Large eddy simulations at rotor and farm scales

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Wind turbines and wakes



Wind turbines and wakes



Airfoil and
Blade aerodynamics



Rotor control
Loads



Farm level interactions
Control

- Spectrum of temporal and spatial scales
- Untractable by a single numerical approach
- Embedding and coupling of
  - methodologies (BEM results -> LES)
  - experimental results (e.g. polars, dynamic stall models)

Wind turbines and wakes

Large Eddy Simulation tools



Rotor control

Loads



Farm level interactions

Control

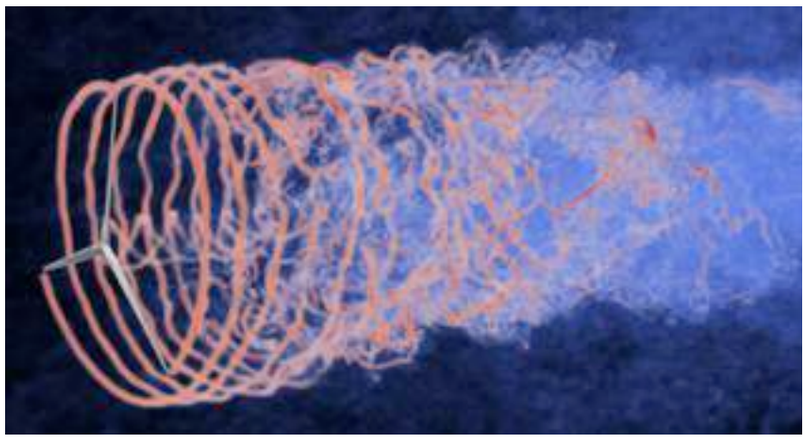
Outline

Large Eddy Simulation tools

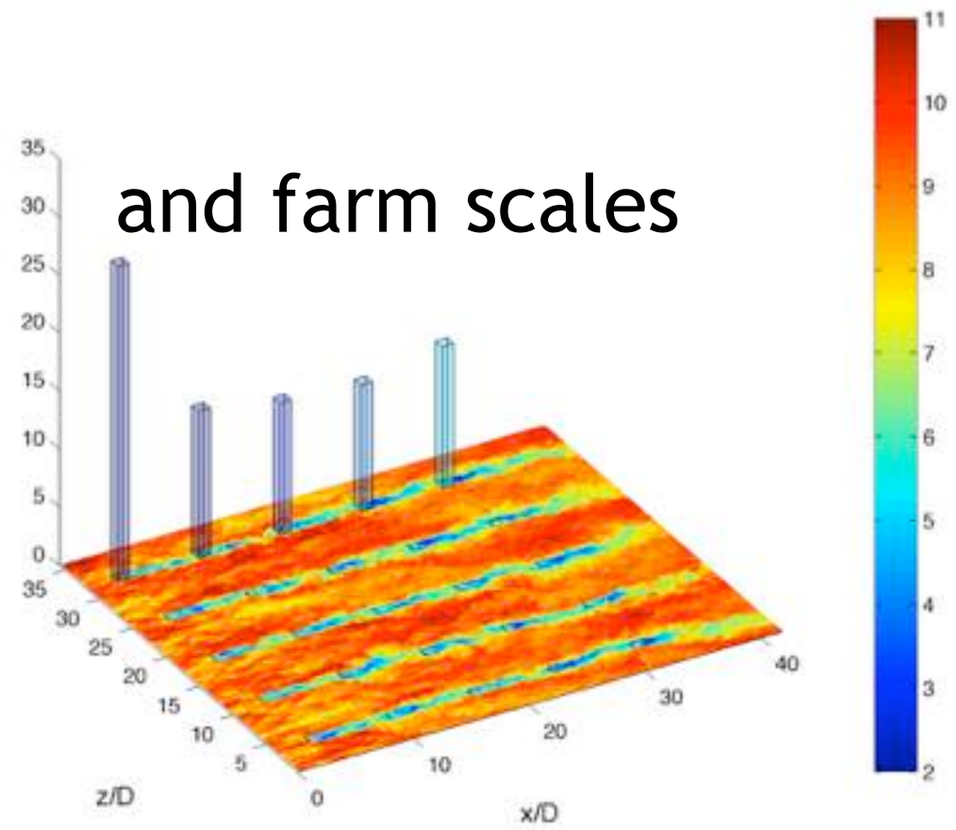
Formulation — Rotor model — Implementation

used at

rotor…



and farm scales



Vortex Particle-Mesh method
Lifting lines

⇄

Finite Difference method
Actuator disk

cross-verification

fidelity improvement

Vortex Particle-Mesh (VPM) methods

Vortex …

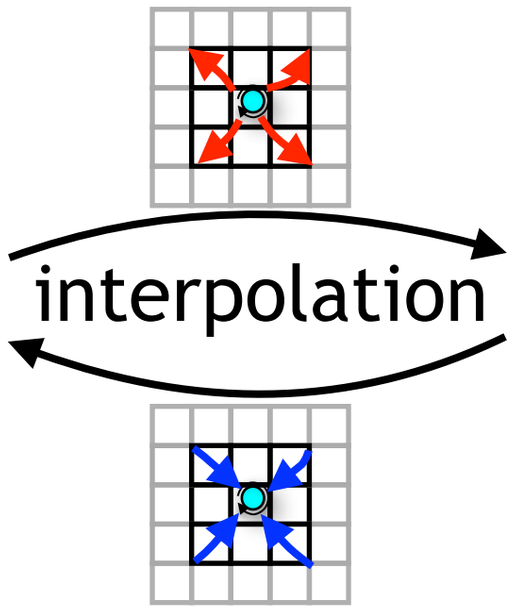
$$\boldsymbol{\omega} = \nabla \times \mathbf{u} \qquad \frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega} \cdot \nabla)\mathbf{u} + \nu \nabla^2 \boldsymbol{\omega}$$

… Particle - Mesh method

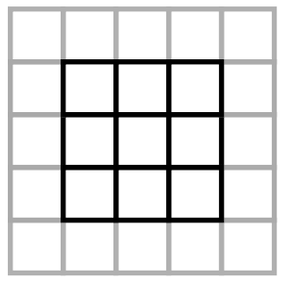
Advection

$$\mathbf{x}_p \quad \boldsymbol{\alpha}_p = \int_{V_p} \boldsymbol{\omega}\, dV \simeq \boldsymbol{\omega}_p V_p$$





Differential operators
Elliptic problems
Remeshing of particles



$\boldsymbol{\omega}_{ij}$
$\mathbf{u}_{ij}$
$\Delta\boldsymbol{\omega}_{ij}$

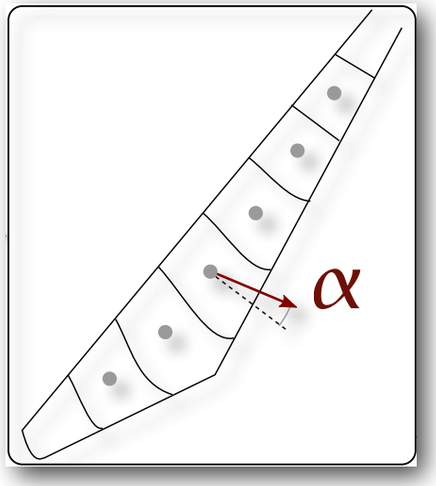
➡ Efficiency, low dispersion, low dissipation — Cottet & Koumoutsak

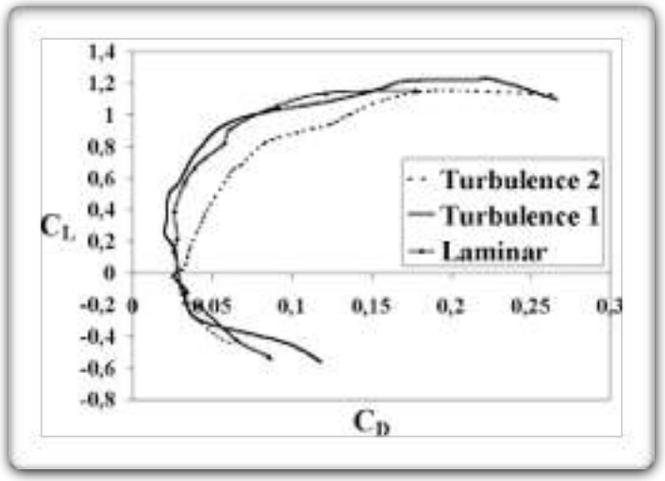
\+ FFT-based Poisson solver — Chatelain & Koumoutsakos, JCP, 2010

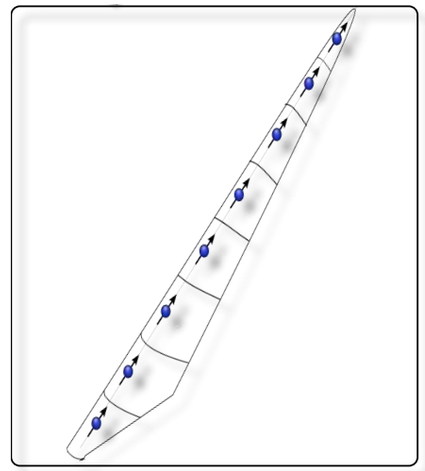
\+ Multiscale SGS model — Cocle et al., Phys. Fluids, 2009

\+ Lagrangian turbulent inflow (Mann alg. based)

Slender lifting bodies: Immersed Lifting Lines







Flow relative to lifting line

Line configuration (chord)

