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Formation Flights Will Play A Key Role In Airbus' Sustainability Plan



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Why passenger jets could soon be flying in formation

Howard Slutsken, CNN • Published 15th September 2020



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Boeing/FedEx 777 Test Confirms Wake Fuel-Burn Benefit

Guy Norris December 13, 2019

Demos Formation-
fuel Saving On
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Innovation

Airbus and its partners demonstrate how sharing the skies can save airlines fuel and reduce CO2 emissions



Completes transatlantic formation flight

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os Formation-
Saving On
ntic Flight

Formation flight: wake sensing and assessment of hazard for external traffic

October 5th – TFM ASA Workshop 2022, University of Bordeaux

Ignace Ransquin, Matthieu Duponcheel, Philippe Chatelain

Institute of Mechanics, Materials and Civil Engineering
UCLouvain, Louvain-la-Neuve, Belgium

Denis-Gabriel Caprace

Oak Ridge Associated Universities
NASA Ames Research Center, Moffett Field, California

Acknowledgments: Jeff Eldredge (UCLA)

Formation flight

Wake exploitation:

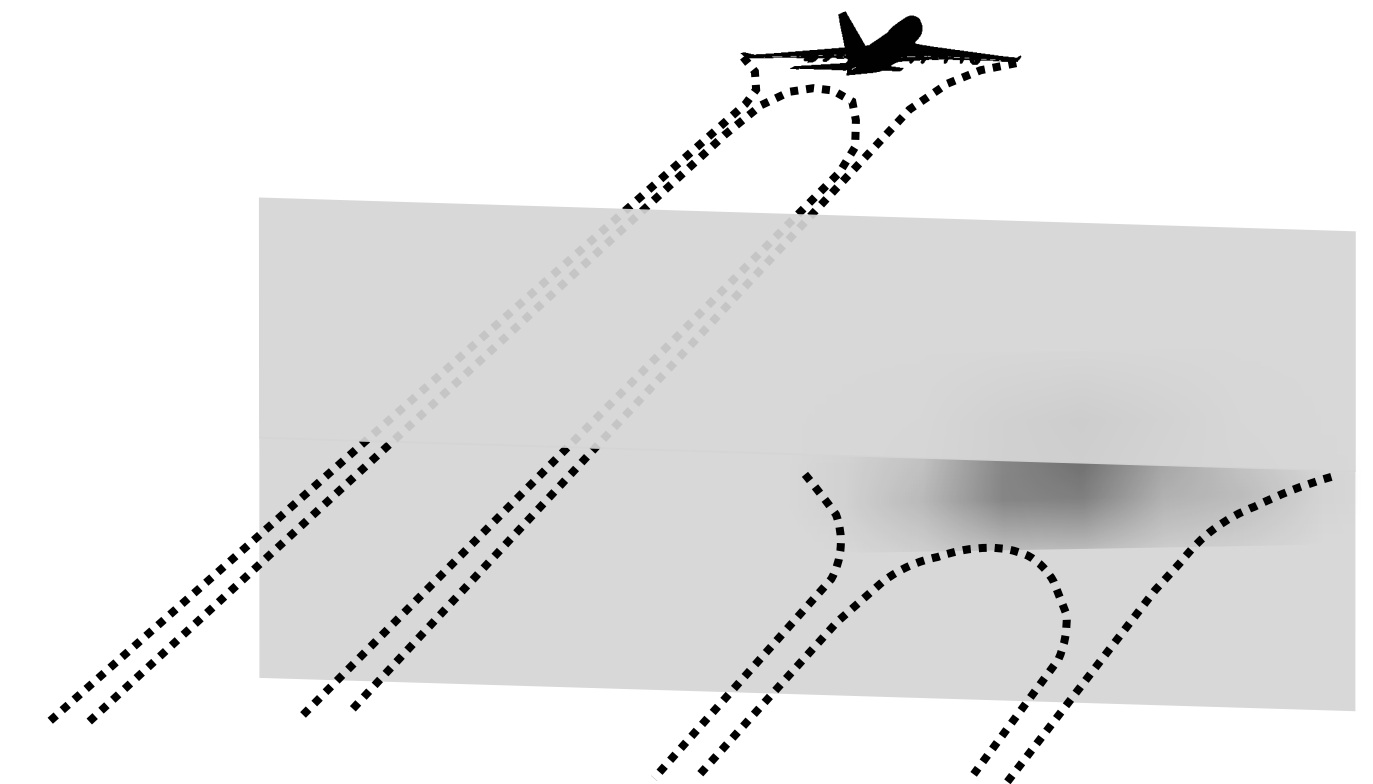
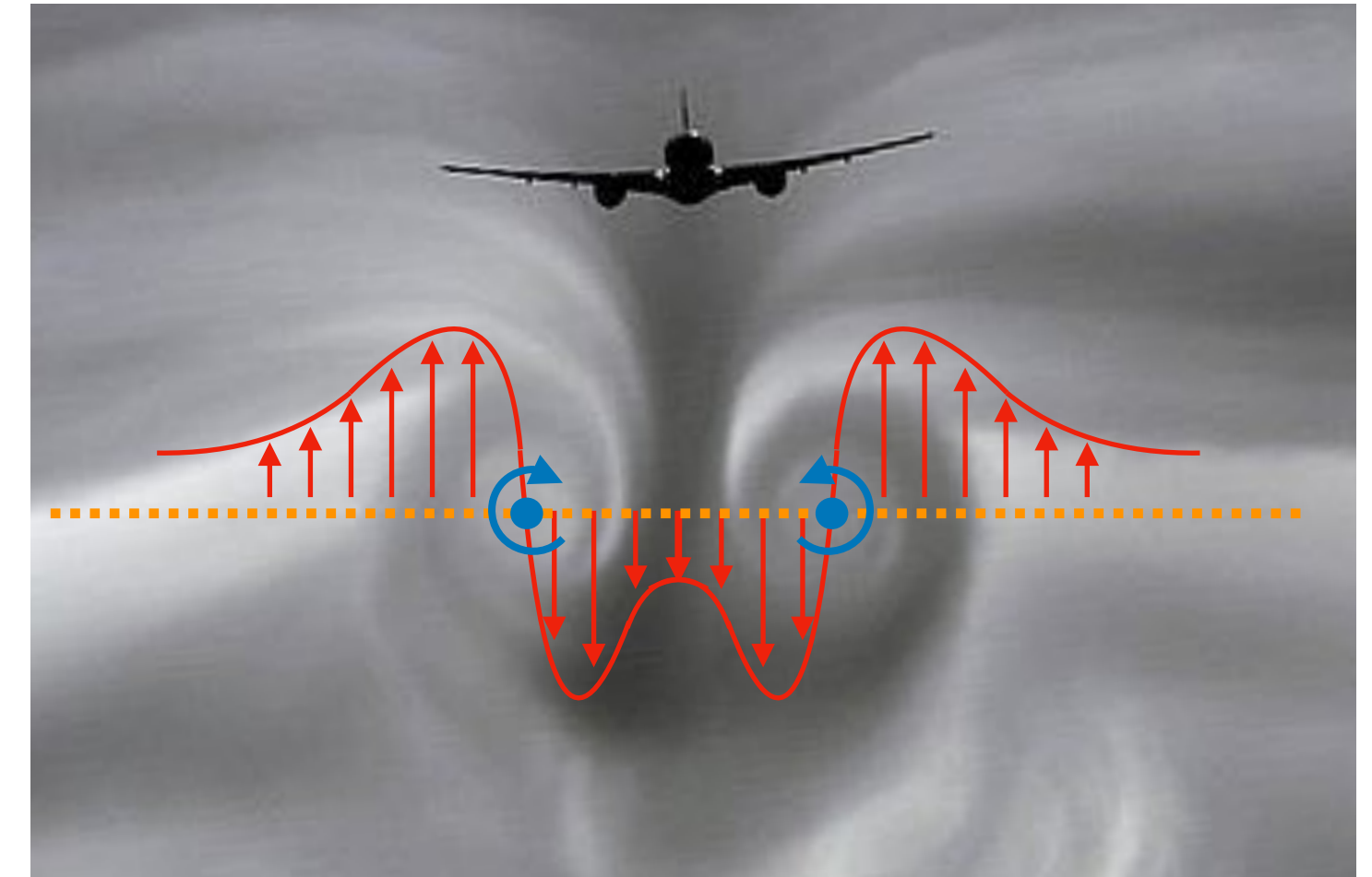
- Fly in the upwash region
- Achieve ~15% gain in fuel consumption
- Maintain an optimal offset w.r.t. leader, ~ 1 span

Challenges :

- Sensitivity of benefit: position error of 10% span leads to 50% loss on fuel savings
- Avoid wake encounter: major upset in roll and downward velocity
- **Need to track** the leader's wake

Wake **tracking** techniques relying on :

- model-based predictions of wake position
- communications between aircraft (ADS-B)
- on-board **sensing** of wake
- controller/auto-pilot



Formation flight

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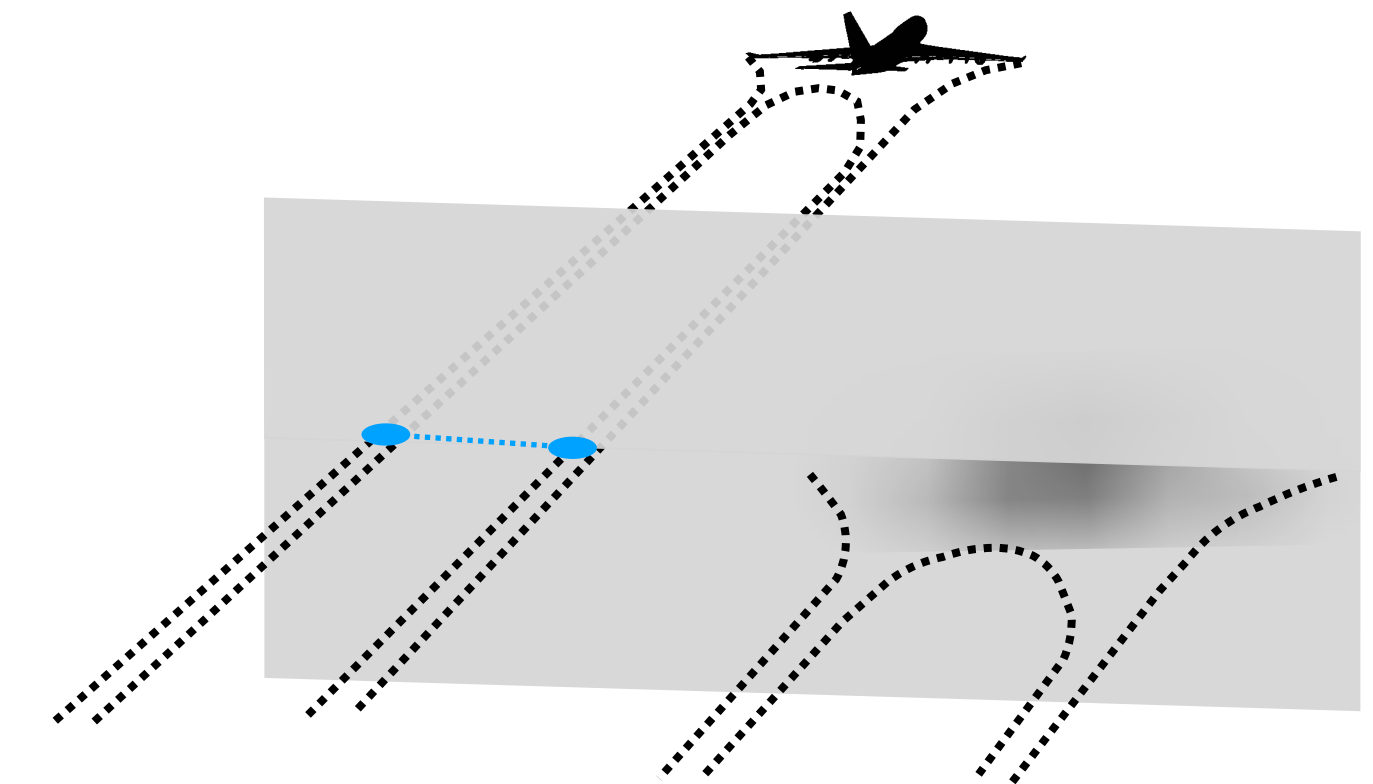
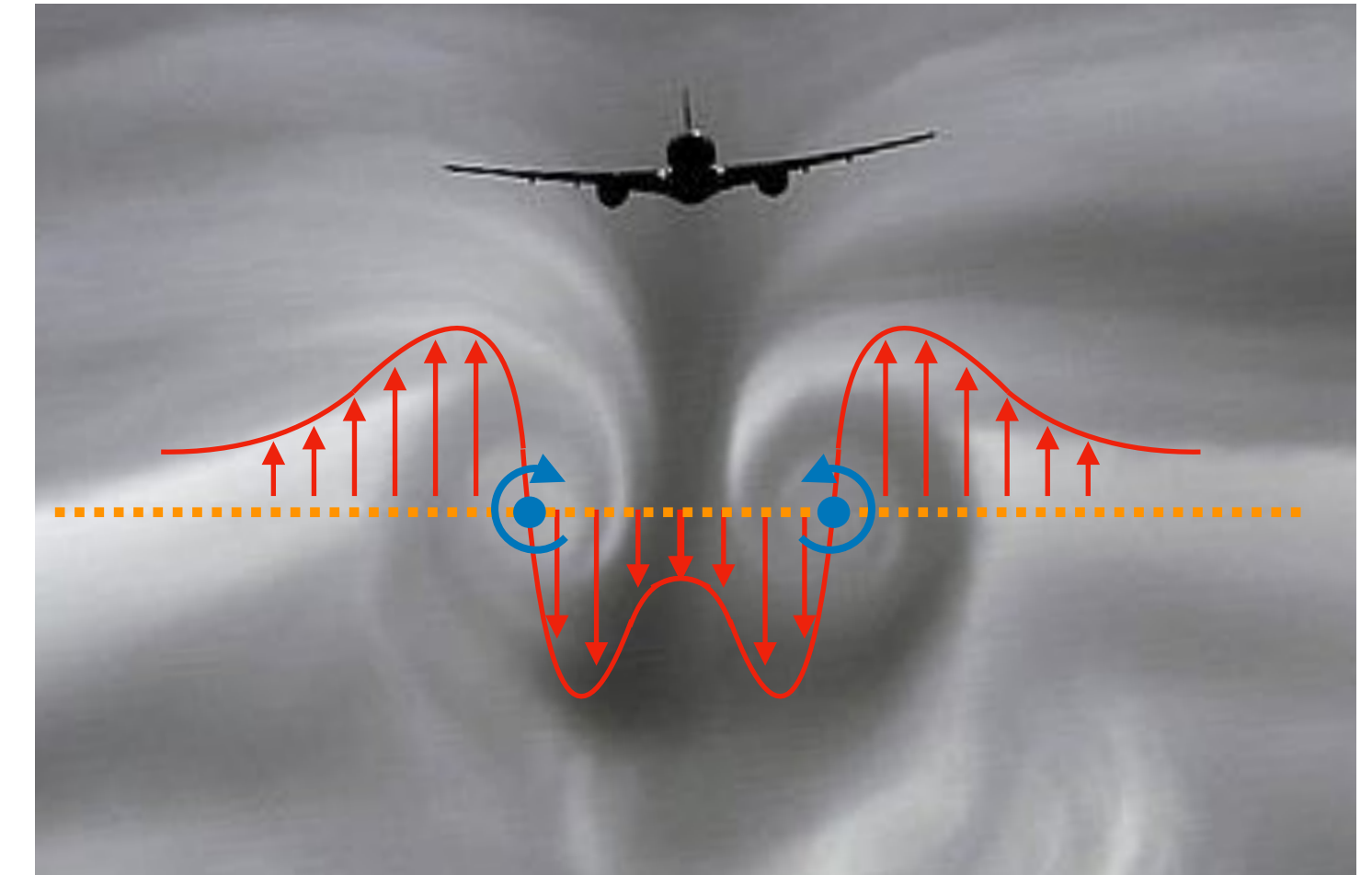
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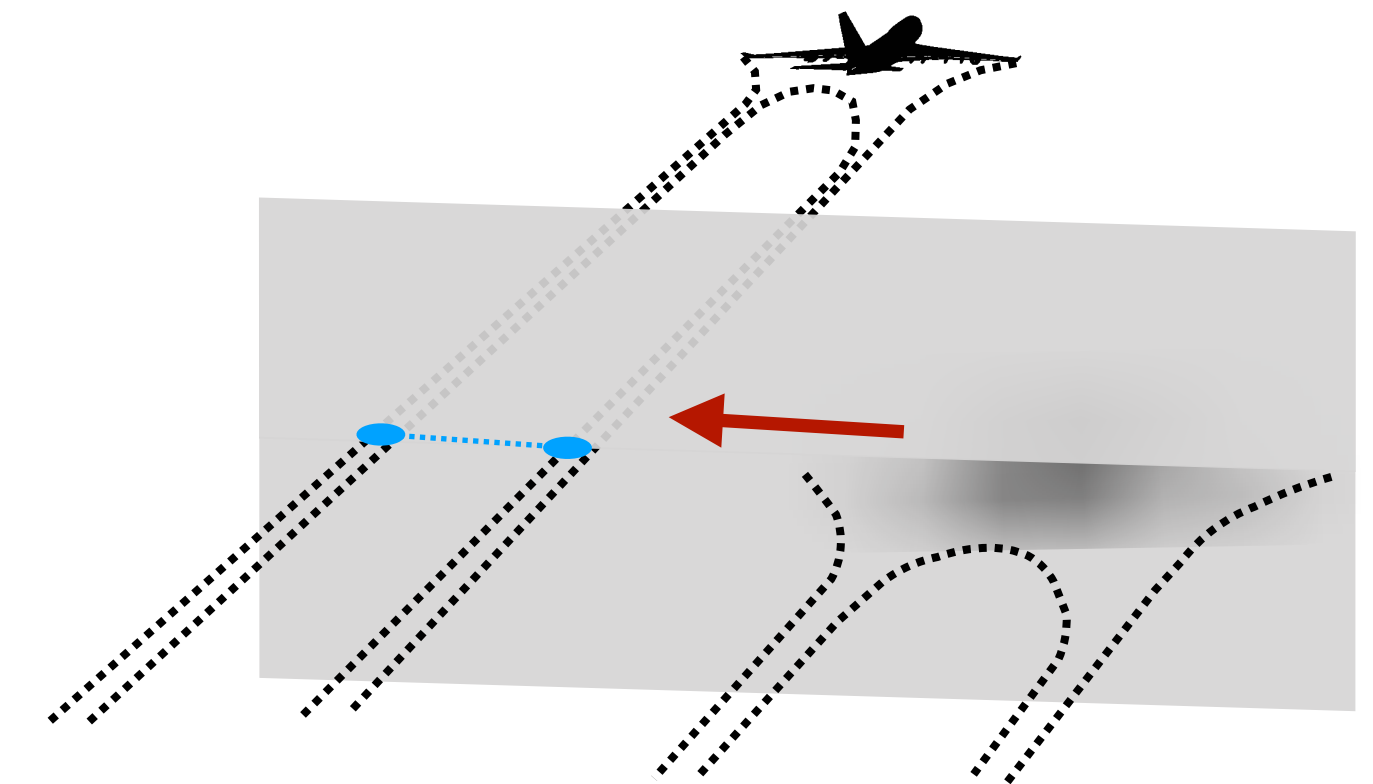
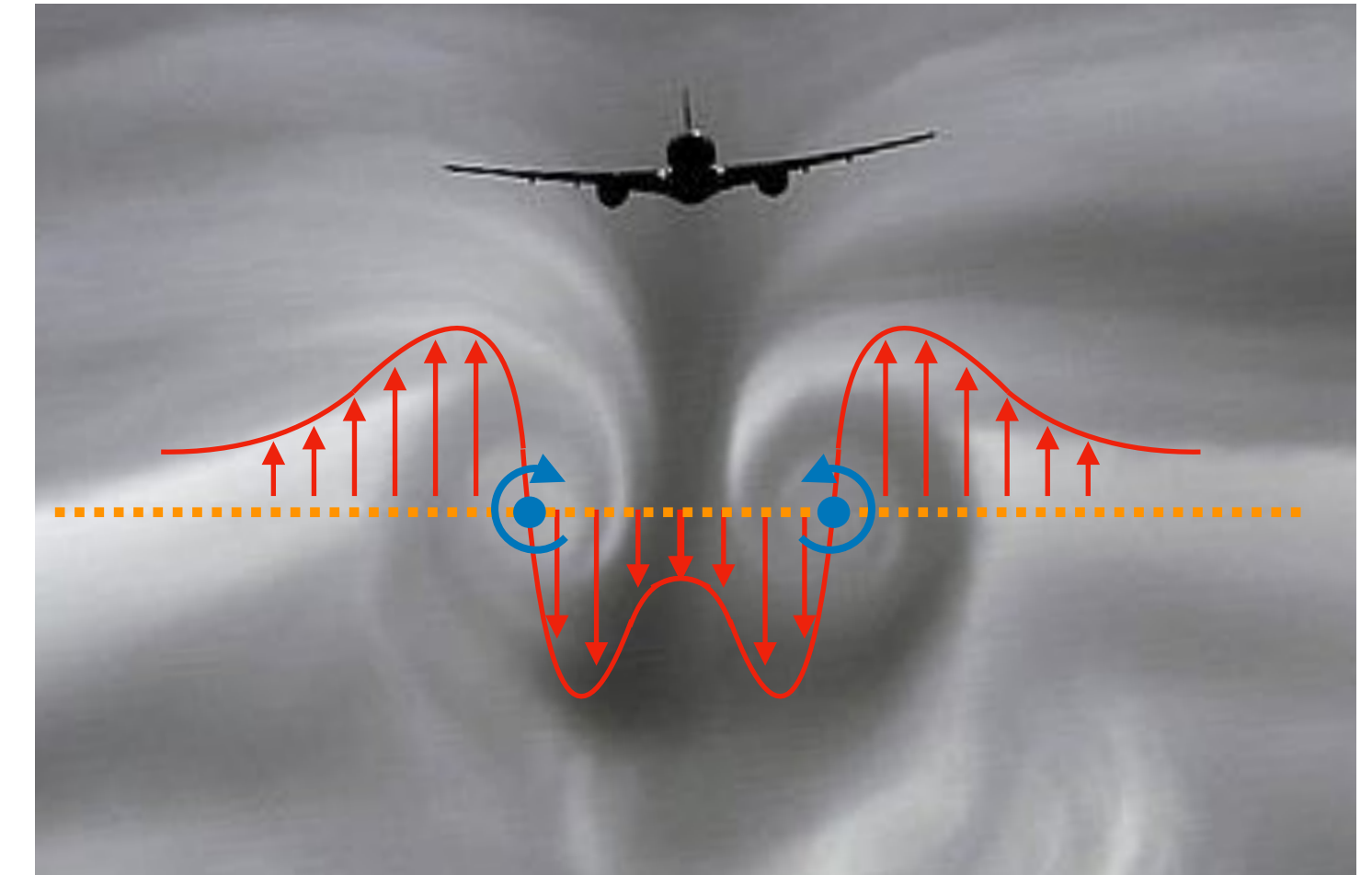
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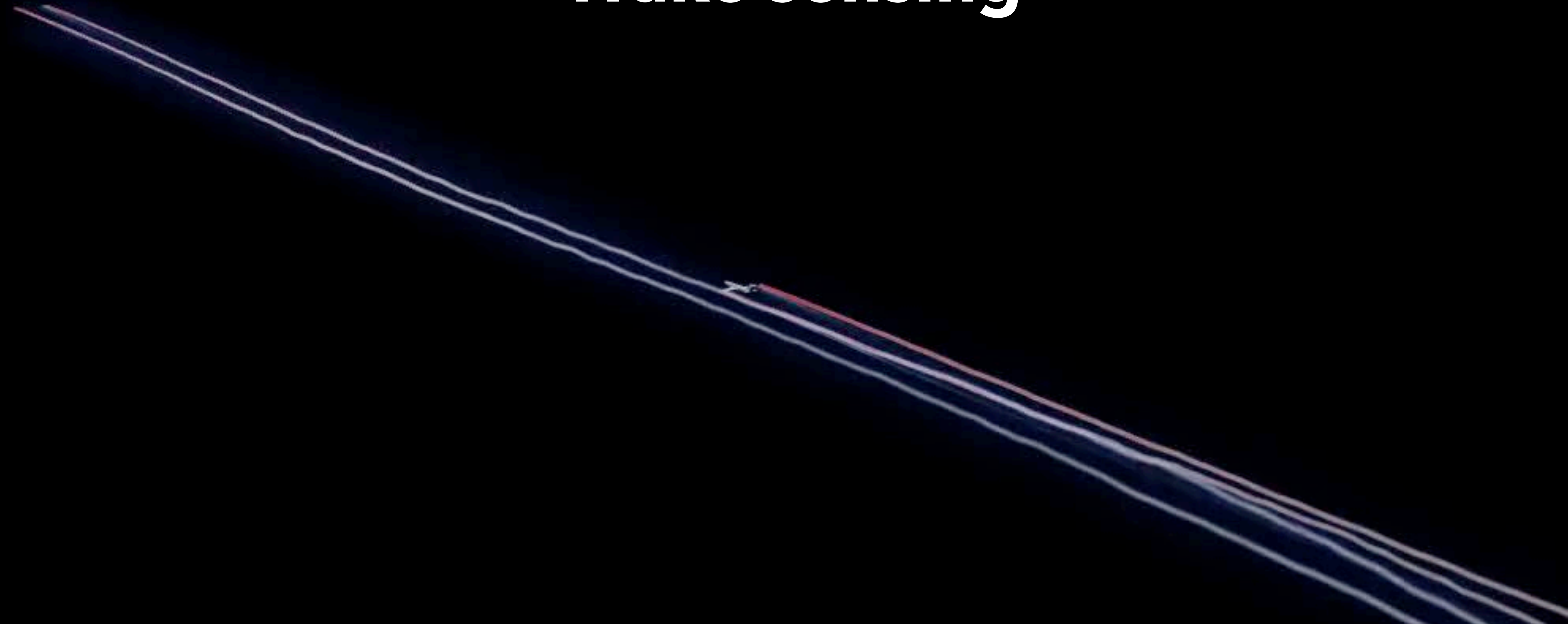
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Wake sensing



