Wind tunnel experiments on wind turbine wakes in yaw: Redefining the wake width

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[4] Fraunhofer IWES, Oldenburg, Germany

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Motivation

Field measurements

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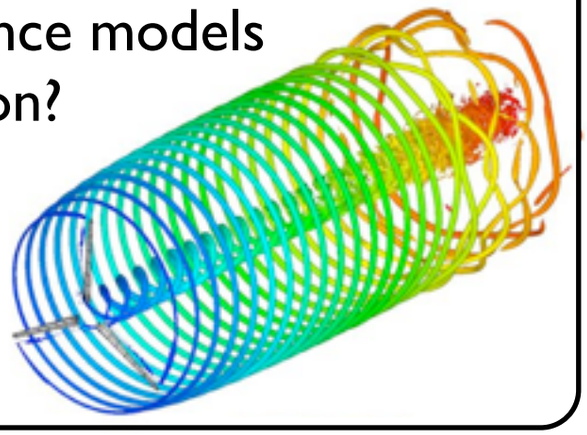
- turbulence models
- validation?



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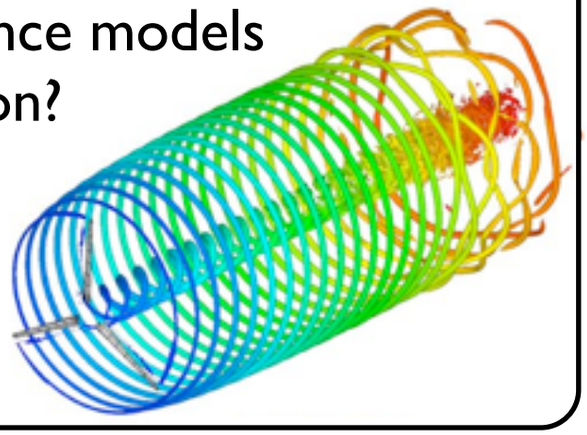

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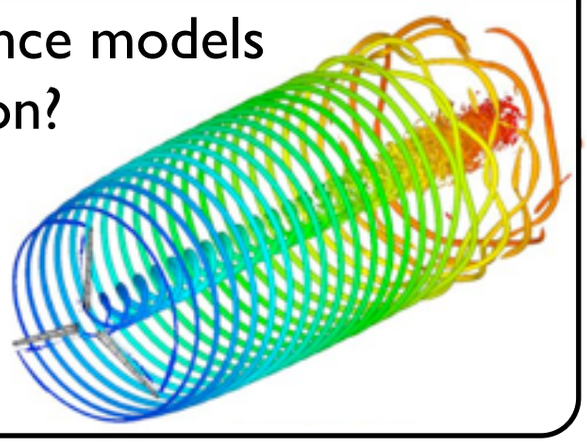

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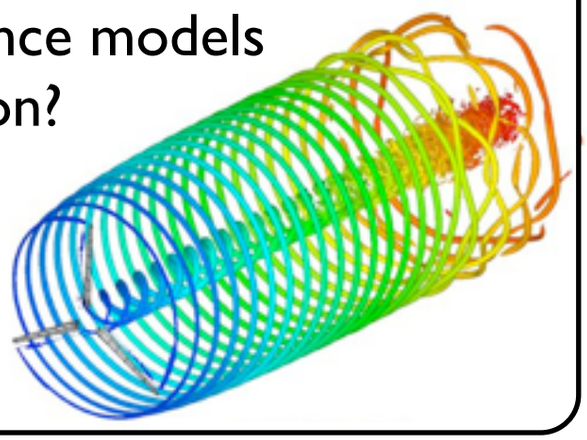

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Campagnolo, Politec Milano
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Thorough analyses of wakes
from mean velocity to **two-point statistics**,
including **yaw misalignment**

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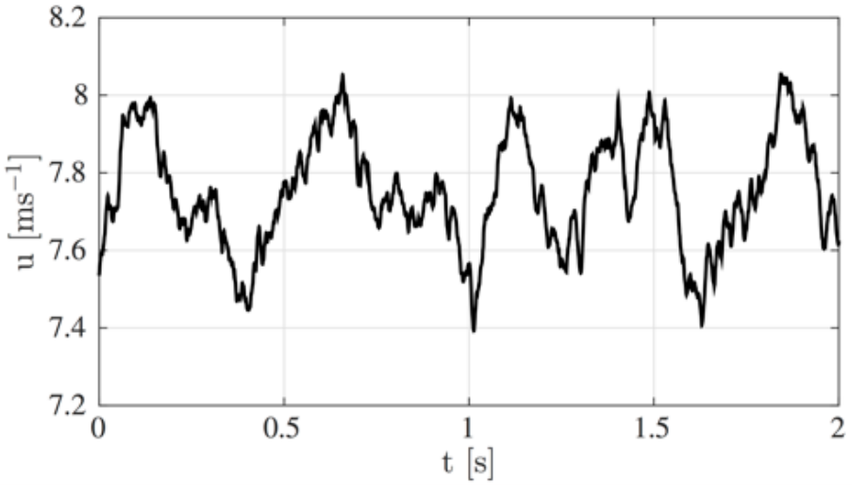
Two-point statistics

time series



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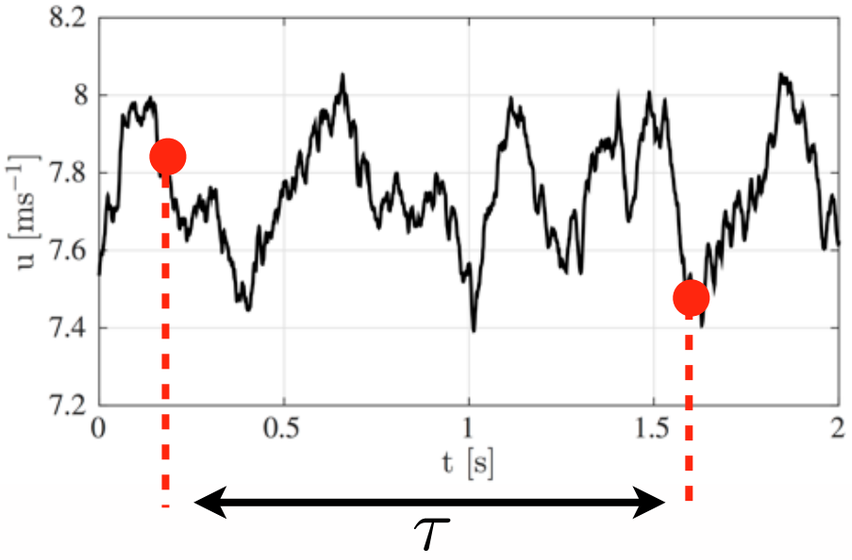

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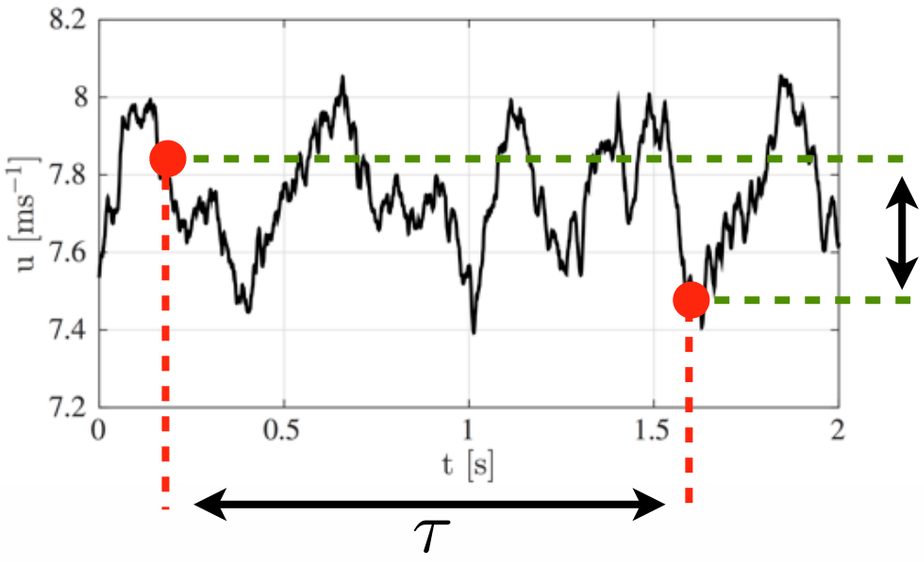

velocity increment

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

Two-point statistics

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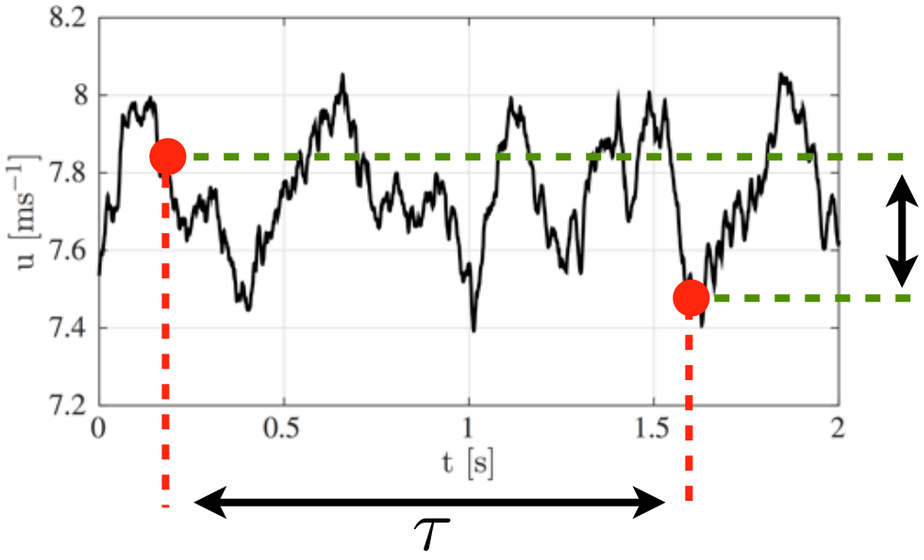

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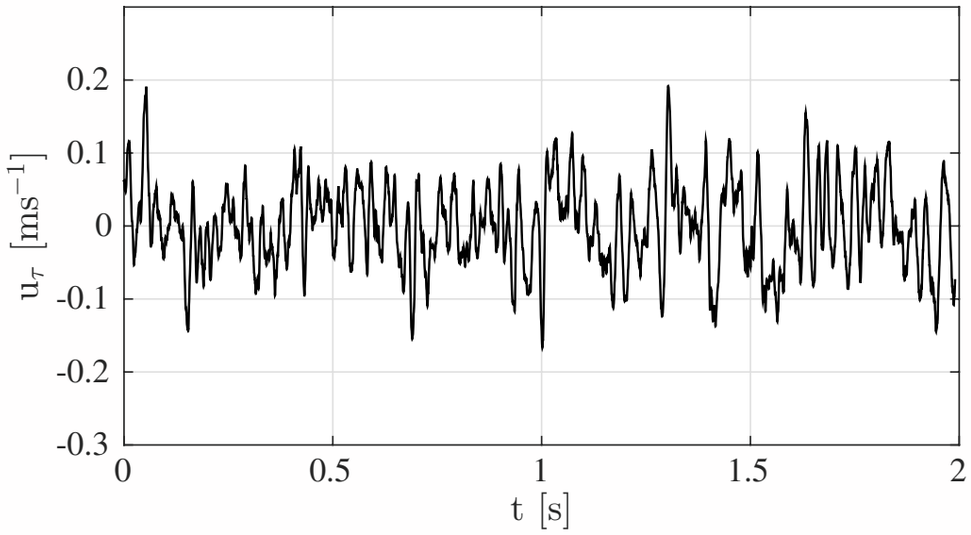

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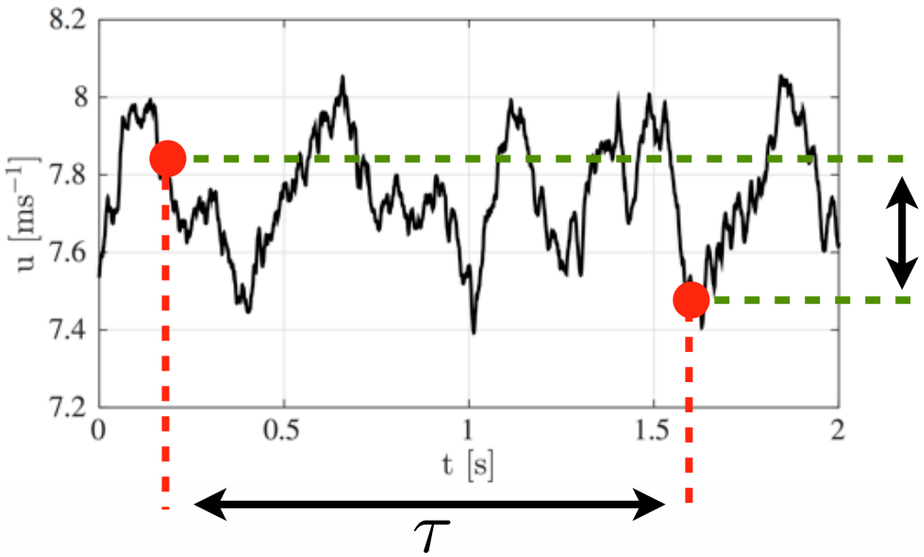

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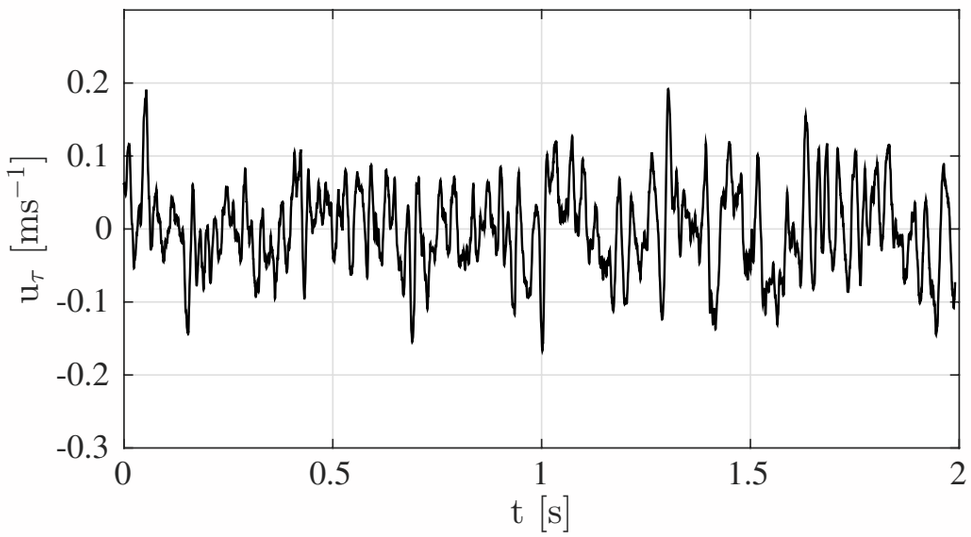
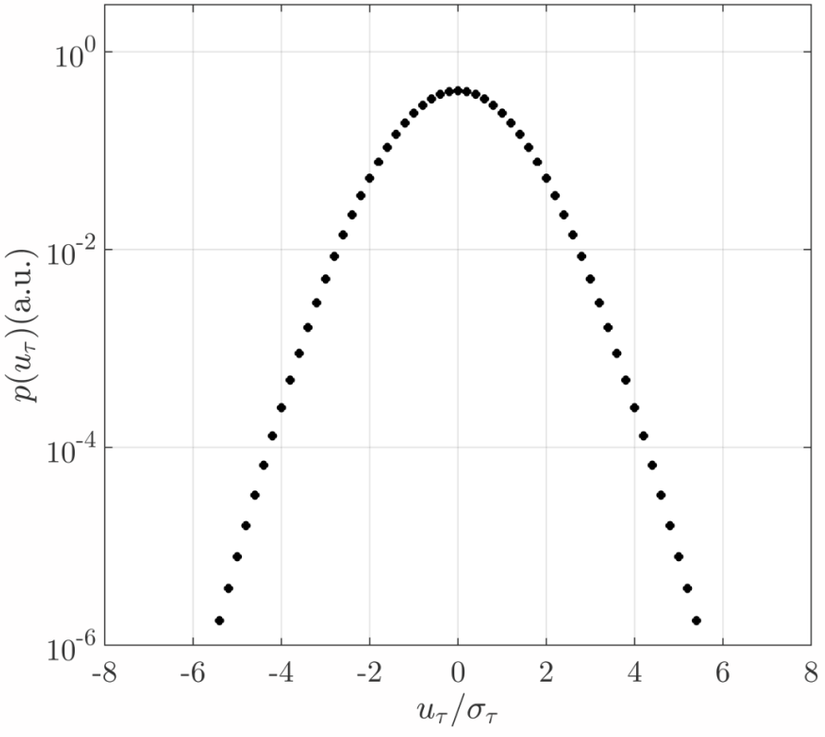


increment PDF



$$\lambda^2 = 0.01$$

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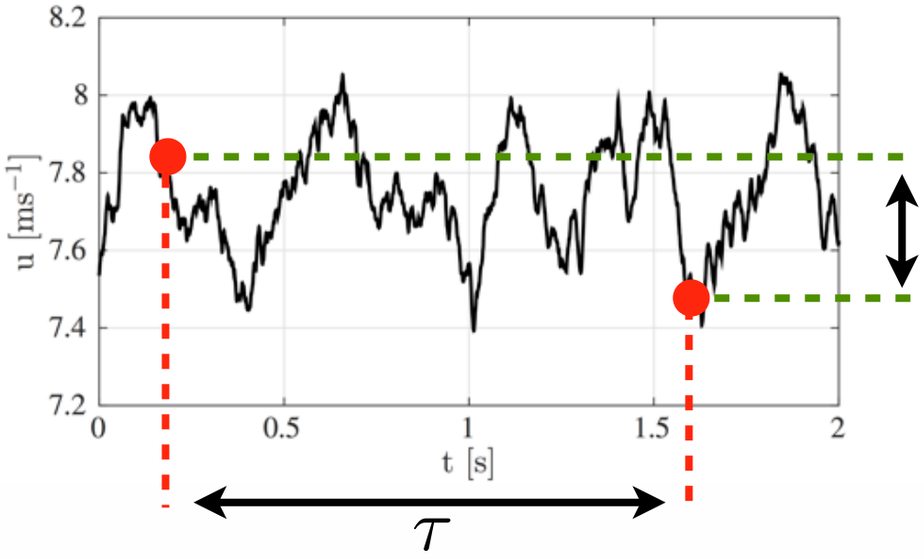

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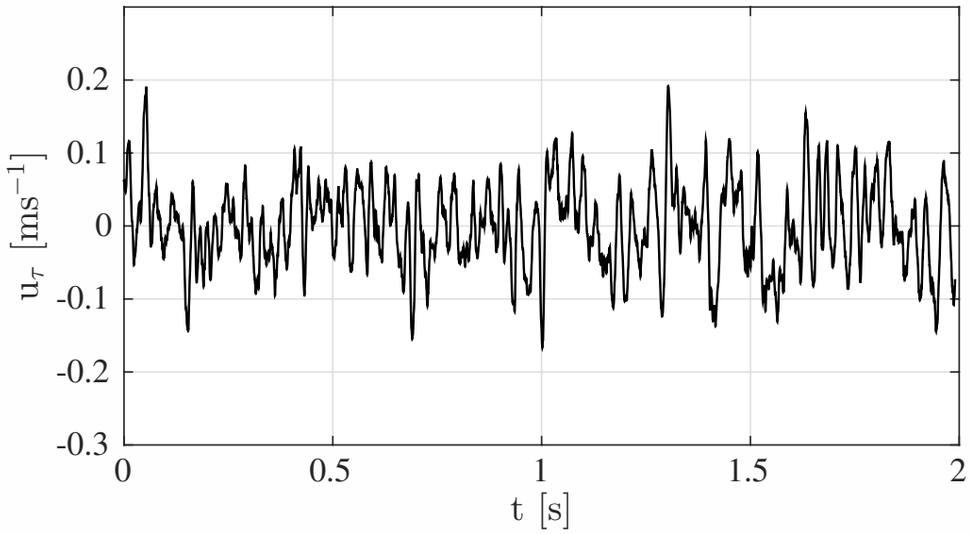

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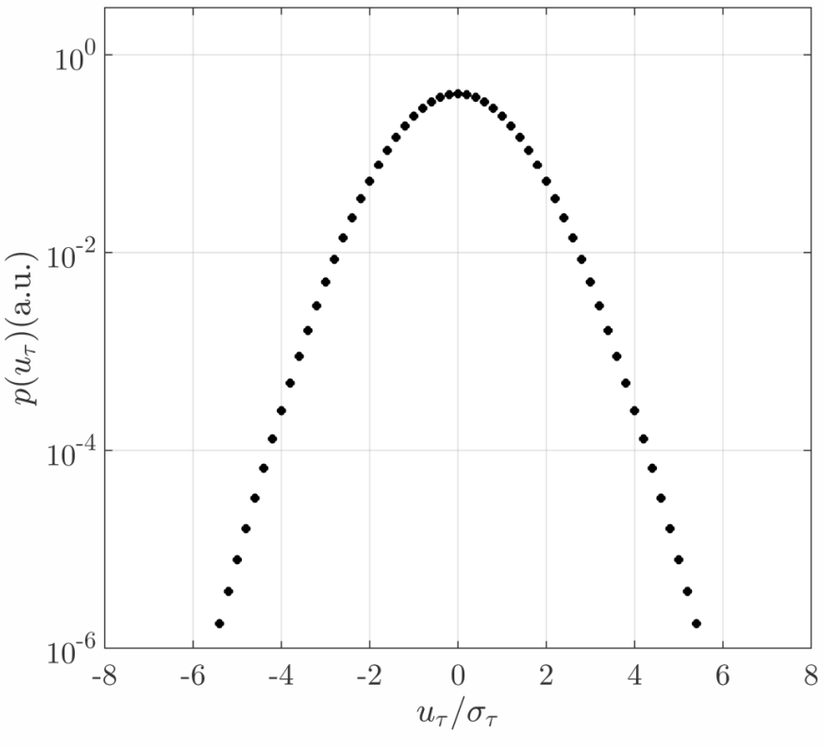

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Quantify incr. PDFs shape:

$$\lambda^2(\tau) = \frac{ln\left(F(u_\tau)/3\right)}{4}$$

[Chillà 1996]

with $$F(u_\tau) = \frac{\langle (u_\tau - \langle u_\tau \rangle)^4 \rangle}{\langle u_\tau^2 \rangle^2}$$

Two-point statistics

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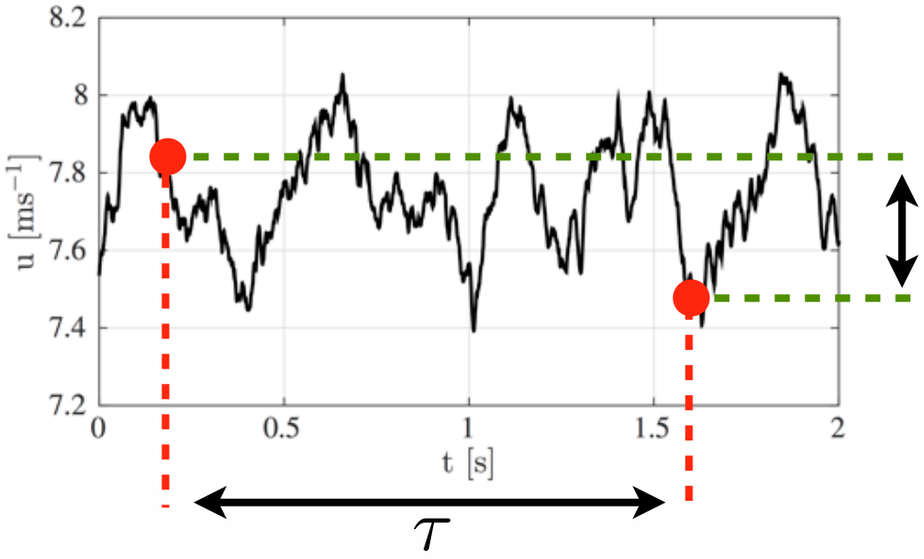

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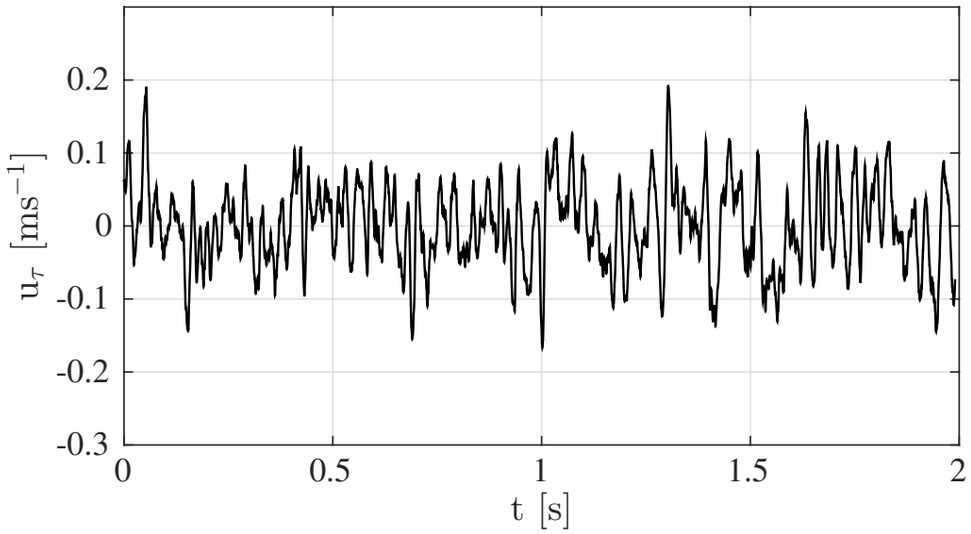

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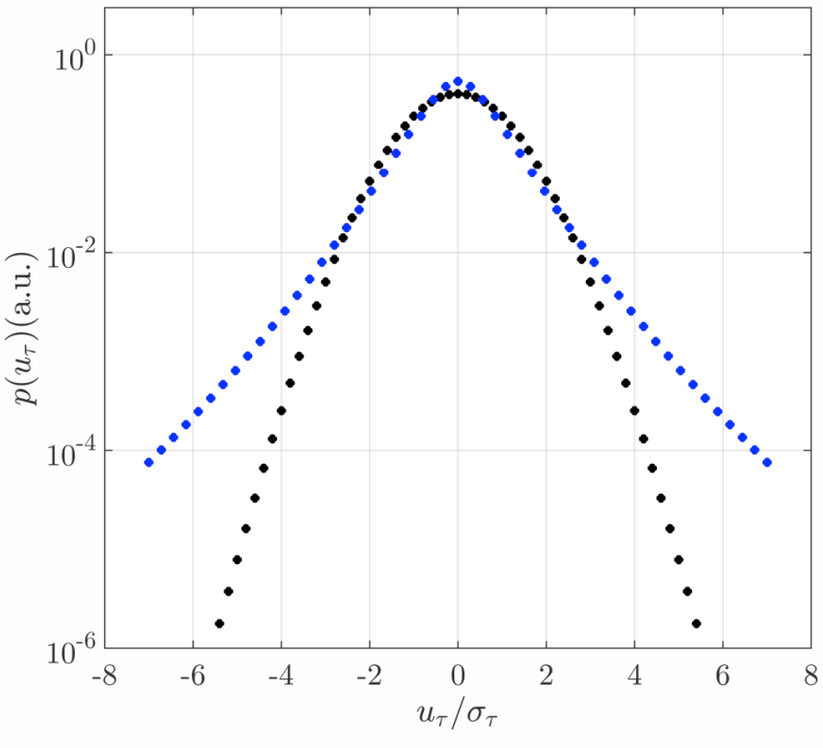

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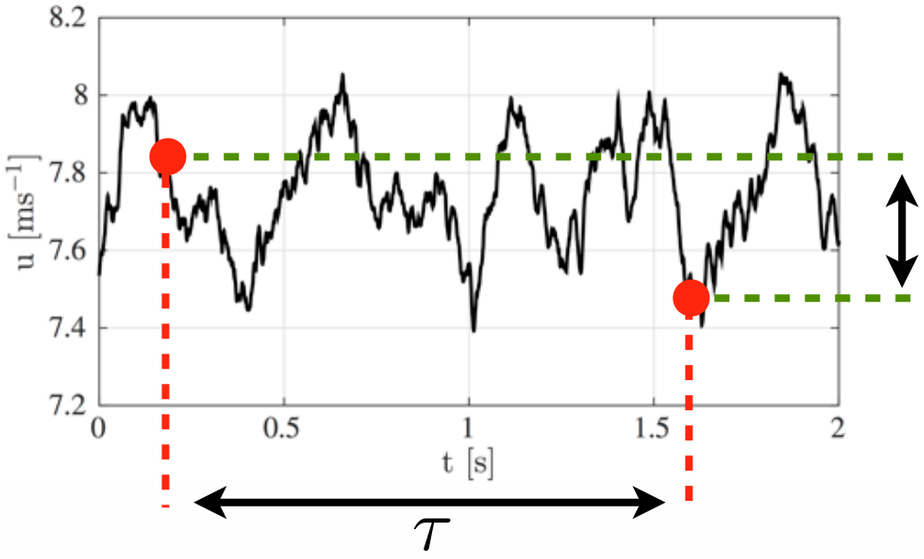

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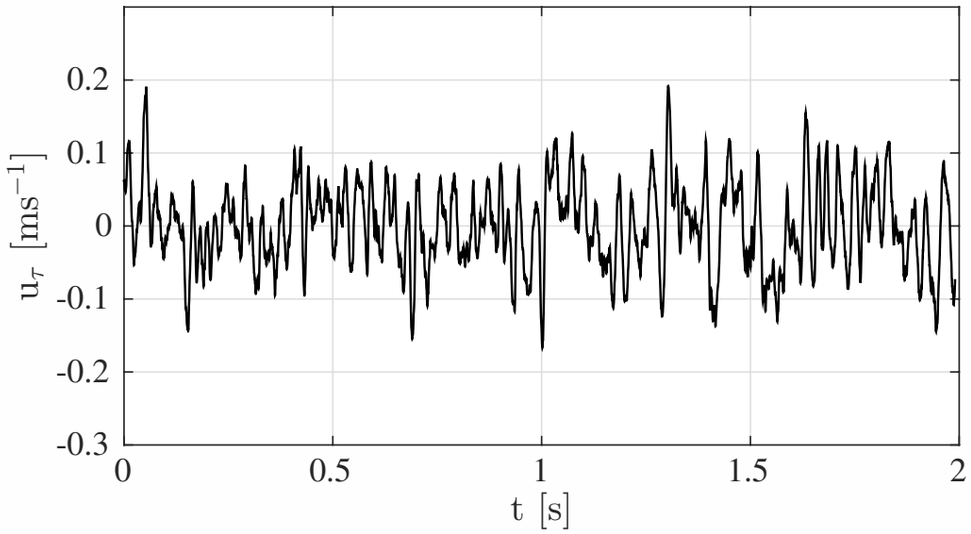

