

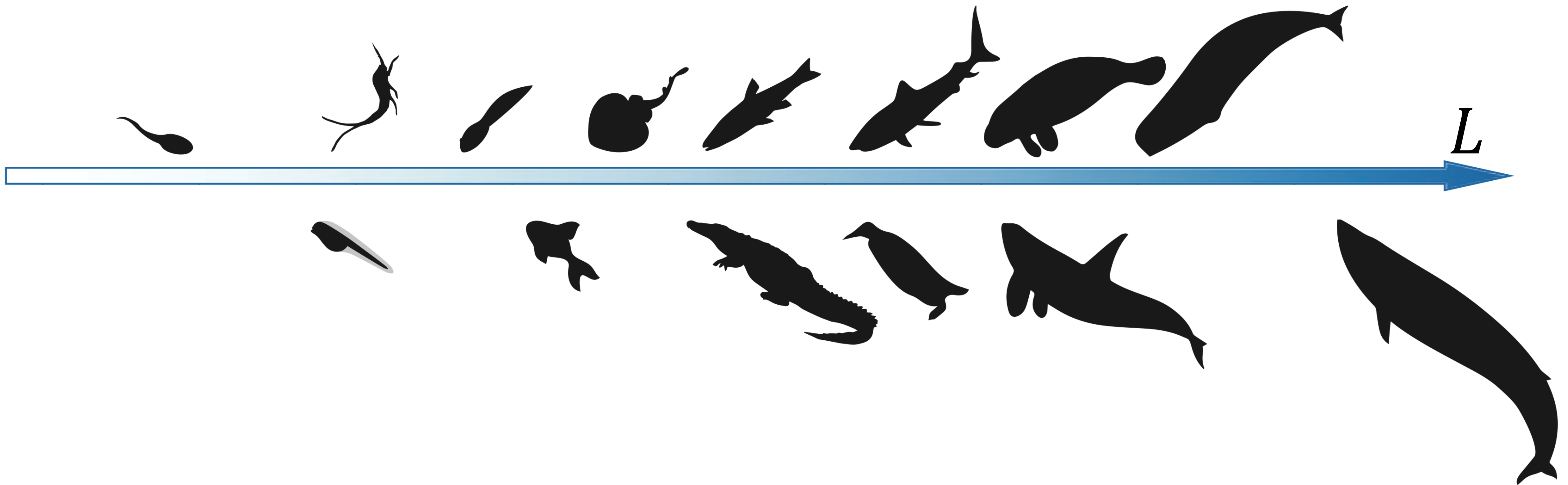
# Strategies to produce highest underwater swimming velocities

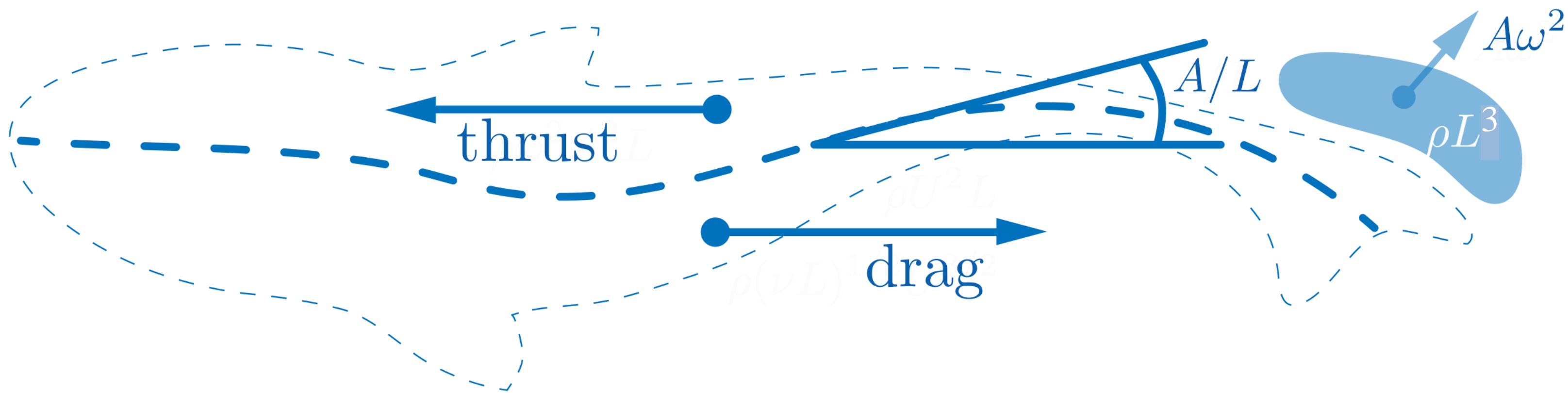
M. Argentina  
Institut de Physique de Nice  
Université Côte d'Azur  
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INSTITUT DE PHYSIQUE DE NICE

UNIVERSITÉ  
**CÔTE D'AZUR** 

Is there a unifying principle linking speed to kinematics?





- $\rho$  = fluid density
- $\mu$  = fluid dynamic viscosity
- $\nu$  = fluid kinematic viscosity
- $\delta$  = thickness boundary layer

**Thrust :** force generated by pushing the fluid mass of fluid times the fin acceleration

**Drag :**

Large swimmers: proportional to  $U^2$  (pressure drag)

Moderately large swimmers : proportional to  $U^{3/2}$  (skin drag or boundary layer drag)

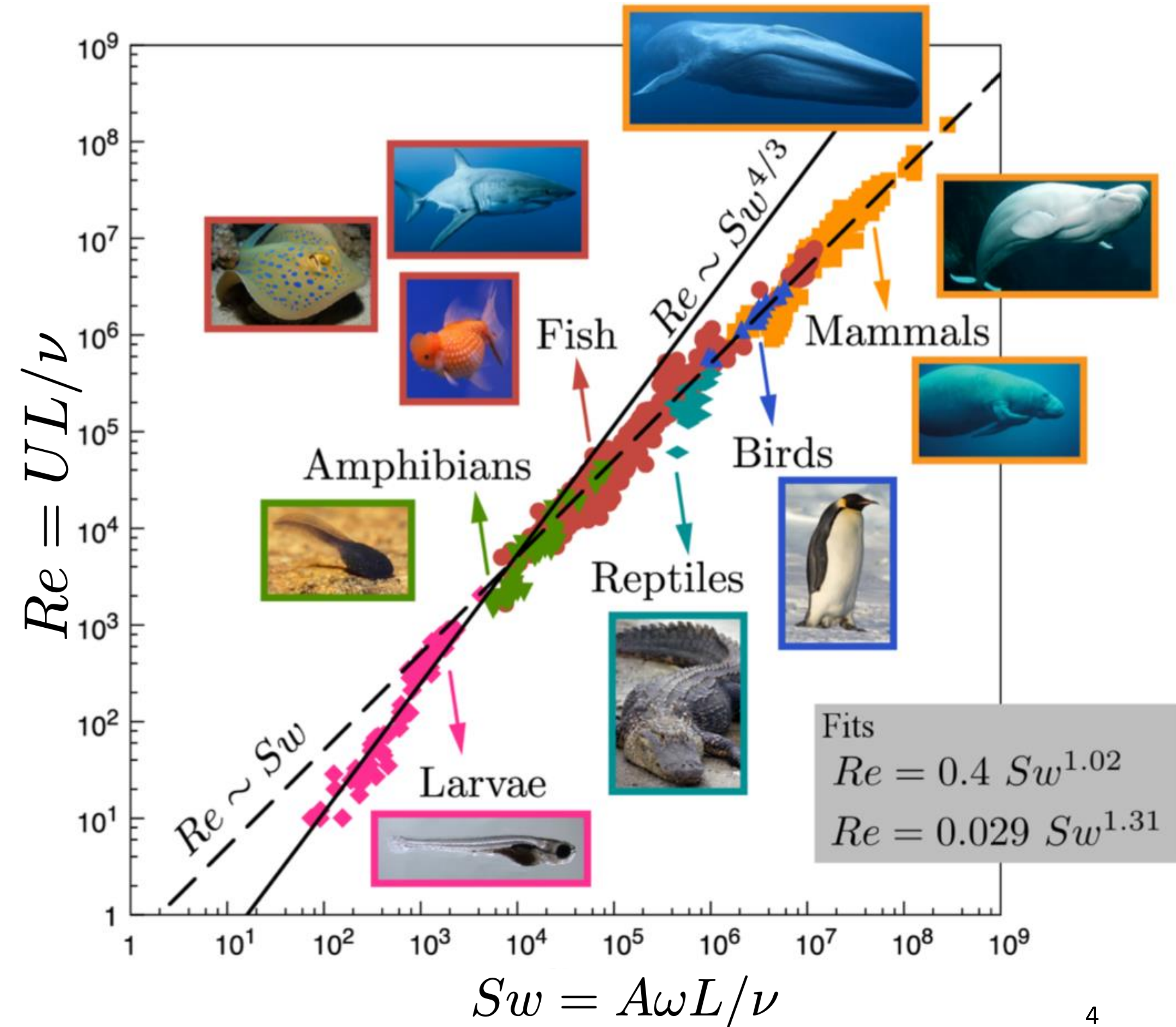
**Balancing Thrust and Drag : two scalings**

$$U \propto A\omega, \text{ for large animals}$$

$$U \propto \left( \frac{A^4 \omega^4 L}{\nu} \right)^{1/3}, \text{ for smaller animals}$$



