KΩ TURBULENCE MODEL: SHOCK UNSTEADINESS MODIFICATION

Volker Hannemann

Spacecraft Department

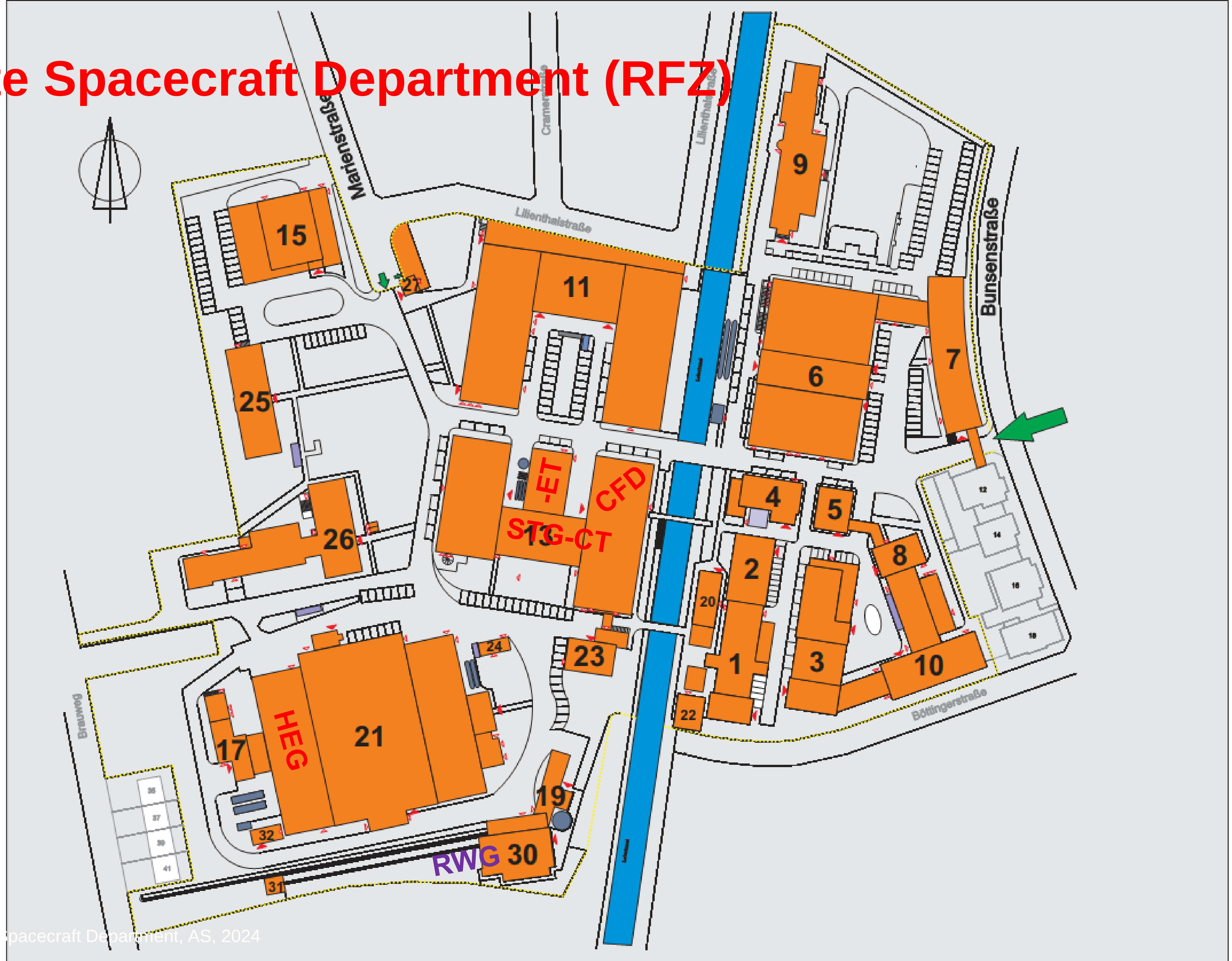
Institute of Aerodynamics and Flow Technology

DLR – German Aerospace Center in 2024

About 10 000 employees in about 50 institutes and installations in about 20 locations.

Offices in Brüssel, Paris, Tokio and Washington.

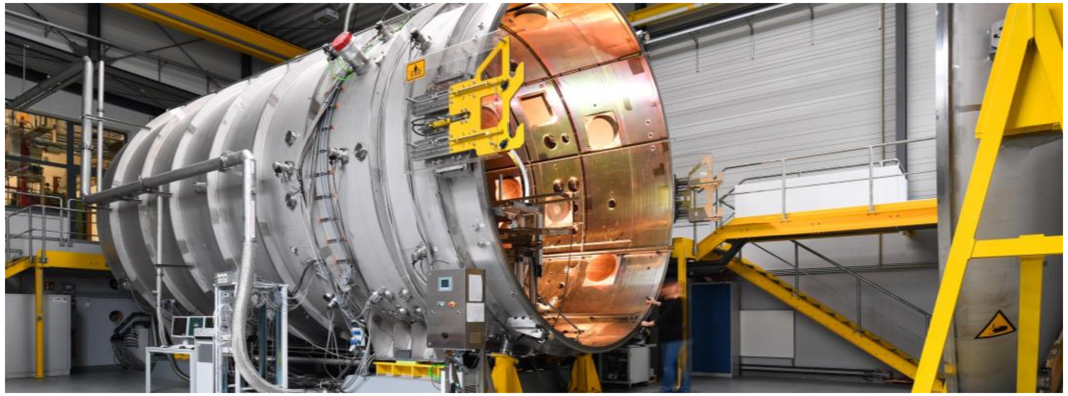
Locate Spacecraft Department (RFZ)



Spacecraft Department

DLR Göttingen – Dr. Jan Martinez Schramm

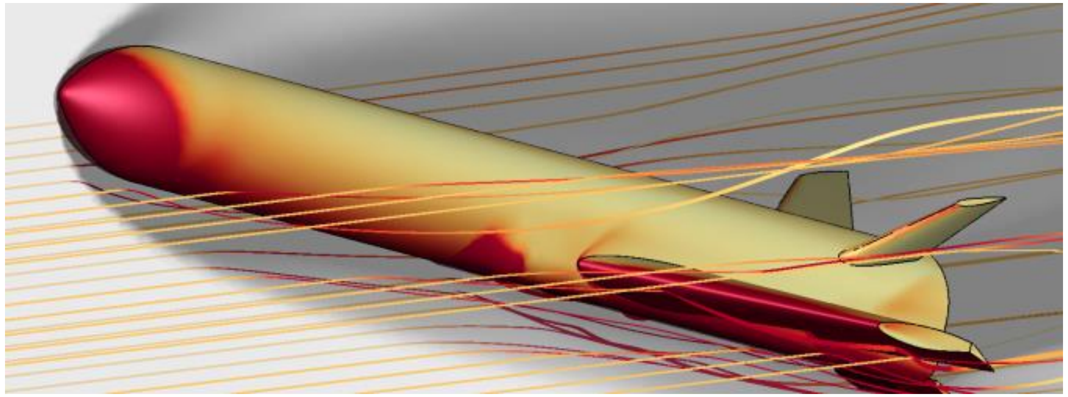
Rarefied Flows (Electric Space Propulsion)



Rarefied Flows (Chemical Space Propulsion)

