Oak Ridge National Laboratory

Characterization of buoyancy-driven eddies of liquid metal MHD flows in breeding blankets

Daniel Suarez
Fusion Energy Division, Blanket and Fuel Cycle Group
Oak Ridge National Laboratory

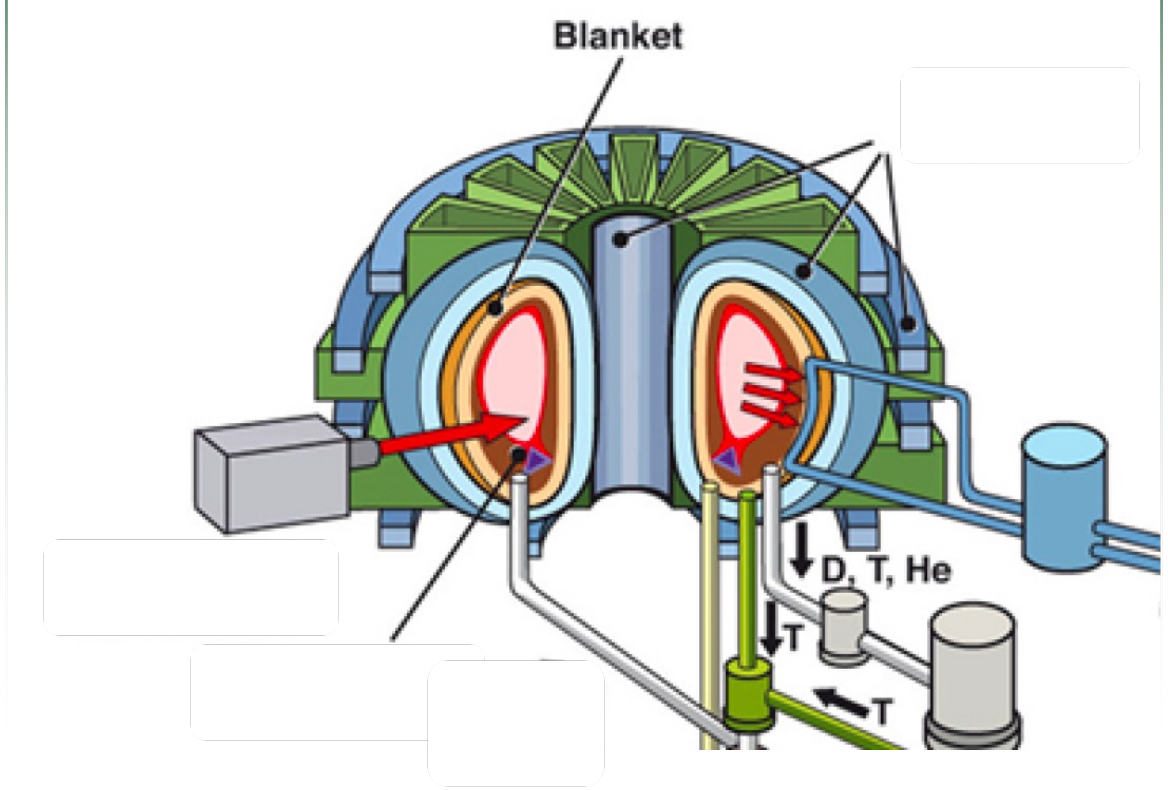
Co: Eduardo Iraola (BSC), Joaquim Serrat (Roquet Hydraulics, SL)

Introduction

- Buoyant liquid metal MHD flows in breeding blankets
- Will the flow show eddies?

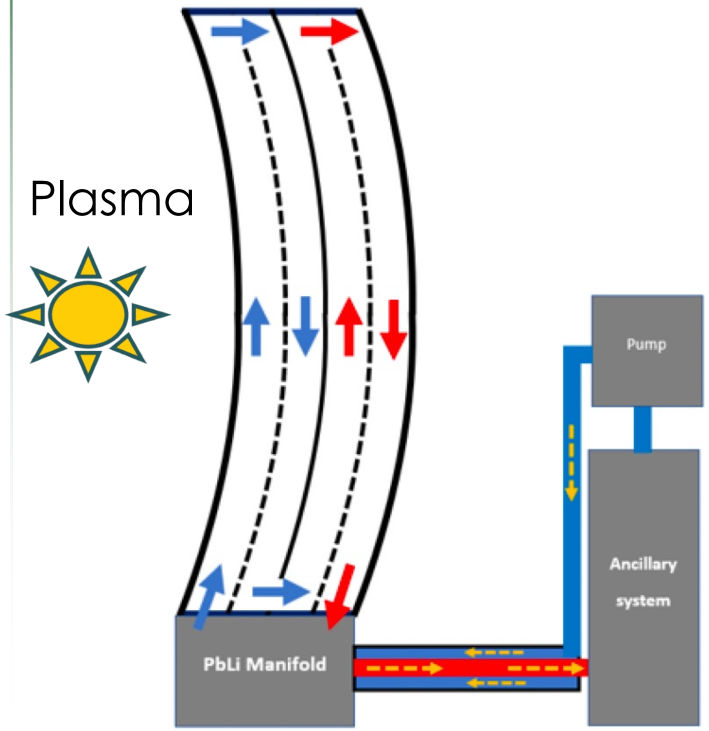
Introduction: liquid metal flows in vertical channels

Breeding blanket



Max Planck Institute of Plasma Physics

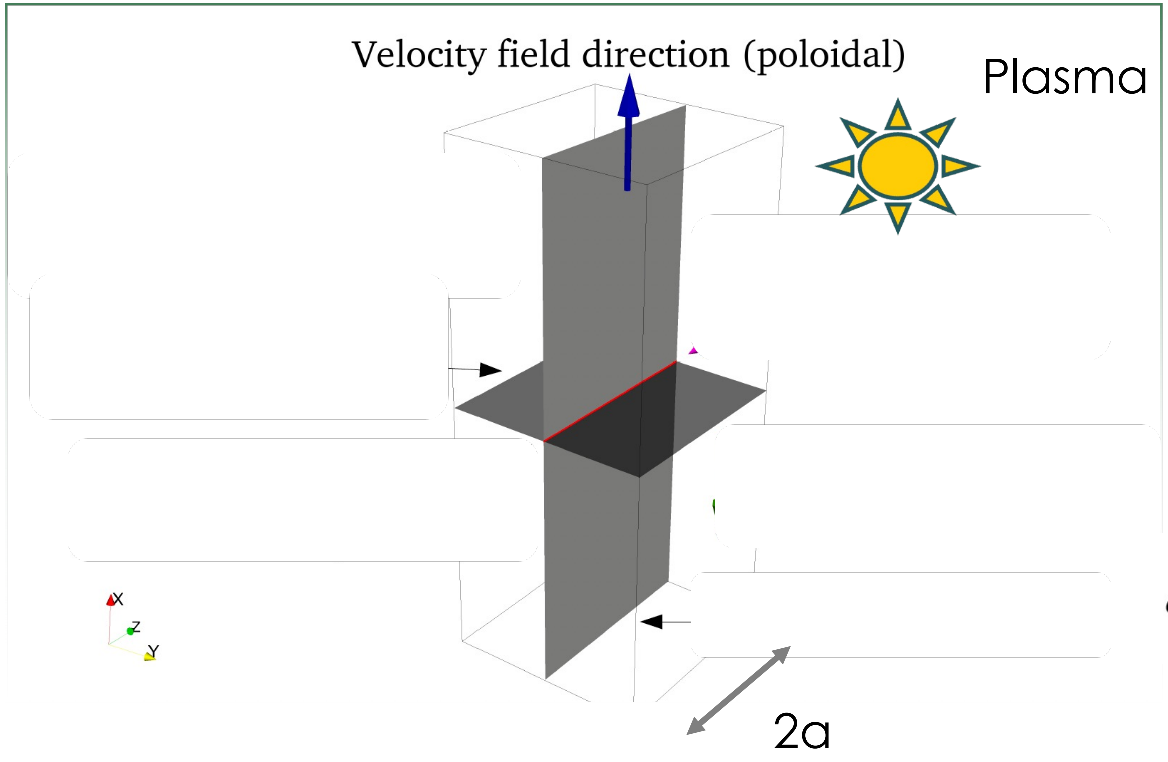
Vertical channels



Smolentsev (2021)

