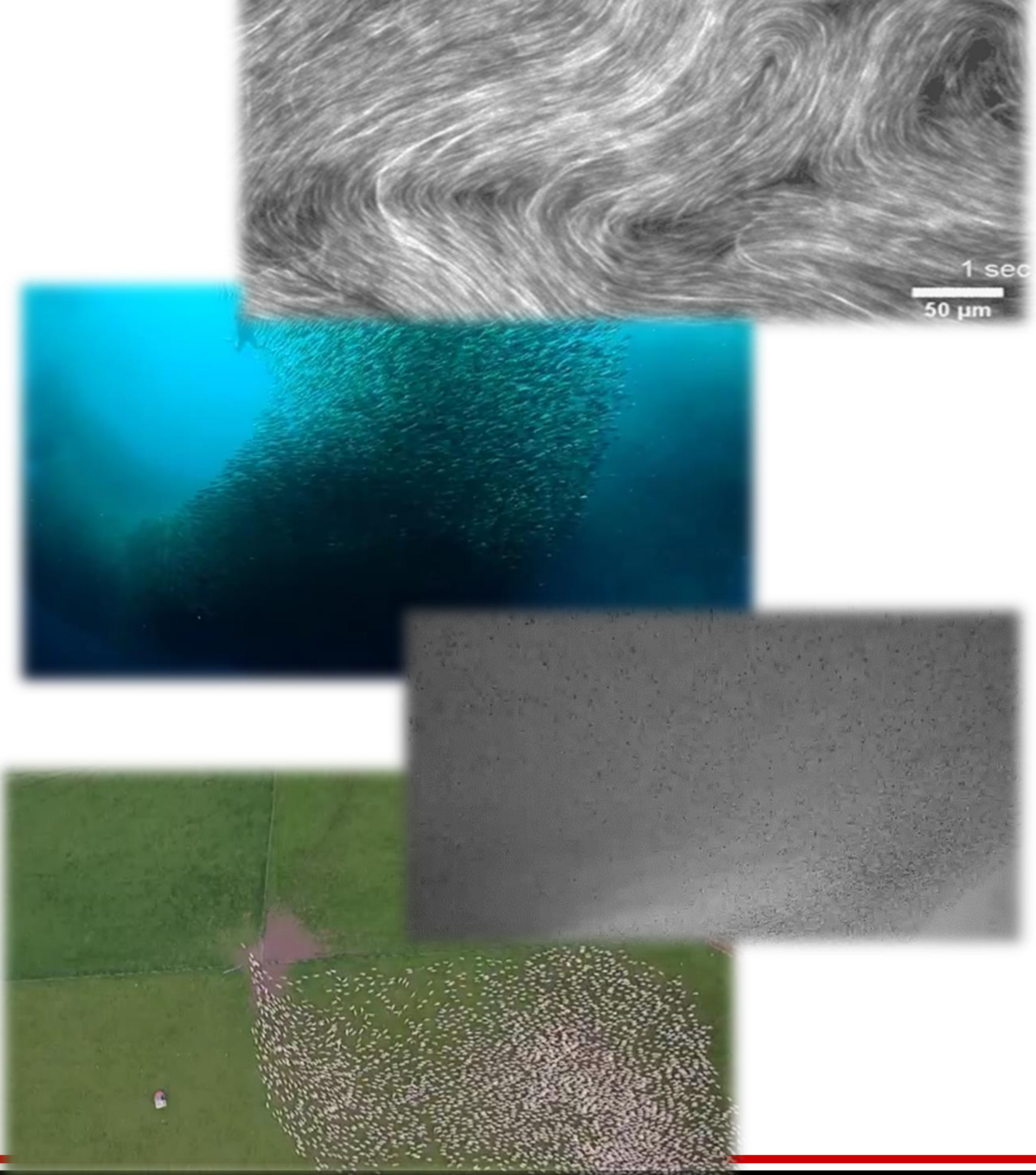


Master's Thesis Presentation

Active Colloids in Shear Flow

Bishwa Ranjan Si

B.Tech M.Tech dual degree student

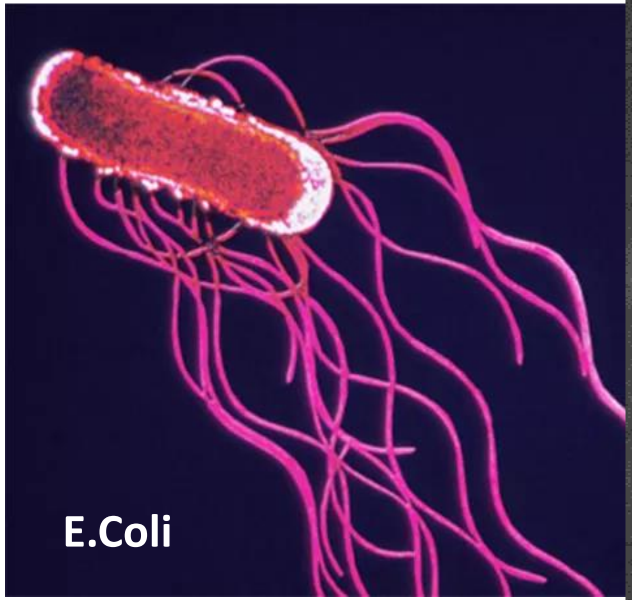
Department of Chemical Engineering
Indian Institute of Technology (IIT) Kanpur

28th June, 2019

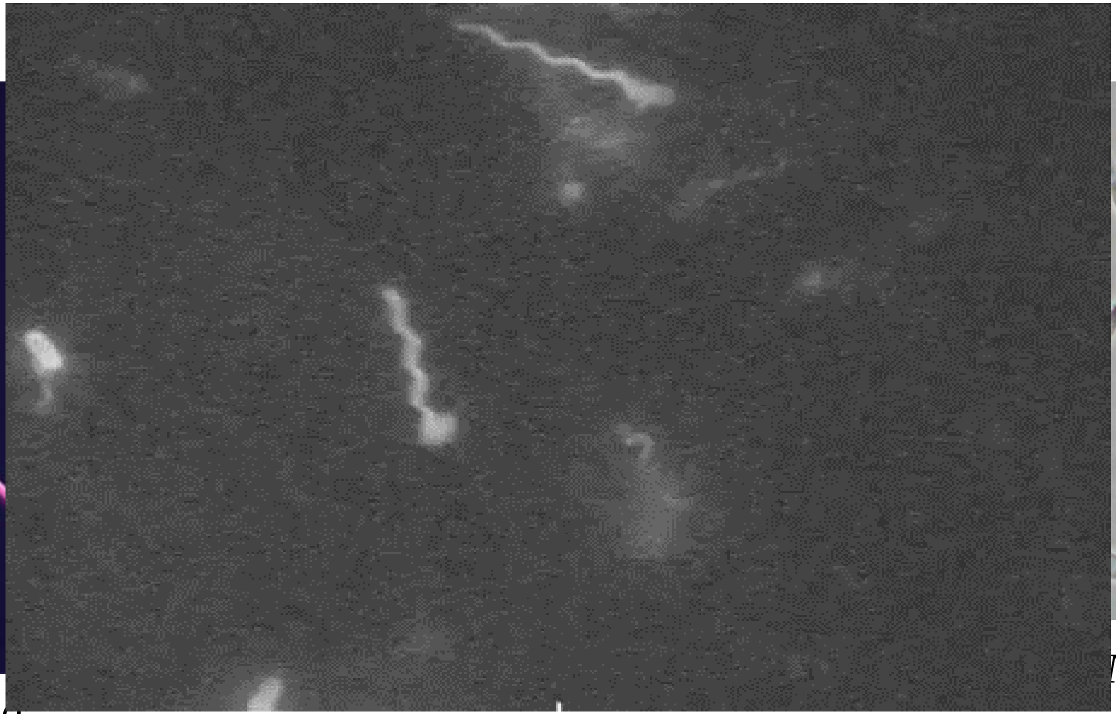
What are Active Particles?

- Colloidal particles (~1 nm – 1000 nm) which can self-propel by using energy from surroundings and perform directed motion at short times.
- Classification : Biological and Artificial

Biological Swimmers



Turner et al. J. Bacteriol, 2000



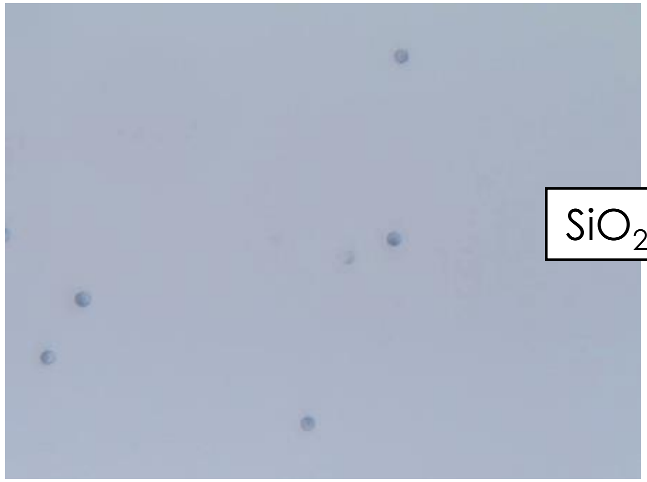
Turner et al. J. Bacteriol, 2000

N. Petkov et al. 2007

Artificial Active Matter

Active colloids

Solid Colloids



SiO_2-Pt Janus particles in H_2O_2

CPPG, IITK (2018)

Au-Pt Microrods in H_2O_2

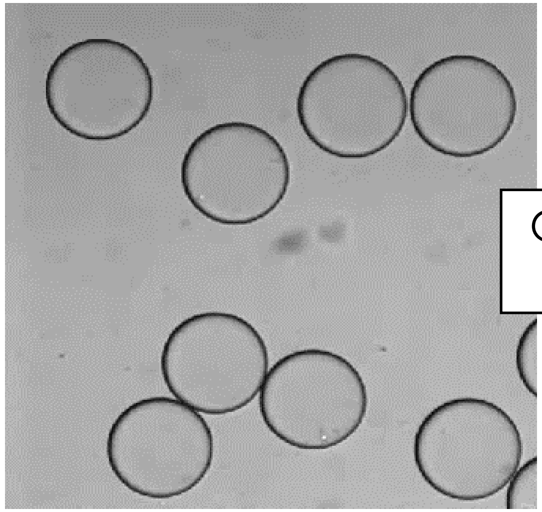
Paxton et al. JACS, (2006)

Active emulsions

Soft Emulsion Droplets

5CB LC droplets in TTAB Solution

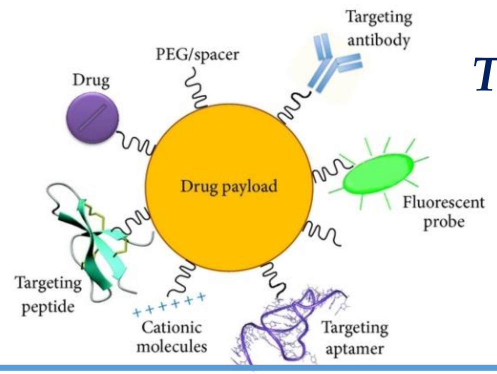
CPPG, IITK (2018)



Oil droplets containing microtubule bundle

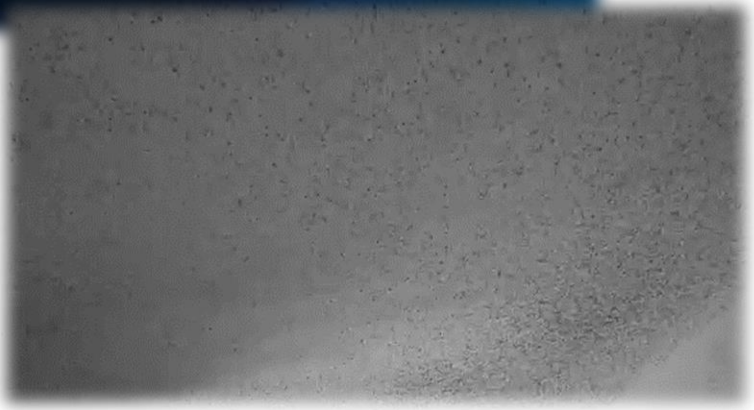
Dogic Lab, UCSB

Artificial Active Colloids : Significance

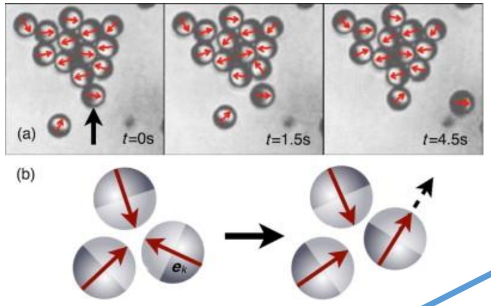


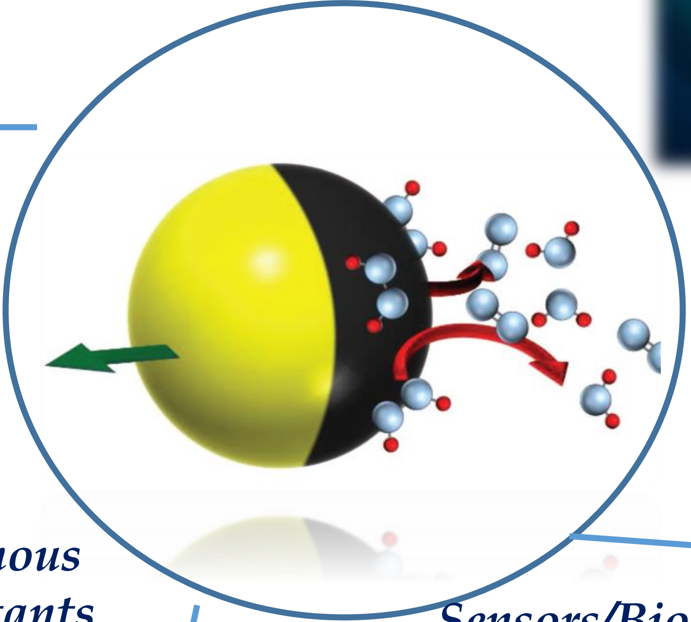
Targeted Drug/Cargo Delivery

Model Systems

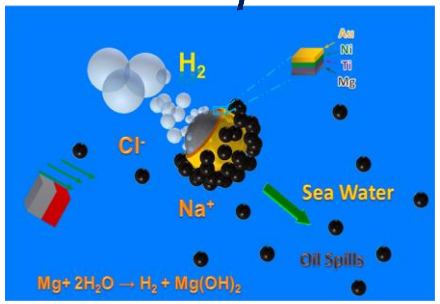


Novel Colloidal Self-assembly

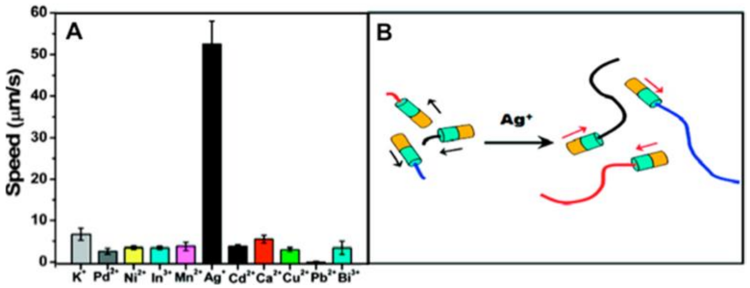




Autonomous De-pollutants



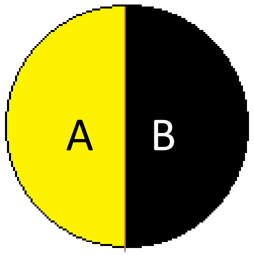
Sensors/Bio-markers



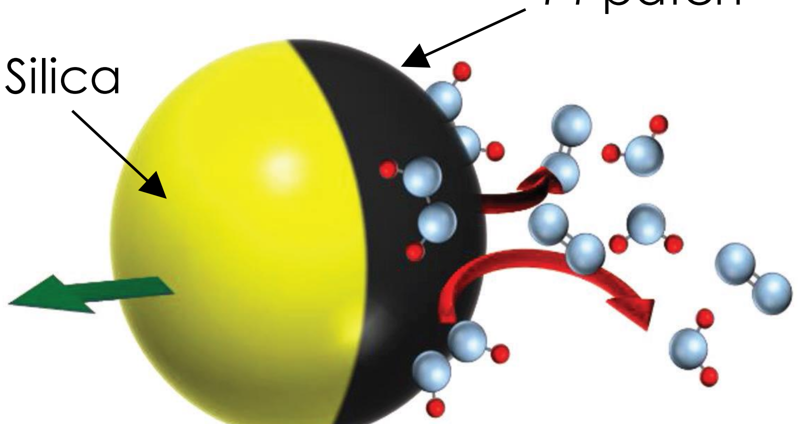
Mechanisms of propulsion

Key requirements:

- A local gradient(chemical /physical)
- Asymmetry in particle composition



Self-Diffusiophoresis



$$H_2O_2 \xrightarrow{Pt} H_2O + \frac{1}{2}O_2$$

Archer et al. Adv. Sc., (2017)

Self-Thermophoresis

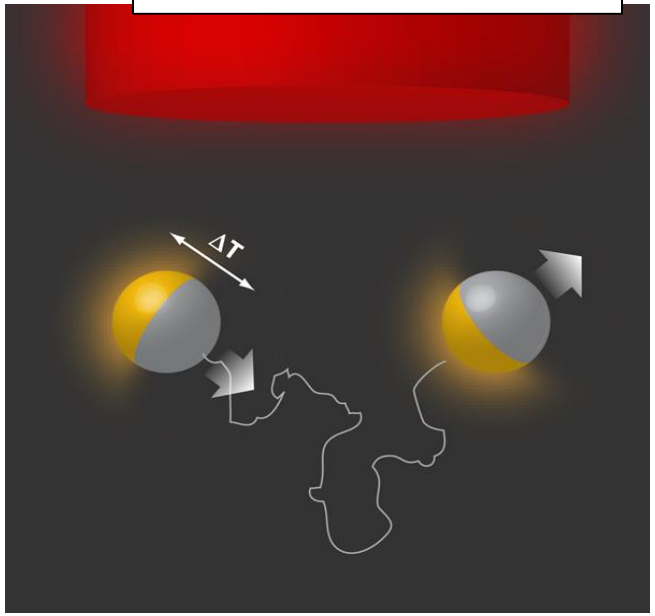
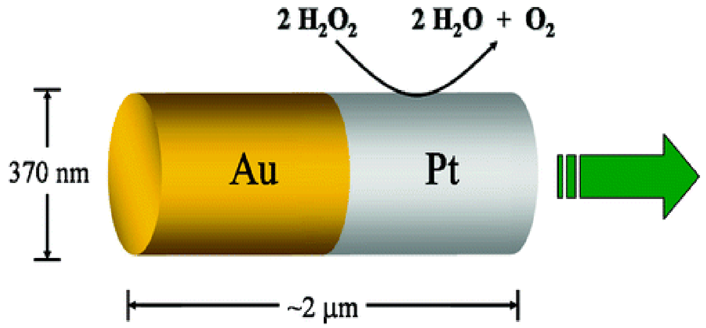


