Lab1 Seminar
2022/07/25

自走する粒子系としての細胞や生物集団のふるまい

Collective behaviors of cells and lives modelled as self-propelled particles

Ryoichi Yamamoto

70 unsolved problems in Physics (JPS 2017)

日本物理学会創立70周年記念企画

物理学70の不思議

16. 原子核の形　19. 格子QCD　5. 素粒子の世代
13. 陽子＝クォーク3つ？　11. ヒッグス粒子　37. 素粒子と物性　36. 量子コンピュータ
14. テトラクォーク　18. 原子核の地図　38. モンテカルロ計算　53. フェルミ液体論
6. ニュートリノ　45. 光誘起相転移　41. トポロジカル秩序
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12. 反物質　7. 暗黒物質　48. 極限環境　46. 界面　52. 銅酸化物高温超伝導
21. 中性子星　2. 4次元時空　3. インフレーション　31. 量子電磁力学
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25. 宇宙線　35. 量子通信　65. タンパク質　32. 原子時計
23. ブラックホールと情報　67. 分子機械　61. 粉体　63. 生物の運動　42. 観るの極み
70. 物理学はどこへ？　64. シマウマの縞　66. 電子と生命　40. 還元と創発
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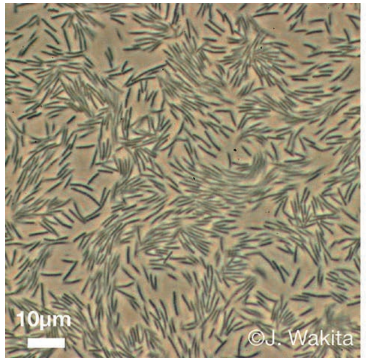
#63: Collective behaviors of cells and lives modelled as self-propelled particles

63 自走する粒子系としての細胞や生物集団のふるまい

混雑した駅の通路や交差点を歩いているうちに，行き交う人の流れに自然と「レーン」が形成されていることに気づくことがある．こうしたヒトの群集に限らず，動物の群れや微生物の集団を観察してみると，何かに命令されることなく，運動の様子や配置・配列に，ある種のパターンや構造が自発的に現れる例がいくつも見つかる（図左：バクテリア（枯草菌）が集団運動している様子）．

互いに影響し合いながら運動する同種の粒子や要素が呈する巨視的なふるまいを知り，その背後にある数理的な共通性や差異を明らかにするのは，統計物理の重要なテーマの1つである．細胞や動物，人工的な移動物体である自動車など，自ら運動する粒子や物体を「同種の粒子」とみなし，自己駆動粒子系やアクティブマターとよんで，その多体的・統計的なふるまいを明らかにしようという試みが広がっている．自己駆動粒子系は複雑でその例は多岐にわたるため，それらをすっきりと分類することは難しい．一般に，粒子自体が異方的で，エネルギー散逸と注入をともない，粒子間の実効的な相互作用に作用・反作用の法則が成り立たない．また，局所的なゆらぎが緩和せず系全体におよび，疎密や対流，渦などが自己組織される（図右：竜巻



状の鳥（ムクドリ）の渦巻き）などの点において，アクティブではない粒子の系とはふるまいが大きく異なる．

ゆらぎをともないながら自走する粒子を単純化した数理モデルとして，ビチェックモデル（Vicsek model）がよく調べられている．周囲と進行方向をそろえようとする効果とゆらぎとの競合によって，運動方向の秩序が不連続的に相転移することが知られている．はじめはランダムに歩行していた昆虫の集団が，ある密度を超えると1方向に行進をはじめる現象などが，このモデルでよく説明できるという報告もある．こうした研究によって，生物や人工物の「群れ」の数理的な理解が進みつつある．

Major categories of self-propelled particles

Dry particles

in which hydrodynamics is not important

ex. flock of birds

Wet particles

in which hydrodynamics plays crucial role

ex. school of fish

bioGraphicMagazine on YouTube

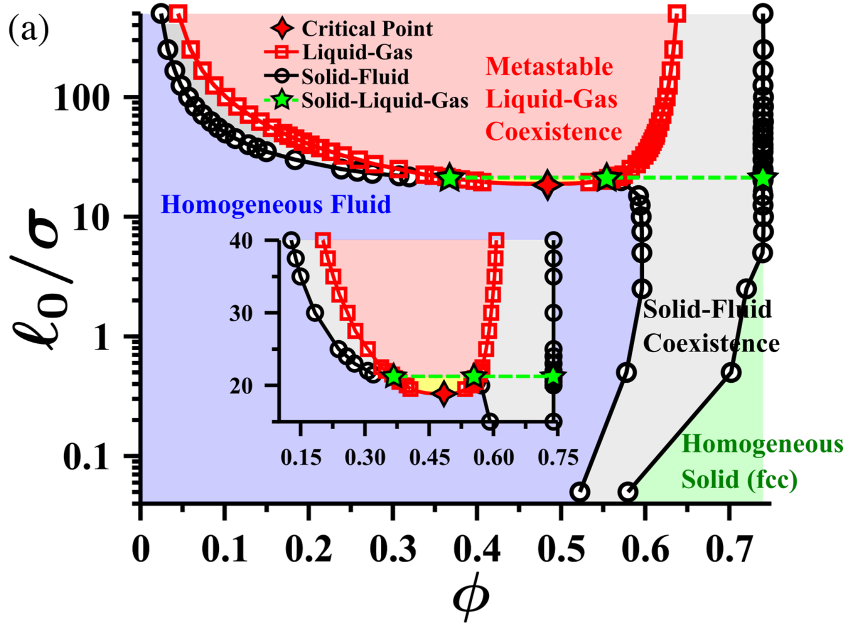
A popular dry particles: Active Brownian particles

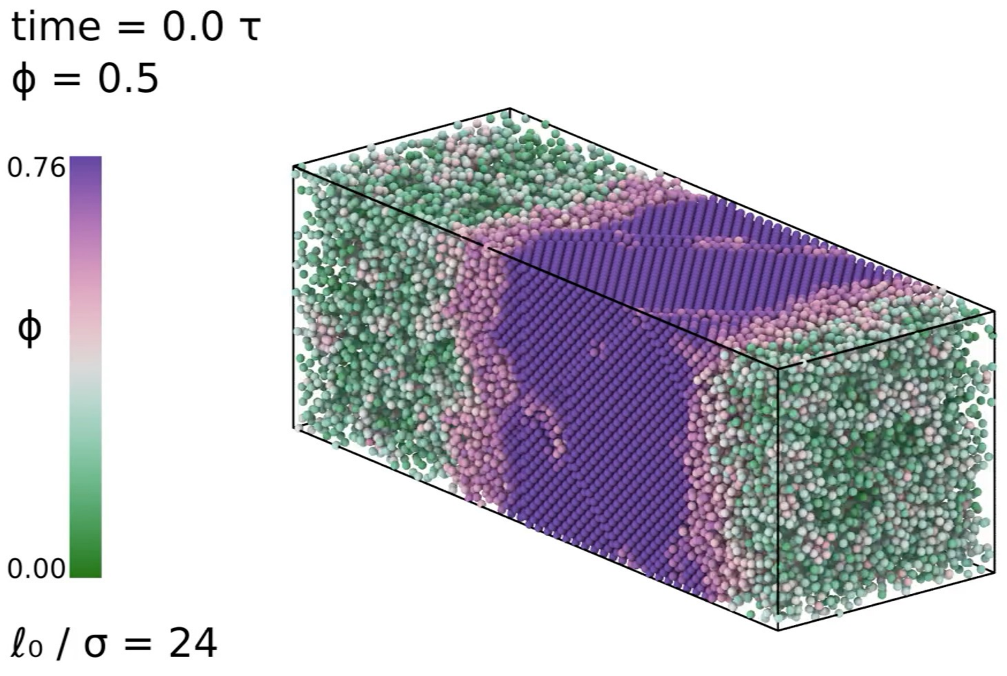
- MIPS: Cates, Tailleur, Ann. Rev. Cond. Matt. 6, 219 (2015)
- Omar, Klymko, GrandPre, Geissler, PRL 126, 188002 (2021)

$$\dot{\mathbf{r}} = v_0 \hat{\mathbf{n}} - (m\xi)^{-1} \nabla V(\mathbf{r}) + \sqrt{2D}\, \boldsymbol{\eta}_{\mathrm{trans}}(t)$$

$$\hat{\mathbf{n}} = (\cos\theta, \sin\theta)$$

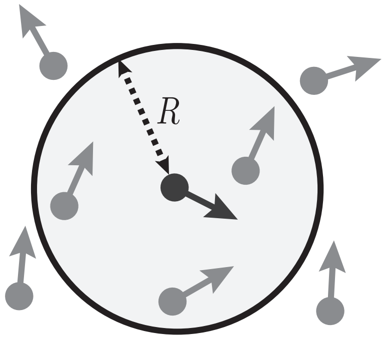
$$\dot{\theta} = \sqrt{2D_r}\, \eta_{\mathrm{rot}}(t).$$





Another popular dry particles: Vicsek model

- Tamás Vicsek et al., PRL 75, 1226 (1986)



$$\theta_j^{t+1} = \arg \sum_{k\sim j} \mathrm{e}^{\mathrm{i}\theta_k^t} + \eta_j^t$$

$$\boldsymbol{r}_j^{t+1} = \boldsymbol{r}_j^t + v_0 \boldsymbol{e}_{\theta_j^{t+1}}$$

$$\partial_t \boldsymbol{v} + \lambda_1 (\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} + \lambda_2 (\boldsymbol{\nabla}\cdot\boldsymbol{v})\boldsymbol{v} + \lambda_3 \boldsymbol{\nabla}(|\boldsymbol{v}|^2)$$
$$= \alpha\boldsymbol{v} - \beta|\boldsymbol{v}|^2\boldsymbol{v} - \boldsymbol{\nabla}P + D_B \boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\boldsymbol{v})$$
$$+ D_T \boldsymbol{\nabla}^2 \boldsymbol{v} + D_2 (\boldsymbol{v}\cdot\boldsymbol{\nabla})^2 \boldsymbol{v} + \boldsymbol{f},$$

$$P = P(\rho) = \sum_{n=1}^{\infty} \sigma_n (\rho - \rho_0)^n,$$

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}\cdot(\boldsymbol{v}\rho) = 0.$$

Vicsek model (discrete) → Toner-Tu model (continuum)

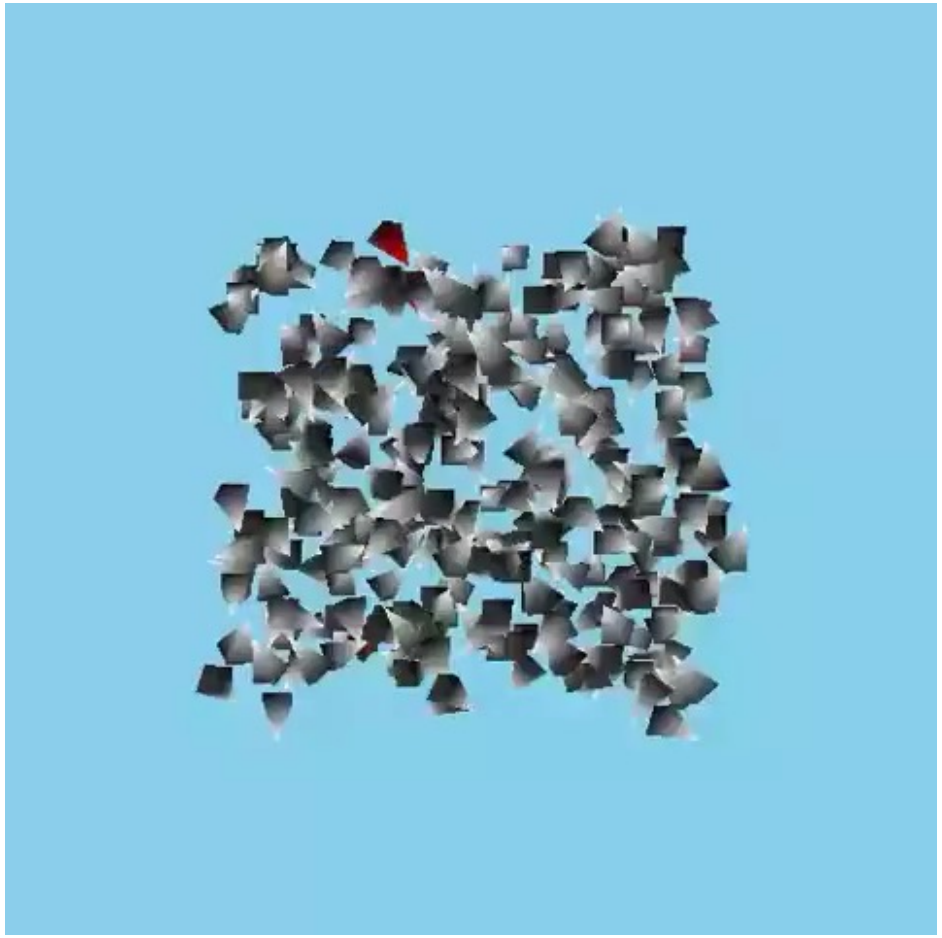
Fluid & Soft Matter UvA on YouTube

Other dry particles

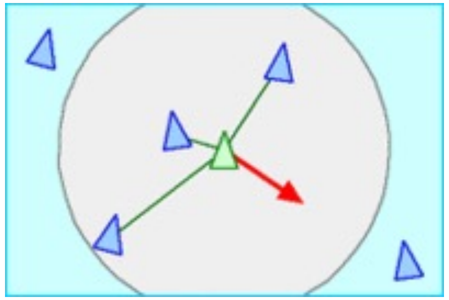
There existed a few good models before Vicsek.

Dry particles for CG: Boids

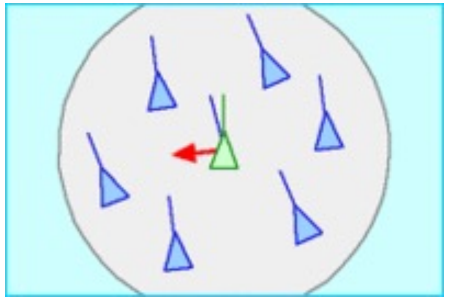
- artificial life program proposed by Craig Reynolds (1986)



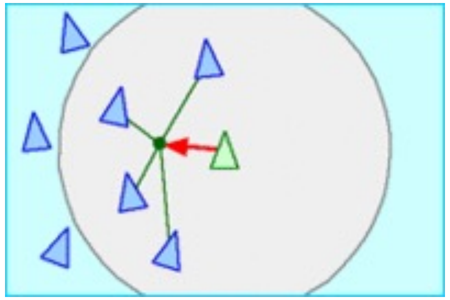
1) Separation



2) Alignment



3) Cohesion



Dry particles in Japanese article: Sakai model

- Sumiko Sakai, 生物物理 13, 83 (1973)

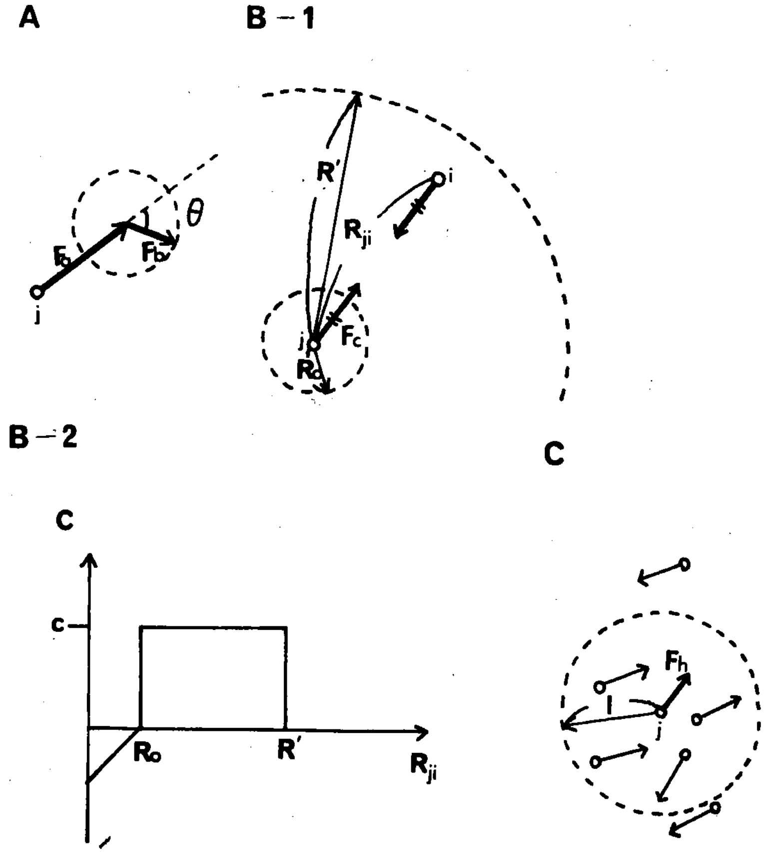


図 1 モデルの説明
(A) 個体 j の自己運動. (B) 接近運動 B−2 は, 引力Cと個体間の距離 R_{ji} との関係を示す. (C) 整列運動.