Experimental Aerothermodynamics

Aerothermodynamics and Propulsion Technology



Aerothermodynamics and Propulsion Technology Group

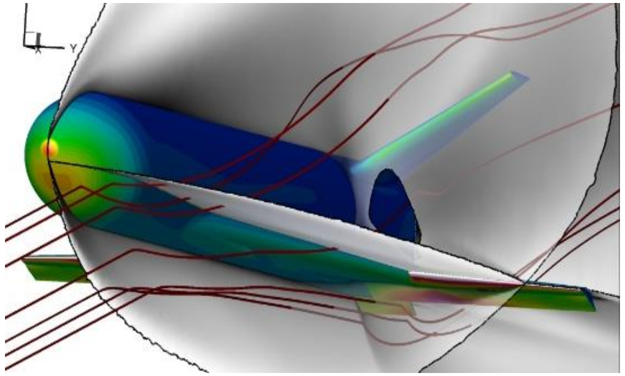
Dr. Tobias Ecker / Dr. Tim Horchler

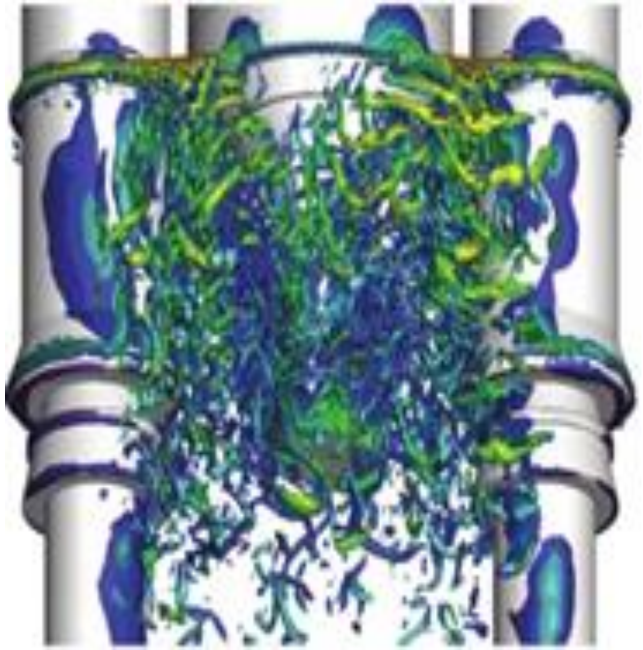
Development of advanced numerical methods and models

- Efficient large scale **HPC**-Application
- Interfaces and infrastructures for interdisciplinary and multi-physics simulations
- Chemically reacting flows, complex multi-phase thermodynamics, advanced turbulence models, radiation

Numerical analyses of vehicles, sub-systems and test stands

- Aerothermodynamic performance, heat loads and design database development
- Propulsion systems
- Fundamental research in high enthalpy reacting flows
- Numerical support for experimental work in test facilities





Rarefied Flows Group

Dr. Martin Grabe

Electric space propulsion

- Advanced plasma beam diagnostics and thrust measurement
- Plume / spacecraft interaction
- Electric propulsion thruster studies and development
- Technology transfer from R&D to application
- Large-scale test facility: **STG-ET**

Chemical space propulsion

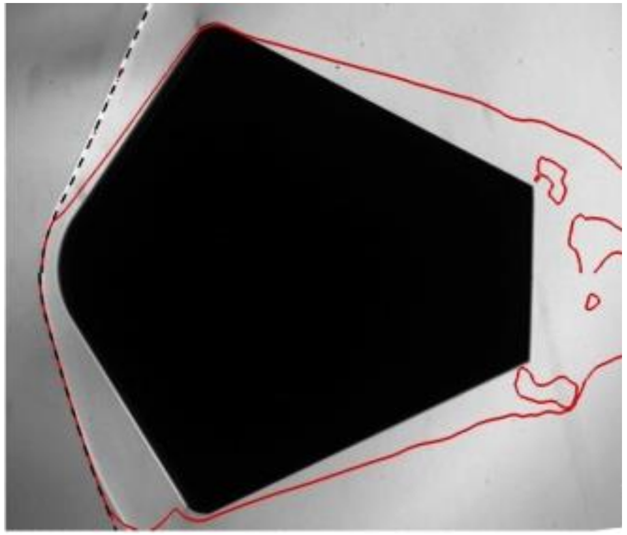
- Thruster plume characterization
- Spacecraft self-contamination (molecular, droplets; erosion)
- Landing site contamination assessment
- Plume / Plume interference in nozzle clusters
- Large-scale test facility: **STG-CT**

Aerothermodynamics for Spacecraft Group

Dr. Alexander Wagner

High enthalpy hypersonic flow

- Hypersonic flight configurations at realistic flight conditions
- High temperature effects on aerodynamics of (re-)entry
- Boundary layer transition control
- Complete supersonic combustion scramjets
- Investigation of magneto-hydrodynamic effects during (re-)entry
- Large-scale test facility: **HEG**



CFD Experiences: Development & Application

Dr. rer. nat. Dipl. phys. Volker Hannemann

DLR-TAU (> 3 decades)	UQ-Eilmer (< 6 month)
C (, Python) - procedural	D, Lua - object oriented
Finite volume on dual grid	Finite volume on primary grid
netcdf, .plt, …	ASCII.zip, .pvd + .vtu
iso99, (tecplot, paraview)	Paraview
Expert	Learner

kω turbulence model

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \text{P} - D_k + Diff_k$$

(details e.g.: turbmodels.larc.nasa.gov/wilcox.html)

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma\omega}{k}\text{P} - D_\omega + Diff_\omega$$

Production term P:

$$P = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij} \right) \frac{\partial u_i}{\partial x_j} - \frac{2}{3}\rho k \delta_{ij}\frac{\partial u_i}{\partial x_j}$$

$$P = \mu_t\, \text{f}\left(\frac{\partial u_i}{\partial x_j}\right) - \frac{2}{3}\rho k\, \underline{\nabla}^T \underline{u}$$

Observation: too much turbulence predicted downstream of shocks (worse the stronger the shocks is)

Explanation of modification (Sinha, Mahesh, Candler: *Modeling shock unsteadiness in shock/turbulence interaction, Physics of Fluids, Vol.15(8),* 2003)

- **Production term is designed for eddies facing a smooth gradient of the mean velocity.**

- **Shocks exist on a smaller length scale than the turbulent eddies**
- **Shocks adjust fast to the changed flow condition within an eddy**

Better production term at shocks with μ_t= 0

$$P = -\frac{2}{3}\rho k\, \underline{\nabla}^T \underline{u}$$

- **Based on 1d linear analysis the damping of the remaining production term due to shock movement depends on the shock strength**

$$P = -\frac{2}{3}\rho k\, \underline{\nabla}^T \underline{u}\left(1 - max\left[0, 0.4\left(1 - e^{1-M}\right)\right]\right) \approx -\frac{2}{3}\rho k\, \underline{\nabla}^T \underline{u}\left(1 - 0.4\left(1 - \frac{1}{M}\right)\right) \quad \text{if } M > 1$$

with M = $\frac{\underline{n}^T \underline{u}}{a}$ upstream of shock in stationary reference system

Implementation issues

- **Shock indicator** to remove locally the μ_t term from the production
- **Shock strength measure** M to dampen the remaining production term
  - Problematic with moving shocks
  - Tedious procedure to find values upstream and downstream of the shock

New idea: (Rathi & Sinha, AIAA Journal, Vol.61, No. 8, 2023)

Transport-Equation-Based Shock Sensor

$$\frac{\partial(\rho\psi)}{\partial t} + \frac{\partial(\rho u_j \psi)}{\partial x_j} = \rho\psi\, \underline{\nabla}^T \underline{u} - \rho(\psi - \psi_0)\frac{\sqrt{\underline{u}^T \underline{u}}}{L}$$

Analytic solution across a shock (without second source term): $\frac{\psi_2}{\psi_0} = \frac{\rho_1}{\rho_2}$

If ψ_0 = 1 (and relaxation fast enough) ψ is a local shock strength measure.

