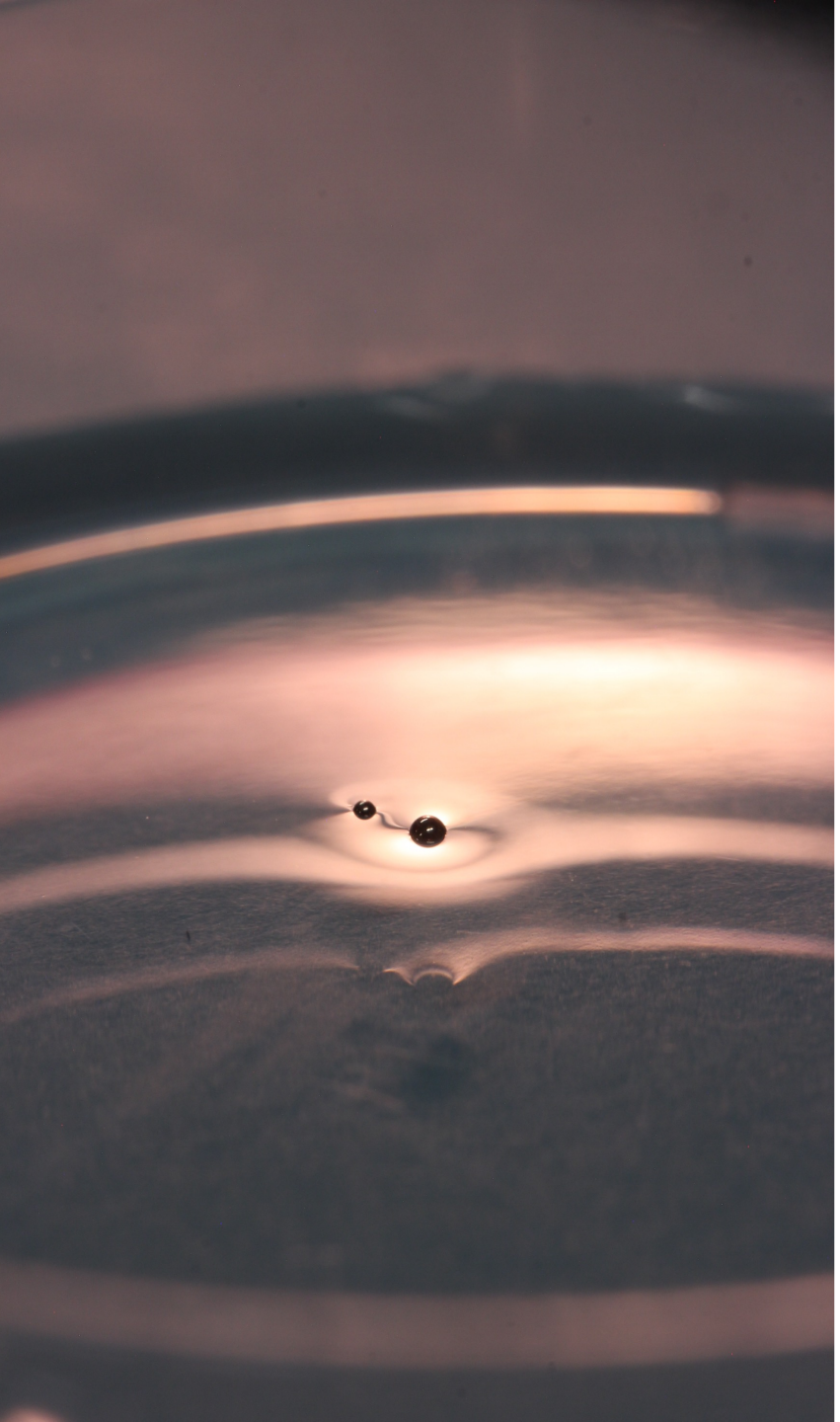

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Induced capillary dipoles in floating particles assemblies

