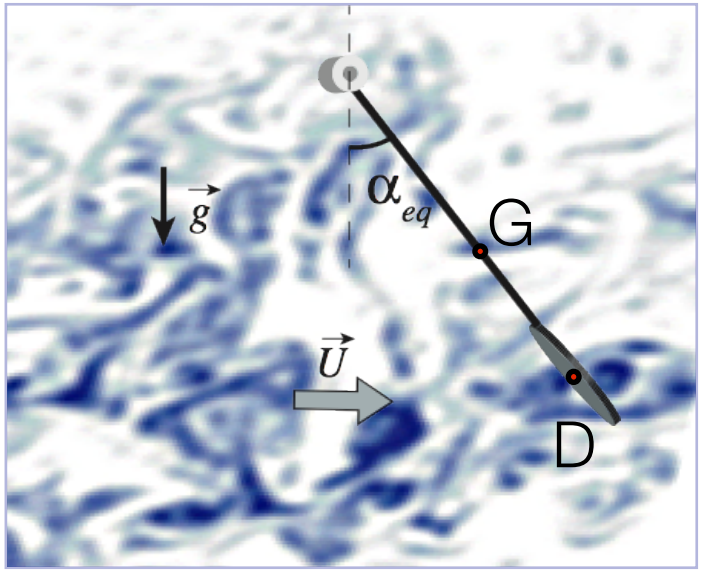
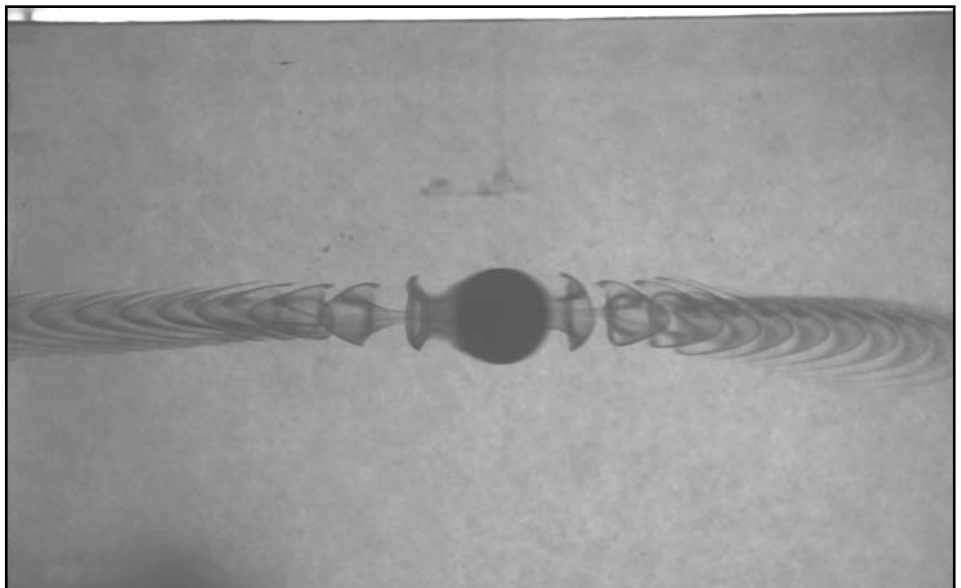
ysteresis of a pendulum subjected to rodynamic forces - The role of turbulence

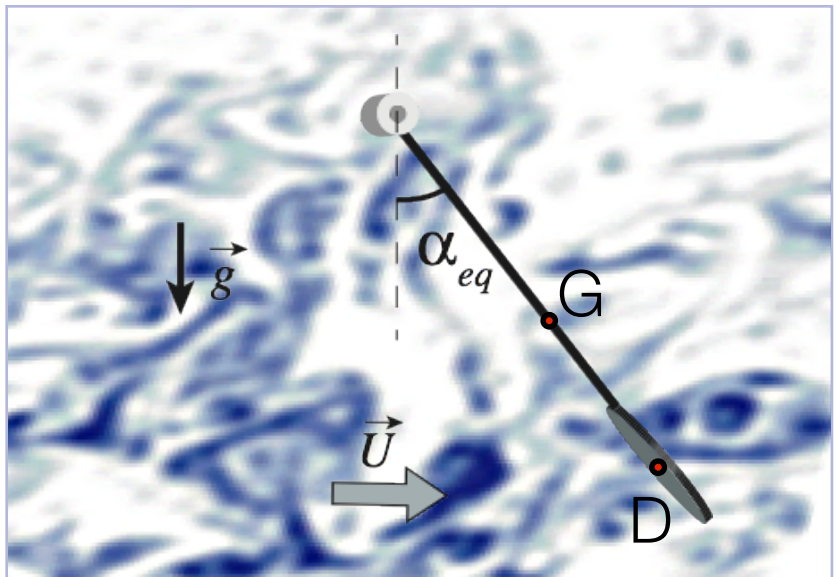
rtin Obligado
kaël Bourgoin
rtin Puy



he pendulum : still many open questions

- Coupling with fluid mechanics
  - Wake interactions (*Bolster et al., 2010*)
  - Added mass effects (*Neil et al., 2007*)
  - Influence of surrounding turbulence on equilibrium position
  - Influence of surrounding turbulence on oscillations
  - ...





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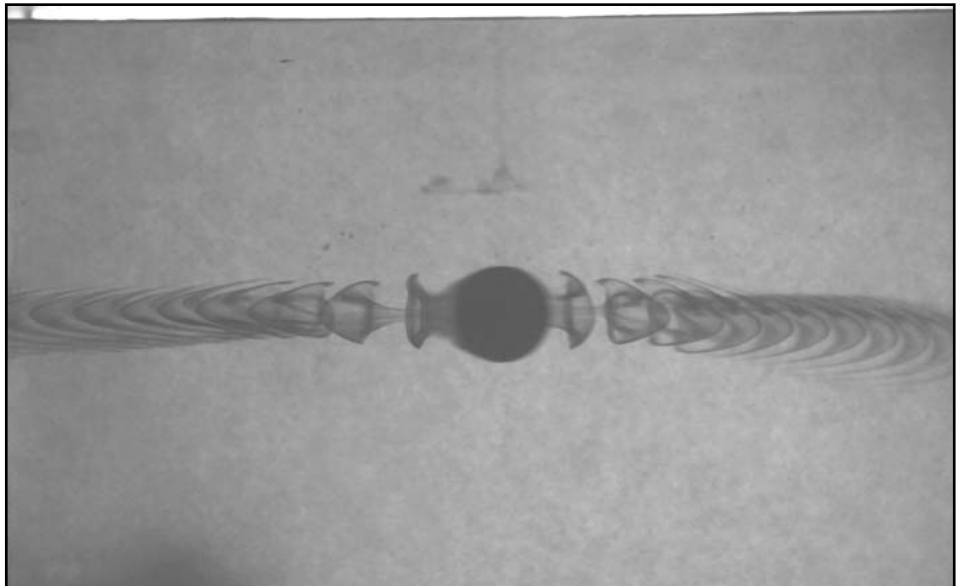
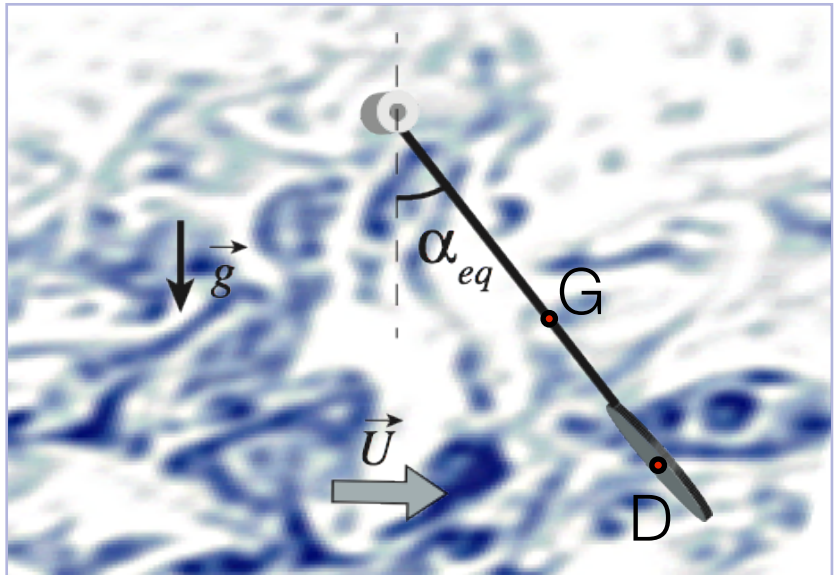
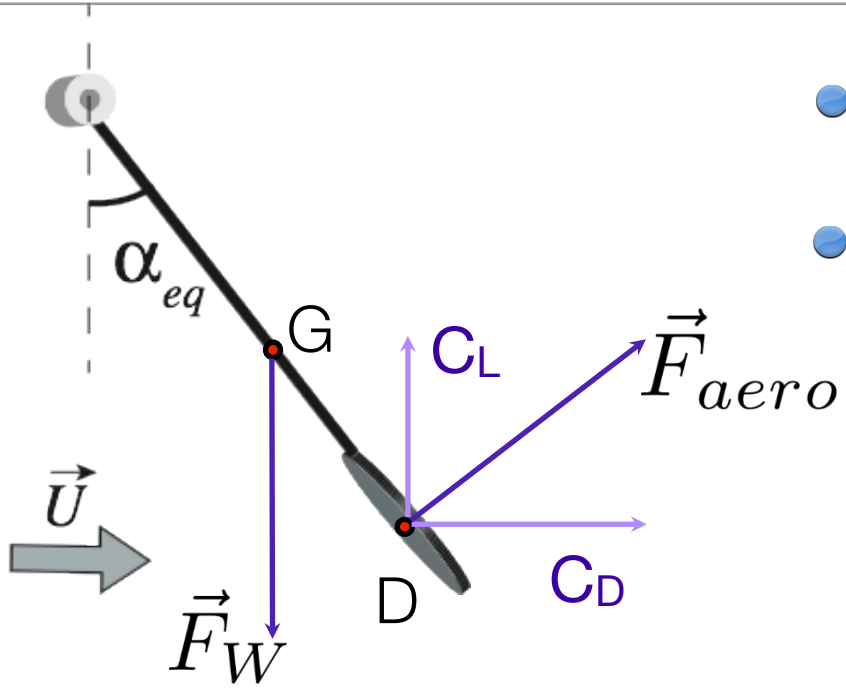




orces on the pendulum



- Weight $\vec{F}_W = -mg\vec{e}_y$
- Aerodynamic force $\vec{F}_{aero} = \vec{F}_D + \vec{F}_L$
  - Drag $\vec{F}_D = \frac{1}{2} C_D \rho S_D U^2 \vec{e}z$
  - Lift $\vec{F}_L = \frac{1}{2} C_L \rho S_D U^2 \vec{e}y$

