



**FUNEVOL**  
Function & Evolution

La locomotion des serpents : pourquoi autant de redondance dans les systèmes vivants et sont-ils de bons modèles pour la robotique ?



MUSÉUM NATIONAL  
D'HISTOIRE NATURELLE

# Perfect systems but poor design Why living systems are NOT perfect

# Why lose limbs ?

*Two commonly proposed hypotheses:*

1. adaptation to a burrowing life-style ?
  - loss of legs minimises the cross sectional surface area  $\sim$  force needed to burrow
2. adaptation to an aquatic life-style ?
  - loss of legs reduces 'resistance' & results in streamlined body shape
  - use of axial musculature allows for an efficient & continuous type of locomotion

# Limbless lizards (including snakes)

> 4000 species (10 cm to 10 m)

enormous variation in habitat use despite similar morphology



*Tetracheilostoma carlae*



*Dendrelaphis punctulata*



*Eryx jaculus*



*Cerberus rhynchops*

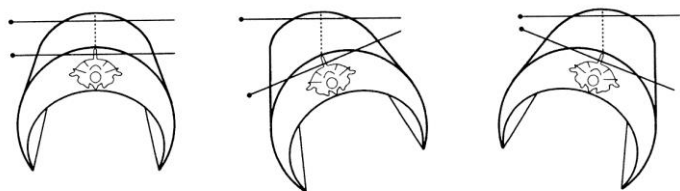
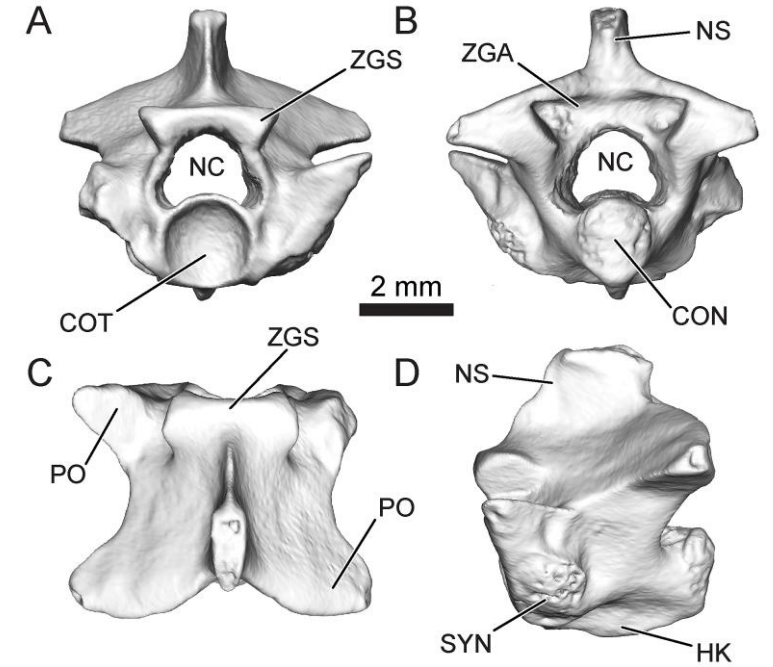
# Snake locomotion

- versatile: can be used in different contexts (land, water, soil, trees)
- different modes of locomotion for different contexts by a single individual
- ‘same’ morphology yet versatility in locomotion patterns
- narrow diameter, can move in tunnels

properties of interest for robotics

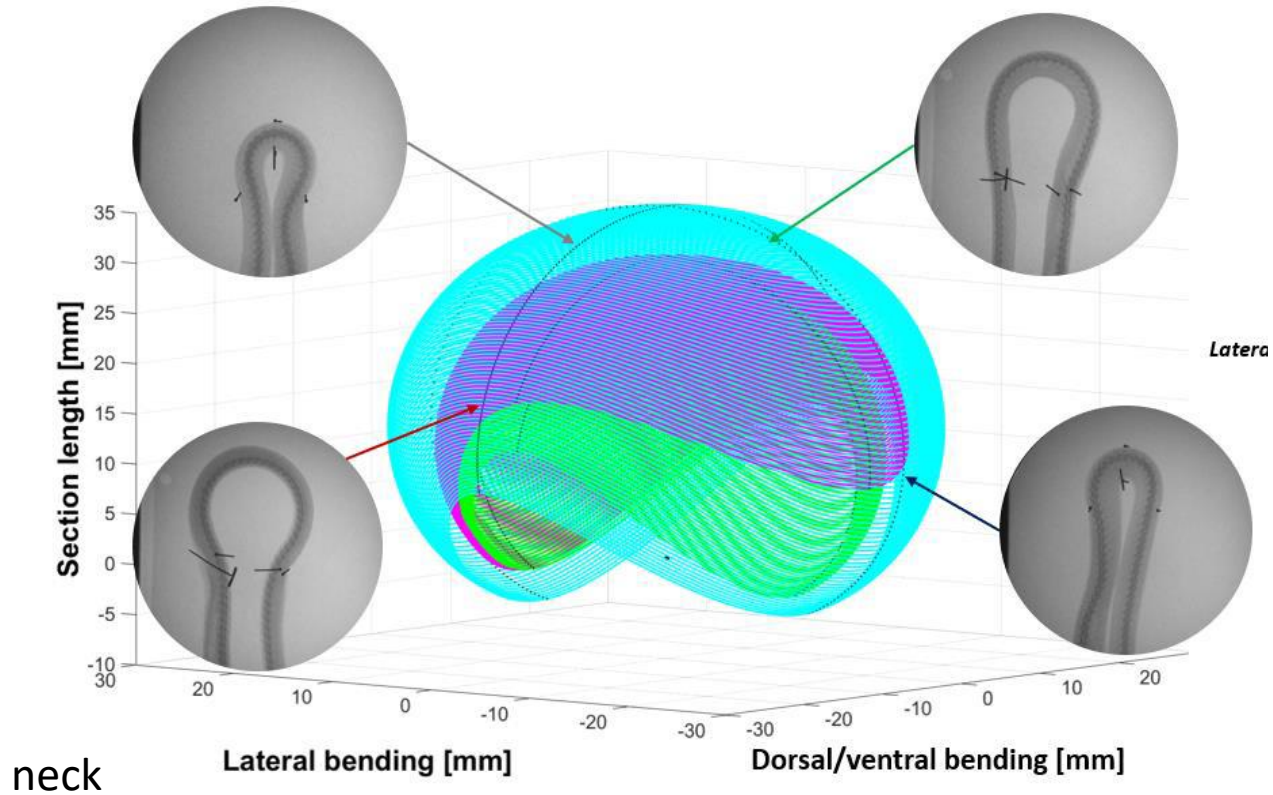
# Osteology

- large # vertebrae (up to 400)
- up to 5 articulation sites between the vertebrae:
  - \* vertebral centrum
  - \* left & right pre- & post zygapophyses
  - \* left & right zygosphene-zygantrum articulation
- mobility is limited
  - \* horizontal plane ( $\pm 9^\circ$  per vertebra)
  - \* vertical plane ( $\pm 3^\circ$  per vertebra)
  - \* torsion ( $\pm 2^\circ$  per vertebra)