M. Delens, Y. Collard, and N. Vandewalle, Phys. Rev. Fluids **8**, 074001 (2023)

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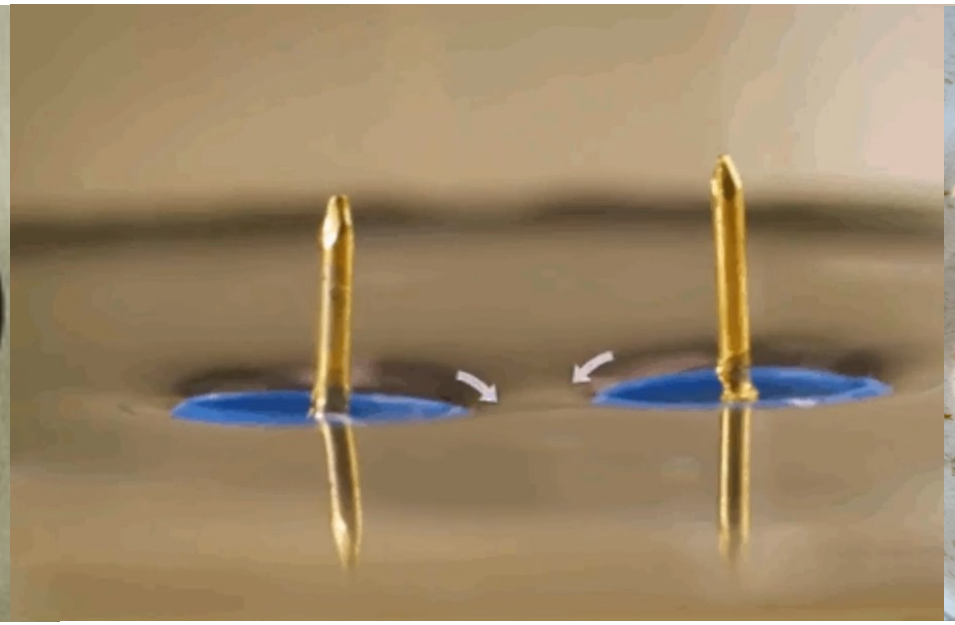
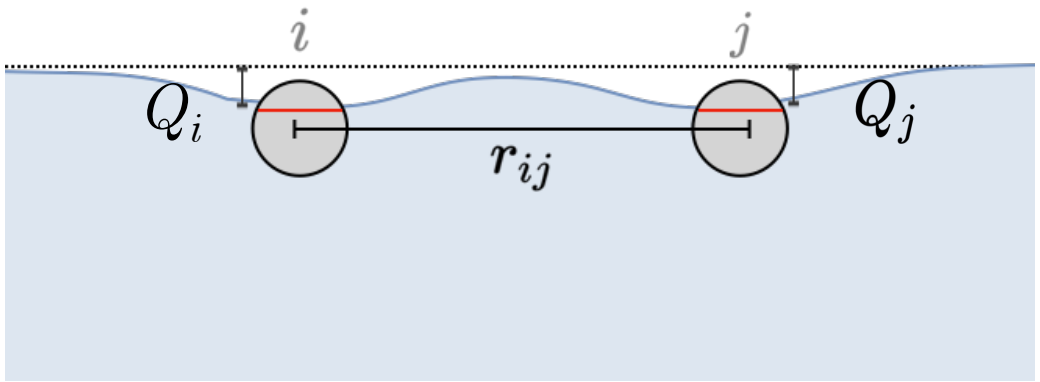
Our inspiration – The Cheerios Effect



Two beads

- Competition between surface tension and gravity distorts the liquid interface
- Typical distortion depth of the surface $z(r)$: *capillary charge* Q $\longrightarrow$ $z(r) = QK_0\left(\frac{r}{\lambda}\right)$
- Nicolson's approximation: Linear superposition of the menisci if $r_{ij} > 2D$



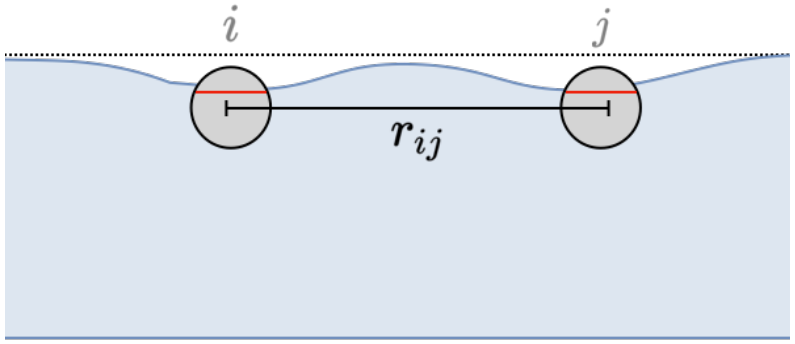
$$\gamma \nabla^2 h = \rho g h$$

$$U_{ij} = -2\pi\gamma Q_i Q_j K_0\left(\frac{|\vec{r_i} - \vec{r_j}|}{\lambda}\right)$$

D. Vella & L. Mahadevan, American journal of physics, 2005
M. Nicolson, Math. Proceedings of the Cambridge Philosophical Society, 1949

