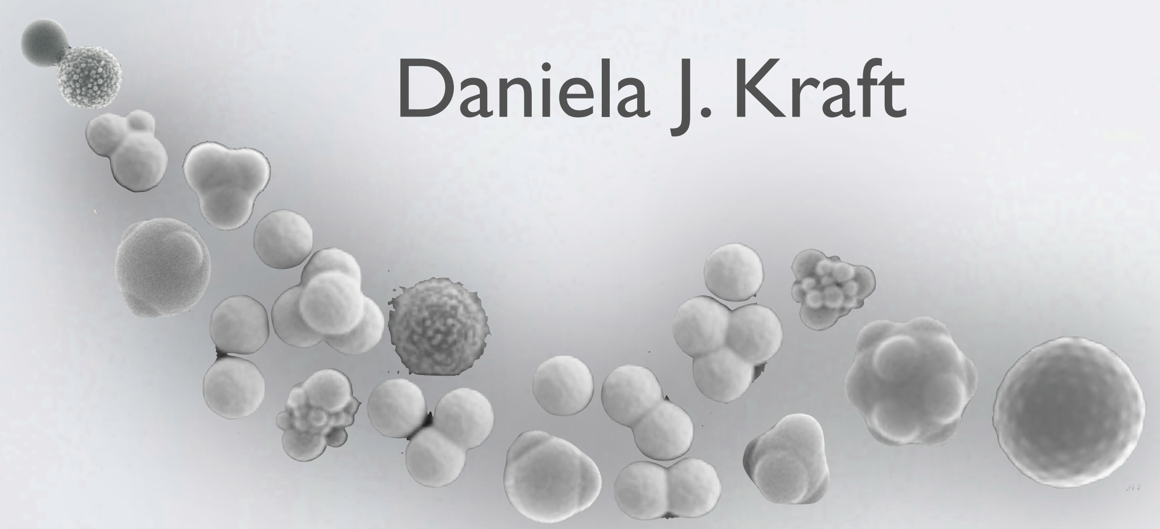
SELF-ASSEMBLY AND DIFFUSION OF ANISOTROPIC PARTICLES

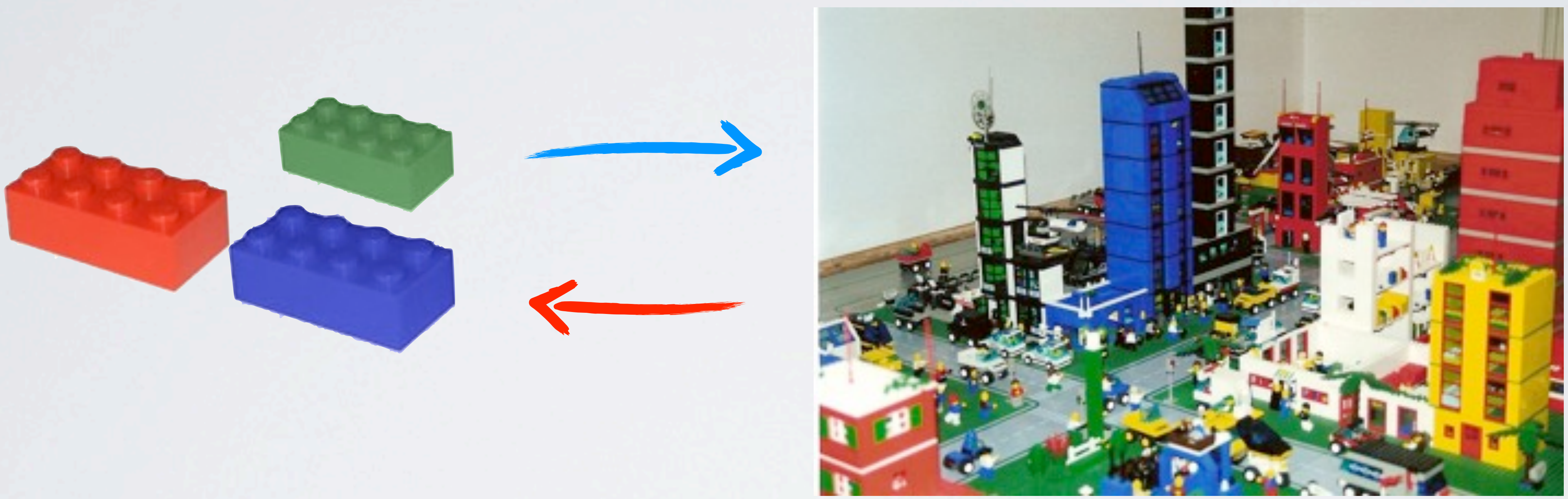


Daniela J. Kraft

Universiteit Leiden

COST workshop, Lagrangian transport: from complex flows to complex fluids
Soft Matter Physics, LION, Leiden University, The Netherlands
March 7 2016

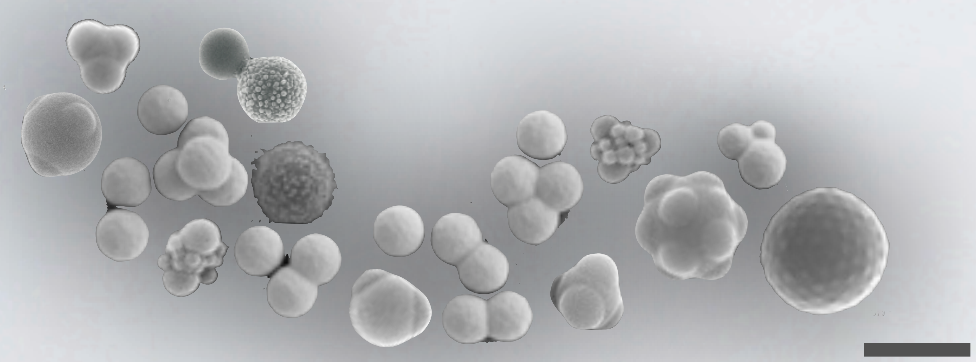
Leiden Institute of Physics



"What I cannot create, I do not understand."

R. Feynman

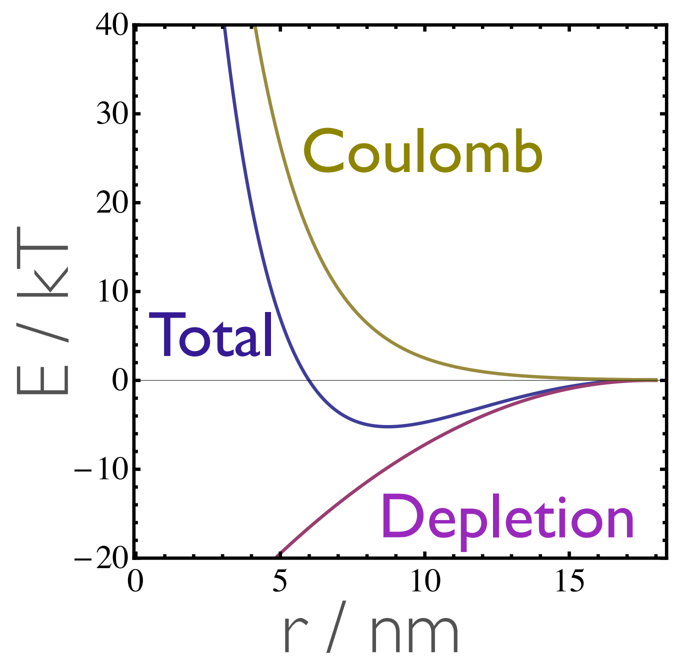
WHY COLLOIDAL PARTICLES?

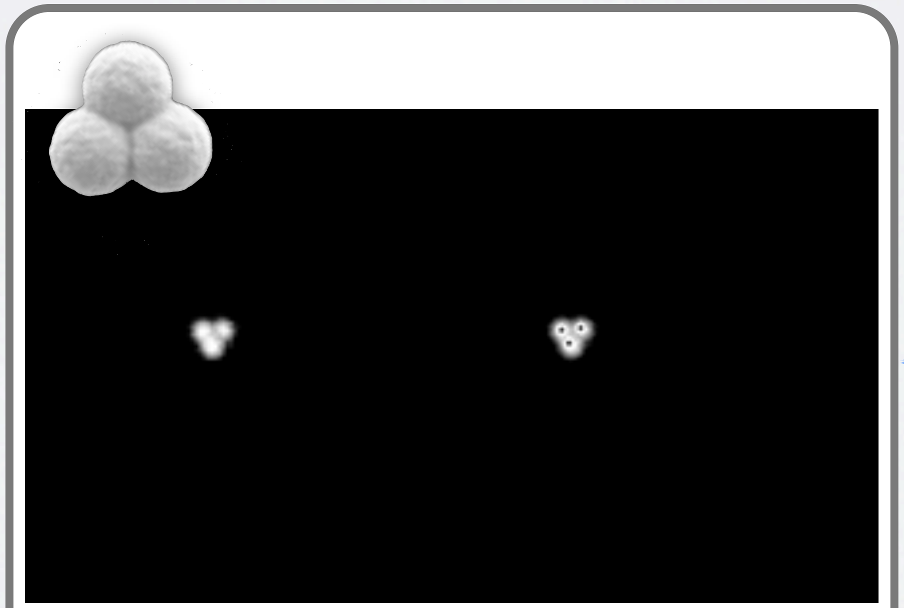


Size:

~10nm-10μm

SOFT, SLOW, SEEABLE



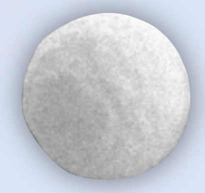


Kraft et al. PRE 88(2013)

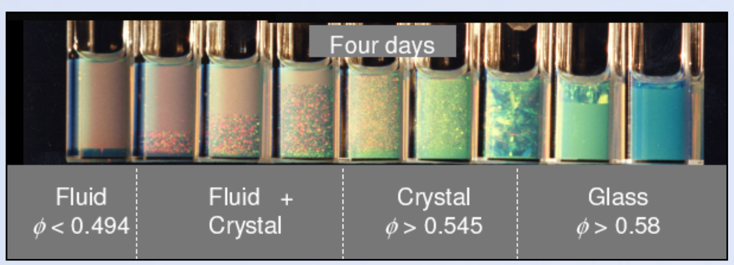
Ideal Model System
For Doing
Fundamental Physics

Applications

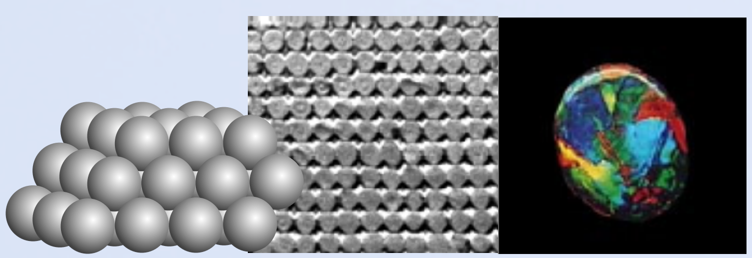
FROM SPHERES TO COMPLEX PARTICLES



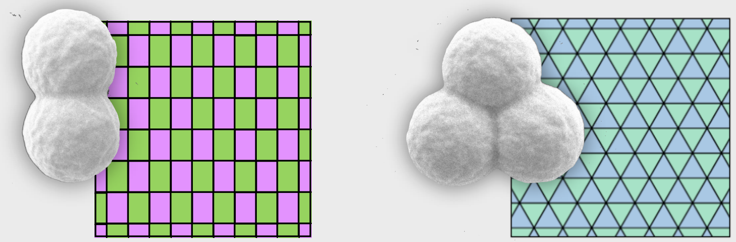
model 'atom'



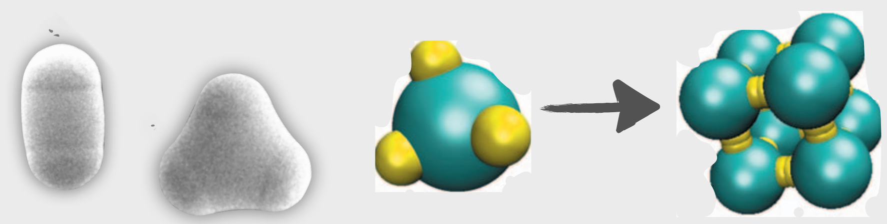
Pusey, van Megen, Nature (1986)



Anisotropic shape

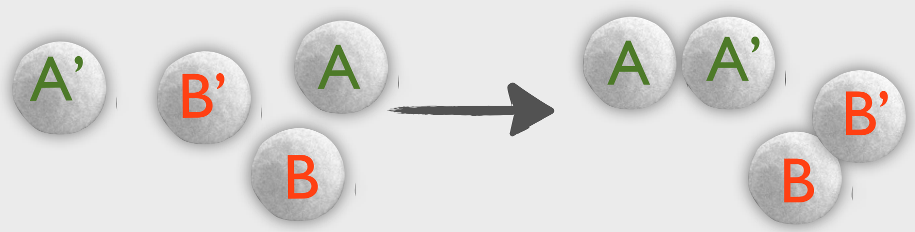


Anisotropic interactions



Wilber et al. JCP (2009)