$$m\frac{d^2\mathbf{X}}{dt^2}+\nu\frac{d\mathbf{X}}{dt}=\mathbf{F}, \qquad (1)$$

$$\mathbf{F}_{aj}=a\left(\frac{d\mathbf{X}_j}{dt}\right)\Big\backslash\left|\frac{d\mathbf{X}_j}{dt}\right|, \qquad (2)$$ propulsion

$$\mathbf{F}_{cj}=\frac{1}{N-1}\sum_{i=1}^{N}\frac{C(R_{ji})(\mathbf{X}_i-\mathbf{X}_j)}{R_{ji}}, \qquad (3)$$ attraction + collision

$$\mathbf{F}_{hj}=\frac{1}{M}\sum_{\mathbf{X}_i\in A_j}h\left(\frac{d\mathbf{X}_i}{dt}-\frac{d\mathbf{X}_j}{dt}\right), \qquad (4)$$ aligning

$$\mathbf{F}_b=\mathbf{b}(t) \qquad (5)$$ random

Dry particles in Japanese article: Sakai model

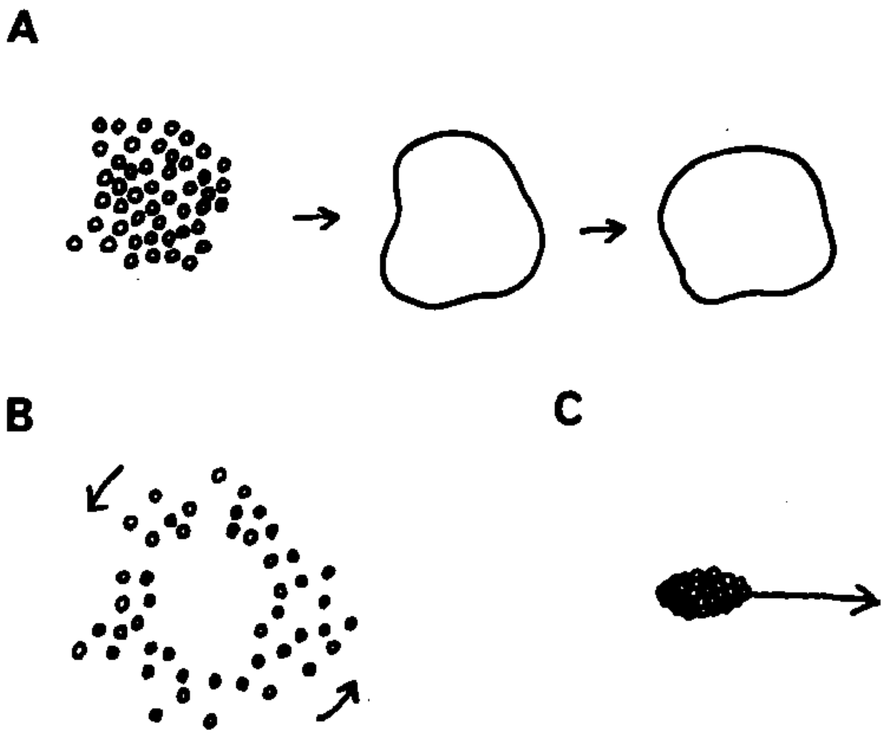


図 3　群れのパターンの種類

（i）　アメーバ状運動

推進力が小さく擾乱が大きいと，群れは小さくかたまりほとんど止っている．形はほぼ円形であるが，周辺の形状は刻々様々に変化する(図3－A)．

（ii）　ドーナツ形運動

推進力が大きくなると互いに輪状になって回転し，中心部に空洞のある群れになる．群れの重心はほとんど移動せず一ケ所に止って回転している(図3－B)．

(iii)　直進形運動

更に，整列作用が加わると小さくひとかたまりになって直進運動をする(図3－C)．

Dry particles in Japanese article: Sakai model

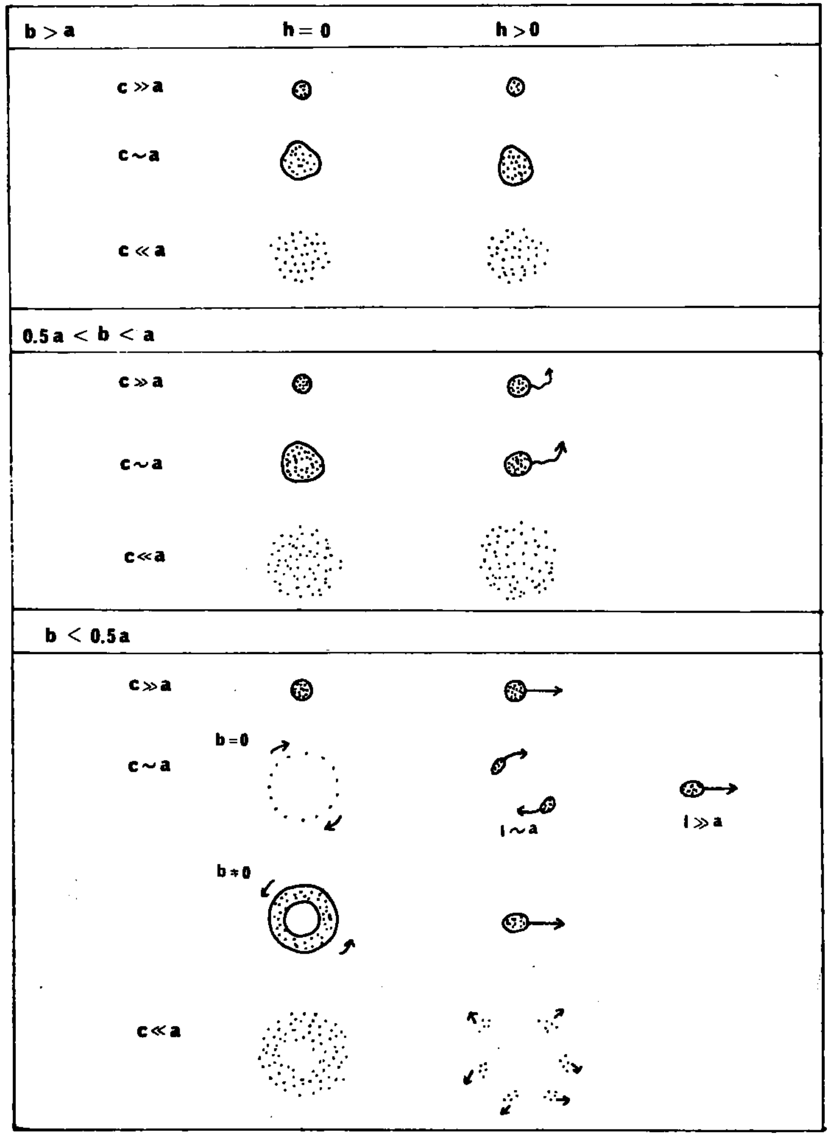


図 4 パラメータの変化による群れのパターンの変化

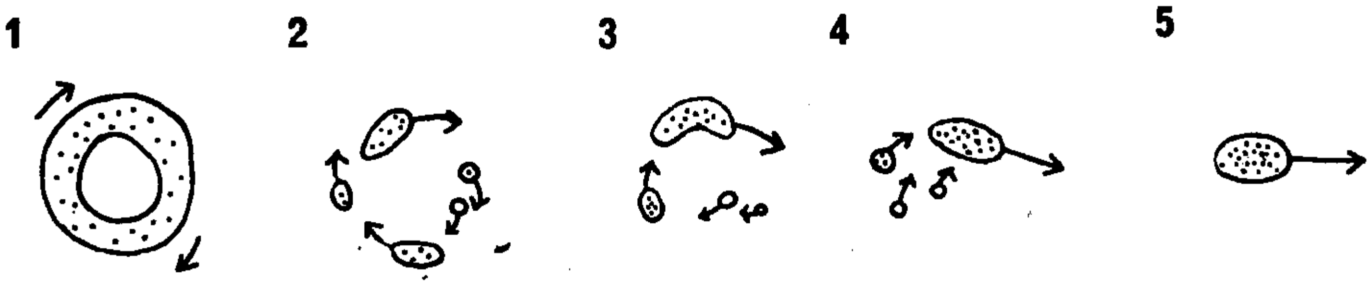


図 7 ドーナツ形から直進形の群れへの時間変化

Other dry particles

There proposed many models after Vicsek including …

Dry particles with vision: Hybrid Projection model

- Pearcea, Millera, Rowlandsa, Turner, PNAS 111, 10422 (2014)

$$\underline{v}_i^{t+1} = \phi_p \underline{\delta}_i^t + \phi_a \widehat{\left\langle \underline{v}_k^t \right\rangle}_{n.n.} + \phi_n \underline{\eta}_i^t,$$

opacity

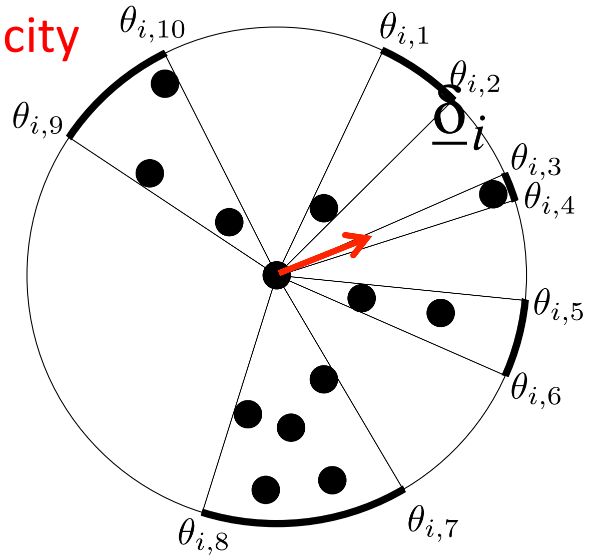
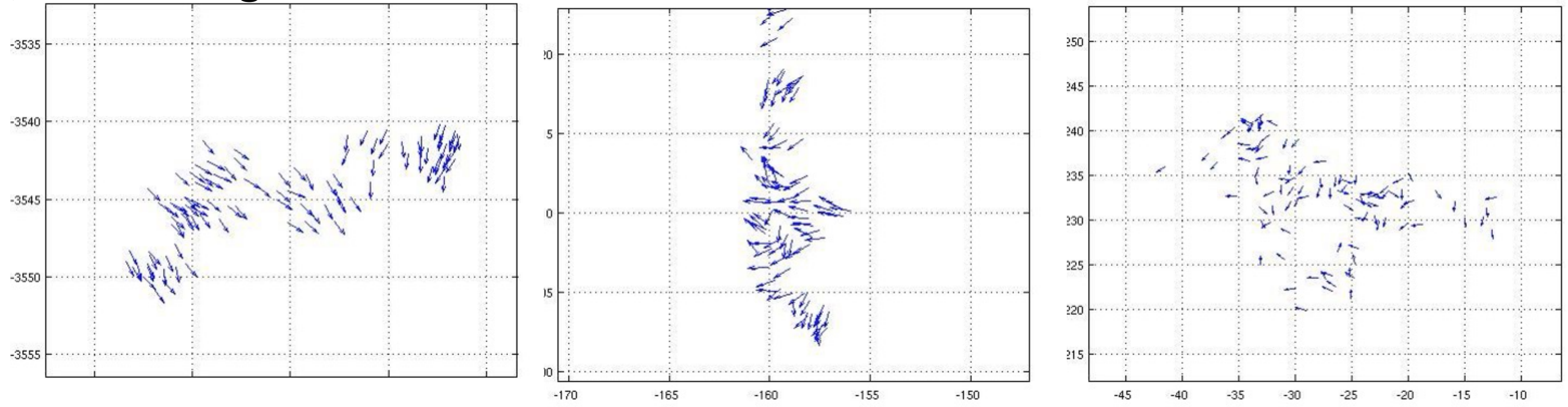


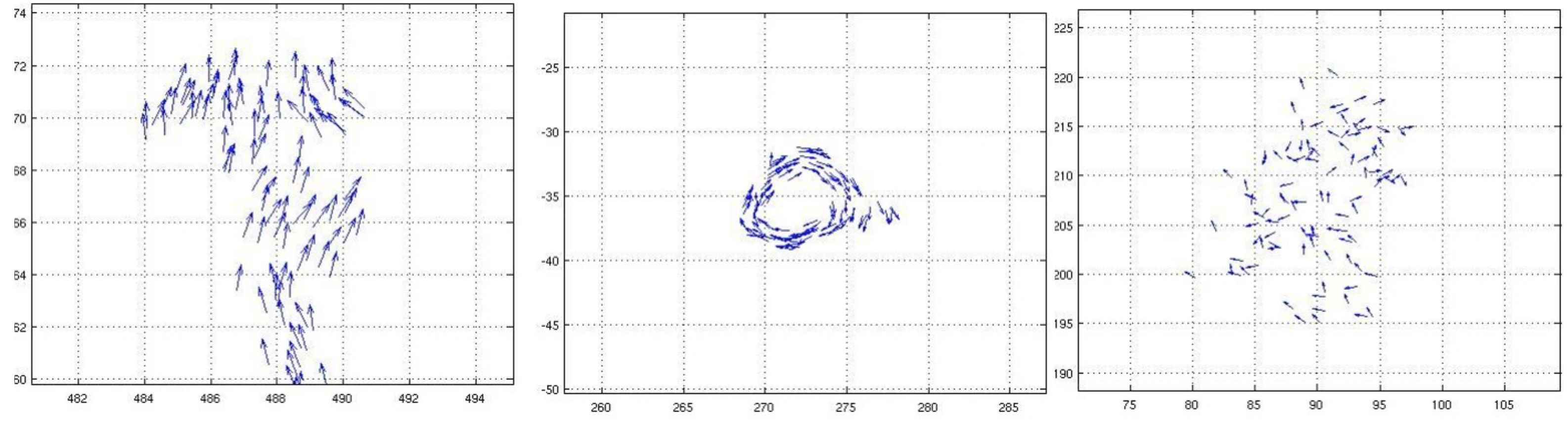
Fig. 1. Sketch showing the construction of the projection through a 2D swarm seen by the i^{th} individual, which here happens to be one near the center of the swarm. The thick dark arcs around the exterior circle (shown for clarity; there is no such boundary around the swarm) correspond to the angular regions where one or more others block the line of sight of the i^{th} individual to infinity. The sum of unit vectors pointing to each of these domain boundaries, at the angles shown, gives the resolved vector $\underline{\delta}_i$, shown in red, that enters our equation of motion. See *SI Appendix* for the extension to 3D.

$\phi_p = 0.1, \phi_a = 0.75$ | $\phi_p = 0.45, \phi_a = 0.45$ | $\phi_p = 0.175, \phi_a = 0.45$

w/o blind angle



with blind angle



Major categories of self-propelled particles

Dry particles

in which hydrodynamics is not important

ex. flock of birds

Wet particles = Swimmers

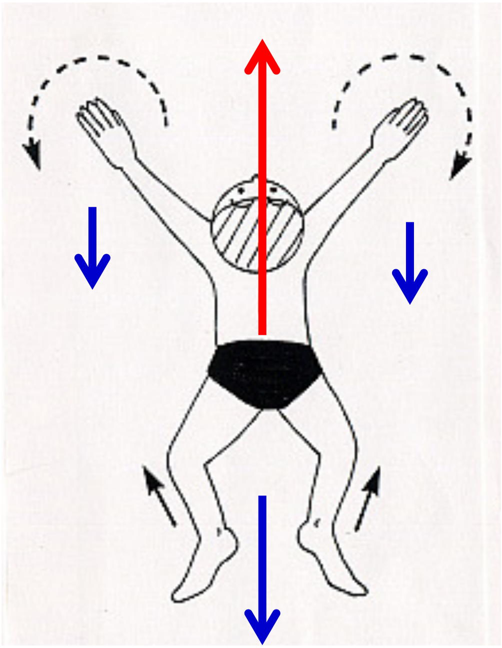
in which hydrodynamics plays crucial role

ex. school of fish

bioGraphicMagazine on YouTube

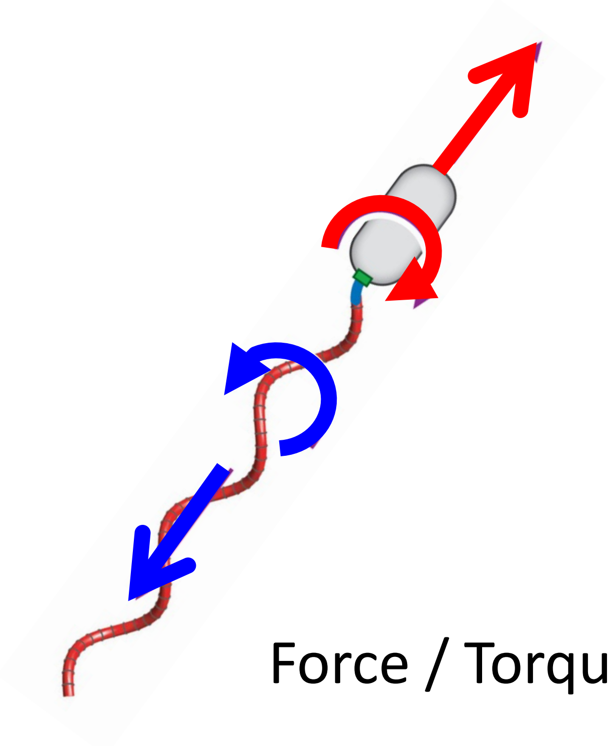
How can swimmers swim?

