MAX-PLANCK-GESELLSCHAFT

Driven/Active Transport of Magnetic Particles in Microfluidic Environments

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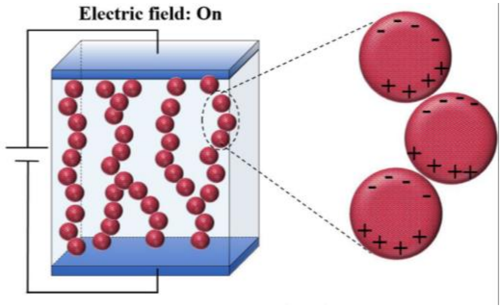
1. Driven Annealing of Magnetic Colloid

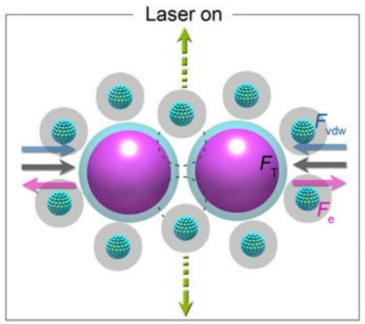
Solid-Liquid Colloid



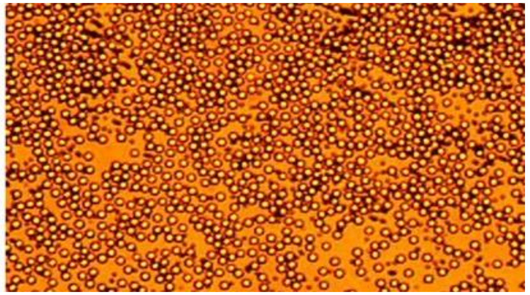

External-Field cued colloid



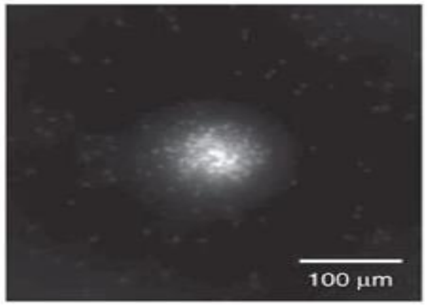
Adapted from Nanomater. 5, 2249 (2015)



Adapted from Sci. Adv. 3, e1700458 (2017)



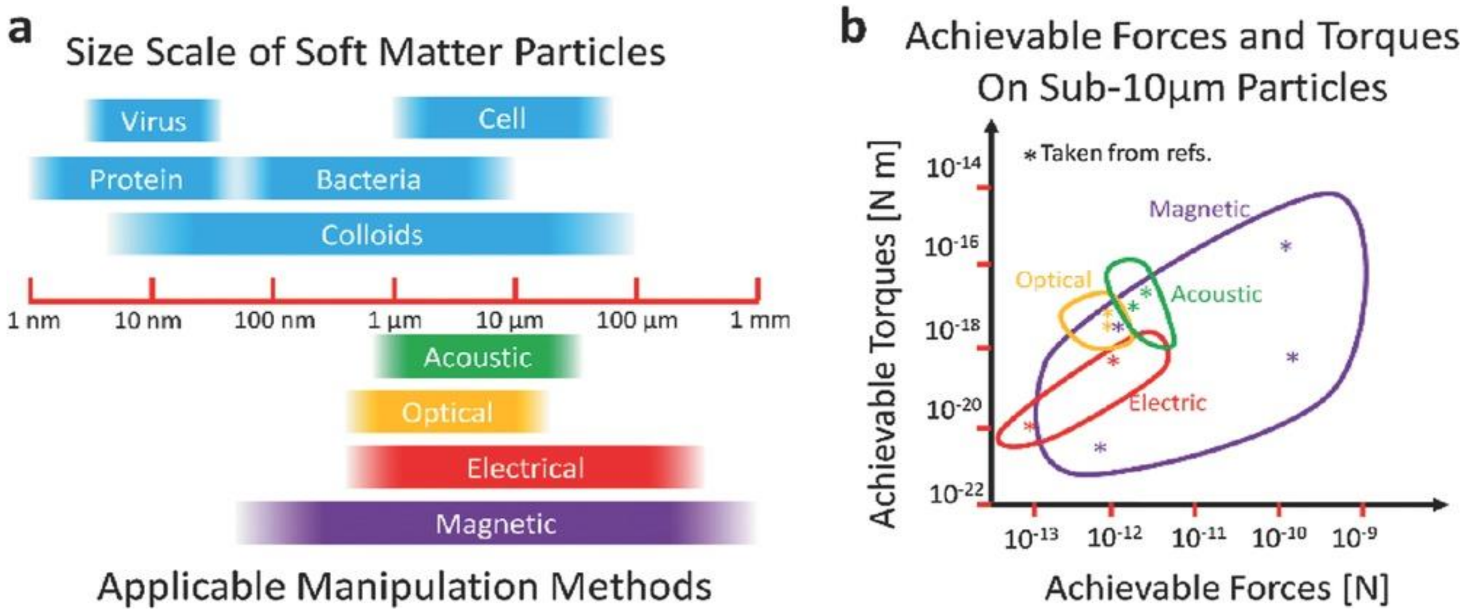
Adapted from PNAS 115 , 10618 (2018)



Adapted from Nat. Comm. 7, 10694 (2016)

