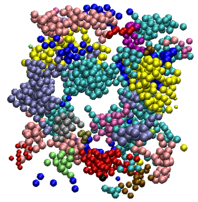
Living clusters and crystals from low-density suspensions of active colloids

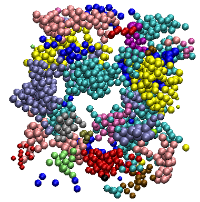


Chantal Valeriani

Universidad Complutense de Madrid

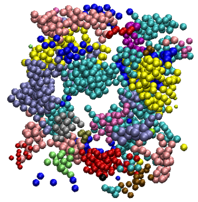
KITP, 13Th of February 2014

Outline



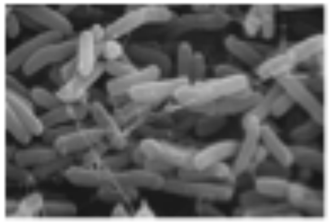
- ✓ Active colloids
- ✓ Self-assembly of active colloids
- ✓ What happens in a bacteria & polymer mixture?
- ✓ Can we make living clusters of active colloids in low concentrated suspensions?

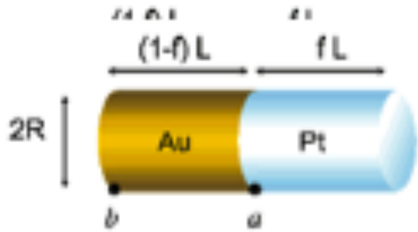
Active colloids

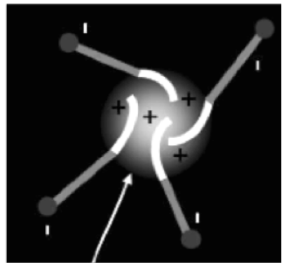


active colloids: absorb energy from their surroundings
or from an internal fuel and
dissipate it while moving around

examples: living bacteria,
self-propelled colloids,
synthetic centrosomes



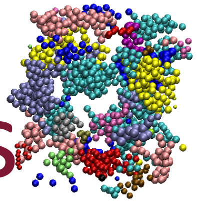




Ramaswamy (2004) & Marchetti (2013)

a suspension of active colloids is driven
out of equilibrium by its active nature

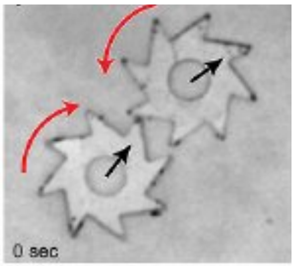
Self-assembly of active colloids



Why? Technologically relevant

active colloids can be used to self-assemble novel smart materials, that could perform tasks such as

produce energy



perform directional motion

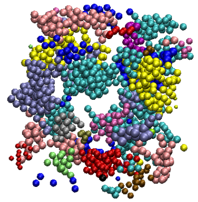
Di LeonardoPNAS (2009)

Sokolov PNAS (2009)

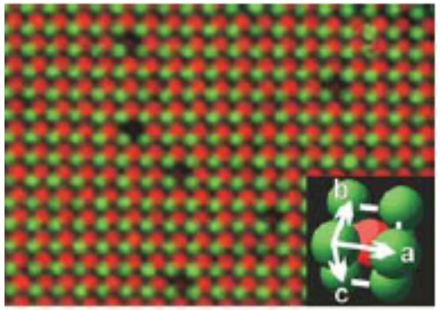
“Fundamentally” relevant

the Physics of a suspension of intrinsically out of equilibrium systems still needs to be fully understood

Self-assembly
in Soft Matter (passive colloids)

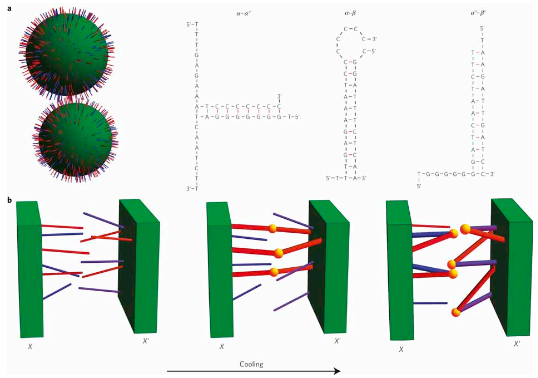


Oppositely charged colloids



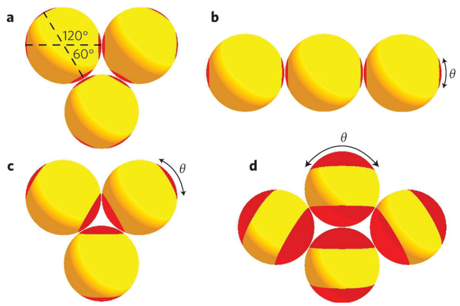
Leunissen, Dijkstra,
van Blaaderen

DNA-coated colloids



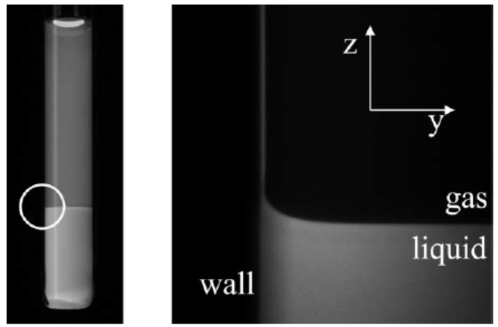
Frenkel&Eiser
Pine&Chaikin

Patchy colloids



Sciortino
Delgado
Granick
Glotzer

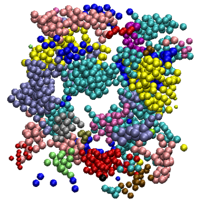
Colloid&Polymer mixture



Aarts & Lekkerkerker

What happens in a suspension of active colloids?

What happens in a bacteria & polymer mixture?



The team:

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Angelo Cacciuto

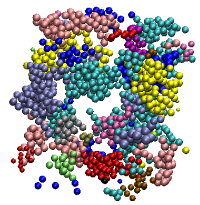
University of Edinburgh

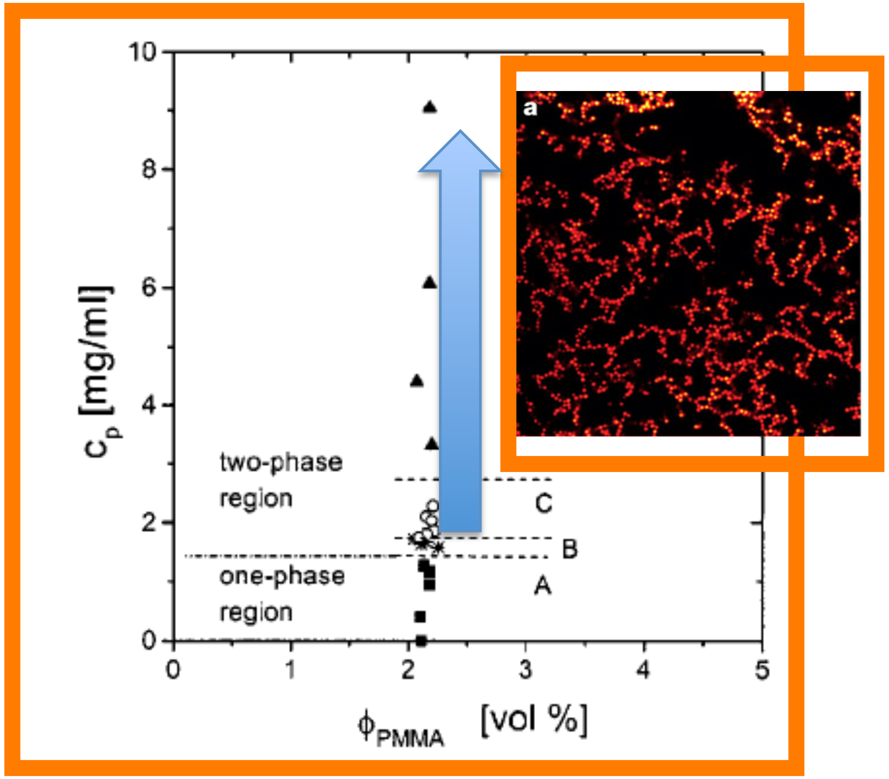
Mike Cates

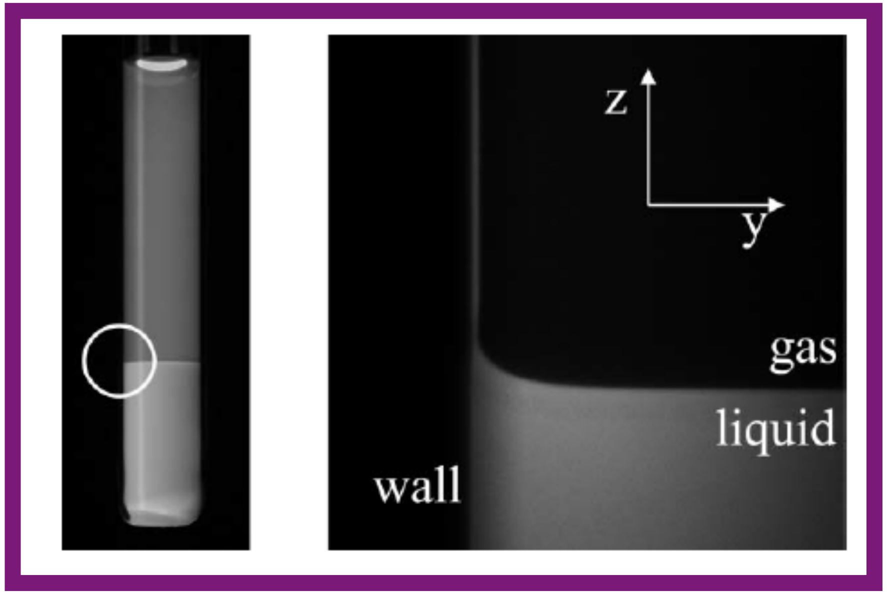
Wilson Poon

Davide Marenduzzo

Colloid & Polymer mixture







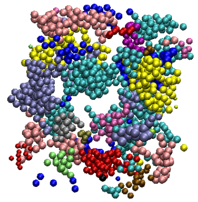
Asakura, Oosawa, Vrij (1954, 1976)

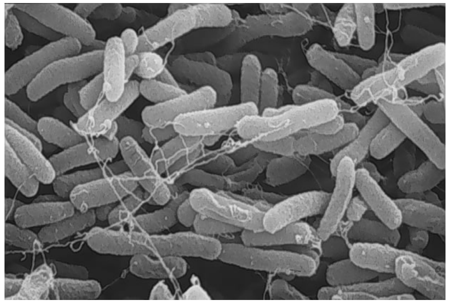
Lekkerkerker (1992, 2002)

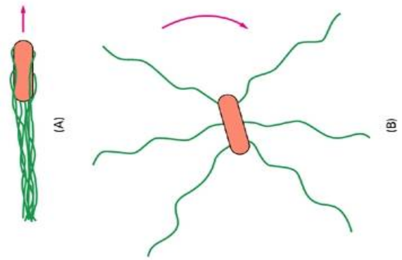
Dijkstra (1999)