Introduction: an orthogonal simplified model

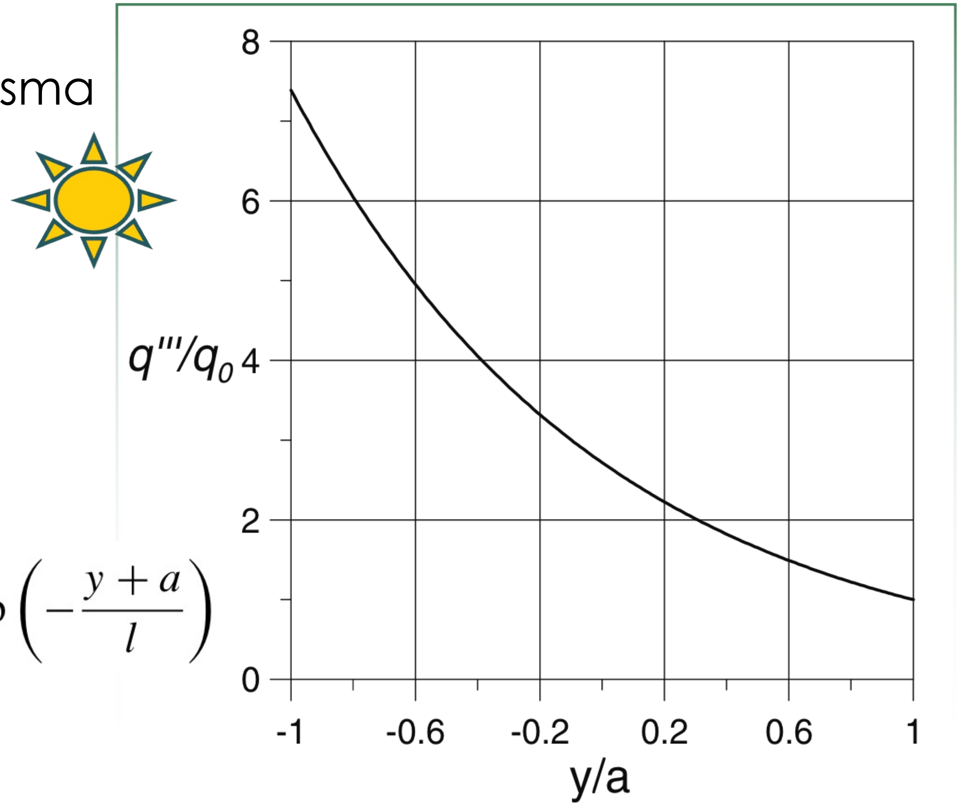
Relevant directions of the problem



Suarez (2022)

Non-uniform volumetric heat source

Plasma

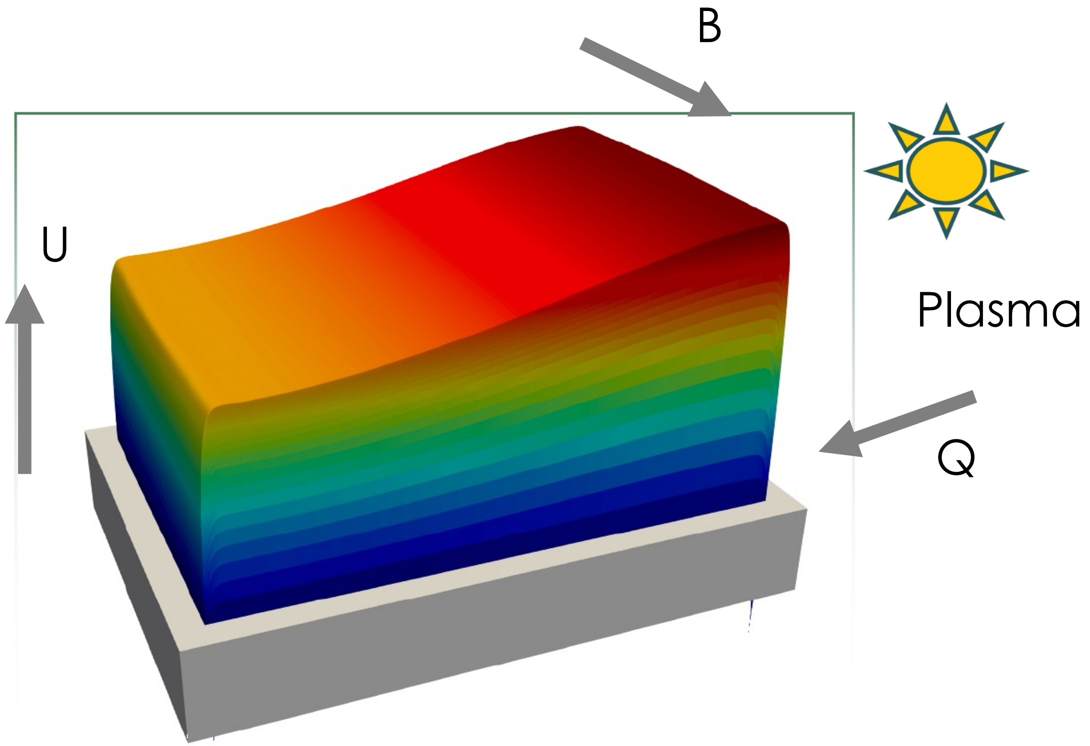


$$q'''(y) = q_0 \exp\left(-\frac{y+a}{l}\right)$$

Vetcha et al. (2013)

Introduction: a Quasi 2-Dimensional (Q2D) flow

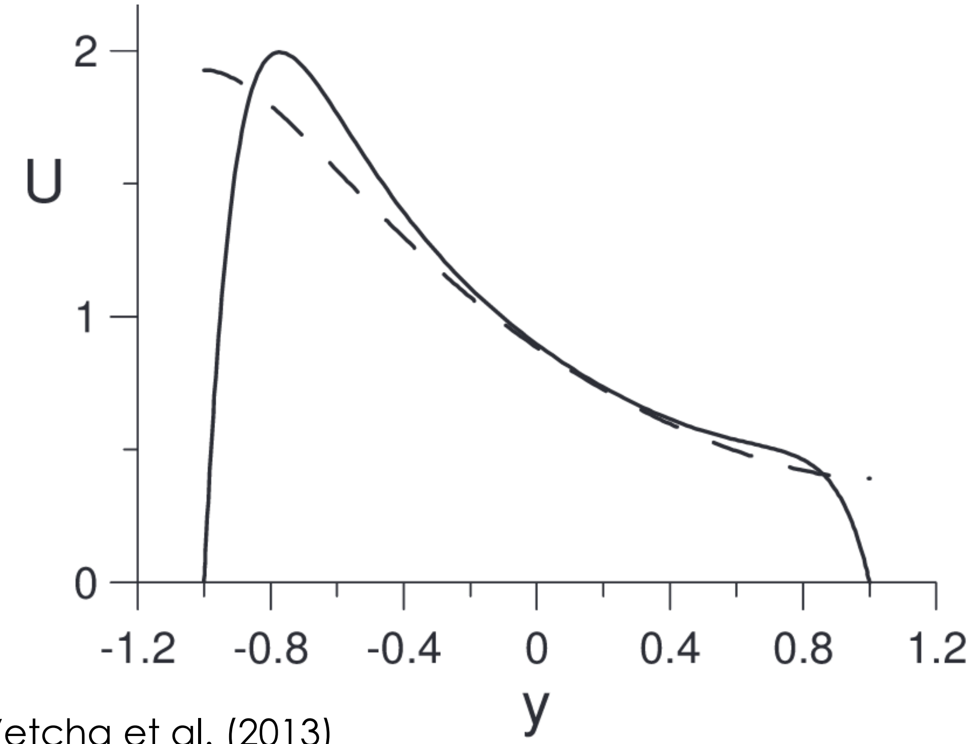
The velocity is distributed in a Q2D arrangement



Suarez et al. (2021)

The velocity field and possible instabilities result after balancing the following forces:

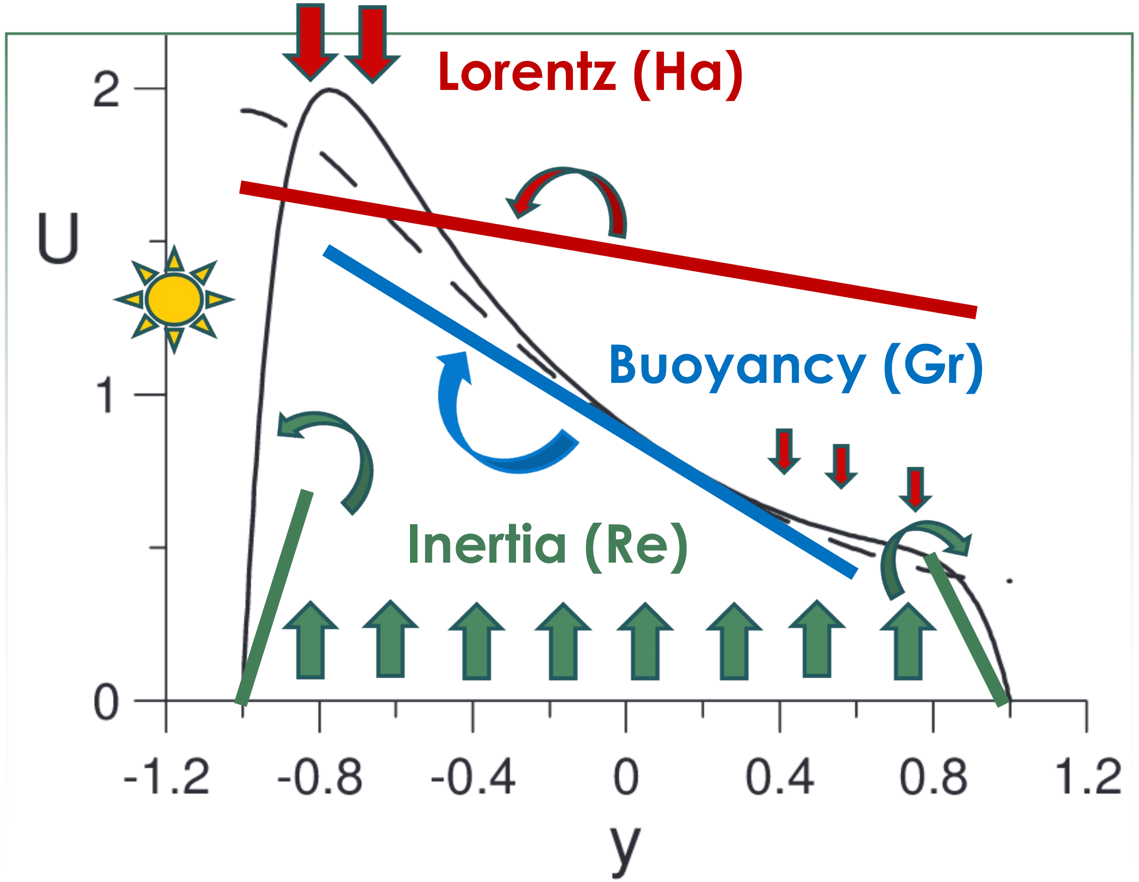
- Viscous force
- Inertial force (Re)
- Lorentz force (Ha)
- Buoyant force (Gr)