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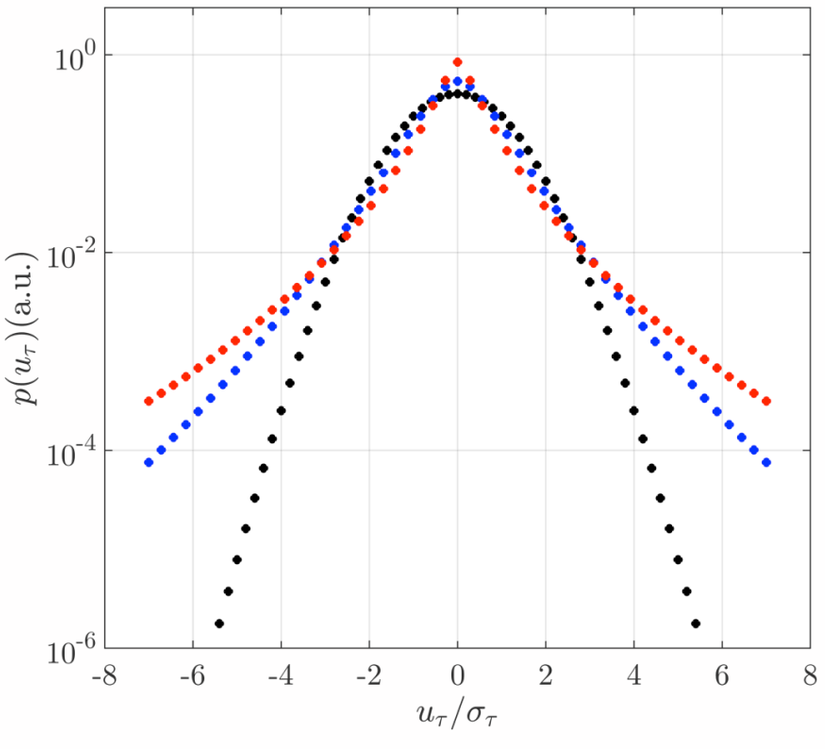

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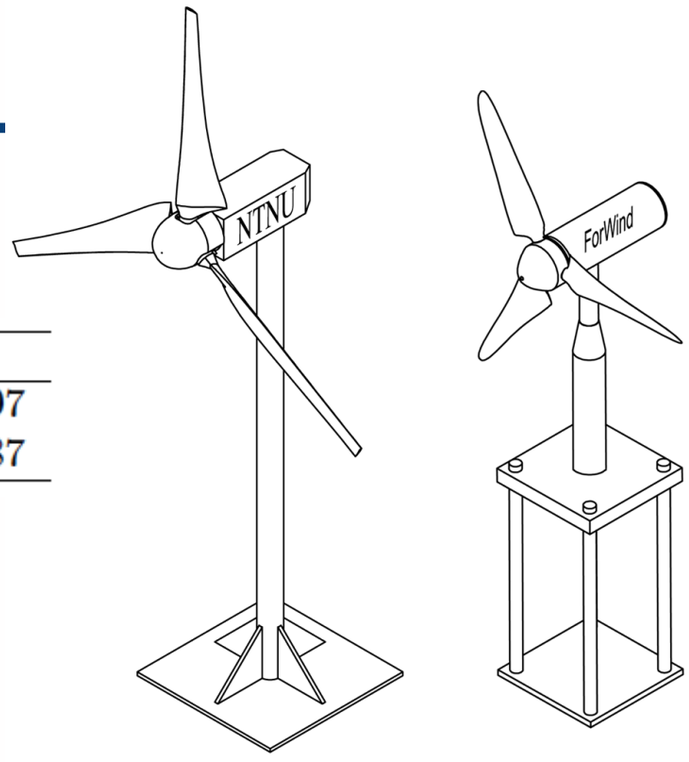
Setup & Overview

Turbine	Rotor diameter	Hub diameter	Blockage	TSR	Re_{tip}	Rotation	c_T
ForWind	0.580 m	0.077 m	5.4 %	6	$\approx 6.4 \times 10^4$	cw	0.97
NTNU	0.894 m	0.090 m	13 %	6	$\approx 1.1 \times 10^5$	ccw	0.87



Full plane, Laser Doppler Anemometer measurements

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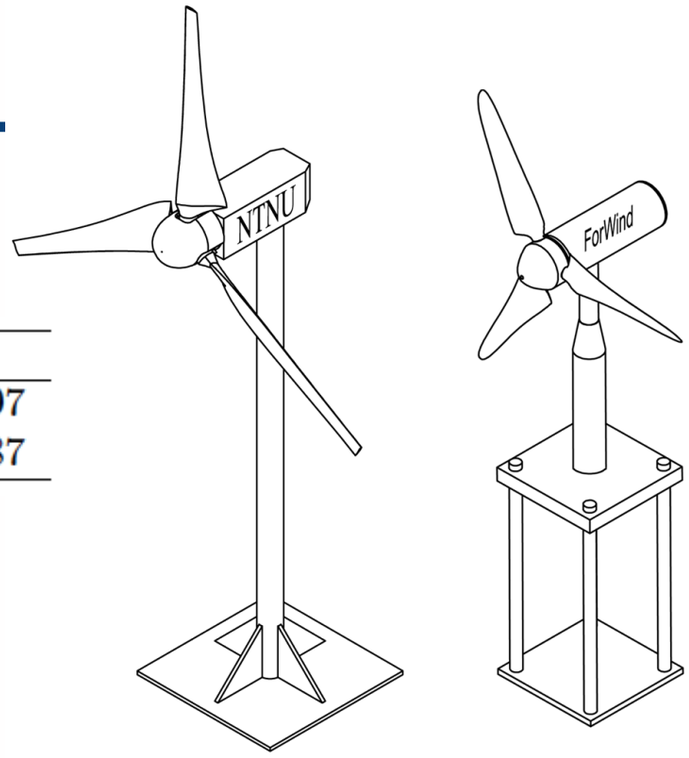

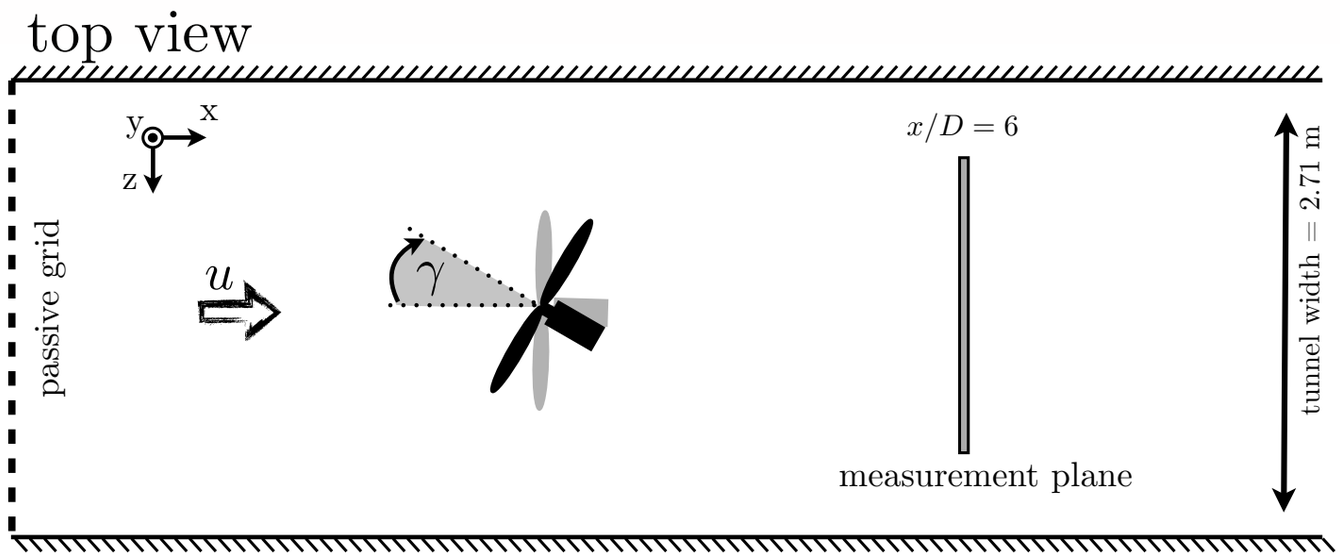

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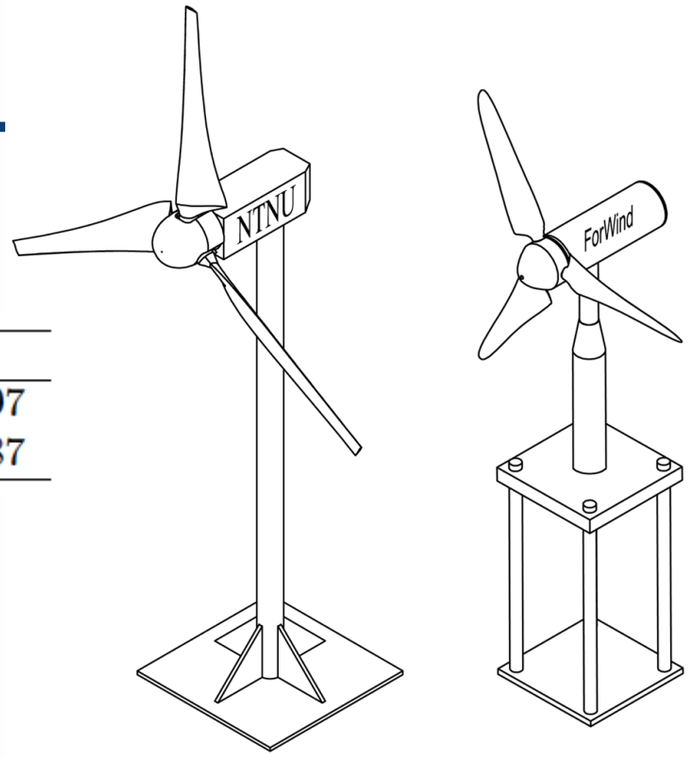

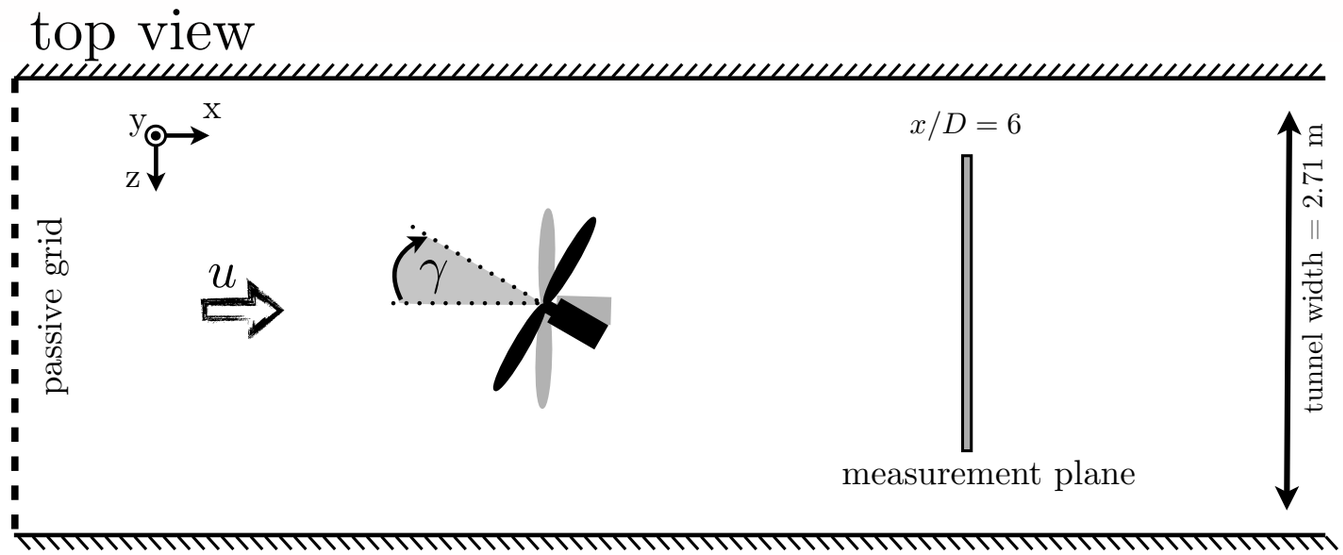

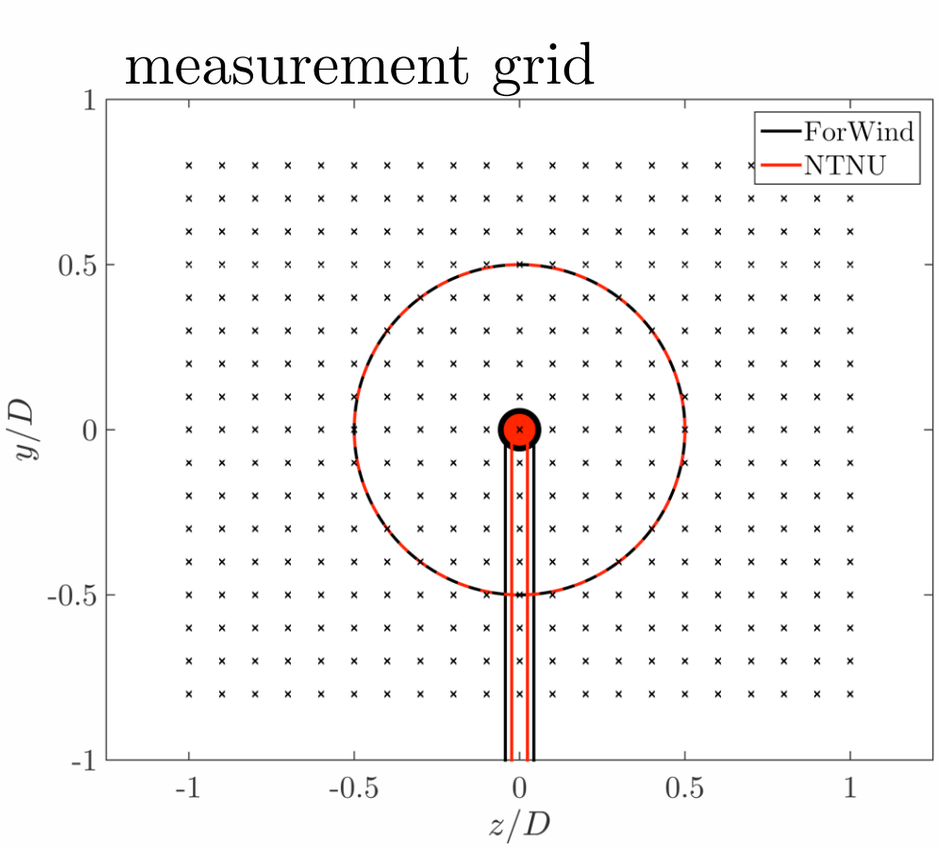

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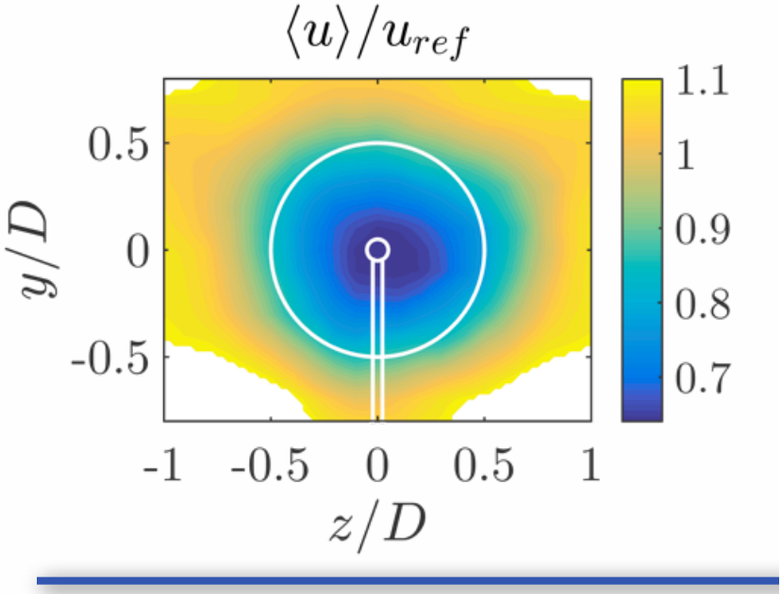
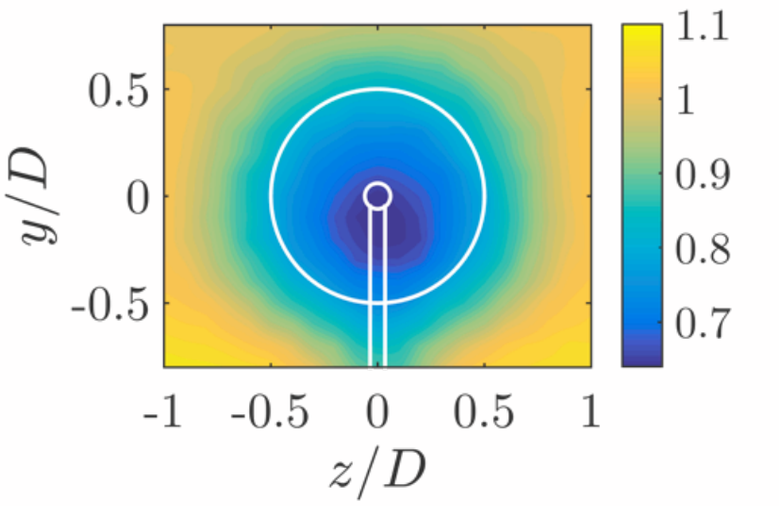
The non-yawed wakes





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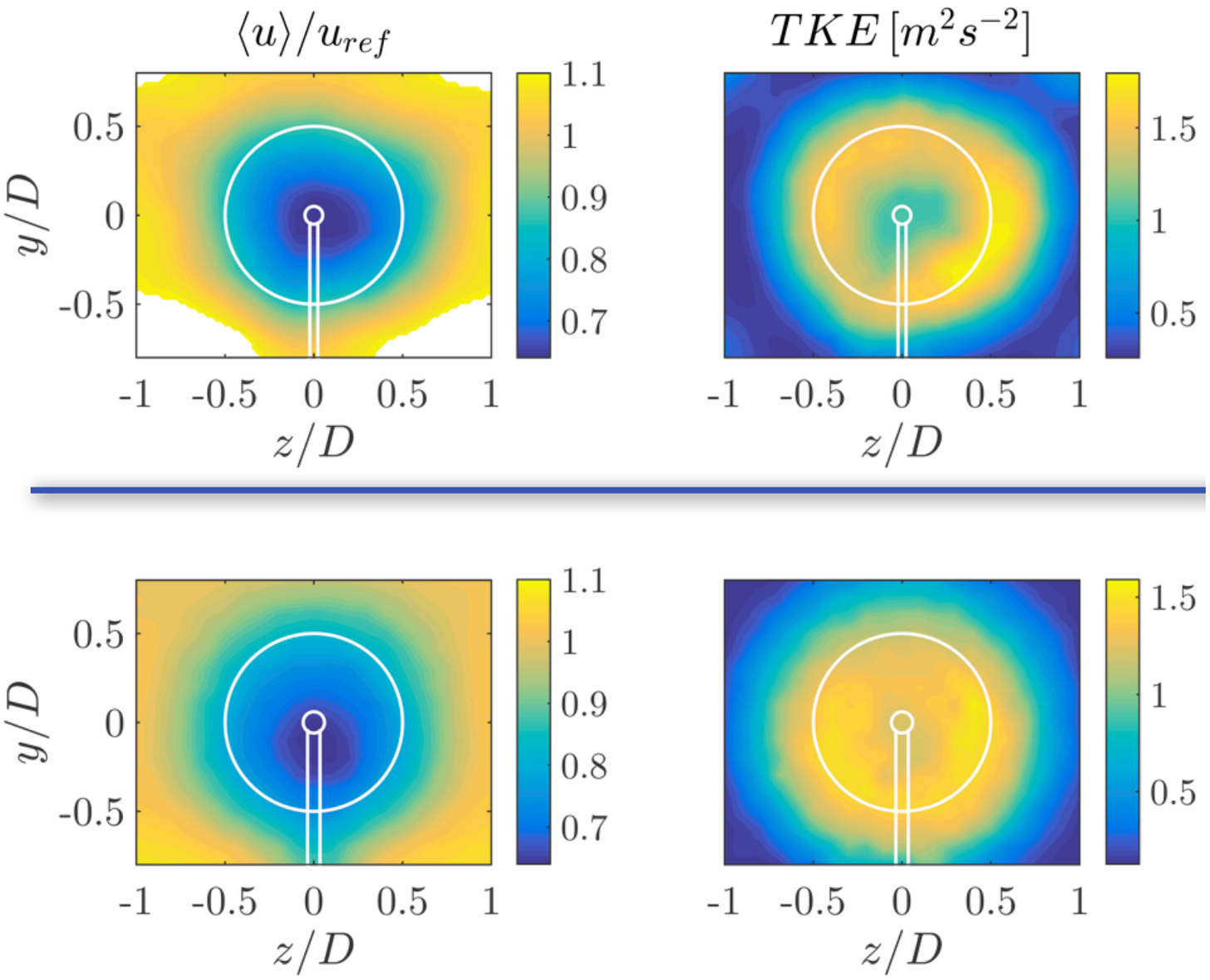

NTNU

ForWind
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Bremen
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Oldenburg

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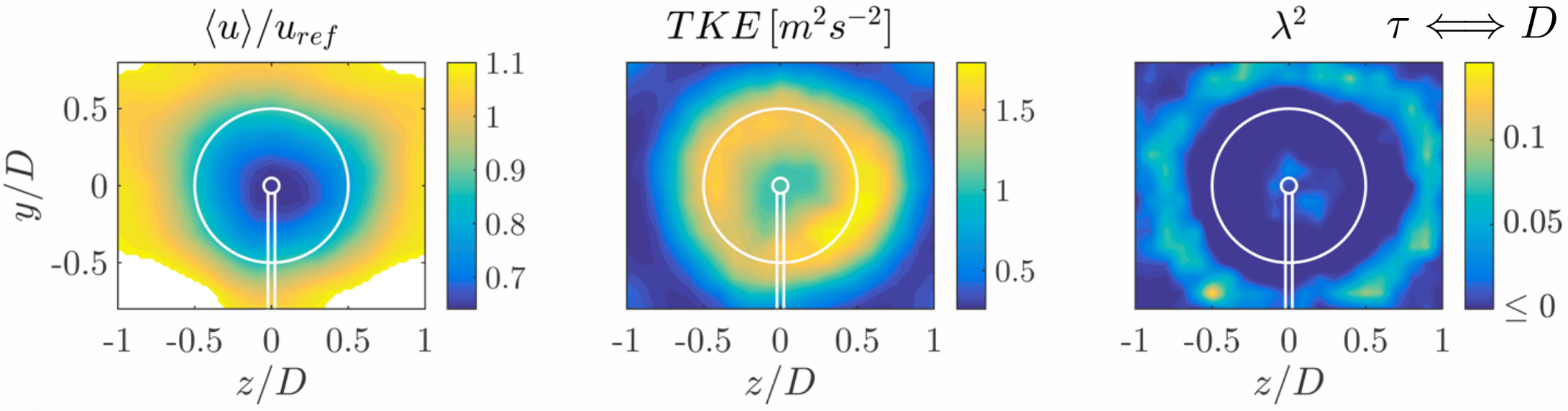
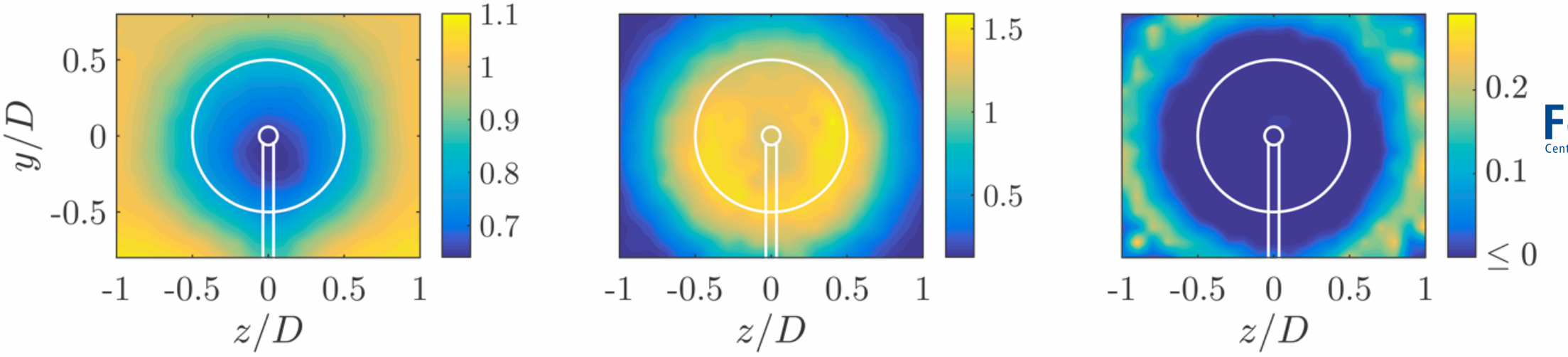
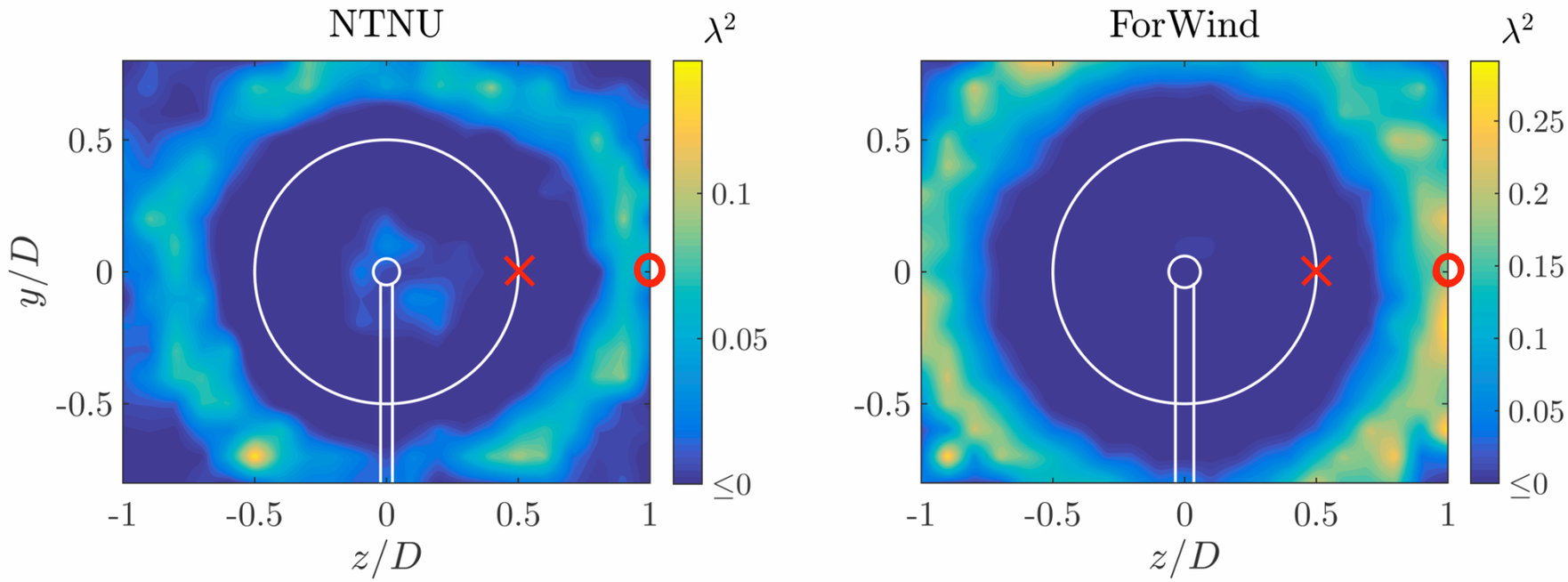




Shape parameter $\lambda^2(\tau)$

qualitative



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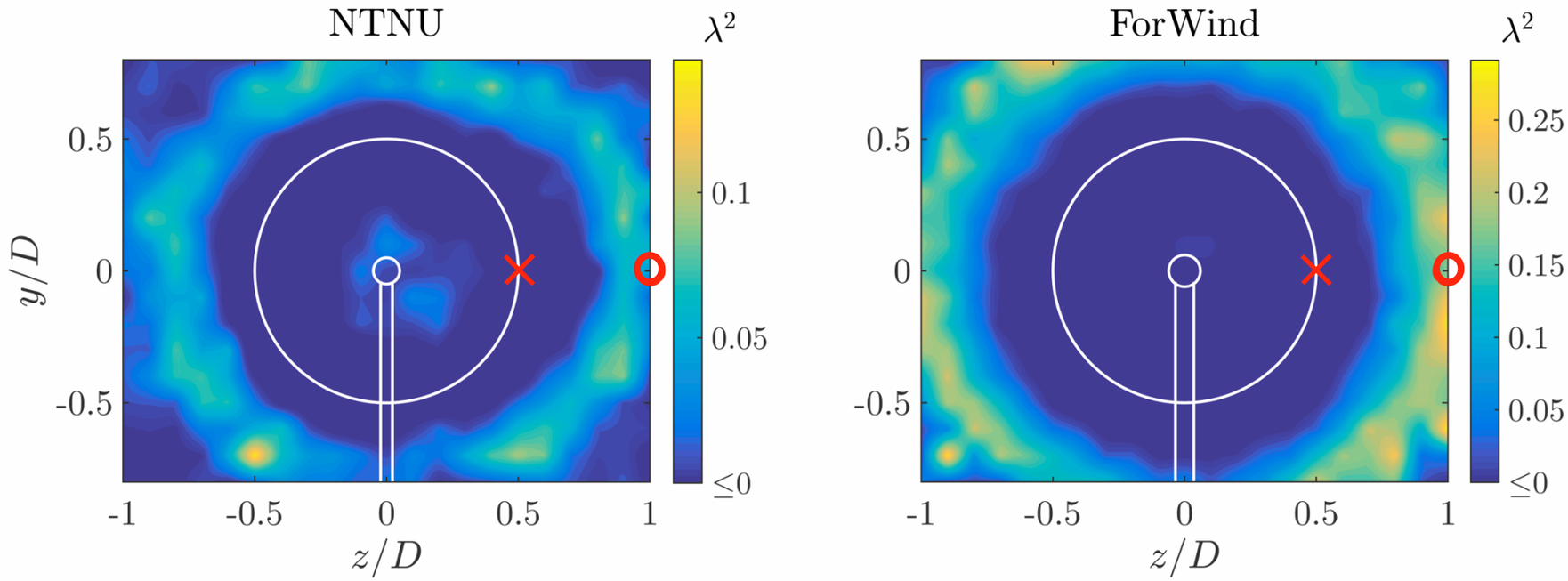