Highly specific interactions



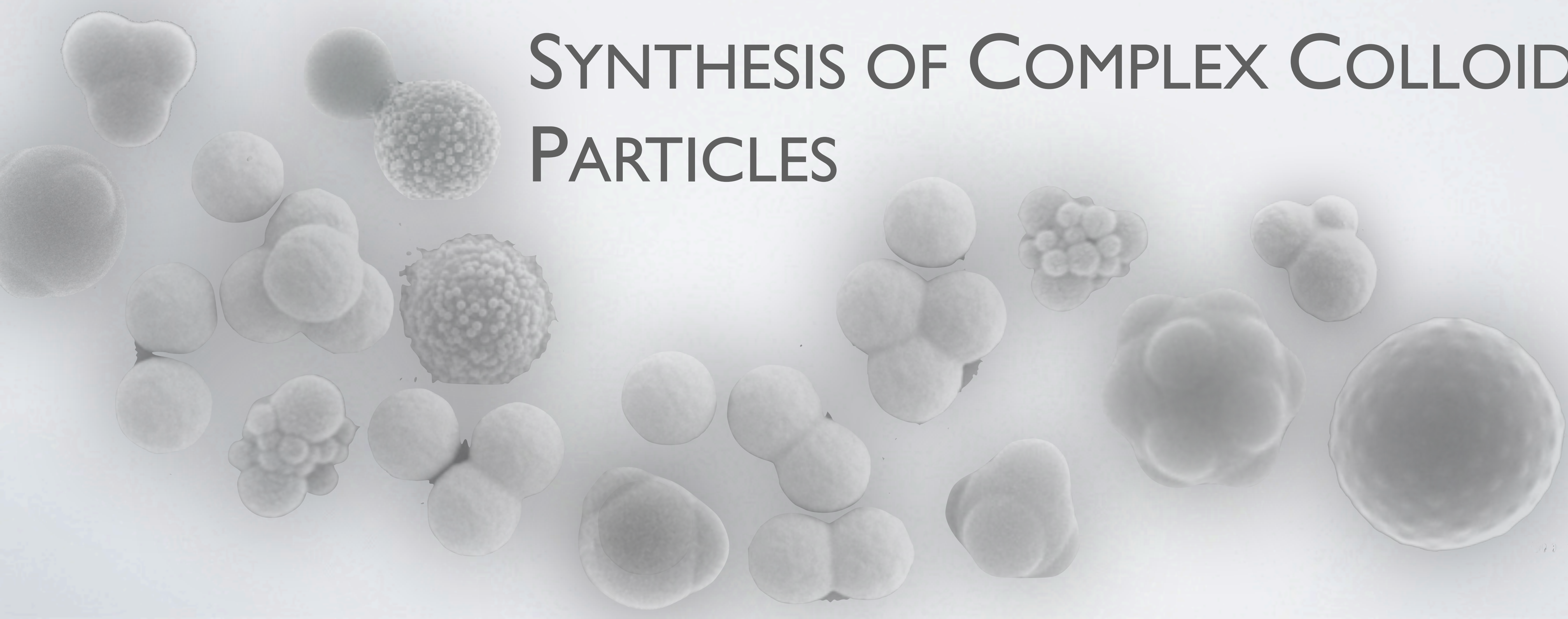
+ External guiding rules
+ activity

Particle shape
and interactions

Assembled structure

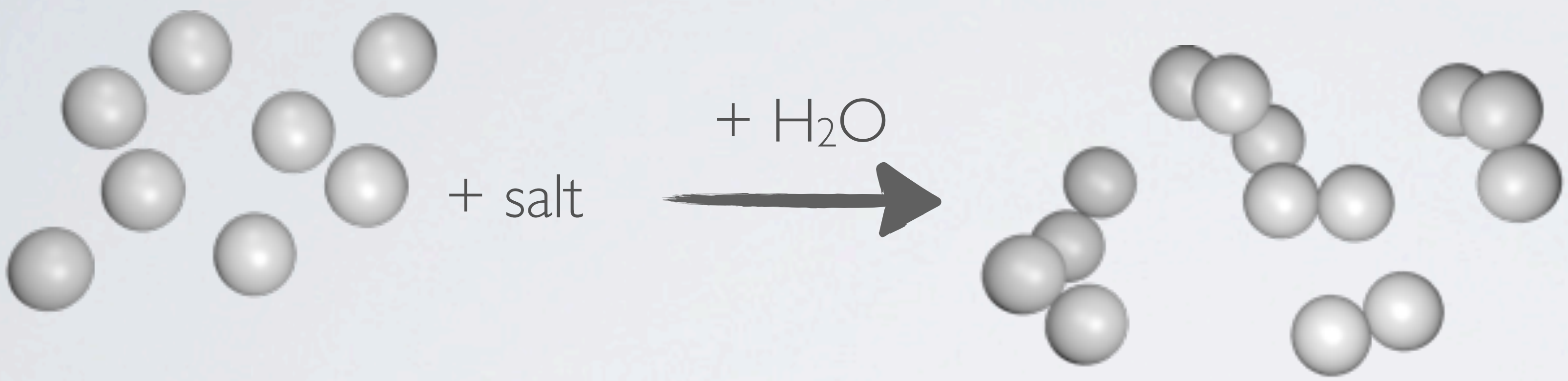
Understand & Design
self-assembly

Colloidal Recycling: Synthesis of Complex Colloidal Particles



Reshaping Random Colloidal Clusters

random clusters

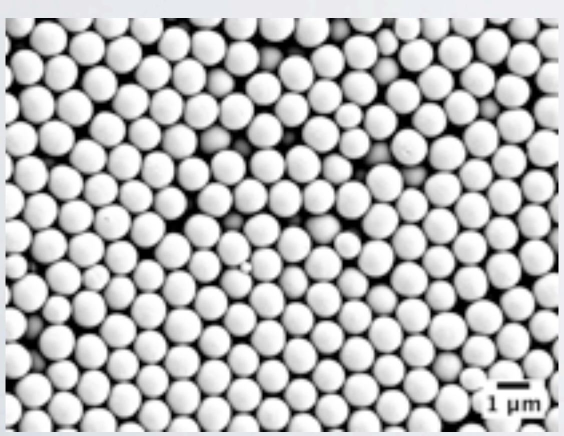


induce aggregation

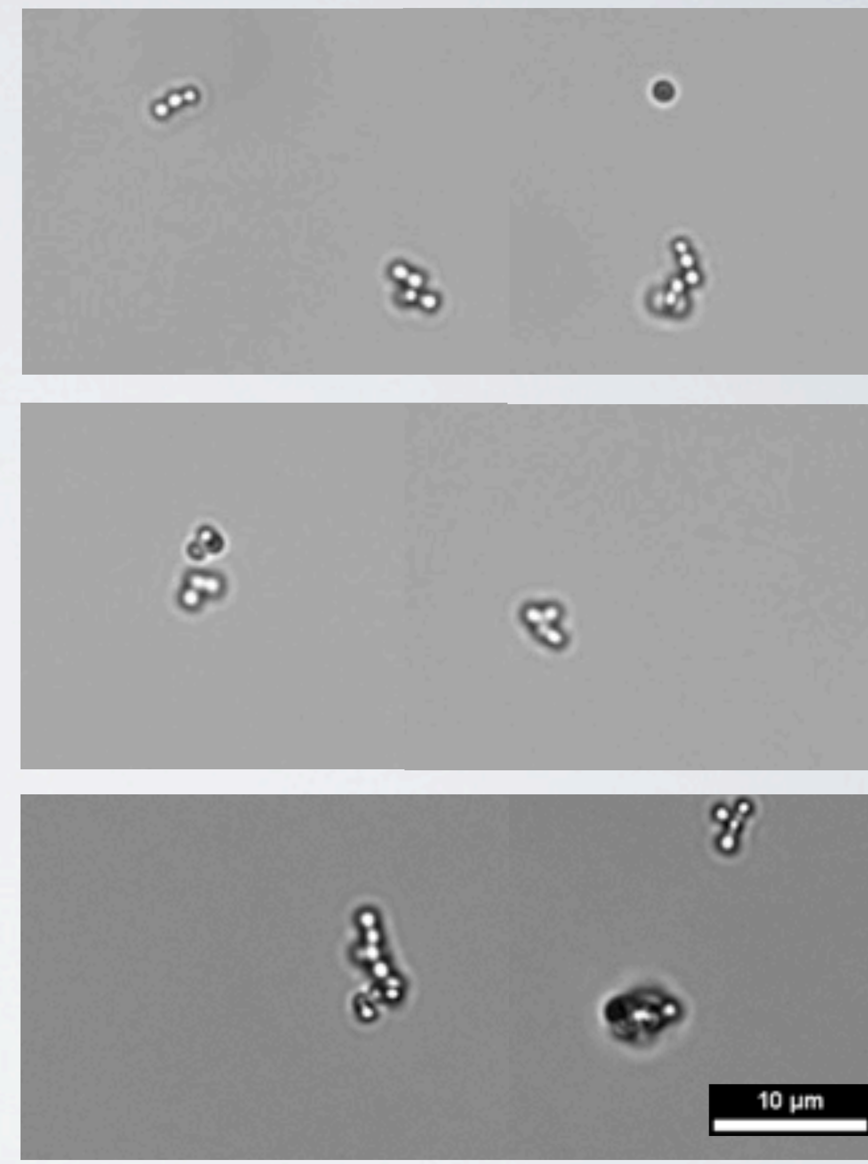
quench

swelling

Charge stabilized PS colloids

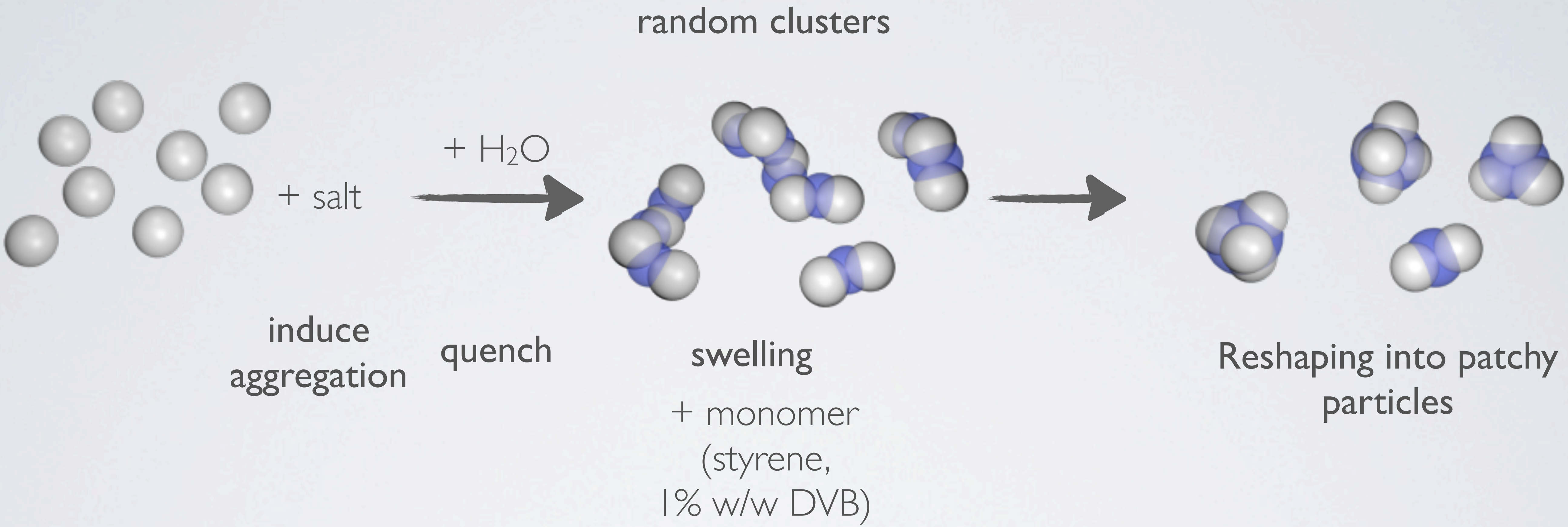


~1µm diameter, 1% crosslink density, purchased from Magsphere

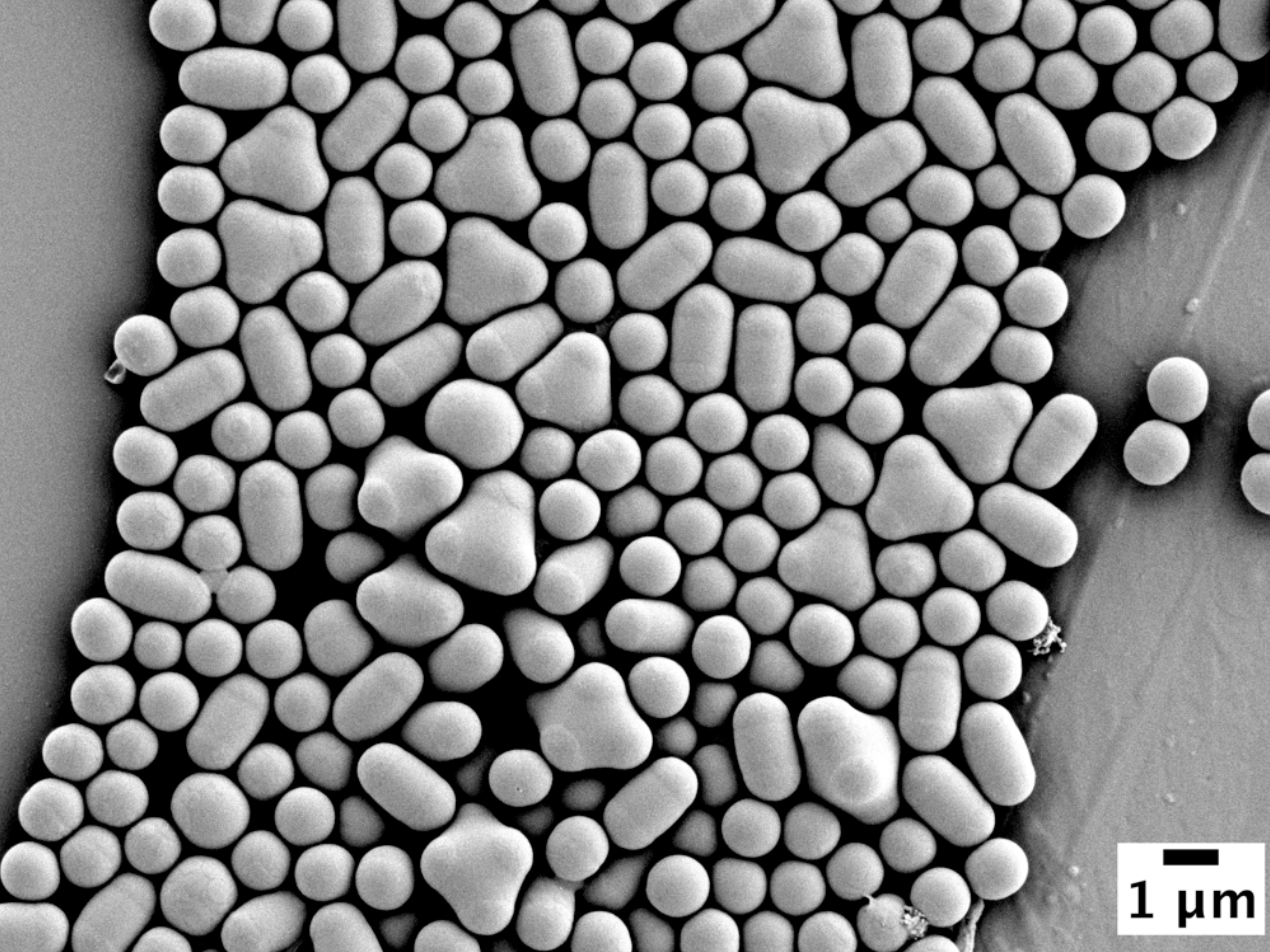


Meester, Verweij, vd Wel, Kraft, ACSNano (2016)

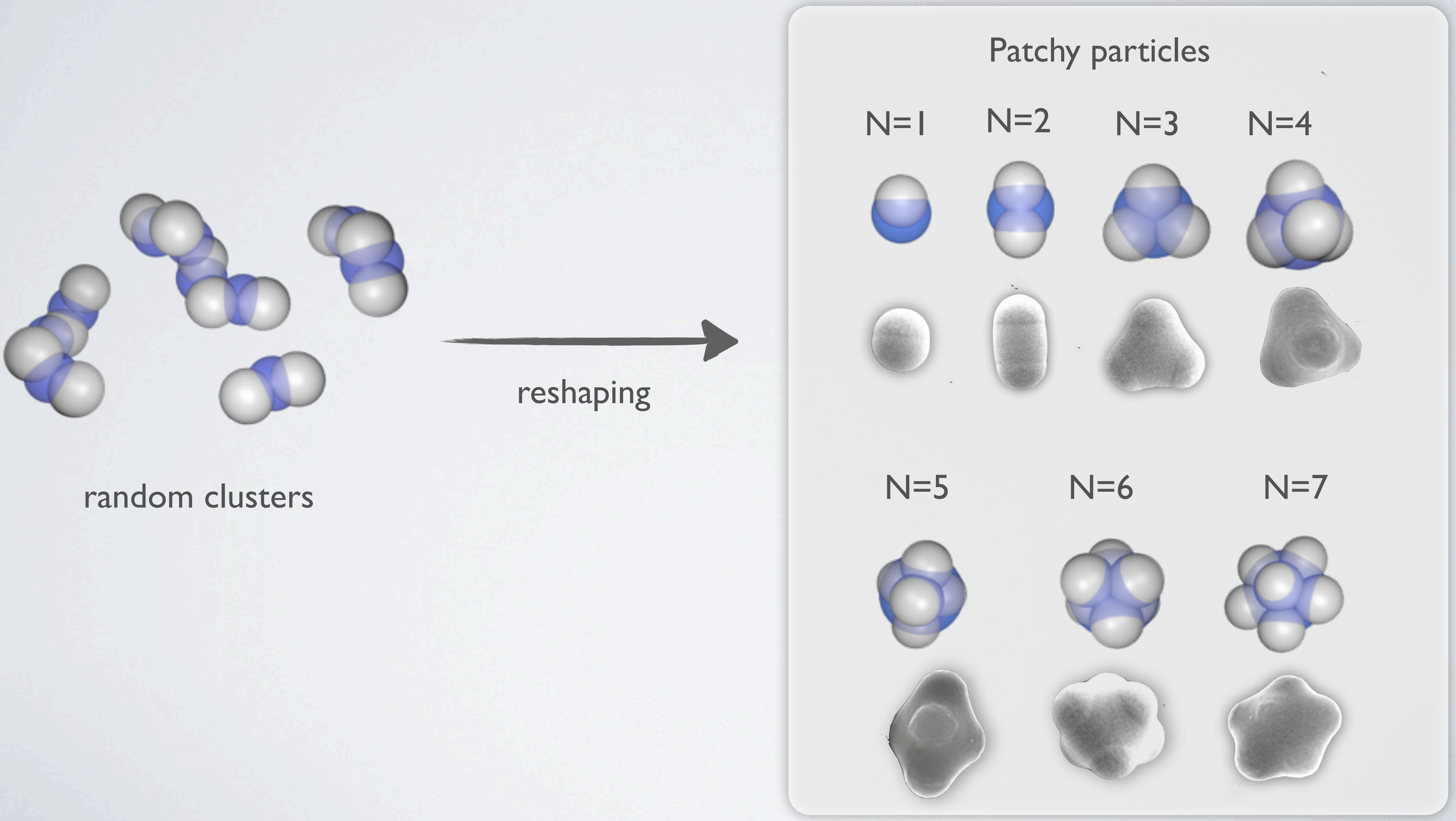
Reshaping Random Colloidal Clusters



Meester, Verweij, vd Wel, Kraft, ACSNano (2016)