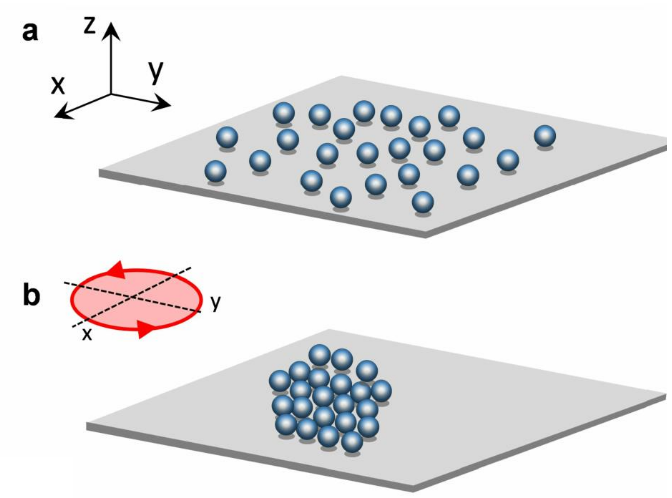
External-Field Cued Soft Matter Particles

Why magnetic?



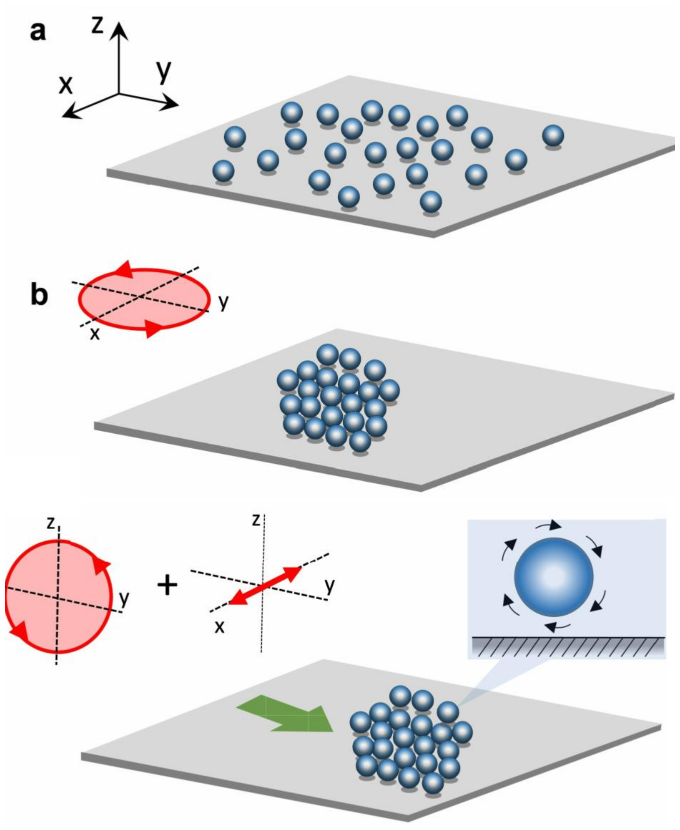
Erb et al. *Adv. Funct. Mater*, 26, 3859 (2016)

Phenomenon

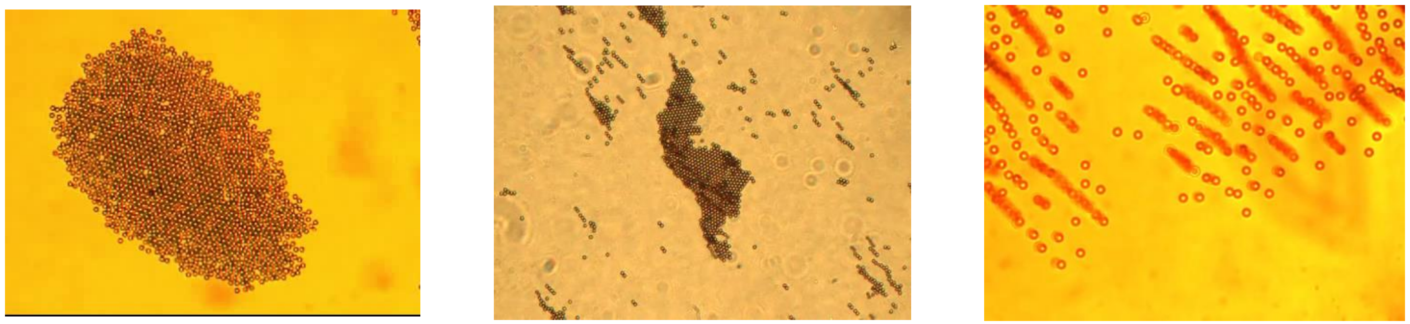


Magnetic field $\boldsymbol{B} = B_0[\cos(\omega t)\hat{\boldsymbol{x}} - \sin(\omega t)\hat{\boldsymbol{y}}]$

Phenomenon



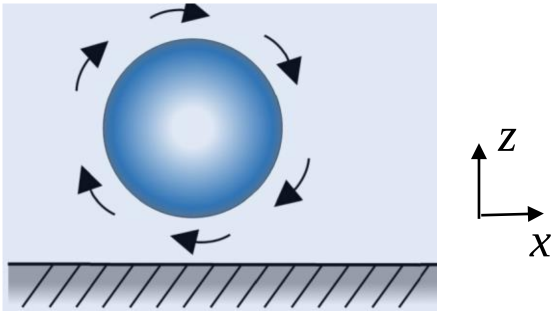
Increasing B_z



Why this and how to control

Magnetic field $\boldsymbol{B} = B_0[\sin(\omega_x t)\hat{\boldsymbol{x}} + \cos(\omega t)\hat{\boldsymbol{y}} - (B_z/B_0)\sin(\omega t)\hat{\boldsymbol{z}}]$