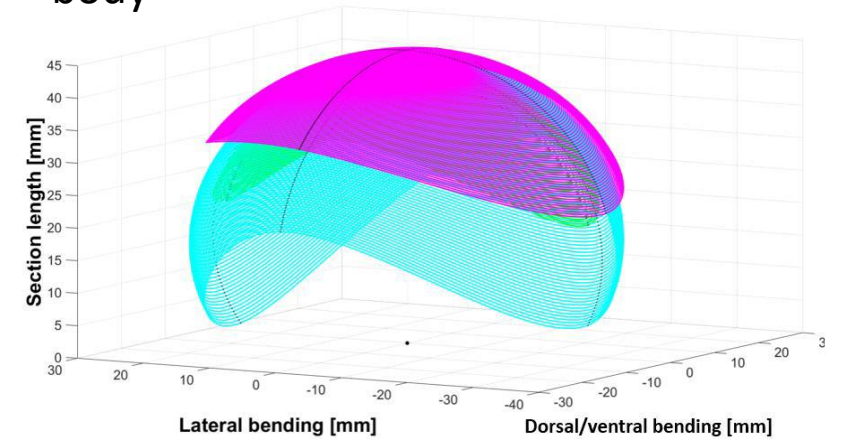


torsional capacity of 10 vertebrae in *P. melanoleucus*

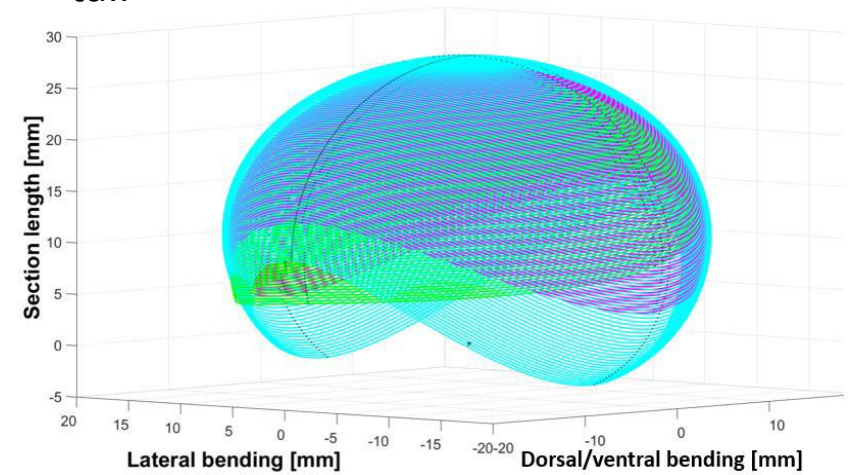
# Intervertebral mobility



body

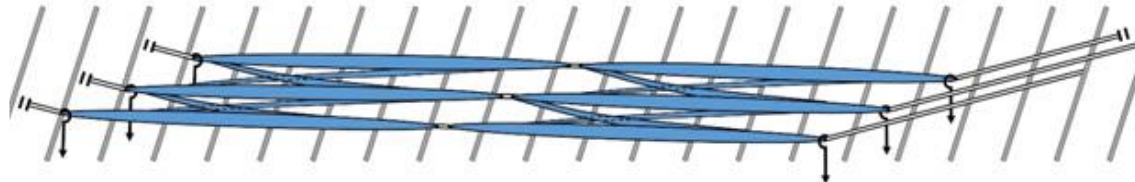
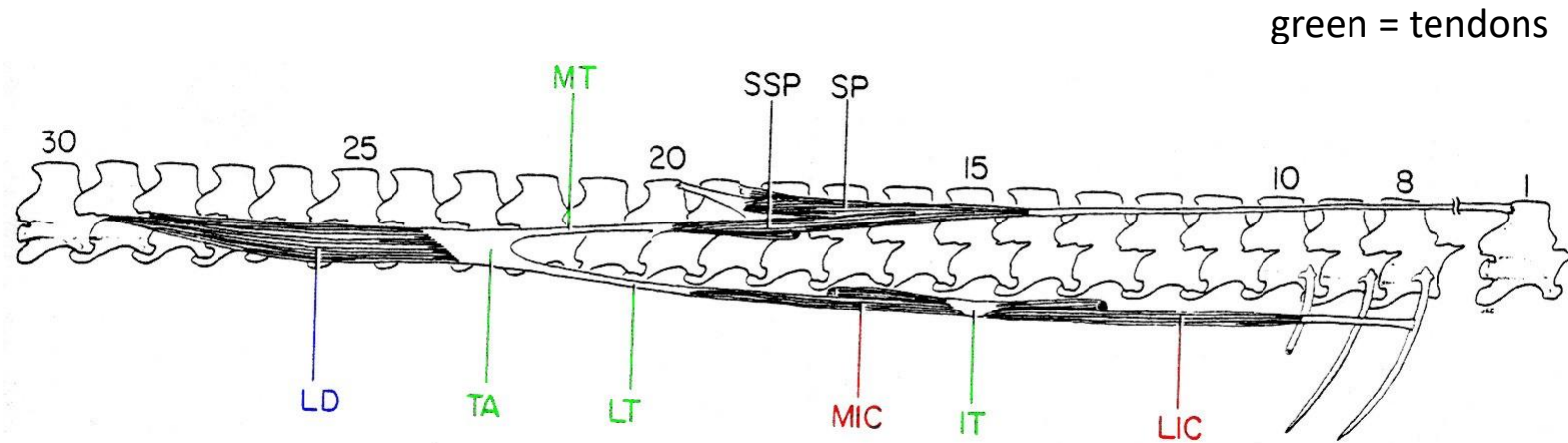


