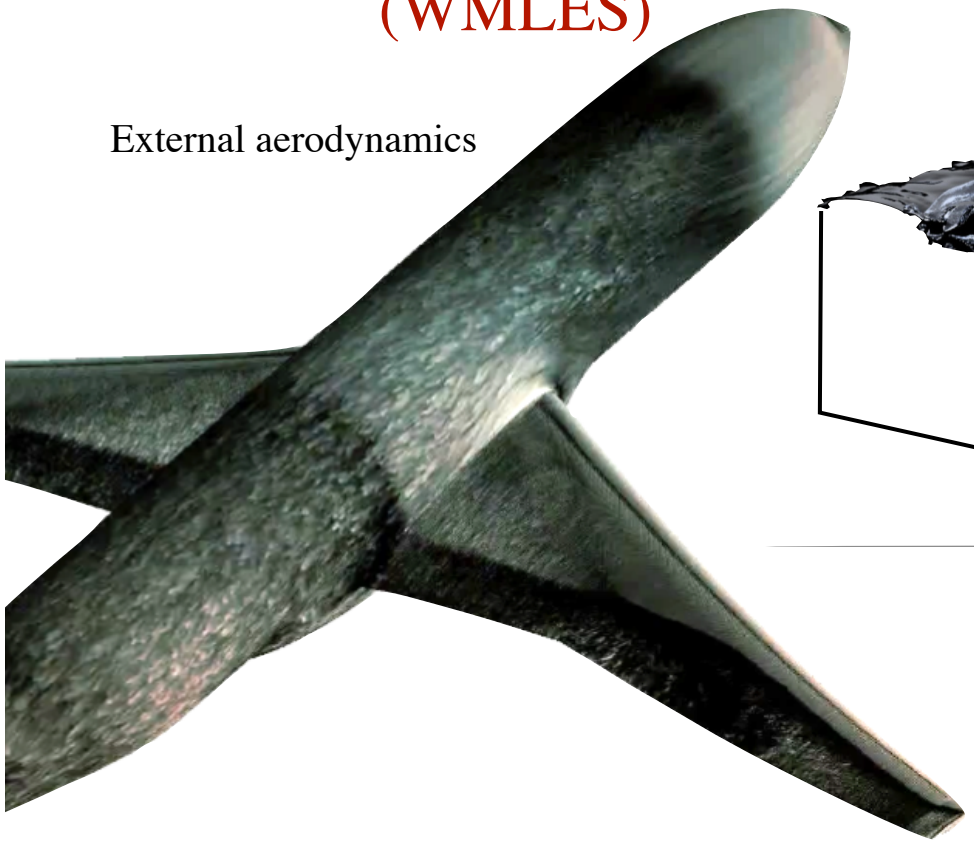
Stanford
University

Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, February 27, 2020

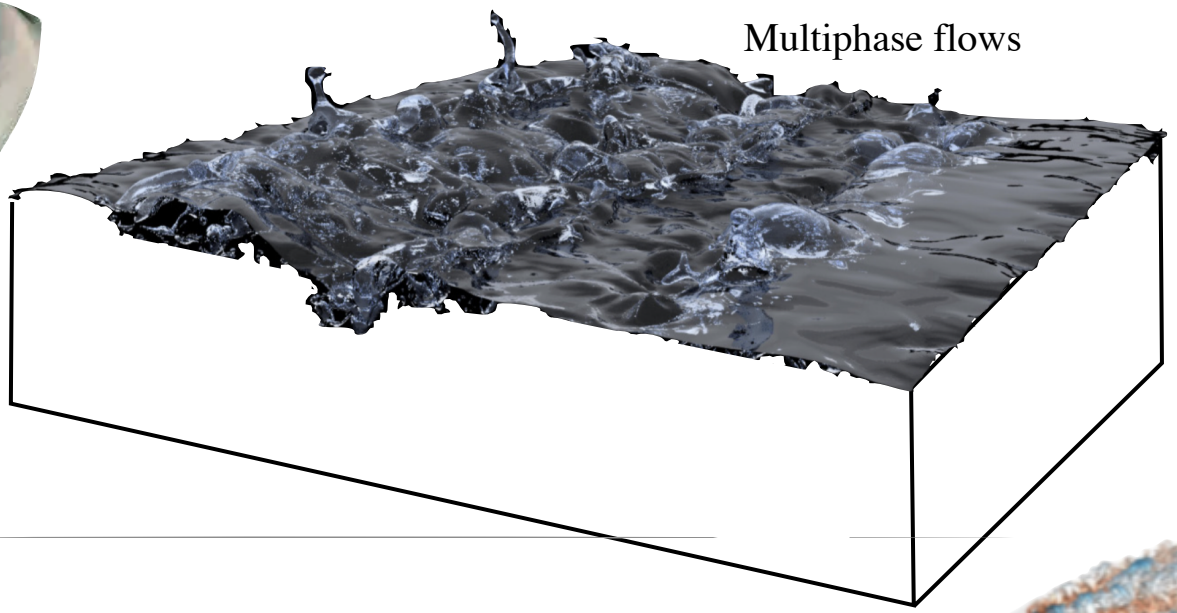
Wall-modeled large-eddy simulation at CTR

(WMLES)

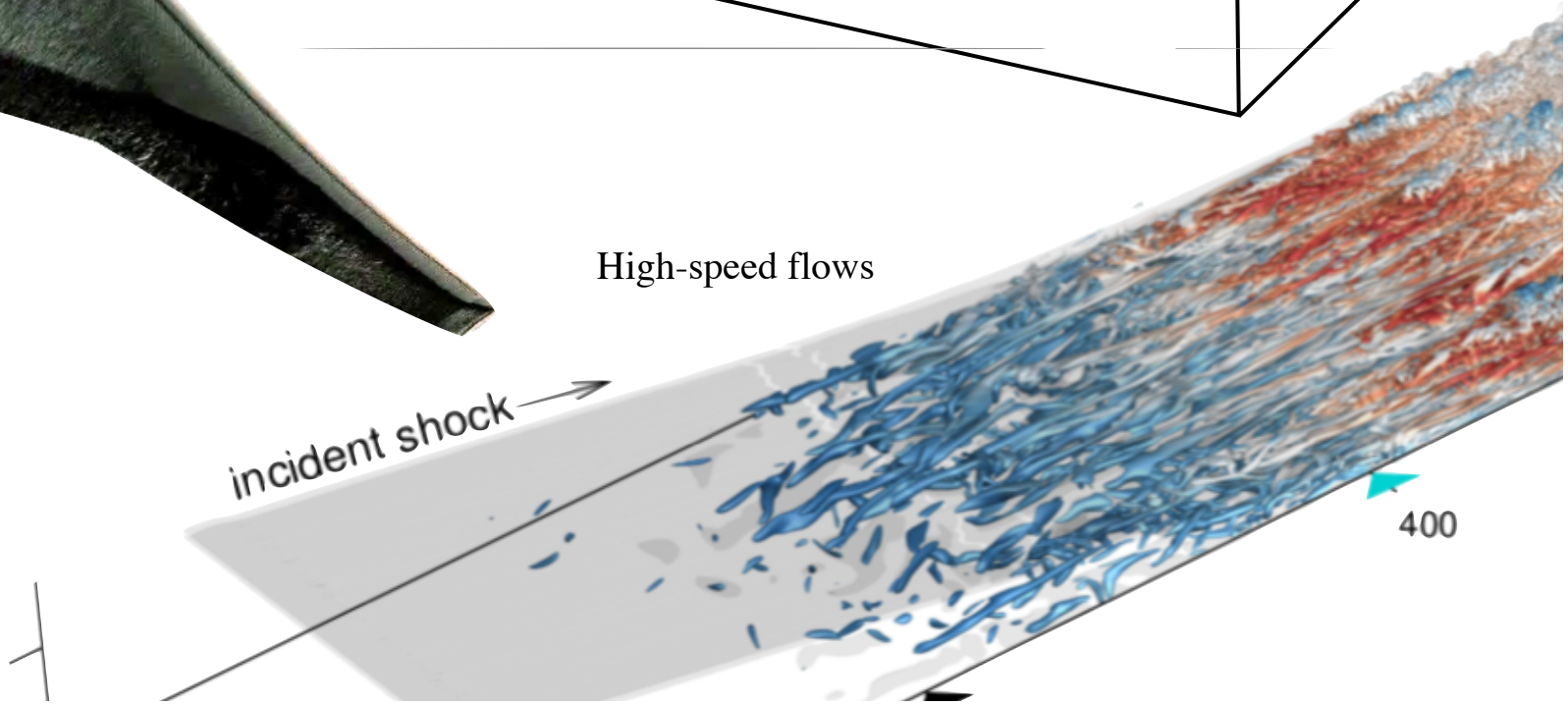
External aerodynamics



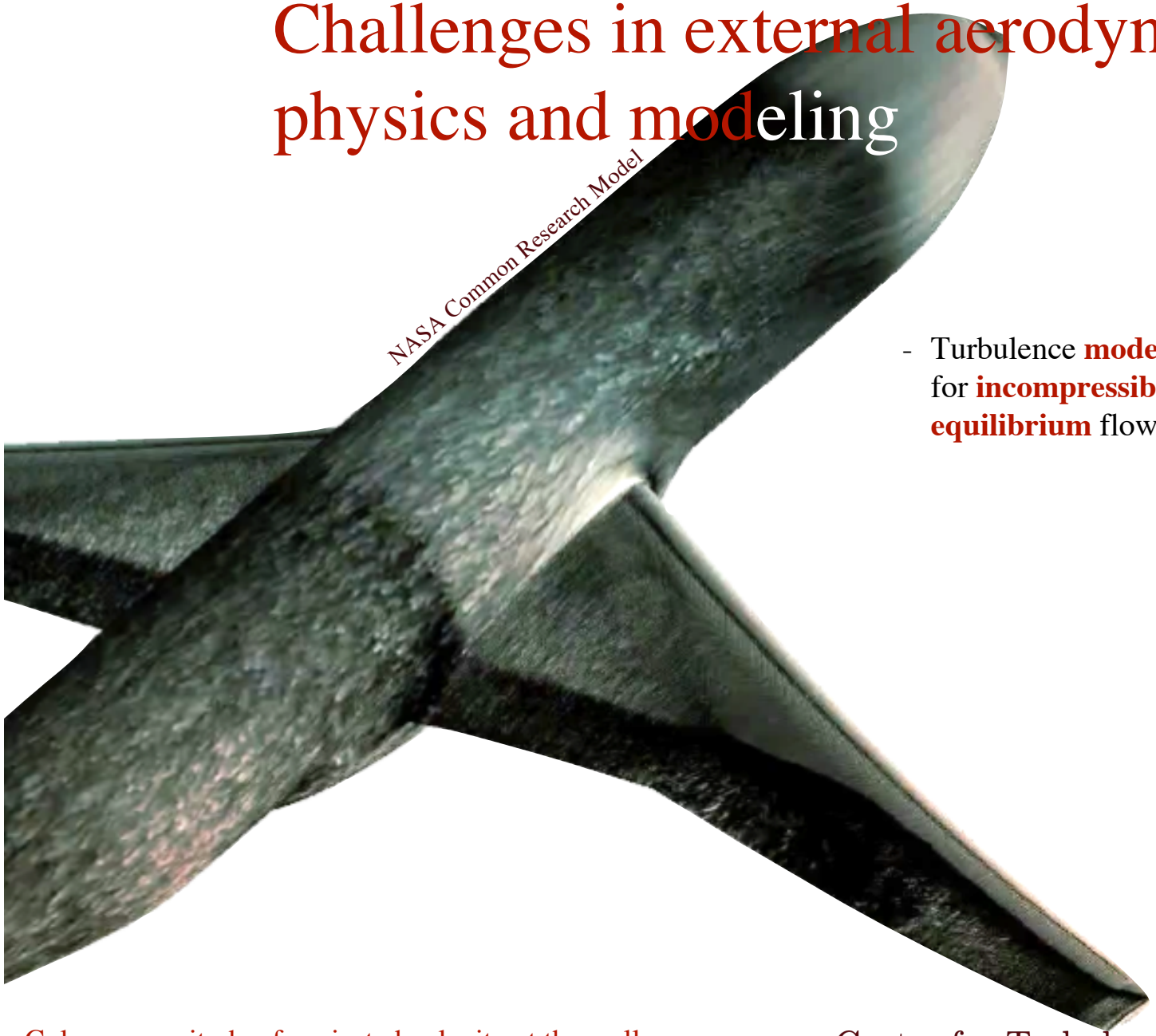
Multiphase flows



High-speed flows



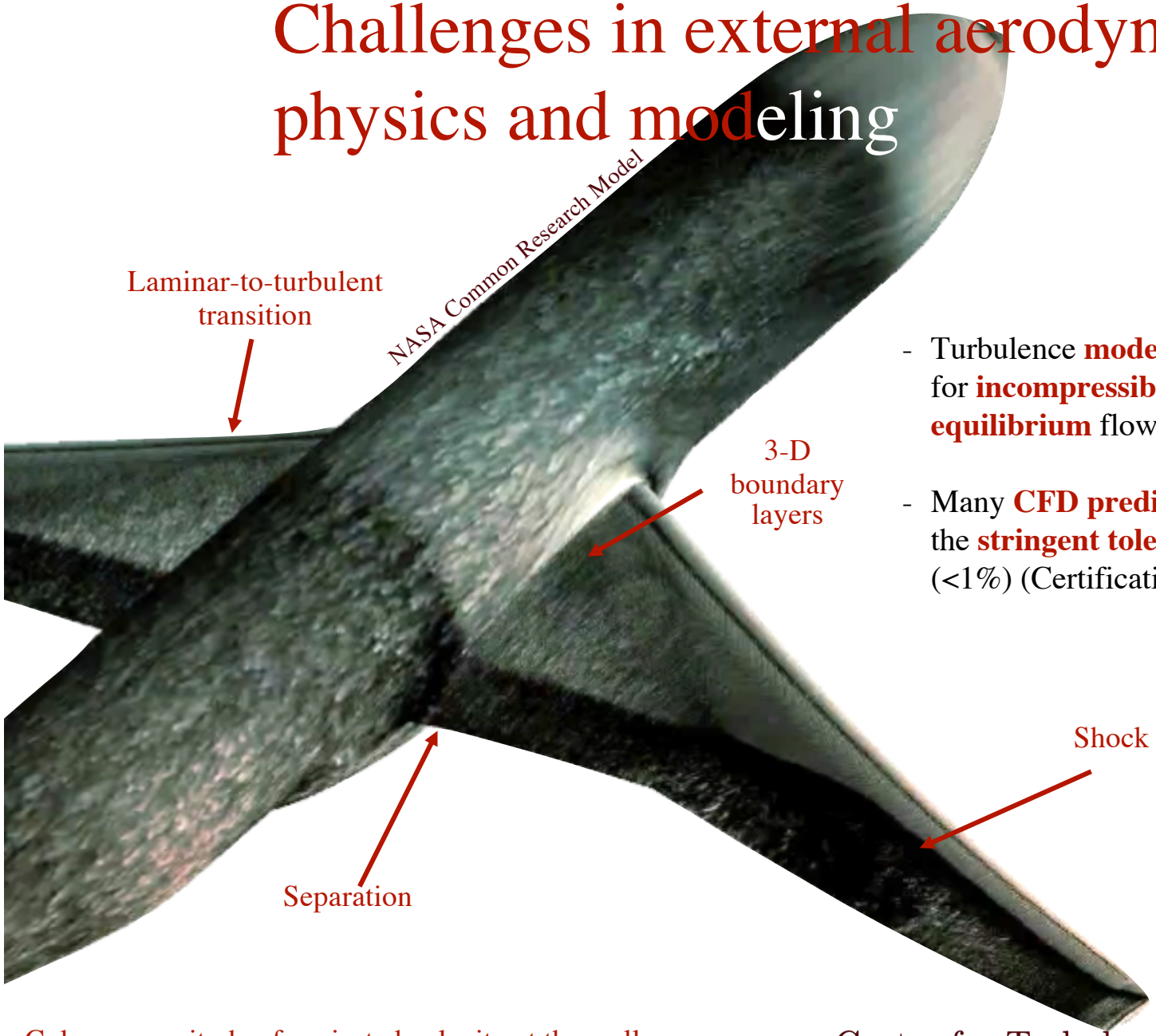
Challenges in external aerodynamics: physics and modeling



- Turbulence **models** have been established mainly for **incompressible, statistically steady, 2-D, equilibrium** flows.

Colors: magnitude of projected velocity at the wall

Challenges in external aerodynamics: physics and modeling



- Turbulence **models** have been established mainly for **incompressible, statistically steady, 2-D, equilibrium** flows.
- Many **CFD predictions** need to be pushed within the **stringent tolerance** demanded by the industry (<1%) (Certification by Analysis)

Colors: magnitude of projected velocity at the wall

Team members & Collaborators

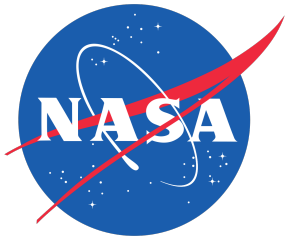
Konrad Goc (CTR Stanford University)

Sanjeeb T. Bose (CTR Stanford University & Cascade Tech.)

Parviz Moin (CTR Stanford University)

Oriol Lehmkuhl (Barcelona Supercomputing Center)

Ivette Rodriguez (Universitat Politecnica de Catalunya)



NASA Transformational Tools and Technologies Grant #15AU93A

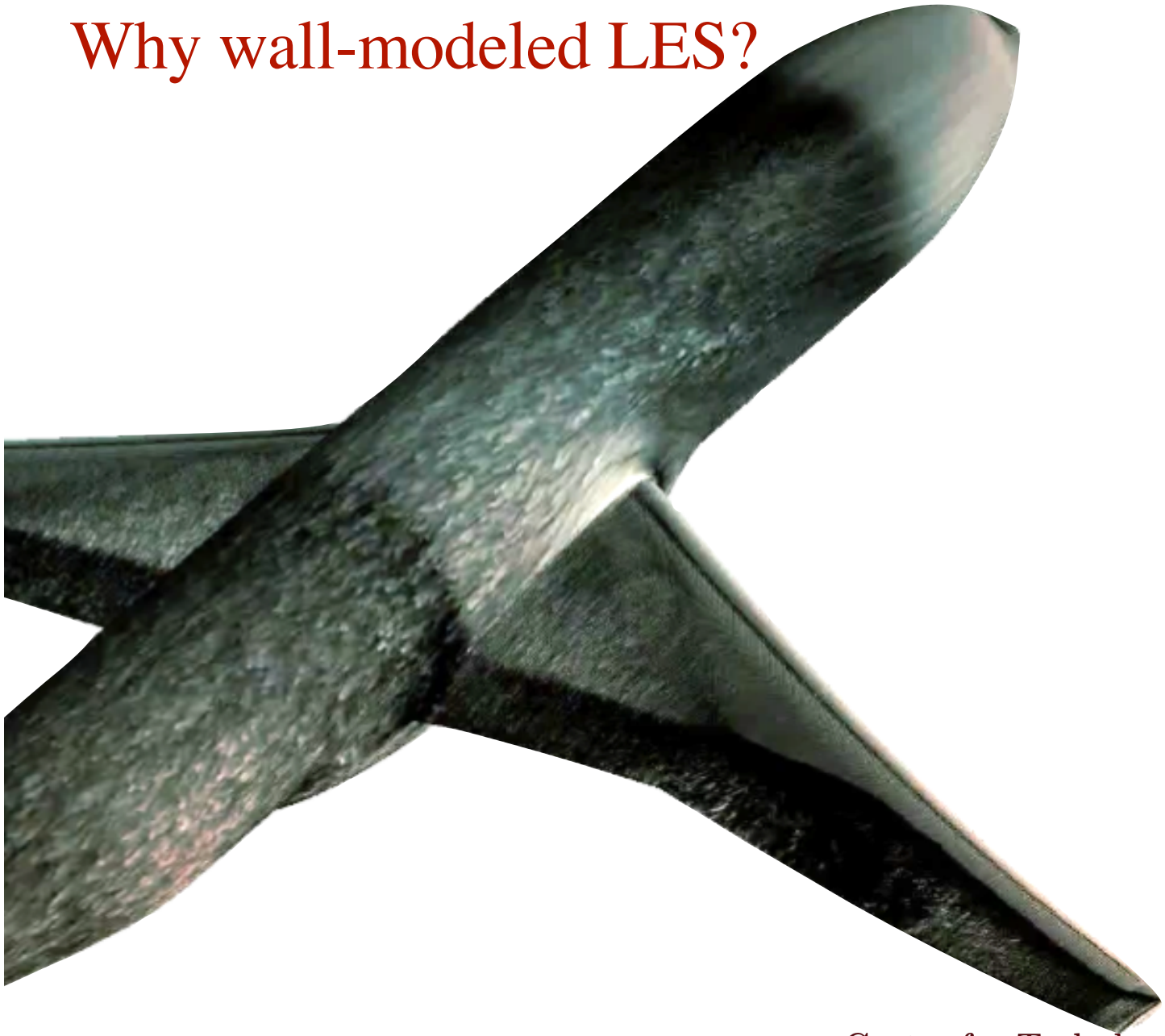
Outline

- **Why** wall-molded LES?
- **What** is wall-modeled LES?
- **Accuracy** & **Cost** of wall-modeled LES for external aerodynamics:
  - Prediction of lift & drag forces: JSM high-lift.
  - Prediction of mean velocity, Reynolds stresses, pressure coefficient & separation: NASA Juncture flow.

Outline

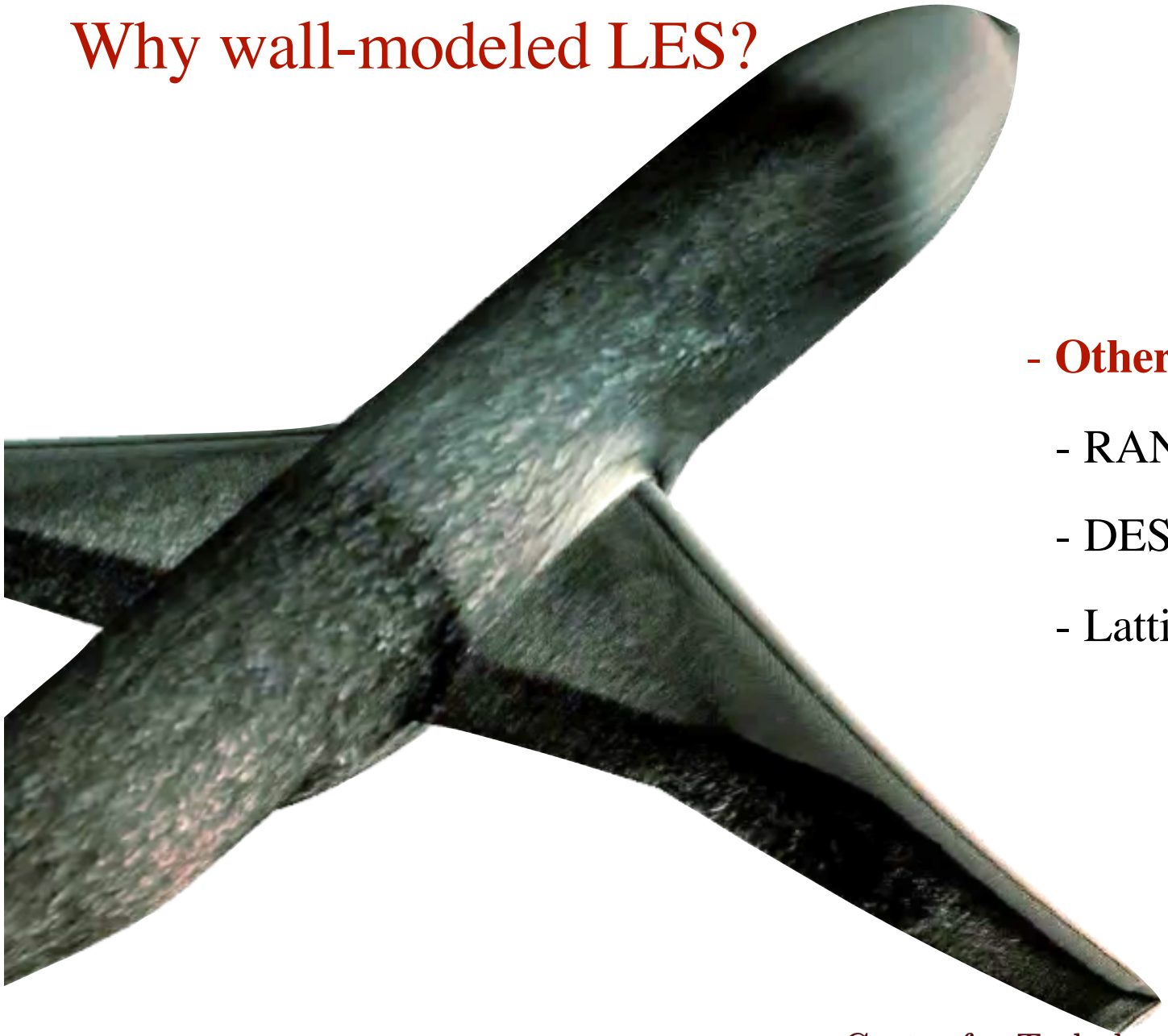
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Why wall-modeled LES?



Spalart 2000, 2009,…

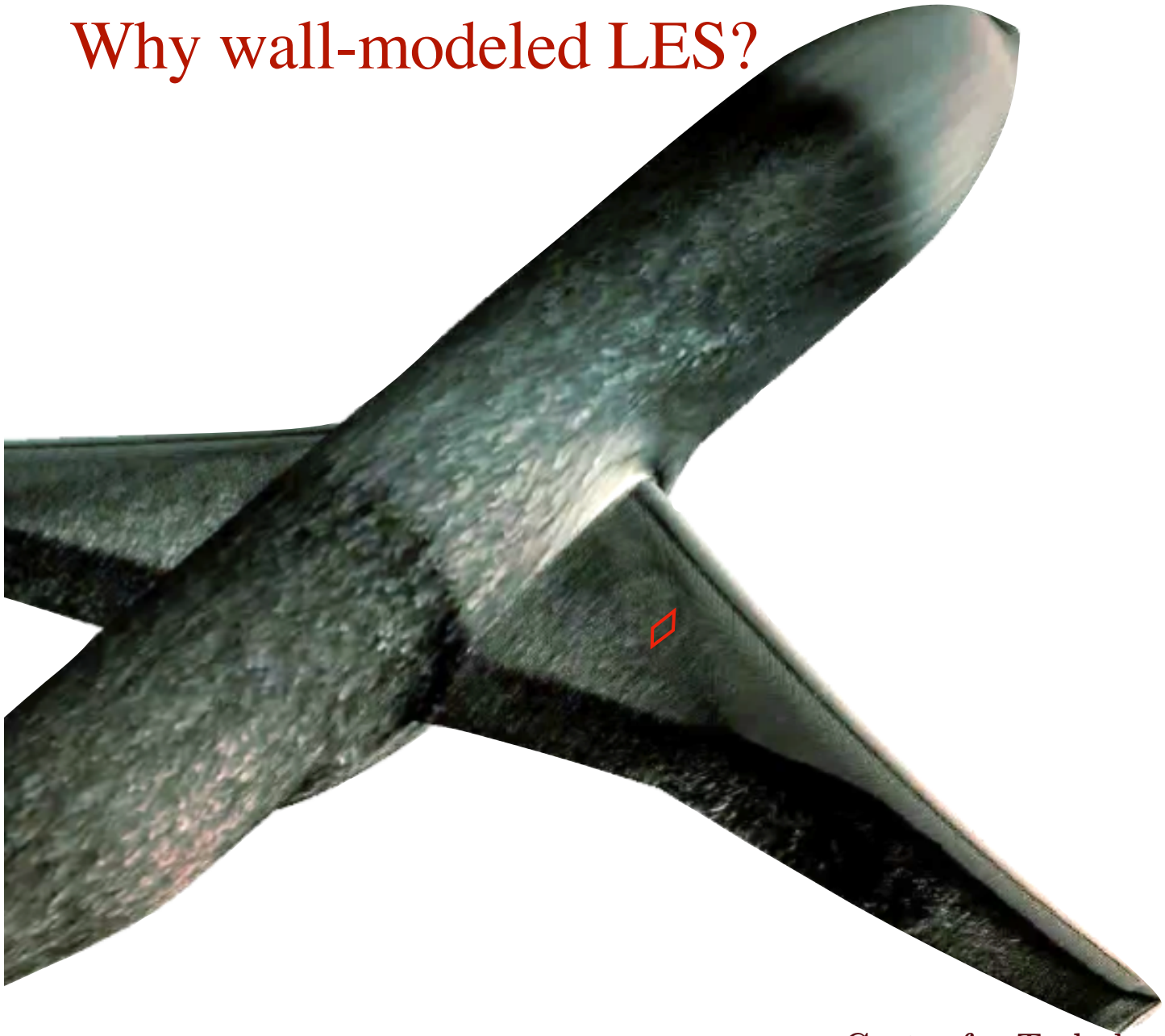
Why wall-modeled LES?



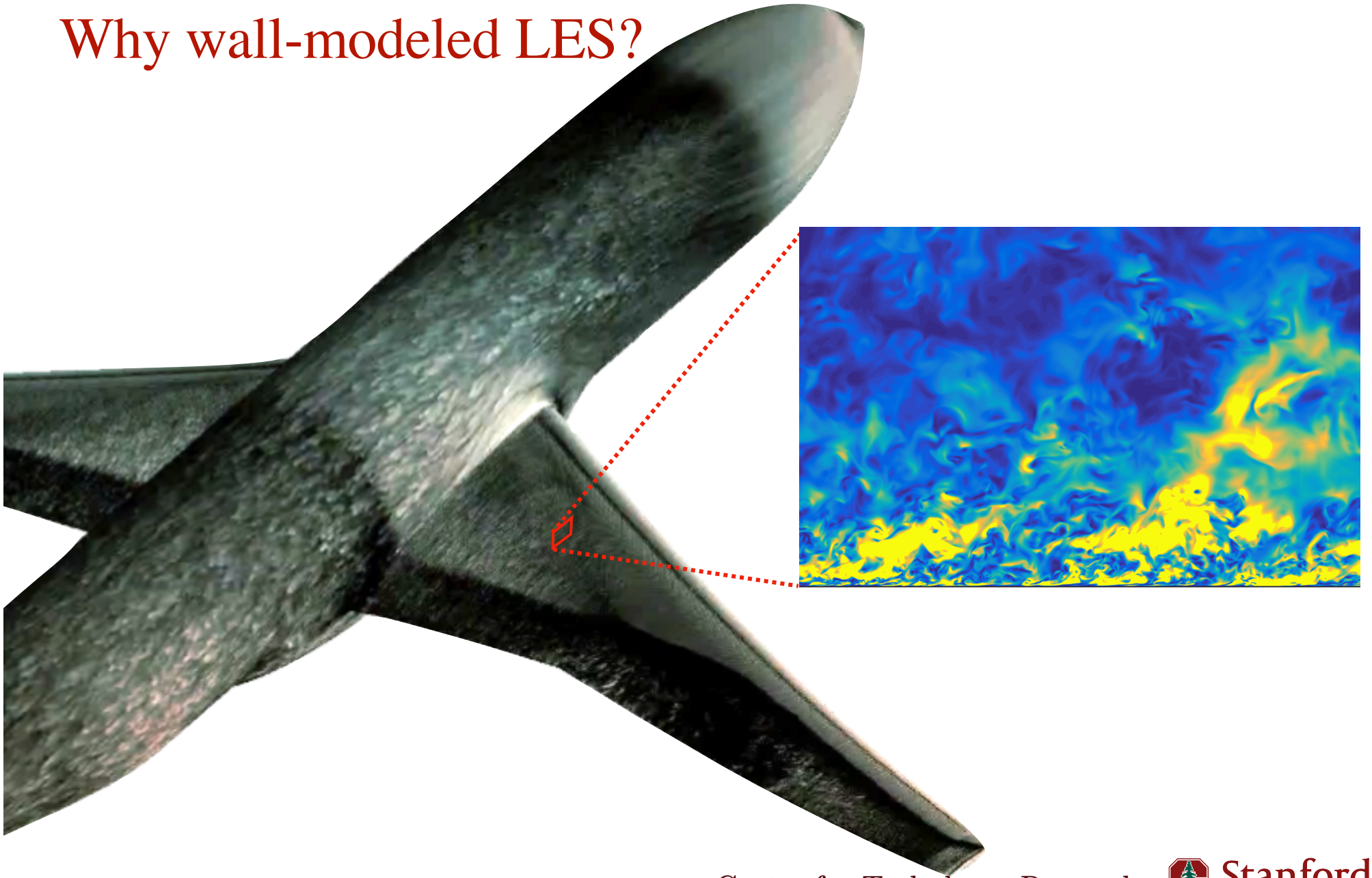
- **Other approaches:**
  - RANS
  - DES and variants
  - Lattice-Boltzmann

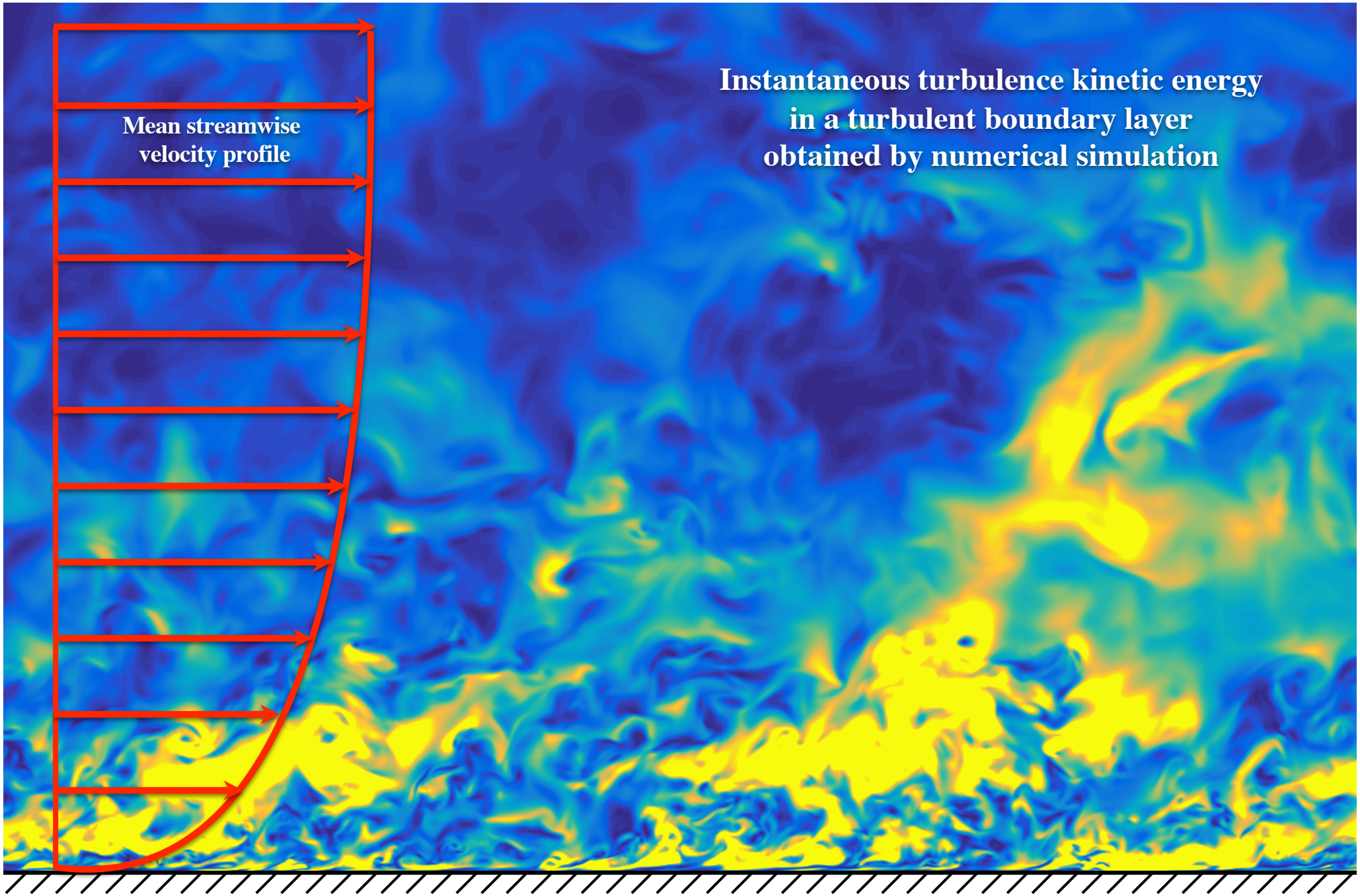
Spalart 2000, 2009,…

Why wall-modeled LES?

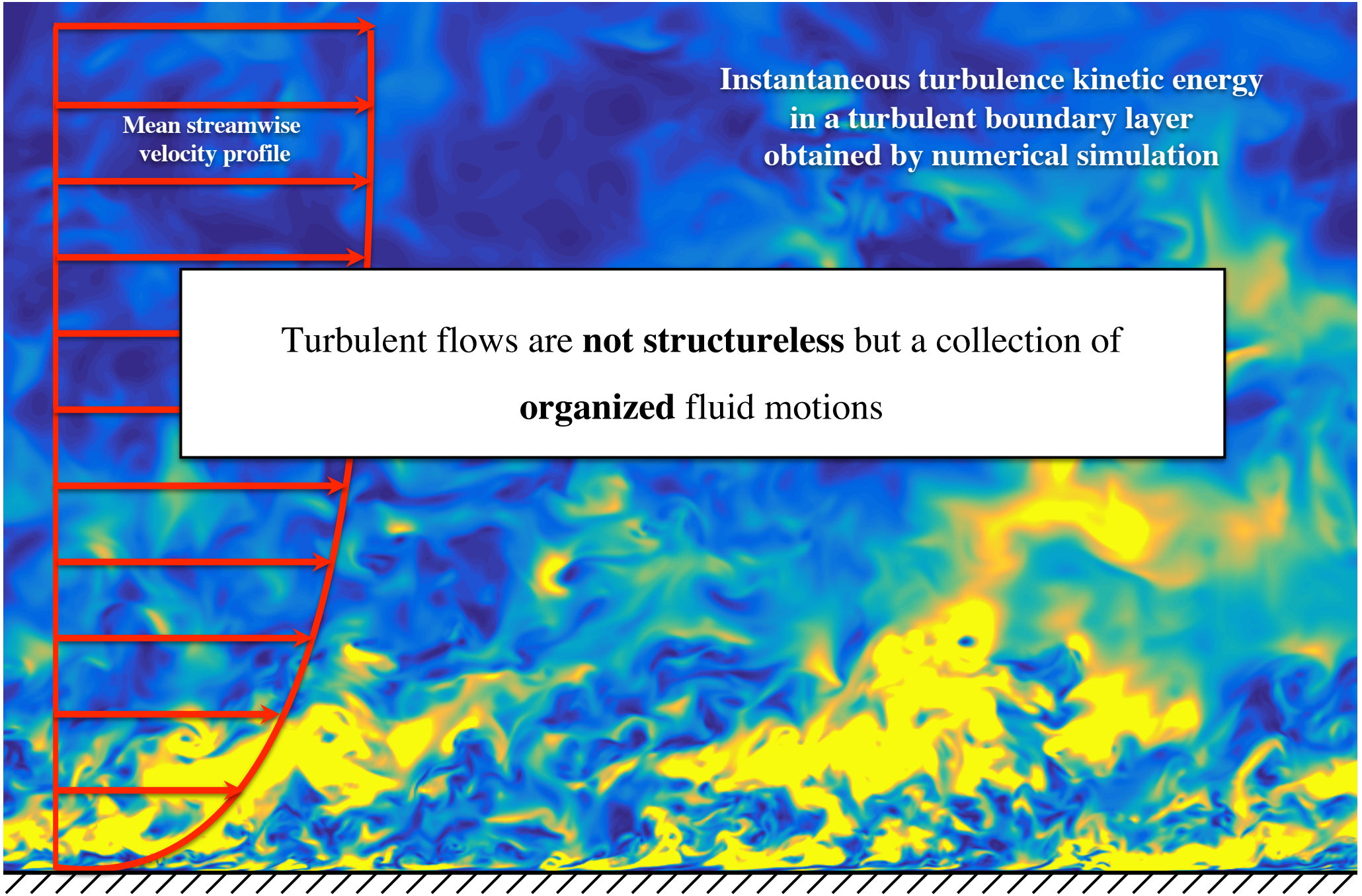


Why wall-modeled LES?