1 μm

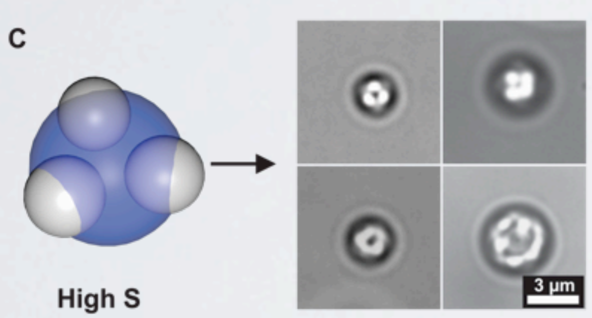
Particle Swelling Reconfigures the Random Clusters into Uniform Patchy Particles

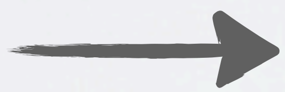


Coalescence driven Reconfiguration

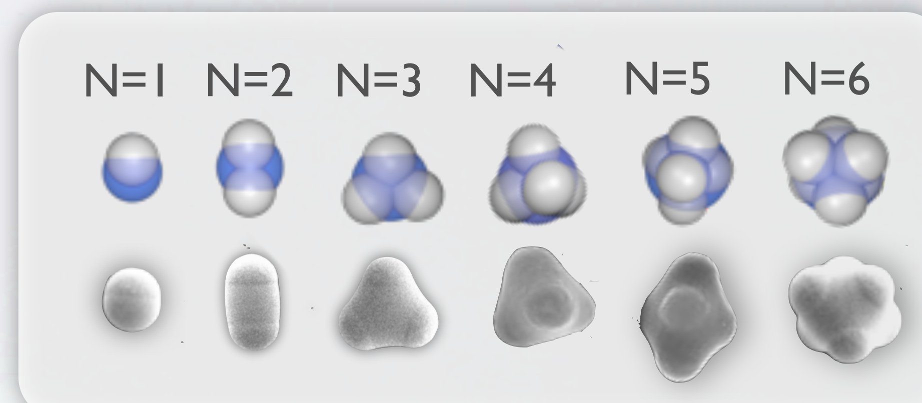
Liquid droplet
coalescence drive
rearrangement

Liquid droplet
confines the spheres



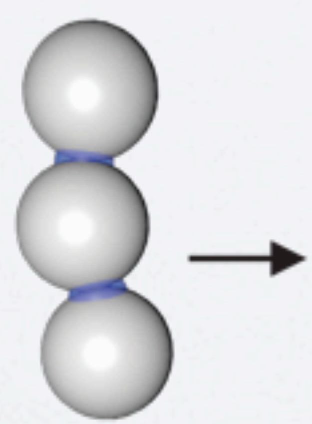


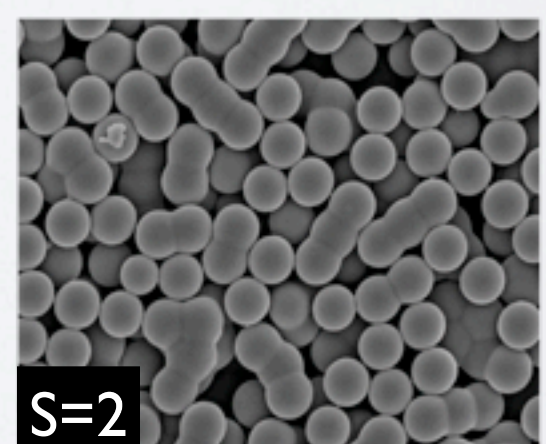
Cluster minimize the
second moment of the
mass distribution

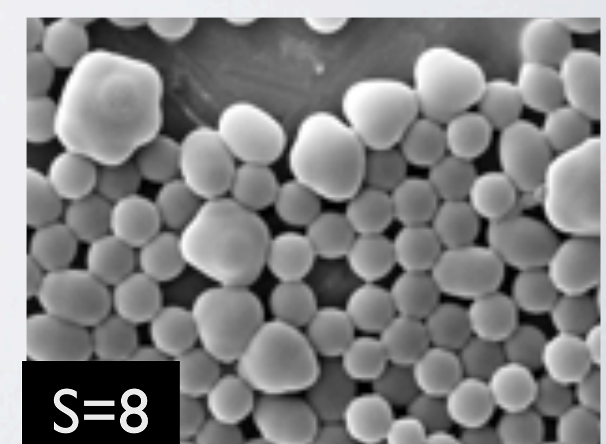


Insufficient swelling

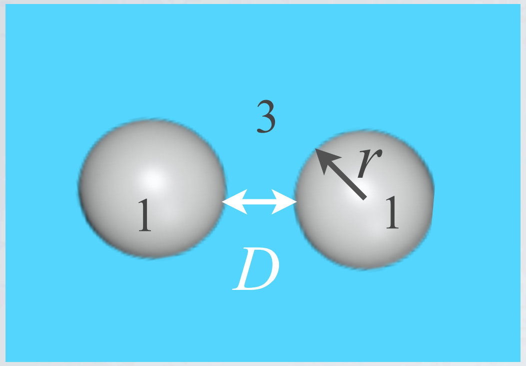
- ➡ no / small liquid bridges
- ➡ no reconfiguration!







WHAT ENABLES RECONFIGURATION?



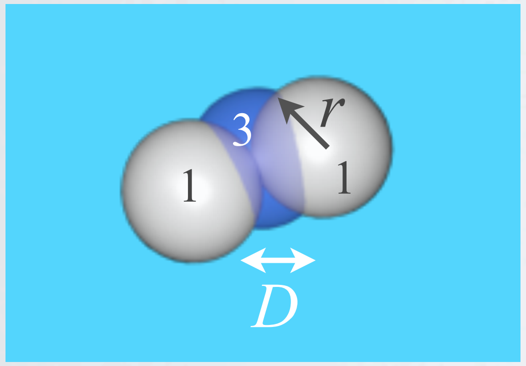
Van der Waals interaction energy $W(D) = -\frac{Ar}{12D}$

with the Hamaker constant A (Lifshitz theory)

$$A = \frac{3}{4}k_B T\left(\frac{\epsilon_1 - \epsilon_3}{\epsilon_1 + \epsilon_3}\right)^2 + \frac{3h\nu_e}{16\sqrt{2}}\frac{(n_1^2 - n_3^2)^2}{(n_1^2 + n_3^2)^{3/2}}$$

polystyrene spheres: $\epsilon_{PS} = 2.55 \quad n_{PS} = 1.557$

polystyrene spheres in water: $\epsilon_w = 80 \quad n_w = 1.333 \qquad A_{PS-w} = 1.5 \cdot 10^{-20} J$

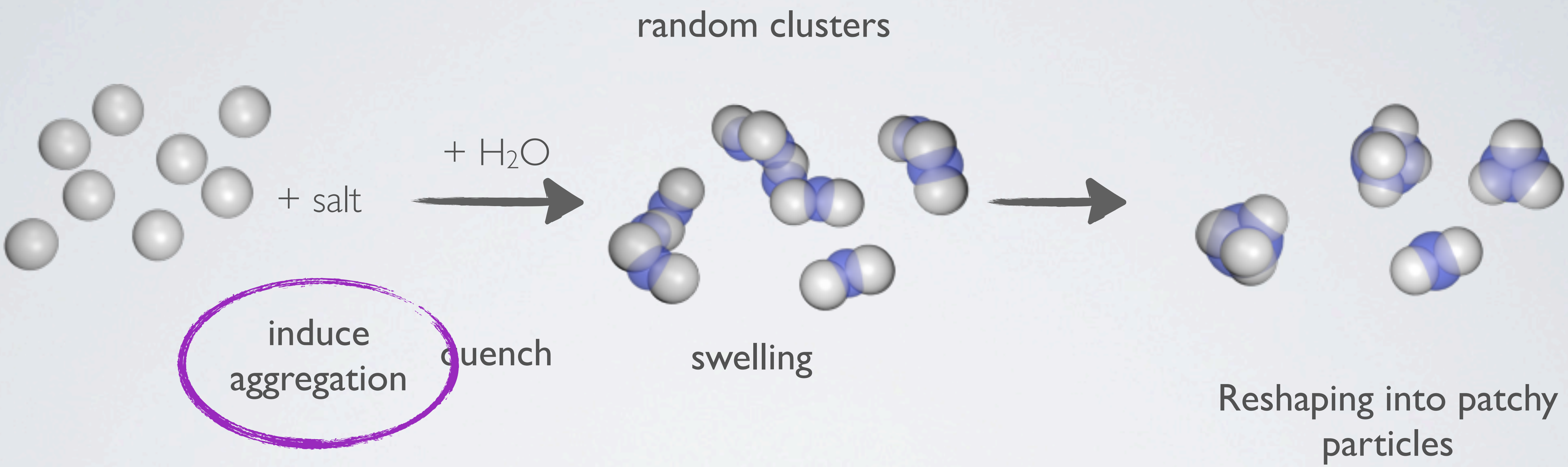


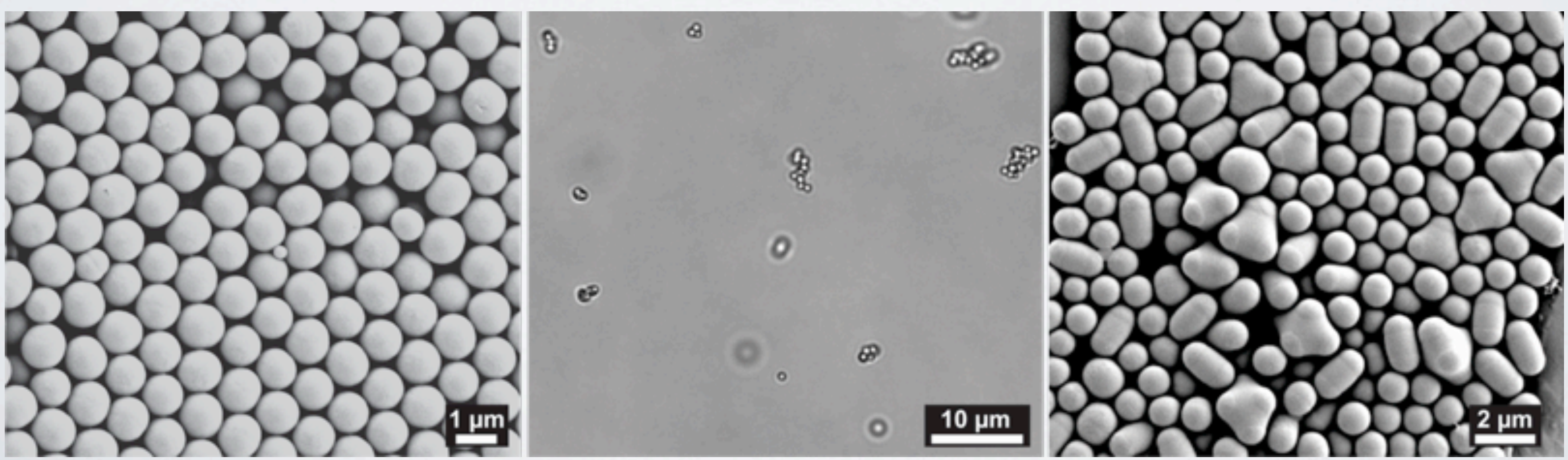
polystyrene spheres in styrene:

$\epsilon_{st} = 2.47 \quad n_{st} = 1.547 \qquad A_{PS-st} = 2.5 \cdot 10^{-23} J$

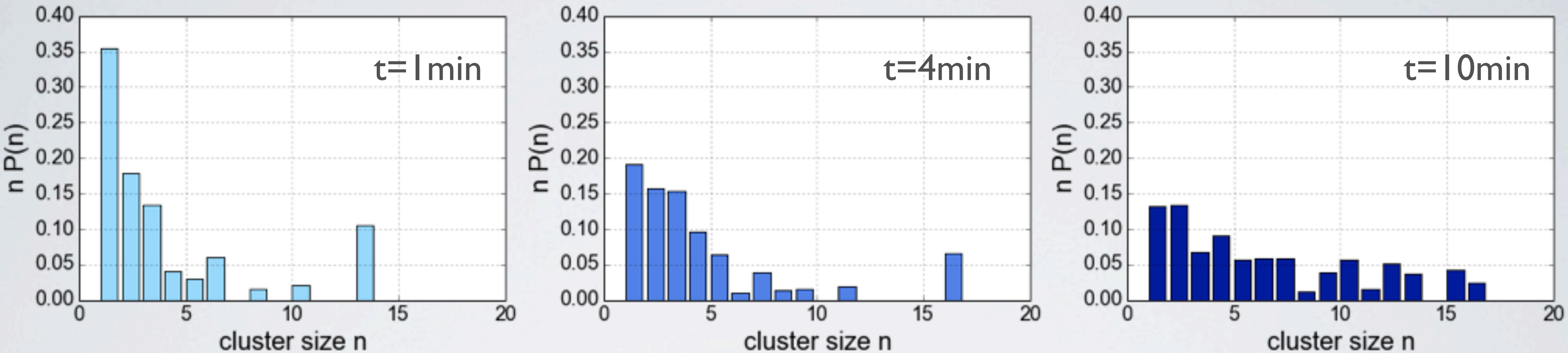
600x reduction of van der Waals attraction due to liquid bridges!