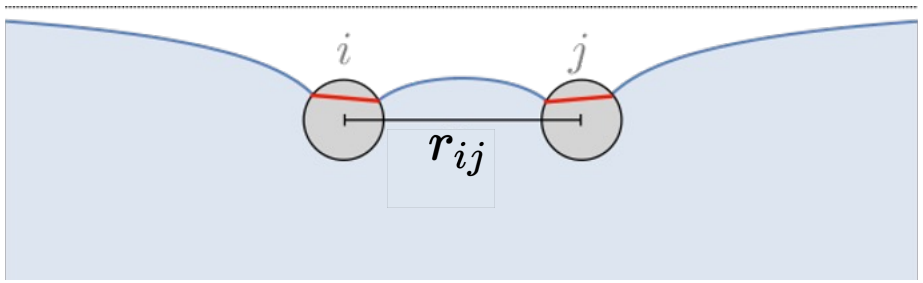
Two beads

- Superposition principle does not hold when $r_{ij} < 2D$



$r_{ij} > 2D$

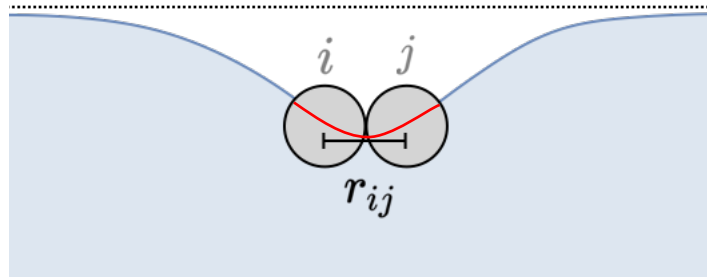
- Two capillary monopoles Q_i, Q_j



$r_{ij} < 2D$

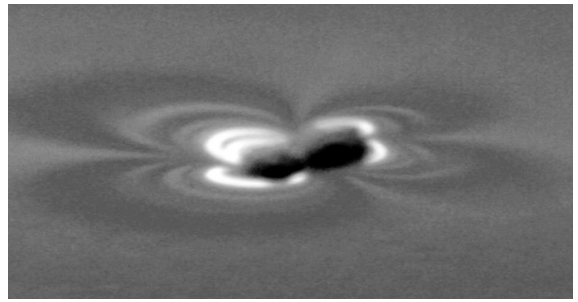
- Tilted contact lines if pinned
- Extra attraction is observed

Does not happen if contact angle is fixed !



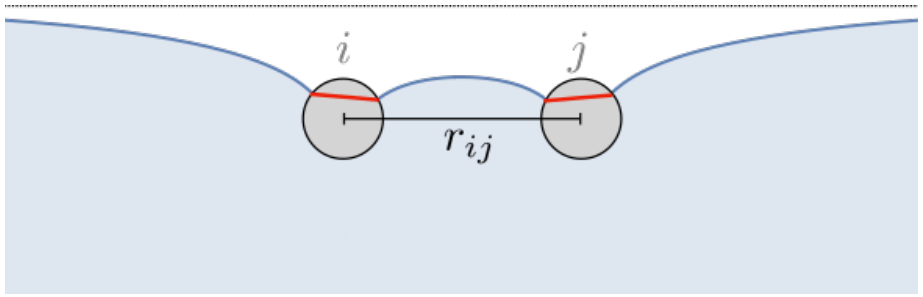
$r_{ij} = D$

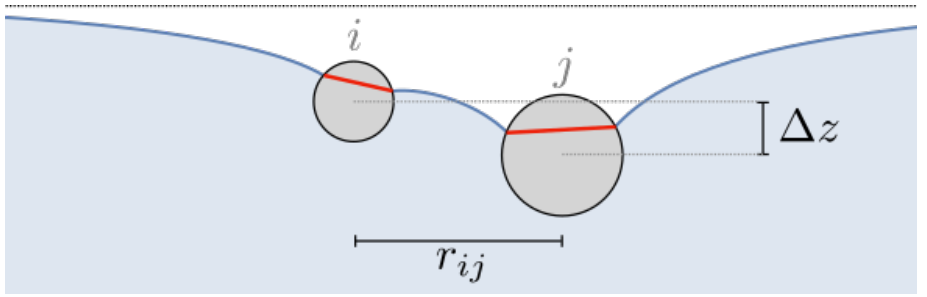
- Undulation of the contact line: One capillary quadrupole



Inclined contact lines

- The attraction is enhanced for asymmetric situation due to the height difference Δz





- Numerical simulations with identical objects predicted 30% of extra attraction for close spherical beads. H. Cooray, P. Cicuta, and D. Vella, Langmuir, 2017.

Our Goals

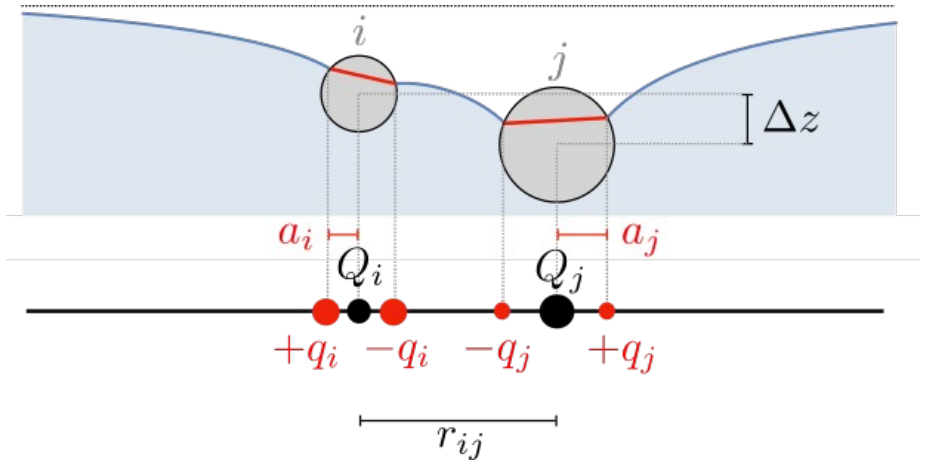
→ A simple analytical model that follows the same electrostatics analogy

