Geneviève Comte-Bellot

Fifty Years of Research on Turbulence and Acoustics

SHOCK IMPINGEMENT AND TURBULENT WALL-BOUNDED FLOW DYNAMICS

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SHOCK BOUNDARY LAYER INTERACTION (SWBLI)

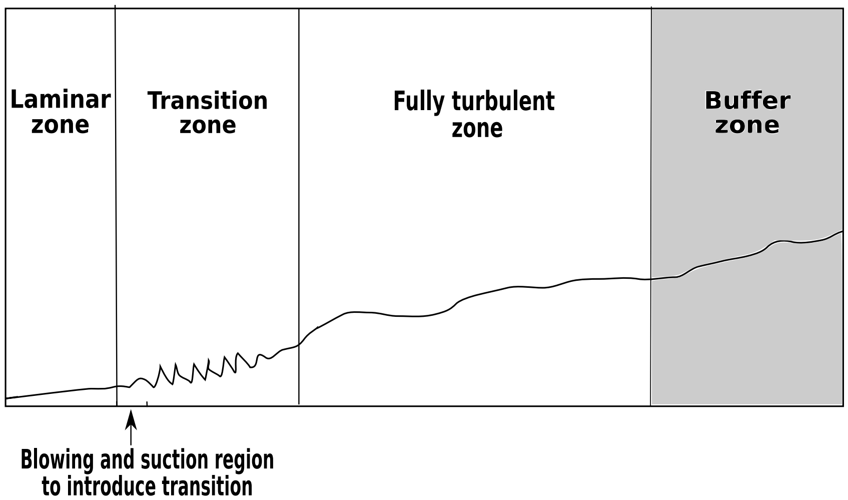
- One of the most challenging problems of high speed flow dynamics (aircrafts, rockets, and projectiles)
- Detailed understanding of phenomenon essential for efficient aerodynamics and design of propulsion system
- Characteristics
  - Unsteady, three dimensional behavior
  - Large thermodynamic fluctuation levels
  - Large variations on velocity fluctuation correlations

OBJECTIVES

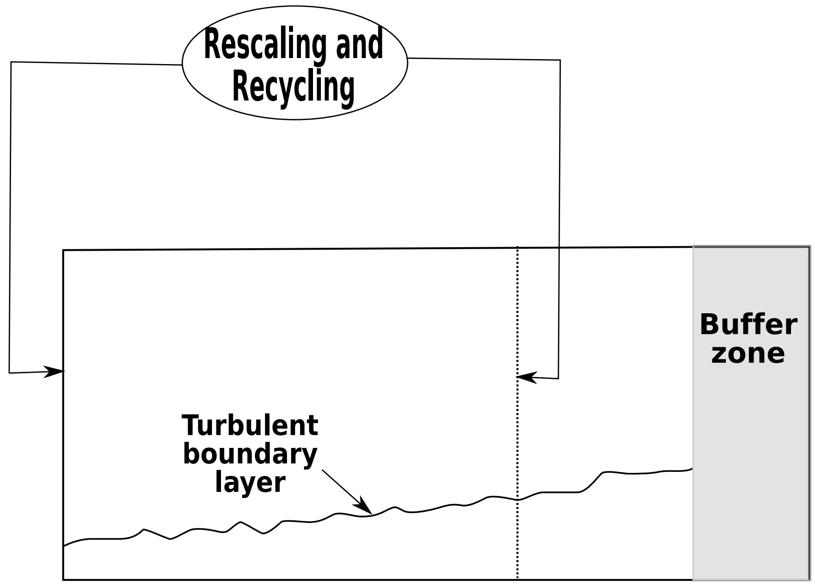
- To compare higher-order statistical moments with experimental and simulation results
- To analyze variation of turbulent structural dynamics due to interaction with shock (anisotropy invariant map and intermittency distribution)
- To show how turbulent statistical moments altered due to shock presence
- To highlight the alteration of mass and heat flux terms are influenced by shocks
- To study influence on shock wave interaction under isothermal wall conditions

DEVELOPED AND SUSTAINED TURBULENCE

- Two different techniques to generate turbulent inflow conditions for shock boundary layer interaction simulations



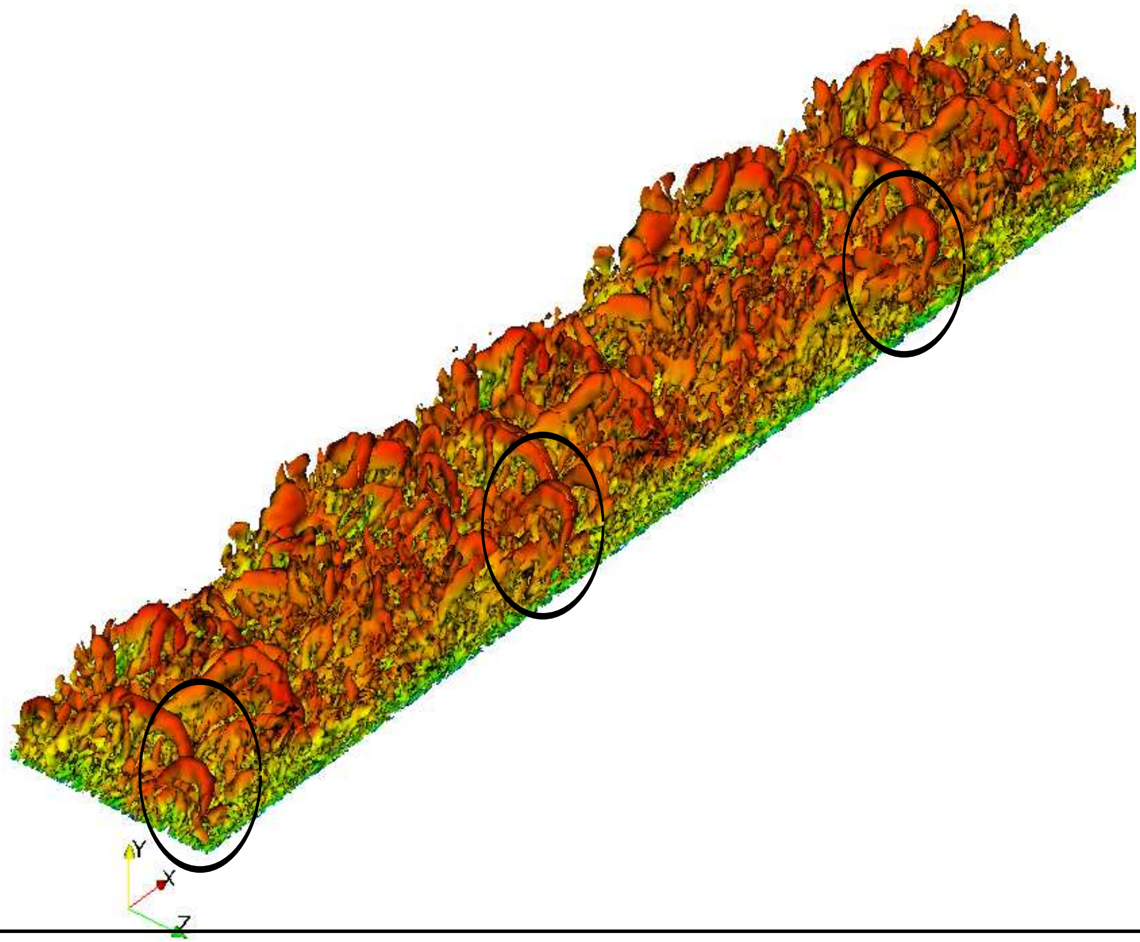
Developed



Sustained

SUSTAINED TURBULENCE CASE STUDY

- Case study based on rescaling and recycling technique proposed by Stolz and Adams (Phys. Fluids, 2003)