tail



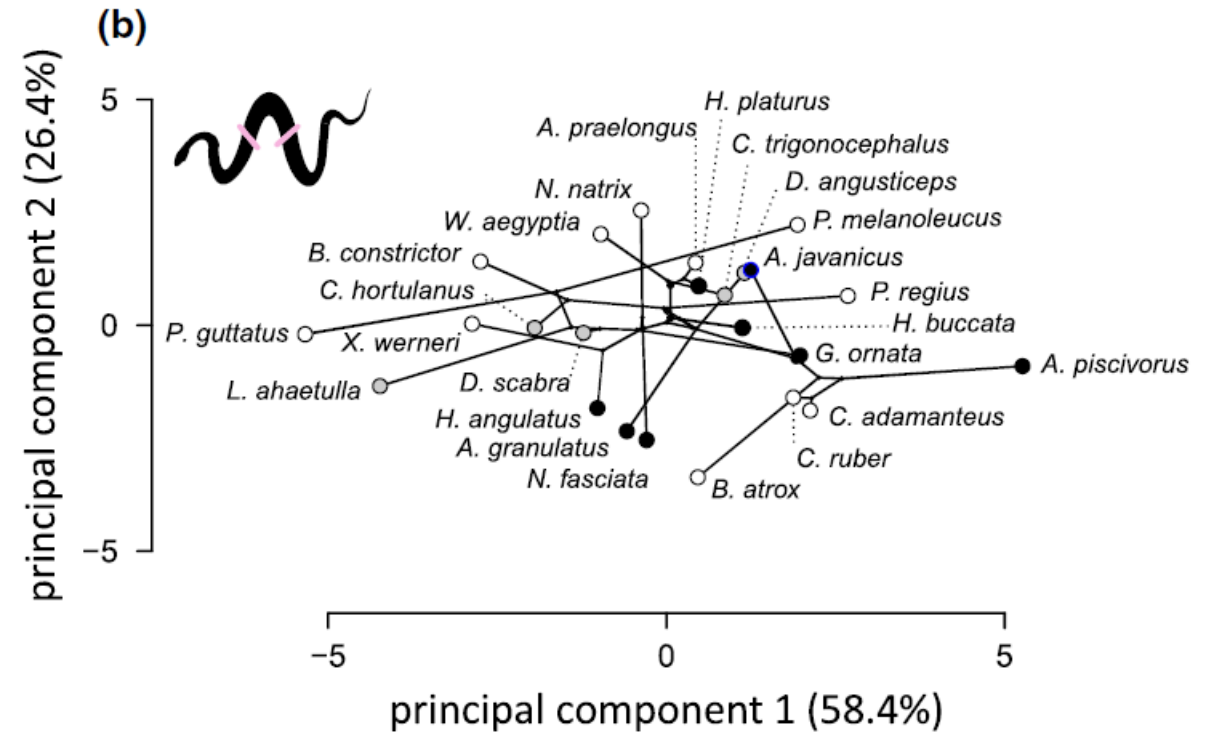
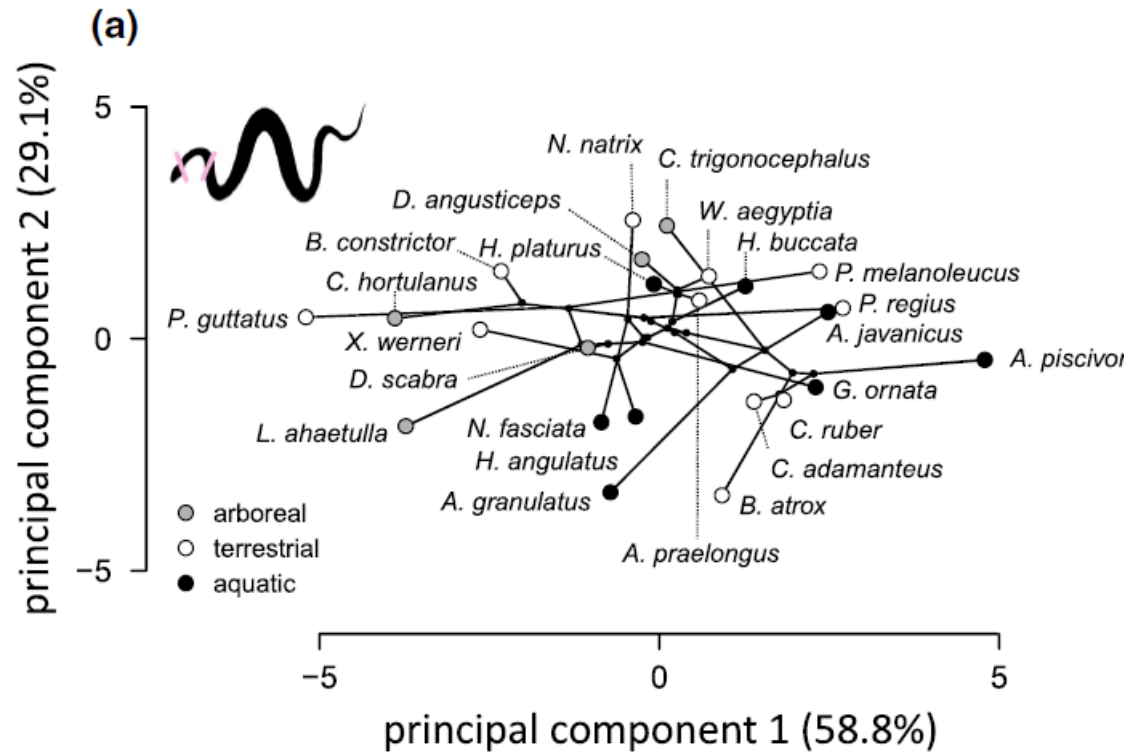
# Muscle morphology in snakes

- very complex muscle-tendon systems !

