The allure of active matter

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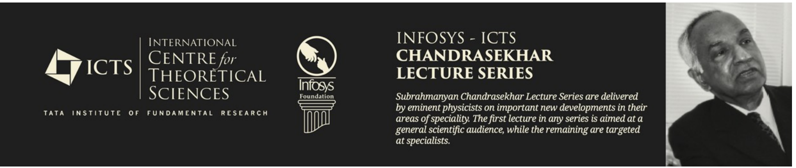

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LECTURE SERIES

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Outline

- Lecture 1: a self-contained tour
  - early results & link to the latest
- Lecture 2: active dynamics in a fluid
  - and a connection to sedimentation
- Lecture 3: non-reciprocal dynamics
  - flocking without moving, odd mechanics, oscillation without inertia

Lecture 1

- Introduction
  - origins & prehistory; fundamentals
- Dry active matter
  - active nematics; motility in granular layers; chemotactic colloids
- Wet active matter
  - rheology, instability, active turbulence
- Summary

Lecture 2

- Active fluids with inertia
  - outswimming the instability
- Many-particle sedimentation
  - Kepler orbits; emergent elasticity
  - non-normal dynamics

Lecture 3

- Non-reciprocal dynamics: fundamentals
  - a world out of (detailed) balance
- Flocking without moving
  - order and defects; spontaneous waves on curved surfaces
- Chiral active matter
  - odd and odder elasticity
- Summary and prospect

Group


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(with Subroto Mukerjee)


Raushan Kant (with AK Sood)

Ramita Mondal
(UG, w/ M Barma)

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(with Ambarish Ghosh)

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IoE postdoc


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(with C Dasgupta & S Mukerjee)

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- Ananyo Maitra: CNRS, Cergy Univ Paris
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Rangan Lahiri: TIFR Mumbai

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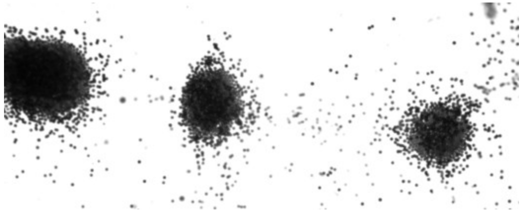
- Yashodhan Hatwalne: Raman Research Institute
- Yatin Marathe (w/ N Kumar)

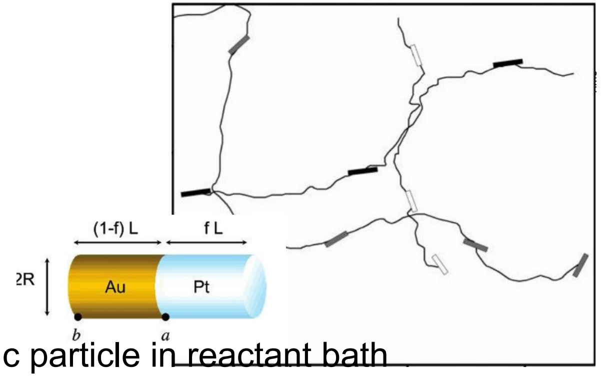
INTRODUCTION

- Active particles:
  - living creatures; their powered components; gadgets
  - Time’s Arrow at particle scale: free-energy ––> work
  - collectively: active matter

The many kinds of active matter

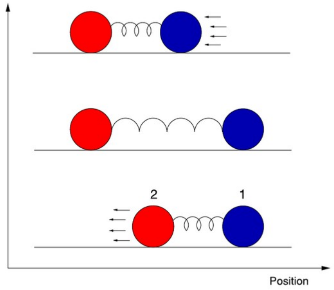


Scalar active matter
Chemically propelled droplets
S Thutupalli NCBS



Catalytic particle in reactant bath
Sen, Mallouk, ... 2004; Golestanian et al. 2005

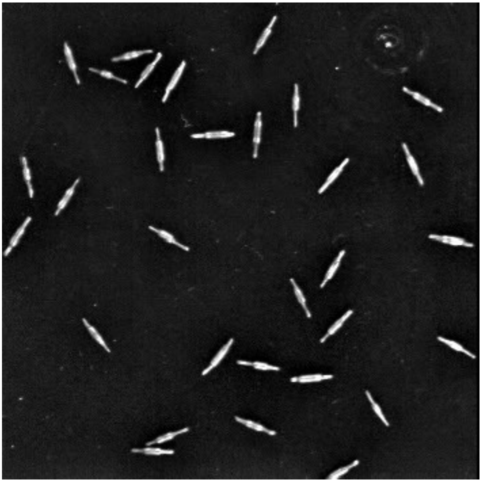
vector



A Baule et al 2008
K V Kumar et al 2008

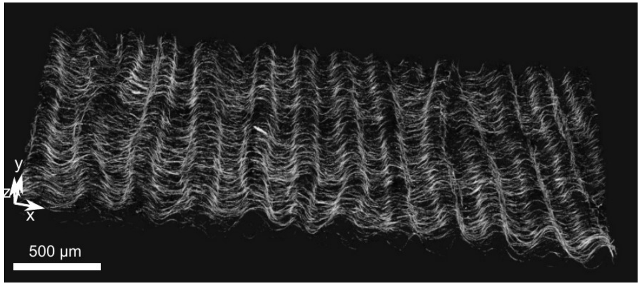
[a motile dimer: noise turned into directed movement]

A motile rod transducing vertical shaking into horizontal motion: Nitin Kumar

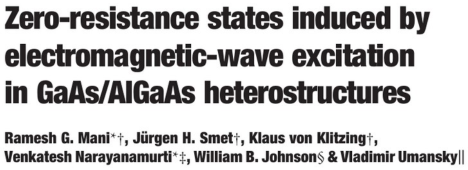


[broken equipartition -- Vijay Narayan 2007]

tensor



Extracts from a cell
Senoussi et al 2019

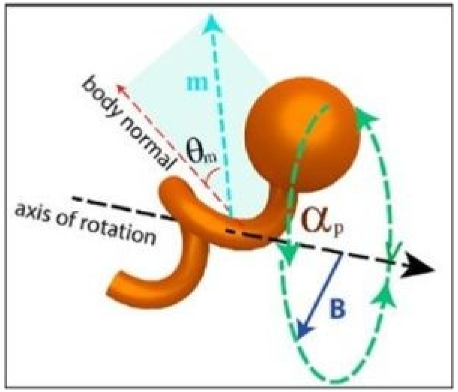


Zero-resistance states induced by electromagnetic-wave excitation in GaAs/AlGaAs heterostructures

Ramesh G. Mani*†, Jürgen H. Smet†, Klaus von Klitzing†, Venkatesh Narayanamurti*‡, William B. Johnson§ & Vladimir Umansky||

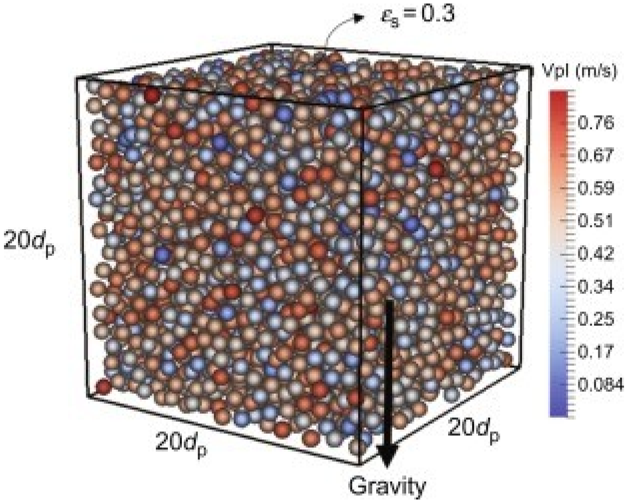
R.G. Mani et al. 2002
Alicea et al. PRB 2005: "... connection ot our work to the well-studied phenomenon of 'flocking'"

quantum



chiral

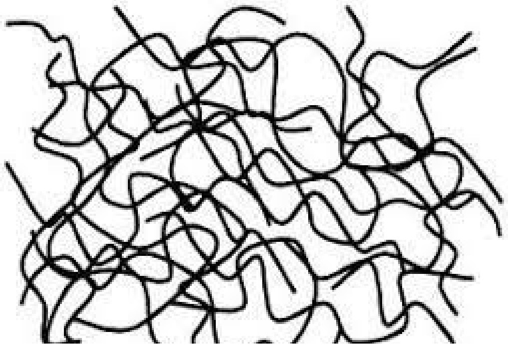
Magnetic nanopropellors: Ambarish Ghosh,



How do these differ structurally & dynamically?

https://t3.ftcdn.net/jpg/02/39/58/76/240_F_239587680_TmqOkl8wT5OVOyhBBJD4drE9ADmnnQZ6.jpg

https://www.sciencedirect.com/topics/chemistry/hard-sphere-model

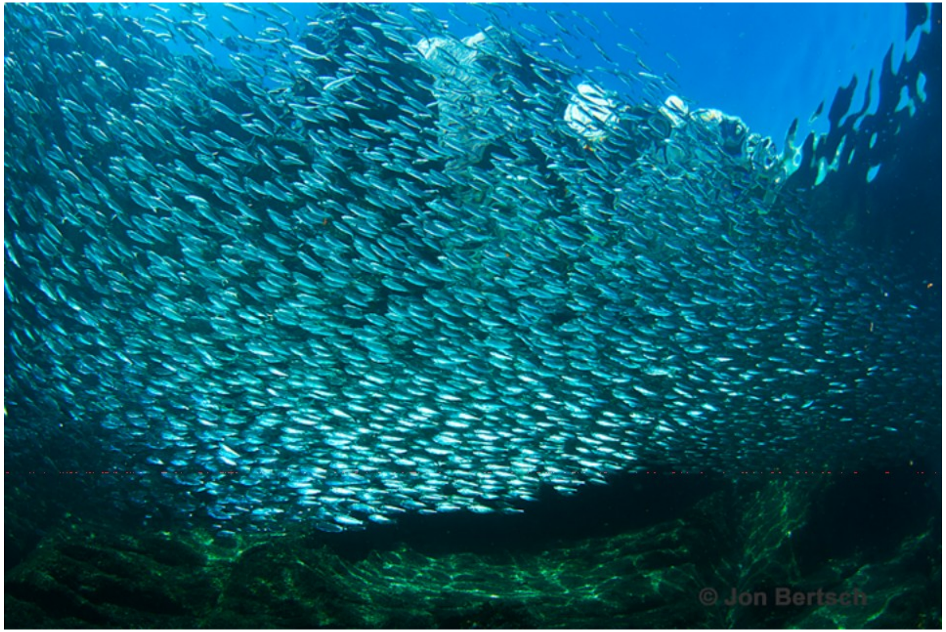


https://www.nytimes.com/2016/05/07/science/narcisse-snake-pits.html

http://franklin.chem.colostate.edu/szamel/group/sbrown/figs/melt.html

Dynamical regimes

Wet*: suspended in a fluid



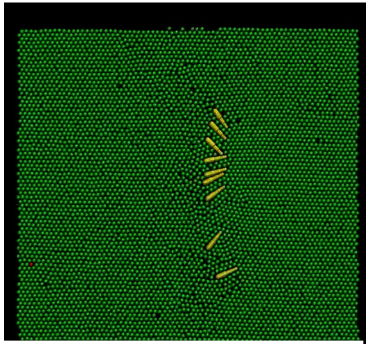
J Bertsch http://www.thalassagraphics.com/blog/?p=167

Dry*: with a passive momentum sink

DARIUSZ PACIOREK/GETTY https://www.wired.com/2013/03/powers-of-swarms/

* not Feynman’s wet & dry, sorry

Why should you care?



nine particles turning to find each other

- A grand challenge
  - the emergent laws governing (self-)driven matter
- Understand living matter as a physical material
  - the role of mechanics in cell, tissue, organism and beyond
- Imitate the functionalities of living matter
  - smart active matter: motility, signalling, sensing

Prehistory and history

self-electrophoresis 1956 fluids with energy sources 1969 hydrodynamics of swimmers 1975

animals/animation 1982/87 living LCs 1990s dry flocks 1995 active membranes ‘96

motile polymers, cytoskeleton 2001 flocks in fluid theory ‘02-04 dry active nematics: theory 2003

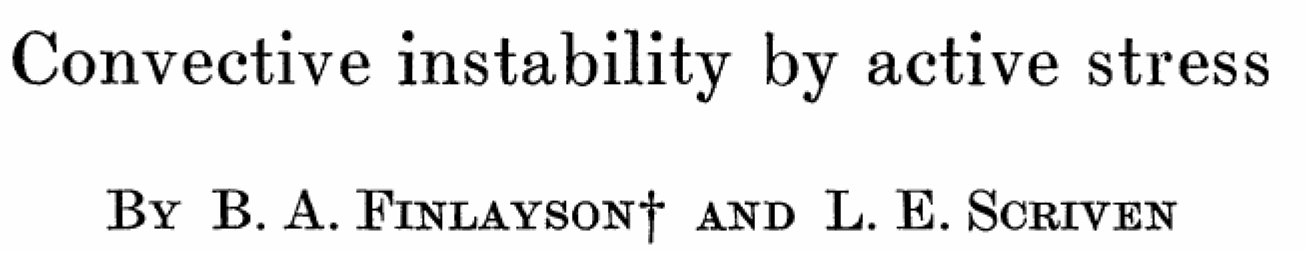
vibrated grains 2003 active colloids 04-05 Dry active nem sim/expt 06/07 rheo 2007+

bands ‘08 starling flocks ‘08 Dense active, tissue 2009+ microswimmers ‘11 MIPS ‘12

wet active nem expts 2012 Quinke expts 2013 pressure 2014 defect dynamics (wet)

thermo, entropy production morphogenesis turbulence active baths Command and control

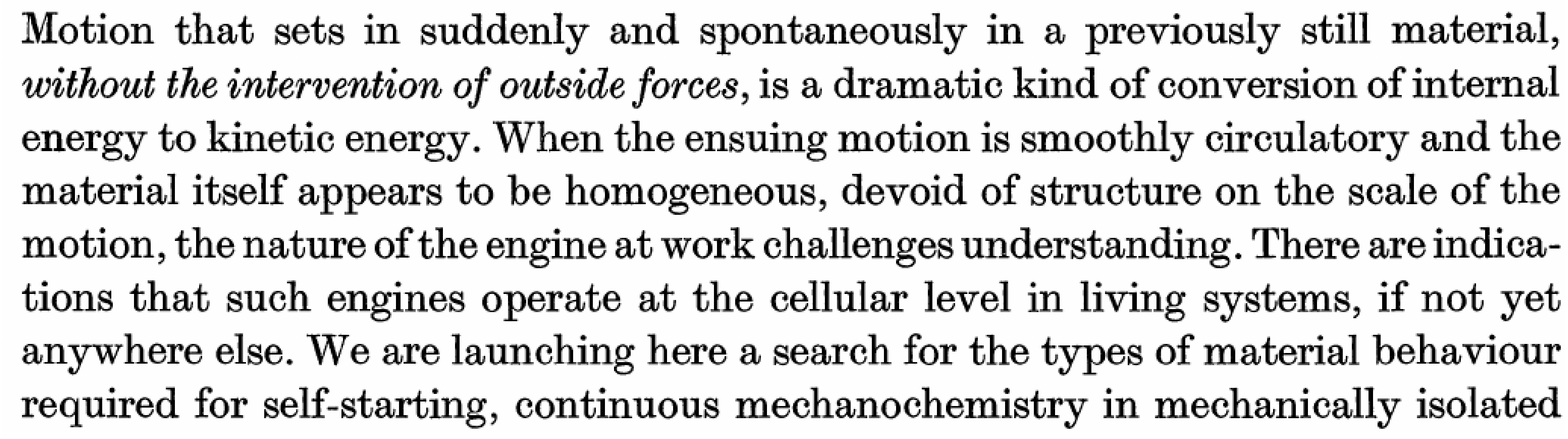
non-reciprocal interactions interfaces chirality



Convective instability by active stress

By B. A. Finlayson† and L. E. Scriven

Proc. R. Soc. Lond. A **310**, 183–189 (1969)

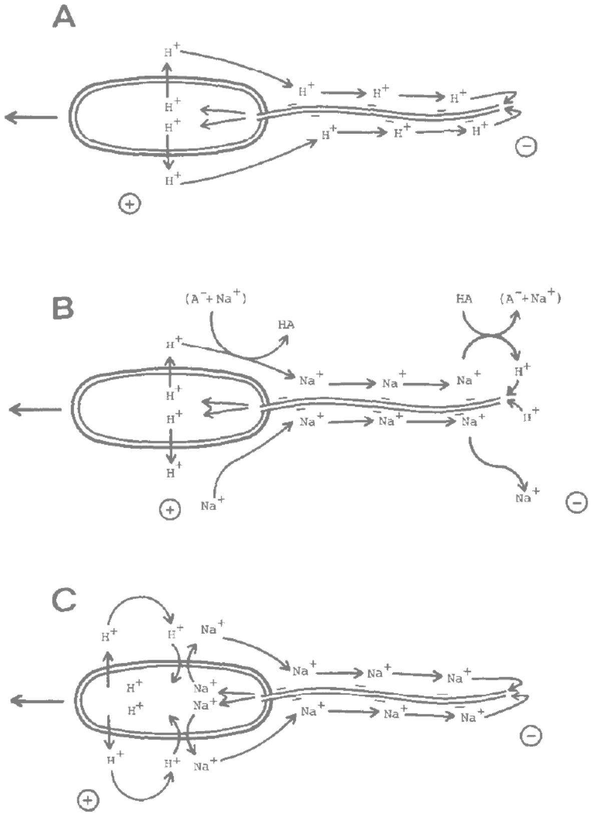


Motion that sets in suddenly and spontaneously in a previously still material, *without the intervention of outside forces*, is a dramatic kind of conversion of internal energy to kinetic energy. When the ensuing motion is smoothly circulatory and the material itself appears to be homogeneous, devoid of structure on the scale of the motion, the nature of the engine at work challenges understanding. There are indications that such engines operate at the cellular level in living systems, if not yet anywhere else. We are launching here a search for the types of material behaviour required for self-starting, continuous mechanochemistry in mechanically isolated

Before its time ... broken-symmetry hydrodynamics as yet unavailable ...
Still largely ignored in the literature

Mitchell: self-electrophoresis

P Mitchell, FEBS Lett **28** (1972) 1
see also Proc R Phys Soc Edin **25** (1956) 32



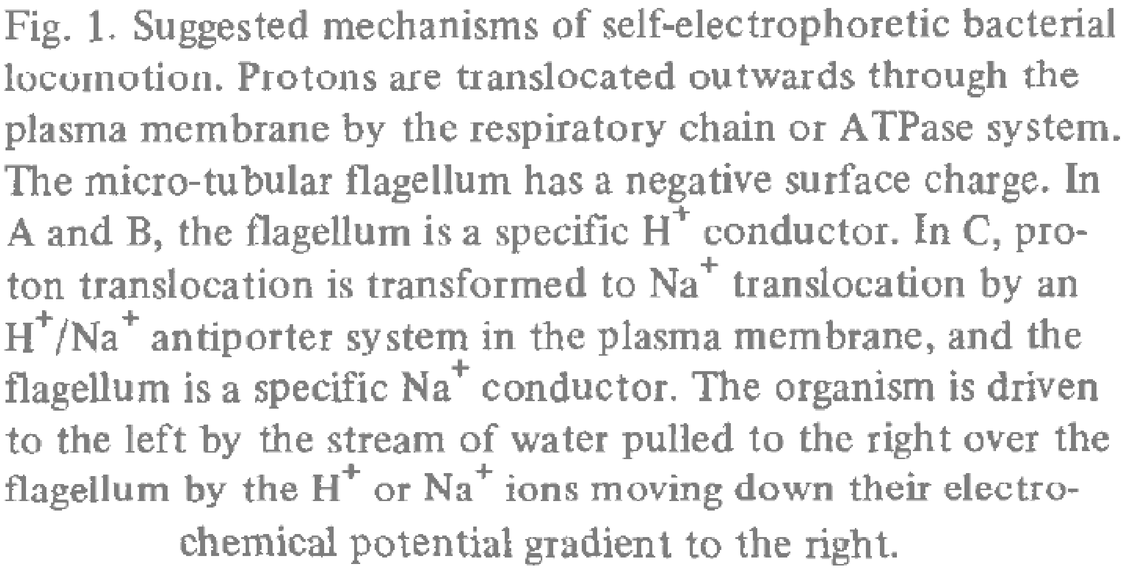


Fig. 1. Suggested mechanisms of self-electrophoretic bacterial locomotion. Protons are translocated outwards through the plasma membrane by the respiratory chain or ATPase system. The micro-tubular flagellum has a negative surface charge. In A and B, the flagellum is a specific H^+ conductor. In C, proton translocation is transformed to Na^+ translocation by an H^+/Na^+ antiporter system in the plasma membrane, and the flagellum is a specific Na^+ conductor. The organism is driven to the left by the stream of water pulled to the right over the flagellum by the H^+ or Na^+ ions moving down their electrochemical potential gradient to the right.