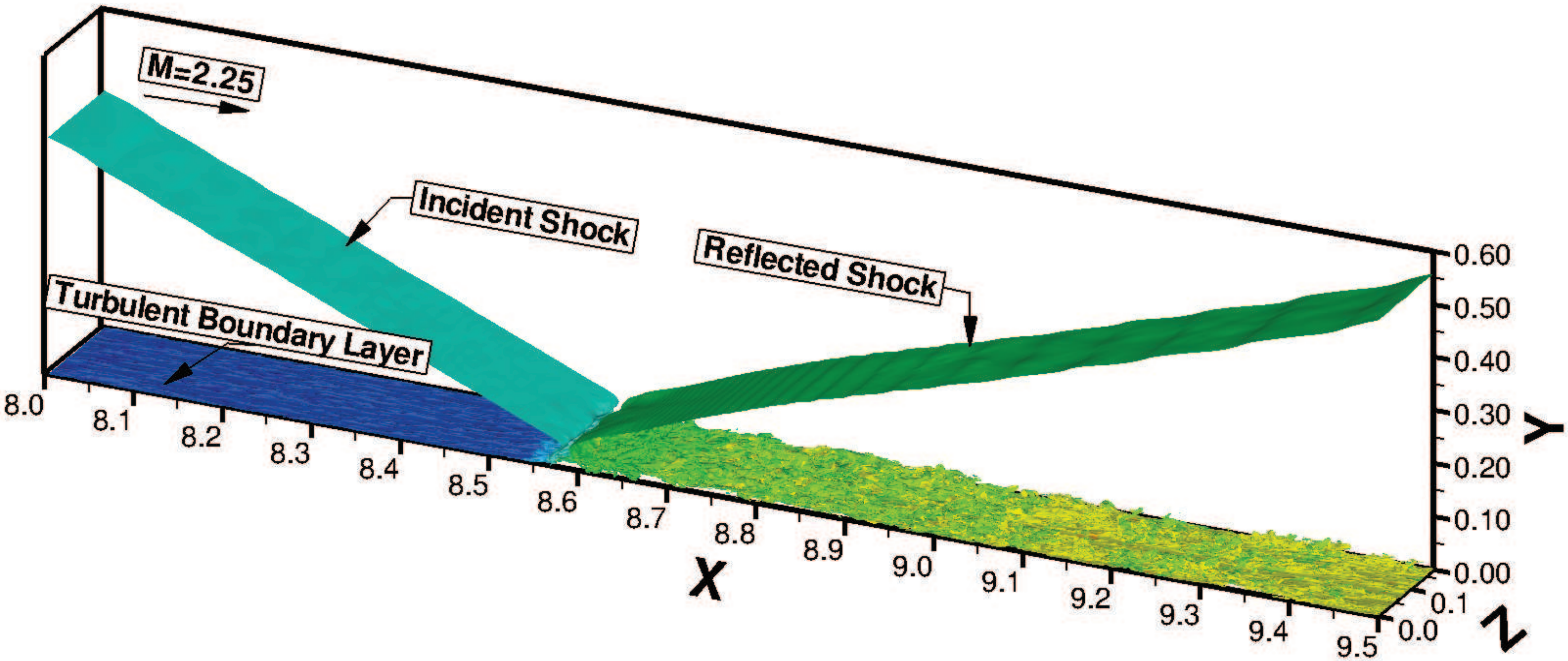


SIMULATION PARAMETERS

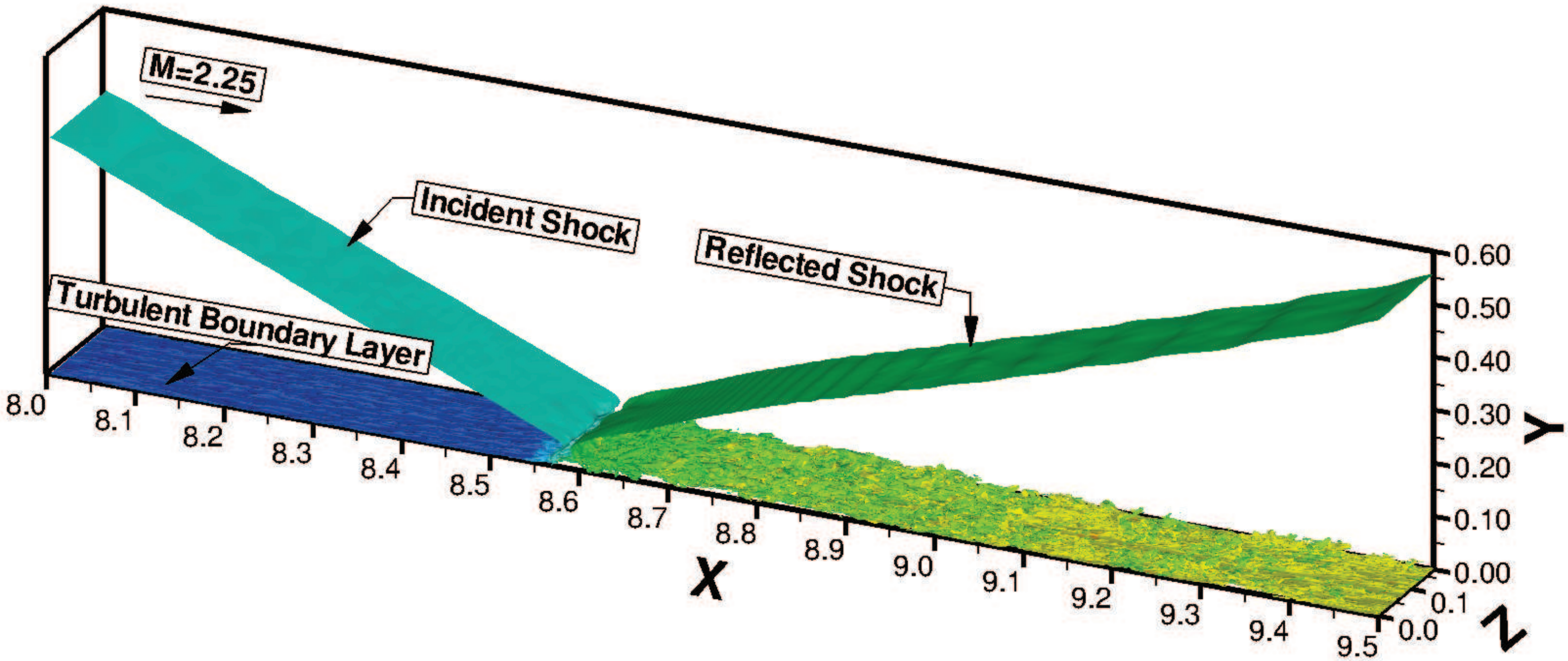
- Freestream Mach Number M_∞ =2.25
- Freestream unit Reynolds number Re/m. = 25×10^6
- Momentum Thickness Reynolds number Re_θ = 3133 ($plane$1)
- Grid Points (N_x, N_y, N_z) = (2650 x 111 x 255)
- Mesh spacing in well resolved region $(\Delta x^+, \Delta y^+, \Delta z^+)$ = (14.1, 1.01, 6.6)
- Shock angle α (w.r.t horizontal) = 33.2°

COMPUTATIONAL SUB-DOMAIN

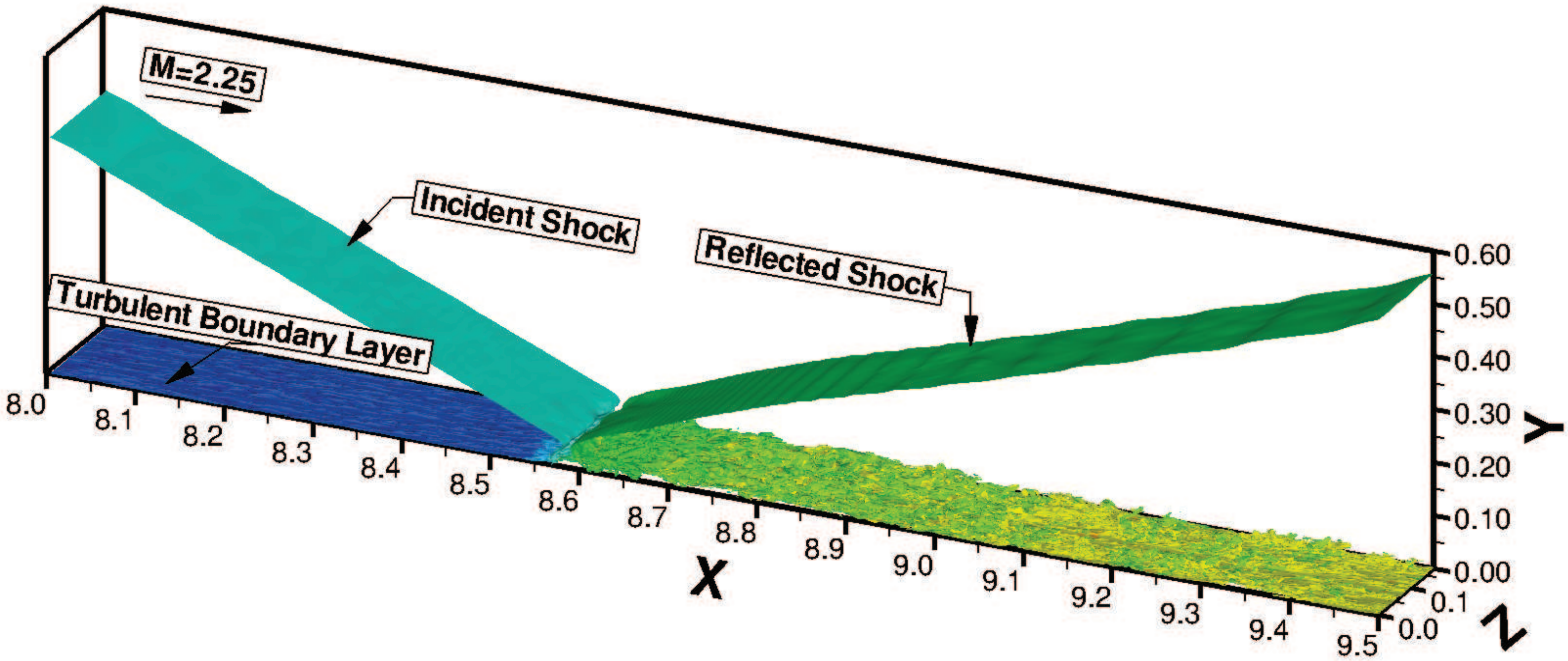
- Computational sub-domain in vicinity of the incident/reflected shock intersection (shading based on pressure levels)



