Numerical study on turbulence induced vibrations of fuel rods

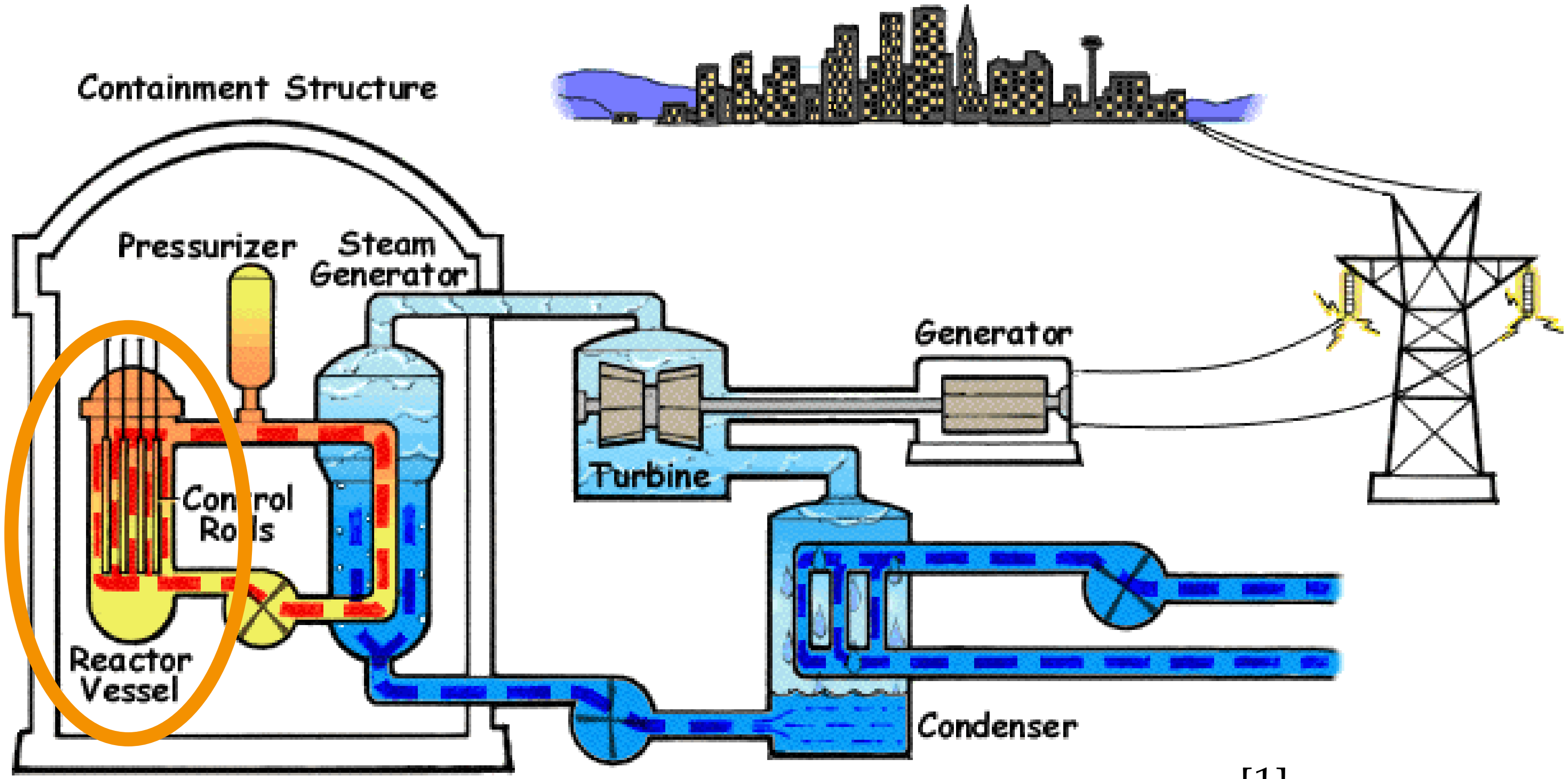
Using an Anisotropic Pressure Fluctuations Model

Author:	Andre Freitas	
Supervisors:	Dr. ir. A.H. Van Zuijlen,	TU Delft
	ir. K. Zwijsen,	NRG

Funded by the European Union

The *AQTIVATE* project receives funding from the European Union's HORIZON MSCA Doctoral Networks programme, under Grant Agreement No. 101072344.

Overview of a Nuclear Reactor (PWR)



[1]

Motivation

- Axial flow over the fuel rods can lead to turbulence induced vibrations (TIV).
- Can lead to structural damage of the rods (fatigue, fretting wear).

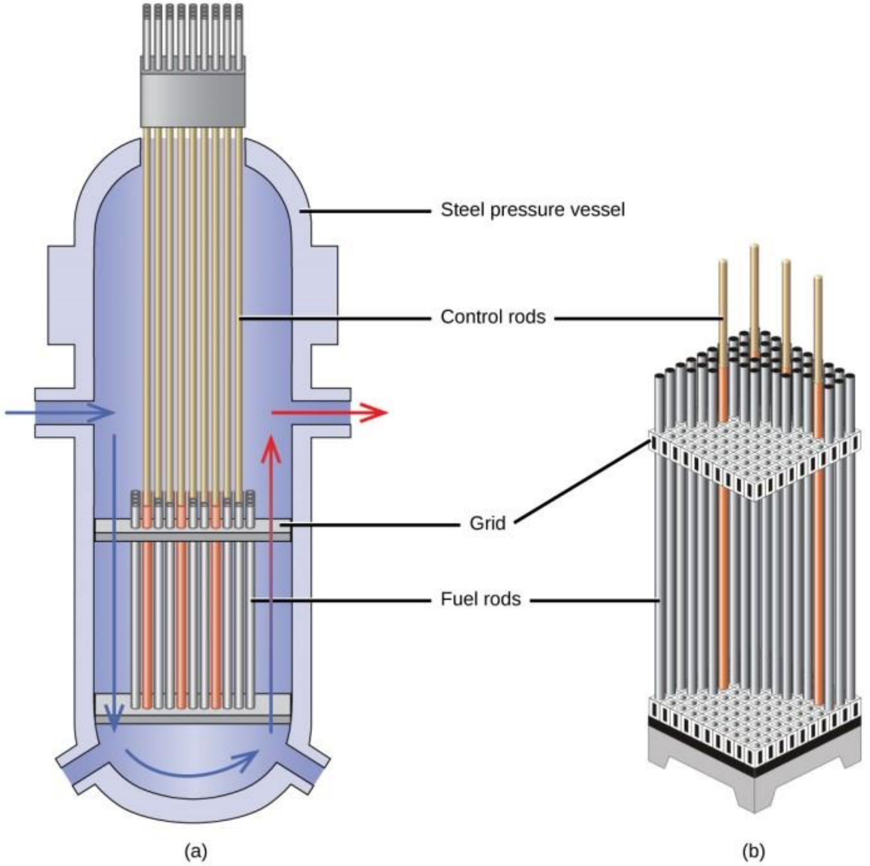
Modeling TIV

↓

Better maintenance prediction

↓

Increased safety



[2]