Breaststroke



Force free

E-coli bacteria



Force / Torque free

Swimming = Propulsion without external Force or Torque

$\mathbf{u}(\mathbf{r}) \sim |\mathbf{r}|^{-2}$

cf. driven colloid $\mathbf{u}(\mathbf{r}) \sim |\mathbf{r}|^{-1}$

A detailed swimmer model

- boundary element method:
  Ishikawa, Sekiya, Imai, Yamaguchi, Biophys. J. 93, 2217 (2007)

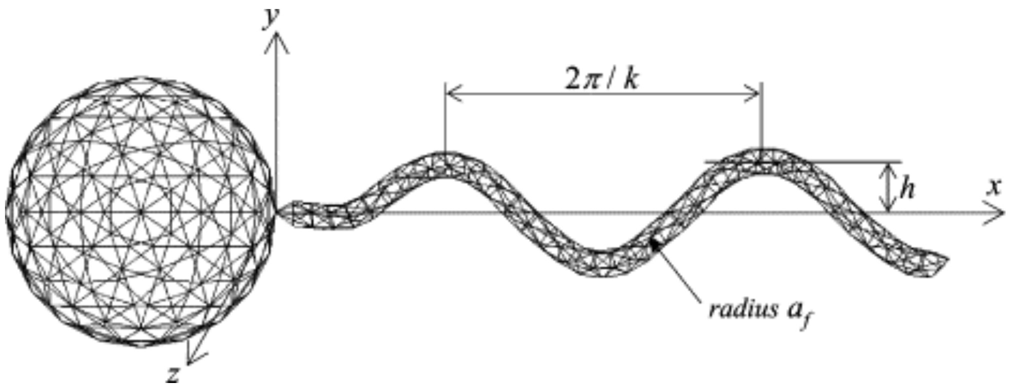
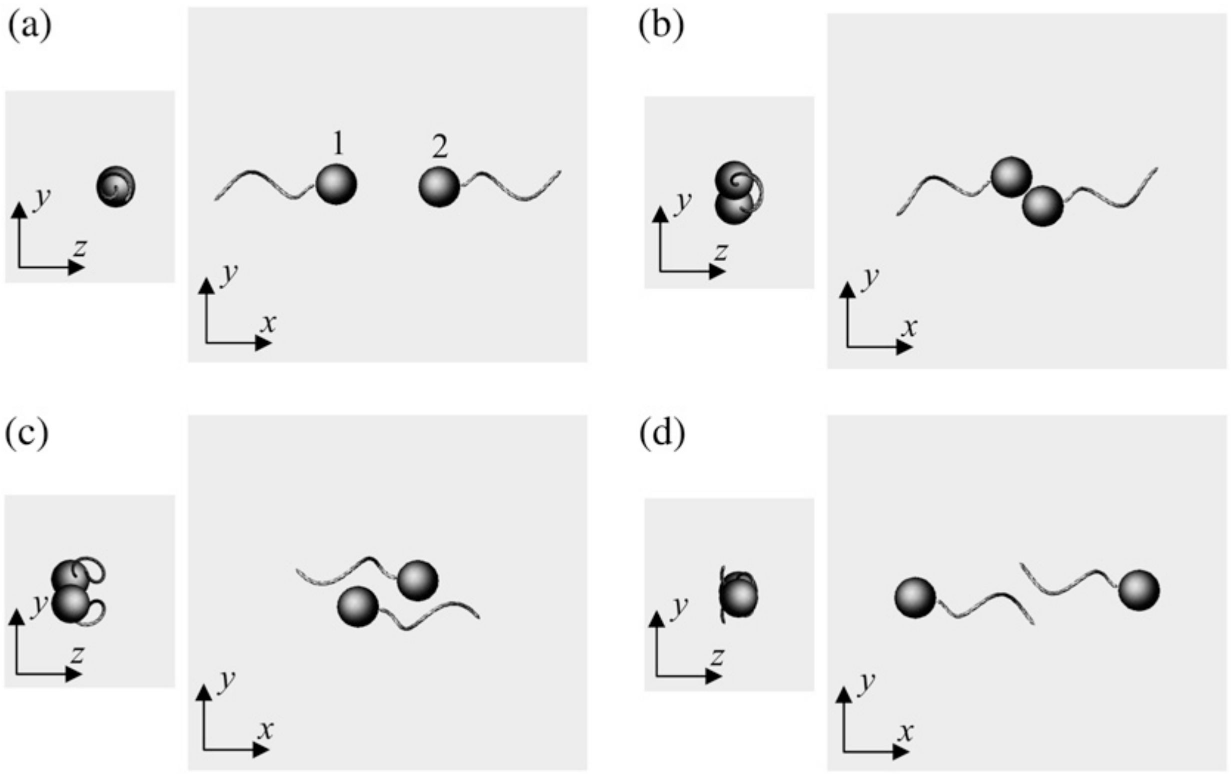


FIGURE 1 Shape parameters for a bacterial model with 360 and 320 triangle elements for the flagellum and spherical body, respectively. The total number of elements per bacterium is 680. (*a*) Shape A ($h = 0.77$, $k = k_E = 1.3$, and $a_f = 0.1$), (*b*) shape B ($h = 0.77/2$), and (*c*) shape C ($h = 0.77/2$, $k = 2.6$).



More detailed swimmer model

- PMC dynamics:
  Hu, Yang, Gompper, Winkler, Soft Matter 11, 7867 (2015)

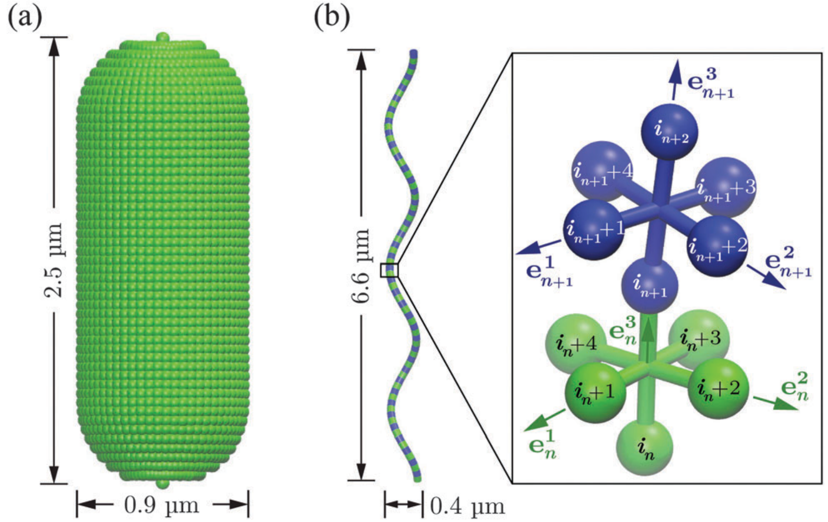


Fig. 2 (a) Model of the spherocylindrical cell body of diameter d = 0.9 μm and length ℓ_b = 2.5 μm. It is composed of 51 circular sections of particles, which are connected by the bond potential of eqn (1). (b) The flagellum, a three-turn left-handed helix of radius R = 0.2 μm, pitch Λ = 2.2 μm and contour length L_c = 7.6 μm (corresponding to the parallel length $L_{\parallel}$ = 6.6 μm), consists of 76 consecutive segments.

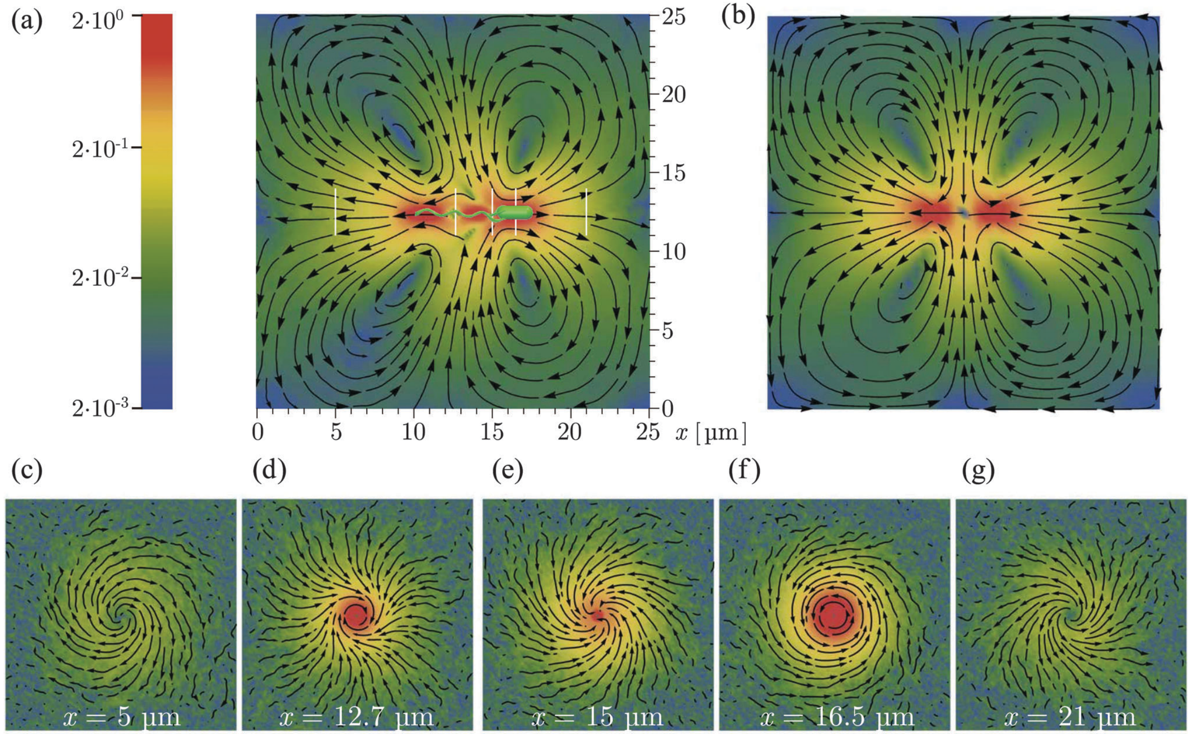


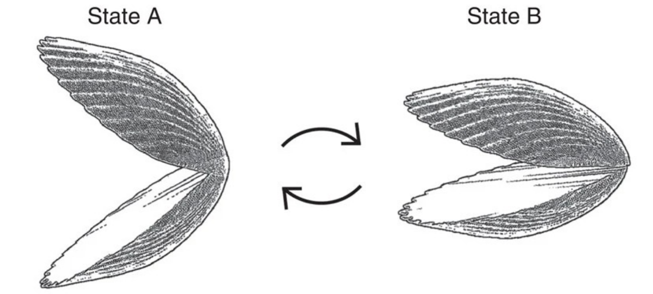
Fig. 5 Time-averaged flow field generated by a single swimming bacterium as obtained from simulations: (a) flow field in the swimming plane (b) the theoretical flow pattern for a finite-distance force dipole as illustrated in Fig. 6(a) as superposition of two Stokeslets within the same periodic box as for our simulations. (c–g) Flow fields in planes perpendicular to the swimming plane at positions indicated by the white vertical lines in (a). The streamlines indicate the flow direction, and the logarithmic color scheme indicates the magnitude of the flow speed scaled by the bacterial swimming velocity.

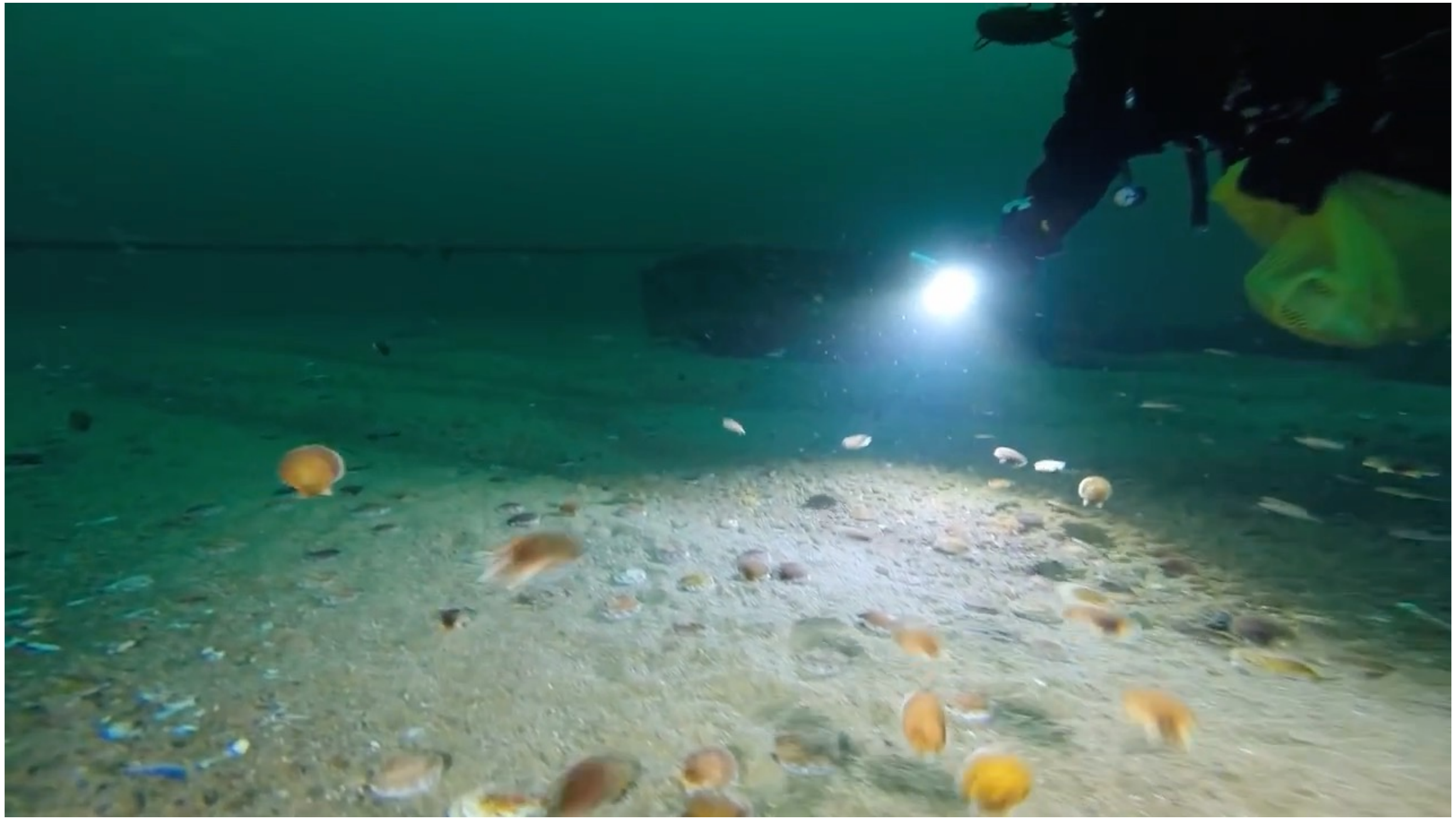
Simpler swimmers in a real-world

Q. Can scallops swim using simple reciprocal motion?

A. Yes, in a real-world (= at moderate Re).

simple reciprocal motion

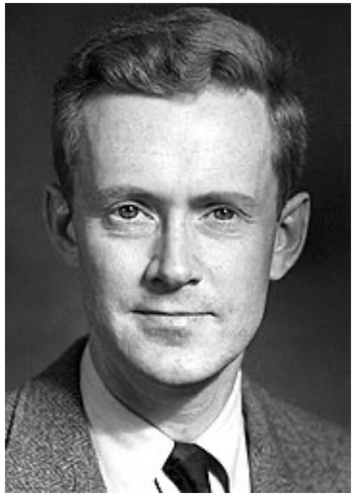




Simpler swimmers in a small-scale

A. No, in a small-world (= at low Re).

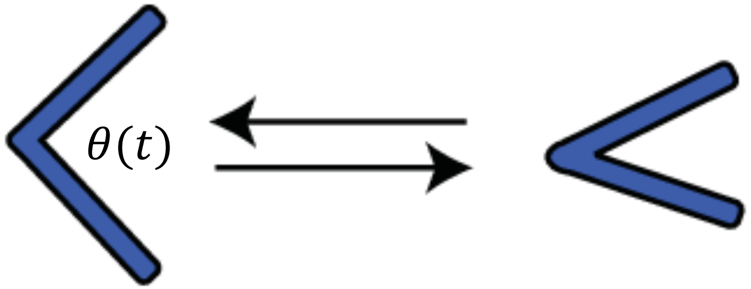
- Purcell theorem: Purcell, AJP 45, 3 (1977)



Edward Mills Purcell
(1912 –1997)
1952 Nobel Prize for Physics: Discovery of NMR

Reciprocal

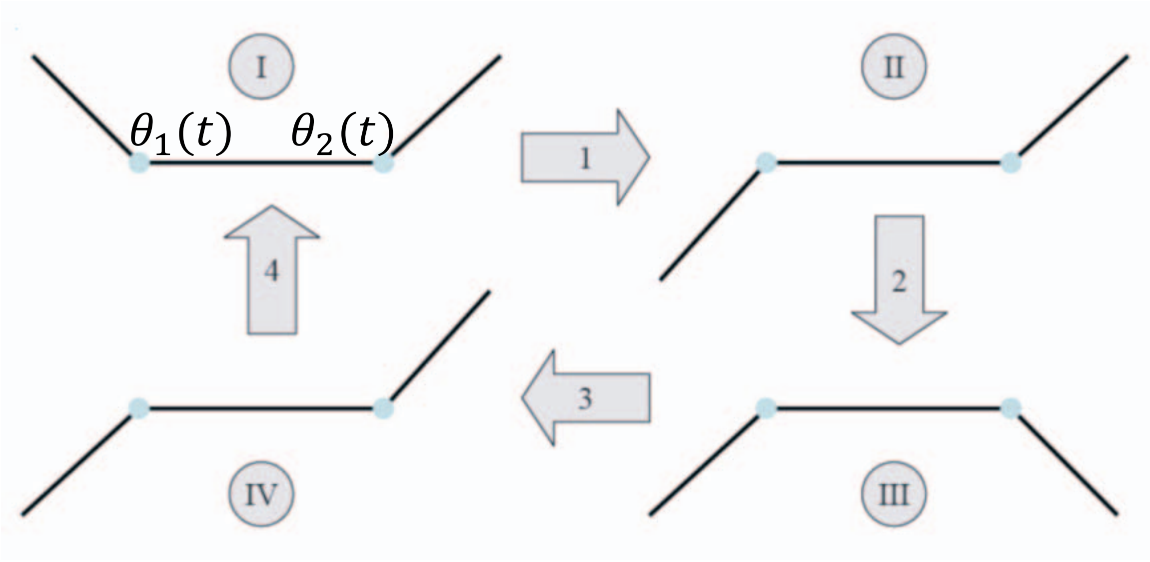
$$\langle V \rangle = 0$$



Scallop

Non-reciprocal (Circulative)

$$\langle V \rangle \neq 0$$



Purcell's swimmer

A model microswimmer (3-linked spheres)