Not a theory of bacterial swimming, but see
Lammert, Prost, Bruinsma J Theor Biol **178** (1996) 387-391

Not quite self-phoresis

J L Anderson, Annu Rev Fluid Mech **21** (1989) 61-99

Says: “... microfields established by active processes within a particle ... could self-propel ...”

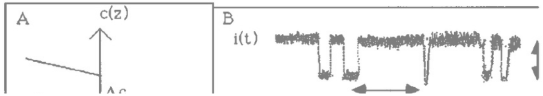
Does: small external gradient --> electric field --> slip velocity --> phoretic propulsion

$$U = -\frac{1}{3}\left(\frac{\varepsilon\zeta}{4\pi\eta}\right)\frac{\chi}{k_c}\boxed{\nabla C_\infty}$$

For true self-phoresis see Golestanian, Liverpool, Ajdari PRL **94**, 220801(2005)

Membranes with active “force centres”

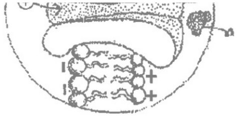
Prost & Bruinsma EPL **33** (1996) 321



$$\frac{\partial u(\mathbf{q},t)}{\partial t} + \tau(q)^{-1} u(\mathbf{q},t) = \eta(\mathbf{q},t) + \Gamma \sum_k S_k(t) \exp[i\mathbf{q}\cdot\mathbf{R}_k(t)]$$

with a relaxation rate $\tau(q)^{-1}$

$$\tau^{-1}(q) = \frac{\kappa}{4\eta} q^3 + \kappa\lambda_{\mathrm{p}} q^4$$



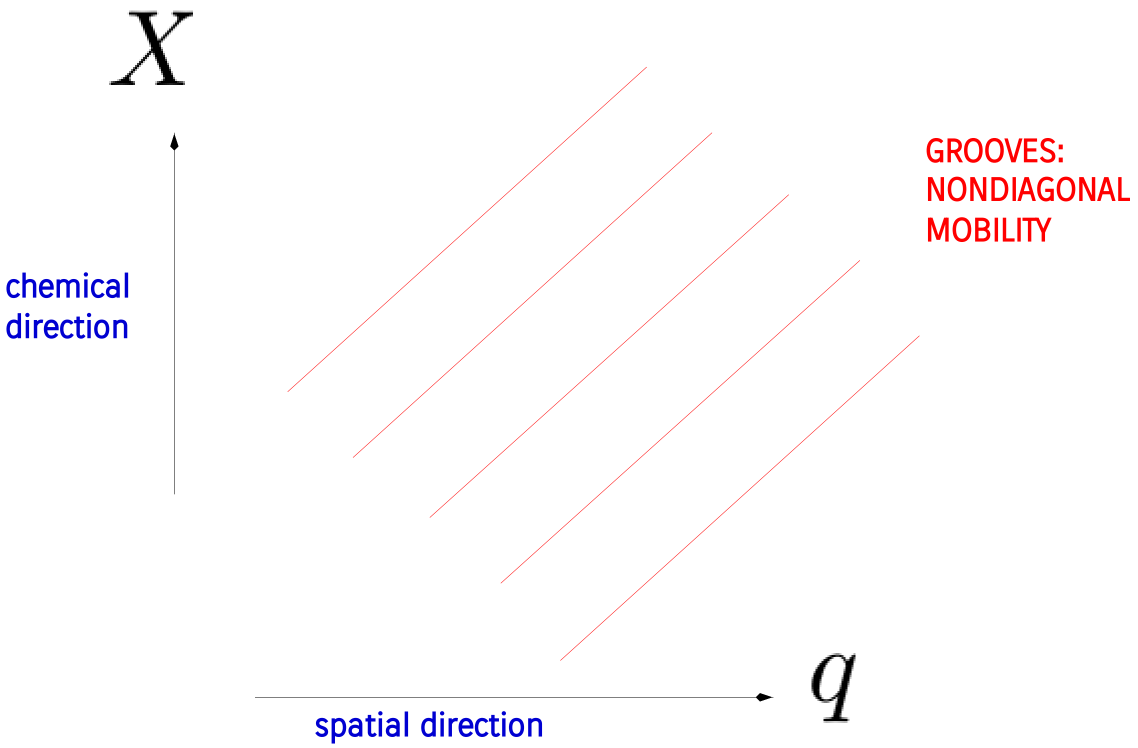
Enormous fluctuations if coupling one way.
Story changes if membrane acts back on pumps.
SR, Toner, Prost PRL **84** (2000) 3494

Microbial hydrodynamics

Pedley & Kessler, Annu Rev Fluid Mech **24** 313 (1992)

- Coarse-graining: PDEs for concentration, orientation
- Gravity, imposed flow: bioconvection, focusing
- Don’t discuss instability of aligned swimmers

From equilibrium Langevin equations to active dynamics



Jülicher, Ajdari, Prost RMP Colloq 1993
Marchetti et al. RMP 2013
SR JSTAT 2017
Dadhichi, Maitra, SR JSTAT 2018

Apply chemical force, get physical (i,.e. spatial) motion
Formalise this: build active dynamics; discover “new” terms

From equilibrium Langevin equations to active dynamics

$$\text{“physical” position, momentum}\, q, p \,\text{chemical}\, X$$

$$\text{Hamiltonian}\, H(p, q, X), \text{ temperature}\, T$$

$$\dot{q} = \partial_p H$$

$$\dot{p} + \Gamma \partial_p H - \Omega(q) \partial_X H = -\partial_q H + f \qquad \langle f f \rangle \propto 2 k_B T \Gamma$$

$$\dot{X} + \Omega(q) \partial_p H = -\mathcal{M} \partial_X H + \xi \qquad \langle \xi \xi \rangle \propto 2 k_B T \mathcal{M}$$

$$\Omega(q) : \text{ chemomechanical coupling}$$

From equilibrium Langevin equations to active dynamics

$$\text{“physical” position, momentum}\, q, p \,\text{chemical}\, X$$

$$\text{Hamiltonian}\, H(p, q, X),\ \text{temperature}\, T$$

$$\dot{q} = \partial_p H$$

$$\dot{p} + \Gamma \partial_p H - \Omega(q) \partial_X H = -\partial_q H + f \qquad \langle f f \rangle \propto 2 k_B T \Gamma$$

$$\dot{X} + \Omega(q) \partial_p H = -\mathcal{M} \partial_X H + \xi \qquad \langle \xi \xi \rangle \propto 2 k_B T \mathcal{M}$$

Active? Hold chemical force $-\partial_X H \equiv \Delta\mu$ = constant

From equilibrium Langevin equations to active dynamics

$$\dot{q} = \partial_p H$$

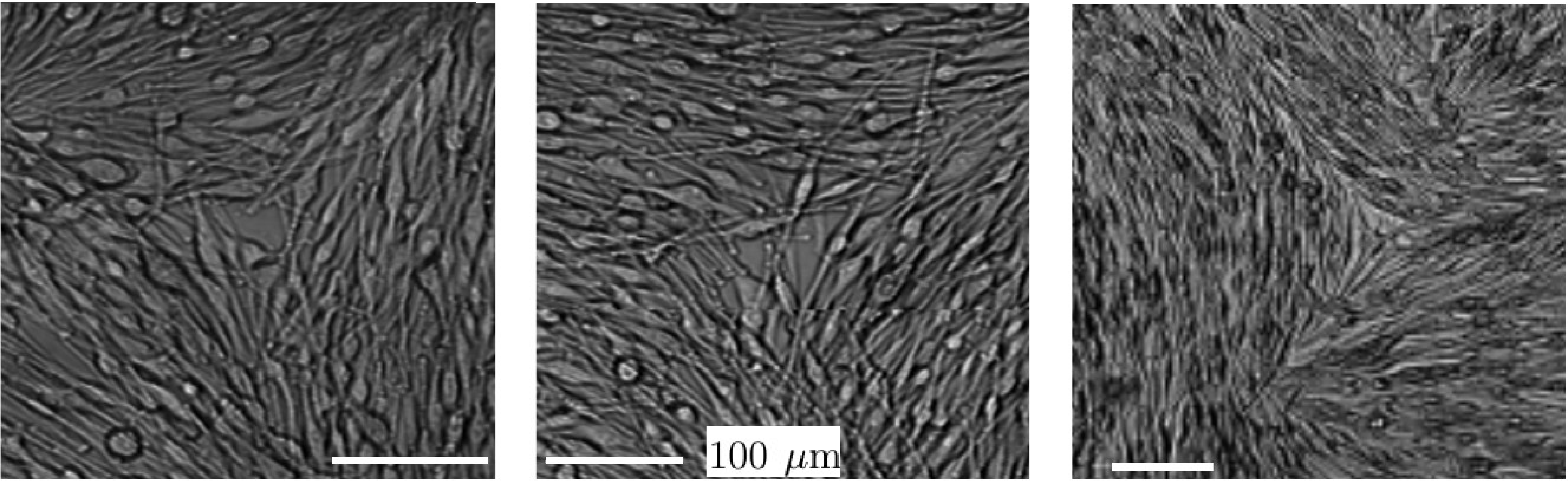
$$\dot{p} + \Gamma \partial_p H + \Delta\mu\, \Omega(q) = -\partial_q H + f$$

$$\Omega(q) : \text{ ``new term'' in equation of motion}$$

Elastic properties of nematoid arrangements formed by amoeboid cells

R. Kemkemer[1], D. Kling[1], D. Kaufmann[2], and H. Gruler[1,a]

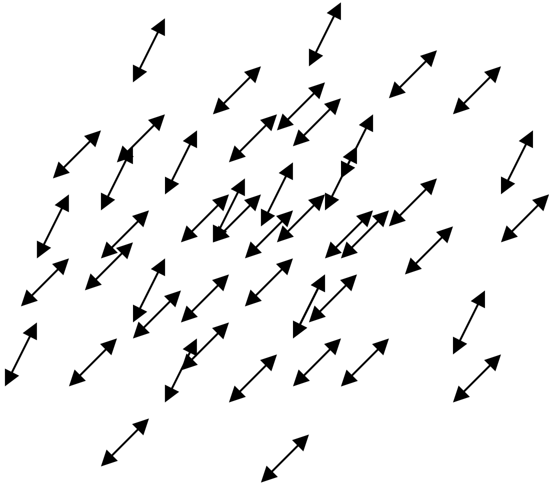
Eur. Phys. J. E **1**, 215–225 (2000)



Strength one-half defects: living proof of nematic nature

DRY ACTIVE MATTER

the nematic phase



Apolar ordering: no macroscopic velocity

On substrate: forget momentum

Slow variables: concentration $c(\boldsymbol{x},t)$

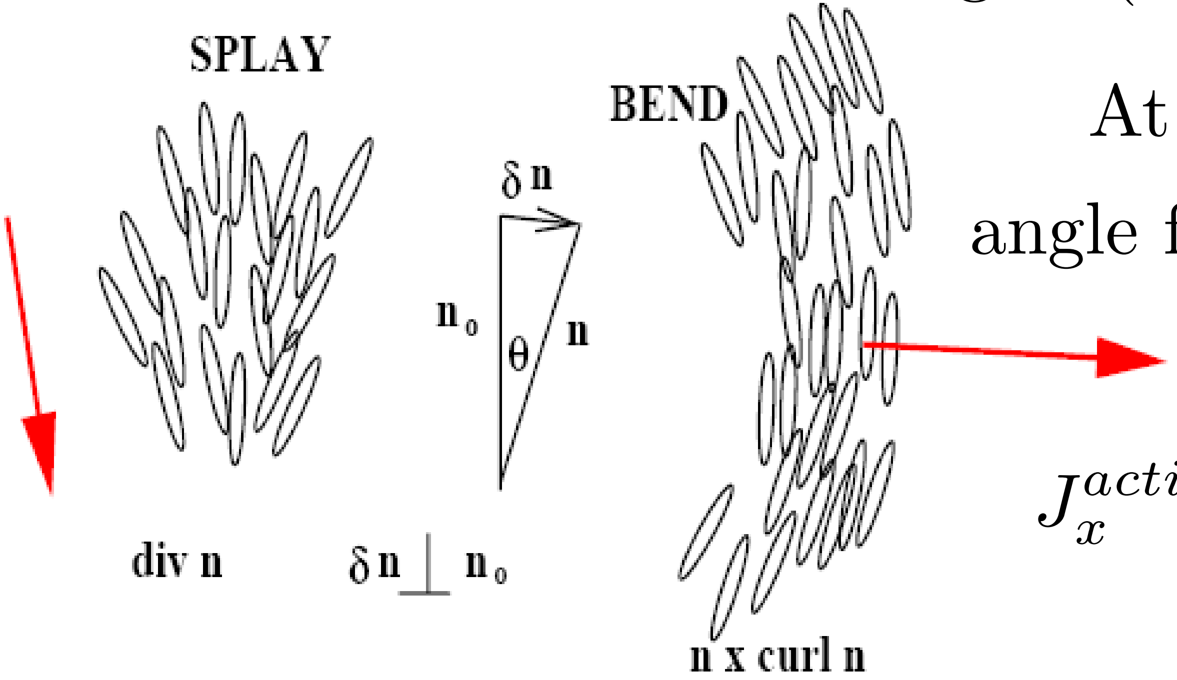
traceless symmetric order parameter $\boldsymbol{Q}_{ij}$

SR, Simha, Toner EPL 2003; Mishra, Simha, SR JSTAT 2010

Giant density fluctuations in active nematics

SR, Simha, Toner 2003

Langevin PDEs for concentration c (conserved)
and angle θ (Nambu-Goldstone) fields



At wavevector $\mathbf{q}$:

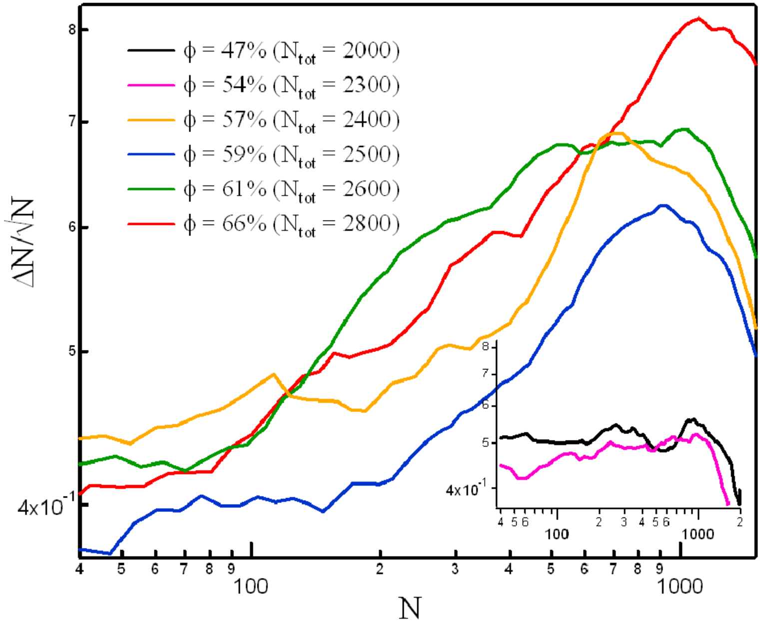
angle fluctuation $\langle|\theta_{\mathbf{q}}|^2 \sim 1/q^2$

diffusive current $\sim \nabla c$

$$J_x^{active} \sim \partial_y \theta;\ J_y^{active} \sim \partial_x \theta;$$

giant number-density fluctuations: $\langle|c_{\mathbf{q}}|^2\rangle \sim 1/q^2$

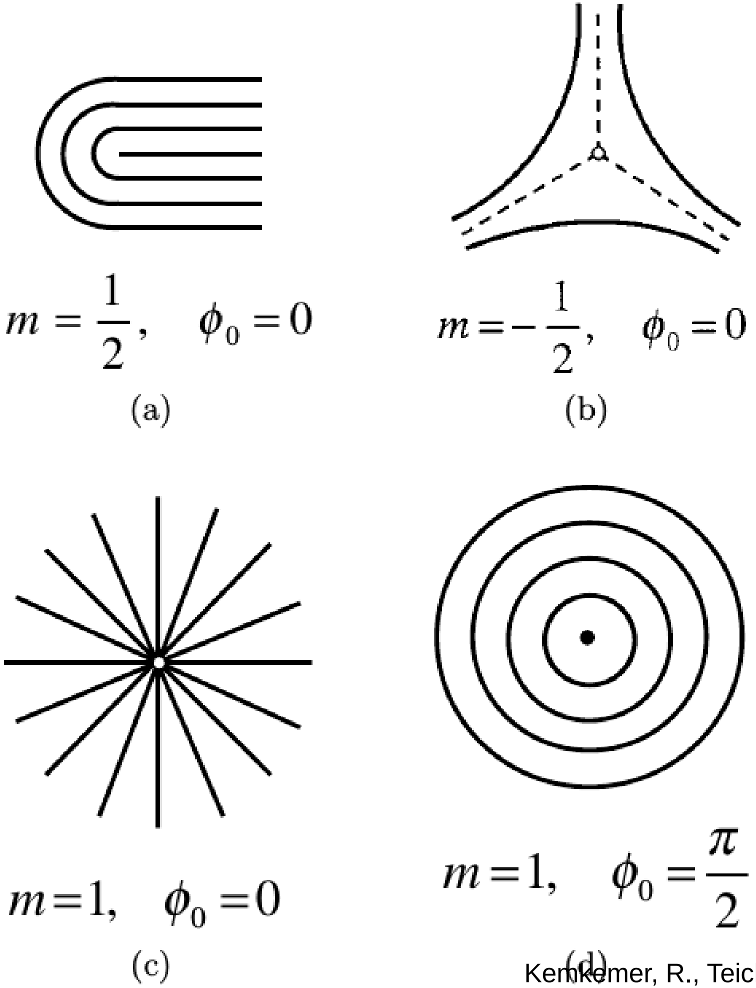
Experiments: giant number fluctuations
in a nonliving active nematic
V Narayan, SR, N Menon 2007



Computer experiments
Ngo et al 2014
Vicsek-style model
$\Delta n \sim n^a$, $1/2 < a < 1$
Linear theory inadequate?

Shankar et al 2018
Active current ~ div Q
Magnitude of Q ~ $L^{-\eta(\Delta)}$
Number fluctuations
non-universal, weakened by
quasi-long-range order?

Topological defects in a nematic



$m = \frac{1}{2}, \quad \phi_0 = 0$

(a)

$m = -\frac{1}{2}, \quad \phi_0 = 0$

(b)

$m = 1, \quad \phi_0 = 0$

(c)

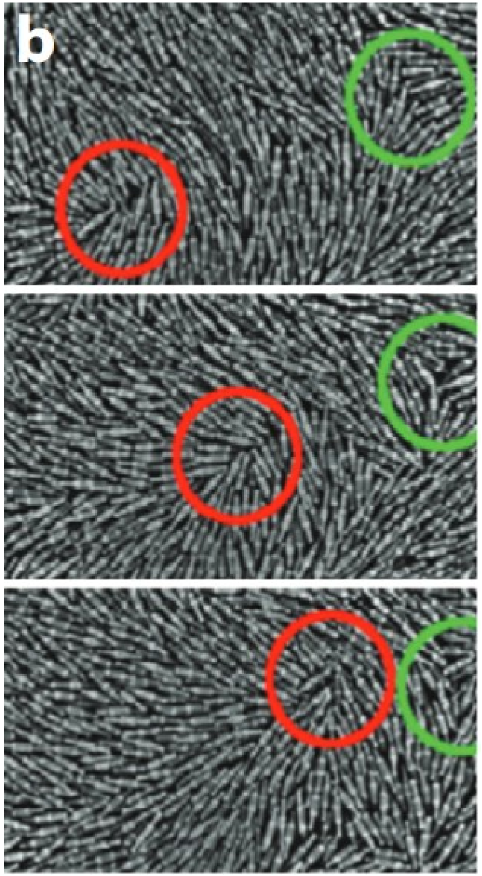
$m = 1, \quad \phi_0 = \frac{\pi}{2}$

(d)

Kemkemer, R., Teichgräber, V., Schrank-Kaufmann, S. et al. Eur. Phys. J. E **3** 101 (2000)

Self-propulsion of +1/2 defects in active nematics

prediction & observation



The symmetry of the field around the strength -1/2 defect will result in no net motion, while the curvature around the +1/2 defect has a well-defined polarity and hence should move in the direction of its "nose" as shown in the figure.
V Narayan et al., Science **317** (2007) 105

motile +1/2 defect, static -1/2 defect

Defects as particles:
+1/2 motile, -1/2 not
+1/2 velocity ~ divQ
Giomi, Bowick, Ma, Marchetti PRL 2013
Thampi, Golestanian, Yeomans PRL 2014
DeCamp et al NMat 2015 ....