Aarts (2006)

Bacteria & polymer mixture

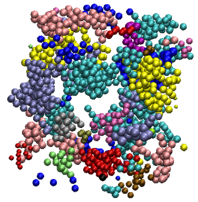


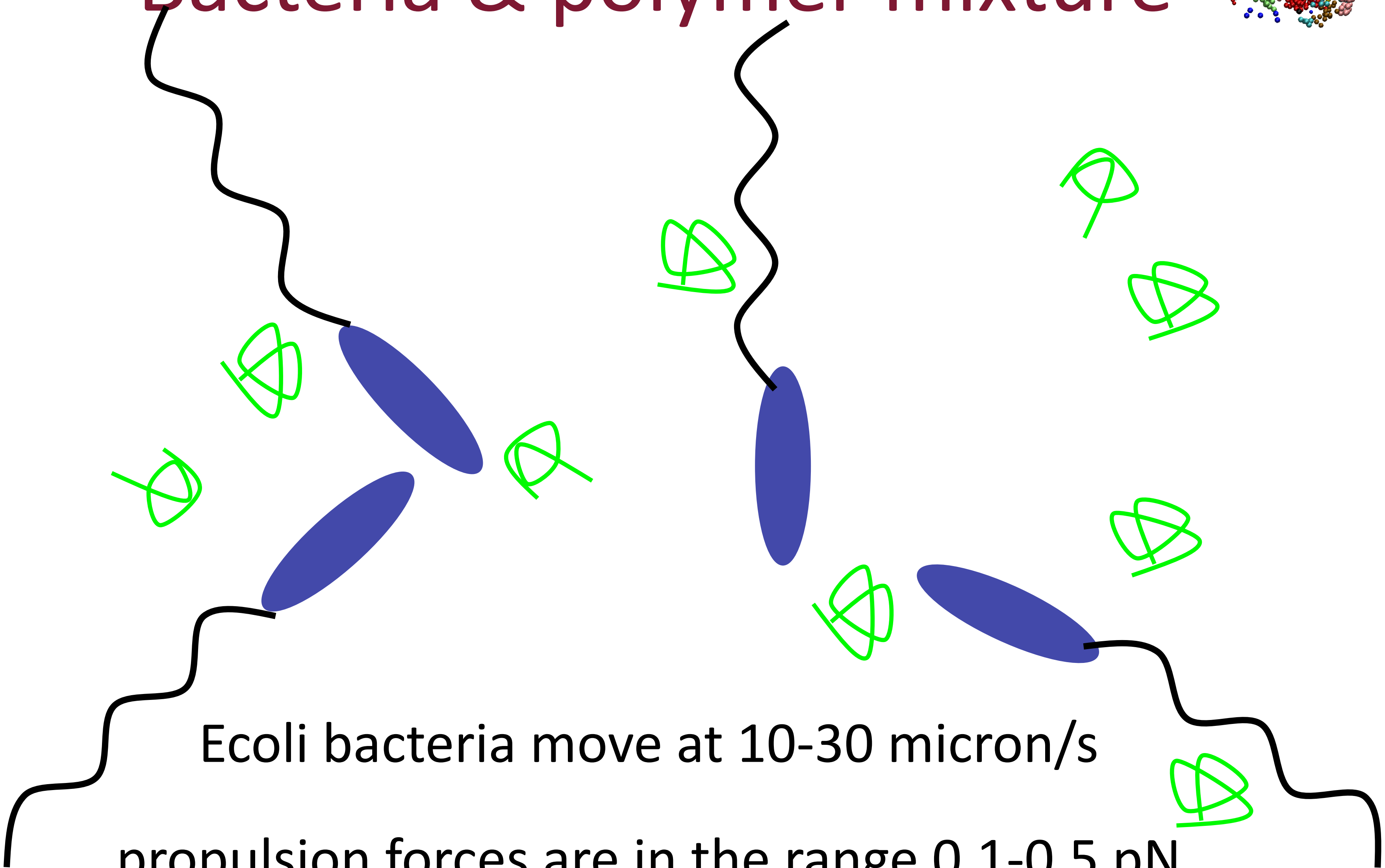




Bacteria swim (self-propel)
due to the presence of flagella

Bacteria & polymer mixture

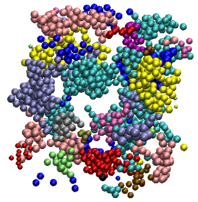


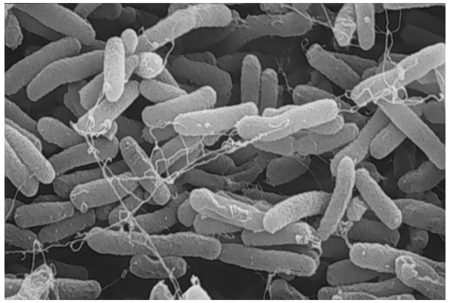


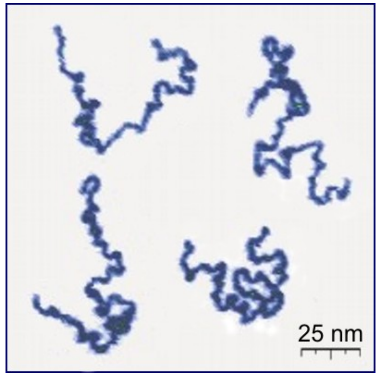
Ecoli bacteria move at 10-30 micron/s

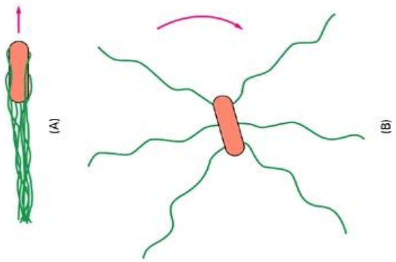
propulsion forces are in the range 0.1-0.5 pN

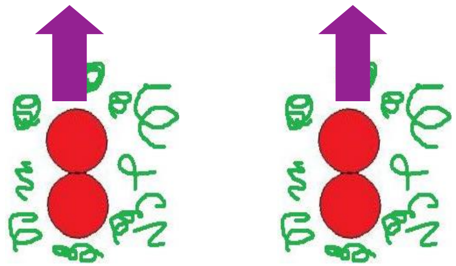
Bacteria & polymer mixture









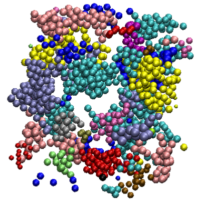


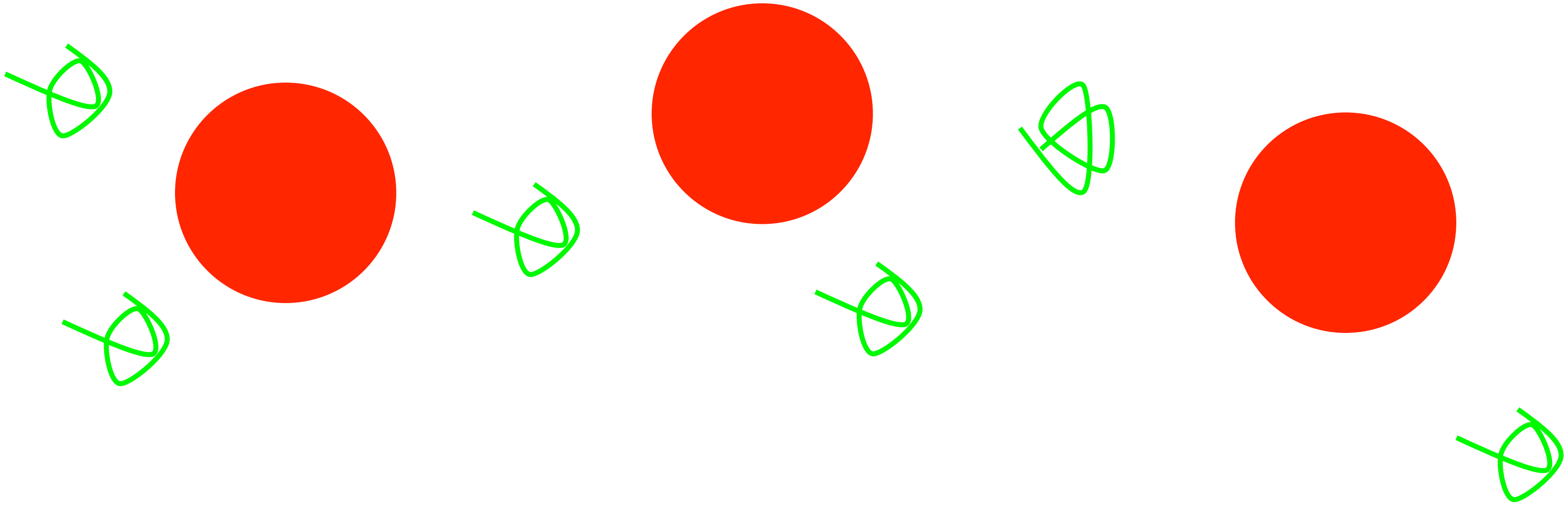
bacteria swim (self-propel)
due to the presence of flagella

polymers lead to depletion
attraction between
non-motile bacteria

Schwarz-Linek, Soft Matter(2010)

Bacteria & polymer mixture



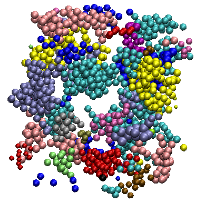


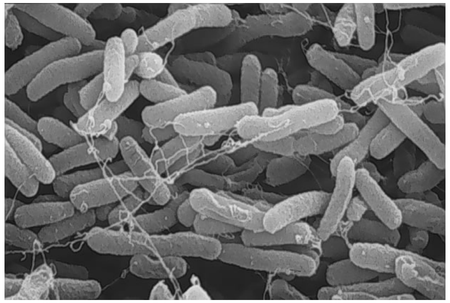
in a colloid-polymer mixture

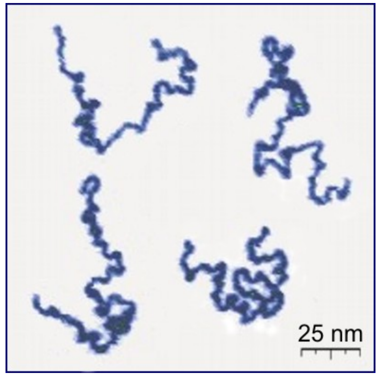
depletion forces are ~ k_BT/giration radius (~10-100 nm)

so in the range of 0.05-0.5 pN

Bacteria & polymer mixture

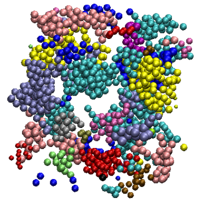






competition between
propulsion and attraction

Bacteria & polymer mixture



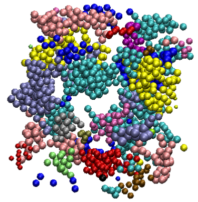
experiments

Ecoli ✚ NaPSS

simulations

self-propelled hard dumbbells ✚ short-range attractions

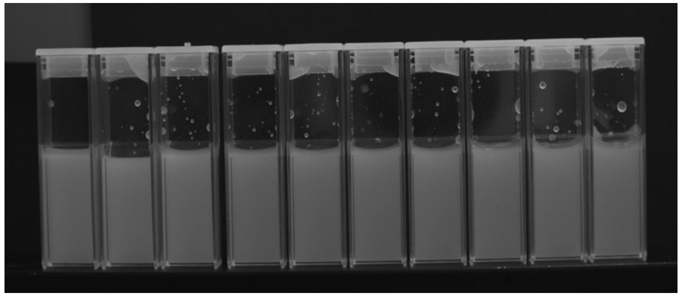
competition between propulsion and attraction