COLLOIDAL RECYCLING

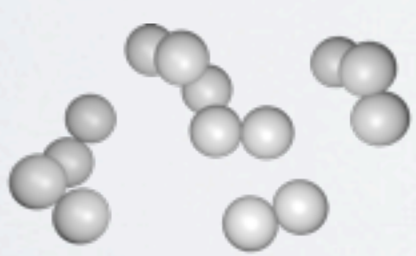


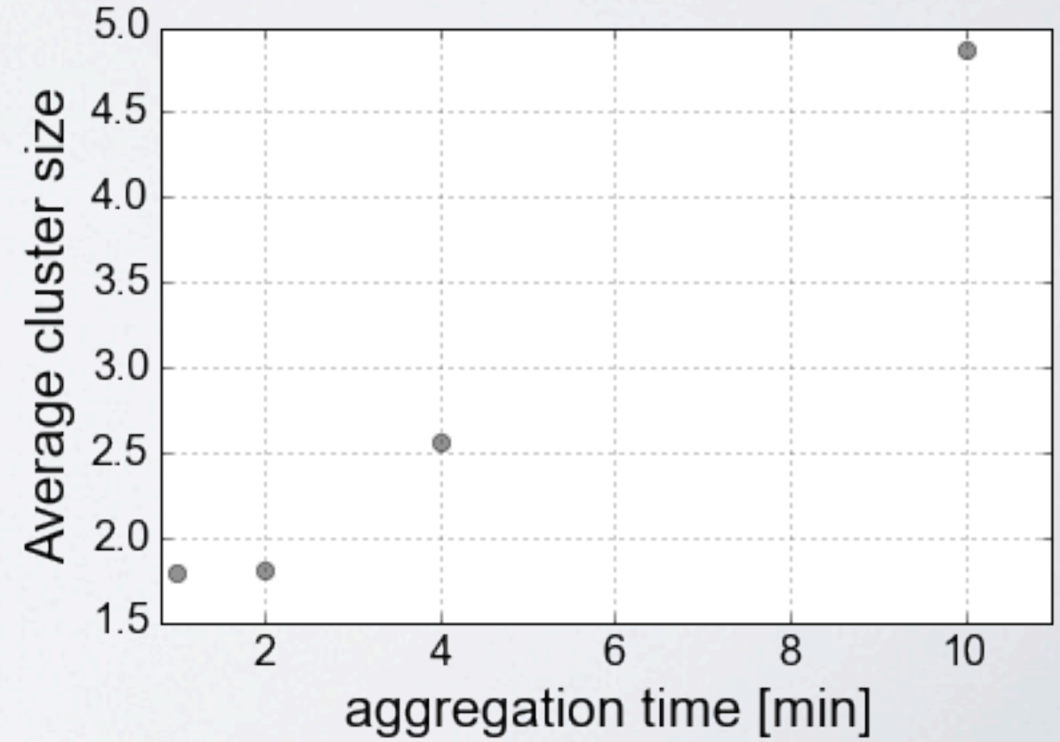


Cluster Size is Tunable by Aggregation Time

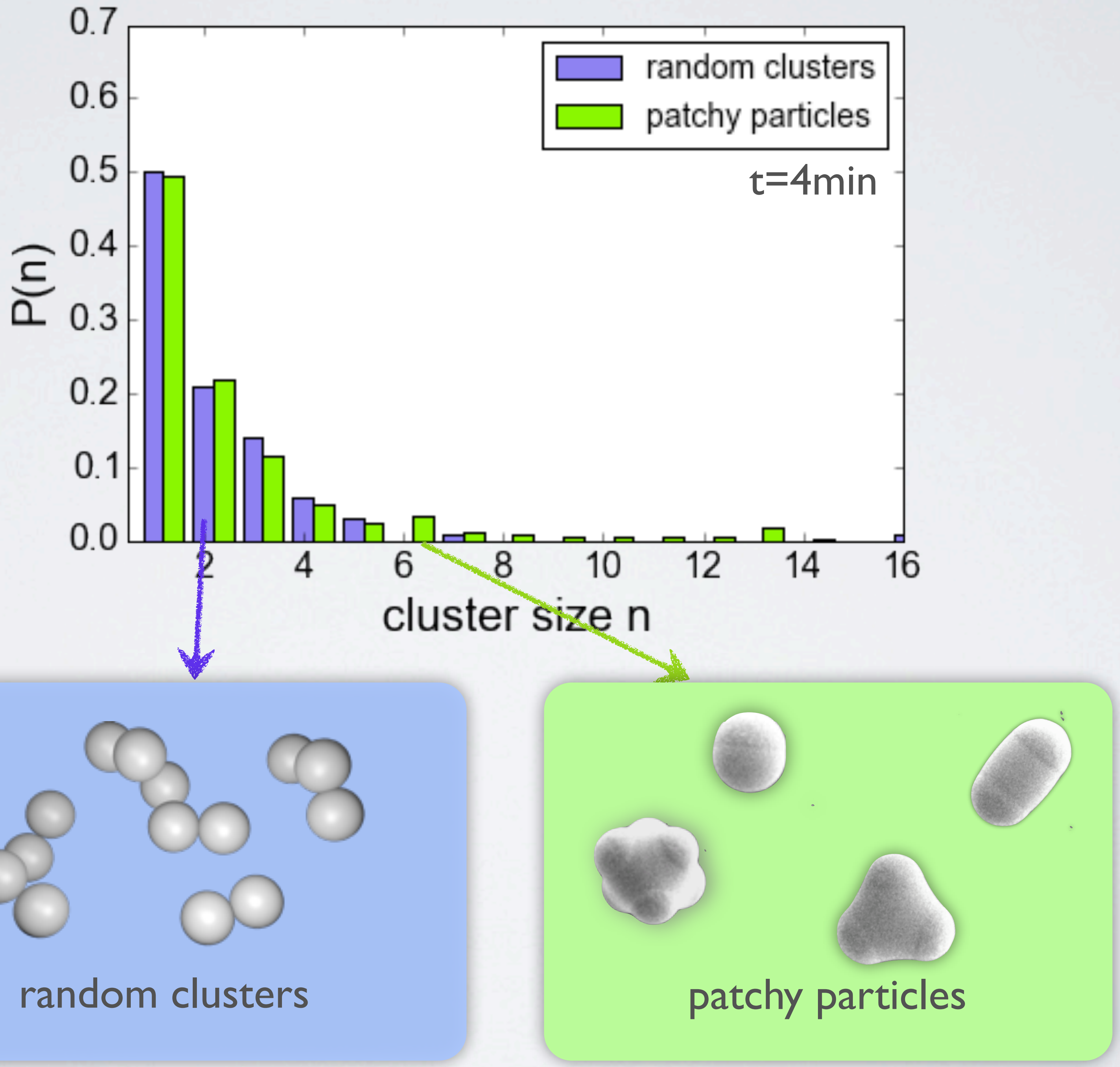


time

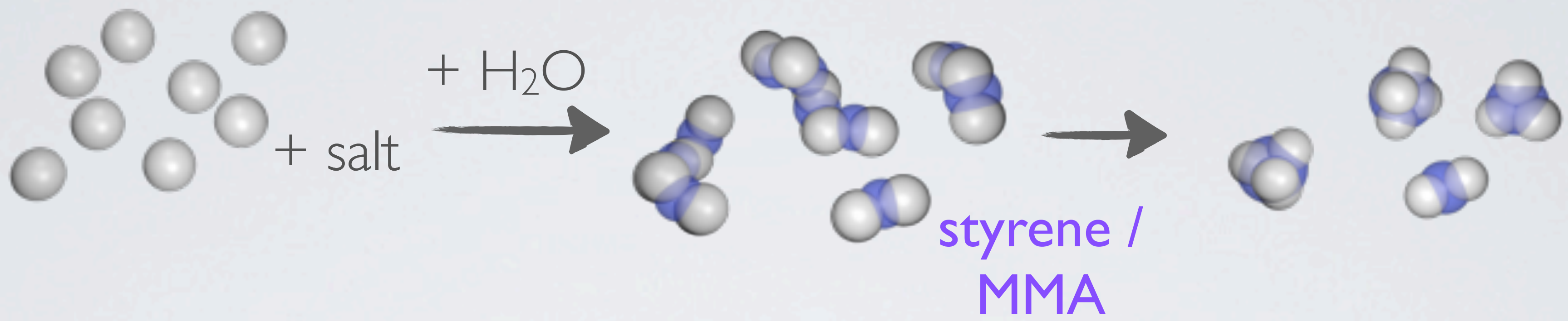




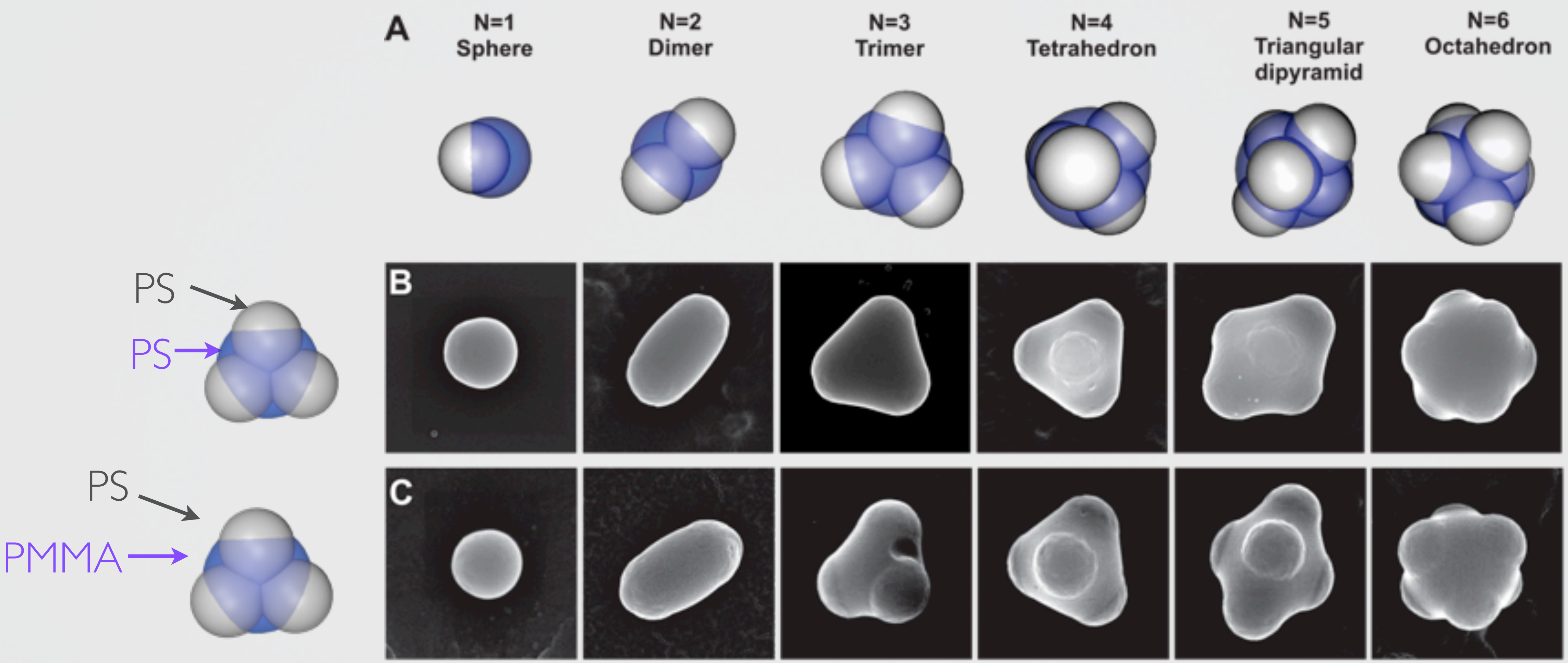
ONLY RESHAPING DURING SWELLING, NO FURTHER AGGREGATION



Composite PS / PMMA Colloidal Molecules



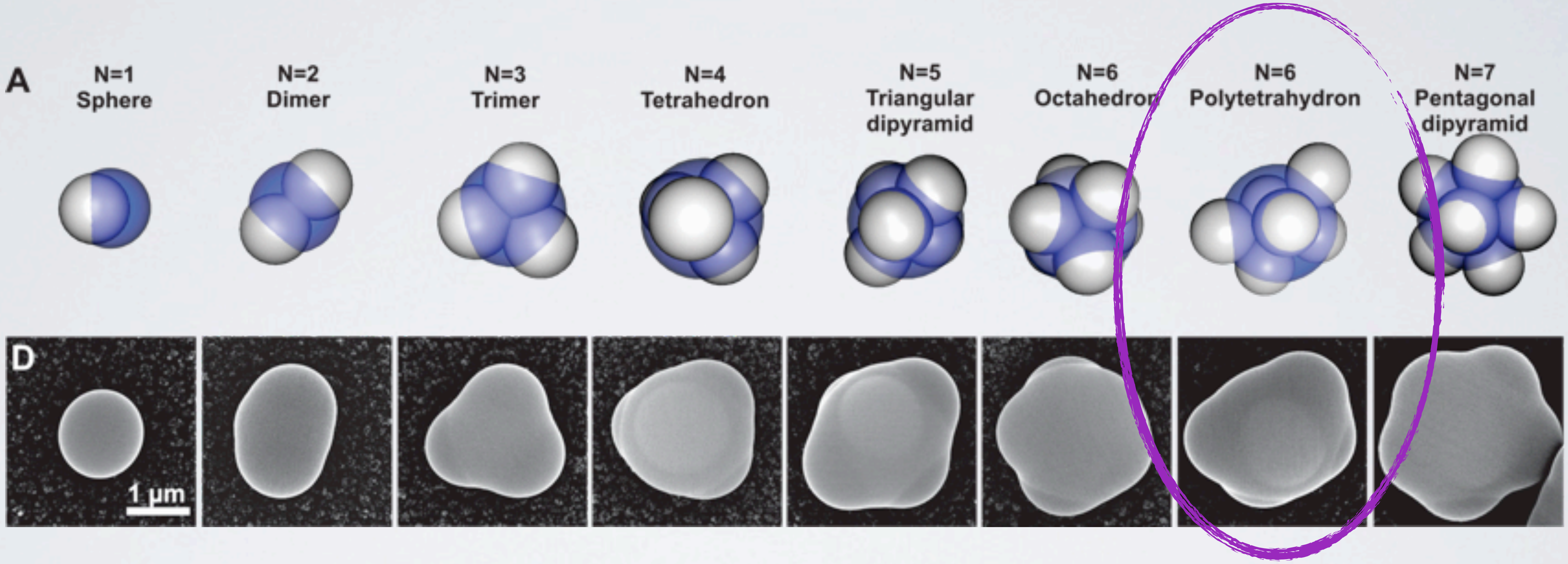
Patchy particles



Meester, Verweij, vd Wel, Kraft, ACSNano (2016)

Beyond Droplet Confined Clusters

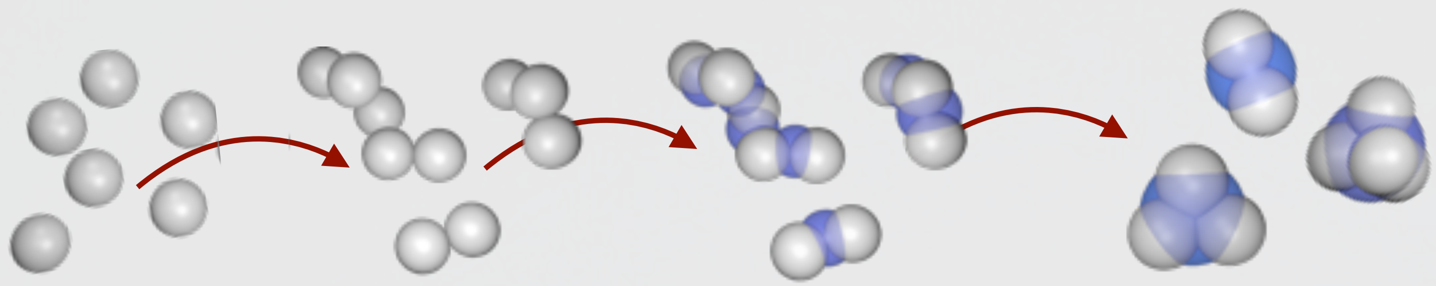
"homemade" soft PS swollen with toluene

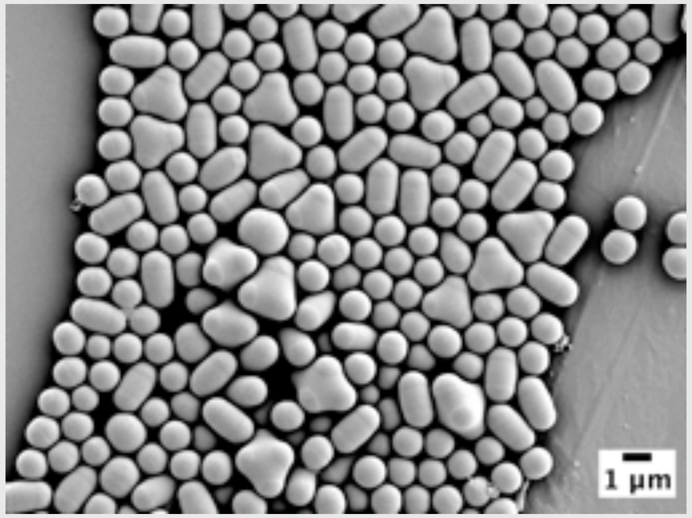


In clusters made up of softer particles and in the absence of cluster spanning droplets, **entropy** becomes important in determining the cluster shape!

