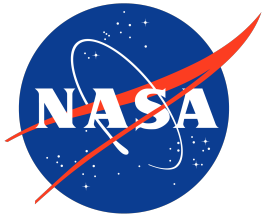
SESSION FD-06: TURBULENT FLOWS: COMPRESSIBLE

Compressibility, curvature and variable density effects on turbulent shear layers

K. V. MATSUNO, S. K. LELE, R. E. CHILDS

AIAA SciTech Forum 2022
3 January 2022



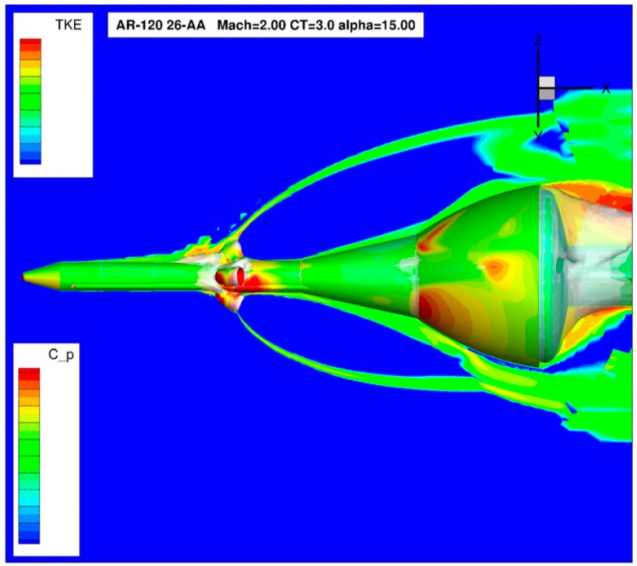


Funding provided by NASA AETC

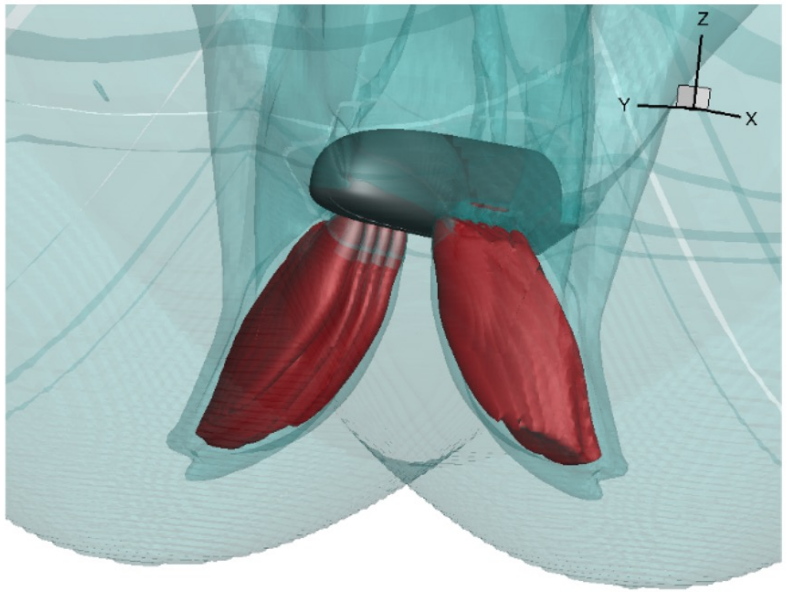
Outline

- Background
- Flow configuration and visualization
- Validation: comparison with literature
- Turbulence statistics

Background



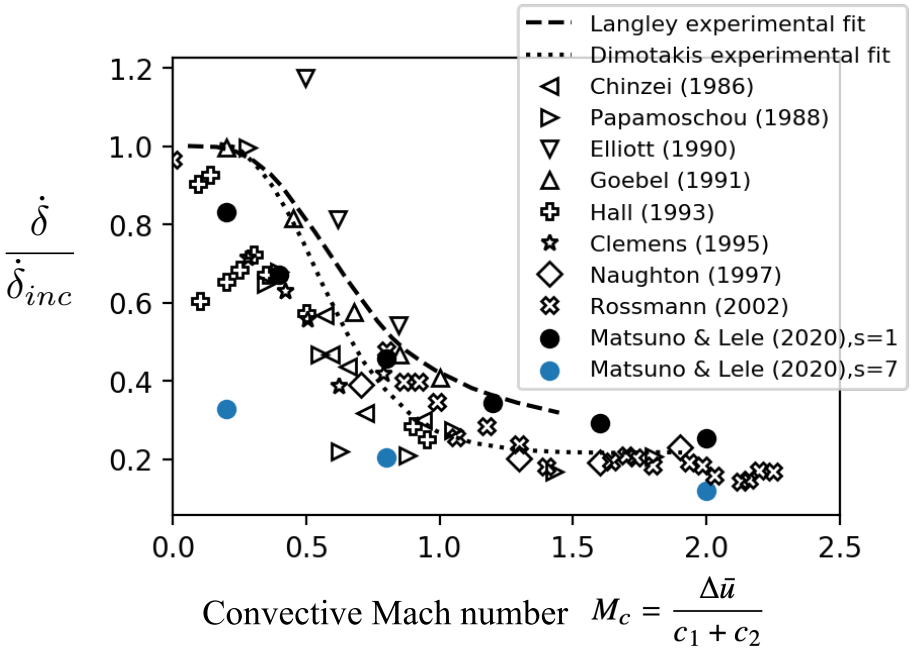
TKE contours highlighting a curved plume shear layer from the Orion Launch Abort Vehicle

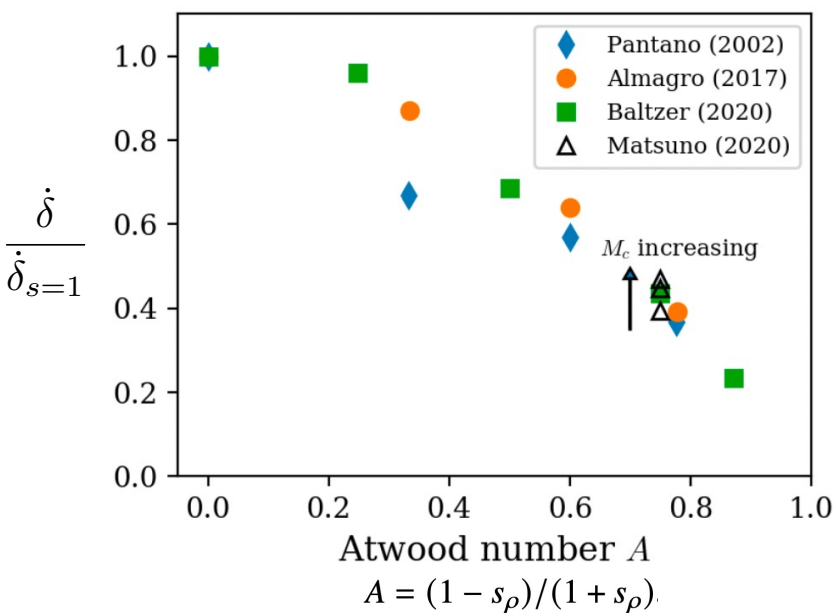


Plume curvature exhibited by the CobraMRV under supersonic retropropulsion

Childs, R., Garcia, J., Melton, J., Rogers, S., Shestopolov, A., and Vicker, D., "Overflow Simulation Guidelines for Orion Launch Abort Vehicle Aerodynamic Analyses,"29th AIAA Applied Aerodynamics Conference, 2011, p. 3163.
Matsuno, K., Childs, R., Pulliam, T., Stremel, P., and Garcia, J., "OVERFLOW Analysis of Supersonic Retropropulsion Testing on the CobraMRV Mars Entry Vehicle Concept (submitted),"AIAA Scitech 2022 Forum, 2022.

