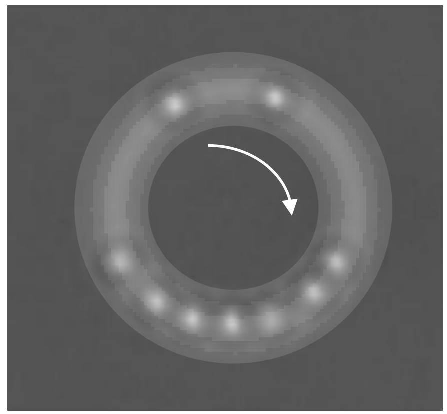
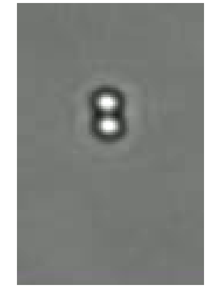
Non-equilibrium pair attraction between driven colloidal particles



Yulia sokolov, Derek Frydel,
Haim Diamant and Yael Roichman

Optical trapping



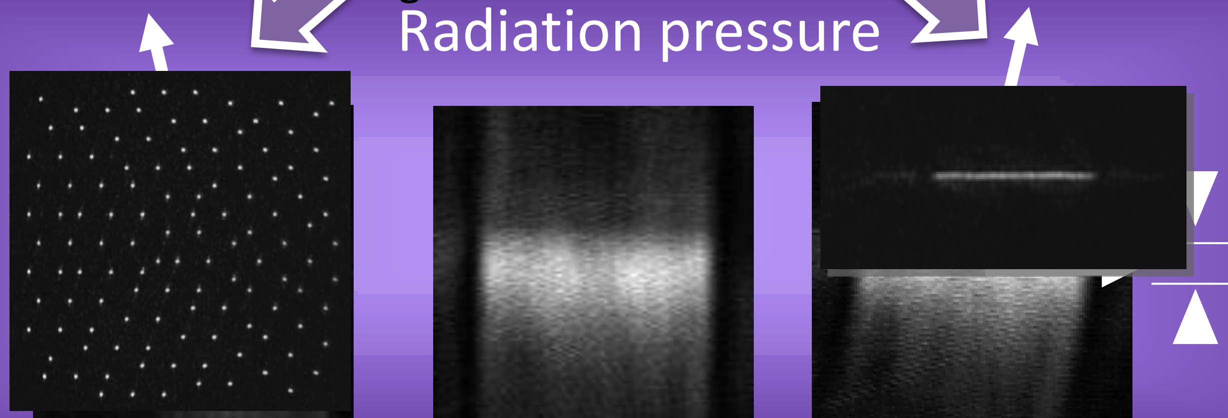
$$F = \alpha \nabla \vec{I} + \beta I \nabla \vec{\phi}$$