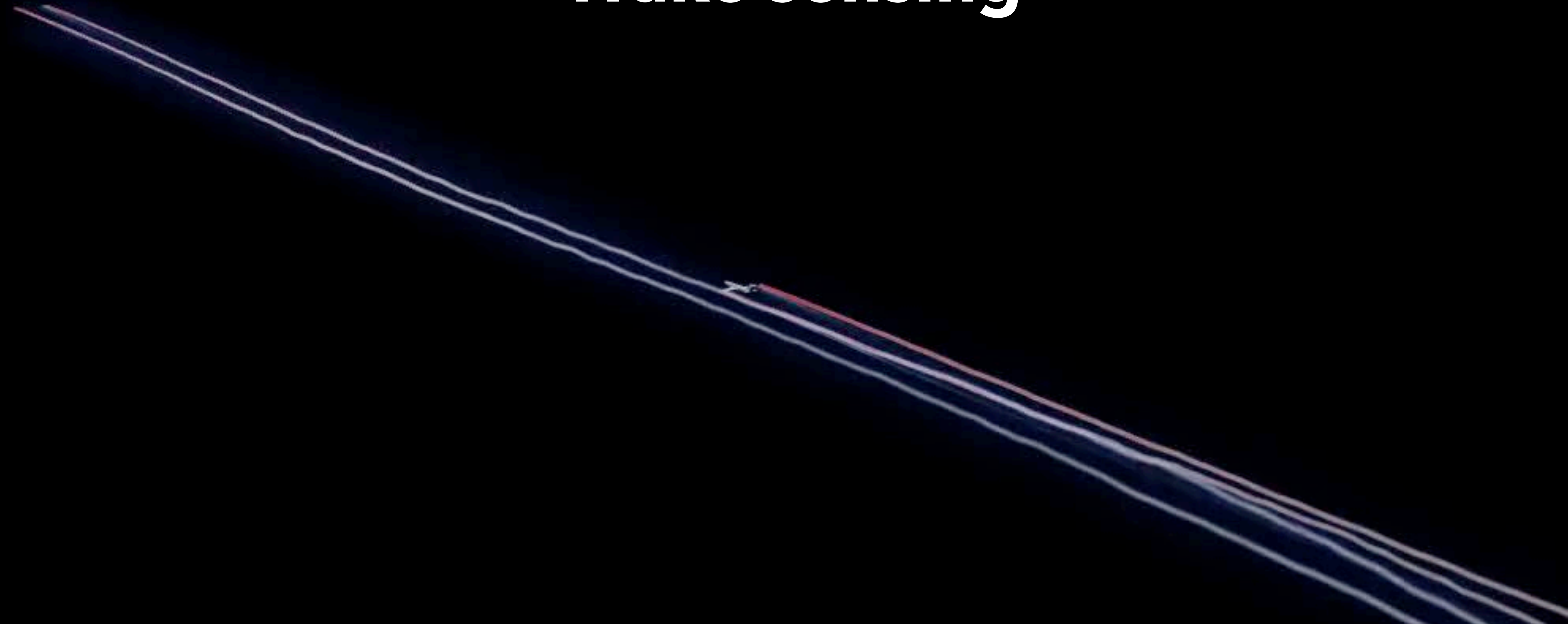
Volume rendering of $\|\omega\|$

Ransquin et al., JGCD, 2021

Caprace et al., AIAA Forum, 2019

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Wake sensing



Volume rendering of $\|\omega\|$

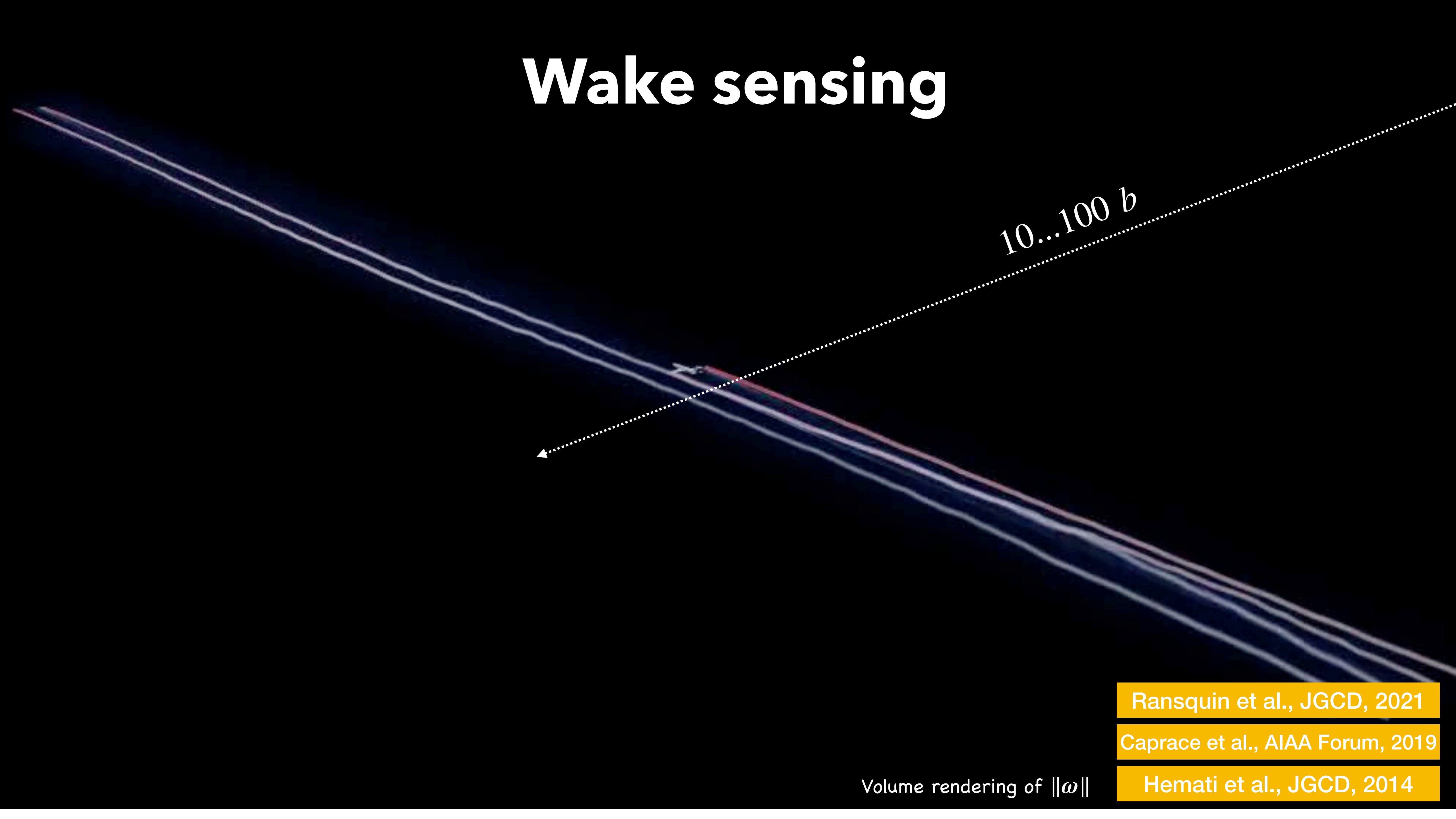
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Wake sensing

10...100 b



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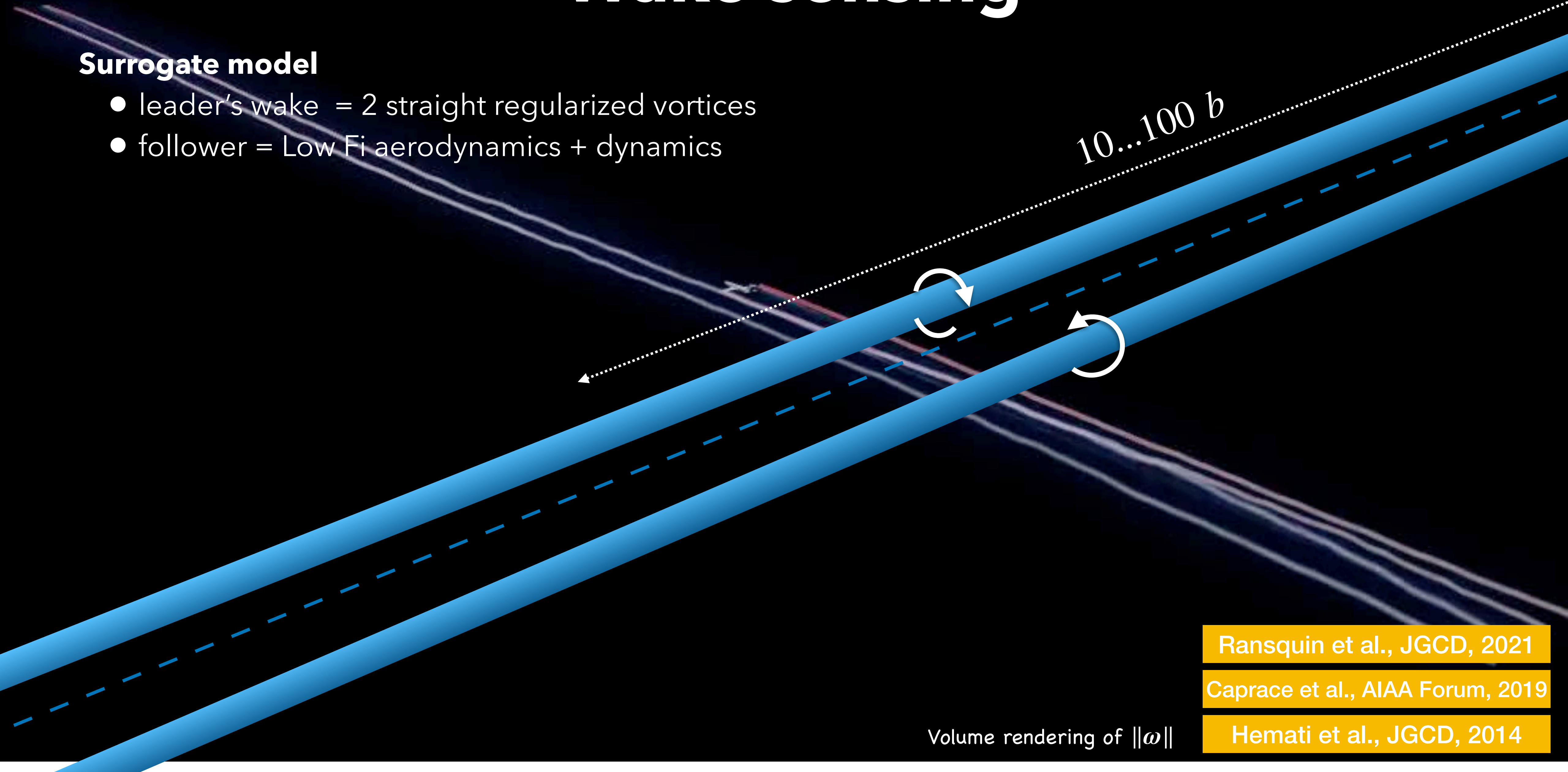
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Wake sensing

Surrogate model

- leader's wake = 2 straight regularized vortices
- follower = Low Fi aerodynamics + dynamics



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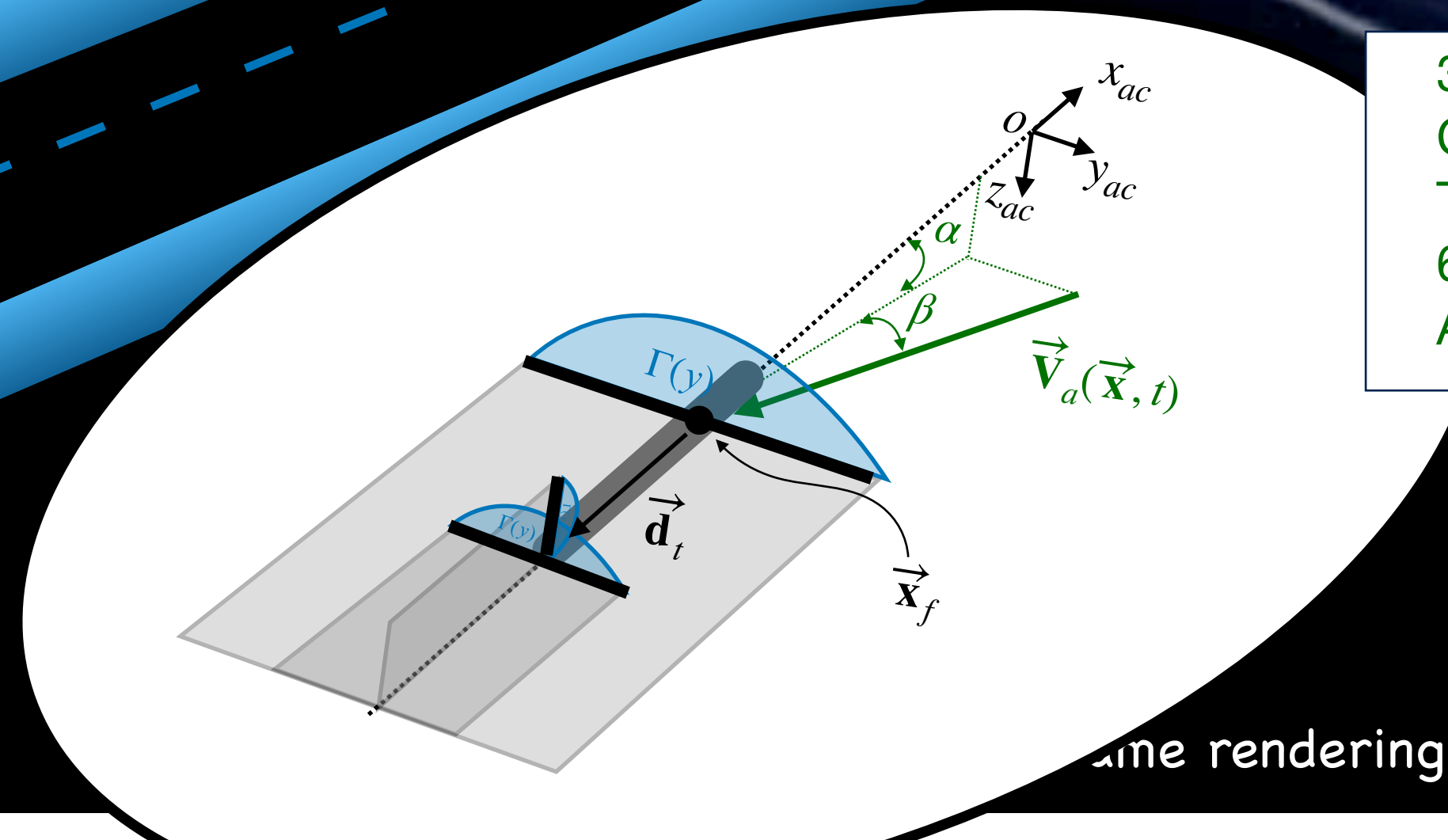
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3 Prandtl Lifting Lines
Control surfaces
Throttle
6 d.o.f. dynamics
Autopilot

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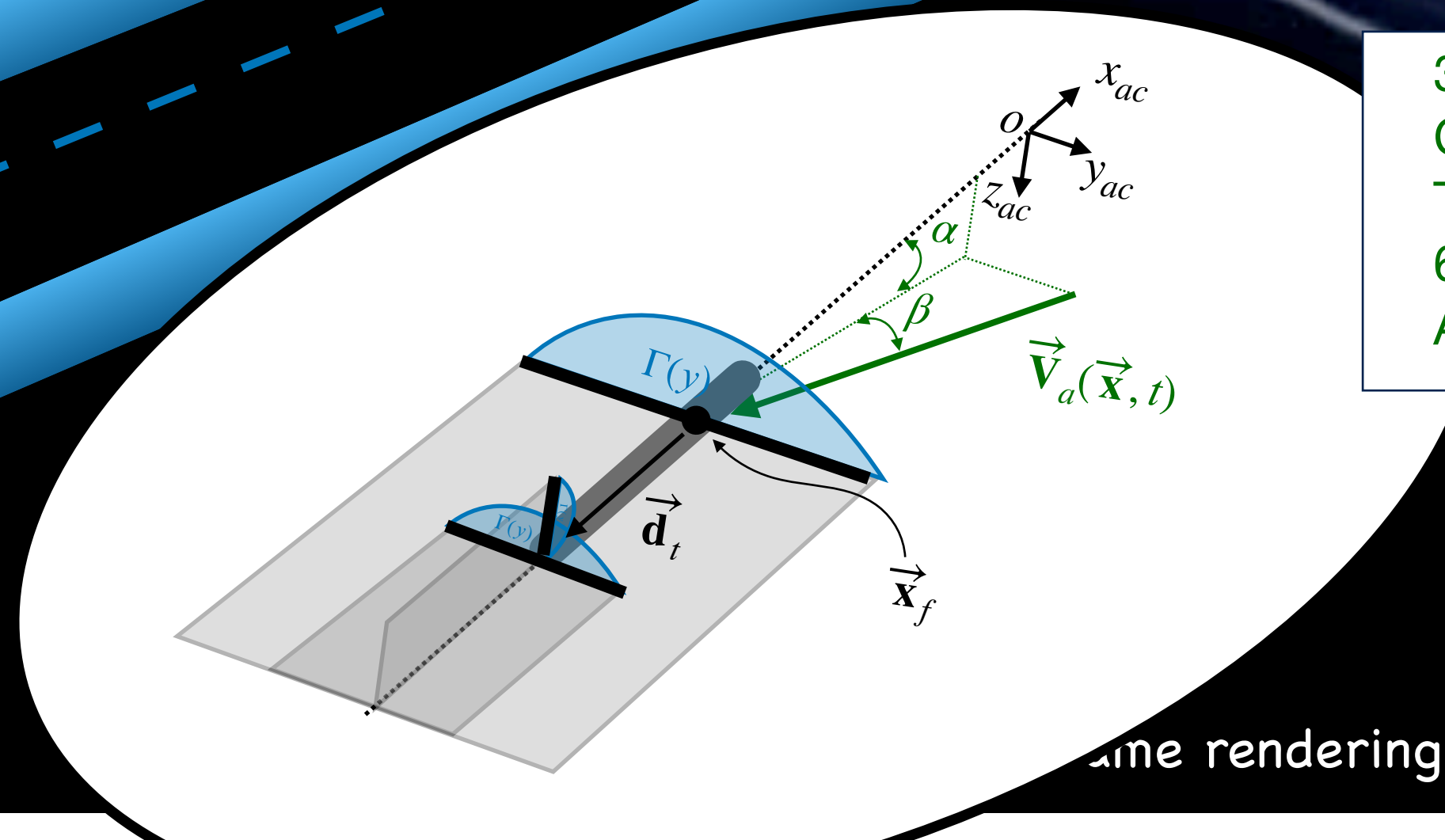
Proprioceptive Wake sensing

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- leader's wake = 2 straight regularized vortices
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Follower's measurements

- own dynamics (as available from INS)
- angles of incidence and sideslip
- control surface deflections



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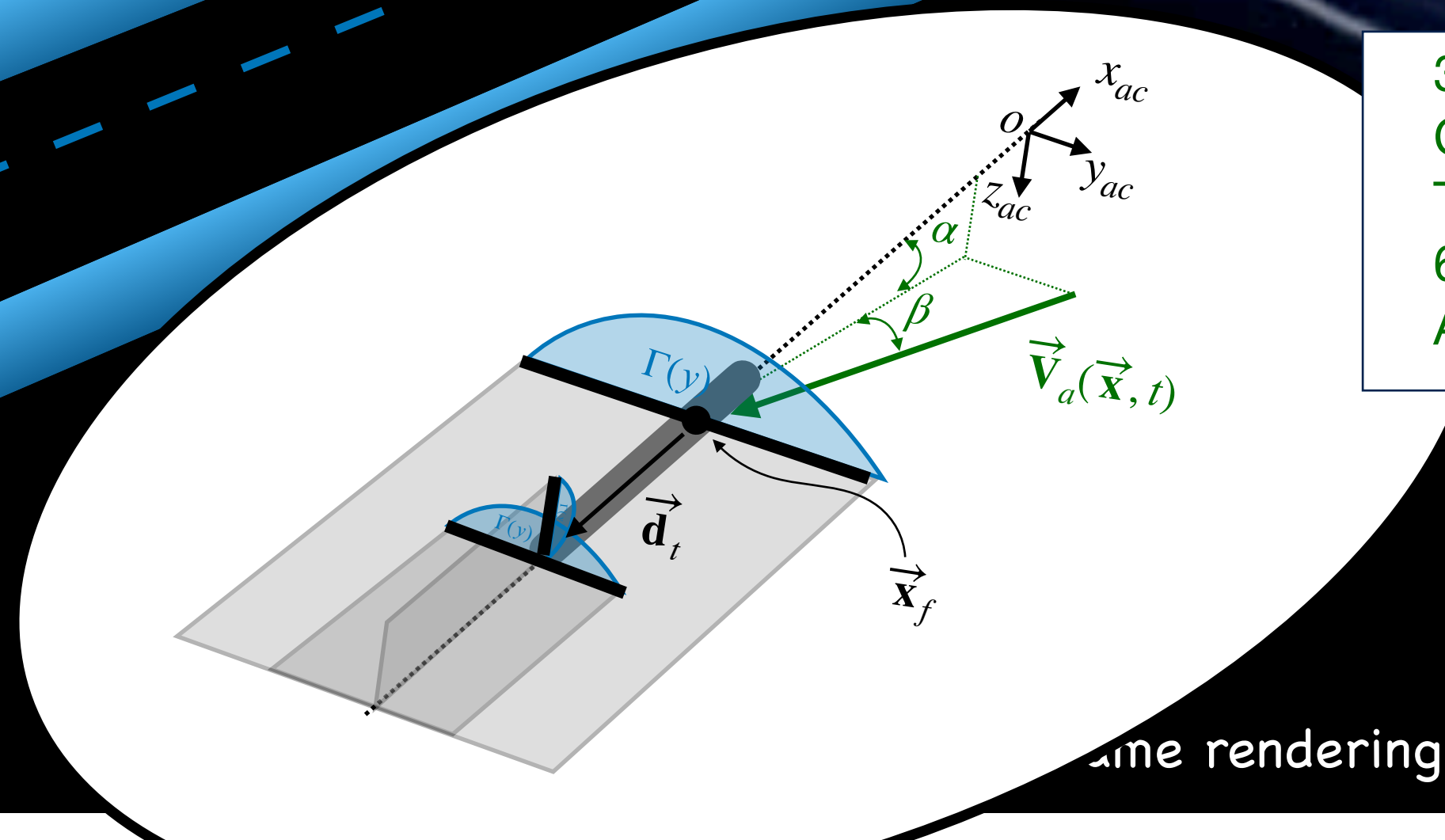
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No dedicated sensors!

$10 \dots 100 b$



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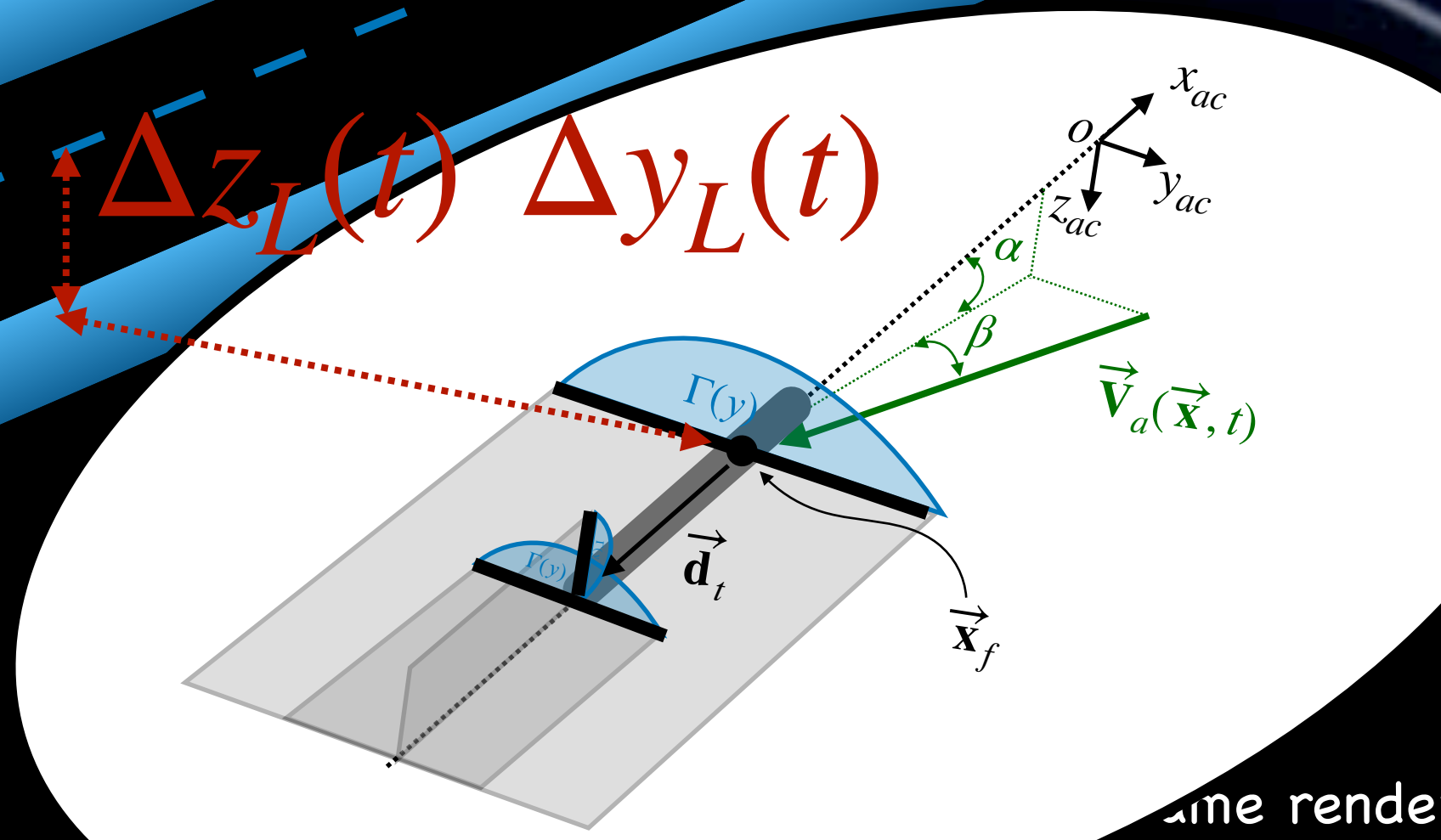
Follower's measurements

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Estimation (data assimilation)

- relative position
- wake characteristics

No dedicated sensors!