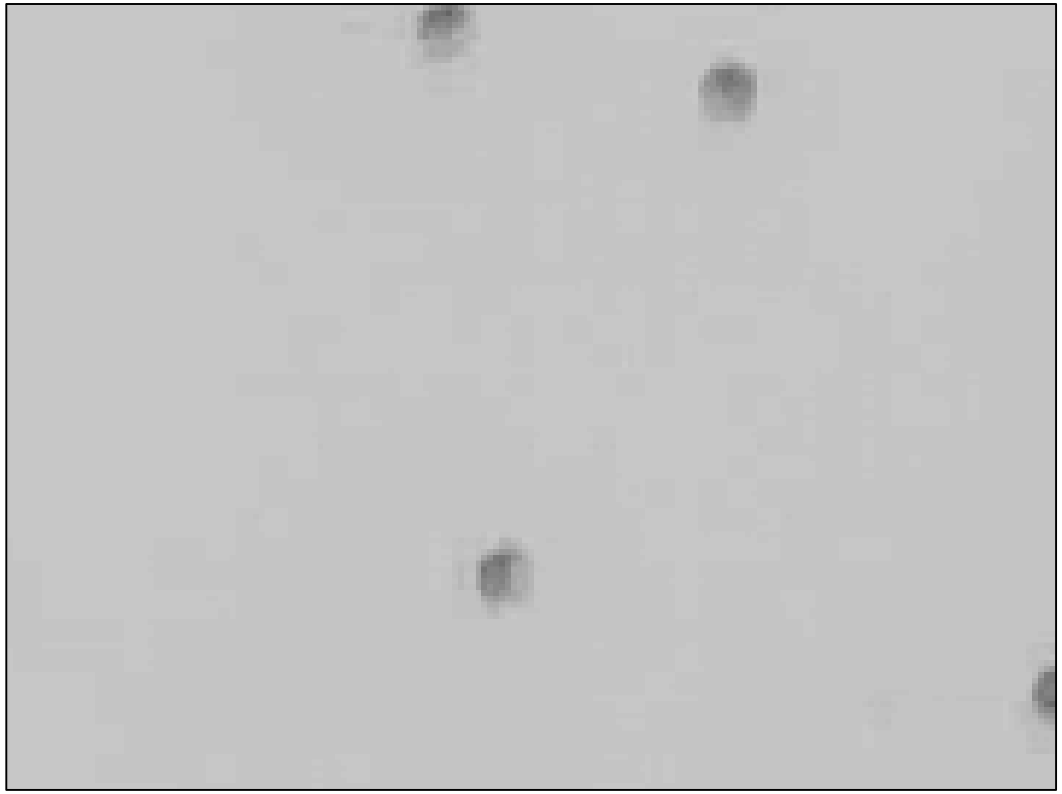
Image from APS Physics

Self-electrophoresis



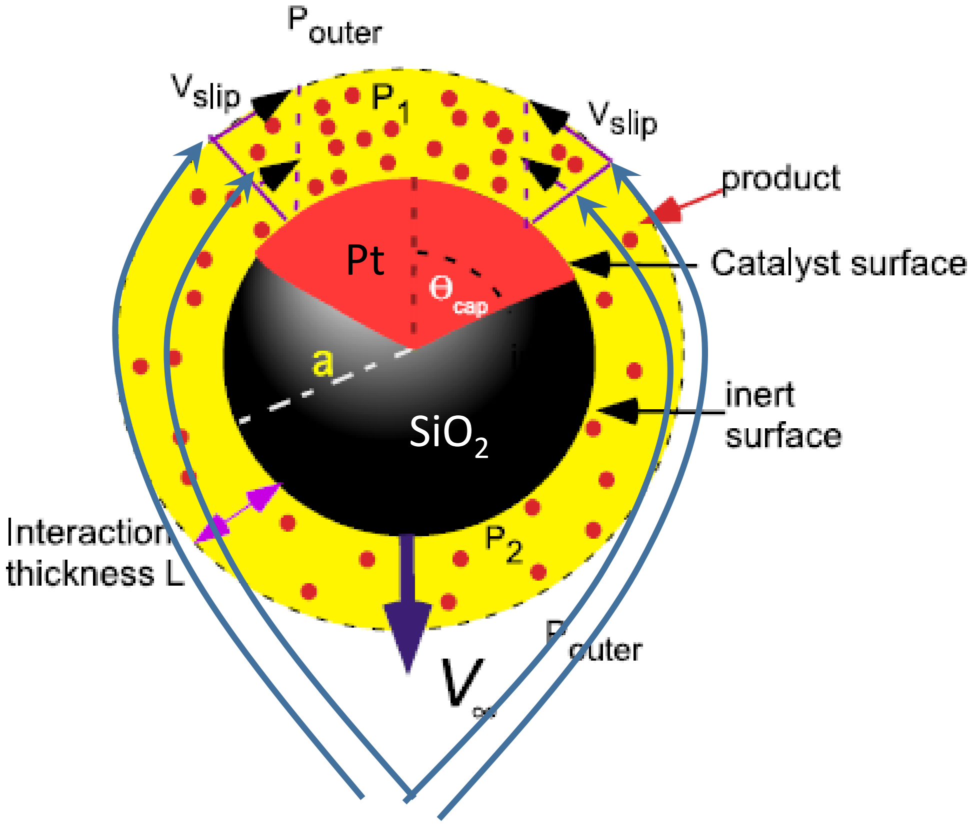
Paxton et al. JACS, (2006)

Self-propelling **Janus particle** (made of silica and Platinum(Pt)) in water + H_2O_2 medium



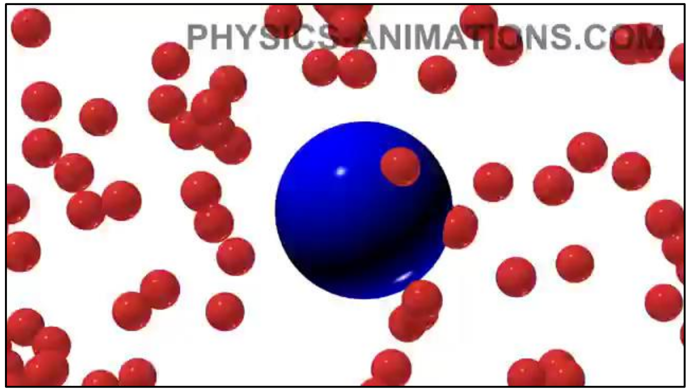
<u>2 wt% H_2O_2 in water</u>

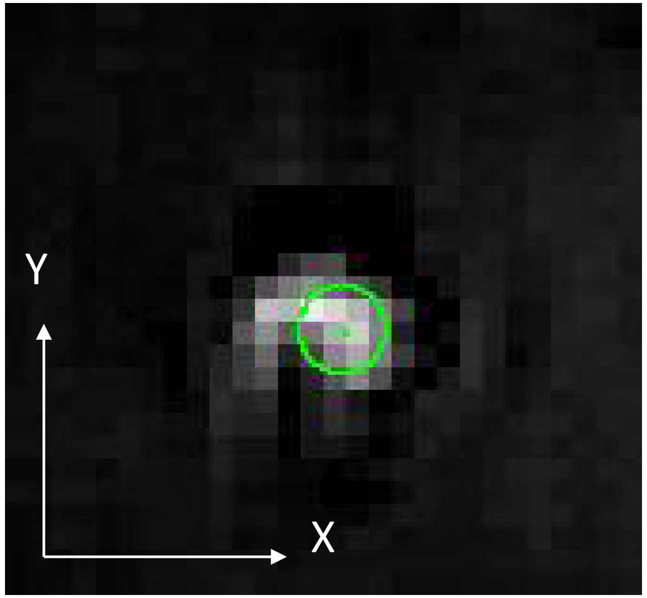
$$H_2O_2 \longrightarrow 2H_2O + O_2$$

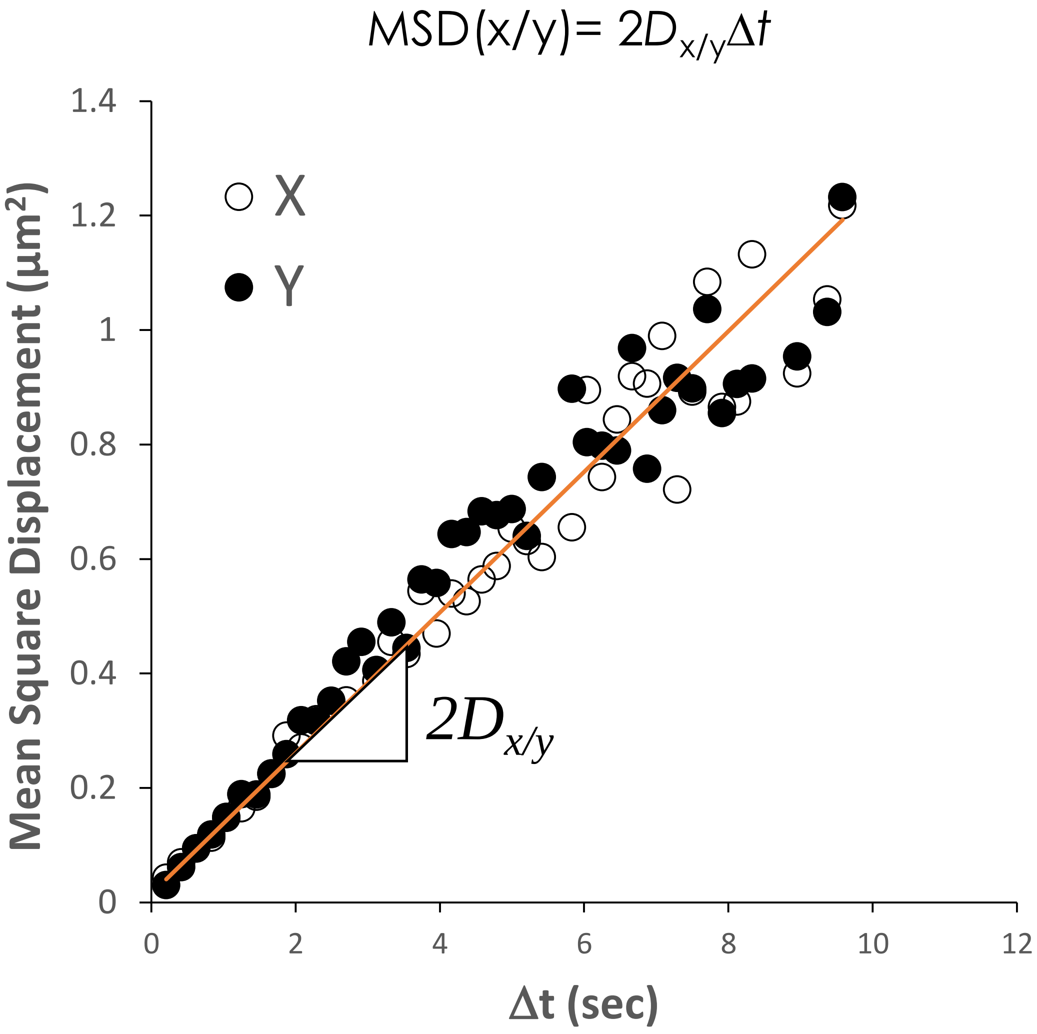


Maldrelli et al. Phy. Of. Fluid.,(2016)

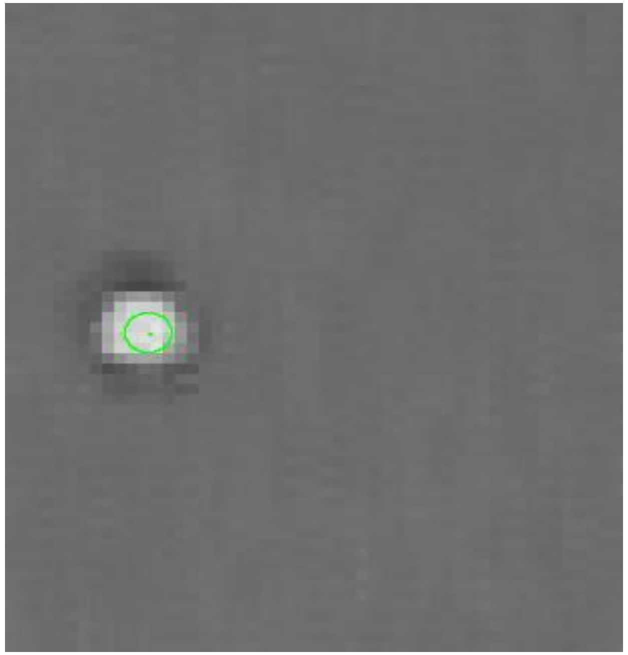
Brownian Motion

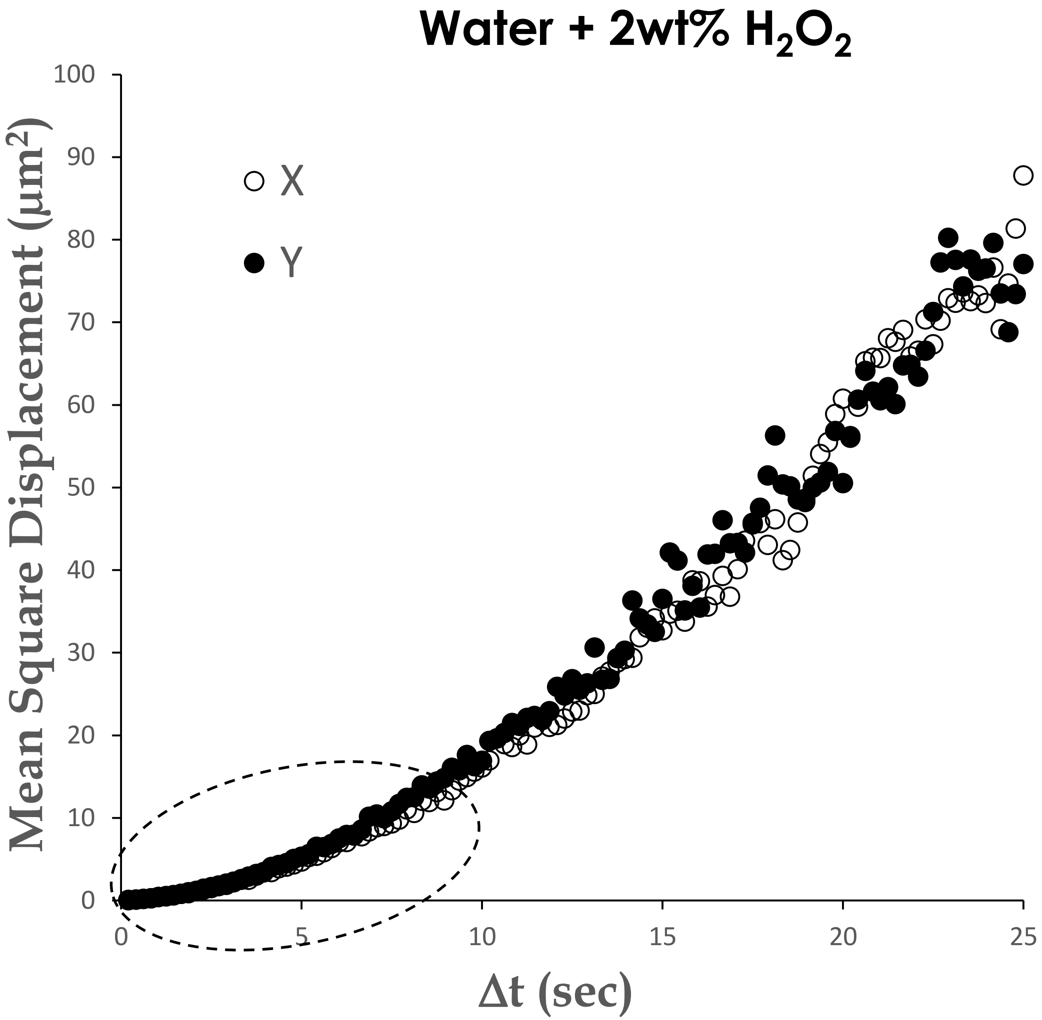






- Colloid undergoes random ***Brownian Motion***
- Slope of MSD vs time elapsed gives ***Brownian Diffusivity 'D'.***
- Stokes Einstein Relation $$D = \frac{kT}{6\pi\eta a}$$





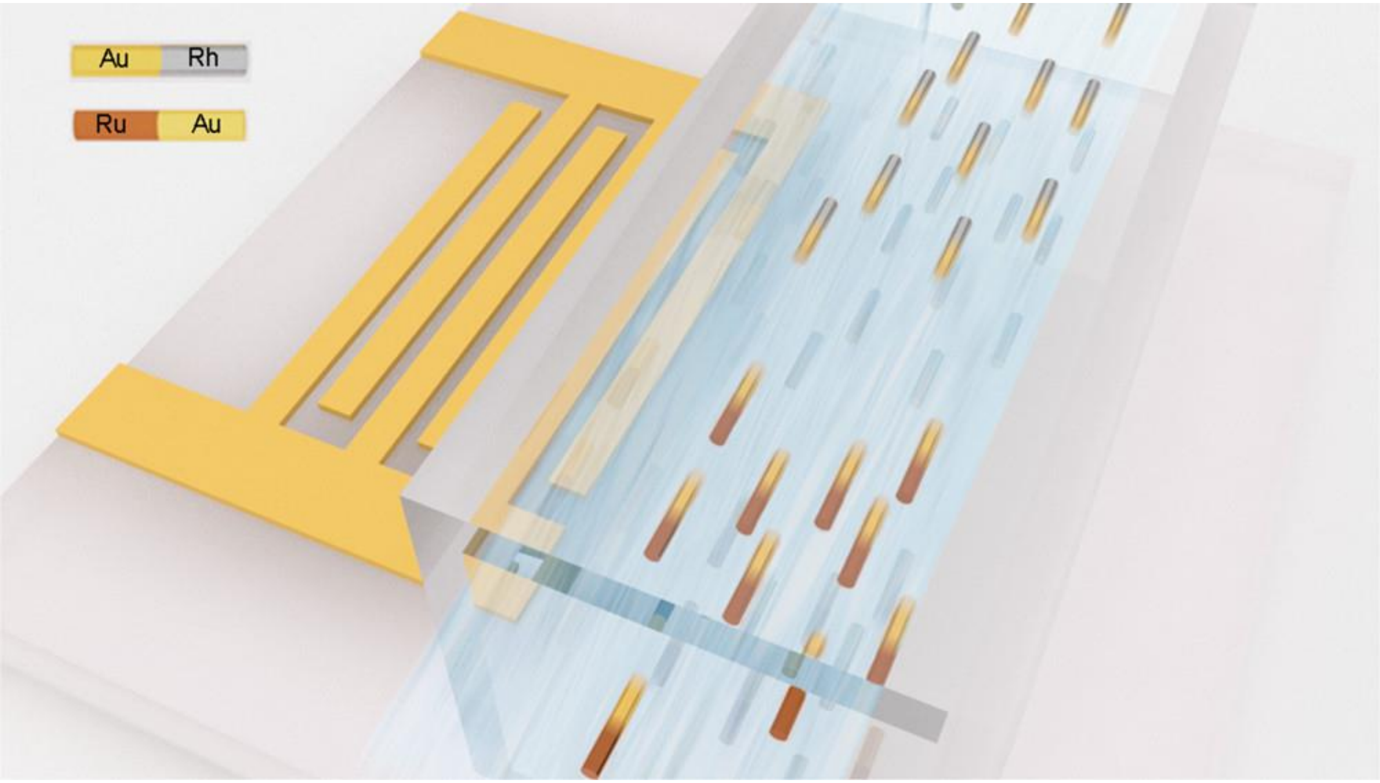
- Rotational Diffusion $\tau_R = \frac{kT}{8\pi\eta R^3}$

$$MSD = 2D\Delta t + v^2 \Delta t^2 \quad \Delta t << \tau_R$$

What so far?