$\alpha \quad \boldsymbol{u}_{\mathrm{rel}}$ →

Aerodynamic performance

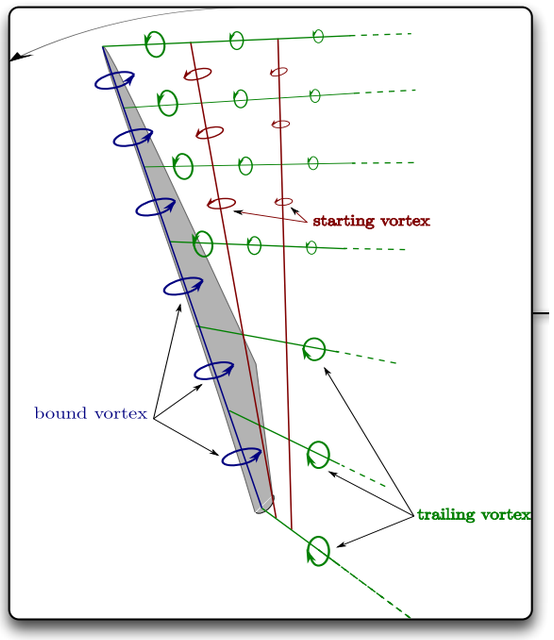
↓

Lift

Circulation

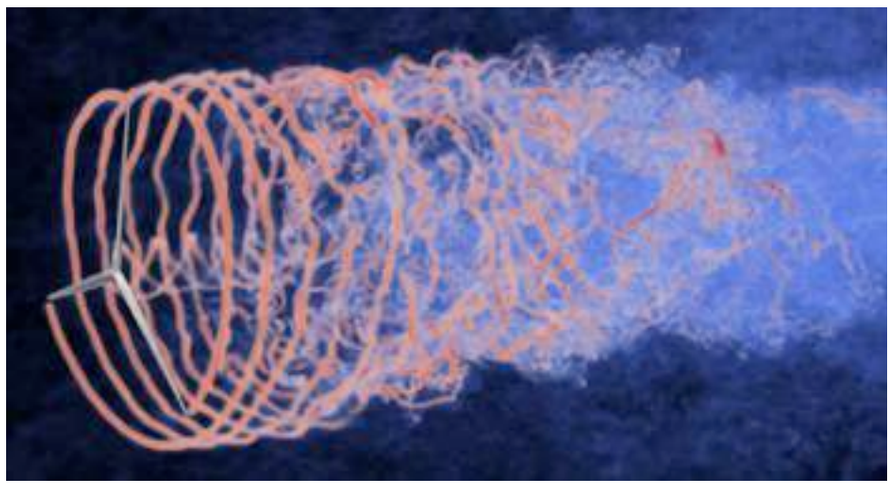
→ Bound vorticity

Shed vorticity

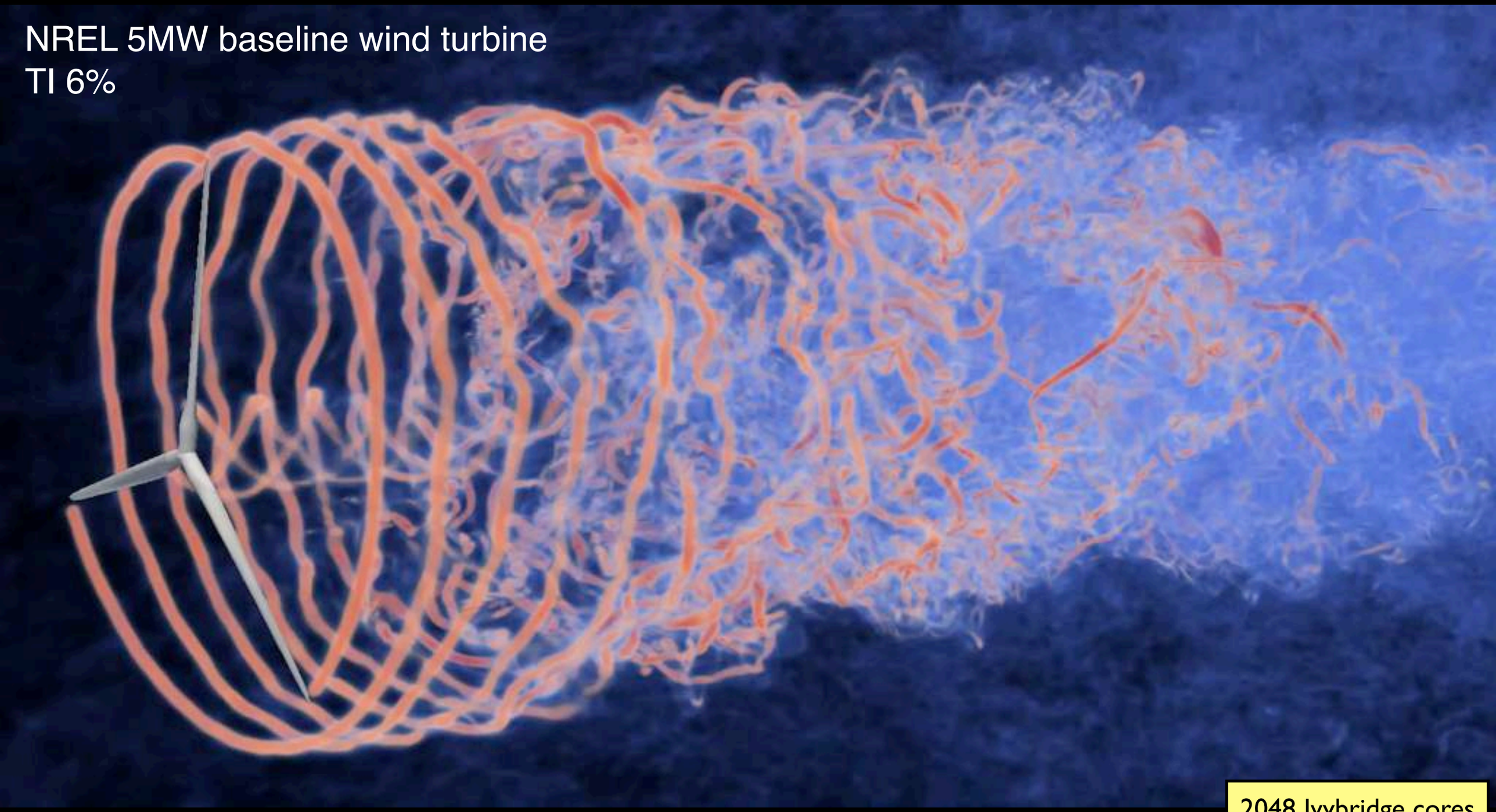


→

Added to bulk vorticity



Rotor-scale simulations:
HAWT near to far-wake transition



Volume rendering of $||\omega||$

2048 Ivybridge cores
16 hours
Np~ $3\ 10^8$

Vortex Particle-Mesh method + lifting lines

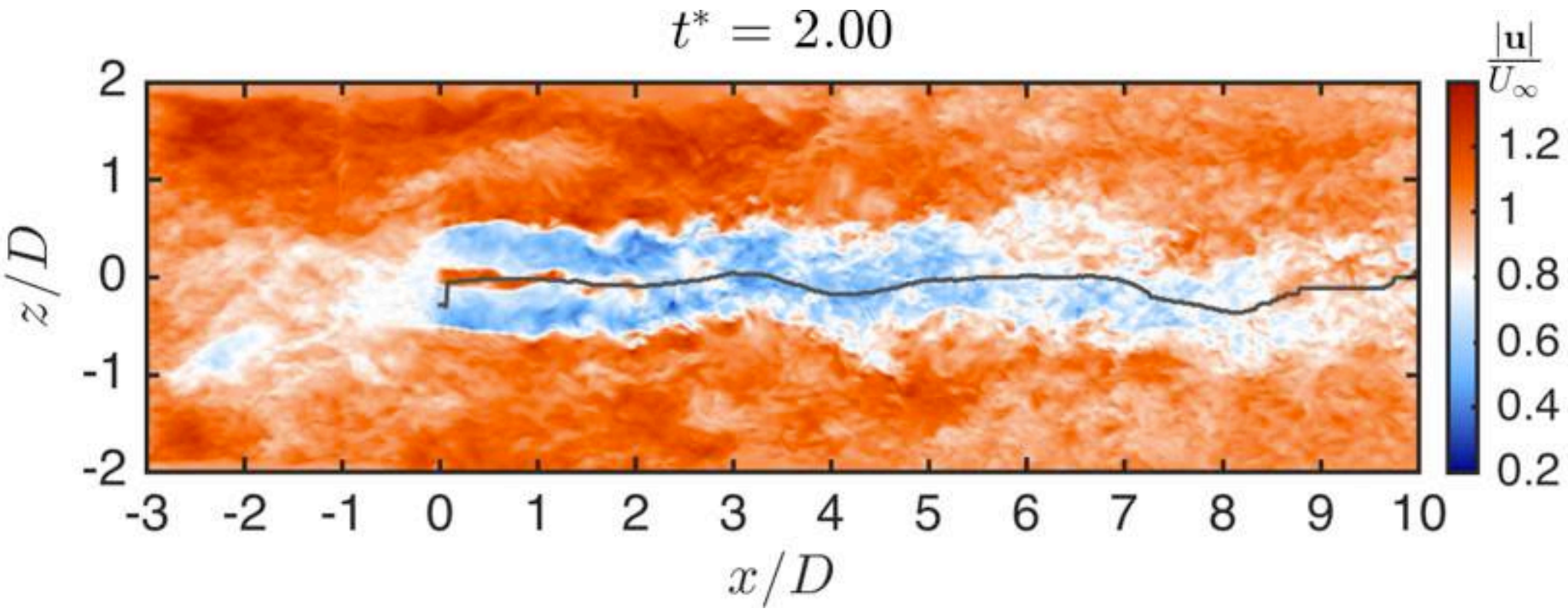
- Leveraged in
  - Wake physics: decay and meandering
  - Development of operational wake models
  - Wind turbine design tool
  - Wind turbine control, dynamics and loads

➡ **small wind turbine study…**

- Cross-validation of tools: rotor tool <-> farm tool

Vortex Particle-Mesh method + lifting lines

- Leveraged in
  - Wake physics: decay and meandering



Coudou et al., Torque 2018

Vortex Particle-Mesh method + lifting lines

- Leveraged in
  - Wake physics: decay and meandering
  - Development of operational wake models

Marichal et al., Wake conference 2017

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➡ **small wind turbine study…**

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Small wind turbines (50kW)

- Three technologies
  - turbine geometry, dynamics, and control (fixed speed vs MPPT)

Upwind HAWT,
variable speed (MPPT),
variable pitch
active yaw



Hacked
AOC 15/50

Downwind HAWT,
fixed speed,
fixed pitch,
passive yaw



AOC 15/50

H-type VAWT,
variable speed (MPPT)



Fairwind F180-50

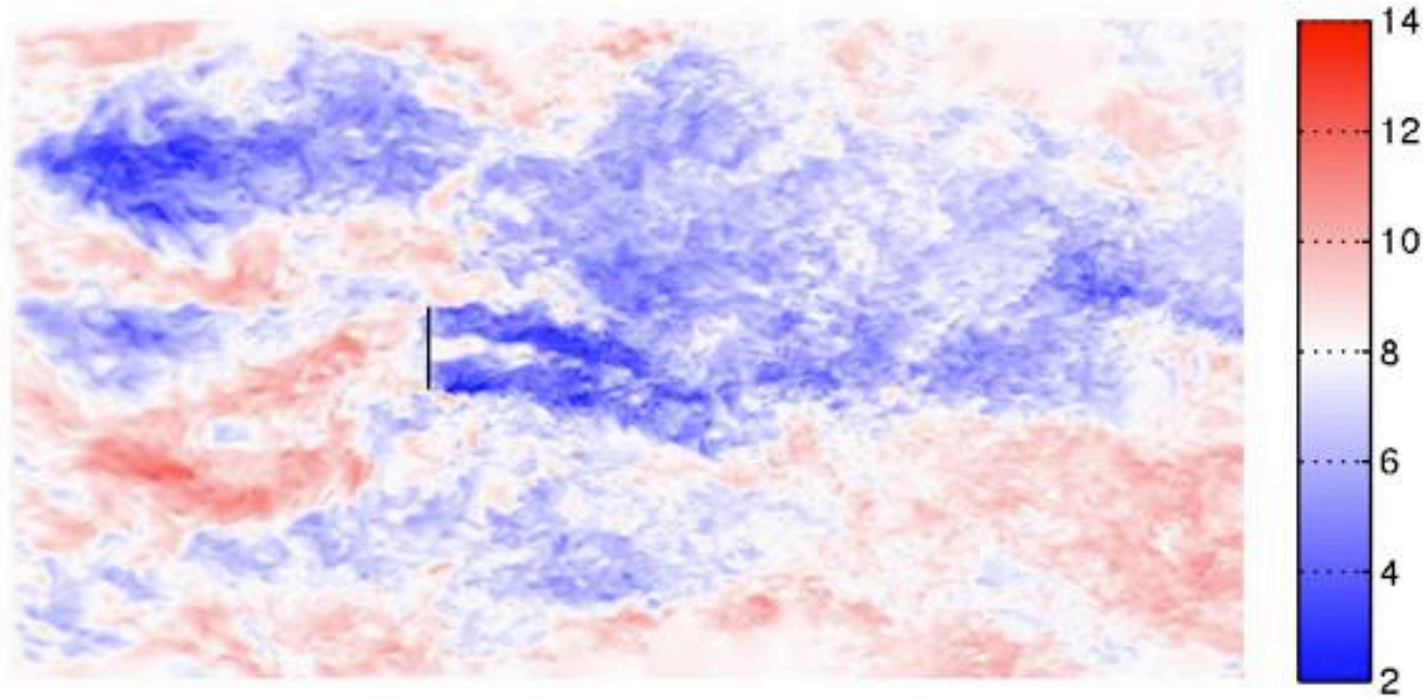
- Behaviors compared in low (TI = 6%) and high (15%) turbulence
- **Identical** turbulent winds!

Dynamics and wakes (high turbulence)