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Control surfaces
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6 d.o.f. dynamics
Autopilot

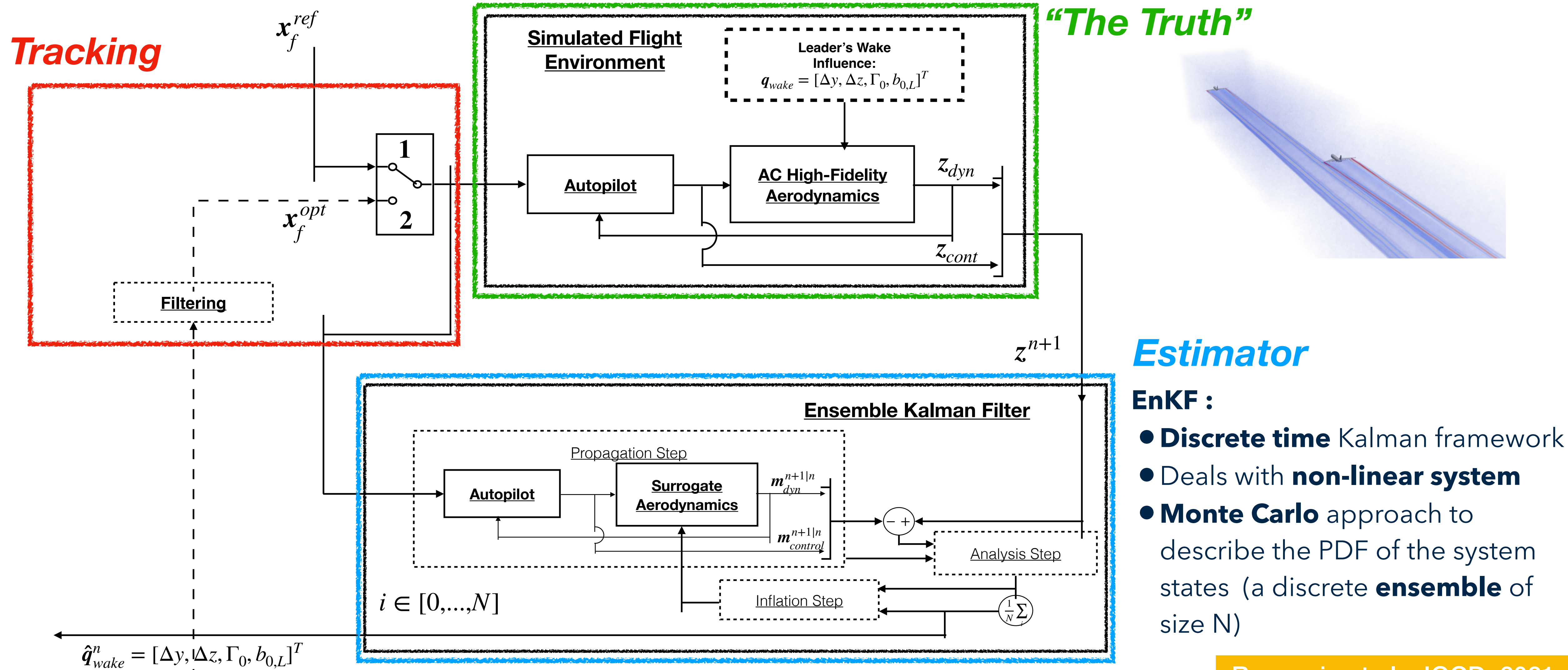
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same rendering of $\|\omega\|$

Wake sensing: Ensemble Kalman Filter (EnKF)

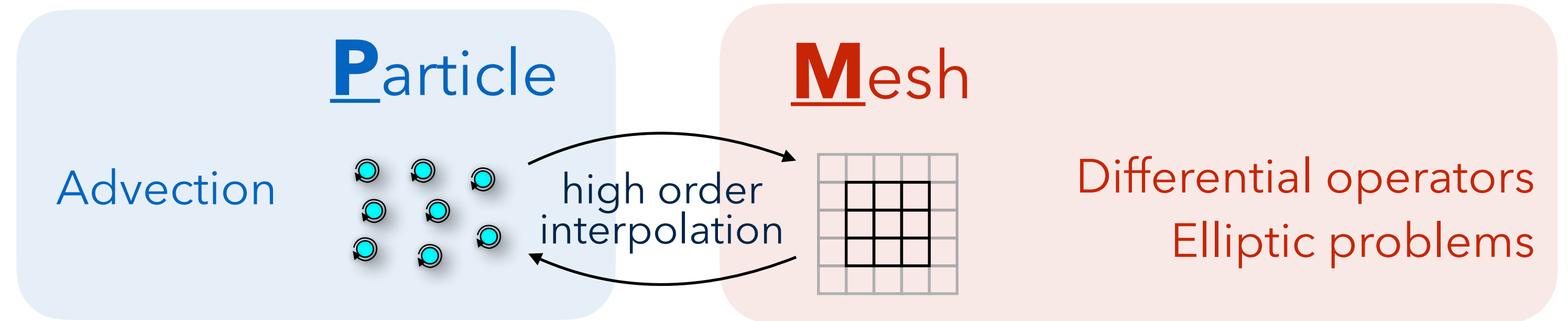


LES Flow Solver: Vortex Particle-Mesh Method (VPM) with Immersed Lifting Lines (ILL)

“The Truth”

$$\omega = \nabla \times u \quad \underline{\mathbf{V}}_{\text{ortex}}$$
$$\frac{D\omega}{Dt} = (\omega \cdot \nabla)u + \nu \nabla^2 \omega$$

Chatelain et al. 2008



LES Flow Solver: Vortex Particle-Mesh Method (VPM) with Immersed Lifting Lines (ILL)

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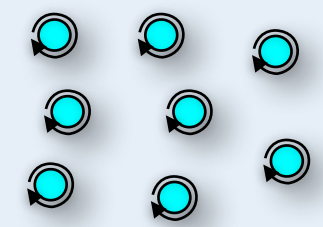
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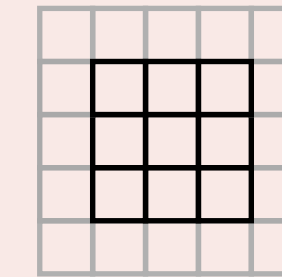
Particle

Advection



high order
interpolation

Mesh

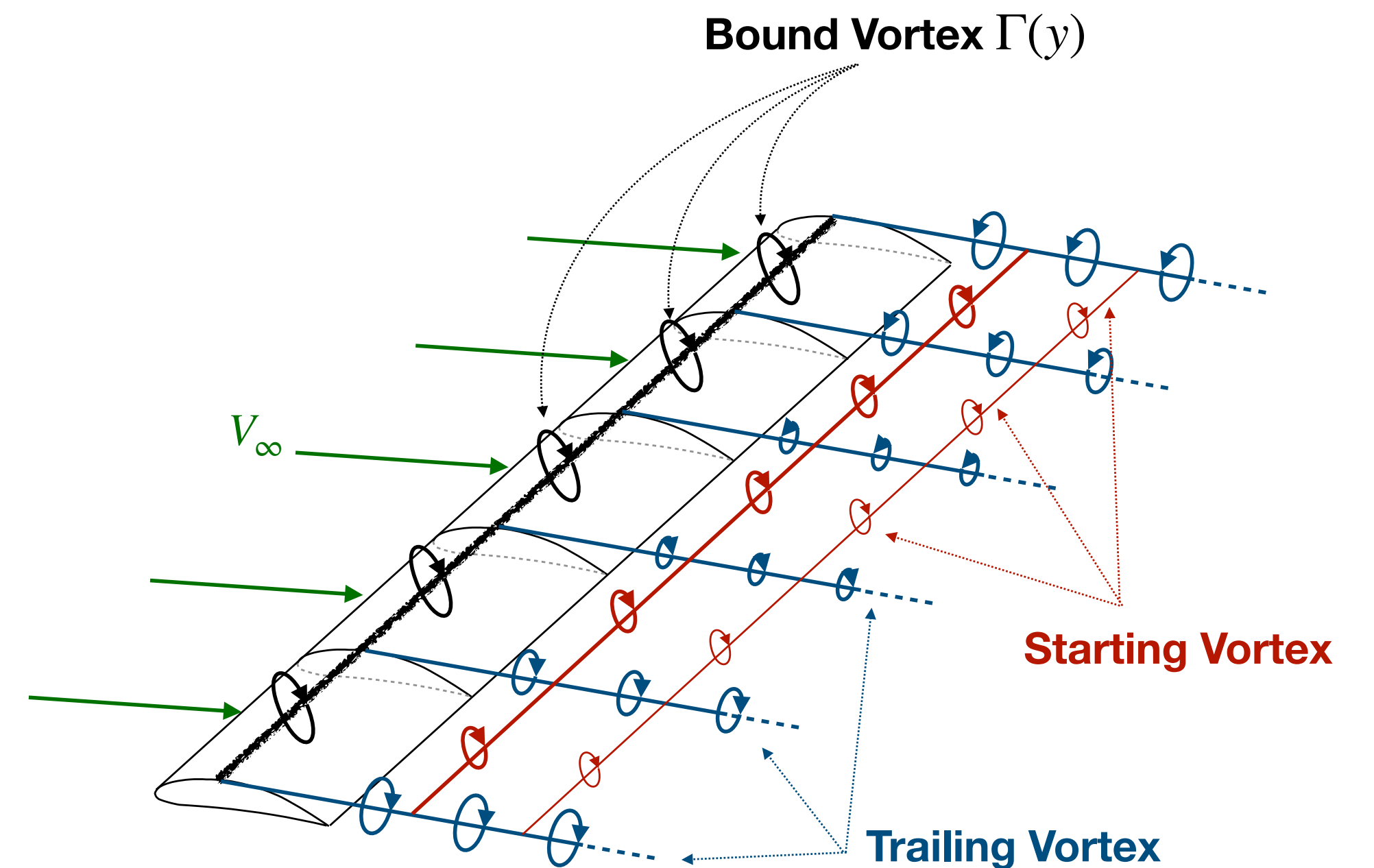


Differential operators
Elliptic problems

Immersed Lifting Line:

1. V_{rel} and α at every section
2. Sectional lift l from polar
3. Bound Vortex $l = \rho V_{rel} \times \Gamma$
4. Shed vorticity in the flow

➡ **Computational efficiency
and low dissipation**



Caprace et al. 2020

Wake sensing and tracking

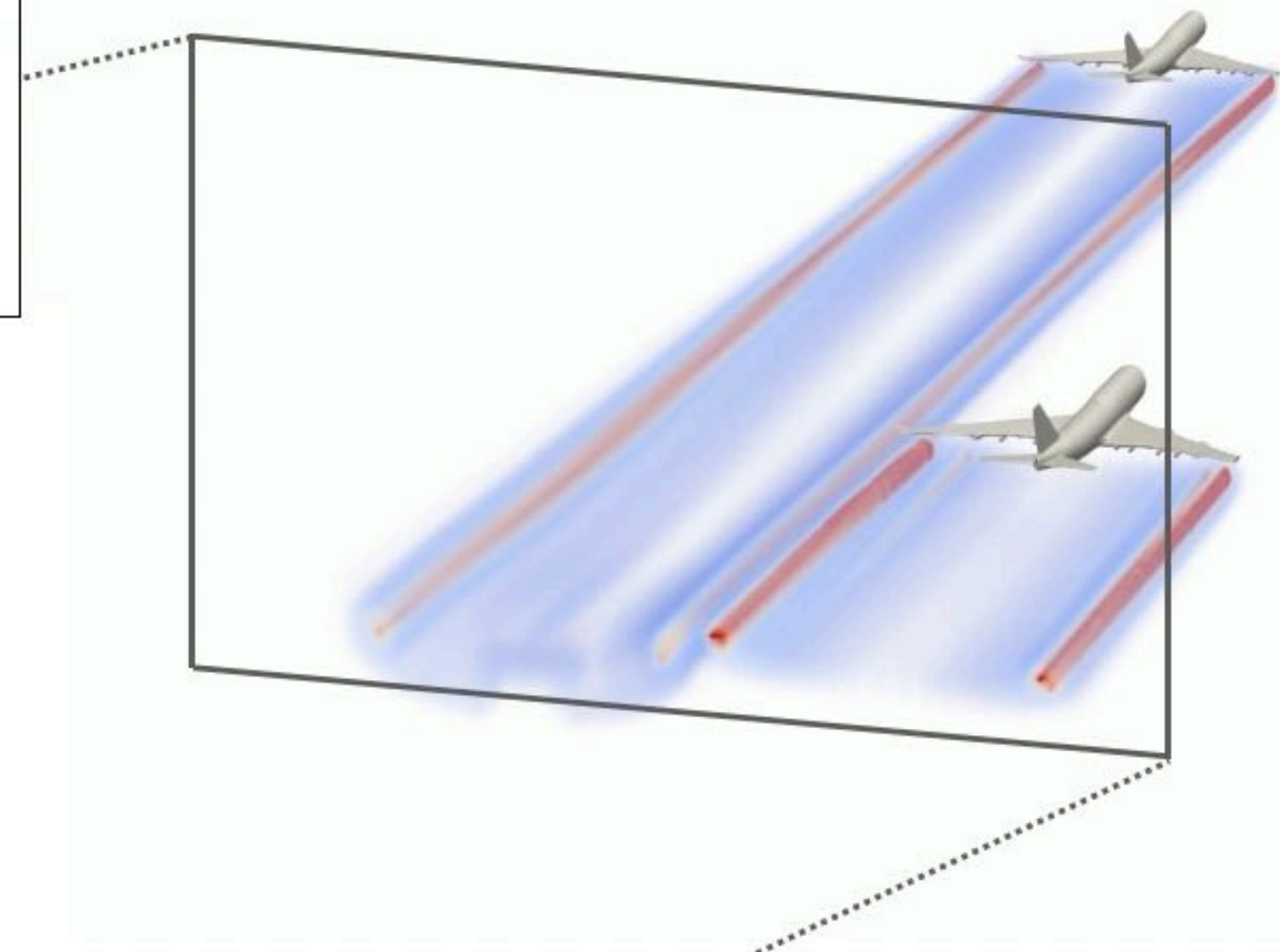
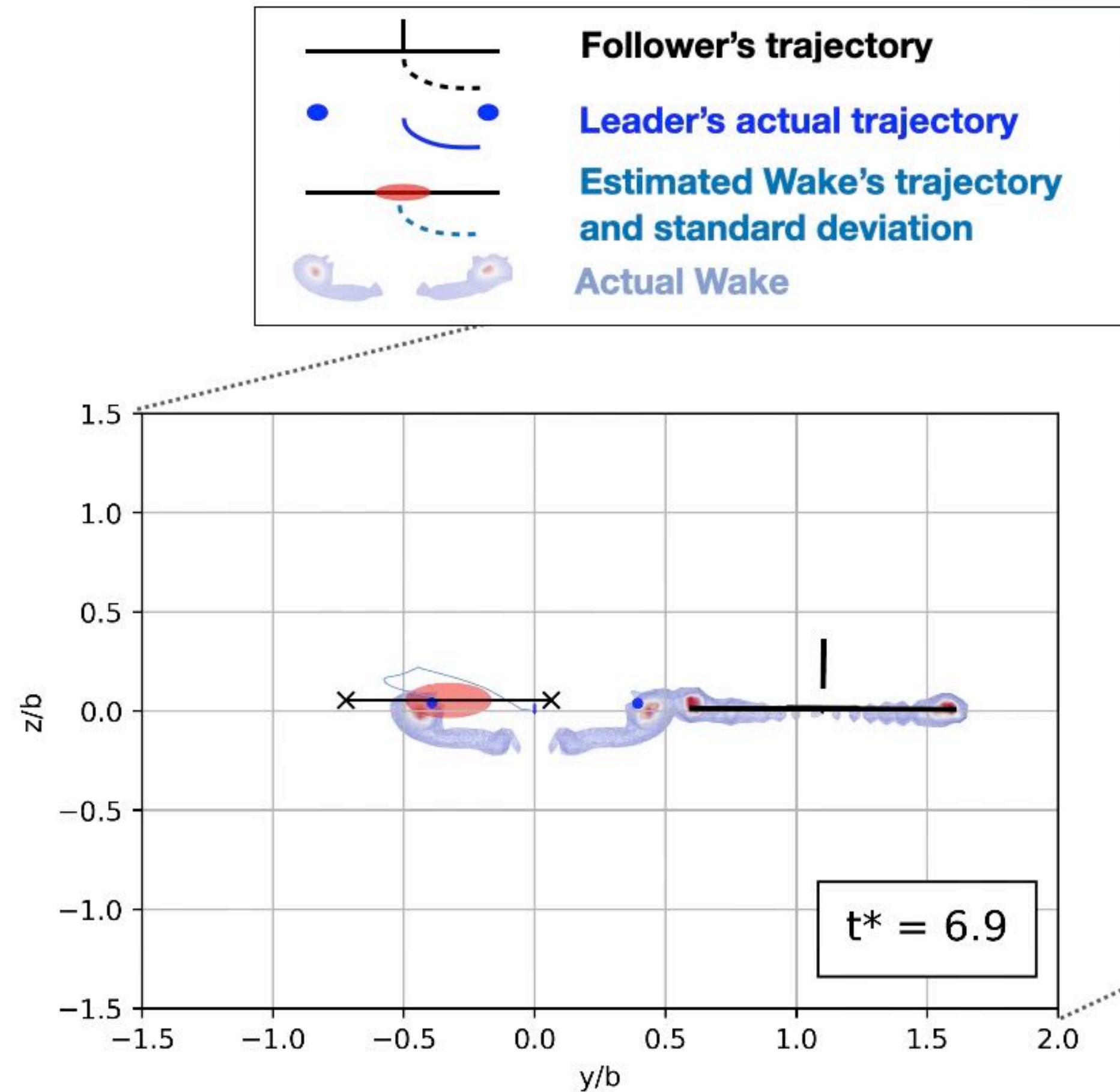
Objectives :

- Track preset offset point
- Characterize wake and ambient conditions
- Avoid wake encounter

However...