SHOCK INDUCED FLOW ALTERATION

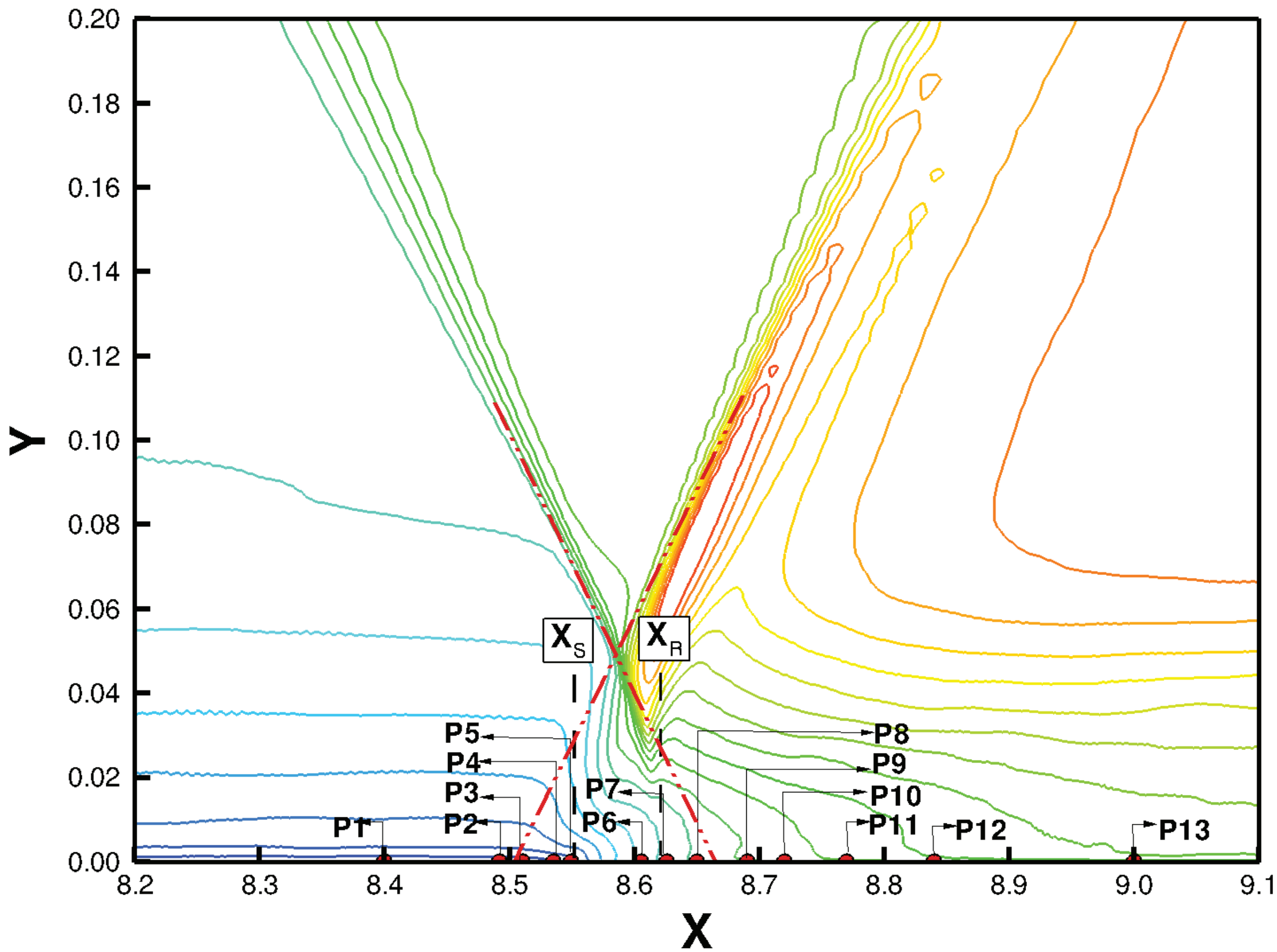


SHOCK INDUCED FLOW ALTERATION



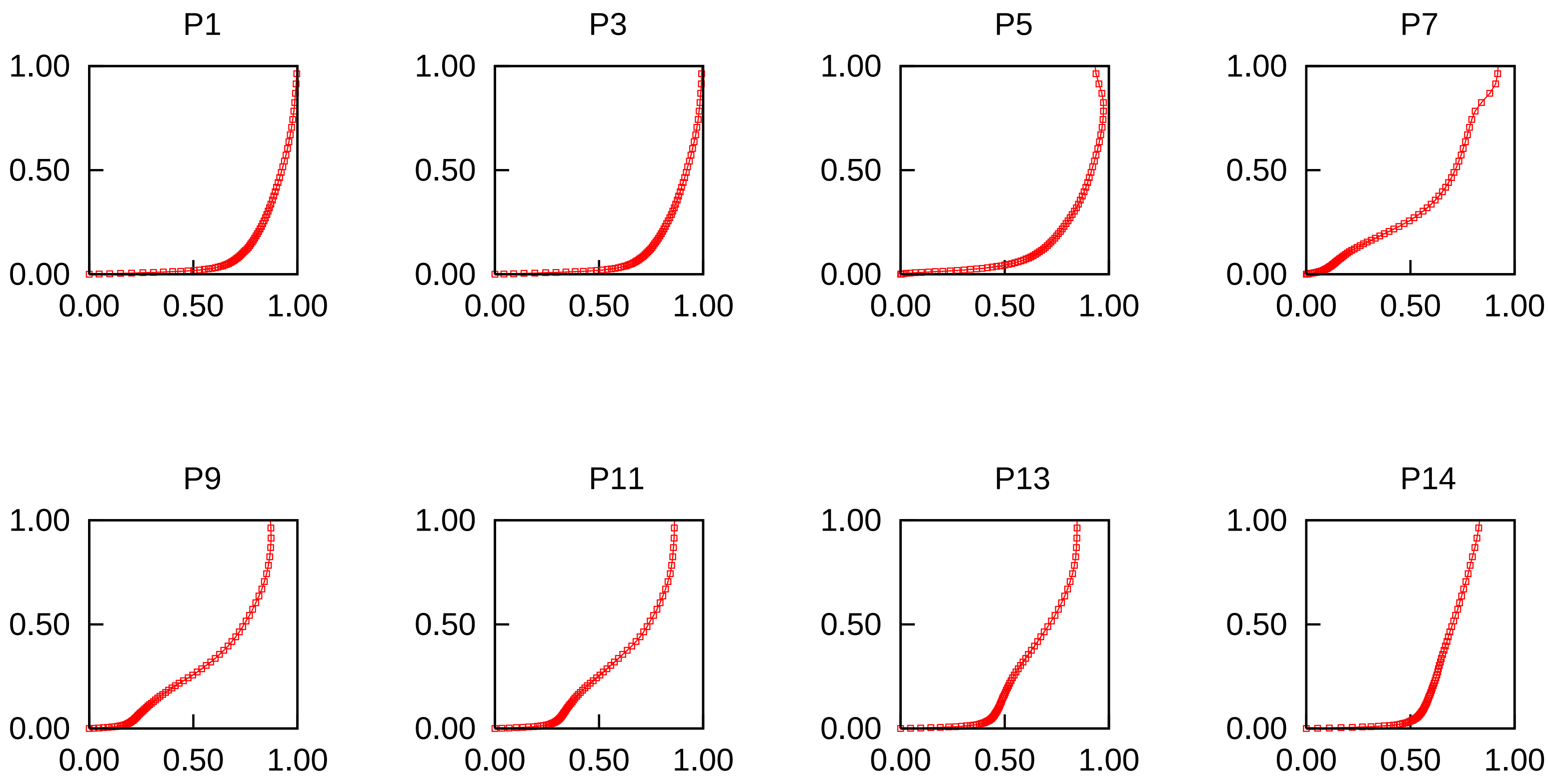
DIAGNOSTIC PLANES - POSITIONS

- Streamwise location of $y - z$ planes in proximity of separation bubble



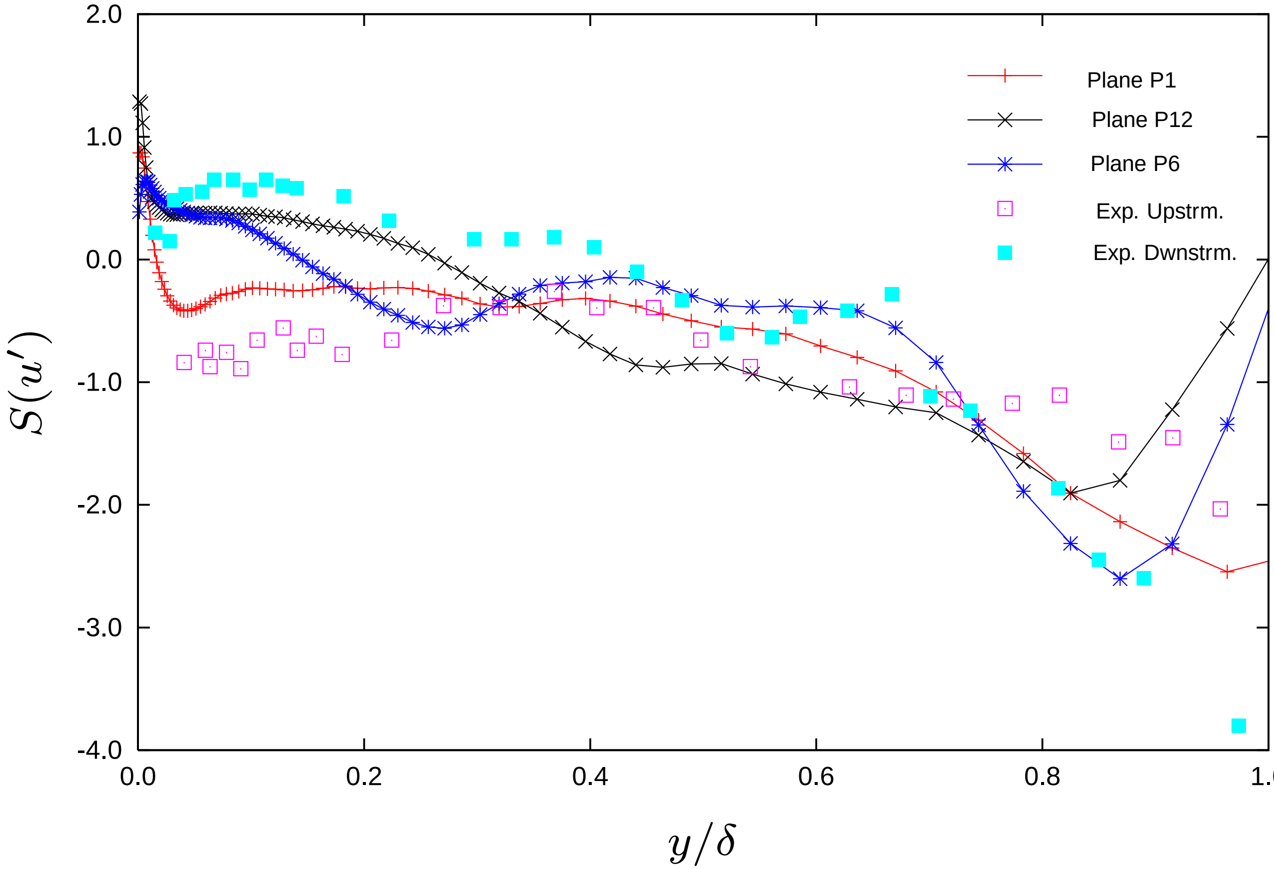
DIAGNOSTIC PLANES - POSITIONS

- Mean streamwise velocity profiles at diagnostic $y - z$ planes