Dipole in electromagnetic field

Radiation pressure

Radiation pressure

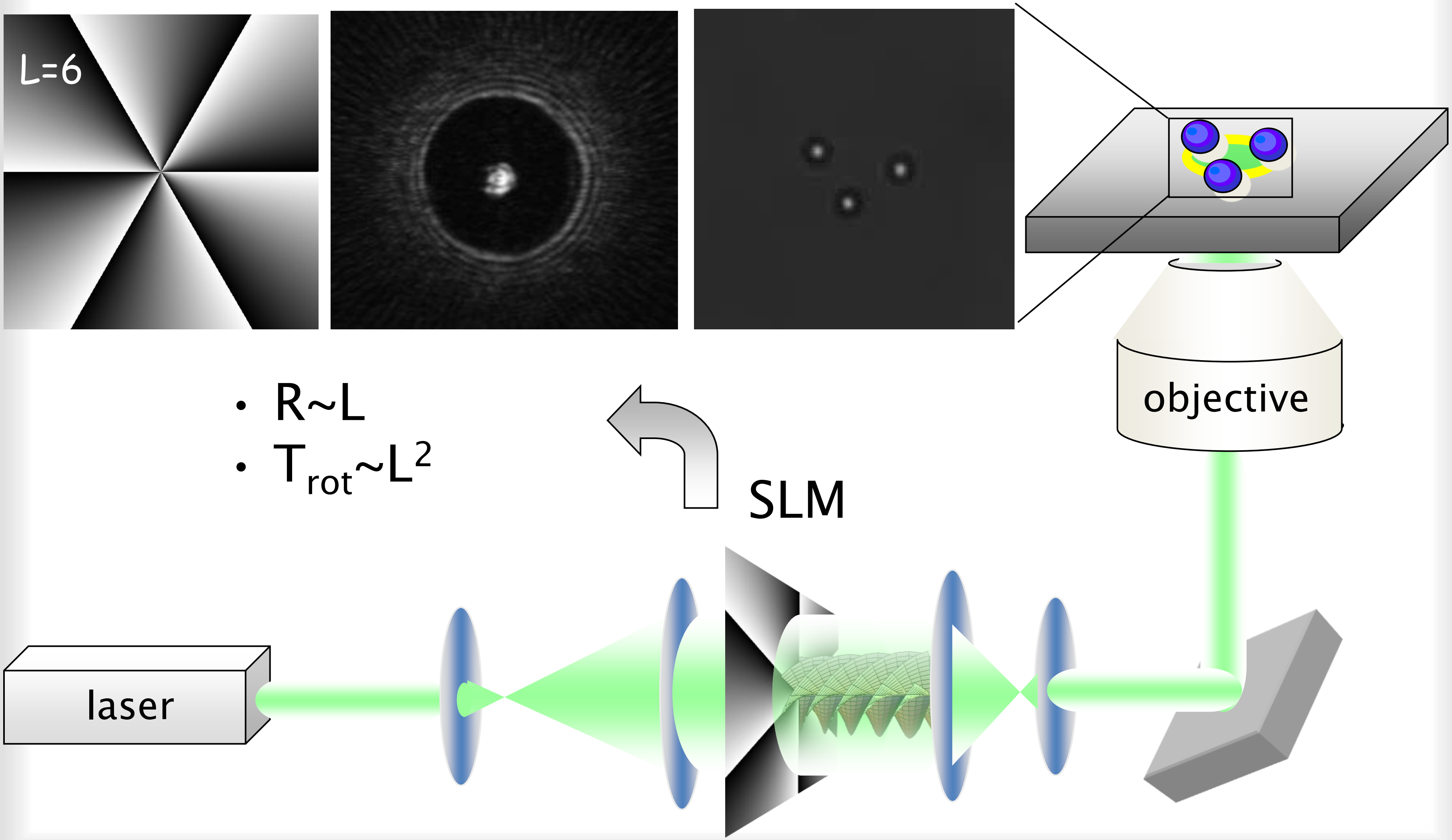
Phase gradient



Gradient force

Holographic optical tweezers

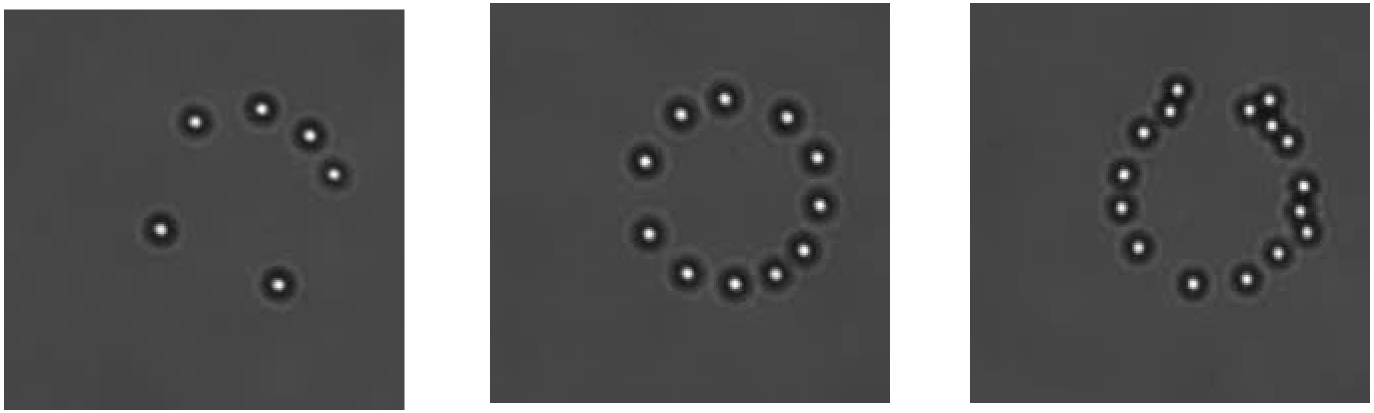
Static traps



- $R \sim L$
- $T_{rot} \sim L^2$

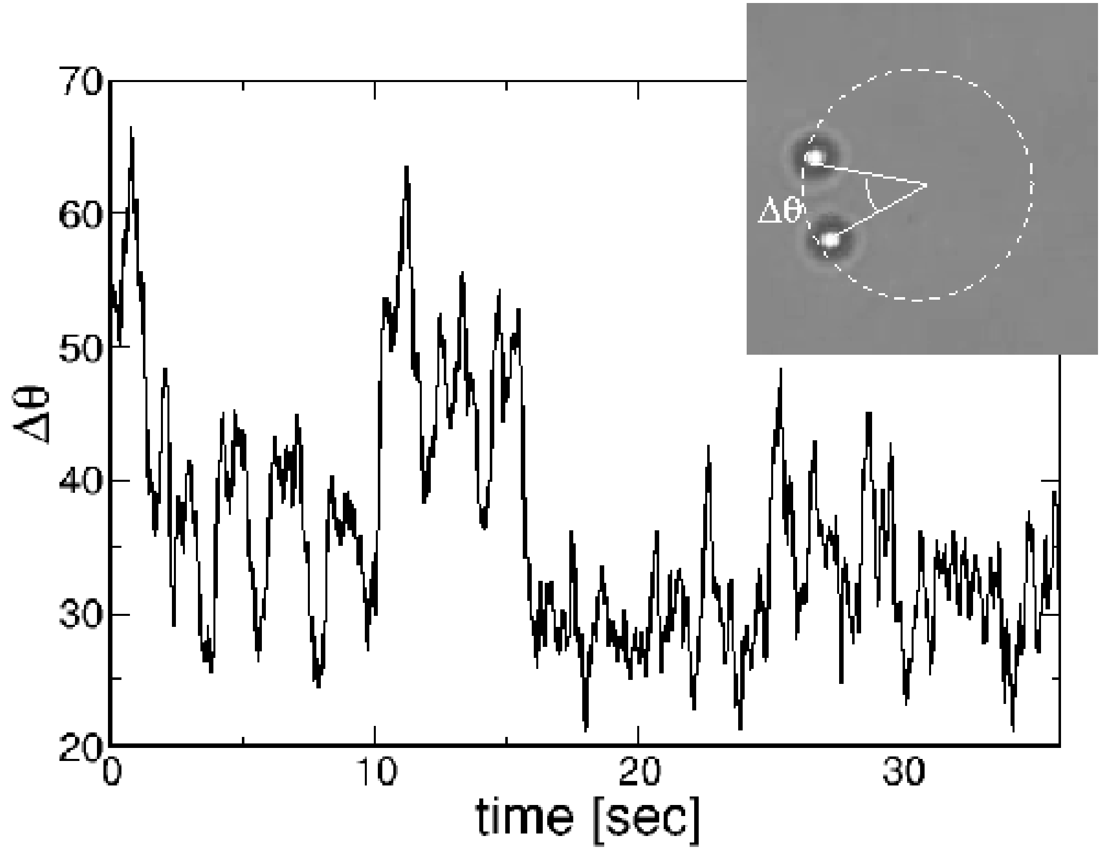
Many particles in an optical vortex

Driven dissipative model system - experiments

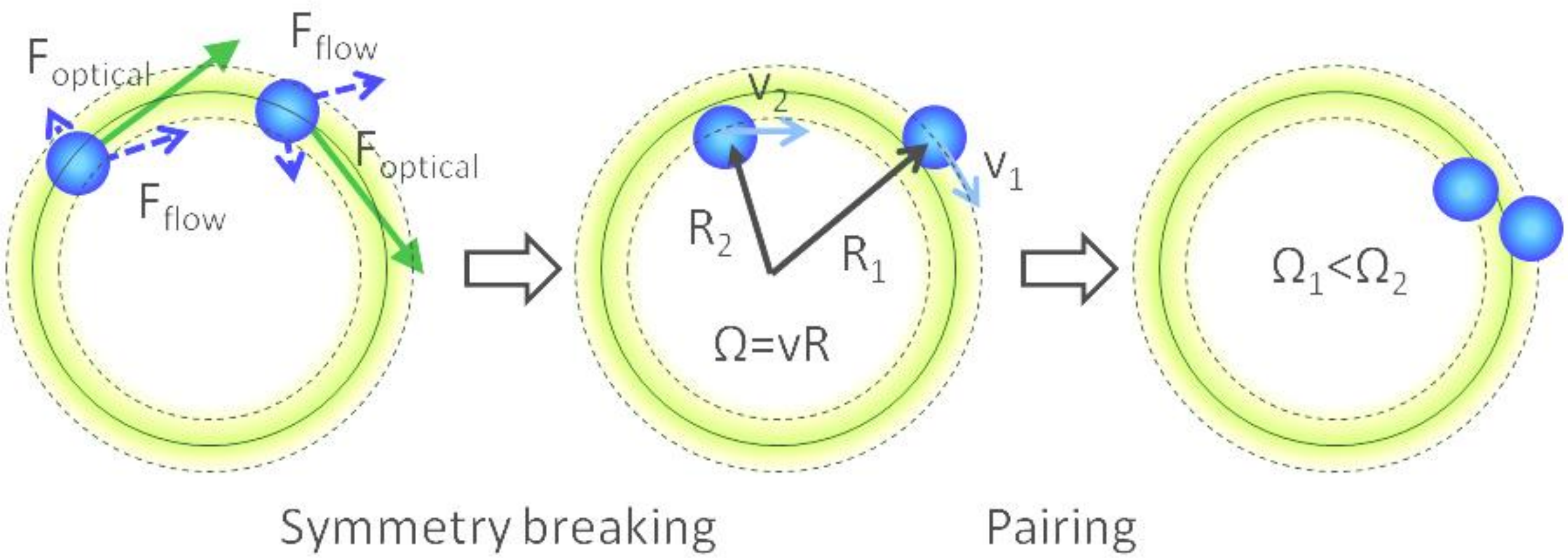


Non-equilibrium, hydrodynamic interaction
phonons, single file diffusion

