Magnetic Navigation of Artificial Bacteria Flagella in Blood and Water

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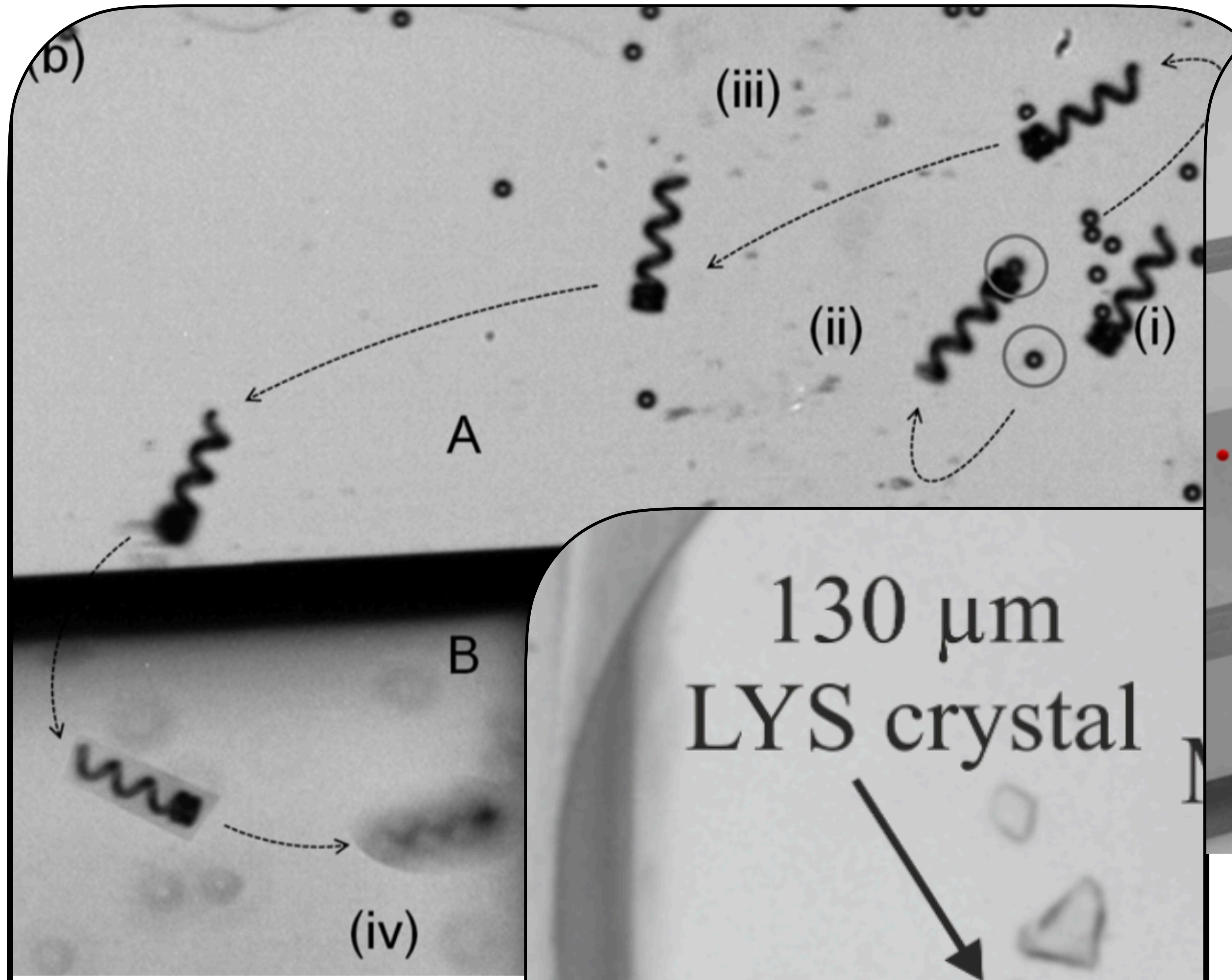
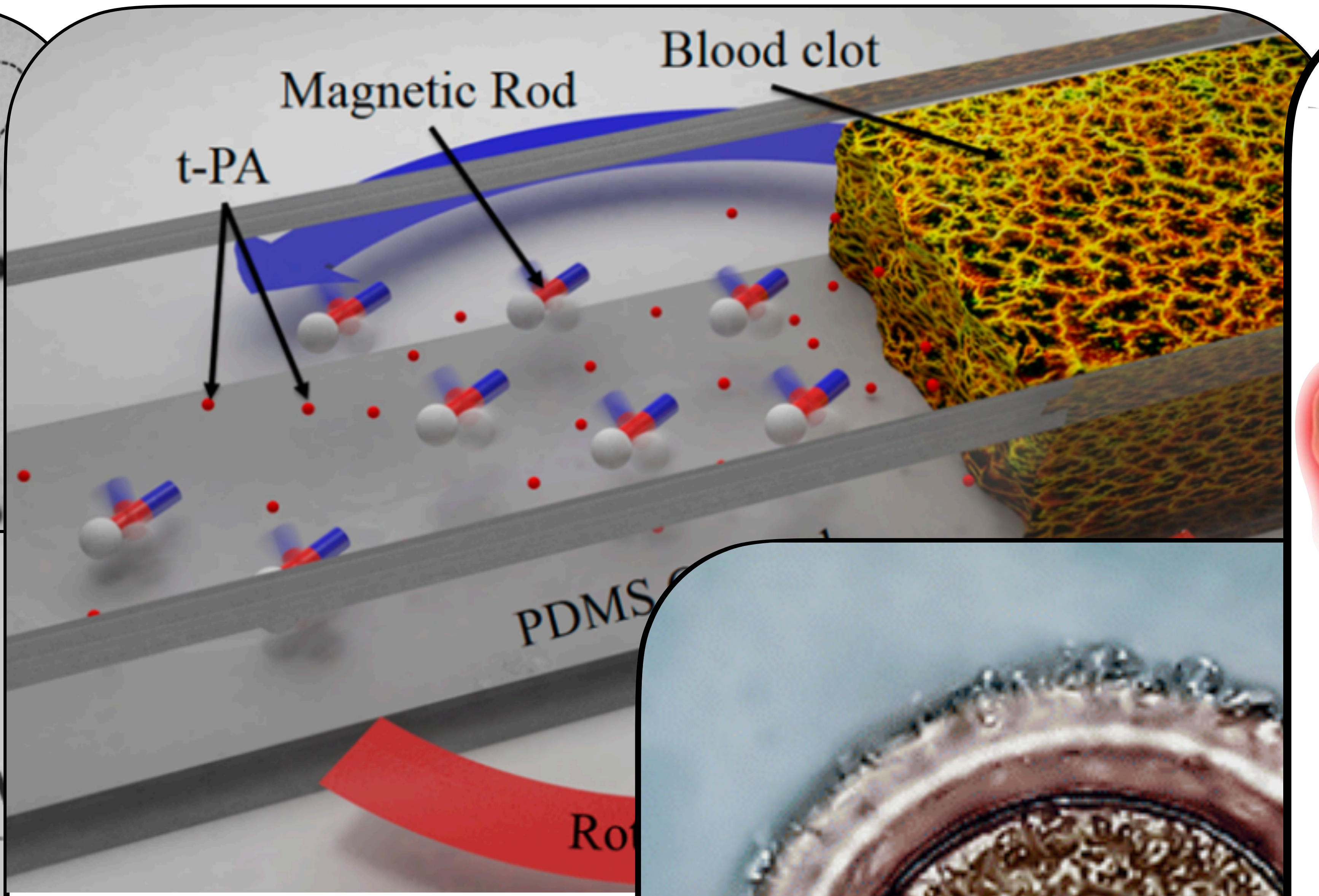
Artificial Microswimmers



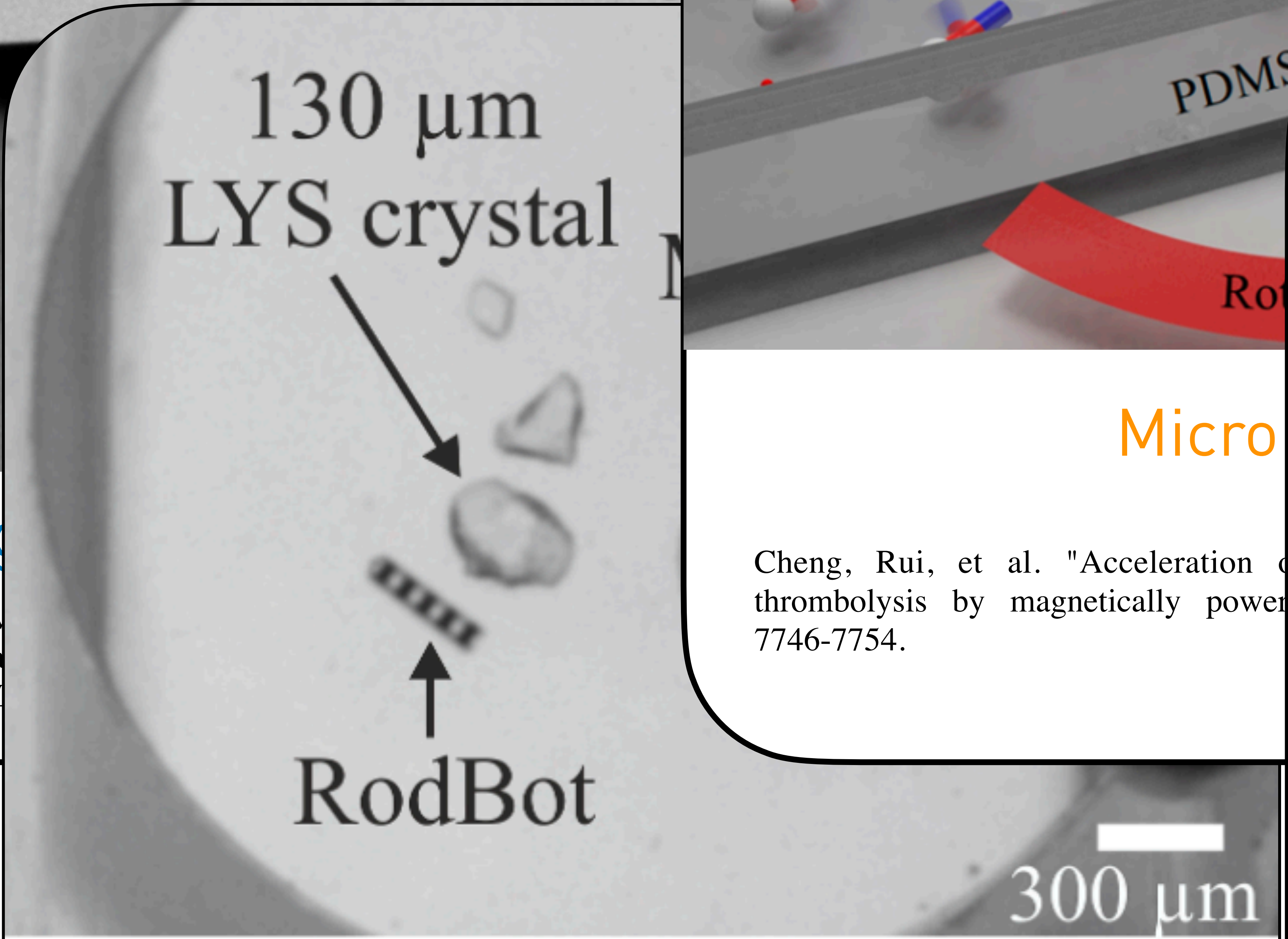
Carg

Tottori, S.; Zhang, L.; Qiu, F.; Kraw
Magnetic helical micromachines: fa
Advanced materials, Wiley Online L



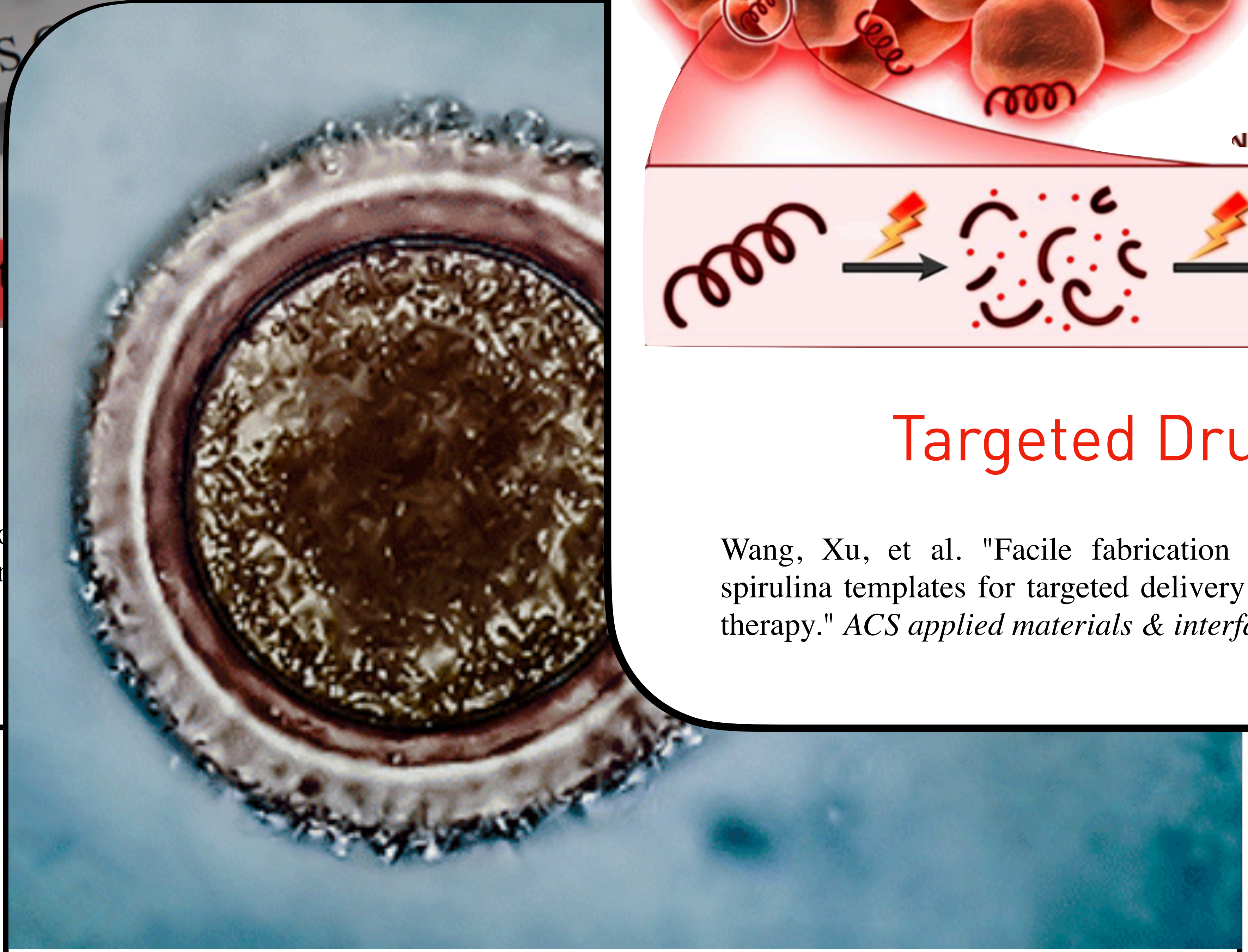
Micro

Cheng, Rui, et al. "Acceleration
thrombolysis by magnetically powe
7746-7754.