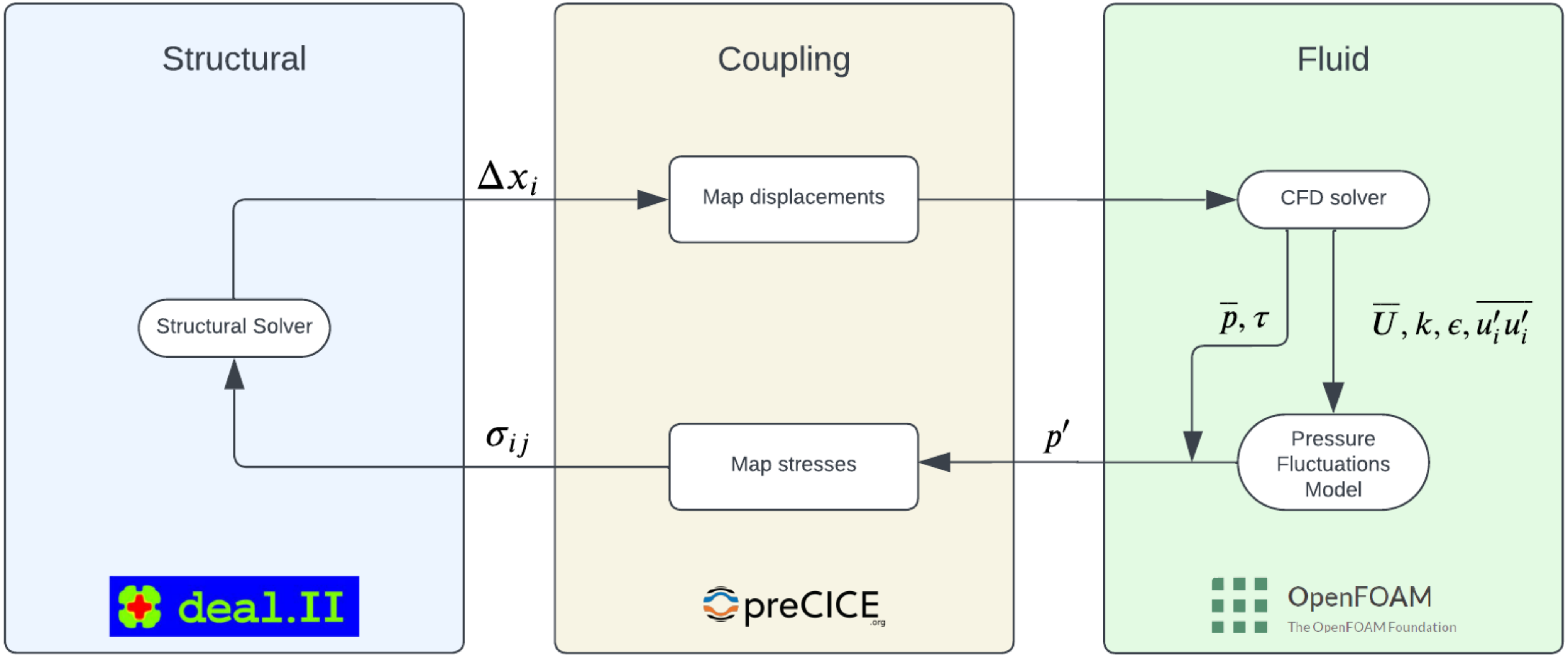
Numerical simulations of TIV

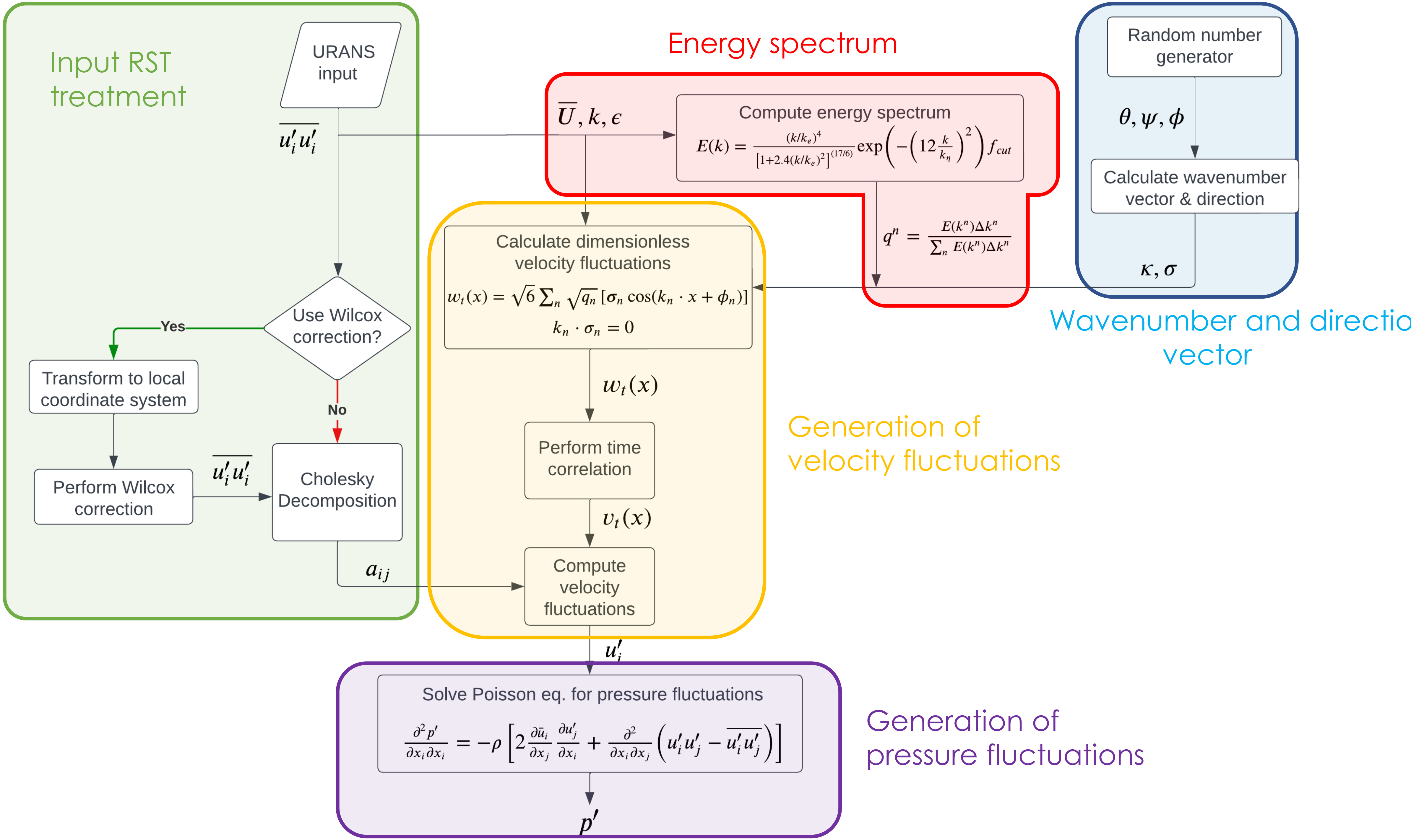
- TIV can be simulated through Fluid-Structure Interaction (FSI) simulations.

- Turbulence modelling/solving:
  - RANS — Fails in modeling the fluctuations that excite the structure
  - LES — Too computationally expensive
  - DNS

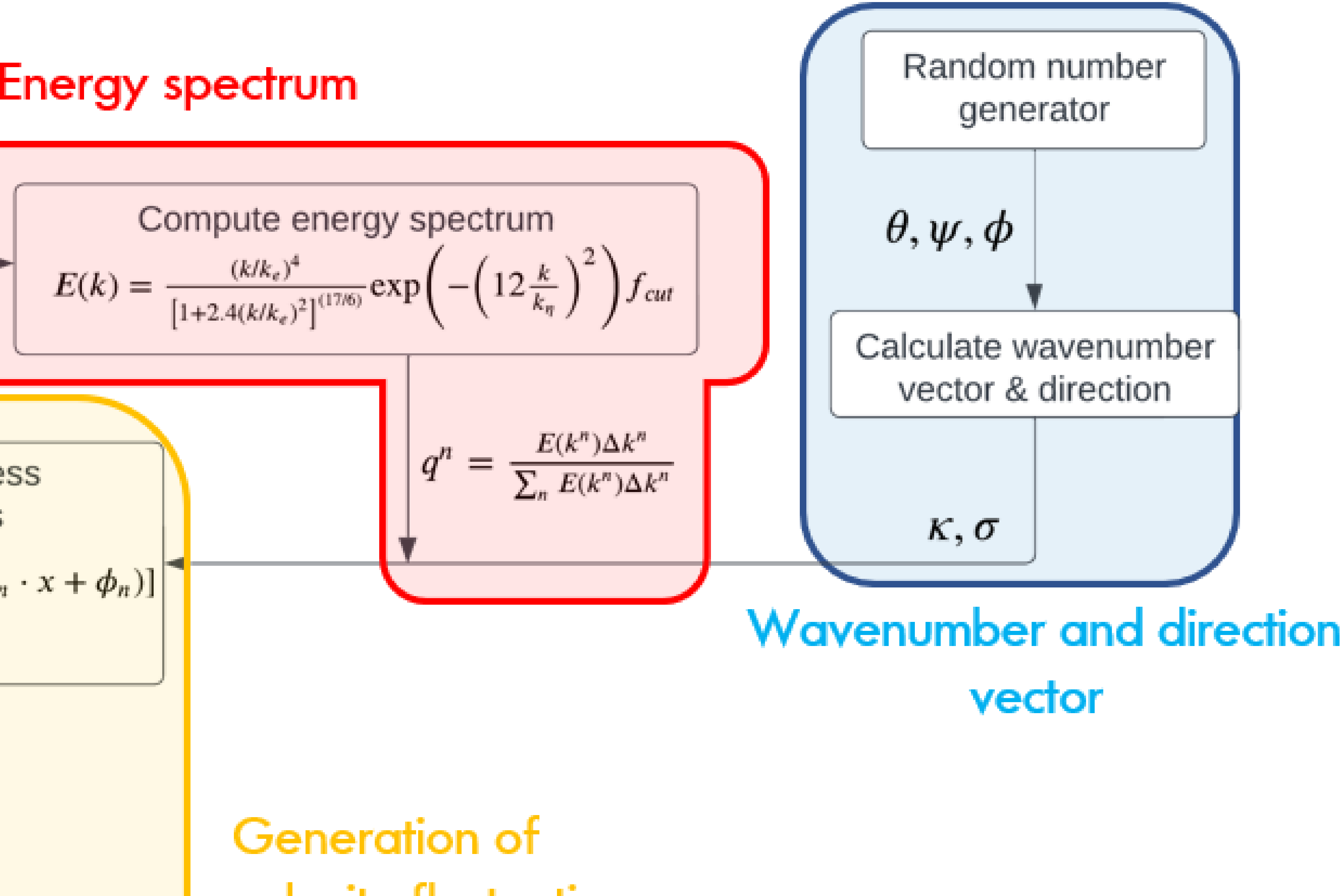
Solution → **URANS + Pressure Fluctuations Model**

