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Multi-Fidelity Methods for Aerodynamic Flows

Andrew Mole (PhD Student)

with Alistair Revell and Alex Skillen
The Modelling & Simulation Centre

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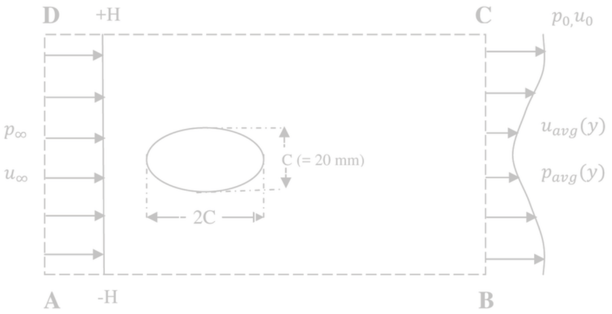
Motivations

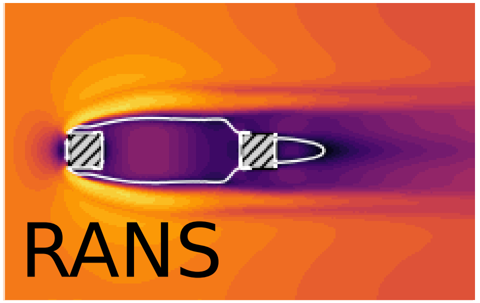
*Often in a test campaign a large range of the parameter space is of interest, but **resources are limited**. Multiple methods are available to predict the aerodynamic performance with different levels of **fidelity**. Often the methods that provide the highest fidelity require the most resources.*

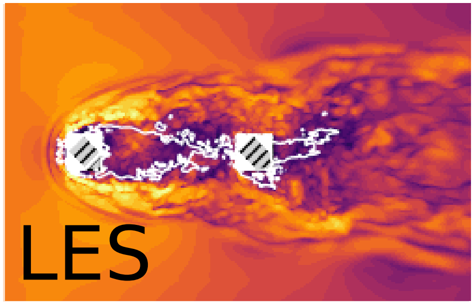
Multi-Fidelity

Analytical Models



CFD





Experimental Tests

Accuracy

Resources

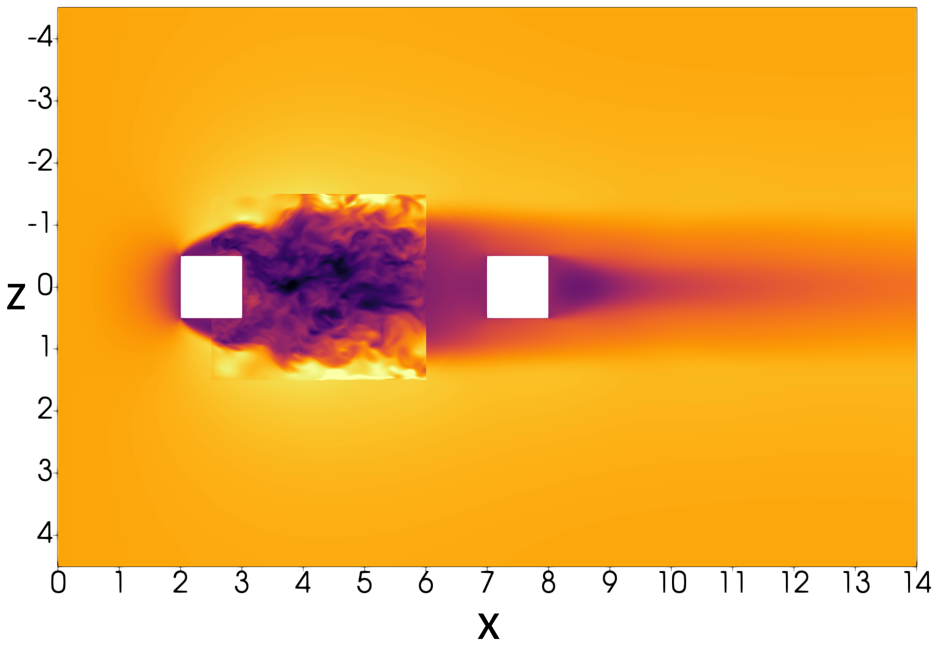
Multi-fidelity methods are frameworks that combine multiple approaches with different confidence levels and disparate sizes of data sets.

Methods

Reduce the amount of LES that is needed, replacing with RANS.

