Collective response and emergent morphologies in swimmer suspensions

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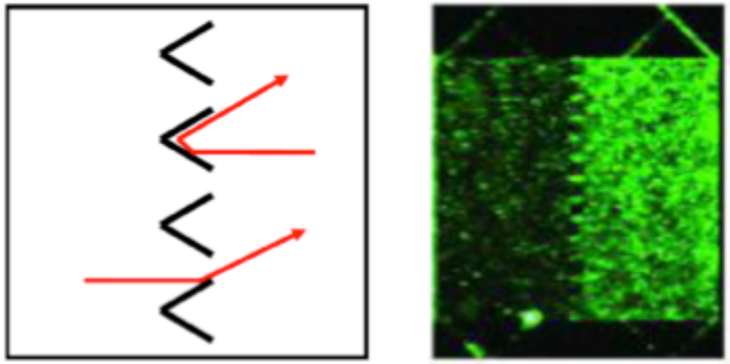
University of Barcelona

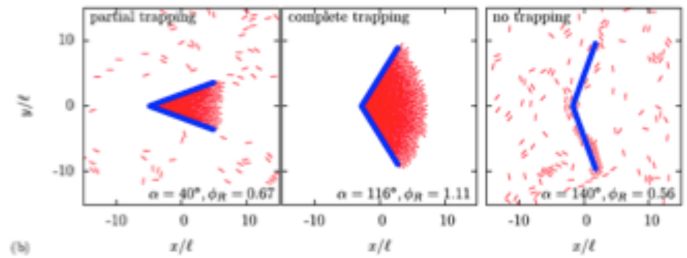
1. Introduction



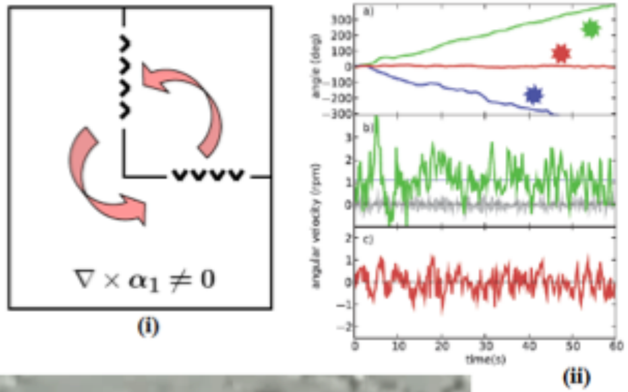
Galajda et al. J Bacter. (2007)

Energy from small scales
Systems intrinsically out of equilibrium

Non-equilibrium distributions
no detailed balance

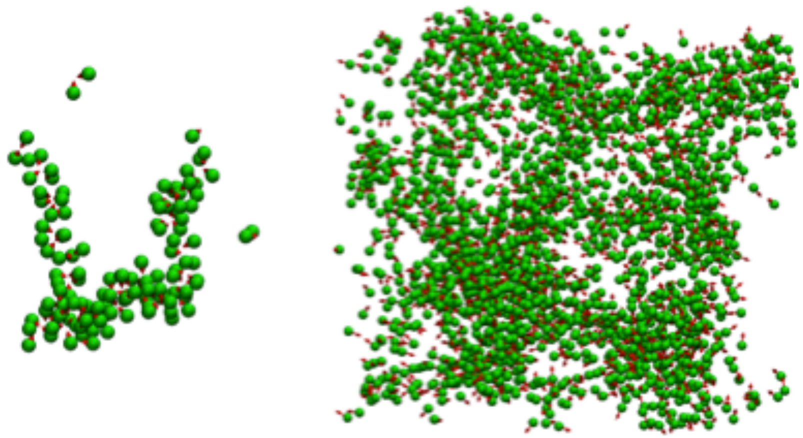


Kaiser et al. PRL (2012)



Ratchets

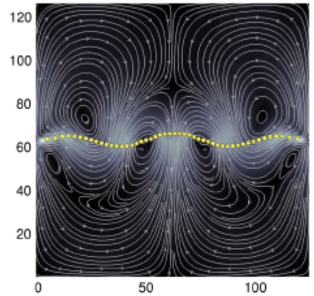
Emerging patterns
and phases

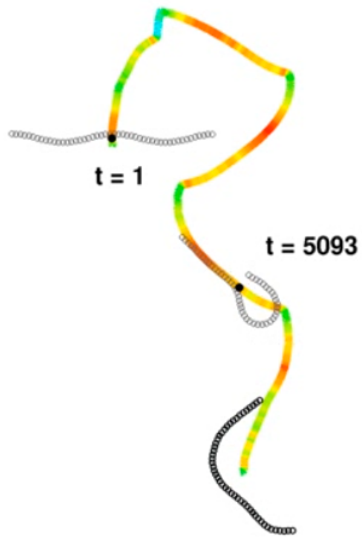


Di Leonardo et al. PNAS (2010)

1. Introduction

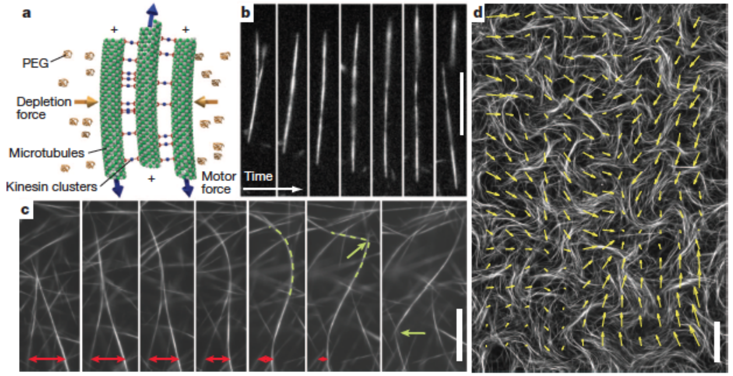
Jaramayan et al. PRL (2012)





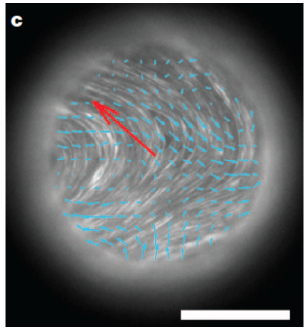
Internal activity
new materials

Biomimetic cilia
flagella

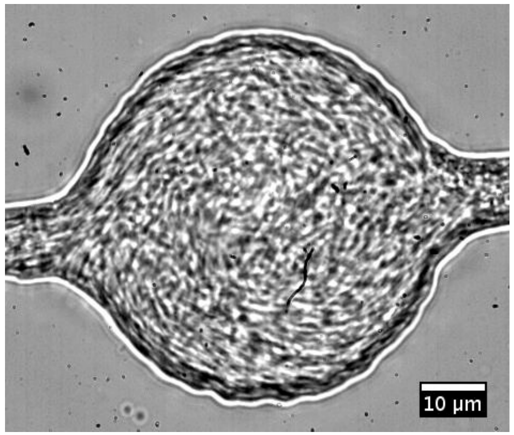


Sanchezet al. Nature (2013)

Active drops



Left: Active Droplets
Right: Passive Droplets
10X Magnification
100μm bar



Microfluidic flows

Wioland et al. PRL (2013)

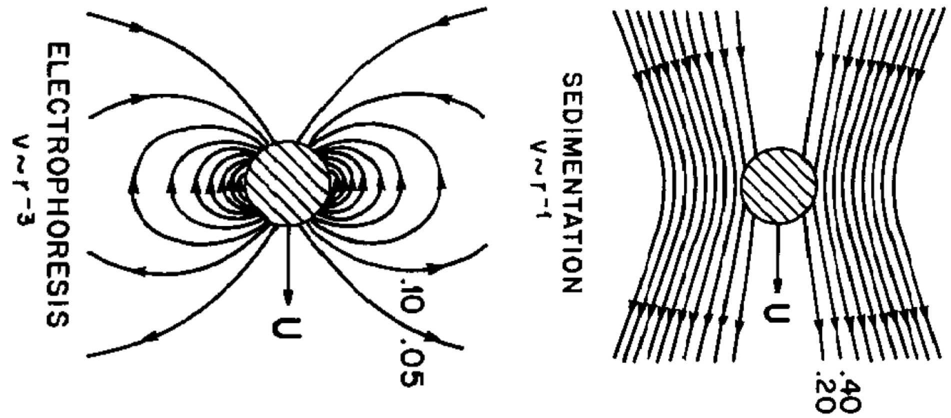
Desired structures, adaptive, capable of self repair

2. Microswimmers

Dynamics of active particles

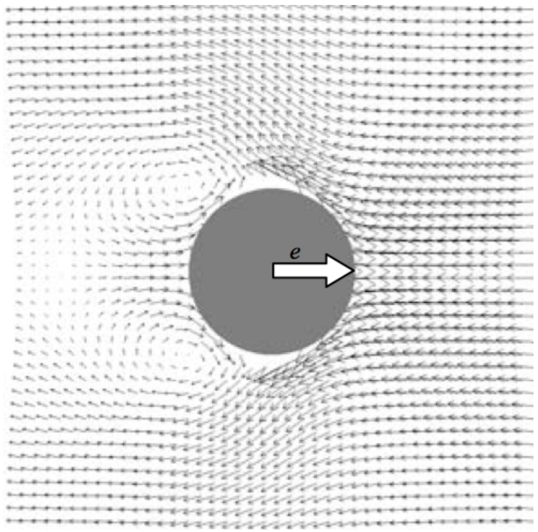
Low Reynolds numbers

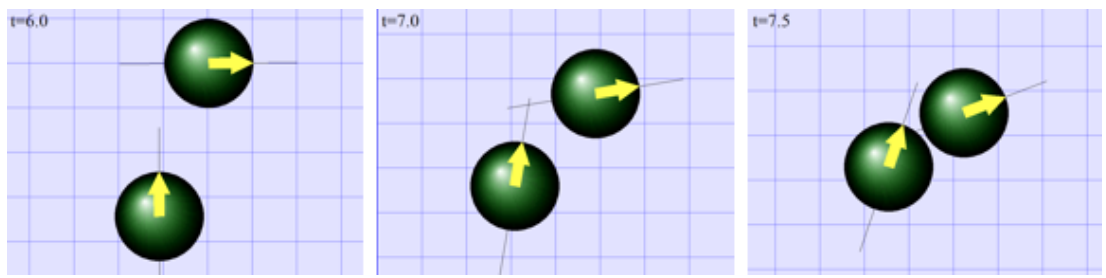
Absence of external driving
closer to electrophoresis?