Vetcha et al. (2013)

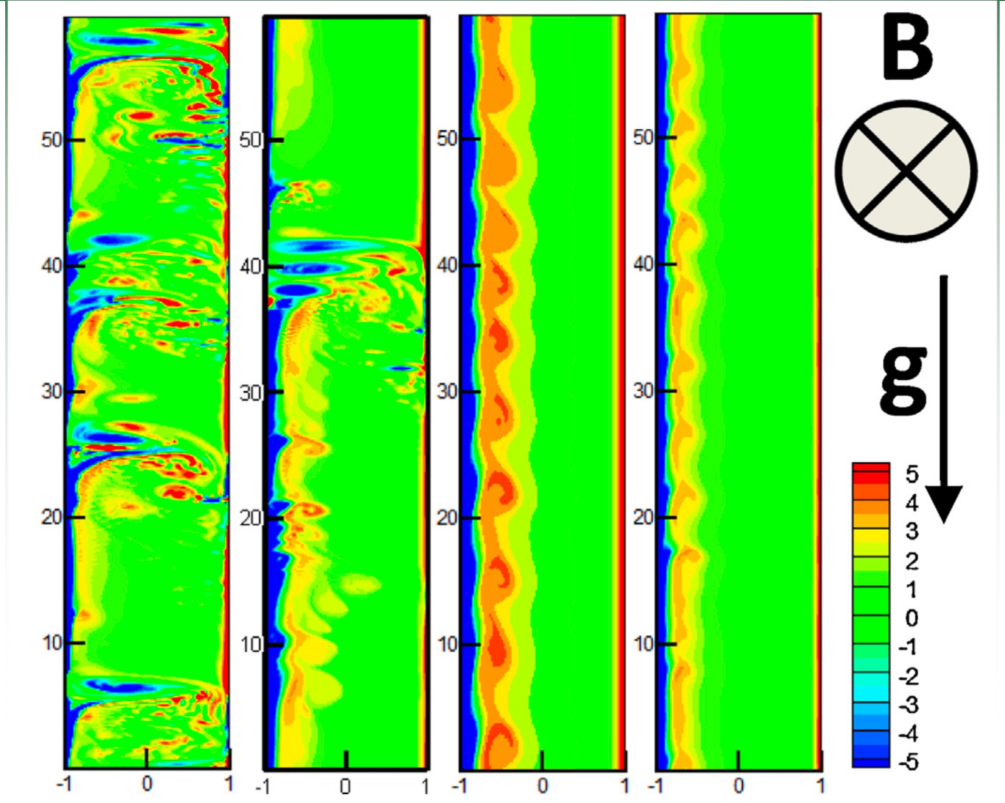
Introduction: the balance of forces

Effects of unbalancing forces



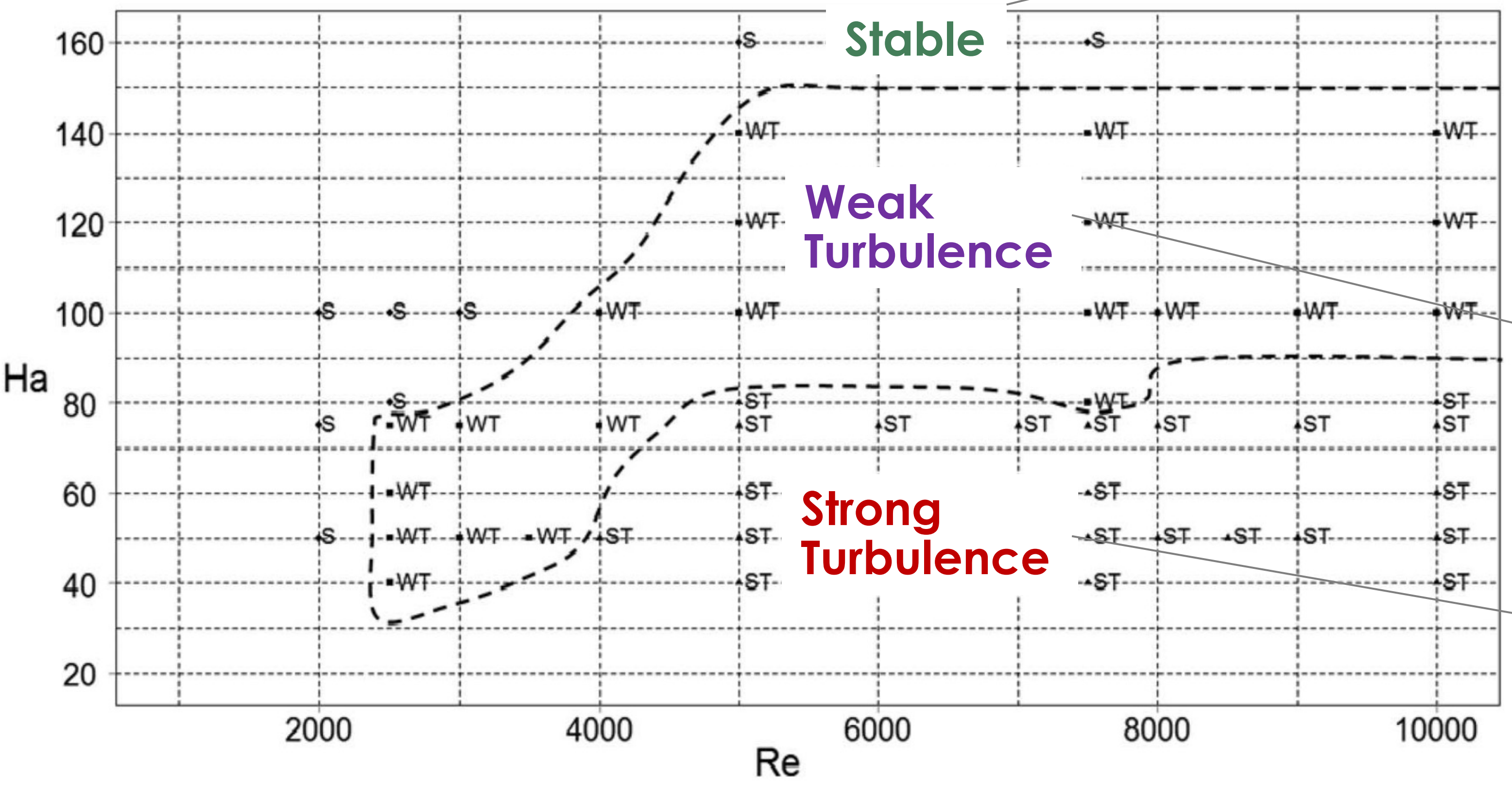
Vetcha et al. (2013)

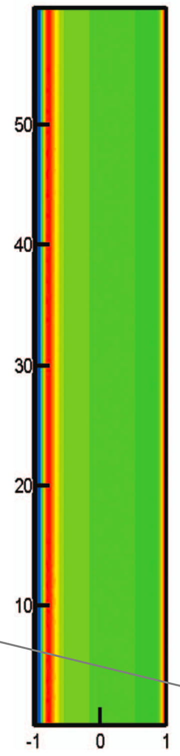
Different kind of instabilities and regimes may appear

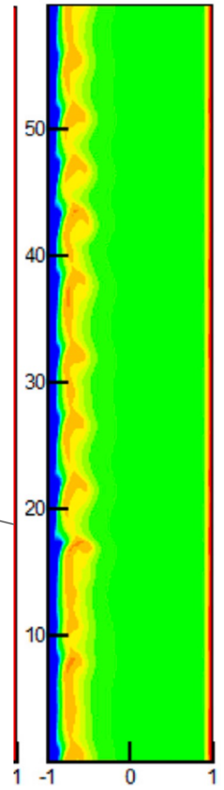


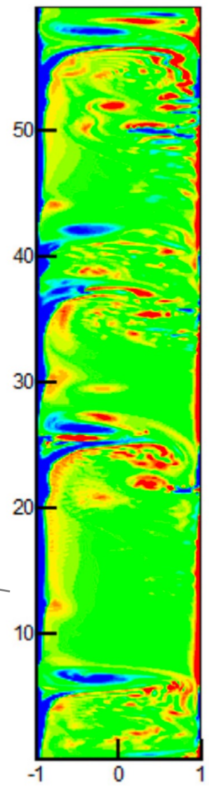
Smolentsev et al. (2013)