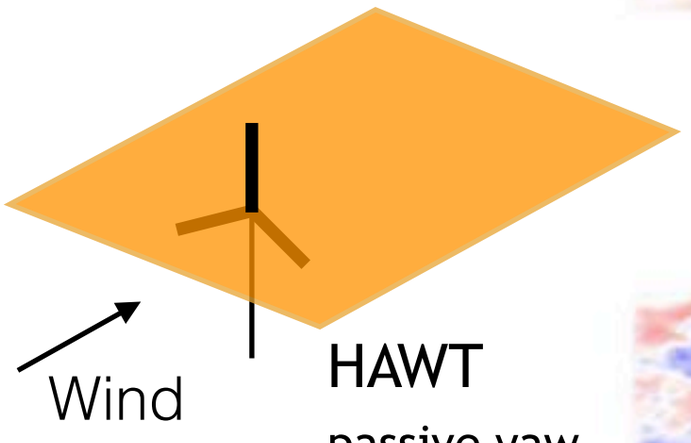
HAWT

active yaw

MPPT



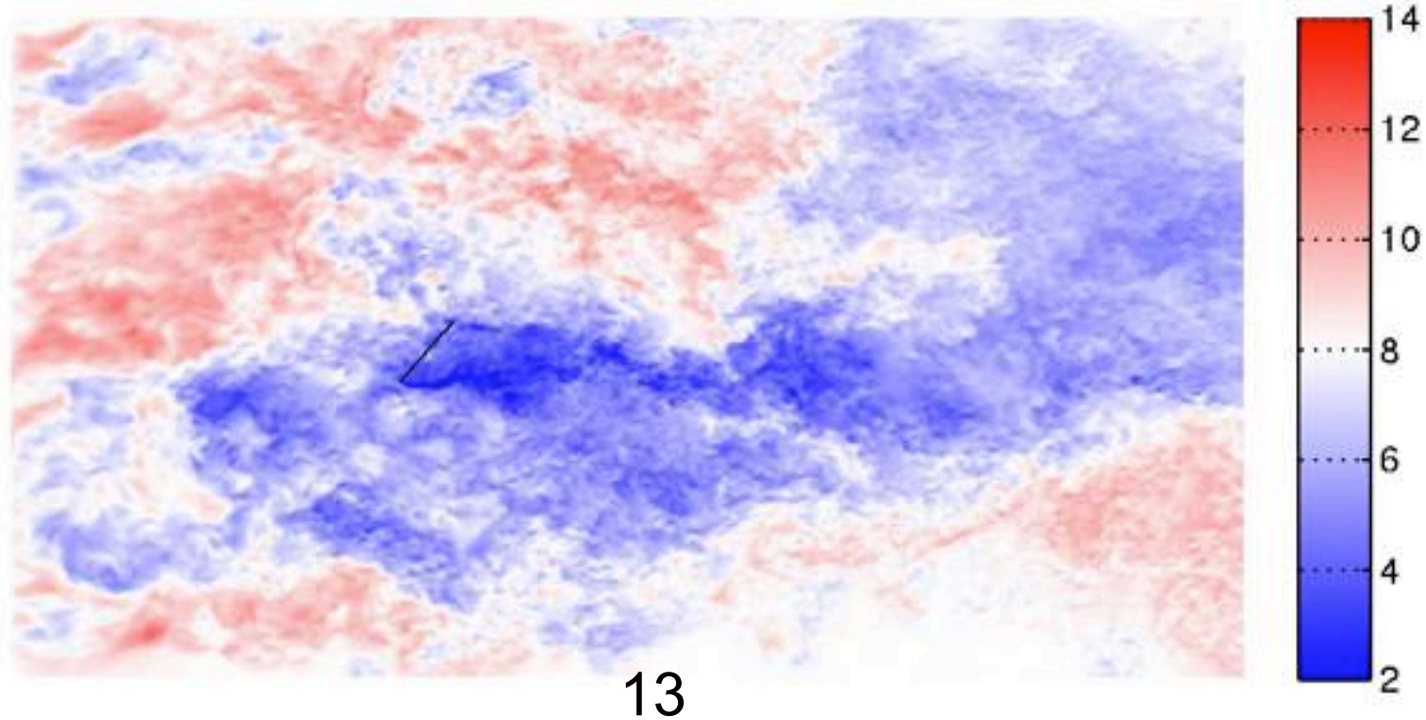
Wind speed [m/s]



HAWT

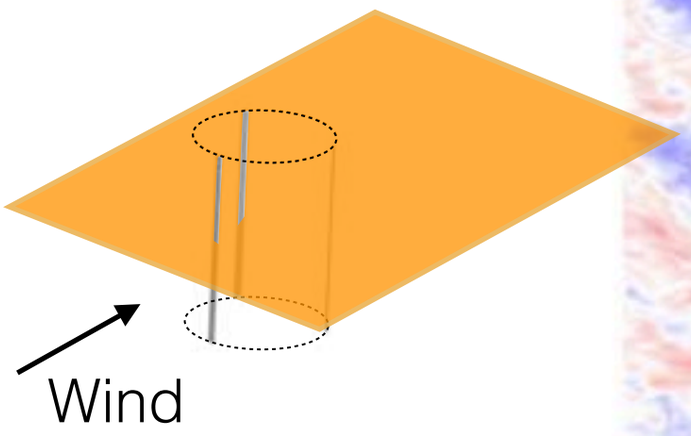
passive yaw

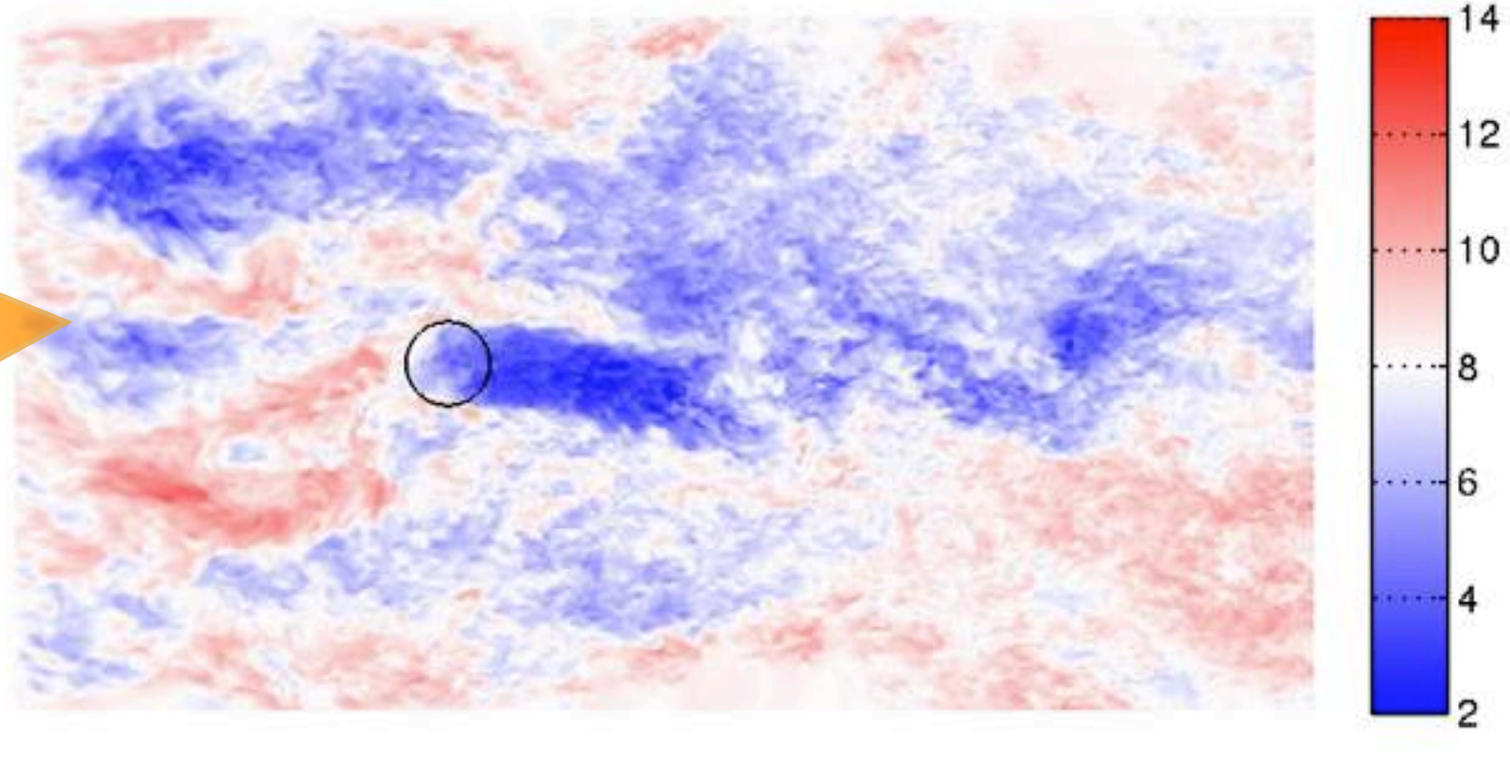
fixed speed



Dynamics and wakes (high turbulence) (2)

VAWT





Wind speed [m/s]

- Passive tracking of wind direction is *hard*!
- Passive yaw HAWT consistently *behind* wind direction
- VAWT insensitive to wind direction
- Small differences in the HAWTs wake trajectories…

Vortex Particle-Mesh method + lifting lines

- Leveraged in

  - Wake physics: decay and meandering

  - Development of operational wake models

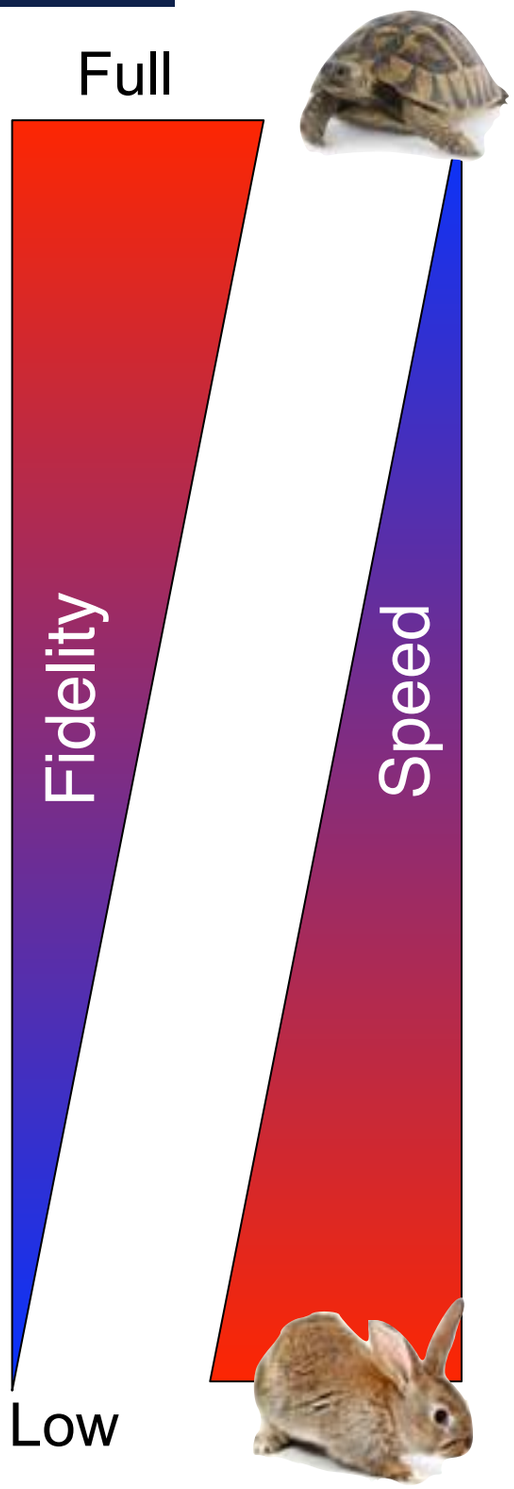
  - Wind turbine design tool

  - Wind turbine control, dynamics and loads

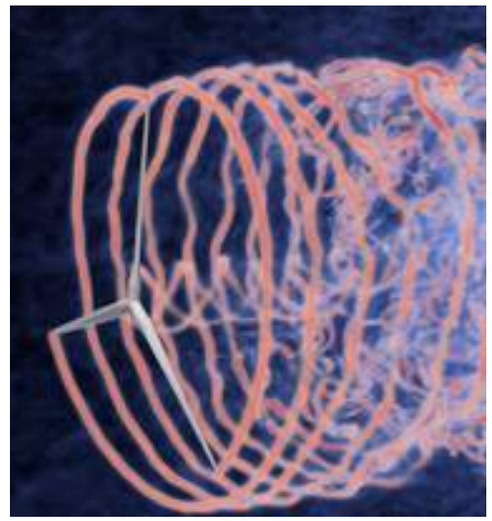
➡ small wind turbine study…

- **Cross-validation of tools: rotor tool <-> farm tool**

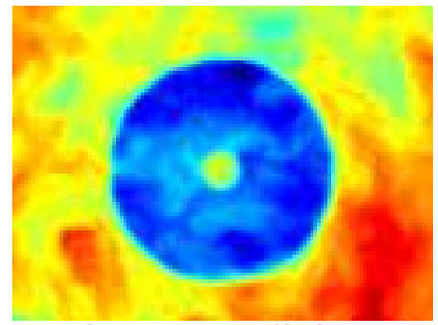
Fidelity - speed compromise



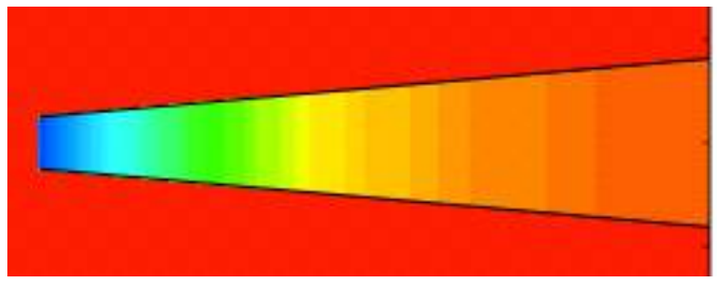
- Actuator lines/Lifting lines in unsteady flow simulations