# Does it work?



~50 years of experiments  
 ~1000 data points  
 ~8 orders of magnitude in  $Re$

$$U \propto \left( \frac{A^4 \omega^4 L}{\nu} \right)^{1/3}, Re < 3000$$

$$U \propto A\omega, Re > 3000$$

Gazzola, Argentina, Mahadevan, **Nature Physics** 2014

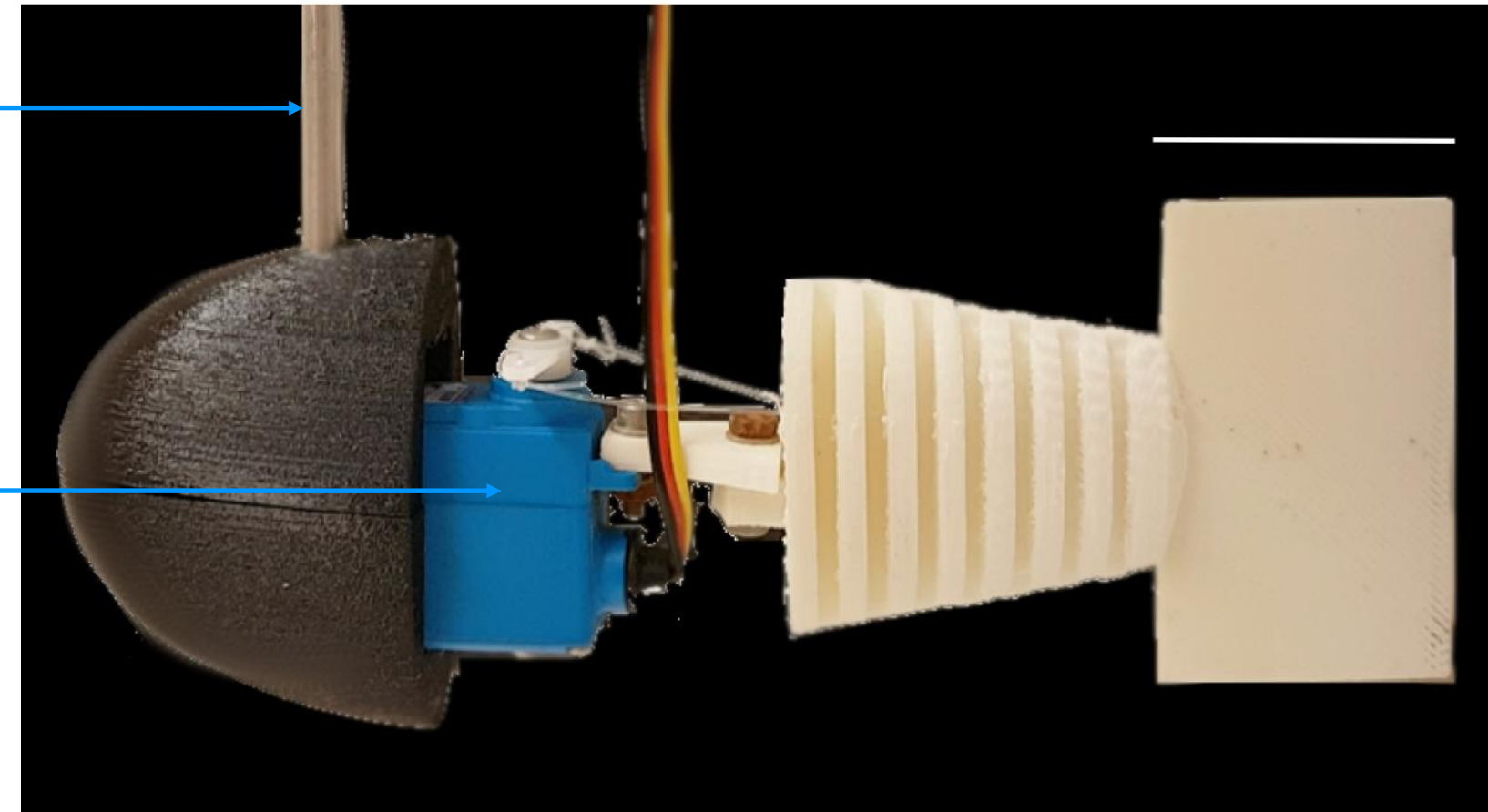
Gazzola, Argentina, Mahadevan, **PNAS** 2015