- 3-sphere NG model: Najafi, Golestanian, PRE 69, 062901 (2004)

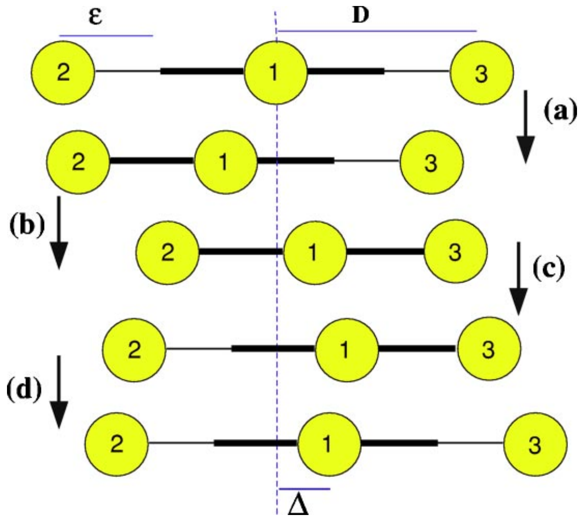


FIG. 2. Complete cycle of the proposed nonreciprocal motion of the swimmer, which is composed of four consecutive time-reversal breaking stages: (a) the left arm decreases its length with the constant relative velocity W, (b) the right arm decreases its length with the same velocity, (c) the left arm opens up to its original length, and finally, (d) the right arm elongates to its original size. By completing the cycle the whole system is displaced to the right side by an amount Δ.

$$v_1 = \frac{f_1}{6\pi\eta a_1} + \frac{f_2}{4\pi\eta L_1} + \frac{f_3}{4\pi\eta(L_1+L_2)}$$

$$v_2 = \frac{f_1}{4\pi\eta L_1} + \frac{f_2}{6\pi\eta a_2} + \frac{f_3}{4\pi\eta L_2}$$

$$v_3 = \frac{f_1}{4\pi\eta(L_1+L_2)} + \frac{f_2}{4\pi\eta L_2} + \frac{f_3}{6\pi\eta a_3}$$

$$L_1 = l_1 + u_1, \qquad u_1(t) = d_1 \cos(\omega t + \varphi_1)$$

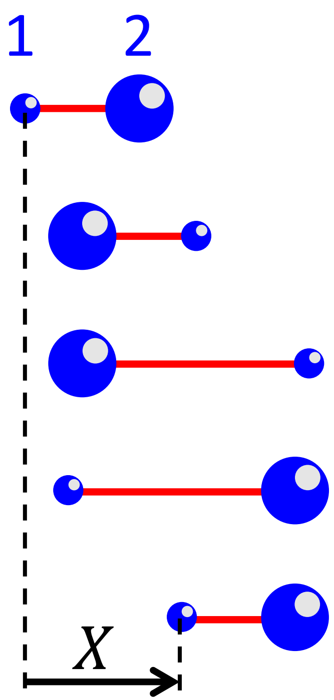
$$L_2 = l_2 + u_2, \qquad u_2(t) = d_2 \cos(\omega t + \varphi_2)$$

$$\overline{V_0} = \frac{K}{2} d_1 d_2 \omega \sin(\varphi_1 - \varphi_2)$$

phase shift between two actuators

A model microswimmer (2-linked spheres)

- push-me-pull-you (PMPY) model:
  Avron, Kenneth, Oaknin, NJP 7, 234 (2005)
  Silverberg et al., Bioinspiration and Biomimetics 15, 64001 (2020)



	$a_1(t)$	$a_2(t)$	$l(t)$
1)	$a_S \to a_L$	$a_L \to a_S$	l_S
2)	a_L	a_S	$l_S \to l_L$
3)	$a_L \to a_S$	$a_S \to a_L$	l_L
4)	a_S	a_L	$l_L \to l_S$

$$\dot{v}_1 + \dot{v}_2 = 0$$

w/o HI (2005)

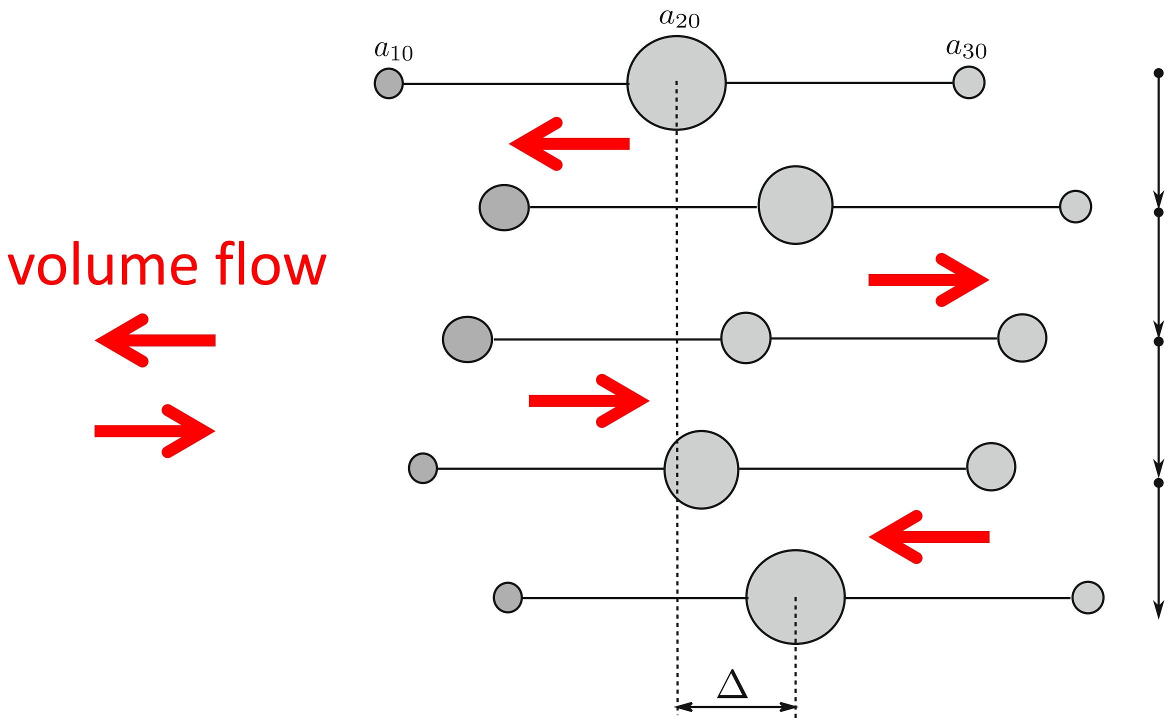
$$X = \frac{a_L - a_S}{a_L + a_S}(l_L - l_S)$$

with HI by Oseen tensor (2020)

$$X = \frac{a_L - a_S}{a_L + a_S}(l_L - l_S) + \frac{3a_S a_L}{(a_S - a_L)} \ln \frac{l_L}{l_S}$$

A model microswimmer (3-linked spheres)

- 3-sphere volume exchange (VE) model:
  Wang, Hu, Othmer, IMA 155, 185 (2012)



(1) $\delta a_1 = \delta_1 > 0$ while $\delta a_3 \equiv 0$;

(2) $\delta a_3 = \delta_3 > 0$ while $\delta a_1 \equiv 0$;

(3) $\delta a_1 = -\delta_1 > 0$ while $\delta a_3 \equiv 0$;

(4) $\delta a_3 = -\delta_3 > 0$ while $\delta a_1 \equiv 0$.

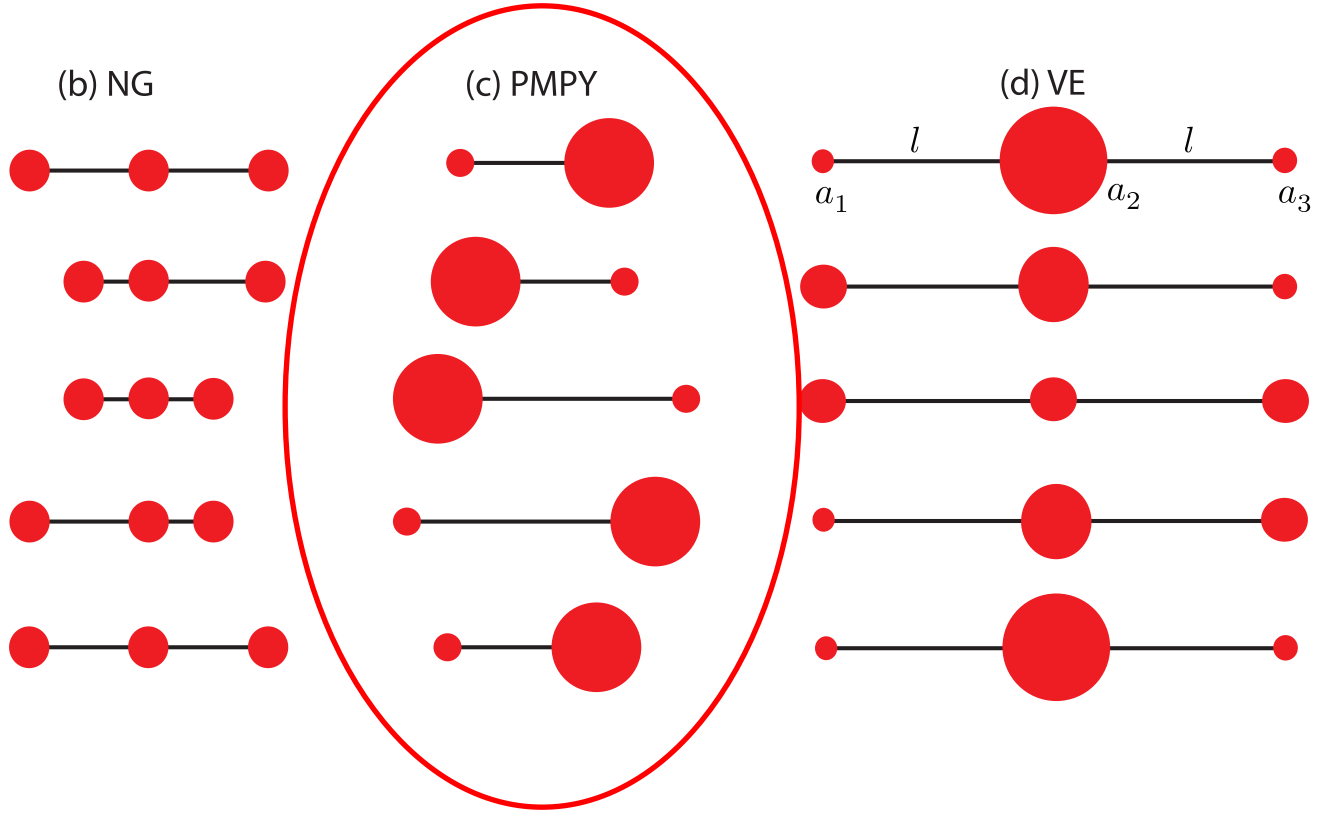
$$\dot{v}_1 + \dot{v}_2 + \dot{v}_3 = 0$$

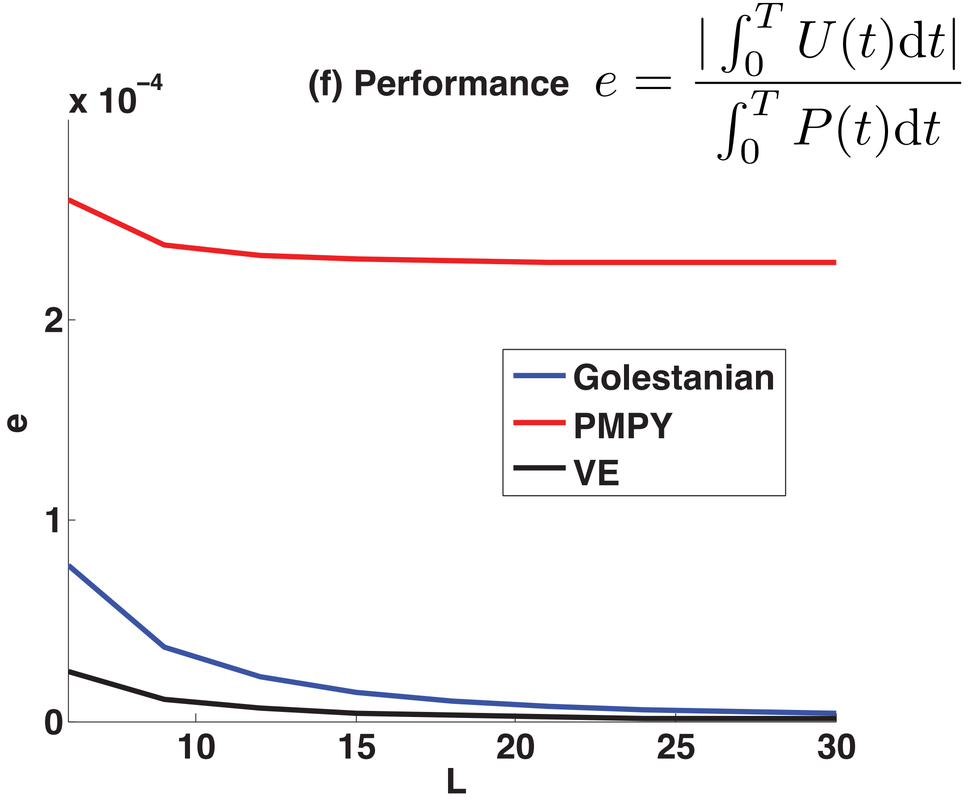
Comparisons of model microswimmers

- NG vs PMPY vs VE

  Wang, Othmer, MBE 12, 1303 (2015)

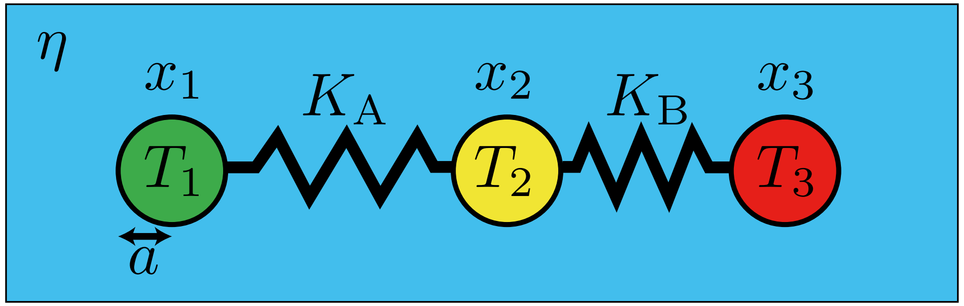
total volume in all spheres are the same, and the stroke amplitudes are the same for each mode.





A model microswimmer (3-linked spheres)

- Thermally driven elastic microswimmer: Hosaka, Yasuda, Sou, Okamoto, Komura, JPSJ 86, 113801 (2017)



Oseen tensor

$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{pmatrix} = \begin{pmatrix}M_{12} & M_{12} & M_{13}\\ M_{21} & M_{22} & M_{23}\\ M_{31} & M_{32} & M_{33}\end{pmatrix} \cdot \begin{pmatrix}f_1\\ f_2\\ f_3\end{pmatrix} + \begin{pmatrix}\xi_1\\ \xi_2\\ \xi_3\end{pmatrix}$$

$$\langle \xi_i(t)\xi_j(t')\rangle = k_B \bar{T}_{ij} M_{ij} \delta(t-t')$$

$$\bar{T}_{ii} = T_i, \quad \bar{T}_{ij} = \mathrm{ave}[T_i, T_j]$$

$$F_A = -K_A(x_2 - x_1 - l)$$
$$F_B = -\lambda K_A(x_3 - x_2 - l)$$

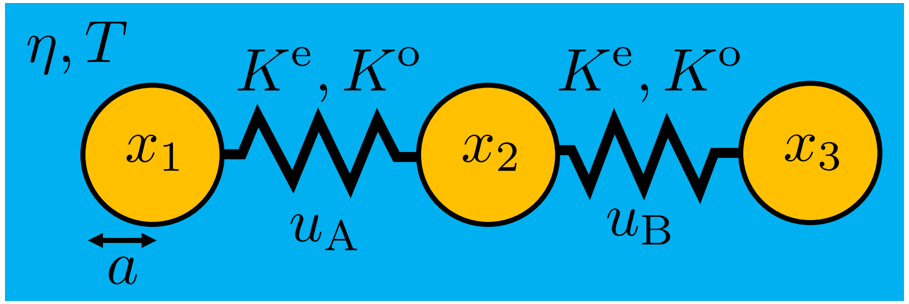
$$f_1 = -F_A$$
$$f_2 = F_A - F_B,$$
$$f_3 = F_B$$

$$\langle V\rangle \equiv \frac{(\dot{x}_1 + \dot{x}_3 + \dot{x}_3)}{3}$$
$$= \frac{k_B}{144\pi\eta l^2(1+\lambda)}[(2-5\lambda)T_1 - (7-7\lambda)T_2 + (5-2\lambda)T_3]$$

Temperature gradient drives the elastic microswimmer

A model microswimmer (3-linked spheres)