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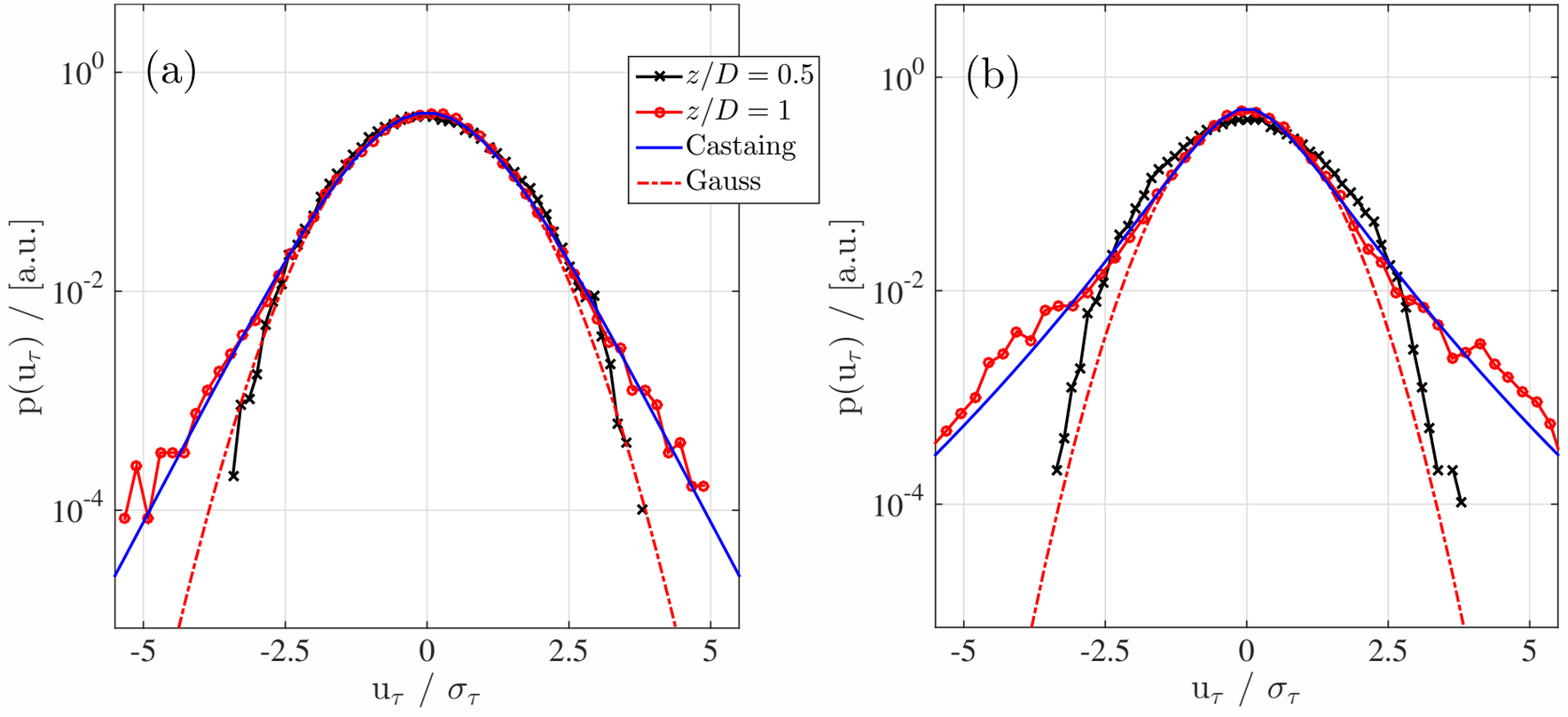

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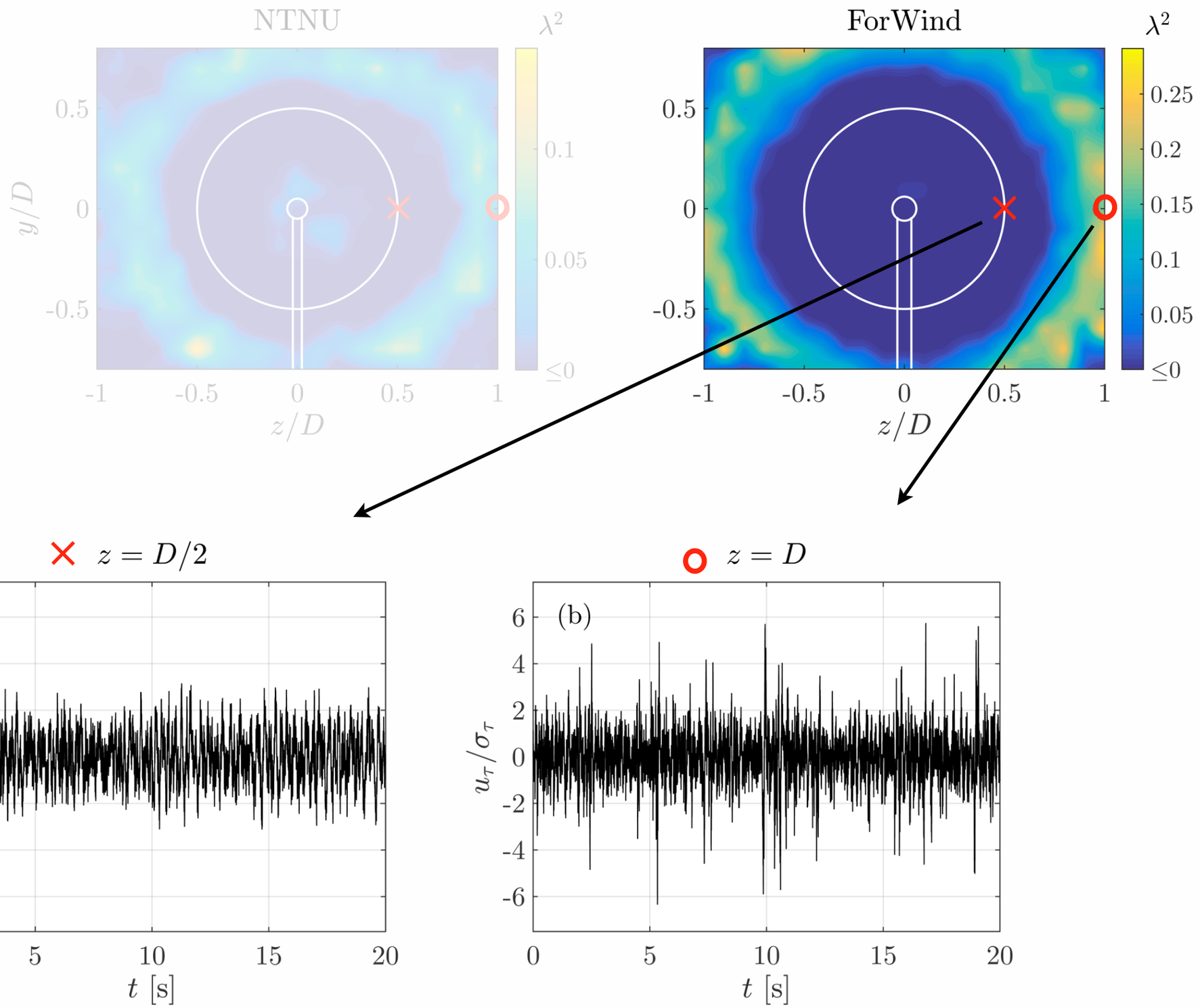
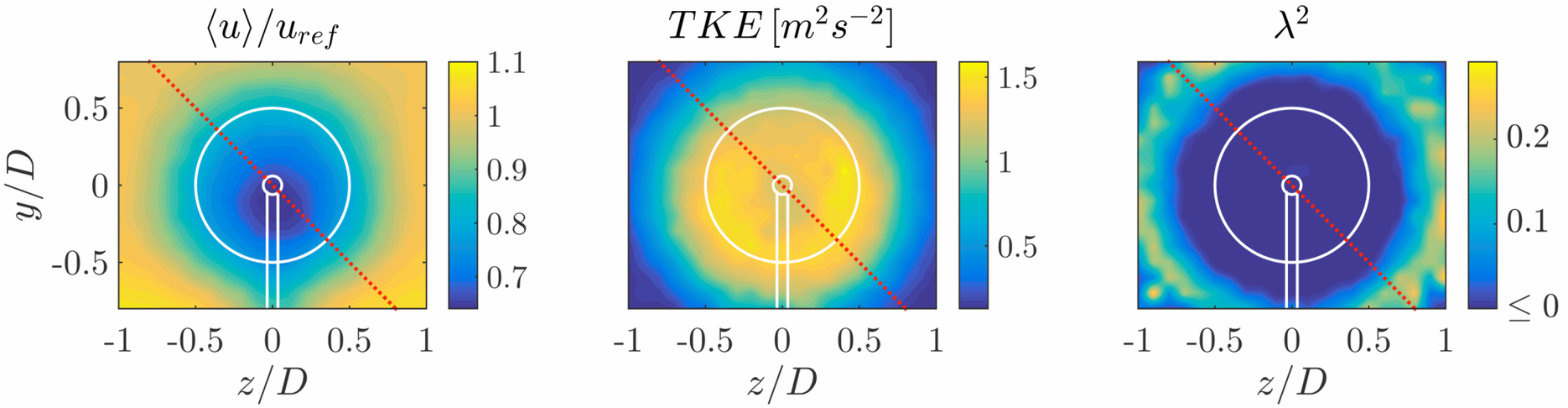


Radial wake areas



Different radial areas of interest !

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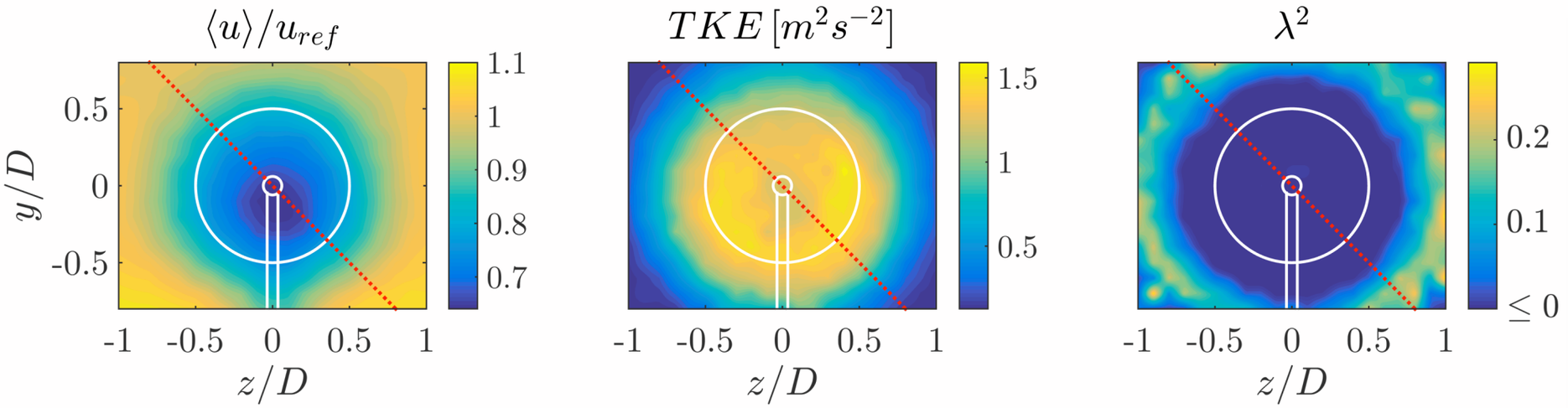

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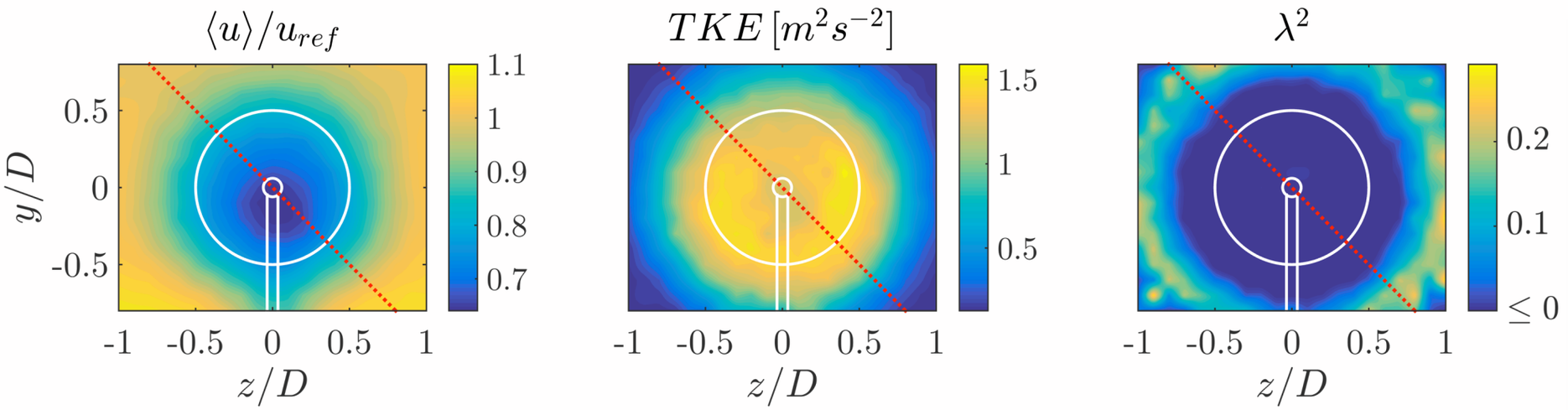

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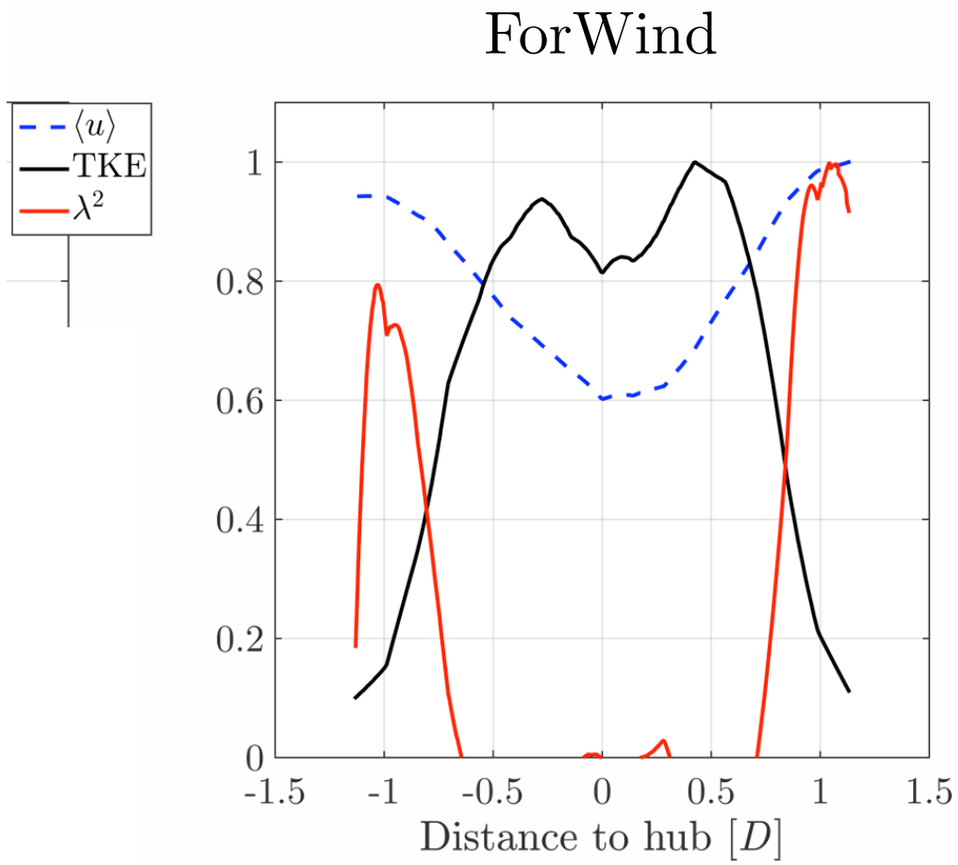

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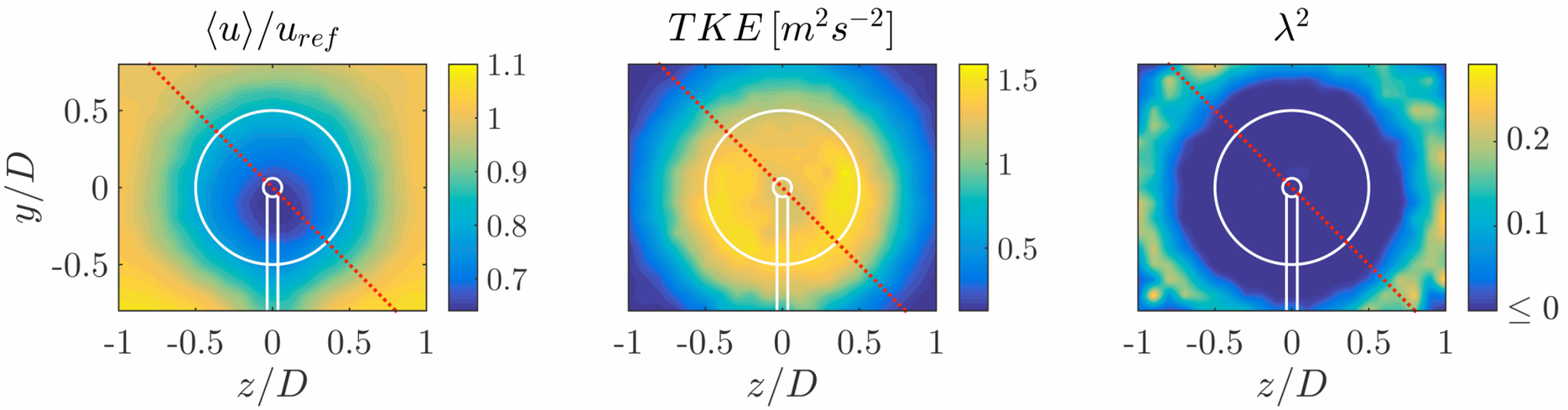

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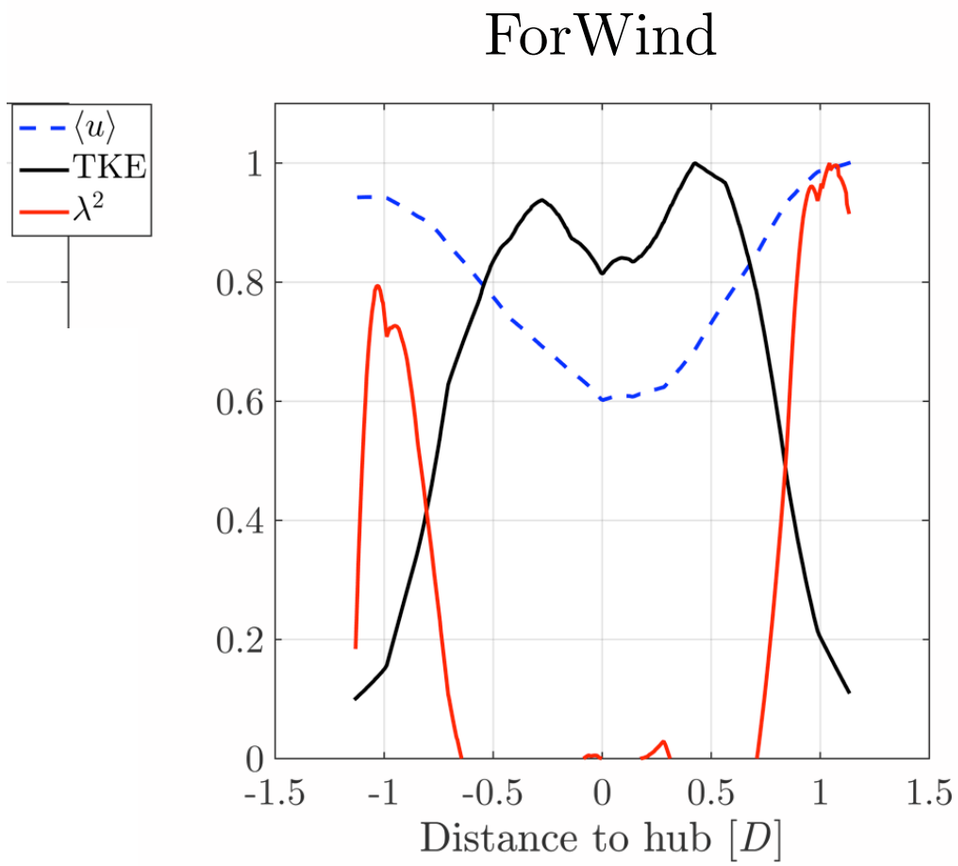

Areas of heavy-tailed increment PDFs (high λ^2) where <u> already recovered!

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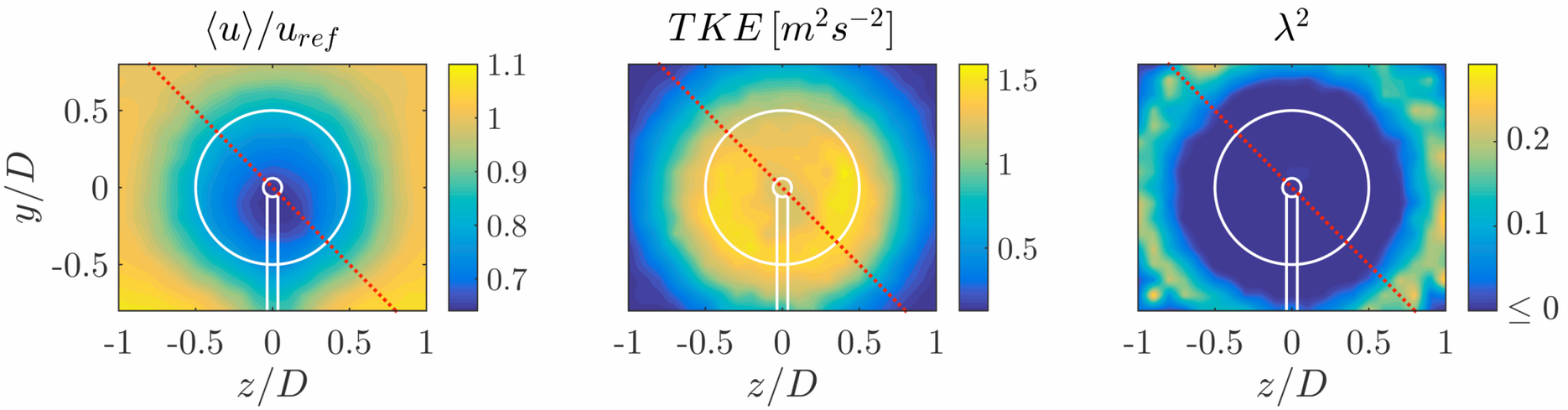

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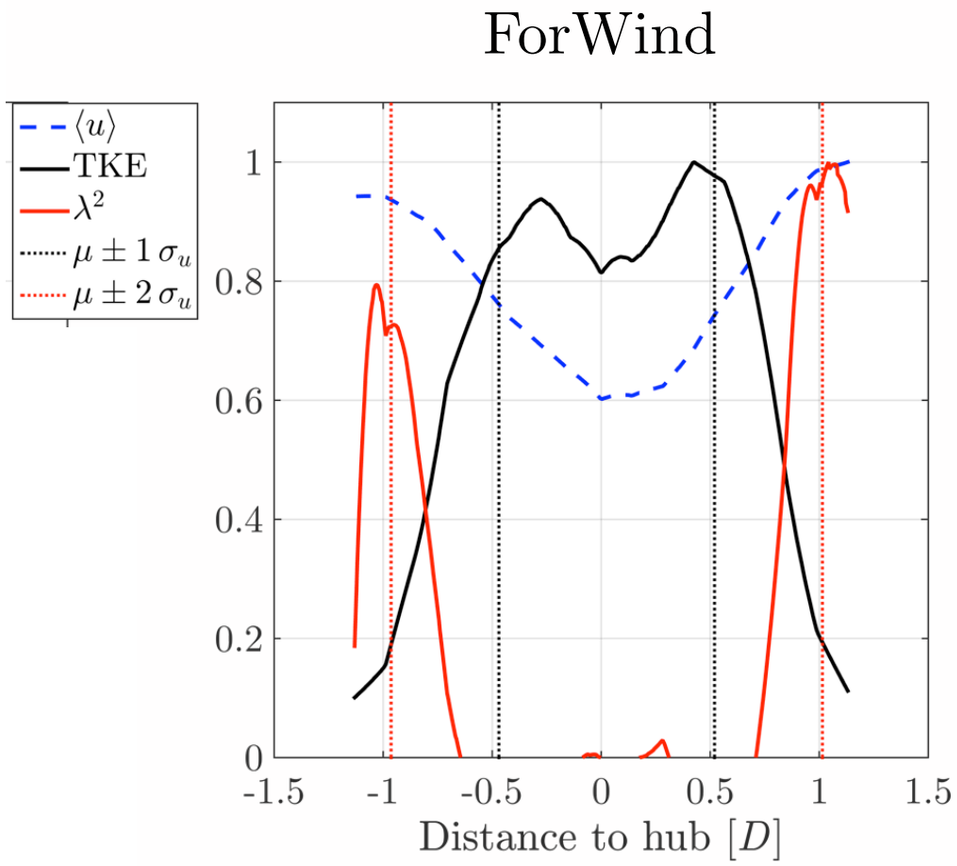

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Approximation of high λ^2 values by $\mu \pm 2\sigma_u$

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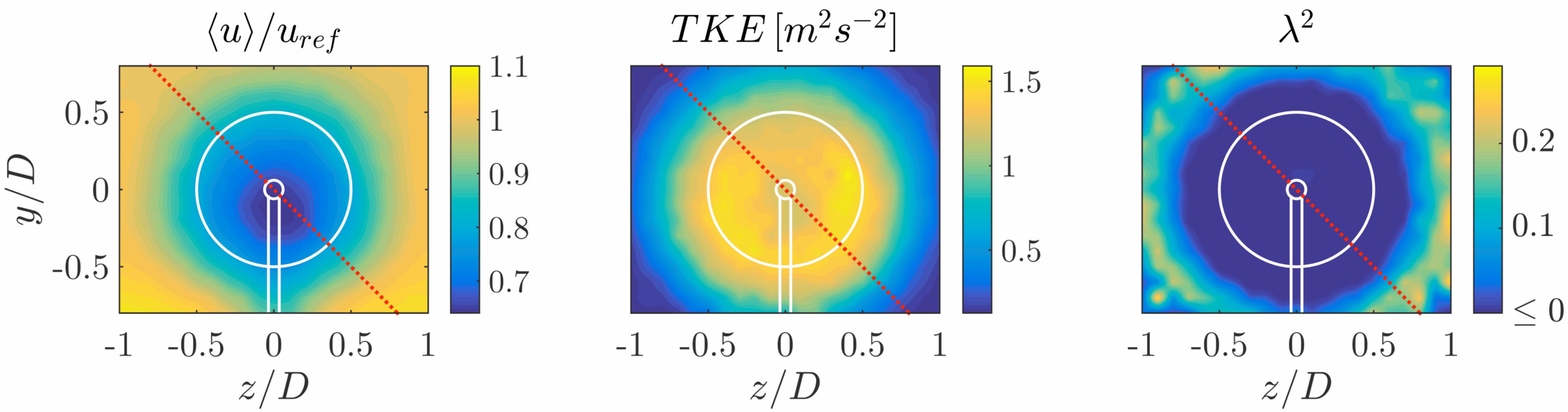

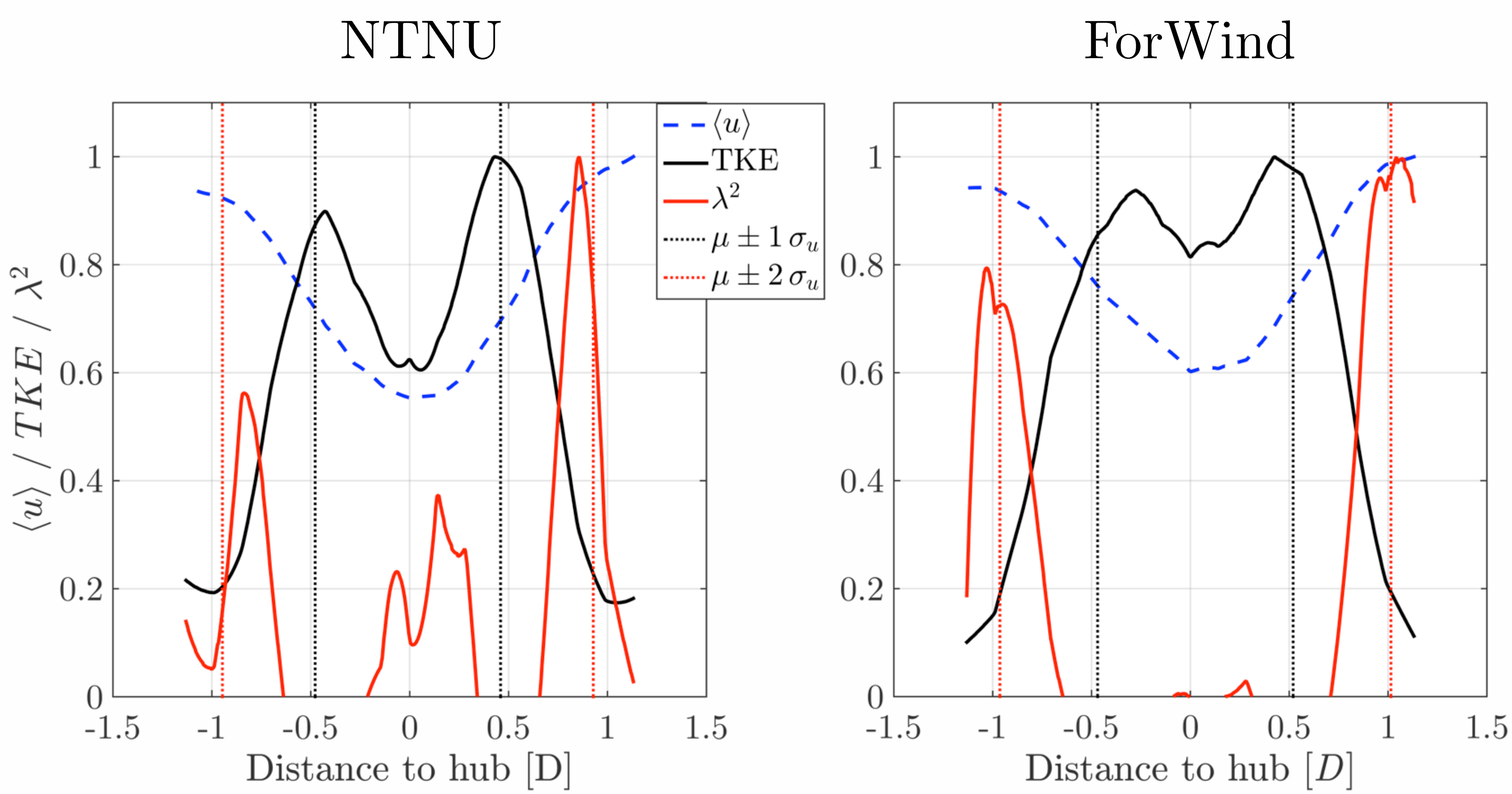

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Areas of heavy-tailed increment PDFs (high λ^2) where <u> already recovered!