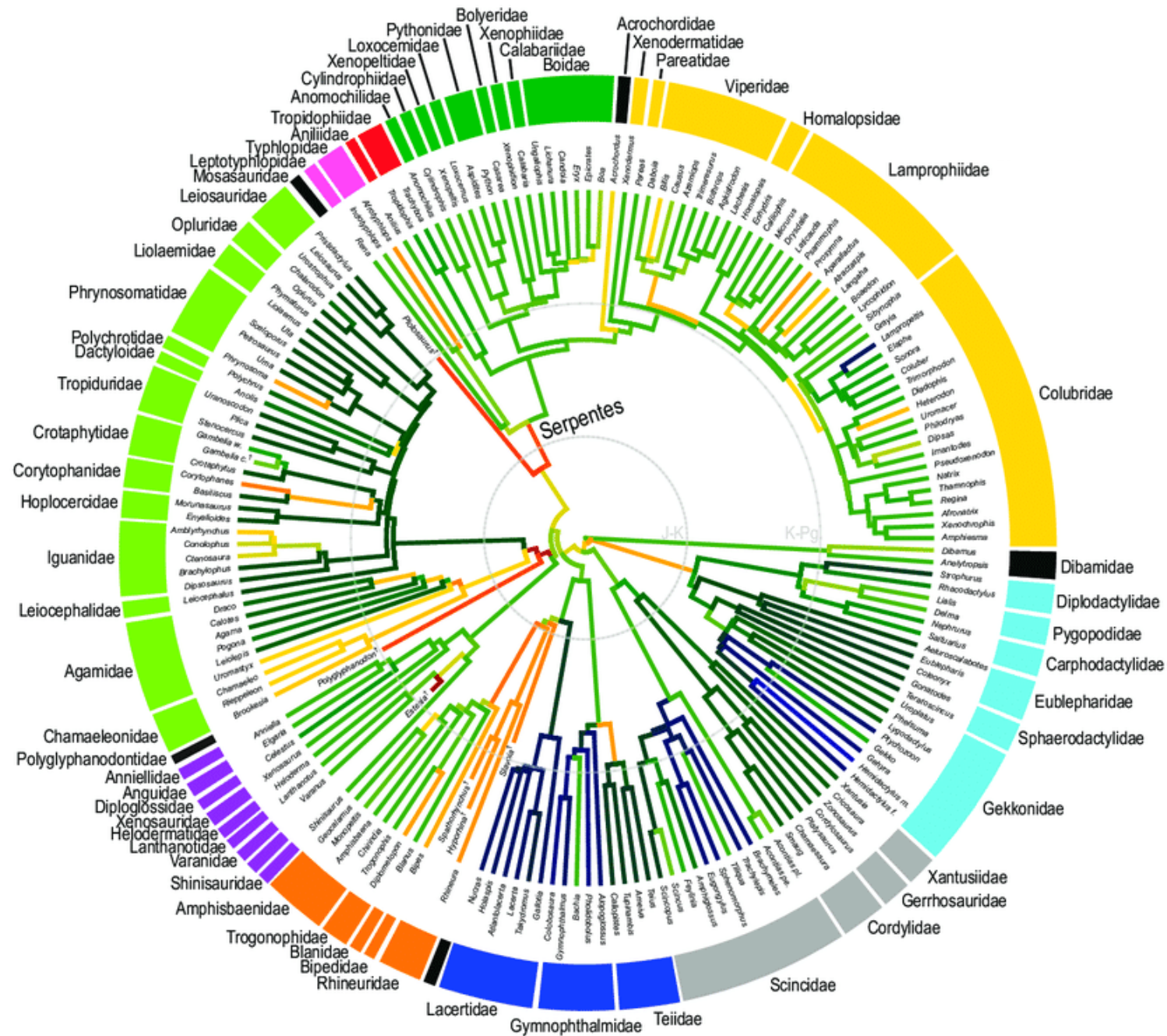




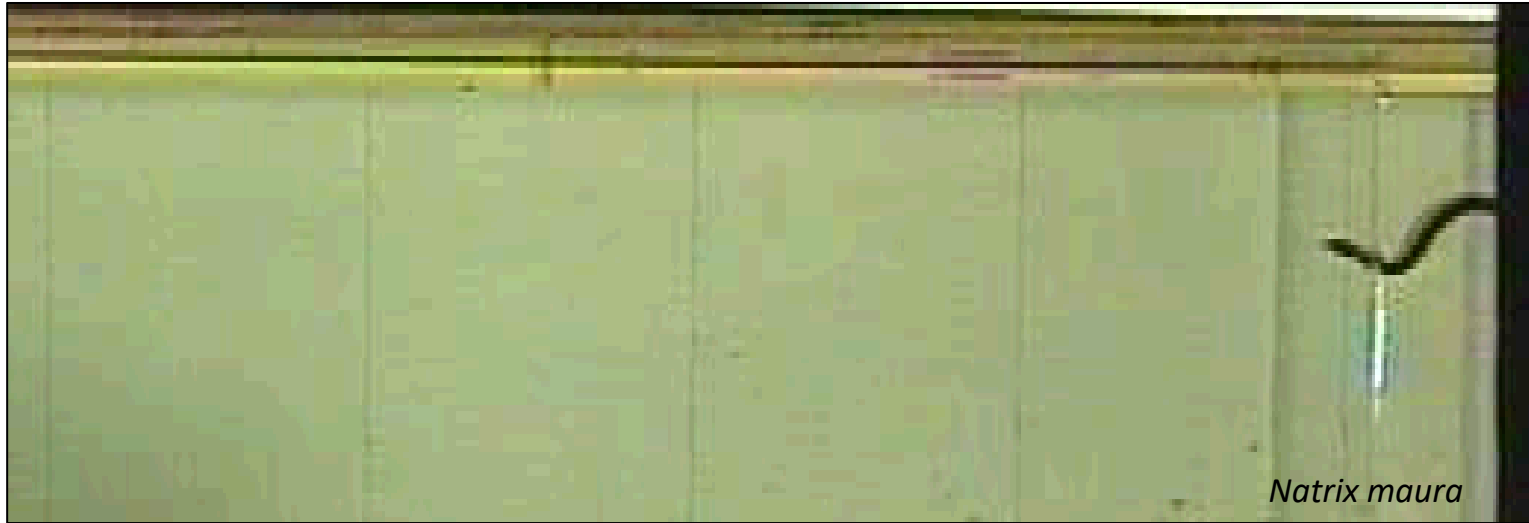
# Muscle morphology in snakes



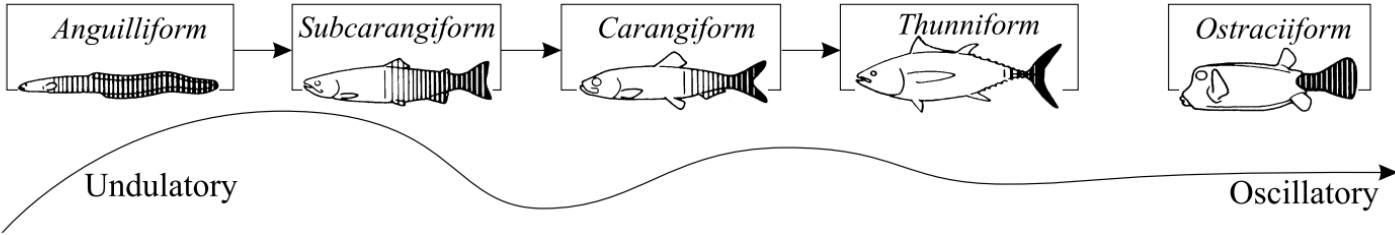
# Why so complex ?



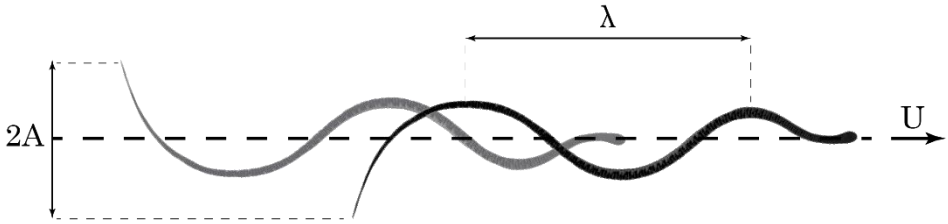
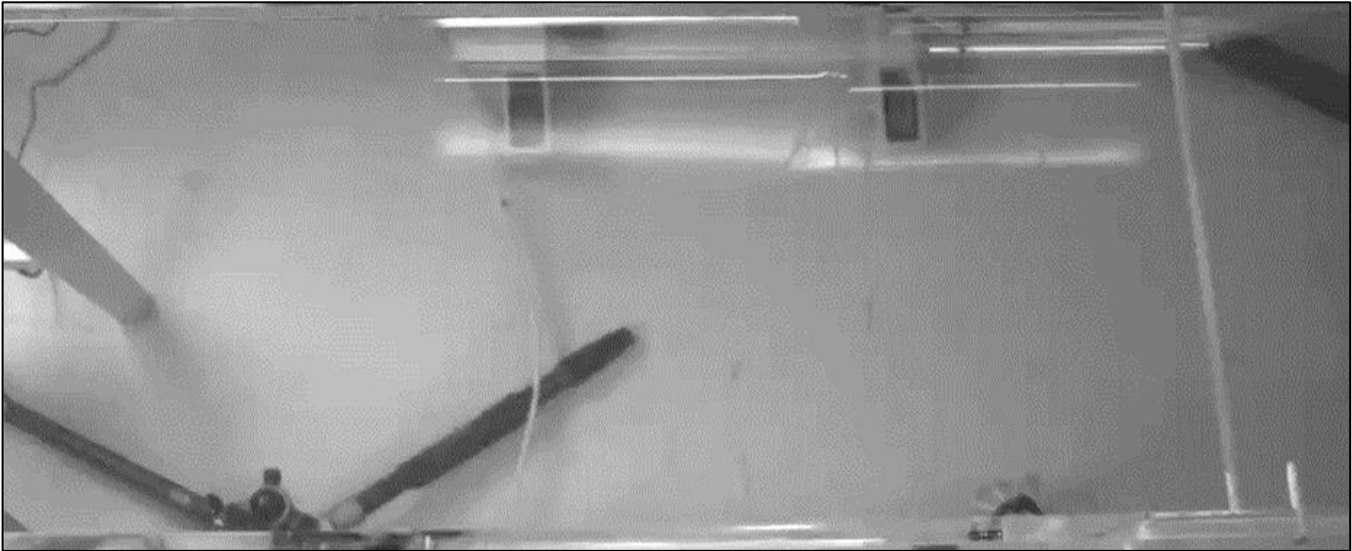
# Swimming: simplest form of locomotion