Phase separation

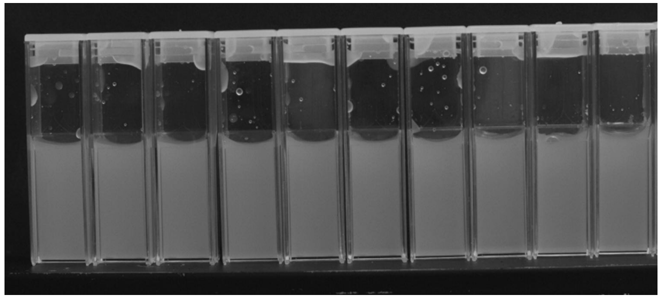
experiments

Non-motile Ecoli (alive, no flagella)

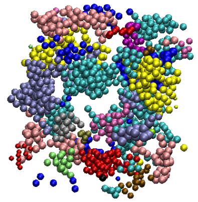


increasing polymer (NaPSS) concentration

Motile Ecoli (alive, swimming)



increasing polymer (NaPSS) concentration



Phase separation

experiments

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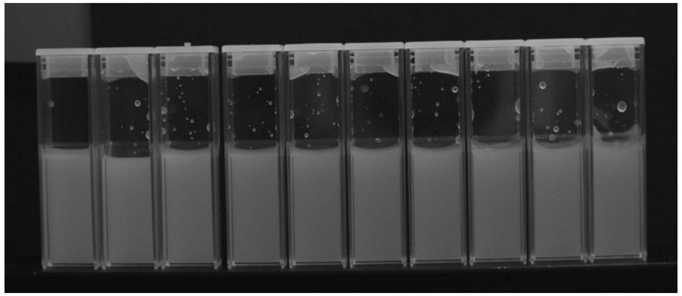
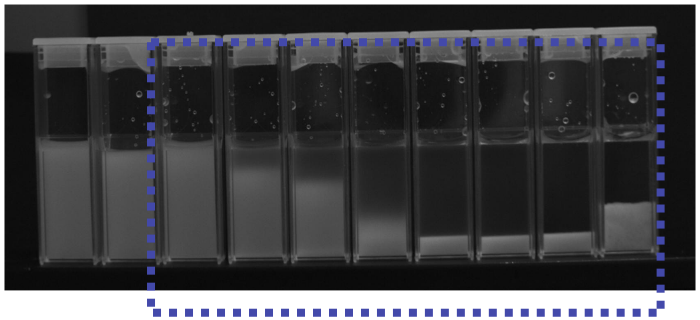
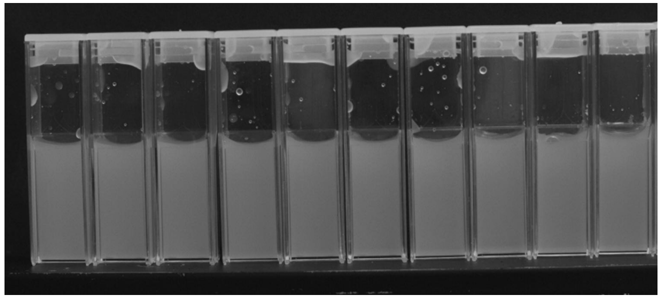


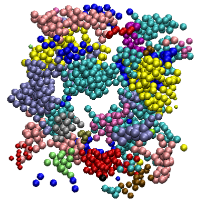


2 hours: phase separation

if NaPSS > 0.2 wt %

Motile Ecoli (alive, swimming)

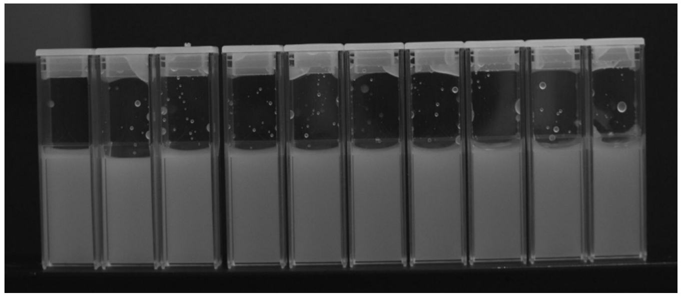


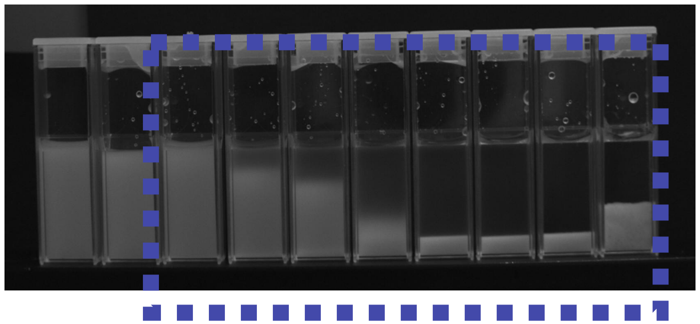


Phase separation

experiments

Non-motile Ecoli (alive, no flagella)

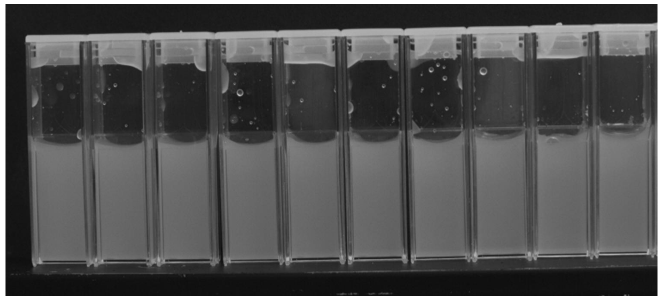


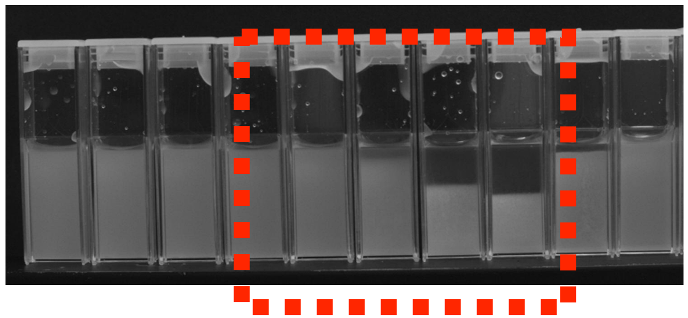


2 hours: phase separation

if NaPSS > 0.2 wt %

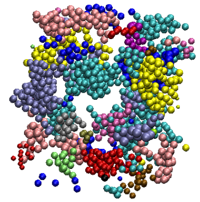
Motile Ecoli (alive, swimming)





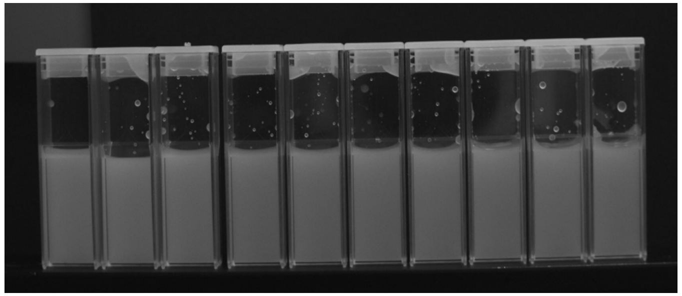
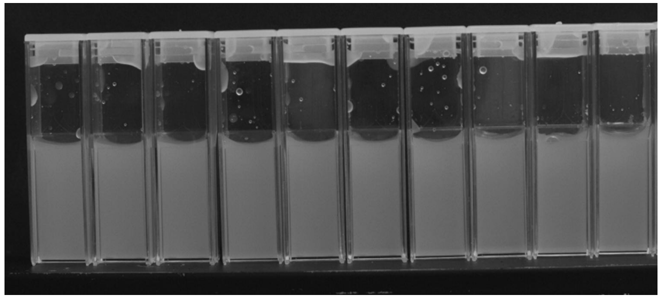
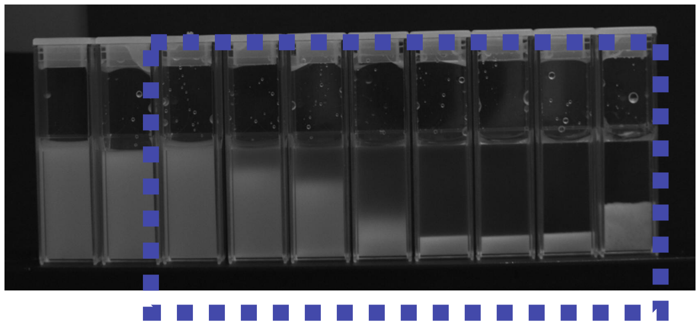
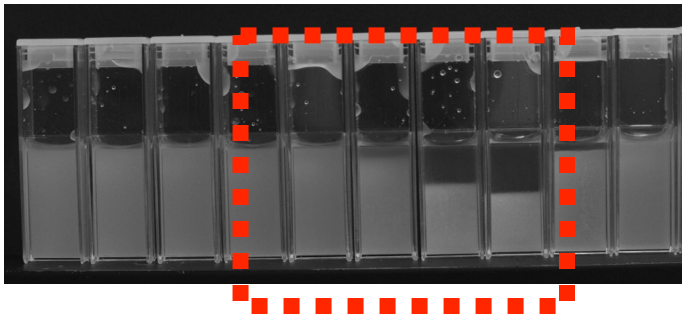
2 hours: phase separation