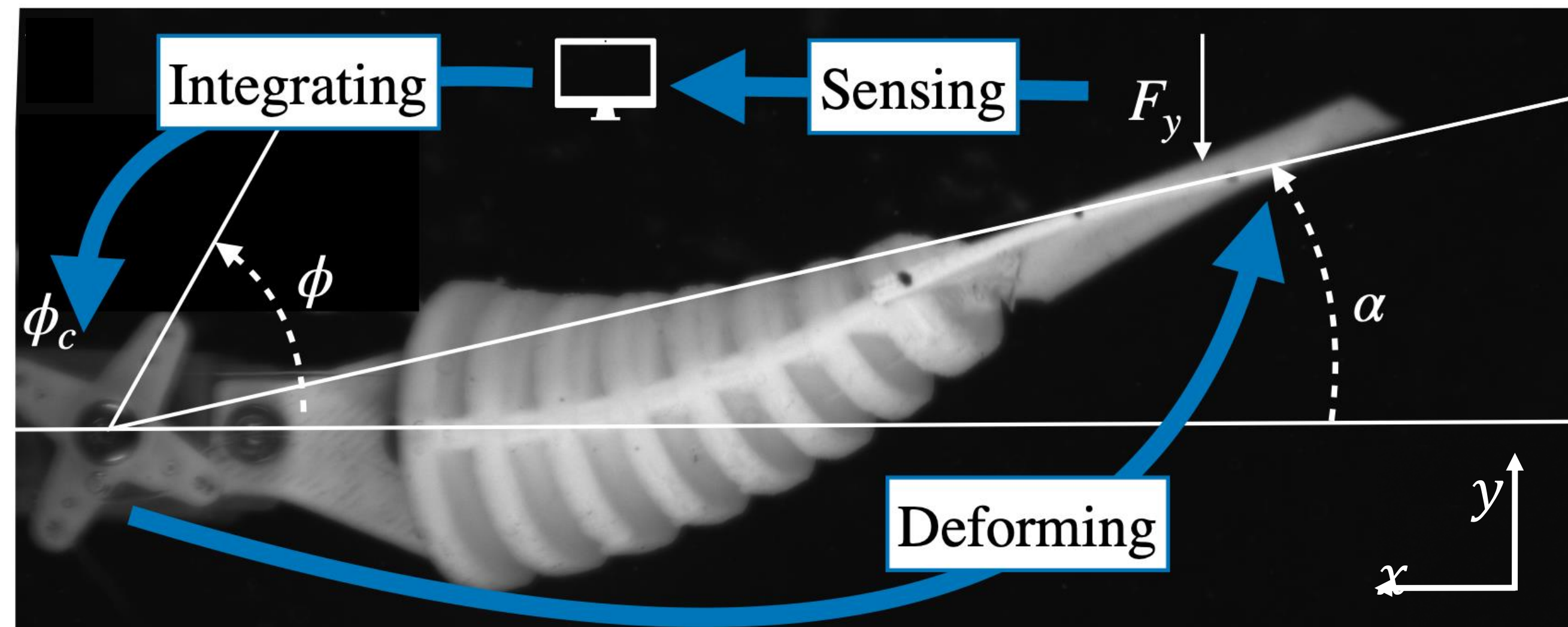
# Experiments for a robotic swimmer

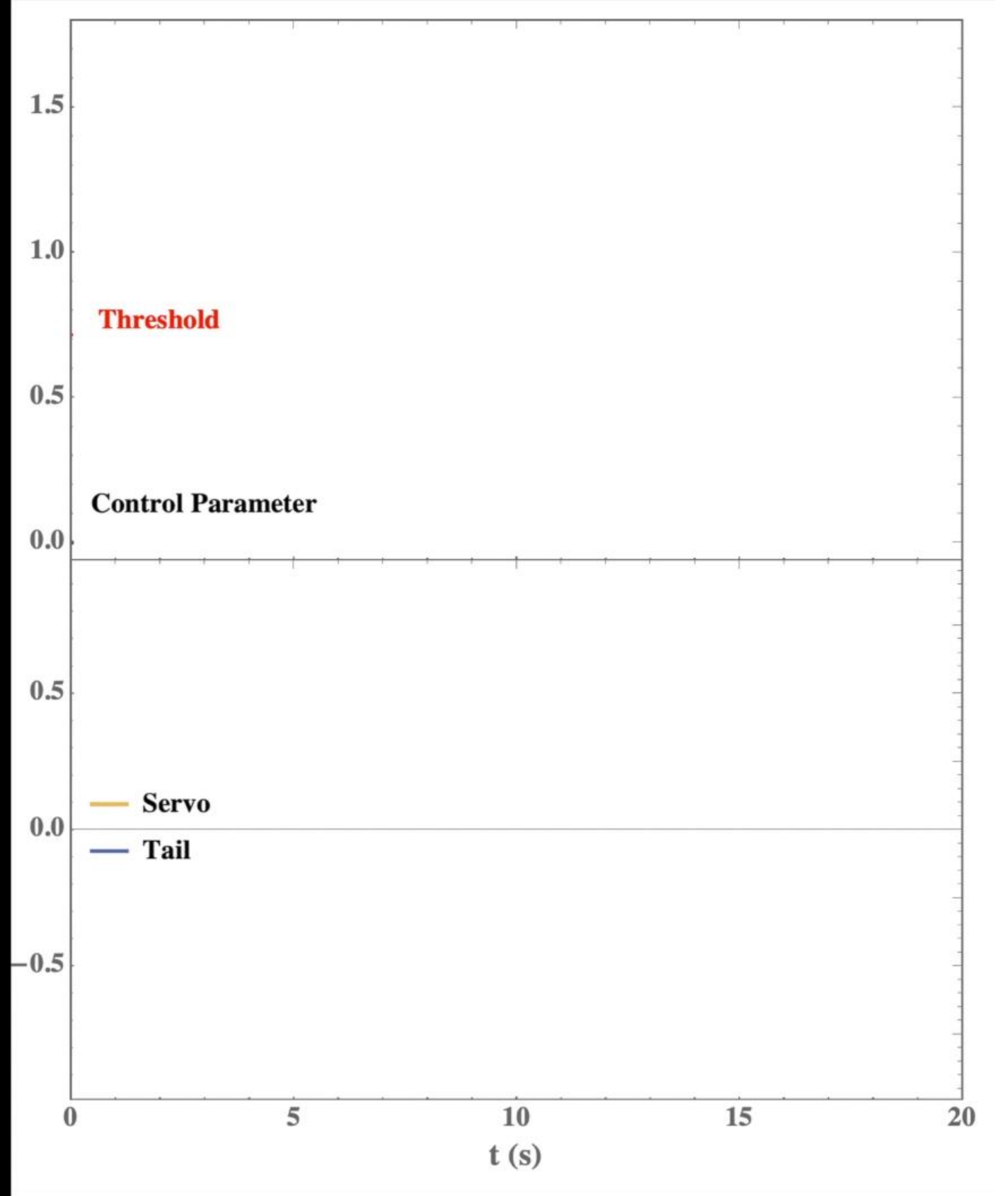
Forces sensor

Servo motor



**Objective: determine the action of the servomotor**

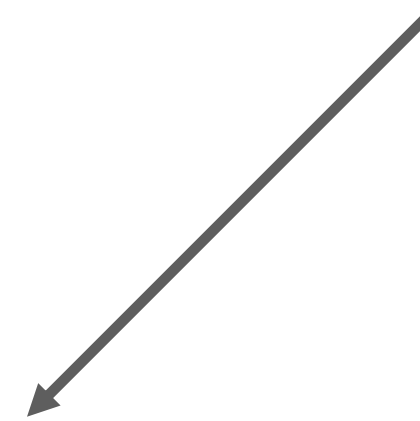
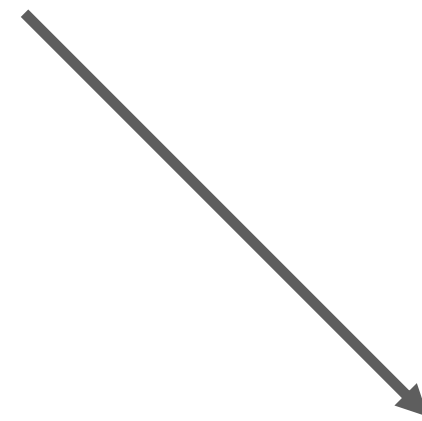




# *Optimizing Swimming gaits ?*

Complex fluid-structure  
interactions

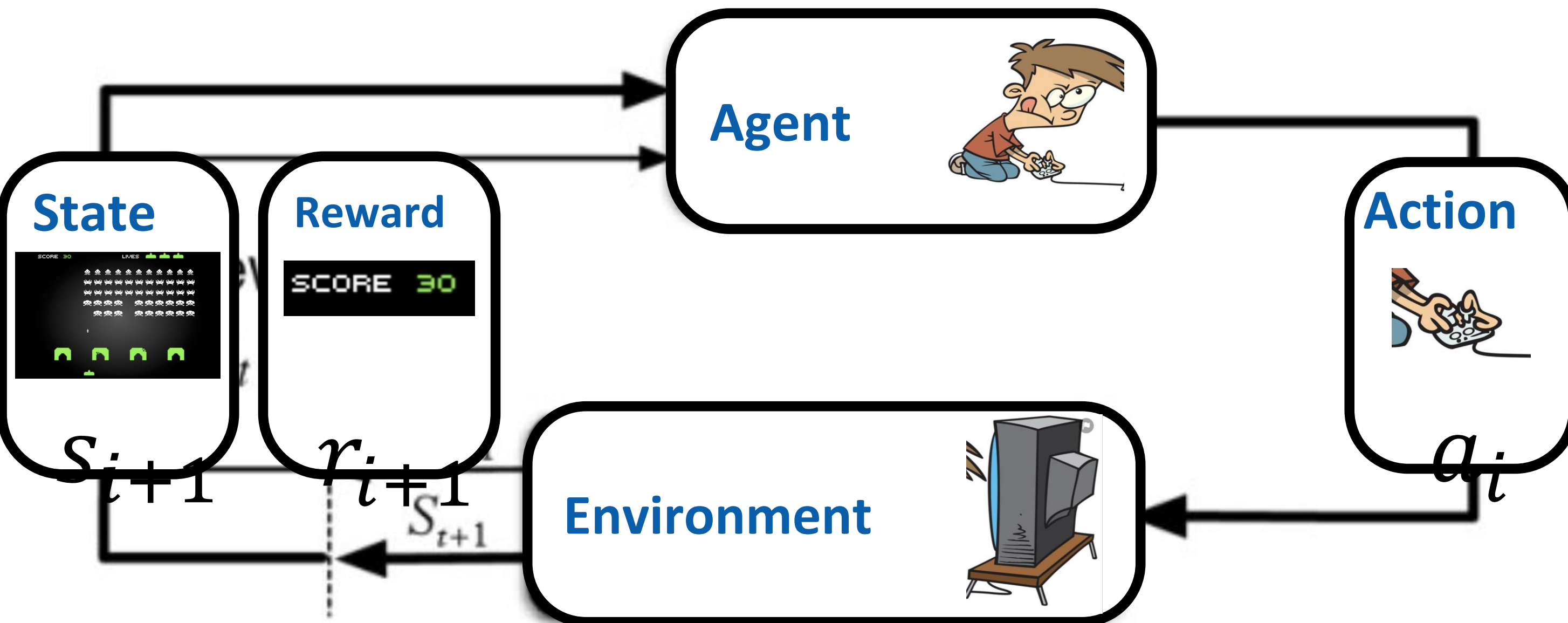
Control theory



***Machine Learning  
(Reinforcement Learning)***



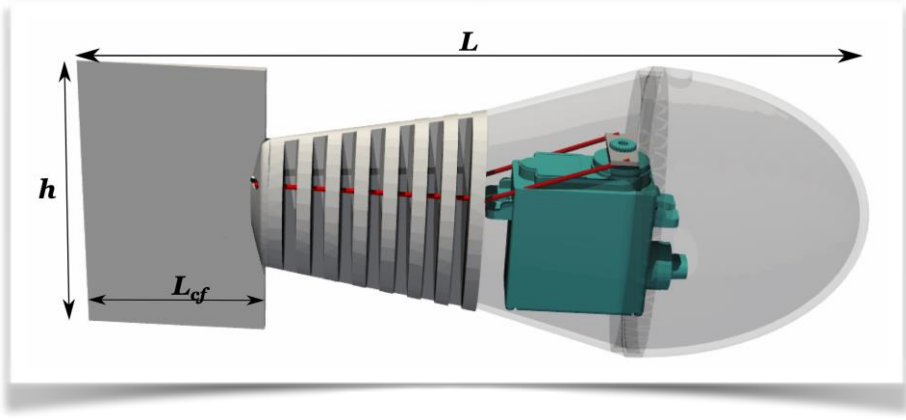
# What is the *reinforcement learning* ?



Action: Left, Right, Shoot  
Reward: Score increment  
State: buffer of screenshots

