

# COLLECTIVE BEHAVIOR OF SELF-STEERING POLAR MICROSWIMMERS

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THEORETICAL PHYSICS OF LIVING MATTER, INSTITUTE FOR ADVANCED SIMULATION

24.07.2024 SEOUL I NSPCS 2024

arXiv:2406.17704

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# ADAPTIVE SELF-STEERING

**Relevant examples**

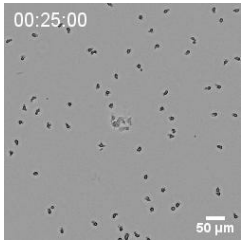
- **Biological systems**
- **Microrobots**
  - Janus particles
  - Bioinspired microrobots

**Cognitive self-steering active particles**

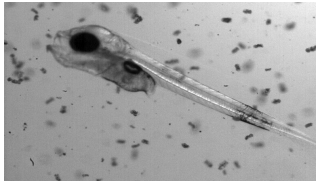
⇒ **Sensing, Information processing, adaptation**

⇒ **Noise**

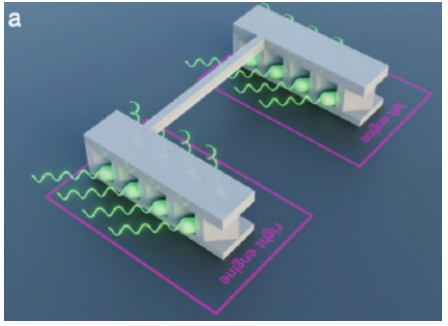
⇒ **Hydrodynamic interactions**

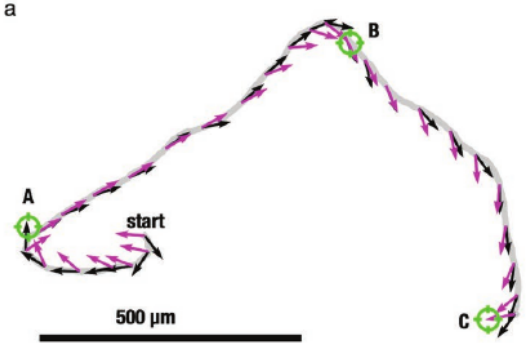



Swimming neutrophils
Biol. Cell **113**, 28 (2021)



Hydrodynamic starvation
PNAS **111**, 8083 (2014)



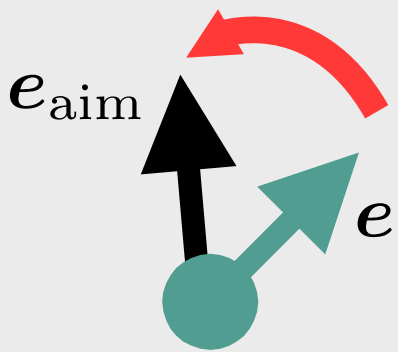

Adv. Funct. Mater. 2214801 (2023)

# MODEL

## Intelligent active Brownian particle (iABP)

$$\dot{\boldsymbol{r}}(t) = v_0\,\boldsymbol{e}(t) + \sqrt{2D_T}\boldsymbol{\eta}_T(t),$$
$$\dot{\boldsymbol{e}}(t) = \boldsymbol{f}_A(t) + \sqrt{2D_R}\boldsymbol{\eta}_R(t) \times \boldsymbol{e}(t)$$

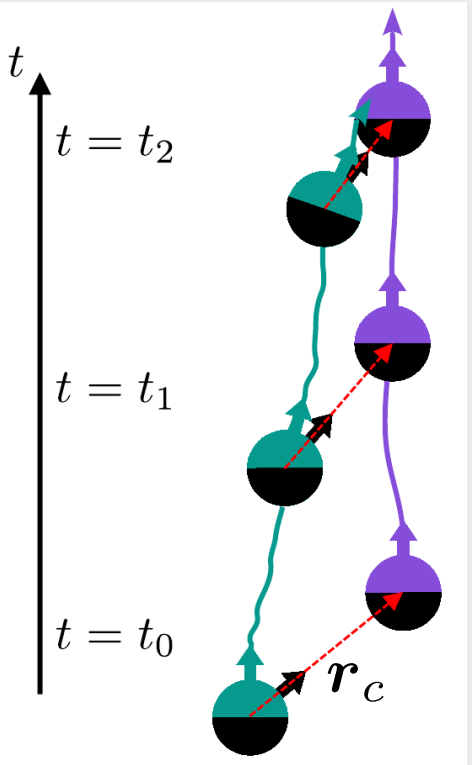
## Adaptation $\boldsymbol{f}_A = C(\boldsymbol{e} \times \boldsymbol{e}_{\mathrm{aim}}) \times \boldsymbol{e}$




**External cue** $\boldsymbol{e}_{\mathrm{aim}}$

- **Instantaneous**
- **No memory**

## Sensing $\boldsymbol{e}_{\mathrm{aim}} = \boldsymbol{r}_c/r_c$

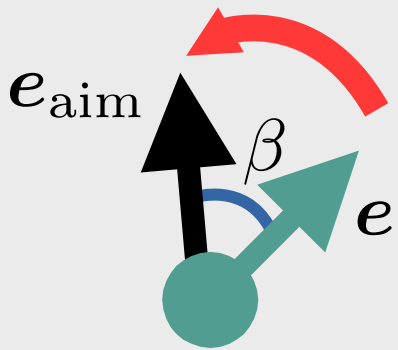


# MANEUVERABILITY

**iABP**

$$\dot{\boldsymbol{e}}(t) = C\,\boldsymbol{e} \times \left( \frac{\boldsymbol{r}_c}{r_c} \times \boldsymbol{e} \right) + \sqrt{2D_R}\boldsymbol{\eta}_R(t) \times \boldsymbol{e}(t)$$

$$\dot{\beta} = -\left( \Omega - \frac{\mathrm{Pe}}{r} \right) \sin\beta + \text{noise}$$