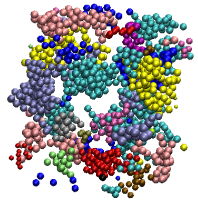
if NaPSS > 0.4 wt %



Phase separation

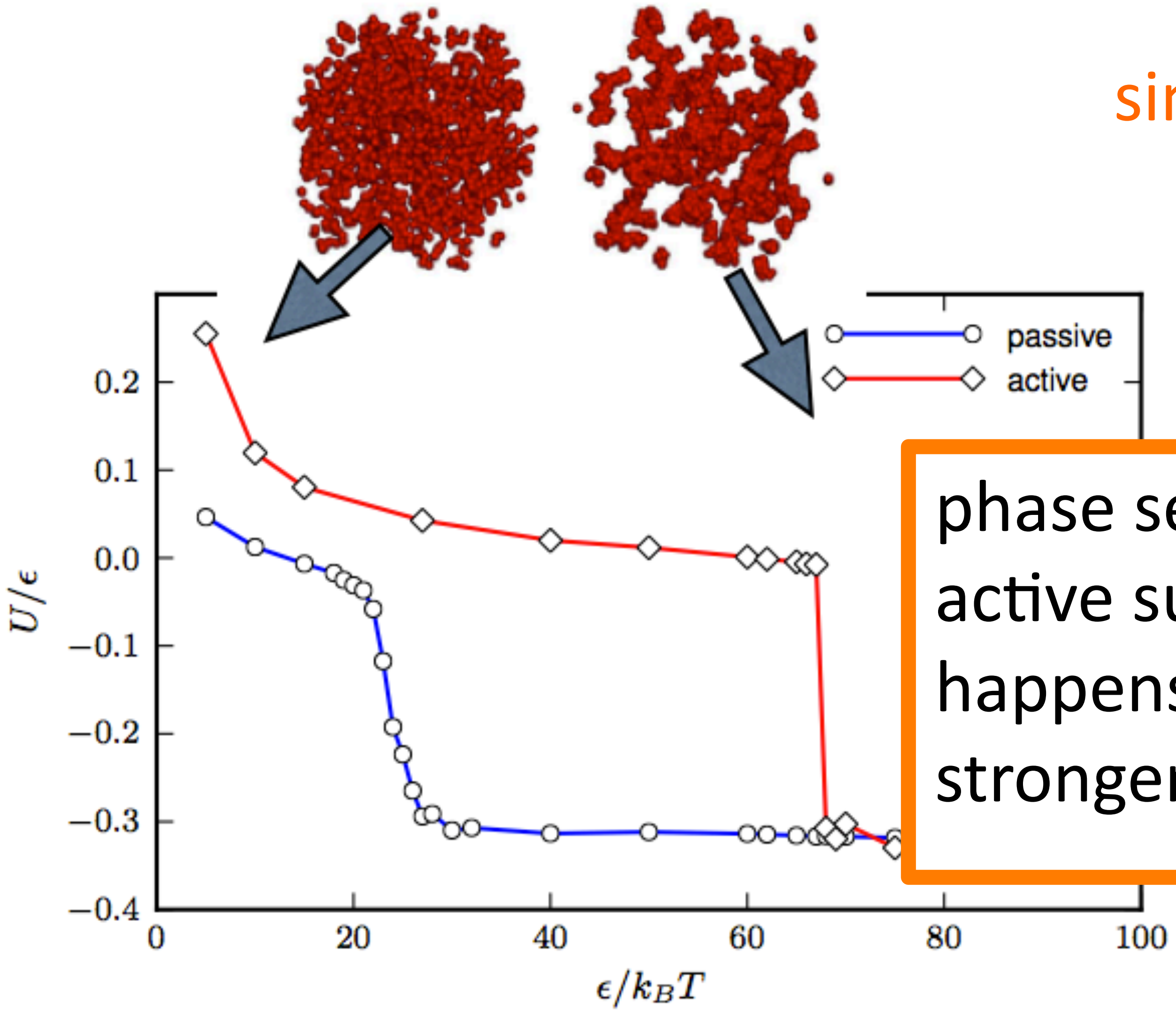
experiments

Non-motile Ecoli (alive, no flagella)	Motile Ecoli (alive, swimming)
	
	
2 hours: phase separation	this corresponds to a
if NaPSS > 0.2 wt %	stronger depletion attraction



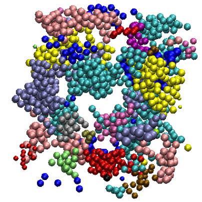
Phase separation

simulations

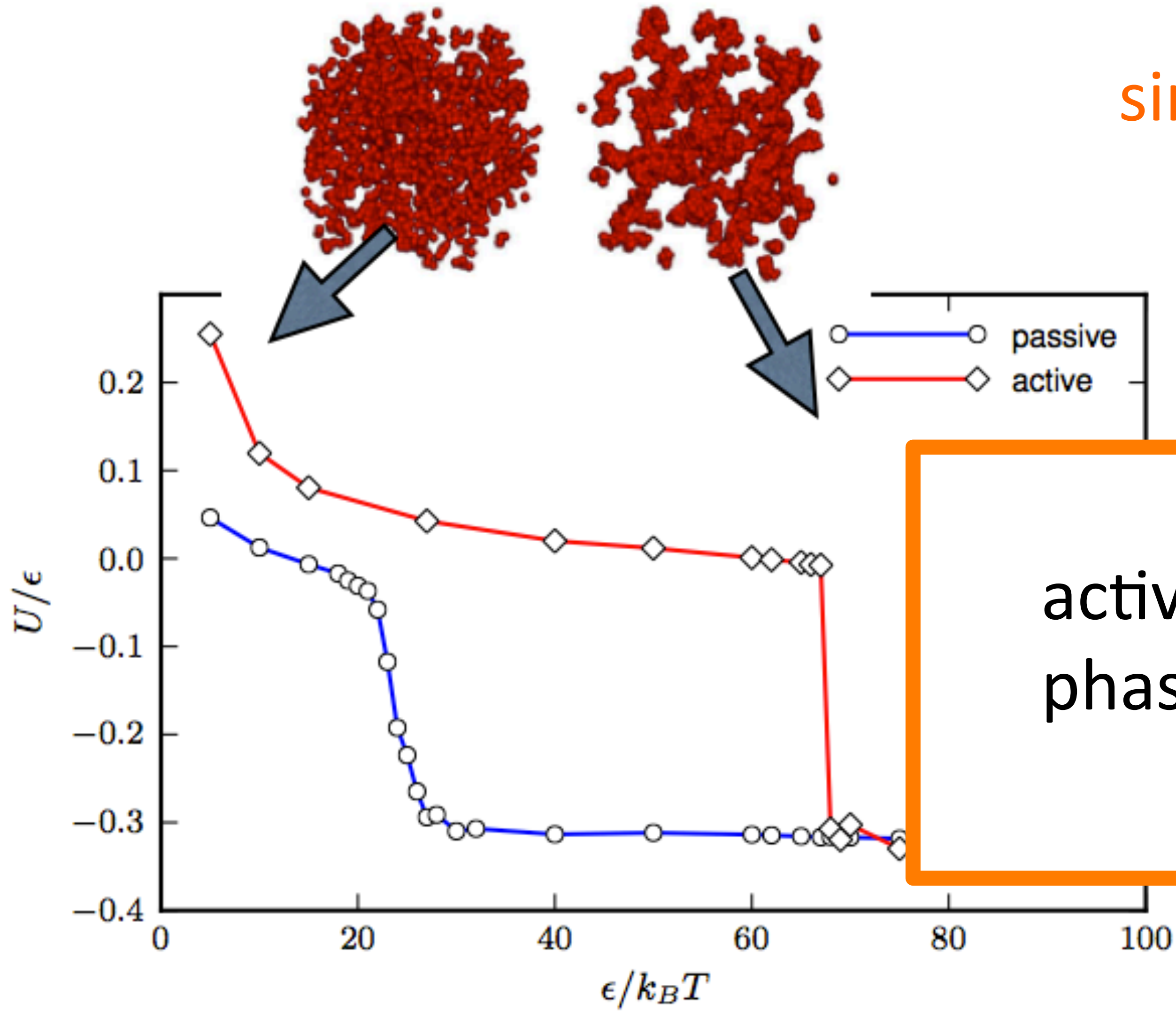


phase separation in an active suspension happens for stronger attraction

Phase separation

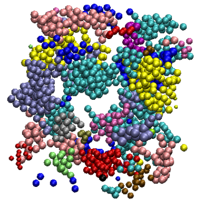


simulations

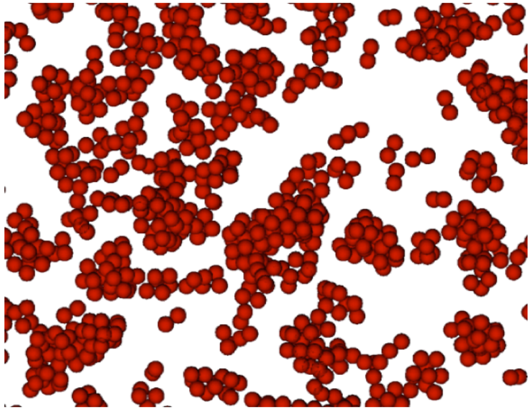


activity suppresses phase separation

What happens just before phase separation takes place?



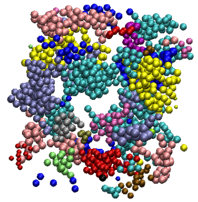
transient clusters

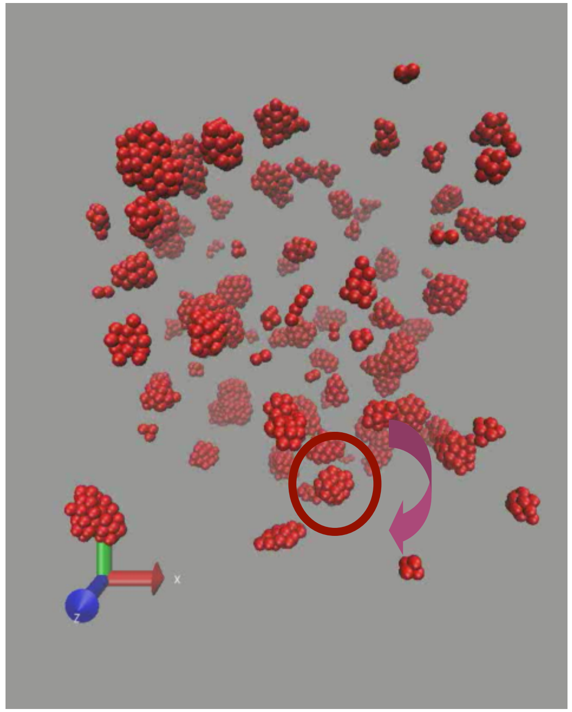


finite-size clusters of variable size (simulations)

small clusters (flagella of external bacteria may screen interactions) (experiments)

