Numerical Investigation of Turbulence Suppression in Rotating Flows

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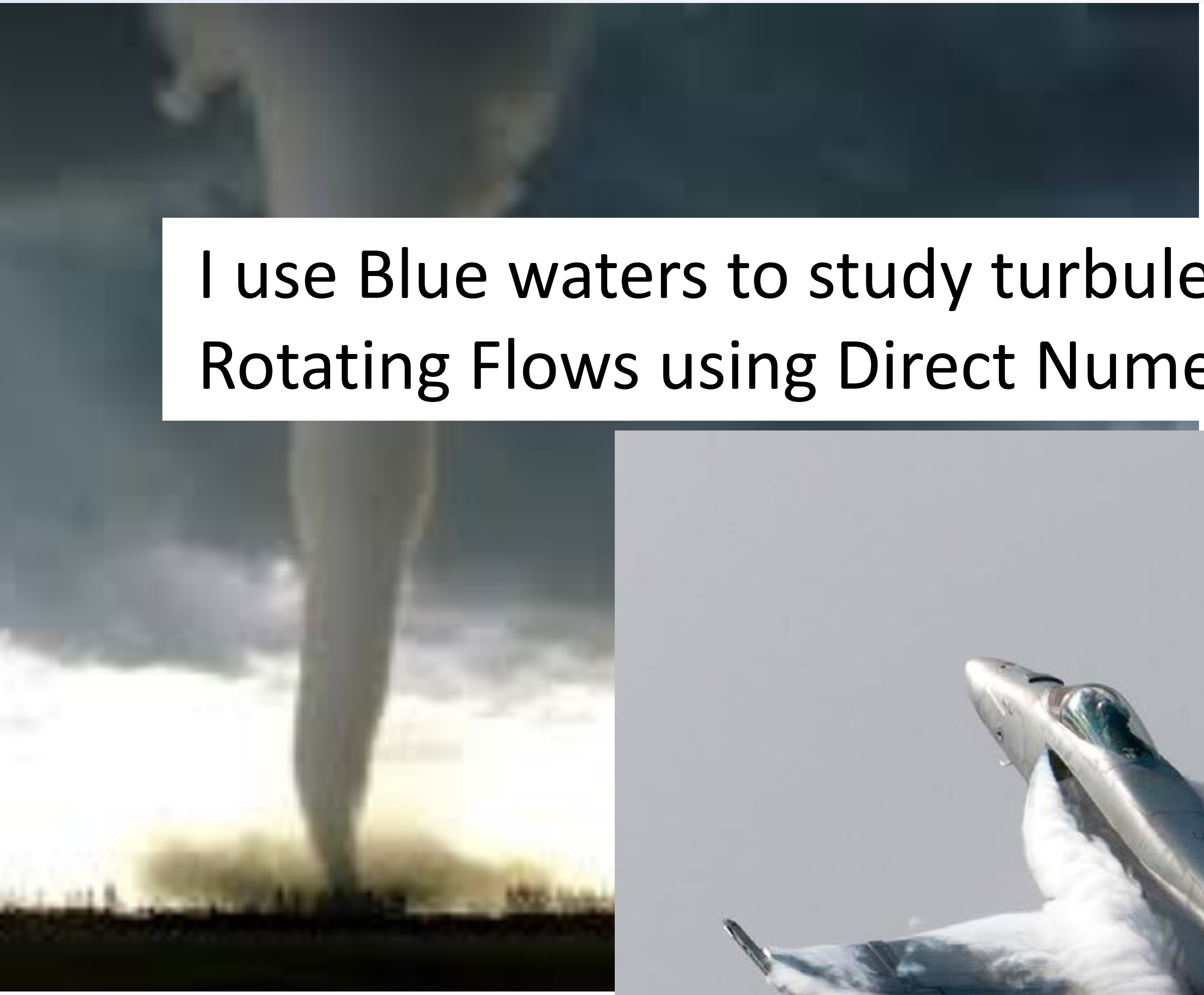
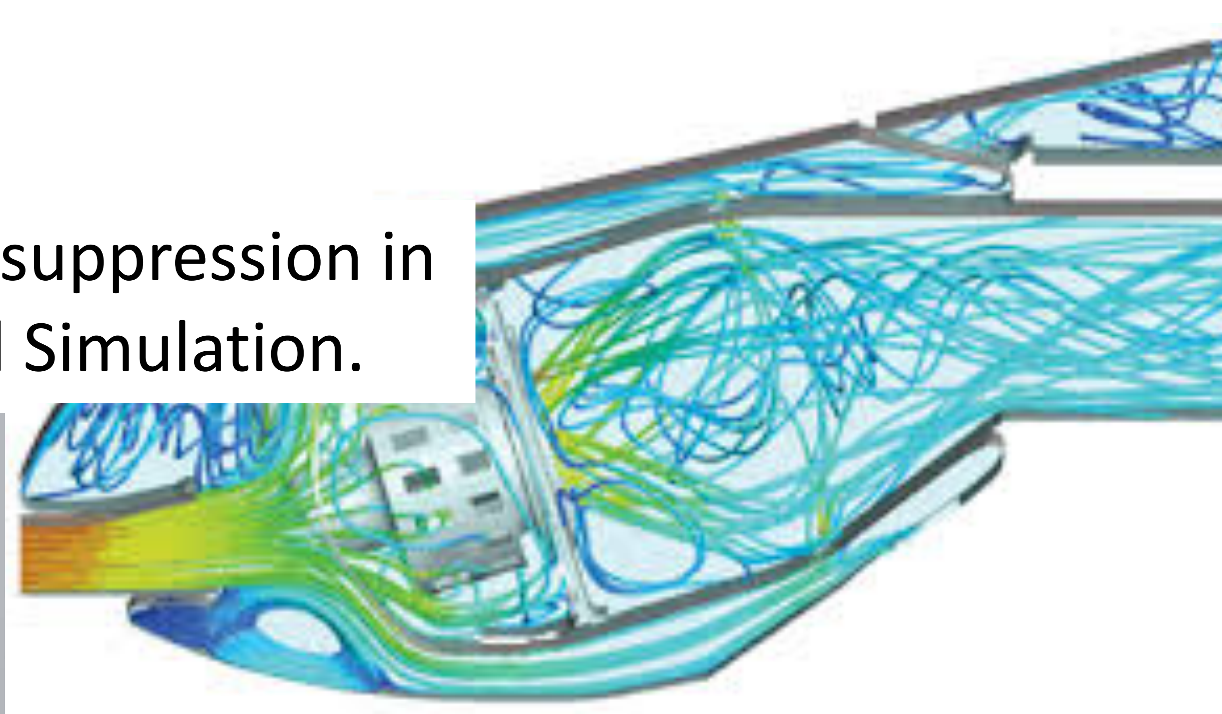
Blue Waters Symposium, June 3-6, 2019

Brief Background on Rotating Turbulent Flows



I use Blue waters to study turbulence suppression in Rotating Flows using Direct Numerical Simulation.



Images: www.johnstonhealth.org (left)
U.S. Navy (middle)
www.enginsoft.com (right)

Outline

Background on Rotating Turbulent Flows

Relevance to practical applications, turbulence suppression, past research, etc.

Simulation Setup

Simulation setup, solver and experiments.

Simulation Results

- *Effects on Mean Flow.*
- *Quantifying Turbulence Suppression.*
- *Structure of Reynolds Stress Tensor.*

RANS Turbulence Modeling

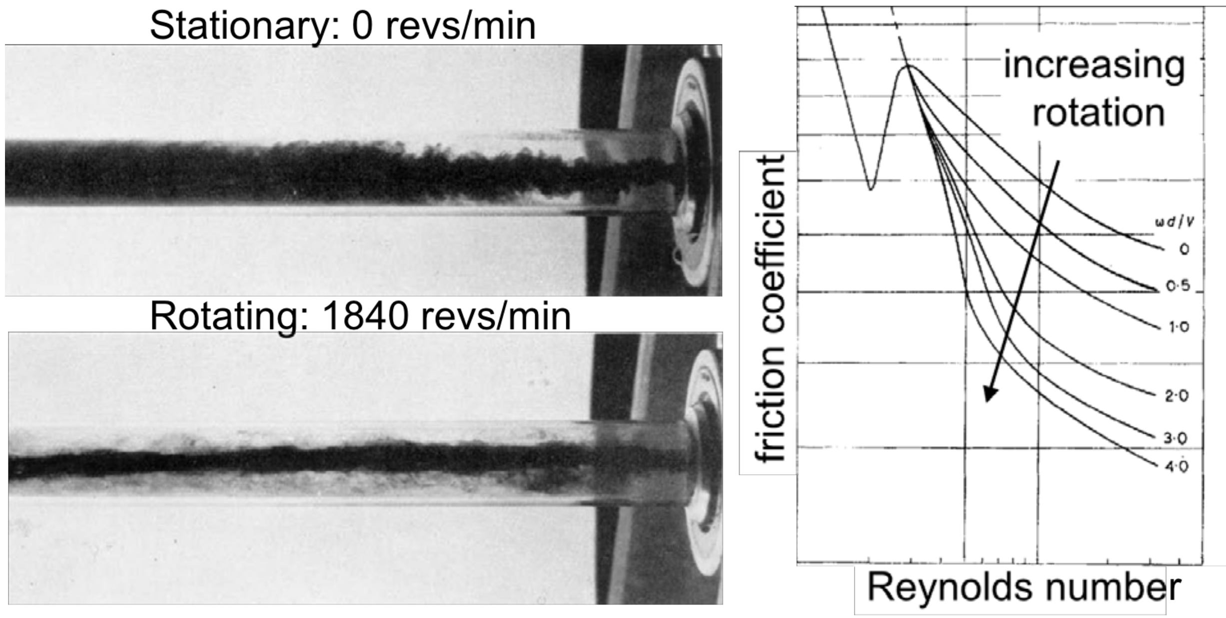
Comparison of DNS results against state-of-the-art RANS models.

Summary & Outlook

Summary of presented research and what is next.

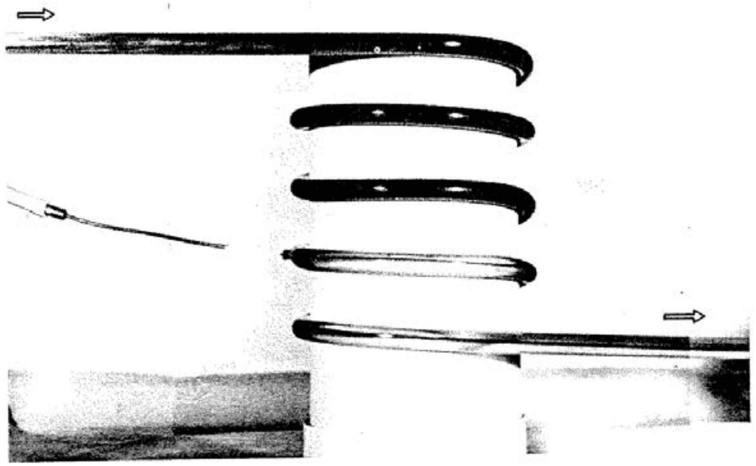
Brief Background on Rotating Turbulent Flows

- Rotation has strong effects on turbulence, i.e. suppression of turbulence, reducing skin friction and leading to a laminar appearance of the average velocity profile (White, 1964).
- "Relaminarization" has been observed in experiments such as those conducted by Viswanath *et al. (1978)* in experiments on coiled tubes.
- Very limited DNS data available, see Orlandi (JFM 1997).



From *White (1964)*

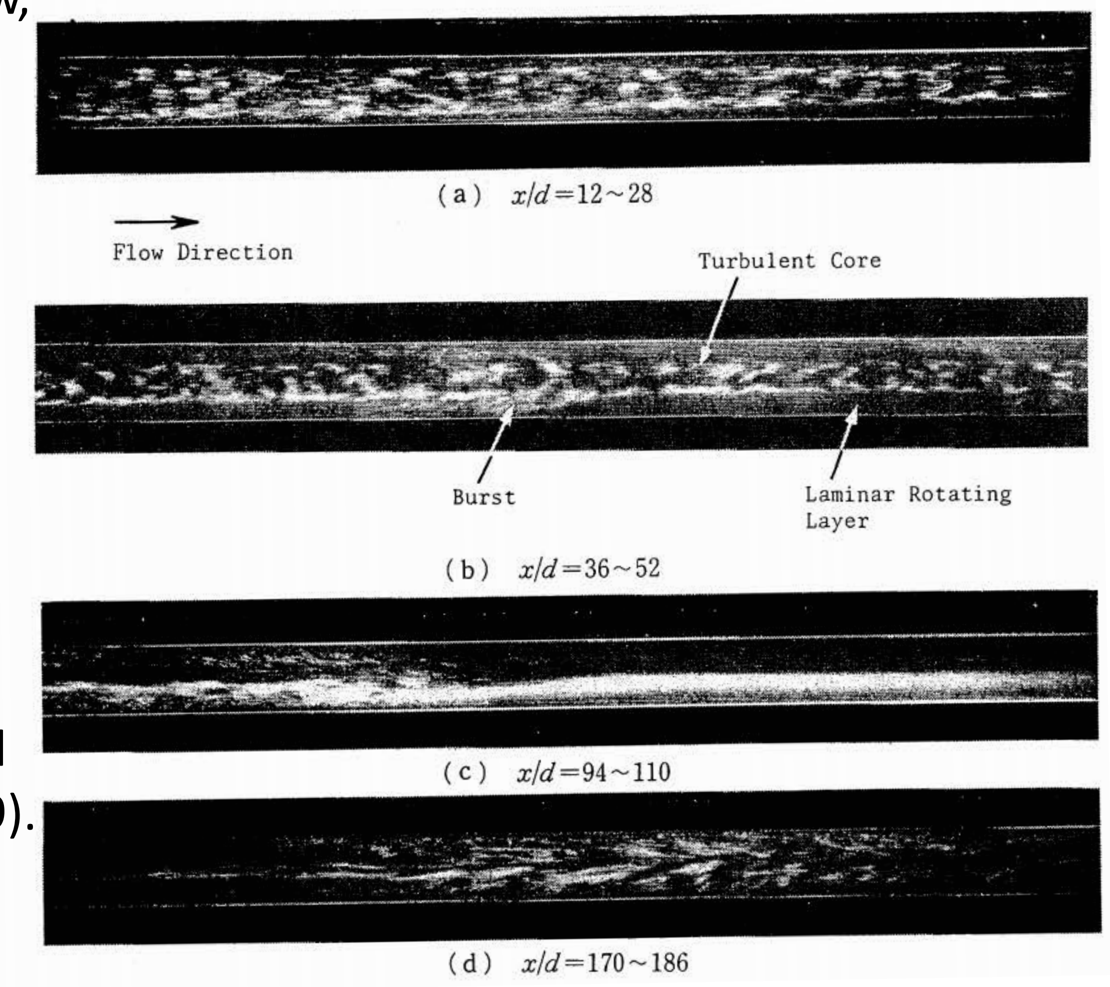
- Mechanisms causing turbulence suppression are not well understood, with present knowledge limited to the identification of the basic physical mechanisms including:
  - Dominance of pressure forces over slowly responding Reynolds stresses through rapid acceleration.
  - Dissipation of turbulent energy by molecular transport.
  - Absorption/destruction of turbulent energy by exerting work through external force.