Known compressibility and variable density effects





Compressibility decreases mixing layer growth rate significantly

VD also decreases mixing layer growth rate, not decoupled from compressibility effects

Stanford University

Note: Matsuno & Lele results shown from *PadeOps* (structured DNS/LES solver), not OVERFLOW

Motivating questions

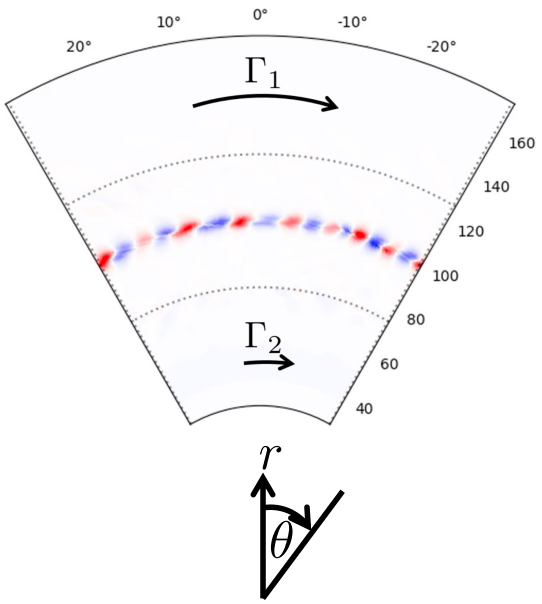
1. What are the combined effects of compressibility and variable density in curved shear layers?

2. How do these effects vary with increasing curvature intensity?

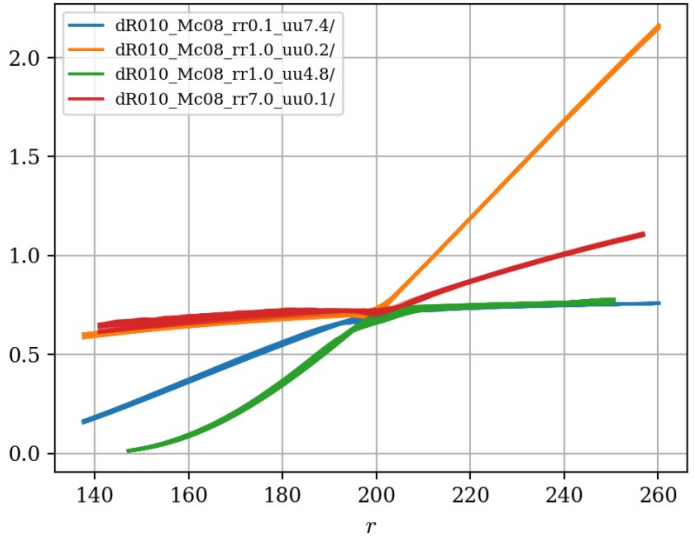
Flow configuration

- Temporally evolving
- Spanwise periodic, θ periodic w/ rotation
- Constant total pressure, entropy and circulation in free streams (the fluid is free of vorticity except along the shear layer centerline)

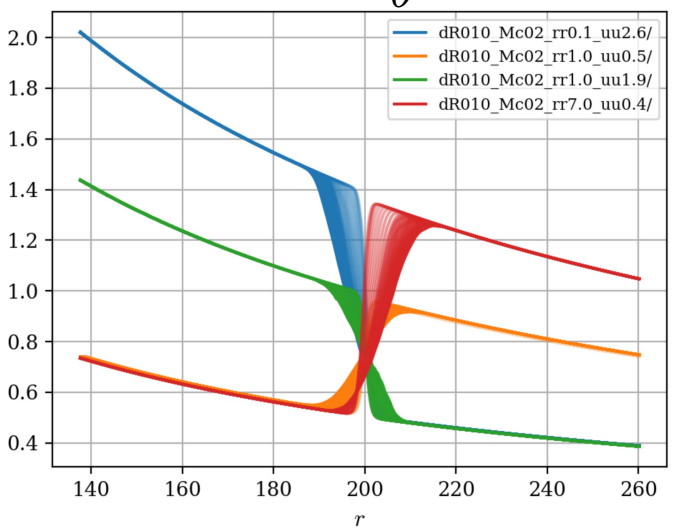
$$P_0 = P_{01} + (P_{02} - P_{01})0.5(1 + \tanh(y))$$
$$s = s_1 + (s_2 - s_1)0.5(1 + \tanh(y))$$



$\bar{\rho}$



$\tilde{u}_\theta$



Note: line opacity indicates solution time

Parameter space

- Curvature level: initial thickness to radius of curvature

$$\delta_0 / r_c$$

- Compressibility: convective Mach number

$$M_c = \frac{\Delta u}{c_1 + c_2}$$

- Density ratio:

$$\rho_2 / \rho_1$$

- Centrifugal stability: Eckhoff's criterion

$$\frac{u_\theta^2}{r}\left(\frac{1}{\rho}\frac{d\rho}{dr} - \frac{u_\theta^2}{c^2 r}\right) = \Phi > 0$$

Parameter space

Low and high curvature intensity

Case ID	δ/R_0	M_c	ρ_2/ρ_1	u_2/u_1
dR001_Mc02_rr0.1_uu2.7	0.001	0.2	1/7	2.7
dR001_Mc02_rr1.0_uu0.5	0.001	0.2	1	0.5
dR001_Mc02_rr1.0_uu1.9	0.001	0.2	1	1.9
dR001_Mc02_rr7.0_uu0.4	0.001	0.2	7	0.4
dR001_Mc08_rr0.1_uu7.5	0.001	0.8	1/7	7.5
dR001_Mc08_rr1.0_uu0.2	0.001	0.8	1	0.2
dR001_Mc08_rr1.0_uu4.6	0.001	0.8	1	4.6
dR001_Mc08_rr6.9_uu0.1	0.001	0.8	7	0.1
dR010_Mc02_rr0.1_uu2.7	0.010	0.2	1/7	2.7
dR010_Mc02_rr1.0_uu0.5	0.010	0.2	1	0.5
dR010_Mc02_rr1.0_uu1.9	0.010	0.2	1	1.9
dR010_Mc02_rr7.0_uu0.4	0.010	0.2	7	0.4
dR010_Mc08_rr0.1_uu7.7	0.010	0.8	1/7	7.7
dR010_Mc08_rr1.0_uu0.2	0.010	0.8	1	0.2
dR010_Mc08_rr1.0_uu4.8	0.010	0.8	1	4.8
dR010_Mc08_rr6.9_uu0.1	0.010	0.8	7	0.1

Parameter space

Low and high speed (compressibility)