Self-assembly of nano-rotors

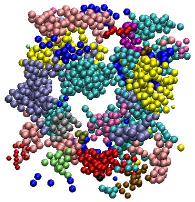


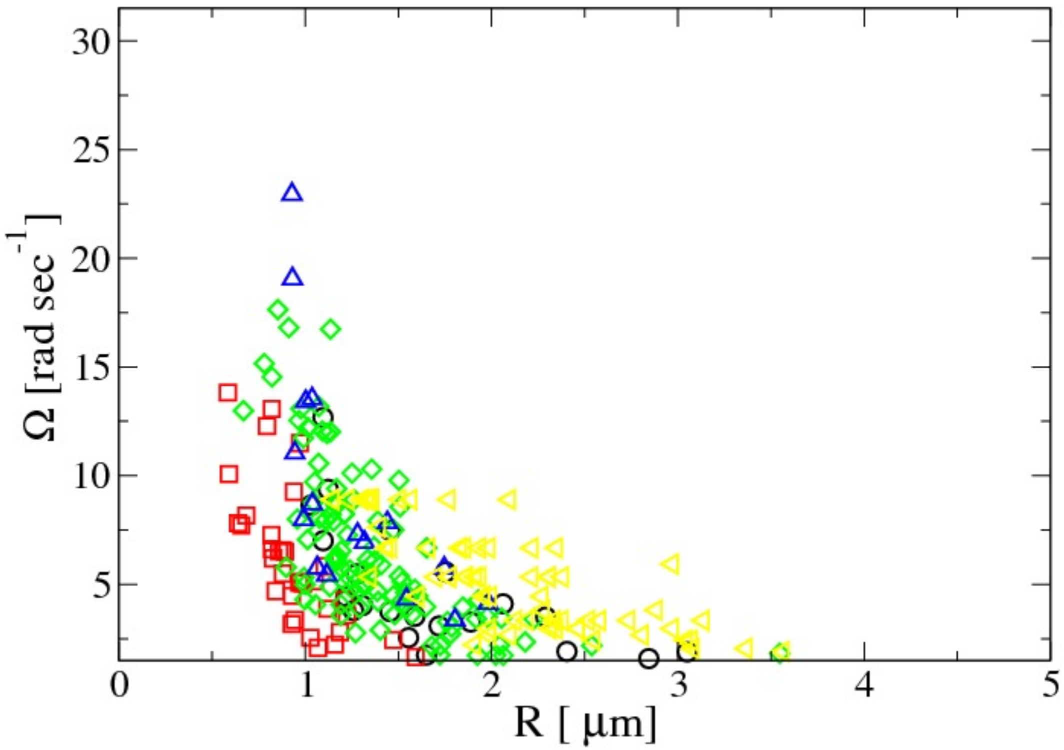


experiments   simulations

persistent clusters rotate unidirectionally

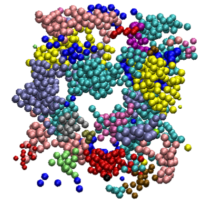
Clusters' angular velocity is a function of their size





angular velocity of a cluster decreases with its size

Conclusions

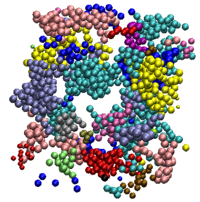


- ✓ Activity suppresses phase separation
- ✓ At lower polymer concentrations, formation of self-propelled and unidirectionally rotating clusters
- ✓ Activity & propulsion are the ingredients to self-assemble functional clusters

PNAS 106 4052 (2012)

Research highlight in
Nature Materials/Nature Physics (2012)

However…

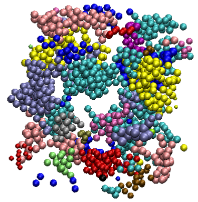


- ✓ in the bacteria & polymer mixture, we changed the attraction strength (polymer concentration) between active colloids

- ✓ but we did not modify their speed…

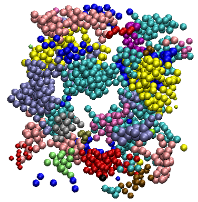
- ✓ therefore clusters were just transient and would aggregate at long times

Outline



- ✓ Active colloids
- ✓ Self-assembly of active colloids
- ✓ What happens in a bacteria & polymer mixture?
- ✓ Can we make living clusters of active colloids in low concentrated suspensions

Living clusters



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Daan Frenkel

Columbia University

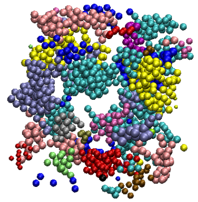
Stefano Angioletti Uberti

Angelo Cacciuto

Andela Sairc

Bortolo Mognetti

Phase separation/clusters in 2 dim self-propelled systems



2 dim rod-shaped (at low/high concentrations) steric/ideal

Peruani, Deutsch, Bar (2006)

Yan, Marceau, Gompper (2010)

Ginelli, Peruani, Bar, Chate(2006)

or 2dim spherical shaped interacting via a repulsive potential (at high concentration)

Stenhammar,Tirabocchi, Allen, Marenduzzo, Cates (2011)

Redner, Hagan, Baskaran (2013)

Tailleur, Cates (2013)

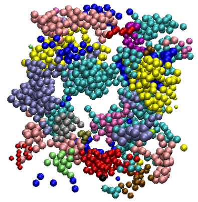
Henke, Fily, Marchetti (2011)

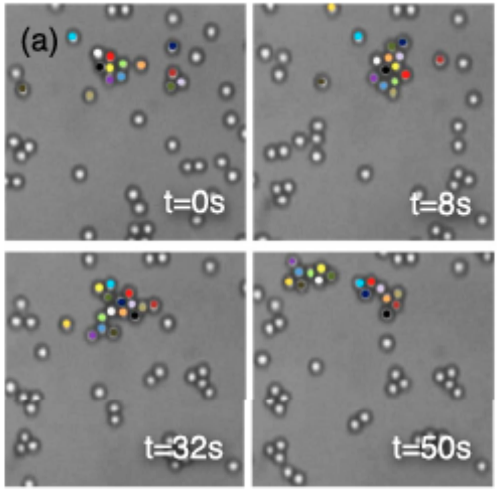
or 2dim spherical shaped interacting via an attractive potential (at high concentration)

Redner, Baskaran, Hagan (2013)

What happens for attractive self-propelled spheres at low concentrations?

Experimental evidences for living clusters in 2 dim



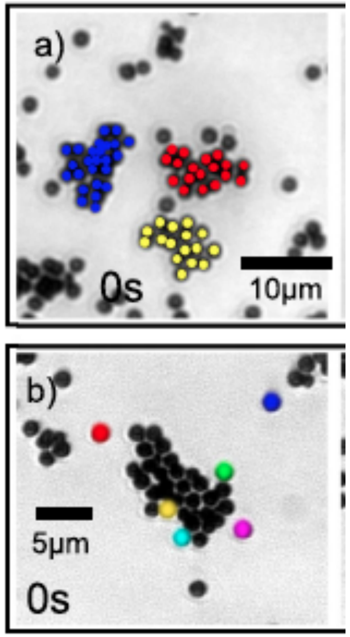


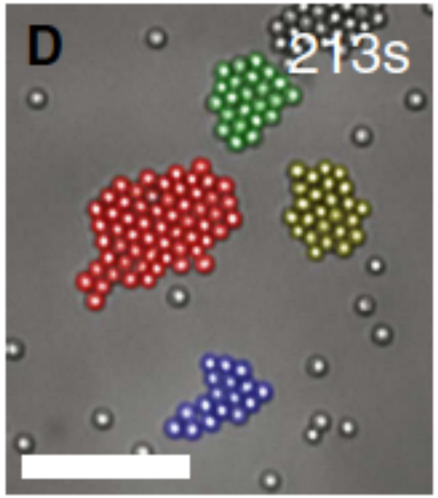
Buttinoni,Bialke, Kummel, Lowen, Bechinger, Speck (2013)

dynamic clusters at low densities in a 2dim suspension of SP purely repulsive colloids

Theurkauff, Cottin-Bizonne, Palacci,Ybert, Bocquet (2012)

cluster phase at intermediate densities

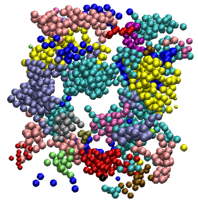


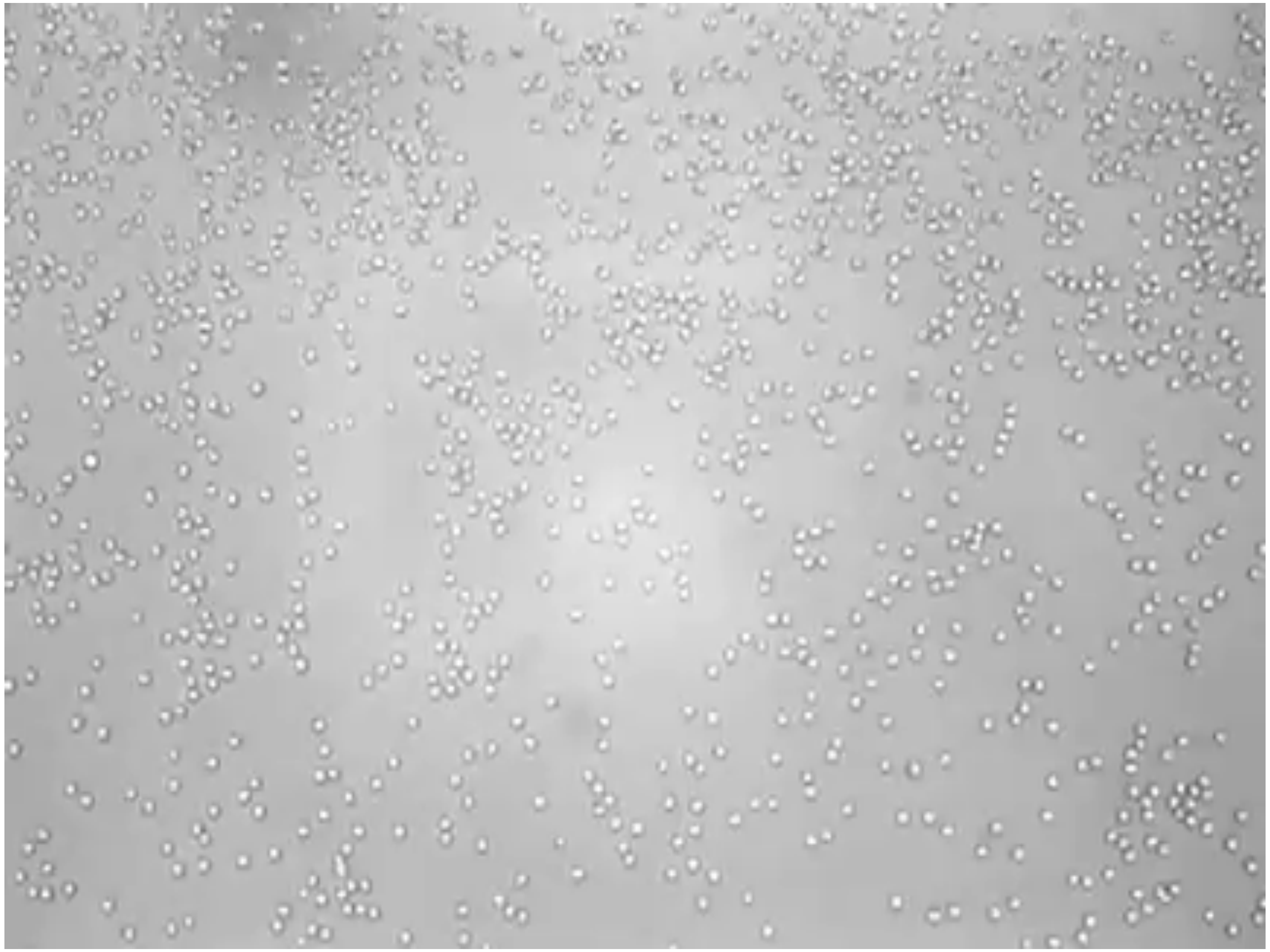


Palacci, Sacanna, Steinberg, Pine, Chaikin (2013)

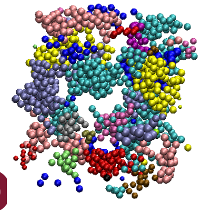
living clusters and crystals

Experimental evidences for living clusters in 2 dim

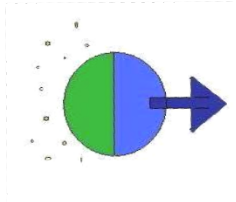




Which low concentrated suspensions of active colloids?