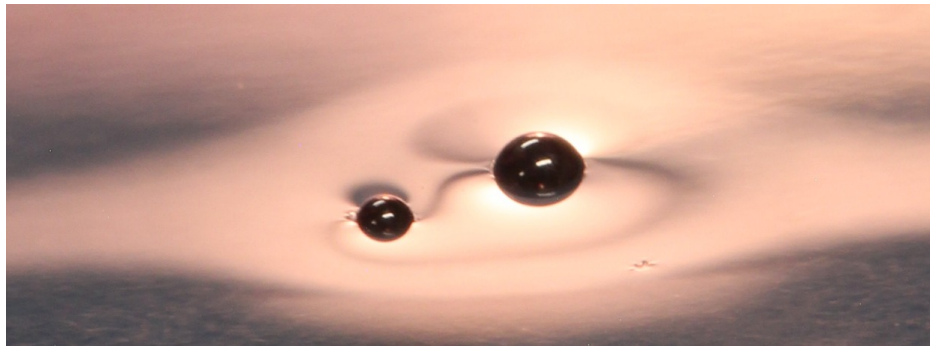
→ Experimental measurements of the capillary force as a function of spacing

→ Observe the effect of inclined contact lines on large self-assemblies

Induced capillary dipoles

Induced capillary dipoles are used to consider the tilt of the contact lines: $q_i = a_i \dfrac{\partial z}{\partial r} = \dfrac{a_i Q_j}{\lambda} K_1\left(\dfrac{r_{ij}}{\lambda}\right)$





$$U_{c^+} = U_{QQ} + U_{Qd} + U_{dd}$$

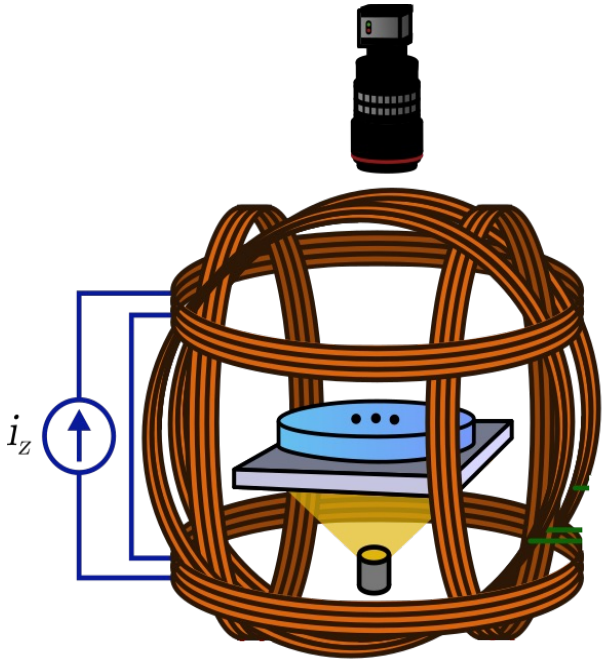
$$U_{c^+} \approx -2\pi\gamma Q_i Q_j \left[K_0(x_{ij}) + 2\left(\frac{Q_i^2 a_j^2 + Q_j^2 a_i^2}{\lambda^2 Q_i Q_j} \right) K_1^2(x_{ij}) \right]$$

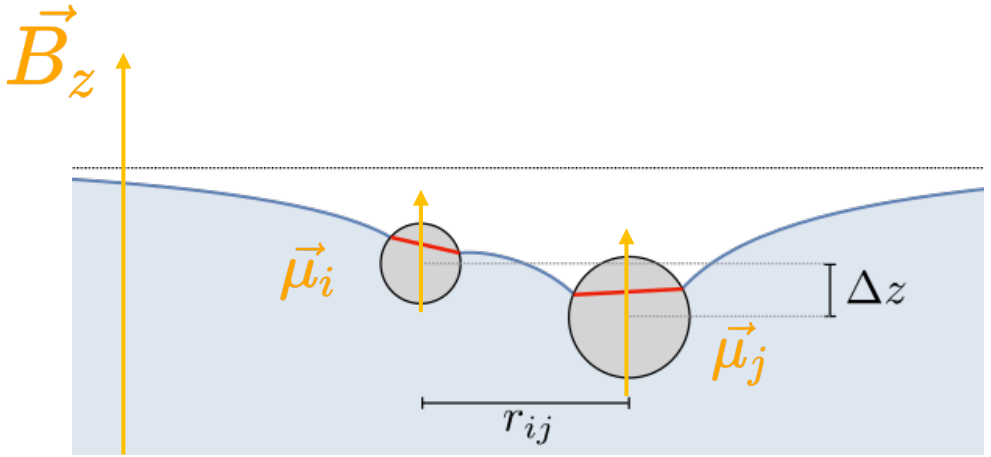
Experimental Setup

- Capillary attraction VS Magnetic repulsion
- Soft ferromagnetic beads under vertical magnetic field : $\mu \propto B_z$

→Equilibrium distances are tunable!