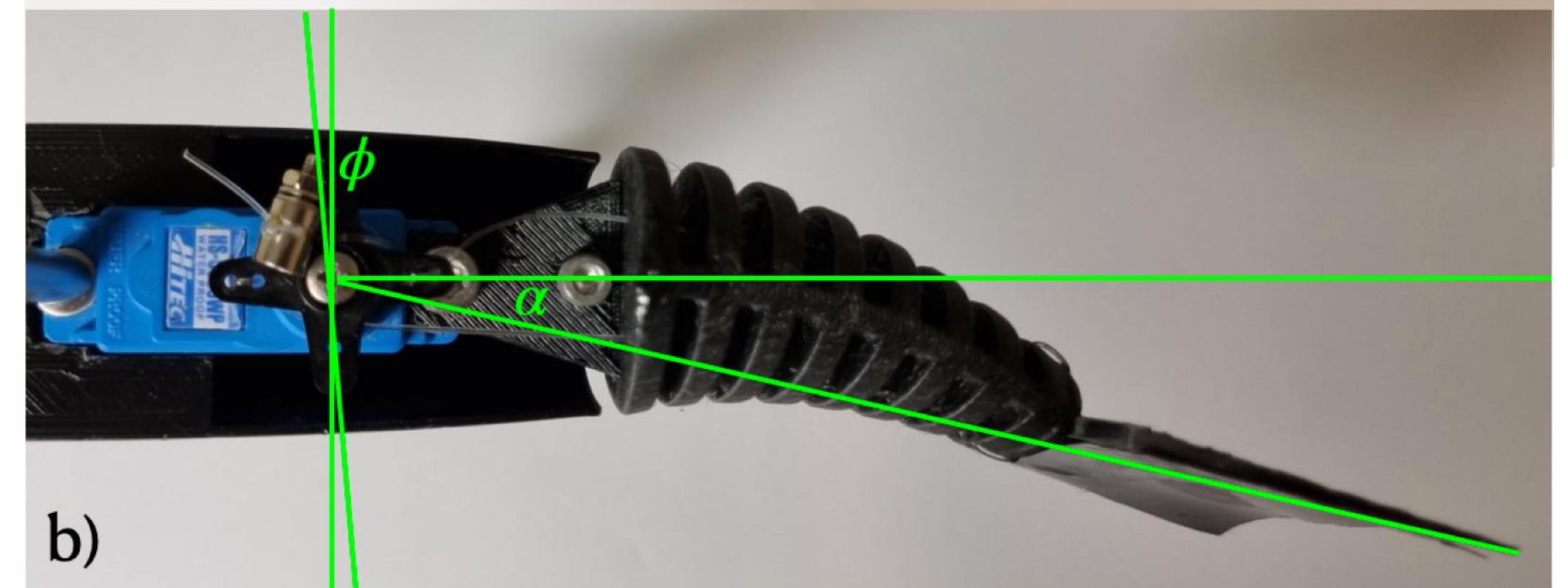
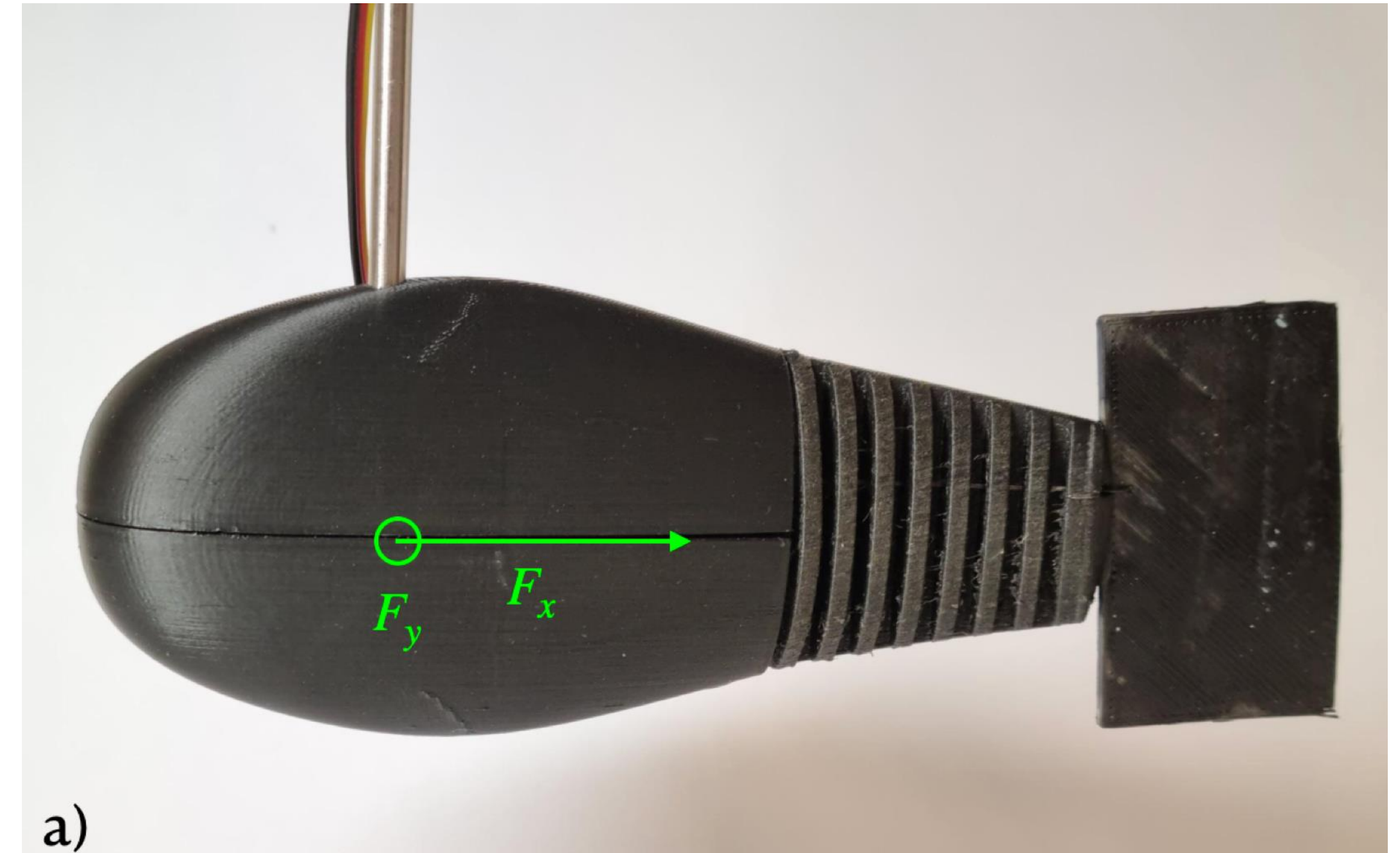


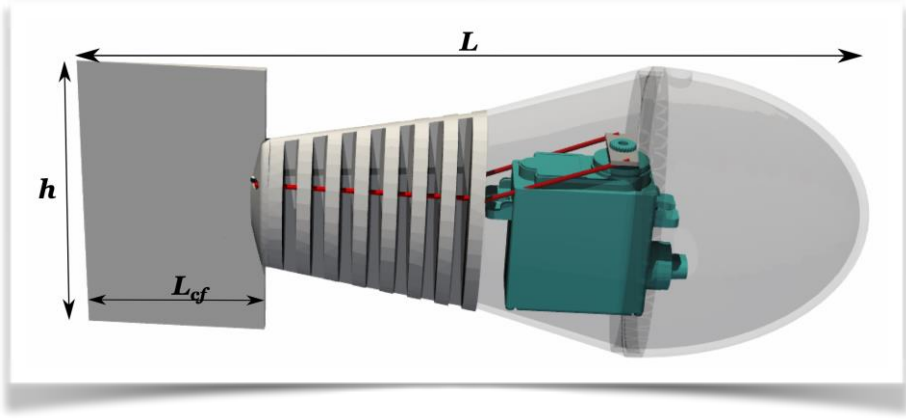
# Reinforcement Learning for the robotic swimmer



## Robotic swimmer

- State :  $F_y(t), \dot{F}_y(t)$
- Set of actions  $\phi_c = -0.5, 0, 0.5(\text{rad})$
- Reward:  $F_x(t)$