- Thermally driven odd-elastic microswimmer:
  Yasuda, Hosaka, Sou, Komura, JPSJ 90, 075001 (2021)



$$\begin{pmatrix} F_A \\ F_B \end{pmatrix} = -\begin{pmatrix} K^e & K^0 \\ -K^0 & K^e \end{pmatrix} \cdot \begin{pmatrix} x_2 - x_1 - l \\ x_3 - x_2 - l \end{pmatrix}$$

$$f_1 = -F_A$$
$$f_2 = F_A - F_B,$$
$$f_3 = F_B$$

Oseen tensor

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{pmatrix} = \begin{pmatrix} M_{12} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix} \cdot \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} + \begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{pmatrix}$$

$$\langle \xi_i(t)\xi_j(t') \rangle = k_B T M_{ij} \delta(t - t')$$

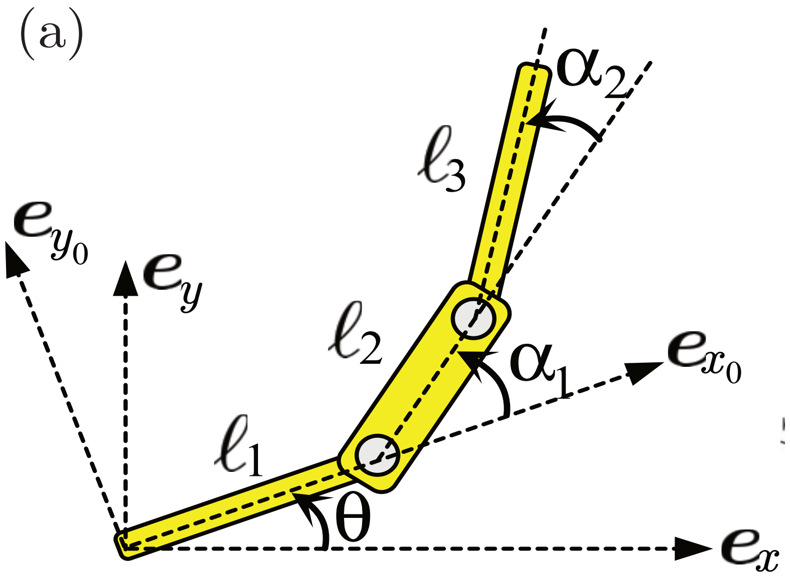
$$\langle V \rangle \equiv \frac{(\dot{x}_1 + \dot{x}_3 + \dot{x}_3)}{3} = \frac{7 a k_B T \lambda}{8 l^2 K^e \tau} + \mathcal{O}$$

$$\lambda \equiv K^0 / K^e$$
$$\tau \equiv 6\pi\eta a / K^e$$

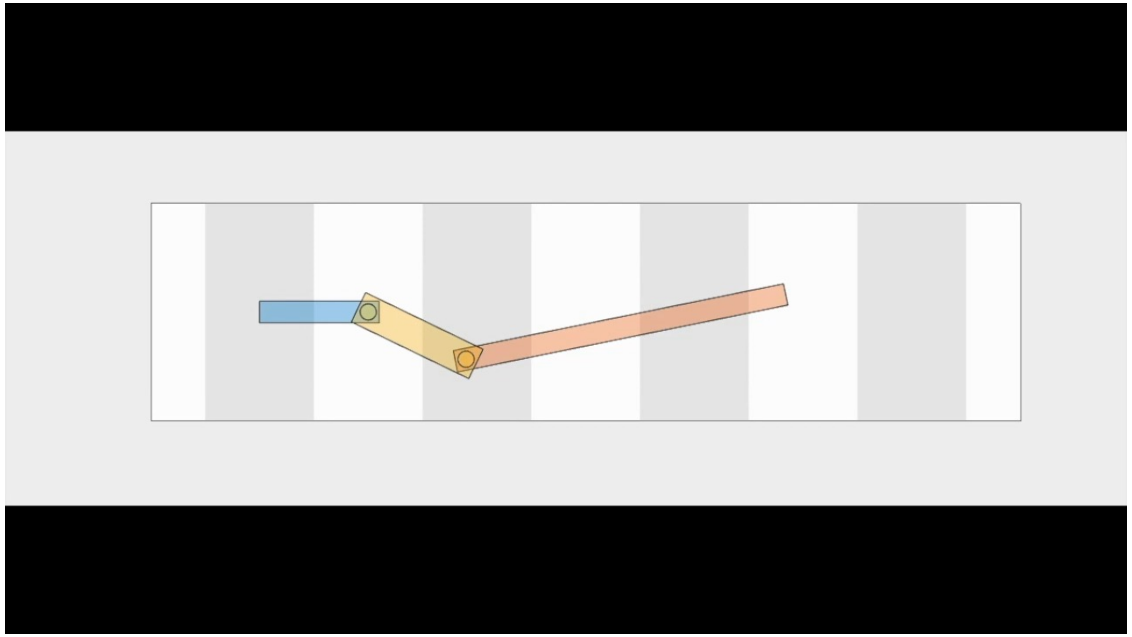
The odd-elastic microswimmer can spontaneously propel in a heat bath!!

A model microswimmer (3-linked rods)

- Purcell's swimmer with odd-elasticity:
  Ishimoto, Moreau, Yasuda, PRE 105, 064603 (2022)



$$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix} = -\begin{pmatrix} \kappa_e & \kappa_0 \\ -\kappa_0 & \kappa_e \end{pmatrix} \cdot \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} \qquad \gamma \equiv \kappa_0/\kappa_e$$



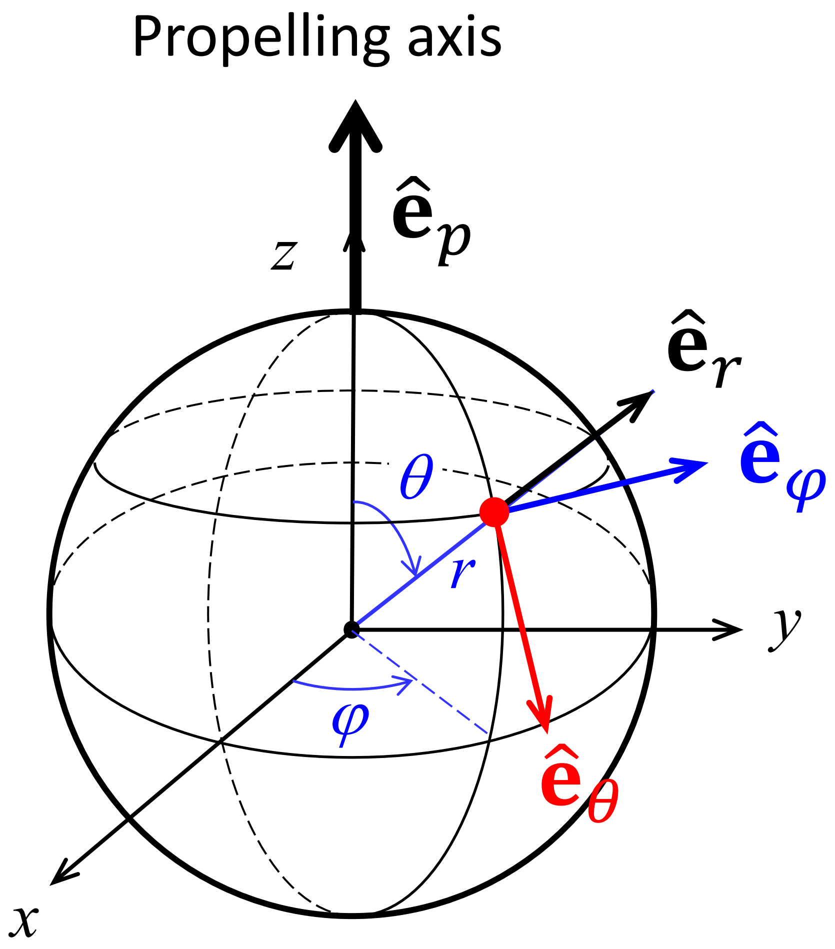
Spontaneous and autonomous motion can be sustained in viscous media by the odd-elasticity!!!

Unsolved problems of microswimmers

(of my personal choice)

A spherical microswimmer

- Squirmer model: Lighthill (1952), Blake (1971)



Sliding velocity $\boldsymbol{u}^{(s)}$ using polynomial expansion

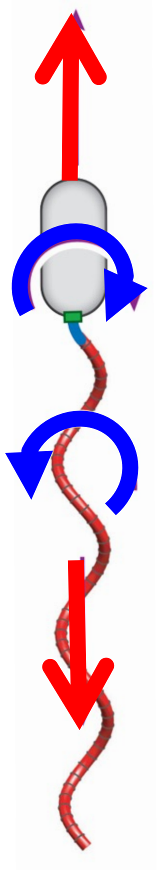
$$\boldsymbol{u}^{(s)} = \sum_{n=1}^{n=\infty} \frac{2}{n(n+1)} B_n \left(\hat{\boldsymbol{e}} \cdot \hat{\boldsymbol{r}}\hat{\boldsymbol{r}} - \hat{\boldsymbol{e}}\right) P_n'(\hat{\boldsymbol{e}} \cdot \hat{\boldsymbol{r}})$$

$$= \sum_{n=1}^{\infty} \frac{2}{n(n+1)} B_n P_n'(\cos\theta) \sin\theta \hat{\boldsymbol{\theta}}$$

↓ neglecting n>2

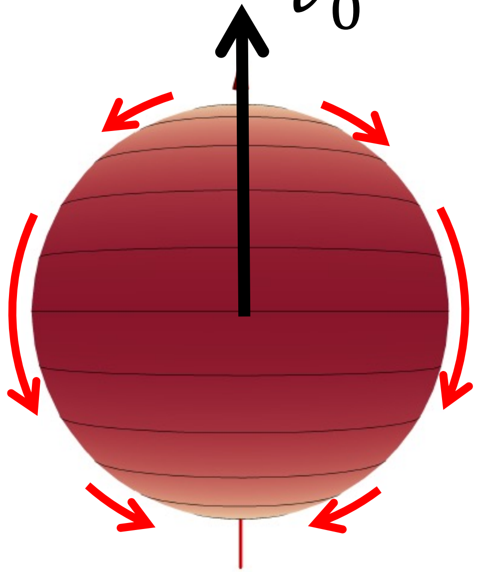
$$\mathbf{u}^{(s)} = \left(B_1 \sin\theta + B_2 \sin 2\theta\right) \hat{\boldsymbol{\theta}}$$

A spherical microswimmer

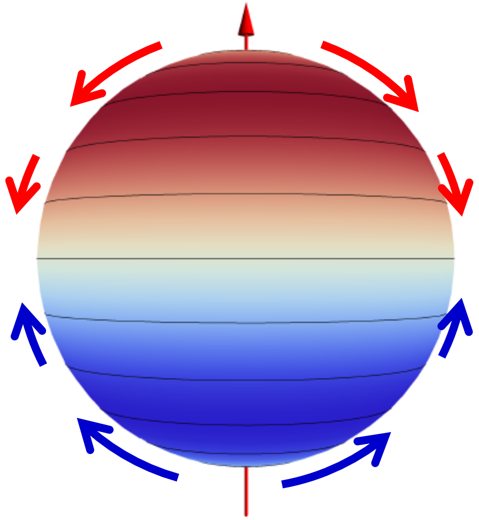


$\approx$

$$v_0 = \frac{2}{3} B_1$$



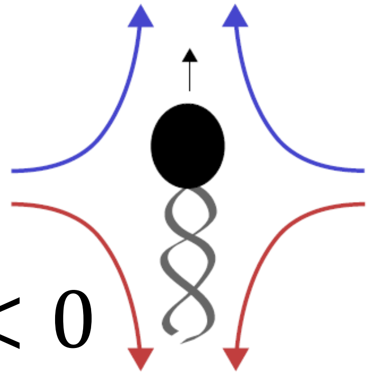
$+$



$B_1 \sin\theta \; \hat{\mathbf{e}}_\theta$ $\qquad$ $B_2 \sin 2\theta \; \hat{\mathbf{e}}_\theta$

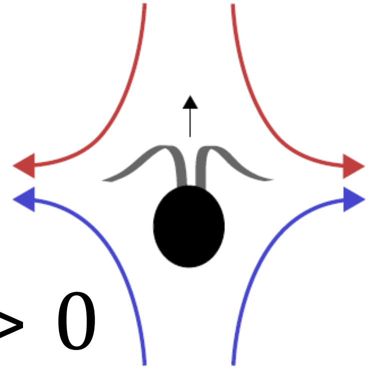
$$\beta \equiv \frac{B_2}{B_1}$$

$\beta < 0$



E-coli bacteria
(Pusher)

$\beta > 0$

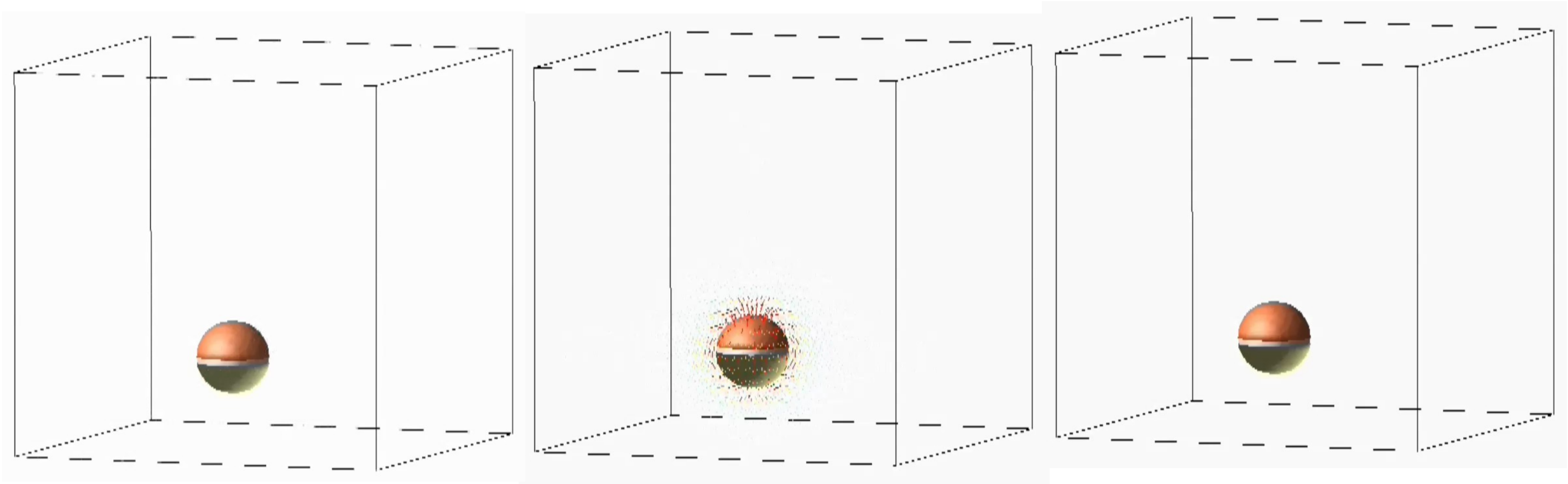


Chlamydomonas
(Puller)

Single squirmer motions

Pusher	Neutral	Puller
$\alpha = -2$	$\alpha = 0$	$\alpha = 2$

$$\alpha \equiv \frac{B_2}{B_1}$$



$$\boldsymbol{U} = \frac{2}{3} B_1 \hat{\boldsymbol{e}}$$

Pusher	Neutral	Puller
$\mathbf{u}(\mathbf{r}) \sim \lvert \mathbf{r} \rvert^{-2}$	$\mathbf{u}(\mathbf{r}) \sim \lvert \mathbf{r} \rvert^{-3}$	$\mathbf{u}(\mathbf{r}) \sim \lvert \mathbf{r} \rvert^{-2}$

Box: 64 x 64 x 64 with PBC, Particle radius: a=6, ϕ=0.002
Re=0.01, Pe=∞, Ma=0

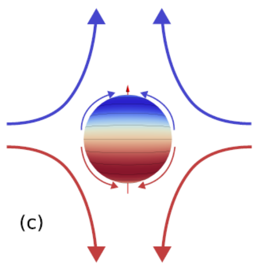
PRE 2016

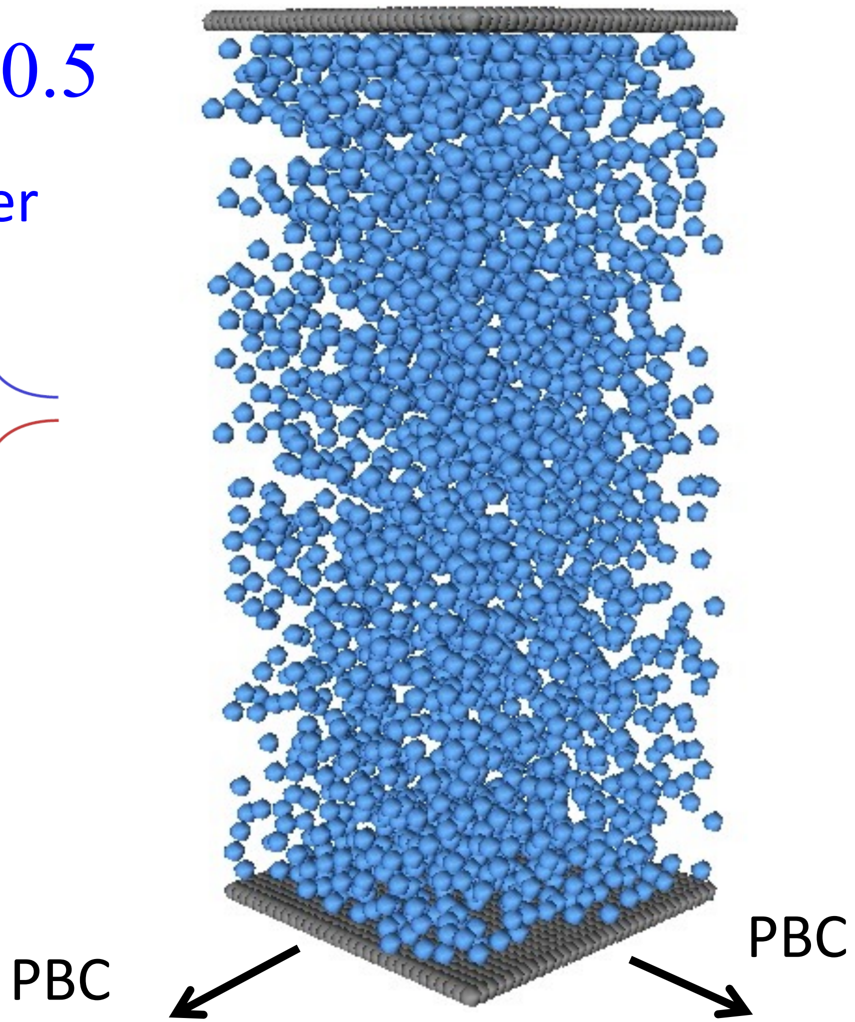
Collective behaviors of many pushers /pullers