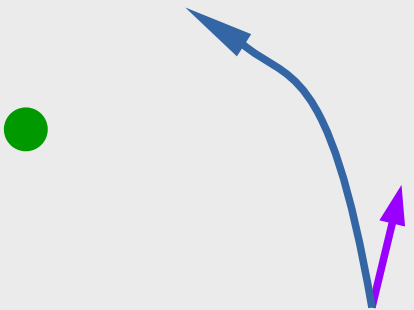

Dimensionless parameters

$$\Omega \equiv C/D_R, \quad \mathrm{Pe} \equiv v_0/(\sigma D_R)$$

**Maneuverability** $\Omega$



Strong maneuverability



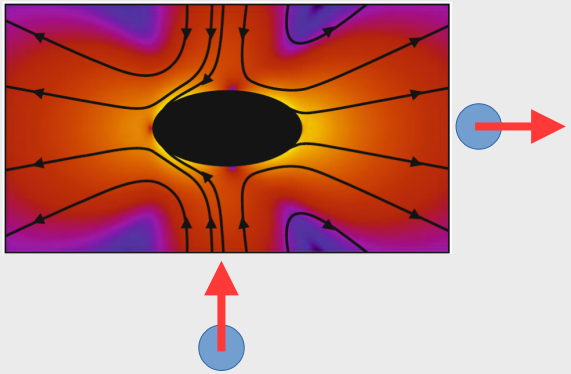
Weak maneuverability

New J. Phys. **24**, 093039 (2022)

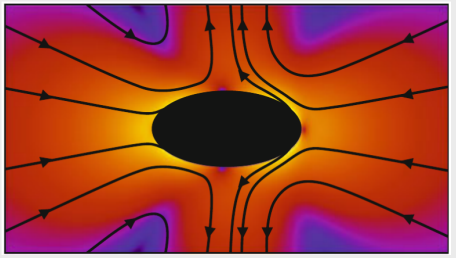
# HYDRODYNAMIC SELF-STEERING

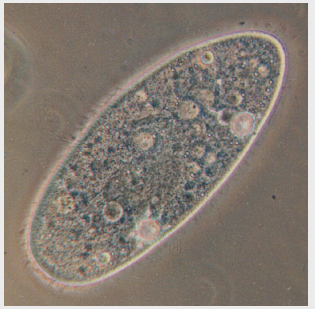
- **Hydrodynamic interactions** in **3D**
- Model microswimmer: **squirmer**, fluid: **MPC**

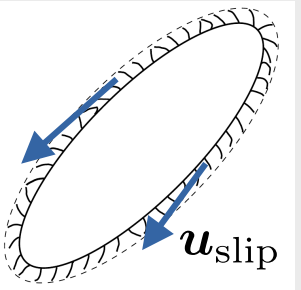
**Pusher**



**Puller**



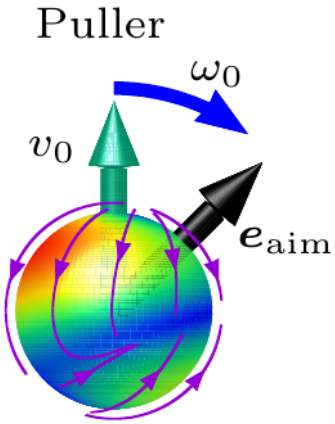


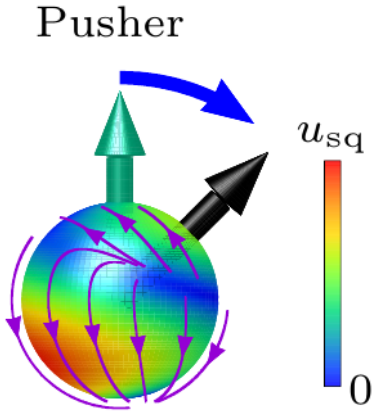



Soft Matter **12**, 7372 (2016)

