

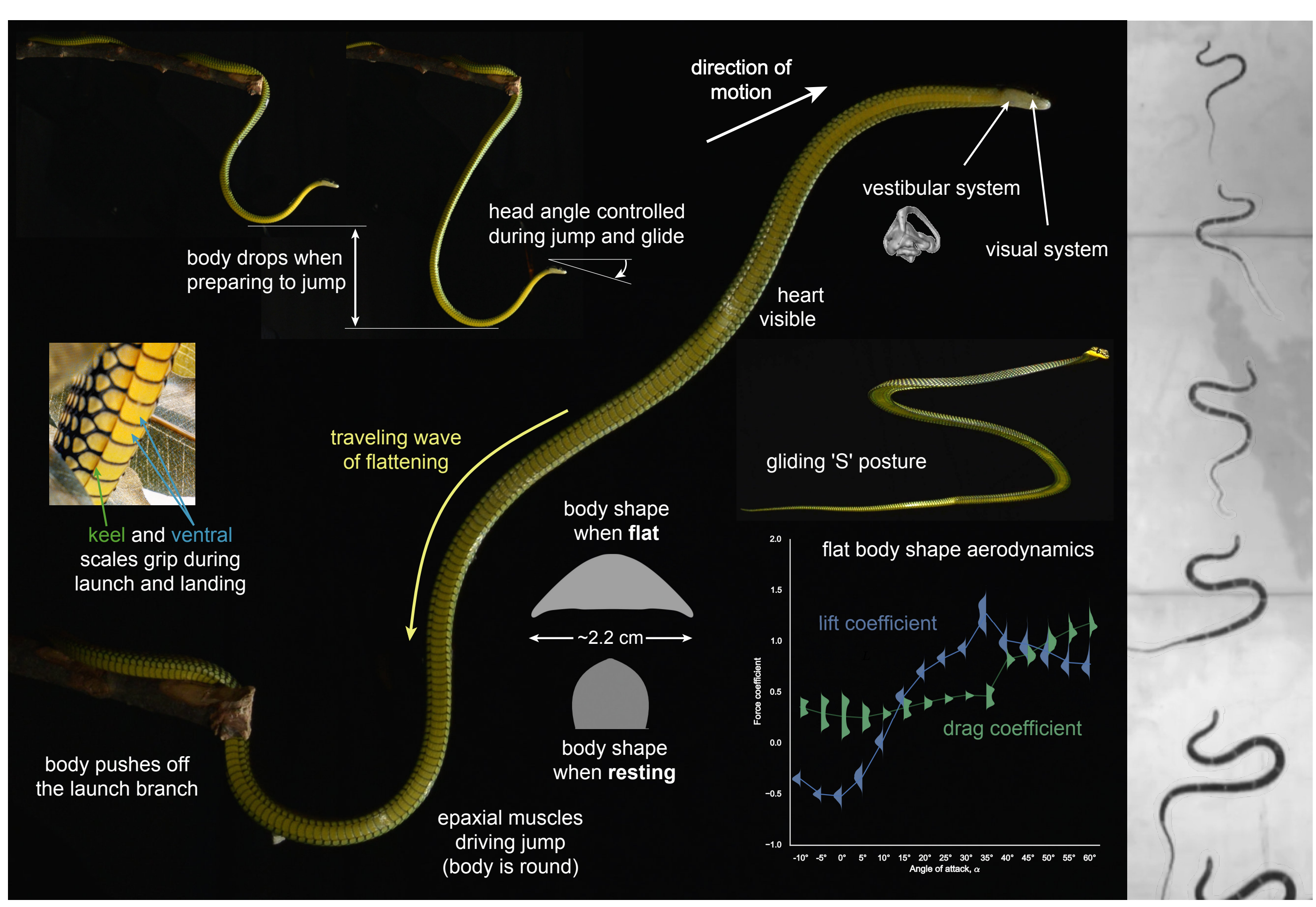
# Stability properties of flying snakes during transient glides

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## "Flying snakes" are unique gliders

Flying snakes (*Chrysopelea*) are the only animals capable of limbless flight. Found in the tropical forests of southeast Asia, flying snakes jump, flatten their bodies, and glide through the forest canopy using a unique body waveform called aerial undulation. Aerial undulation consists of a flattened airfoil-like cross-section, a large amplitude 'S'-shaped body planform, and a low undulation frequency of 1–2 Hz.

Other gliding animals, such as flying squirrels, squid, fish, lizards, and frogs, use a static body posture. Flying snakes are the only animals to use large-amplitude reciprocating motion when gliding.