From *Viswanath et al.(1978)*

Brief Background on Rotating Pipe Flows

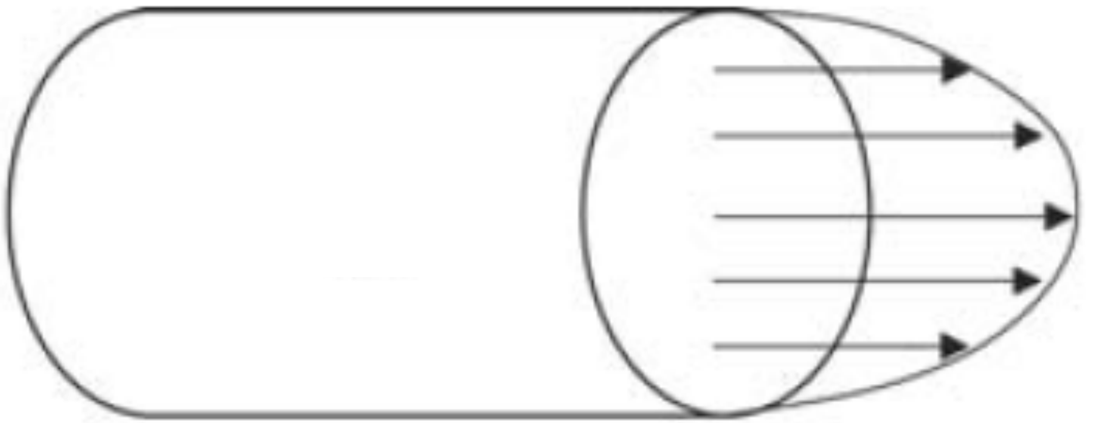
- Rotation in laminar pipe flows is known to destabilize the flow, reducing the critical Reynolds number for transition.
- Rotation in turbulent flows has been shown through experiment to reduce pressure loss and wall friction. (Kikuyama *et al*. 1983)
- High rotation rates have even been shown to cause relaminarization of the flow near the wall. These flows are characterized a non-rotating turbulent core surrounded by a rotating laminar region at the wall. (Nishibori *et al. 1987)*
- The change in behavior observed when rotating a turbulent flow is still not understood, but experiments have found general connections between the state of the turbulence and the centrifugal force (Nishibori *et al.* 1987, Reich & Beer 1989).
- DNS of low Reynolds number flows furthered this understanding by showing rotation contributes to the formation of more coherent near-wall structures (Orlandi & Fatica 1997).

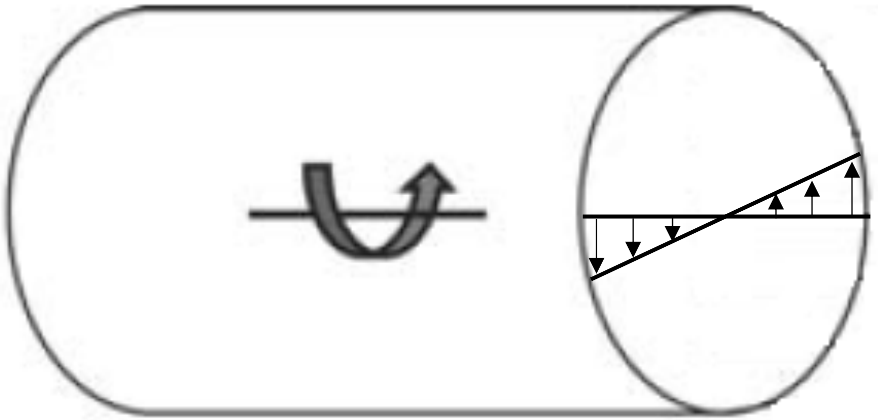


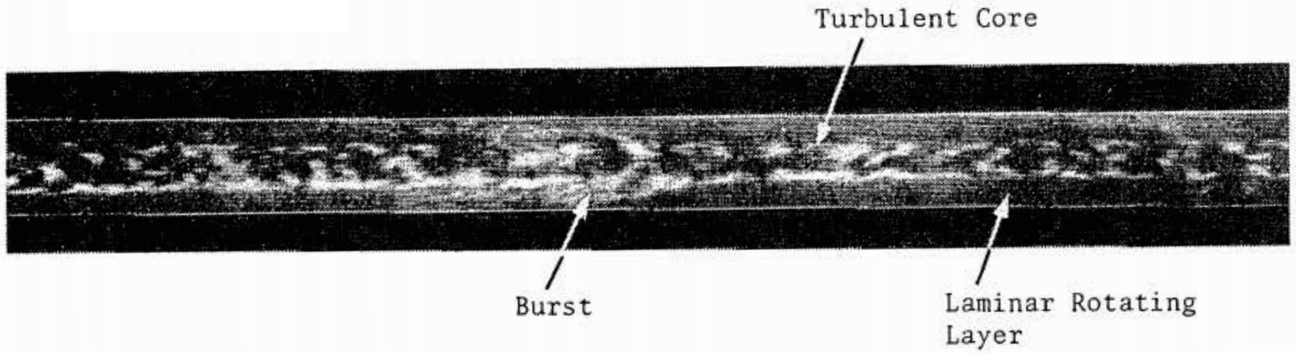
Flow visualizations of relaminarization at Re = 10^4 N = 3 from experiments by Nishibori *et al. (1987)*

Brief Background on Rotating Pipe Flows

- Rotational pipe flow can be described by two competing flow regimes, the axial pipe flow regime and the rotating cylinder regime
- Axial pipe flow is characterized by the bulk Reynolds number, where:
  - $Re = \frac{U_b D}{\nu}$
- Rotating cylindrical flow is characterized by the azimuthal Reynolds number, where:
  - $Re_\theta = \frac{U_W D}{\nu}$
- The ratio of these two Reynolds numbers is described by the rotation number $N = \frac{Re_\theta}{Re}$.







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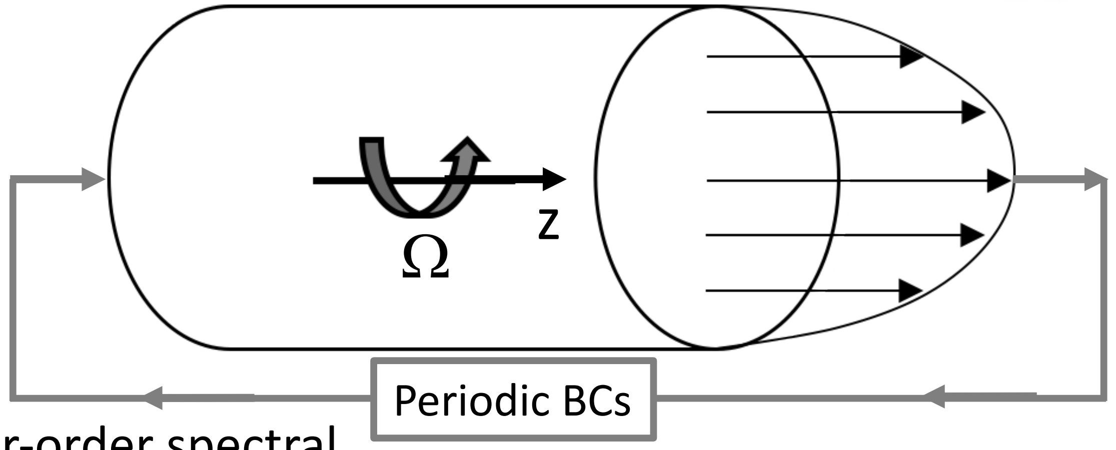
Governing Equation and Simulation Setup

Momentum: $\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla P + \frac{1}{Re} \Delta \boldsymbol{u} + \boldsymbol{F}$

Continuity: $\nabla \cdot \boldsymbol{u} = 0$

Source Term: $\boldsymbol{F} = \boldsymbol{F}_{cen} + \boldsymbol{F}_{cor} = -\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{r}) - 2\boldsymbol{\Omega} \times \boldsymbol{u}$

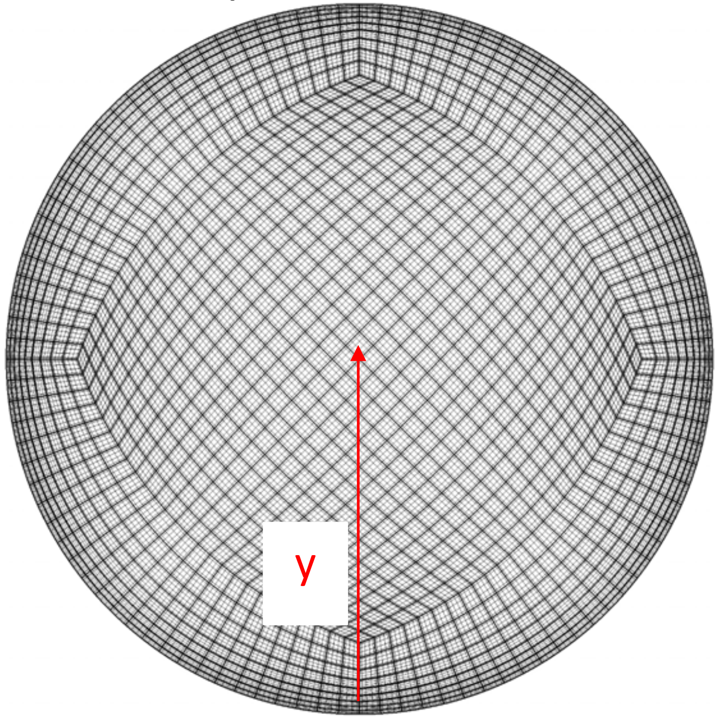
Rotation Number: $N = \frac{\Omega D}{2U_b}$, $\boldsymbol{\Omega} = (0,0,\Omega)^T$



- Incompressible Navier-Stokes Equations are solved with higher-order spectral element solver (NEK5000, Fischer 2008)
  - A 6th order spectral element scheme is used along with an algebraic multigrid presolver to reduce simulation time.
- Validation with Khoury et al. (2013) for non-rotating pipe flow
- Good agreement with Orlandi & Ebstein (2000) for turbulent budgets and Orlandi (1997) for Reynolds stresses at Re=4,900'
- Details of Simulation Setup (L=12.5D):

Re	$\Delta r^+ / \Delta R\Theta^+ / \Delta z^+$	$N_{\Delta x} \times 10^6$
5,300	0.14–4.4/1.5–4.5/3.0–9.9	20
11,700	0.16–4.7/1.5–5.0/3.0–9.9	120
19,000	0.15–4.5/1.5–4.8/3.0–10.	440

Cross-Section of Computational Mesh



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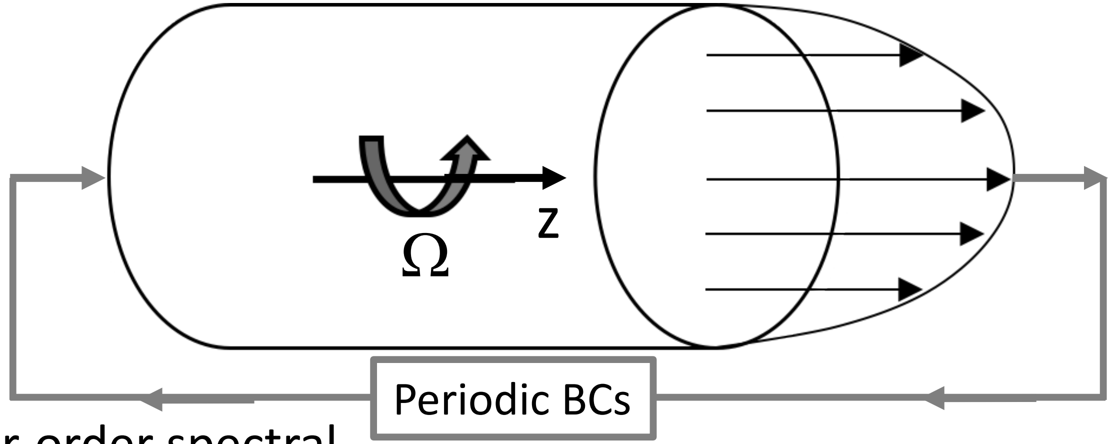