Defect-unbinding theory: Suraj Shankar, M C Marchetti, SR, MJ Bowick

Defect unbinding in active nematics

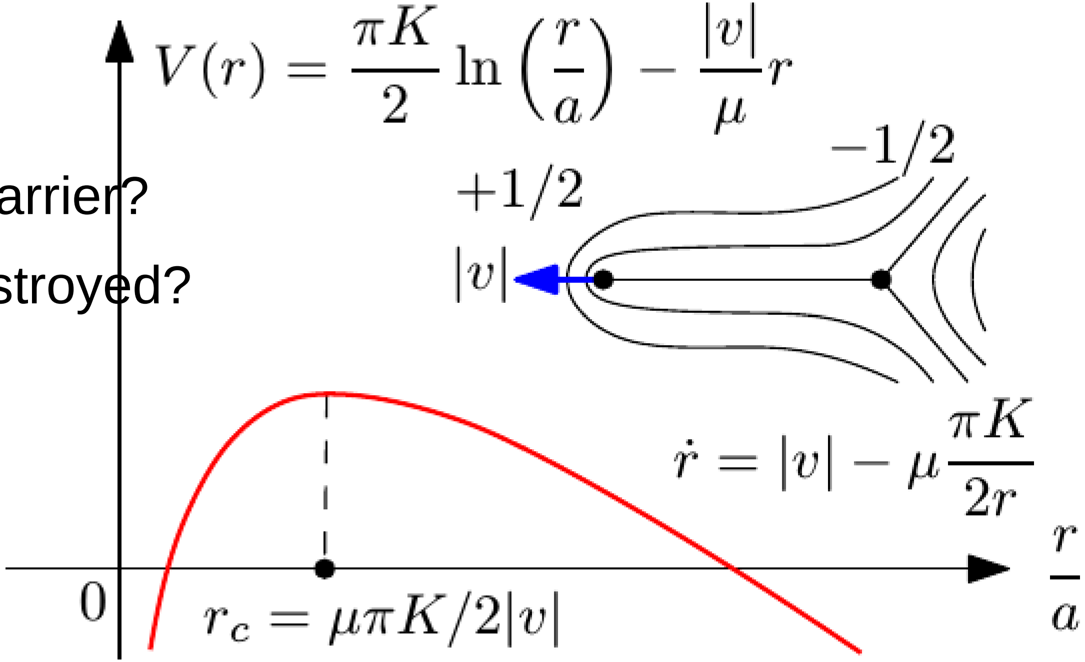
Shankar
et al. PRL 2018

Recall equil BKT transition:

but +1/2 defect is motile!

Like insulator in a field? Finite barrier?

Active nematic order always destroyed?



But active nematics exist!
Bertin et al. NJP 2013
NGO et al. PRL 2014
Shi et al NJP 2014

Langevin equations for +/- 1/2 defects: positions and polarization

Shankar et al. 2018:

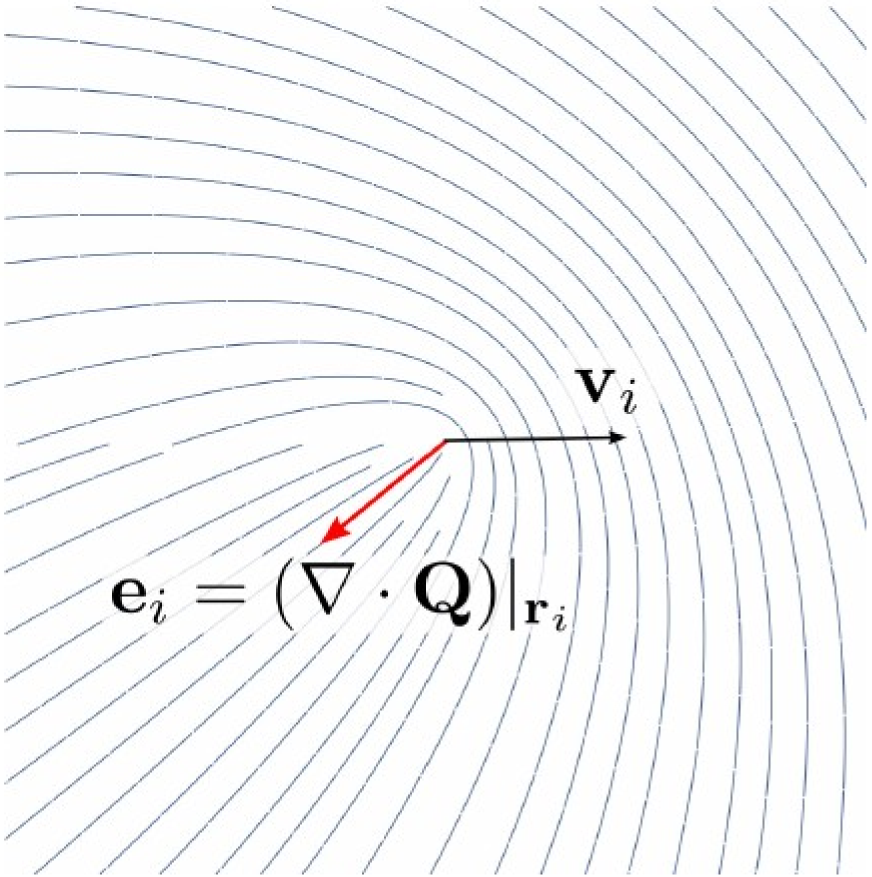
From active nematic dynamics

+1/2 self-velocity ∝ polarization

$$\dot{\mathbf{r}}_i^+ = \boxed{v\mathbf{e}_i} - \mu\nabla_{\mathbf{r}_i}\mathcal{U} + \sqrt{2\mu T}\,\boldsymbol{\xi}_i(t)$$

$$\dot{\mathbf{r}}_i^- = -\mu\nabla_{\mathbf{r}_i}\mathcal{U} + \sqrt{2\mu T}\,\boldsymbol{\xi}_i(t)$$

$$\mathcal{U} = -2\pi K \sum_{i\neq j} q_i q_j \ln\left|\frac{\mathbf{r}_i - \mathbf{r}_j}{a}\right|$$



Langevin equations for +/- 1/2 defects: positions and polarization

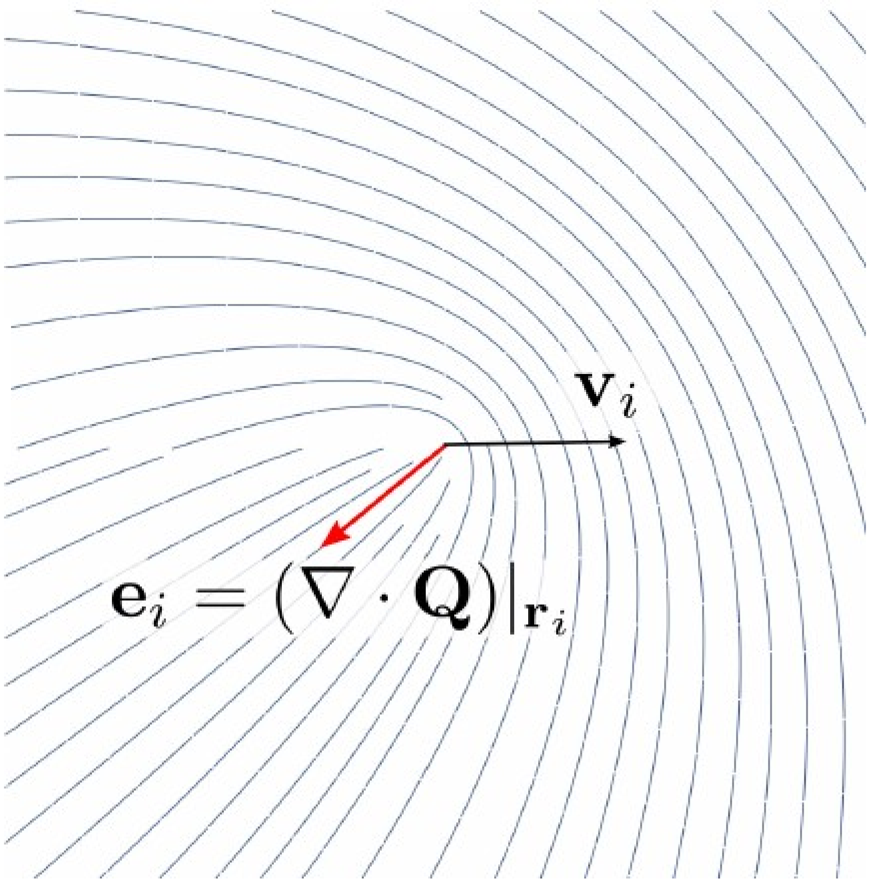
Shankar et al. 2018:

$$\mathbf{e}_i = |\mathbf{e}_i|(\cos\theta_i, \sin\theta_i)$$

$$\mathbf{F}_i \equiv -\nabla_i \mathcal{U} = |\mathbf{F}_i|(\cos\psi_i, \sin\psi_i)$$

$$\partial_t\theta_i = v|\mathbf{F}_i| \times \mathrm{const.}\ \sin(\theta_i - \psi_i)$$

+ angular noise

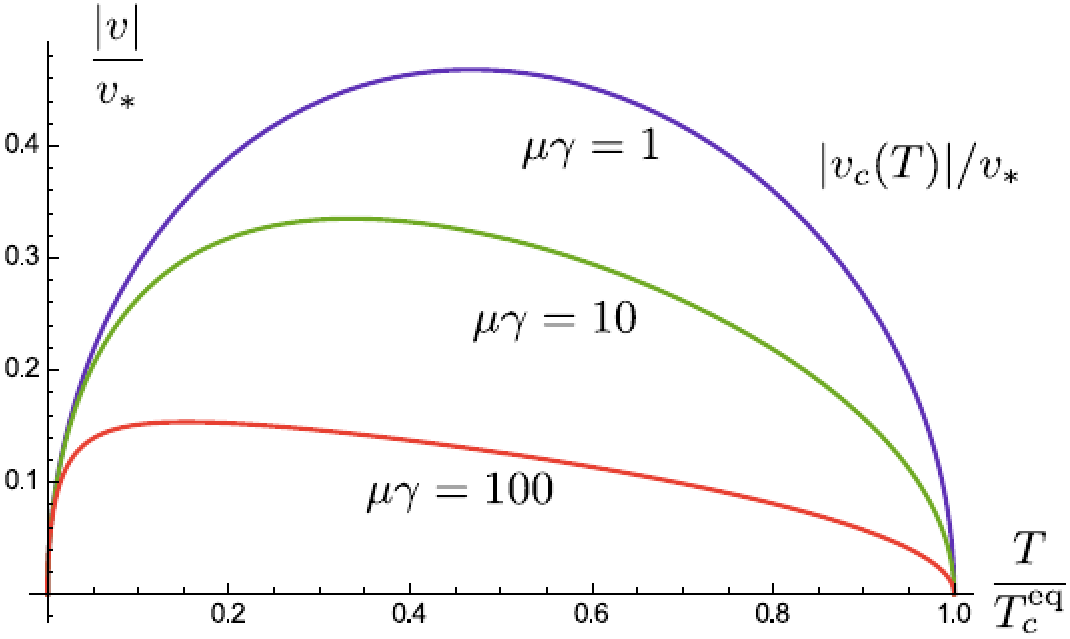


Alignment torque: v<0: alignment; v>0: anti-alignment

Re-entrance!

Shankar et al. 2018:

Threshold activity

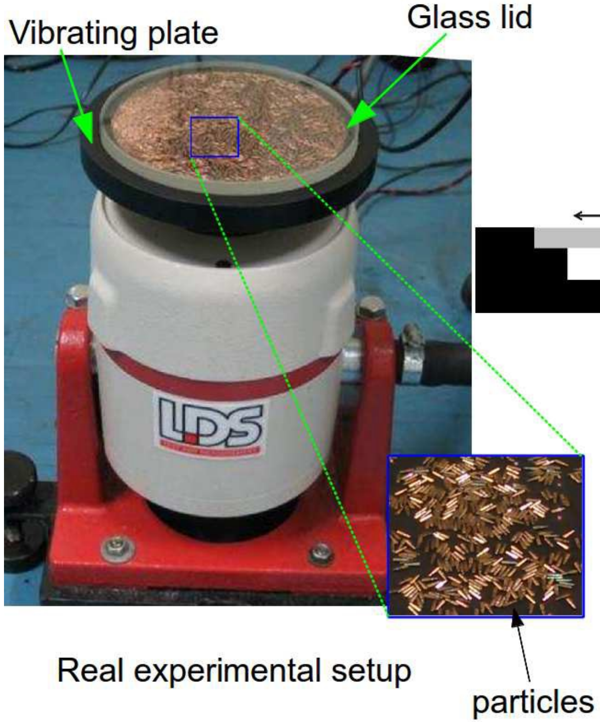


$$\frac{|v_c(T)|}{v_*} = \sqrt{\frac{16\ \tilde{T}(1-\tilde{T})}{\pi\left[1+(3\pi/32)\mu\gamma\tilde{T}\right]}}$$

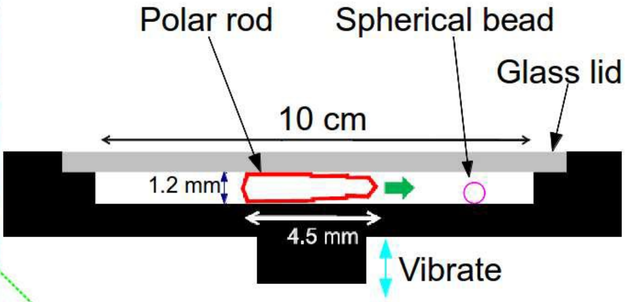
At low enough T, D_R goes to zero, i.e., persistence length grows
Directed motion of +1/2 wins, defects liberated, order destroyed
(A Maitra)

Defect ordering:
Shankar & Marchetti
PRX 2019

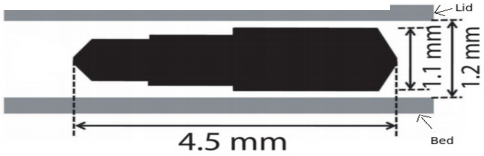
Flocking at a distance



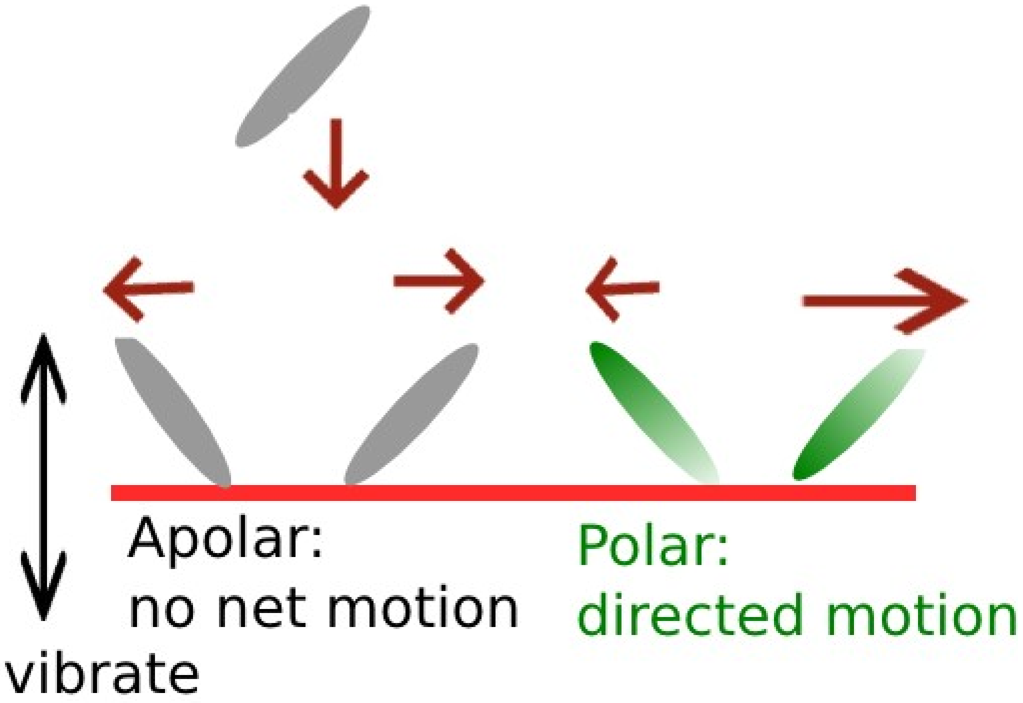
Real experimental setup

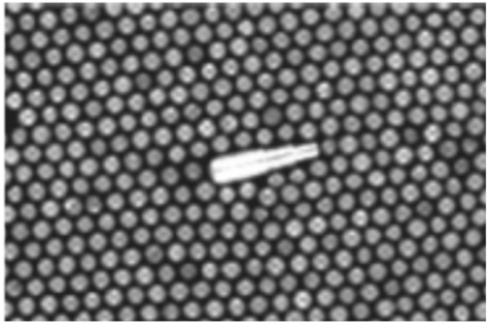


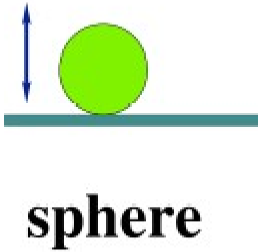
Schematic diagram



Horizontal motility from vertical shaking







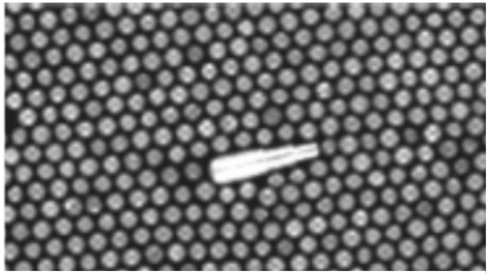
A motile rod transducing vertical shaking into horizontal motion: Nitin Kumar

static friction ⇒ centre of mass moves

Yamada, D., Hondou, T. & Sano, M. Phys. Rev. E **67**, 040301 (2003)

First look at a fluid bead-layer

1-particle rendition of Kumar, Soni, SR, Sood Nature Comm 2014



A motile rod transducing vertical shaking into horizontal motion: Nitin Kumar

$$\dot{\mathbf{R}}(t) = v_0\mathbf{n}(t)$$

motility

$$\partial_t(\rho\mathbf{v}) + (\zeta - \eta\nabla^2)\mathbf{v} = f\mathbf{n}(\mathbf{t})\delta\left[\mathbf{r} - \mathbf{R}(t)\right] - \nabla P$$

Substrate drag, viscosity

Motile rod pushes beads

pressure

$$\dot{\mathbf{n}} = (\mathbf{I} - \mathbf{nn})\cdot(\mathbf{v} + \nabla\mathbf{v}\cdot\mathbf{n} + \ldots)$$

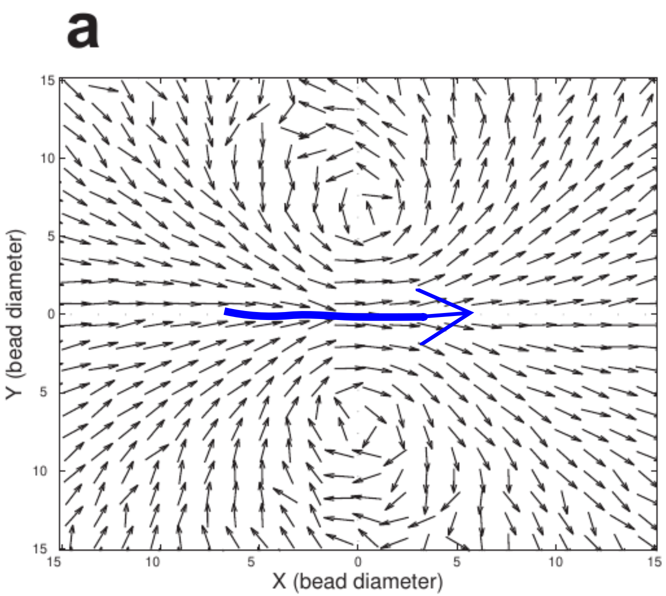
(schematically)

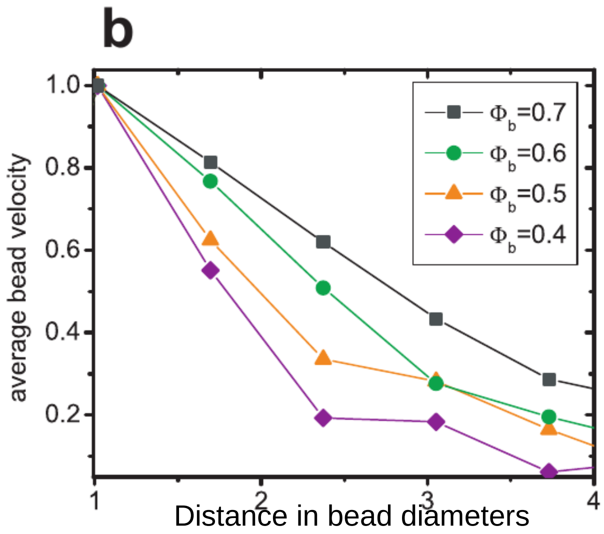
flow reorients $\mathbf{n}$ parallel to $\mathbf{v}$