Case ID	δ/R_0	M_c	ρ_2/ρ_1	u_2/u_1
dR001_Mc02_rr0.1_uu2.7	0.001	0.2	1/7	2.7
dR001_Mc02_rr1.0_uu0.5	0.001	0.2	1	0.5
dR001_Mc02_rr1.0_uu1.9	0.001	0.2	1	1.9
dR001_Mc02_rr7.0_uu0.4	0.001	0.2	7	0.4
dR001_Mc08_rr0.1_uu7.5	0.001	0.8	1/7	7.5
dR001_Mc08_rr1.0_uu0.2	0.001	0.8	1	0.2
dR001_Mc08_rr1.0_uu4.6	0.001	0.8	1	4.6
dR001_Mc08_rr6.9_uu0.1	0.001	0.8	7	0.1
dR010_Mc02_rr0.1_uu2.7	0.010	0.2	1/7	2.7
dR010_Mc02_rr1.0_uu0.5	0.010	0.2	1	0.5
dR010_Mc02_rr1.0_uu1.9	0.010	0.2	1	1.9
dR010_Mc02_rr7.0_uu0.4	0.010	0.2	7	0.4
dR010_Mc08_rr0.1_uu7.7	0.010	0.8	1/7	7.7
dR010_Mc08_rr1.0_uu0.2	0.010	0.8	1	0.2
dR010_Mc08_rr1.0_uu4.8	0.010	0.8	1	4.8
dR010_Mc08_rr6.9_uu0.1	0.010	0.8	7	0.1

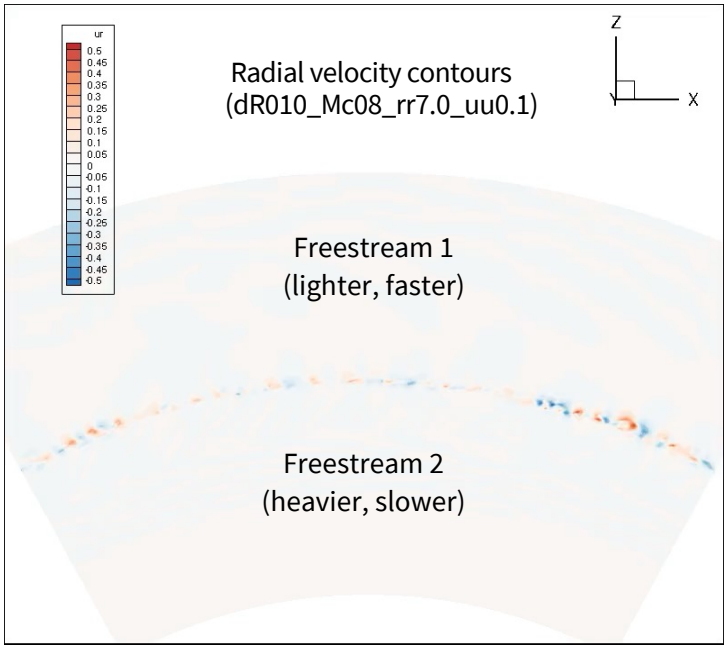
Parameter space

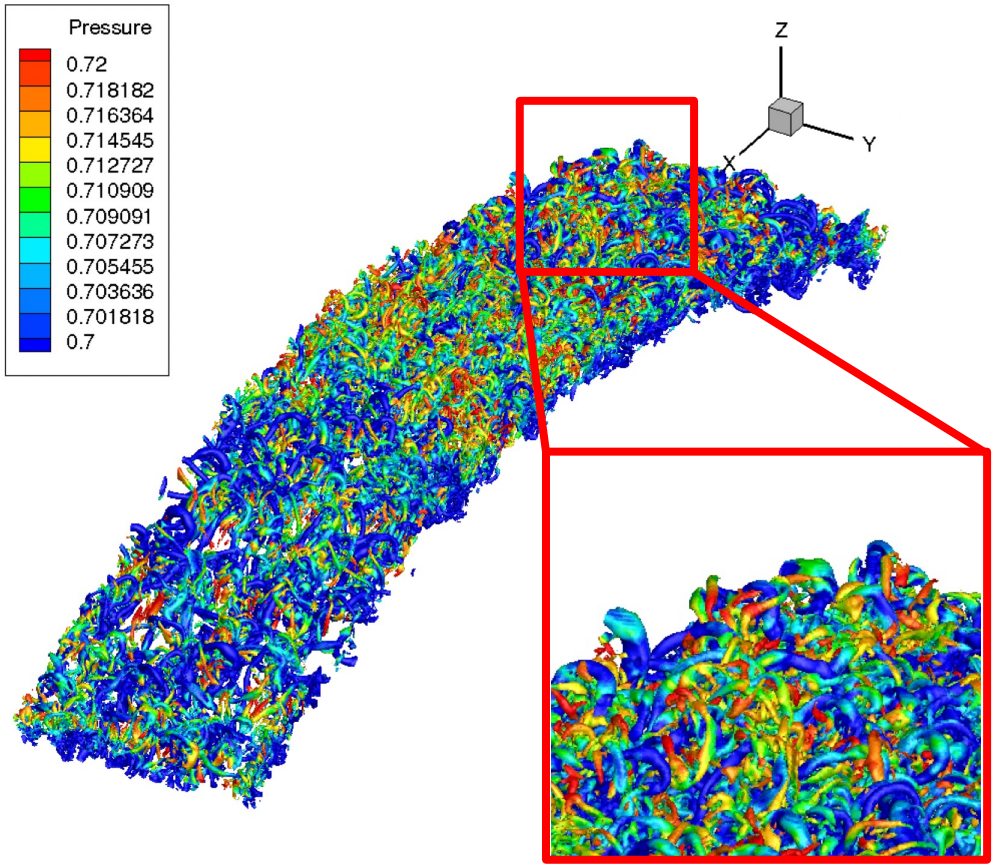
Centrifugally stable and unstable

Case ID	δ/R_0	M_c	ρ_2/ρ_1	u_2/u_1
dR001_Mc02_rr0.1_uu2.7	0.001	0.2	1/7	2.7
dR001_Mc02_rr1.0_uu0.5	0.001	0.2	1	0.5
dR001_Mc02_rr1.0_uu1.9	0.001	0.2	1	1.9
dR001_Mc02_rr7.0_uu0.4	0.001	0.2	7	0.4
dR001_Mc08_rr0.1_uu7.5	0.001	0.8	1/7	7.5
dR001_Mc08_rr1.0_uu0.2	0.001	0.8	1	0.2
dR001_Mc08_rr1.0_uu4.6	0.001	0.8	1	4.6
dR001_Mc08_rr6.9_uu0.1	0.001	0.8	7	0.1
dR010_Mc02_rr0.1_uu2.7	0.010	0.2	1/7	2.7
dR010_Mc02_rr1.0_uu0.5	0.010	0.2	1	0.5
dR010_Mc02_rr1.0_uu1.9	0.010	0.2	1	1.9
dR010_Mc02_rr7.0_uu0.4	0.010	0.2	7	0.4
dR010_Mc08_rr0.1_uu7.7	0.010	0.8	1/7	7.7
dR010_Mc08_rr1.0_uu0.2	0.010	0.8	1	0.2
dR010_Mc08_rr1.0_uu4.8	0.010	0.8	1	4.8
dR010_Mc08_rr6.9_uu0.1	0.010	0.8	7	0.1

Flow visualization

- Numerical methods
  - OVERFLOW overset grid solver
  - 4th order Runge-Kutta time integration
  - WENO5 w/ 2nd order viscous terms
  - No SGS model
  - Re~1e6



