Flow sensing for improved wake harvesting in formation flight

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Intelligent and Bio-Inspired Mechanics seminar series

UCLouvain
Institute of Mechanics, Materials and Civil Engineering

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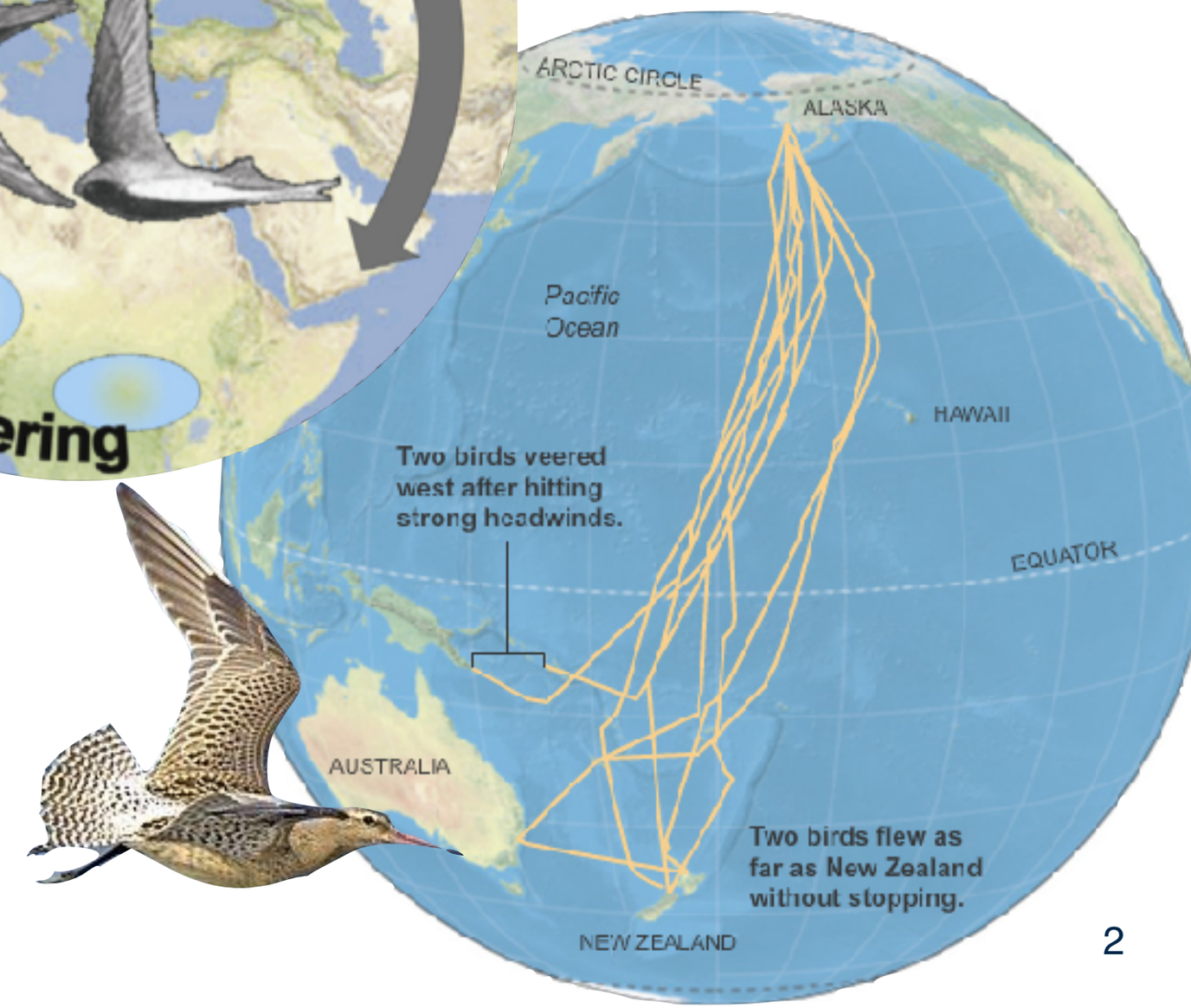
A formidable source of inspiration…



Migrating birds fly in formation

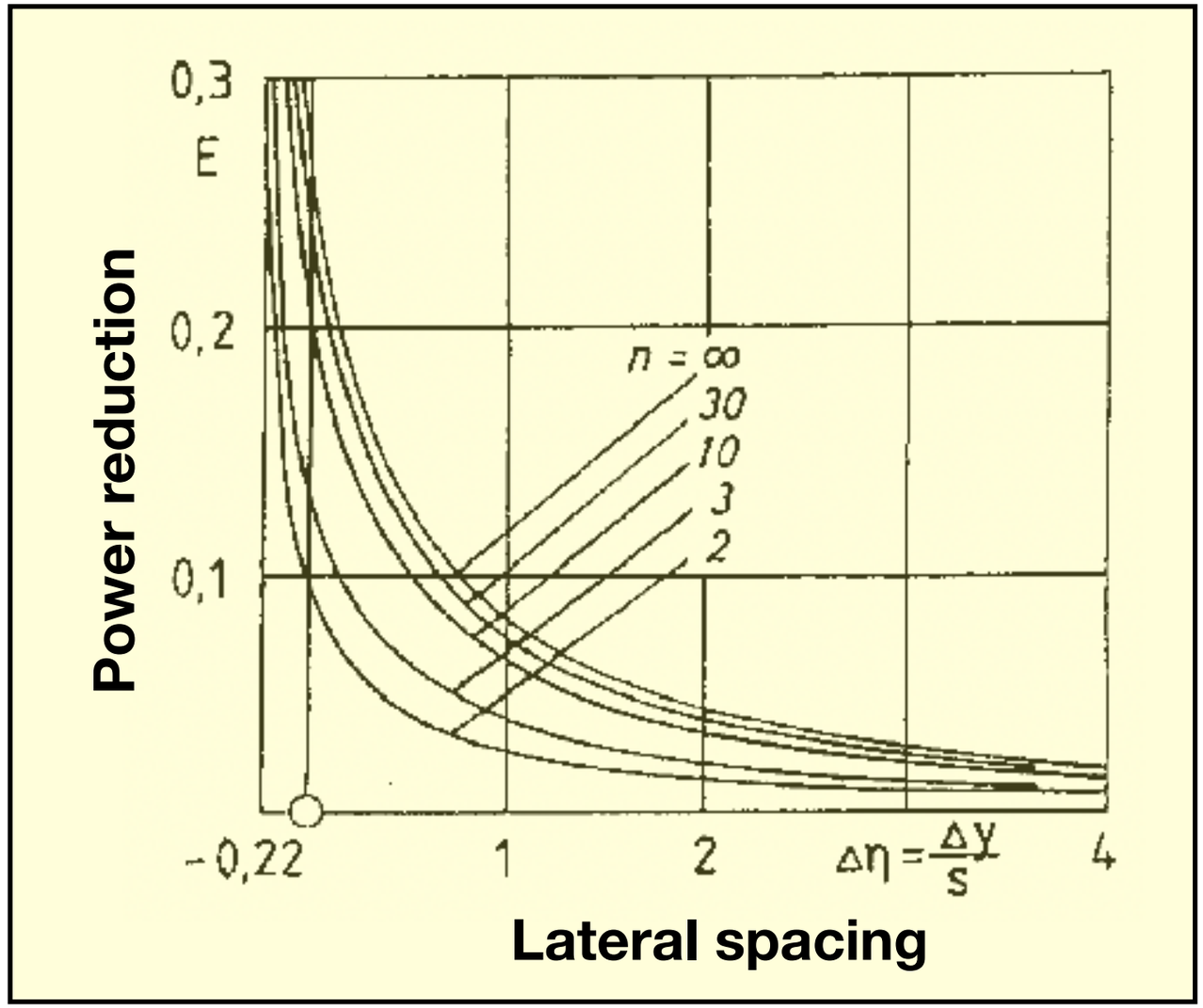
Credit: Peter Pearsall

Credit: Markus Unsöld

Credit: Richard Wignall

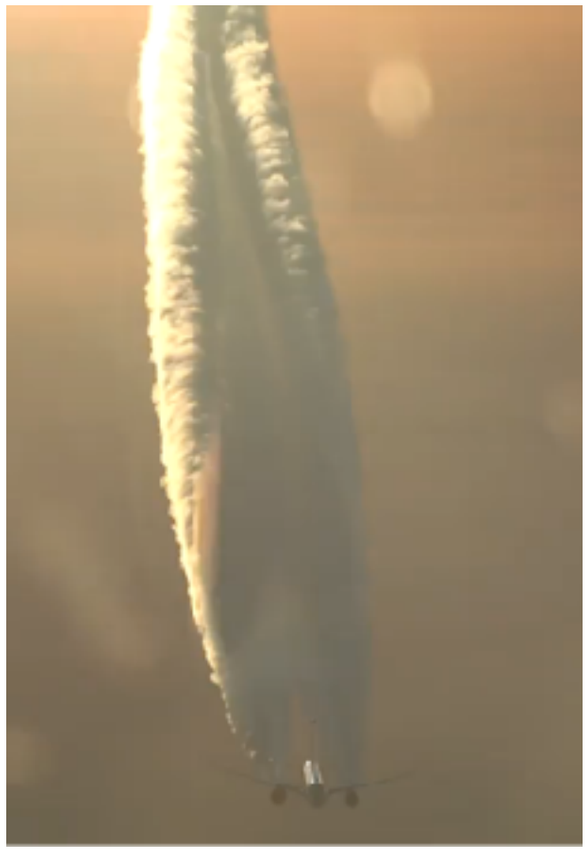
Fundamentals of formation flight: history

- **The first to show it theoretically**
  - Munk, NACA, 1923
  - Maskew, NASA, 1977
  - Hummel, J. theor. biol., 1983
  - …



- **Max power reduction >20% for 2 similar individuals**

Formation Flight & Wake Surfing



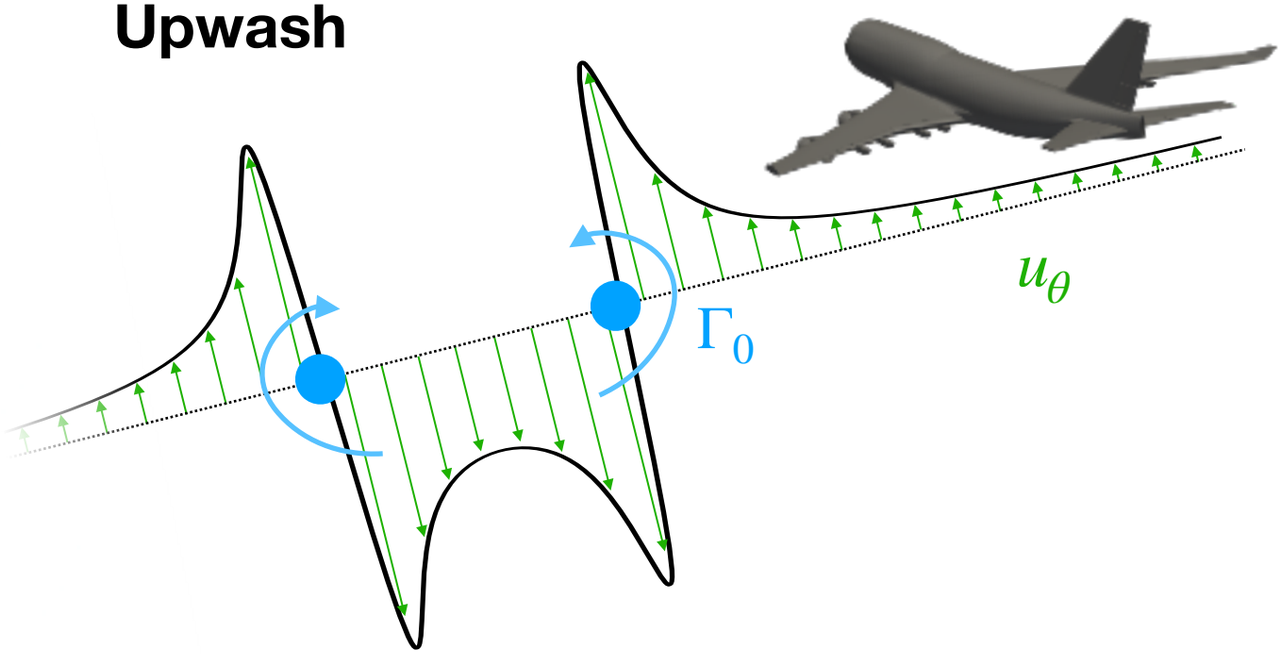
credit: LouB747, www.youtube.com/watch?v=epa6WxEw1Xk

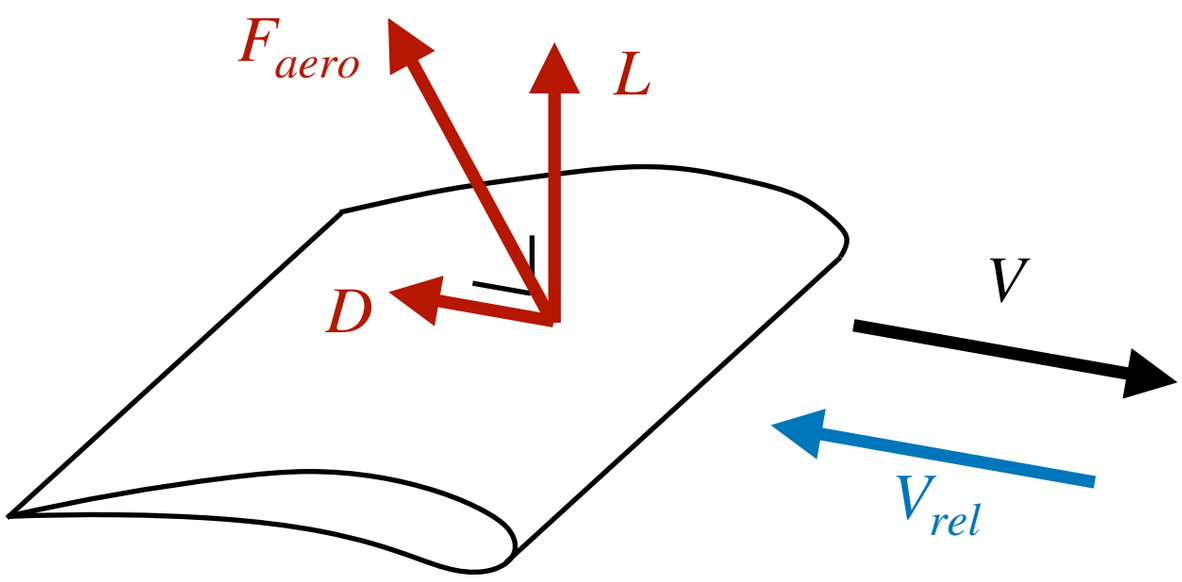
credit: pinterest.fr

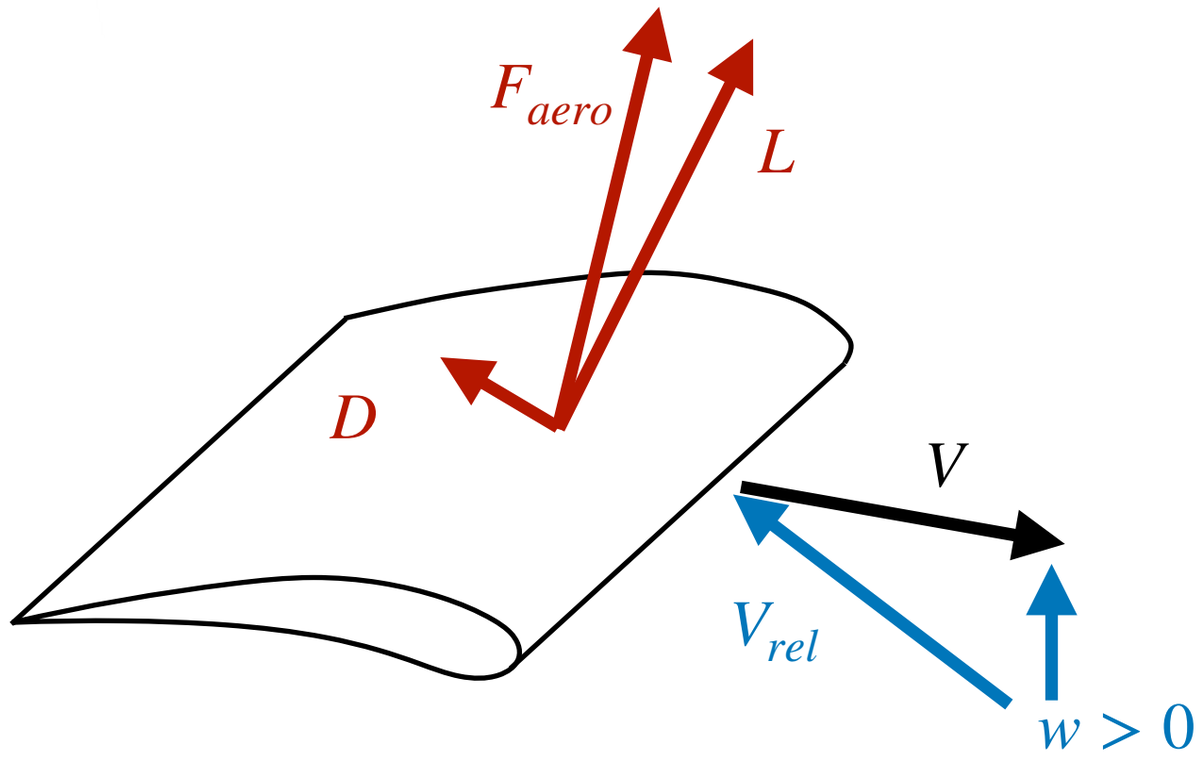
Aerodynamic benefit

Isolated

Upwash







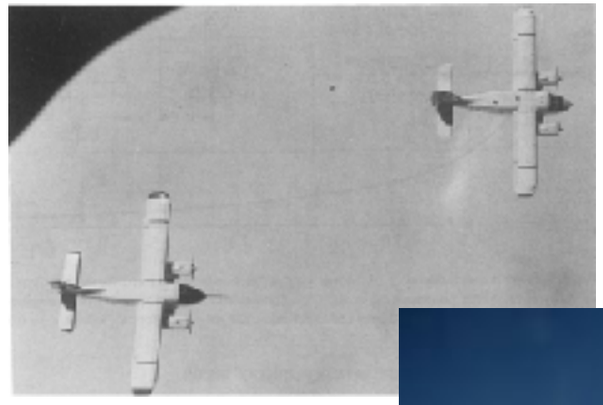
Experiment in formation flight

- **Hummel (90's)**
  - Actual savings around 10%

- **NASA (2003 and 2018)**
  - Savings between 18 and 22%
  - Up to 10% fuel flow reduction
    - limited to 3% for smooth ride

