Xcompact3d: a high-order finite-difference framework to study turbulent flows on supercomputers

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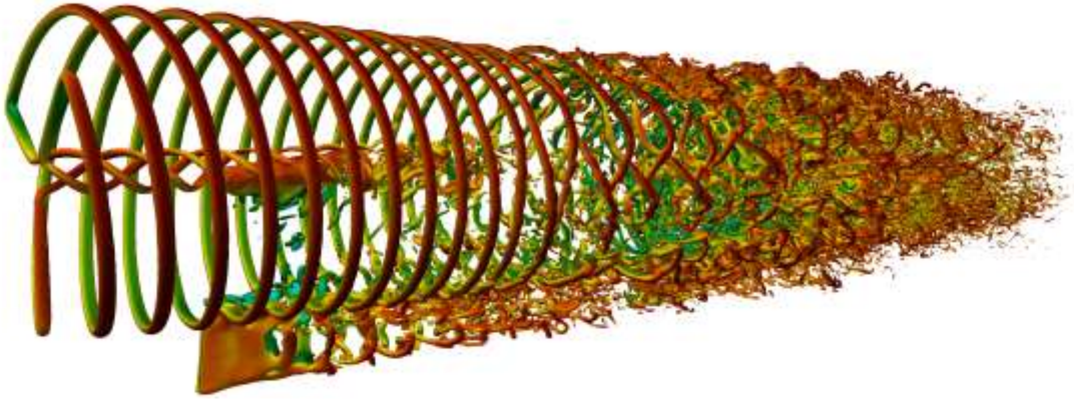
Imperial College London



Imperial College London

Who am I?

- Reader (associate professor) in computational fluid dynamics
- Based at Imperial College London (UK) in Aeronautics
- Lead of the Turbulence Simulation Group
- French (and British)
- PhD from Poitiers (France)

I study numerically turbulent flows and how to manipulate them to the benefit of society

I use the most powerful supercomputers in the world

Turbulence

”Turbulence is the most important unsolved problem of classical physics”

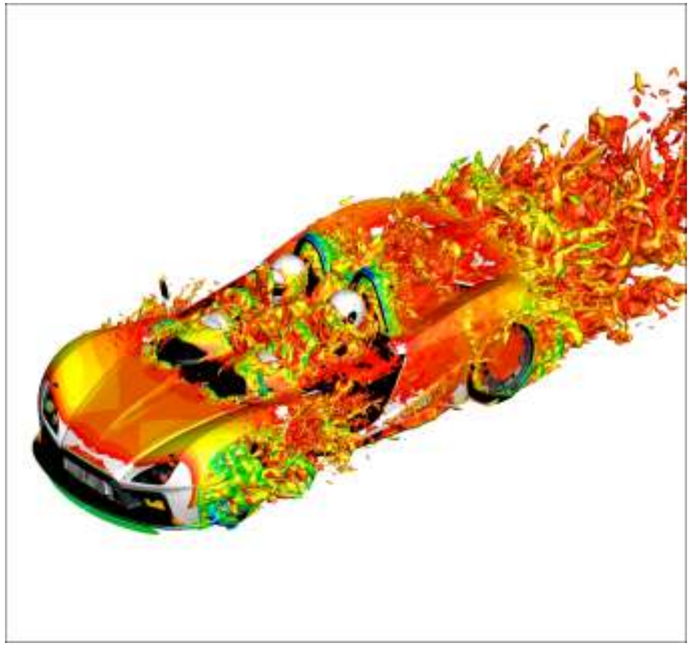
Richard Feynman

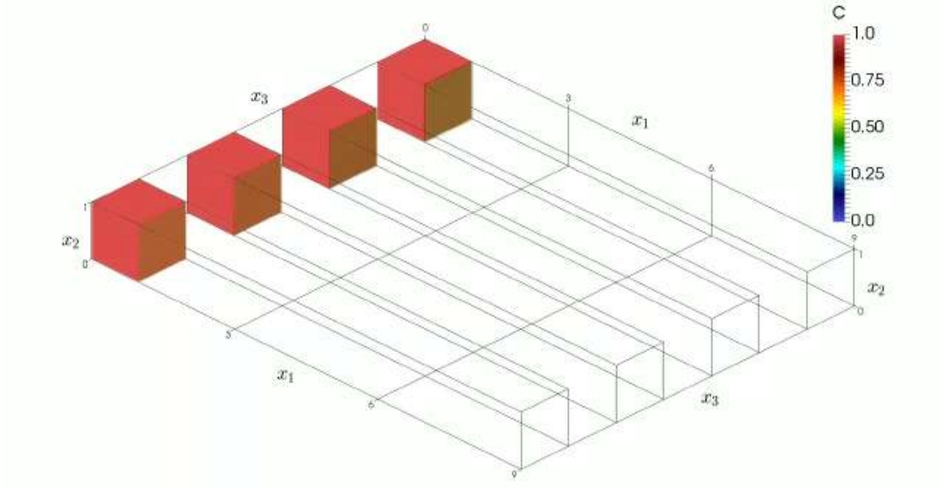


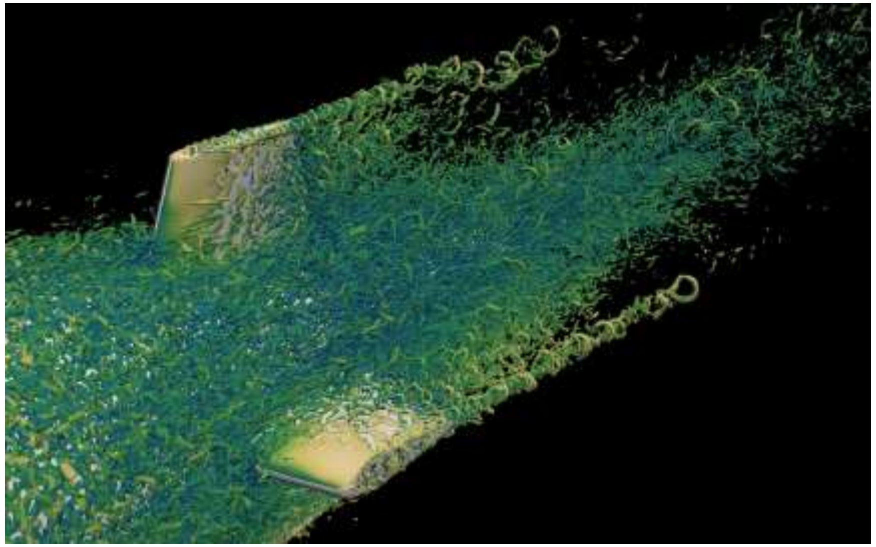




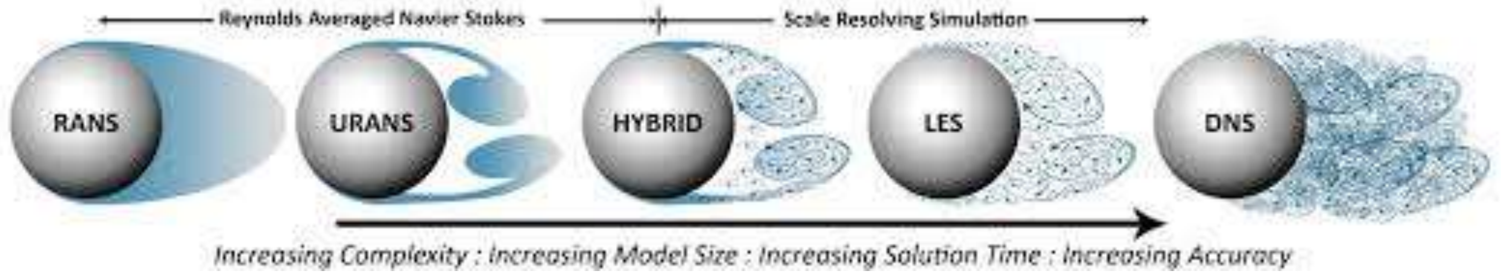

Turbulence and CFD

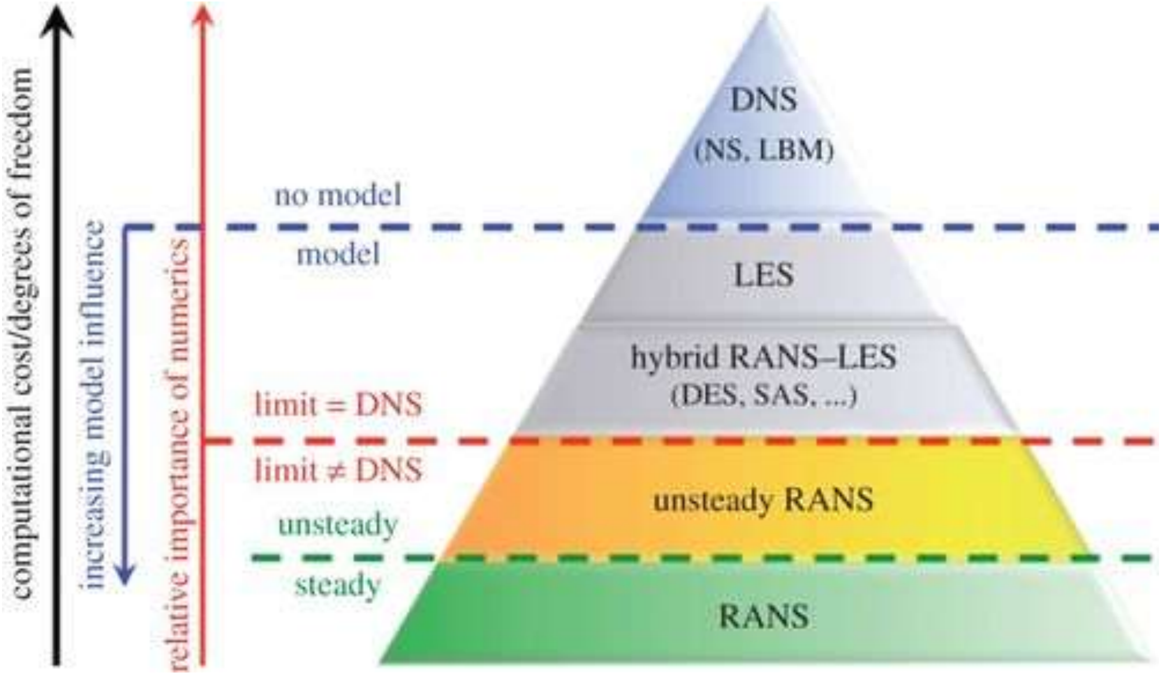


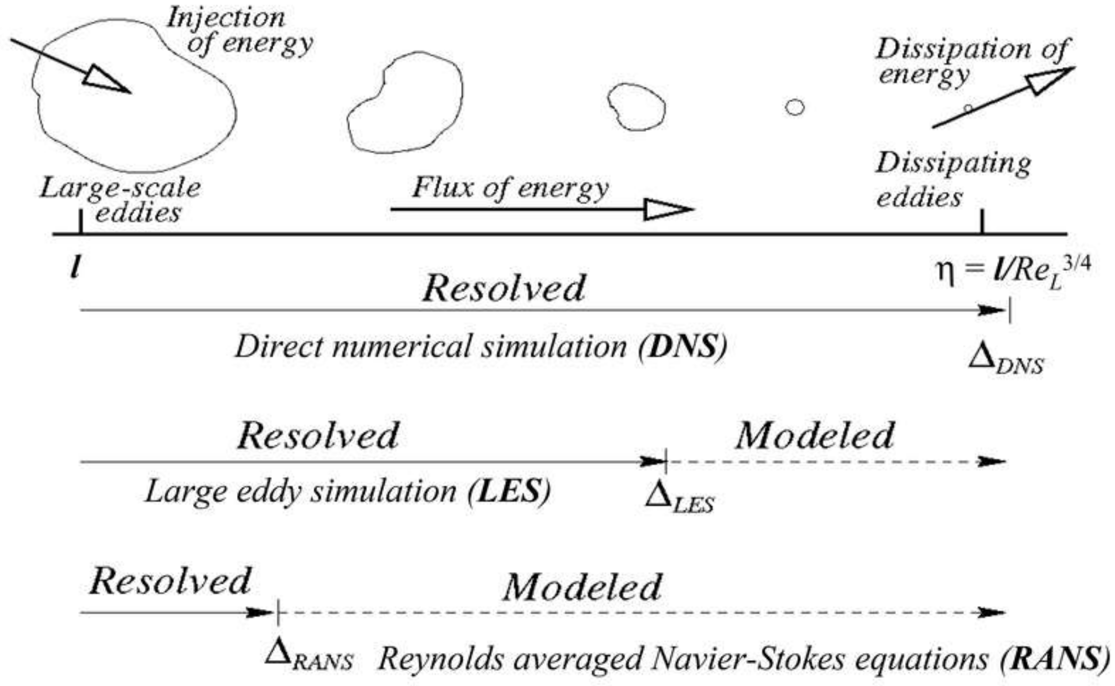




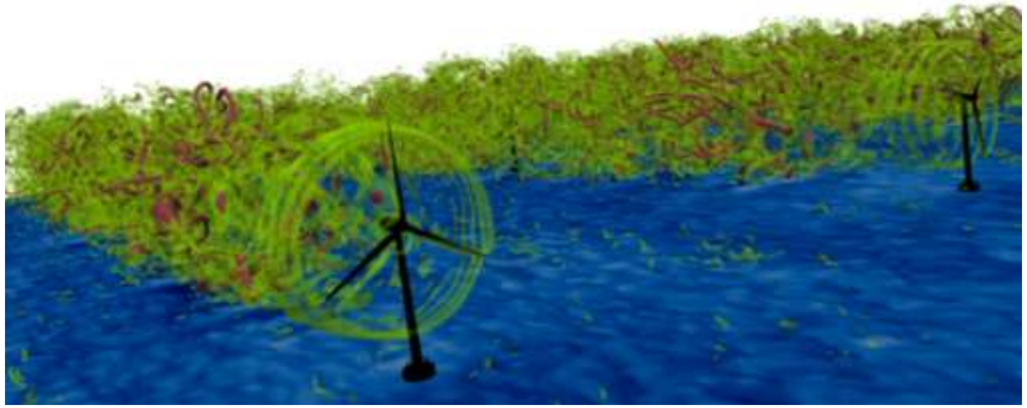
Turbulence and CFD

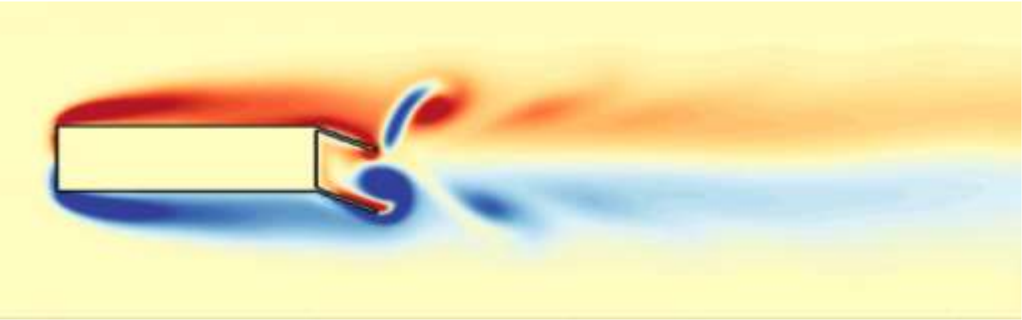






Xcompact3d





Strategy:

1. Cartesian mesh
2. High-order finite-difference schemes
3. Immersed Boundary Method
4. Spectral solver for Poisson equation
5. 2D Domain Decomposition
6. A zest of numerical dissipation

A little bit of history

Incompact3d

- Created at the end of the 90’s in France
- Pure Fortran code
- Re-designed in 2003/2004 with Fortran 90 and new capabilities
- Re-designed in 2006 with MPI (1D slabs)
- Re-designed in 2009/2011 with 2DECOMP&FFT library (2D pencils

Xcompact3d

- Created in 2019
- Only one single code for incompressible flows, compressible flows in the low Mach number limit and wind farm simulator
- ~40k lines of code (+ ~15k lines of codes for 2DECOMP&FFT)
- Currently being re-designed for GPUs

Navier-Stokes equations

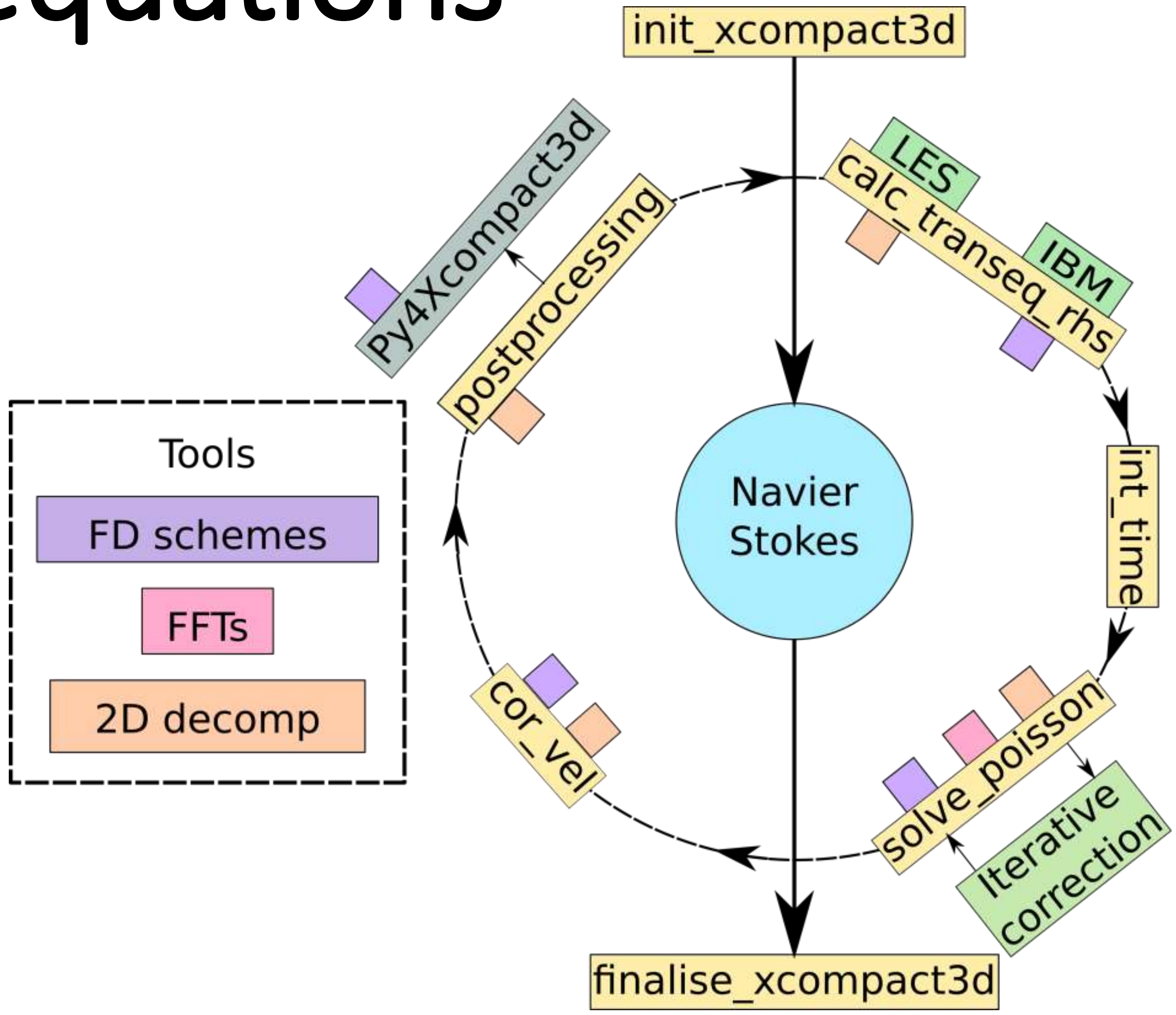
$$\frac{D\rho}{Dt} = -\rho\frac{\partial u_i}{\partial x_i}$$

$$\frac{\partial p^{(0)}}{\partial x_j} = 0$$

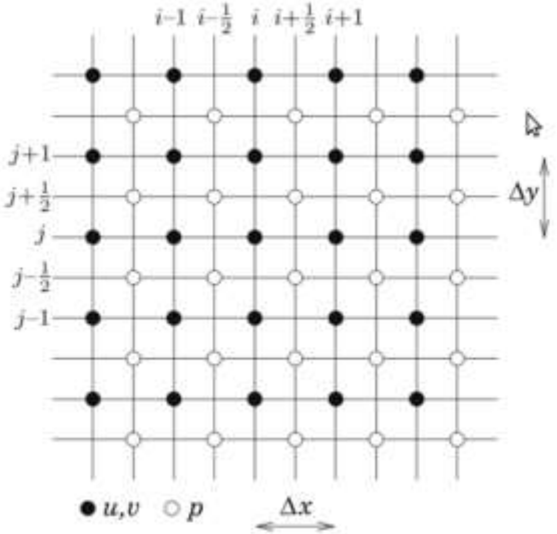
$$\rho\frac{DT}{Dt} = \frac{1}{Re\ Pr}\frac{\partial}{\partial x_j}\kappa\frac{\partial T}{\partial x_j}$$

$$\rho\frac{Du_i}{Dt} = -\frac{\partial p^{(1)}}{\partial x_i} + \frac{1}{Re}\frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i$$

$$p^{(0)} = \rho T$$



Compact H-O schemes



- ✓ **Collocated mesh for convective and diffusive terms**
- ✓ **Staggered mesh for the pressure treatment**

First derivative on a collocated mesh

$$\alpha f'_{i-1} + f'_i + \alpha f'_{i+1} = a\,\frac{f_{i+1} - f_{i-1}}{2\Delta x} + b\,\frac{f_{i+2} - f_{i-2}}{4\Delta x}$$

First derivative on a staggered mesh

$$\alpha f'_{i-1/2} + f'_{i+1/2} + \alpha f'_{i+3/2} = a\,\frac{f_{i+1} - f_i}{\Delta x} + b\,\frac{f_{i+2} - f_{i-1}}{3\Delta x}$$

Compact H-O schemes

$$\alpha f'_{i-1/2} + f'_{i+1/2} + \alpha f'_{i+3/2} = a\frac{f_{i+1} - f_i}{\Delta x} + b\frac{f_{i+2} - f_{i-1}}{3\Delta x}$$

Physical space

equivalence

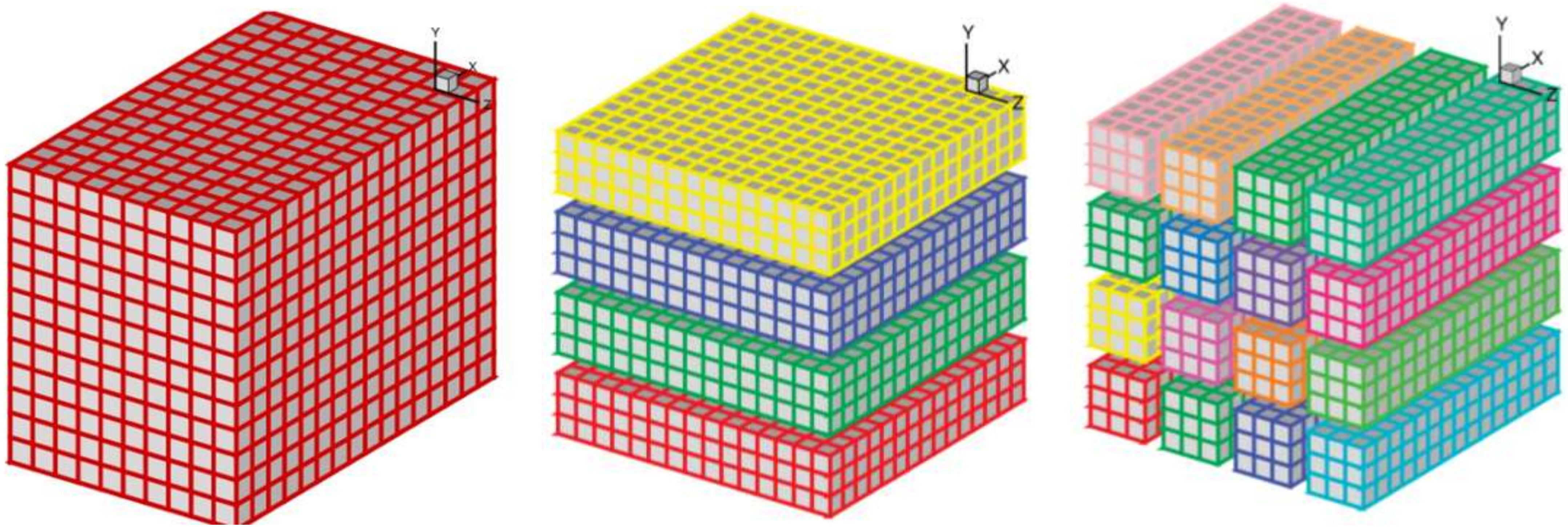
Fourier space

$$\hat{f}'_l = \imath k'_x \hat{f}_l$$

Modified wave number

$$k'_x \Delta x = \frac{a\sin(k_x\Delta x) + (b/2)\sin(2k_x\Delta x)}{1 + 2\alpha\cos(k_x\Delta x)}$$

2D Domain Decomposition



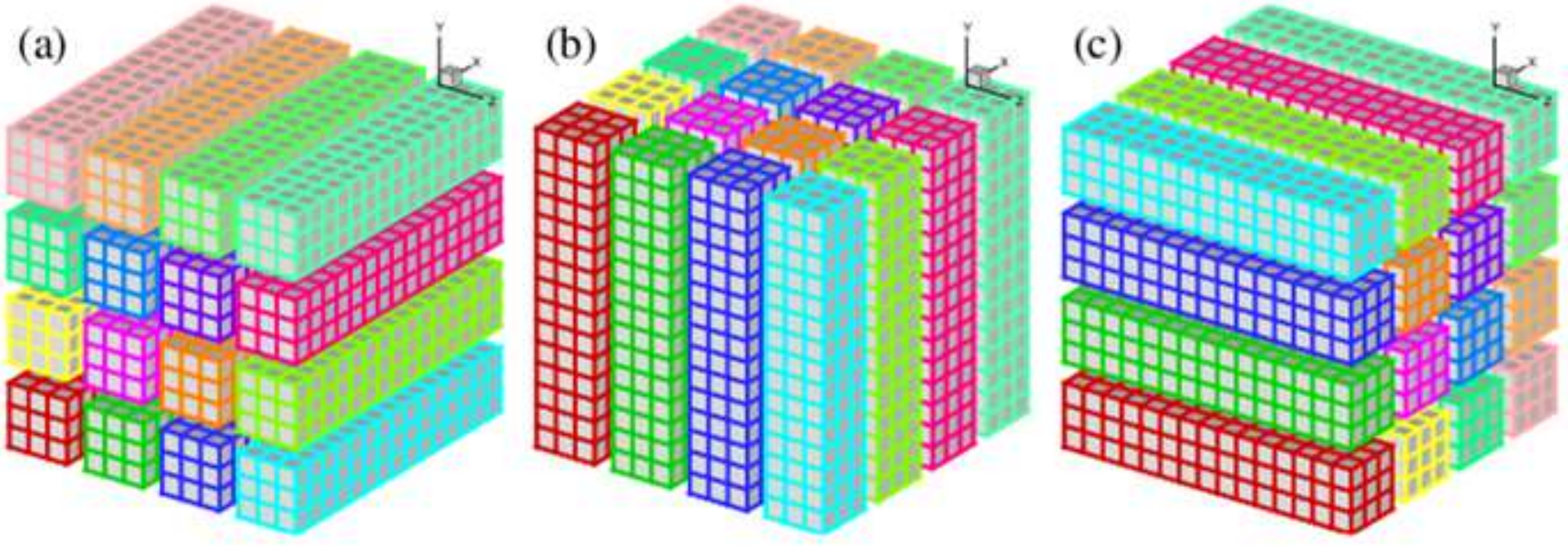
✓From 1 CPU core to one million CPU cores

✓From 30 million mesh nodes to dozens billion mesh nodes

✓CPU-friendly only (GPU-friendly version is coming soon)