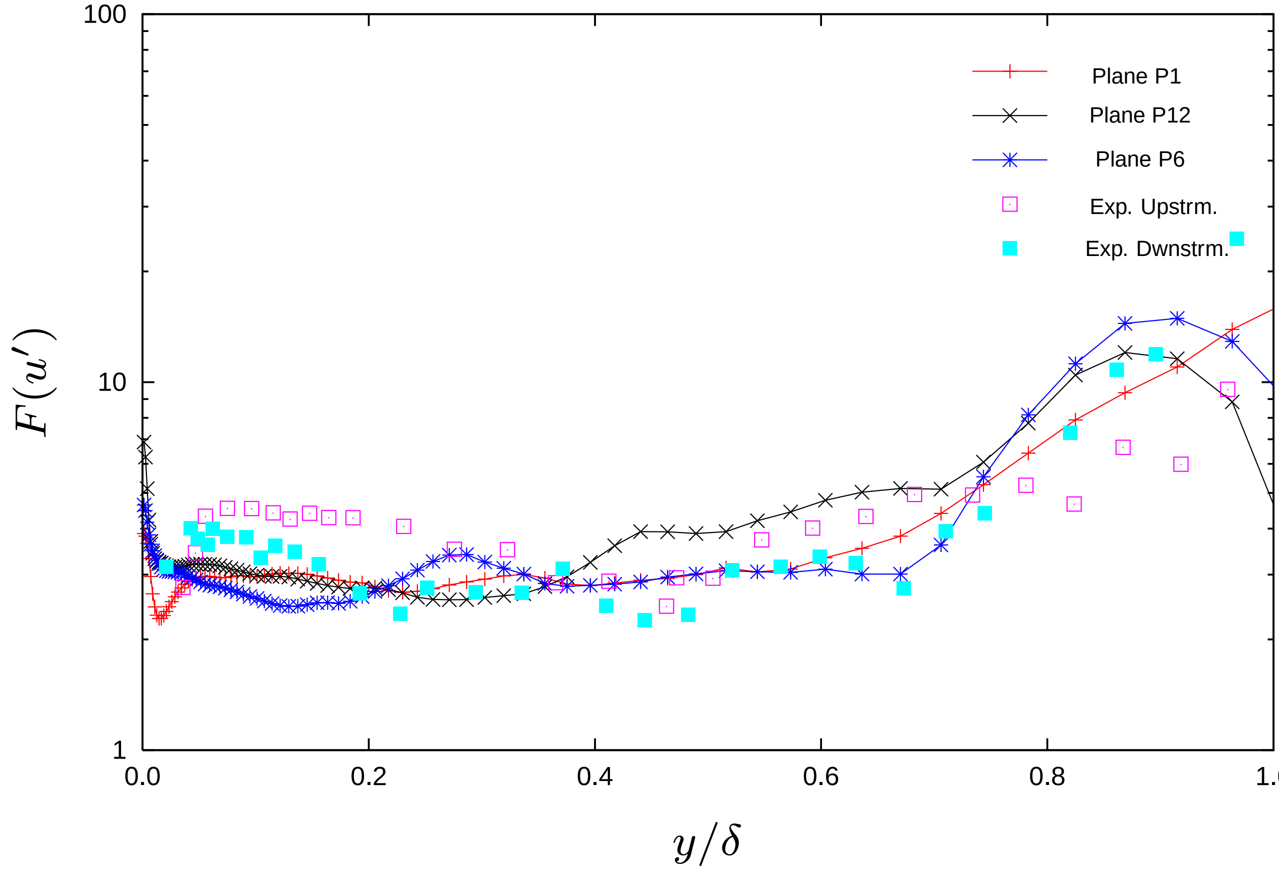
DISTRIBUTION OF SKEWNESS / FLATNESS

- Comparison of experimental (Deleuze, 1995) and simulation streamwise velocity skewness



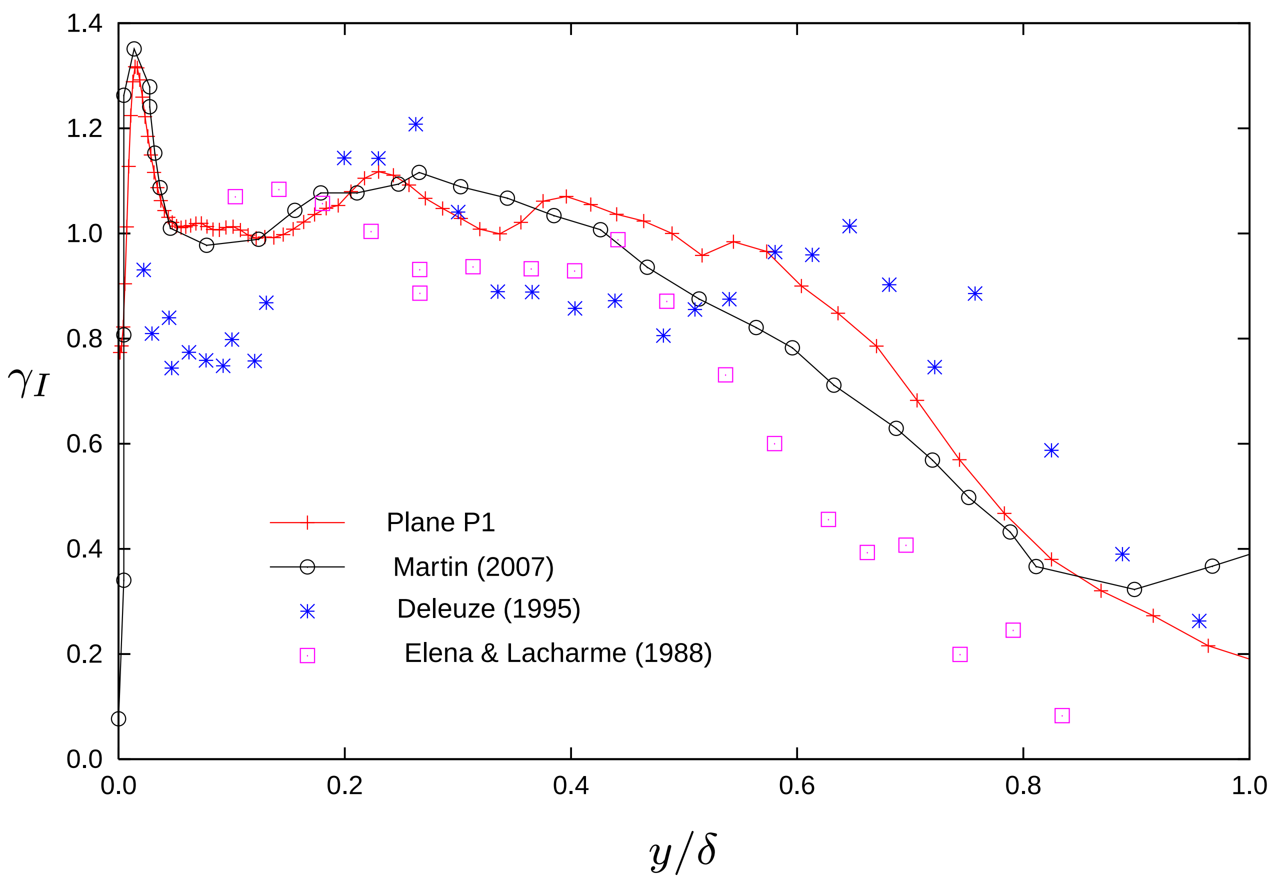
DISTRIBUTION OF SKEWNESS / FLATNESS

- Comparison of experimental (Deleuze, 1995) and simulation streamwise velocity flatness