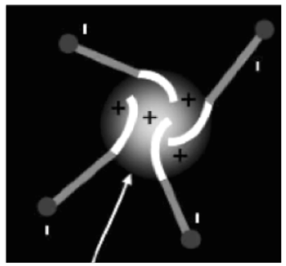


✓Self-propelled colloids (SP)



to mimic reactive colloids

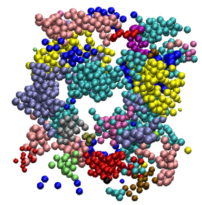
✓Self-displaced colloids (SD)



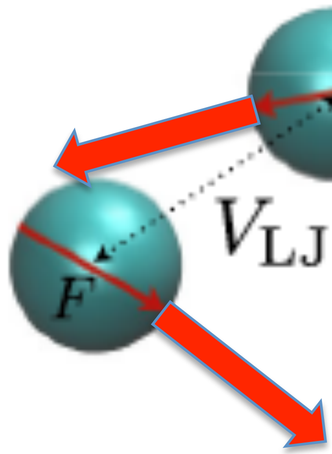
to mimic synthetic centrosomes
(colloids & microtubules)

(Spoerke Langmuir (2008)

Self-propelled colloids



$$m\ddot{\boldsymbol{r}}_i = -\sum_{j\neq i}\frac{\partial V(r_{ij})}{\partial \boldsymbol{r}_i} - \zeta\dot{\boldsymbol{r}}_i + \boldsymbol{F}_i + \boldsymbol{F}_{R,i}$$

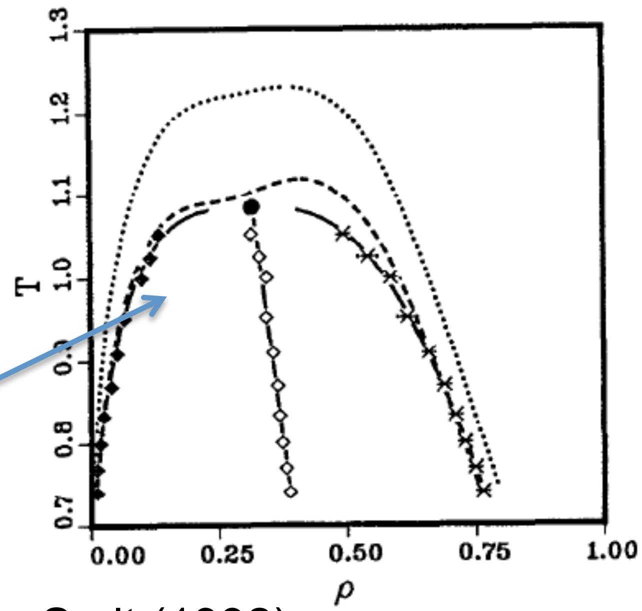


$$V(r_{ij}) = 4\epsilon\left[\left(\frac{\sigma_p}{r_{ij}}\right)^{12} - \left(\frac{\sigma_p}{r_{ij}}\right)^{6}\right]$$

truncated and shifted
Lennard-Jones interaction

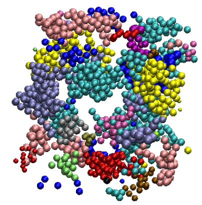
at low concentrations (ϕ=0.01-0.1)

LAMMPS

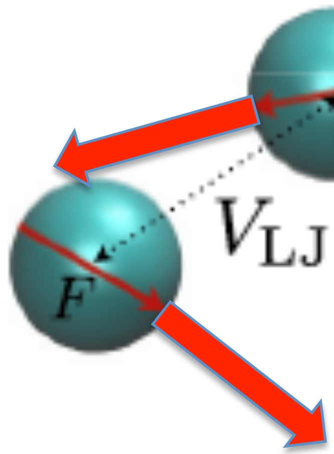


Smit (1992)

Self-propelled colloids



$$m\ddot{\boldsymbol{r}}_i = -\sum_{j\neq i} \frac{\partial V(r_{ij})}{\partial \boldsymbol{r}_i} - \zeta \dot{\boldsymbol{r}}_i + \boldsymbol{F}_i + \boldsymbol{F}_{R,i}$$

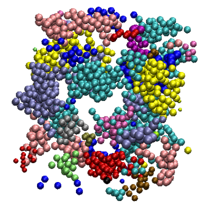


equilibrium: Lennard-Jones attraction

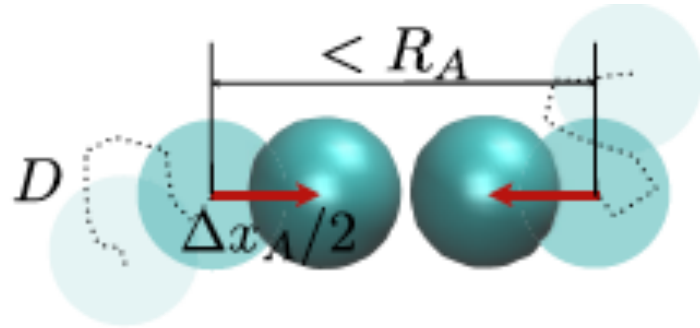
non-equilibrium: self-propulsion

Active versus equilibrium force

Self-displaced colloids

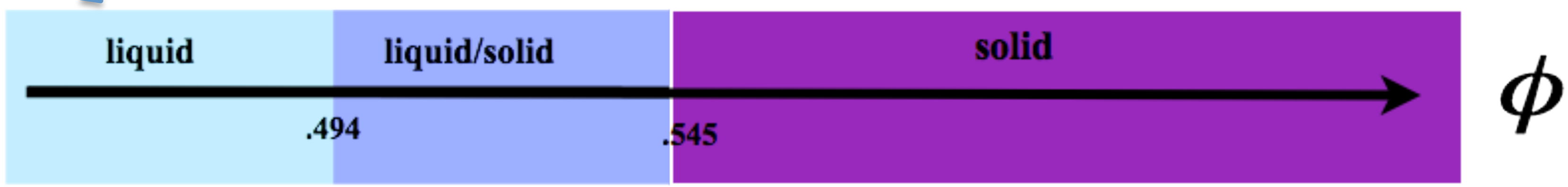


In the presence of ATP
two centrosomes are cross-linked
by molecular motors
and displaced towards each others

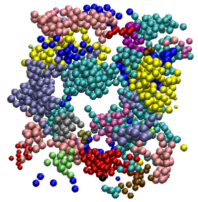


Monte Carlo

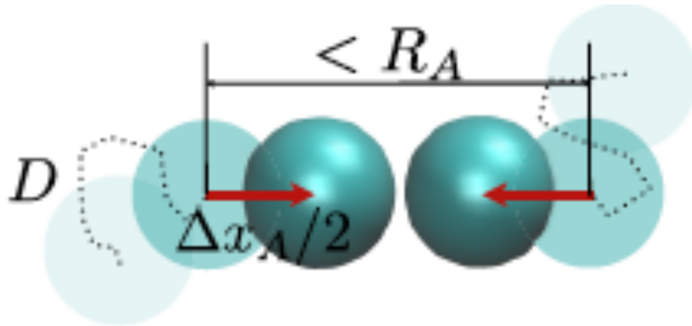
at low concentrations (ϕ=0.01-0.1)



Alder&Wainwrigth (1957), Pusey&van Megen (1986)



Self-displaced colloids

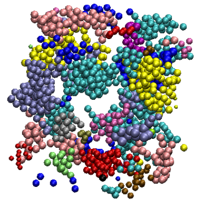


equilibrium: Brownian motion of hard-spheres with diffusion D

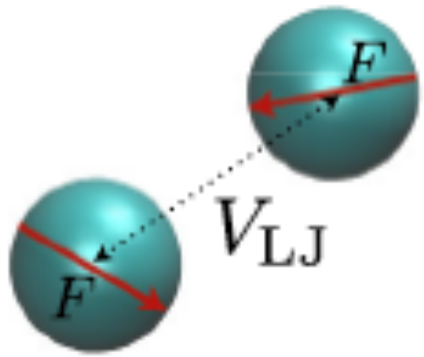
non-equilibrium: two colloids are displaced toward each other by molecular motors with a pulling rate v

Active versus equilibrium force

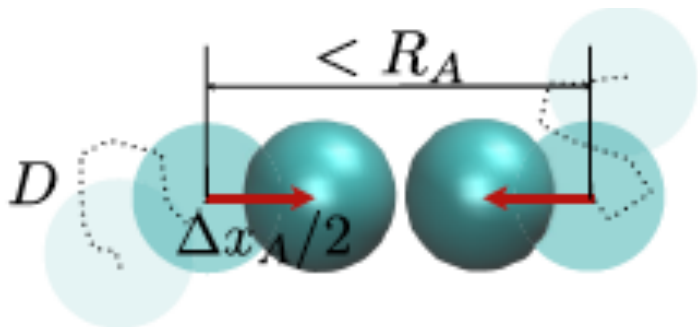
Is there a propensity for aggregation?