- **SAVE experiment with C-17s (2012)**
  - Fuel savings of about 10%

- **Boing Ecodemonstrator (2019)**
- **Airbus Fello'fly (2021)**



credit: Hummel, 1995

credits: NASA

credits: USAF

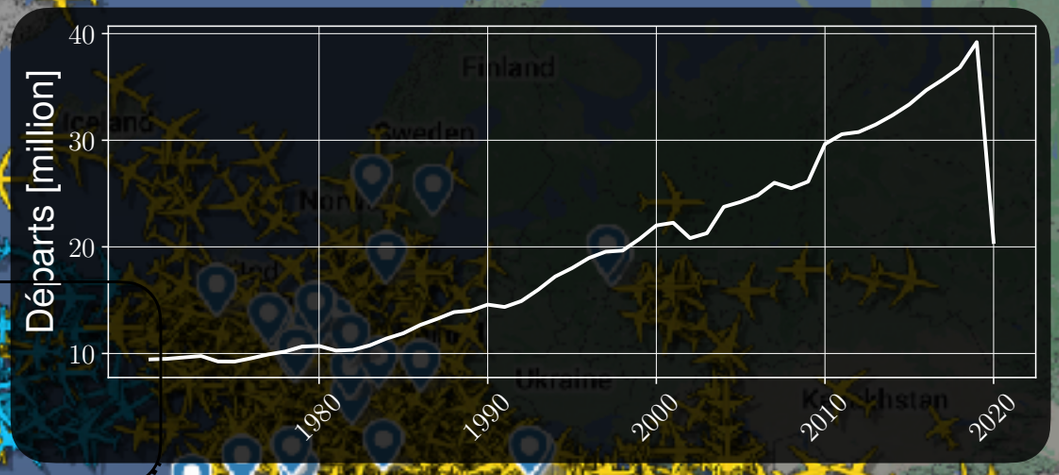
credits: Airbus

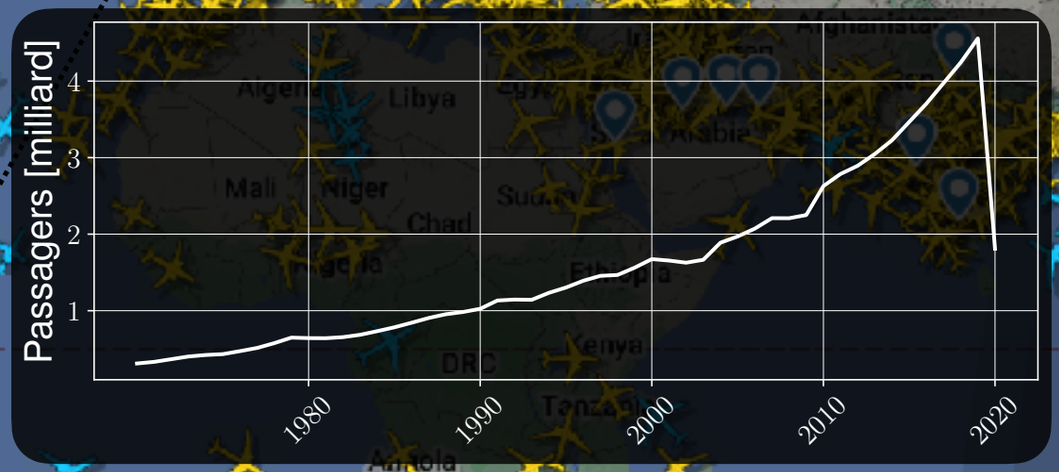
flightradar24
LIVE AIR TRAFFIC

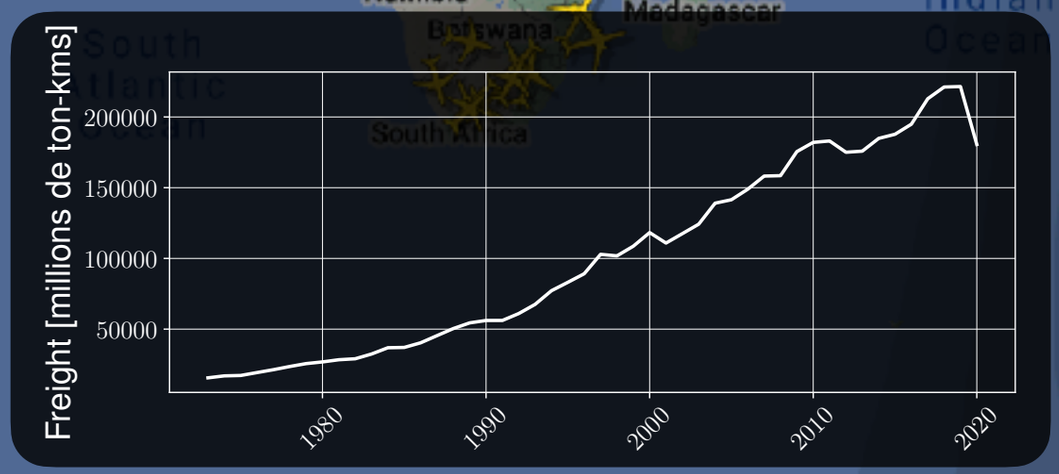
UTC 12:47

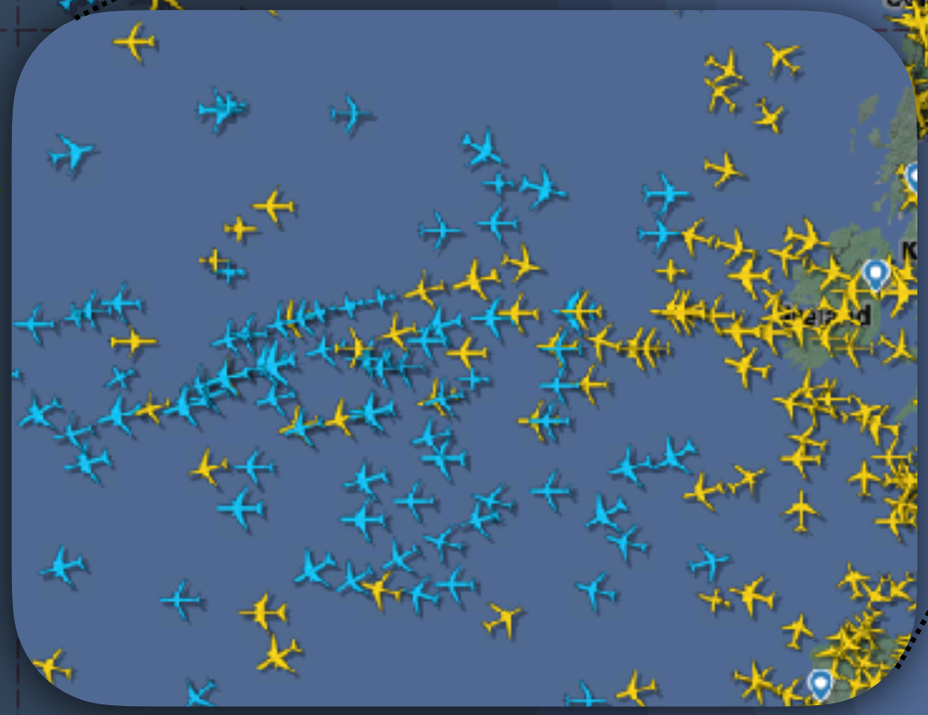
In 2019 worldwide:

- 110 000 flights per day on average
- 4.5 billion passengers
- 220 000 million ton-kms *freight*

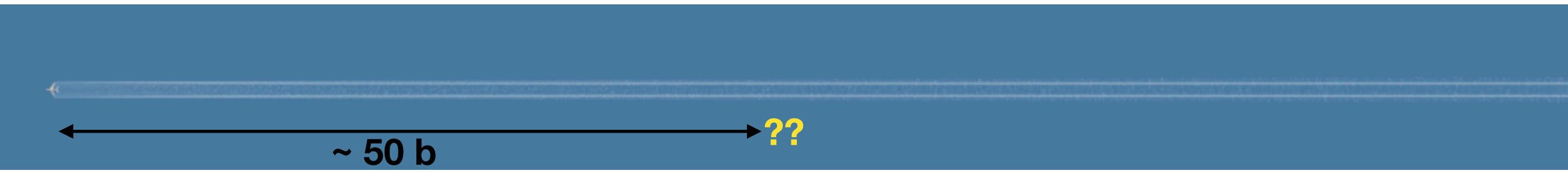








Challenges of extended formation flight



- **How can we guarantee safety:**
  - during the approach of the vortex?
  - regarding vortex encounter?
- **How to locate the vortex?**
- **Is there significant discomfort?**
- **How many aircraft can safely join the same formation?**
- **How to integrate formation flight in ATM?**
- **…**

Outline

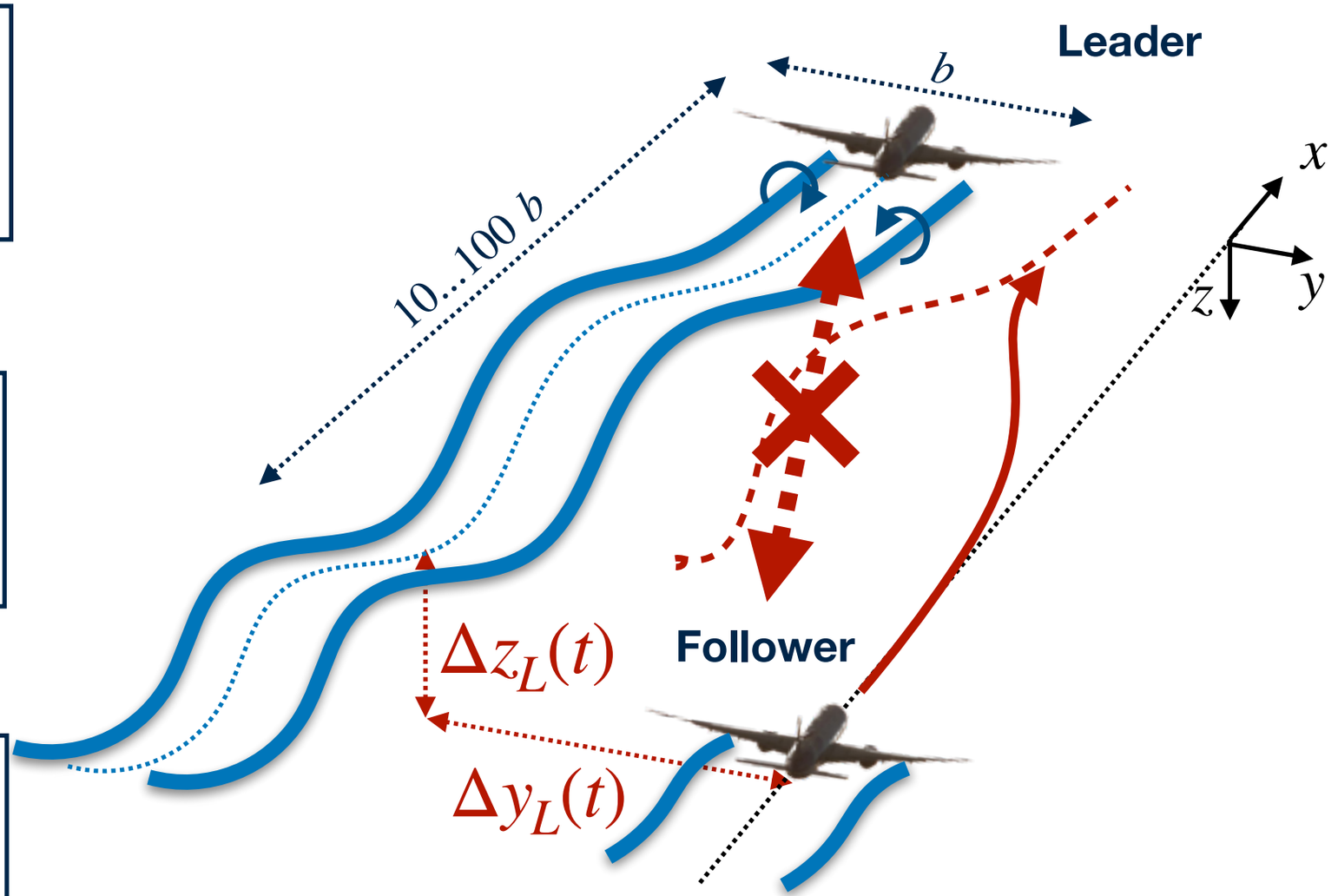
- Introduction
- **Modeling of an aircraft in formation flight**
- **Wake sensing & tracking**
- **Wake of a bird**
- **Conclusions**

How to locate wake vortices?

① …knowing how they propagate?

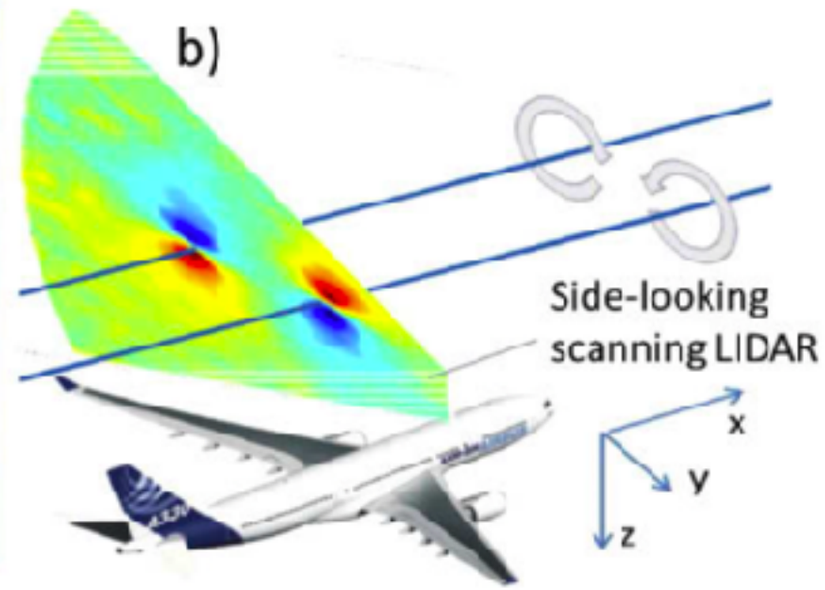
② …using on-board available information?

③ …in order to maintain at the optimal position?



What measurements can we use?