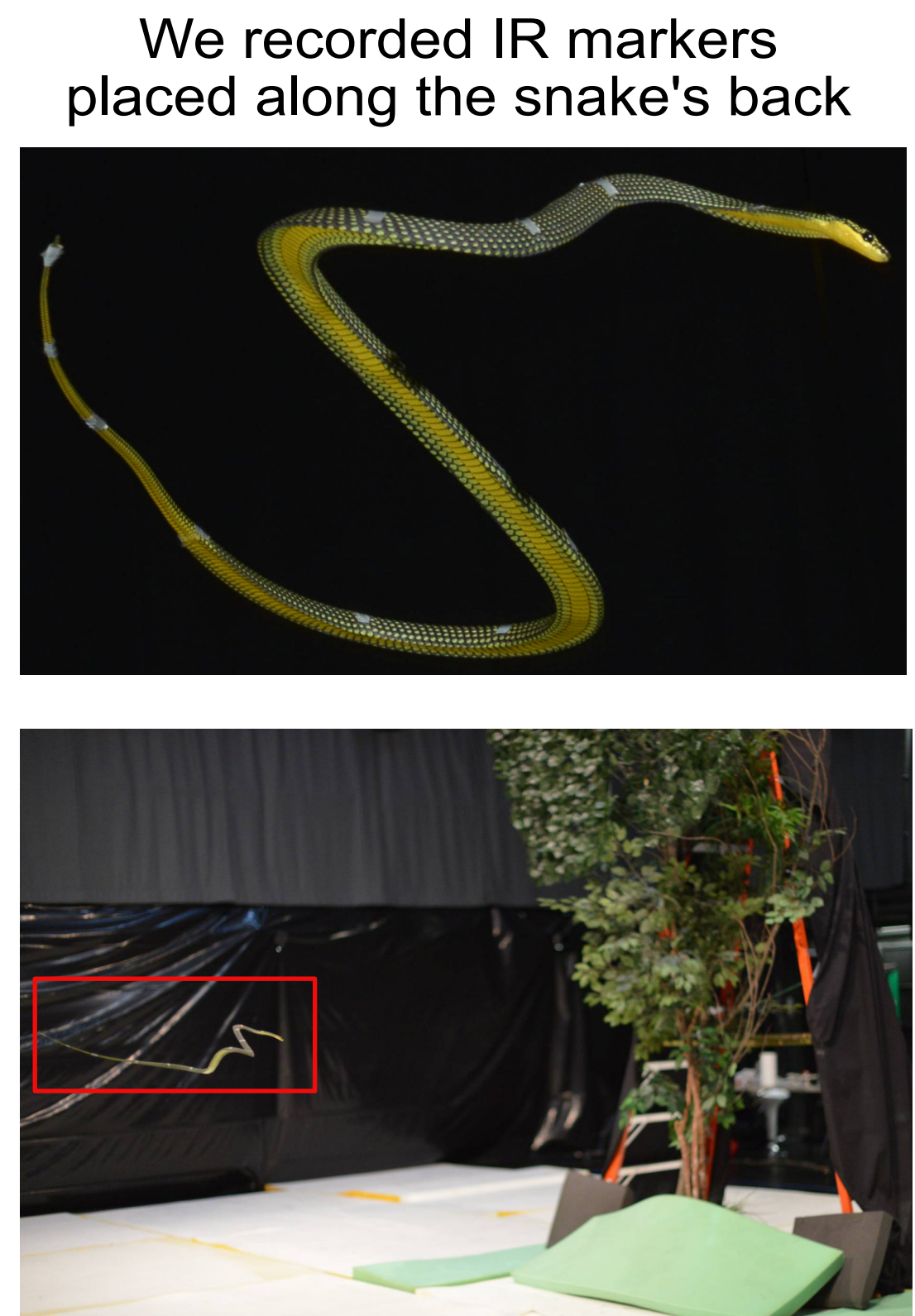
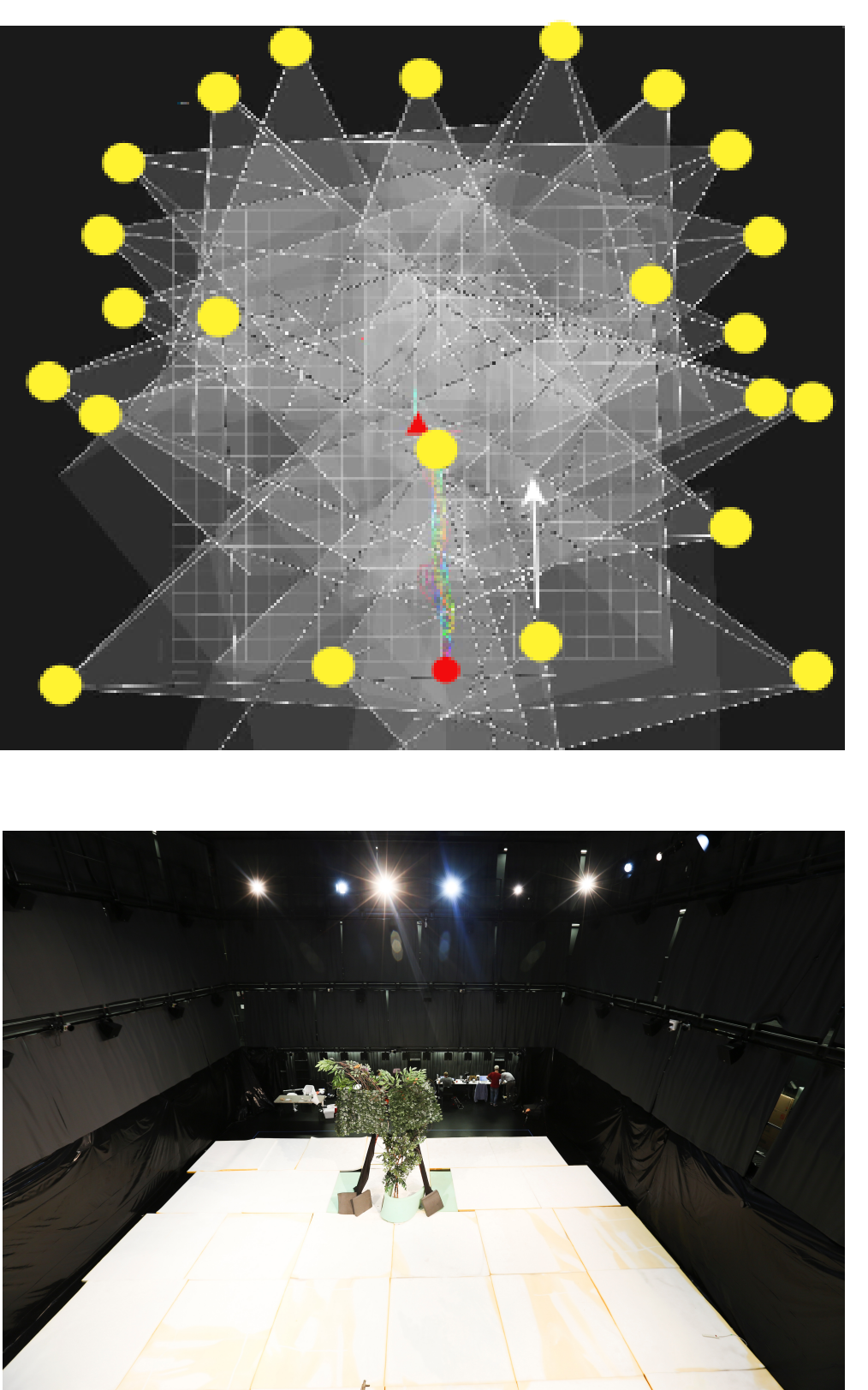