- Ambient turbulence
- Leader maneuvers
- Tracking noise

lead to noise / uncertainty in formation configuration



Wake sensing and tracking

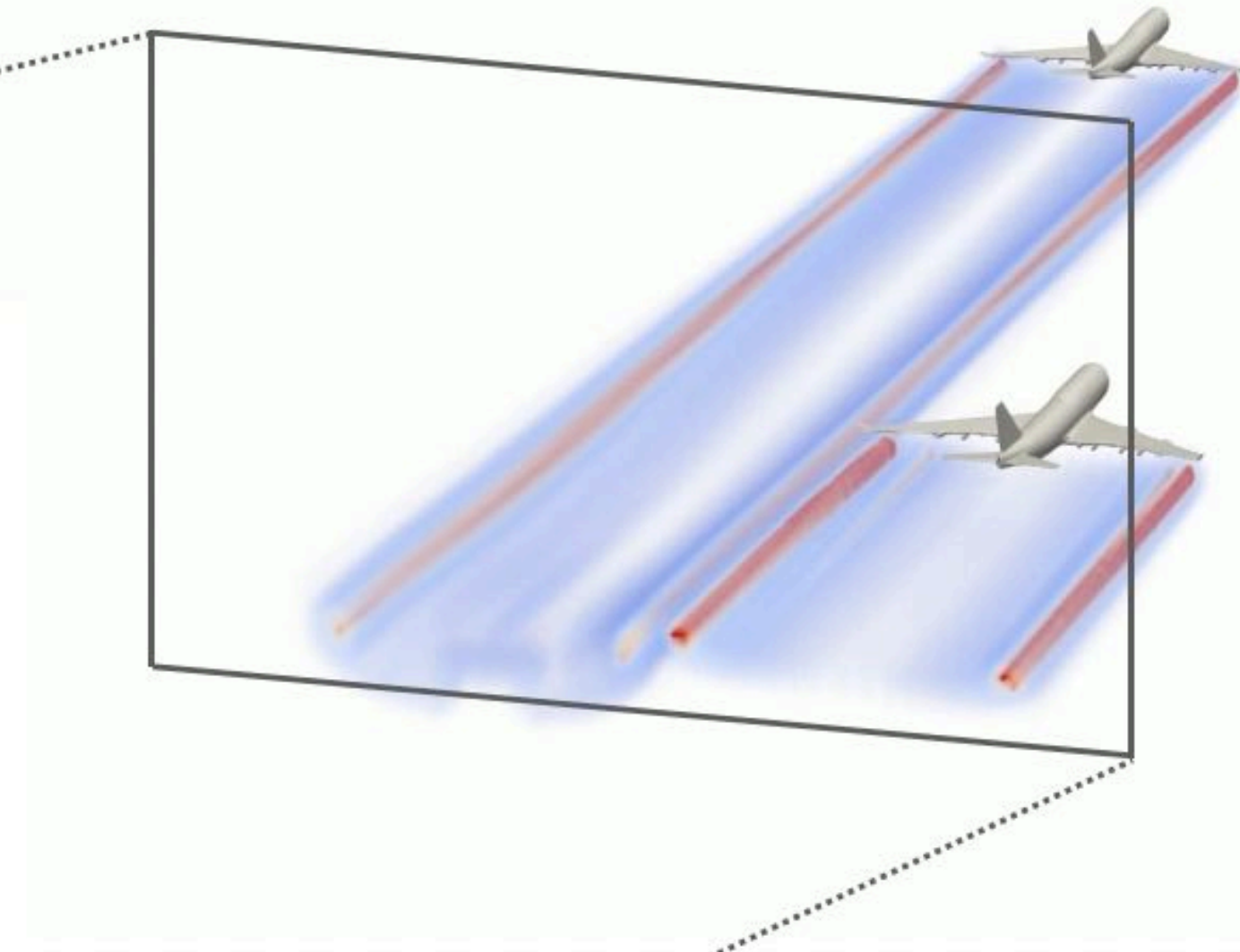
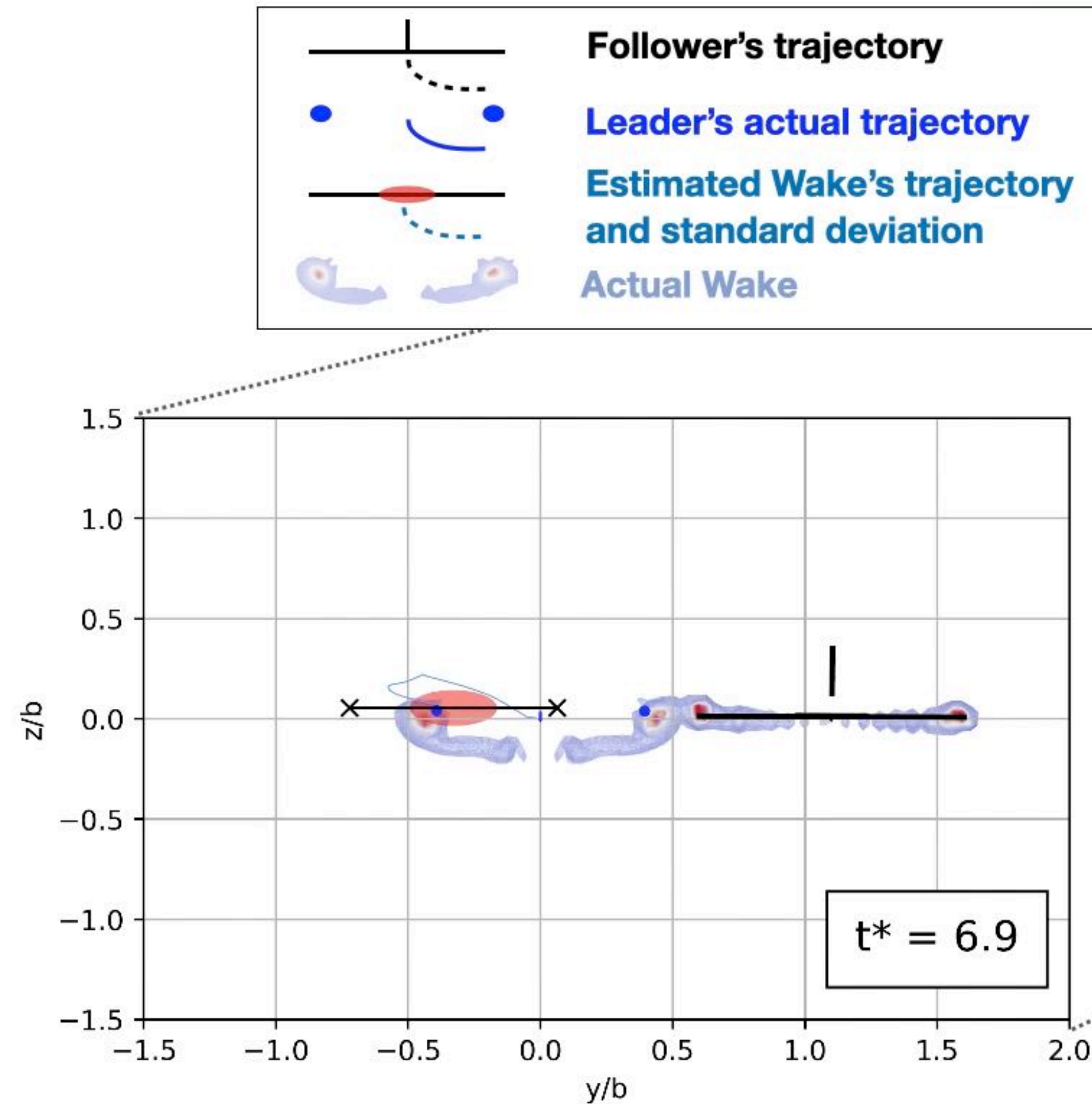
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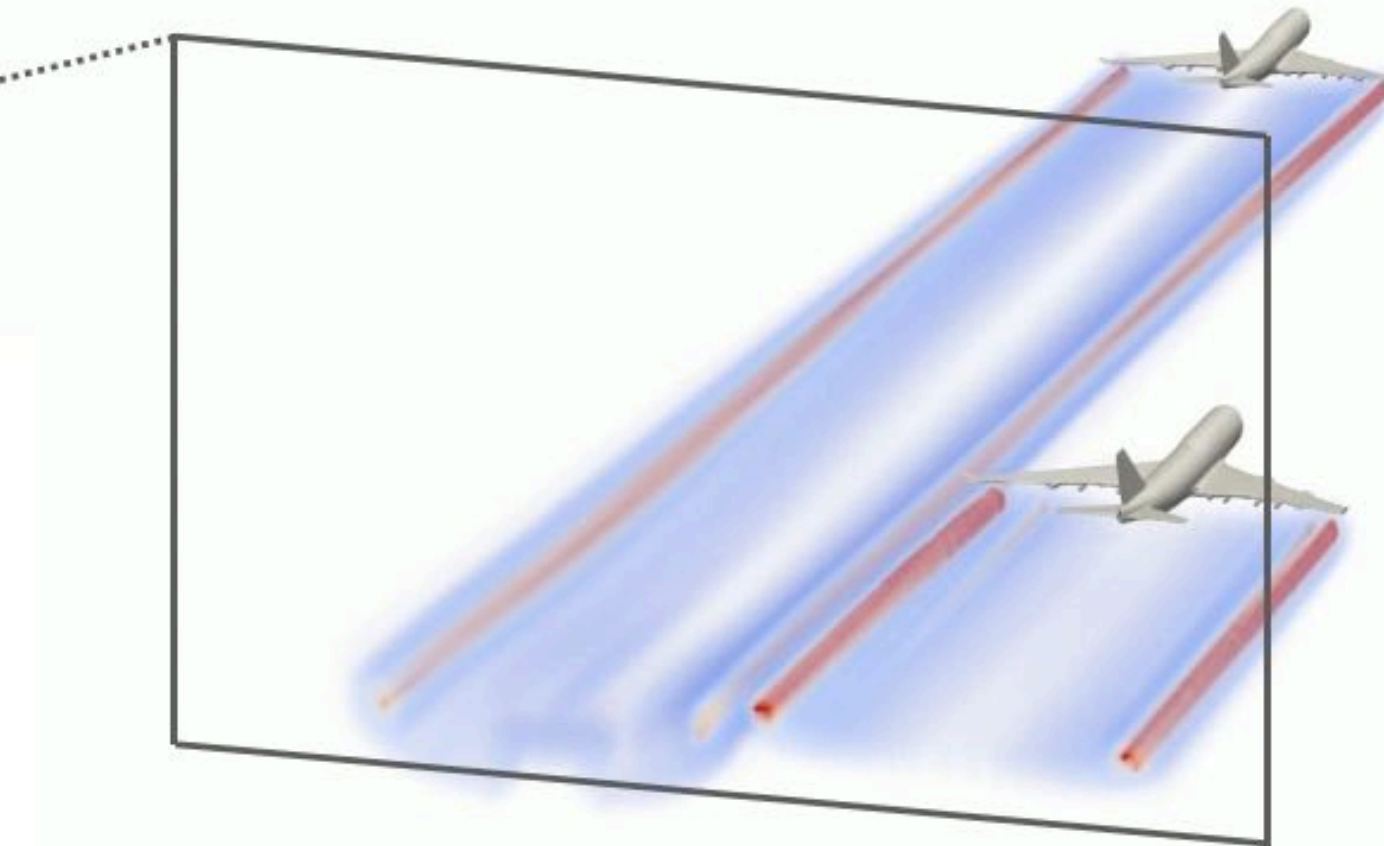
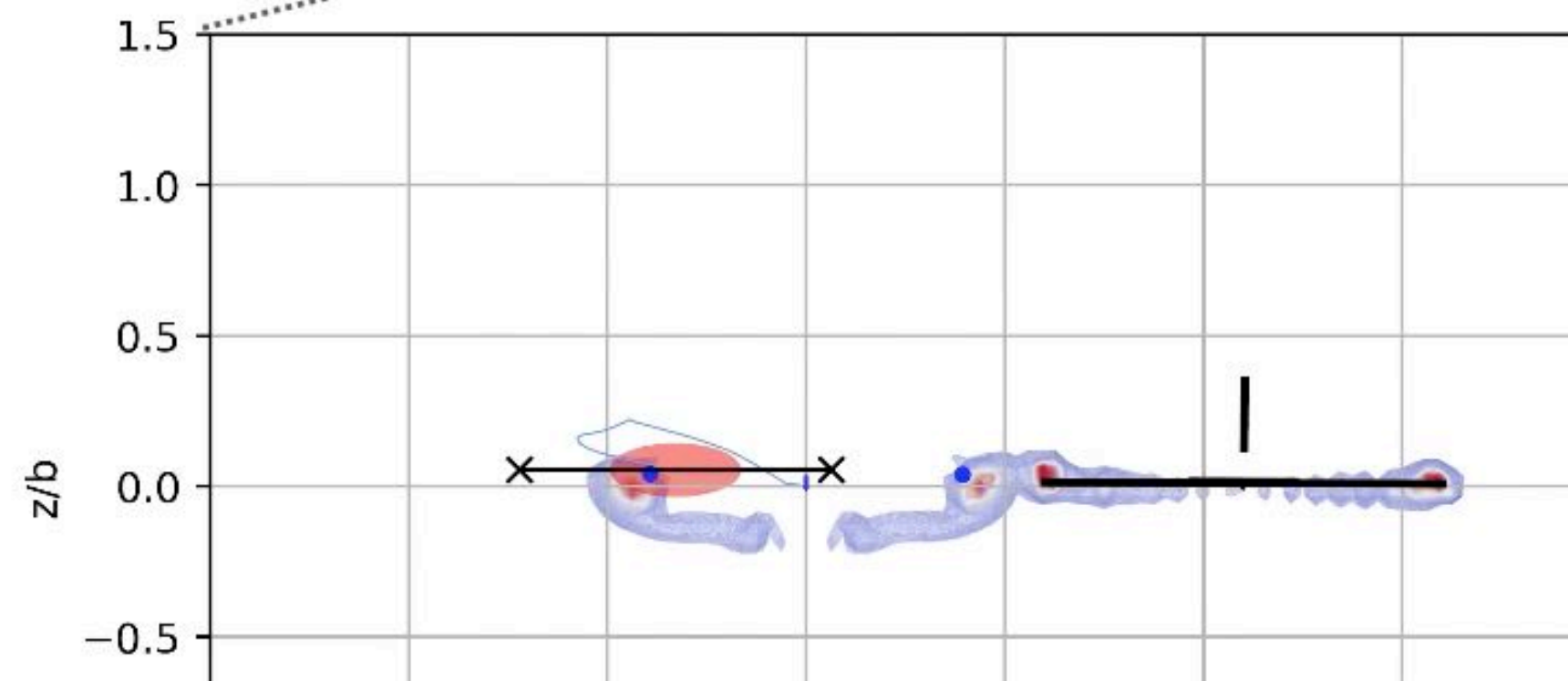
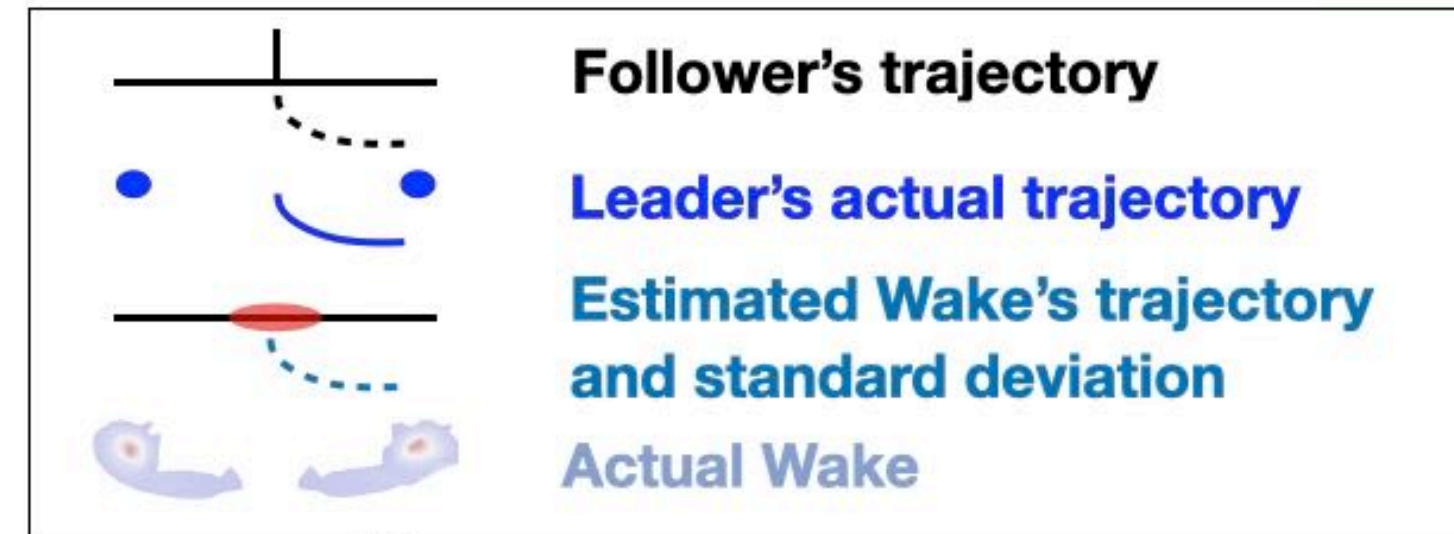
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→ Uncertainty on the wake propagation and behavior far downstream

- Quantify that uncertainty
- Assess consequences for extra aircraft joining formation and air traffic management

Long time propagation of formation wakes

Long times

- Extended formations : streamwise spacing of 20 - 40 spans
- Need to capture wake development up to "old age", $t^* = t/t_0 > 1$

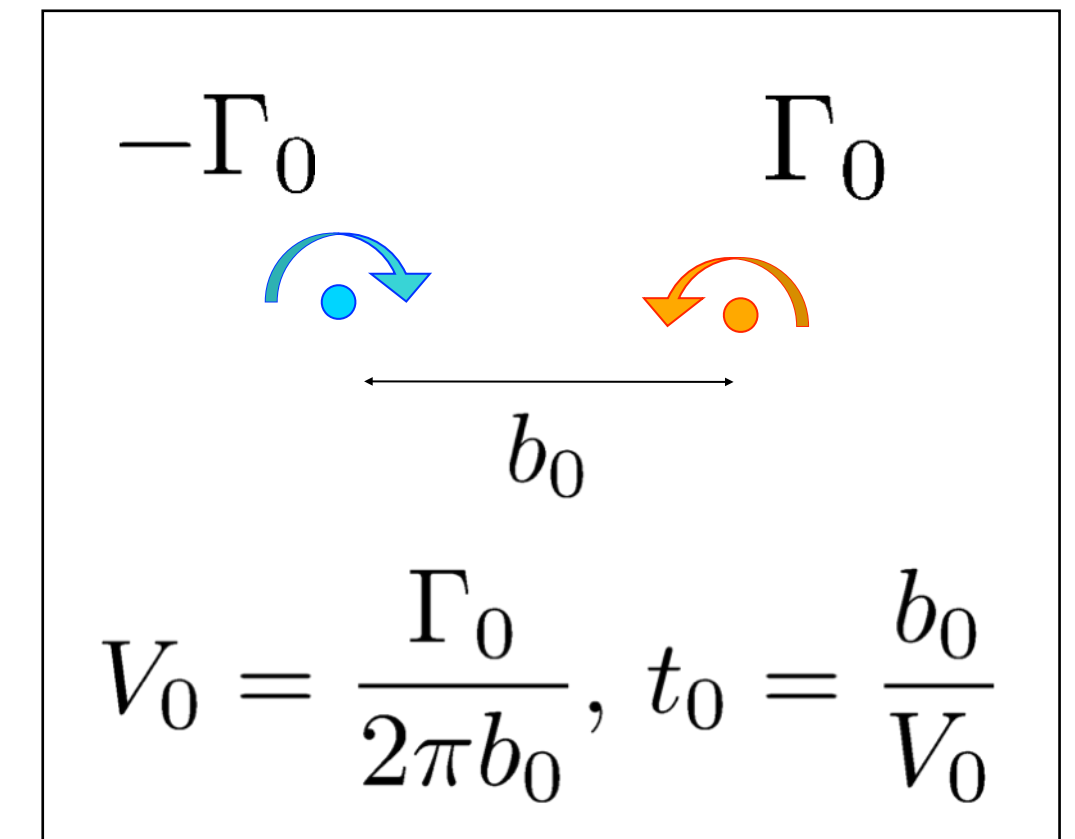
Representative flight scenarios

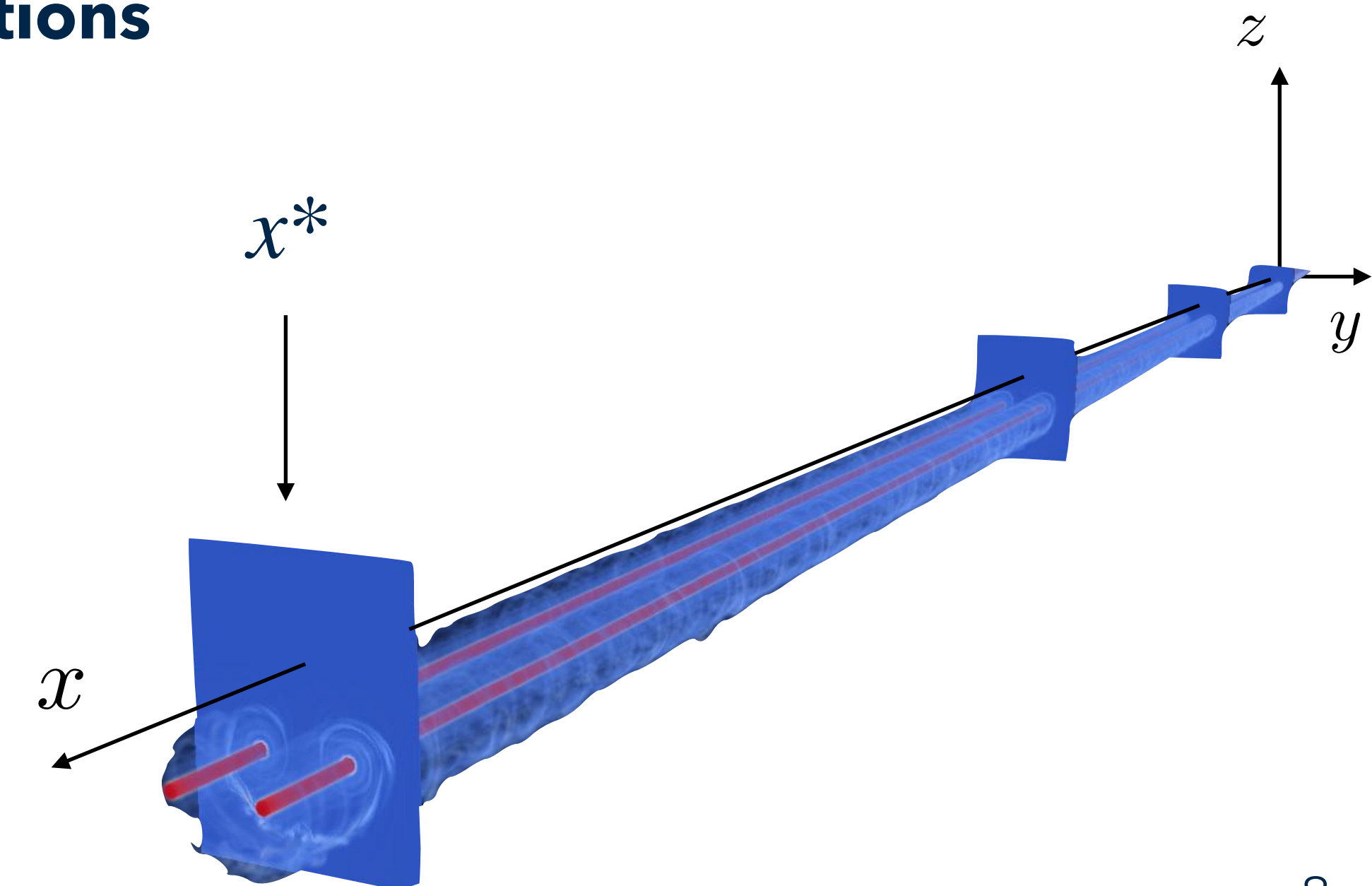
$$b \simeq 64 \text{ m} \quad U_\infty \simeq 250 \text{ m/s} \quad \Gamma_0 \simeq 480 \text{ m}^2/\text{s} \quad t_0 \simeq 33 \text{ s}$$

- lead to computational domains $> 200b$ long
- e.g. 64 pts/span represent **10^9 grid points /particles simulations**

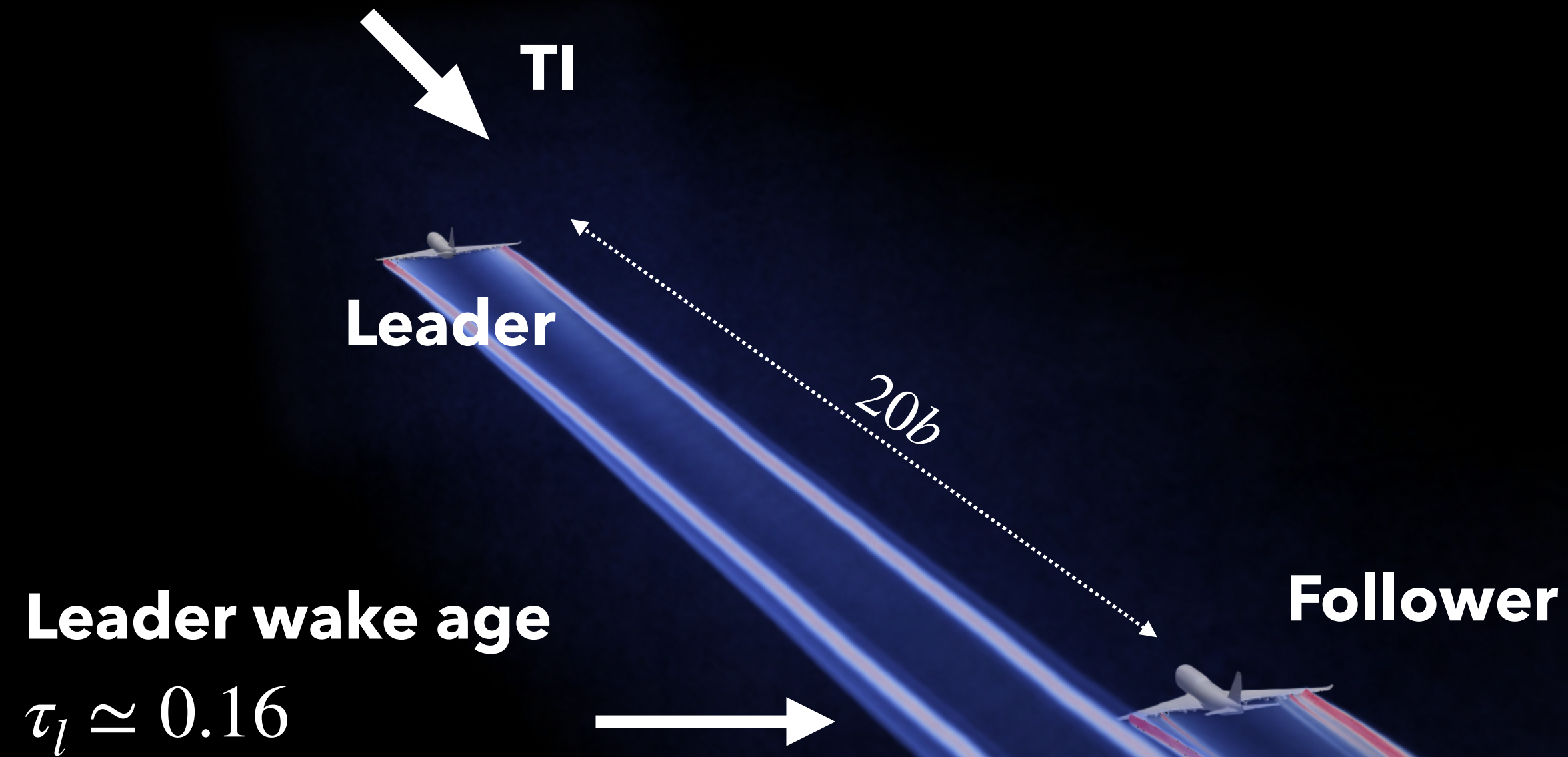
Time-space equivalence

- Development mostly 2D
but 3D effects in initial roll-up
- Wake age $\tau = t^* = x^* = \frac{x}{U_\infty b_0}$
- Can perform time-developing simulations on shorter domains


$$V_0 = \frac{\Gamma_0}{2\pi b_0}, \quad t_0 = \frac{b_0}{V_0}$$



Combination of Space Developing and Time Developing simulations for long time propagation



Space Developing:

- Turbulence injection
- Vortex Sheet Roll up
- Asymmetry between the leader and the follower
- Model of Aileron deflection

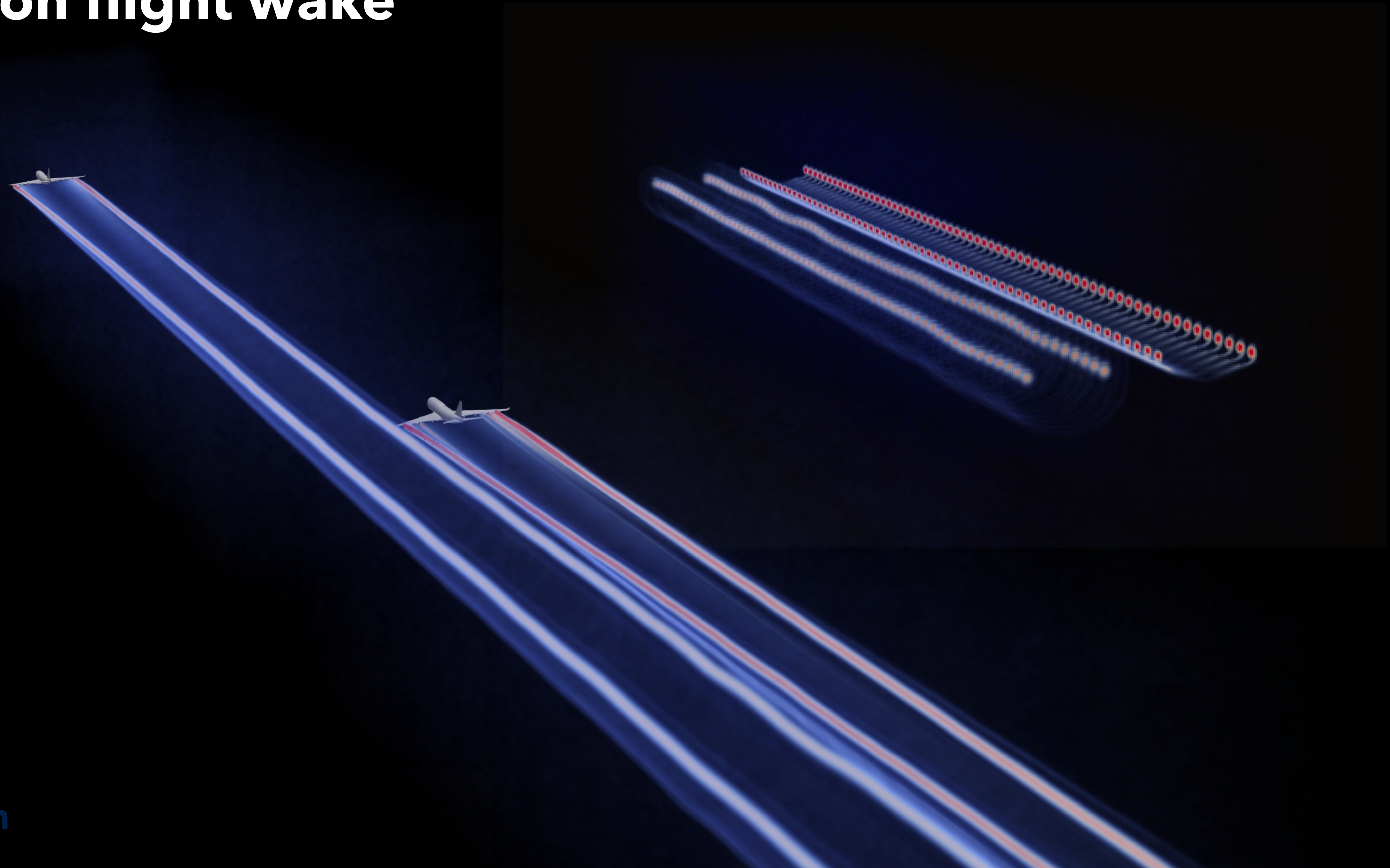
Combination of Space Developing and Time Developing simulations for long time propagation