VPM + lifting lines

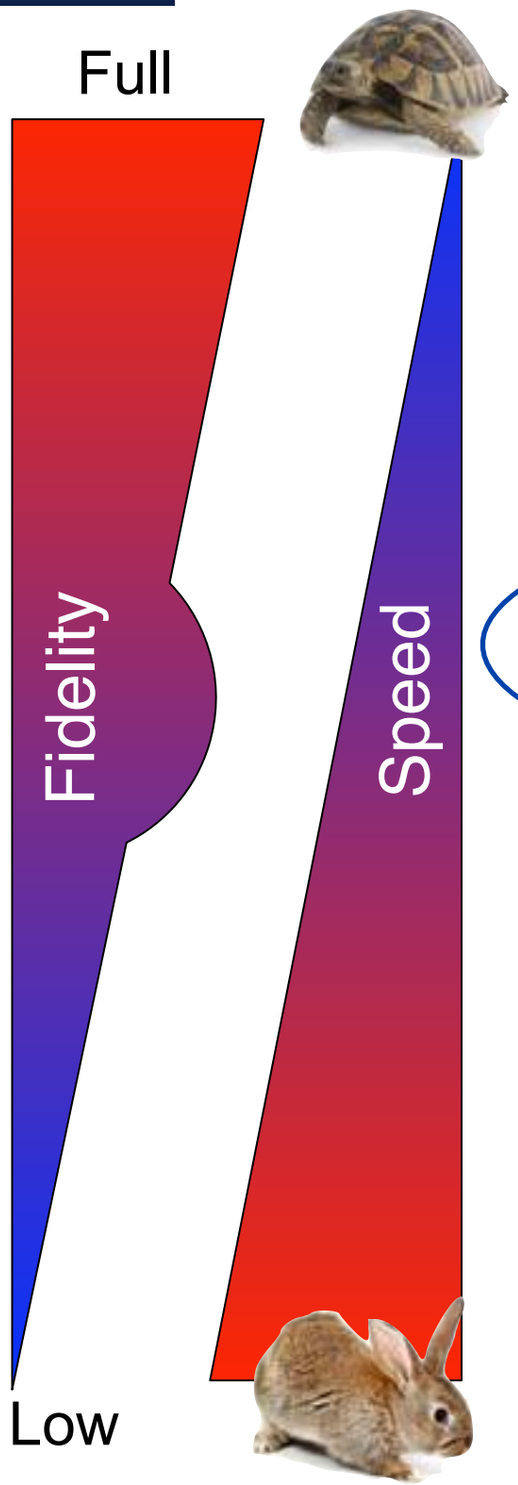
- Actuator disks in unsteady flow simulations


Actuator disk

- Engineering wake models



Fidelity - speed compromise

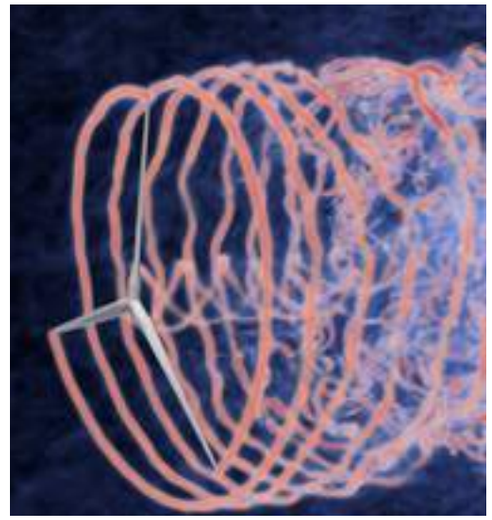


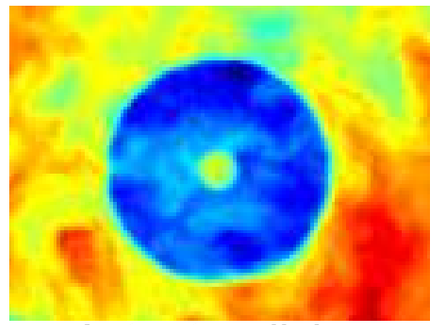
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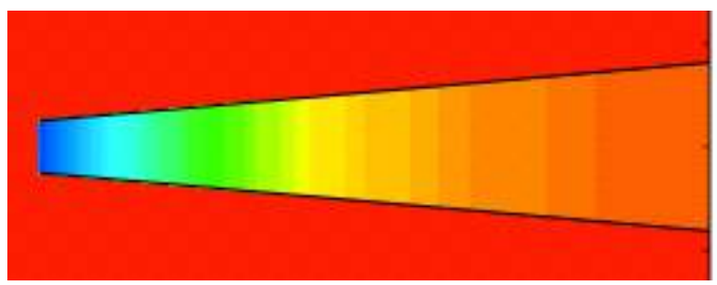
Fidelity **improvement** verified by means of VPM + LL results

- Actuator disks in unsteady flow simulations

- Engineering wake models


VPM + lifting lines


Actuator disk



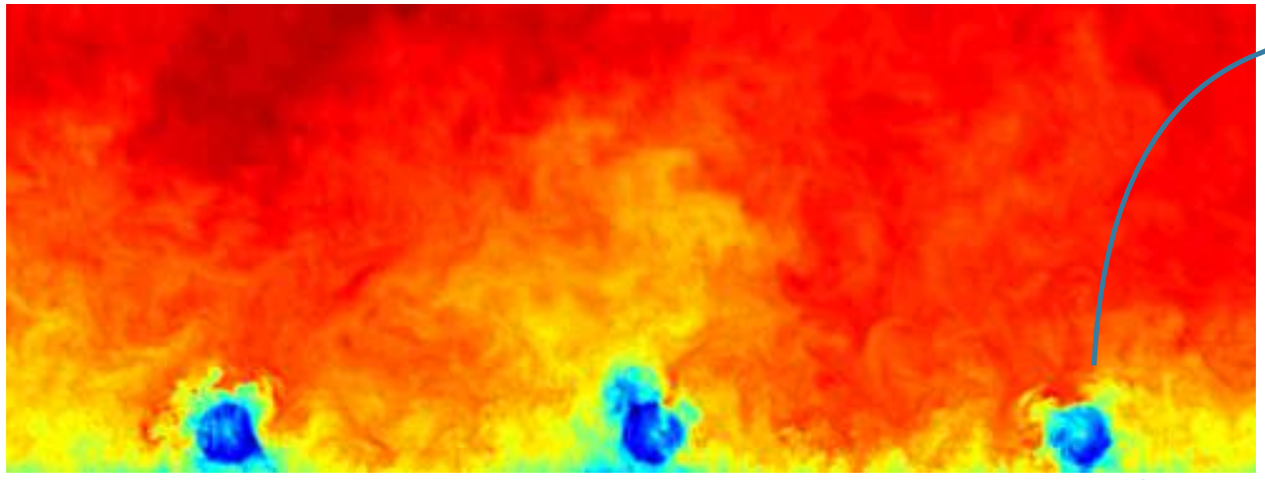
Effort made in the rotor representation

- Wind turbine model: **Actuator Disk (AD)** in **coarse resolution**

  ⟶ Blades replaced by body force terms acting over the surface swept by the rotor

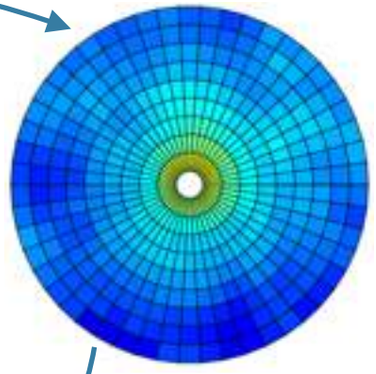
- **Torque** effects and **non-uniform forces** repartition

Large eddy Simulation



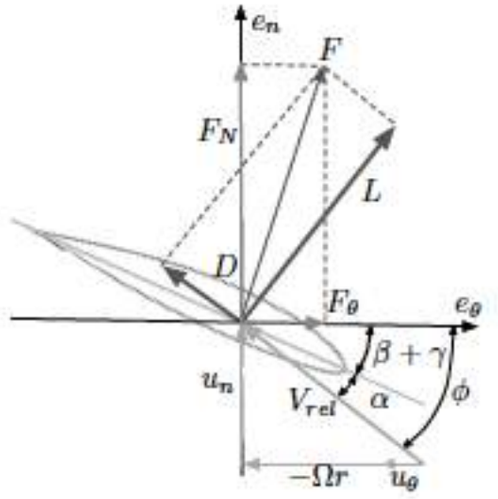
Flow solver : 4th order finite differences code

