Contributions of Wind Physics on further Development of Wind Power

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Content

- Research program on wind physics
  - Multi-scale problems
  - Simulations – laboratory tests – open field experiments
- Small-scale turbulence
- Wind farm flow and wind farm control
- Mesoscale modelling and wind power forecasting
- Conclusions

Wind physics: Complex interaction of wind energy systems and environment

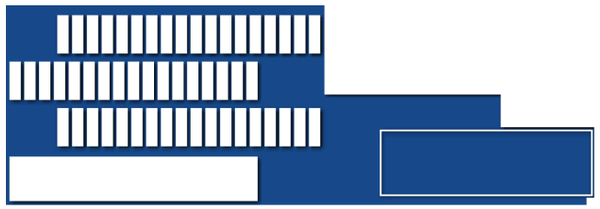
Challenge

Consistent modelling along many scales (spatial & temporal)

Simulation

Computing

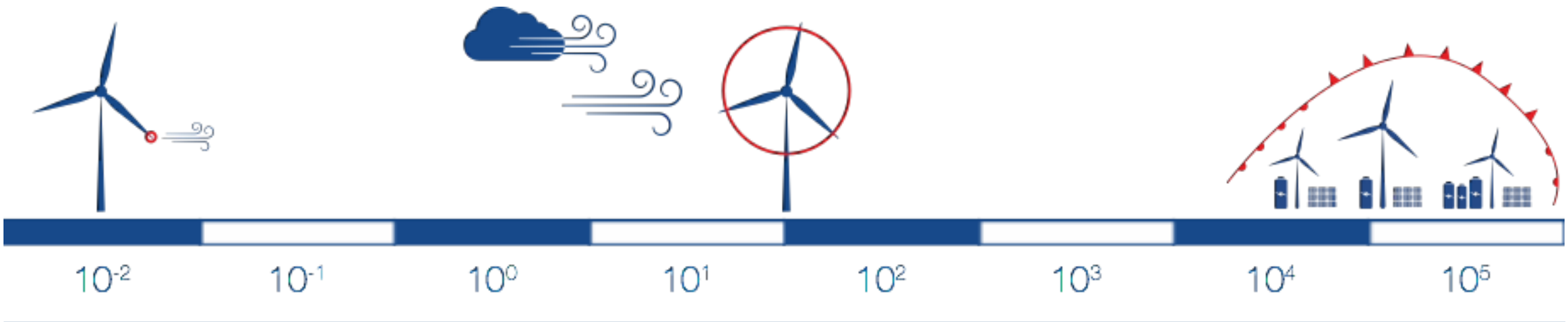
Experiment



Laboratory

In situ

Open field



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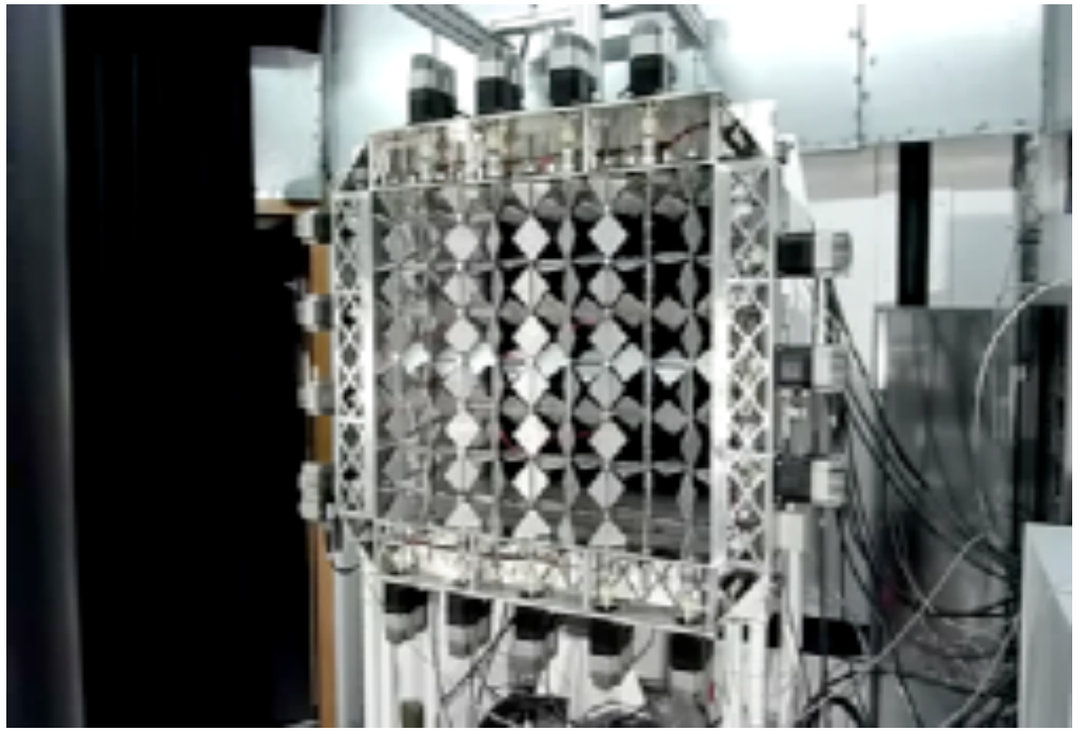
HPC – High Performance Computing

13.000+ Prozessoren, 457 TFlop/s, Rank 363 of 500

WindLab: Research Laboratory for Turbulence and Wind Energy Systems

New *WindLab* facility (2016)

- up to 140 researchers & students
- physicists, meteorologists, engineers



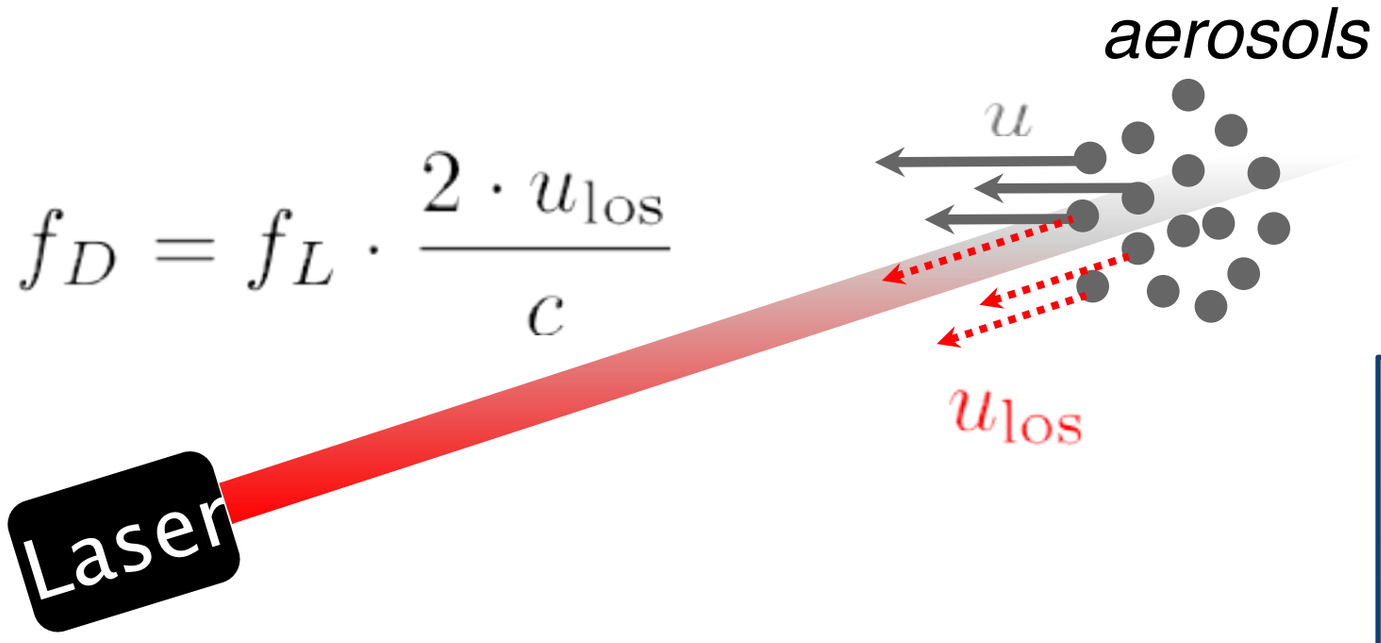
Main infrastructure

- turbulent wind tunnel 3 x 3 x 30 m^3
- active grid for reproduction of realistic turbulence

Open field experiments:
Doppler Wind Lidar (Light detecting and ranging)

- Velocity information via Doppler shift

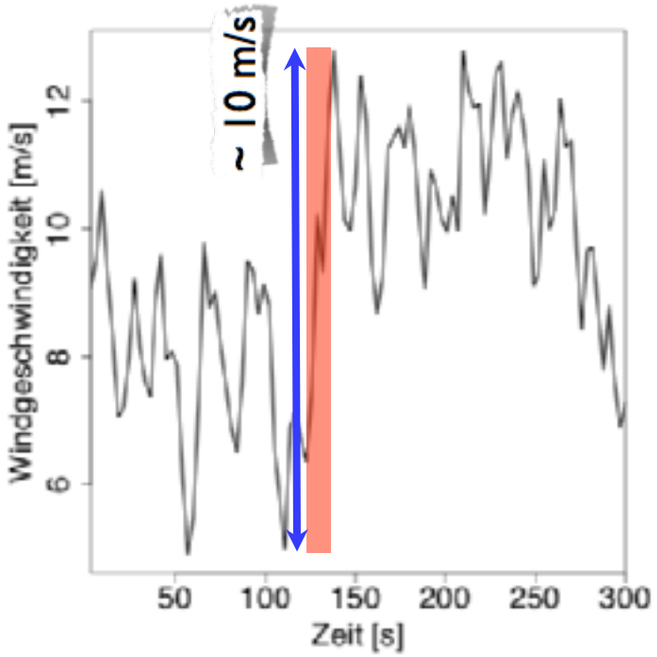
$$f_D = f_L \cdot \frac{2 \cdot u_{\mathrm{los}}}{c}$$



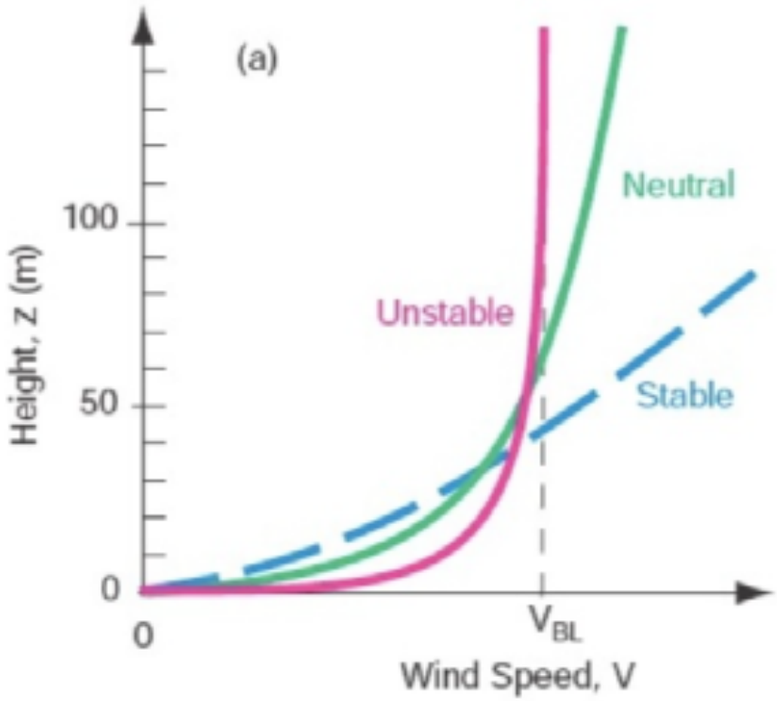
- Problem: frequency $f_L \sim 10^{15}$ Hz (PHz)
  - superposition with reference light
  - measuring the beat frequency ($f_D \sim$ MHz)
  - line of sight wind velocity (u_{los})

Multi-scale description of wind resource

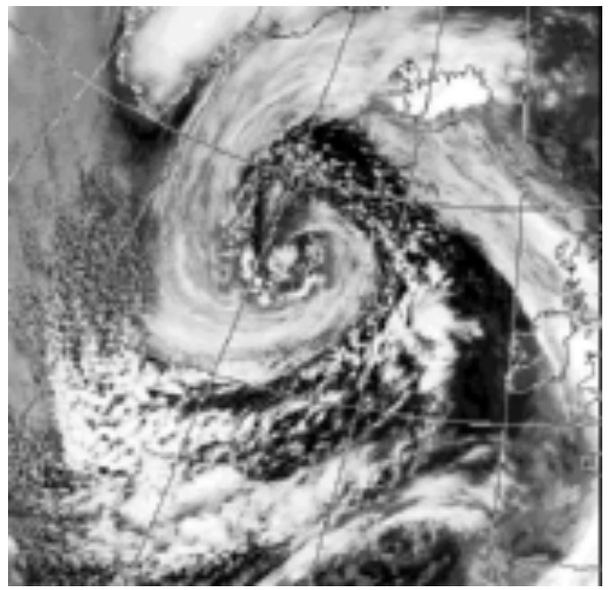
Small-scale turbulence
e.g. intermittent gusts