Individual Paramagnetic Particle



Magnetic field

$$\boldsymbol{B} = B_0[\cos(\omega t)\hat{\boldsymbol{x}} - \sin(\omega t)\hat{\boldsymbol{z}}]$$

Magnetic torque

volume   susceptibility   relaxation time

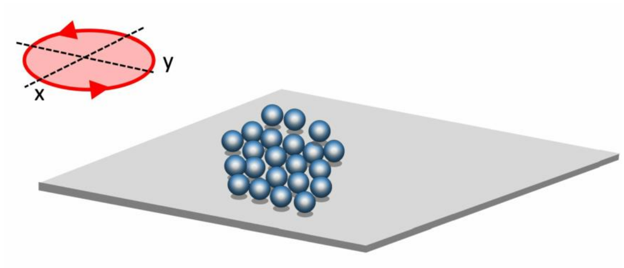
$$\boldsymbol{T}_c = \frac{B_0^2 V \chi \tau_r \omega}{\mu_0(1+\tau_r^2\omega^2)}\hat{\boldsymbol{y}}$$

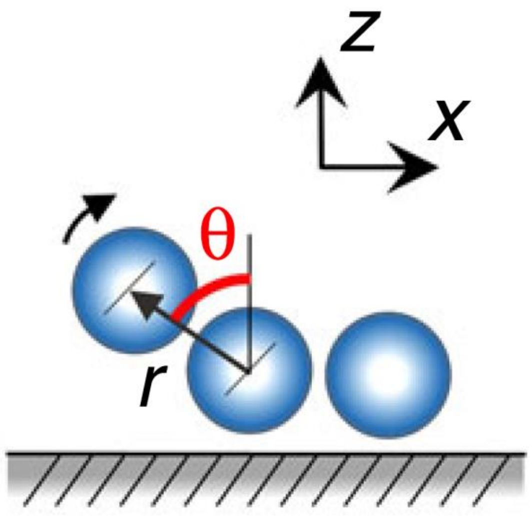
In presence of a wall in xy plane

$$\mathbf{v}_0 = \frac{T_c a^2}{32\pi\eta h^4}\hat{\boldsymbol{x}}$$

Cebers and Kalis, Euro. Phys. J. E 34, 1292 (2011)
Martinez-Pedrero, Ortiz-Ambriz, Pagonabarraga, and Tierno, Phys. Rev. Lett. 115, 138301 (2015)

Magnetic Dipole-Dipole Interaction and Hydrodynamic Interaction





Magnetic dipole-dipole interaction

$$U_{\mathrm{m}} = -\sum_{i,j\neq i} \frac{\mu_0 \left[3(\boldsymbol{m}_i \cdot \boldsymbol{r}_{ij})(\boldsymbol{m}_j \cdot \boldsymbol{r}_{ij}) - \boldsymbol{m}_i \cdot \boldsymbol{m}_j r_{ij}^2\right]}{4\pi r_{ij}^5}$$

Hydrodynamic interaction

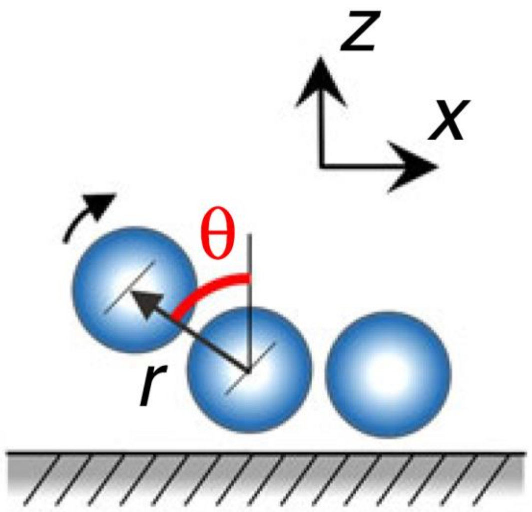
$$\boldsymbol{v} = \frac{\boldsymbol{T} \times \boldsymbol{r}}{8\pi\eta r^3} = \frac{a\boldsymbol{\omega}_c \times \hat{\boldsymbol{r}}}{4}$$

Effective torque

$$\boldsymbol{T}_{\mathrm{h}} = 3\pi\eta a^3 \boldsymbol{\omega}_c = \frac{\pi a^3 B_0 B_z \chi \tau_r \omega}{2\mu_0(1+\tau_r^2\omega^2)}\hat{\boldsymbol{y}}.$$

Massana-Cid #, **Meng** #, Matsunaga, Golestanian, and Tierno, Nat. Comm. 10, 2444 (2019)

Many Particles: Effective Energy Form



Effective energy

$$U_{tot} = U_m + U_h \qquad U_h = T_h\theta$$

Dynamic equation

$$\begin{aligned}\dot{\theta} \quad &= \quad \frac{1}{4\zeta a^2}\frac{3(V\chi B_0)^2}{64\mu_0\pi a^3}\left(1 - \frac{B_z^2}{B_0^2}\right)\sin 2\theta - \\ &\quad\quad \frac{1}{4\zeta a^2}\frac{\pi a^3 B_0 B_z \chi \tau_r \omega}{2\mu_0(1+\tau_r^2\omega^2)}\end{aligned}$$