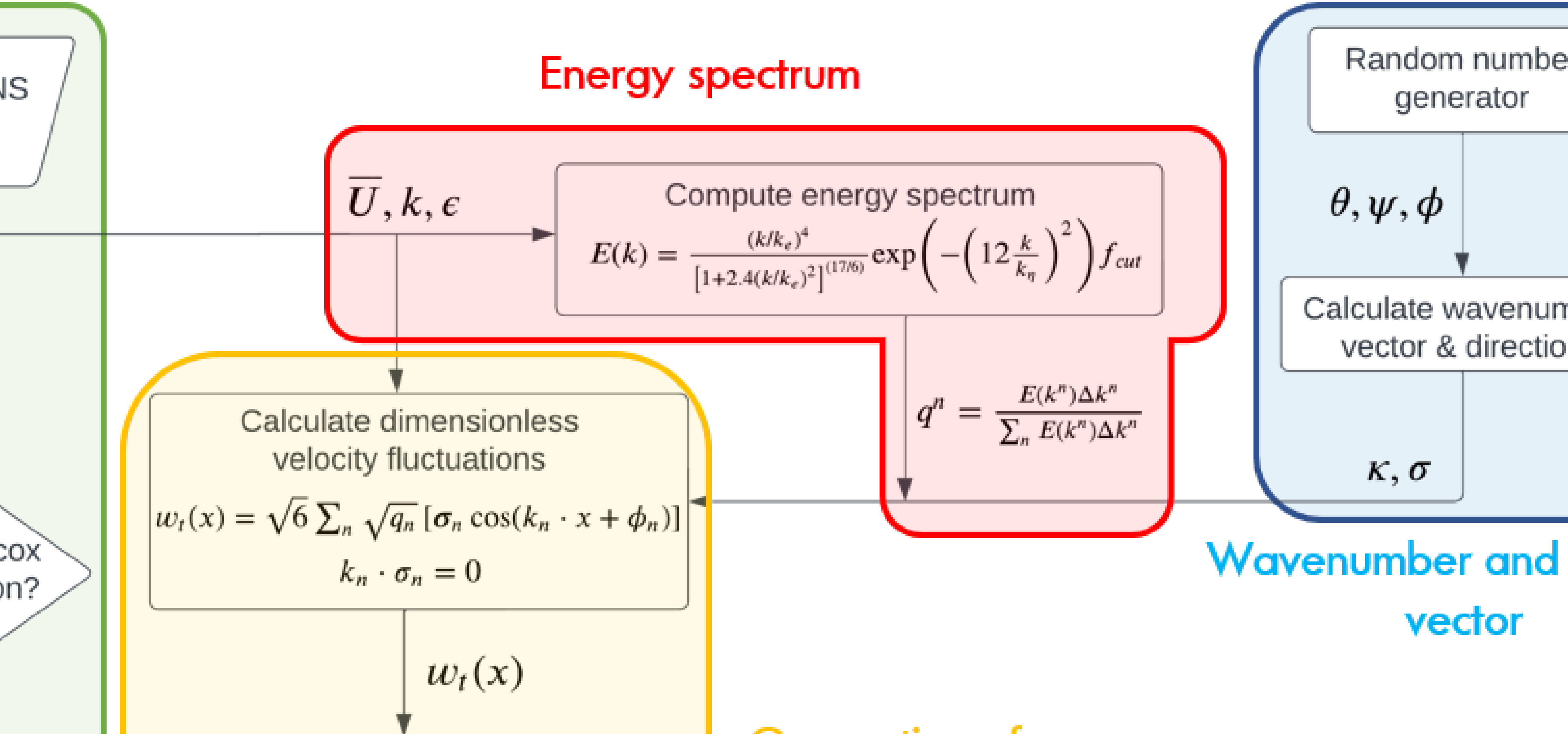
FSI framework



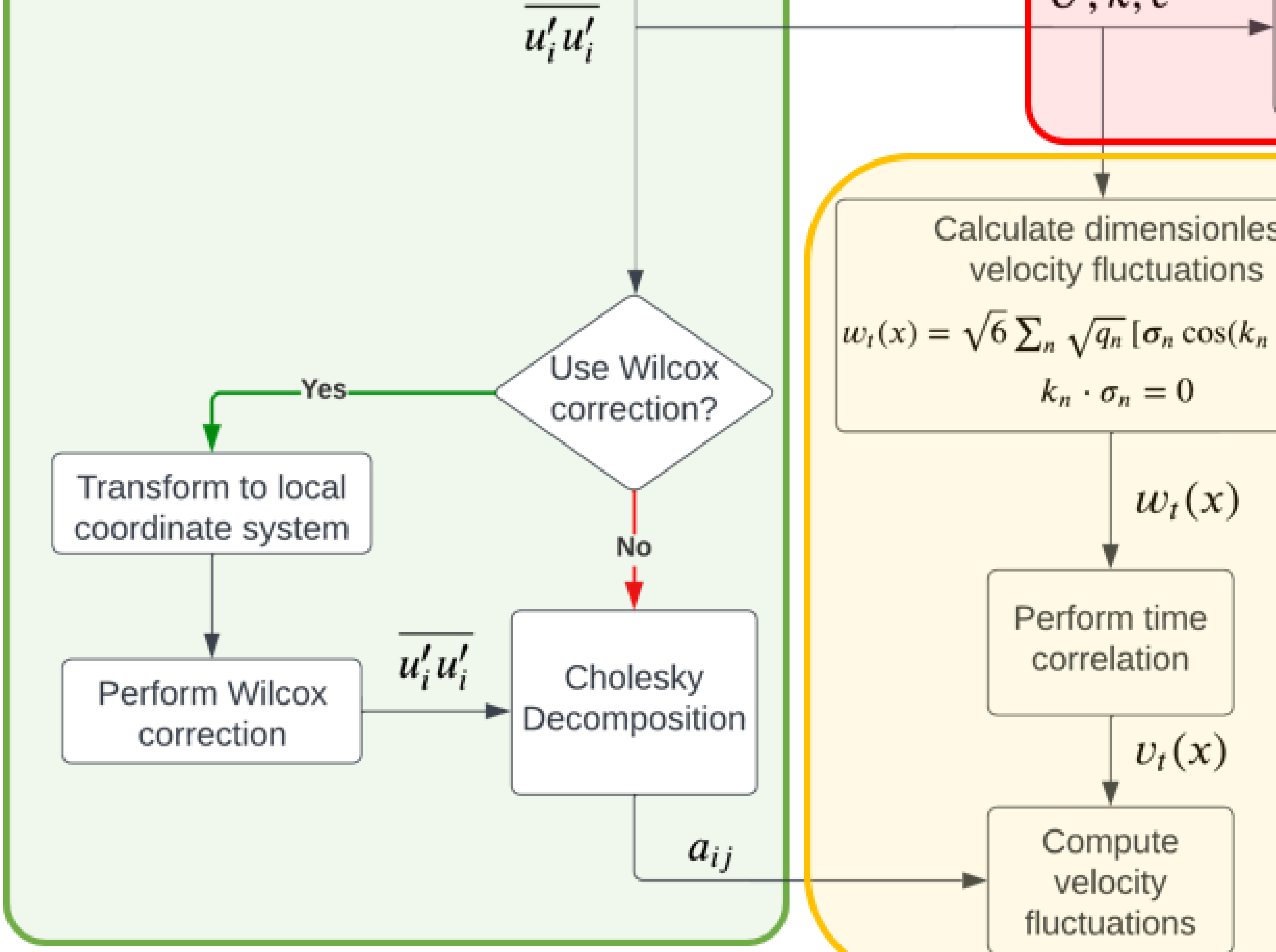


Input RST treatment
URANS input
$\overline{u_i' u_i'}$
Use Wilcox correction?
Yes
No
Transform to local coordinate system
Perform Wilcox correction
$\overline{u_i' u_i'}$
Cholesky Decomposition
a_{ij}
Energy spectrum
$\overline{U}, k, \epsilon$
Compute energy spectrum
$E(k) = \frac{(k/k_e)^4}{[1+2.4(k/k_e)^2]^{(17/6)}} \exp\left(-\left(12\frac{k}{k_\eta}\right)^2\right) f_{cut}$
$q^n = \frac{E(k^n)\Delta k^n}{\sum_n E(k^n)\Delta k^n}$
Random number generator
θ, ψ, ϕ
Calculate wavenumber vector & direction
κ, σ
Wavenumber and directio
vector
Calculate dimensionless velocity fluctuations
$w_t(x) = \sqrt{6} \sum_n \sqrt{q_n} [\sigma_n \cos(k_n \cdot x + \phi_n)]$
$k_n \cdot \sigma_n = 0$
$w_t(x)$
Perform time correlation
$v_t(x)$
Compute velocity fluctuations
Generation of velocity fluctuations
u_i'
Solve Poisson eq. for pressure fluctuations
$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\rho \left[2 \frac{\partial \bar{u}_i}{\partial x_j} \frac{\partial u_j'}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j} \left(u_i' u_j' - \overline{u_i' u_j'}\right)\right]$
p'
Generation of pressure fluctuations