Confined in parallel walls (V.F. of Squirmer = 0.13)

$\alpha = -0.5$

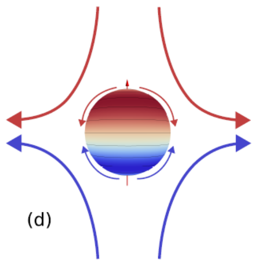
Pusher

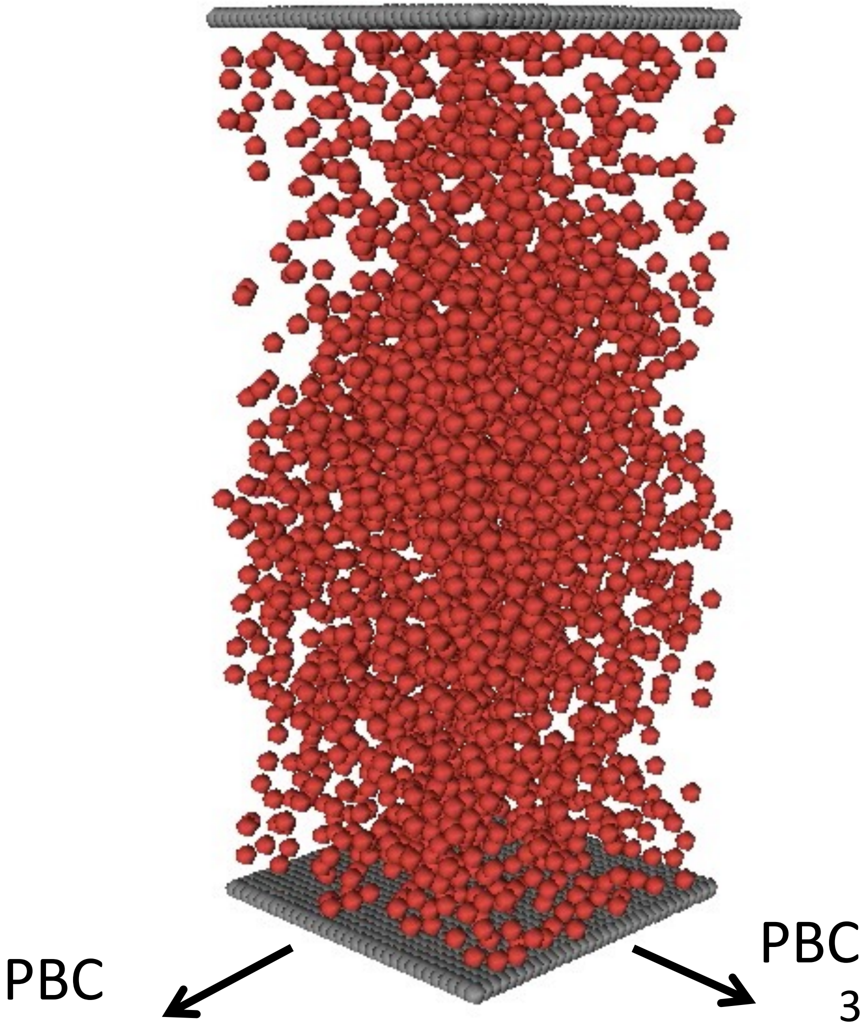




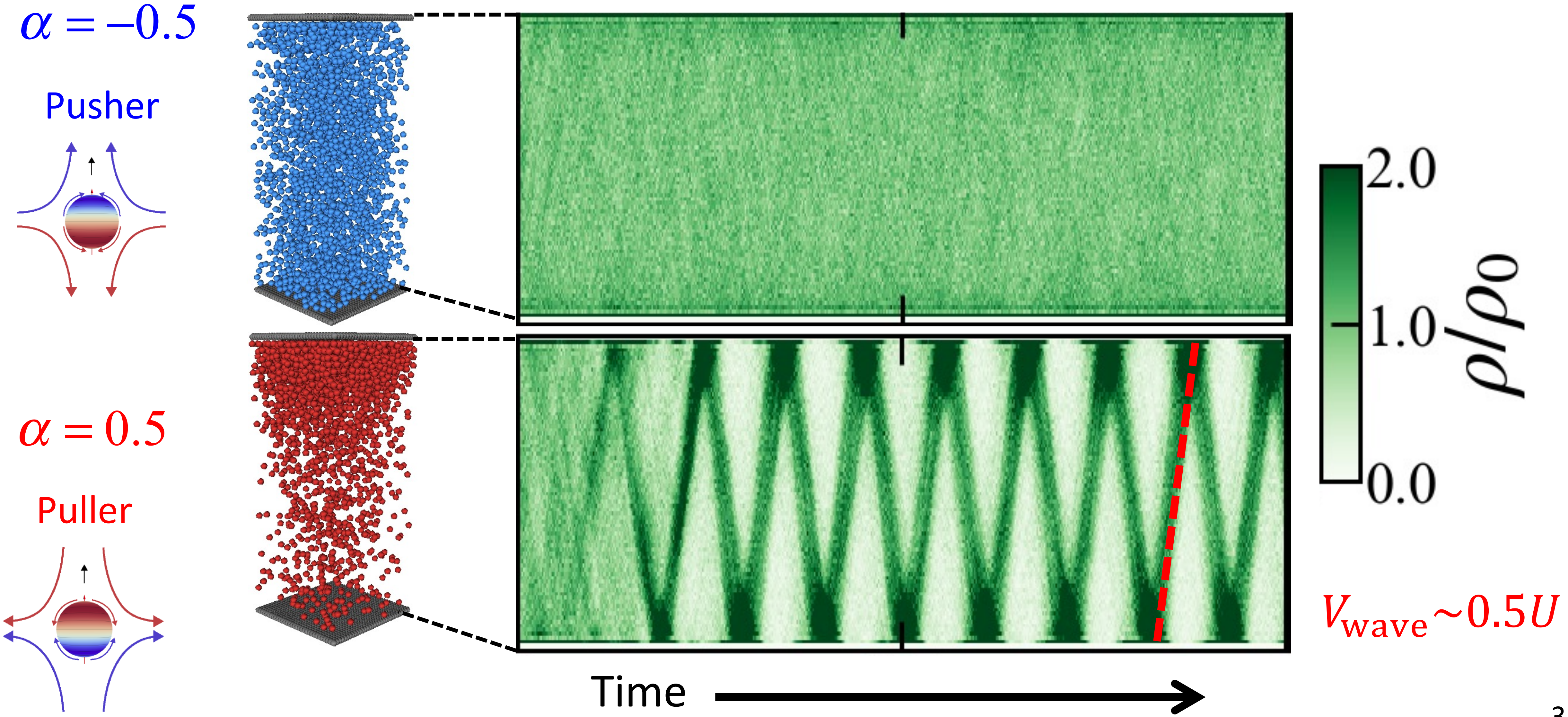
$\alpha = 0.5$

Puller

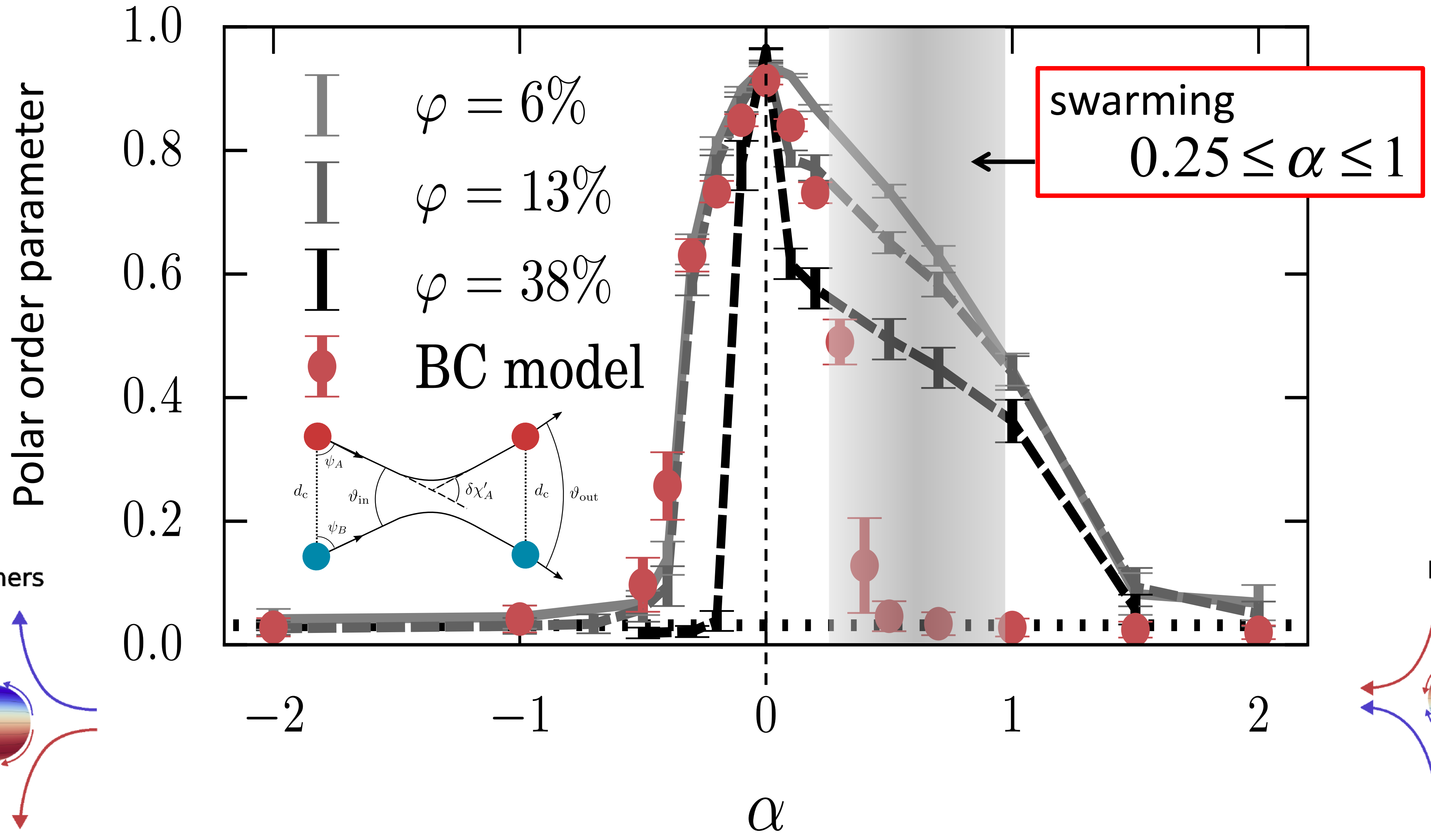


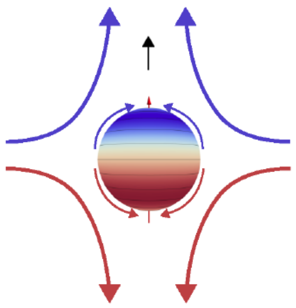


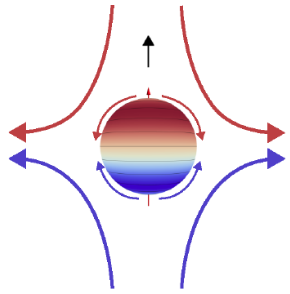
Collective behaviors of many pushers /pullers



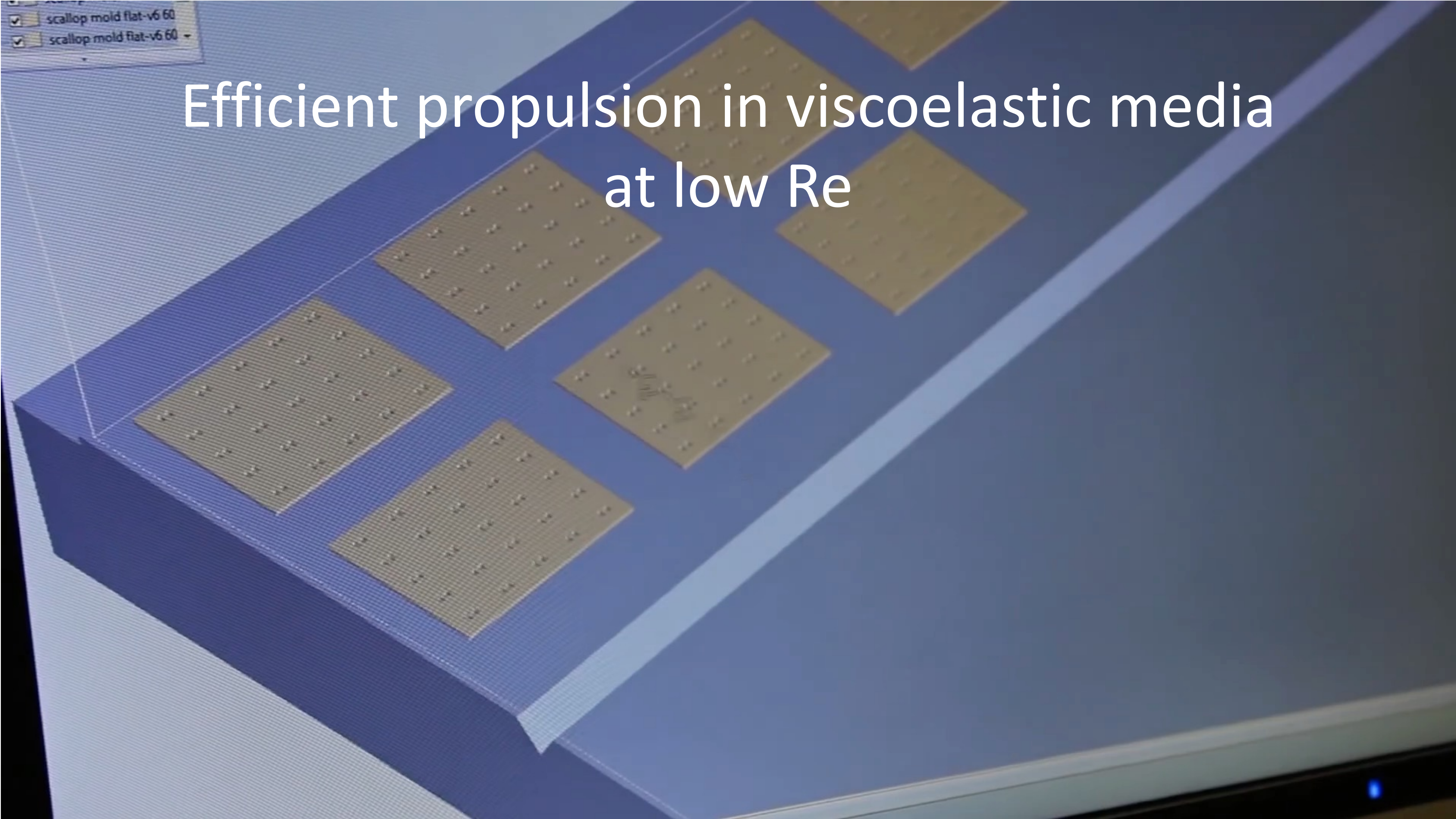
Collective behaviors of many pushers /pullers







Efficient propulsion in viscoelastic media at low Re



Squirmer in viscoelastic fluid

Oldroyd-B model

total stress: $\mathbf{T} = 2\eta_s \mathbf{D} + \tau$

solvent polymer

where $\tau + \lambda_1 \overset{\nabla}{\tau} = 2\eta_p \mathbf{D}$

upper convective Maxwell model

with

$$\overset{\nabla}{\mathbf{T}} = \frac{\partial}{\partial t}\mathbf{T} + \mathbf{v}\cdot\nabla\mathbf{T} - \left((\nabla\mathbf{v})^T \cdot \mathbf{T} + \mathbf{T}\cdot(\nabla\mathbf{v})\right)$$