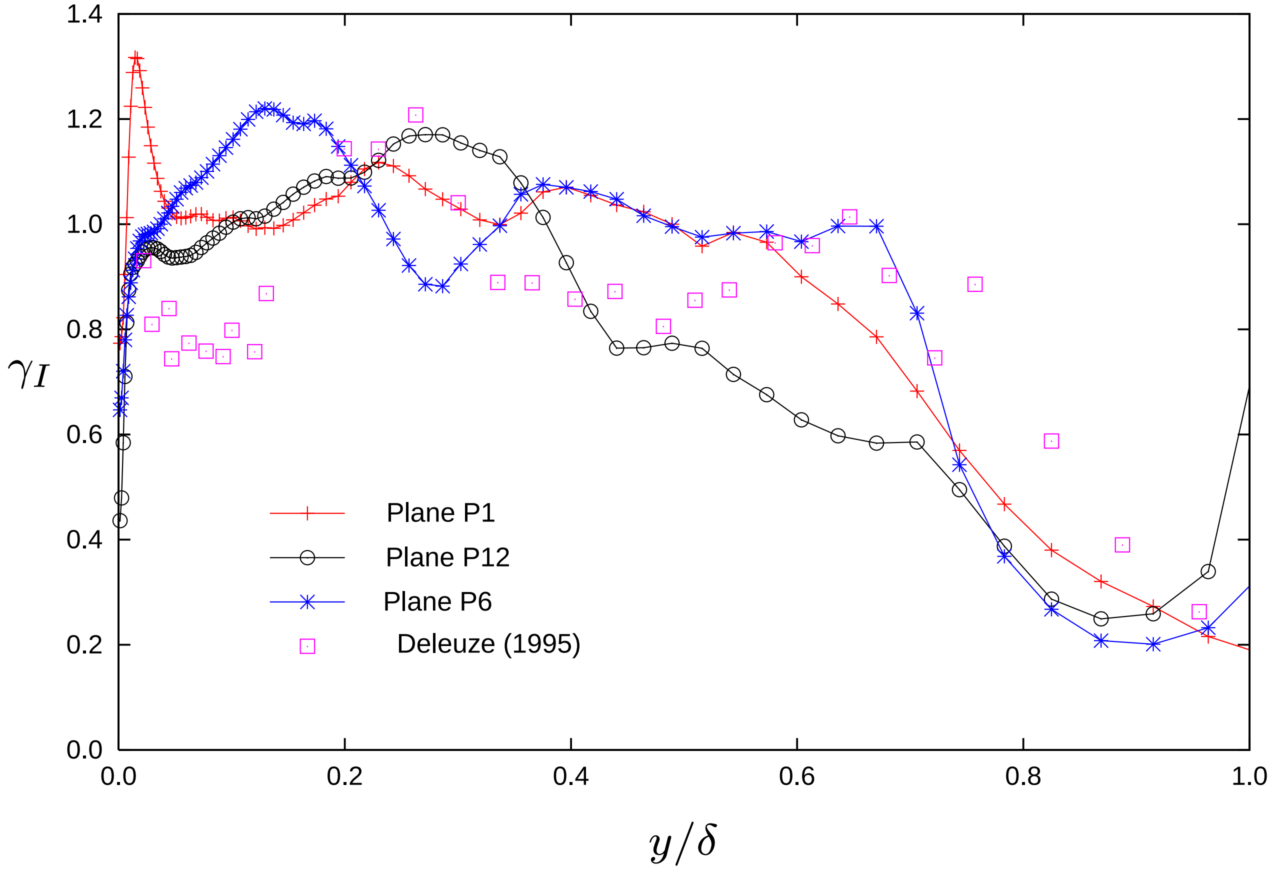
INTERMITTENCY DISTRIBUTION

- Comparison of experimental and simulation intermittency data upstream of shock interaction zone



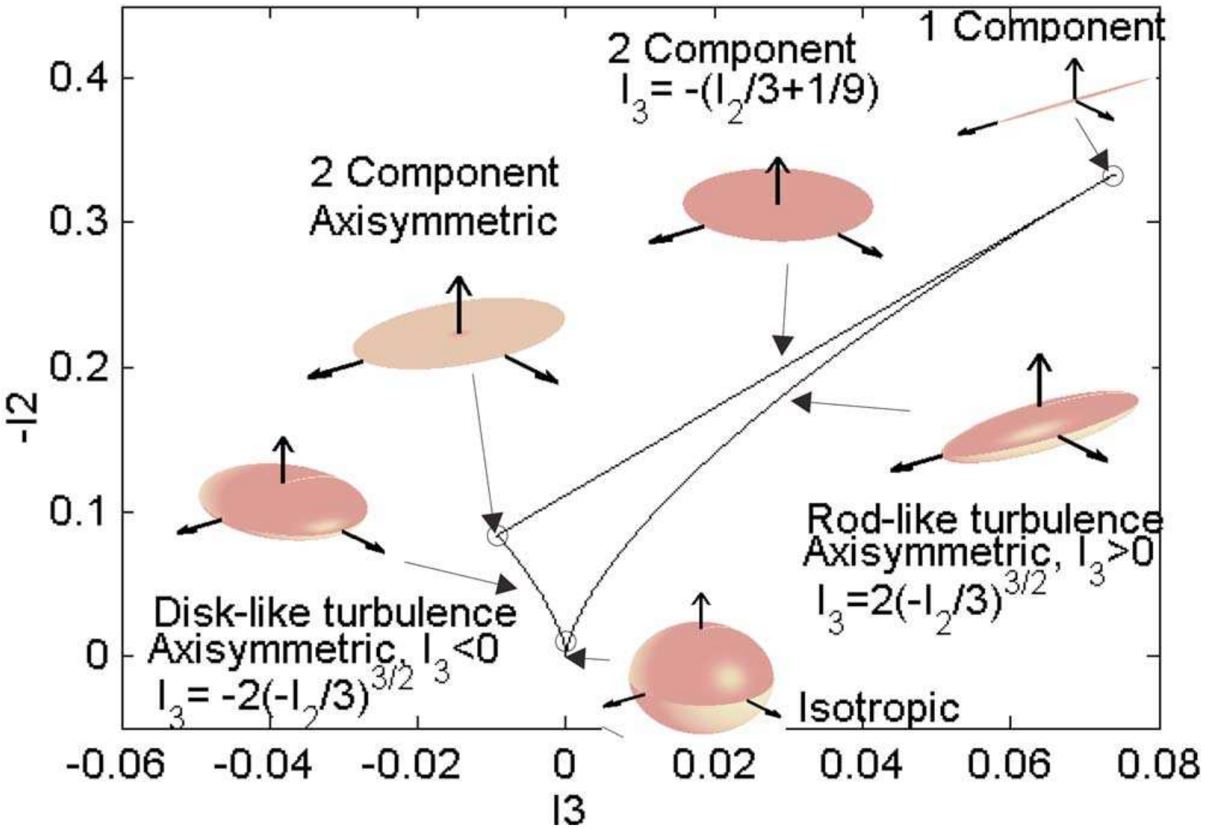
INTERMITTENCY DISTRIBUTION

- Intermittency function at various streamwise locations



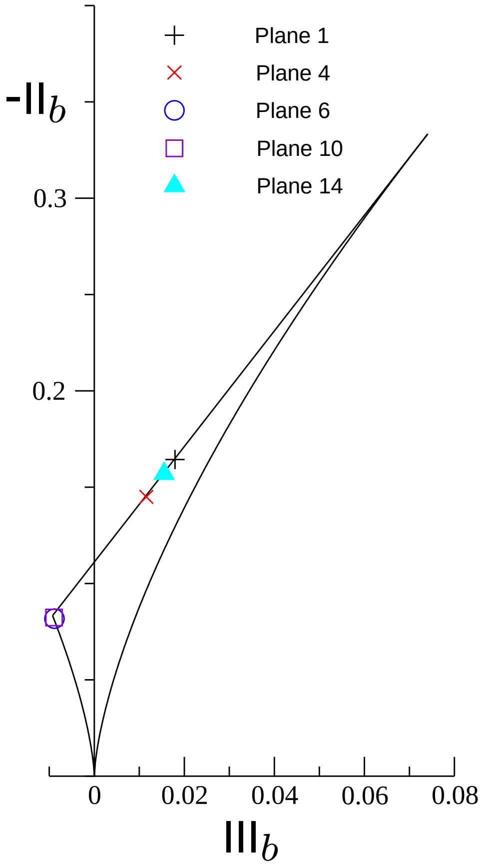
ANISOTROPY INVARIANT MAP

- Structural description of turbulence (Simonsen & Krogstad, Phys. Fluids, 2005)

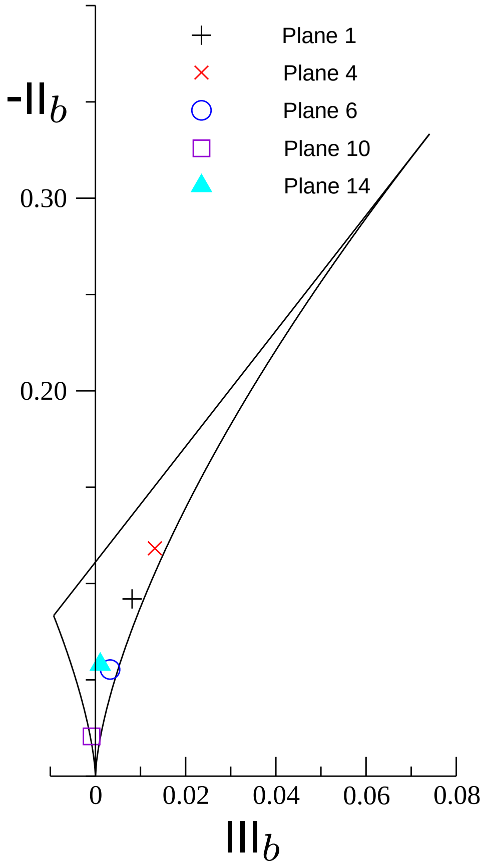


ANISOTROPY INVARIANT MAP

- Invariant mapping of turbulent stress anisotropy at fixed y/δ



$y/\delta = 0.0027$



$y/\delta = 0.047$

TURBULENT STRESSES IN INTERACTION ZONE

- Relationship between density-weighted (Favre) and the Reynolds averaged velocity second moments