Introduction: the frontiers between stable and turbulent **for fully-developed flows**







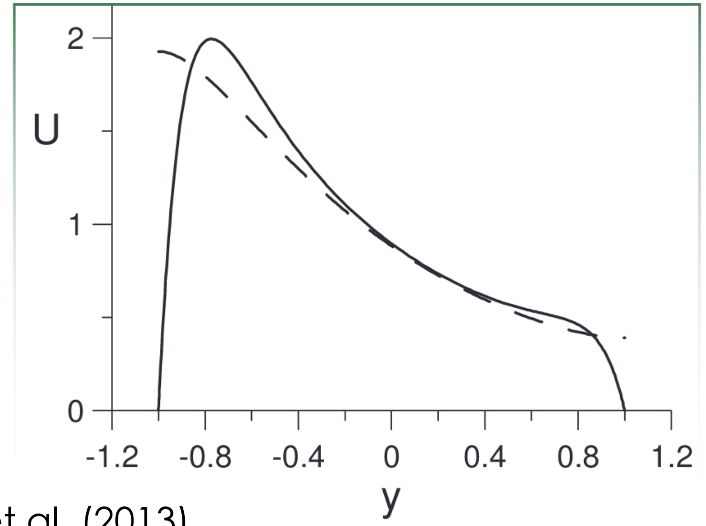


Vetcha et al. (2013)

Gr = 10^8

Introduction: the motivation

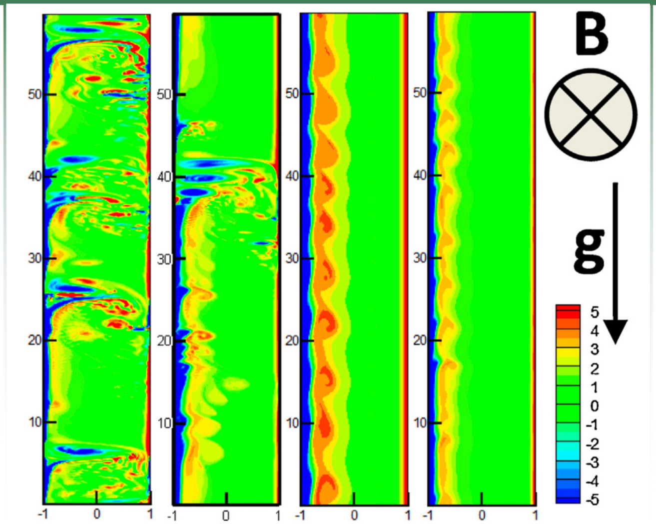
Fully-developed flow profile



Vetcha et al. (2013)

vs.

Turbulent structures



Smolentsev et al. (2013)

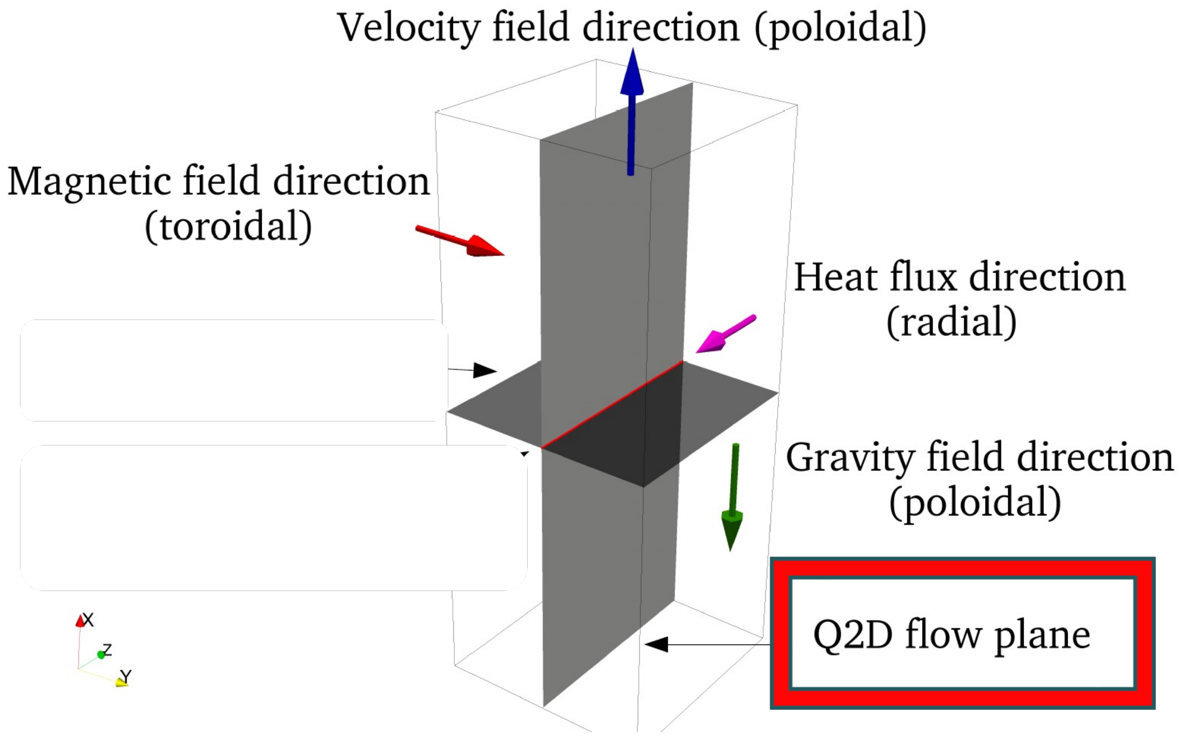
What flow conditions promote turbulent structures in blanket channels?

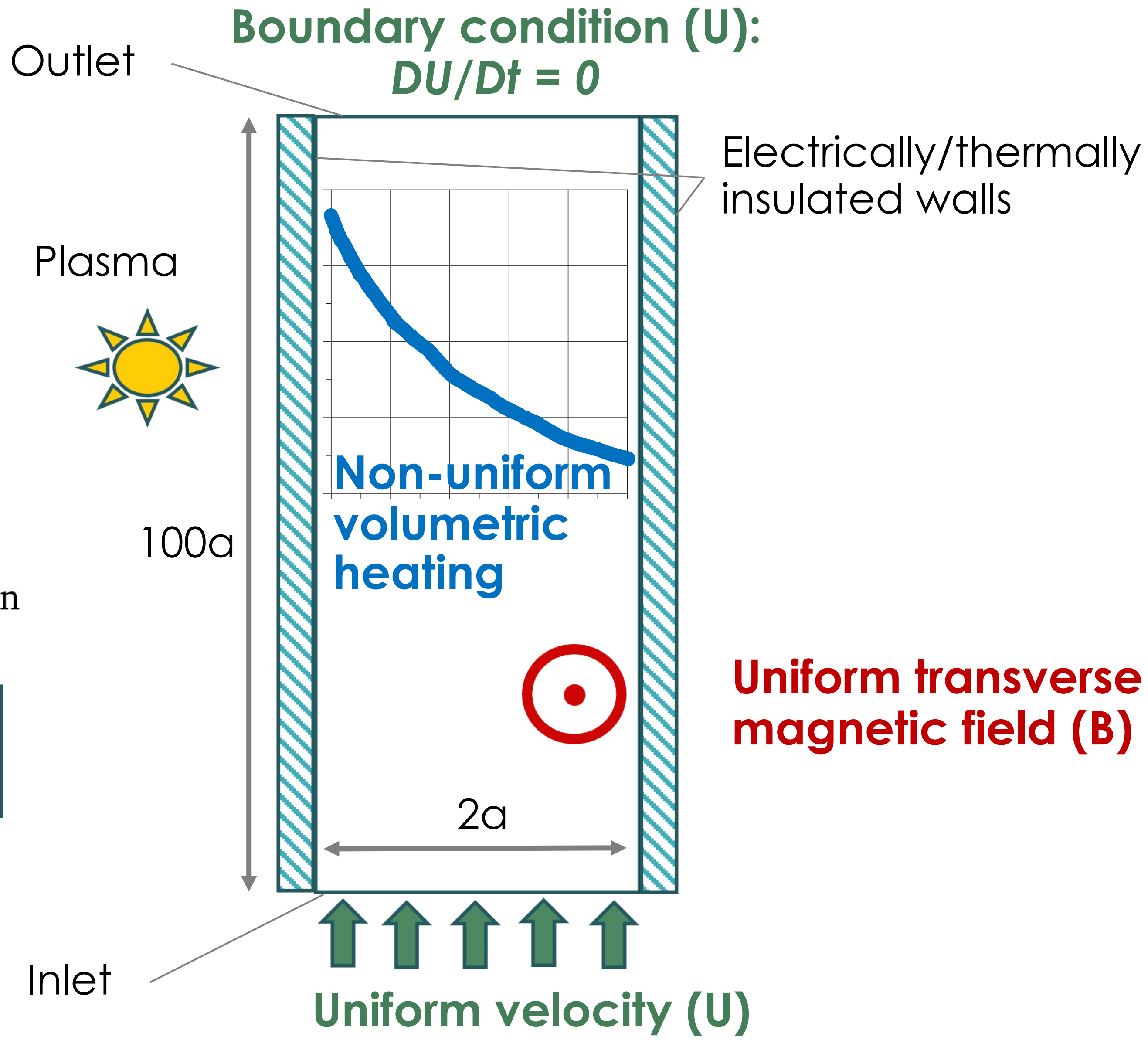
OAK RIDGE National Laboratory

Procedures and Methods

- Case description
- Buoyant Q2D code based on SM82
  - For the non-linear fluid flow calculation
- Bi-dimensional Fast Fourier Transform
  - For the characterization of eddies in the flow field
- CADES HPC