- Incompressible Navier-Stokes Equations are solved with higher-order spectral element solver (NEK5000, Fischer 2008)
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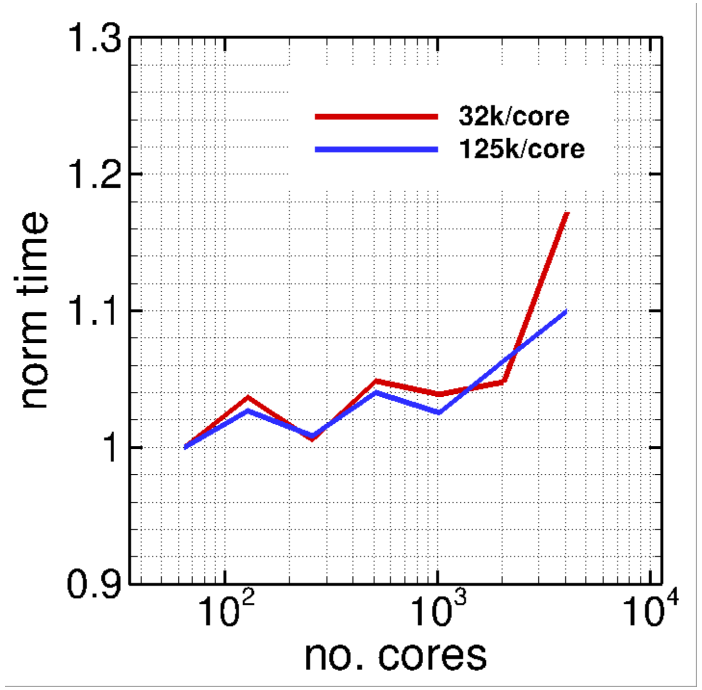
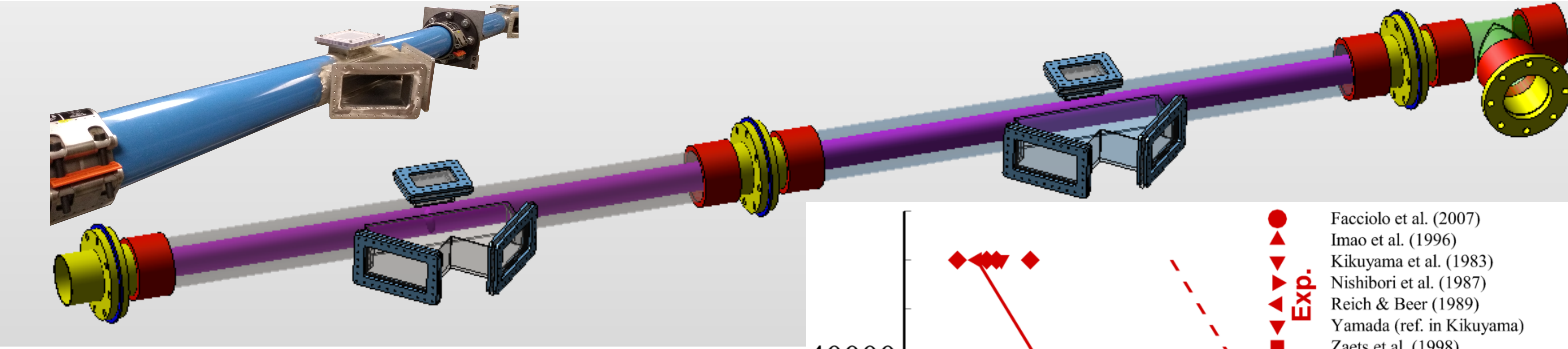
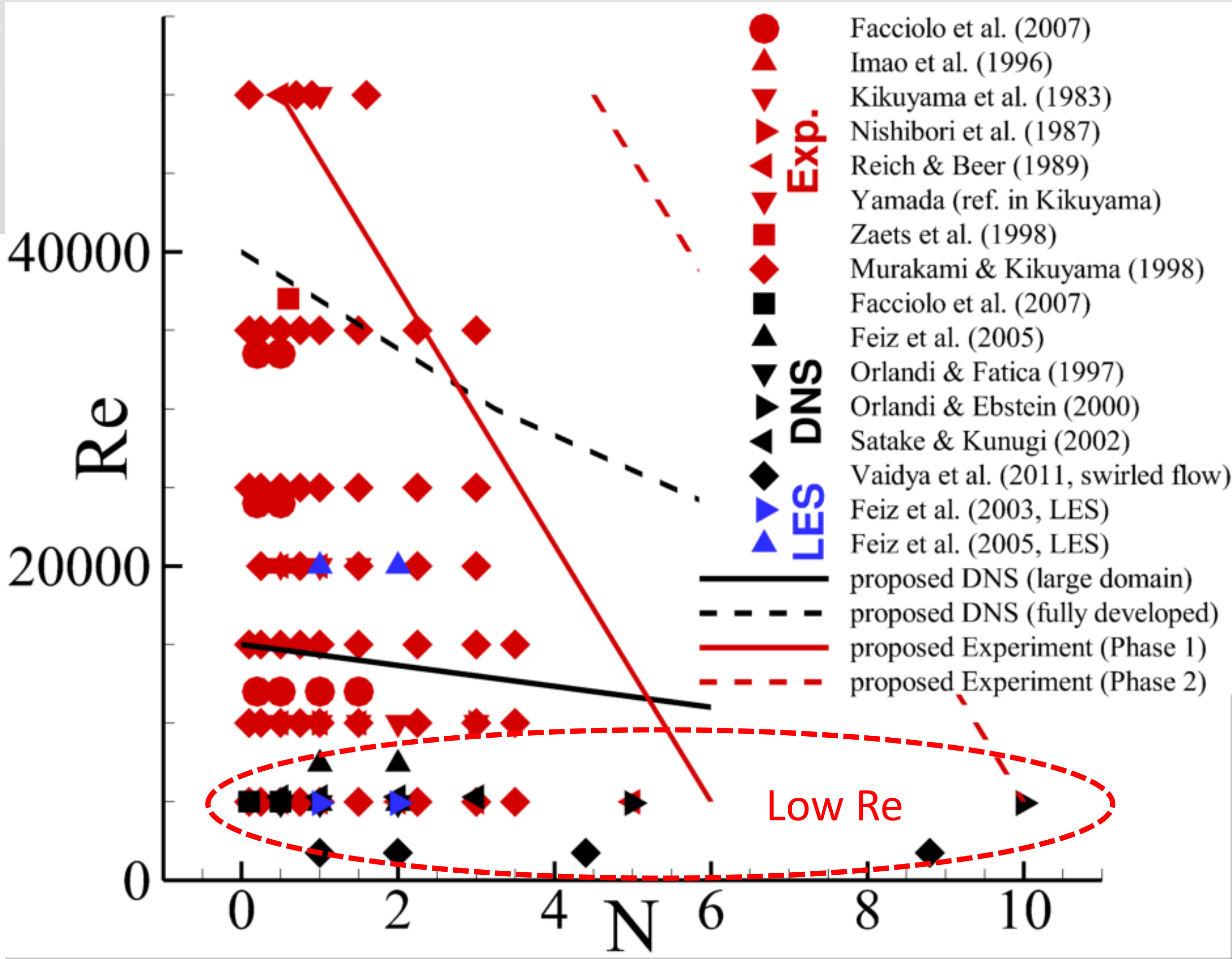
Scaling on Blue Waters



Part II of NSF Project - Experiment





- DNS are conducted in conjunction with high-fidelity experiments at UK (Dr. S. Bailey)
- Prior DNS and LES conducted at low Re and N
- Larger range of experiments but little detailed flow information

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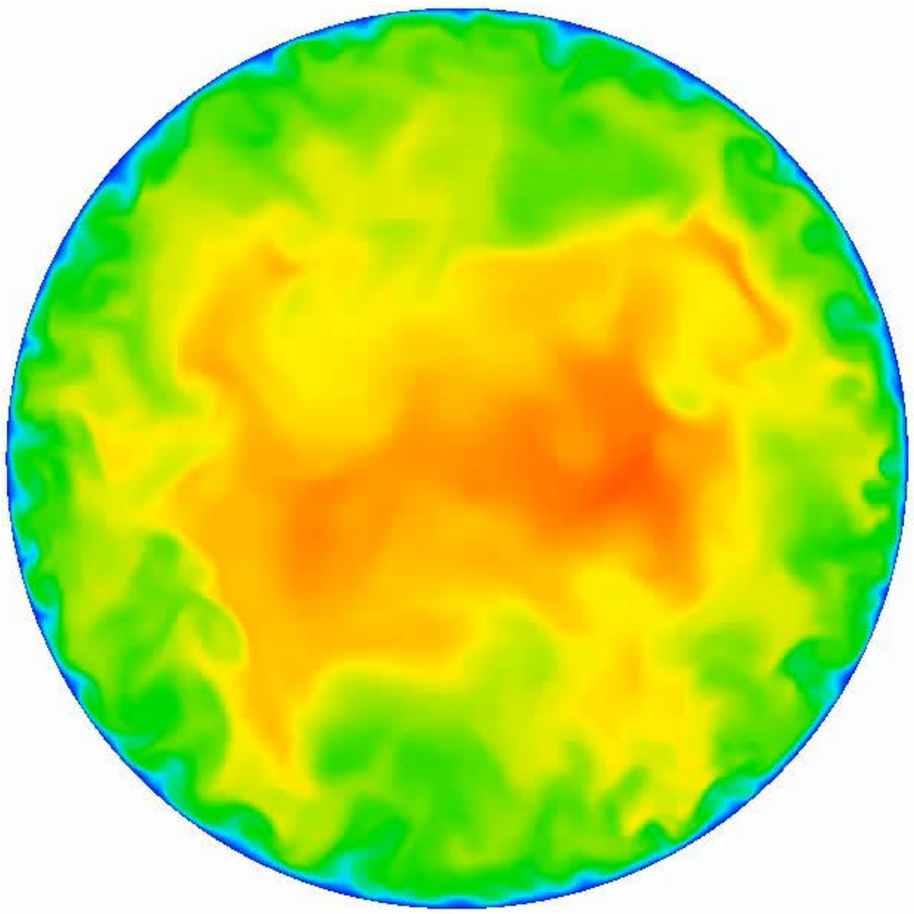
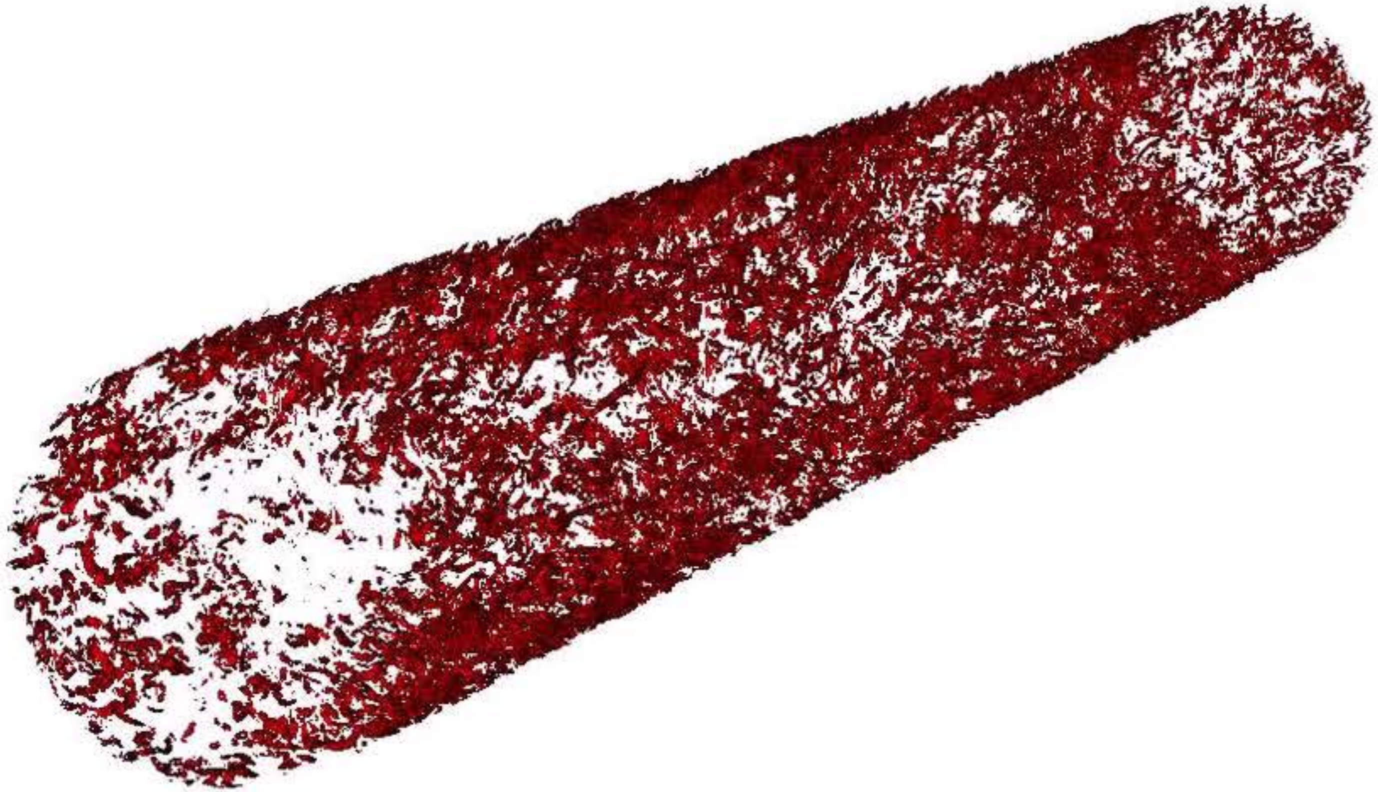
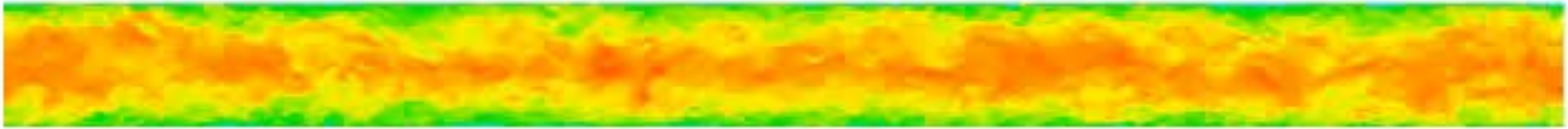
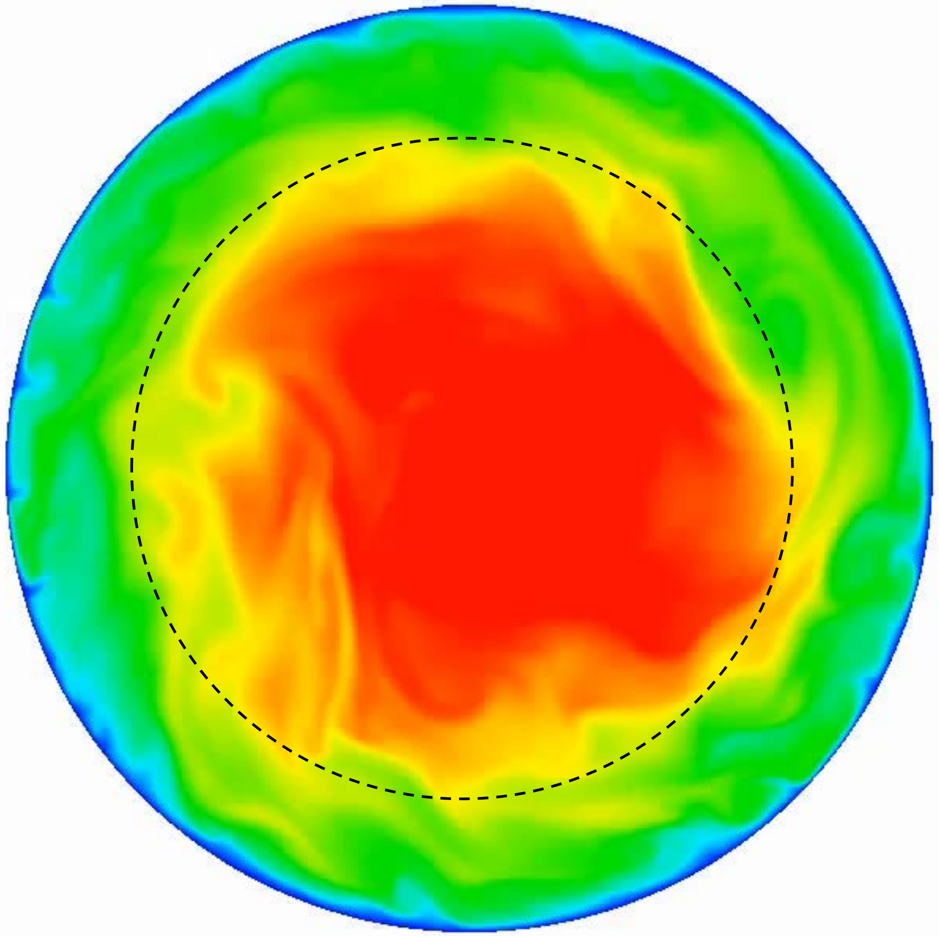
Flow Visualization Non-Rotating Flow