Embedded LES

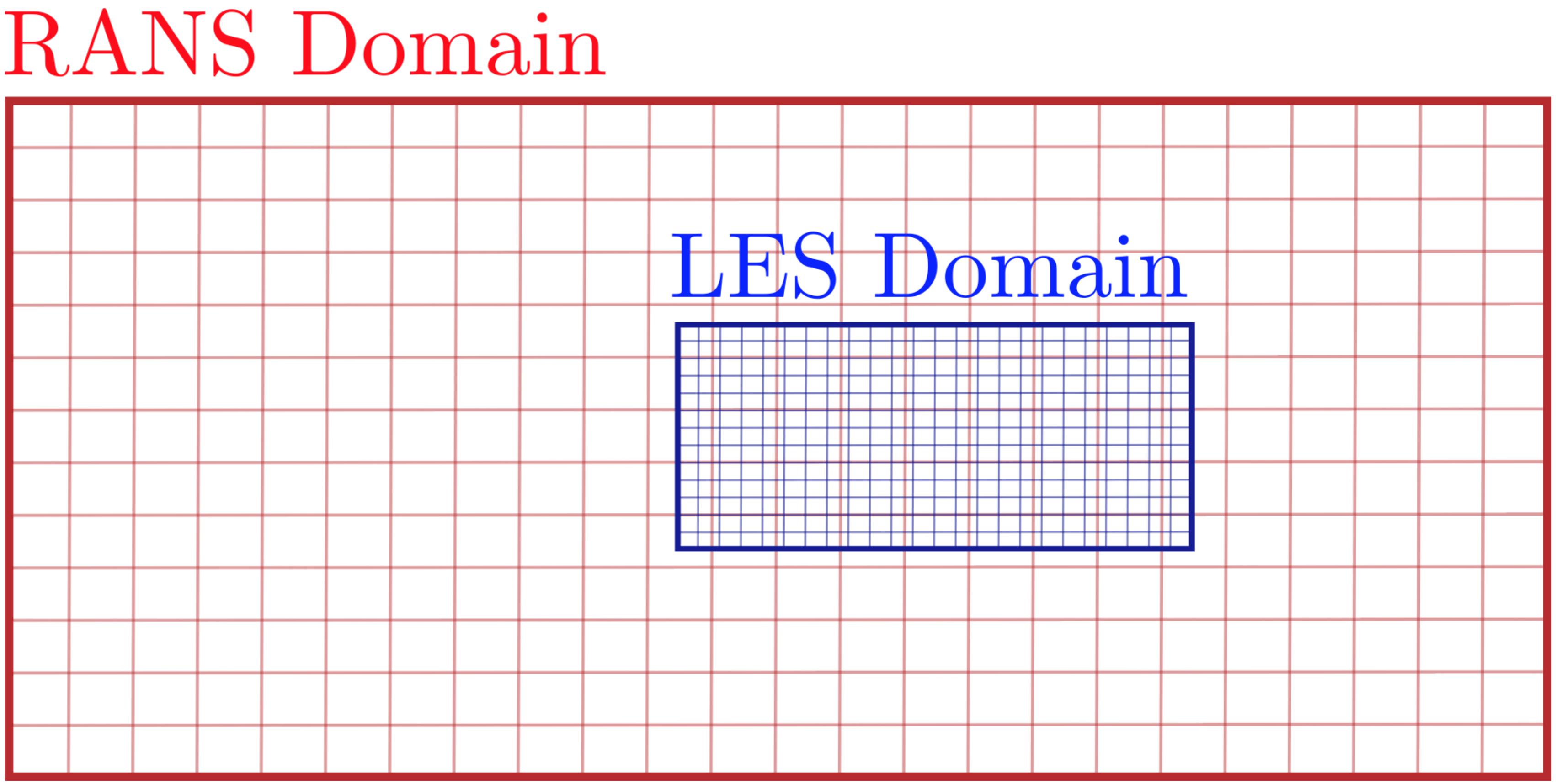
Limit the LES in ***physical*** space



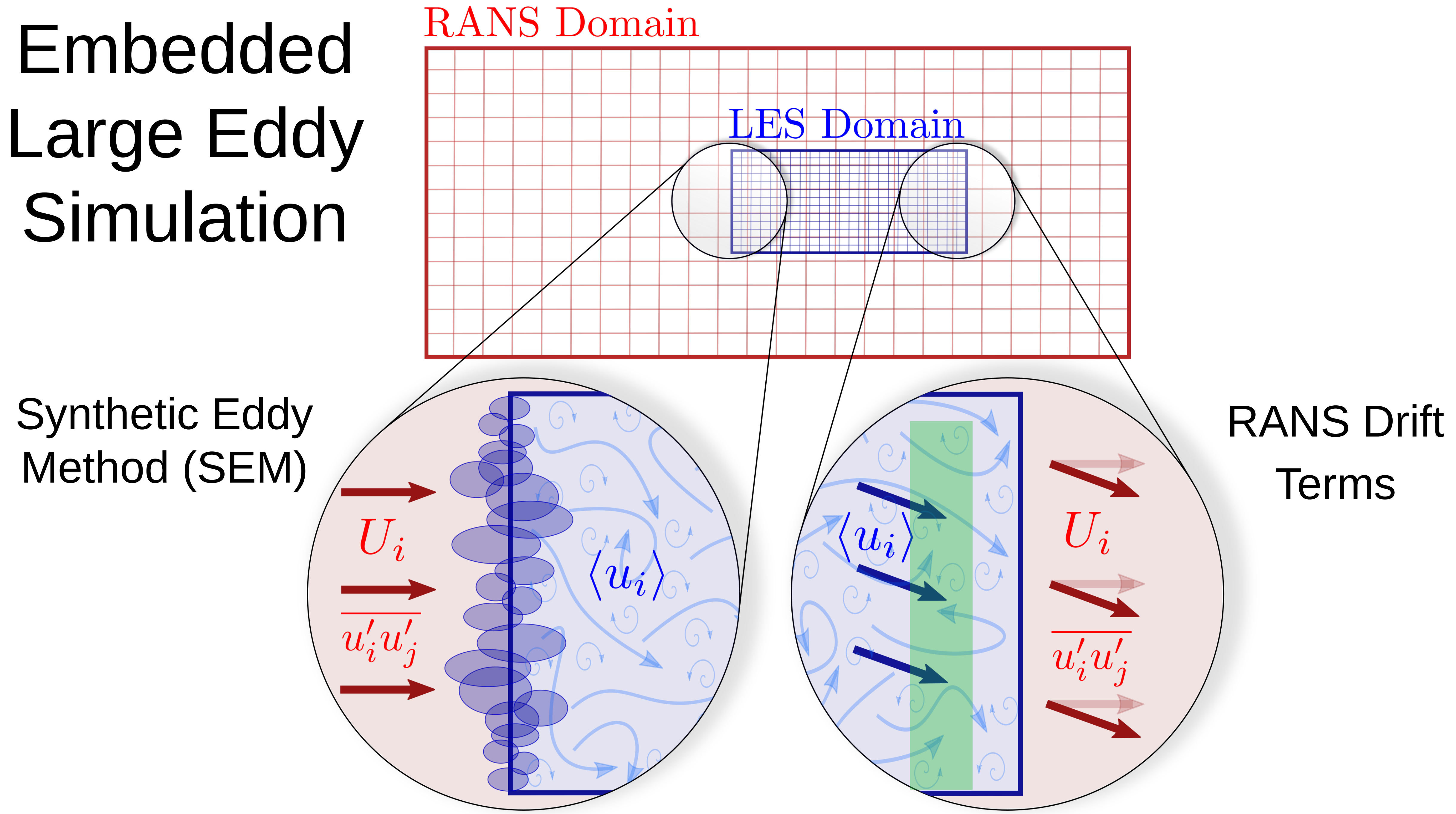
Multi-Fidelity Surrogate Model

Limit the LES in ***parameter*** space

Embedded Large Eddy Simulation



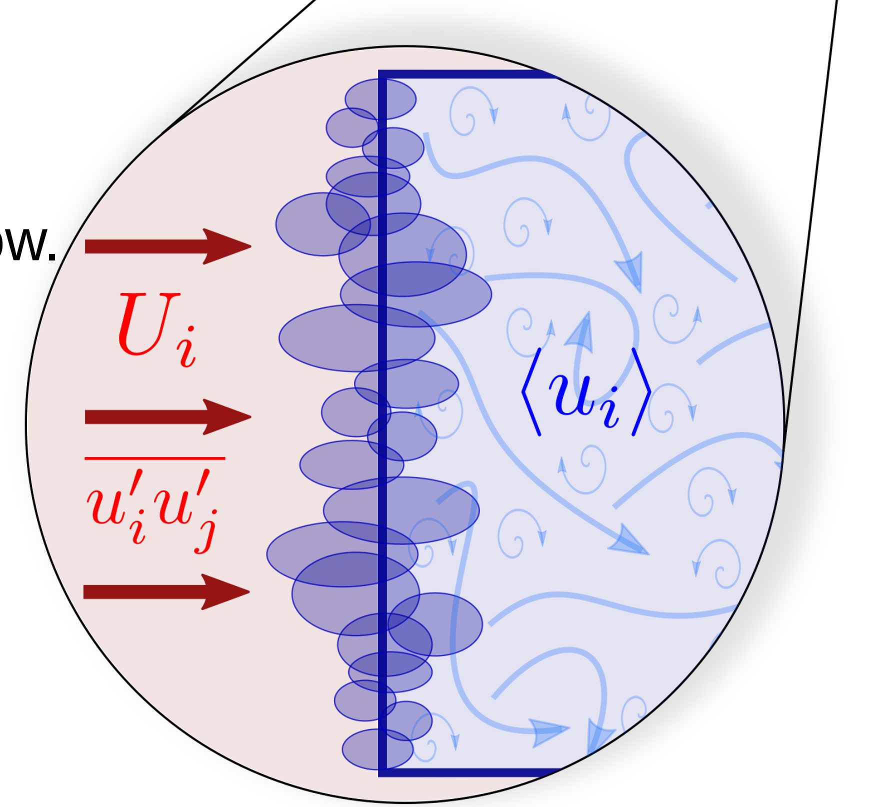
Embedded LES *(ELES) uses small areas of LES within a large RANS domain to provide the* ***details*** *and* ***accuracy*** *where it is needed.*


Embedded Large Eddy Simulation
RANS Domain
LES Domain
Synthetic Eddy Method (SEM)
U_i
$\overline{u'_i u'_j}$
$\langle u_i \rangle$
RANS Drift Terms
$\langle u_i \rangle$
U_i
$\overline{u'_i u'_j}$

Synthetic Eddy Method

A fluctuating velocity field is ***superimposed*** on to the mean flow.

$$u_j = \overline{u_j} + a_{ij} u'_j$$



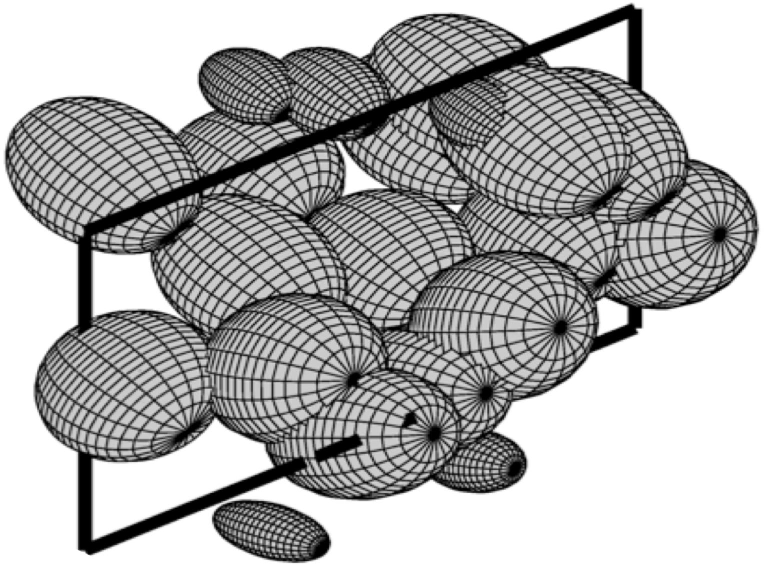
A collection of ***eddies*** contribute to the fluctuating velocity.

$$u'_j(x_j, t) = \frac{\sum_{i=1}^{N} \epsilon_{ij} f(x_j - x_{ij}, \sigma_{ij})}{\sqrt{\left\langle \sum_{i=1}^{N} f^2(x_j - x_{ij}, \sigma_{ij}) \right\rangle^{avg}}}$$

The size, shape and strength of these eddy structures are controlled to ***match the RANS*** turbulence statistics.