Ren et. al (2017)

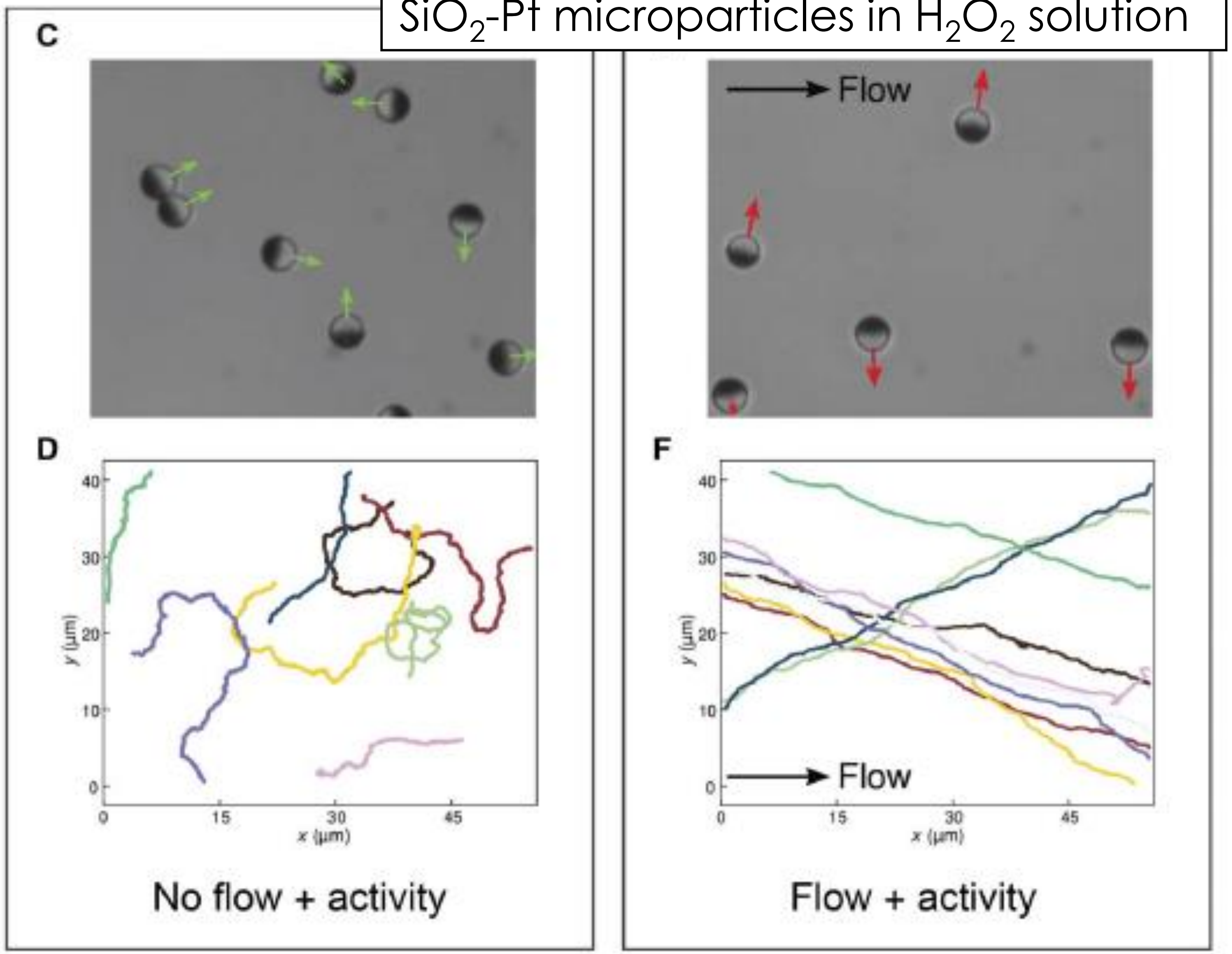
Au-Rh microrods in H_2O_2 solution, Chemical - Acoustic hybrid propulsion



Particles exhibit upstream Rheotaxis

Katuri et. al (2018)

SiO_2-Pt microparticles in H_2O_2 solution



Particles exhibit Cross-Stream migration

- **When ?**

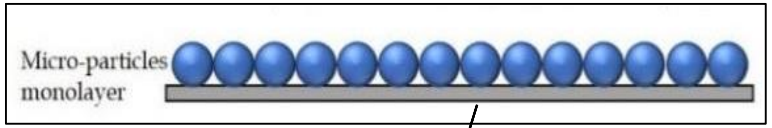
Conditions in which cross migration will be present

- **How much?**

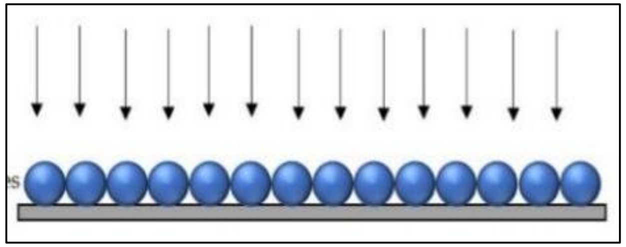
Variation in extent of cross migration with varying flow

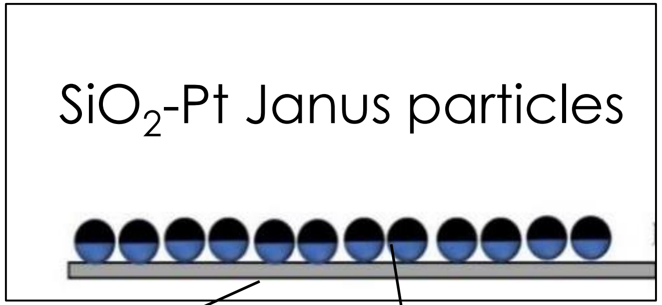
Synthesis of Janus particles

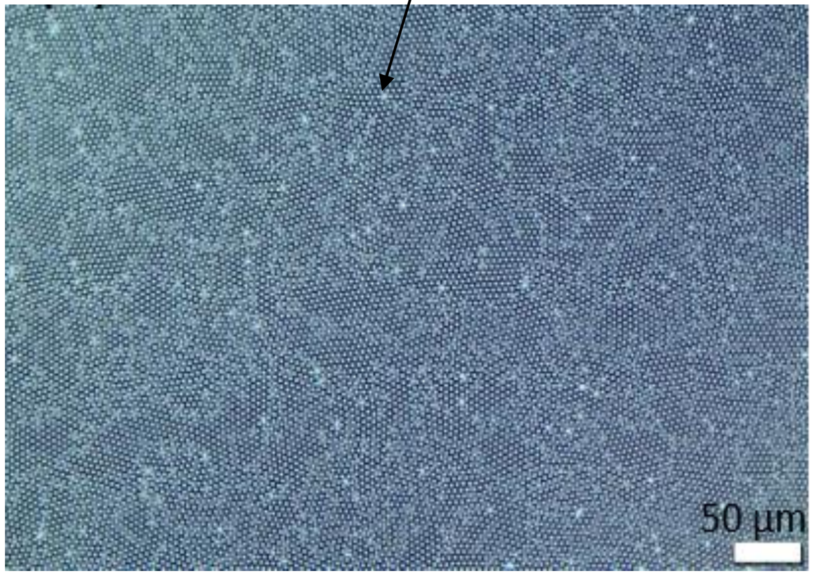
SiO_2 (~ 5 μm)



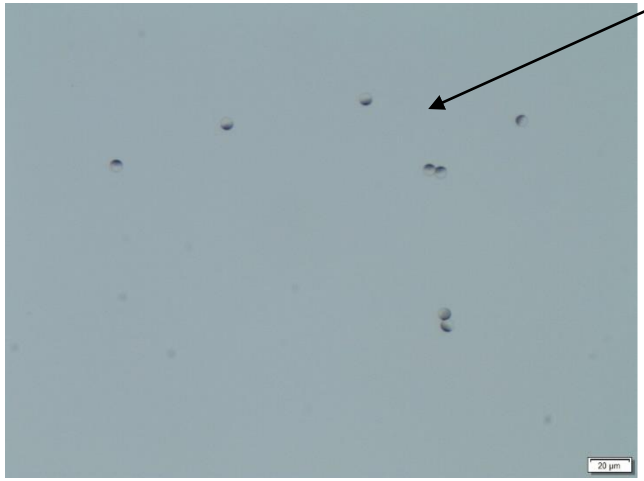
Pt vapor (~ 20 nm)



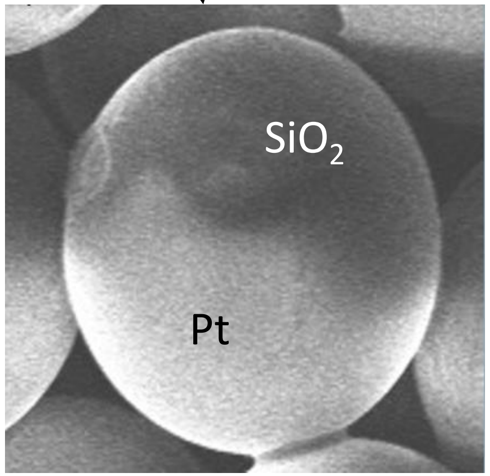




Optical Microscopy image of silica micro-particles monolayer



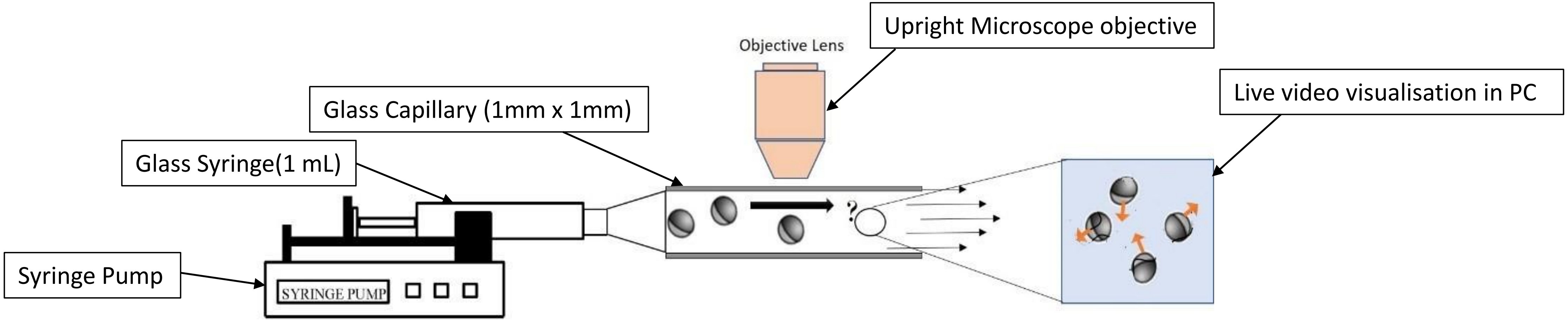
Janus particles on a glass slide



SEM image of a Janus particle

Experimentation

Flow Experiments and Data Analysis



Schematic of the experimental set-up

<u>Control Experiments</u>

- Active Motion (0.5 wt%, 1 wt%, 2 wt% of H_2O_2)
- Flow without activity (100, 200, 500, 750, 900, 1000μL/hr)

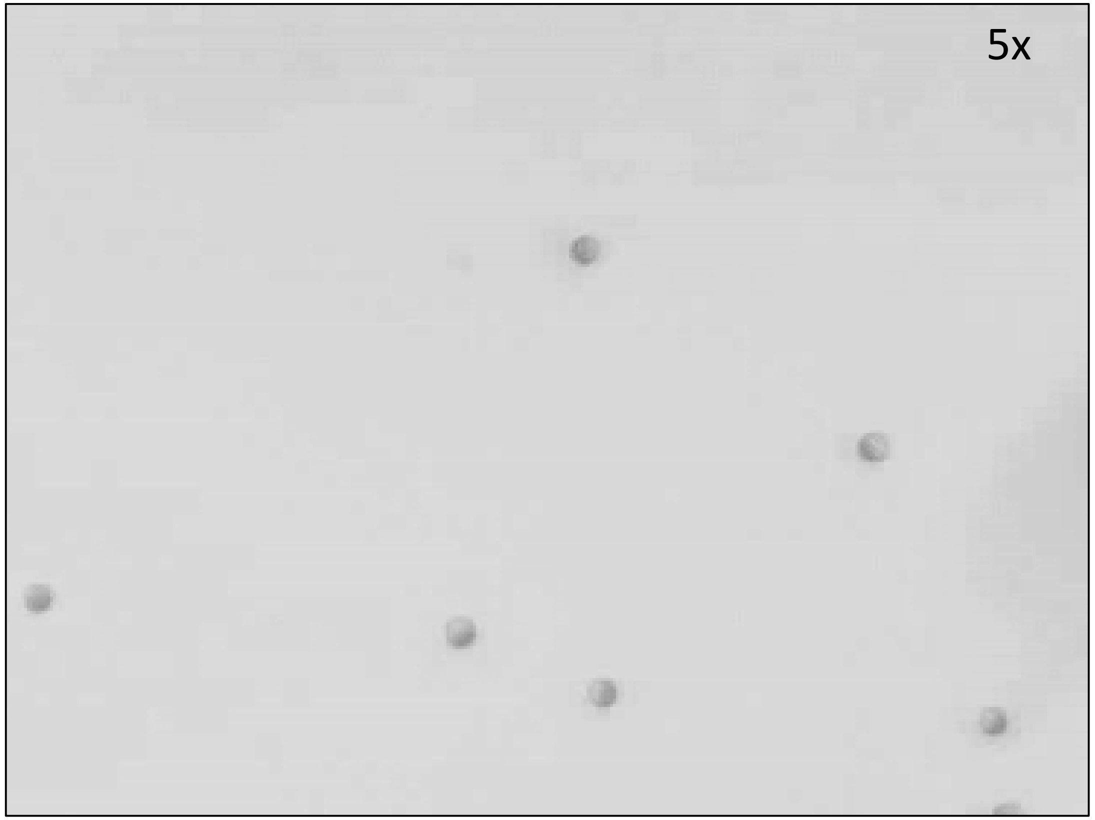
<u>Active motion in shear flow experiment</u>

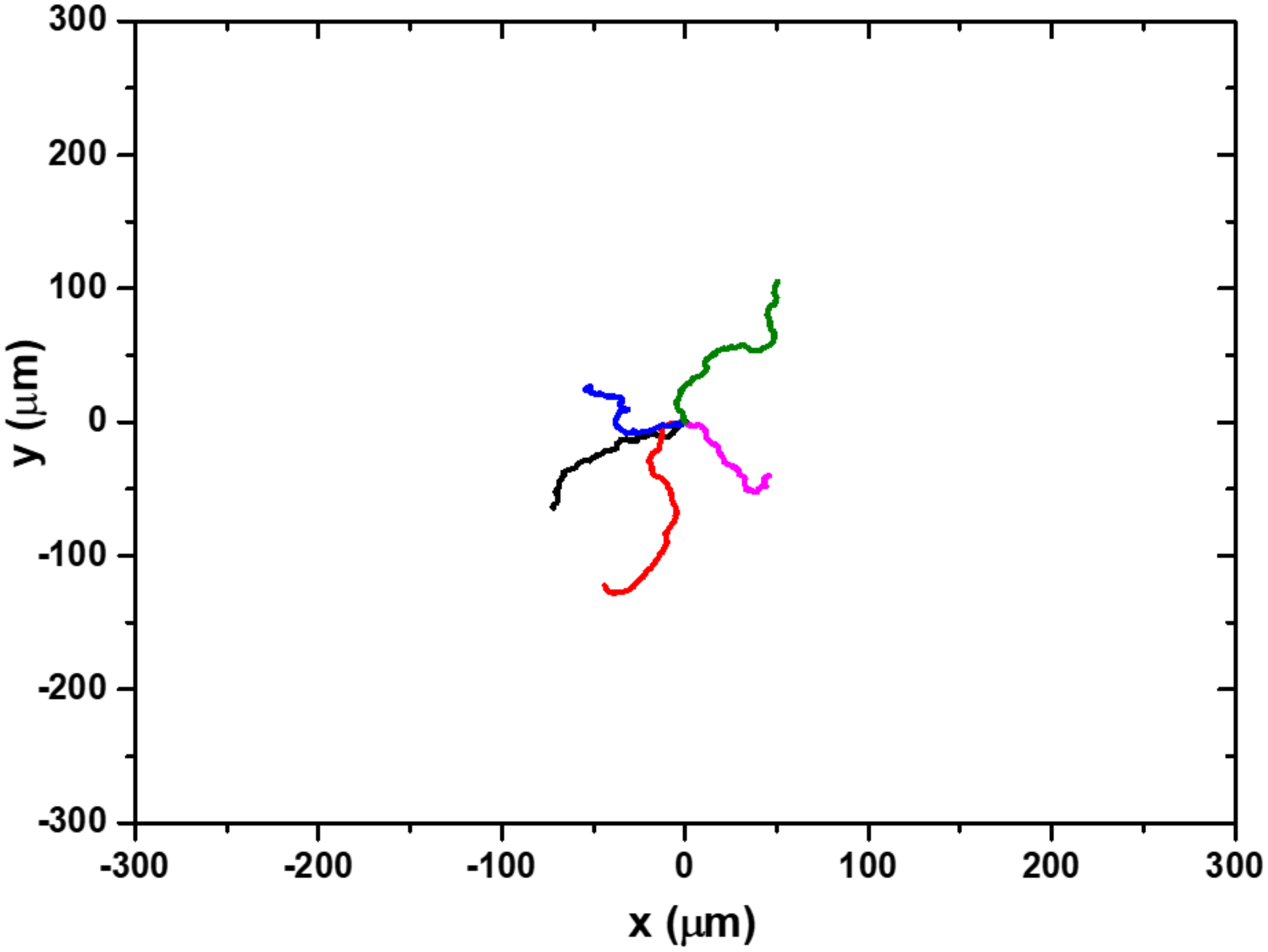
- Combination of different H_2O_2 concentrations and flow rates.

- Single particle tracking using Microscope
- Data anslysis using Image J and Matlab