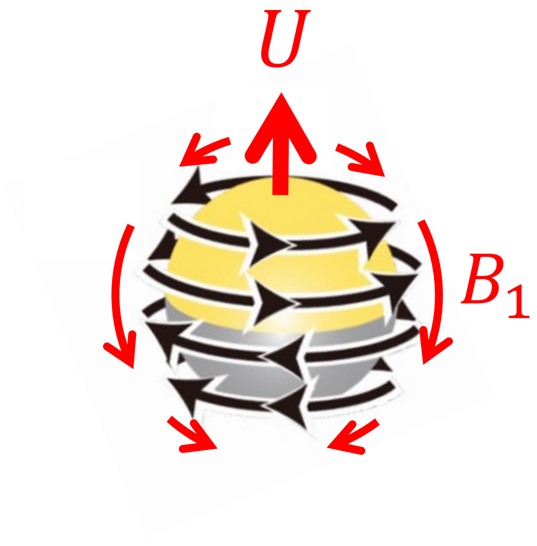
$$\mathbf{D} = \frac{1}{2}\left[\boldsymbol{\nabla}\mathbf{v} + (\boldsymbol{\nabla}\mathbf{v})^T\right]$$

$$\beta \equiv \frac{\eta_s}{\eta_s + \eta_p}$$

$$\mathrm{Wi} \equiv \frac{\lambda_1 B_1}{a}$$

T. Kobayashi (on-going)

Squirmer in viscoelastic fluid



Neutral swimmer

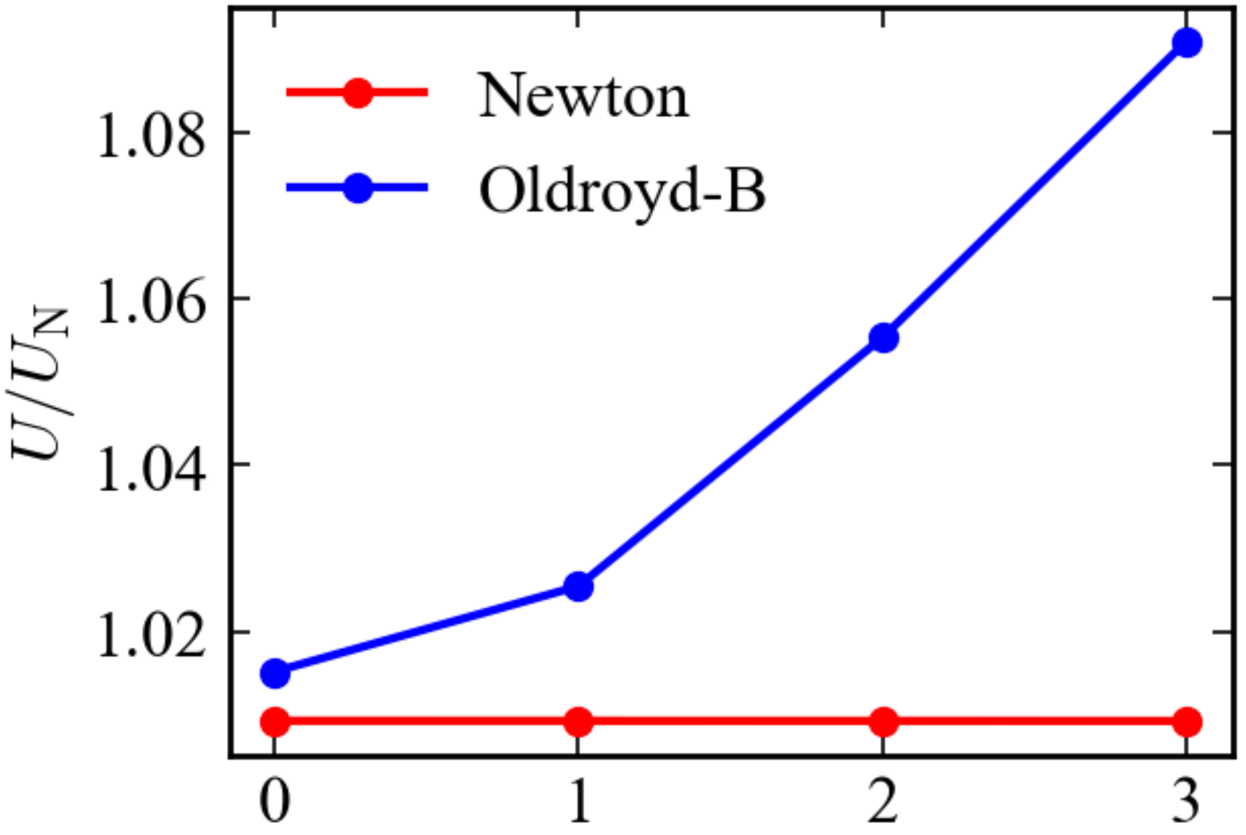
$B_2 = 0$

$$\alpha = 0$$

$$\zeta > 0$$

$$\beta \equiv \frac{\eta_s}{\eta_s + \eta_p} = 0.5$$

$$\mathrm{Wi} \equiv \frac{\lambda_1 B_1}{a} = 0.2$$

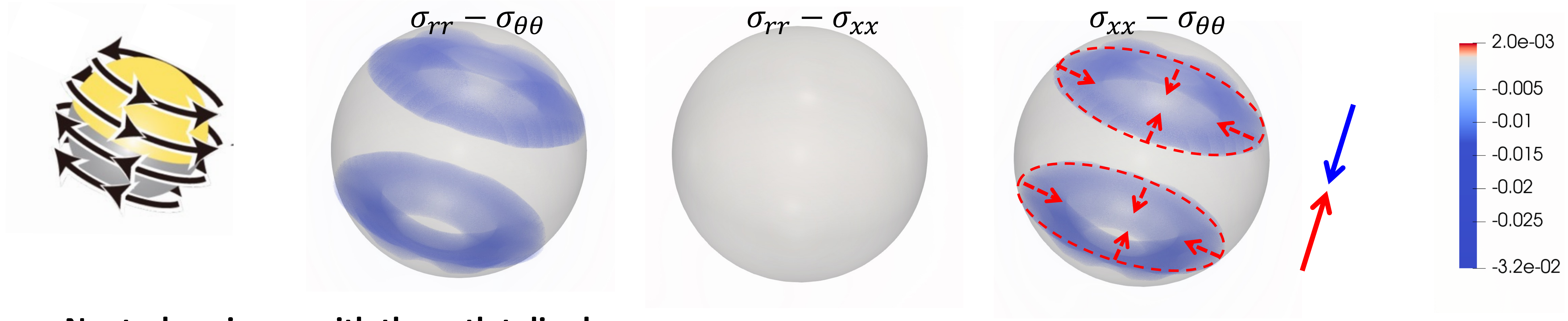


$$\zeta \equiv \frac{C_2}{B_1}$$

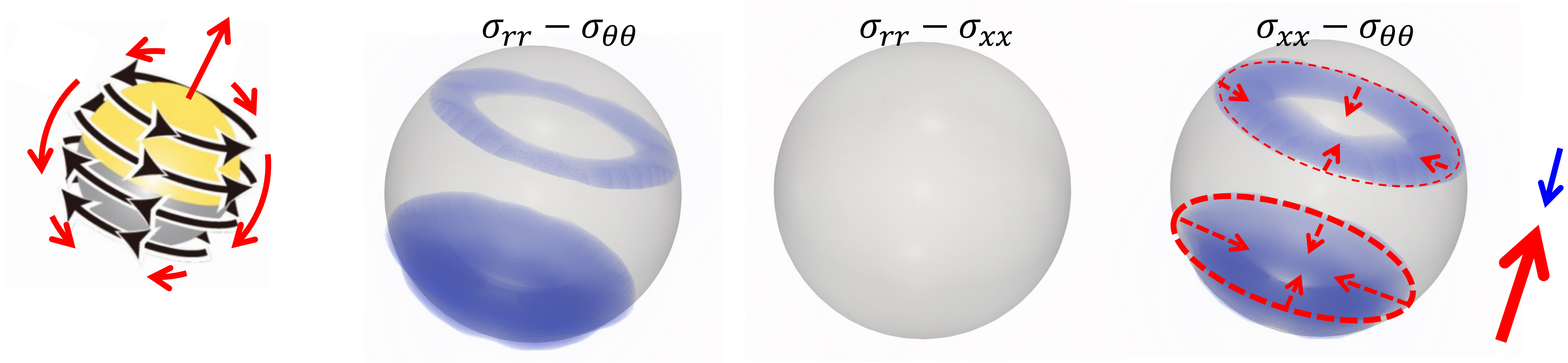
T. Kobayashi (on-going)

Squirmer in viscoelastic fluid

Squirmer with only rotlet dipole

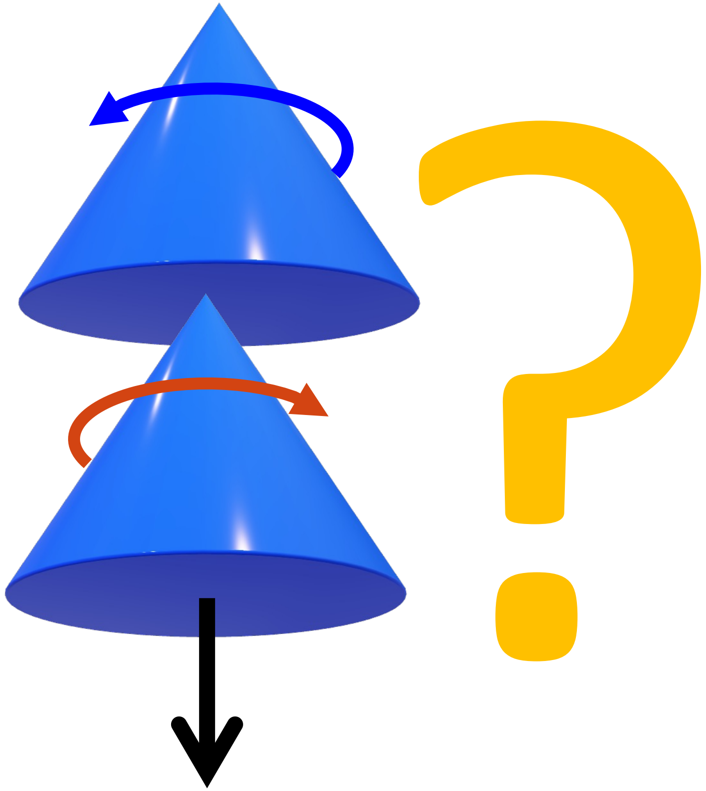


Neutral squirmer with the rotlet dipole



Efficient propulsion in viscoelastic media

Weissenberg effect



Visco-elastic propeller

Thank you for your kind attention.

Model microswimmer (1 sphere)

- DDFT model:
  Menzel, Saha, Hoell, Löwen, JCP 144, 024115 (2016)

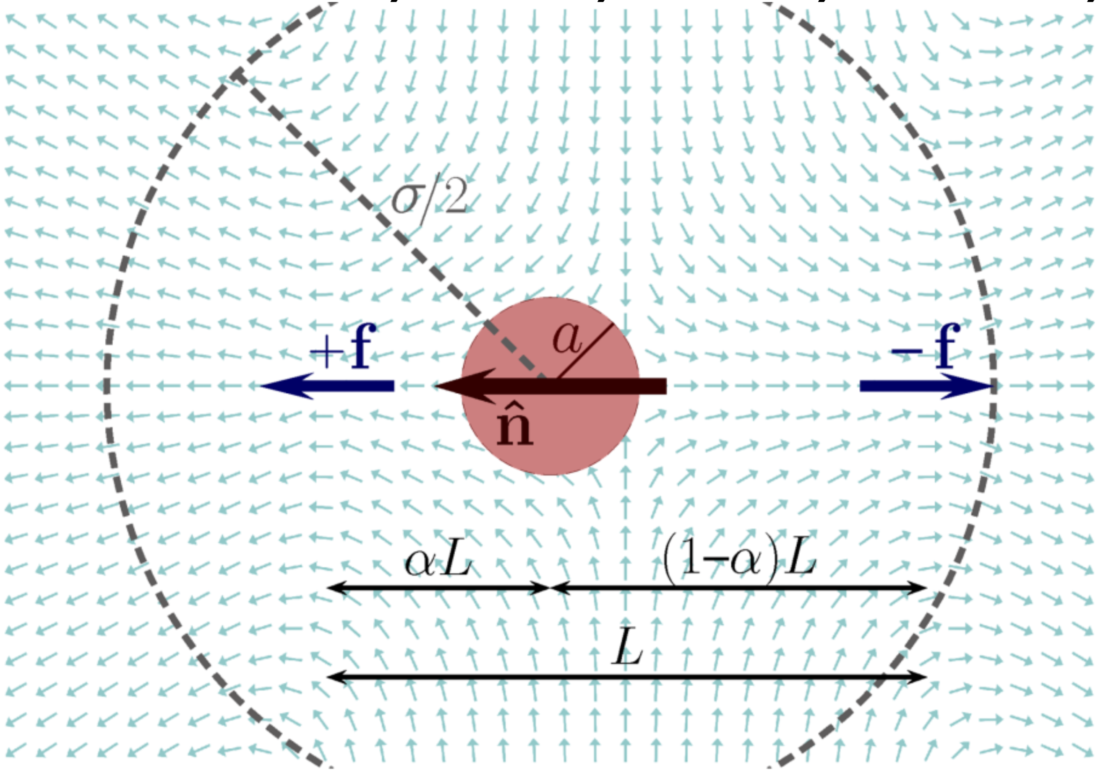


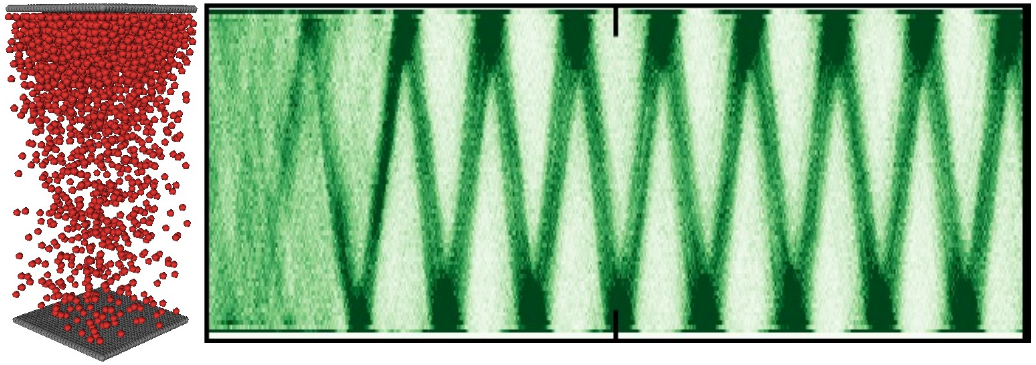
FIG. 1. Individual model microswimmer. The spherical swimmer body of hydrodynamic radius a is subjected to hydrodynamic drag. Two active point-like force centers exert active forces $+\mathbf{f}$ and $-\mathbf{f}$ onto the surrounding fluid. This results in a self-induced fluid flow indicated by small light arrows. L is the distance between the two force centers. The whole setup is axially symmetric with respect to the axis $\hat{\mathbf{n}}$. If the swimmer body is shifted along $\hat{\mathbf{n}}$ out of the geometric center, leading to distances αL and $(1-\alpha)L$ to the two force centers, it feels a net self-induced hydrodynamic drag. The microswimmer then self-propels. In the depicted state (pusher), fluid is pushed outward. Upon inversion of the two forces, fluid is pulled inward (puller). We consider soft isotropic steric interactions between the swimmer bodies of typical interaction range σ, implying an effective steric swimmer radius of $\sigma/2$.