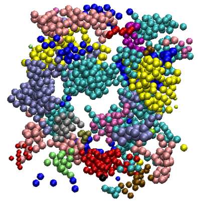
$$P_{agg}(SP) = \frac{\varepsilon}{F\sigma}$$

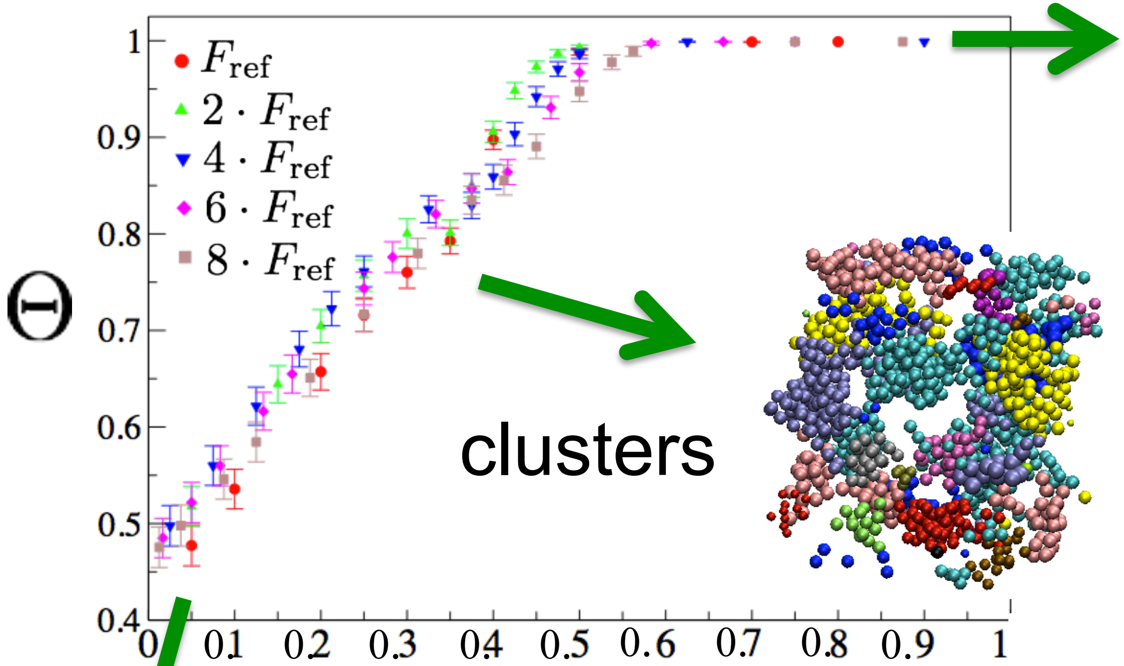


$$P_{agg}(SD) = \frac{\nu}{D/(R_A - \sigma)^2}$$



Is there a propensity for aggregation?





one large aggregate (liquid&gas)

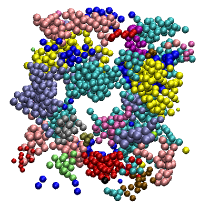
clusters

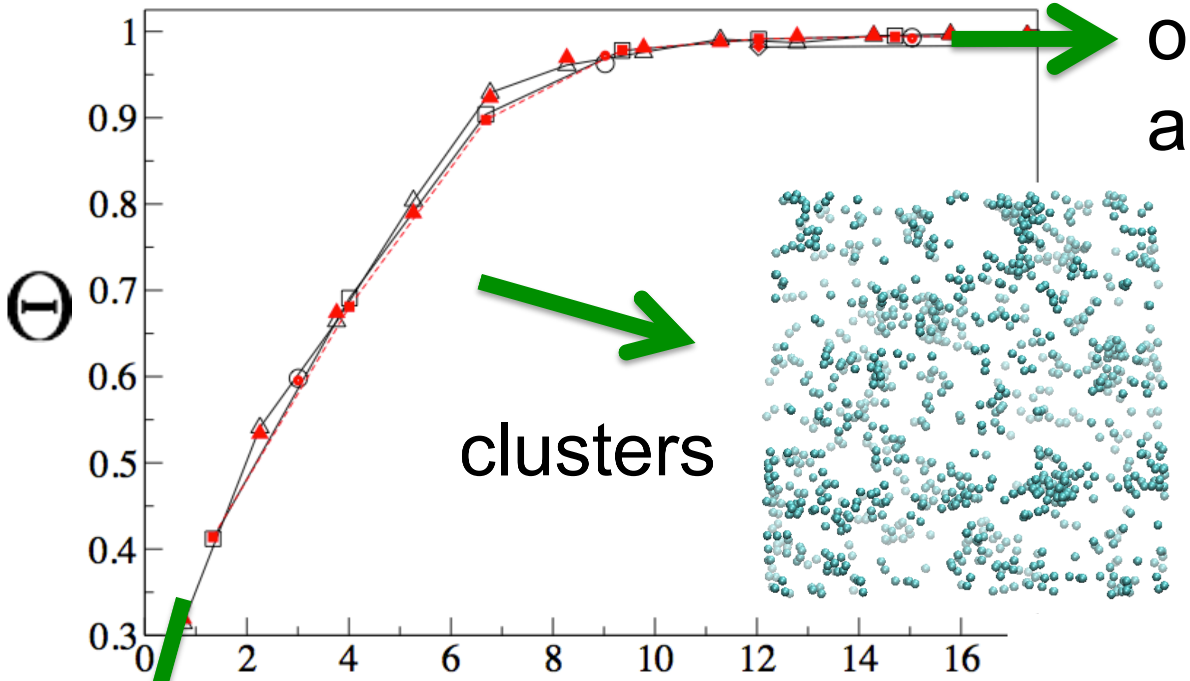
mainly monomers (gas)

$$P_{agg}(SP) = \frac{\varepsilon}{F\sigma}$$

Self-propelled colloids

Is there a propensity for aggregation?





one large aggregate (liquid&gas)

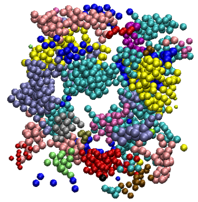
clusters

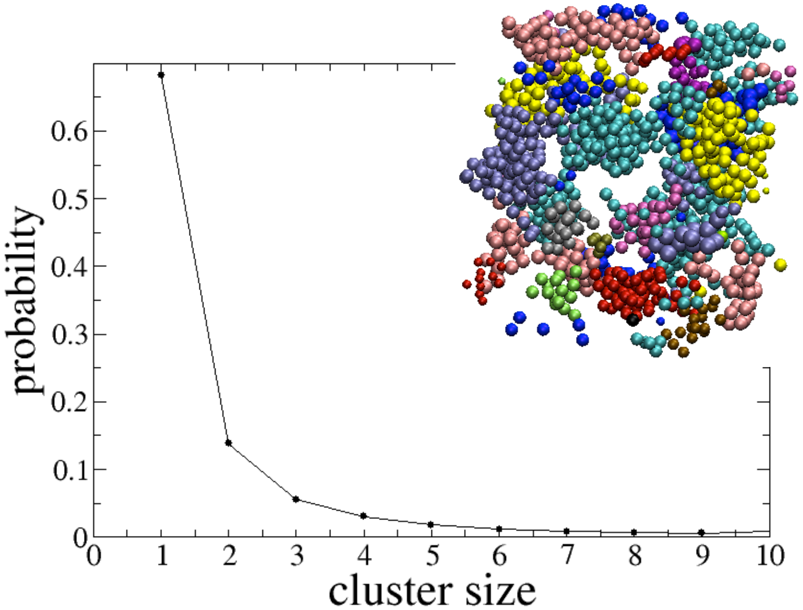
Self-displaced colloids

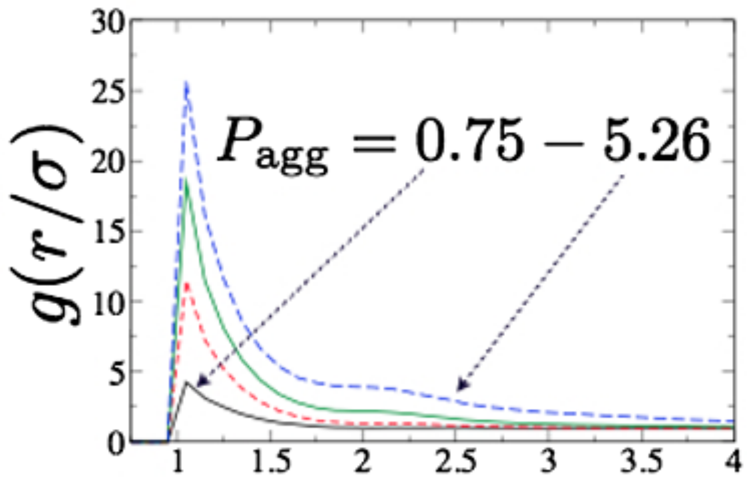
$$P_{agg}(SD) = \frac{\nu}{D/(R_A - \sigma)^2}$$

mainly monomers (gas)

Preliminary characterization of the clusters





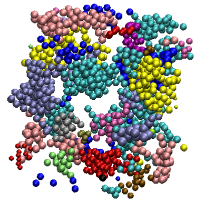


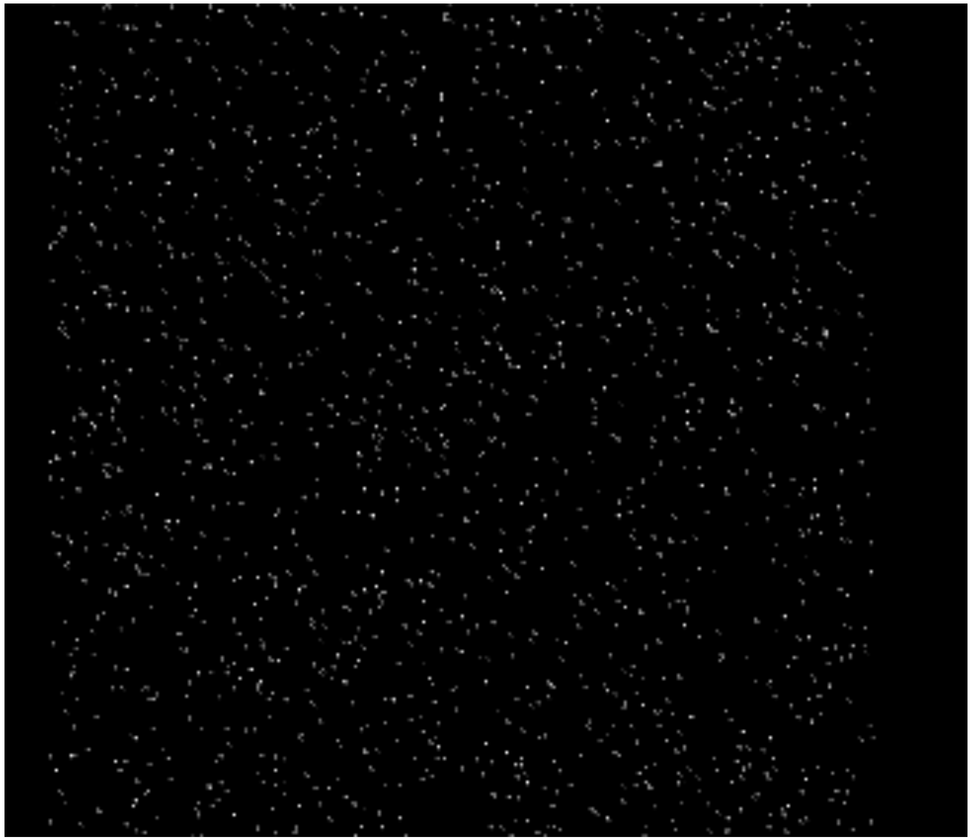
cluster-size distribution seems power-law