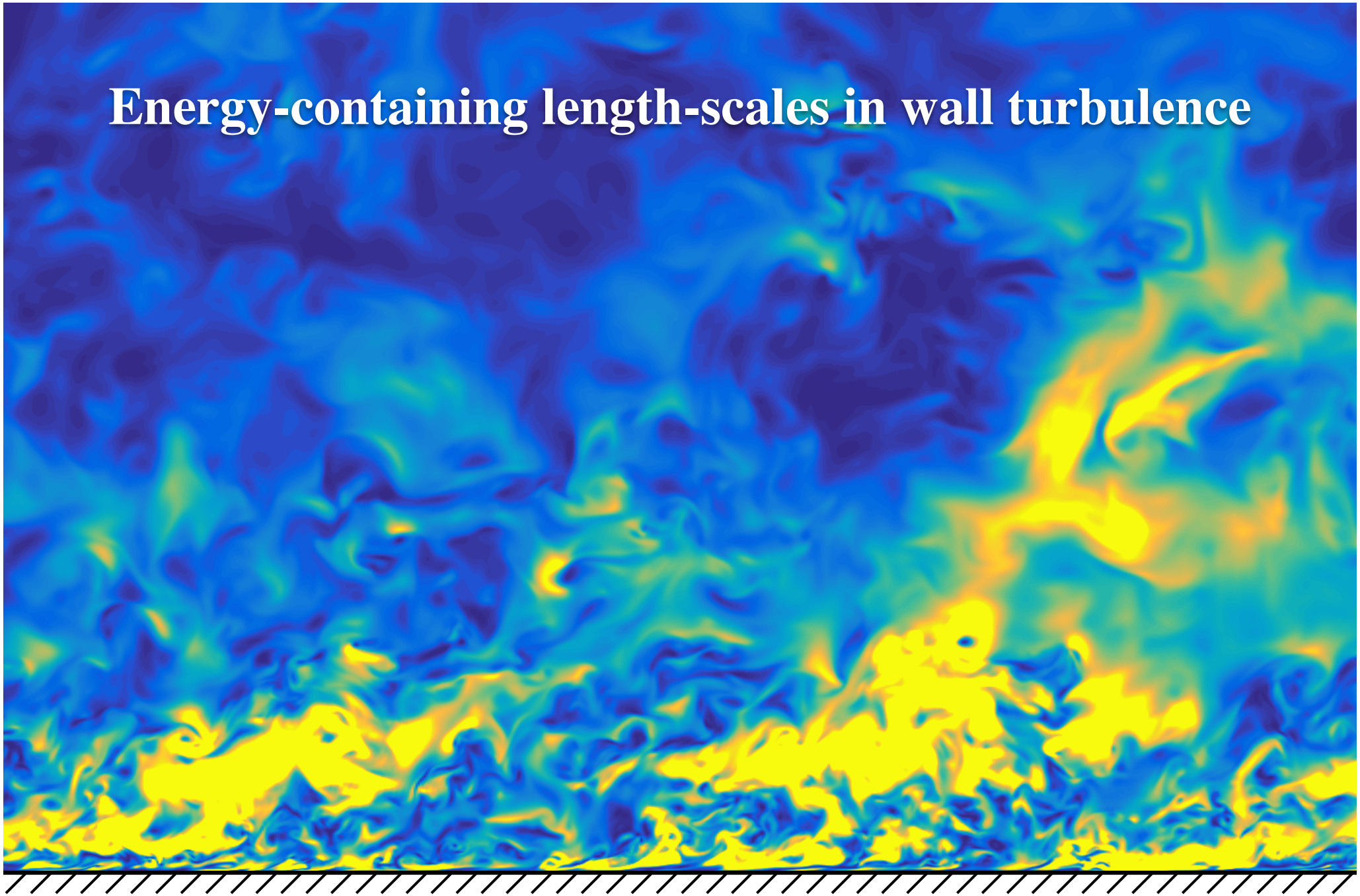


Data from Lozano-Durán & Jiménez 2014



Data from Lozano-Durán & Jiménez 2014

Energy-containing length-scales in wall turbulence

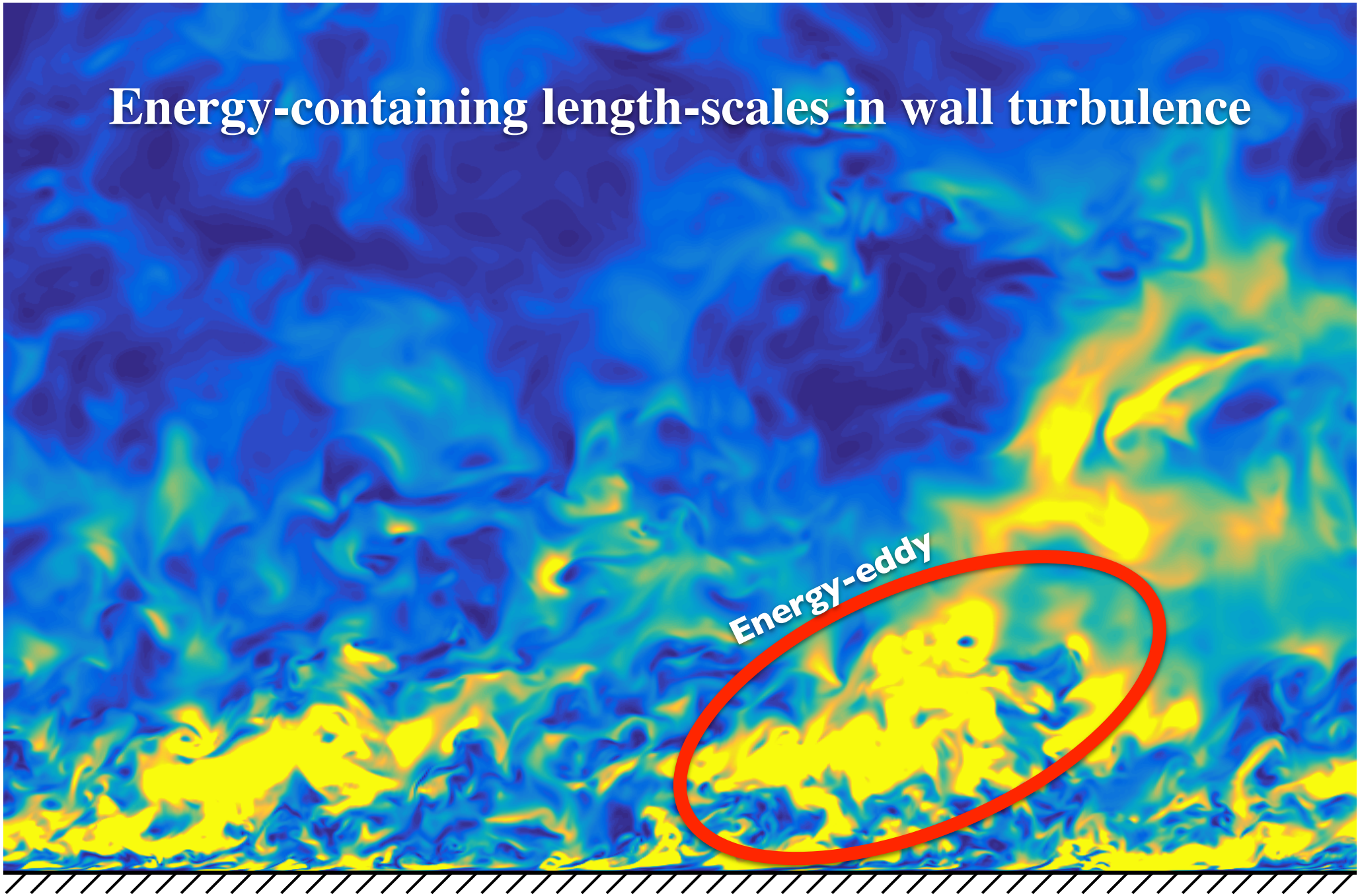


wall

colors are high (yellow) and low (blue) turbulence kinetic energy

Data from Lozano-Durán & Jiménez 2014

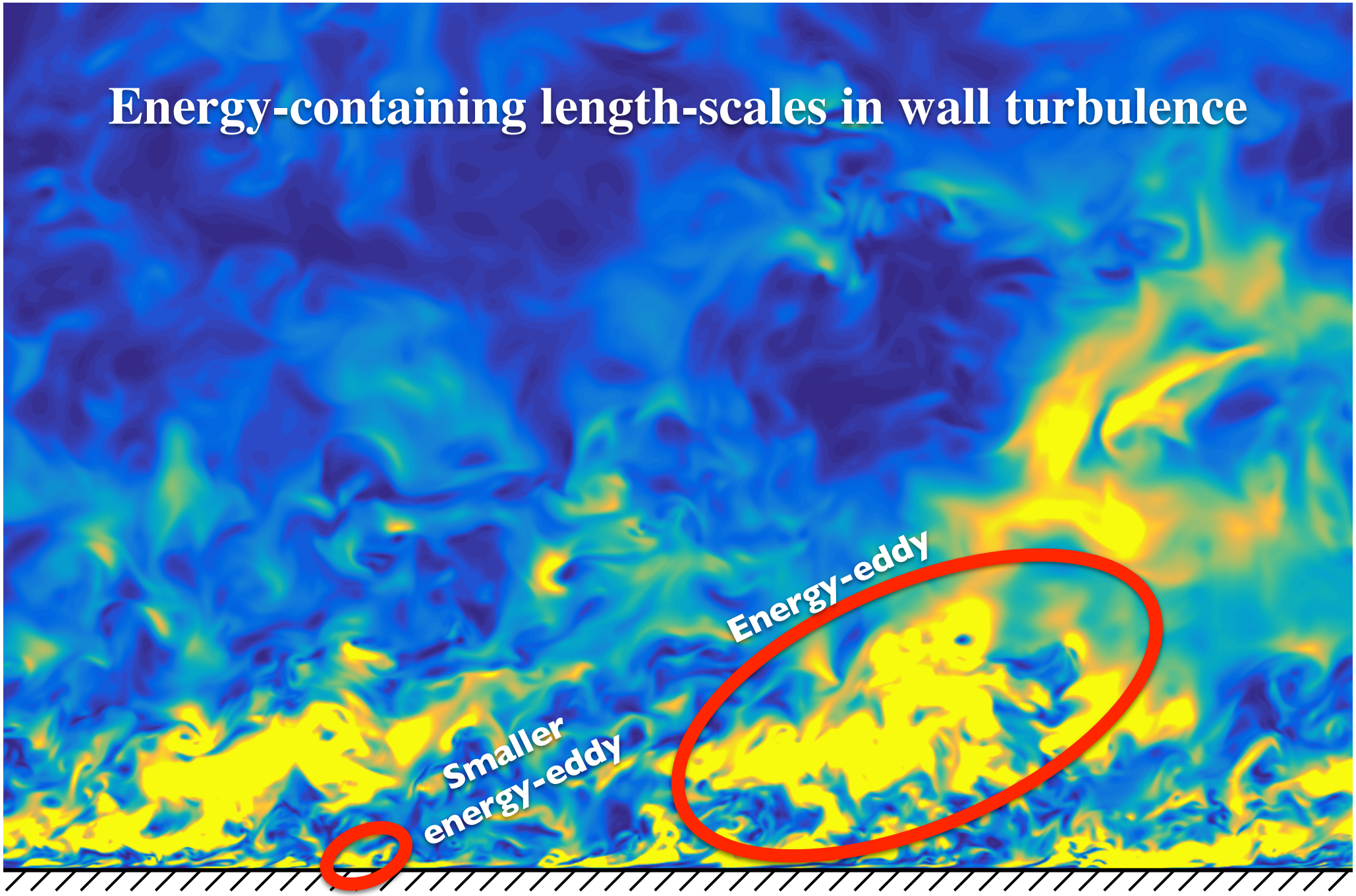
Energy-containing length-scales in wall turbulence



colors are high (yellow) and low (blue) turbulence kinetic energy

Tennekes & Lumley 1972

Energy-containing length-scales in wall turbulence



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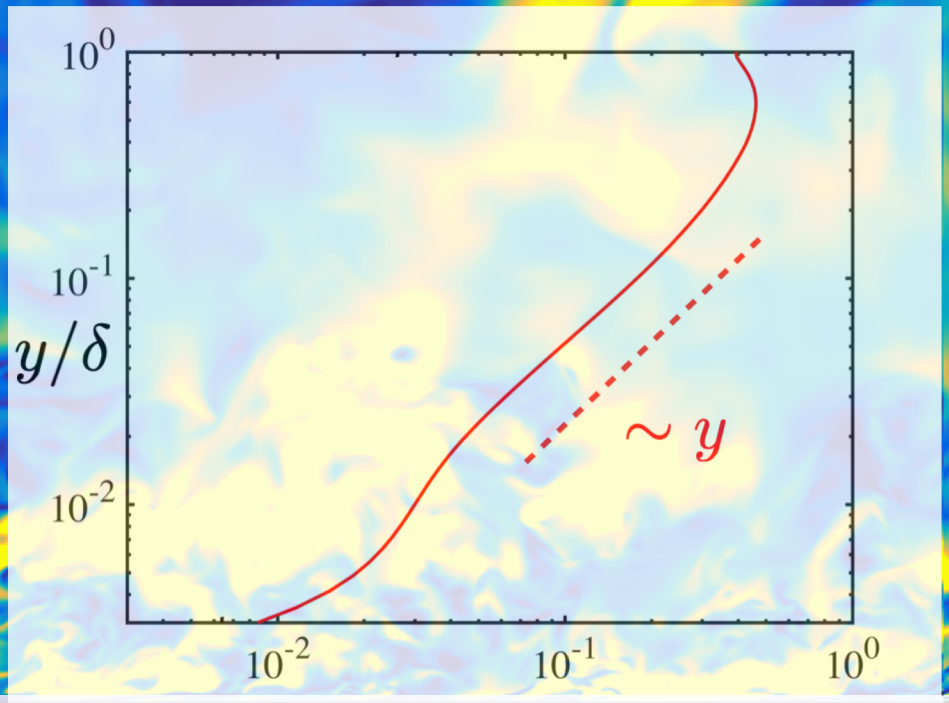
Tennekes & Lumley 1972

Energy-containing length-scales in wall turbulence

y

Energy length-scale $L_e = \dfrac{u'^3}{\varepsilon}$

(integral length-scale)



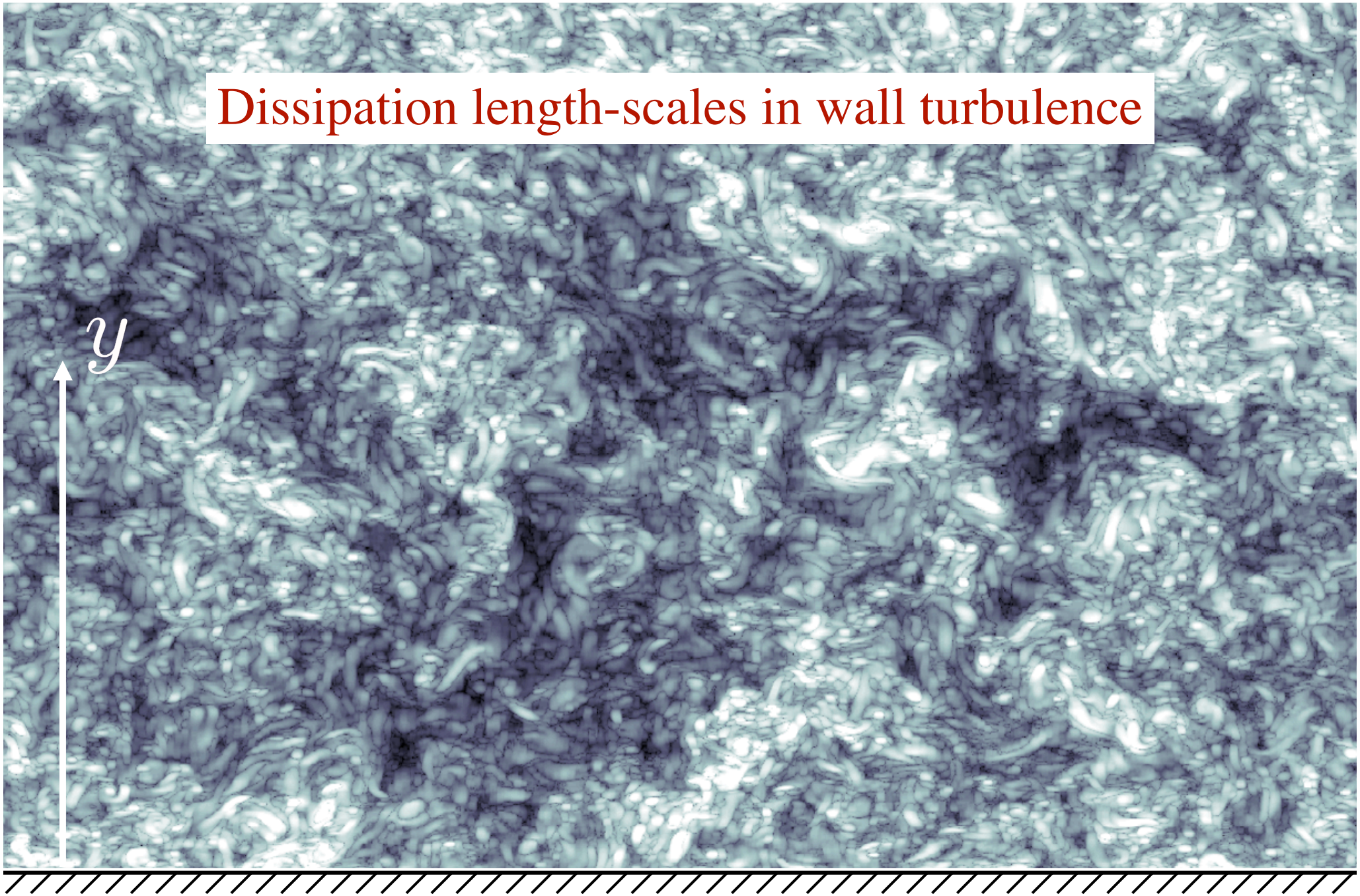
wall

u' characteristic fluctuation velocity

ε rate of dissipation of turbulence kinetic energy per unit mass

Tennekes & Lumley 1972

Dissipation length-scales in wall turbulence



colors are high (light) and low (dark) dissipation

Dissipation length-scales in wall turbulence

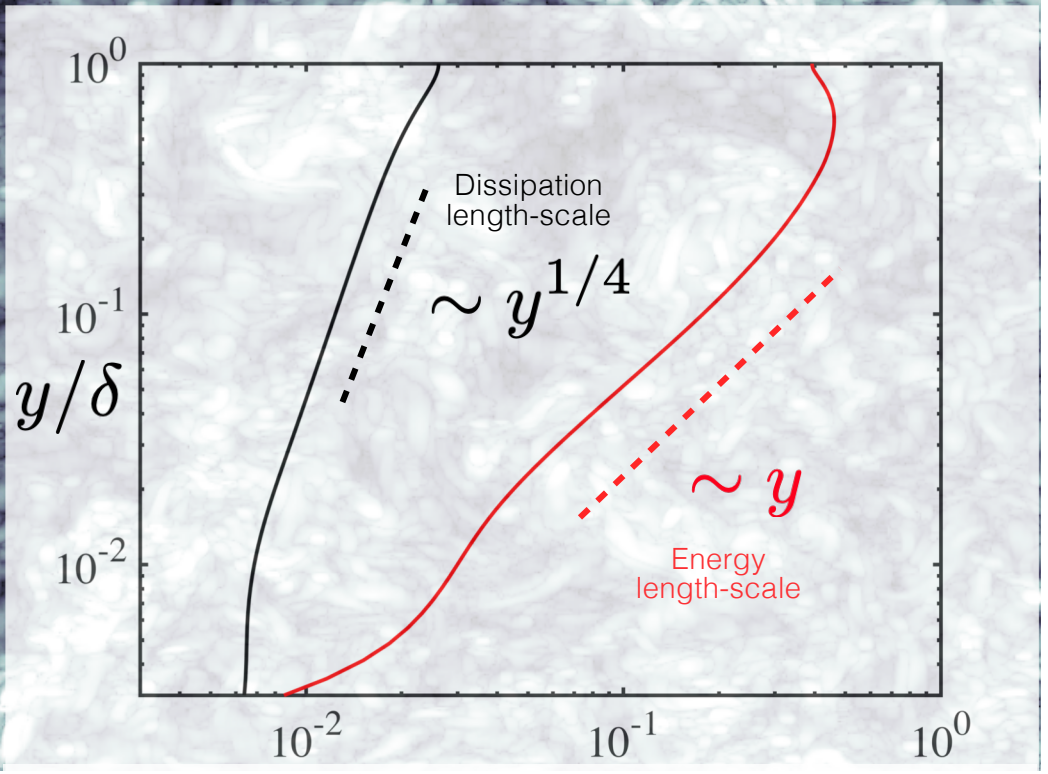
y

Energy length-scale (integral)

$$L_e = \frac{u'^3}{\varepsilon}$$

Dissipation length-scale (Kolmogorov)

$$L_d = \frac{\nu^{3/4}}{\varepsilon^{1/4}}$$



wall

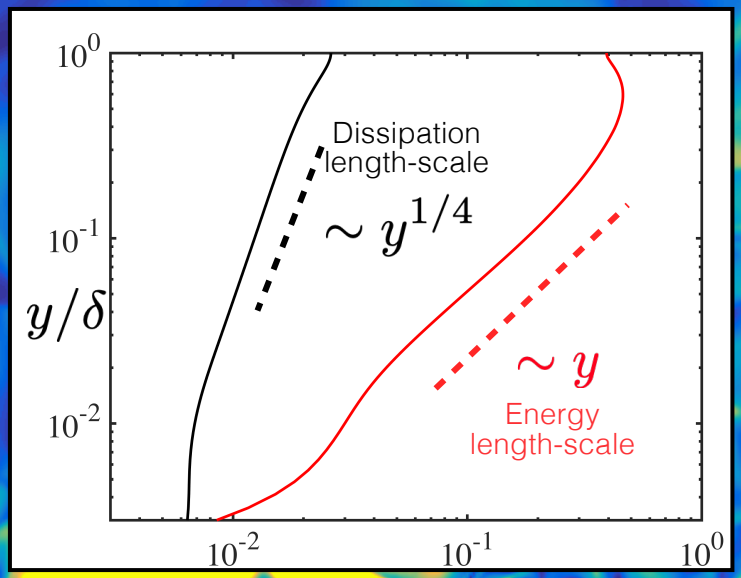
ε rate of dissipation of turbulence kinetic energy per unit mass

Tennekes & Lumley 1972

Grid requirements for DNS of wall turbulence

Navier-Stokes equations

$$\frac{\partial u_i}{\partial t} = -\frac{\partial u_i u_j}{\partial x_j} - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_k \partial x_k}$$



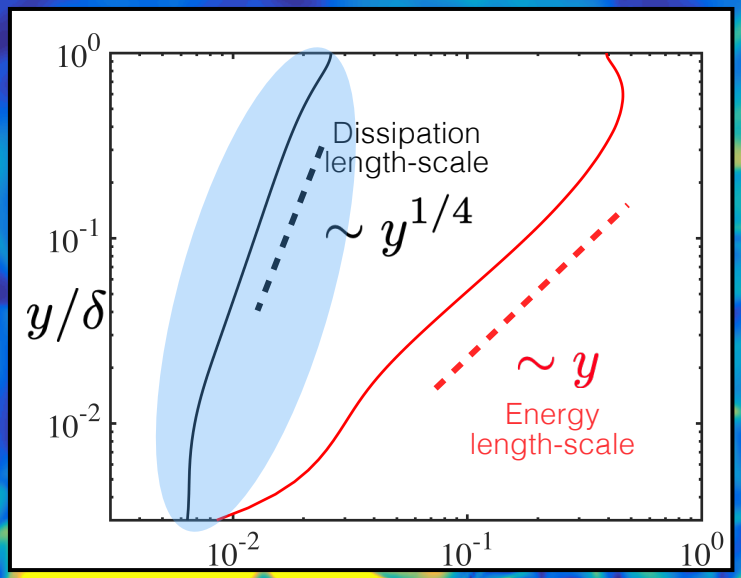
y

Lozano-Durán & Bae, JCP (2019)

Grid requirements for DNS of wall turbulence

Navier-Stokes equations

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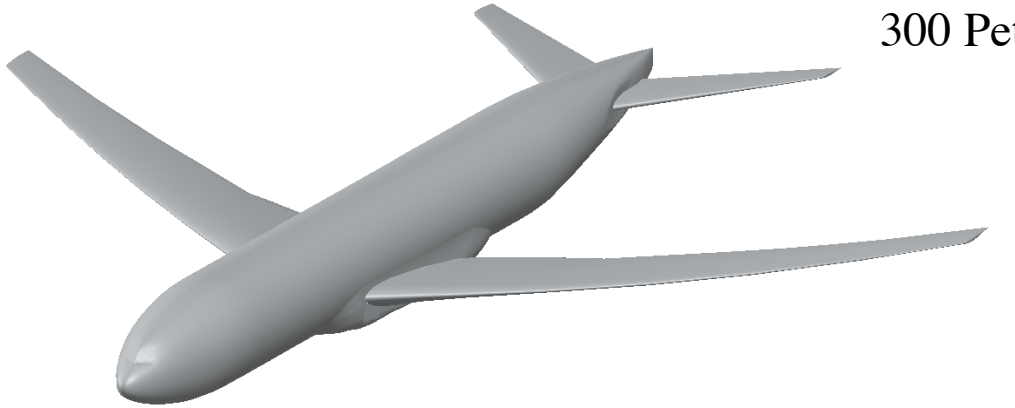


Lozano-Durán & Bae, JCP (2019)

Grid requirements for DNS of wall turbulence

Cost of DNS

$$N_{\text{points}} \sim \text{Re}^{2.5} \qquad N_{\text{points}} \sim 10^{16}$$
$$\Delta t \sim \text{Re}^{-1} \qquad N_{\text{steps}} \sim 10^{8}$$



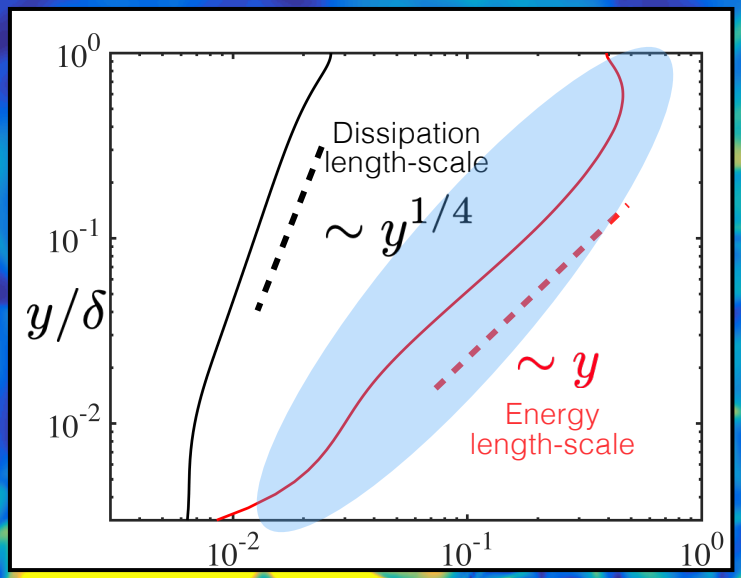
300 Petabytes per flow field

Lozano-Durán & Bae, JCP (2019)

Grid requirements for wall-resolved LES

Wall-resolved LES approach

$$\frac{\partial \bar{u}_i}{\partial t} = -\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_k \partial x_k} - \frac{\partial \tau_{ij}^{\mathrm{SGS}}}{\partial x_j}$$



y

$\bar{u}_i = 0$

Grid requirements for wall-resolved LES

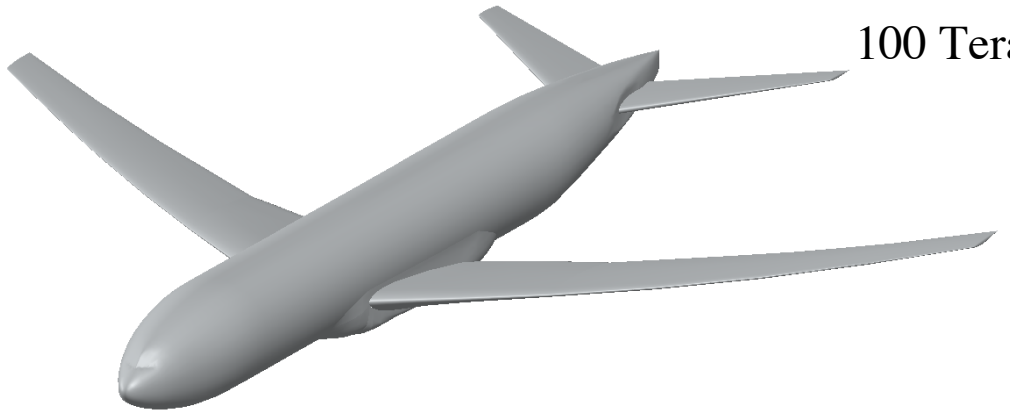
Cost of wall-resolved LES

$$N_{\text{points}} \sim \text{Re}^2$$

$$\Delta t \sim \text{Re}^{-1}$$

$$N_{\text{points}} \sim 10^{12}$$

$$N_{\text{steps}} \sim 10^{8}$$

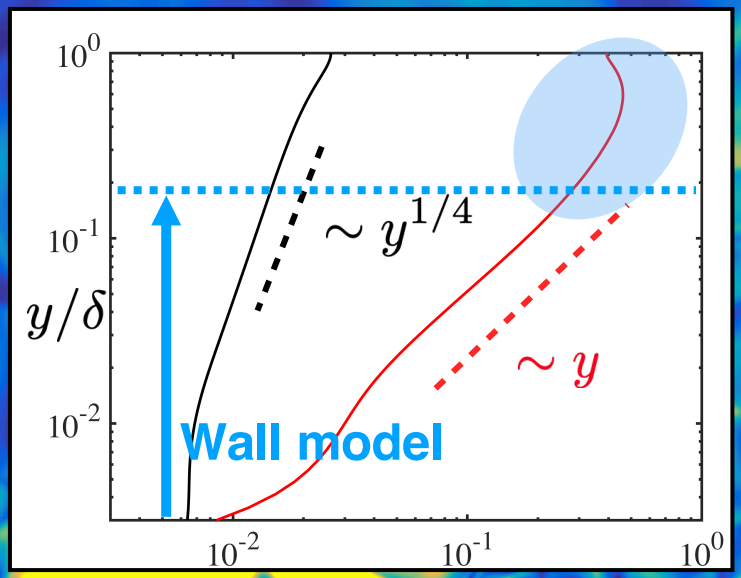


100 Terabytes per flow field

Grid requirements for wall-modeled LES

Wall-modeled LES approach

$$\frac{\partial \bar{u}_i}{\partial t} = -\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_k \partial x_k} - \frac{\partial \tau_{ij}^{\mathrm{SGS}}}{\partial x_j}$$

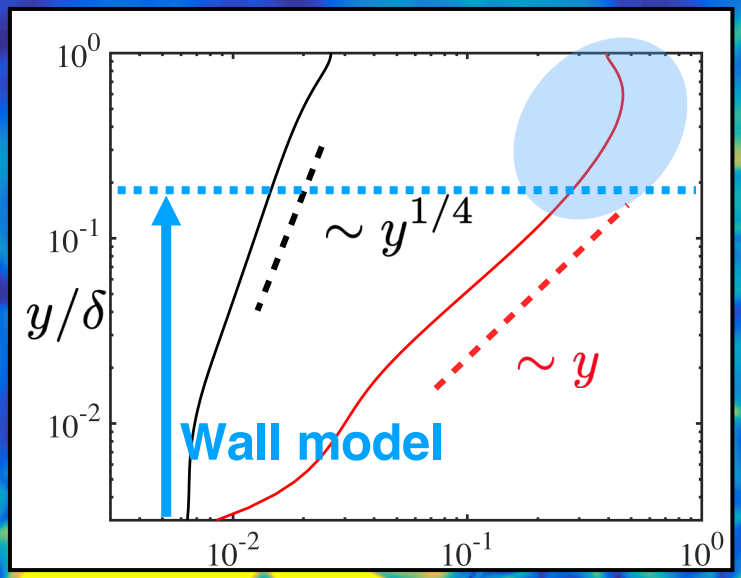


y

Grid requirements for wall-modeled LES

Wall-modeled LES approach

$$\frac{\partial \bar{u}_i}{\partial t} = -\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_k \partial x_k} - \frac{\partial \tau_{ij}^{\mathrm{SGS}}}{\partial x_j}$$



y

$\bar{u}_i \neq 0$

Grid requirements for wall-modeled LES

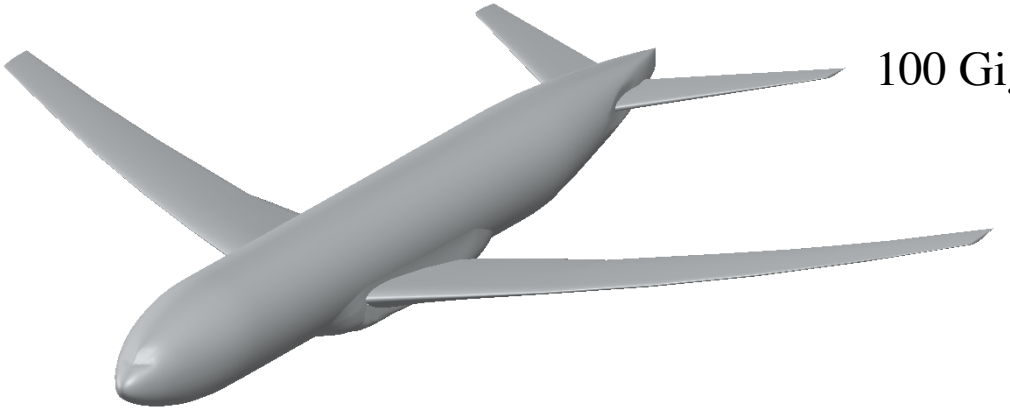
Cost of wall-modeled LES

$$N_{\text{points}} \sim \text{Re}$$

$$\Delta t \sim \text{Re}^{-0.15}$$

$$N_{\text{points}} \sim 10^{8-9}$$

$$N_{\text{steps}} \sim 10^{6}$$



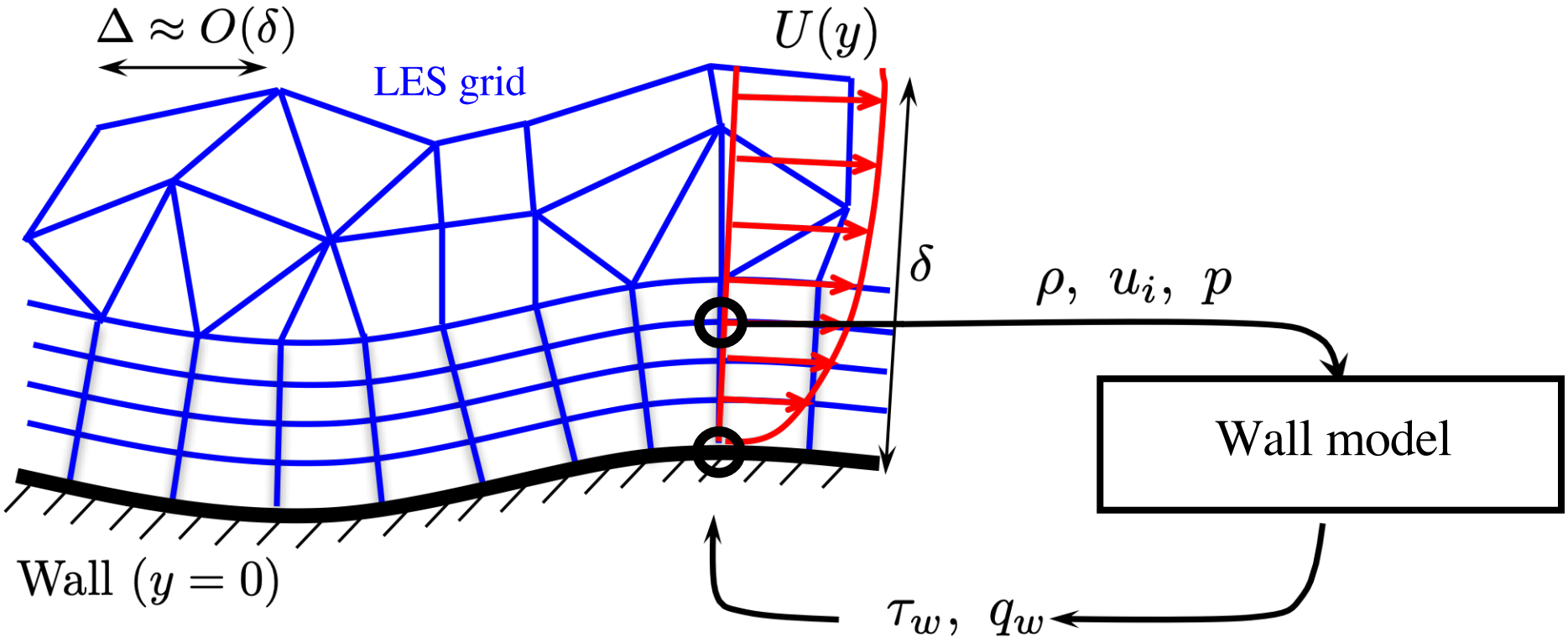
100 Gigabytes per flow field

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- **What** is wall-modeled LES?
- **Accuracy** & **Cost** of wall-modeled LES for external aerodynamics:
  - Prediction of lift & drag forces: JSM high-lift.
  - Prediction of mean velocity, Reynolds stresses, pressure coefficient & separation: NASA Juncture flow.

What wall-modeled LES?