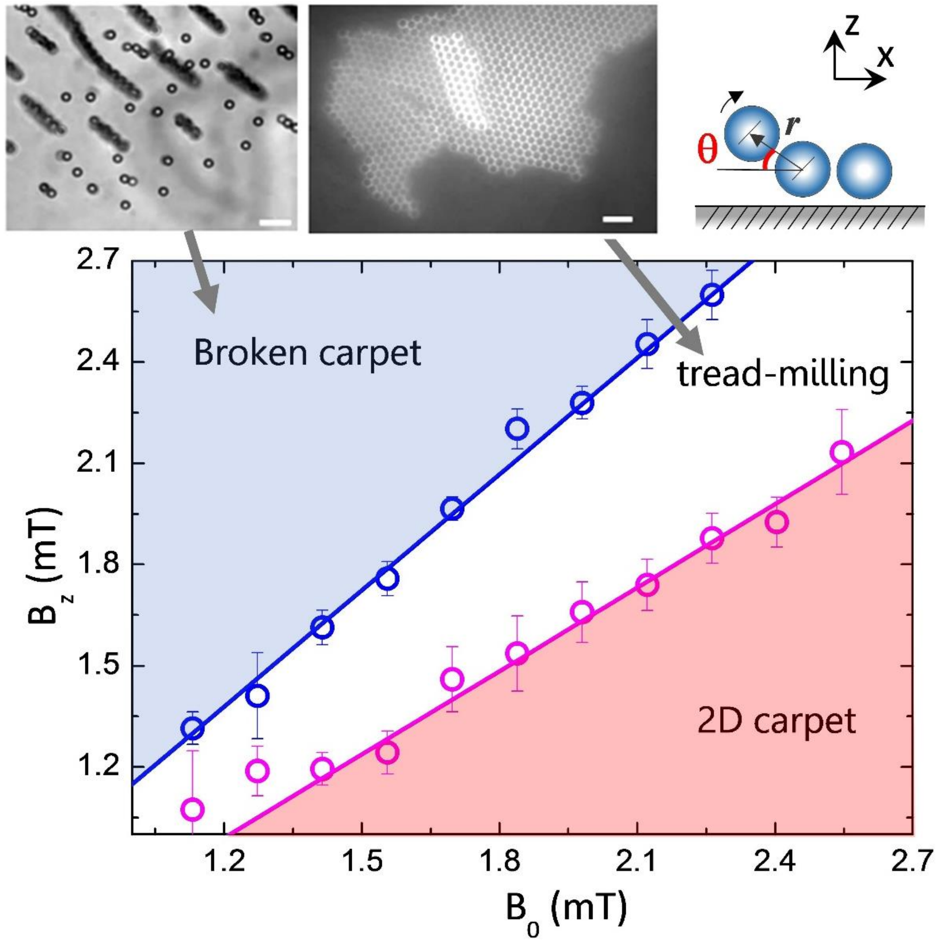
Many Particles: Dynamic Regimes

$$\frac{B_z}{B_0} \leq \frac{-c+\sqrt{c^2+4}}{2} \quad (\theta\sim\pi/2)$$

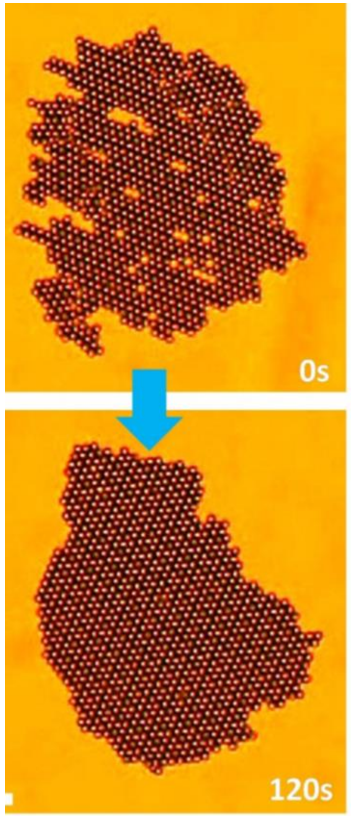
$$\frac{B_z}{B_0} \geq \frac{c+\sqrt{c^2+4}}{2} \quad (\theta\sim 0)$$