Relevance of swimming mechanism

Fluid flows with vorticity

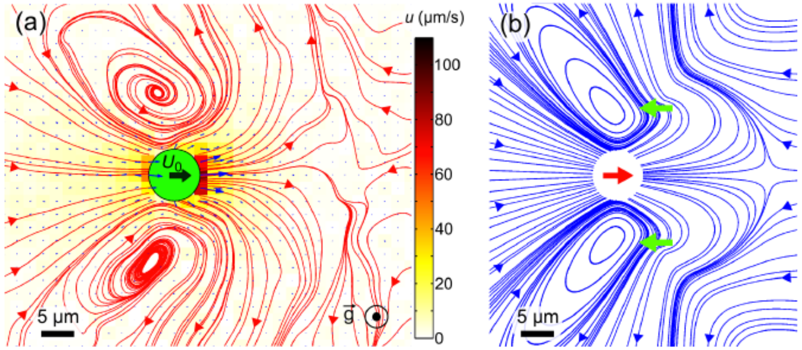




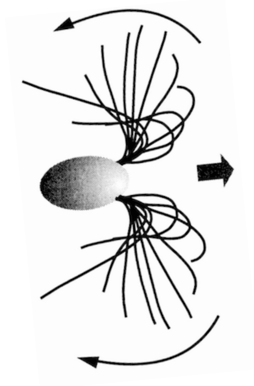
Coupling translation/rotation
relevance of near field interactions

2. Microswimmers

Flow measurements

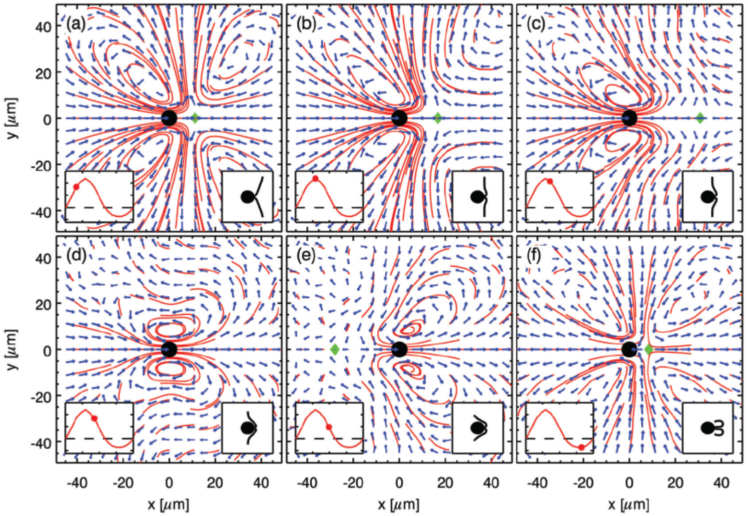


Chlamydomonas

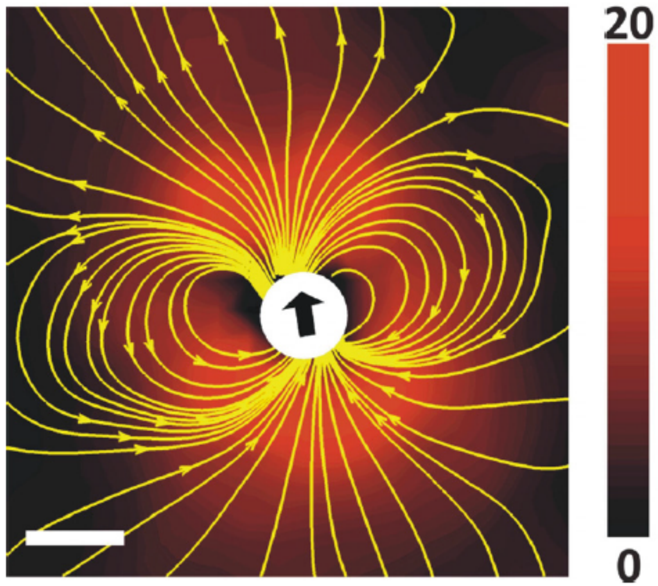


Time dependent flow

cycle averaged

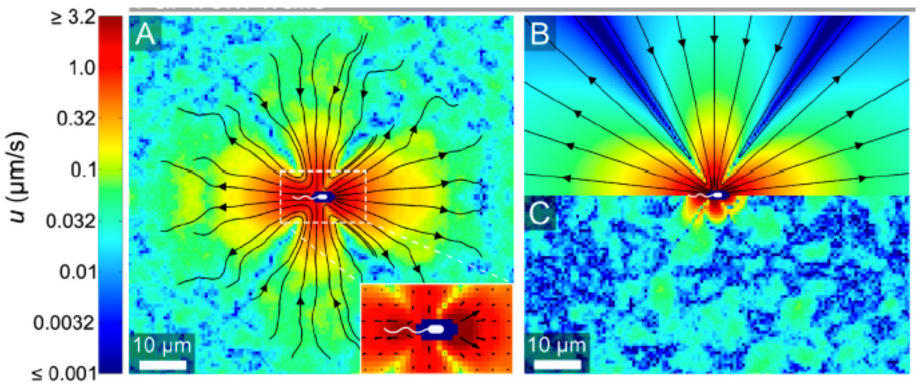


Guasto et al. PRL (2010)



Flagellum

dipolar flow

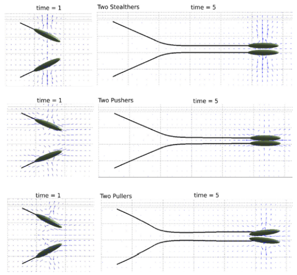


emulsions

Thutupalli et al. NJP (2011)

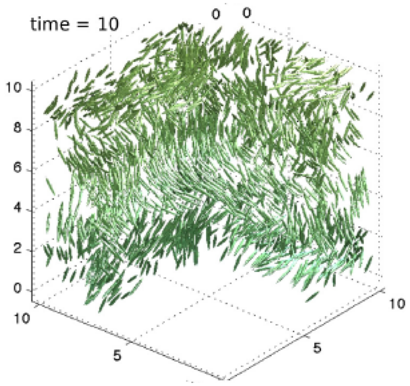
Drescher et al. PNAS (2011)

2. Microswimmers



Hydrodynamic coupling - long range

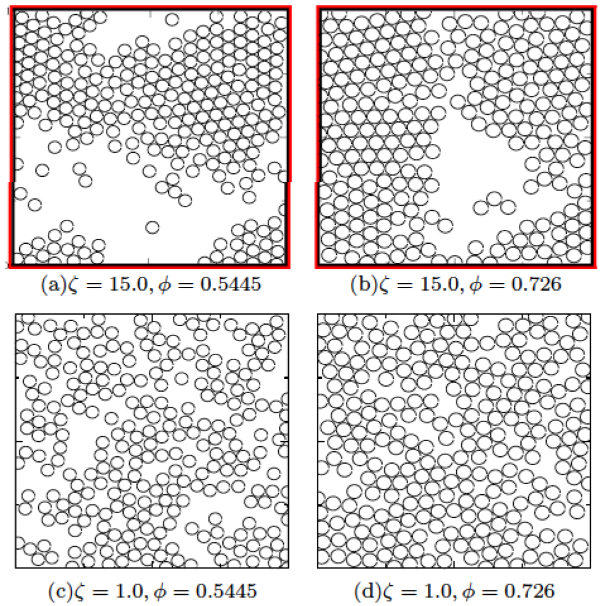
Relevance of shape



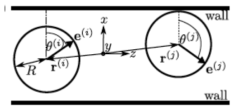
Lushi et al. (2013)

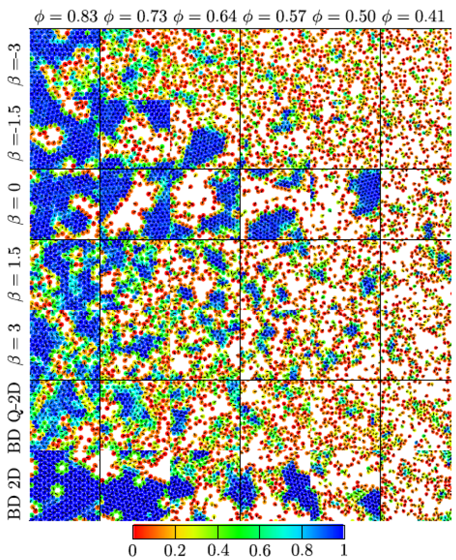
Disks/spheres

prevent crystallization?



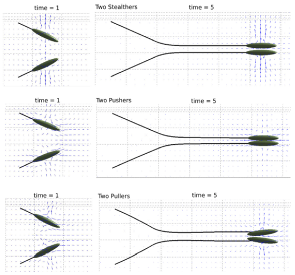
Matas-Navarro et al. (2014)





Zottl et al. (2014)

2. Microswimmers



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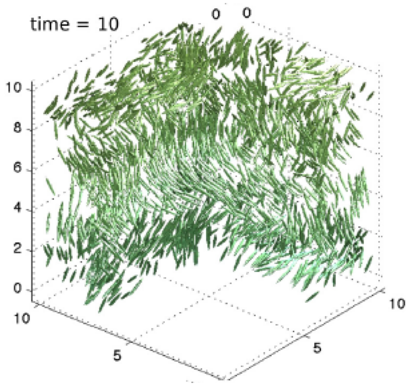
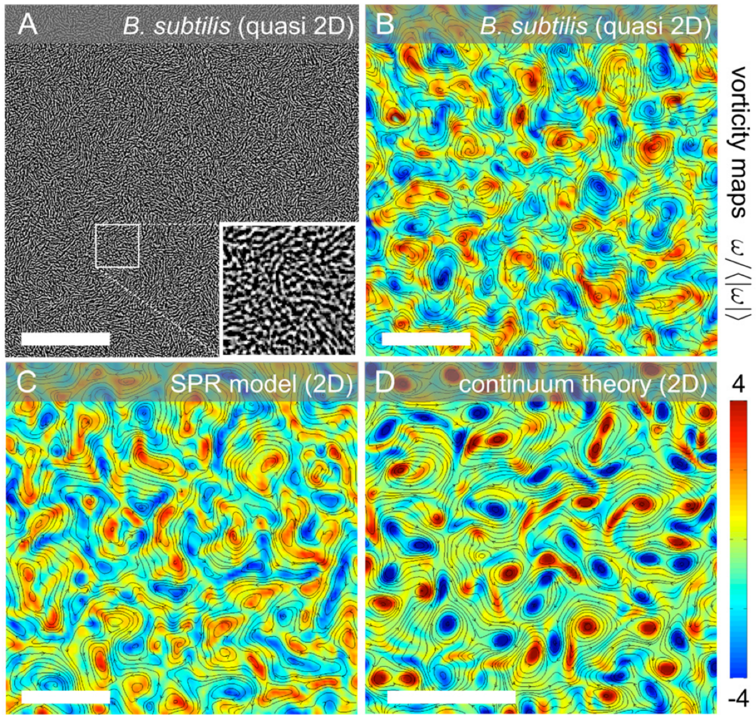
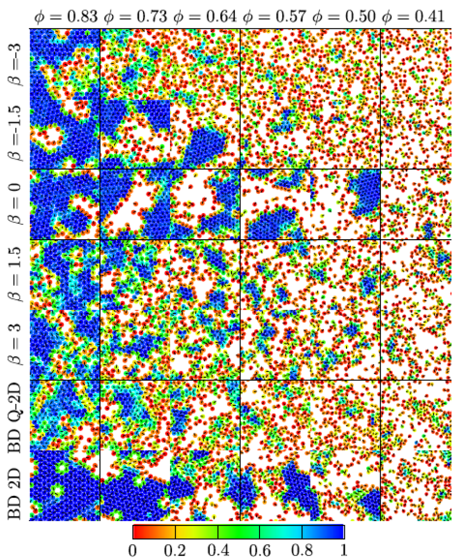


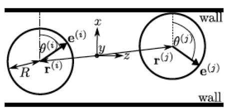
Lushi et al. (2013)

Unsteady flows

Meso-scale turbulence







Zottl et al. (2014)

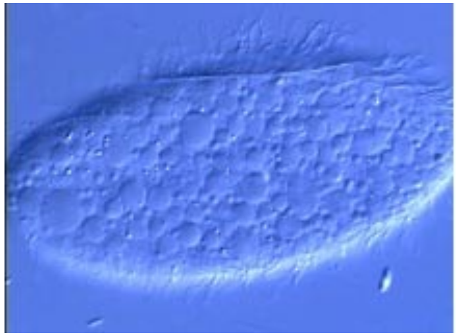
Wensick et al. (2012)

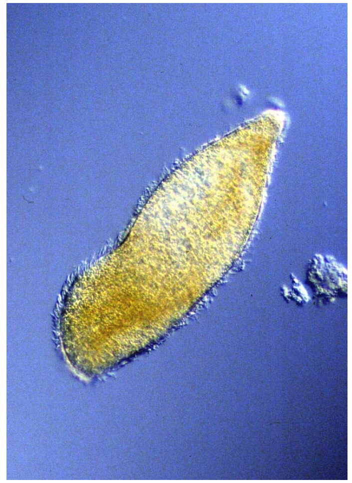
2. Microswimmers

Squirmers

Metachronal wave on Opalina, Paramecium.