Approximation of high λ^2 values by $\mu \pm 2\sigma_u$

So far:

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- circular wake shape
- intermittent flow regions surrounding the velocity deficit
- increased wake width
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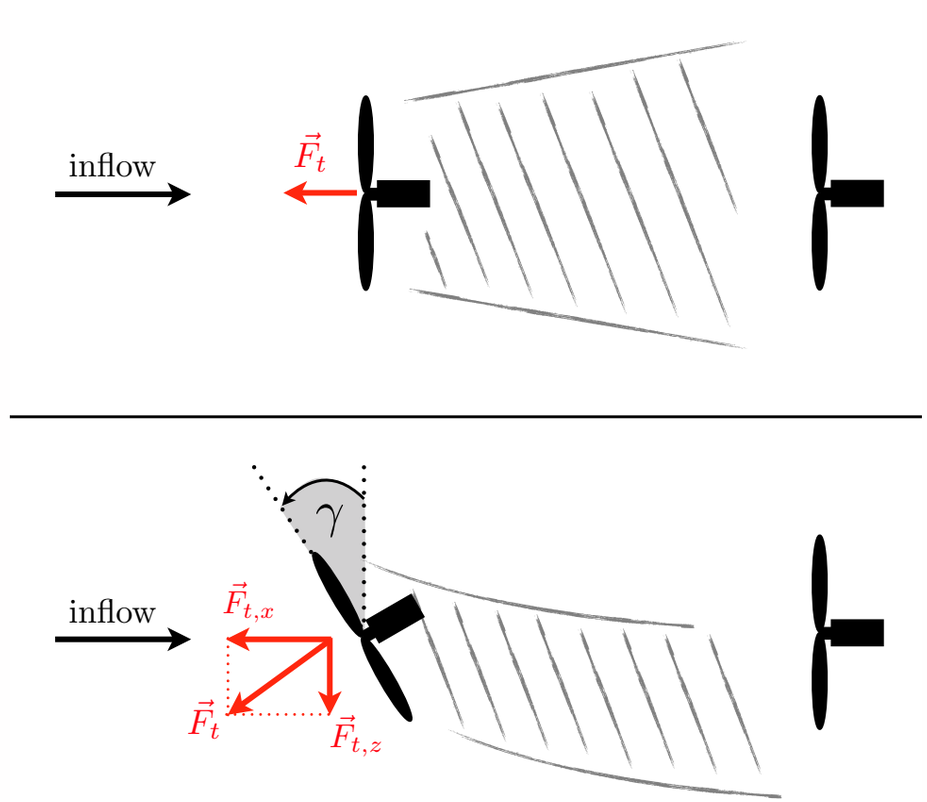
yaw misalignment:

$$\gamma = \pm 30°$$



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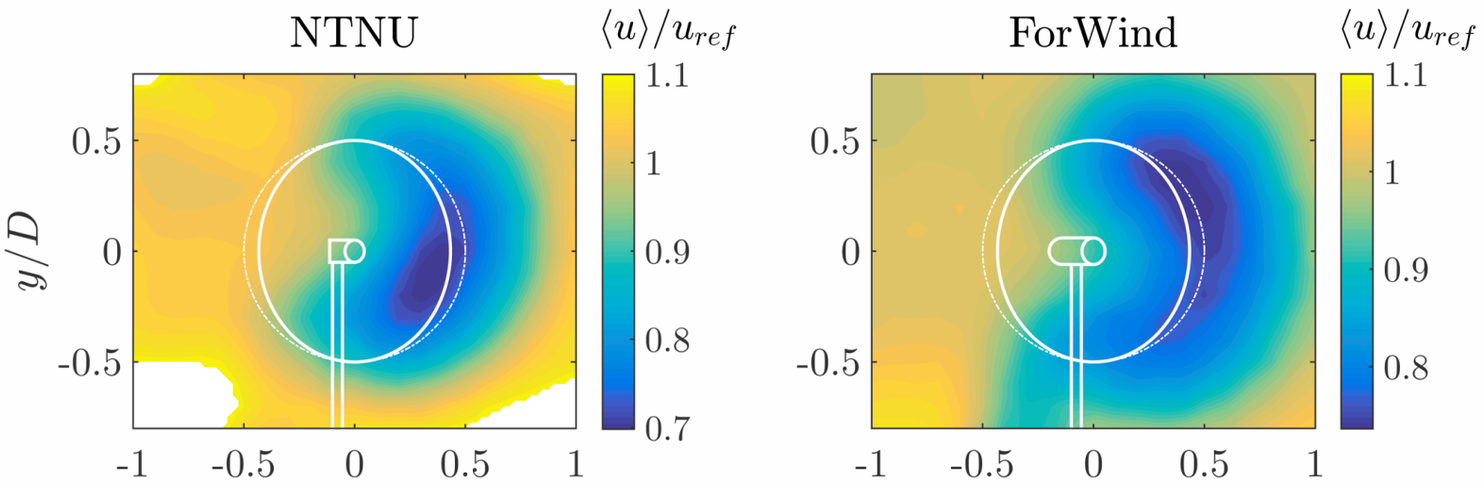
Yaw misalignment y/D



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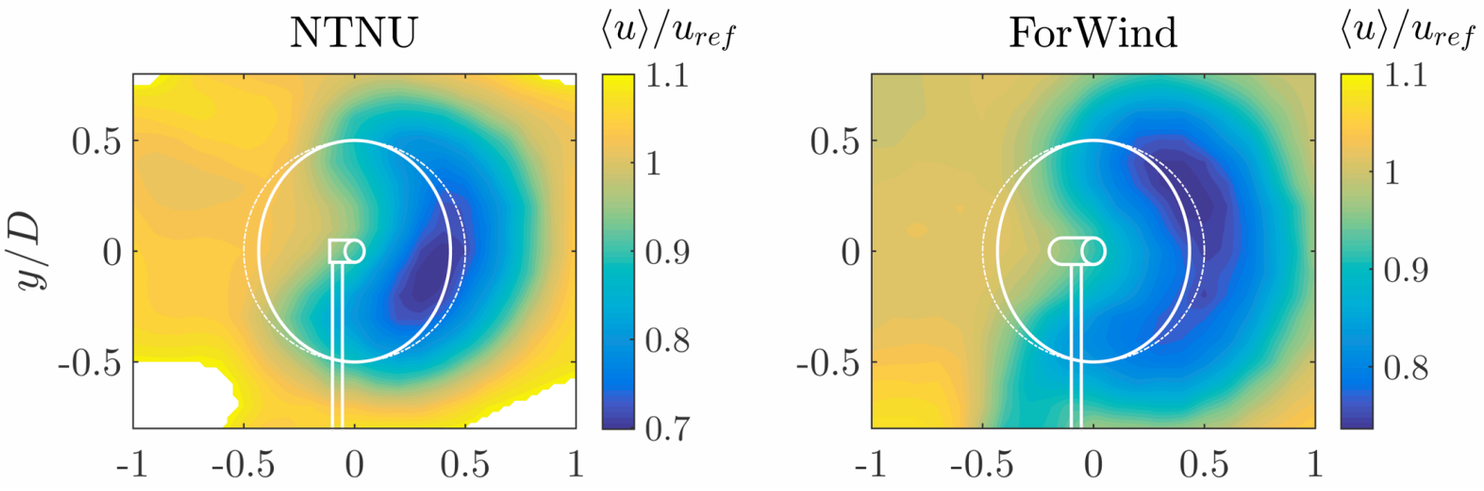

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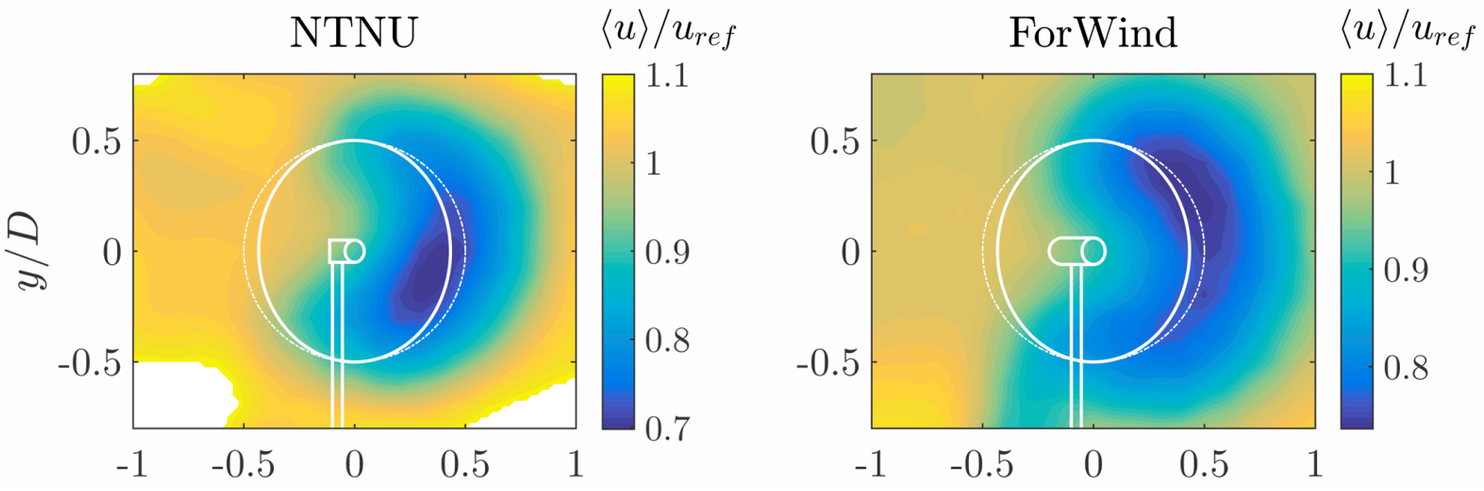

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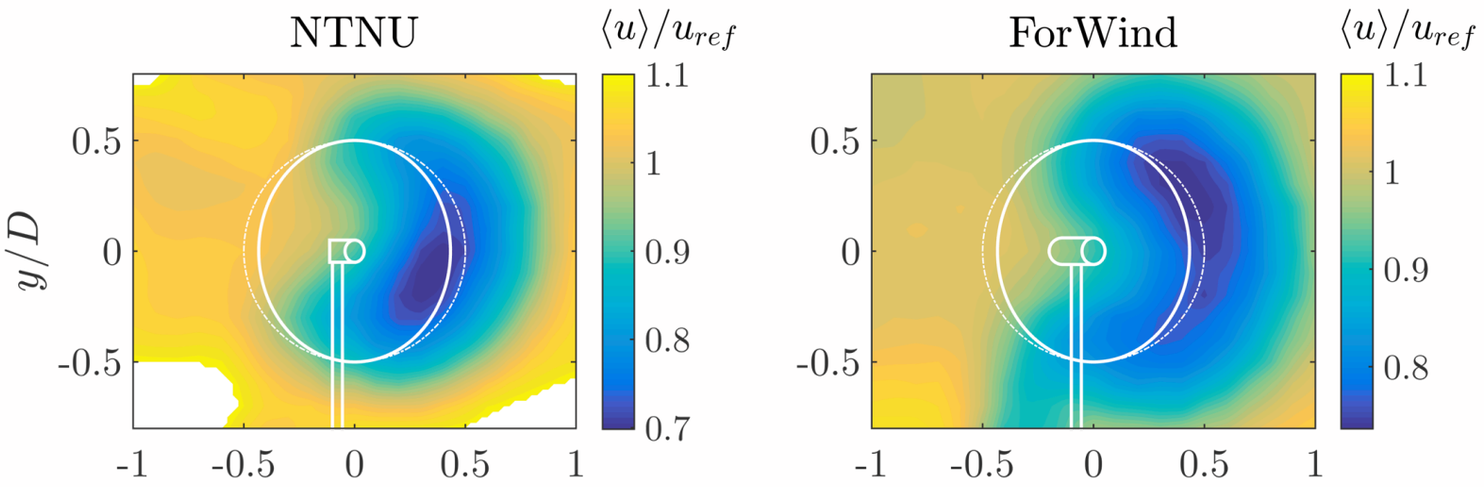

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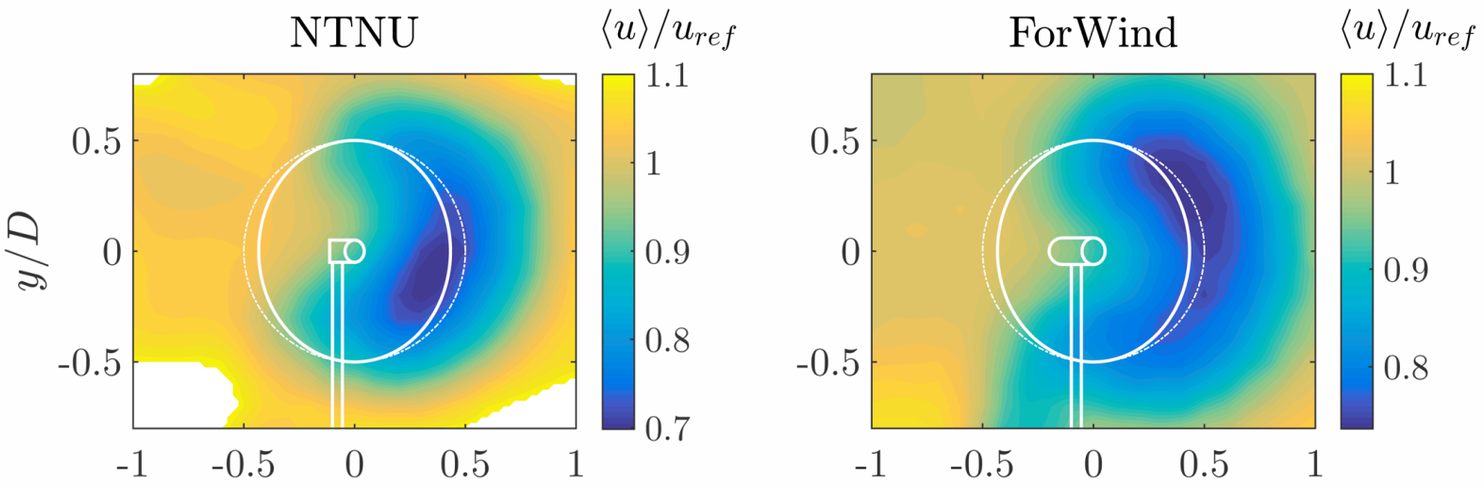

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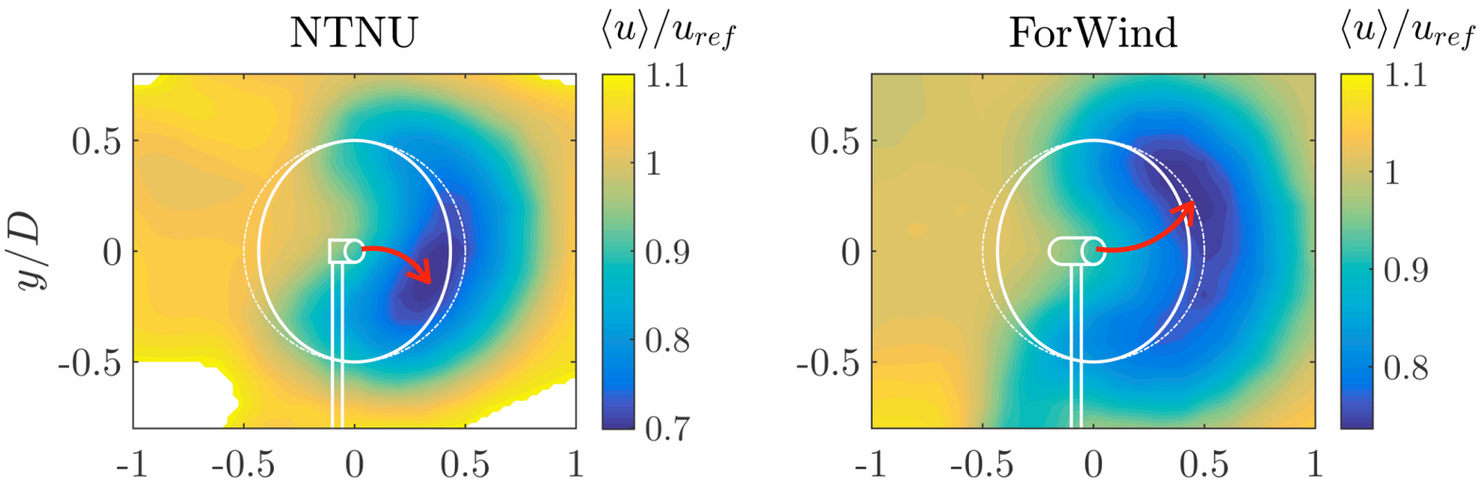

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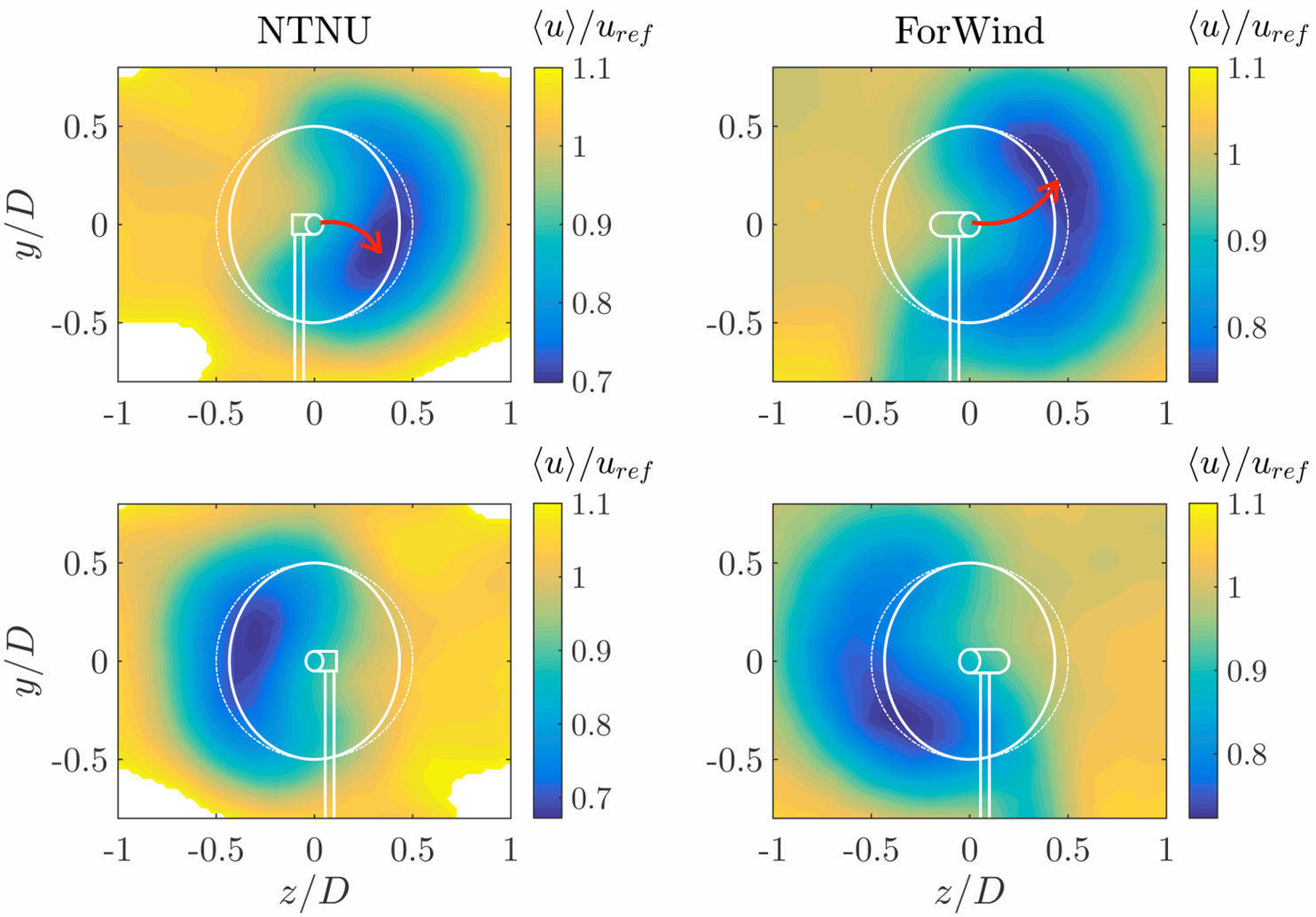

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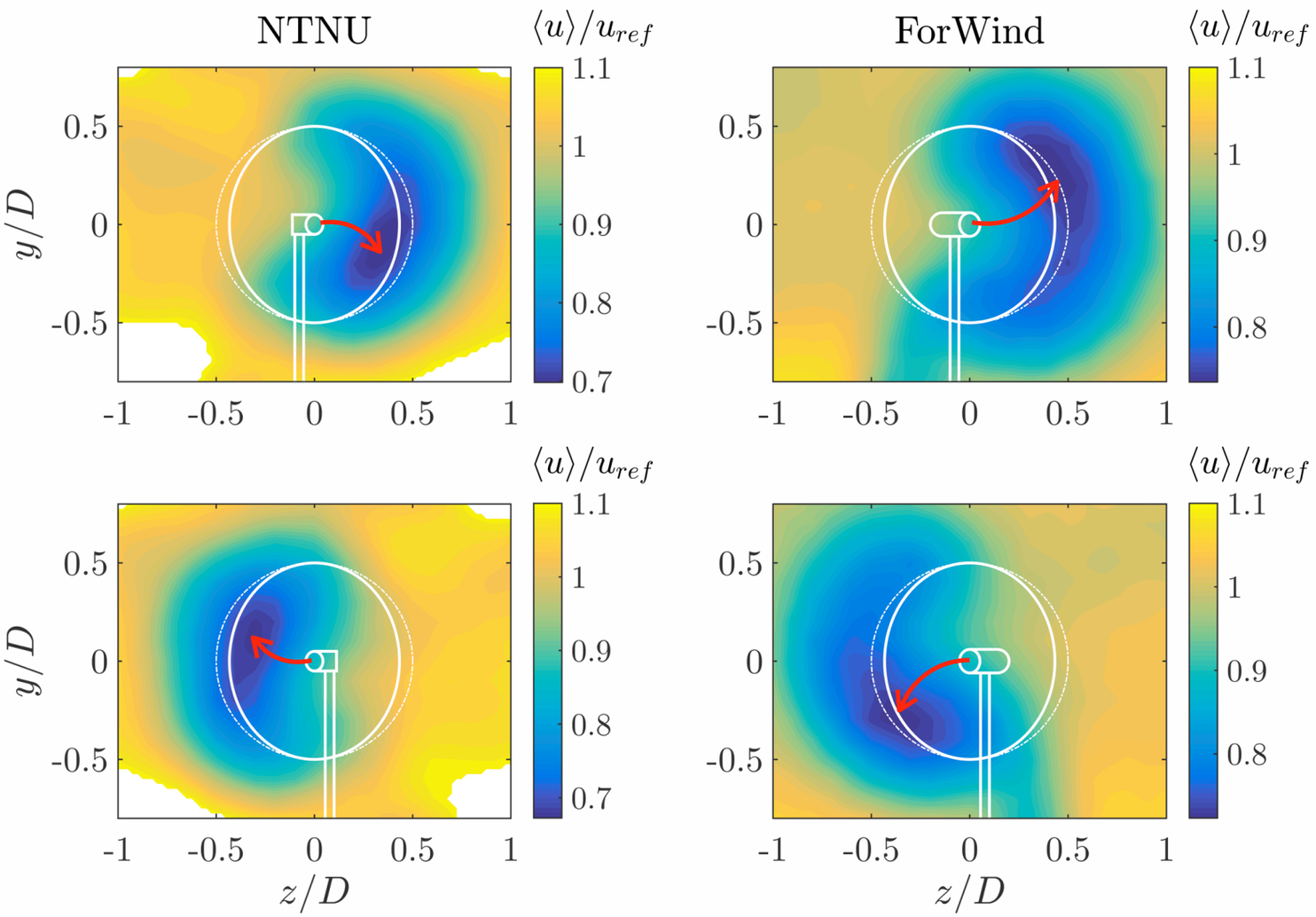

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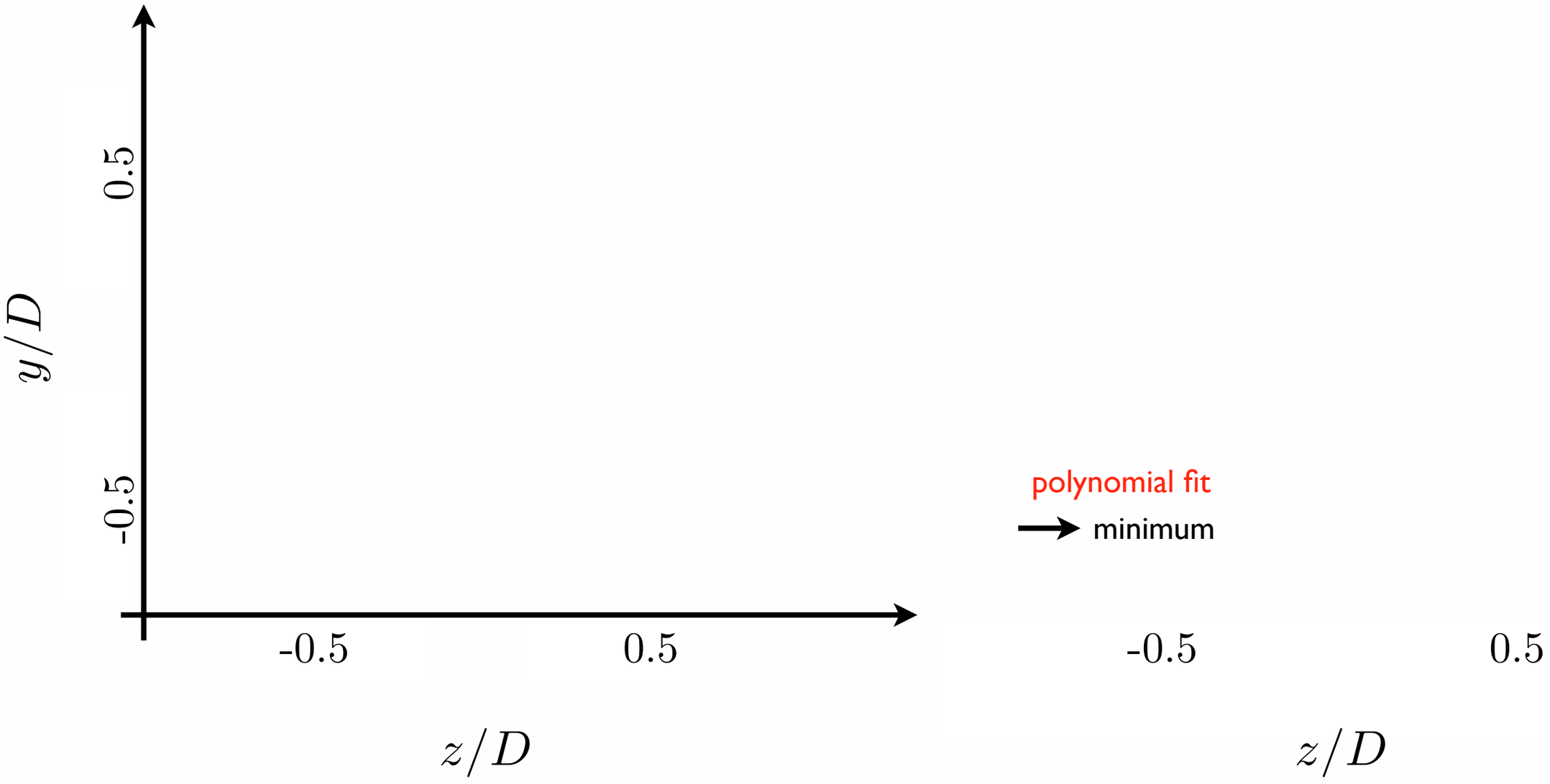
Curled Wake in yaw - towards quantification