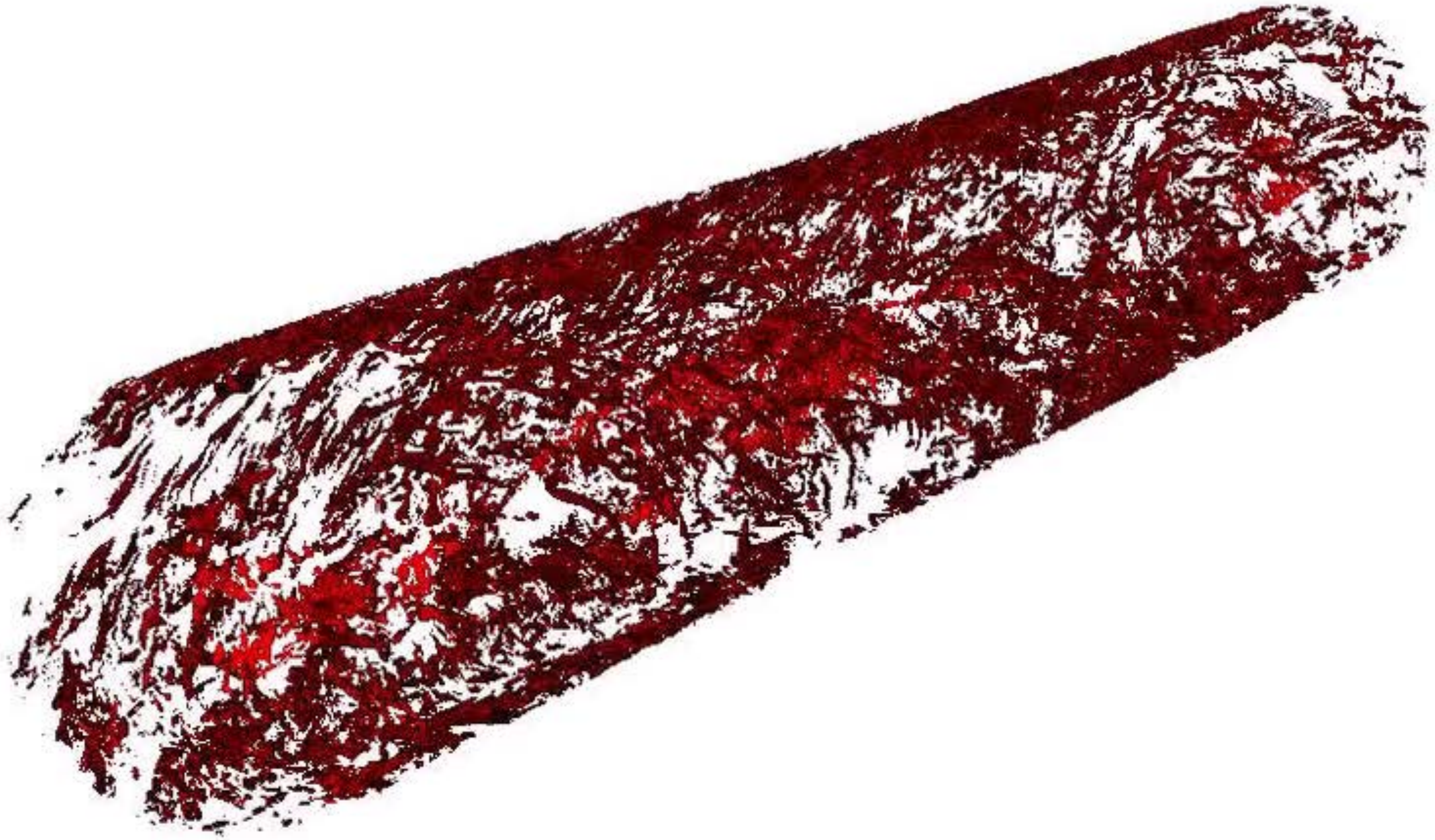


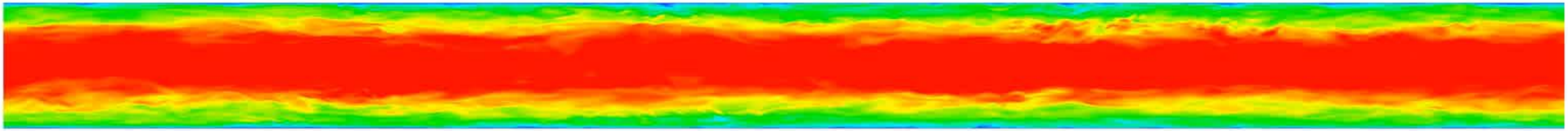




Flow Visualization Rotating Flow (N = 3)

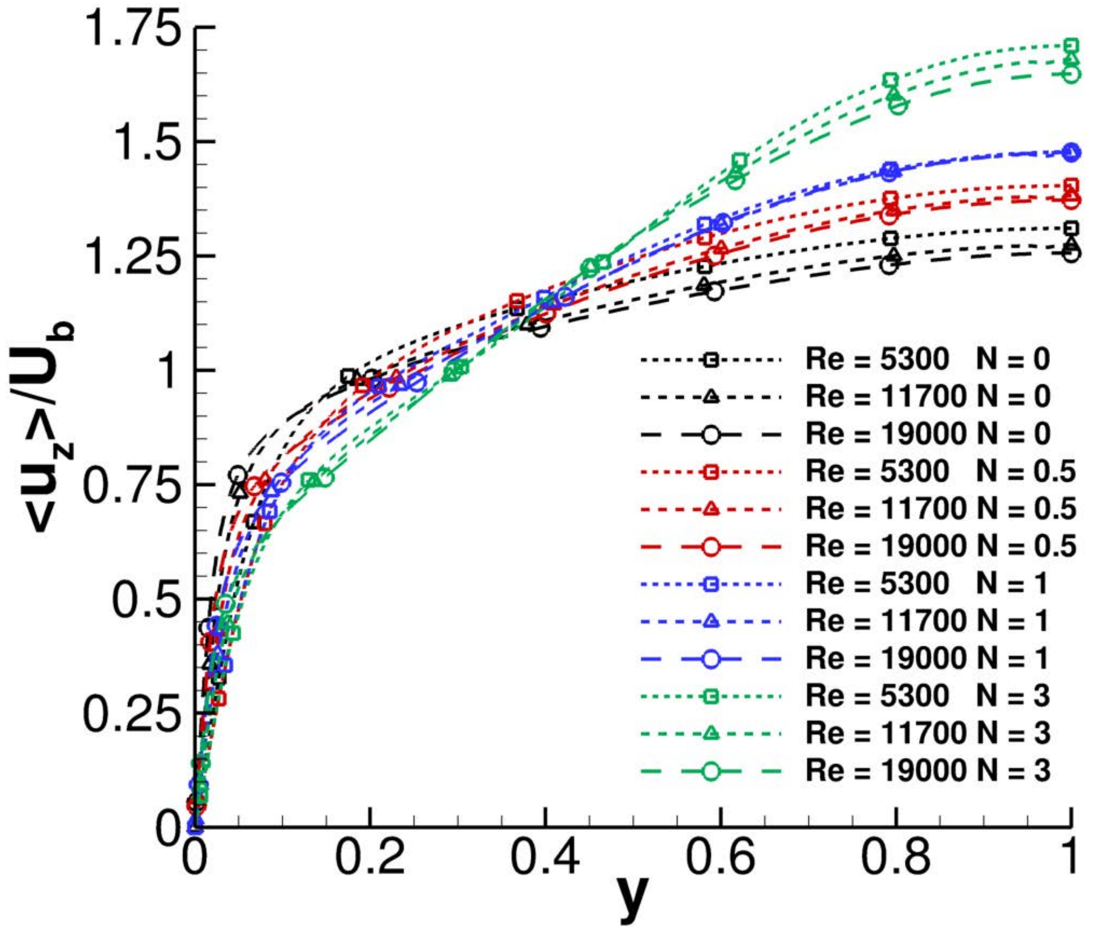




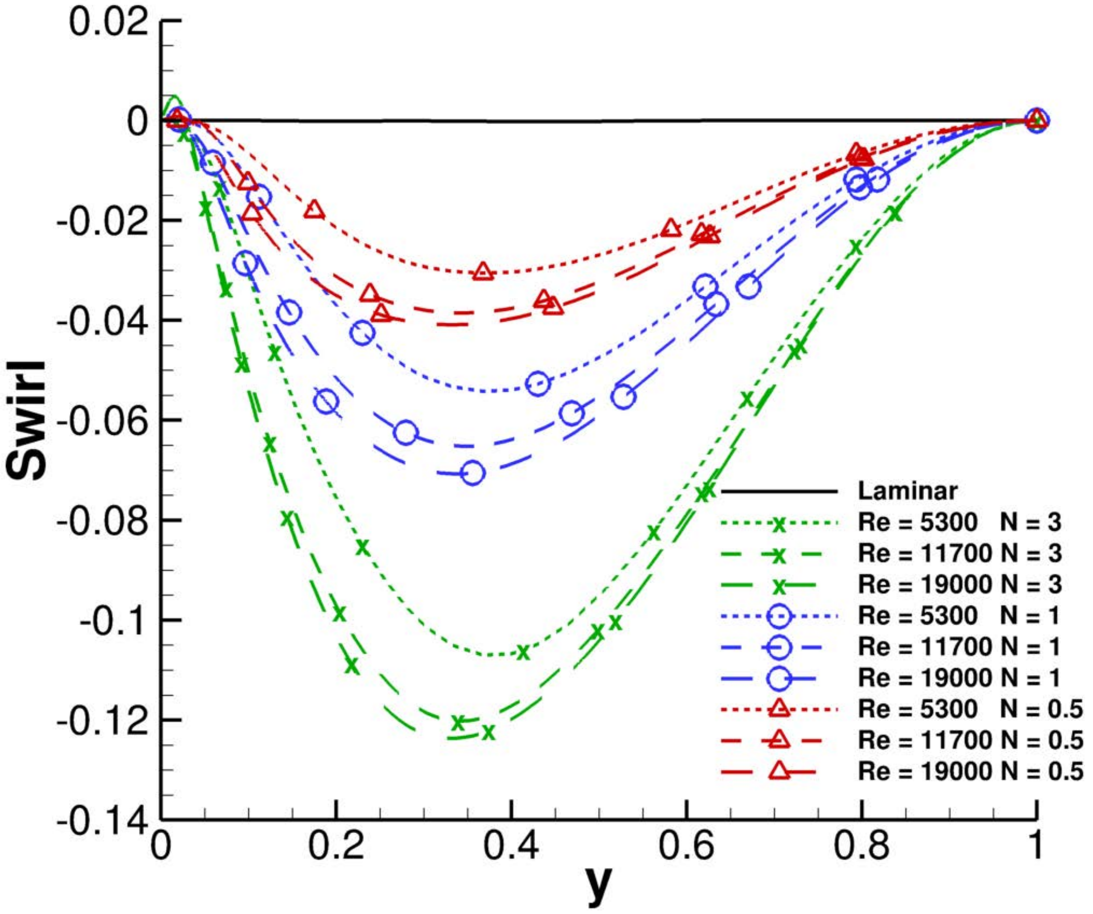


Effects on Mean Flow

Streamwise Velocity

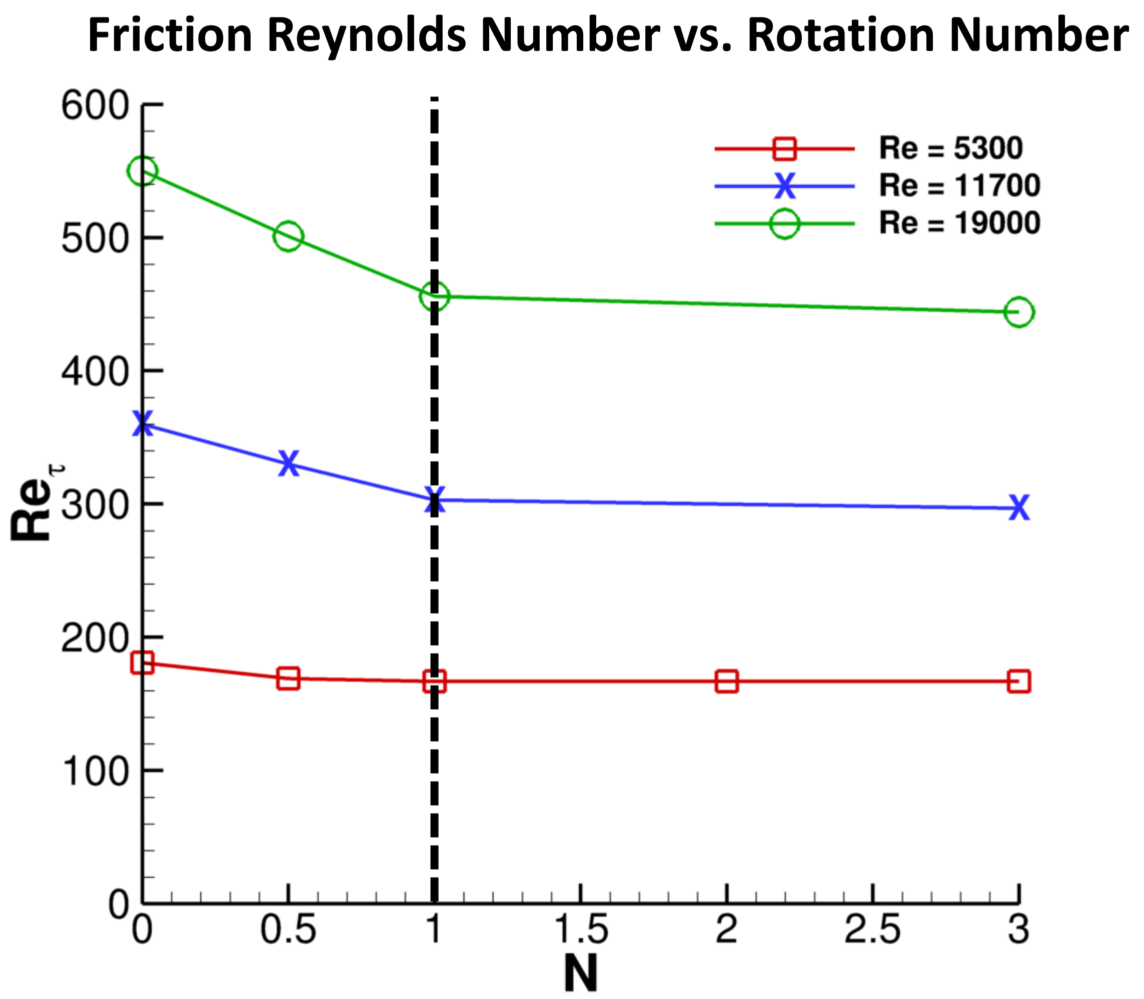


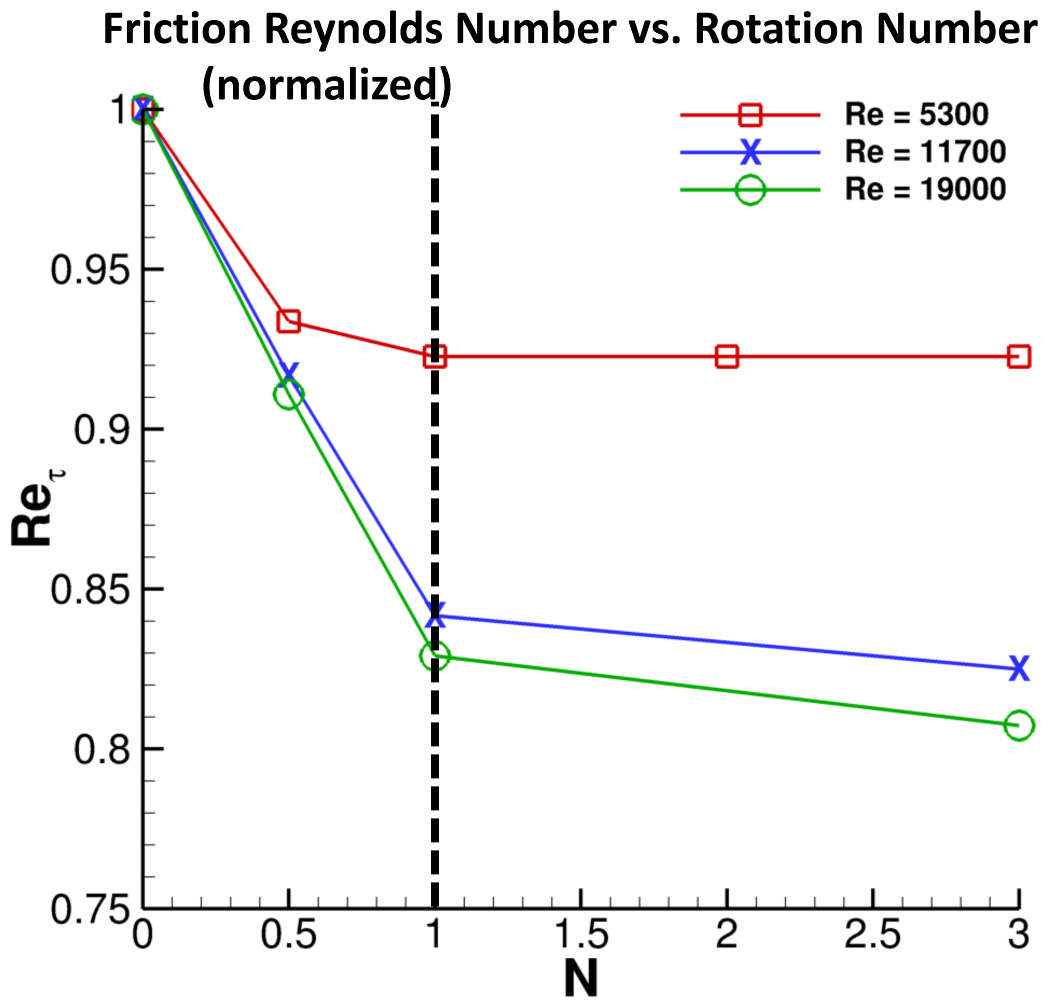
Swirl ($r\langle u_\Theta \rangle$)



- Mean Streamwise velocity profiles show high dependence on rotation number, tending to a more parabolic profile with increasing N.
- Swirl profiles also show significant dependence on N as well as some Reynolds number dependence.