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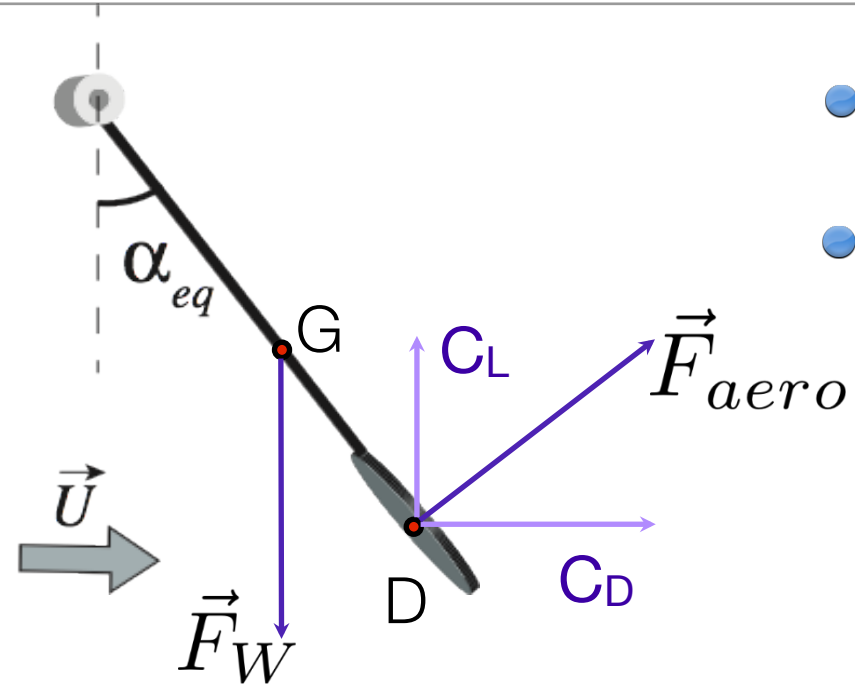

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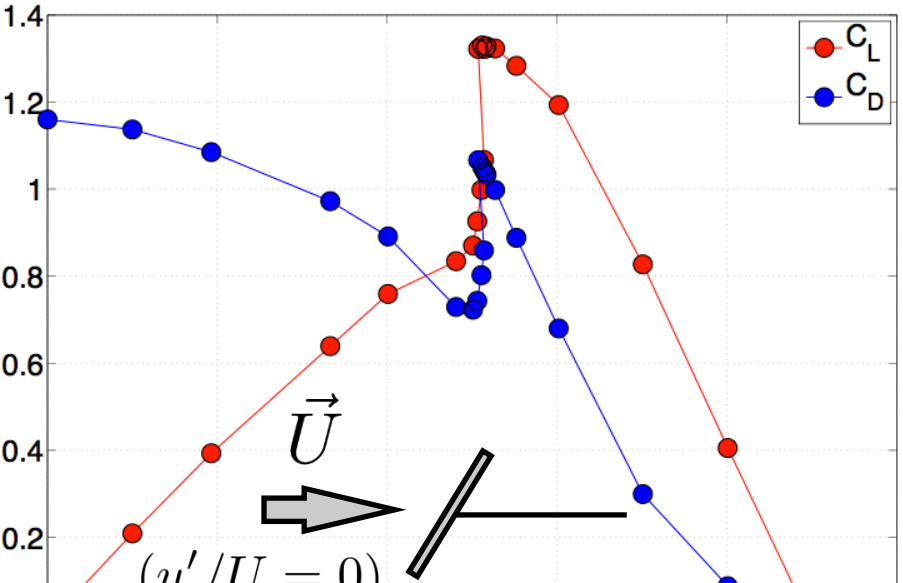

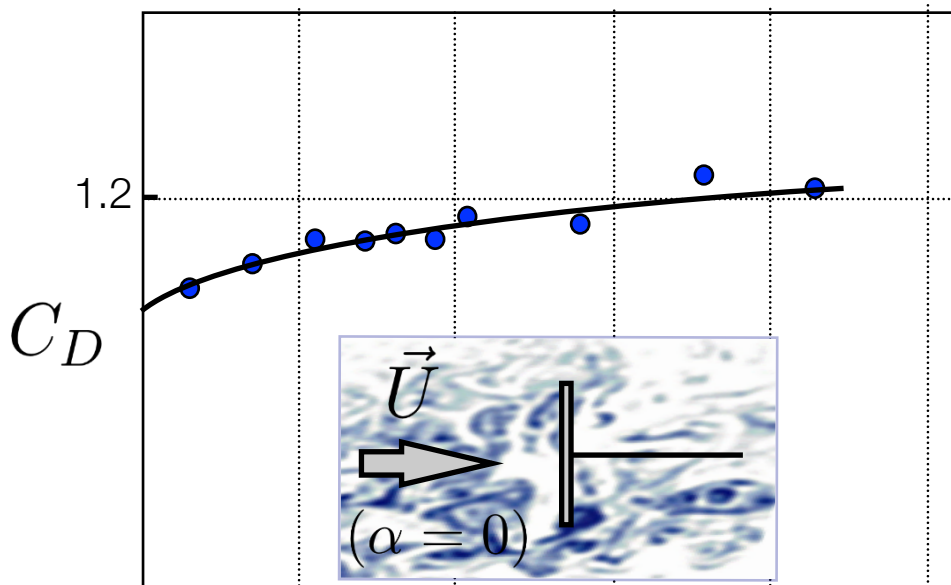

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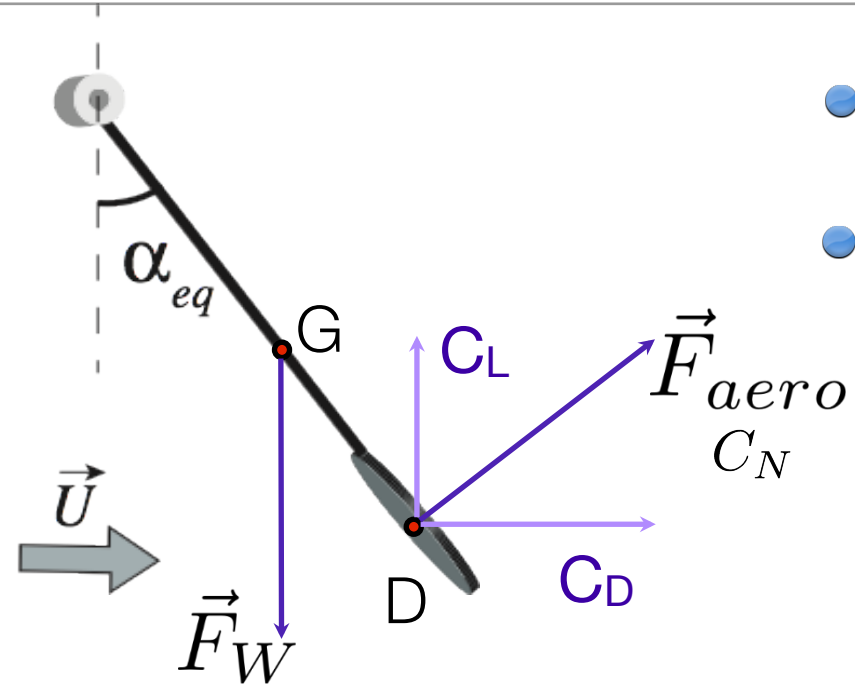

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Drag and lift coefficients depend on angle of attack and of turbulence rate.
How ? How does this affect the equilibrium of the pendulum ?