Gradients rotate & align $\mathbf{n}$

in pictures:

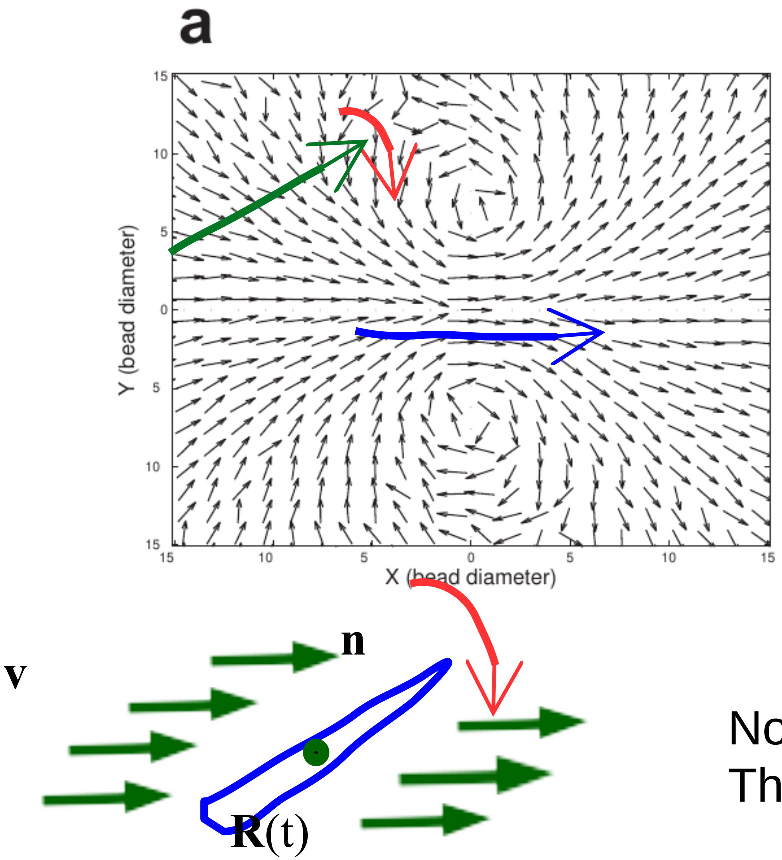
Flow-field around a mover in a fluid layer

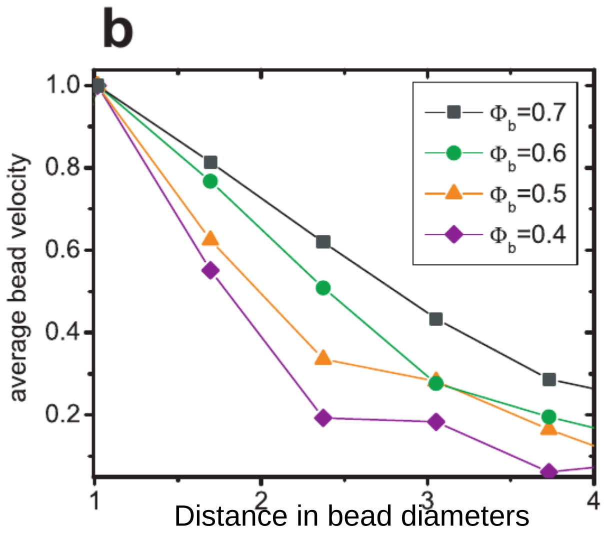




Kumar, Soni, SR, Sood 2014

An emergent aligning interaction





Nonuniform drag: flow reorients $\mathbf{n}$ parallel to $\mathbf{v}$
The weathercock effect

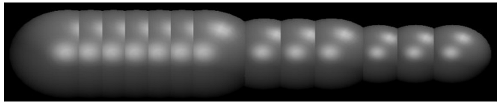
A granular flock at very low concentration

Kumar, Soni, Sood, SR Nature Communications 2014; arXiv:1402.4262

Nitin Kumar (student of A K Sood, IISc)

/home/sriram/talks/activemattertalks/current/Video1.avi

/home/sriram/talks/activemattertalks/current/Video2.avi



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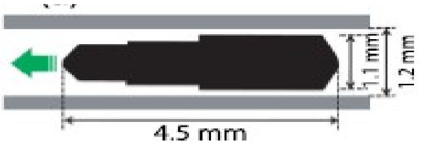


Confined quasi-2d geometry

Granular dynamics simulation: Harsh Soni

/home/sriram/talks/activemattertalks/current/Video3.avi

/home/sriram/talks/activemattertalks/current/Video4.avi

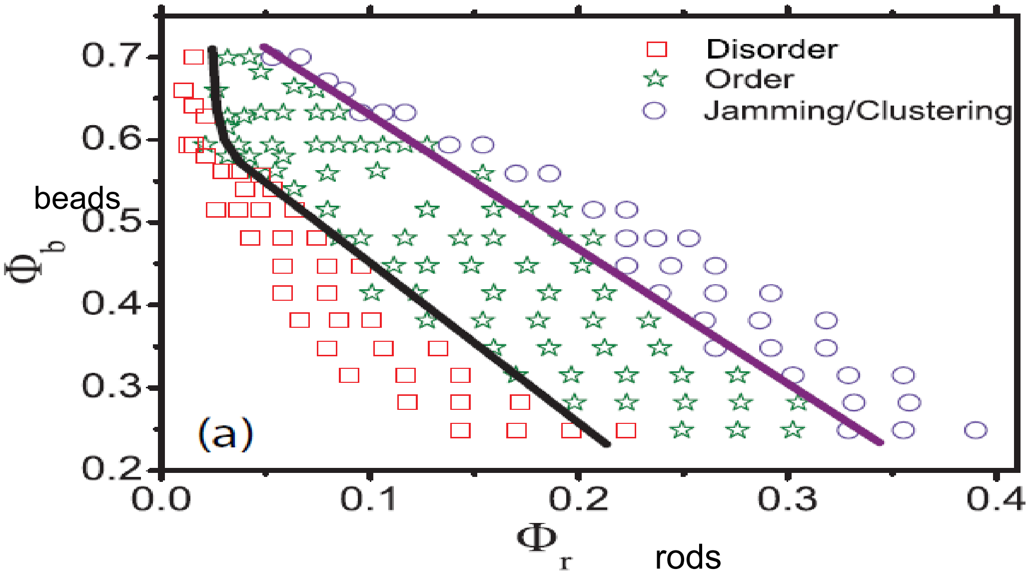
/home/sriram/talks/activemattertalks/current/Video5.avi

/home/sriram/talks/activemattertalks/current/Video6.avi

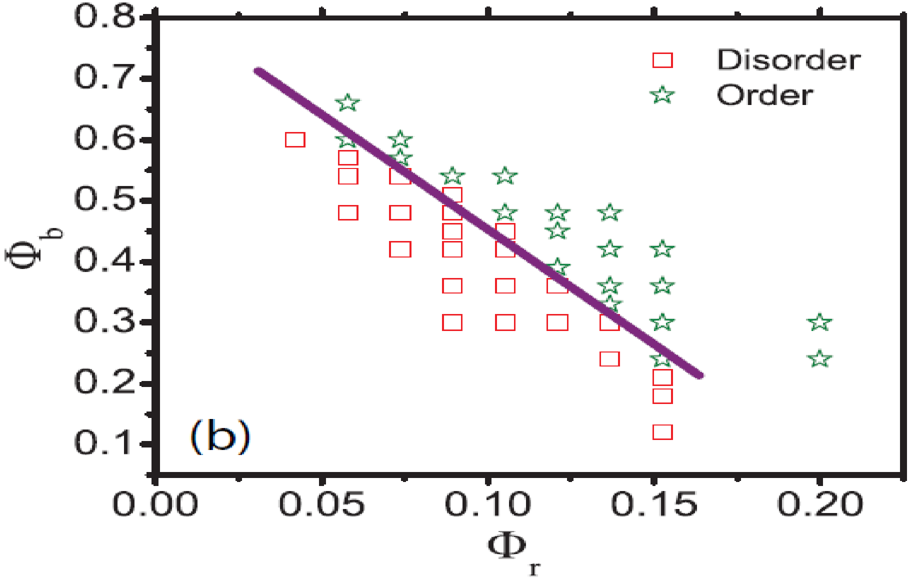
cf Deseigne et al PRL 2010
Weber et al PRL 2013

Phase diagram

Flocking by increasing inert-particle concentration



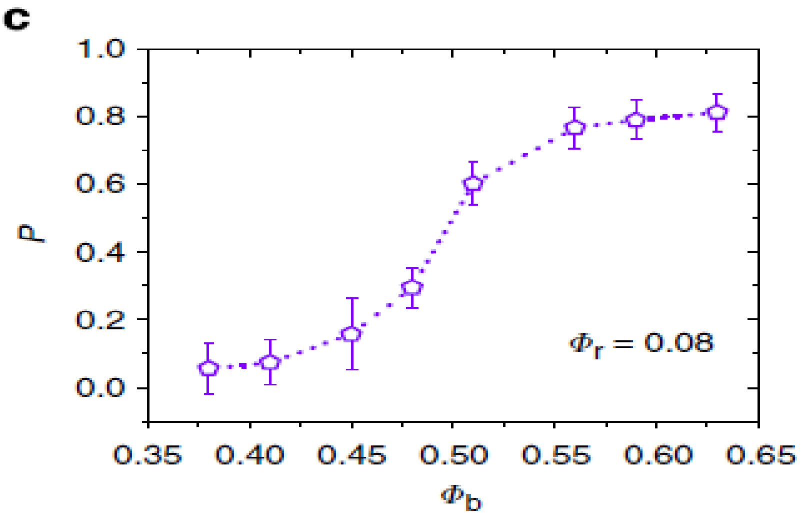
Experiment



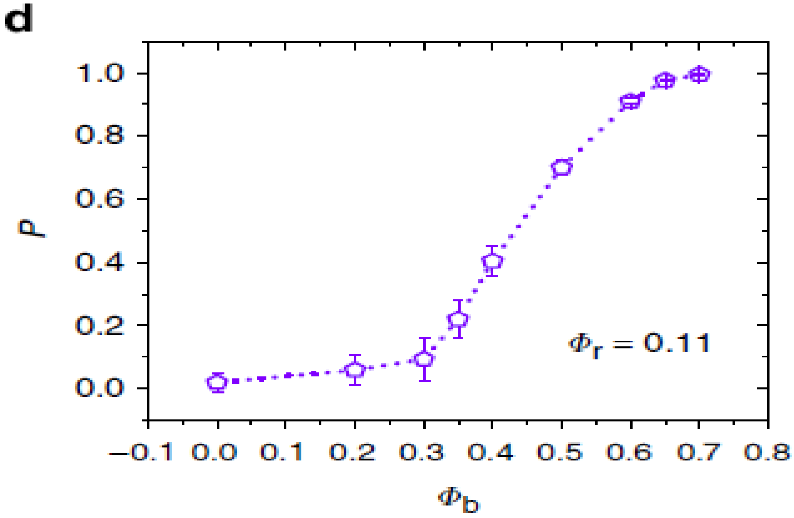
Simulation

A phase transition

Amount of order as function of inert-particle concentration



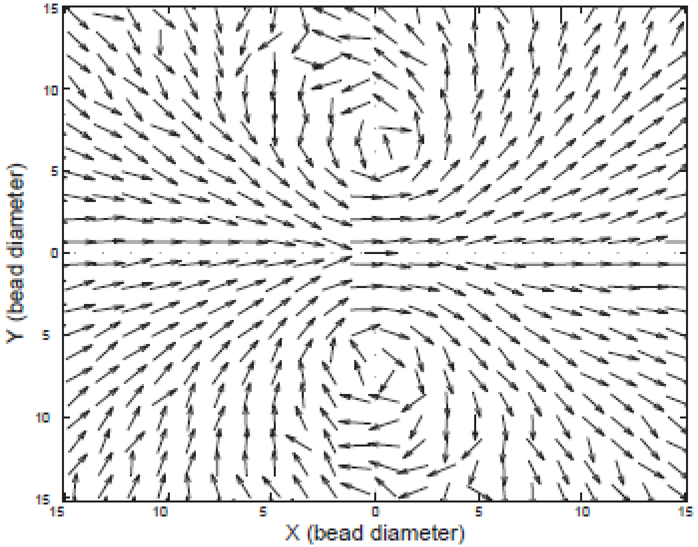
Experiment

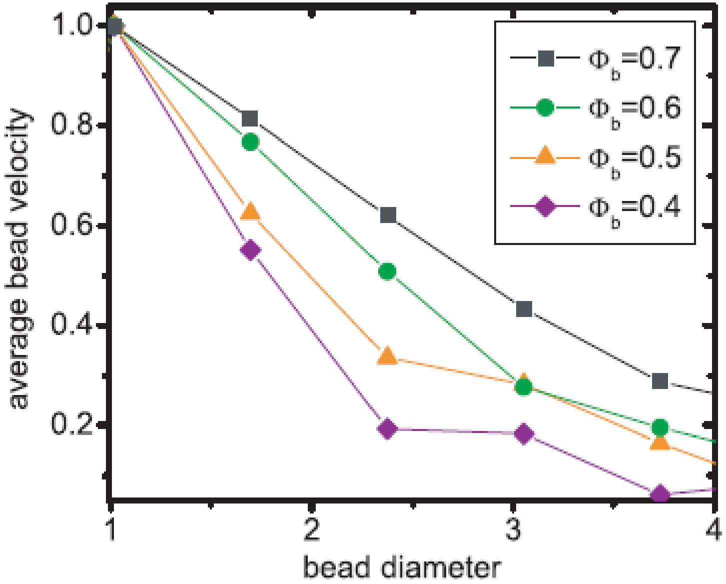


Simulation

The mechanism: moving polar rod creates flow

Simulation: H Soni





Increase Φ_b --> increase decay length of velocity

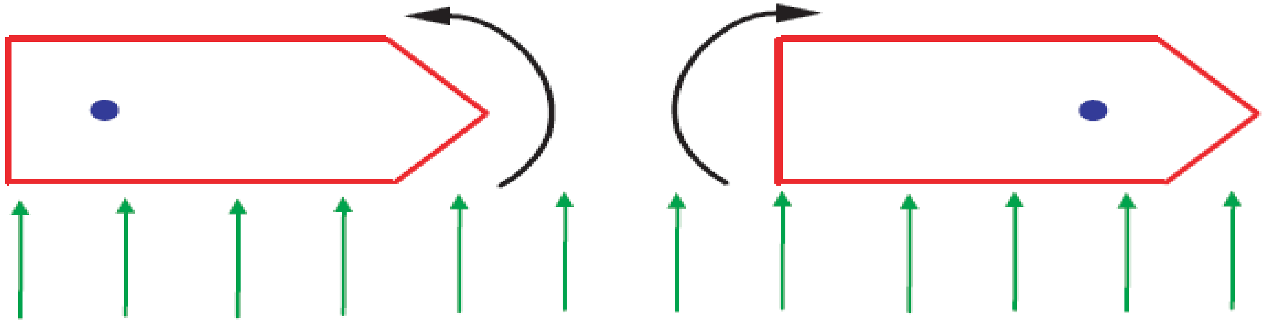
Screened monopole
cf Brotto et al. PRL 2013

The mechanism: flow orients polar rod

Flow rotates polar particles to point the right way: the weathercock effect
Need a substrate

/home/sriram/talks/activemattertalks/current/Video7.avi

Could have been either way
Design problem



qualitatively similar to Bricard et al. colloidal rollers Nature 2013

- flow field simpler, medium compressible
- single-rod motility from solid contact mechanics
- Crucial difference: non-motile-bead concentration is control parameter
- purely 2d system

Theory of flocking at a distance

Kumar, Soni, Sood, SR arXiv:1402.4262, Nat Comm 2014

Order parameter $\mathbf{P}$,
velocity $\mathbf{v}$,
number density ρ

continuity

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0$$

damping

forcing

$$\rho \partial_t \mathbf{v} = -(\Gamma - \eta \nabla^2)\mathbf{v} + \alpha \mathbf{P} - B \nabla \rho + \ldots$$

$$\partial_t \mathbf{P} = \lambda \mathbf{v} - (a - K \nabla^2)\mathbf{P} - A \nabla \rho + \ldots$$

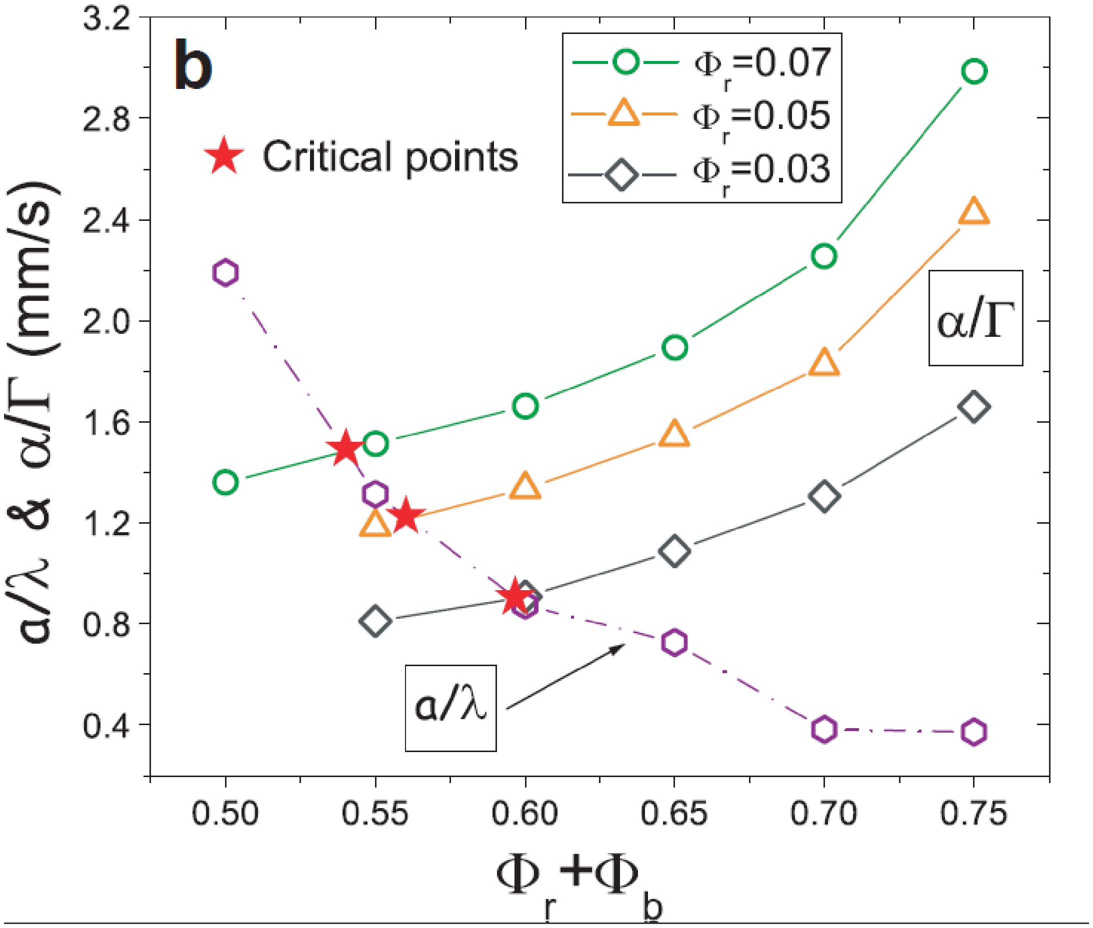
Flow coupling

Rotational relaxation

Transition determined by effective coupling $\bar{a} = a - \lambda\alpha/\Gamma$

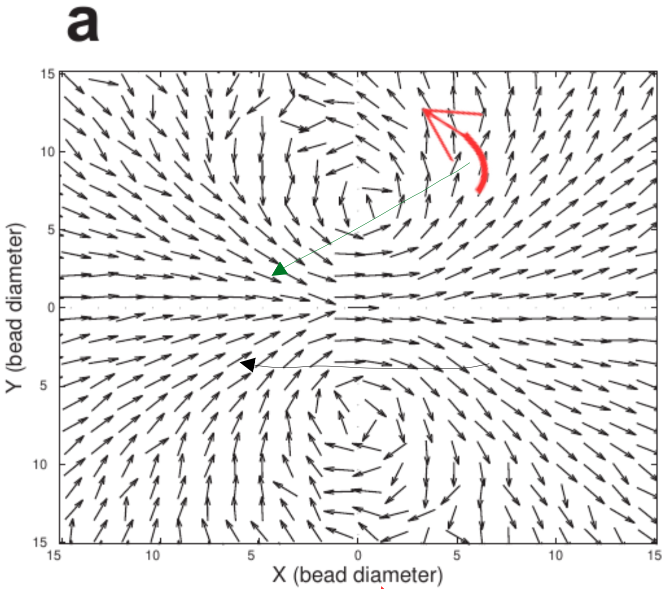
- Independent measurements in simulation (H Soni)
- $\alpha > 0$, $\lambda > 0$ and increases with ρ
- So: increase ρ: get transition to ordered state of P