**iSquirmer** $\omega_0 = C\, \boldsymbol{e}_p \times \boldsymbol{e}_{\mathrm{aim}}$ Commun. Phys. **6**, 310 (2023)

- **Actuation**: Slip velocity **adapting** to **external cue**



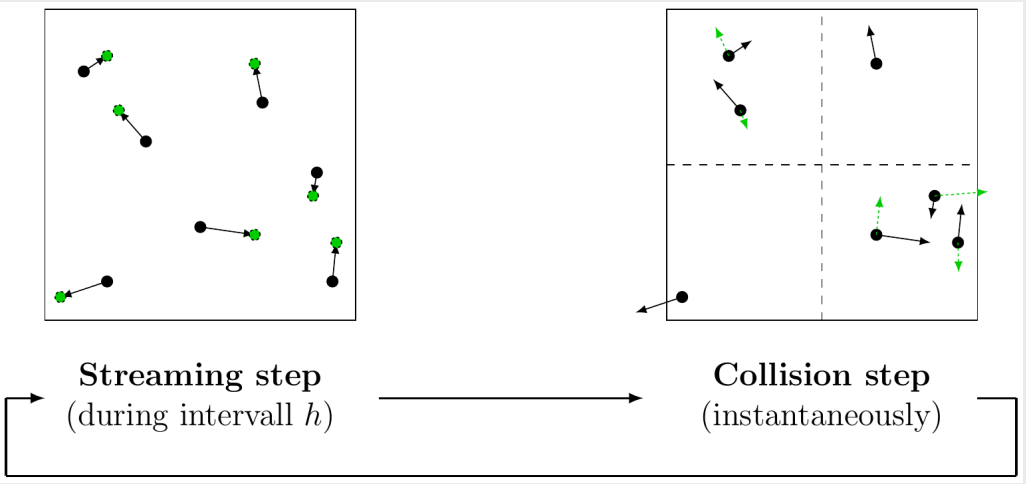



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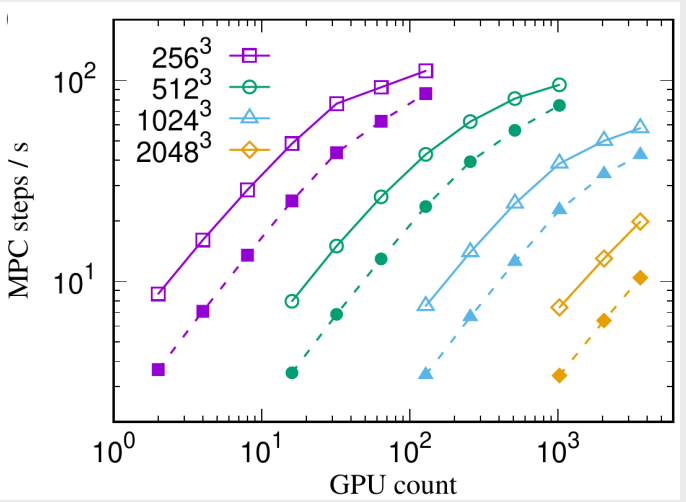
# MULTIPARTICLE COLLISION DYNAMICS (MPC)

**Particle-based mesoscale** hydrodynamic simulation

**Streaming** + **collision** steps




$$\boldsymbol{r}_i(t+h) = \boldsymbol{r}_i(t) + h\boldsymbol{v}_i(t) \qquad \boldsymbol{v}_i(t+h) = \boldsymbol{u}(t) + \mathbf{R}\cdot(\boldsymbol{v}_i(t) - \boldsymbol{u}(t))$$




Parallelized implementation (CPU/GPU):
**HTMPC** (heavily templated MPC)

– up to 1.5 **trillion** MPC particles

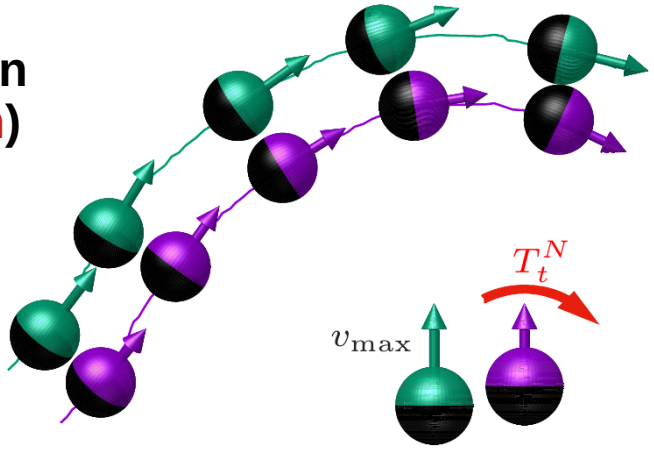
arXiv:2406.15236 (2024)

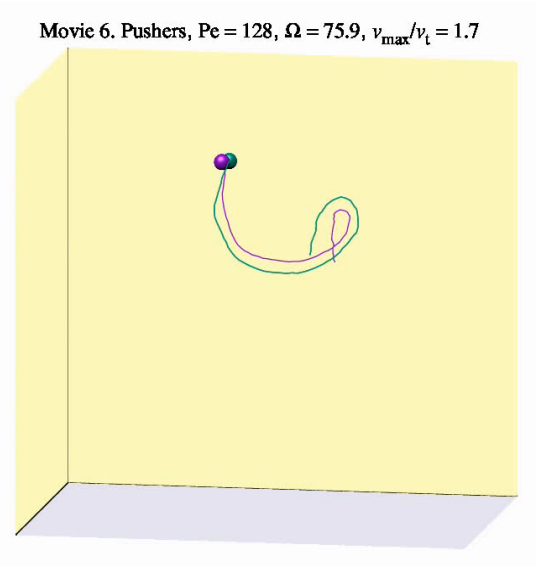
# PURSUIT: PROPULSION ALIGNMENT (PUSHERS)

**Side-by-side configuration (hydrodynamic attraction)**

**+**

**Speed adaptation**




Near-field Hydrodynamics
⇒ **Induce torque**

**Circular** motion:
indirect **steering** of target

Commnun. Phys. **6**, 310 (2023)

# HYDRODYNAMIC ALIGNMENT: POLAR ORDER?

**Polar order** in **dry Vicsek** system

- **Long-range** orientational order in **2D**, **3D**

**Wet** active polar fluid

- Aligning effect of near-field hydrodynamics

  Reinken *et al.*, PRE **97**, 022613 (2018)

- Hydrodynamics prevent polar ordering

  Simha *et al.*, PRL **89**, 058101 (2002)

- Toner-Tu-Swift-Hohenberg model
  – Homogeneous density (pushers → turbulence)

  Wensink *et al.*, PNAS **109**, 14308 (2012)