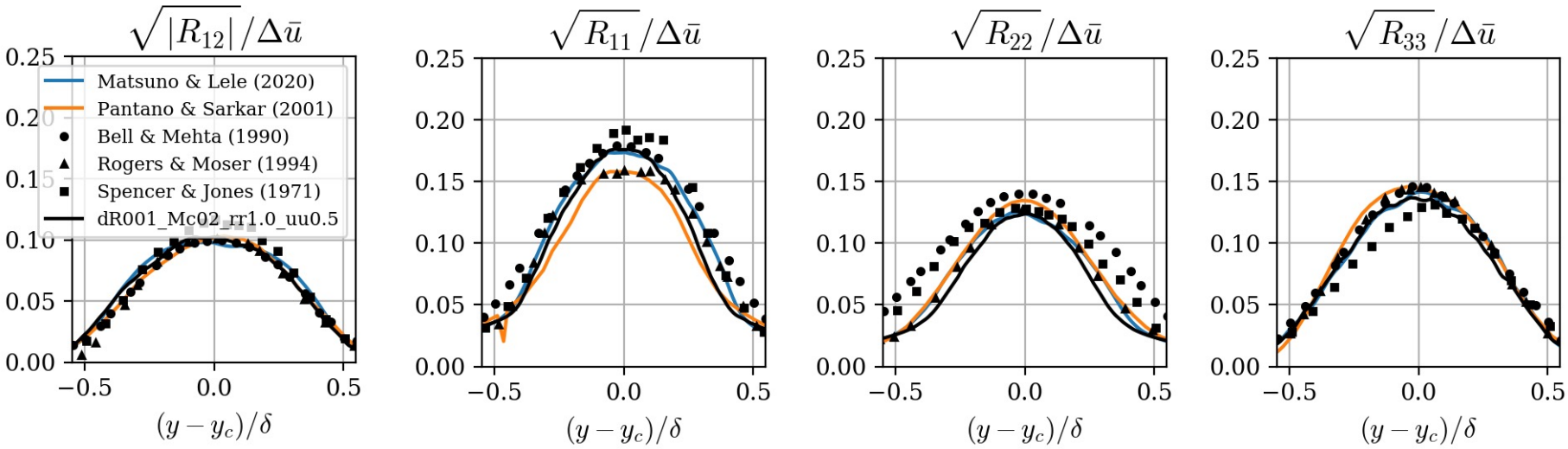


Iso-surfaces of normalized Q-criterion=0.3
Colored by pressure
dR010_Mc02_rr1.0_uu1.9
Visualized at instance:
delta/delta0 = 2.5
delta/R0 = 0.05

Comparison to literature

Comparison of peak stress magnitudes at
low curvature, low & high speed, unity density ratio

$$\frac{\sqrt{R_{ij}}}{\Delta\bar{u}} = \sqrt{\frac{\overline{\rho u_i'' u_j''}}{\bar{\rho}\Delta\bar{u}^2}}$$

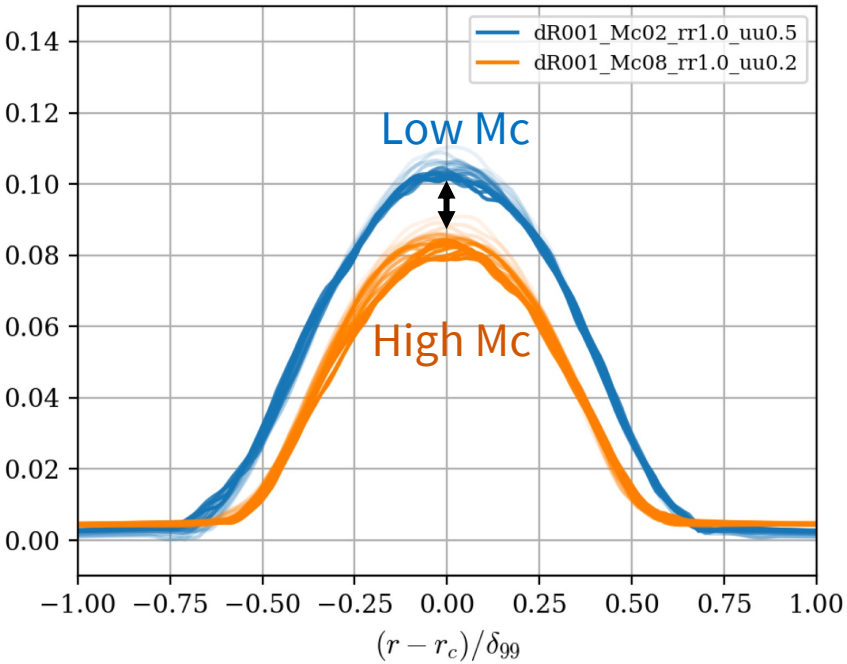


Turbulent stress magnitudes consistent
with previously published studies

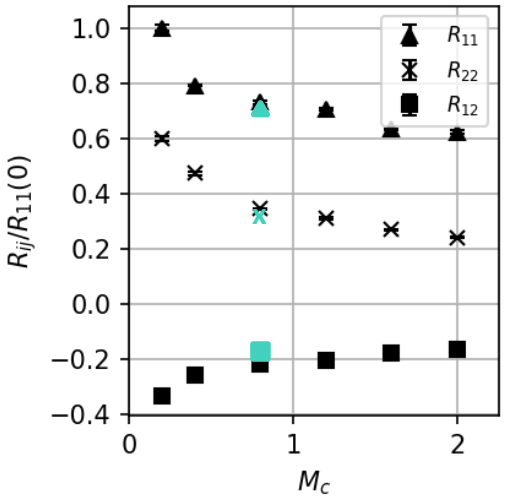
Comparison to literature

Comparison of peak stress magnitudes at
low curvature, low & high speed, unity density ratio

$$\frac{\sqrt{R_{12}}}{\Delta\bar{u}} = \sqrt{\frac{\overline{\rho u_1'' u_2''}}{\bar{\rho}\Delta\bar{u}^2}}$$