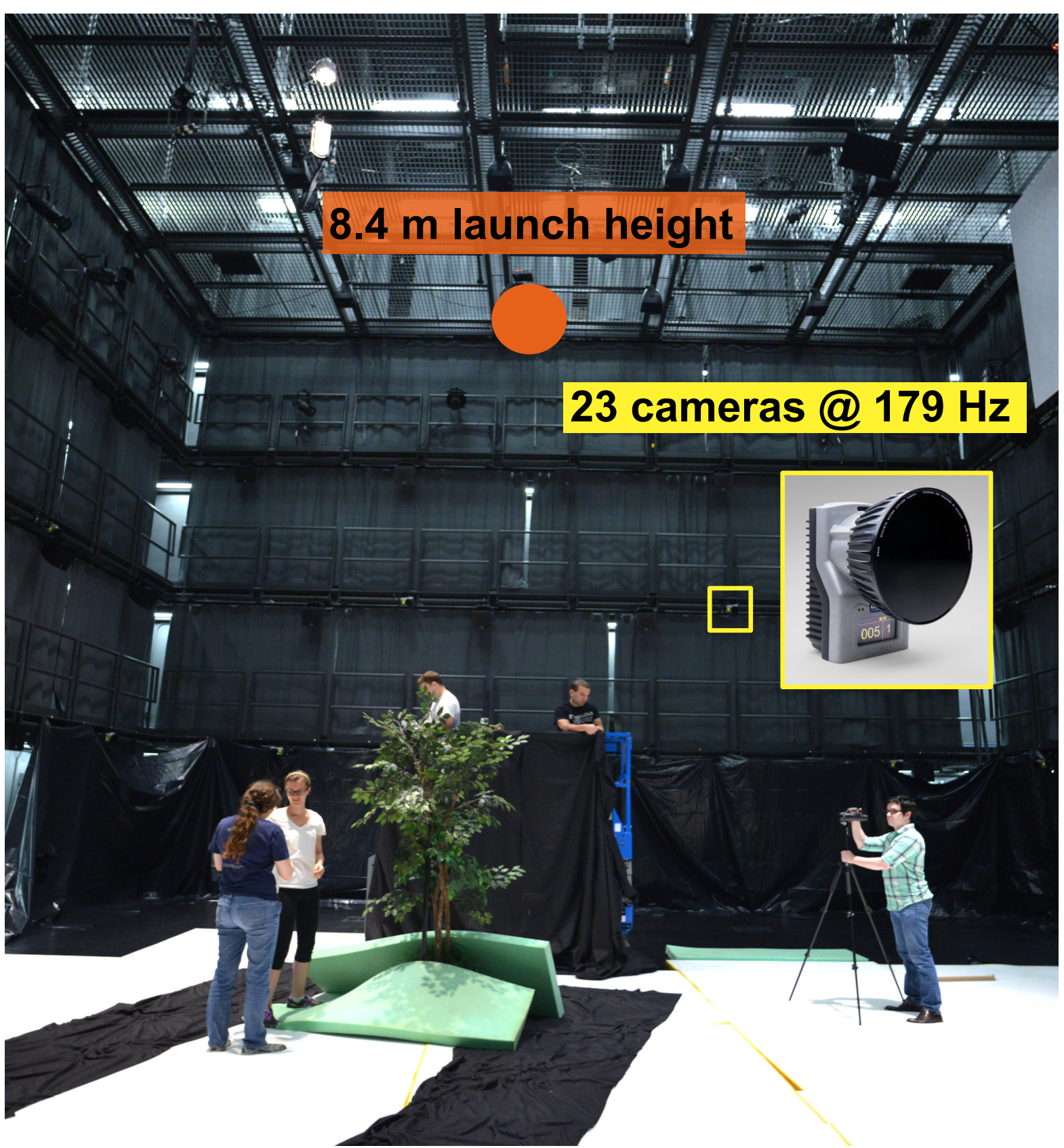
## What is the mechanical role of undulation on gliding?