**Autonomously aligning microswimmers**

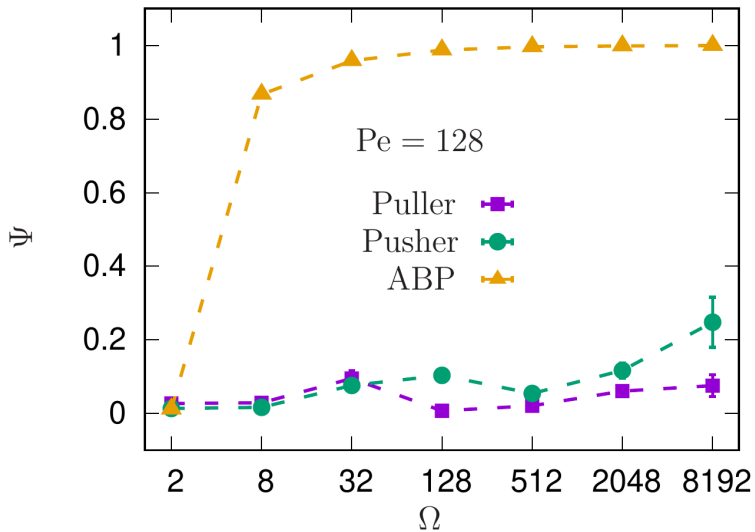
$$e_{\mathrm{aim},i} = \frac{1}{N_i} \sum_{j \in \Gamma_i} e_j$$

**Alignment range**

$$R_a = 4R_{\mathrm{sq}}$$

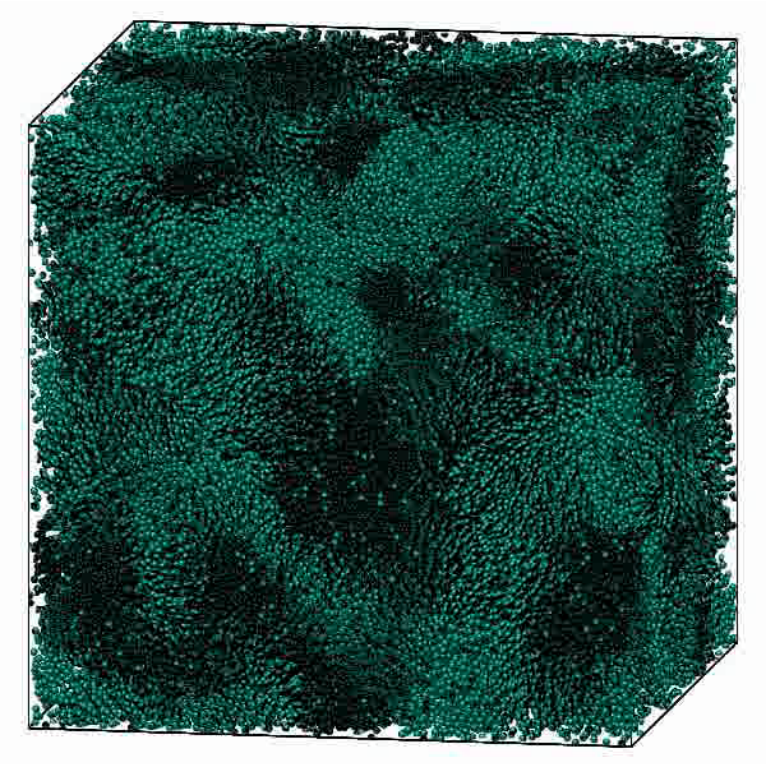
**Density:**

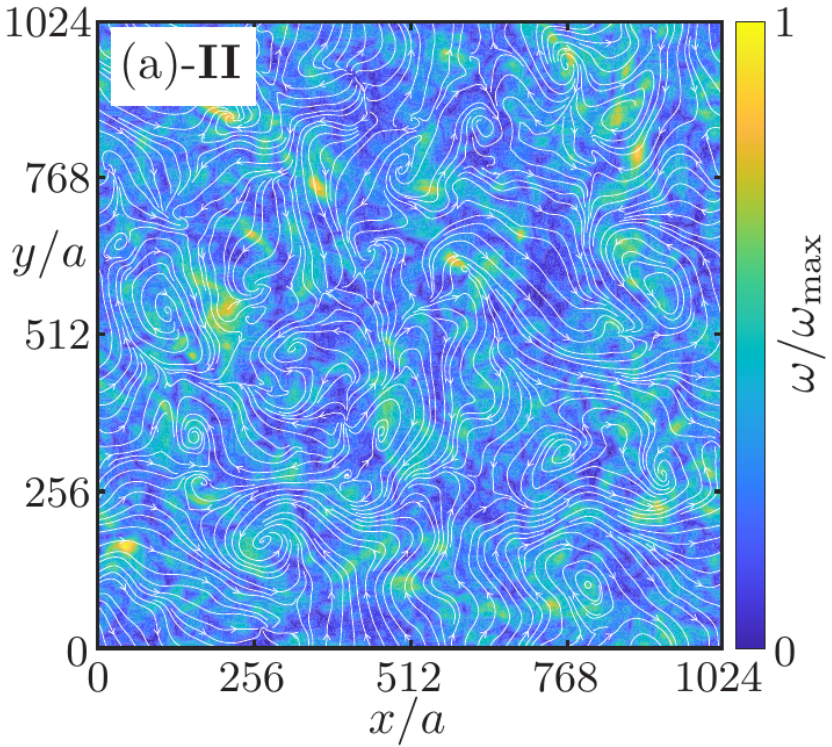
- **0.093 (radius)**
- **6.0 (alignment)**