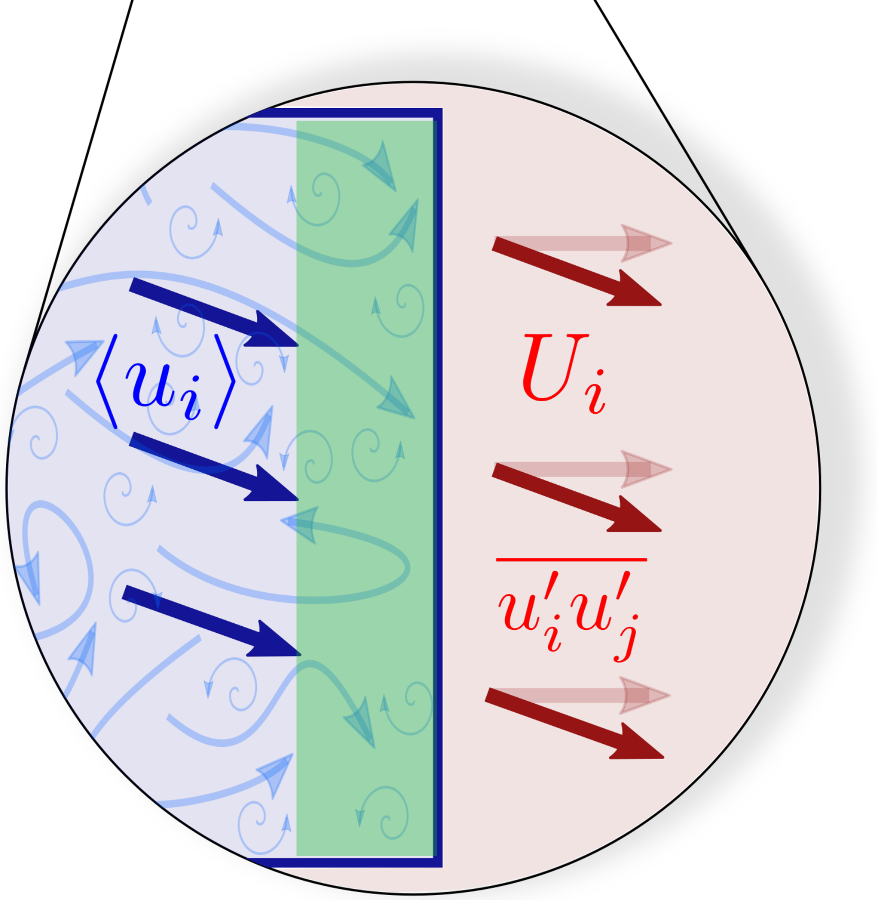
$$a_{ij} = \begin{bmatrix} \sqrt{R_{11}} & 0 & 0 \\ R_{21}/a_{11} & \sqrt{R_{22} - a_{21}^2} & 0 \\ R_{31}/a_{11} & (R_{32} - a_{21}a_{31})/a_{22} & \sqrt{R_{33} - a_{31}^2 - a_{32}^2} \end{bmatrix}$$

$$\sigma_{ij} = \max\left(\min\left(\frac{R_{jj}^{3/2}}{\varepsilon}, \sigma_{max}\right), \Delta_{max}\right)$$



Drift Terms

Drift terms are introduced to the RANS equations as ***source terms*** to correct RANS towards LES solution in ***overlapping region***.



Momentum Force

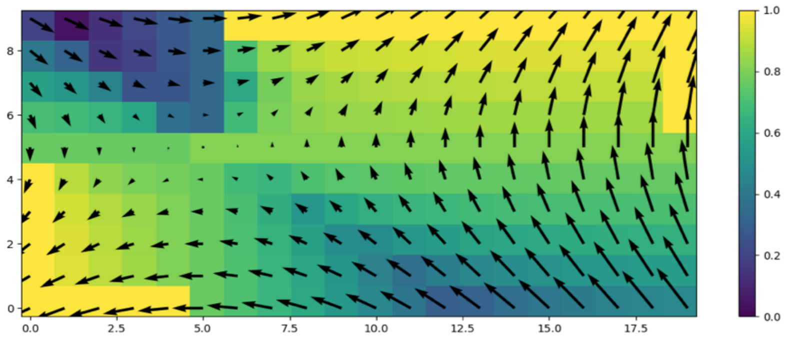
$$F_i = \frac{\overline{\langle u_i \rangle}^{LES} - U_i^{RANS}}{\gamma_R} \times Vw$$

T.K.E. Force

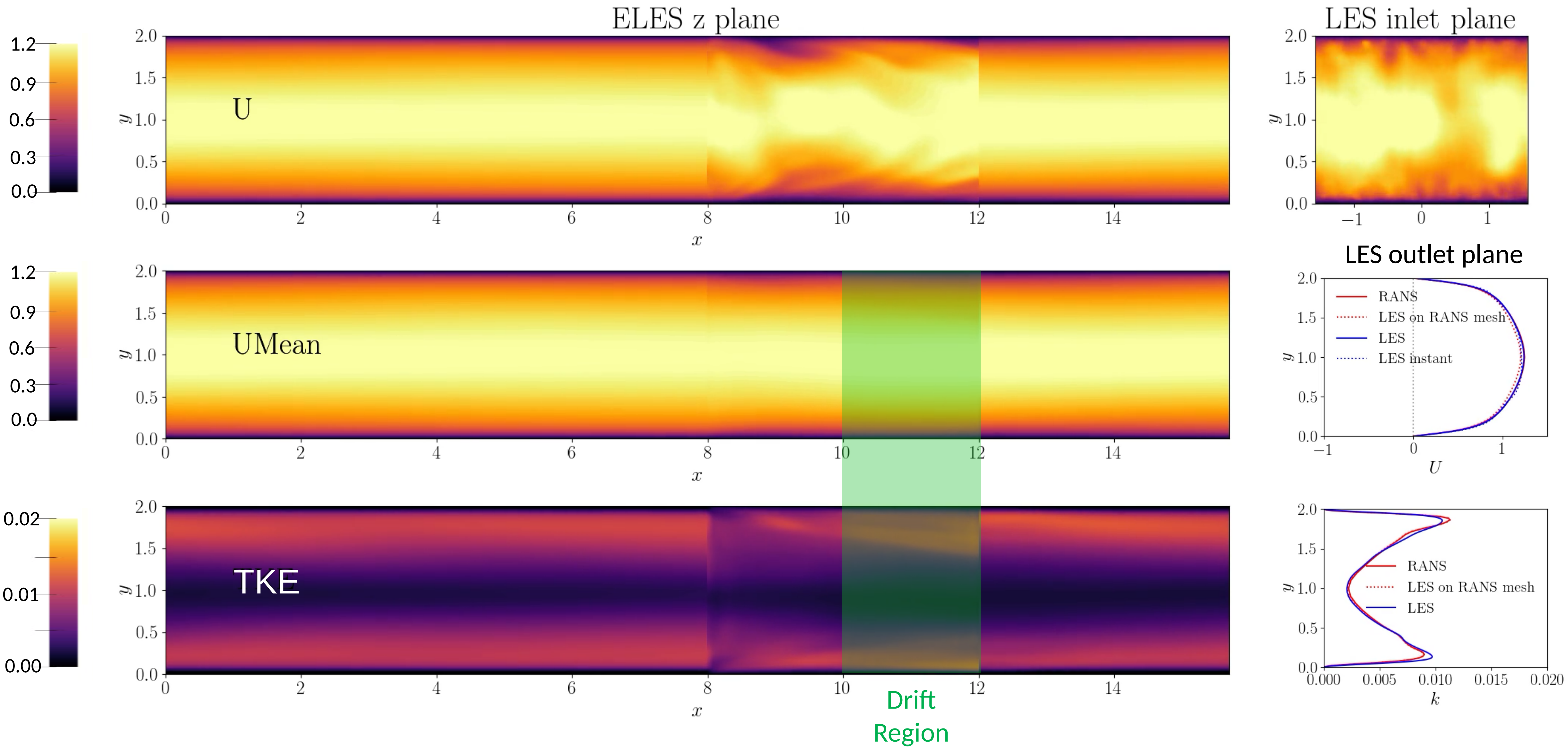
$$F_k = \frac{0.5\, tr\left(\overline{\langle u_i \rangle \langle u_j \rangle}\right)^{LES} + k_{SGS}^{LES} - k^{RANS}}{\gamma_R} \times Vw$$

Time Relaxation

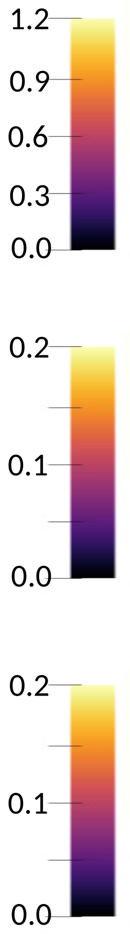
$$\gamma_R = \max\left(C_\gamma \frac{k}{\varepsilon},\ dt\right)$$