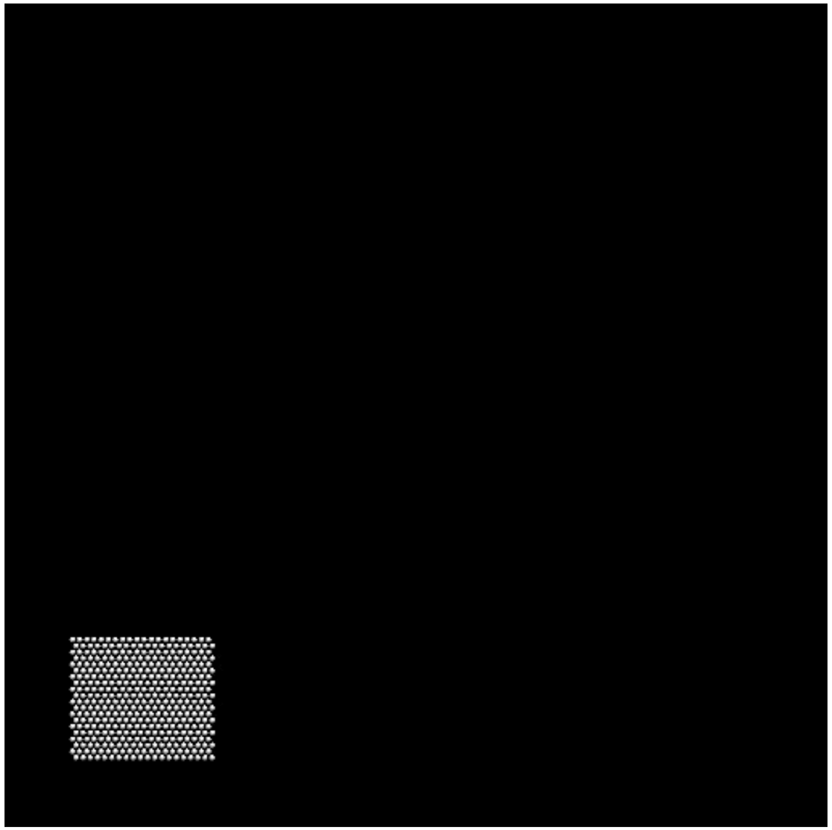
clusters are amorphous

clusters grow and shrink dynamically

Preliminary characterization of the clusters





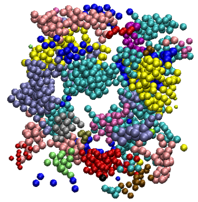


initial configuration: gas

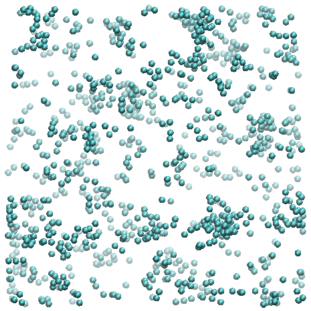
initial configuration: crystal

we observe them for different initial conditions

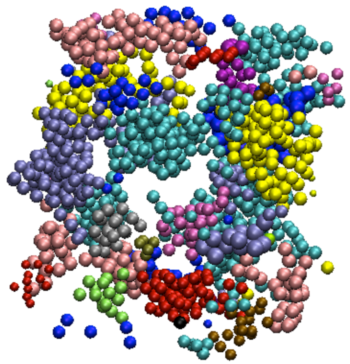
Therefore



the formation of living clusters at low concentrations is independent on the active suspension under study



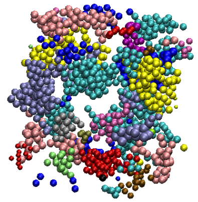
whether self-displaced
or self-propelled

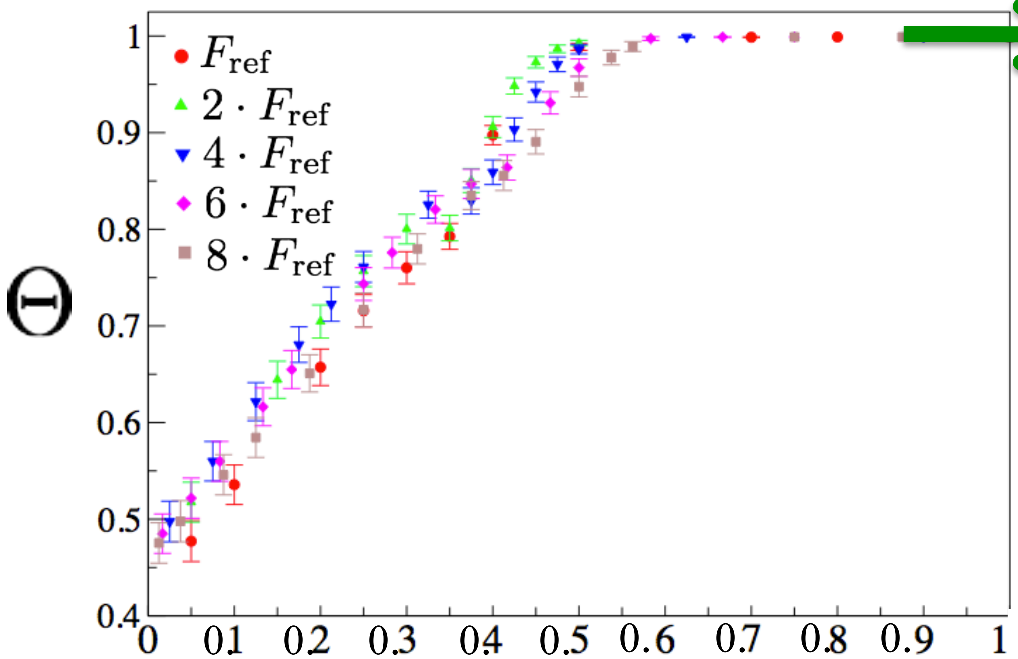


as long as there is a competition

between equilibrium and active force

Is there anything special in the structure formed at large P_{agg}?





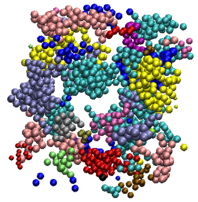
$P_{agg}(SP)$

the system forms one large amorphous aggregate that crystallizes thanks to the activity

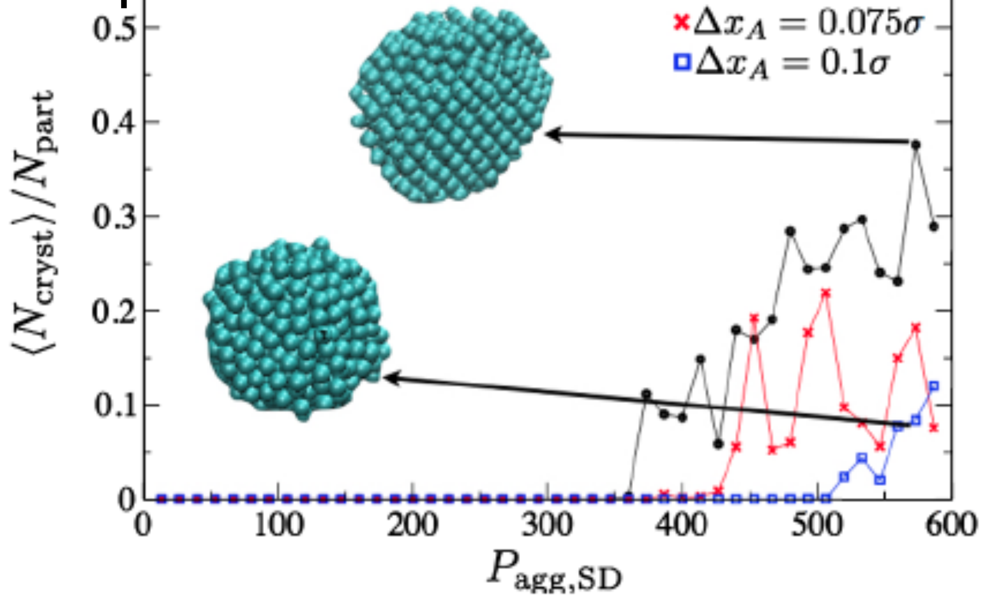
activity helps annealing defects!

irreversible crystallization, not living crystals

Is there anything special in the structure formed at large P_{agg}?

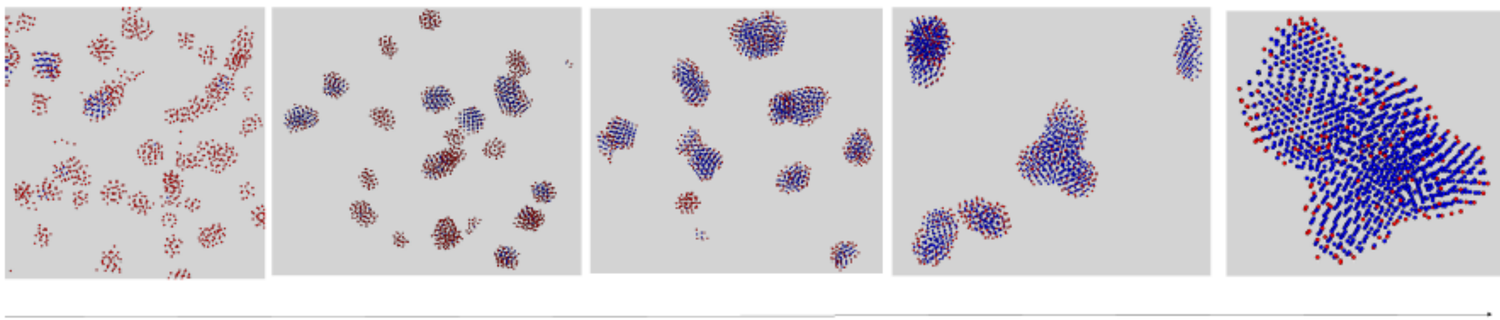


SD particles



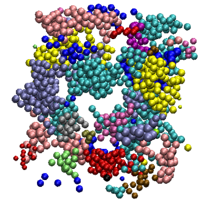
the system forms one large amorphous aggregate that crystallizes thanks to the activity

SP particles



t

Conclusions

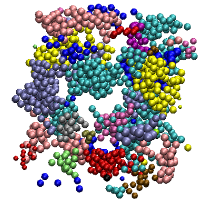


- ✓ In a diluted suspension of active colloids where an active force competes with an equilibrium one, the system can aggregate into living clusters
- ✓ When attraction dominates, the clusters can irreversibly crystallize

Physical Review Letter, 111 245702 (2013)

Focus article: Physics, 6 134 (2013)

Take-home message



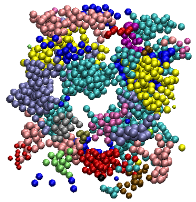
- ✓ Activity suppresses phase separation
- ✓ Activity & propulsion are the ingredients to self-assemble functional clusters
- ✓ In a diluted suspension of active colloids where an active force competes with an equilibrium one, the system can aggregate into living clusters

Physical Review Letter, 111 245702 (2013) Focus article: Physics, 6 134 (2013)

PNAS 106 4052 (2012)

Research highlight in
Nature Materials/Nature Physics (2012)

Questions and ongoing work



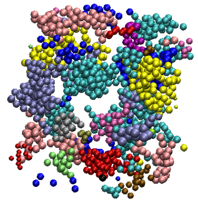
- ✓ Can we better characterize the clusters?
- ✓ What is the effect of hydrodynamic interactions?
- ✓ What is the effect of particles' shape in the process of self-assembly?
- ✓ What if we make the attraction anisotropic?
- ✓ What happens if we consider active and passive colloids?

University of Barcelona

Paco Alarcon

Ignacio Pagonabarraga

Living clusters and crystals from low-density suspensions of active colloids



Muchas gracias!

Living clusters

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Bacteria & Polymers

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