Active motion – No flow

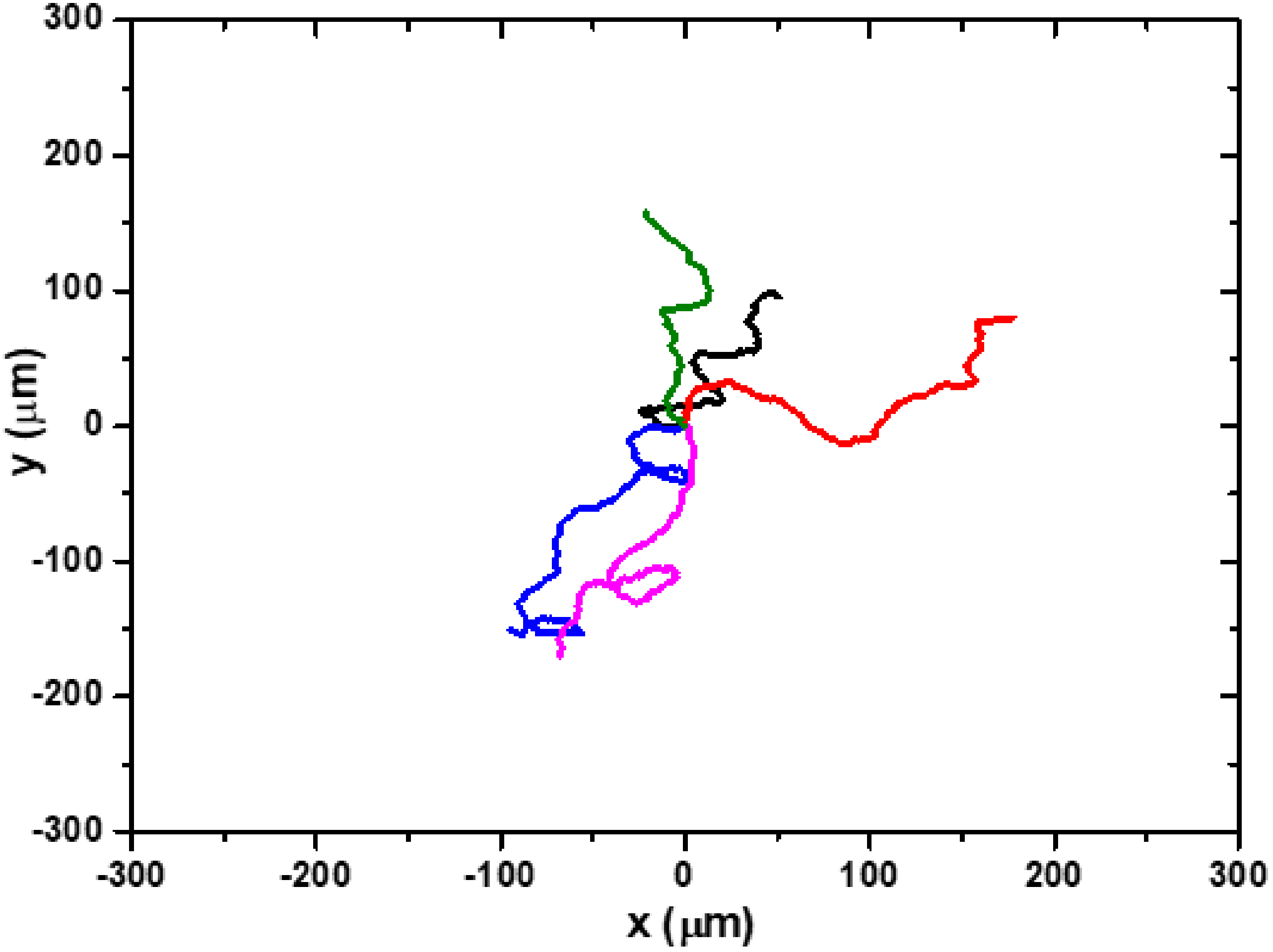
<u>0.5 wt% H_2O_2 in water</u>





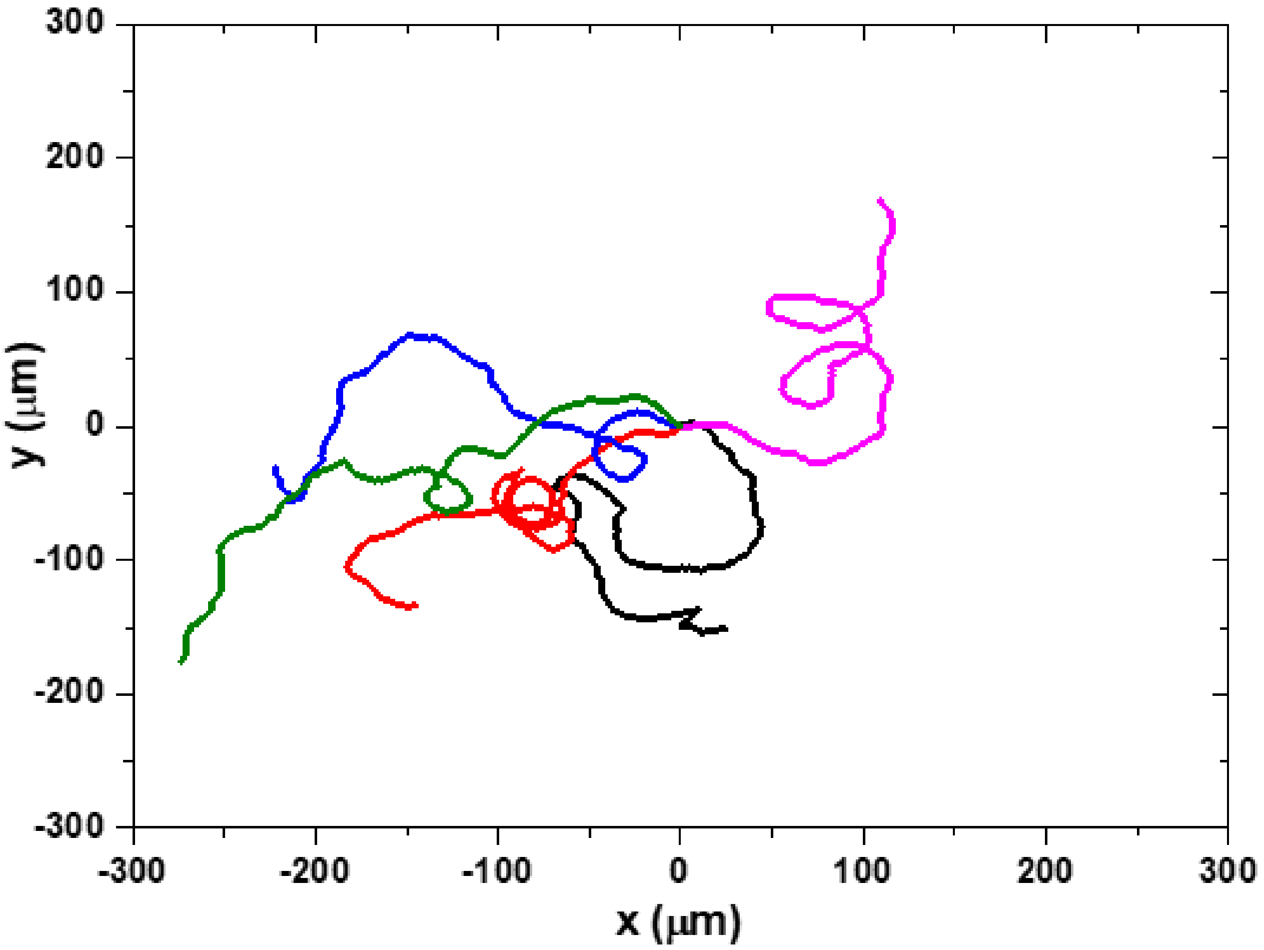
Active motion – No flow

1 wt% H_2O_2 in water



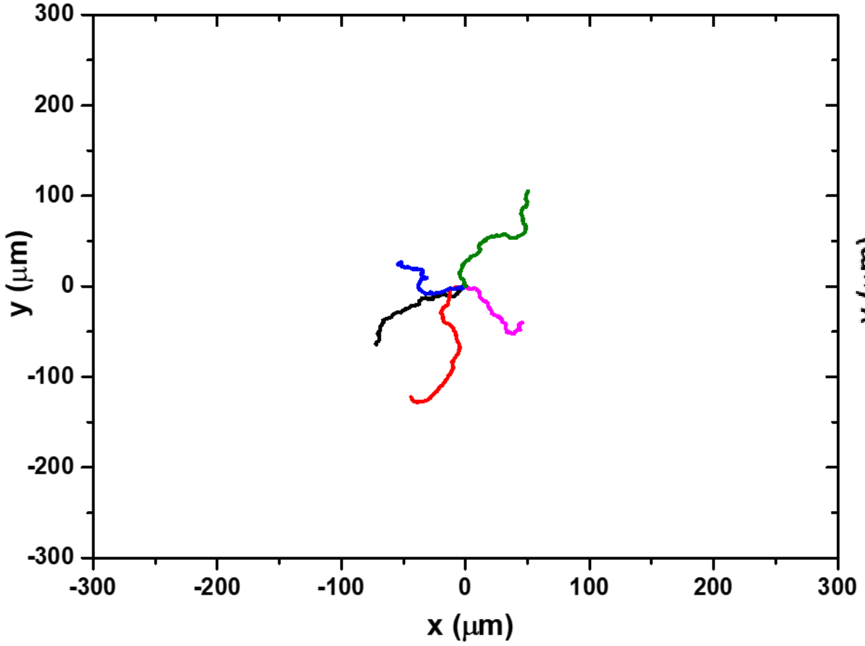
Active motion – No flow

2 wt% H_2O_2 in water

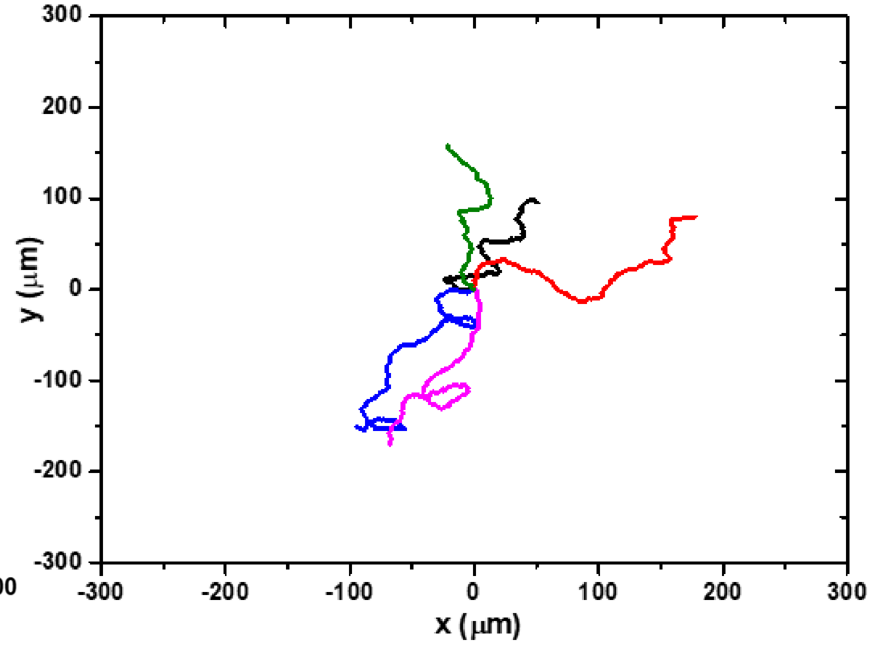


Active motion – No flow

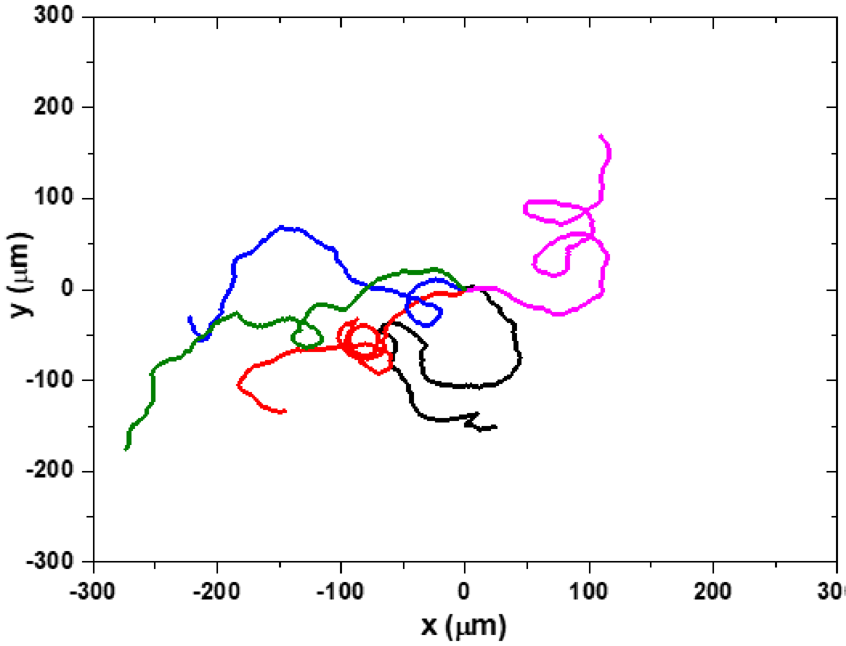
0.5 wt% H_2O_2 in water



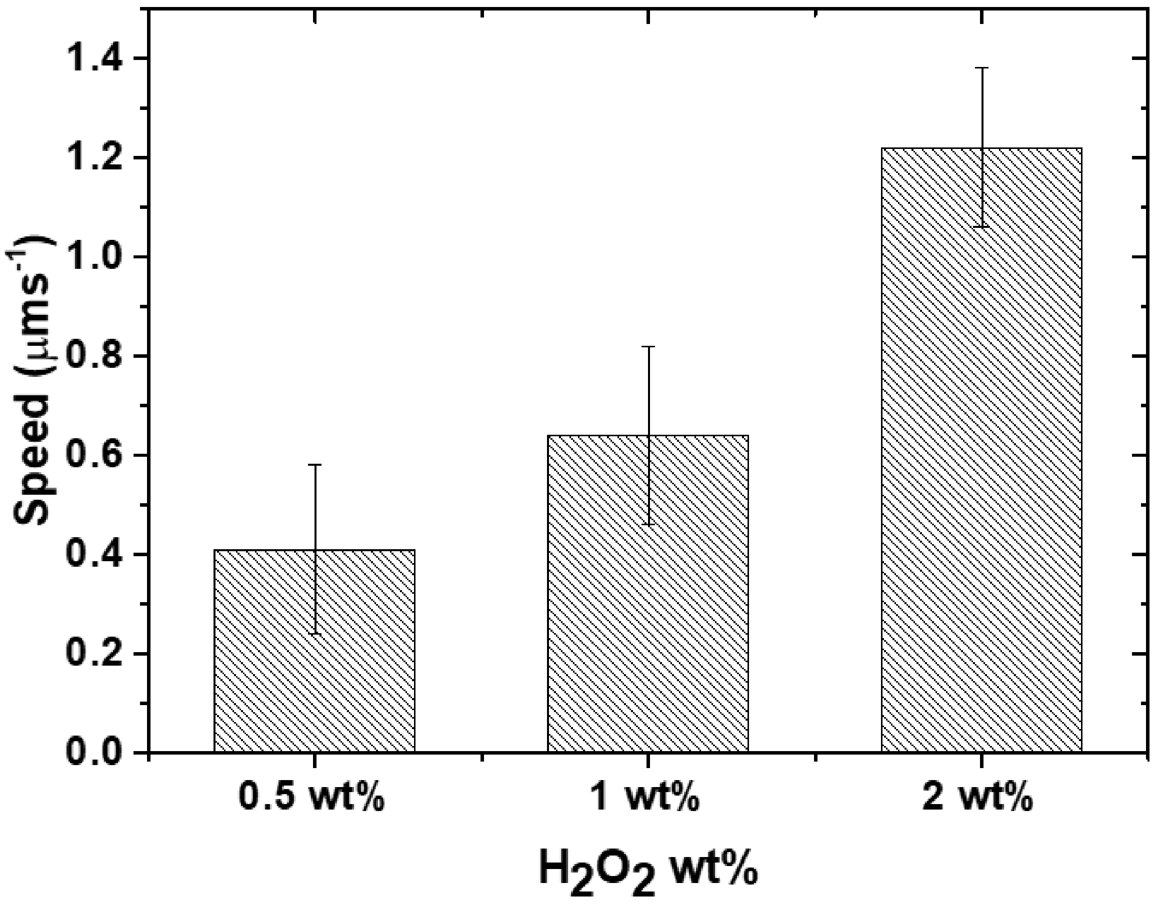
1 wt% H_2O_2 in water



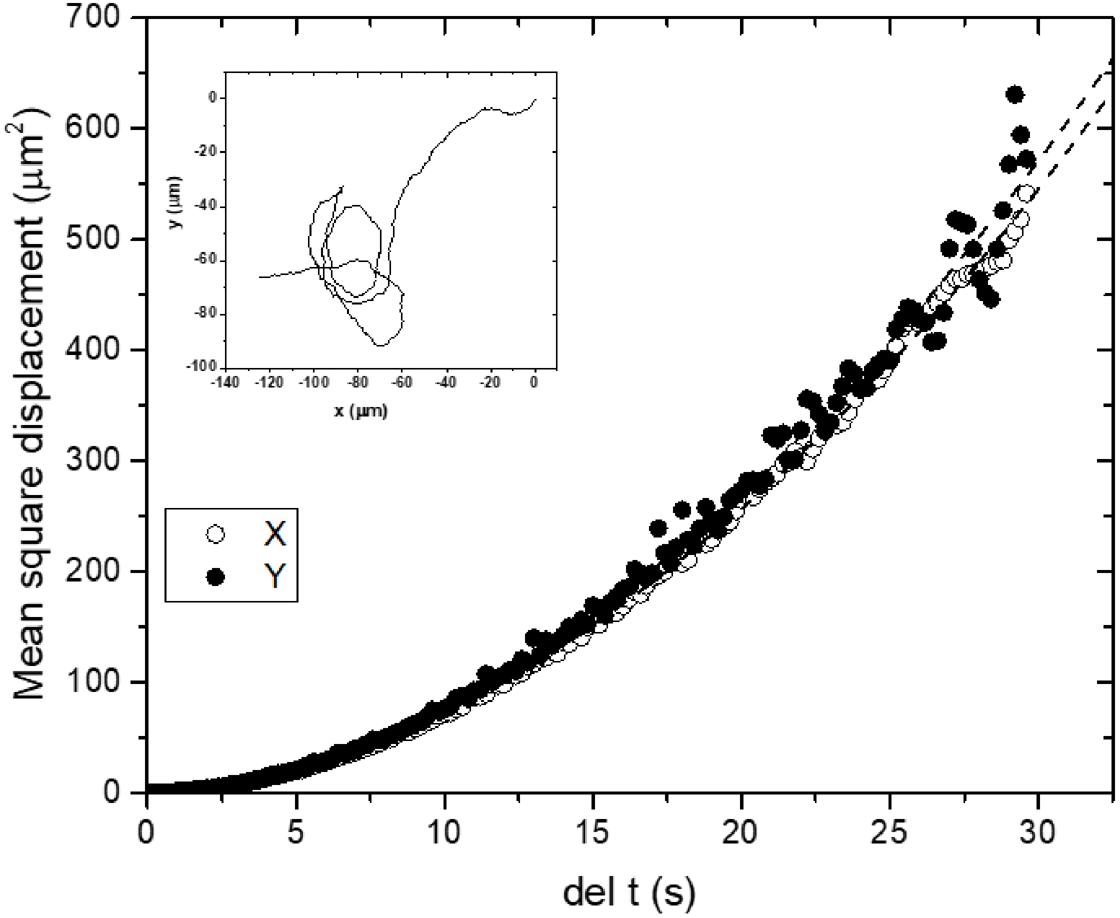
2 wt% H_2O_2 in water



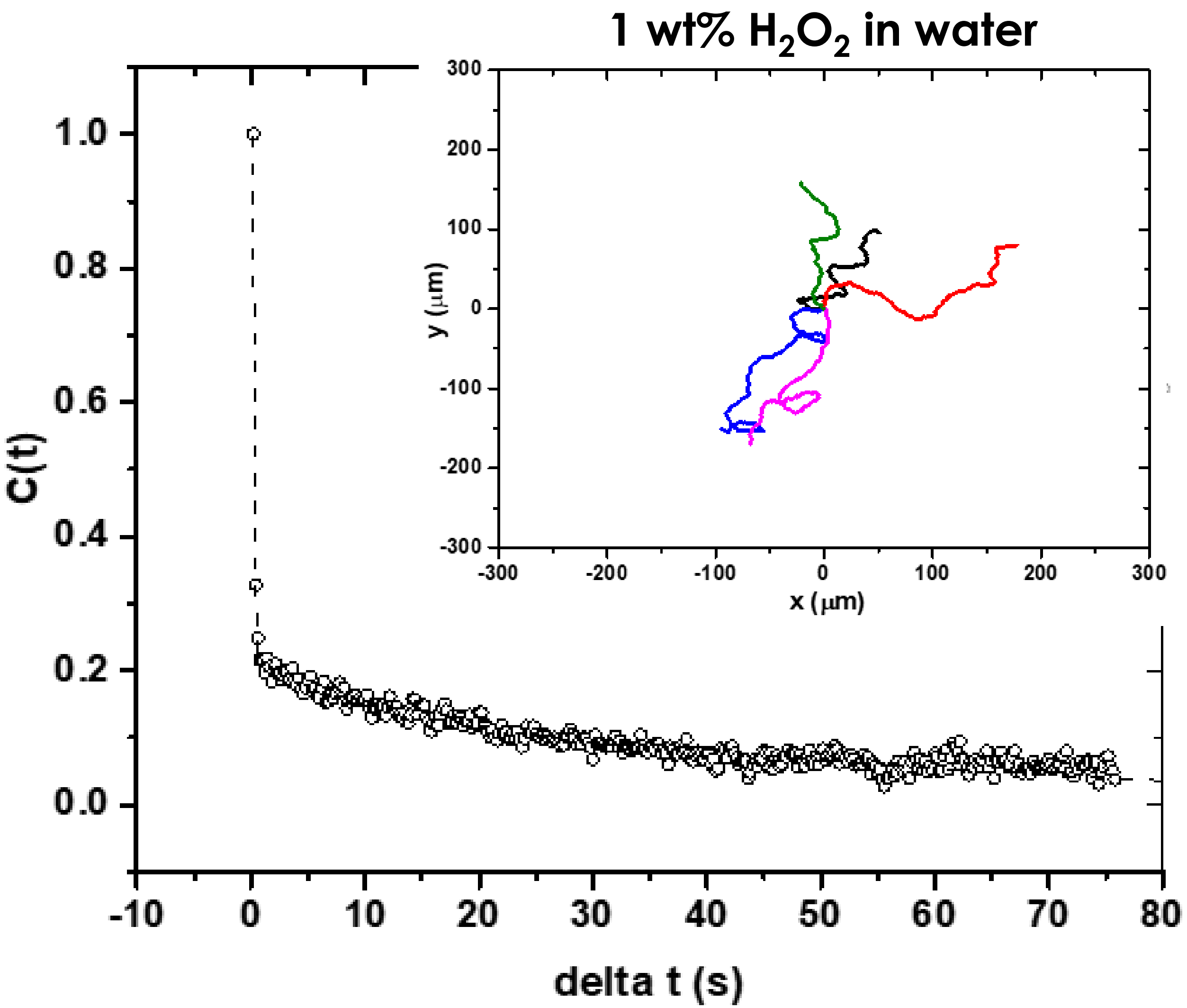
Active motion – Speed Calculation



$$MSD = 2D\Delta t + v^2 \Delta t^2 \quad \Delta t << \tau_R$$



Active motion - τ_R Calculation

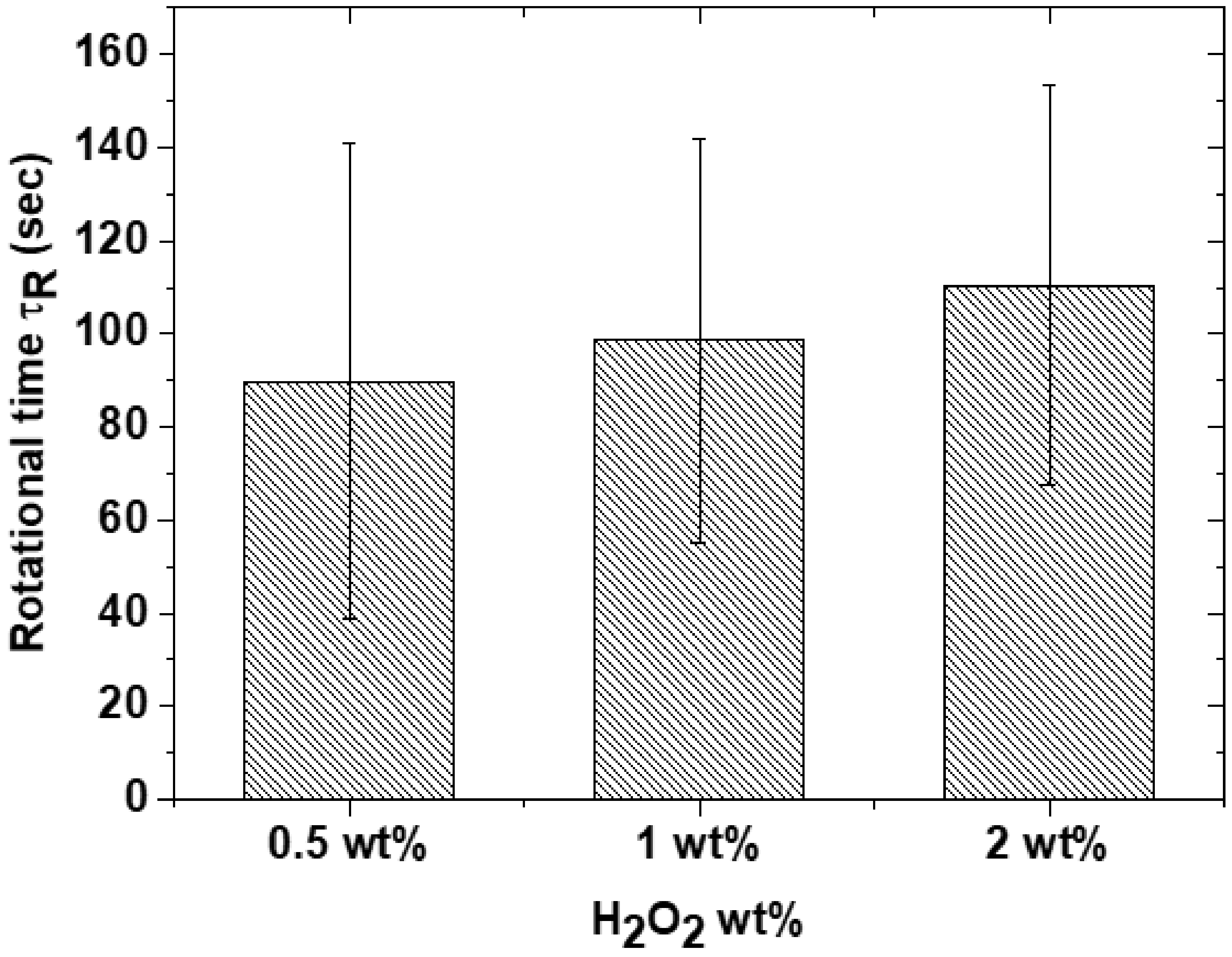


$$C(t) = \left\langle \frac{\vec{v}(t+\Delta t).\vec{v}(t)}{|v(t+\Delta t)||v(t)|} \right\rangle$$