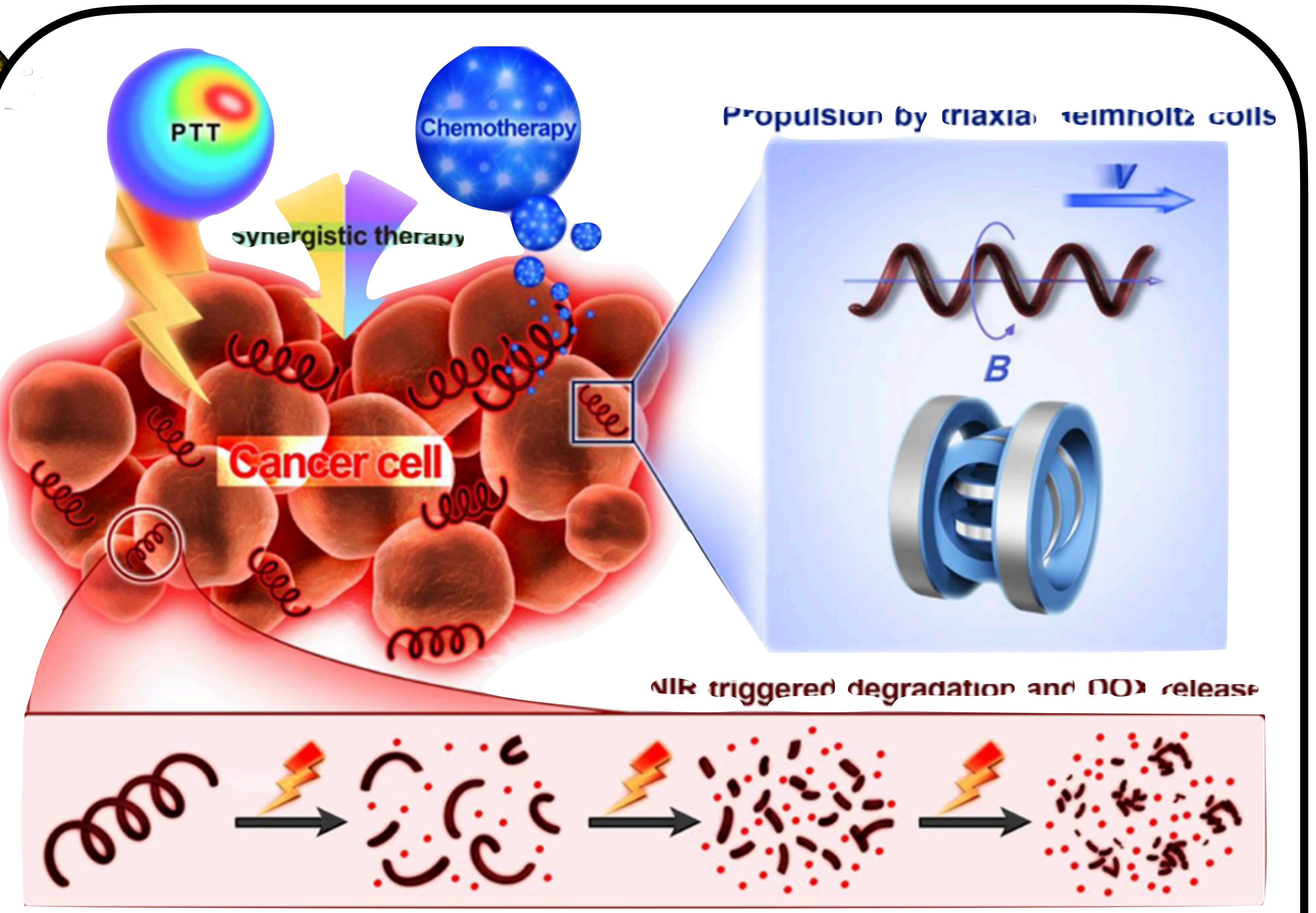
Micro-manipulation

Pieters, Roel S., et al. "Non-contact manipulation for automated protein crystal harvesting using a rolling microrobot." *IFAC Proceedings Volumes* 47.3 (2014): 7480-7485.



Assisted Fertilization

Medina-Sánchez, Mariana, et al. "Cellular cargo delivery: Toward assisted fertilization by sperm-carrying micromotors." *Nano letters* 16.1 (2016): 555-561.



Targeted Drug Delivery

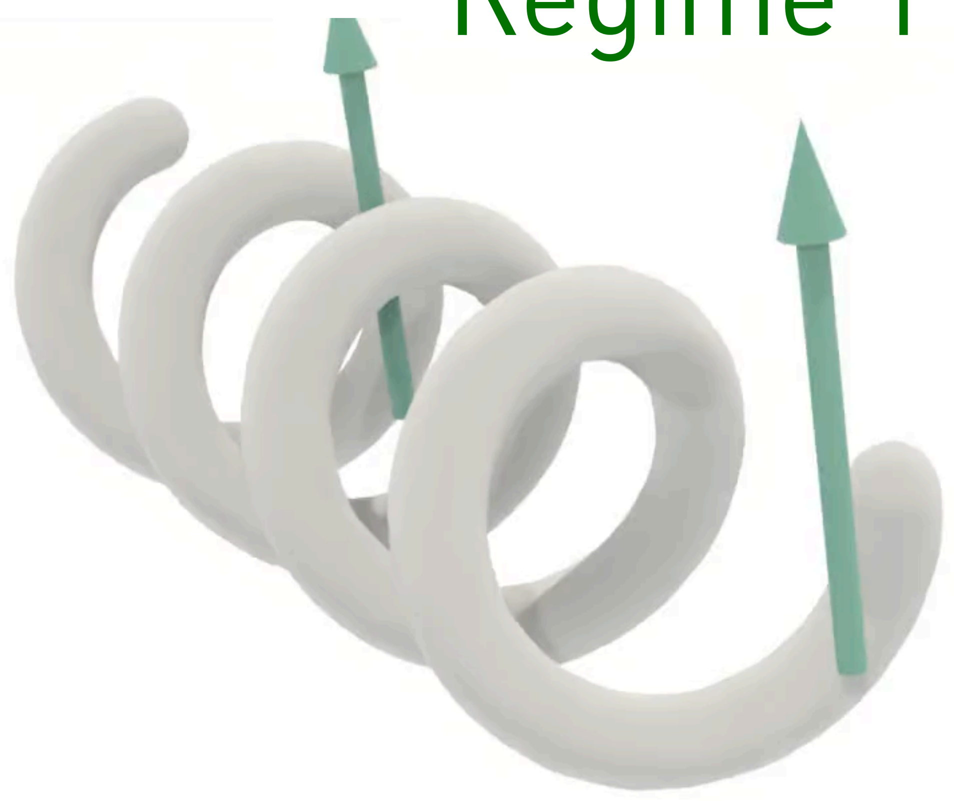
Wang, Xu, et al. "Facile fabrication of magnetic microrobots based on spirulina templates for targeted delivery and synergistic chemo-photothermal therapy." *ACS applied materials & interfaces* 11.5 (2019): 4745-4756.

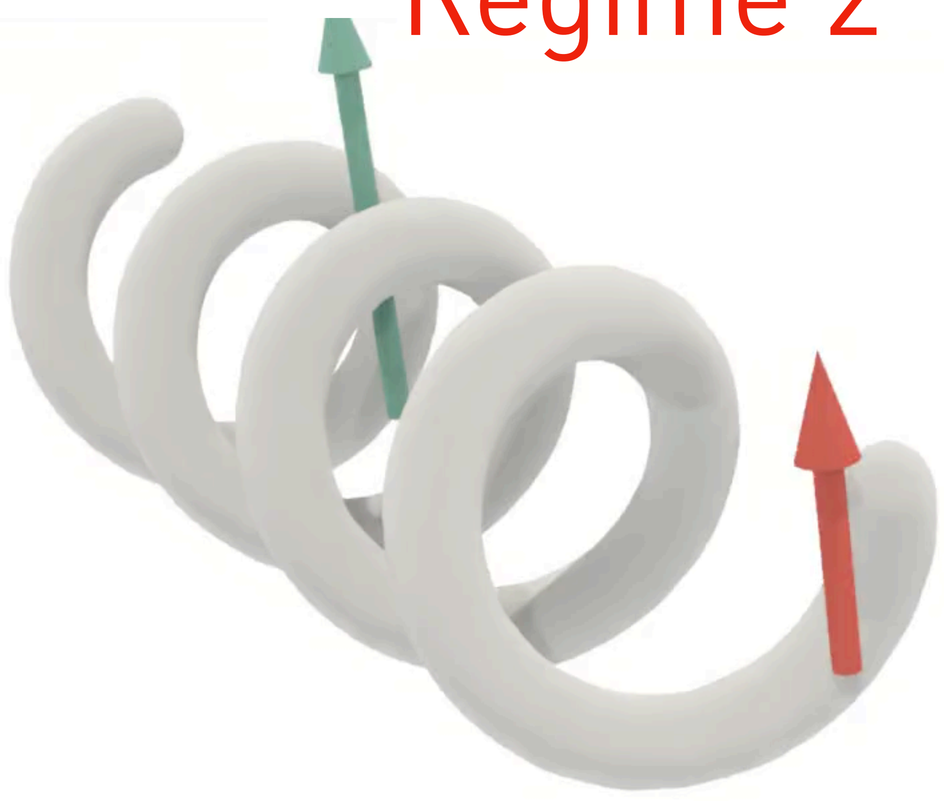
Outline

1. Independent Control and Path Planning of artificial bacterial flagella

2. Artificial bacterial flagella swimming in blood

Artificial Bacterial Flagella (ABF)





$\mathrm{Re} \approx 10^{-4} \ll 1 \Rightarrow$ Stokes flow.

