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## Nonlinear Subgrid-Scale Models for Large-Eddy Simulation of Rotating Turbulent Flows

Silvis, Maurits H.; Verstappen, R.W.C.P.

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# Nonlinear subgrid-scale models for large-eddy simulation of rotating turbulent flows

Maurits H. Silvis\* & Roel Verstappen

University of Groningen,  
The Netherlands

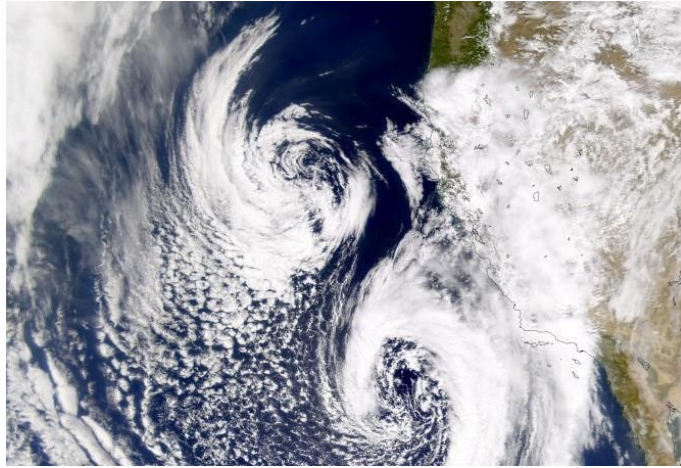
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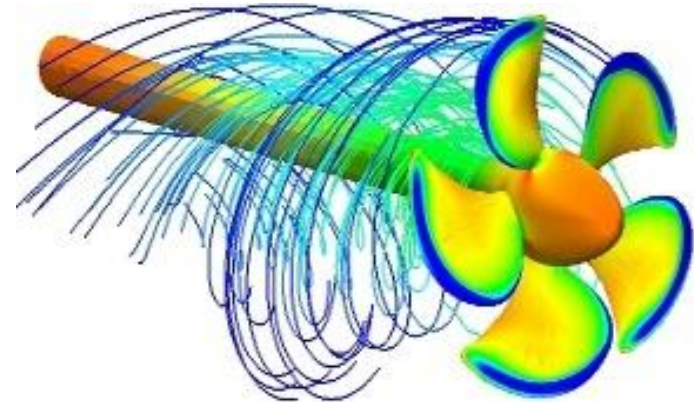
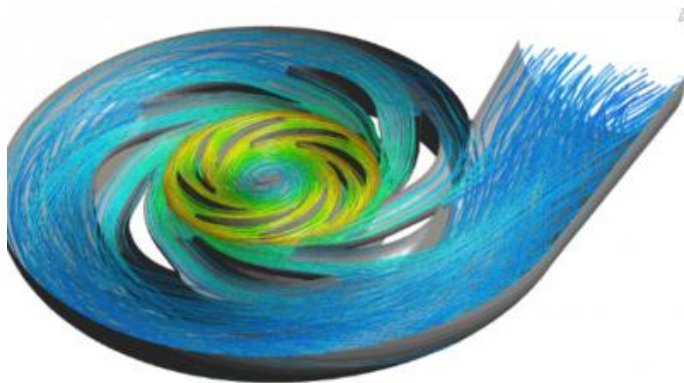