Fixed tangential velocity profile on the surface (Lighthill, 1952; Blake, 1971)





Opalina

Surface tangential velocity

$$\mathbf{v}_S = \sum_{n=1}^{\infty} B_n V_n(\cos\theta)\mathbf{t}$$

$$\mathbf{v}_S = (B_1 \sin\theta + B_2 \sin\theta\cos\theta)\mathbf{t}$$

$\beta = B_2/B_1$

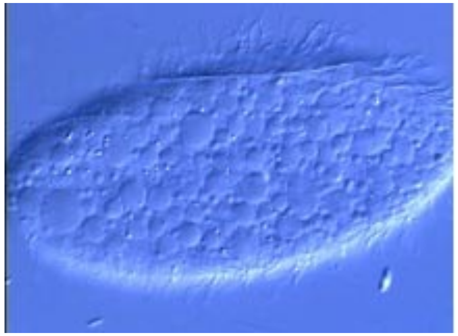
$$u_\infty = \frac{2}{3} B_1$$

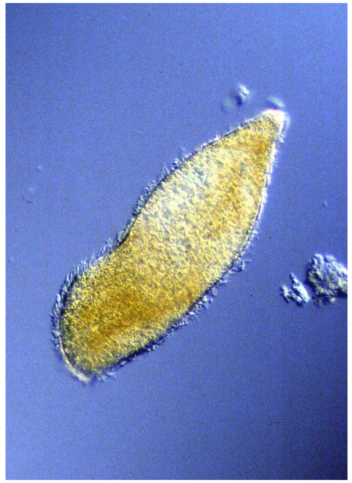
Steady squirmer

(Pedley 1986)

Propulsion velocity

2. Microswimmers





Opalina

Squirmers

Metachronal wave on Opalina, Paramecium.

Fixed tangential velocity profile on the surface (Lighthill, 1952; Blake, 1971)

Balantidium coli

Surface tangential velocity

$$\mathbf{v}_S = \sum_{n=1}^{\infty} B_n V_n(\cos\theta)\mathbf{t}$$

oligotrich

$$\mathbf{v}_S = (B_1 \sin\theta + B_2 \sin\theta\cos\theta)\mathbf{t}$$

$\beta = B_2/B_1$

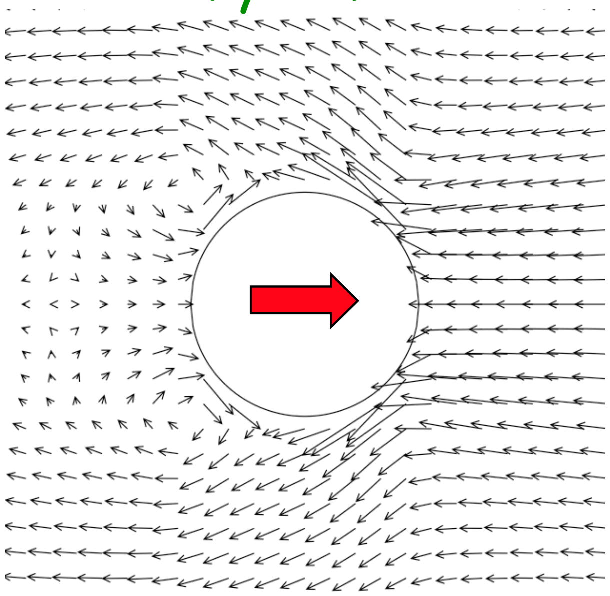
Steady squirmer

$$u_\infty = \frac{2}{3} B_1$$

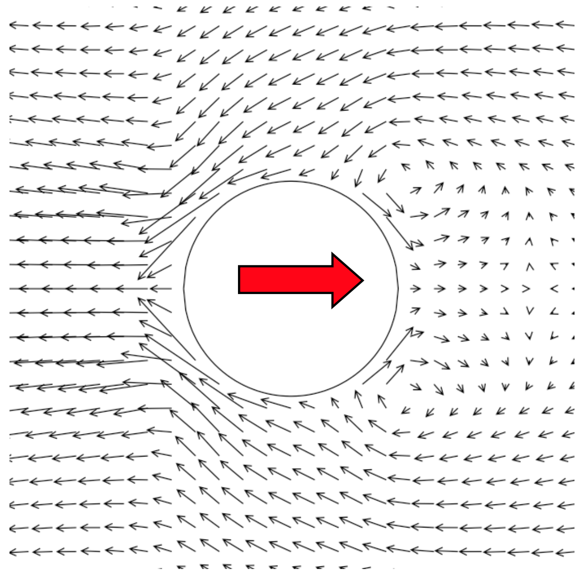
(Shun Pak et al, 2014)

Propulsion velocity

Chlamydomonas



E. coli



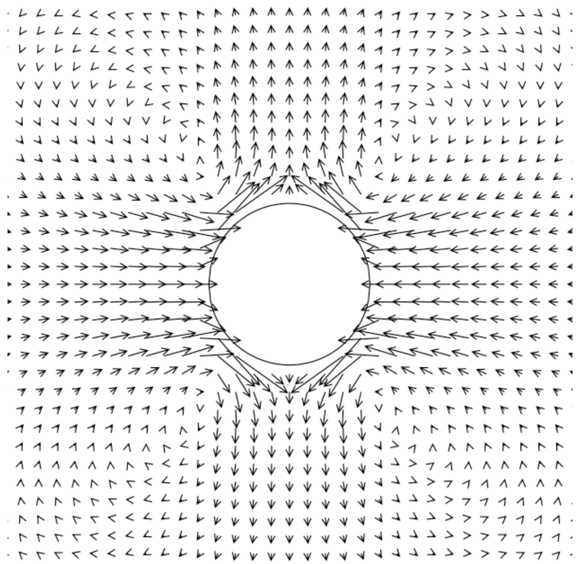
$v \sim 1/r^2$

$\beta > 0$

puller

$\beta < 0$

pusher



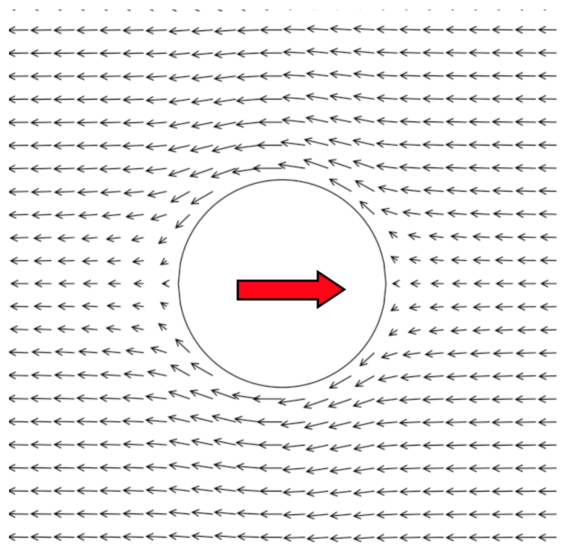
$B_1 = 0$

$B_2 \neq 0$

Apolar

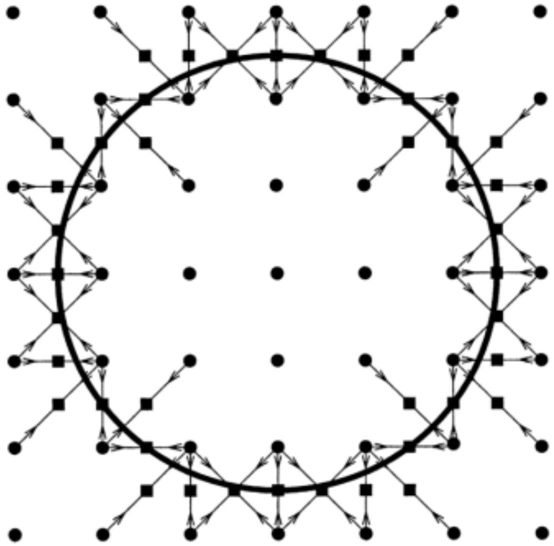
$\beta = 0$

Passive squirmer



$v \sim 1/r^3$

2. Microswimmer suspension: Model



Hard core

No temperature

No tumbling

focus on hydrodynamic coupling

$$\mathbf{v}_S = (B_1 \sin\theta + B_2 \sin\theta \cos\theta)\mathbf{t}$$

Slip velocity as a local bounce-back

Additional attraction

competition with activity

Stokes Law, small Reynolds

$$F_d = 6\pi\eta R_p v_s \qquad v_s = \frac{2}{3} B_1$$

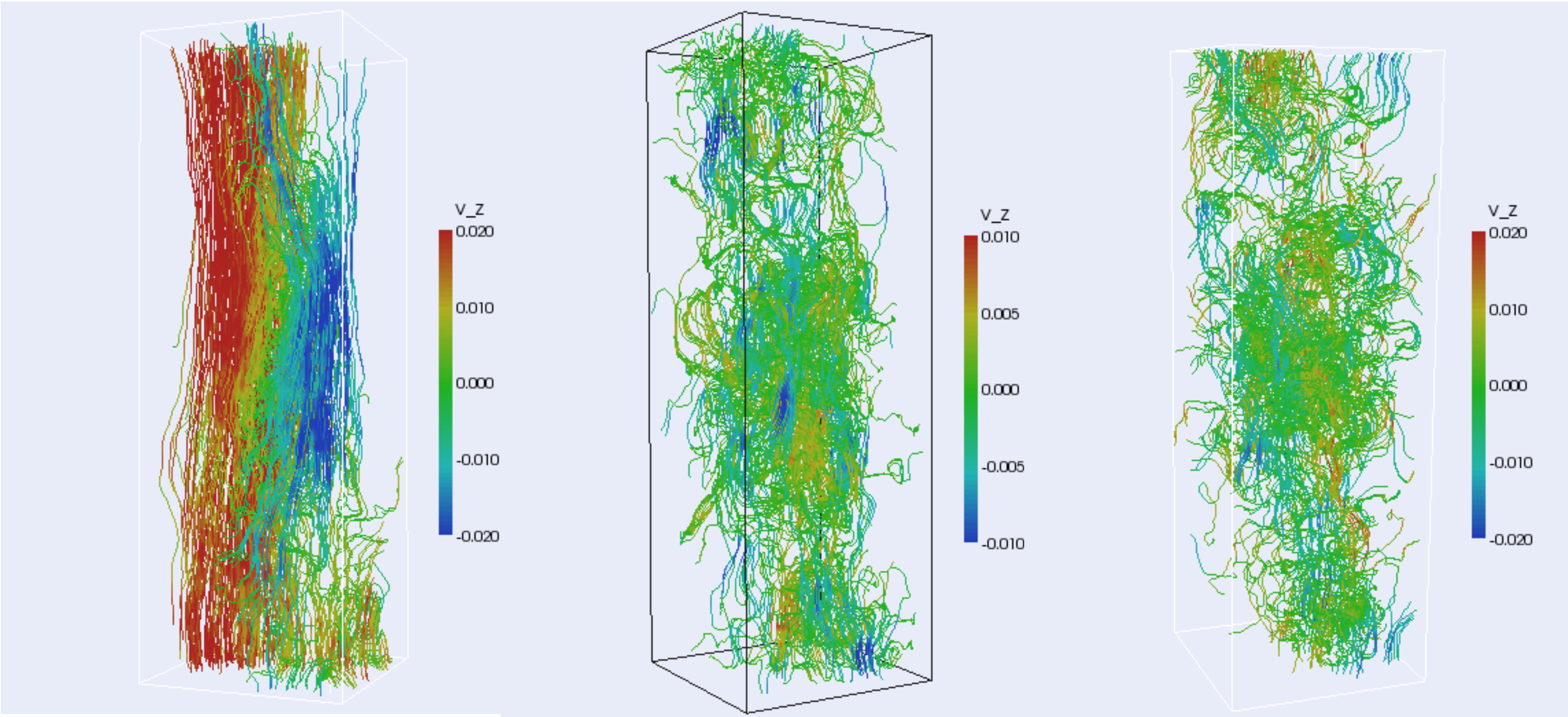
$\eta = 0.5,\ R_p = 2.3$

Transition to an ordered phase:
LJ interaction strength is reduced and
B2 is not too big.