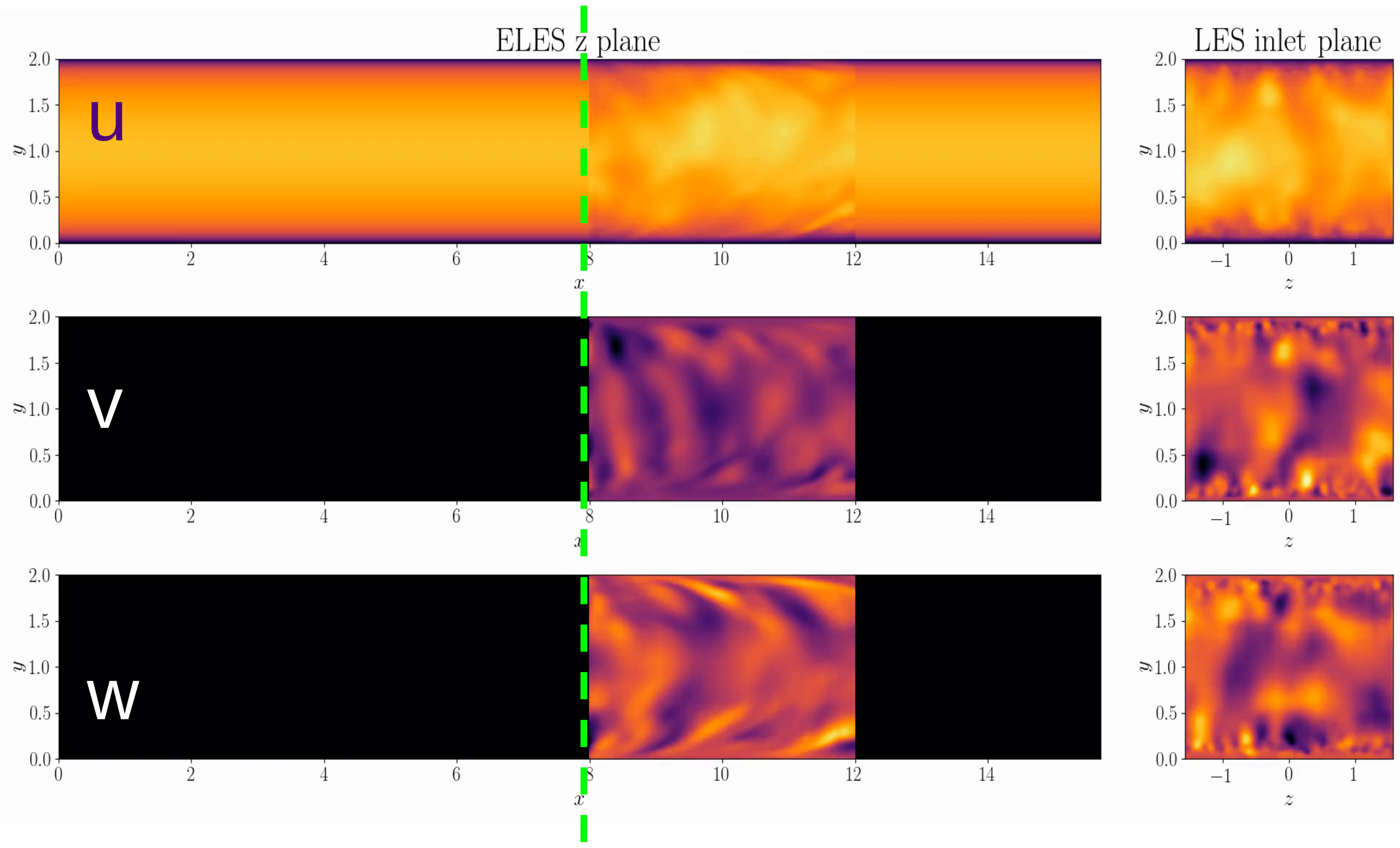


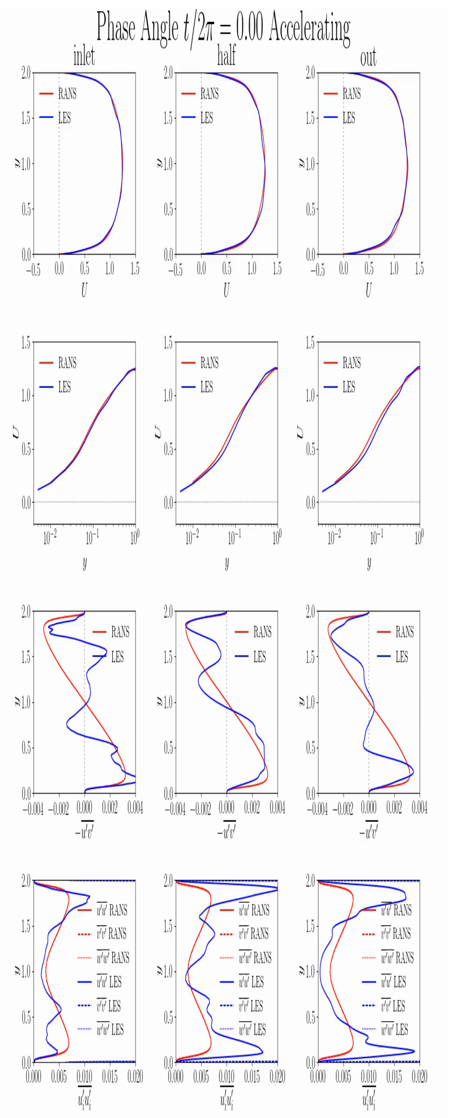
ELES Channel Flow



ELES Pulsating Channel Flow





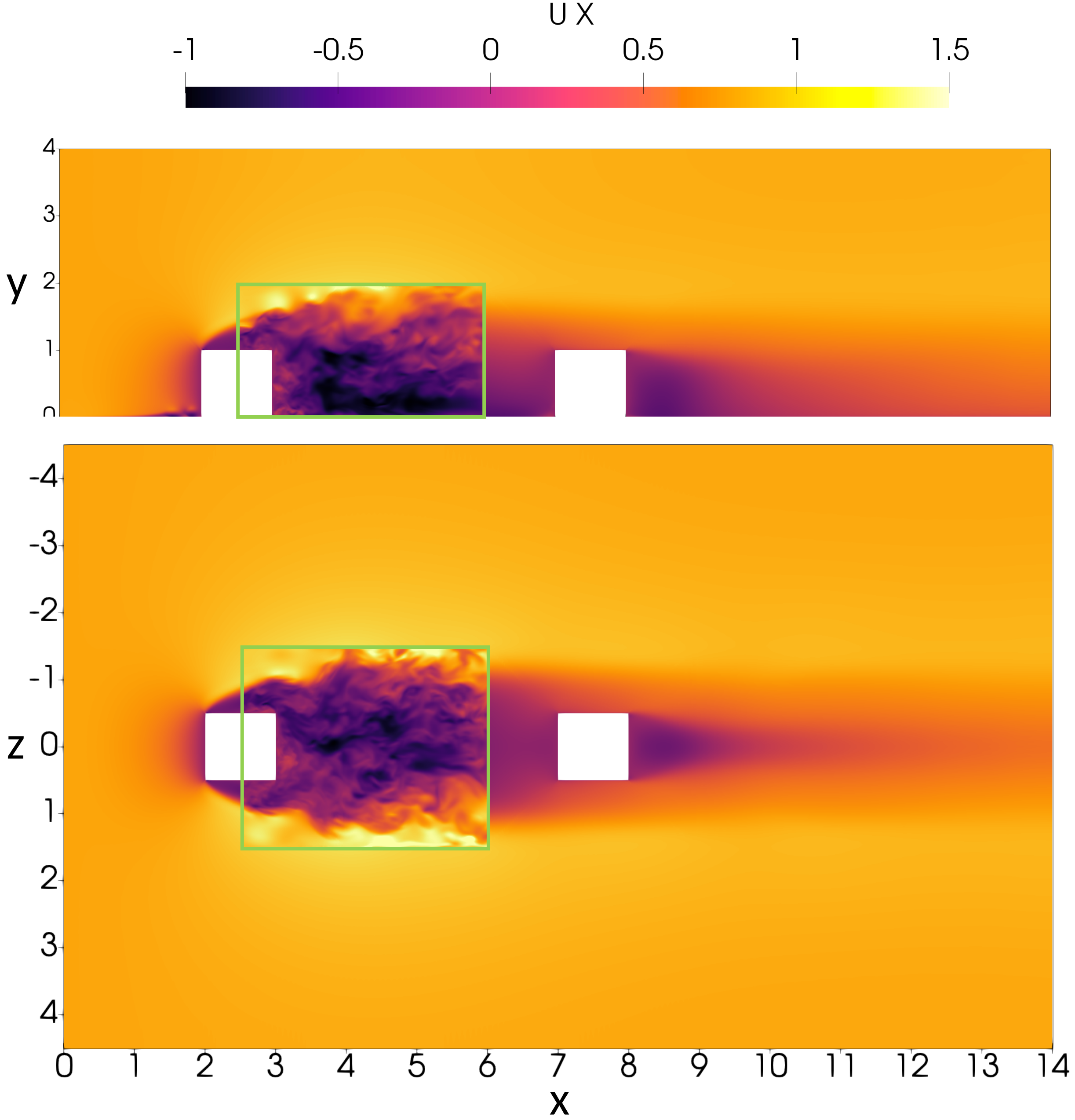


ELES Tandem Cubes

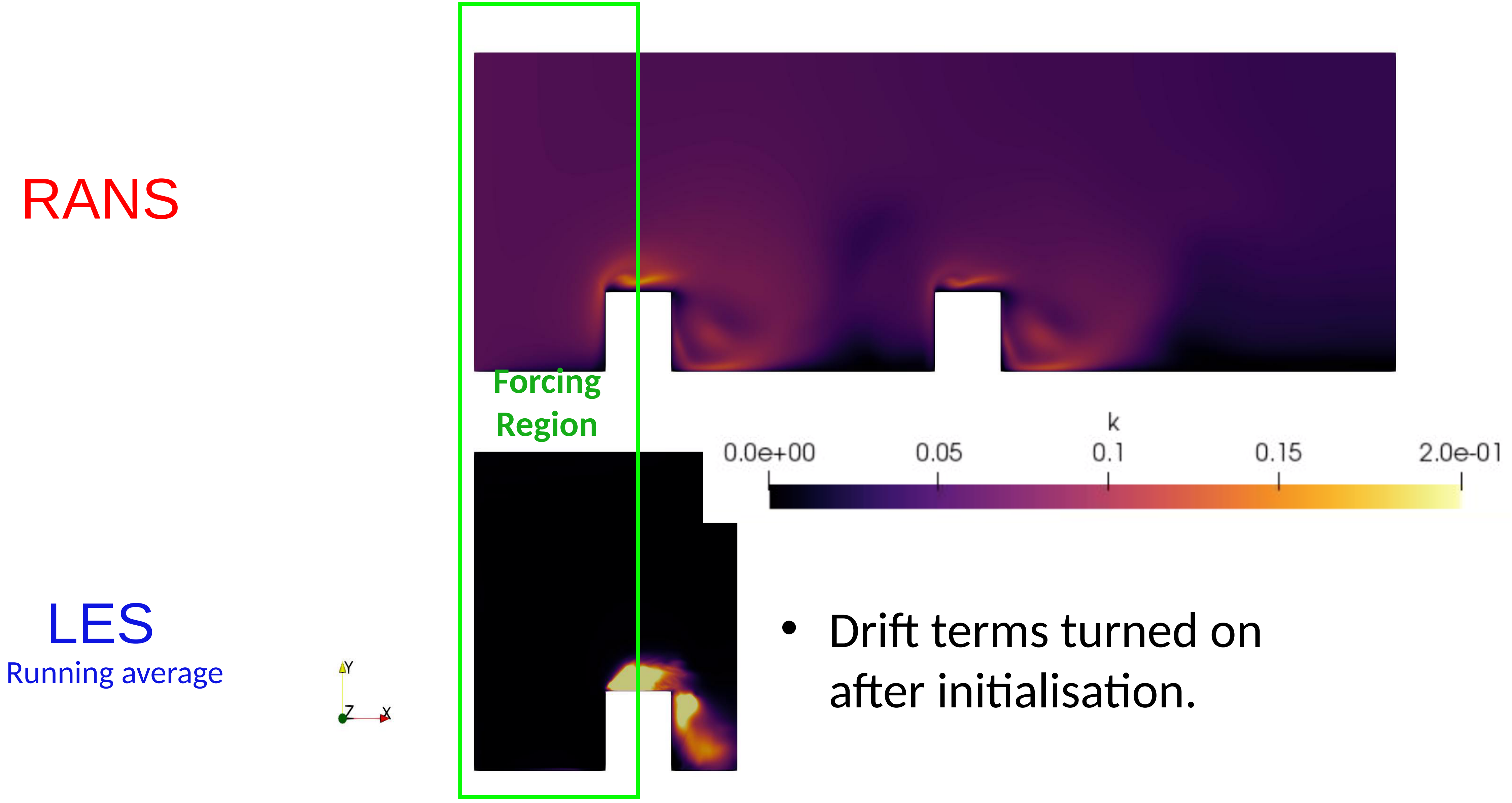
- ***Confined*** the LES to a small region of the domain.

- Multiple boundaries ***switching*** between inlet and outlet conditions.