# Introduction

## Rotating turbulent flows



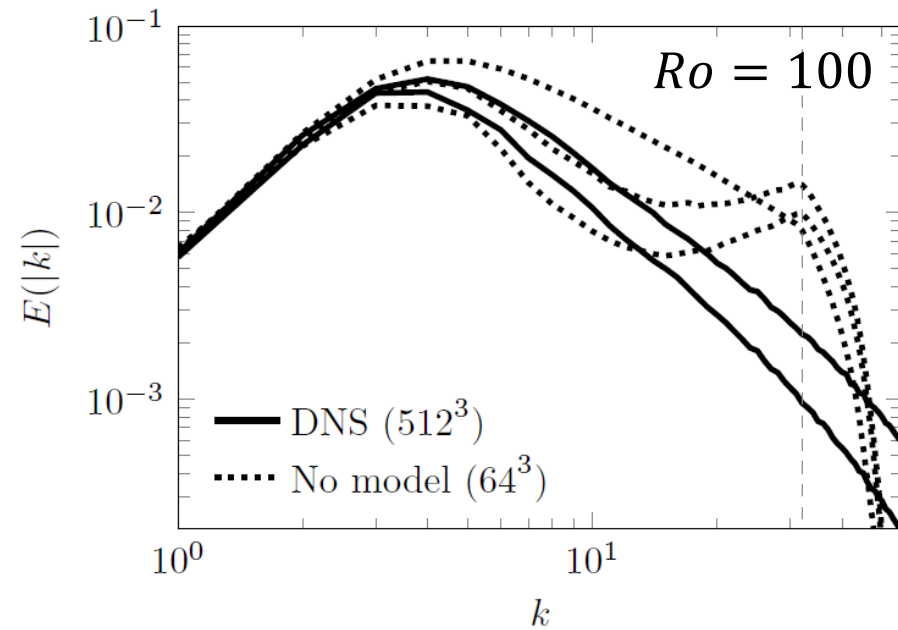
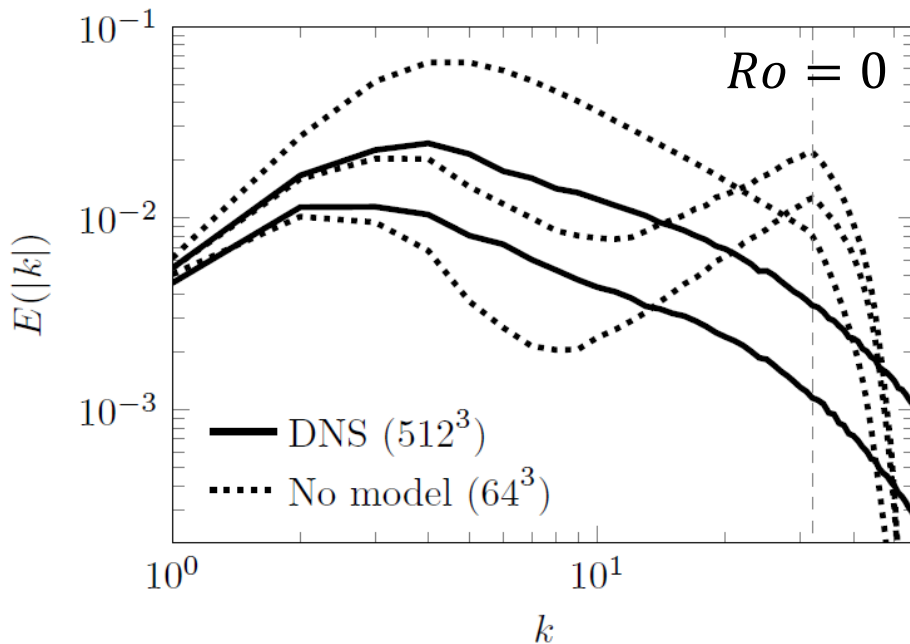
Ubiquitous in nature and engineering



# Introduction

## Challenges

- Coriolis force
  - Conserves total kinetic energy, but does redistribute it
  - Anisotropy
  - Observations: *rotating homogeneous isotropic turbulence*



# Introduction

## Large-eddy simulation of rotating turbulent flows

- Navier-Stokes equations in a rotating frame

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (u_i u_j) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + 2\nu \frac{\partial}{\partial x_j} S_{ij} + 2\epsilon_{ijk} u_j \Omega_k$$

convection
pressure
diffusion
Coriolis

- Large-eddy simulation without explicit filtering

- Coarse grid
- Extra forcing term

$$-\frac{\partial}{\partial x_j} \tau_{ij}^{\text{mod}}$$

model

# Introduction

## Nonlinear subgrid-scale models

- Focus: velocity-gradient-based models:

$$\tau^{\text{mod}} = \underbrace{-2\nu_e S}_{\text{eddy viscosity}} + \underbrace{\mu_e (S \Omega - \Omega S)}_{\text{nonlinear}}$$

- Eddy viscosity term:
  - Describes dissipation
  - Models well established
- Nonlinear term:
  - Stable part of gradient model
  - Nondissipative
  - Describes transport?

Nondynamic vortex-stretching-based coefficients:

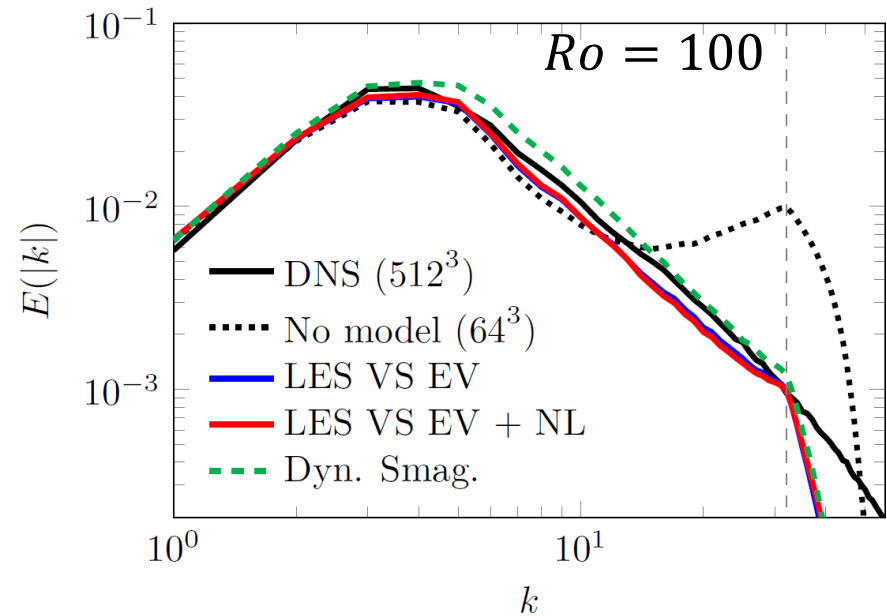
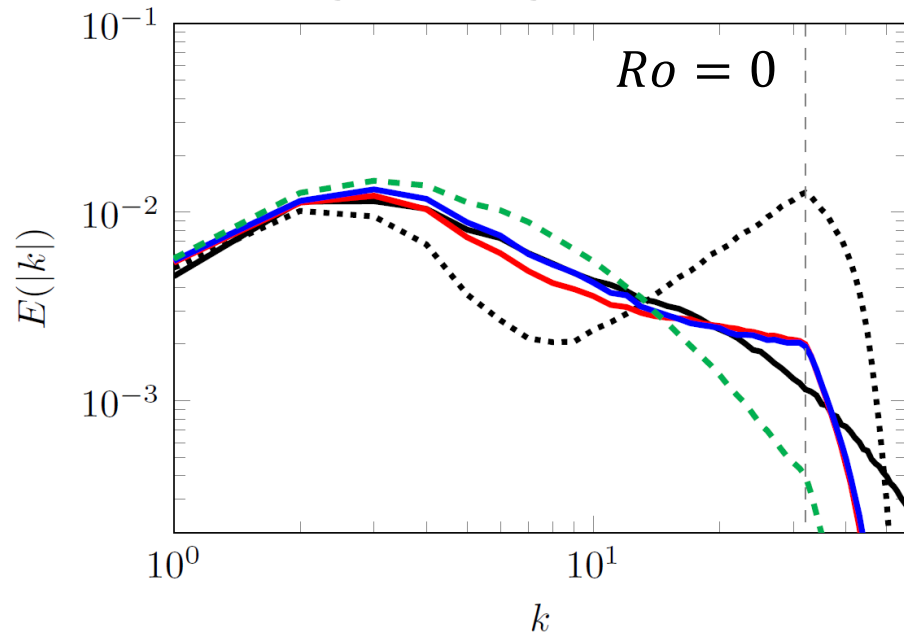
$$\nu_e = C_v^2 \delta^2 \sqrt{2|S|} f(|S\vec{\omega}|^2)$$

$$\mu_e = C_\mu^2 \delta^2 g(|S\vec{\omega}|^2)$$

# Introduction

## Nonlinear subgrid-scale models

- Rotating homogeneous isotropic turbulence



- Nonlinear model term can in-/decrease energy transport



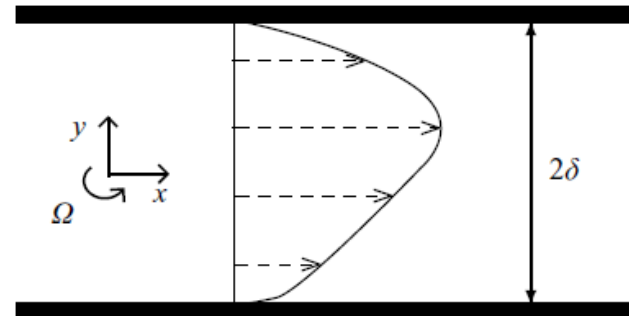
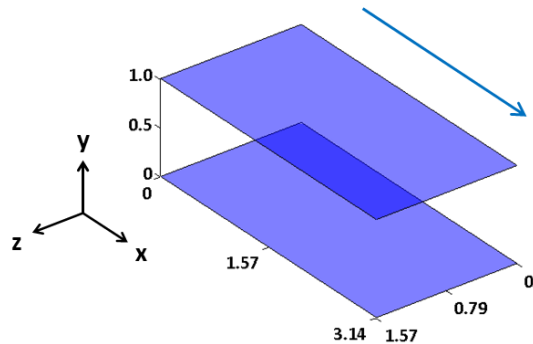
# Introduction