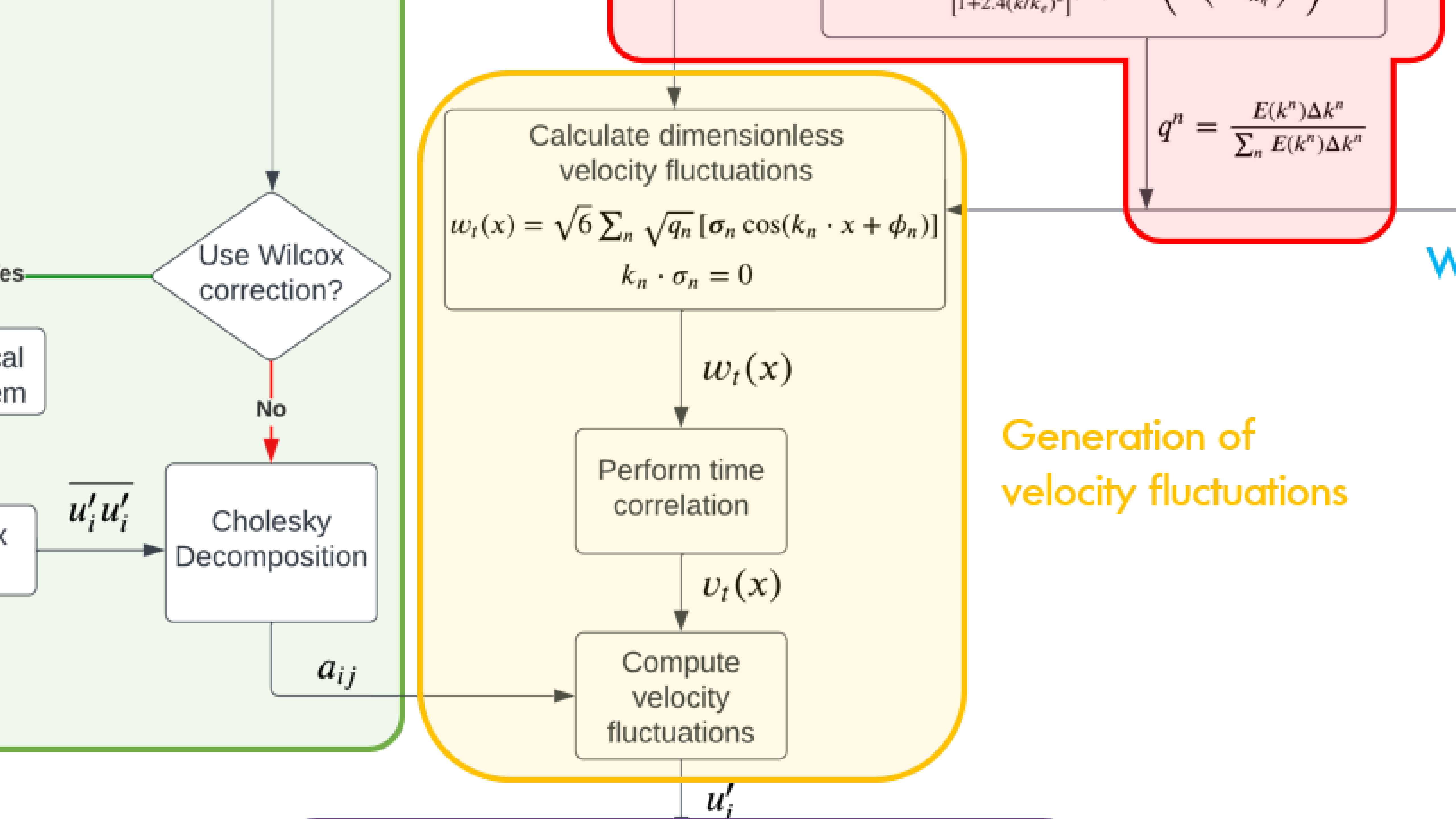

Energy spectrum
Compute energy spectrum
$E(k) = \frac{(k/k_e)^4}{[1+2.4(k/k_e)^2]^{(17/6)}} \exp\left(-\left(12\frac{k}{k_\eta}\right)^2\right) f_{cut}$
$q^n = \frac{E(k^n)\Delta k^n}{\sum_n E(k^n)\Delta k^n}$
Random number generator
θ, ψ, ϕ
Calculate wavenumber vector & direction
κ, σ
Wavenumber and direction vector
Generation of



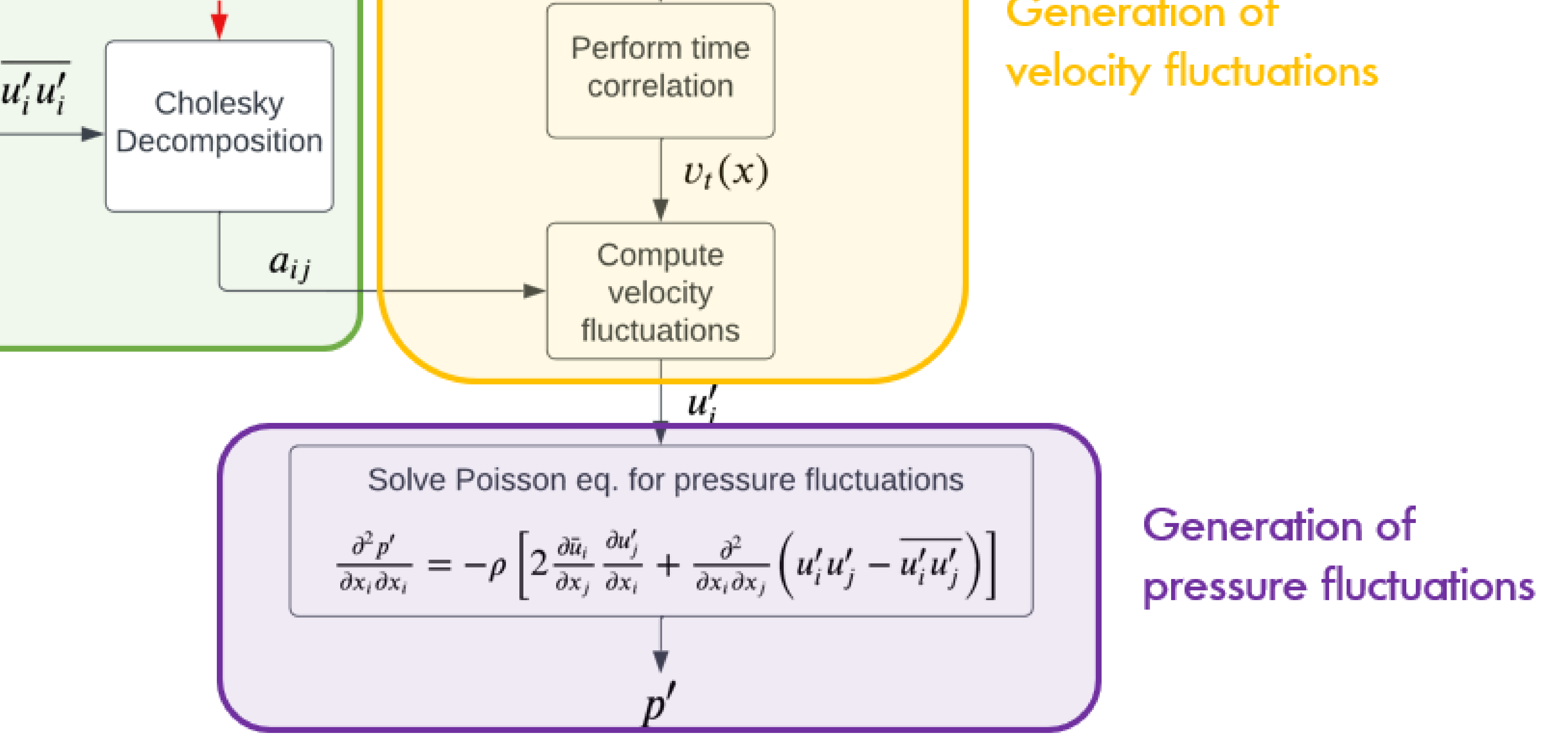
Energy spectrum
$\overline{U}, k, \epsilon$
Compute energy spectrum
$E(k) = \frac{(k/k_e)^4}{[1+2.4(k/k_e)^2]^{(17/6)}} \exp\left(-\left(12\frac{k}{k_\eta}\right)^2\right) f_{cut}$
$q^n = \frac{E(k^n)\Delta k^n}{\sum_n E(k^n)\Delta k^n}$
Random number generator
θ, ψ, ϕ
Calculate wavenum vector & directio
κ, σ
Wavenumber and vector
Calculate dimensionless velocity fluctuations
$w_t(x) = \sqrt{6} \sum_n \sqrt{q_n} [\sigma_n \cos(k_n \cdot x + \phi_n)]$
$k_n \cdot \sigma_n = 0$
$w_t(x)$