**Which form of self-organization?**

# ALIGNING PUSHERS: ACTIVE TURBULENCE



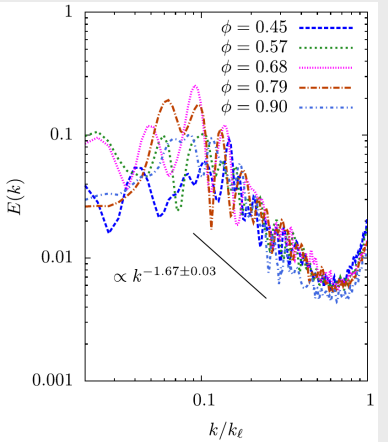



vorticity: $\boldsymbol{\omega} = \nabla \times \boldsymbol{u}$

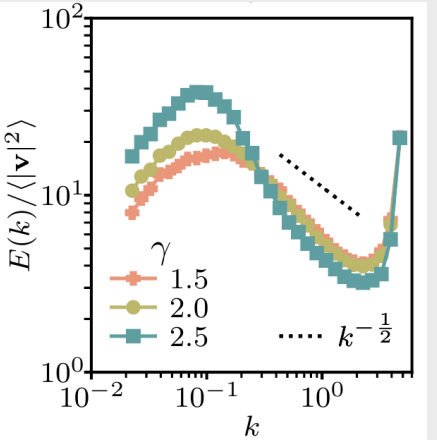
# ENERGY SPECTRUM

## Fast advection

- **Squirmer motion 20 times faster than $v_0$ for Ω = 8192 (MSD)**
- **Not in dry systems**
- **Driven by collective fluid flow**



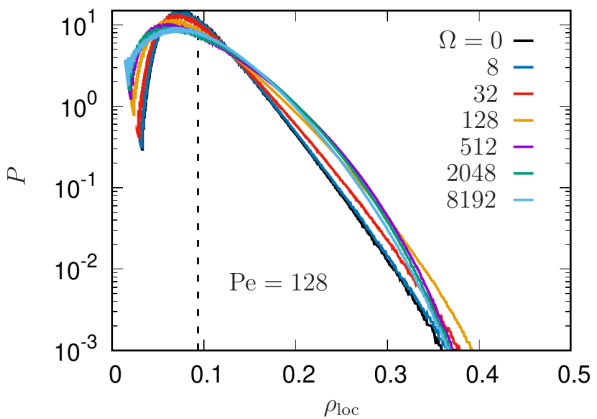

Wensink *et al.*, JPCM (2012)



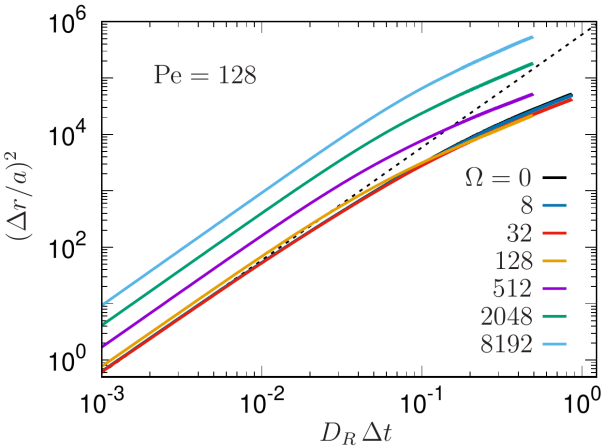

Keta *et al.*, PRL (2024)