- Particles sizes are 400, 500 and 800 µm

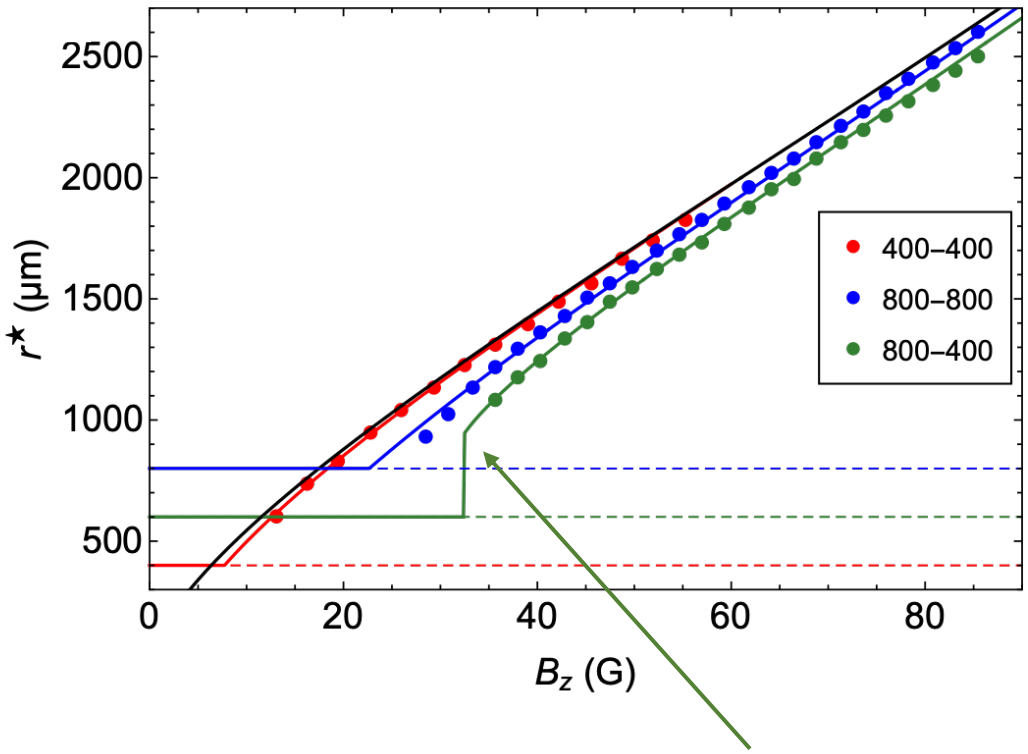


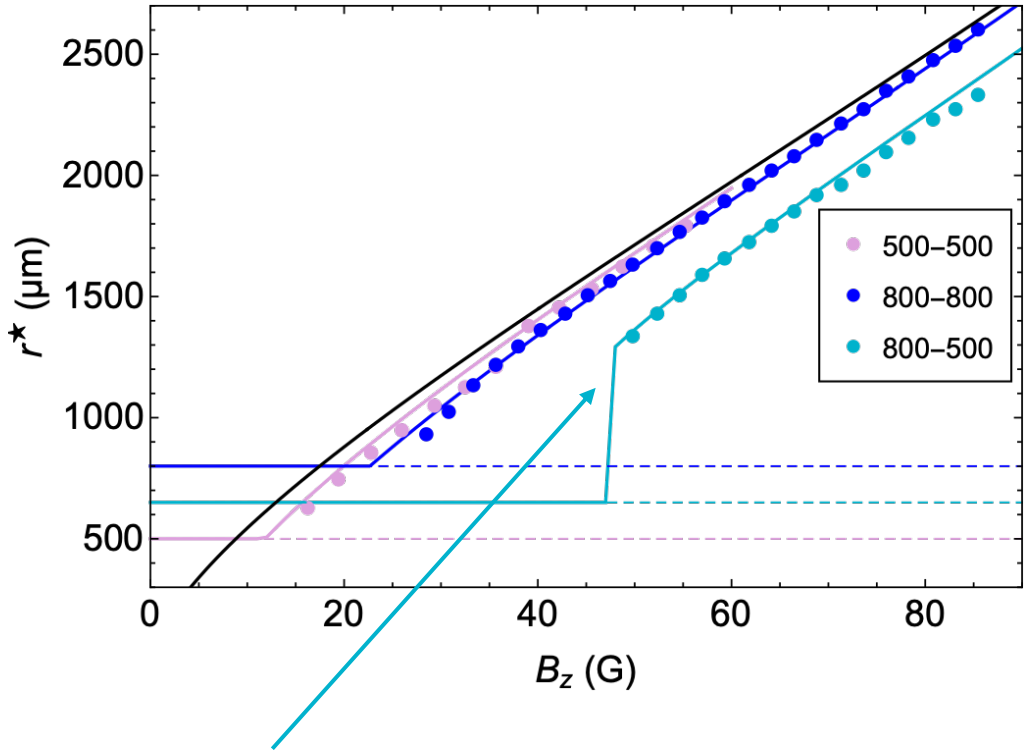


$$u_{\mathrm{Mc}^+} = -\left[K_0(x_{ij}) + 2\left(\frac{Q_i^2 a_j^2 + Q_j^2 a_i^2}{\lambda^2 Q_i Q_j}\right) K_1^2(x_{ij})\right] + \frac{\kappa B_z^2}{x_{ij}^3}\left[1 - 