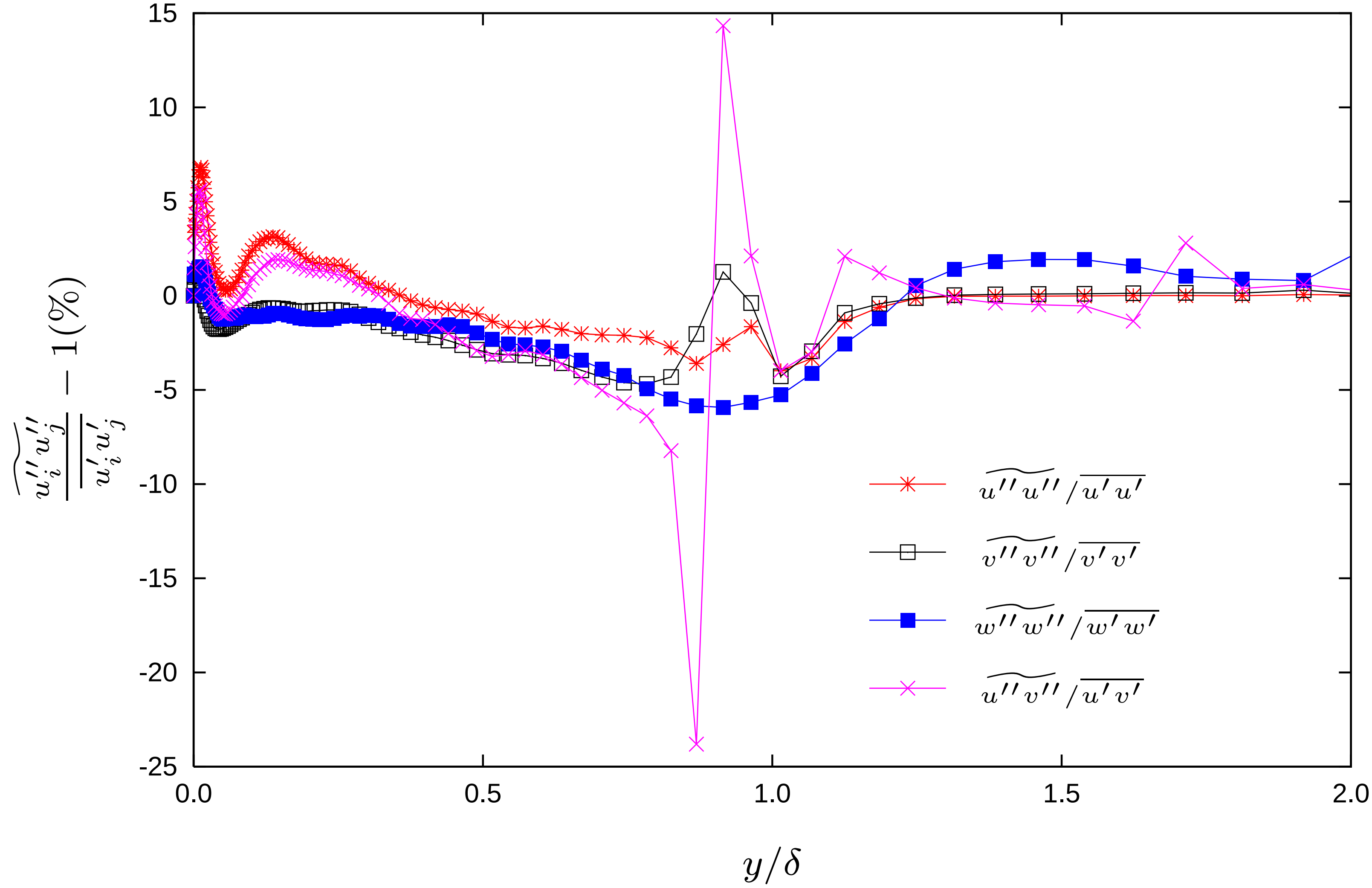
$$\widetilde{u_i'' u_j''} = \overline{u_i' u_j'} + \frac{\overline{\rho' u_i' u_j'}}{\overline{\rho}} - \frac{\left(\overline{\rho' u_i'}\right)\left(\overline{\rho' u_j'}\right)}{\overline{\rho}^2} ,$$

$$\widetilde{u_i'' \phi''} = \overline{u_i' \phi'} + \frac{\overline{\rho' u_i' \phi'}}{\overline{\rho}} - \frac{\left(\overline{\rho' u_i'}\right)\left(\overline{\rho' \phi'}\right)}{\overline{\rho}^2} ,$$

- Favre and Reynolds averaged anisotropy tensors

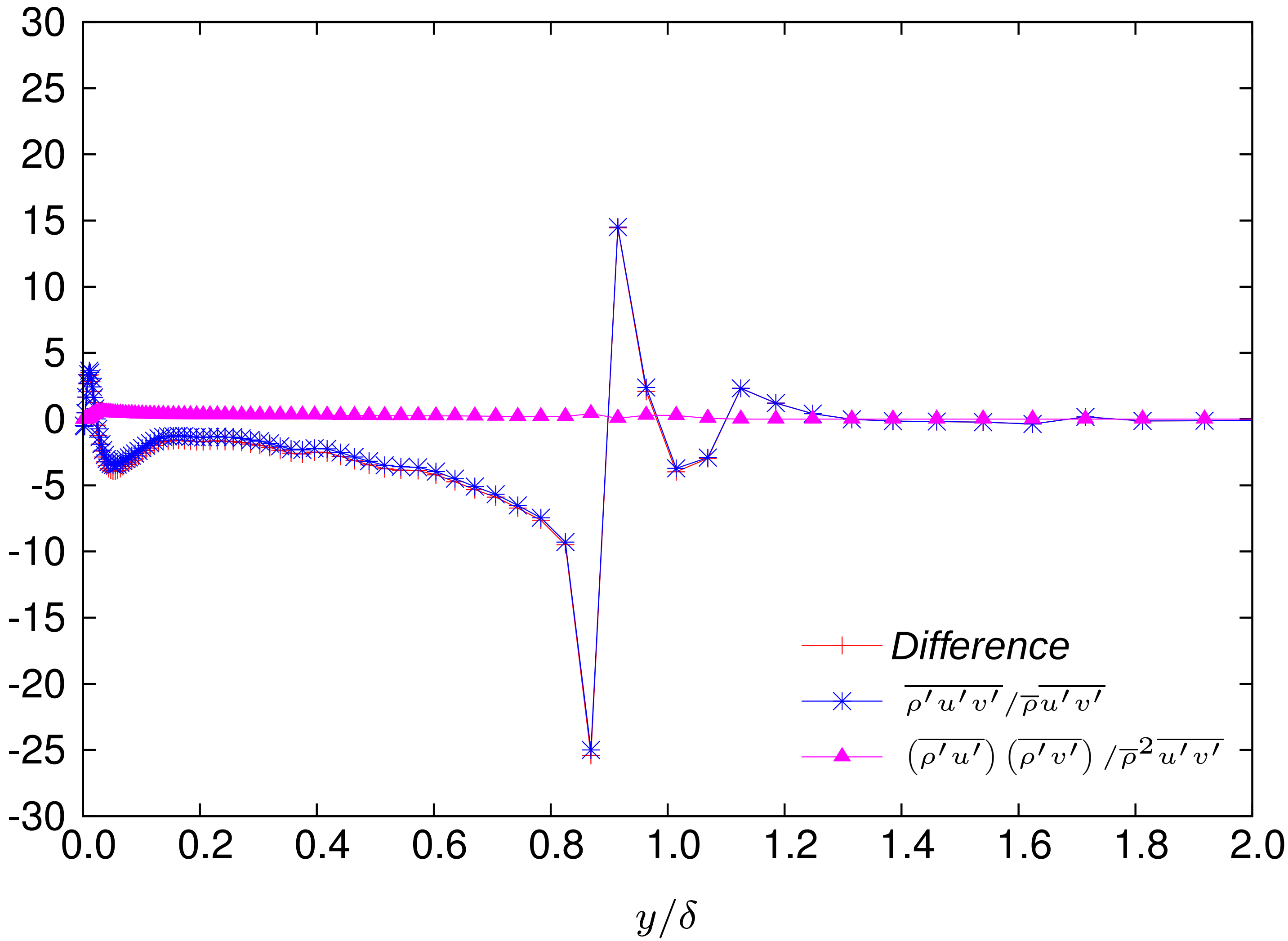
$$\widetilde{b}_{ij} = \frac{\widetilde{u_i'' u_j''}}{\widetilde{u_i'' u_i''}} - \frac{\delta_{ij}}{3} \quad \text{and} \quad \overline{b}_{ij} = \frac{\overline{u_i' u_j'}}{\overline{u_i' u_i'}} - \frac{\delta_{ij}}{3} .$$