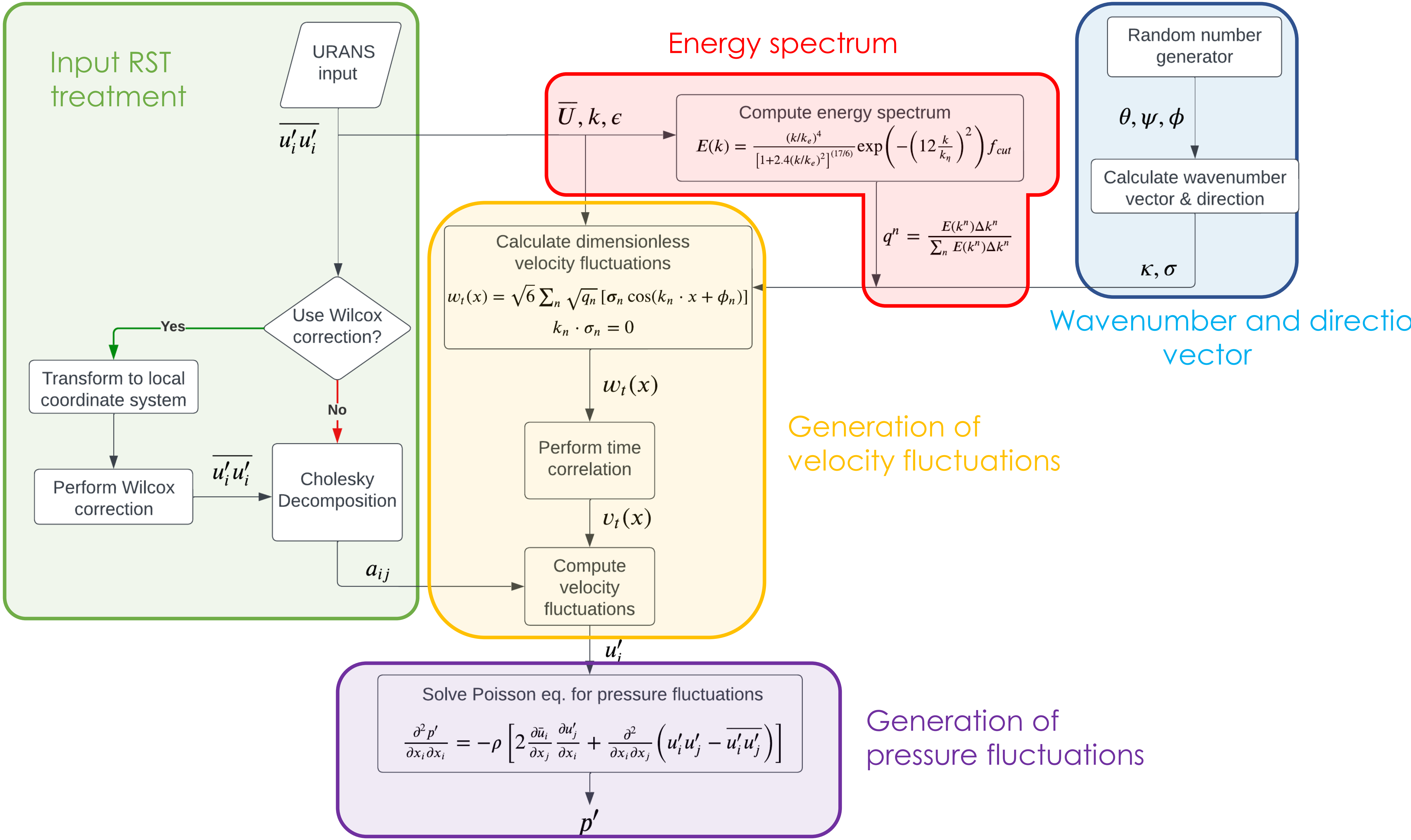


$\overline{u_i' u_i'}$
Use Wilcox correction?
Yes
No
Transform to local coordinate system
Perform Wilcox correction
$\overline{u_i' u_i'}$
Cholesky Decomposition
a_{ij}
Calculate dimensionles
velocity fluctuations
$k_n \cdot \sigma_n = 0$
$w_t(x)$
Perform time correlation
$v_t(x)$
Compute velocity fluctuations



Calculate dimensionless velocity fluctuations
$w_t(x) = \sqrt{6}\sum_n \sqrt{q_n}\,[\sigma_n \cos(k_n \cdot x + \phi_n)]$
$k_n \cdot \sigma_n = 0$
$q^n = \frac{E(k^n)\Delta k^n}{\sum_n E(k^n)\Delta k^n}$
Use Wilcox correction?
No
$\overline{u_i' u_i'}$
Cholesky Decomposition
a_{ij}
$w_t(x)$
Perform time correlation
$v_t(x)$
Compute velocity fluctuations
u_i'
Generation of velocity fluctuations

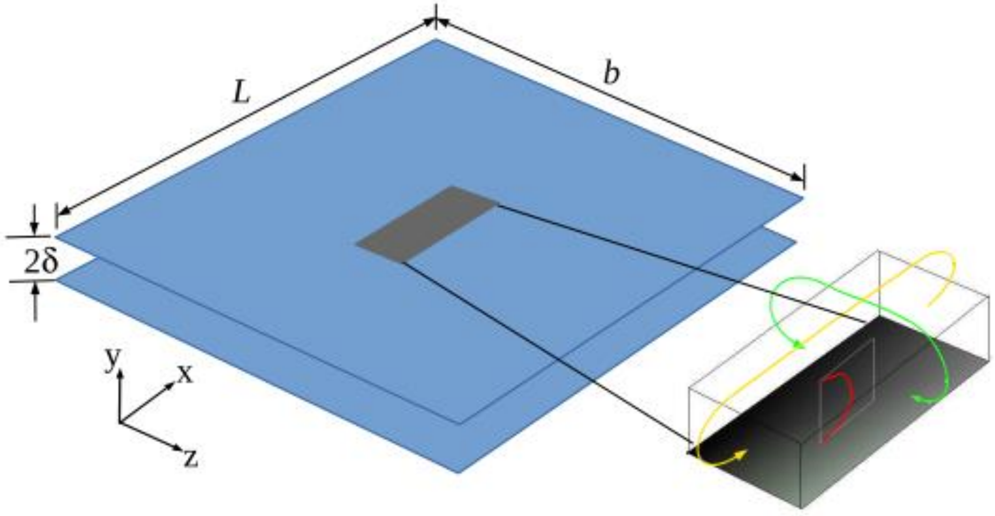

Generation of
velocity fluctuations
$\overline{u_i' u_i'}$
Cholesky Decomposition
Perform time correlation
$v_t(x)$
a_{ij}
Compute velocity fluctuations
u_i'
Solve Poisson eq. for pressure fluctuations
$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\rho \left[2 \frac{\partial \bar{u}_i}{\partial x_j} \frac{\partial u_j'}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j} \left(u_i' u_j' - \overline{u_i' u_j'} \right) \right]$
p'
Generation of
pressure fluctuations



Input RST treatment
URANS input
$\overline{u_i' u_i'}$
Use Wilcox correction?
Yes
No
Transform to local coordinate system
Perform Wilcox correction
$\overline{u_i' u_i'}$
Cholesky Decomposition
a_{ij}
Energy spectrum
$\overline{U}, k, \epsilon$
Compute energy spectrum
$E(k) = \frac{(k/k_e)^4}{[1+2.4(k/k_e)^2]^{(17/6)}} \exp\left(-\left(12\frac{k}{k_\eta}\right)^2\right) f_{cut}$
$q^n = \frac{E(k^n)\Delta k^n}{\sum_n E(k^n)\Delta k^n}$
Random number generator
θ, ψ, ϕ
Calculate wavenumber vector & direction
κ, σ
Wavenumber and directio
vector
Calculate dimensionless velocity fluctuations
$w_t(x) = \sqrt{6}\sum_n \sqrt{q_n}\,[\sigma_n \cos(k_n \cdot x + \phi_n)]$
$k_n \cdot \sigma_n = 0$
$w_t(x)$
Perform time correlation
$v_t(x)$
Compute velocity fluctuations
Generation of velocity fluctuations
u_i'
Solve Poisson eq. for pressure fluctuations
$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\rho\left[2\frac{\partial \bar{u}_i}{\partial x_j}\frac{\partial u_j'}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j}\left(u_i' u_j' - \overline{u_i' u_j'}\right)\right]$
p'
Generation of pressure fluctuations

Turbulent channel flow (TCF)

- Flow between two infinitely long and wide flat plates.
- Only statistical inhomogenous direction is the wall normal.
- $Re_\tau = 640$
- DNS data of Abe et al. [4] used as validation.