Our objective is to understand how aerial undulation enables a stable and controlled descent. This includes how aerodynamic force production, inertial mechanics, and the visual and sensory systems couple to enable gliding. Because undulation is not a general requirement for force production in gliding, we hypothesize undulation is used to enhance midair rotational stability, a prerequisite for stable flight.

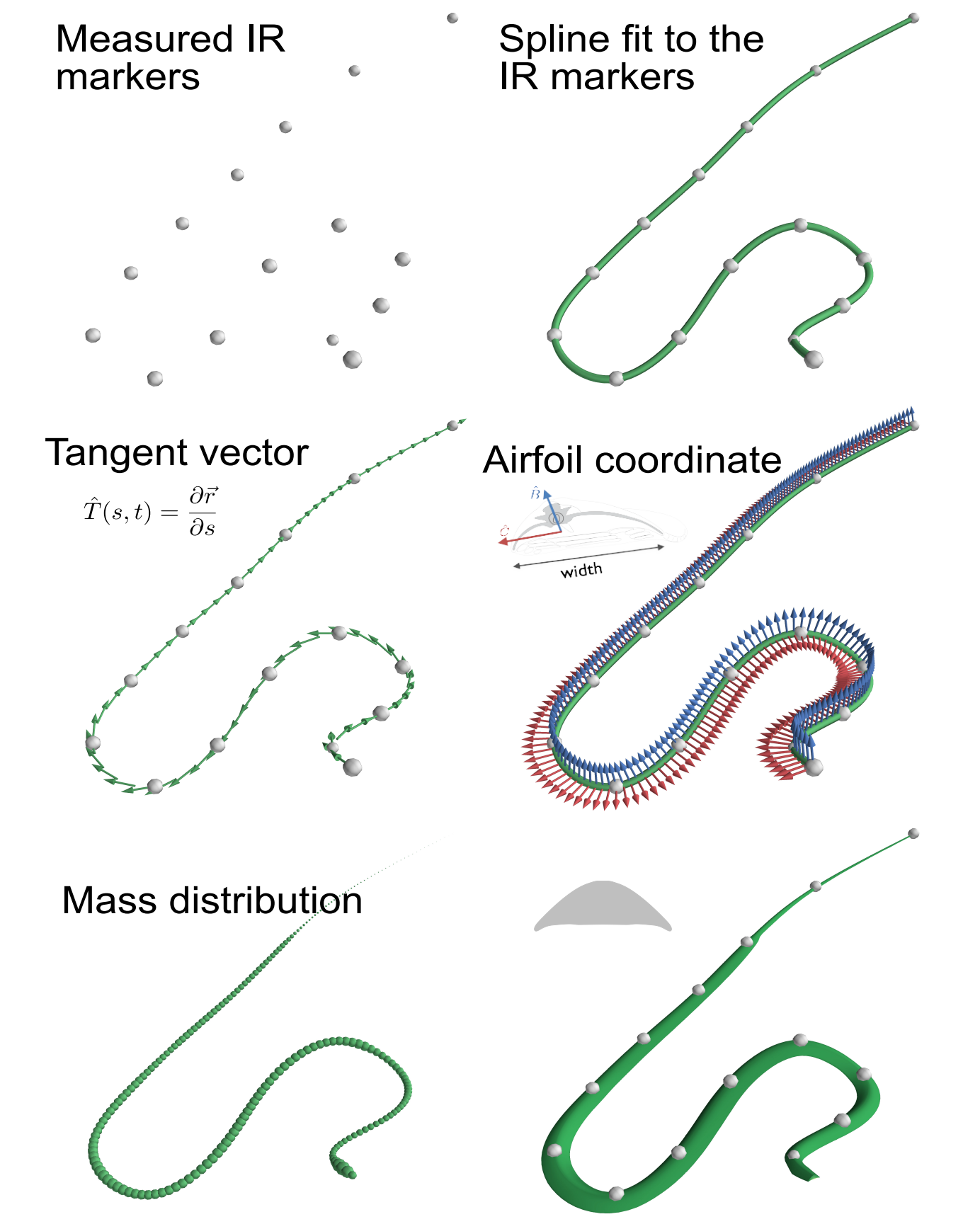
- To test the effects of undulation on snake gliding, we
- 1) Measure the body posture of six snakes, using a high-speed motion capture system, as they glide in a large indoor arena, and then
  - 2) Model their passive dynamical behavior with and without undulation.