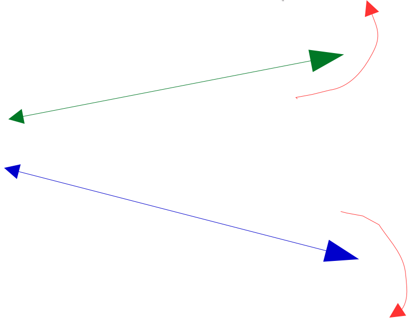
Estimating mean-field critical point from simulation

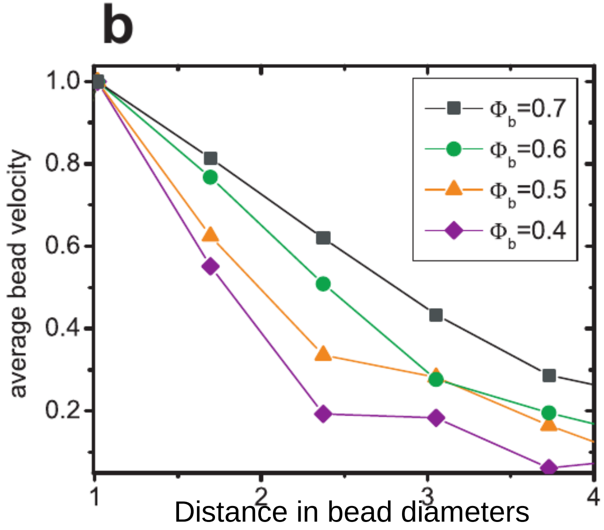


Side-by-side: rotation by vorticity

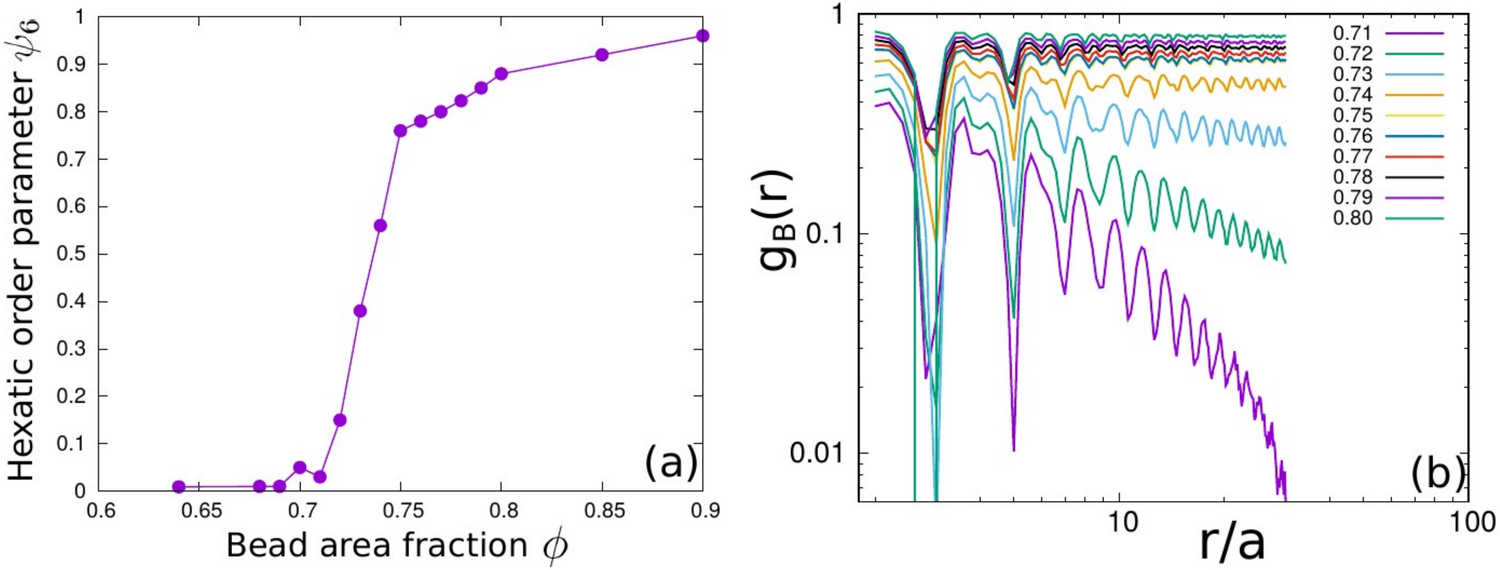
negative taxis: “repulsion”





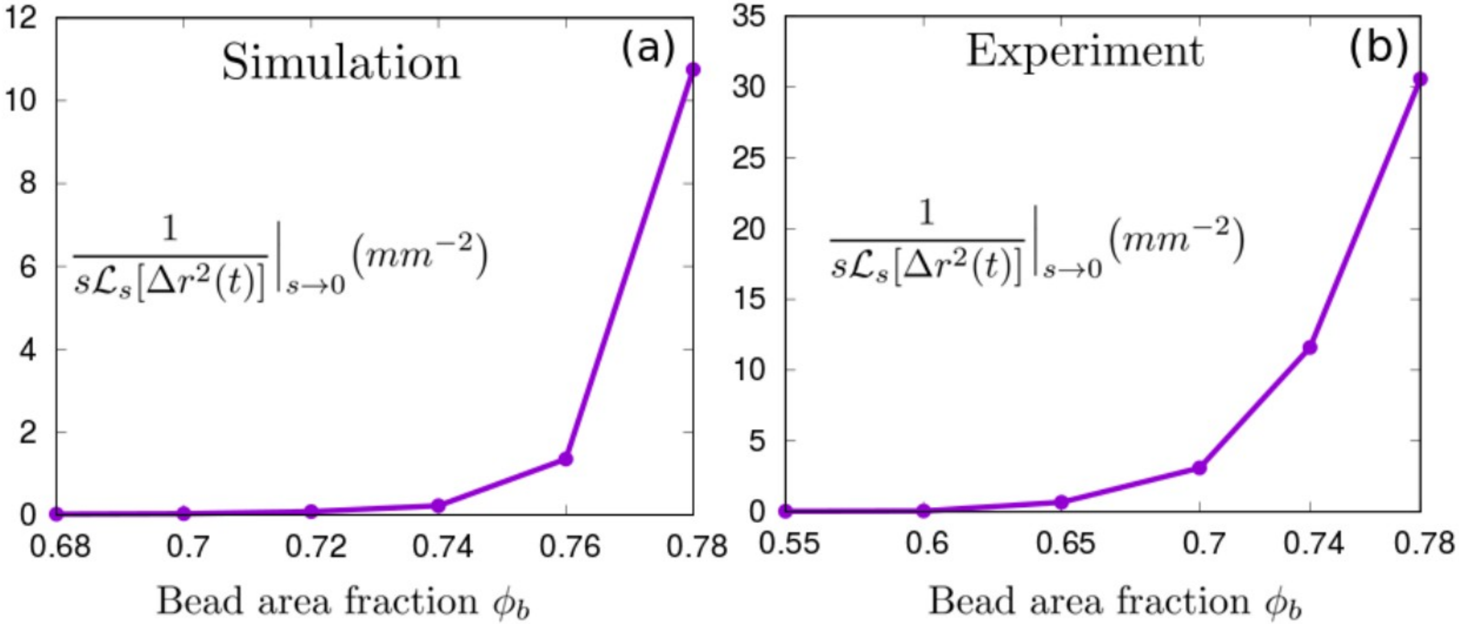


Dense bead layer: crystalline



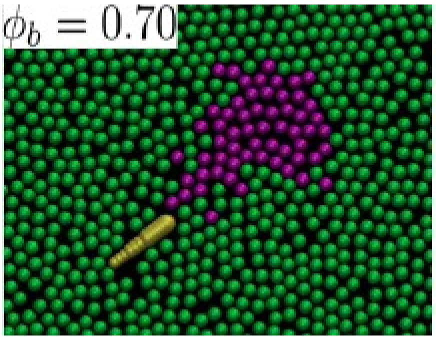
Increase bead packing, transition to crystal
Long-range 6-fold order as proxy

Onset of rigidity



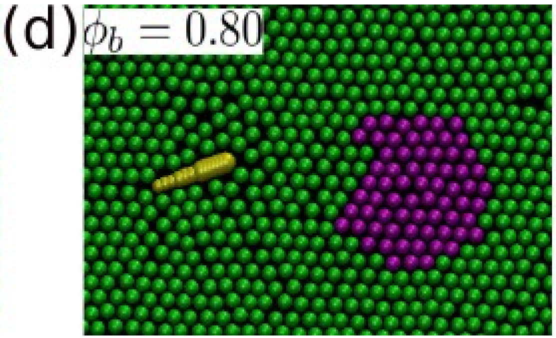
Single-particle microrheology in real and numerical experiments

Comparison: crystal vs fluid



fluid

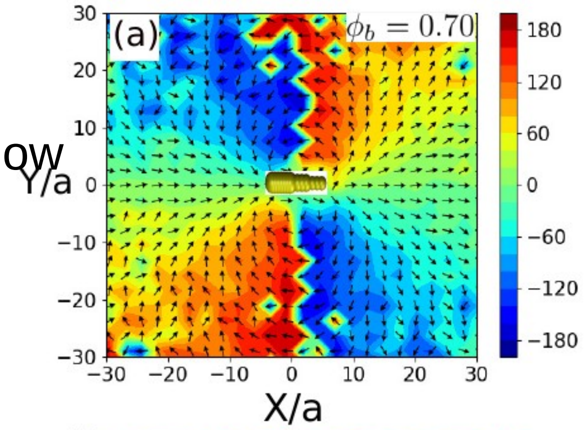
fluid phase: motile rod drags beads



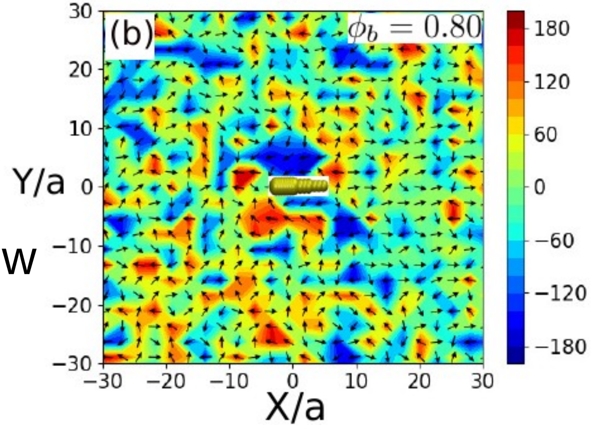
crystal

crystal: no dragging

Fluid: bead flow



crystal: no flow



Crawling through a crystal: theory?

- Safran et al: force dipoles in elastic medium
  - motility ignored

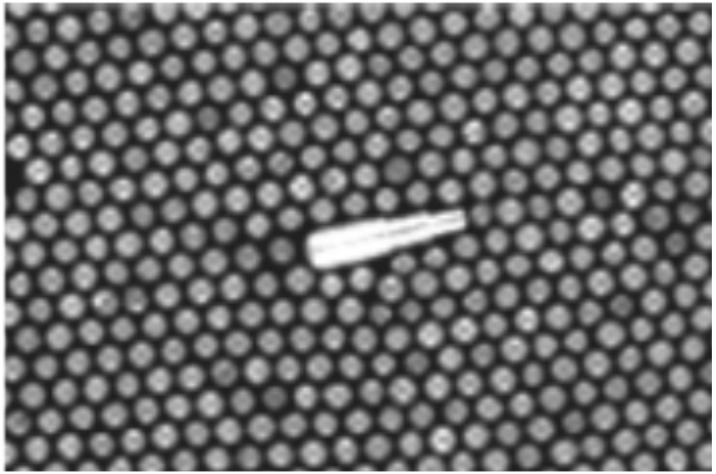
cell/tissue mechanics

- Henkes et al. 2020: elastic medium made of ABPs
  - active forcing + repulsive pair potential, no reorienting by medium
- This work: coupled dynamics
  - motile particles strain medium, strain reorients particles
  - naturally non-reciprocal dynamics

Rahul Gupta, Raushan Kant,
Harsh Soni, Ajay Sood, SR
PRE 2022

Motile particles in elastic medium on substrate

Particle position **R**(t), orientation **n**(t)
Displacement field of medium **u**(**r**,t)
Lamé elastic free energy F
Friction ζ, self-prop force f, speed v_0

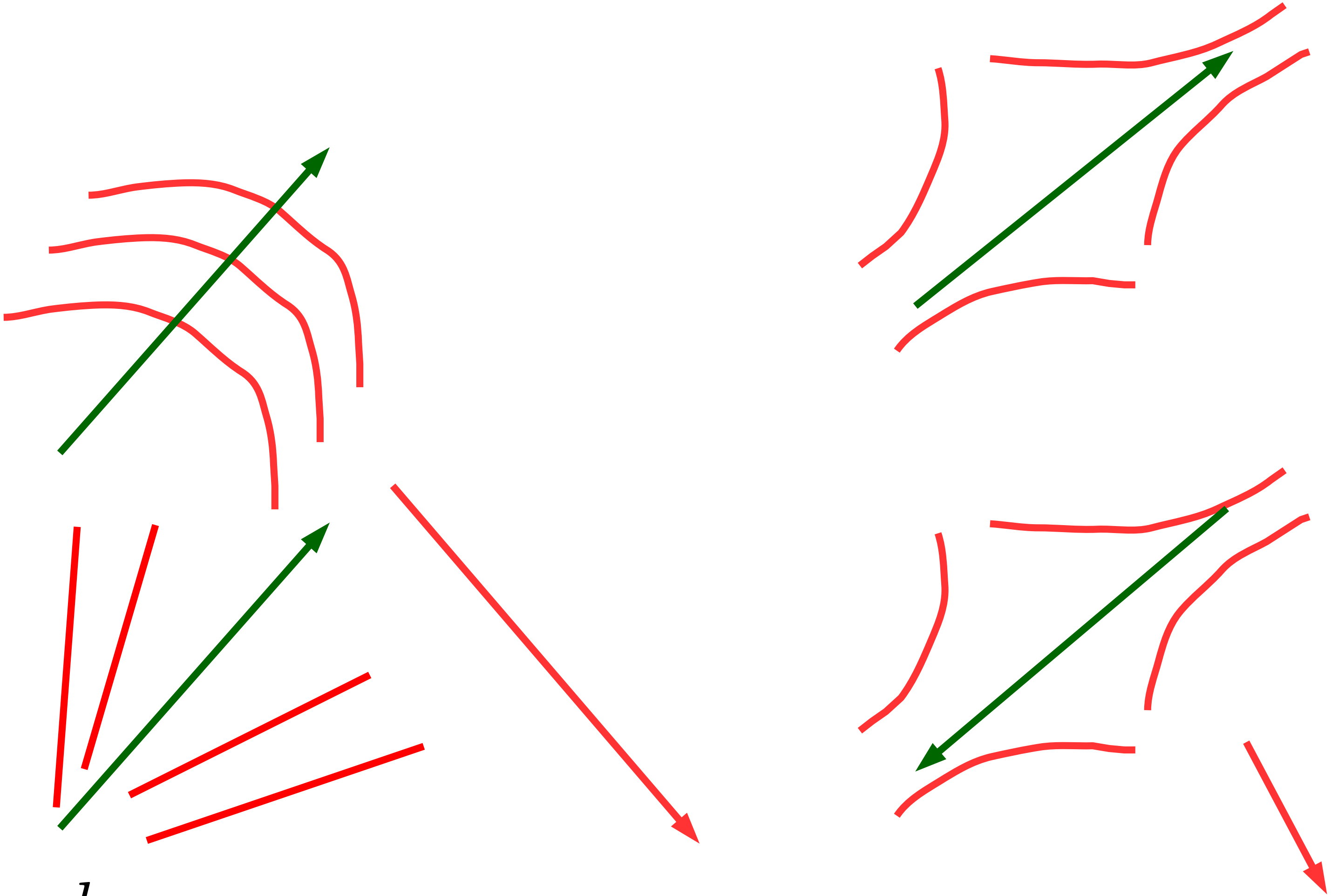


A motile rod transducing vertical shaking into horizontal motion: Nitin Kumar

$$\dot{\mathbf{R}}(t) = v_0 \mathbf{n}(t)$$

$$\zeta \partial_t \mathbf{u} = -\delta F/\delta \mathbf{u} + f\mathbf{n}(\mathbf{t})\delta(\mathbf{r} - \mathbf{R}(t))$$

driving through a crystal



$$\frac{d\mathbf{n}}{dt} = (\mathbf{I} - \mathbf{nn}) \cdot \left(\gamma_1 \nabla^2 \mathbf{u} + \gamma_2 \nabla\nabla \cdot \mathbf{u} + \kappa\varepsilon \cdot \mathbf{n}\right)$$

Strain field of a motile particle

U= displacement field in frame comoving and corotating with particle

$$[-\zeta v_0 \partial_x - (\mu\nabla^2 + \lambda\nabla\nabla\cdot)]\mathbf{U} = f\delta(\mathbf{r})\hat{\mathbf{x}}$$

Screening

$$\alpha = \zeta v_0/\mu$$

$$\beta = \zeta v_0/\lambda$$

$$U_x = \frac{f}{4\pi\mu}\left\{\left[K_0\left(\frac{\alpha r}{2}\right) - \frac{x}{r}K_1\left(\frac{\alpha r}{2}\right)\right]e^{-\frac{\alpha x}{2}} + \frac{\beta}{\alpha}\left[K_0\left(\frac{\beta r}{2}\right) + \frac{x}{r}K_1\left(\frac{\beta r}{2}\right)\right]e^{-\frac{\beta x}{2}}\right\}$$

and similarly U_y

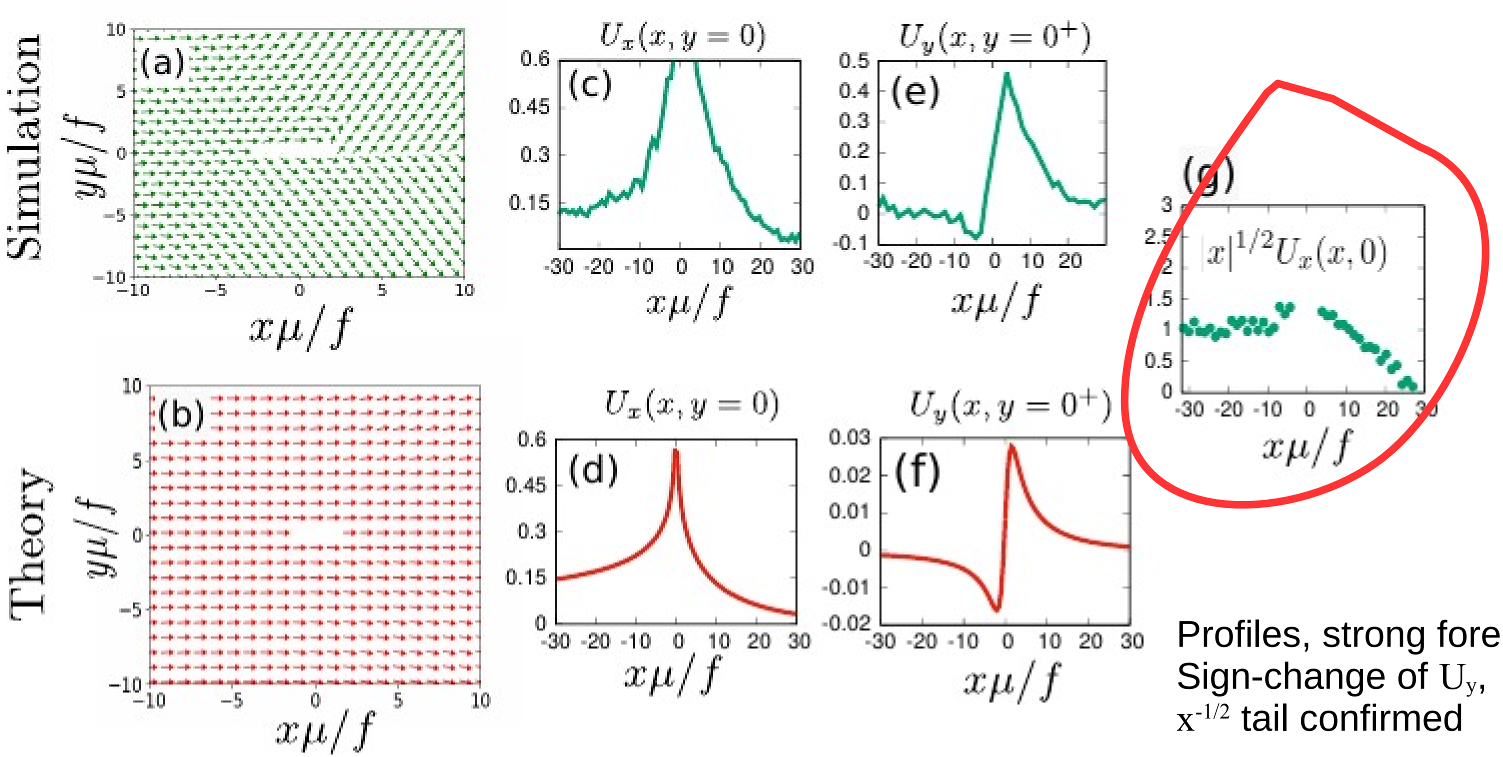
Crucial: asymp forms of $K_0 \Rightarrow$ exponential decay for x>0, $|x|^{-1/2}$ for x<0