# Snakes are anguilliform swimmers



Sfakiotakis et al., 1999



**Exponentially increasing amplitude**

$$z(s, t) = Ae^{\alpha(s/L)} \sin\left(2\pi\left(\frac{S}{\lambda} - ft\right)\right)$$

(Tytell et al., 2004)

Theory



*Large Amplitude Elongated Body Theory (Lighthill, 1971)*

2D PIV

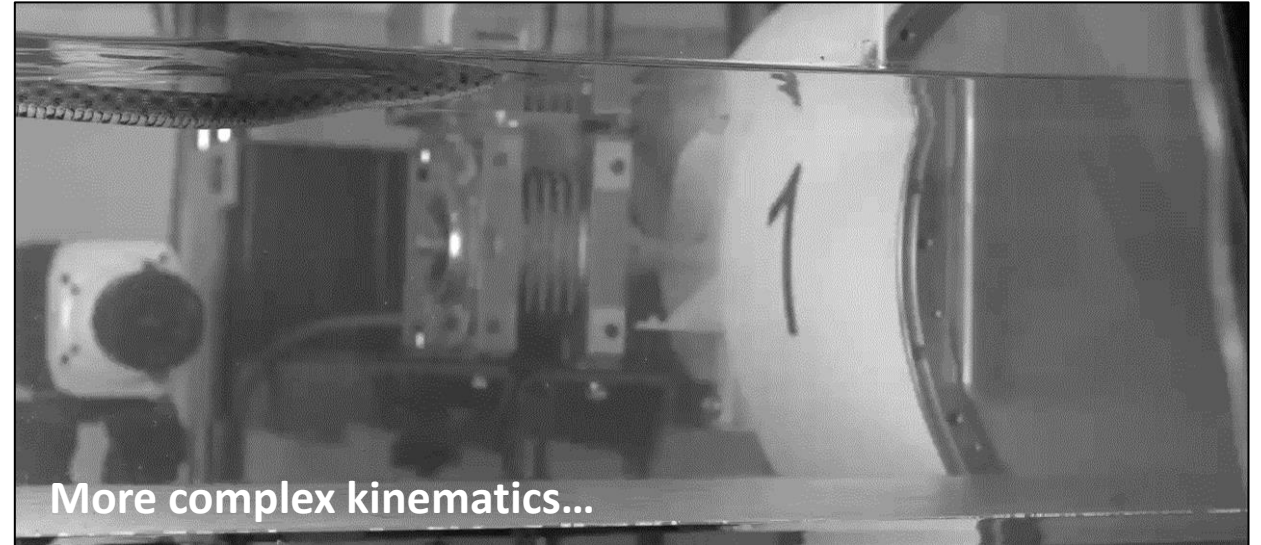


*Swimming lamprey (Du Clos et al., 2019)*

3D CFD



*Swimming eel model (Borazjani & Sotiropoulos, 2009)*



Need for a characterisation of the 3D wake

# Volumetric PIV setup (TSI V3V 9000)

## Laser

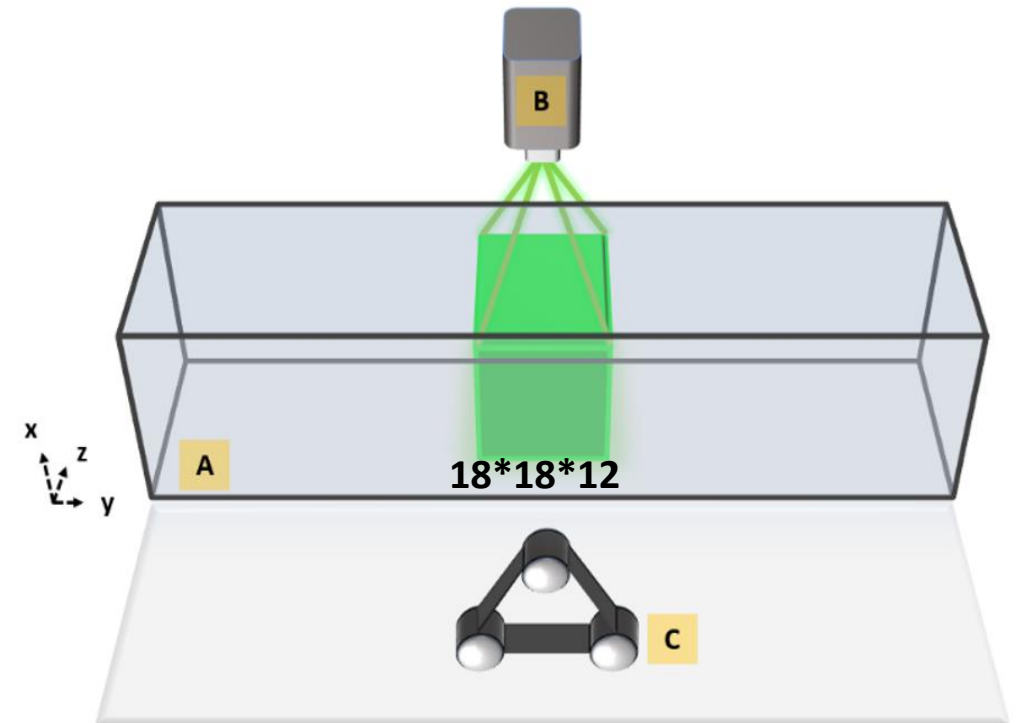
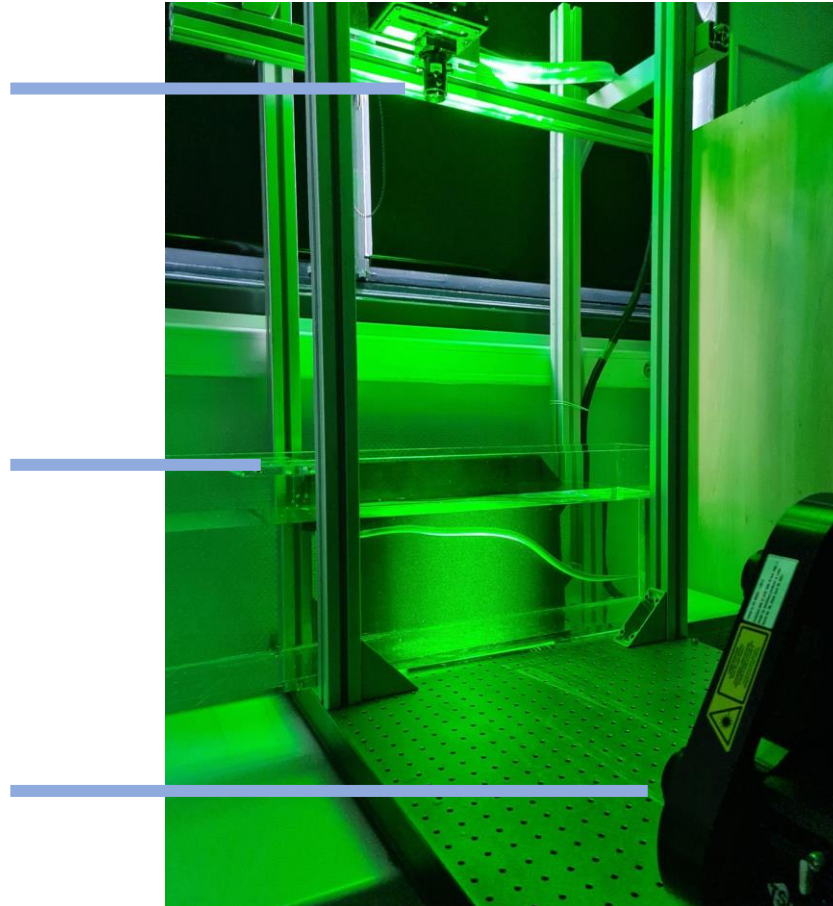
Quantel Evergreen  
200mJ, 15Hz