## Code

- Incompressible Navier-Stokes solver
- Finite-volume method on a staggered grid
- Pressure projection method
- One-leg explicit second-order time integration method
  
- Second-order symmetry-preserving spatial discretization
  - Kinetic energy conservation by ...
    - convection
    - Coriolis force
    - nonlinear subgrid-scale model

# Test case

## Spanwise-rotating plane-channel flow



- Domain size:  $2\pi d \times 2d \times \pi d$
- Periodic in  $x$  and  $z$  directions
- Rotation about the spanwise axis

- Characterized by

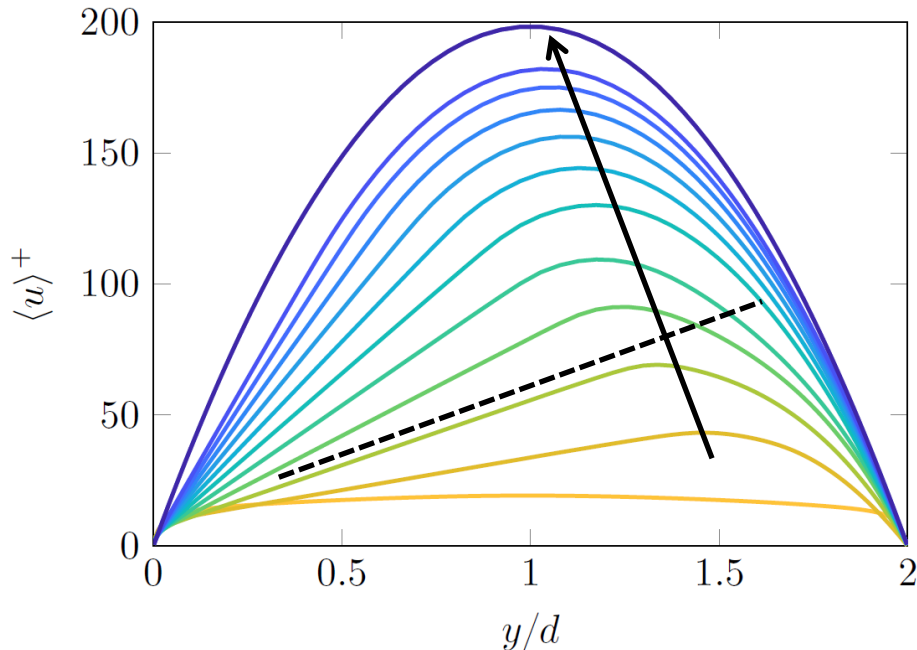
$$Re_{\tau} = \frac{u_{\tau} d}{\nu} \approx 395$$

$$Ro^{+} = \frac{2\Omega d}{u_{\tau}} = 0 - 1000$$

# Spanwise-rotating plane-channel flow

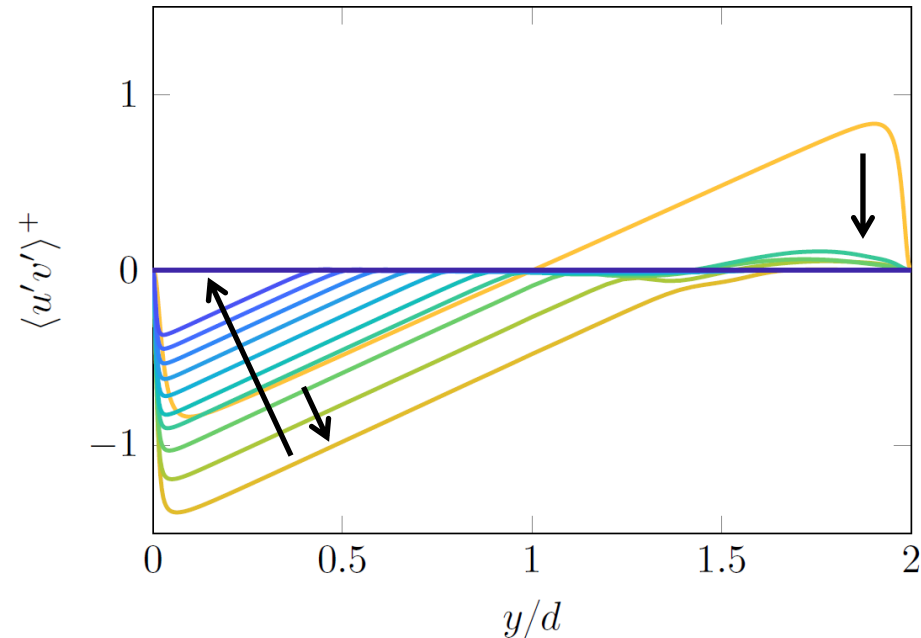
## Typical observations: $Ro^+$ dependence