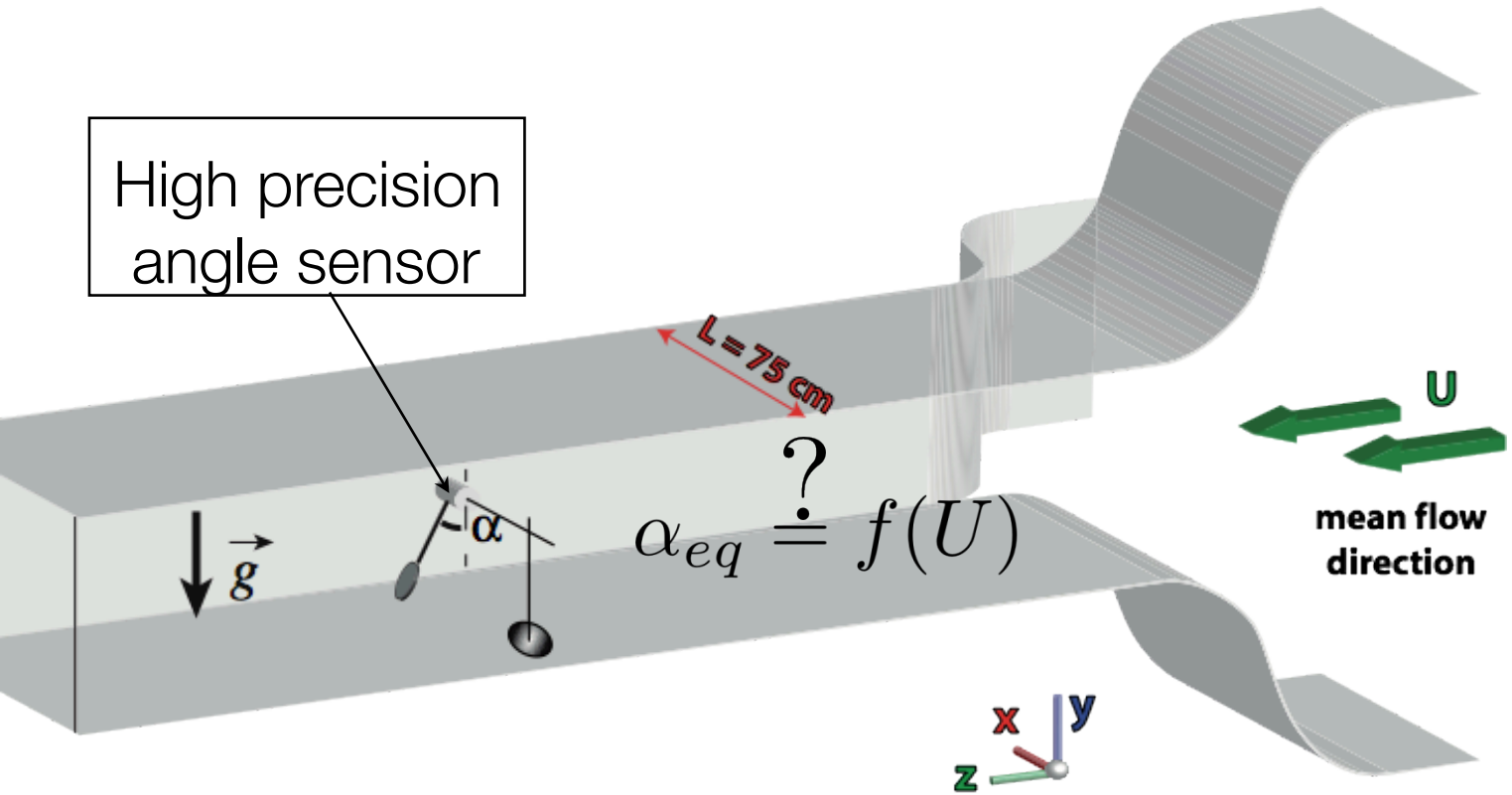
equilibrium

$$N_{aero} = mg\sin\alpha_{eq}\frac{L_{OG}}{}$$

From the equilibrium position we can measure the aerodynamic force **(lift + drag)** normal to the plate

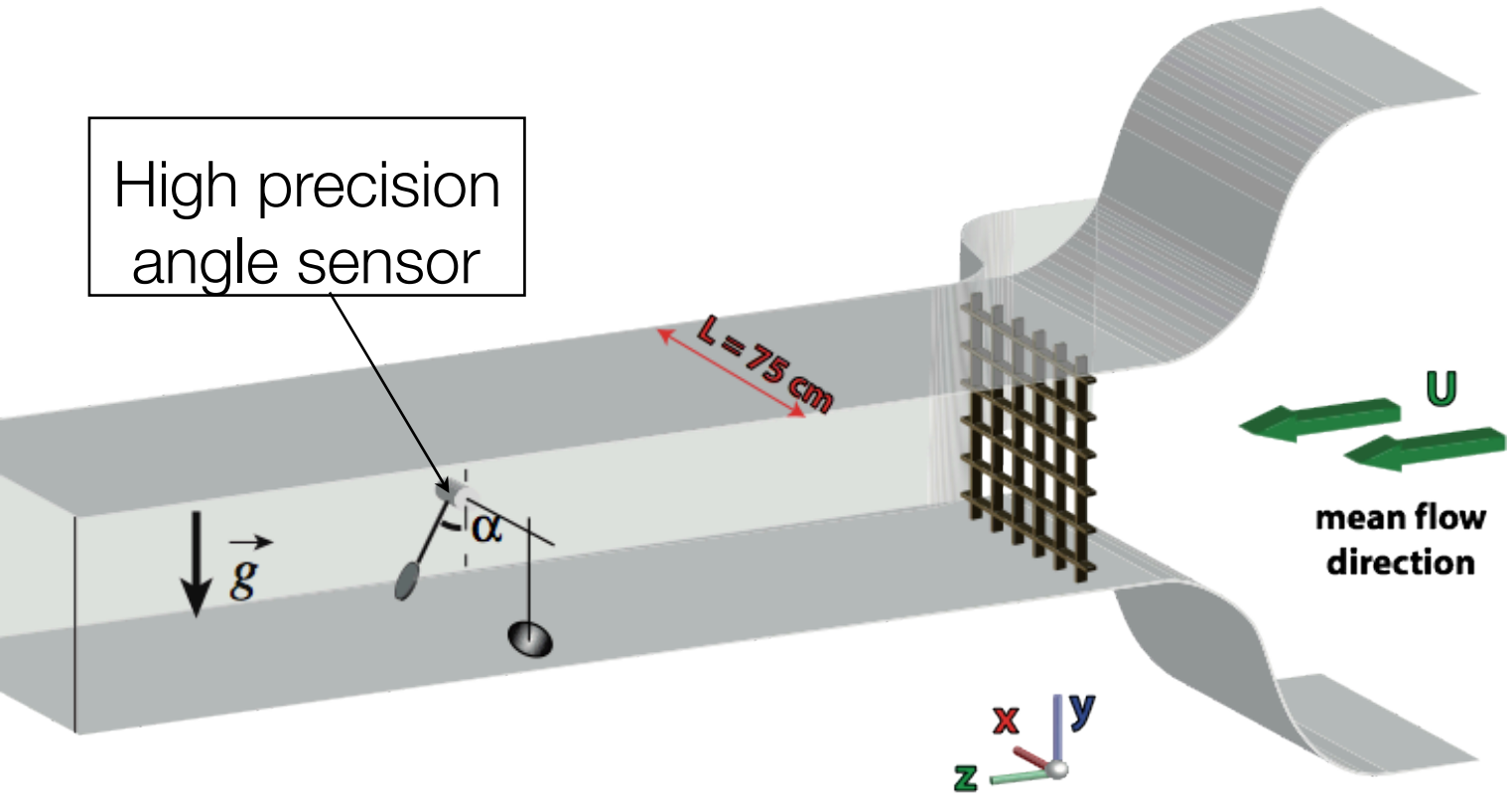
$$N = \frac{1}{}$$

xperimental setup - 1 (Laminar)



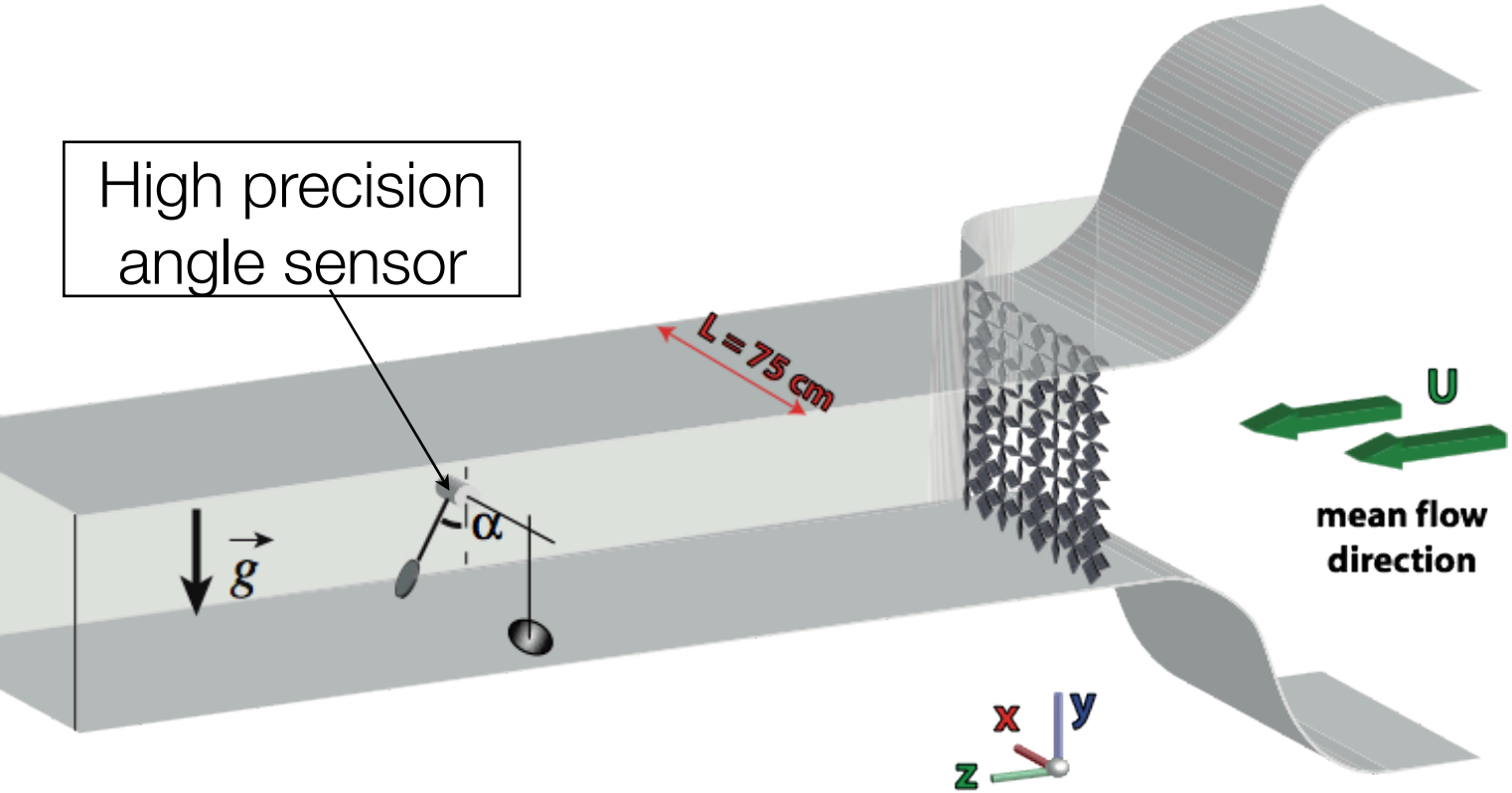
$u'/U = 5\,\%$

xperimental setup -2 (Moderate turbulence rate)