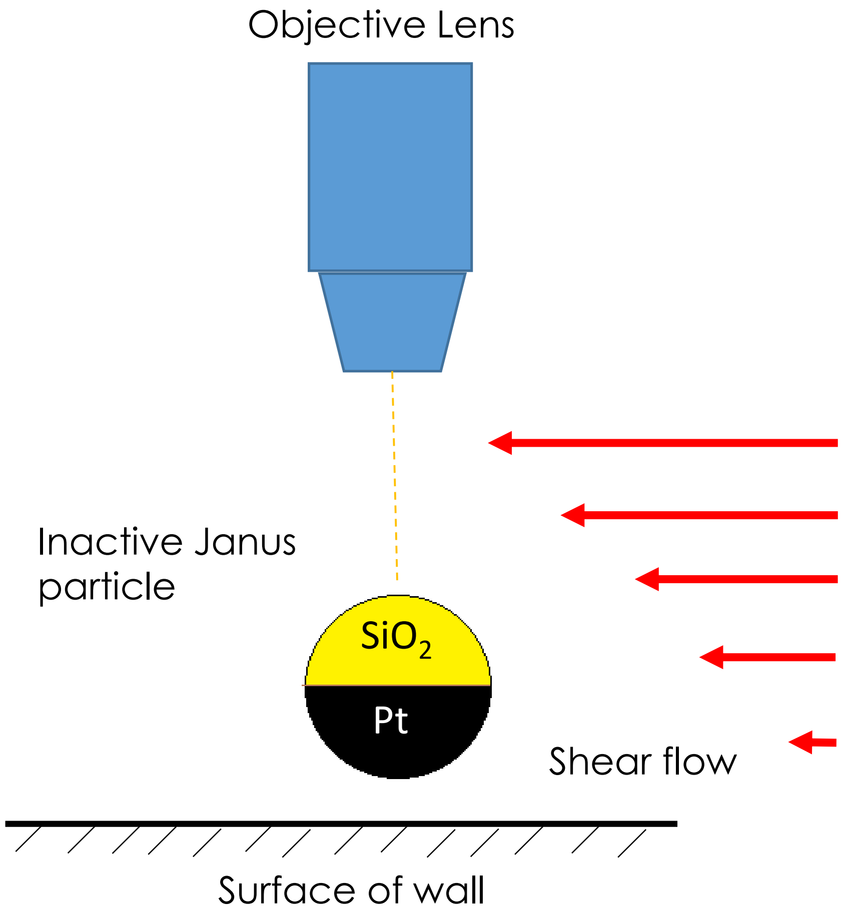
where,
C(t) = autocorrelation function
v(t) = velocity of particle at time 't'
Δt = lag time

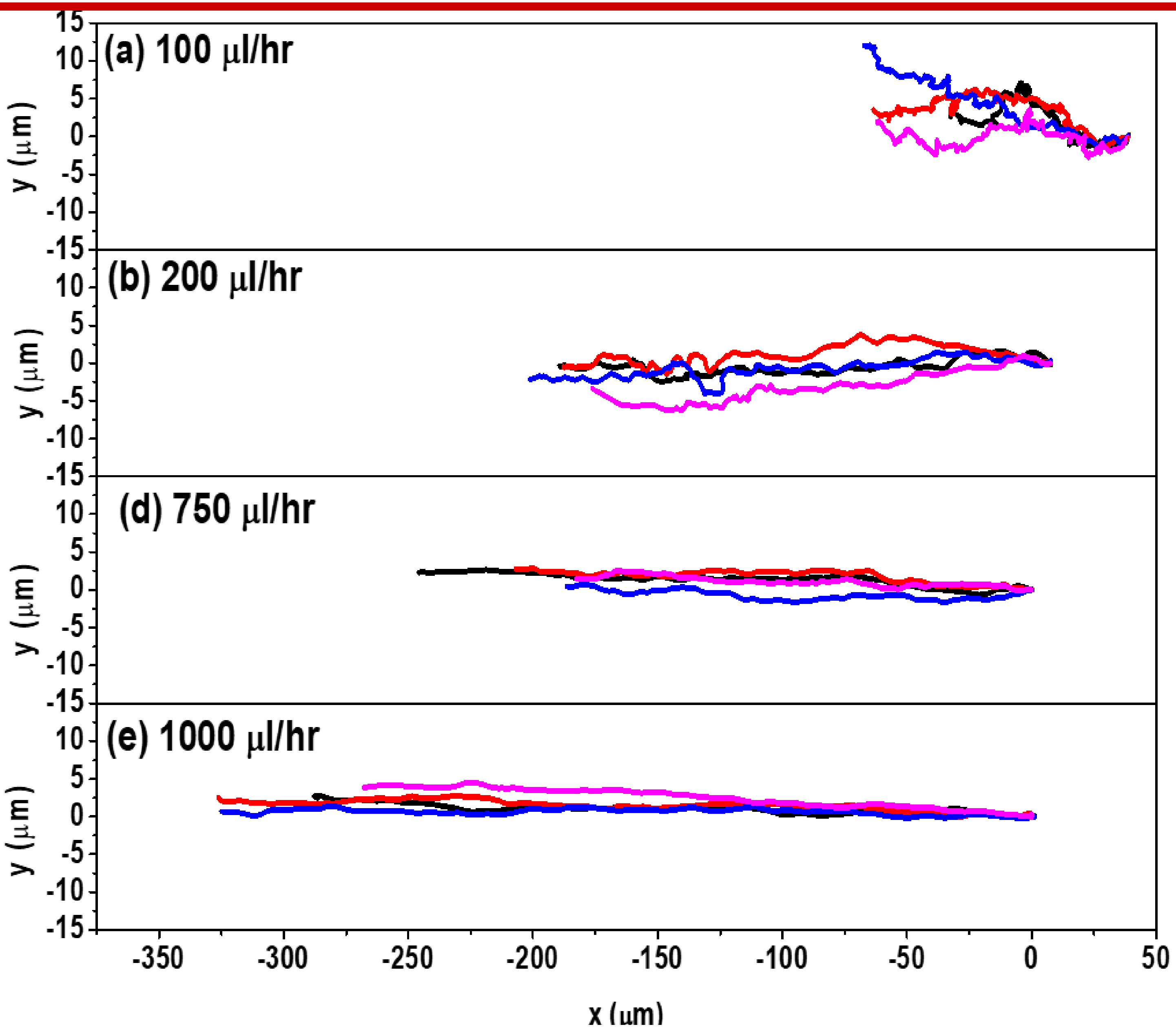
$$C(\Delta t) = 4D\delta(\Delta t) + e^{-2\Delta t/\tau_R}$$

Active motion(Autocorrelation function)

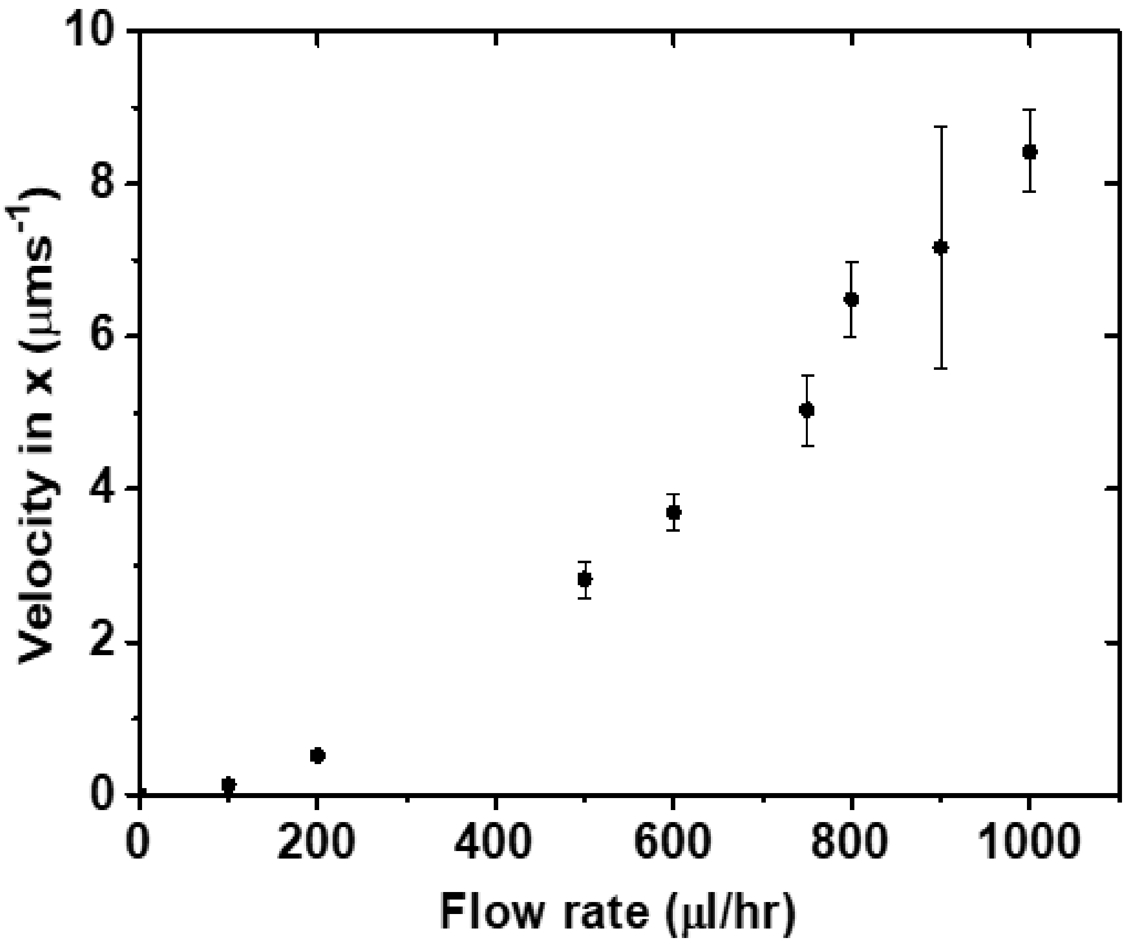


Inactive motion in flow





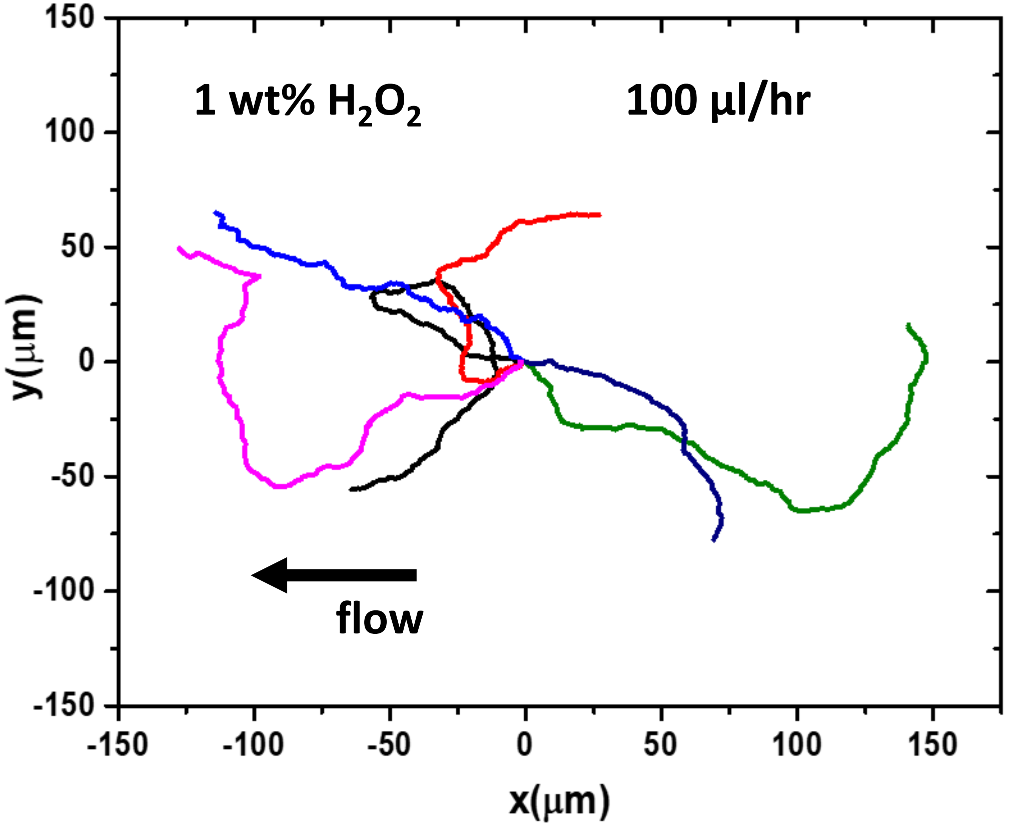
Inactive motion in flow



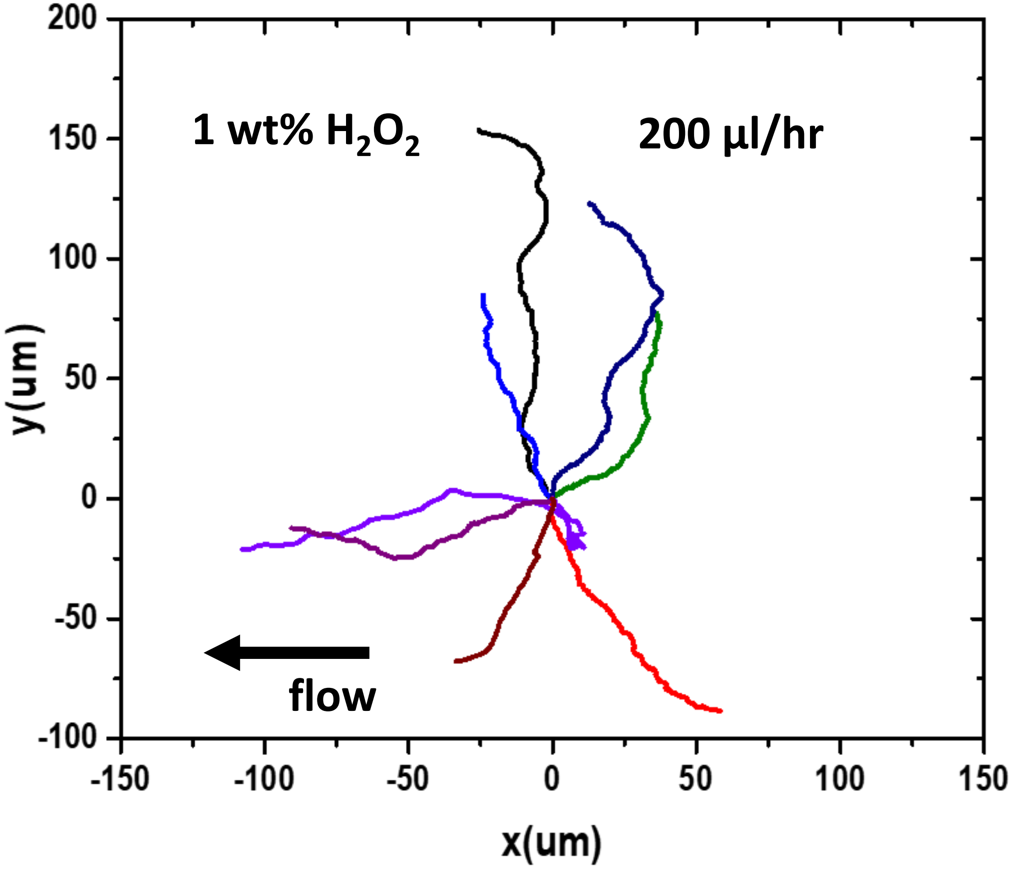
Note:

- Reynold's No. $\mathrm{Re} = \dfrac{\rho v_x a}{\eta} = 4.77\mathrm{x}10^{-5}$ (very low ~10^{-5})
- Effect of flow on reaction is minimal
- $Pe = \dfrac{v_x a}{D_s} = 0.0053$ (very low <<1)