- Mean velocity profile



- Linear slope  $\sim Ro^+$
- Flow laminarizes with  $Ro^+$

- Reynolds shear stress



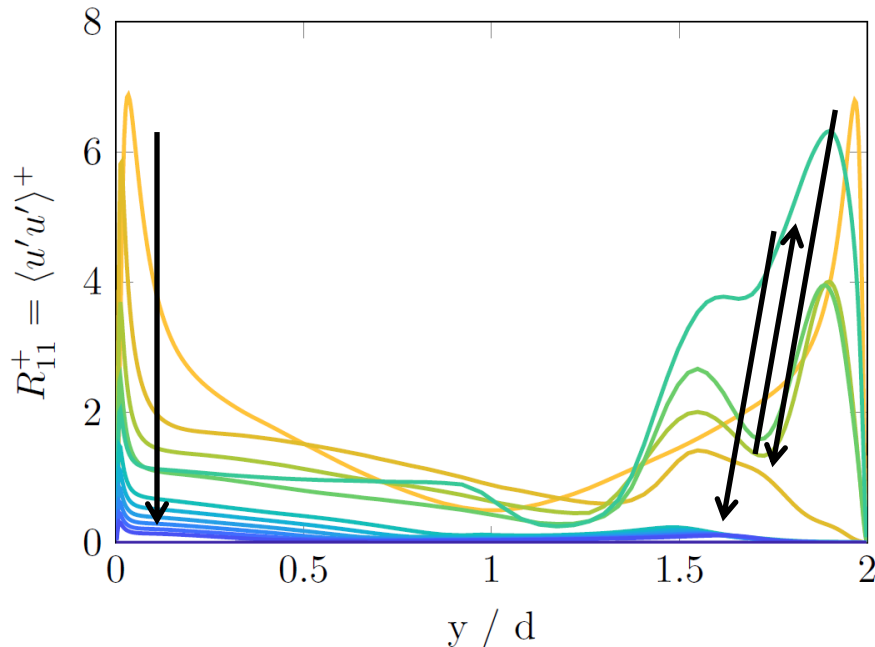
- Turbulent and laminar side

$$\begin{aligned}
 Re_\tau &\approx 395, \quad Ro^+ = 0 - 1000 \\
 n_x \times n_y \times n_z &= 128 \times 128 \times 128
 \end{aligned}$$

# Spanwise-rotating plane-channel flow

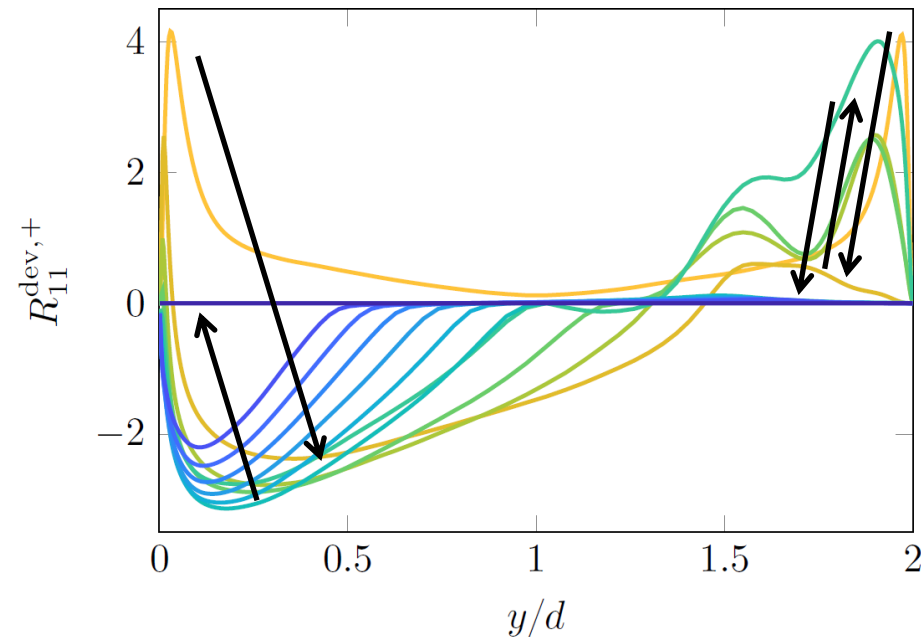
## Typical observations: $Ro^+$ dependence