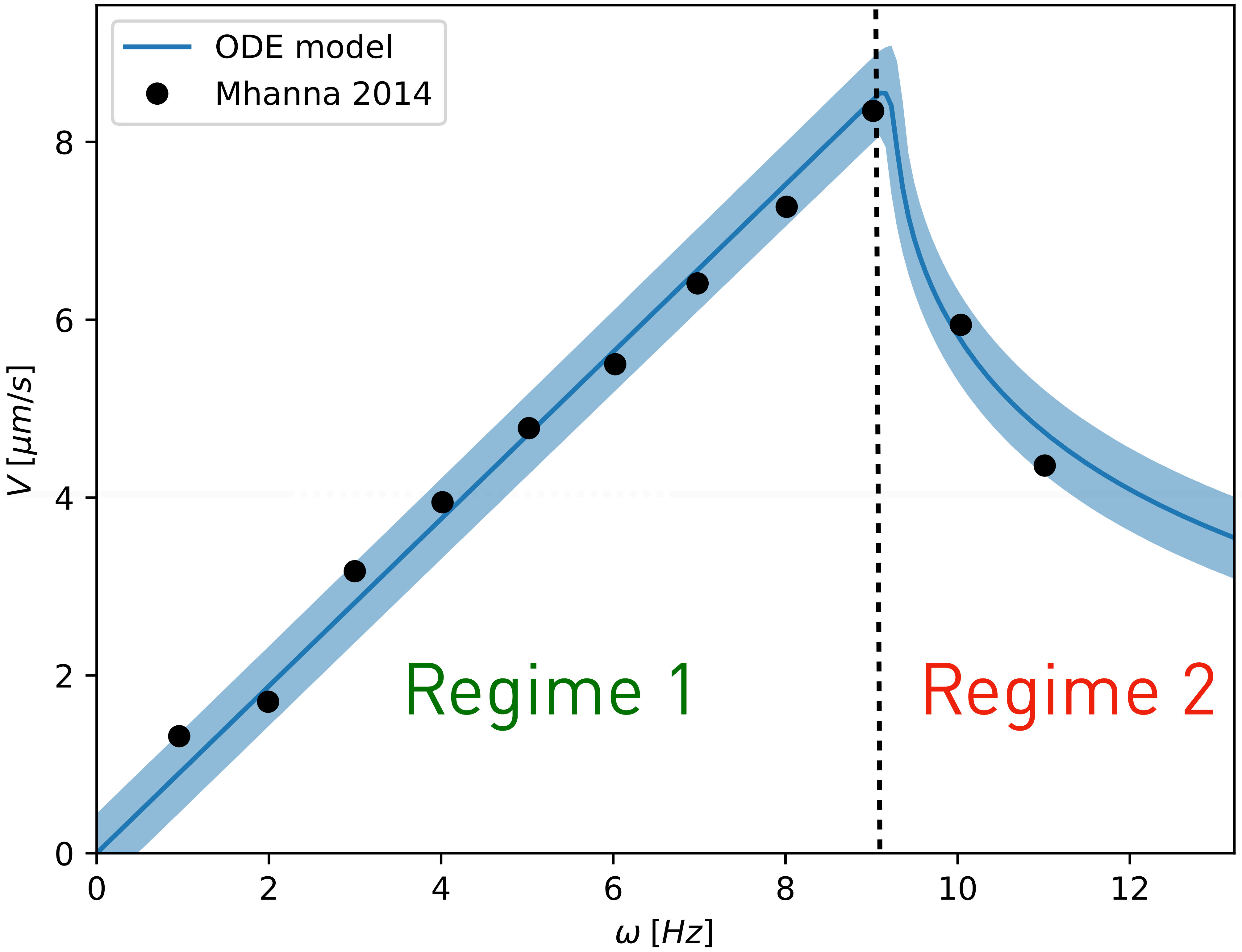
Magnetic torque: $\mathbf{T} = \mathbf{m} \times \mathbf{B}$

$$\begin{bmatrix} \mathbf{V}^B \\ \mathbf{\Omega}^B \end{bmatrix} = \begin{bmatrix} \mathscr{A} & \mathscr{B} \\ \mathscr{B} & \mathscr{C} \end{bmatrix} \begin{bmatrix} \mathbf{F}^B \\ \mathbf{T}^B \end{bmatrix}$$

ODE model

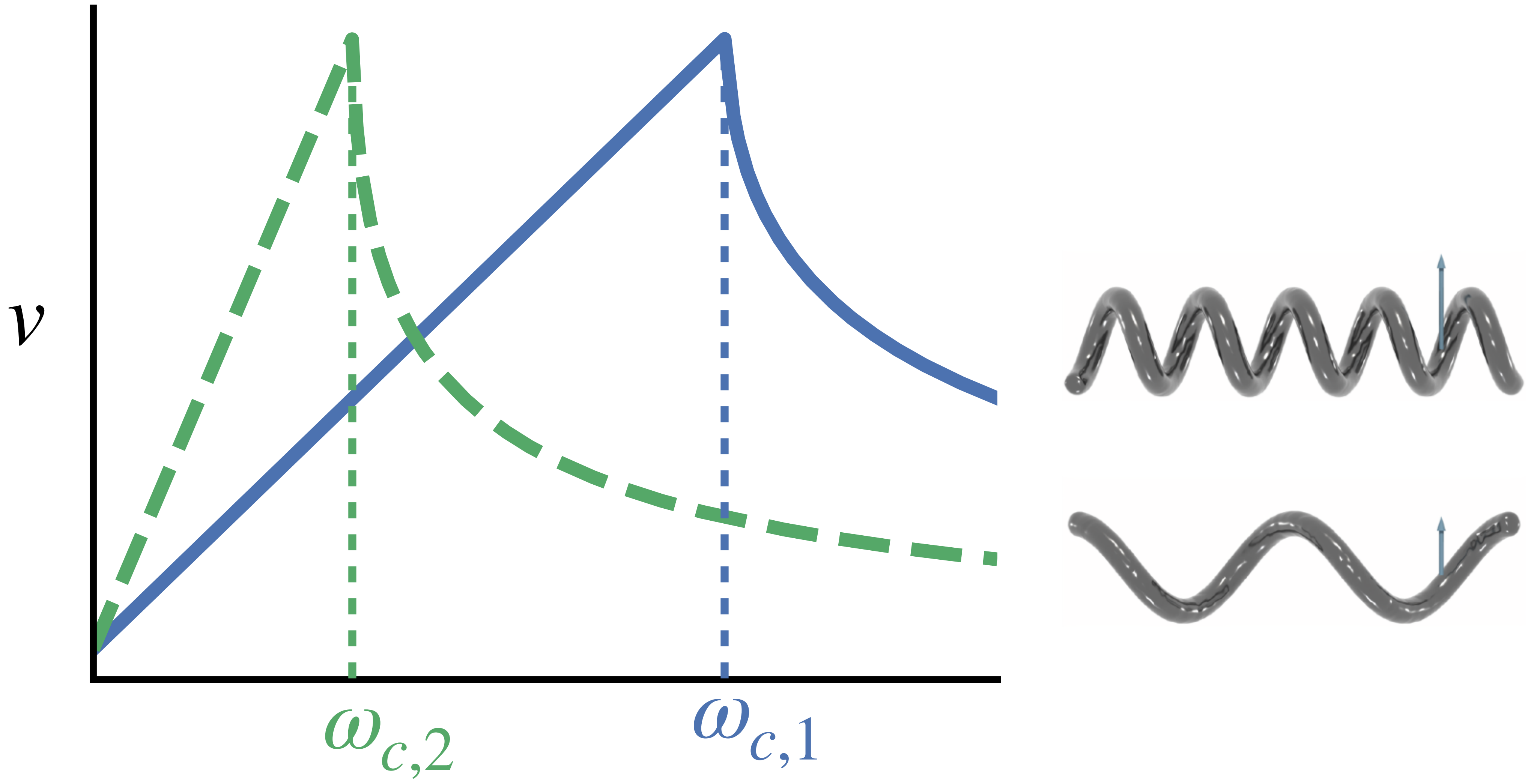
$$\dot{q} = \frac{1}{2} q \otimes \hat{\mathbf{\Omega}}, \qquad \mathbf{V}^B = \mathscr{B}\mathbf{T}^B,$$

$$\dot{\mathbf{x}} = \mathbf{V}, \qquad \mathbf{\Omega}^B = \mathscr{C}\mathbf{T}^B.$$



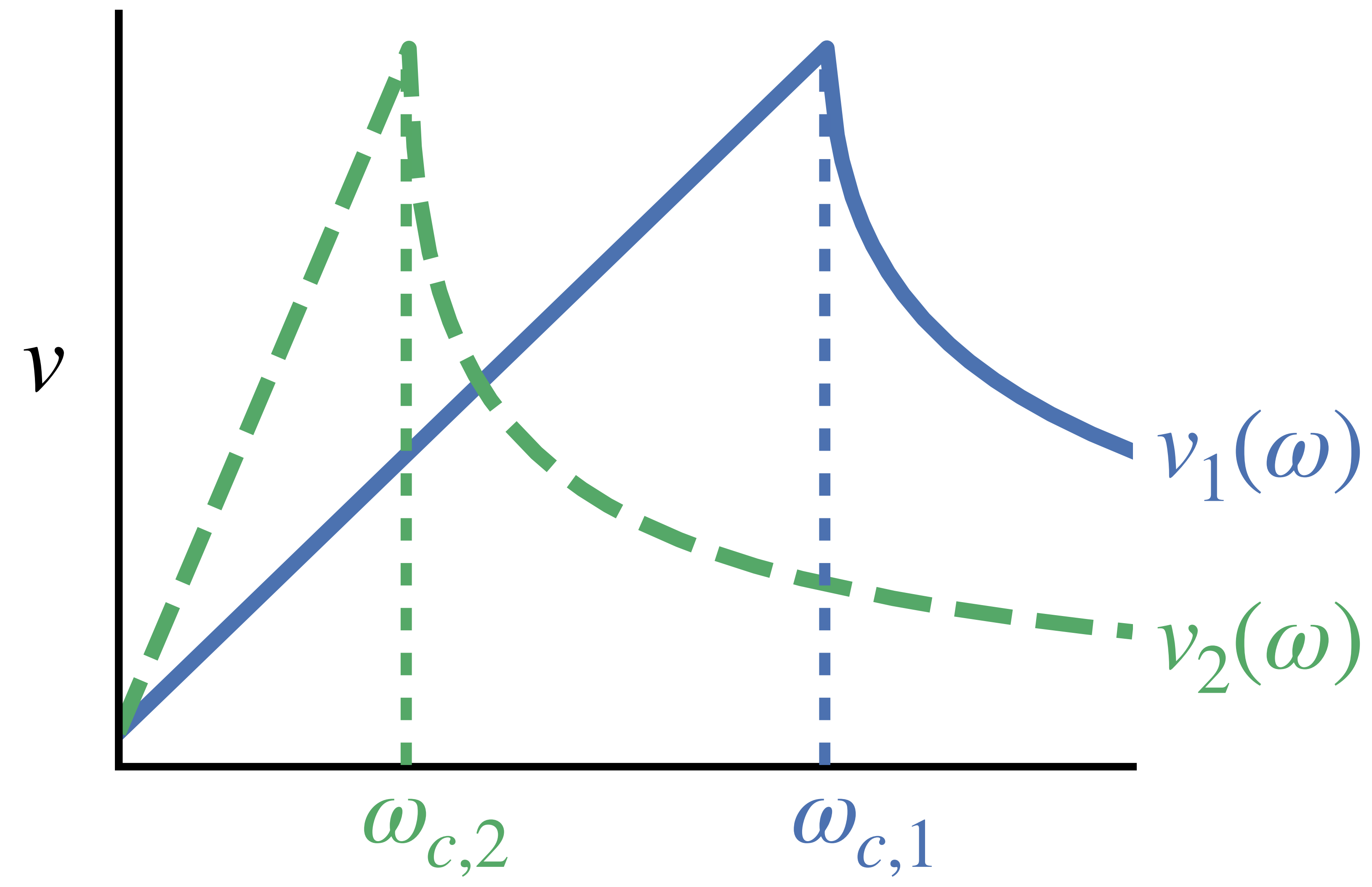
Different geometries allow independent control

The geometry governs the response to the rotation frequency of the magnetic field

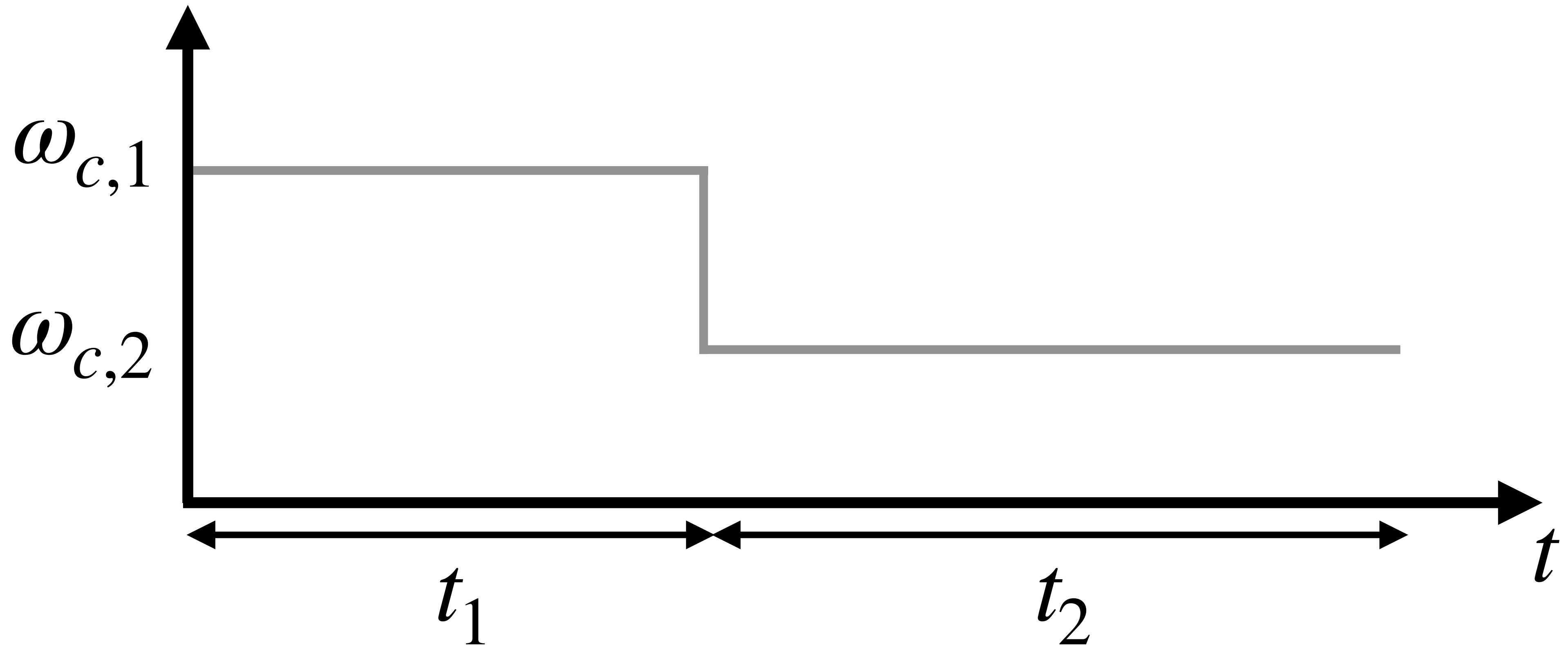


Swimming different distances along a direction

Constraint: All swimmers are subjected to the same magnetic field



Alternate the magnetic field rotation frequency:



Velocity matrix: $U_{ij} = v_i(\omega_{c,j})$

(signed) distance made by swimmer i: $d_i = \sum_j U_{ij} t_j s_j = U_{ij} b_j$,

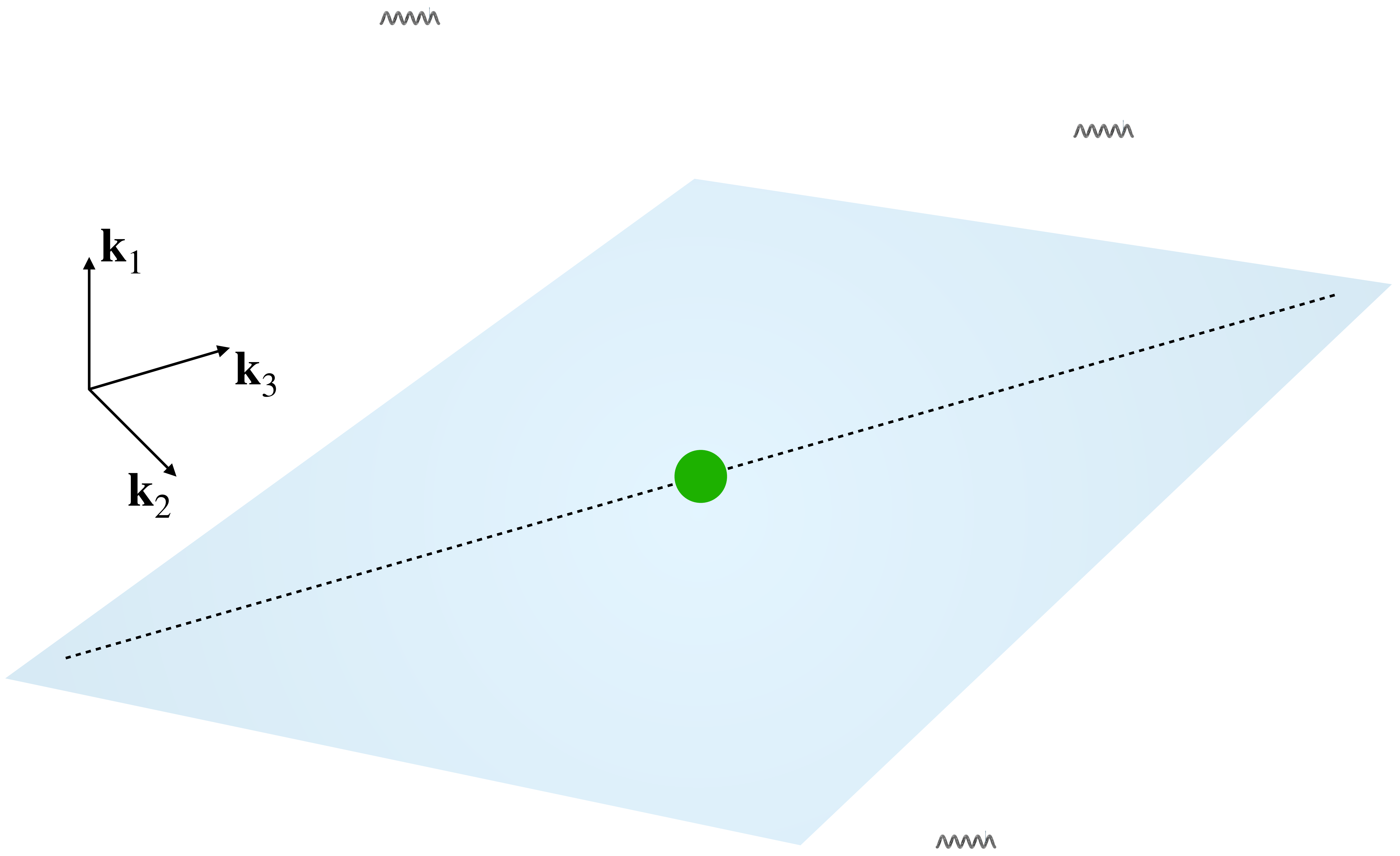
where $s_j = -1$ (clockwise) or $s_j = +1$ (anti-clockwise)

$$\Rightarrow \mathbf{b} = U^{-1}\mathbf{d}$$

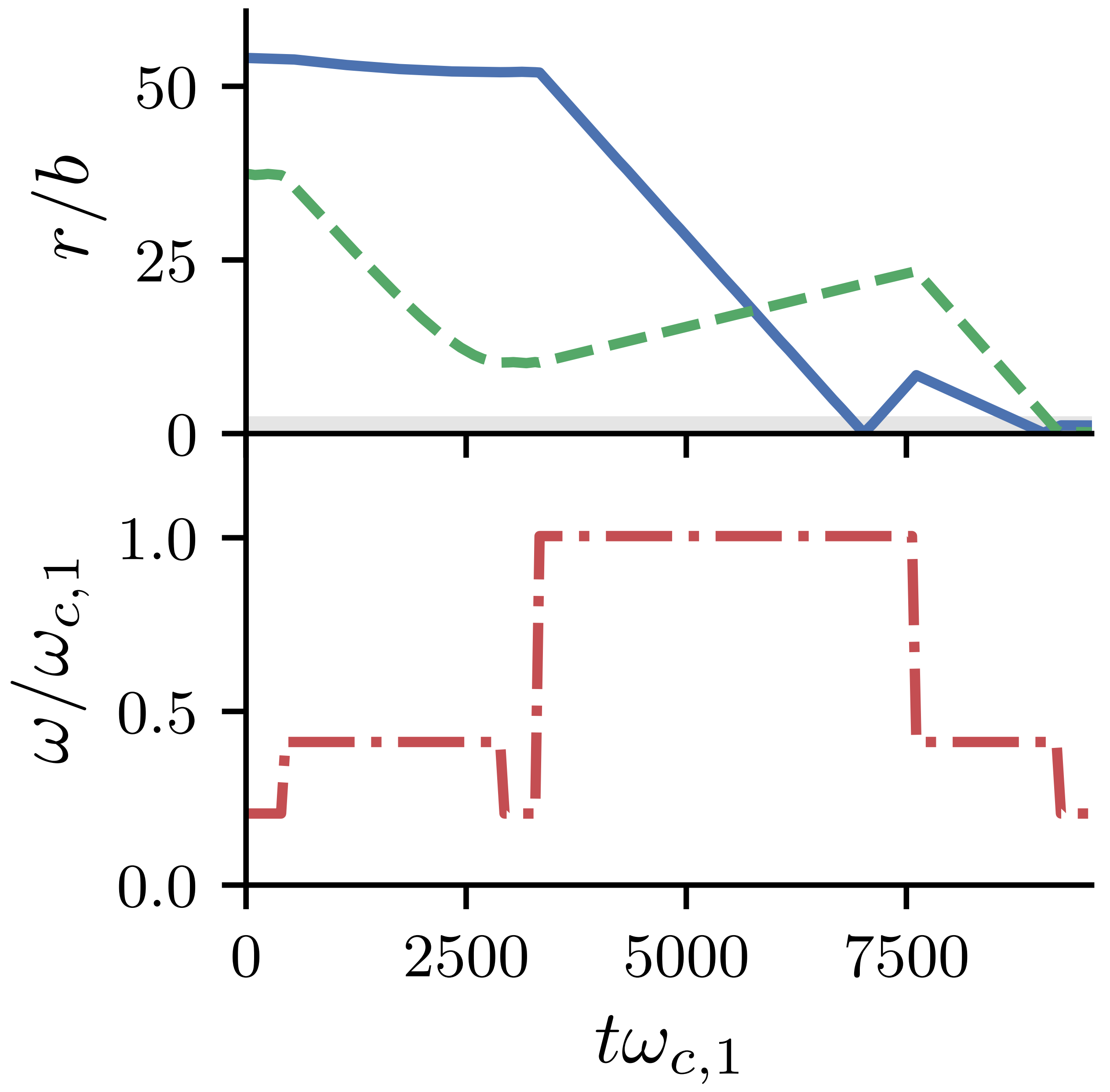
Gathering swimmers to a target

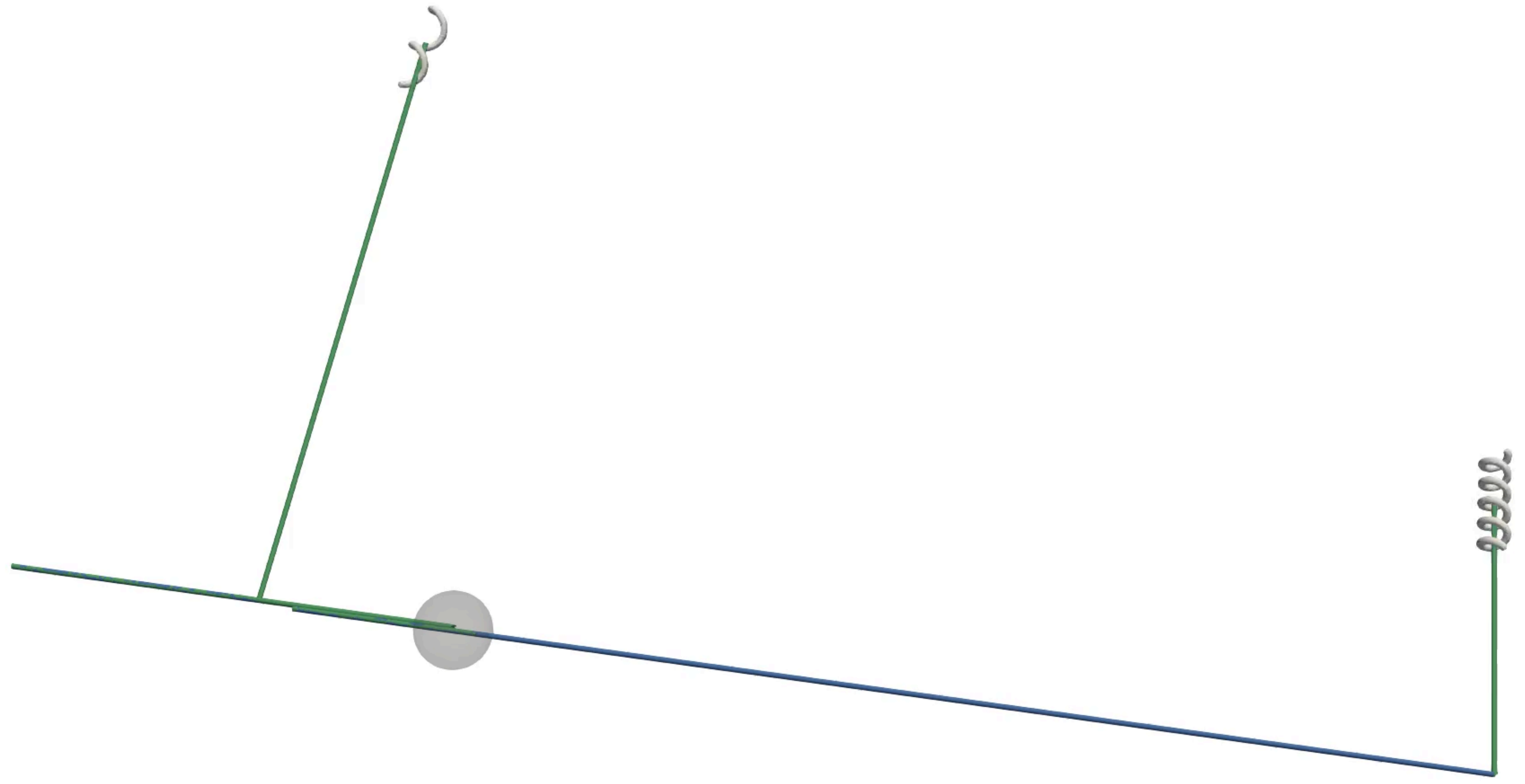
In 3 dimensions: 3 steps to reach the target