## High-speed motion capture enables us to fully quantify aerial undulation

### Indoor glide arena equip with motion capture system



### Reconstructing the snake's body

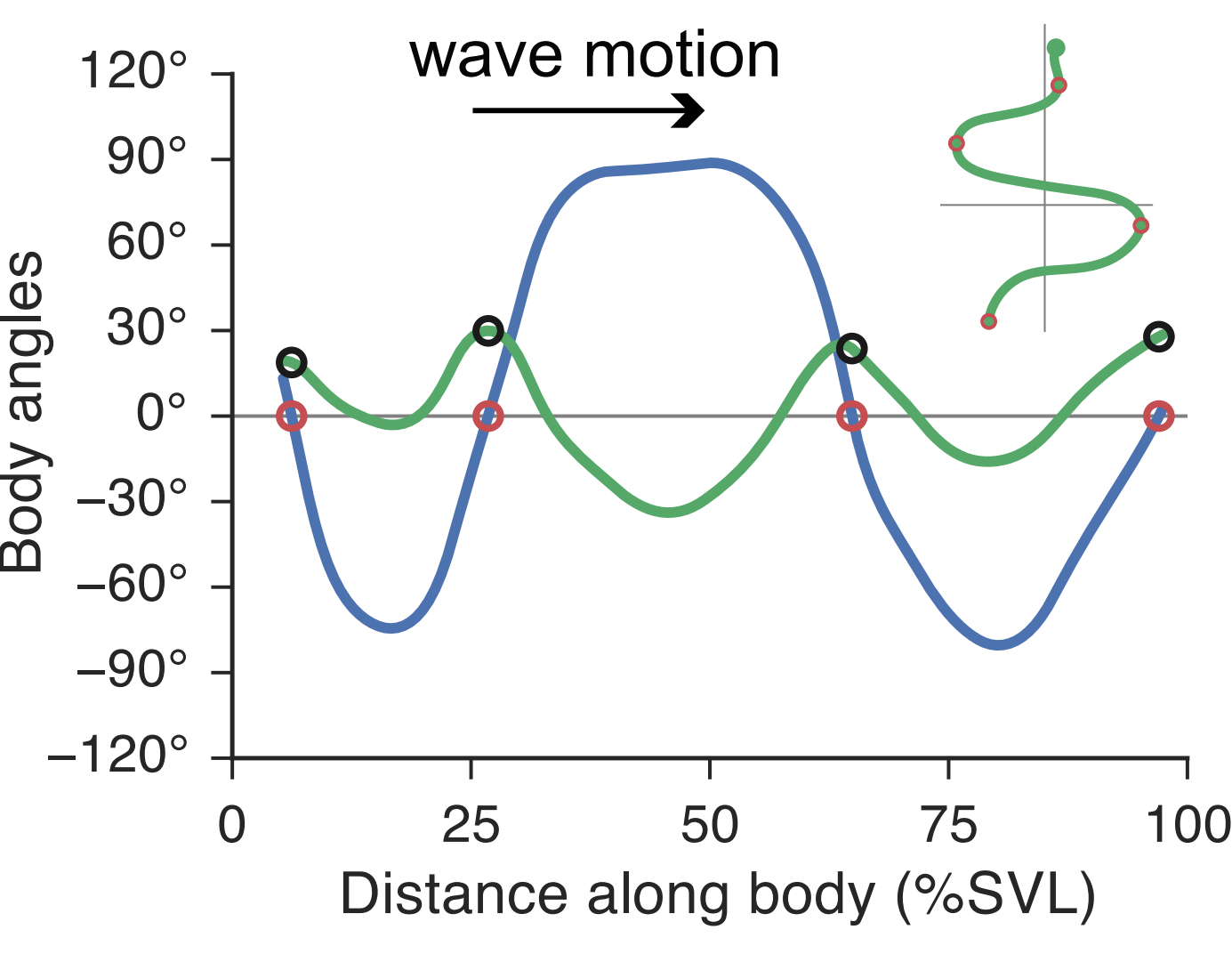


### Characterizing aerial undulation

Using the unit tangent vector of the spline fit, we decompose the 3D body posture into two traveling waves of horizontal and vertical bending

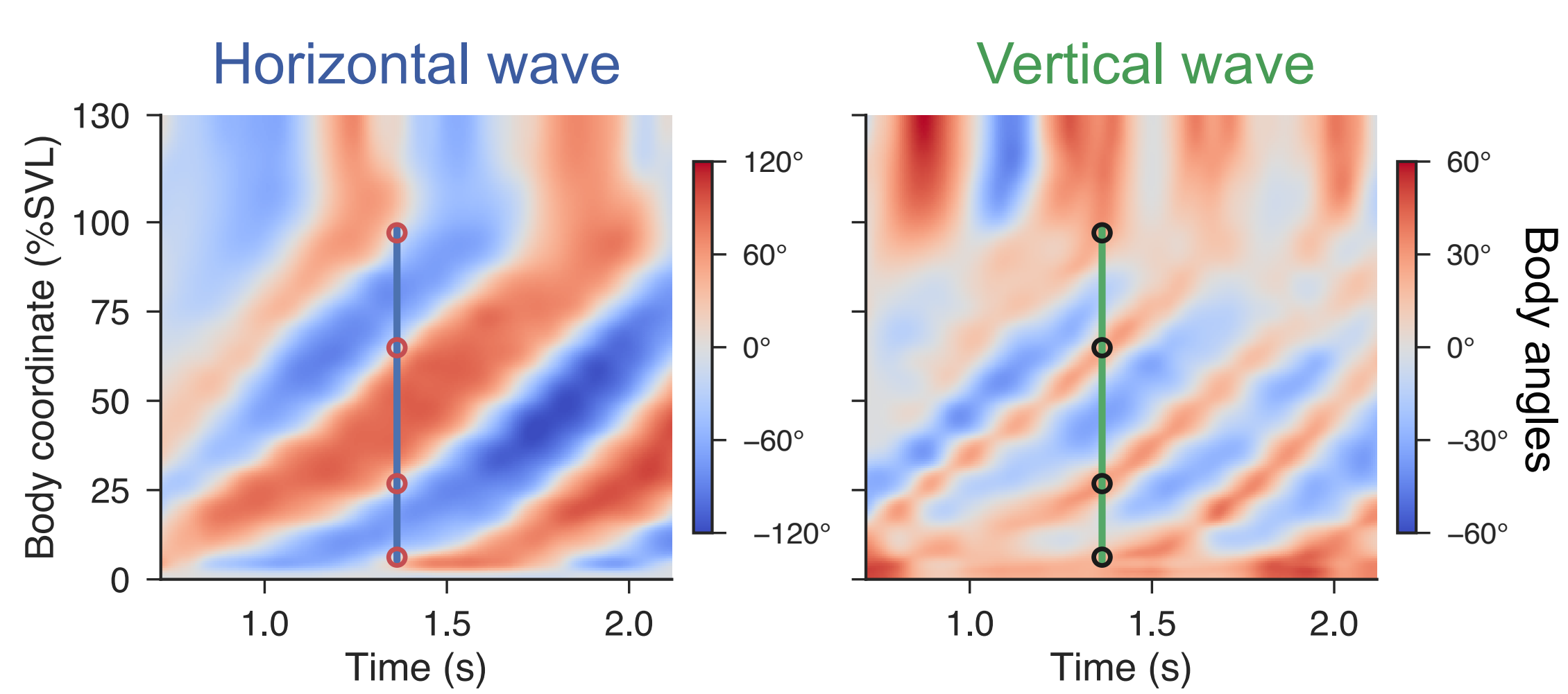
$$\text{Horizontal wave} = \tan^{-1} \left( \frac{\hat{T}_x}{\hat{T}_y} \right)$$

$$\text{Vertical wave} = \sin^{-1} \hat{T}_z$$



### Overview of aerial undulation

- 1) The vertical wave has twice the spatial and temporal frequency as the horizontal wave.
- 2) Zero crossings of the horizontal wave occur at the 'U' bends.
- 3) The vertical wave is phase shifted by 90°
- 4) Maximum bending occurs at the 'U' bends



## Undulation enhances stability, enabling gliding in flying snakes

### Kinematic model based on measured aerial undulation waveforms

We propose the following analytical expressions for aerial undulation:

Horizontal wave  

$$\theta(s,t) = \theta_0(s) \sin \left[ \frac{\pi}{2} \cos \left( \frac{2\pi\nu_\theta}{L} s - 2\pi f_\theta t + \phi_\theta \right) \right]$$

Vertical wave  

$$\psi(s,t) = \psi_0(s) \cos \left( \frac{2\pi\nu_\psi}{L} s - 2\pi f_\psi t + \phi_\psi \right)$$

### Reconstructing the snake body:

$$x(s,t) = \int_0^s \cos \psi \sin \theta ds'$$

$$y(s,t) = \int_0^s -\cos \psi \cos \theta ds'$$

$$z(s,t) = \int_0^s \sin \psi ds'$$

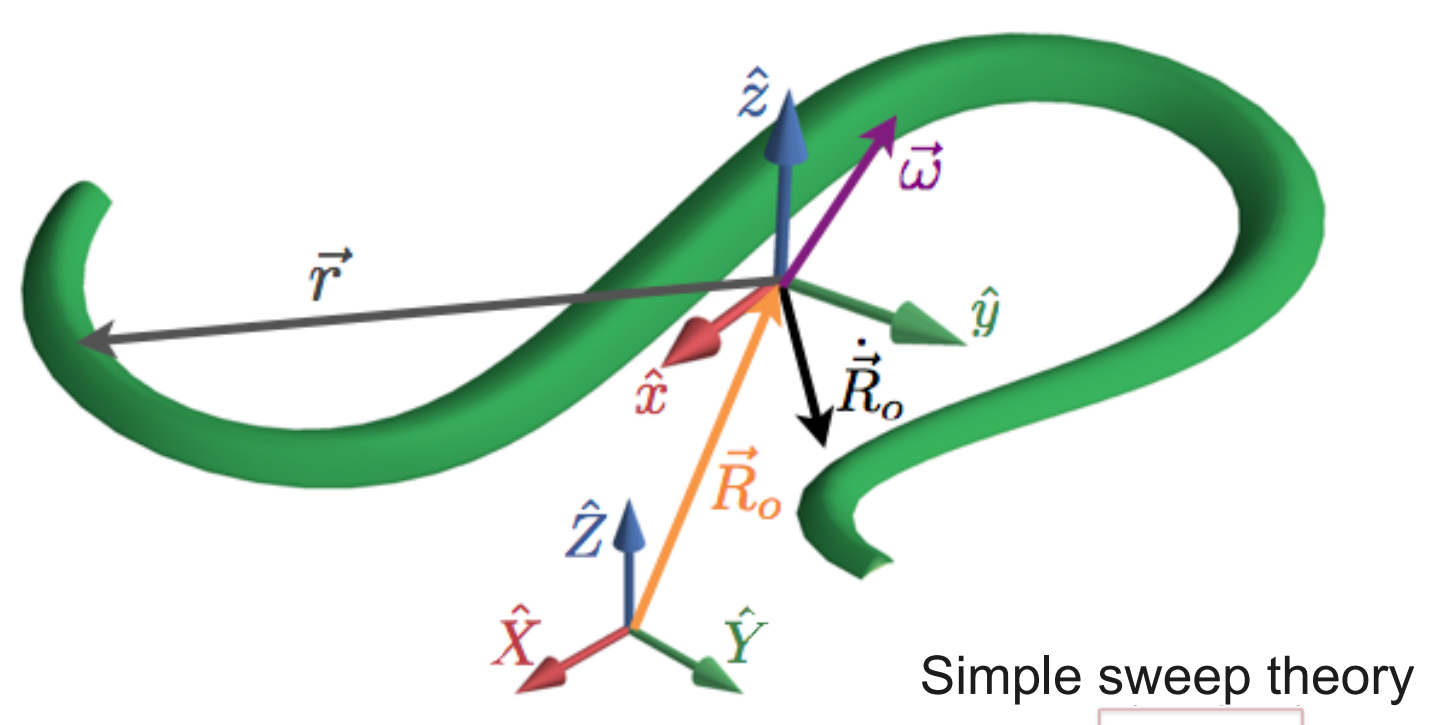
$$\vec{r} = [x(s,t), y(s,t), z(s,t)]$$

### Variable-geometry rigid-body model of snake flight

$$\int_0^L (d\vec{F}_L + d\vec{F}_D) ds - m\vec{g} = m\ddot{\vec{r}}_o$$

$$\int_0^L \vec{r} \times (d\vec{F}_L + d\vec{F}_D) ds = \mathbf{I}_o \cdot \dot{\vec{\omega}} + \vec{\omega} \times (\mathbf{I}_o \cdot \vec{\omega}) + [\mathbf{I}_o] \cdot \dot{\vec{\omega}} + \vec{\omega} \times \vec{h}_o + [\dot{h}_o]$$