TURBULENT STRESSES IN INTERACTION ZONE



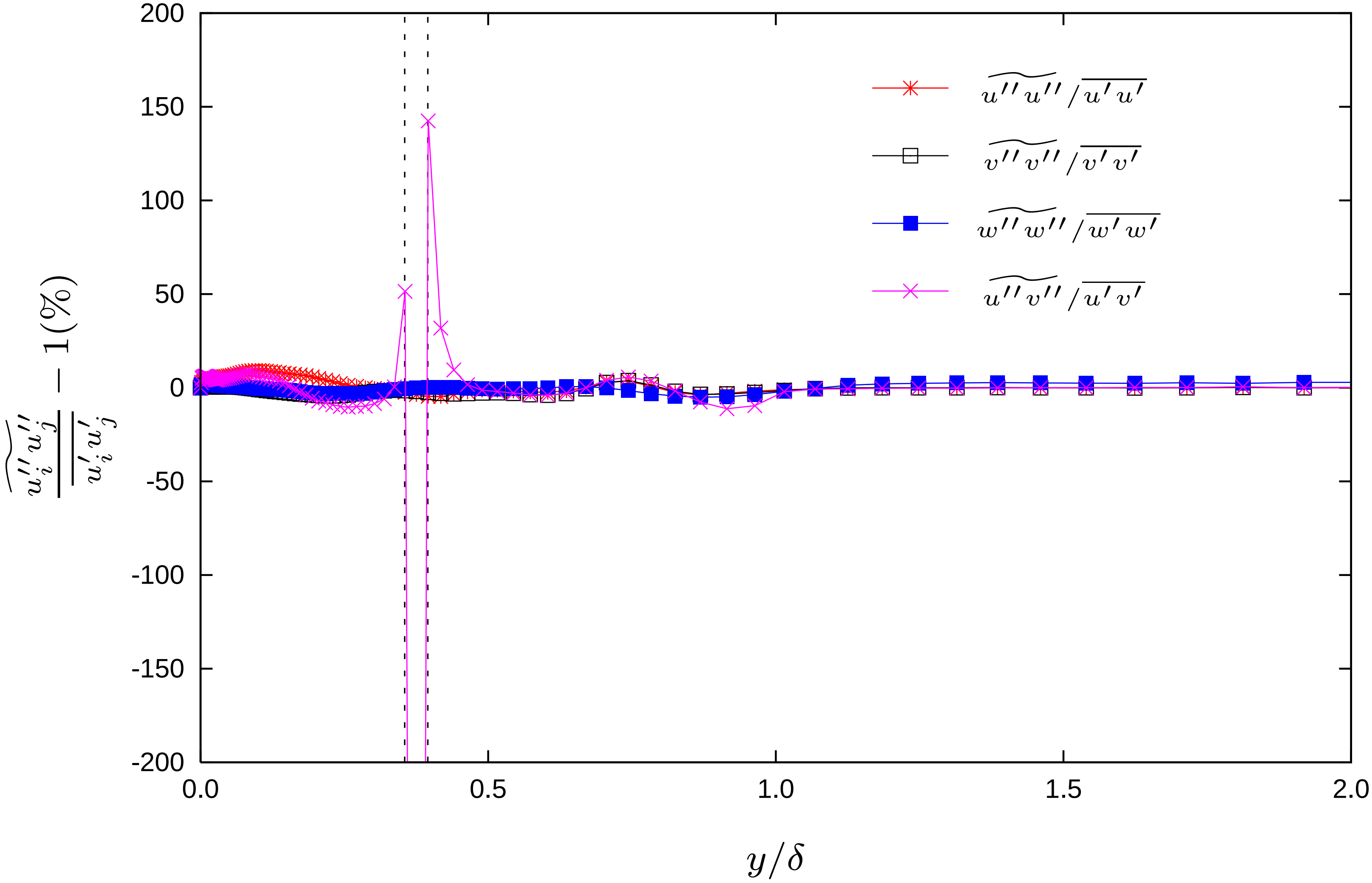
Plane P4

TURBULENT STRESSES IN INTERACTION ZONE



Plane P4

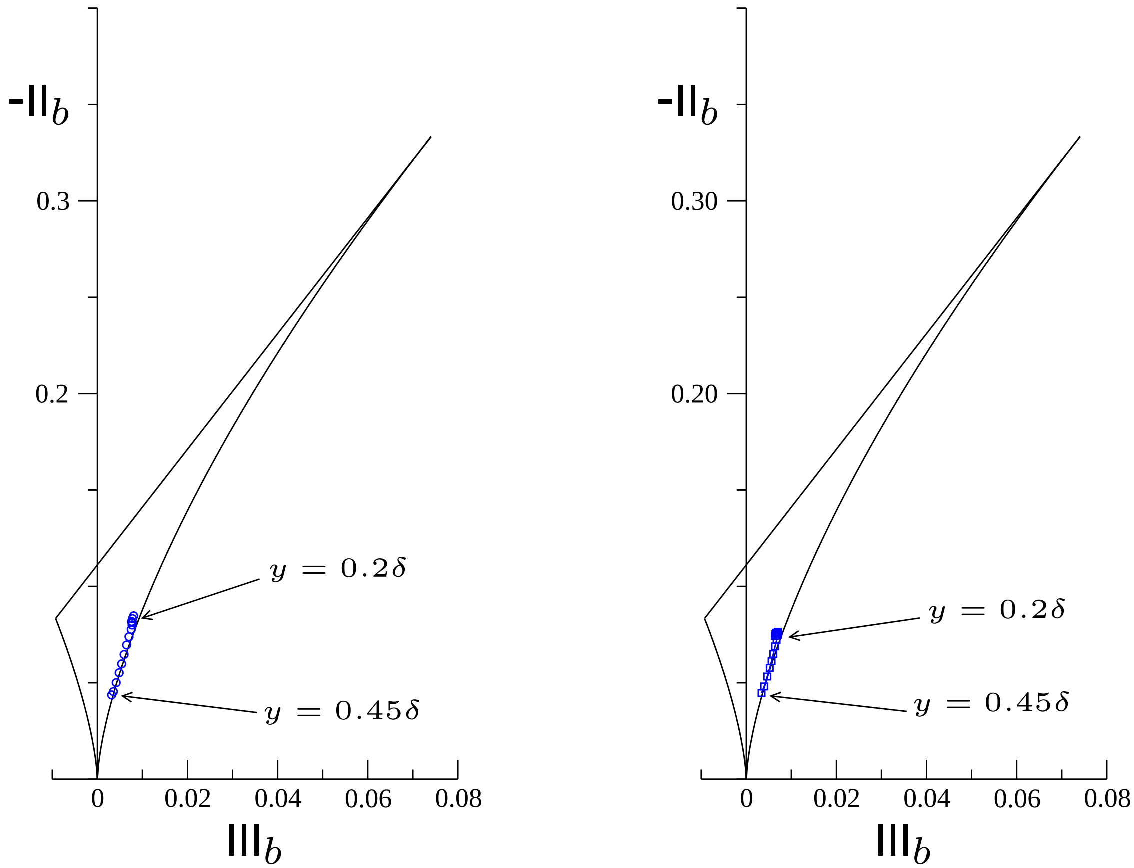
TURBULENT STRESSES IN INTERACTION ZONE



Plane P6

TURBULENT STRESSES IN INTERACTION ZONE

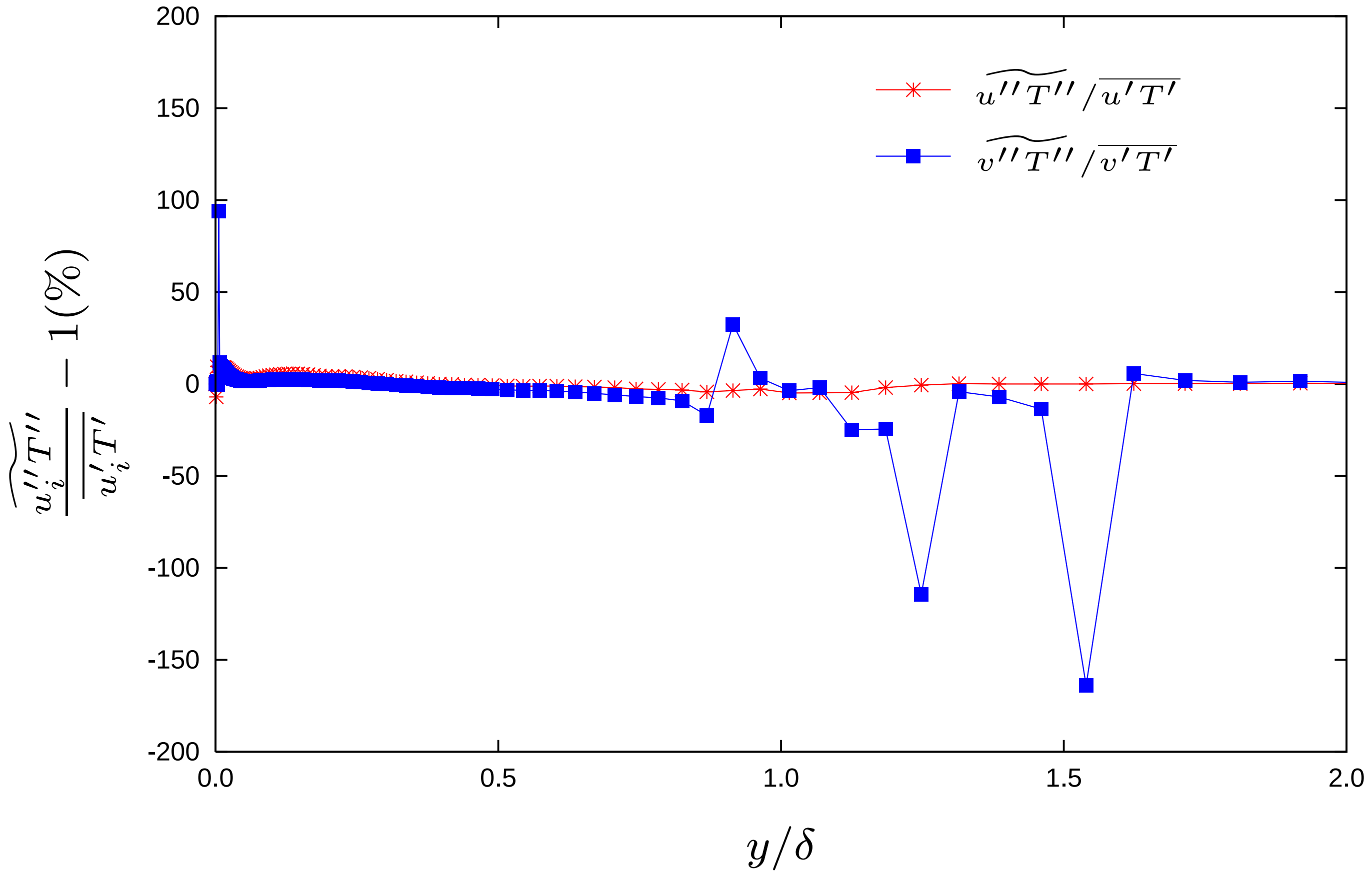
- Anisotropy invariant maps at Plane P6



Favre average　　Reynolds average

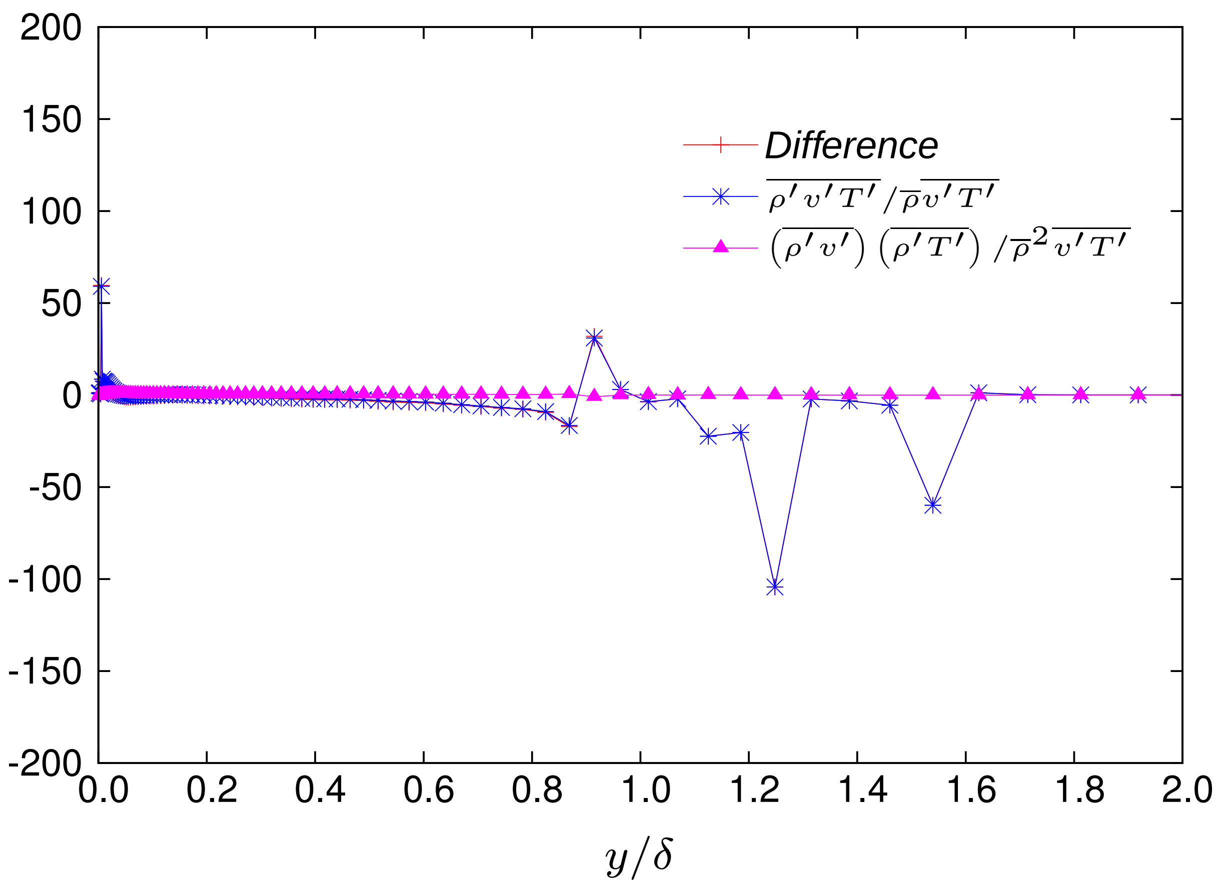
HEAT FLUX RELATIONSHIP

- Normalized turbulent heat fluxes