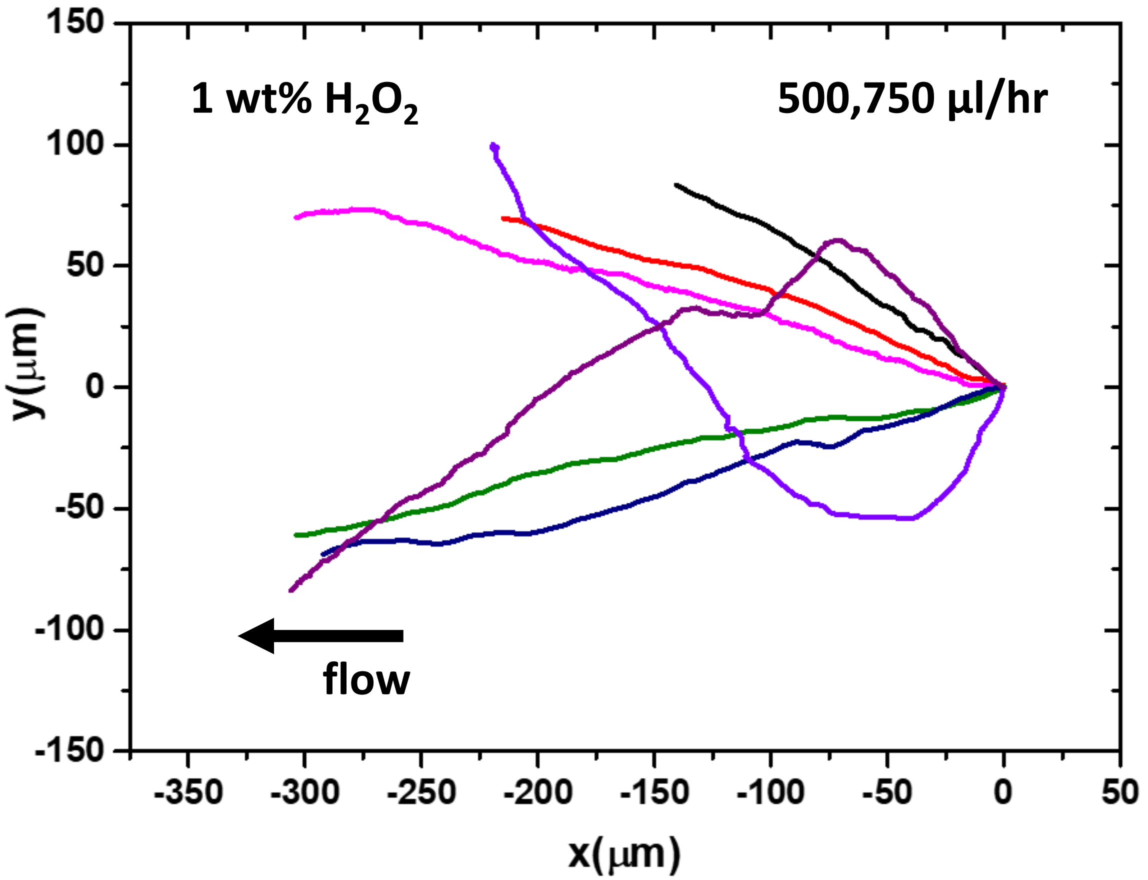
Active motion in flow



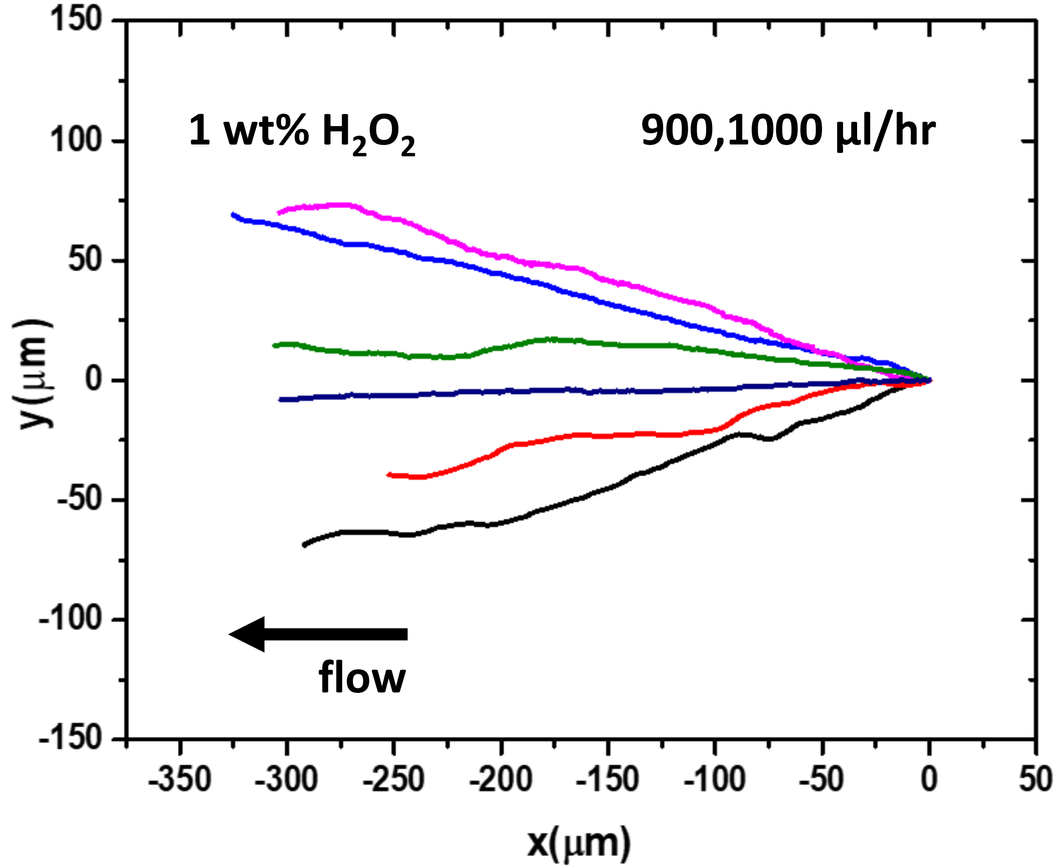
Active motion in flow



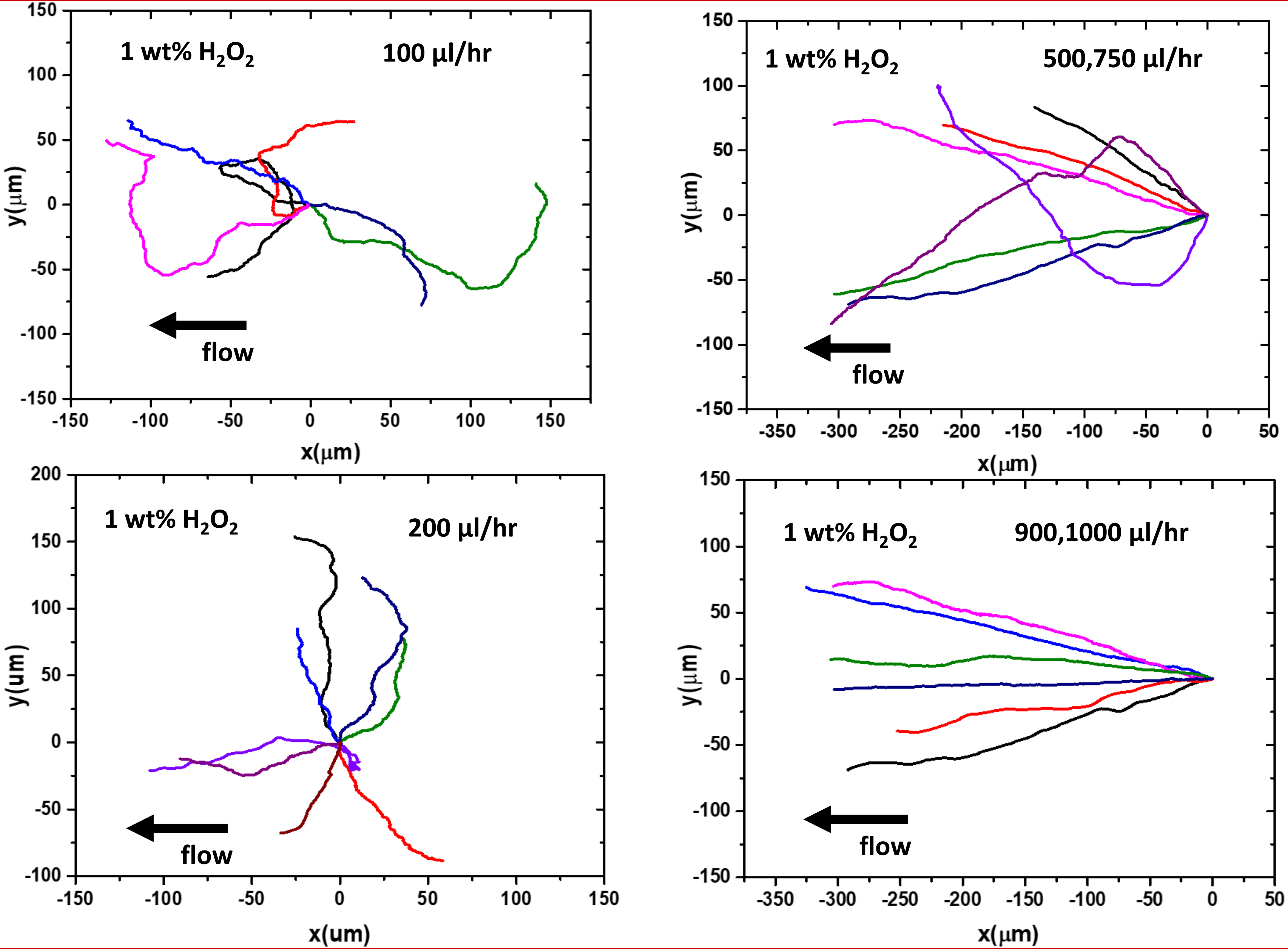
Active motion in flow



Active motion in flow



Active motion in flow

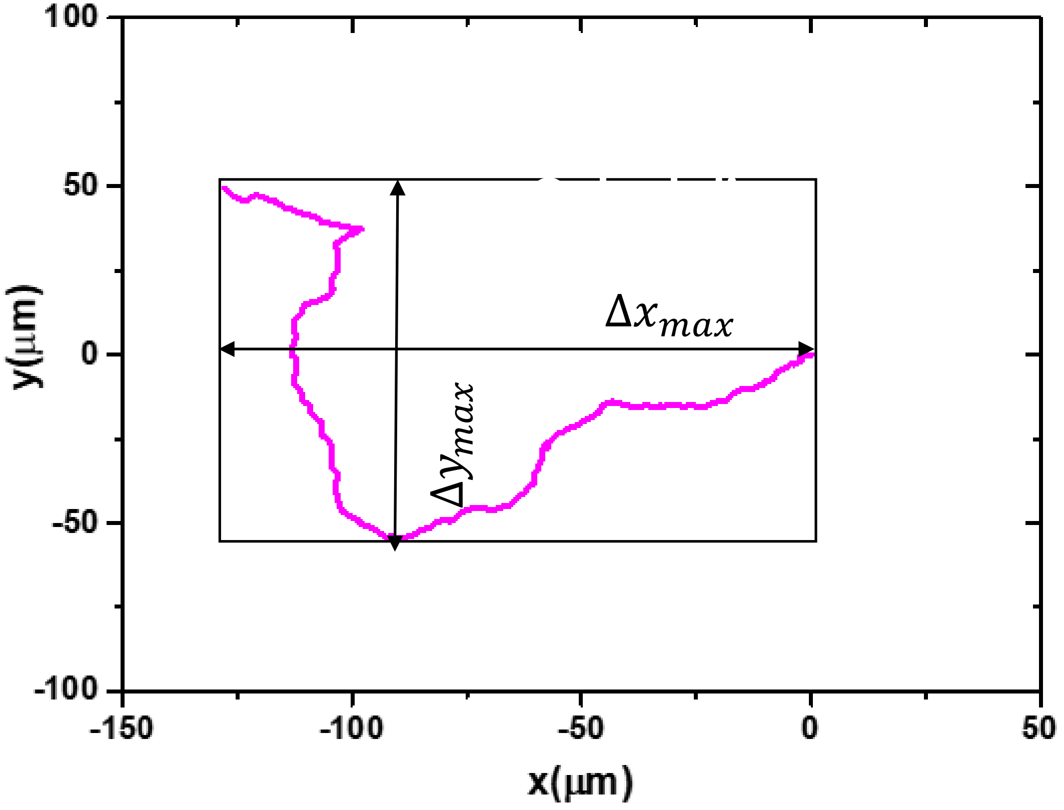


Defining anisotropy (α) in the system

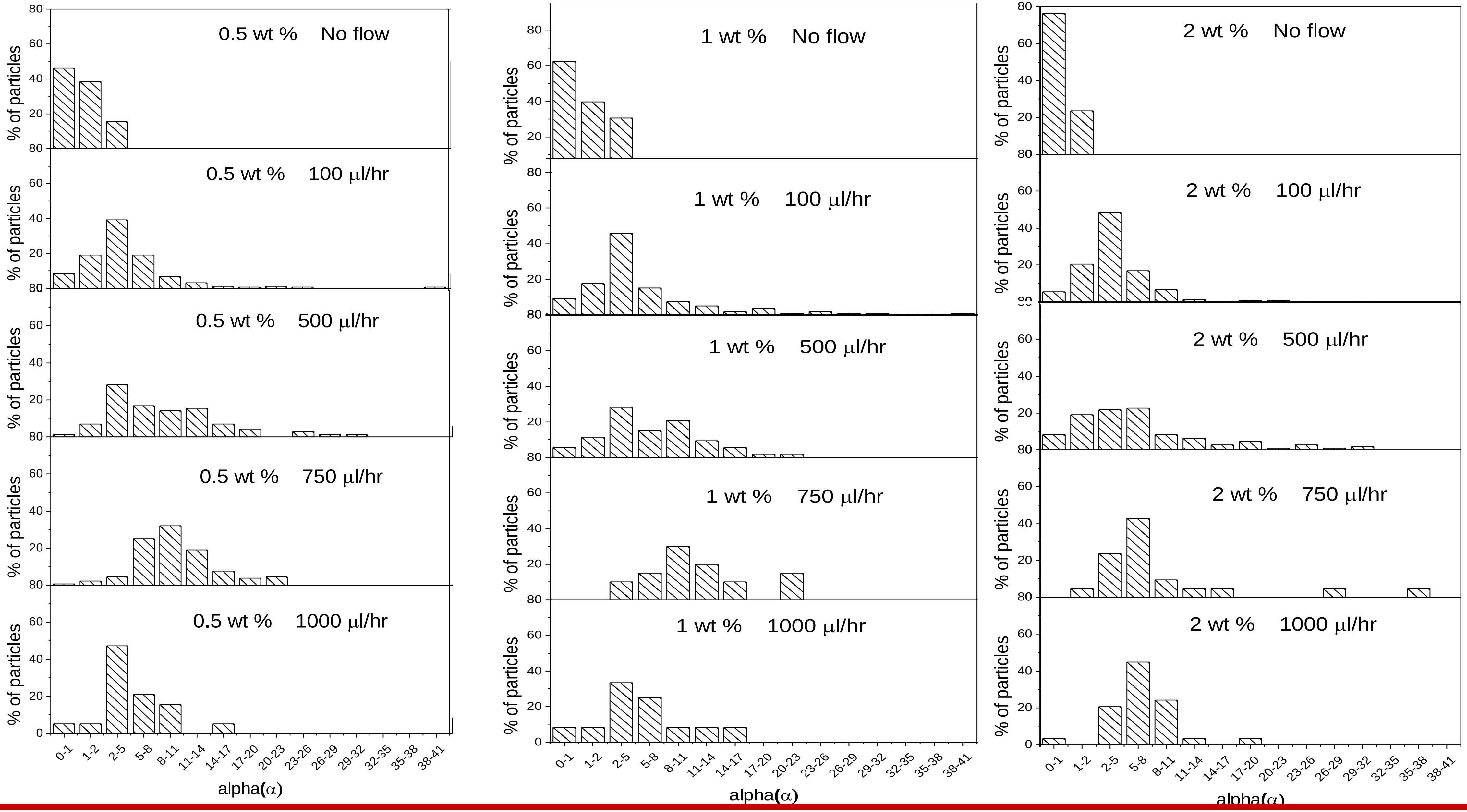
We define anisotropy alpha as

$$\alpha = \frac{\left(\Delta y_{\max} / \Delta x_{\max} \right)_{activity+flow}}{\left(\Delta y_{\max} / \Delta x_{\max} \right)_{flow}}$$

For a given trajectory,



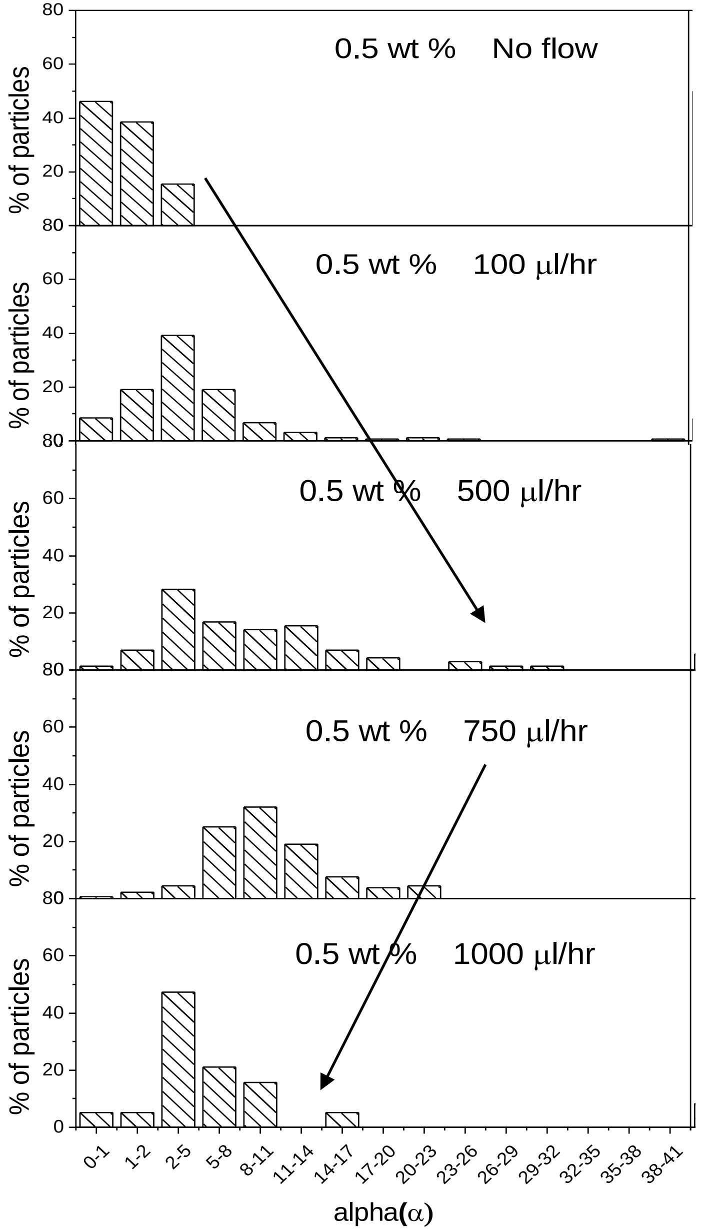
Distribution of α for different systems



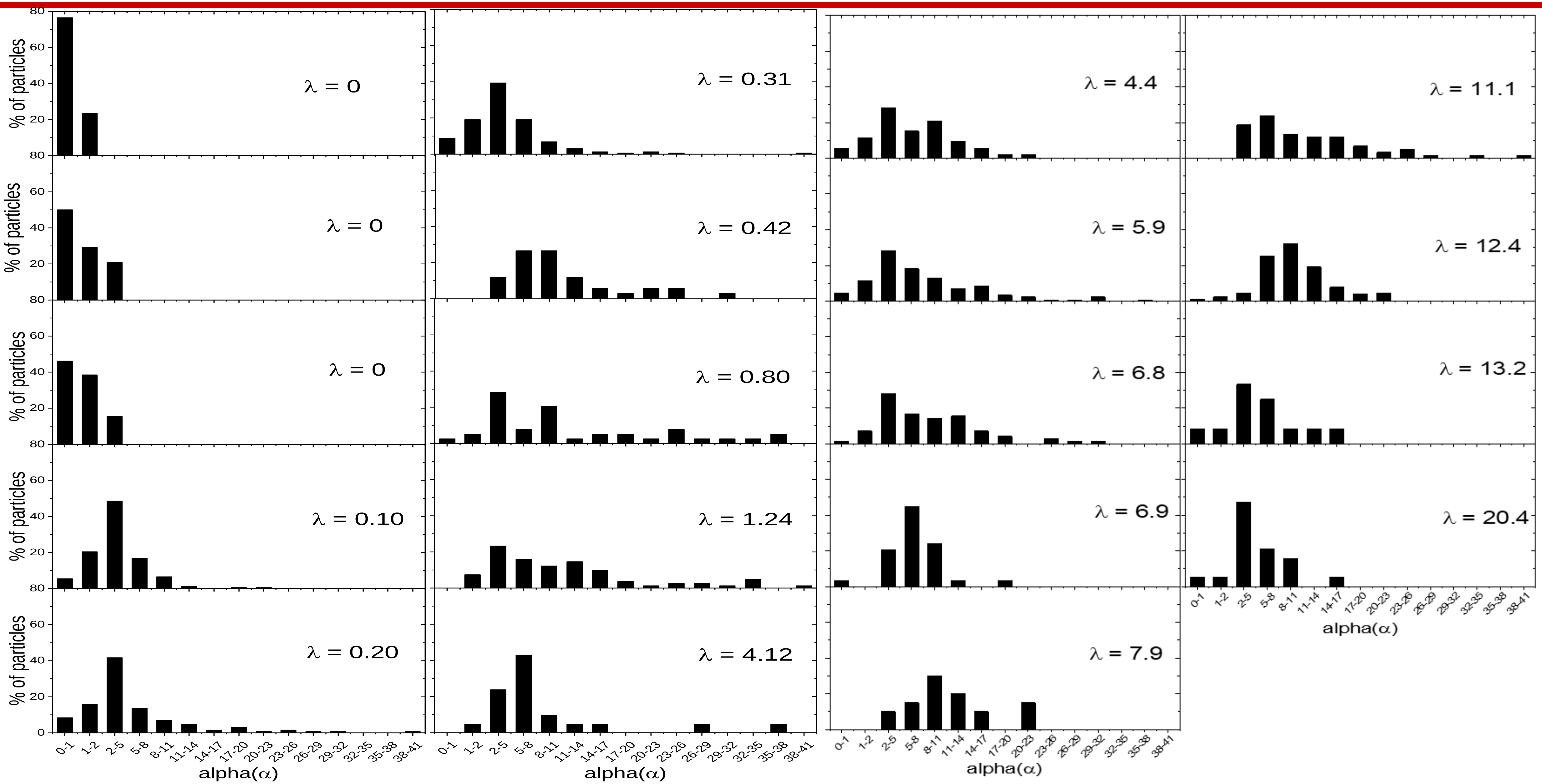
Key observations

- Low flow → α ~ 1
- Moderate flow → range of α widens towards higher values
- High flow → Range of α starts to shrink
- Behaviour universal and dependent on the activity of particle