3\left(\frac{\Delta z}{\lambda x_{ij}}\right)^2\right]$$

Experimental data and model verification

Equilibrium distance r^* between 2 beads as function of B_z for 6 pairs of particles.



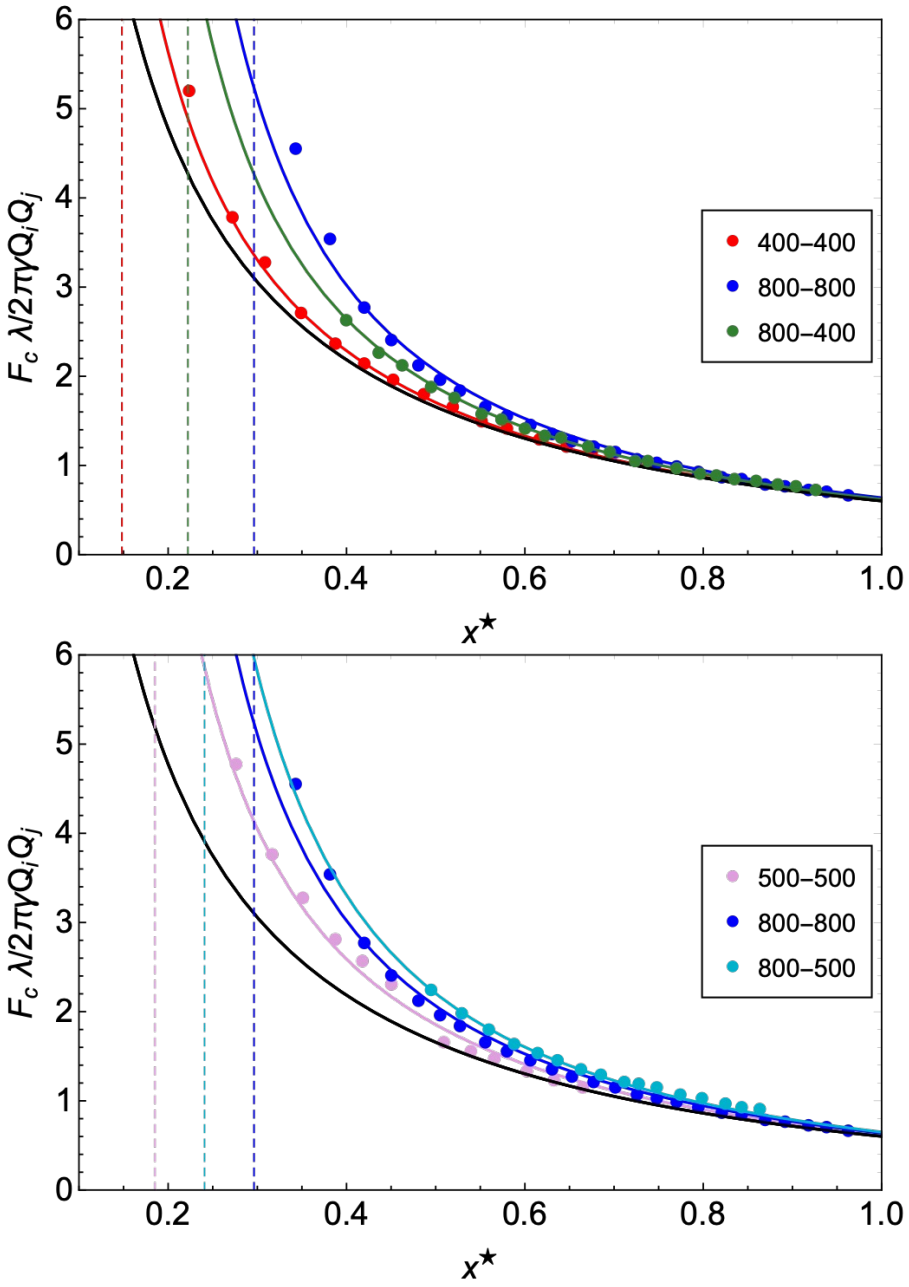


The values of B_z at which asymmetric assemblies collapse are predicted !