local disk velocities



forces distribution

Actuator Disk



- Addition of a **tip-loss correction**

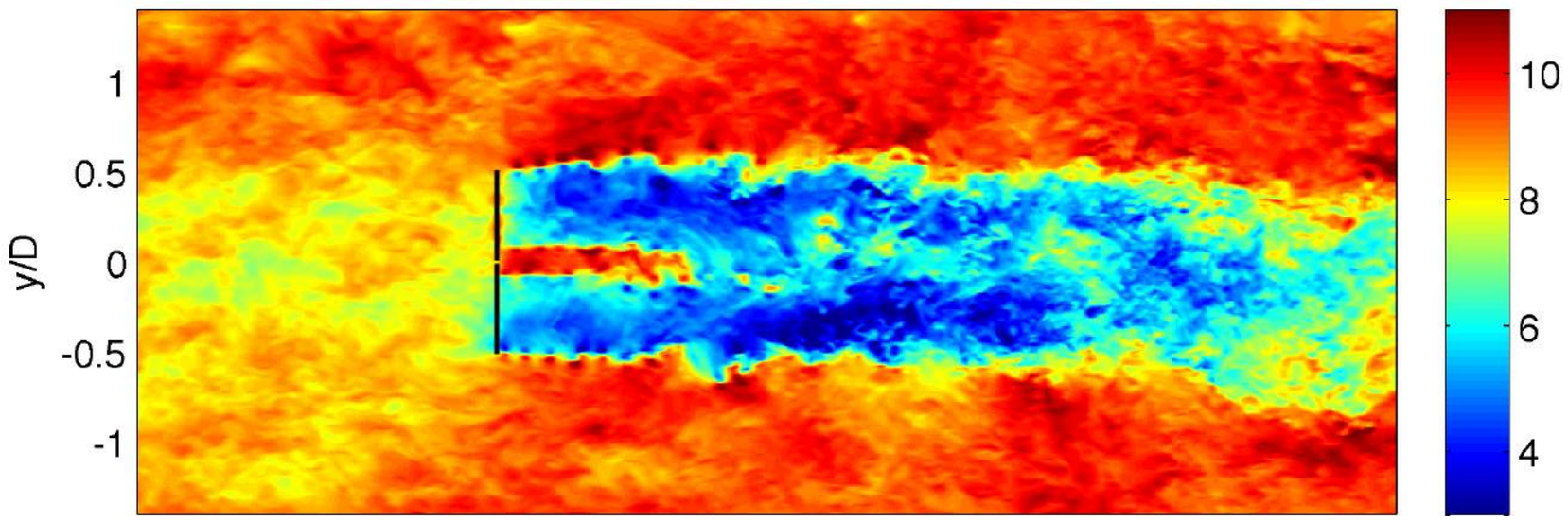
Moens et al., Wind Energy, 2018

Rotor in turbulent flows

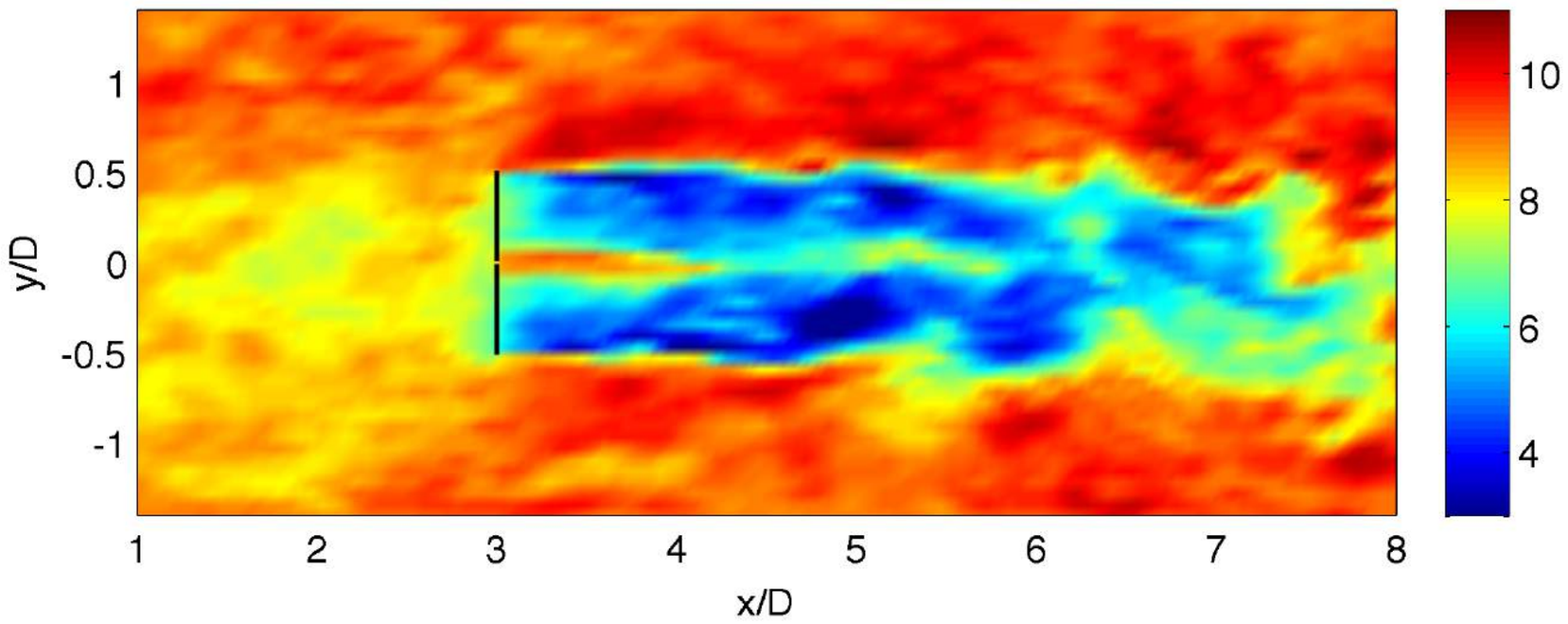
TSR = 7.55, C_T ~= 0.8

Streamwise velocity m/s

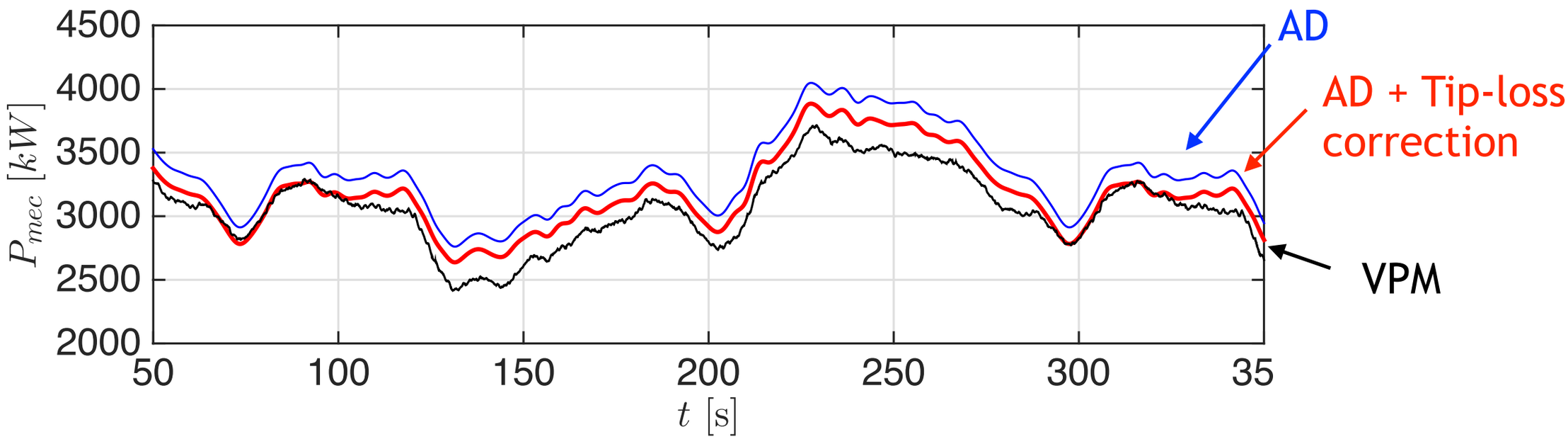
VPM
128 pts/D



AD
16 pts/D



Power and loads in turbulent flow

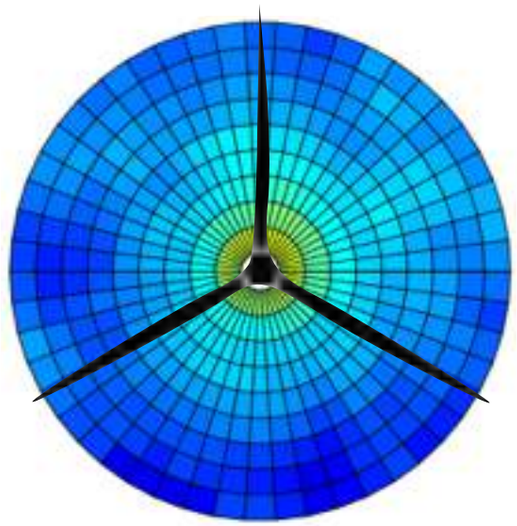


Power difference with VPM ~9.5% → ~4.7%

- Power decreases with the tip-loss factor
- The production is closer to the VPM one

Power and loads in turbulent flow (2)

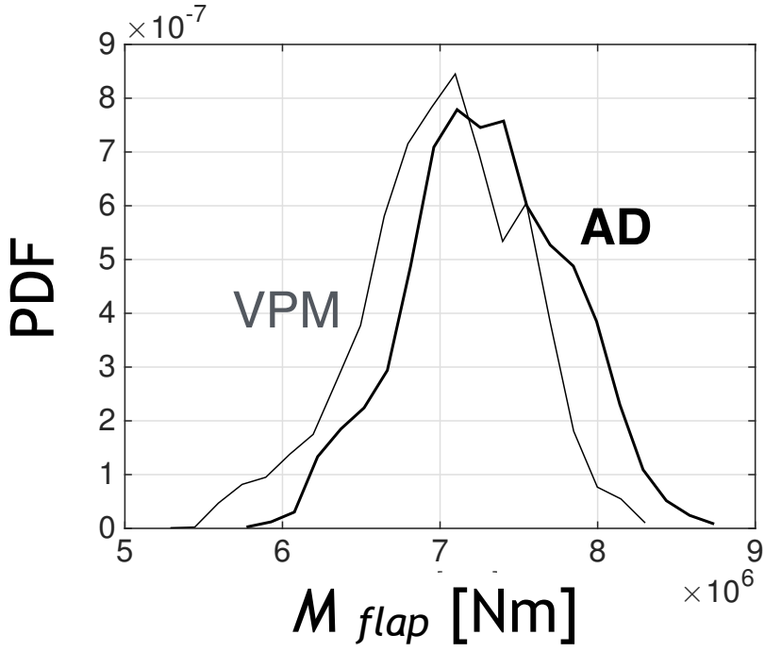
- Time- and blade-resolved loads

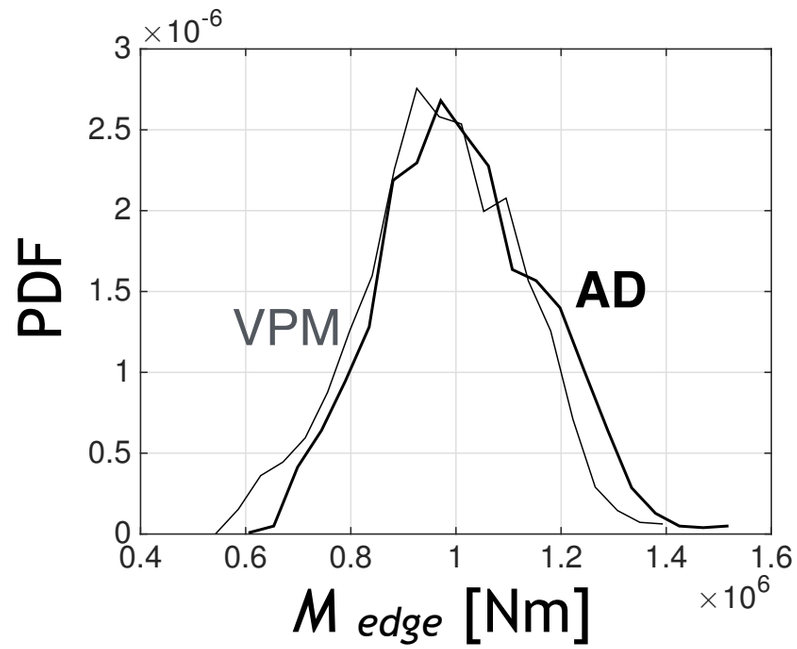


Blade-attached quantities

- recovery of blade attached quantities
- time/space interpolation onto virtual blades
- can be done as a post-processing step

- Blade loads probability density functions

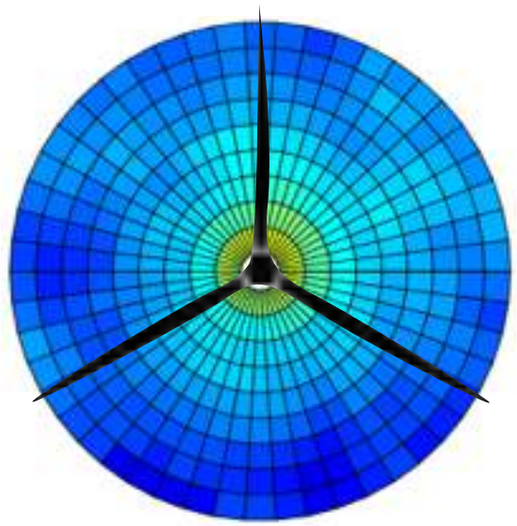




TSR = 7.55

Power and loads in turbulent flow (2)

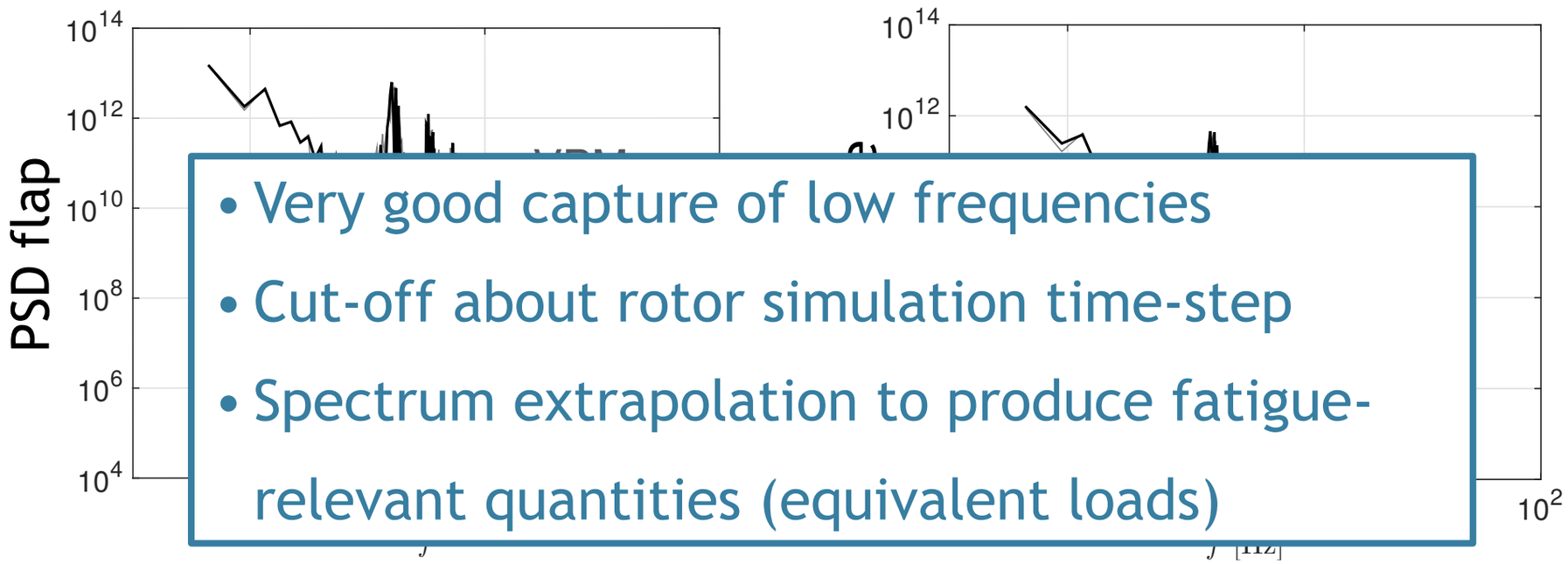
- Time- and blade-resolved loads



Blade-attached quantities

- recovery of blade attached quantities
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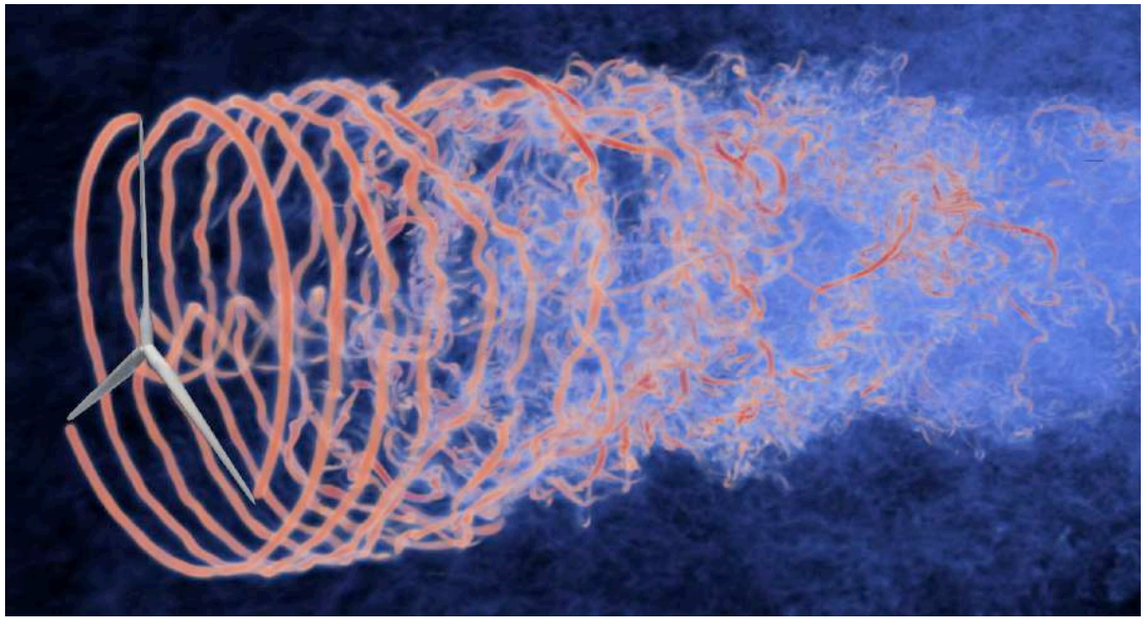
- Blade loads power spectra