- Streamwise stress



- Turbulent and laminar side
- Flow laminarizes with  $Ro^+$

- Deviatoric streamwise stress



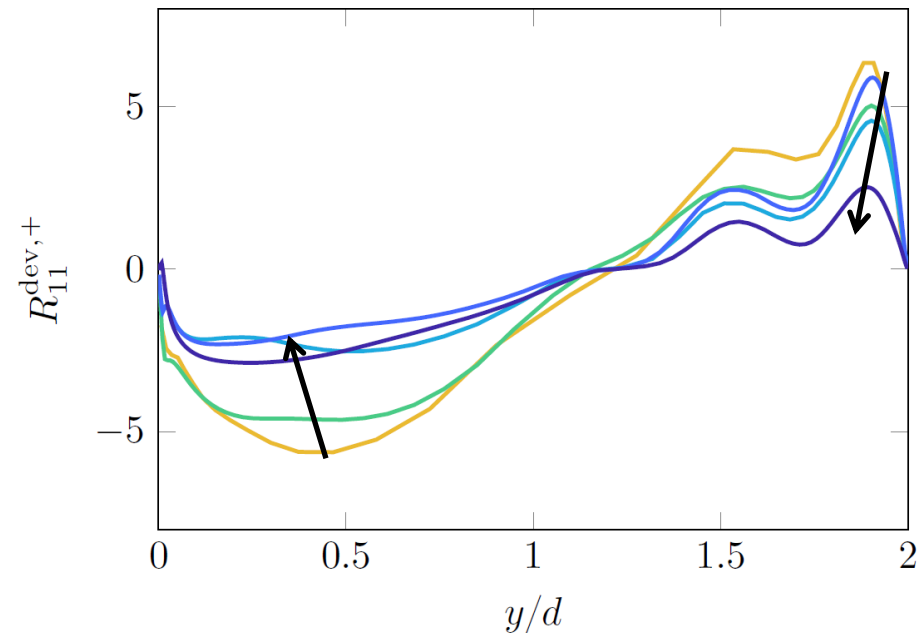
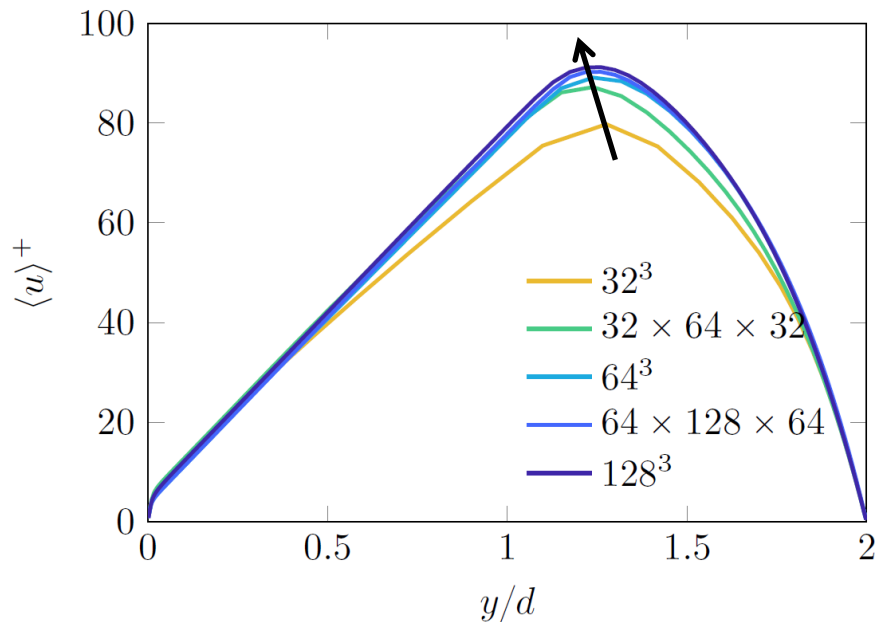
- Traceless subgrid-scale models: deviatoric stresses

$$Re_\tau \approx 395, Ro^+ = 0 - 1000 \\
 n_x \times n_y \times n_z = 128 \times 128 \times 128$$