Procedure: case description





Open slide master to edit

Methods: development of a buoyant Q2D code

The Quasi 2-Dimensional model

- Based on the derivation by Sommeria and Moreau (1982):

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{\nabla p}{\rho} + \nu \nabla^2 \mathbf{u} - \frac{1}{\tau_{Ha}}\mathbf{u} + \beta \mathbf{g}(T - T_0)$$

$$\tau_{Ha} = \frac{b}{B}\sqrt{\frac{\rho}{\sigma \nu}}$$

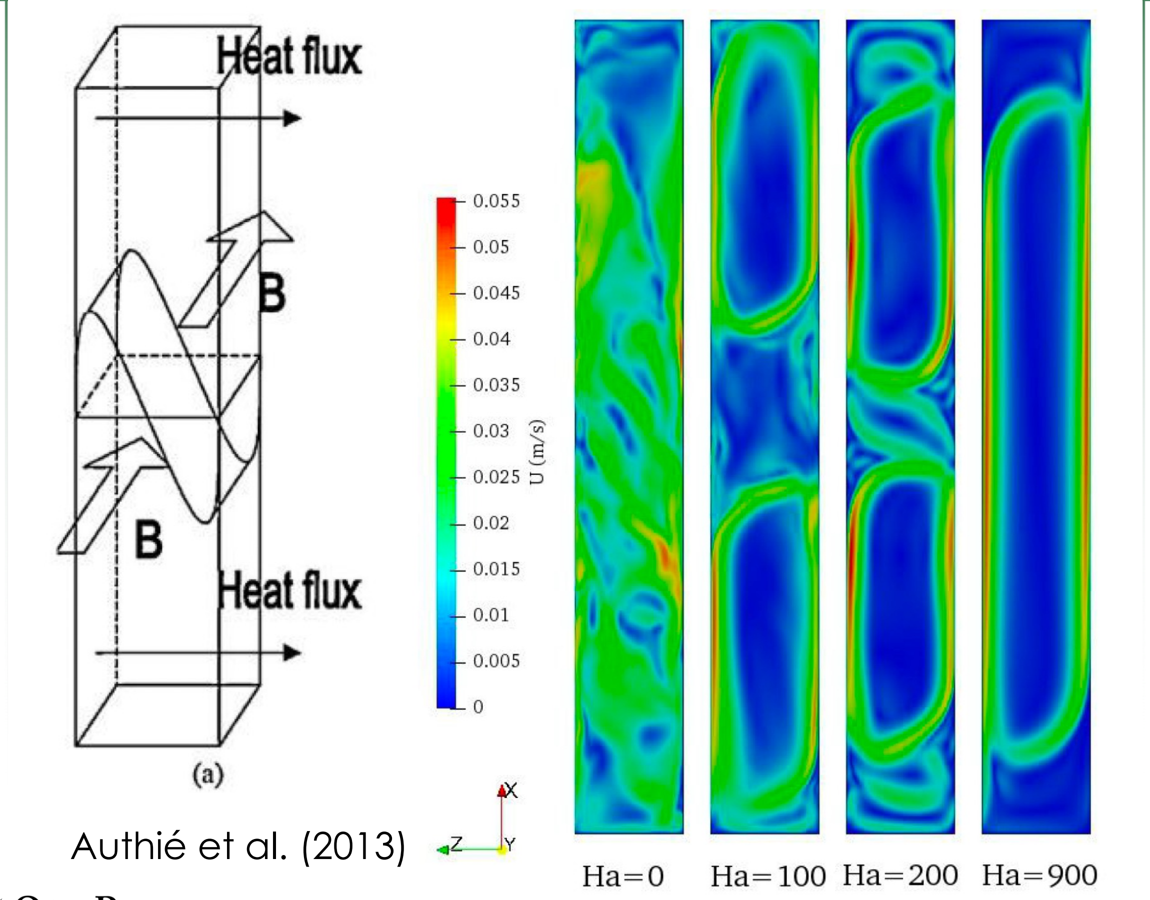
$$\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{u}T) = \alpha_t \nabla^2 T + S_{th}$$

Benchmarked with:

- 3D finite enclosure (Authié et al., 2003)
- Natural convection infinite enclosure (Tagawa et al., 2002)
- Mixed convection infinite enclosure (fully-developed flow)

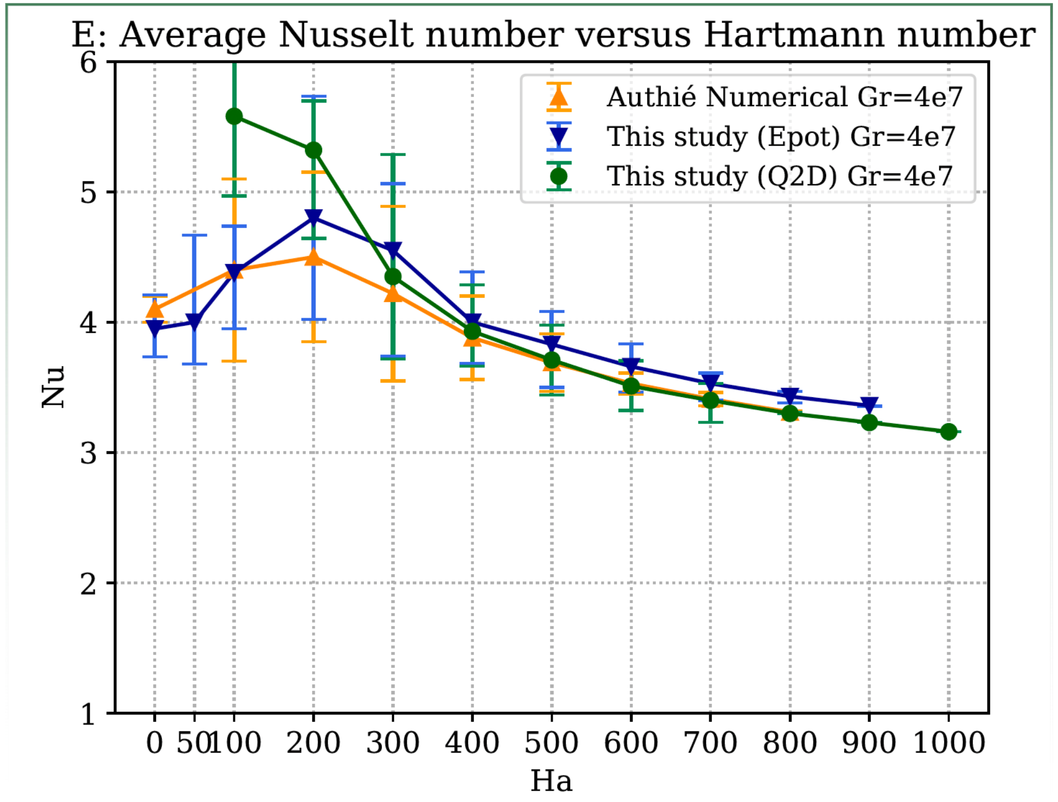
Methods: benchmarking the Q2D code: Authié et al., 2003

Natural convection in a 3D **finite** enclosure



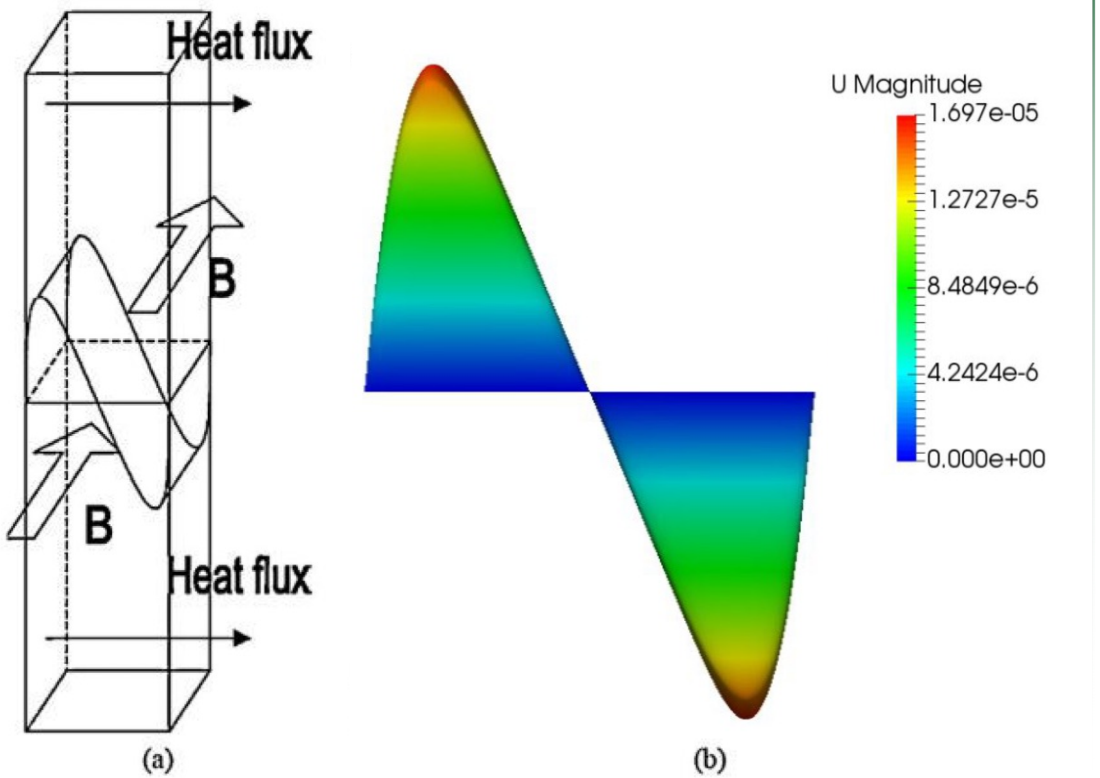
Authié et al. (2013)