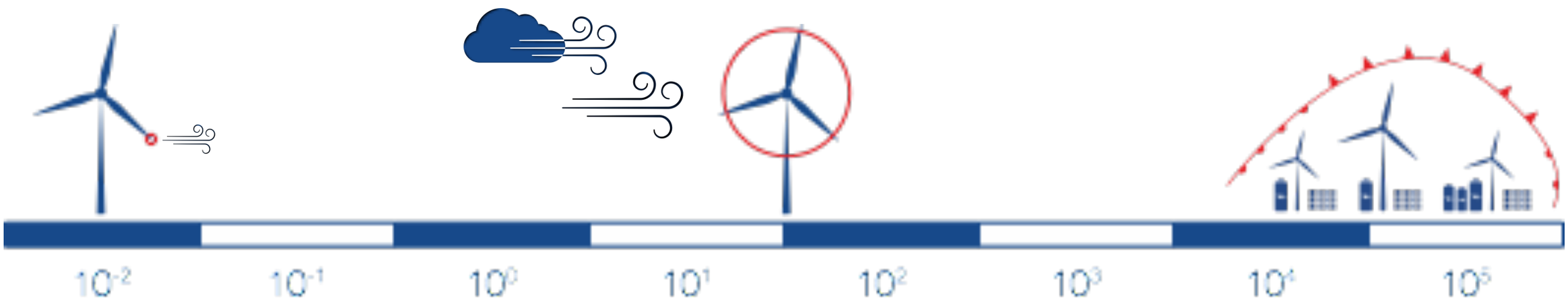


Boundary layer meteorology
e.g. thermal stratification



Mesoscale effects
e.g. system stability





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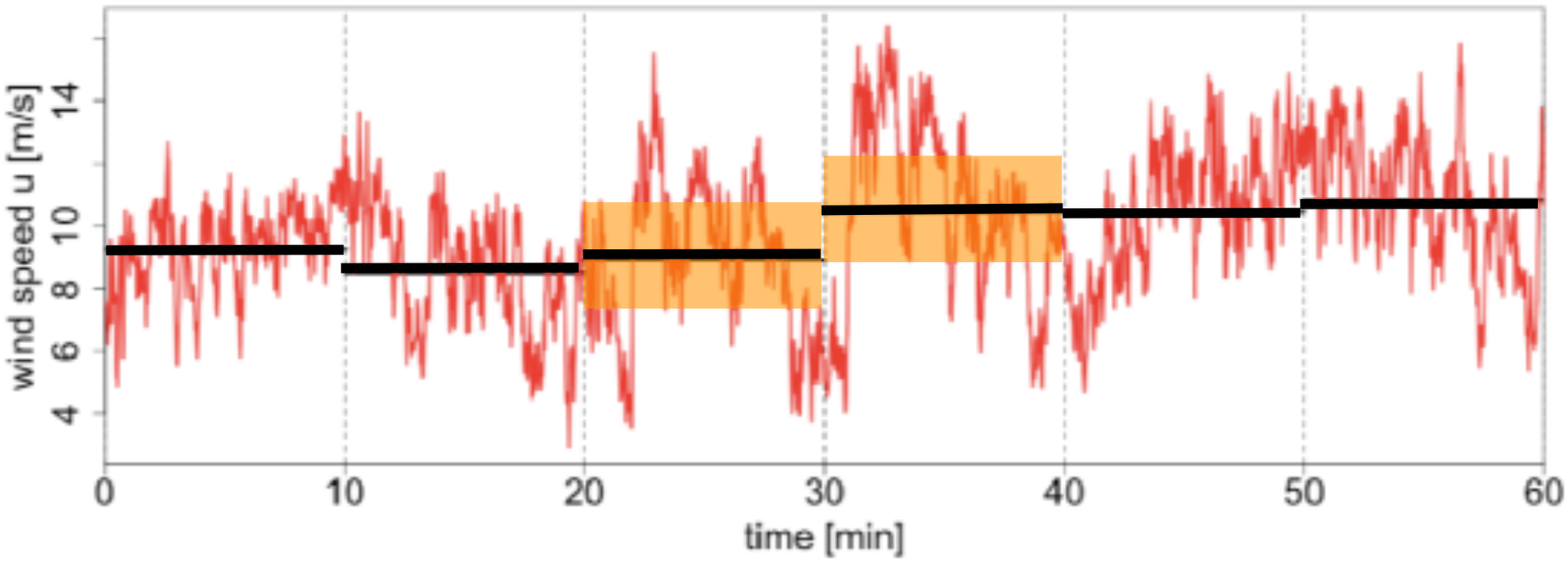
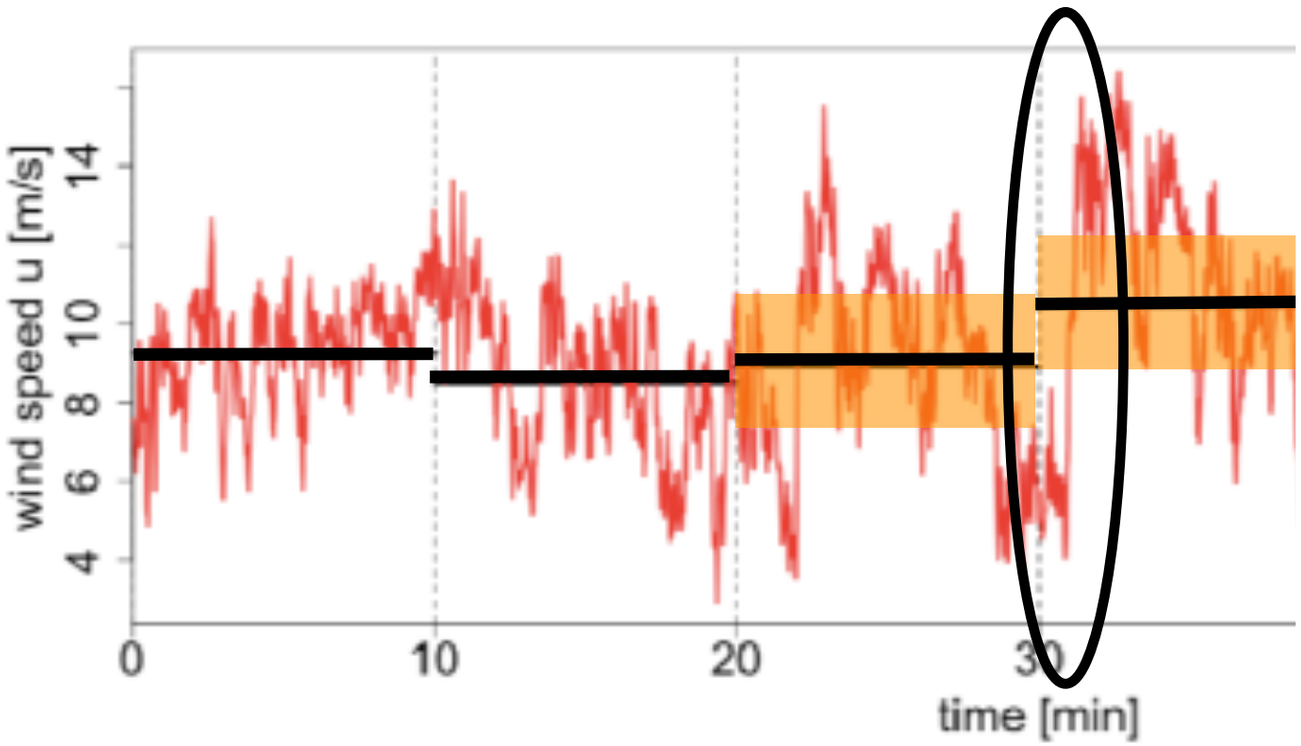
SMALL-SCALE TURBULENCE

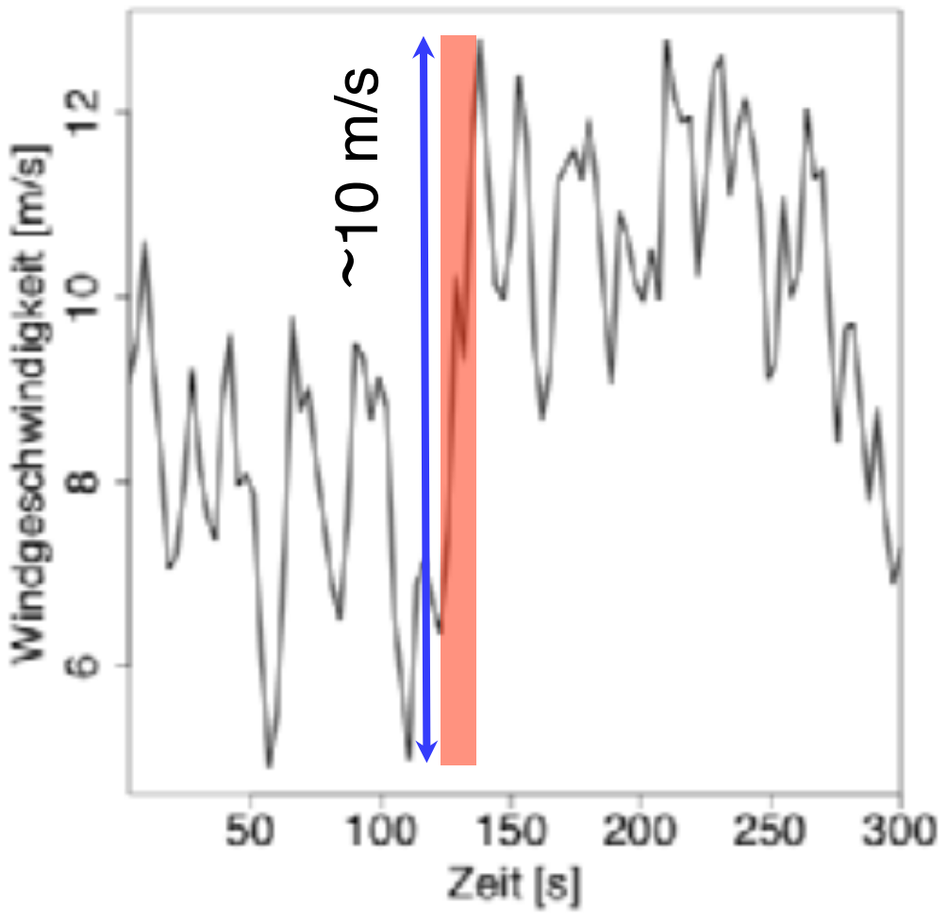
Wind measurements and data analysis



- Characterization according to IEC 61400
  - 10 min mean value
  - turbulence intensity

Wind measurements and data analysis





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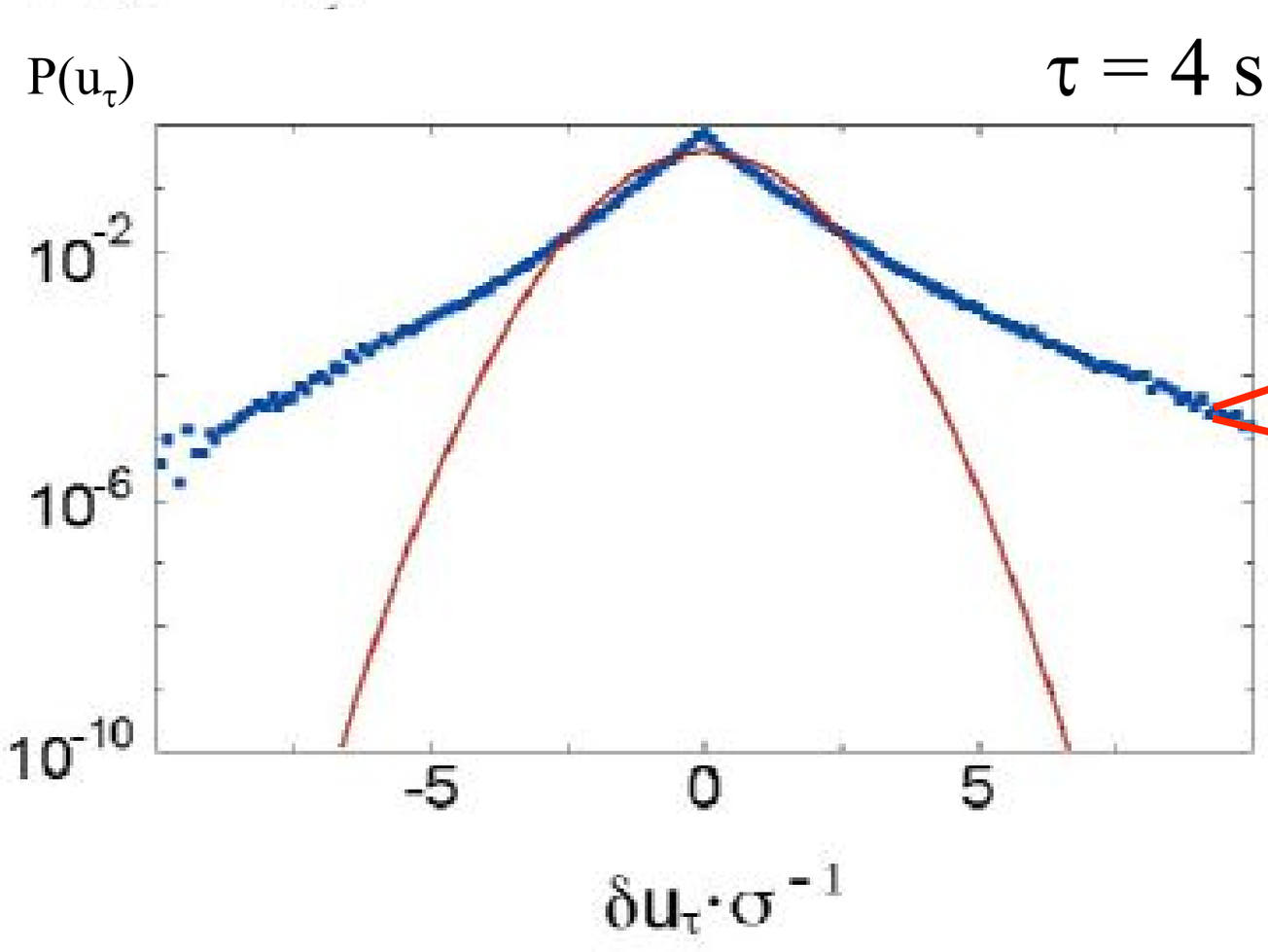
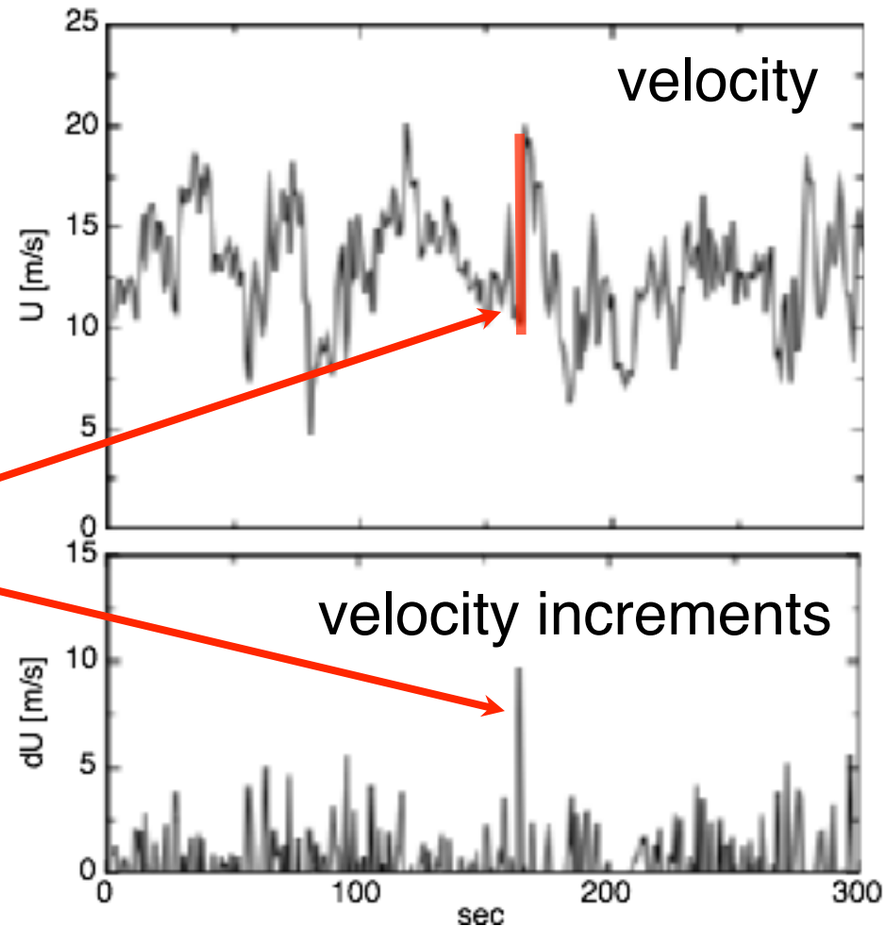
  - turbulence intensity