1. Gather on a plane
2. Gather on a line
3. Gather at the target

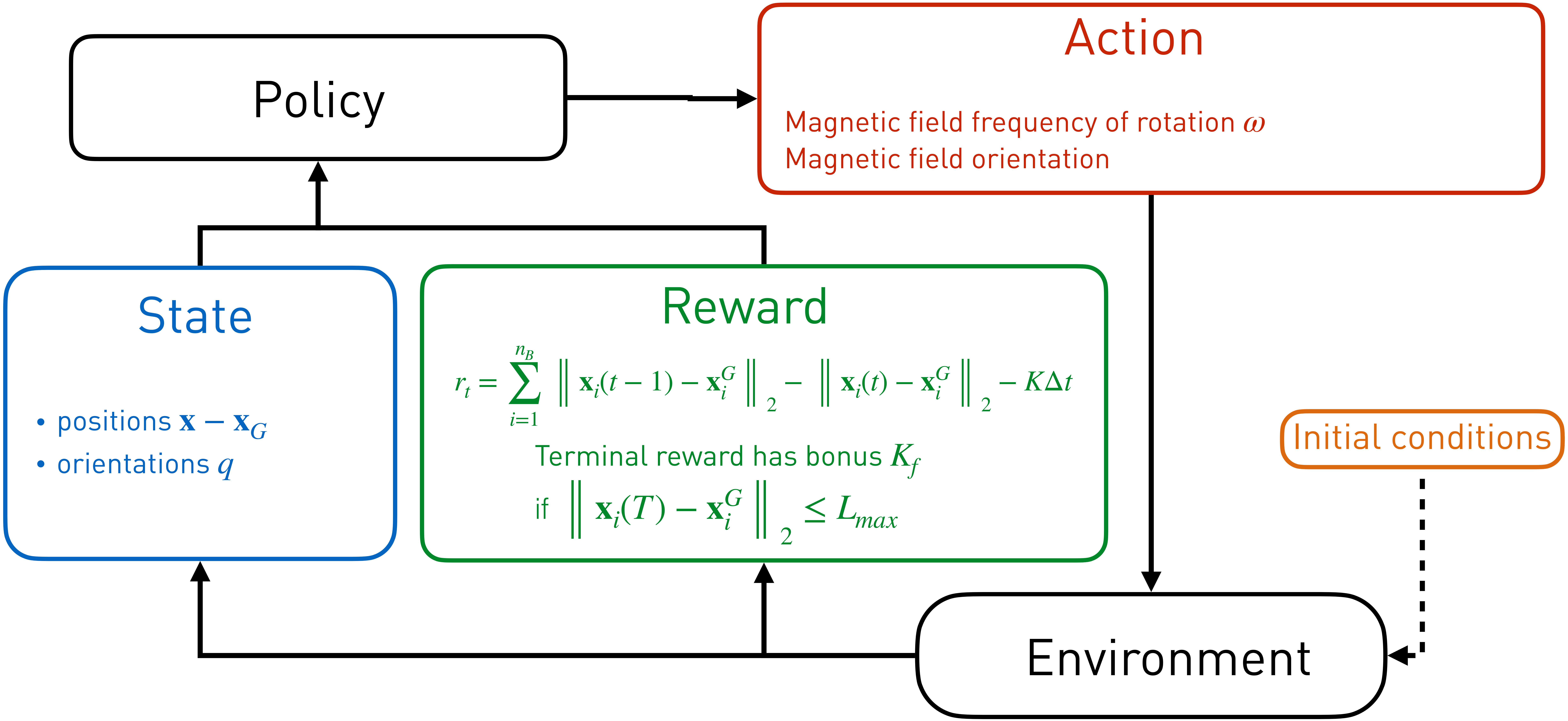


Independent control in free space

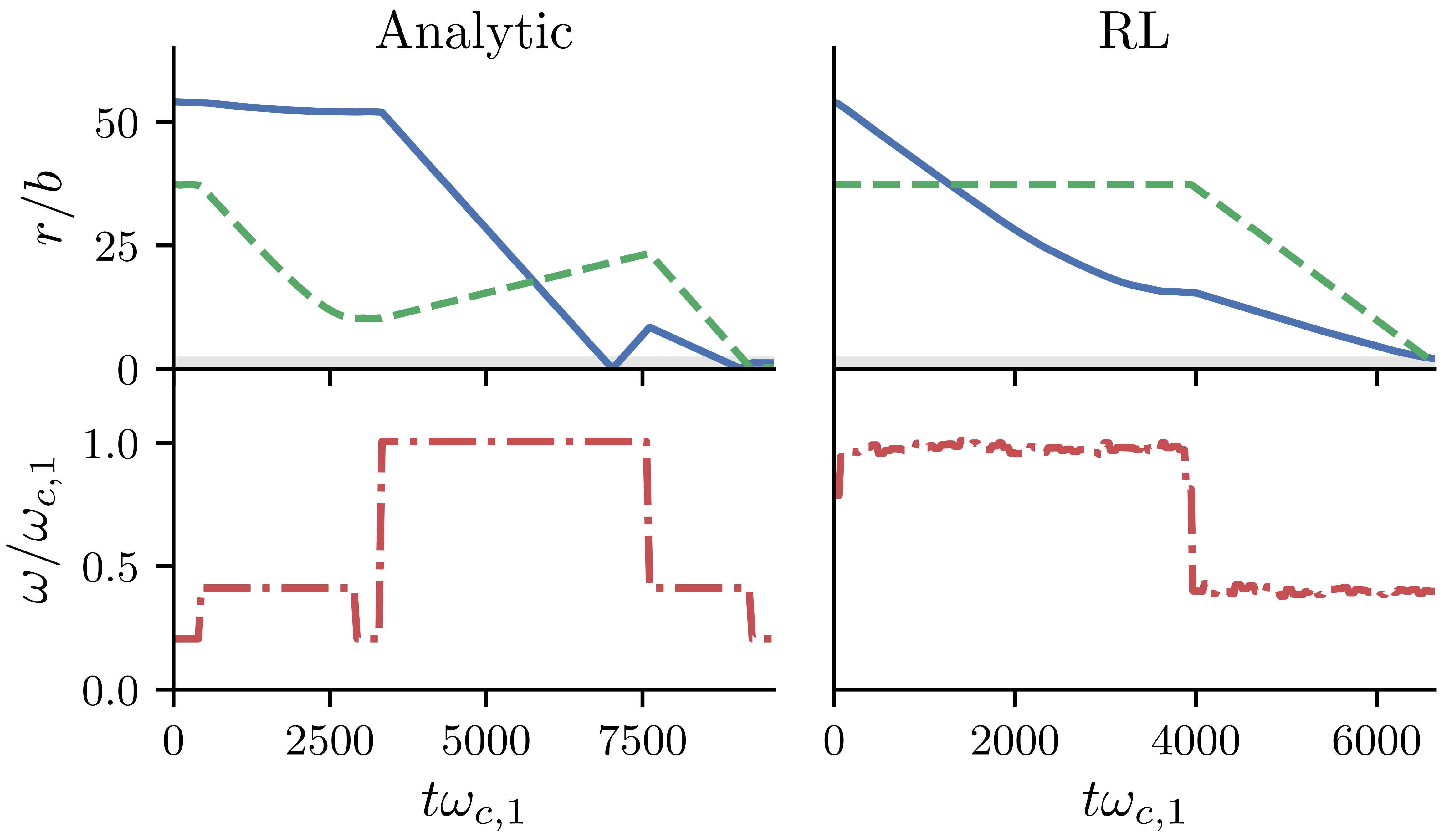


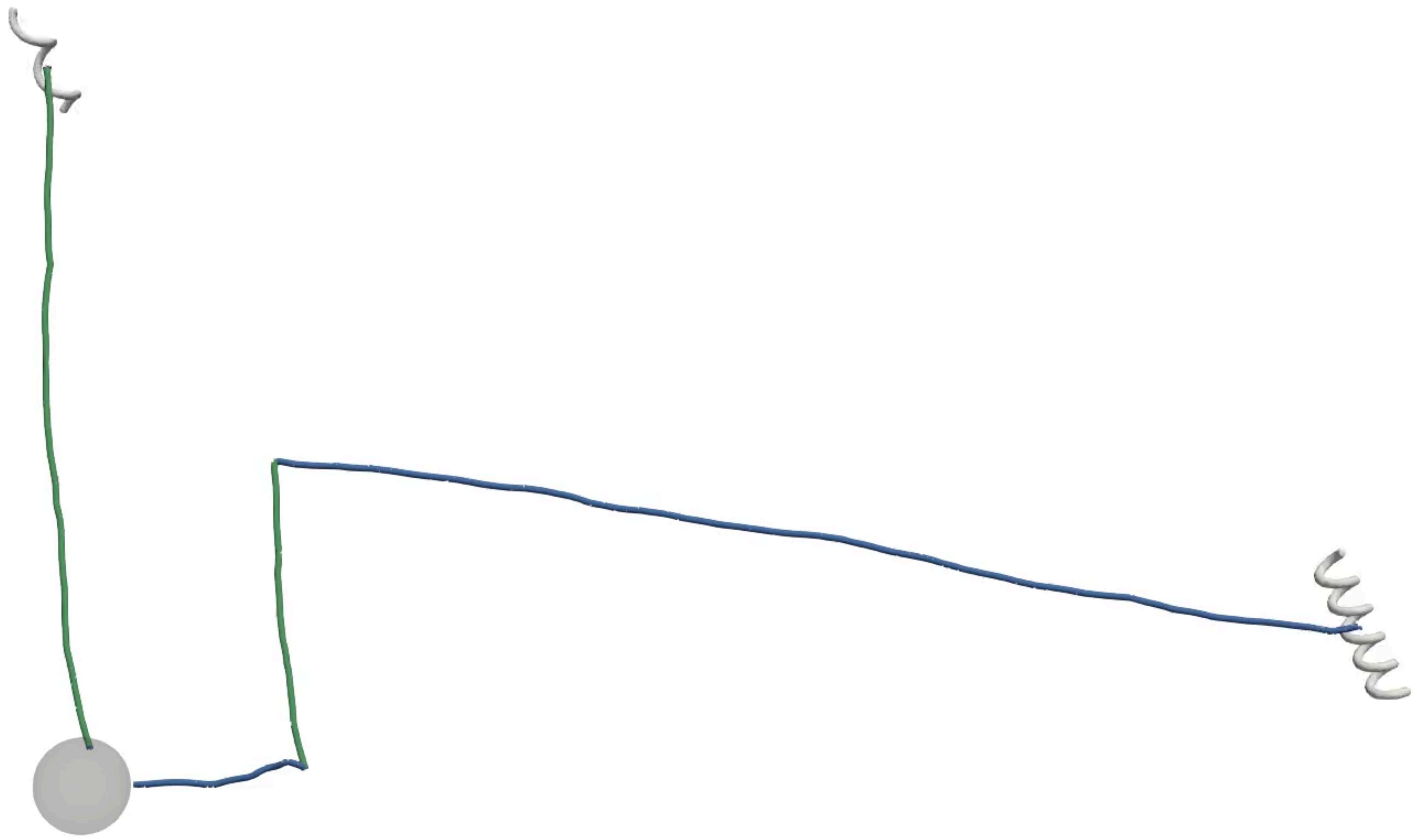


Reinforcement Learning



Independent control in free space: RL

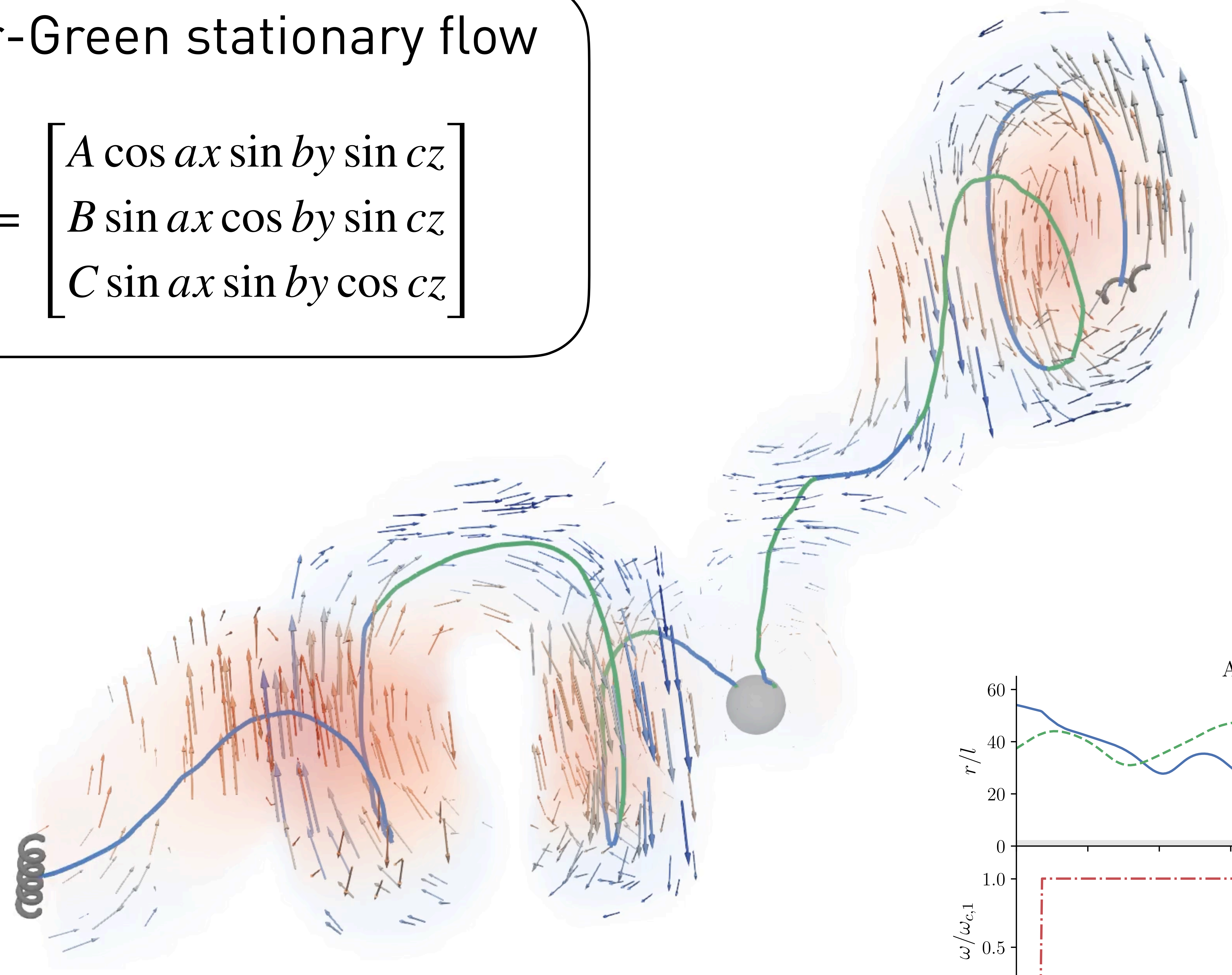


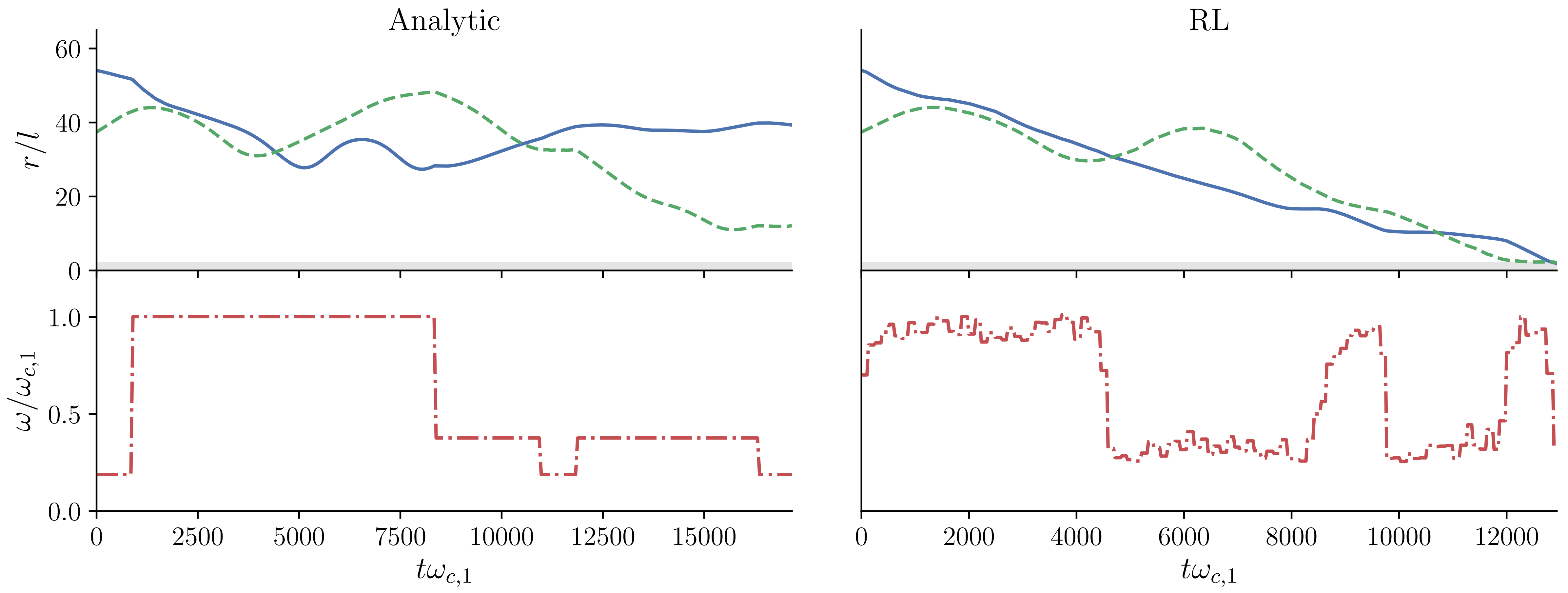


Independent control with a background flow

Taylor-Green stationary flow

$$\mathbf{u}_\infty(\mathbf{r}) = \begin{bmatrix} A\cos ax \sin by \sin cz \\ B \sin ax \cos by \sin cz \\ C \sin ax \sin by \cos cz \end{bmatrix}$$





Outline

1. Independent Control and Path Planning of artificial bacterial flagella

2. Artificial bacterial flagella swimming in blood

Blood Model

Bending Energy

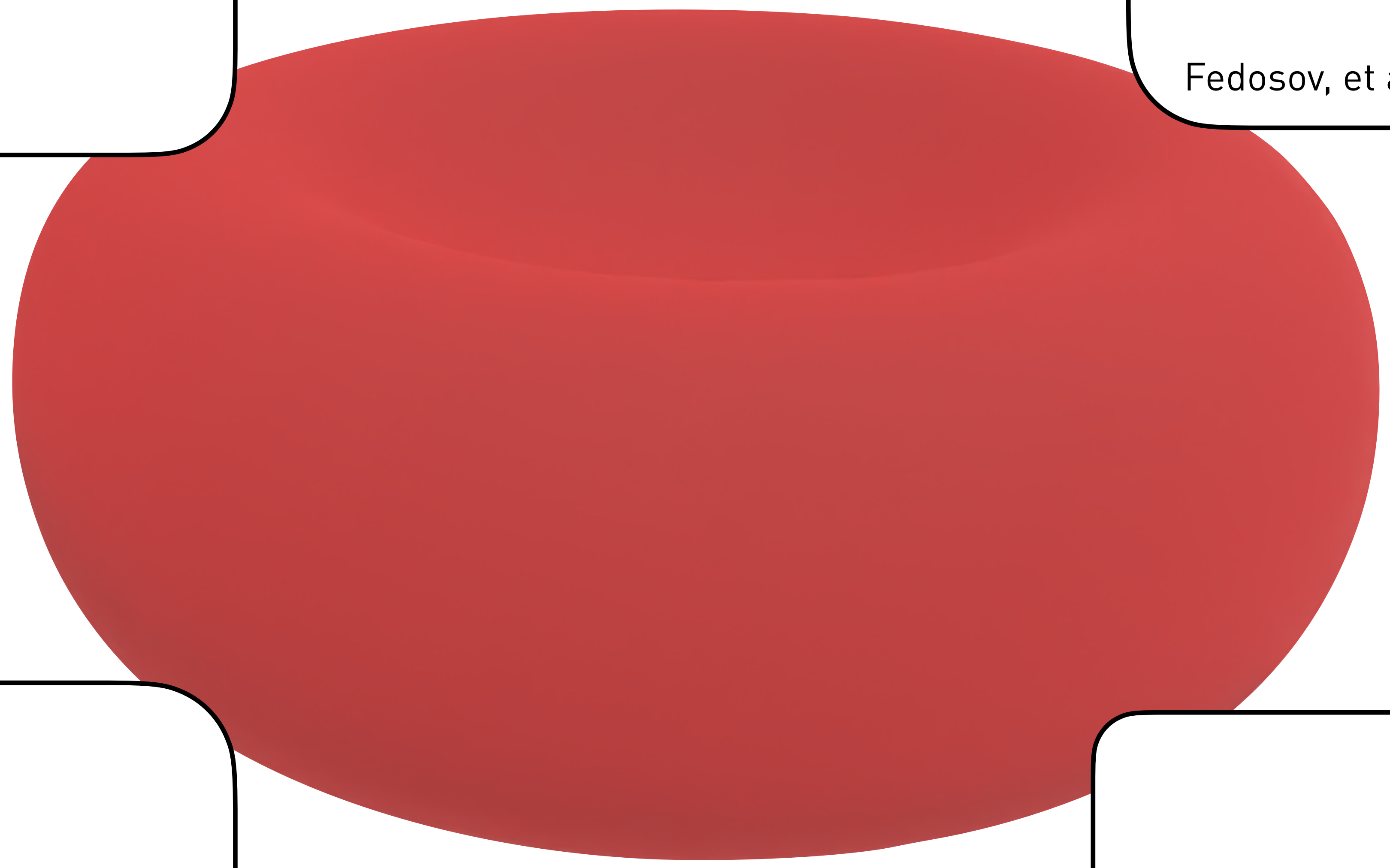
$$E_b = 2\kappa_b \oint (H - H_0)^2 \, dA$$

Jülicher, F. 1996. Journal de Physique II, 6(12), 1797–1824.