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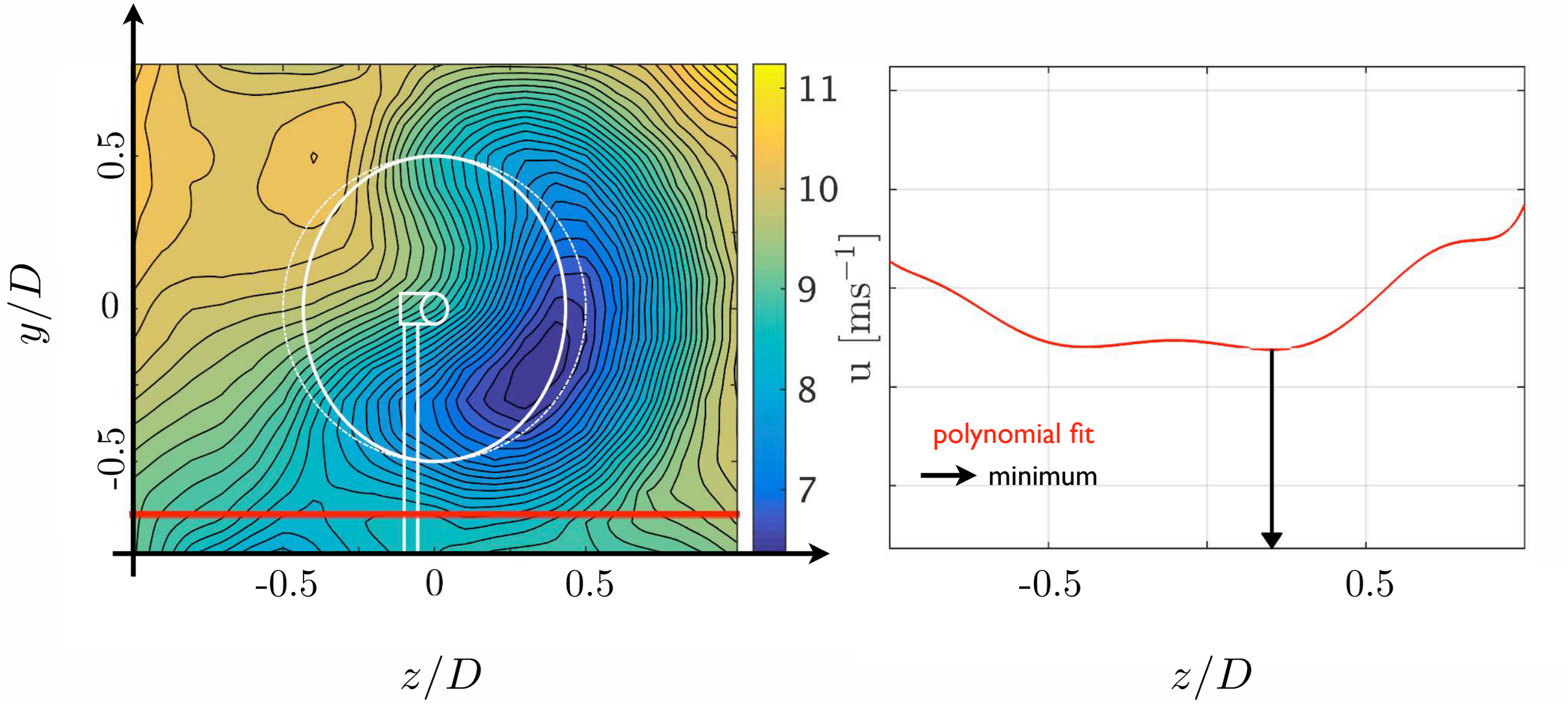

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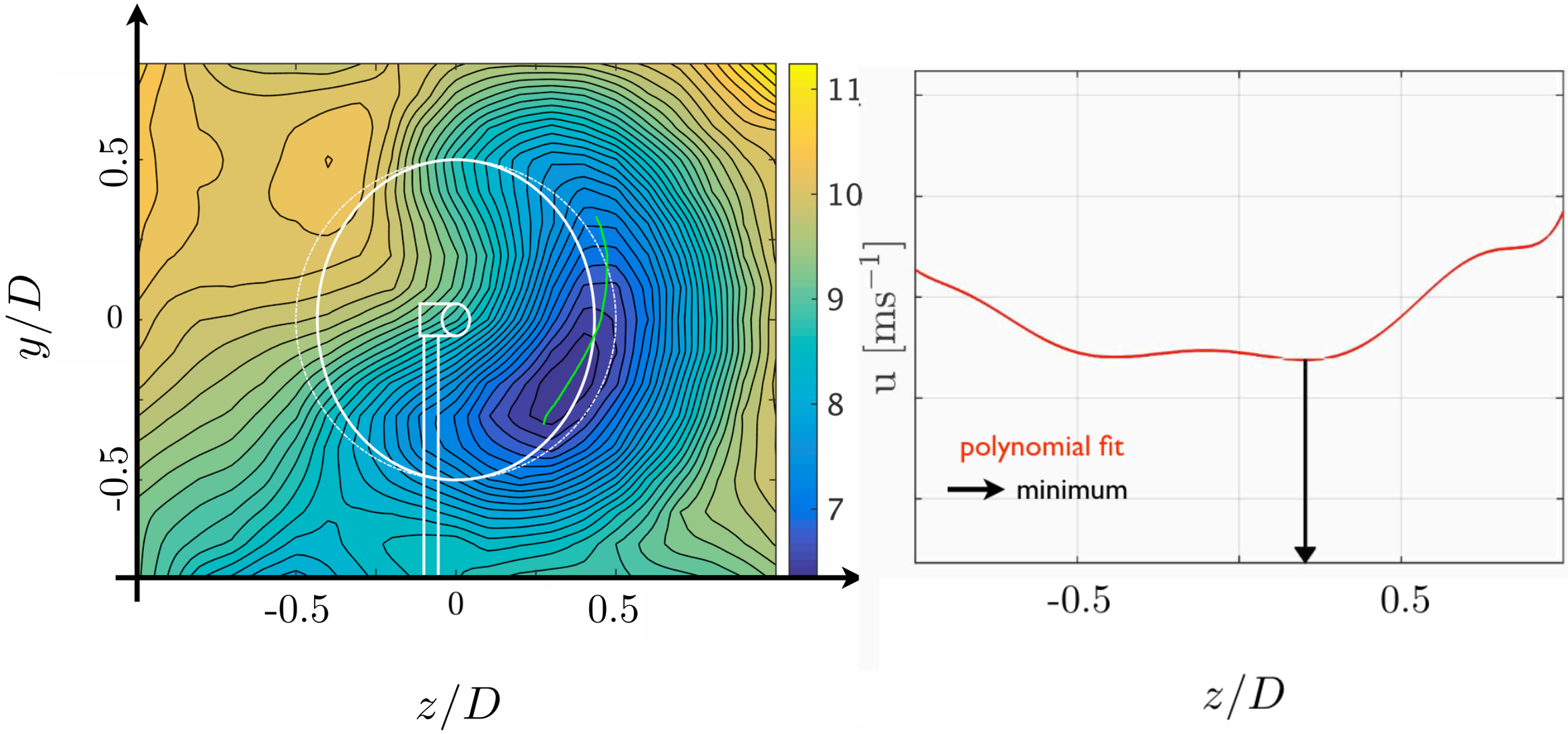

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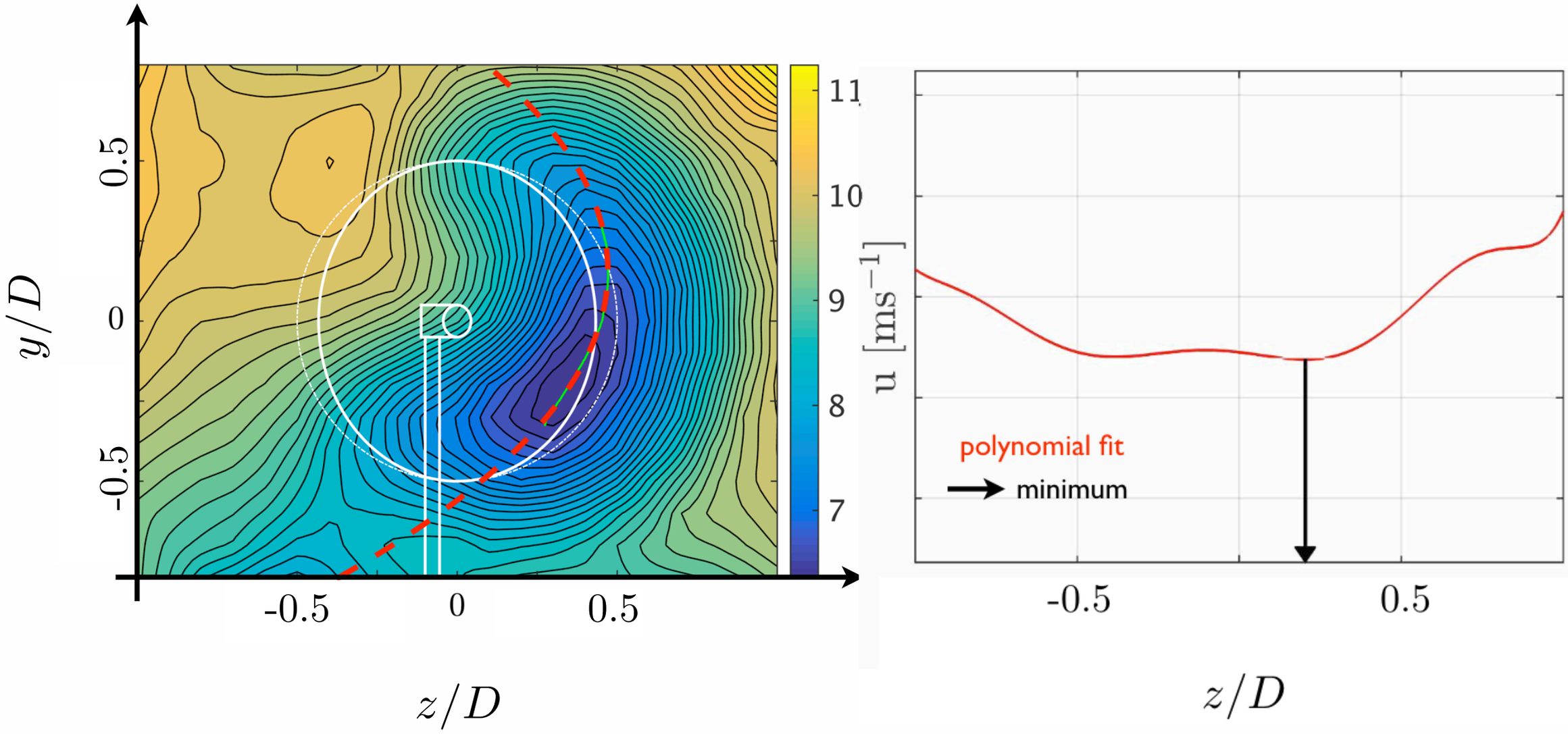

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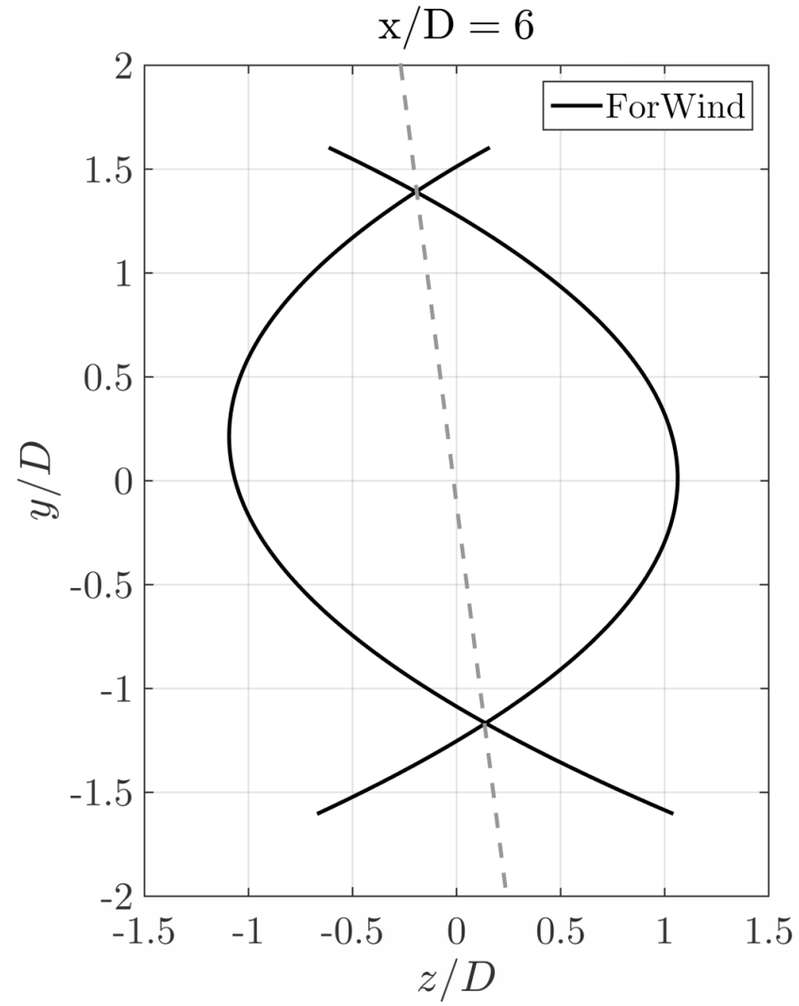

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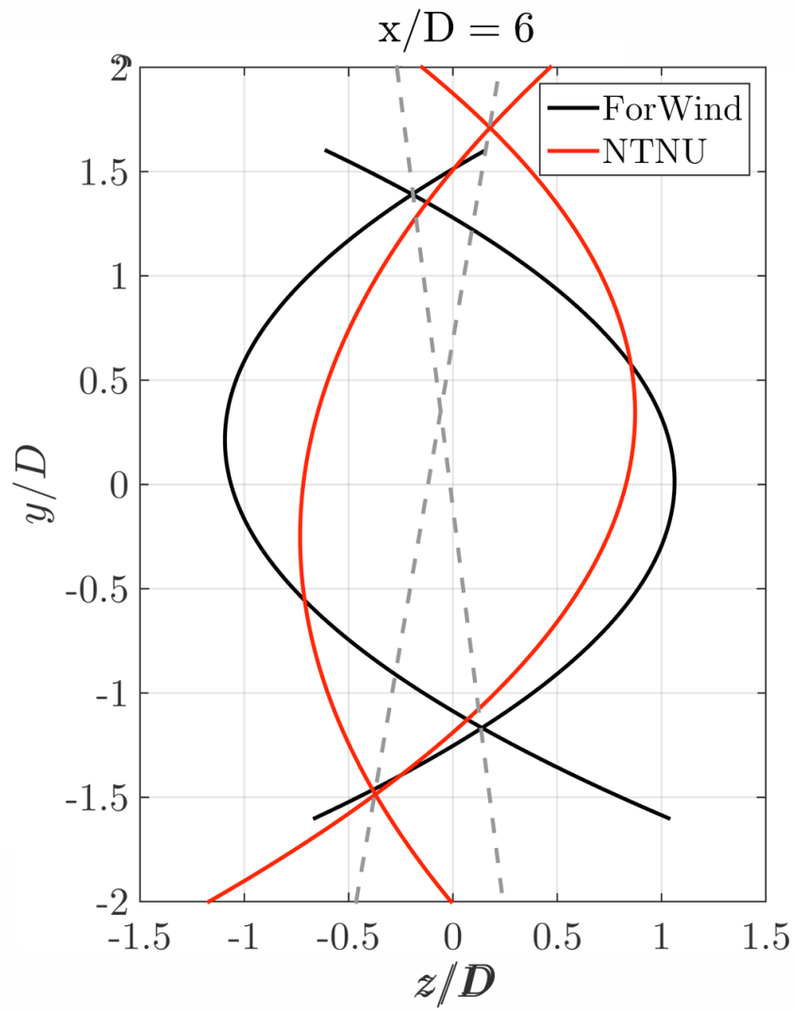

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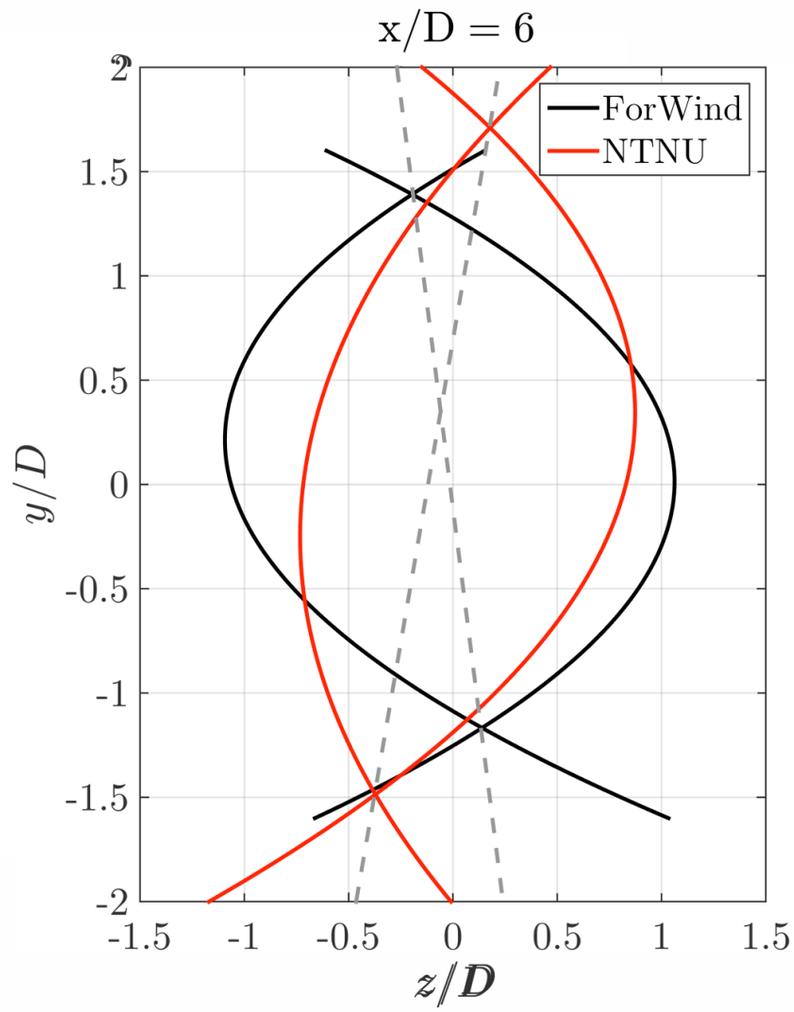

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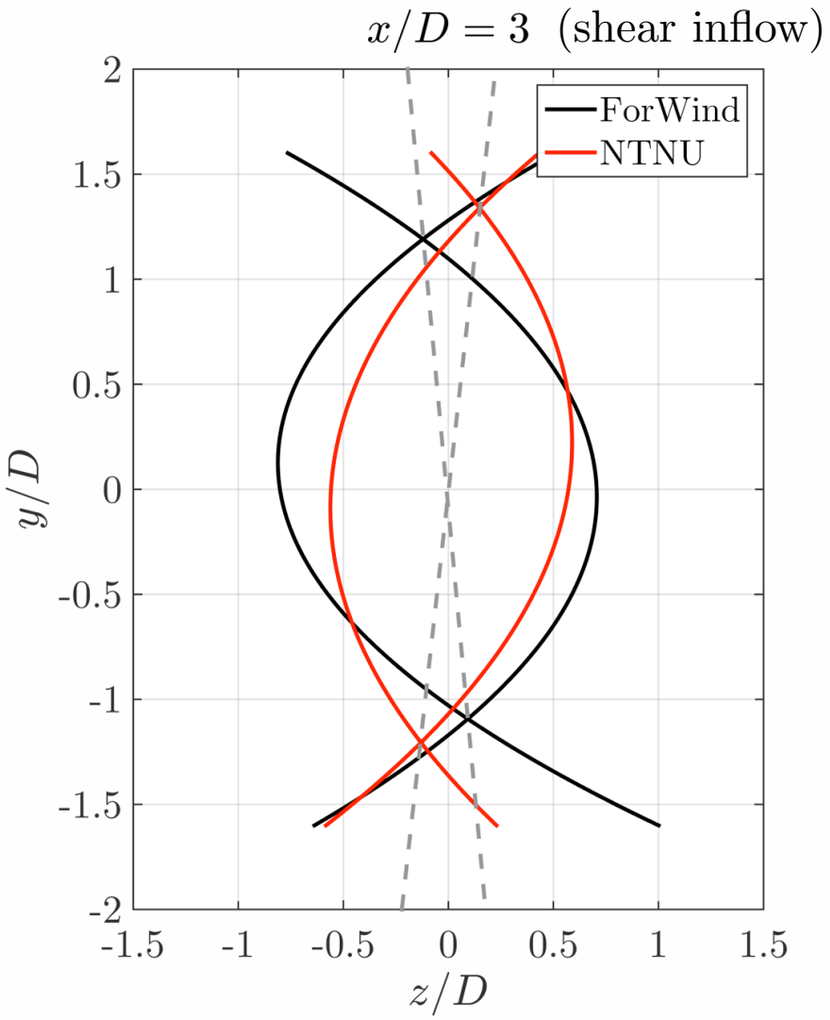

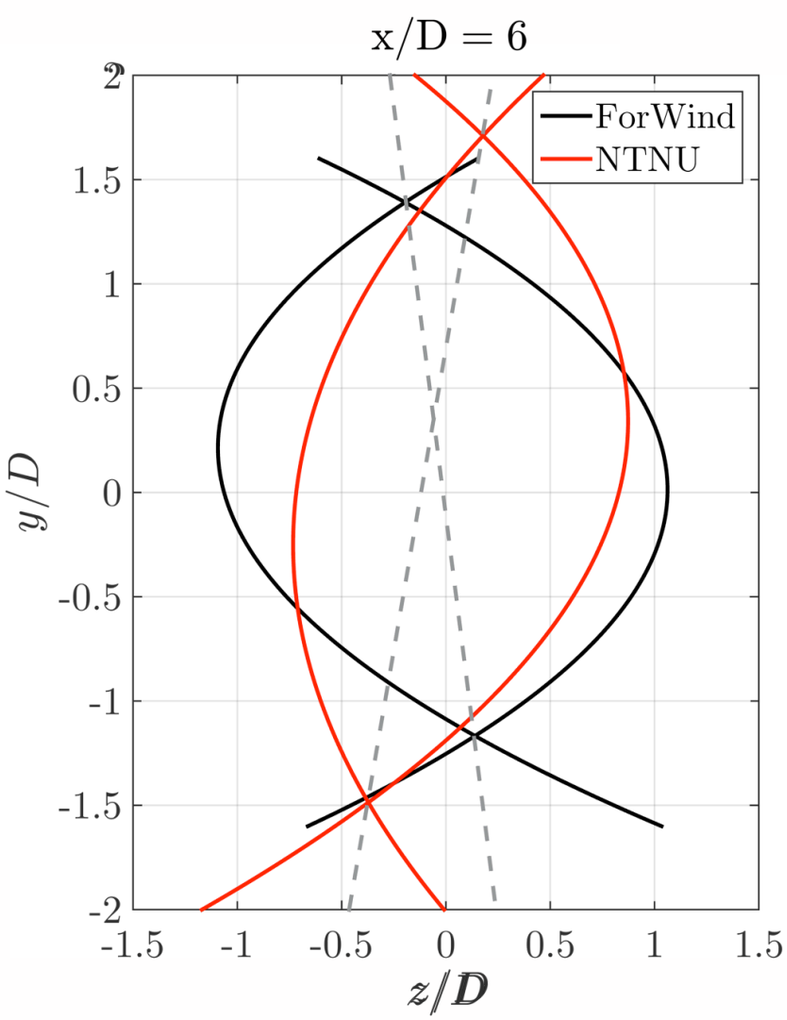

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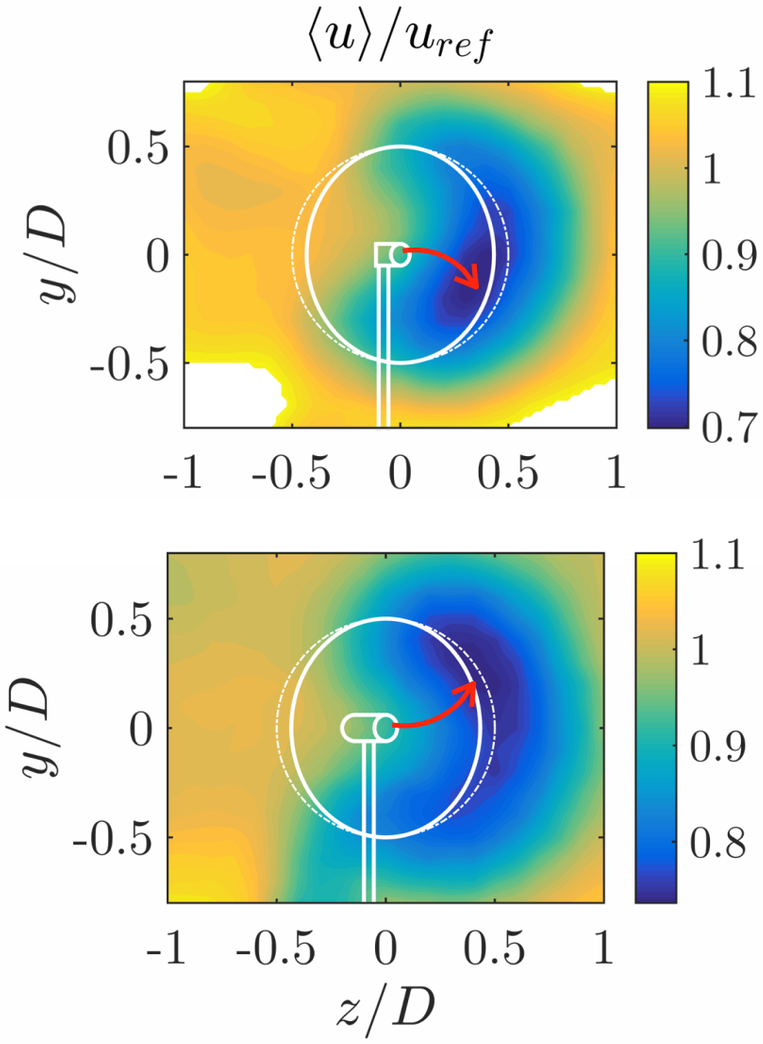

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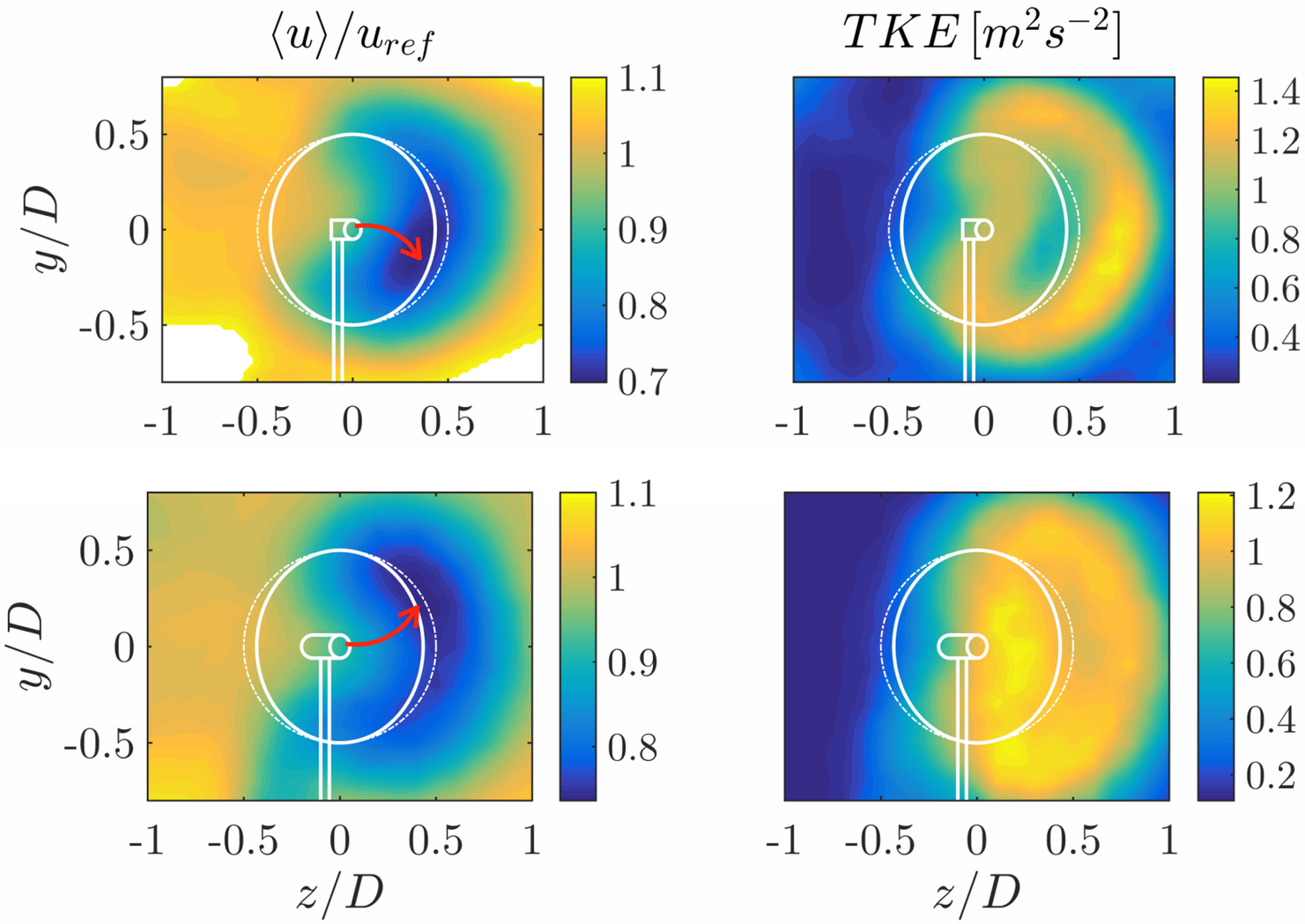