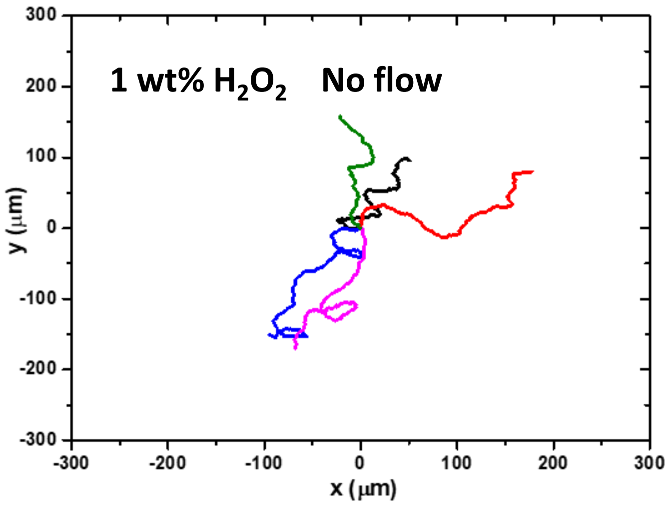
We define dimensionless parameter $$\lambda = \frac{v_{x,\,flow}}{v_{activation}}$$

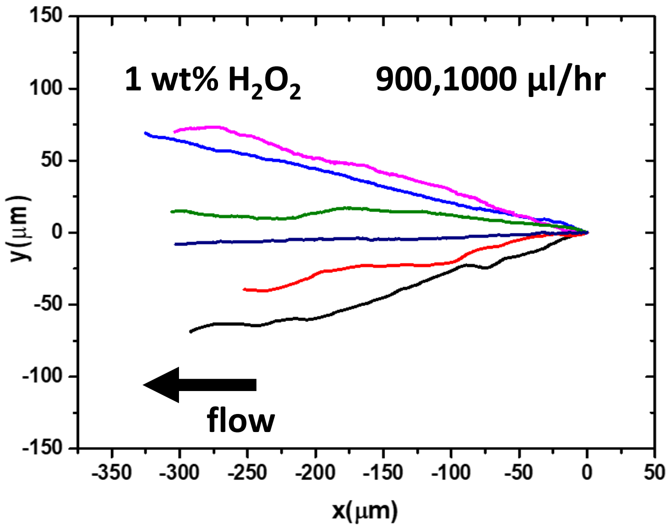


Variation with λ

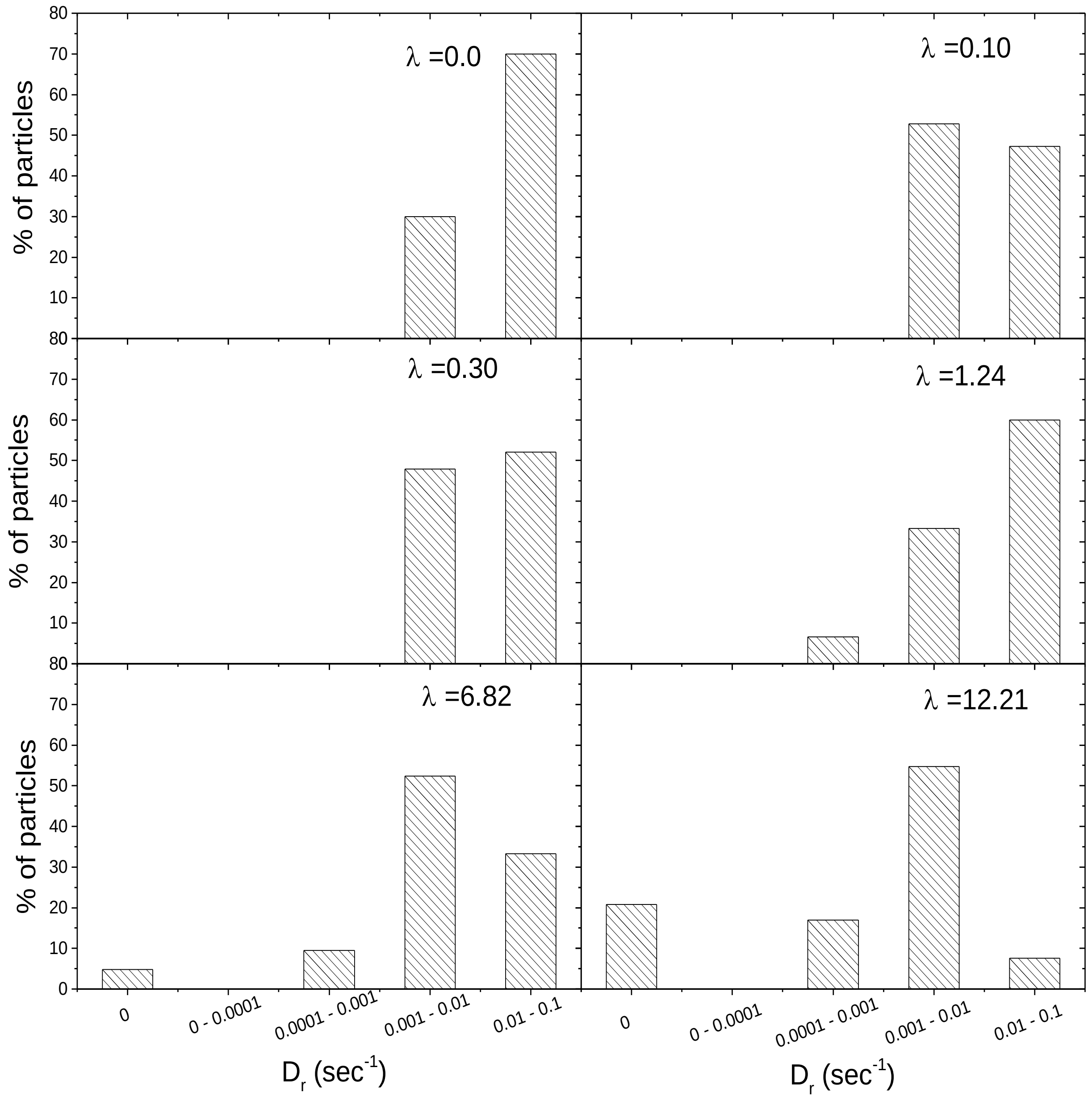


Variation of D_r with λ

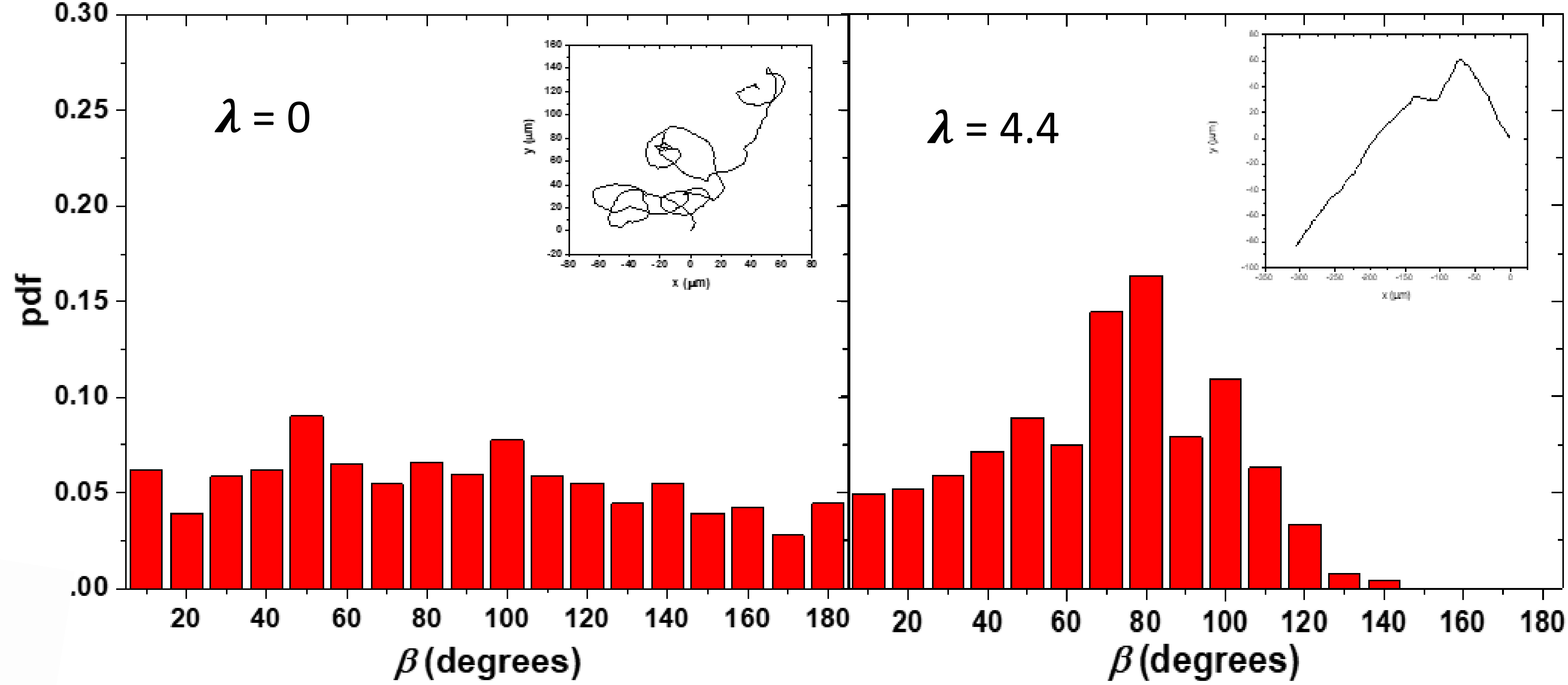


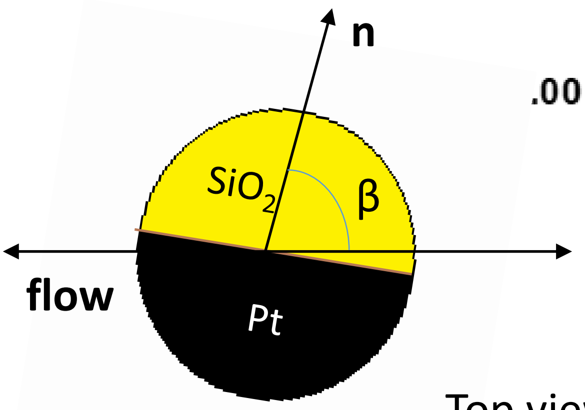


$$D_r = \frac{1}{\tau_r}$$



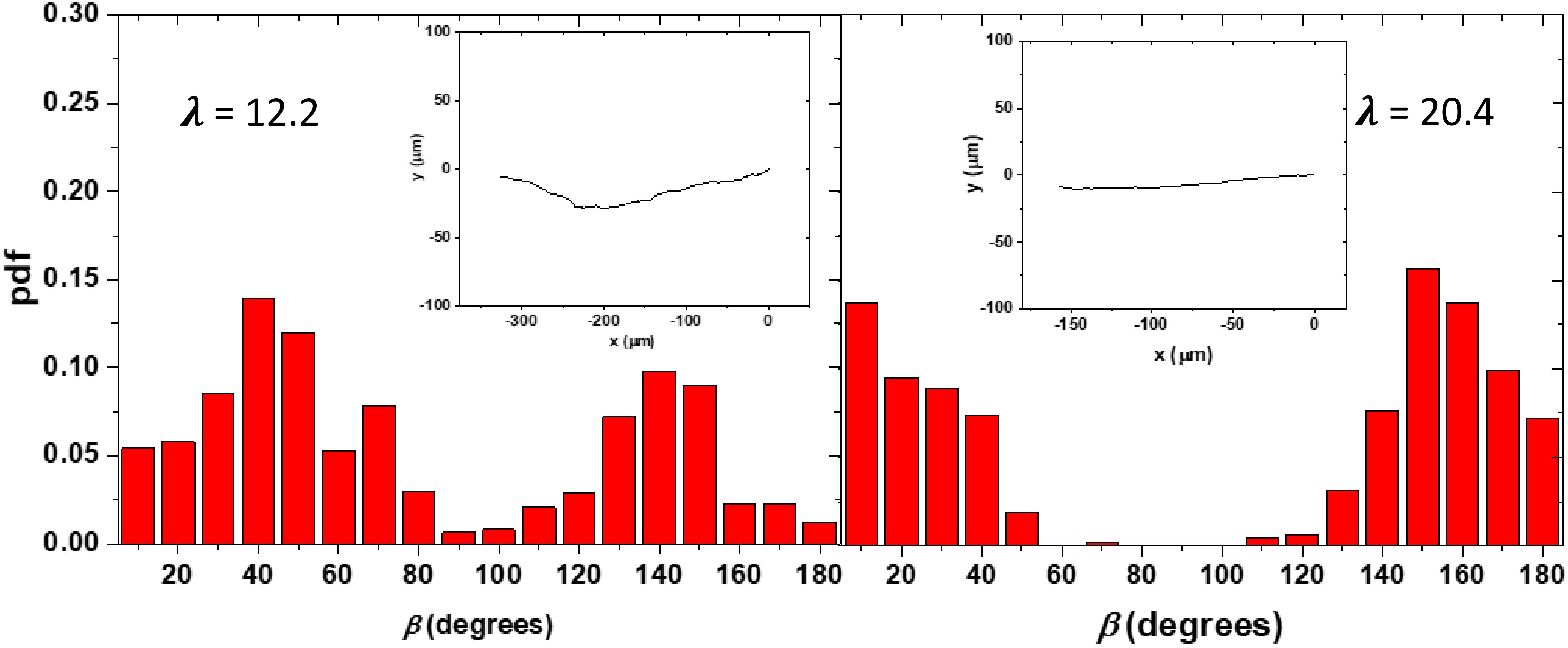
Angle β as a function of λ



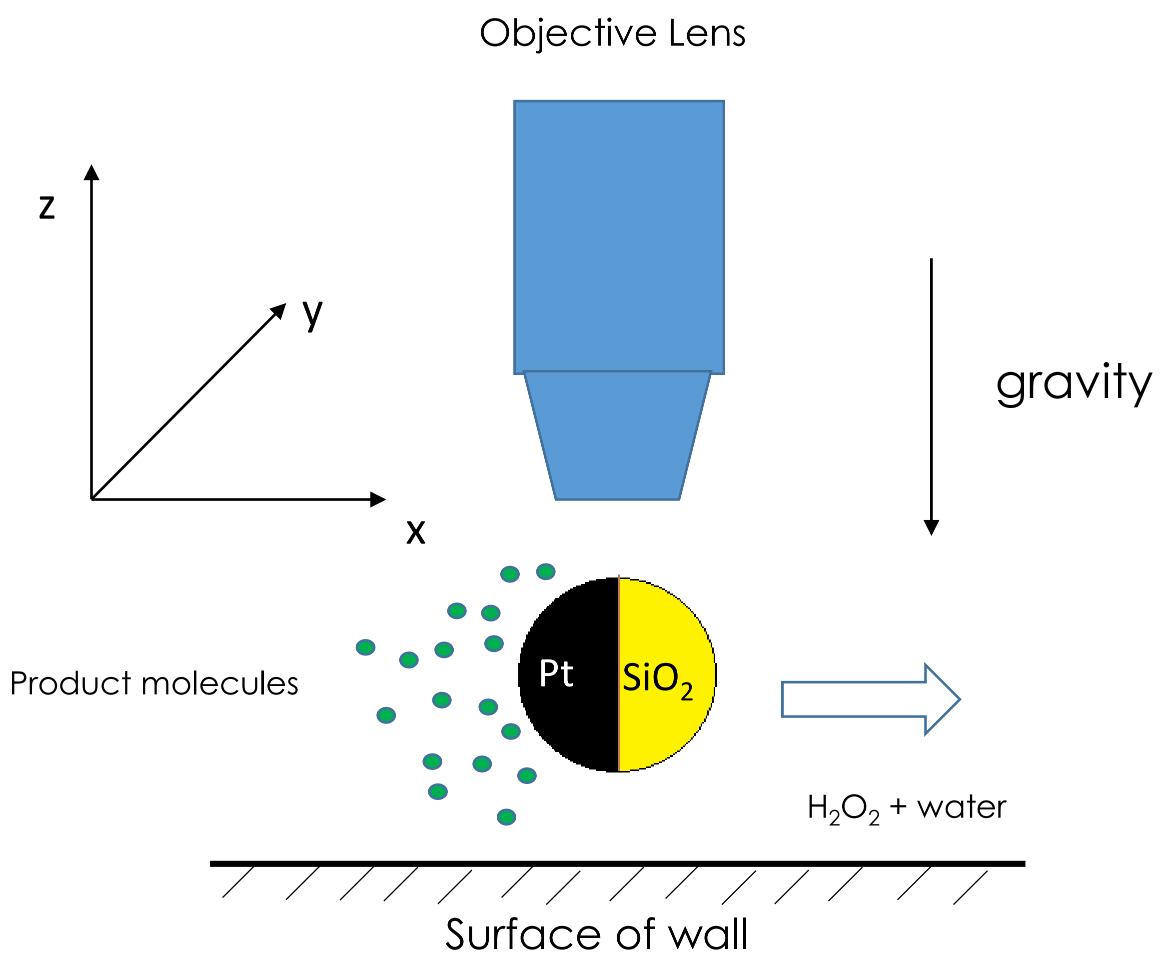


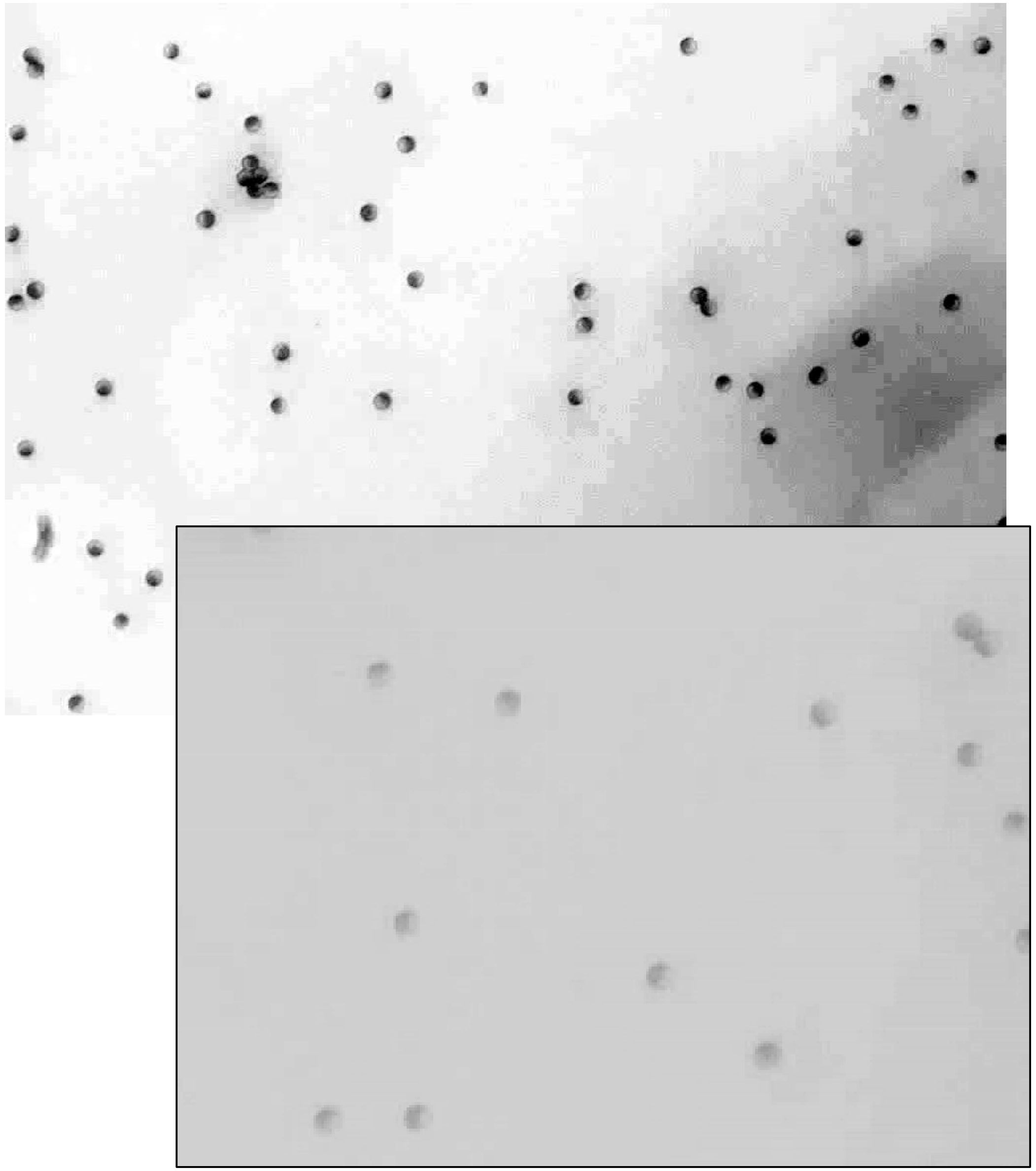
Top view

Angle β as a function of λ



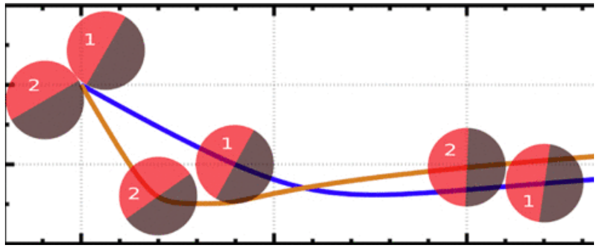
Active motion



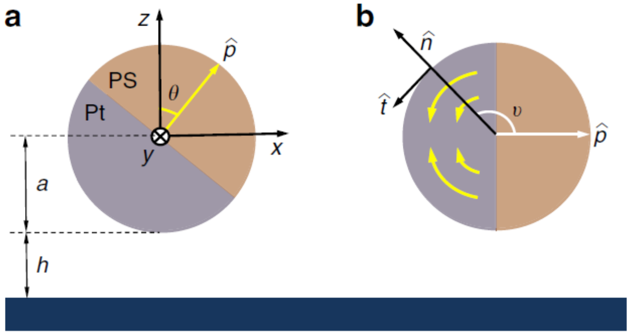


Competing mechanisms

No flow + Active motion



Maldrelli et al. Phy. Of. Fluid.,(2016)