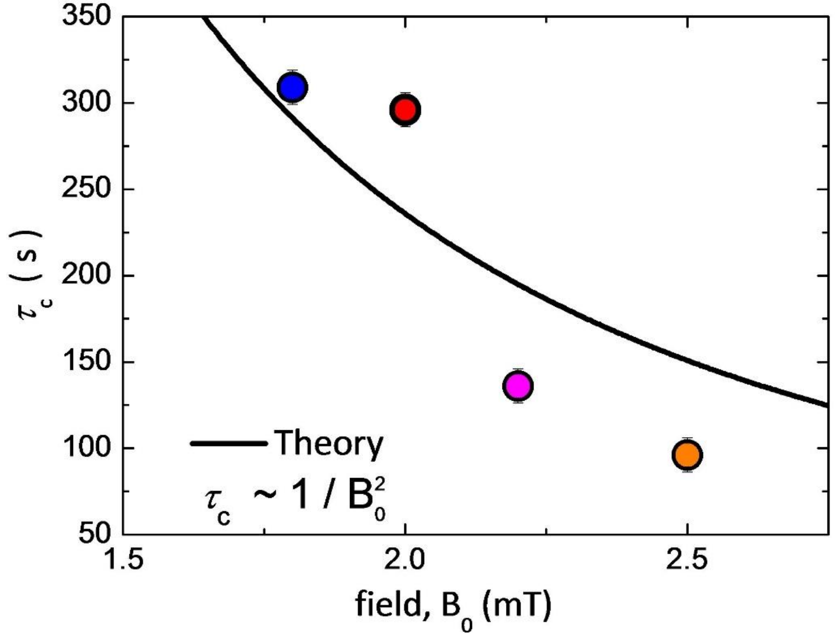
where

$$c = 6\tau_r\omega/[\chi(1+\tau_r^2\omega^2)]$$

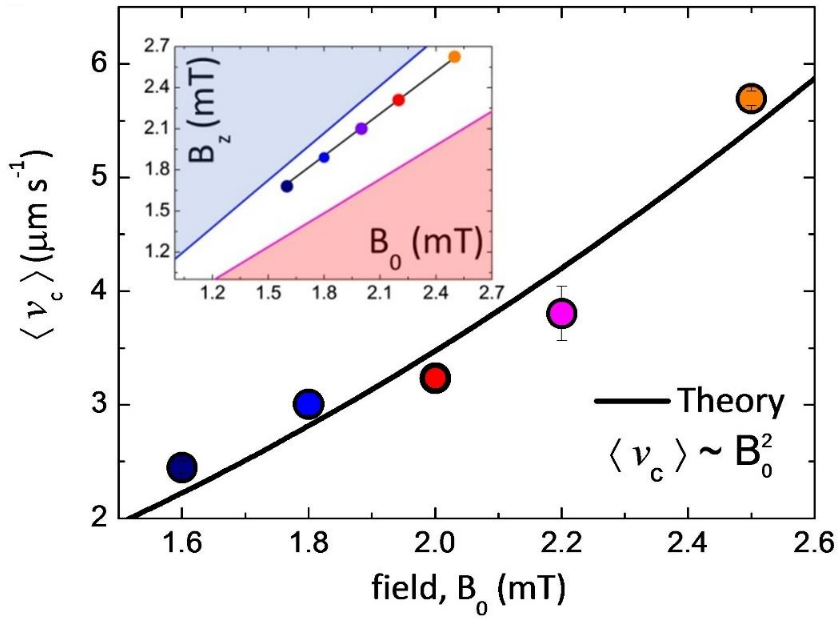


Tread-Milling: Driven Annealing





Annealing time ~ $1/B_0^2$

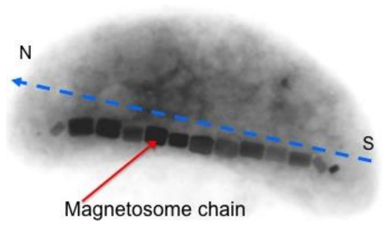


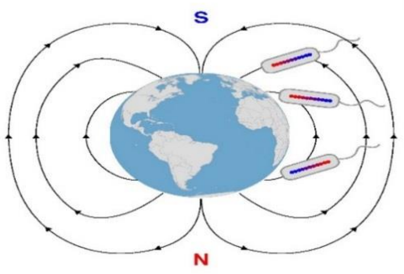
Propagation speed ~ B_0^2

2. Active Clustering of Magnetic Microswimmers

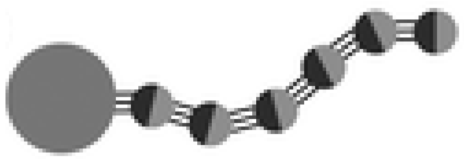
Magnetic Microswimmer

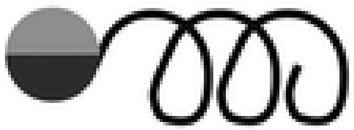
- Natural: magnetotactic bacteria (Blakemore, Science 1975)

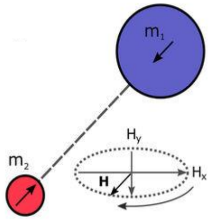




- Synthetic:





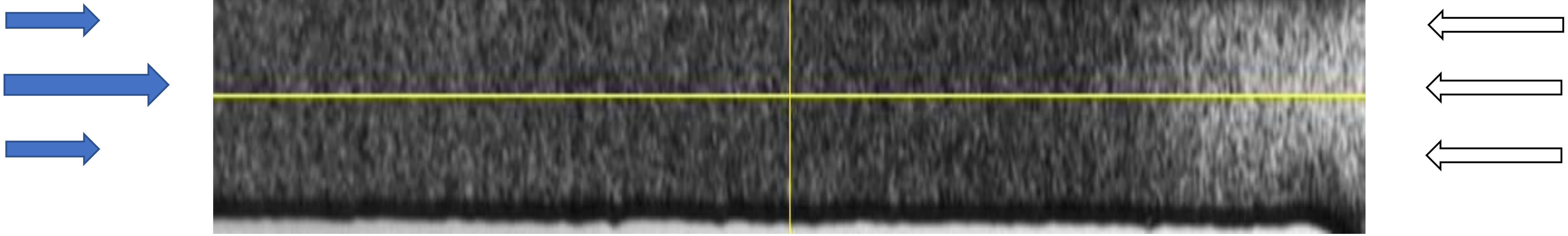


Dreyfus et al. Nature 437, 862 (2005)

Ghosh and Fischer, Nano Lett. 9, 2243 (2009)

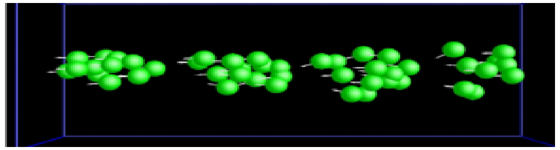
Hamilton et al. Sci. Rep. 7, 44142 (2017)

Magnetotactic Bacteria in Microfluidic Channel



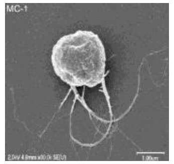
Waisbord, Lefevre, Bocquet, Ybert, Cottin-Bizonne, *PRFluids* **1**, 053203 (2016)

Why clustering?