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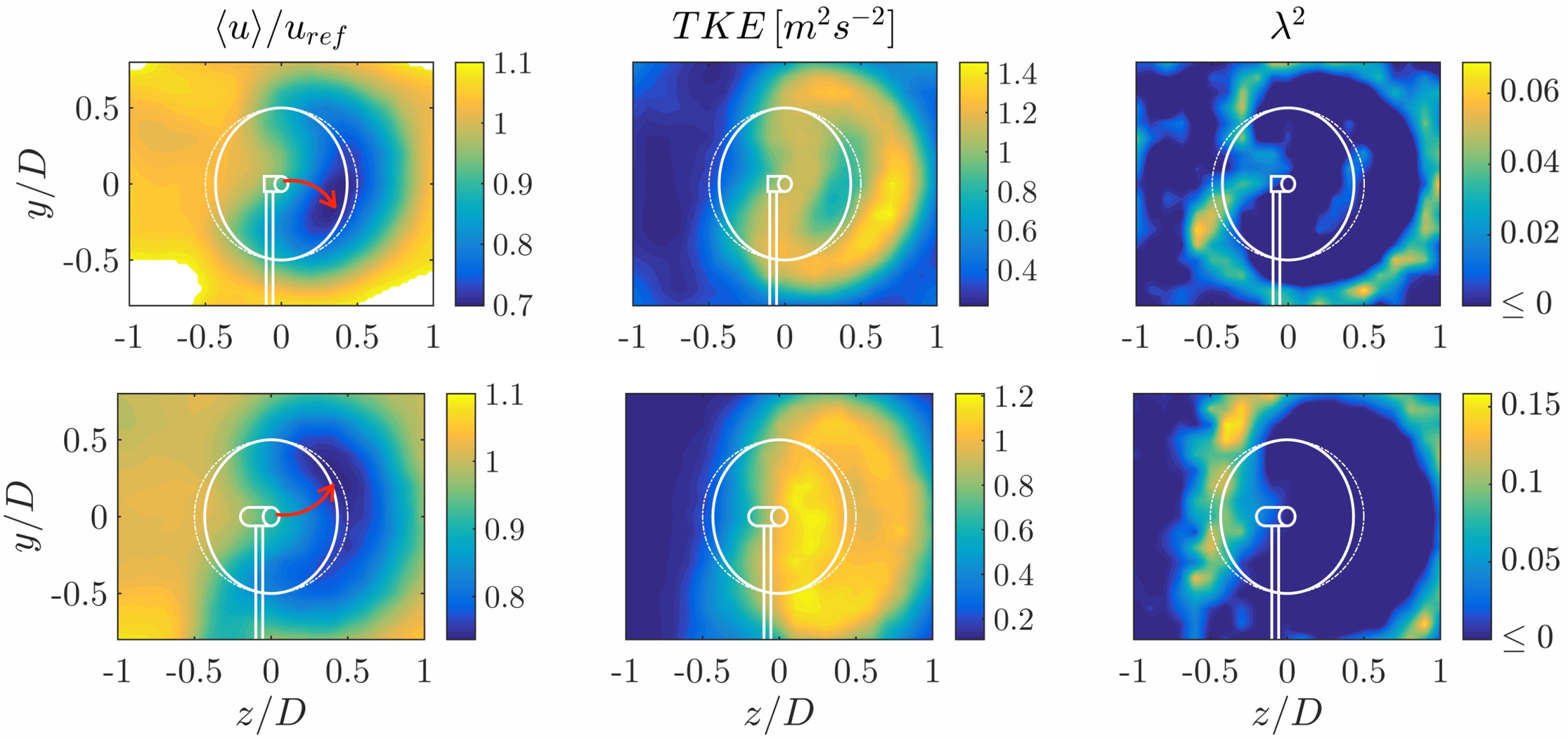

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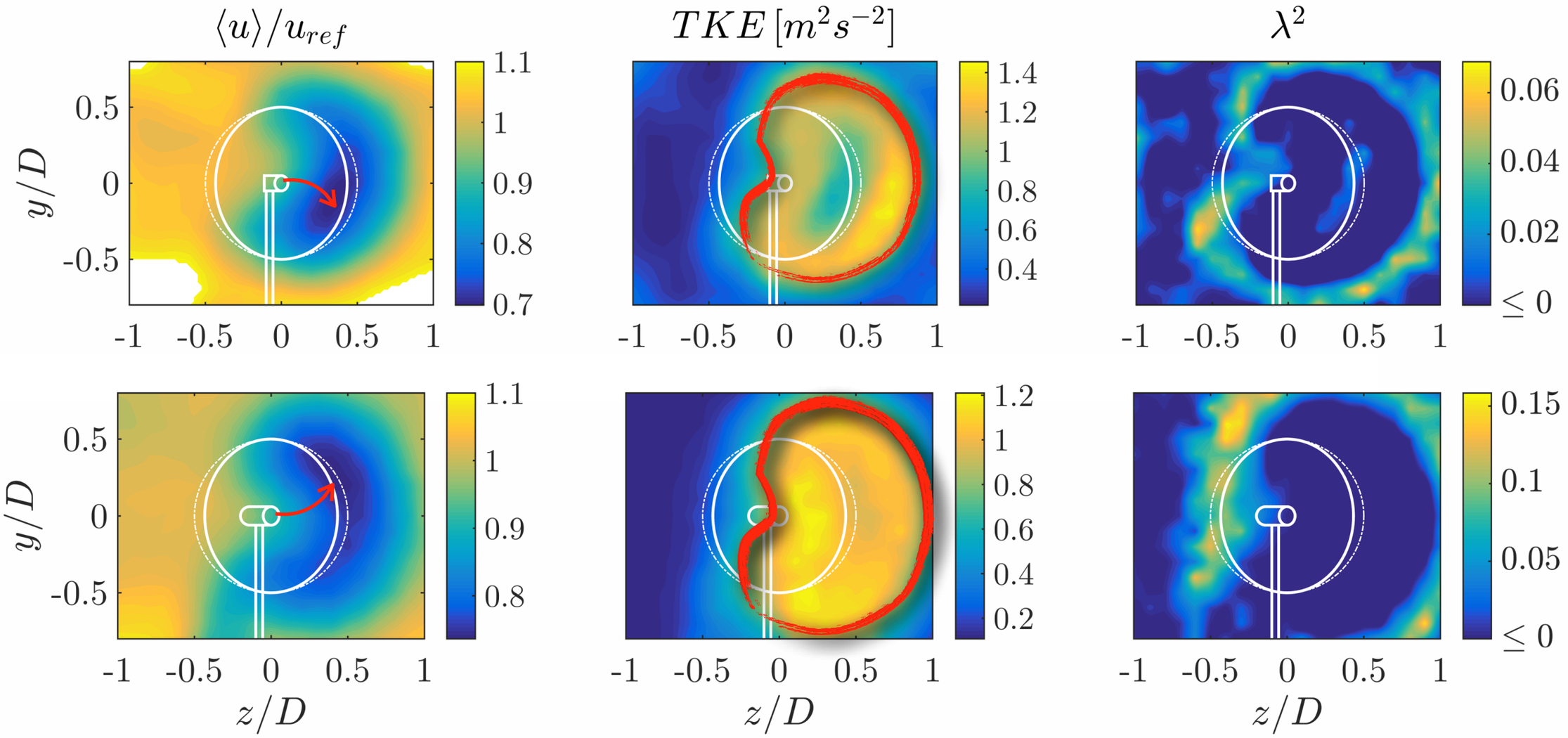

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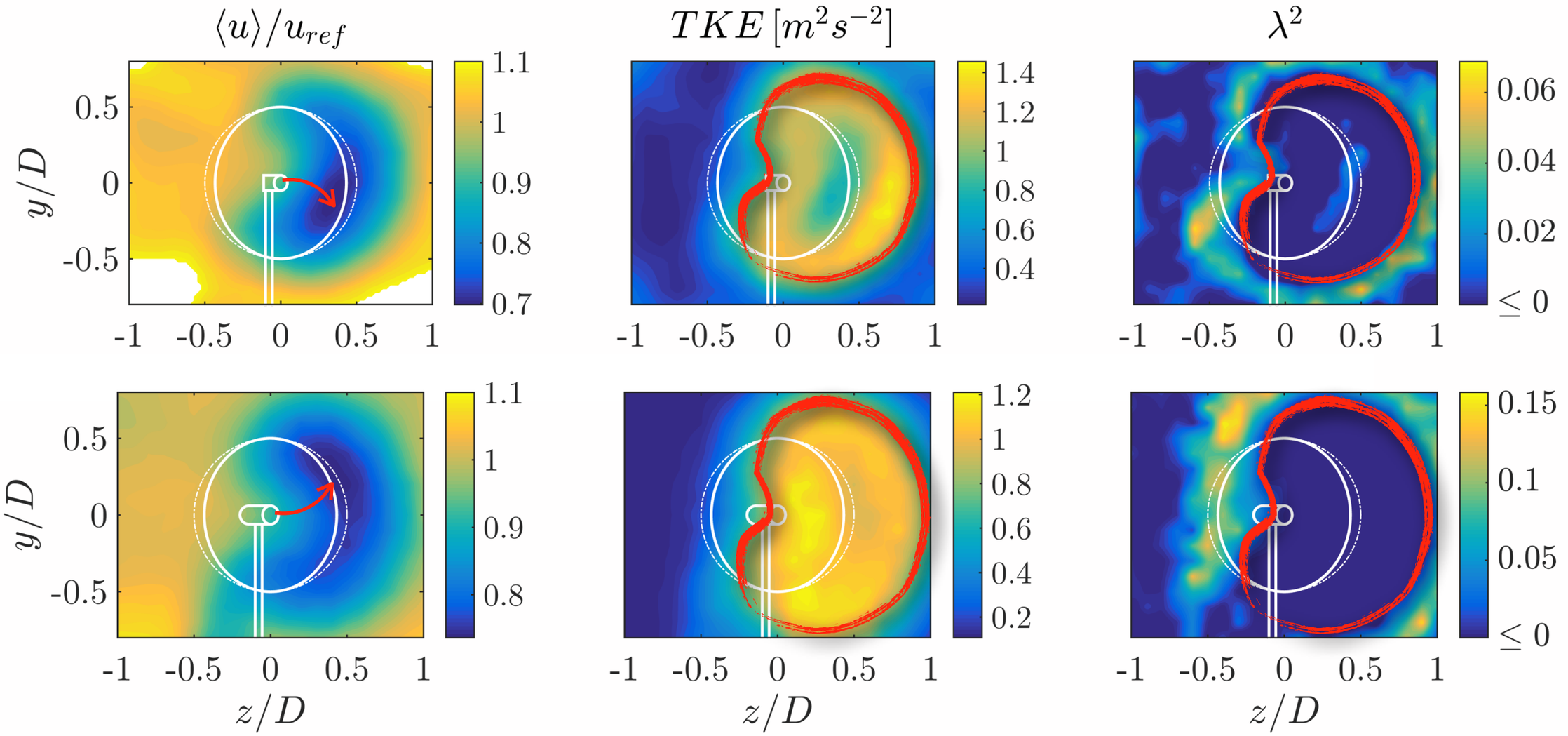

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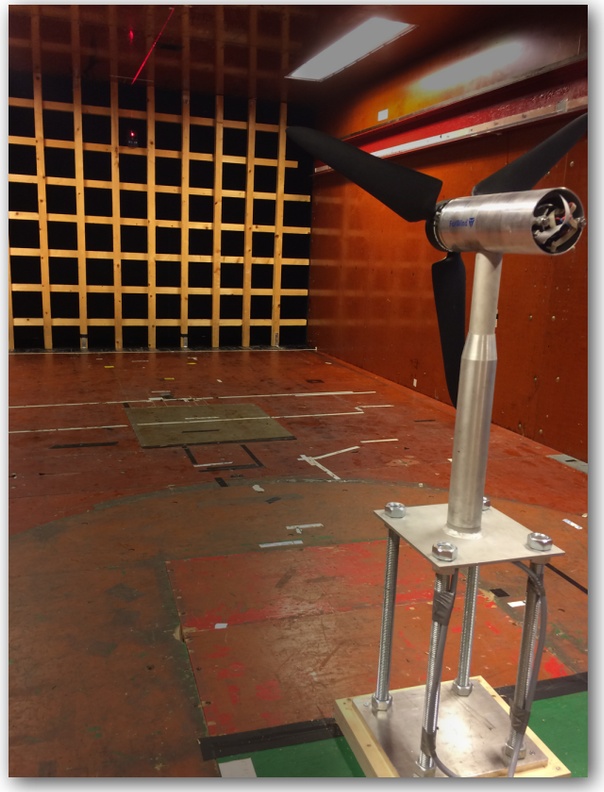
this talk

- Blind test 5 coming up
- data available for cooperation/validation

outlook

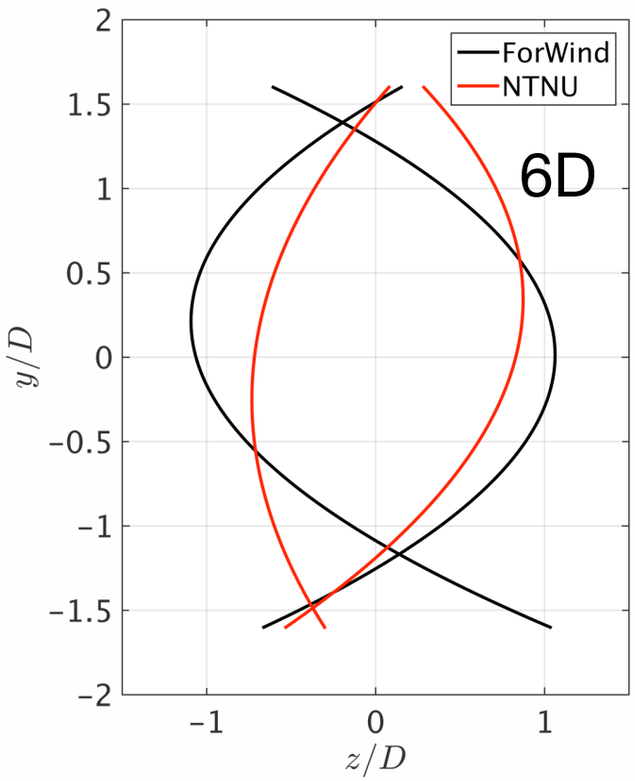
Thank you!



REINER LEMOINE STIFTUNG
Partly funded by the Reiner Lemoine Foundation

jannik.schottler@forwind.de

Curl parametrization



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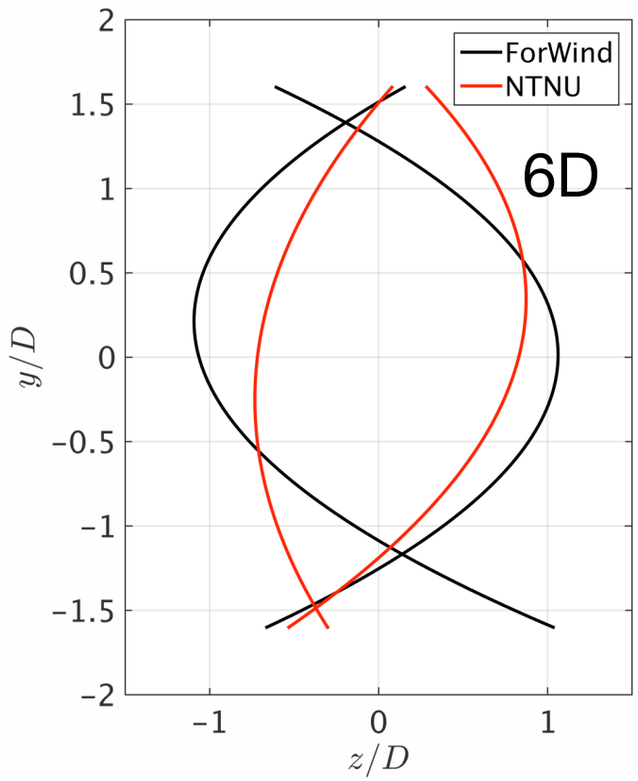

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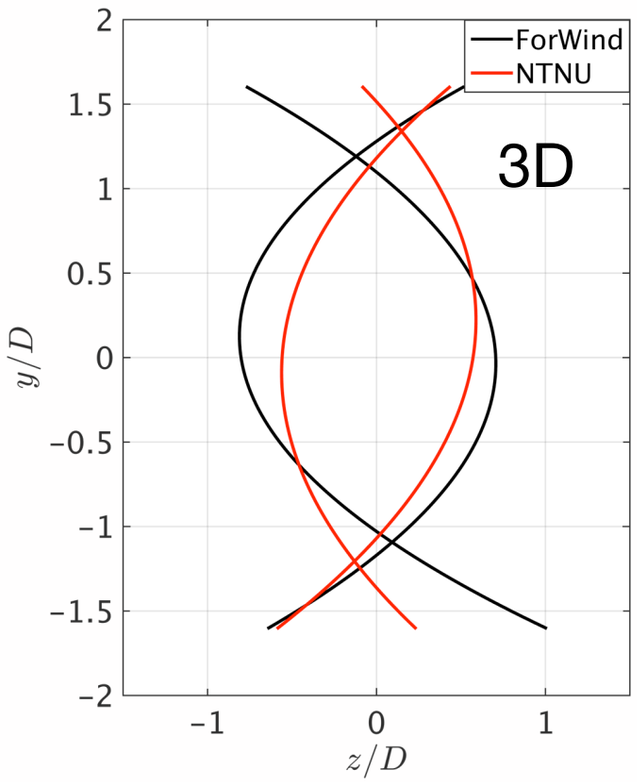

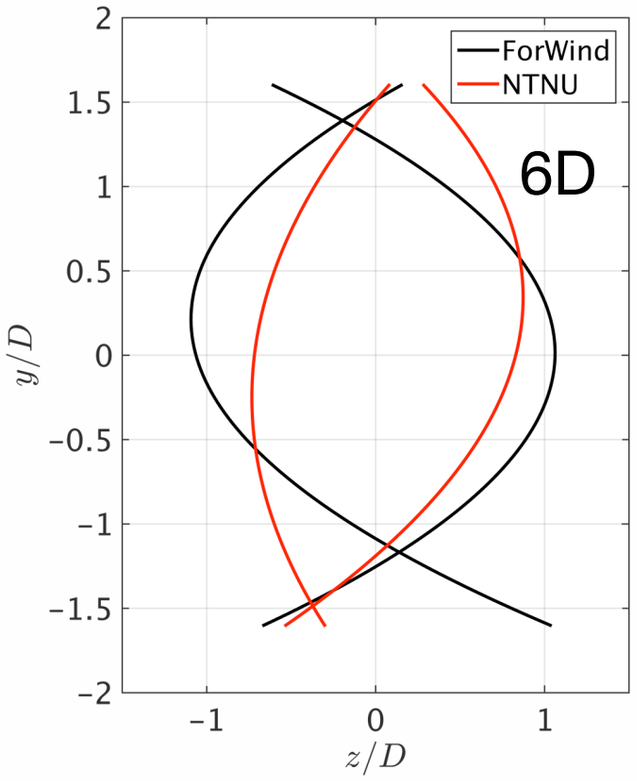

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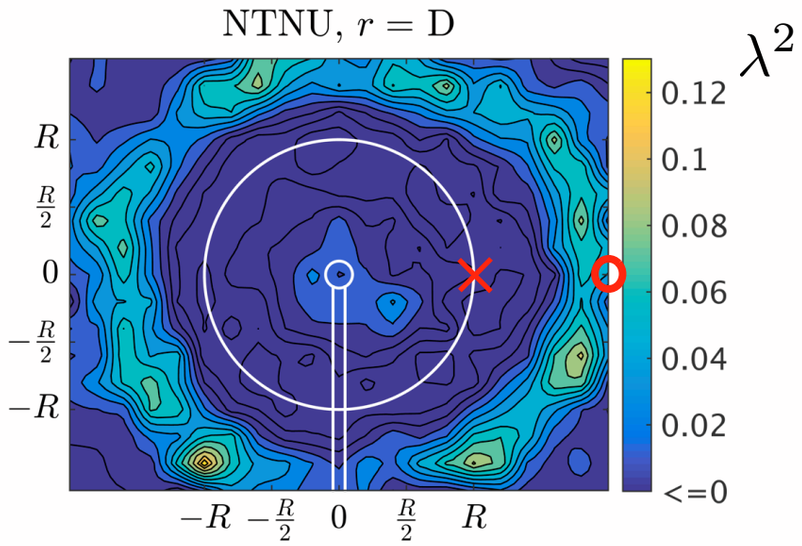
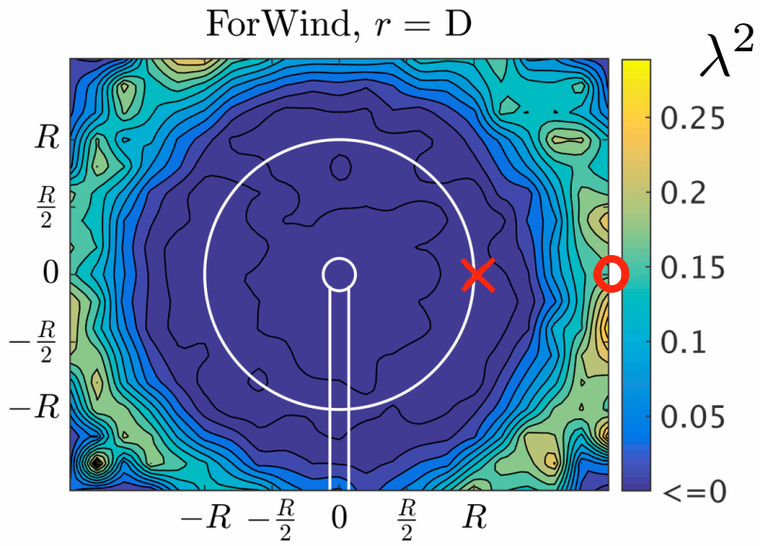
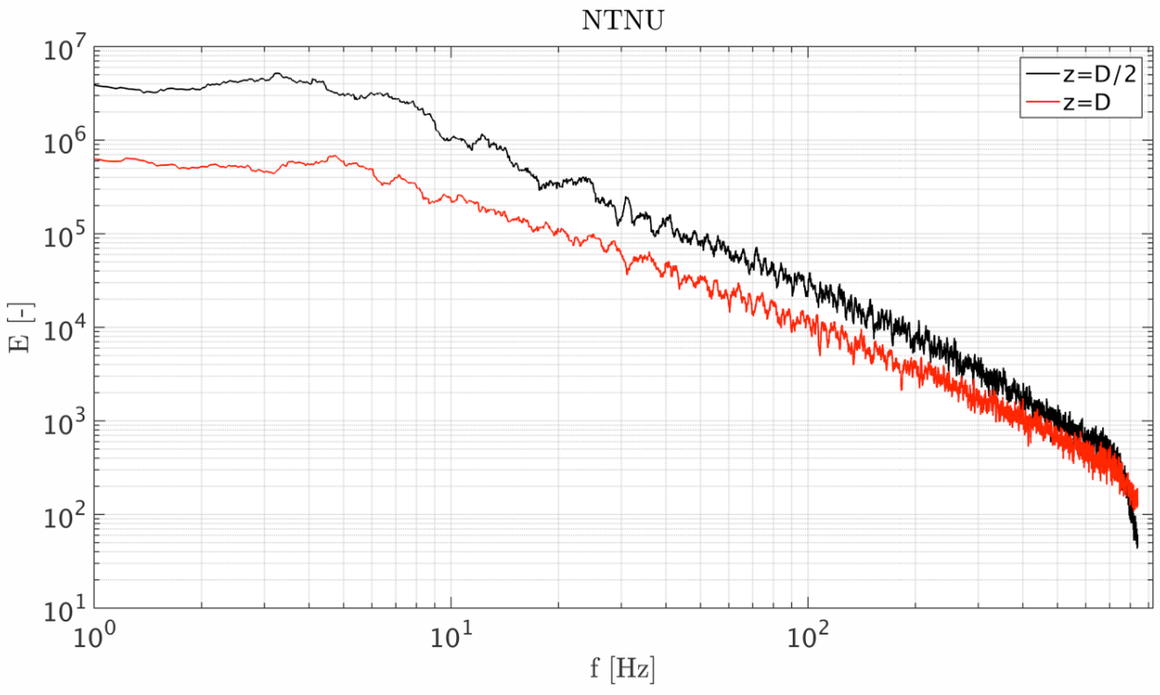
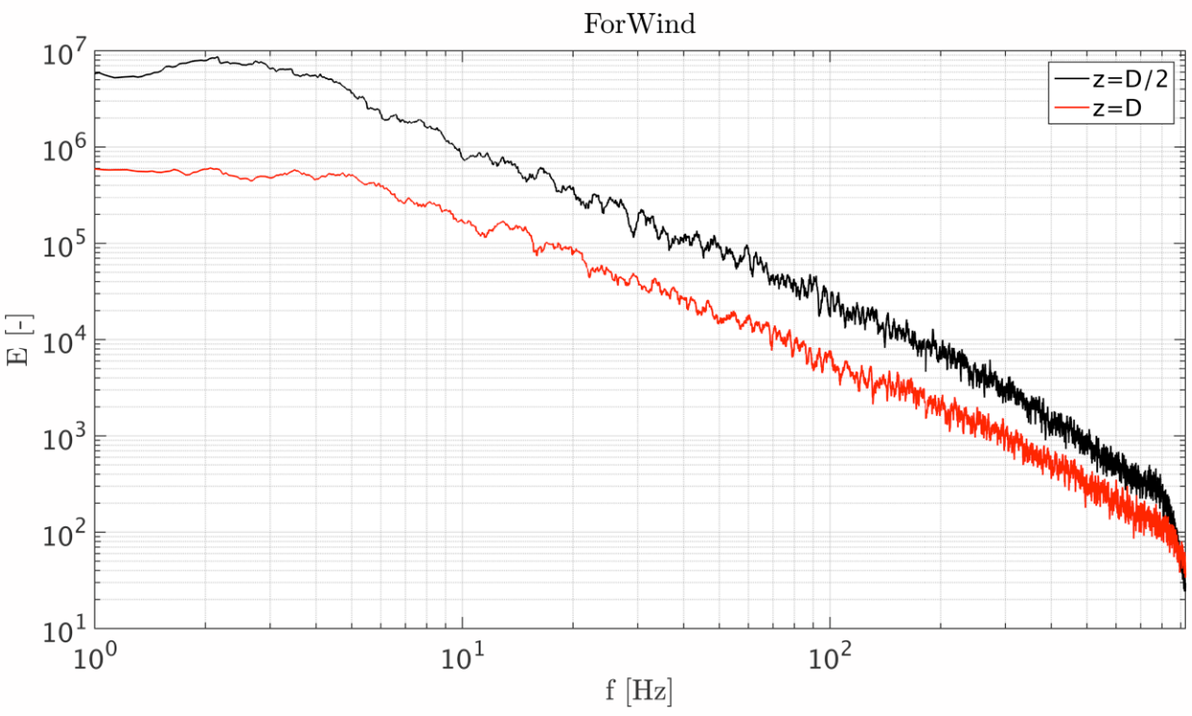
Shape parameter $\lambda^2(\tau)$

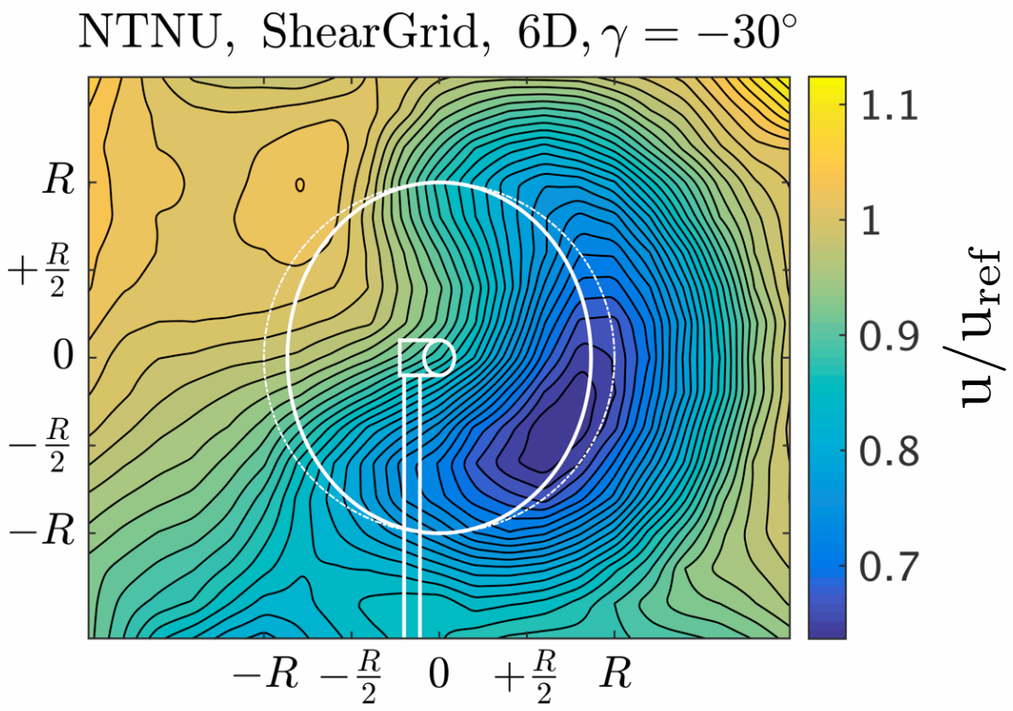








Wake center detection



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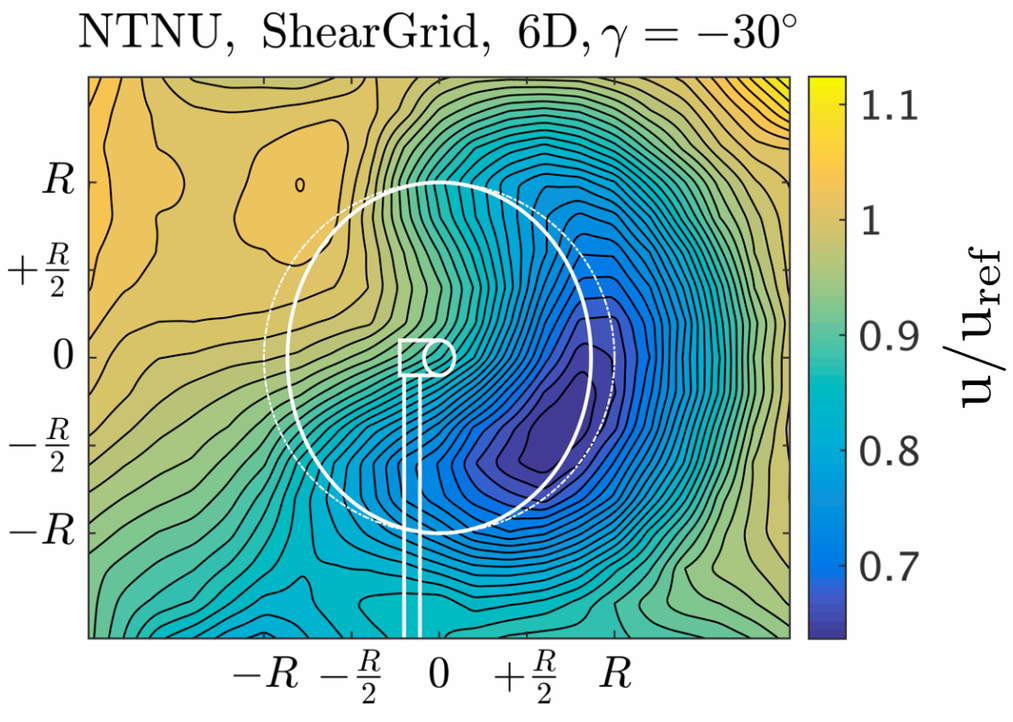