Das et al. Nature Comm.,(2015)

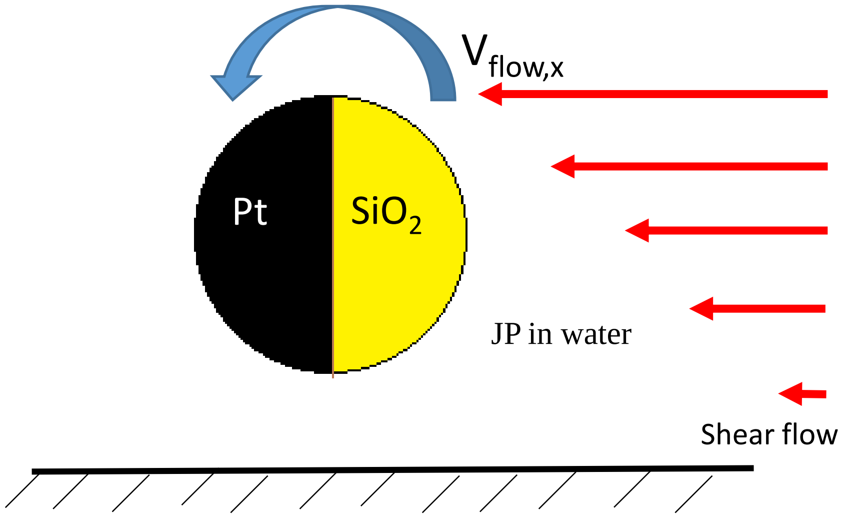
Restoring rotation to bring the Janus boundary perpendicular to the plane

$$\Omega_y(\theta) = -\Gamma(\theta - \theta_s)$$

$$\boxed{\Gamma_{activity} \sim \frac{v_{activity}}{a}}$$

$$\boxed{\frac{\Gamma_{shear}}{\Gamma_{activity}} \sim \frac{v_{x,\,flow}}{v_{activity}} = \lambda}$$

No Activity + Shear flow

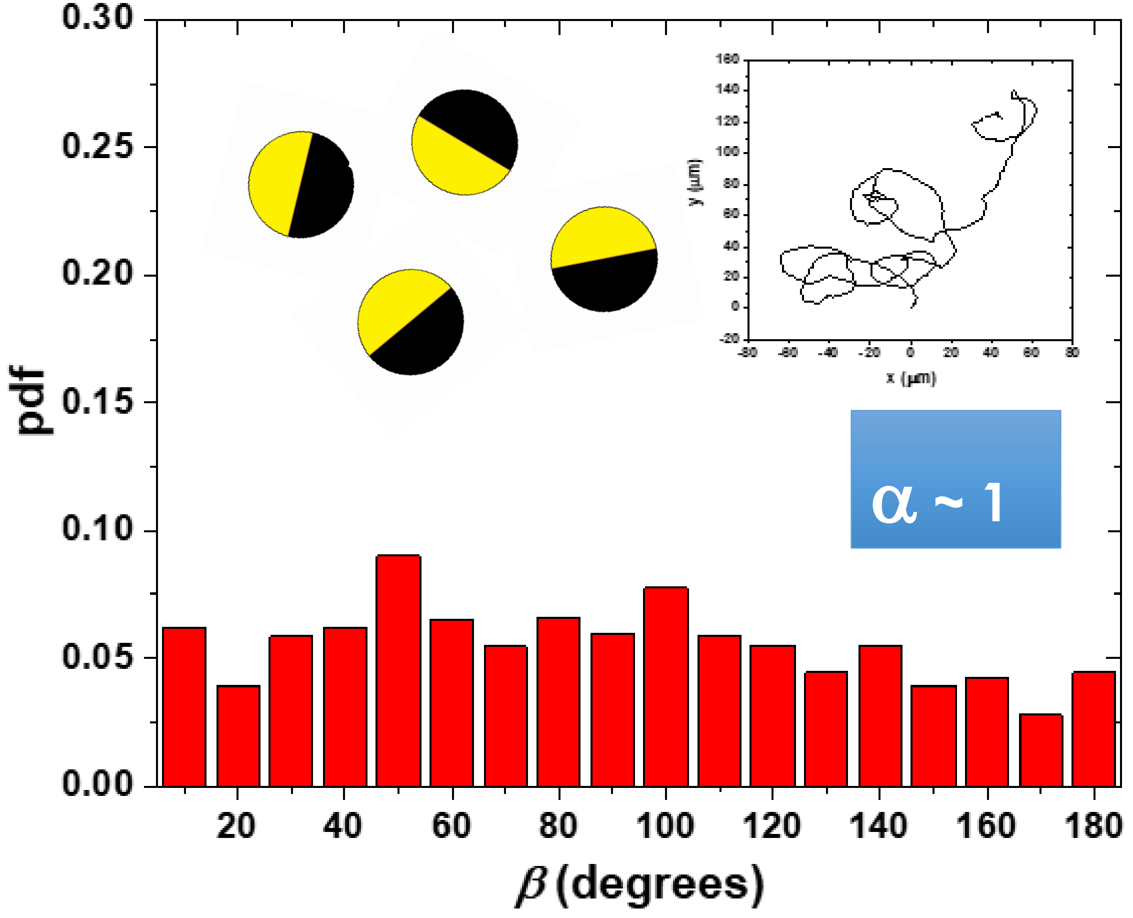


Out of plane rotation of Janus boundary

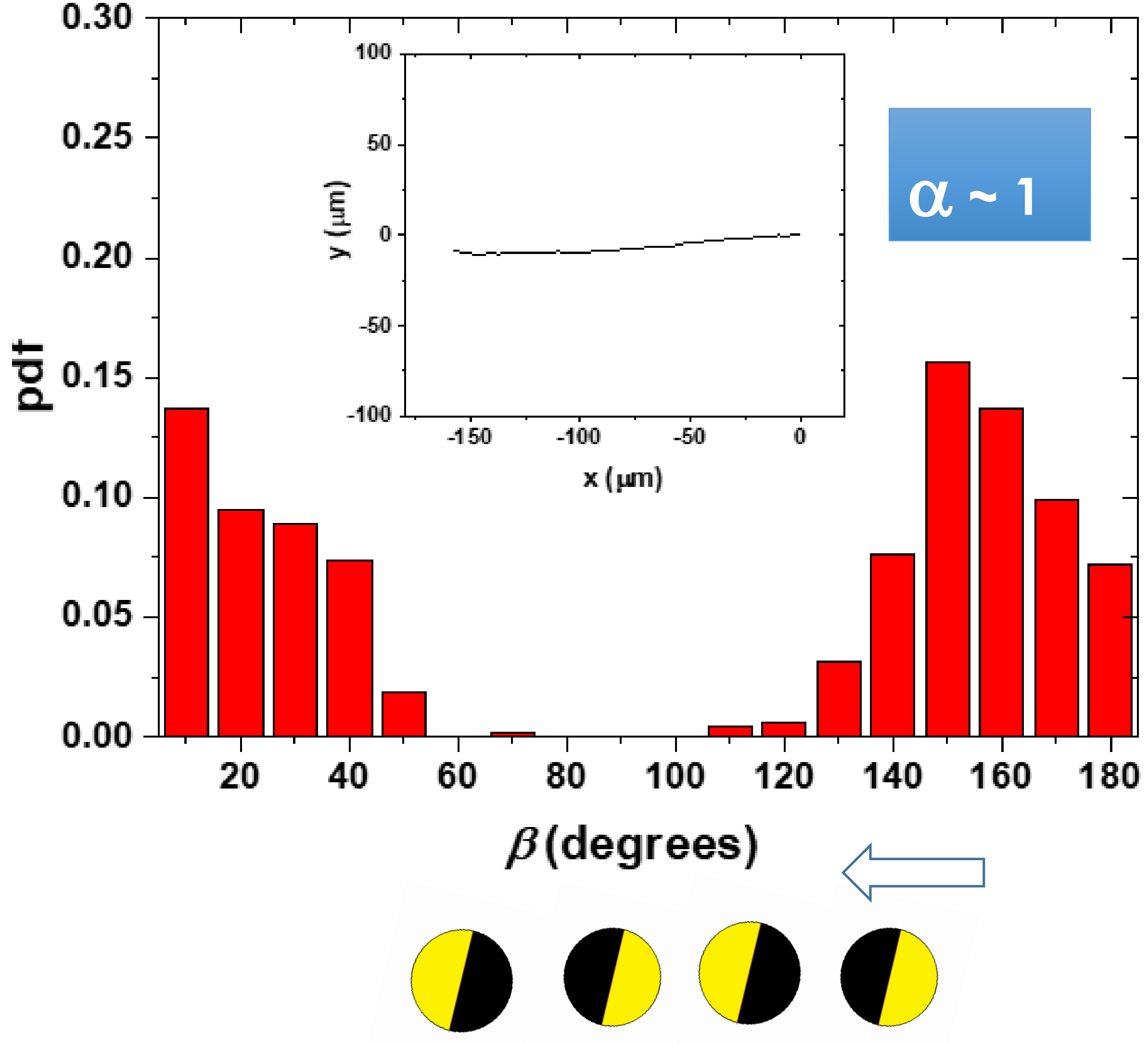
$$\boxed{\Gamma_{shear} \sim \frac{v_{x,\,flow}}{a}}$$

Random motion and migration along flow

$\lambda << 1 \quad \Gamma_{activity} >> \Gamma_{flow,x}$



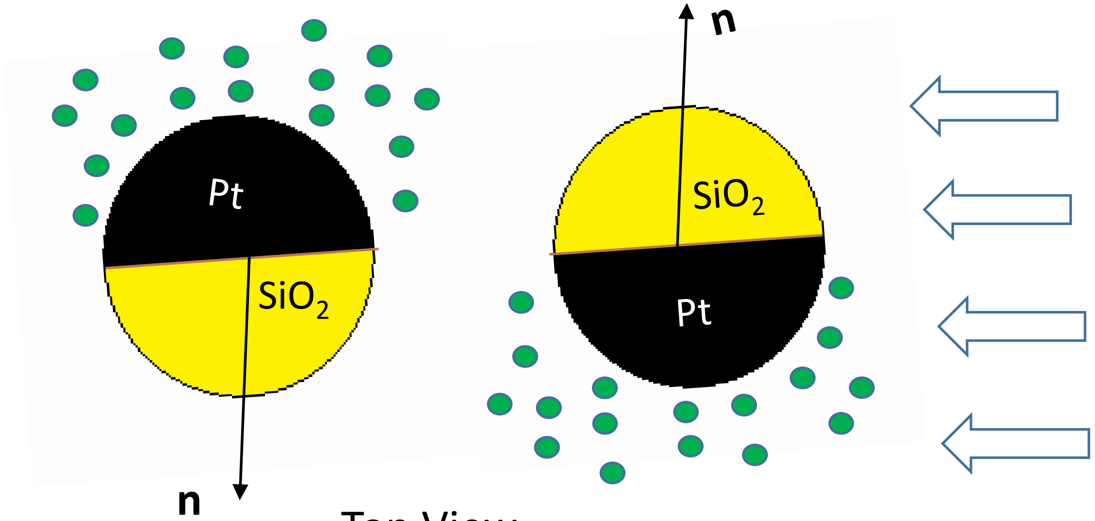
$\lambda >> 1 \quad \Gamma_{activity} << \Gamma_{flow,x}$



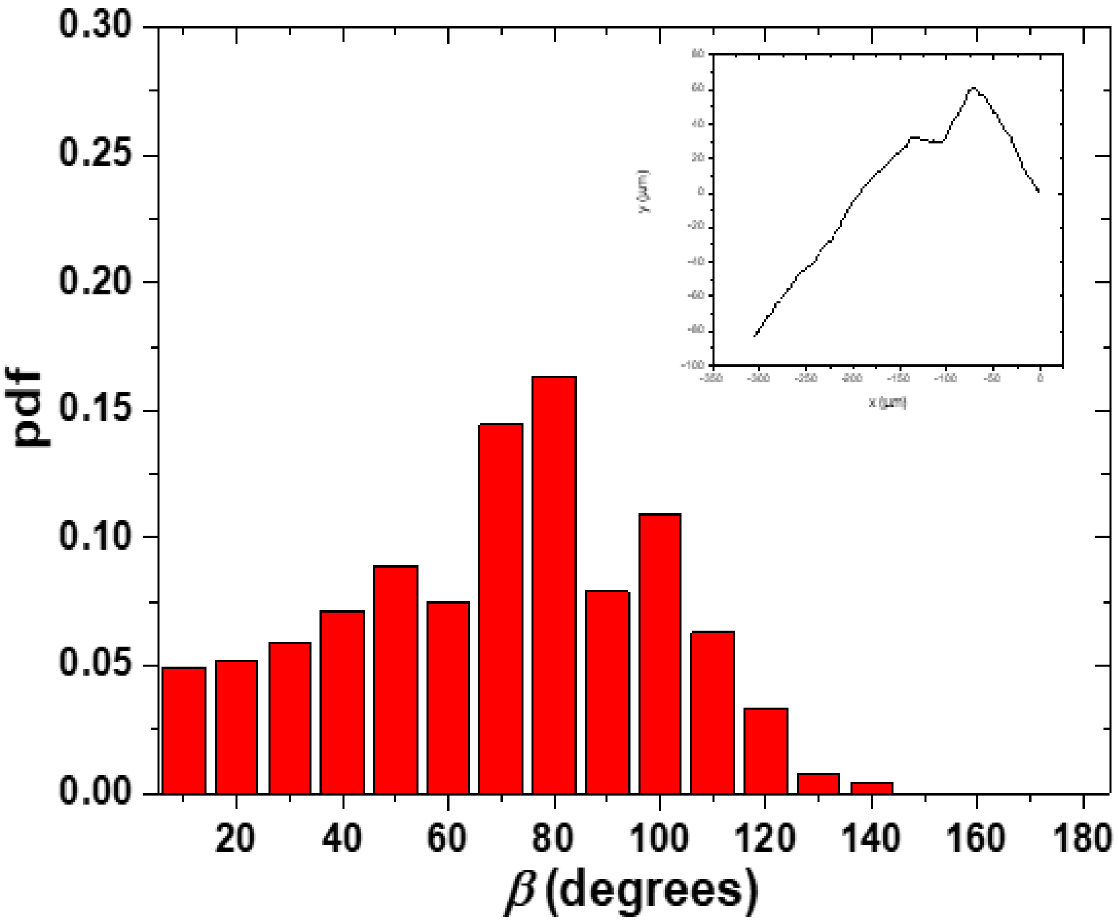
Migration across Stream Lines

$\lambda \sim 1 \qquad \Gamma_{activity} \sim \Gamma_{flow,x}$

$\beta \sim 90°$



Top View



$\alpha > 1$

Conclusions

Because of presence of wall Active Propulsion brings the Janus boundary perpendicular to the plane

Shear flow tries to rotate the Janus boundary out of plane

Low Flow rates restoring rotation due to activity is quick compared to rotation due to flow

→ Random motion

High Flow rates rotation due to flow is quicker than restoring rotation due to activity

→ Migration along flow

Moderate flow rates due to competing rotational mechanisms → Particles migrate across streamlines

Non-dimensional parameter λ explains the observations universally

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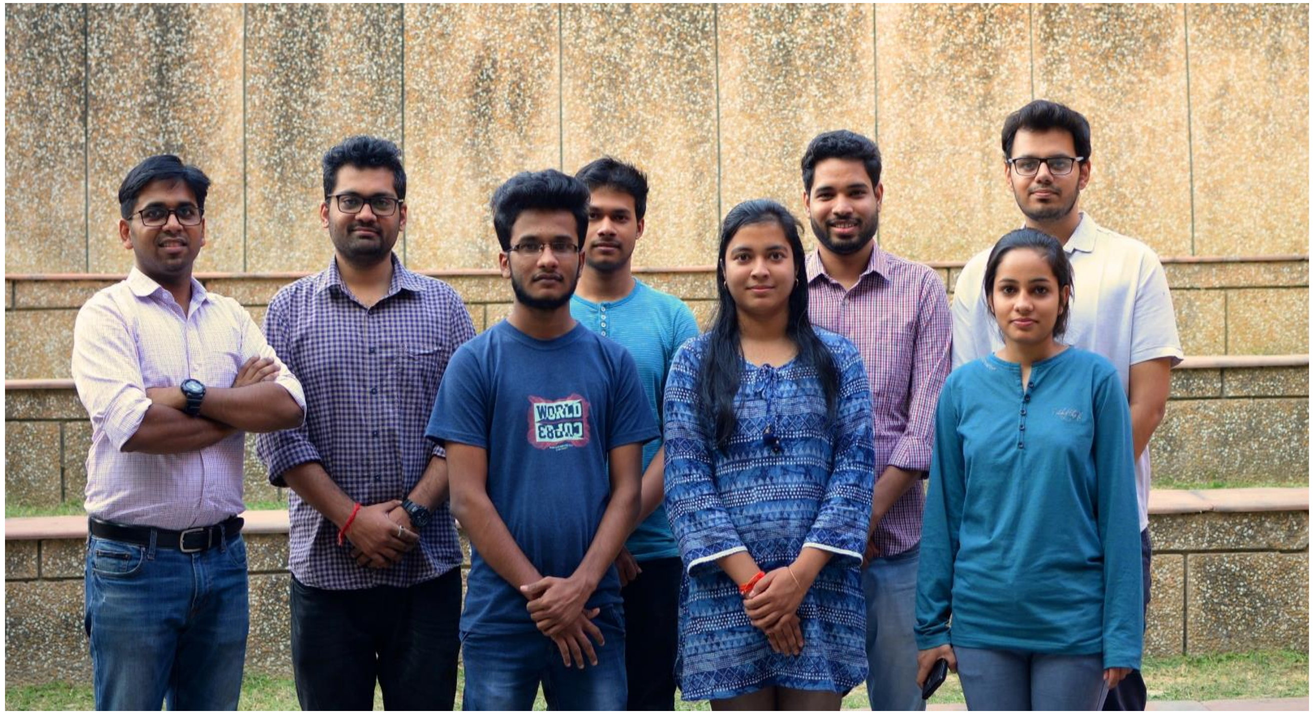

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