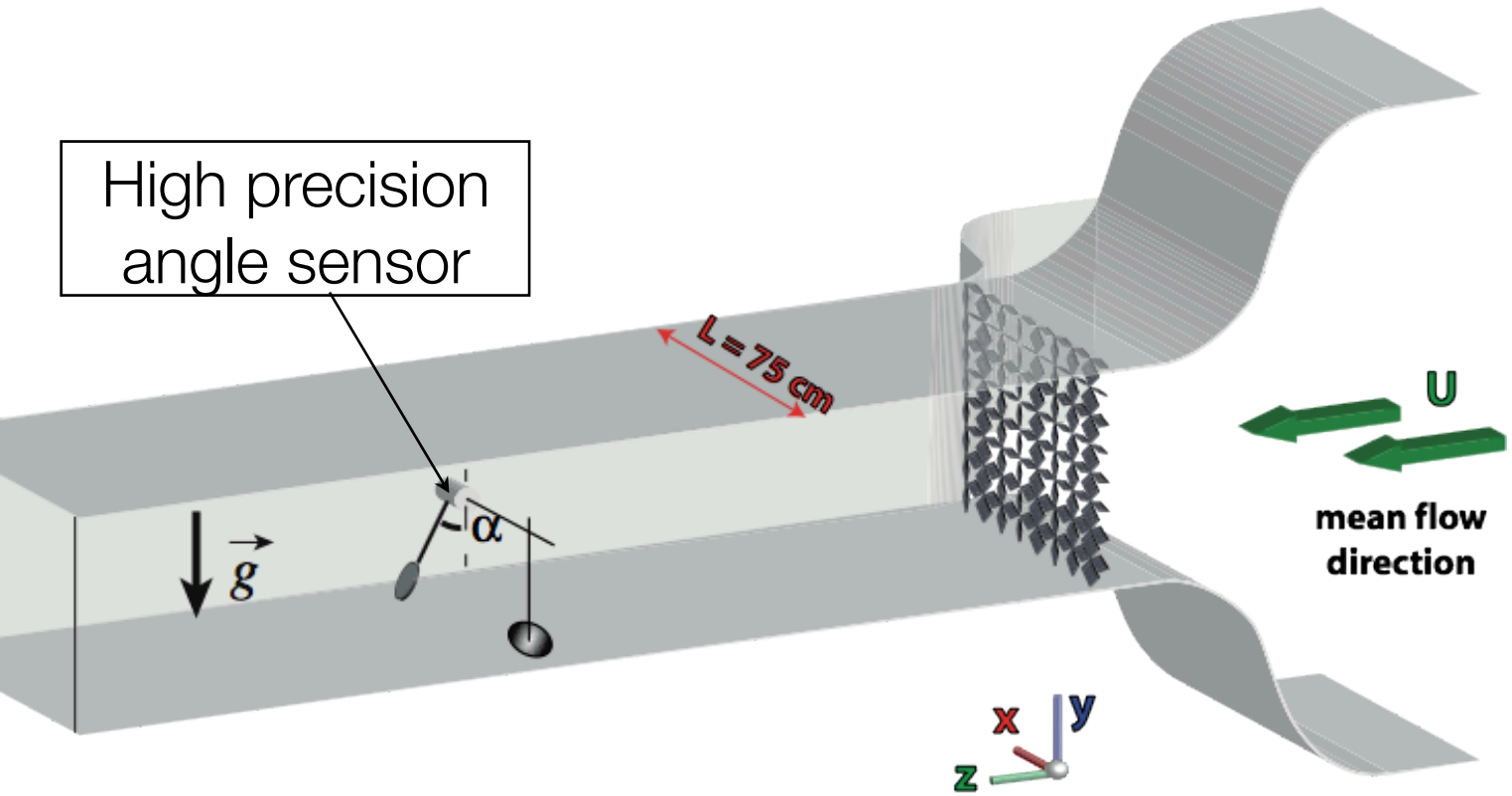
$$u'/U = 3\%$$

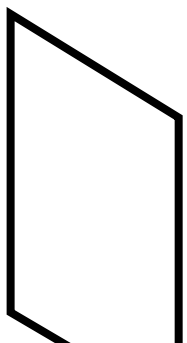
xperimental setup - 3 (high turbulence rate)

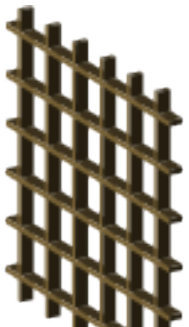


$$u'/U = 20\%$$

xperimental setups



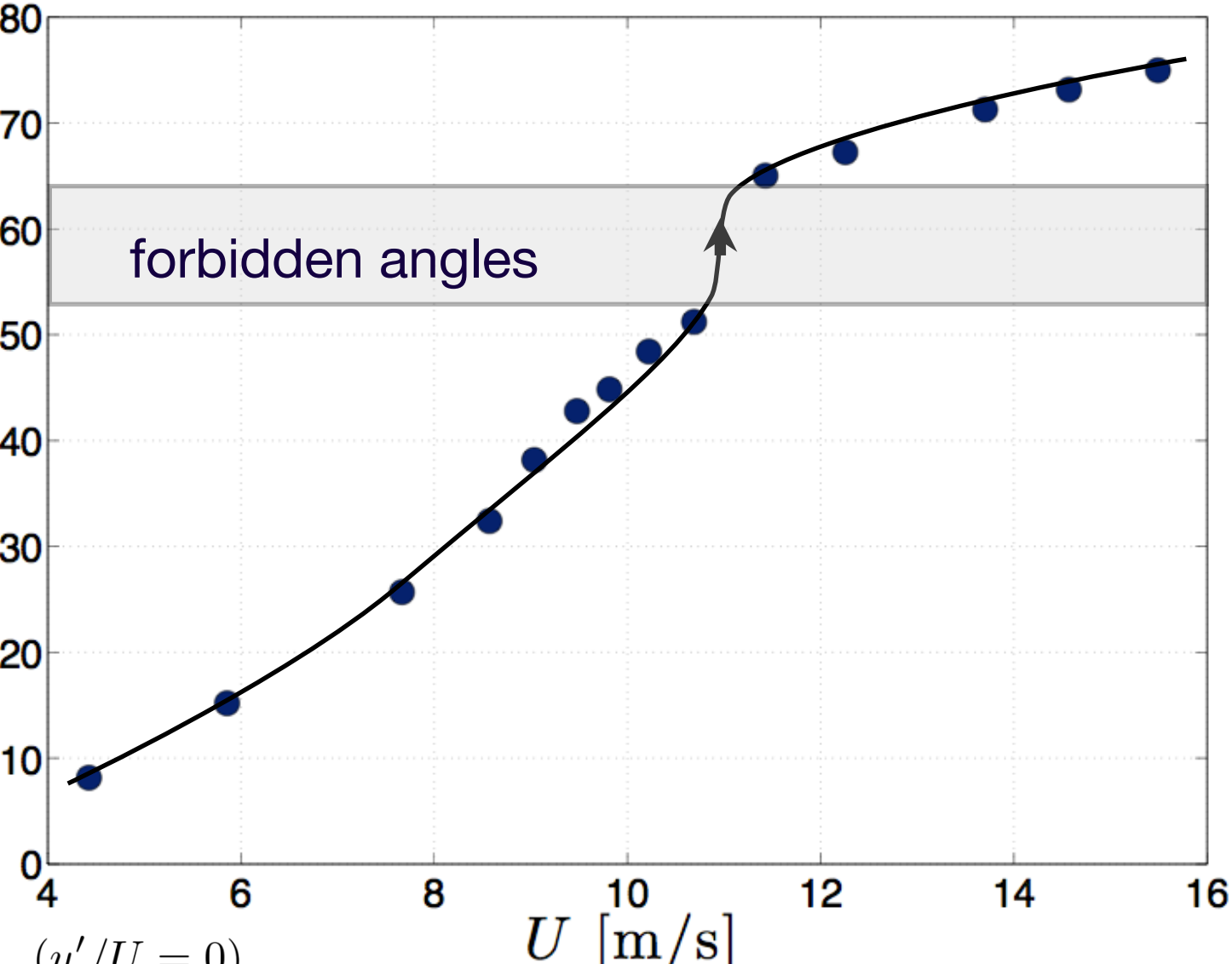




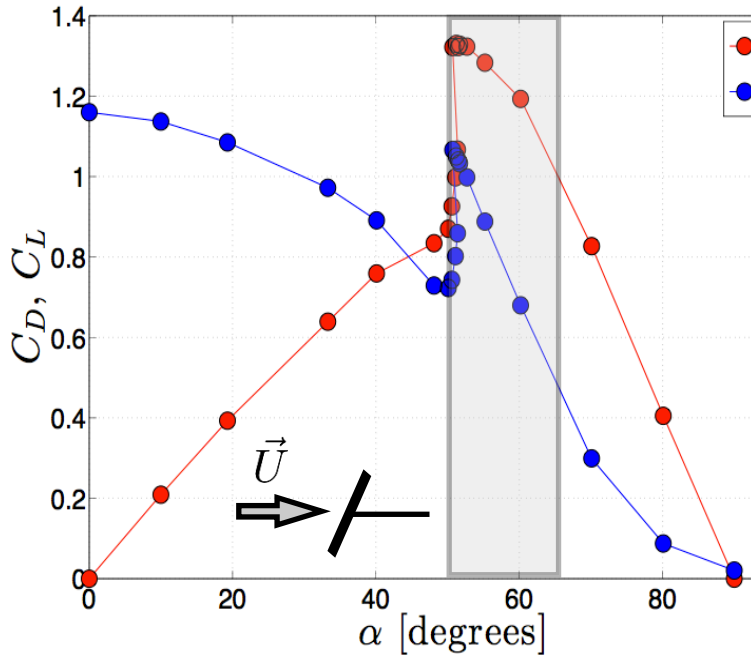
...inal case at **increasing** speed

...ilibrium angle of the pendulum

$u'/U =$



- sudden jump of equilibriu... position
- range of «forbidden angl...