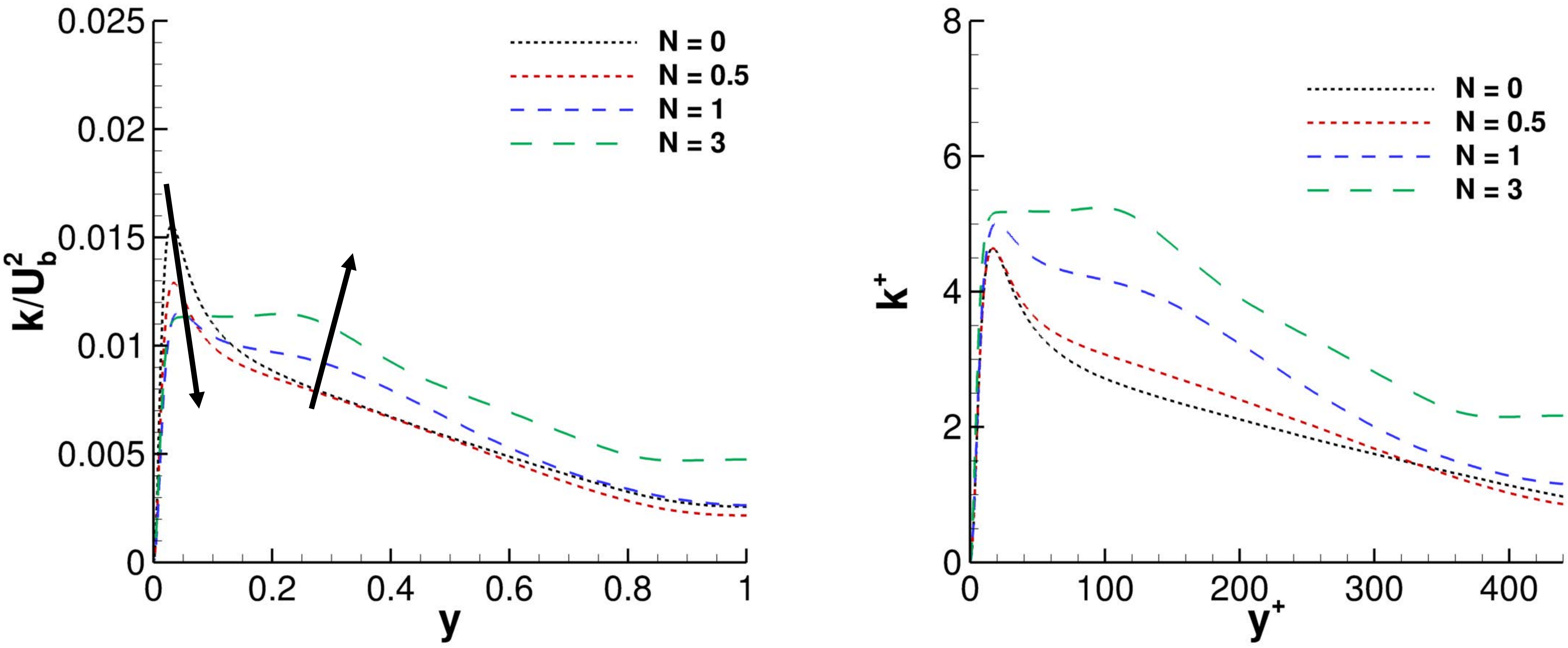
Effects on Mean Flow





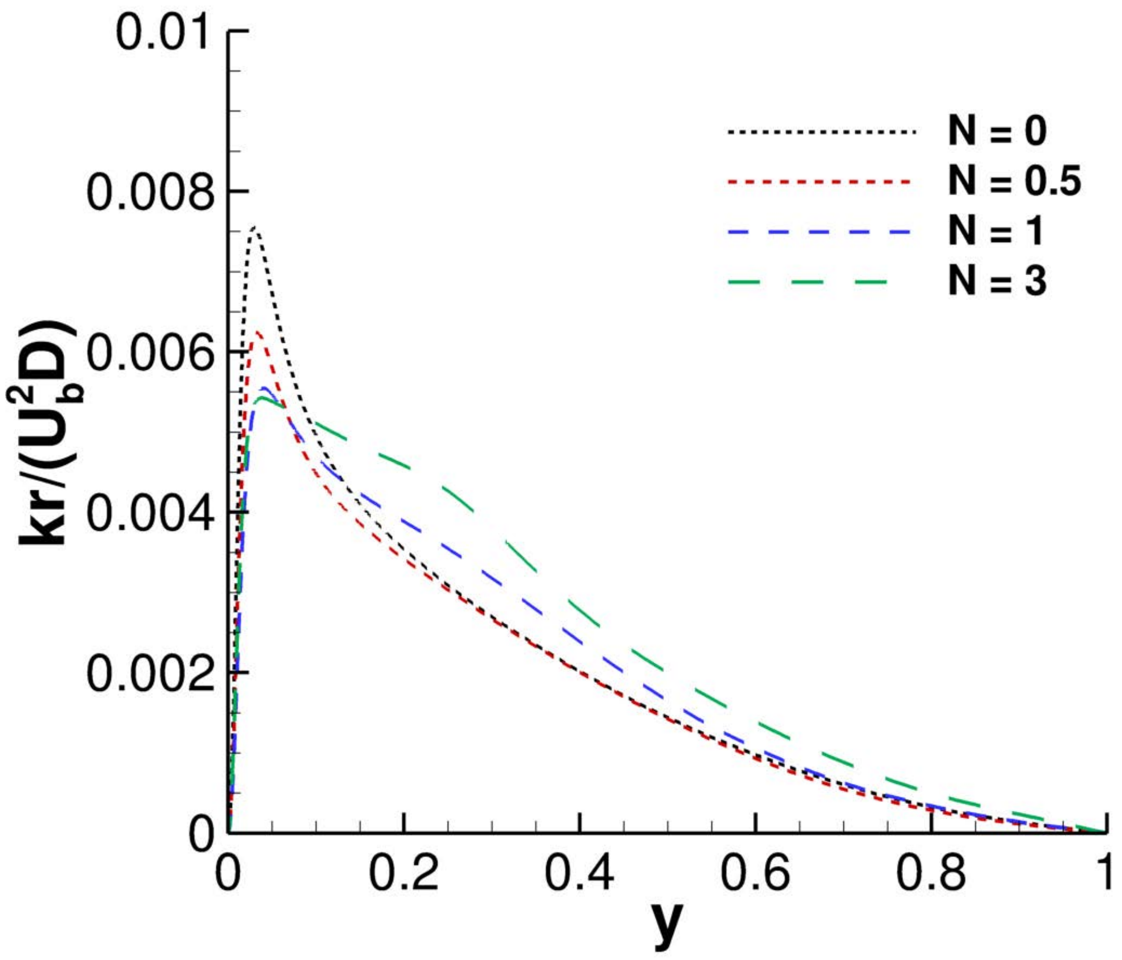
- Analysis of the friction Reynolds number shows a reduction in friction with increasing rotation.

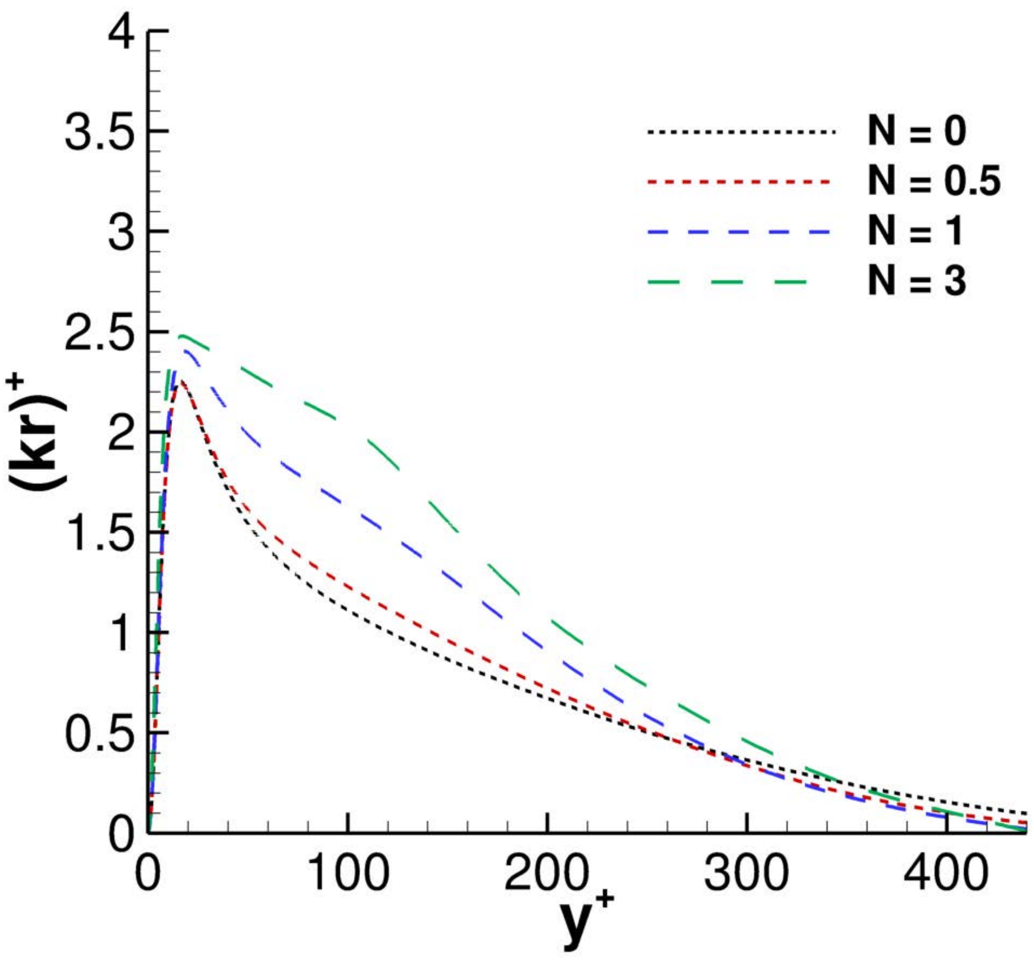
Quantifying Turbulence Suppression



- Turbulent kinetic energy shows an increase towards the center of the flow for high rotation rates as well as a decrease in the near-wall peak when normalized by U_b^2.