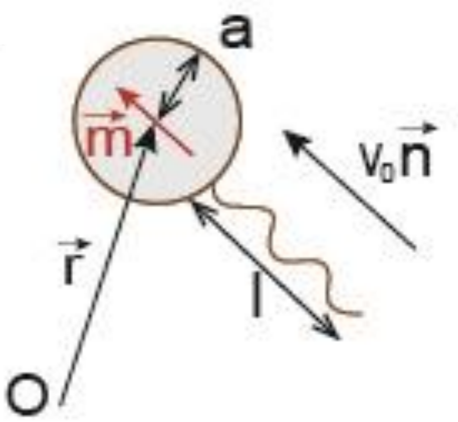
Pullers: attractive hydrodynamic interaction

Garcia, et.al., PRL (2013) Jibuti, et.al., PRE (2014) Lauga, et.al., EPL (2016)



magnetic dipole-dipole interaction

Individual Magnetic Microswimmer



magnetotactic bacterium

Equation of motion

$$\frac{d\boldsymbol{n}}{dt} = \left[\frac{m_0 \boldsymbol{n} \times (\boldsymbol{B}_{\text{ext}} + \boxed{\boldsymbol{B}_{\text{int}}})}{\zeta_R} + \frac{\boldsymbol{\nabla} \times \boldsymbol{V}_{\text{f}}}{2} + \boldsymbol{\xi}_R\right] \times \boldsymbol{n}$$

$$\frac{d\boldsymbol{r}}{dt} = v_0 \boldsymbol{n} + \boldsymbol{V}_{\text{f}} + \frac{1}{\zeta} \boldsymbol{\nabla} \left(m_0 \boldsymbol{n} \cdot \boxed{\boldsymbol{B}_{\text{int}}}\right) + \boldsymbol{\xi}$$

Meng, Matsunaga, Golestanian, Phys. Rev. Lett., **120**, 188101 (2018)

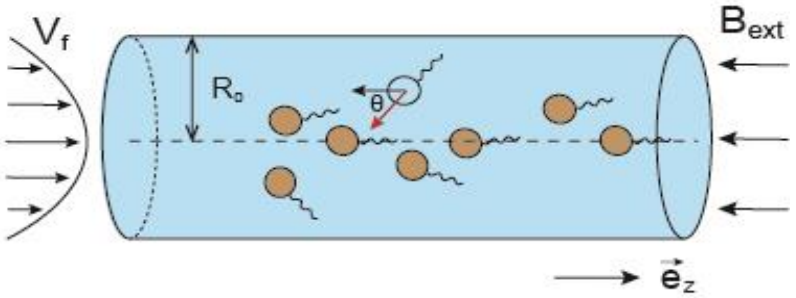
Orientation: Pinned

Faster relaxation of rotation than translation

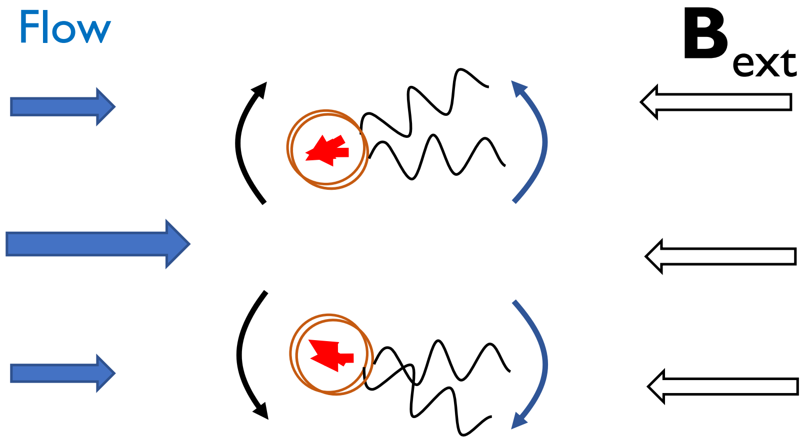
$$\frac{d\boldsymbol{n}}{dt} = \left[\frac{m_0\boldsymbol{n}\times(\boldsymbol{B}_{\mathrm{ext}}+\boldsymbol{B}_{\mathrm{int}})}{\zeta_R} + \frac{\boldsymbol{\nabla}\times\boldsymbol{V}_{\mathrm{f}}}{2} + \boldsymbol{\xi}_R\right]\times\boldsymbol{n} = 0$$

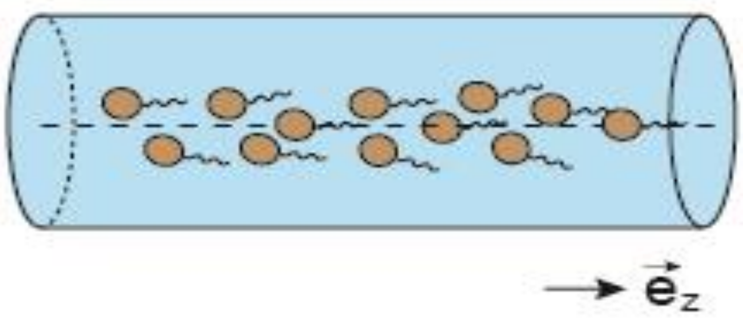
Swimmers are pinned in orientations, depending on the radial positions

$$\sin\theta \simeq \frac{v_{\mathrm{f}}k_{\mathrm{B}}T\boxed{r}}{(D_r R_0^2 m_0 B_{\mathrm{ext}})}$$



Translation: Radial Focusing





Brownian particle in a quadratic potential well

$$\dot{r} + \frac{k_B T v_0 v_{\mathrm{f}}}{m_0 B_{\text{ext}} D_R R_0^2} r + \frac{k_B T v_0}{m_0 B_{\text{ext}} D_R} \xi_R^{\phi} = 0$$