aerodynamic moments      rigid body terms      inertial moments

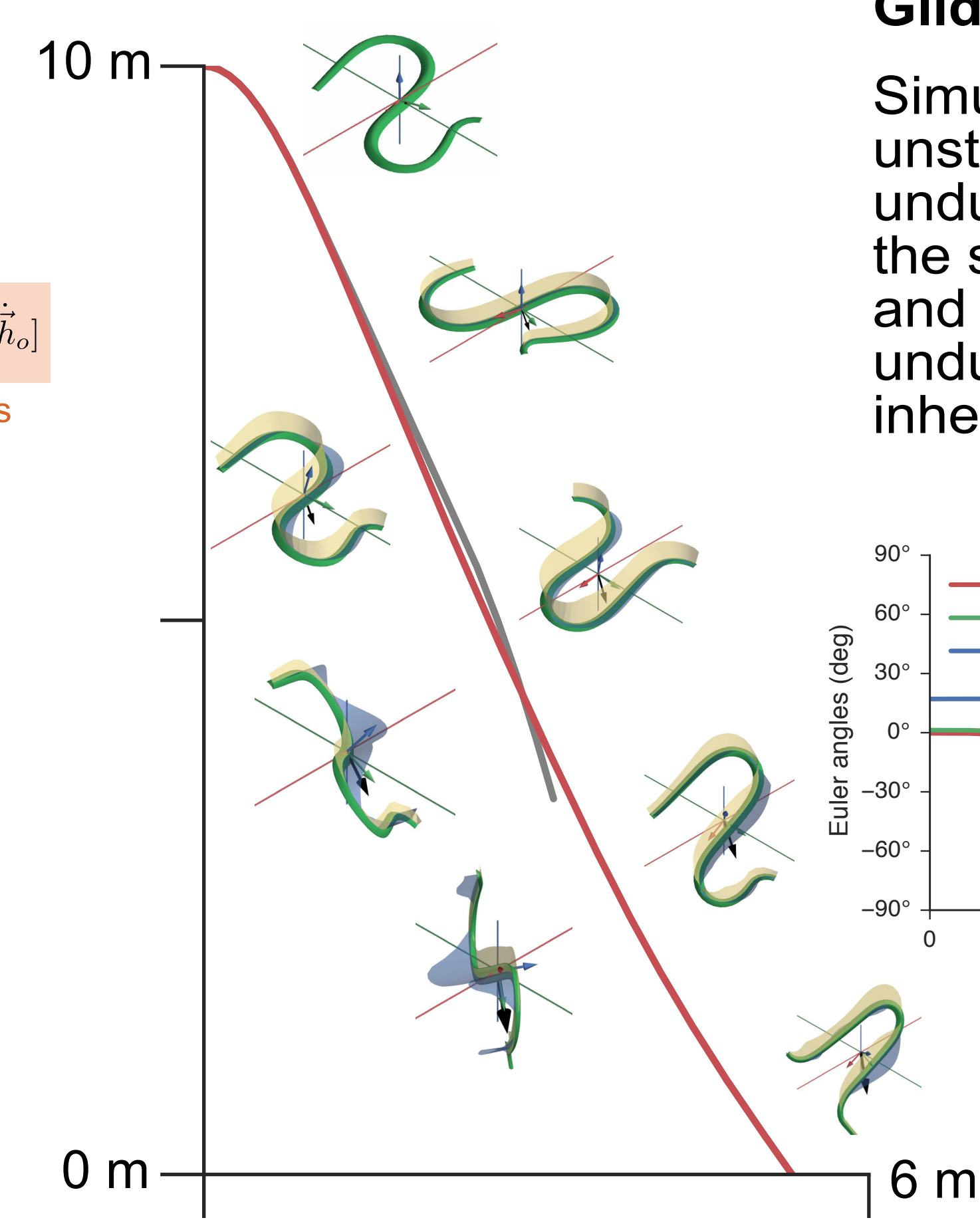


Aerodynamic forces

$$\vec{F}_L = \frac{\rho U_\infty^2}{2} \cdot dS \cdot C_L(\alpha, Re) \cdot \hat{L}$$

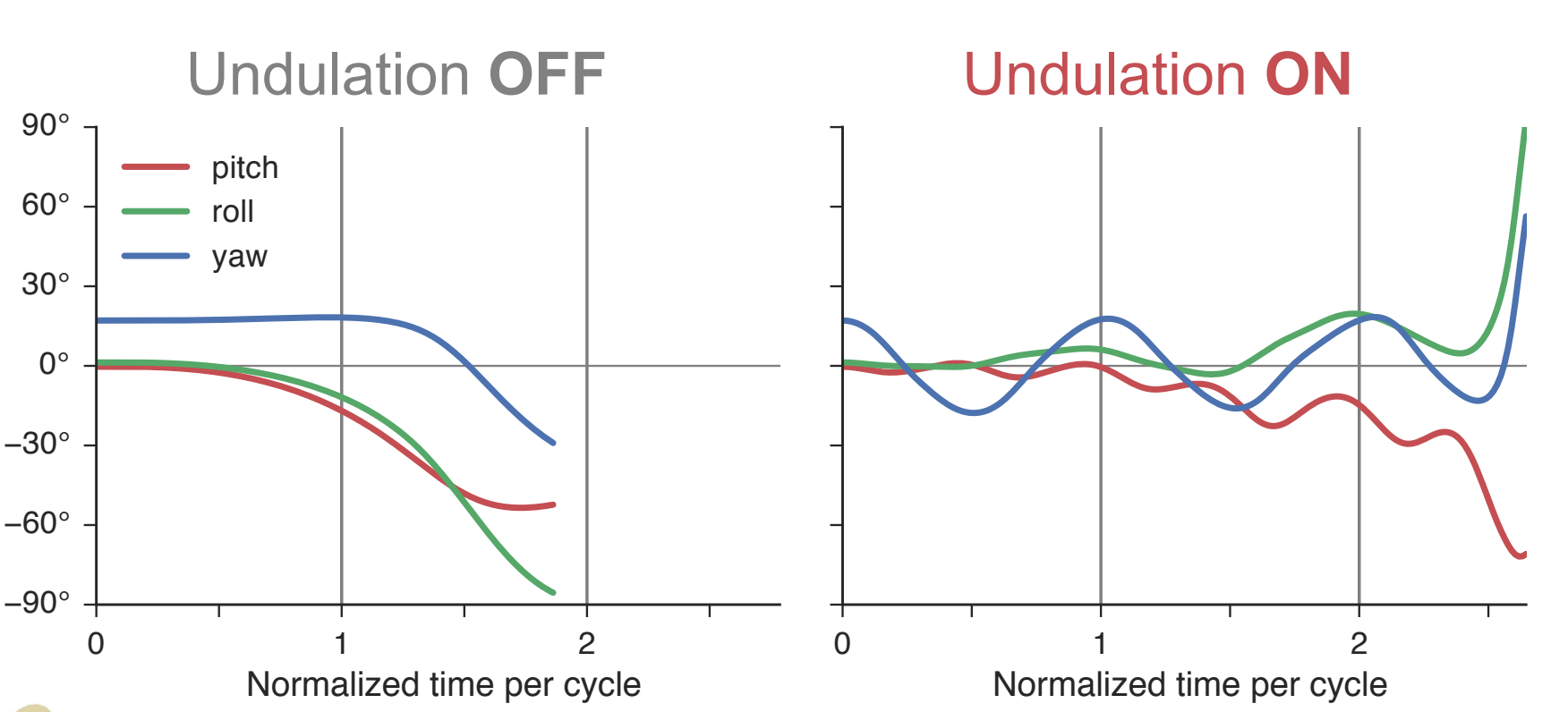
$$\vec{F}_D = \frac{\rho U_\infty^2}{2} \cdot dS \cdot C_D(\alpha, Re) \cdot \hat{D}$$