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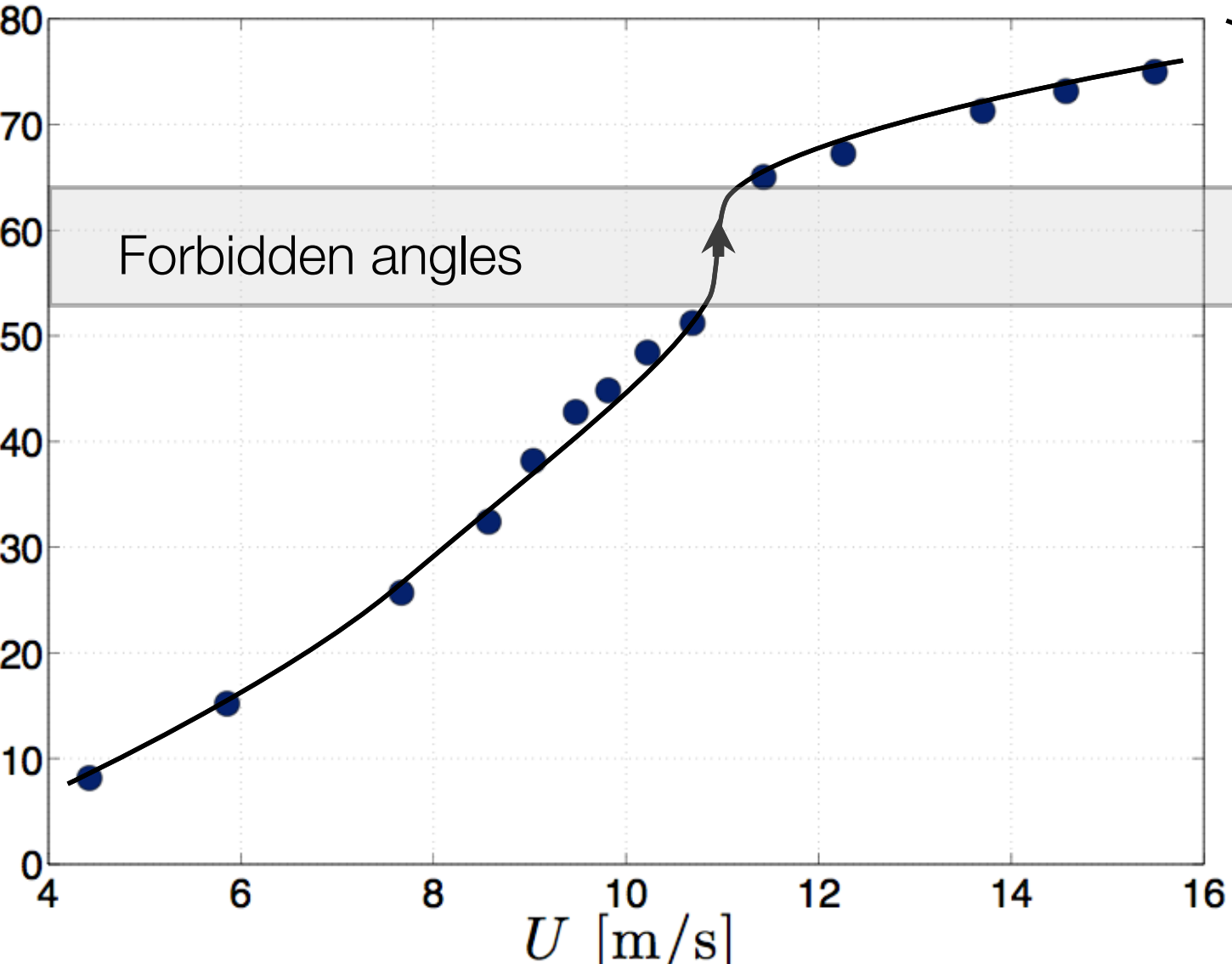
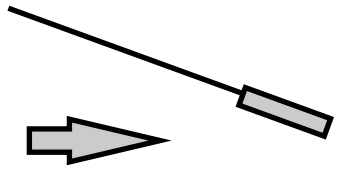
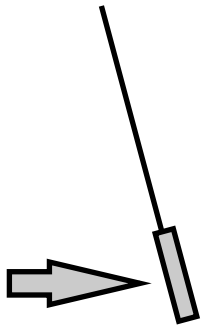