Statistics of gusts



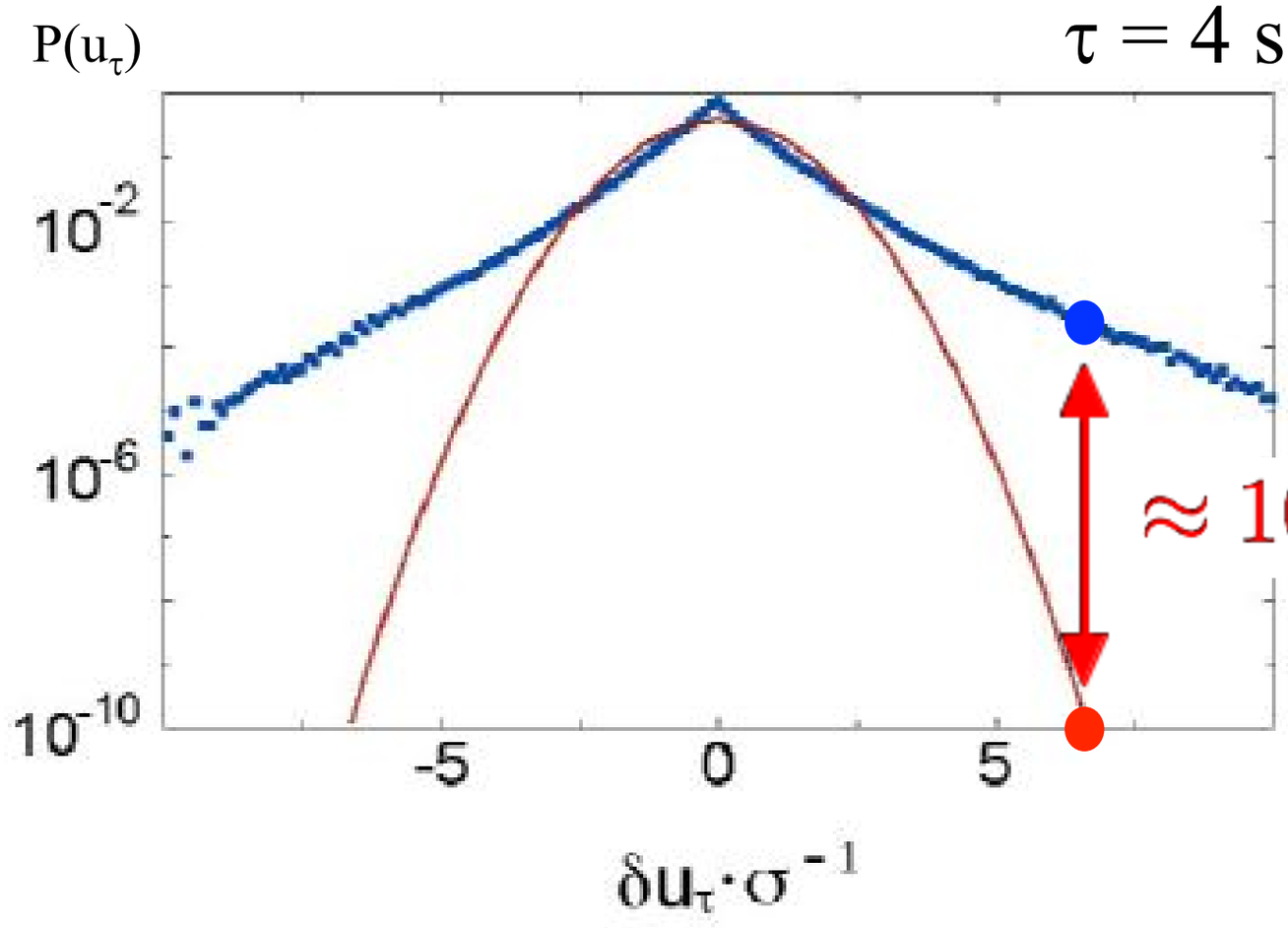


- wind fluctuations can be measured by velocity increments

$$u_\tau = u(t+\tau) - u(t)$$

Boundary-Layer Meteorology **108** (2003)

Statistics of gusts



$$Prob(u_\tau > 6\sigma) \approx 10^{-4}$$

→ 1/day

$$Prob(u_\tau > 6\sigma) \approx 10^{-10}$$ → 1/3,000 years

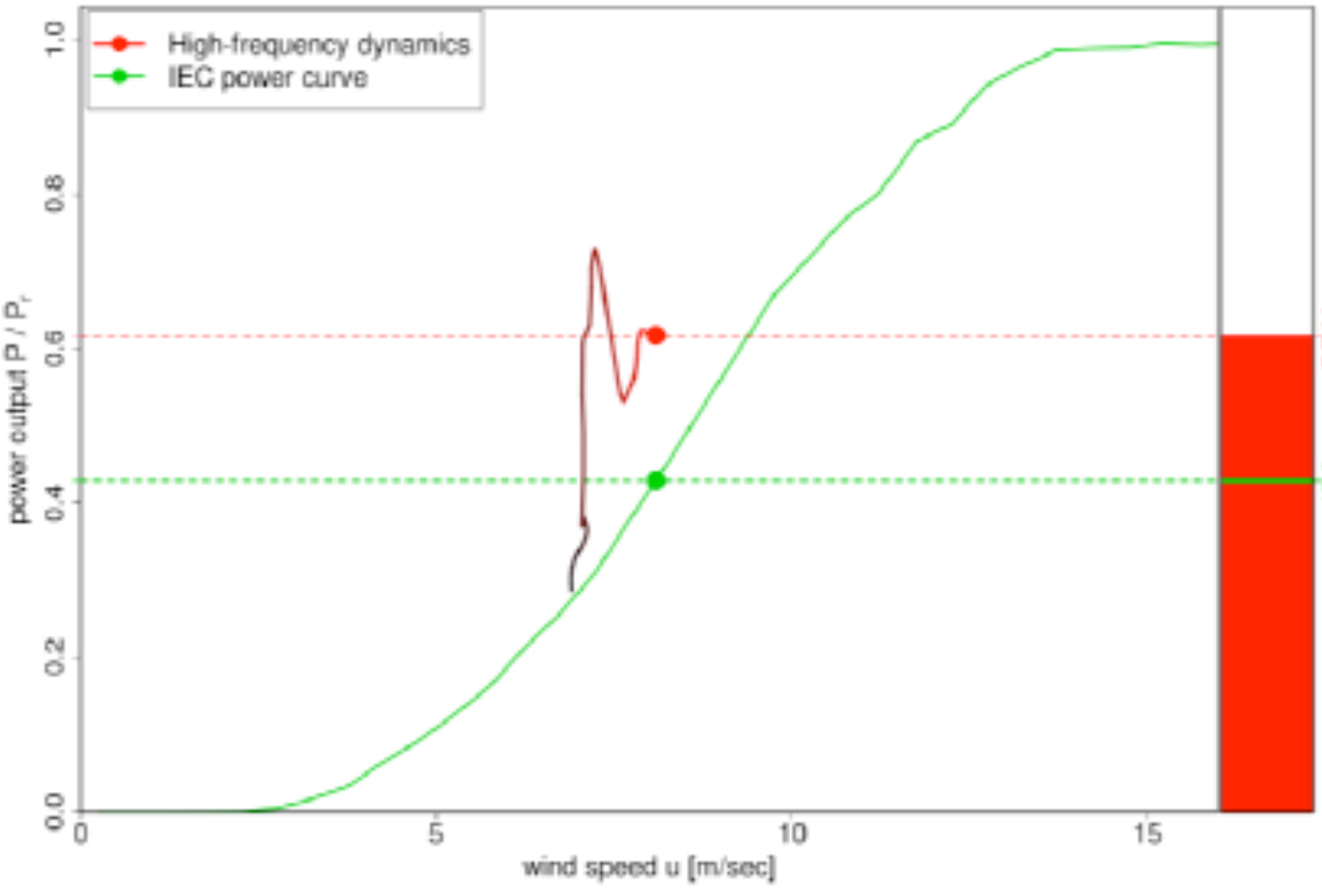
Boundary-Layer Meteorology **108** (2003)

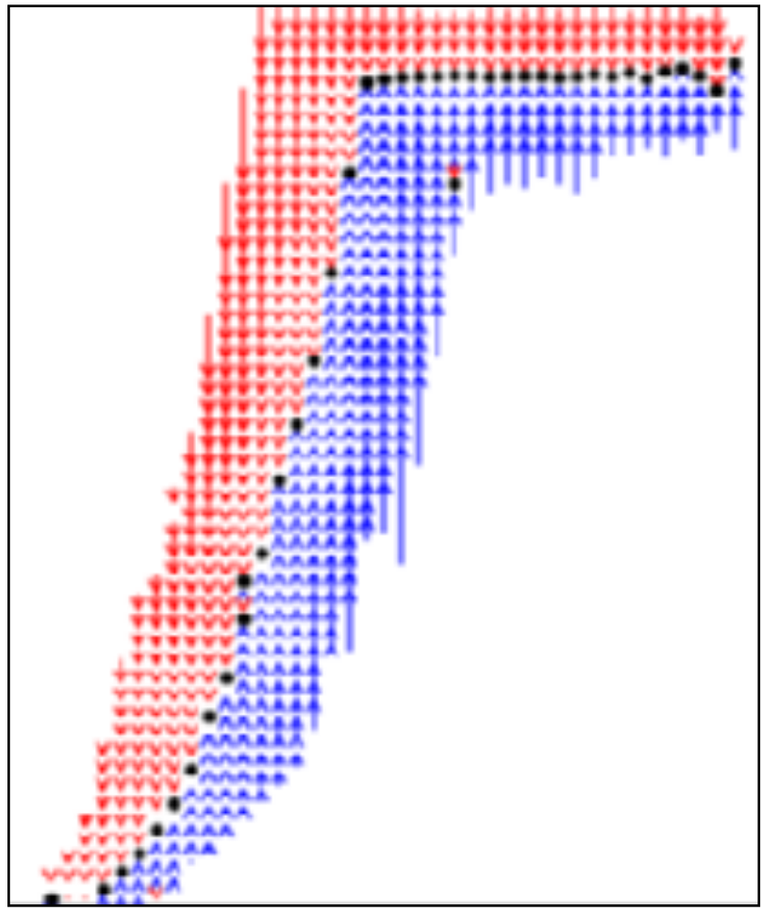
Stochastic modelling of wind turbine power curve

high frequency power curve

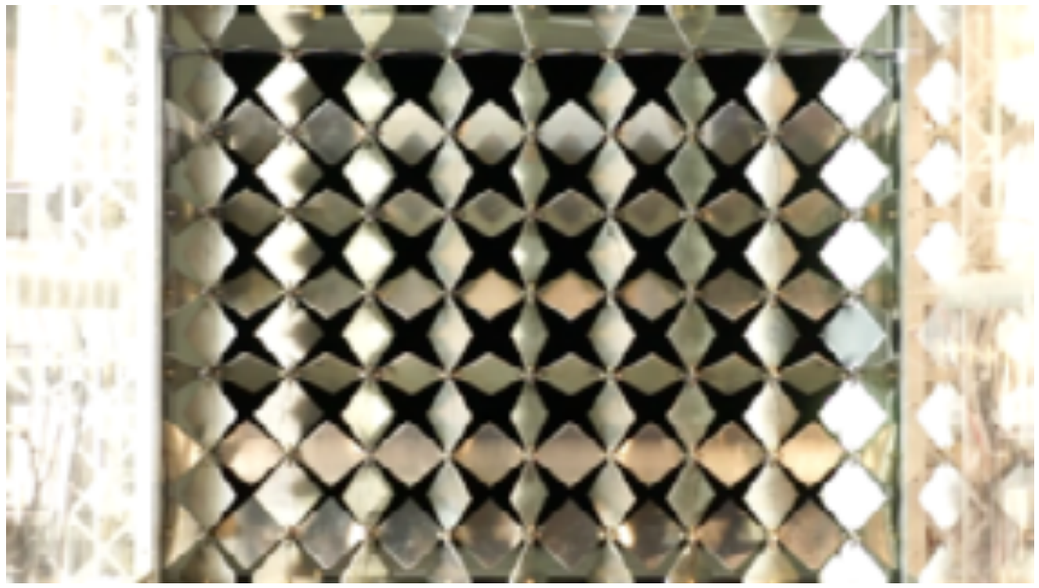
IEC power curve

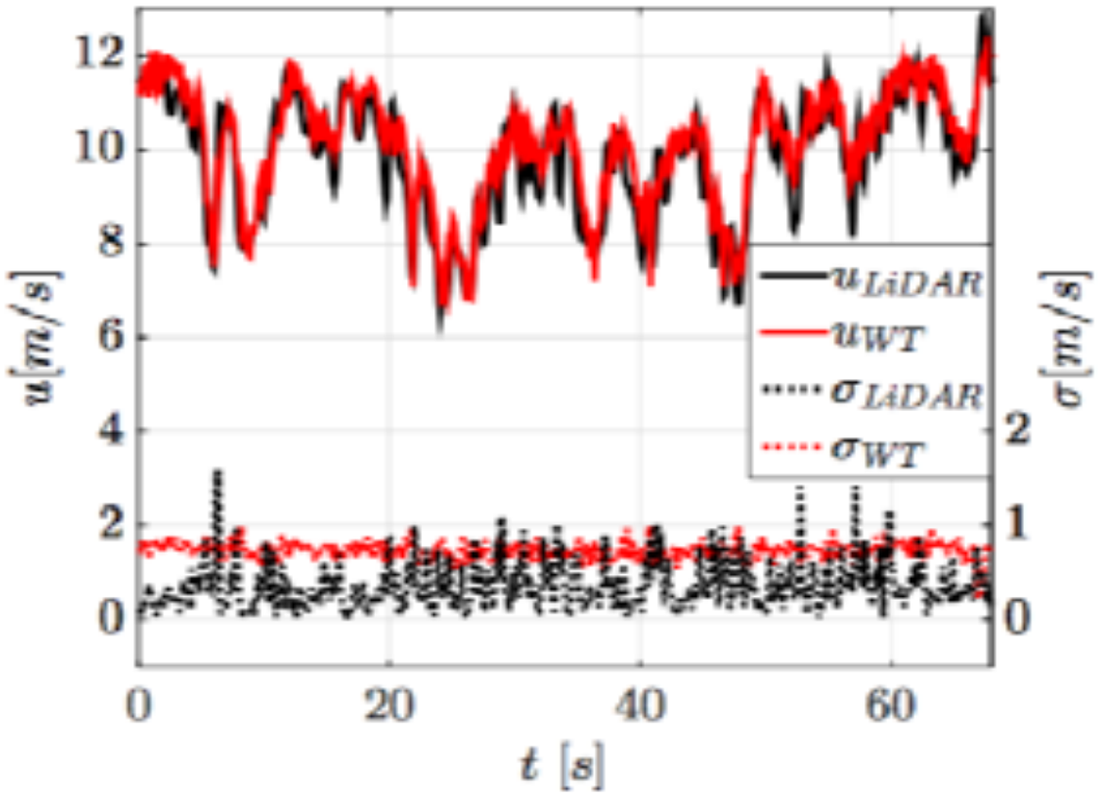
dynamic Langevin power curve with drift field