Area and Volume penalization

$$E_A = k_A \frac{(A - A_0)^2}{A_0}, \quad E_V = k_V \frac{(V - V_0)^2}{V_0}$$

Fedosov, et al. 2010. Biophysical Journal, 98(10), 2215–2225.



Dissipation forces

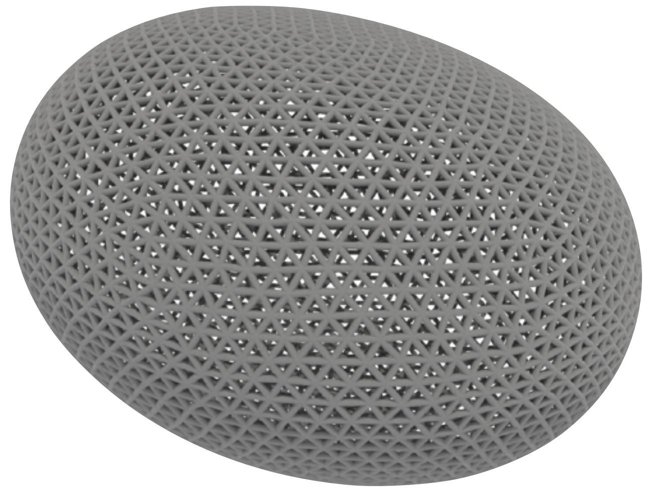
$$\mathbf{f}_i^{visc} = -\sum_j \gamma \left(\mathbf{v}_{ij} \cdot \mathbf{e}_{ij}\right) \mathbf{e}_{ij}$$

Fedosov, et al. 2010. Biophysical Journal, 98(10), 2215–2225.

Shear Energy

$$E_s = \frac{K_\alpha}{2} \oint \left(\alpha^2 + a_3\alpha^3 + a_4\alpha^4\right) dA_0 + \mu \oint \left(\beta + b_1\alpha\beta + b_2\beta^2\right) dA_0$$

with respect to stress-free shape:



Lim et al. 2008. Soft Matter, 4.

Solvent Model

Newton motion

$$\dot{\mathbf{r}}_i = \mathbf{v}_i,$$
$$\dot{\mathbf{v}}_i = \frac{1}{m_i}\mathbf{f}_i,$$

Bounce Back on the membrane

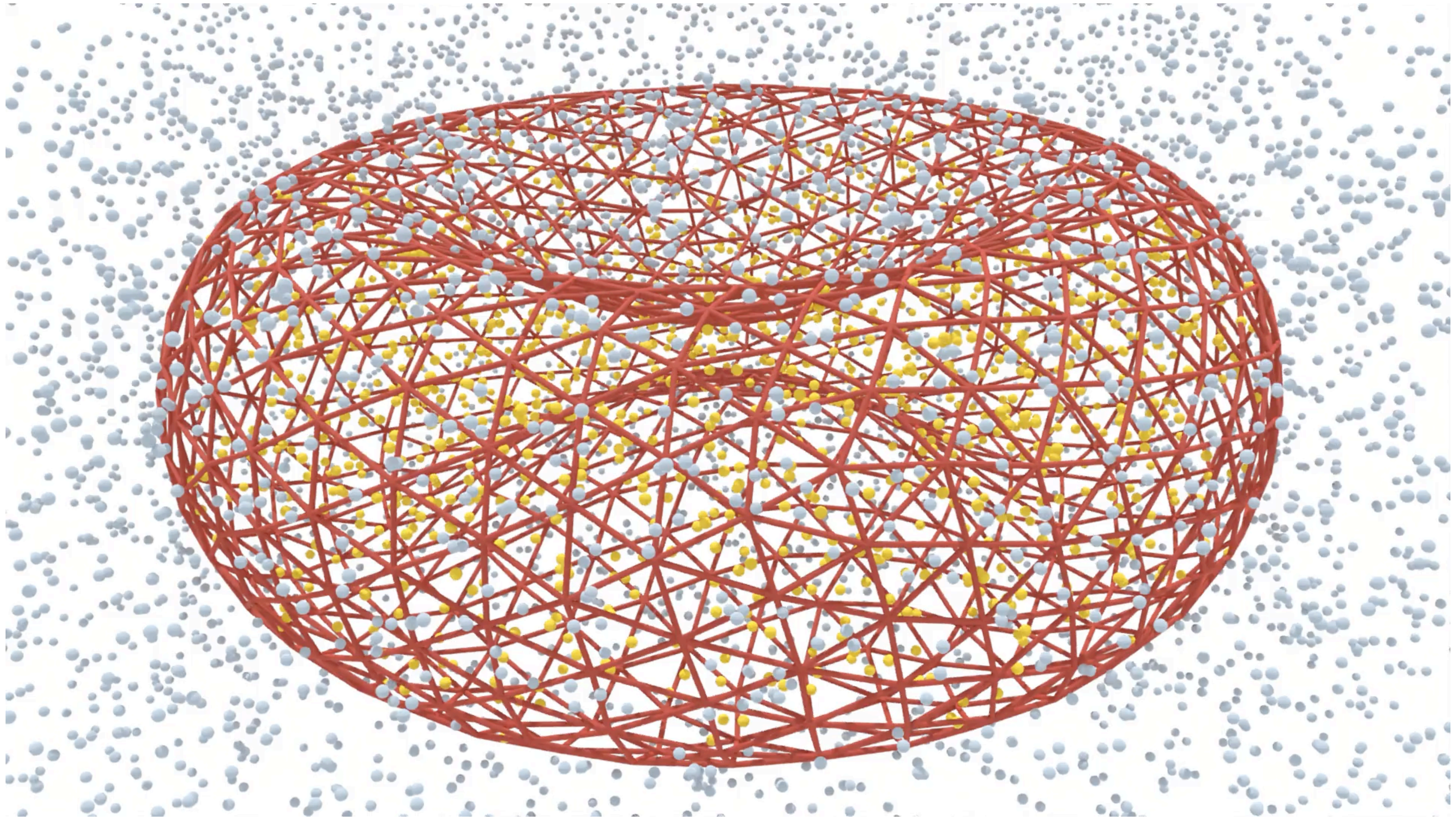
$$\mathbf{v}(t+dt) = 2\mathbf{v}_{RBC}(t_{collision}) - \mathbf{v}(t)$$