- Allows for ***arbitrary placement*** of LES within domain.



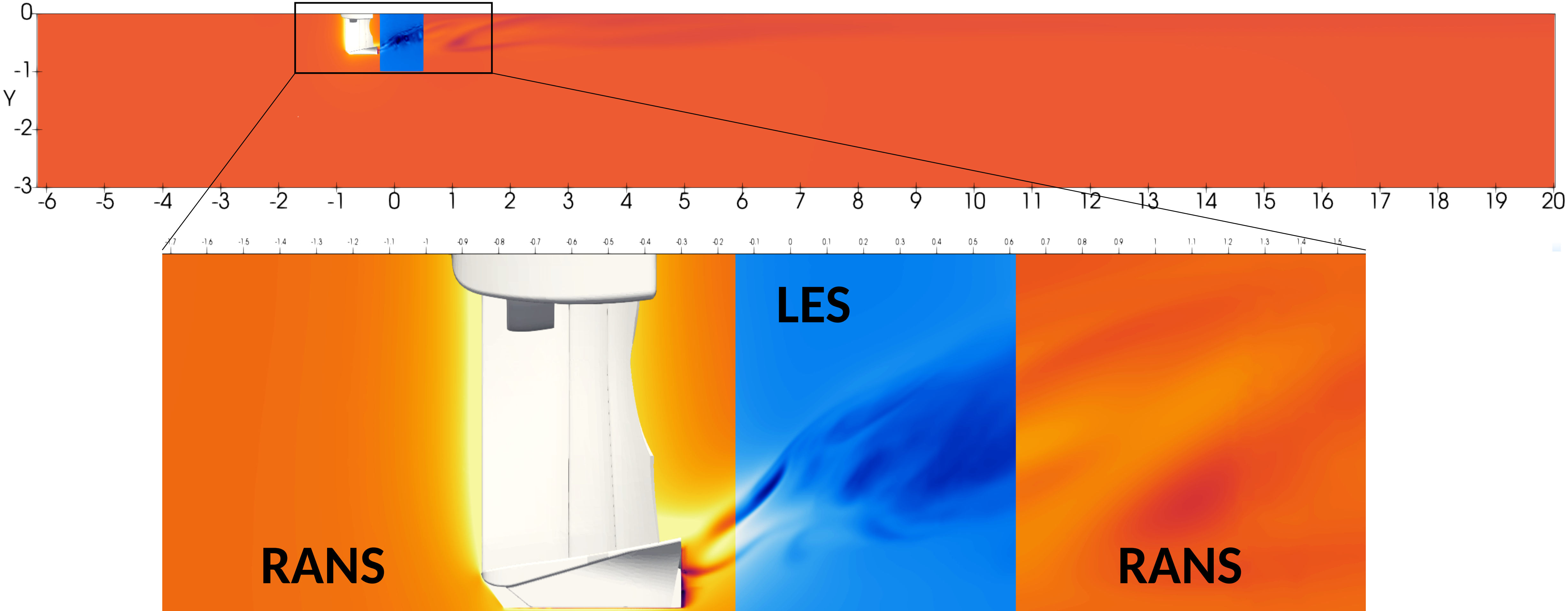
Tandem Cubes – Drift Terms



- Drift terms turned on after initialisation.

ELES F1 Front W

*Initial testing with an LES region confined to **directly behind** the front wing to capture the **vortex interactions** in this region.*



Methods

Reduce the amount of LES that is needed, replacing with RANS.