$$\xi = \frac{F_d}{F_{LJ}(r = \sigma_{LJ})}$$

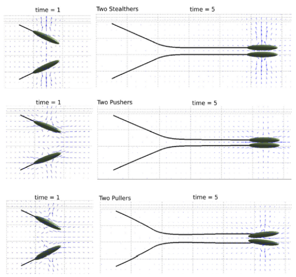
2. Microswimmers

Streamlines



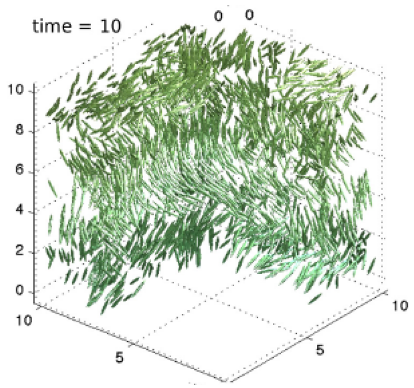
Polar Passive Apolar

2. Microswimmers



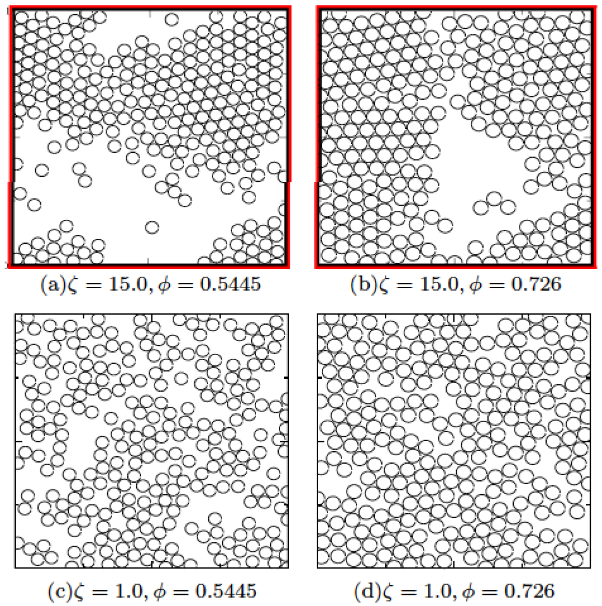
Hydrodynamic coupling - long range

Relevance of shape

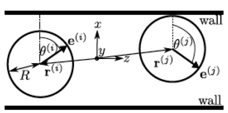


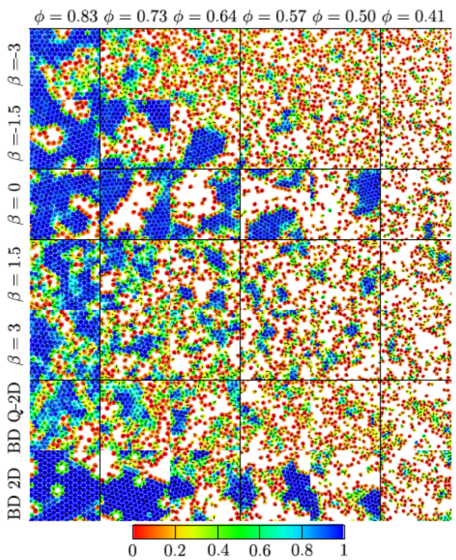
Lushi et al. (2013)

Disks/spheres
prevent crystallization?



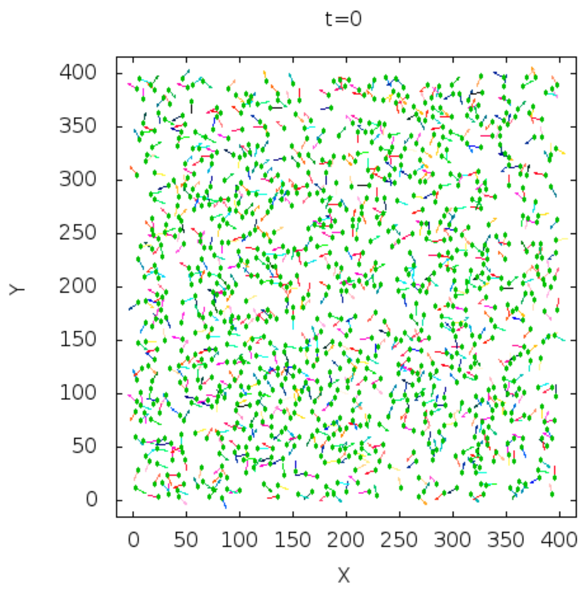
Matas-Navarro et al. (2014)

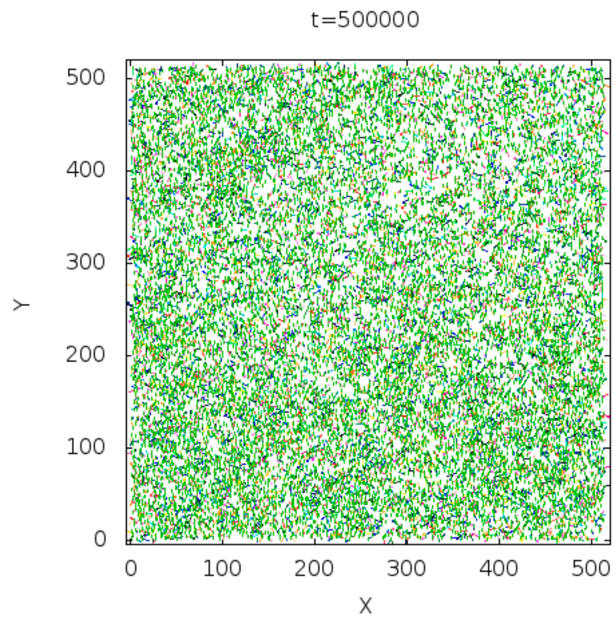




Zottl et al. (2014)

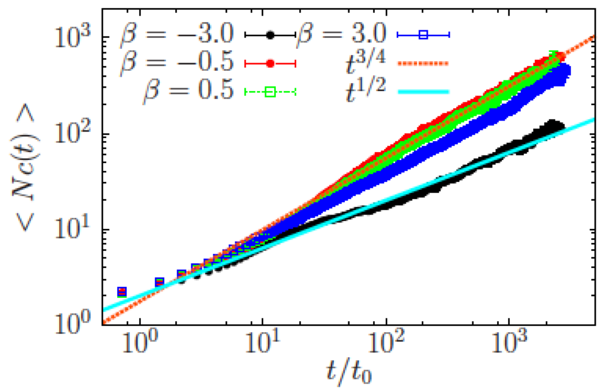
3. Cluster morphologies

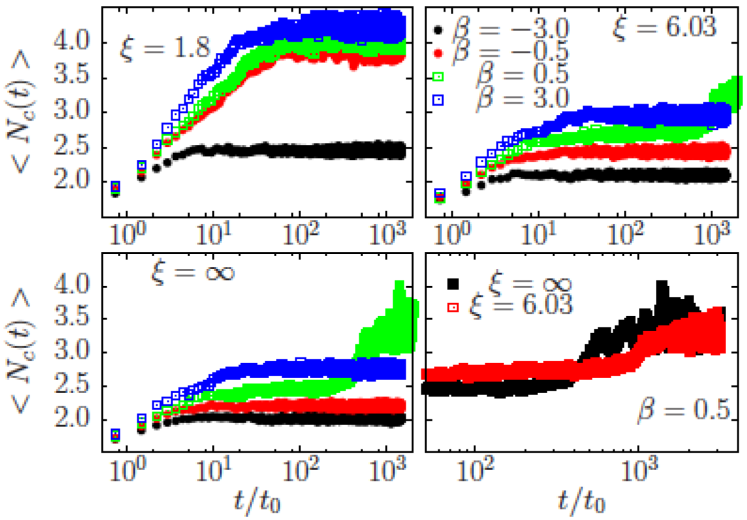




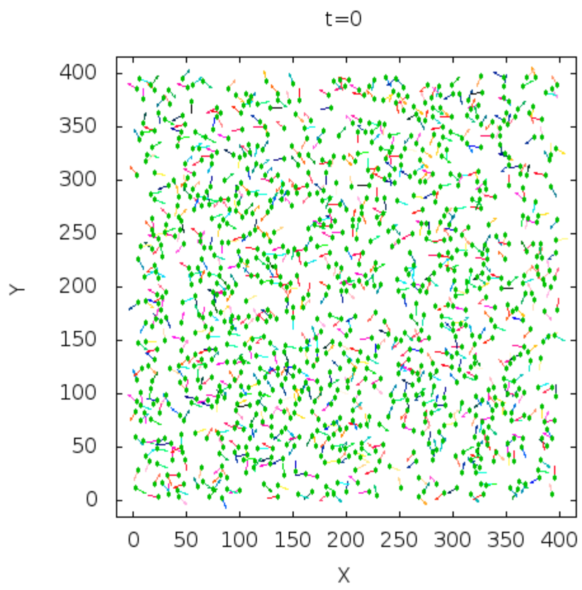
Dynamic structures

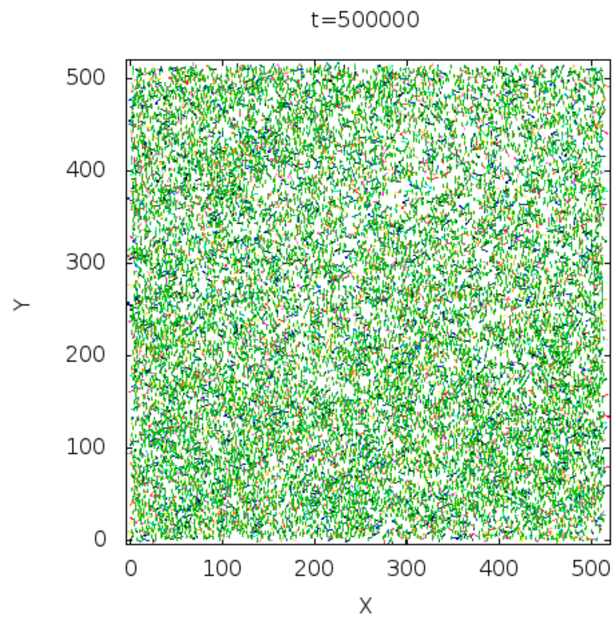
Morphological characterization?





3. Cluster morphologies

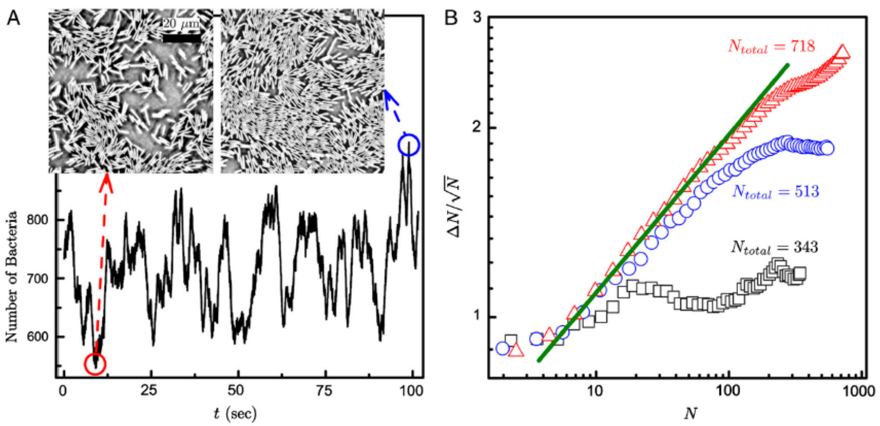




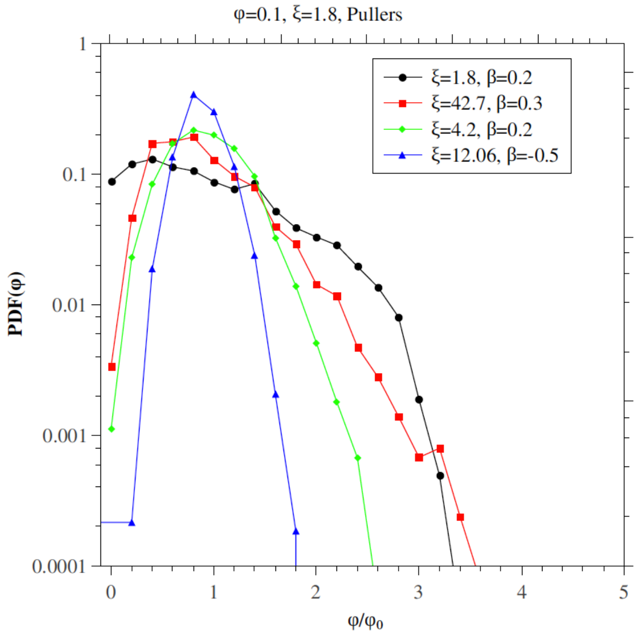
Dynamic structures

Morphological characterization?