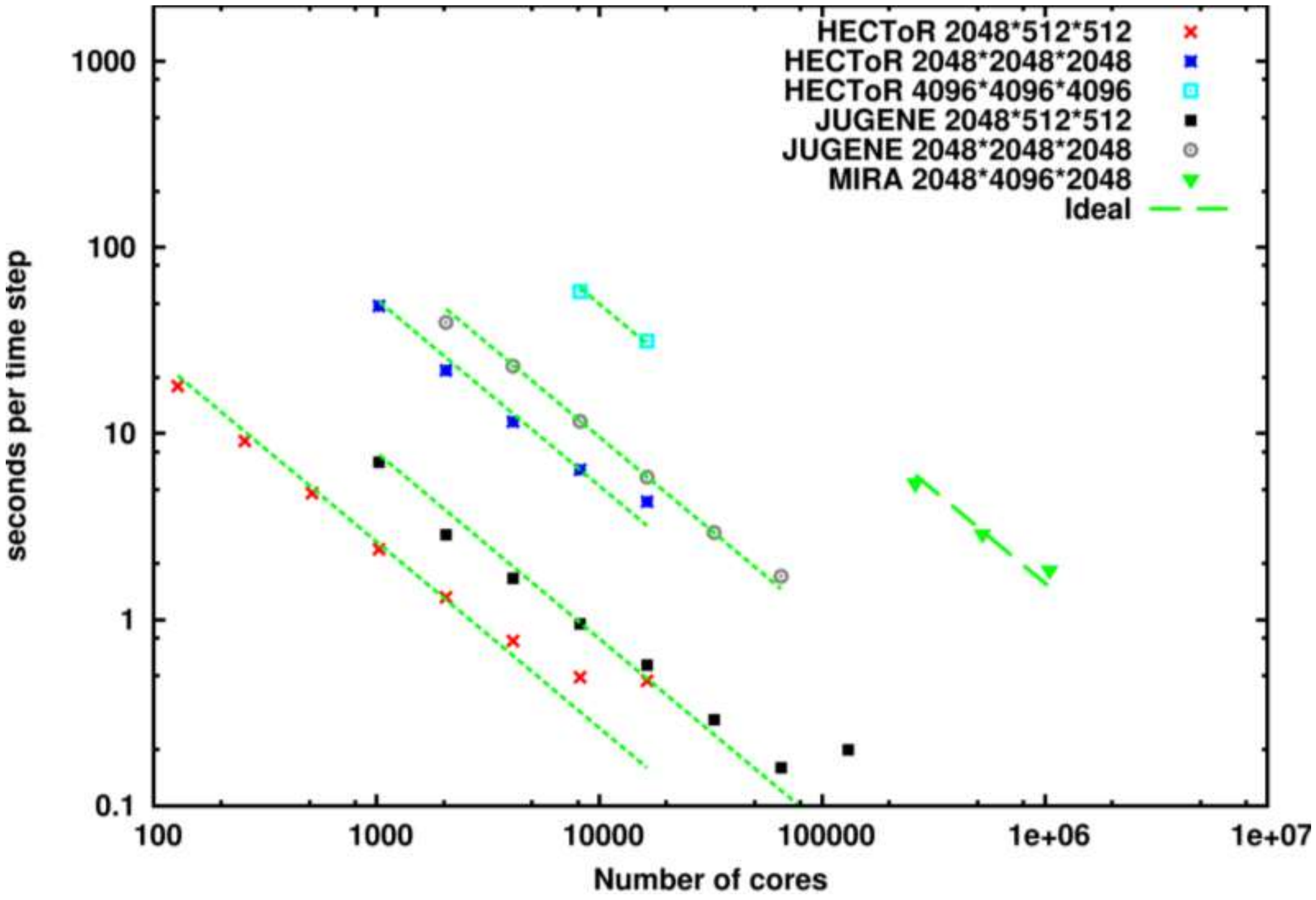
✓2D Decomp & FFT, open source library → http://www.2decomp.org

2D Domain Decomposition

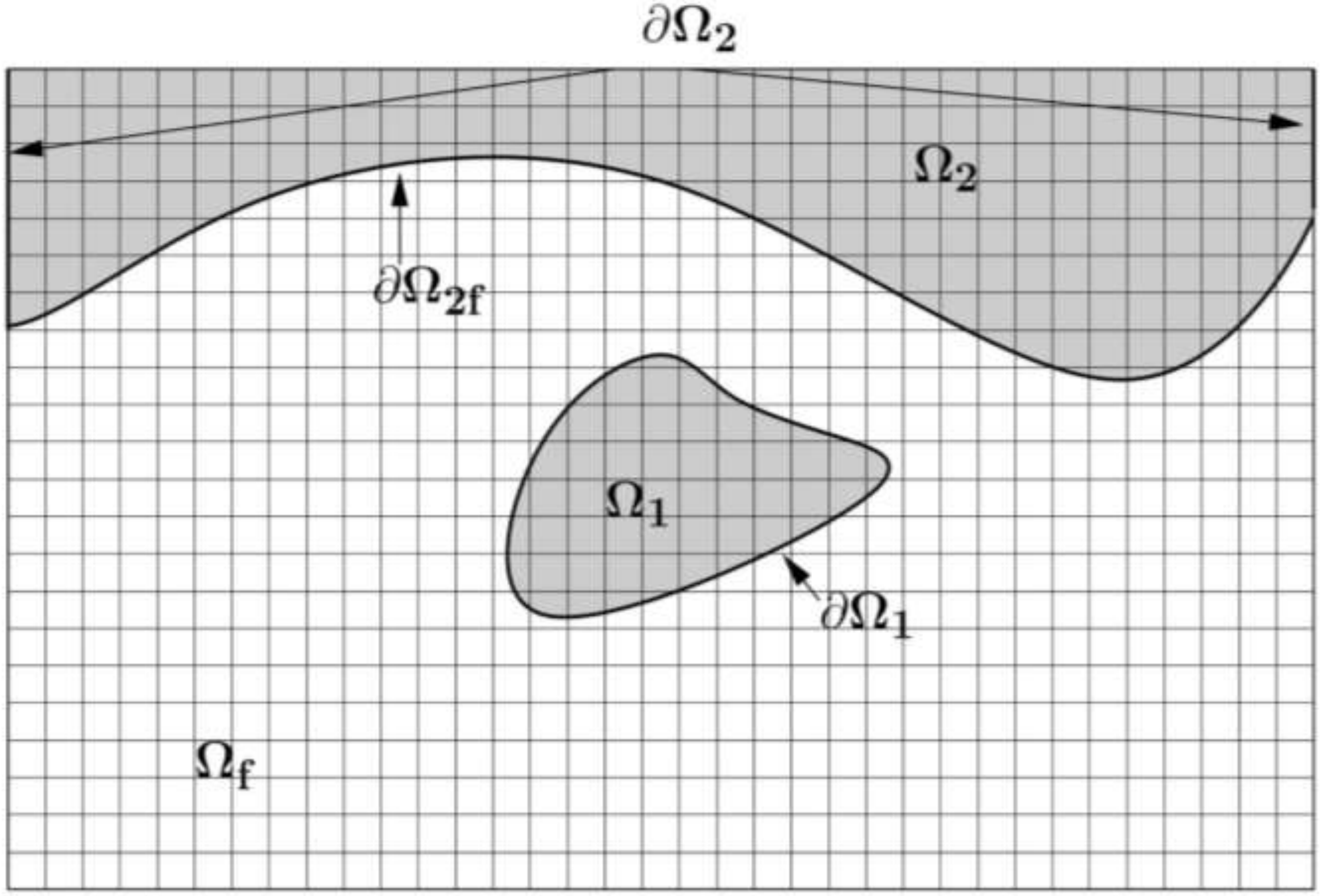


- ✓**Widely used for spectral codes (compatible with implicit schemes in space)**
- ✓**Nproc < N^2 for a N^3 simulations**
- ✓**No need to modify derivative/interpolation subroutines**
- ✓**Customized global MPI_ALLTOALL transpositions**
- ✓**From 30% to 80% in communication (up to 70 transpositions per time step)**

2D Domain Decomposition

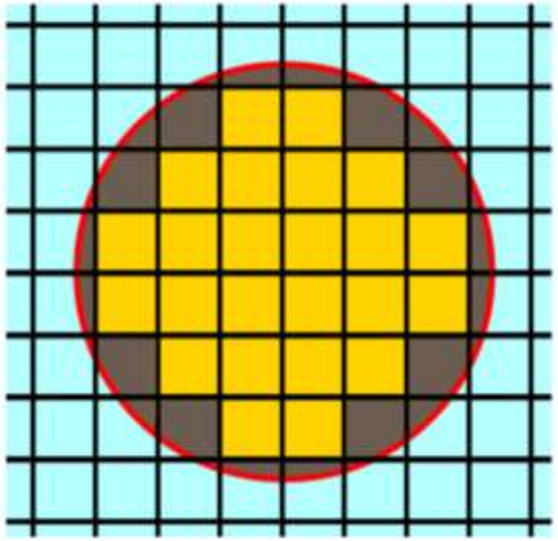


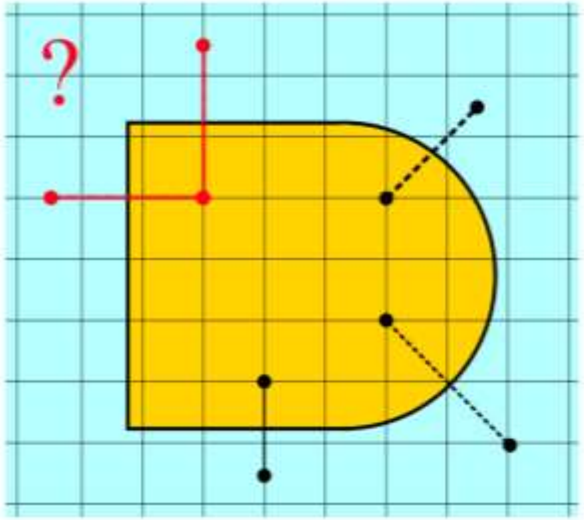
IBM

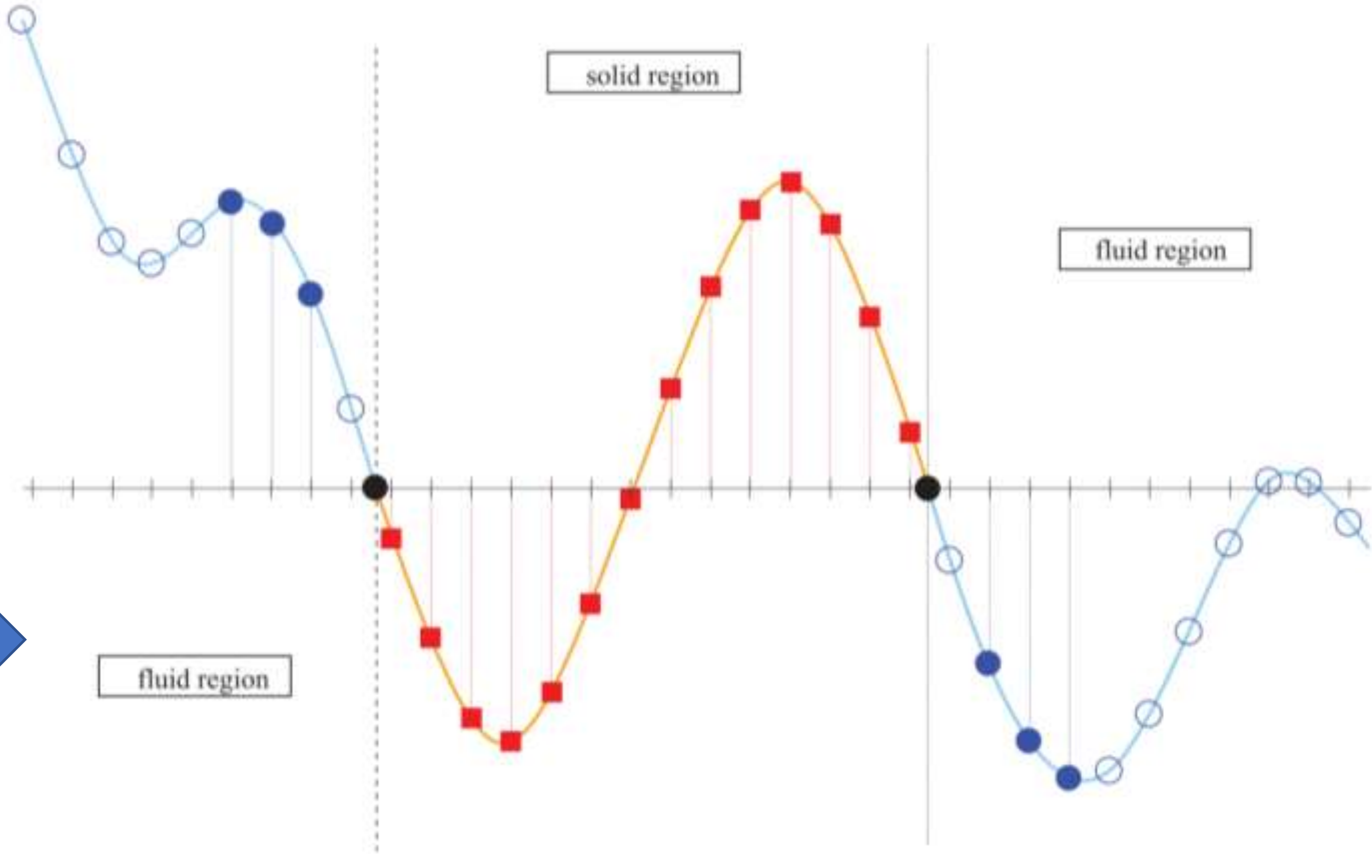


- Forcing term in the Navier-Stokes equations
- Use of a scalar field to cancel NS equations inside solids:
  - $\epsilon = 1$ inside solids
  - $\epsilon = 0$ for the fluid

IBM







-1D reconstructions: cubic spline / Lagrange polynomials
-1 reconstruction per velocity component per direction
-Compatible with 2D domain decomposition
-Compatible with moving objects