Lift dominates
The plate «flies»
in the wind

«Stall» of the plat

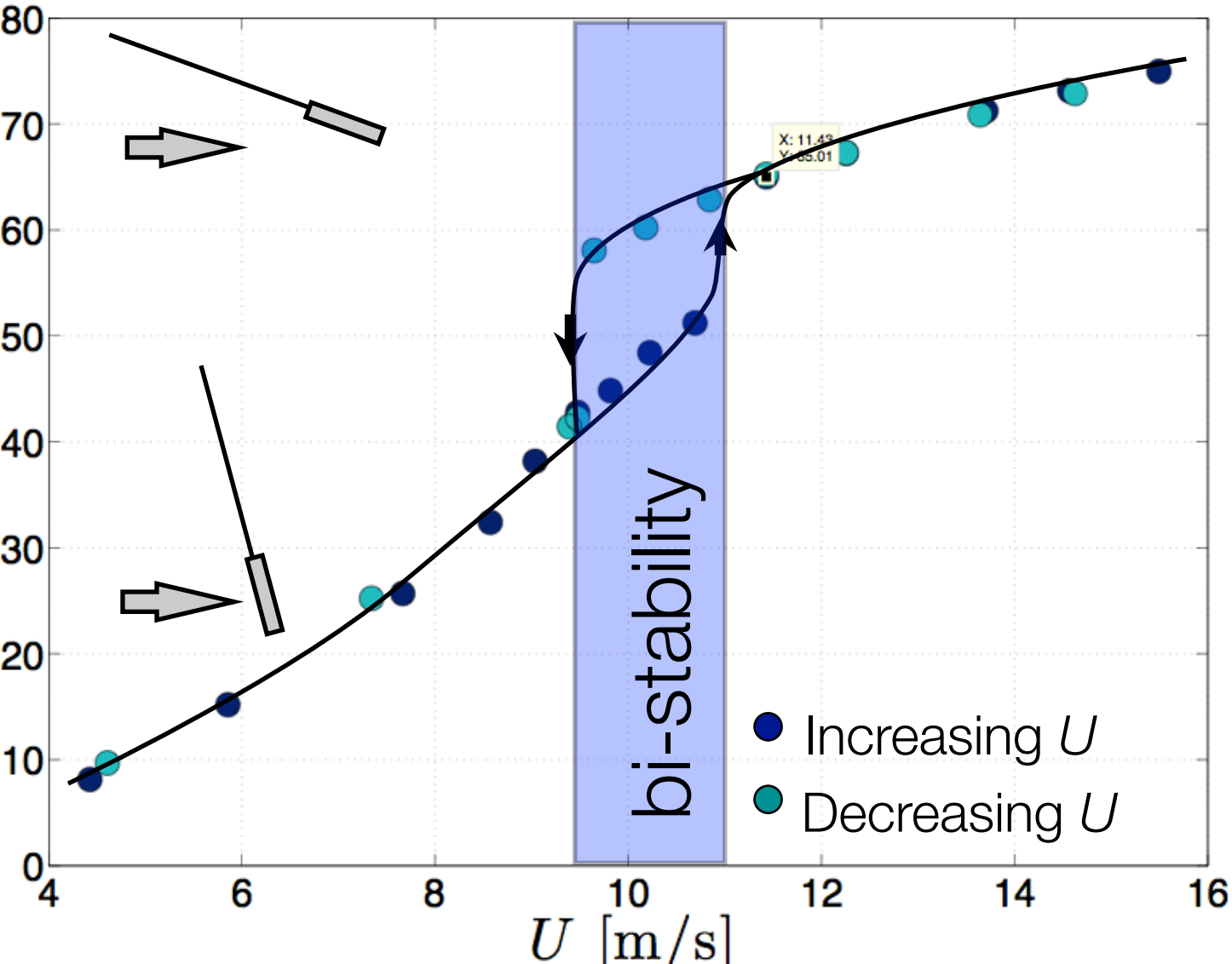


Drag dominates
The wind pushes
the plate

...inal case at **decreasing** speed

...ilibrium angle of the pendulum

$u'/U =$



- Hysteretic behavior

  (bi-stability of the pendul

- Extended «Lift dominatec branch

- almost not «forbidden an the overall

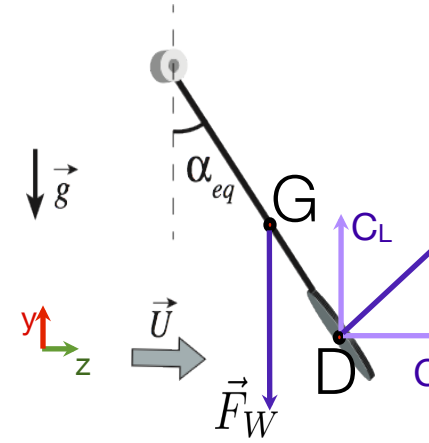
Terminal case at **decreasing** speed

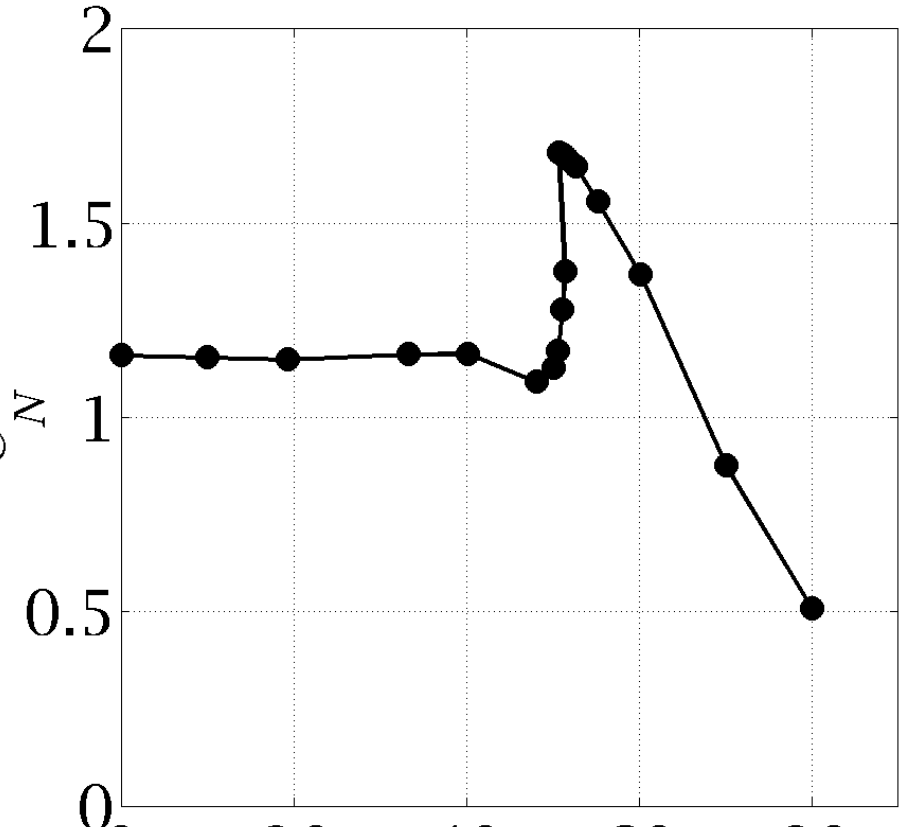
Equilibrium angle of the pendulum

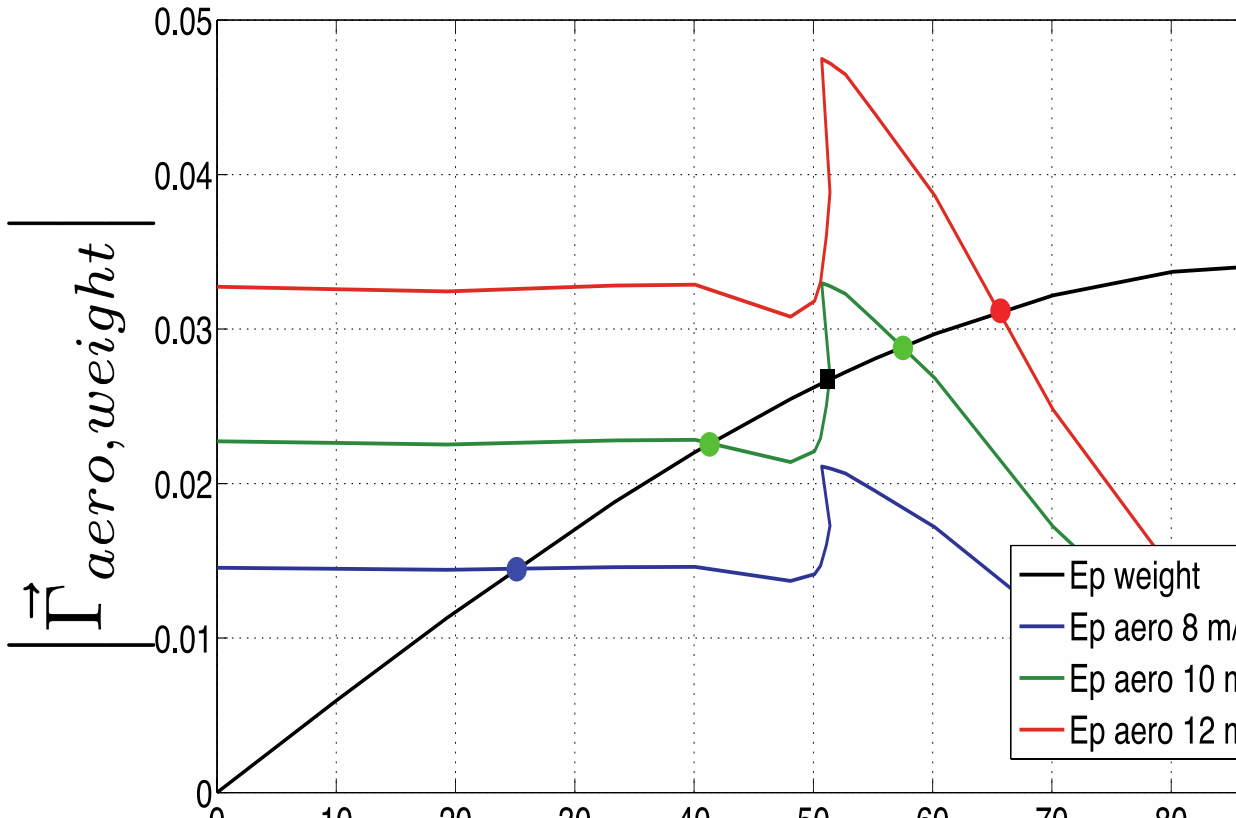
$u'/U =$

$$\vec{\Gamma}_{weight}(\alpha) = mgL_{OG}\sin\alpha\vec{e}_x$$

$$\vec{\Gamma}_{aero}(\alpha) = -\frac{1}{2}L_{OD}\rho S_d C_N(\alpha)U^2\vec{e}_x$$







...inal case at **decreasing** speed

...ilibrium angle of the pendulum

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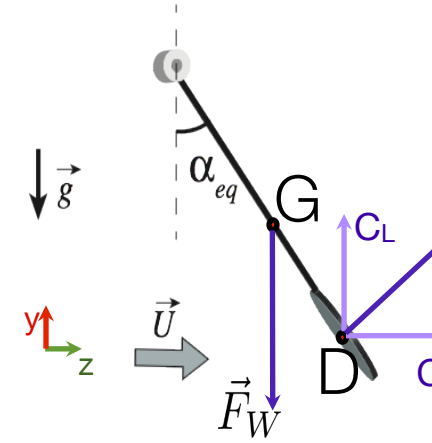