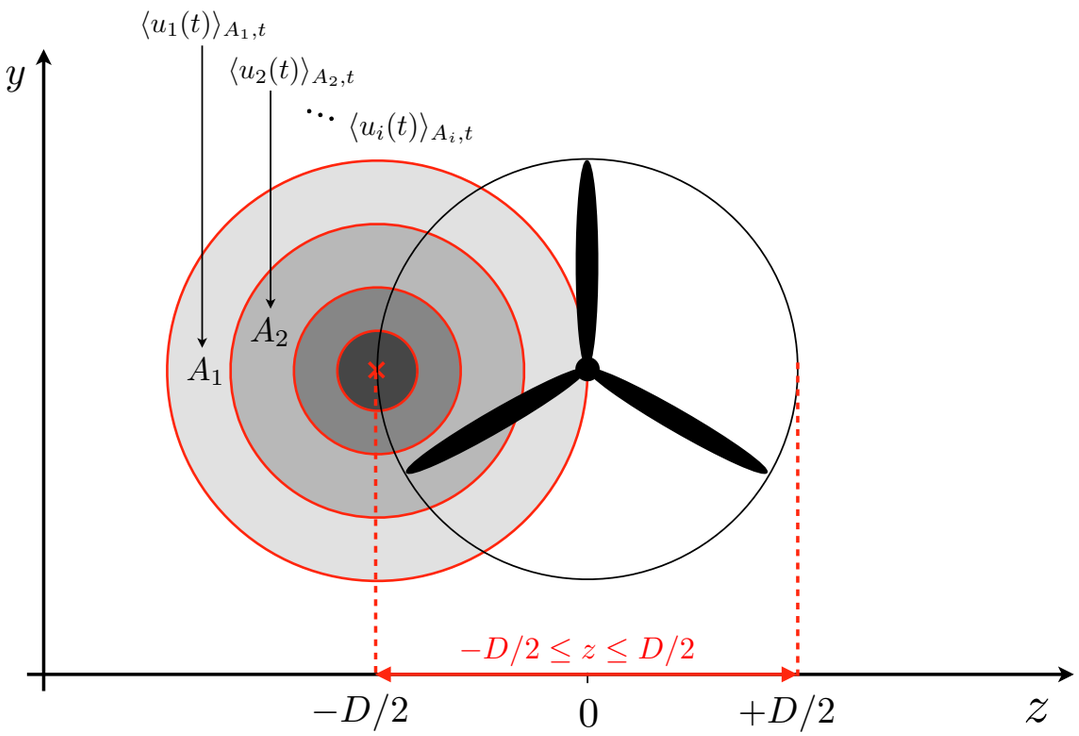

For $-D/2 \le z \le D/2$

$$P^* = \sum_{i=1}^{10} \rho A_i \langle u_i(t)\rangle^3_{A_i,t}$$

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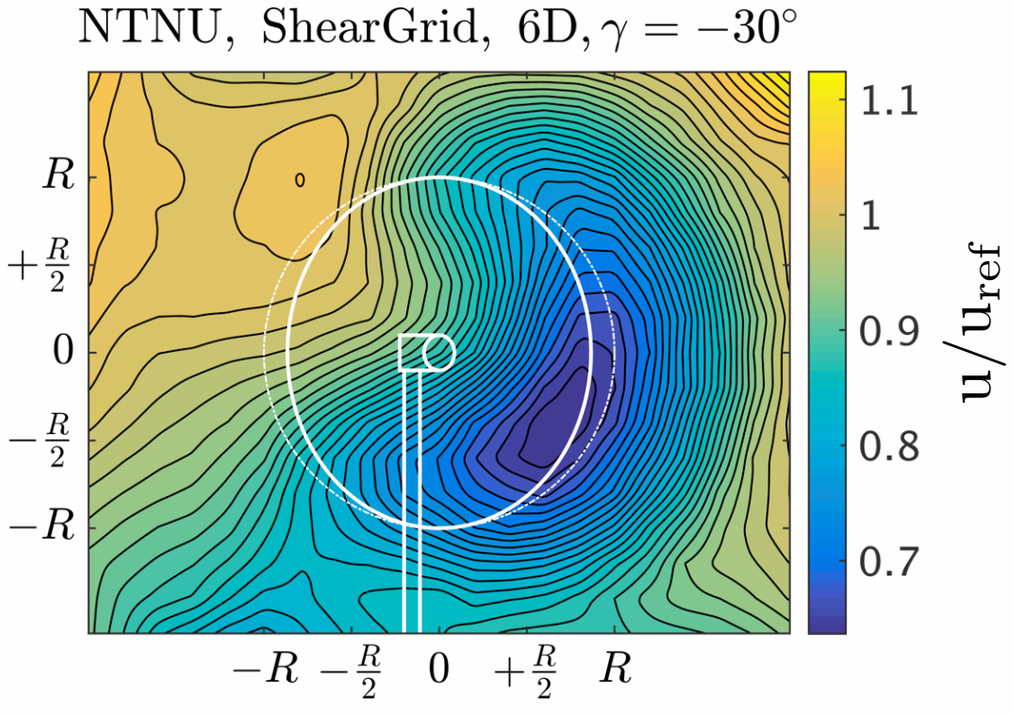

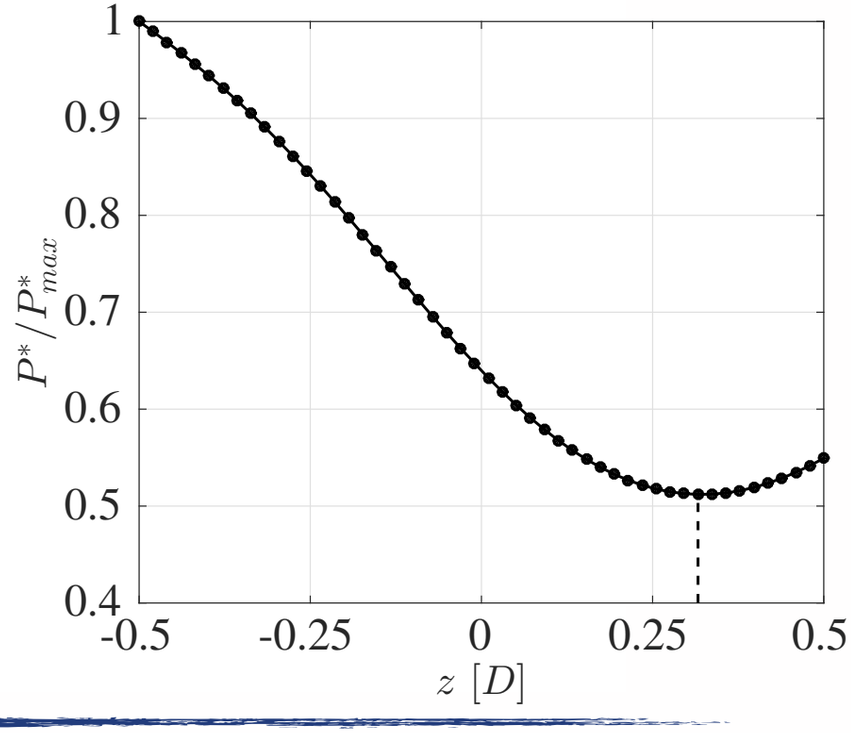

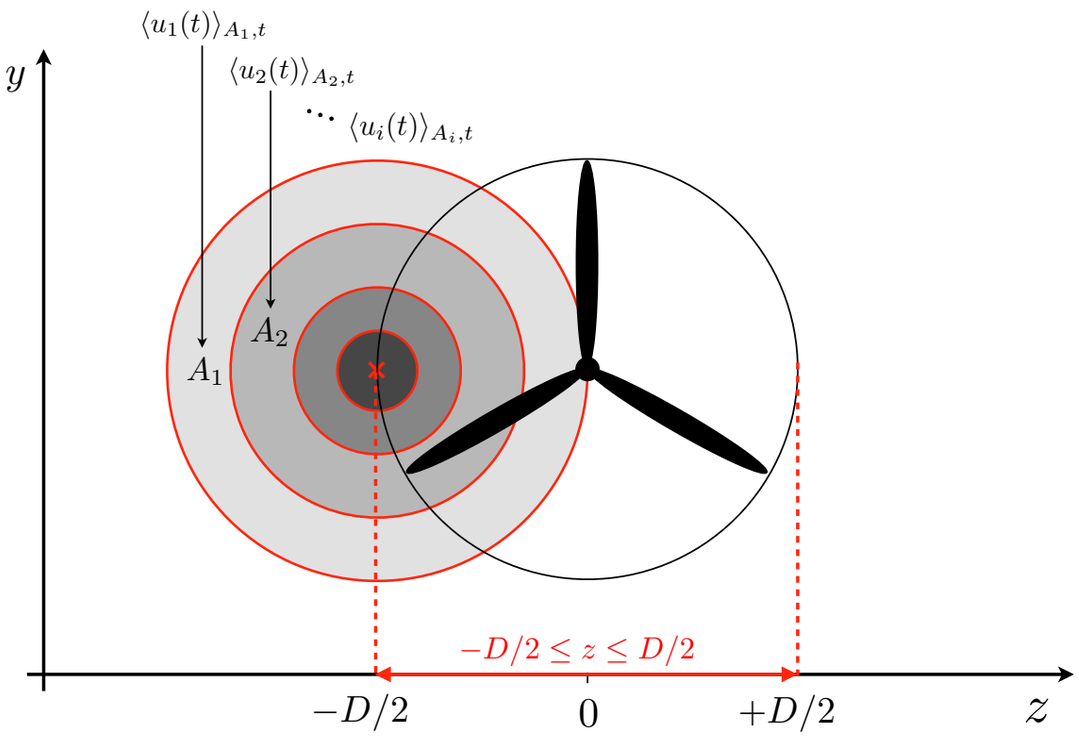

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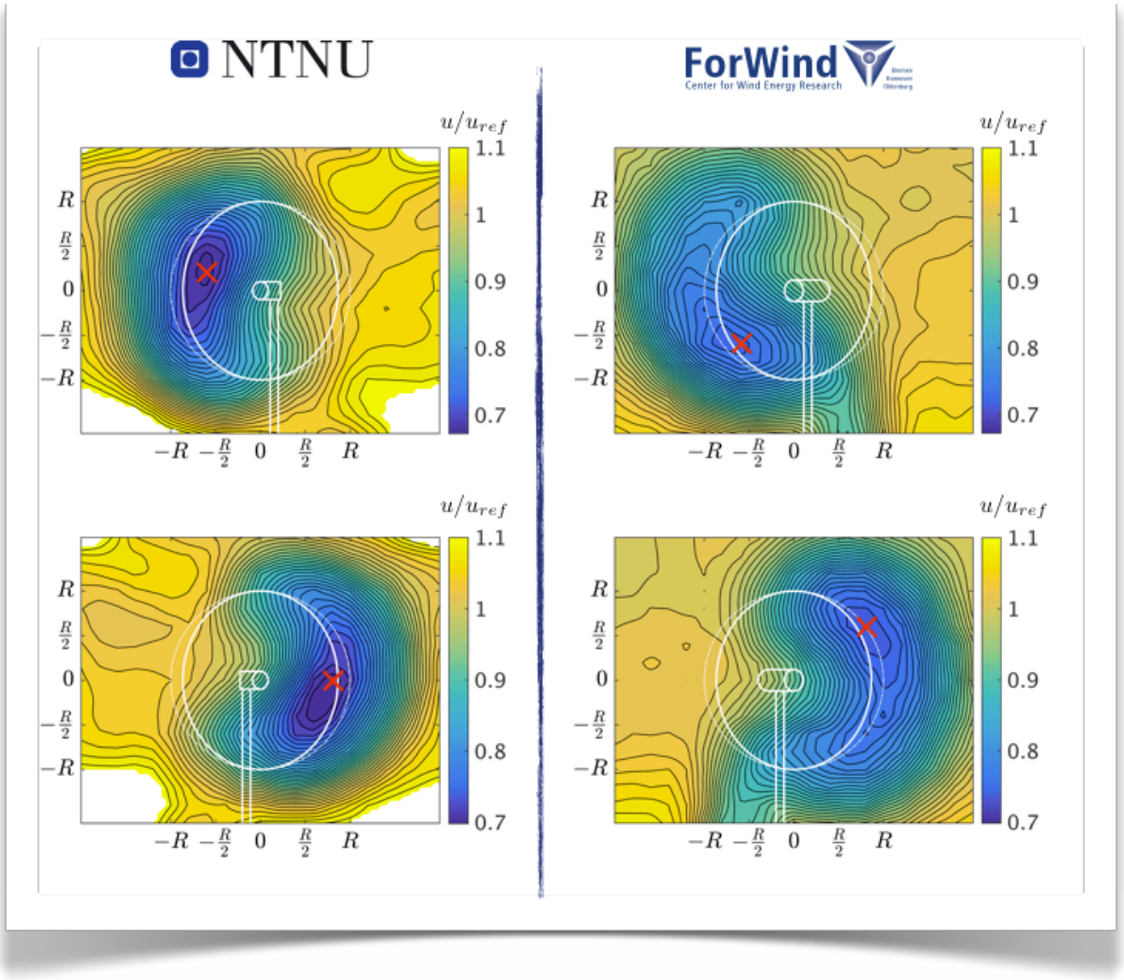

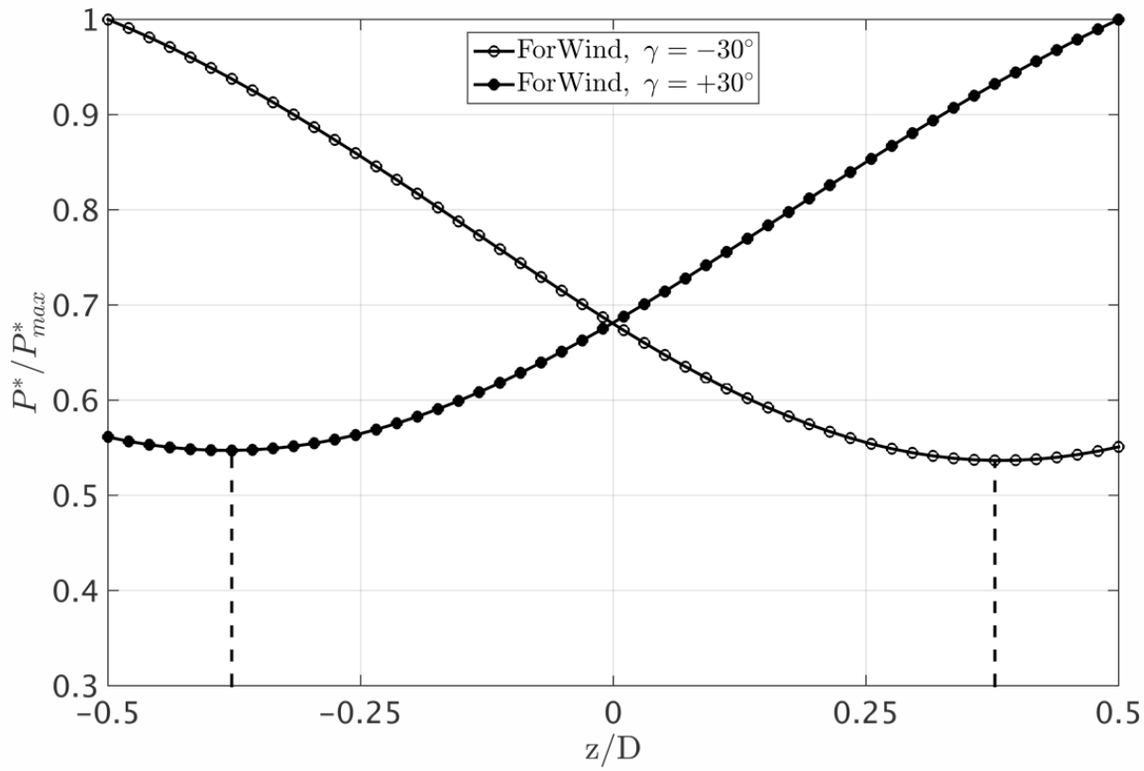

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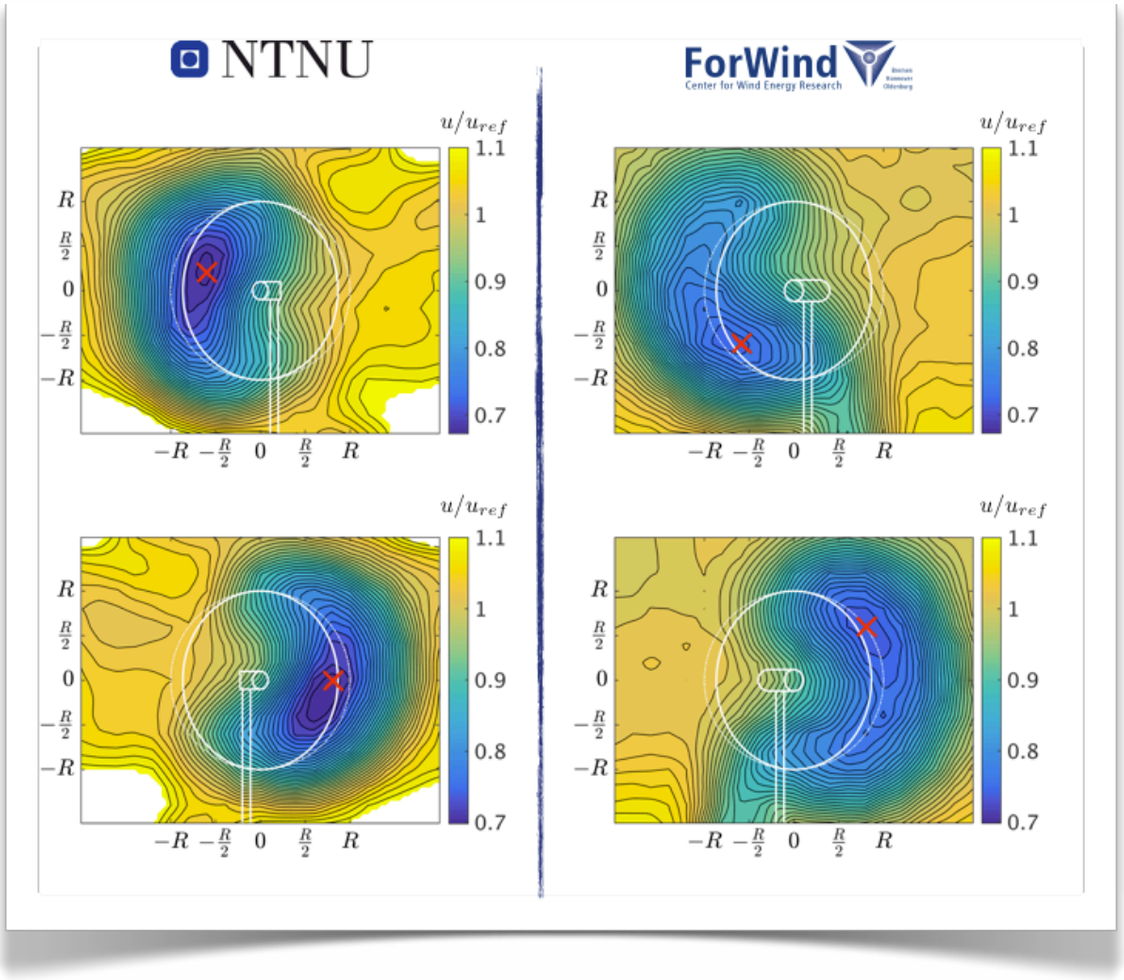

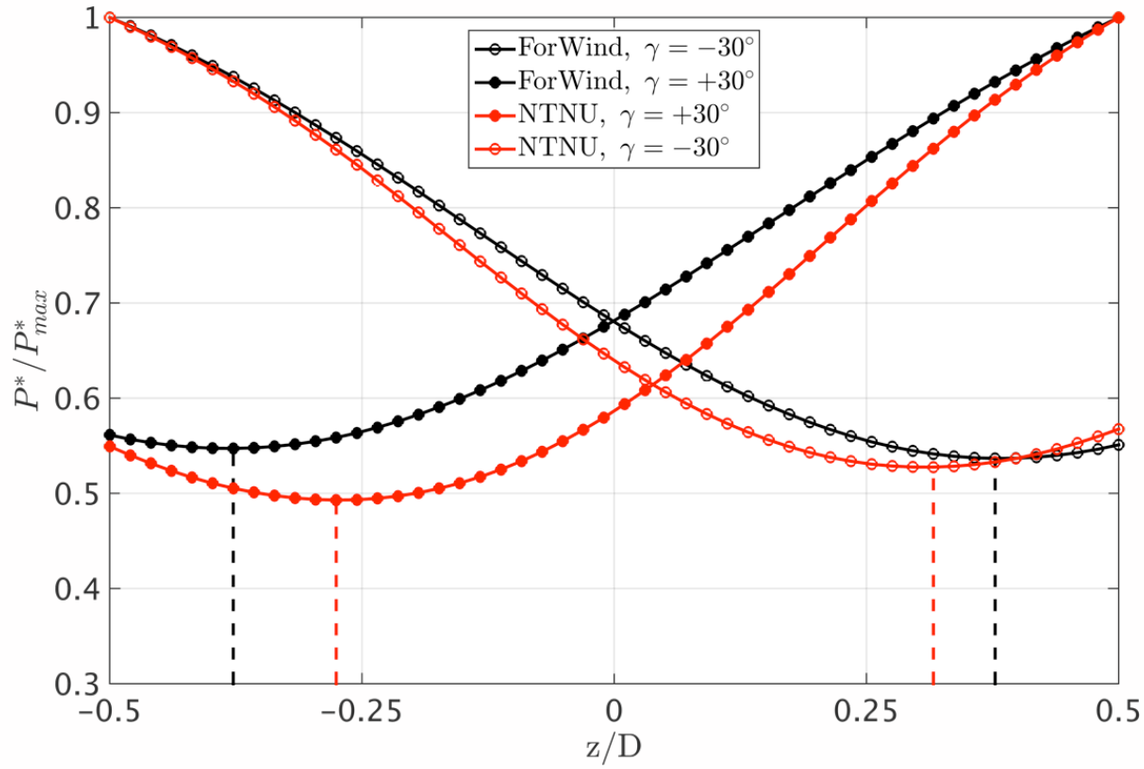

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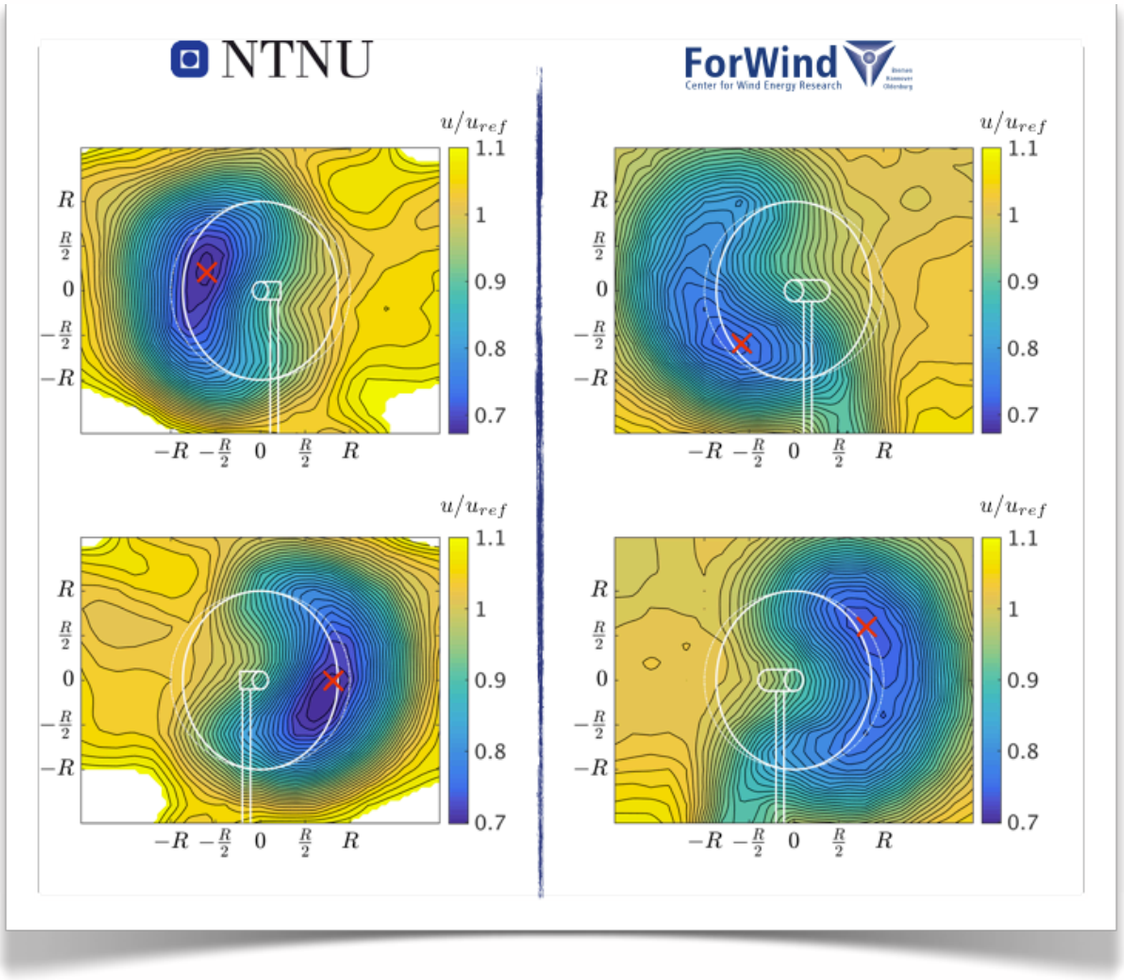

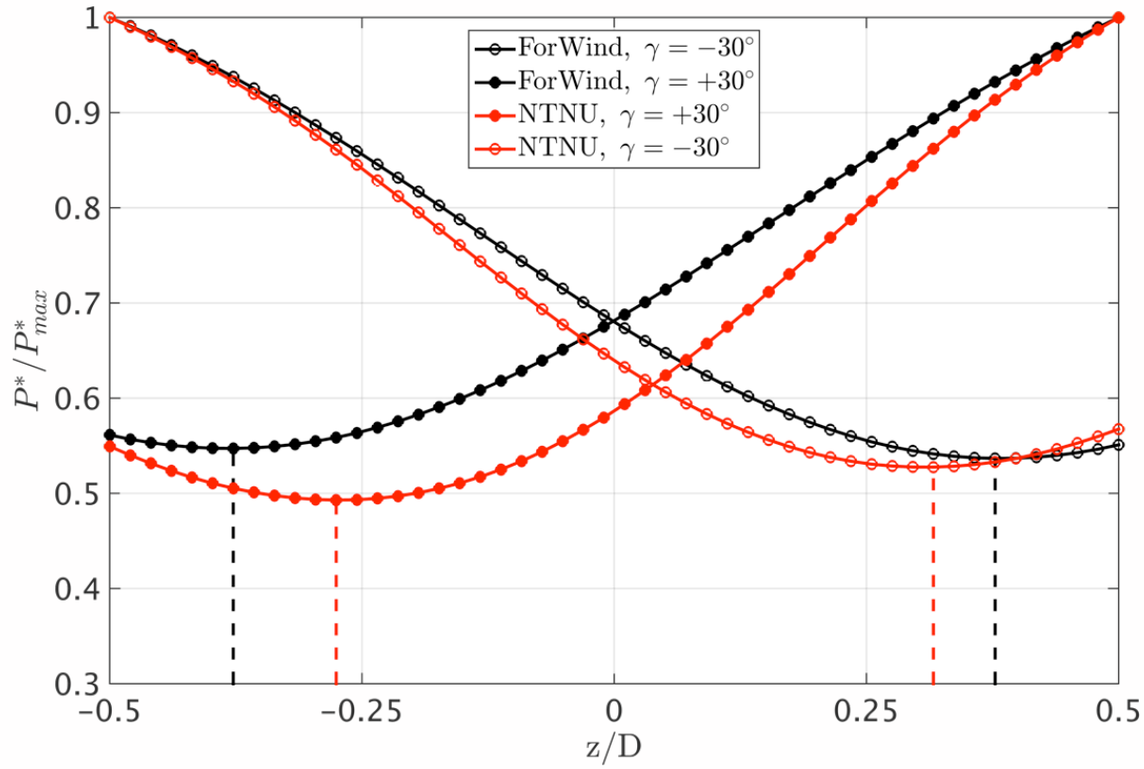

Turbine	γ	Wake center	Skew angle
NTNU	$30°$	$-0.28D$	$\approx -2.6\,°$
NTNU	$-30°$	$0.32D$	$\approx 3.0\,°$
ForWind	$30°$	$-0.38D$	$\approx -3.6\,°$
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Curled wake in yaw - a general effect ?

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Hannover
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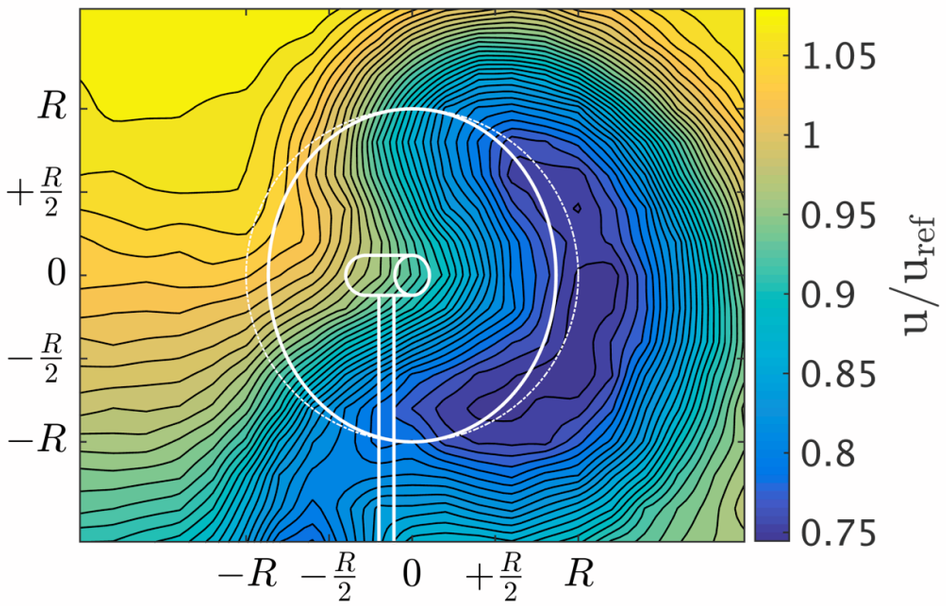
NTNU



Curled wake in yaw - a general effect ?