Reproducing measured wind speed series in the wind tunnel

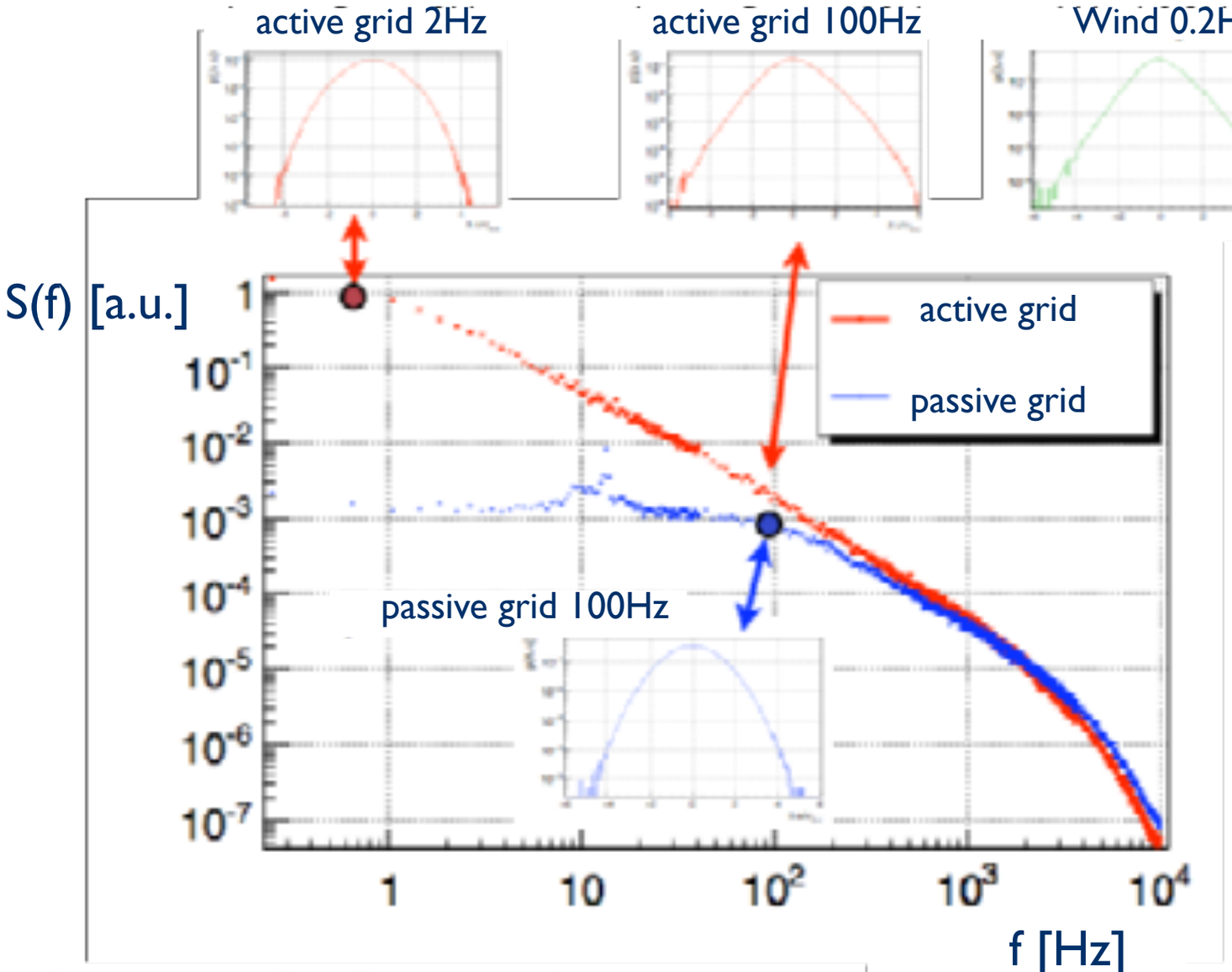




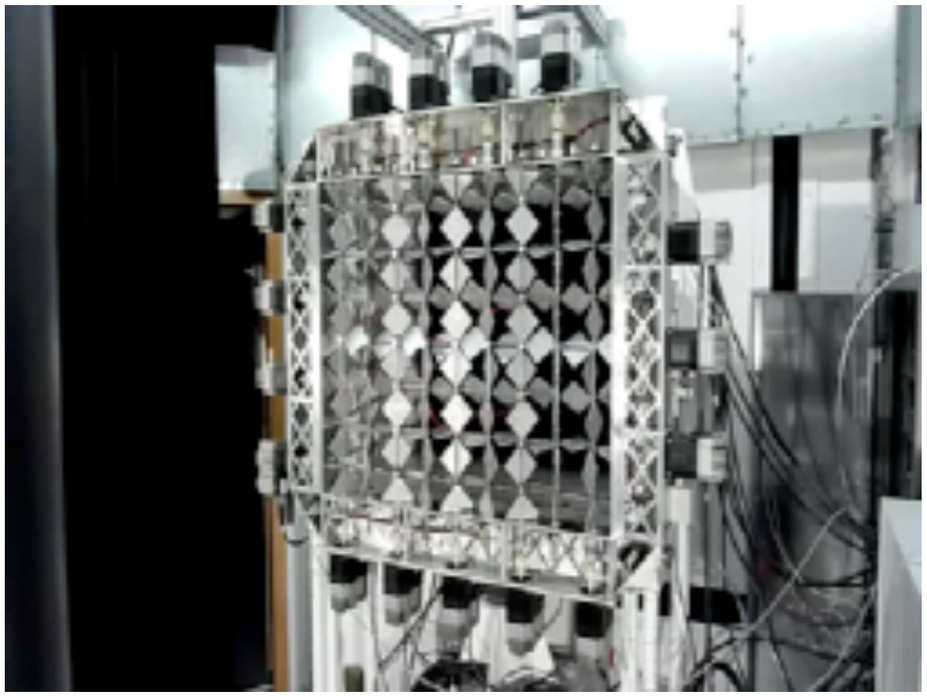
- active grid in the wind tunnel
- reproduction of wind time series measured by lidar

[Abb.: N. Reinke, AG TWiST, ForWind-OL]

Generation of wind fields with an active grid



[Knebel e.a., Exp Fluids, 2011]



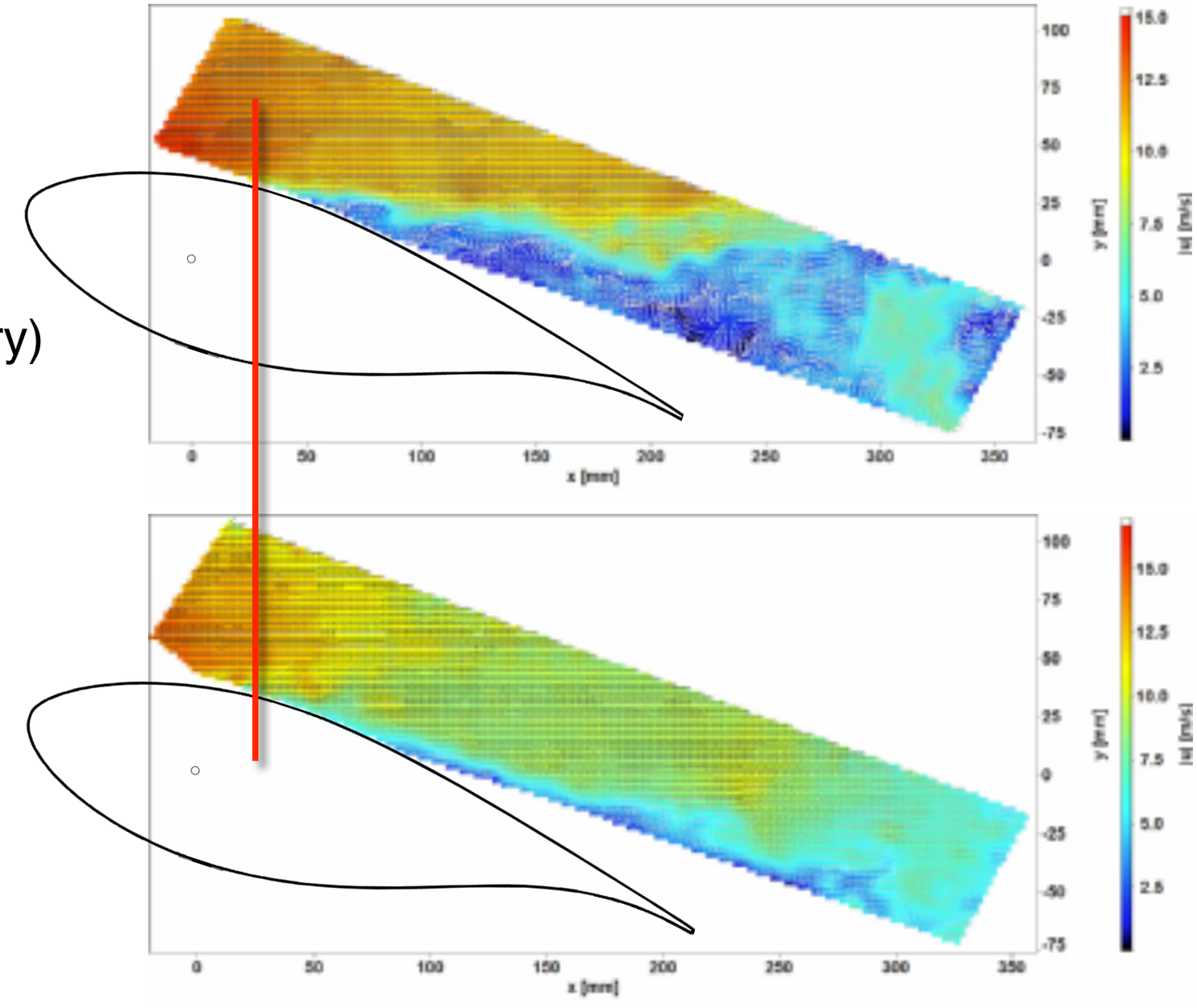
Reproducing realistic atmospheric inflow conditions in the wind tunnel

PIV measurements

(particle image velocimetry)

at laminar inflow

at turbulent inflow



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WIND FARM FLOW
AND WIND FARM CONTROL