Density fluctuations

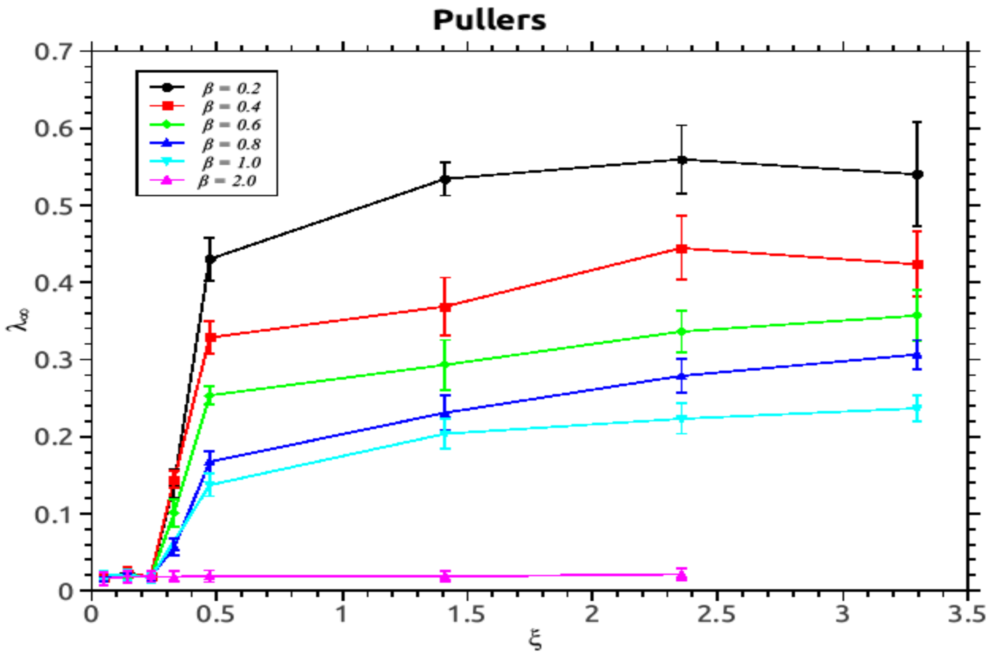


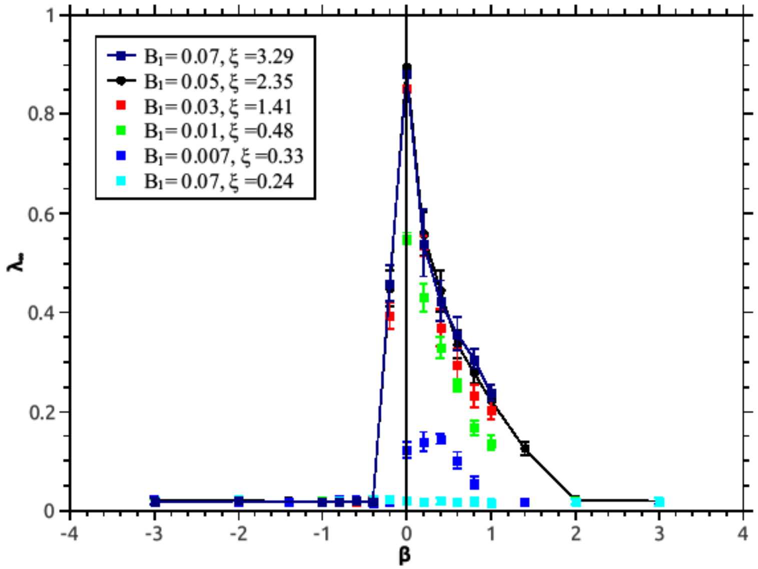
Zhang et al. PNAS (2010)

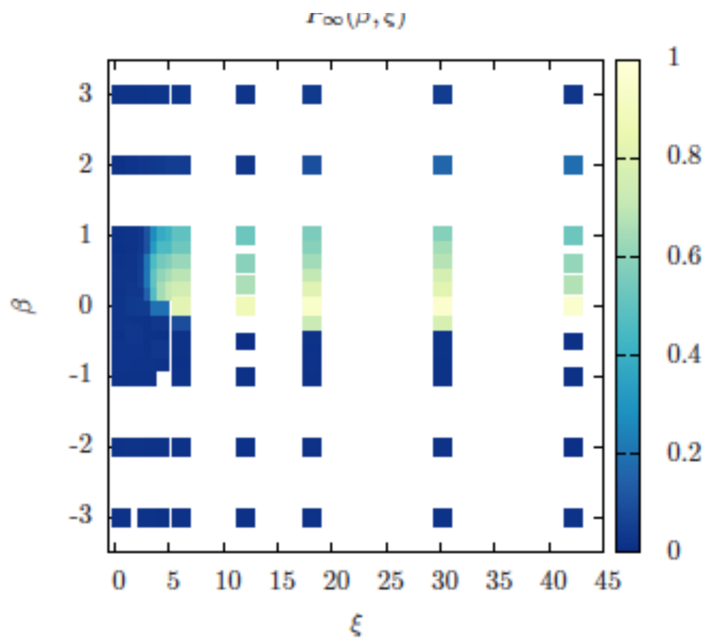


3. Squirmer suspensions: density fluctuations

Quantify degree of ordering
sensitive to active stresses
distinguish puller/pusher



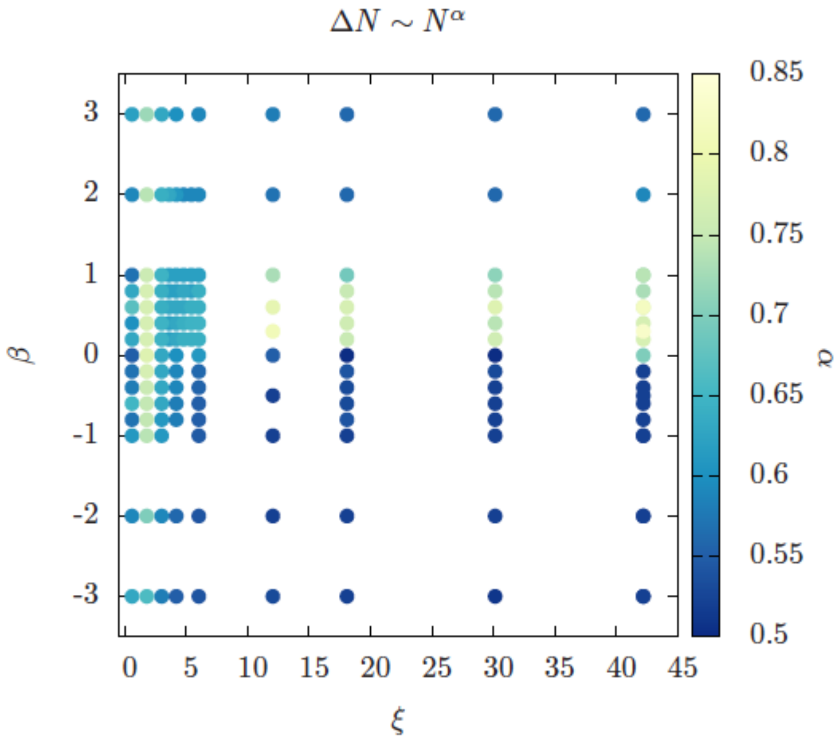


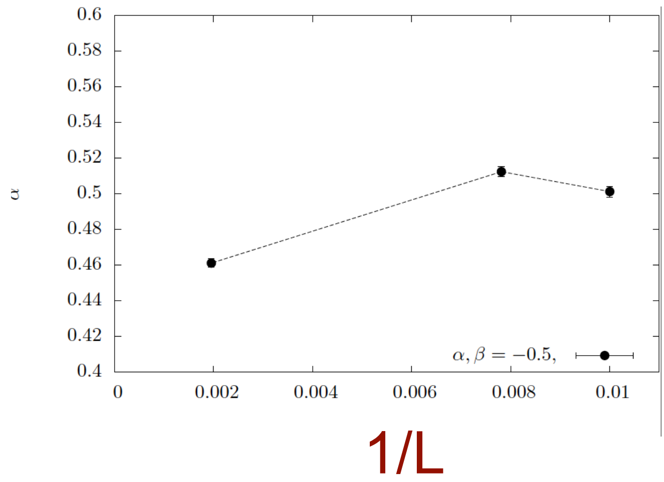


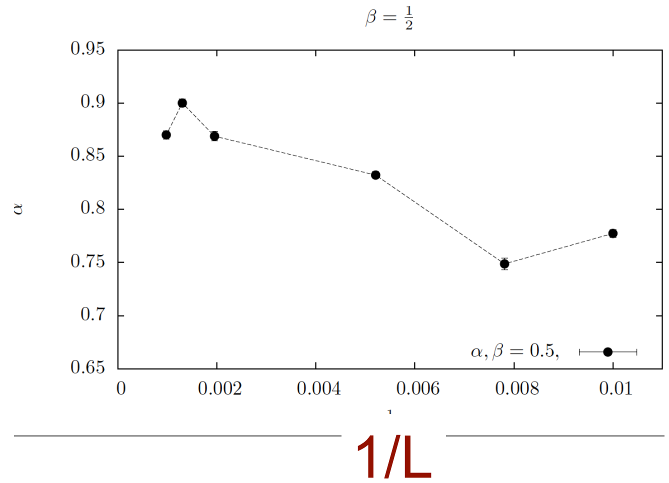
Squirmer attraction
enhances cohesion
destroys ordering