Overdamped elastic wake

Banerjee, Mondal, Banerjee, Thutupalli, Rao arXiv 2109.10438
Same behaviour for density field in a compressible fluid layer

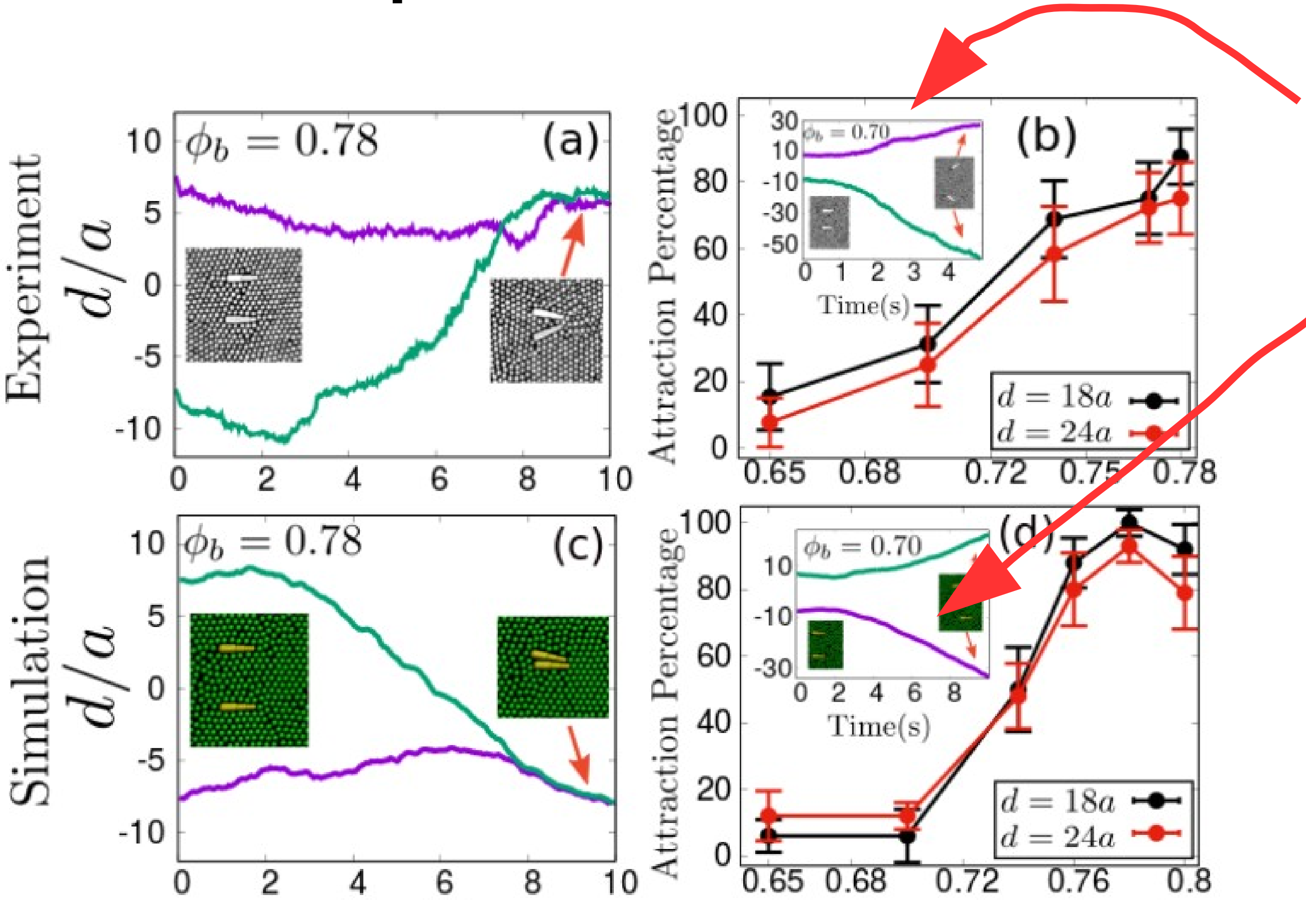
Comparison with measured fields

Numerical experiment on vibrated layer of grains
Inelasticity, static friction, base, lid all included



Profiles, strong fore-aft asymmetry,
Sign-change of U_y,
$x^{-1/2}$ tail confirmed

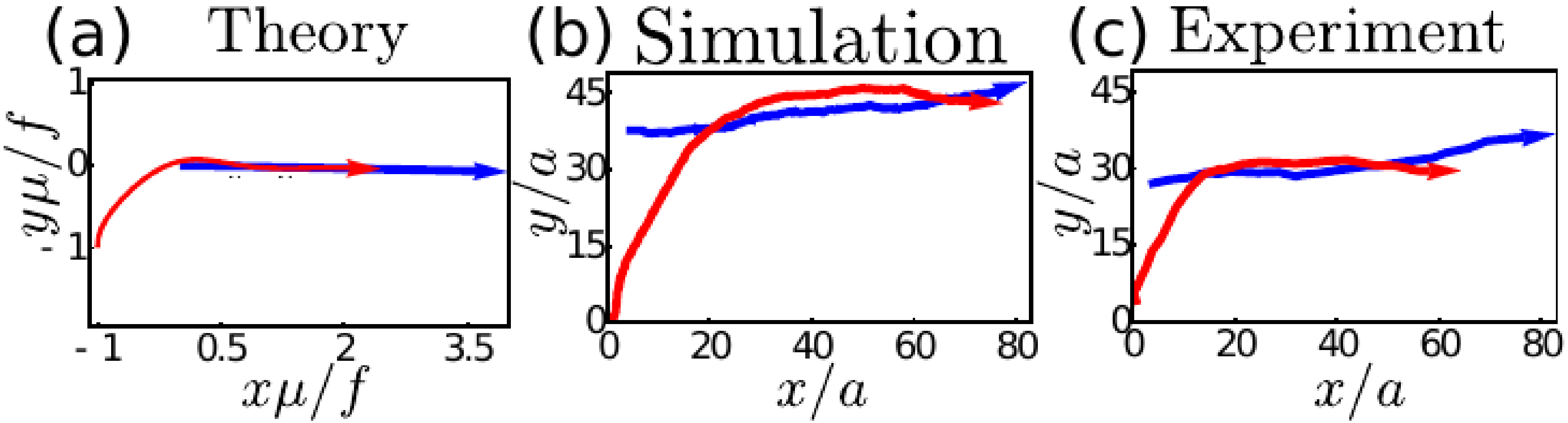
Capture in experiment and simulation



Repel when beads
are fluid

$$\frac{d\mathbf{n}}{dt} = (\mathbf{I} - \mathbf{nn}) \cdot \left(\gamma_1 \nabla^2 \mathbf{u} + \gamma_2 \nabla\nabla \cdot \mathbf{u} + \kappa \varepsilon \cdot \mathbf{n}\right)$$

Non-reciprocal interaction



(arXiv:2007.04860)

Particle in front gets no indication of particle behind
Pursuer particle senses distortion field of pursued particle!

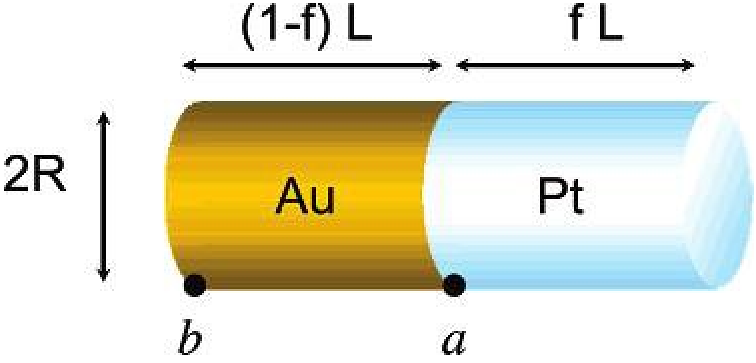
pursuit and capture: laboratory experiment

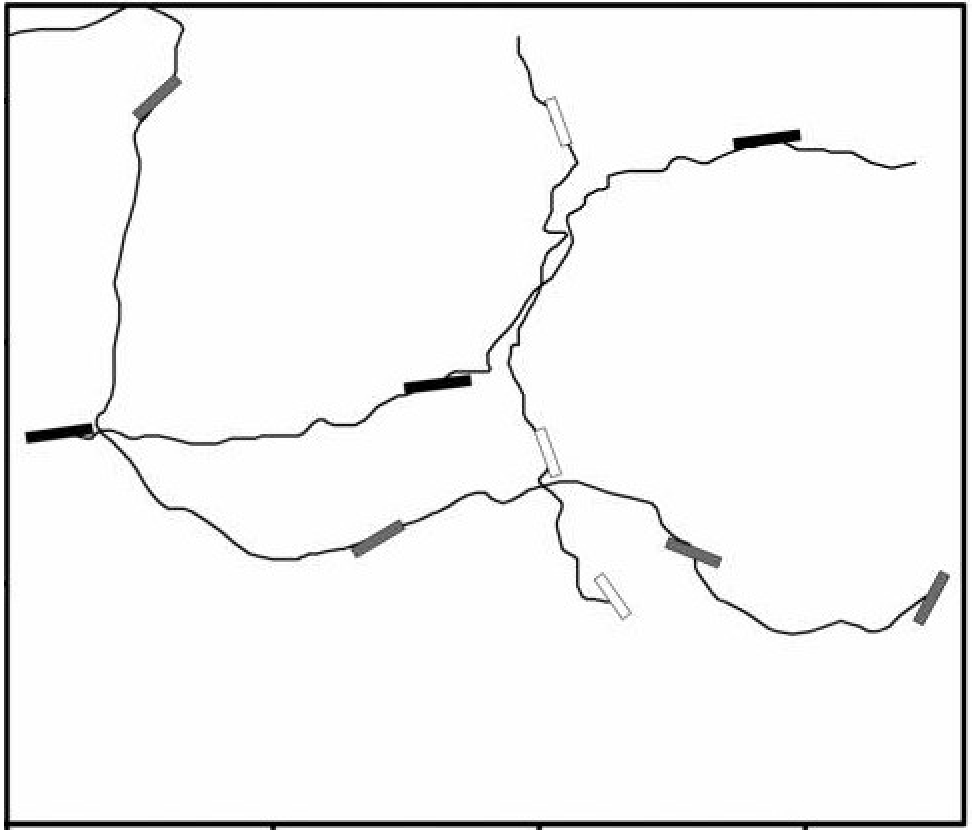
pursuit and capture: numerical experiment

Currently: bead-rod segregation; motile minority condenses non-motile majority
Raushan Kant / Rahul Gupta / Ajay Sood, Soft Matt 2020, PRE 2022 and in prep

Chemotactic colloids*

*not “dry” exactly, but ...



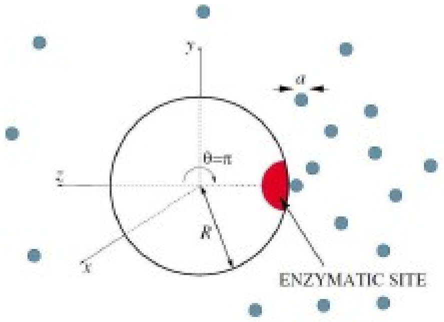


Paxton et al. JACS 2004

Golestanian, Liverpool, Ajdari PRL 2005
Howse .... Golestanian PRL 2007

How?

Force-free chemical self-propulsion



Sphere with enzyme coat $\sigma(\theta, \phi)$ in a reactant bath.

Particle makes its own gradient
Asymmetric distribution of reaction products
Asymmetric stresses
Flow
Propulsion

Properties of motile organisms

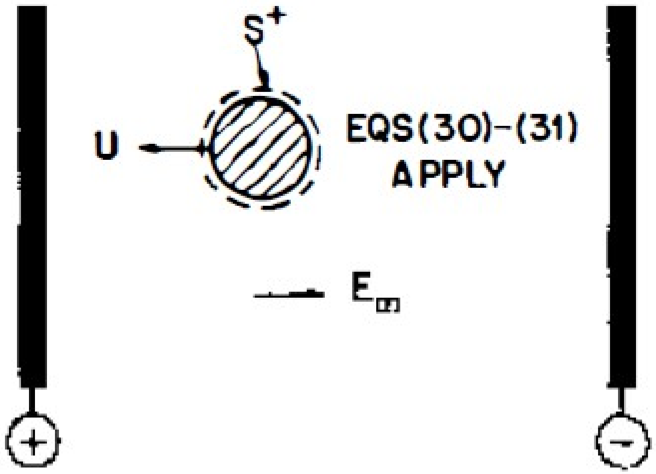
- Directed force-free motion
- Flocking
- Gradient-sensing
- Signalling
- Clumping
- Patterns

Suropriya Saha, Ramin Golestanian, SR
Phys Rev E 2014

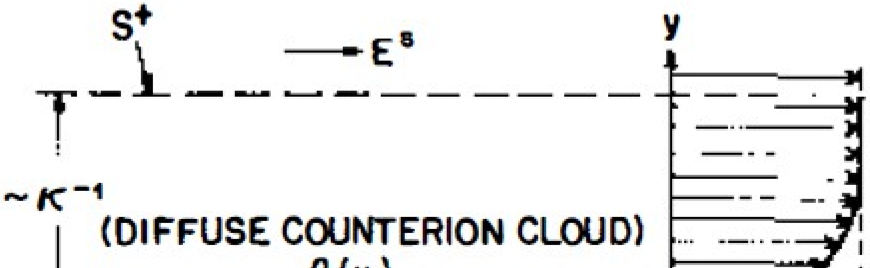
Phoresis:
field-driven force-free propulsion

J.L. Anderson
Annu Rev Fluid Mech 1989

VIEW FROM OUTER REGION



VIEW FROM INNER REGION

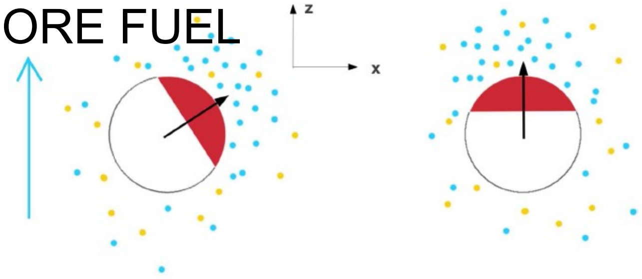


Apparent slip velocity v_s

Imitate chemotaxis?

Suropriya Saha, R Golestanian, SR
Phys Rev E 2014

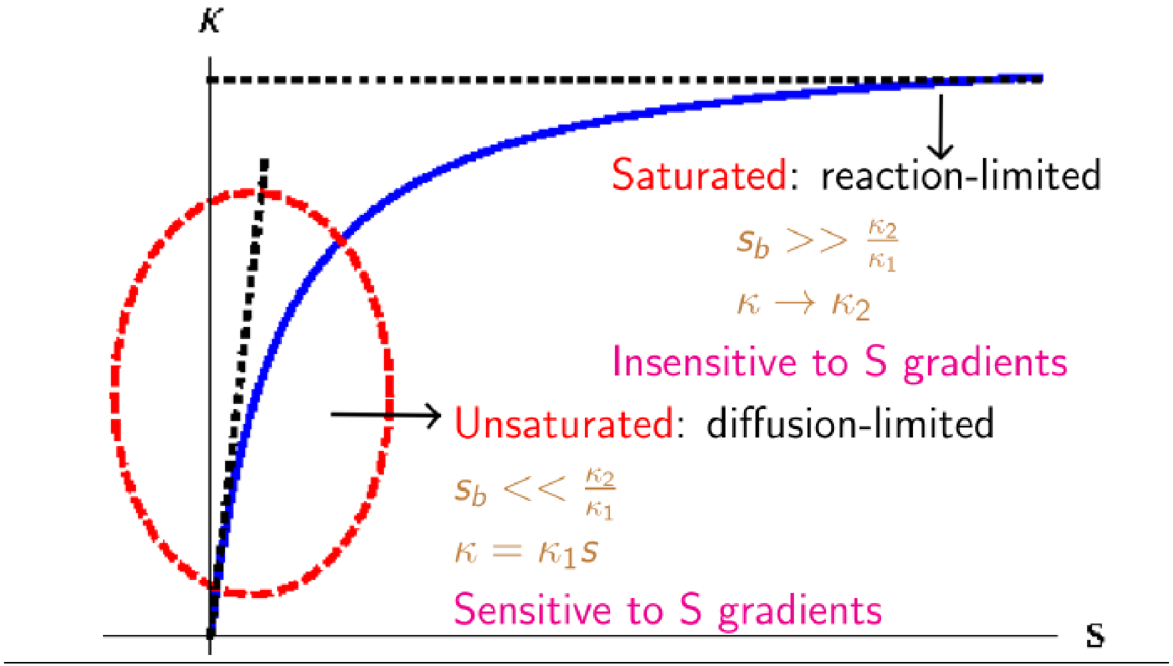
- Polar profile of reactivity, uniform medium --> motion
- Can particle orient in response to gradient?
- Yes! Can design chemotactic or antichemotactic particles
- Need $l = 1$ in interaction with surface and $l = 2$ in reactivity or v.v.



MORE FUEL

LESS FUEL

Interaction range from MM



Saturated: reaction-limited

$s_b >> \frac{\kappa_2}{\kappa_1}$

$\kappa \to \kappa_2$

Insensitive to S gradients

Unsaturated: diffusion-limited

$s_b << \frac{\kappa_2}{\kappa_1}$

$\kappa = \kappa_1 s$

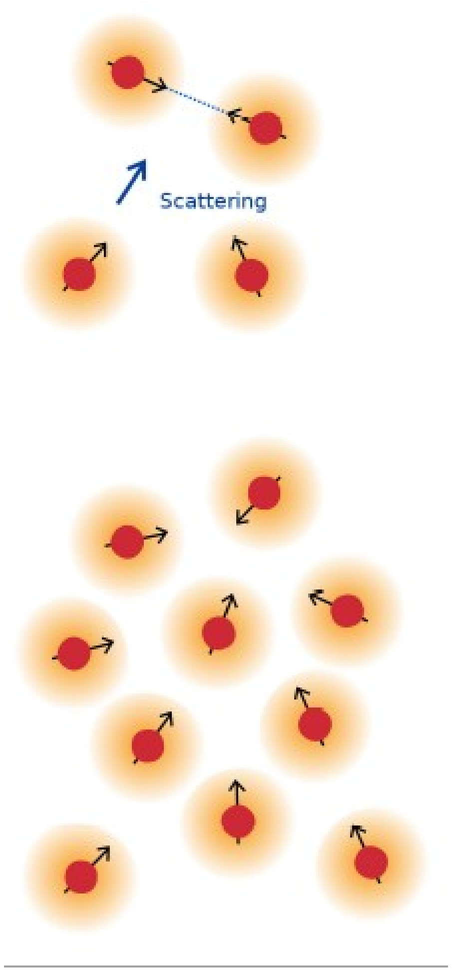
Sensitive to S gradients

$$\xi_s = [N\rho_0\kappa'(s_0)/D_s]^{-1/2}$$

Abundant reactant: long-range
Sparse reactant; screened

Interactions between active colloids

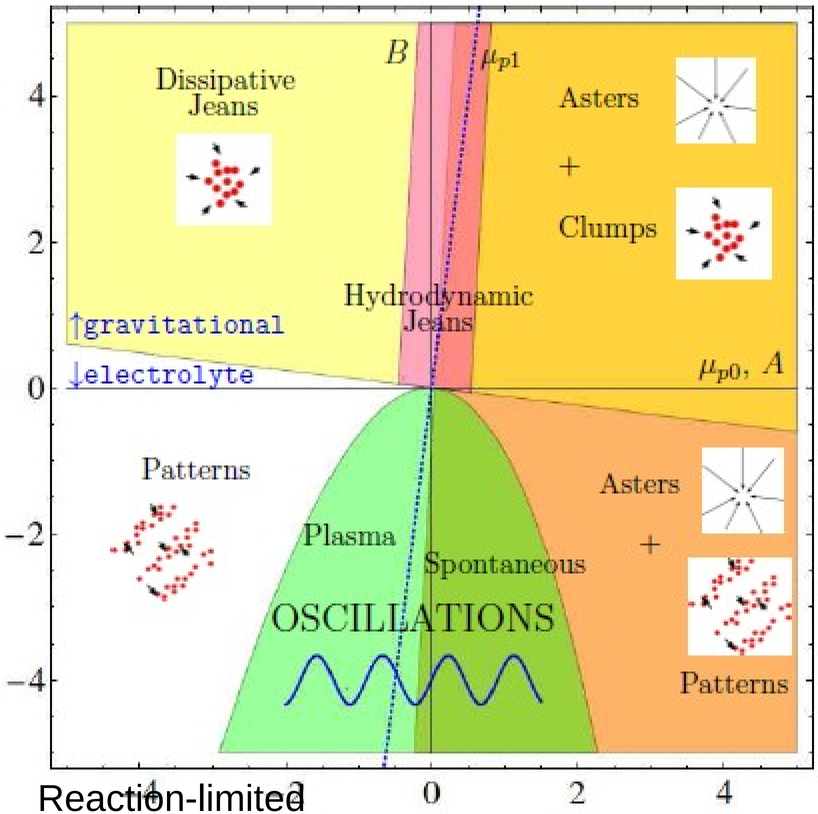
- Active colloid modifies cloud
- Another senses the resulting gradient
- Reorients, moves towards or away
- Diffusion: 1/r interaction, long ranged