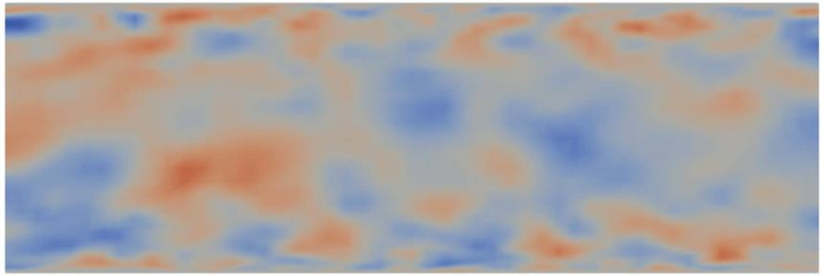


[3]

Time correlation

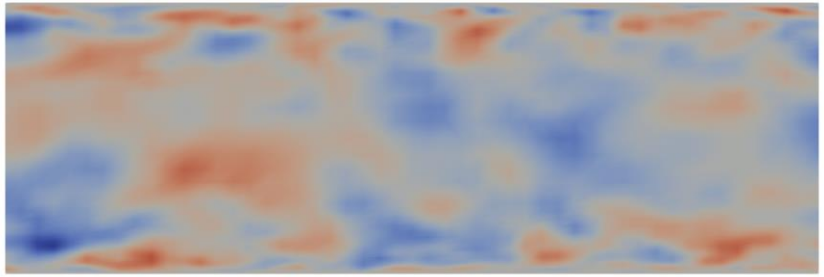
- Pure Convection

$$\boldsymbol{v}_t(\boldsymbol{x}) = \sqrt{6}\sum_n \sqrt{q_n}\left[\sigma_n \cos\left(\boldsymbol{k}_n \cdot (\boldsymbol{x} - \boldsymbol{U}t) + \phi_n\right)\right]$$

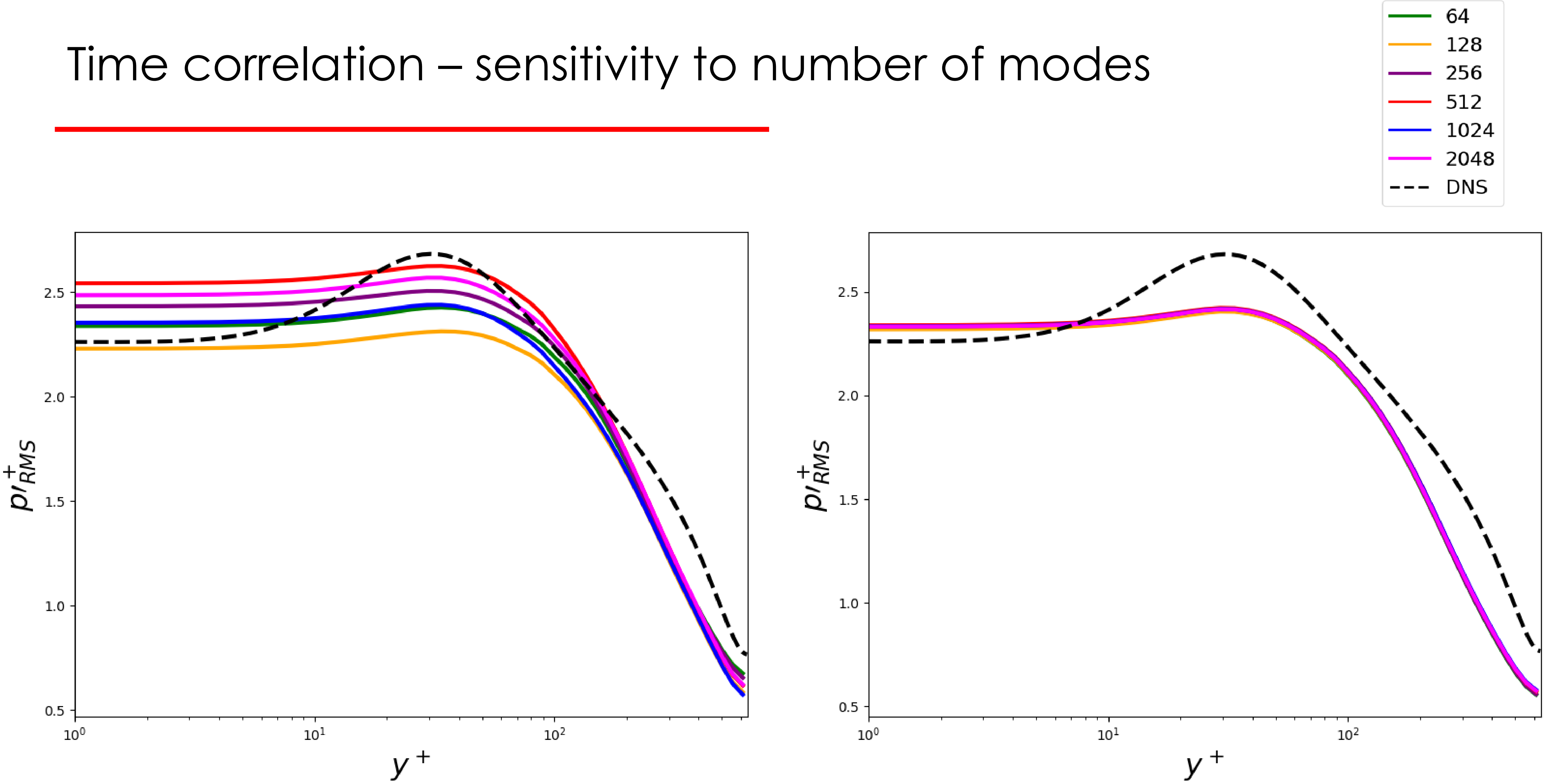


- Convection & Exponential Correlation

$$\begin{cases} \dfrac{\partial \boldsymbol{v}_t^{m-1}}{\partial t} + U_j \dfrac{\partial \boldsymbol{v}_t^{m-1}}{\partial x_j} = 0 \\ \boldsymbol{v}_t^m(\boldsymbol{x}, t) = a\tilde{\boldsymbol{v}}_t^{m-1}(\boldsymbol{x}) + b\boldsymbol{w}_t^m(\boldsymbol{x}) \end{cases}$$