Plane P4

HEAT FLUX RELATIONSHIP



Plane P4

HEAT FLUX RELATIONSHIP

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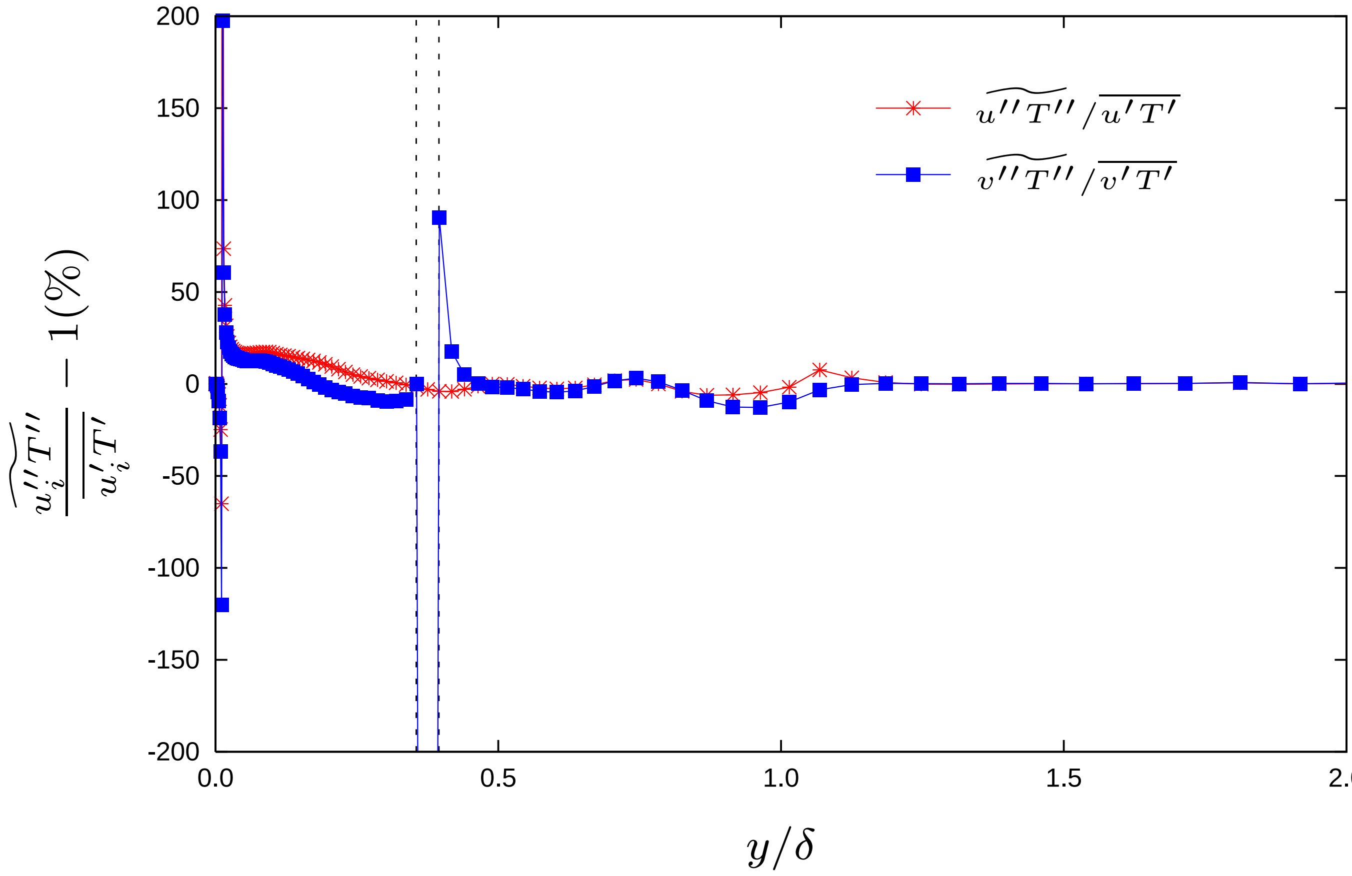

Plane P6

SUMMARIZING COMMENTS

- Shock impingement induces small separation zone with BL
- Turbulent shear stress distribution significantly affected by shock
  - Anisotropy map less sensistive to distortion
- Key element in model development is turbulent correlation relaxation from shock distortion