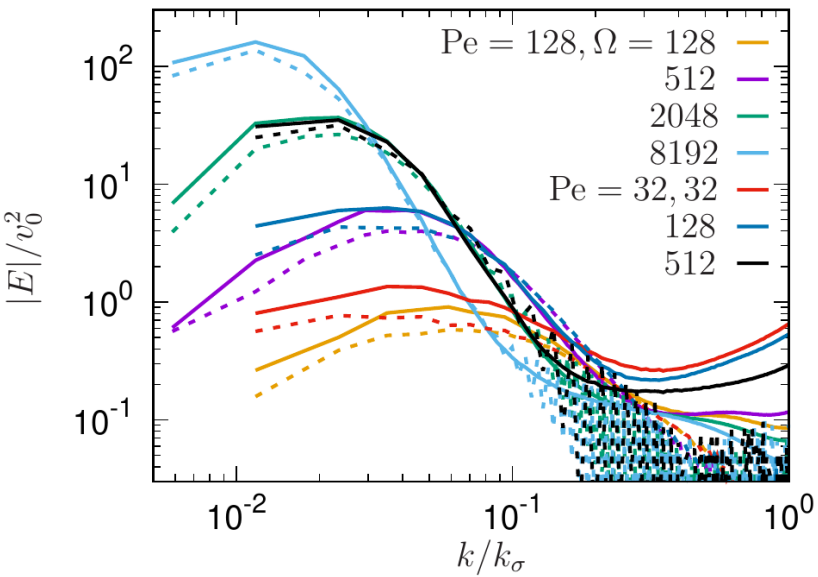
Dry systems: high density

Voronoi

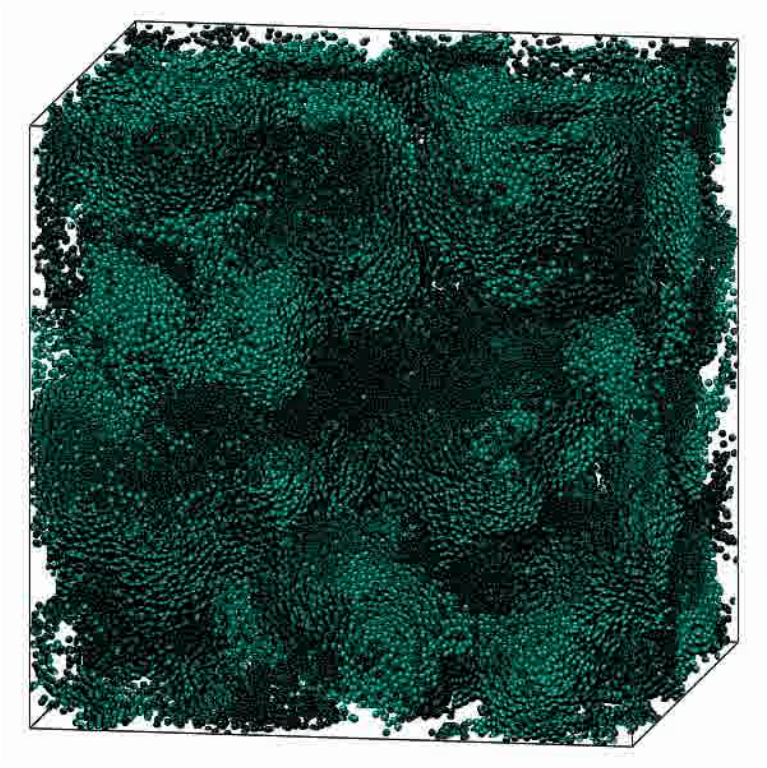


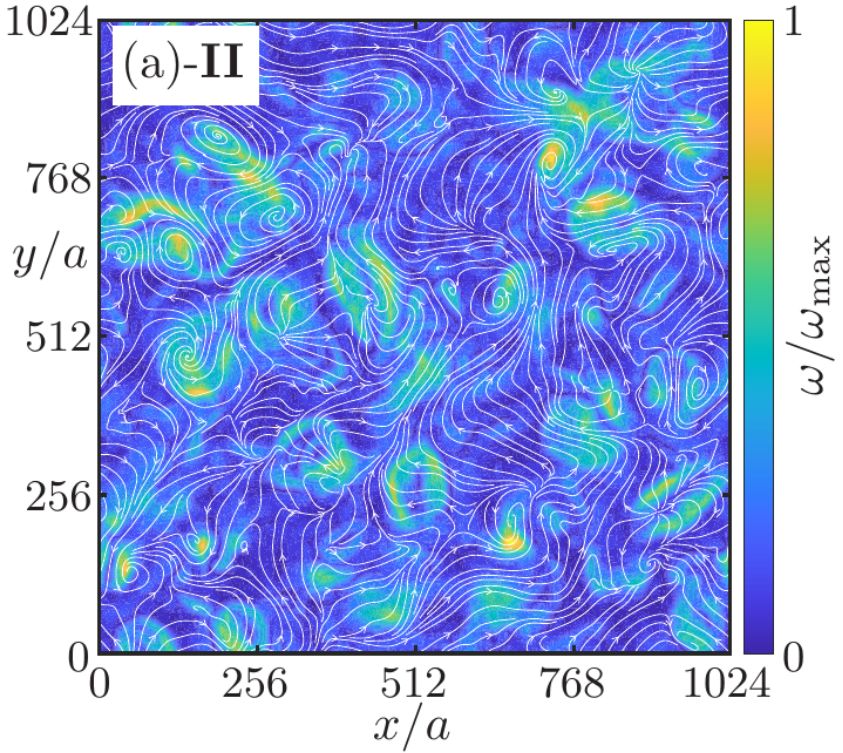

MSD



# ALIGNING PULLERS: NEW TYPE OF CHAOTIC ADVECTION



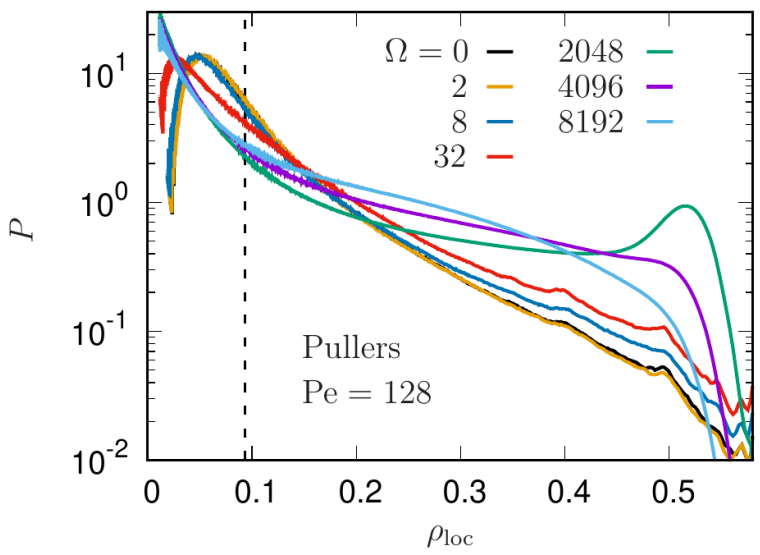



vorticity: $\boldsymbol{\omega} = \nabla \times \boldsymbol{u}$

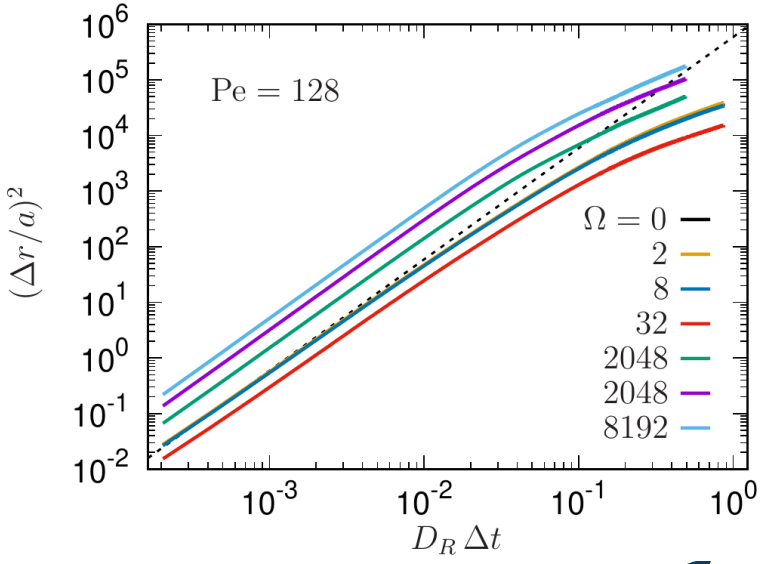
# DENSITY MODULATION

**Pullers: formation of dynamic clusters**

- **No MIPS: collective speed faster than the single-particle speed**

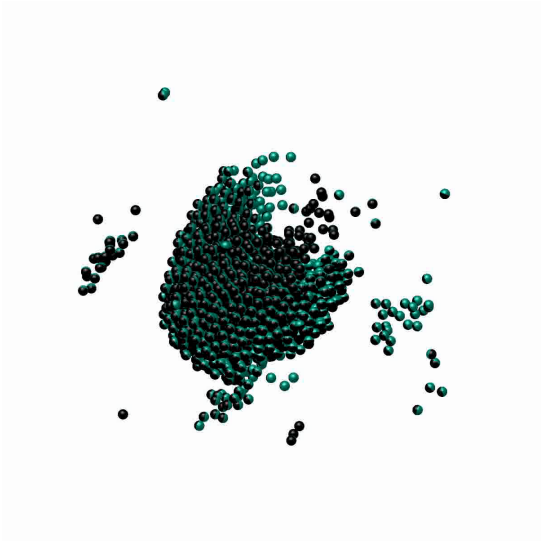


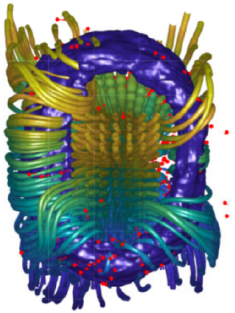