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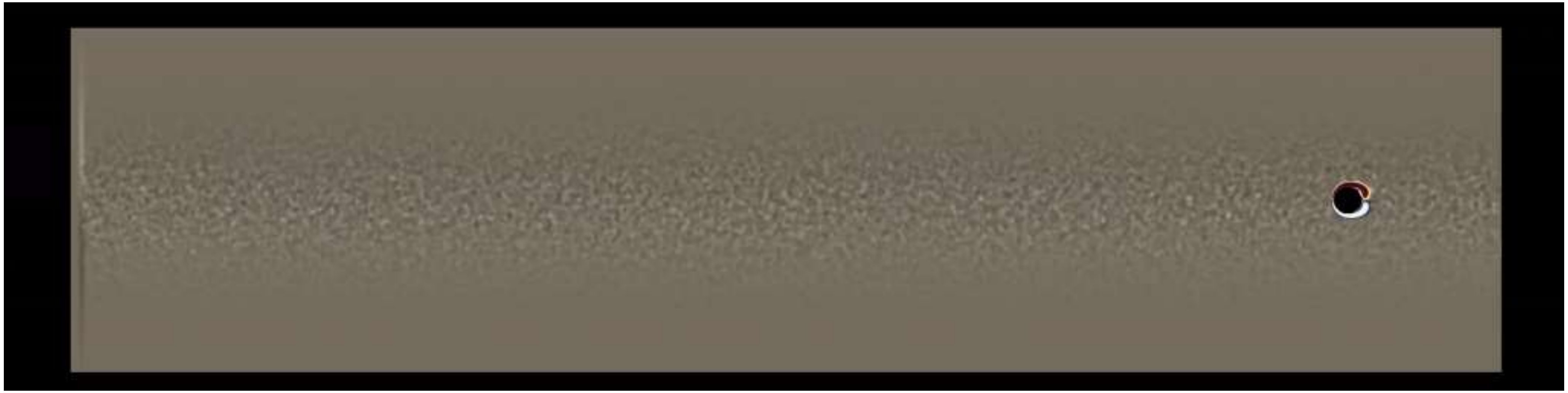
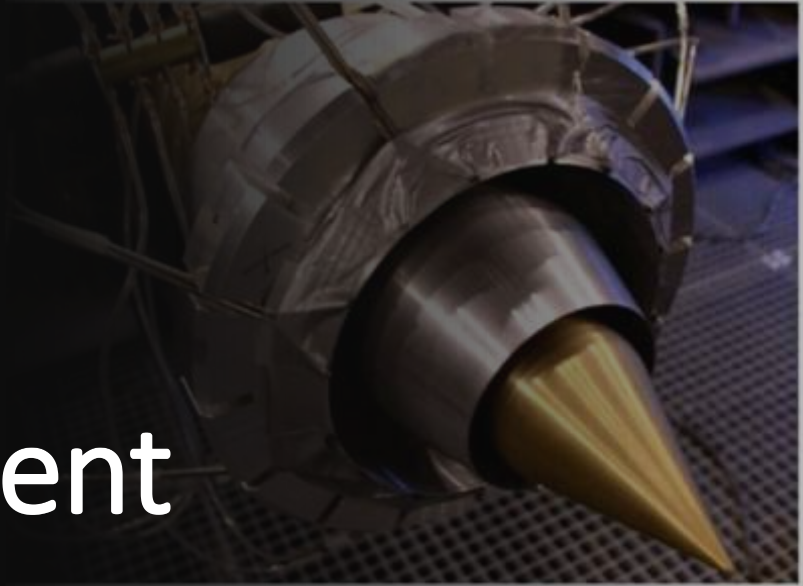
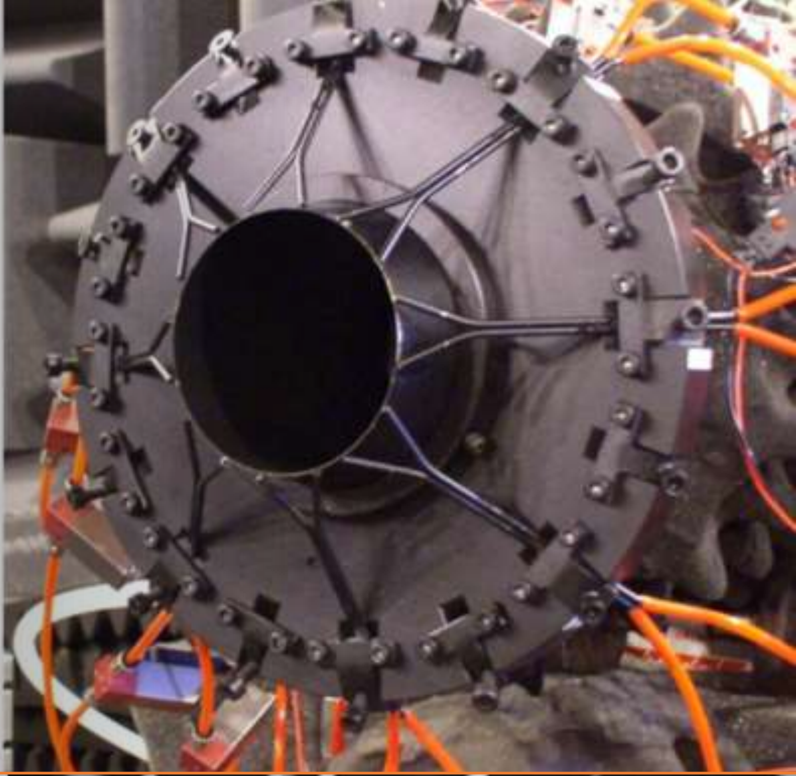
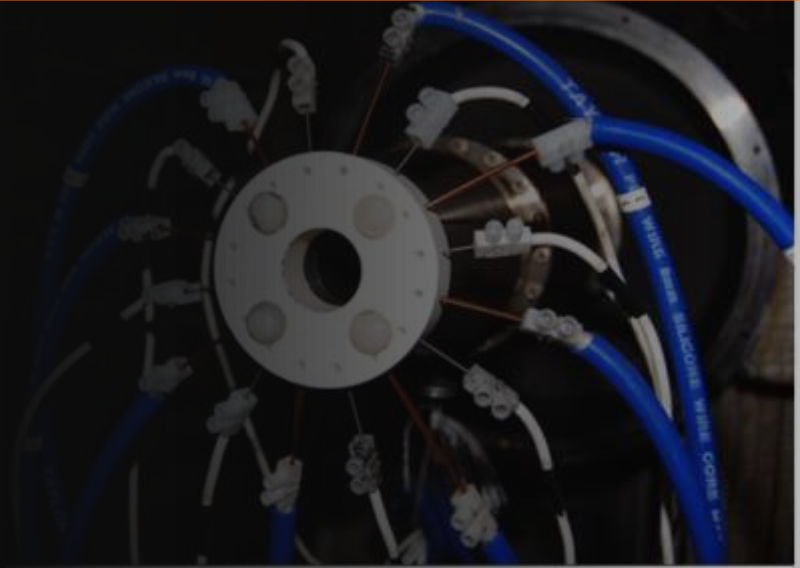


Control Turbulent jets

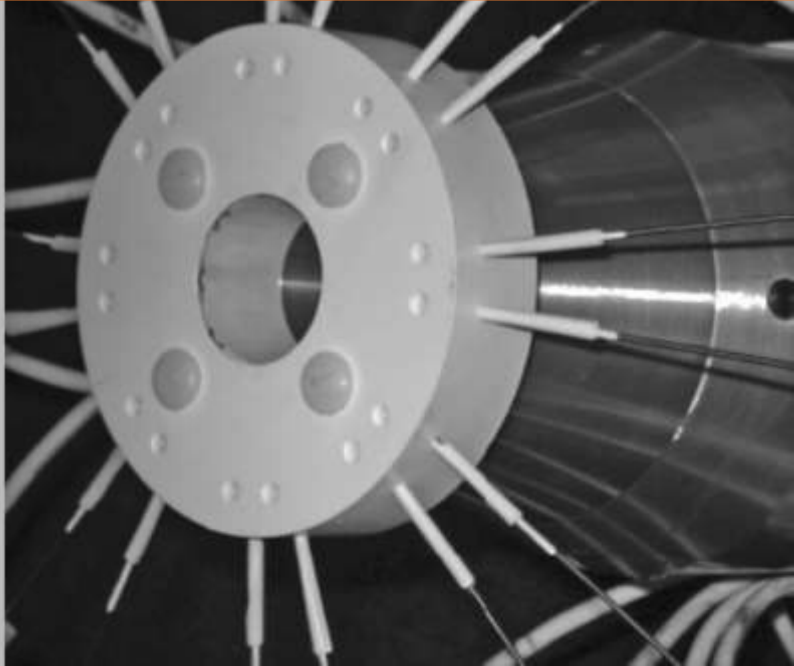


Micro-Fluidic Actuators



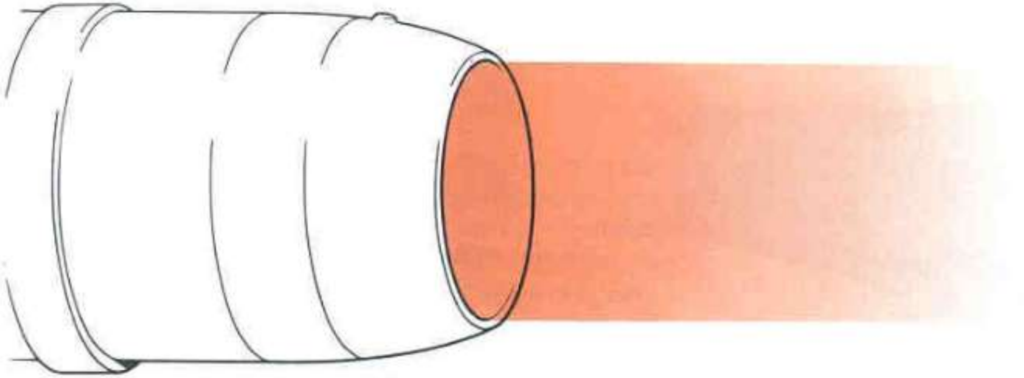


Plasma Actuators

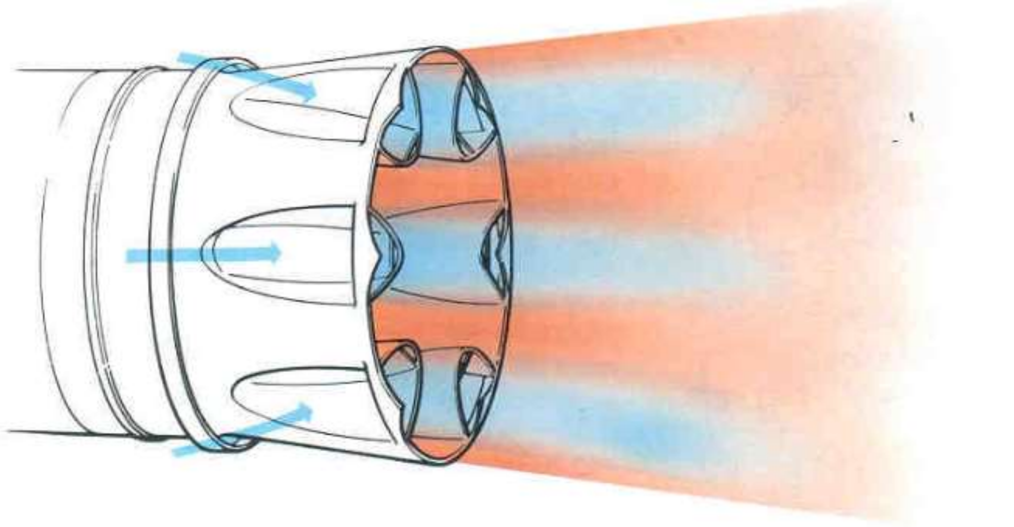


Control Turbulent jets

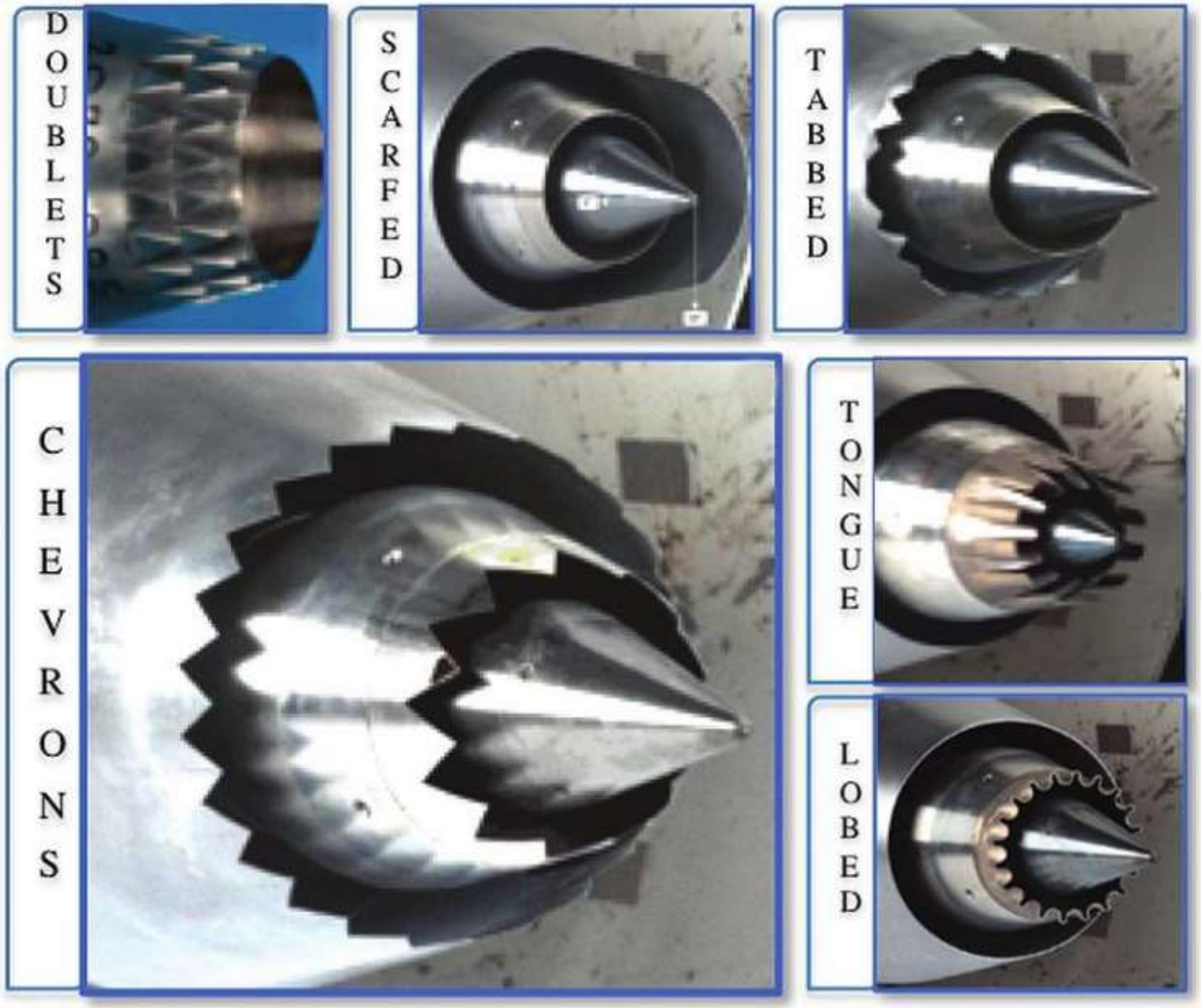
Control Turbulent jets



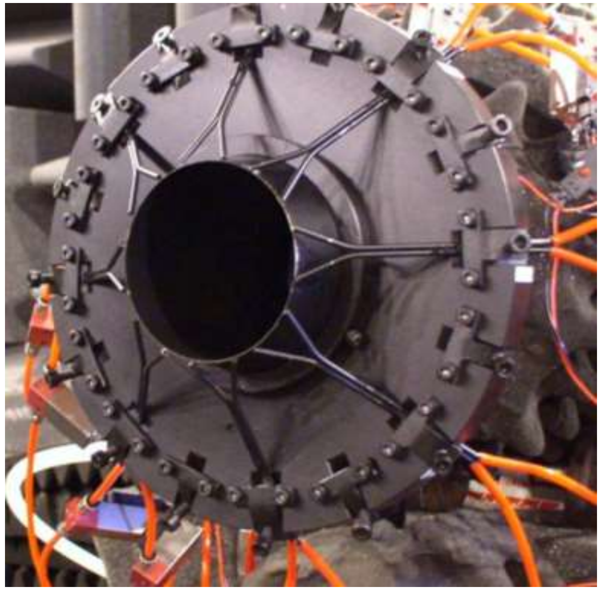
PLAIN NOZZLE (low mixing rate) HIGH NOISE LEVEL