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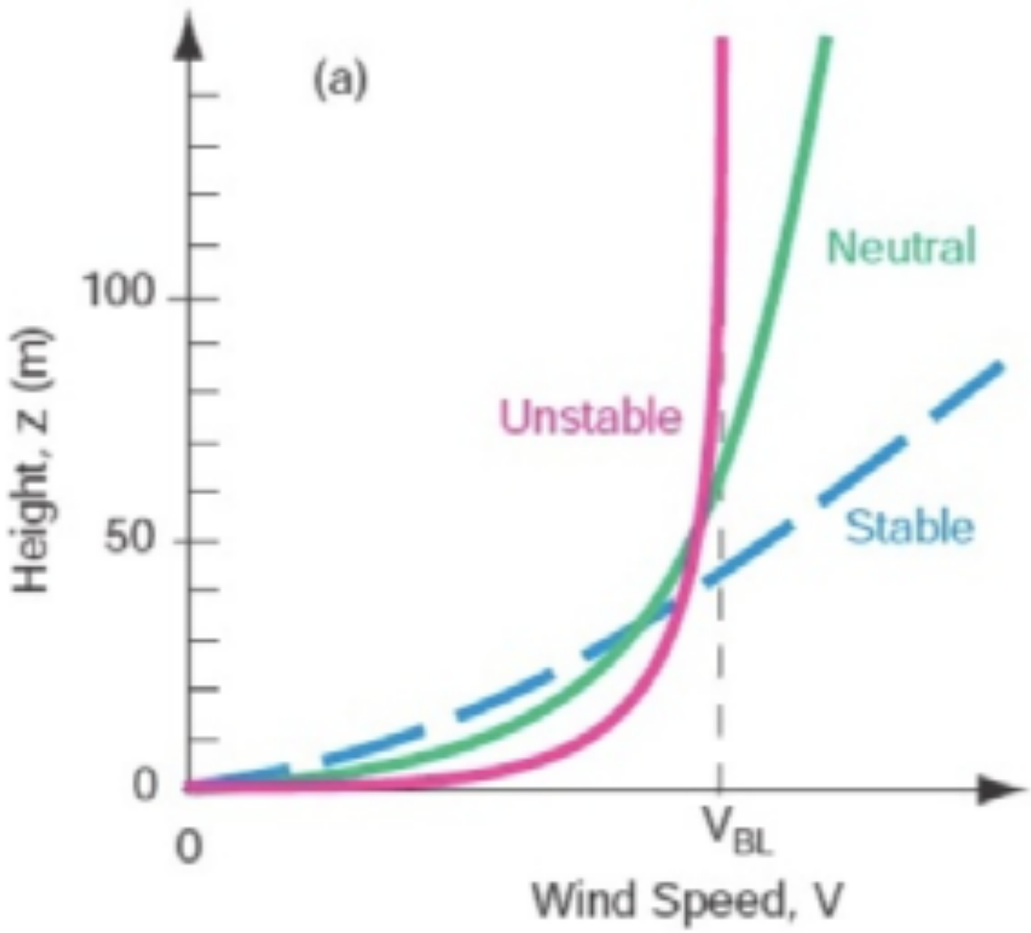
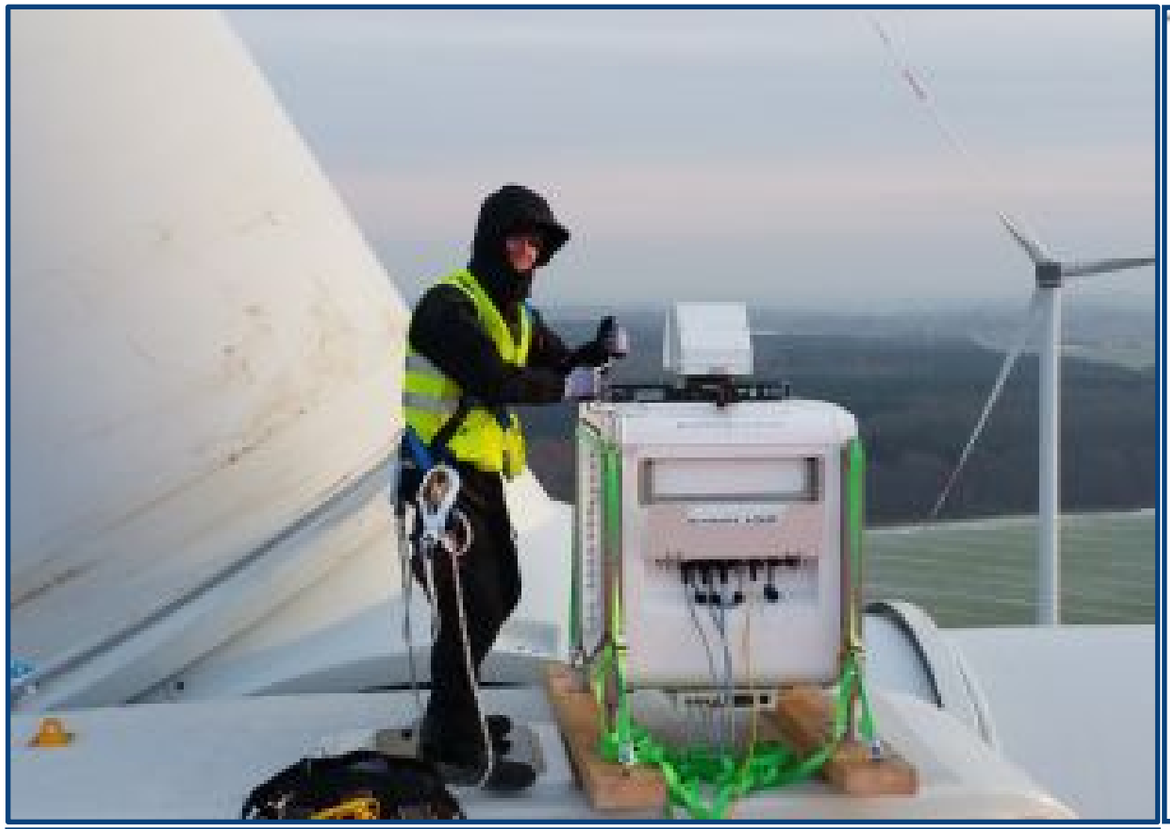
Effect of thermal stratification on wind farm flow

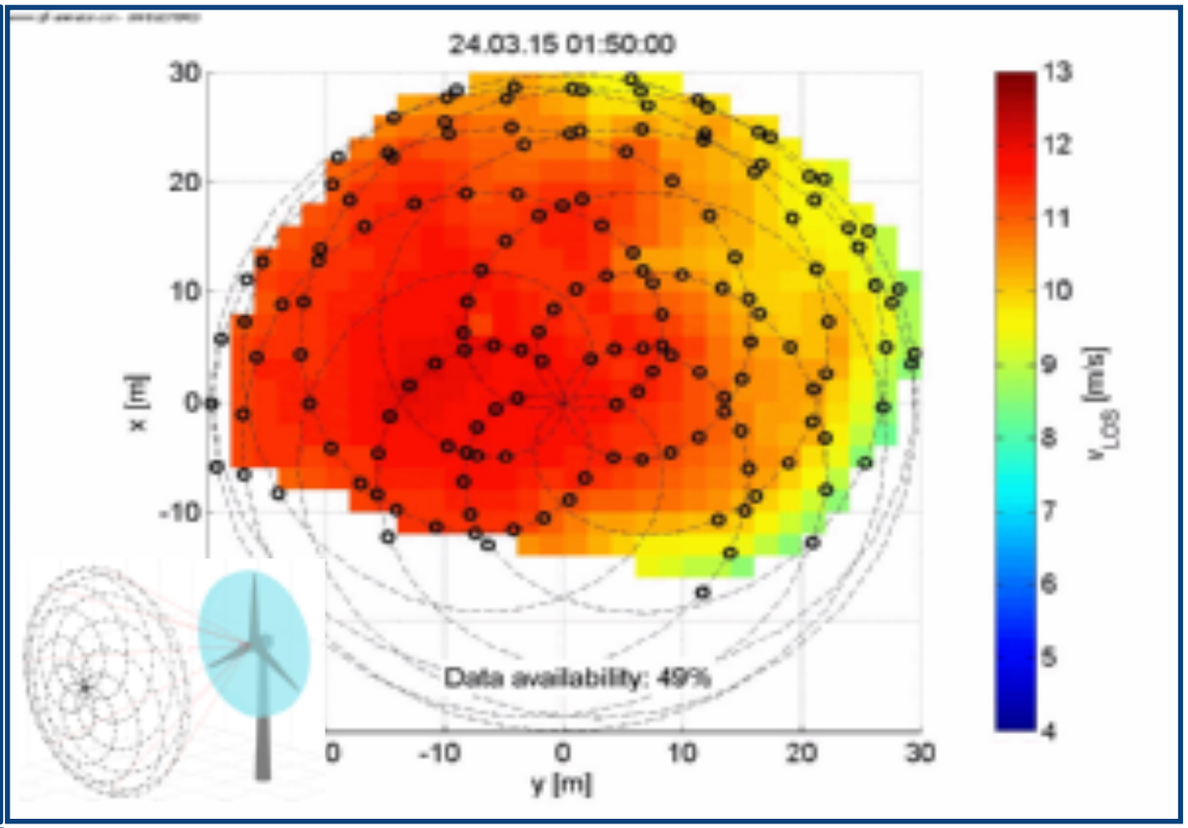
[Photo Christian Steiness]

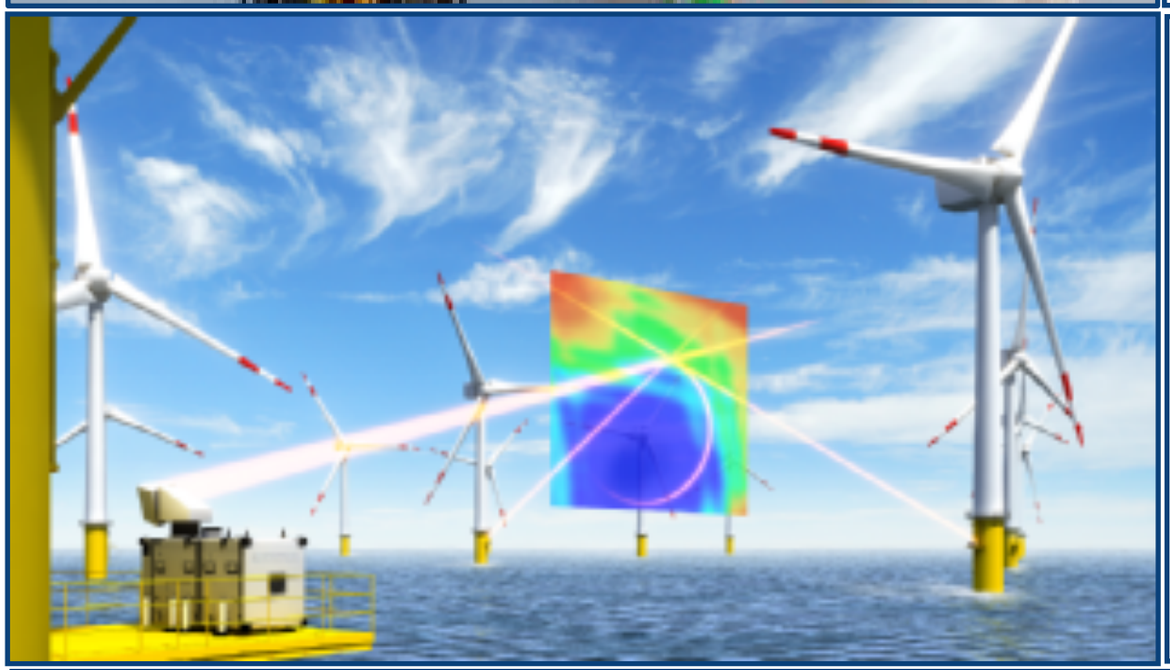
Stratification	Array efficiency (8 m/s wind along the rows)
• convective	74%
• neutral	66%
• stable	61%