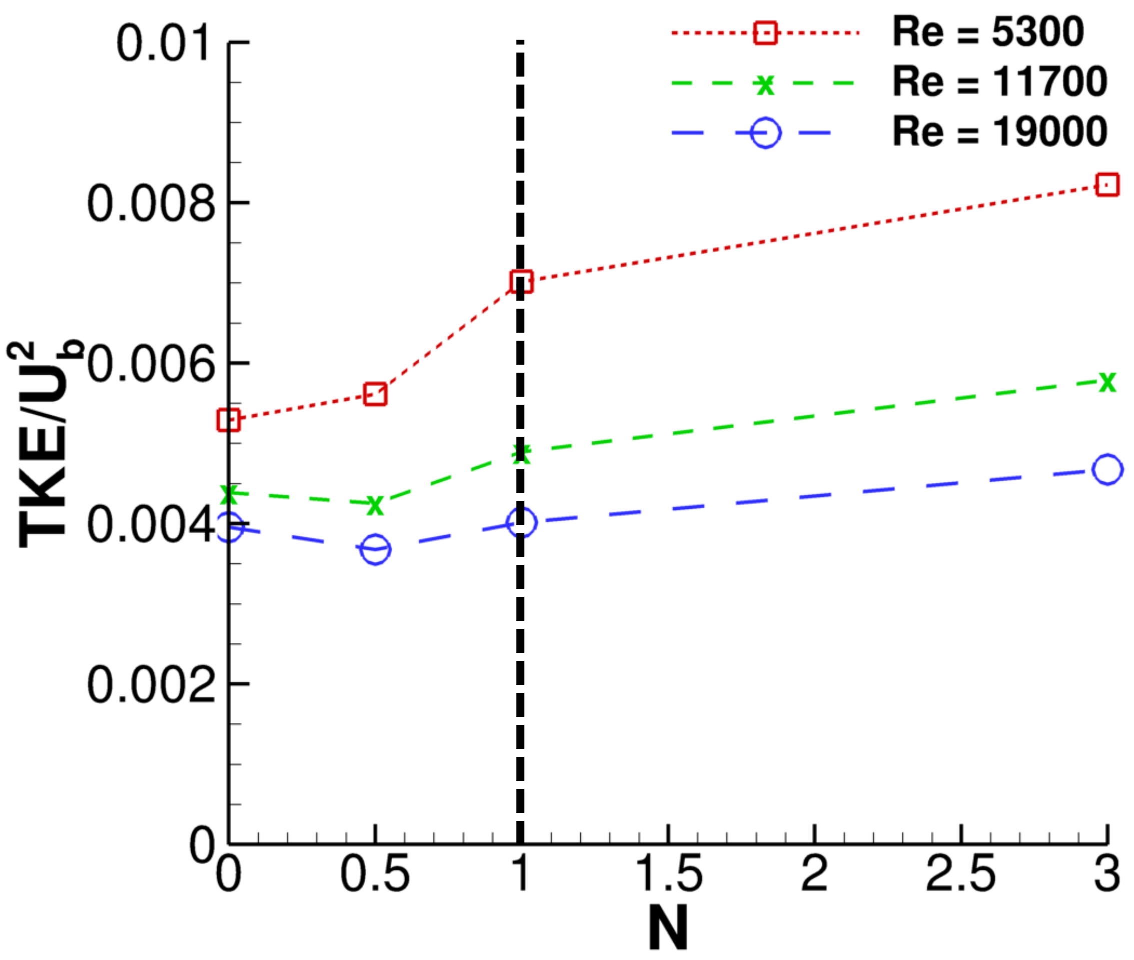
Quantifying Turbulence Suppression

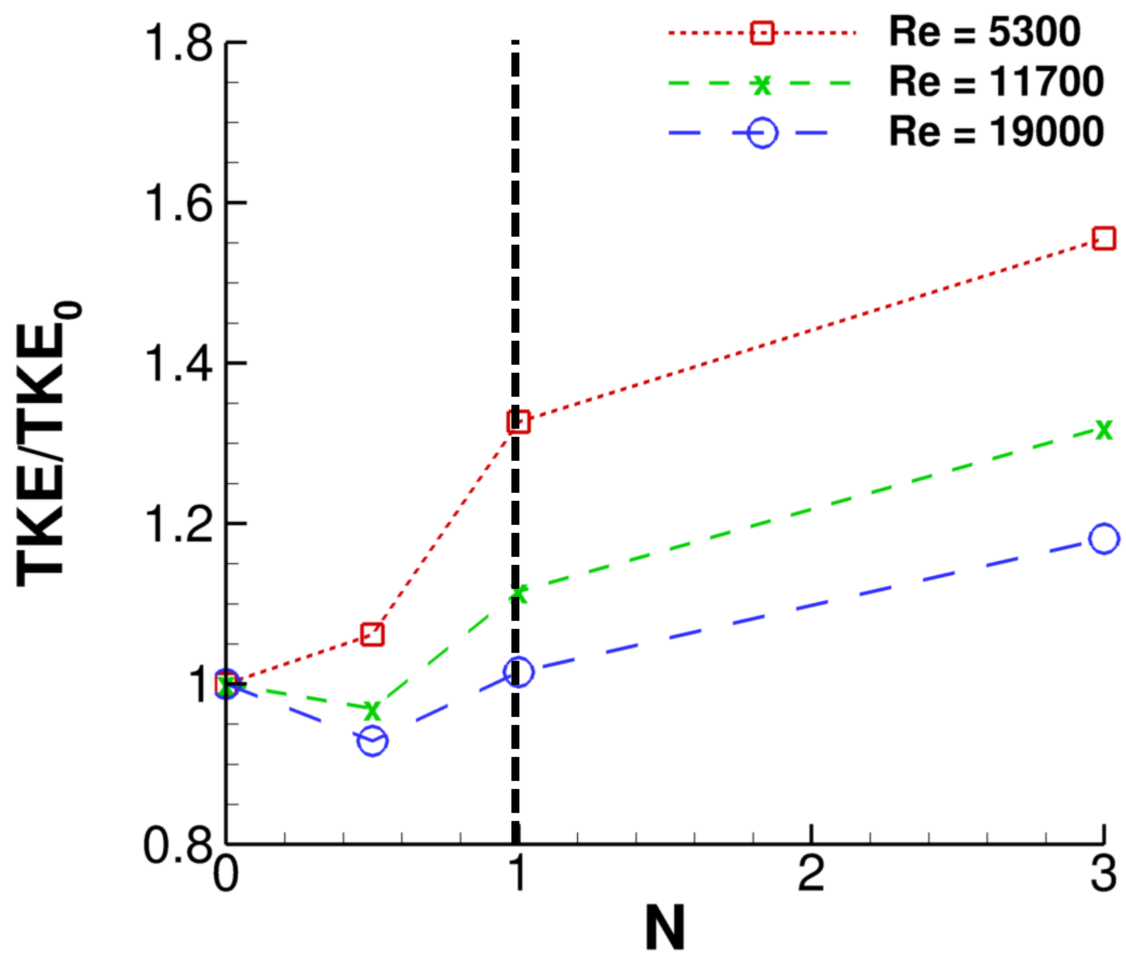




- By multiplying k with radial position, the overall contribution to the integral value of k can be observed
- Here, the increase in the center of the flow is greatly reduced, as this contributes less to the total TKE .

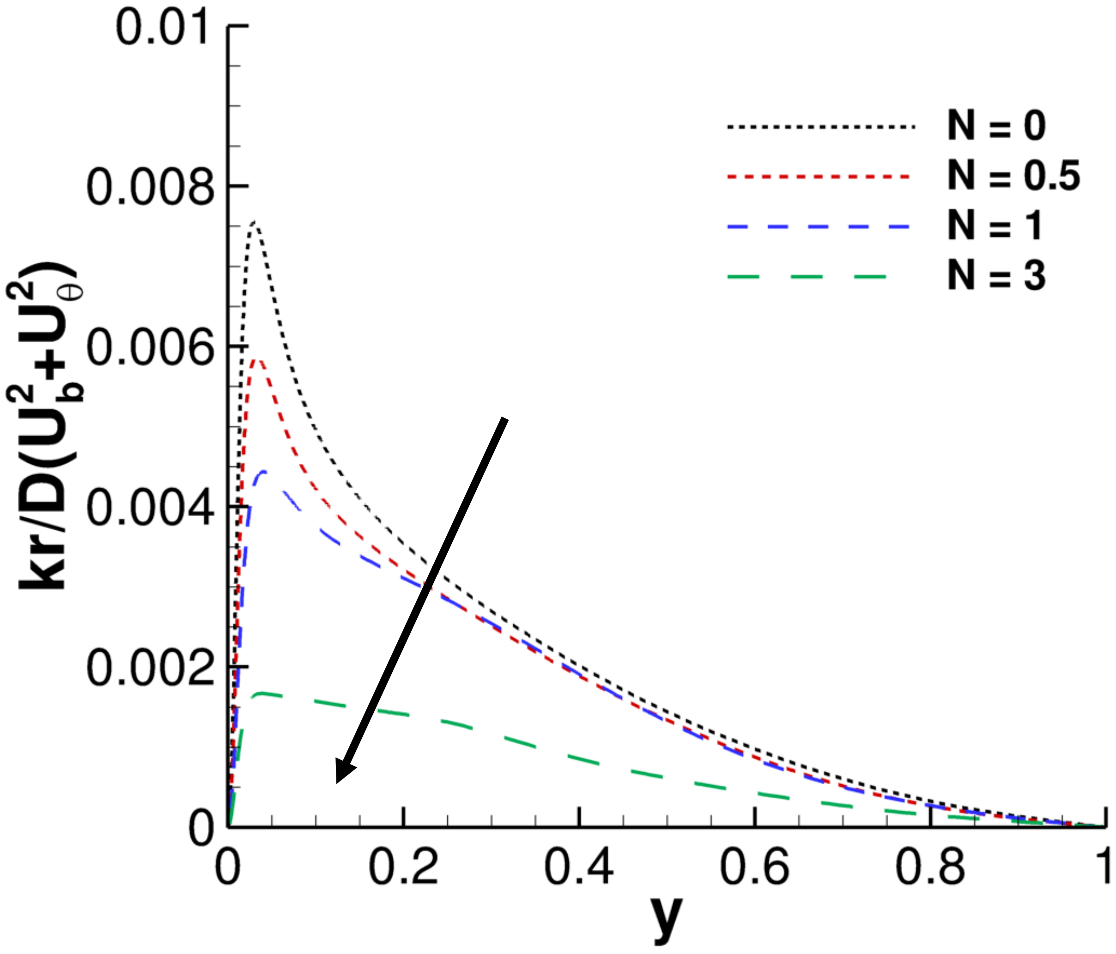
Quantifying Turbulence Suppression

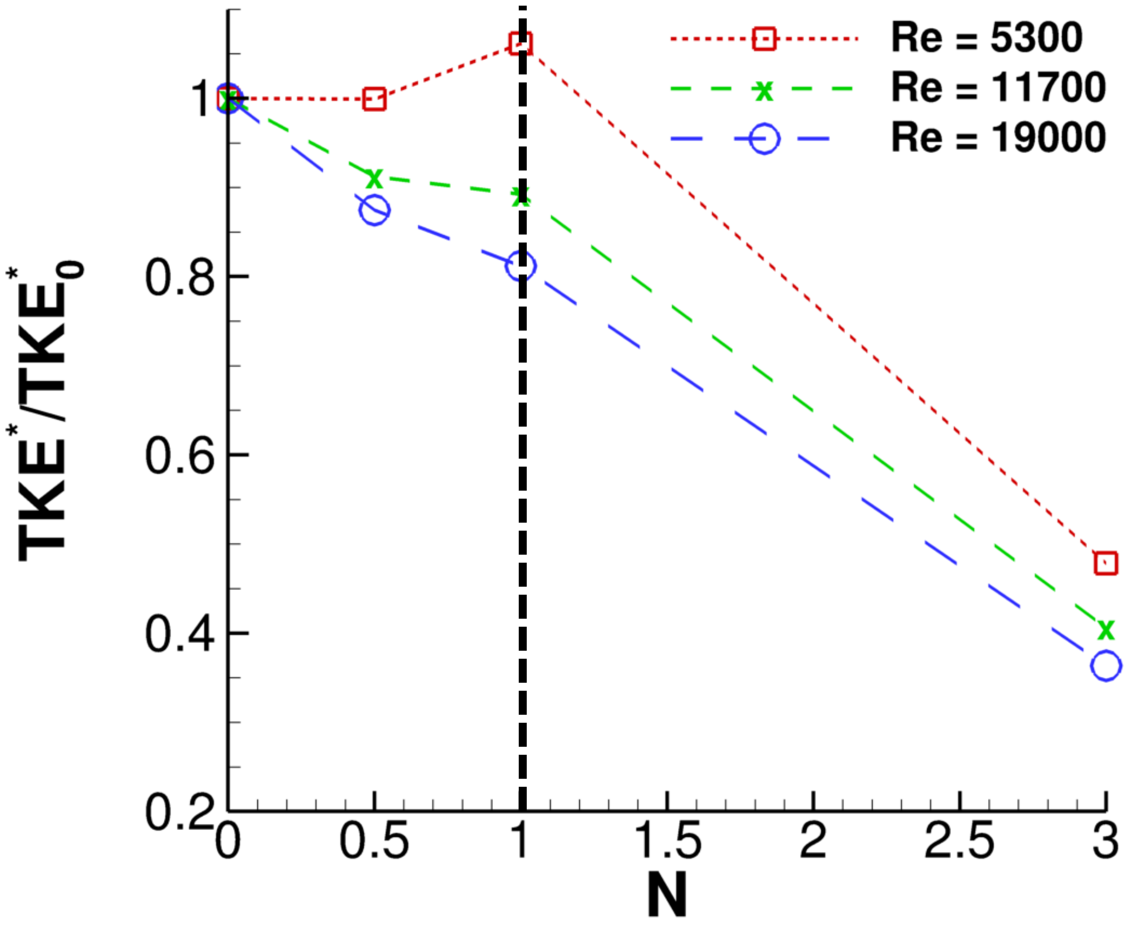




- Plotting the total turbulent kinetic energy as a function of rotation number shows an increase for high rotation rates and a slight reduction for $N = 0.5$ at low Re.
- Normalizing k by U_b^2 fails to account for the additional mean kinetic energy added to the base flow through rotation

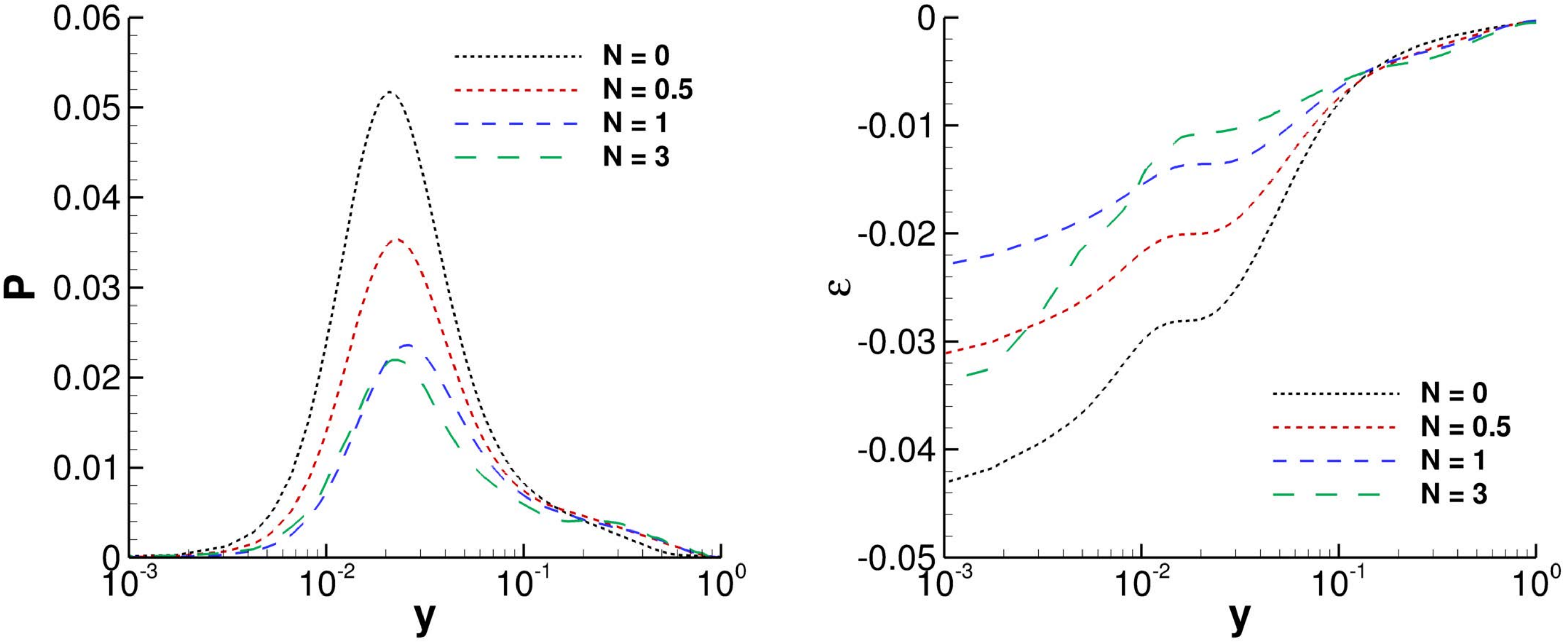
Quantifying Turbulence Suppression





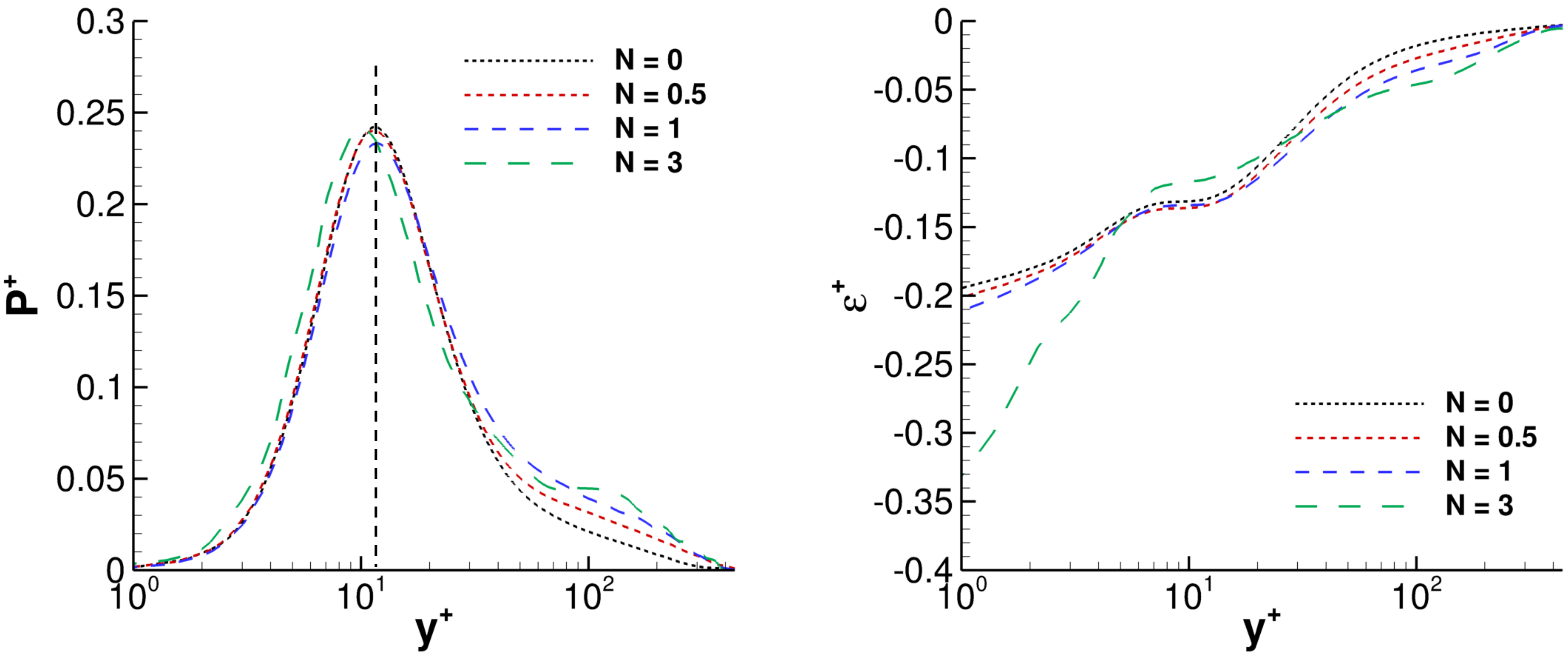
- To account for the additional mean kinetic energy, k is normalized by $(U_b^2 + U_\theta^2)$. In this normalization, turbulence suppression is evident at all rotation rates for sufficiently high Re, though an overall increase to TKE is noted for $Re = 5{,}300$ at low N.