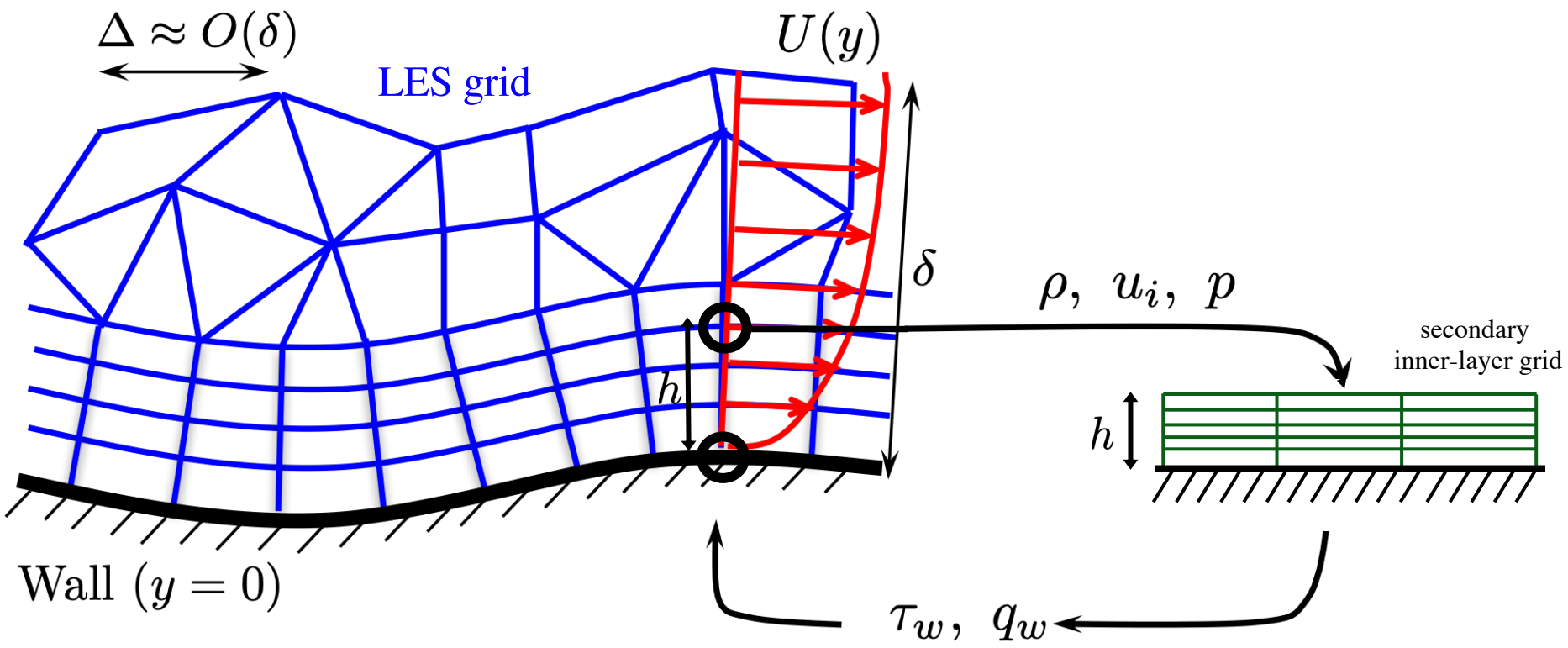
Compute only the outer layer using a grid that does not resolve the inner layer, while modeling the transport of momentum and heat from the inner- to the outer layer.



fluxes imposed as boundary condition for LES

Larsson *et al.* (2016)
Bose & Park (2018)

Wall-modeling methodologies

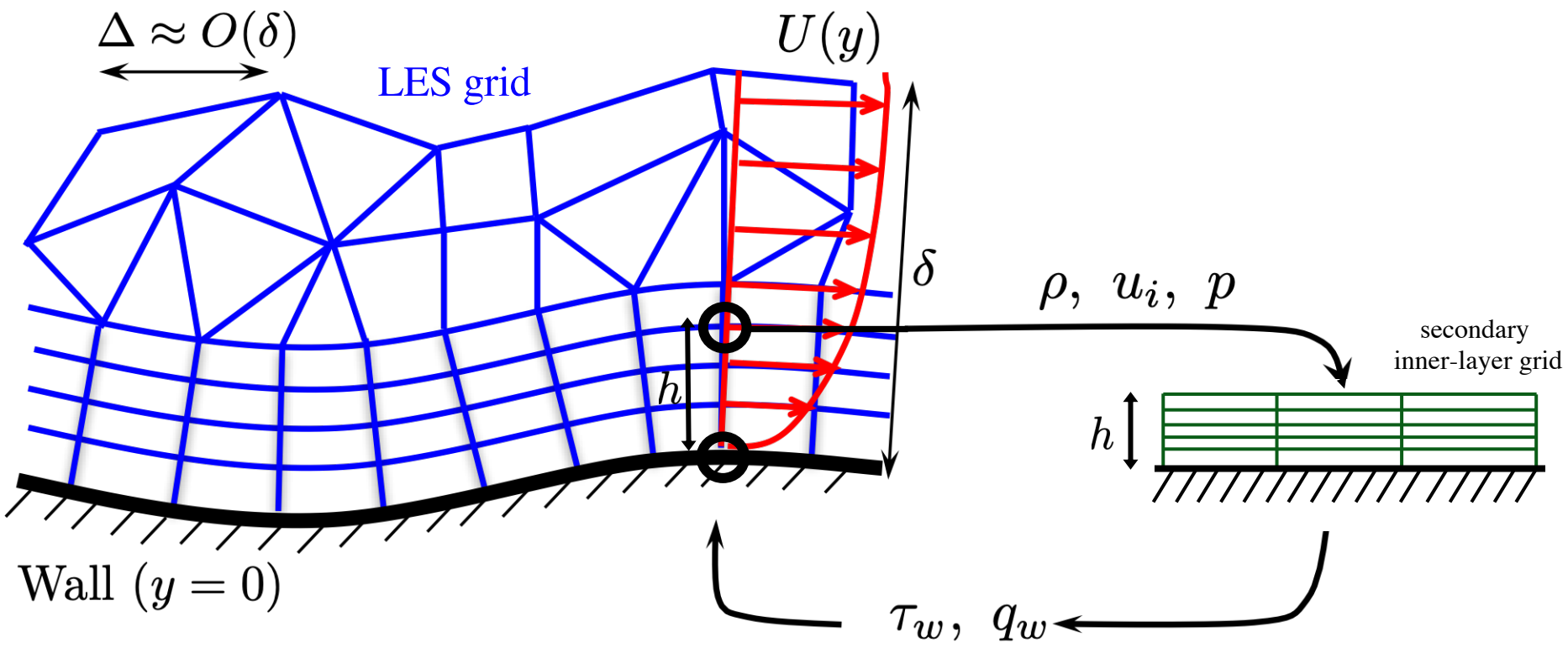


RANS: PDE non-equilibrium wall models:

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} + \frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} = \frac{\partial}{\partial x_k}\left[(\nu + \nu_R)\frac{\partial \tilde{u}_i}{\partial x_k}\right]$$

Balaras *et al.* (1996)
Wang & Moin (2002)
Kawai & Larsson (2013)
Park & Moin (2014, 2016)
...

Wall-modeling methodologies

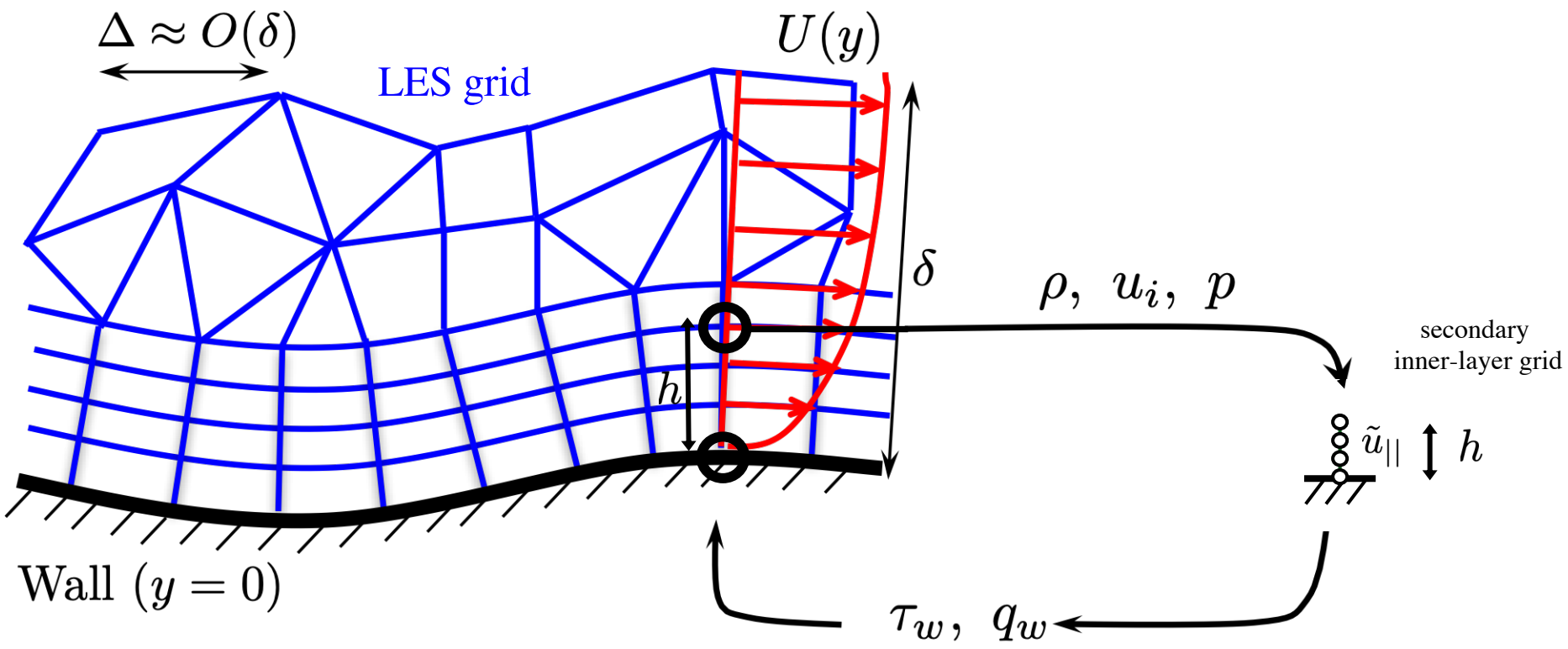


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$$\cancel{\frac{\partial \tilde{u}_i}{\partial t}} + \cancel{\frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j}} + \cancel{\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i}} = \frac{\partial}{\partial x_k}\left[(\nu + \nu_R)\frac{\partial \tilde{u}_i}{\partial x_k}\right]$$

Balaras *et al.* (1996)
Wang & Moin (2002)
Kawai & Larsson (2013)
Park & Moin (2014, 2016)
...

Wall-modeling methodologies



ODE equilibrium wall-models:

$$\frac{d}{dy}\left[(\mu + \mu_{t,\mathrm{wm}})\frac{du_\parallel}{dy}\right] = 0$$

$$\frac{d}{dy}\left[(\mu + \mu_{t,\mathrm{wm}})u_\parallel\frac{du_\parallel}{dy} + c_p\left(\frac{\mu}{Pr} + \frac{\mu_{t,\mathrm{wm}}}{Pr_{t,\mathrm{wm}}}\right)\frac{dT}{dy}\right] = 0$$

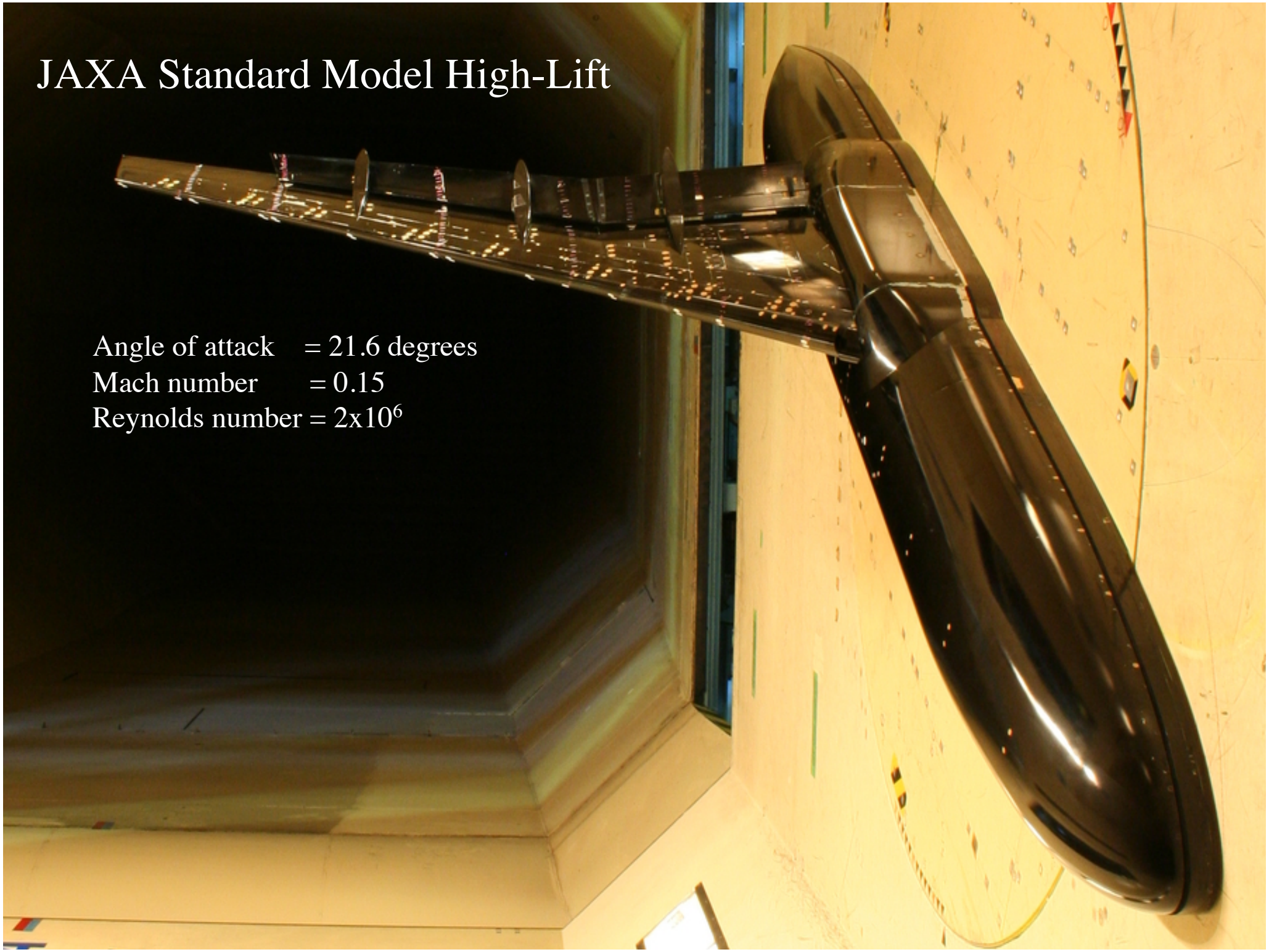
Kawai & Larsson (2012)
Bodart & Larsson (2012)
Yang *et al.* (2015)

...

Outline

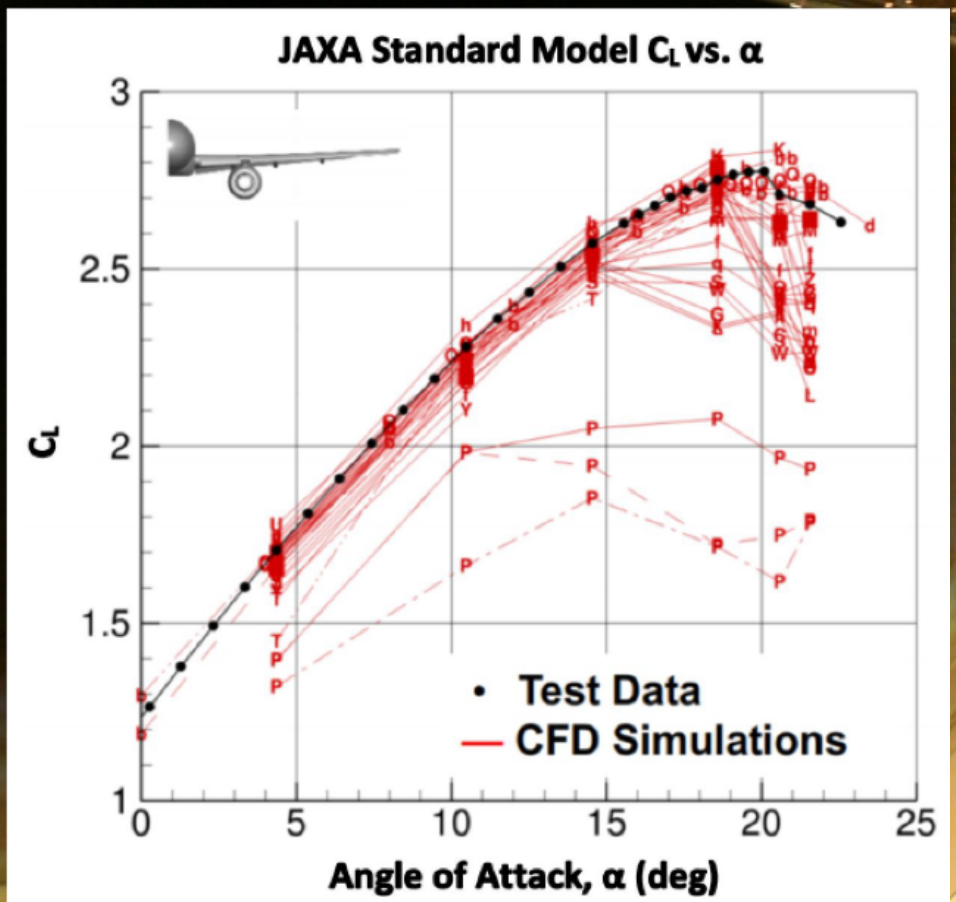
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JAXA Standard Model High-Lift

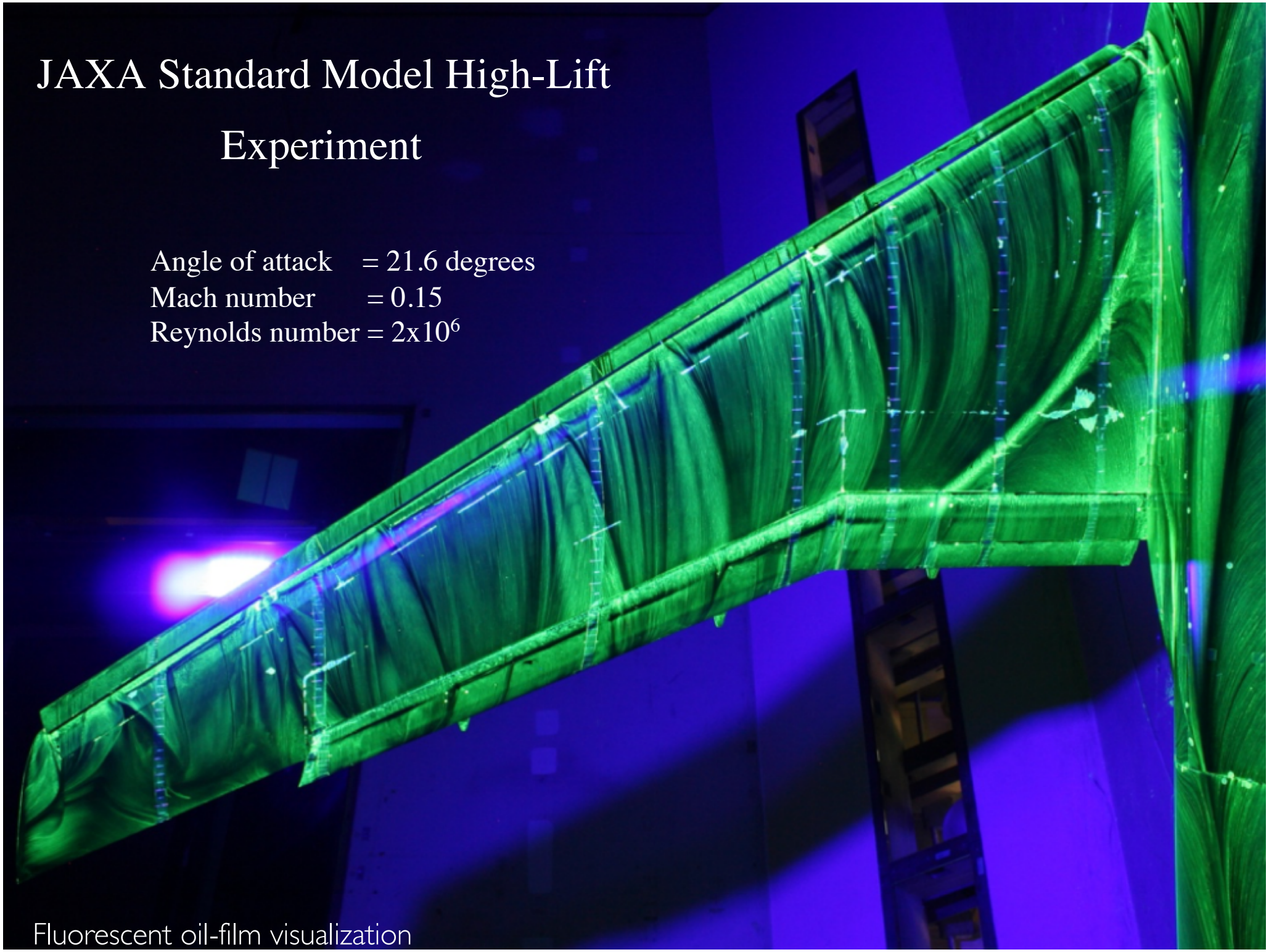


Angle of attack = 21.6 degrees
Mach number = 0.15
Reynolds number = 2×10^6

JAXA Standard Model High-Lift



Rumsey et al. "Overview and summary of the third AIAA High Lift Prediction Workshop." *2018 AIAA Aerospace Sciences Meeting*. 2018.

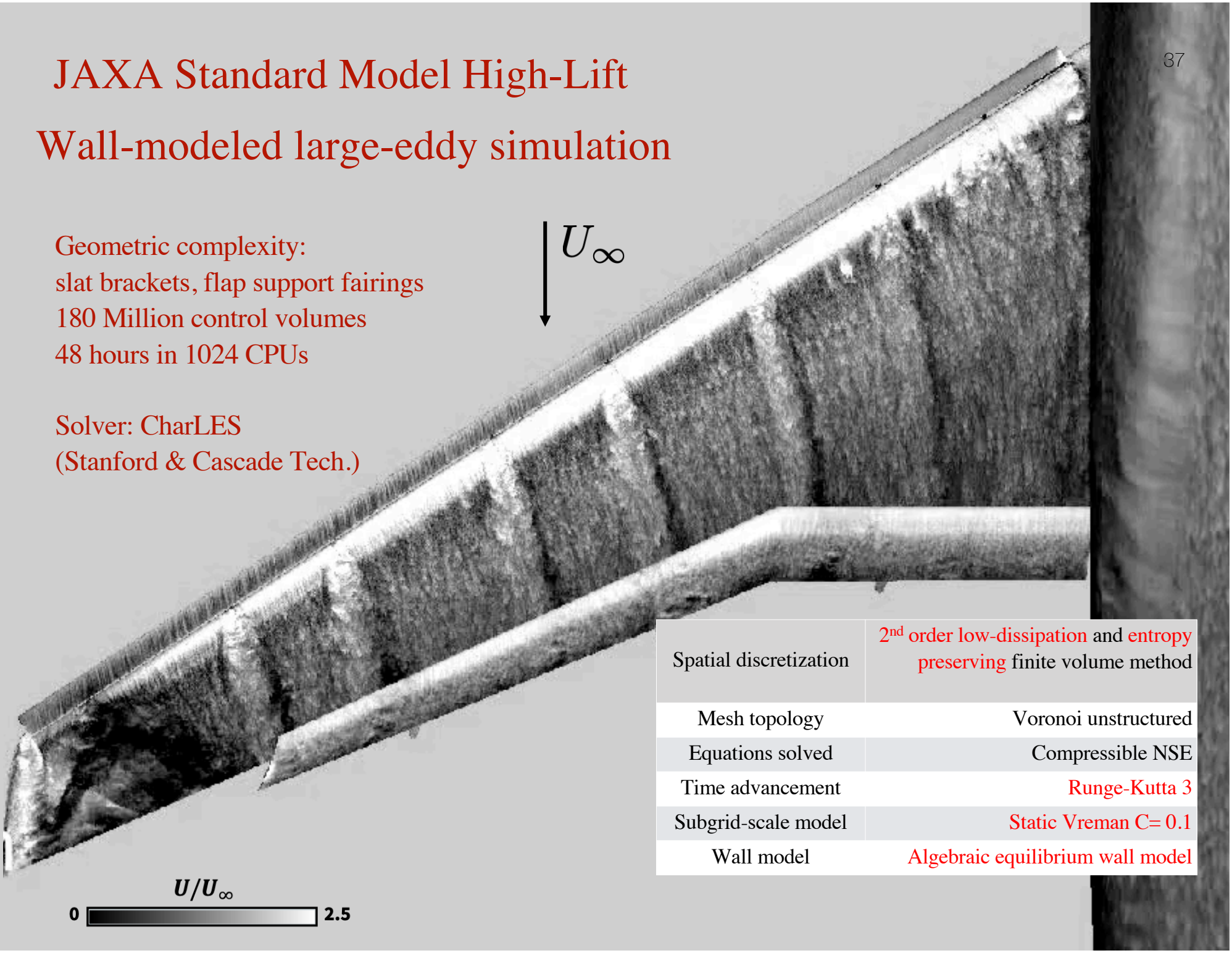

JAXA Standard Model High-Lift
Experiment
Angle of attack = 21.6 degrees
Mach number = 0.15
Reynolds number = 2x10^6
Fluorescent oil-film visualization

JAXA Standard Model High-Lift

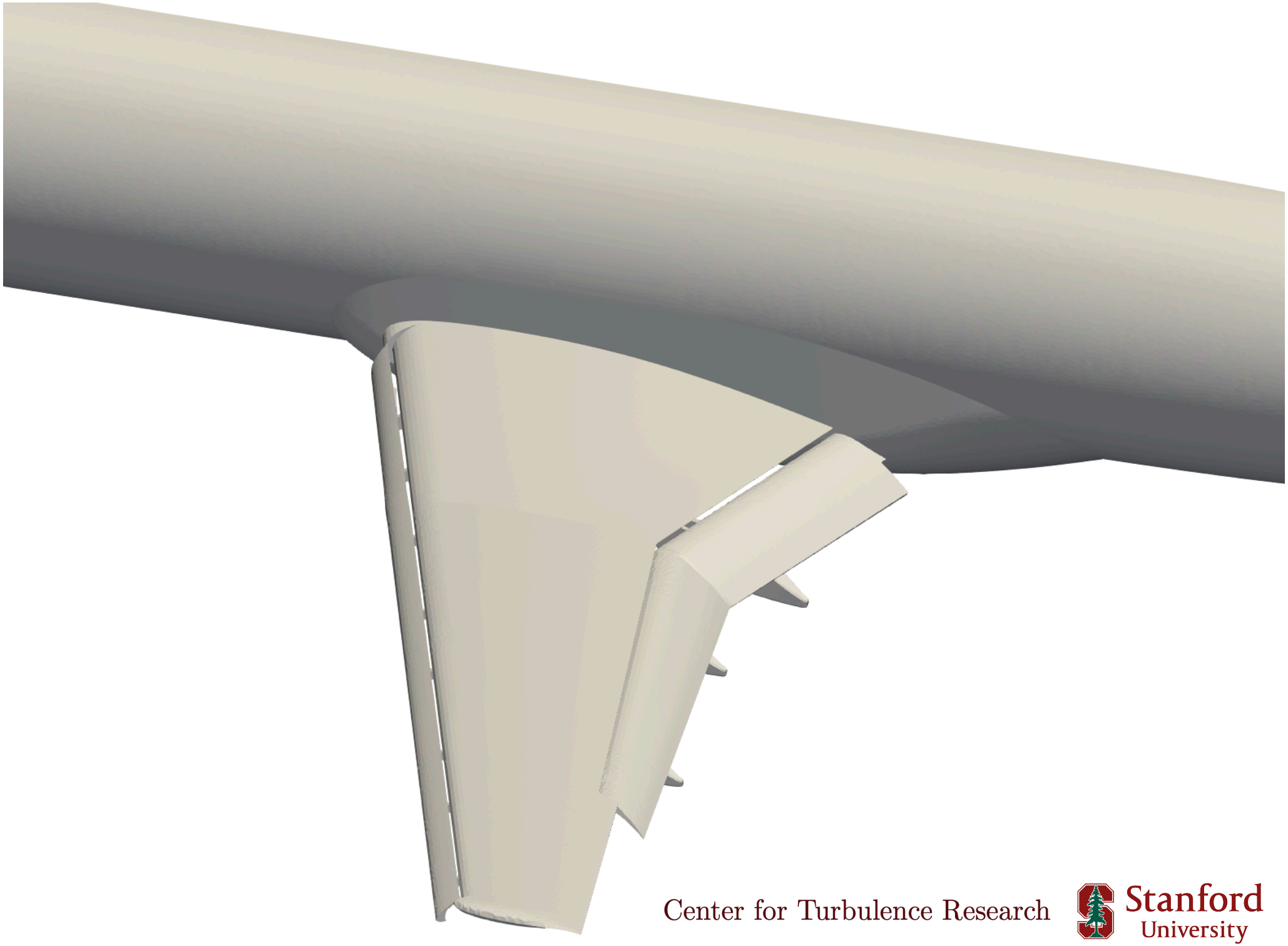
Wall-modeled large-eddy simulation

Geometric complexity:
slat brackets, flap support fairings
180 Million control volumes
48 hours in 1024 CPUs

Solver: CharLES
(Stanford & Cascade Tech.)



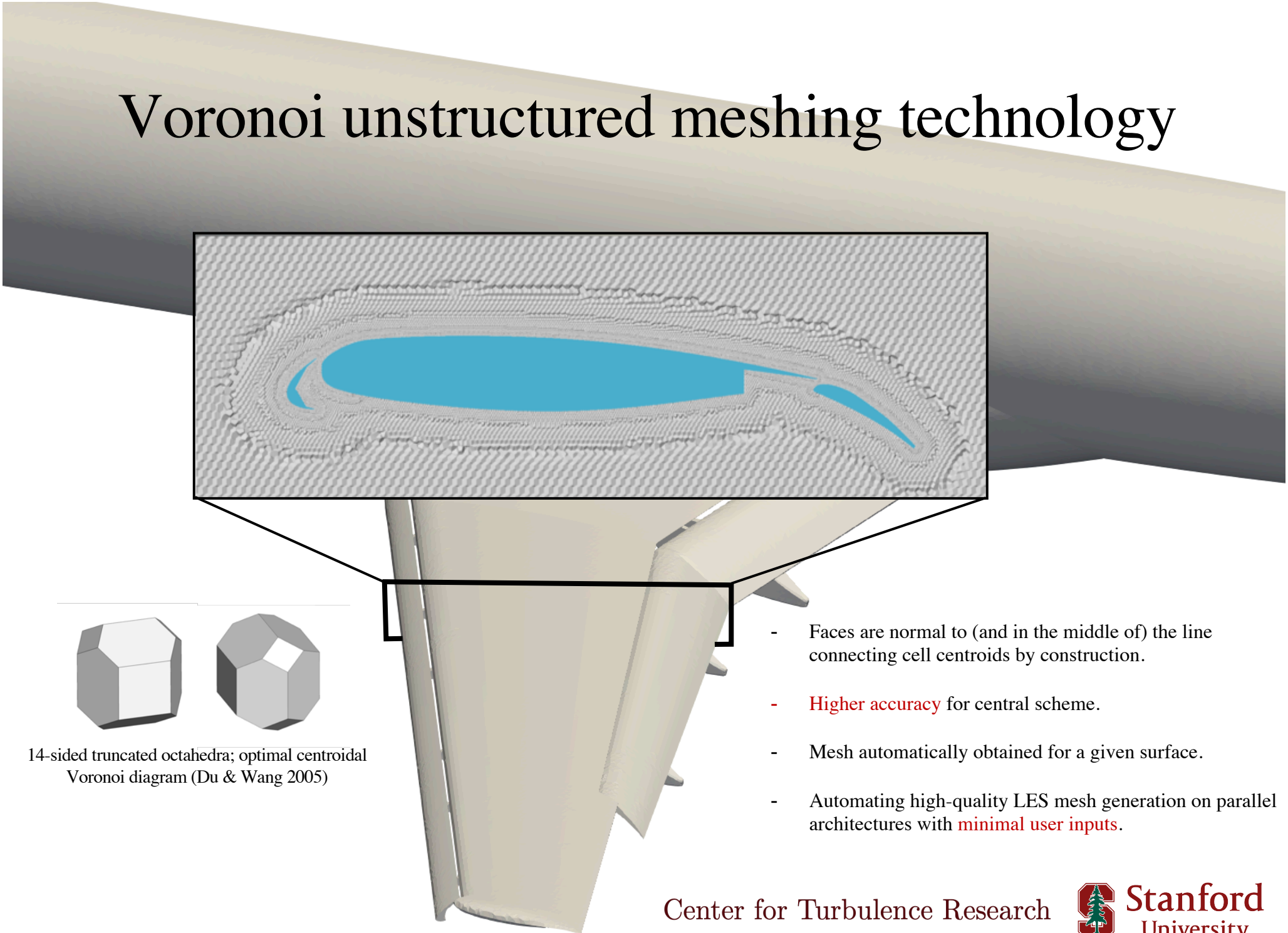
Spatial discretization	2nd order low-dissipation and entropy preserving finite volume method
Mesh topology	Voronoi unstructured
Equations solved	Compressible NSE
Time advancement	Runge-Kutta 3
Subgrid-scale model	Static Vreman C= 0.1
Wall model	Algebraic equilibrium wall model



Center for Turbulence Research

Stanford University

Voronoi unstructured meshing technology



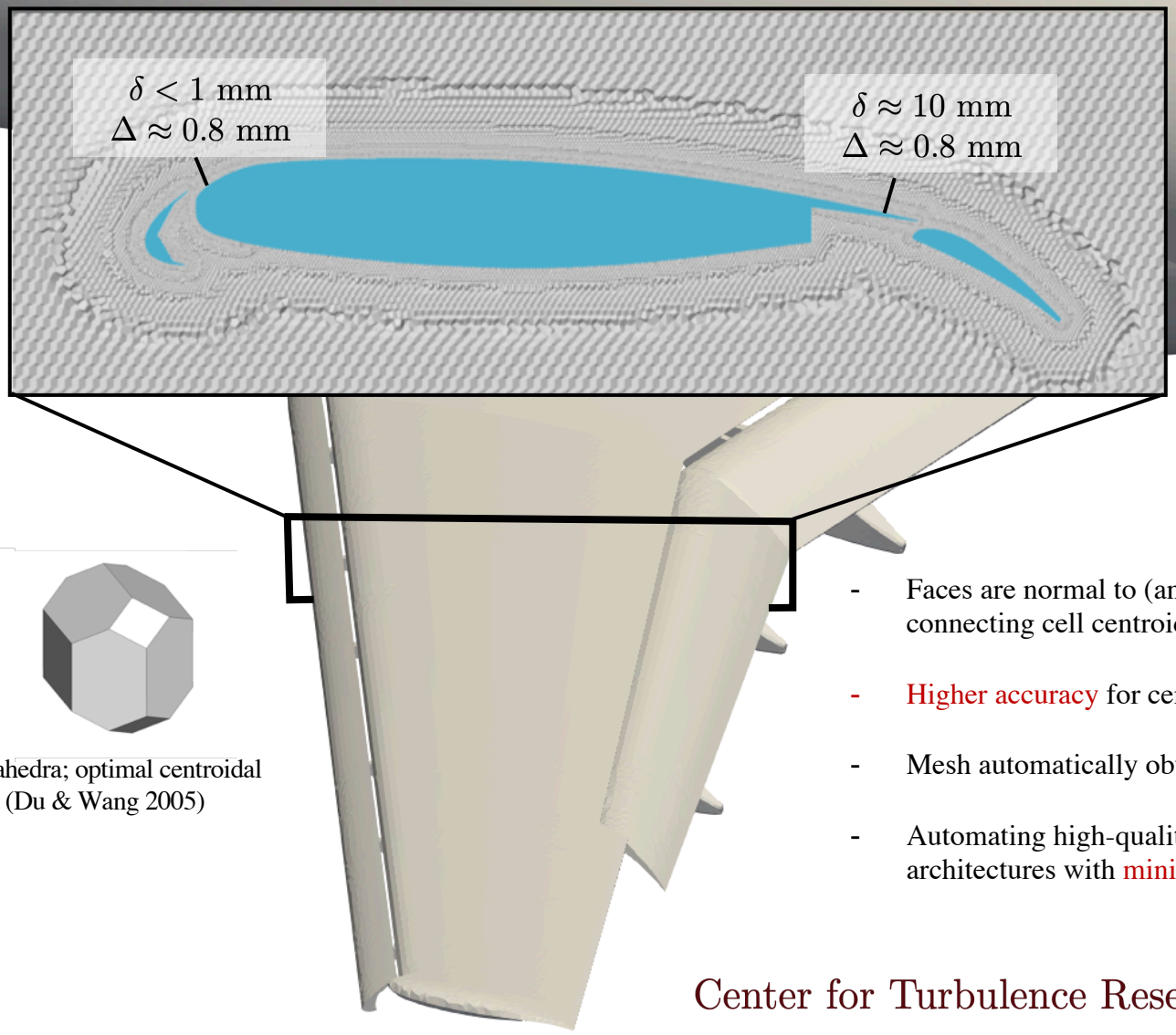
14-sided truncated octahedra; optimal centroidal Voronoi diagram (Du & Wang 2005)

- Faces are normal to (and in the middle of) the line connecting cell centroids by construction.
- Higher accuracy for central scheme.
- Mesh automatically obtained for a given surface.
- Automating high-quality LES mesh generation on parallel architectures with minimal user inputs.

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Voronoi unstructured meshing technology



Δ = grid resolution at wall

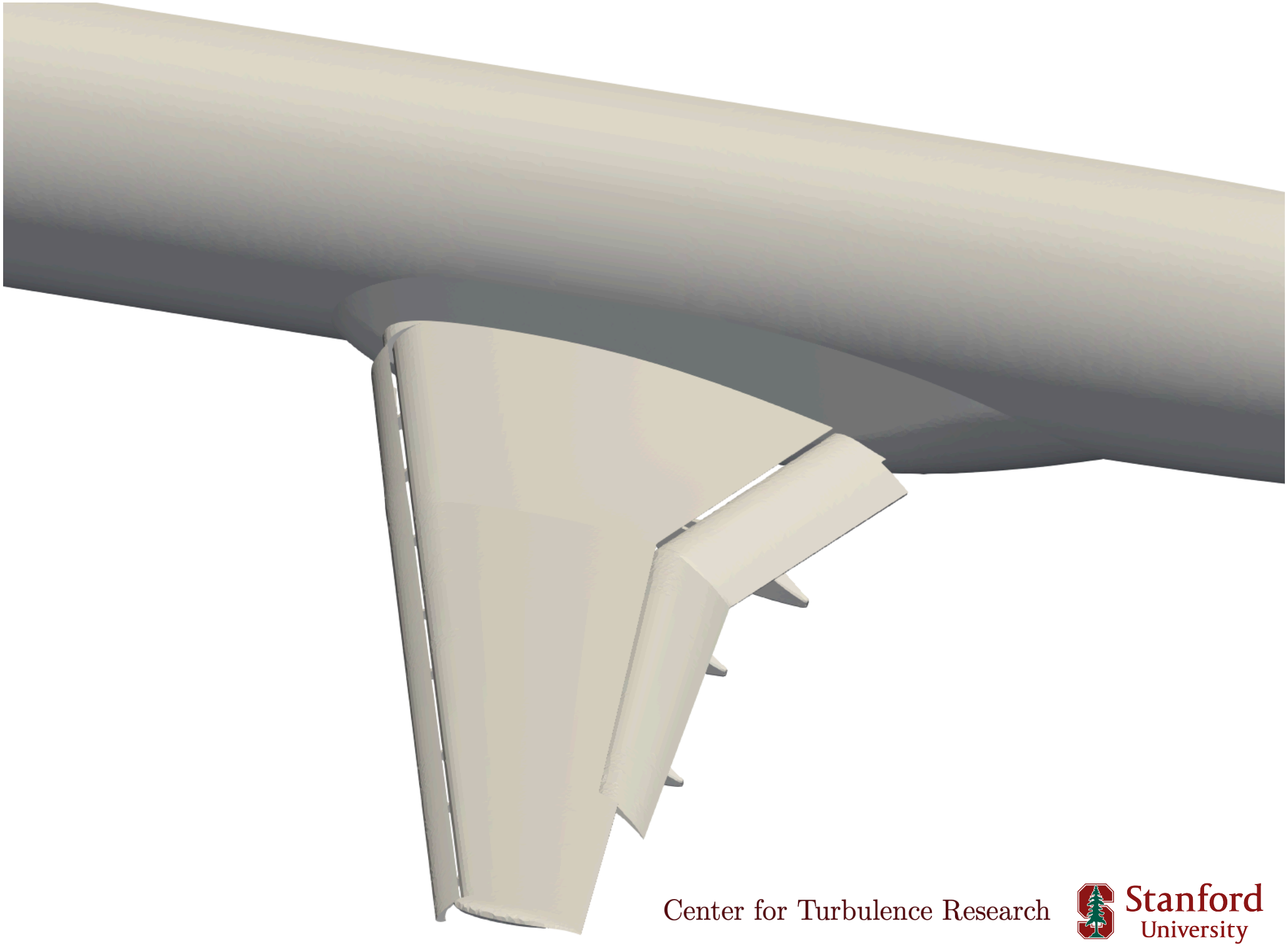
δ = 99% boundary layer thickness

14-sided truncated octahedra; optimal centroidal Voronoi diagram (Du & Wang 2005)

- Faces are normal to (and in the middle of) the line connecting cell centroids by construction.
- Higher accuracy for central scheme.
- Mesh automatically obtained for a given surface.
- Automating high-quality LES mesh generation on parallel architectures with minimal user inputs.