Embedded LES

Limit the LES in ***physical*** space

Multi-Fidelity Surrogate Model

Limit the LES in ***parameter*** space

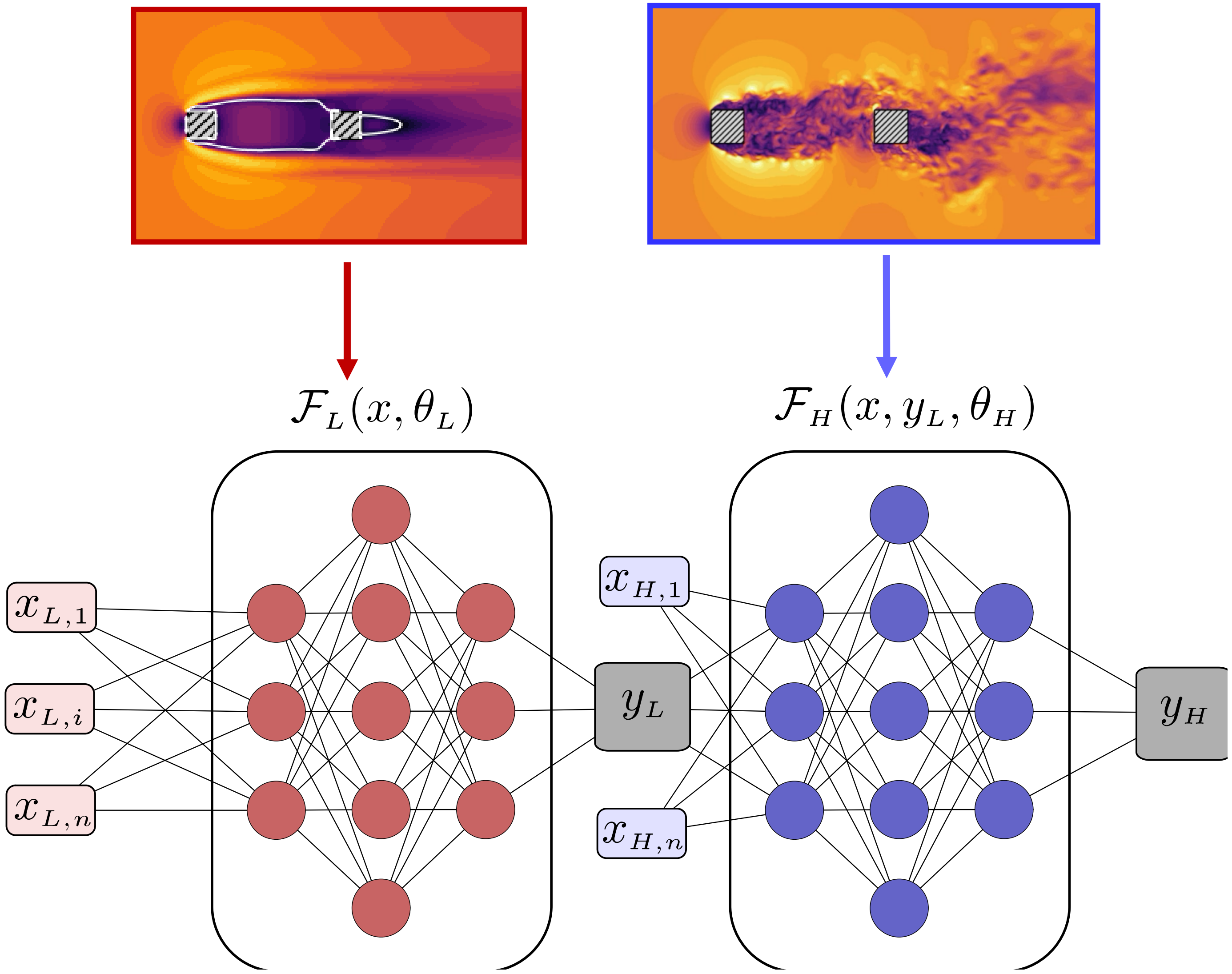
Multi-Fidelity Surrogate Model

Combine RANS and LES in parameter space.

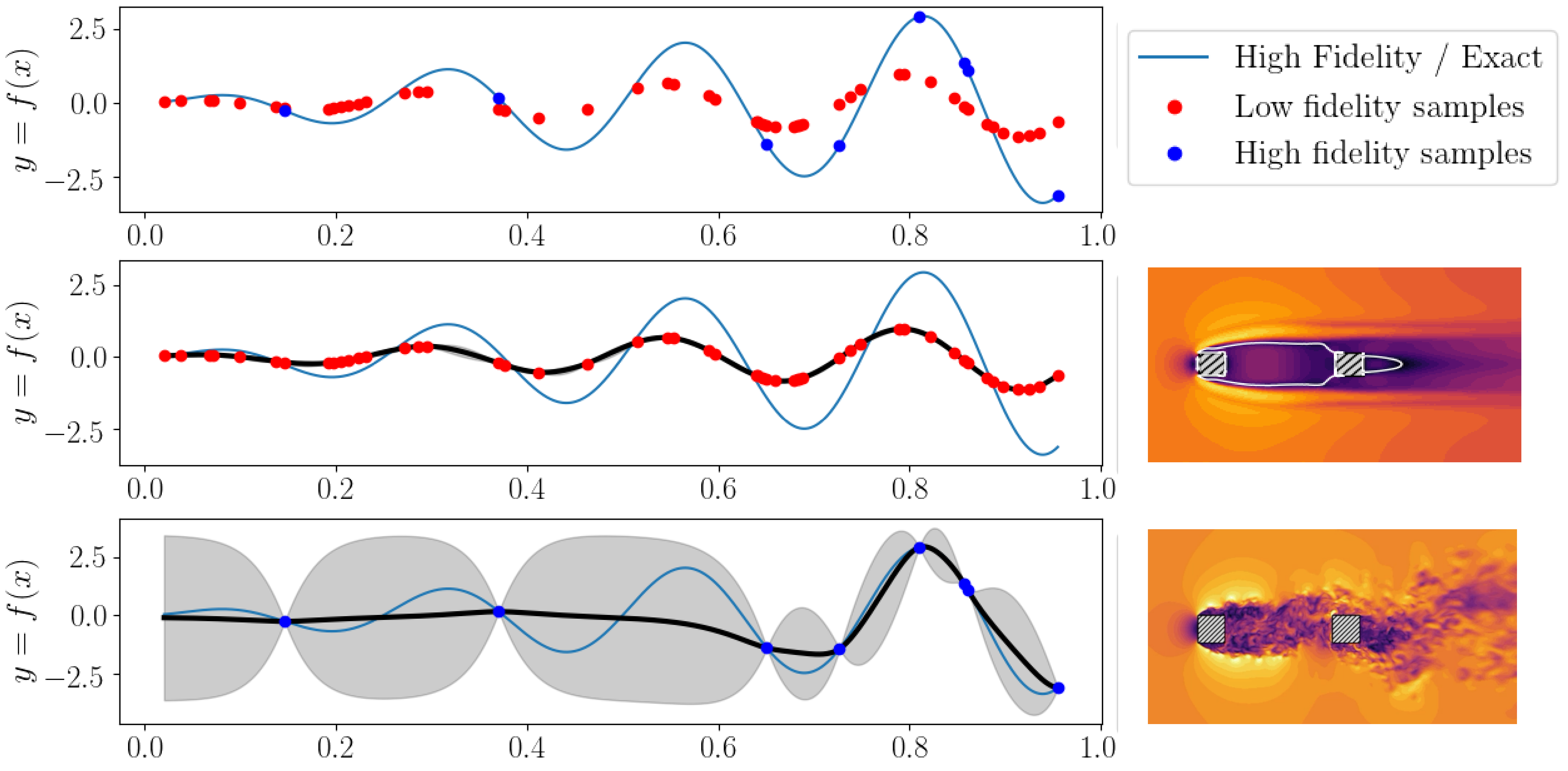
- Using ***two regression models*** (GPR or MLP) to generate the multi-fidelity surrogate model.

- ***Low-fidelity*** model provides additional input to the ***high-fidelity*** model.

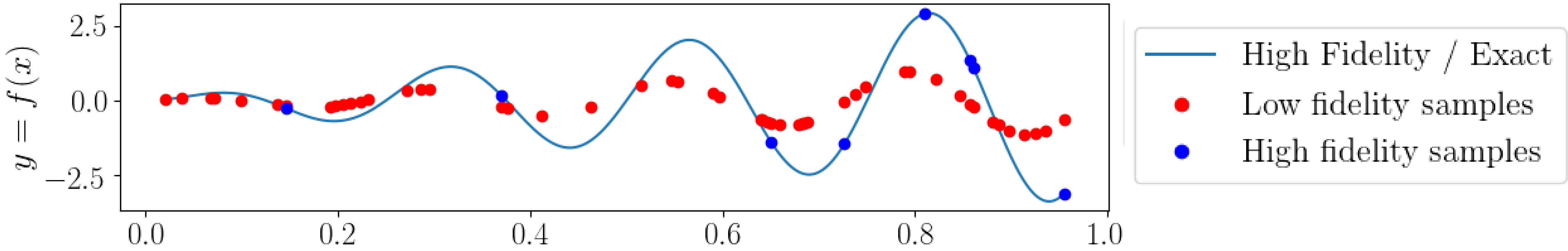
- Works by identifying the ***relationship*** between the