Production and Dissipation of TKE



- The addition in rotation leads to a large reduction in the peak of TKE production up to $N = 1$, while further increase in rotation rate leads to a shift in the peak location towards the wall.
- A similar trend is noted for dissipation, in which the magnitude is decreased with increasing N for moderate rotation rates, whereas a secondary trend develops at rotation rates greater than 1.

Production and Dissipation



- Inner-scaling shows good collapse for moderate rotation rates in both TKE production and dissipation while the highest rotation rate exhibits behaviors not well characterized by pipe flow, *i.e.* a shift in the peak in production towards the wall and greatly enhanced dissipation near the wall.

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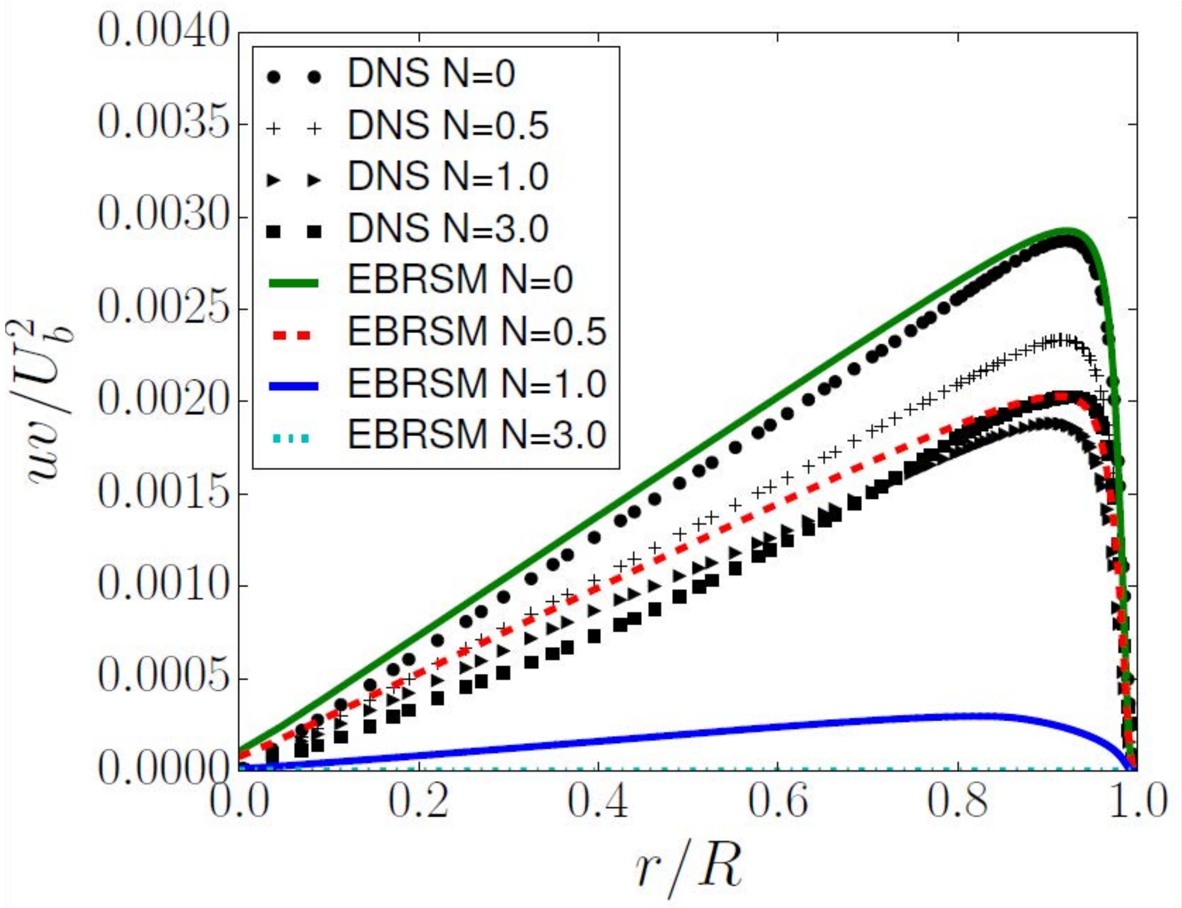
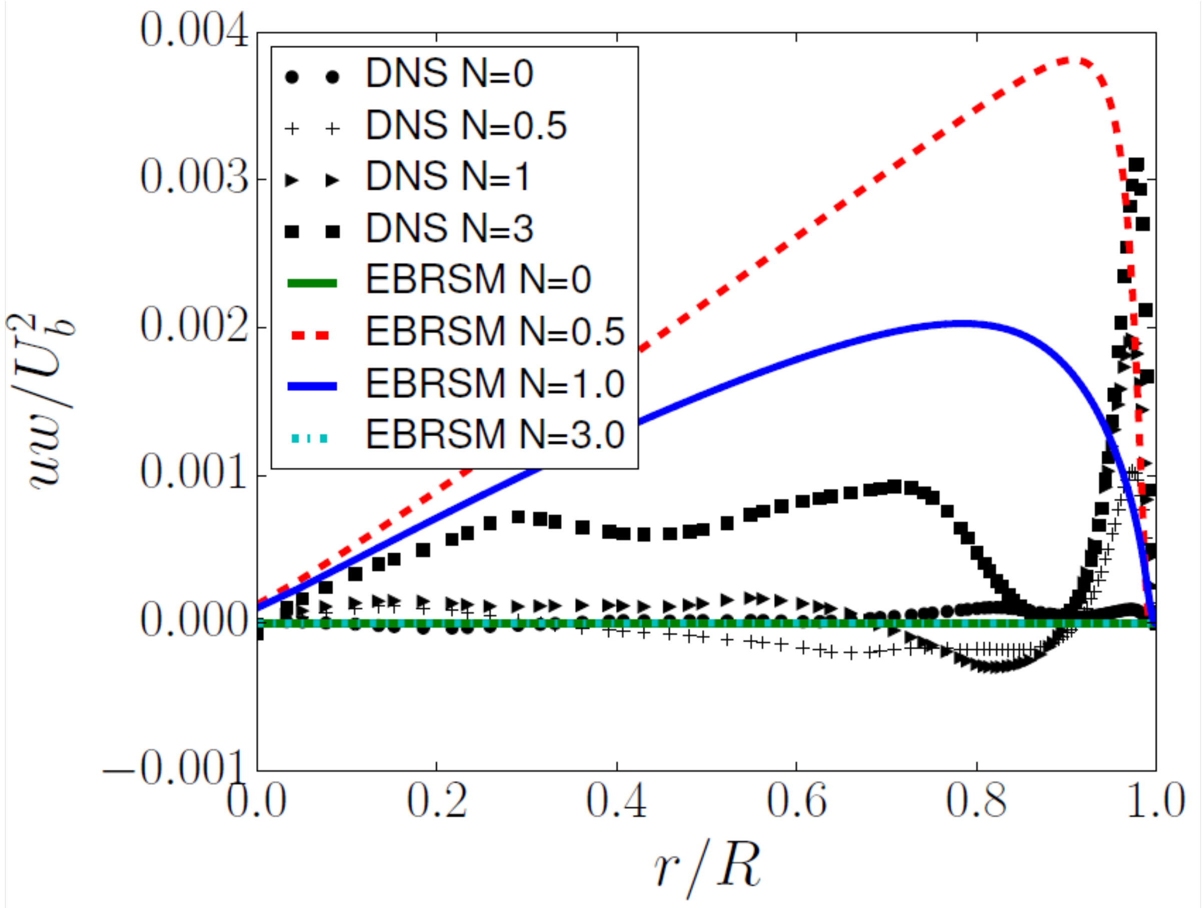
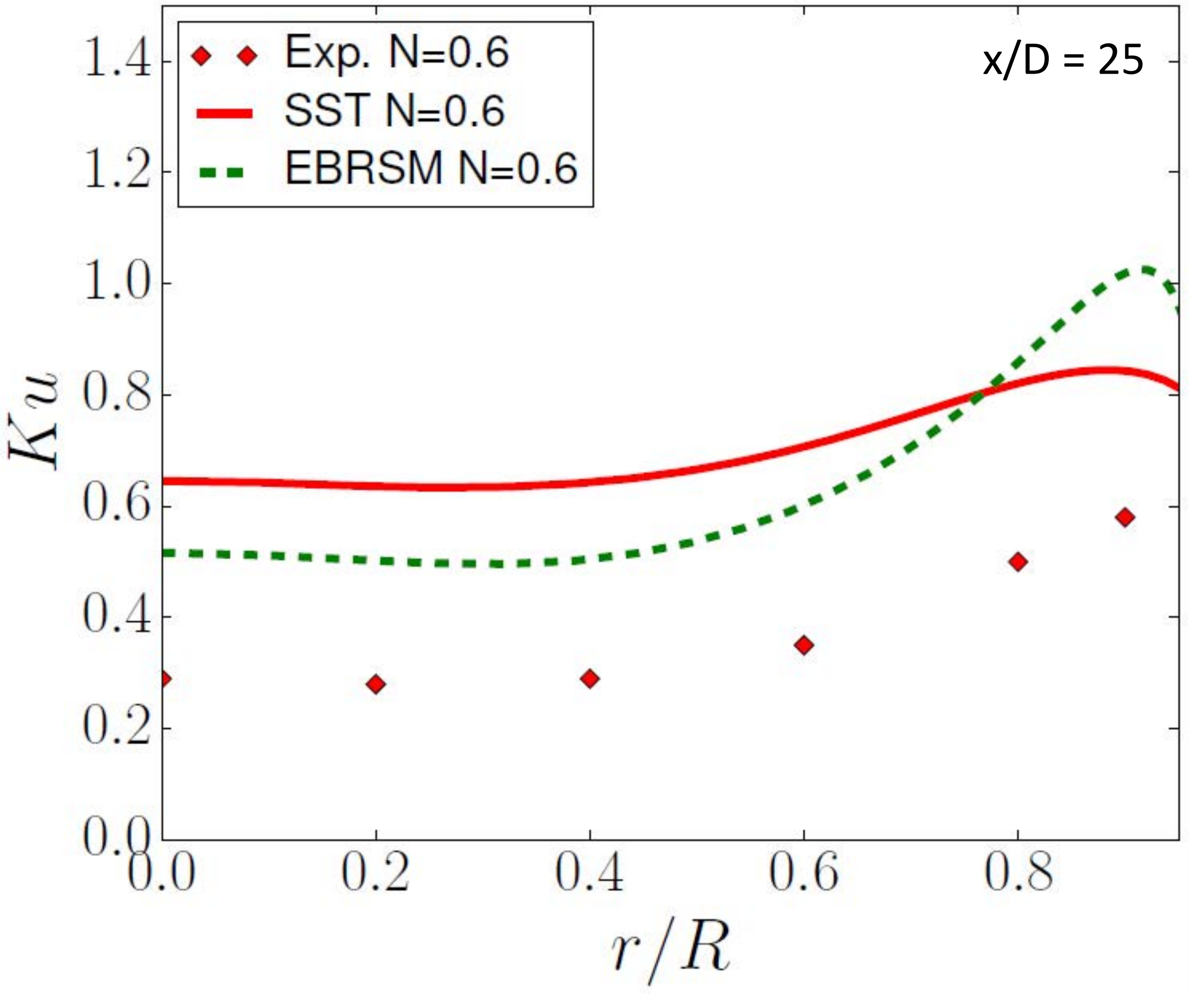
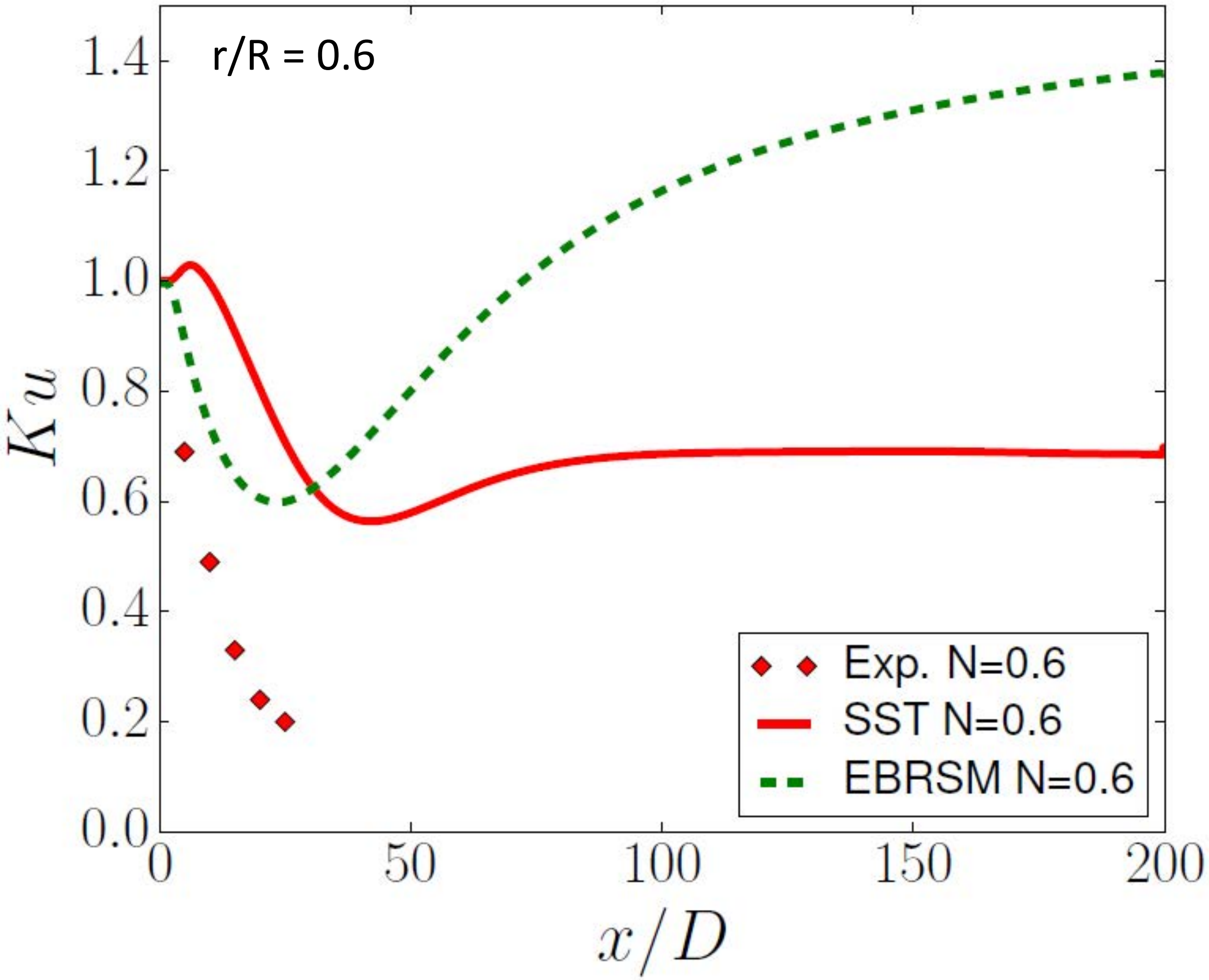




- Analysis of the Elliptic Blending Reynolds Stress Model (EBRSM) was conducted by our collaborators at Oxford and compared with the present DNS data.
- EBRSM utilizes transport terms for each component of the Reynolds stress tensor, and offers significant improvement in modelling rotational flows over other RANS techniques, however, shortcomings are still noted in the shear terms of the Reynolds stress tensor when evaluating fully developed flows.