## Seeded tank

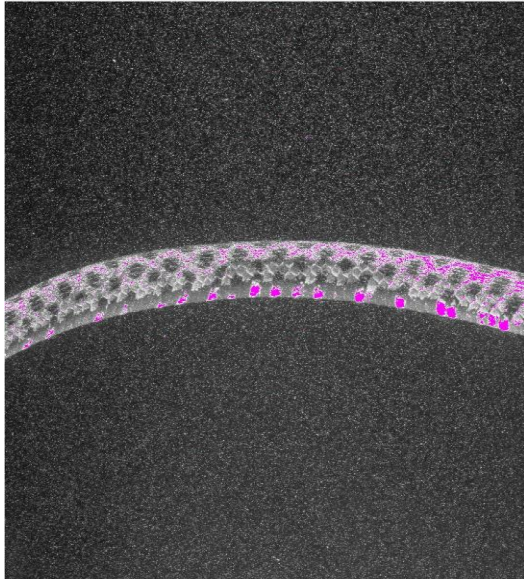
50 $\mu$ m Polyamide  
particles

## Cameras

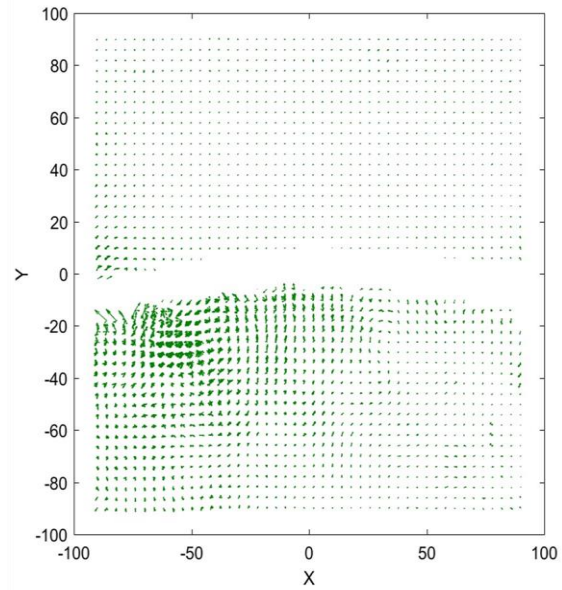
2048 x 2048 pxl,  
50mm, f#16



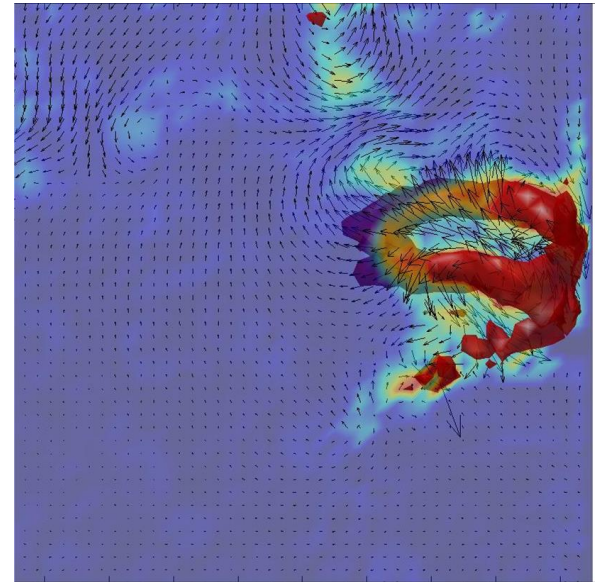
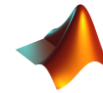
# Image processing pipeline