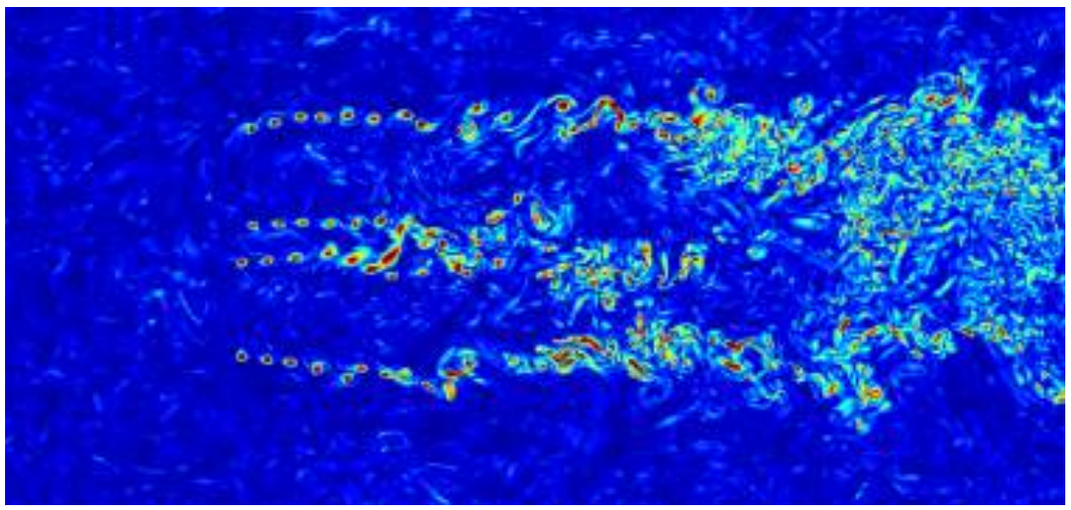
- Very good capture of low frequencies
- Cut-off about rotor simulation time-step
- Spectrum extrapolation to produce fatigue-relevant quantities (equivalent loads)