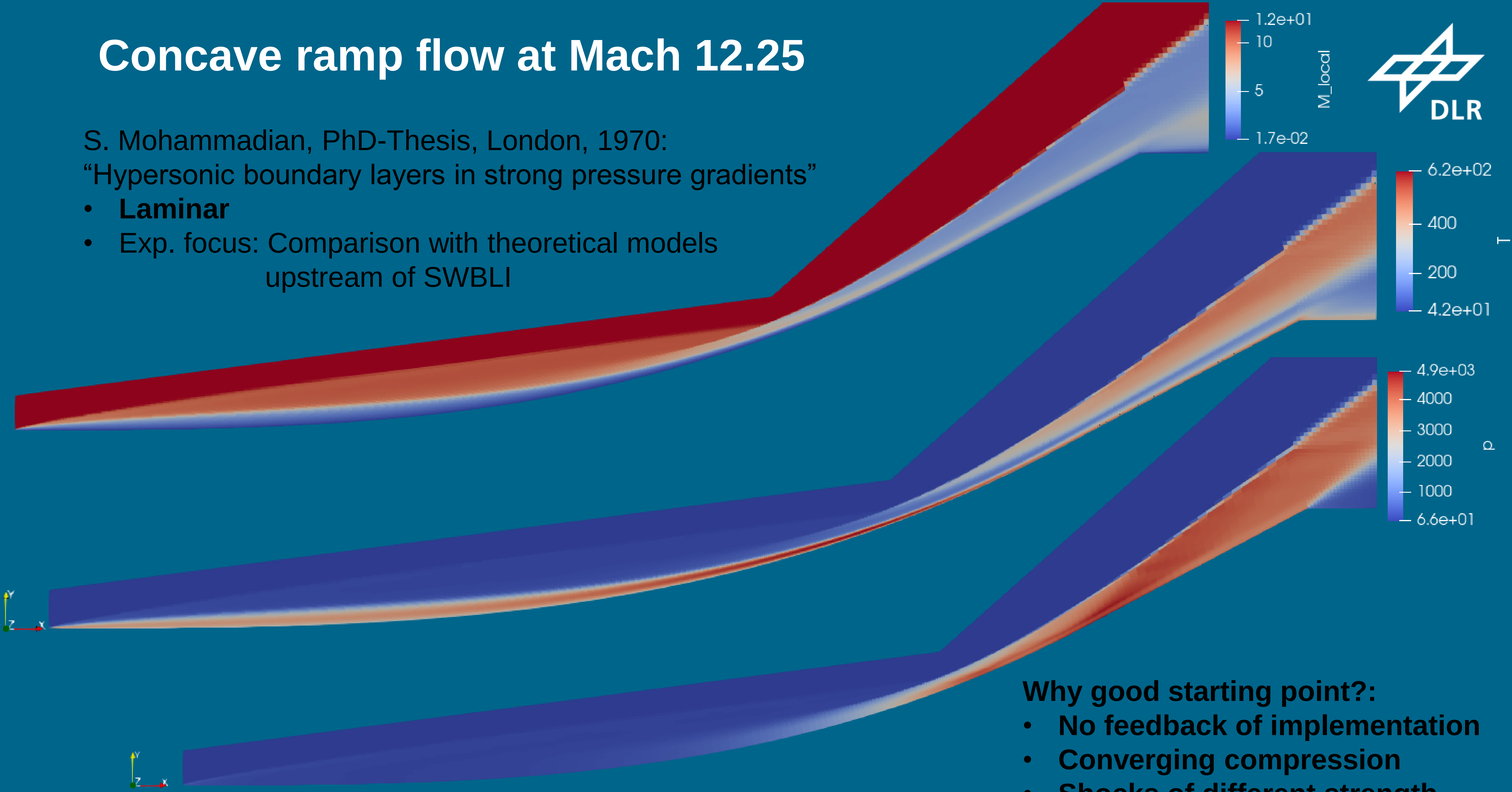
$$P = -\frac{2}{3}\rho k\, \underline{\nabla}^T \underline{u} \left(1 - 0.4\left(1 - \sqrt{\frac{\psi - \psi_{min}}{1 - \psi_{min}}}\right)\right)$$

with $\psi_{min} = \frac{\gamma - 1}{\gamma + 1}$ and $\psi \geq \psi_{min}$

Concave ramp flow at Mach 12.25

S. Mohammadian, PhD-Thesis, London, 1970:
“Hypersonic boundary layers in strong pressure gradients”

- **Laminar**
- Exp. focus: Comparison with theoretical models
  upstream of SWBLI



Why good starting point?:

- **No feedback of implementation**
- **Converging compression**
- **Shocks of different strength**

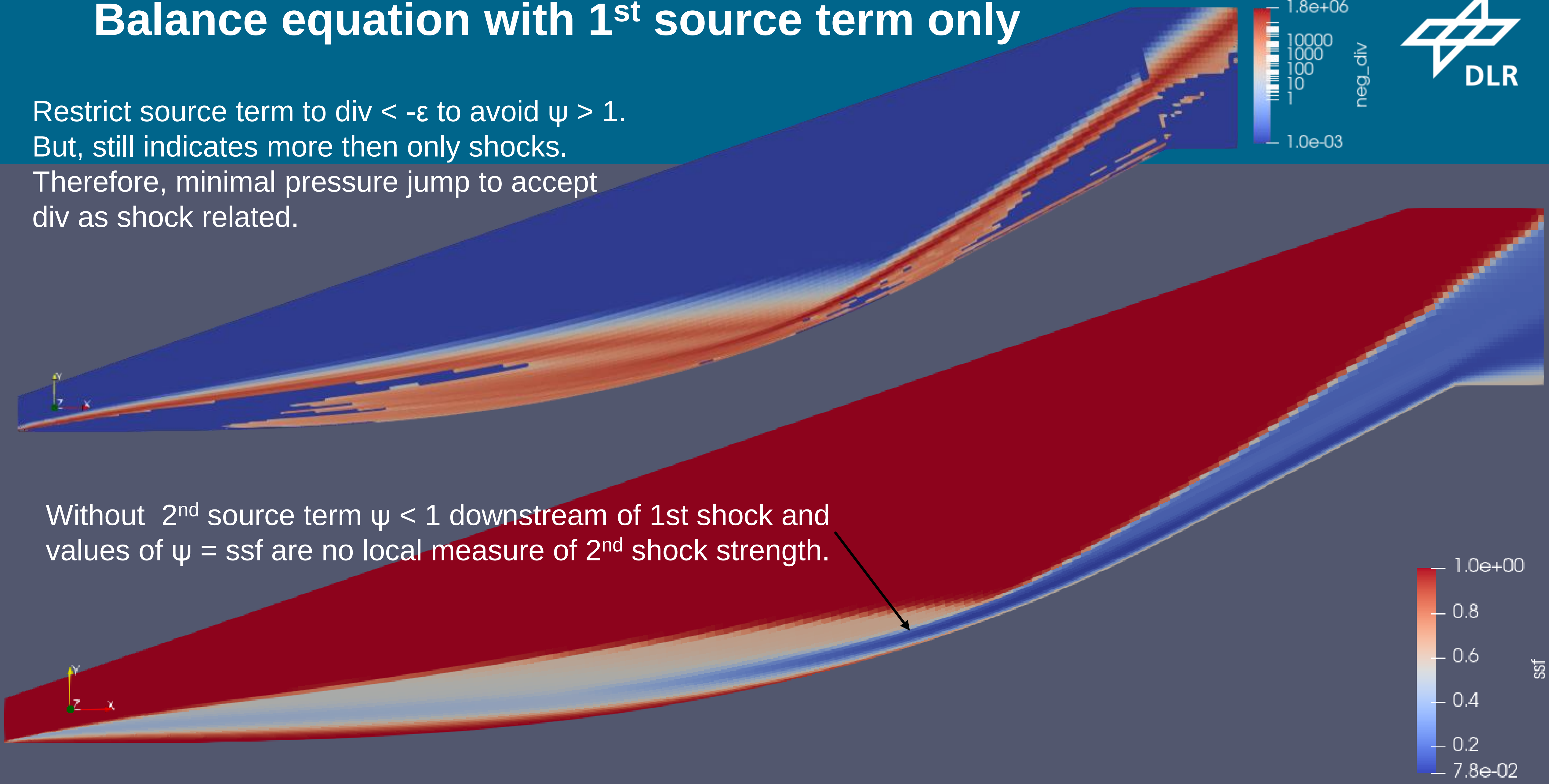
Divergence of the velocity field

Shocks: div < 0

Expansions: div > 0

Balance equation with 1st source term only

Restrict source term to div < -ε to avoid ψ > 1.
But, still indicates more then only shocks.
Therefore, minimal pressure jump to accept div as shock related.