3. Squirmer suspensions: density fluctuations

Effect on density fluctuations
favours large dynamic clusters



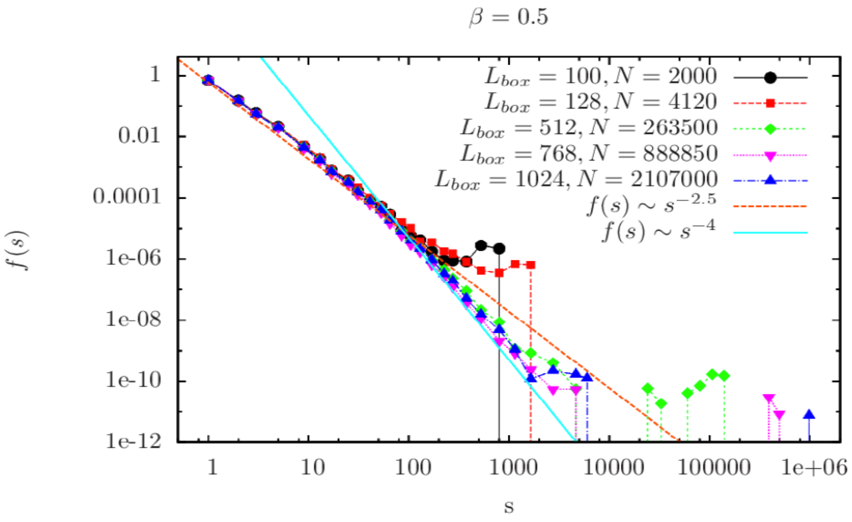


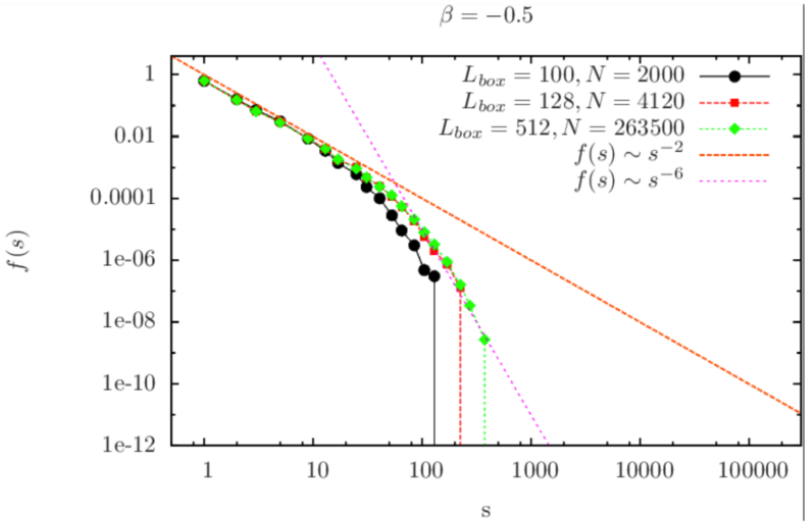


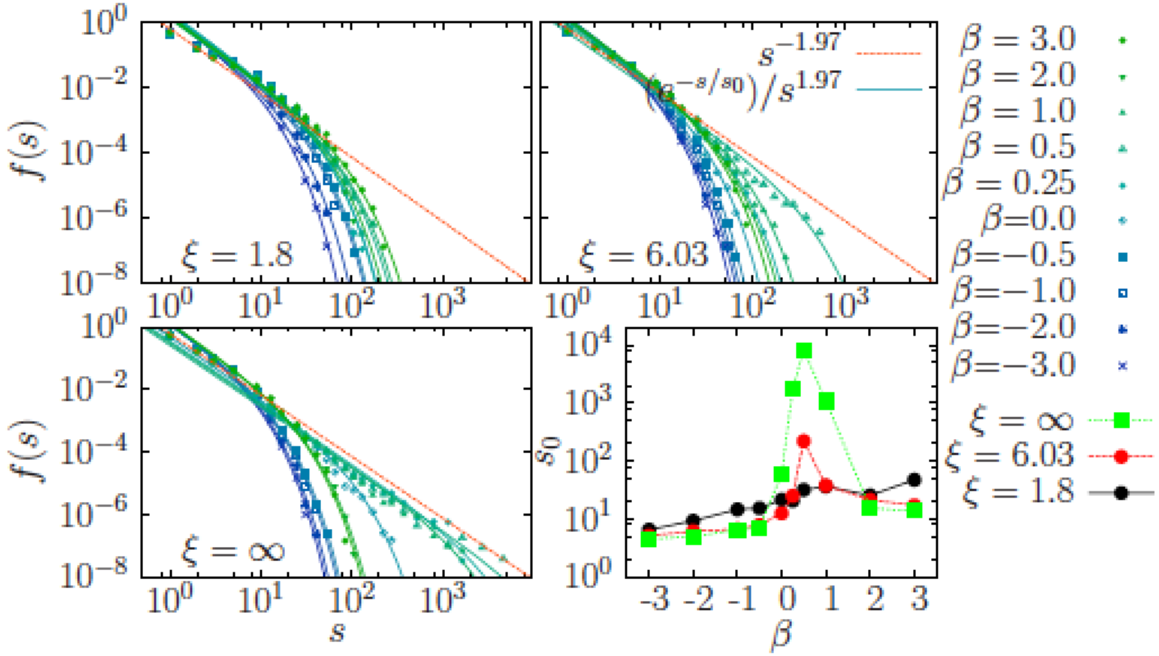
Need to reach large system sizes
Strong correlations

Significant finite size effects

3. Squirmer suspensions: Cluster distributions







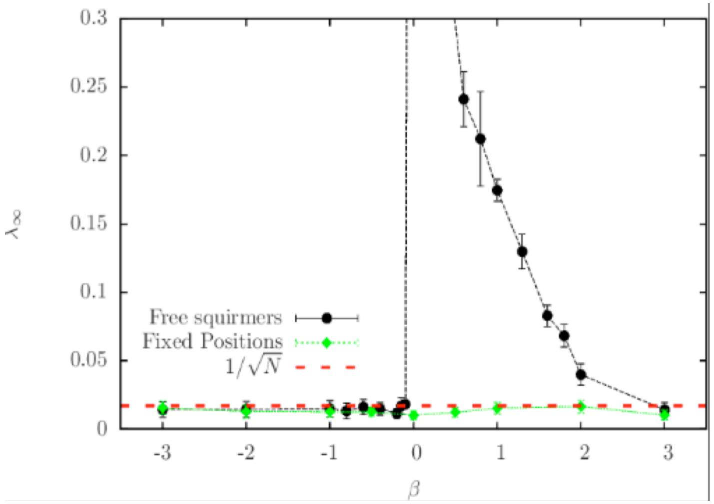
$$f(s) \sim s^{-\gamma_0} \exp(-s/s_0)$$