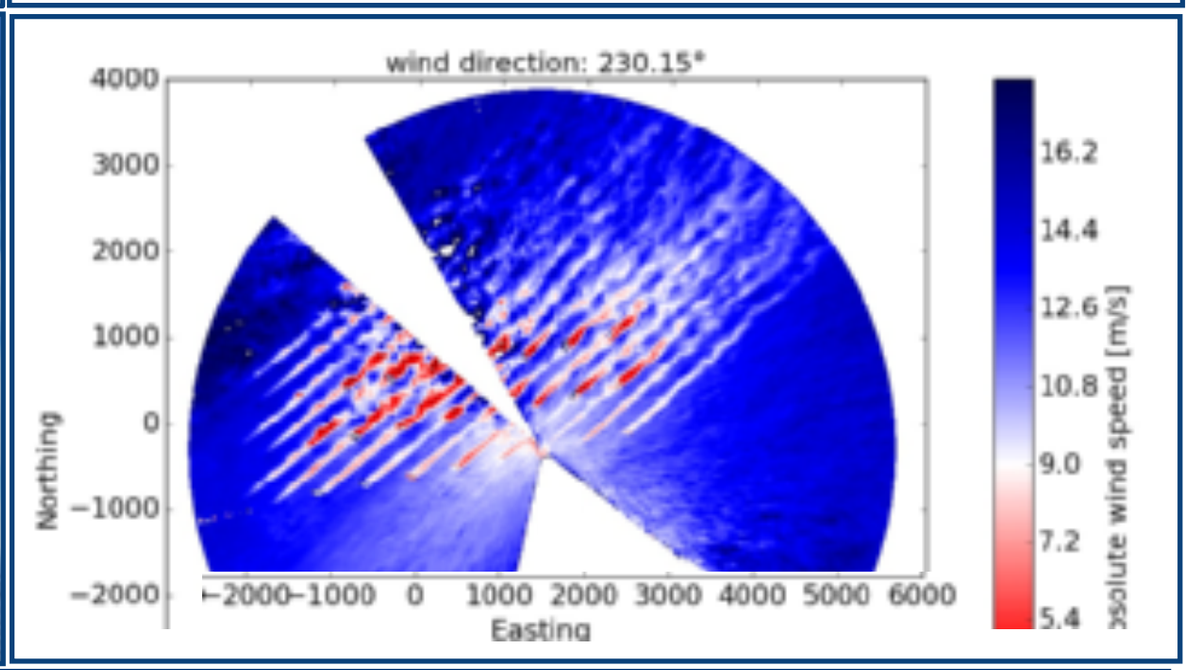


Lidar WindScanners









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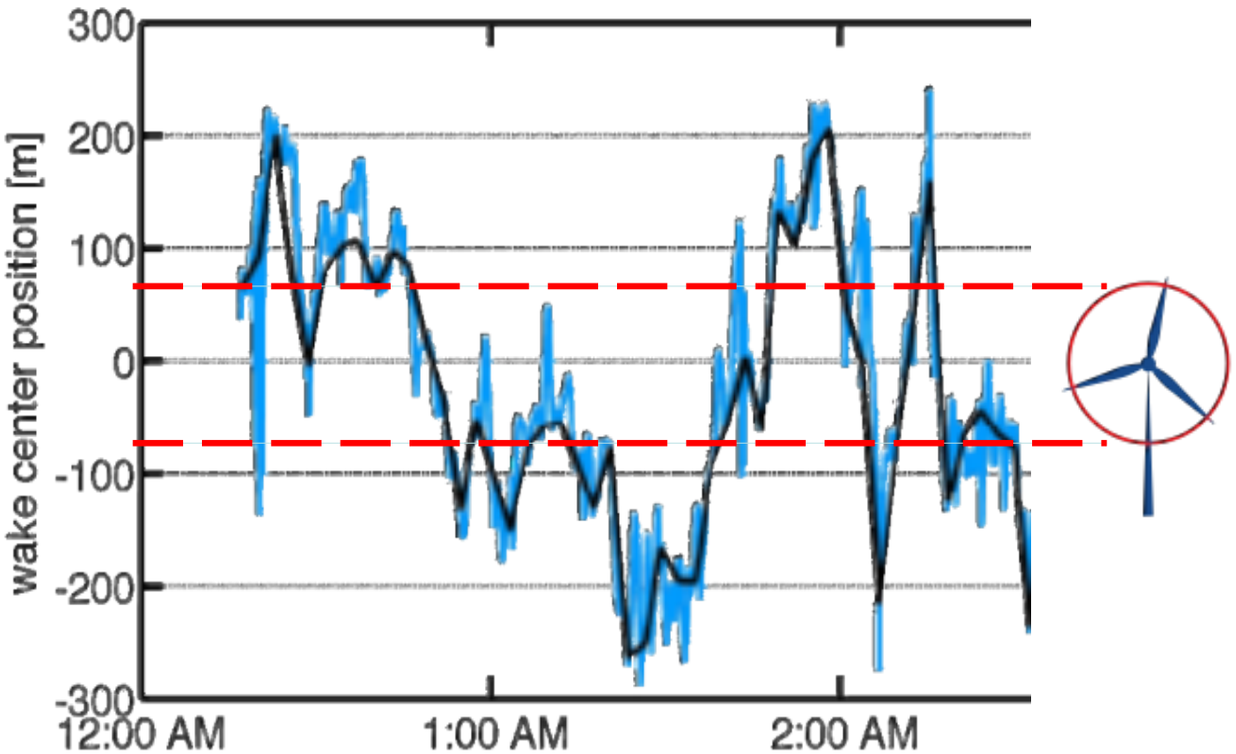
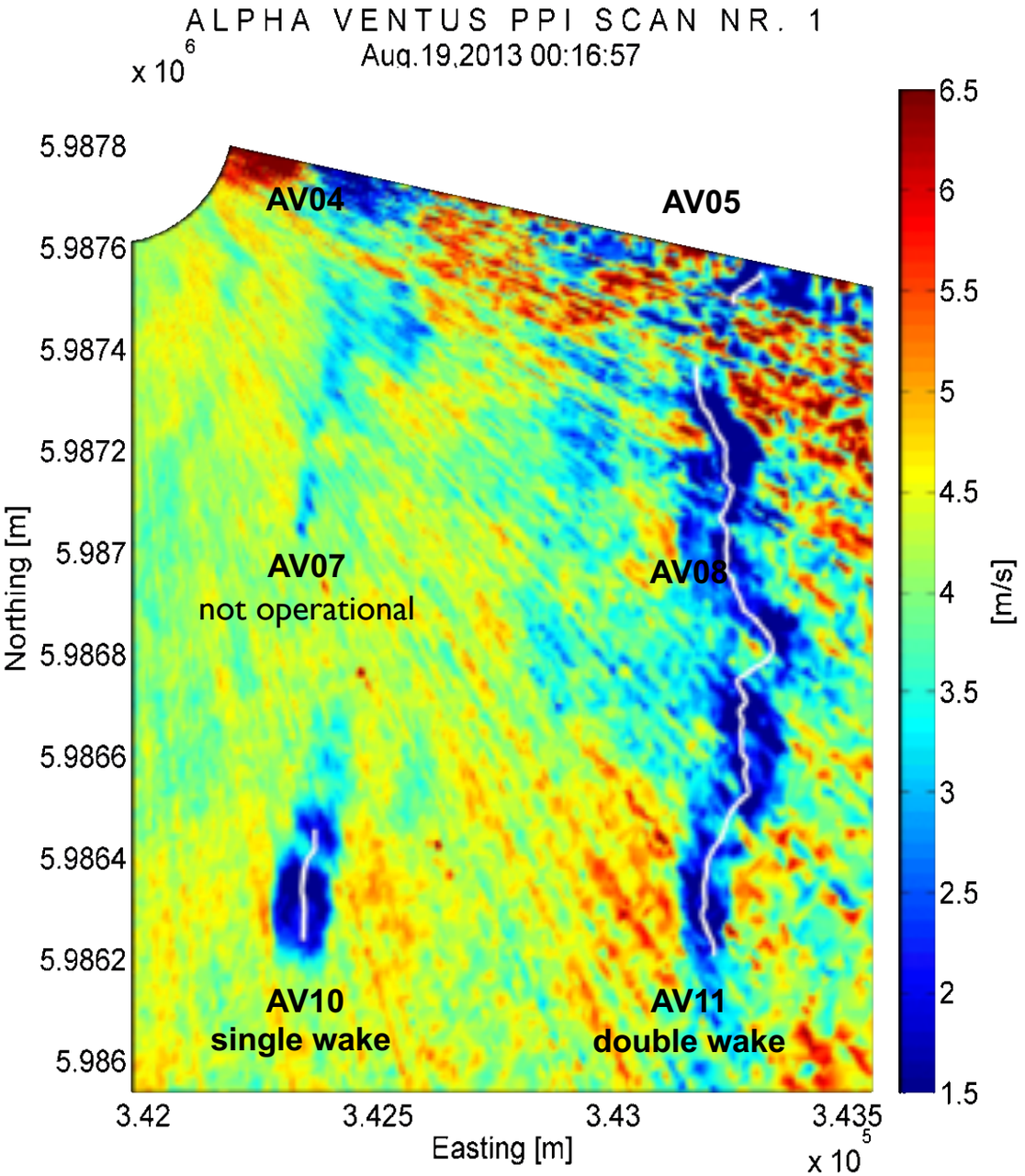
Effect of large scale atmospheric structures on wind farm flow measured by long-range WindScanner

Offshore site »alpha ventus«

- horizontal scans of wake meandering
- wake sweeping generates high loads

Wake centre offset at turbine AV04





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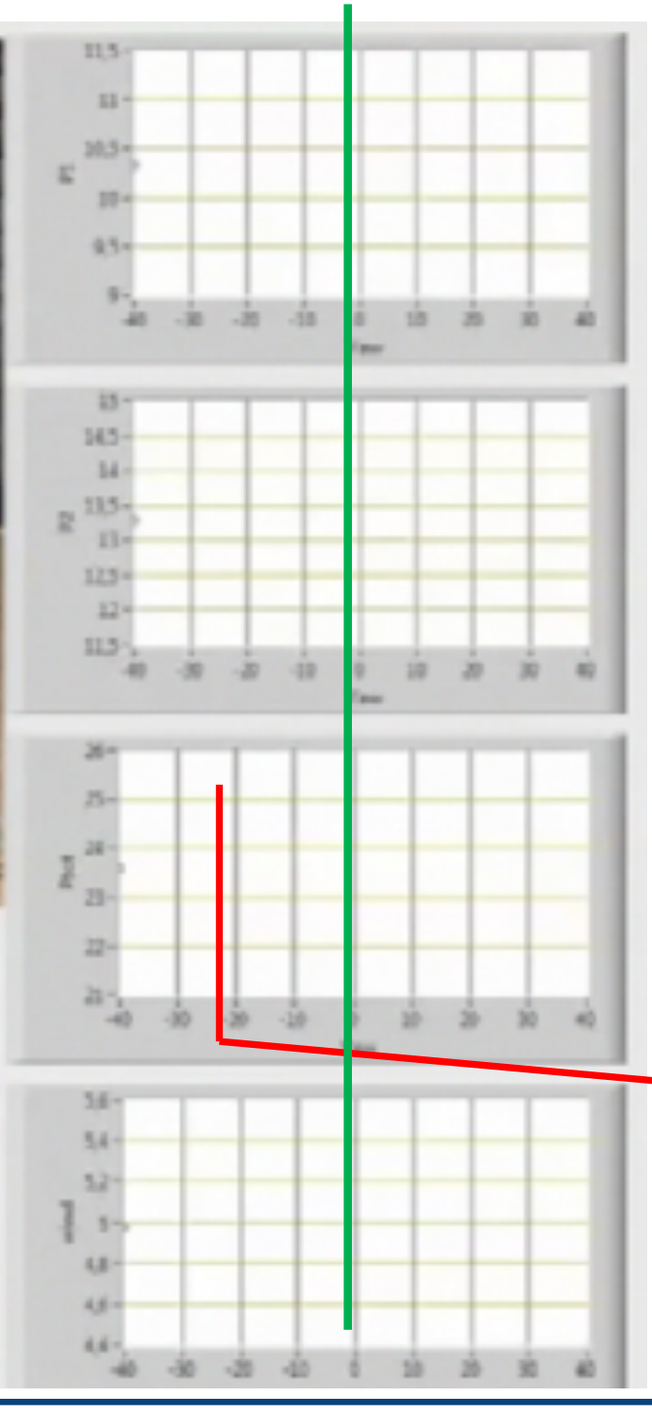
Wind farm flow control

Basic concept

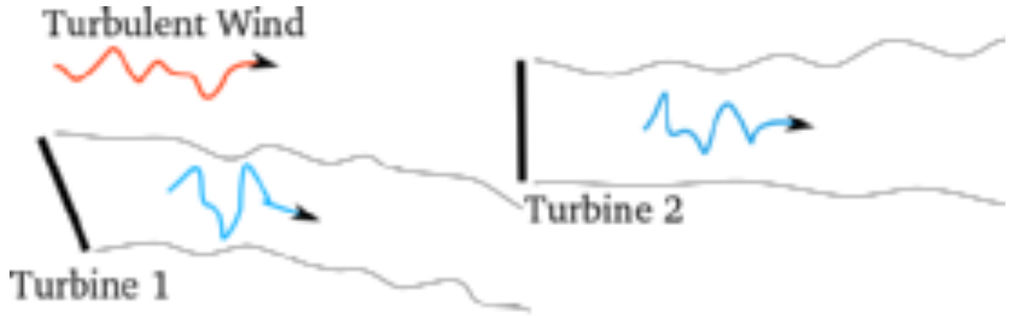
- maximising power output of the system rather than greedy control of individual turbines
- wake deflection by yawing upstream turbine out of wind direction

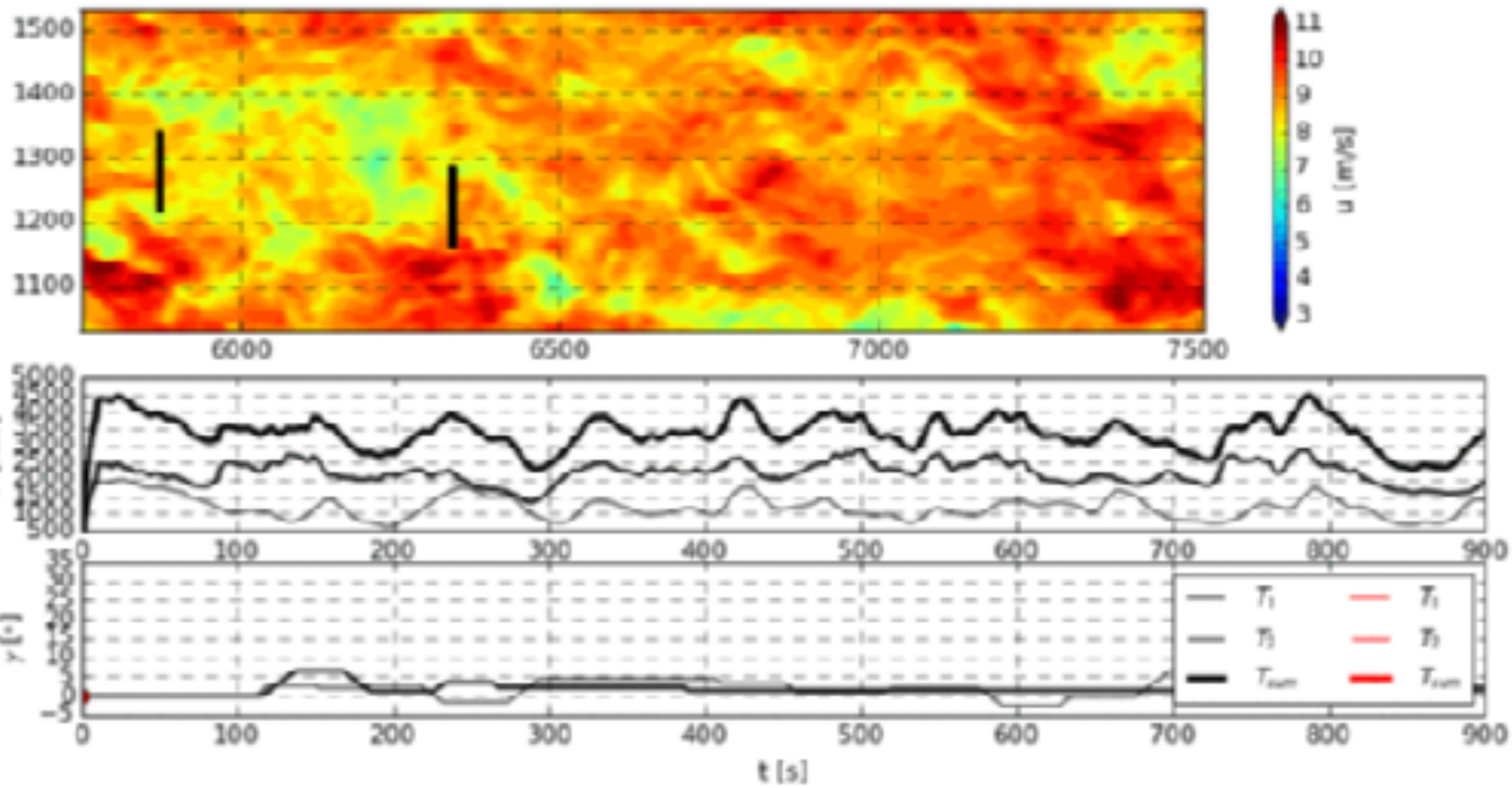
Wind farm flow control: Wind tunnel experiment



Wind farm flow control: Large eddy simulations

- Open-loop test of wake deflection control
- Increase of total power
- Lower dynamic fatigue loads at turbine #2





Black: conventional yaw control
Red: yaw control of turbine #1

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Effect of thermal stratification on wake deployment and deflection

No yaw misalignment Yaw misalignment -30°

Stable

- low turbulence => persistent wake
- directional distortion due to wind veer
- strong deflection due to yawing