Without 2nd source term ψ < 1 downstream of 1st shock and values of ψ = ssf are no local measure of 2nd shock strength.

Balance equation with relaxation term

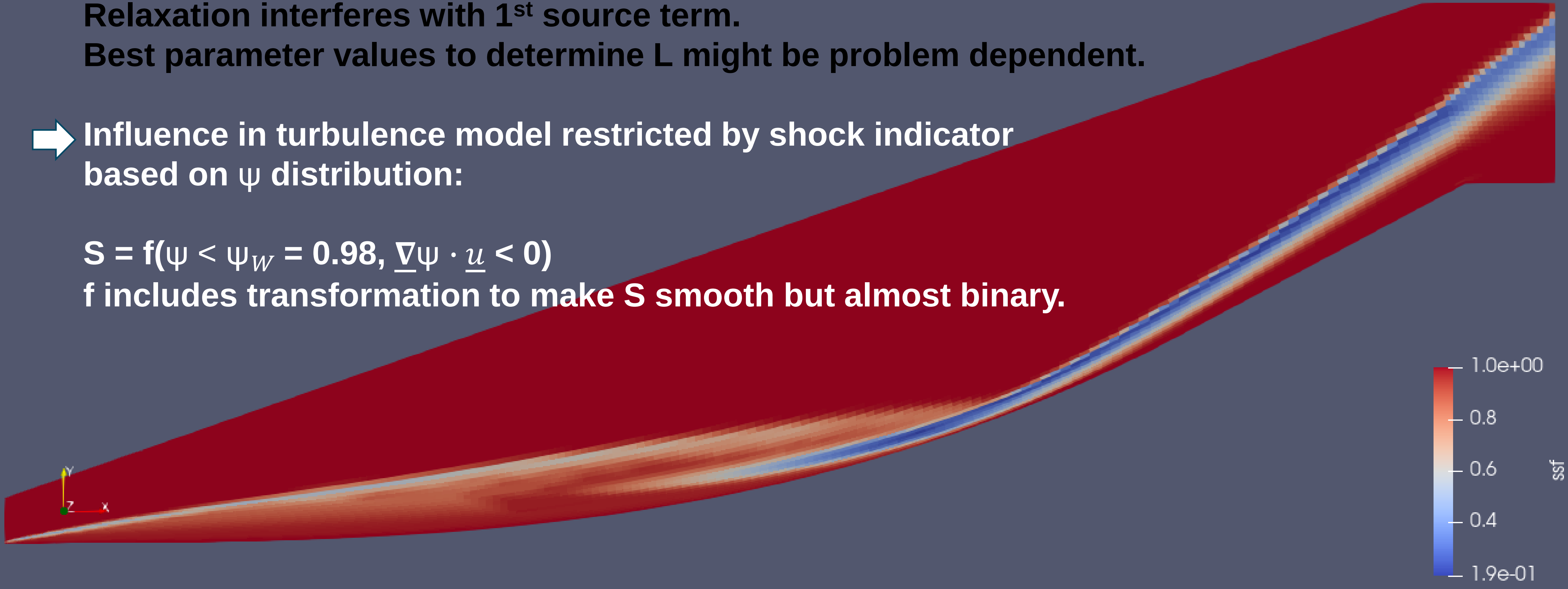
++ Local shock strength measure downstream of second shock!

-- Stronger relaxation gives better localization but less accurate values.
Relaxation interferes with 1st source term.
Best parameter values to determine L might be problem dependent.

➡ Influence in turbulence model restricted by shock indicator based on ψ distribution:

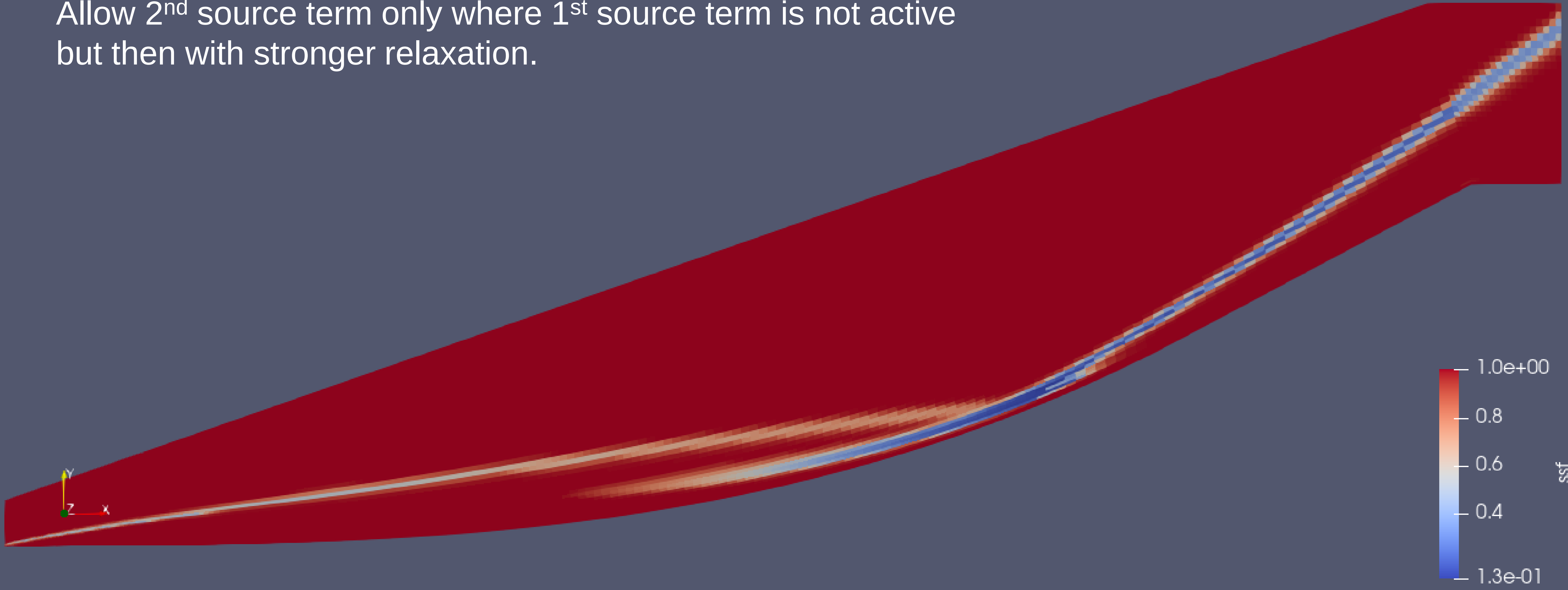
$S = f(\psi < \psi_W = 0.98, \underline{\nabla}\psi \cdot \underline{u} < 0)$

f includes transformation to make S smooth but almost binary.