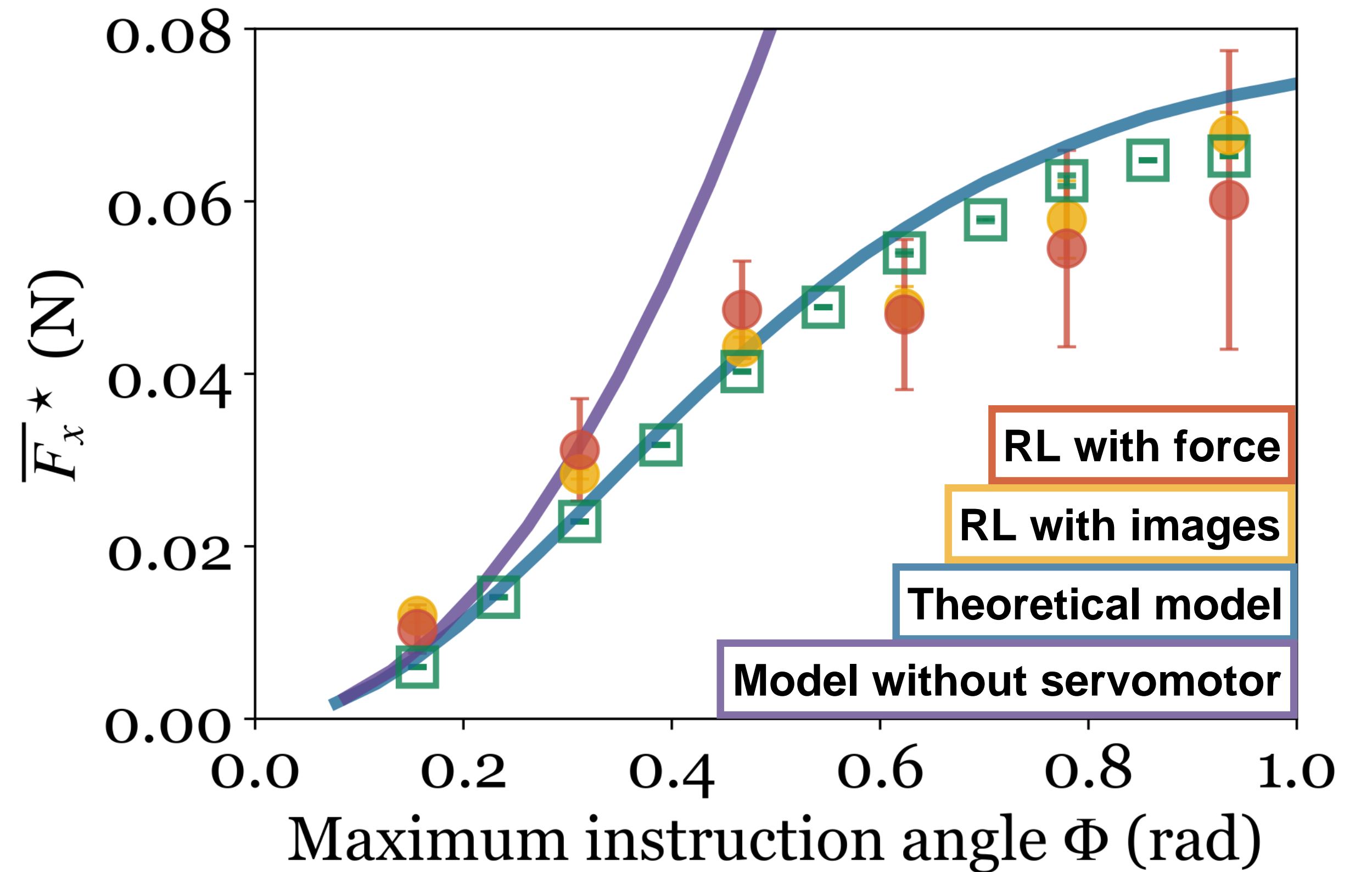
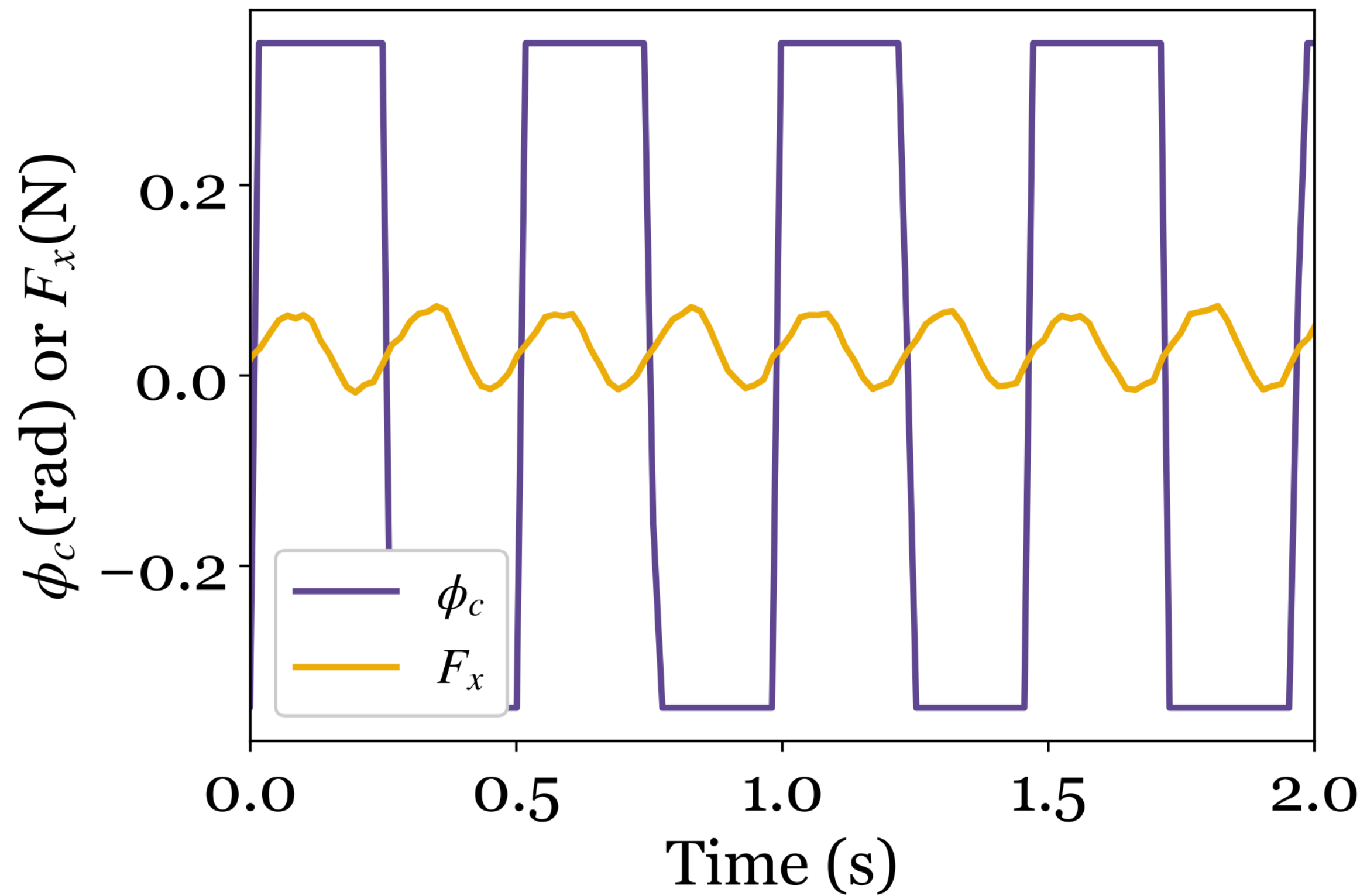


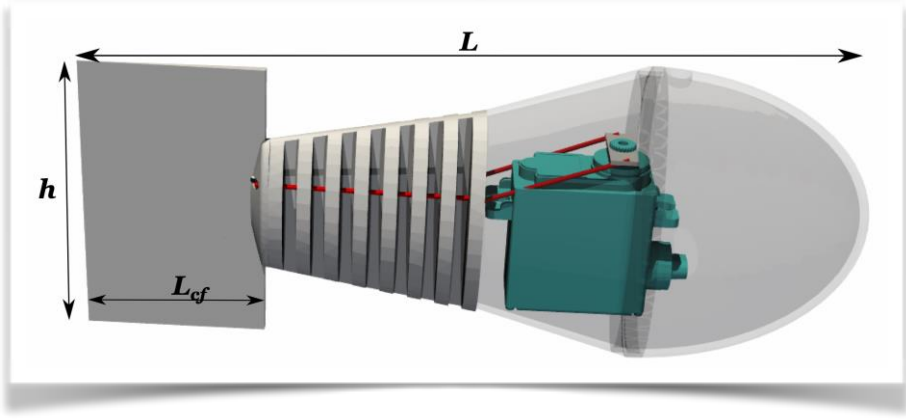


# Reinforcement Learning for the robotic swimmer

## Results

- It learned !
- 1.5h of training
- 50 episodes





# Learning with Images and a PPO RL approach

## Robotic swimmer

- State : 4 successive pictures
- Set of actions  $\Phi = -60^\circ, 0, 60^\circ$
- Reward:  $F_x(t)$