Raw image

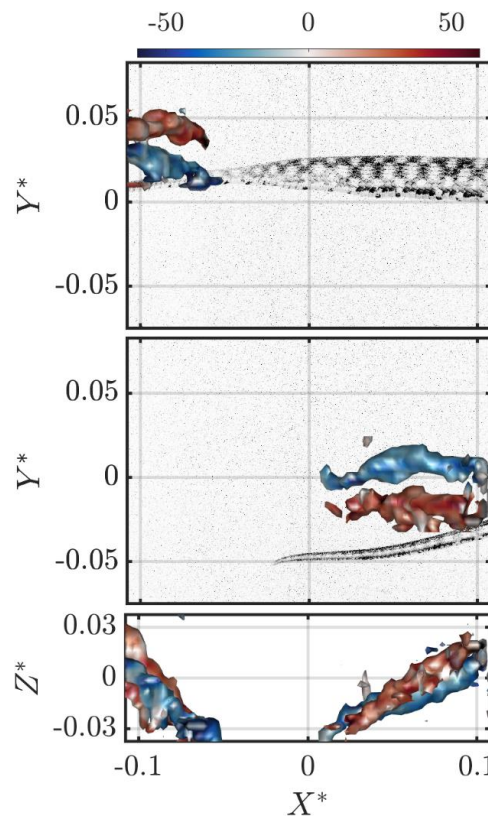
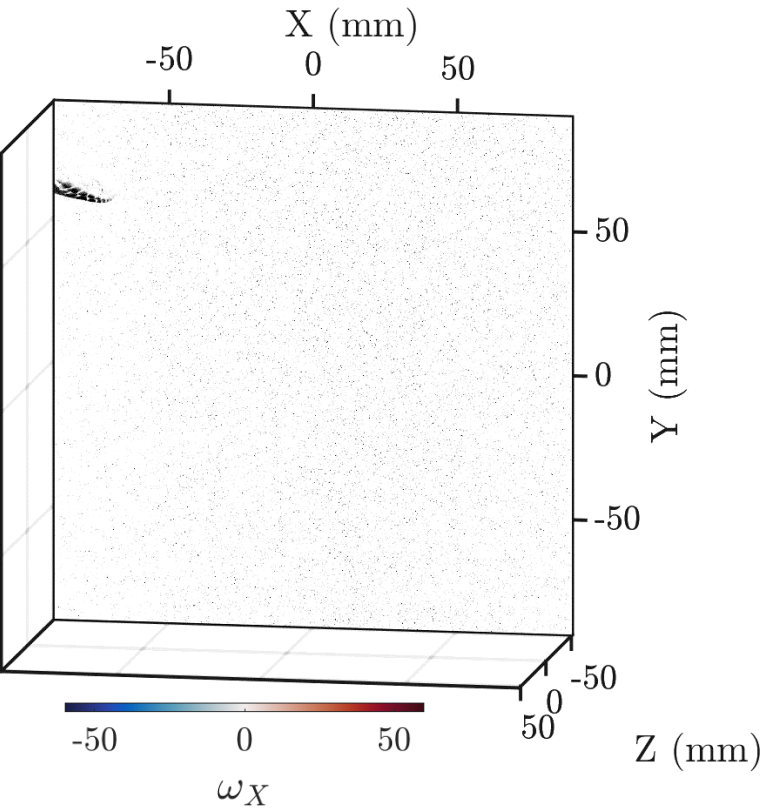


Vector field

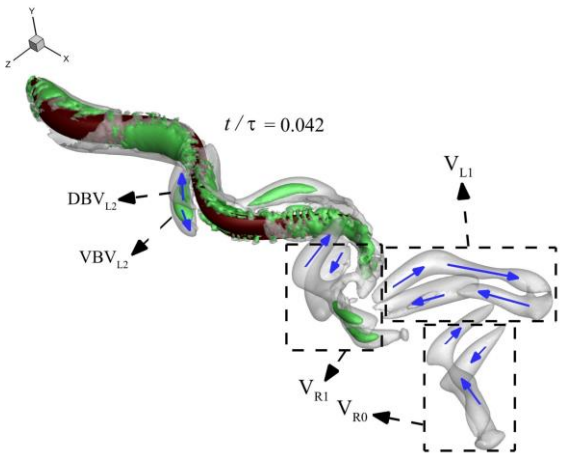


Wake analysis

# Trailing edge vortices highlighted with Q-criterion



$$Q = \|\Omega\|^2 - \|S\|^2$$



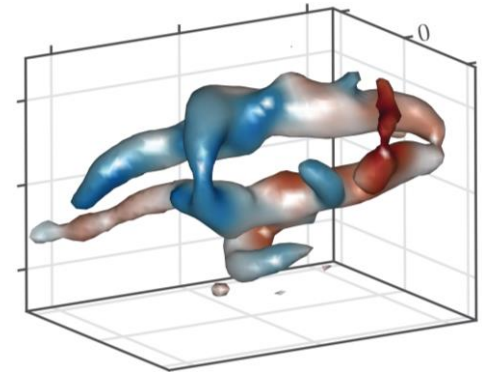
Computed eel vortex street  
(Khalid et al., 2021)

Tailbeats create stretched vortex loops of alternating rotation

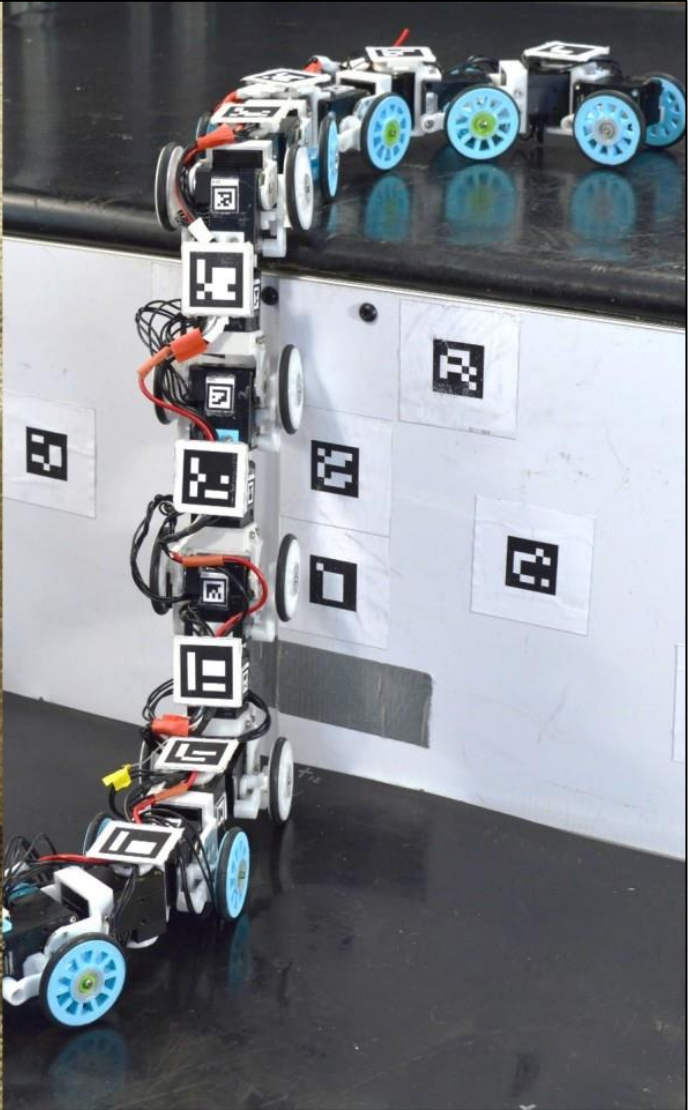
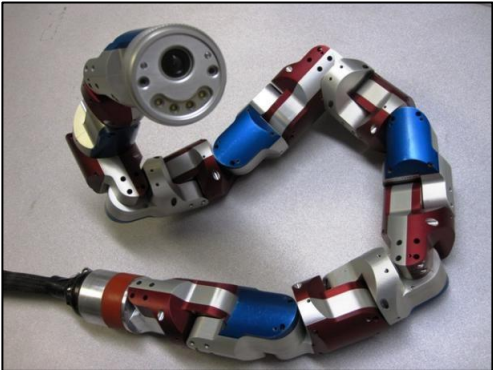
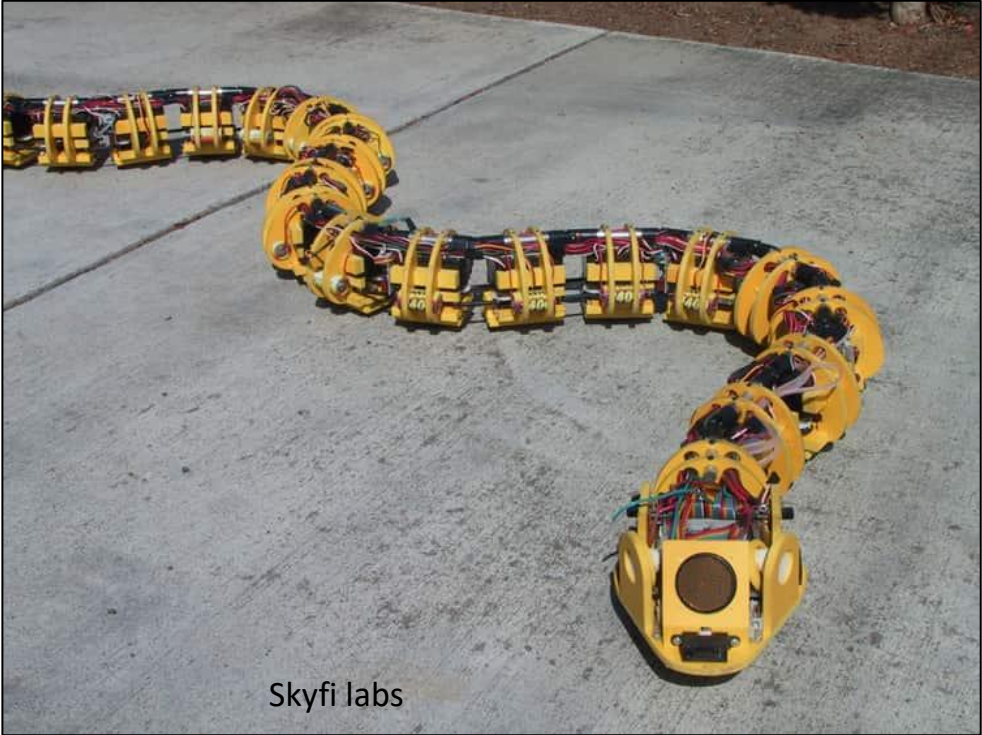