Center for Turbulence Research

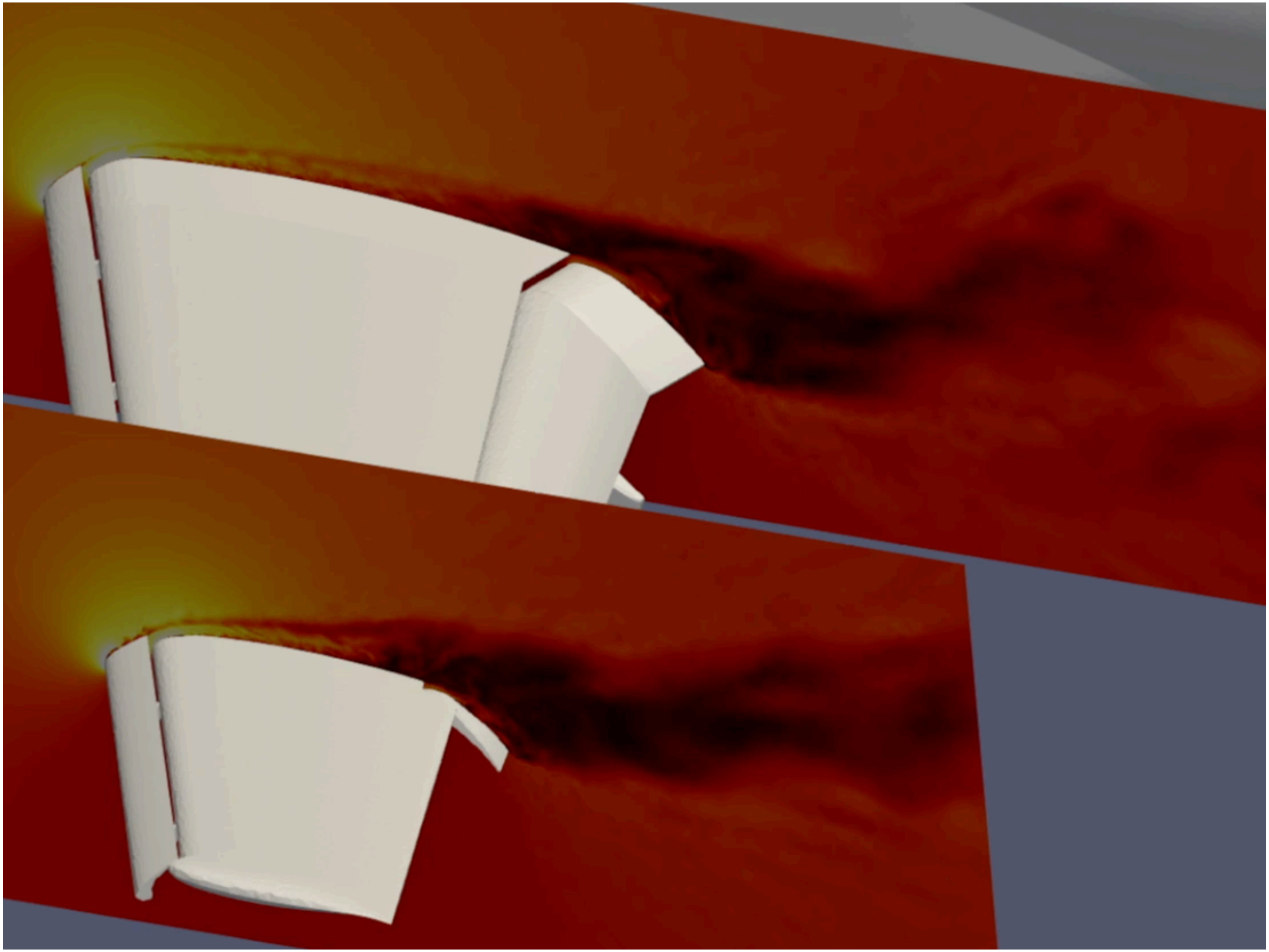
Stanford University



Center for Turbulence Research

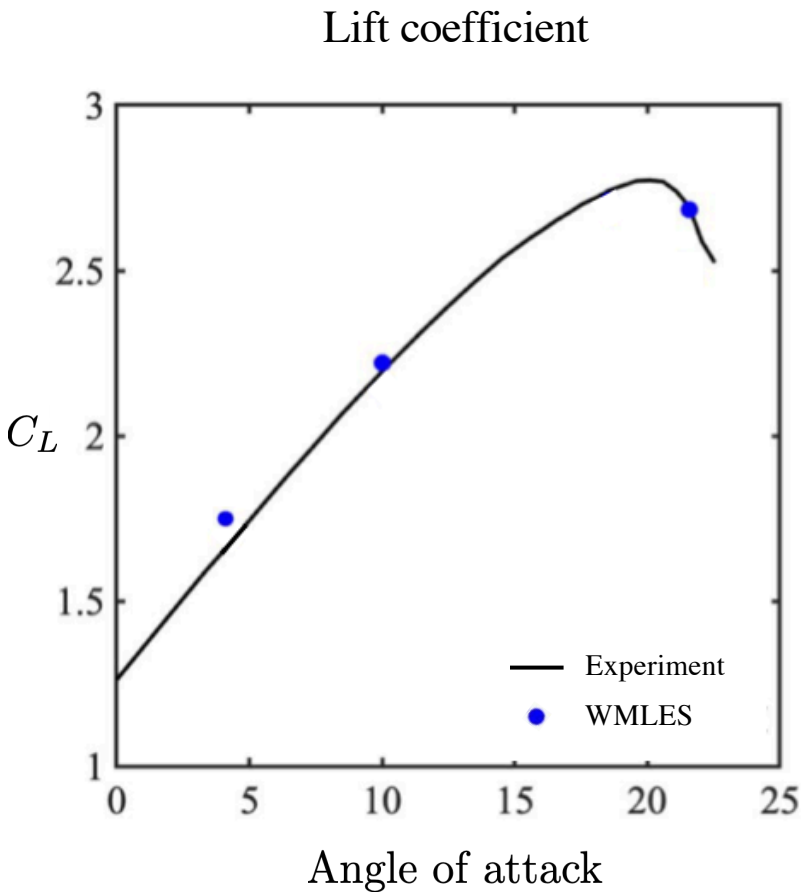
Stanford University

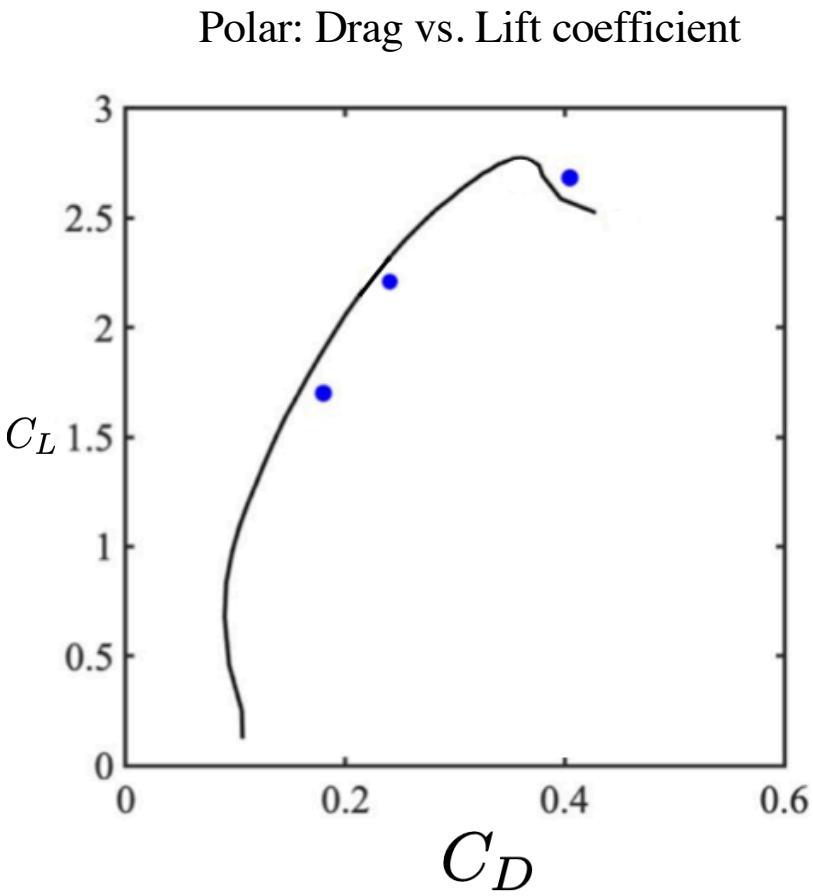




JAXA Standard Model High-Lift

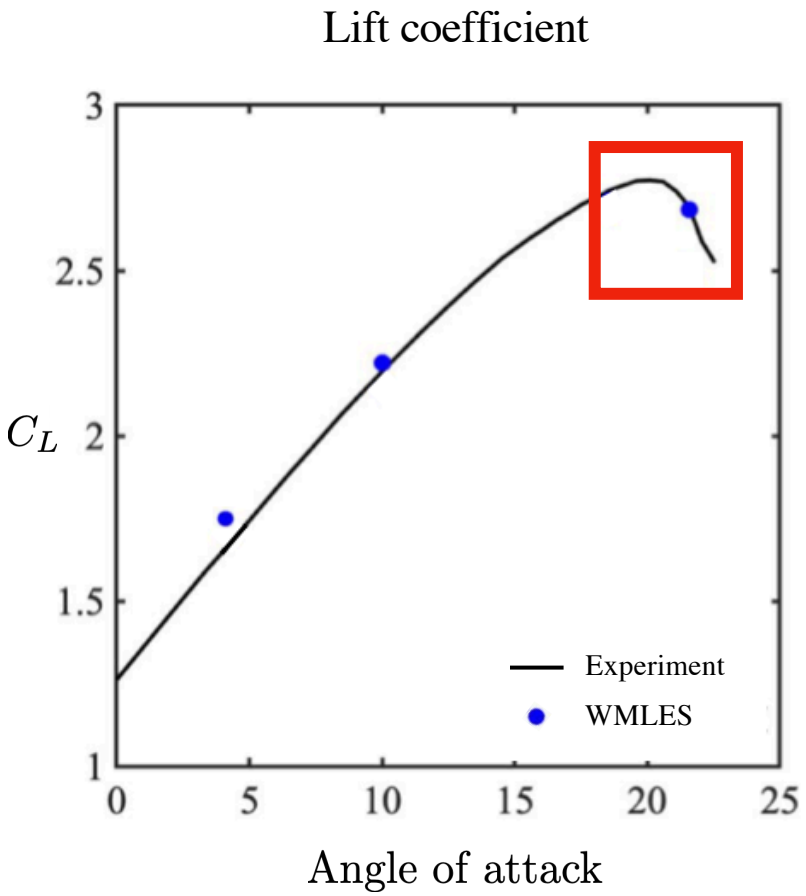
Wall-modeled large-eddy simulation

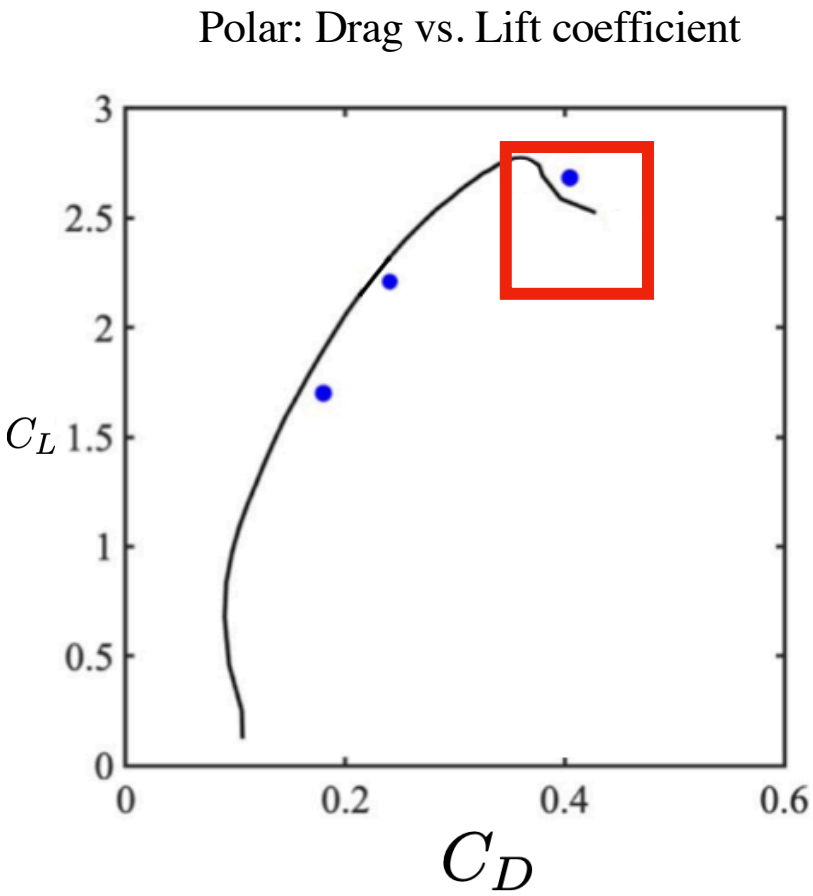




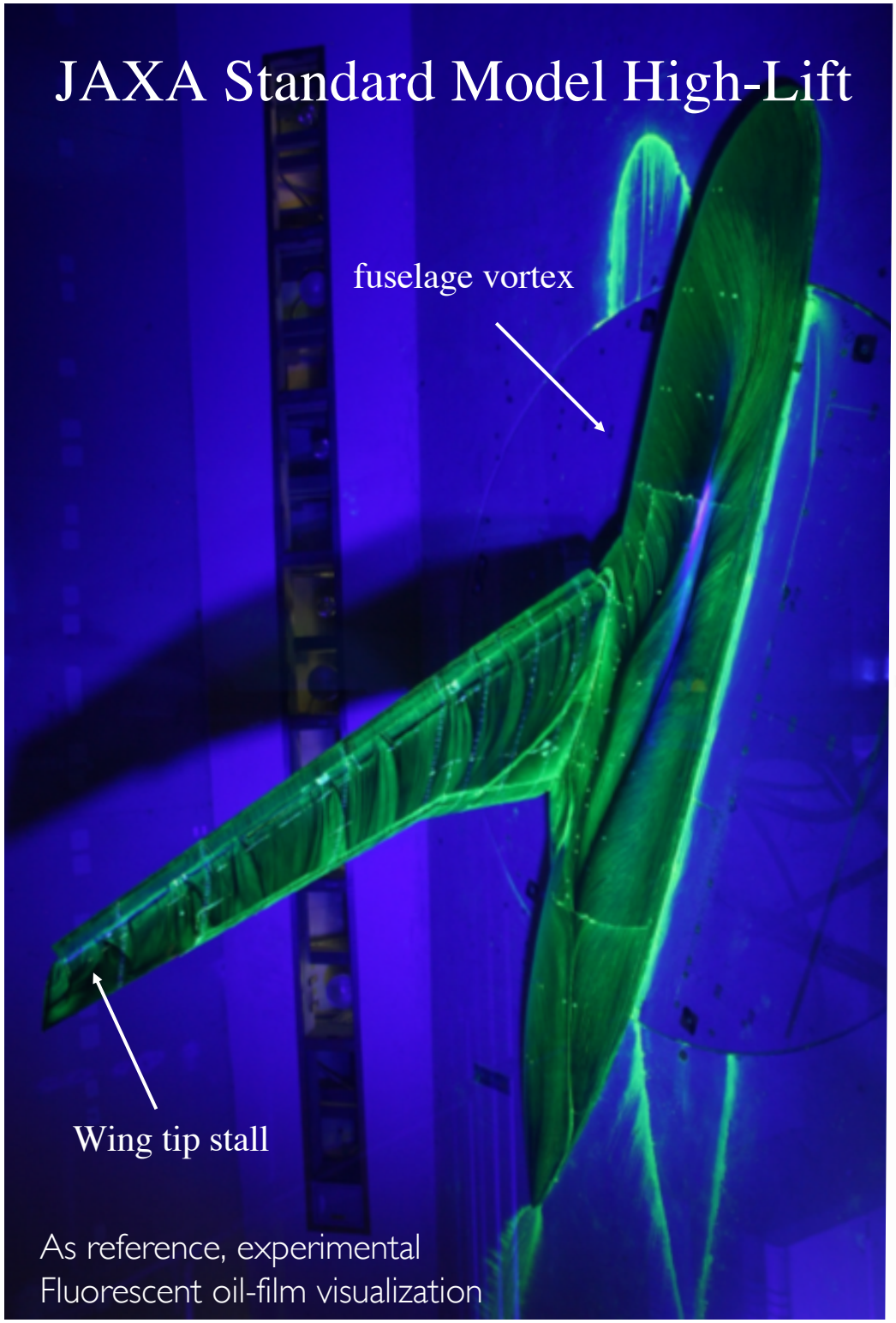
JAXA Standard Model High-Lift

Wall-modeled large-eddy simulation



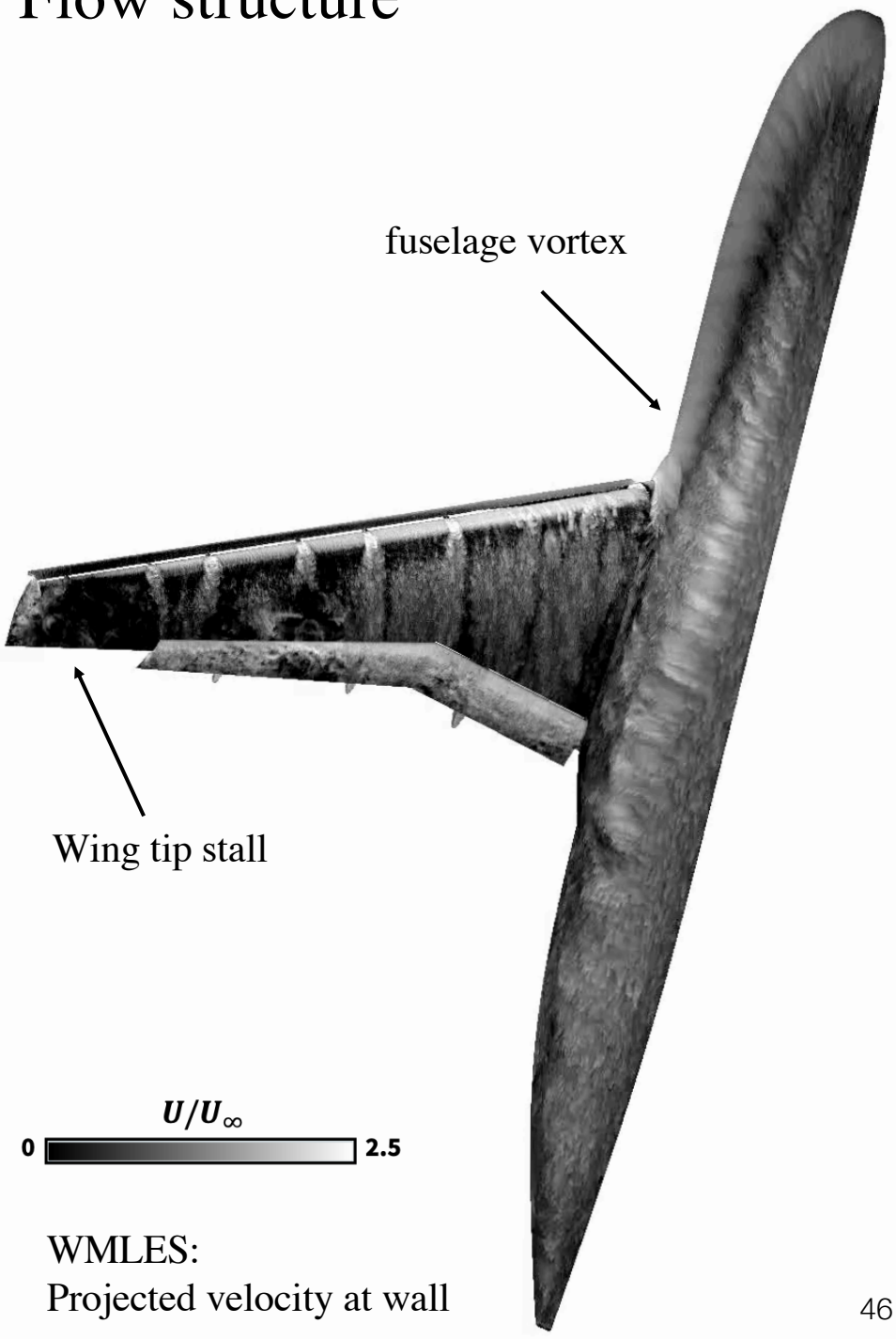


JAXA Standard Model High-Lift



As reference, experimental
Fluorescent oil-film visualization

Flow structure



WMLES:
Projected velocity at wall

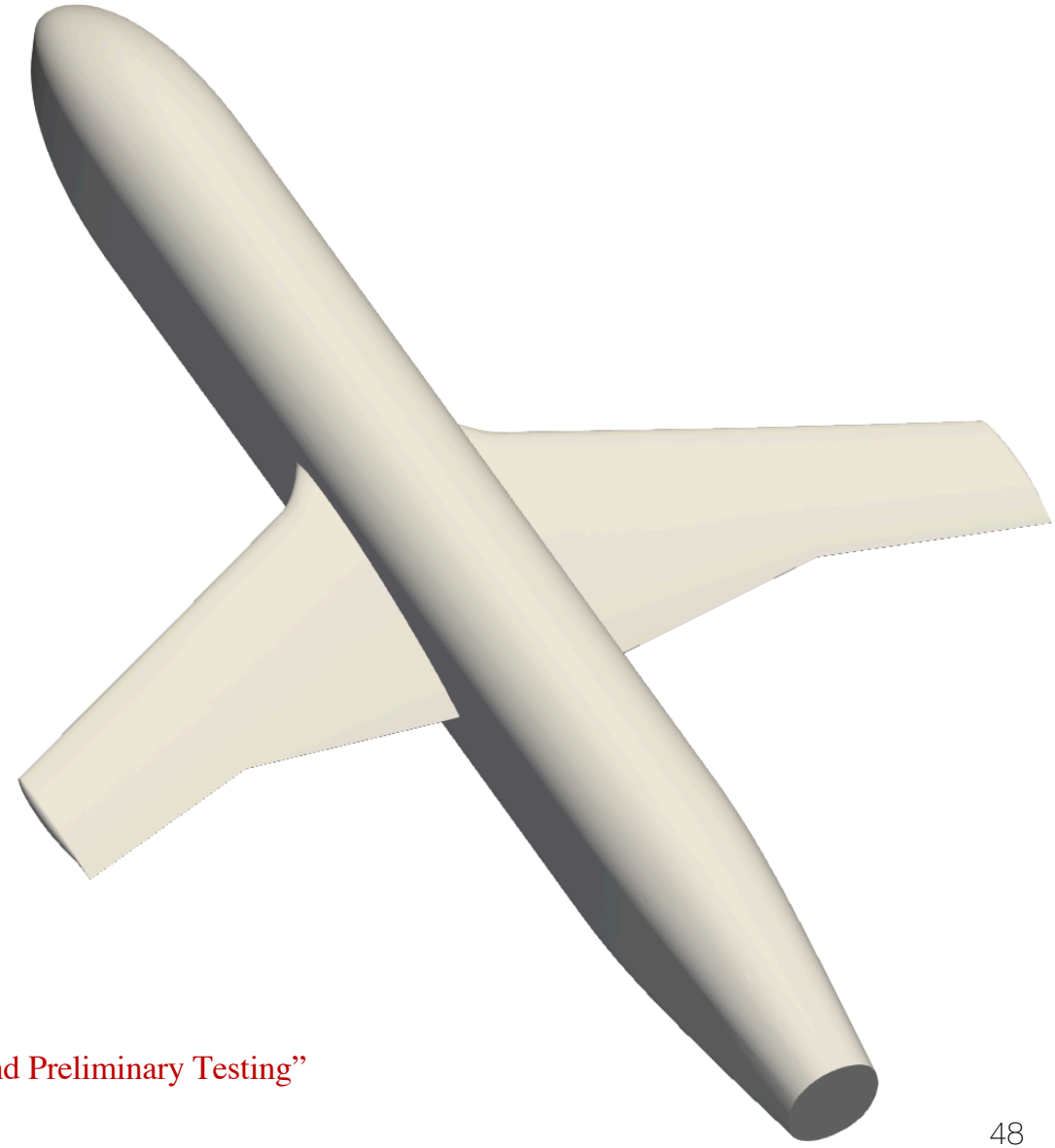
Outline

- **Why** wall-molded LES?
- **What** is wall-modeled LES?
- **Accuracy** & **Cost** of wall-modeled LES for external aerodynamics:
  - Prediction of lift & drag forces: JSM high-lift.
  - Prediction of mean velocity, Reynolds stresses, pressure coefficient & separation: NASA Juncture flow.

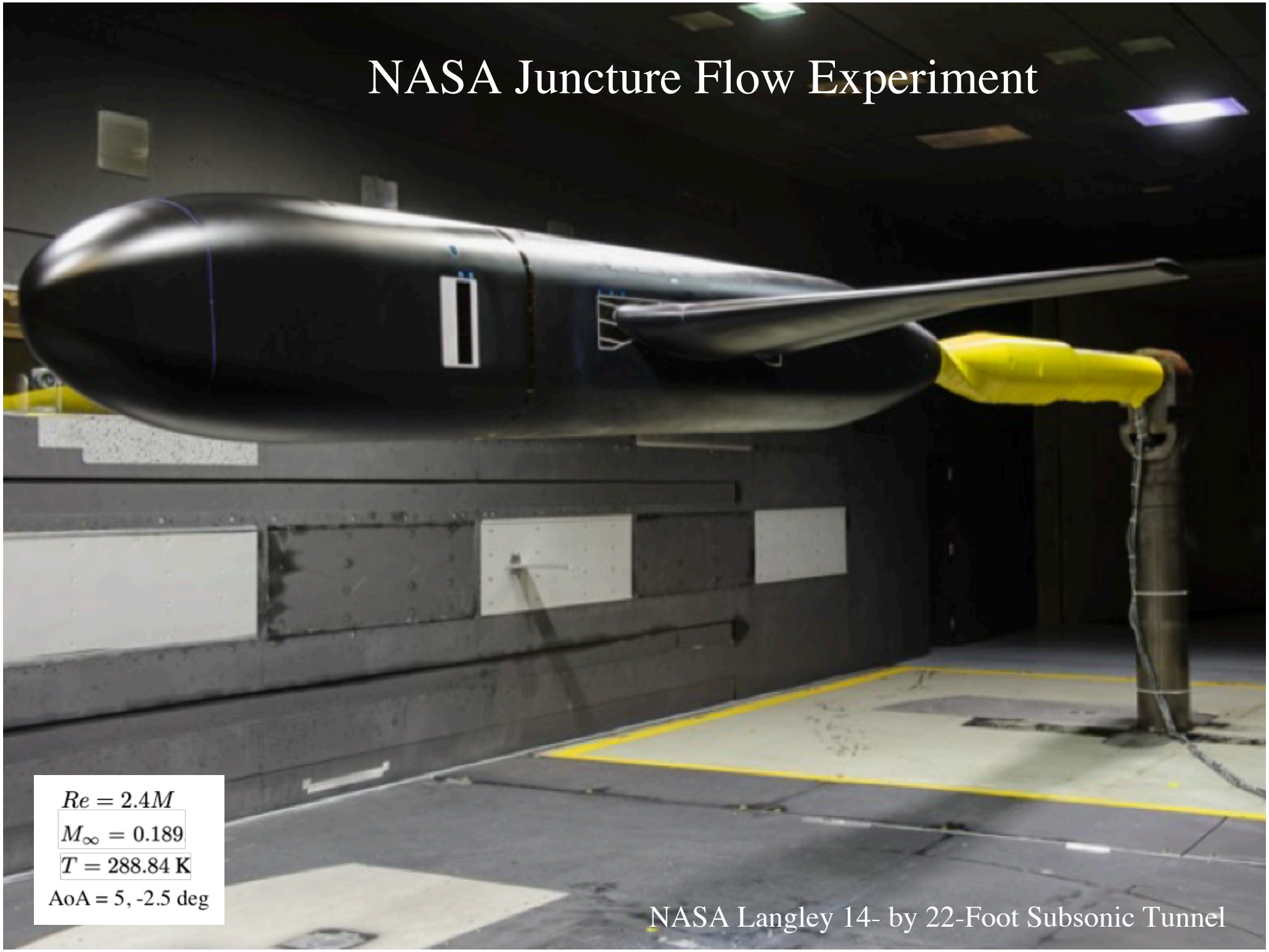
Prediction of NASA Juncture flow with WMLES

Current turbulent models routinely employed by RANS CFD are **inconsistent** in their prediction of corner flow separation in aircraft juncture regions.

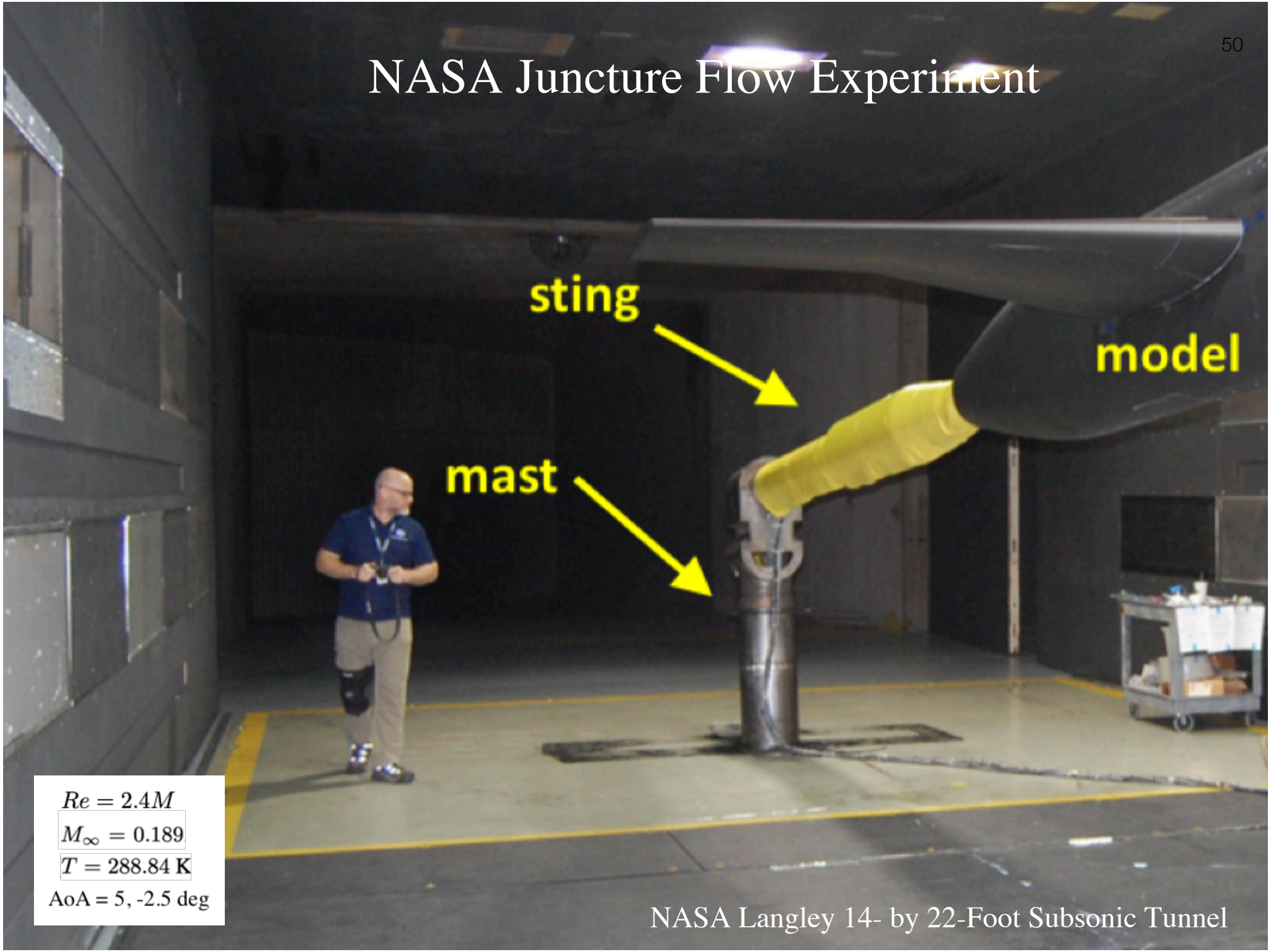
The goal of the **juncture flow validation experiment** is to provide a **challenging test** to distinguish turbulence model prediction of the onset and progression of turbulent separated flow.



"The NASA Juncture Flow Experiment: Goals, Progress, and Preliminary Testing"
Rumsey et al., AIAA Paper 2016


NASA Juncture Flow Experiment
$Re = 2.4M$
$M_\infty = 0.189$
$T = 288.84$ K
AoA = 5, -2.5 deg
NASA Langley 14- by 22-Foot Subsonic Tunnel