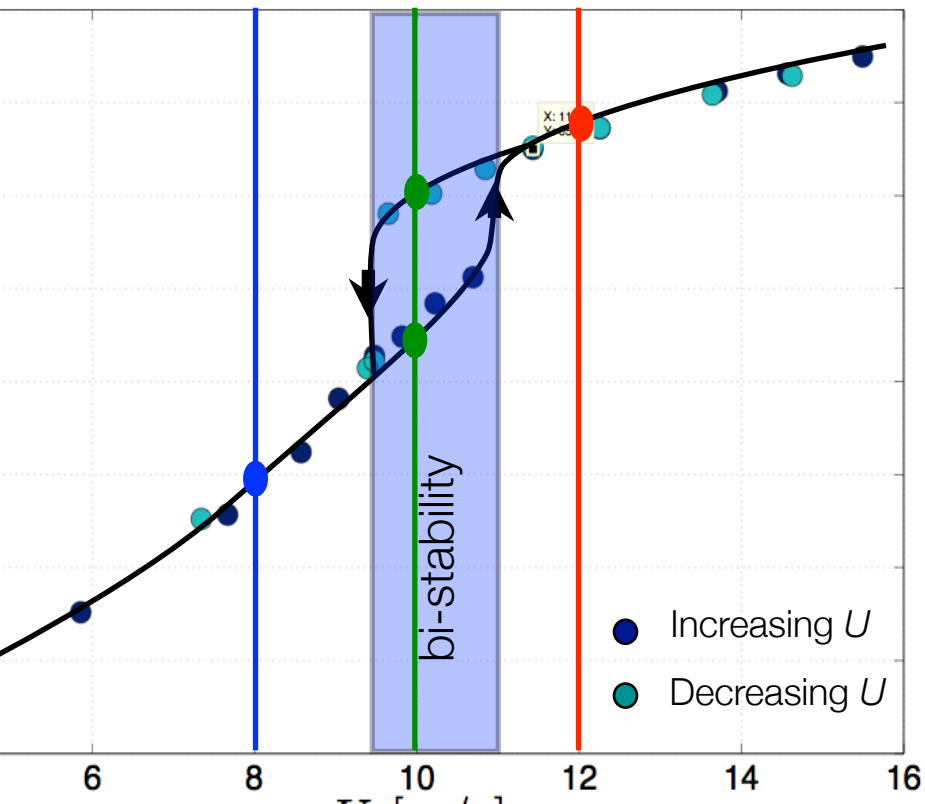

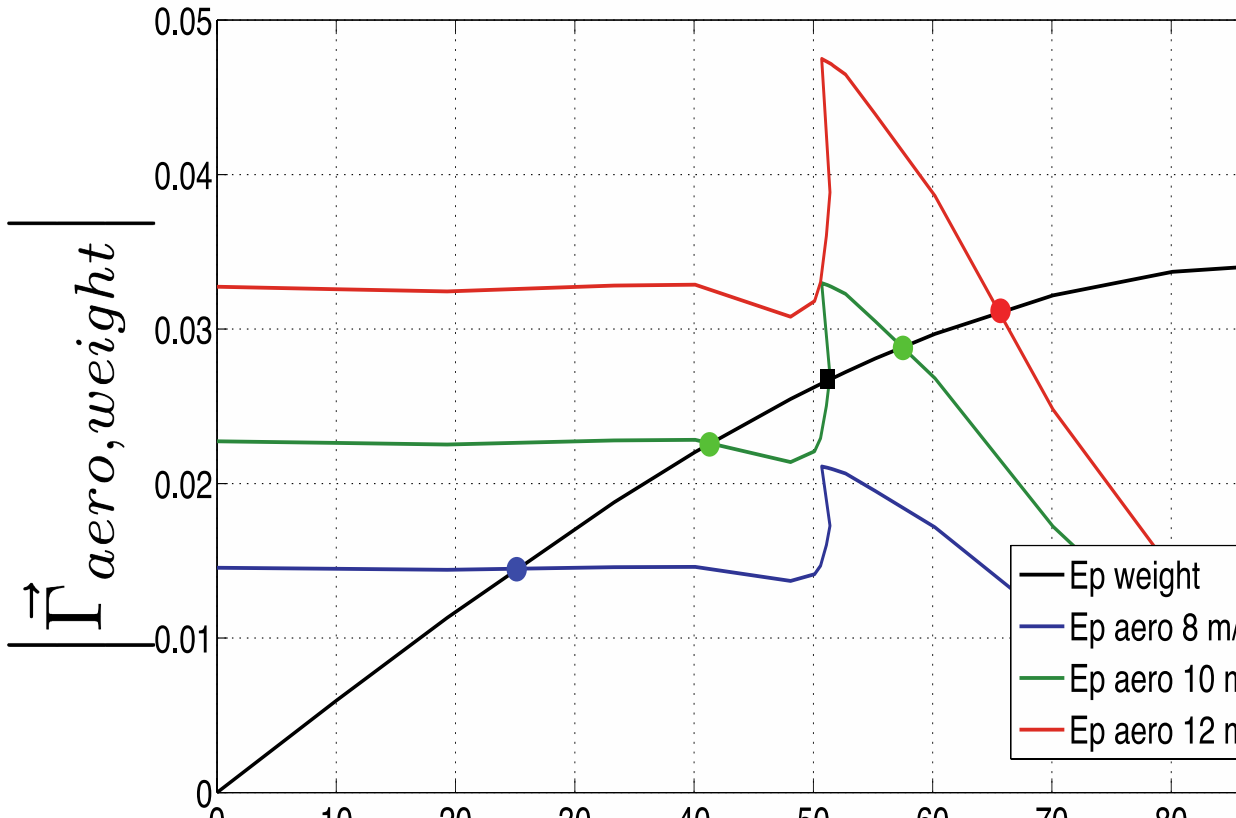

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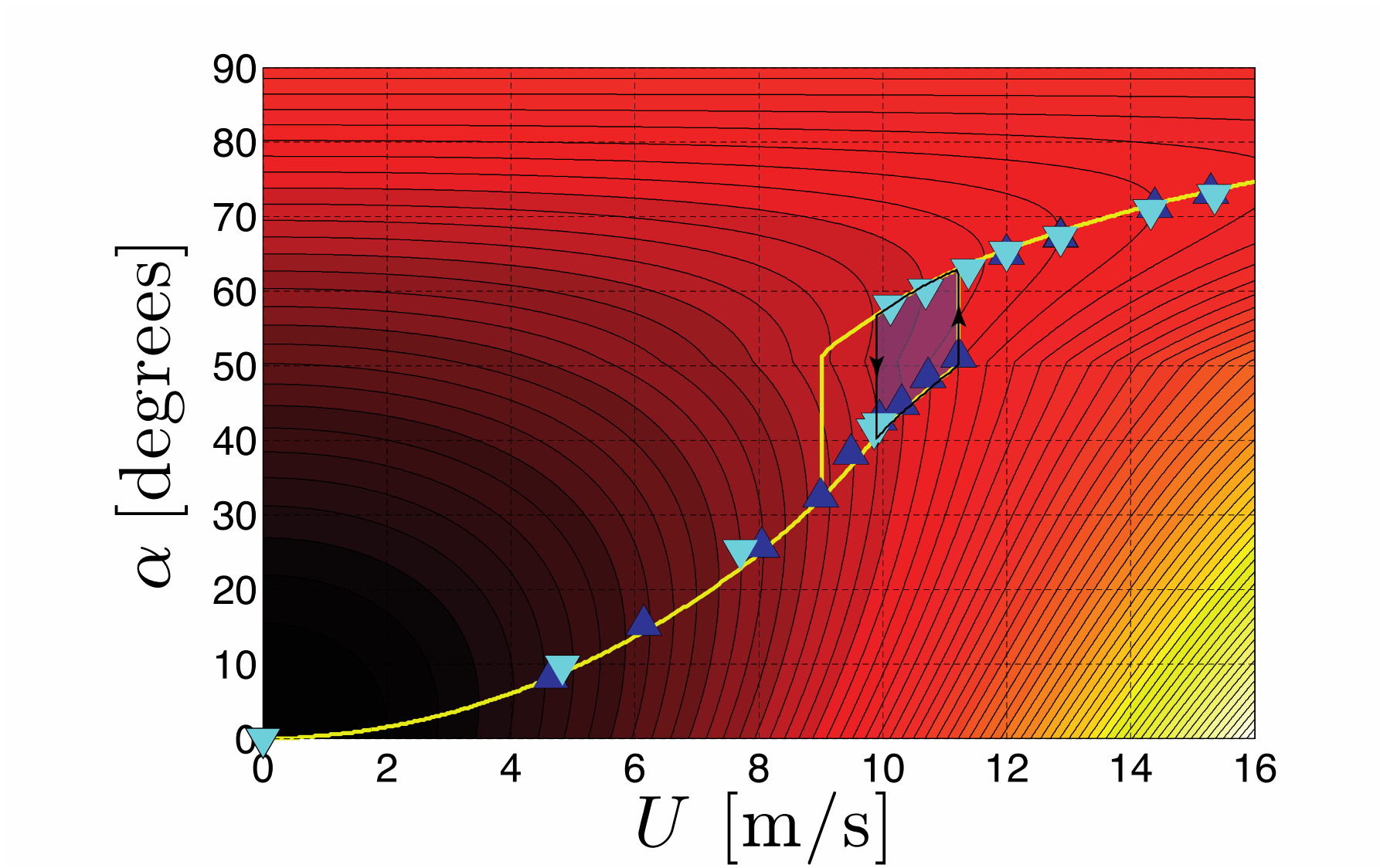
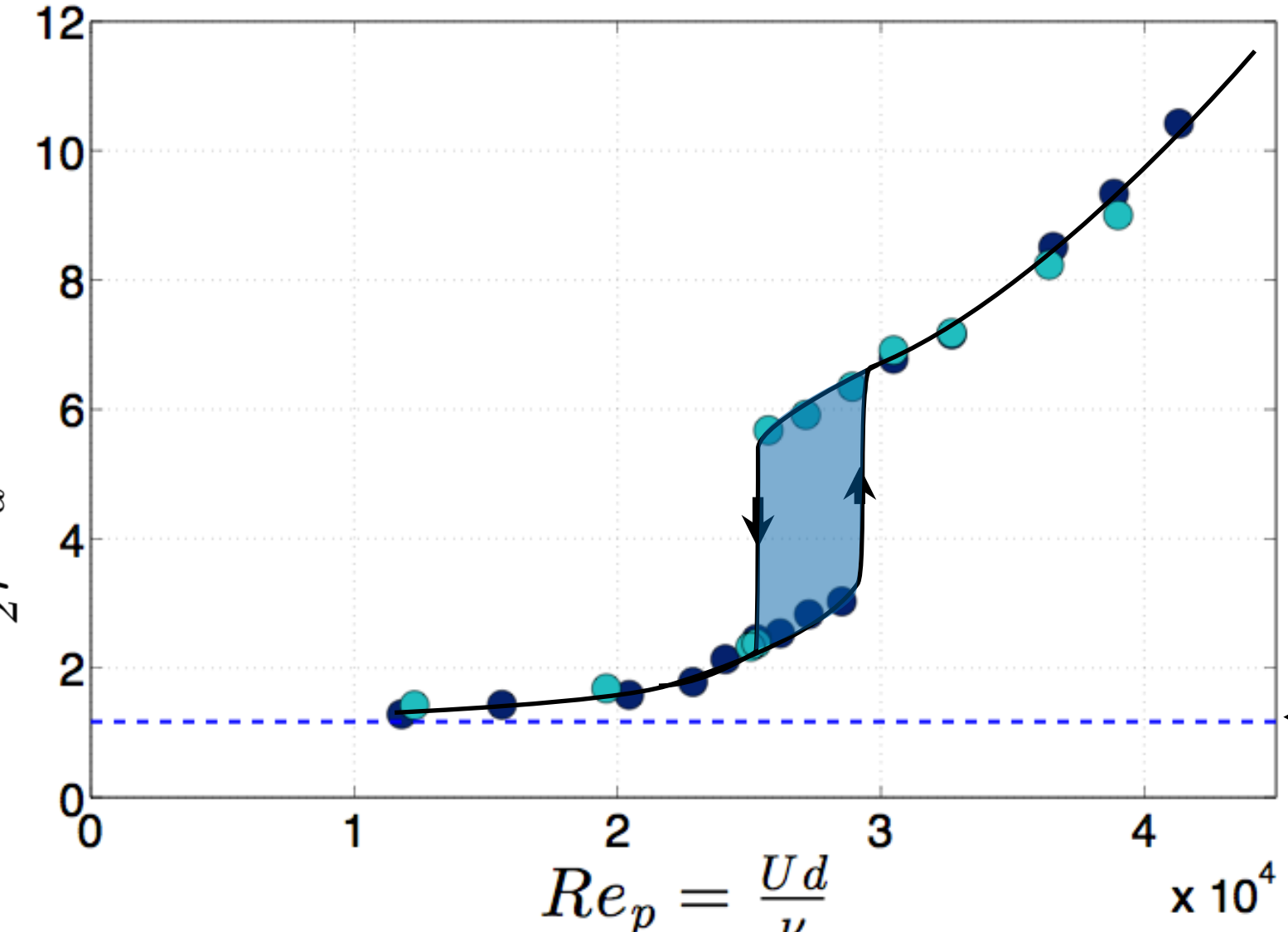