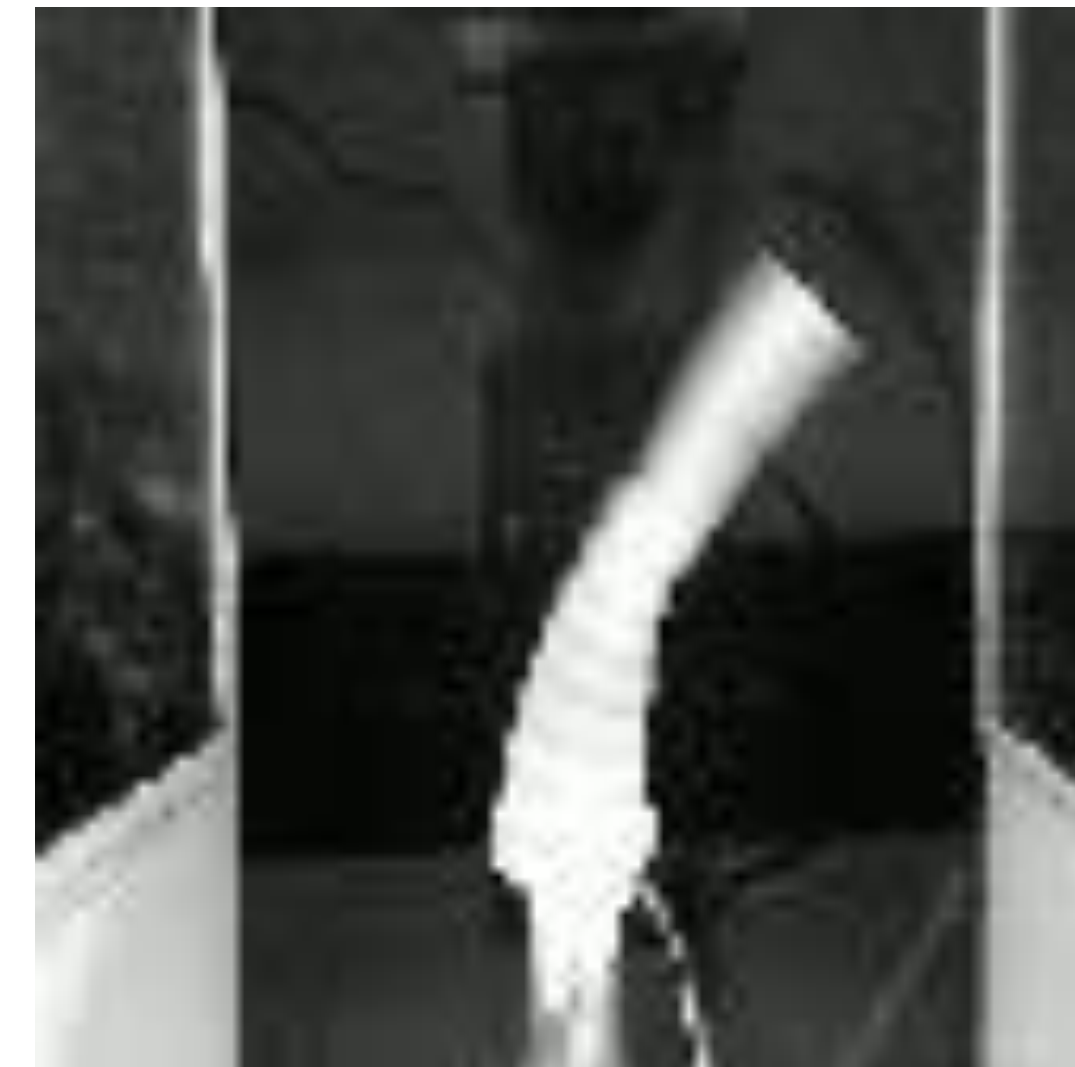
3<sup>rd</sup> episode



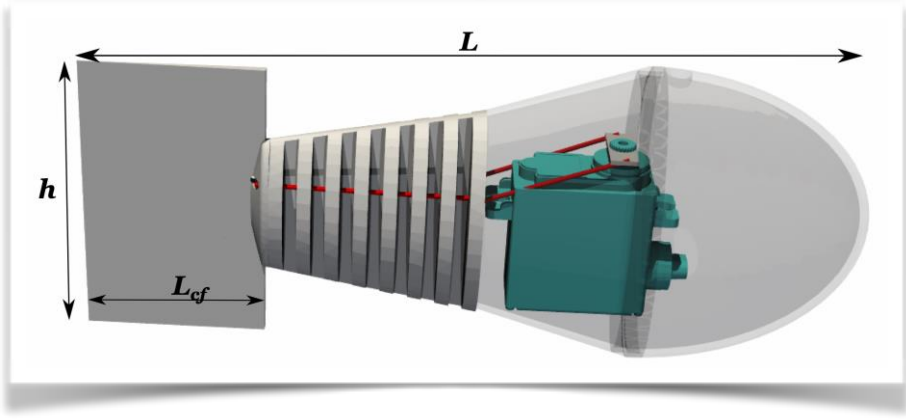
21<sup>st</sup> episode



156<sup>st</sup> episode

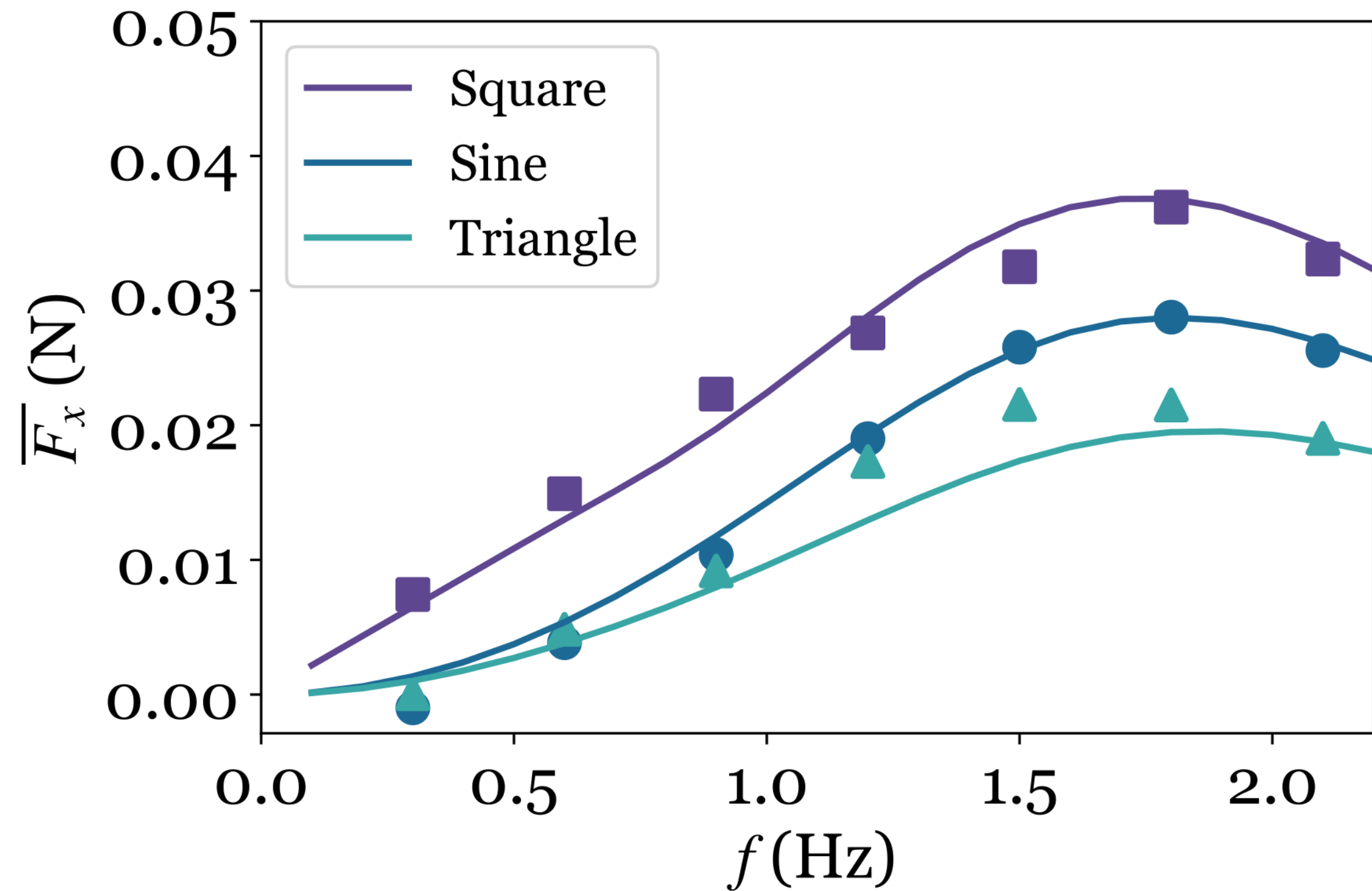






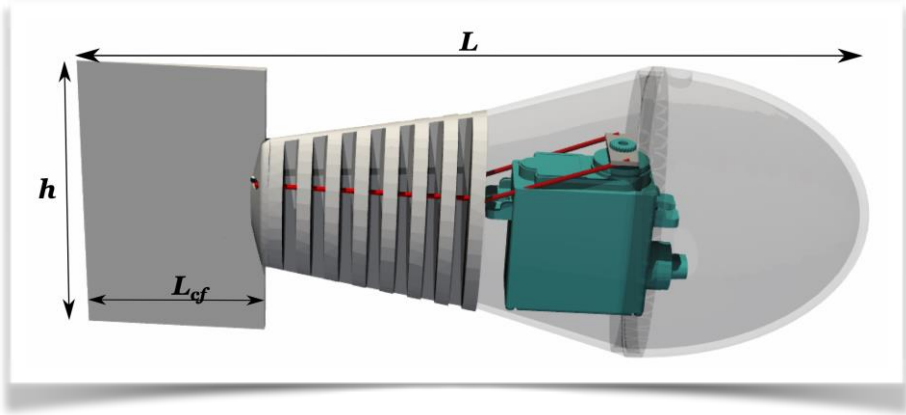
# *A strategy to achieve highest velocities?*