# Spanwise-rotating plane-channel flow

## Typical observations: resolution dependence

- Mean velocity profile
- Deviatoric streamwise stress



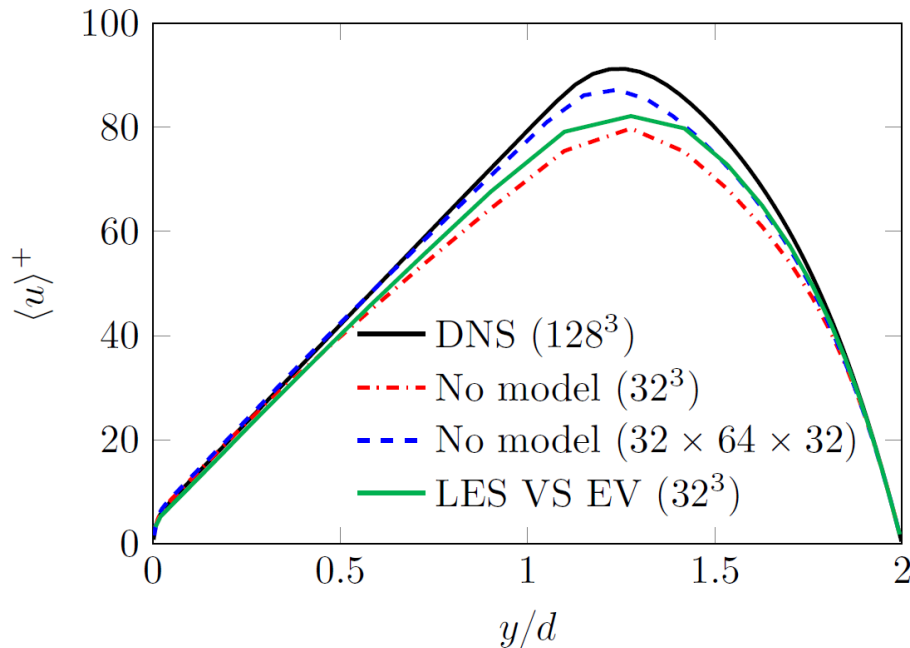
– Ample opportunity for LES, even at  $Re_\tau \approx 395$

$$Re_\tau \approx 395, Ro^+ = 75$$

# Numerical results

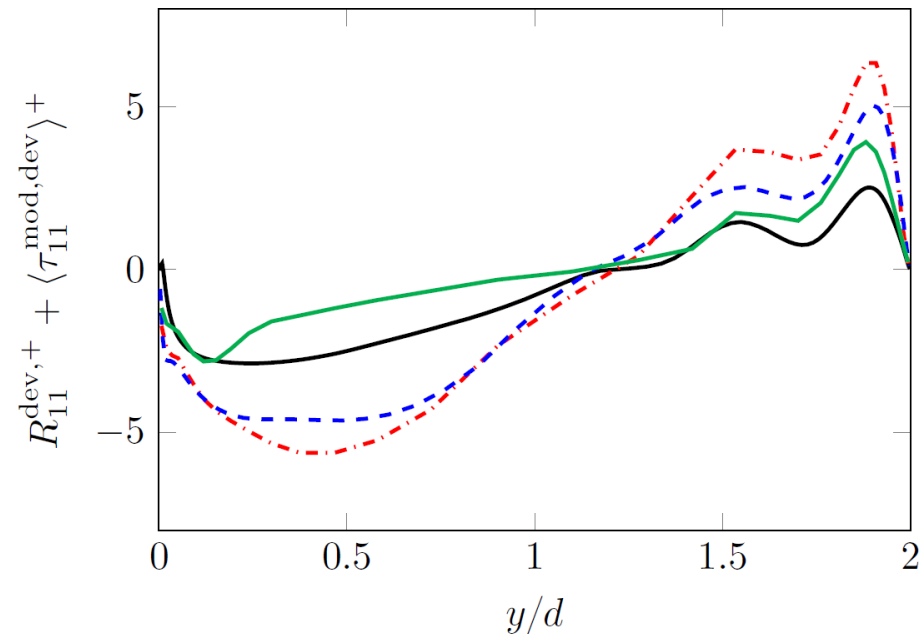
## Large-eddy simulation with eddy viscosity model