Number density at time t and location **r**

$$\rho = \rho_z(z;t) \frac{R_0^2}{2R^2} \exp[-\frac{r^2}{2\boxed{R^2}}]$$

Focusing radius: $R^2 = \frac{v_0 k_B T}{v_{\mathrm{f}} m B_{\text{ext}}} R_0^2$

Translation: Longitudinal Clustering

Fokker-Planck equation describing the evolution of number density at time t and location **r**

$$\frac{\partial \langle \rho(r,z;t) \rangle_r}{\partial t} = -\nabla_z \left[\boxed{\langle \rho(r,z;t) v_0 \boldsymbol{n} \cdot \boldsymbol{e}_z \rangle_r} + \boxed{\langle \rho(r,z;t) V_{\mathrm{f}} \rangle_r} \right]$$

$$\boxed{-\nabla_z \left[\frac{1}{\zeta} \langle \rho(r,z;t) \nabla_z (m_0 \boldsymbol{n} \cdot \boldsymbol{B}_{\mathrm{int}}) \rangle_r \right]} + \boxed{D \left\langle \nabla_z^2 \rho(r,z;t) \right\rangle_r}$$

Dispersion Relation

By assuming $\rho_z(z;t) = \rho_z^0 + \delta\rho_z(z;t)$ and expressing the perturbation in its Fourier transformed form, $\delta\rho_z(z;t) = \frac{1}{4\pi^2}\int\int d\omega dk_z \exp[-i\omega t + ik_z z]\delta\hat{\rho}_z(k_z,\omega)$

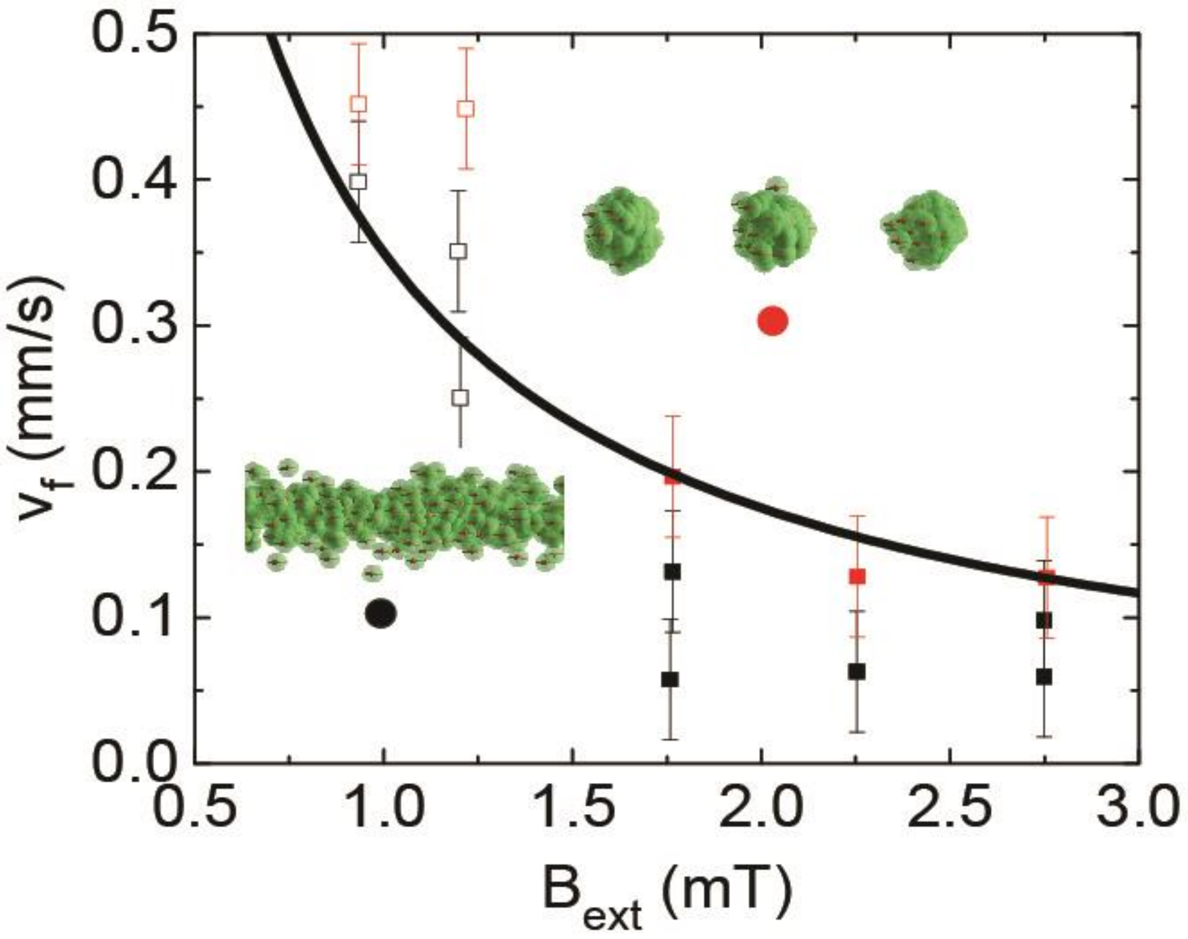
The dispersion relation

$$-i\omega \quad = \quad \boxed{\frac{k_z^2}{\zeta}\left[\frac{\mu_0\rho_0 m^2 R_0^2}{4R^2}g(k_zR) - k_BT\right]} + \boxed{ik_z[v_0 - v_\mathrm{f}]} \qquad g(q) = [1 + q^2\exp(q^2)\mathrm{Ei}(-q^2)]$$

growth rate (stability factor) propagation factor

clustering condition: $\underbrace{\frac{\mu_0\rho_0 m^2}{4k_BT}}_{\langle 1\rangle}\underbrace{\frac{mB_\mathrm{ext}}{k_BT}}_{\langle 2\rangle}\underbrace{\frac{v_\mathrm{f}}{v_0}}_{\langle 3\rangle} \geq 1$