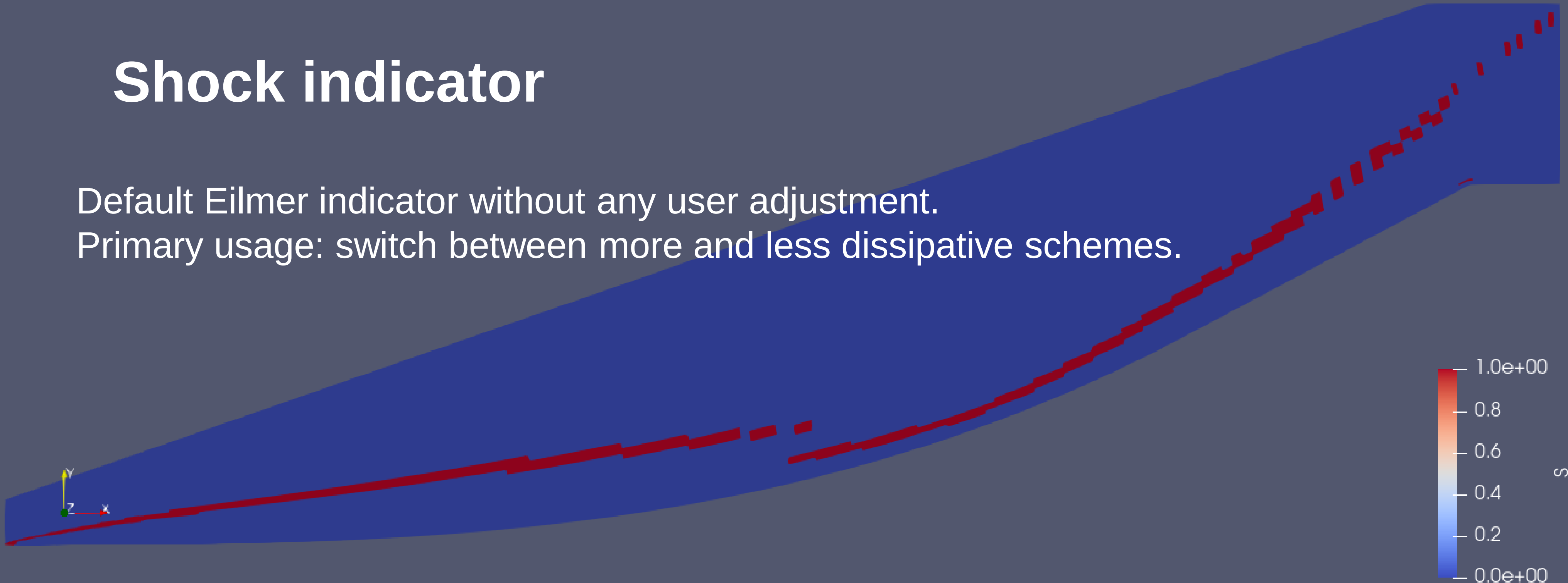
Modification

Allow 2nd source term only where 1st source term is not active but then with stronger relaxation.

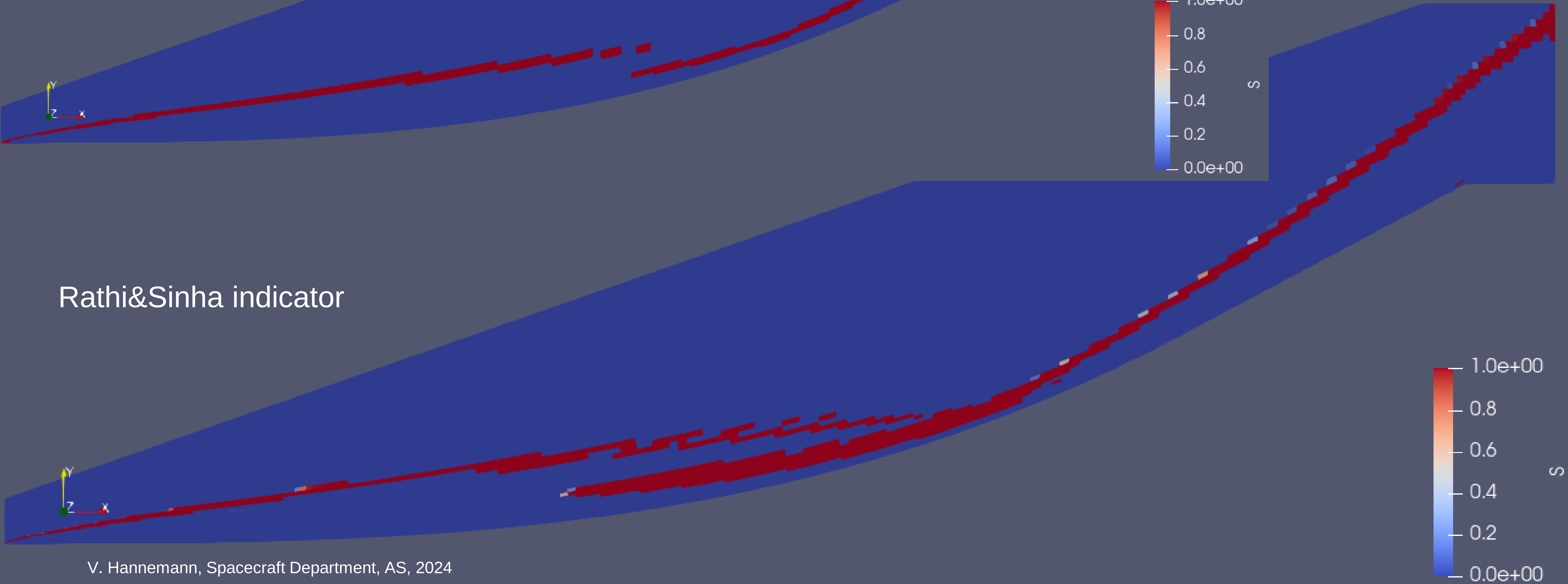


Shock indicator

Default Eilmer indicator without any user adjustment.
Primary usage: switch between more and less dissipative schemes.