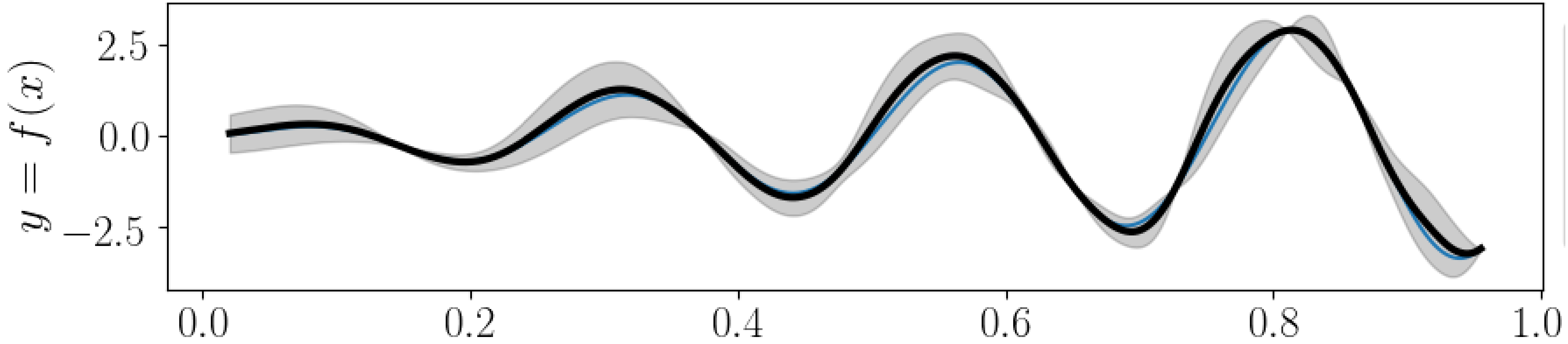


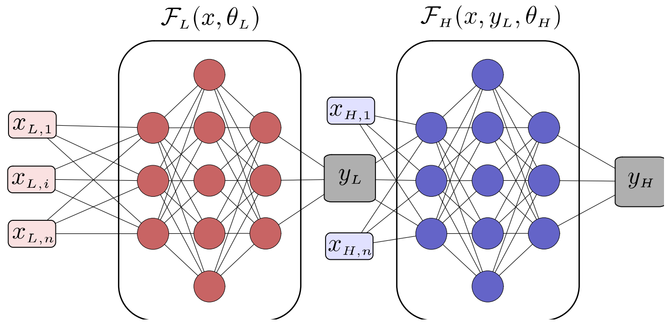
Multi-Fidelity Surrogate Model

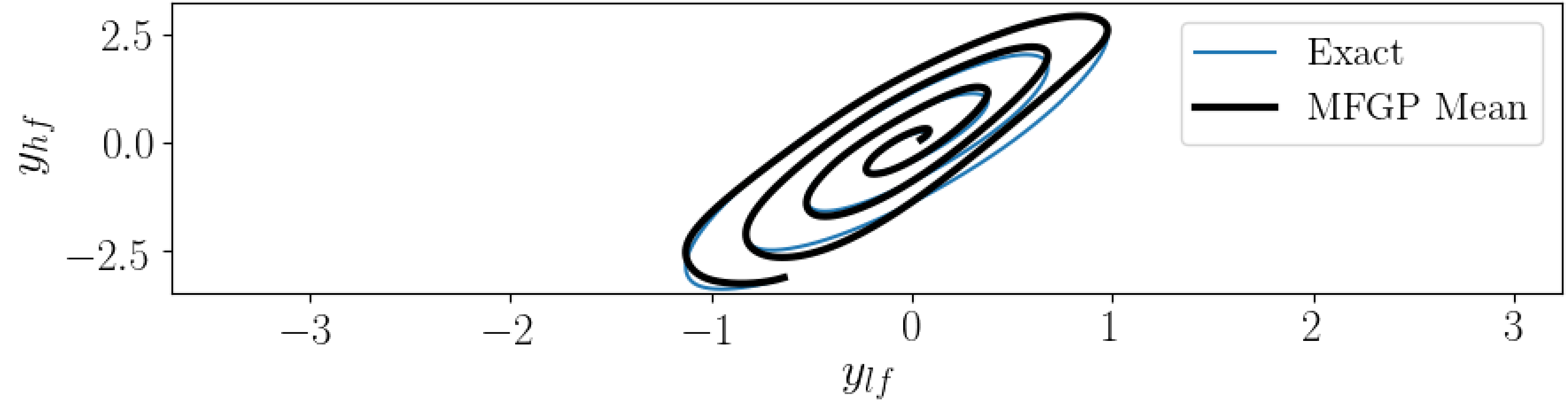


Multi-Fidelity Surrogate Model



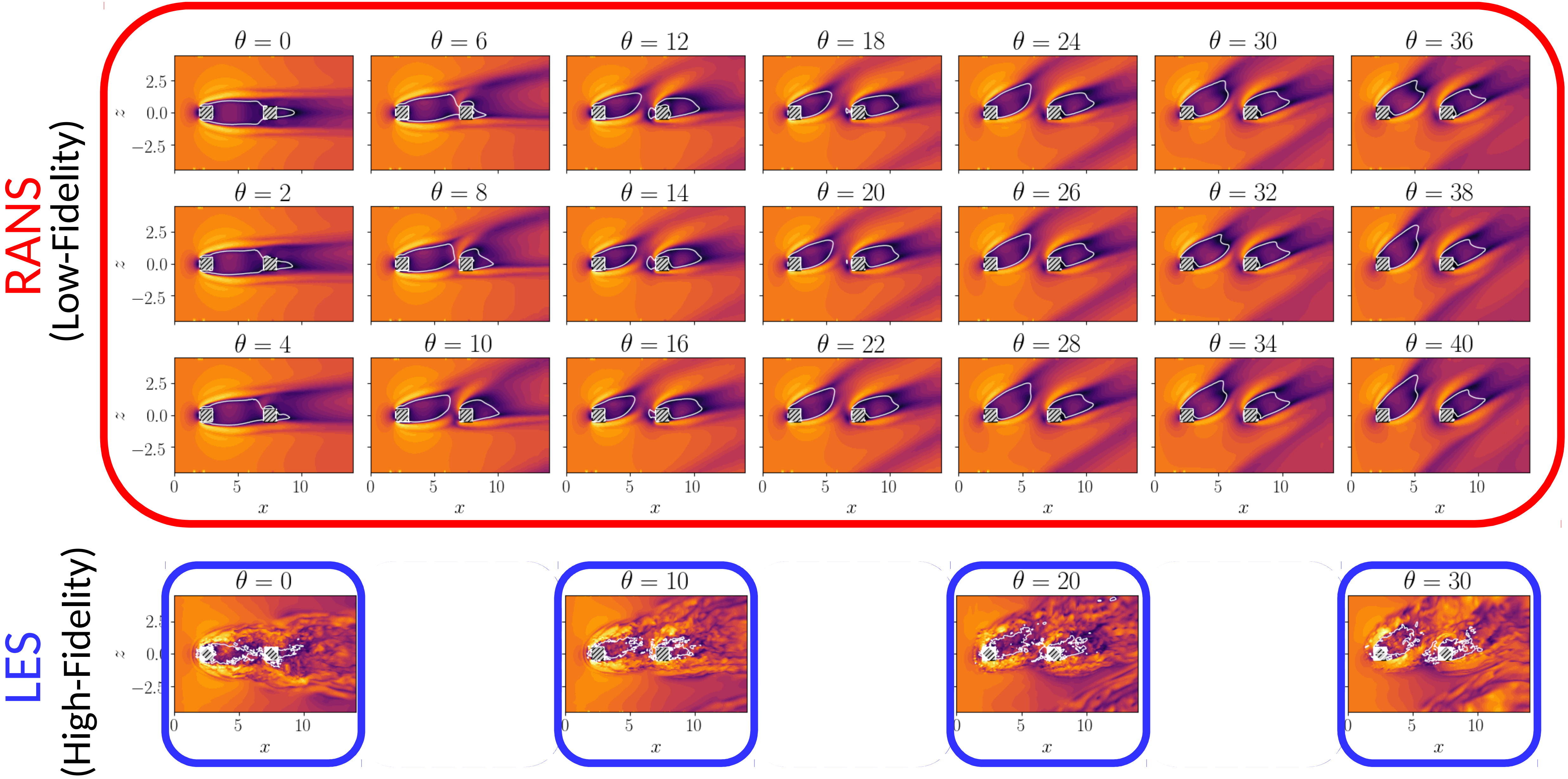






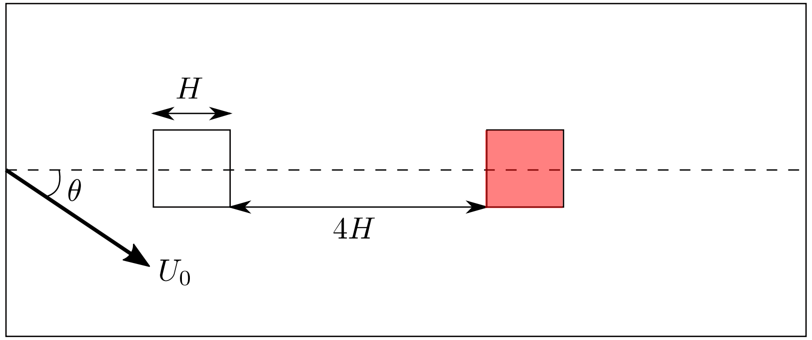
The model predicts the nonlinear relationship between low-fidelity and high-fidelity data