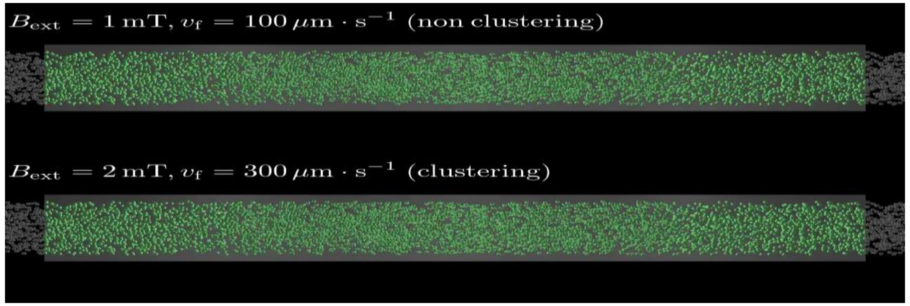
Comparison with Experiment



clustering condition:

$$\underbrace{\frac{\mu_0 \rho_0 m^2}{4 k_B T}}_{\langle 1 \rangle} \underbrace{\frac{m B_{\text{ext}}}{k_B T}}_{\langle 2 \rangle} \underbrace{\frac{v_{\text{f}}}{v_0}}_{\langle 3 \rangle} \geq 1$$

Langevin simulations:

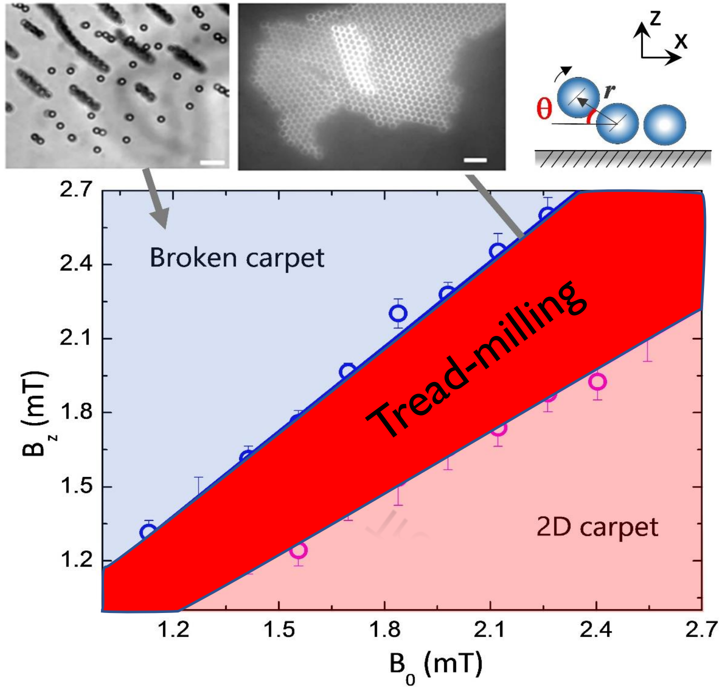


Long time responses:

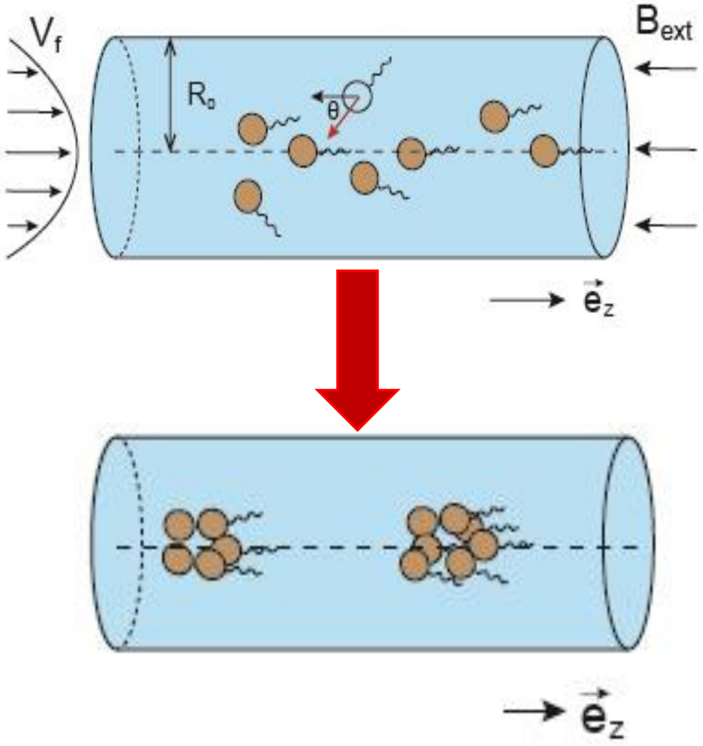
Cahn-Hilliard type phase transition

Take Home Message

1. Dynamic modes of magnetic colloid



2. Clustering of magnetic microswimmers in a channel



Massana-Cid #, **Meng** #, Matsunaga, Golestanian, and Tierno, Nat. Comm. 10, 2444 (2019)
Meng, Matsunaga, Golestanian, Phys. Rev. Lett., 120, 188101 (2018)

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