Dissipative Particle Dynamics interactions

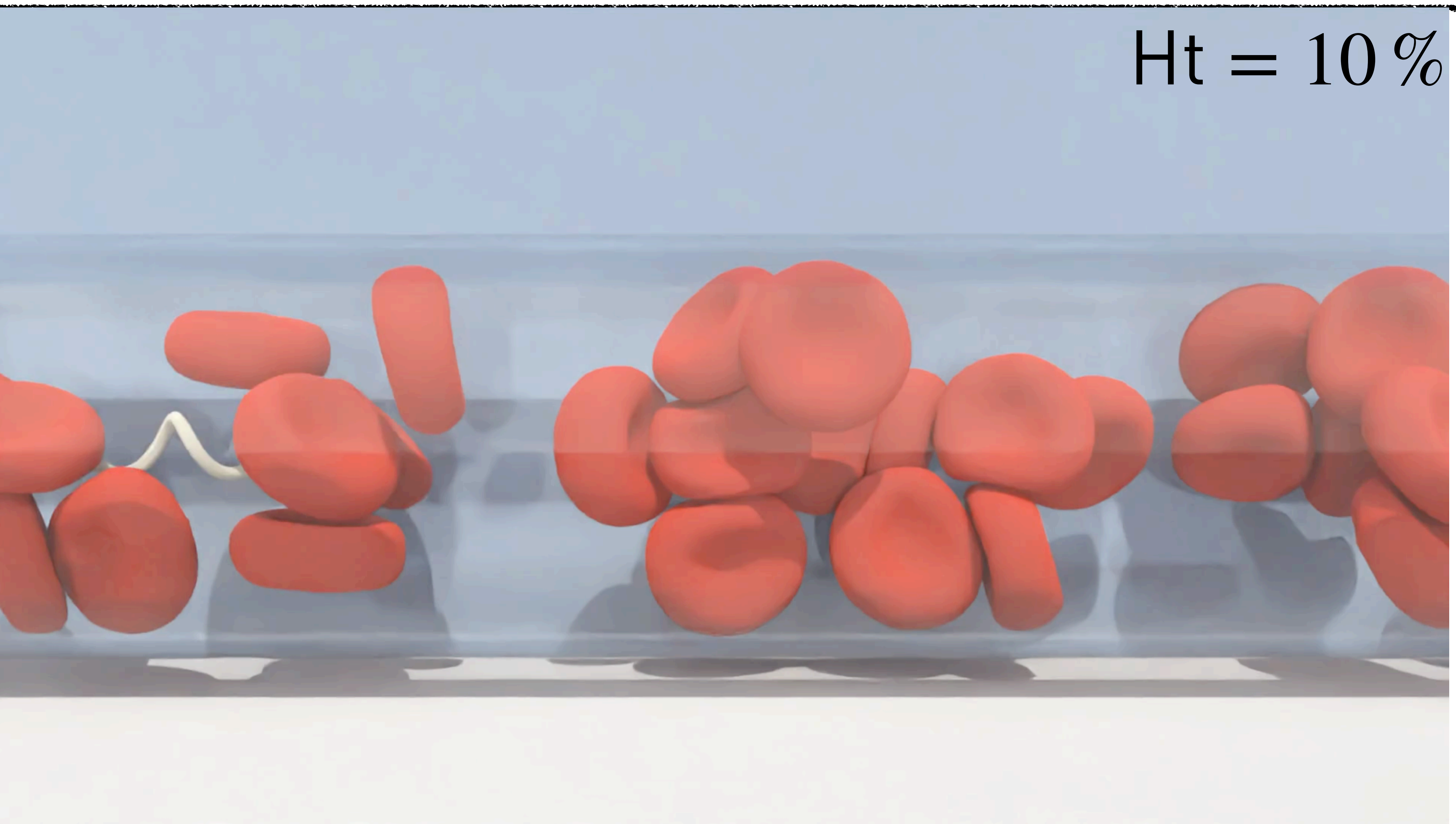
$$\mathbf{f}_{ij}^C = a w(r_{ij})\mathbf{e}_{ij},$$ hydrostatic pressure

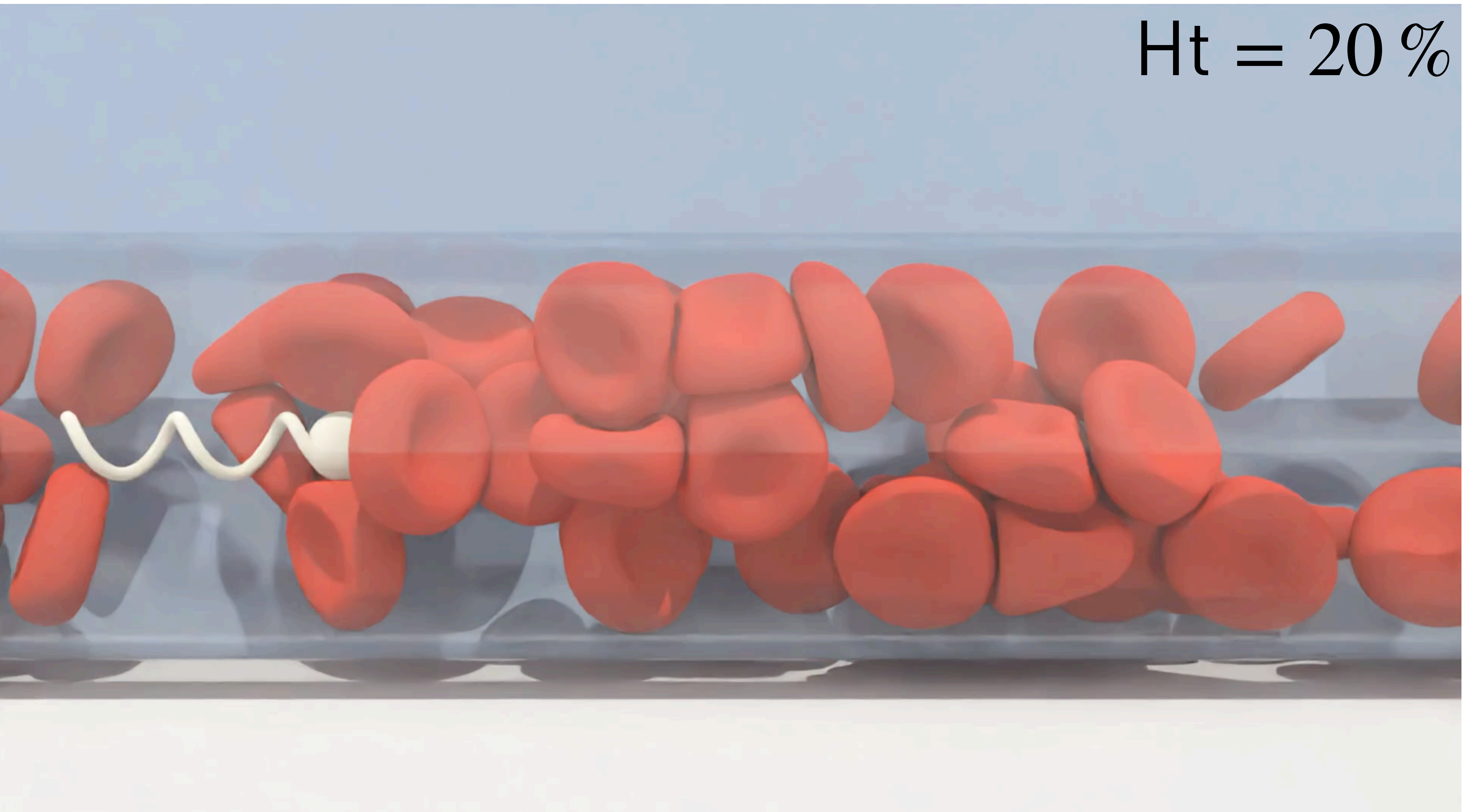
$$\mathbf{f}_{ij}^D = -\gamma w_D(r_{ij})\left(\mathbf{e}_{ij}\cdot\mathbf{v}_{ij}\right)\mathbf{e}_{ij},$$ viscosity