- Aircraft relative position
  - GPS, dGPS, visual clue
- Direct measurement of the vortices
  - LiDAR, UV-LiDAR

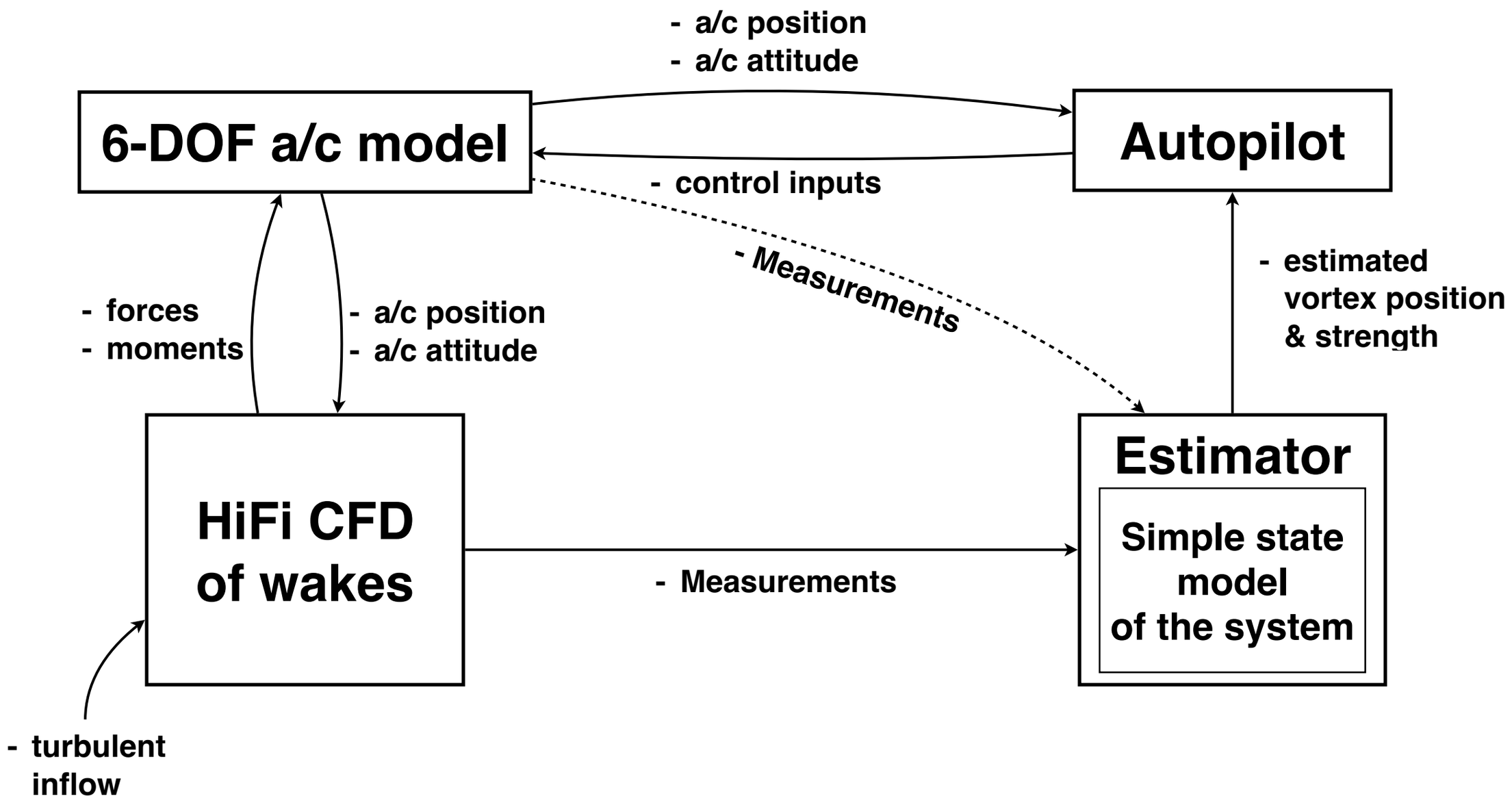


Credit: Michel *et al.*, Optics Expr., 2020

- Distributed measurement across the follower wing
  - pressure, strain

- Follower aircraft dynamics and flight controls
  - position, velocity, attitude, control surface deflection

A comprehensive simulation framework



High-fidelity wake flow solver

Vortex Particle-Mesh (VPM) method with Immersed Lifting Lines

Inflow turbulence

Modeled lifting surfaces

Lagrangian discretization to solve advection

Eulerian discretization to solve stretching, diffusion, sub-grid scale model

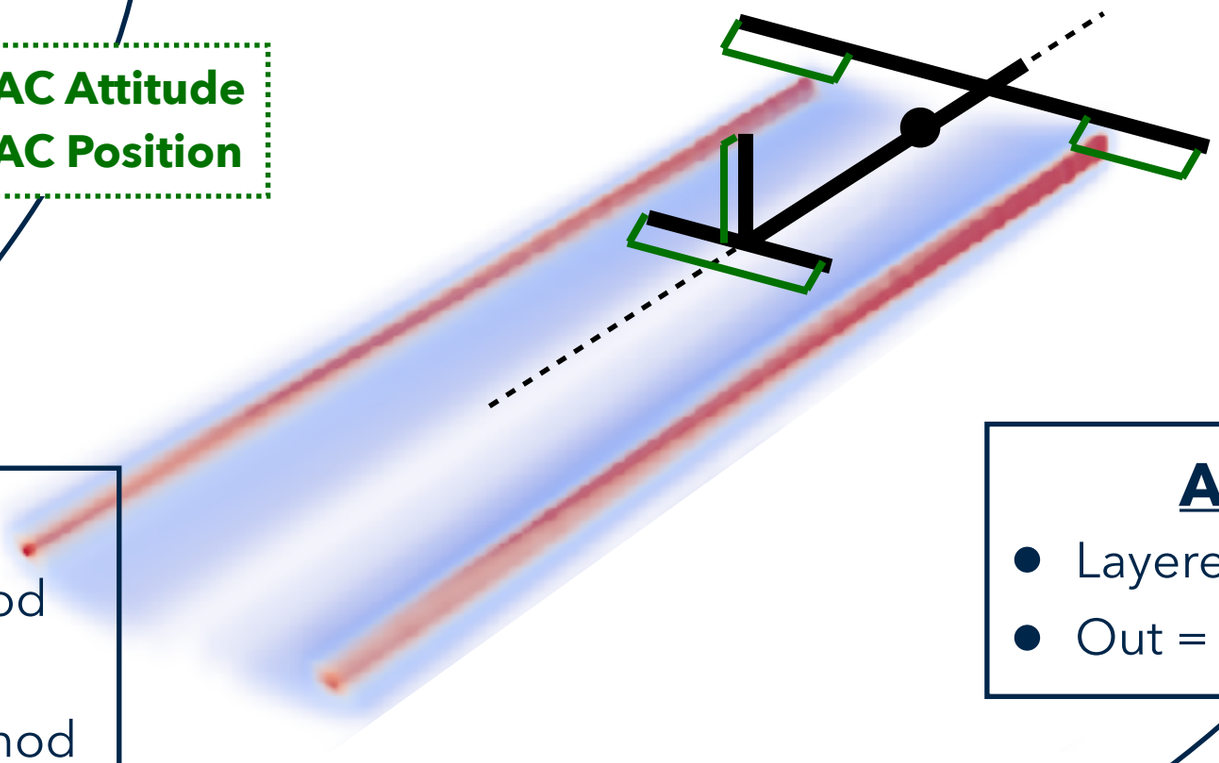
Aircraft model

Aircraft

- 6 degrees-of-freedom
- In a multi-body solver

- **Forces**
- **Moments**

- **AC Attitude**
- **AC Position**



- **AC Attitude**
- **AC Position**

Wake Flow Solver:

- Vortex Particle-Mesh method
- LES using SGS model
- Immersed lifting-lines method

Autopilot:

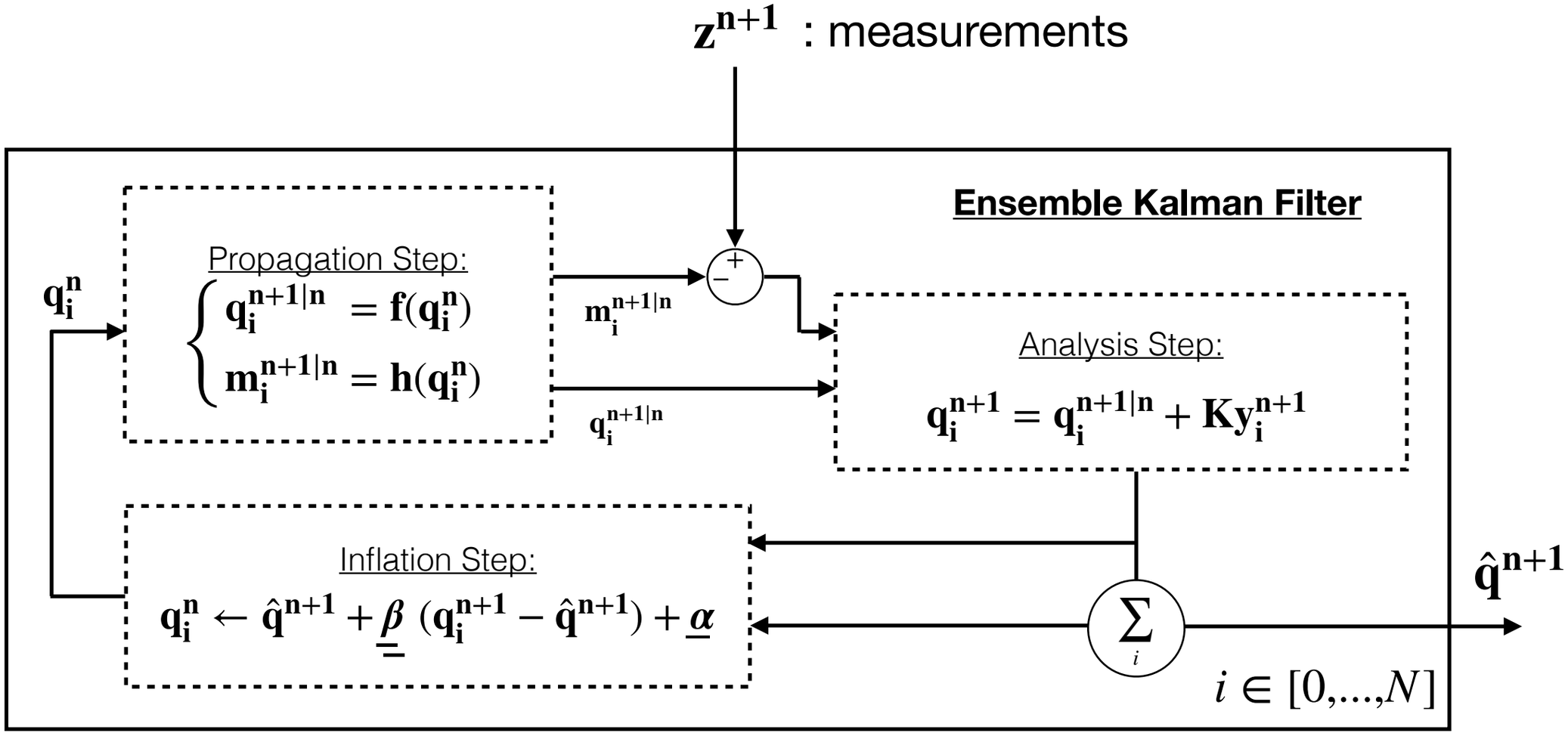
- Layered Control loops
- Out = $\delta_{Ail}, \delta_{VT}, \delta_{HT}, \delta_{Th}$

- **Control Inputs**

- **Target in position or speed**

Ensemble Kalman Filter (EnKF)

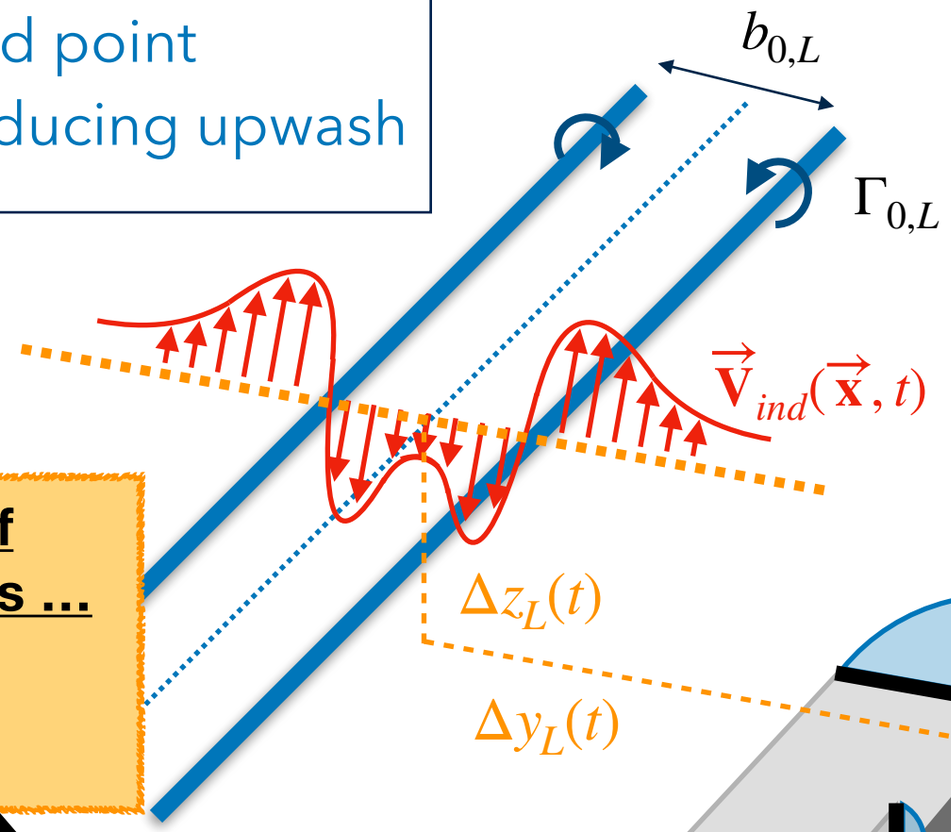
- **Discrete time** Kalman framework
- Deals with **non-linear** system
- Uses a **Monte Carlo** approach to describe the probability density function of the states of the systems $\boldsymbol{q}$, represented as a discrete **ensemble** of size N

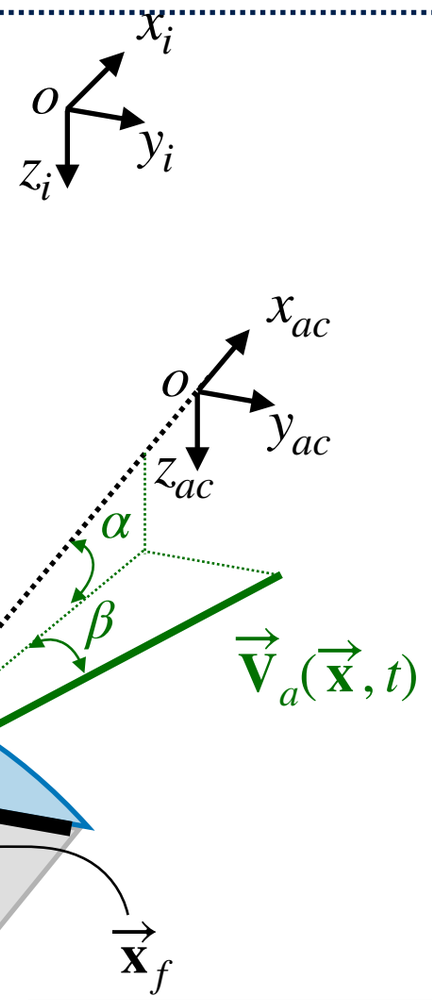


Low fidelity aerodynamic model of a follower in the wake of a leader

Leader =

Regularized point vortices inducing upwash





Integration of Estimated States …

$\hat{\boldsymbol{q}}_{aero}$

$\hat{\boldsymbol{q}}_{dyn}$

… gives estimated measurements:

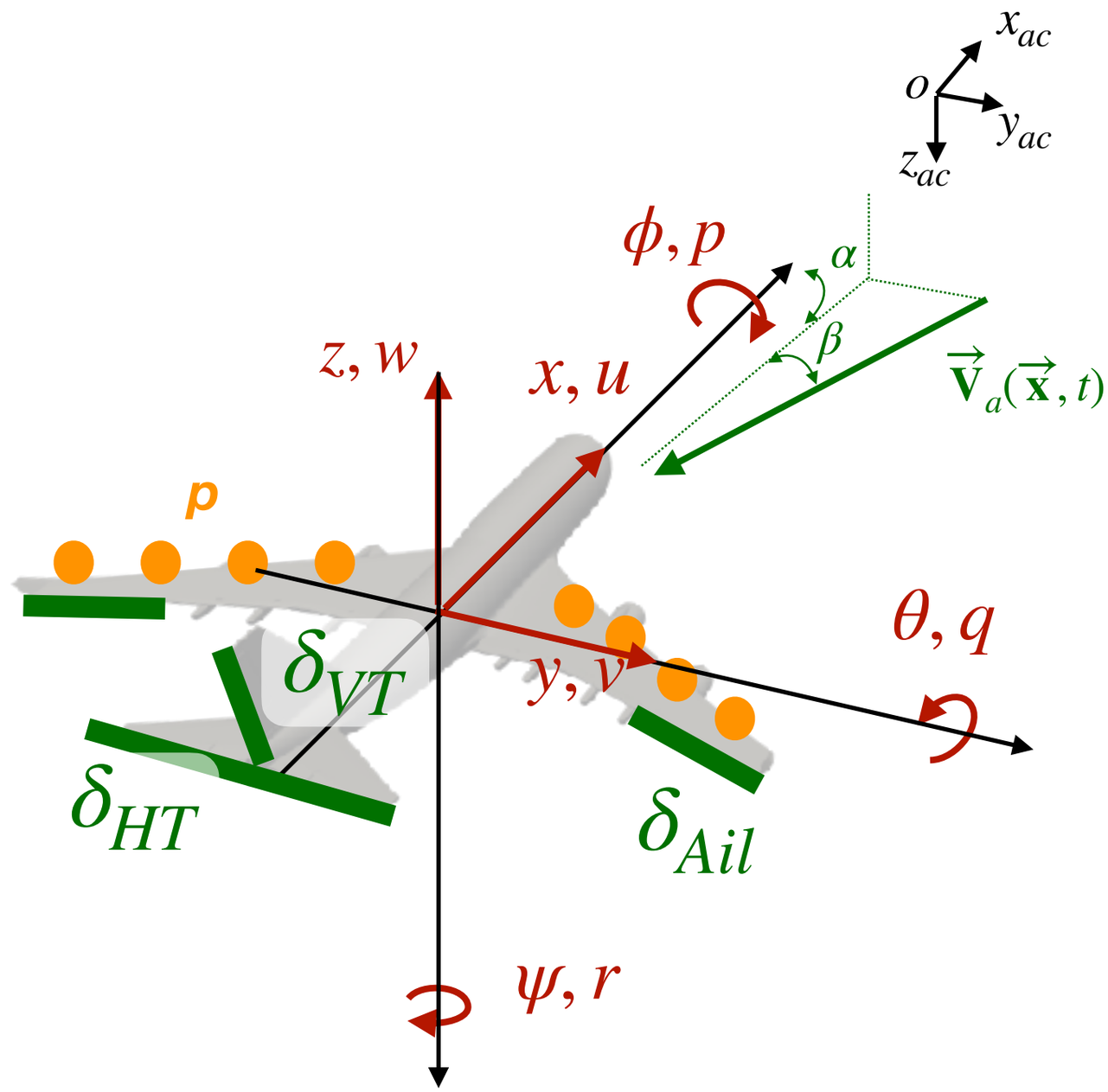
$\boldsymbol{m}_{dyn}$

$\boldsymbol{m}_{control}$

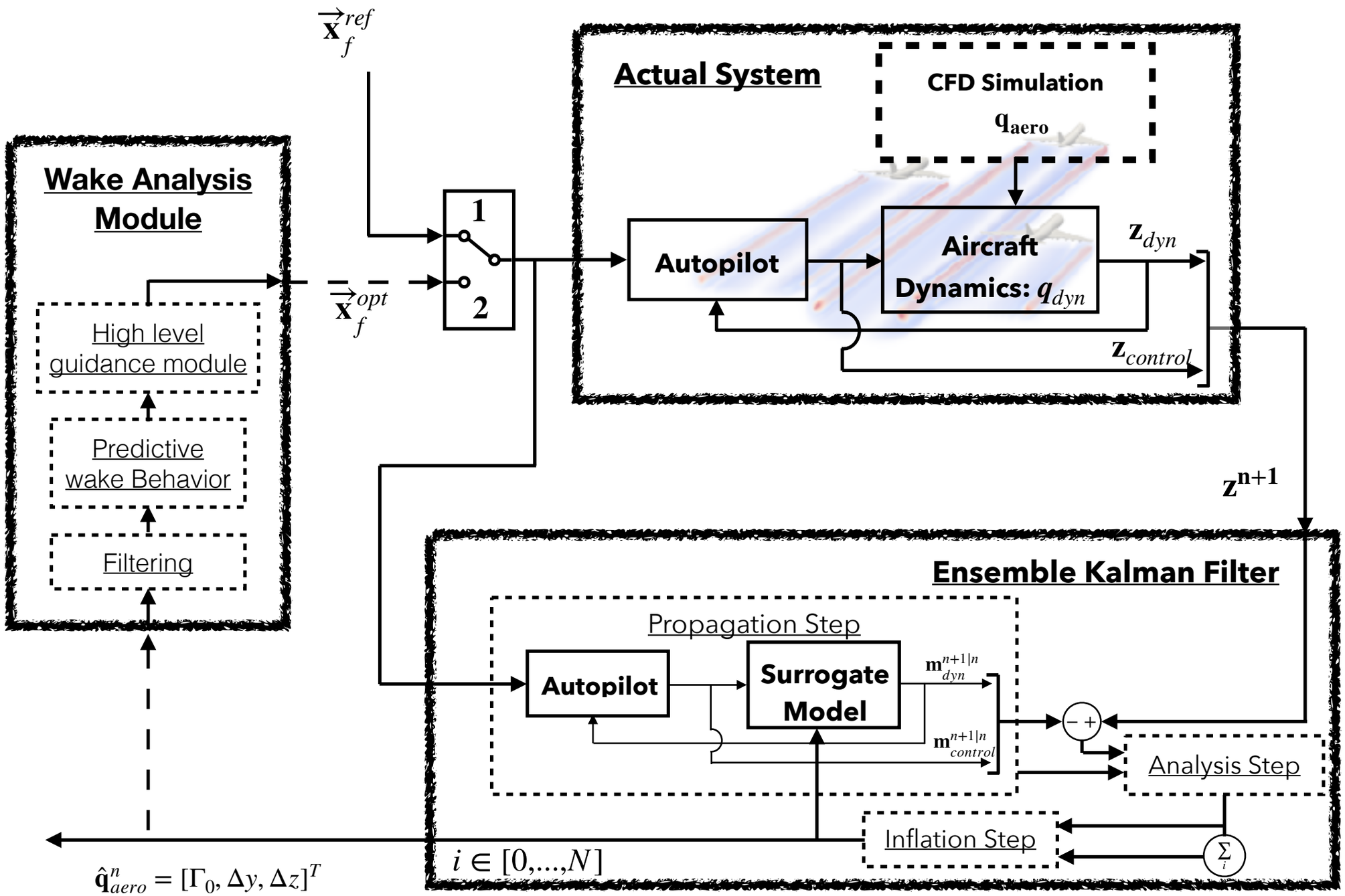
Follower =

+ 3 Prandtl Lifting Lines
+ 6 Degrees-of-freedom
+ Autopilot

Many possible measurements



Summary of the framework



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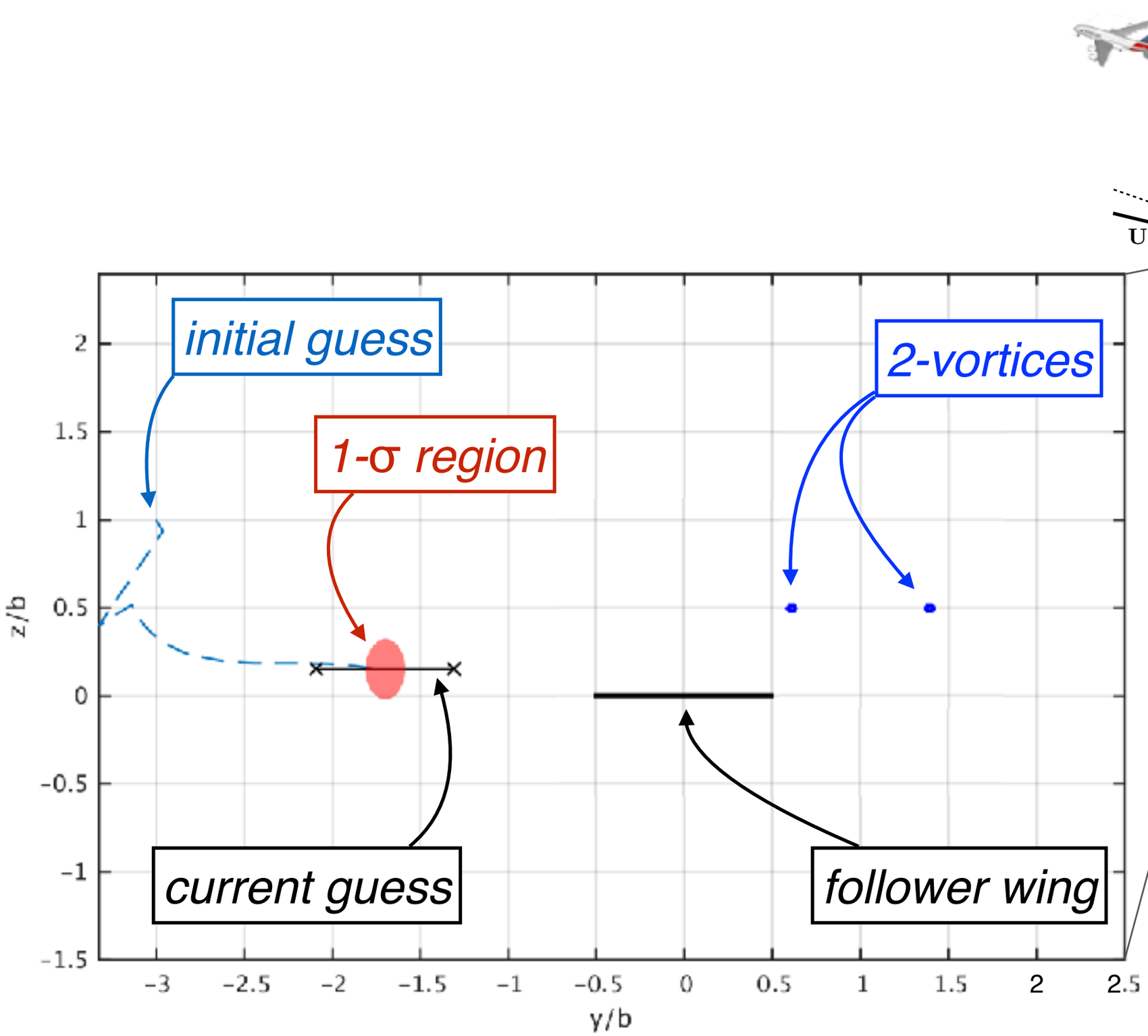
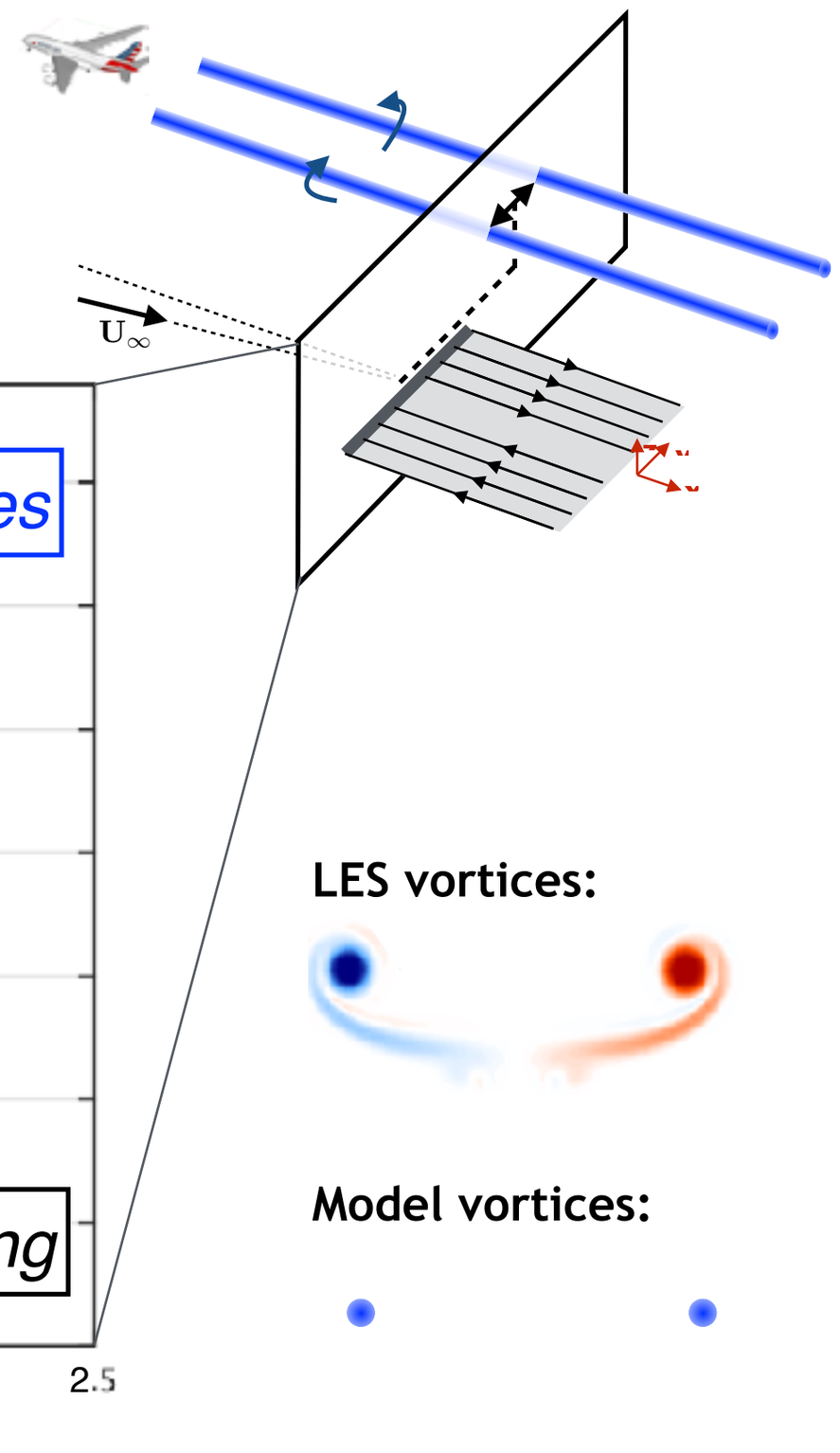
Quick guide on how to read the results



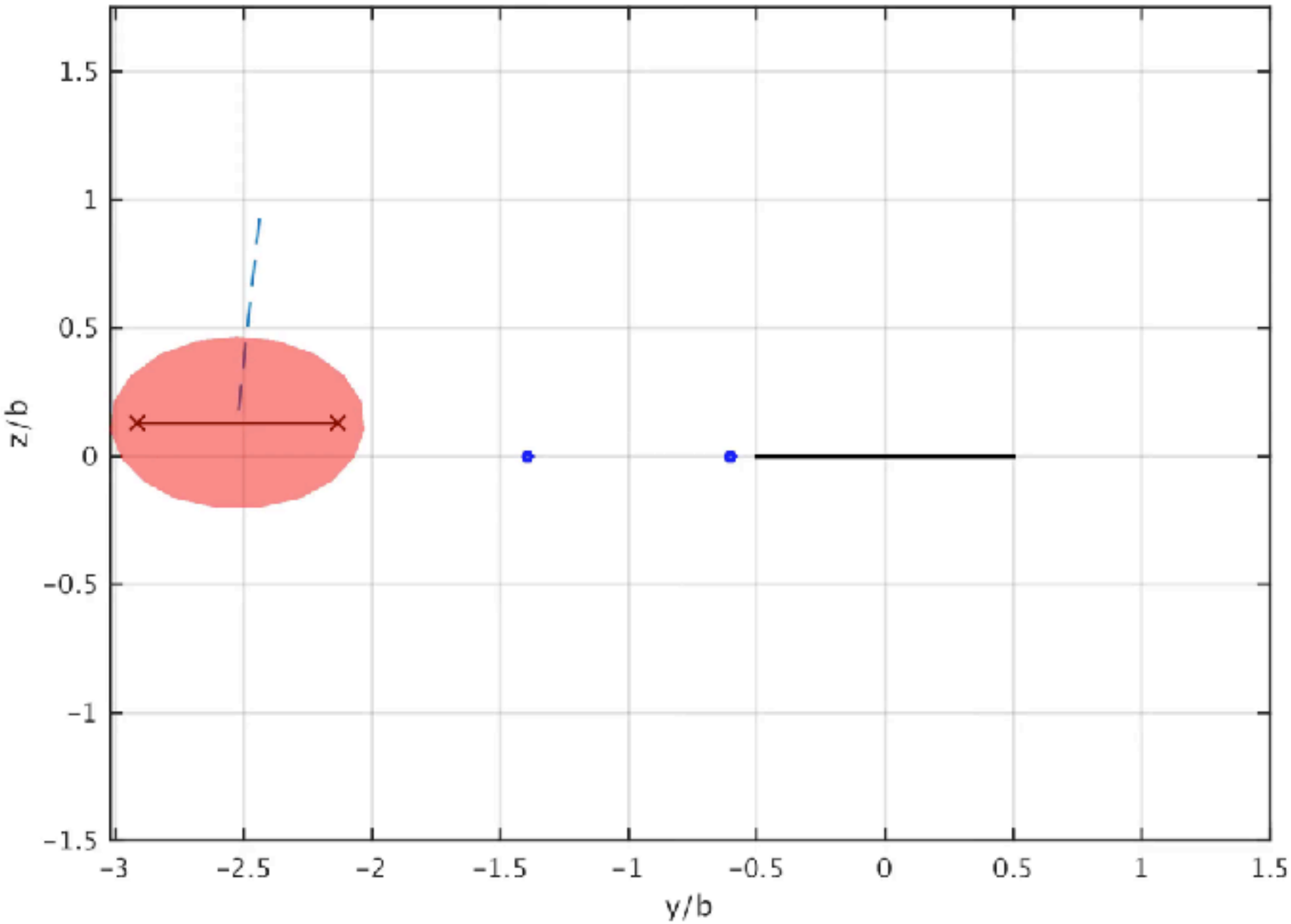


LES vortices:

Model vortices:

Steady, optimal setup

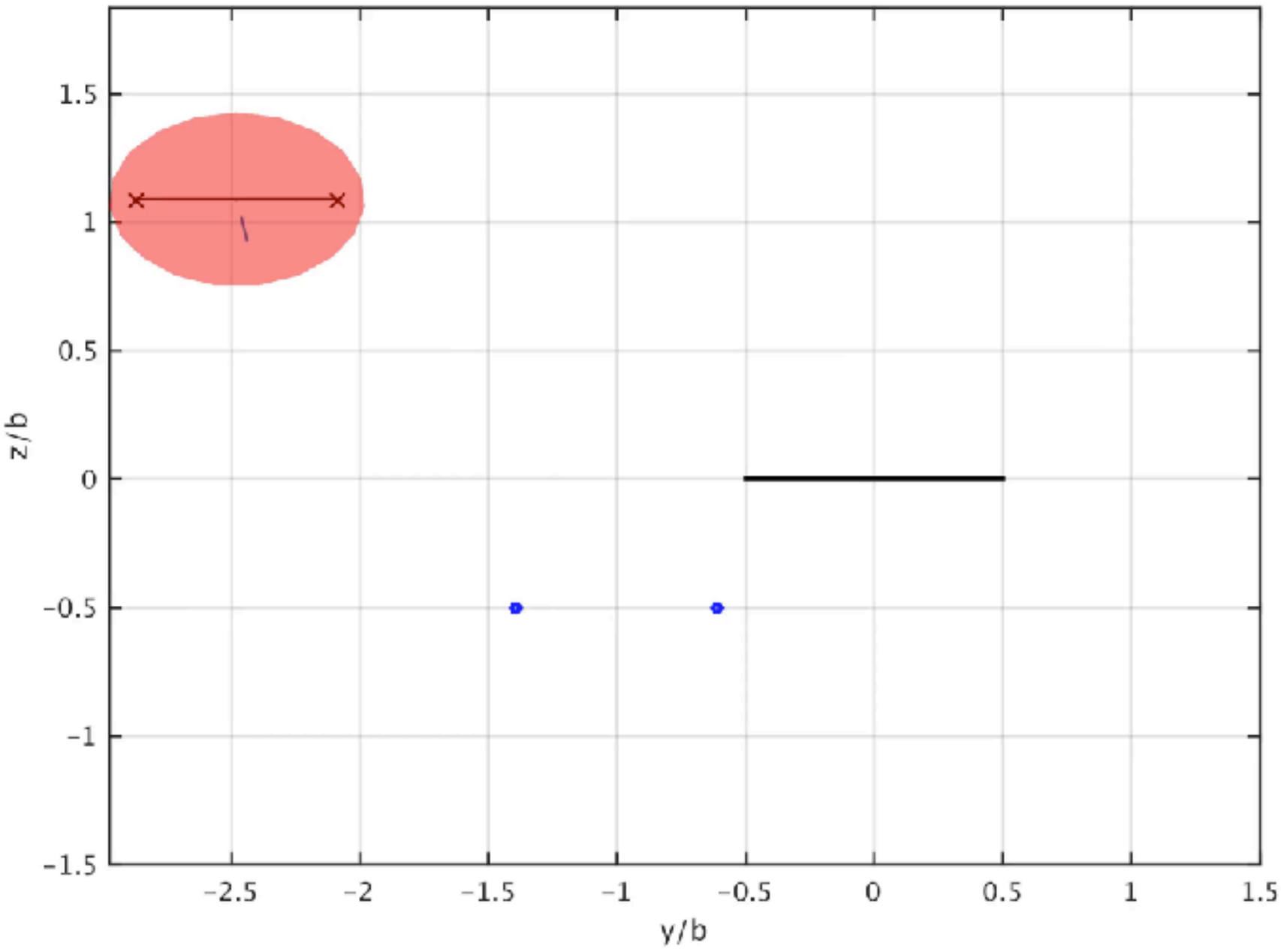
With pressure meas.



- *ensemble size = 50*
- *catch the solution after less than 50 iterations*
- *similar to literature results*

Steady setup with vertical offset

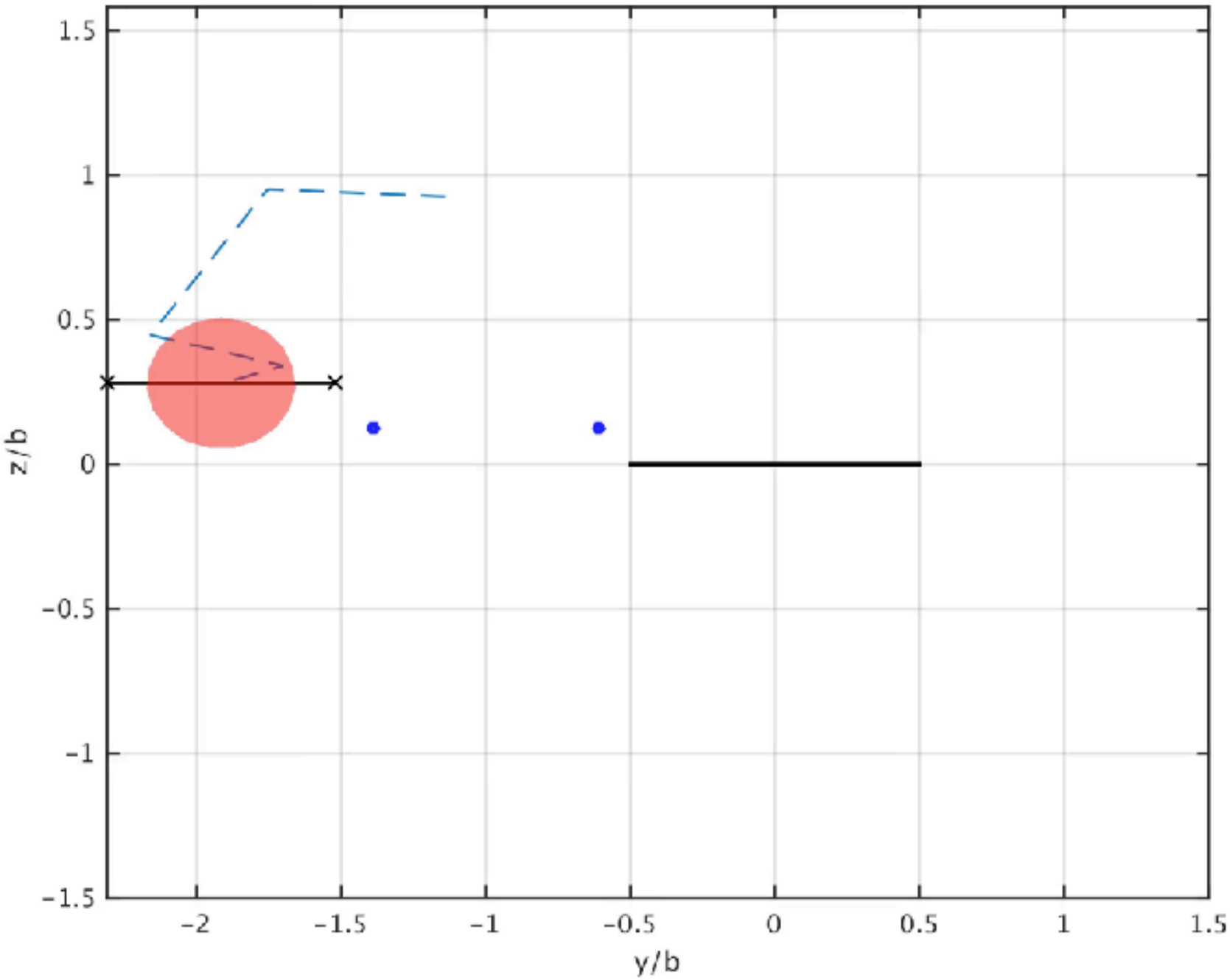
With pressure meas.



- *Impossible to discriminate symmetric solutions due to the symmetry of the problem*

Case 3. Unsteady setup

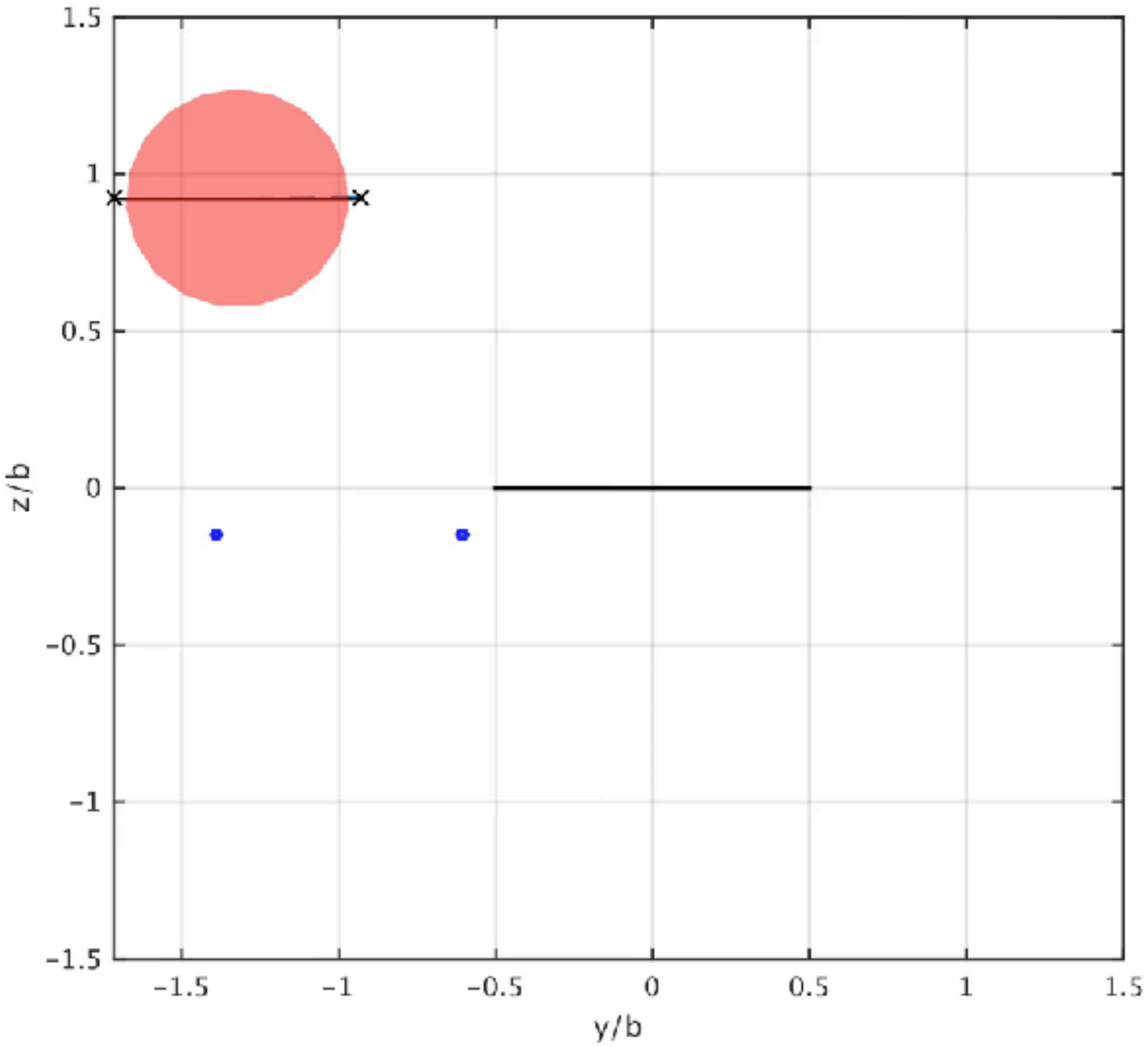
With pressure meas.



- *Fast convergence*
- *Not ensured to catch the correct solution*

Dynamics contains information

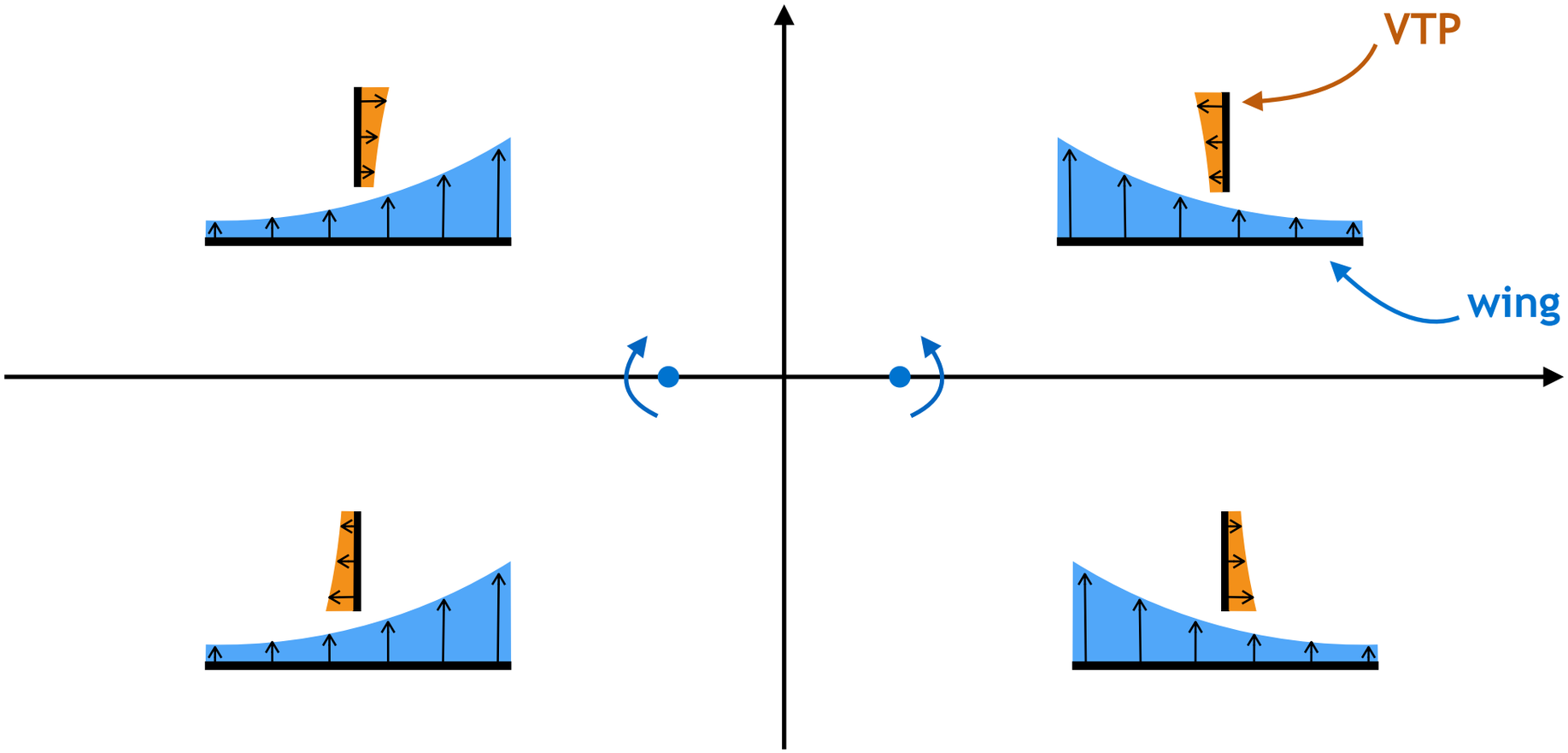
With pressure meas.