Simple sweep theory



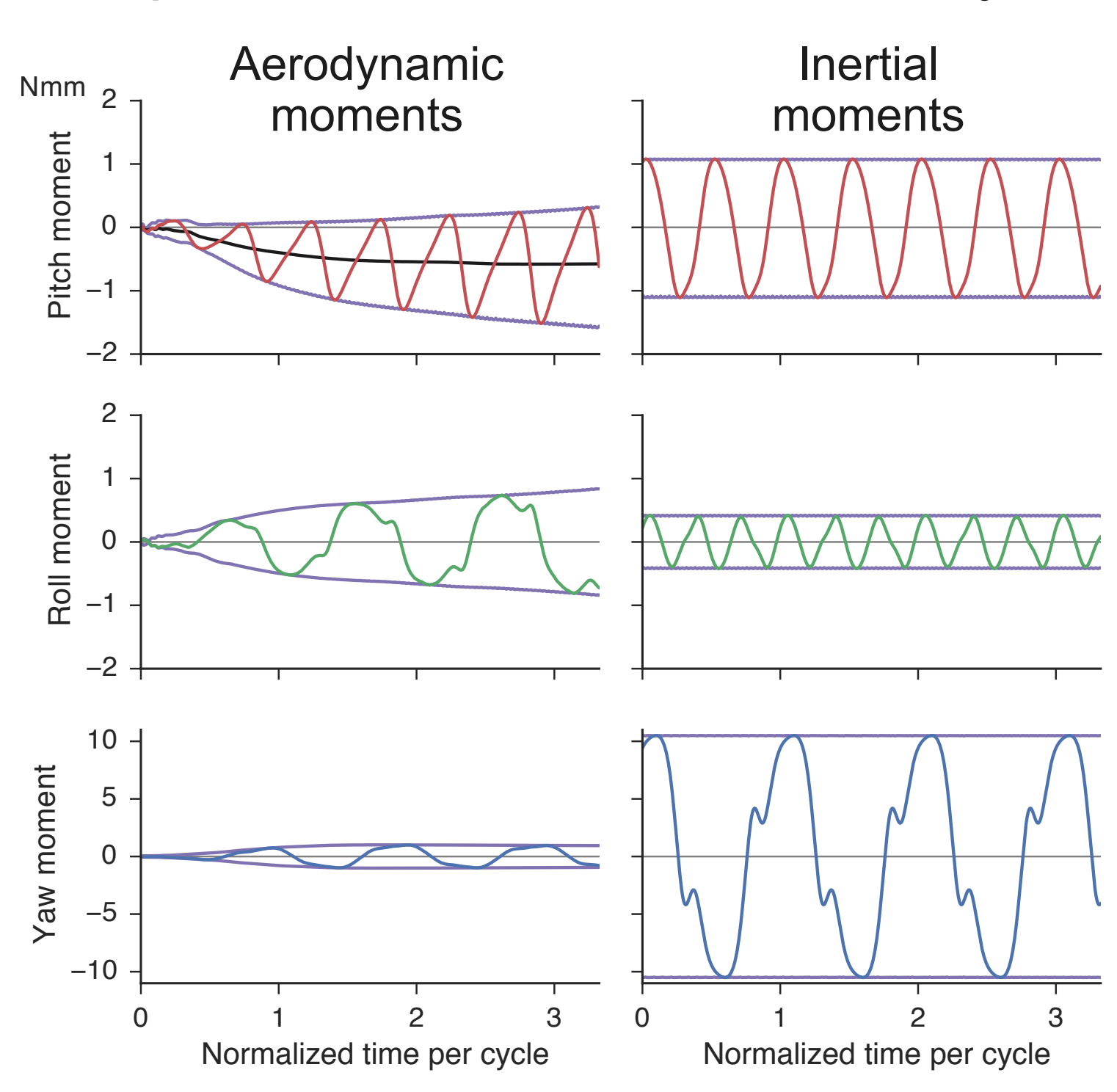
### Gliding with and without undulation

Simulated glides without undulation become unstable more quickly than glides with undulation. Undulation induces stability in the system, making the Euler angles periodic and increasing the flight distance. However, undulation is insufficient to prevent an inherent pitch instability.



### Inertial vs. Aerodynamic moments

Initially, inertial moments about pitch and roll axes dominate, then become comparable after one undulation cycle



### Overview of modeling

Unlike other undulatory animals, flying snakes use undulation for stability, not propulsion. Our model shows that

- 1) Undulation stabilizes about the yaw and roll axes
- 2) Flying snakes are likely unstable in pitch
- 3) Inertial moments dominate about the yaw axis

### References

Yeaton, I.J., Socha, J.J. and Ross, S.D., 2017. Global dynamics of non-equilibrium gliding in animals. *Bioinspiration & Biomimetics*, 12(2), p.026013.