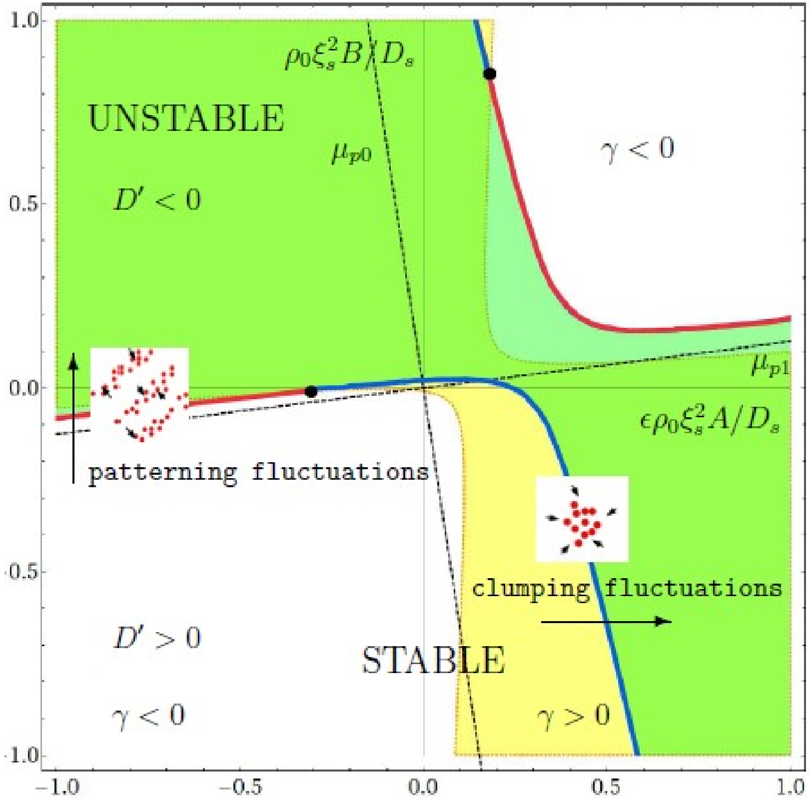


Collective behaviour

Reorienting tendency

Signs of coefficients
gravity-like or Coulomb-like
Oscillations seen
in computer expts
– Stark et al



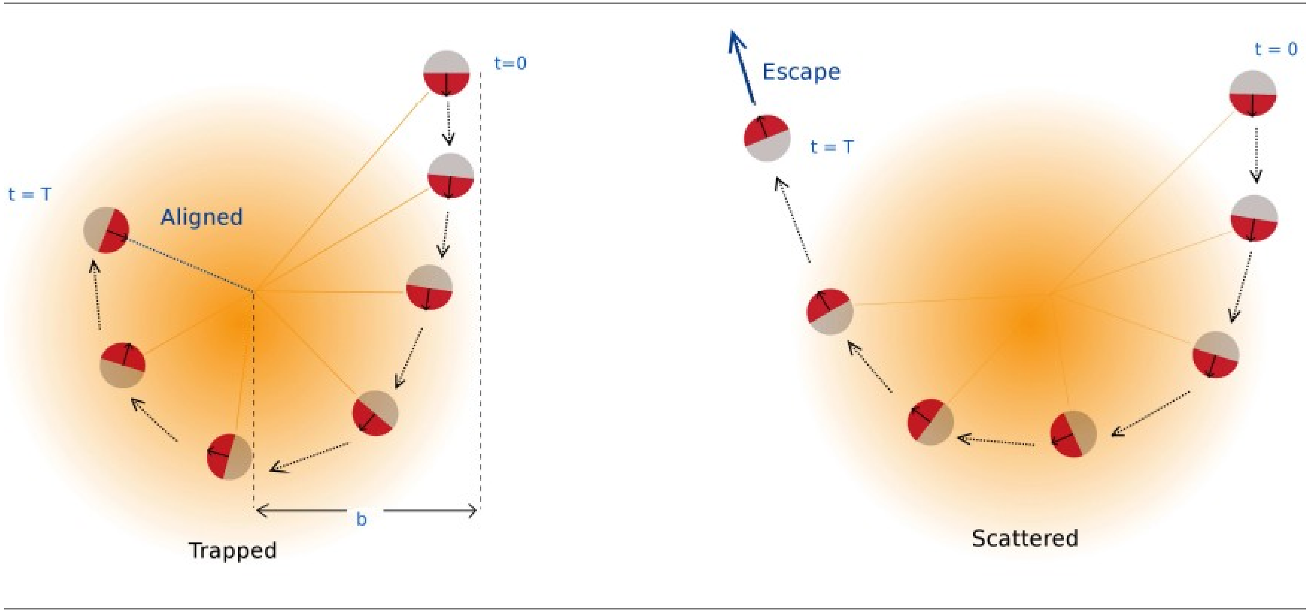


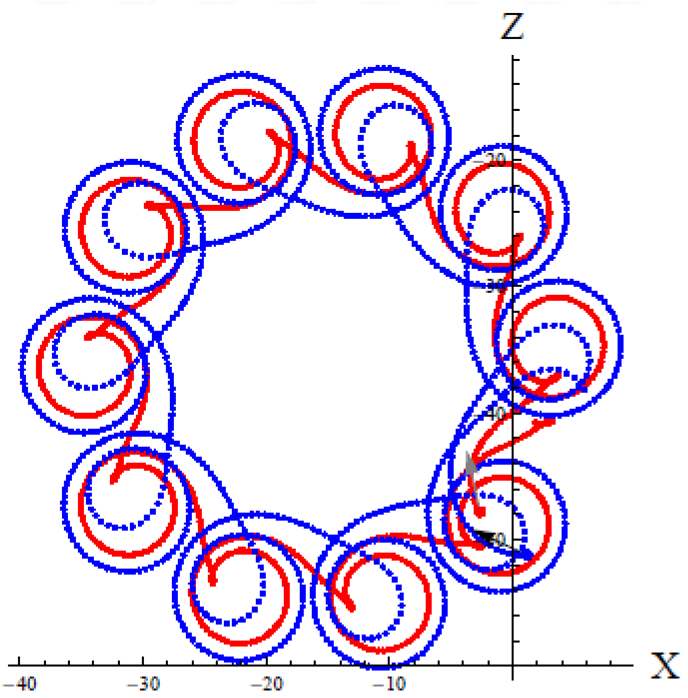
Reaction-limited
Fuel abundant
Long-range effects

Gradient-climbing tendency

DIffusion-limited
Fuel scarce
screening

Scattering or trapping, pair dances





More recent: Saha, SR, Golestanian NJP 2019
Pairing, waltzing .... Non-reciprocality

WET ACTIVE MATTER

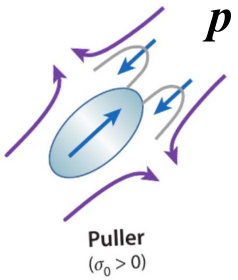
flock in fluid

Comoving co-rotating derivative

Extensional flow orients

Thermodynamic relaxation

orientation
$$\mathcal{D}_t \boldsymbol{p} = \lambda \boldsymbol{S} \cdot \boldsymbol{p} - \Gamma \frac{\delta F}{\delta \boldsymbol{p}}$$



flow
$$-\mu \nabla^2 \mathbf{u} = -\sigma_a \nabla \cdot (\boldsymbol{pp}) + \text{elasticity} + \text{pressure}$$

Viscosity

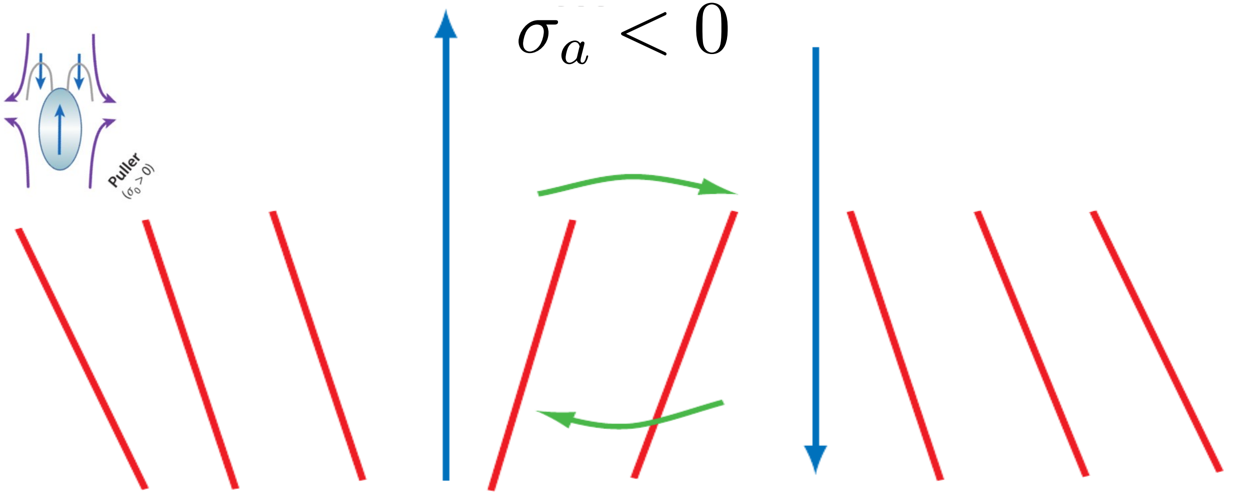
Active stress ∝ $\boldsymbol{pp}$

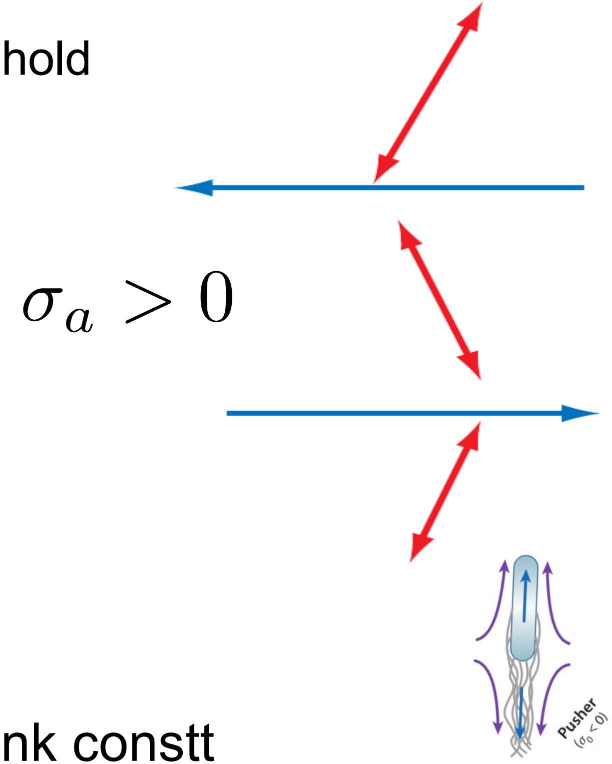
F = free energy favouring alignment; $\mathbf{u}$ = incompressible velocity field
$\boldsymbol{p}$ = orientation (*not quite, but $\boldsymbol{p} \to -\boldsymbol{p}$ invariant), $\boldsymbol{S}$= deformation rate

Simha and SR PRL 2002; Hatwalne, SR, Rao, Simha PRL 2004
Kruse, Juelicher, Joanny, Prost, Voituriez, Sekimoto PRL 2004 – cytoskeleton

Swimmers are force dipoles

viscous hydrodynamics, neglect inertia: unstable without threshold





Growth-rate → σ_a/μ for length scales > $\xi=(K/\sigma_a)^{1/2}$, K = Frank constt
viscosity/active stress: a single timescale

Simha & SR PRL 2002, Voituriez et al 2005, SR & Rao NJP 2007; polar: Giomi, Marchetti, Liverpool 2008
Active turbulence: Saintillan-Shelley/Yeomans/Dogic/Bausch/Sagues/Doostmohammadi ....

Stable Stokesian flocks
A Maitra Nat Phys 2023

A single timescale, direction dependent

$$\omega = i\frac{\sigma_a}{\mu}\cos 2\theta(1+\lambda\cos 2\theta)$$

bend-splay

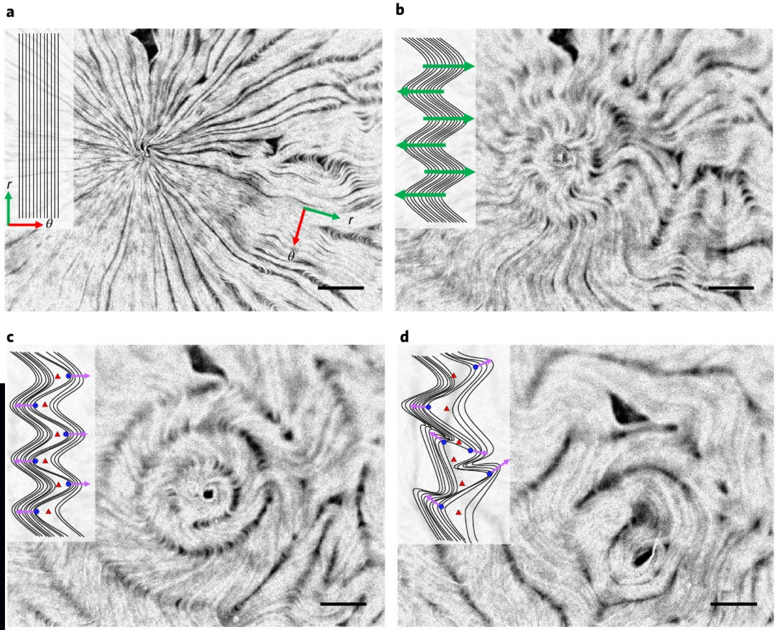
$$\omega = i\frac{\sigma_a}{\mu}\cos^2\theta(1+\lambda)$$

bend-twist

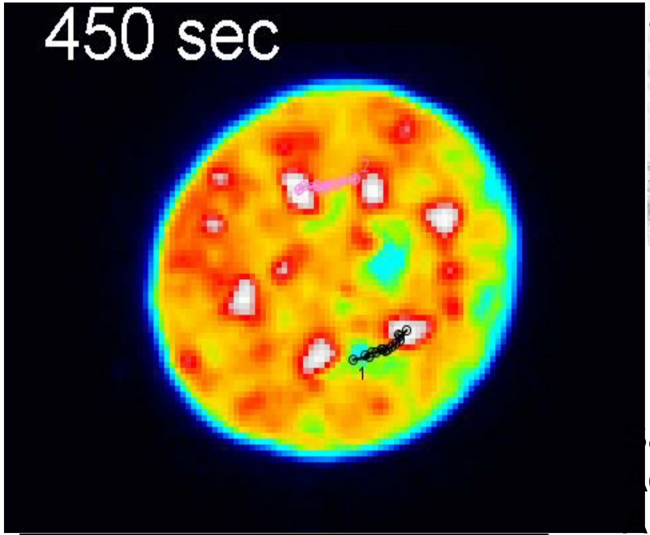
Bend-Twist not mitigated by interpolation to splay; should dominate in 3D extensile

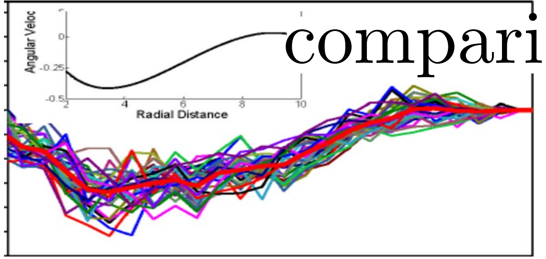
see Shendruk, Thijssen, Yeomans, Doostmohammadi, PRE 2018

Detailed confirmation: active nematic of microtubules + motors + ATP
Martínez-Prat, Ignés-Mullol, Casademunt & Sagués,
Nat Phys 2019



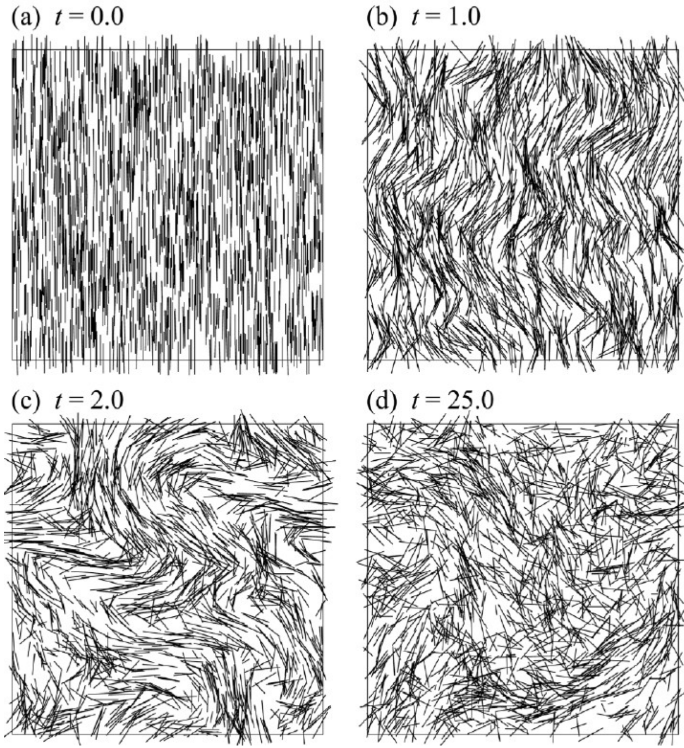
Other evidence, e.g. nuclear rotation in cell:
Kumar, Maitra, Sumit, SR, Shivashankar 2014





comparison

aintillan & Shelley 2007
ctive turbulence
lert, Casademunt, Joanny ARCMP 2023

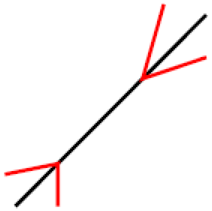


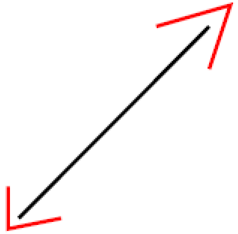
Swimming affects viscosity: theory and experiment

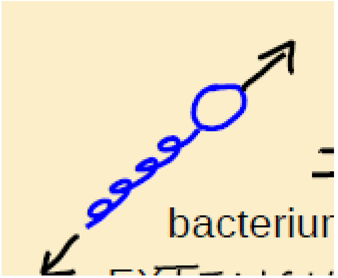
Hatwalne et al. PRL 2004

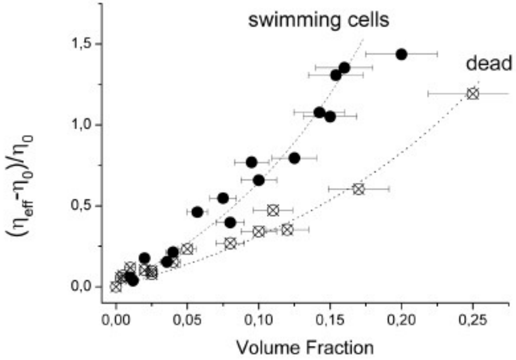
more viscous alive than dead

less viscous alive than dead

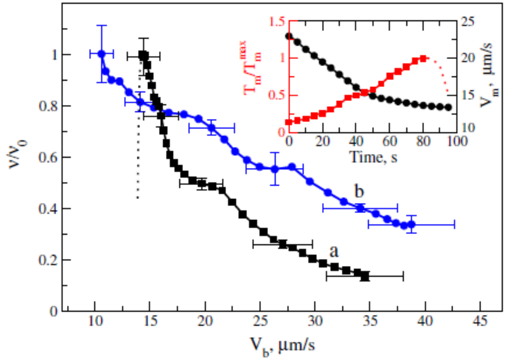








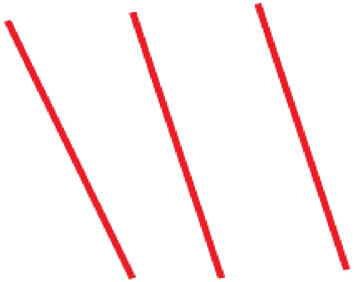
Rafai et al 2010
Sokolov & Aranson 2009
Gachelin et al 2012