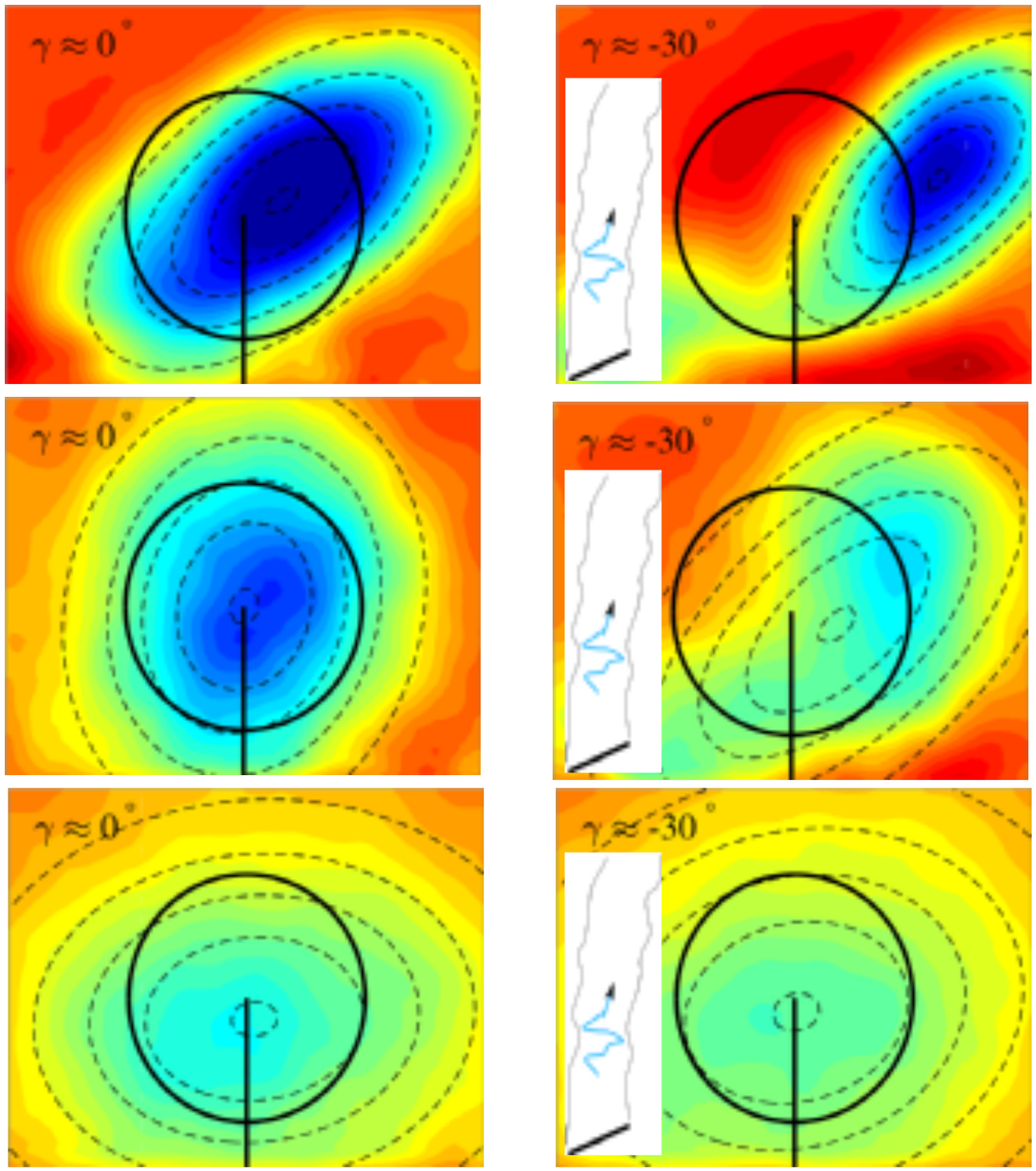
Neutral

- little wake distortion
- less wake deflection

Convective

- fast recovery of wake deficit
- wide, elliptical wake deficit
- hardly any wake deflection

(Large eddy simulations,
wake deficit at 5 diameters downstream)



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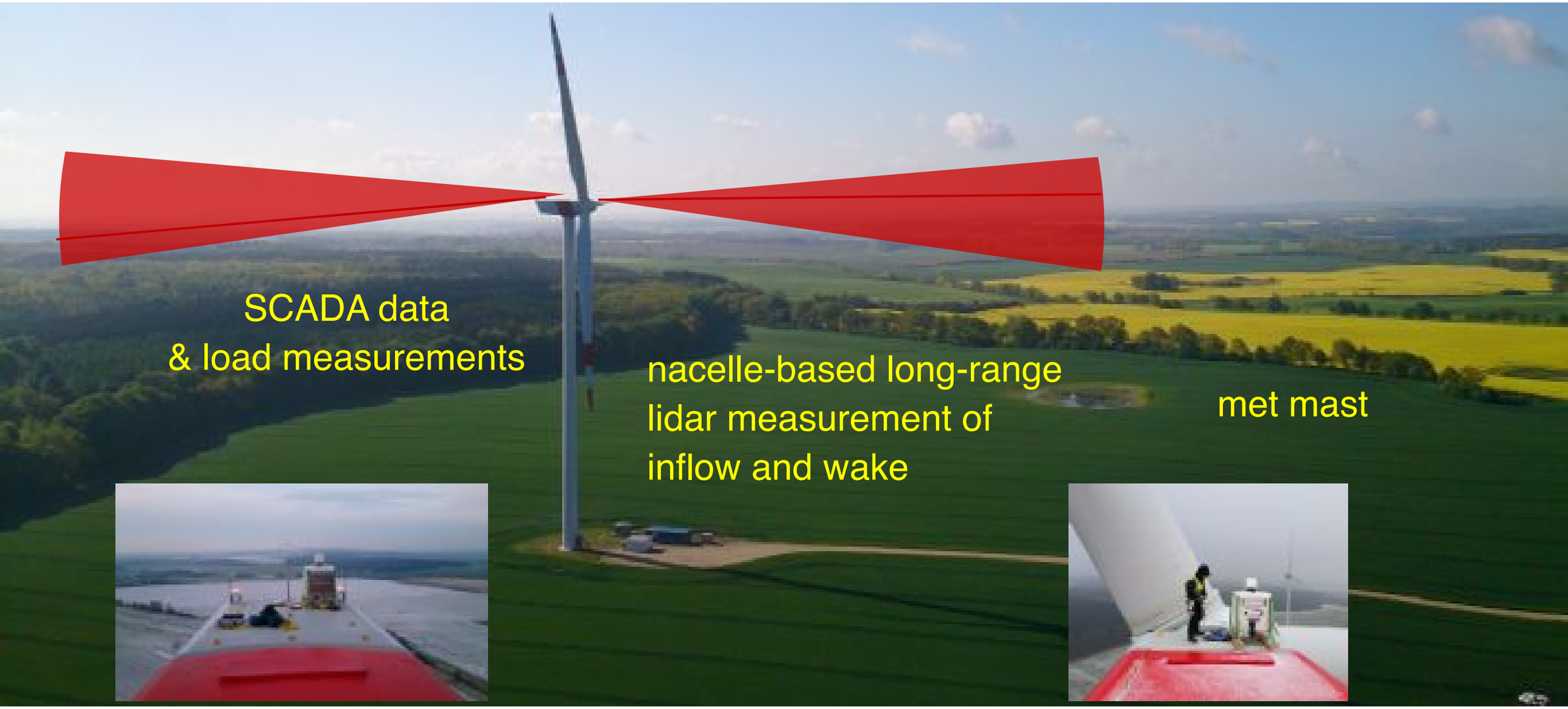
Full field wake deflection experiments at 3.5 MW turbine (114 m diameter)



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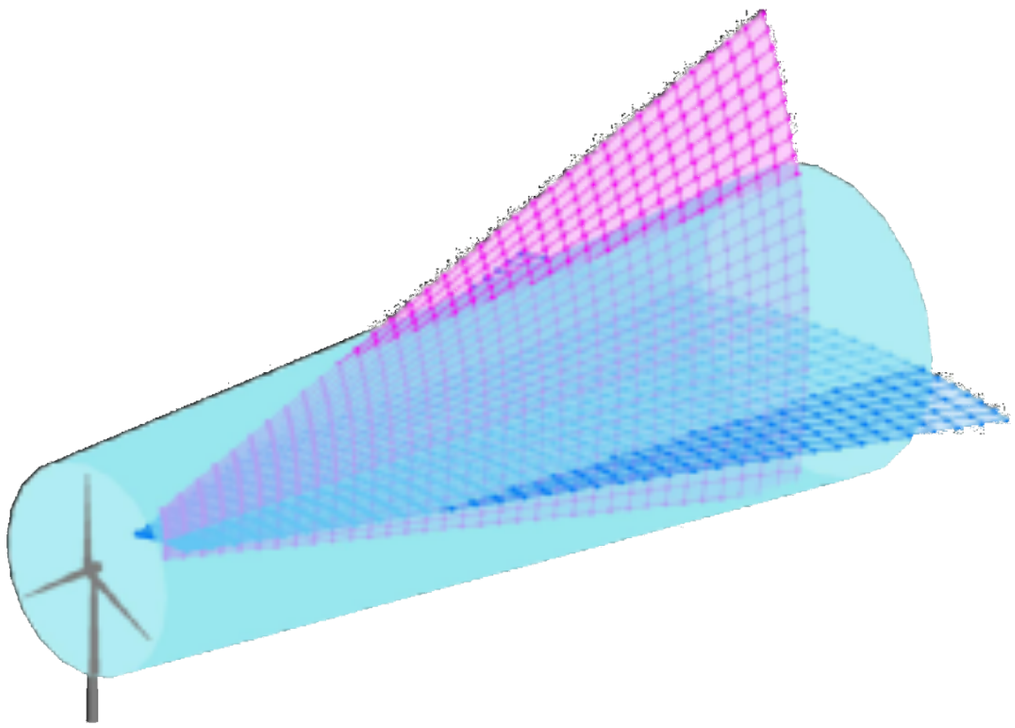
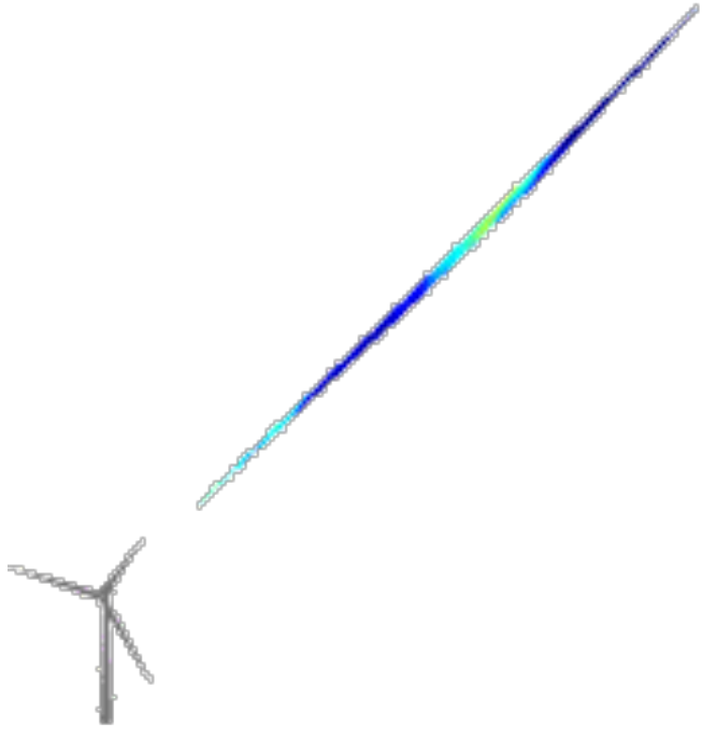
Full field wake deflection experiments

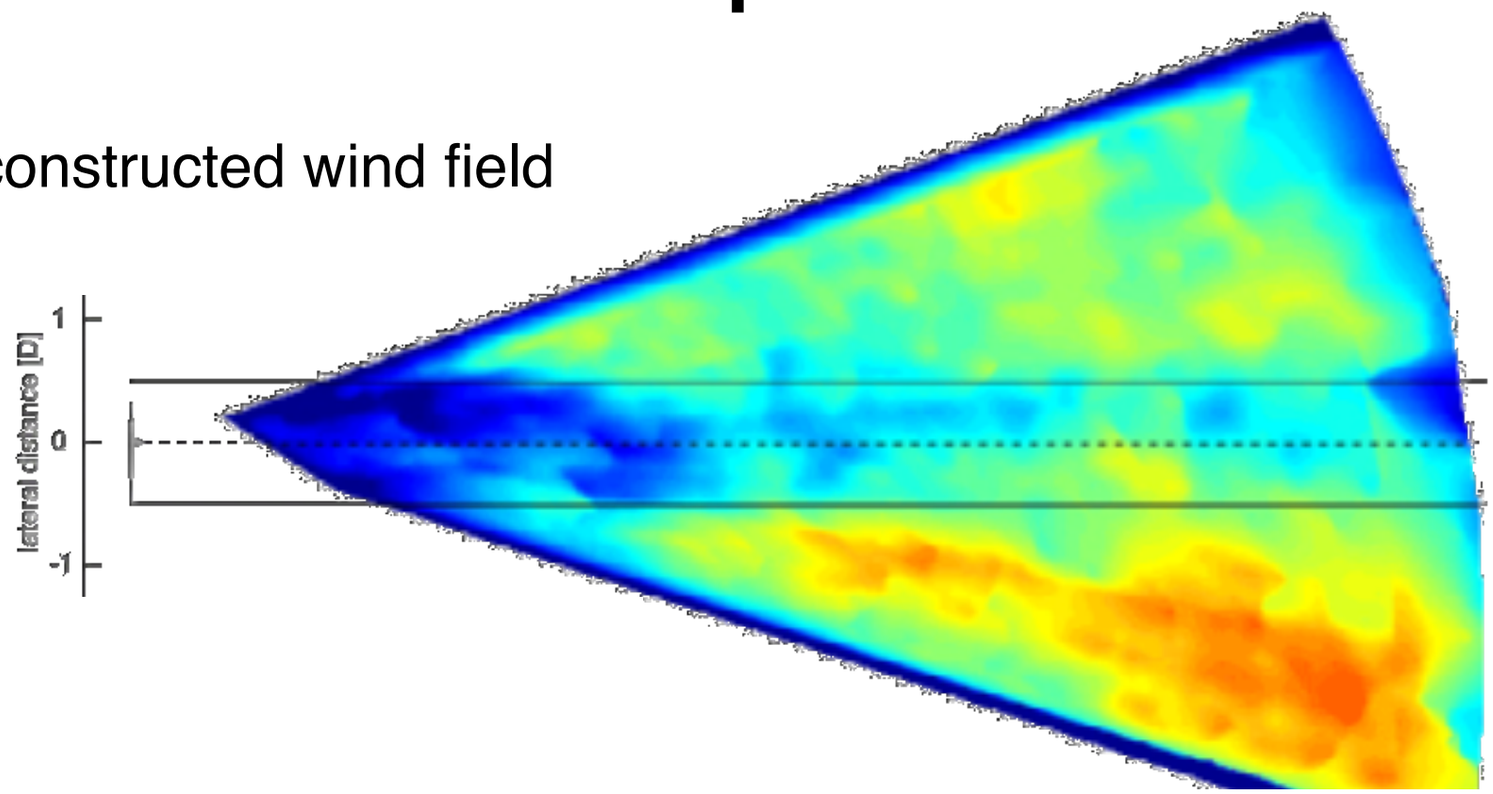
Non-synchronzied horizontal and vertical lidar scans of the wake