Summary - Recycling Colloidal Aggregates into Patchy Particles

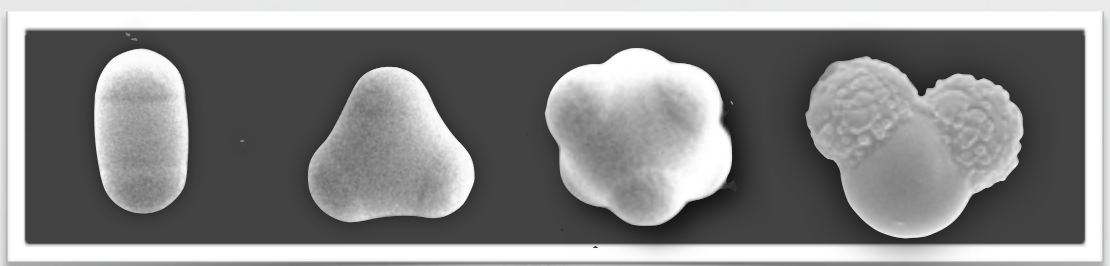
Reorganization of random clusters of spheres



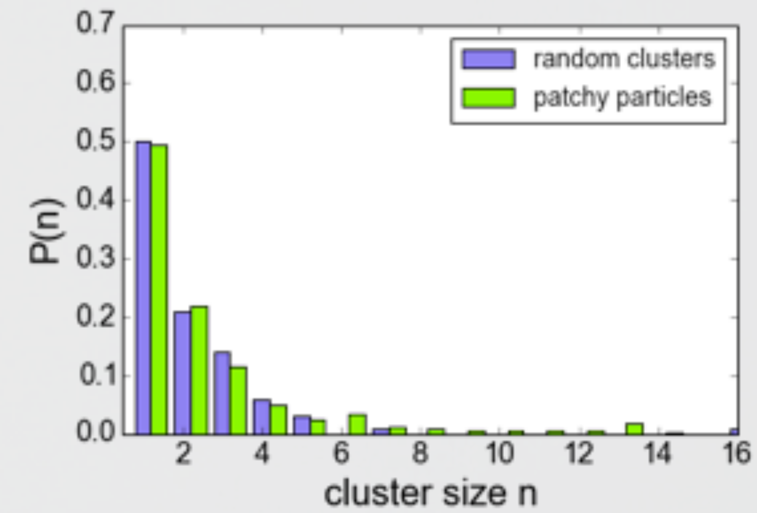


Meester, Verweij, van der Wel, Kraft, ACSNano (2016)

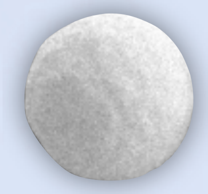
Variety of complex patchy particles



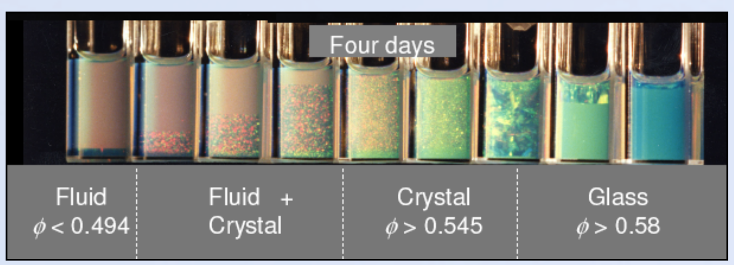
Control over size distribution



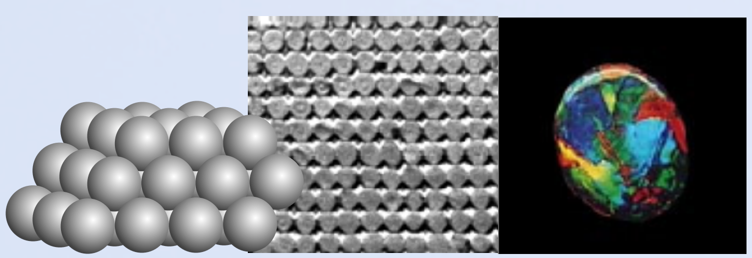
FROM SPHERES TO COMPLEX PARTICLES



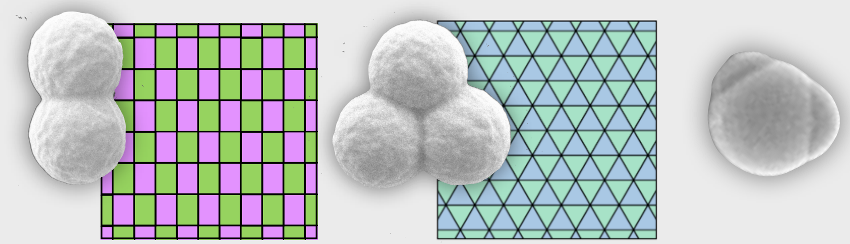
model 'atom'



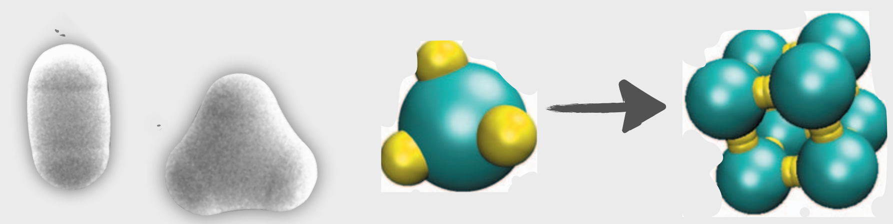
Pusey, van Megen, Nature (1986)



Anisotropic shape

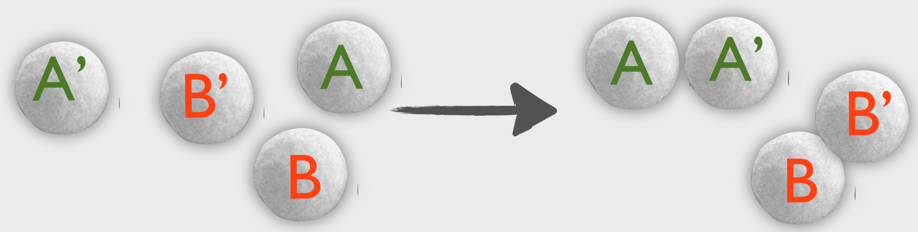


Anisotropic interactions



Wilber et al. JCP (2009)

Highly specific interactions



+ External guiding rules
+ activity

Particle shape
and interactions

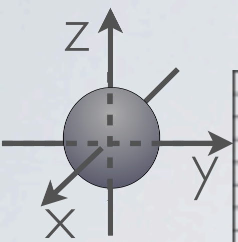
Assembled structure

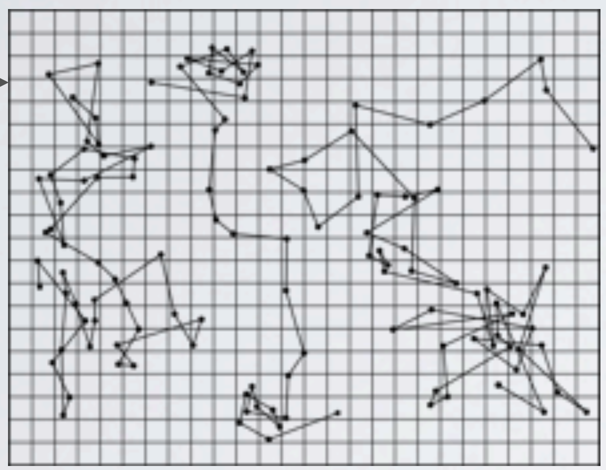
"Design and understand self-assembly"

Brownian motion of Anisotropic Colloidal Particles

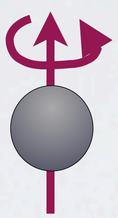
BROWNIAN MOTION OF ANISOTROPIC PARTICLES

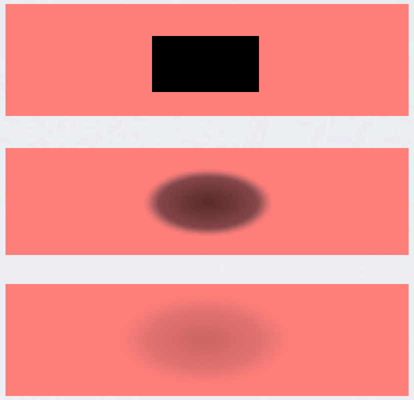
Translation	Rotation





J.B. Perrin, Les Atomes

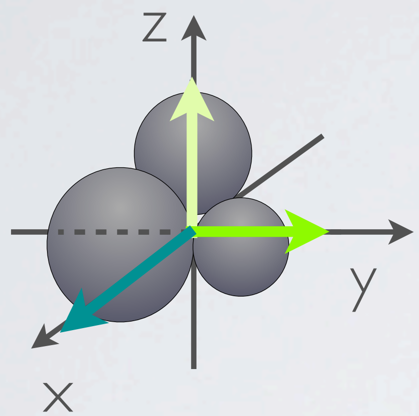




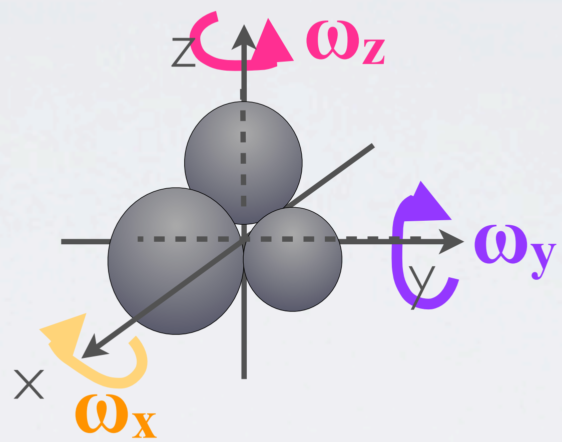
polarized FRAP

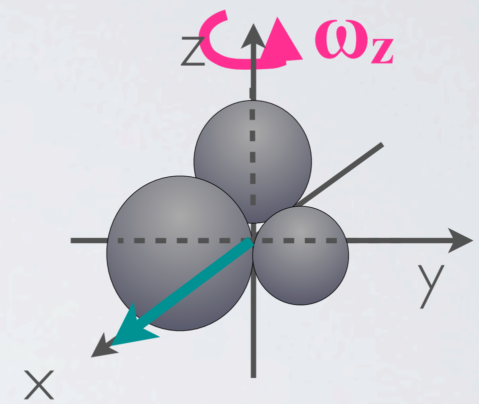
BROWNIAN MOTION OF ANISOTROPIC PARTICLES

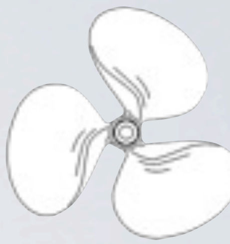
Translation	Rotation	Coupling



Origin of coordinate system determines 'meaning' of diffusion coefficients







Can we measure the shape-dependent diffusion coefficients?

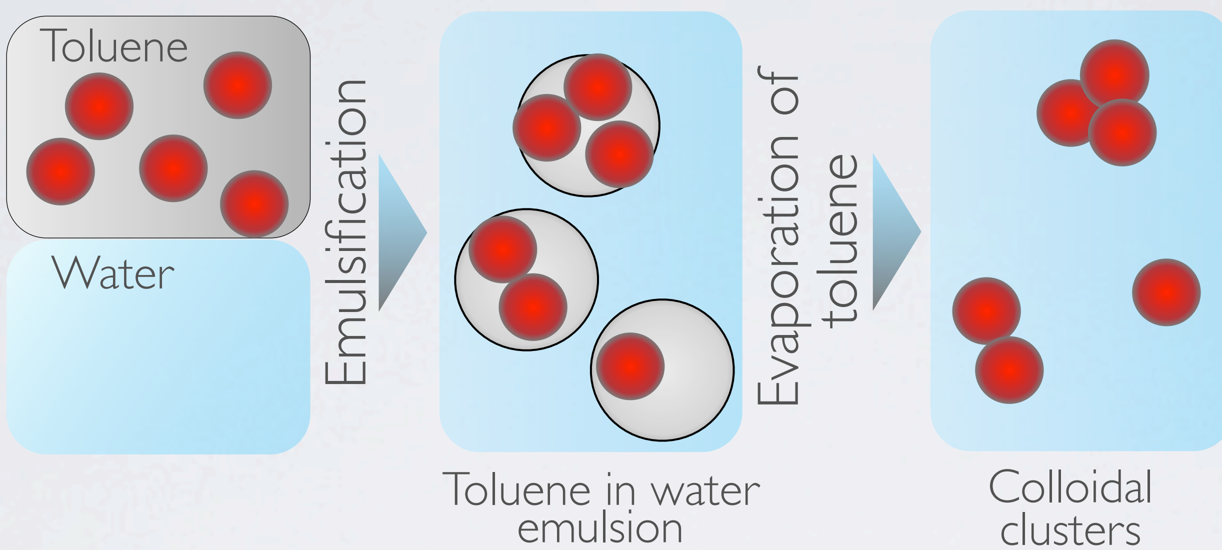
http://de.wikipedia.org/wiki/Ahorne
http://www.pt-boat.com/propeller/propeller.html