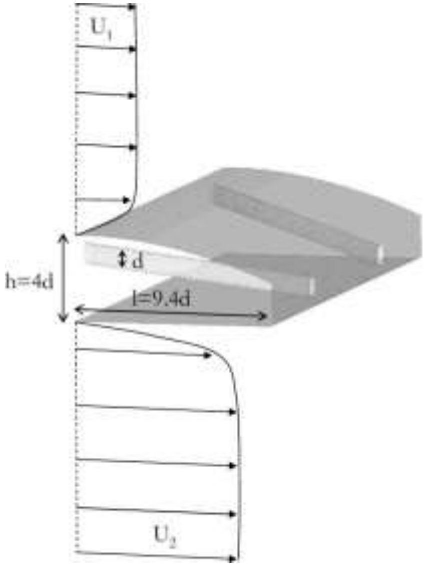


SUPPRESSOR NOZZLE (high mixing rate) REDUCED NOISE LEVEL



Control Turbulent jets



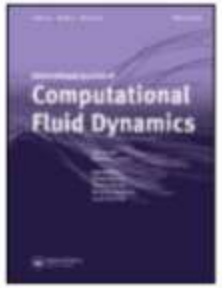


Home > Physics of Fluids > Volume 20, Issue 10 > 10.1063/1.3006424
Full . Published Online: 31 October 2008 Accepted: September 2008

Subsonic jet noise reduction by fluidic control: The interaction region and the global effect

Physics of Fluids **20**, 101519 (2008); https://doi.org/10.1063/1.3006424

E. Laurendeau, P. Jordan, J. P. Bonnet[a], J. Delville, P. Parnaudeau, *and* E. Lamballais

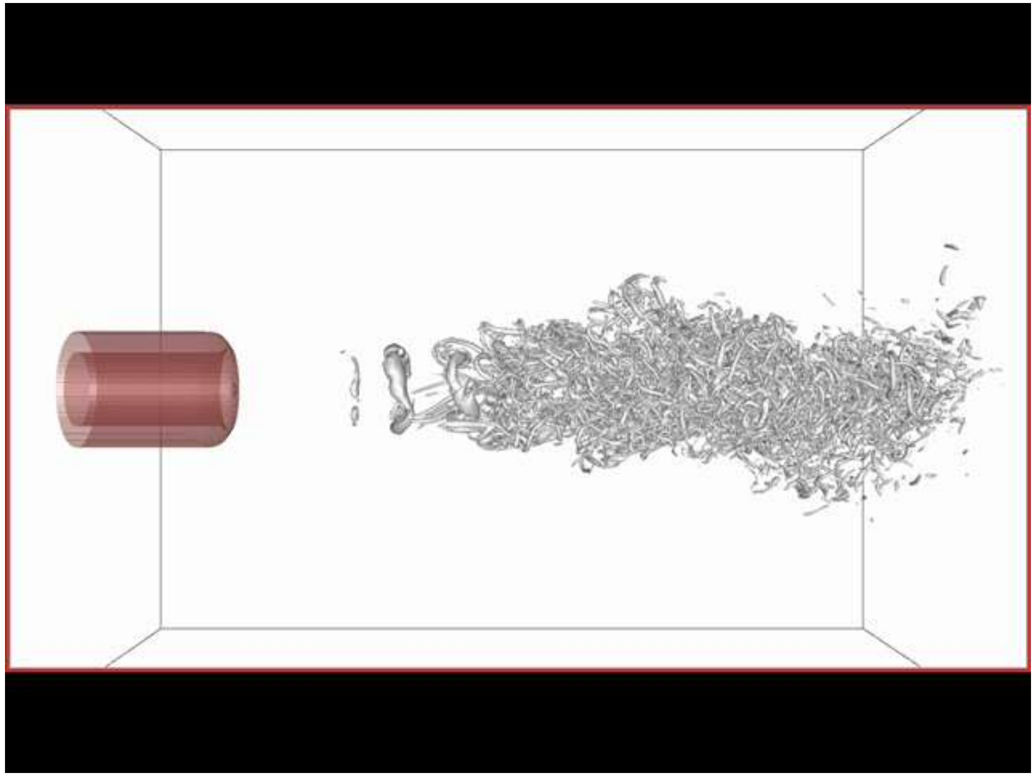


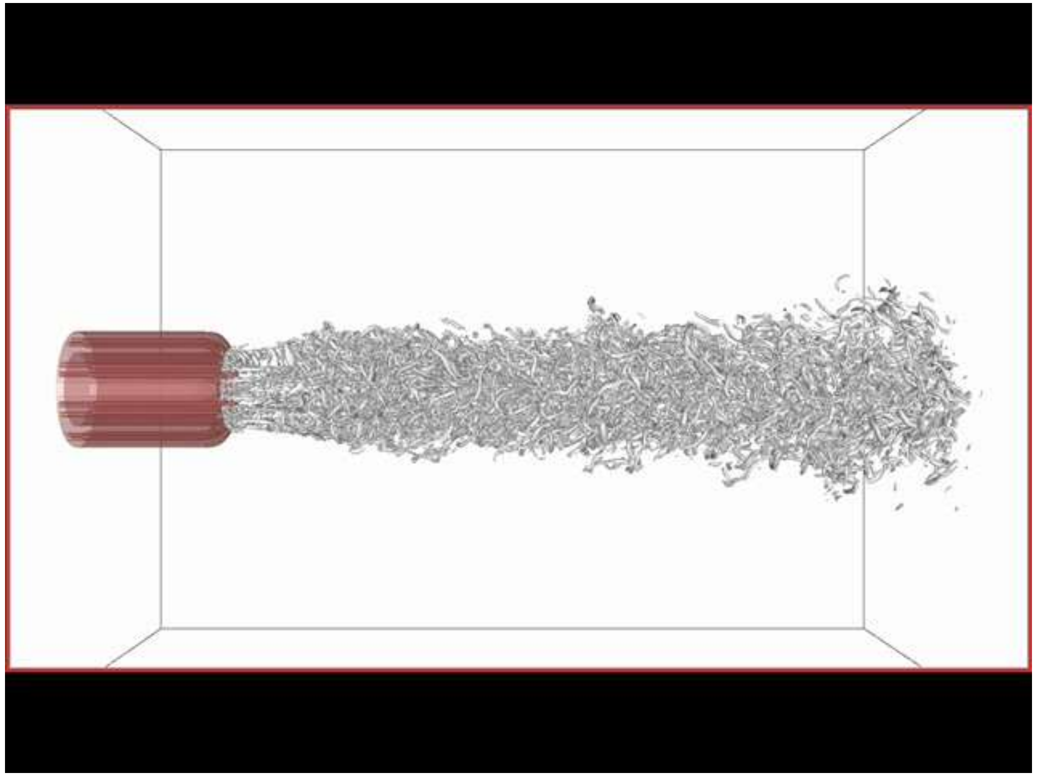
Taylor & Francis
International Journal of Computational Fluid Dynamics
ISSN: 1061-8562 (Print) 1029-0257 (Online) Journal homepage: https://iahr.tandfonline.com/loi/gcfd20

A DNS study of jet control with microjets using an immersed boundary method

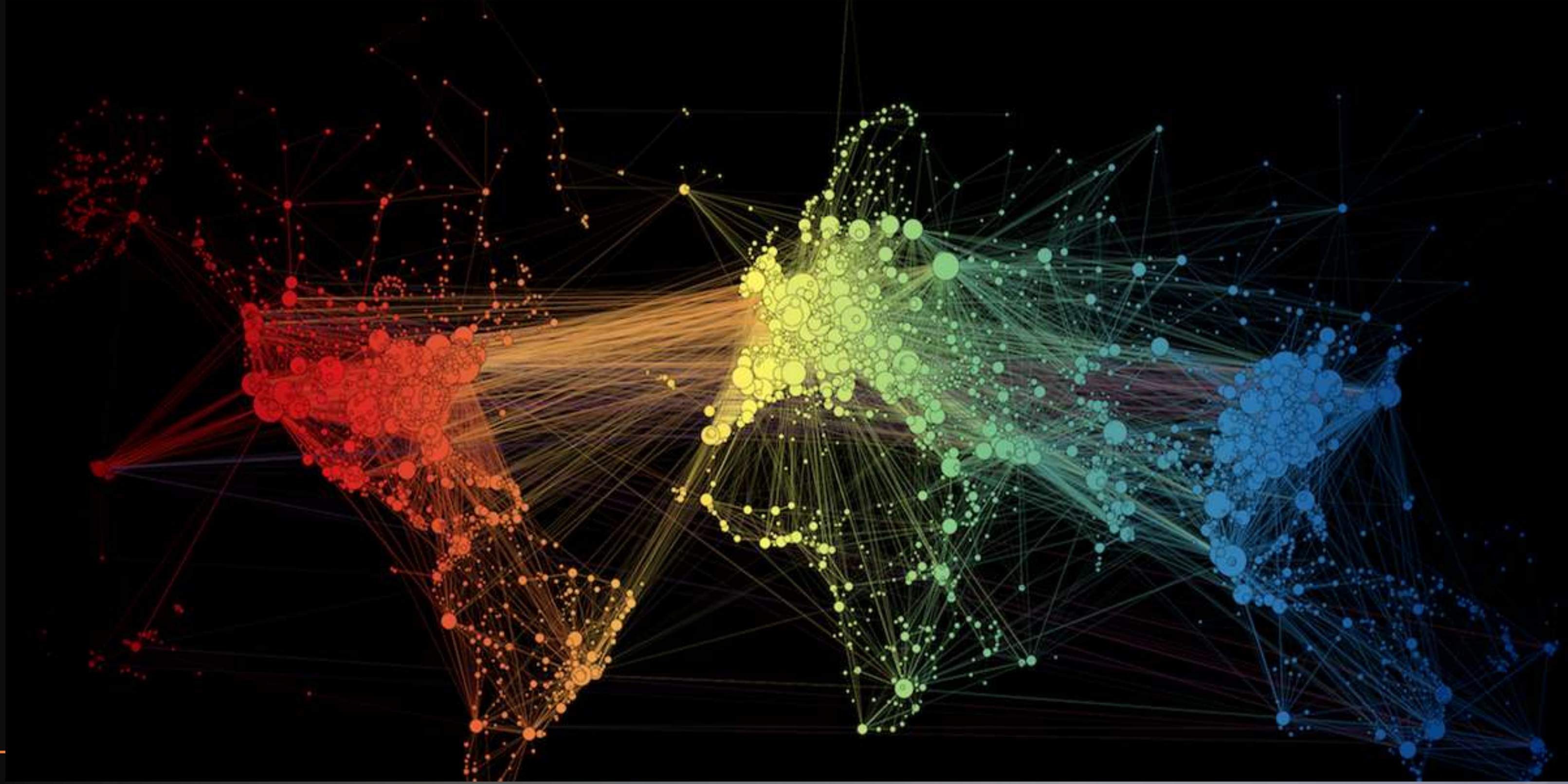
Rémi Gautier, Sylvain Laizet & Eric Lamballais

Control Turbulent jets





Control TBL

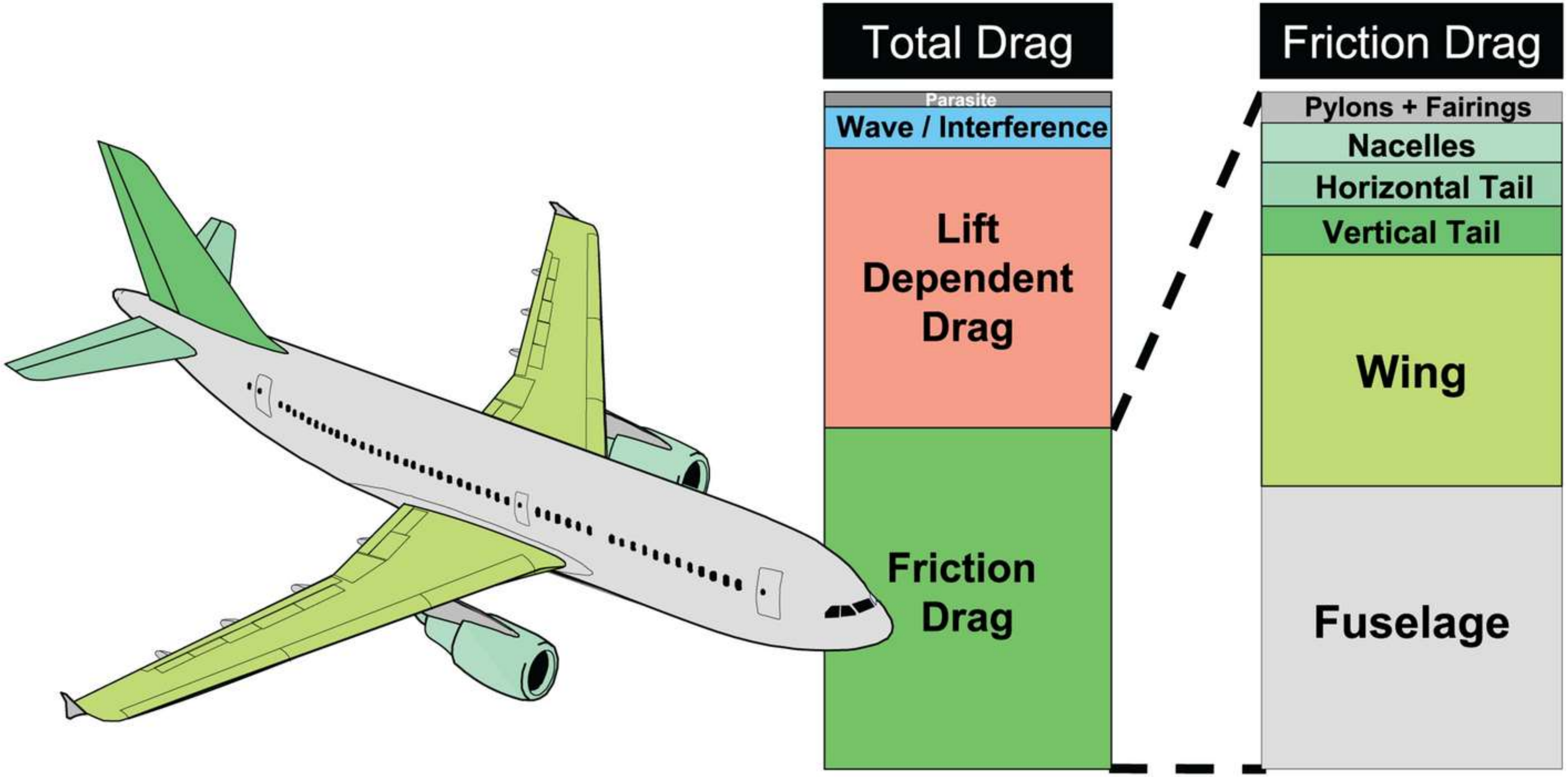


Control TBL

Flow, Turbulence and Combustion (2021) 106:81–108
https://doi.org/10.1007/s10494-020-00157-7