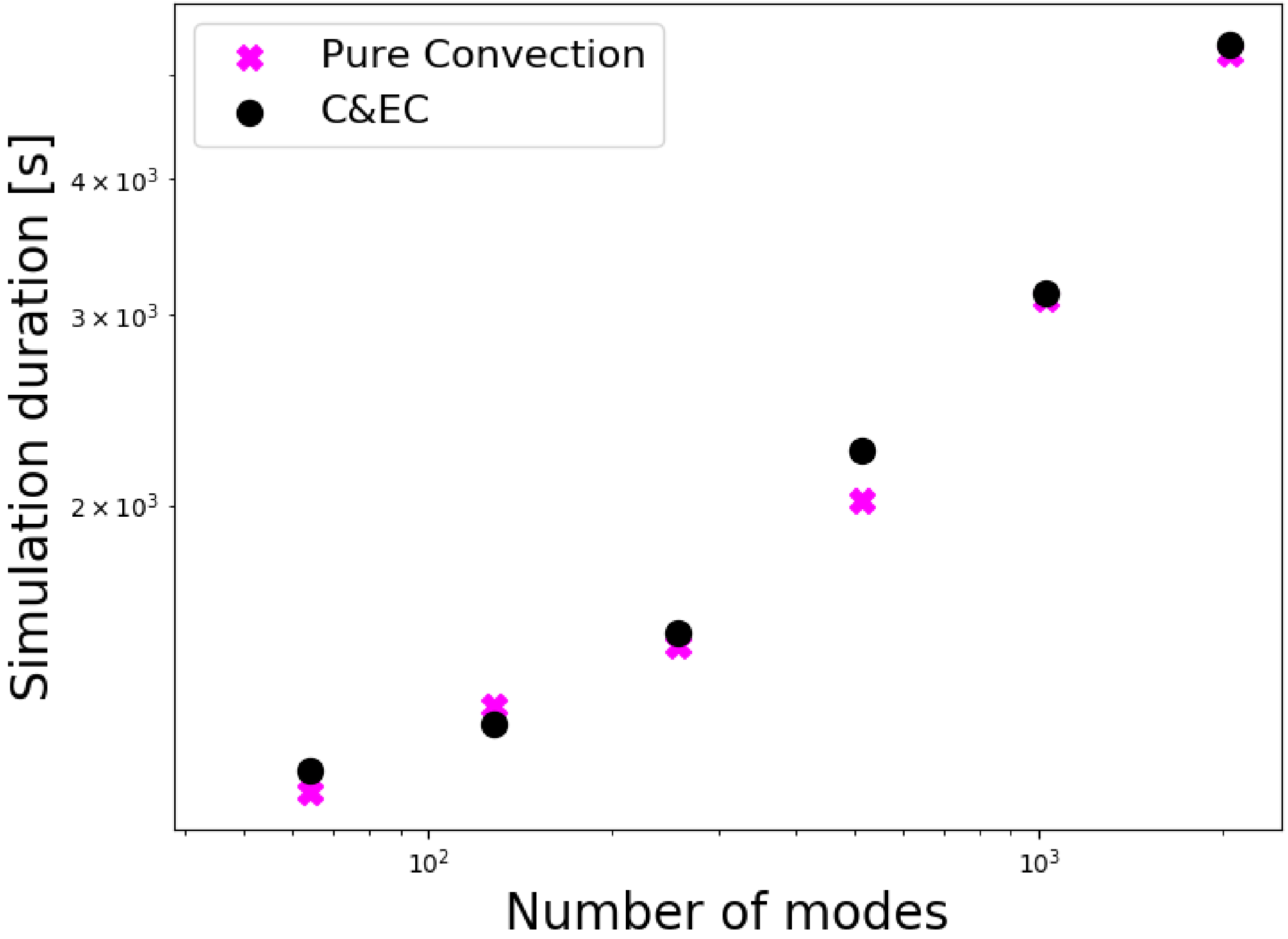


Time correlation – sensitivity to number of modes



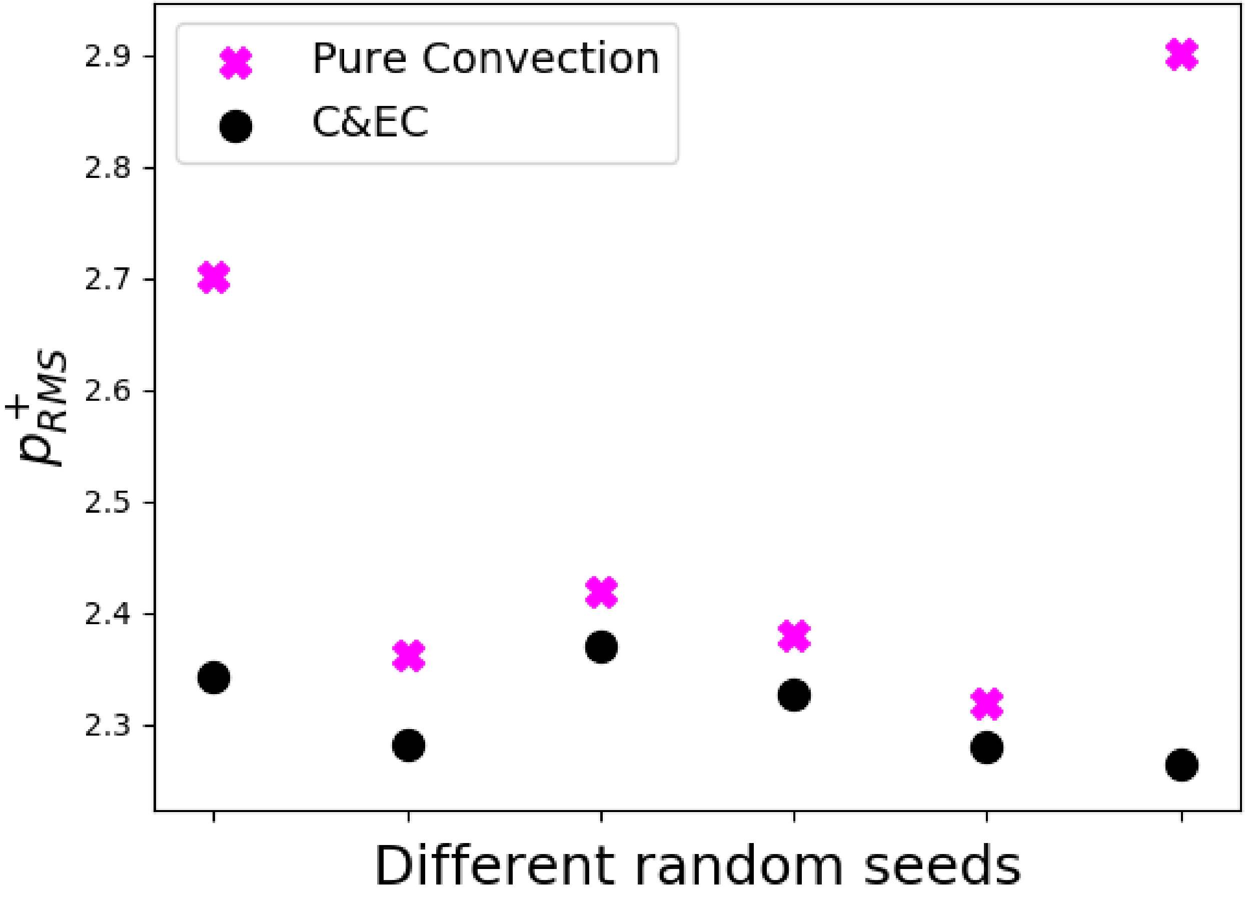
AQTIVATE

Time correlation – sensitivity to number of modes

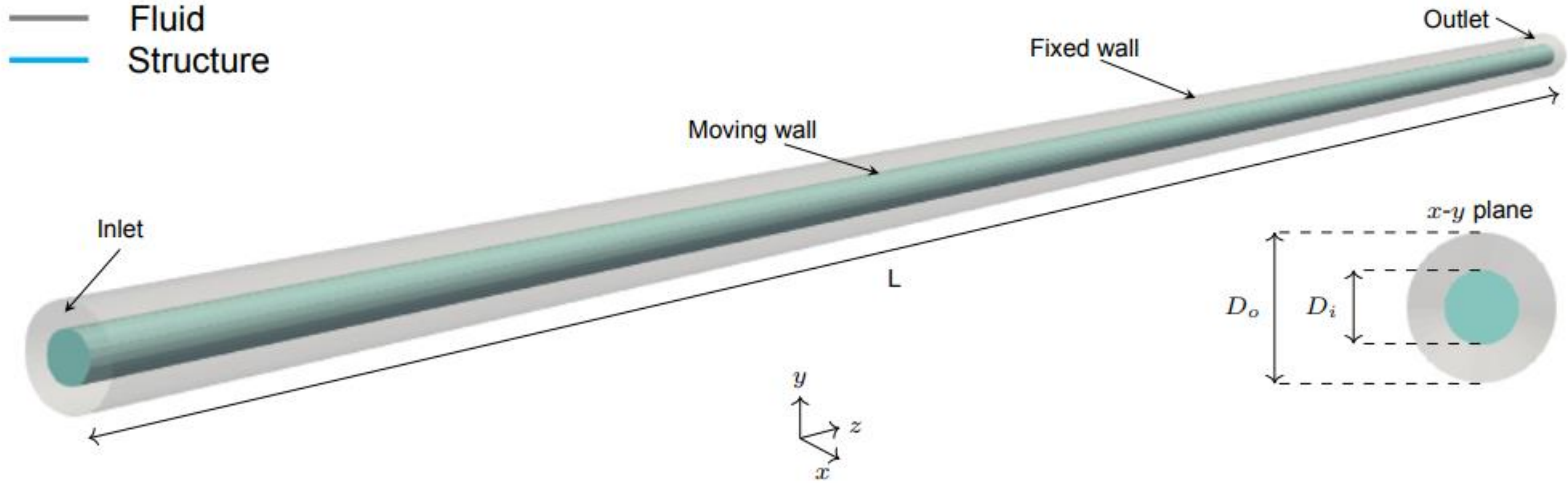


AQTIVATE

Time correlation – sensitivity to random seed

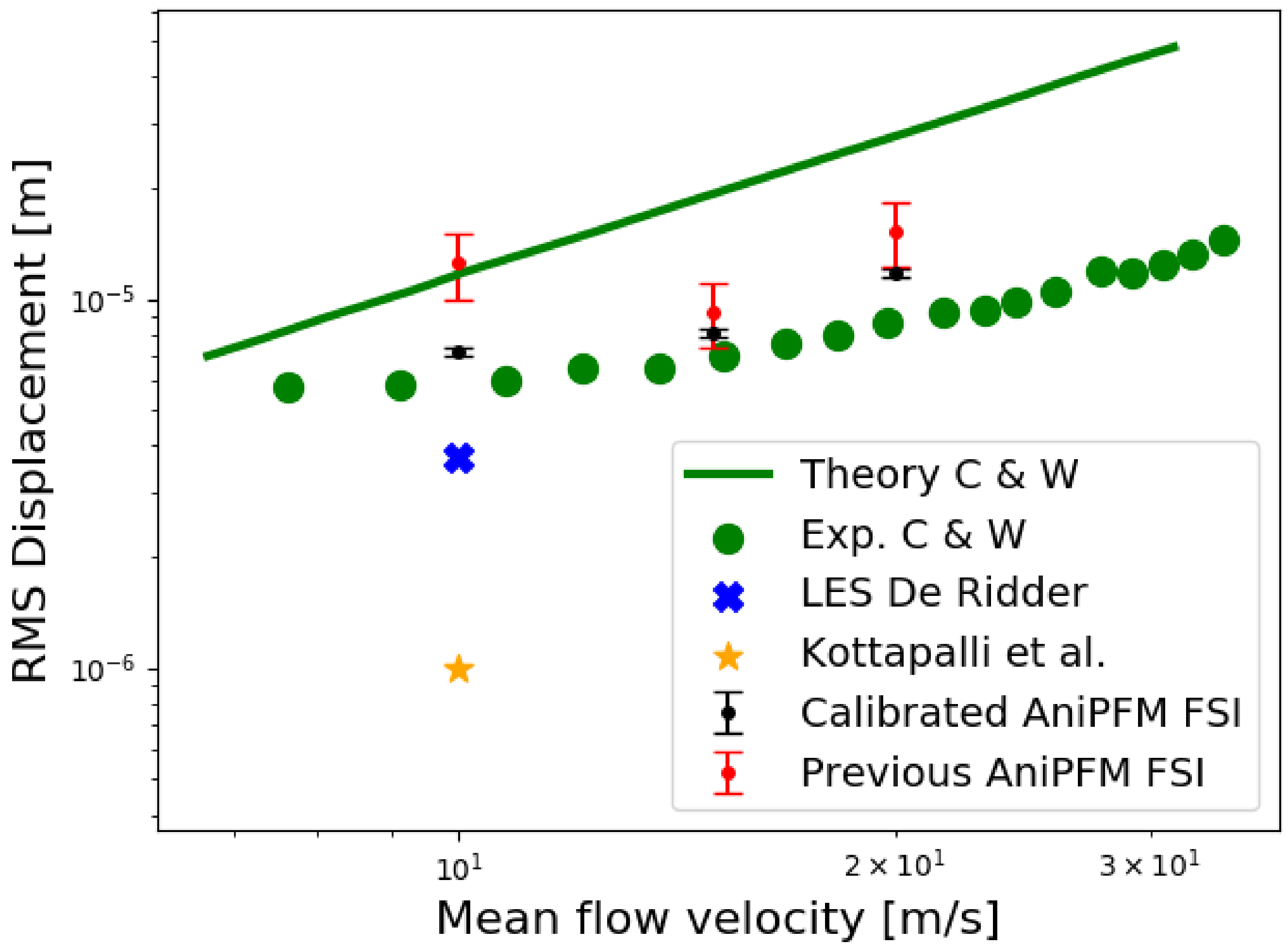


Brass Beam – FSI case

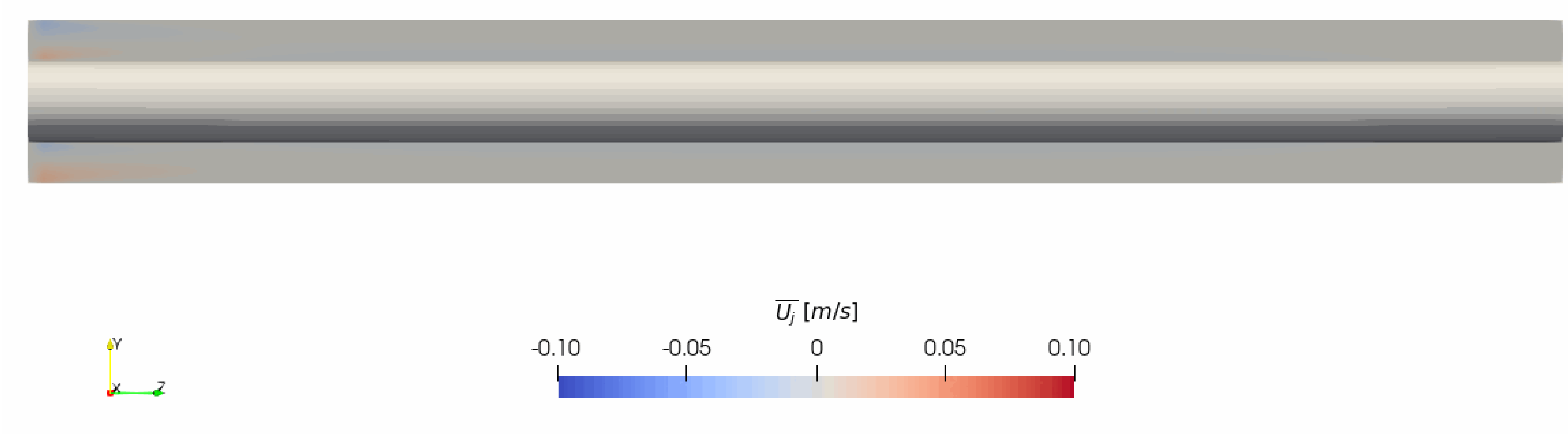


AQTIVATE

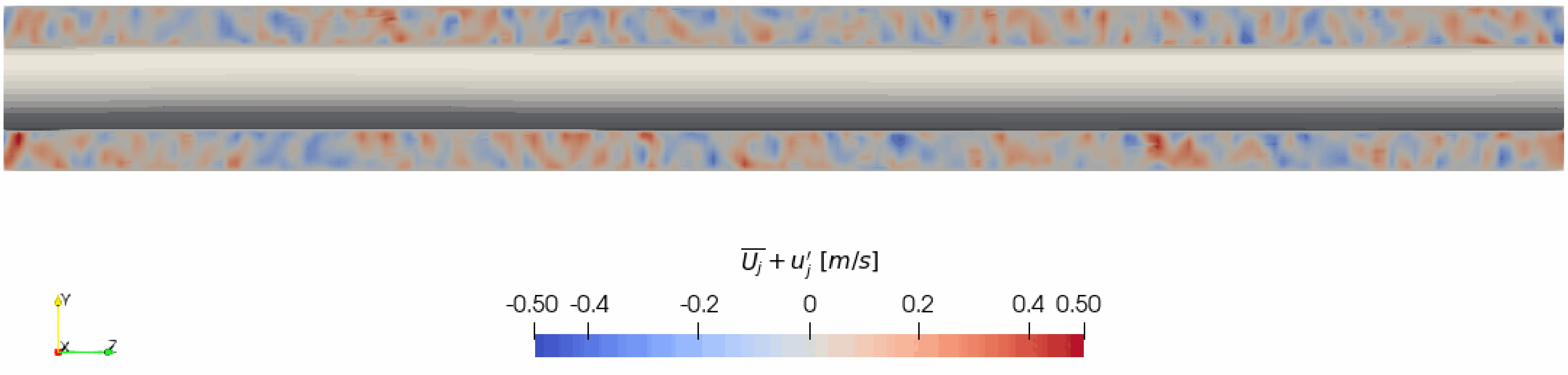
Comparison w/ validation data and other approaches [5-8]



URANS FSI



URANS + AniPFM



References

[1] The pressurized water reactor https://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

[2] P. Flowers, W.R. Robinson, R. Langley, and K. Theopold. Chemistry. OpenStax, 2015

[3] S. Hickel and S. Hulshoff. CFD 3 lecture notes: Wall bounded turbulence. Delft University of Technology, 2021.

[4] H. Abe, H. Kawamura, and Y. Matsuo. Direct numerical simulation of a fully developed turbulent channel flow with respect to the Reynolds number dependence. Journal of Fluids Engineering, 123(2):382–393, Feb 2001.

[5] S. sheng Chen, M. W. Wambsganss, Parallel-flow-induced vibration of fuel rods, Nuclear Engineering and Design 18 (2) (1972) 253–278 doi:10.1016/0029-5493(72)90144-6.

[6] J. de Ridder, Computational analysis of flow-induced vibrations in fuel rod bundles of next generation nuclear reactors, Ph.D. thesis, Ghent University (2015).

[7] S. Kottapalli, A. Shams, A. Zuijlen, M. Pourquie, Numerical investigation of an advanced URANS based pressure fluctuation model to simulate non-linear vibrations of nuclear fuel rods due to turbulent parallel-flow, Annals of Nuclear Energy 128 (2019) 115–126. doi:10.1016/j.anucene.2019.01.001.

[8] N. van den Bos, Turbulence-induced vibrations prediction through use of an anisotropic pressure fluctuation model, Master's thesis, TU Delft (2022)

Thank you!