Power-law decay

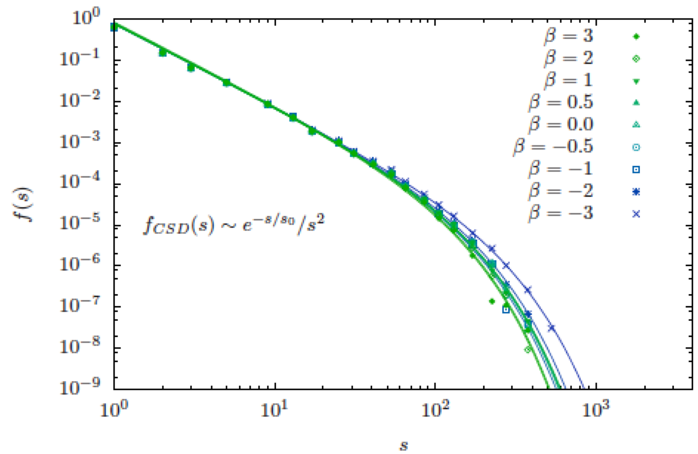
Wide range dynamic structures

3. Squirmer suspensions: Cluster distributions

Relevance of translational motion



.. and reorientation

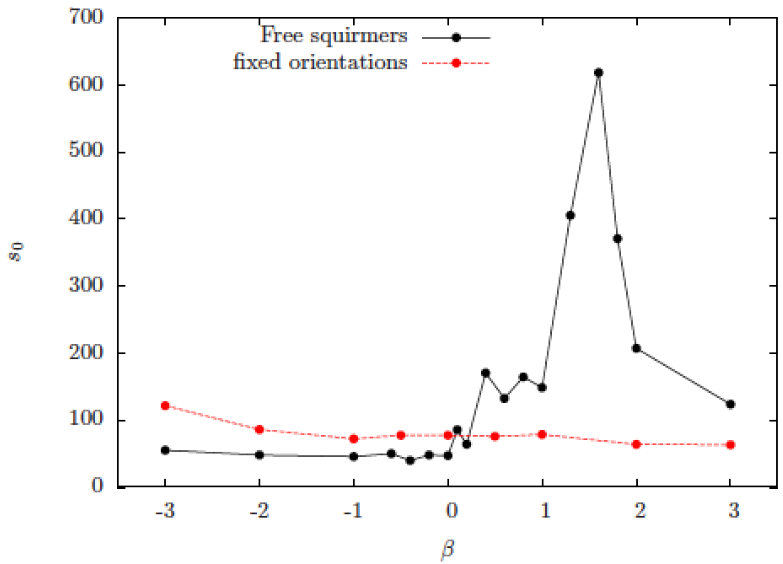


Hydrodynamic coupling

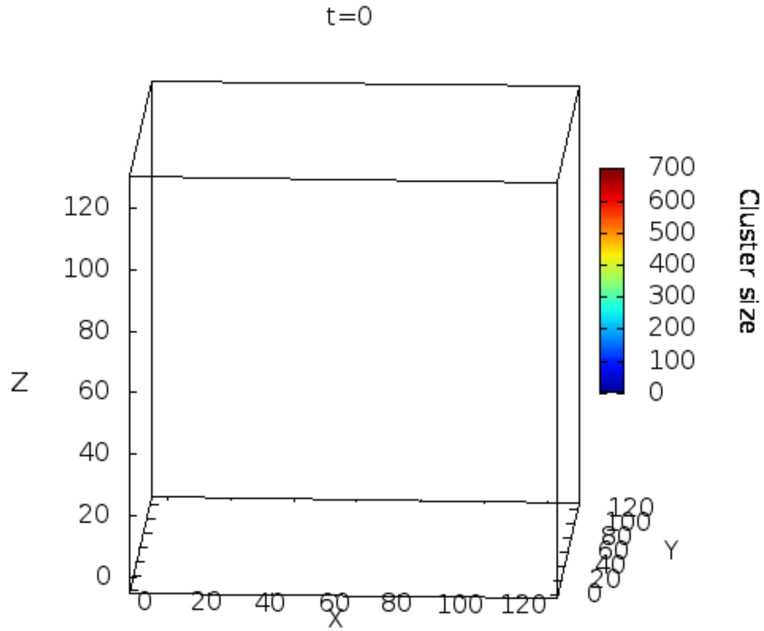
lack of translation/rotation coupling

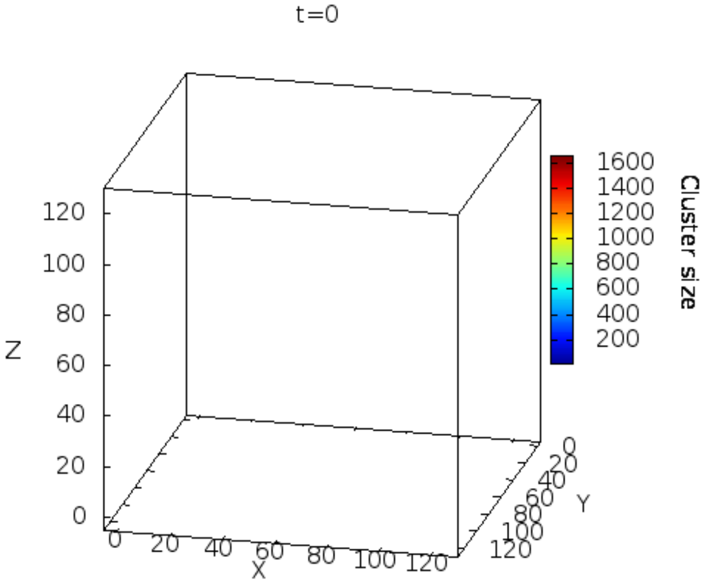
Nematogenic character lost

$$f(s) \sim s^{-\gamma_0} \exp(-s/s_0)$$

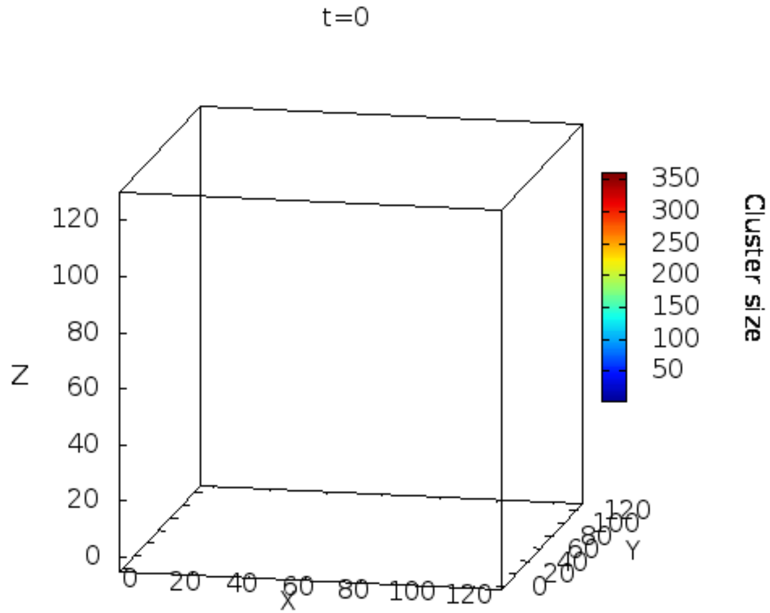


pullers β=3



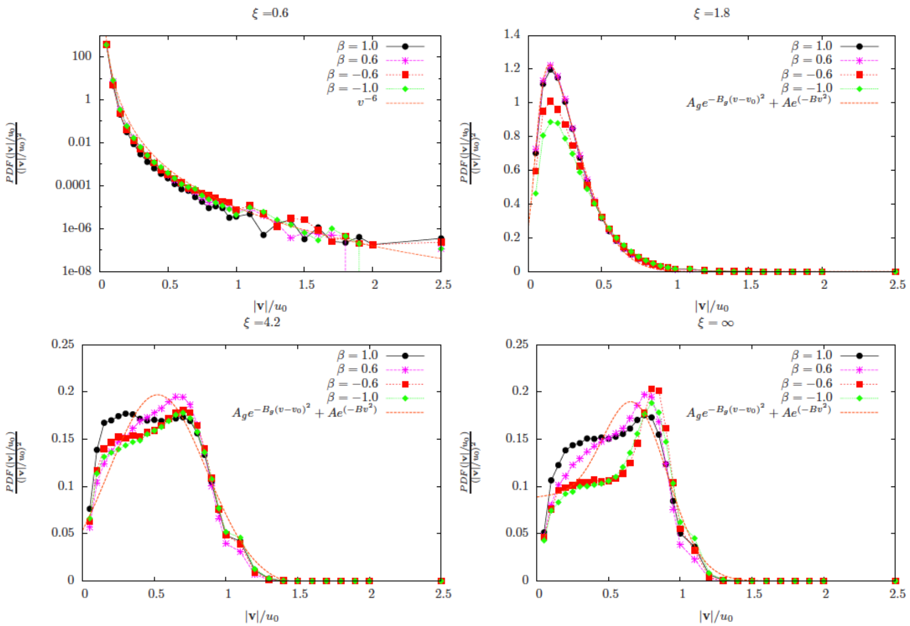


pullers β=1/2



pushers β=-3

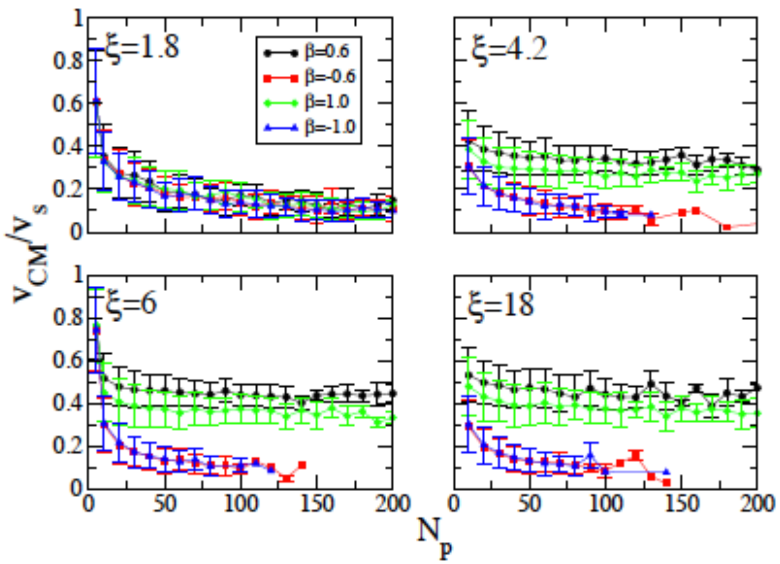
3. Squirmer suspensions

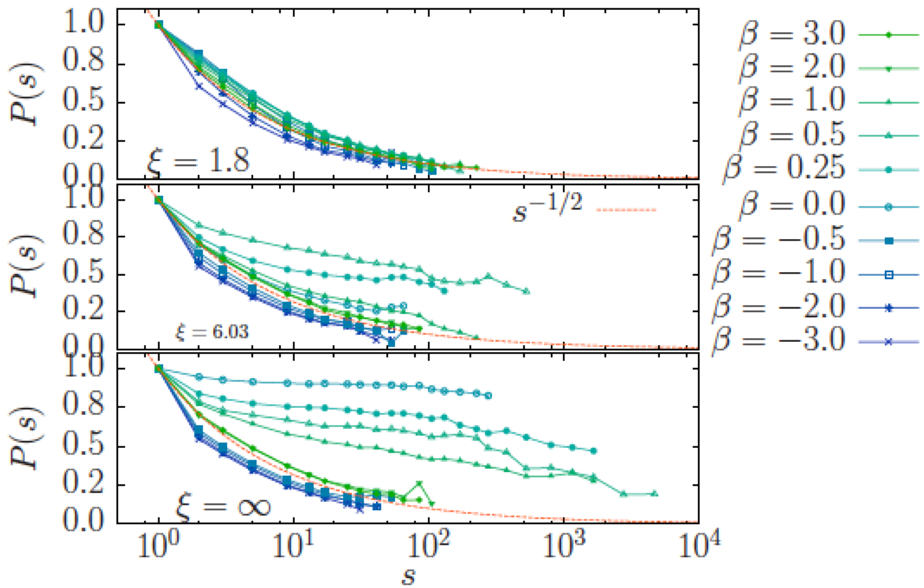


velocity distributions

impact of HI

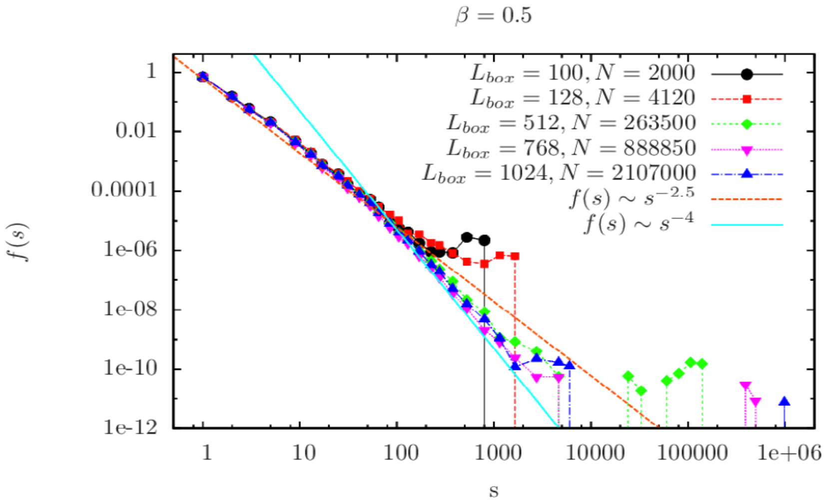
wider distributions for pullers

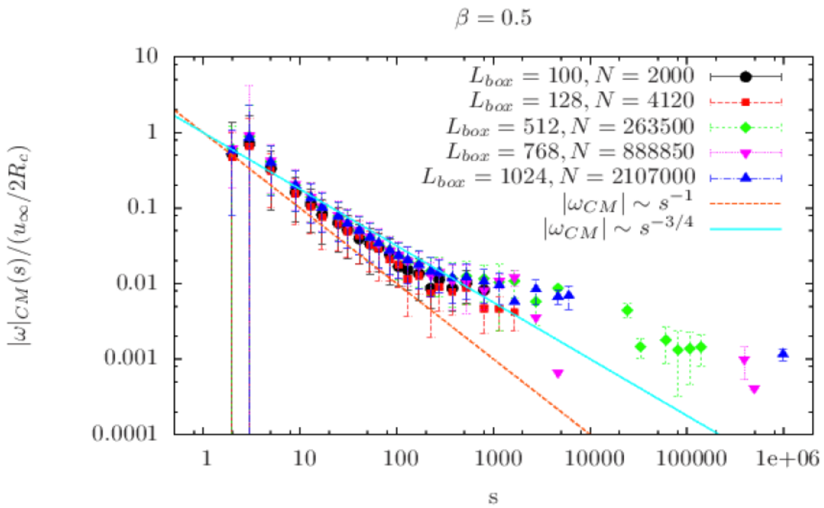


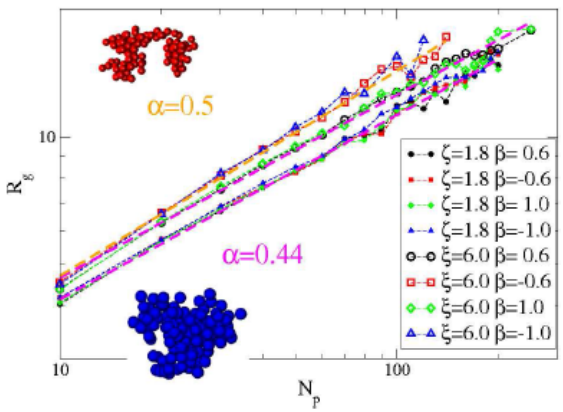


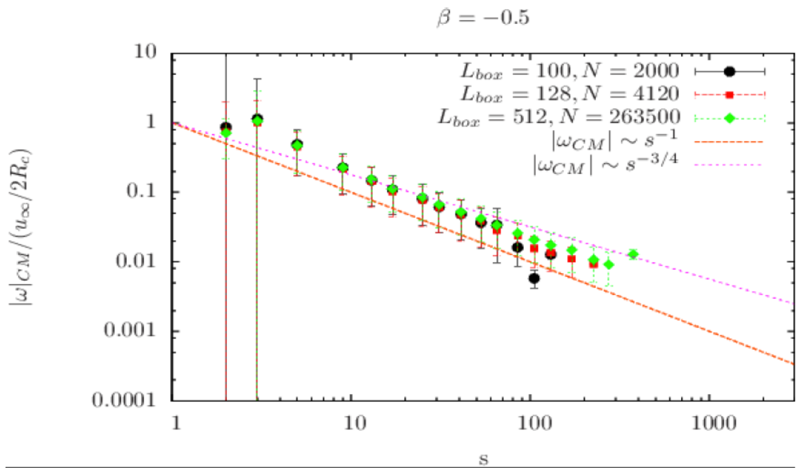
Generic polar order inside clusters

3. Squirmer suspensions: Cluster distributions



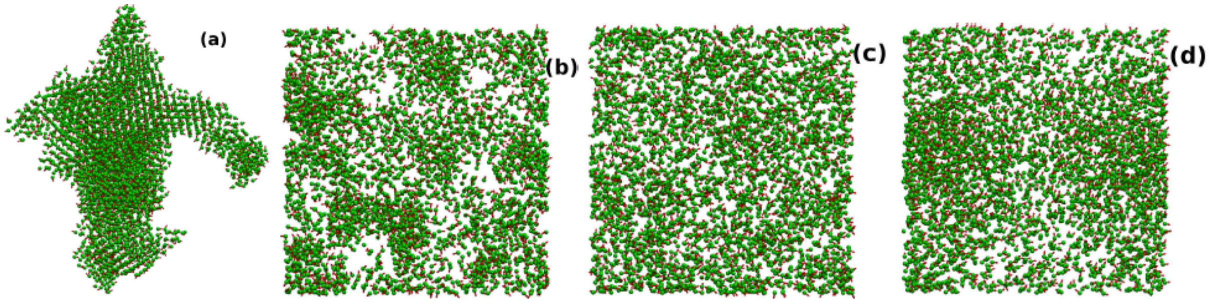






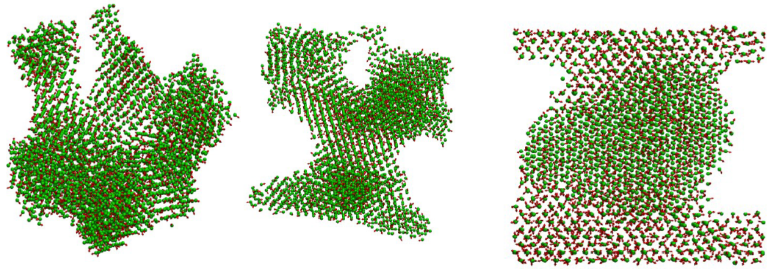
3. Cluster morphologies

Dynamic clusters

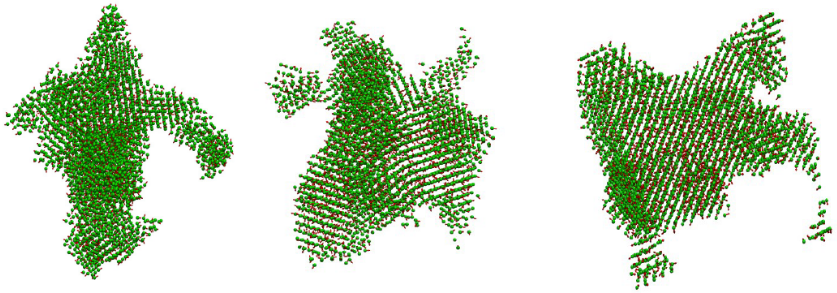


$\xi = 0.6$ $\xi = 1.8$ $\xi = 4.2$

ξ=0.6



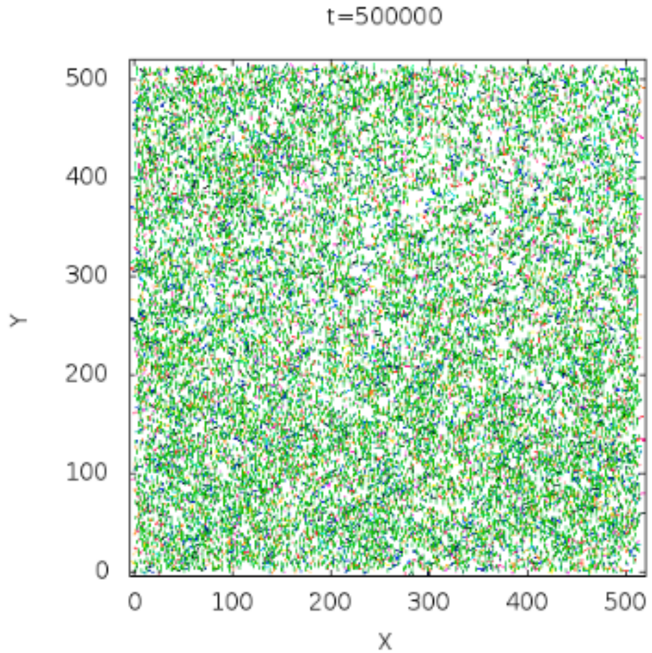
β=-0.6 β=-1.0 β=-10



B=0.6 β=5 β=10

crystal structures

pullers more robust



Percolating clusters

6. Conclusions

Active matter

Release energy at small scales (natural/synthetic)