# Hydrodynamics of swimming

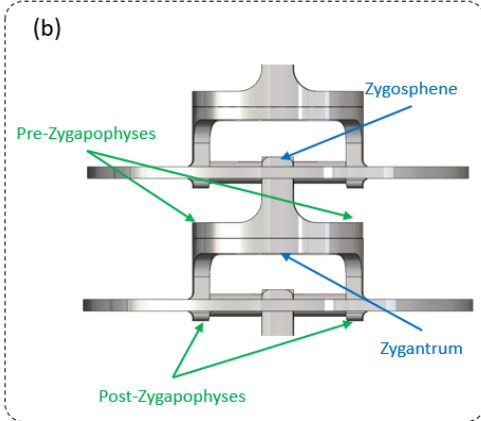
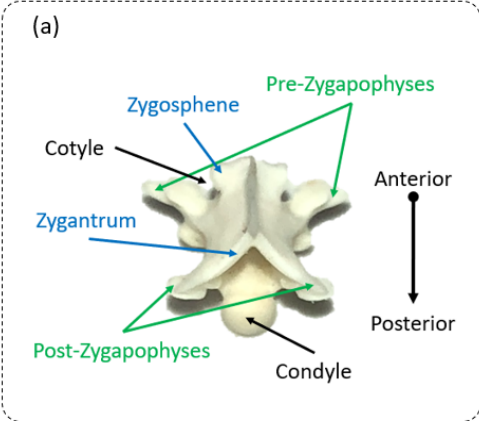
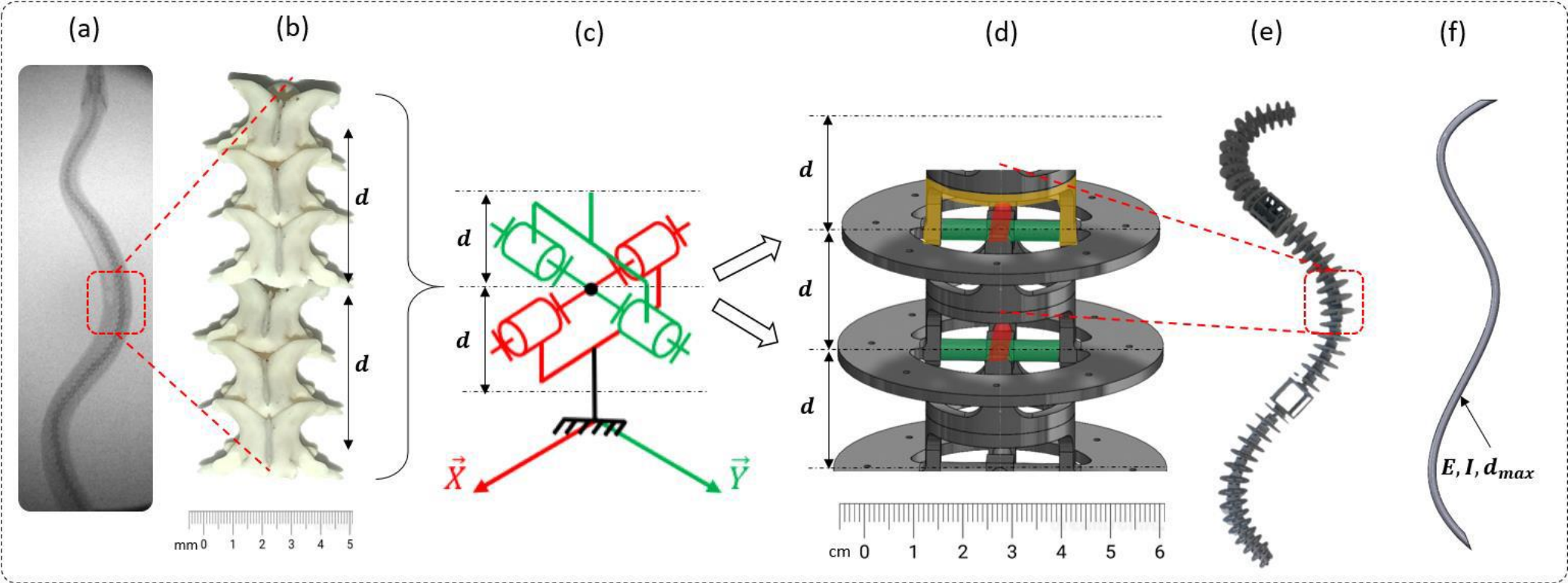
- First experimental 3D characterisation of the wake of an anguilliform swimmer
- Vortices are shed when the body wave reaches a maximum and changes direction
- Vortex tubes are linked and form hairpin-like structures
- dependent on the swimming behaviour



# Snake robots



# Snake robot – Dragon2



# Conclusions

- Living systems have a history and are constrained
- Living systems are constrained by development and materials
- Living systems are governed by trade-offs
- Snakes are perfect systems but snake anatomy is a poor model for robotic inspiration
- Be inspired by, do not copy!

# Acknowledgements

- GDR BIOMIM for inviting me
- ANR Dragon2 team