Combined Blowing/Suction Flow Control on Low-Speed Airfoils

Vladimir Kornilov[1]



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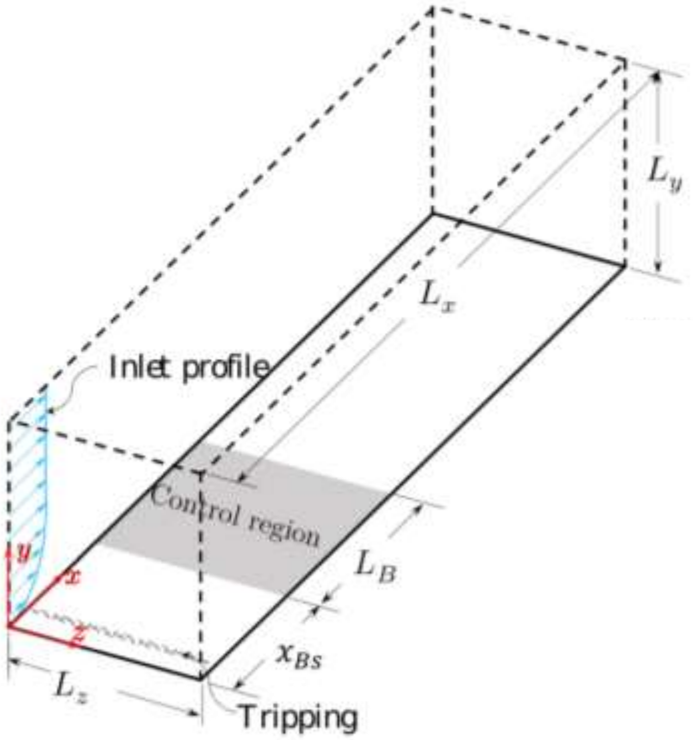
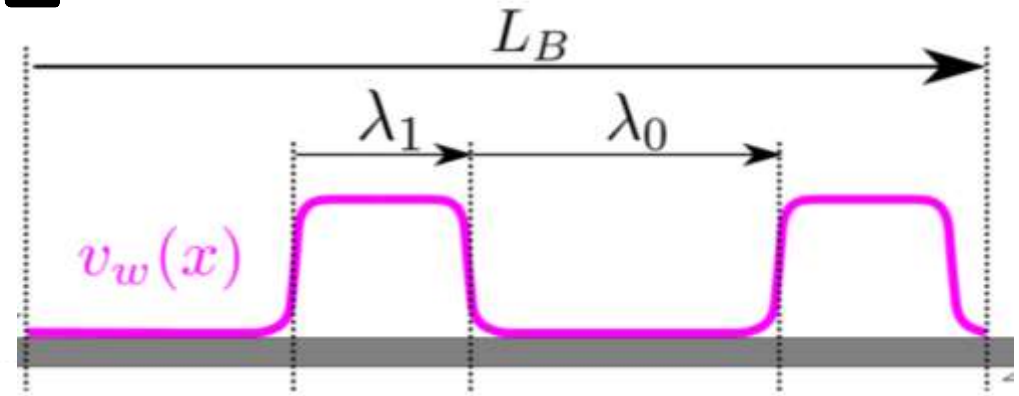
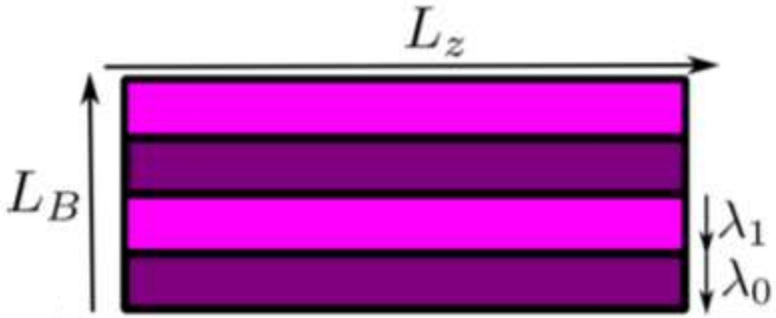
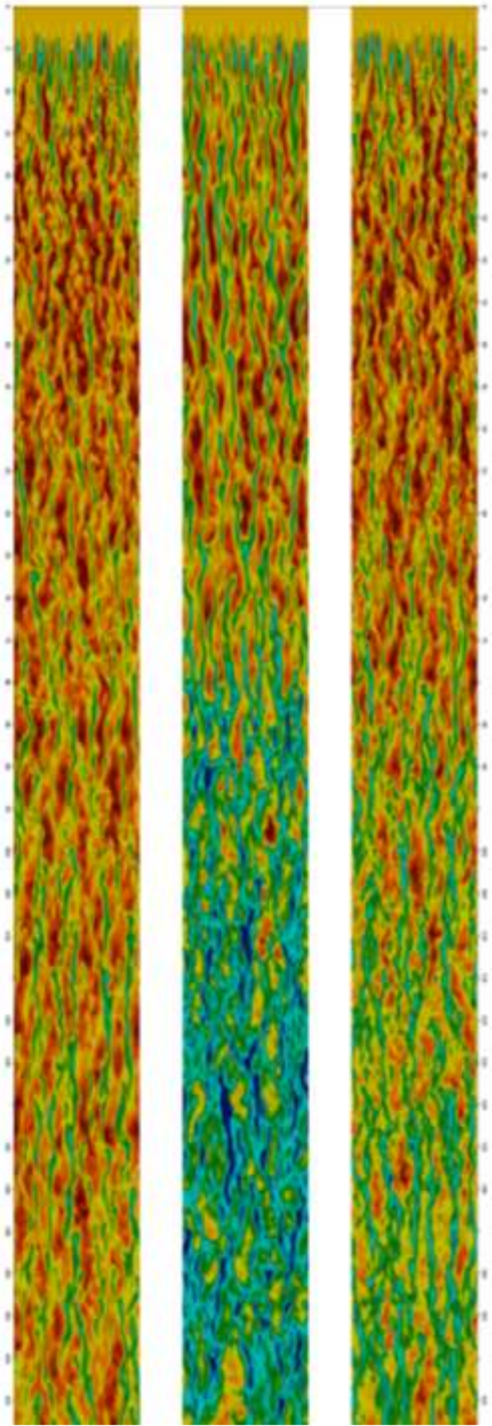








$L_x \times L_y \times L_z = 750\delta_0 \times 40\delta_0 \times 15\delta_0$

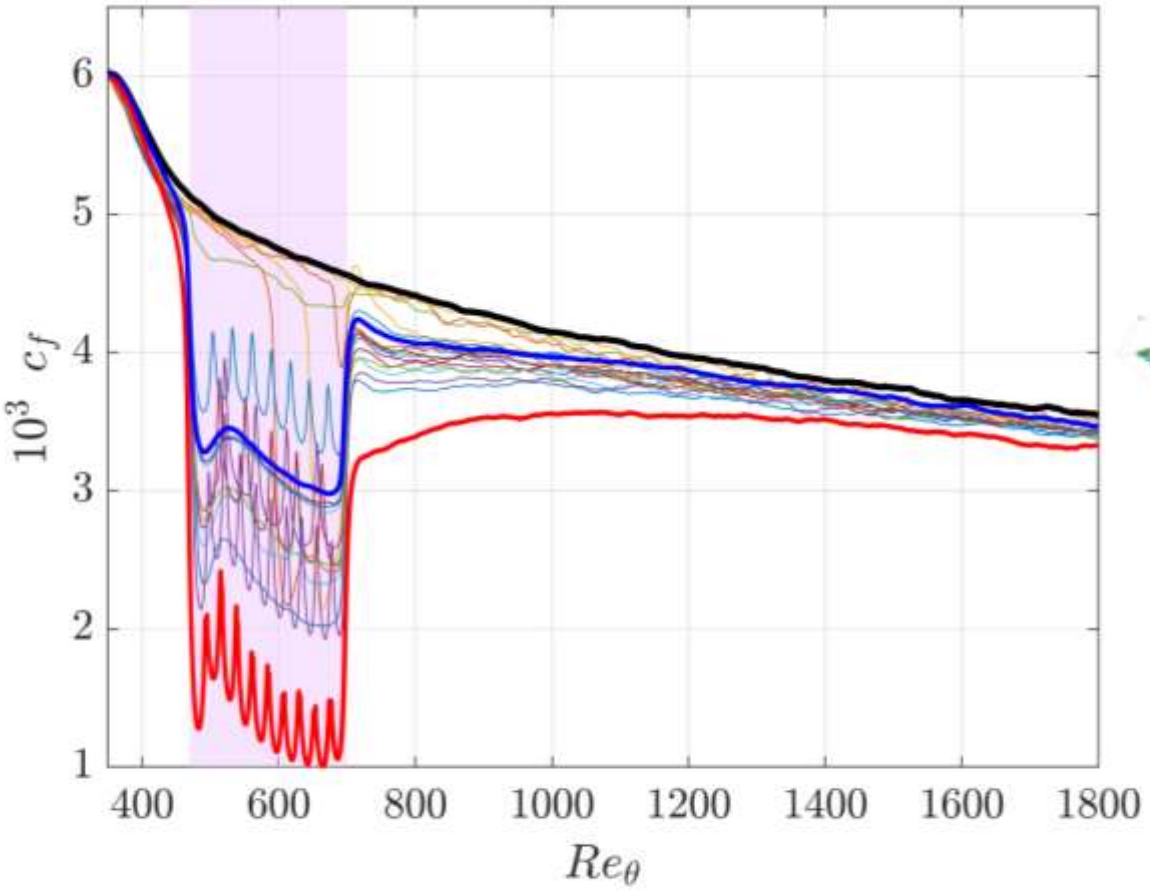
δ_0 is the boundary layer thickness at the inlet

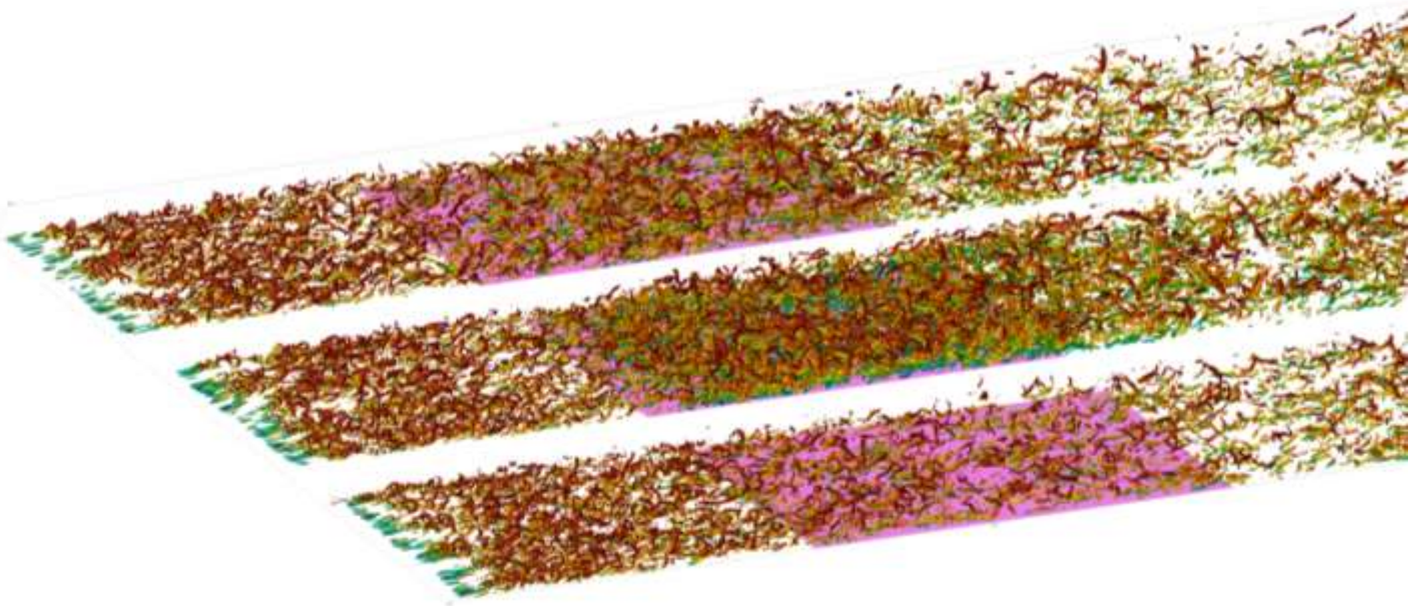
$n_x \times n_y \times n_z = 3073 \times 321 \times 128$ mesh nodes (2,048 cores)