Follower/formation wake age
 $\tau_f \simeq 0.00$

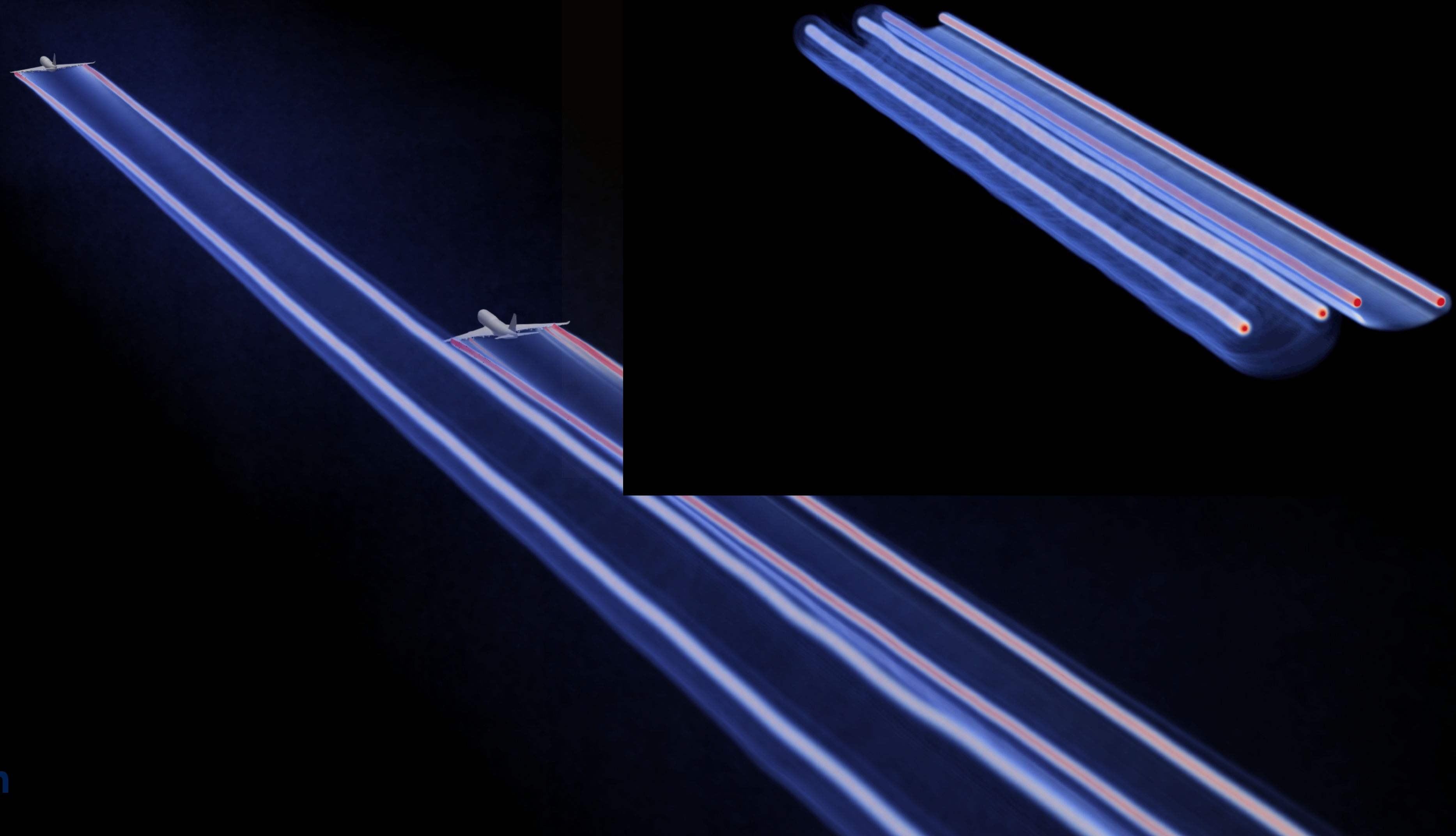
Time Developing:

- Initial conditions extruded from **one** slice behind the follower (Time $\leftrightarrow$ Space)
- Domain length: capture of the instability modes

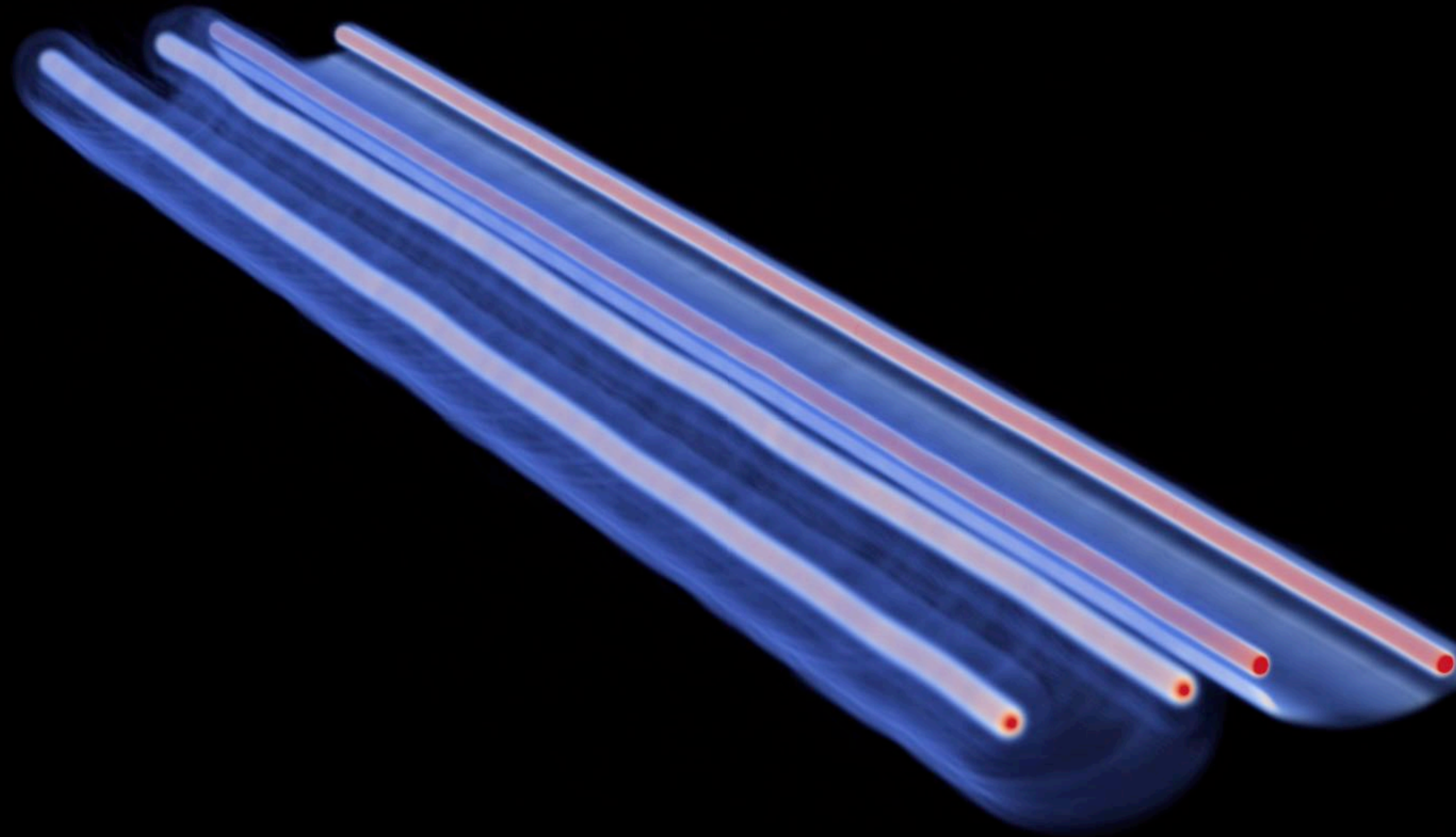
Simulation of the full phenomenological chain of a formation flight wake



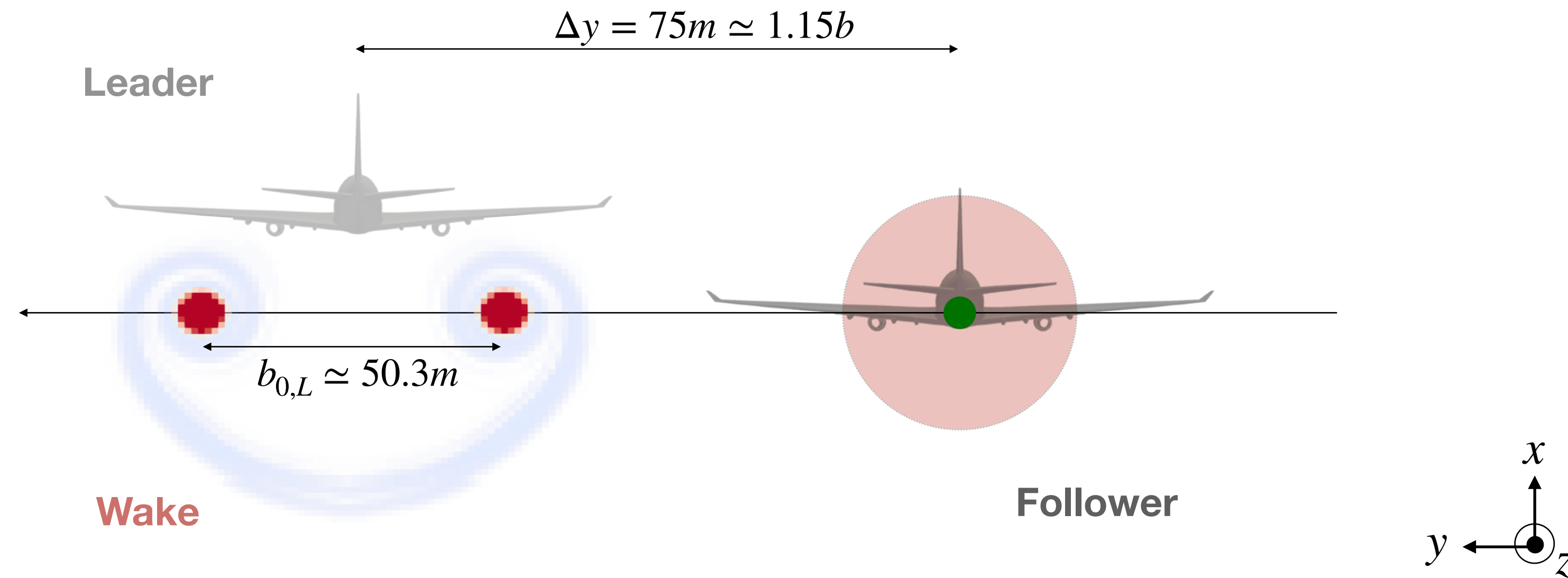
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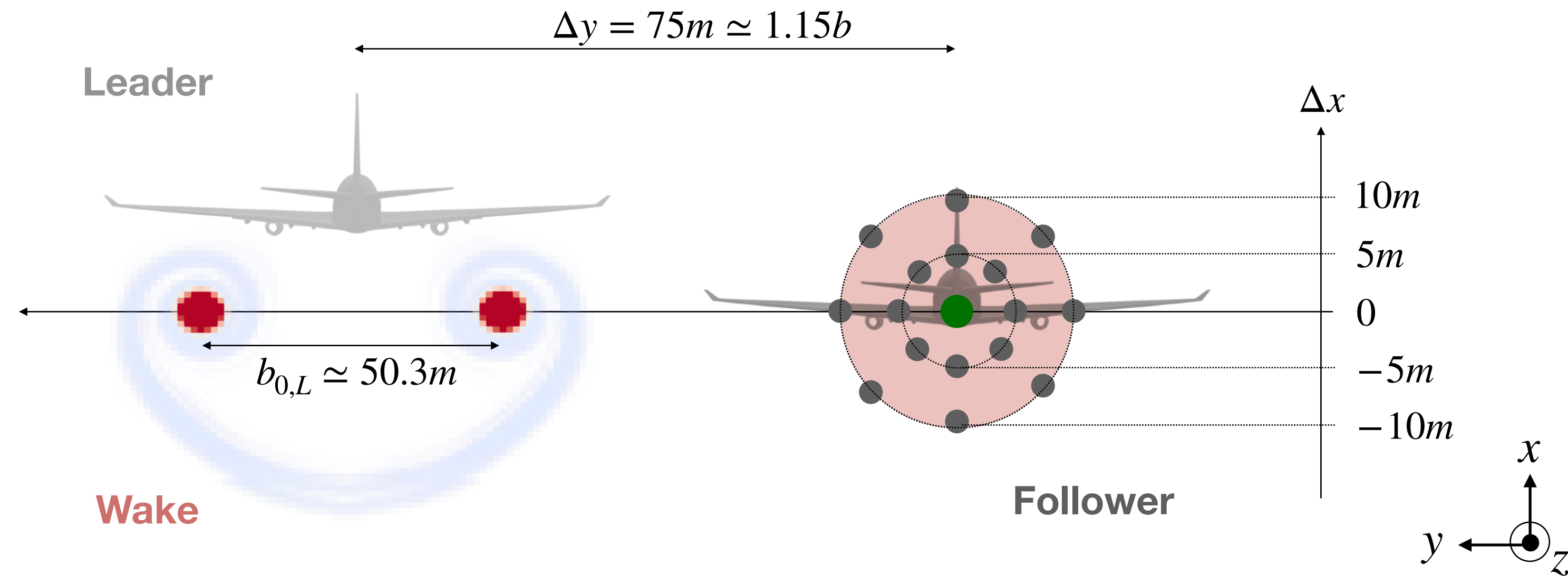
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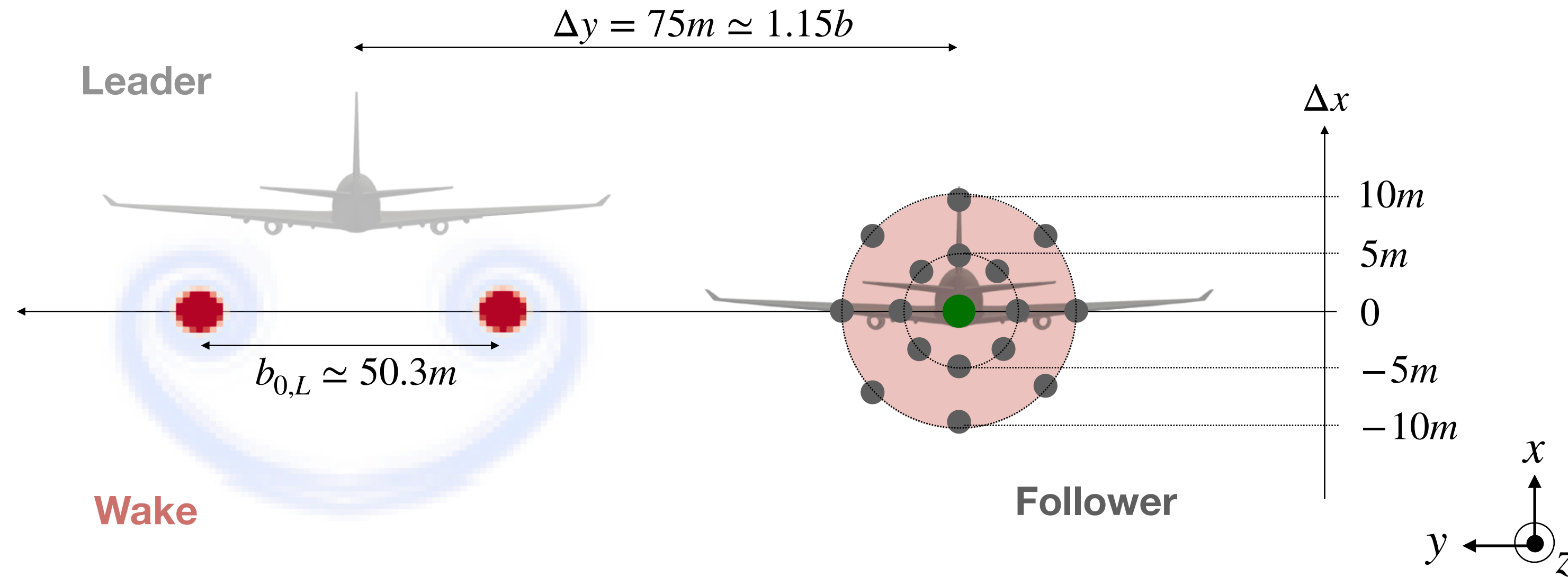
Uncertainty on the relative position: Sampling of 16 Configurations around a Reference



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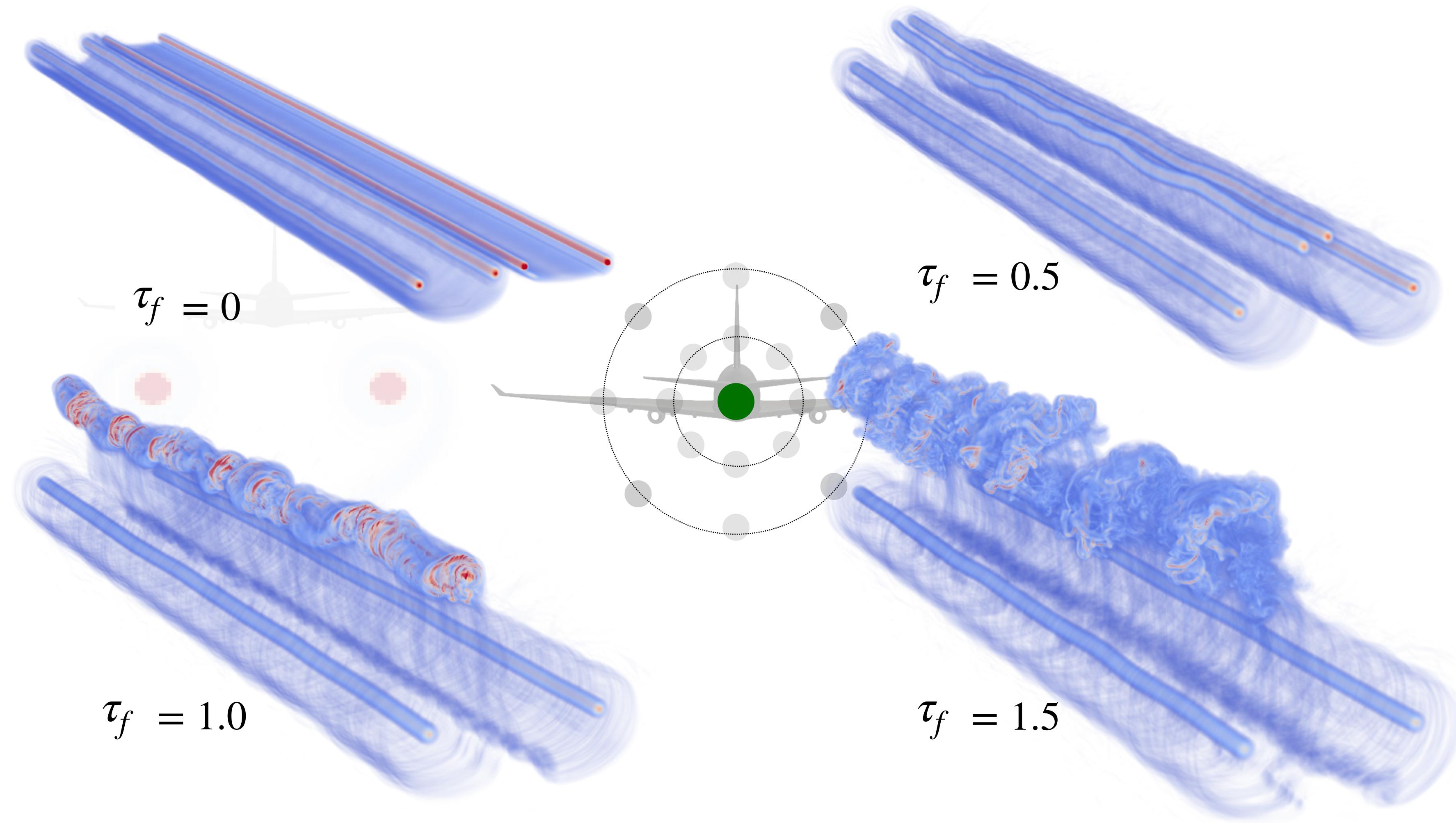
Aircraft:

- $b = 64[m]$, $V_\infty = 250[m/s]$, $m = 250[T]$
- Elliptic Chord distribution: $b_0 \simeq 50[m]$,
 $\Gamma_0 \simeq 485[m^2/s]$
- $V_0 = \Gamma_0 / 2\pi b_0$, $t_0 = b_0 / V_0$
- $Re \sim 5 \cdot 10^7$

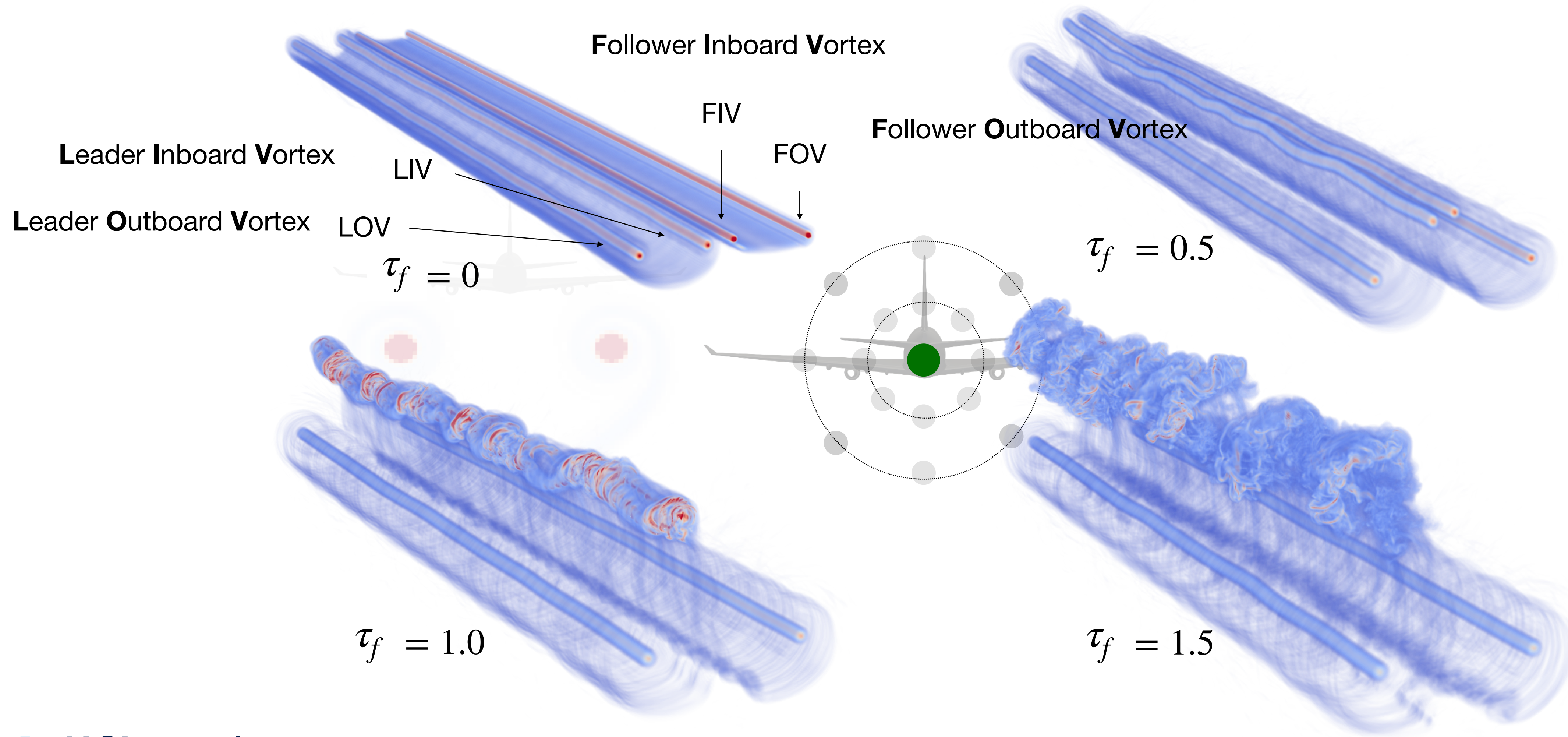
Simulation Setup:

- Space Developing:
 $4b \times 4b \times 40b$,
 $\epsilon^* = \epsilon b_0 / V_0^3 = 2 \cdot 10^{-4}$
- Time Developing:
 $4b \times 4b \times 16b$

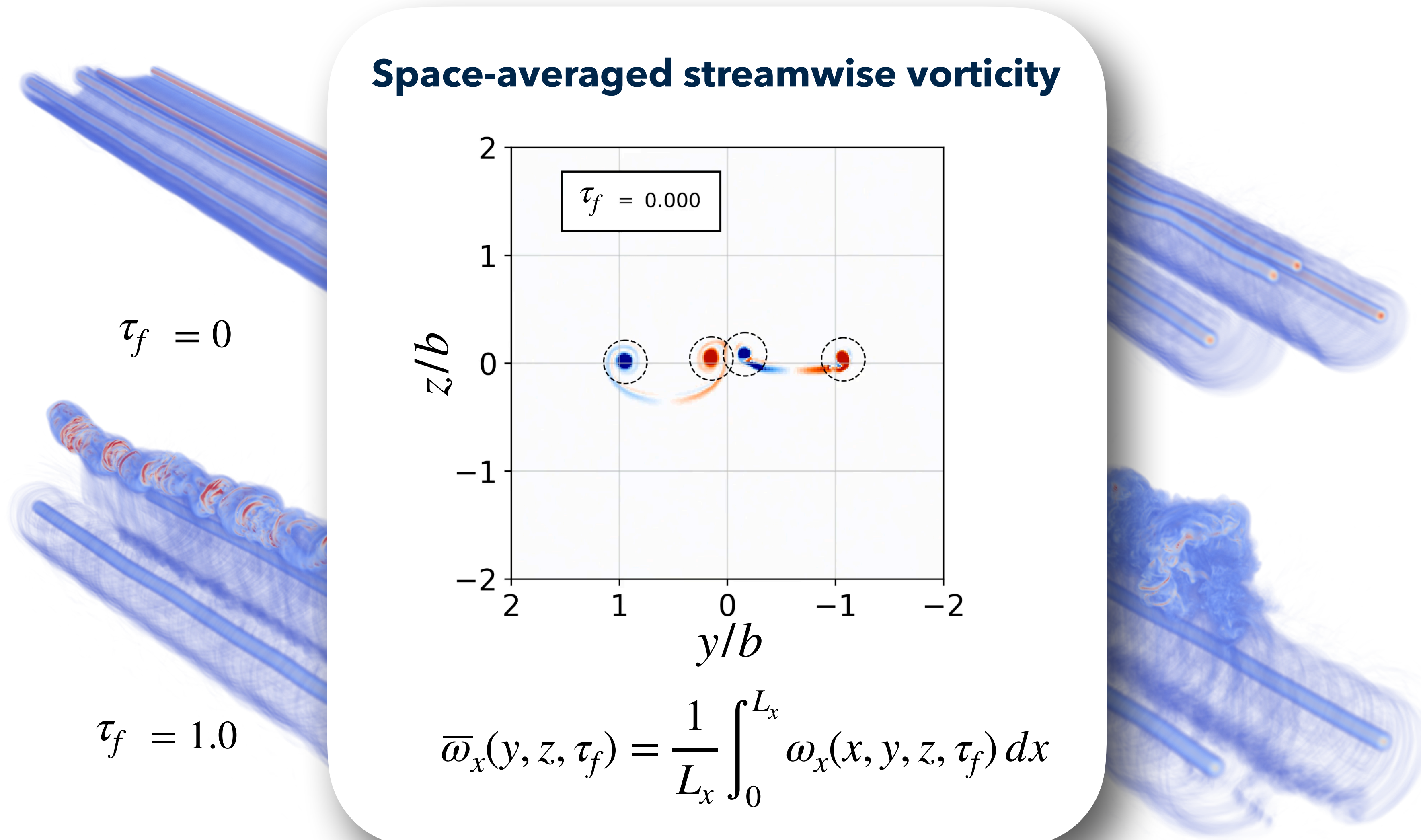
Time Developing Simulation: reference configuration



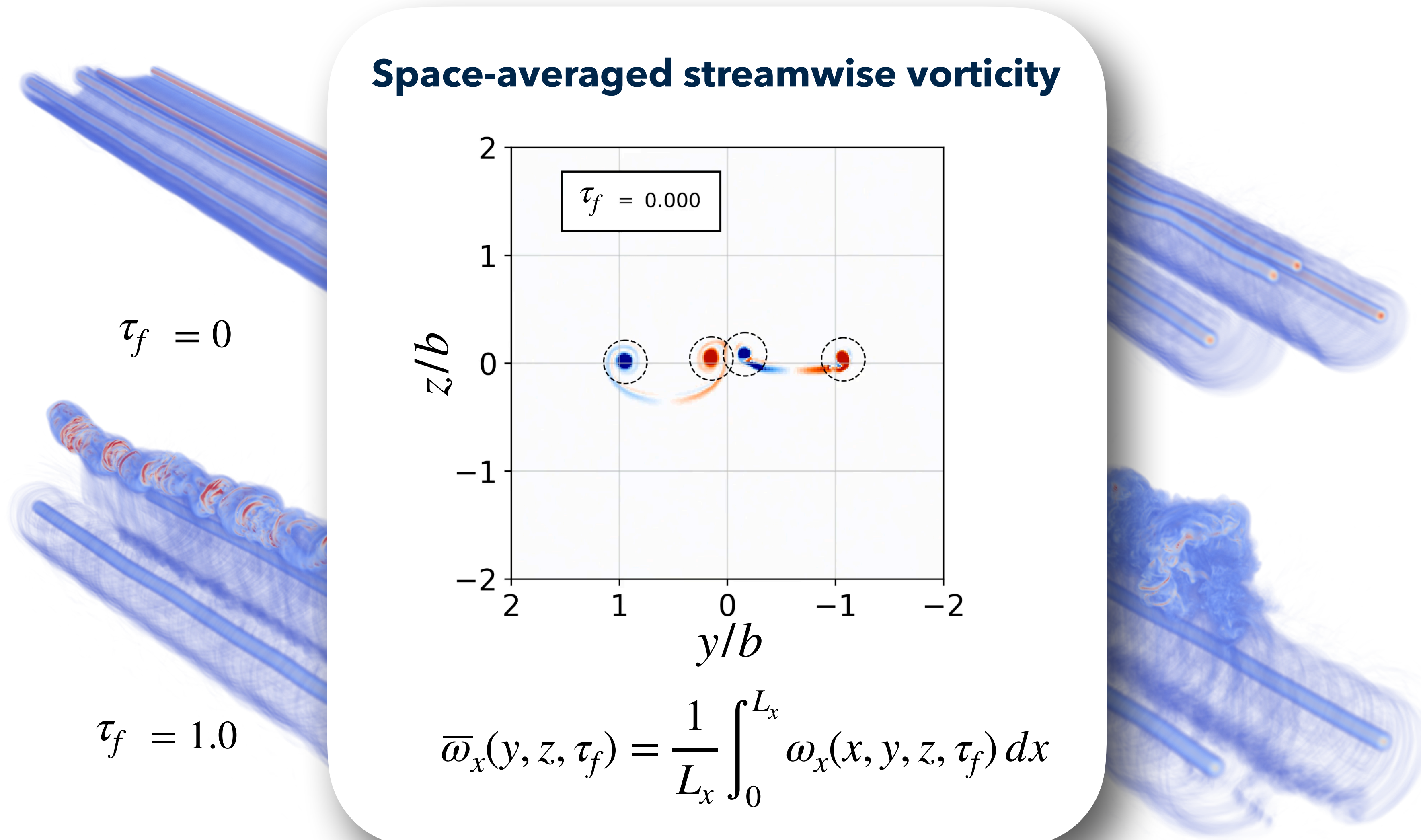
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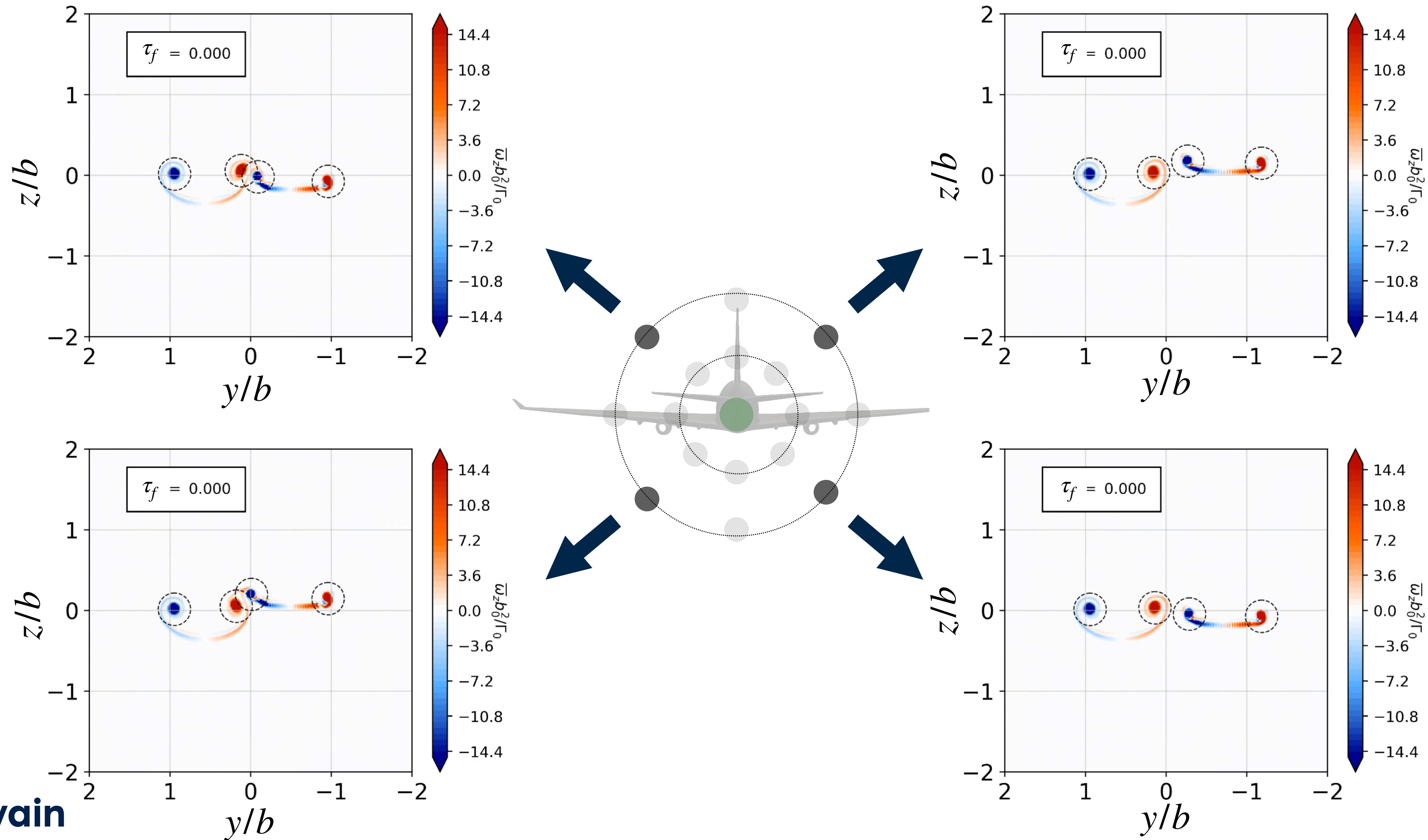
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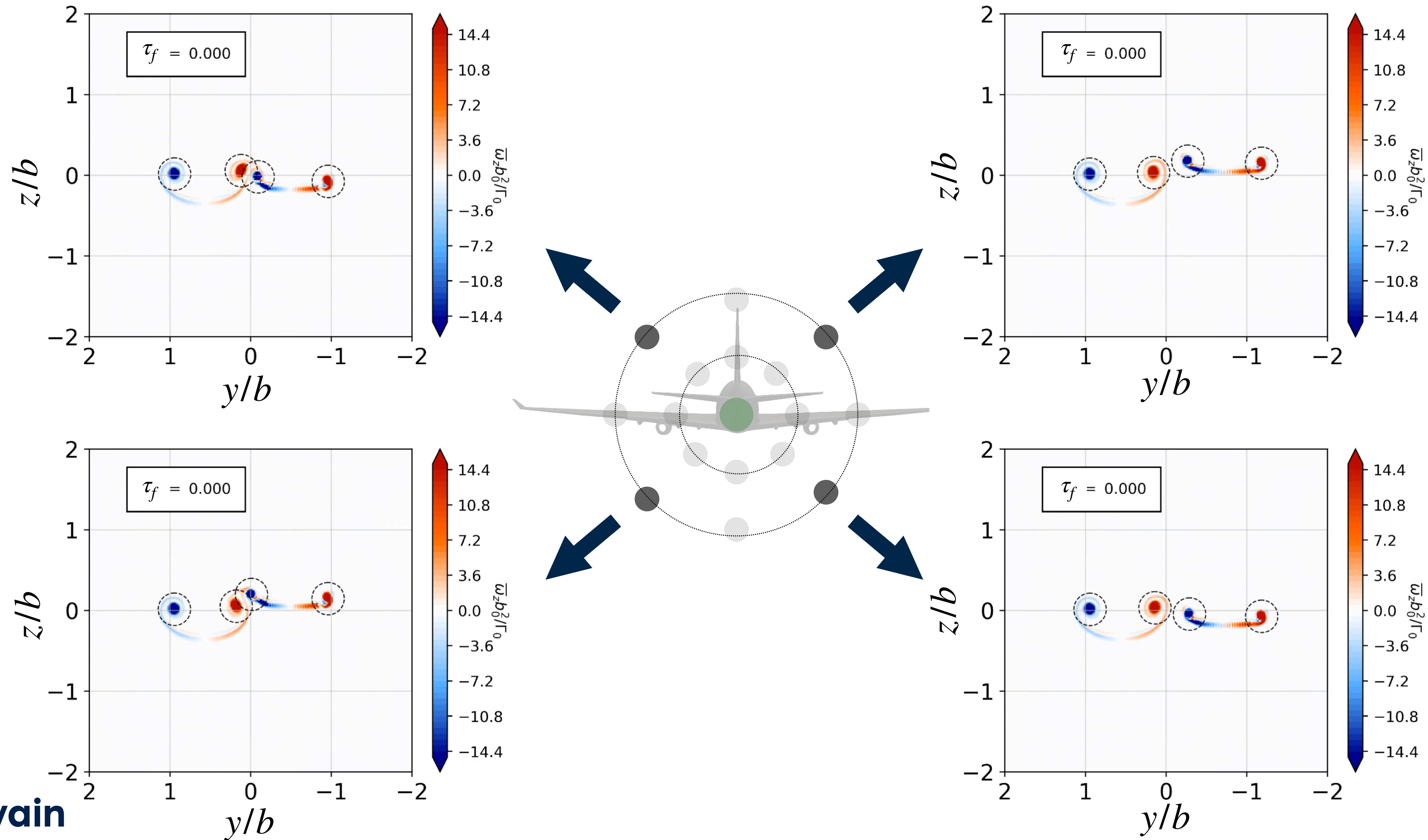
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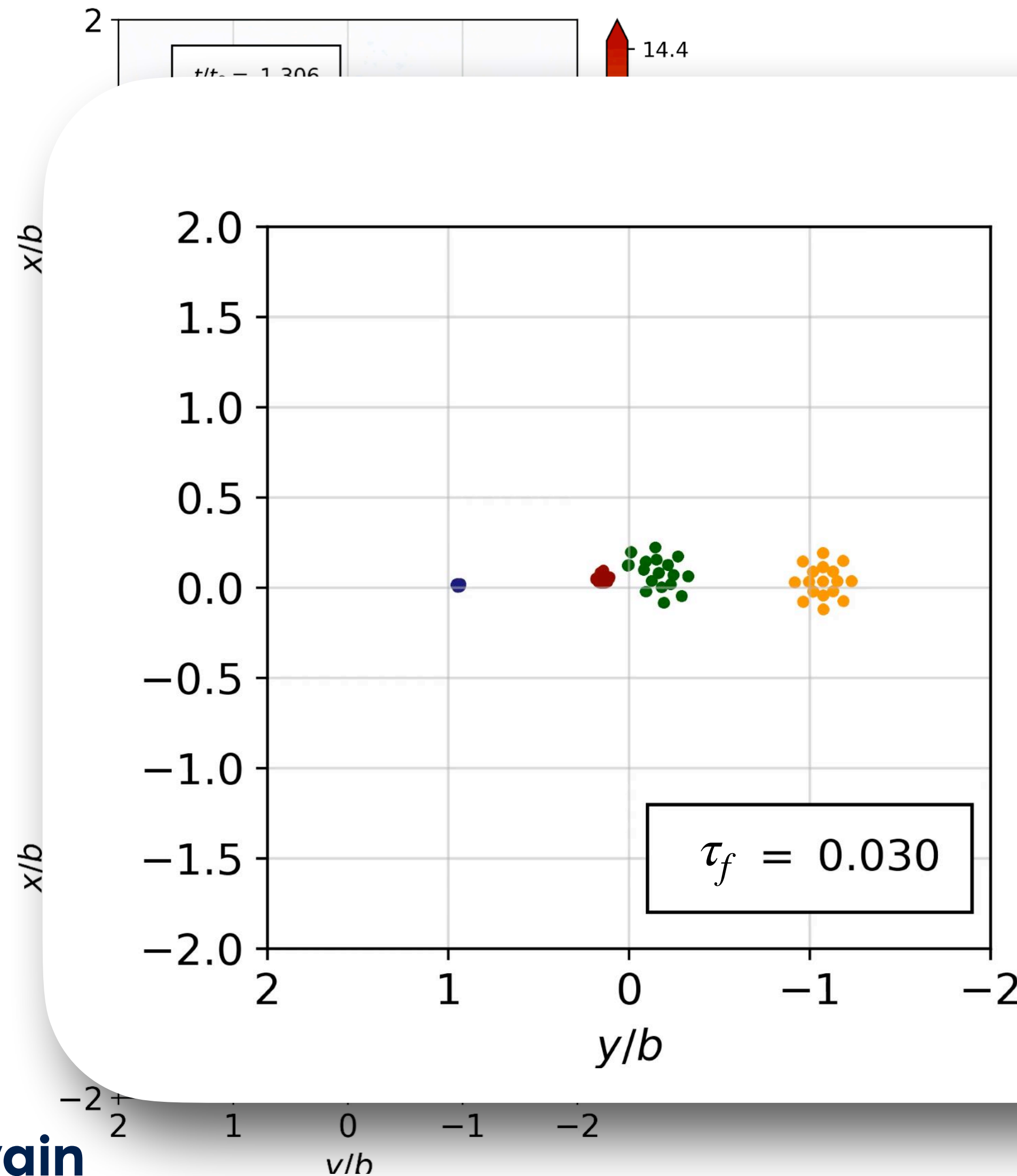
Wake vorticity



Wake vorticity



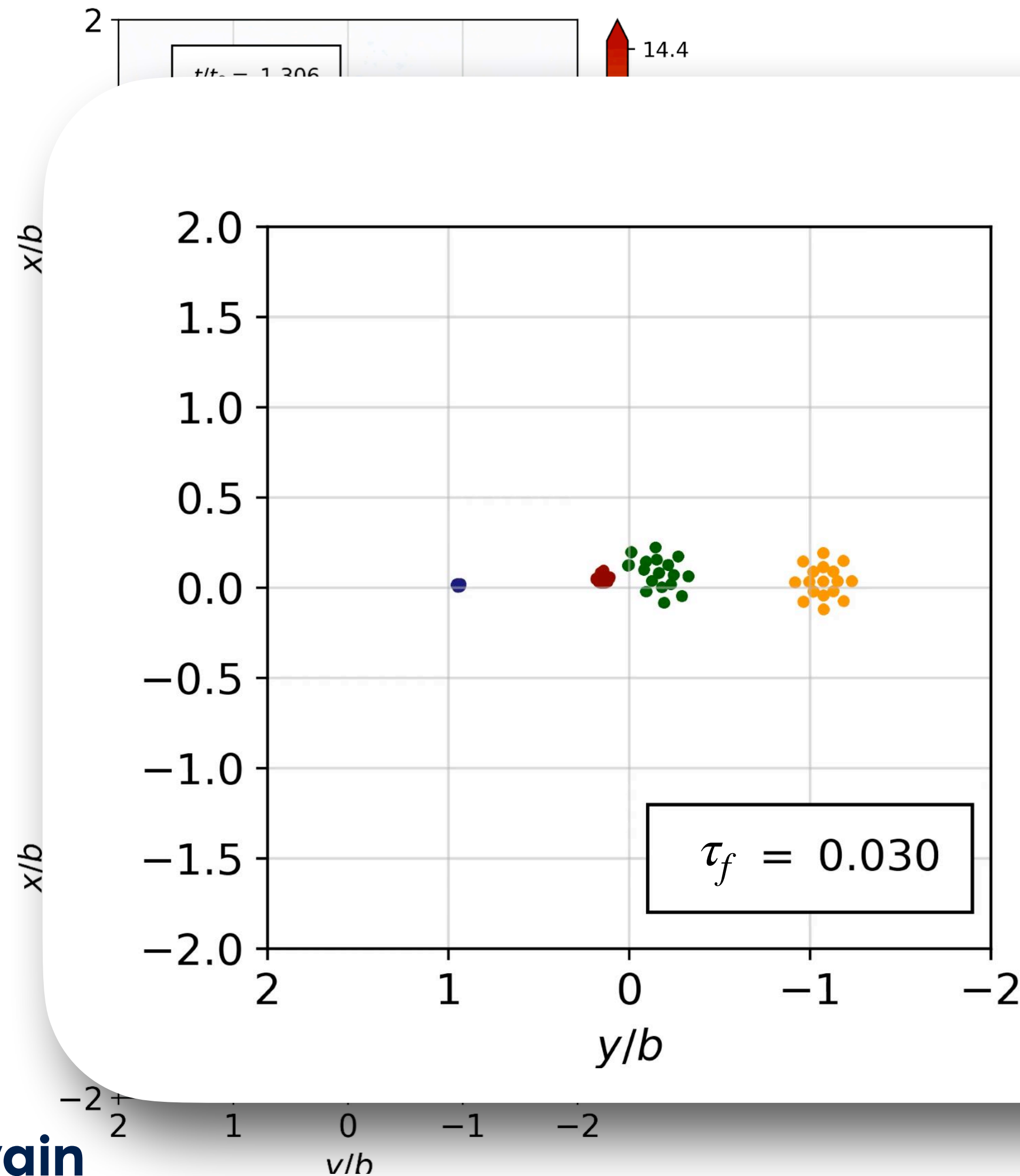
Wake vorticity



Vortex positions vs time:

- Sampling over $N=17$ simulations
- Position of the 4 vortices
- Retrieved from $M=32$ instantaneous vorticity slices

Wake vorticity



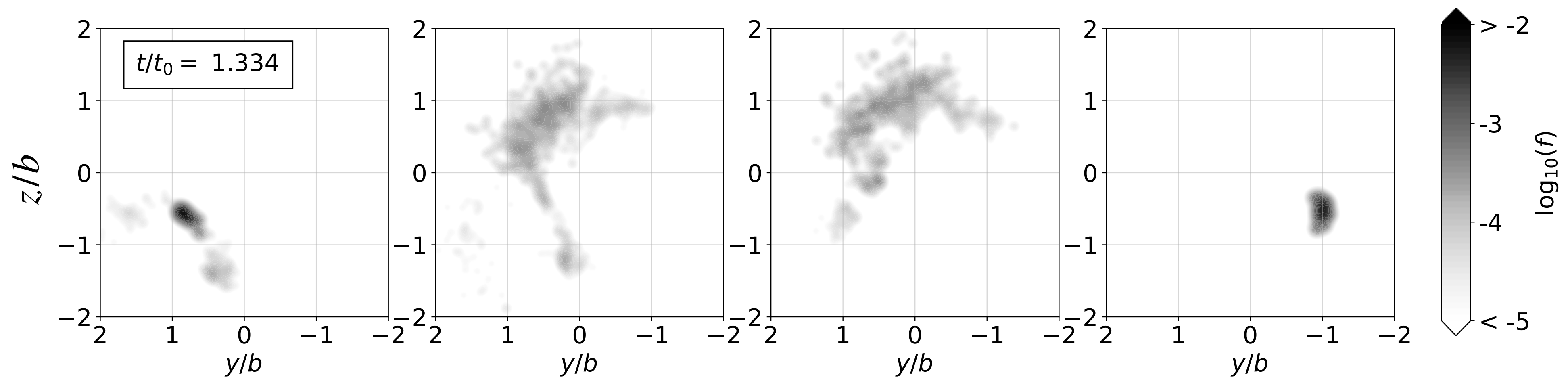
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Vortex positions

Regularized probability density function

$$f_{V_k}(x, y, t) = \sum_{i=1}^N \bar{w}_i \sum_{j=1}^M \frac{1}{M} \frac{1}{\pi \sigma_v^2} \exp \left(\frac{- \left((x - x_{V_k}^j(t))^2 + (y - y_{V_k}^j(t))^2 \right)}{\sigma_v^2} \right)$$