Two particles - experiments



Two particles - calculation

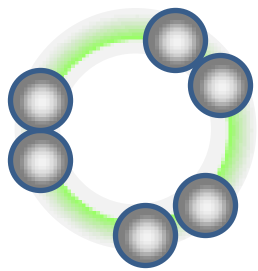


$$\frac{\gamma\Omega_i}{K_\theta} = 1 + \frac{3a}{16\sqrt{2}}\frac{1}{R}\left[\frac{1+3\cos\theta_{ij}}{\sqrt{1-\cos\theta_{ij}}}\right] \qquad \frac{\gamma V_{\rho,i}}{K_\theta} = \frac{3a}{16\sqrt{2}}\left[\frac{3\sin\theta_{ij}}{\sqrt{1-\cos\theta_{ij}}}\right]$$

Collective mobility

calculation

<u>The model:</u>



- Paired particles with “pair” mobility.
- Equidistanced.
- Collective mode.
- Stokeslet approximation.

$$G_{ij} = \frac{1}{8\pi\eta r}\left(\delta_{ij} + \frac{\overline{r_1}\,\overline{r_2}}{r^2}\right)$$

$$collective \quad mobility = \begin{cases} even \quad N/2 & \dfrac{1}{Q\pi\eta r}\left[1 + \dfrac{Qr}{8\sqrt{2}R}\left(-\dfrac{1}{\sqrt{2}} + \displaystyle\sum_{n=1}^{(N-4)/4} K(nx)\right)\right] \\ odd \quad N/2 & \dfrac{1}{Q\pi\eta r}\left[1 + \dfrac{Qr}{8\sqrt{2}R}\left(\displaystyle\sum_{n=1}^{(N-2)/4} K(nx)\right)\right] \end{cases}$$