Voronoi

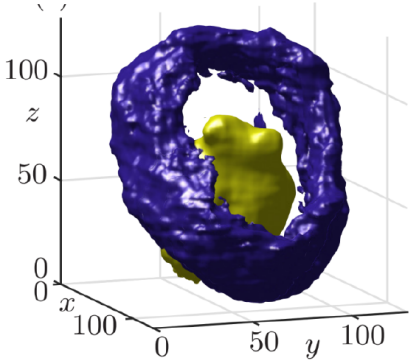


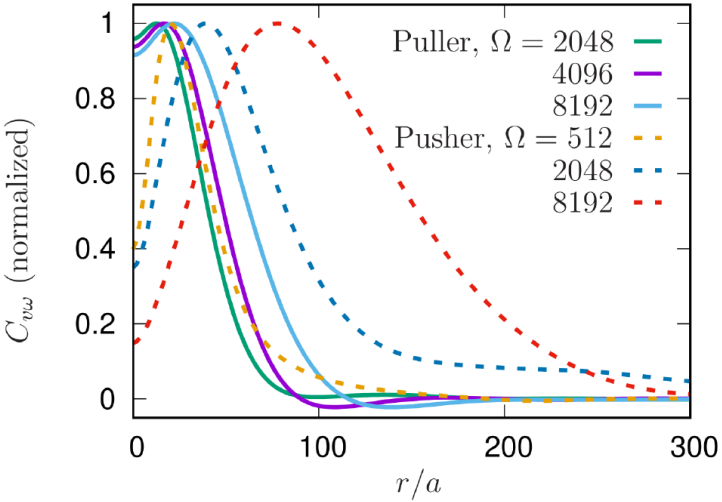

MSD

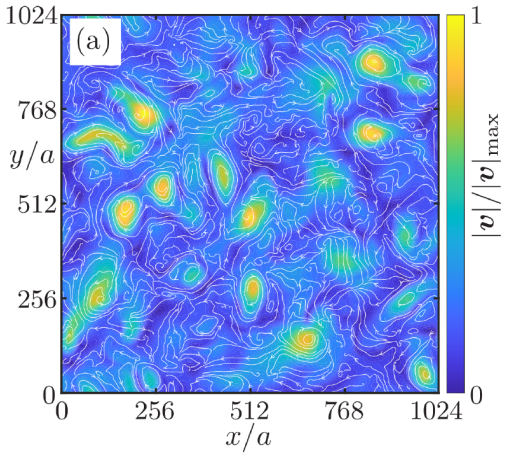
# FLUID JET AND VORTEX RING







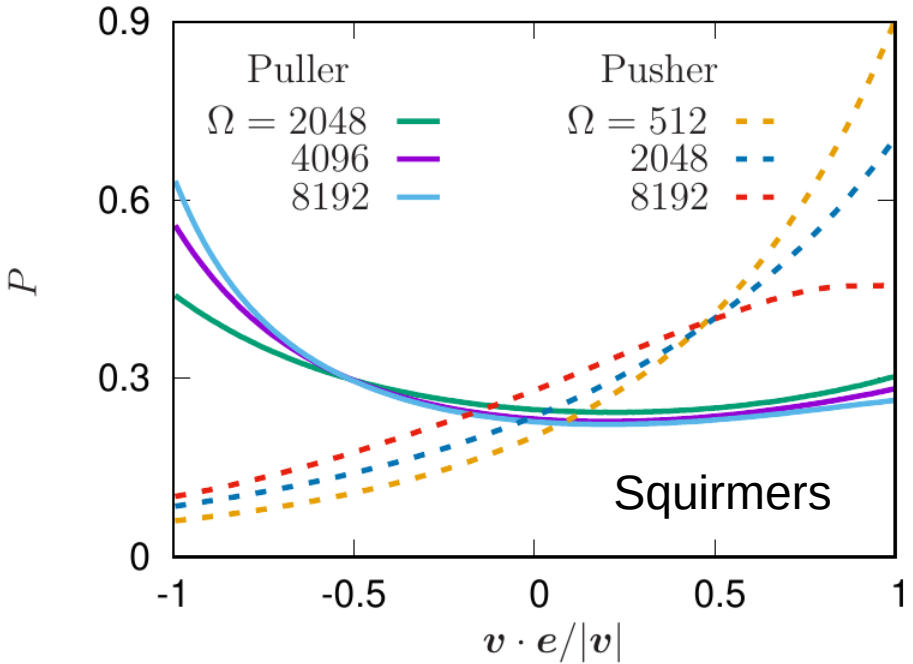




**Scenario for pullers:** **arXiv:2406.17704 (2024)**

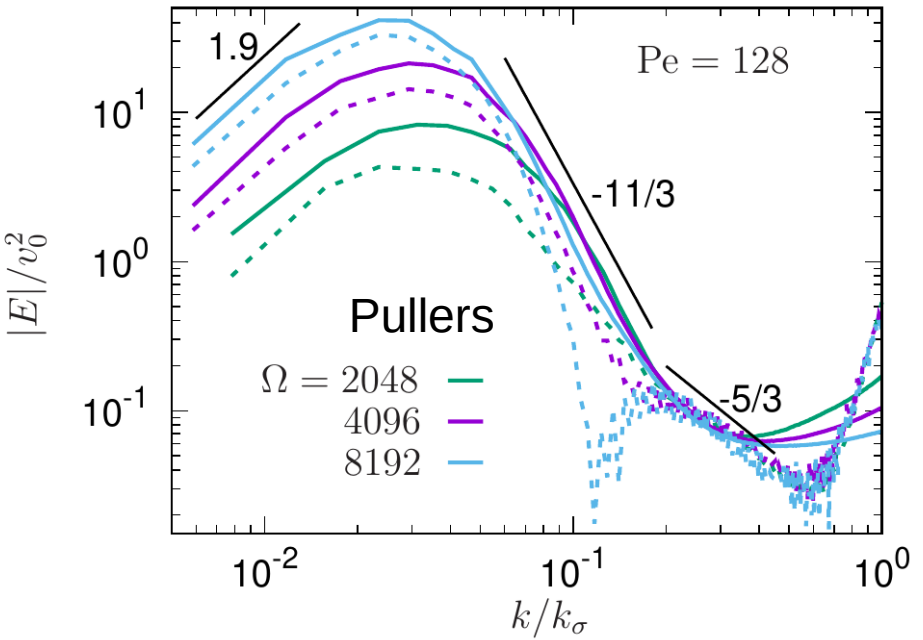
**Aligned cluster → Strong fluid jet → formation of a vortex ring**

# RICH COUPLING BETWEEN POLARITY AND VELOCITY

**Polarity** (*e*) and **velocity** (*v*) fields of **squirmers**




**Velocity** fields of **squirmers** (dashed) and **fluid** (solid)



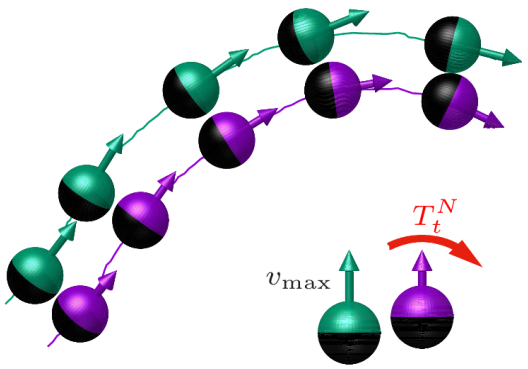