The Q2D model is more precise at high Ha



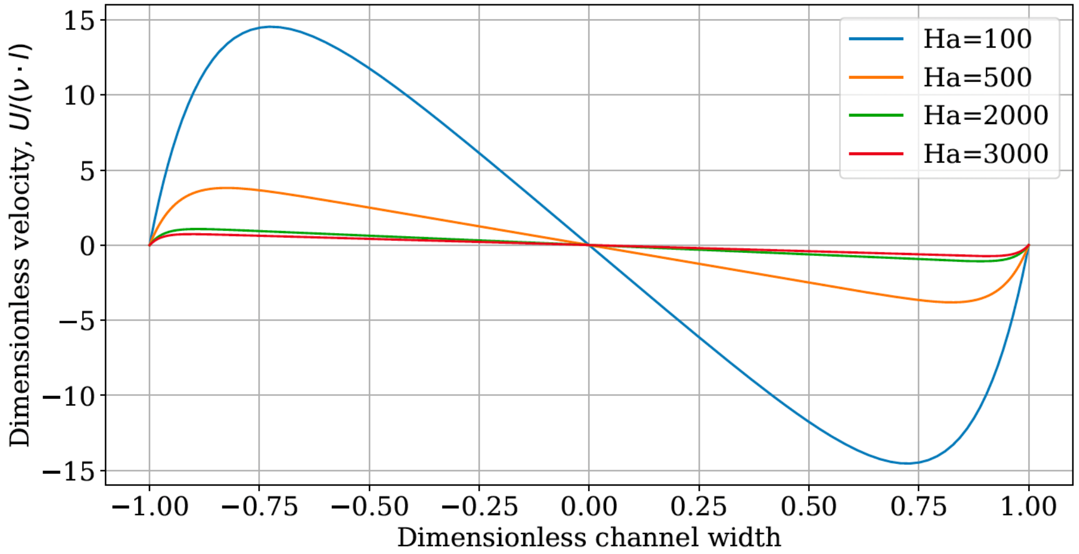
Methods: benchmarking the Q2D code: Tagawa et al., 2002

Natural convection in a 2D **infinite** enclosure



Tagawa et al. (2012)

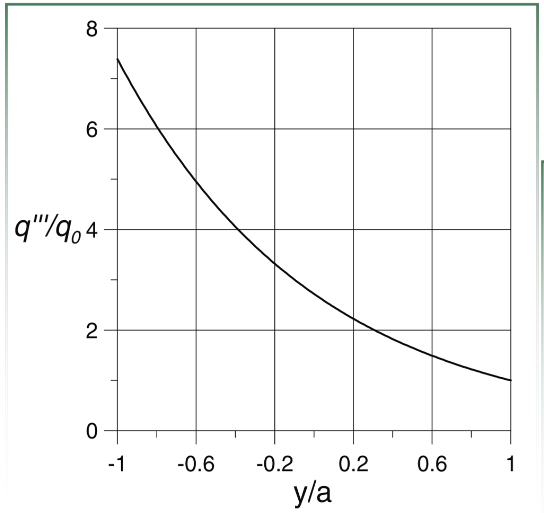
The Q2D model is more precise at high Ha

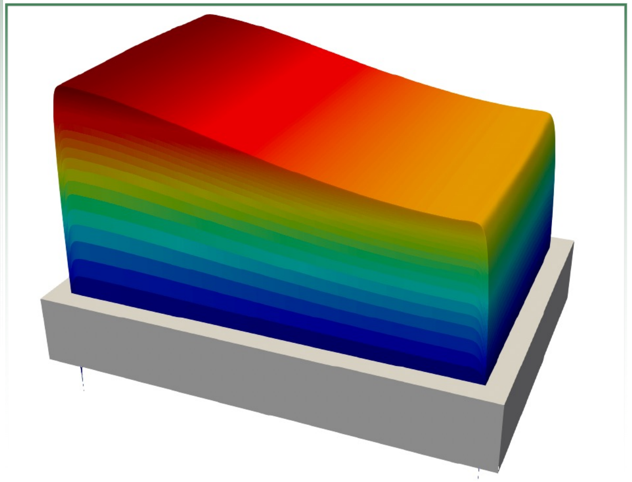


Ha	U_{max} (Tagawa)	U_{max} (Q2D)	Relative Error
0	73.11	79.99	9.41%
100	16.43	14.52	11.61%
500	4.07	3.80	6.60%
2000	1.12	1.07	4.51%
3000	0.71	0.73	2.09%

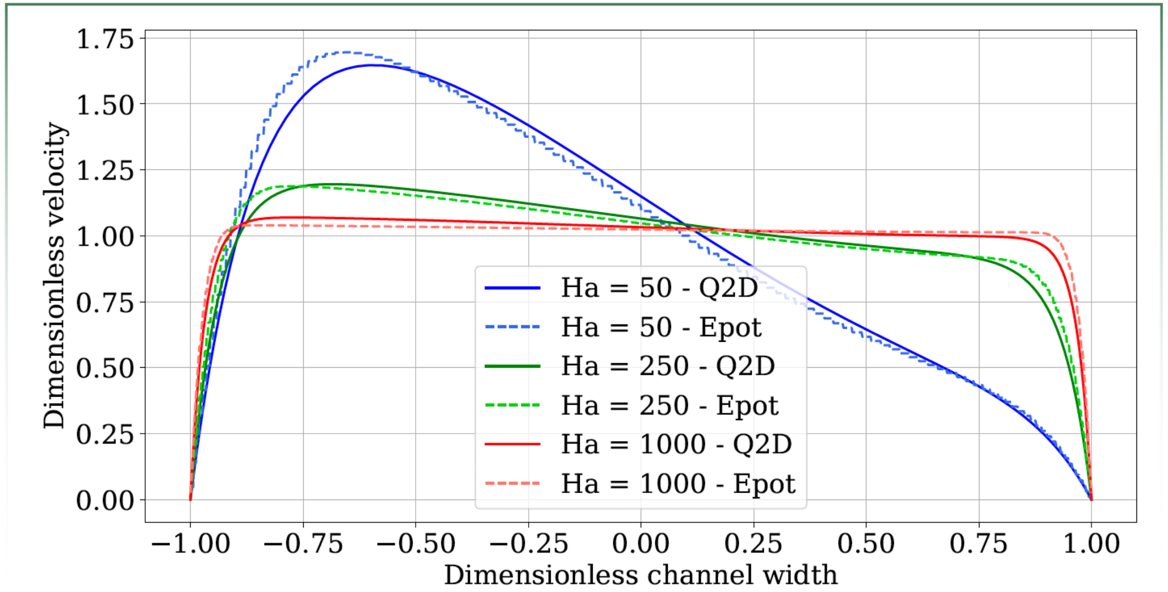
Methods: benchmarking the Q2D code: mixed convection flow code-to-code comparison