$$K(nx) = \frac{1 + 3\cos(nx)}{\sqrt{1 - \cos(nx)}}$$

$$x = \frac{4\pi}{N}$$

Collective mobility

model vs. experiment

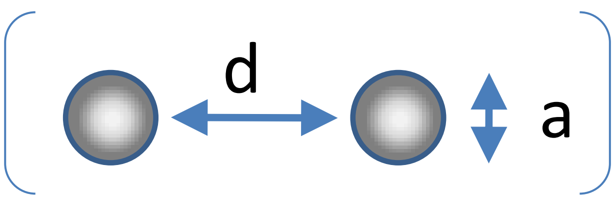
Fitting parameter $\equiv Q$

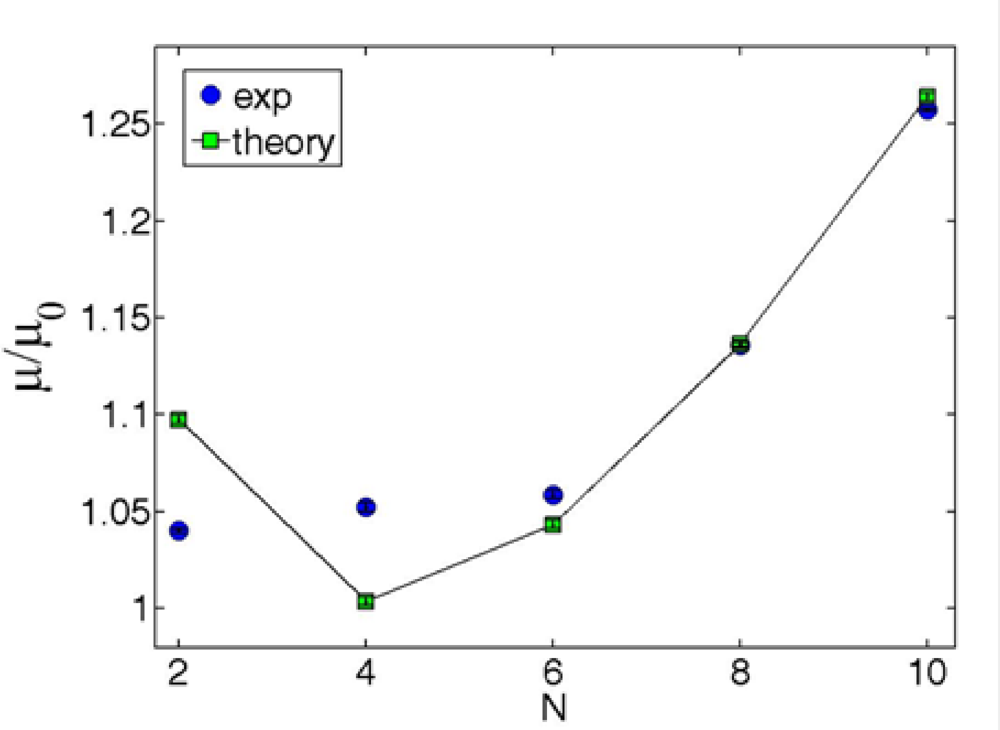
Drag of a single sphere in fluid

$$\gamma = 6\pi\eta r$$

Drag of coupled spheres in fluid

$$\gamma = Q\pi\eta r$$





Simulation

<u>Stokesian dynamics:</u>

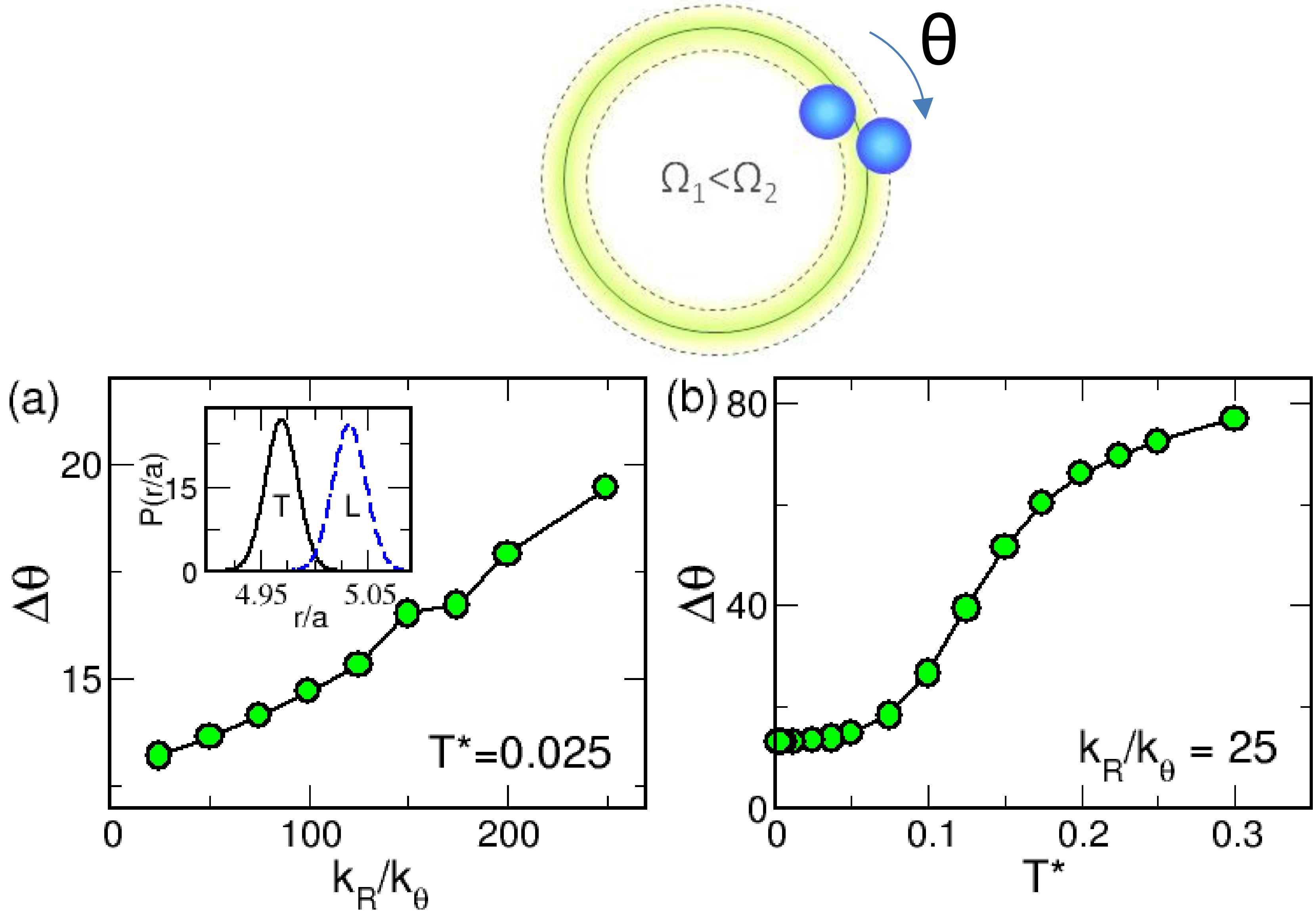
- Many body hydrodynamic interactions (Rotne Prager).
- Suitable for systems out of equilibrium.
- Thermal noise included.