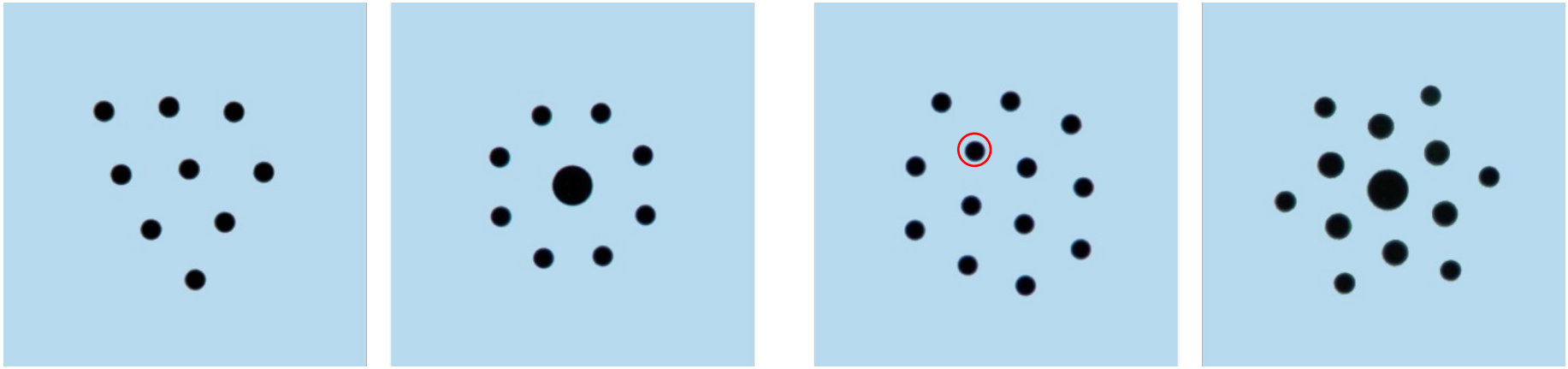
Extra capillary attraction

$$\vec{F}_{magnetic} = \vec{F}_{capillary}$$

- The magnetic force is easily found
- Direct access to the capillary force without additional experimental setup
- Up to **30%** increase for F_c for identical beads
- Up to **40%** increase for F_c between different beads due to the non-linear dipole-monopole term in u_{mc}^{+}



Effect on large assemblies



N = 9 N = 13

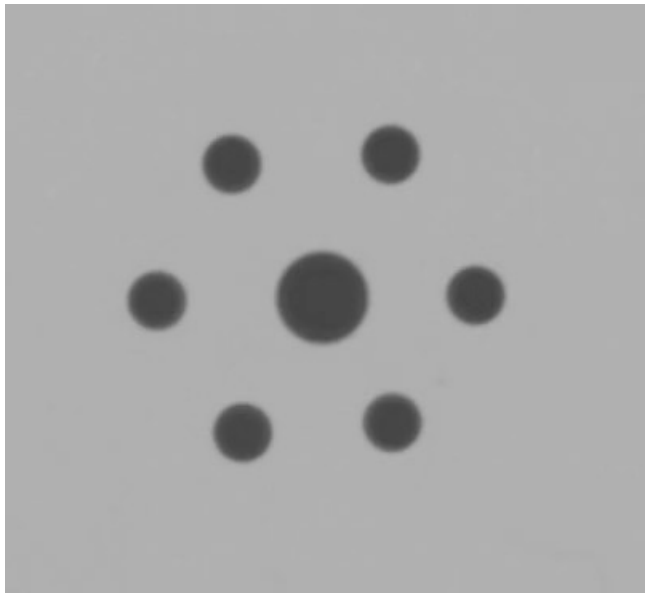
- Influence on the shape, symmetry and pattern of the structure