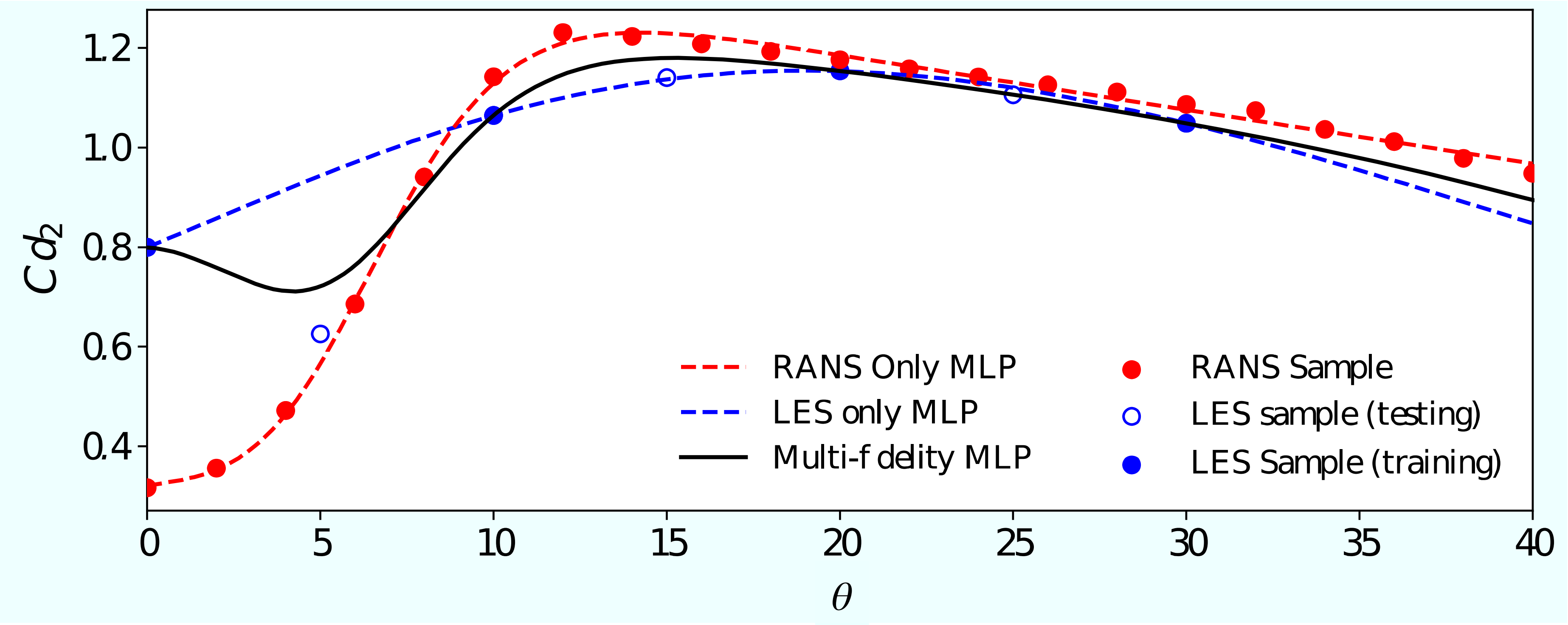
Multi-Fidelity Simulations



Yaw - Drag Surrogate Model

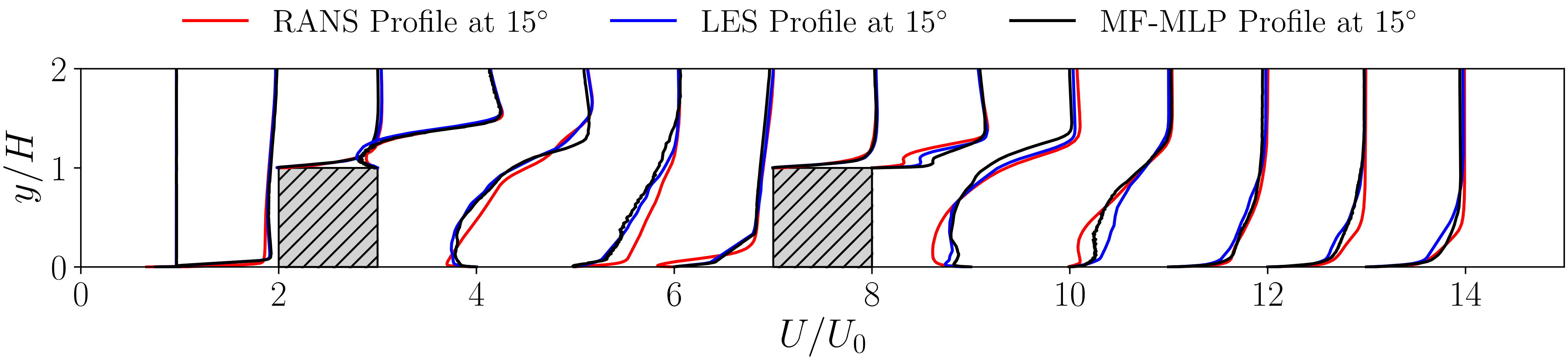
- ***Drag coefficient*** of the second cube (Cd_2), at varying yaw angles (θ).



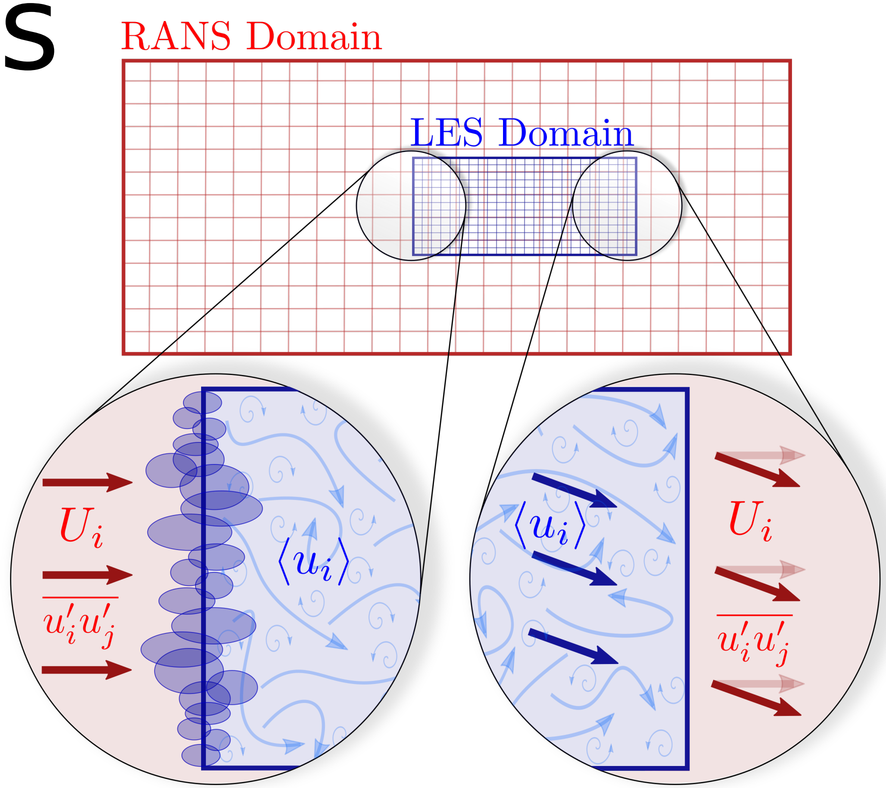


Surrogate Model Profiles

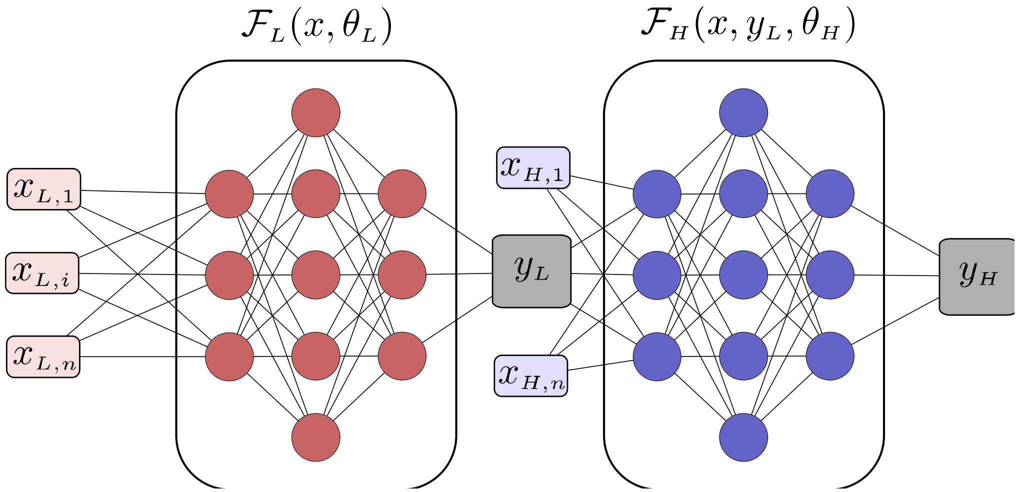
- Model ***multiple local variables*** to reconstruct flow at unseen locations in parameter space.
- Model learning using the whole ***velocity profile*** rather than a individual data points.
- Constructed centreline velocity profiles are ***compared to untrained LES*** velocity profiles.



Conclusions



- ***Embedded LES*** uses small areas of LES within a large RANS domain to provide the details and accuracy only where it is needed whilst limiting the computational expense by using RANS elsewhere.



- ***Multi-fidelity surrogate models*** extend the range of data points in parameter space obtained with LES using additional data points from RANS.