NASA Juncture Flow Experiment



$Re = 2.4M$

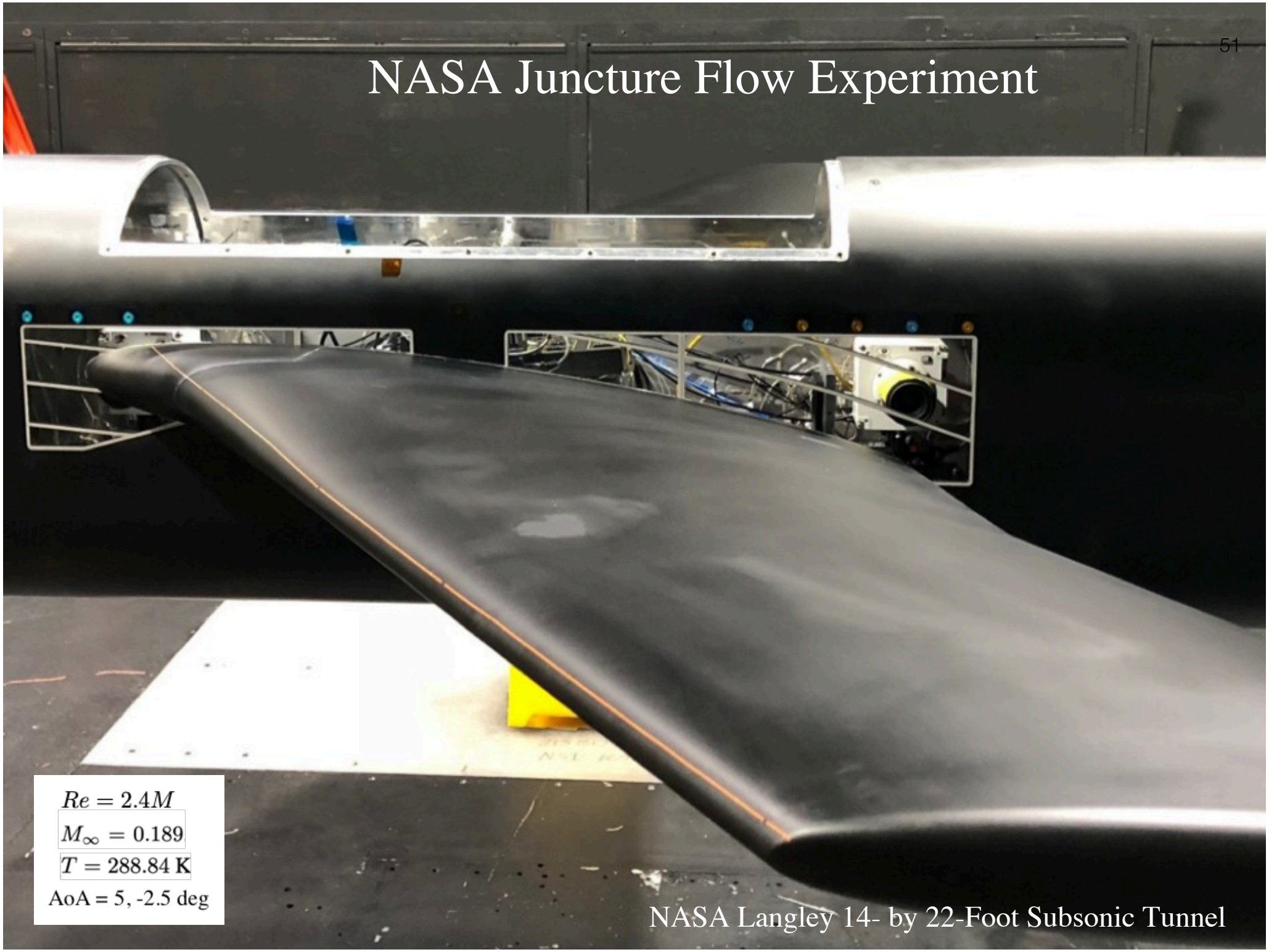
$M_\infty = 0.189$

$T = 288.84$ K

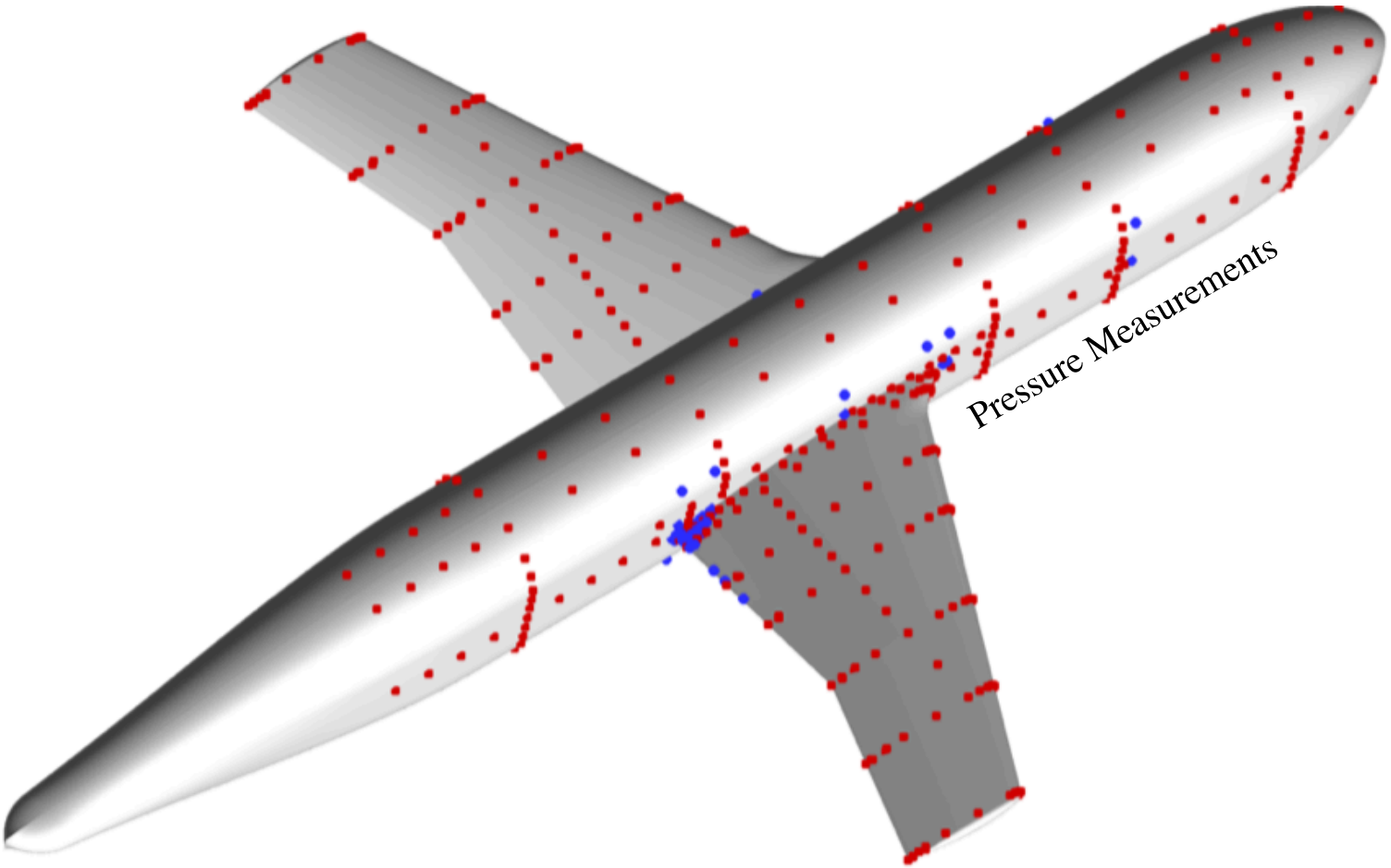
AoA = 5, -2.5 deg

NASA Langley 14- by 22-Foot Subsonic Tunnel

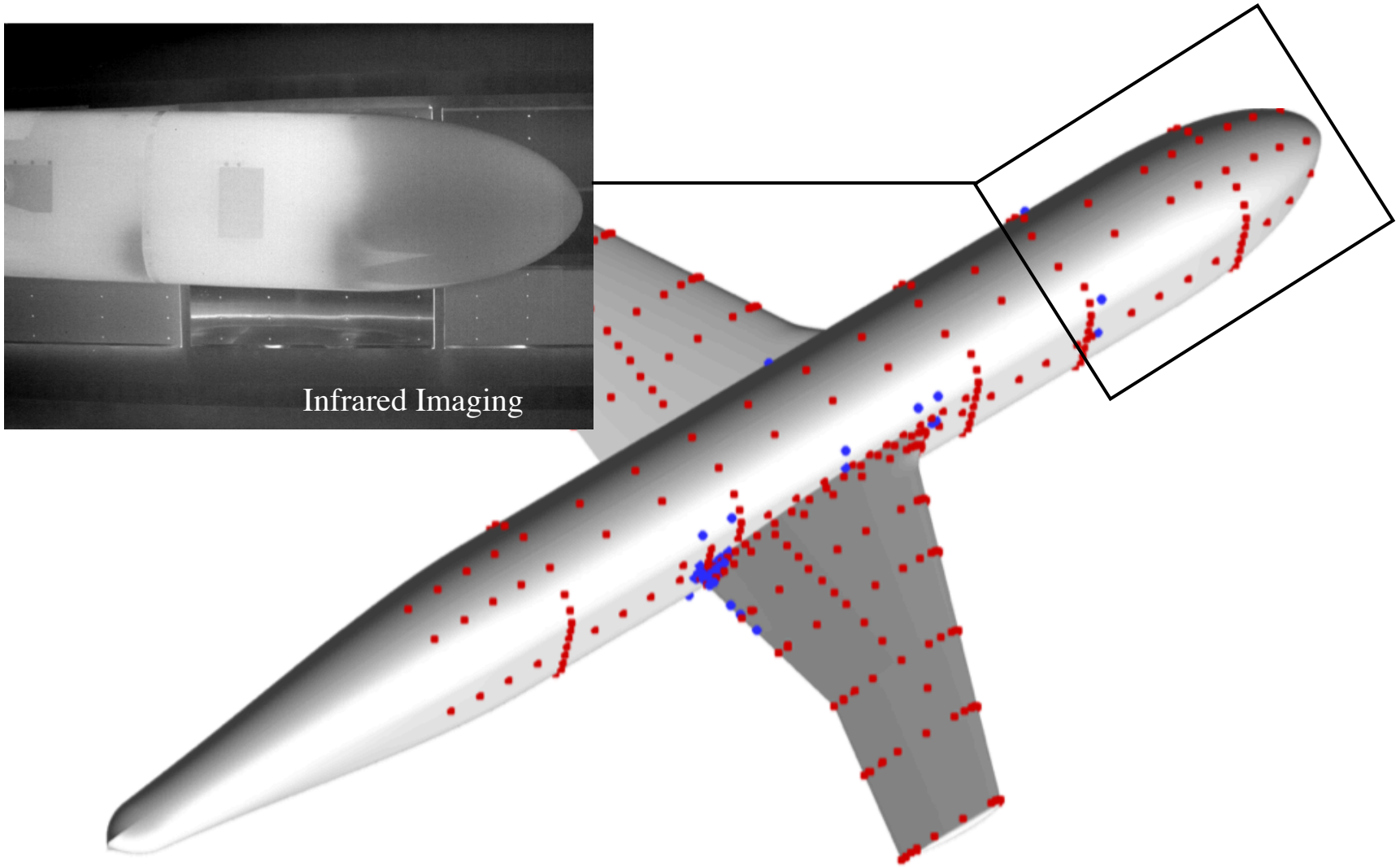
NASA Juncture Flow Experiment



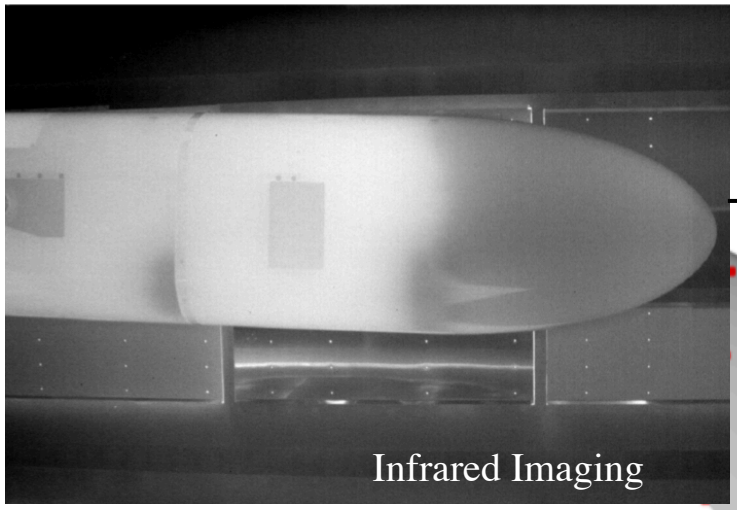
NASA Juncture Flow Experiment: Measurements



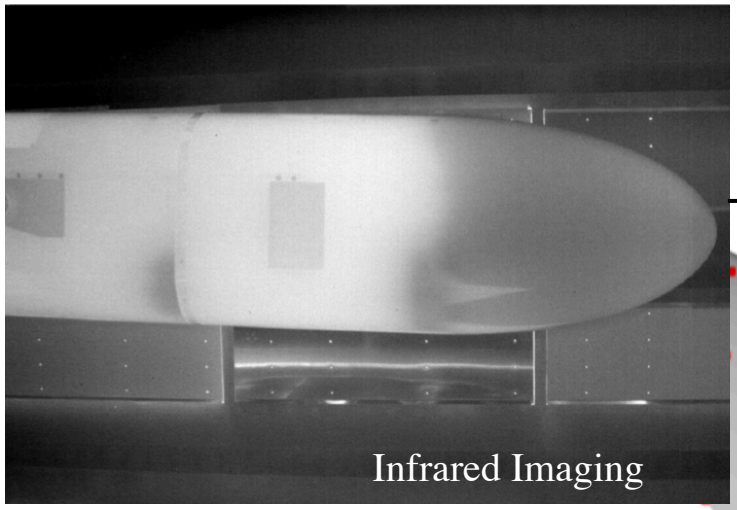
NASA Juncture Flow Experiment: Measurements

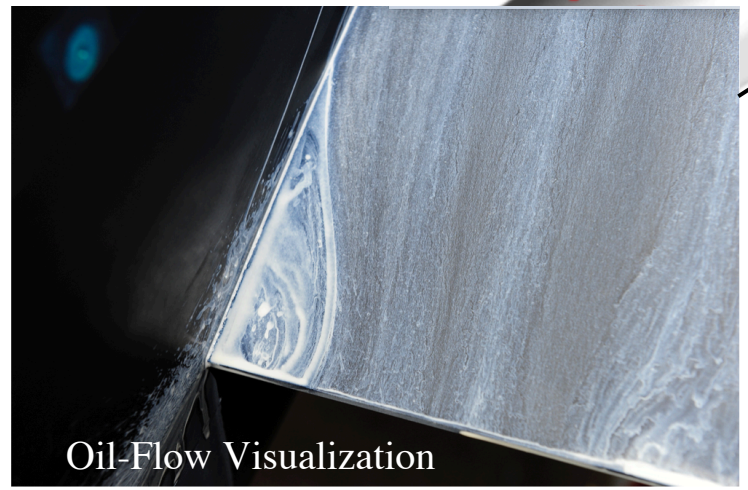


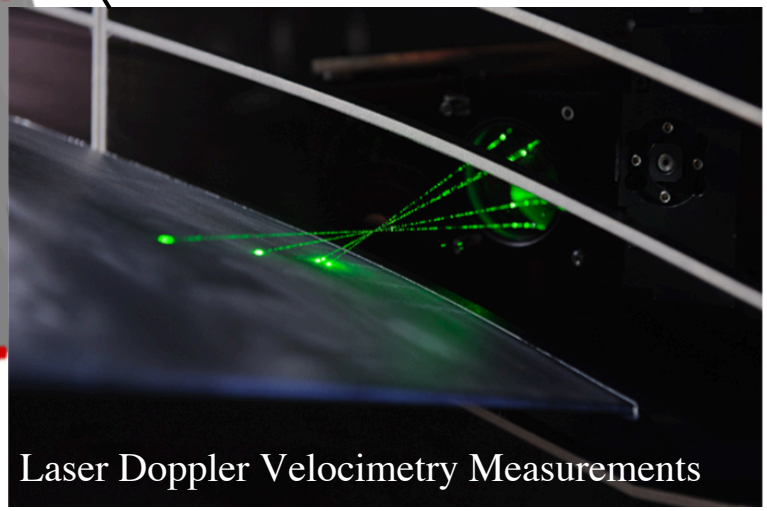
NASA Juncture Flow Experiment: Measurements



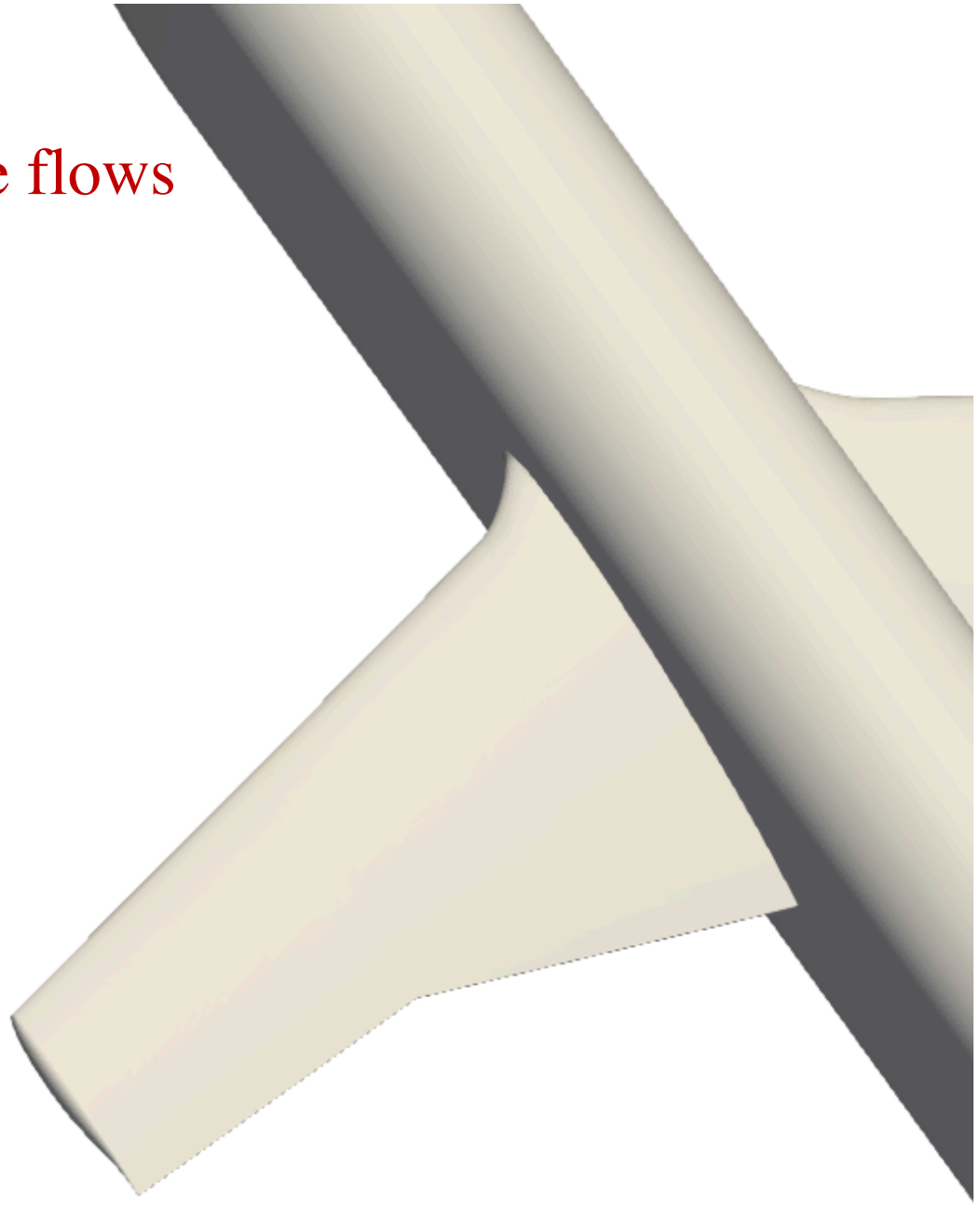
NASA Juncture Flow Experiment: Measurements







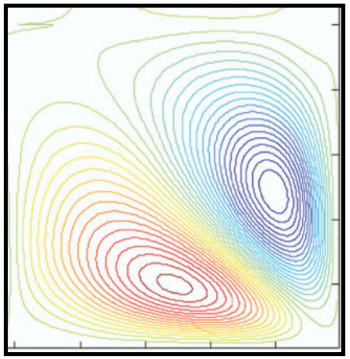
Modeling challenges of juncture flows



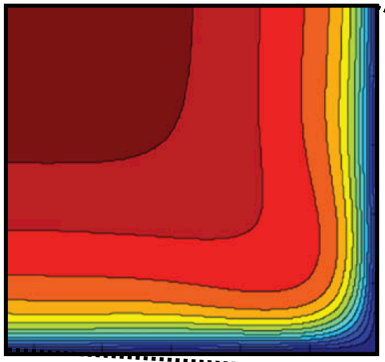
Modeling challenges of juncture flows

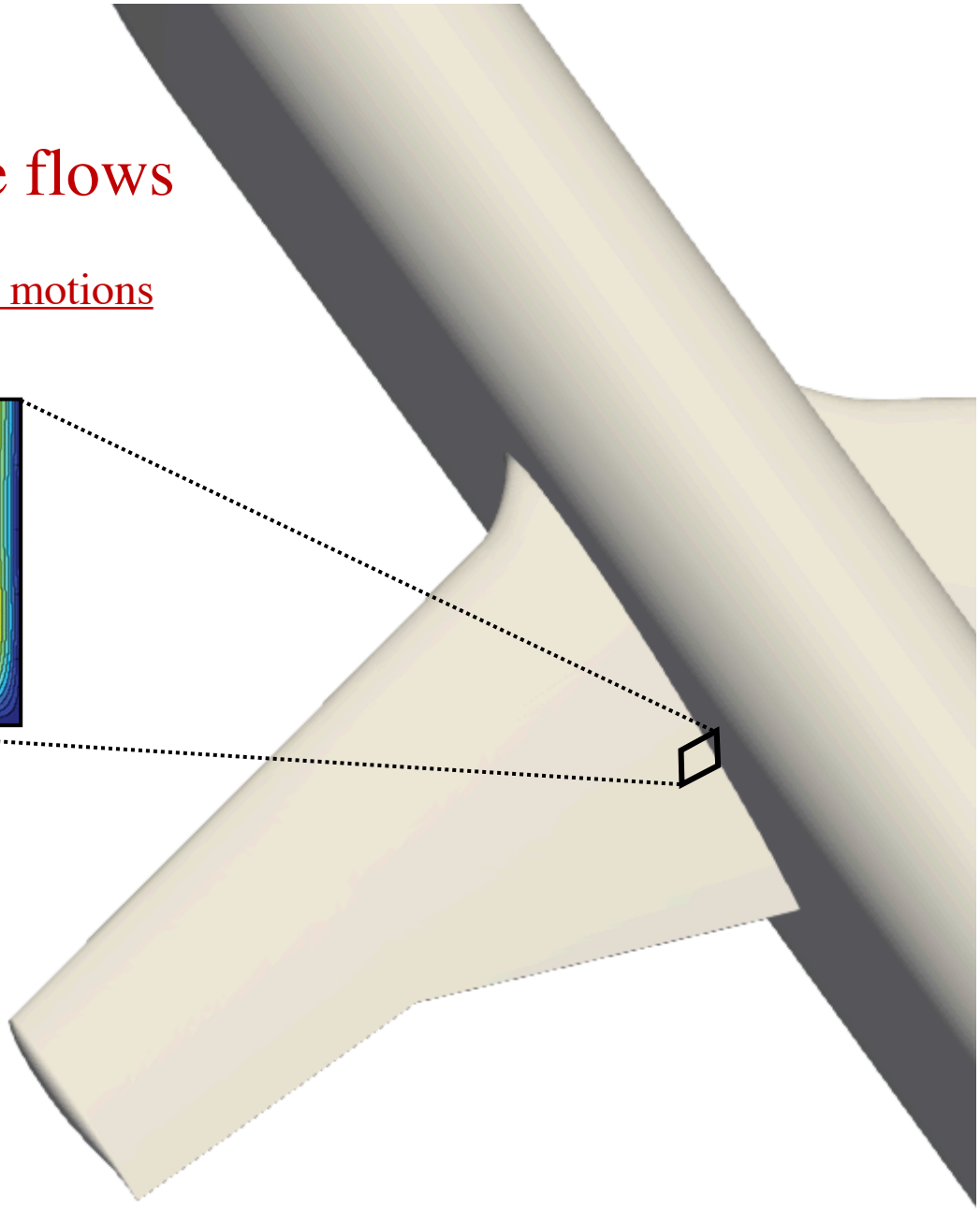
Three-dimensional mean velocity & secondary motions

Mean streamwise vorticity



Mean streamwise velocity

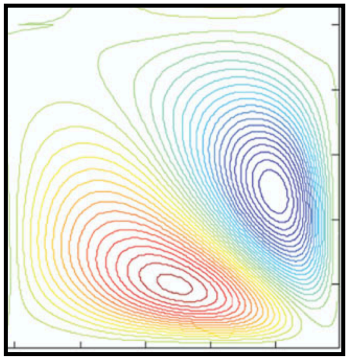




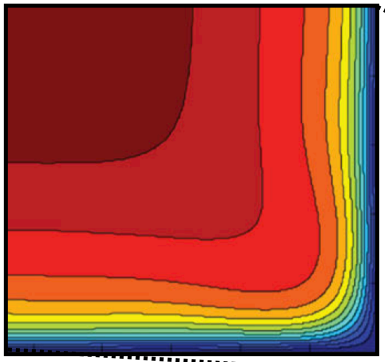
Modeling challenges of juncture flows

Three-dimensional mean velocity & secondary motions

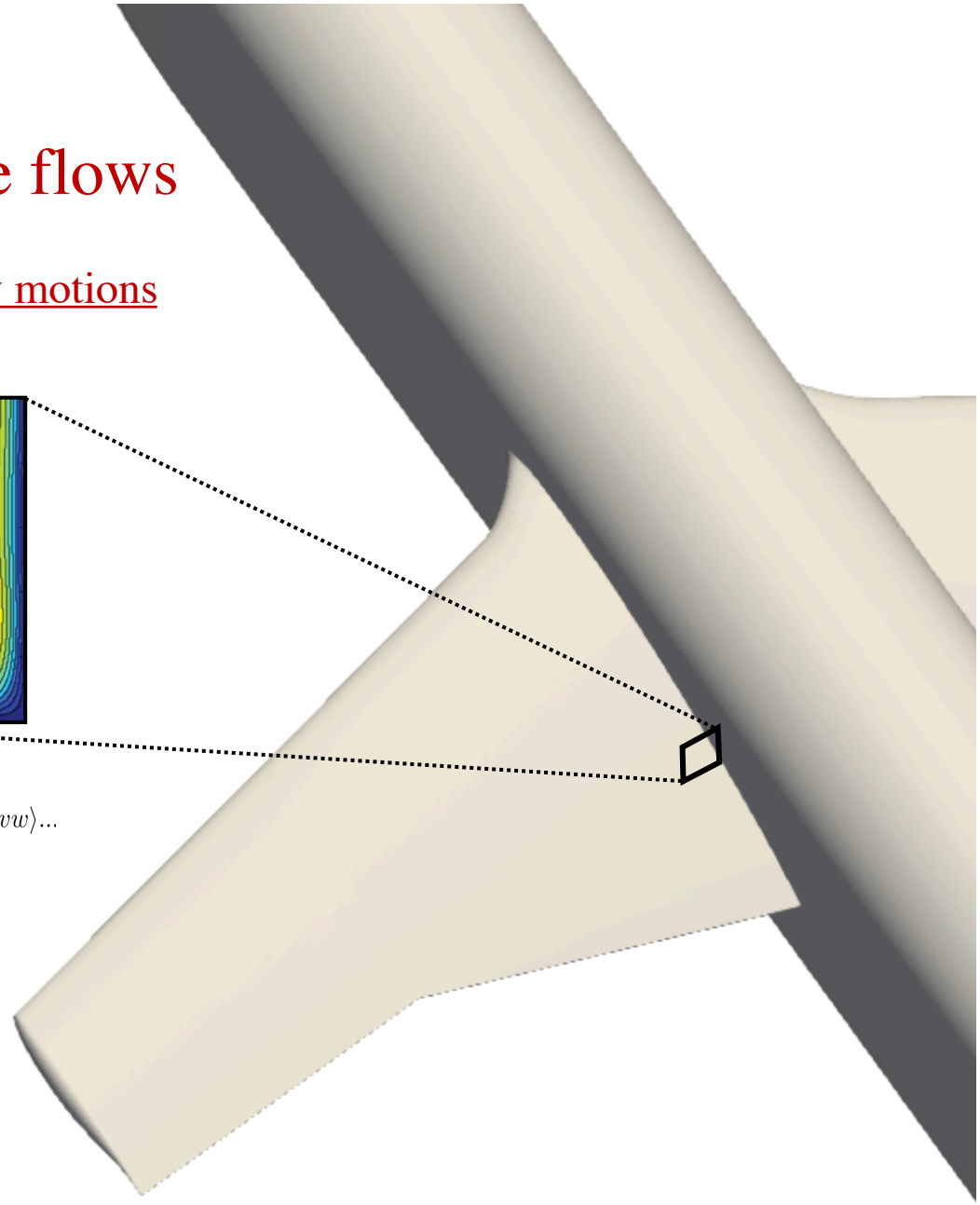
Mean streamwise vorticity



Mean streamwise velocity



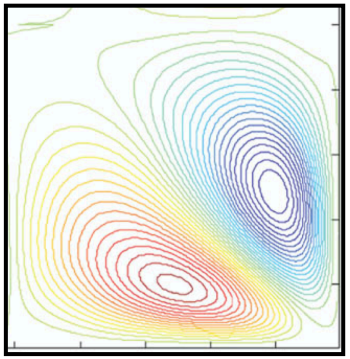
$$\frac{D\Omega_x}{Dt} = \frac{\partial}{\partial x}\left(\frac{\partial\langle uv\rangle}{\partial z} - \frac{\partial\langle uw\rangle}{\partial y}\right) + \frac{\partial^2}{\partial y\partial z}\left(\langle v^2\rangle - \langle w^2\rangle\right)\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2}\right)\langle vw\rangle ...$$



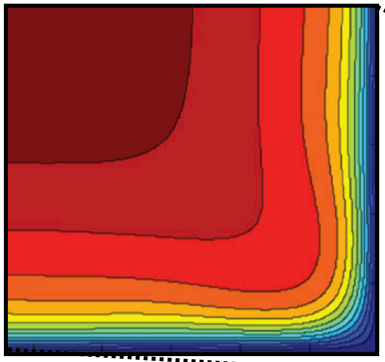
Modeling challenges of juncture flows

Three-dimensional mean velocity & secondary motions

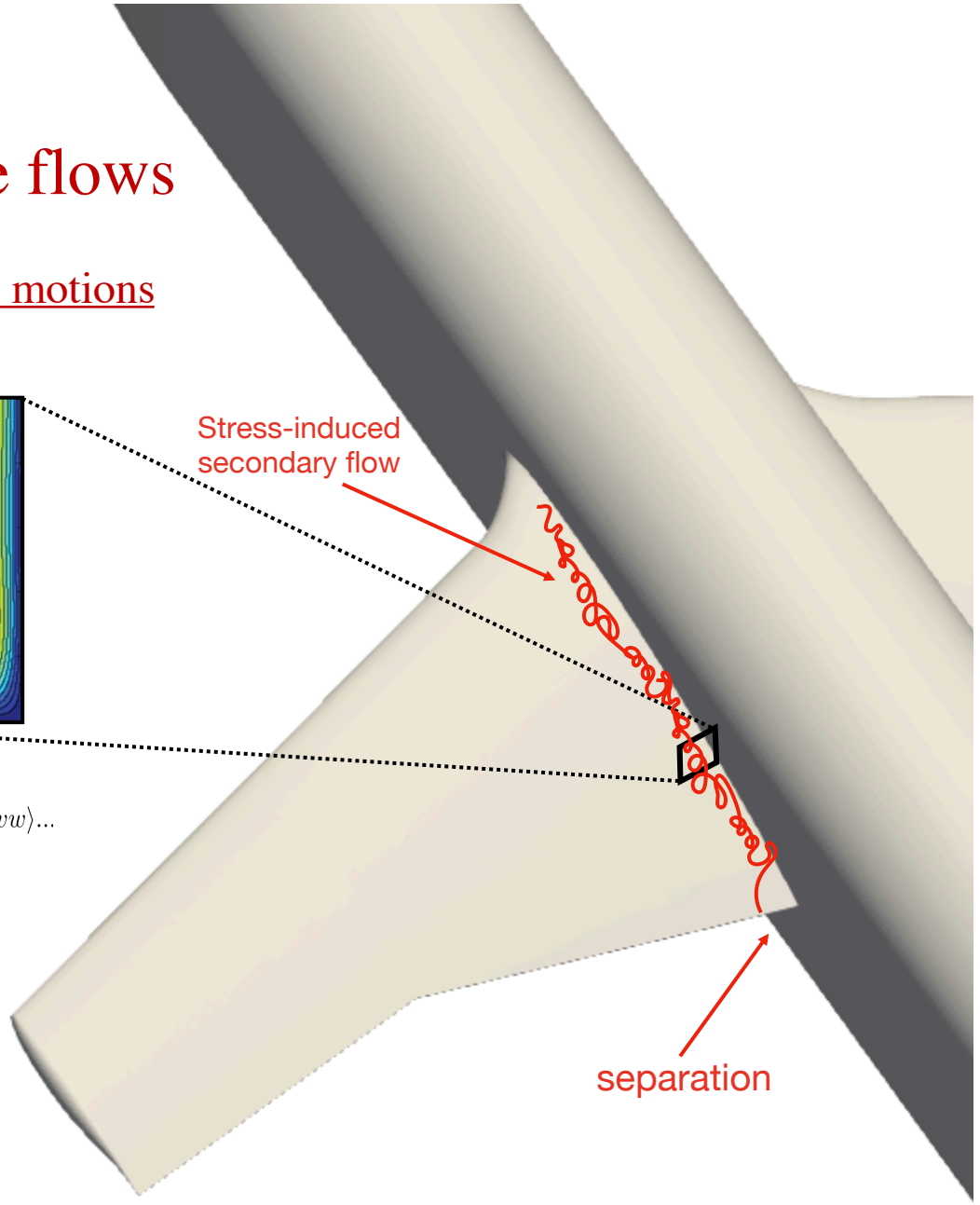
Mean streamwise vorticity



Mean streamwise velocity



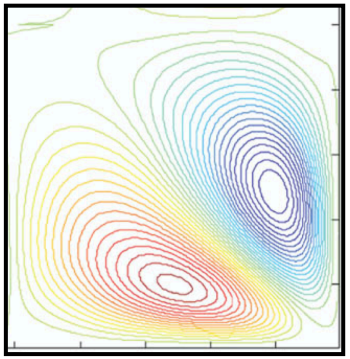
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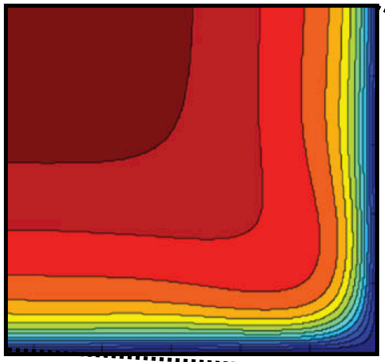
Modeling challenges of juncture flows

Three-dimensional mean velocity & secondary motions

Mean streamwise vorticity

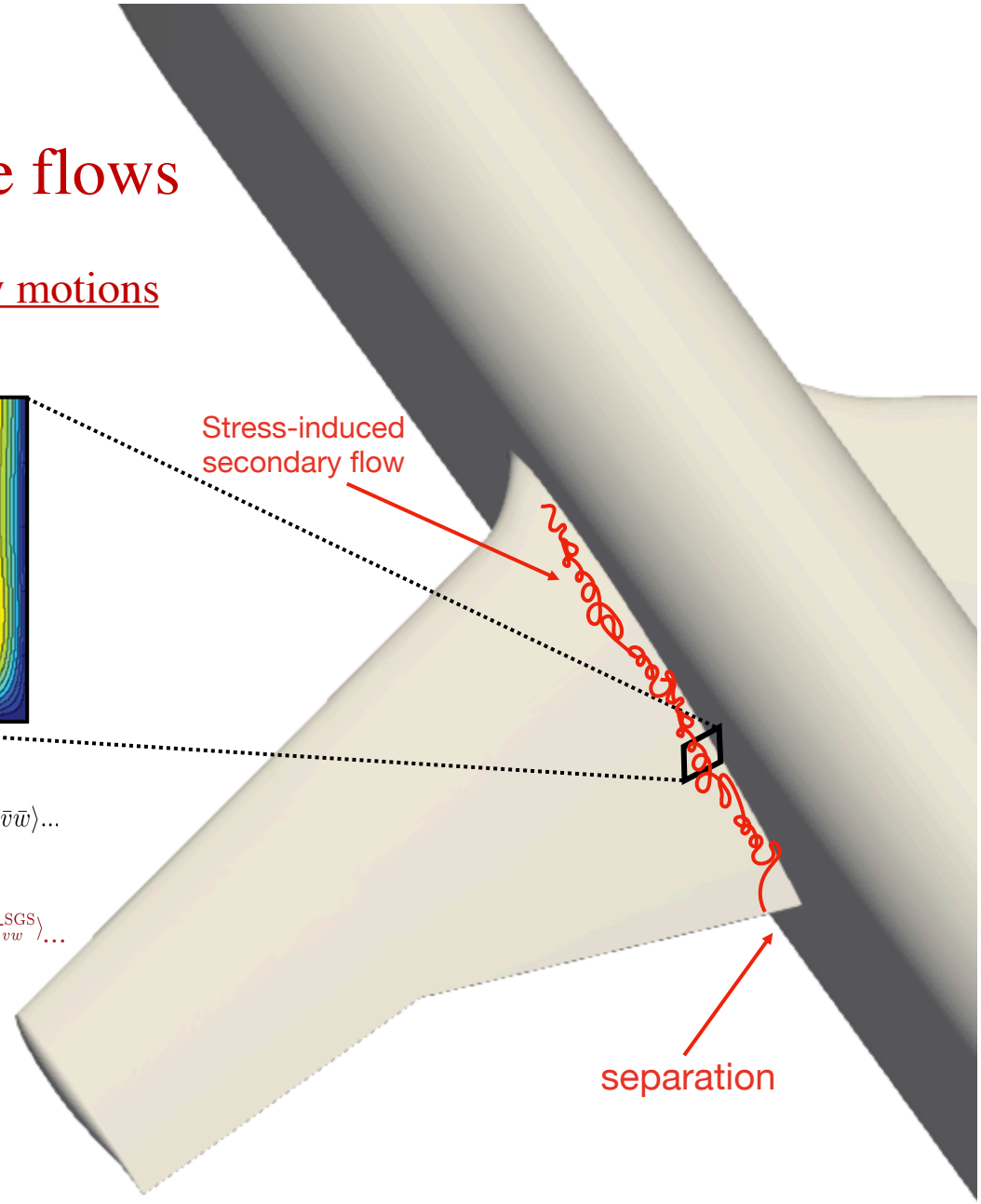


Mean streamwise velocity



$$\frac{D\bar{\Omega}_x}{Dt} = \frac{\partial}{\partial x}\left(\frac{\partial\langle\bar{u}\bar{v}\rangle}{\partial z} - \frac{\partial\langle\bar{u}\bar{w}\rangle}{\partial y}\right) + \frac{\partial^2}{\partial y\partial z}\left(\langle\bar{v}^2\rangle - \langle\bar{w}^2\rangle\right)\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2}\right)\langle\bar{v}\bar{w}\rangle \ldots$$

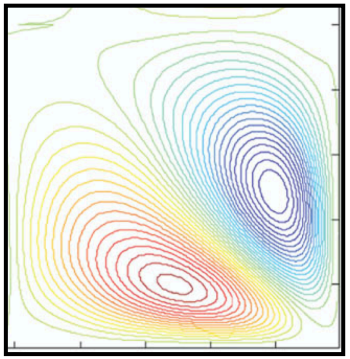
$$+\frac{\partial}{\partial x}\left(\frac{\partial\langle\tau_{uv}^{\mathrm{SGS}}\rangle}{\partial z} - \frac{\partial\langle\tau_{uw}^{\mathrm{SGS}}\rangle}{\partial y}\right) + \frac{\partial^2}{\partial y\partial z}\left(\langle\tau_{vv}^{\mathrm{SGS}}\rangle - \langle\tau_{ww}^{\mathrm{SGS}}\rangle\right)\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2}\right)\langle\tau_{vw}^{\mathrm{SGS}}\rangle \ldots$$



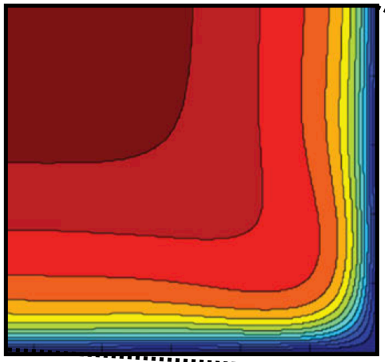
Modeling challenges of juncture flows

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$$\frac{D\bar{\Omega}_x}{Dt} = \frac{\partial}{\partial x}\left(\frac{\partial\langle\bar{u}\bar{v}\rangle}{\partial z} - \frac{\partial\langle\bar{u}\bar{w}\rangle}{\partial y}\right) + \frac{\partial^2}{\partial y\partial z}\left(\langle\bar{v}^2\rangle - \langle\bar{w}^2\rangle\right)\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2}\right)\langle\bar{v}\bar{w}\rangle ...$$

$$+\frac{\partial}{\partial x}\left(\frac{\partial\langle\tau_{uv}^{\mathrm{SGS}}\rangle}{\partial z} - \frac{\partial\langle\tau_{uw}^{\mathrm{SGS}}\rangle}{\partial y}\right) + \frac{\partial^2}{\partial y\partial z}\left(\langle\tau_{vv}^{\mathrm{SGS}}\rangle - \langle\tau_{ww}^{\mathrm{SGS}}\rangle\right)\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2}\right)\langle\tau_{vw}^{\mathrm{SGS}}\rangle ...$$

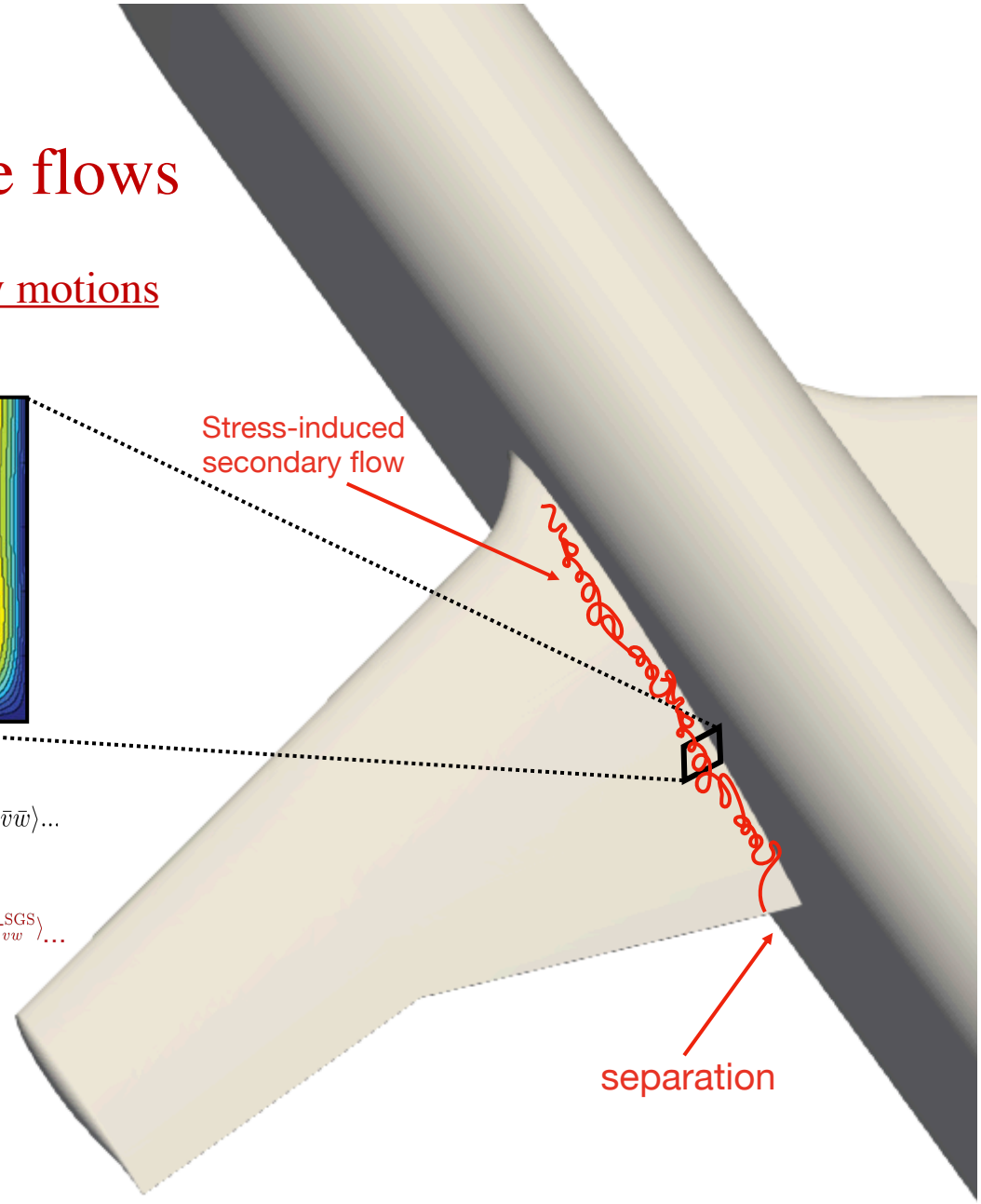
Subgrid-scale modeling

Most models assume:

$$\tau_{ij}^{\mathrm{SGS}} \propto \nu_t \bar{S}_{ij}$$

Due to secondary motions:

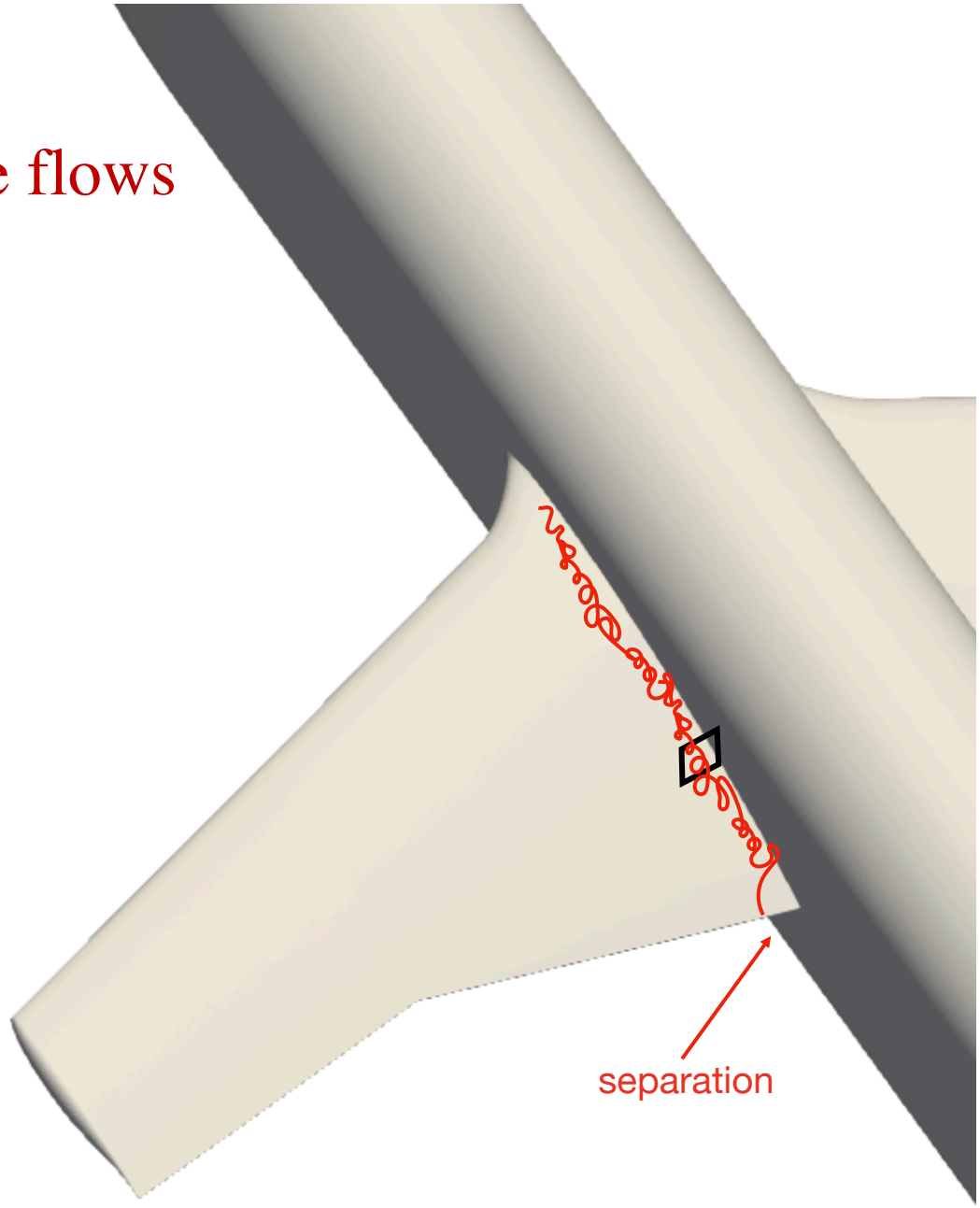
$$\tau_{ij}^{\mathrm{SGS}} \not\propto \nu_t \bar{S}_{ij}$$



Modeling challenges of juncture flows

Wall modeling

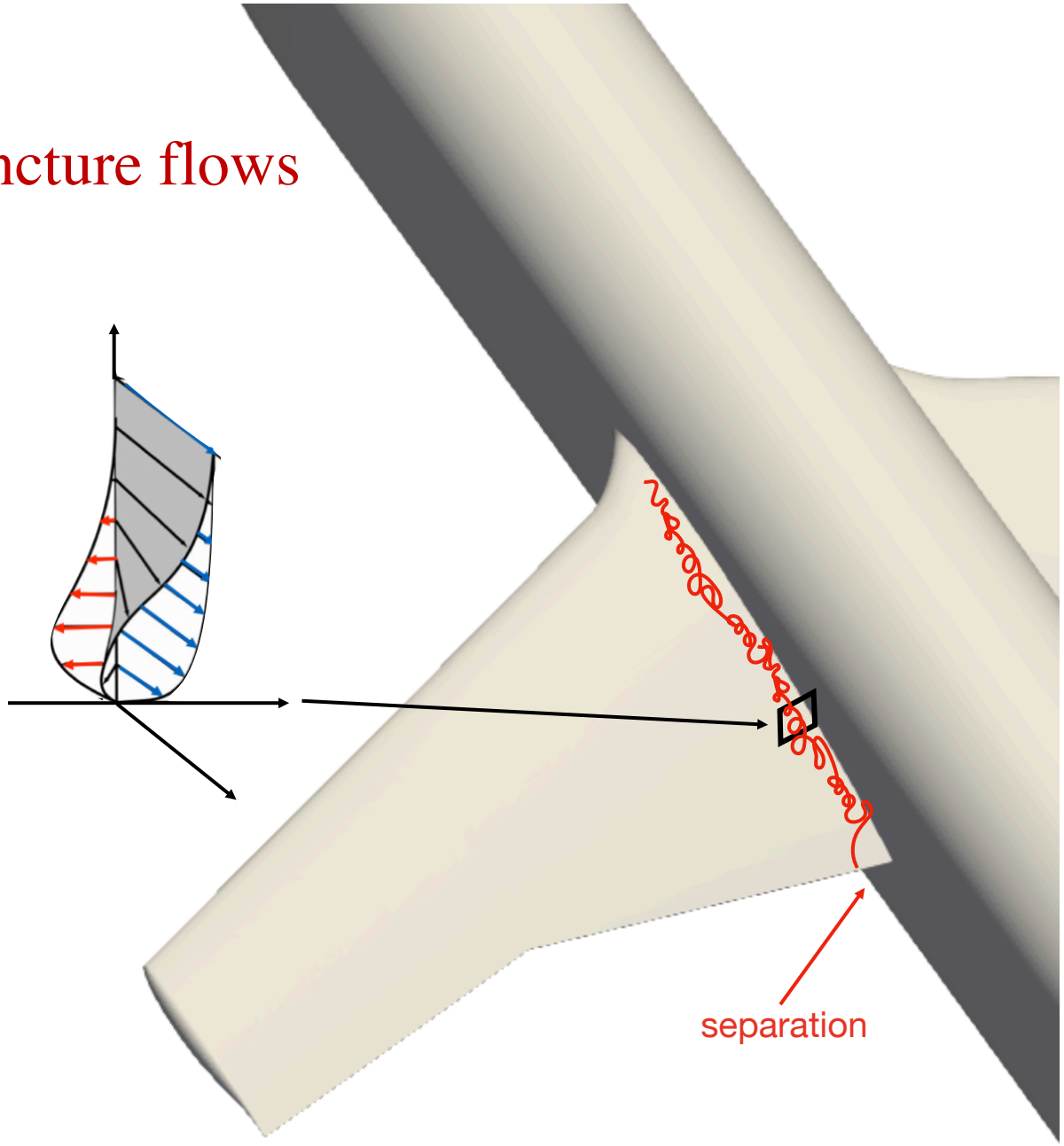
Most models assume 2-D equilibrium turbulence



Modeling challenges of juncture flows

Wall modeling

Most models assume 2-D equilibrium turbulence

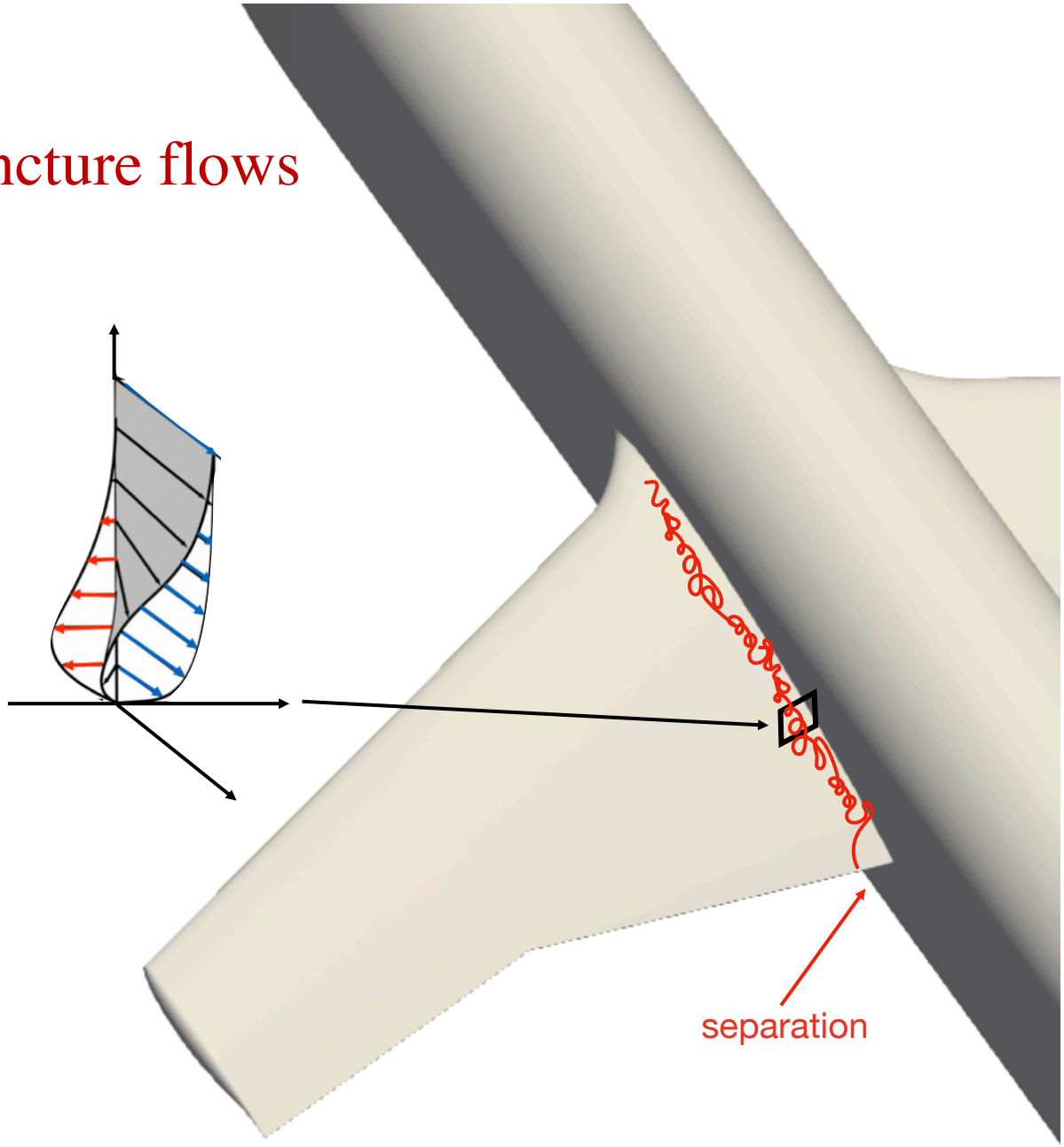


Modeling challenges of juncture flows

Wall modeling

Most models assume 2-D equilibrium turbulence

$$\vec{\tau}_{\text{wall}} \propto \nu_t |S| \frac{\vec{u}_{\text{LES}}}{|\vec{u}_{\text{LES}}|}$$

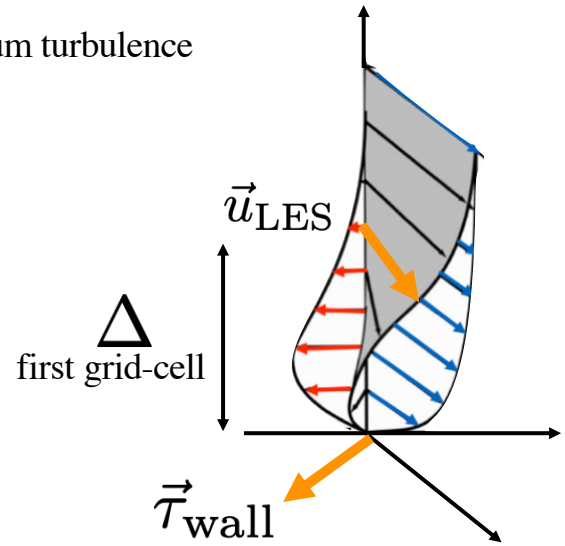


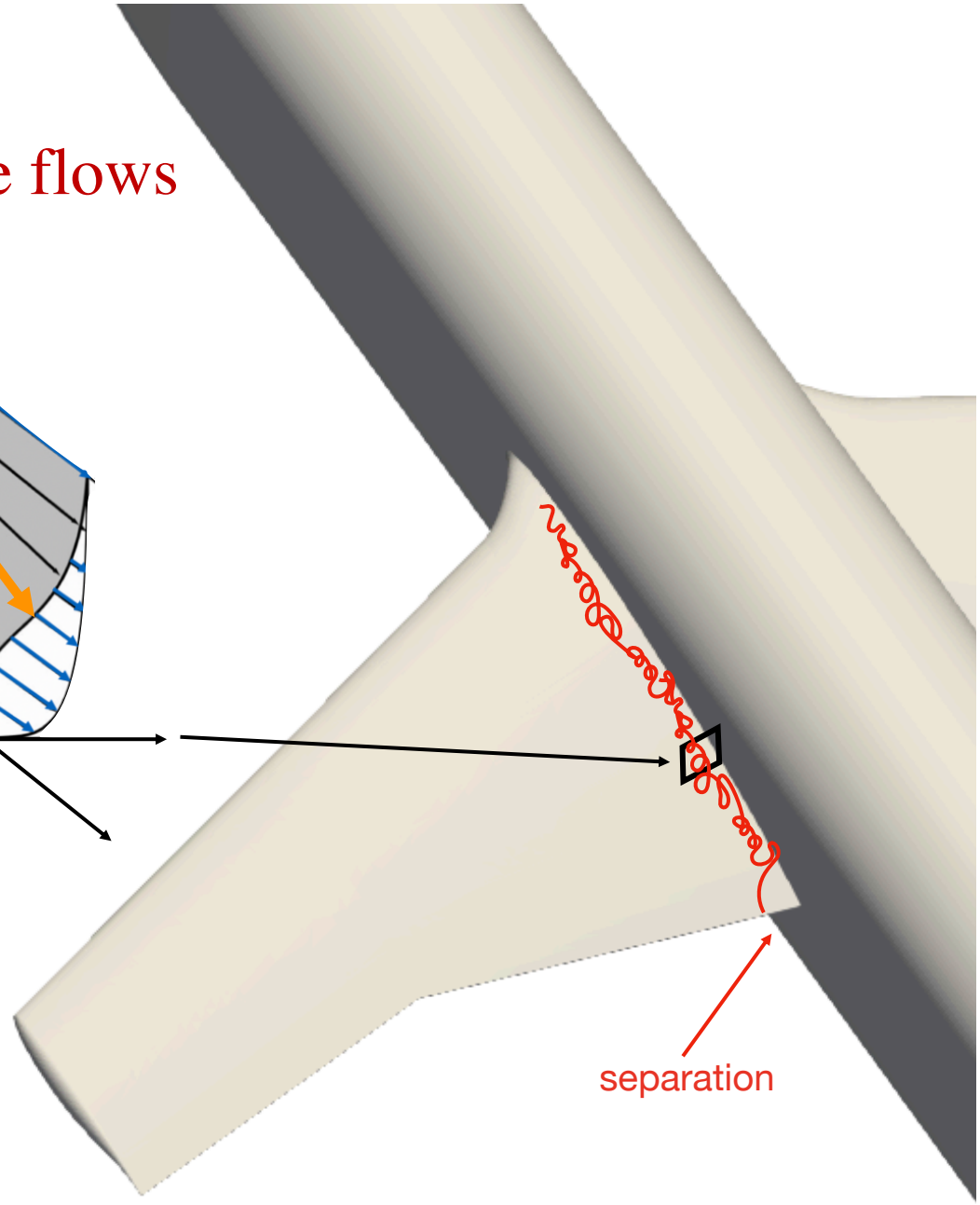
Modeling challenges of juncture flows

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Modeling challenges of juncture flows

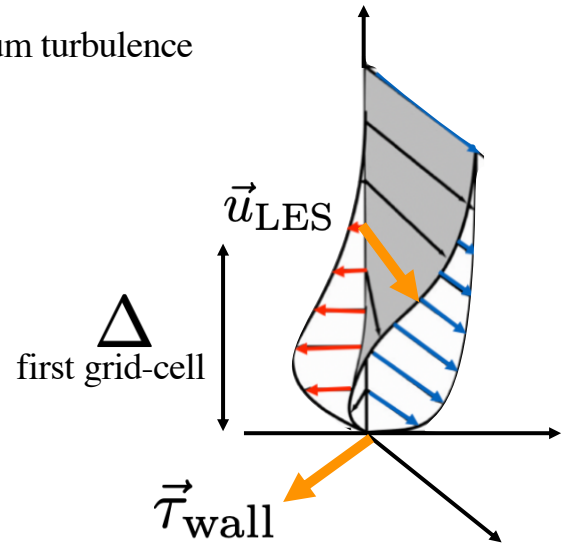
Wall modeling

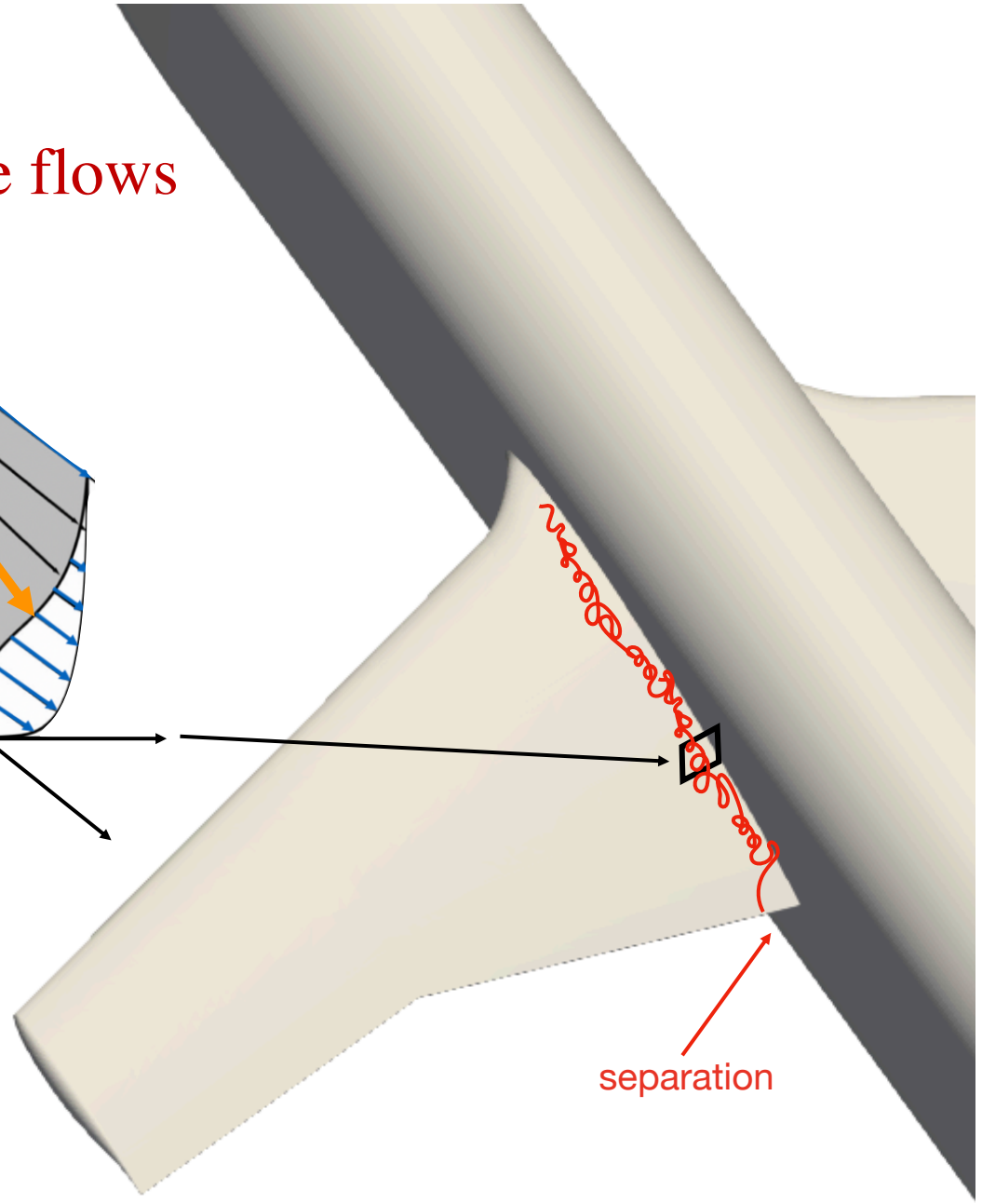
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$$\vec{\tau}_{\text{wall}} \propto \nu_t |S| \frac{\vec{u}_{\text{LES}}}{|\vec{u}_{\text{LES}}|}$$

3-D mean flow dimensionality unresolved by LES grid

Misalignment wall stress and LES velocity





Modeling challenges of juncture flows

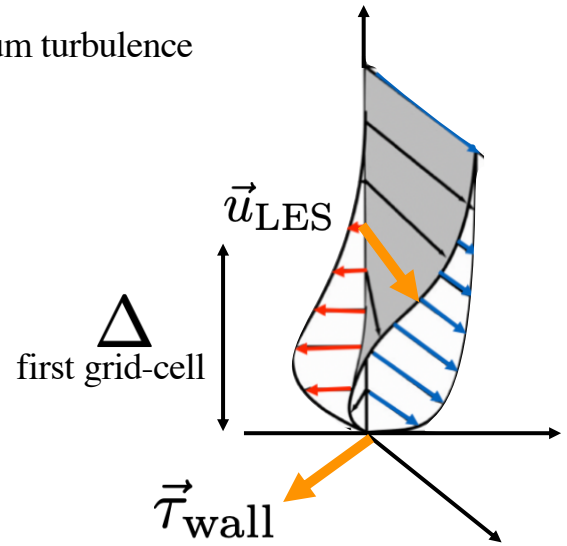
Wall modeling

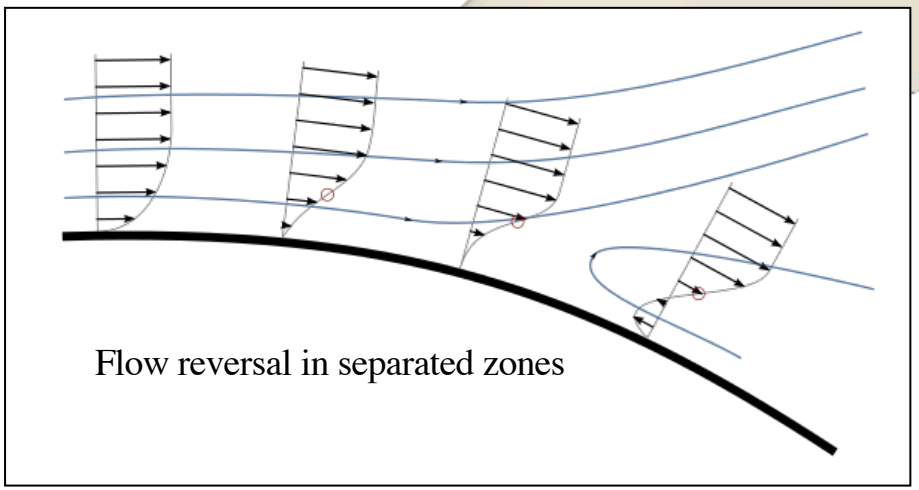
Most models assume 2-D equilibrium turbulence

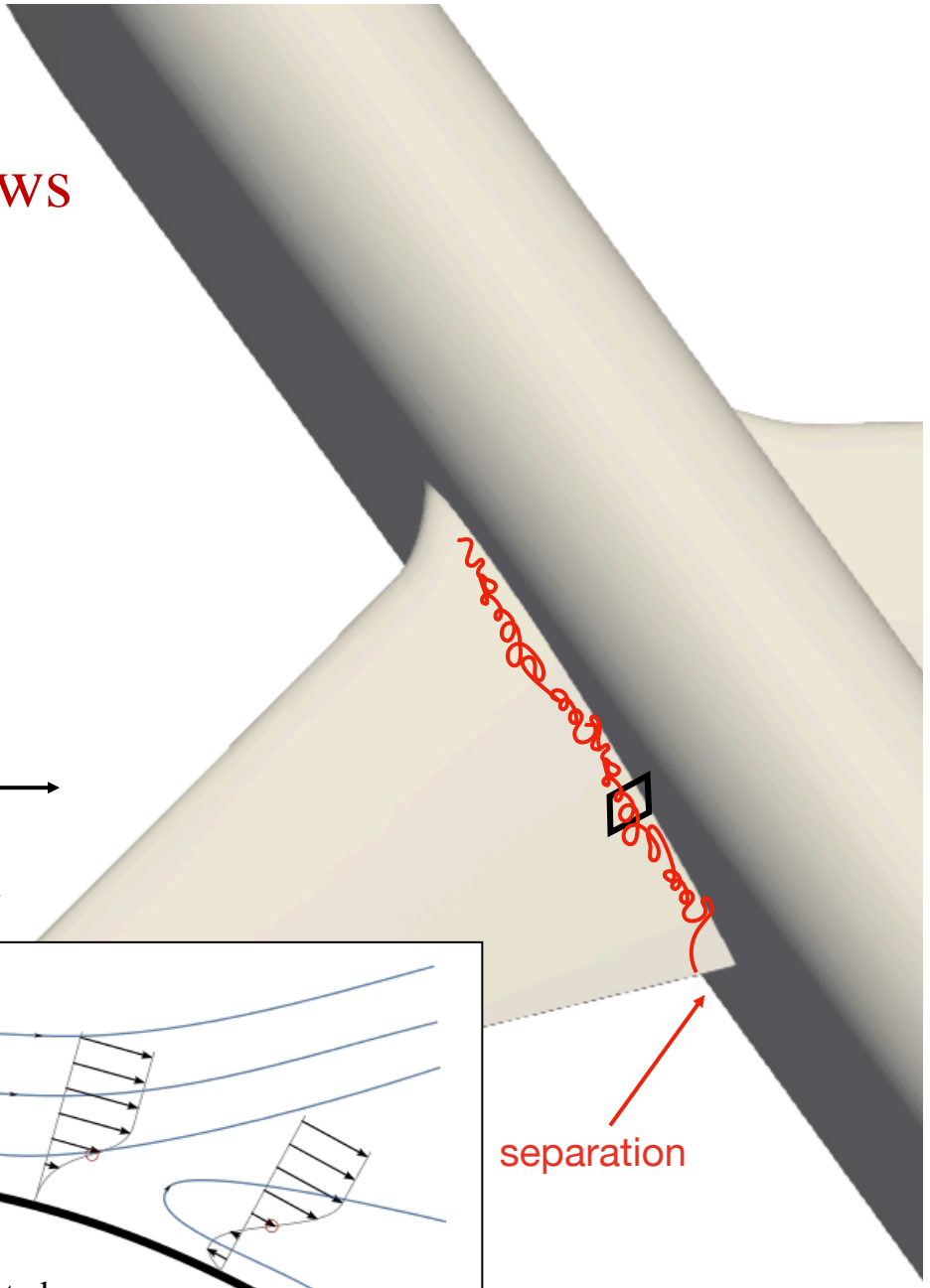
$$\vec{\tau}_{\text{wall}} \propto \nu_t |S| \frac{\vec{u}_{\text{LES}}}{|\vec{u}_{\text{LES}}|}$$

3-D mean flow dimensionality unresolved by LES grid

Misalignment wall stress and LES velocity





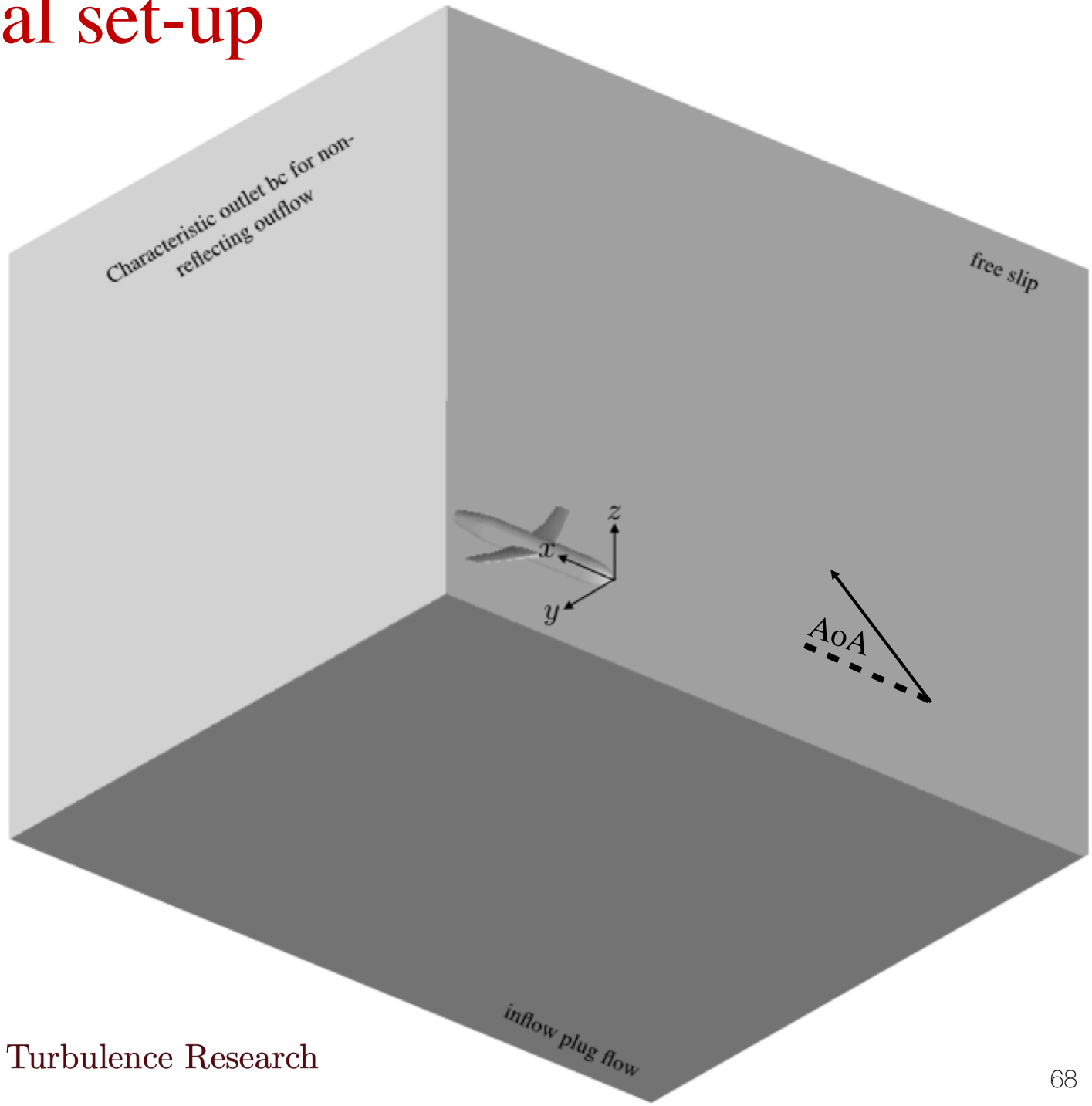


Computational set-up

Flow solver: CharLES
(Cascade Technologies, Inc.)

All calculations are performed
in free air conditions
(sting and mast ignored)

AoA = 5 degrees

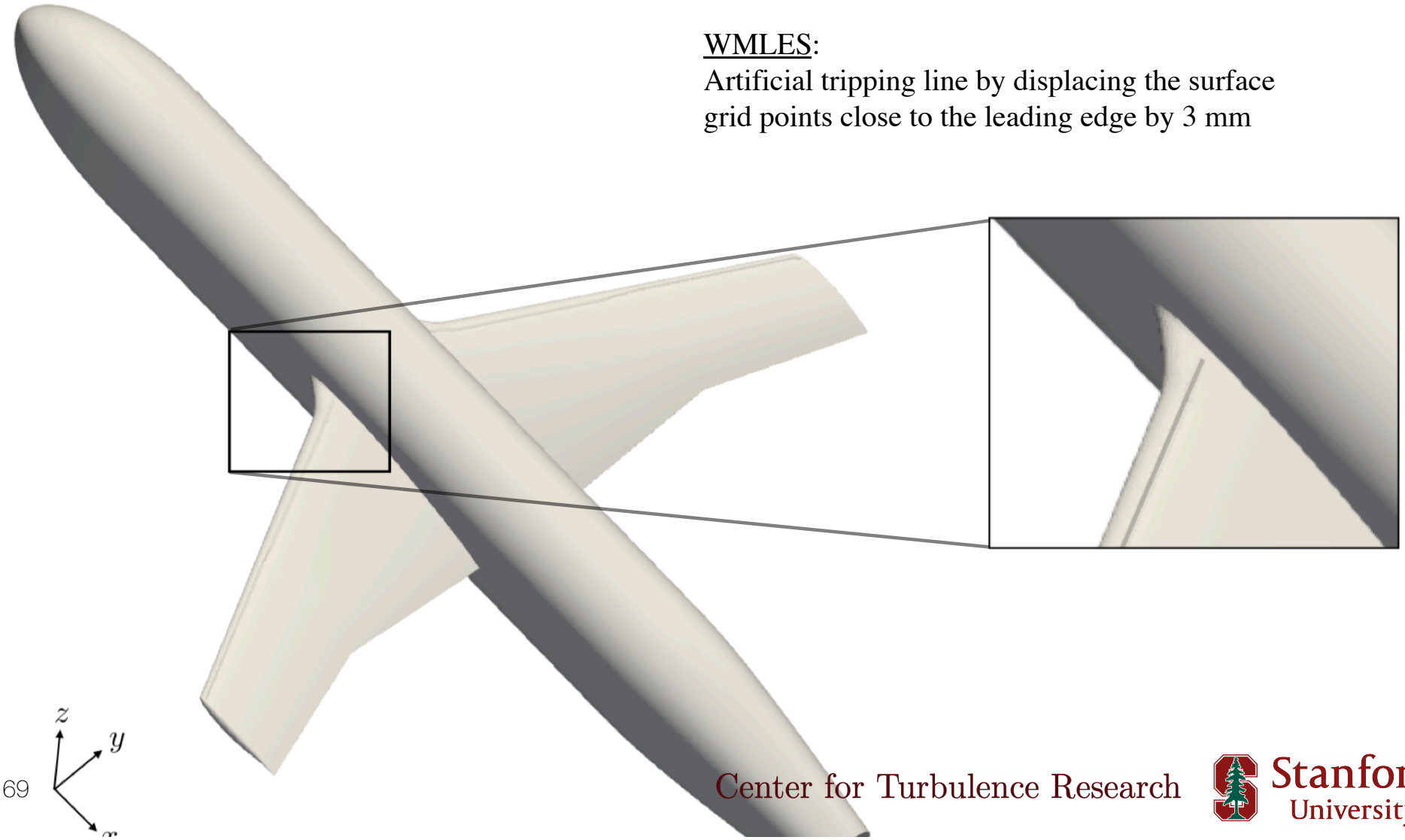


Juncture flow geometry: tripping

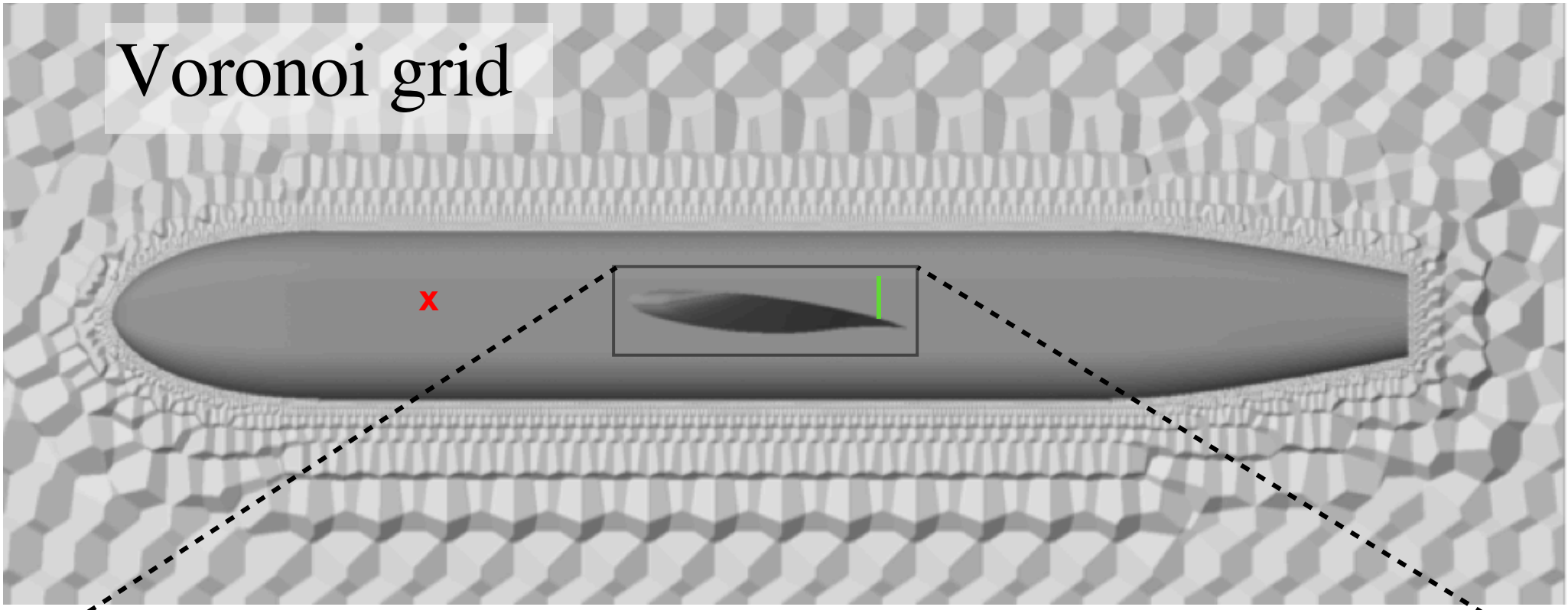
DLR-F6 –base wing with
leading-edge extension

Experiment:
Tripping dots of ~0.2 mm diameter

WMLES:
Artificial tripping line by displacing the surface grid points close to the leading edge by 3 mm



Voronoi grid



Δ	≈ δ/Δ	≈ δ/Δ	Control Volumes
0.4 mm	16	13	122M

Δ = grid resolution at wall

δ = 99% boundary layer thickness

Prediction of NASA Juncture flow using WMLES

Computational cost

Wall-clock time for grid generation using 64 cores:

122M CVs: 180 minutes

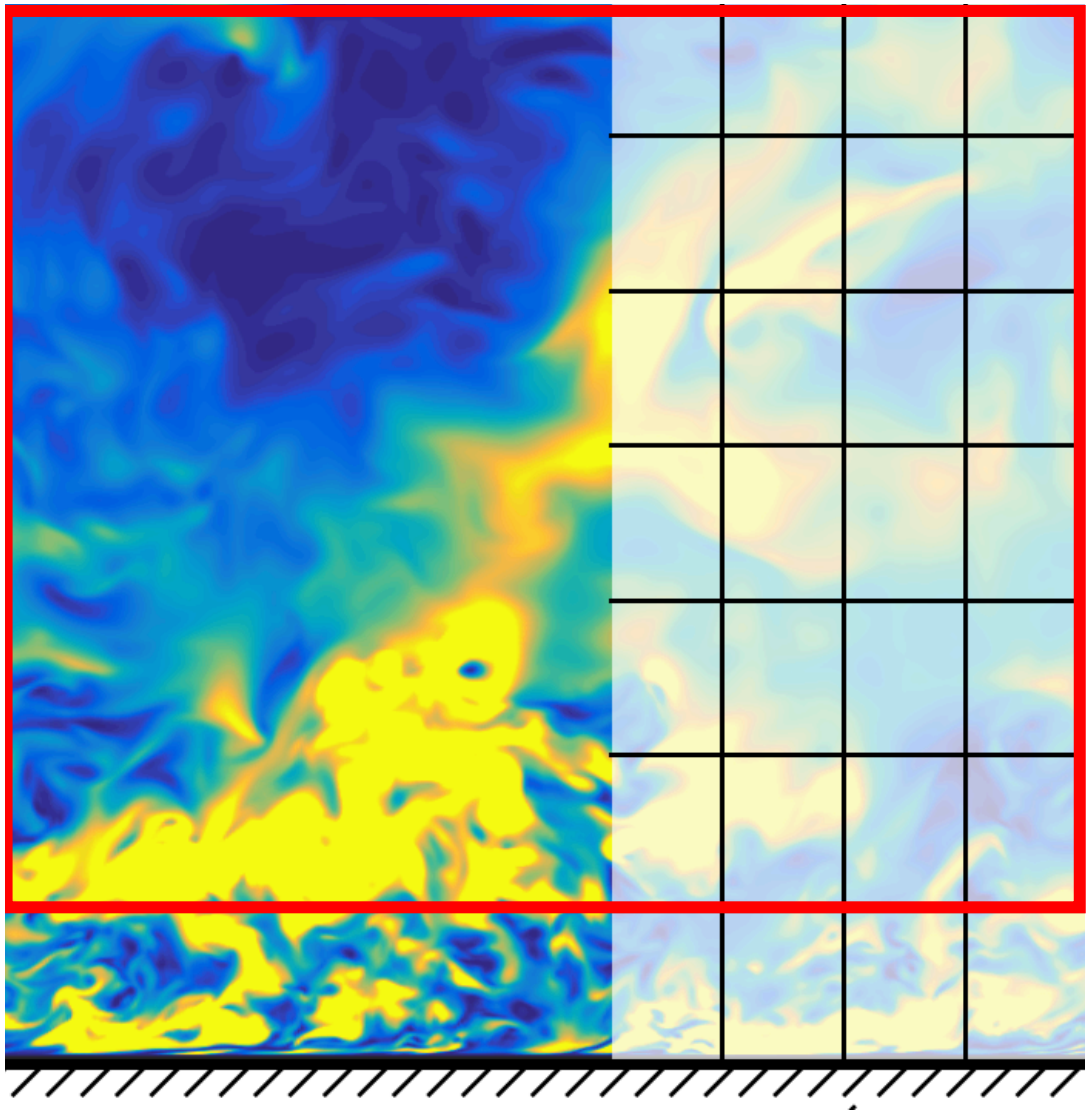
Wall-clock time for WMLES using 2048 cores, starting from uniform-velocity initial condition for 20 flow throughs (based on the streamwise length of the model):

122M CVs: 24 hours

The grid generation and the simulations run on Solo HPC from Sandia National Labs. (2.1 GHz Intel Broadwell E5-2695 v4)

Prediction of NASA Juncture flow using WMLES

Error quantification

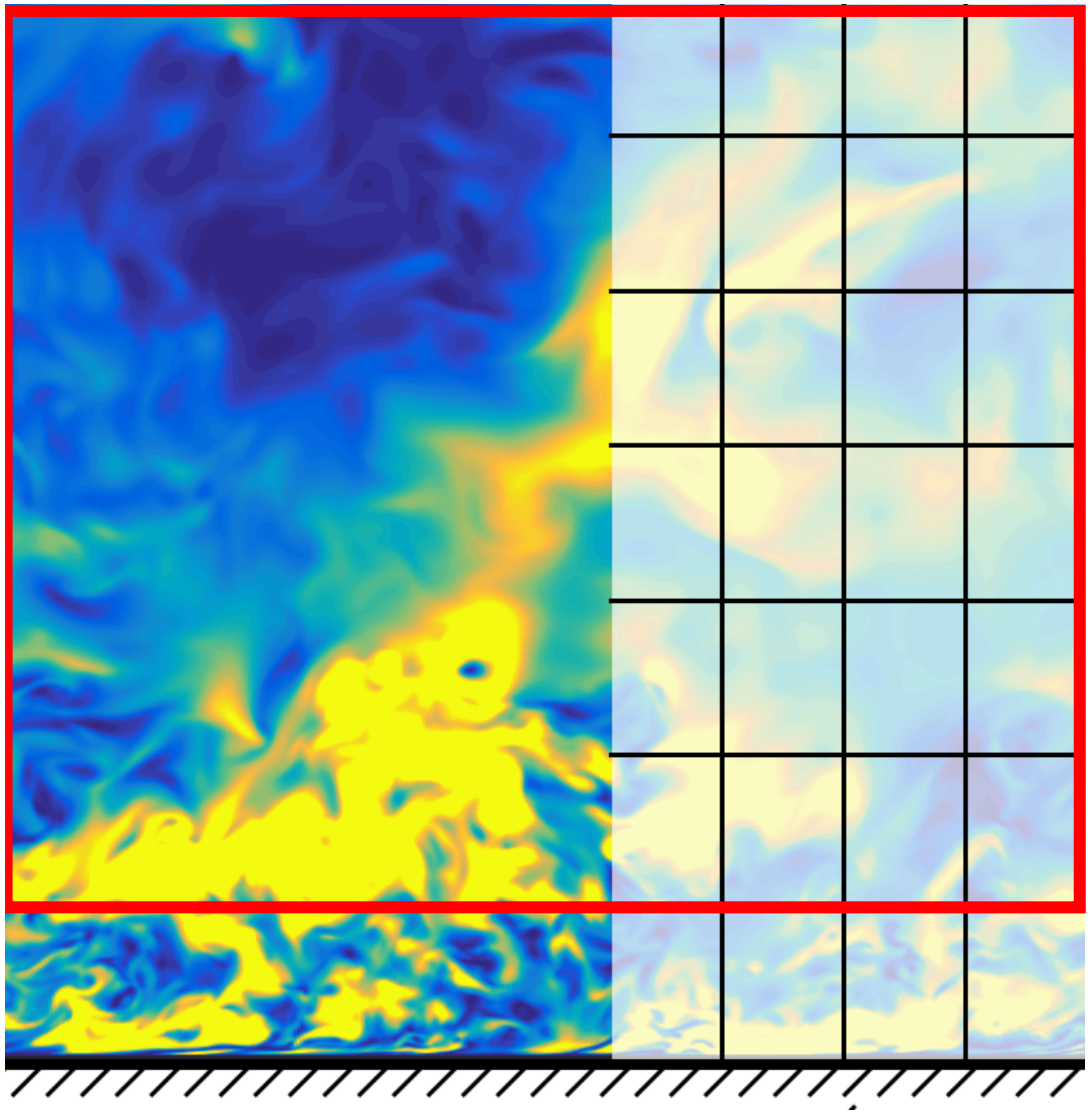


Error in mean Quantity:

$$Q \equiv \frac{||Q_{\text{exp}} - Q_{\text{LES}}||}{||Q_{\text{exp}}||}$$

Prediction of NASA Juncture flow using WMLES

Error quantification



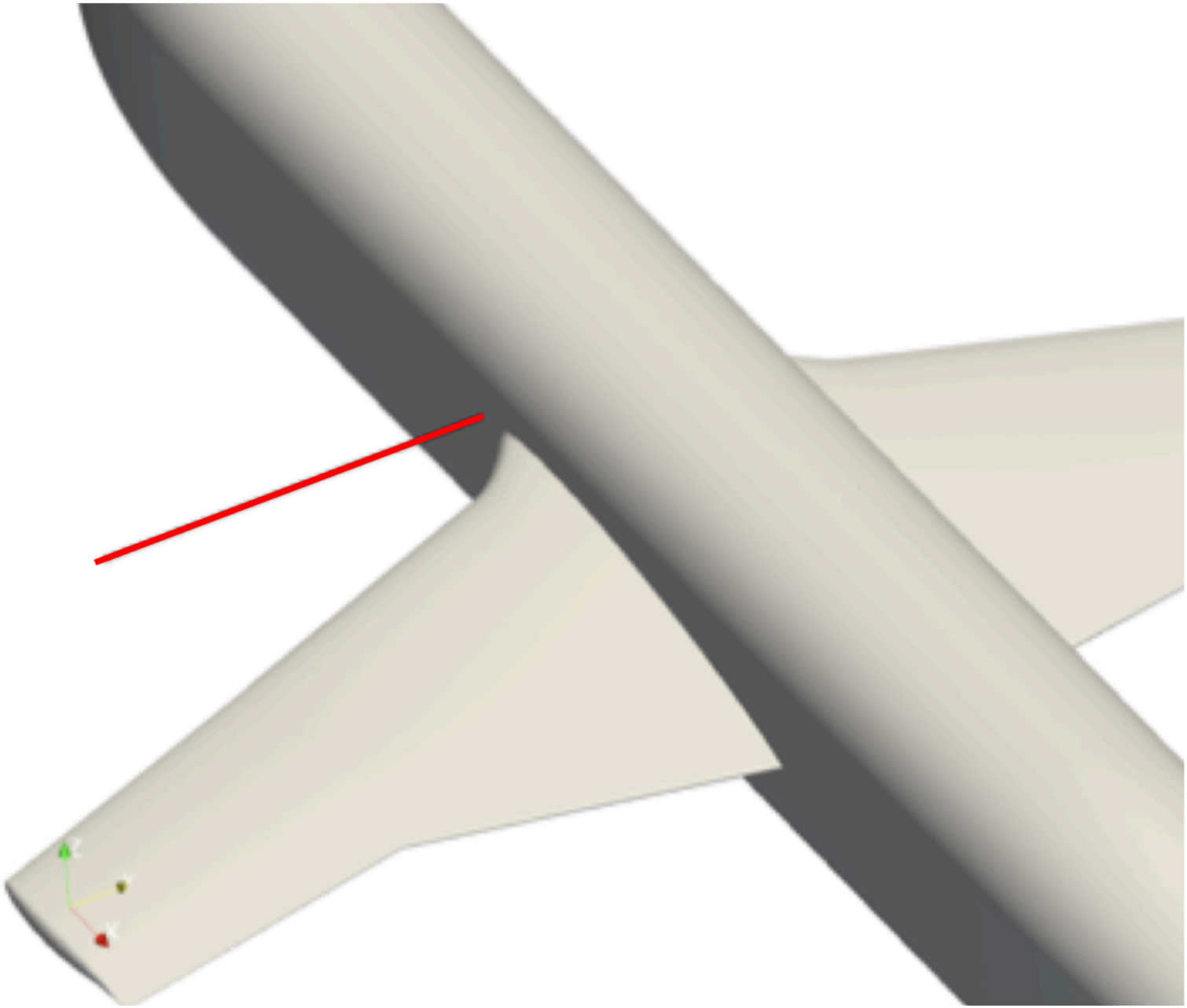
Expected error in WMLES of a canonical zero-pressure gradient turbulent boundary layer:

$$\text{Error in mean velocity} \approx 0.4 \left(\frac{\Delta}{\delta}\right)^{1} \mathrm{Re}^{0}$$

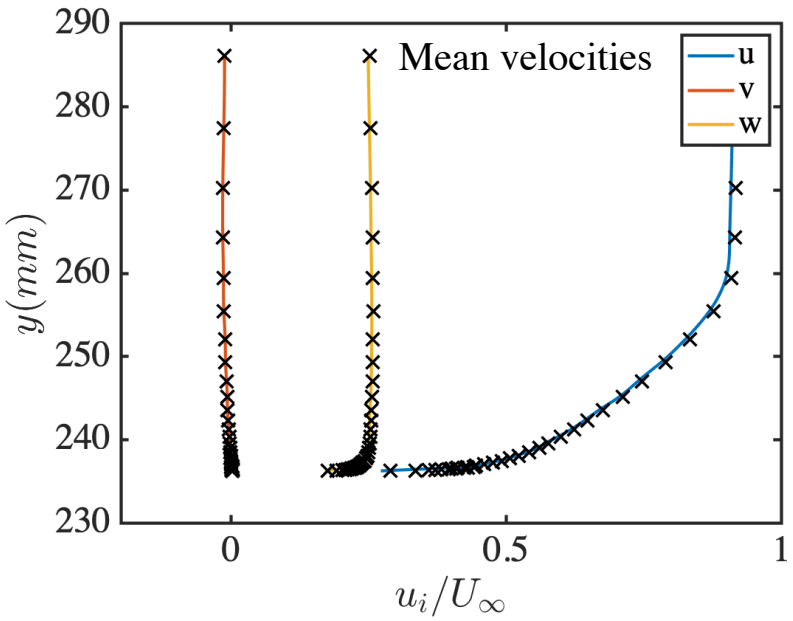
$$\text{Error in resolved turbulent kinetic energy} \approx \left(\frac{\Delta}{\delta}\right)^{2/3} \mathrm{Re}^{0}$$

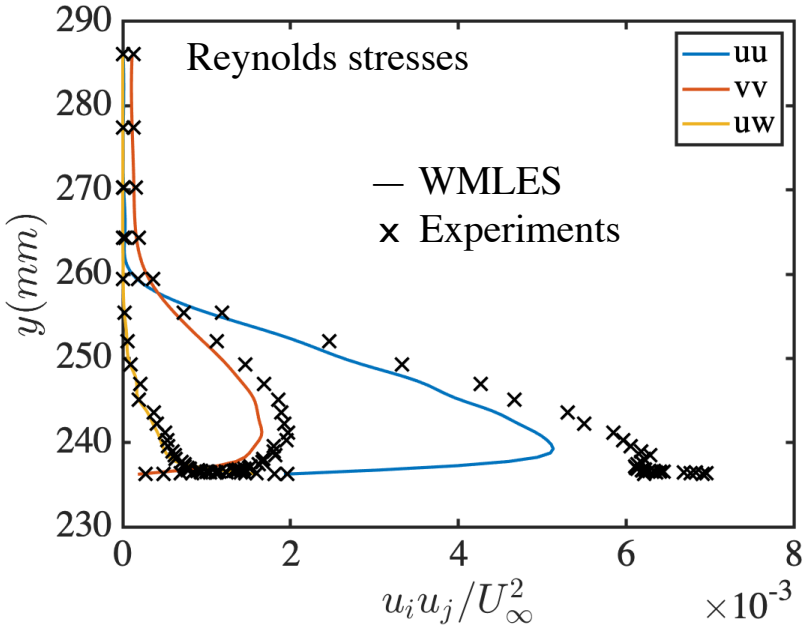
Lozano-Duran & Bae,
J. Comp. Phys. 392 (2019) 532–555

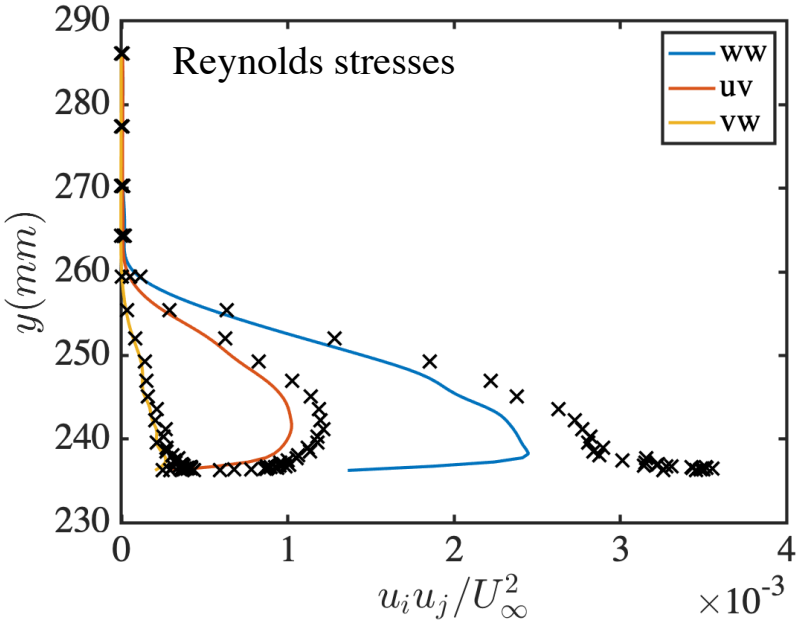
Prediction of NASA Juncture flow with WMLES

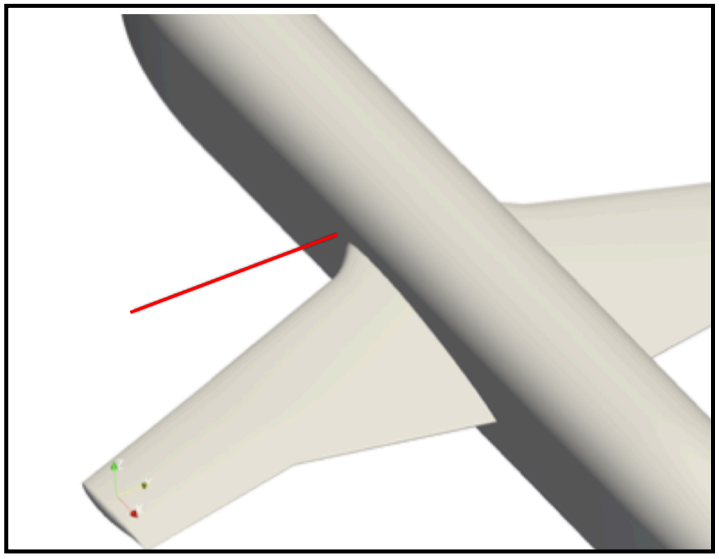


Prediction of NASA Juncture flow with WMLES

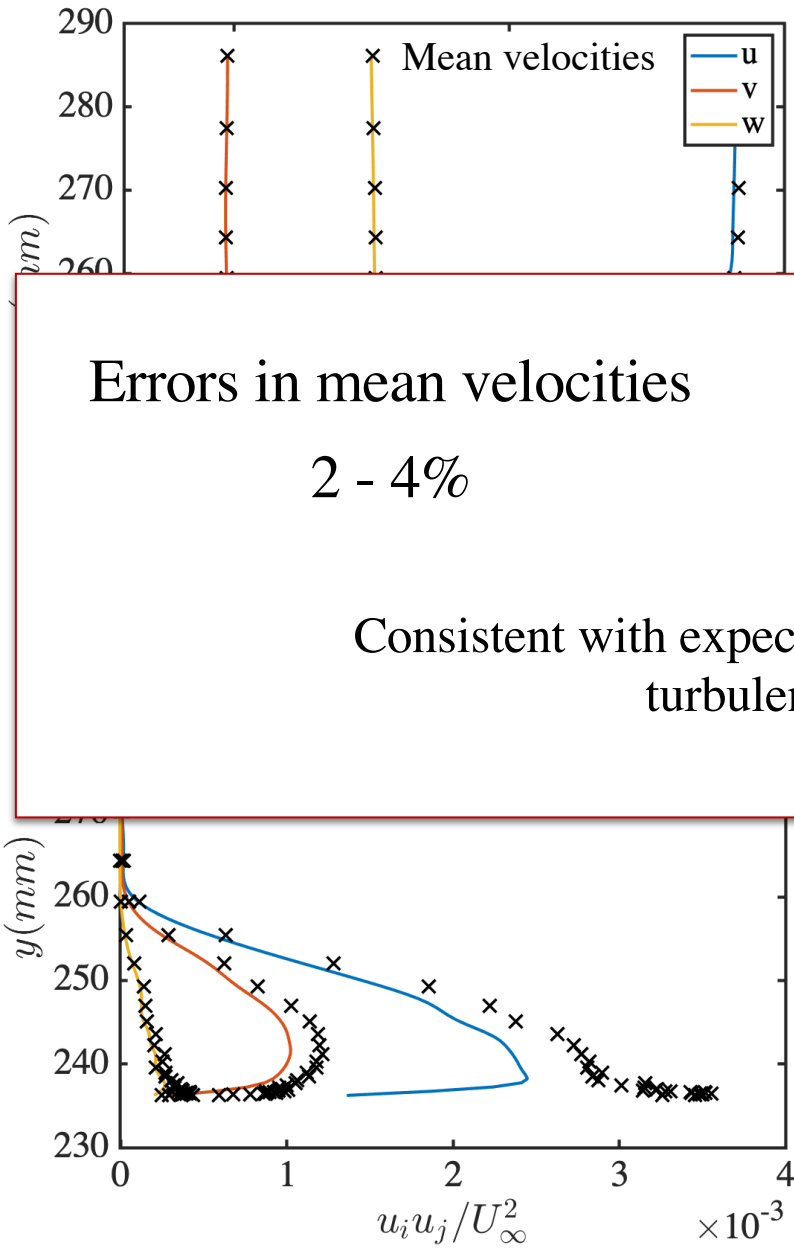


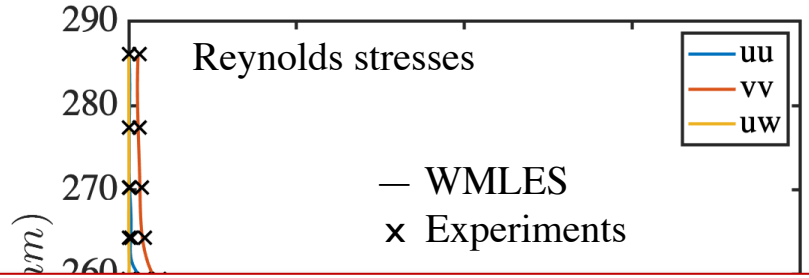






Prediction of NASA Juncture flow with WMLES





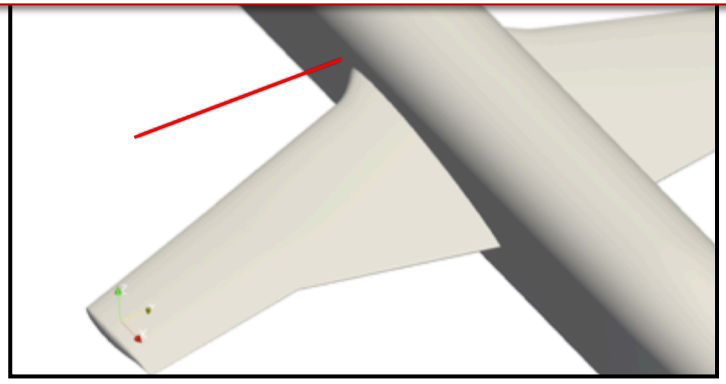
Errors in mean velocities

2 - 4%

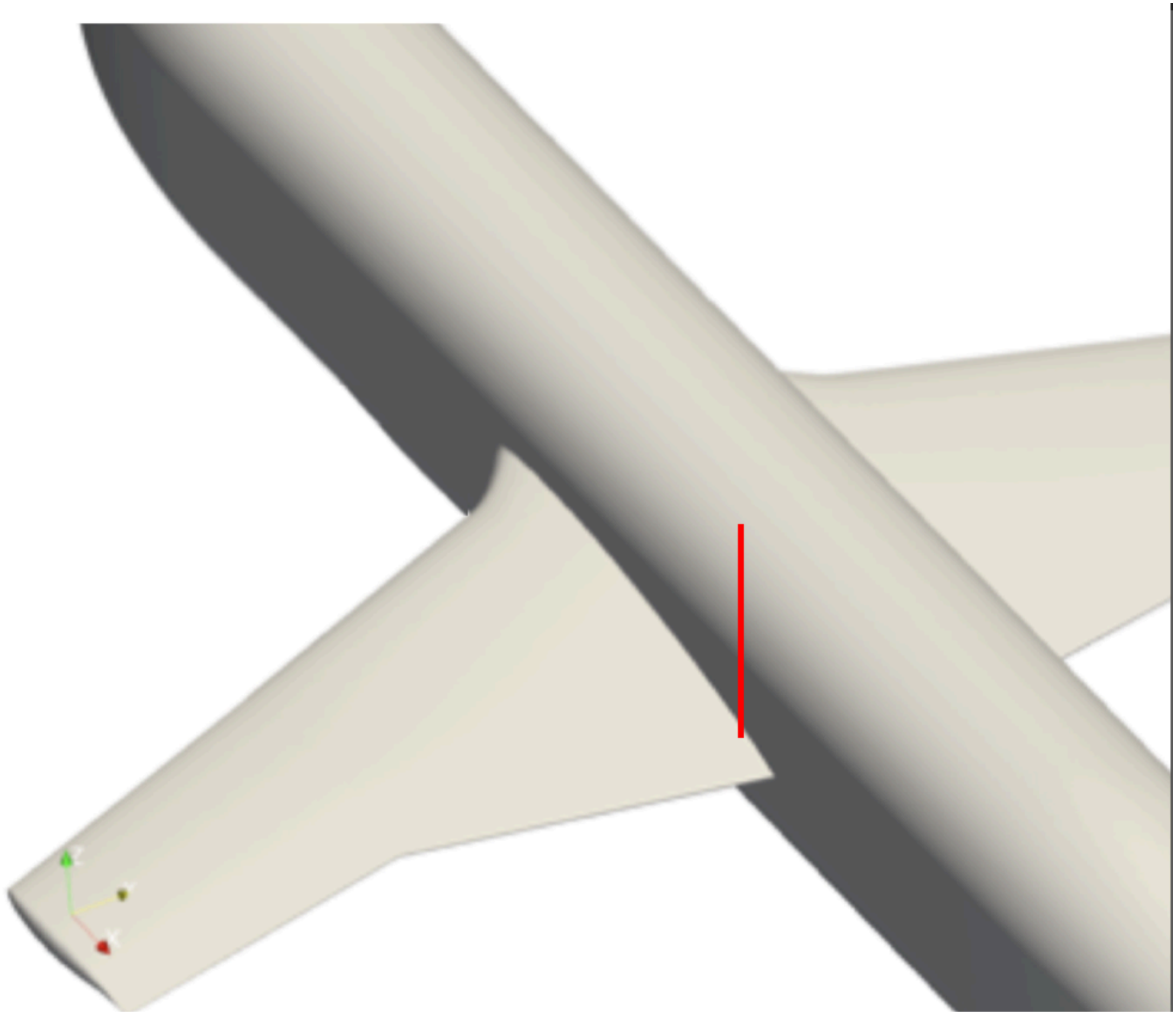
Underprediction in Reynolds stresses

10 - 20%

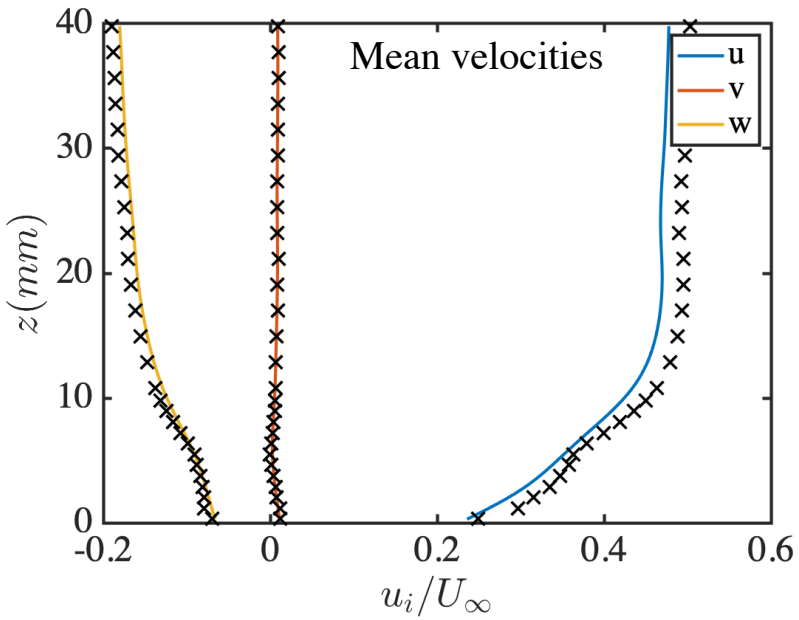
Consistent with expected errors in canonical flat plate turbulent boundary layer

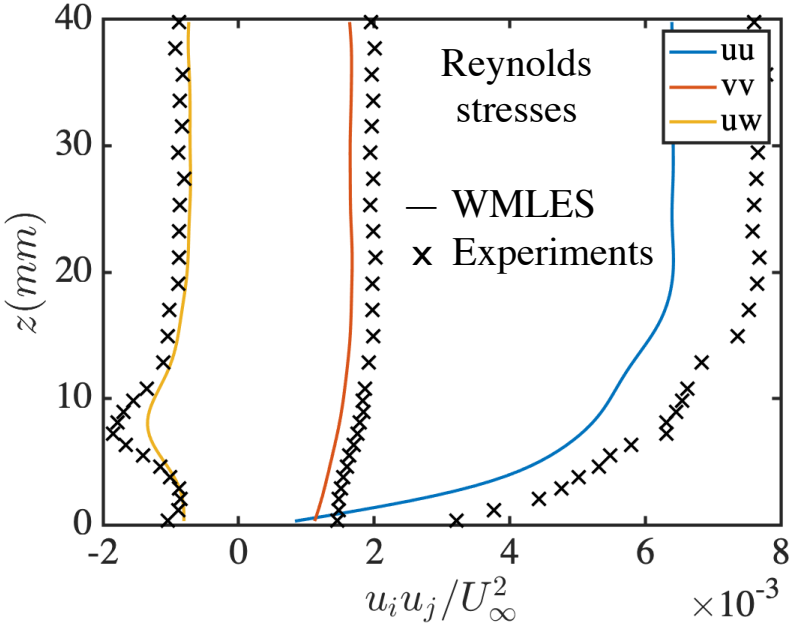


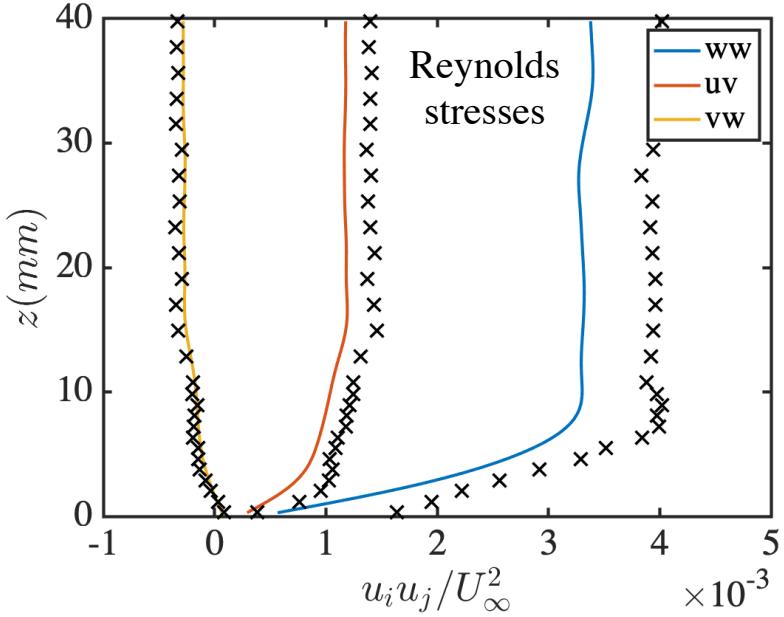
Prediction of NASA Juncture flow with WMLES

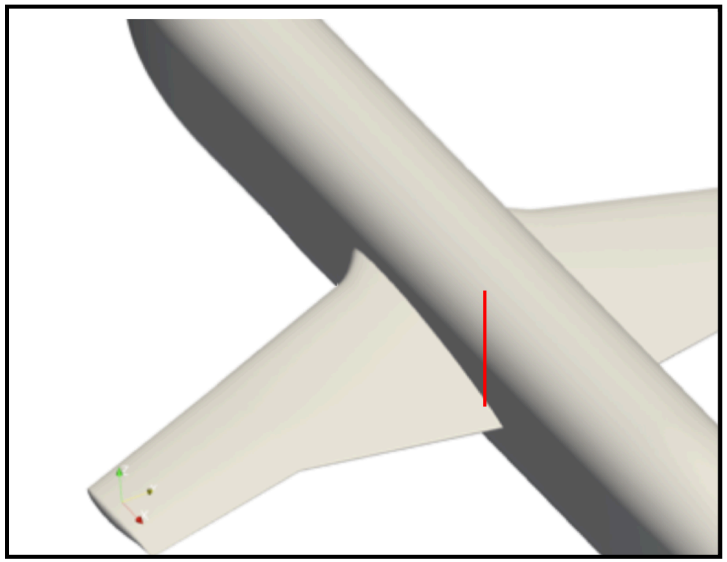


Prediction of NASA Juncture flow with WMLES

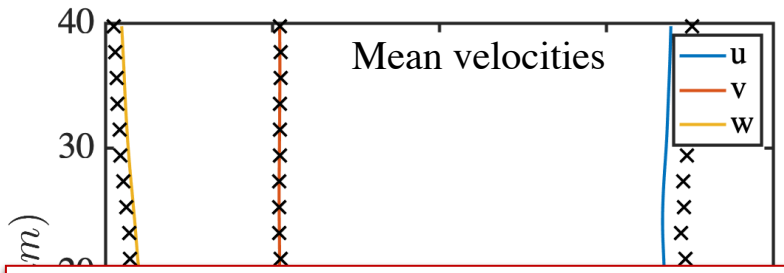


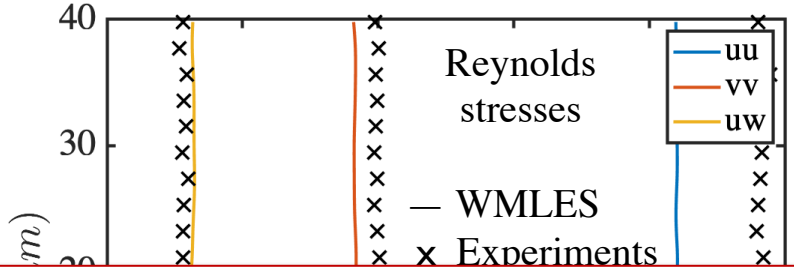






Prediction of NASA Juncture flow with WMLES





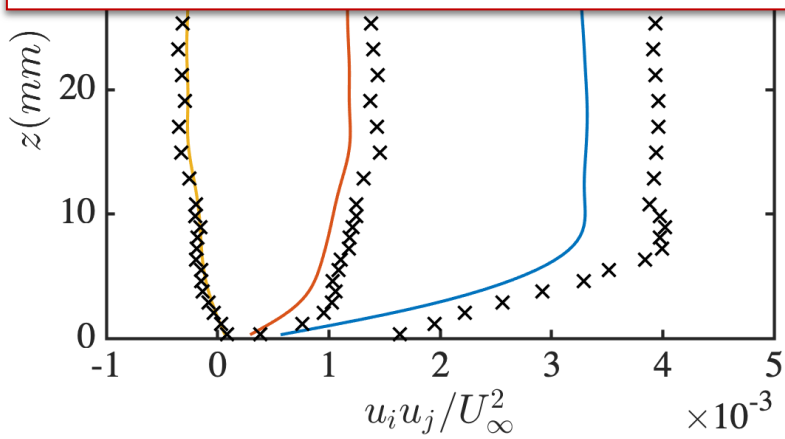
Errors in mean velocities

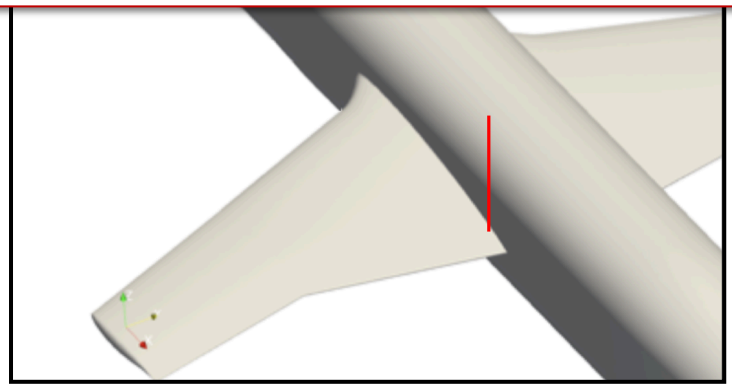
5 - 10%

Underprediction in Reynolds stresses

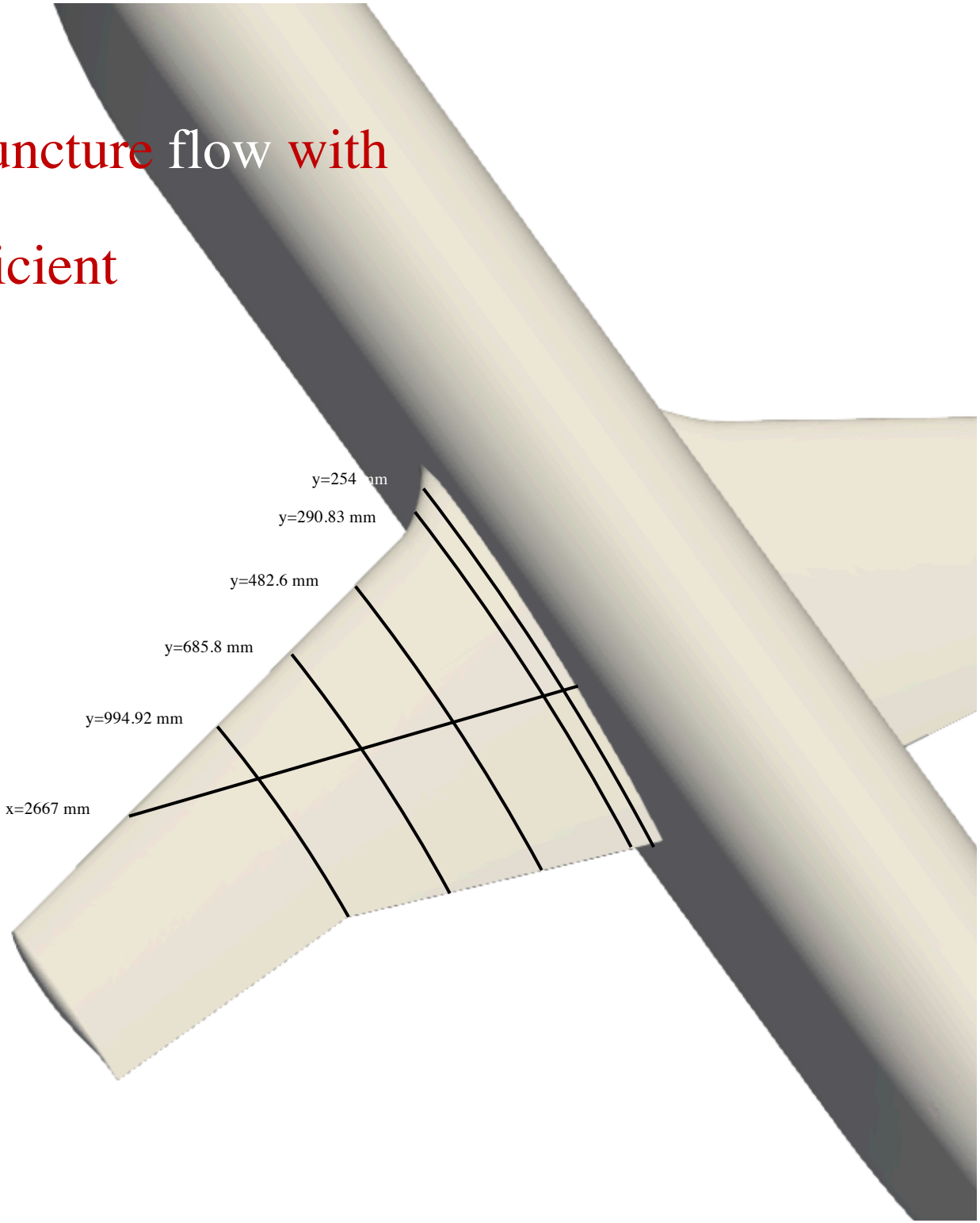
10 - 30%

larger than expected errors in canonical flat plate turbulent boundary layer
Potential source: 3-D mean & secondary motions