We use it to study temperature effects.

$$m\frac{dv}{dt} = F^{Hydrodynamic} + F^{Brownian} + F^{Particles}$$

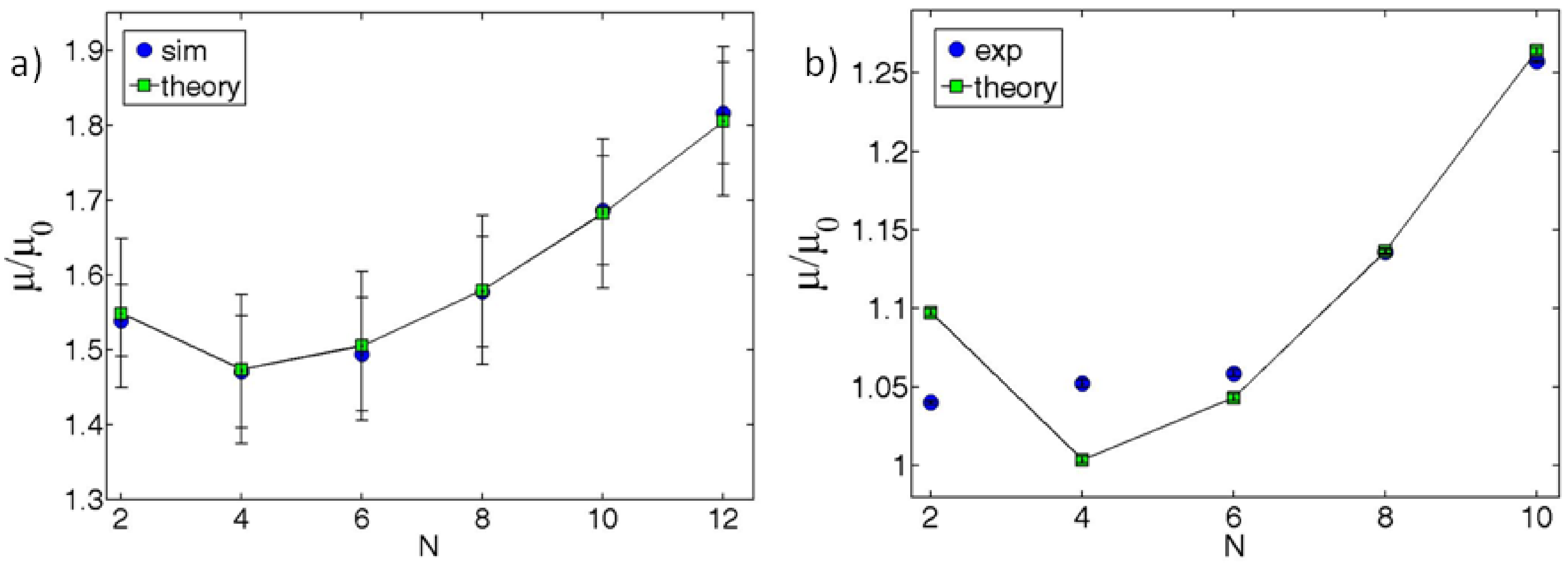
Yulia sokolov, Derek frydel, Haim Diamant and Yael Roichman, in preparation.