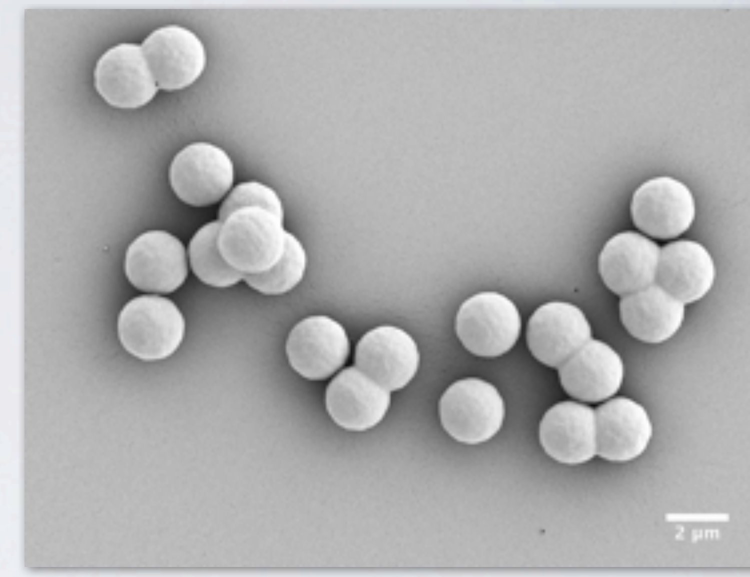
Synthesis of Anisotropic Particles

"Symmetric" particles

SEM

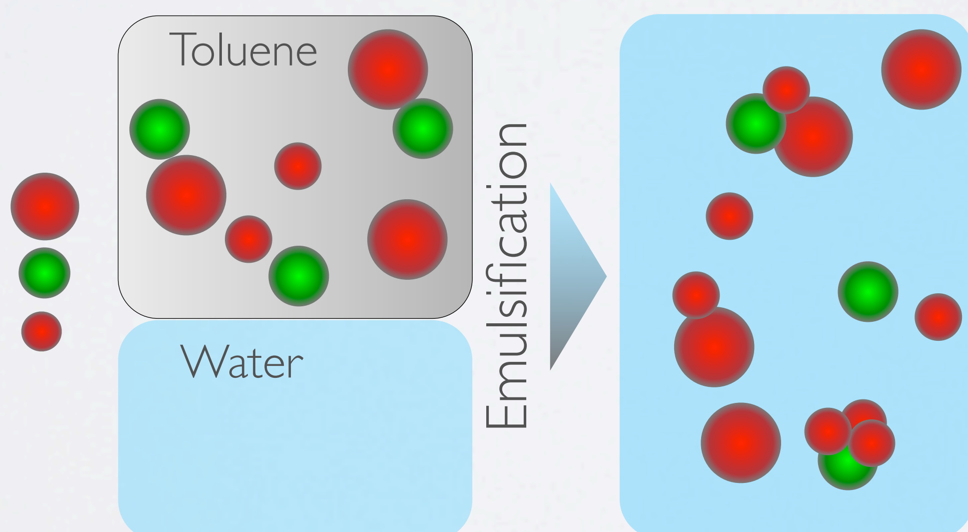
RITC dyed PMMA r=1.1μm

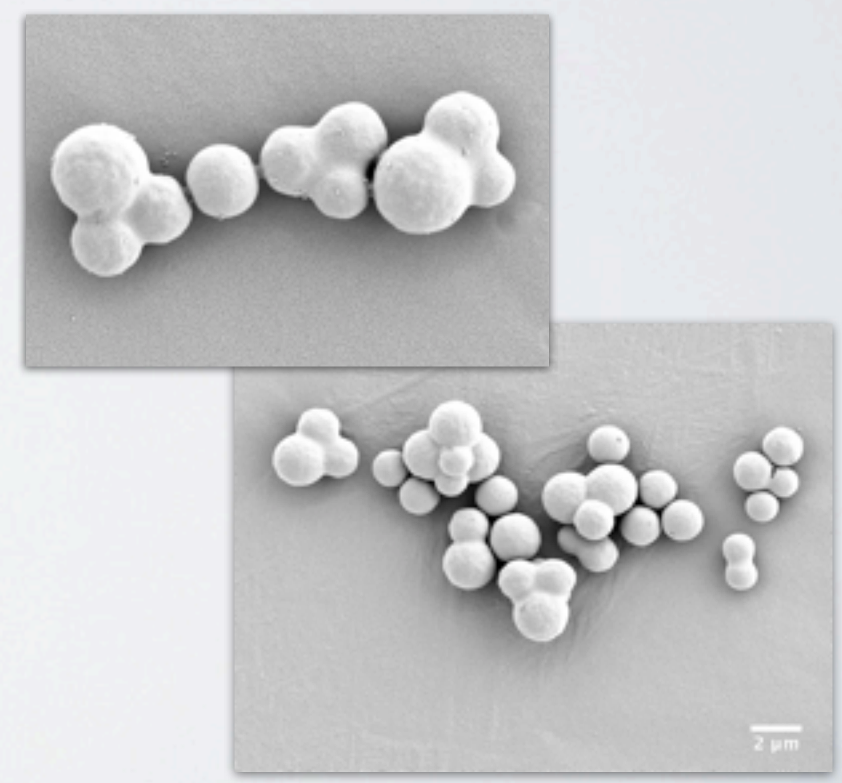




Asymmetric particles

- RITC dyed PMMA r=1.15μm
- NBD dyed PMMA r=830 nm
- RITC dyed PMMA r=650 nm

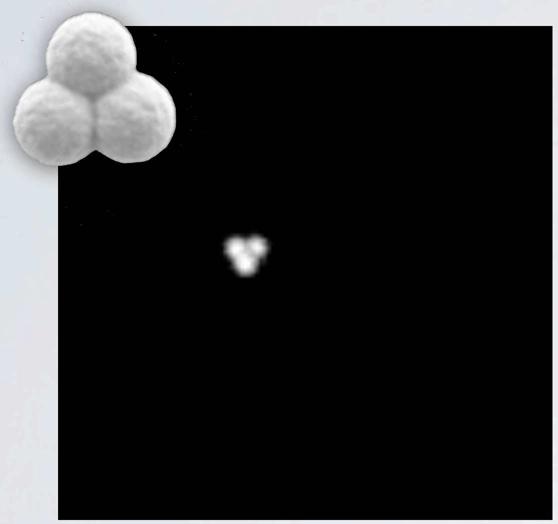




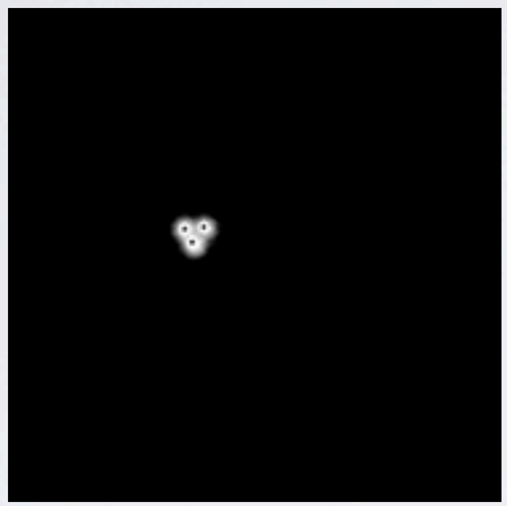
Manoharan, V.N. et al., 2003. Science, 301(5632), pp.483

Determination of the Diffusion Constant Matrix from 3D Confocal Microscopy

Confocal microscopy of fluorescent PMMA particles



Track particle positions using IDL or Trackpy

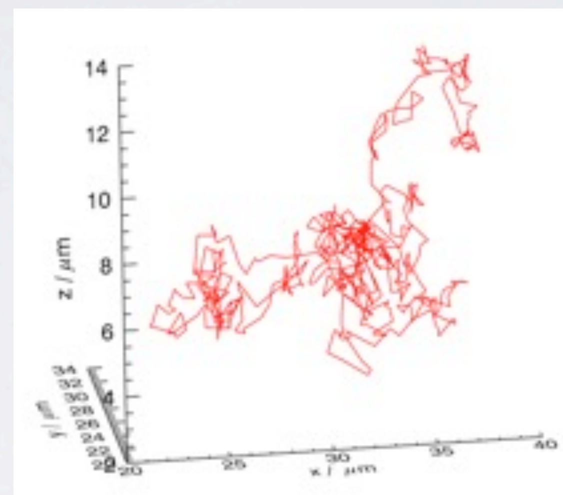


10x real speed

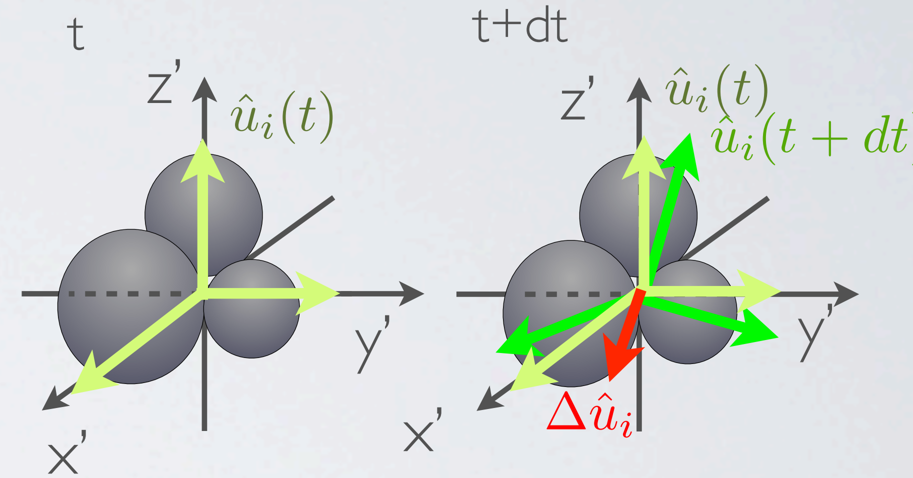
Analyze trajectory and rotations using IDL

Center of mass motion

$\vec{x} = (x, y, z)$



Change in body fixed axes



- center of mass position

$$\Delta\vec{x}(t) = \vec{x}(t) - \vec{x}(0)$$

- orthonormal orientation vectors $\hat{u}_i(t)$

$$\Delta\hat{u}(t) = \frac{1}{2}\sum_{i=1}^{3}\hat{u}_i(0) \times \hat{u}_i(t)$$

$$\vec{\xi}(t) = (\Delta\vec{x}(t), \Delta\hat{u}(t))$$

Calculate diffusion constant matrix from cross-correlations

$$\mathcal{D} = \frac{1}{2}\lim_{t\to 0}\frac{\partial}{\partial t}\langle\vec{\xi}(t)\otimes\vec{\xi}(t)\rangle$$

or

$$\mathcal{D}_{i,j} = \frac{1}{2}\lim_{t\to 0}\frac{\partial}{\partial t}\langle\xi_i(t)\xi_j(t)\rangle$$

Translation | **Coupling trans. & rotation**

$$\mathcal{D} = \begin{array}{c|cccccc} & \Delta x & \Delta y & \Delta z & \Delta u_x & \Delta u_y & \Delta u_z \\ \hline \Delta x & * & * & * & * & * & * \\ \Delta y & * & * & * & * & * & * \\ \Delta z & * & * & * & * & * & * \\ \Delta u_x & * & * & * & * & * & * \\ \Delta u_y & * & * & * & * & * & * \\ \Delta u_z & * & * & * & * & * & * \end{array}$$

Coupling trans. & rot. | **Rotation**

THE HYDRODYNAMIC FRICTION MATRIX

Diffusion constant matrix still depends on temperature and viscosity

$$\mathcal{D}_0 = \frac{1}{2}\lim_{t\to 0}\frac{\partial}{\partial t}\langle\vec{\xi}(t)\otimes\vec{\xi}(t)\rangle$$

Hydrodynamic friction matrix

$$\mathcal{H} = \frac{1}{\beta\eta}\,\mathcal{D}_0^{-1}$$

Only particle **shape and size** define the hydrodynamic friction matrix

β inverse thermal energy

η viscosity

k_B Boltzmann constant

Translation | Coupling trans. & rotation | Coupling trans. & rot. | Rotation

$$\mathcal{H} = \begin{pmatrix} * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \end{pmatrix}$$

Symmetries in the particle shape reduce the complexity of the matrix

Orthotropic particle (3 planes of symmetry)

$$\mathcal{H}(\mathrm{iso}) = \begin{pmatrix} * & 0 & 0 & 0 & 0 & 0 \\ 0 & * & 0 & 0 & 0 & 0 \\ 0 & 0 & * & 0 & 0 & 0 \\ 0 & 0 & 0 & * & 0 & 0 \\ 0 & 0 & 0 & 0 & * & 0 \\ 0 & 0 & 0 & 0 & 0 & * \end{pmatrix}$$

One plane of symmetry (x-y plane)

$$\mathcal{H} = \begin{pmatrix} * & * & 0 & 0 & 0 & * \\ * & * & 0 & 0 & 0 & * \\ 0 & 0 & * & * & * & 0 \\ 0 & 0 & * & * & * & 0 \\ 0 & 0 & * & * & * & 0 \\ * & * & 0 & 0 & 0 & * \end{pmatrix}$$

Rotational symmetry about x axis

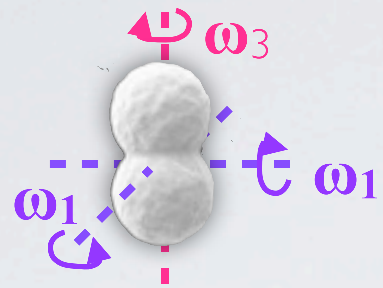
$$\mathcal{H} = \begin{pmatrix} \mathcal{H}_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \mathcal{H}_{22} & 0 & 0 & 0 & -\mathcal{H}_{53} \\ 0 & 0 & \mathcal{H}_{22} & 0 & \mathcal{H}_{53} & 0 \\ 0 & 0 & 0 & \mathcal{H}_{44} & 0 & 0 \\ 0 & 0 & \mathcal{H}_{53} & 0 & \mathcal{H}_{55} & 0 \\ 0 & -\mathcal{H}_{53} & 0 & 0 & 0 & \mathcal{H}_{55} \end{pmatrix}$$

[1] Happel and Brenner, Low Reynolds Number Hydrodynamics, Prentice Hall

Dimers: Uniaxial particles

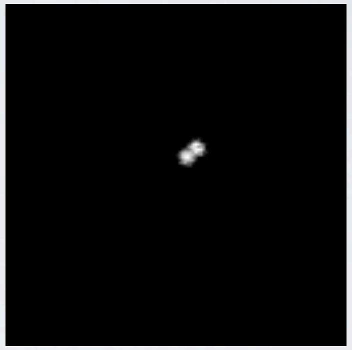
Symmetries

- Rotational symmetry and discrete rotational symmetry
- Mirror symmetries for three perpendicular planes (orthotropic shape)

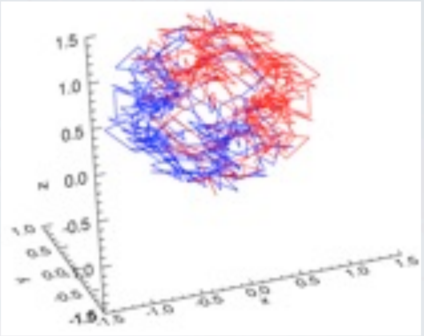


Experiments

Confocal data



10x real speed



$$\mathcal{H}^{exp}(\text{dimer}) = \begin{pmatrix} 25.2 & 0.8 & -1.2 & -0.4 & -1.8 & - \\ 0.8 & 25.7 & 0.7 & -5.6 & -1.1 & - \\ -1.2 & 0.7 & 19.7 & -1.5 & -0.2 & - \\ -0.4 & -5.6 & -1.5 & 128.8 & 1.7 & - \\ -1.8 & -1.1 & -0.2 & 1.7 & 114.5 & - \\ - & - & - & - & - & - \end{pmatrix}$$

$D_{t,\perp} = 0.073 \mu\text{m}^2/s$

$D_{t,\parallel} = 0.093 \mu\text{m}^2/s$

$D_{t,\parallel}/D_{t,\perp} = 1.28$

$D_r = 0.016\ \text{rad}^2/s$

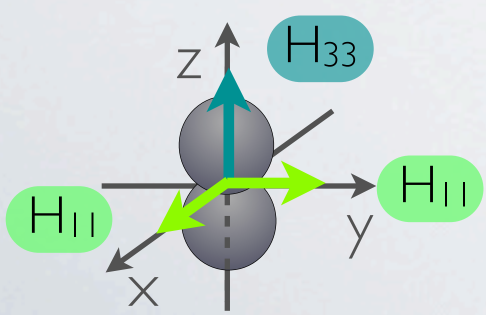
Hydrodynamic friction matrix

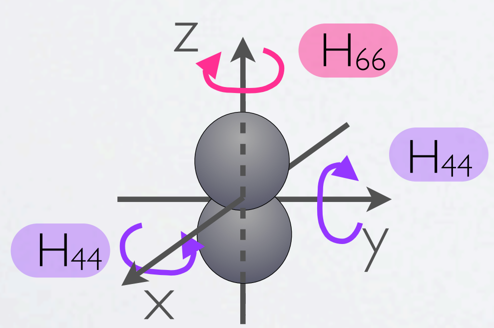
$$\mathcal{H} = \begin{pmatrix} \mathcal{H}_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \mathcal{H}_{11} & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathcal{H}_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathcal{H}_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathcal{H}_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathcal{H}_{66} \end{pmatrix}$$

no coupling

Translation

Rotation





Numerical calculation (Hydrosub code)