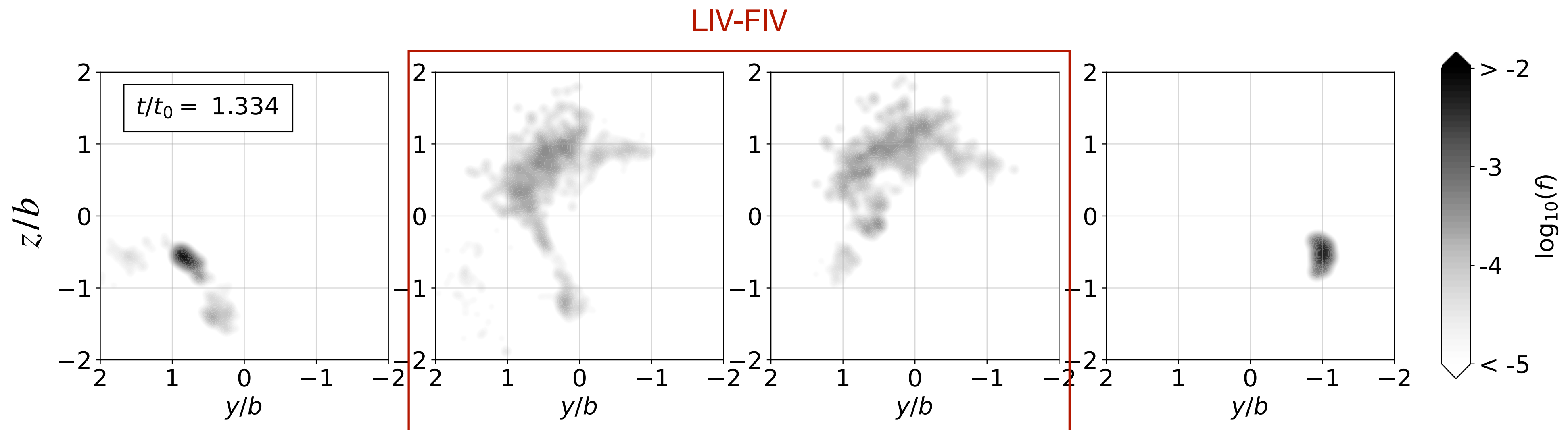


- Large statistical distribution of the inboard vortices
- Concentrated distribution for the leader and the follower outboard vortices

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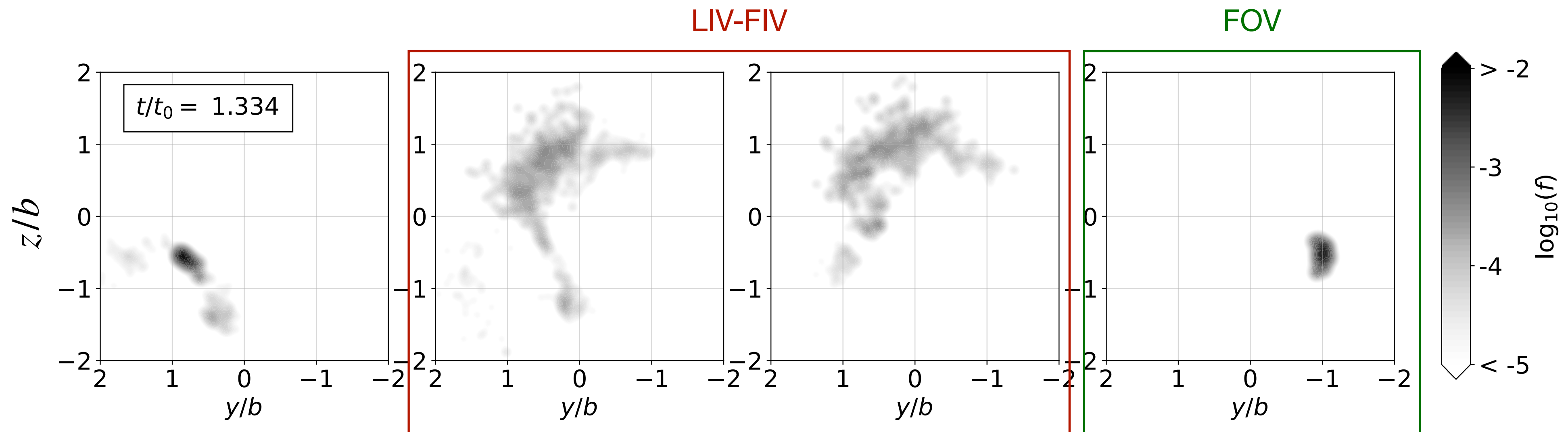


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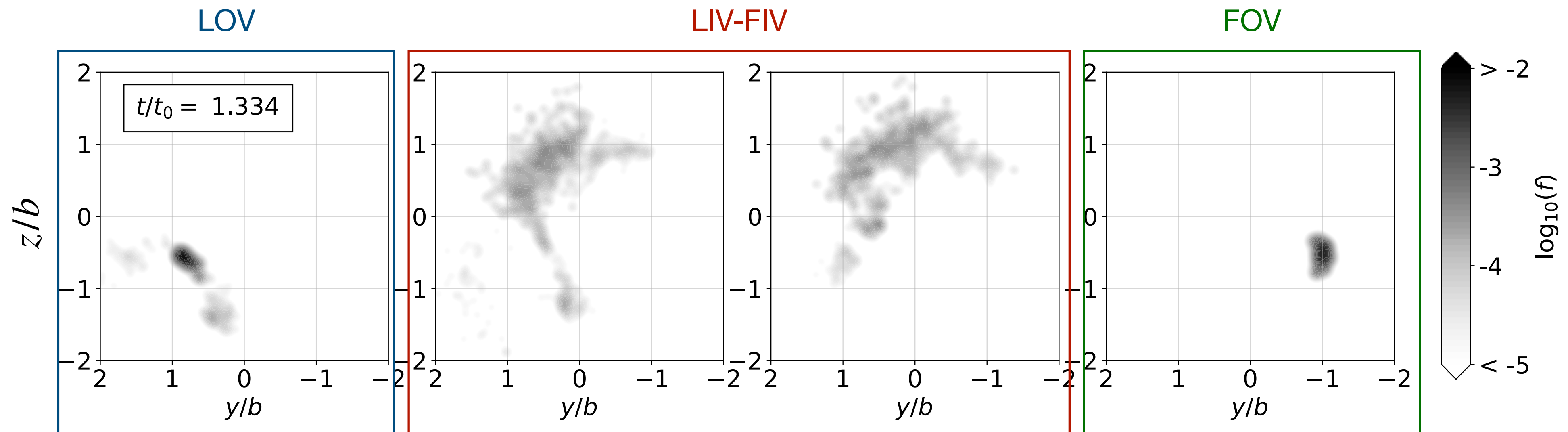


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Regularized probability density function

$$f_{V_k}(x, y, t) = \sum_{i=1}^N \bar{w}_i \sum_{j=1}^M \frac{1}{M} \frac{1}{\pi \sigma_v^2} \exp \left(\frac{- \left((x - x_{V_k}^j(t))^2 + (y - y_{V_k}^j(t))^2 \right)}{\sigma_v^2} \right)$$

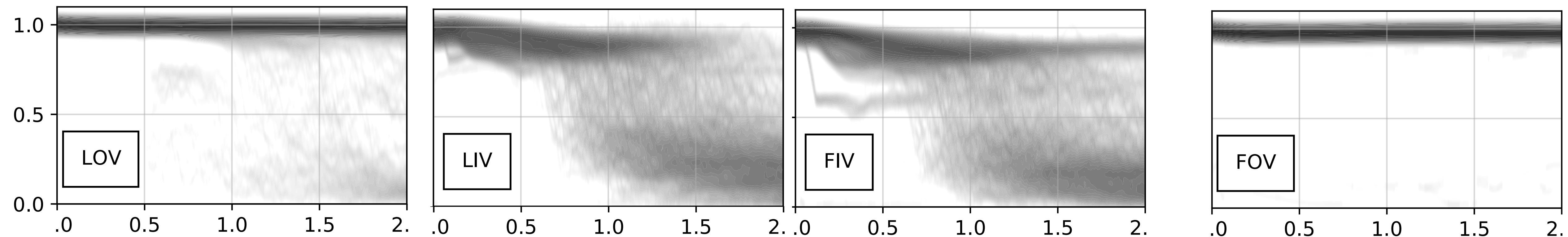


- Large statistical distribution of the inboard vortices
- Concentrated distribution for the leader and the follower outboard vortices

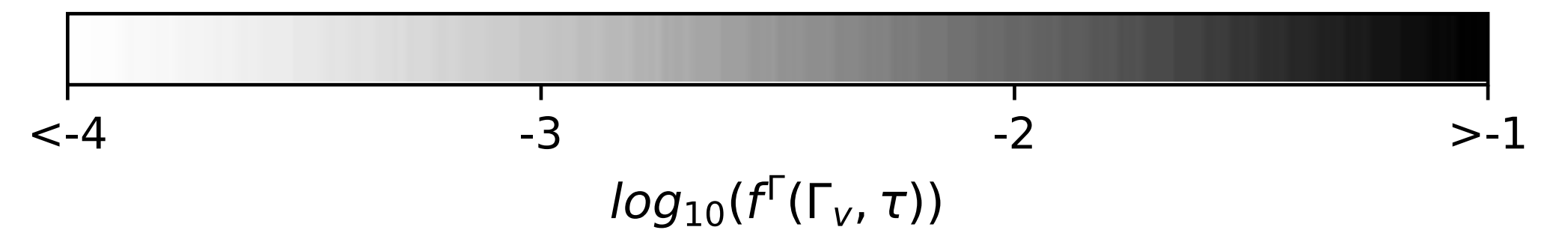
Vortex Circulation

Regularized probability density function

$$f_{V_k}(\Gamma, t) = \sum_{i=1}^N \bar{w}_i \sum_{j=1}^M \frac{1}{M} \frac{1}{\sqrt{\pi\sigma_v}} \exp\left(\frac{-(\Gamma - \Gamma_{V_k}^j(t))^2}{\sigma_v^2}\right)$$



- No decay of the Follower outboard vortex
- Bi-modal distributions for inboard vortices: onset of instability, reconnections, and dissipation
- Possible slow Decay of the Leader Outboard vortex

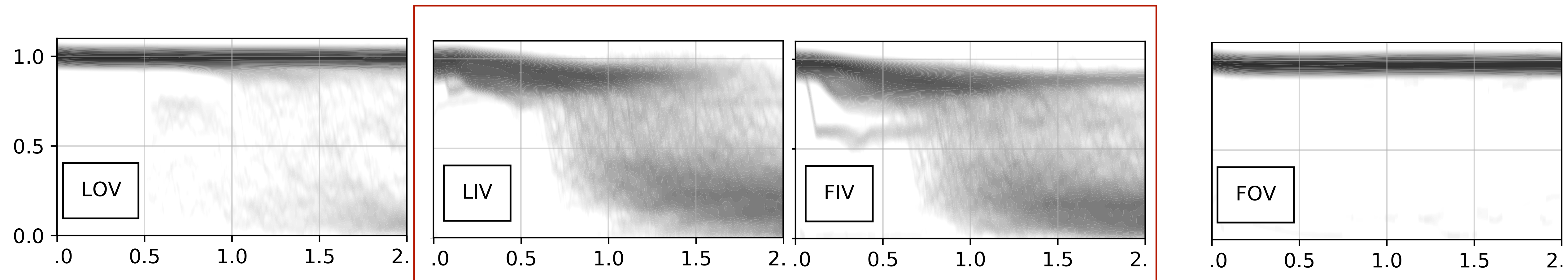


Vortex Circulation

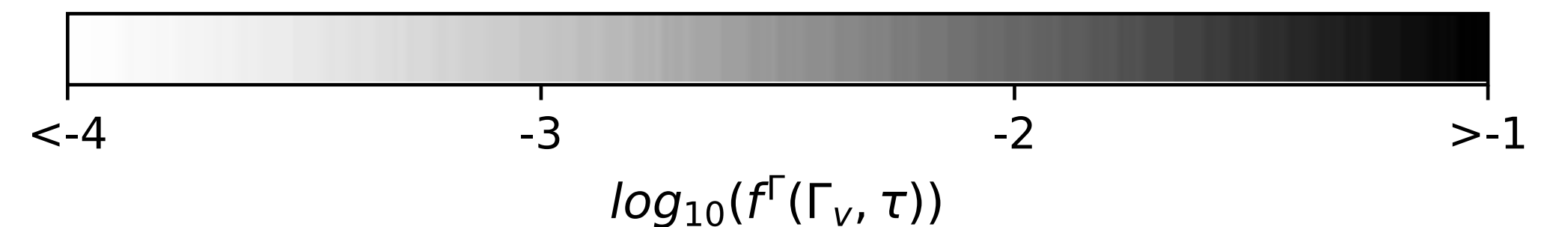
Regularized probability density function

$$f_{V_k}(\Gamma, t) = \sum_{i=1}^N \bar{w}_i \sum_{j=1}^M \frac{1}{M} \frac{1}{\sqrt{\pi\sigma_v}} \exp\left(\frac{-(\Gamma - \Gamma_{V_k}^j(t))^2}{\sigma_v^2}\right)$$

LIV-FIV



- No decay of the Follower outboard vortex
- Bi-modal distributions for inboard vortices: onset of instability, reconnections, and dissipation
- Possible slow Decay of the Leader Outboard vortex



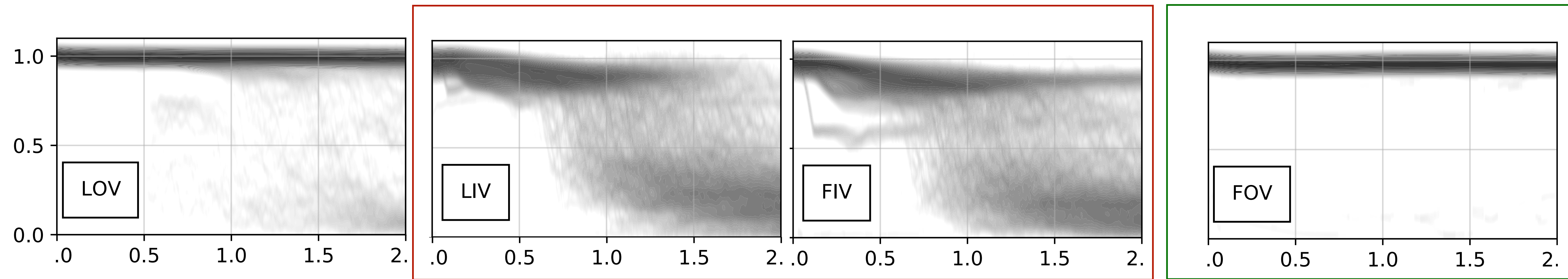
Vortex Circulation

Regularized probability density function

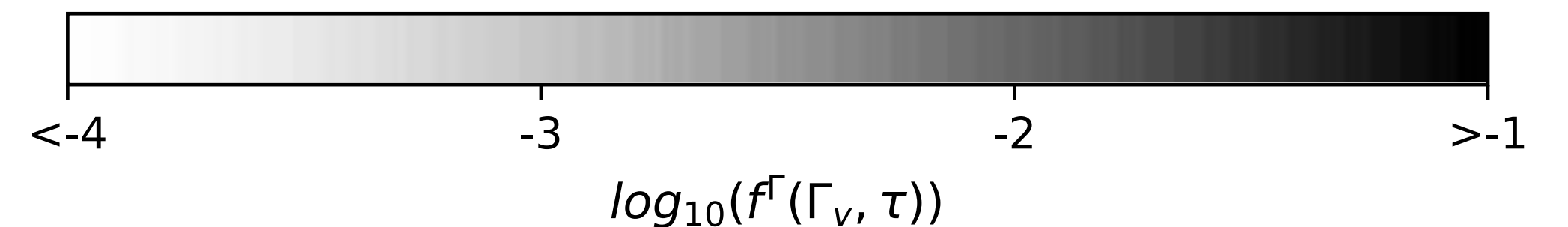
$$f_{V_k}(\Gamma, t) = \sum_{i=1}^N \bar{w}_i \sum_{j=1}^M \frac{1}{M} \frac{1}{\sqrt{\pi\sigma_v}} \exp\left(\frac{-(\Gamma - \Gamma_{V_k}^j(t))^2}{\sigma_v^2}\right)$$

LIV-FIV

FOV



- No decay of the Follower outboard vortex
- Bi-modal distributions for inboard vortices: onset of instability, reconnections, and dissipation
- Possible slow Decay of the Leader Outboard vortex



Vortex Circulation

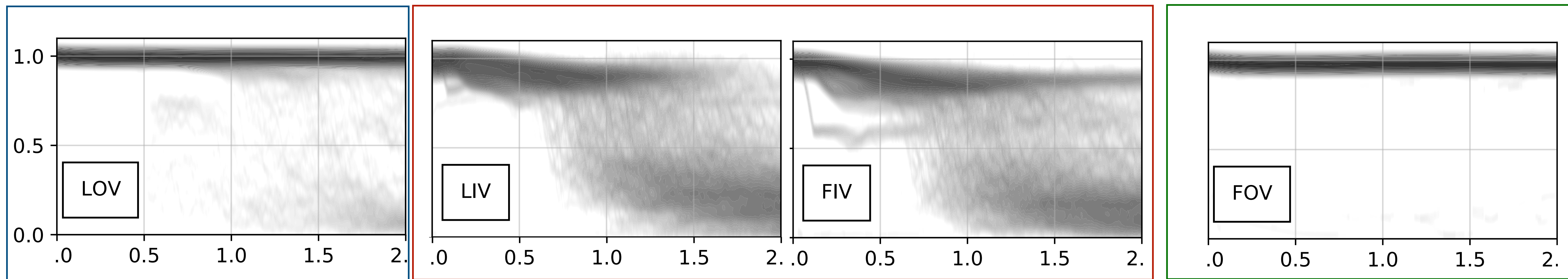
Regularized probability density function

$$f_{V_k}(\Gamma, t) = \sum_{i=1}^N \bar{w}_i \sum_{j=1}^M \frac{1}{M} \frac{1}{\sqrt{\pi\sigma_v}} \exp\left(\frac{-(\Gamma - \Gamma_{V_k}^j(t))^2}{\sigma_v^2}\right)$$

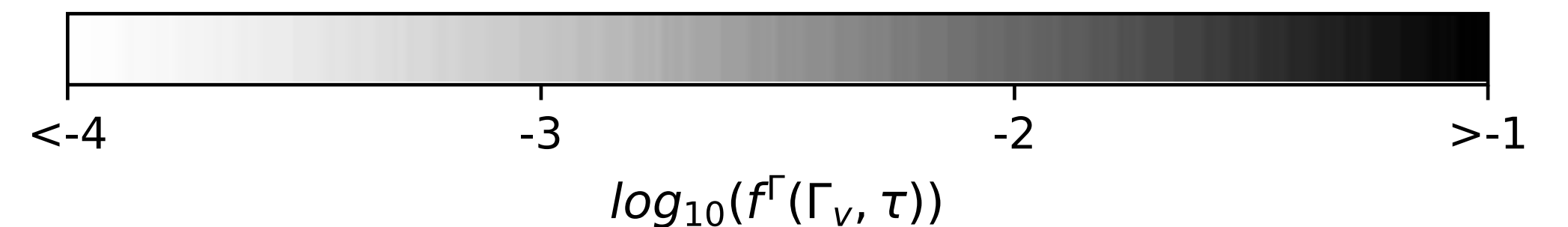
LOV

LIV-FIV

FOV



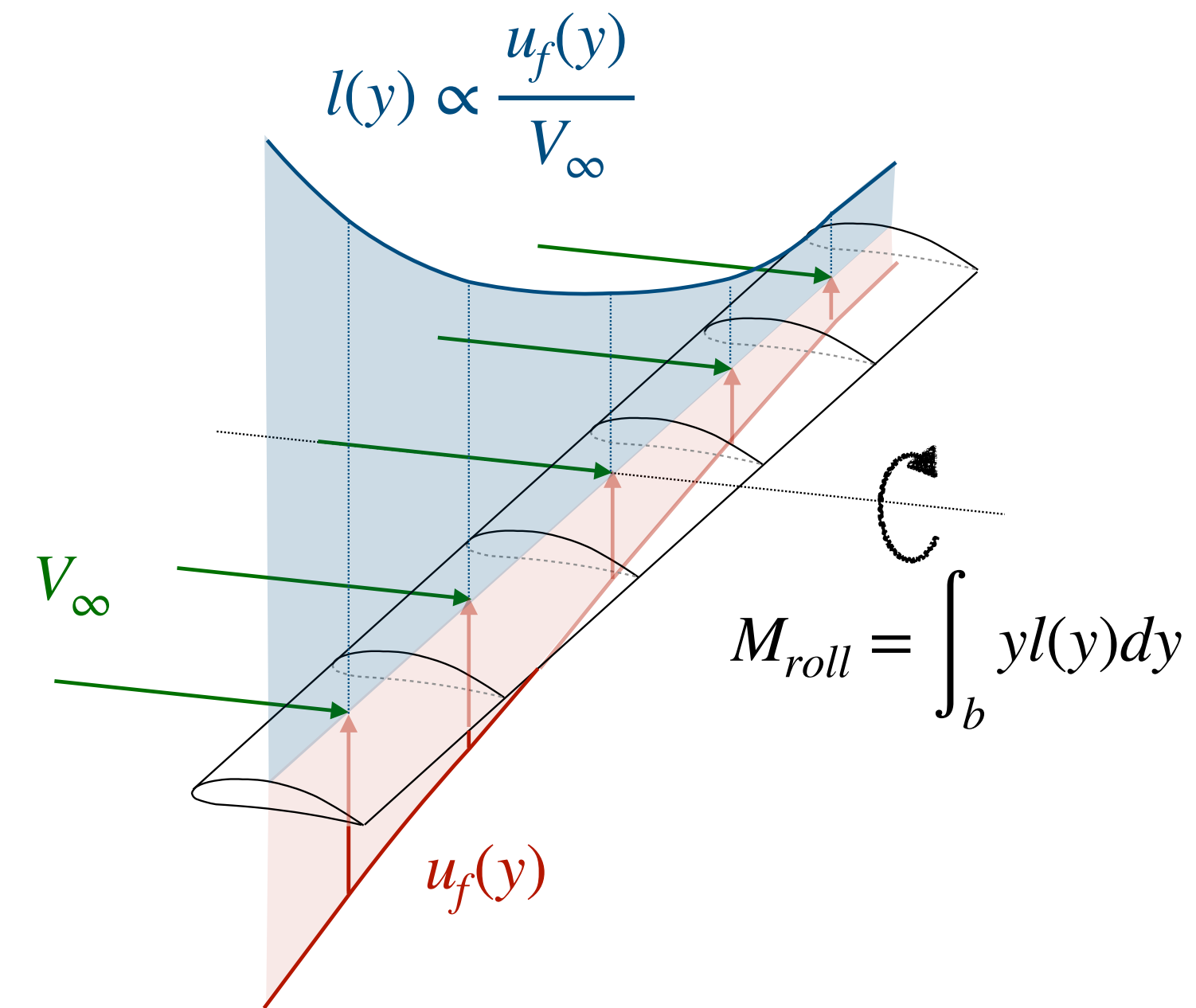
- No decay of the Follower outboard vortex
- Bi-modal distributions for inboard vortices: onset of instability, reconnections, and dissipation
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Air Traffic Management: Rolling Moment Coefficient (RMC)

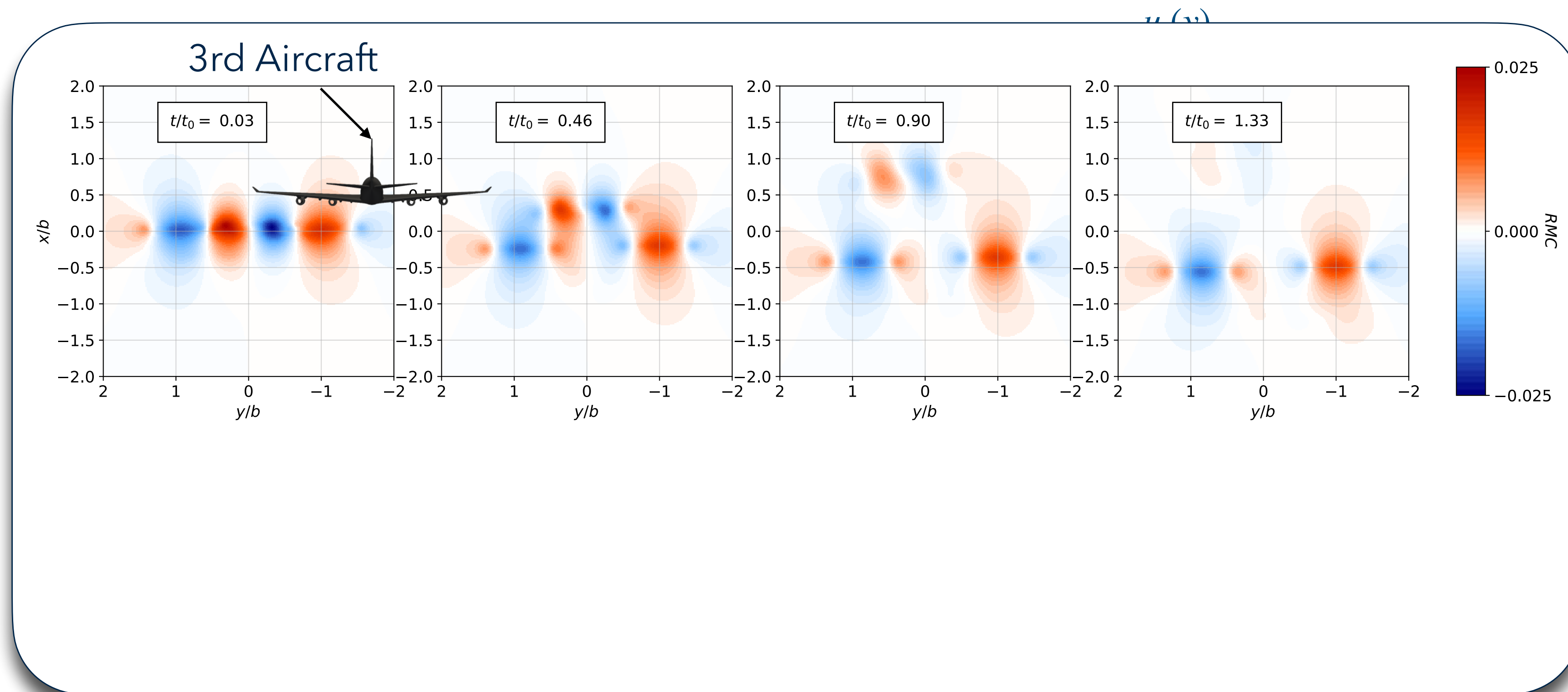
1. Vertical velocity field $u_f(x, y)$ for each configuration along time
2. Local equivalent angle of attack

$$\alpha_e = \frac{u_f(y)}{V_\infty}$$
3. Integration along a generic wing, to deduce M_{roll}