$170 < Re_\theta < 1850$

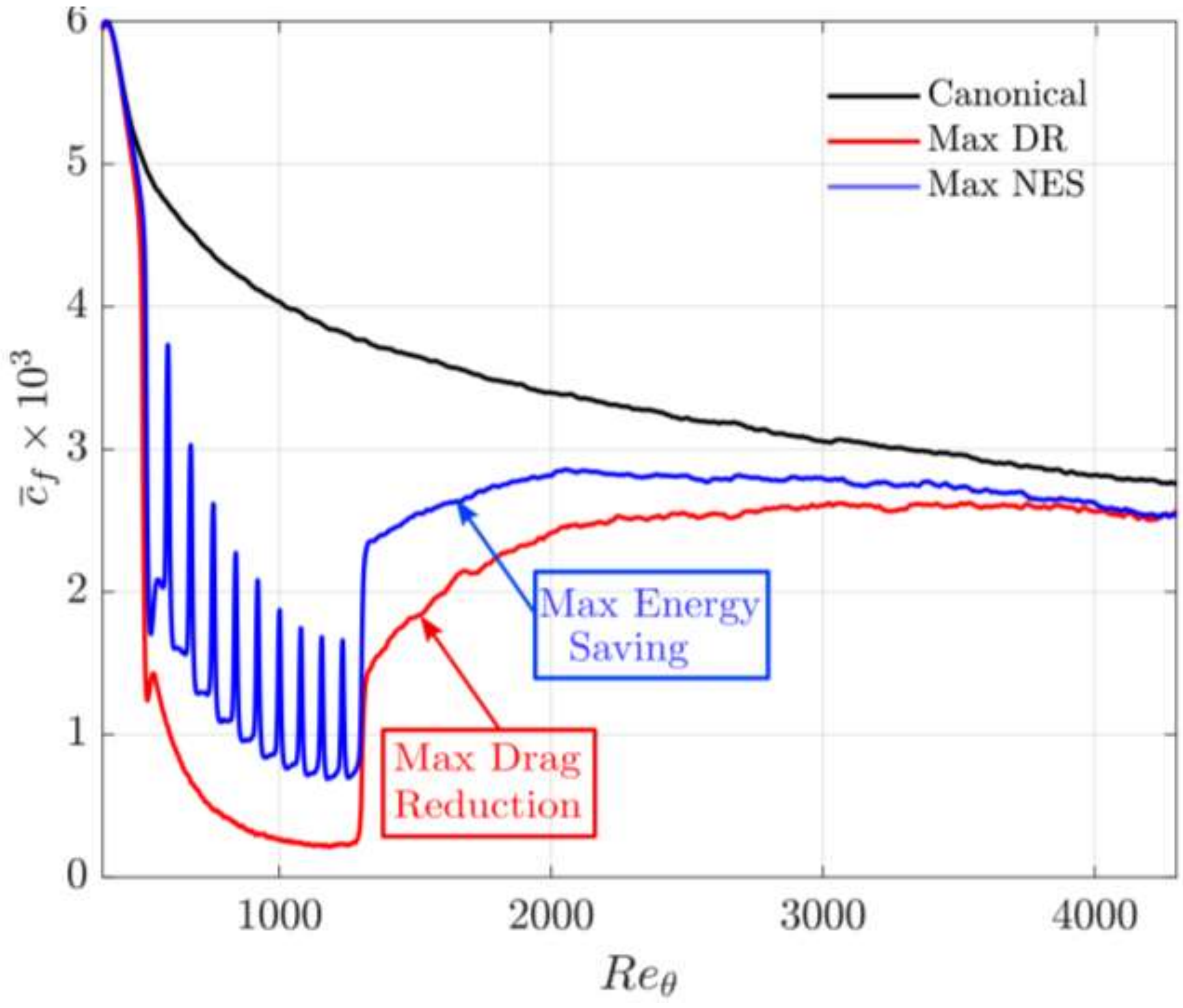
For $Re_\theta = 365$: $\Delta x^+ = 0.84$, $0.027 \leq \Delta y^+ \leq 6.8$ and $\Delta z^+ = 0.4$

Control TBL





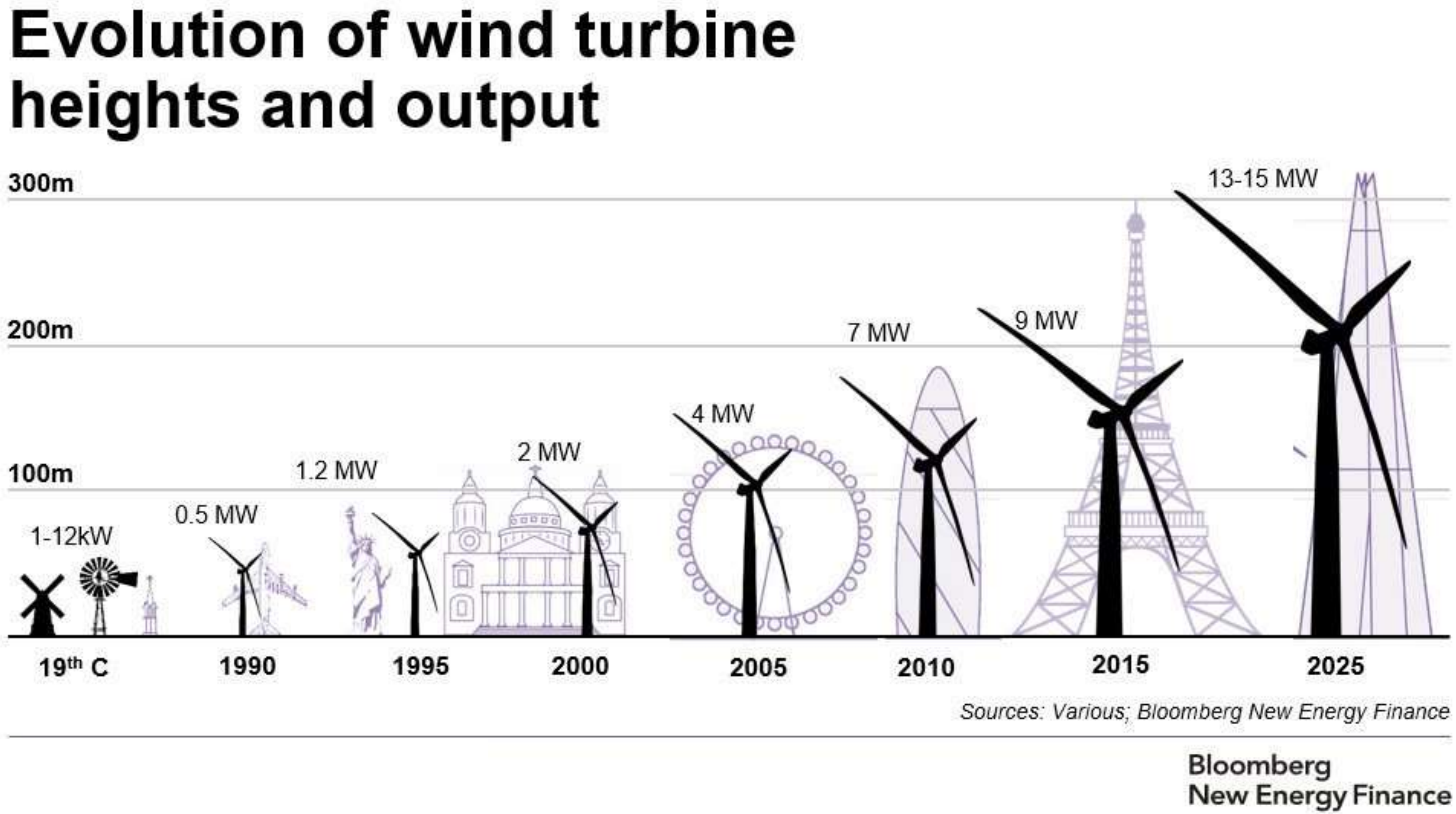
Control TBL



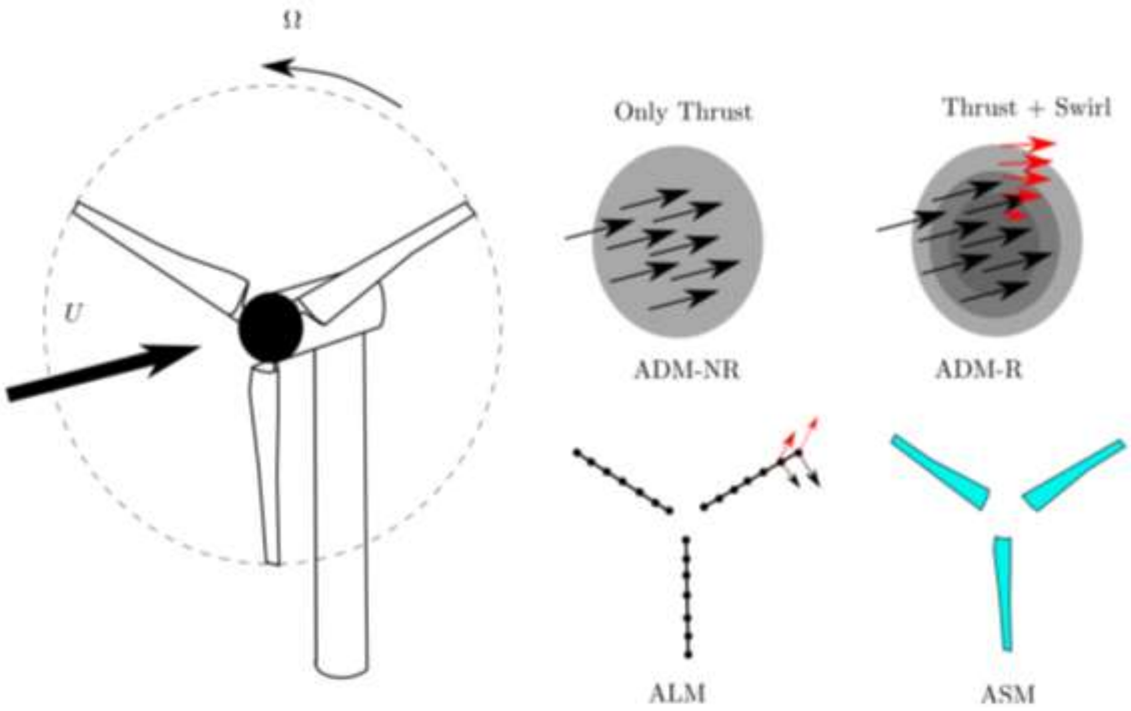
Case	C_B ×100	α	N_B	Max DR	GDR	Energy Saving
1	0.925	0.225	5	78.4	8.8	1.1
2	0.3	1	1	46.7	12.5	0.97
3	0.5	0.775	10	66.6	15.8	1.89
4	1	1	1	94.5	34.7	-1.76
5	0.8	1	1	88.6	29.4	1.71
6	1	0.775	1	93.6	26.8	-1.47
7	1	0.5	1	90.4	18.6	0.34
8	0.75	0.975	1	85.6	27.6	2.32
9	0.5	0.325	10	56.8	6.8	1.02
10	0.8	0.675	3	83.3	21.1	2.34
11	0.575	0.8	9	72.2	18.8	2.65
12	0.675	1	8	82.5	26.4	3.04
13	0.7	0.75	2	79.7	20.6	2.41
14	0.75	0.775	8	82.5	23.3	3.21
15	0	0	10	0	0	0
16	0.725	0.4	2	74.8	12.1	2.06
17	0.725	1	10	85.1	27.6	2.51
18	0.675	0.875	10	79.7	23.5	3.09
19	0.725	0.675	10	79.2	19.9	3.01
20	0.725	0.9	10	82.1	24.5	3.24
21	0.7	0.825	8	81.0	22.6	2.6
22	0.7	0.85	8	81.3	22.9	2.31
23	0.725	0.8	9	81.6	22.8	2.77
24	0.725	0.825	8	82.0	23.2	2.57