Mixed convection 2D infinite channel



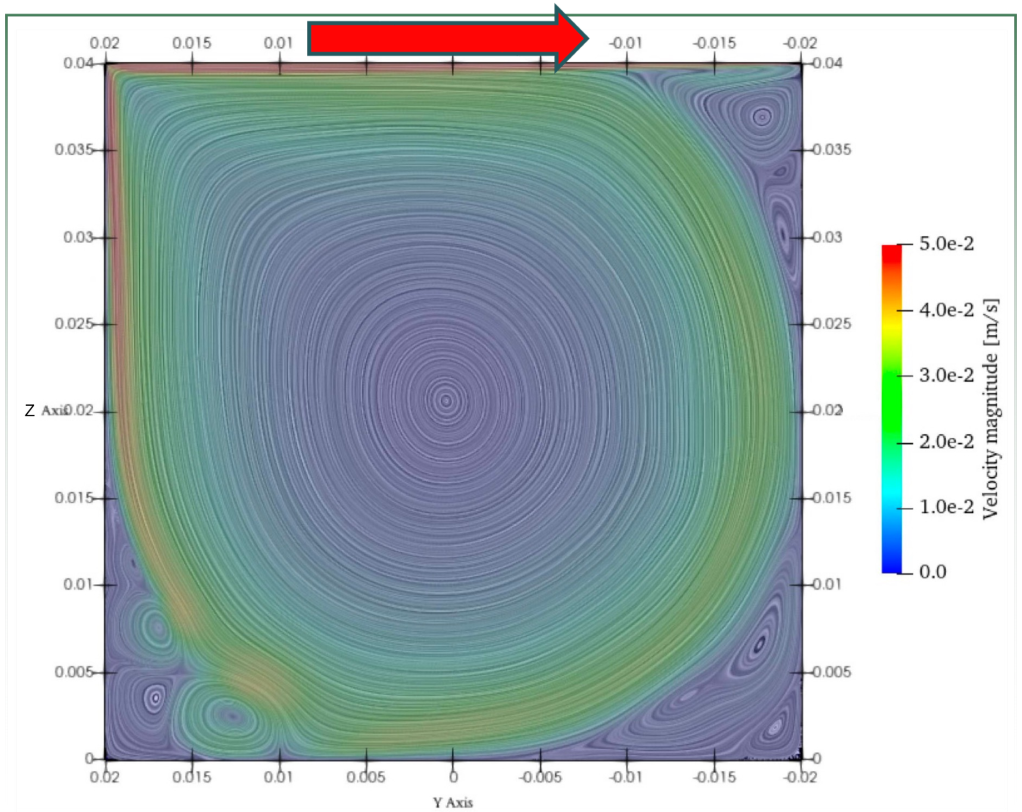


The Q2D model is more precise at high Ha

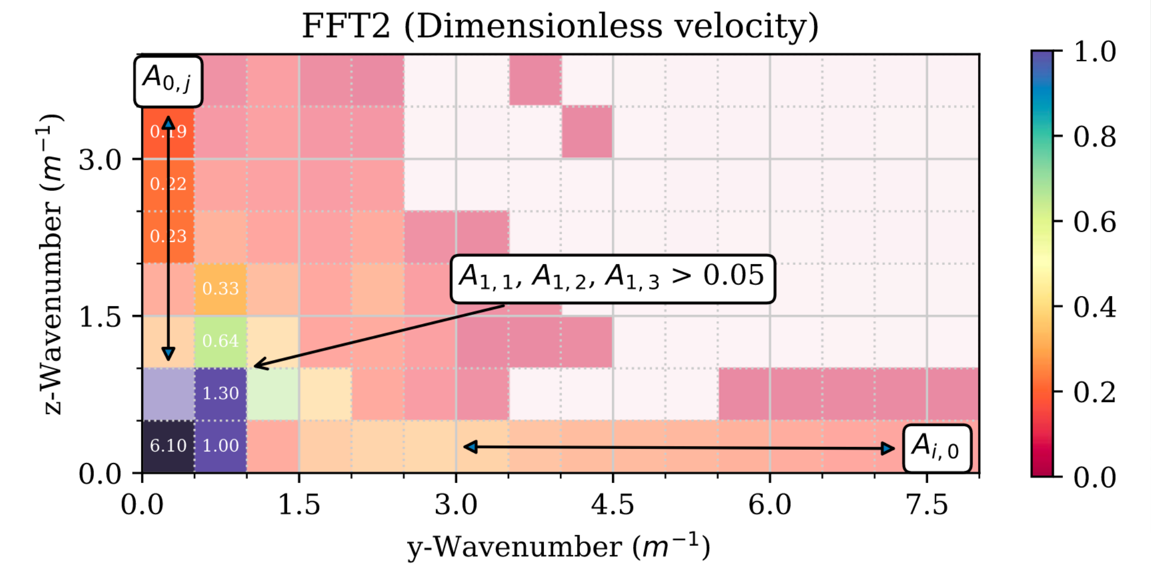


Methods: Bi-dimensional Fast Fourier Transform (FFT2) for eddie detection

A cavity flow with moving wall shows domain-scale eddies



The FFT2 analysis results in:



FFT2: $$A_{kl} = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} a_{mn} \exp\left\{ -2\pi i \left(\frac{mk}{M} + \frac{nl}{N} \right) \right\}$$

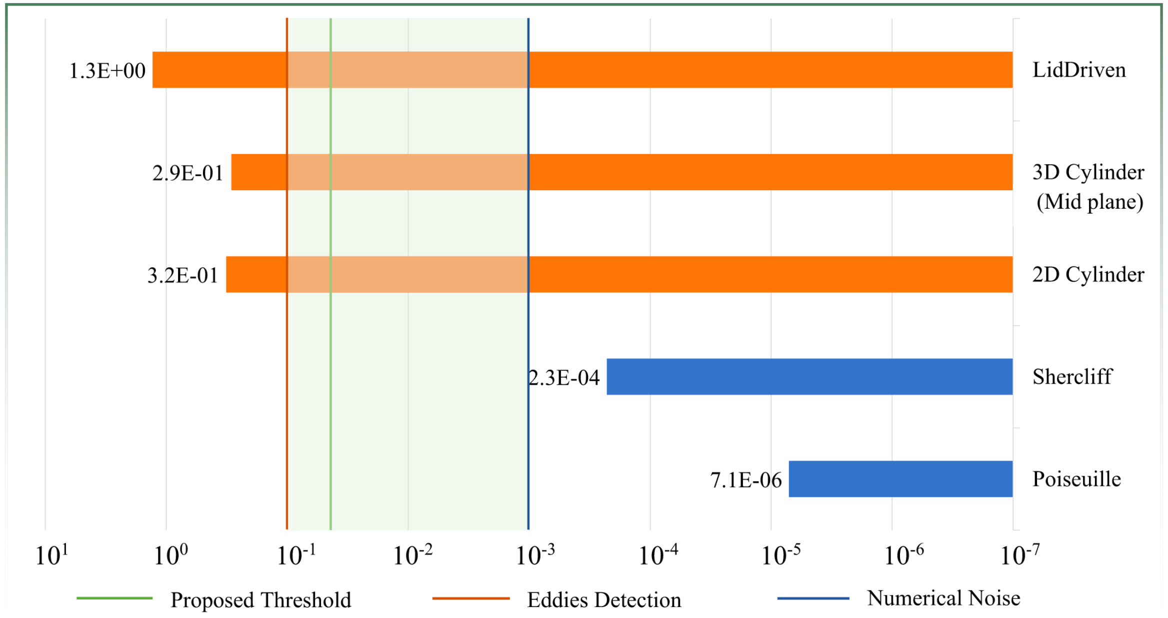
$$k \in \{0, \ldots, M/2-1\} \quad l \in \{0, \ldots, N/2-1\}$$

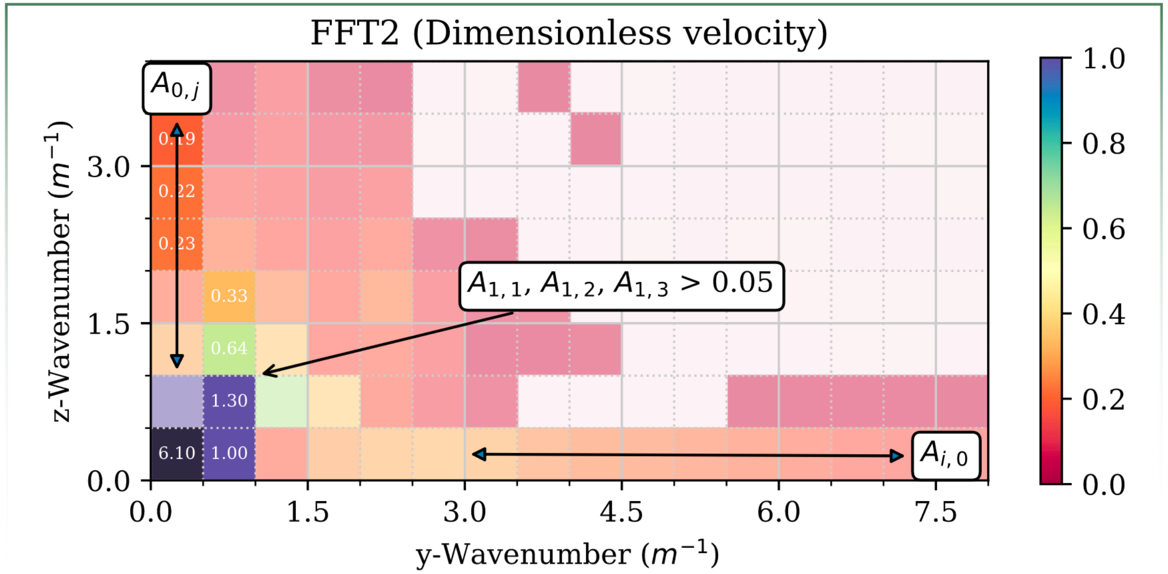
Wavenumber in y and z directions: $\nu_k = \frac{k}{L} \quad \nu_l = \frac{l}{L}$.