RANS Turbulence Modeling





- Analysis of transitional flows over a domain of $L = 200D$ were also conducted using EBRSM. While this model fails to reproduce experimental data, overall trends could not be compared, due to the lack of available experimental data over long domain lengths, highlighting the need for additional experiments as well as DNS.

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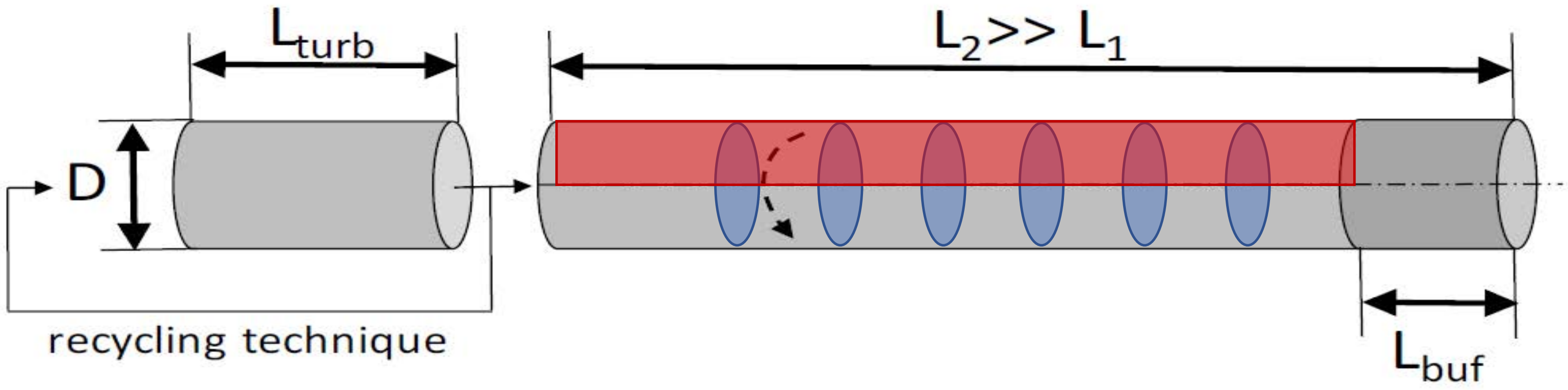
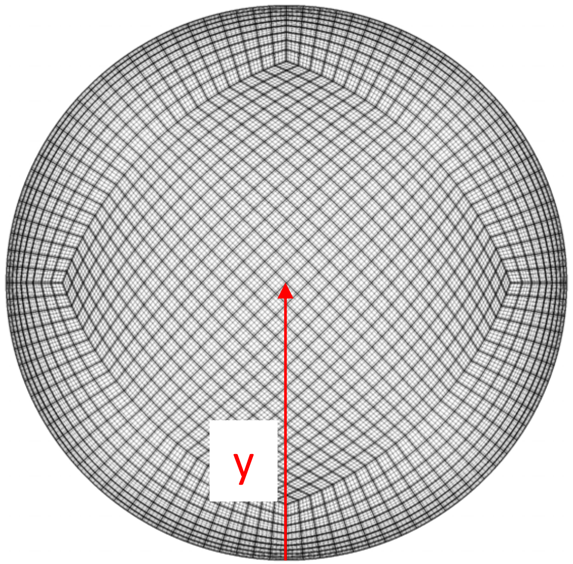
Current Simulation Setup

Reverse Transition Simulation Setup:





- Based on simulations by Khouri *et al.* we estimated 13.9M (12th-order) elements for a total of 24B points.
- Details of turbulent pipe flow simulations

Re	f	$\Delta r^+/\ \Delta R\Theta^+/\ \Delta z^+$	$N_{\Delta x} \times 10^9$	Δt	$N_{\Delta t}$	ft
37,000	0.0230	0.15–5.1/1.0–4.9/2.0-10.	22	0.000075	2,010,000	12.5

- Overview of required resources

Re & N	$N_{\Delta t}$	T_{it} [sec]	Resources cores × hours × runs	node hours
Re=37,000, N= 0.5, 1.0, 3.0	2.01M	2.64	75008 × 1,474 × 3	**10.4M**

Data Output

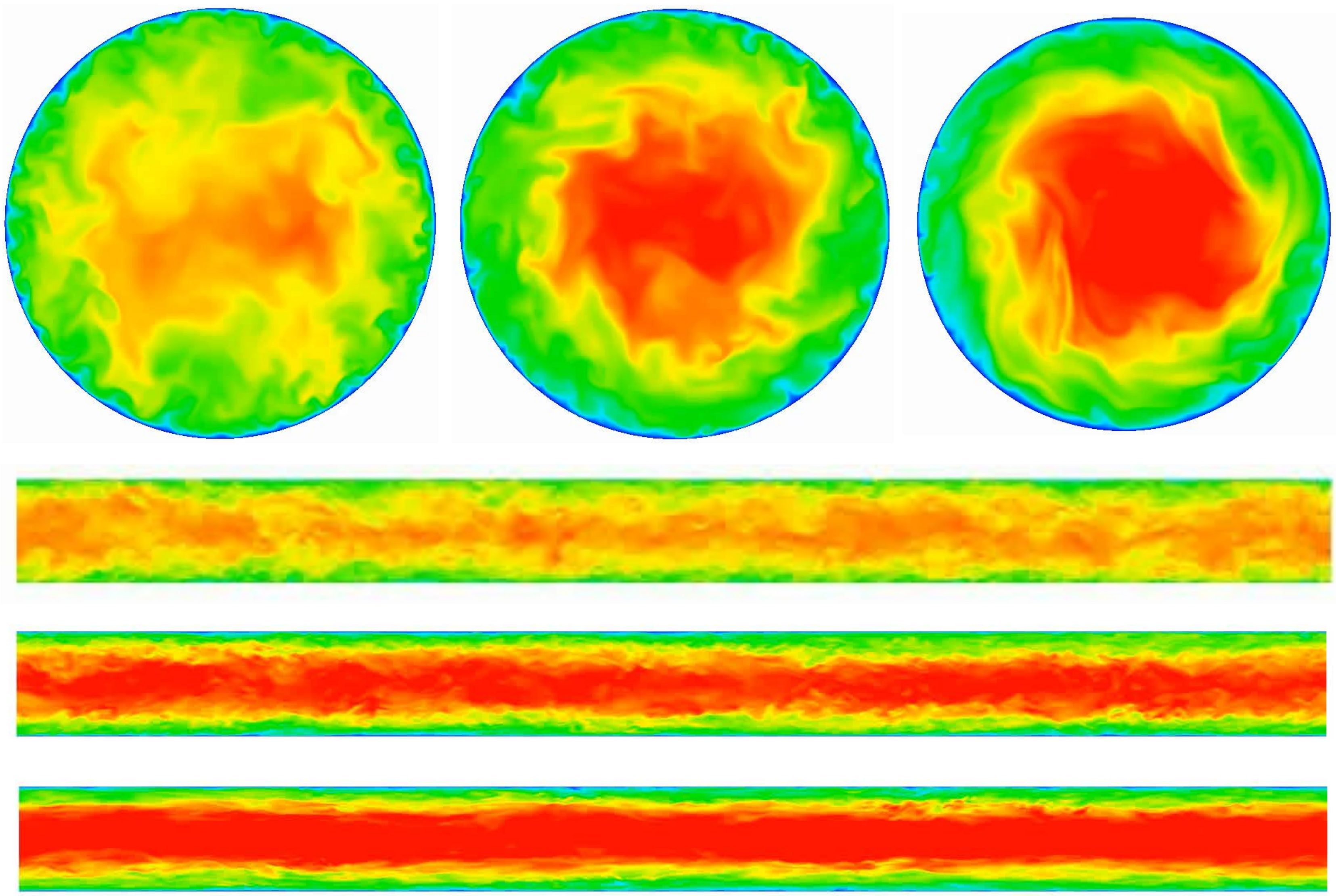
- Velocity, velocity gradients, and pressure will be captured at ten cross sections of 3696 elements each and a single stream-wise slice of 154,406 elements.
- All instantaneous data is written to file in parallel. Currently with 1 file per point for a total of 27.5M points.
- Instantaneous flow data will be output every 10th timestep for 1 FT time.
  - 10 streamwise-normal cross-sections throughout the Rotating Domain
  - 1 streamwise-tangential slice through half the diameter.
  - ~260TB of instantaneous flow data will be collected per case.

- ~640 volume outputs (240TB) of instantaneous volume output will be collected.
- Data written to file:

No. Of Elements in Z	No. Of Points in Z	No. Of Elements in the Cross-Section	No. Of Points in the Cross-Section	Total No. Of Elements	Total No. Of Points	Memory per Cross-Section	Memory for Stream-wise Slice
3766	543K	3696	533K	14M	24B	53 MB	2.15 GB

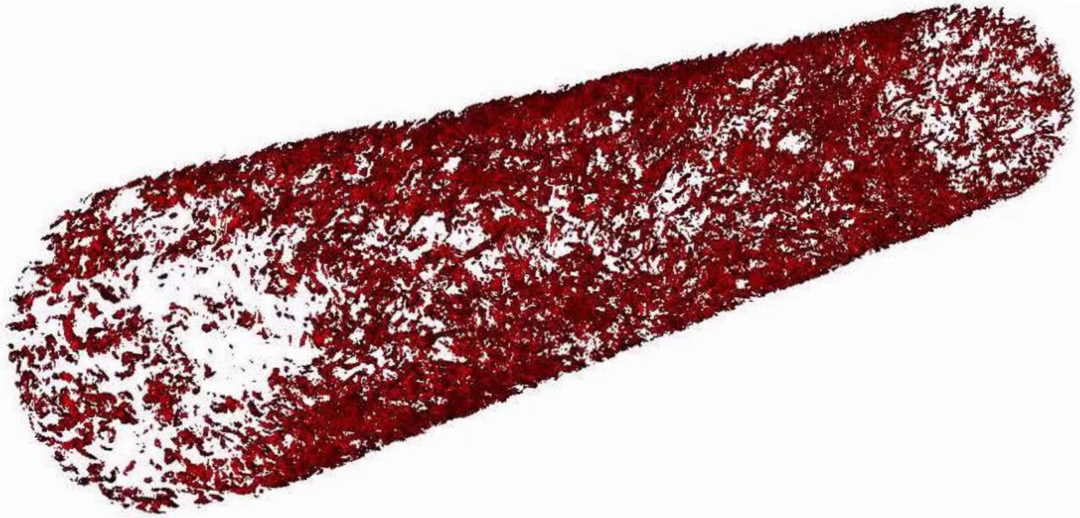
Why Blue Waters?

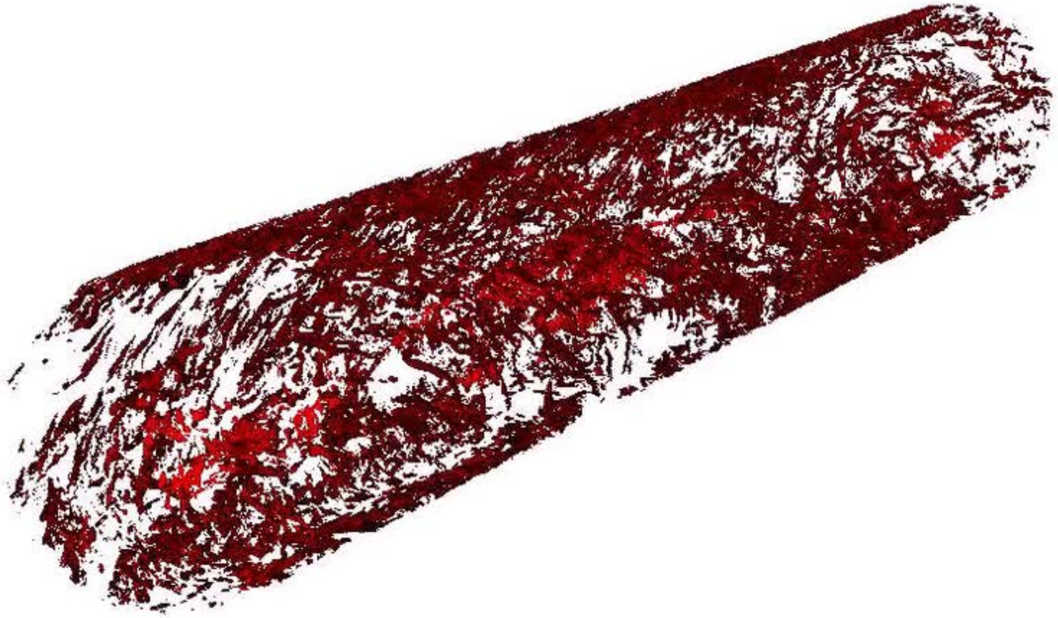
- DNS studies of rotational turbulence have previously been restricted to lower Reynolds numbers and shorter domains.
- By using the capabilities of Blue Waters, our research team has been able to conduct highly resolved simulations at Reynolds numbers that are high enough to ensure sufficient scale separation and accurately examine turbulence suppression in rotating pipe flows at engineering relevant Reynolds numbers.
- The power of Blue Waters makes DNS analysis of the full reverse transition process in rotating pipe flows possible for the first time.



Summary & Outlook

- DNS of rotating pipe flows were conducted over the range Re = 5,300-19,000.
- Mean turbulent statistics, Reynolds stresses, turbulent kinetic energy, and turbulent kinetic energy budgets were computed.
- TKE/MKE was found to be an effective measure of turbulence suppression in rotating pipe flows.
- Data captured form these DNS simulations is now being actively used to assist in the development of new RANS models which better predict turbulence suppression.
- The first ever DNS of the full reverse transition process is currently being conducted on Blue Waters. These simulations capture the development of the flow from a non-rotational turbulent inlet through a rotational domain of L = 125D.
- A more detailed analysis of these flows will be presented at the 2019 AIAA Aviation forum and can also be found in:





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