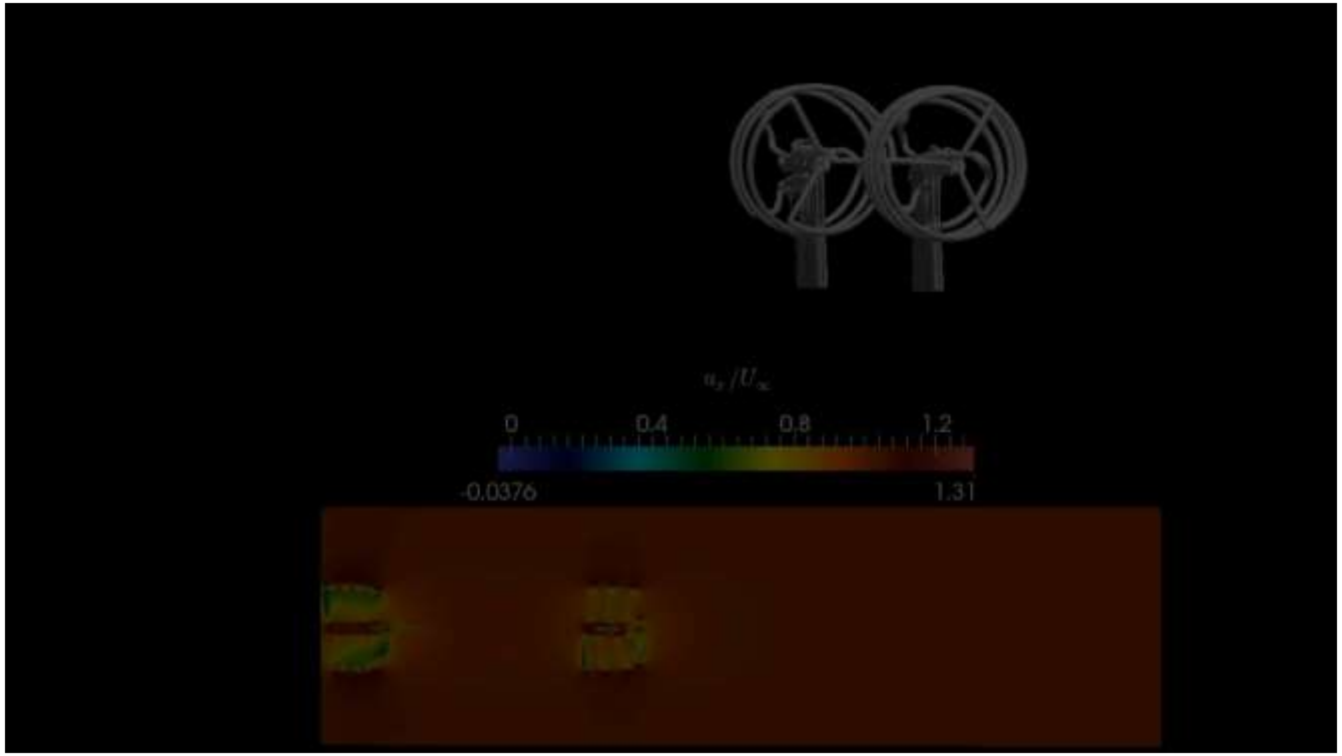
Control Wind Farm

Control Wind Farms



Control Wind Farms





WIND ENERGY
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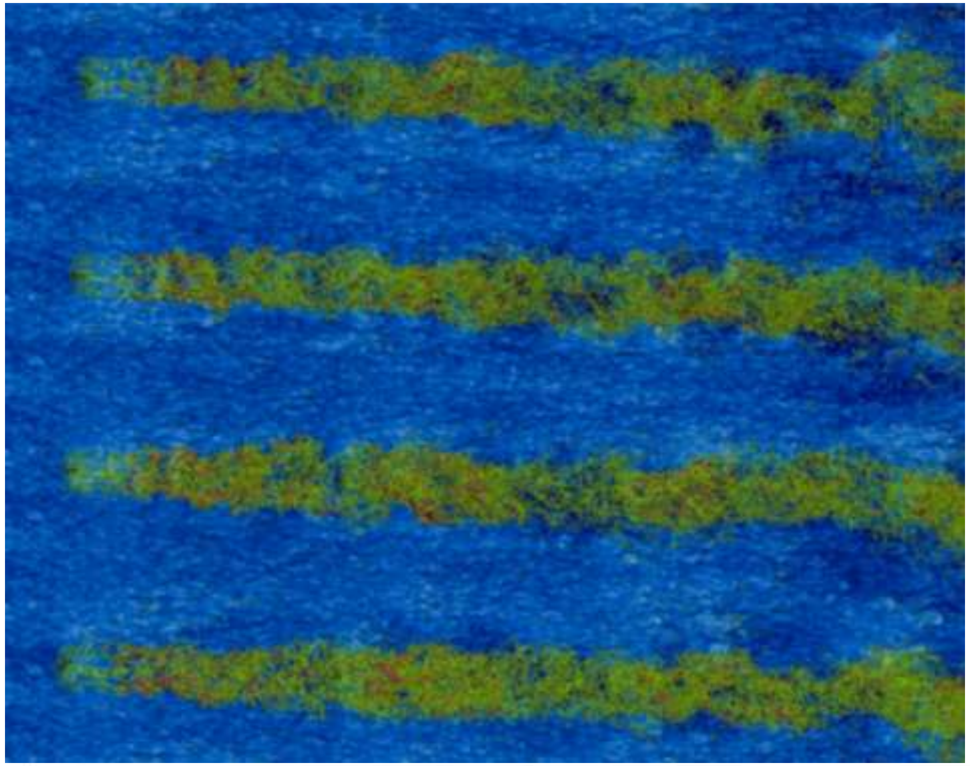
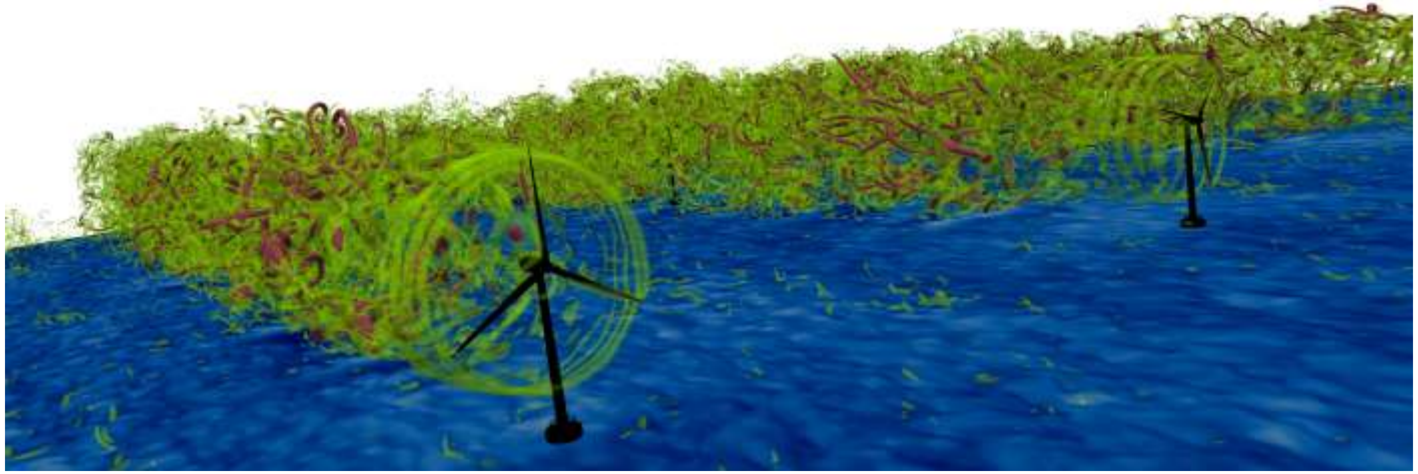
RESEARCH ARTICLE | Free Access

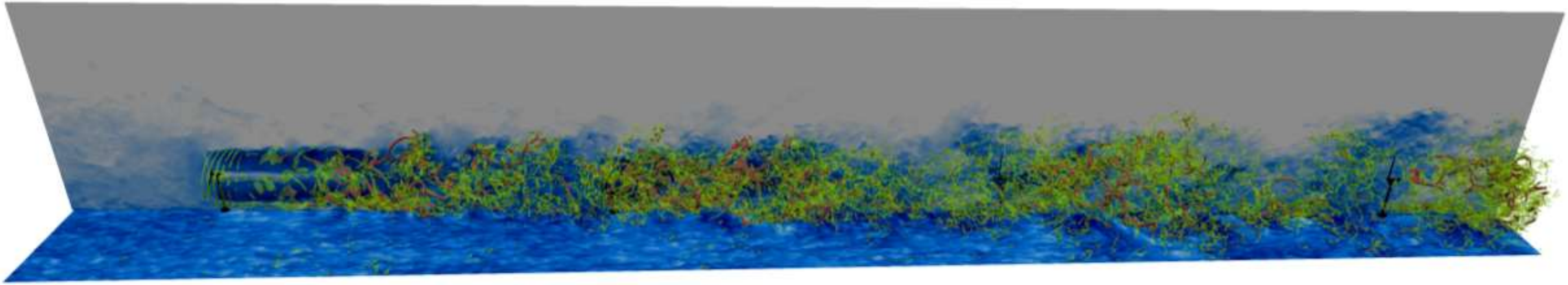
WInc3D: A novel framework for turbulence-resolving simulations of wind farm wake interactions

Georgios Deskos, Sylvain Laizet, Rafael Palacios

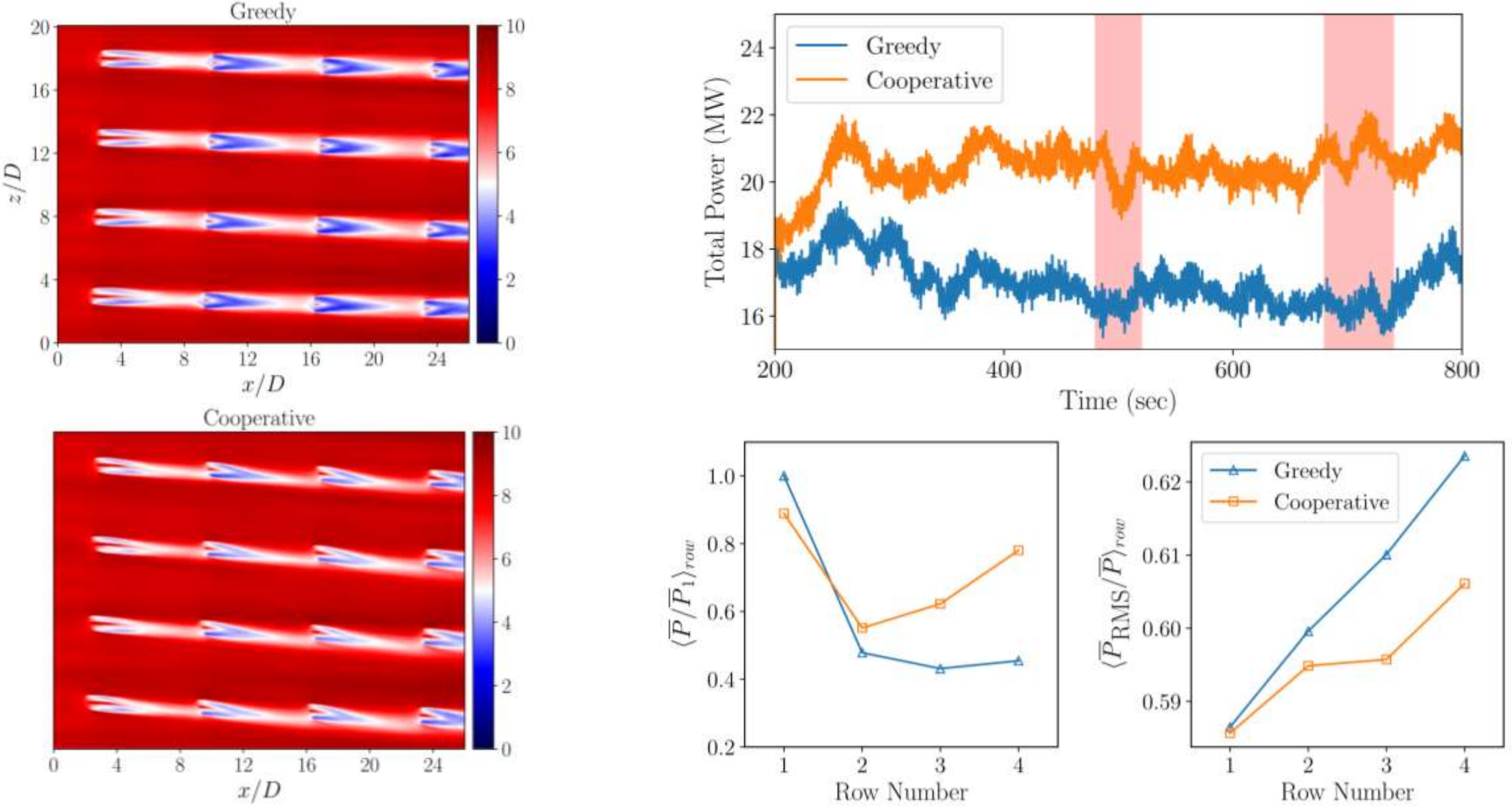
Control Wind Farms





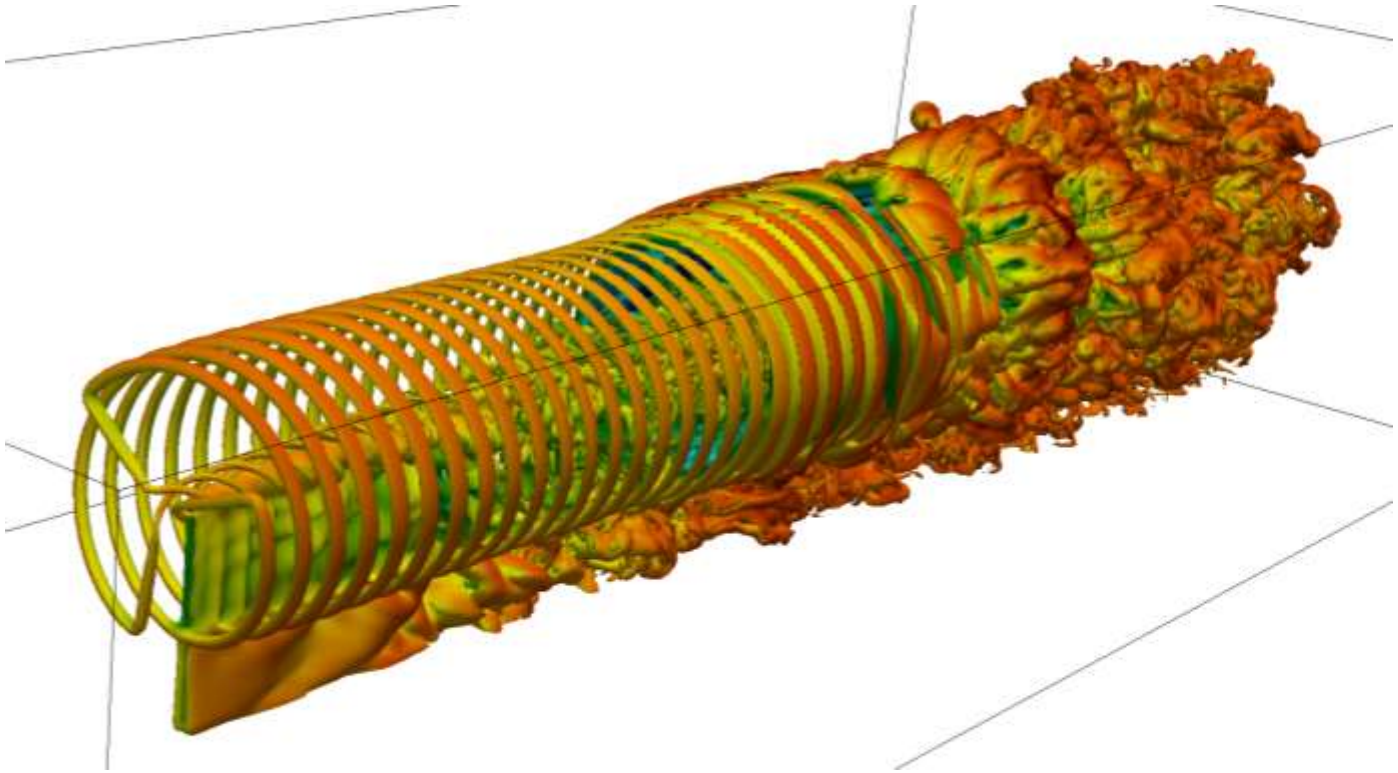


Control Wind Farms



Tasks for the competition

- References
- Overview
- Wind Turbine Simulations
- Configuration Example
- Running the Taylor-Green vortex case
- Running the wind turbine case
- Tunables Parameters
- Tasks and Submissions
  - Input files for the wind turbine simulations
  - Profiling
  - Performance
  - Visualizations
  - Bonus Task

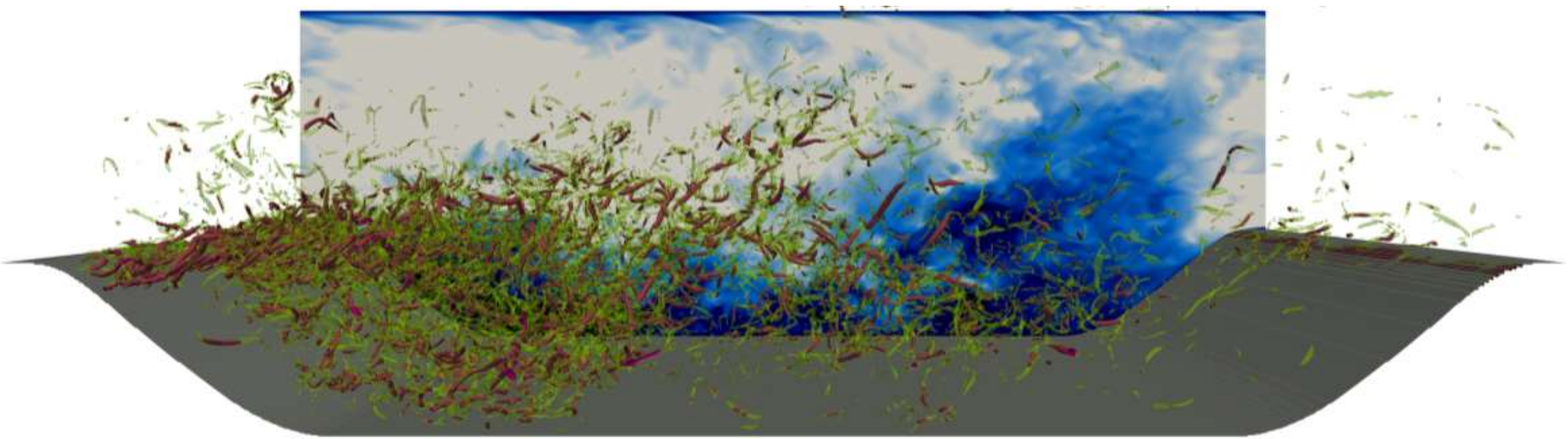


More information

www.incompact3d.com

https://github.com/xcompact3d

Twitter: @incompact3d



Turbulence Simulation group

https://www.turbulencesimulation.com

Q&A