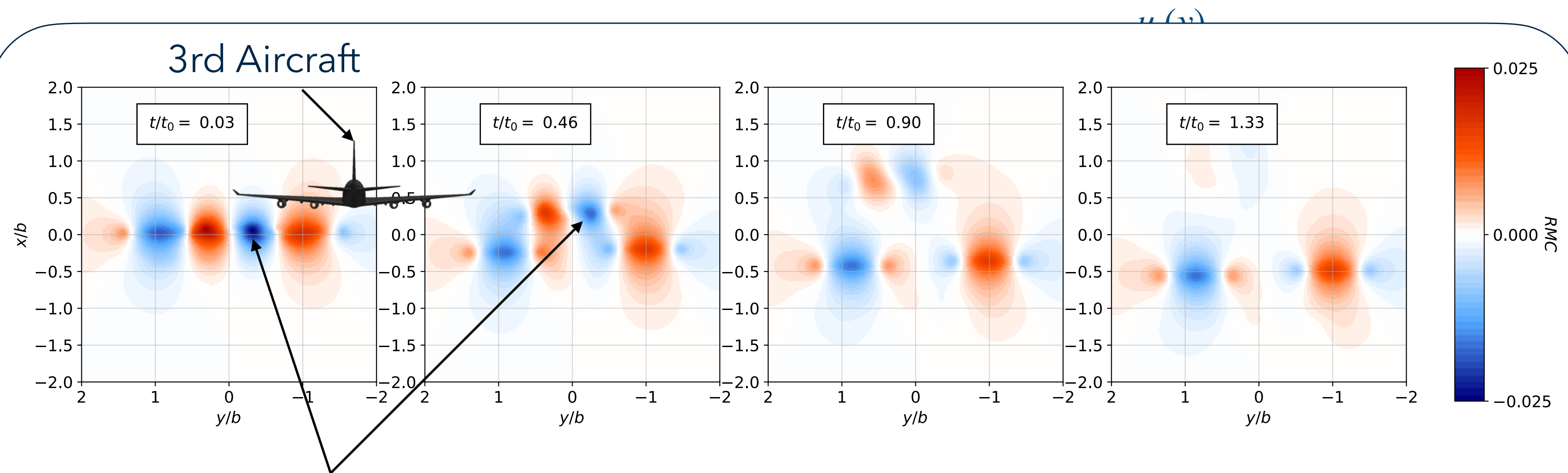
$$\begin{cases} M_{roll} &= \frac{1}{2} \rho V_\infty^2 \int_{-b/2}^{b/2} C_{l,\alpha}(y') c(y') \frac{u_f(y')}{V_\infty} y' dy' \\ RMC &= \frac{M_{roll}}{1/2 \rho V_\infty^2 S b} \end{cases}$$

Air Traffic Management: Rolling Moment Coefficient (RMC)



$$RMC = \frac{M_{roll}}{1/2 \rho V_{\infty}^2 S b}$$

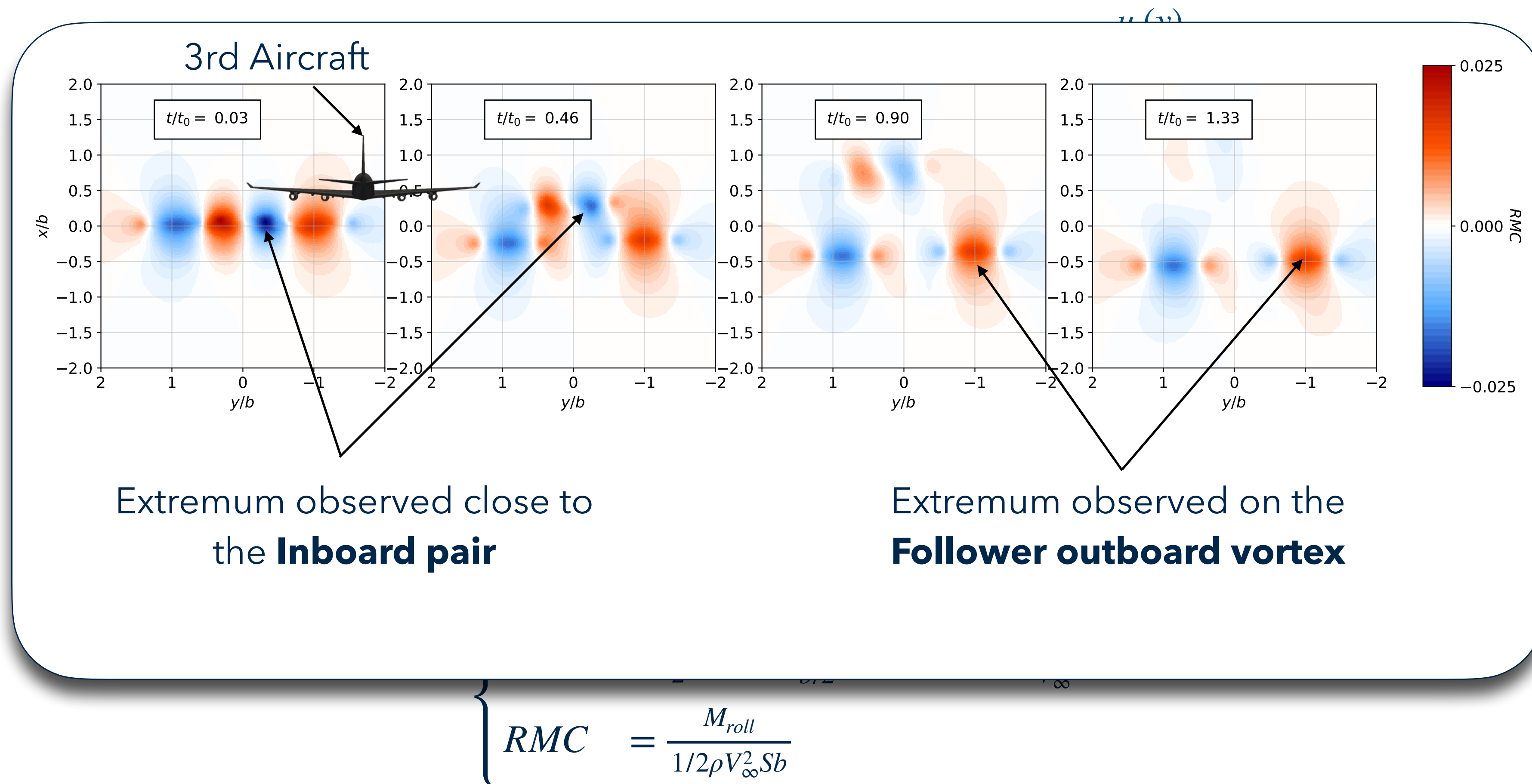
Air Traffic Management: Rolling Moment Coefficient (RMC)



Extremum observed close to the **Inboard pair**

$$RMC = \frac{M_{roll}}{1/2 \rho V_{\infty}^2 S b}$$

Air Traffic Management: Rolling Moment Coefficient (RMC)

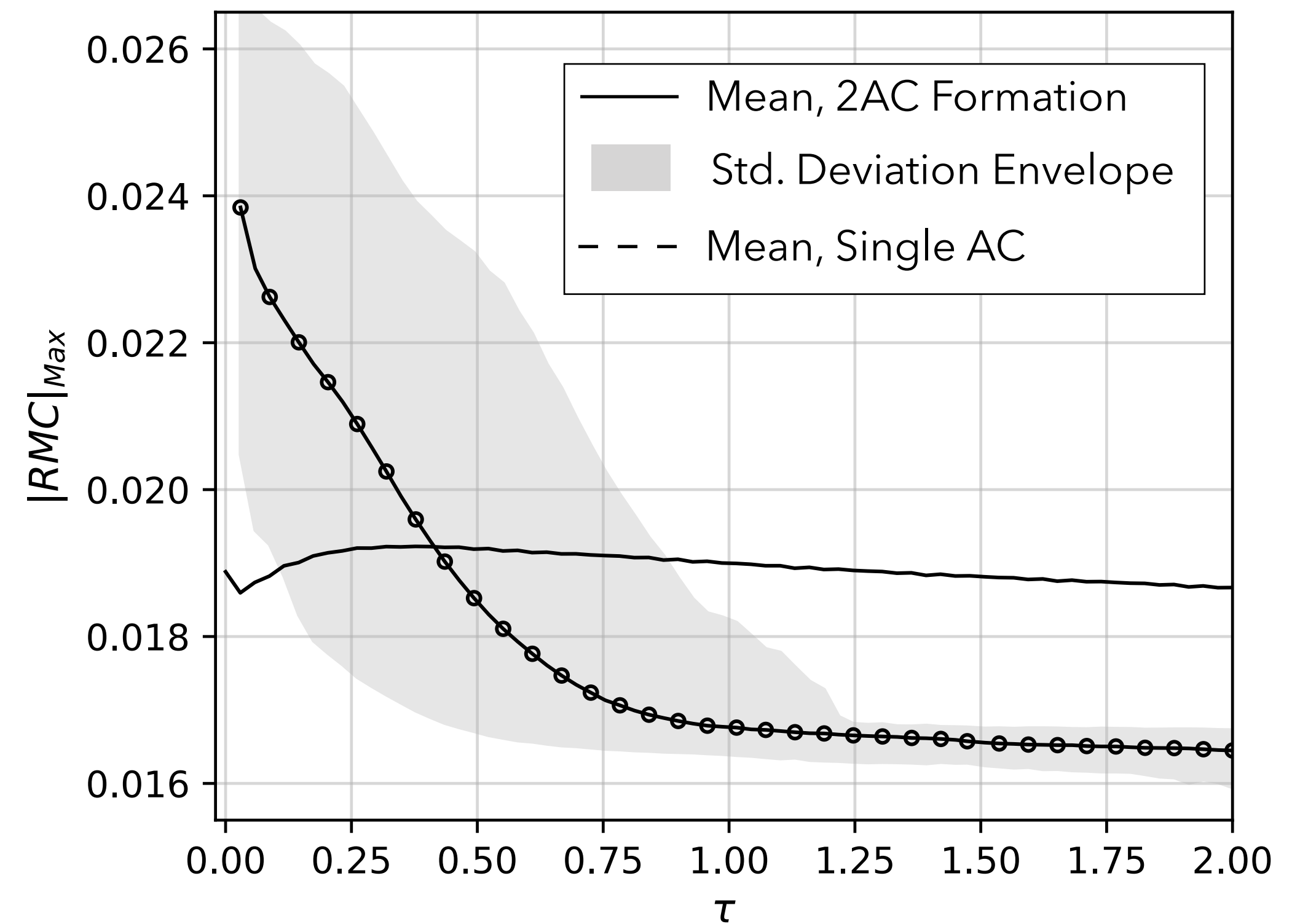


Air Traffic Management: Rolling Moment Coefficient (RMC)

- Maximum RMC important close to the inboard vortex
- Quick decay due to inboard vortices dissipation
- For wake ages ~ 2 , max RMC behind a formation inferior than max RMC behind a single aircraft
- Formation wake: same Γ_0 as single aircraft, spacing $\sim 2b_0$

➡ For intermediate ages $\tau \sim 2$, formation wakes are not more severe than single aircraft wakes

➡ Self-induced velocity 2x slower
➡ Long wavelength instability 2x slower



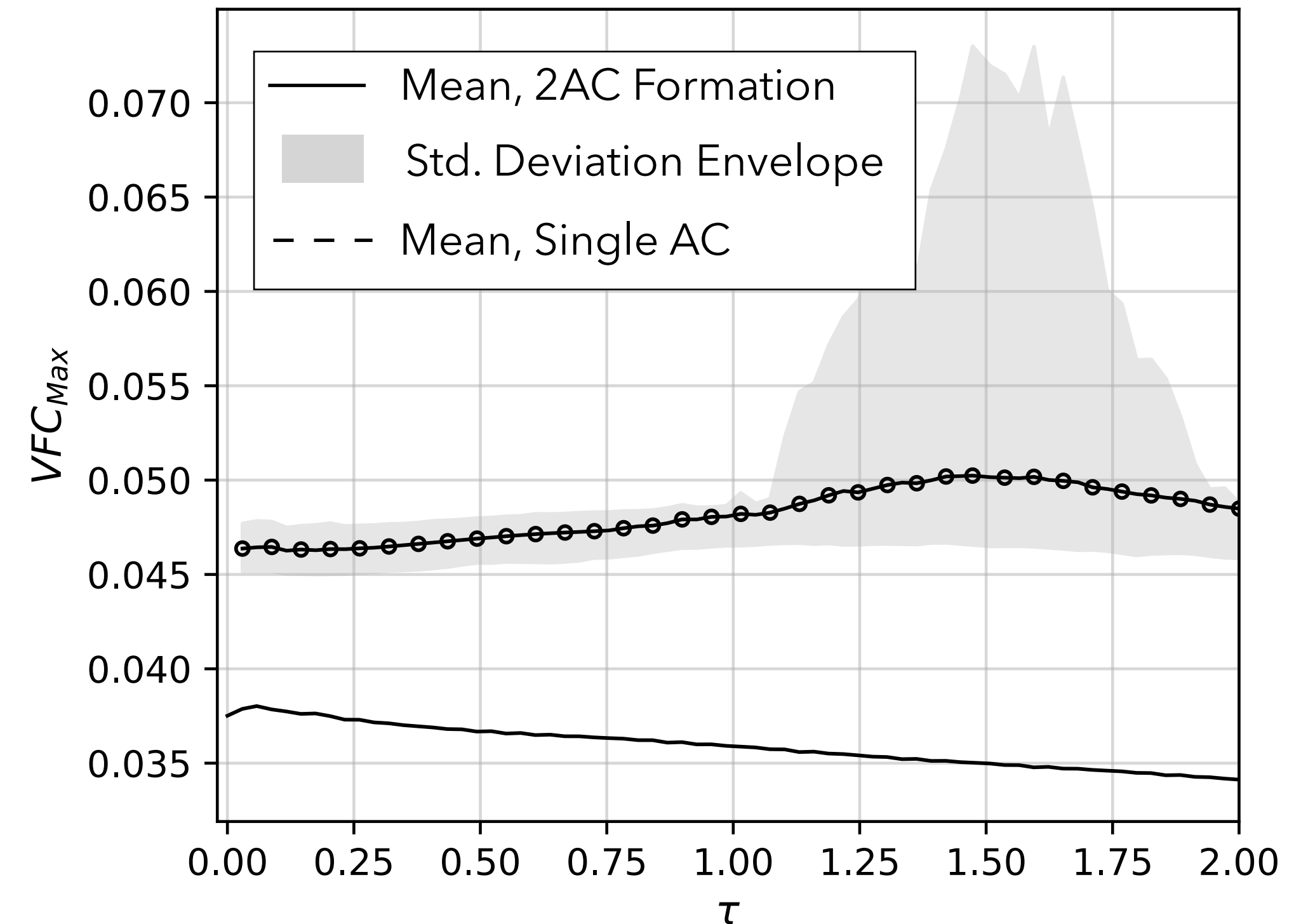
$$M_{roll} = \frac{1}{2} \rho V_{\infty}^2 \int_{-b/2}^{b/2} C_{l,\alpha}(y') c(y') \frac{u_f(y')}{V_{\infty}} y' dy'$$

$$RMC = \frac{M_{roll}}{1/2 \rho V_{\infty}^2 S b}$$

Vertical Force Coefficient (VFC) as a measure of exploitability for additional aircraft

- Maximum VFC mostly observed on the outboard vicinity of the follower outboard vortex
- Reconnections lead to high VFC events in inboard pair
- Max VFC behind a formation always greater than max VFC observed behind a

➡ **A third aircraft in a formation will benefit from an additional gain compared to the second one**



$$F_V = \frac{1}{2} \rho V_\infty^2 \int_{-b/2}^{b/2} C_{l,\alpha}(y') c(y') \frac{u_f(y')}{V_\infty} dy'$$
$$VFC = \frac{F_V}{1/2 \rho V_\infty^2 S}$$

Conclusions

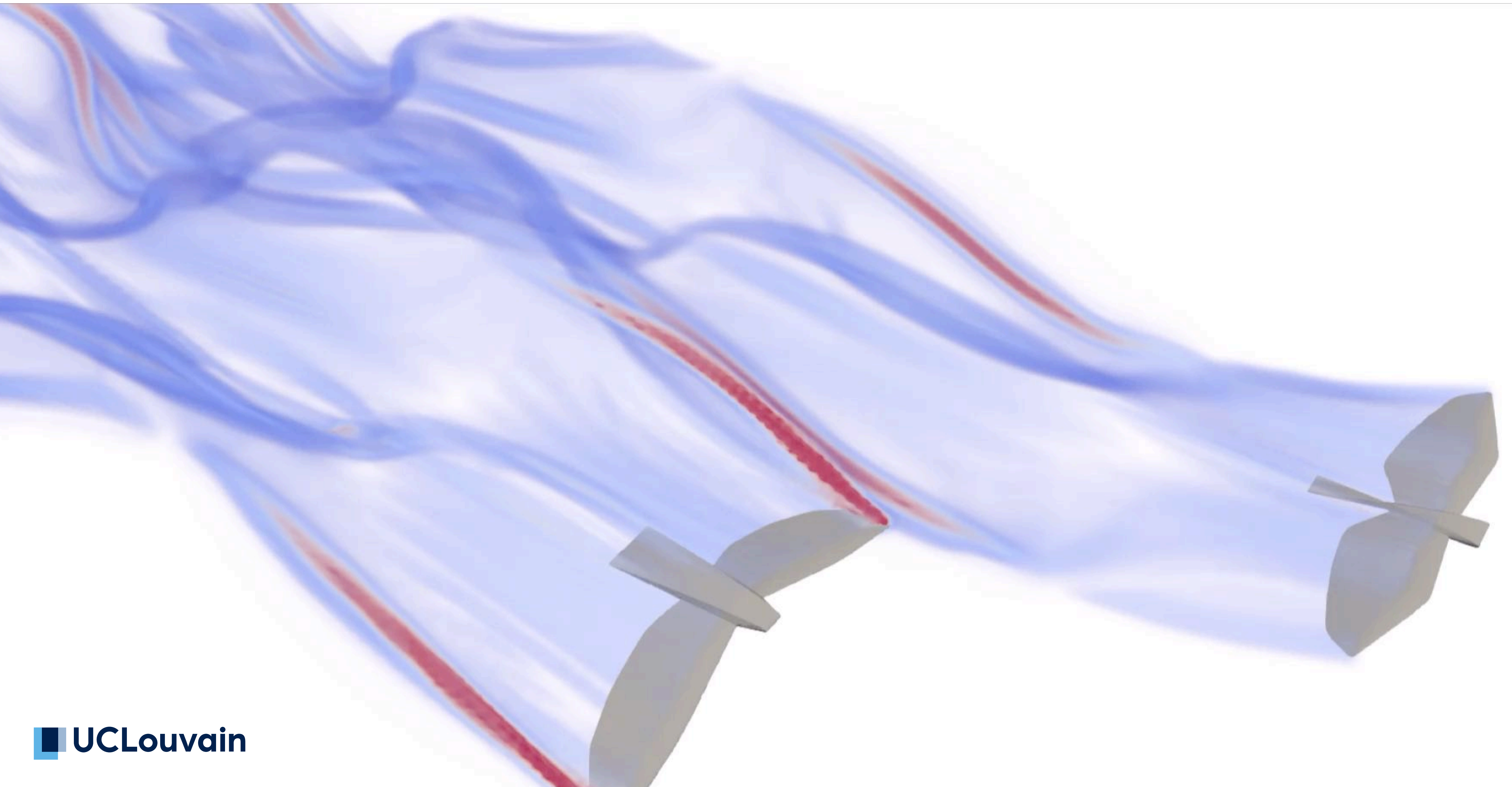
Take away messages

- Importance of capturing the full phenomenological chain of wake propagation behind a formation
- Great sensitivity of the wake vortices propagation to the initial relative position of the aircraft
- Probabilistic model shows dispersion of the inboard wake vortices and concentration of the outboard vortex
- Comparison with the wake of an isolated aircraft shows reduction in RMC and higher VFC, but other factors to account for in an Air Traffic Management case

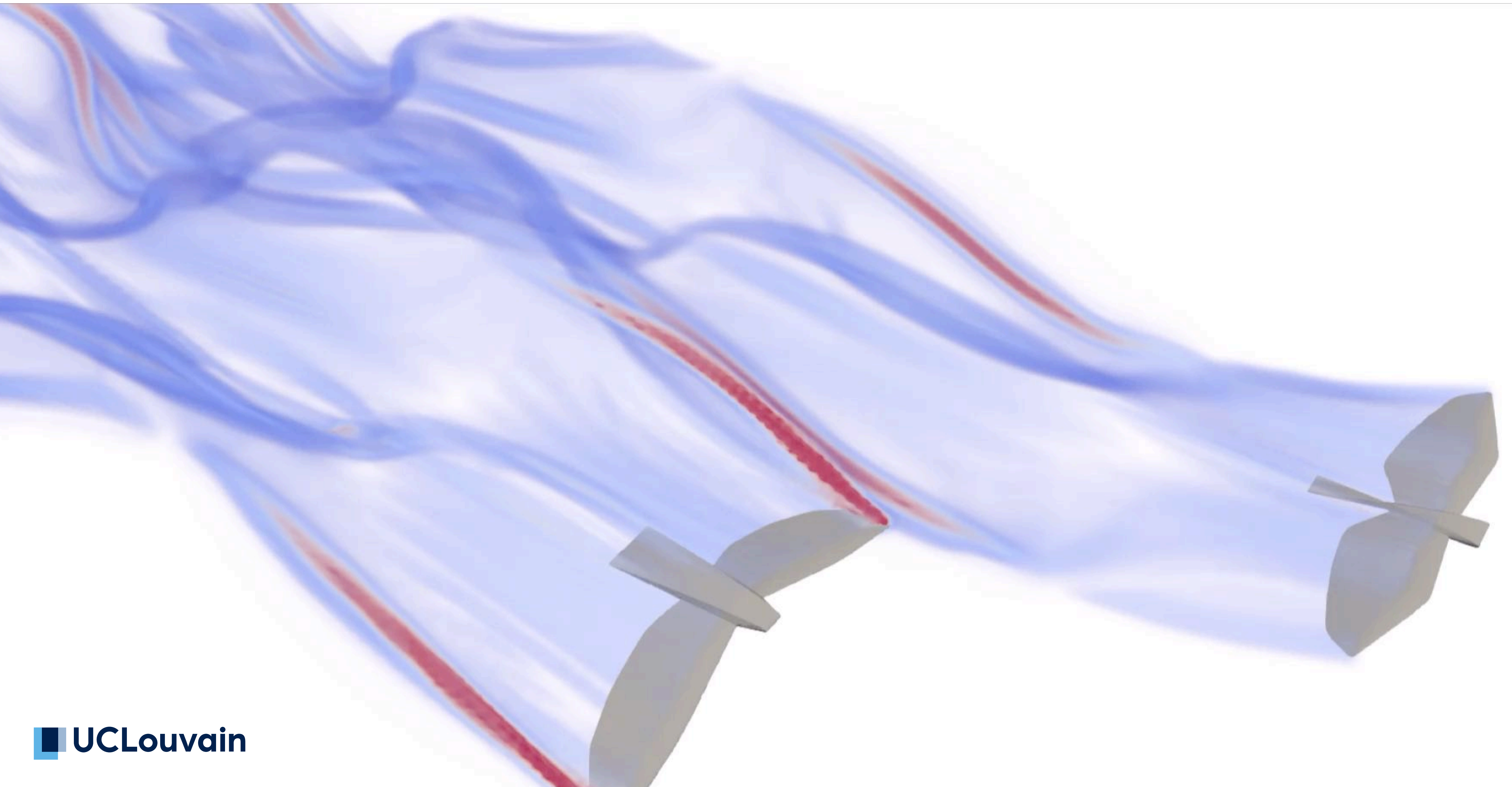
Further improvements / perspectives

- Simulation over longer times, and considering additional parameters i.e., turbulence, atmospheric events (shear, gust,...)
- Basis for a probabilistic wake model that would be valuable for operational prediction

More formation flight...



More formation flight...



Acknowledgments

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