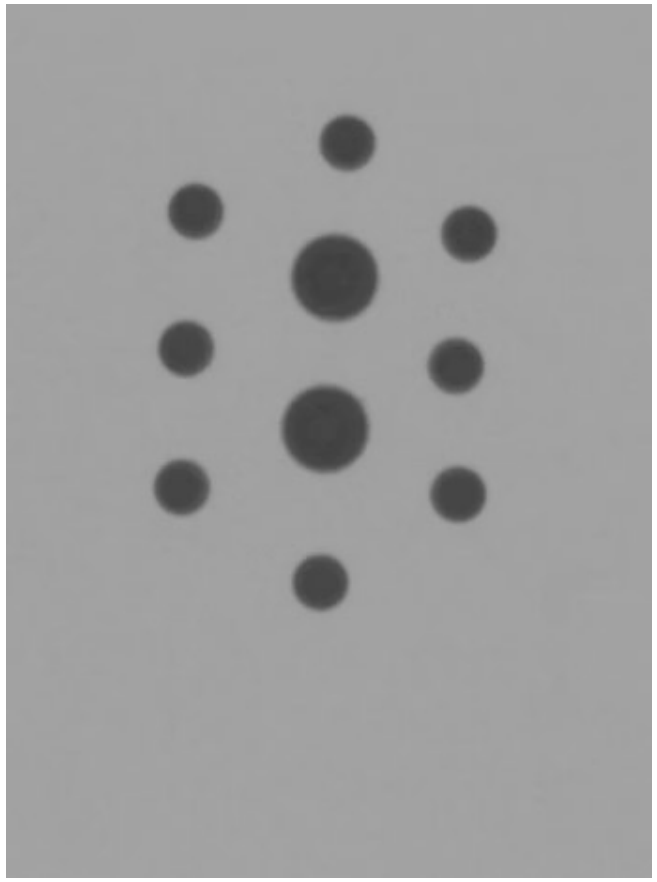
- By adding different bead sizes, you can symmetrize or not an assembly!

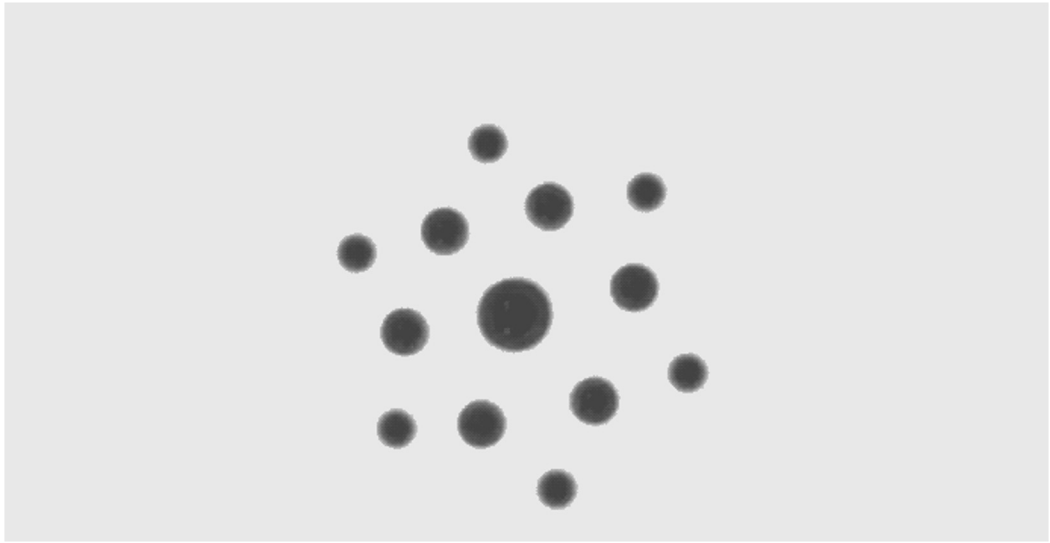
→ More functionalized structures

Effect on motion

- Symmetry and height difference Δz are essential to swim







Conclusion

- Induced capillary dipoles are used to model the tilt of the contact line
- Simple analytical model
- The measured increase of the capillary force between identical beads is consistent with numerical simulations
- Correction of defects by adding different bead sizes leads to motion under dynamical horizontal magnetic fields

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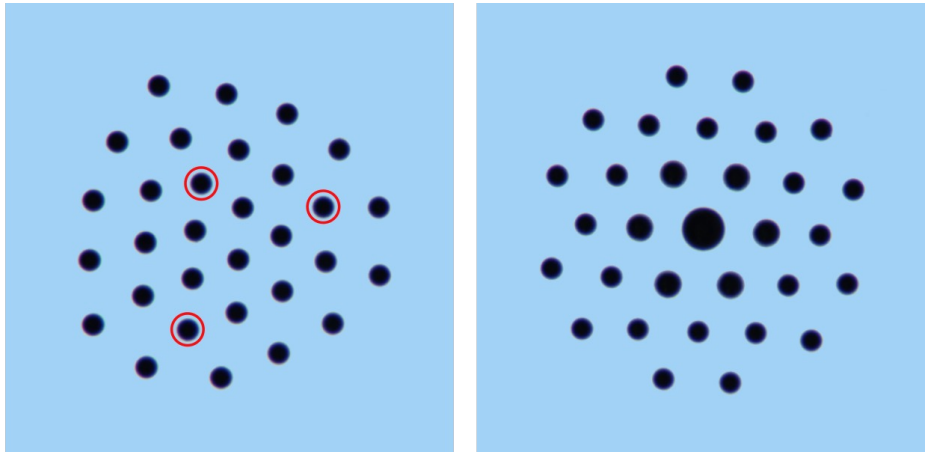

Thank you!