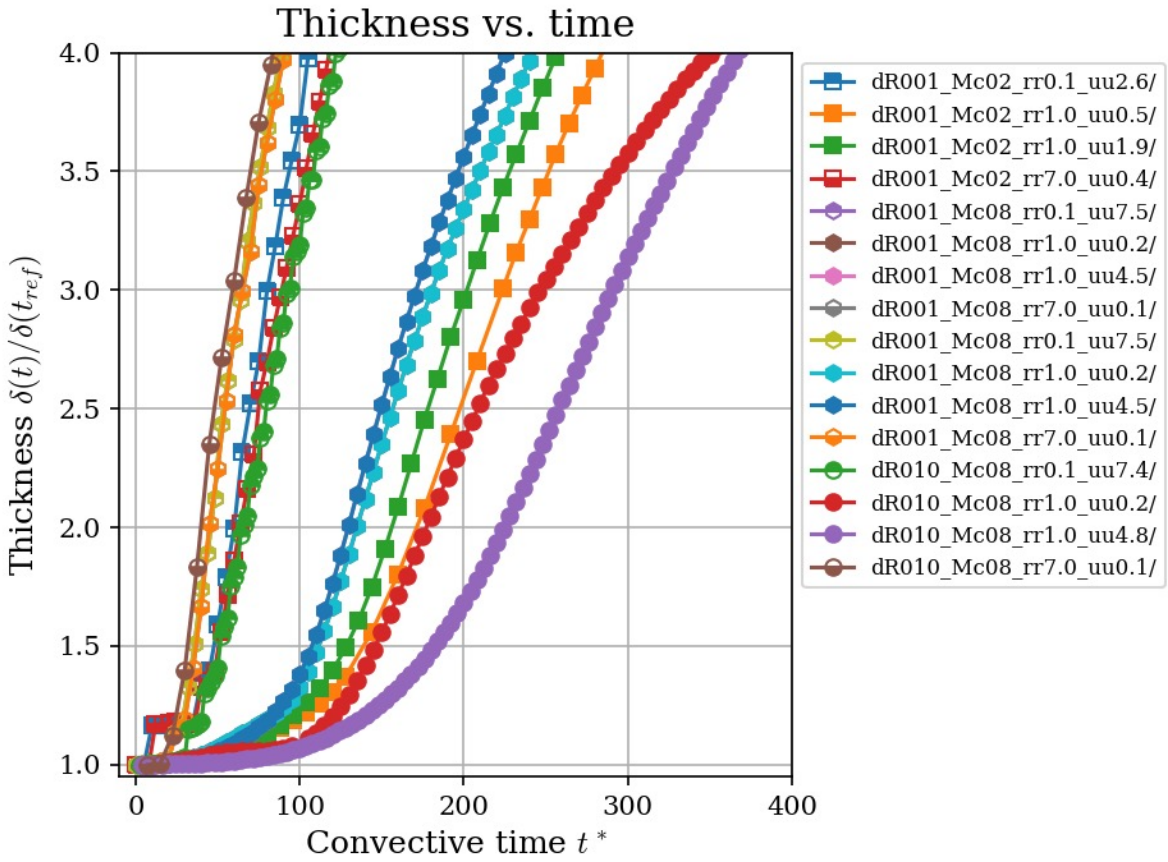


Matsuno & Lele (2020)
Current data



Increasing compressibility decreases turbulent stress magnitude

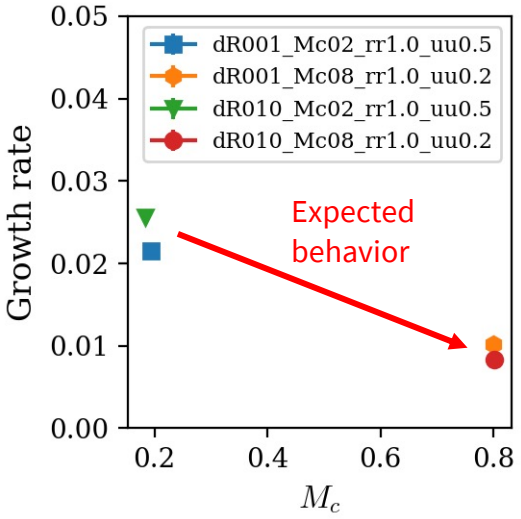
Growth rate trends



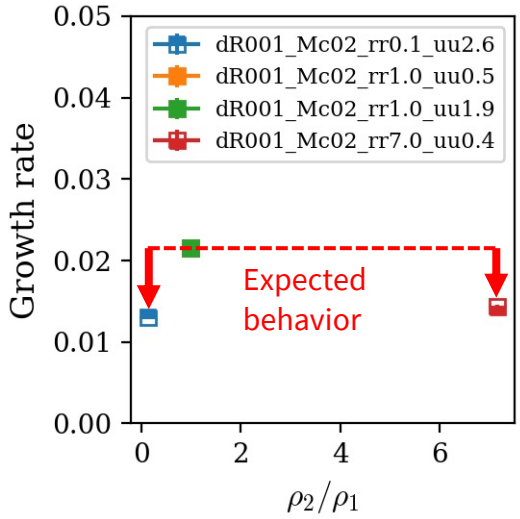
$$t* = t\Delta\bar{u}(0)/\delta(0)$$

Growth rate trends

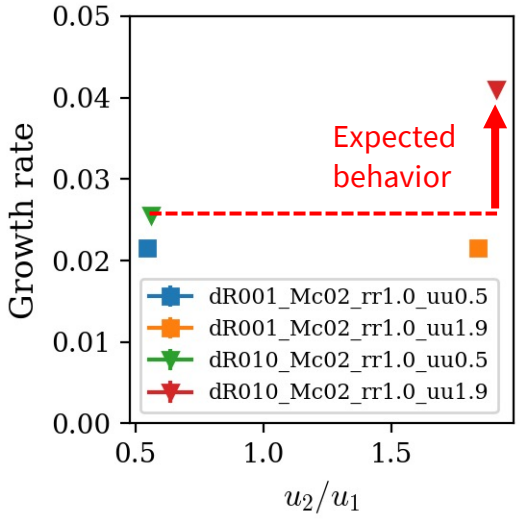
Growth rates decrease with increasing compressibility



Growth rates decrease with density variations



Growth rates increase with curvature levels



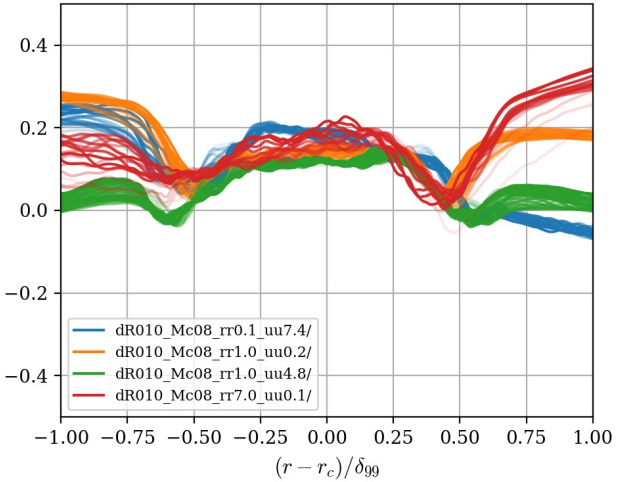
Growth rate trends follow expected behavior

Stress anisotropy

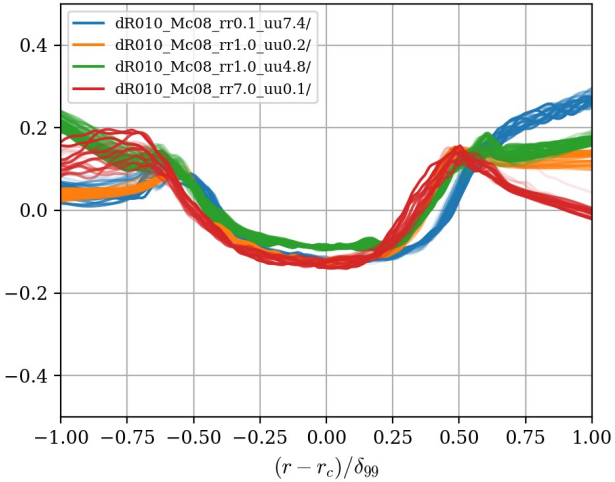
High speed, moderate curvature: varying density

$$b_{ij} = \frac{R_{ij}}{2k} - \frac{\delta_{ij}}{3} = \frac{\overline{\rho u_i'' u_j''}}{\overline{\rho u_k'' u_k''}} - \frac{\delta_{ij}}{3}$$