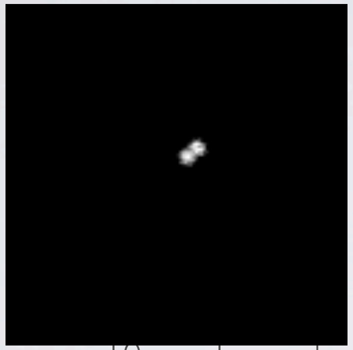
$$\mathcal{H}^{th}(dimer) = \begin{pmatrix} 28.7 & 0 & 0 & 0 & 0 & 0 \\ 0 & 28.7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 26.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 100.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 100.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 62.7 \end{pmatrix}$$

Shape symmetries are well represented in the hydrodynamic friction matrix!

de la Torre and Carasco, Biopolymers 63, 163 (2002)

UNIAXIAL PARTICLES - DIMERS WITH LONGER BOND LENGTH

Particles **Experiments**



10x real speed

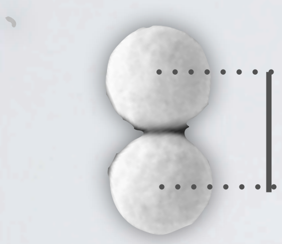
$$\mathcal{H}^{exp}(\text{dimer}) = \begin{pmatrix} 25.2 & 0.8 & -1.2 & -0.4 & -1.8 & - \\ 0.8 & 25.7 & 0.7 & -5.6 & -1.1 & - \\ -1.2 & 0.7 & 19.7 & -1.5 & -0.2 & - \\ -0.4 & -5.6 & -1.5 & 128.8 & 1.7 & - \\ -1.8 & -1.1 & -0.2 & 1.7 & 114.5 & - \\ - & - & - & - & - & - \end{pmatrix}$$

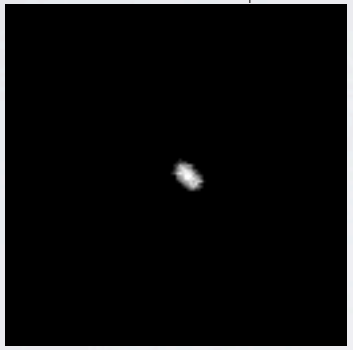
$D_{t,\parallel} = 0.073 \mu\text{m}^2/\text{s}$

$D_{t,\perp} = 0.093 \mu\text{m}^2/\text{s}$

$D_{t,\parallel}/D_{t,\perp} = 1.28$

$D_r = 0.016 \text{ rad}^2/s$





$$\mathcal{H}^{exp}(\text{dimer,2}) = \begin{pmatrix} 25.4 & 0.5 & -0.7 & -1.4 & -1. & - \\ 0.5 & 26.1 & 0.1 & 0. & 1. & - \\ -0.7 & 0.1 & 22.3 & 0.6 & 3.8 & - \\ -1.4 & 0. & 0.6 & 180.3 & -1.5 & - \\ -1. & 1. & 3.8 & -1.5 & 186. & - \\ - & - & - & - & - & - \end{pmatrix}$$

$D_{t,\parallel} = 0.071 \mu\text{m}^2/\text{s}$

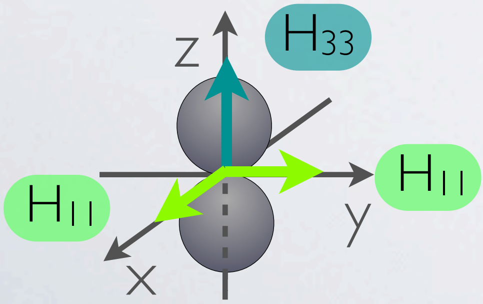
$D_{t,\perp} = 0.082 \mu\text{m}^2/\text{s}$

$D_{t,\parallel}/D_{t,\perp} = 1.15$

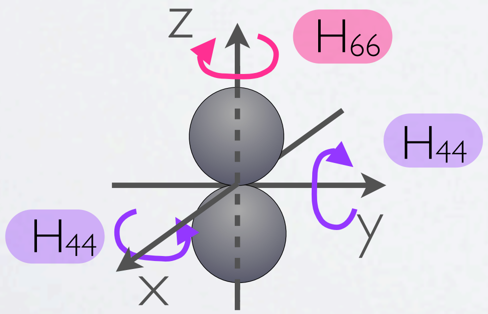
$D_r = 0.010 \text{ rad}^2/s$

Larger aspect ratio yields slower rotational diffusion constant

Translation



Rotation



BIAXIAL PARTICLES

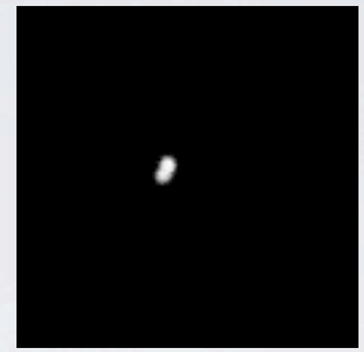
Symmetries

- Discrete rotational symmetries

- Mirror symmetries for two perpendicular planes

Experiments

Confocal data



10x real speed

$$\mathcal{H}^{exp}(\text{trimer}) = \begin{pmatrix} 27.2 & -0.1 & 0. & 6. & 0. & 0. \\ -0.1 & 27.6 & 0. & -0.6 & -2.7 & 0. \\ 0. & 0. & 27. & 0. & 0. & -2.6 \\ 6. & -0.6 & 0. & 82.8 & 0.5 & 0. \\ 0. & -2.7 & 0. & 0.5 & 76.7 & 0. \\ 0. & 0. & -2.6 & 0. & 0. & 75.4 \end{pmatrix}$$

$$D_{t,y} = 0.0685 \mu\text{m}^2/\text{s} \qquad D_{r,x,y} = 0.023\ \text{rad}^2/\text{s}$$

$$D_{t,y} = 0.0665 \mu\text{m}^2/\text{s} \qquad D_{r,z} = 0.024\ \text{rad}^2/\text{s}$$

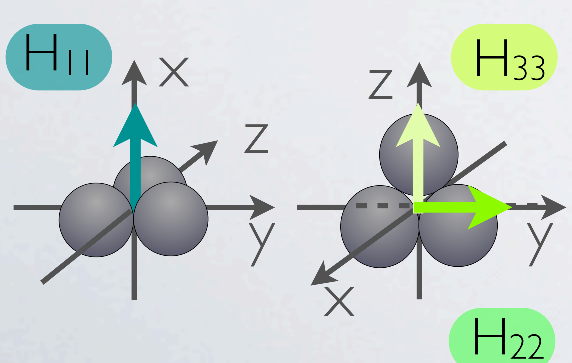
$$D_{t,z} = 0.068 \mu\text{m}^2/\text{s}$$

Hydrodynamic friction matrix

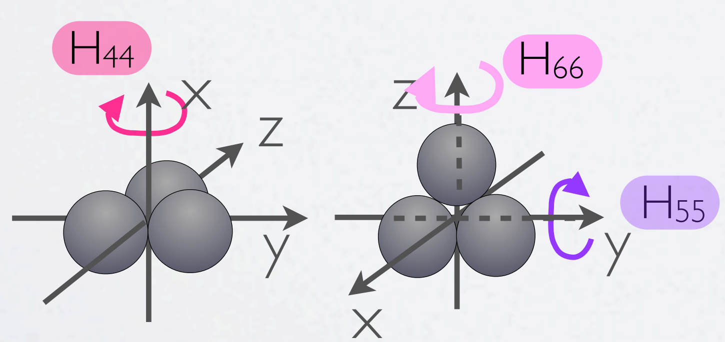
$$\mathcal{H} = \begin{pmatrix} \mathcal{H}_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \mathcal{H}_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathcal{H}_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathcal{H}_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathcal{H}_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathcal{H}_{66} \end{pmatrix}$$

no coupling

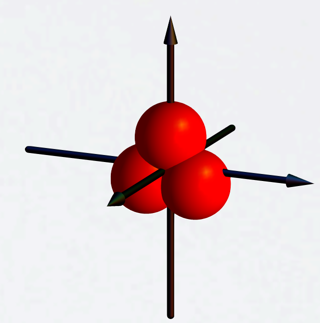
Translation



Rotation



Numerical calculations



$$\mathcal{H}(\text{trimer}) = \begin{pmatrix} 29.1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 27.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 27.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 100.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 79.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 79.7 \end{pmatrix}$$

Shape symmetries are well represented in the hydrodynamic friction matrix

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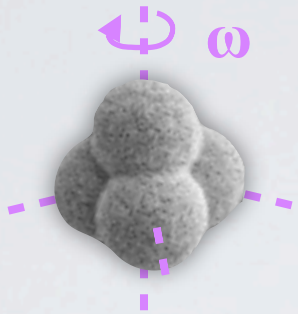
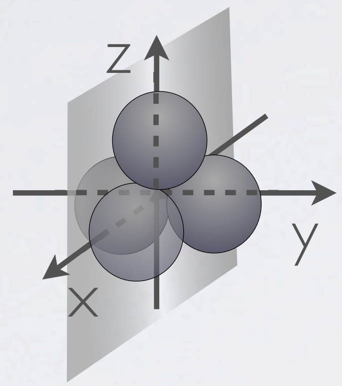
BIAXIAL PARTICLES WITH DISCRETE ROTATIONAL SYMMETRY

Symmetries

- Discrete, helicoidal rotational symmetries ($\varphi \rightarrow \varphi + \Delta\varphi$, with $0 < \Delta\varphi < \pi$)

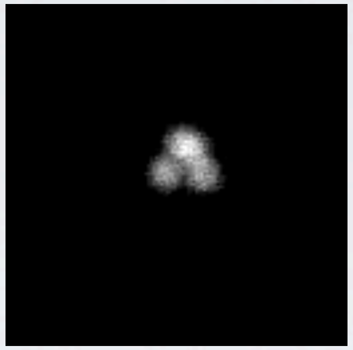


- Mirror symmetry



Experiments

Confocal data



10x real speed

$$\mathcal{H}^{exp}(\text{tetramer}) = \begin{pmatrix} 41.8 & 0 & 0 & -0.9 & -1.5 & 0 \\ 0 & 42.6 & 0 & 1.6 & -0.5 & 0 \\ 0 & 0 & 43.1 & 0 & 0 & -0.6 \\ -0.9 & 1.6 & 0 & 212.6 & 0 & 0 \\ -1.5 & -0.5 & 0 & 0 & 212.2 & 0 \\ 0 & 0 & -0.6 & 0 & 0 & 210.4 \end{pmatrix}$$

- Translational diffusion: $D_t = 0.043 \mu\text{m}^2/\text{s}$
- Rotational diffusion: $D_r = 8.7 \cdot 10^{-3} \text{rad}^2/\text{s}$

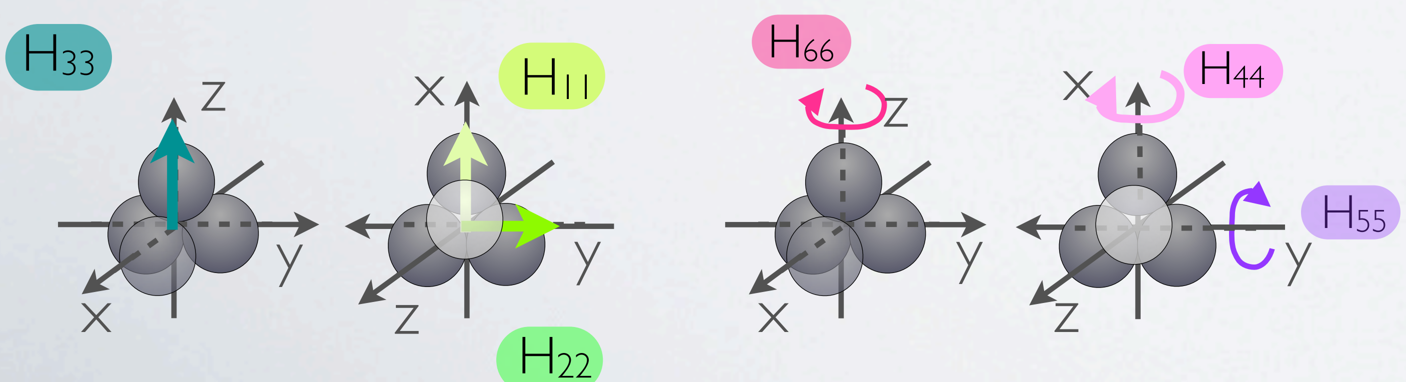
Hydrodynamic friction matrix

$$\mathcal{H} = \begin{pmatrix} \mathcal{H}_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \mathcal{H}_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathcal{H}_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathcal{H}_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathcal{H}_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathcal{H}_{66} \end{pmatrix}$$

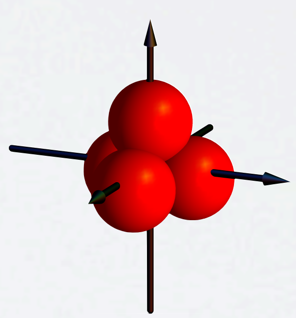
no coupling

Translation

Rotation



Numerical calculations



$$\mathcal{H} = \begin{pmatrix} 39.3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 39.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 39.4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 244.0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 244.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 244.4 \end{pmatrix}$$

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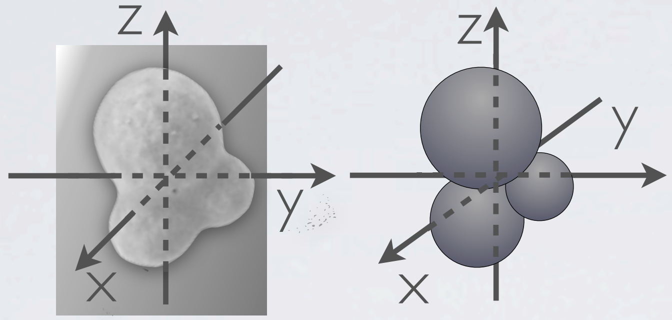
Asymmetric Particles

Symmetries

- No rotational symmetries
- Mirror symmetry only



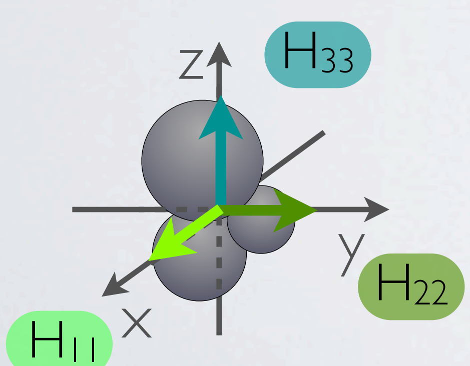
Hydrodynamic friction matrix

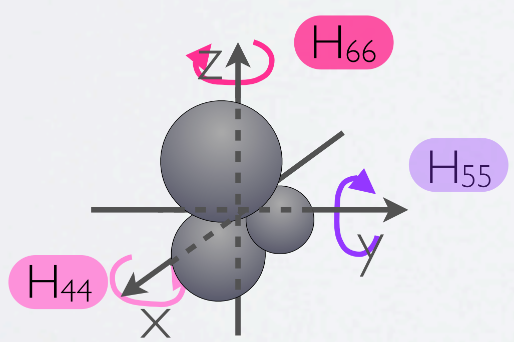
$$\mathcal{H} = \begin{pmatrix} \mathcal{H}_{11} & 0 & 0 & 0 & \mathcal{H}_{51} & \mathcal{H}_{61} \\ 0 & \mathcal{H}_{22} & \mathcal{H}_{32} & \mathcal{H}_{43} & 0 & 0 \\ 0 & \mathcal{H}_{32} & \mathcal{H}_{33} & 0 & 0 & 0 \\ 0 & \mathcal{H}_{42} & \mathcal{H}_{43} & \mathcal{H}_{44} & 0 & 0 \\ \mathcal{H}_{51} & 0 & 0 & 0 & \mathcal{H}_{55} & \mathcal{H}_{65} \\ \mathcal{H}_{61} & 0 & 0 & 0 & \mathcal{H}_{65} & \mathcal{H}_{66} \end{pmatrix}$$

coupling

Translation

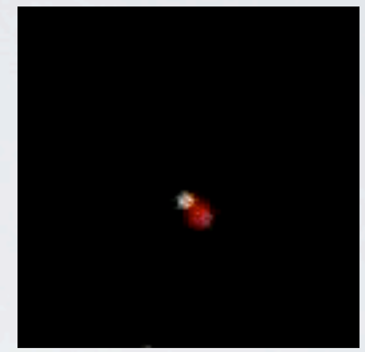
Rotation





Experiments

Confocal data



5x real speed

$$\mathcal{H}^{exp}(\text{irreg.}) = \begin{pmatrix} 27.2 & 3.9 & 0.7 & 6.0 & -7.2 & -6.1 \\ 3.9 & 29.2 & -2.4 & 9.9 & 0.8 & -9.7 \\ 0.7 & -2.4 & 21.7 & -4.1 & 4.0 & 0.6 \\ 6.0 & 9.9 & -4.1 & 137.0 & -4.8 & 8.9 \\ -7.2 & 0.8 & 4.0 & -4.8 & 102.4 & 19.5 \\ -6.1 & -9.7 & 0.6 & 8.9 & 19.5 & 61.2 \end{pmatrix}$$