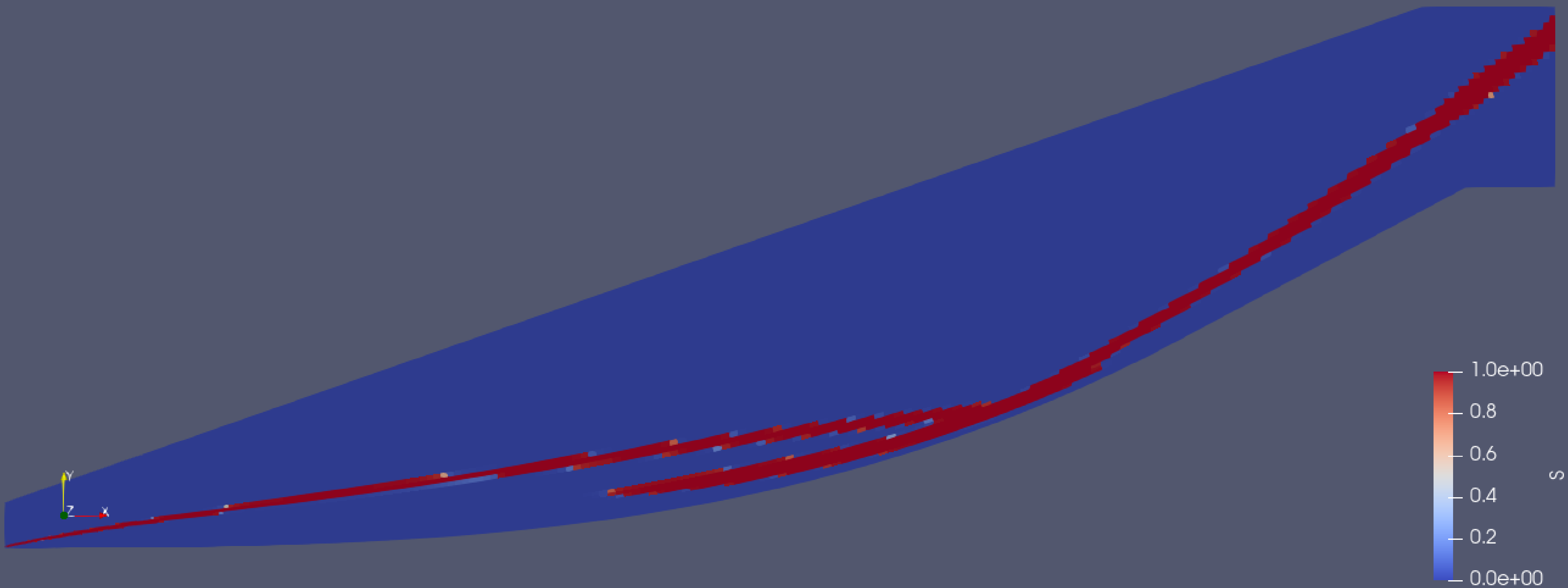


Rathi&Sinha indicator

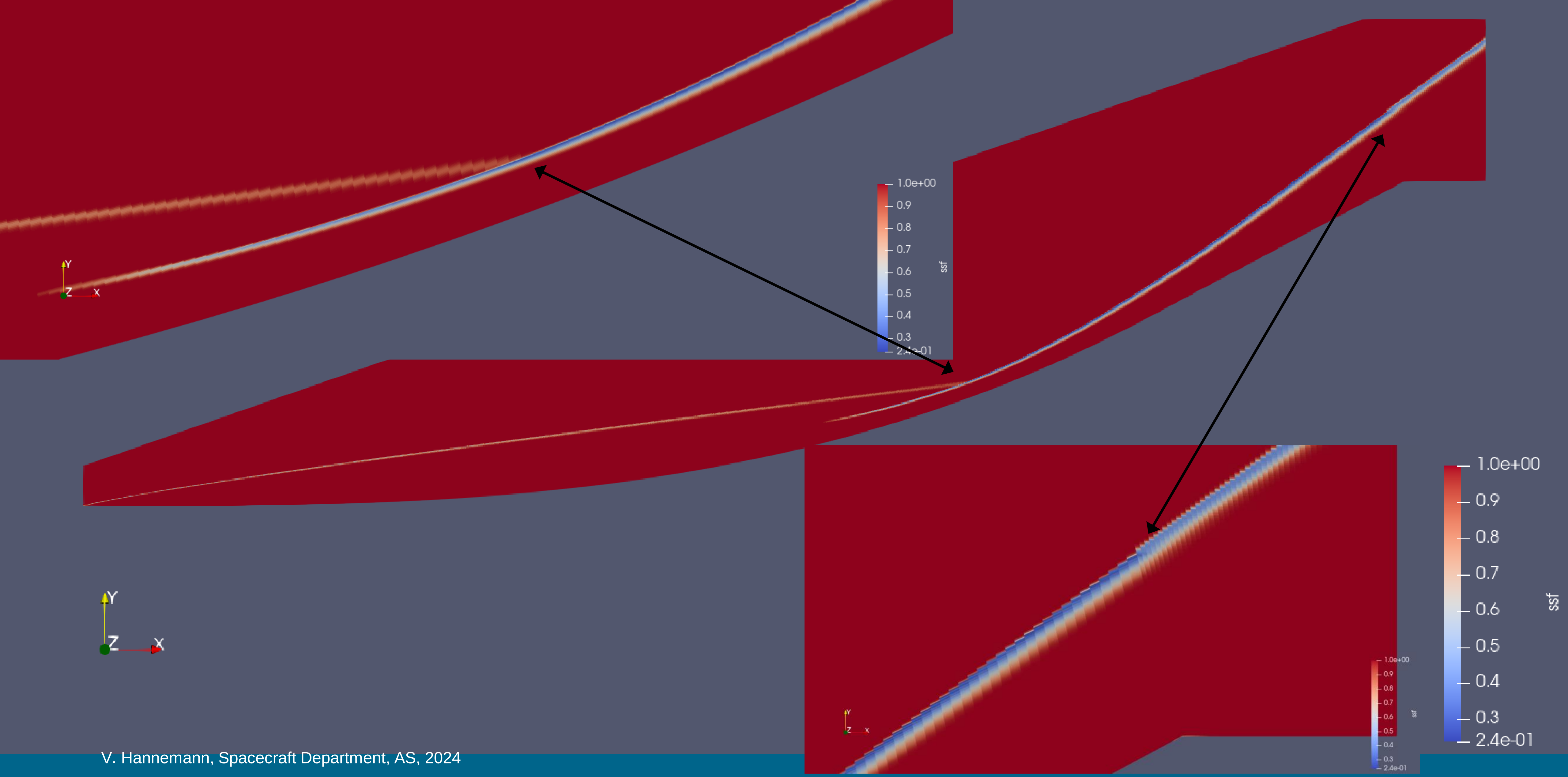


Shock indicator

Simple mapping of S(ψ) towards 0 and 1 depending on ψ_W.