TSR = 7.55

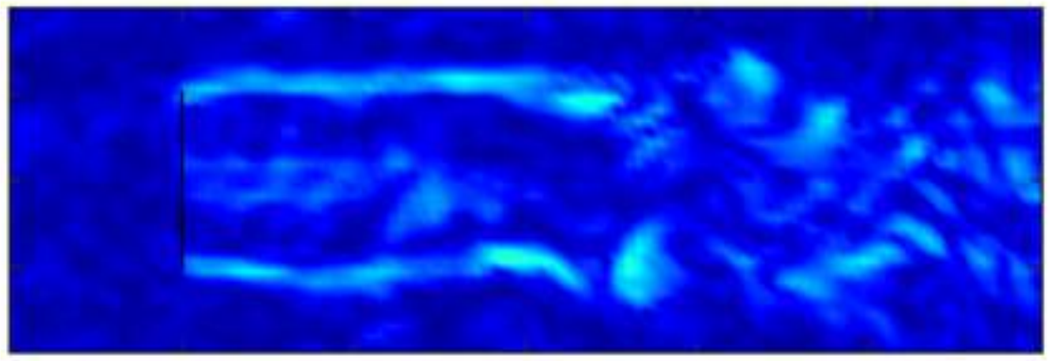
Wake statistics



VPM : discrete tip and root vortices



AD



Wake statistics reproduction

- Time averaged statistics

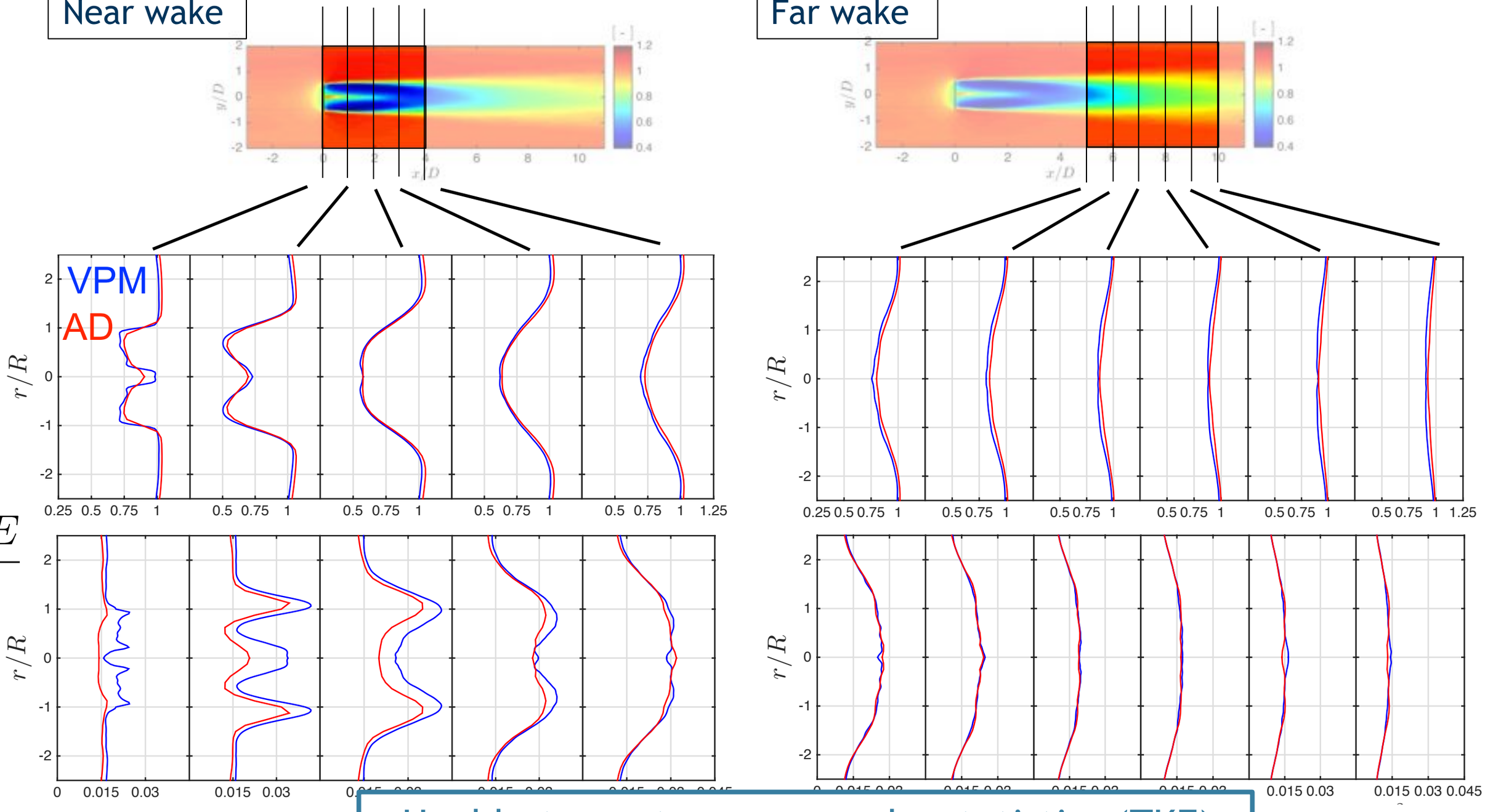
TI = 15%

Near wake

Far wake

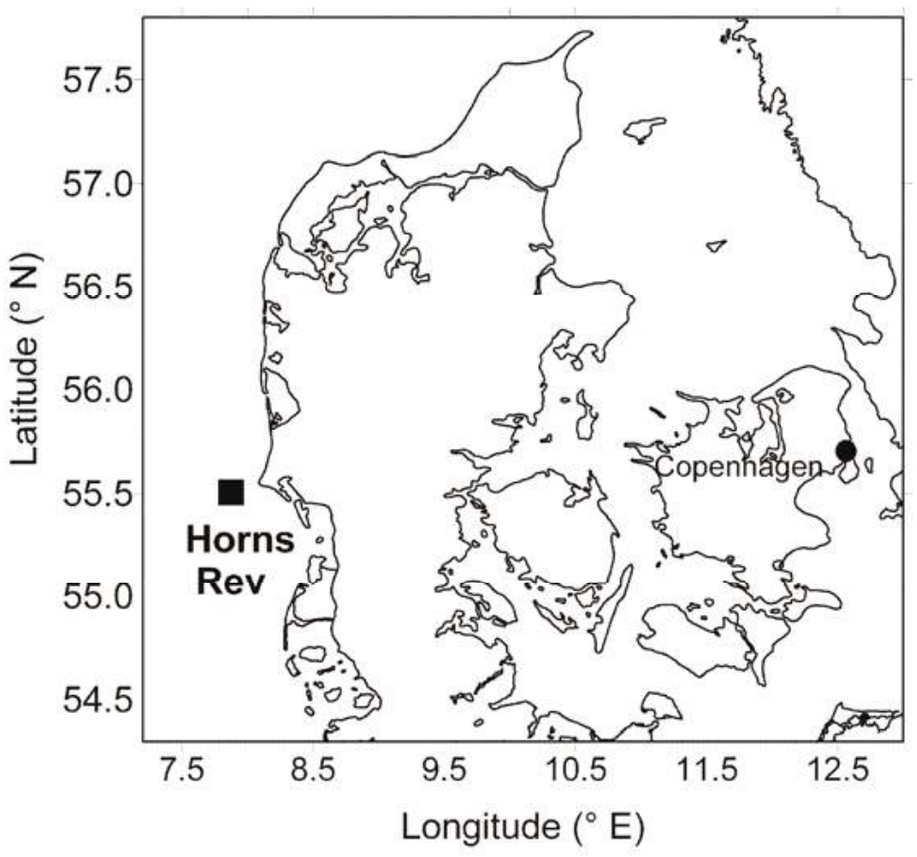
$\frac{\overline{u}}{\overline{U}}$

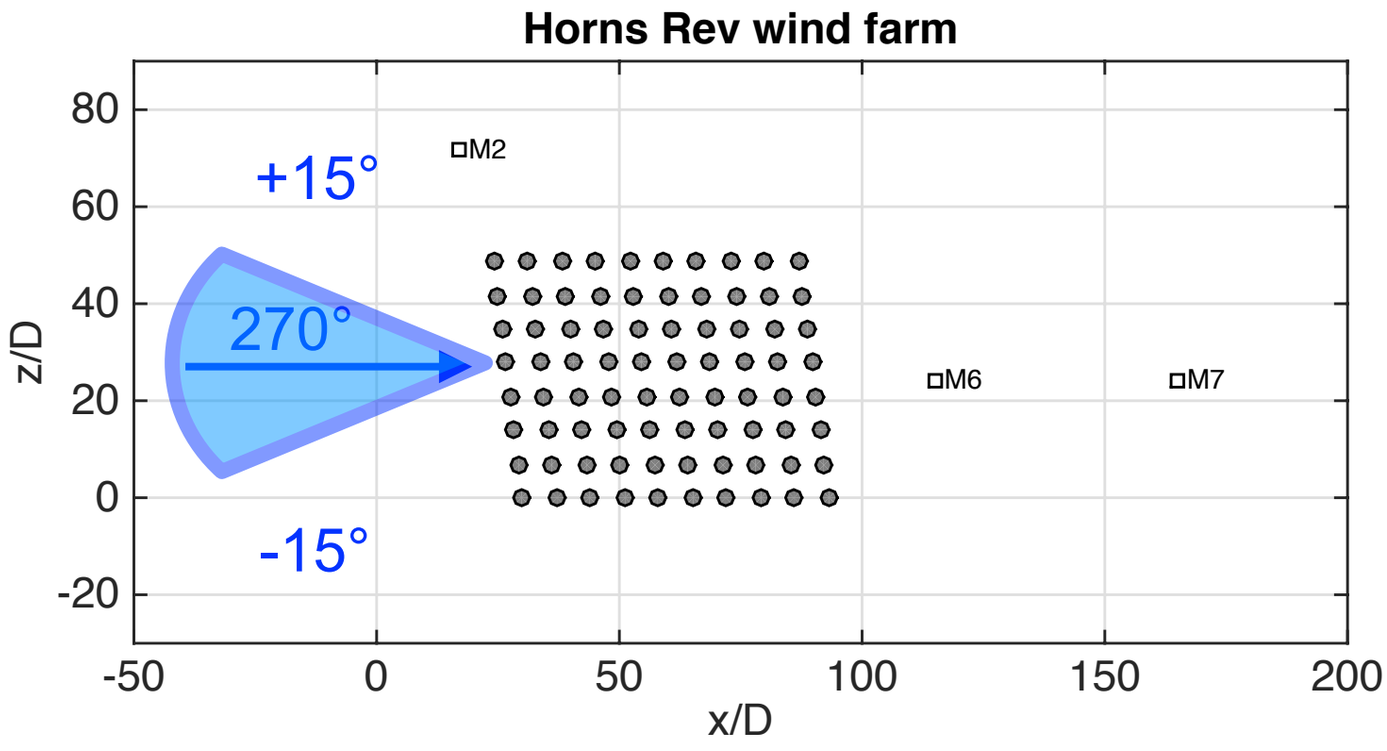
$\frac{TKE}{\overline{U}^2}$



- Unable to capture near-wake statistics (TKE)
- Very good agreement on far-wake

Application: Horns Rev wind farm



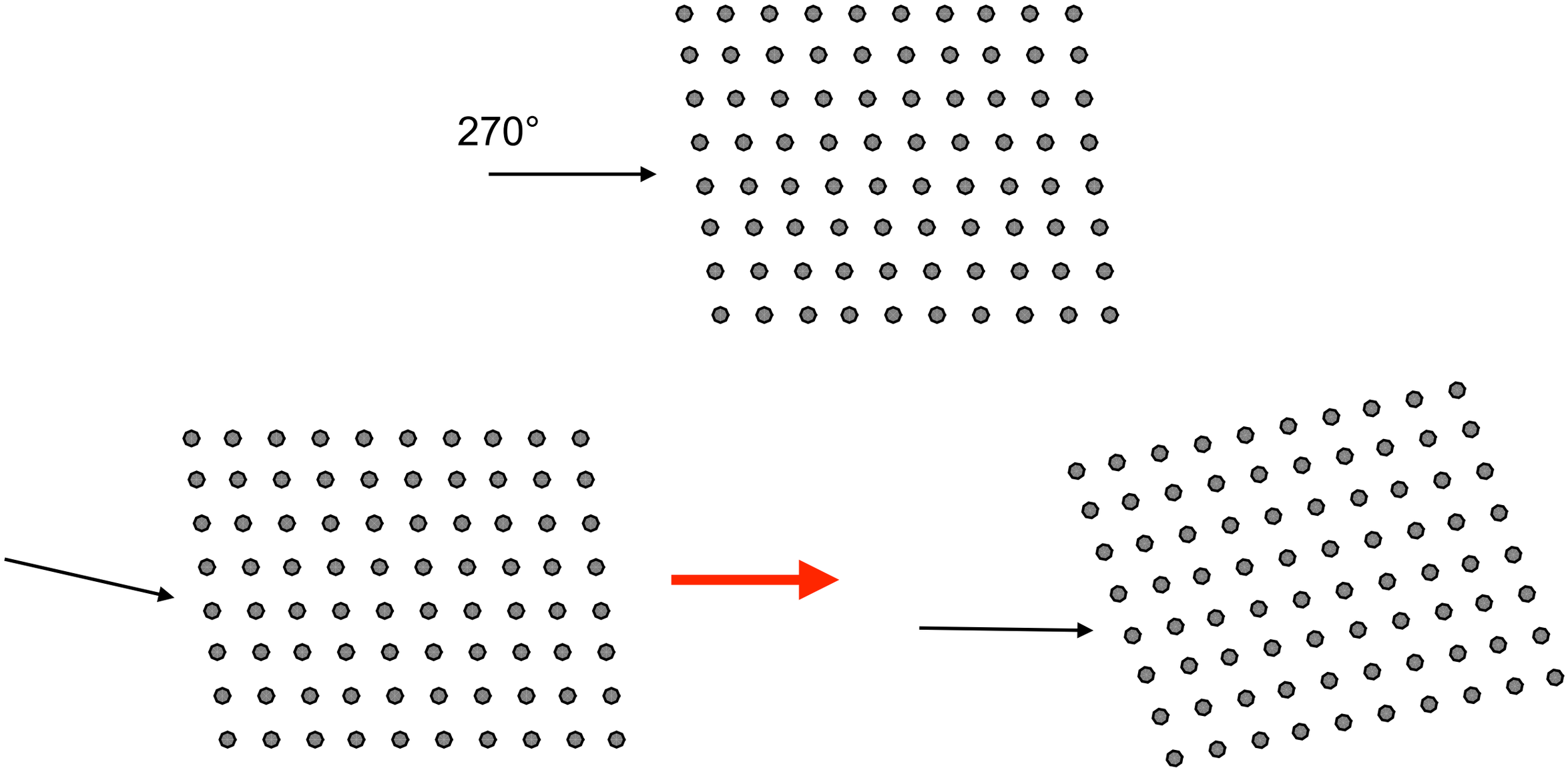


- Large wind farm with 80 Vestas 2MW
- Measurements campaign
- Used for validating wind farm tools

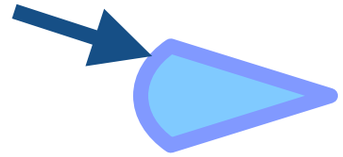
Present simulations

- Inflow = simulation of neutral ABL
- Turbine specs reverse-engineered
- Turbine dynamics and controllers (in region II)
- Yaw control disabled