Swarm propagation: Mixtures

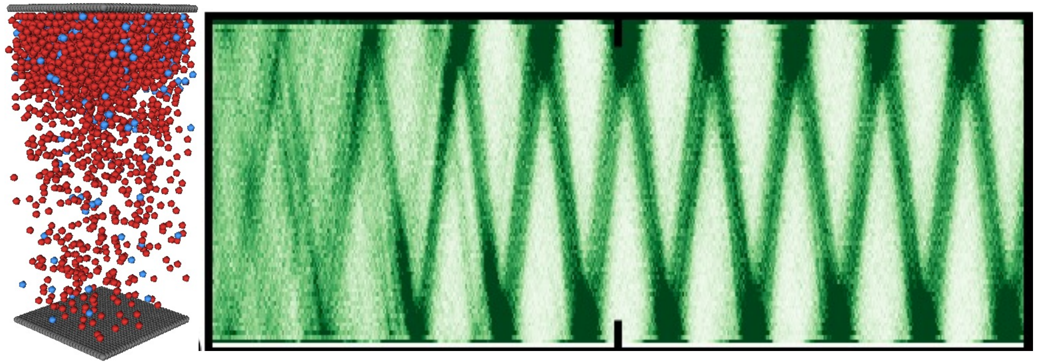
x_{Puller}

↓

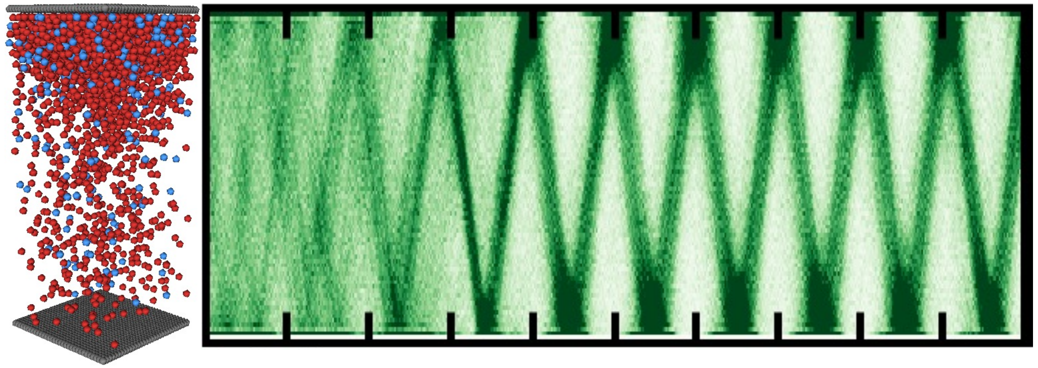
1.0



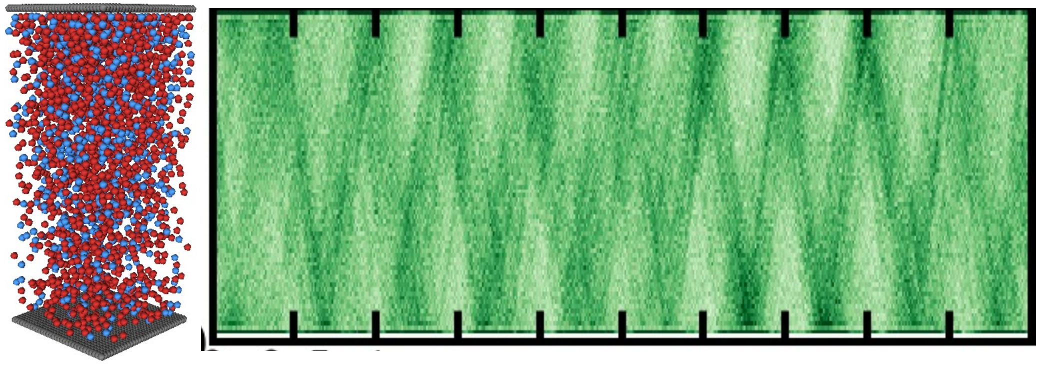
0.9



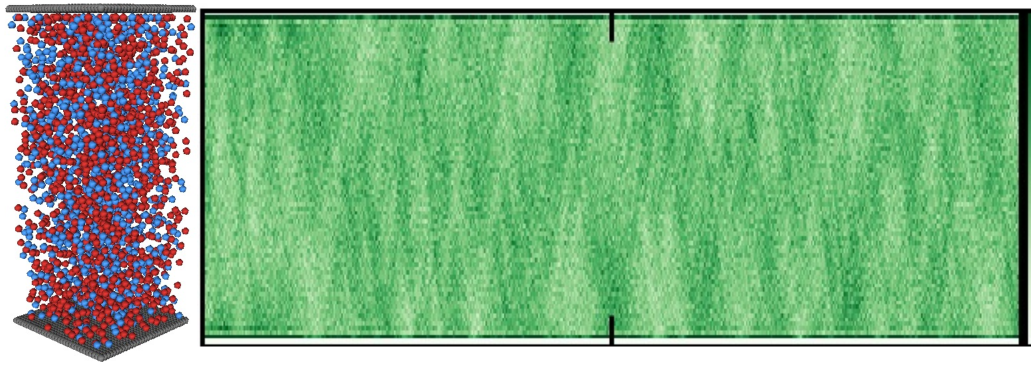
0.8



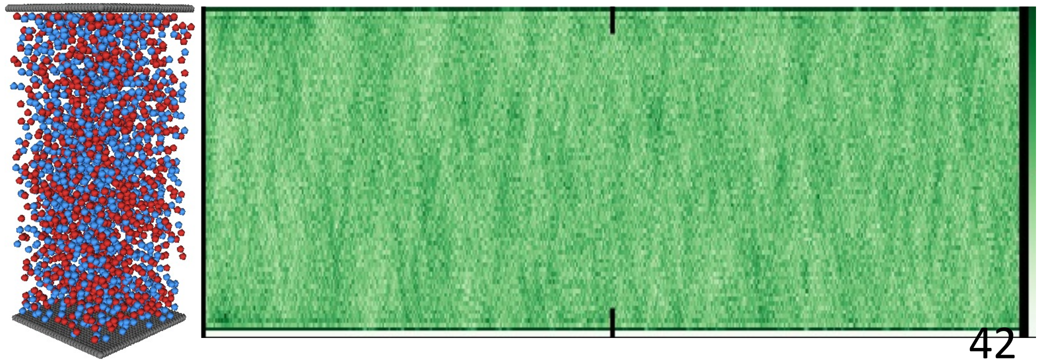
0.7



0.6



0.5



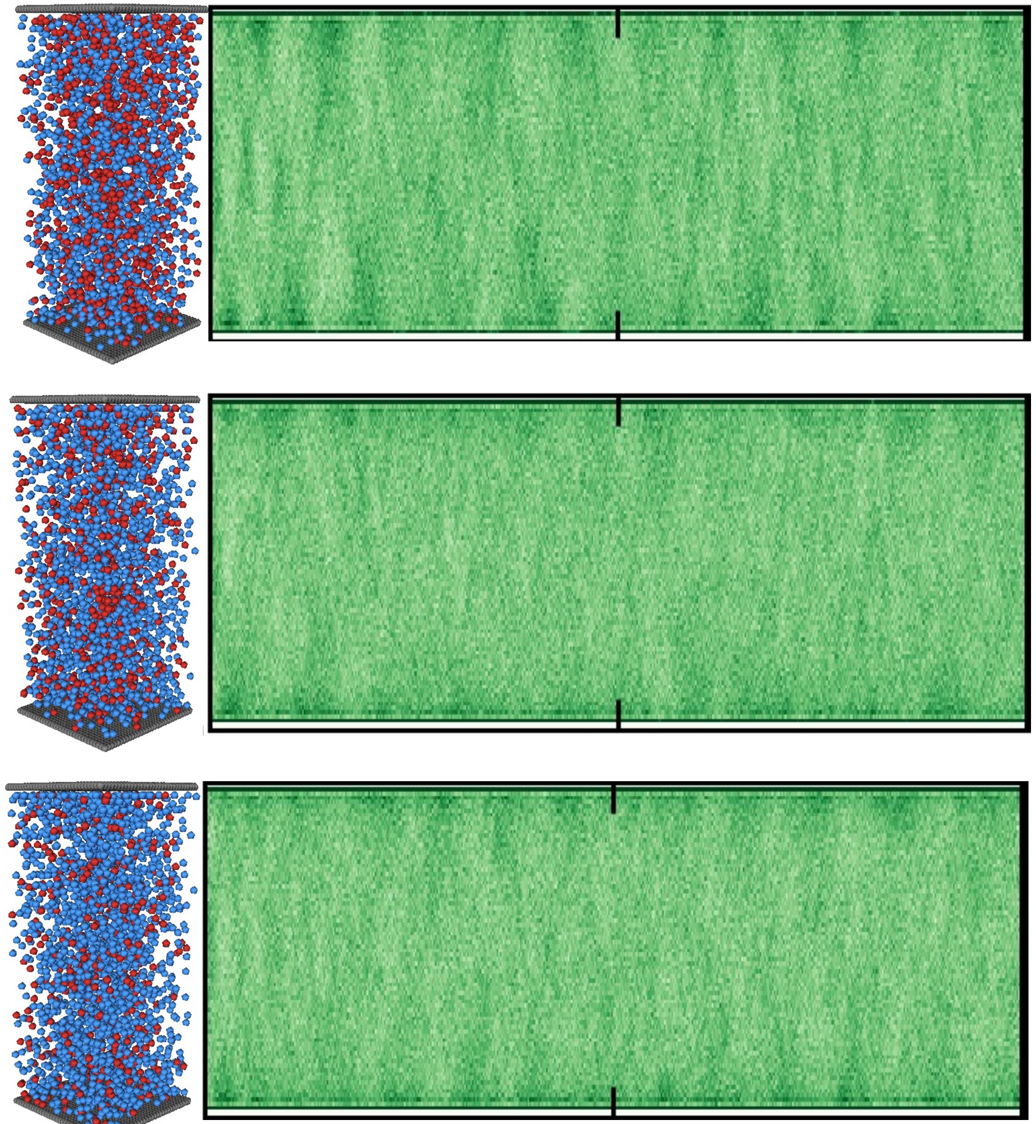
x_{Puller}
↓

Swarm propagation: Mixtures

0.4

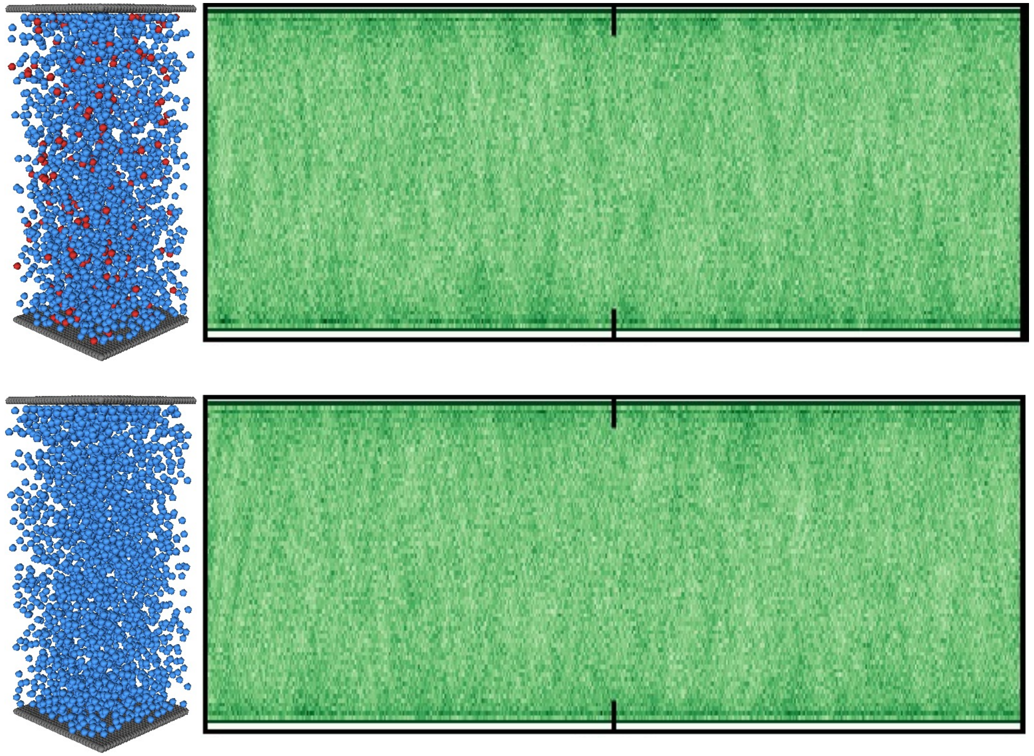
0.3

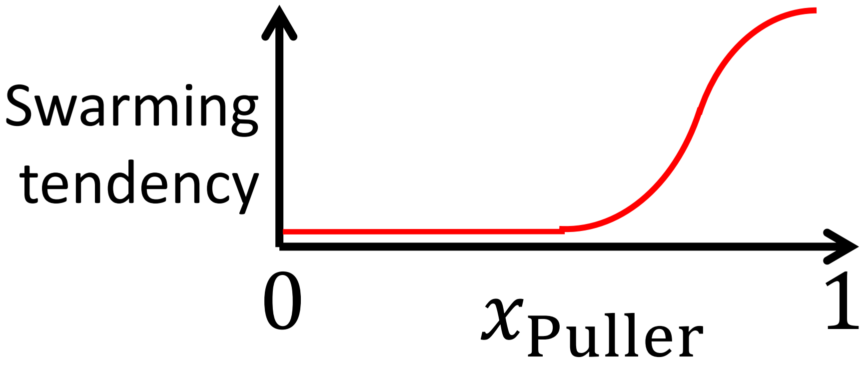
0.2



0.1

0.0



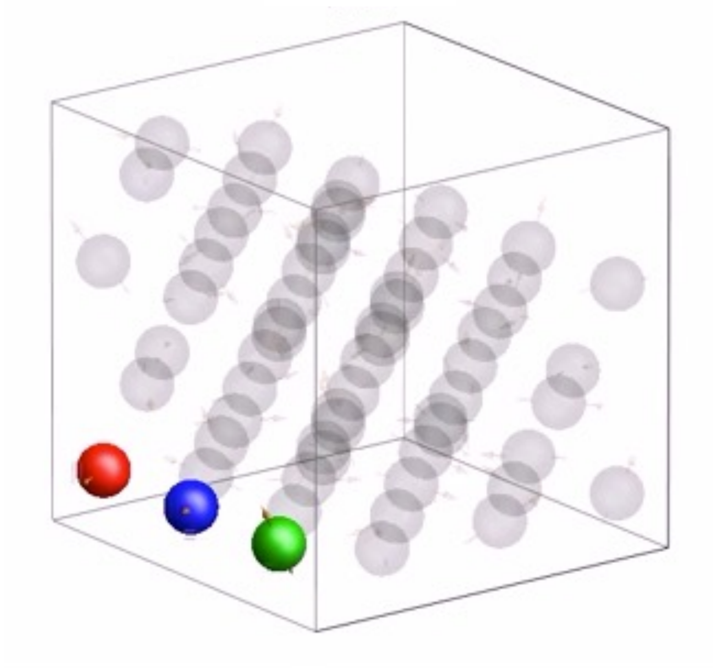


JPSJ 2017

Collective motions in bulk

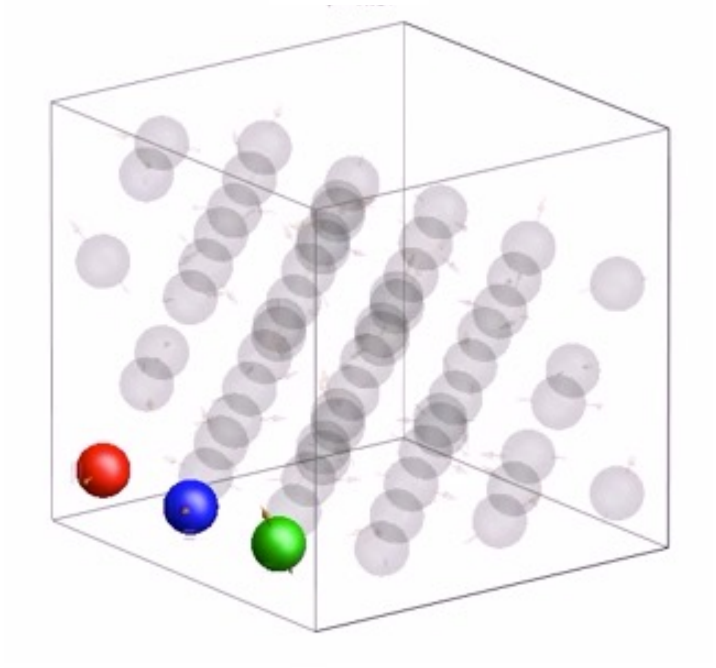
Pusher

$\alpha = -2$



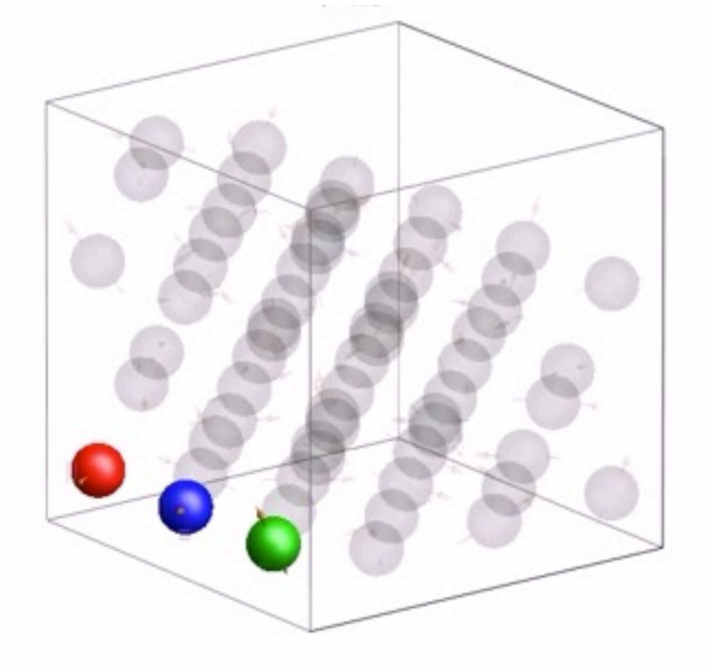
Neutral

$\alpha = 0$



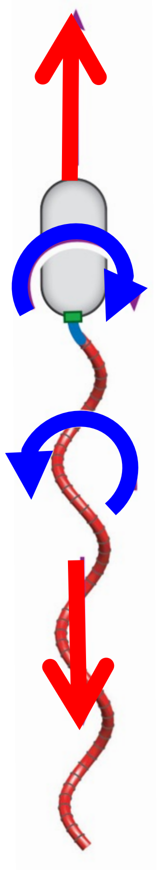
Puller

$\alpha = 2$



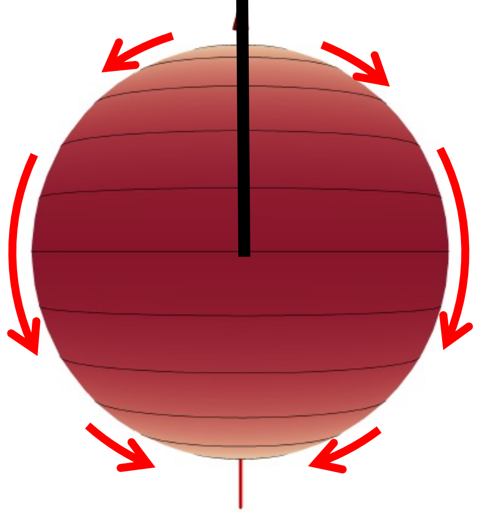
J. R. Blake (1971)

Spherical micro-swimmer with rotlet

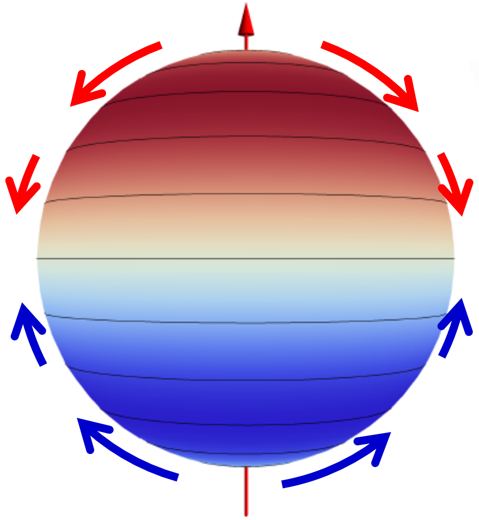


$\approx$

$$v_0 = \frac{2}{3} B_1$$



$+$



$+$

$B_1 \sin\theta \; \hat{\mathbf{e}}_\theta$ — polar

$B_2 \sin 2\theta \; \hat{\mathbf{e}}_\theta$

$C_2 \sin 2\theta \; \hat{\mathbf{e}}_\varphi$ — azimuthal

Important parameter #1

$$\beta \equiv \frac{B_2}{B_1}$$

$$\chi \equiv \frac{C_2}{B_1}$$

Important parameter #2