## Ramping in Frequency

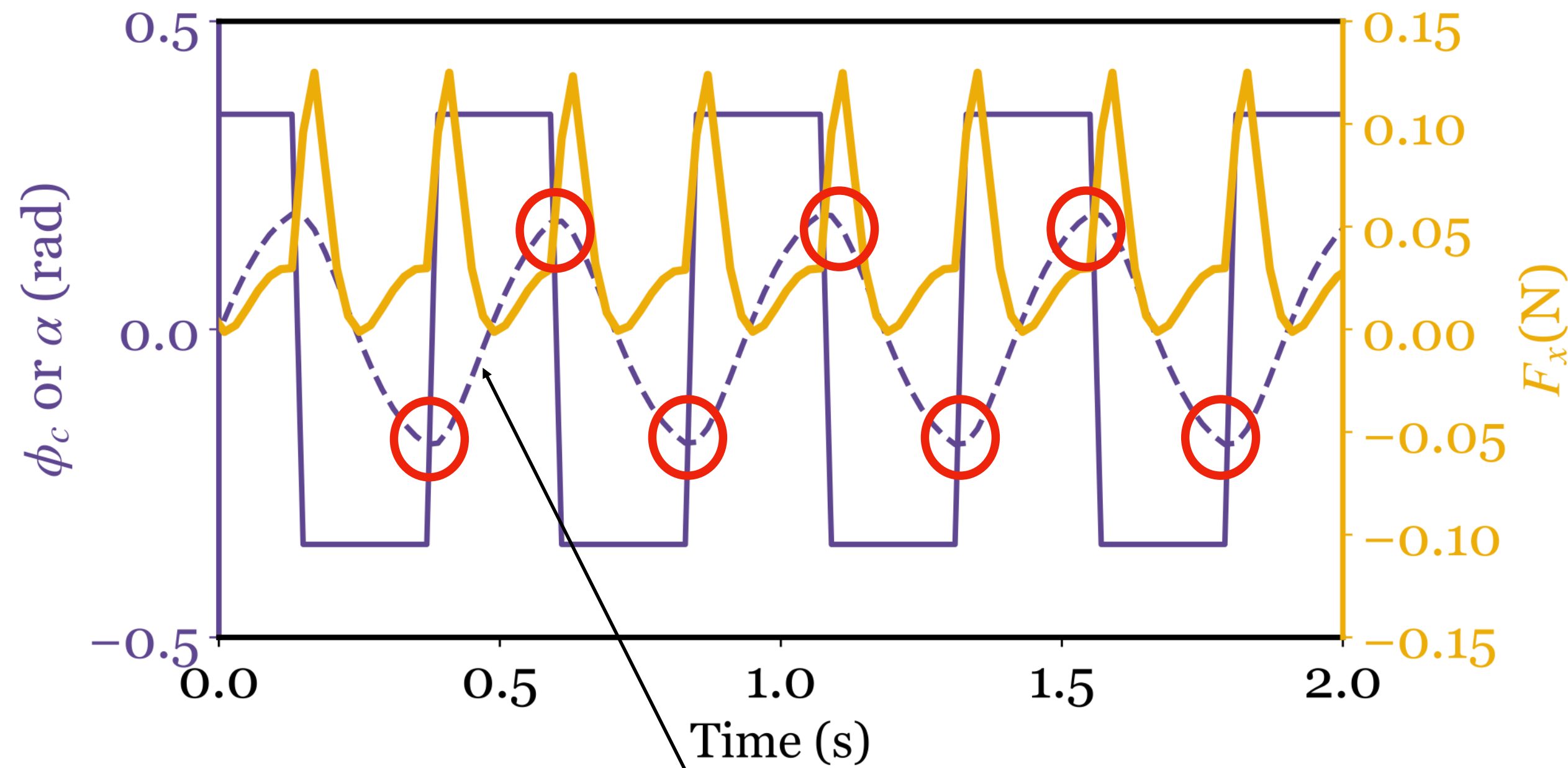


## Results

- Square forcing gives highest velocities
- Frequency needs to be almost resonant



# A strategy to achieve highest velocities?



Angle  $\alpha$

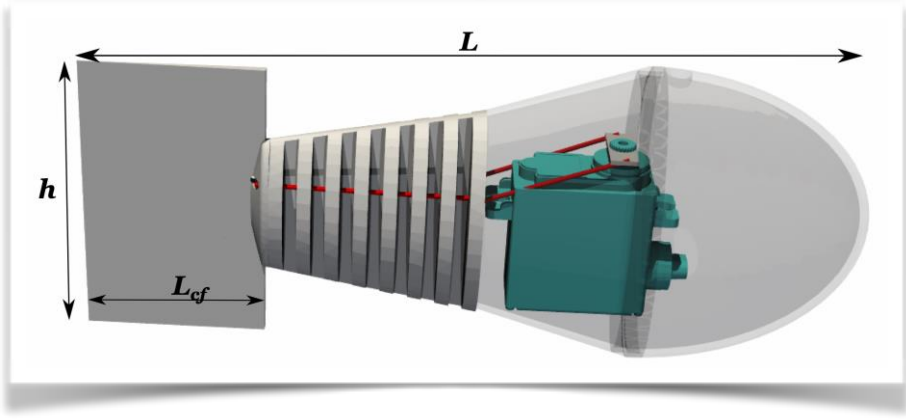
## Swinging Strategy

- Impose a constant angle command
- Switch at the angle velocities zeroes

It automatically select the resonant frequency !

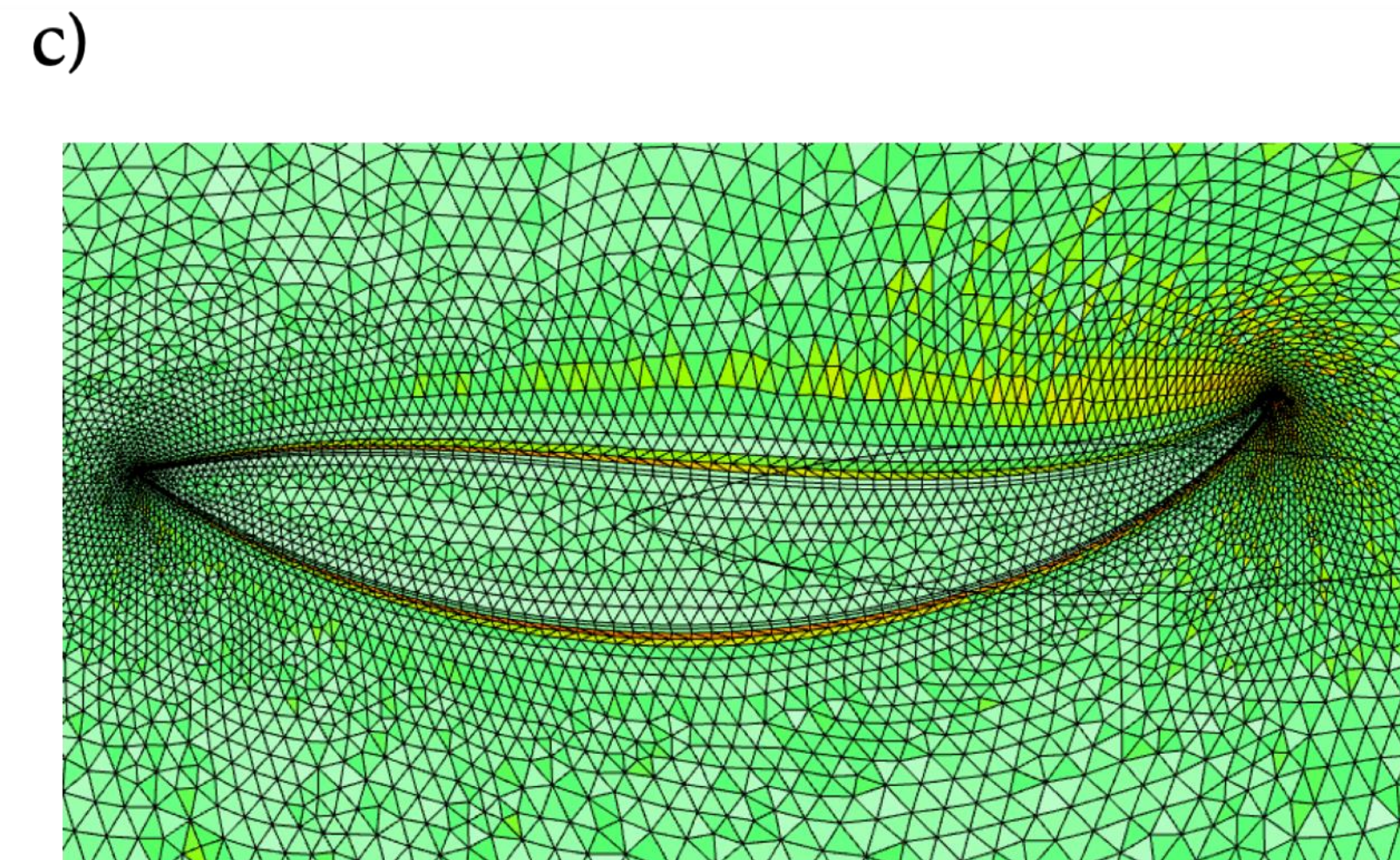
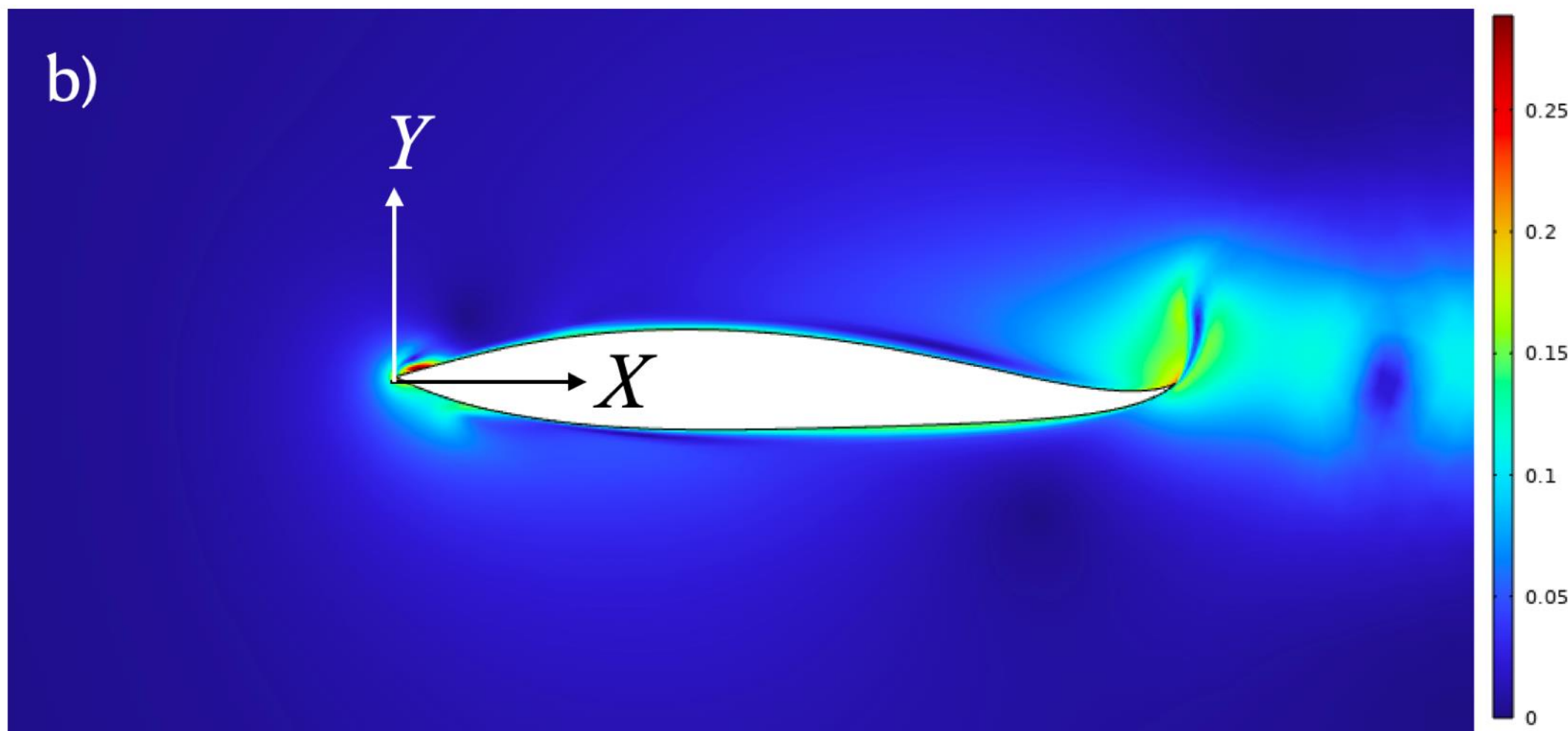
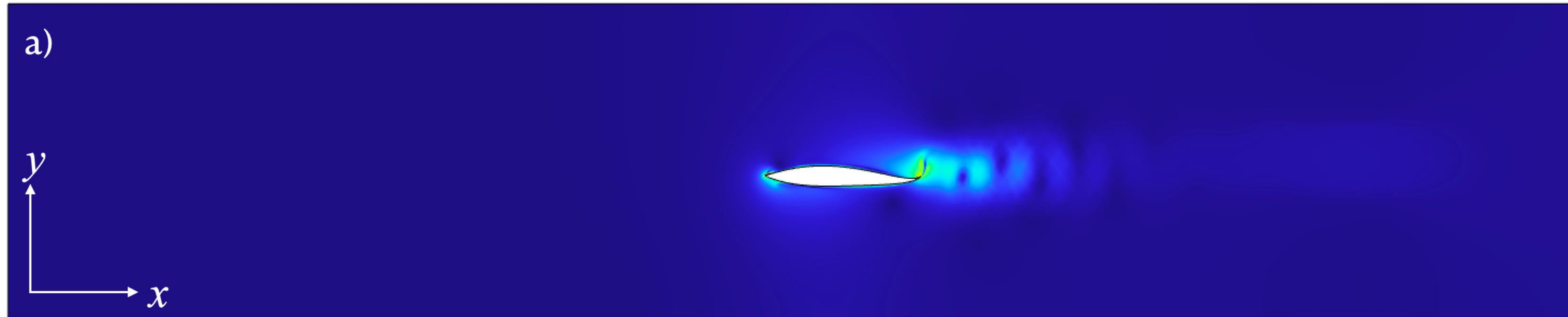