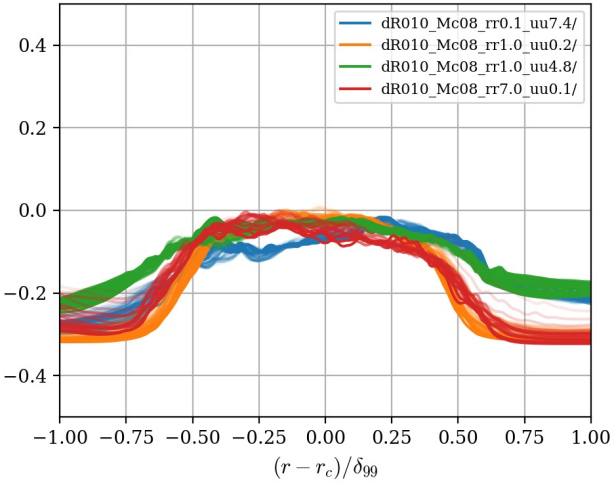
b_{11}



b_{22}



b_{33}

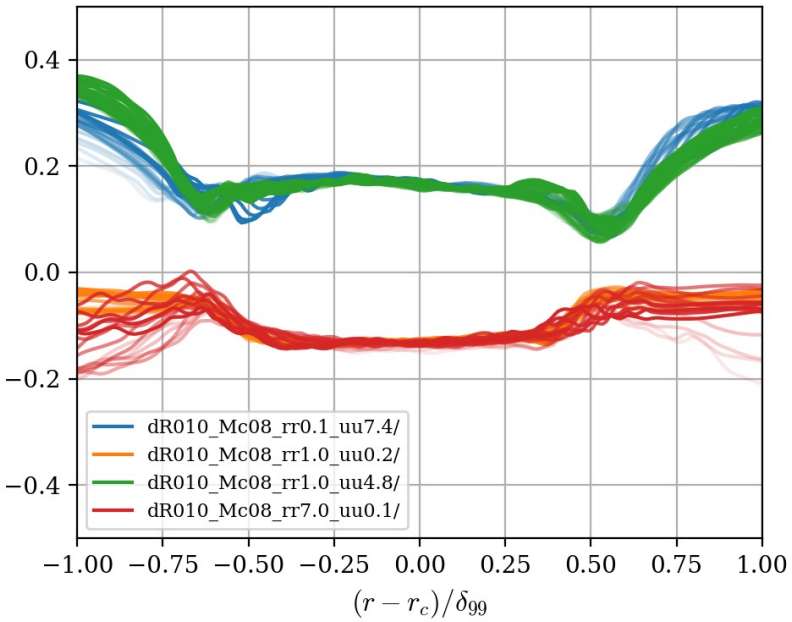


Stress anisotropy

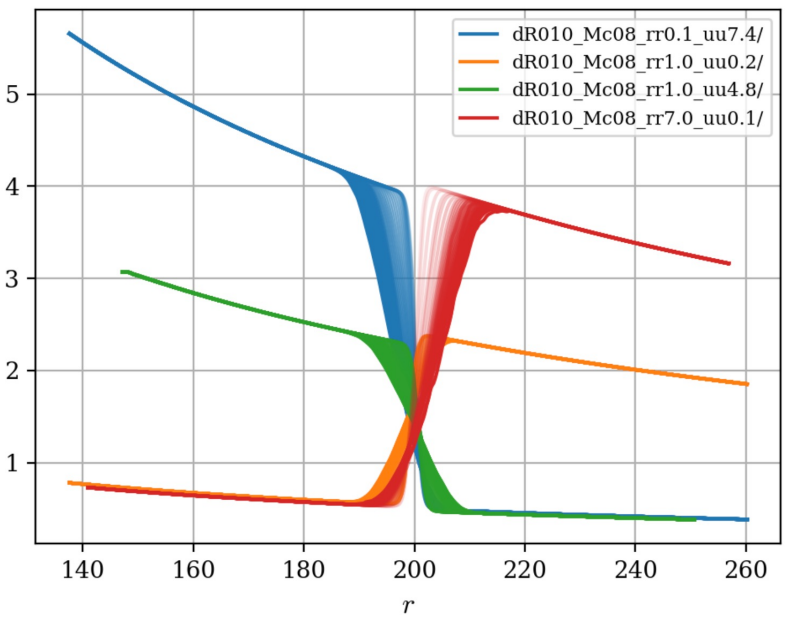
High speed, moderate curvature: varying density

$$b_{ij} = \frac{R_{ij}}{2k} - \frac{\delta_{ij}}{3} = \frac{\overline{\rho u_i'' u_j''}}{\overline{\rho u_k'' u_k''}} - \frac{\delta_{ij}}{3}$$

b_{12}



$\tilde{u}_\theta$

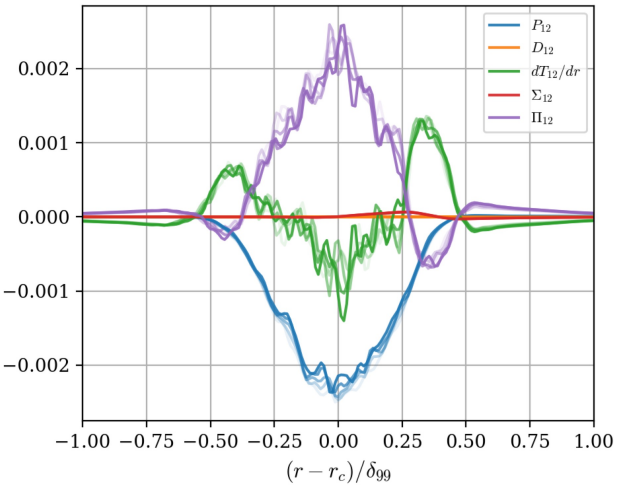


Shear stress budget

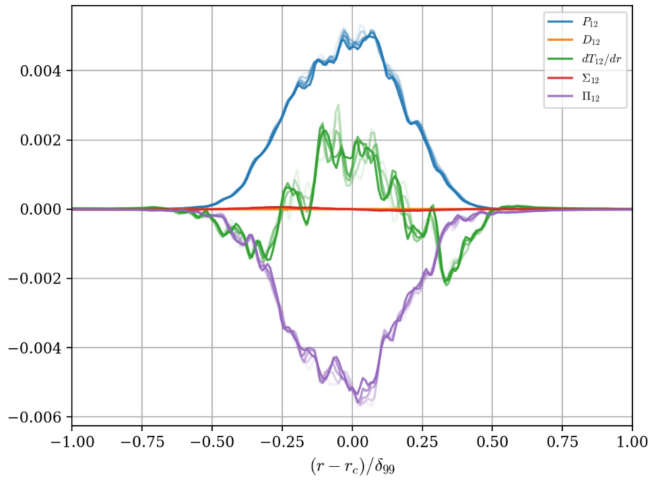
$$\frac{\partial}{\partial t}(\bar{\rho}R_{ij}) + \frac{\partial}{\partial x_k}(\bar{\rho}\tilde{u}_k R_{ij}) = \underbrace{-\bar{\rho}\left(R_{ik}\frac{\partial \tilde{u}_j}{\partial x_k} + R_{jk}\frac{\partial \tilde{u}_i}{\partial x_k}\right)}_{\text{Production } P_{ij}} - \underbrace{\overline{\left(\tau'_{jk}\frac{\partial u''_i}{\partial x_k} + \tau'_{ik}\frac{\partial u''_j}{\partial x_k}\right)}}_{\text{Dissipation } \epsilon_{ij}} + \underbrace{\overline{p'\left(\frac{\partial u''_i}{\partial x_j} + \frac{\partial u''_j}{\partial x_i}\right)}}_{\text{Pressure strain } \Pi_{ij}}$$