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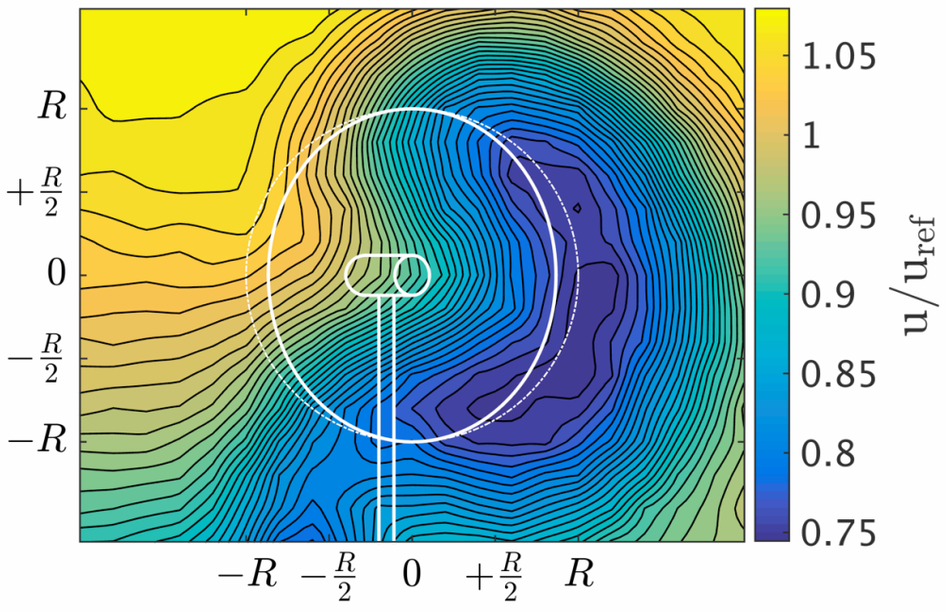

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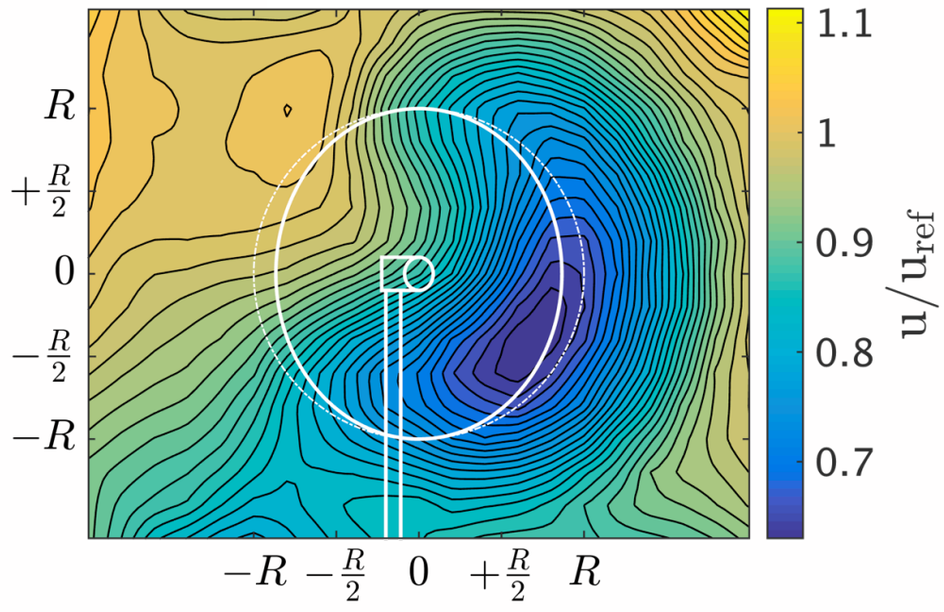

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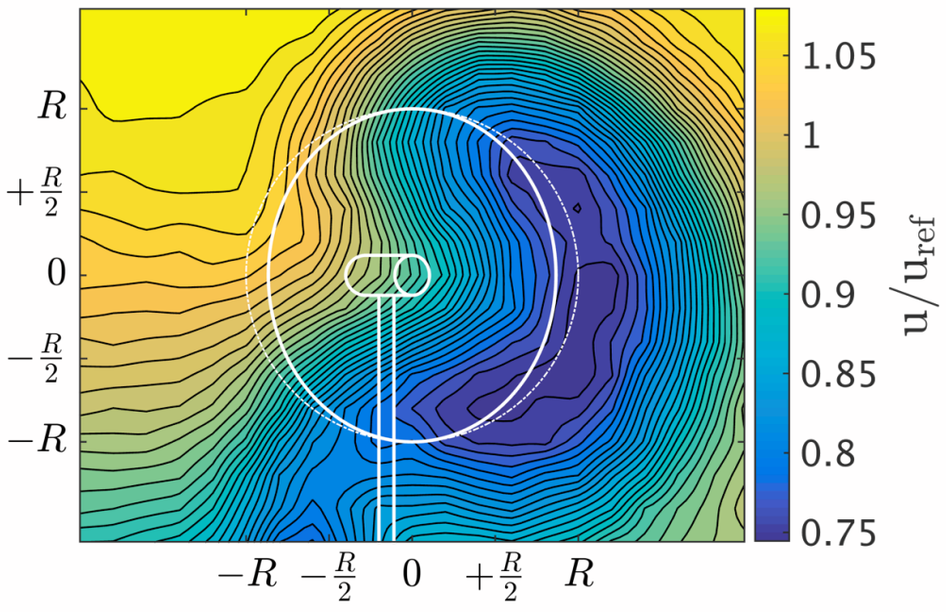
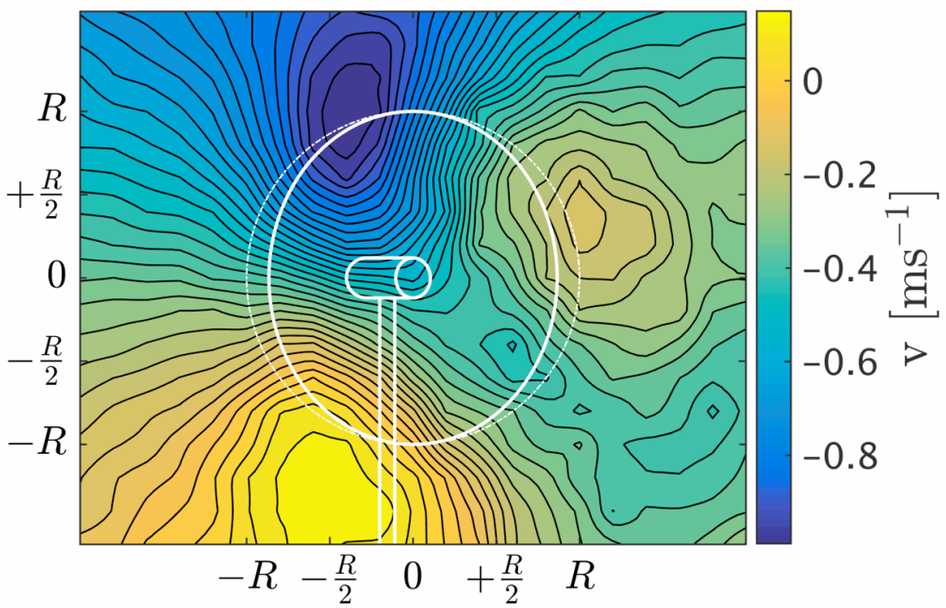
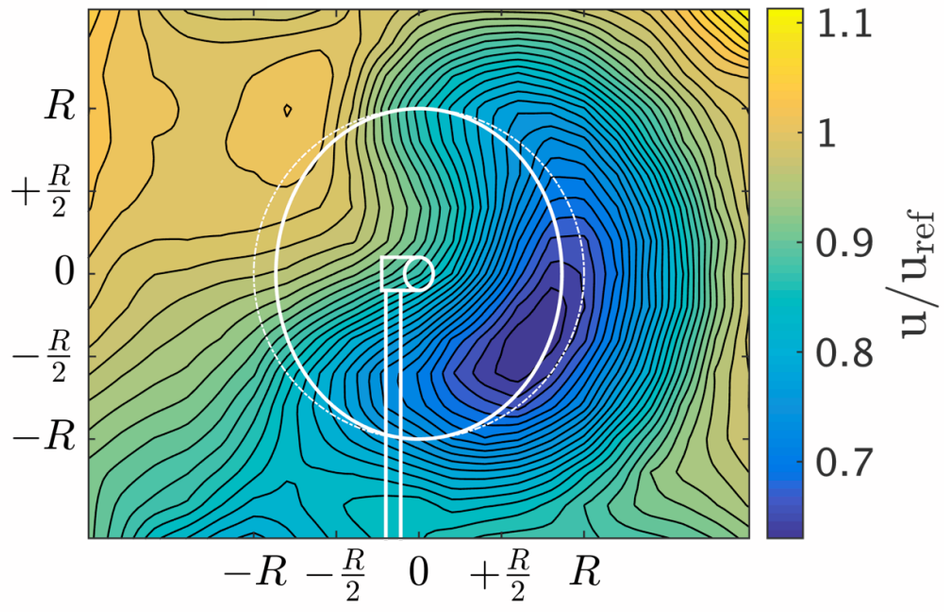
Oldenburg





NTNU



Curled wake in yaw - a general effect ?

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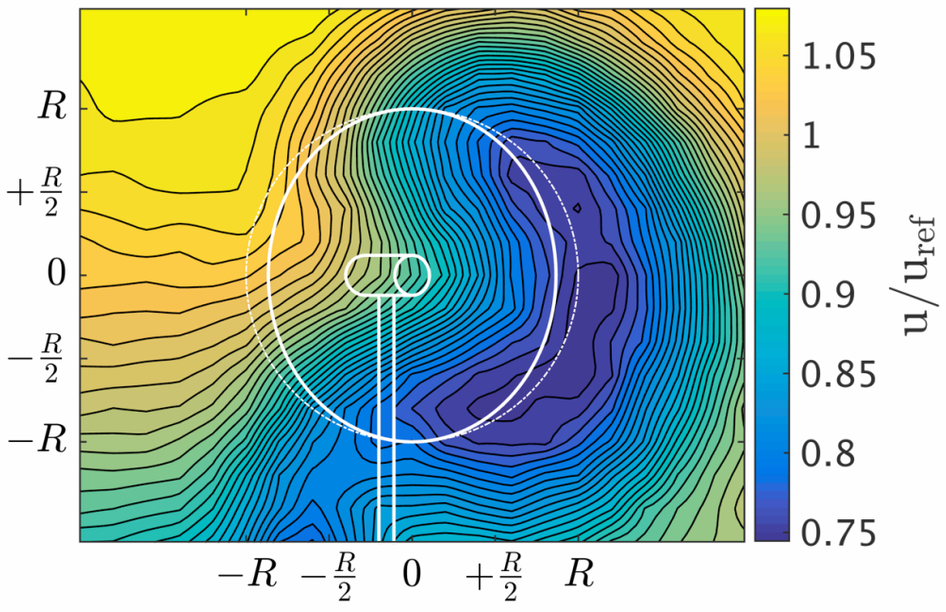

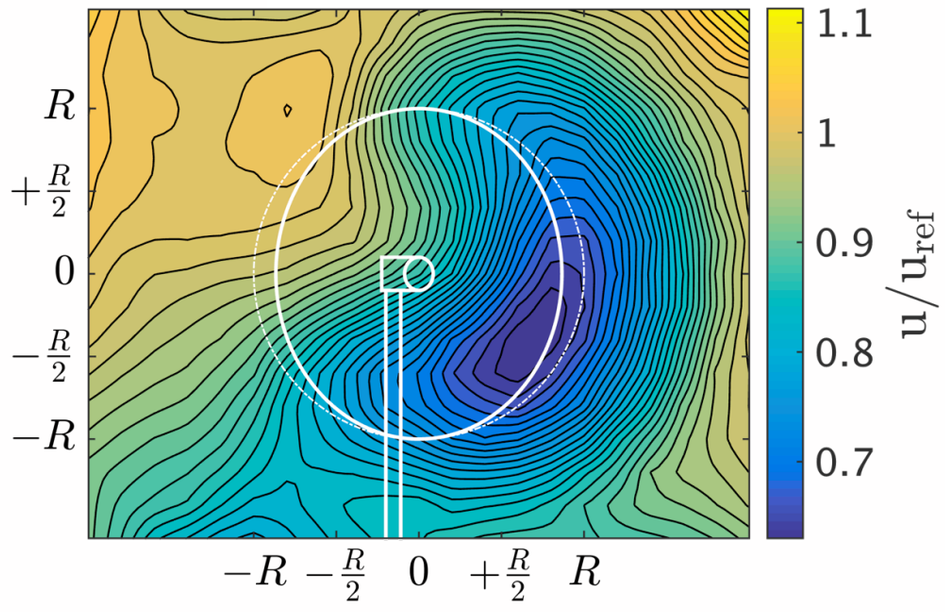

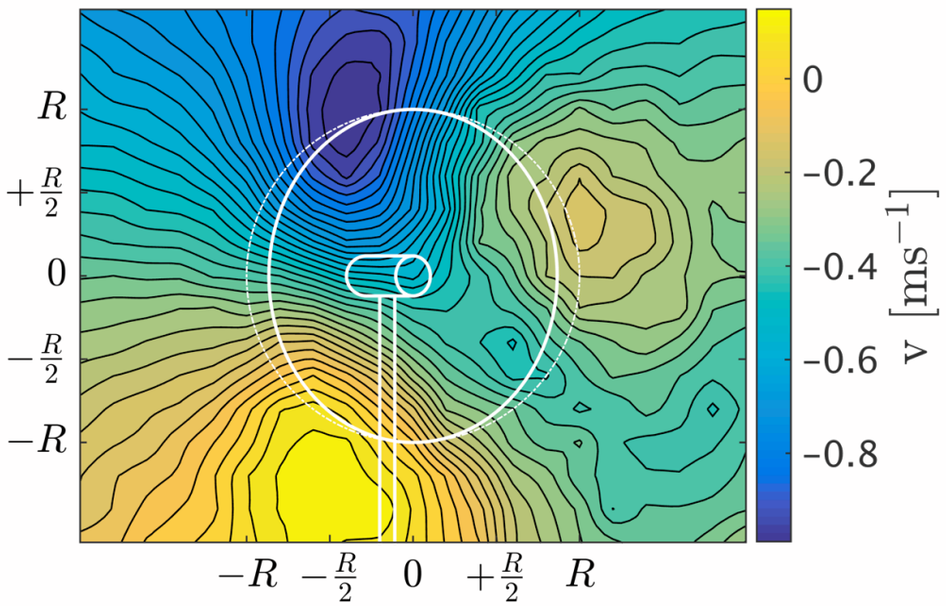

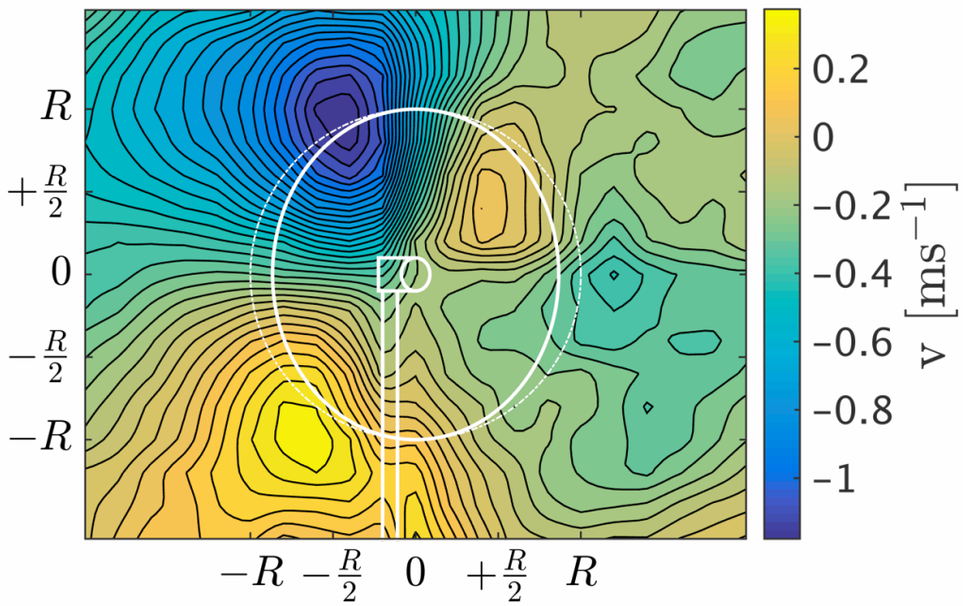

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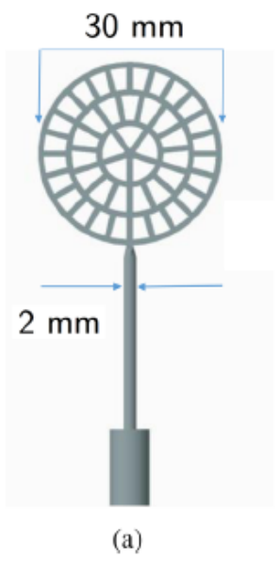
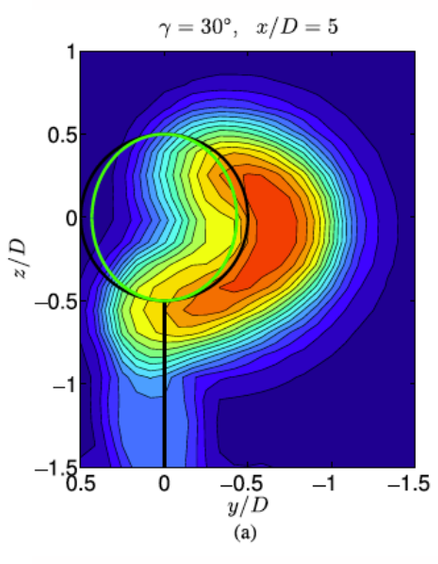
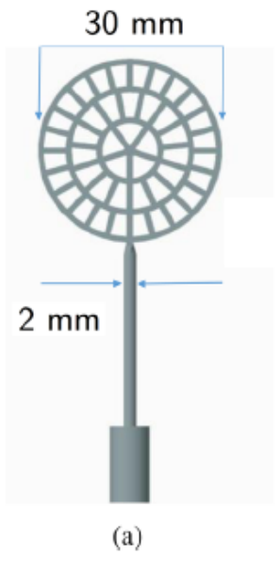
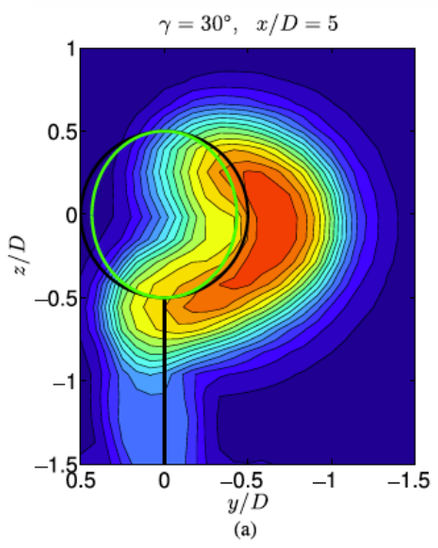


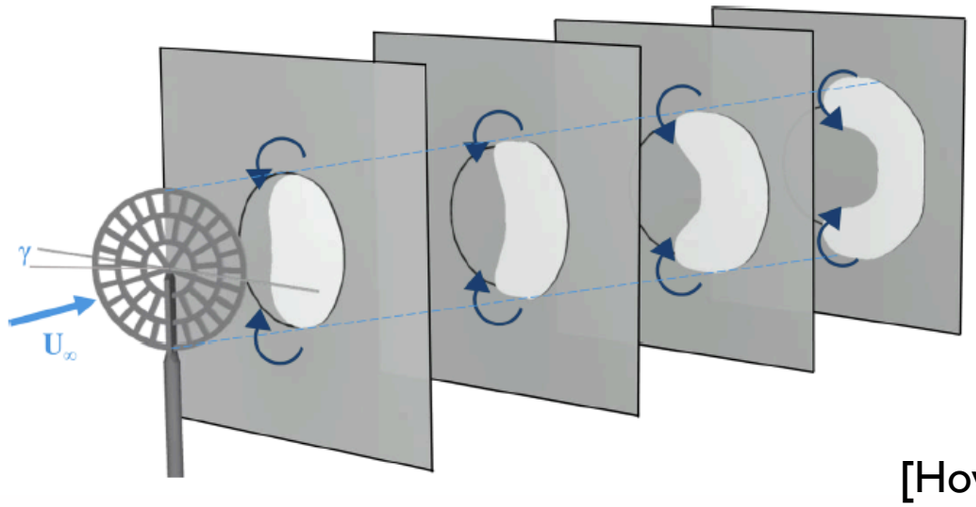


[Howland et al. 2016]

Curled wake in yaw - a general effect !

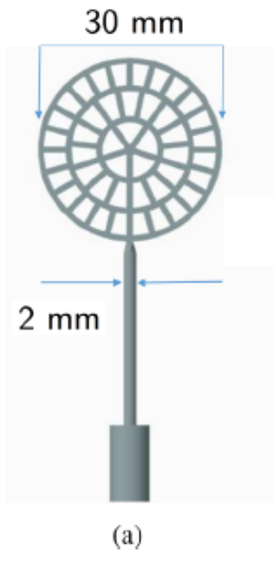


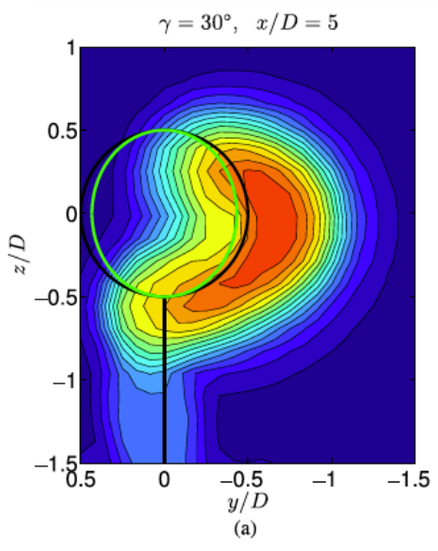


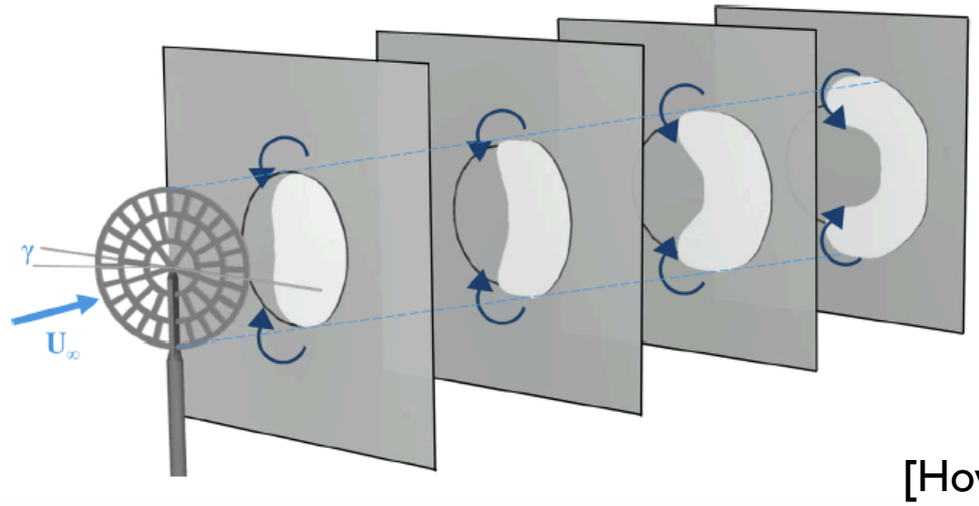


[Howland et al. 2016]

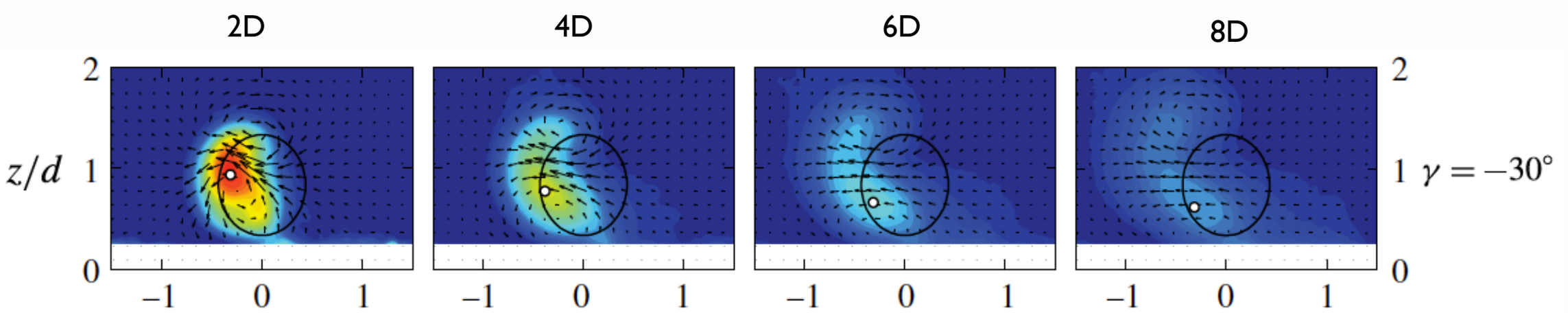
Curled wake in yaw - a general effect !





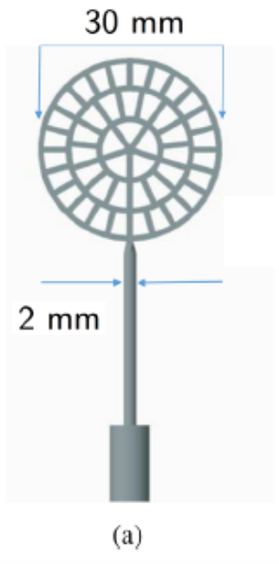


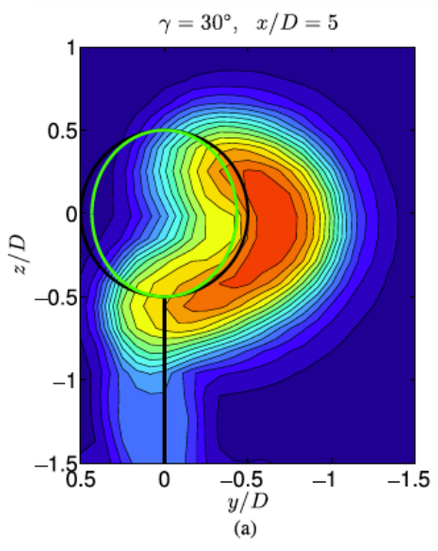
[Howland et al. 2016]

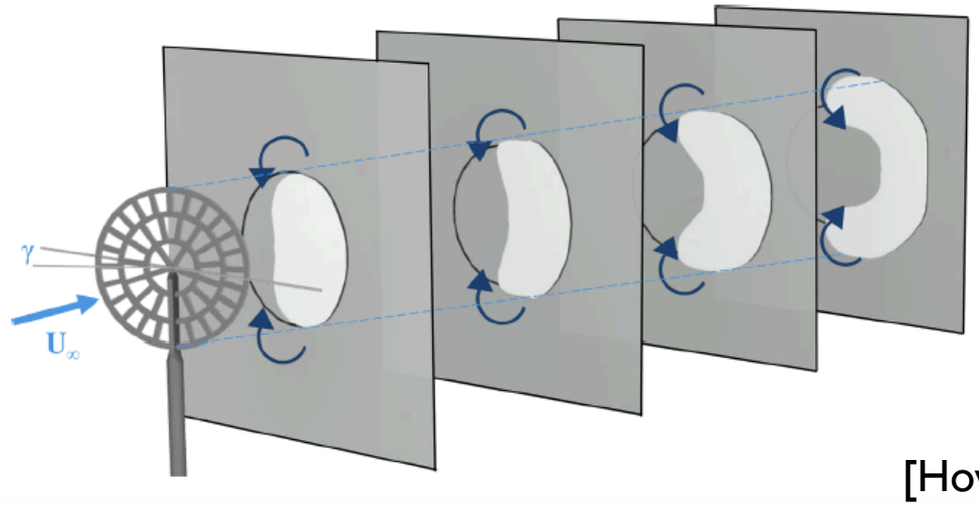


[Bastankhah & Porté-Agel 2016]

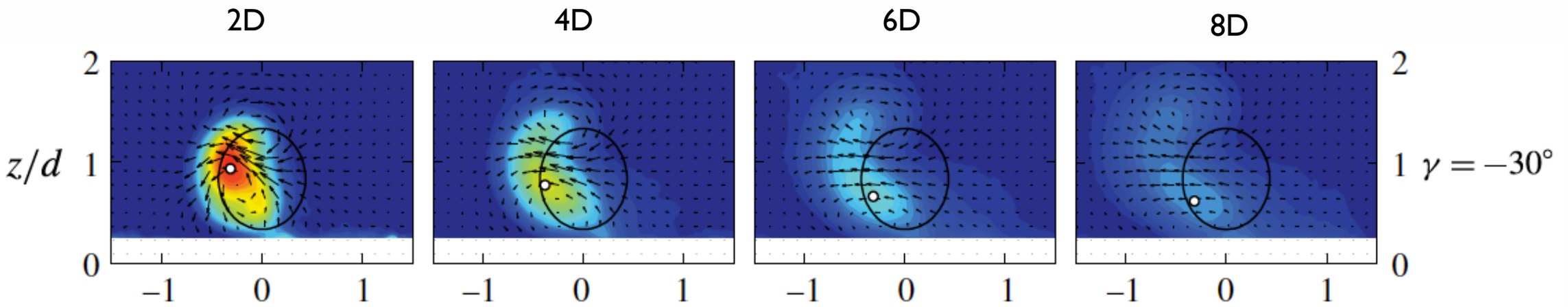
Curled wake in yaw - a general effect !







[Howland et al. 2016]



[Bastankhah & Porté-Agel 2016]

Curled wake observed for drag disc (30mm) model wind turbines (150mm, 580mm, 890mm)