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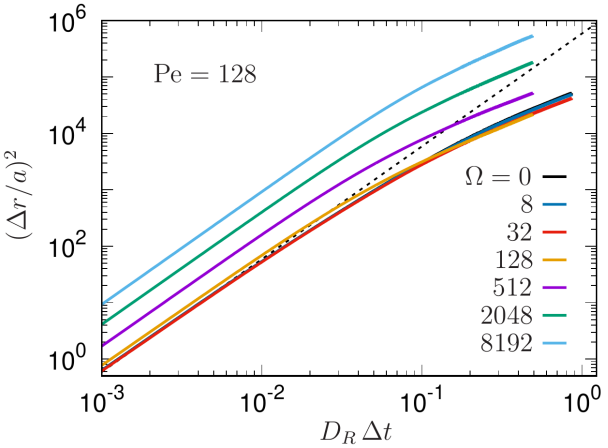
- **Autonomously steering (aligning) microswimmers**
  - **Wet polar** active matter: **no long-range polar order**

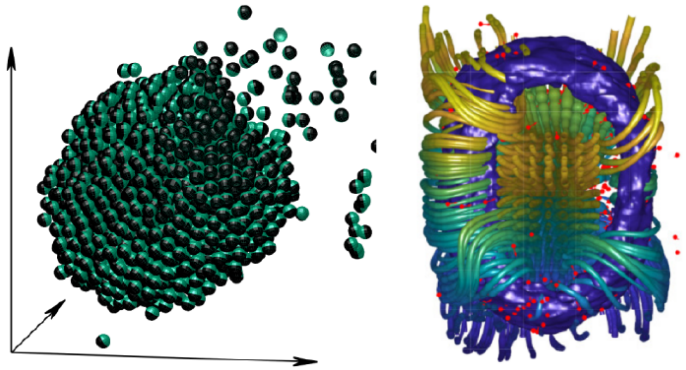
New J. Phys. **24**, 093039 (2022)
Commun. Phys. **3**, 610 (2023)
arXiv:2406.17704 (2024)

- **Pushers: active turbulence**
  - **Fast advection**
  - **Extended vortex size**

- **Pullers:**
  - **Tendency for clustering**
  - **Fluid jets and vortex rings**



# THANK YOU!
# 감사합니다!