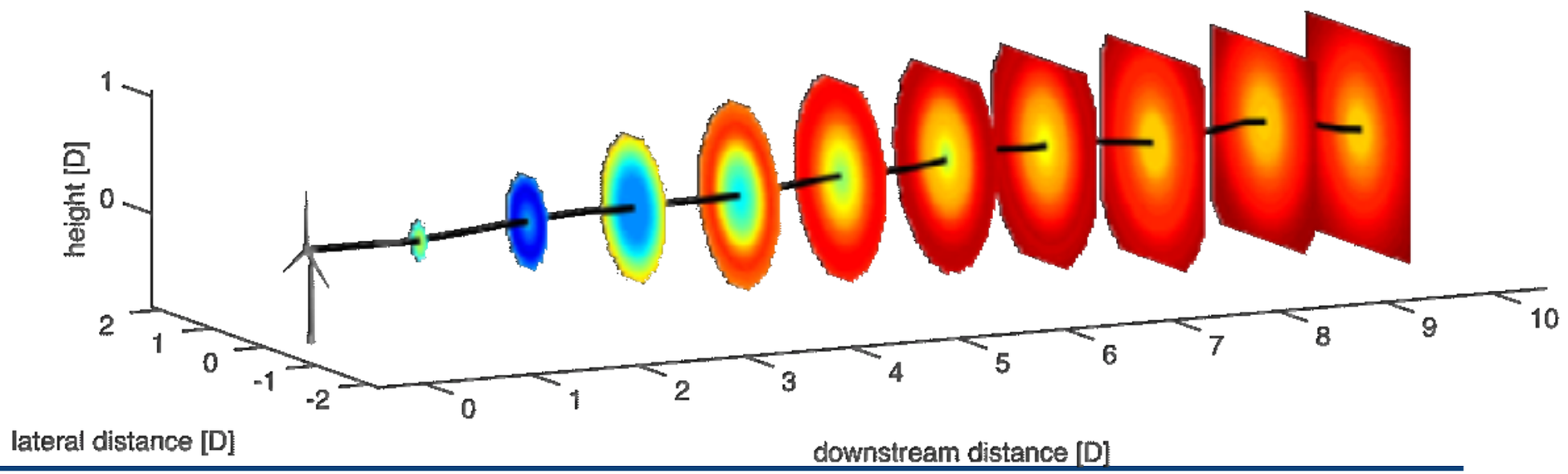


Full field wake deflection experiments

Top view of reconstructed wind field



Parametrization of dynamic wake meandering model



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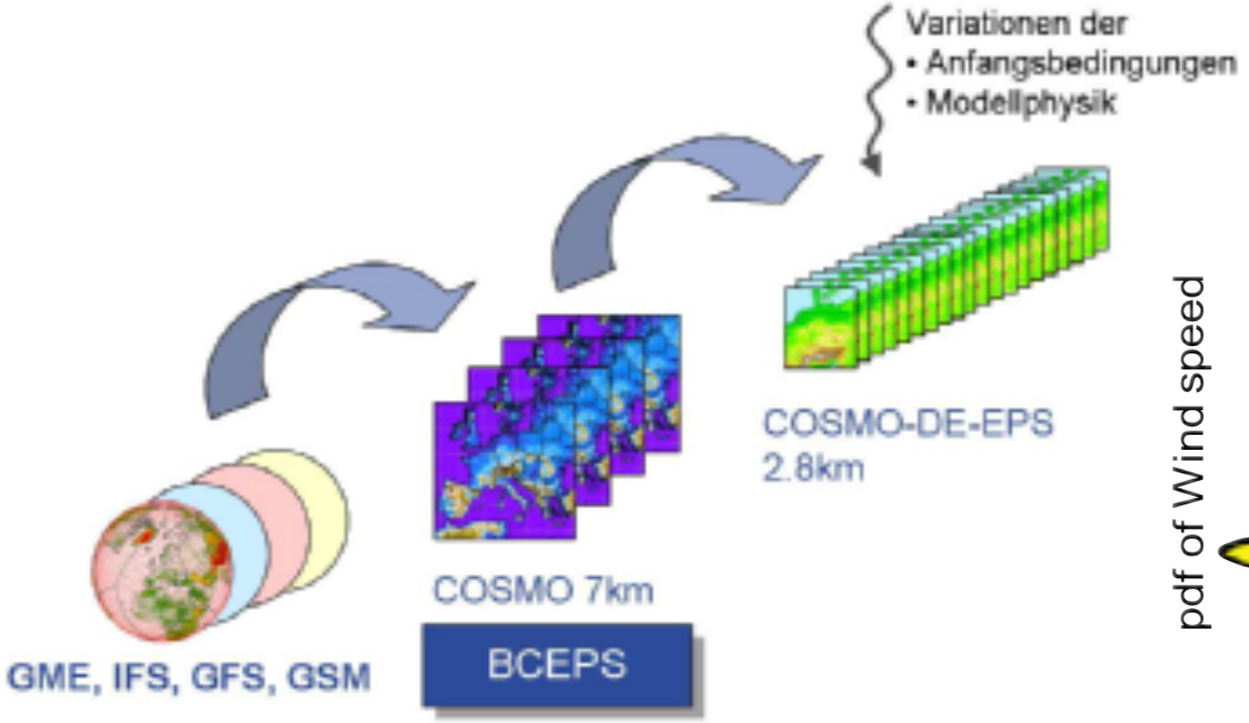
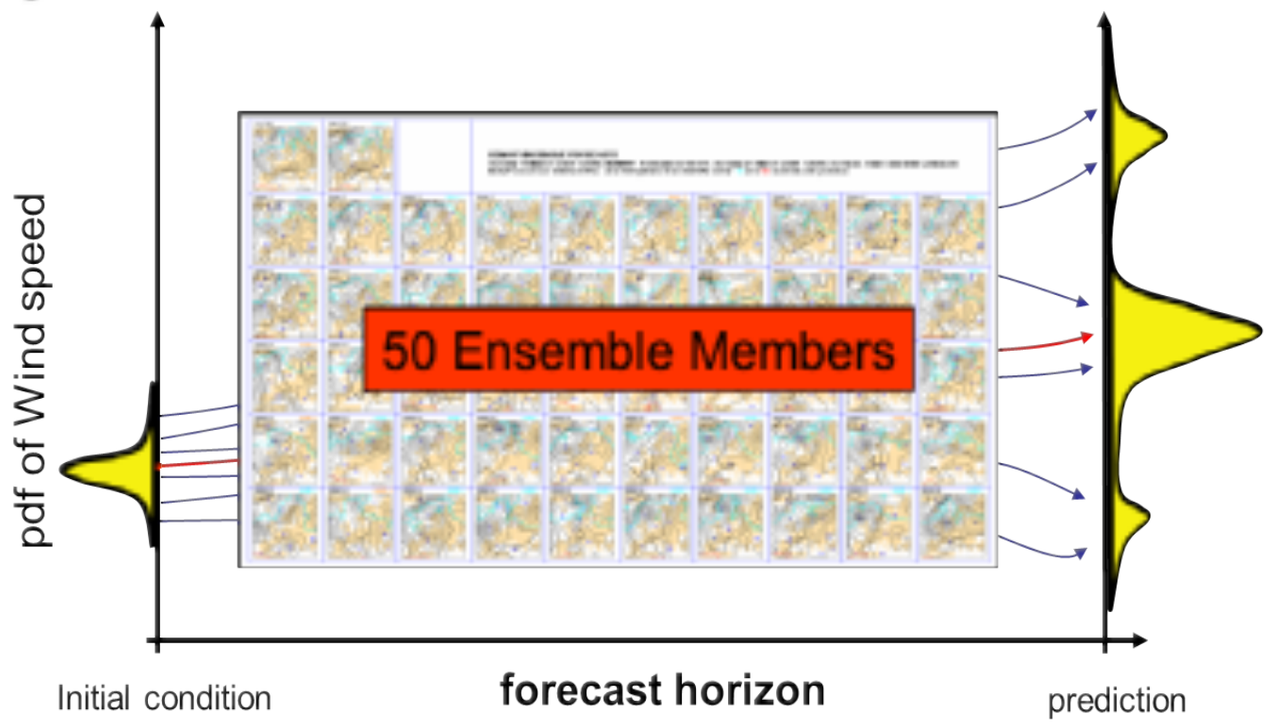
MESOSCALE MODELLING

Probabilistic wind power forecasting

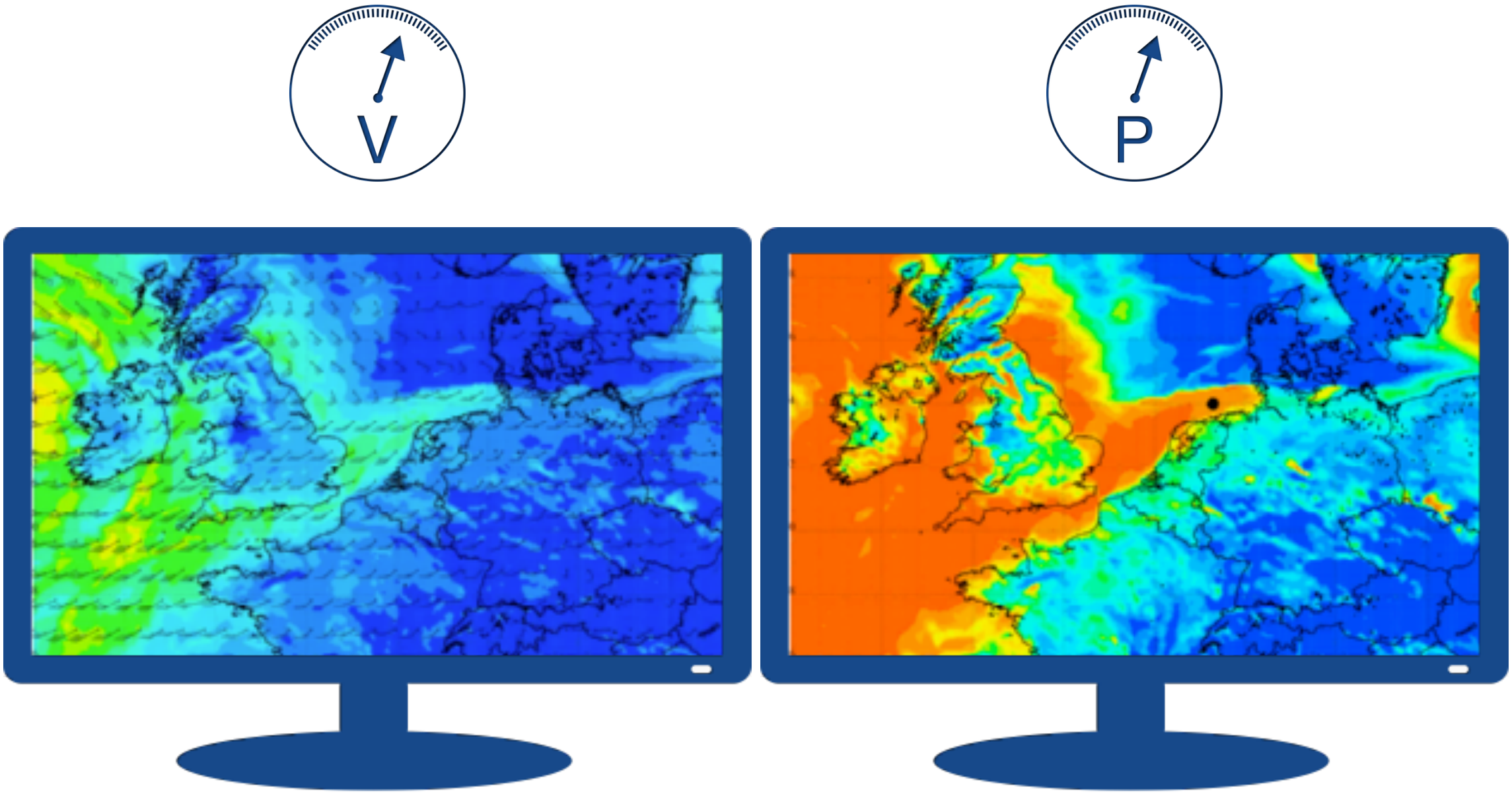
- Initial value problem
- Imperfect physical modelling
- Weather forecast never flawless
- Need for probabilistic forecasts

Ensemble forecast





Wind speed and wind power at extreme events



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Teaching concept on wind physics from BA & MA to PhD and further education

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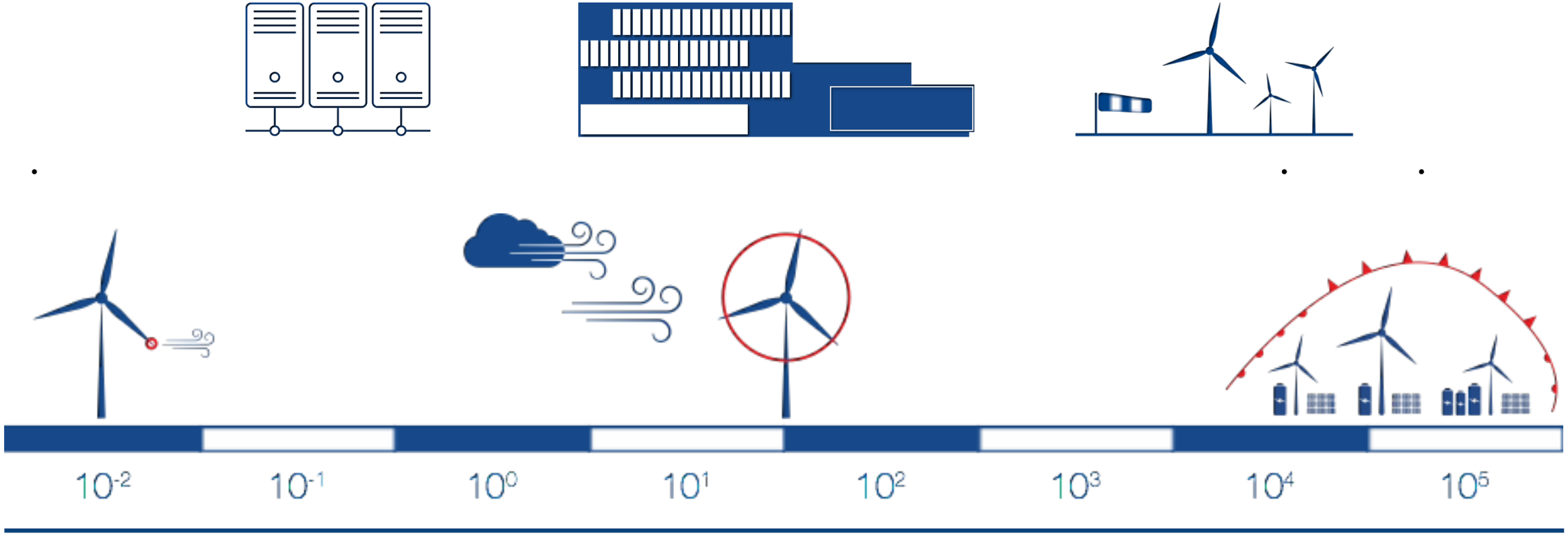
Conclusions

Multi-scale wind physics research program

- characterizing the wind resource
- interaction of wind & turbulence with wind energy systems
- mitigation of turbulence effects by controls

=> understanding and utilizing the major fuel of future electricity supply



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