- *Good news: followers motion is **very efficient** for increasing observability*

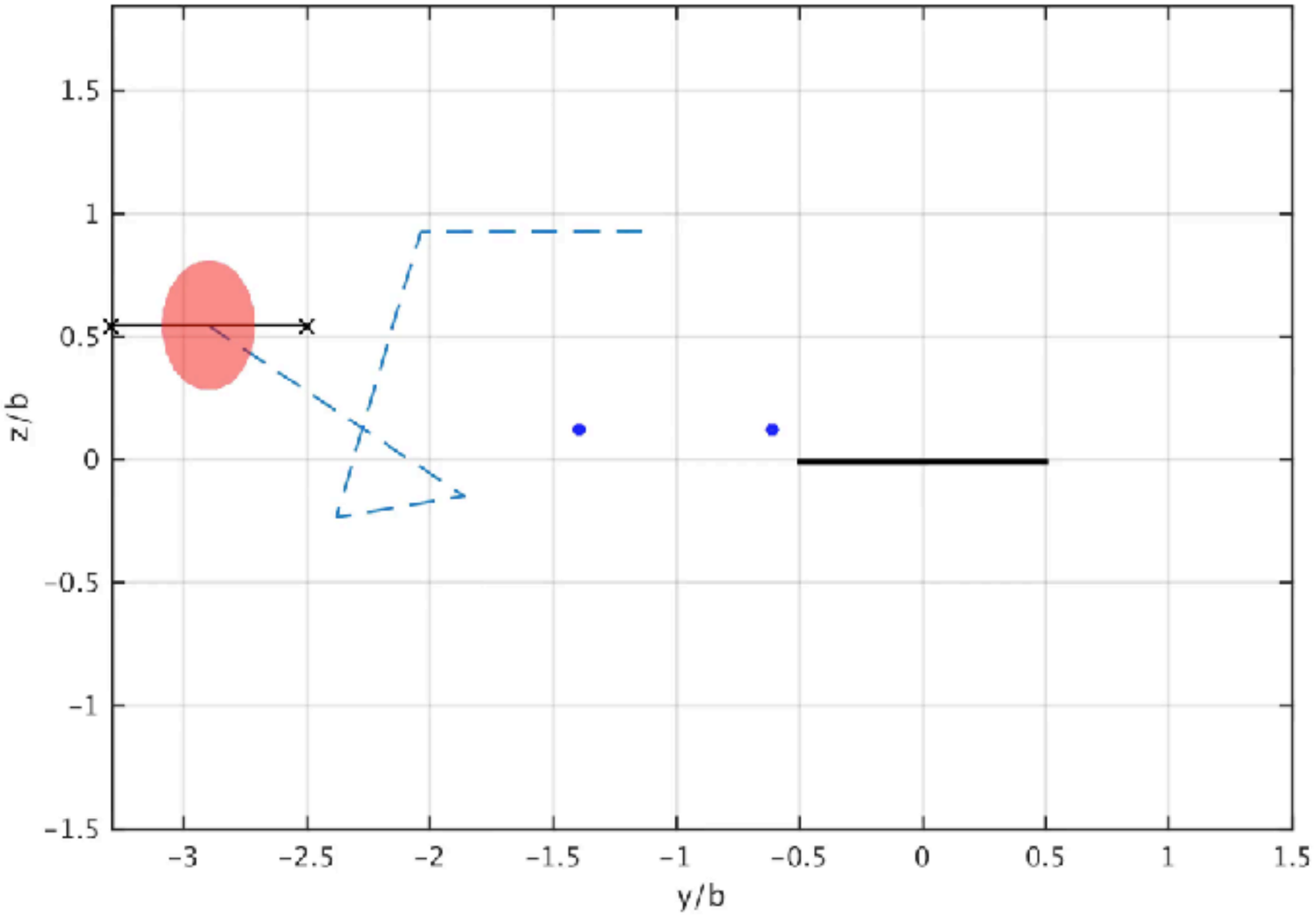
Addition of a measurement from the yaw axis

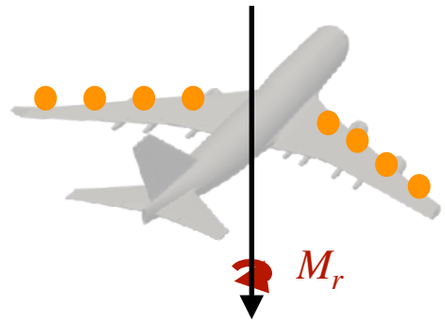
- ★ the leader vortices induce a velocity on the VTP as well
- ★ yawing moment or ‘rudder deflection for trim’ can be used as a measurement to discriminate the vertical position



Exploiting the follower dynamics

With pressure + yaw meas.



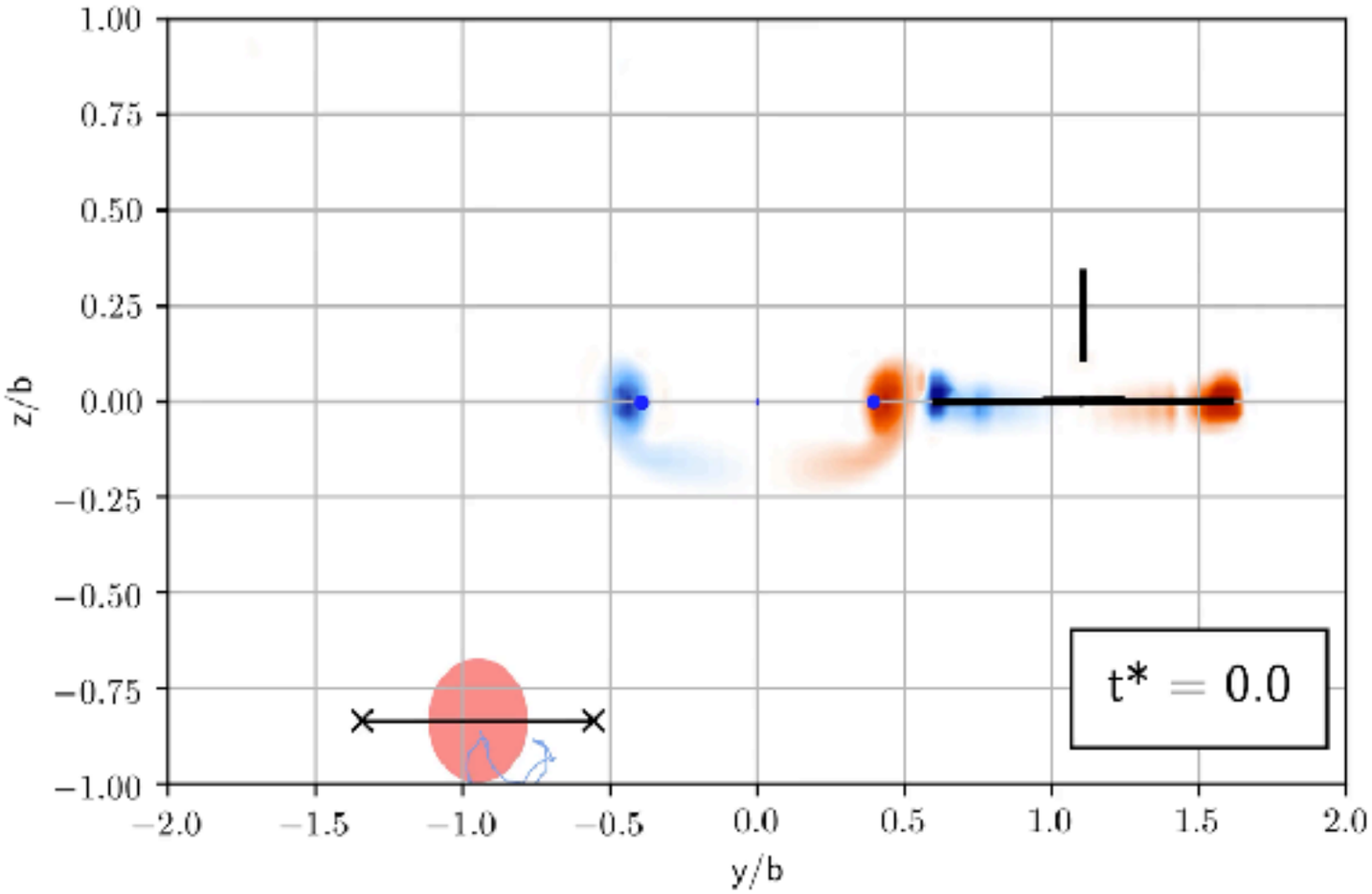


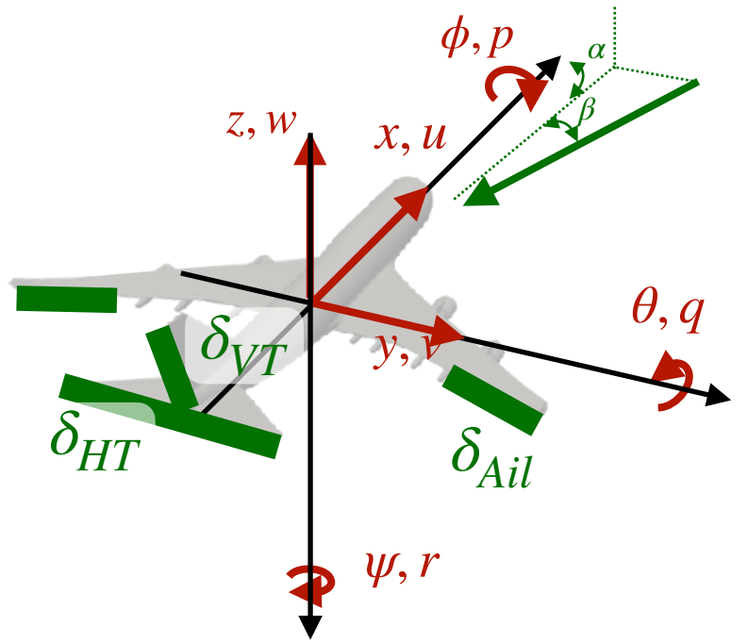
- *Combination of motions enables proper detection*

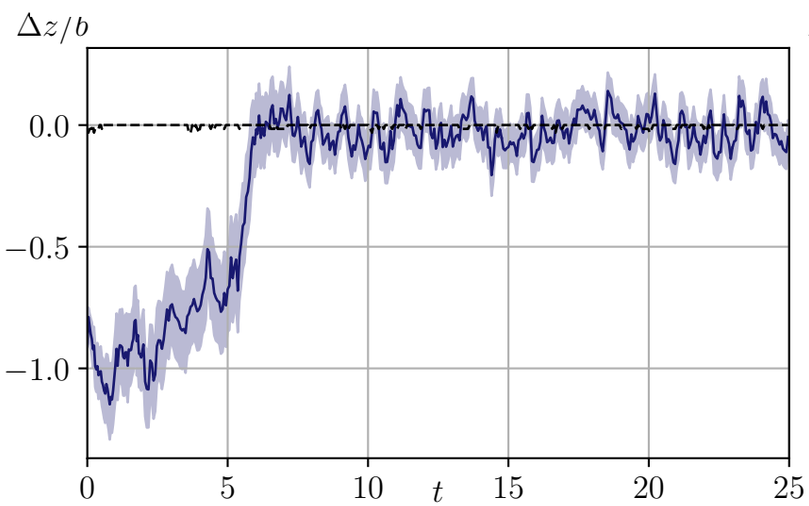
Caprace *et al.*, AIAA, 2019

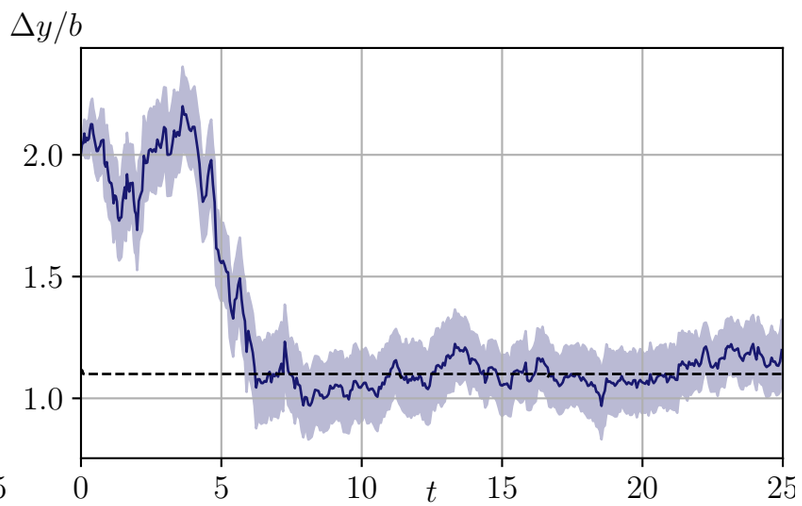
Full-blown wake estimation based on flight dynamics measurements

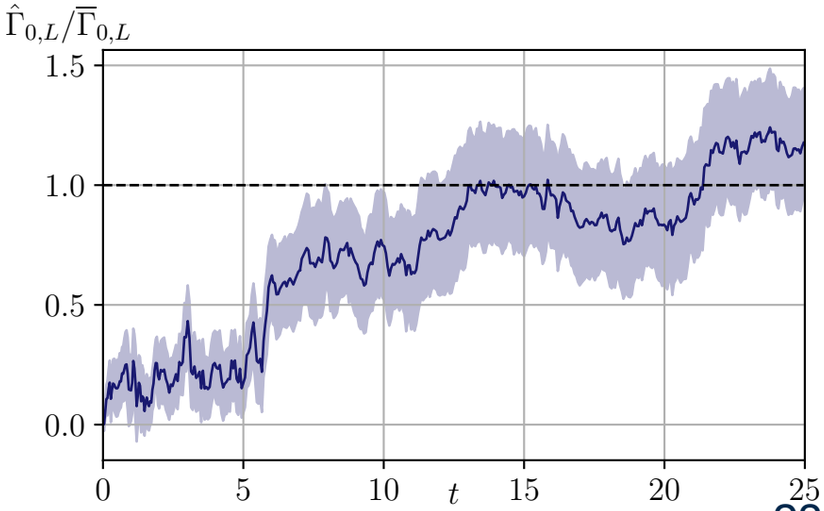
With only dynamics meas.