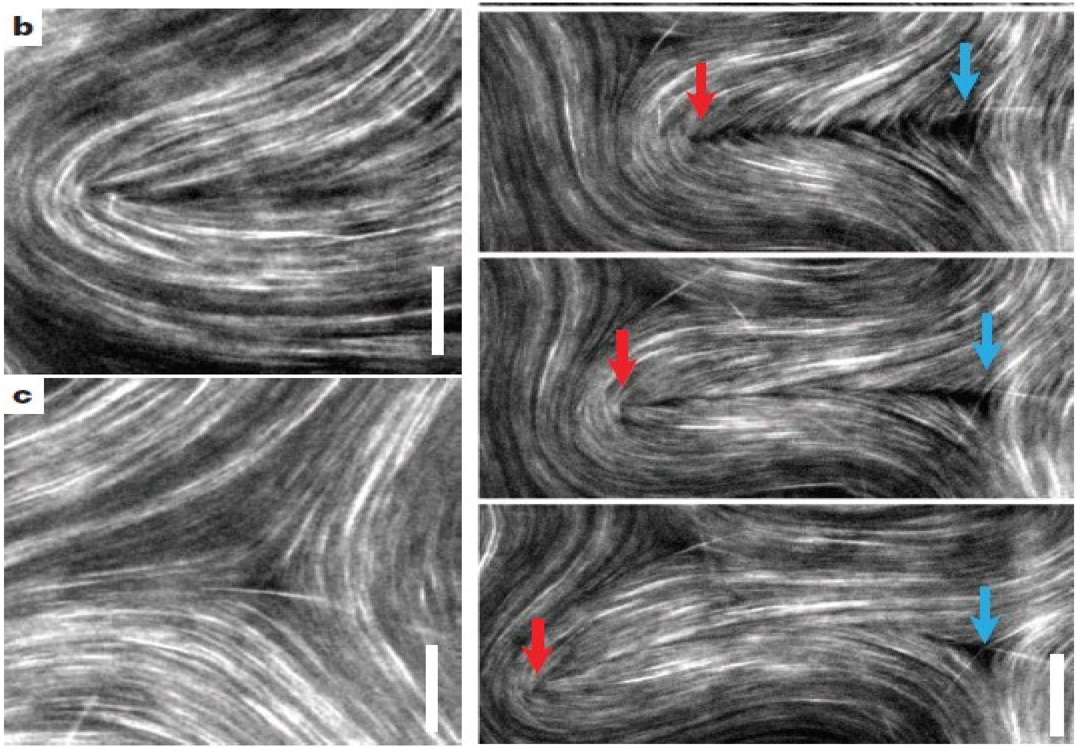


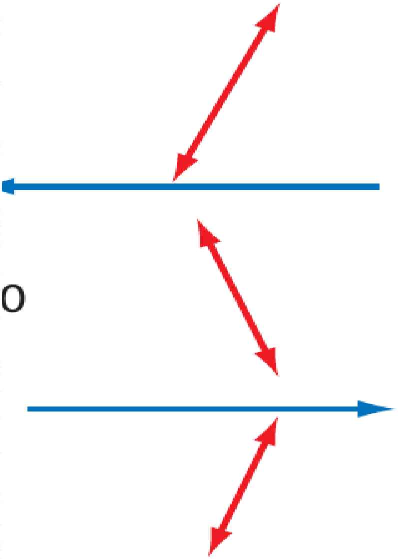
Bulk active LCs are unstable, turbulent

Simha & SR PRL 2002

Sanchez et al 2012
(Dogic group)

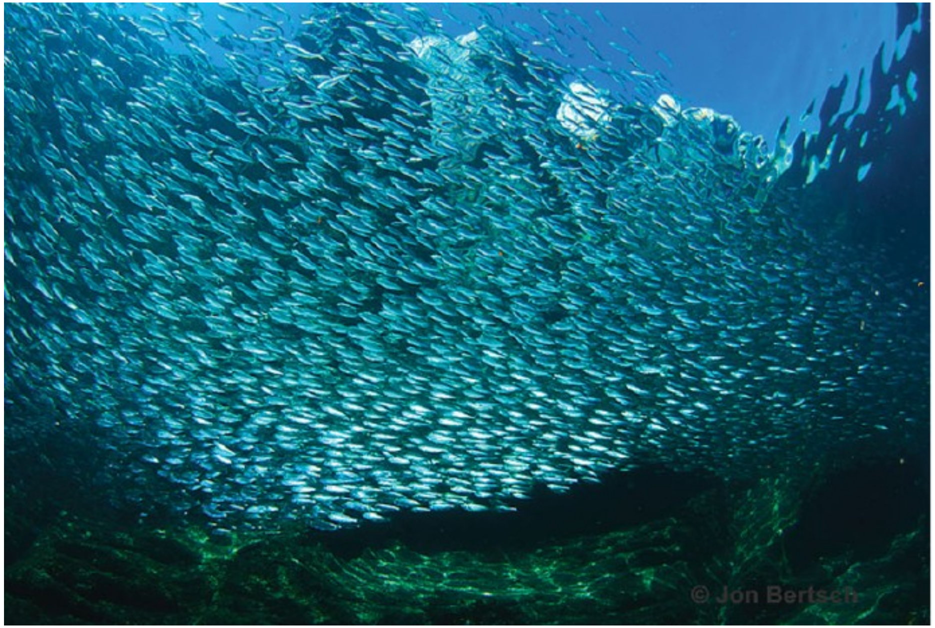






Strength 1/2 defects take over; active turbulence (Yeomans, Marenduzzo, Cates, Marchetti, Dunkel, Giomi ....
Experiments: Sagues .... Also in systems on substrate: epithelia (Sano, Silberzan....); bacteria (Dombrowski, Shuang, Aranson, Lavrentovich....); surprises in confined active nematic & polar systems: Maitra et al PNAS 2018, PRL 2019...

But large fast flocks in fluid are stable



J Bertsch http://www.thalassagraphics.com/blog/?p=167

Chisholm, Legendre, Lauga, Khair JFM 2016
Wang and Ardekani JFM 2012; Li, Ostace, Ardekani PRE 2016
Dombrowski, Jones, Katsikis, Bhalla, Griffith, Klotsa PR Fluids 2019
Klotsa, Baldwin, Hill, Bowley, Swift, PRL 2015

How much inertia do you need to stabilise a flock in fluid?

Becker et al. NComms 2015
Filella et al. PRL 2018

With inertia: outswim the viscous instability?

velocity

$$\underline{\rho(\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u})} = -\nabla P + \mu \nabla^2 \boldsymbol{u} + \nabla \cdot (\boldsymbol{\Sigma}^a + \boldsymbol{\Sigma}^r)$$

pressure

viscosity

Active and passive
order-parameter stresses

orientation

$$\partial_t \boldsymbol{p} + (\boldsymbol{u} + v_0 \boldsymbol{p}) \cdot \nabla \boldsymbol{p} = \lambda \mathbf{S} \cdot \boldsymbol{p} + \boldsymbol{\Omega} \cdot \boldsymbol{p} + \Gamma \boldsymbol{h}$$

Advection

shear-alignment

rotation

relaxation

$$\boldsymbol{\Sigma}^a \equiv -\sigma_a \boldsymbol{p}\boldsymbol{p}$$

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\boldsymbol{h} = -\delta F / \delta \boldsymbol{p}$$

F free-energy functional
favouring nonzero $<p>$

The key dimensionless number

$$R = \rho v_0^2 / 2\sigma_a$$

self-propulsion speed v_0

instability invasion speed $\sqrt{\sigma_a/\rho}$

What’s that?

Recall Stokesian limit: scale-independent growth rate σ_a/μ

Include inertia (linearised Navier-Stokes)
growth rate linear in wavenumber q

$$\omega \propto q \left(v_0^2 - 2\sigma_a \frac{1+\lambda}{\rho} \right)^{1/2}$$

$\text{self-propulsion speed}\, v_0$

$\text{instability invasion speed}\, \sqrt{\sigma_a/\rho}$

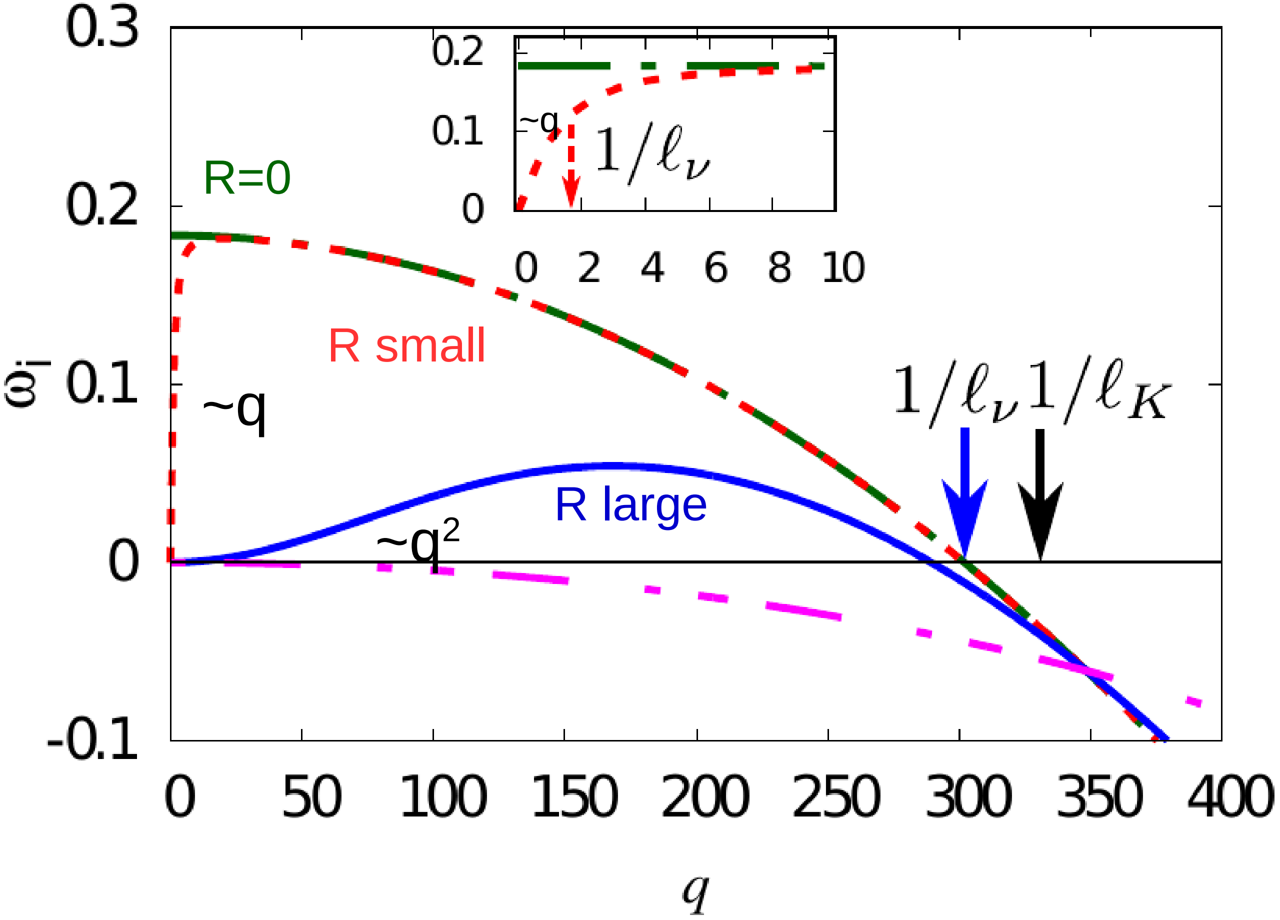
growth/decay of twist-bend mode

$$R \equiv \rho v_0^2 / 2\sigma_0$$

$$\omega \propto q \left(v_0^2 - 2\sigma_a \frac{1+\lambda}{\rho} \right)^{1/2} + i q^2 \frac{\mu}{2\rho} \frac{v_0}{\left(v_0^2 - 2\sigma_a \frac{1+\lambda}{\rho} \right)^{1/2}}$$

for $R \gtrsim 1 + \lambda$

$$q \ll \rho v_0 / \mu, \sqrt{\rho \sigma_a} / \mu$$

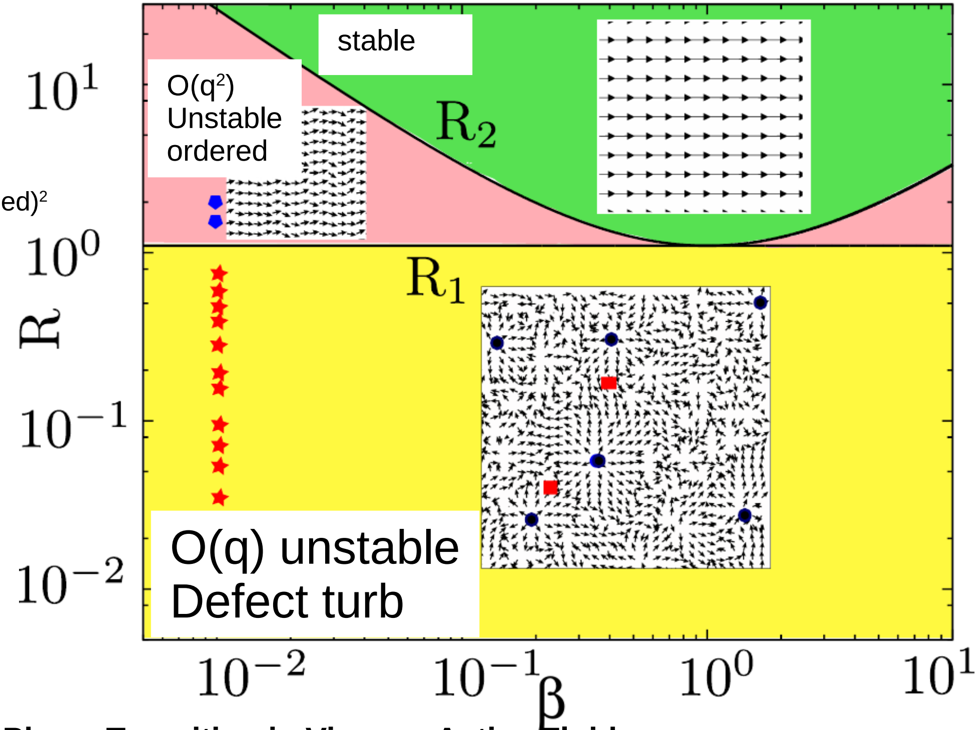


Inertia: outrun Stokesian instability

defect to phase turbulence: disorder to flock

$$R \equiv \rho v_0^2/2\sigma_0$$

(swim speed/instab-invasion speed)^2



$$\beta \equiv \rho \Gamma K/\mu$$

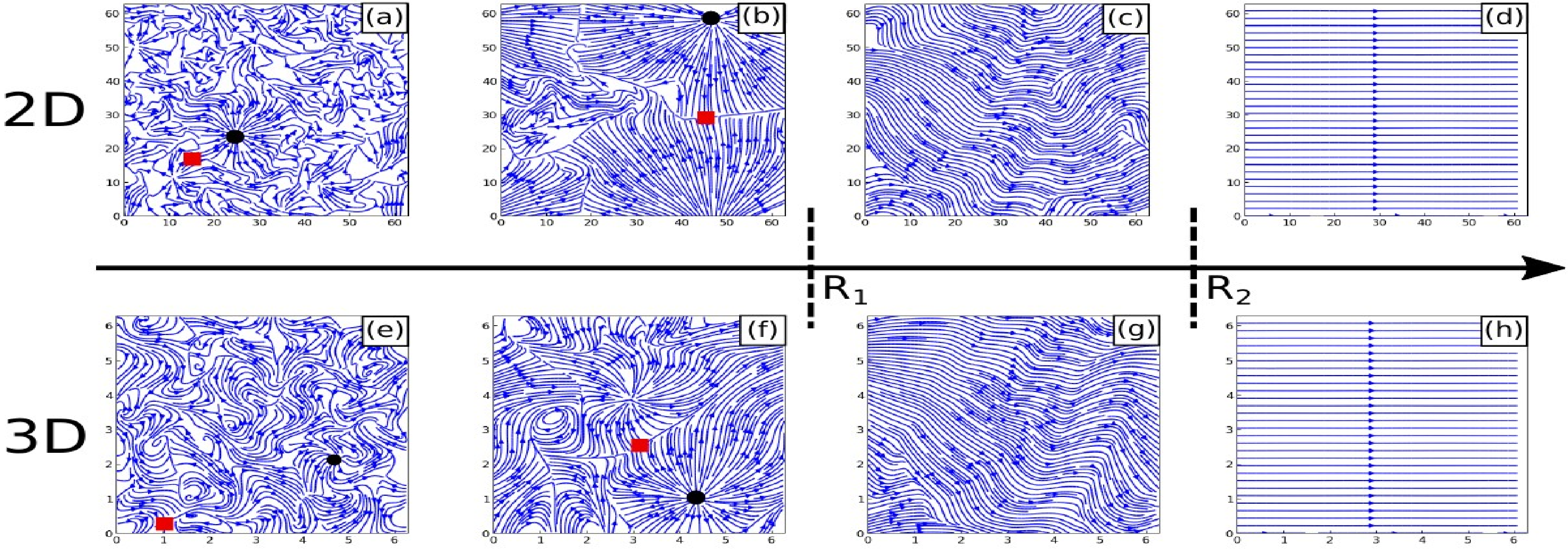
Orientational diffusion / vorticity diffusion

Inertia Drives a Flocking Phase Transition in Viscous Active Fluids

Rayan Chatterjee, Navdeep Rana, R. Aditi Simha, Prasad Perlekar, and Sriram Ramaswamy

Phys. Rev. X **11**, 031063 (2021)

From defect turbulence to phase turbulence



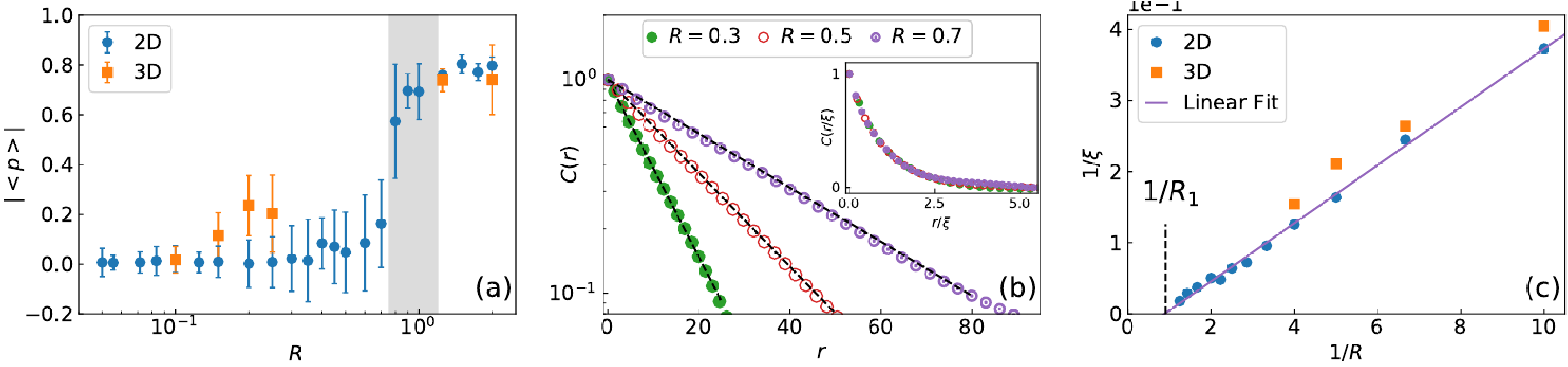
defect turbulence in the O(q) growth regime

phase turbulence in the O(q^2) growth regime

Polar system: defects are hedgehogs (normal and hyperbolic)

Phase turbulence: ordered state

Inertial flocking transition



- Order parameter $|<\mathbf{p}>| = \left\langle \sqrt{\langle p_x\rangle^2 + \langle p_y\rangle^2 + \langle p_z\rangle^2} \right\rangle_t$ onset near $R_I \simeq 1$.
- correlation fn. $C(r) = \dfrac{< p(\mathbf{x}) \cdot p(\mathbf{x}+\mathbf{r}) >}{< p(\mathbf{x})^{\mathbf{2}} >}$ shows scaling collapse.

Chatterjee et al. Phys. Rev. X **11**, 031063 (2021)

- Correl length $\sim$ inter-defect distance ξ grows near $R_I \simeq 1$

SUMMARY

- General framework for “powered” matter
- Phase diagram depends on dynamical regime
- Imitations of motility; complex media
- Active turbulence and escaping it

EXPERIMENTAL
SYSTEM?