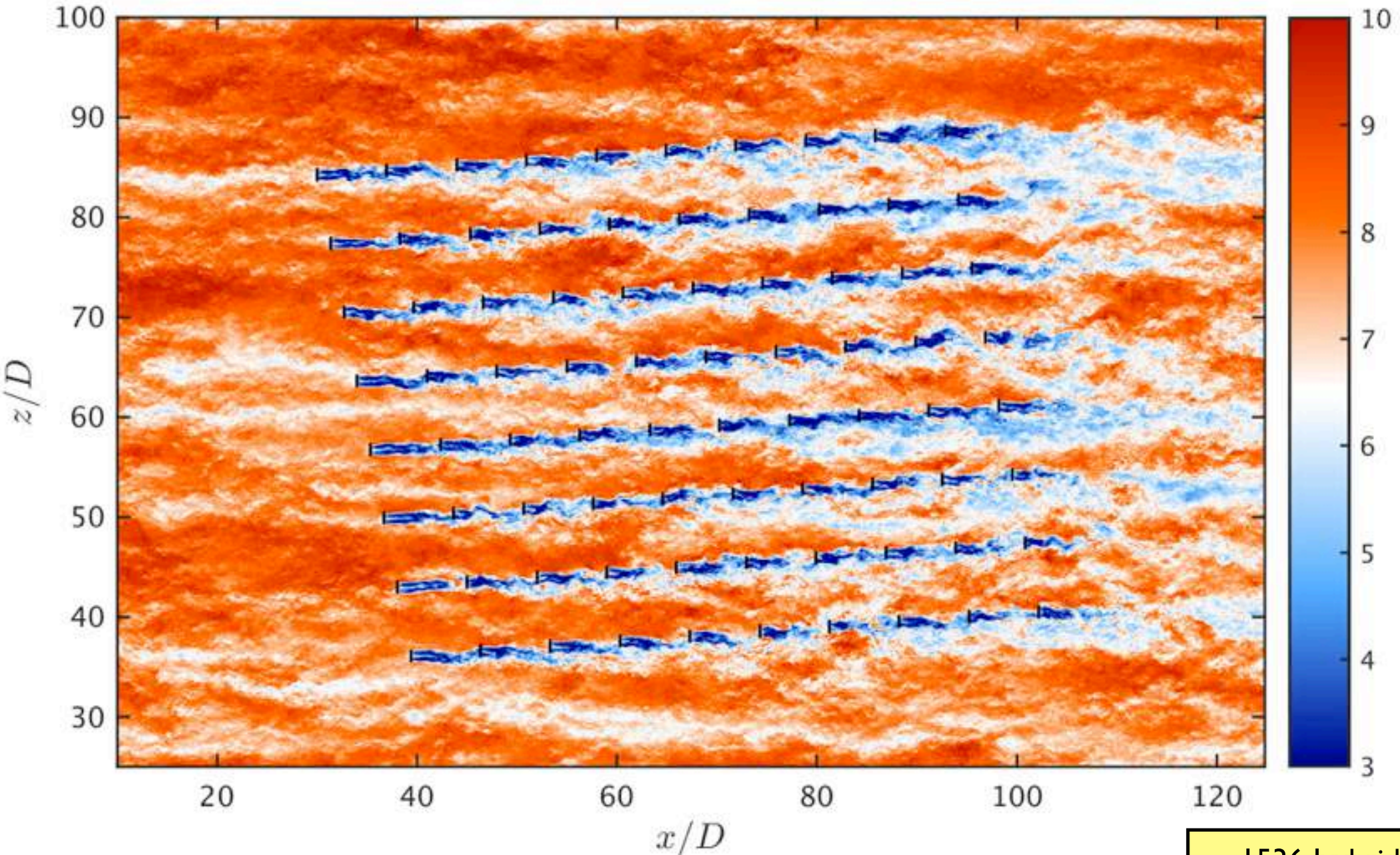
Application: Horns Rev wind farm



Application: Horns Rev wind farm

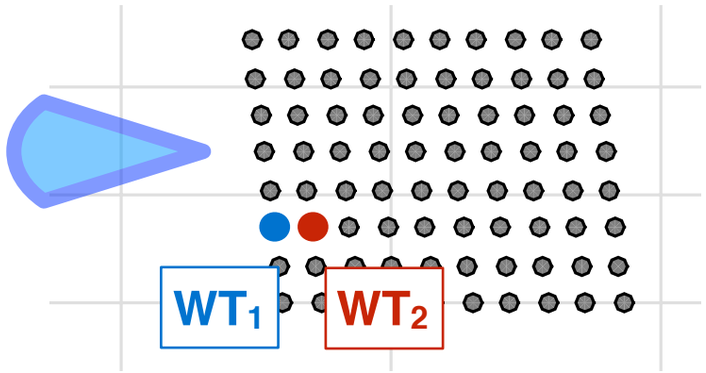


272º

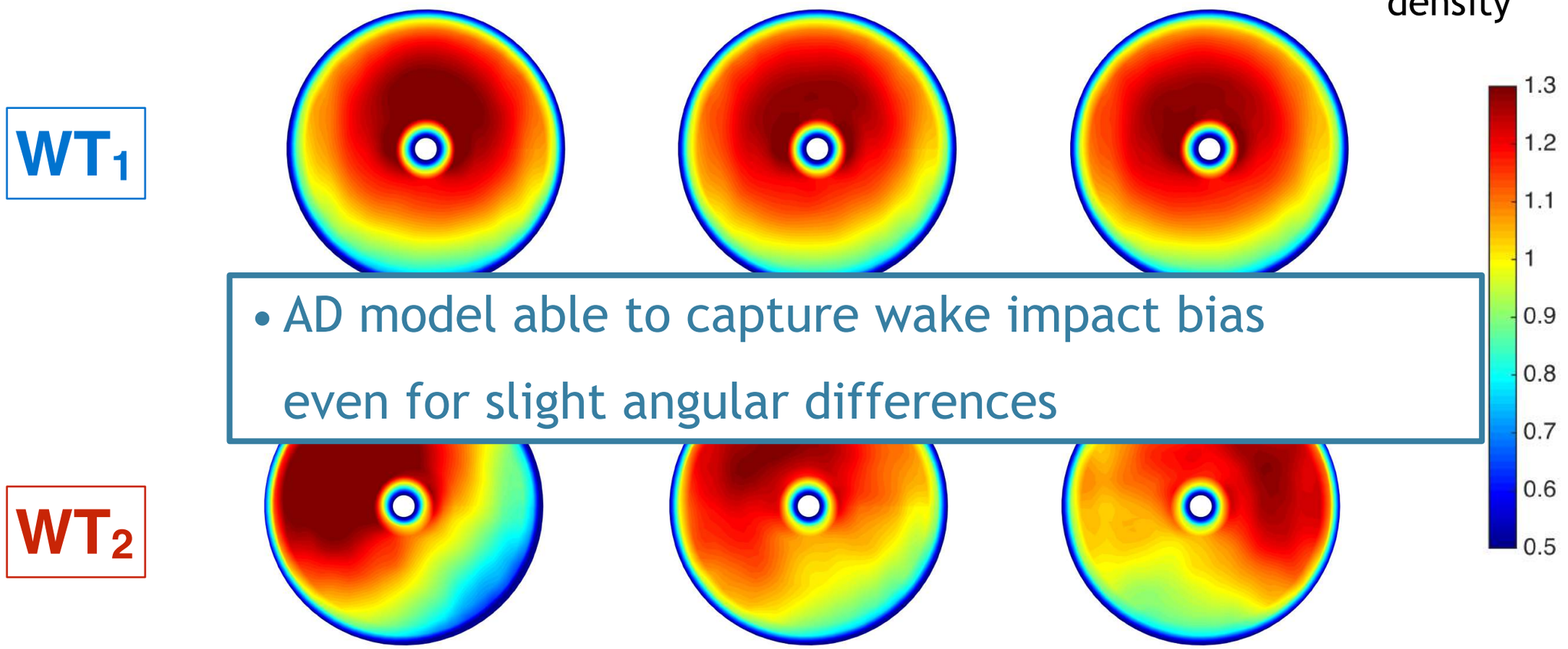


1536 Ivybridge cores
55 hours for about 70 min
Np~ 6.10^8

Going further: wake effect signatures



Power production density



- AD model able to capture wake impact bias even for slight angular differences

Conclusions

- 2 LES tools at rotor and farm scales
- Cross-verification of LES tools enabling to bridge scales
- Enrichment of Actuator Disk model for LES

- Application to Horns Rev wind farm

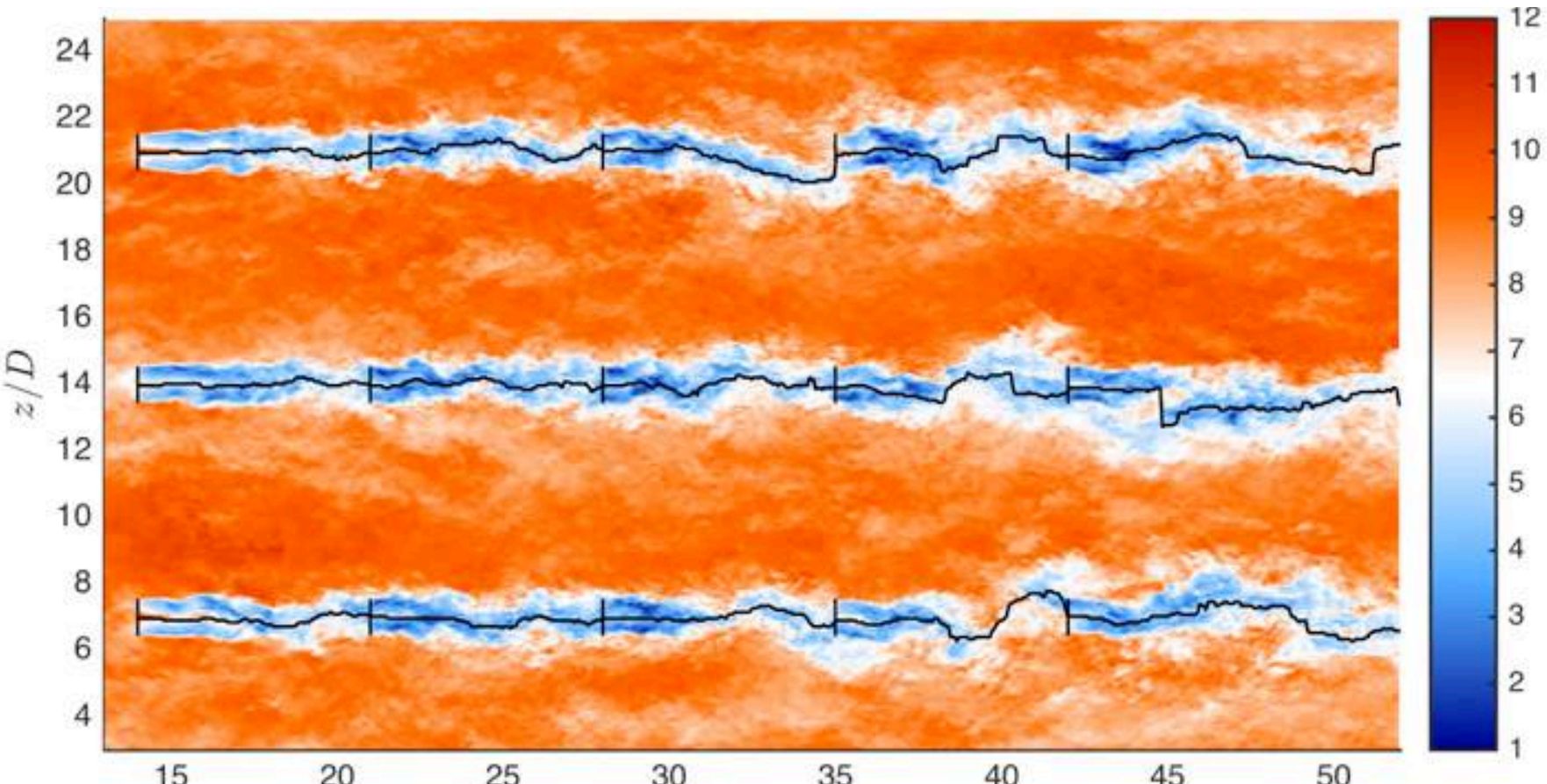
- Leverage farm-level LES tool for
  - wake meandering and merging phenomena
  - operational wake model calibration
  - design of farm level-control schemes

Conclusions

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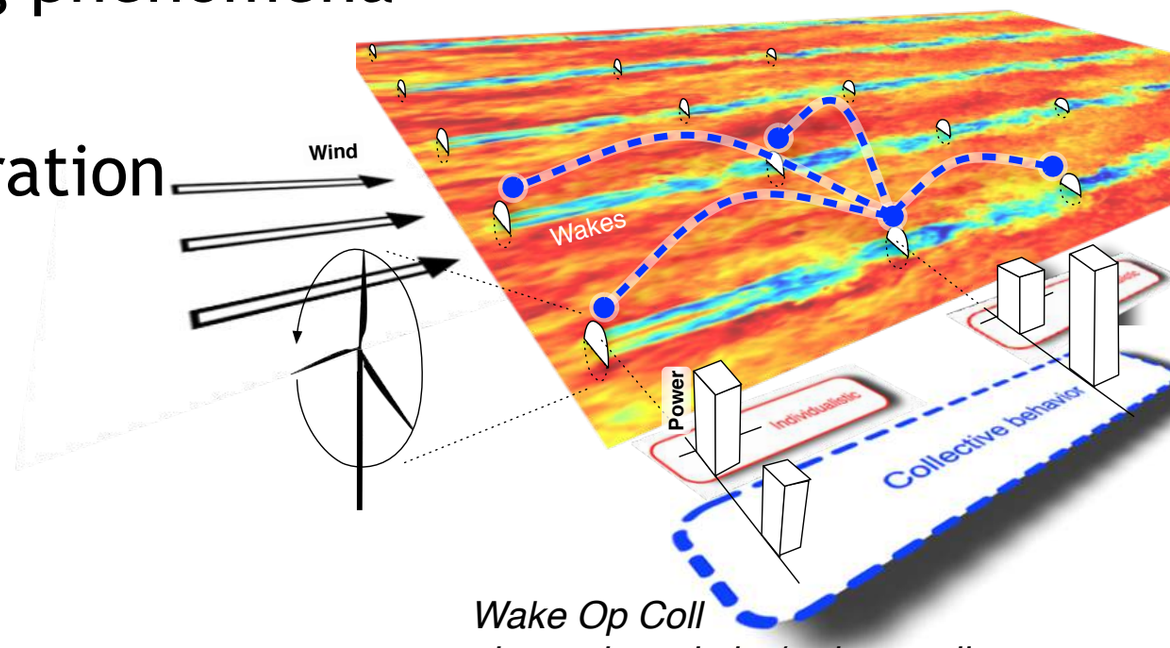
Torque 2018

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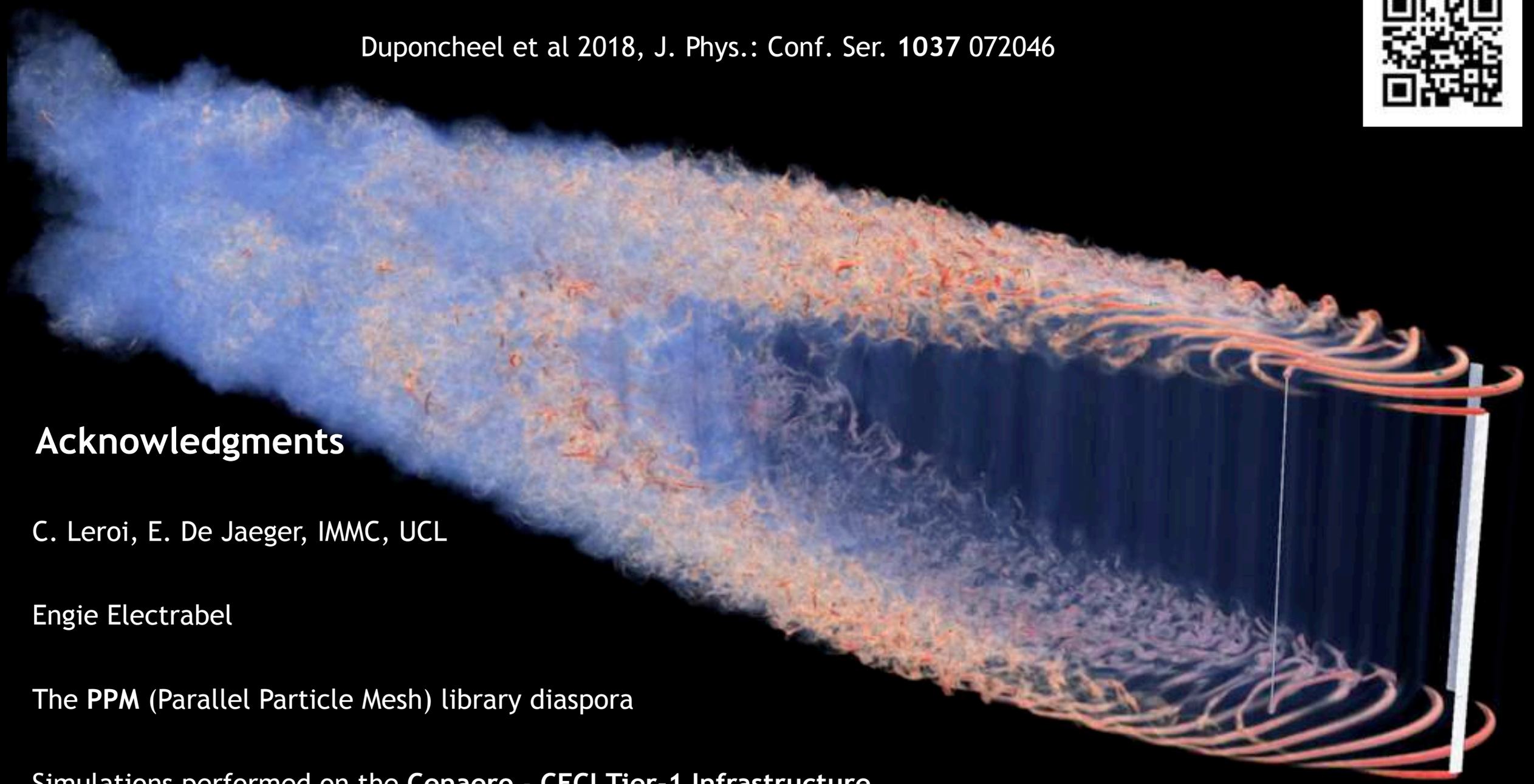


Wake Op Coll
sites.uclouvain.be/wakeopcoll

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CECI - Consortium des Equipements de Calcul Intensif

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