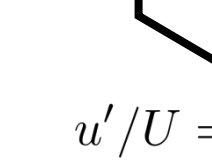
$$...ght = mgL_{OG}(1 - \cos(\alpha))$$

$$E_p^{tot} = E_p^{weight} + E$$

ysteretic aerodynamic force

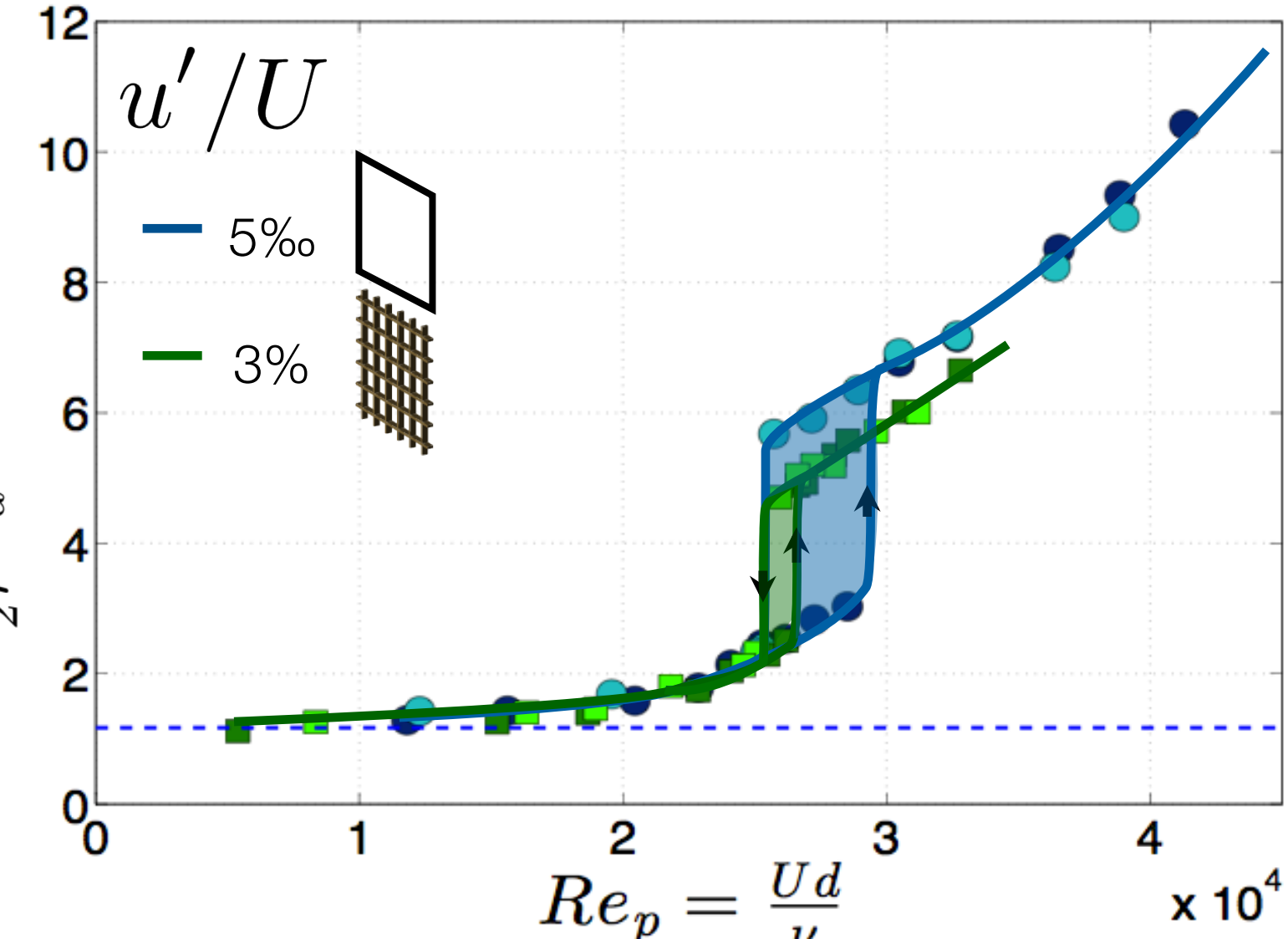
$u'/U =$





...uence of turbulence rate

...derate turbulence level



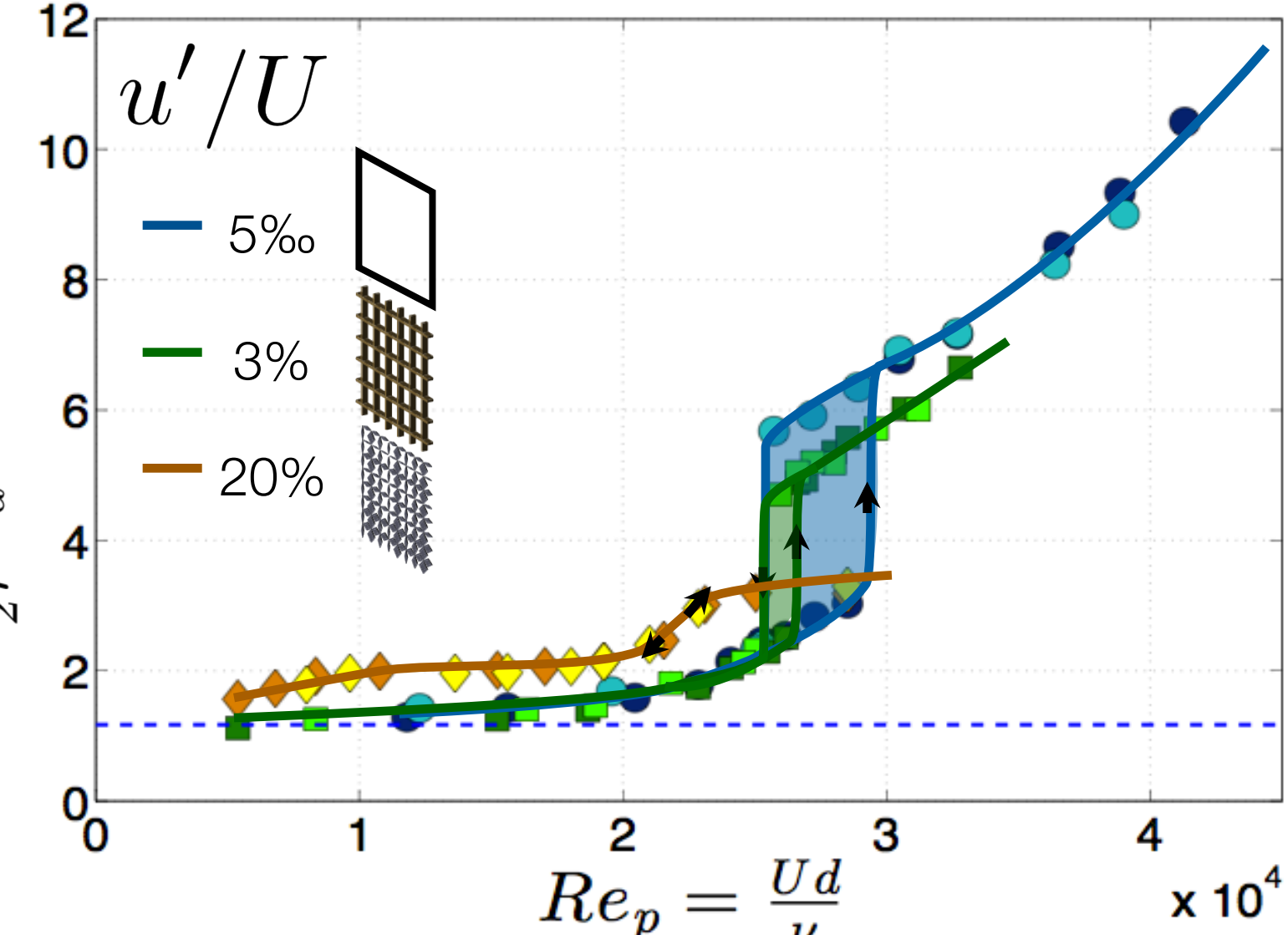
At moderate turbulen...

- Drag branch unchan...
- Lift is reduced (plate flies less)
- Hysteretis is reduce...

...dence of turbulence rate

...derate turbulence level

$u'/U =$



At high turbulence

- Increase of drag
- Reduction of lift (c... does not fly)
- Hysteretis disapp...

ke home message

We still have to learn from the pendulum
(good system to probe fluid mechanics issues)

A plate pendulum is *bi-stable in a laminar flow*
with a *hysteretic* transition from *drag* to *lift* dominated equilibrium

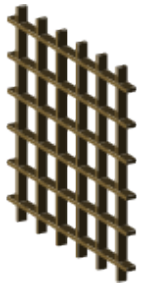
Turbulence :
bi-stability is reduced
lift is reduced
drag is increased

} *disappear at 20% of turbulence*
(no turbulent flight)

do

Oscillations around the hysteretic angles (laminar)

Oscillations in drag and lift dominated regions



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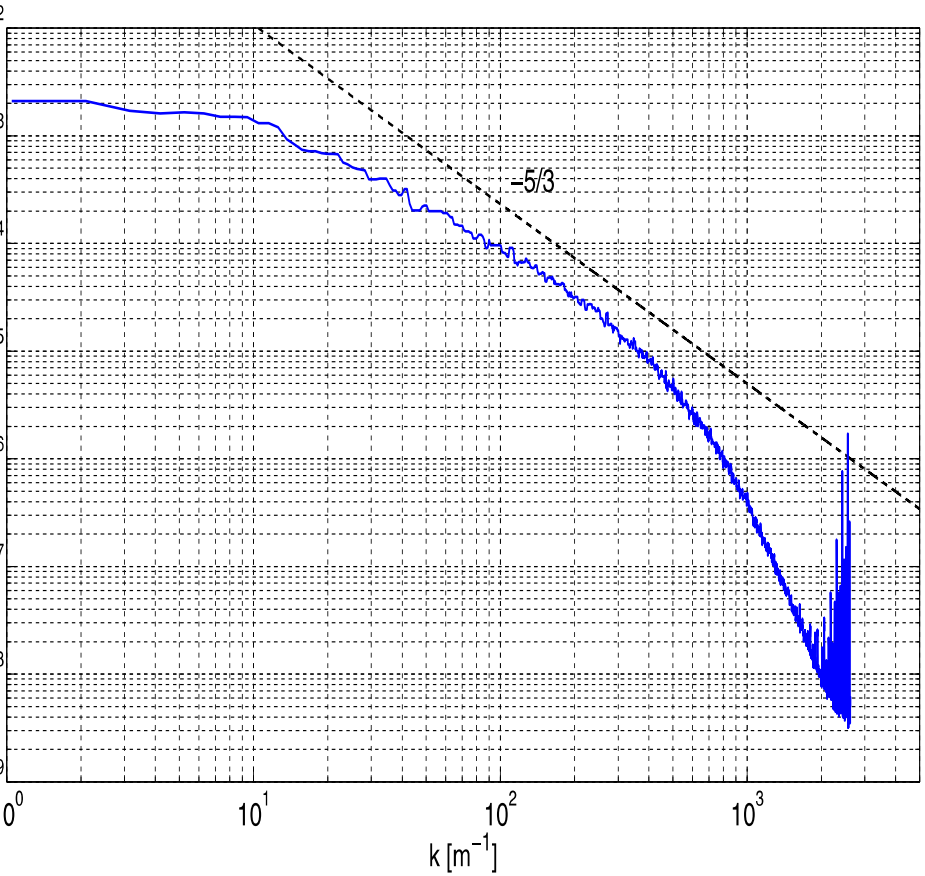

$u'/U = 20\%$