Simulations – the origin of pairing



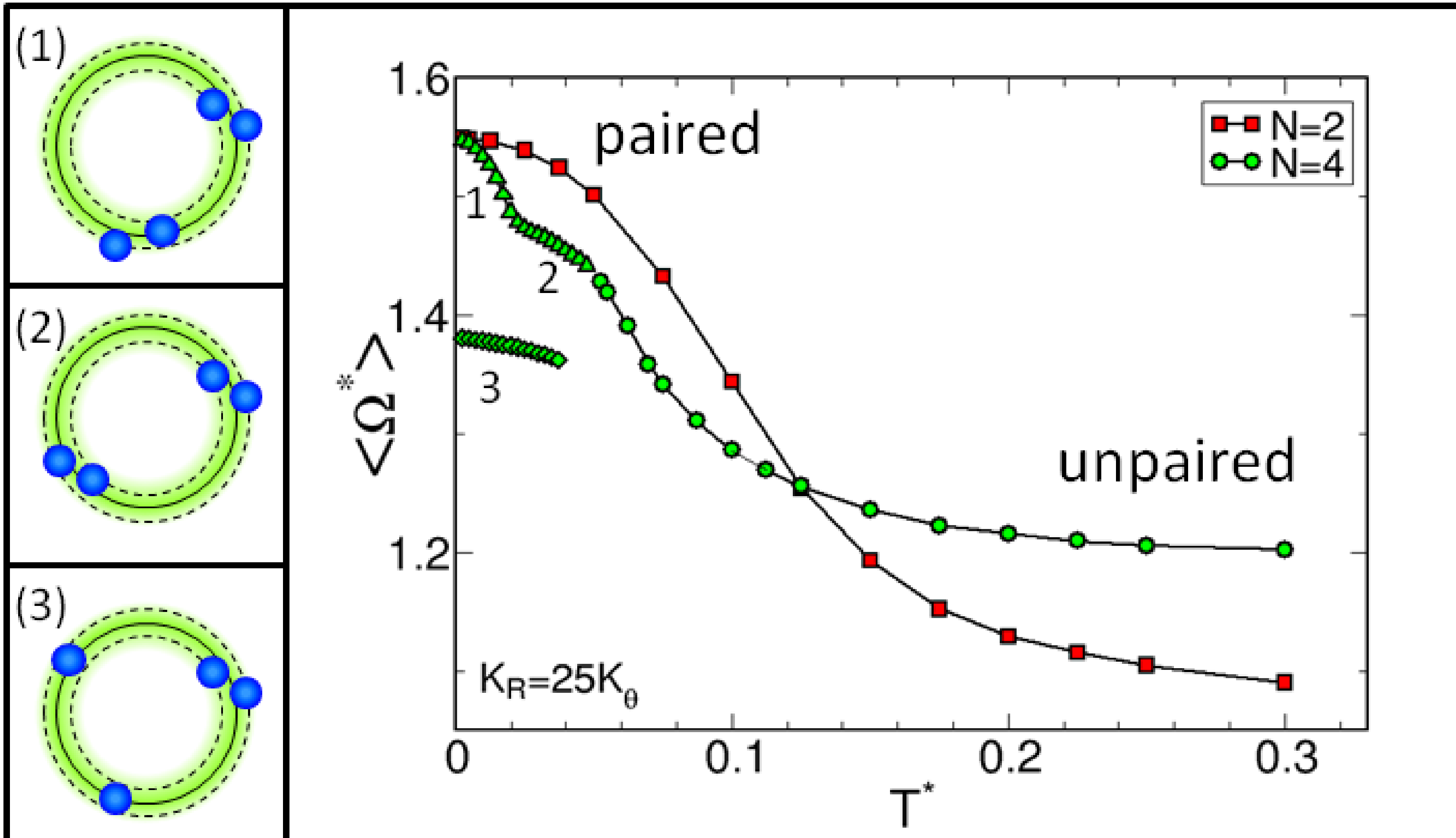
Collective mobility

model, experiment, and simulation



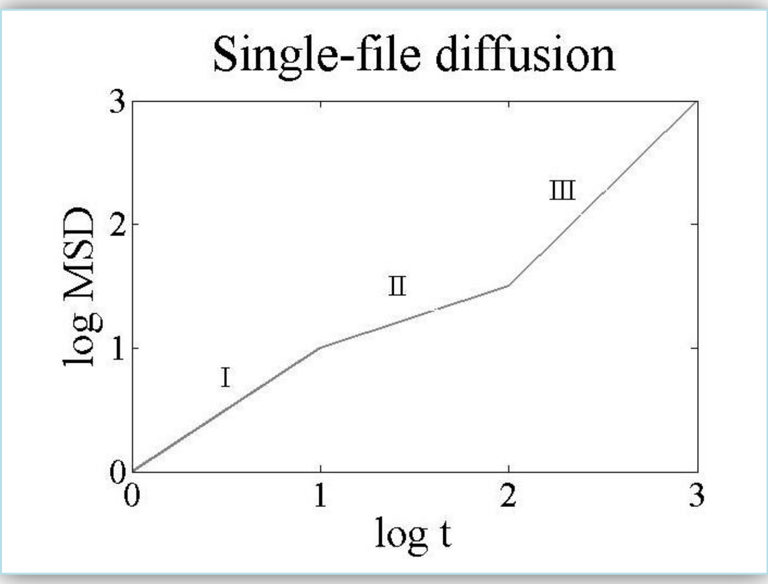
Mean angular velocity

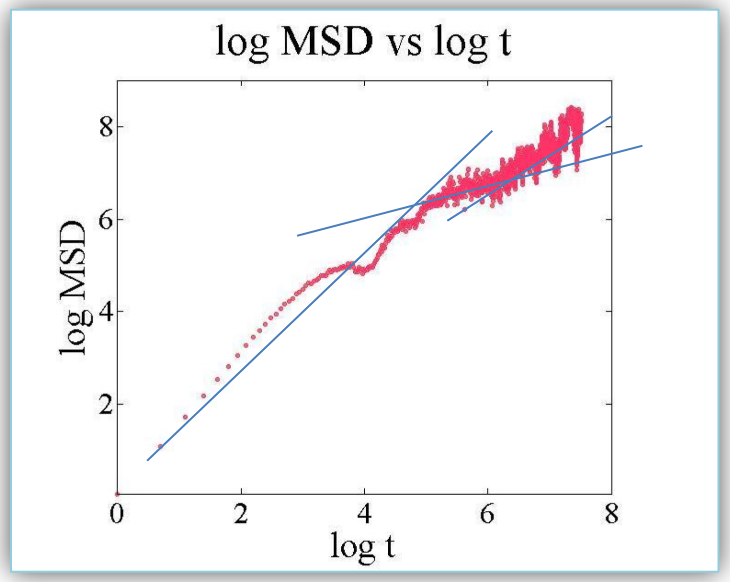
Sensitive macroscopic observable



Single file diffusion

Driven system



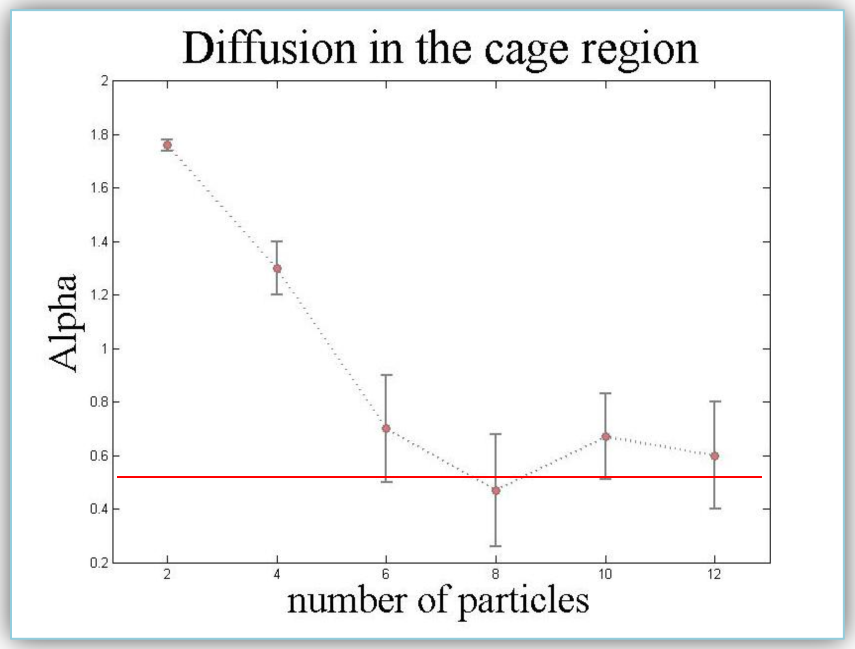


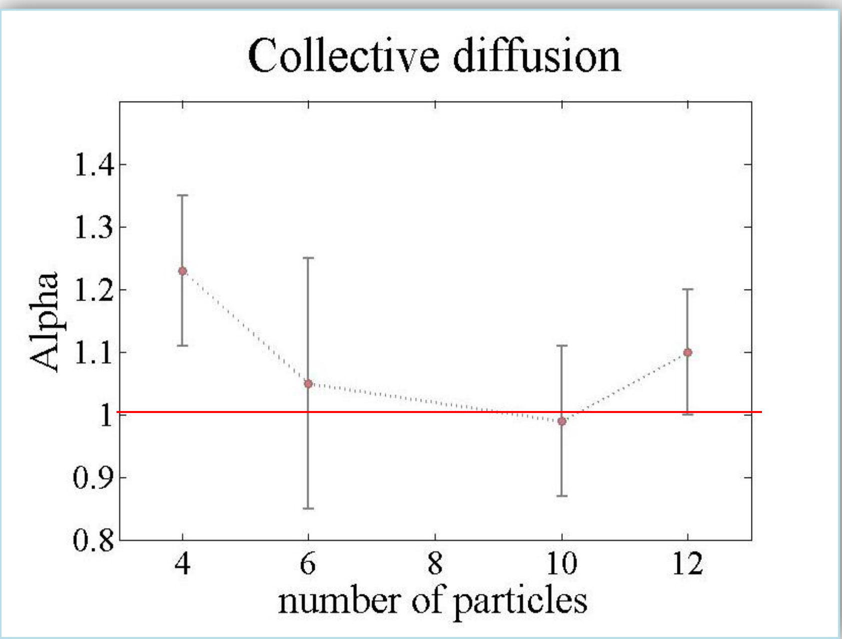
I – one particle diffusion α=1

II - caging effect, subdiffusion 0.5<α<1

III - collective diffusion α=1

Single file diffusion
Driven system





Conclusions

Hydrodynamic Interactions give rise to a pseudo-potential in this out-of-equilibrium system, which result in particle pairing.

For an even number of particles there exists a mode in which particles rotate as a “crystal”. Is the system minimizing dissipation while maximizing stability?

Single file diffusion exists in driven systems. We see the crossover to collective diffusion in this small system.