Finer Grid

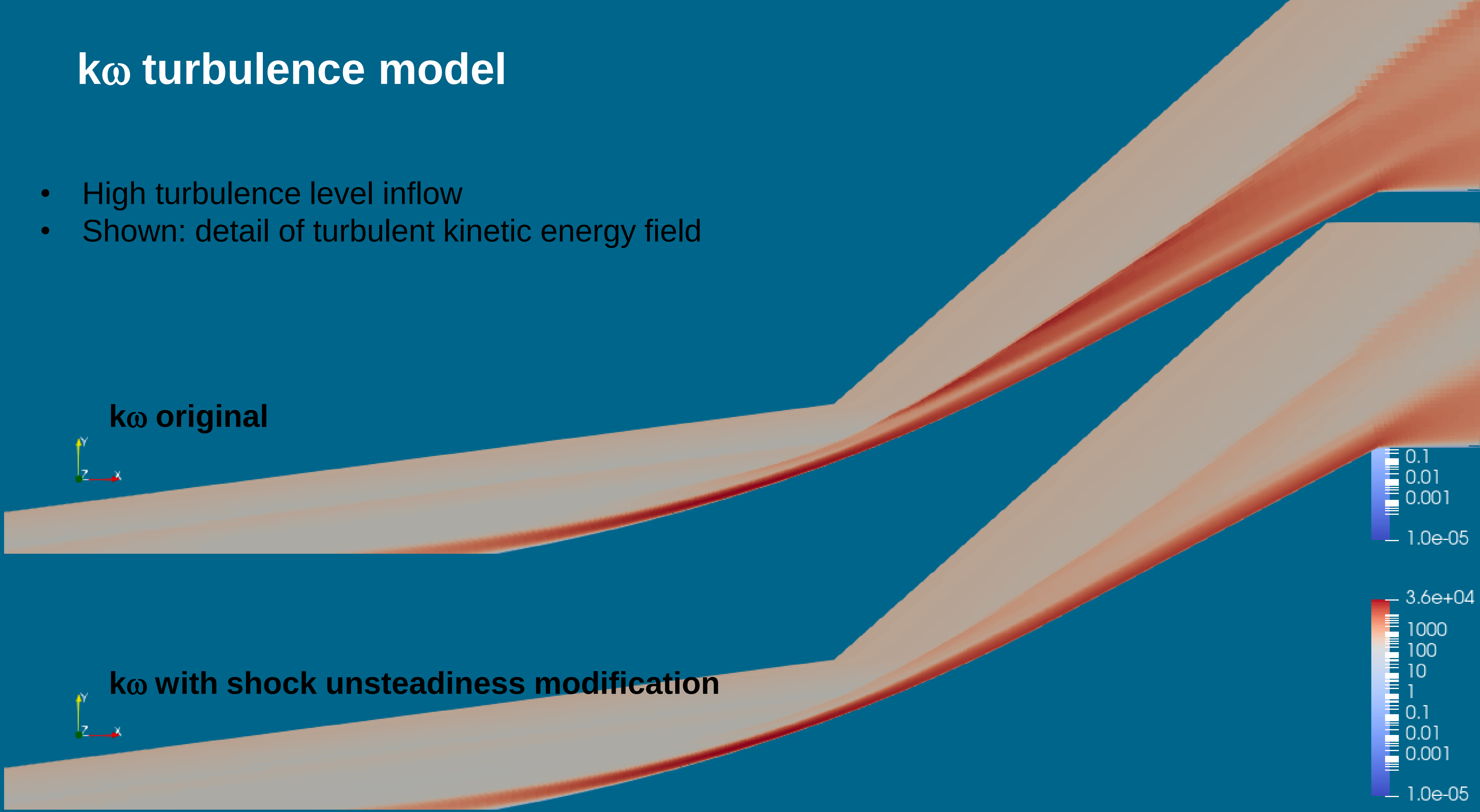


kω turbulence model

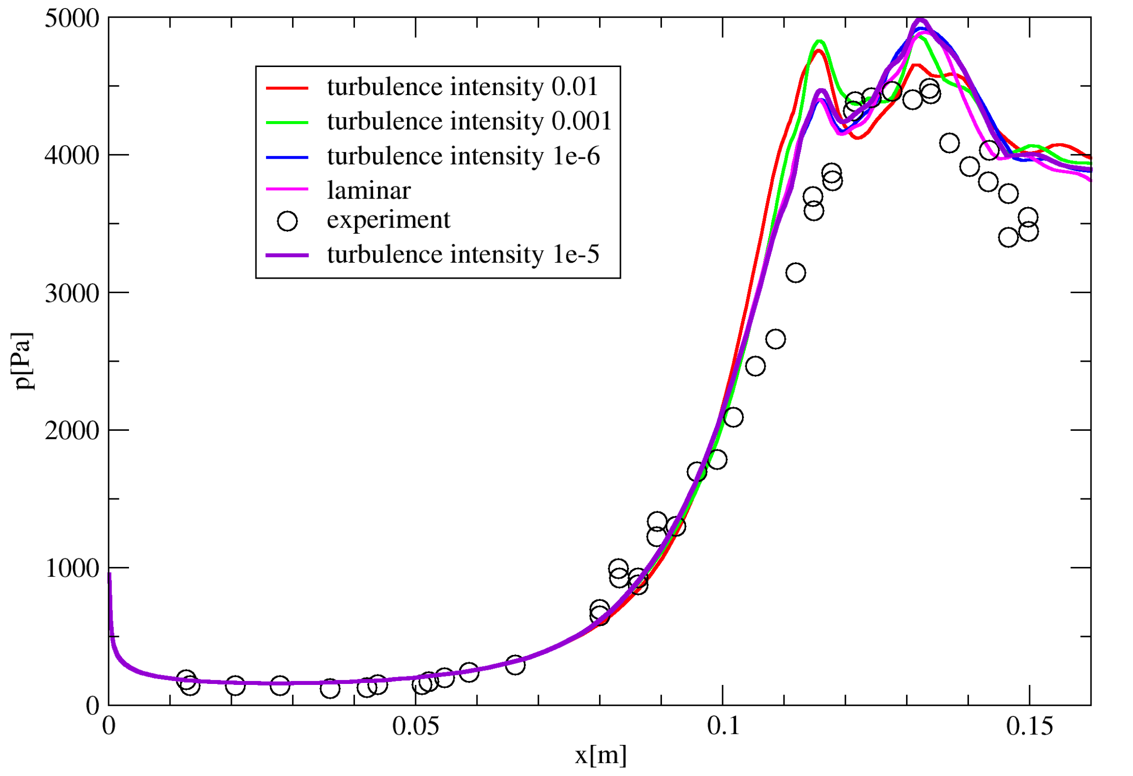
- High turbulence level inflow
- Shown: detail of turbulent kinetic energy field

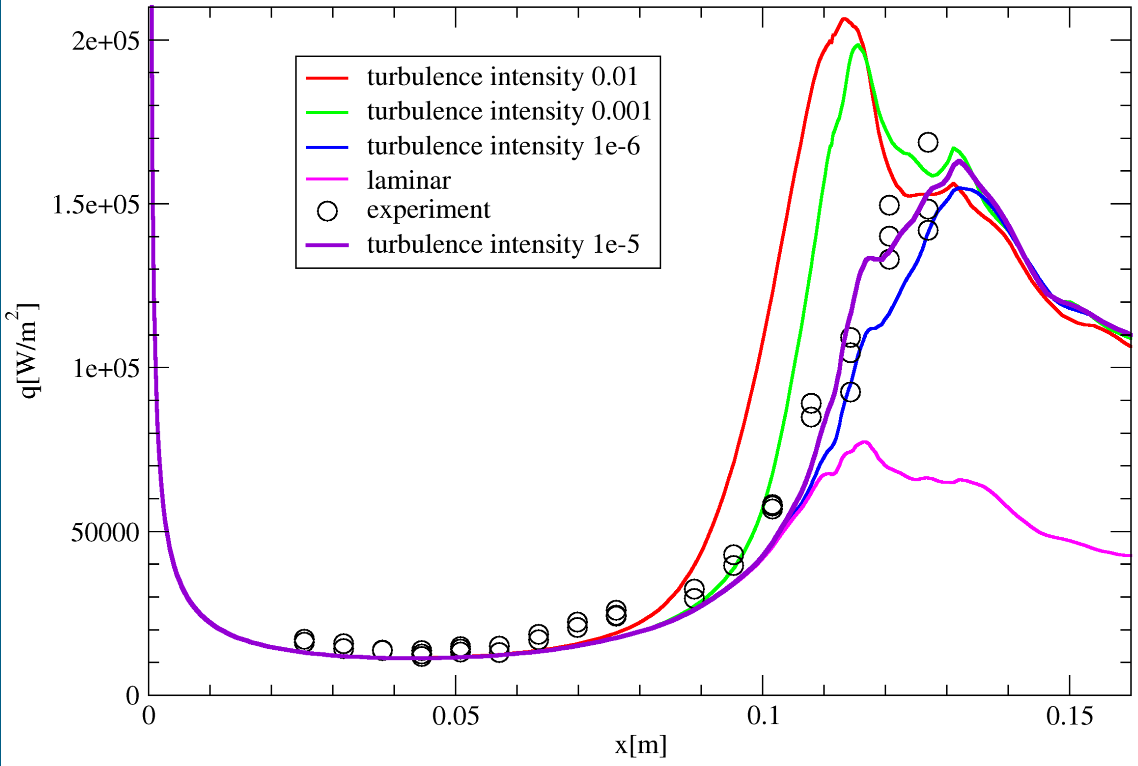
kω original

kω with shock unsteadiness modification



Turbulence model prediction with different turbulence intensities at the inflow





Status of Implementation in Eilmer

- Scalar shock function is added in a pilot version
- Modifications done for Mach 12.25 compression ramp flow
- Lucky punch at a “laminar” test case

Plausible results but further tests necessary to gain trust

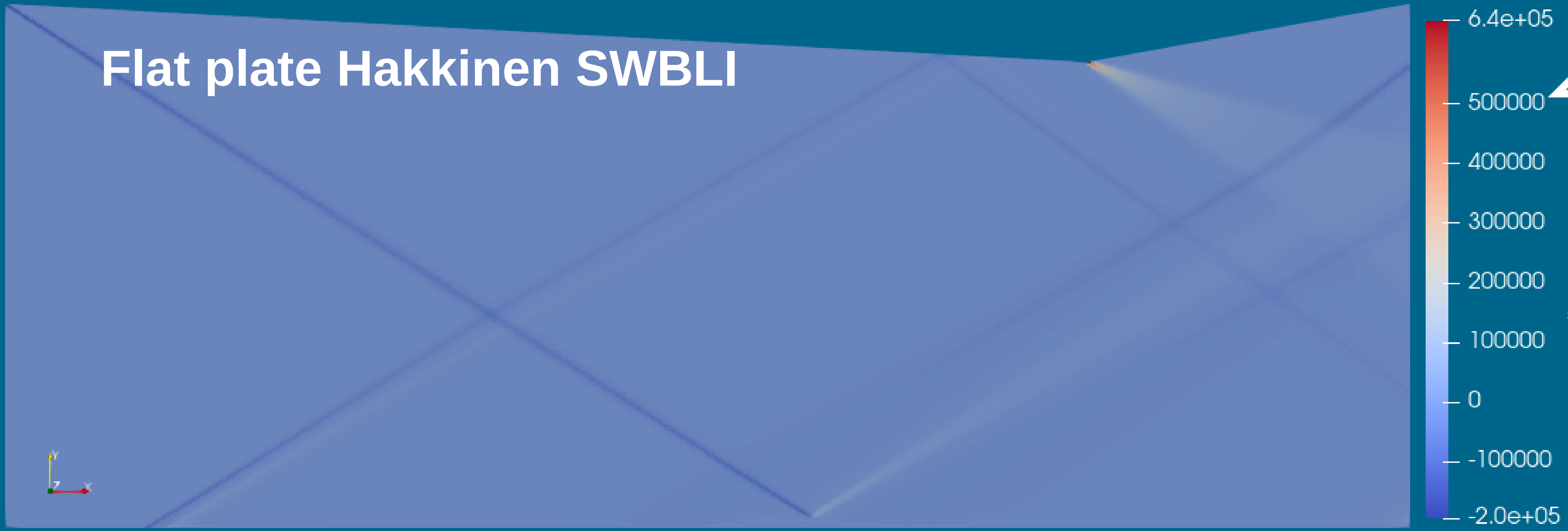
Missing verification against published results:

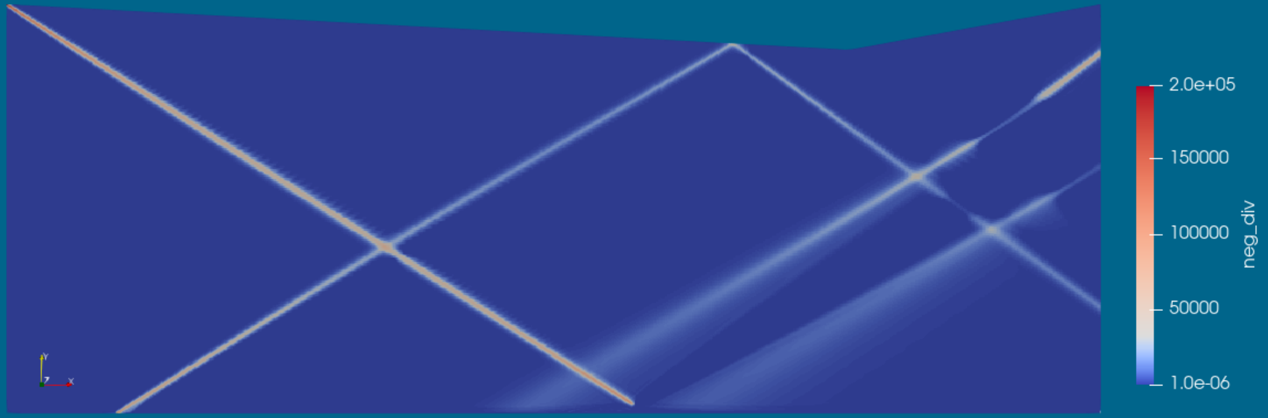
- Rathi&Sinha: SWBLI cases Ma=2.28 and β=8°, DNS different Tw/Tr
- Pasha&Sinha: SWBLI cases Ma=6, β=14° and β=10°, experiments in RWG Re~30*10^6

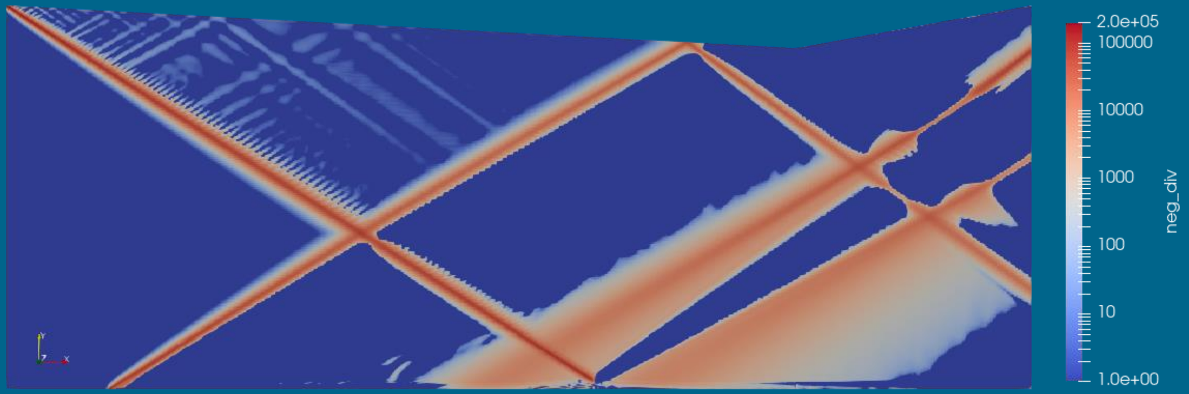
Flat plate Hakkinen SWBLI

Laminar flow
Ma = 2

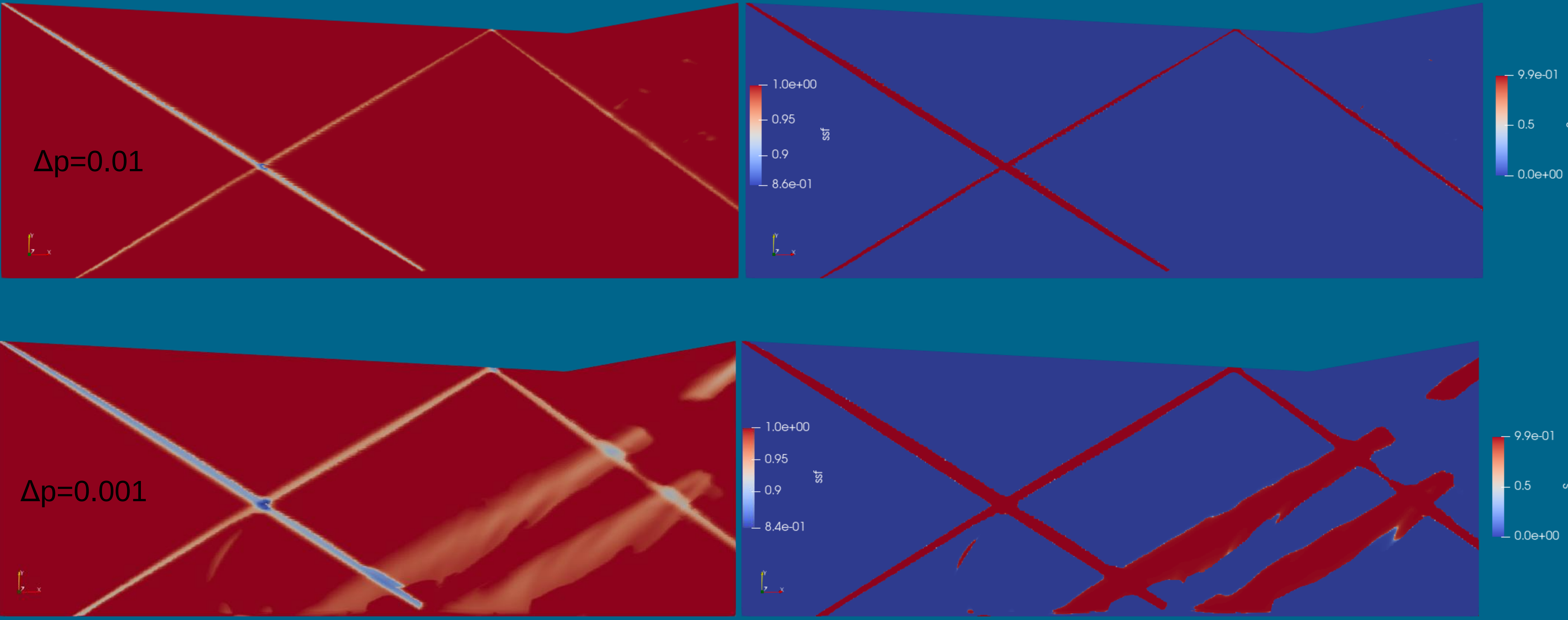
Flat plate Hakkinen SWBLI







Flat plate Hakkinen SWBLI



Lessons learned

- **Pressure jump parameter needs adjustment for the test case at hand**
- **Visualization of shock indicator useful to adjust the sensitivity**
- **Divergence of the velocity is a nice value to analyze supersonic flow fields**

- **This laminar separation bubble generates compression waves rather than shocks**
- **Sinha investigated fully turbulent SWBLI – more complex shock structure**
  (Amjad Ali Pasha & Krishnendu Sinha (2008) Shock-unsteadiness model applied to oblique shock wave/turbulent boundary-layer interaction, International Journal of Computational Fluid Dynamics, 22:8, 569-582, DOI: 10.1080/10618560802290284)

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Thank you for the great work atmosphere at UQ!