Methods: setting a threshold for eddies detection

A suitable threshold was identified for detecting eddies

If the maximum coefficient in the second row is > 0.05, the eddie is captured





Lid-driven cavity FFT2 results

Methods: CADES HPC (https://docs.cades.ornl.gov)

The Compute and Data Environment for Science (CADES)

- CADES at ORNL is providing a compute and data infrastructure coupled with experts in data science to create a new environment for scientific discovery
- CADES resources are located within ORNL's Computational Sciences Building (CSB), which houses some of the world's most powerful supercomputers, including the Oak Ridge Leadership Computing Facility's Summit
- Computations: Cray CPU's, at Birthright CADES open condo, with 543 nodes at 'burst'
- Data is stored using NFS and Lustre systems

Specific requirement for this investigation

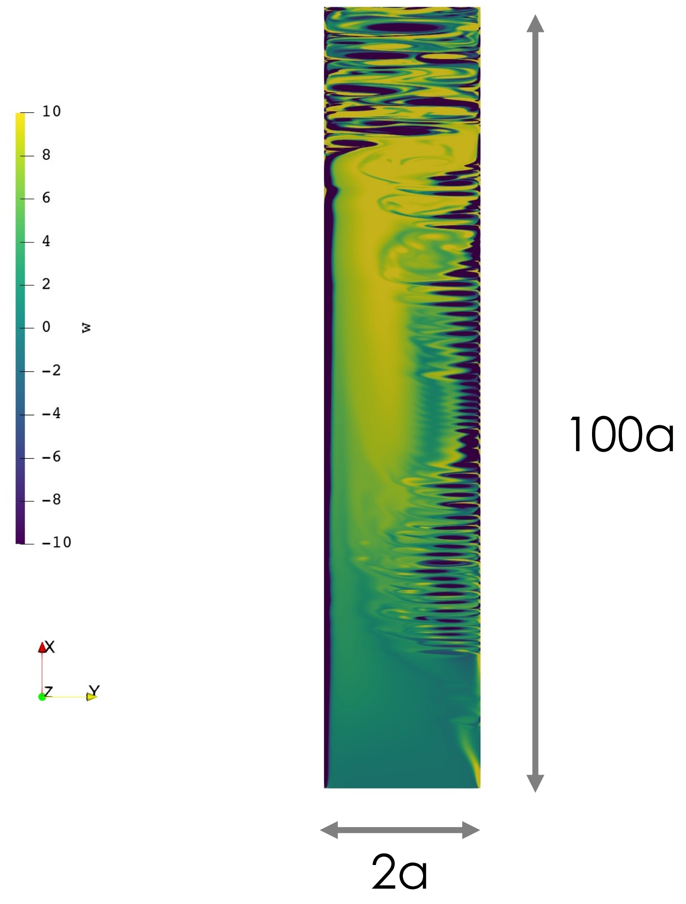
- The cases contain around 2'5M cells
- Optimum parallelization was 2 nodes (64 cpu)
- Each case lasts around 1'5 weeks
- Bottleneck is simulation time: the flow is slow, and the domain is large

Results

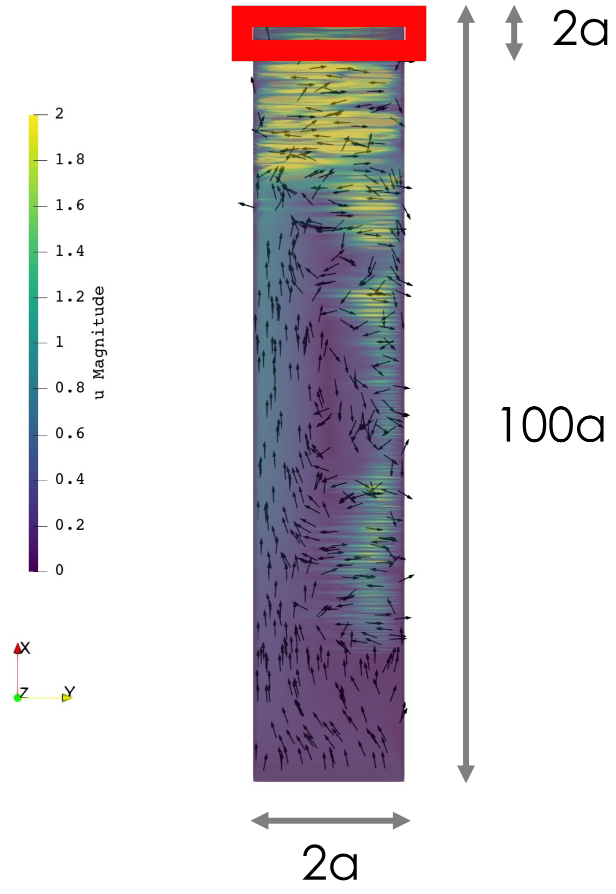
- The flow with *Ha=50, Re=5000,* $Gr=10^8$ shows strong turbulence in full-channel simulations without perturbations

Results: *Ha=50, Re=5000, Gr=10^8*

Dimensionless vorticity field

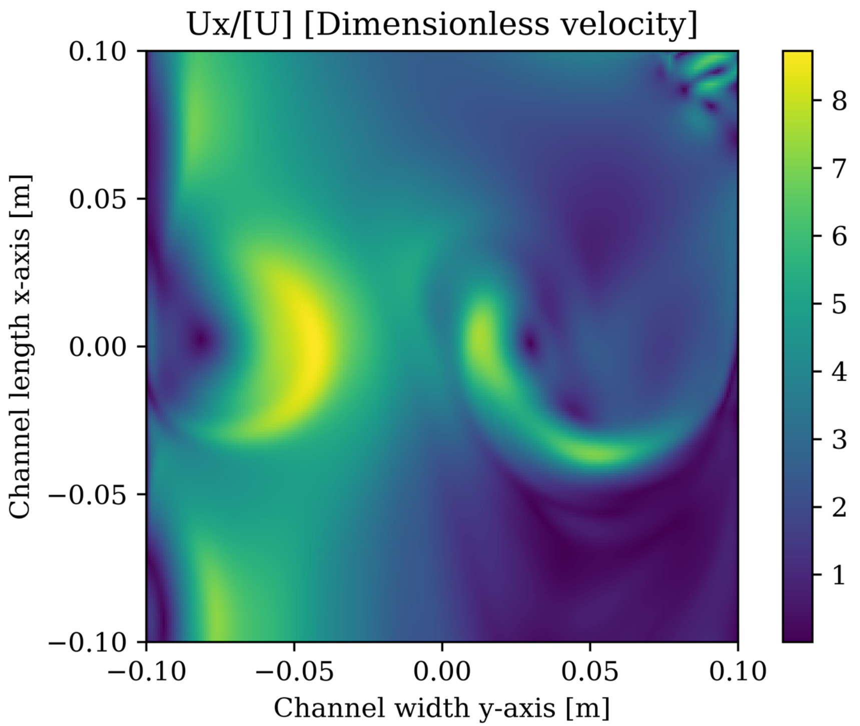


Dimensionless velocity field

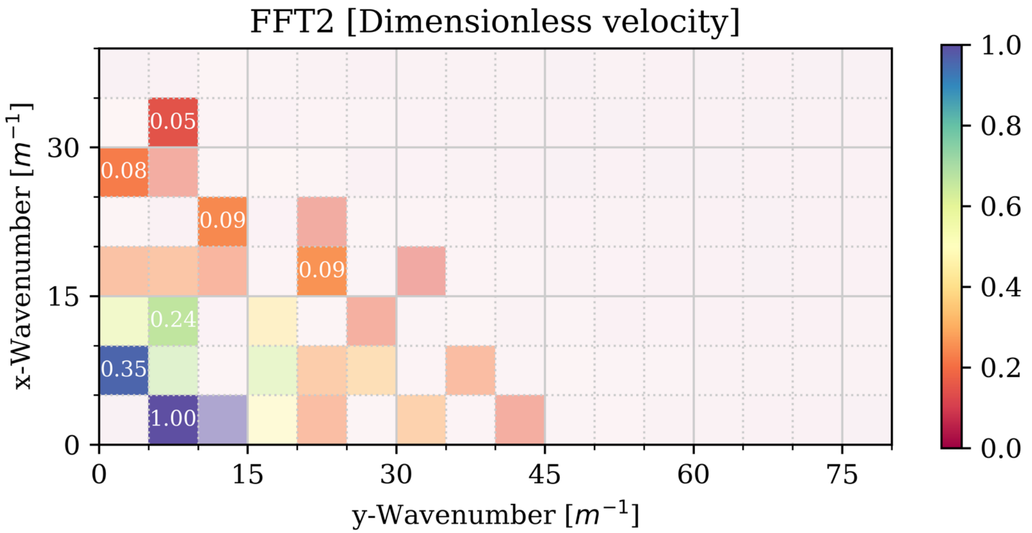


Results: *Ha=50, Re=5000, Gr=10^8*

Dimensionless velocity field at the exit



FFT2 analysis: coefficients above the threshold (**0.35 > 0.05**)



- The FFT2 method identifies the eddies

Conclusions

- Validated Q2D and FFT2 methods
- Definition of a systematic method to explore the boundaries of stable-unstable flows
- CADES HPC has been set to solve the multi-parameter analysis
- A first full channel simulation shows a non-fully-developed flow with strong turbulence

Thank you for your attention

suarezcambrd@ornl.gov