$$\mathbf{f}_{ij}^R = \sigma\xi_{ij} w_R(r_{ij})\mathbf{e}_{ij}$$ fluctuations

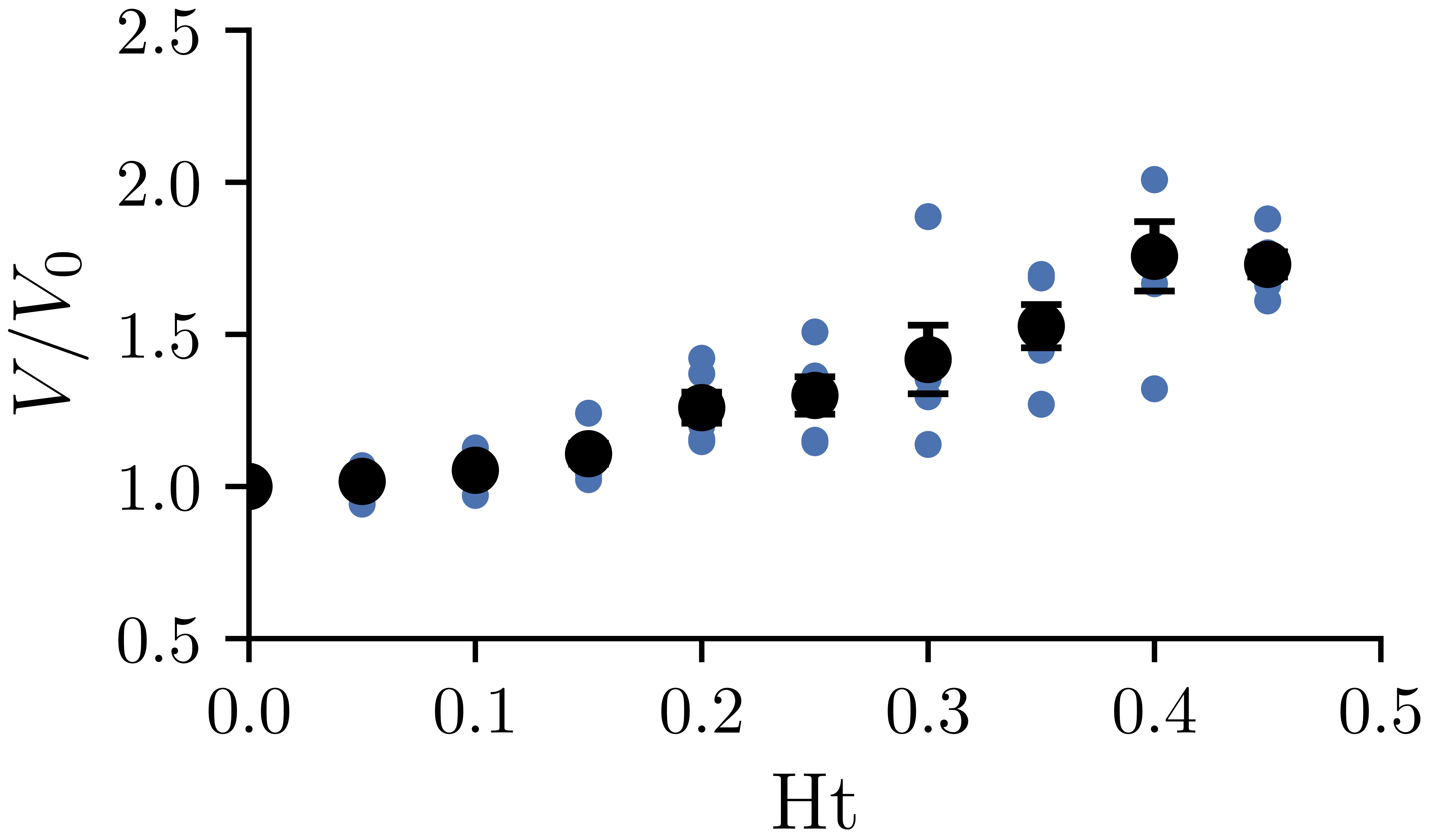


ABFs swimming in blood

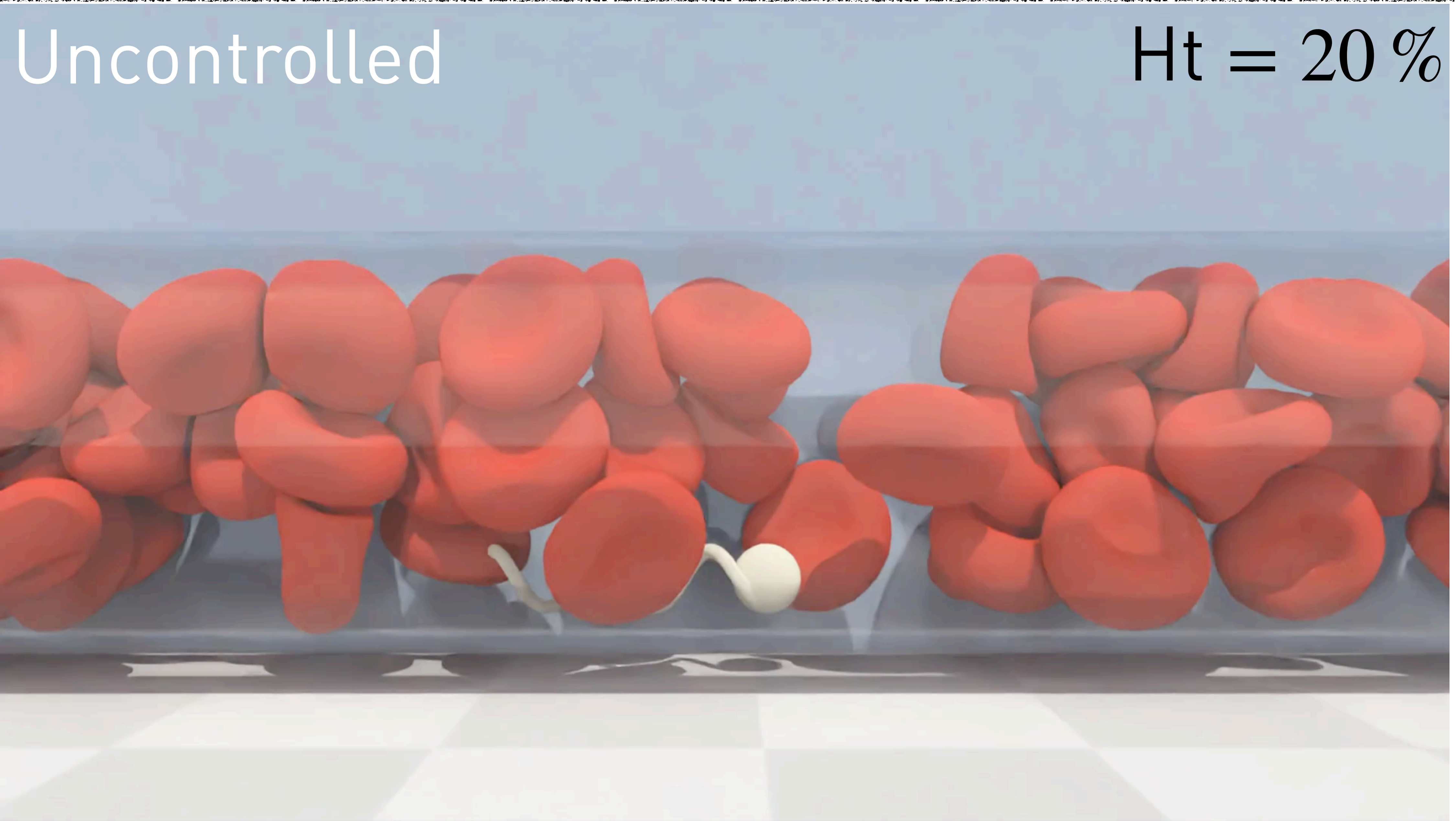


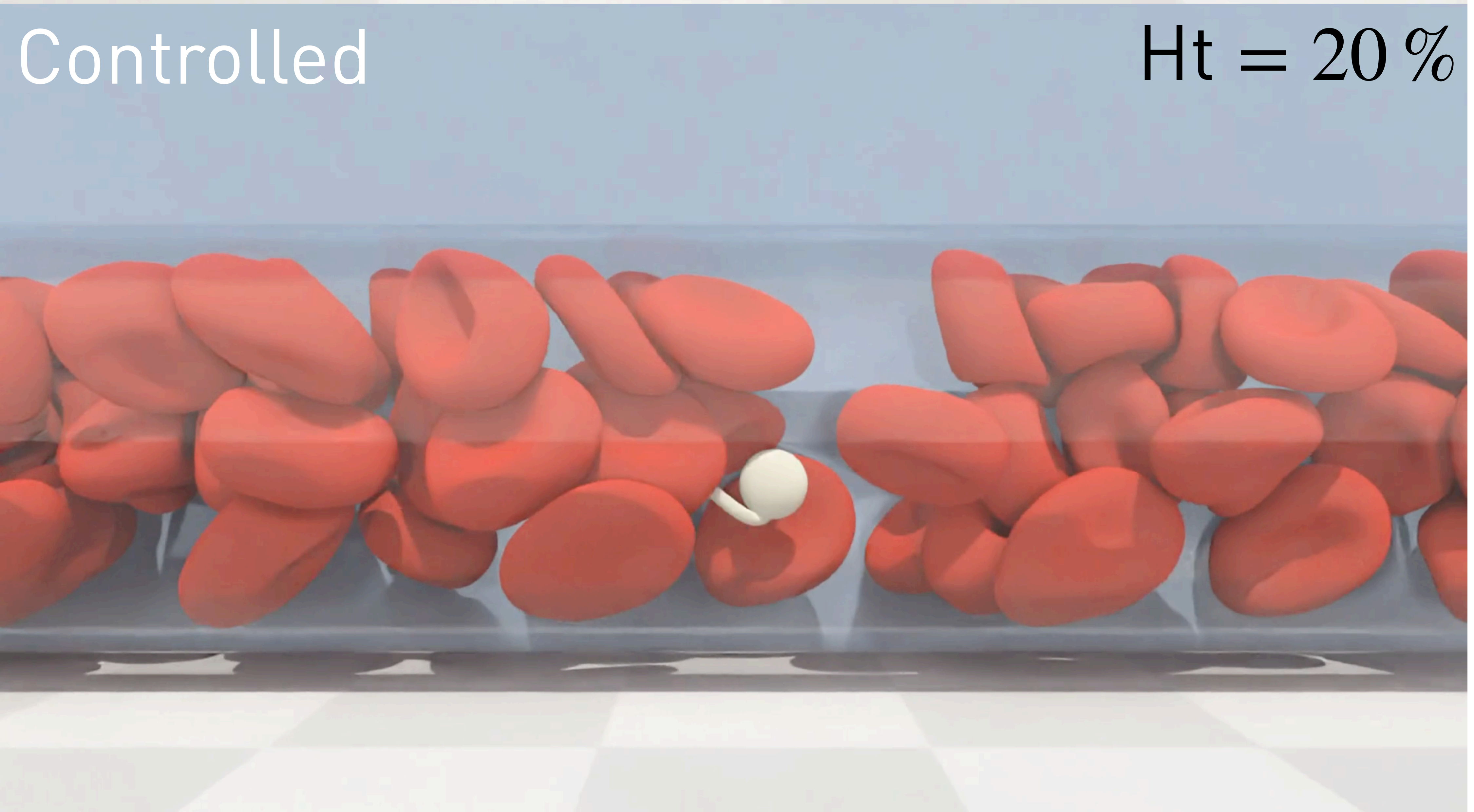


ABFs swim **faster** at **higher hematocrit**

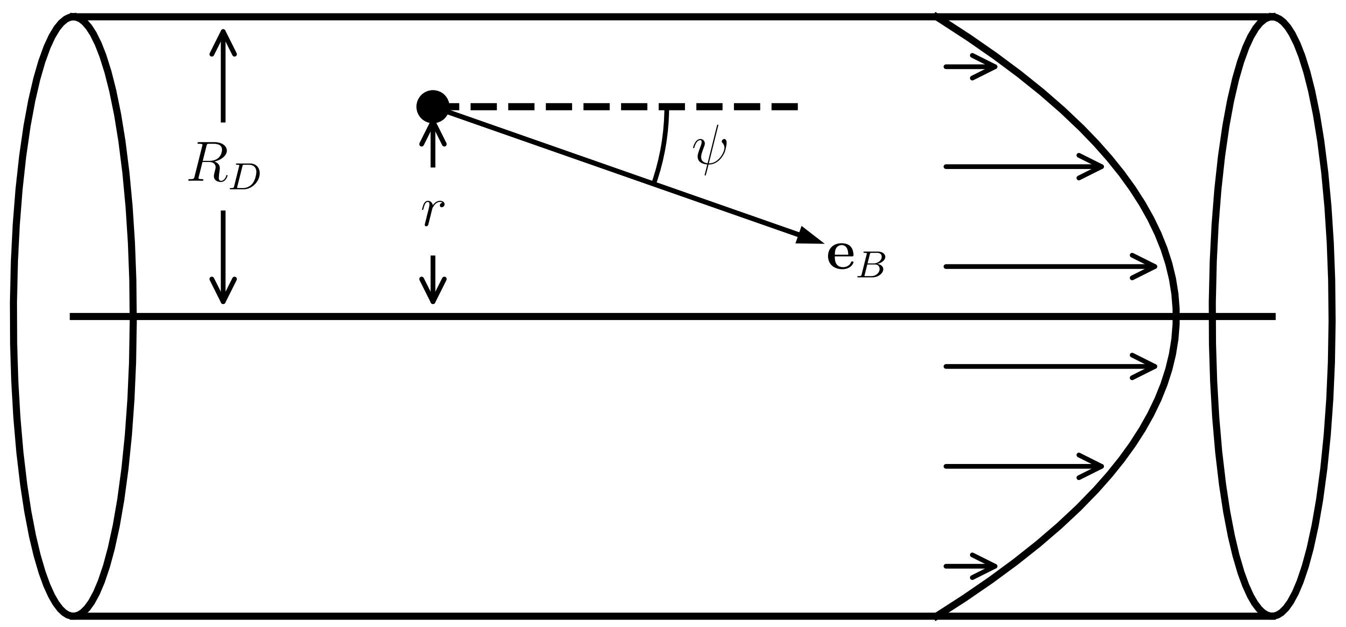


ABF catching a circulating cancerous cell

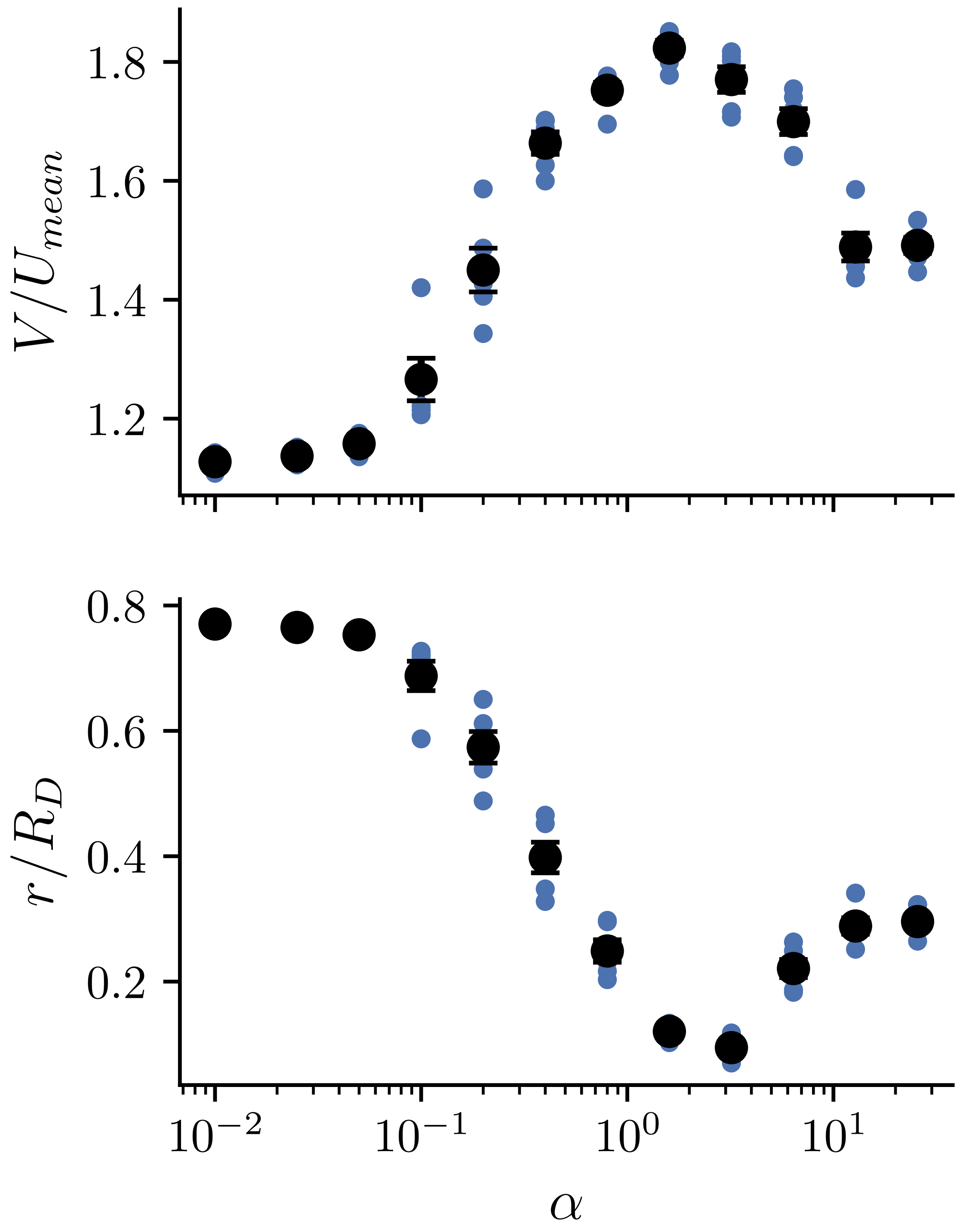




Controlled to stay near the center of the pipe



$$\psi = \arctan\left(\alpha \frac{r}{R_D}\right),$$



Summary

- Reinforcement learning is a good tool for independent control of multiple swimmers under a uniform magnetic field

- Artificial bacterial flagella can navigate in blood efficiently if the magnetic torque is high enough

- Opens the road to optimize the design of single and swarms of swimmers