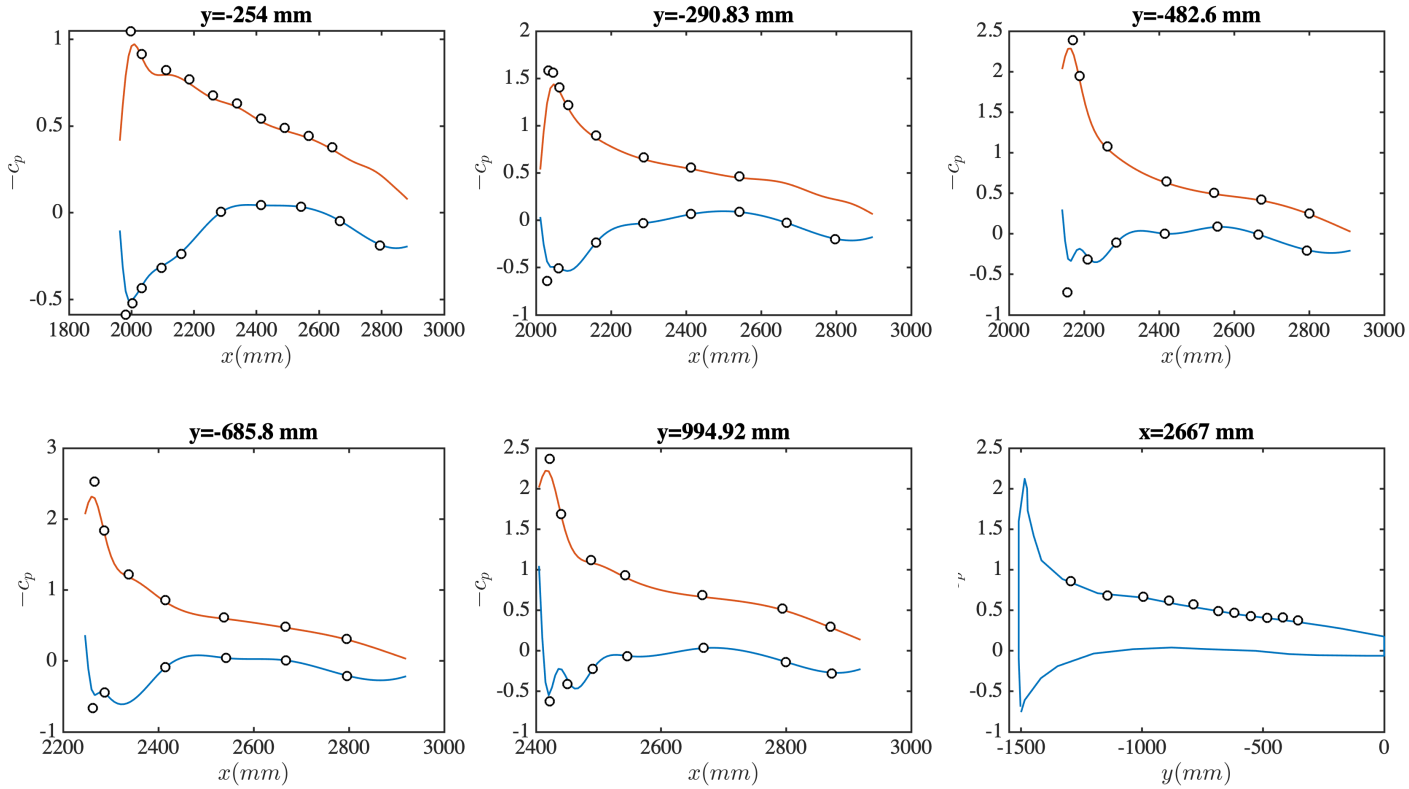


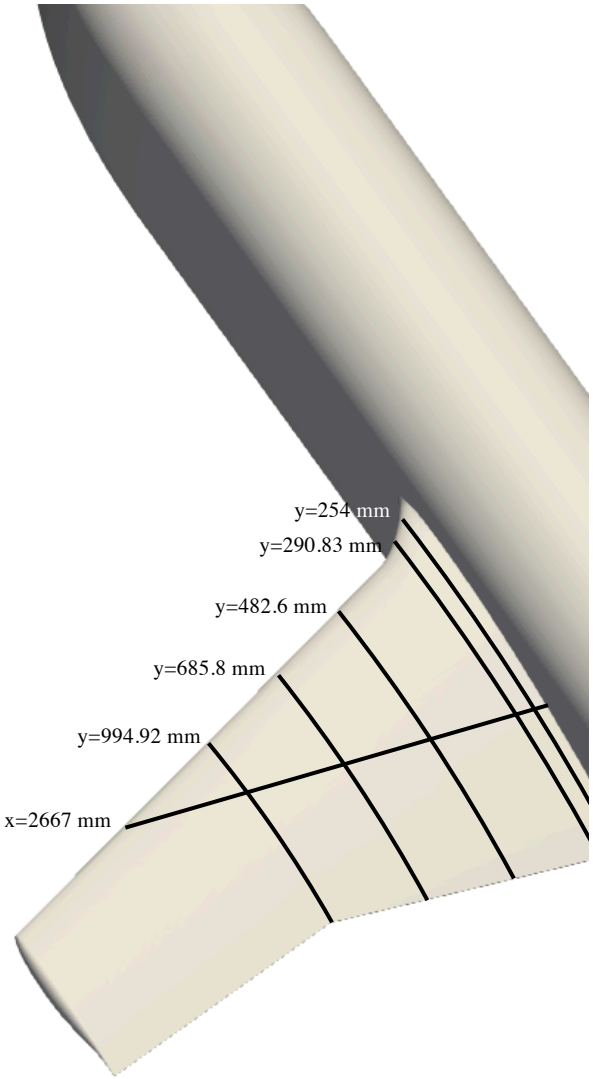


Prediction of NASA Juncture flow with WMLES
Surface pressure coefficient



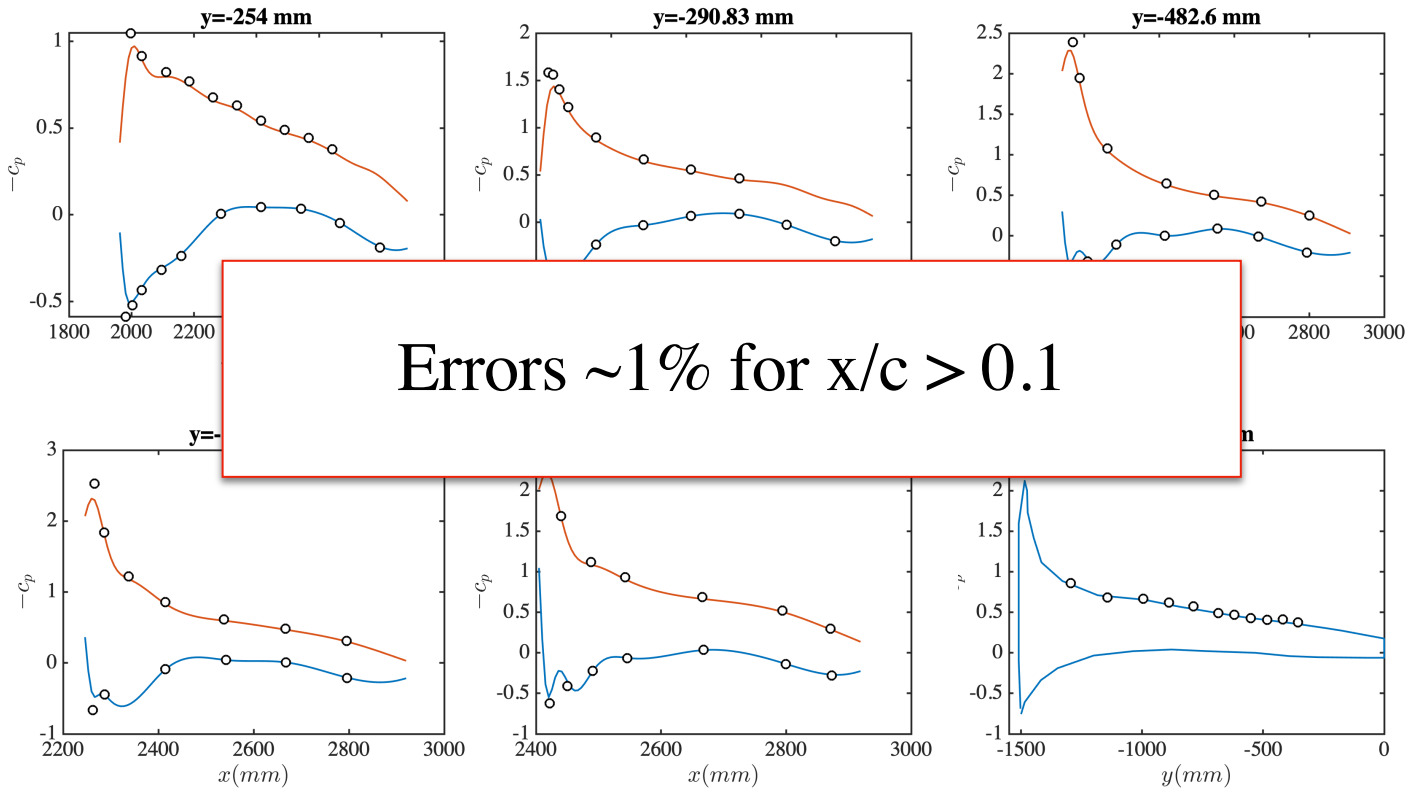
Prediction of NASA Juncture flow with WMLES
Surface pressure coefficient





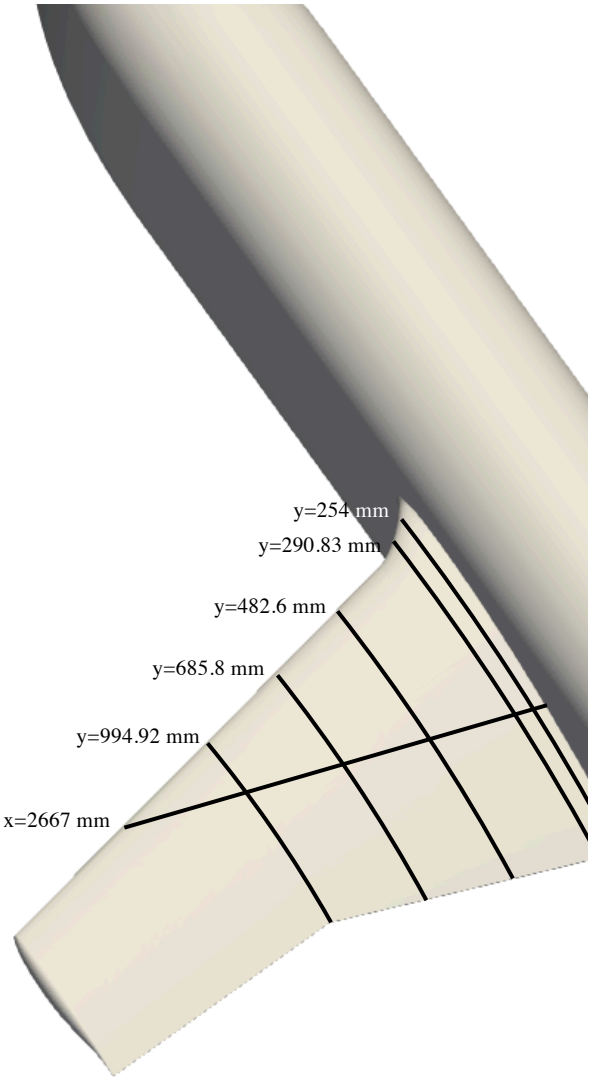
— WMLES
o Experiments

Prediction of NASA Juncture flow with WMLES
Surface pressure coefficient



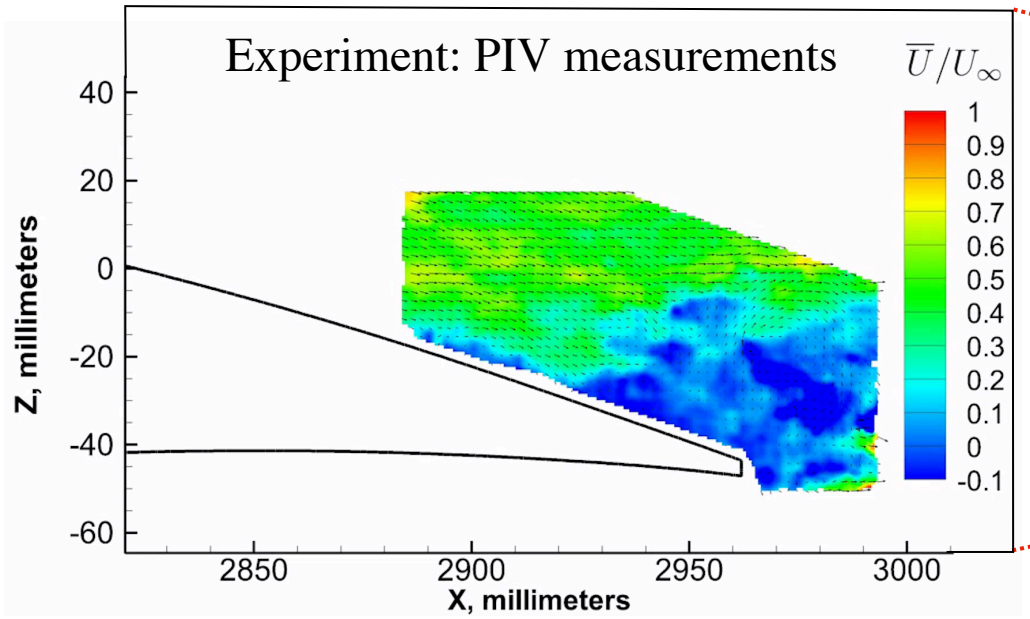
Errors ~1% for x/c > 0.1

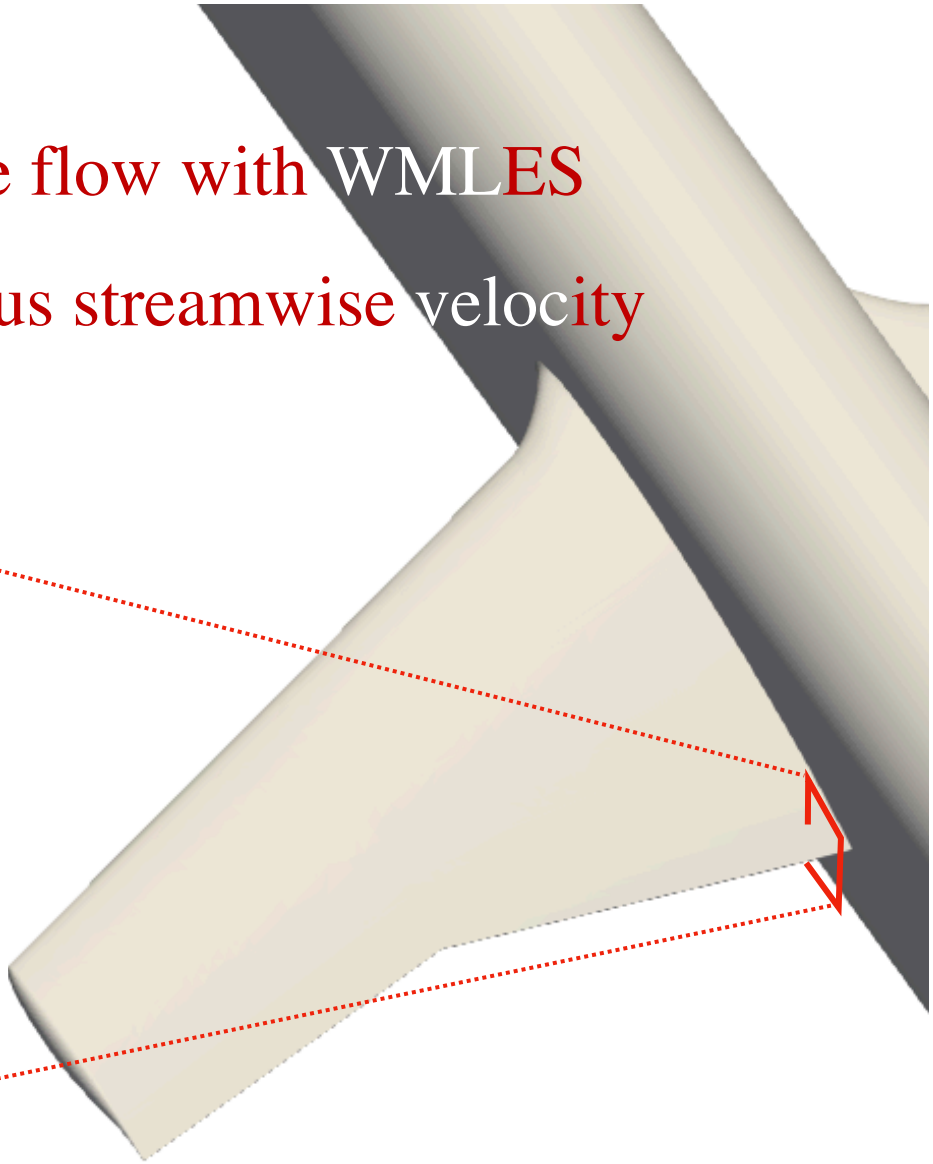
— WMLES
o Experiments



Prediction of NASA Juncture flow with WMLES

Separation zone: instantaneous streamwise velocity

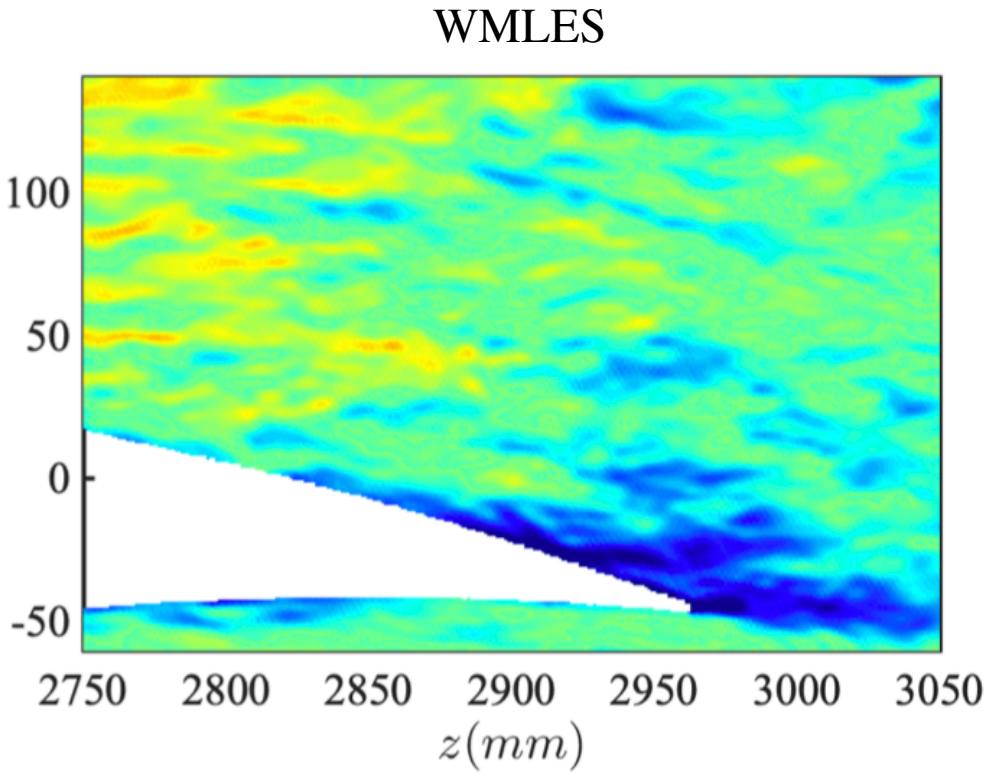


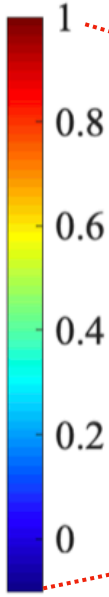


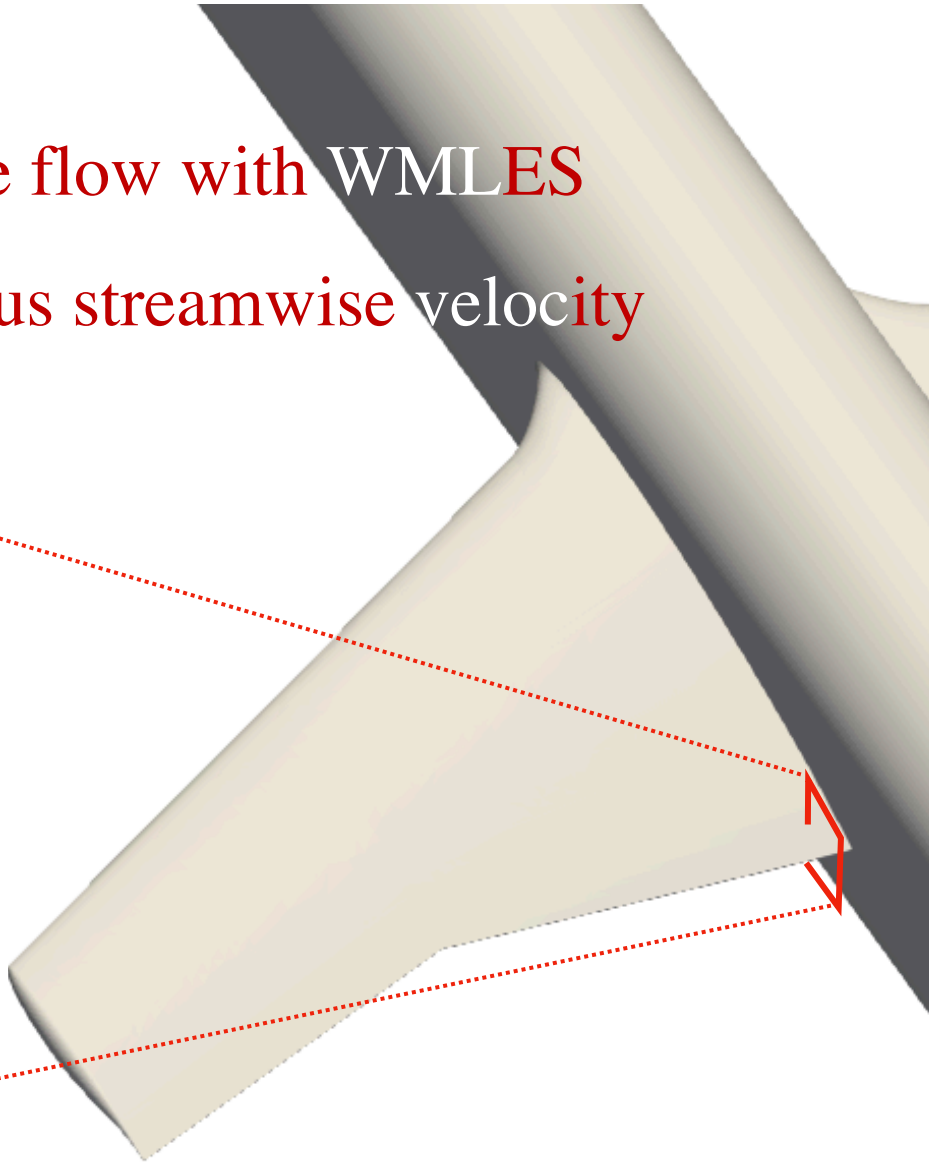
Highly unsteady separation bubble

Prediction of NASA Juncture flow with WMLES

Separation zone: instantaneous streamwise velocity

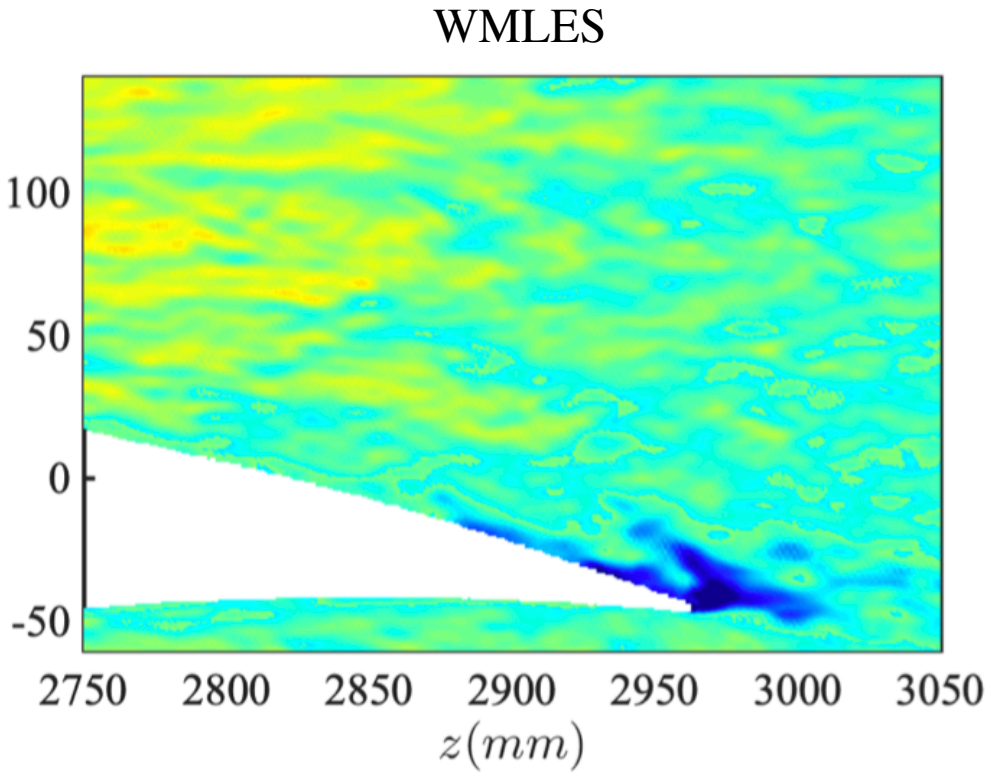


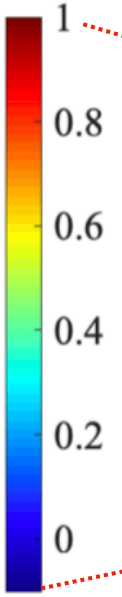


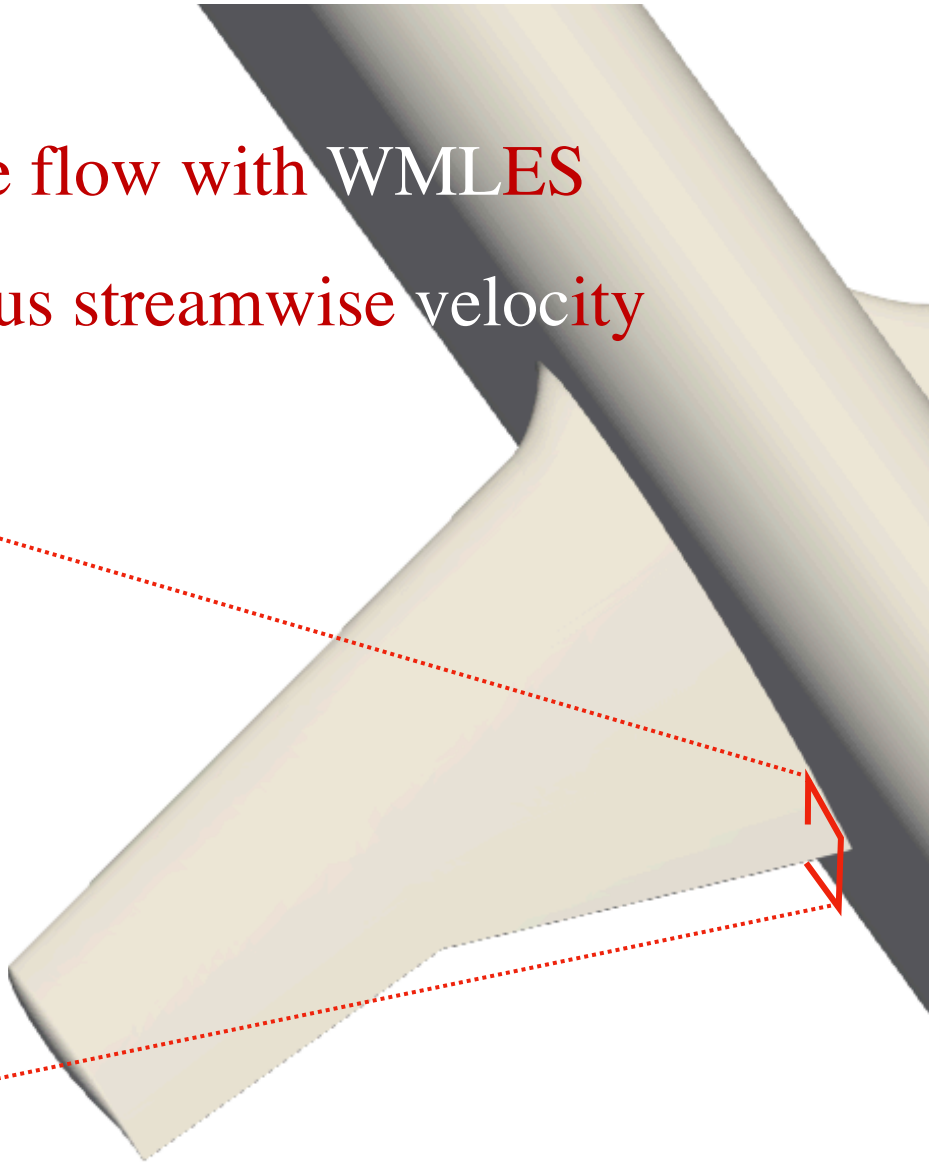


Prediction of NASA Juncture flow with WMLES

Separation zone: instantaneous streamwise velocity



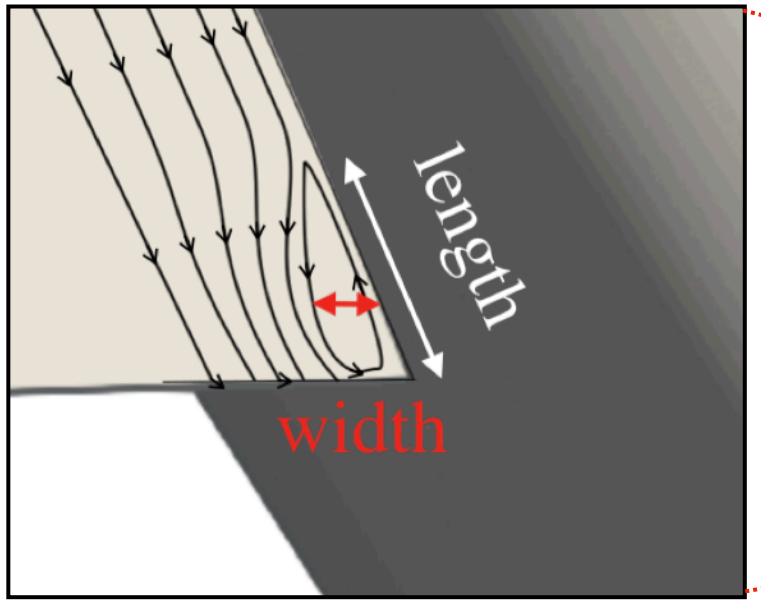


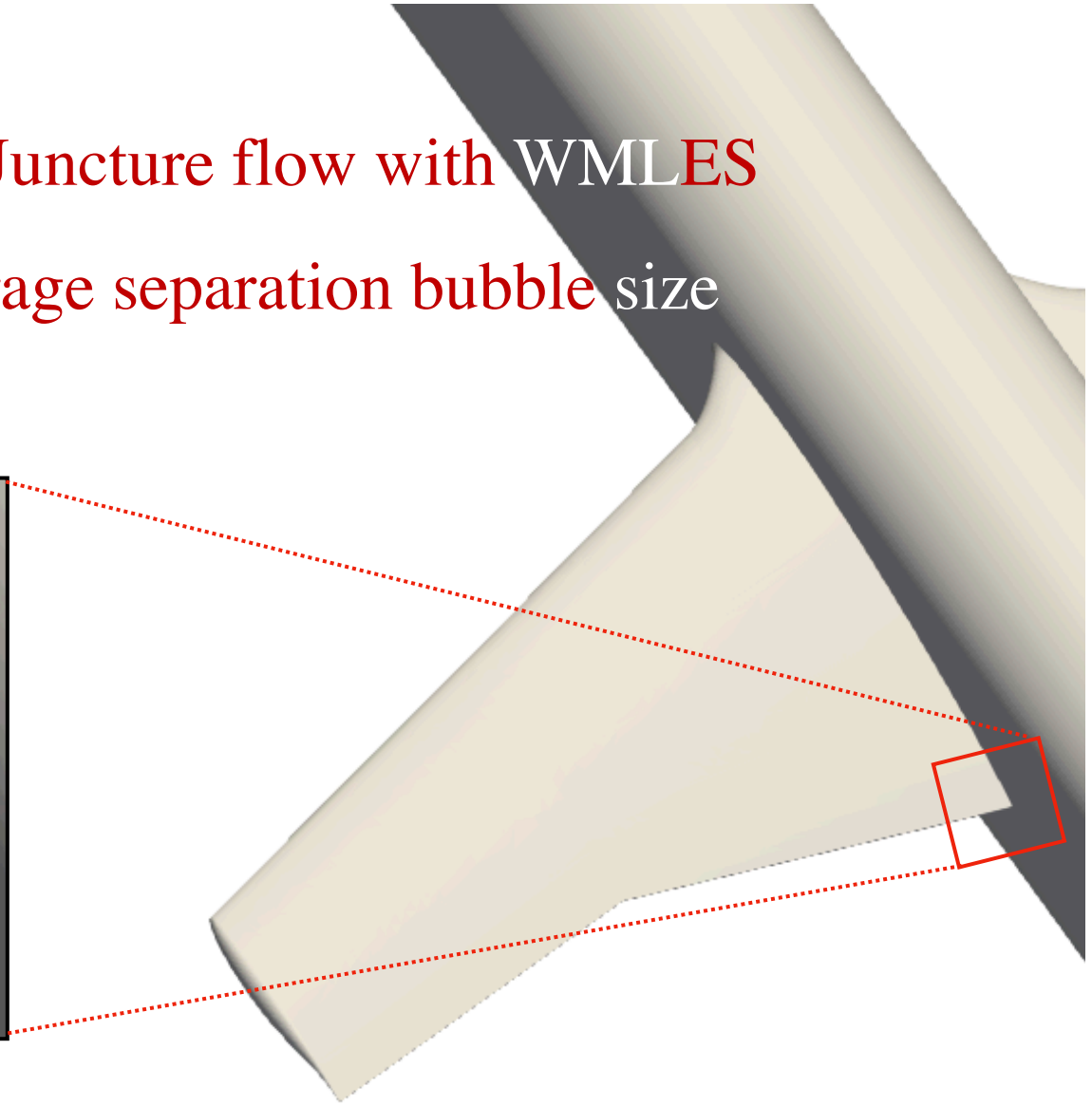


Prediction of NASA Juncture flow with WMLES

Separation zone: average separation bubble size

WMLES average wall stress streamlines





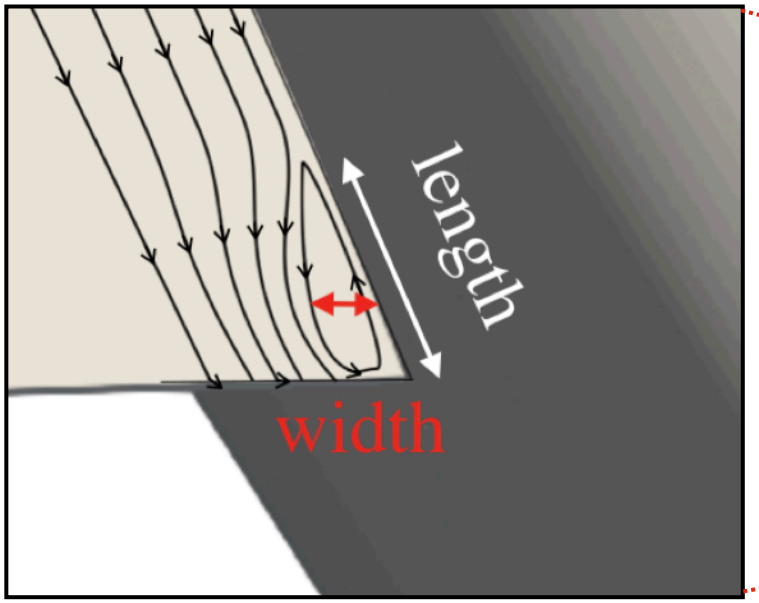
length: 102mm

width: 33mm

Prediction of NASA Juncture flow with WMLES

Separation zone: average separation bubble size

WMLES average wall stress streamlines





length: 102mm

width: 33mm

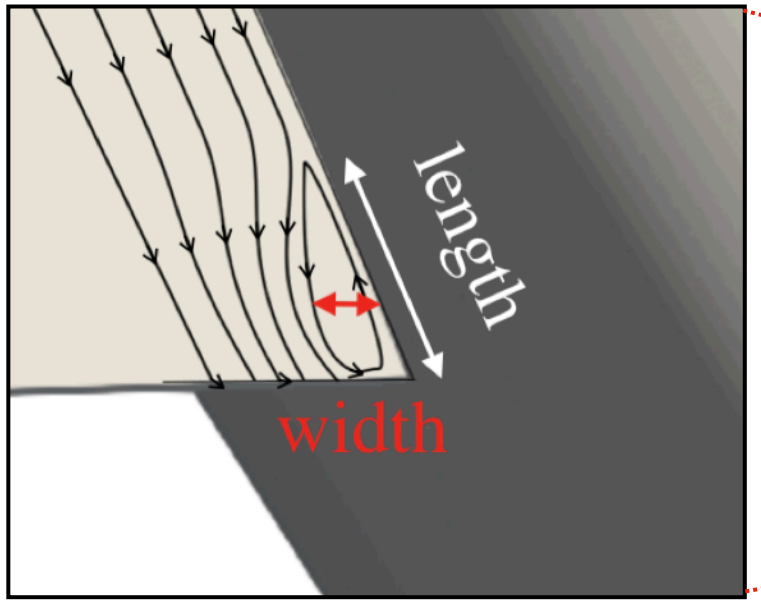
length: 120mm

width: 40mm

Prediction of NASA Juncture flow with WMLES

Separation zone: average separation bubble size

WMLES average wall stress streamlines





length: 102mm

width: 33mm

length: 120mm

width: 40mm

Separation bubble size predicted within 15% accuracy

Conclusions

Wall-modeled large-eddy simulation for real-world external aerodynamics:

- If we impose grid-to-simulation turnaround of ~1 day using ~100M CVs on ~1000 cores
- For JAXA Standard Model & NASA Juncture Flow
- 0 – 15 points per boundary layer thickness
- WMLES is capable of predicting:
  - Lift coefficient 1-5% and drag coefficient 5-10% accuracy.
  - Mean velocity profiles to within 2-10% accuracy.
  - Surface pressure coefficient to within 1% accuracy.
  - Trailing-edge separation bubble size to within 15% accuracy.

Not yet at the **stringent tolerance** demanded by the industry <1%

Outlook:

- Advance models to account for separation, 3-D mean-flows, laminar-to-turbulent transition, non-equilibrium effects, shock waves…
- Strict characterization of WMLES errors
- Routinely use of GPUs
- …