$$+ \underbrace{\frac{\partial}{\partial x_k}\left(\overline{\tau'_{jk}u''_i} + \overline{\tau'_{ik}u''_j} - \overline{\rho u''_i u''_j u''_k} - \overline{p'u''_i}\delta_{jk} - \overline{p'u''_j}\delta_{ik}\right)}_{\text{Turbulent transport } T_{ijk}} + \underbrace{\overline{u''_i}\left(\frac{\partial \bar{\tau}_{jk}}{\partial x_k} - \frac{\partial \bar{p}}{\partial x_j}\right) + \overline{u''_j}\left(\frac{\partial \bar{\tau}_{ik}}{\partial x_k} - \frac{\partial \bar{p}}{\partial x_i}\right)}_{\text{Mass flux coupling } \Sigma_{ij}}$$

High speed, moderate curvature
Centrifugally stable (dR010_Mc08_rr1.0_uu0.2)



High speed, moderate curvature
Centrifugally unstable (dR010_Mc08_rr1.0_uu4.8)



Production of R_{12} switches sign depending on velocity stabilization

Curvature effects on R_{12}

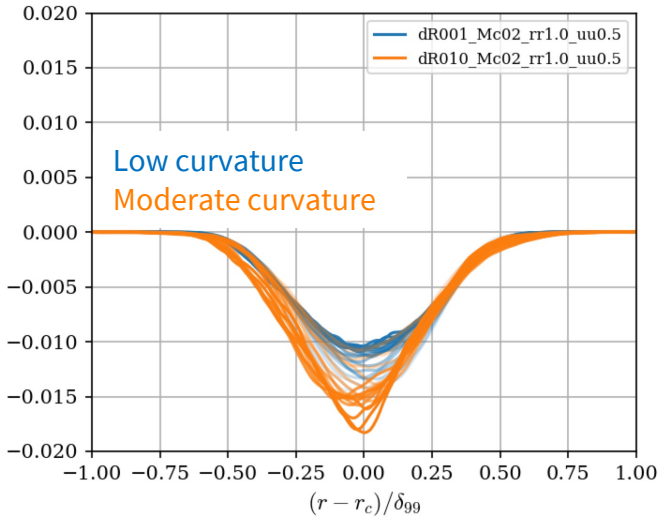
$$\frac{R_{12}}{(\Delta u)^2}$$

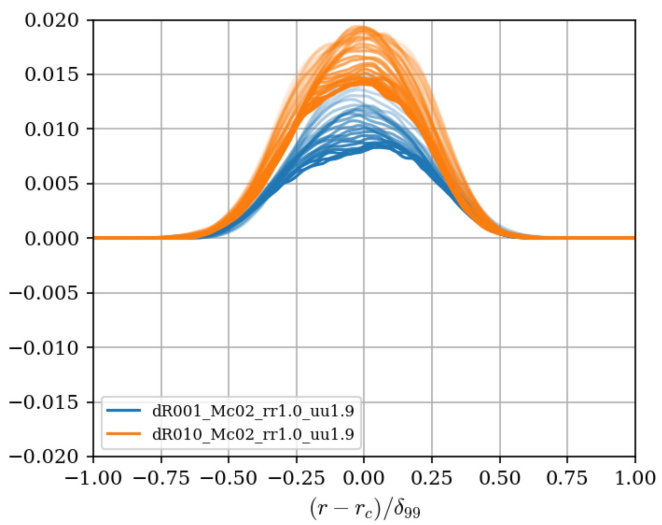
Centrifugally stable

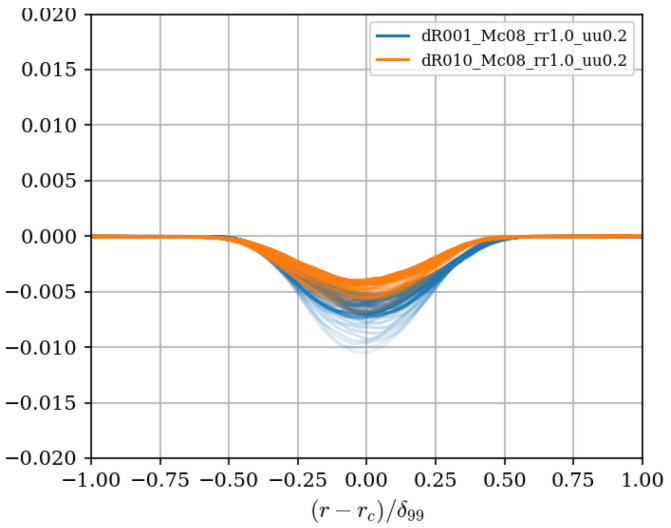
Centrifugally unstable

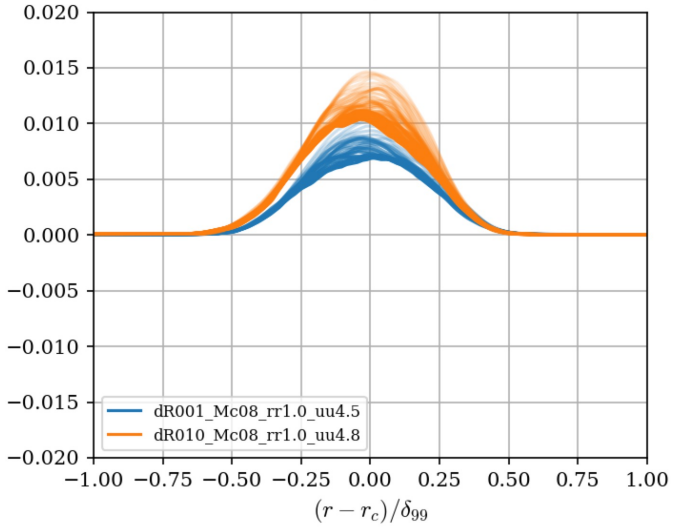
Low speed (Mc=0.2)

High speed (Mc=0.8)