- Mean velocity profile



- Trend: eddy viscosity model improves results

- Deviatoric streamwise stress

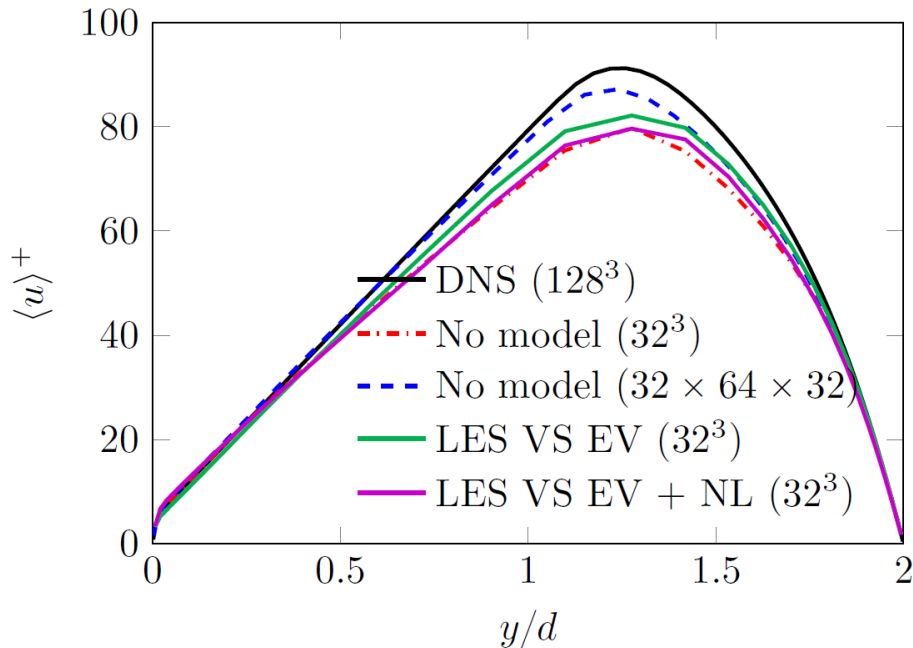


- Even improving upon  $32 \times 64 \times 32$  result

# Numerical results

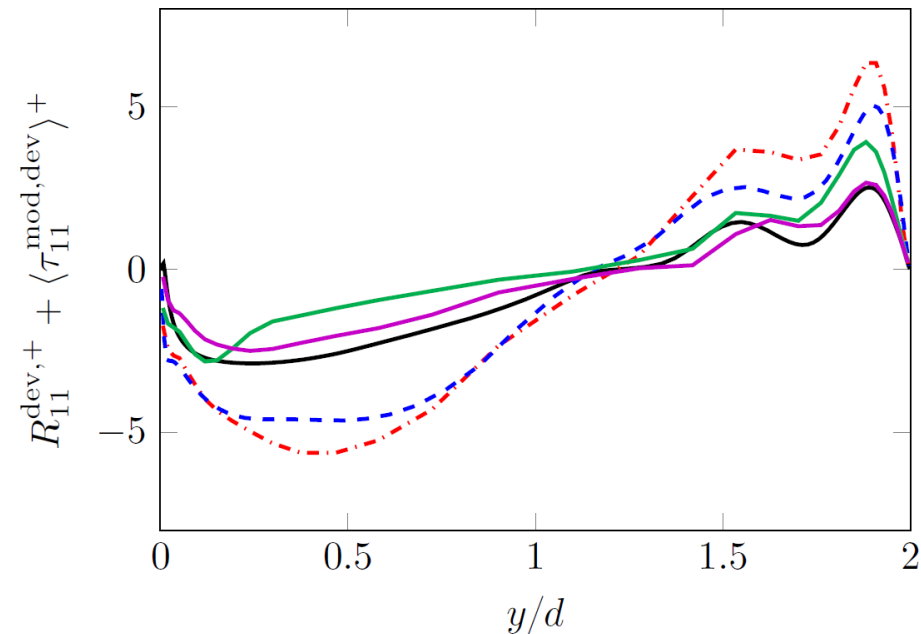
## Large-eddy simulation with nonlinear model

- Mean velocity profile



- Slight improvement on 32<sup>3</sup> result

- Deviatoric streamwise stress



- Nonlinear model improves stresses w.r.t. eddy viscosity model case

$$Re_\tau \approx 395, Ro^+ = 75$$

# Summary & Outlook

## Summary

- Focus:
  - large-eddy simulation of rotating turbulent flows
- Observations:
  - vortex-stretching-based nonlinear model captures energy transport in rotating homogeneous isotropic turbulence
- Test case:
  - spanwise-rotating plane-channel flow
  - rich and interesting test case for large-eddy simulation, even at  $Re_\tau \approx 395$
- Subgrid-scale modeling:
  - vortex-stretching-based eddy viscosity model leads to improved predictions of spanwise-rotating plane-channel flow
  - vortex-stretching-based nonlinear model further improves prediction of the Reynolds stresses



## Summary & Outlook

### Outlook

- Further study of nonlinear subgrid-scale model:
  - behavior on different grids
  - influence of model constants
- Combine subgrid-scale model with different length scales:
  - Trias *et al.* – A new subgrid characteristic length for LES  
Session SW5 – LES modeling II (room A2, 14.00h)



# Thank you for your attention!

Maurits H. Silvis\* & Roel Verstappen

University of Groningen,  
The Netherlands

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\*[m.h.silvis@rug.nl](mailto:m.h.silvis@rug.nl)