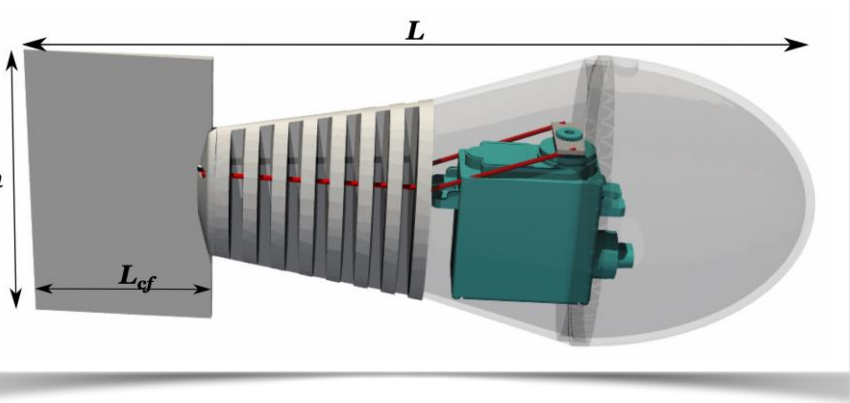


# A strategy to achieve highest velocities

## 2D numerical simulation of the fluid structure problem

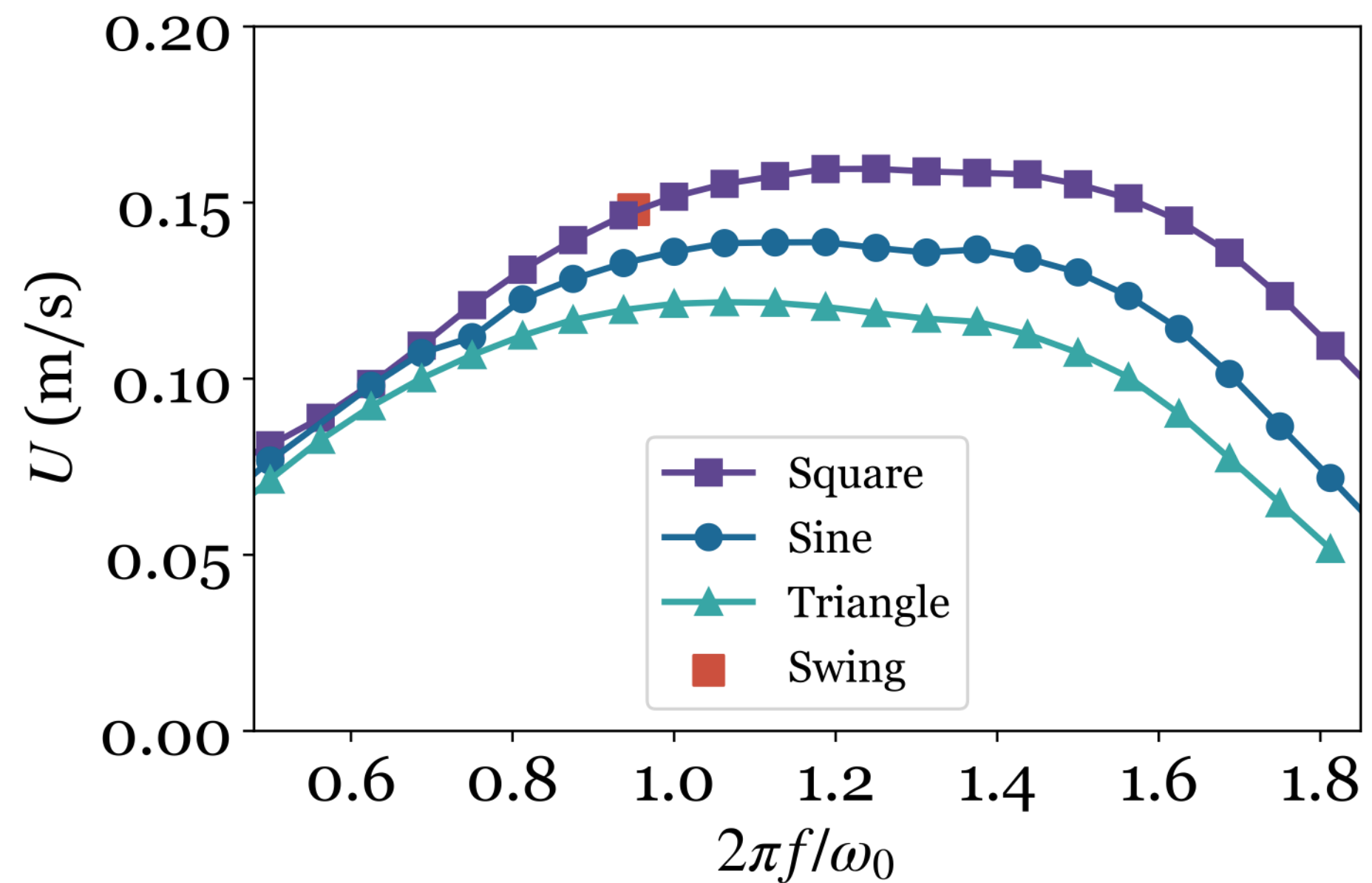


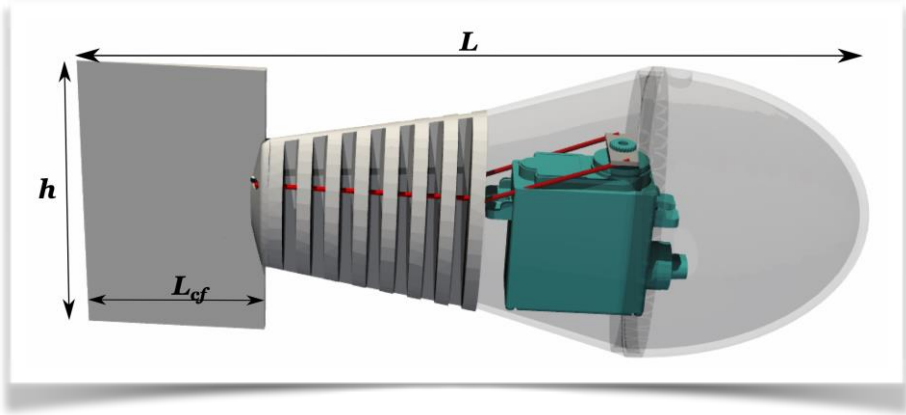




# *A strategy to achieve highest velocities?*

2D numerical simulation of the fluid structure problem





# *A strategy to achieve highest velocities*

## Collaborators

- Li Fu (Centrale Lyon)
- J. Sanchez Rodriguez (EPFL)
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- G. Brouzet (UCA, INPHYNI)
- C. Raufaste (UCA, INPHYNI)

## Summary

- Square forcing is optimal
- Almost resonant frequency
- Swinging strategy permits to achieve almost the highest velocities

## Funding

- DS4H & RISE Academy !