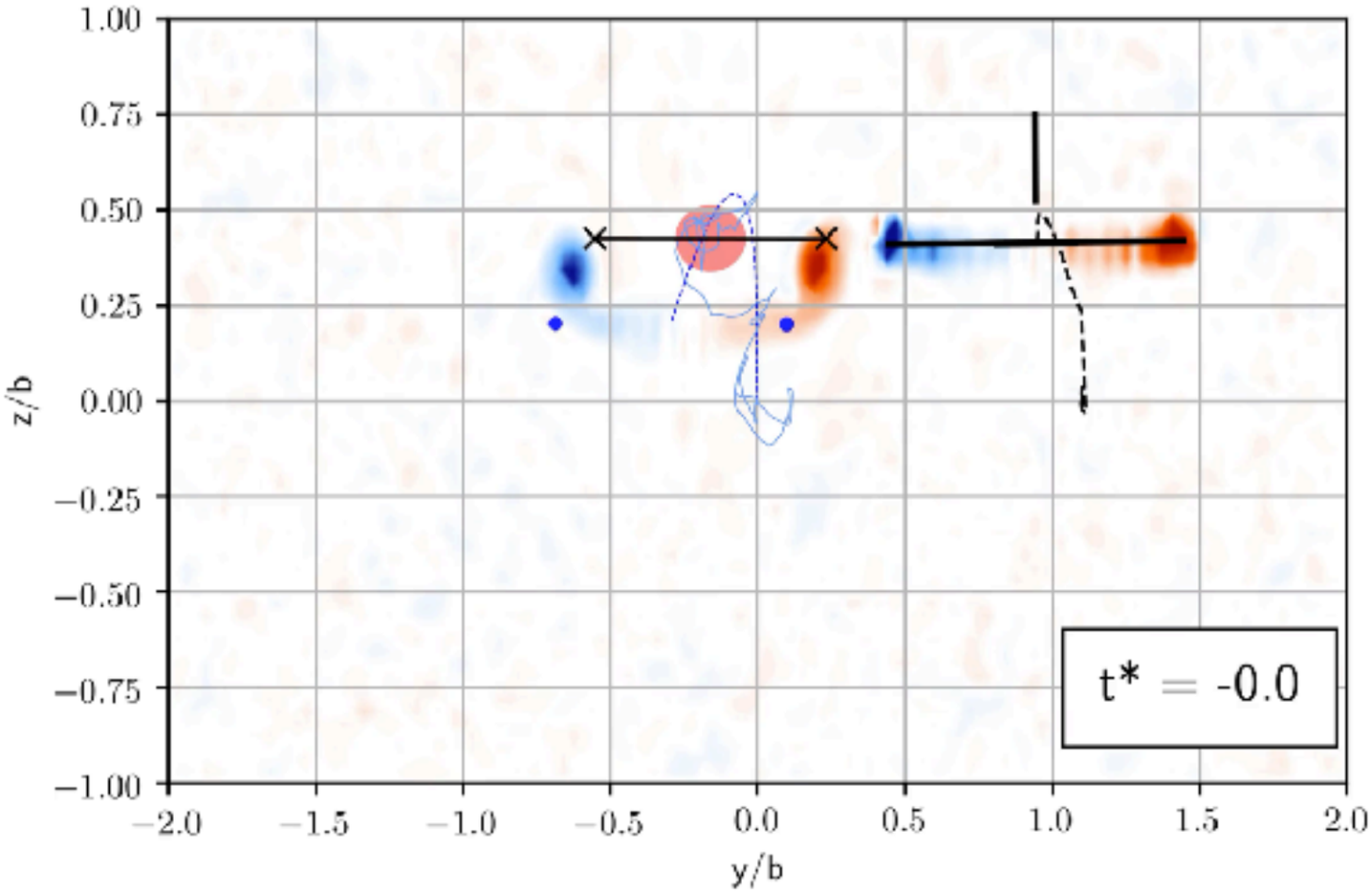


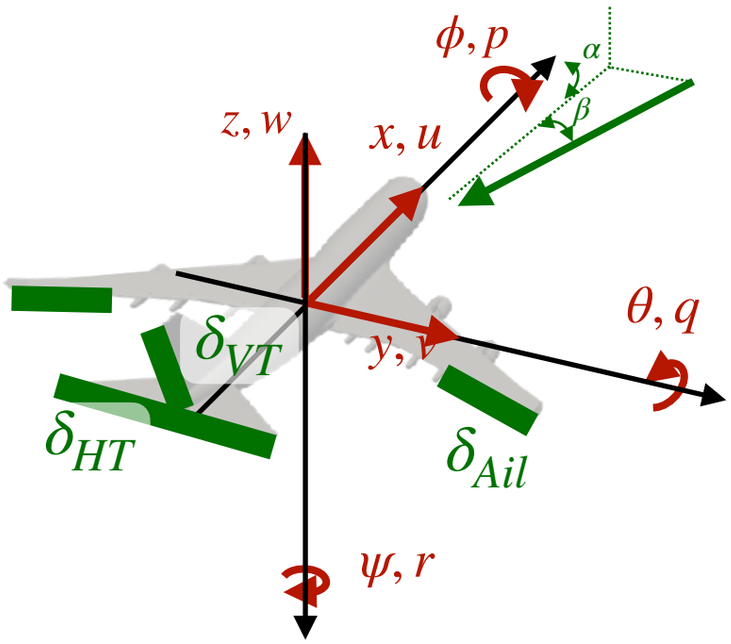


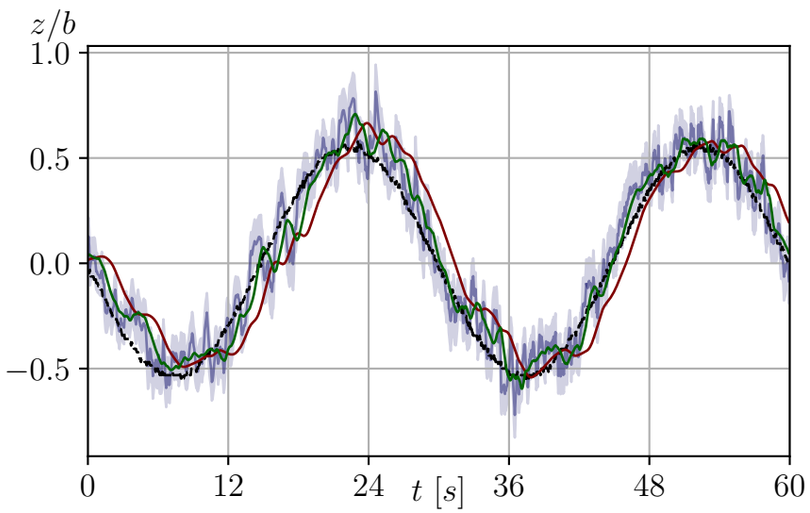


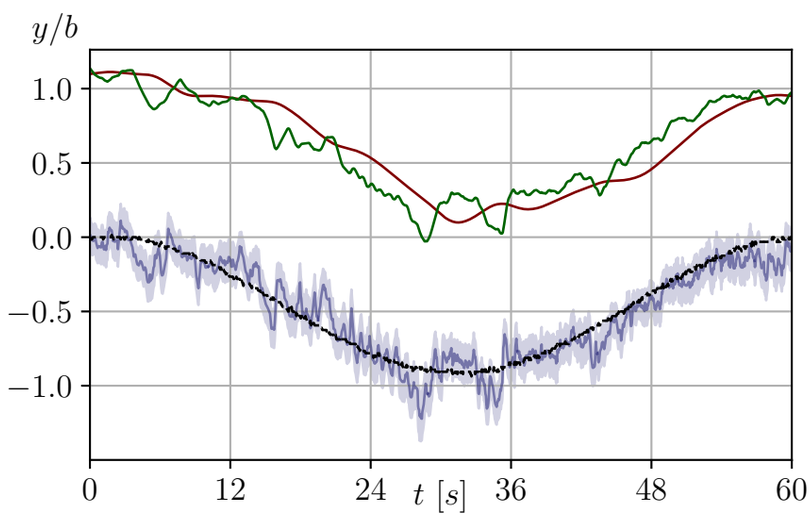
Wake sensing + tracking

With only dynamics meas.



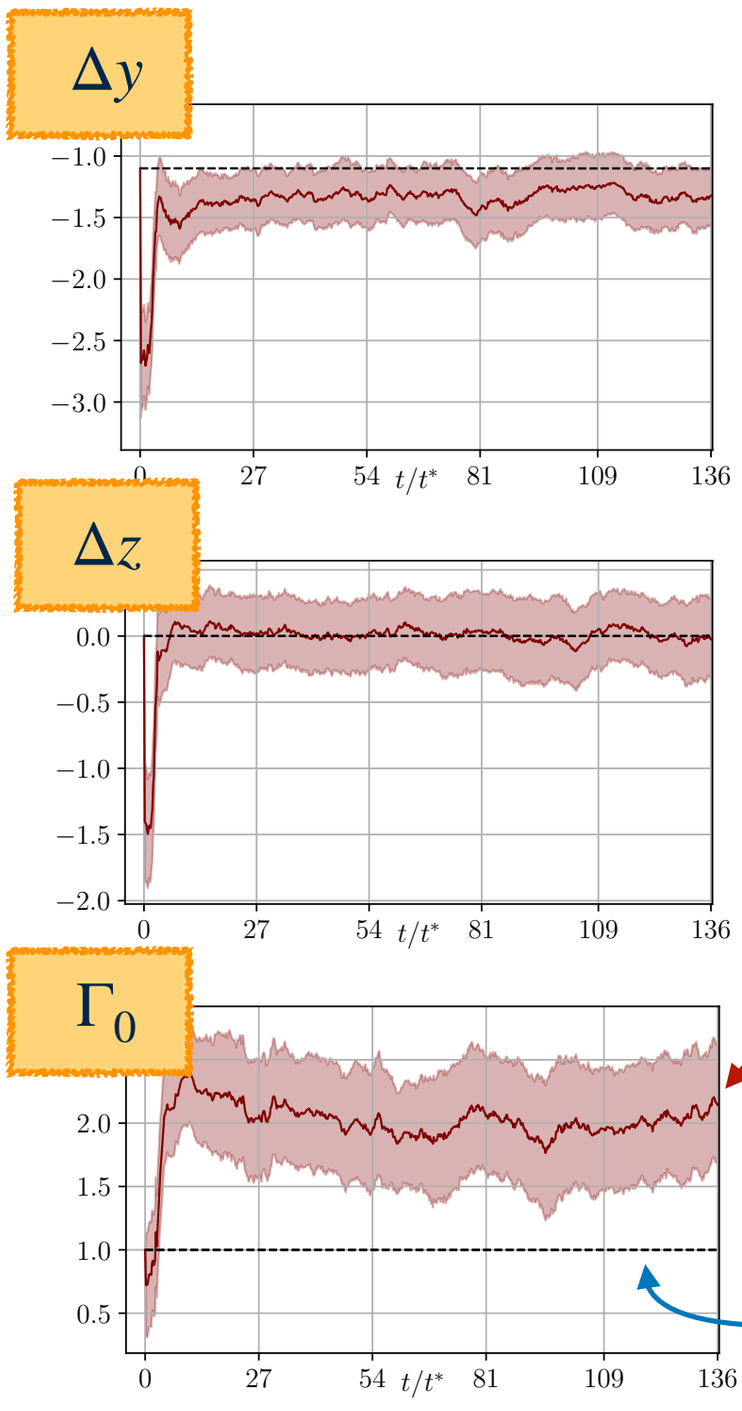






Ransquin *et al.*, JGCD, 2021

Lessons learnt



- Ambiguity due to up/down symmetry
- Ambiguity in the between lateral distance and wake strength
- Dynamics of the isolated low-fidelity model and the actual aircraft must be close

No assumption on Γ_0

Using educated guess on Γ_0

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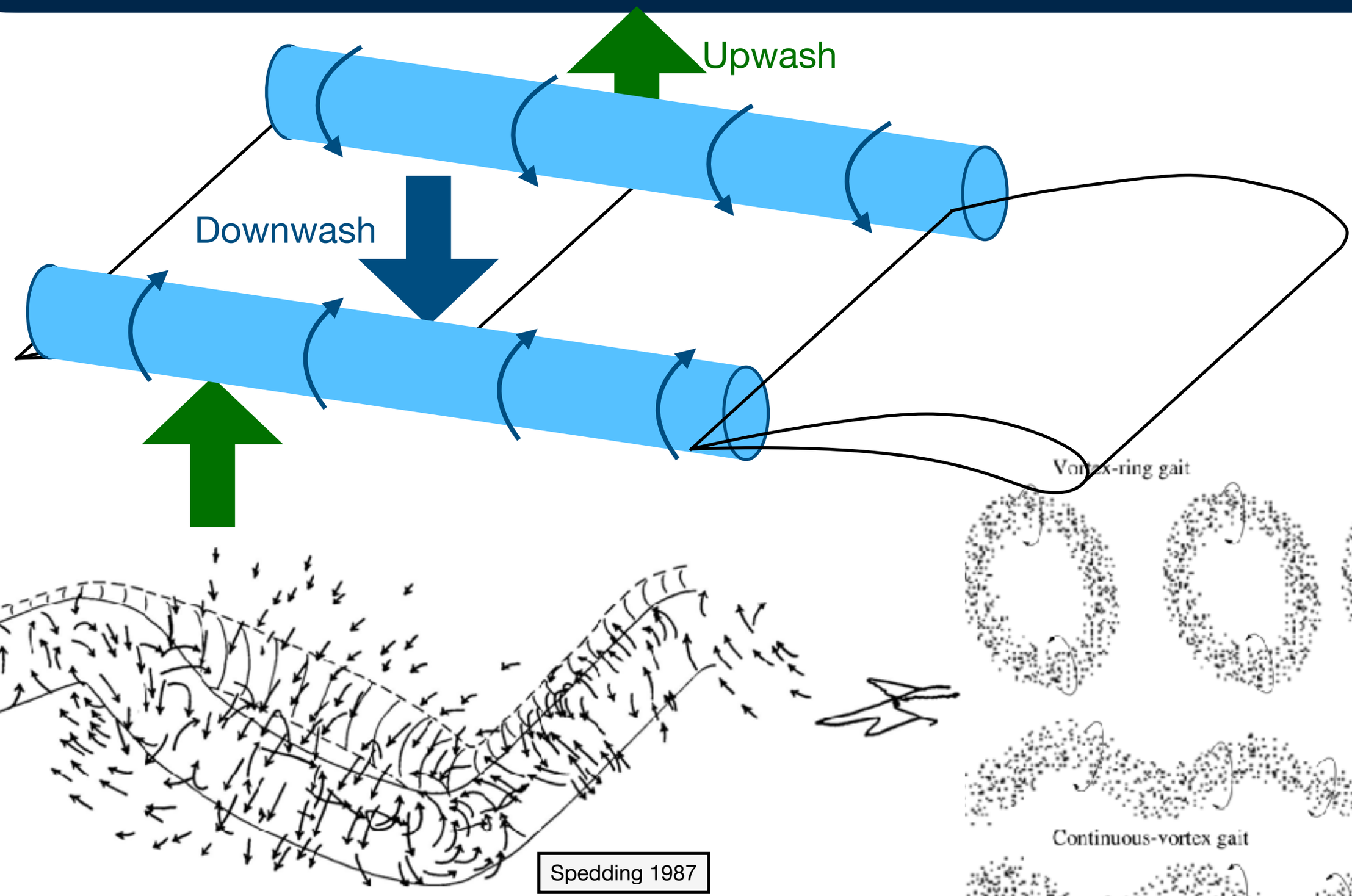
- **Conclusions**

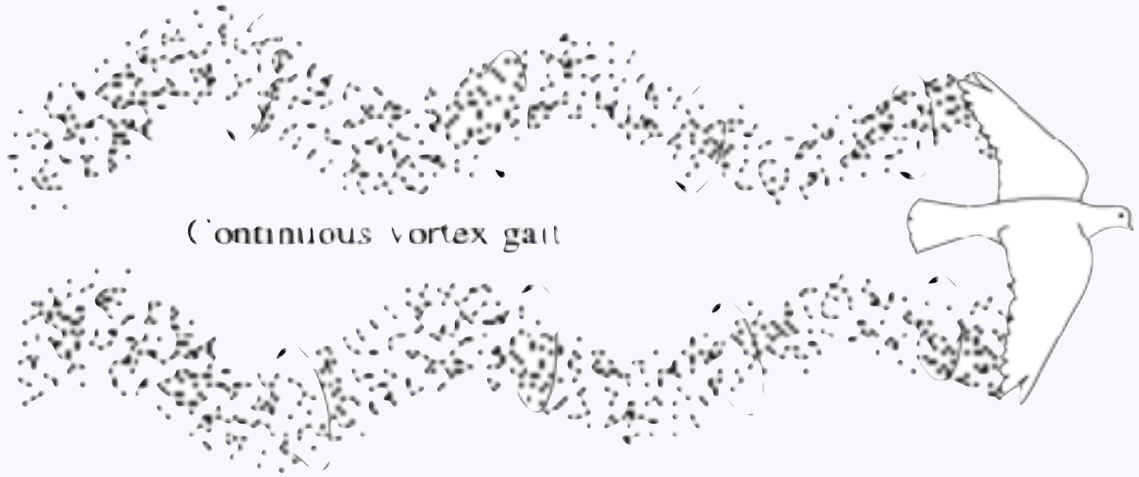
Topology of the wake of a flapping bird



Spedding 1987

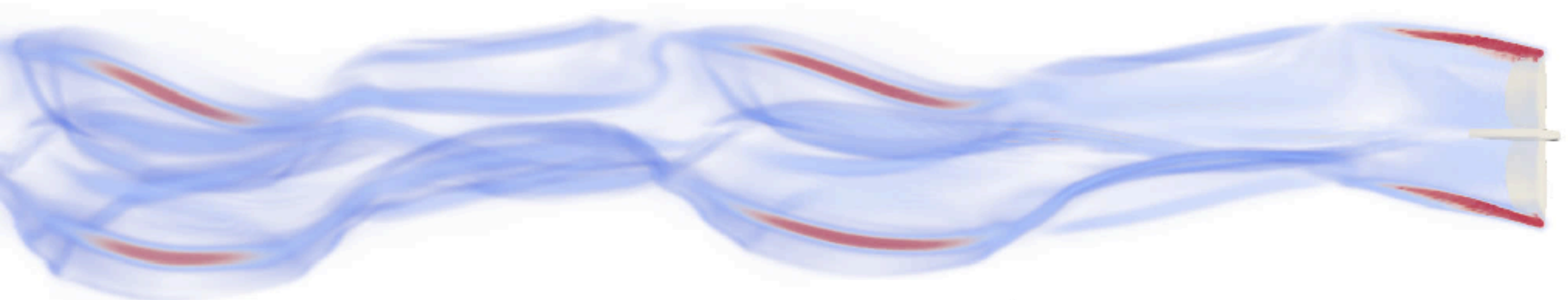
Tobalske 1996

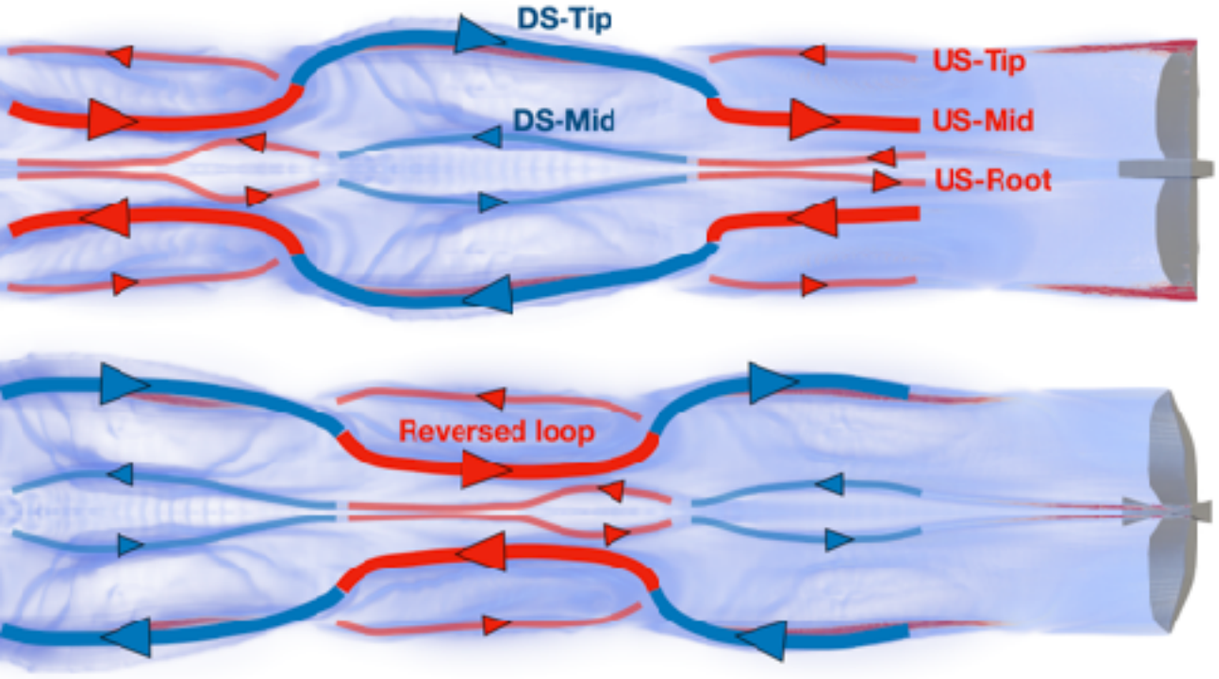
Simulation of the wake (1)