Numerical calculations

$$\mathcal{H} = \begin{pmatrix} 27.9 & 0 & 0 & 0 & -12.6 & -7.2 \\ 0 & 26.1 & 0.3 & 11.0 & 0 & 0 \\ 0 & 0.3 & 24.8 & 6.0 & 0 & 0 \\ 0 & 11.0 & 6.0 & 104.4 & 0 & 0 \\ -12.6 & 0 & 0 & 0 & 90.2 & 11.2 \\ -7.2 & 0 & 0 & 0 & 11.2 & 58.9 \end{pmatrix}$$

- Coupling between translation and rotation
- Coupling between rotational diffusion directions
- Particle shape is reflected in the hydrodynamic friction matrix

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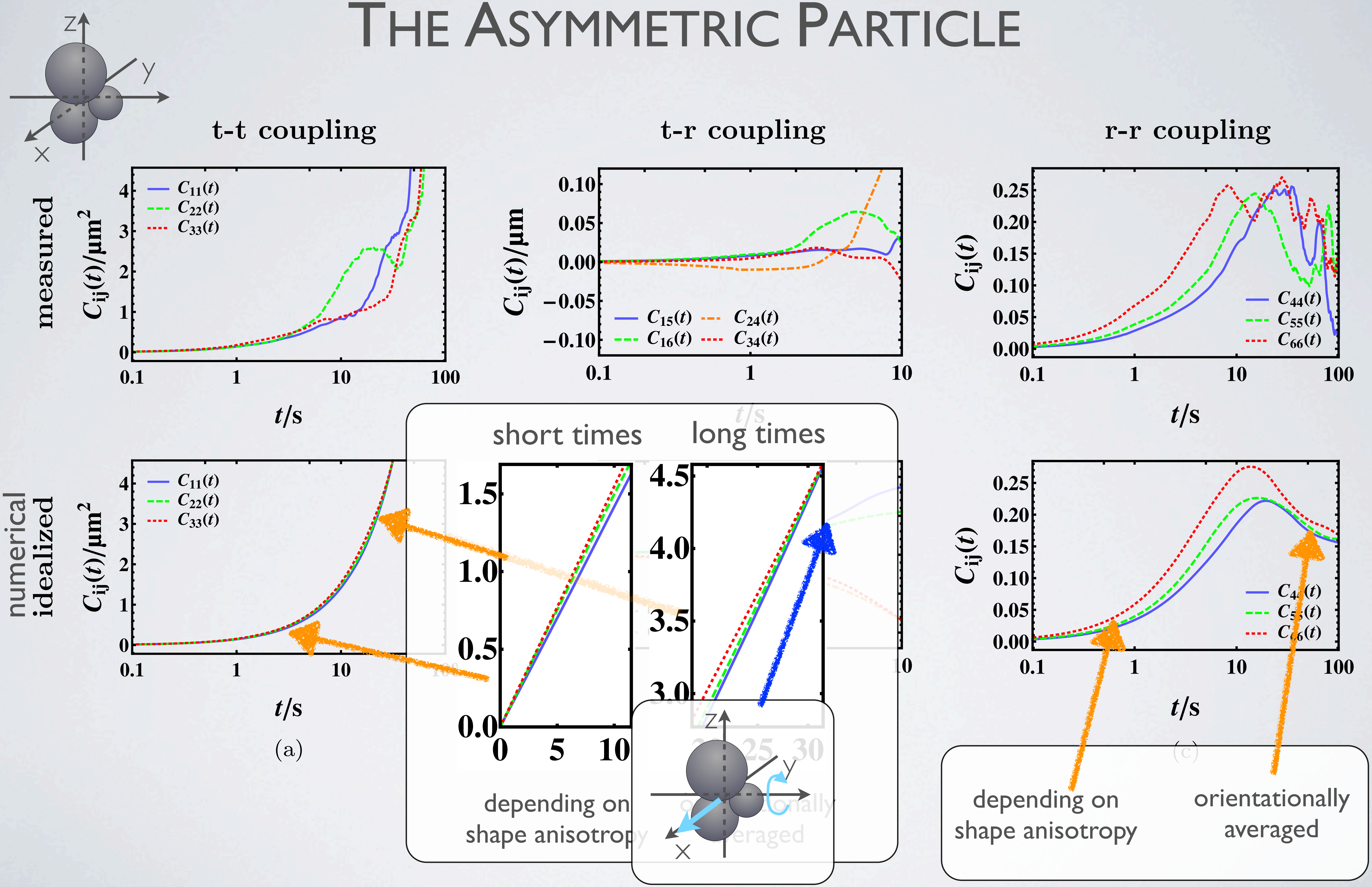
Time Evolution of Correlation Functions of The Asymmetric Particle



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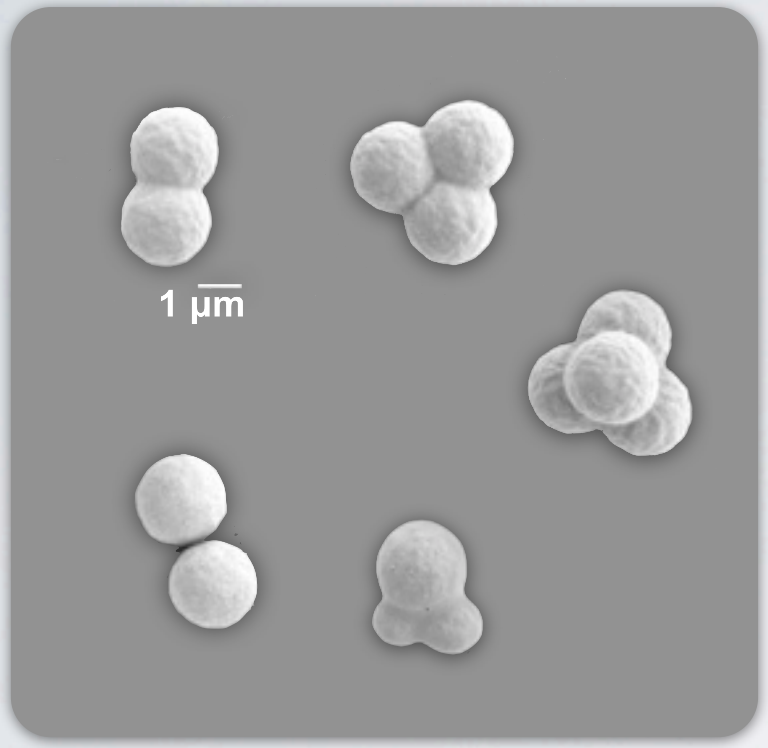
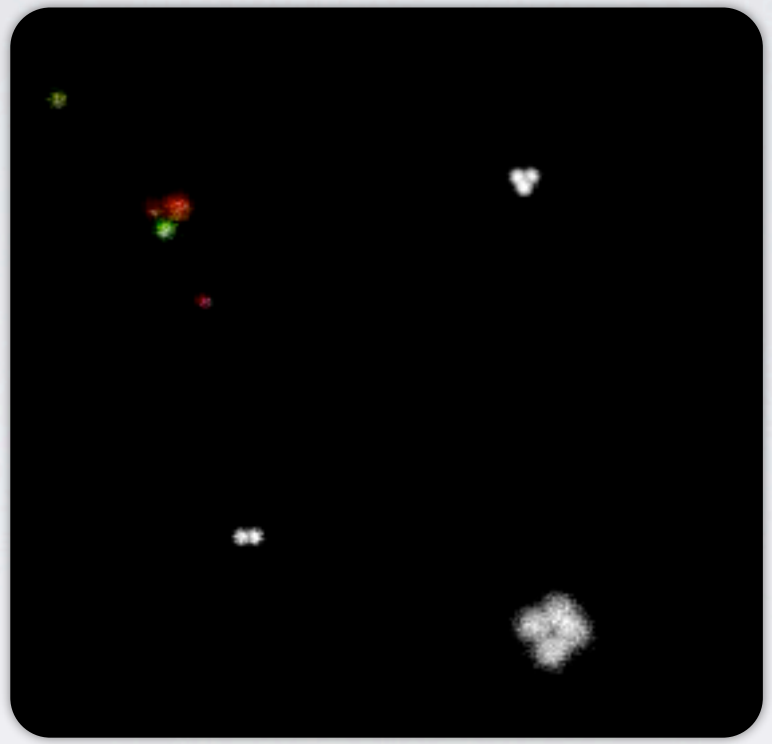
Experimental Determination of the Hydrodynamic Friction Matrix

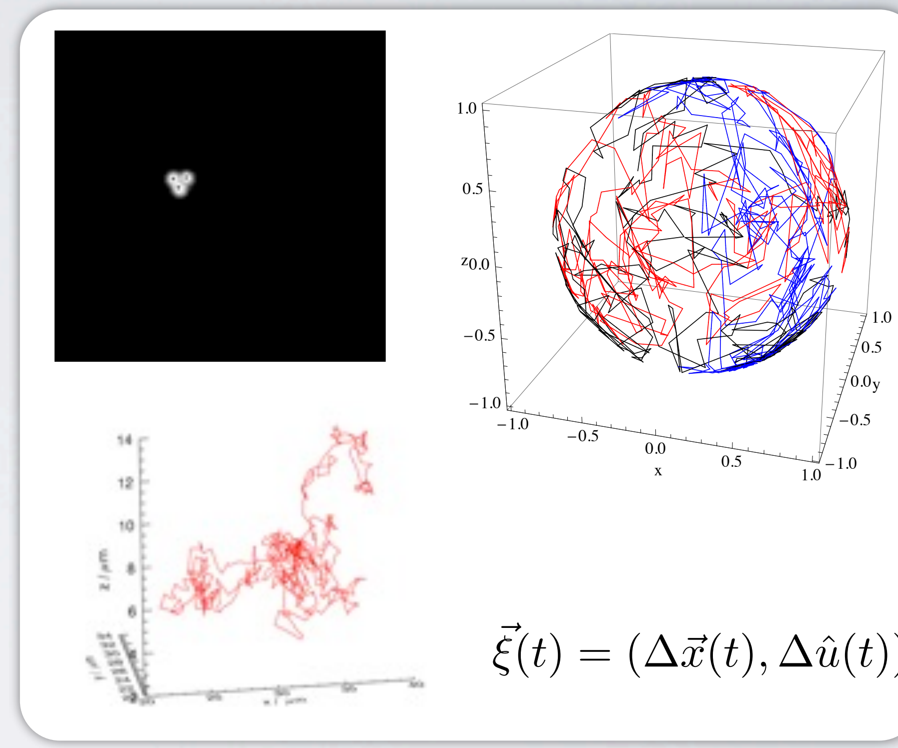
Colloids



Confocal microscopy



Particle tracking



Hydrodynamic friction matrix

Translation

Coupling trans. & rotation

$$\mathcal{H} = \begin{pmatrix} * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \end{pmatrix}$$

Coupling trans. & rot.

Rotation

Depends only particle **shape and size**

✓ First* 3D measurement of the **full hydrodynamic friction matrix** and diffusion matrix of anisotropic particles with different symmetries

✓ **Particle symmetries** determine symmetries in hydrodynamic friction matrix

✓ Good **agreement** between experiments and numerical predictions

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THANK YOU ....

Leiden University

Vera Meester
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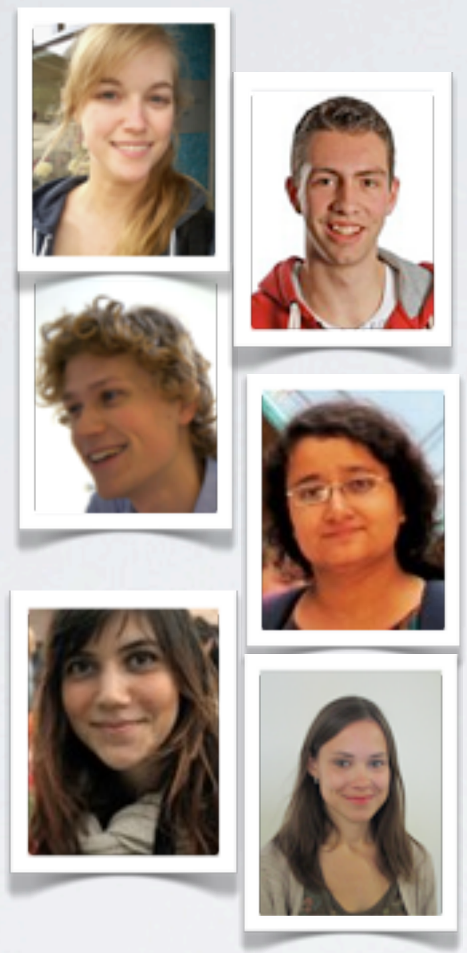
Sabine Matysik
Melissa Rinaldin



Simulations

University of Düsseldorf
Raphael Wittkowski
Borge ten Hage
Hartmut Löwen

Experiments

NYU

David Pine
Andrew Hollingsworth
Kazem Edmond

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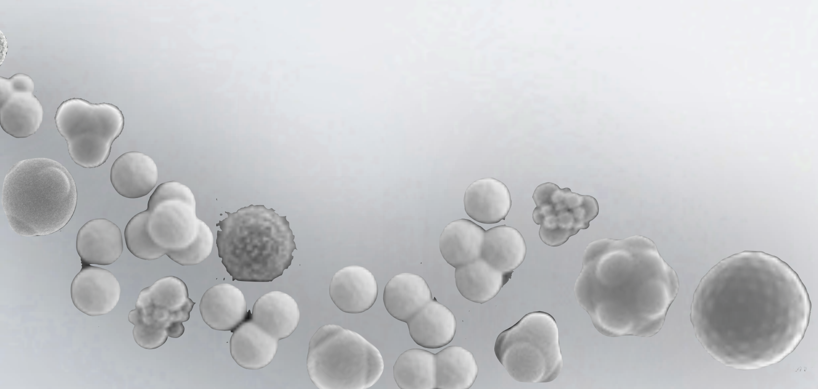
Rubicon fellowship
VENI grant
Sectorplan
Nanofront Gravity grants
DAAD Rise fellowship

NWO

Publications

Meester, Verweij, van der Wel, Kraft,
ACSNano (2016)
Kraft et al. PRE 88 (2013)



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