intrinsically out of equilibrium

New mechanisms to develop patterns and structures

Competition between attraction/activity

Interplay hydrodynamics/attraction

Large density fluctuations

Macroscopic cluster

Induce polar ordering: dominant effect of translation/rotation

Dynamic clusters

Interplay hydrodynamics/attraction

Large density fluctuations

Acknowledgements

Francisco Alarcón-Oseguera

UNIVERSITAT DE BARCELONA

Barcelona Supercomputing Center

3. Motility-induced phase separation

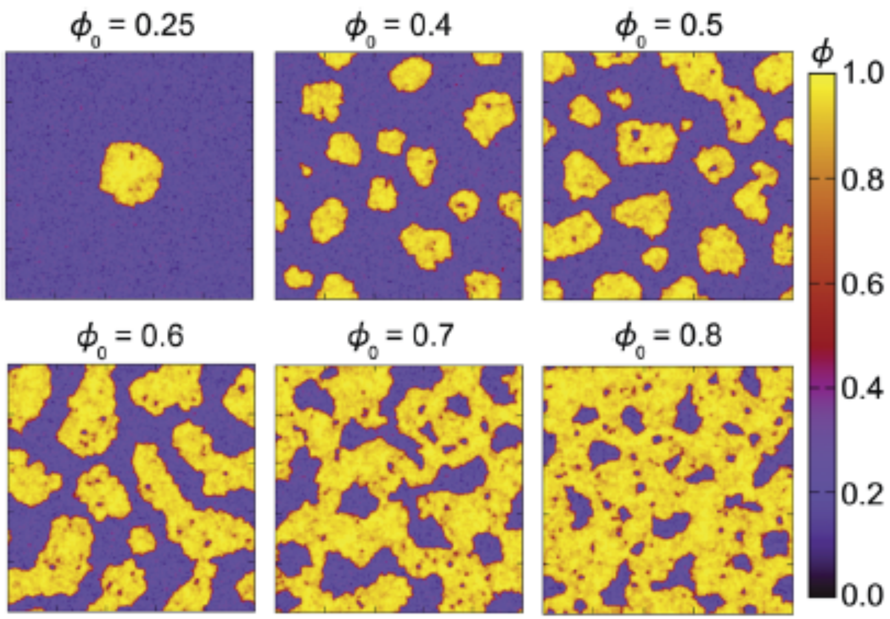
Active Brownian Particles

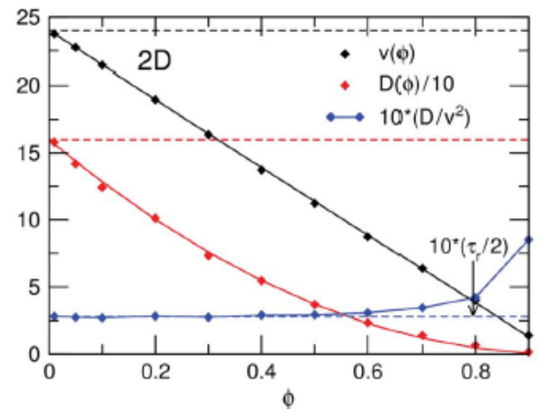
Particles trapped regions low motility

$$\mathbf{J} = -\rho D(\rho)\nabla\left[\frac{\delta \mathscr{F}_0}{\delta \rho}\right]$$

$$D(\rho) = \frac{v^2(\rho)\tau_r}{d(d-1)} = D_0(1 - v_0\sigma_s\tau_c\rho)^2$$

$$\partial_t\rho = -\nabla\cdot\mathbf{J} = -\nabla\cdot\left\{-D(\rho)\rho\nabla\mu + \sqrt{2D(\rho)\rho}\,\boldsymbol{\Lambda}\right\}$$





Stenhammar et al. (2014)

3. Motility-induced phase separation

Active Brownian Particles

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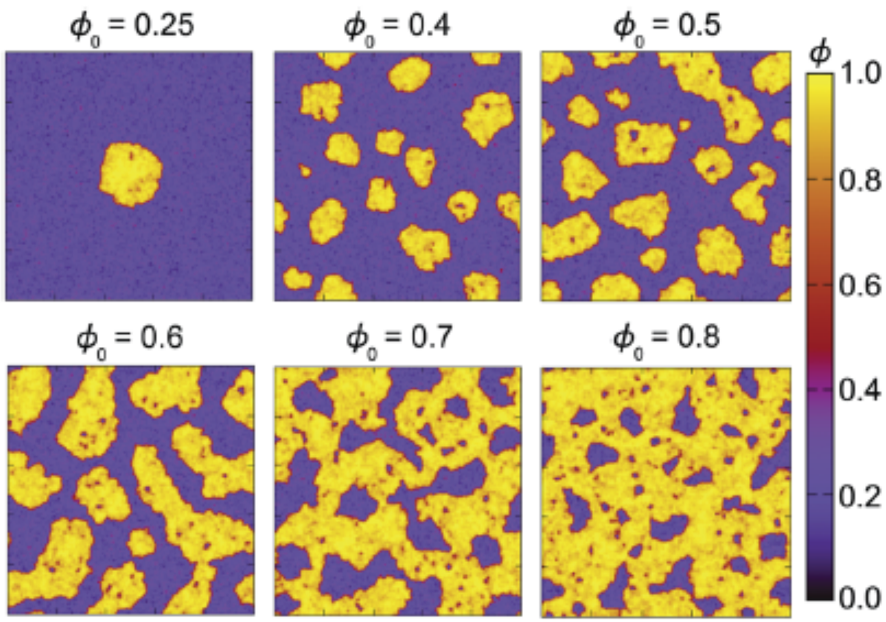
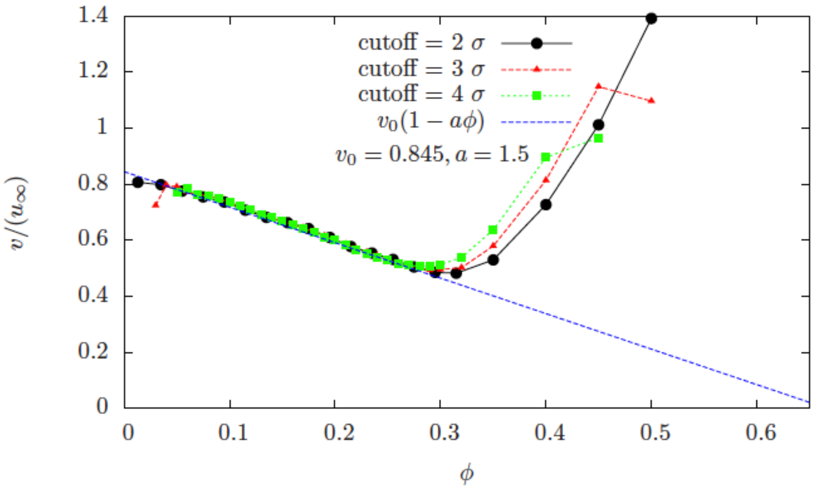
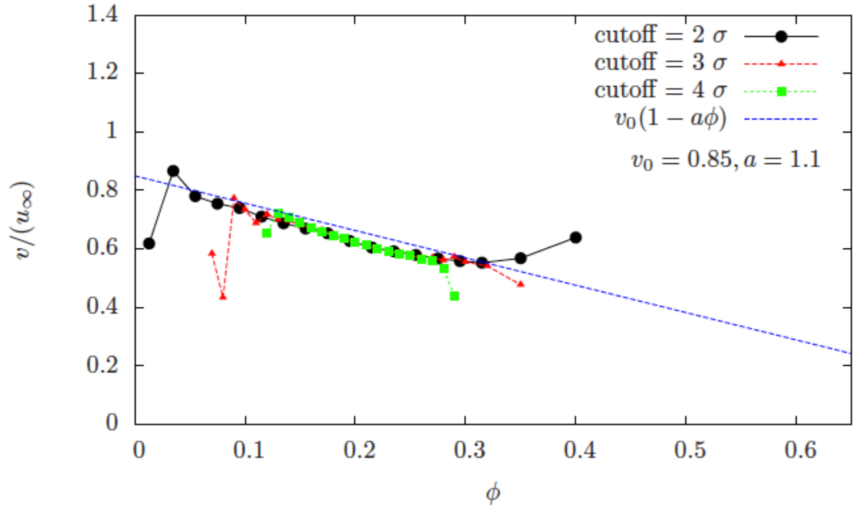
Particles trapped

regions low motility



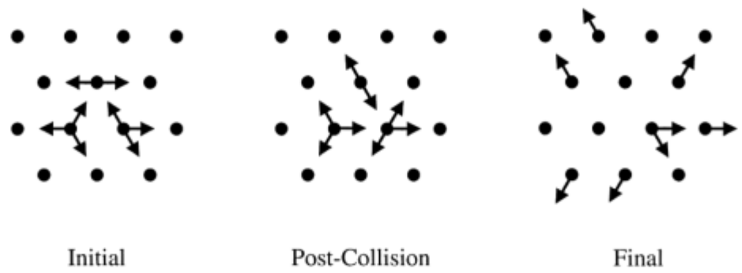




Stenhammar et al. (2014)

2. Microswimmer suspension: Model

Lattice kinetic model: "microscopic" dynamics



$$f_i(r + c_i, t+1) = f_i(r,t) - \omega[f_i(r,t) - f_i^{eq}(r,t)]$$

$$\sum f_i = \rho$$

$$\sum f_i c_i = \rho v$$

$$\sum f_i c_i c_i = \rho v v + P$$

Conserved variables
Proper symmetries

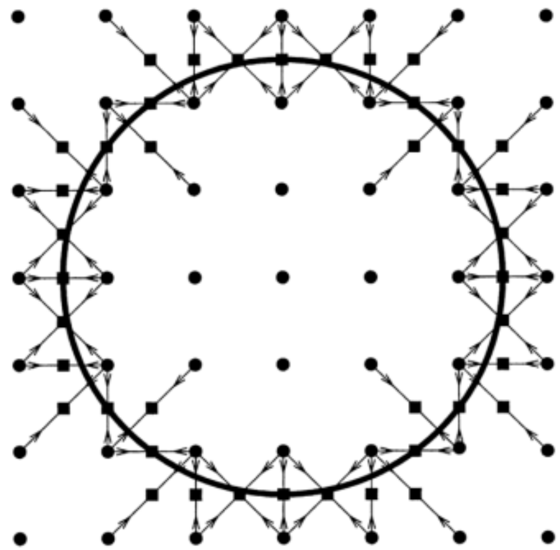
Hydrodynamic equations

Colloid

rigid hollow surface

collision

bounce-back



Hybrid scheme: molecular dynamics

Pre-selection of relevant degrees of freedom