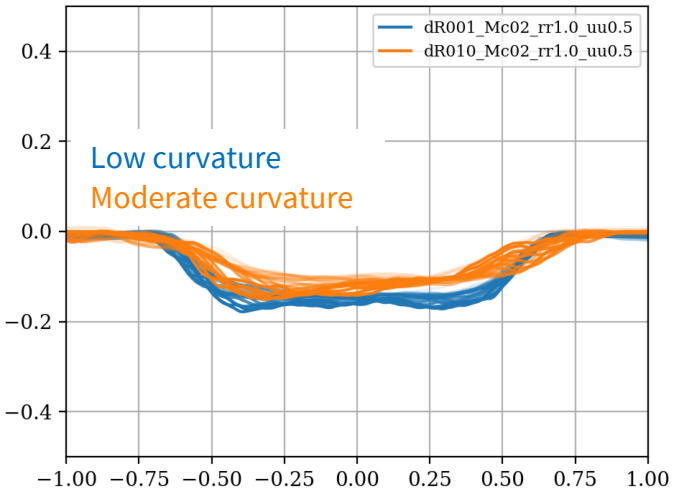
Curvature effects on b_{12}

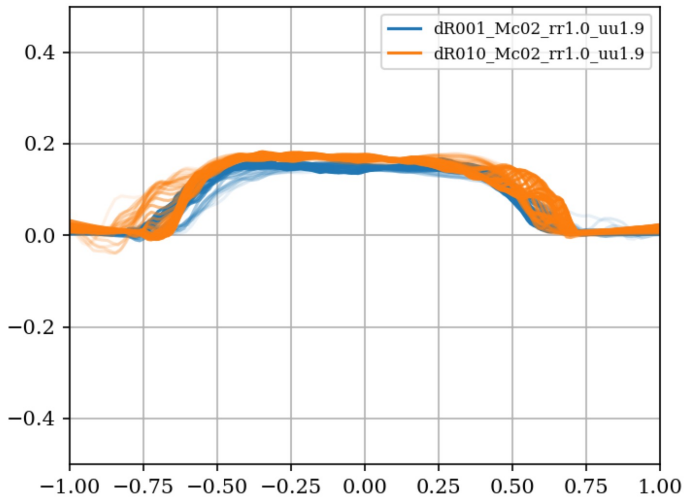
Centrifugally stable

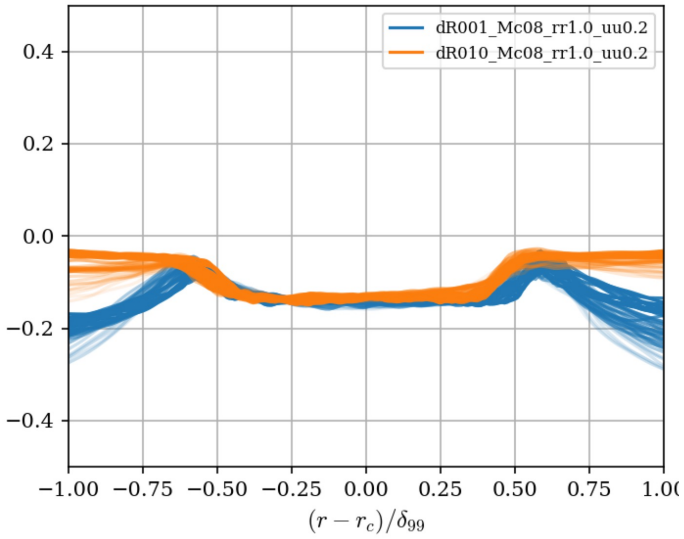
Centrifugally unstable

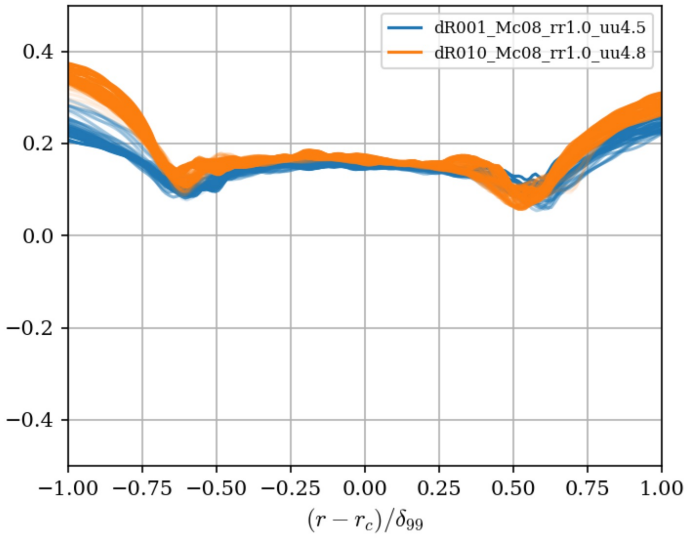
Low speed (Mc=0.2)

High speed (Mc=0.8)



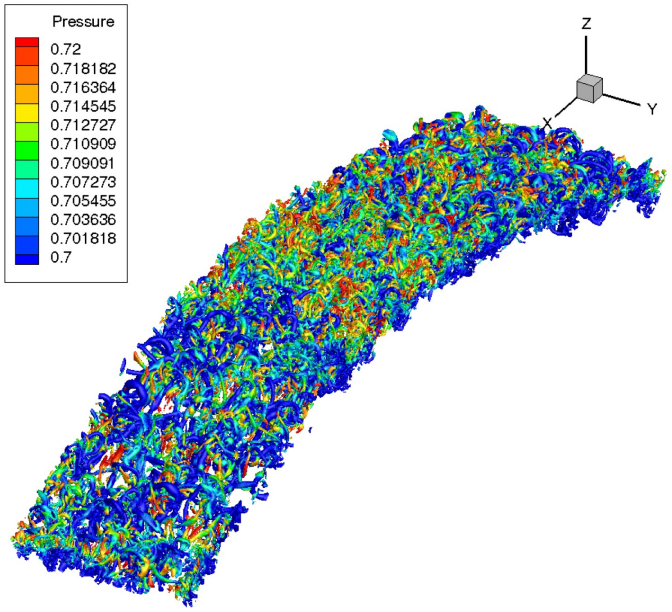


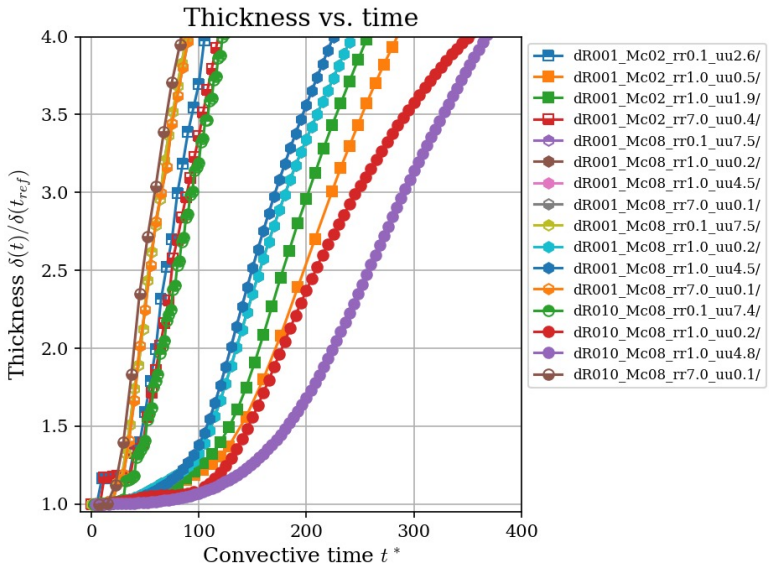




Summary

- LES growth rates follow expected behavior
  - Decreasing with increasing compressibility
  - Decreasing with VD effects
  - Increasing with increasing curvature intensity
- Preliminary observations on
  - Shear stress trends
  - Stress anisotropy
  - Shear stress budget
- Ongoing work:
  - Comparison to RANS models
  - Effect of ICs
  - Use of SGS model
  - Relate to RT mixing





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