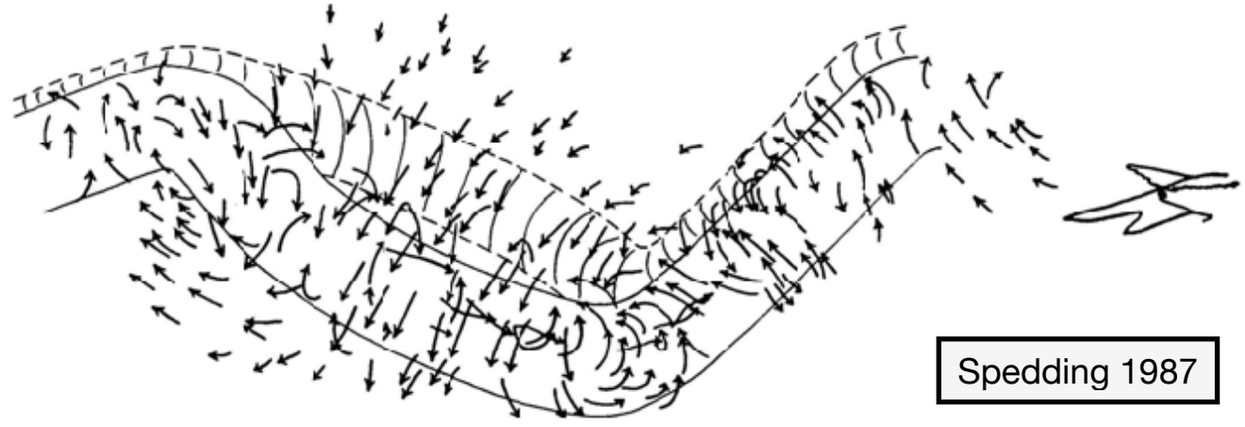


Colognesi *et al.*, Bioinspiration & Biomimetics, 2021

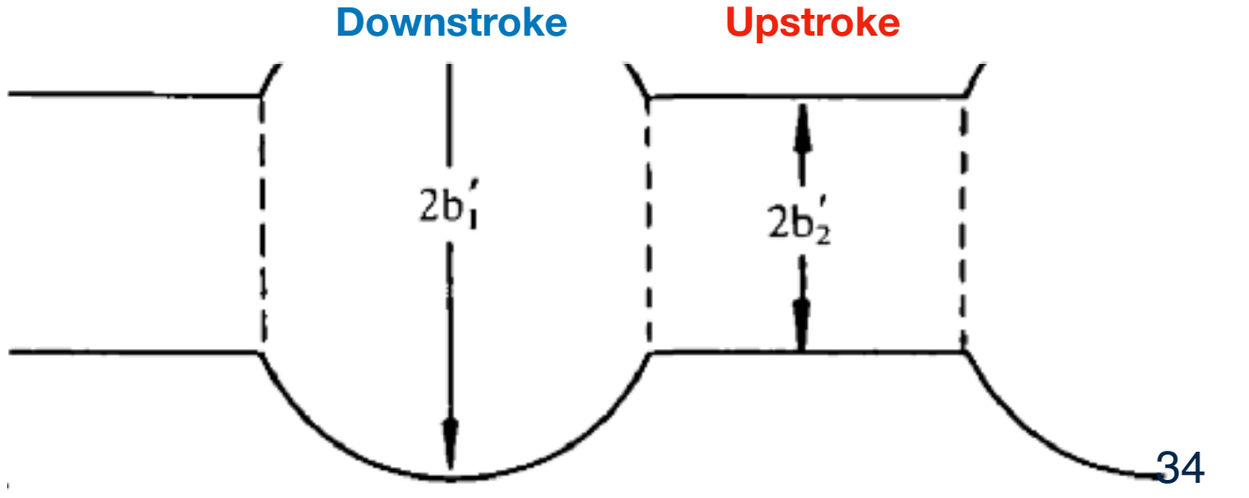
Simulation of the wake (2)



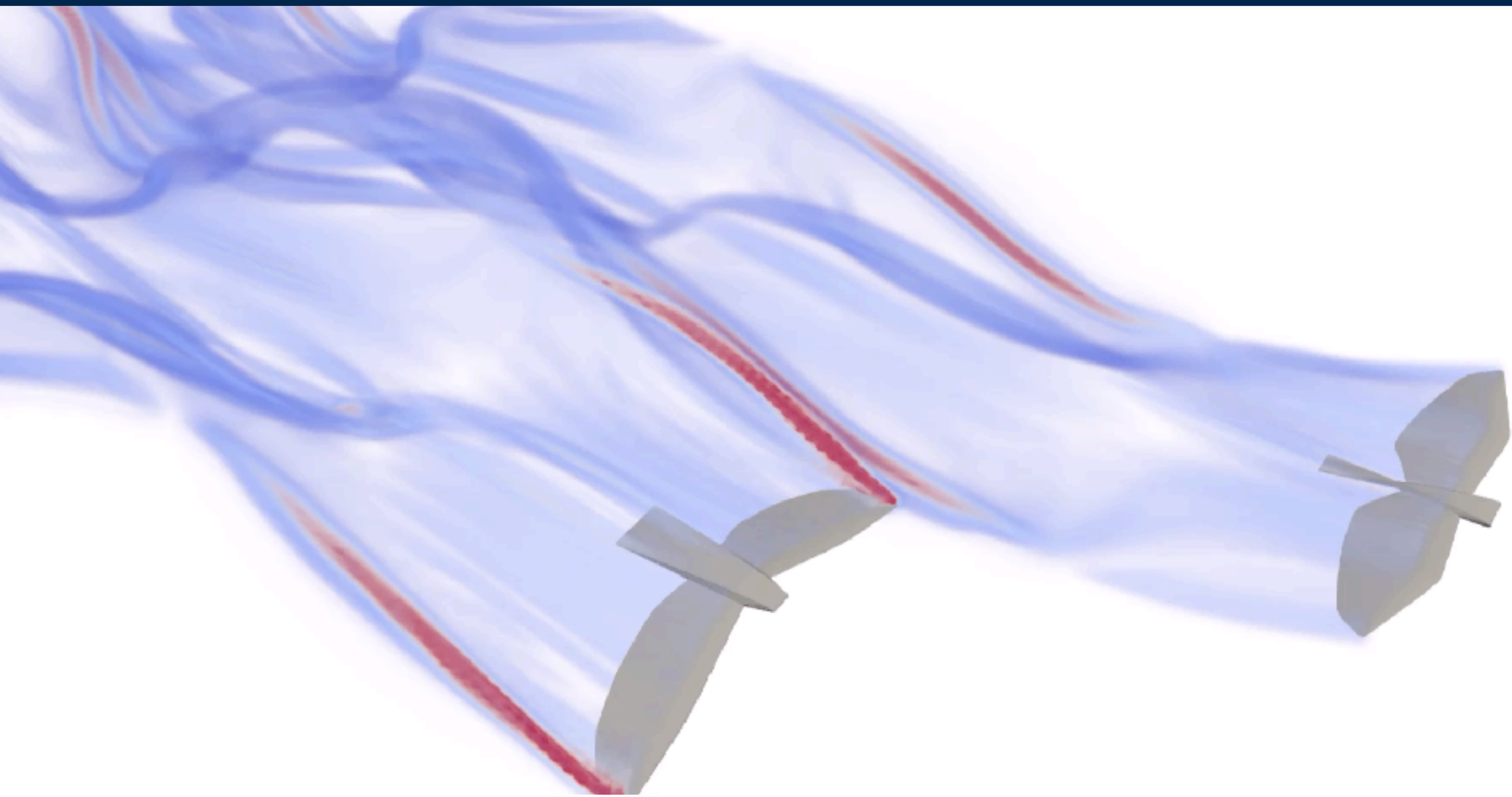




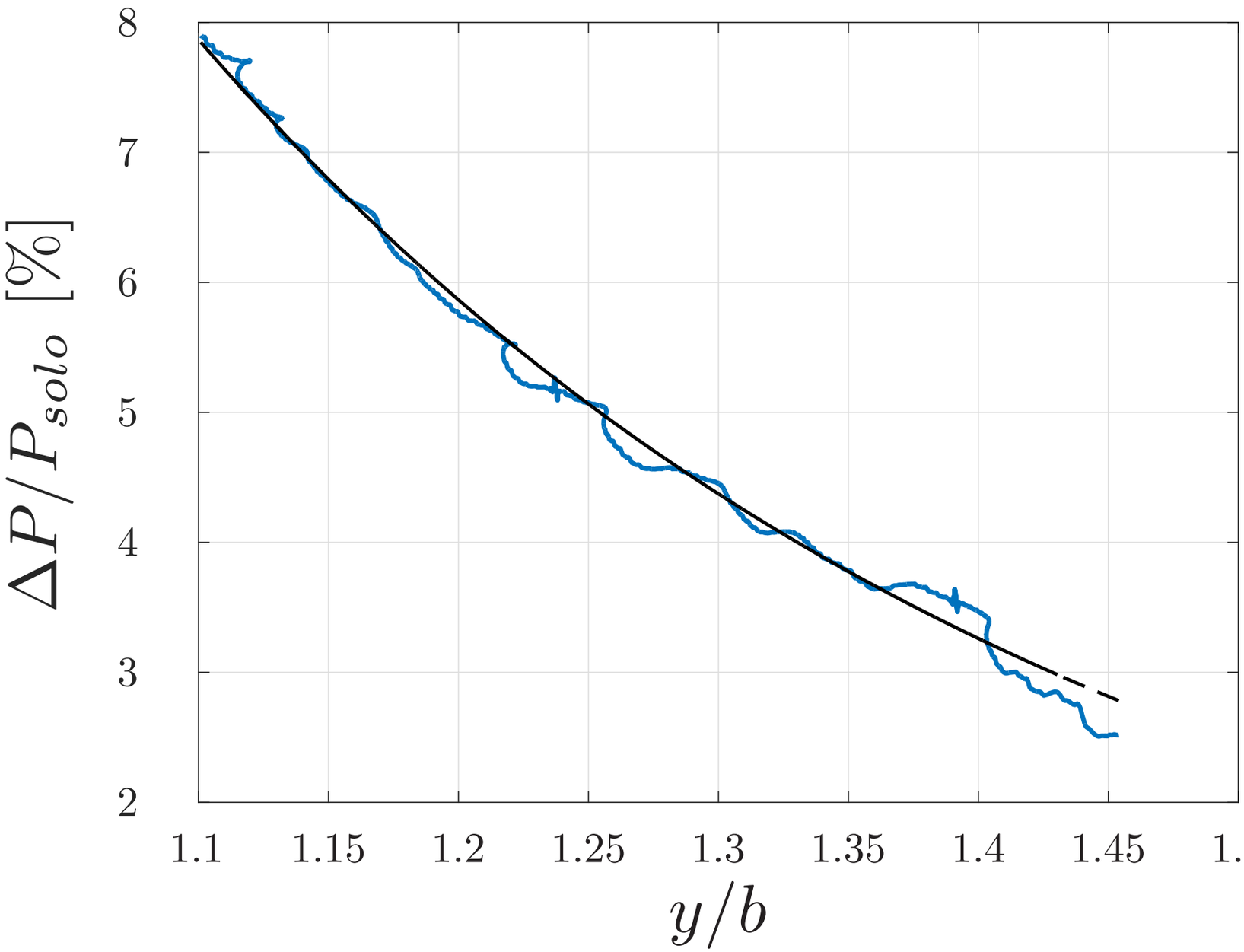
Spedding 1987

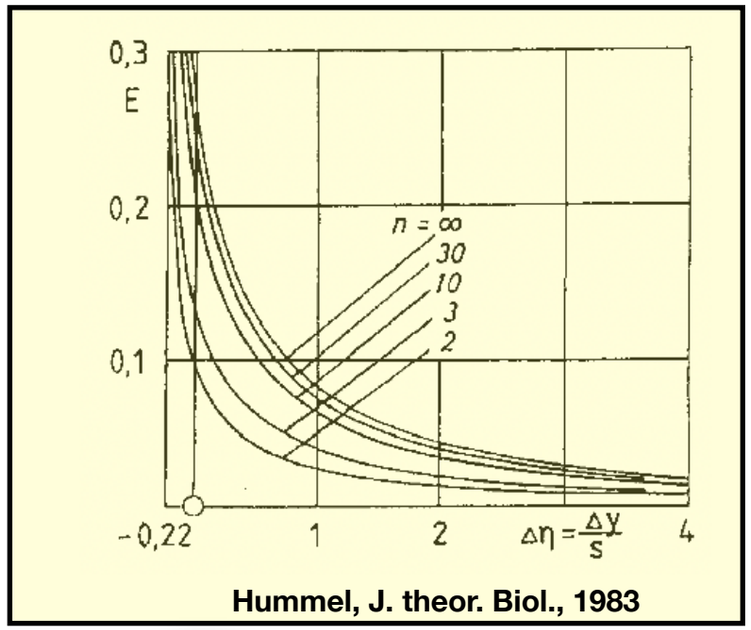


Formation of two birds



“Measured” aerodynamic benefit





Hummel, J. theor. Biol., 1983

Colognesi *et al.*, 2022

Conclusions

- Wake sensing **measurements** need to be carefully chosen
  - Some combinations lead to loss of observability
  - Unsteadiness and dynamics help

- Follower **dynamics can be** used as meaningful measurement, but
  - Requires good knowledge of the out-of-wake dynamics
  - At least 1 external measurement needed to disambiguate wake strength

- Formation expected **benefits**: probably **realistically around 5%**
  - Tracking may help keep that figure up
  - Estimator provides position with confidence interval: good for safety

- **Wake of a birds is more 3D**: more information for the sensing

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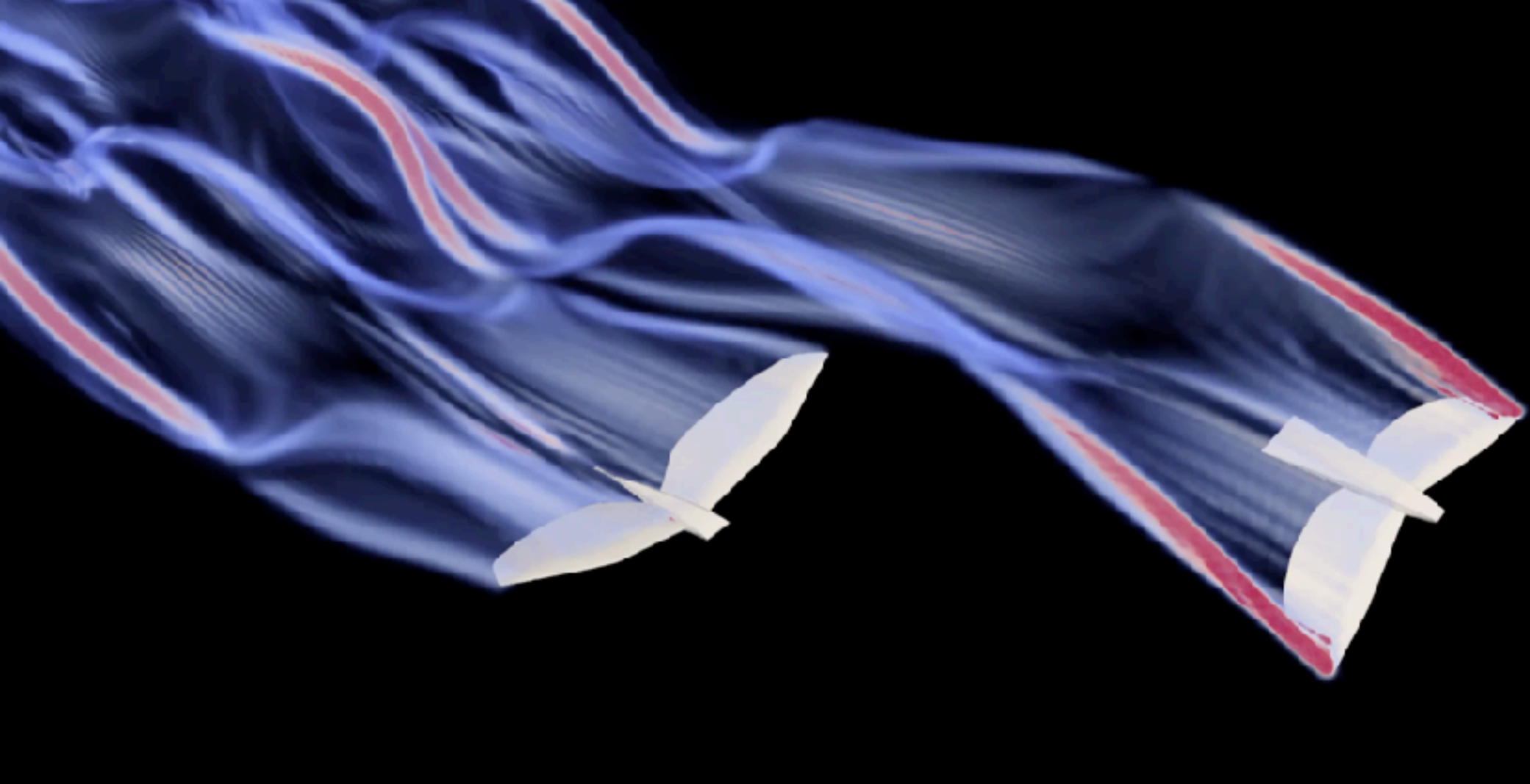

Thank you!